Corfu Summer Institute

Hellenic School and Workshops on Elementary Particle Physics and Gravity

Corfu, Greece

The Dark Side of the Universe - DSU2024

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FIMP DARK MATTER AT LOW TEMPERATURE

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$[q,p]=i\hbar$

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

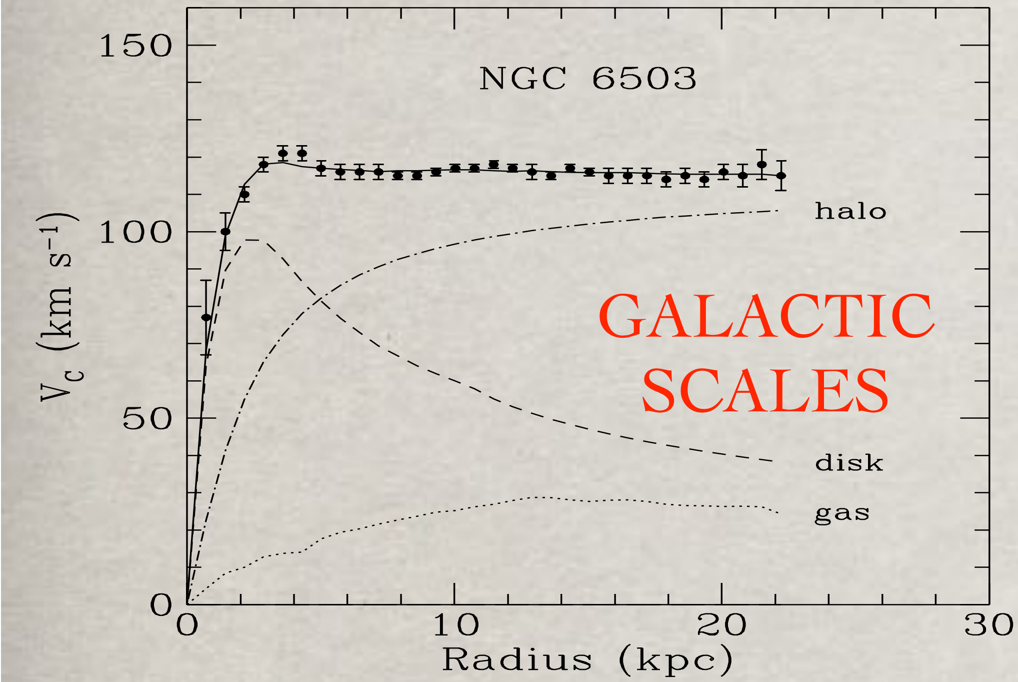
MARIE CURIE ACTIONS

OUTLINE

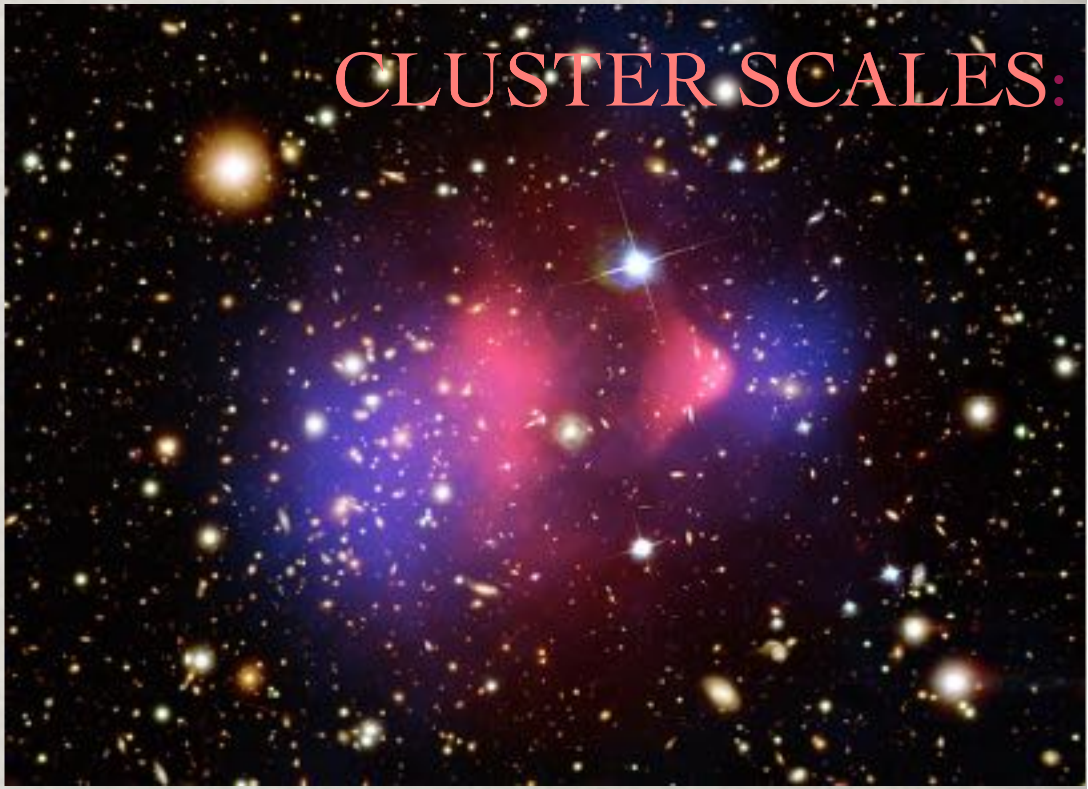
- Introduction to the FIMP mechanism
- Boltzmann suppressed FIMP for spin 3/2
  with Francesco Costa [24xx.xxxxx]
- SuperFIMP: Dark Matter produced by the late decay of a FIMP
  with Sarif Khan [2205.10150]
- Outlook

FIMP Dark Matter

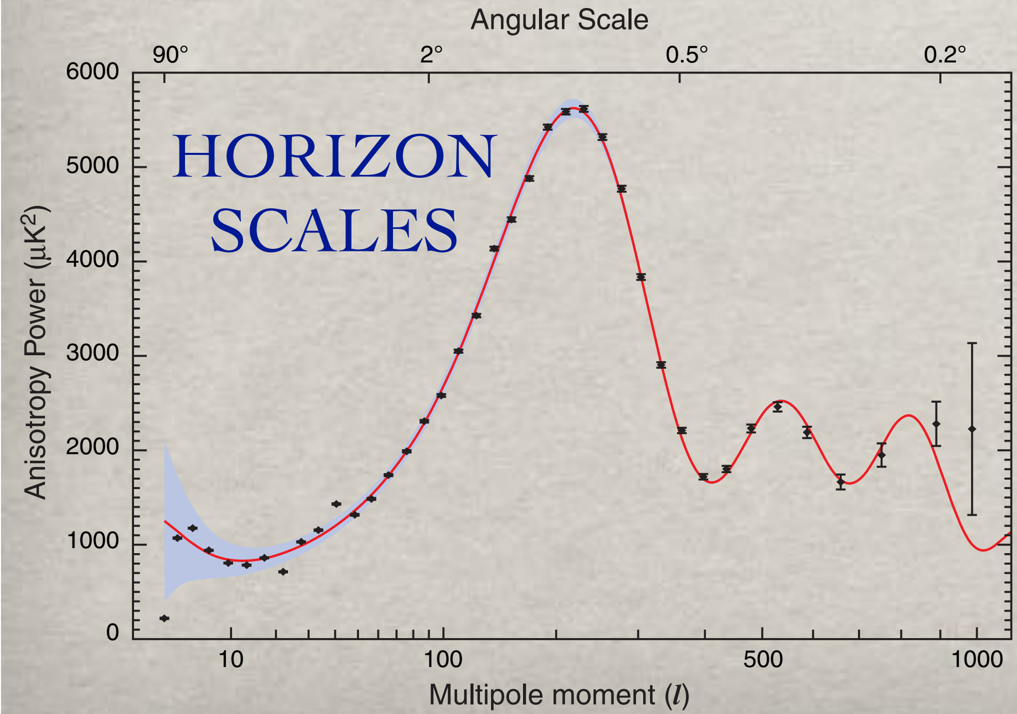
DARK MATTER EVIDENCE



GALACTIC SCALES



CLUSTER SCALES:

