ECT* EUROPEAN CENTRE FOR THEORETICAL STUDIES IN NUCLEAR PHYSICS AND RELATED AREAS

FONDAZIONE BRUNO KESSLER

Neutron Electric Dipole Moment: from theory to experiment

Cosmological implications of the neutron EDM

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$[q,p]=i\hbar$

HIDDeν
Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

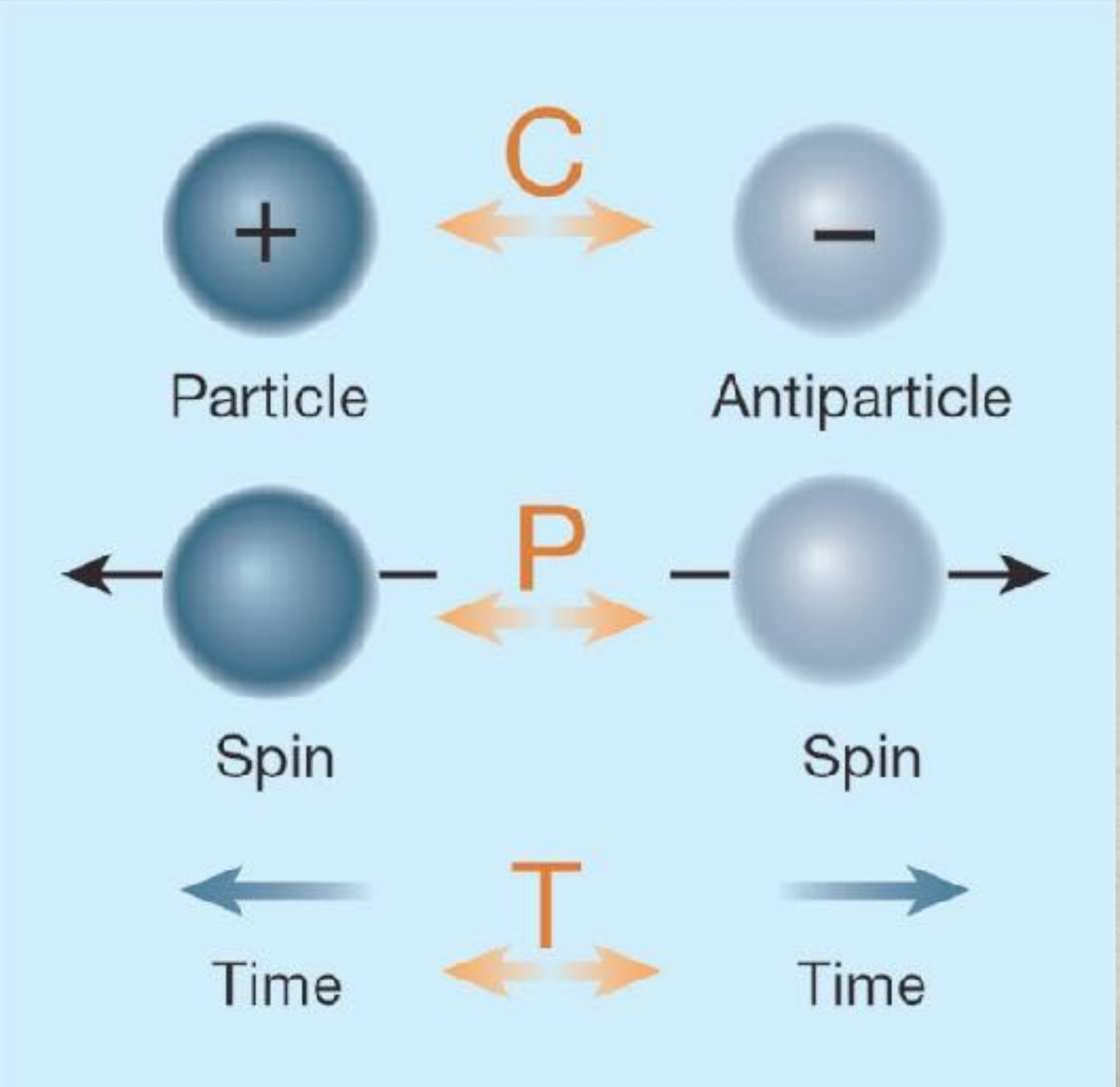
MARIE CURIE ACTIONS

Outline

- Introduction to CP violation in the SM and EDMs
- PQ symmetry as an accidental symmetry from a gauged U(1) and gravitational contribution to EDMs
