DARK MATTER AND STARS

Multi-Messenger Probes of Dark Matter and Modified Gravity

Center for Astrophysics and Gravitation (CENTRA)
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Dark Matter Models and production mechanisms

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$[q,p]=i\hbar$

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

MARIE CURIE ACTIONS

Outline

- Introduction:
  Theoretical guiding principles
- WIMP Dark Matter
- FIMP/SuperWIMP/Decaying Dark Matter
- Asymmetric DM
- (Axion Dark Matter)
- Outlook

Introduction

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.

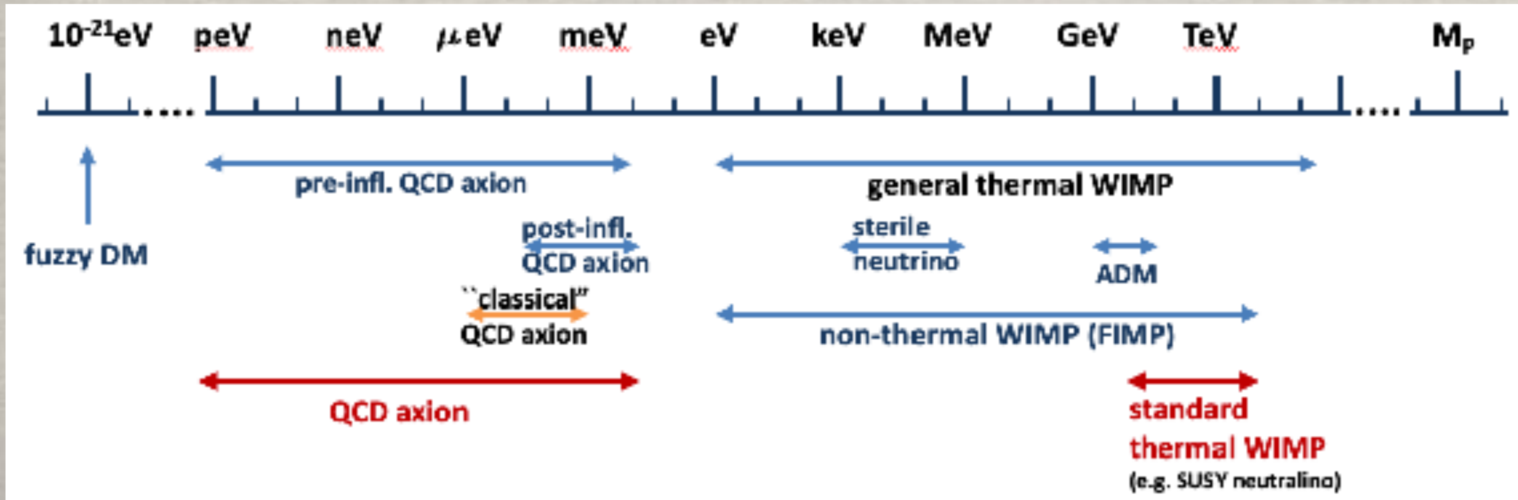
⬇

COLD DARK MATTER

But unfortunately too many realizations !

Guiding principles 4 DM

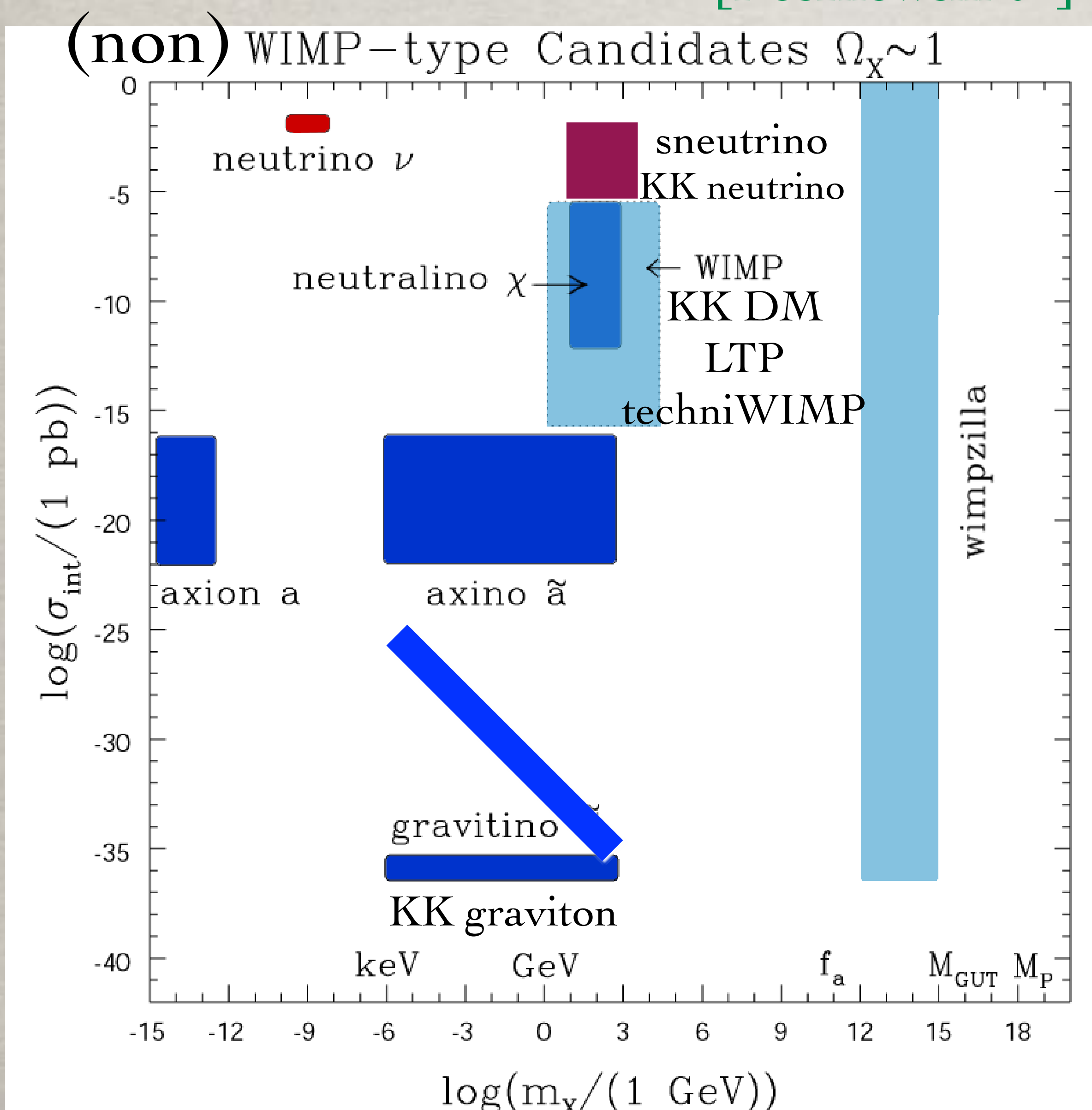
- The DM particle or the DM sector should fit into a BSM model solving more than the DM problem, e.g. hierarchy, neutrino masses, strong CP problem, etc…
- An effective DM production mechanism should be present, possibly independent from initial conditions.
- Possibly detectable Dark sector in the near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



DARK MATTER paradigms

DARK MATTER CANDIDATES

[Roszkowski 04]



Multidimensional space !

DM production paradigms:

WIMPs
(e.g. neutralino)

&

"FIMP/SuperWIMPs"
(e.g. axino/gravitino)

&

Misalignment
(e.g. axion/condensate)

WIMP
Dark Matter

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

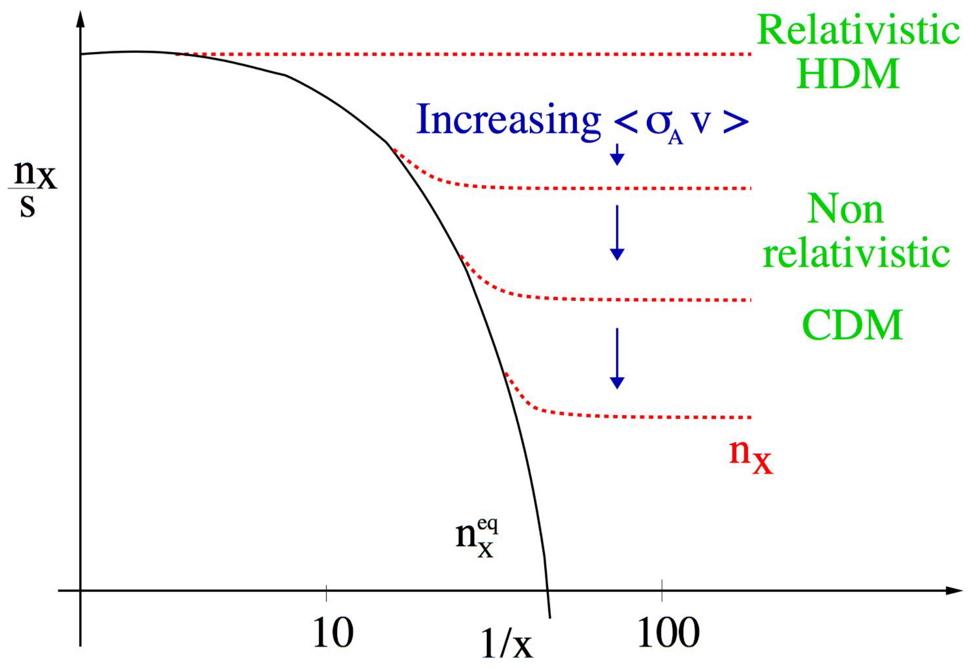
$$\Omega_X = m_X n_X(t_{now}) \quad \propto \quad \frac{1}{\langle\sigma_A v\rangle_{x_f}}$$

Abundance $\Leftrightarrow$ Particle properties

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

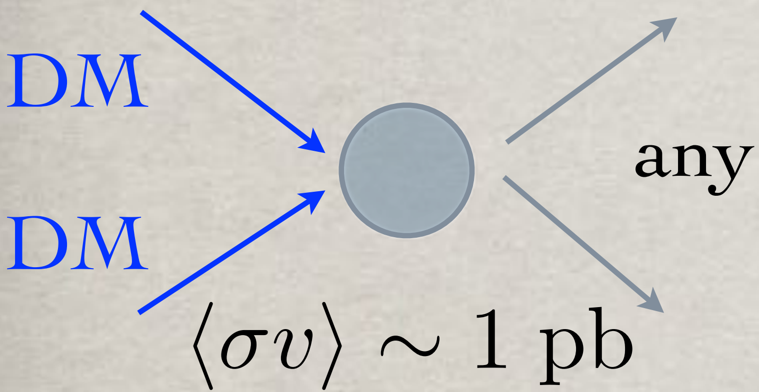
Weakly Interacting Massive Particle

For weaker interactions need lighter masses HOT DM !

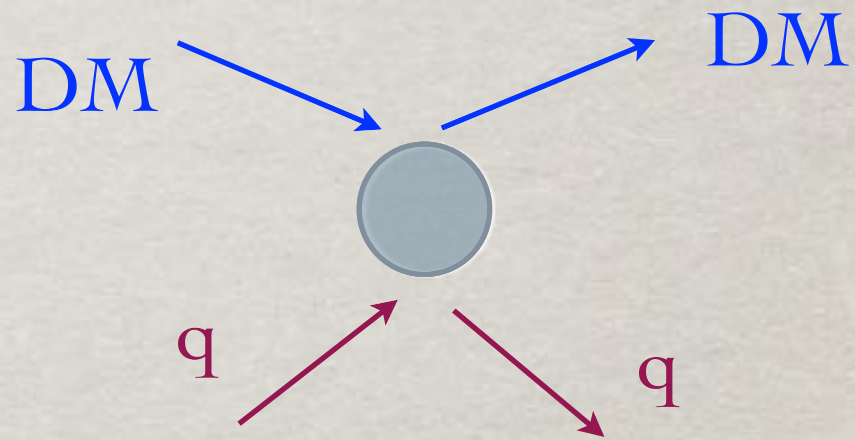


THE WIMP CONNECTION

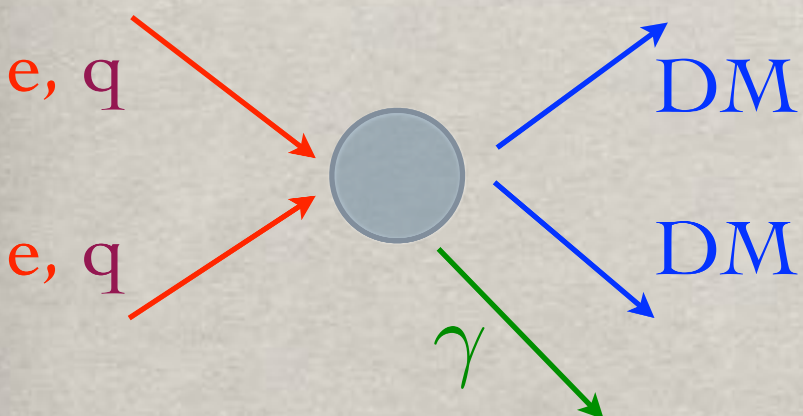
Early Universe: $\Omega_{CDM} h^2$



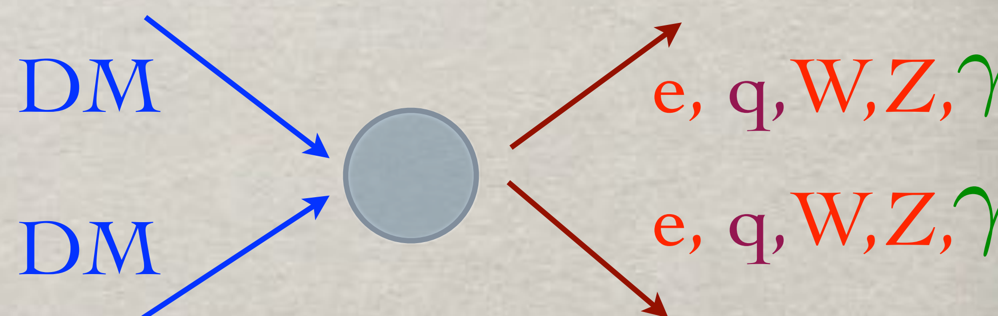
Direct Detection:



Colliders: LHC/ILC



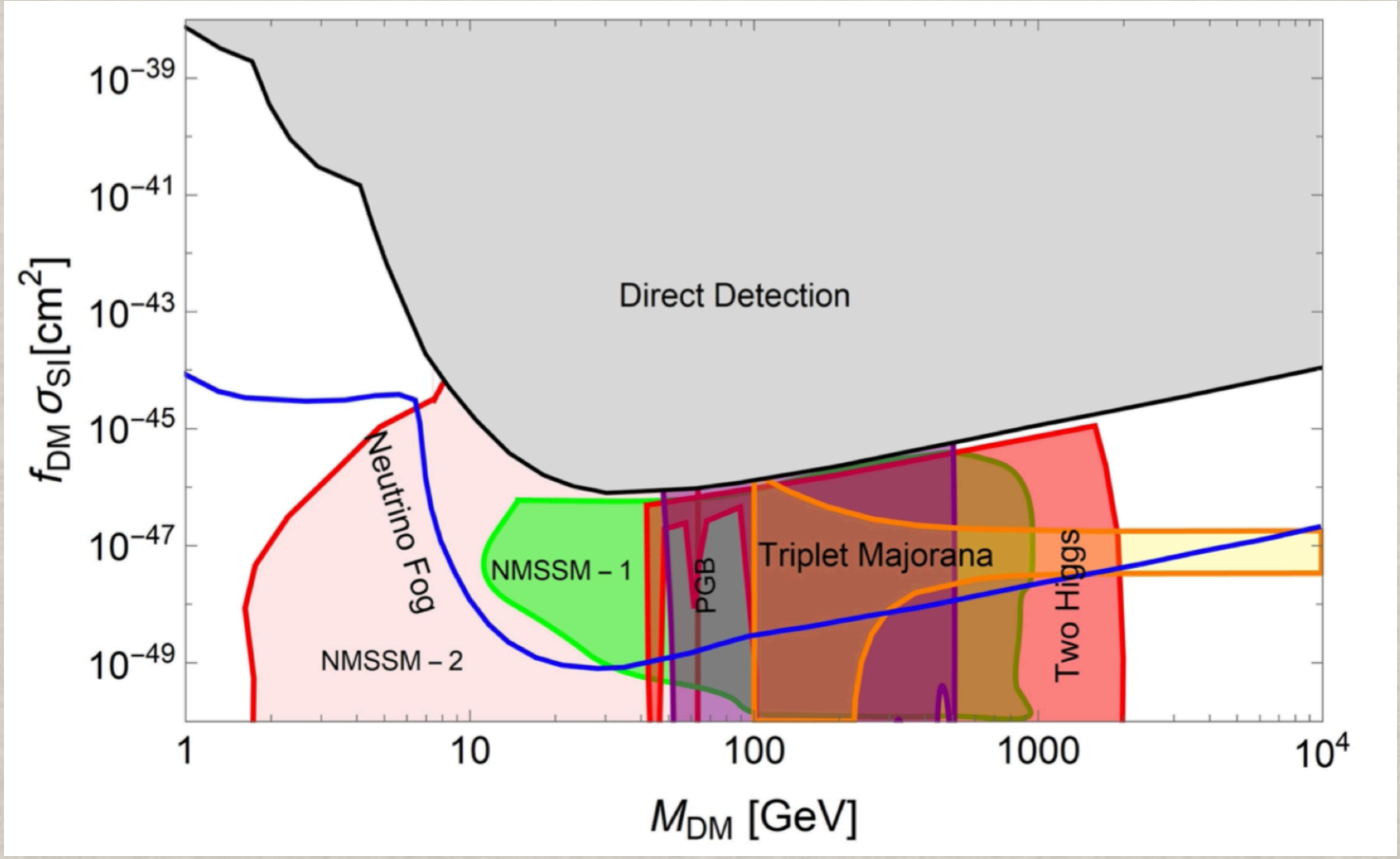
Indirect Detection:



3 different ways to check this hypothesis !!!

WIMP Models...
...not yet excluded !