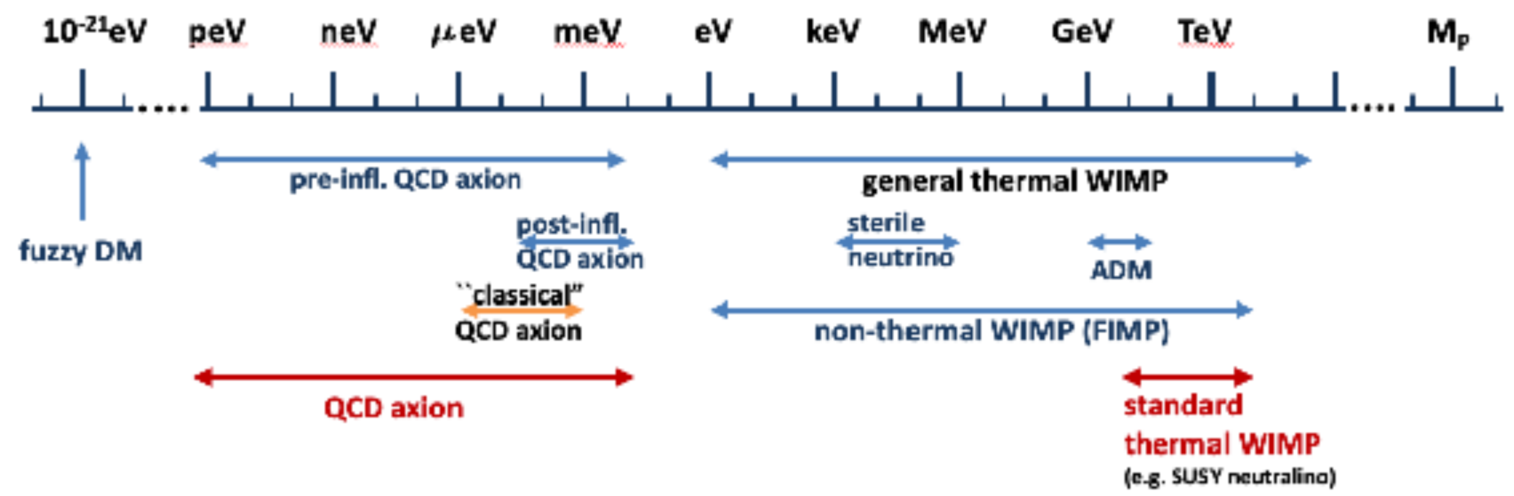


HORIZON SCALES

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

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

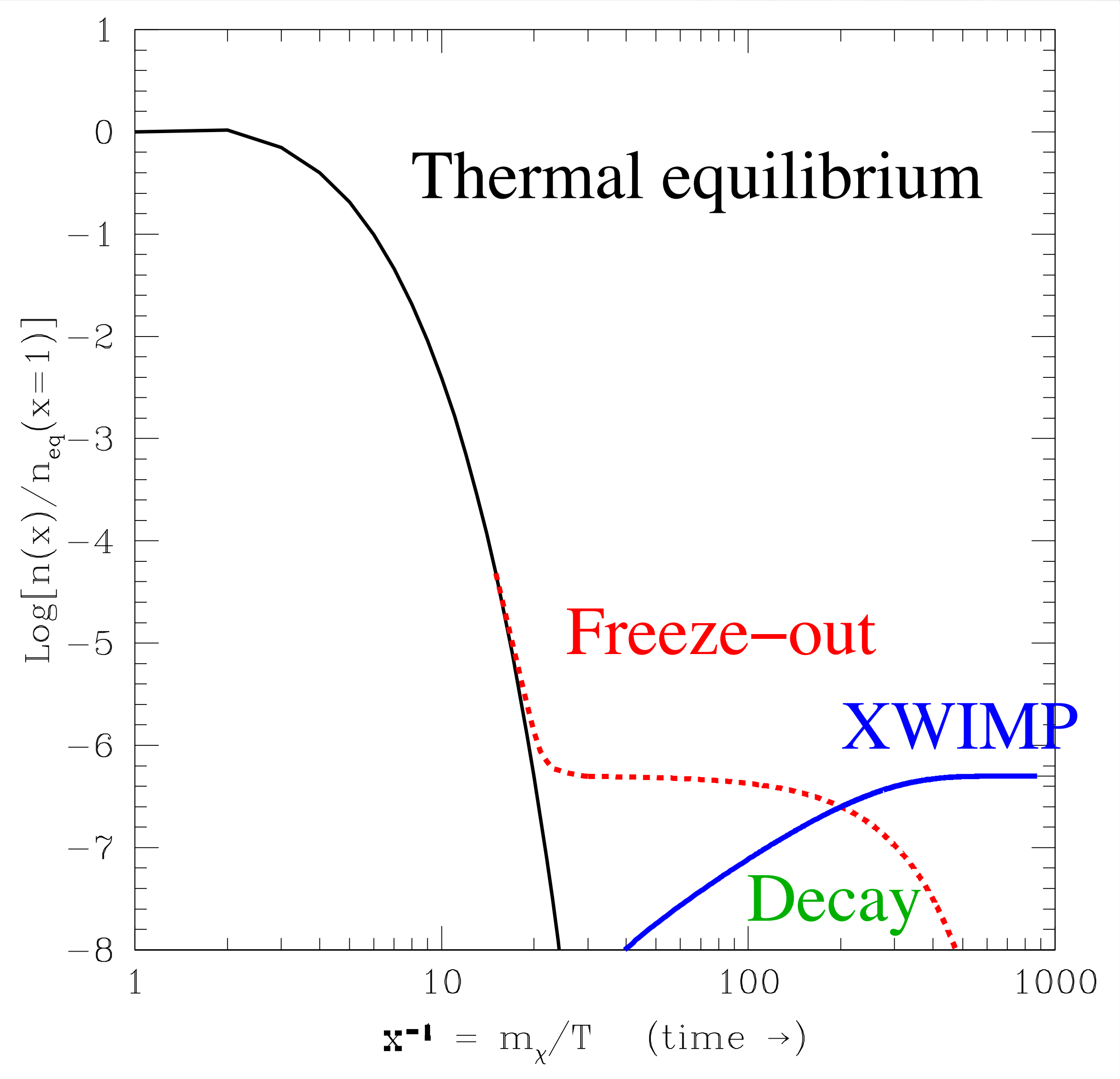
SuperWIMP mechanism

[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]

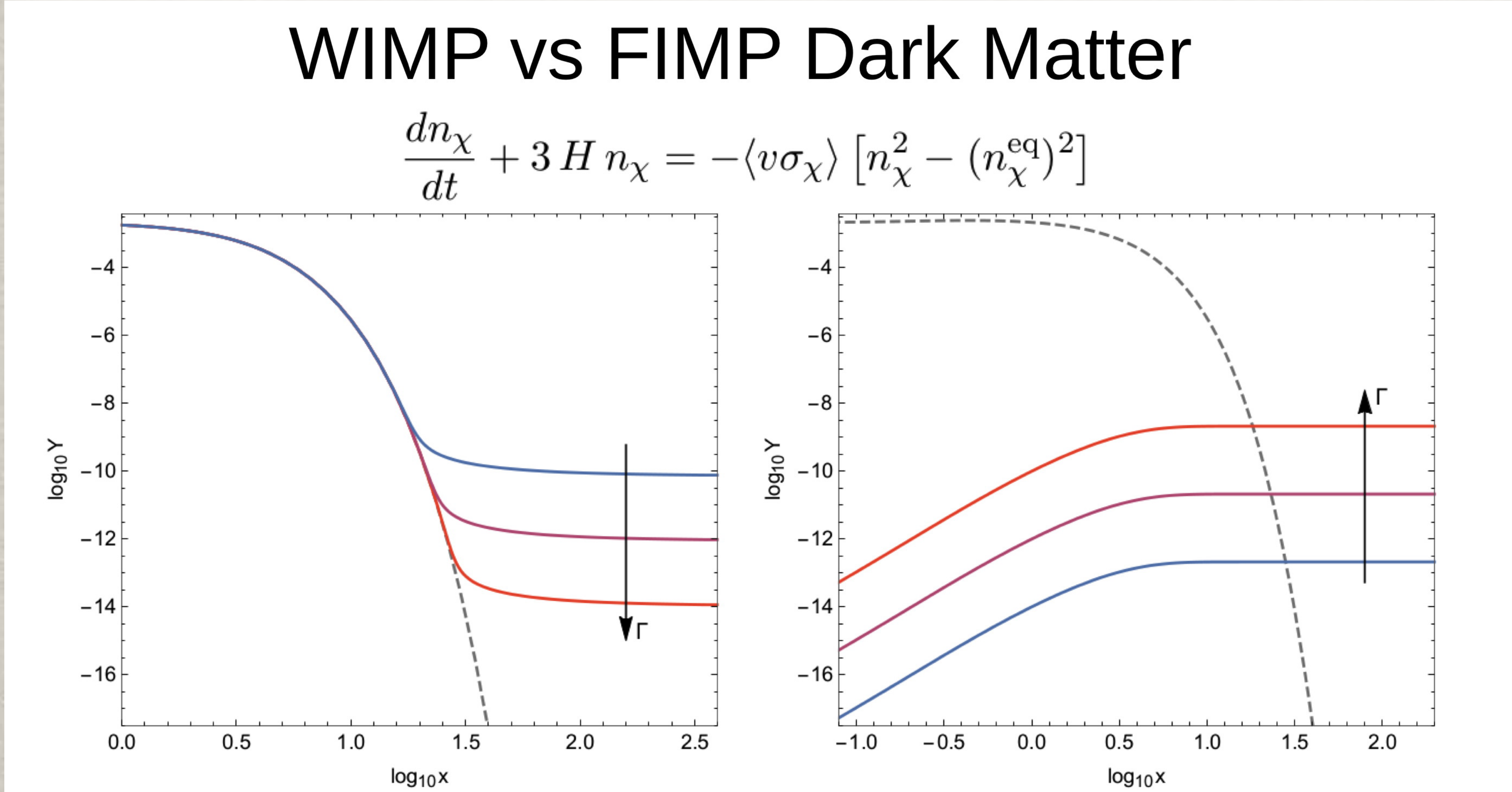
- A long-lived WIMP particle can decay after decoupling and produce the DM population:

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

- 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]

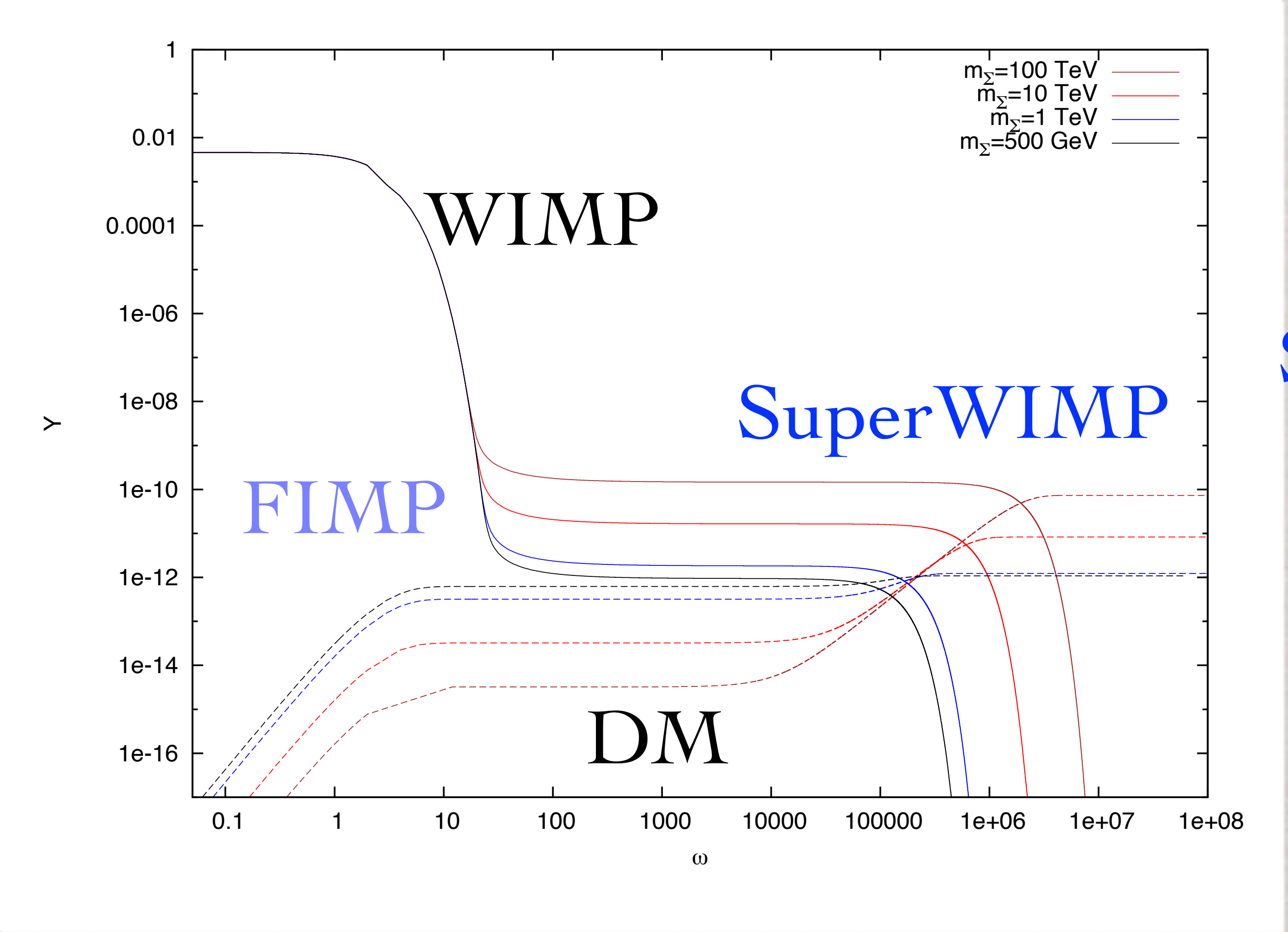
Instead of starting from thermal equilibrium, consider the opposite case: a particle so weakly interacting that is not initially in equilibrium, but it is driven towards it by the interaction with particles in the thermal bath. Same Boltzmann equation, but different dynamics !

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:

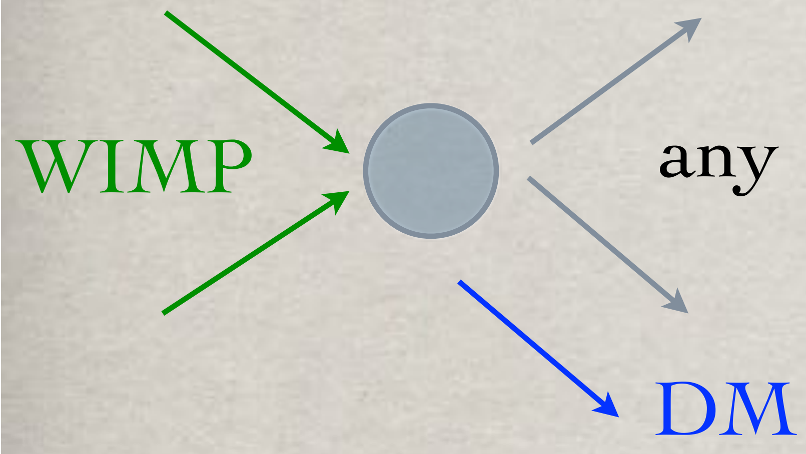
$$\Omega^{SW} h^2 = \frac{m_\psi}{m_\Sigma} BR(\Sigma \to \psi)\, \Omega_\Sigma h^2$$

- 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: $\Omega_{CDM} h^2$



WIMP

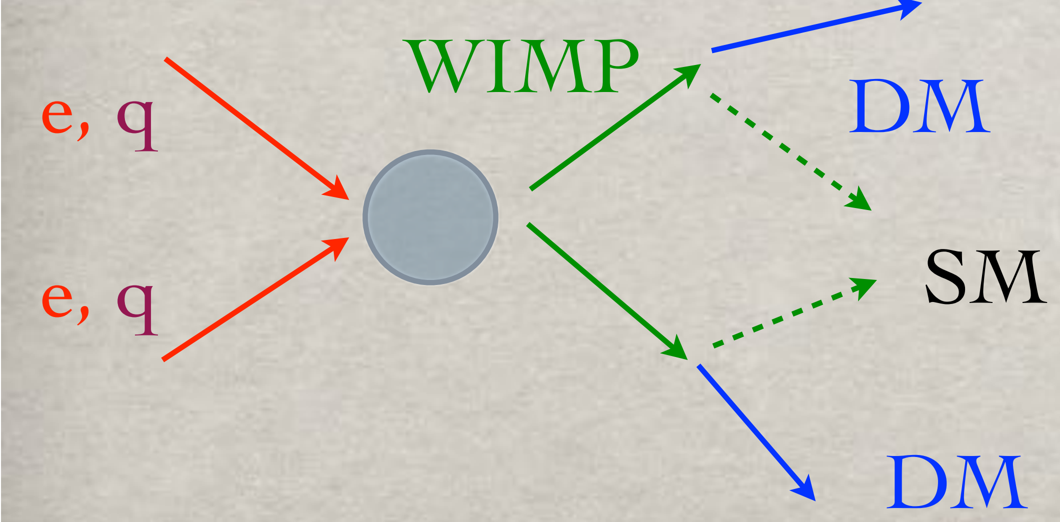
any

DM

Direct Detection:

NONE... ???