- Axions as Dark Matter
- RH Neutrino FIMP Dark Matter
- Outlook

CP violation in the SM & EDMs

C, P, & T symmetries



CPT THEOREM

A Lorentz-invariant QFT with an hermitian Hamiltonian cannot violate the CPT symmetry !

[Lueders & Pauli 1954]

CP violation ⟷ T violation

Consequence of CPT theorem and locality: particle and antiparticle have the same mass !

But not the same decay rate or scattering rate in the full quantum theory...

Electric Dipole moment

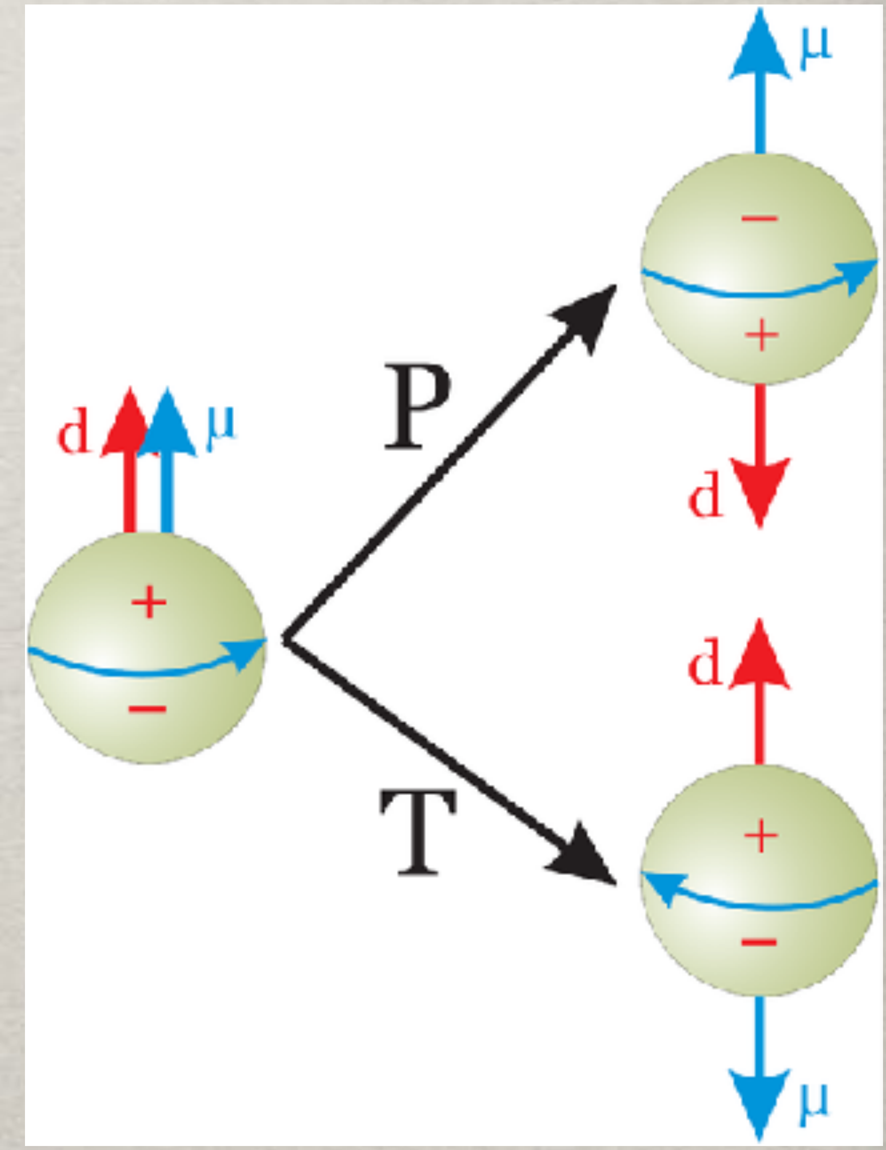
Classically we have:

