ISSP - 60th Course - News from the Four Interactions
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On the Dark side of the Universe (theory)

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HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

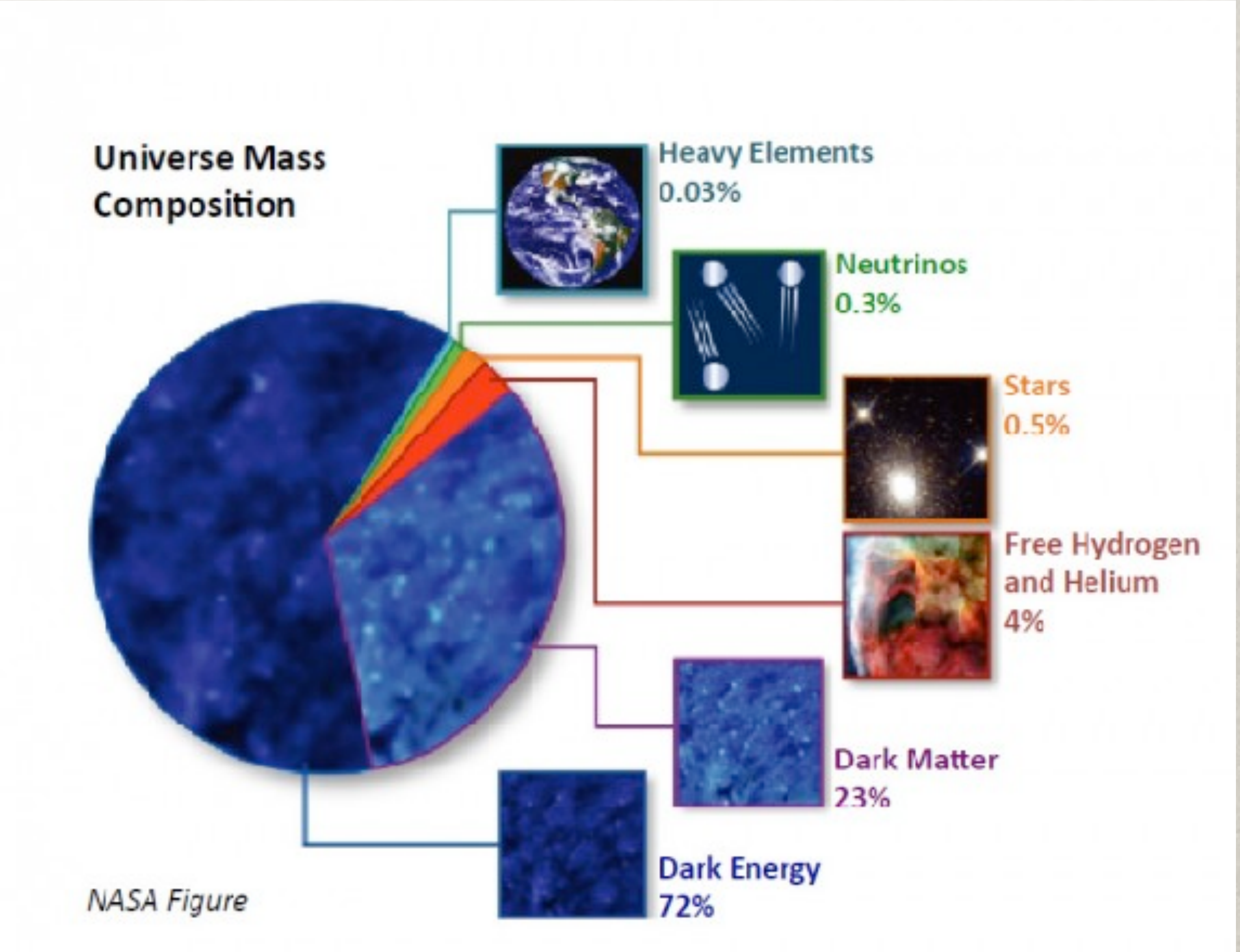
MARIE CURIE ACTIONS

Outline

- Introduction on Dark Matter & Theoretical guiding principles
- Thermal relics:
  - WIMP Dark Matter
  - Asymmetric DM
- Non-thermal relics:
  - FIMP/SuperWIMP/Decaying DM
  - Axion Dark Matter
- Multicomponent DM...
- Outlook

Thermal relics: Asymmetric Dark Matter

Universe composition



Why $\Omega_{DM}h^2 \sim 5\,\Omega_B h^2$?

Sakharov Conditions

Sakharov studied already in 1967 the necessary conditions for generating a baryon asymmetry from a symmetric state:

- B violation: trivial condition since otherwise B remains zero...
- C and CP violation: otherwise matter and antimatter would still be annihilated/created at the same rate
- Departure from thermal equilibrium: the maximal entropy state is for B = 0, or for conserved CPT, no B generated without time-arrow...

Now exactly the same conditions have to hold also for the generation of a Dark Matter Asymmetry !

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.

$$\Psi \rightarrow B + X$$

$$n_{DM} \sim n_b \rightarrow \Omega_{DM} \sim 5\,\Omega_b$$

$$\text{for } m_{DM} \sim 5\,m_p = 5\,\text{GeV}$$

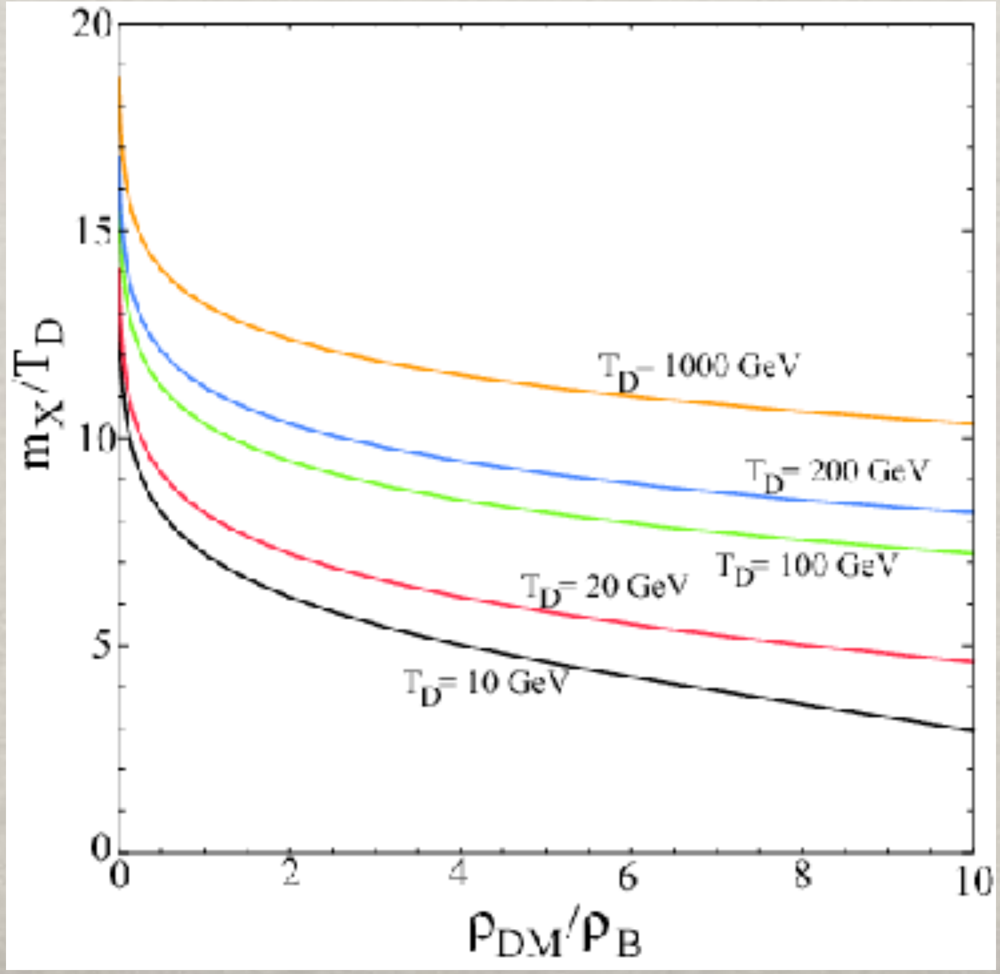
The puzzle of similar densities can be given by similar masses !

Asymmetric Dark Matter

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

The simple picture $m_{DM} = 5\, m_p$ can be extended by taking into account the Boltzmann suppression factor at the time of creation of the asymmetry:

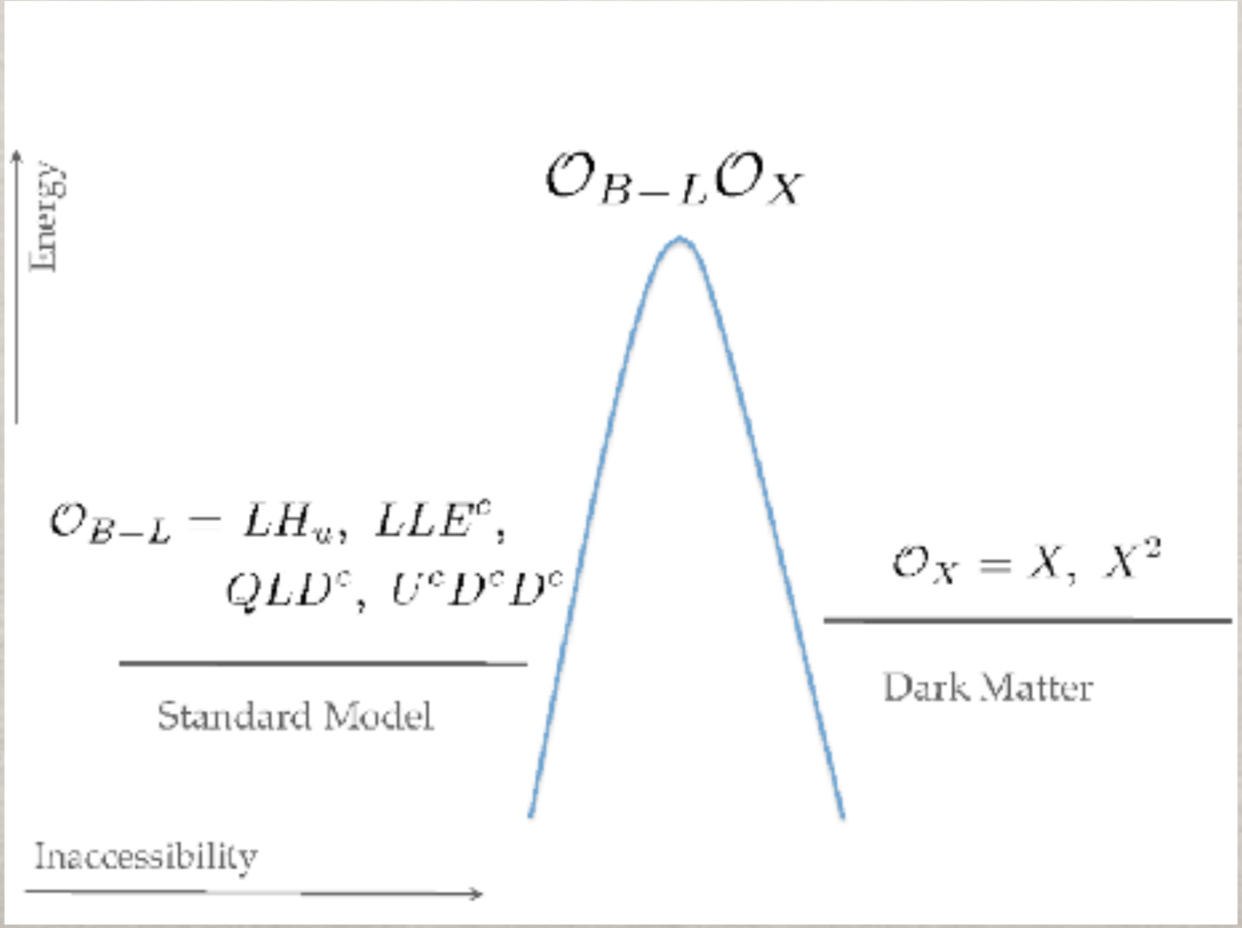
DM Mass/
T_Decoupling



Asymmetric Dark Matter

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

Otherwise B-L can be produced and then reprocessed into DM/B/L by sphaleron processes. All other coupling exchanging DM/B frozen out !

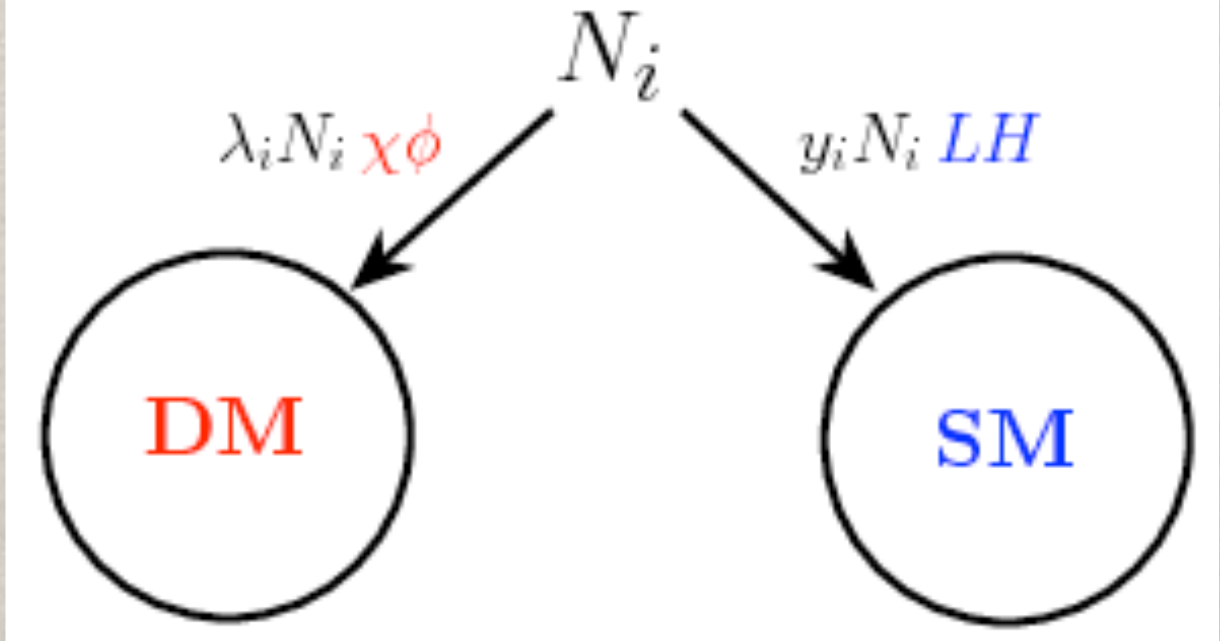


Asymmetric Dark Matter

[Griest & Seckel '87, Kaplan, Luty &Zurek 90, …

Falkowski, Ruderman & Volansky 2011]

Simple mechanism to generate such case: out-of-equilibrium decay of a particle producing both B-L and DM, e.g. even decay of a RH neutrino