Colliders: LHC/ILC



e, q

e, q

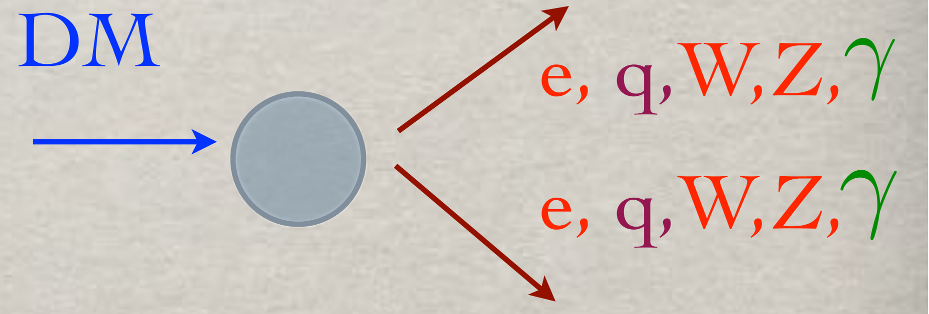
WIMP

DM

SM

DM

Indirect Detection:



DM

e, q, W, Z, γ

e, q, W, Z, γ

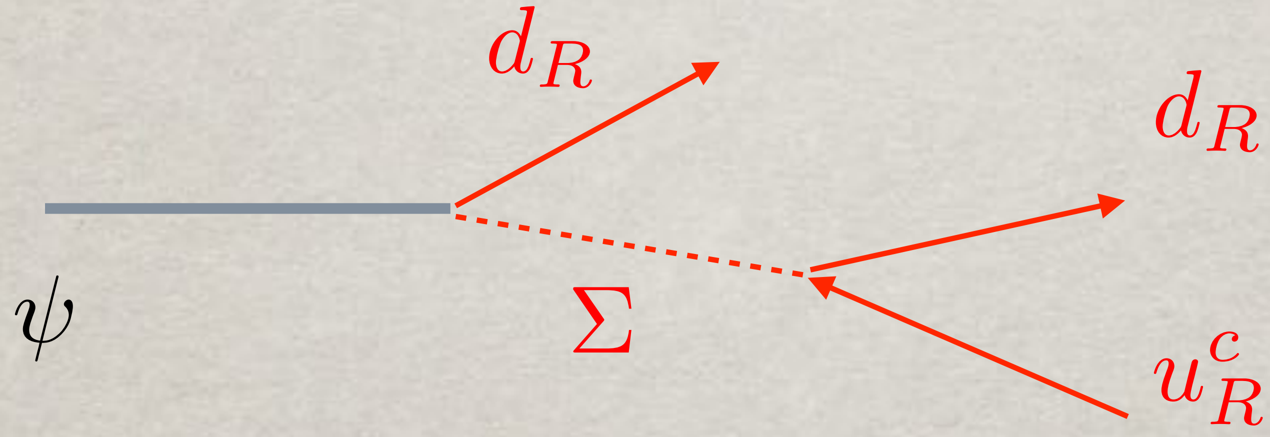
decaying DM !

3 different ways to check this hypothesis !!!

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

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

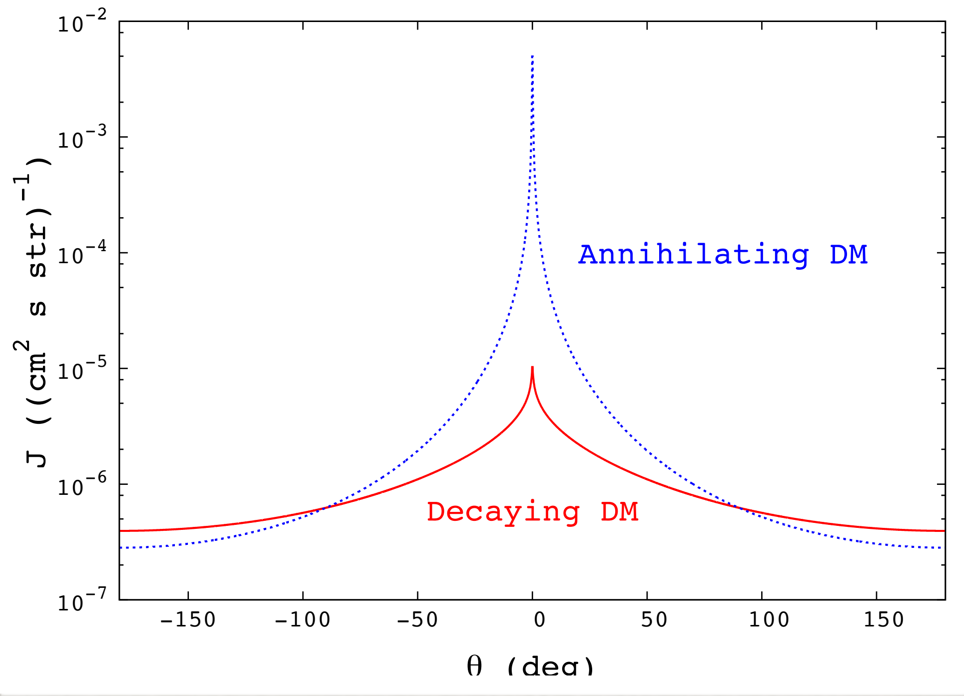
DECAYING DM

- 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...



Σ COMBINED DETECTION

Still possible to have multiple detection of

- DM decay:

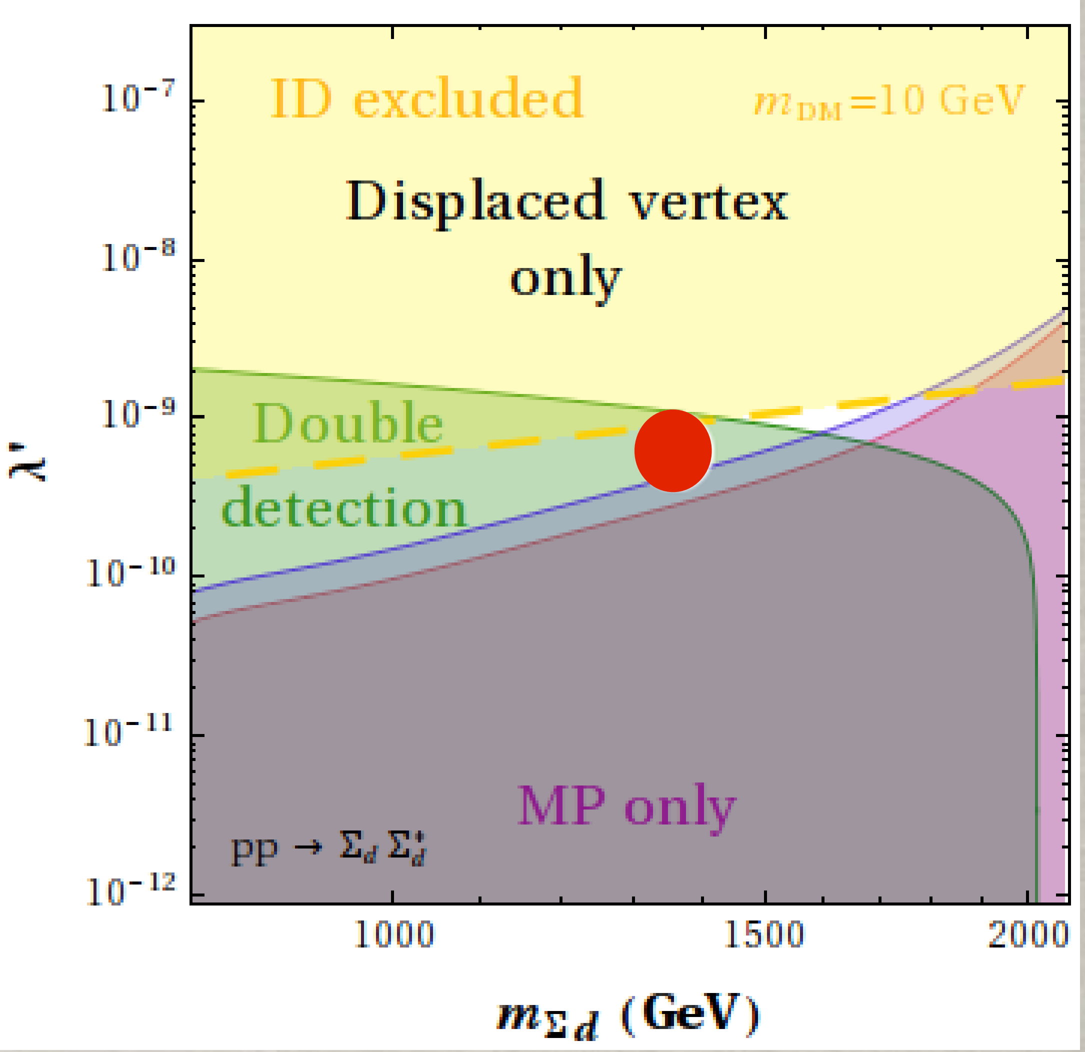
  $m_\psi \quad \Gamma_\psi \to \lambda\lambda'$
- displaced vertices

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

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

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

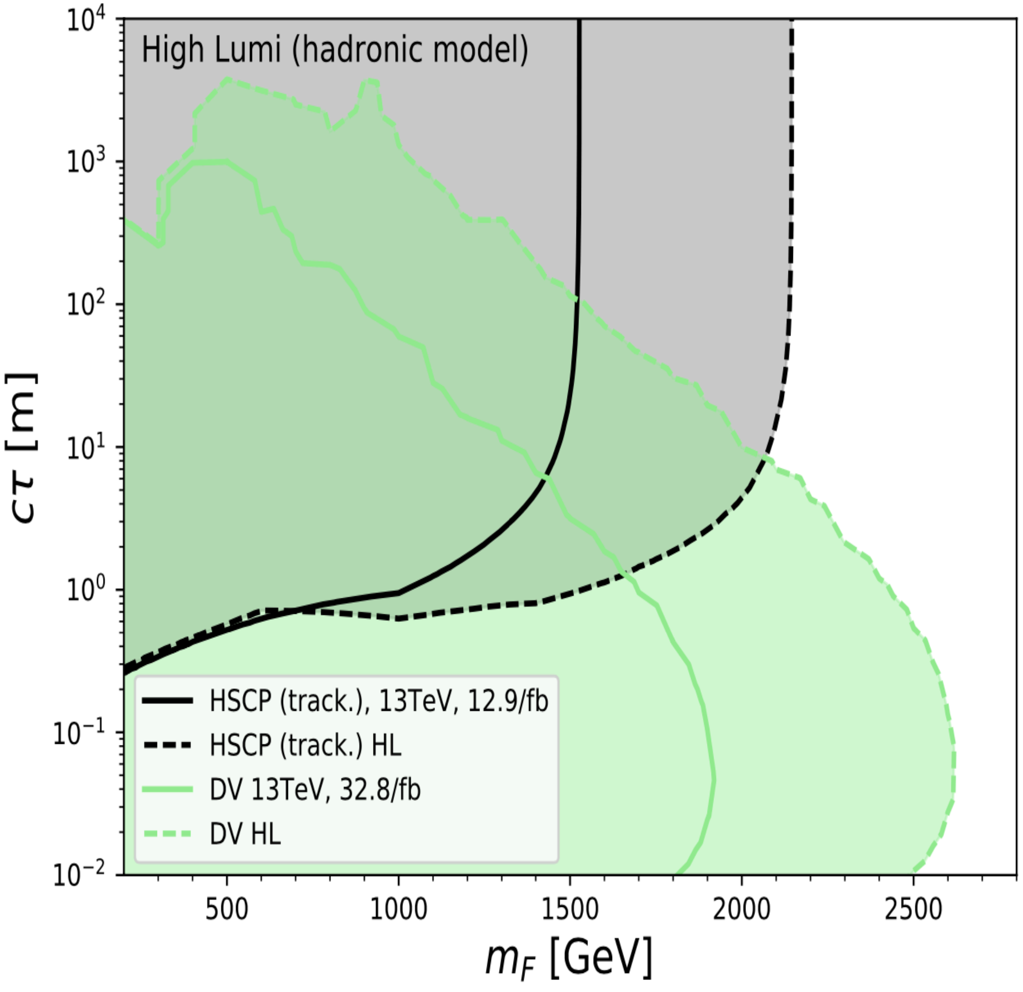
[G. Arcadi, LC & F. Dradi 1408.1005]