[Snowmass 2021 Cosmic Frontier ArXiv:2203.08084]

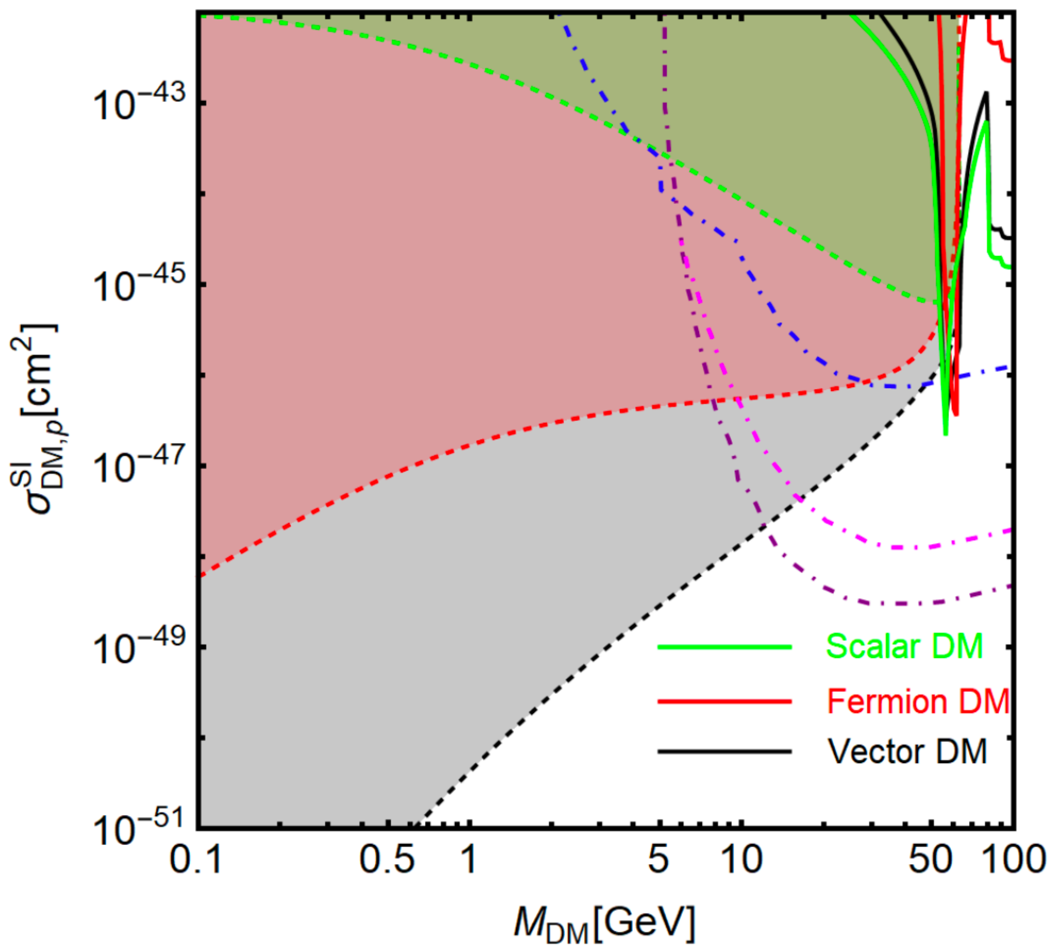


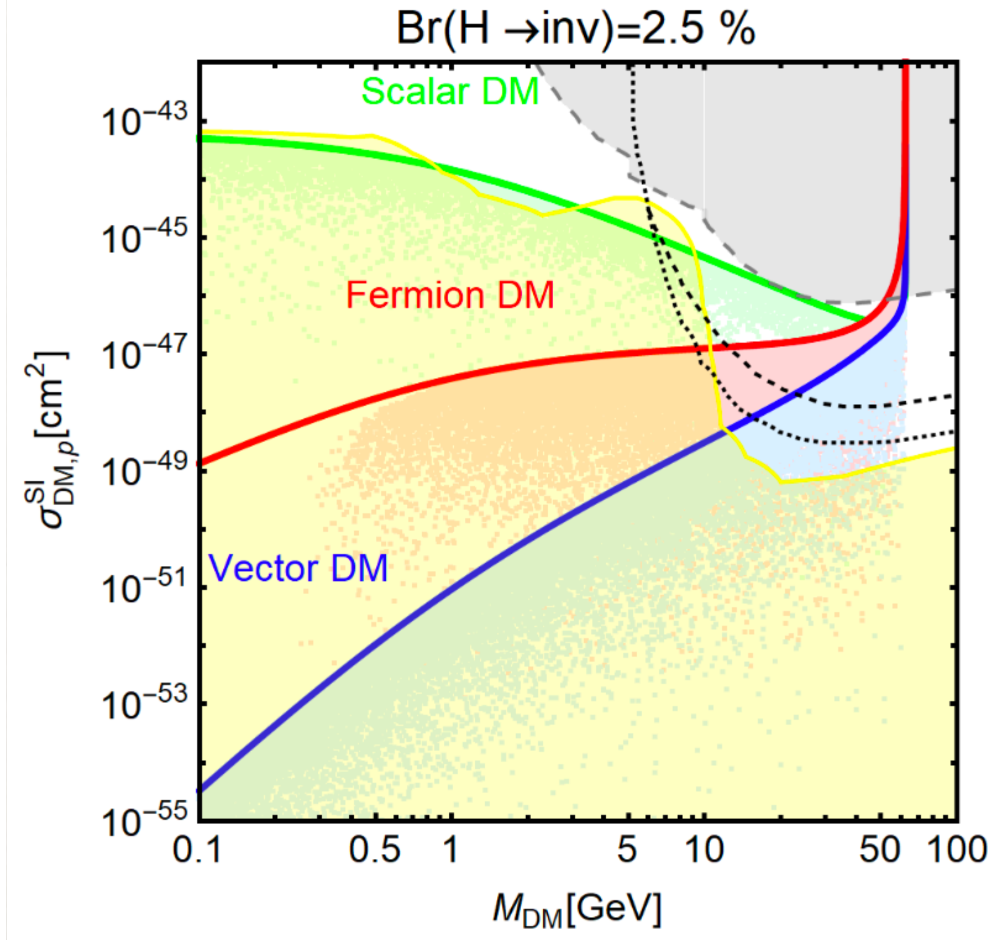
Disentangle production & DD via coannihilation, mixing, etc!

Higgs portal DM

Careful when using EFTs, sometime results change in the full model, e.g. simple example the Higgs portal !

[Arcadi, Djouadi & Kado 2101.02507]

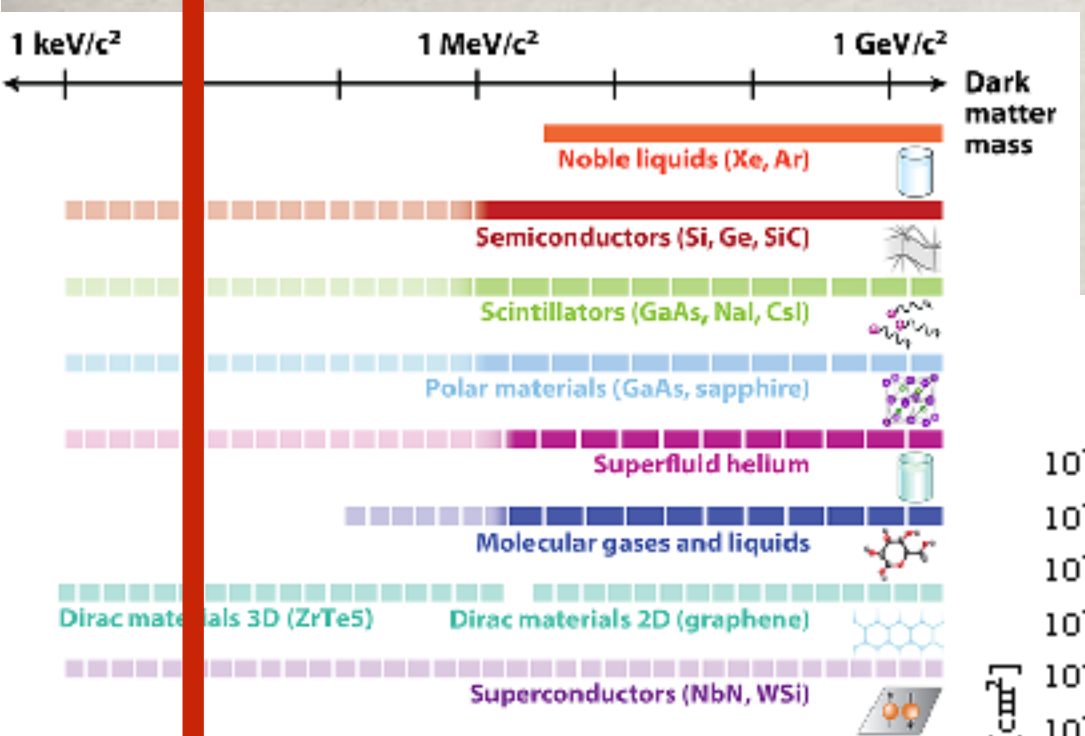




Interference effects can reduce the DD cross-sections !

Low mass WIMPs

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

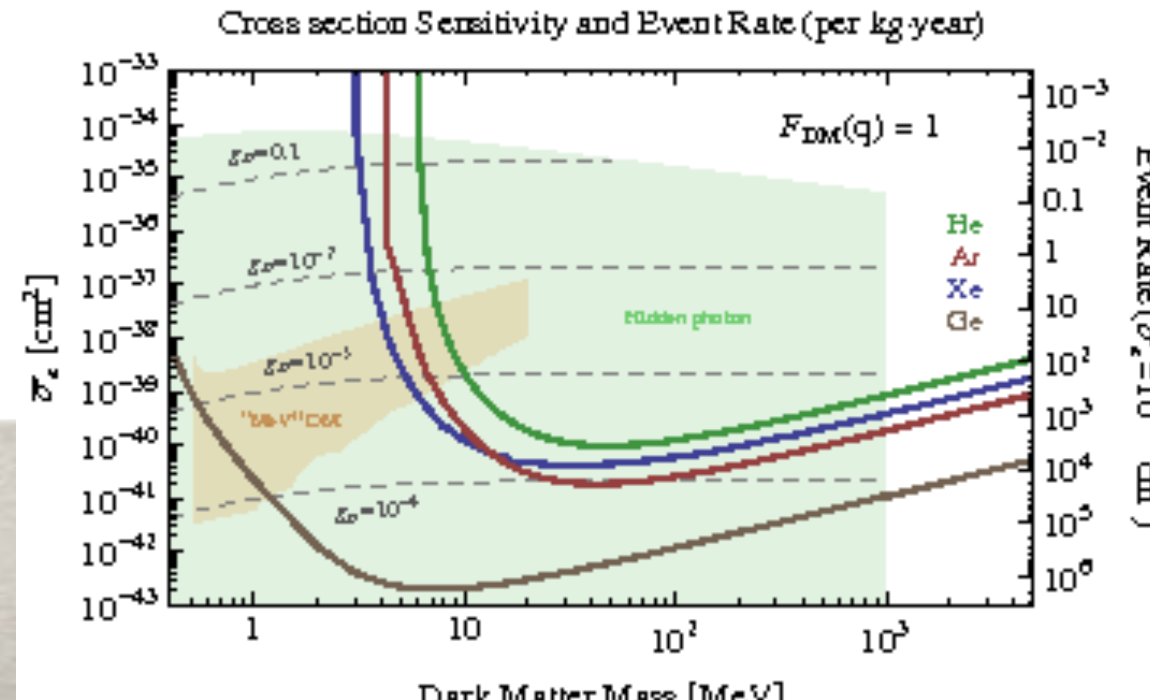


[R. Essig 2104.07634]

Warm DM

Cold Dark Matter

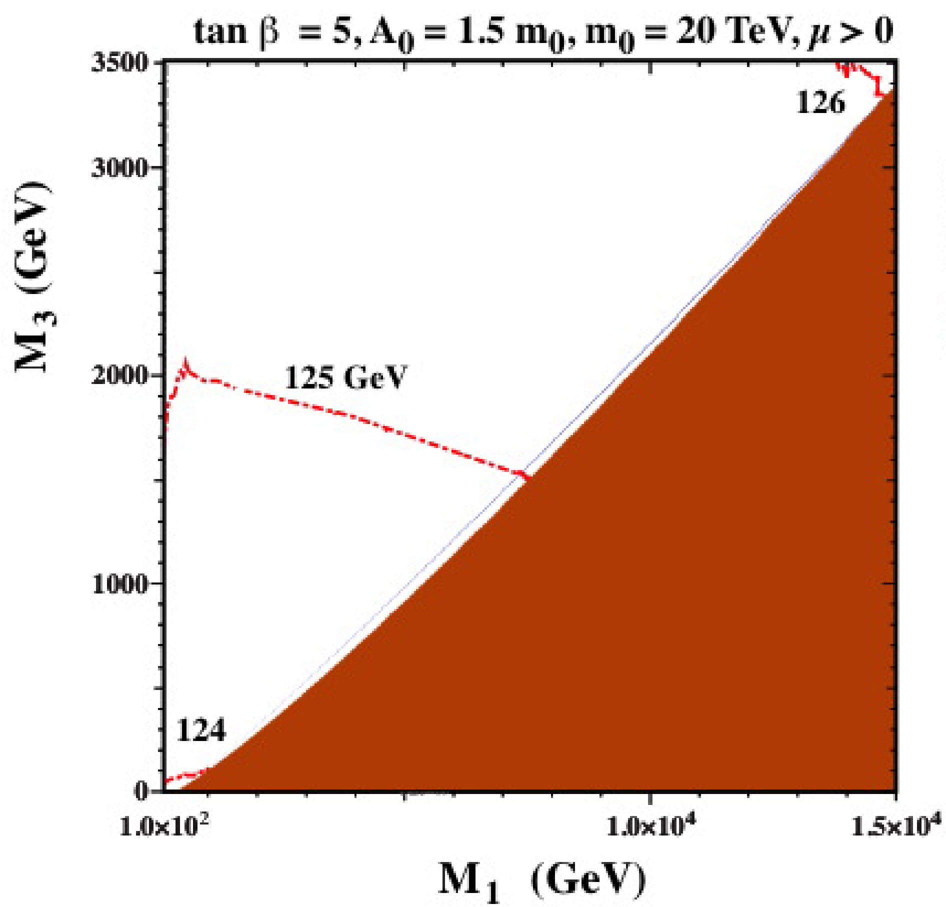
[Essig, Mardon & Volansky 1108.5383]



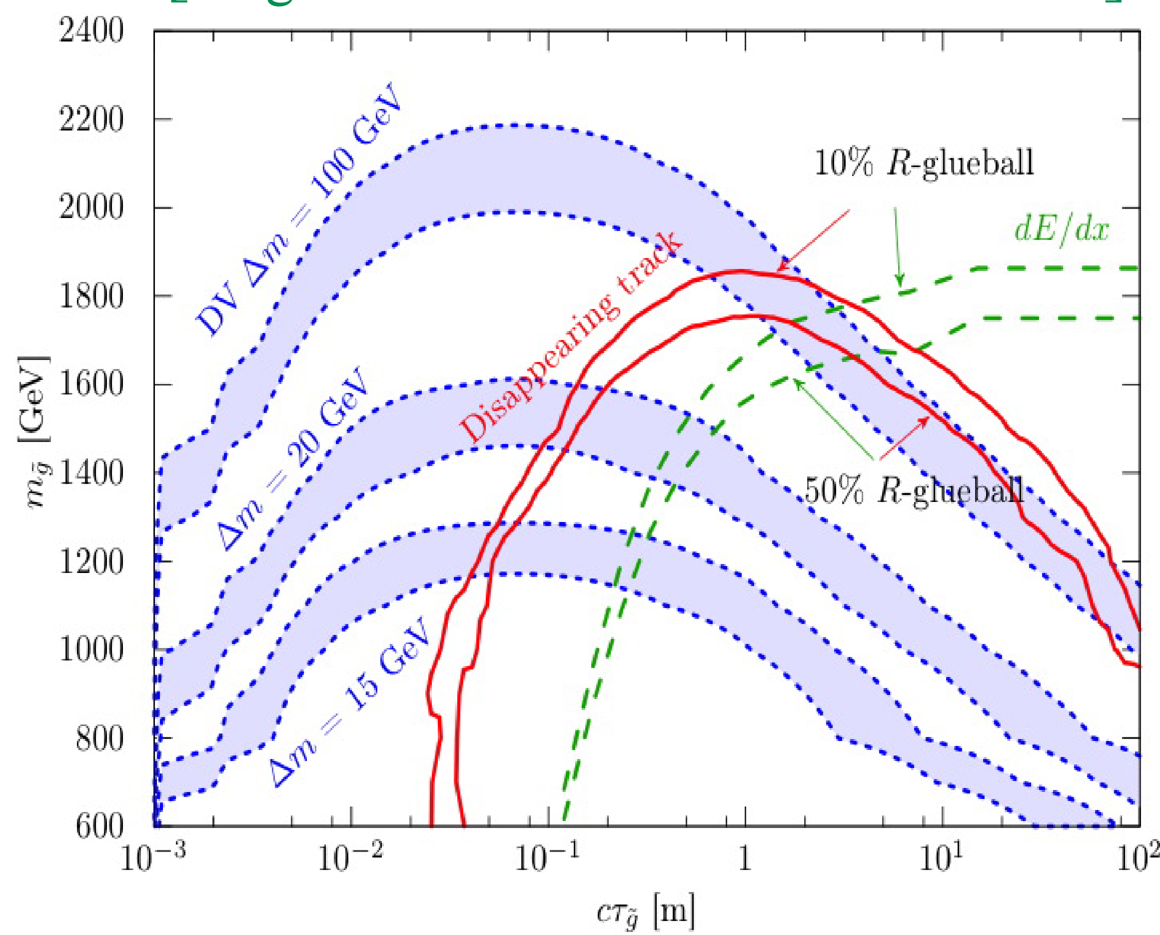
BINO-GLUINO COANNIHILATION

For non-universal gaugino masses also the gluino plays a role and extends the mass to the multiTeVs !