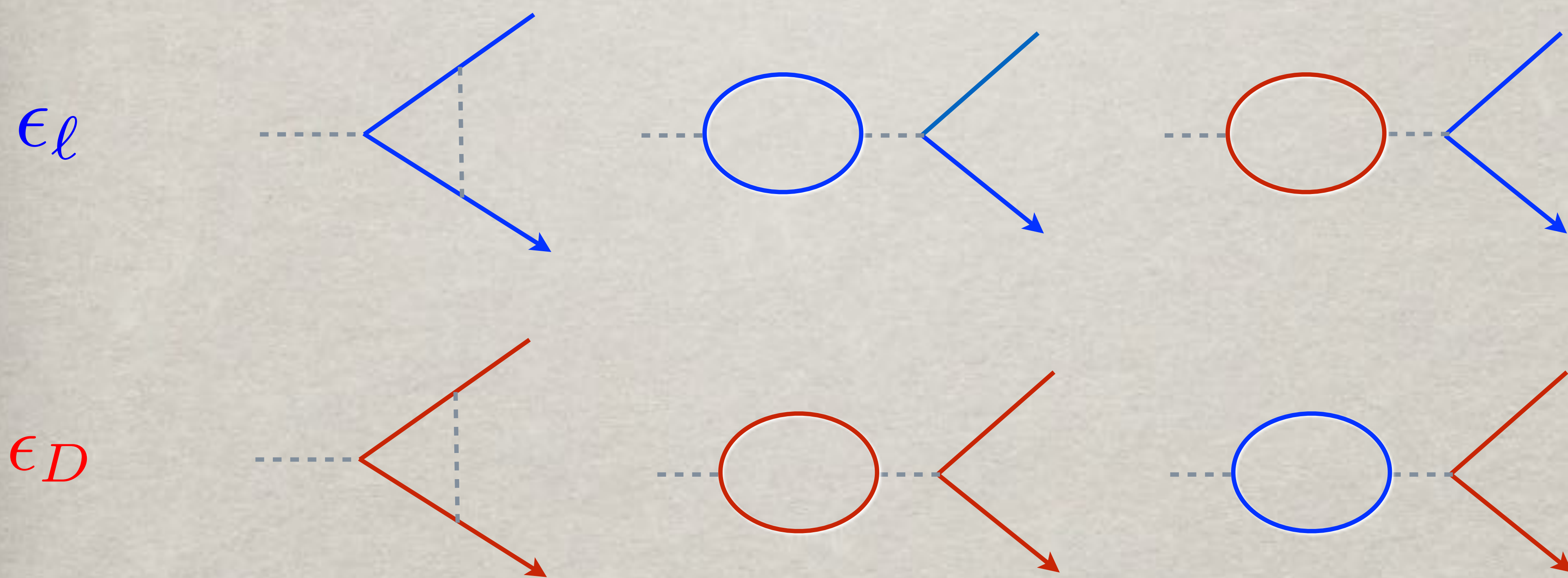


Need similar CP violation in both sectors !

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:



$$\epsilon_\ell = \epsilon_D$$

CP violation for ADM

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

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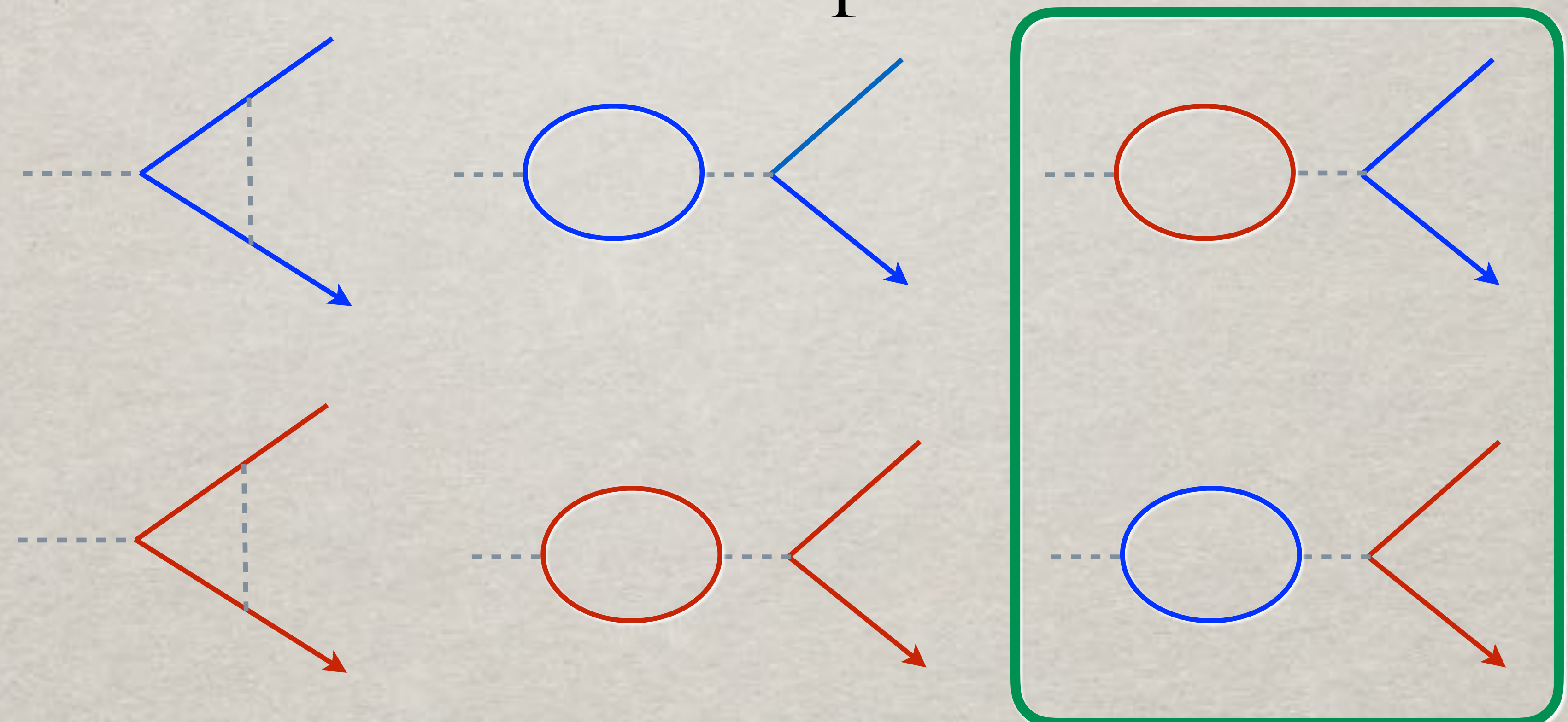
ϵ_ℓ

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:

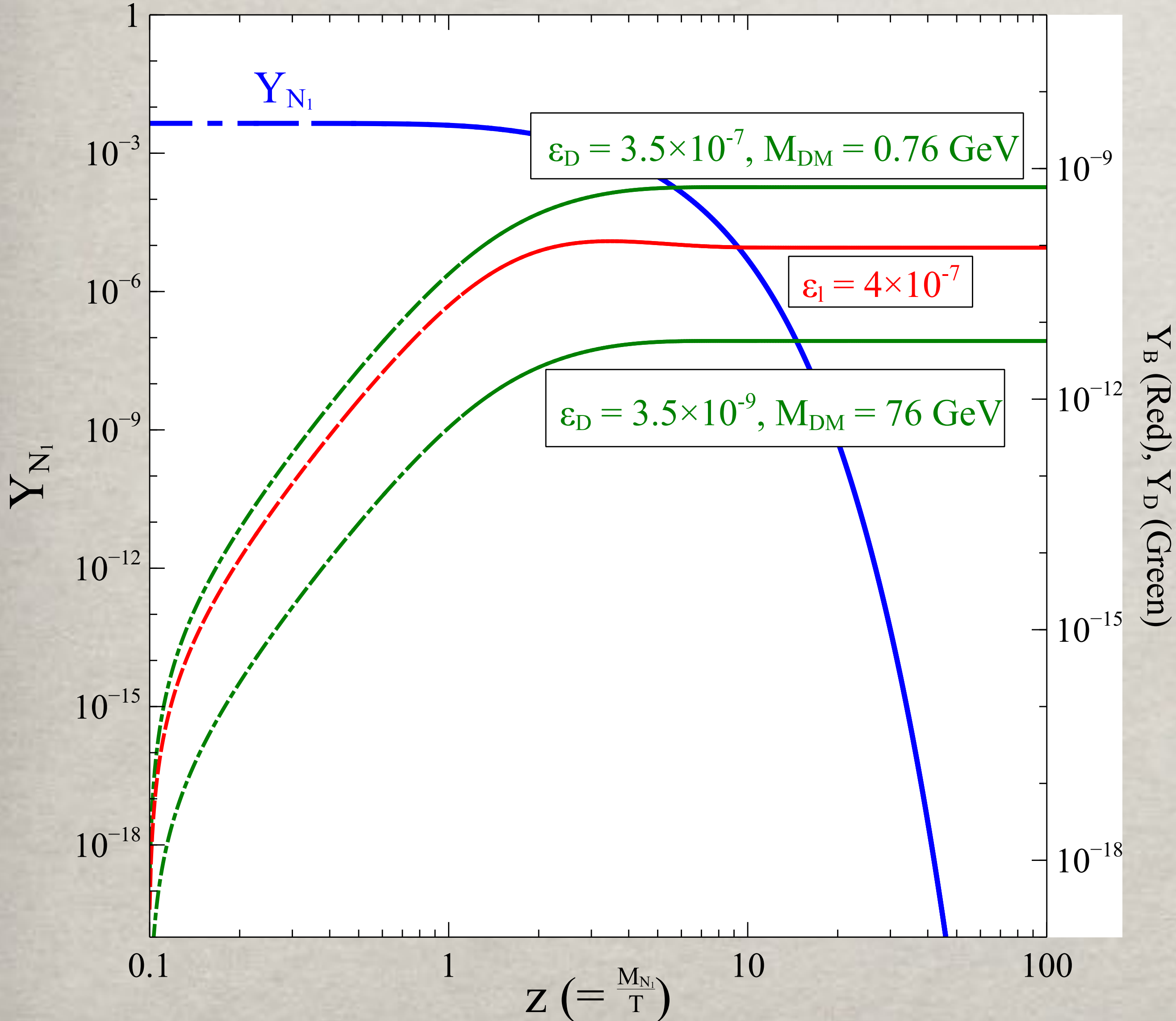
$$\frac{\epsilon_\ell}{\epsilon_D} = 1 + \frac{\mathrm{Im}\left[3((\mathrm{y}^\dagger \mathrm{y})^*_{12})^2\right]}{2\alpha_1\alpha_2 \mathrm{Im}\left[3(\mathrm{y}^\dagger \mathrm{y})^*_{12}\right]}$$

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

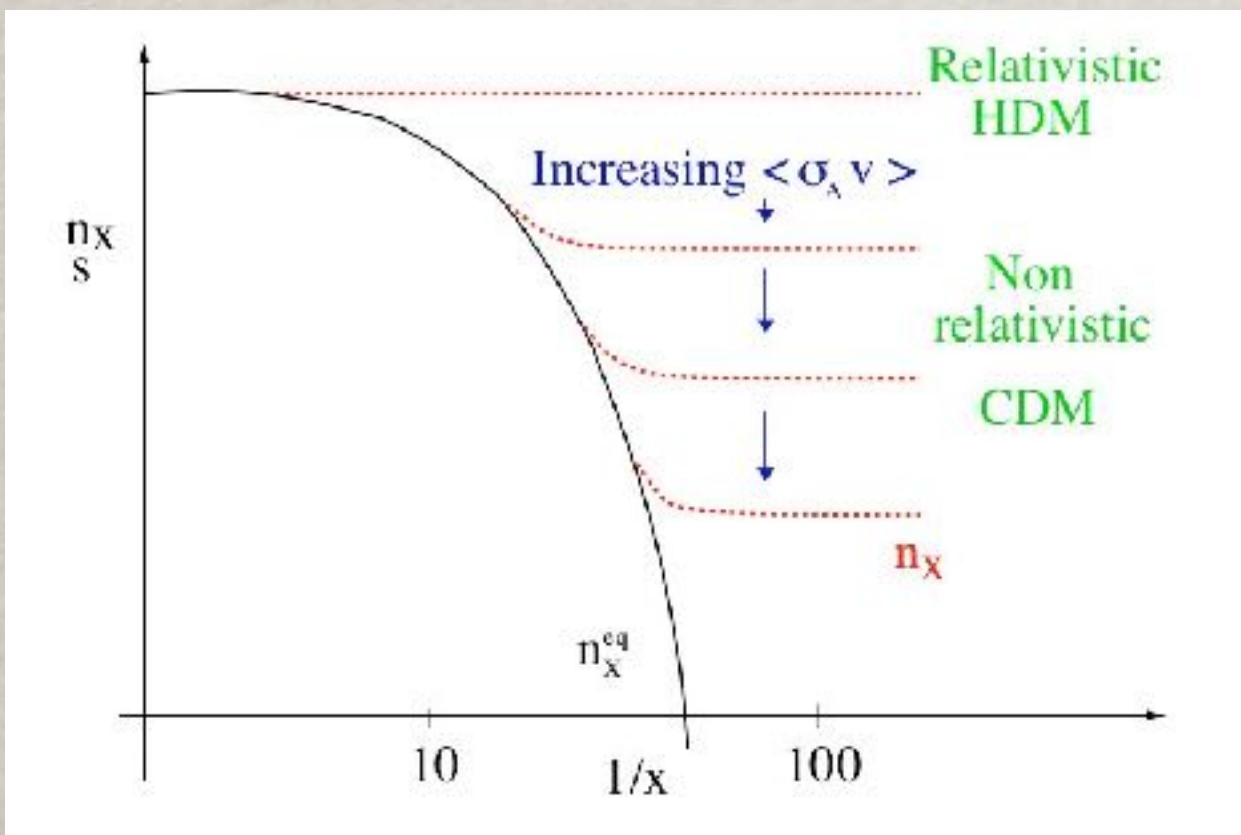
[A. Biswas, S. Choubey, LC & S. Khan 2018]



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).