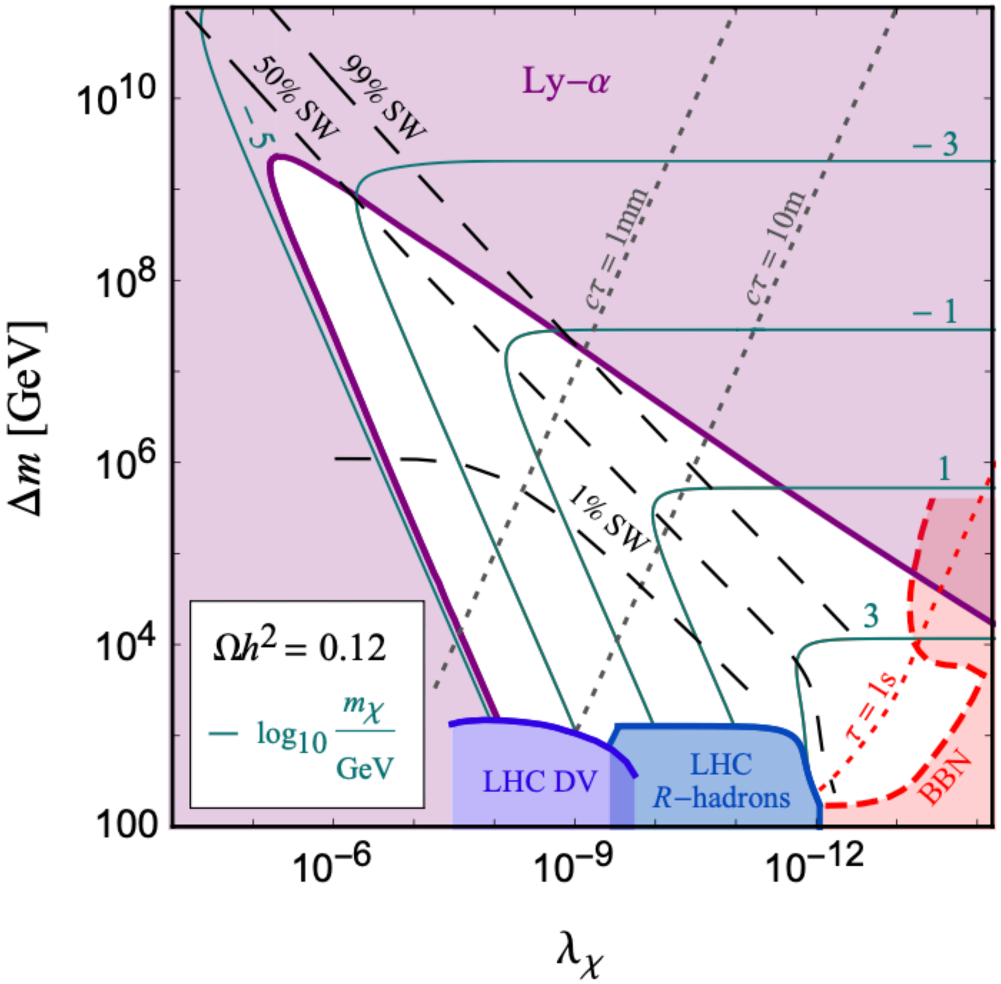
It is possible to over-constraint the model and check the hypothesis of FIMP production !

LHC AND COSMO BOUNDS

[G. Belanger et al. 1811.05478]



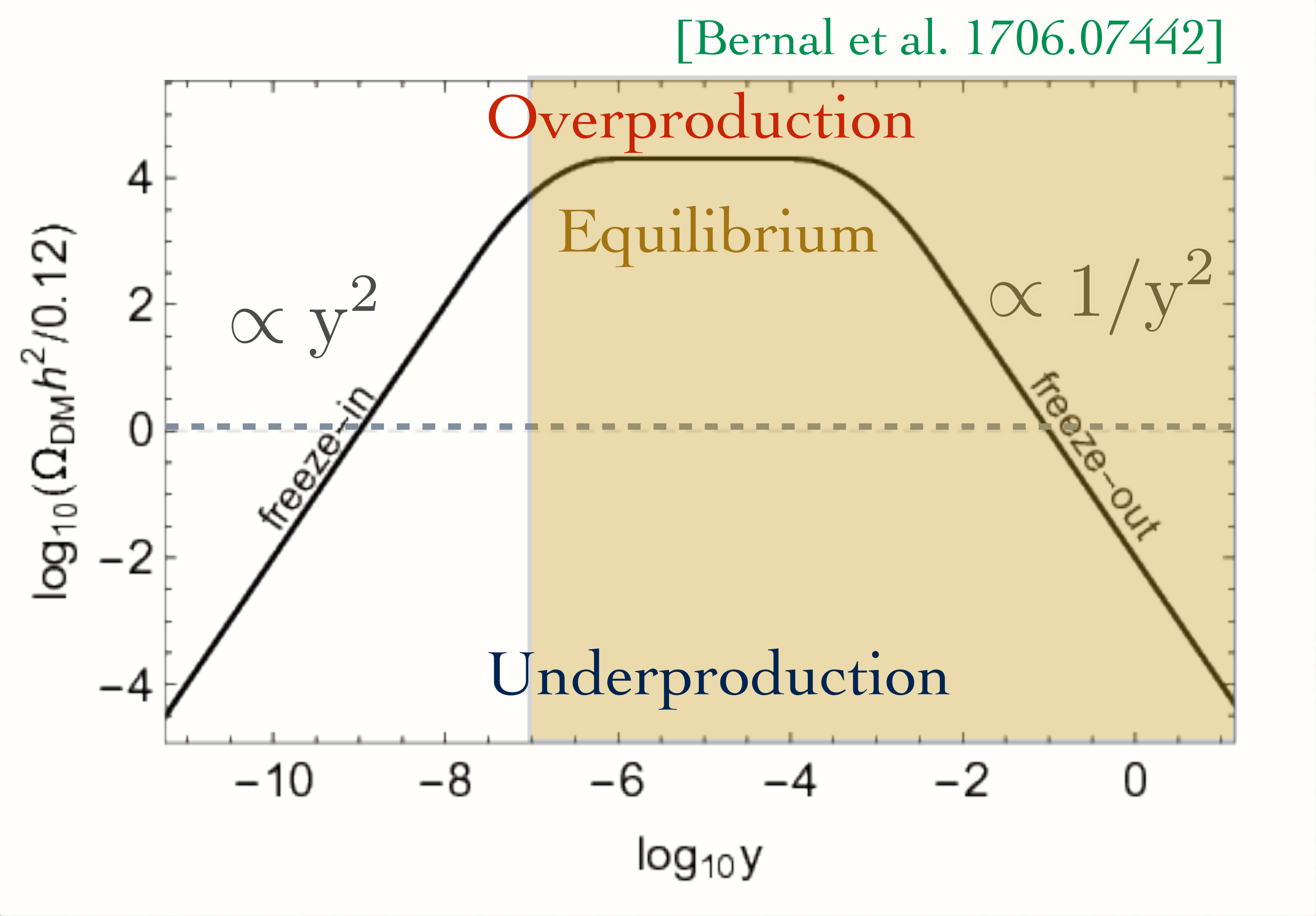
[Q. Decant et al. 2111.09321]



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

FIMP Dark Matter at low temperatures

FIMP VS WIMP COUPLINGS

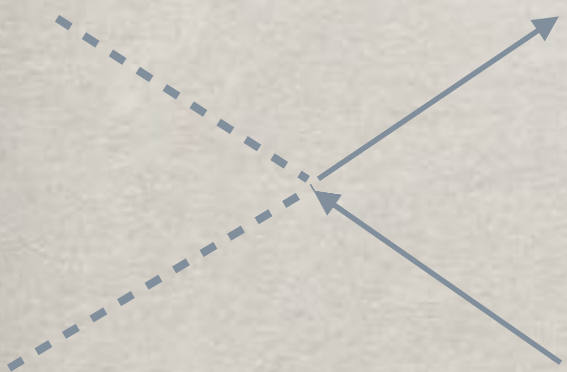


Usually FIMP and WIMP couplings very well separated !
Is it possible to go continuously from FIMP to WIMP ?

BOLTZMANN SUPPRESSED FIMP

[C. Cosme, F. Costa & O. Lebedev 2306.13061,
F. Costa & L. Covi, 24xx.xxxxx]

Consider the case where the FIMP mass is larger than the temperature at the time of production, then the scattering rate is suppressed by a Boltzmann factor:



$$\mathcal{L} = \mathcal{L}_{kin,3/2} + \frac{1}{\Lambda}\psi^\mu \psi_\mu |H|^2 + \dots$$

$$\Downarrow$$

$$\boxed{\Gamma_{hh\to\psi\psi} \sim e^{-\frac{2m_\psi}{T}}\, y^2 \frac{m_\psi^3 T^3}{\pi^4 \Lambda^2}}$$

So need larger couplings to compensate the suppression !

RARITON SPIN 3/2 DM

For the case of spin 3/2 Dark Matter the interactions with the SM appear only at dimension 5, i.e. the freeze-in is UV dominated and so there is a limit on the reheat temperature.

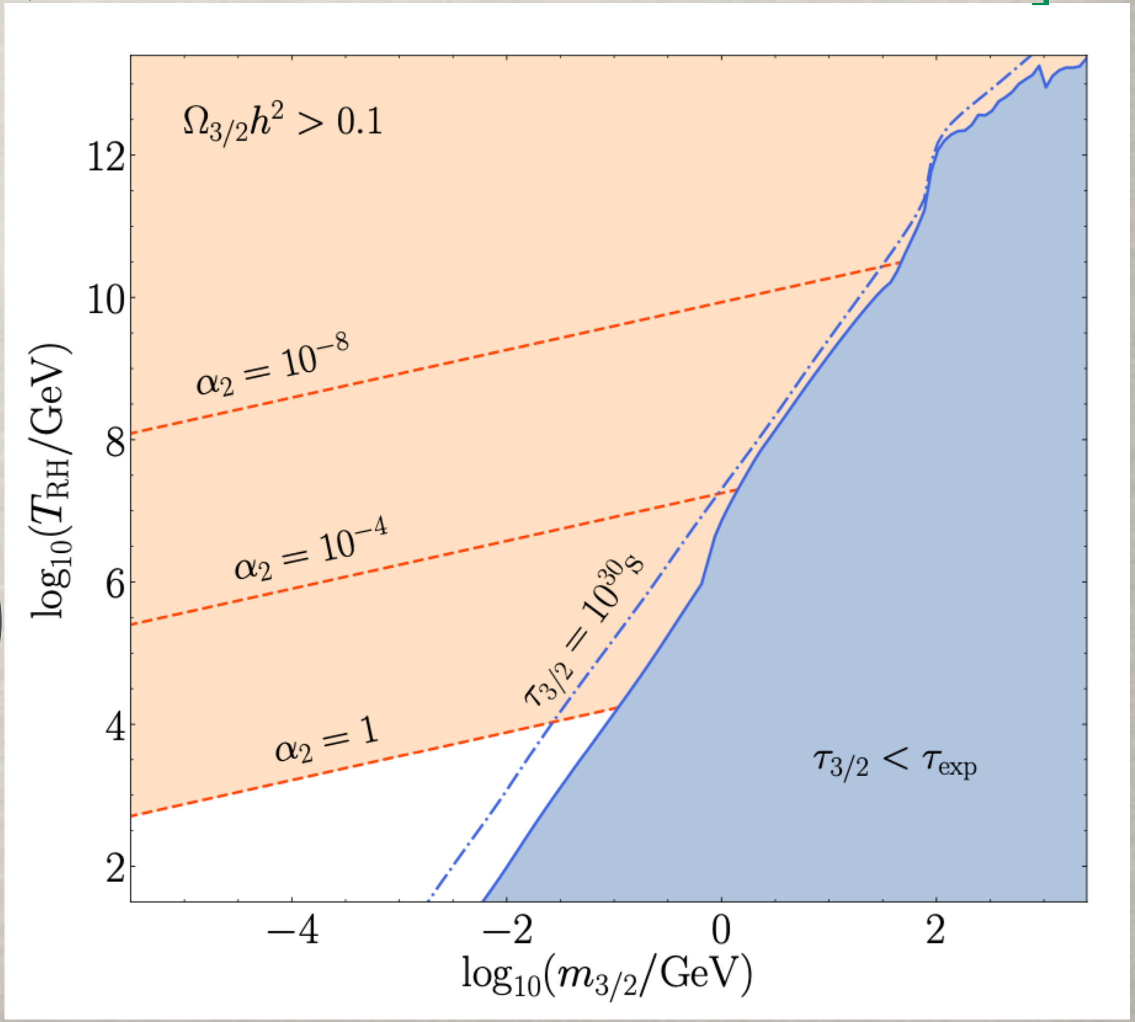
[M.A.G. Garcia, Y. Mambrini, K. A. Olive & S. Verner 2006.03325]

$$\mathcal{L} \ni i\frac{\alpha_2}{2M_P}(D^\mu H)^*(i\sigma_2)\bar{L}\psi_\mu$$

allows for both production and decay and gives

$$\Omega_{3/2}h^2 \sim \left(\frac{\alpha_2}{10^{-8}}\right)^2\left(\frac{T_{RH}}{10^{10}\mathrm{GeV}}\right)^3\left(\frac{1\mathrm{GeV}}{m_\psi}\right)$$

Large masses are excluded by indirect detection !