$$\vec{d} = \int_V d^3\vec{r}\,\vec{r}\,\rho_Q(\vec{r})$$

Quantum mechanically for a bounded state the charge density is related to the wave function:

$$\vec{d} = \int_V d^3\vec{r}\,\vec{r}\,|\psi(\vec{r})|^2 = d\hat{\mu}$$

parallel to the spin of the particle, but with different P/T parities !



Electric Dipole moment

For a fundamental particle like the electron:

$$\mathcal{L} \to \bar{\psi}\left[\gamma^\mu F_1(q^2) + i\frac{\sigma^{\mu\nu}q_\nu}{2m_\psi}F_2(q^2) + i\epsilon_{\mu\nu\rho\sigma}\frac{\sigma^{\nu\rho}q_\sigma}{2m_\psi}F_3(q^2) + \frac{1}{2m_\psi}\left(q^\mu - \frac{q^2}{2m_\psi}\gamma^\mu\right)\gamma_5 F_4(q^2)\right]$$

Magnetic Electric dipole Anapole moment

These terms arise via radiative corrections. In the SM only source of CP violation is the CKM matrix and one needs at least 4 weak vertices to have a non-vanishing phase, i.e. the contributions to the EDMs are strongly suppressed

$$d_n = (10^{-33} - 10^{-34})e\ cm$$

Additional CP violating sources can give the dominant contribution !

Strong CP Problem

['t Hooft 76]

Non-trivial QCD vacuum structure → $\mathcal{L} = \theta \, \frac{\alpha_s}{8\pi} \, G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$

This term violates T/CP since the gluon field strength and its dual have opposite T/CP properties ! But we do not observe any T/CP violation in the QCD sector...

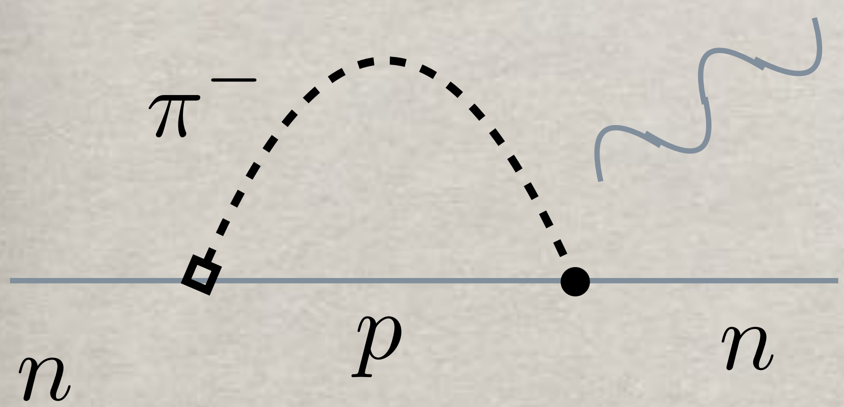
Actually this term can be rotated away by a global U(1)_A transformation on the quark fields, as long as at least one of them is massless. For massive quarks the relevant parameter contains also the phase in the mass matrix:

$$\bar{\theta} = \theta + \arg(\det \mathrm{M_q})$$

Strong CP and EDMs

$$\mathcal{L} = \bar{\theta}\ \frac{\alpha_s}{8\pi}\ G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$

This term generates a non-vanishing electric dipole moment for the neutron proportional to the value of the theta angle:



$$\bar{\theta} = \theta + \arg(\det \mathrm{M_q})$$

$$d_n = -(2.4 \pm 1.0) \times 10^{-16} \bar{\theta}\ e\mathrm{cm}$$

$$\bar{\theta} < 10^{-10}$$

Need to suppress the theta angle at least 10 orders of magnitudes !