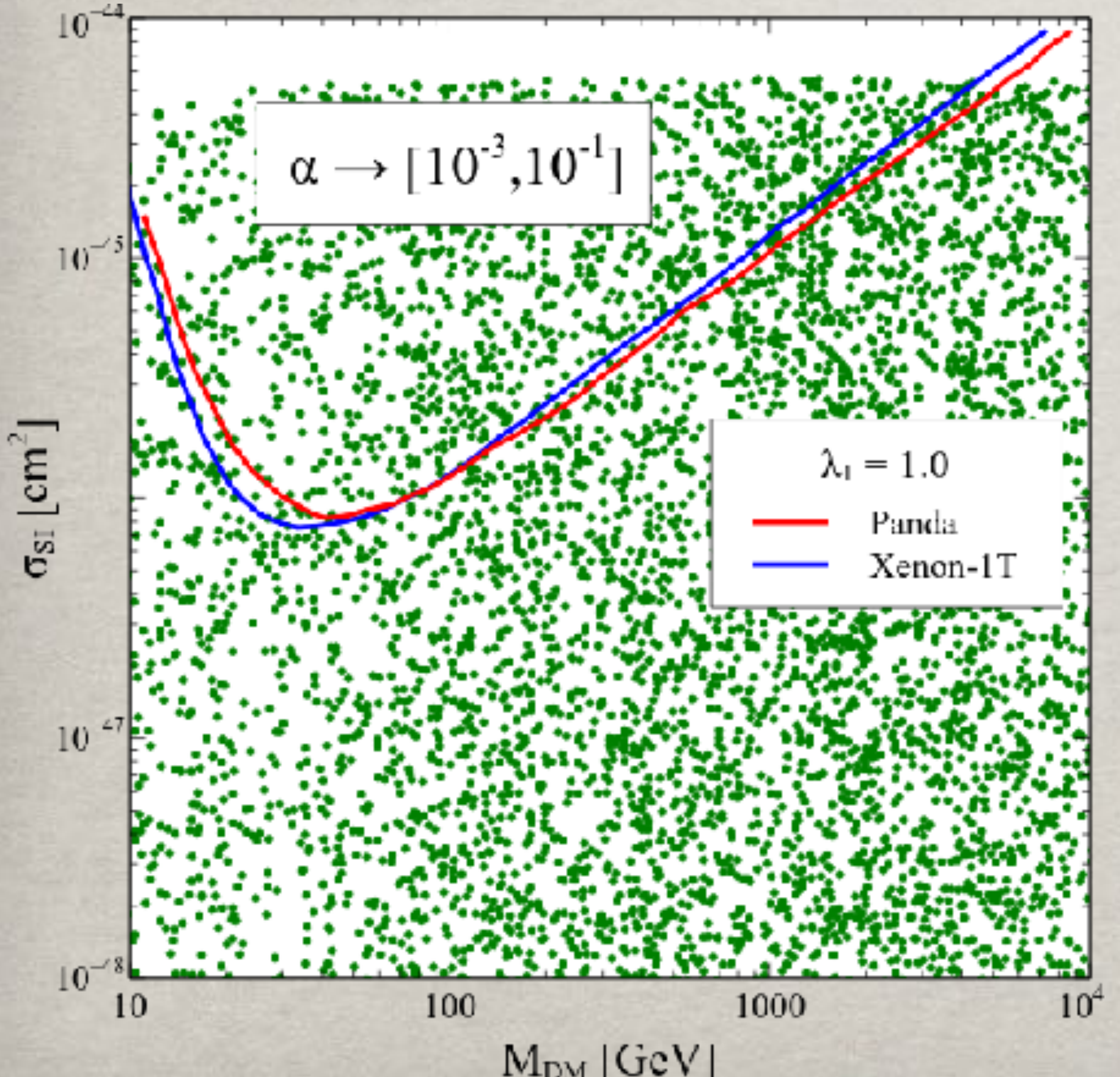


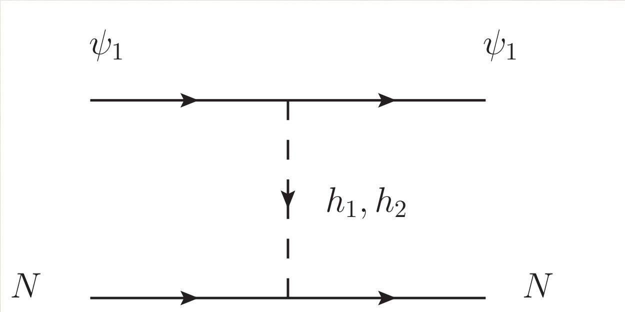
Strong coupling...
...like baryons !

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

DD in an 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!)

FIMP/SuperWIMP/ Decaying Dark Matter

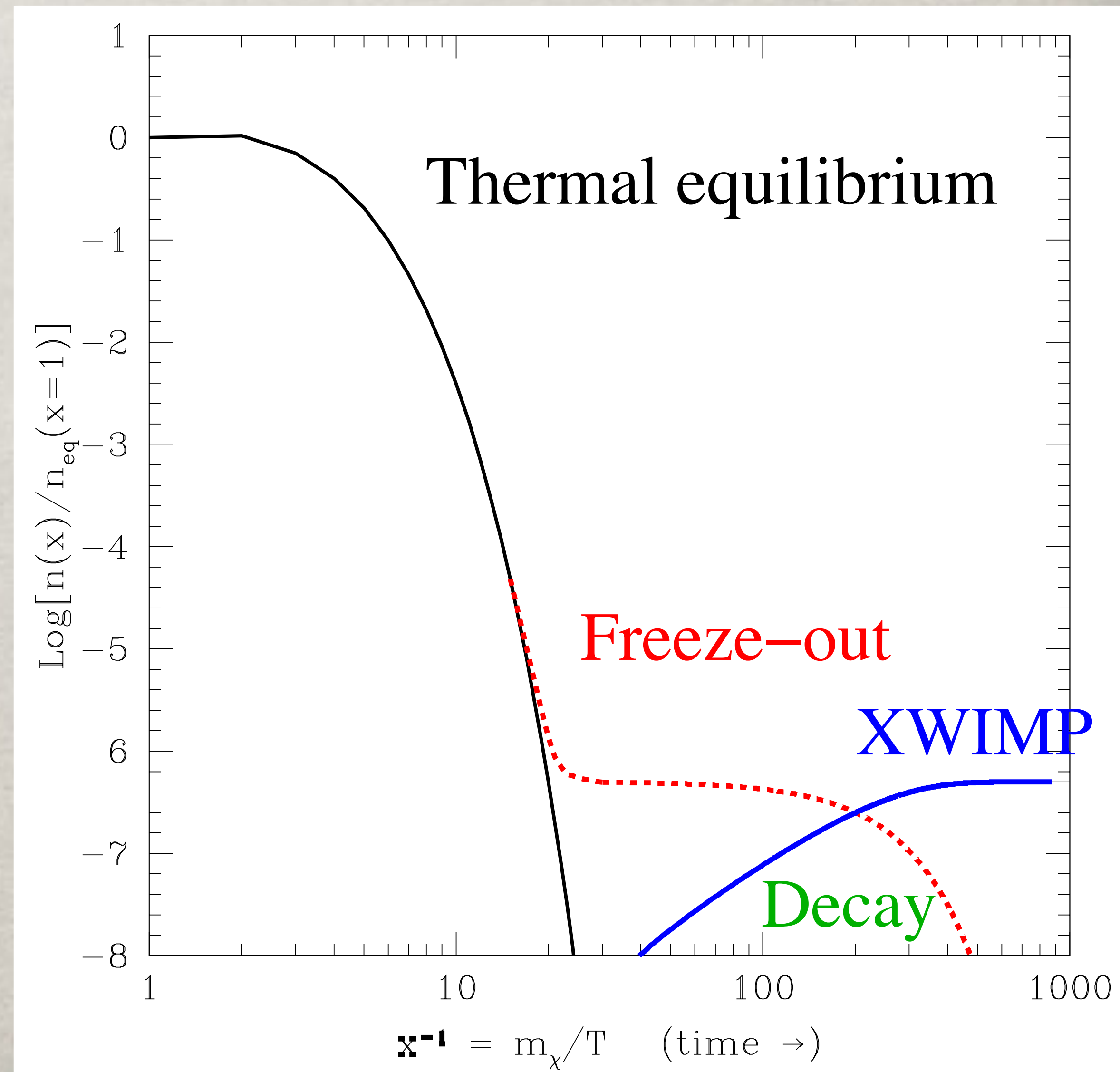
SuperWIMP mechanism

[JE Kim, A.Masiero, D.Nanopoulos *Phys.Lett.B* 139 (1984) 346-350]
[LC, JE Kim, L. Roszkowski *Phys.Rev.Lett.* 82 (1999) 4180-4183]
[J.L. Feng et al. *Phys.Rev.D* 68 (2003)063504]

- A long-lived WIMP particle can decay after decoupling and produce the DM population:

$$\Omega_X^{NT} = \frac{m_X}{m_{NLSP}} \Omega_{NLSP}$$

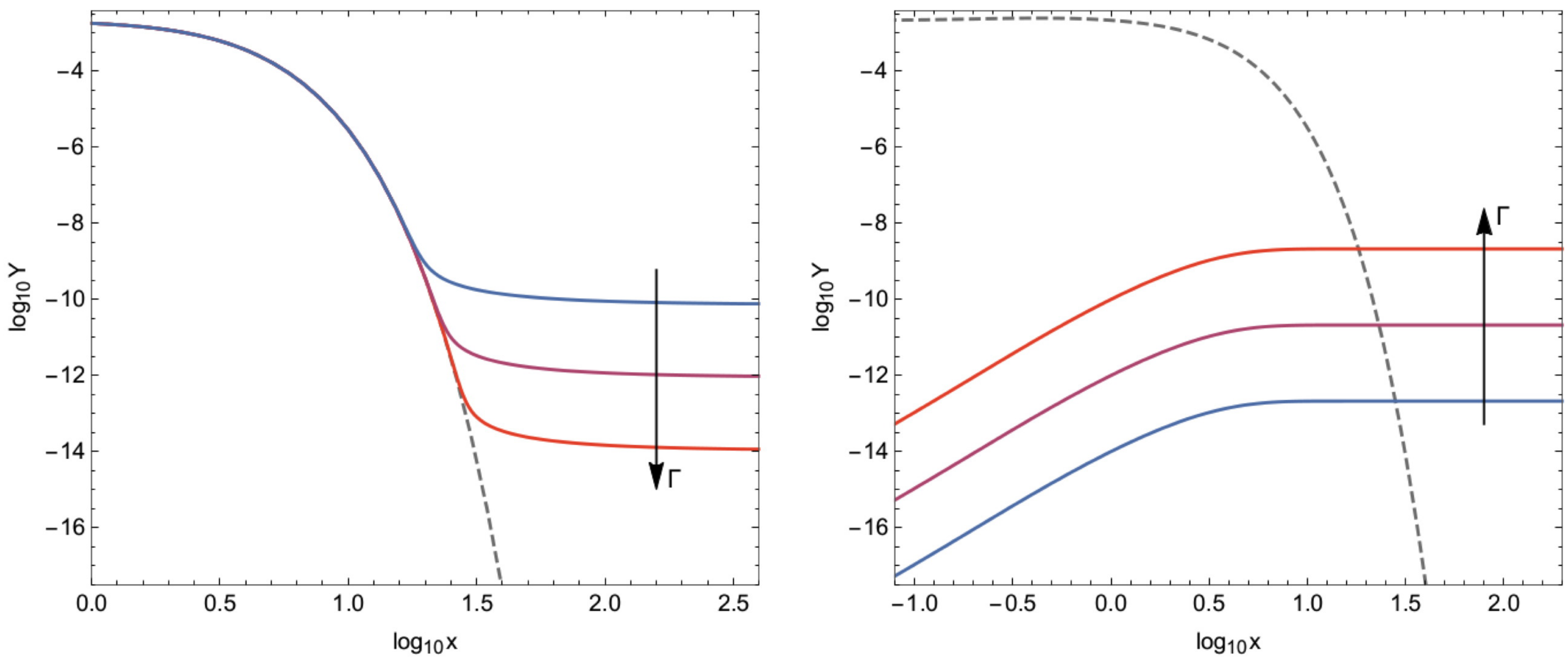
- In the decay also other particles are produced, but they should not disrupt BBN or any other cosmological observable...



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.

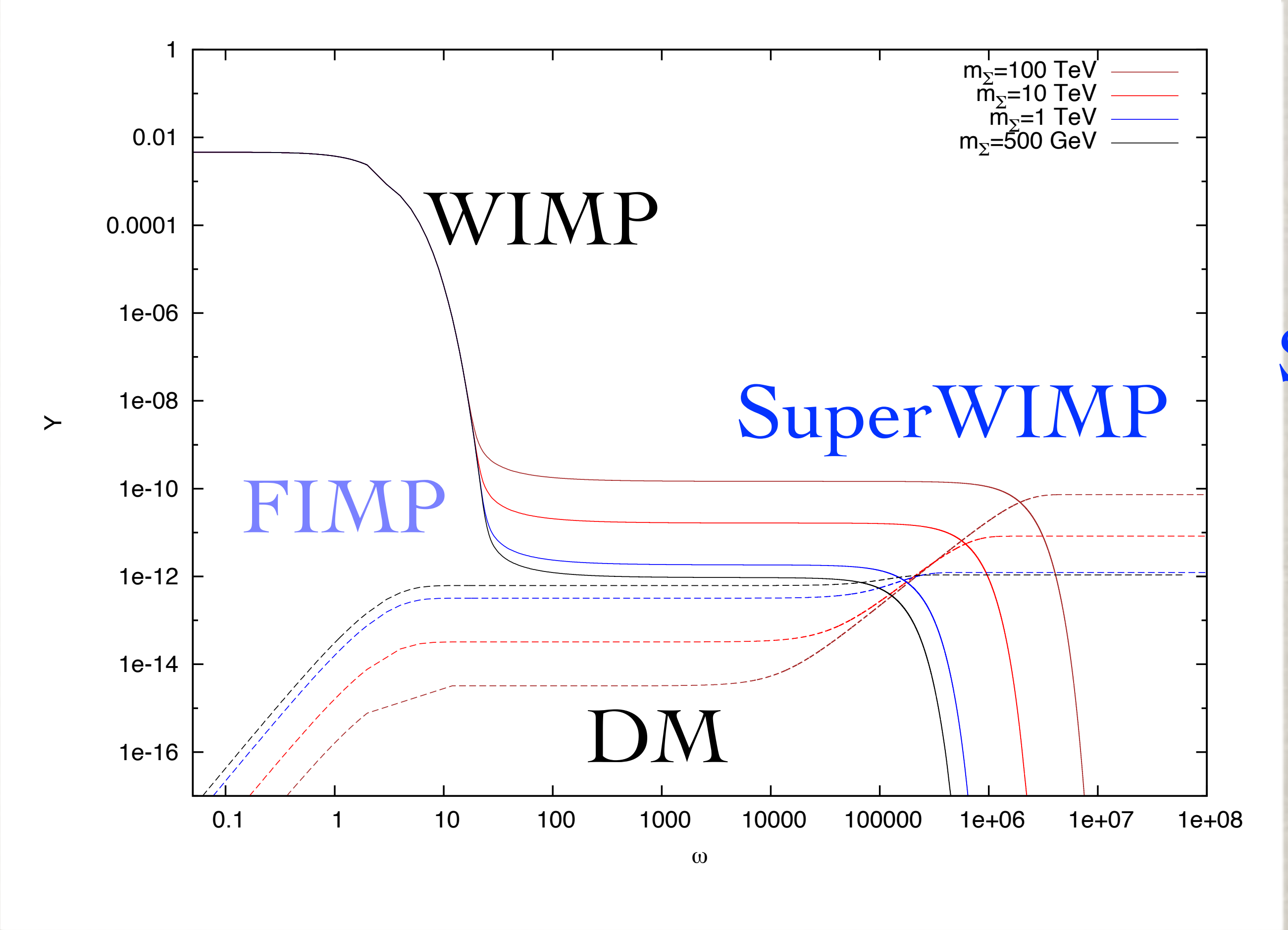
Same Boltzmann equation, but different dynamics !