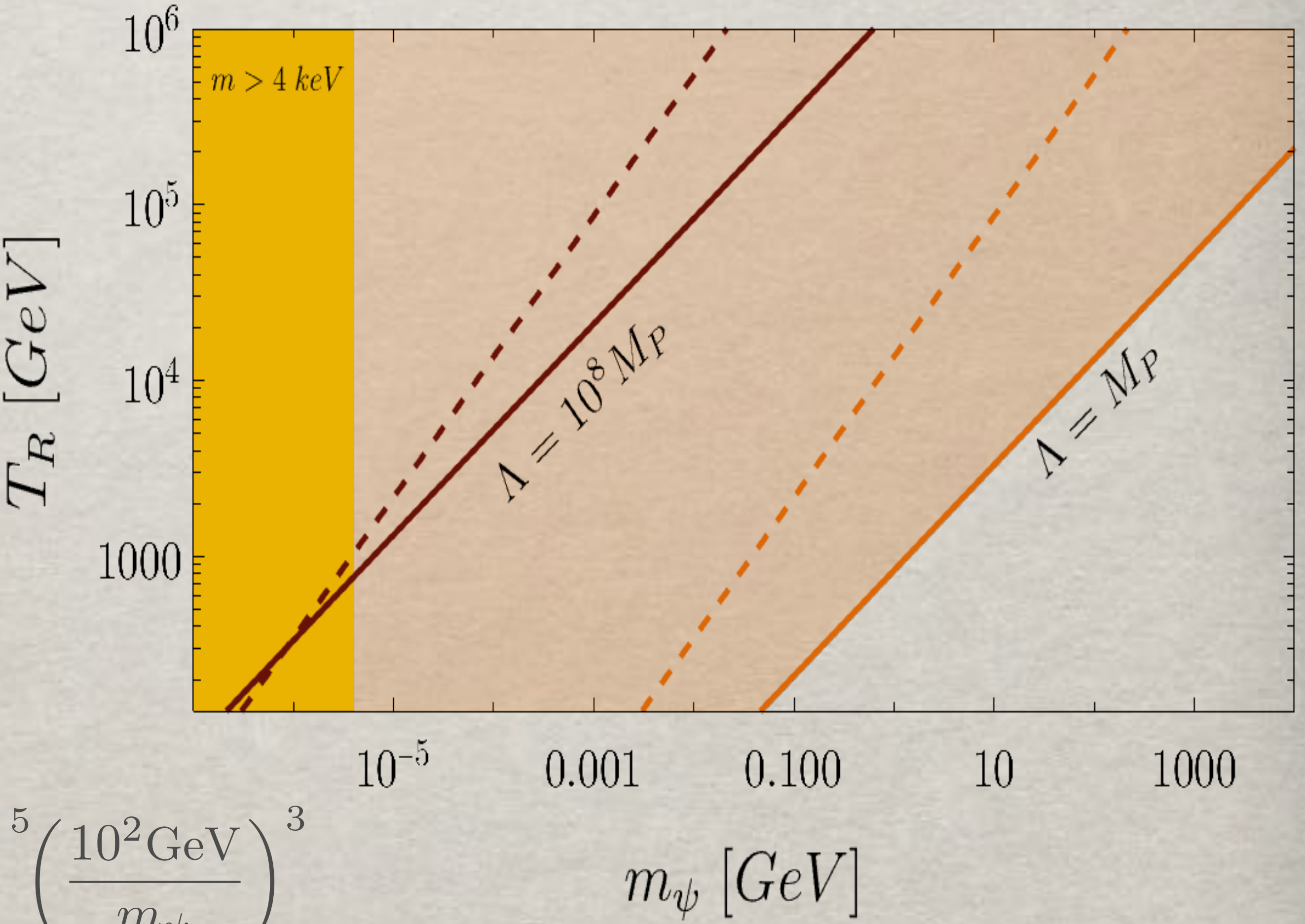
HIGGS PORTAL FOR SPIN 3/2

[F. Costa & L. Covi, 24xx.xxxxx]

For the case of pure Higgs portal couplings, the production is stronger, but there is no decay channel, i.e.

$$\mathcal{L} \ni \frac{1}{\Lambda}\psi^\mu\psi_\mu|H|^2$$

Large masses are less restricted, but need very low Temperature !

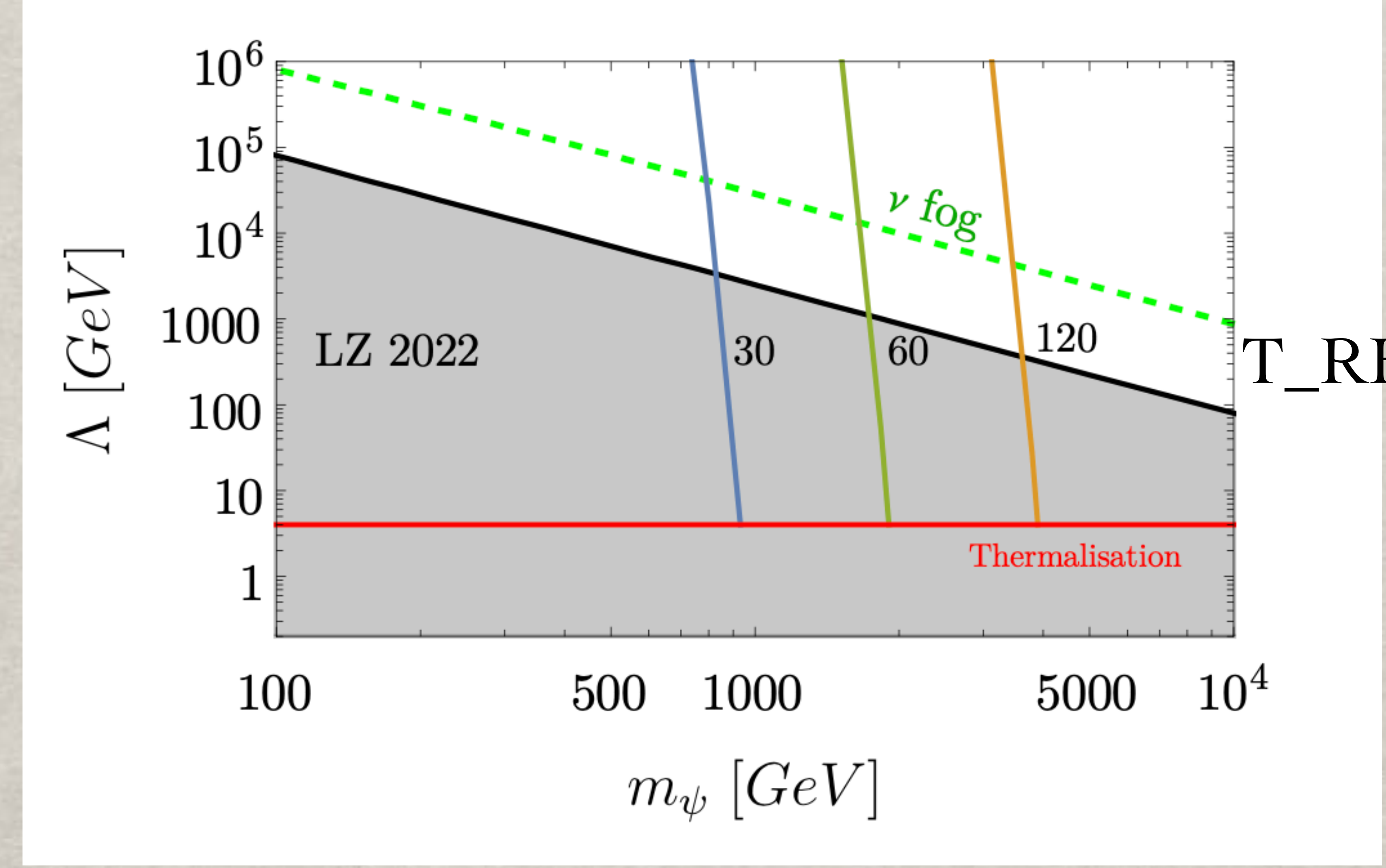


$$\Omega_{3/2}h^2 \sim \left(\frac{10^{17}\mathrm{GeV}}{\Lambda}\right)^2\left(\frac{T_{RH}}{10^4\mathrm{GeV}}\right)^5\left(\frac{10^2\mathrm{GeV}}{m_\psi}\right)^3$$

For the gravitino this coupling is just $\frac{|W|}{M_P^2}\psi^\mu\psi_\mu \sim \frac{\mu}{M_P^2}H_uH_d\psi^\mu\psi_\mu$

BOLTZMANN SUPPRESSED FIMP

[F. Costa & L. Covi, 24xx.xxxxx]

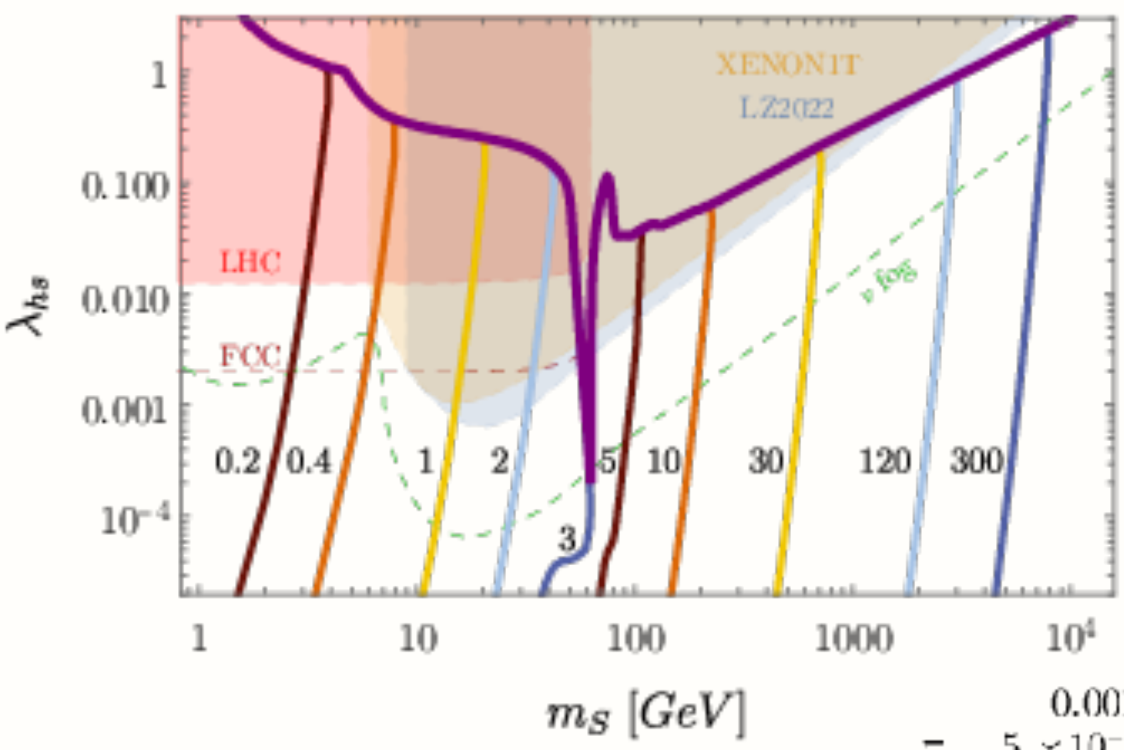


T_RH(GeV)

It is possible to move continuously from FIMP to WIMP and possibly reach direct detection ! And maybe also ID !