[Ellis, Evans, Luo & Olive 1510.03498]

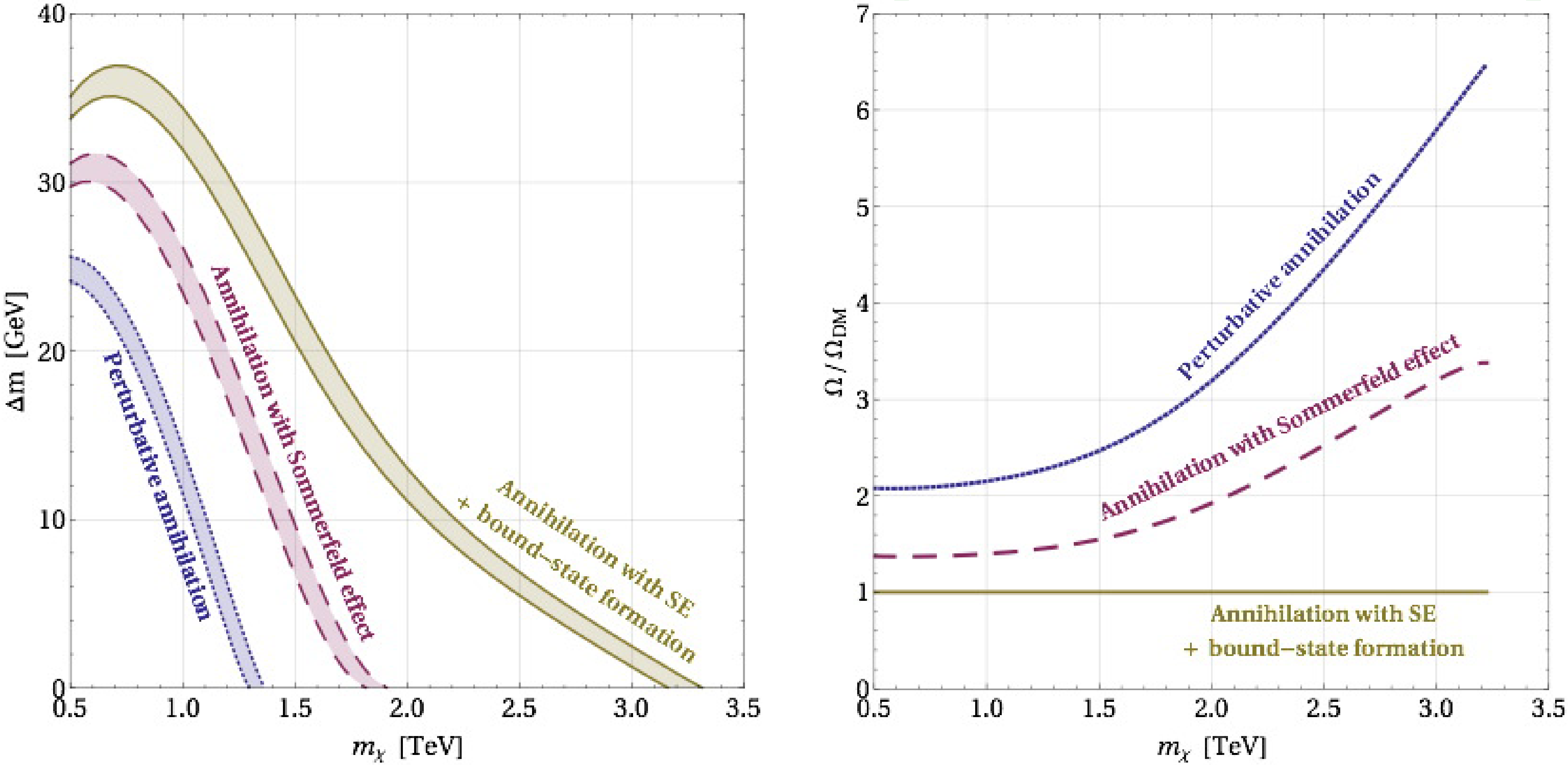


[Nagata, Otono & Shirai 1701.07664]



Sommerfeld Factor for coannihilation

[J. Harz & K. Petraki 2018]

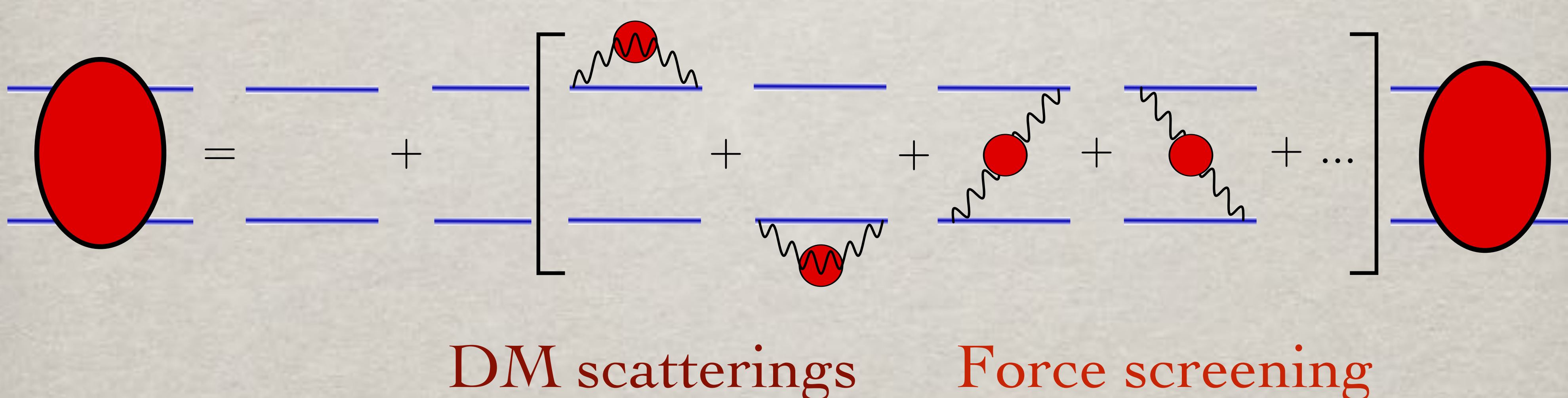


Coannihilation with a colored state:bound states are important !
The stronger annihilation makes higher masses preferred.

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:



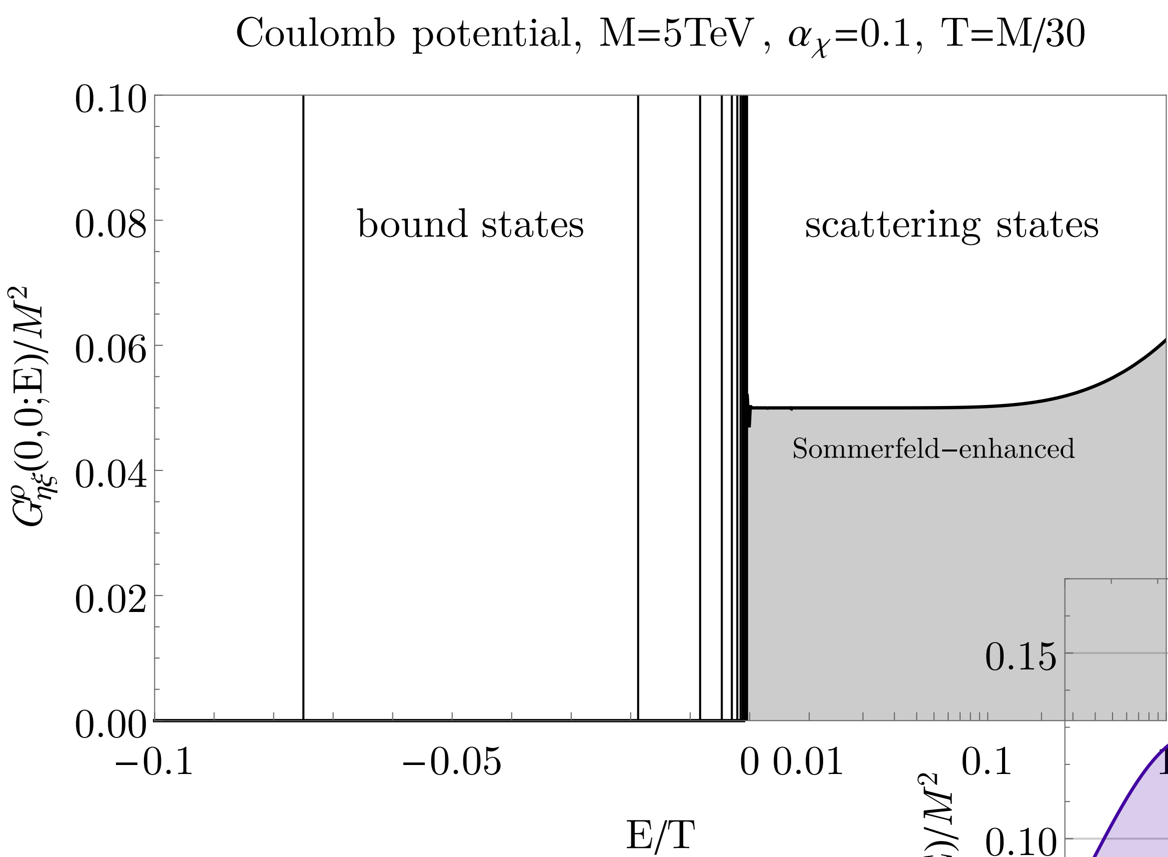
In the DM dilute limit, we obtain from this equation the modified Coulomb potential:

Yukawa-like ! Imaginary

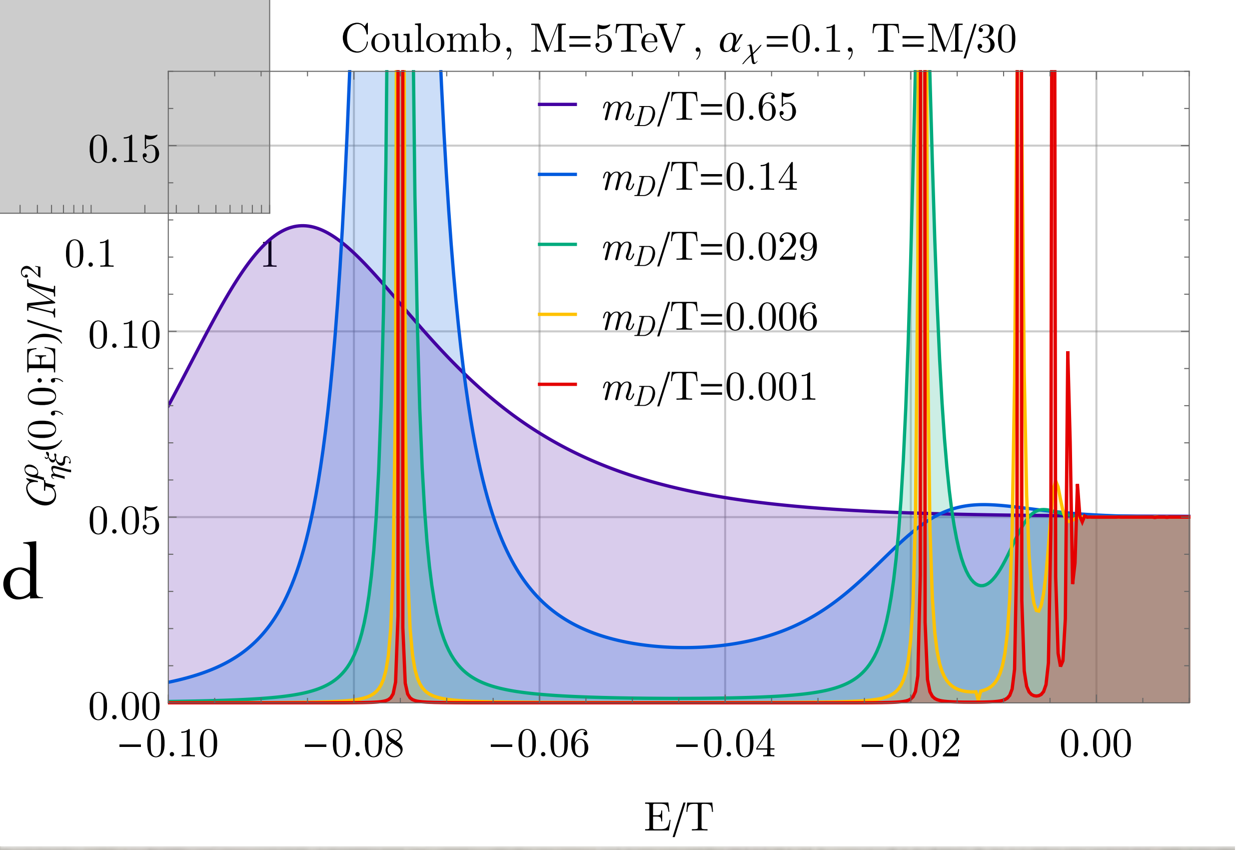
$$V_{eff}(\vec{r}) = -ig^2 \int_{-\infty}^{+\infty} d^3q(1-e^{i\vec{q}\vec{r}})G^{++}(0,\vec{q}) = -\frac{\alpha}{r}e^{-m_D r} - i\alpha T\Phi(m_D r) + \ldots$$

Temperature effects

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



Without thermal corrections we recover the known results.

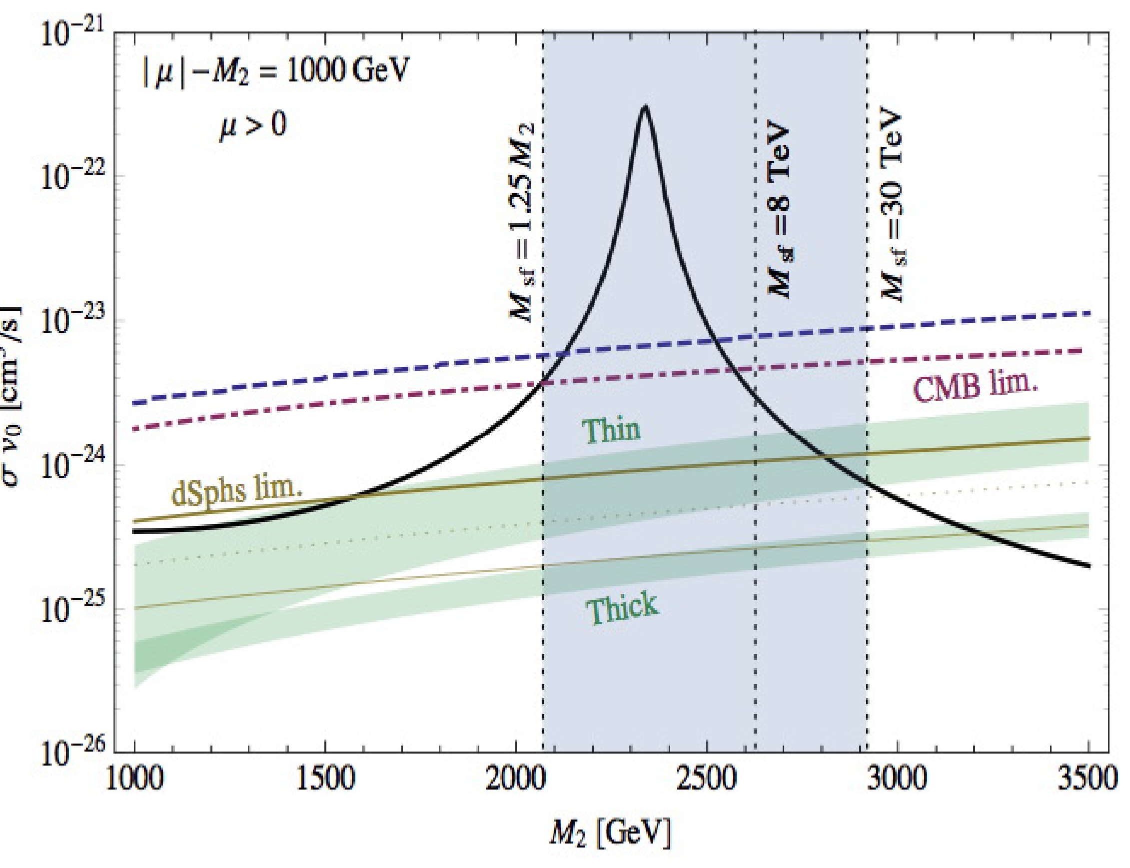


The presence of a plasma strongly modifies the bound states ! Even to the point of complete melting…

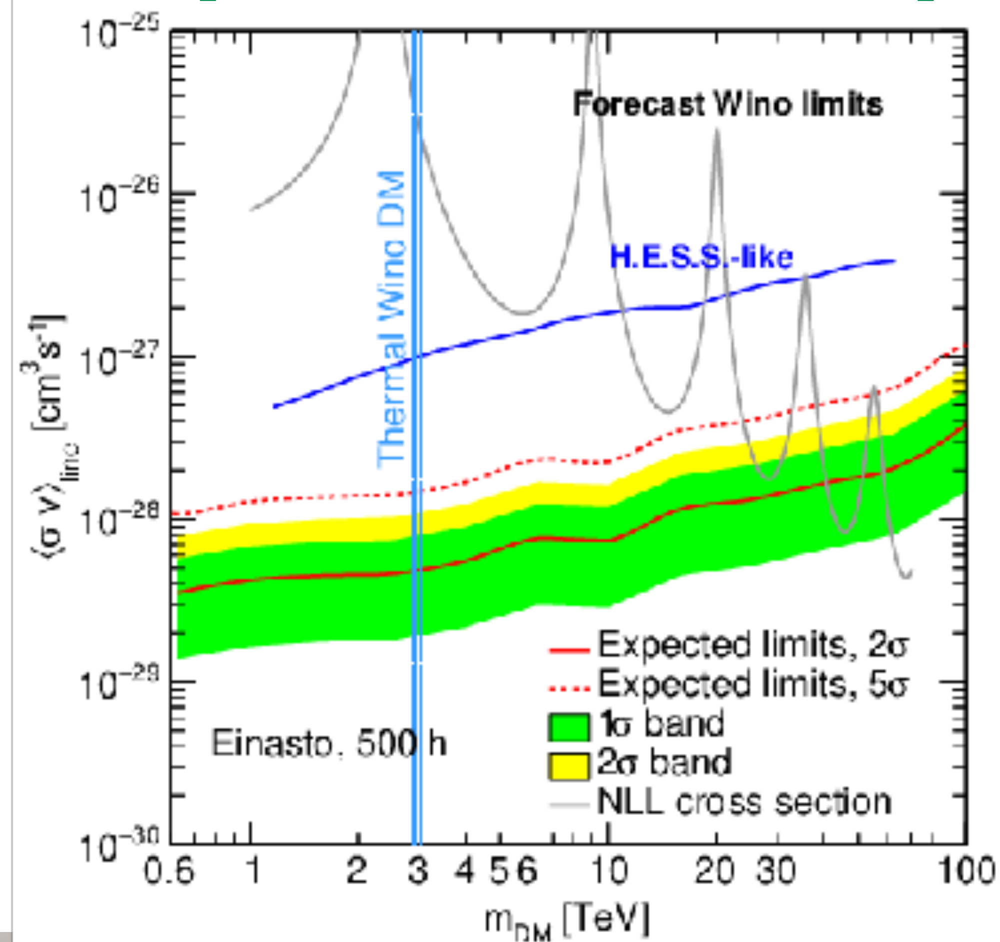
Wino Dark Matter

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]