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

SuperWIMP / FIMP

- 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:

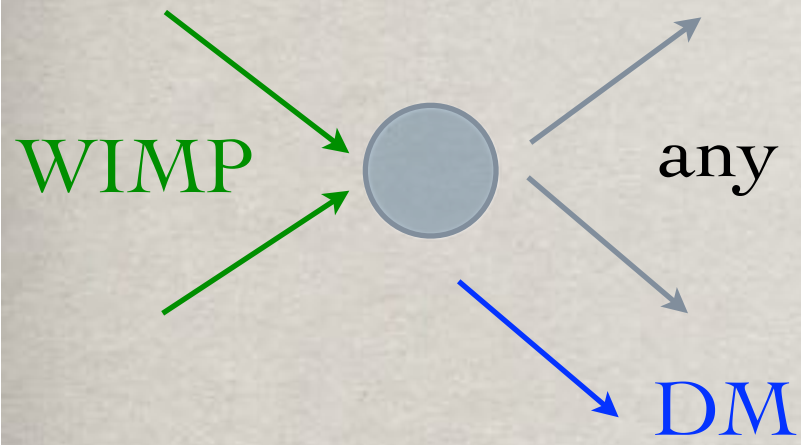
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} \, BR(\Sigma \to \psi) \, \Omega_\Sigma h^2$$

- 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

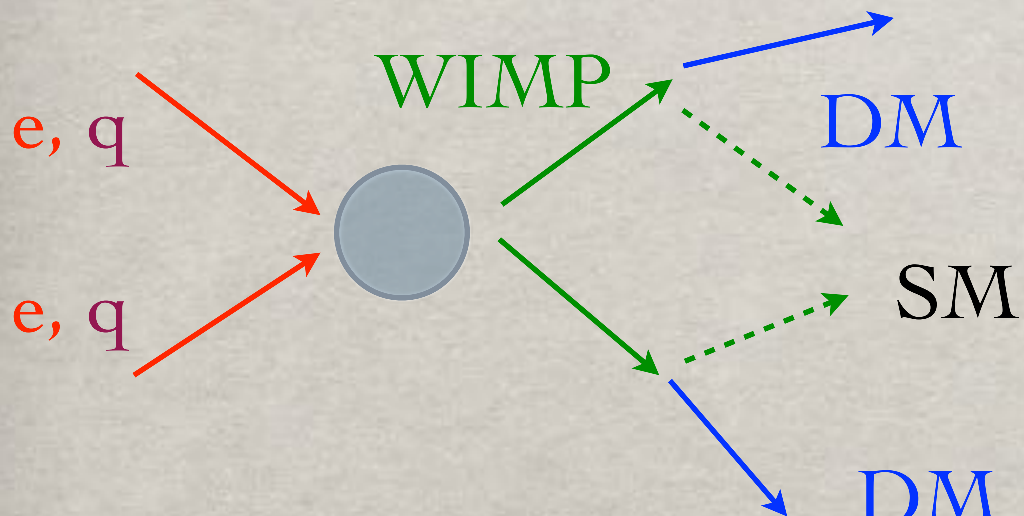
Early Universe: $\Omega_{CDM} h^2$



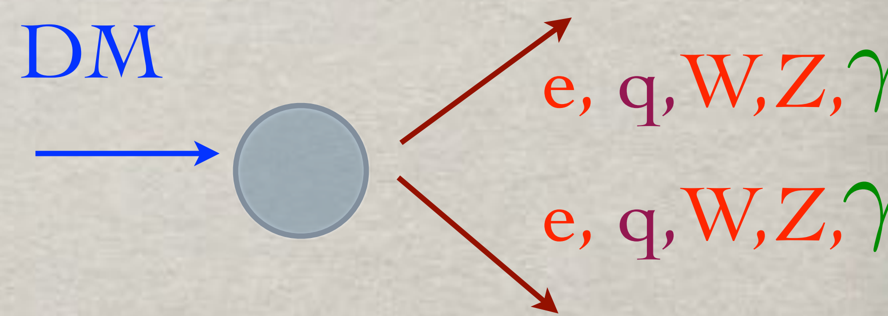
Direct Detection:

NONE...

Colliders: LHC/ILC



Indirect Detection:

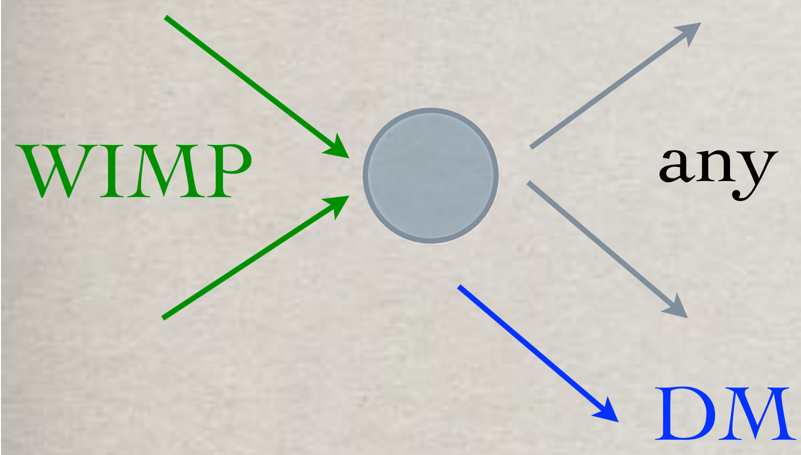


decaying DM !

3 different ways to check this hypothesis !!!

F/SWIMP CONNECTION

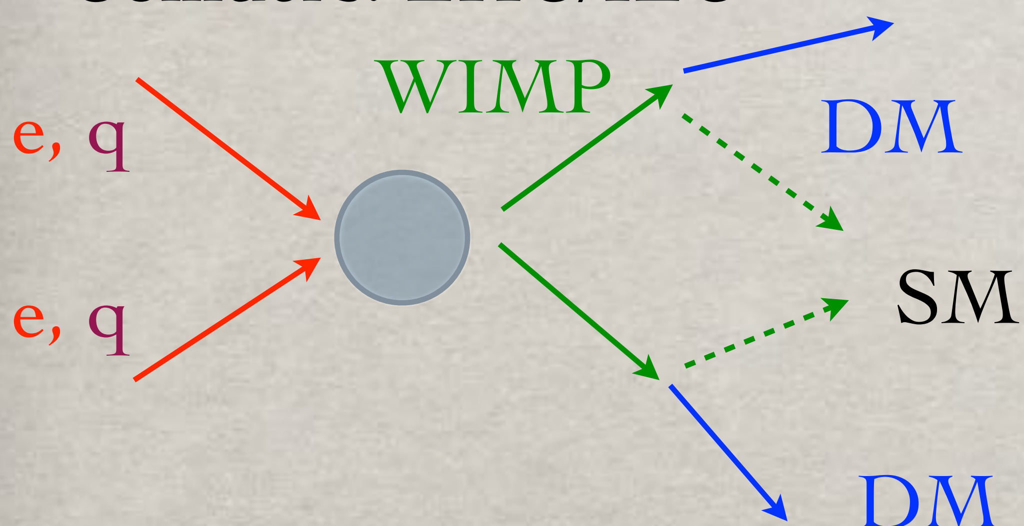
Early Universe: $\Omega_{CDM} h^2$



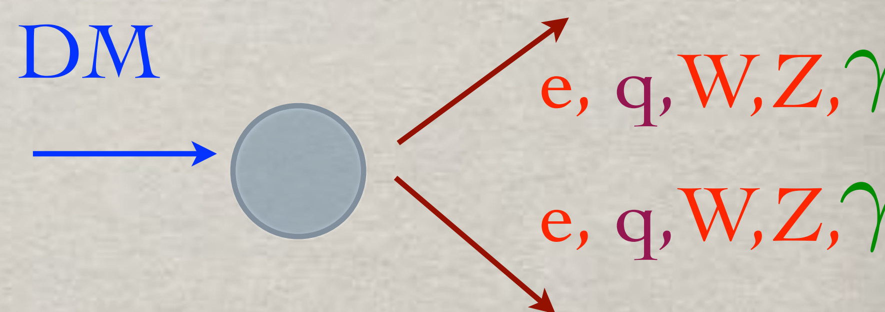
Direct Detection:

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

Colliders: LHC/ILC



Indirect Detection:



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F/SWIMP CONNECTION

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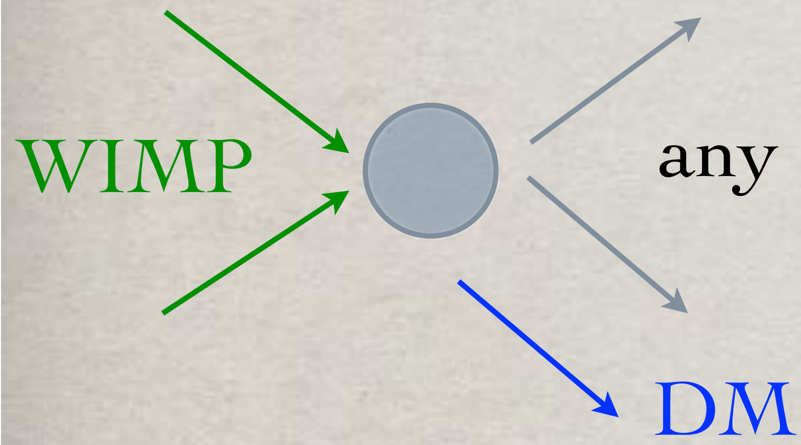

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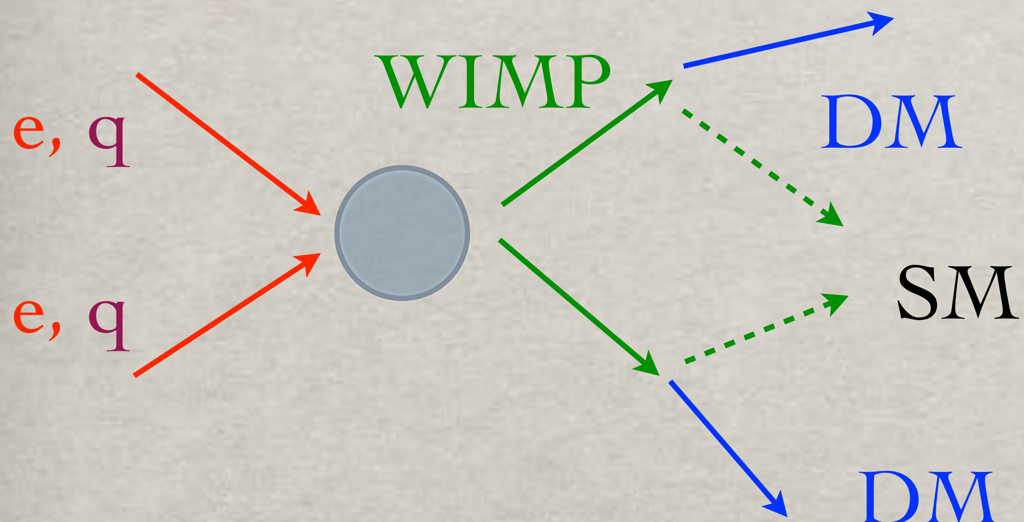
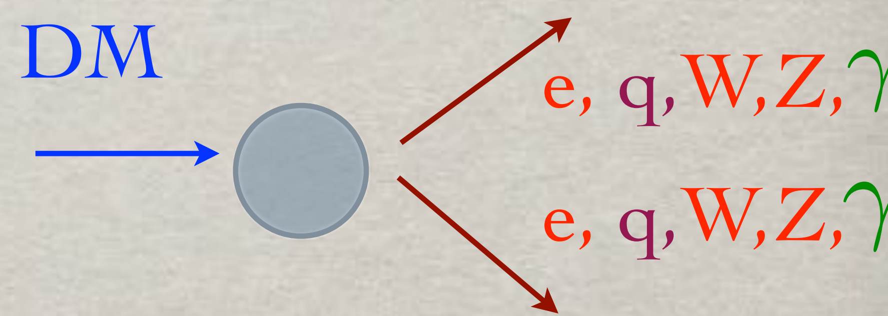


Indirect Detection:



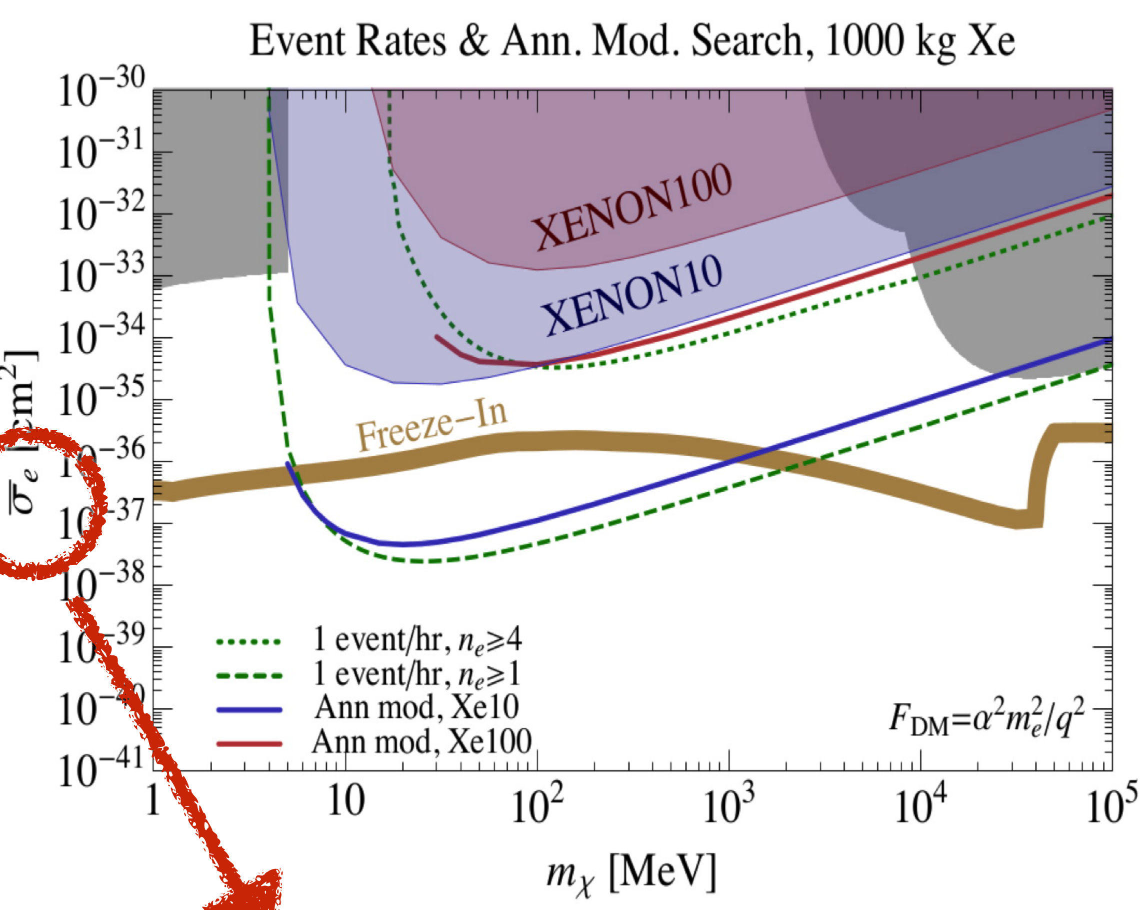
decaying DM !

3 different ways to check this hypothesis !!!