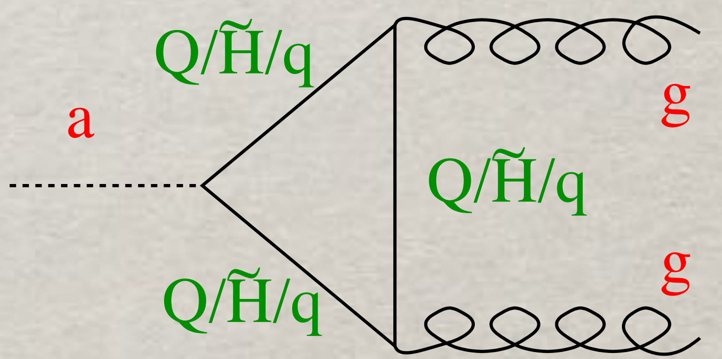
Strong CP & the Axion

$\bar{\theta} < 10^{-10}$ Why is this parameter so small ???

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

[Peccei-Quinn 77, Weinberg & Wilczek 77]

$$\mathcal{L}_{PQ} = \frac{\alpha_s}{8\pi f_a}\, a\, G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a$$



The axion has the same quantum numbers as the pion and it mixes with its neutral component. To suppress the mixing and avoid constraints require $f_a \gg f_\pi$ INVISIBLE !

Axion Relaxation

The axion as a Goldstone boson of the global PQ symmetry is a flat direction before the QCD phase transition breaks the symmetry explicitely:

In the early Universe the axion field has a random value ~ 1.

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 instantons effects and the axion starts to oscillate coherently around this minimum:

theta relaxes to zero dynamically !

PQ symmetry as accidental symmetry from a gauged U(1)

Global symmetry ?

[Kamionkowski & March-Russell 1992, ….]

The Peccei-Quinn solution for the strong CP problem works since the instanton potential has a minimum at theta=0… But is this the only breaking of the PQ symmetry ? In reality we do not expect gravity to satisfy any global symmetry and indeed we can write non-renormalisable operators which depend on the axion field explicitly…

To protect the PQ symmetry and avoid those operators, we can exploit a local spontaneously broken U(1) symmetry and arrange the charges so that the non-renormalisable operators can appear only at very high order. Moreover we require the symmetry to permit operators for Majorana/Dirac neutrino masses and to be fully non-anomalous.

The PQ symmetry is then purely accidental !

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

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 !

Axion field & couplings

Both the U(1)_X and the U(1)_PQ symmetries are broken by the vacuum expectation values of the two exotic scalars:

$$\phi_i \to \frac{v_i + h_i}{\sqrt{2}} e^{i\frac{a_i}{v_i}}$$

The two pseudoscalar parts are Goldstone bosons and one is absorbed into the Z_X gauge boson, while the other remains as the axion and couples to the gluon field:

$$A = \frac{v_2 a_1 + n_\chi v_1 a_2}{\sqrt{n_\chi^2 v_1^2 + v_2^2}} \qquad \mathcal{L} = \frac{g_s^2}{32\pi^2} N_\psi A \frac{\sqrt{n_\chi^2 v_1^2 + v_2^2}}{v_1 v_2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

N_{DW} $\quad 1/f_a$

Gravitational terms

[LC & S. Khan 2022]