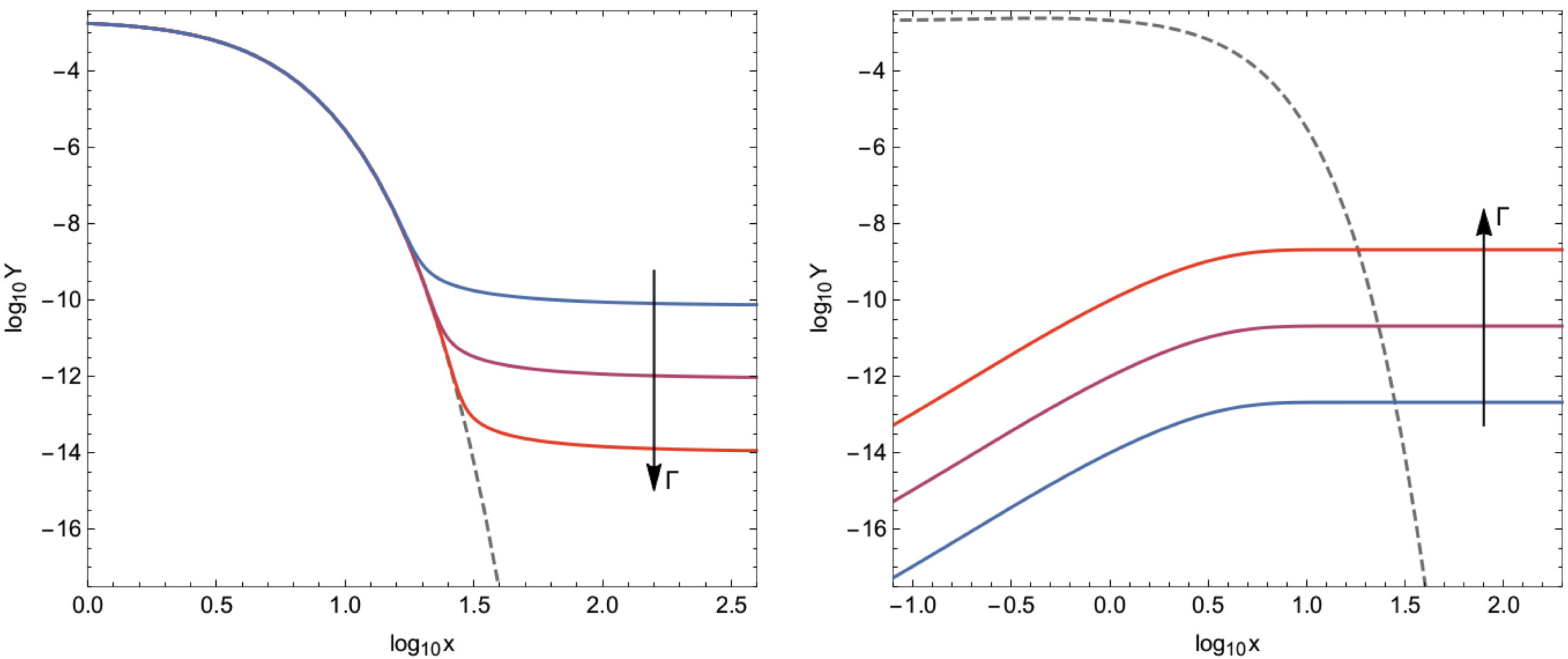


FIMP/SuperWIMP/ Decaying Dark Matter

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.

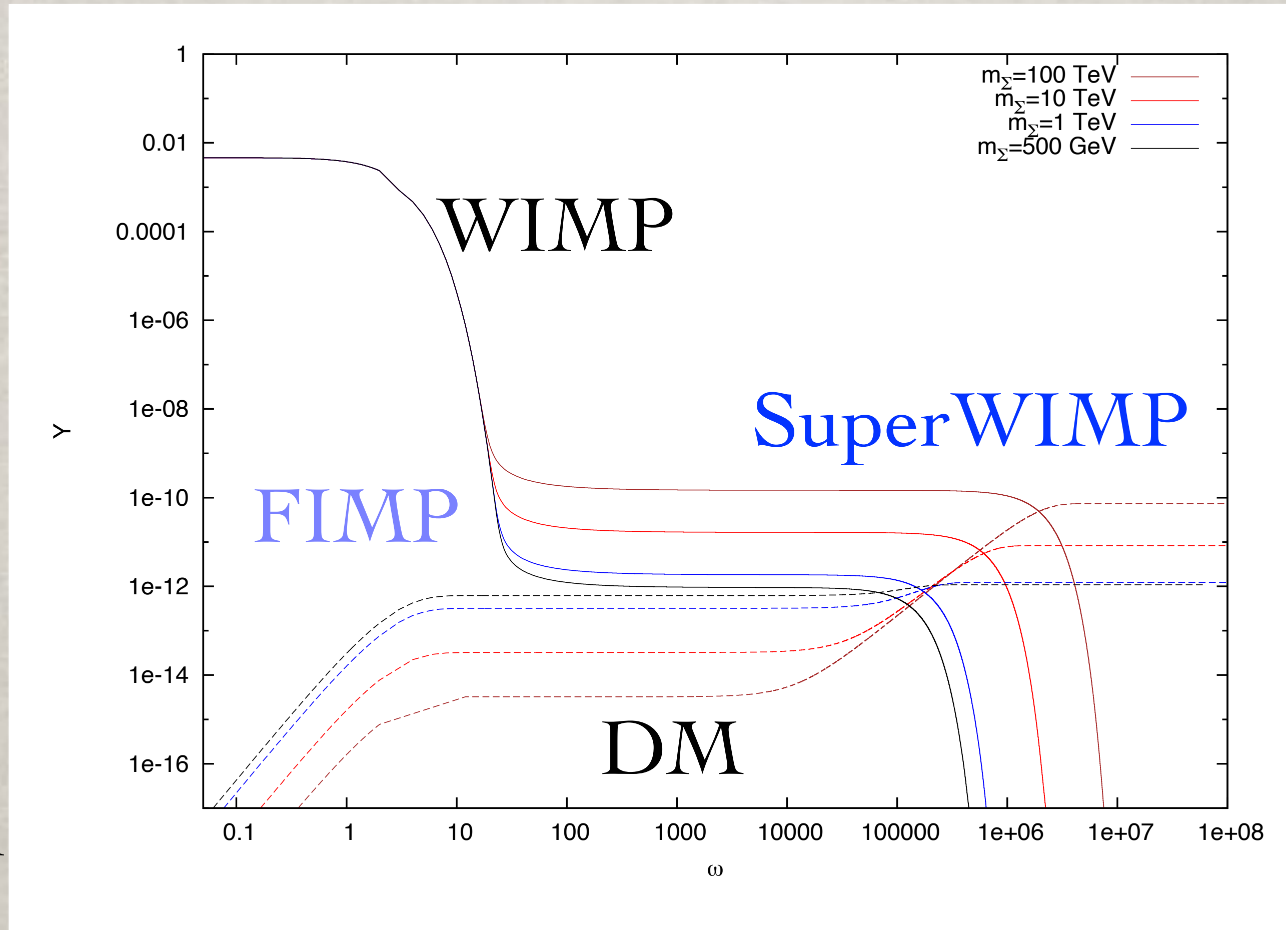
Same Boltzmann equation, but different dynamics !

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:

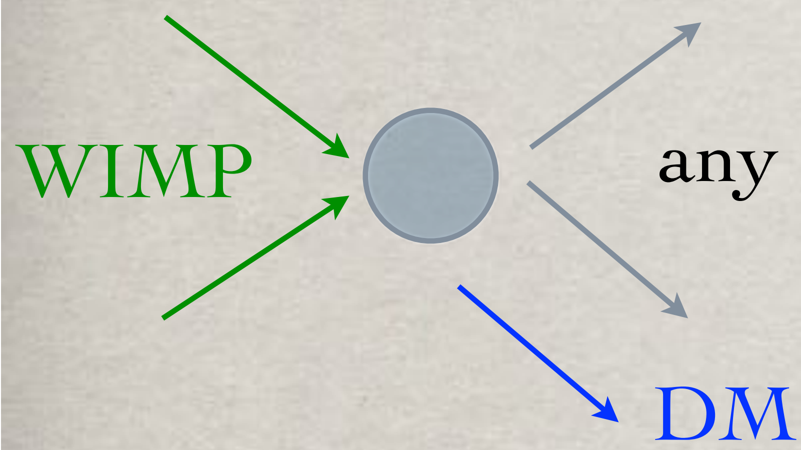
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} \, BR(\Sigma \to \psi) \, \Omega_\Sigma h^2$$

- 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

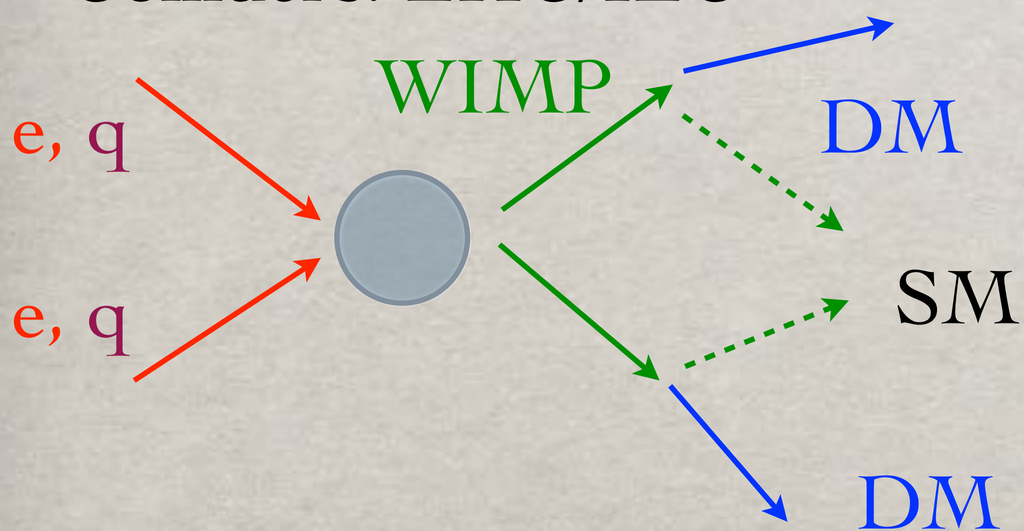
Early Universe: $\Omega_{CDM} h^2$



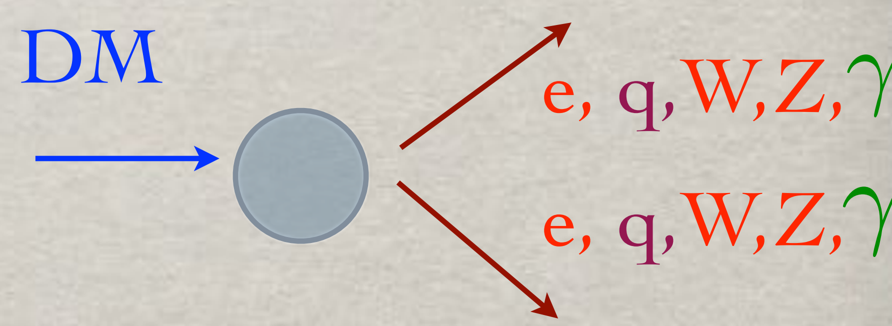
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:

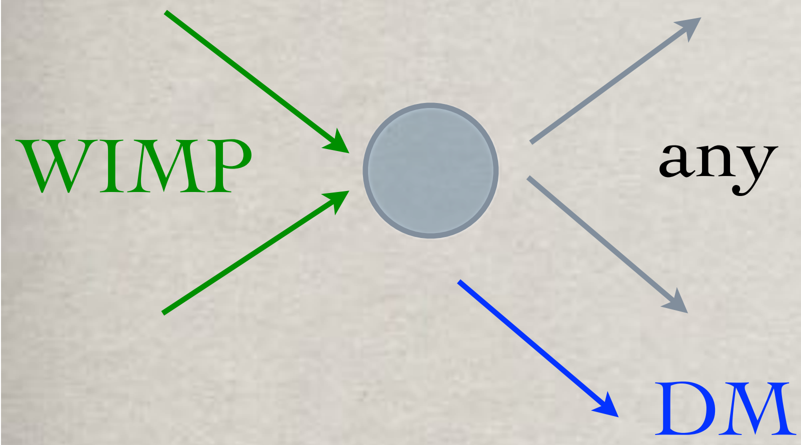


decaying DM !

3 different ways to check this hypothesis !!!

F/SWIMP CONNECTION

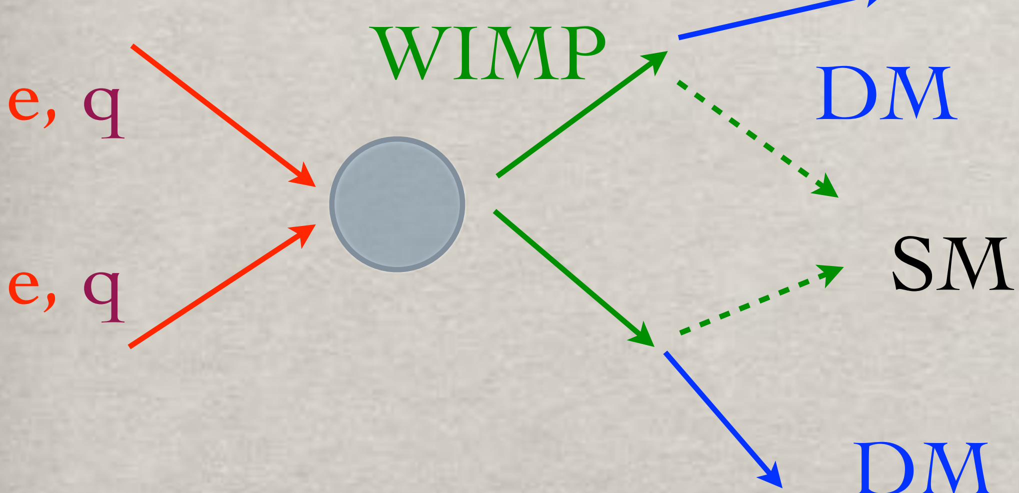
Early Universe: $\Omega_{CDM} h^2$



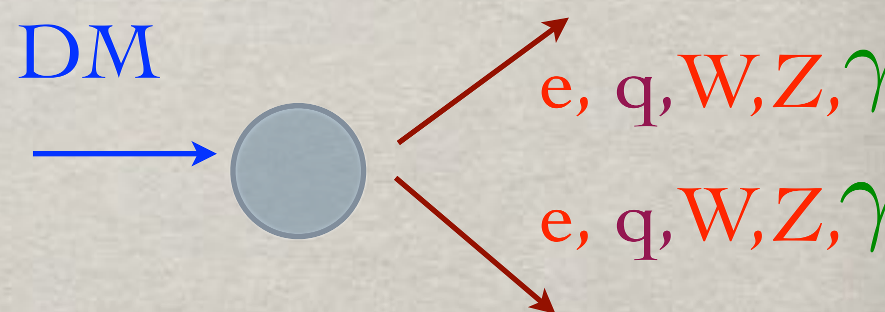
Direct Detection:

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

Colliders: LHC/ILC



Indirect Detection:



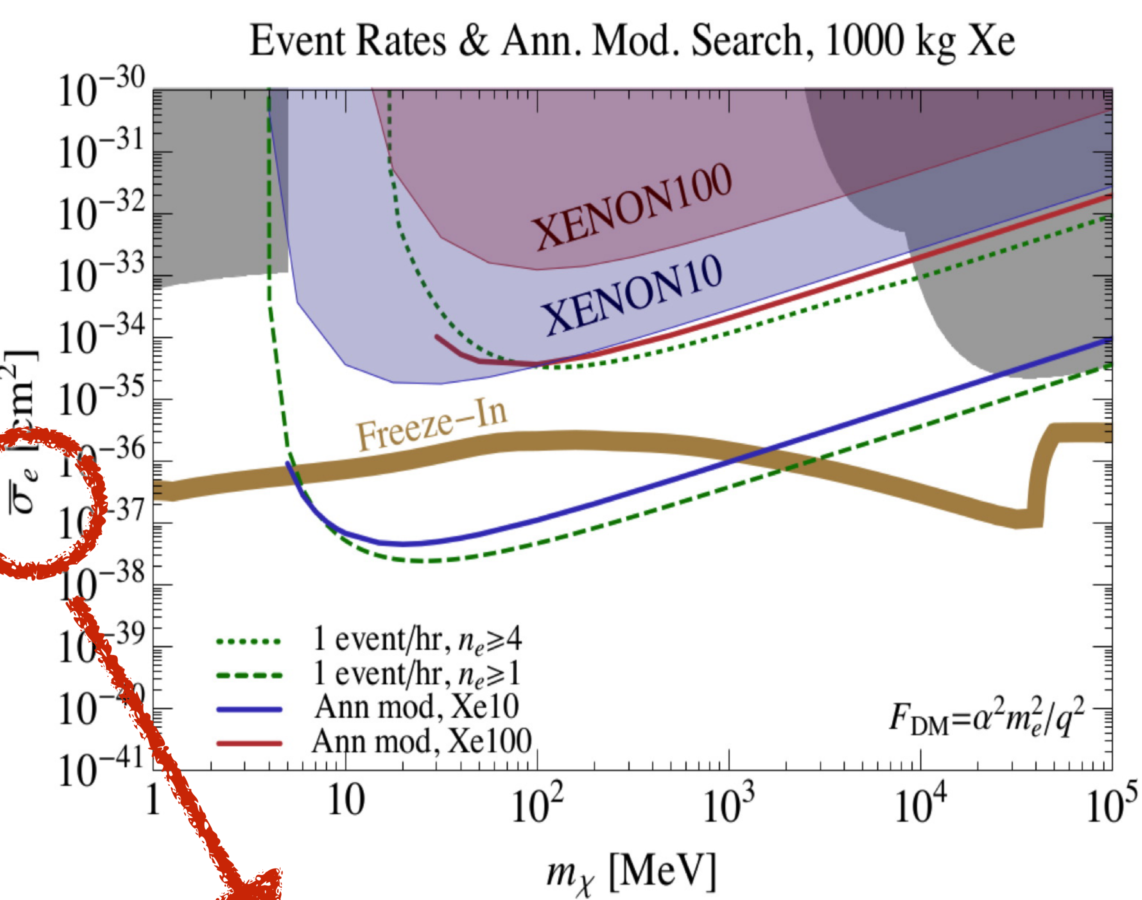
decaying DM !