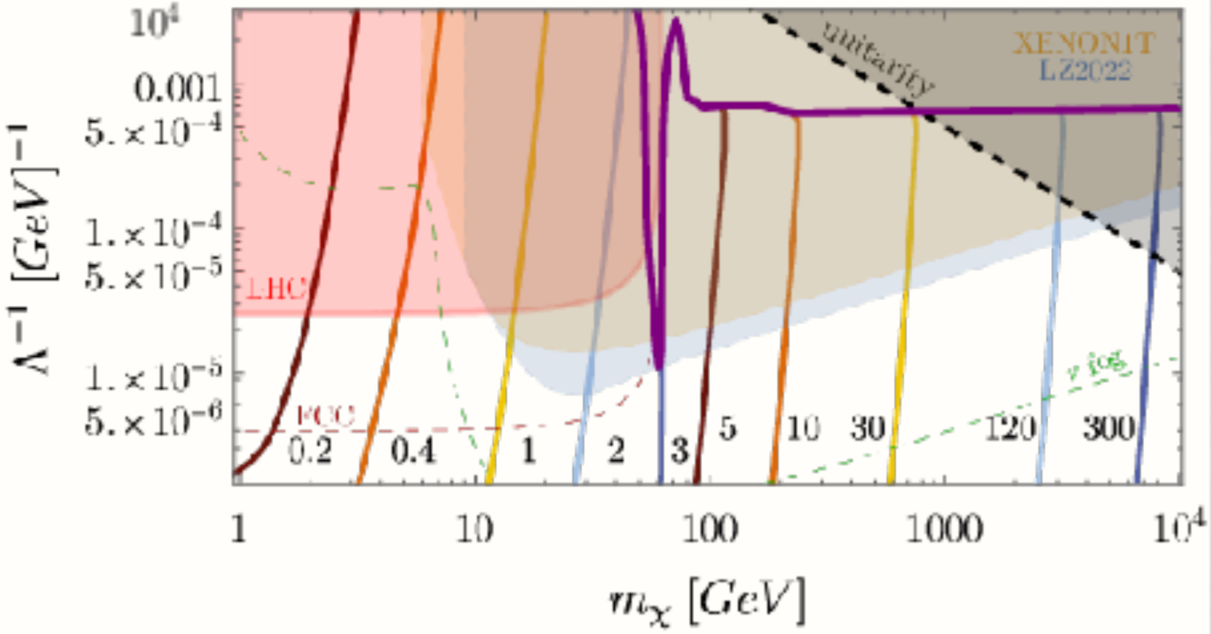
Boltzmann suppressed FIMP

[C. Cosme, F. Costa & O. Lebedev 2306.13061,
G. Arcadi, F. Costa, A. Goudelis and O. Lebedev 2405.03760]



Very similar picture also for the usual scalar Higgs portal !

As well as the fermion Higgs portal.



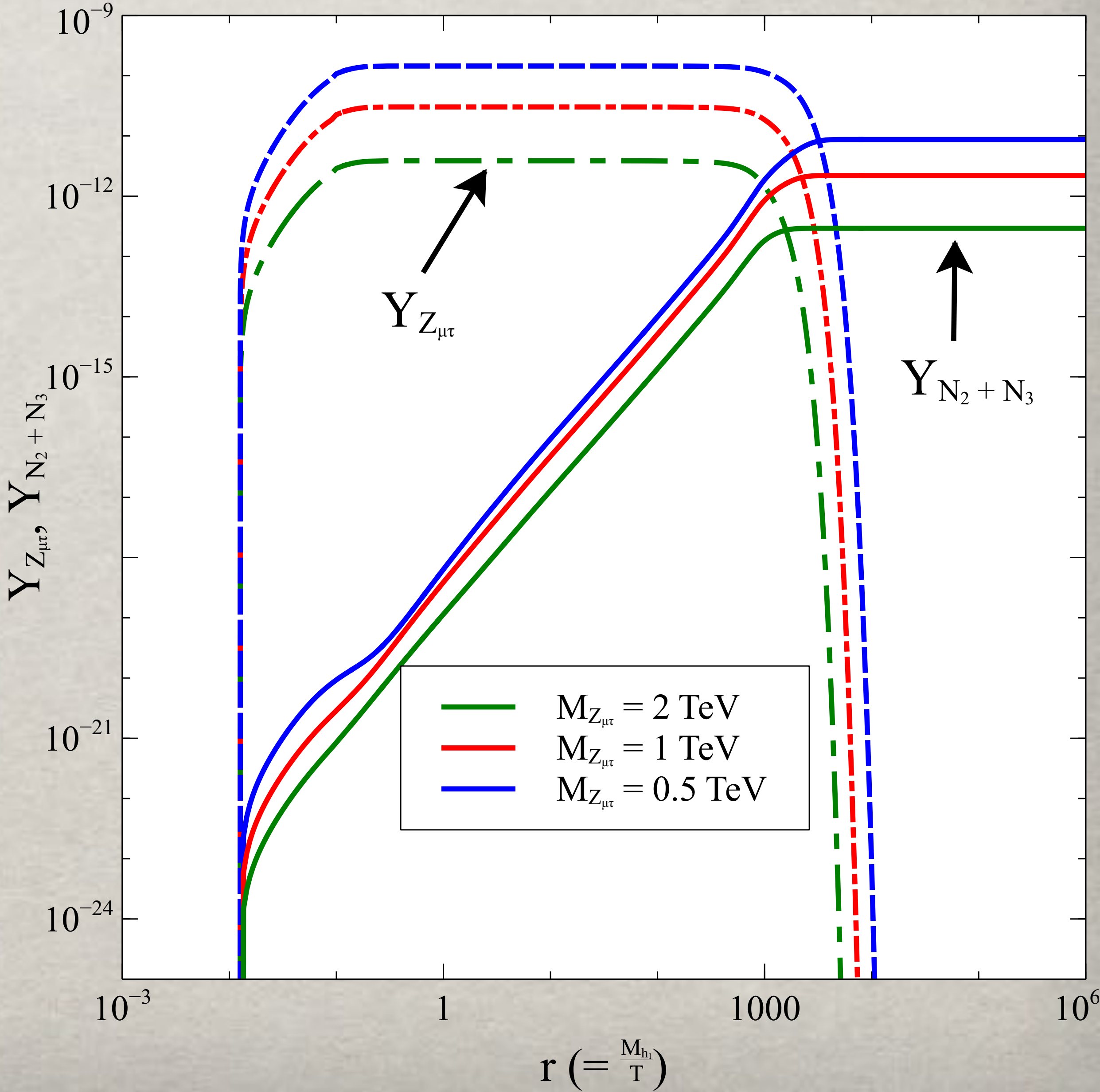
SuperFIMP Dark Matter

SuperFIMP: DM from a FIMP

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

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

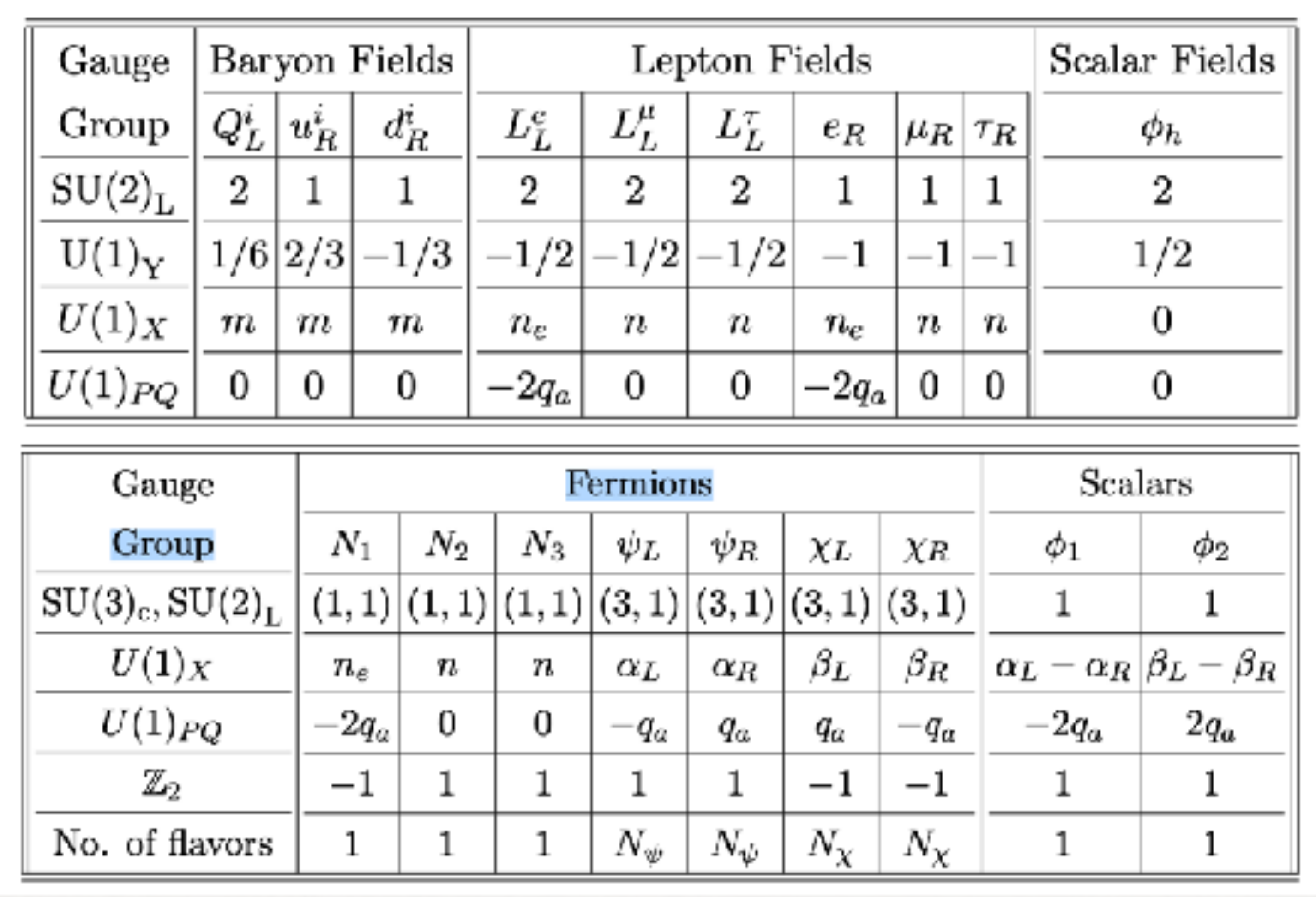
$$g_{\mu\tau} \sim 10^{-11}$$



EXTENDED KSVZ MODEL

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

We add to the SM 3 RH neutrinos, a local U(1) symmetry, two Higgs fields connected to its breaking and two sets of exotic colored fermions to generate the PQ-QCD anomaly:



Gauge	Baryon Fields			Lepton Fields						Scalar Fields
Group	Q^i_L	u^i_R	d^i_R	L^e_L	L^μ_L	L^τ_L	e_R	μ_R	τ_R	ϕ_h
$\mathrm{SU(2)_L}$	2	1	1	2	2	2	1	1	1	2
$\mathrm{U(1)_Y}$	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