As the PQ symmetry is accidental, we expect gravitational non-renormalisable terms to break the symmetry explicitly and add a potential for the axion field. The U(1)_X symmetry forbids many terms but not all…

$$V_{PL}(\phi_1, \phi_2) = \frac{g}{N_\psi! N_\chi!} \frac{\phi_1^{N_\psi} \phi_2^{N_\chi}}{M_{PL}^{N_\psi + N_\chi - 4}} + h.c.$$

leading to

$$\mathcal{V}_g = (M_a^g)^2 F_a^2 \left[1 - \cos(p\, \bar{\theta}_a + \delta)\right]$$

where the mass term is related to the v.e.v.s, $p = N_\psi(n_\chi - 1)$ and the shift delta arises from the imaginary part of g…

The minimum of the axion potential is shifted !

nEDM from Gravity

[LC & S. Khan 2022]

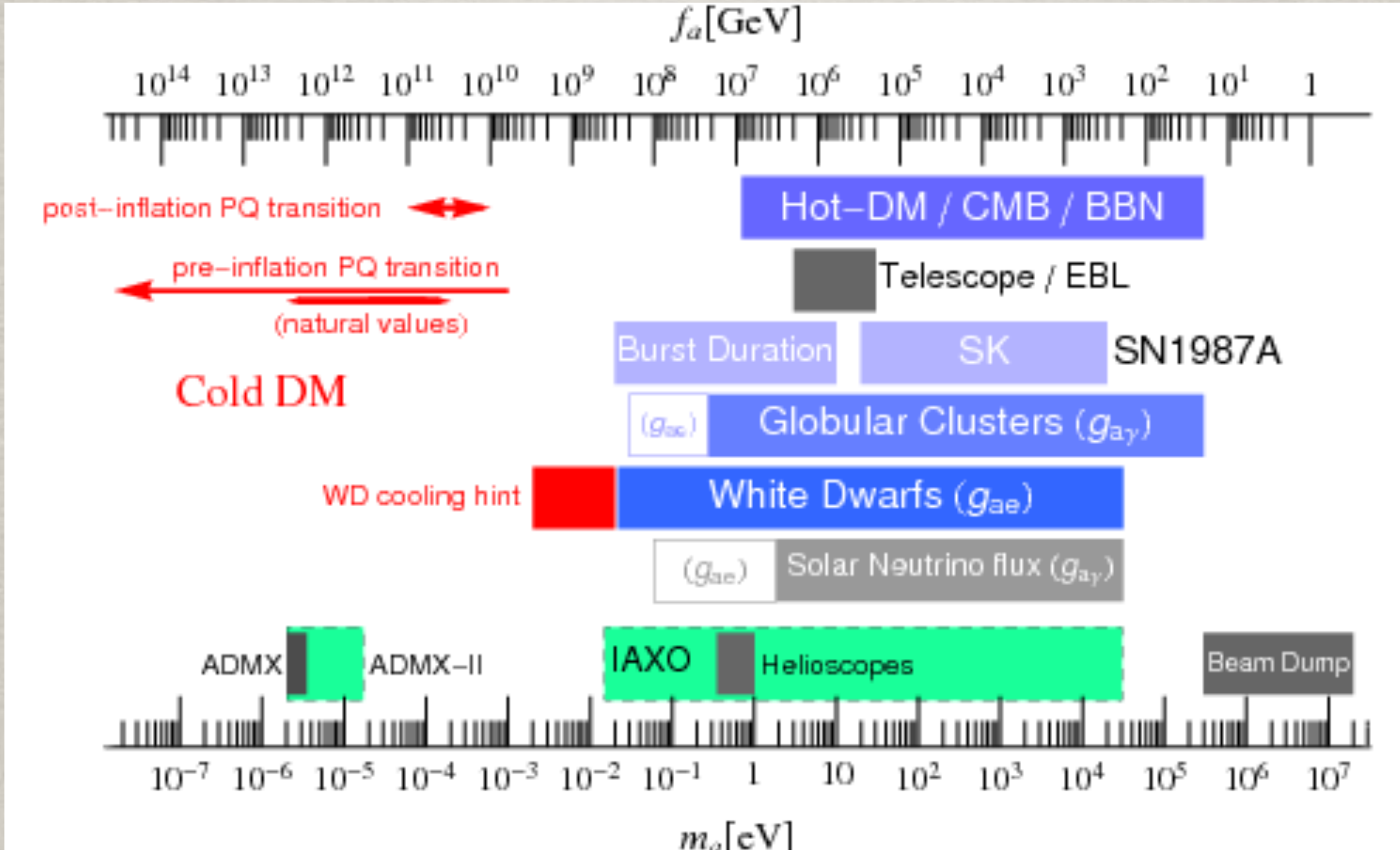
The shift due to the gravitational terms is strongly suppressed due to the different charges and large number of fermions:

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

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's constraints

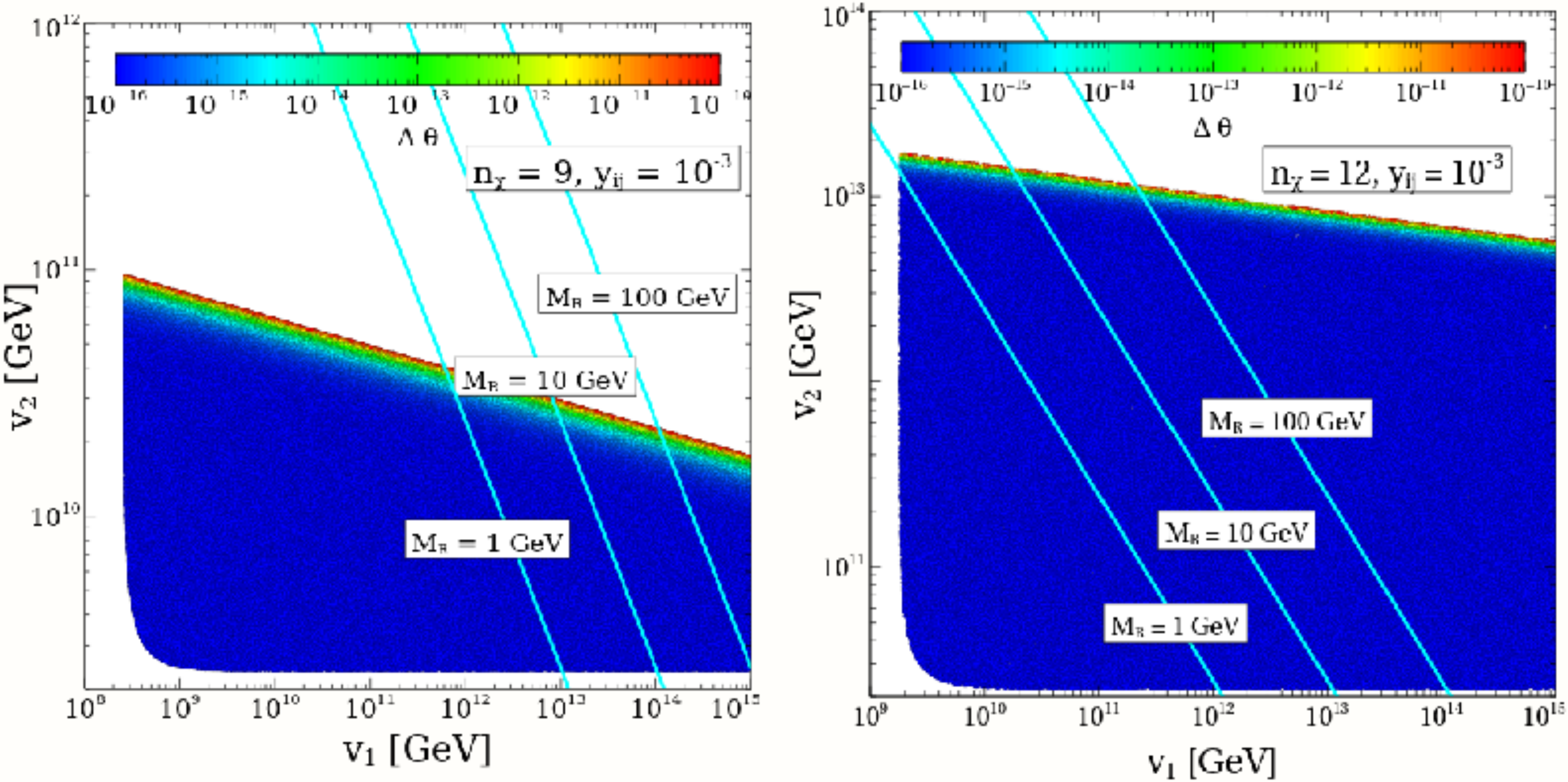


[CERN Report]

Axion & EDMs

Viable axion with EDMs maybe behind the corner…

[LC & S. Khan 2022]