3 different ways to check this hypothesis !!!

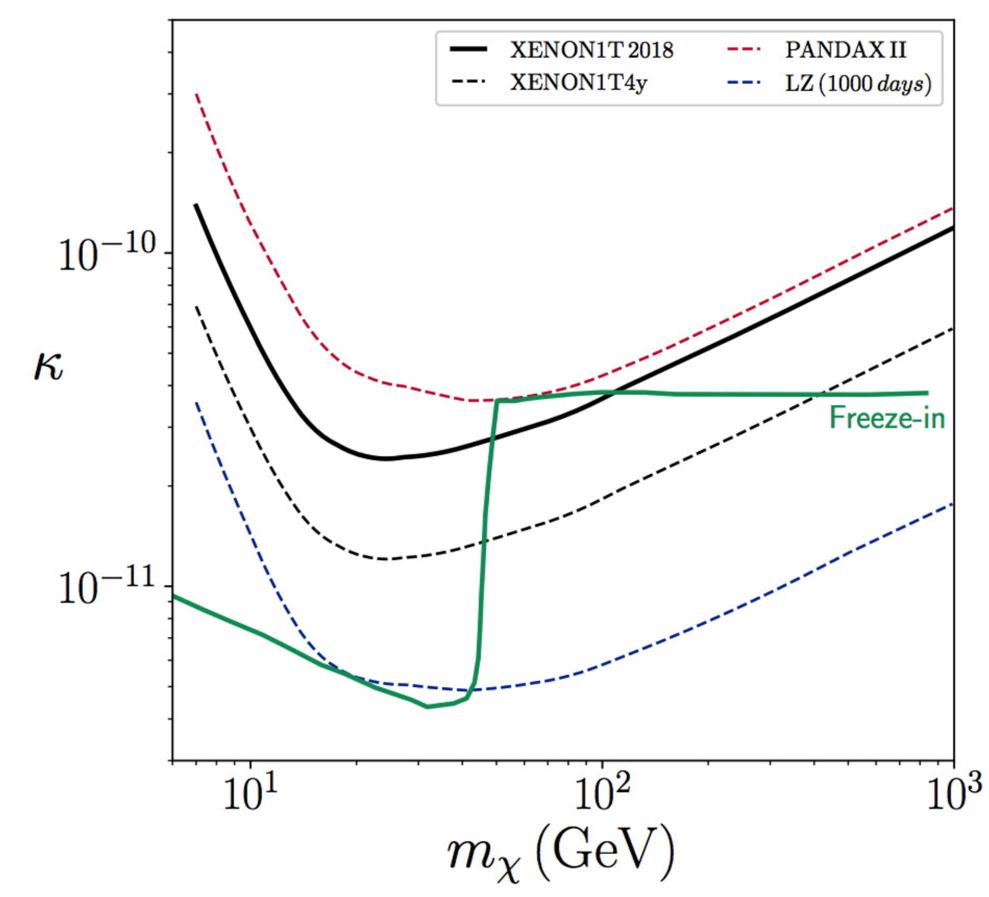
Direct detection of FIMPs

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]

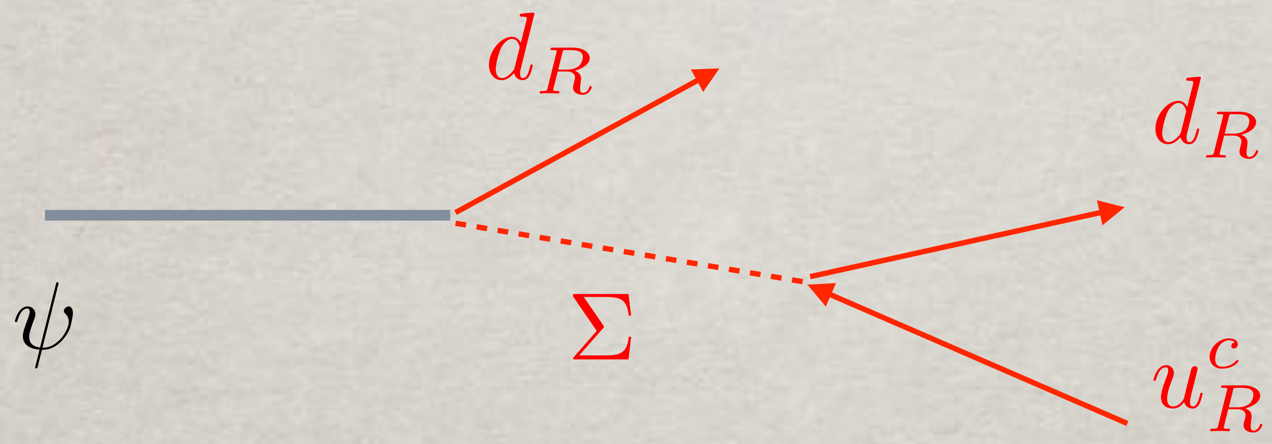


Note: here electron scattering !!!

A simple WIMP/SWIMP model

[G. Arcadi & LC 1305.6587]

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

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

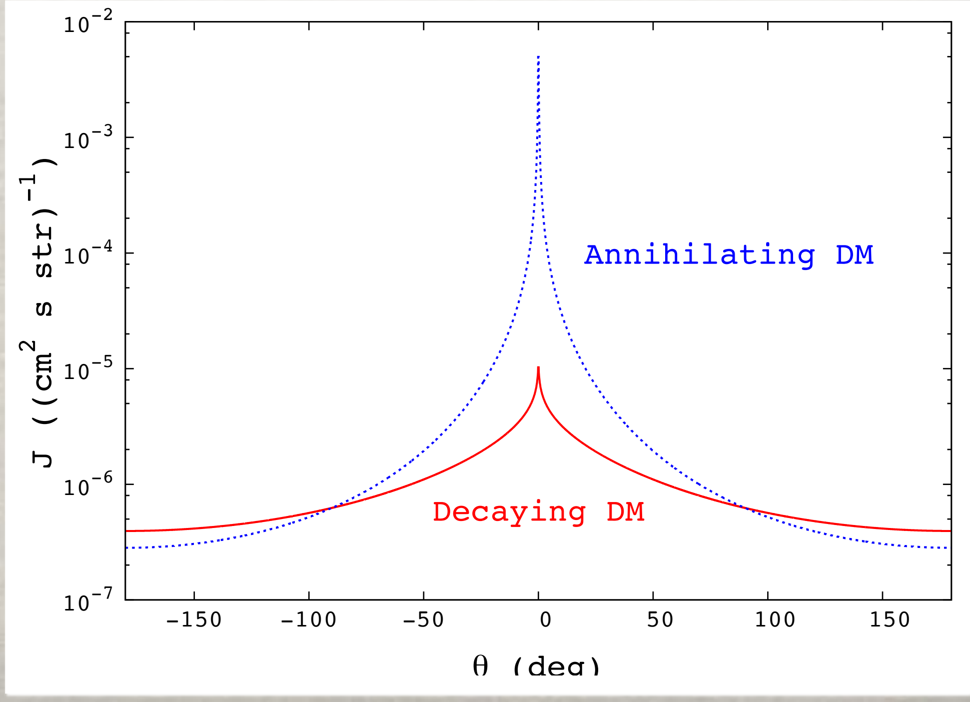
DECAYING DM

- The flux from DM decay in a species i is given by

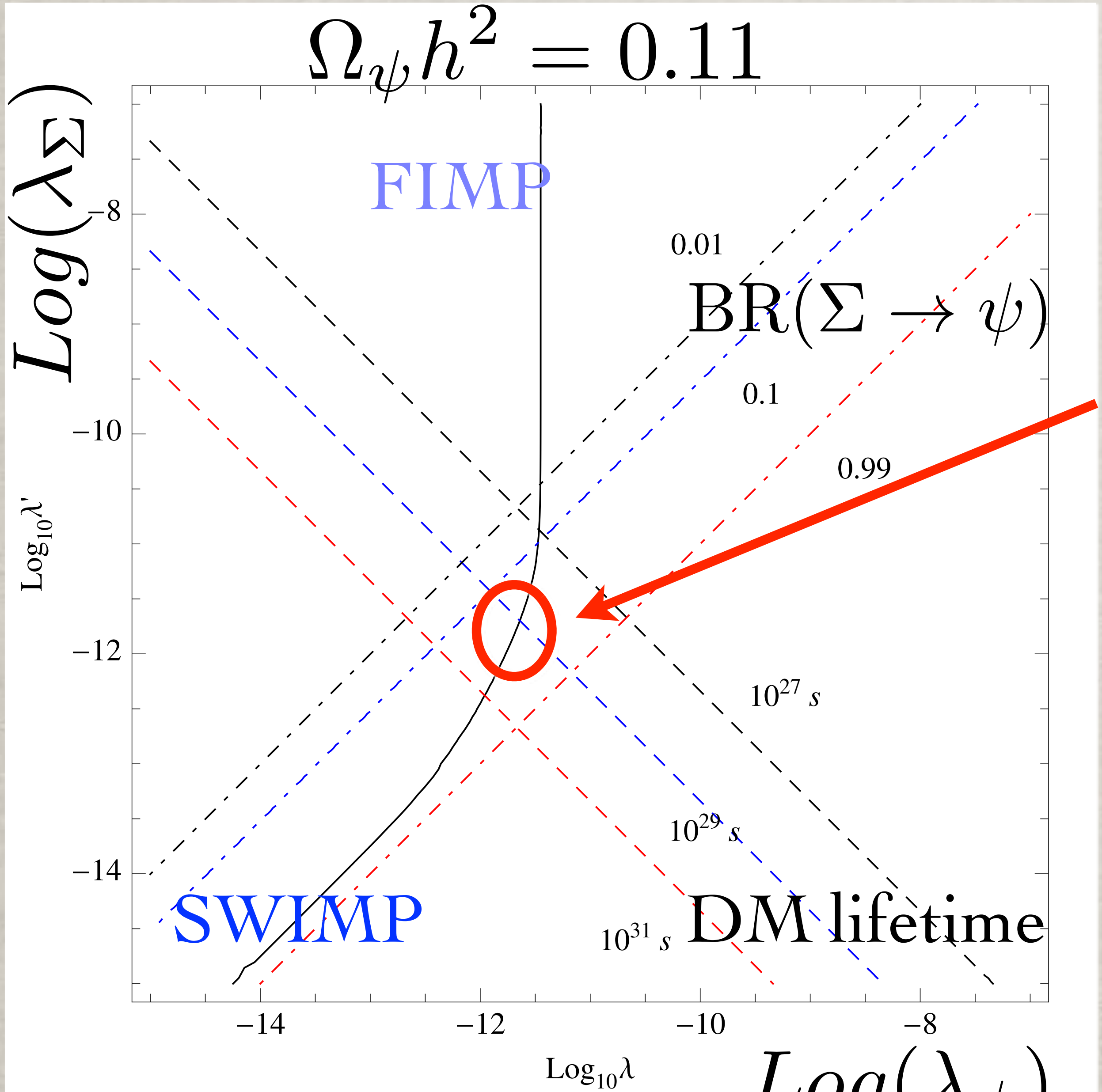
$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\ \rho(r(s,\theta))$$

Particle Physics — Halo property $J(\theta)$

- Very weak dependence on the Halo profile; what matters is the DM lifetime...
- Galactic & extragalactic signals are comparable...
- Spectrum in gamma-rays given by the decay channel! Smoking gun: gamma line...



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...

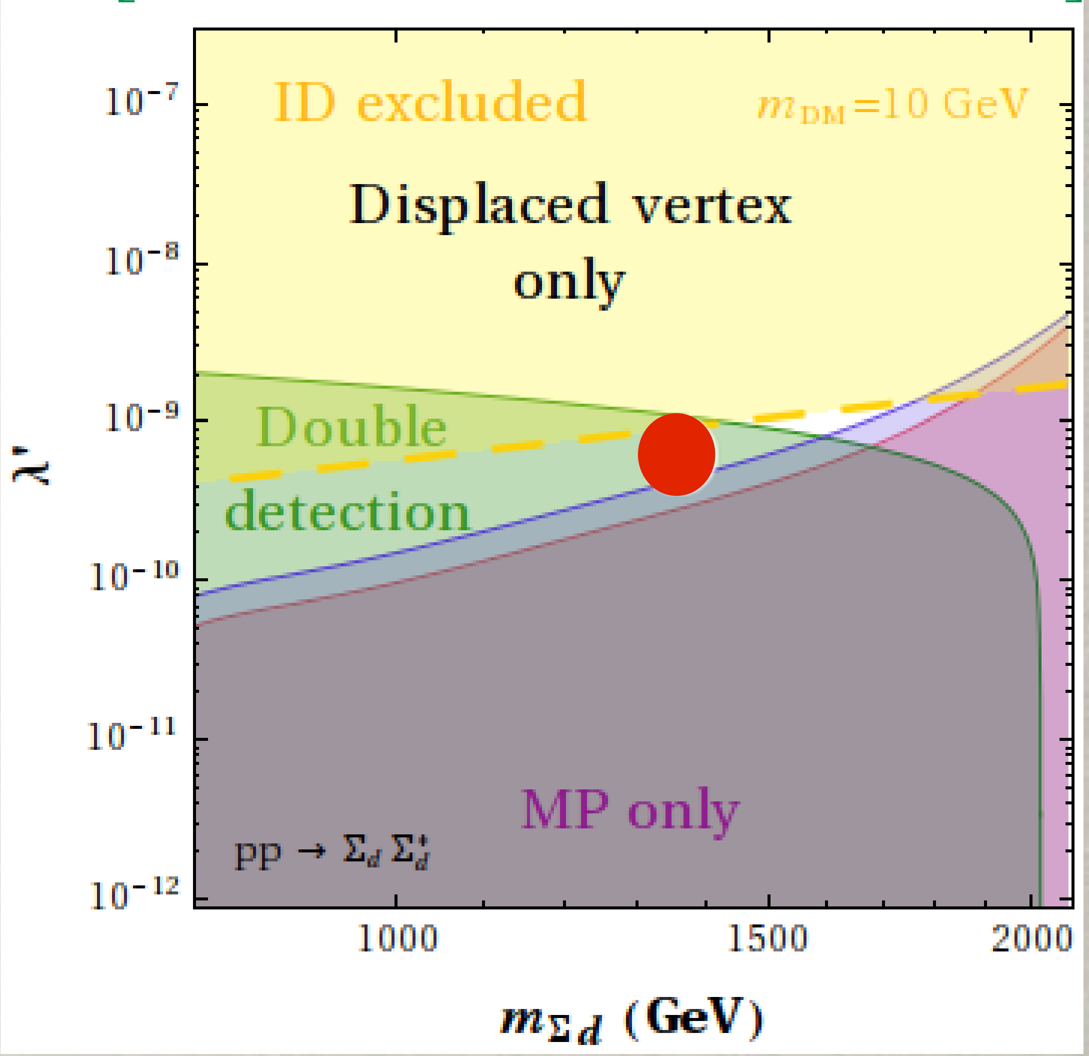
Σ Combined detection

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 $\Gamma_{\Sigma,SM}, \Gamma_{\Sigma,DM}$