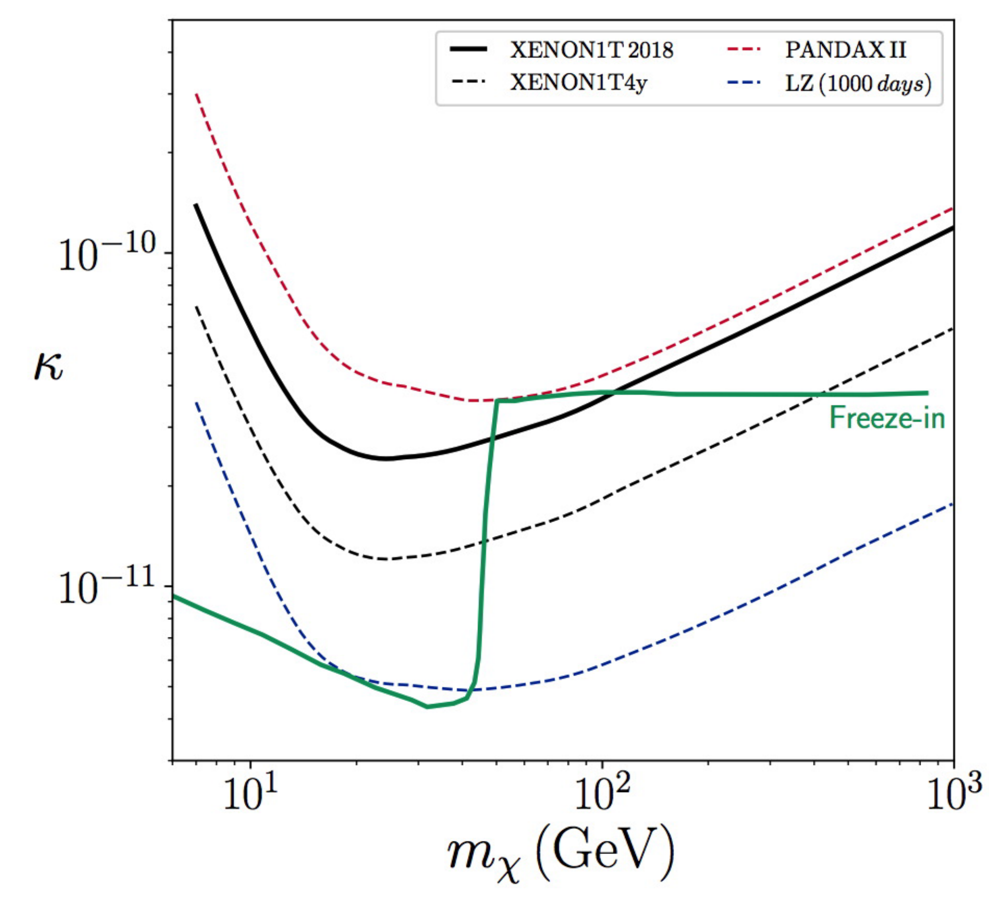
Direct detection of FIMPs

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 !!!

But also low T_RH: F. Costa

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 :

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

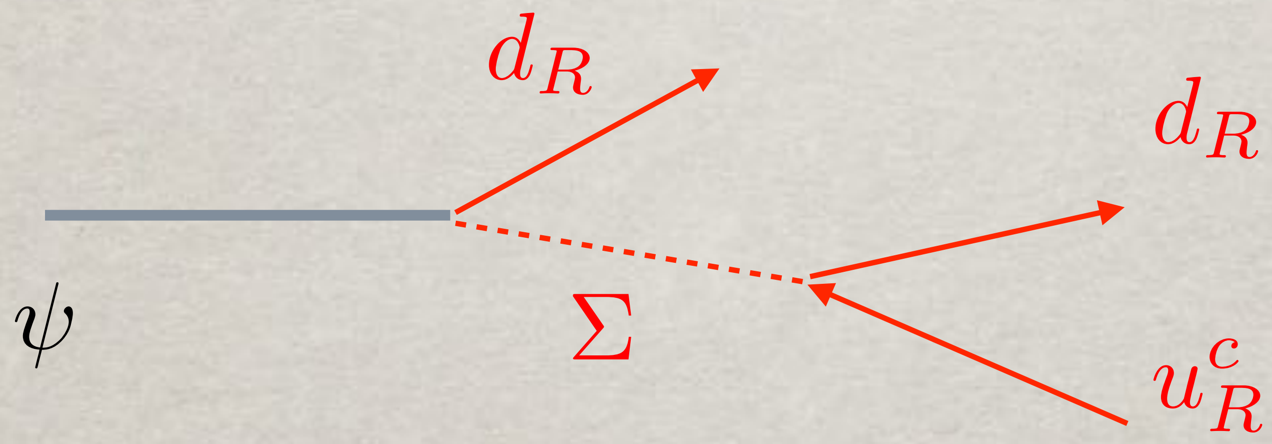
Try to find a cosmologically interesting scenario where the scalar particle is produced at the LHC and DM decays with a lifetime observable by indirect detection.
Then the possibility would arise to measure the parameters of the model in two ways !

→ 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

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

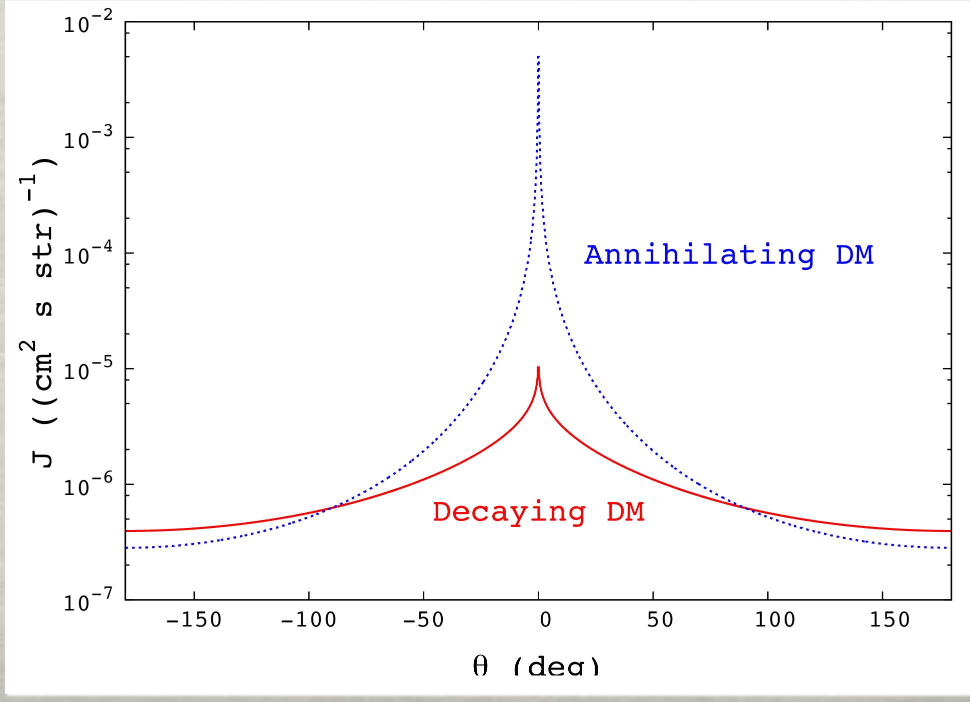
DECAYING DM

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

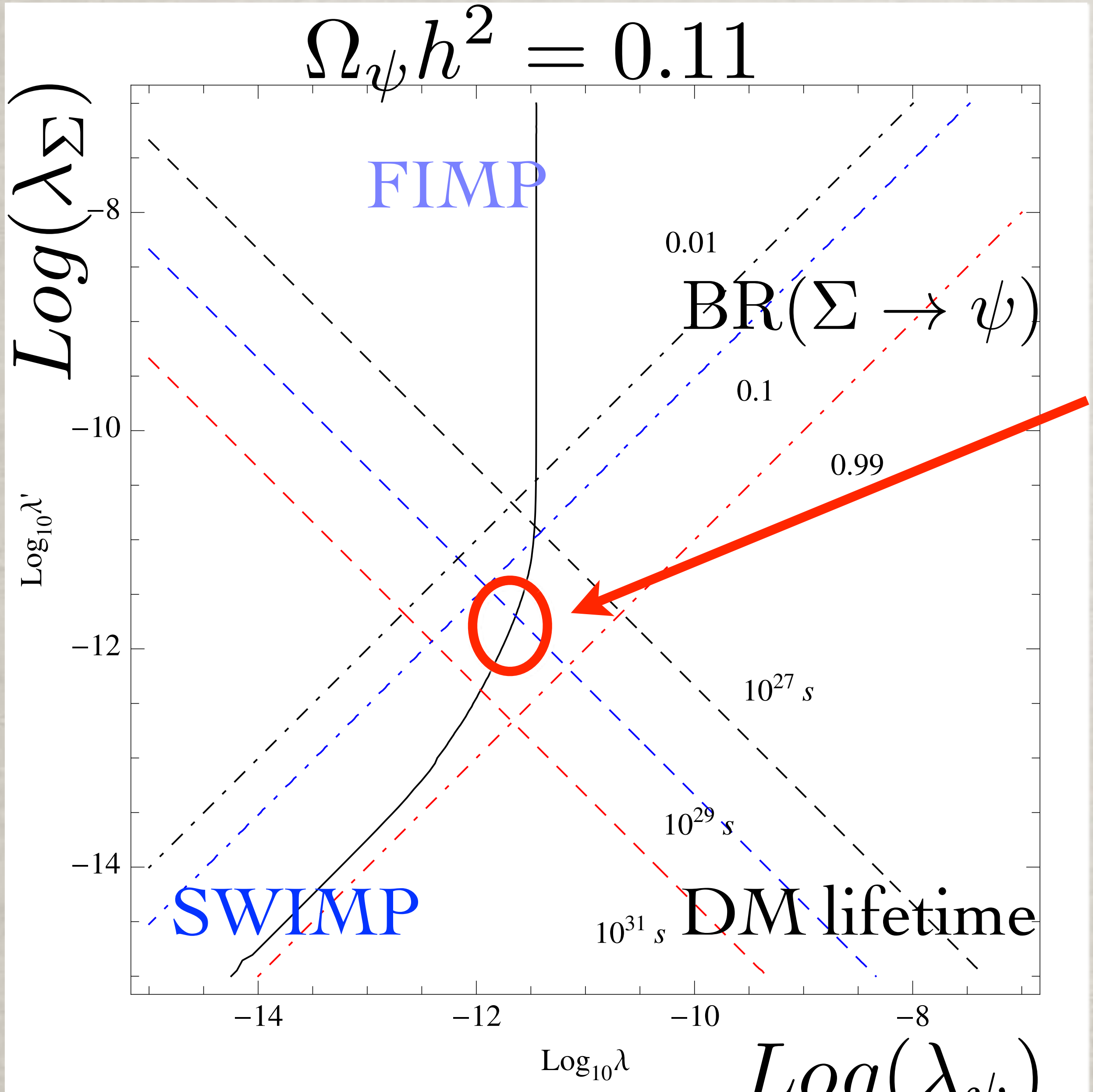
$$\Phi(\theta, E) = \frac{1}{\tau_{DM}} \frac{dN_i}{dE} \frac{1}{4\pi m_{DM}} \int_{l.o.s.} ds\ \rho(r(s,\theta))$$

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...

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

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 !!!

Σ Combined detection

Still possible to have multiple detection of

- DM decay:

$m_\psi \quad \Gamma_\psi \to \lambda\lambda'$

- displaced vertices

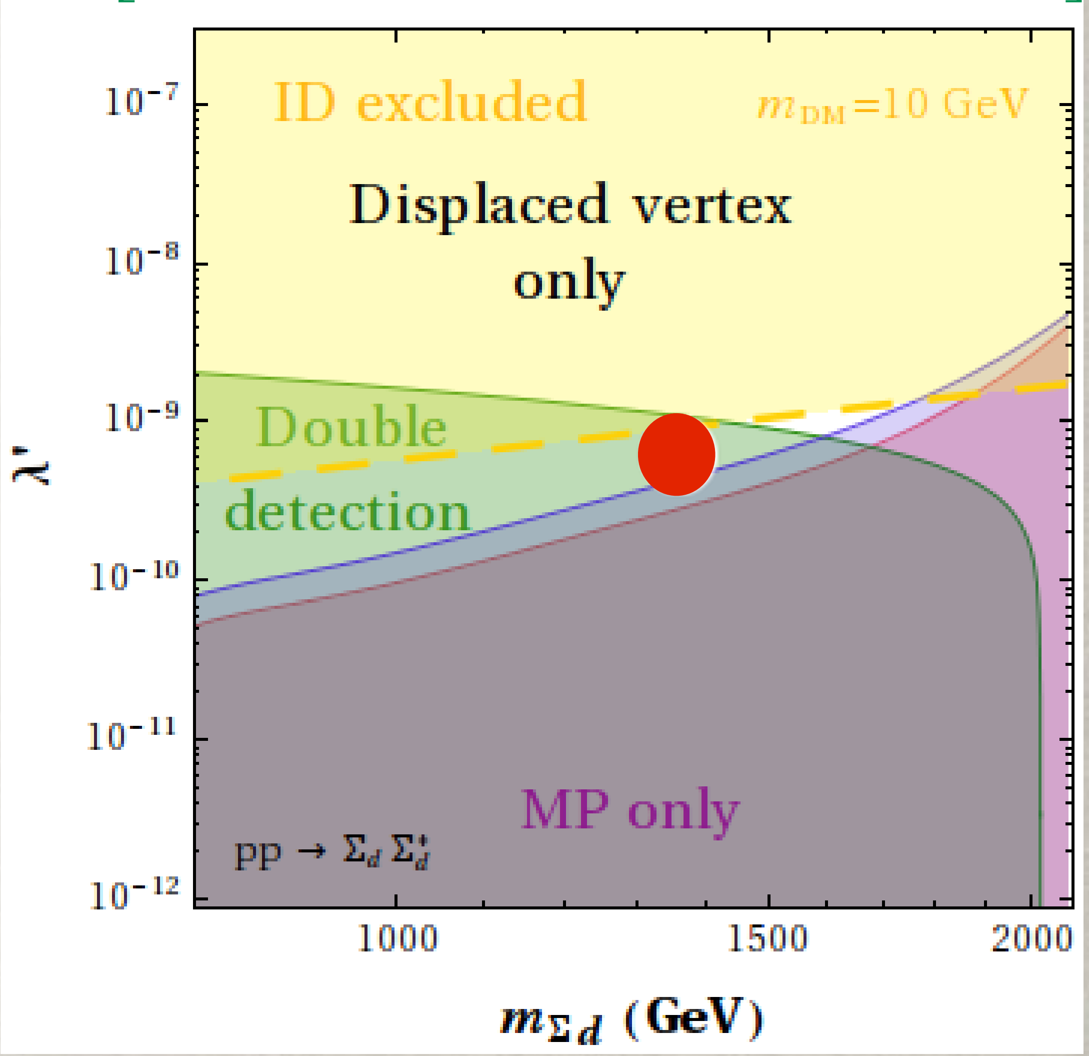
$m_\Sigma \quad \Gamma_{\Sigma,SM} \to \lambda'$