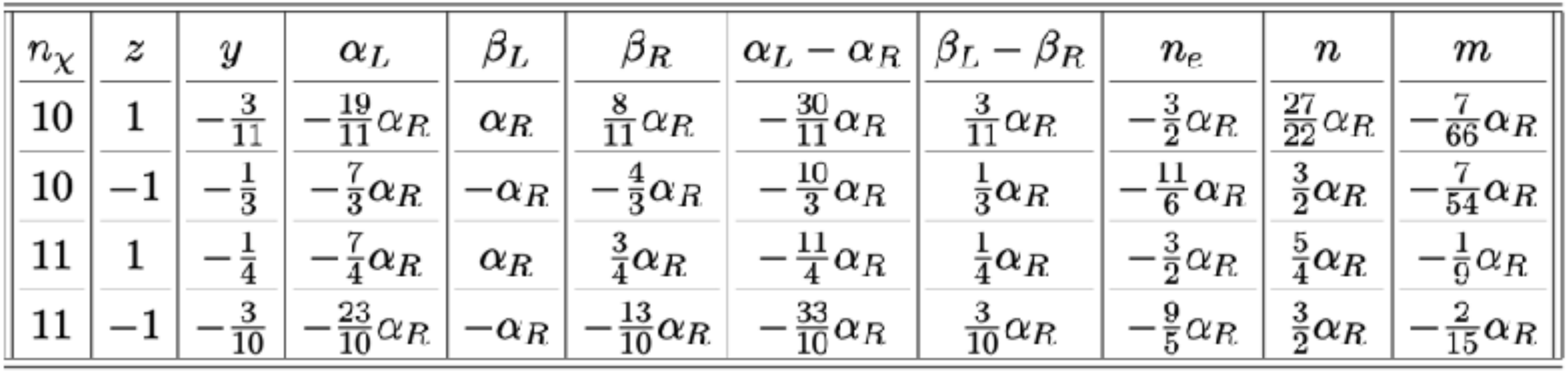
Gauge	Fermions							Scalars	
Group	N_1	N_2	N_3	ψ_L	ψ_R	χ_L	χ_R	ϕ_1	ϕ_2
$\mathrm{SU(3)_c, SU(2)_L}$	(1, 1)	(1, 1)	(1, 1)	(3, 1)	(3, 1)	(3, 1)	(3, 1)	1	1
$U(1)_X$	n_e	n	n	α_L	α_R	β_L	β_R	$\alpha_L - \alpha_R$	$\beta_L - \beta_R$
$U(1)_{PQ}$	$-2q_a$	0	0	$-q_a$	q_a	q_a	$-q_a$	$-2q_a$	$2q_a$
$\mathbb{Z}_2$	−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

ANOMALY CANCELLATION

[LC & S. Khan 2022]

The charges of the different fields are related in order for all the SM-U(1)_X anomalies to cancel. Indeed we have for

$z = \frac{\beta_L}{\alpha_R}$ $y = \frac{\beta_R - \beta_L}{\alpha_R}$ $n_\chi = \frac{N_\chi}{N_\psi}$ purely rational charges:



n_χ	z	y	α_L	β_L	β_R	$\alpha_L - \alpha_R$	$\beta_L - \beta_R$	n_e	n	m
10	1	$-\frac{3}{11}$	$-\frac{19}{11}\alpha_R$	α_R	$\frac{8}{11}\alpha_R$	$-\frac{30}{11}\alpha_R$	$\frac{3}{11}\alpha_R$	$-\frac{3}{2}\alpha_R$	$\frac{27}{22}\alpha_R$	$-\frac{7}{66}\alpha_R$
10	-1	$-\frac{1}{3}$	$-\frac{7}{3}\alpha_R$	$-\alpha_R$	$-\frac{4}{3}\alpha_R$	$-\frac{10}{3}\alpha_R$	$\frac{1}{3}\alpha_R$	$-\frac{11}{6}\alpha_R$	$\frac{3}{2}\alpha_R$	$-\frac{7}{54}\alpha_R$
11	1	$-\frac{1}{4}$	$-\frac{7}{4}\alpha_R$	α_R	$\frac{3}{4}\alpha_R$	$-\frac{11}{4}\alpha_R$	$\frac{1}{4}\alpha_R$	$-\frac{3}{2}\alpha_R$	$\frac{5}{4}\alpha_R$	$-\frac{1}{9}\alpha_R$
11	-1	$-\frac{3}{10}$	$-\frac{23}{10}\alpha_R$	$-\alpha_R$	$-\frac{13}{10}\alpha_R$	$-\frac{33}{10}\alpha_R$	$\frac{3}{10}\alpha_R$	$-\frac{9}{5}\alpha_R$	$\frac{3}{2}\alpha_R$	$-\frac{2}{15}\alpha_R$

Need a large number of fields to suppress non-renormalisable operators sufficiently !

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:

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

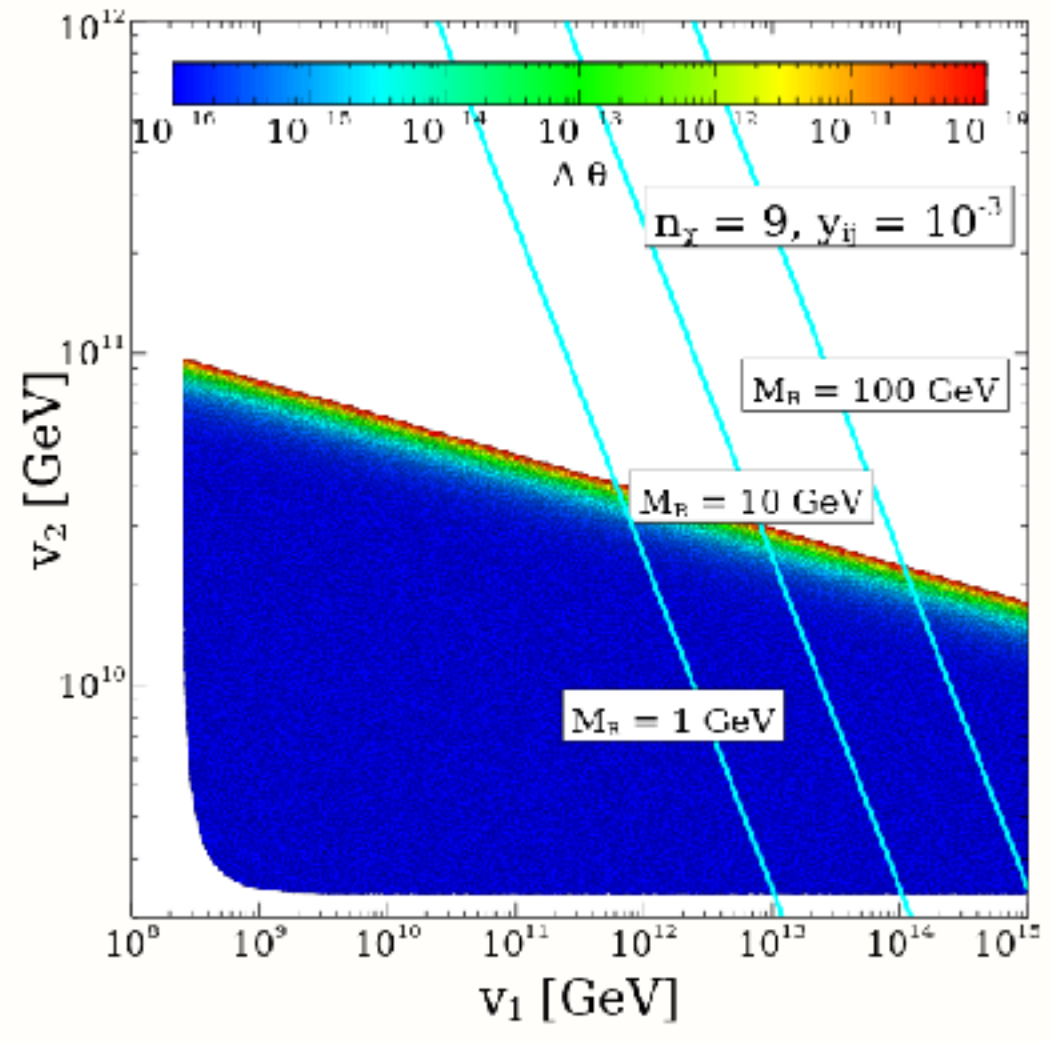
together with the lower bound in f_a from astrophysics, it implies that about 10 exotic fermions should be present to avoid the a too large contribution to the neutron EDM !

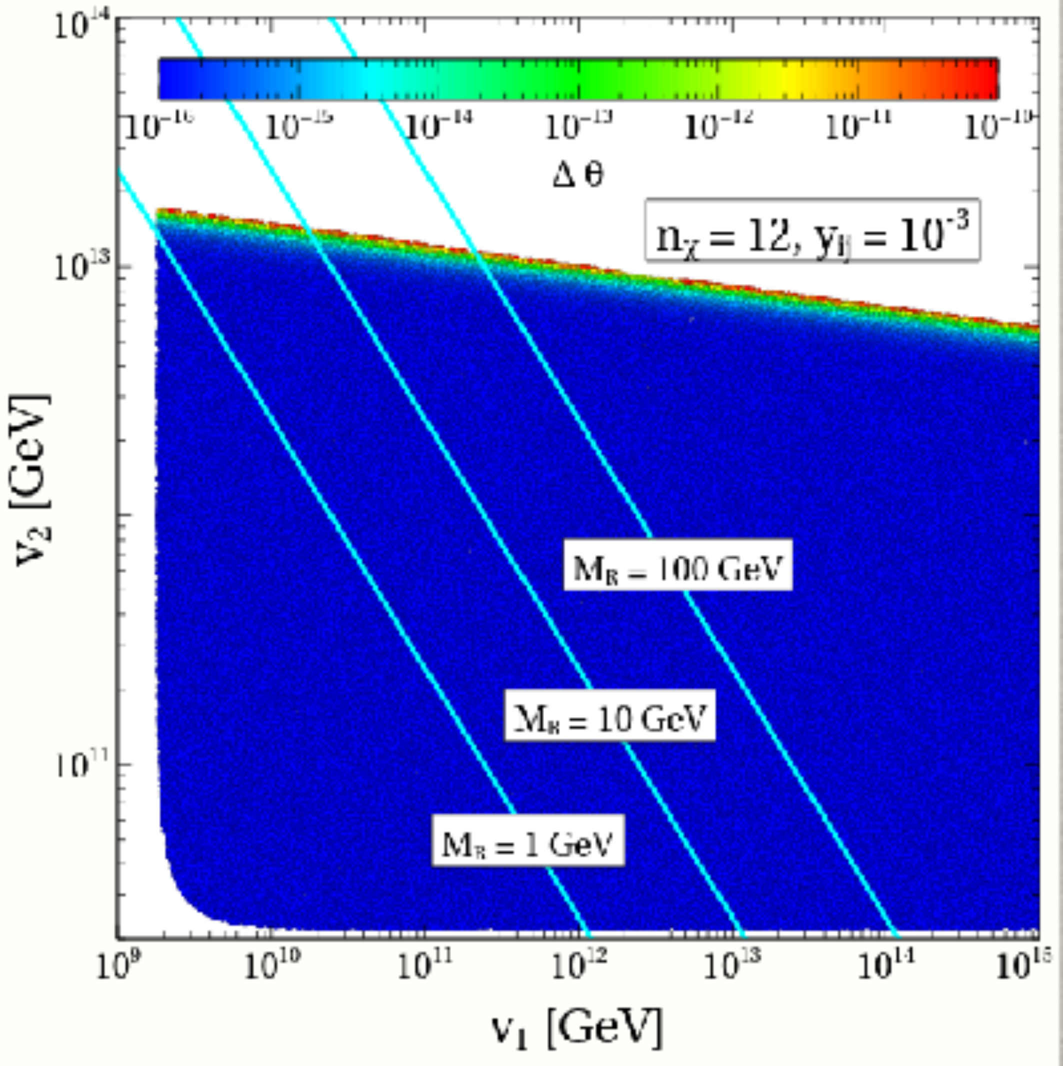
The minimum of the axion potential is shifted !