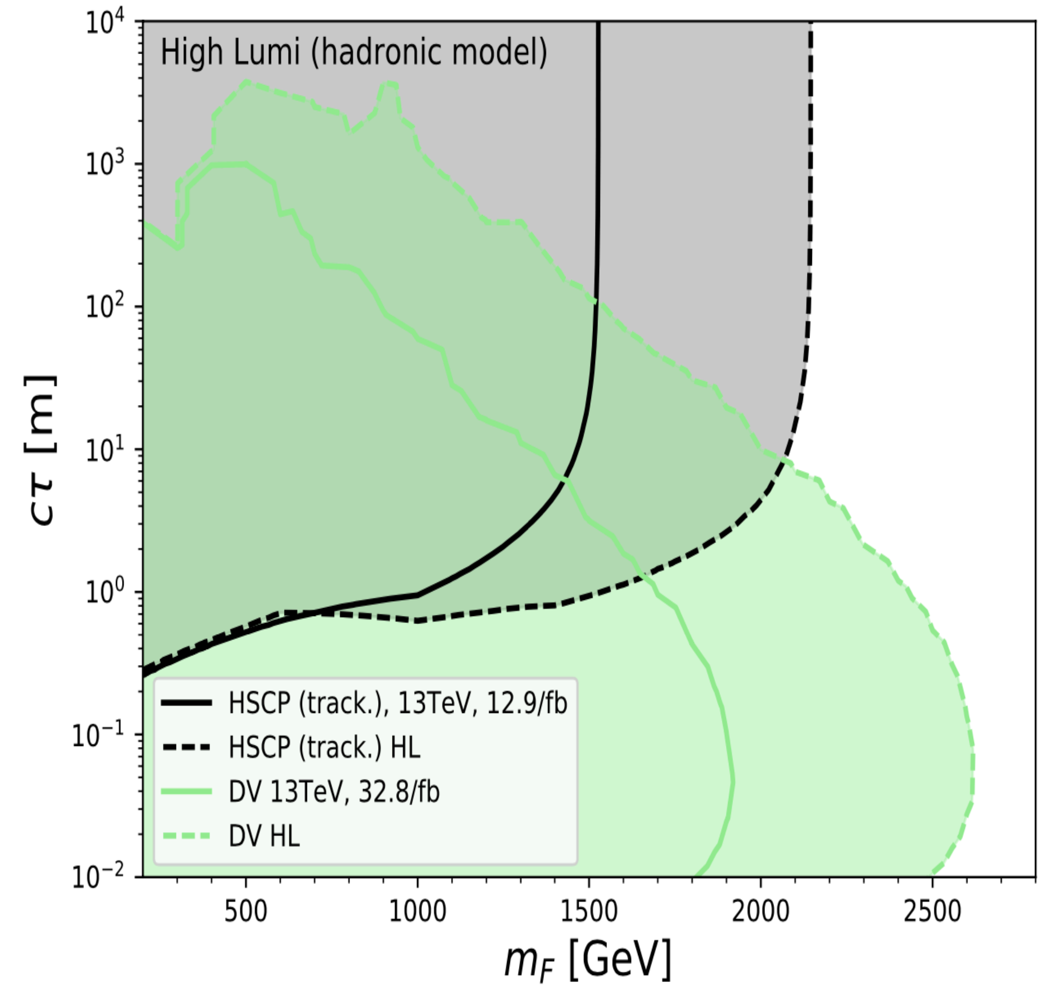
[G. Arcadi, LC & F. Dradi 1408.1005]



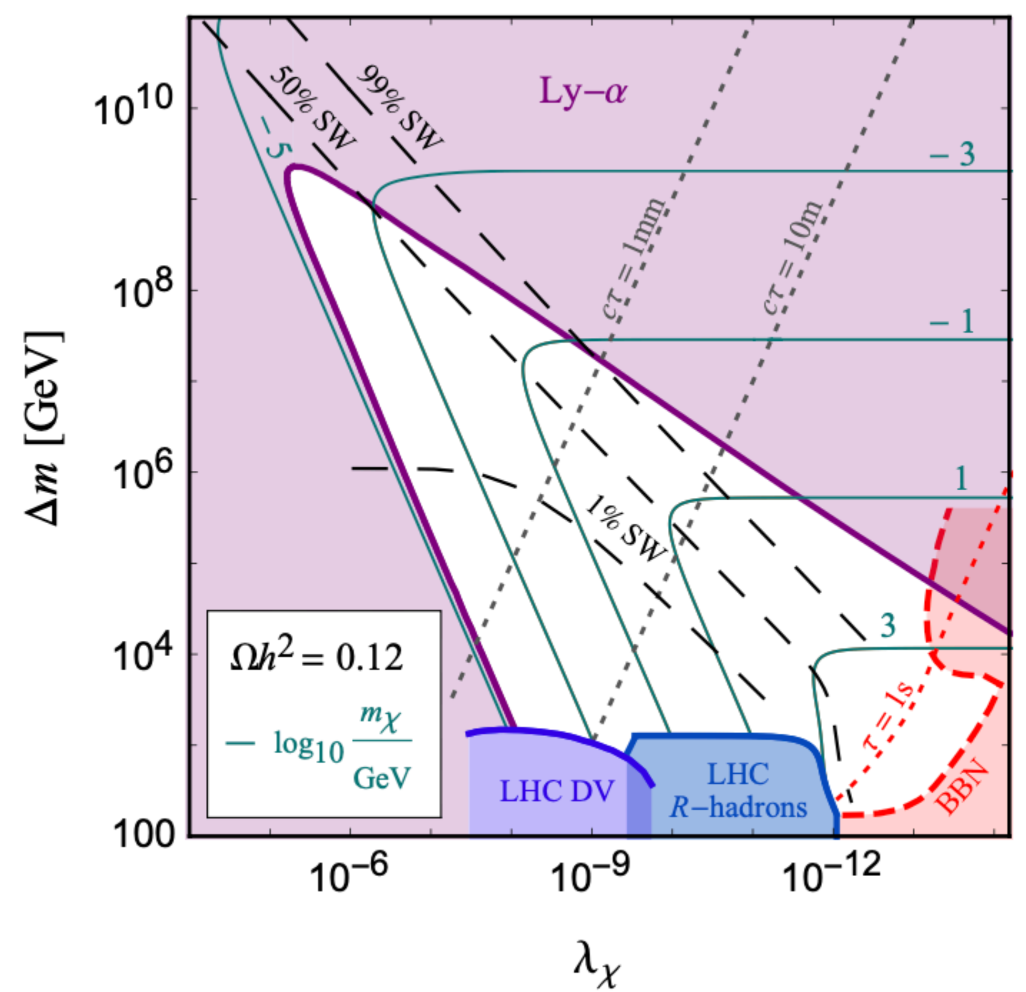
It is possible to over-constraint the model and check the hypothesis of FIMP production !

LHC and Cosmo bounds

[G. Belanger et al. 1811.05478]



[Q. Decant et al. 2111.09321]



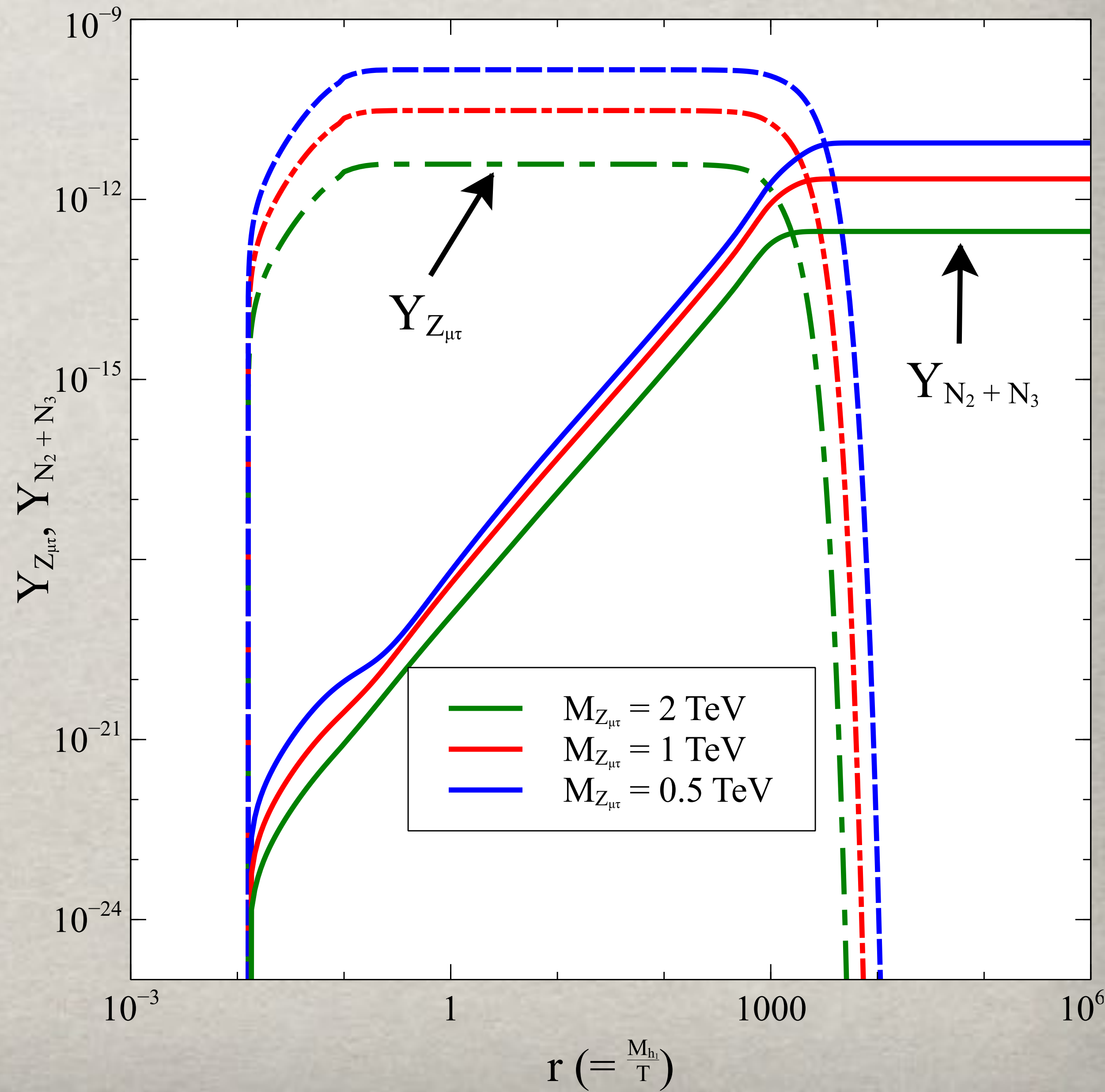
Here DM is the scalar and the Fermion is charged under QCD

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:

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



Asymmetric Dark Matter

Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty & Zurek 90, ...]

Assume instead that there is an asymmetry stored in DM as in baryons: DM asymmetry generated in the same way as the baryon asymmetry..
It may also be generated together with the baryon asymmetry and then it is natural to expect the SAME asymmetry in both sectors.

$$\Psi \to B + X$$

$$n_{DM} \sim n_b \to \Omega_{DM} \sim 5\,\Omega_b$$
$$\text{for } m_{DM} \sim 5\,m_p = 5\,\text{GeV}$$

The puzzle of similar densities can be given by similar masses !

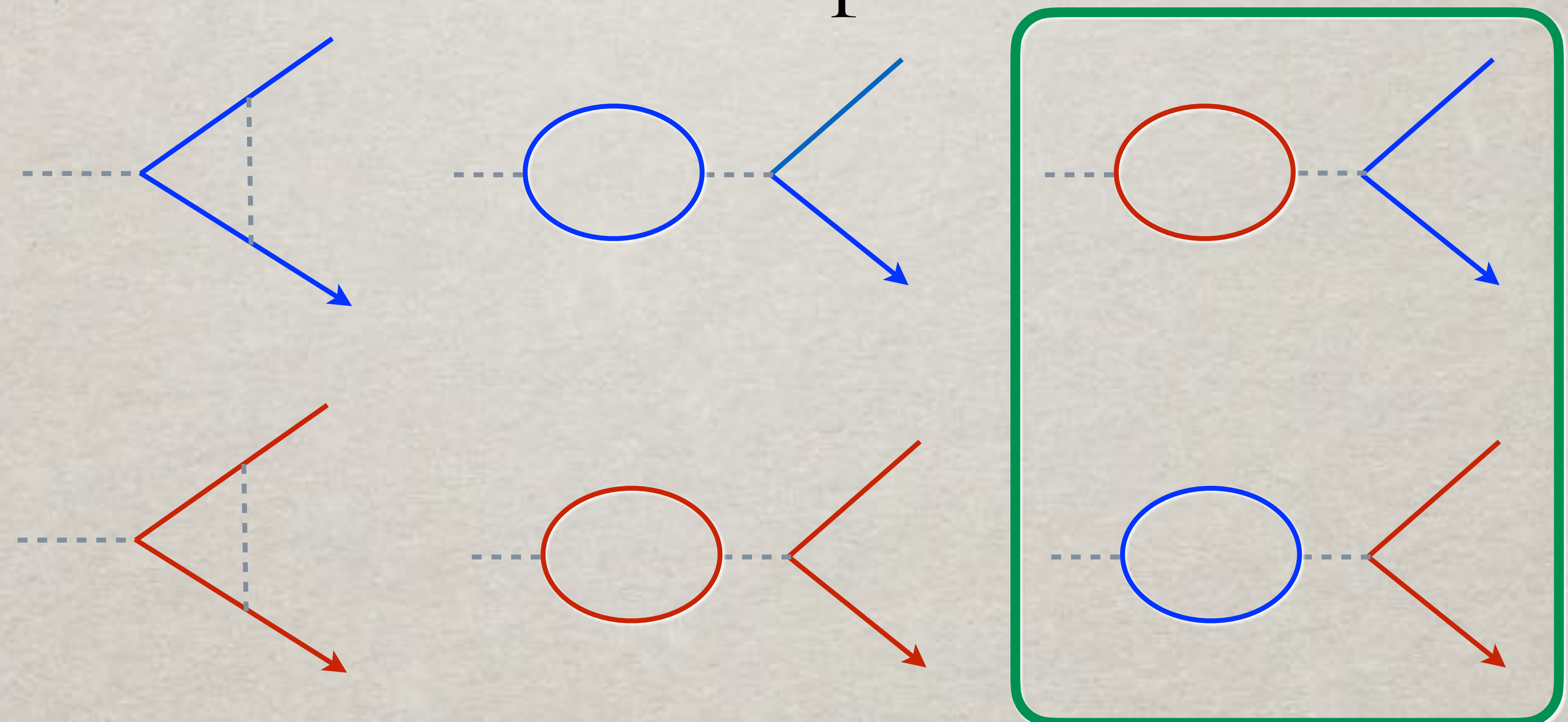
CP violation for ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in the decay has generally contributions from both lepton/DM sectors:

ϵ_ℓ

ϵ_D



But the wave-function contribution with virtual leptons/DM can dominate both asymmetries and give $\epsilon_\ell = \epsilon_D$!

CP violation for ADM

[A. Biswas, S. Choubey, LC & S. Khan 2018]

The CP asymmetry in both decays comes from the same phases, contained in the neutrino sector, since the DM couplings can be chosen real:

$$\frac{\epsilon_\ell}{\epsilon_D} = 1 + \frac{\mathrm{Im}\left[3((\mathrm{y}^\dagger \mathrm{y})^*_{12})^2\right]}{2\alpha_1\alpha_2 \mathrm{Im}\left[3(\mathrm{y}^\dagger \mathrm{y})^*_{12}\right]}$$

For one real and one imaginary columns of Yukawas, then

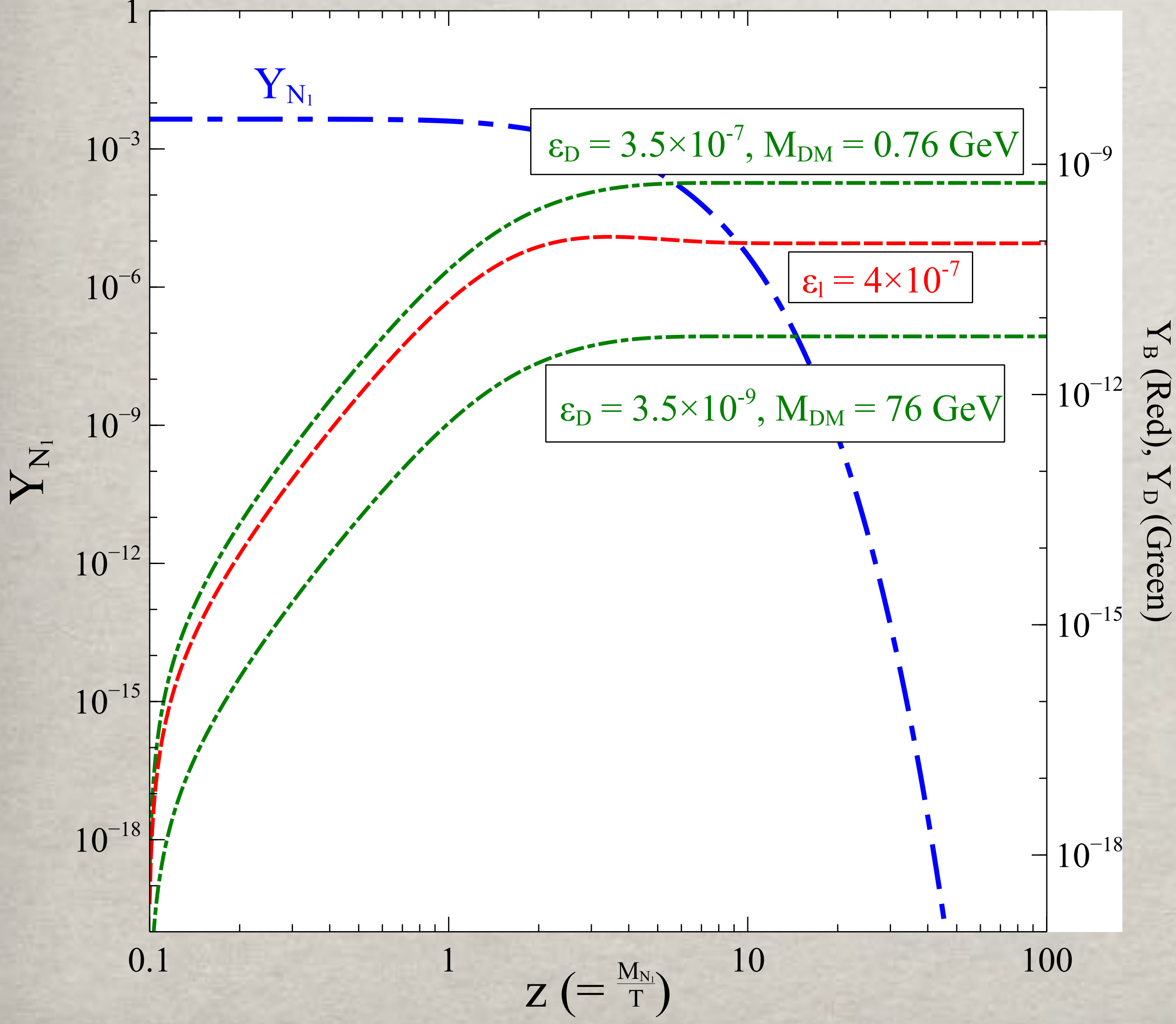
we have Real $((y^\dagger y)^*_{12})^2$ and exactly $\epsilon_\ell = \epsilon_D$.

Similarly in case of $\alpha_1\alpha_2 > |(y^\dagger y)_{12}*|$ we also obtain

practically equal CP violation in the decays.