- metastable tracks

$m_\Sigma \quad \Gamma_{\Sigma,SM} < X \to \lambda'$

with stopped tracks maybe both $\Gamma_{\Sigma,SM}, \Gamma_{\Sigma,DM}$

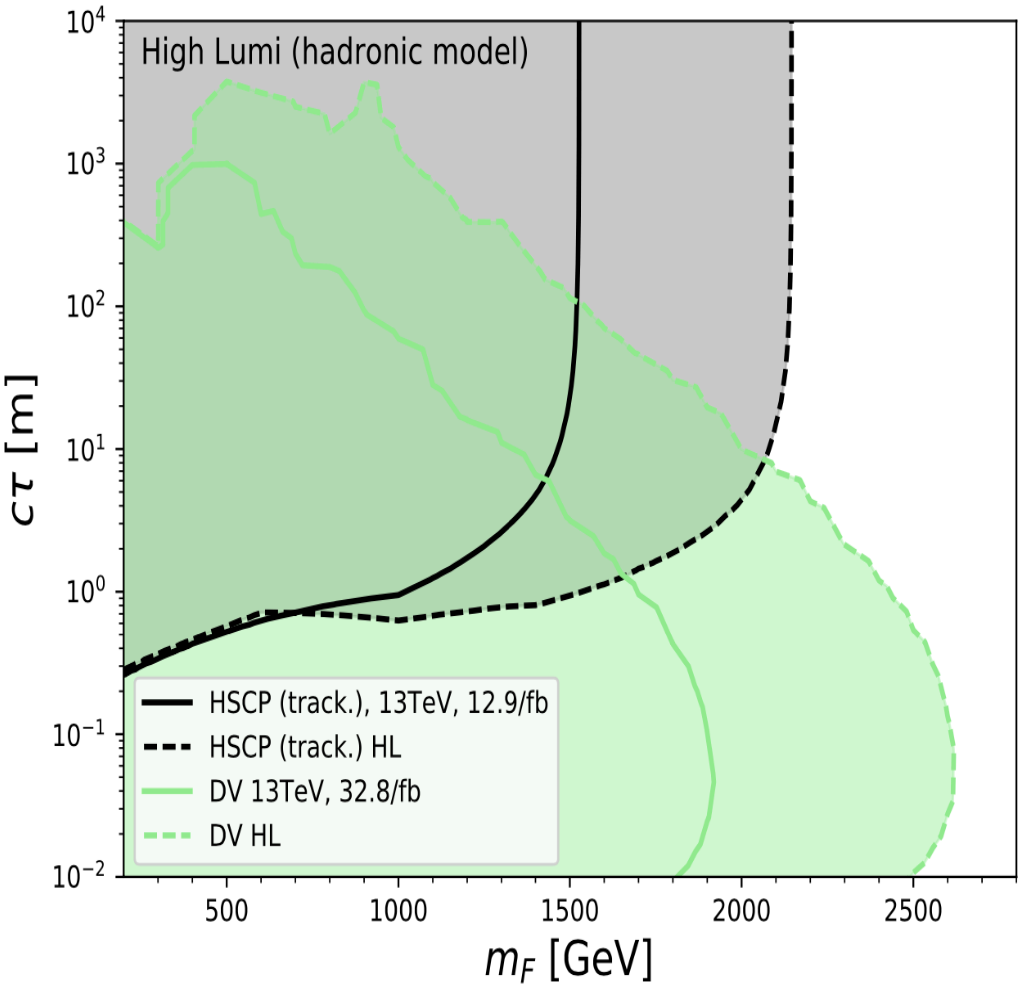
[G. Arcadi, LC & F. Dradi 1408.1005]



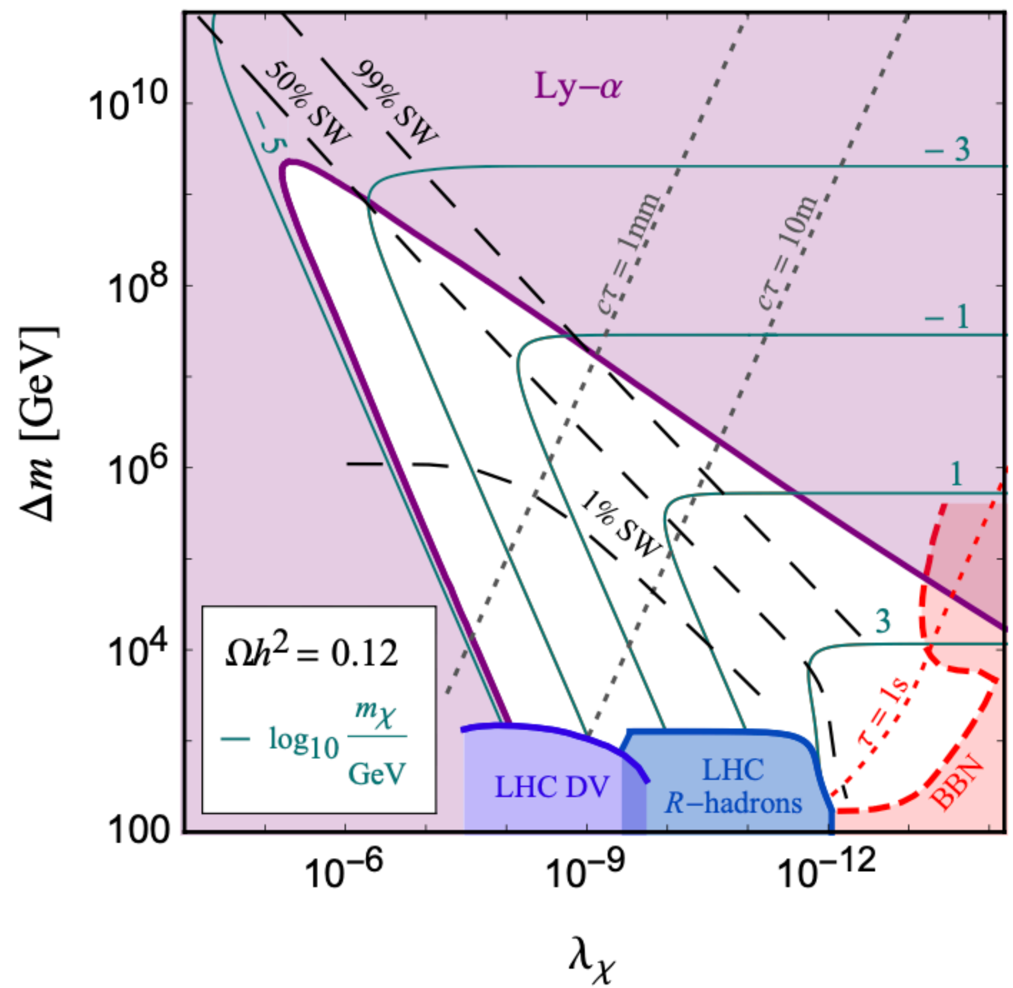
It is possible to over-constraint the model and check the hypothesis of FIMP production !

LHC and Cosmo bounds

[G. Belanger et al. 1811.05478]



[Q. Decant et al. 2111.09321]



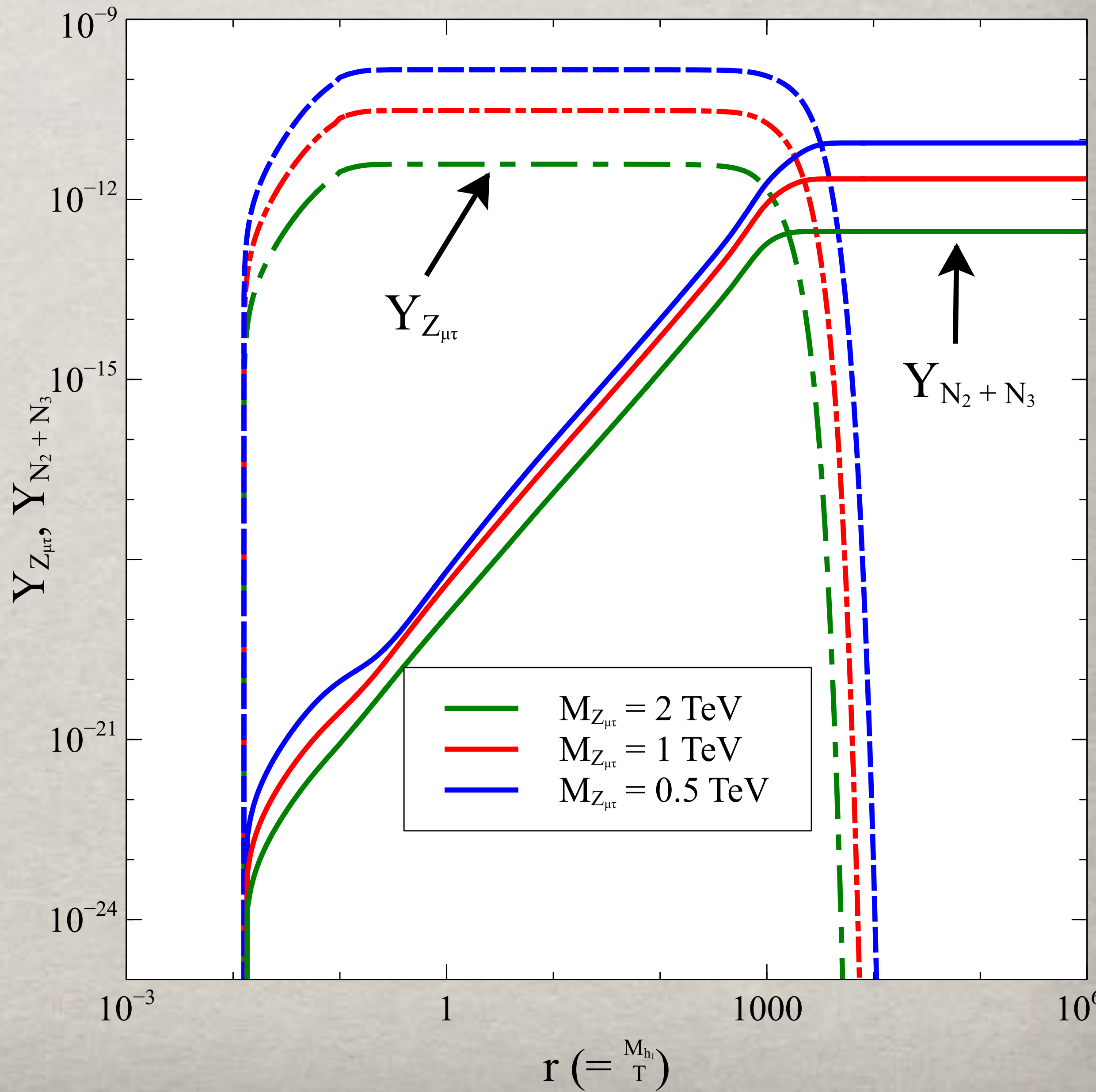
Here DM is the scalar and the Fermion is charged under QCD

FIMP FROM A FIMP: SFIMP

[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:

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



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:

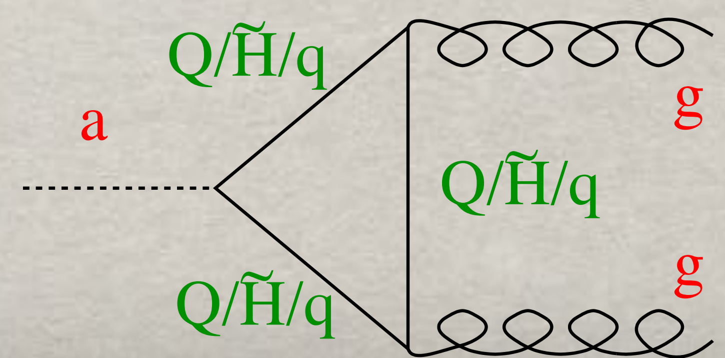
['t Hooft 76]

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

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

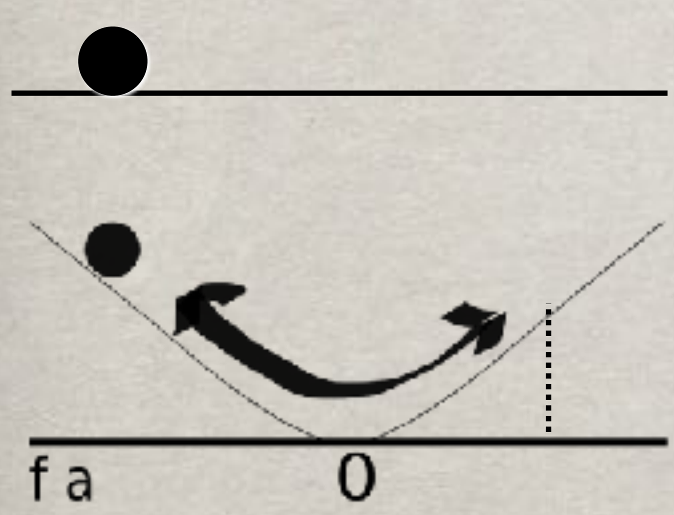
Peccei-Quinn solution: add a chiral global U(1) and break it spontaneously at f_a , leaving the axion, a pseudo-Goldstone boson, interacting as

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



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

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

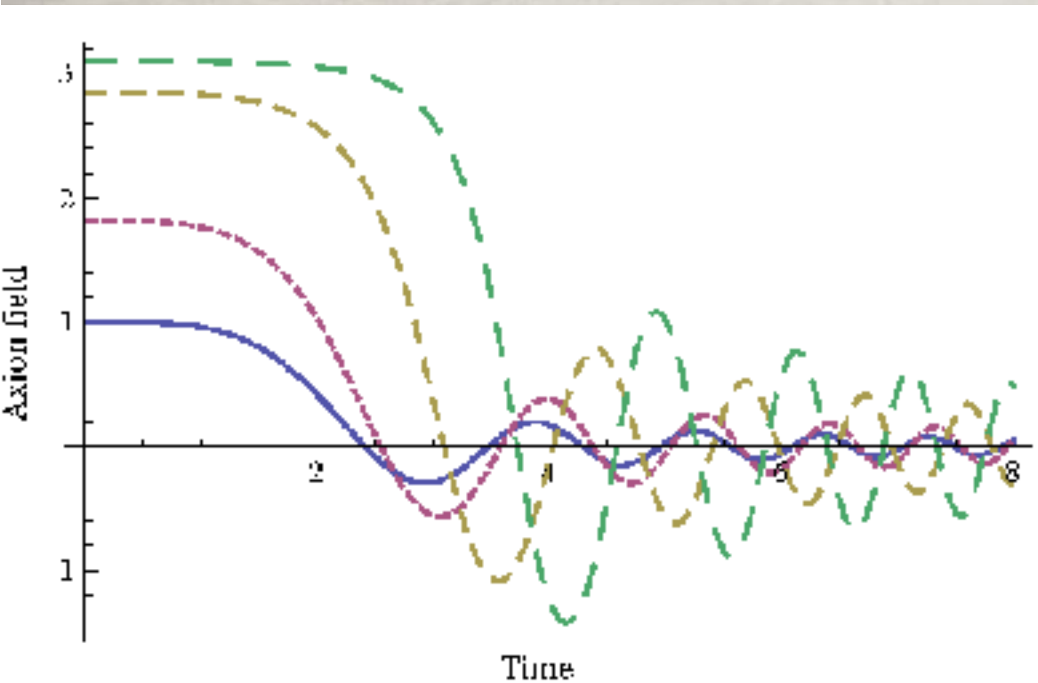
by instanton's effects and the axion starts to oscillate coherently around the minimum:

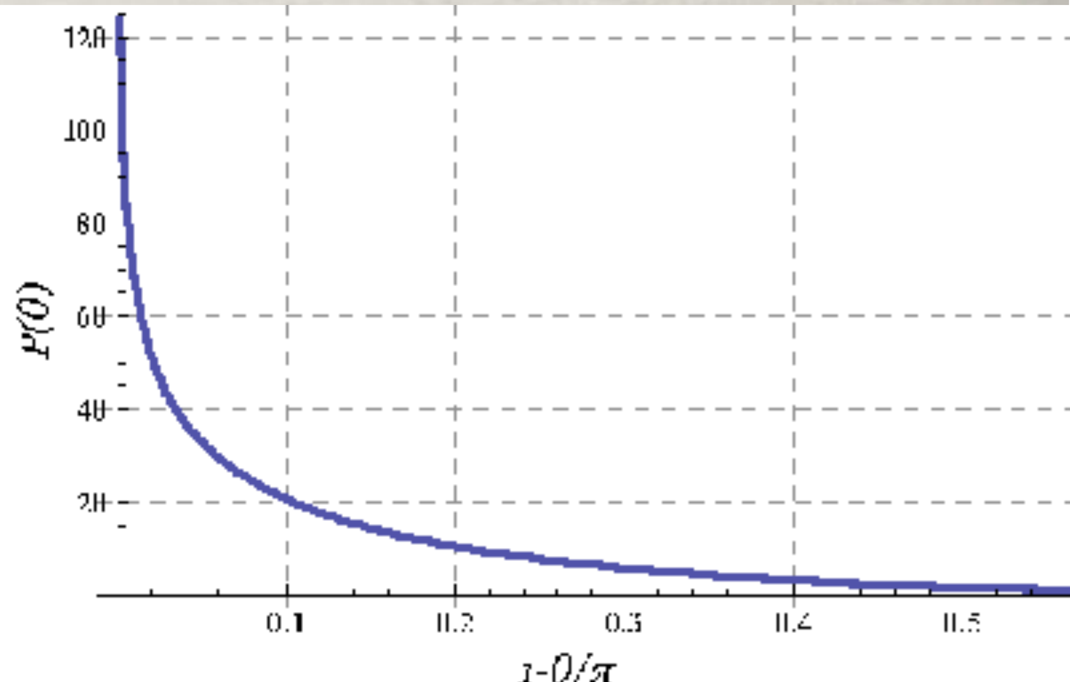
zero momentum particles >> CDM !

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

Axion's 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

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

Axions can contribute to star/SN cooling and so

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

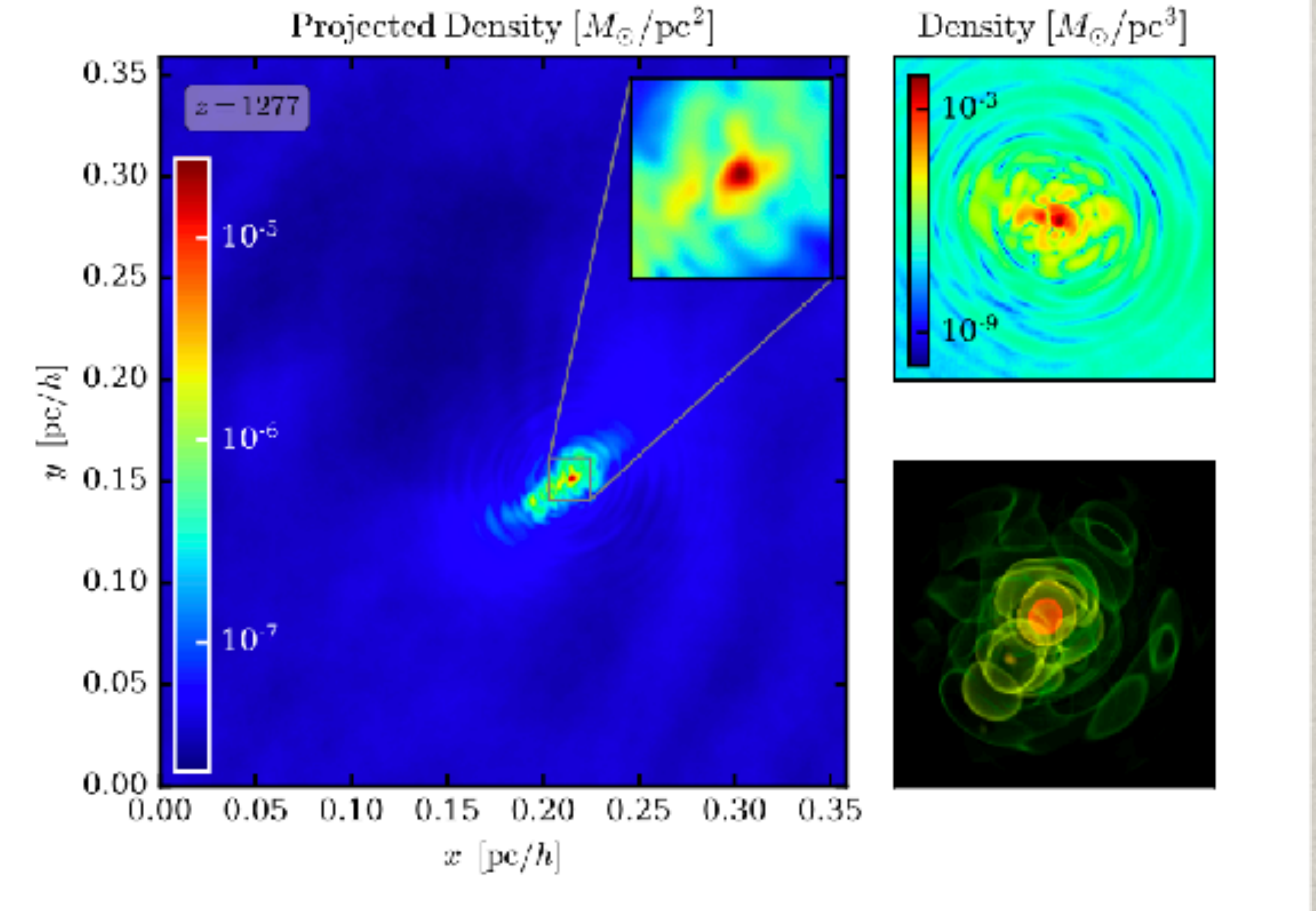
[Raffelt 98]

Therefore the mass for axion DM is very small:

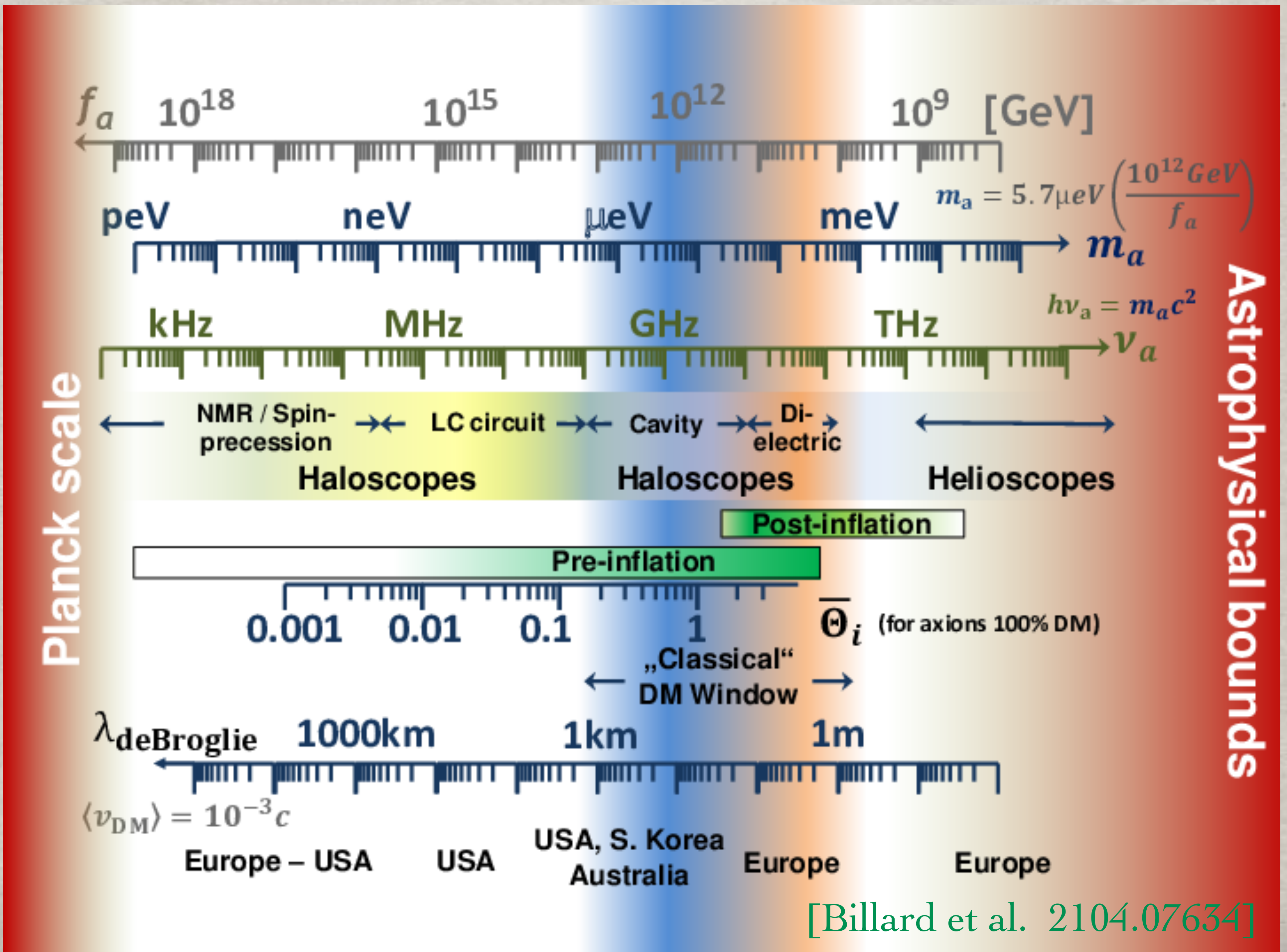
$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\mathrm{eV} \left(\frac{f_a}{10^{11}\mathrm{GeV}} \right)^{-1}$$

Axion miniclusters/stars

[Eggemeier & Niemeyer 2019]



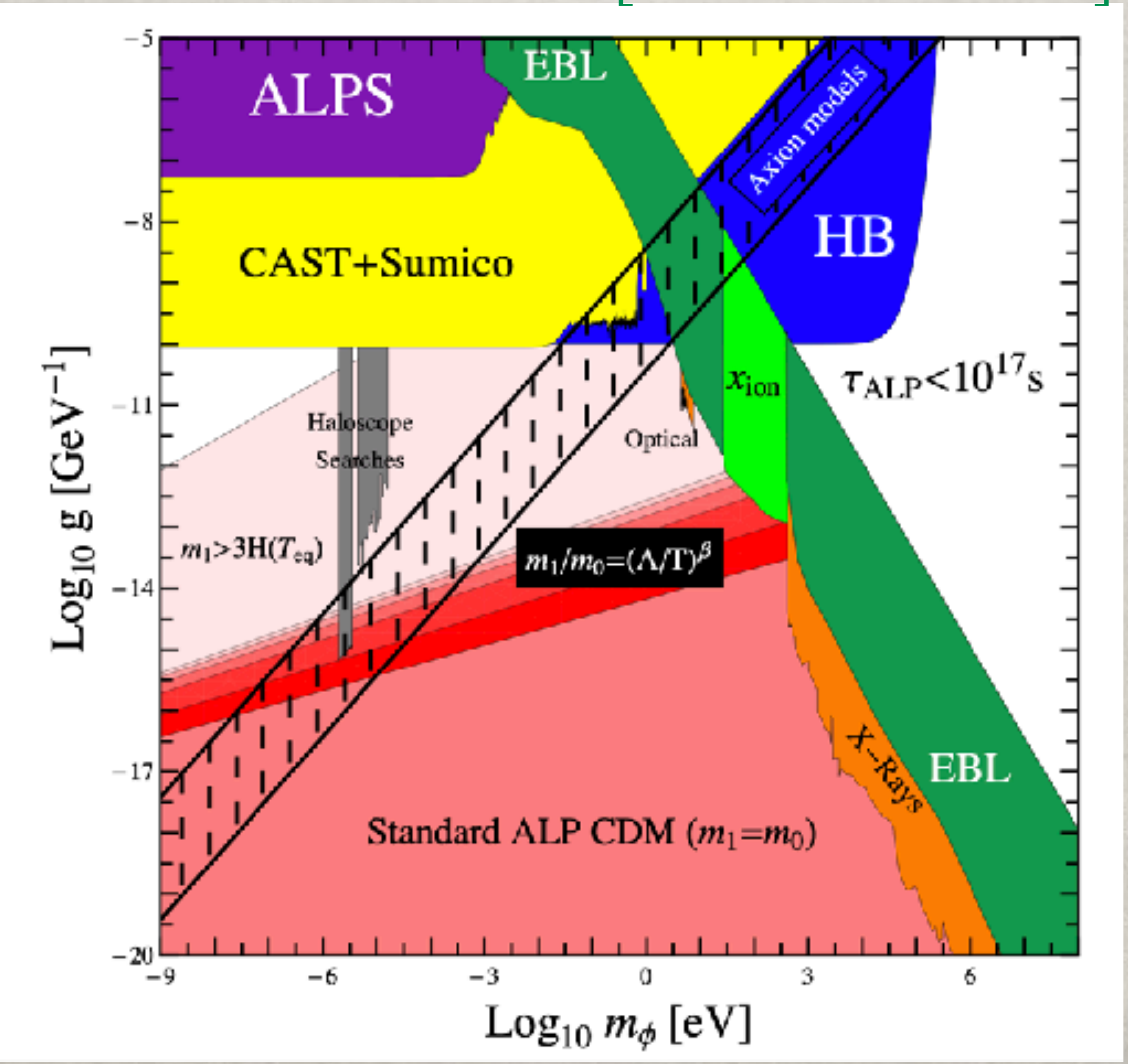
Axion's constraints



[Billard et al. 2104.07634]

ALPS DM

[Arias et al 1201.5902]



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:

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

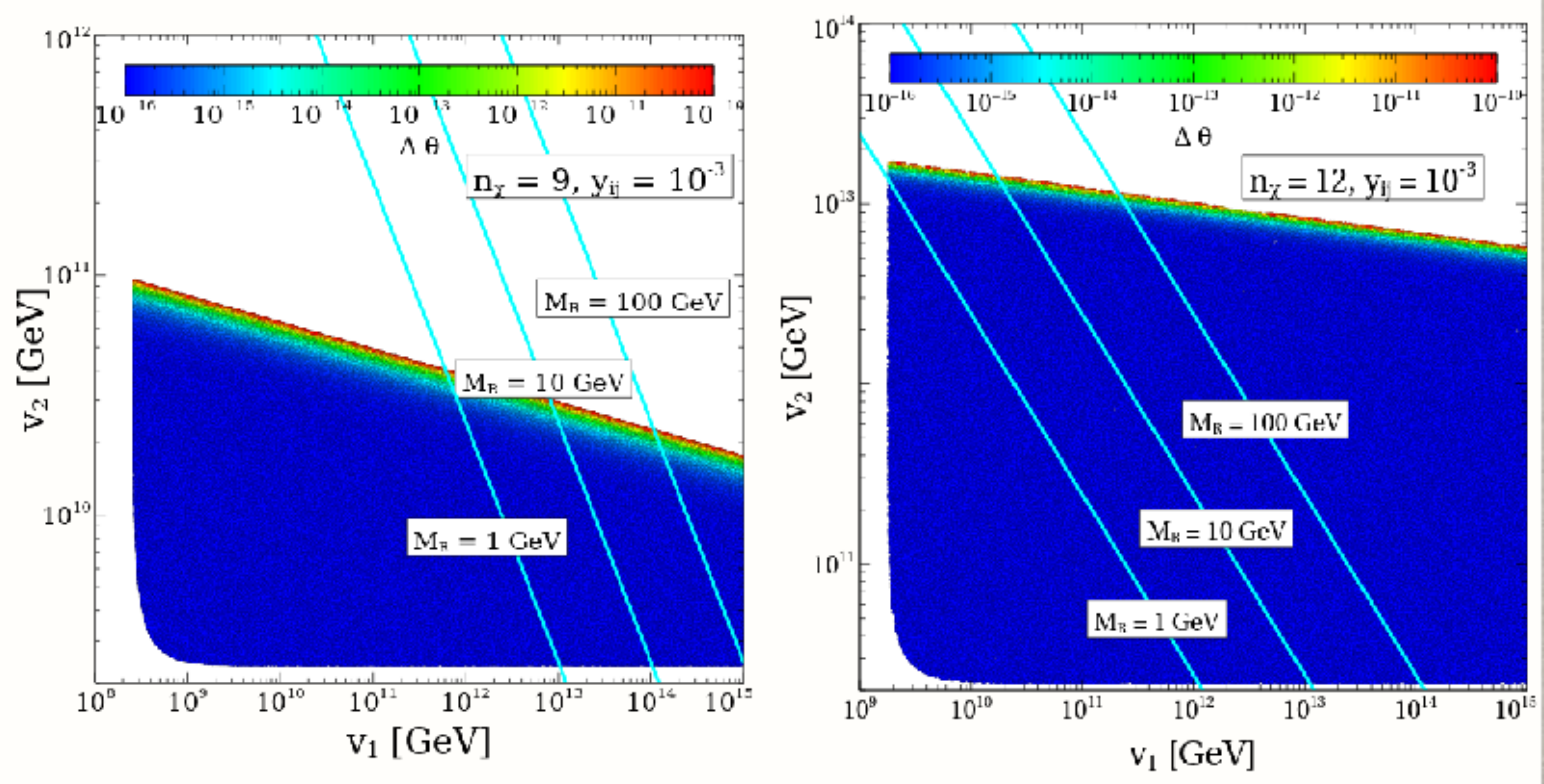
together with the lower bound in f_a from astrophysics, it implies that about 10 exotic fermions should be present to avoid the a too large contribution to the neutron EDM !

The minimum of the axion potential is shifted !

Axion & EDMs

Viable axion with EDMs maybe behind the corner…

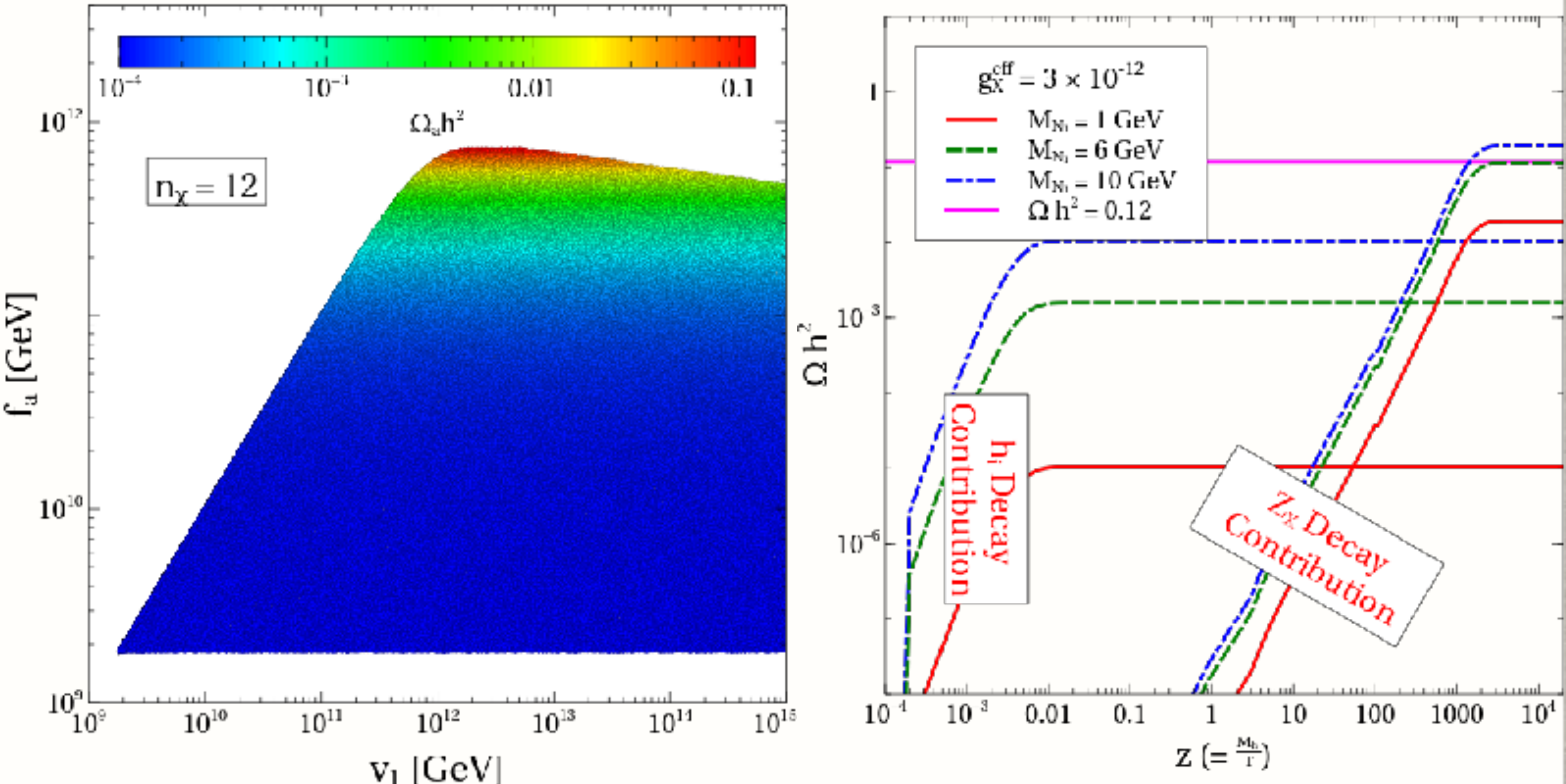
[LC & S. Khan 2022]



Axion & FIMP DM

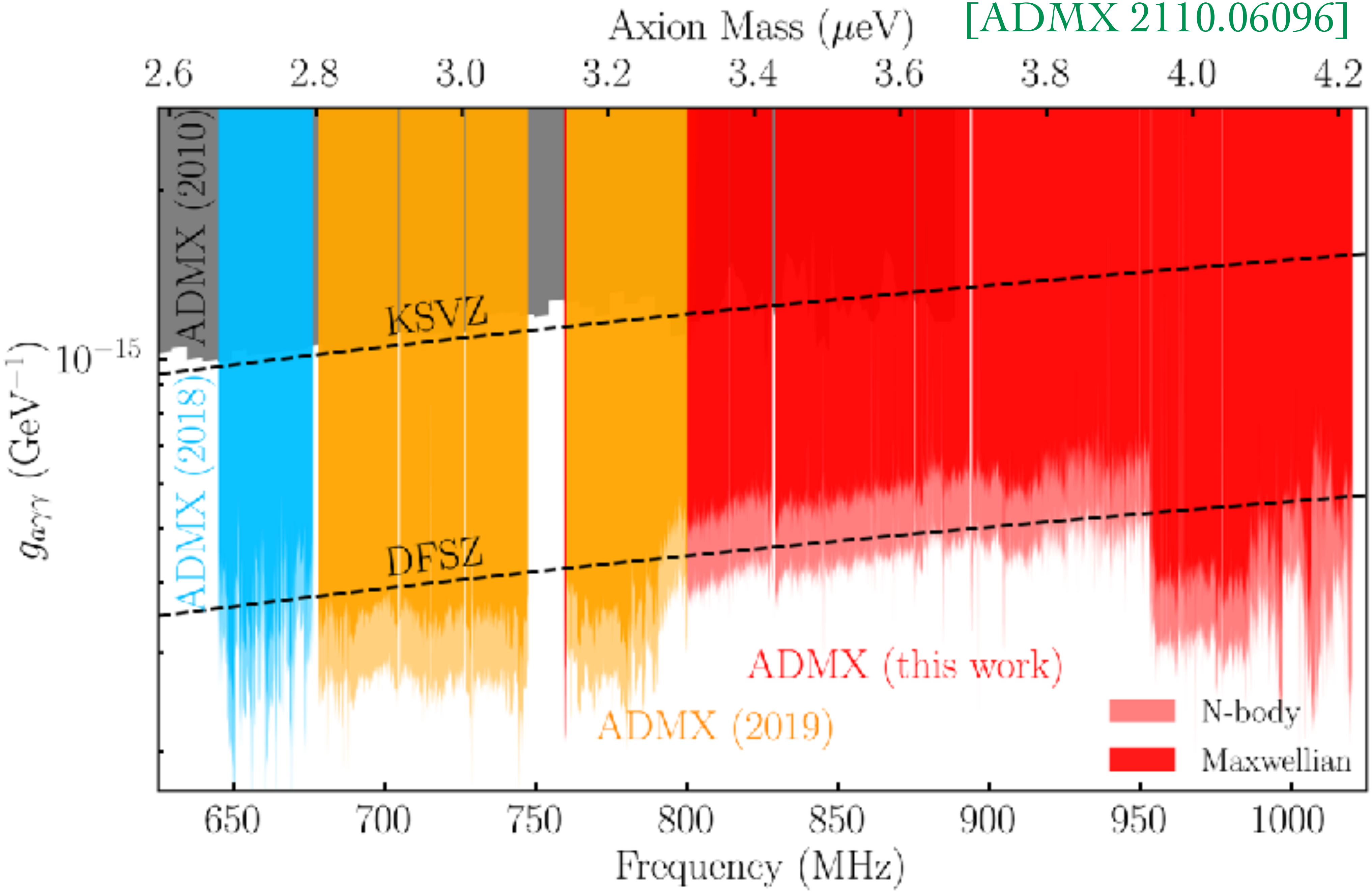
Models with two DM candidates possible, e.g. axions and RH neutrinos FIMPs…

[LC & S. Khan 22]



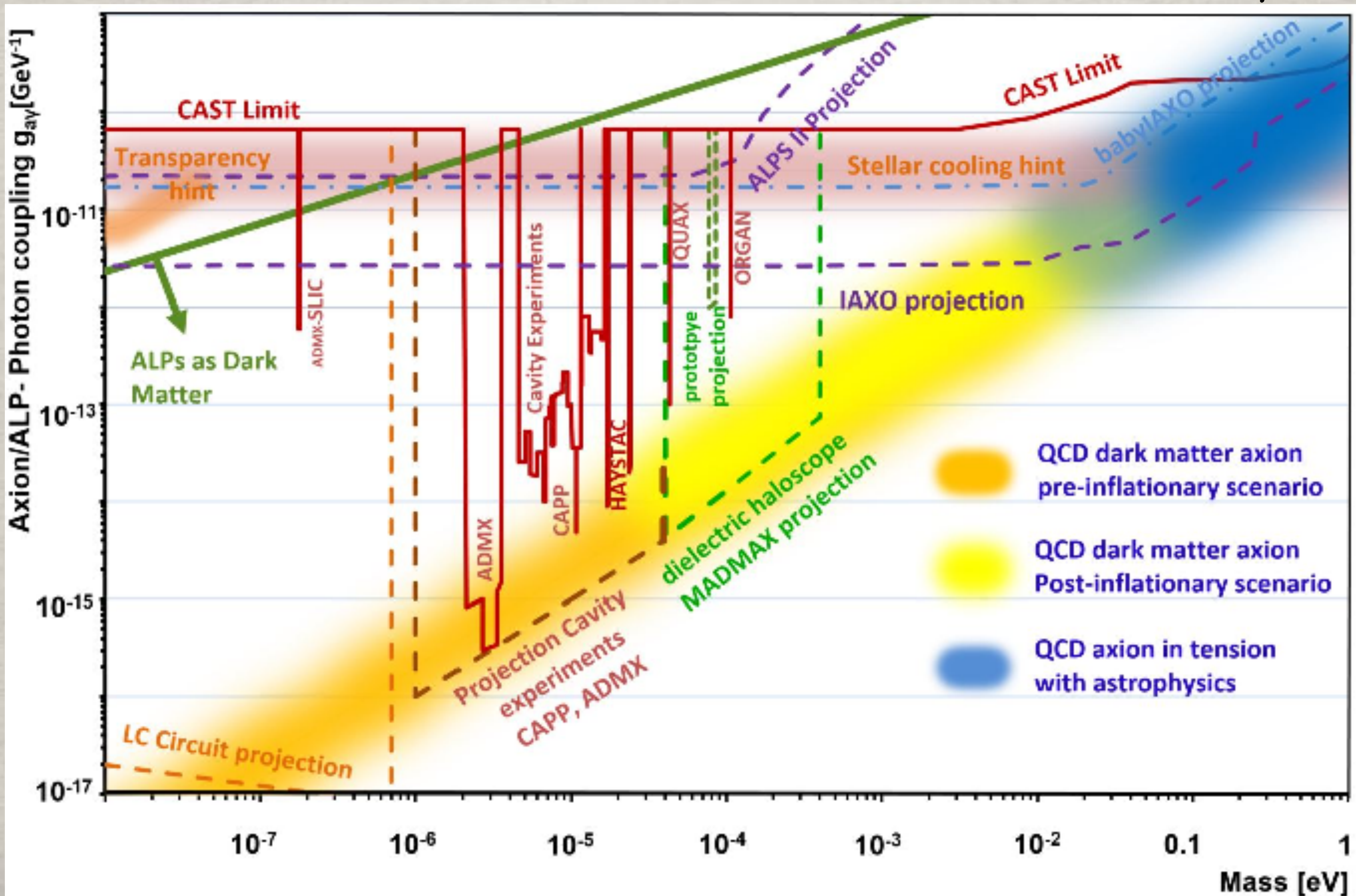
AXION DM SEARCHES

[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 ADM/FIMP/SuperWIMP 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.
- The FIMP/SuperWIMP framework is quite general and could point to heavy metastable particles/displaced vertices at LHC or decaying DM.
- 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…

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