AXION & EDMs

Viable axion with EDMs maybe behind the corner…

[LC & S. Khan 2022]

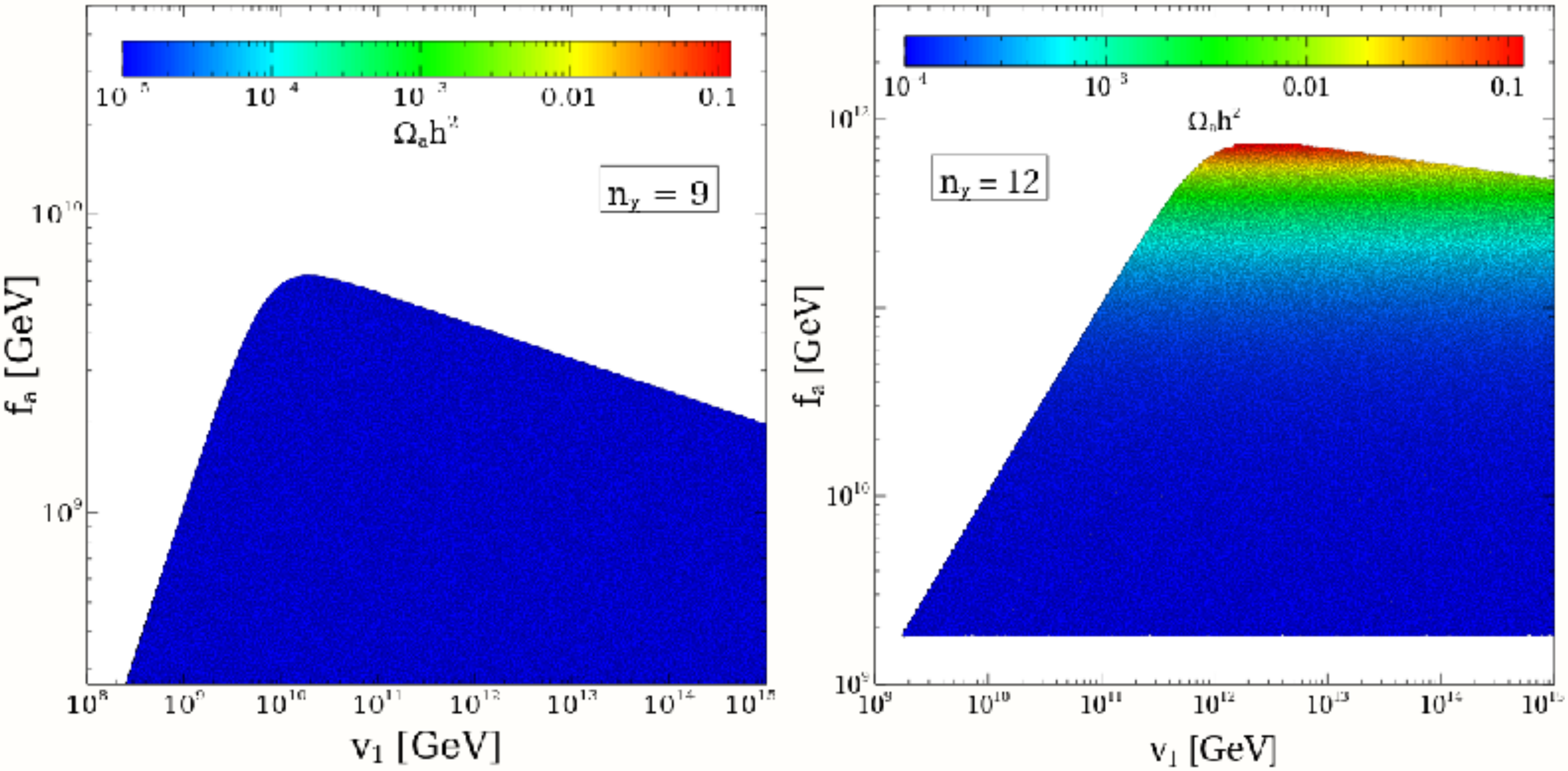




AXION (PART OF) DM

For less than 13 exotic fermions, the DM density turns out to be too small…

[LC & S. Khan 22]



ASYMPTOTIC FREEDOM ?

All the exotic colored fermions contribute to the running of the QCD coupling and modify the beta function:

$$\beta_{QCD} = -\frac{\alpha_s}{2\pi}\left[7 - \frac{2N_\psi}{3}(1+n_\chi)\right]$$

so the sign changes for $N_\psi(1+n_\chi) = N_\psi + N_\chi > 10$

Axion DM is realised only for 13 or more exotic fermions and so not compatible with asymptotic freedom for QCD !

Neutrino as SuperFIMP DM

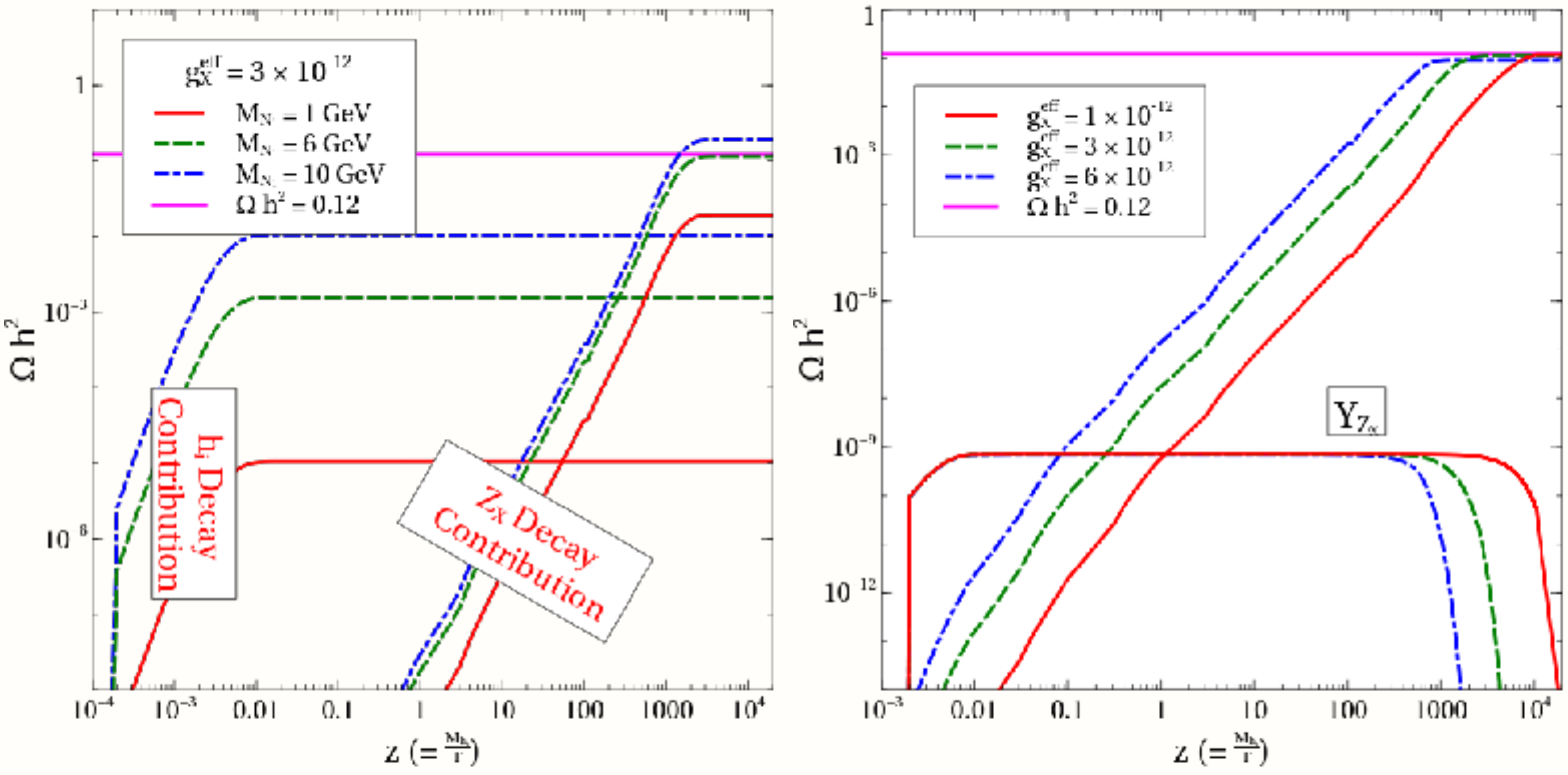
In the parameter range where the axion density is too low, another DM candidate is needed… One of the RH neutrinos can play this role thanks to the special U(1) charges and Z_2 symmetry ! The other two RH neutrinos instead realise the light neutrino masses via the seesaw mechanism.

$$\mathcal{L}_{N_1} = \frac{i}{2}\bar{N}_1\gamma^\mu\left(\partial_\mu - i\, g_X^{eff} Z_X\right)N_1 + y_{11}\bar{N}_1^c N_1 \frac{\phi_1^\dagger \phi_2}{M_{Pl}} + h.c.$$

It cannot be a WIMP as the couplings are suppressed either by the Planck scale or the mass of the Z_X ~ f_a !
But it may be a Feebly Interacting Massive Particle…

NEUTRINO AS FIMP DM

It can be produced by Higgs or Z_X (also FIMP) decays!
Late SuperFIMP production… Z_X is at TeV scale !

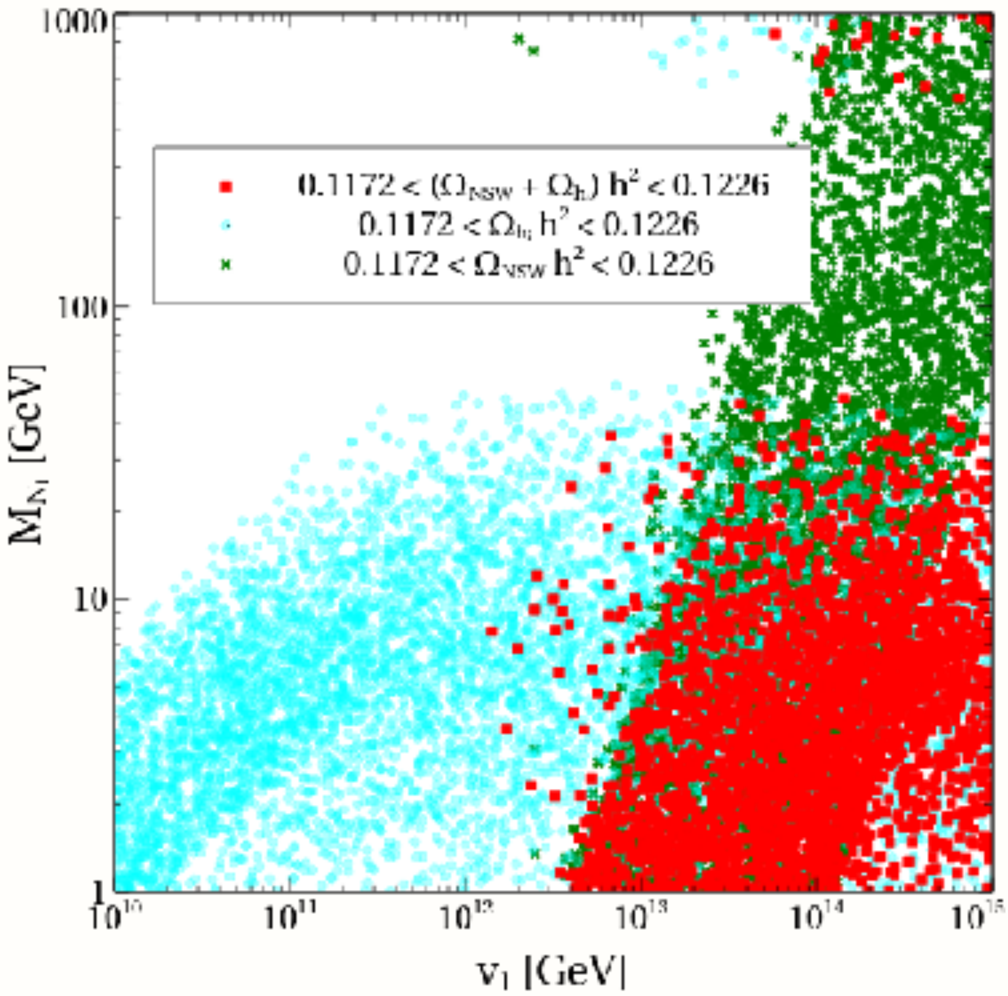


AXION PARAMETERS GIVE DM

$$(\Omega_{N_1}^{SF} h^2) = \frac{2.038 \times 10^{27}}{g_s \sqrt{g_\rho}} \, 2BR_{Z_X \to N_1 N_1} \sum_i \frac{M_{N_1} M_{h_i} F_a^2}{64\pi q_1^2 v_1^2 v_2^2}$$

$$2BR_{Z_X \to N_1 N_1} = \frac{2}{24} \frac{(n_\chi + 1)^2}{n_\chi^2 - 8 n_\chi + 28/3}$$

Also for the RH neutrinos as DM, the axion sector parameters determine the DM density as the mass and couplings contain the PQ breaking v.e.v.s and the BR the charges…



OUTLOOK

- The FIMP mechanism is very simple and can produce DM in the right amount in many different regimes and models.
- The FIMP/SuperWIMP framework can point generically to heavy metastable particles/displaced vertices at LHC or to decaying DM.
- FIMP production could happen very late, either by a Boltzmann suppressed FIMP or by the late decay of a FIMP into another particle (SuperFIMP) giving possible observables signals in DD, ID or in structure formation.
- In axion models with accidental PQ symmetry it can be natural to have only part of DM as axions ! And maybe the EDMs are not completely cancelled…