A minimal ADM model

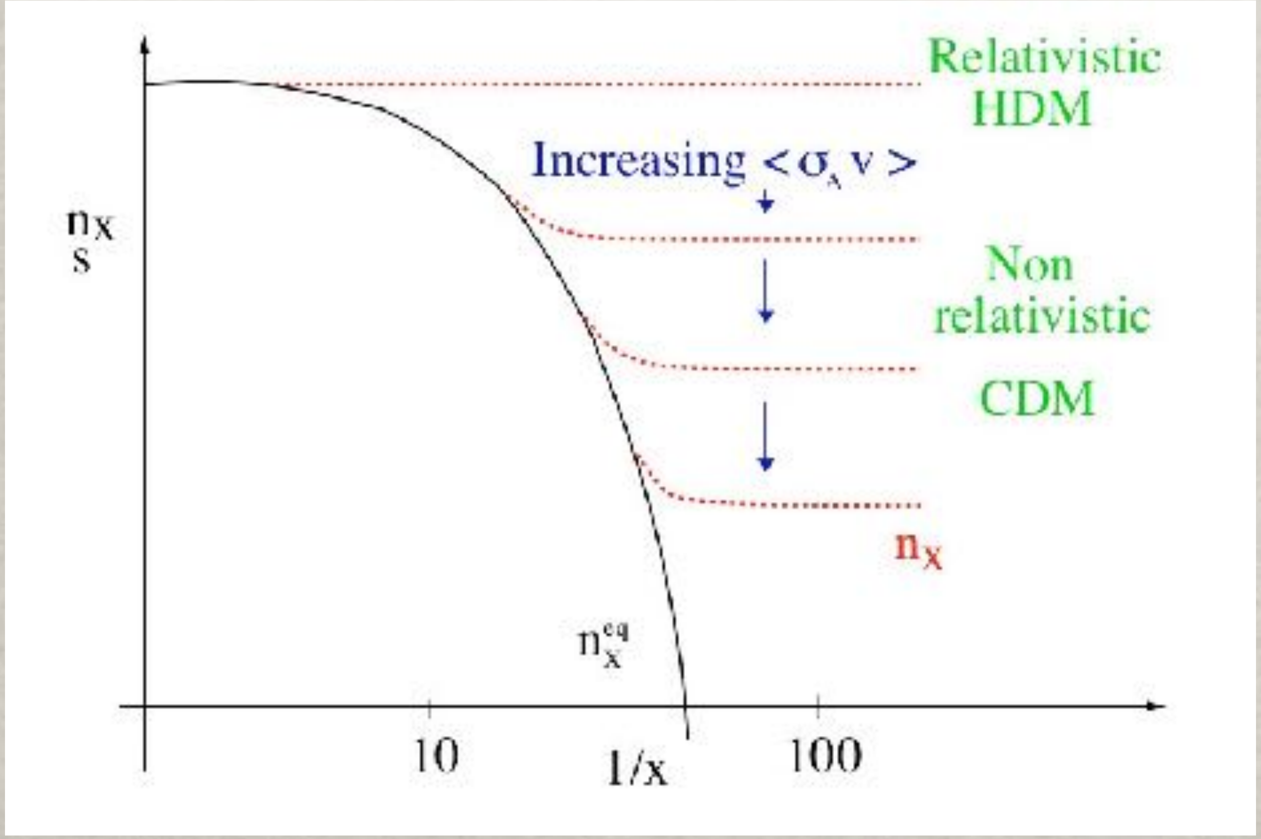
[A. Biswas, S. Choubey, LC & S. Khan 2018]



Even if the CP parameter
is the same, also wash-out processes play a role and naturally give a larger asymmetry in the DM sector than in the lepton sector !

Asymmetric Dark Matter

But DM must annihilate sufficiently strongly to erase the symmetric DM component, so it must interact more strongly than a WIMP (in our case within a hidden sector).

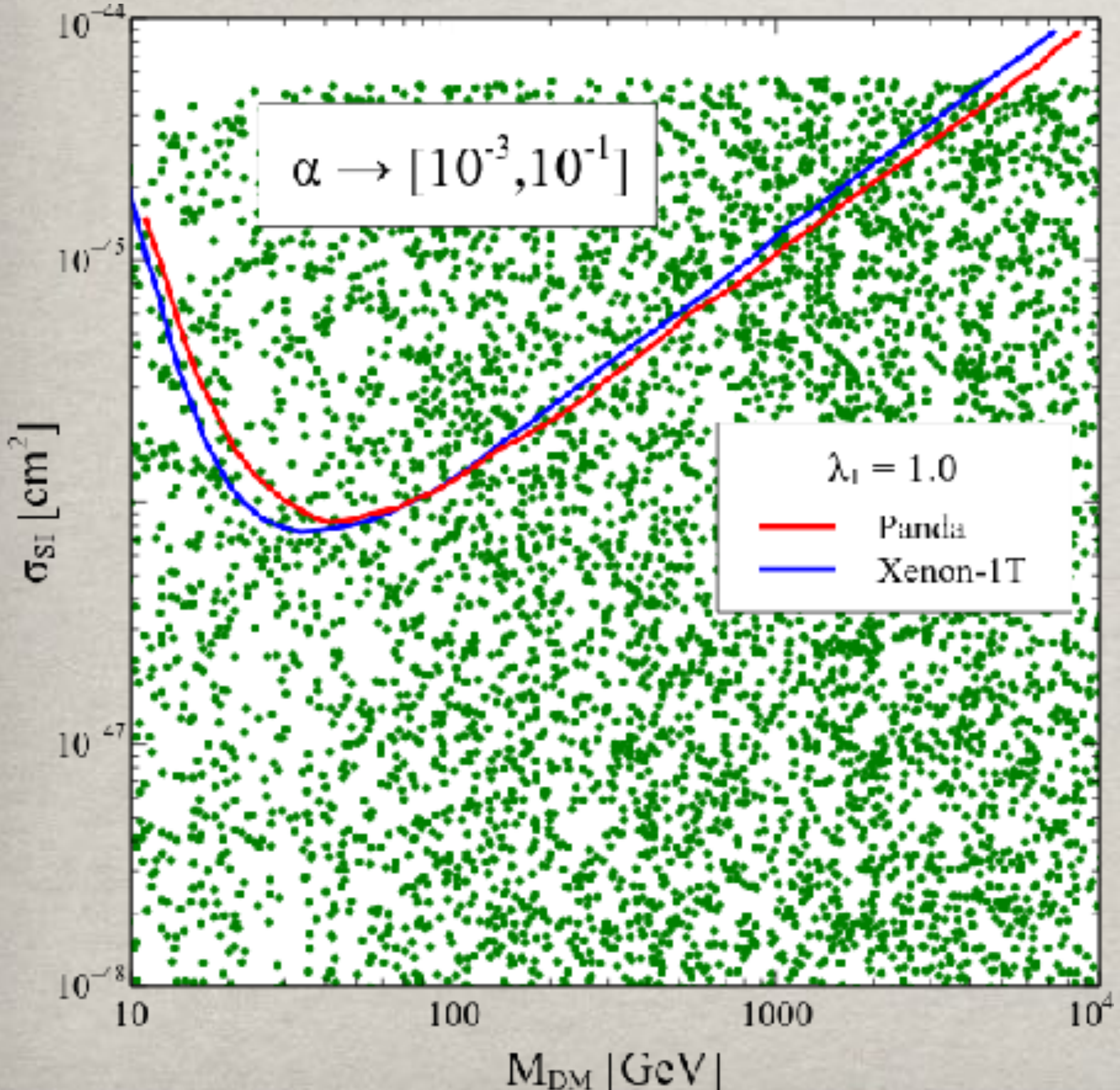


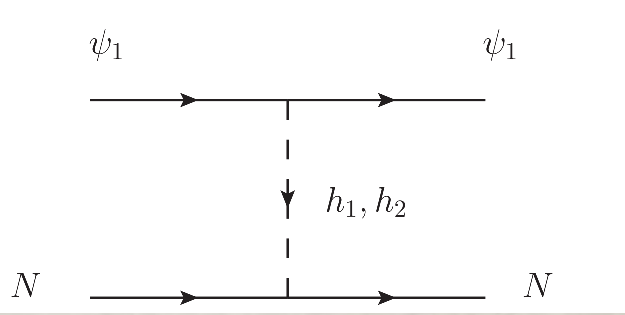
Strong coupling...
...like baryons !

It may accumulate in stars and change the star evolution...

DD in the ADM model

[A. Biswas, S. Choubey, LC & S. Khan 2018]





Due to the mixing of the scalars after EW symmetry breaking, the DM scatters with normal matter via intermediate Higgs and could be detected in DD (but beware of the cancellation!)

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:

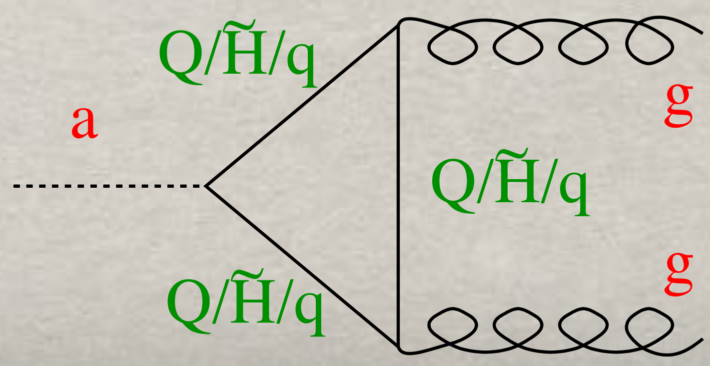
['t Hooft 76]

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

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

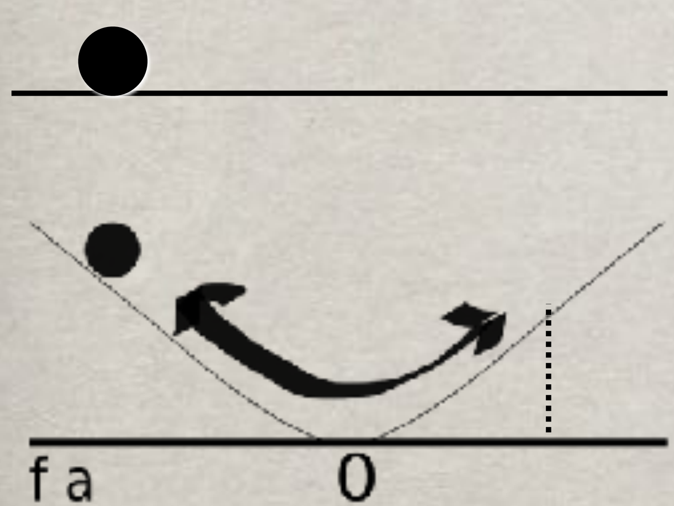
Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a , leaving the axion, a pseudo-Goldstone boson, interacting as

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



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

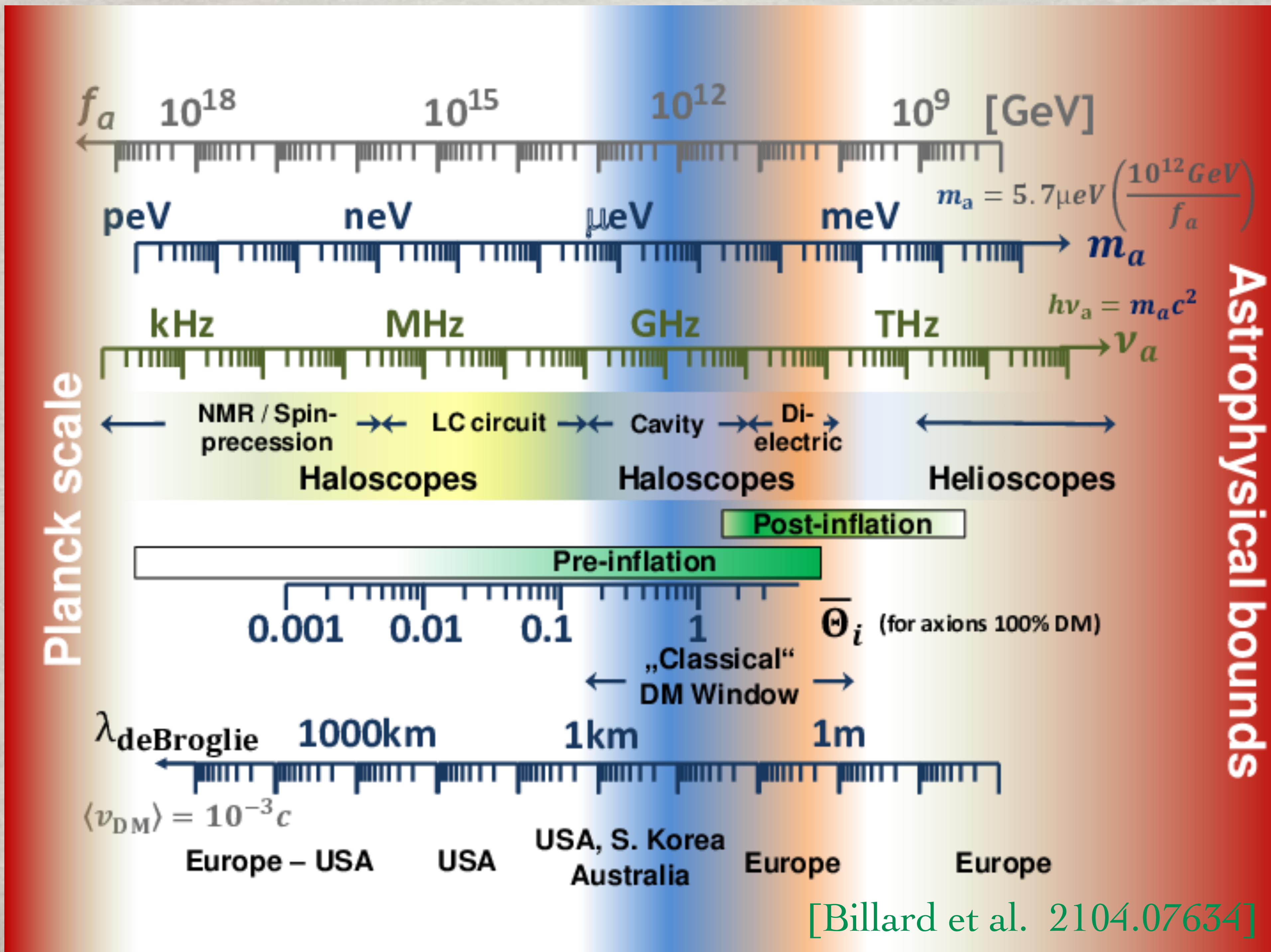
$$V(a) = \Lambda_{QCD}^4 \left(1 - \cos\left(\theta + \frac{a}{f_a}\right)\right)$$

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

zero momentum particles >> CDM !

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

Axion's constraints



[Billard et al. 2104.07634]

Extended KSVZ MODEL

[LC & S. Khan 2205.10150 [hep-ph]]

We add to the SM an additional U(1) symmetry, two Higgs fields connected to its breaking and two sets of exotic colored fermions to generate the PQ-QCD anomaly:

Gauge Group	Baryon Fields			Lepton Fields						Scalar Fields
	Q_L^i	u_R^i	d_R^i	L_L^e	L_L^μ	L_L^τ	e_R	μ_R	τ_R	ϕ_h
$SU(2)_L$	2	1	1	2	2	2	1	1	1	2
$U(1)_Y$	1/6	2/3	−1/3	−1/2	−1/2	−1/2	−1	−1	−1	1/2
$U(1)_X$	m	m	m	n_e	n	n	n_e	n	n	0
$U(1)_{PQ}$	0	0	0	$-2q_a$	0	0	$-2q_a$	0	0	0

Gauge Group	Fermions							Scalars	
	N_1	N_2	N_3	ψ_L	ψ_R	χ_L	χ_R	ϕ_1	ϕ_2
$SU(3)_c, SU(2)_L$	(1, 1)	(1, 1)	(1, 1)	(3, 1)	(3, 1)	(3, 1)	(3, 1)	1	1
$U(1)_X$	n_e	n	n	α_L	α_R	β_L	β_R	$\alpha_L - \alpha_R$	$\beta_L - \beta_R$
$U(1)_{PQ}$	$-2q_a$	0	0	$-q_a$	q_a	q_a	$-q_a$	$-2q_a$	$2q_a$
$\mathbb{Z}_2$	−1	1	1	1	1	−1	−1	1	1
No. of flavors	1	1	1	N_ψ	N_ψ	N_χ	N_χ	1	1

Neutron EDM from Gravity

[LC & S. Khan 2022]

In this model the PQ symmetry is only accidental and it is broken by gravitational effects via higher order operators. The shift of the theta term is strongly suppressed due to the different charges and large number of fermions:

$$\Delta\theta = \frac{(M_a^g)^2}{(M_a^{QCD})^2} = \frac{|g|}{N_\psi! N_\chi! \, (\sqrt{2})^{N_\psi+N_\chi}} \frac{v_1^{N_\psi} v_2^{N_\chi}}{M_{PL}^{N_\psi+N_\chi-4} (f_\pi m_\pi)^2} \frac{(m_u+m_d)^4}{m_u^2 m_d^2}$$

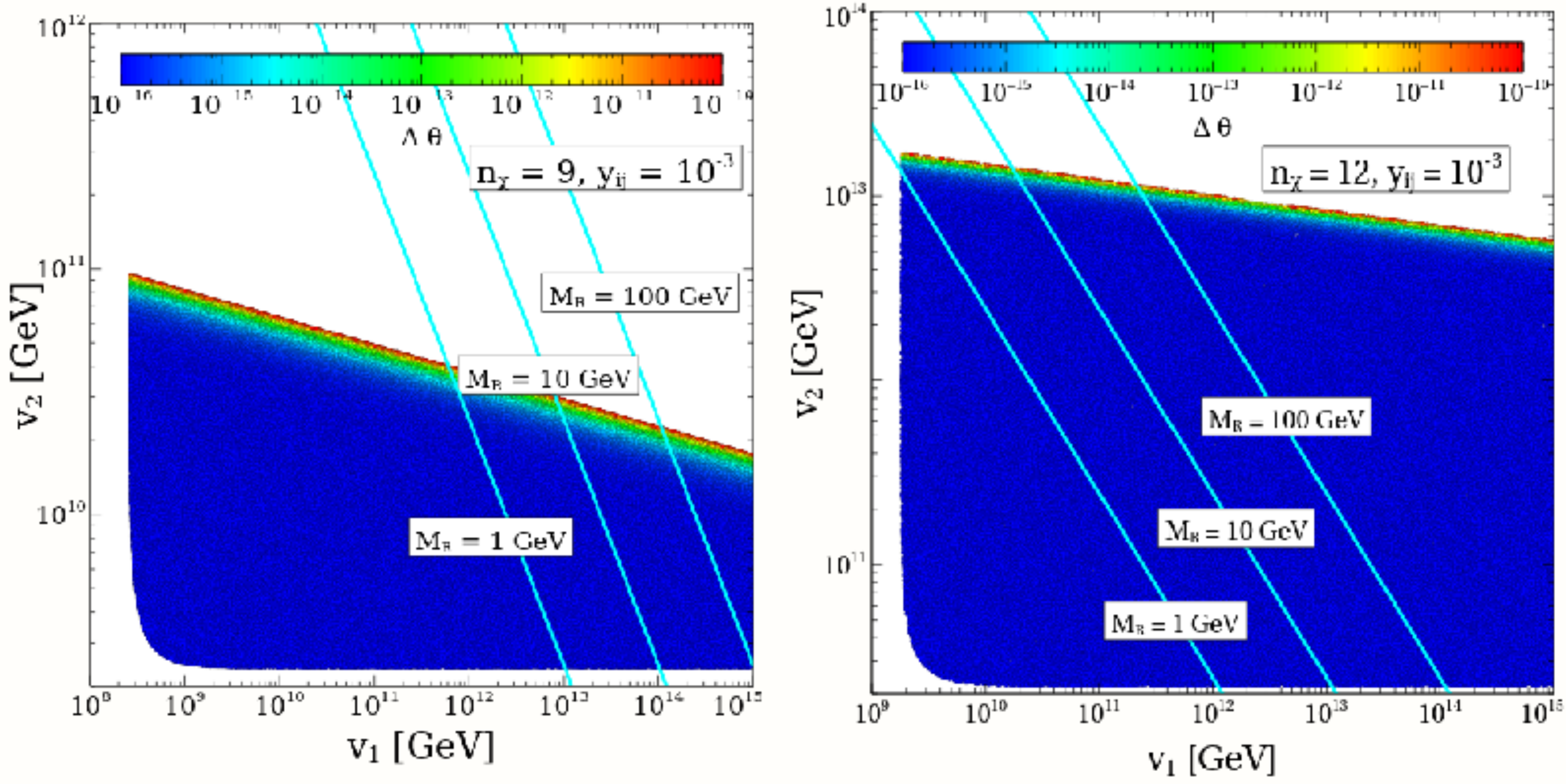
together with the lower bound in f_a from astrophysics, it implies that about 10 exotic fermions should be present to avoid the a too large contribution to the neutron EDM !

The minimum of the axion potential is shifted !

Axion & EDMs

Viable axion with EDMs maybe behind the corner…

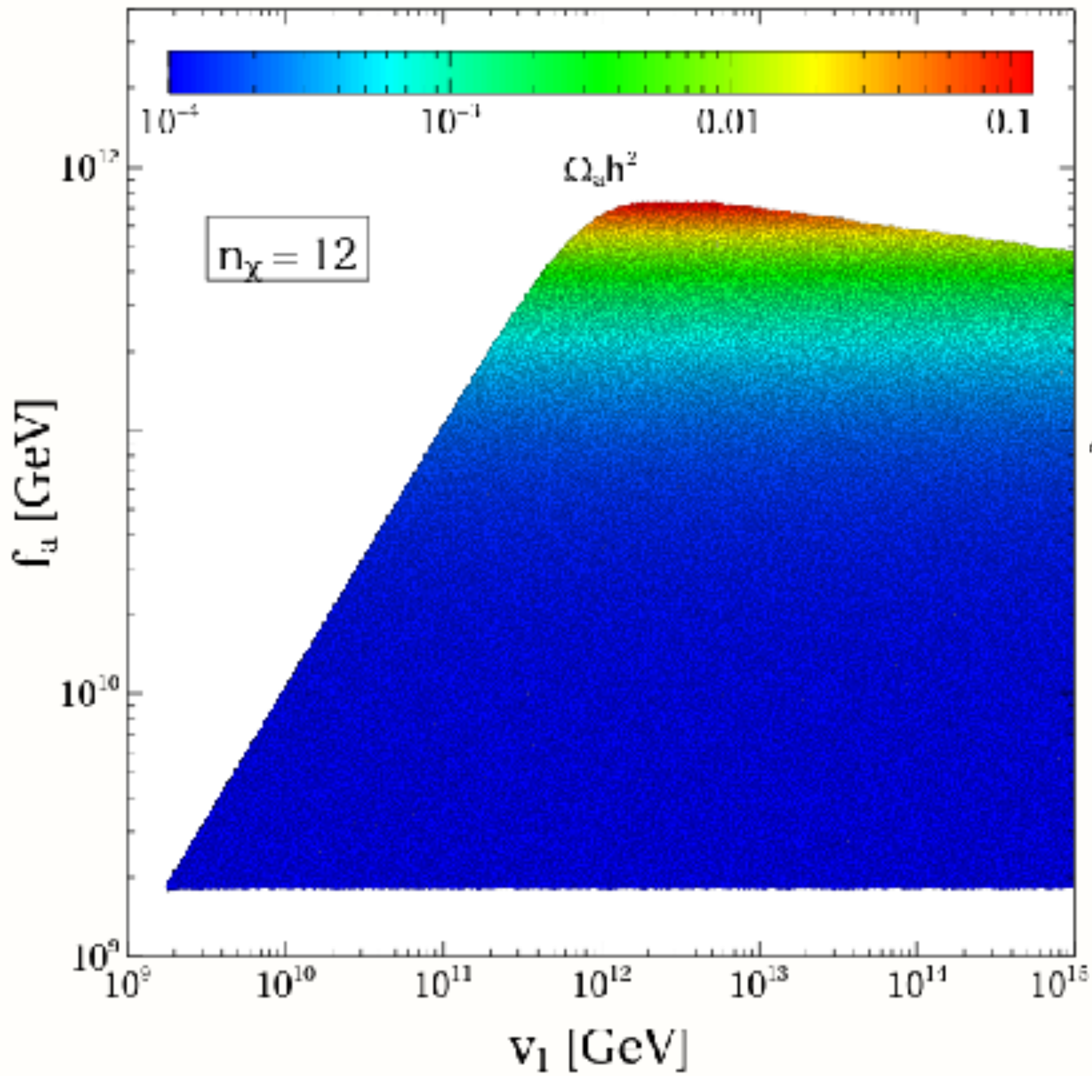
[LC & S. Khan 2022]

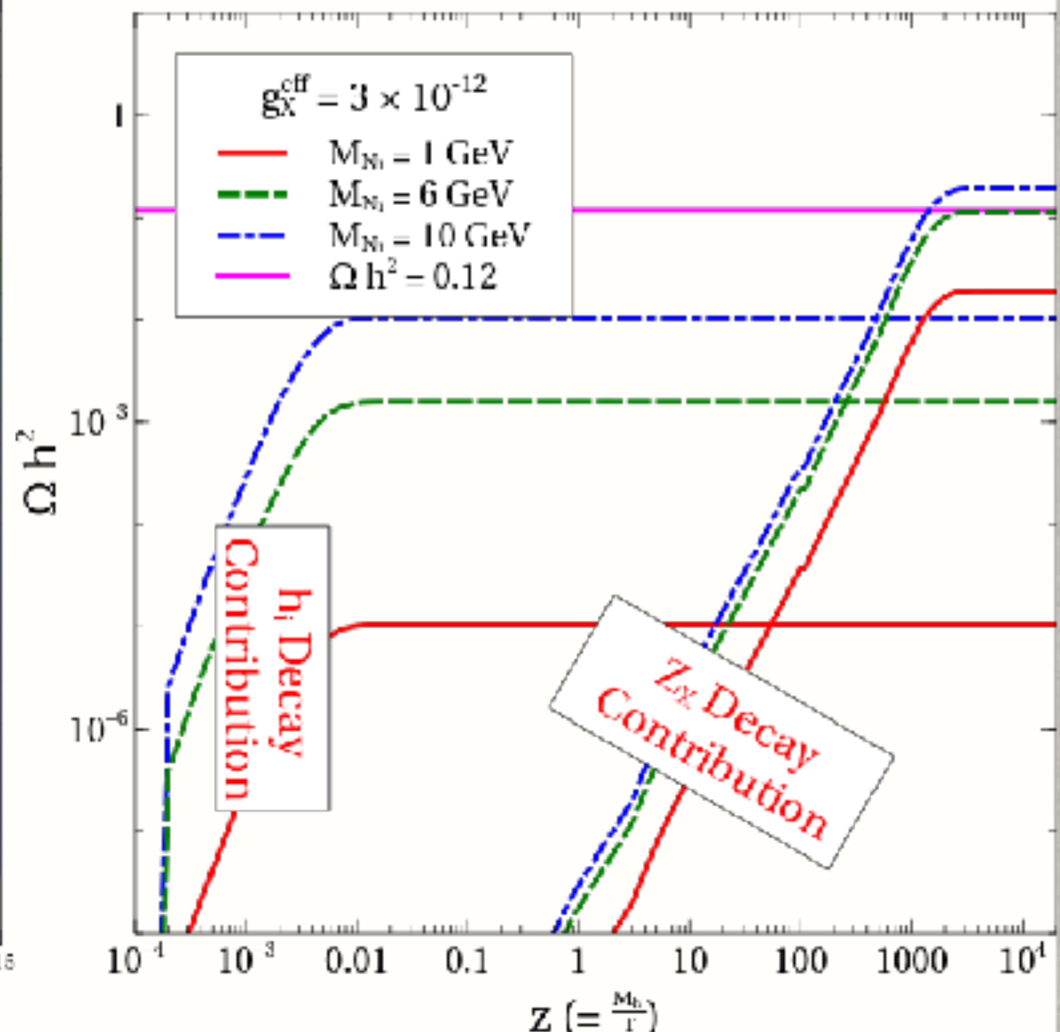


Axion & FIMP DM

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

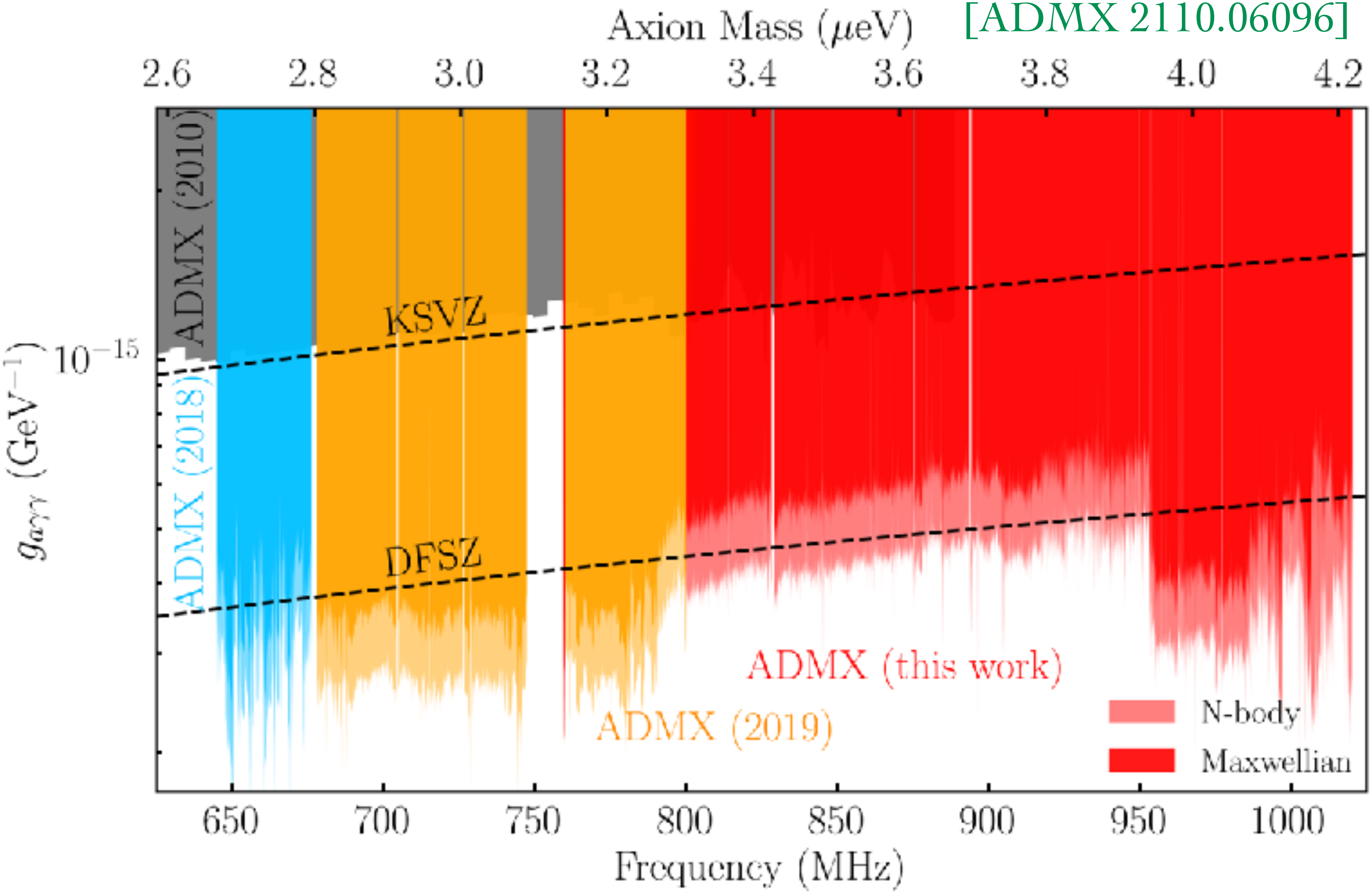
[LC & S. Khan 22]





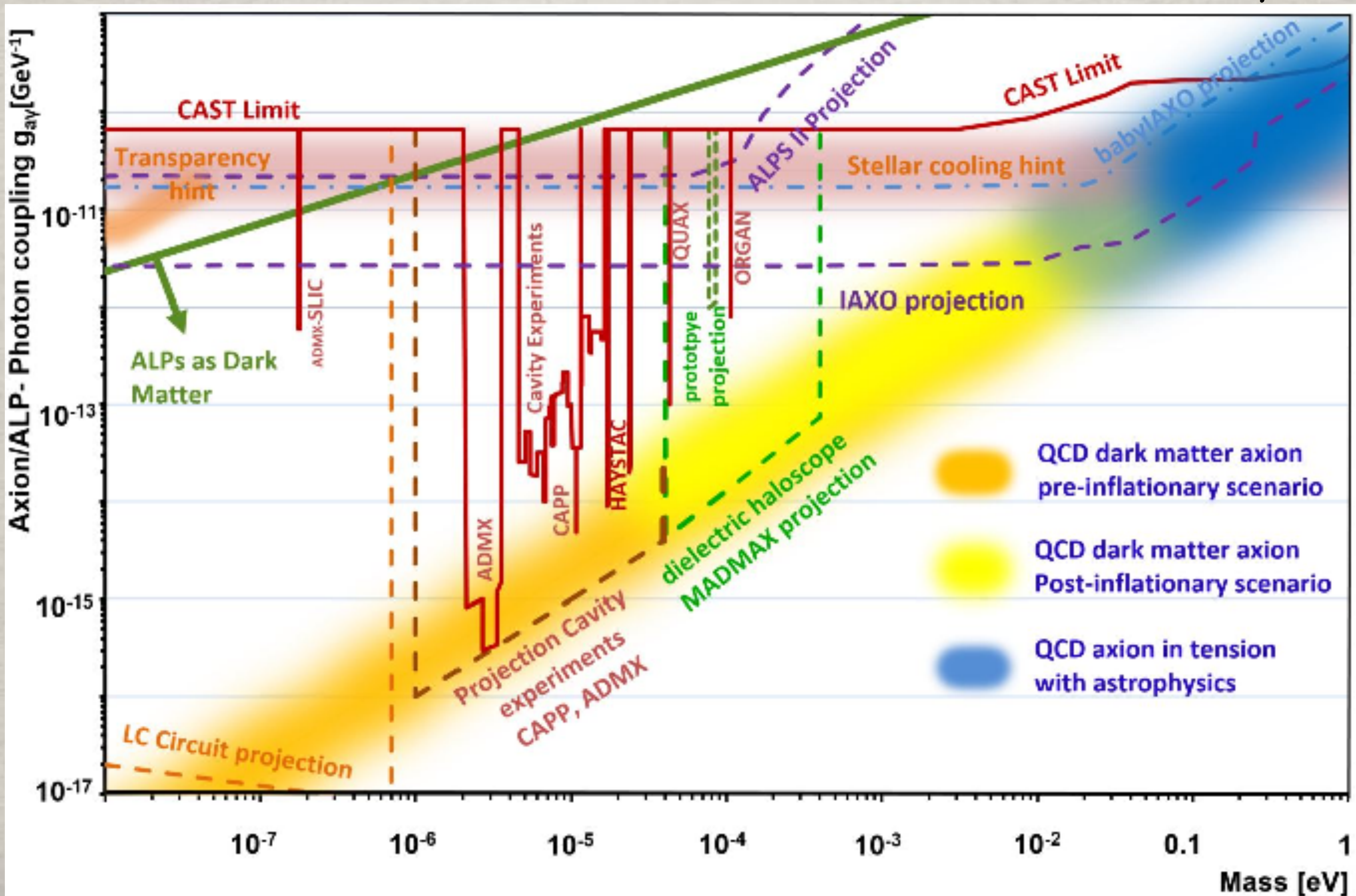
AXION DM SEARCHES

[ADMX 2110.06096]



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.



Outlook

Outlook

- From the theoretical perspective, we have a few "natural" ways for DM production, not only the WIMP, but also the FIMP/SuperWIMP/ADM mechanisms or misalignment for light scalars/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 ongoing.
- 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…