Axions as Dark Matter

Their energy density by misalignment is

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

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] [Cosmology]

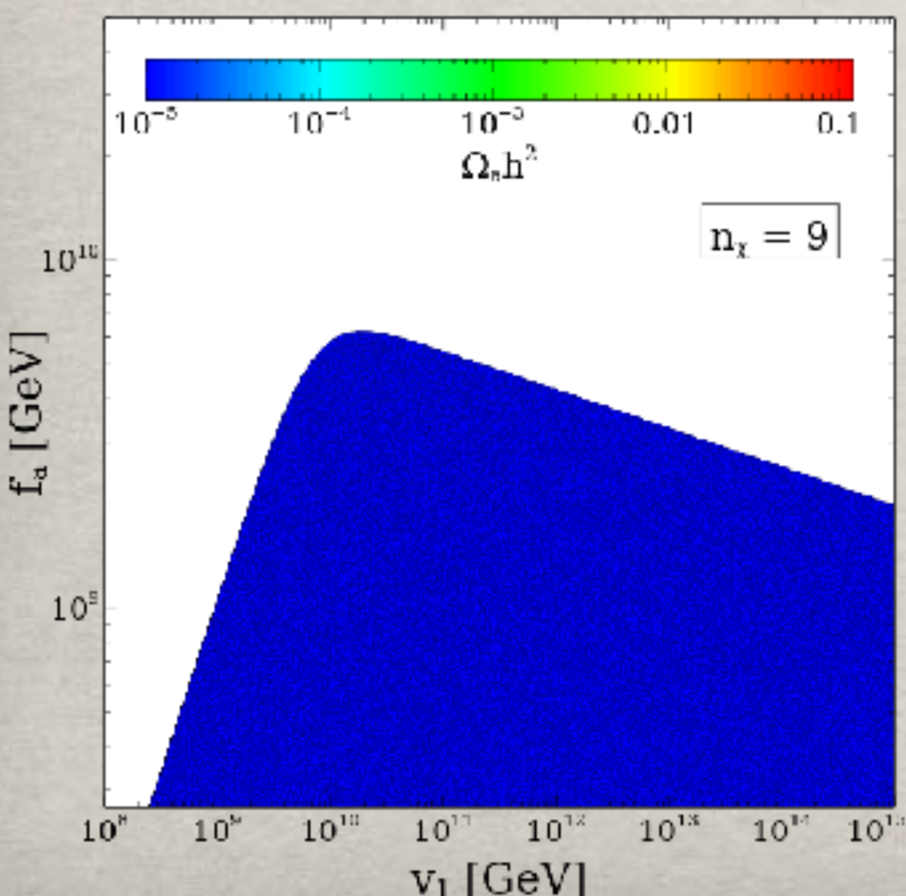
Therefore the mass for axion DM is very small:

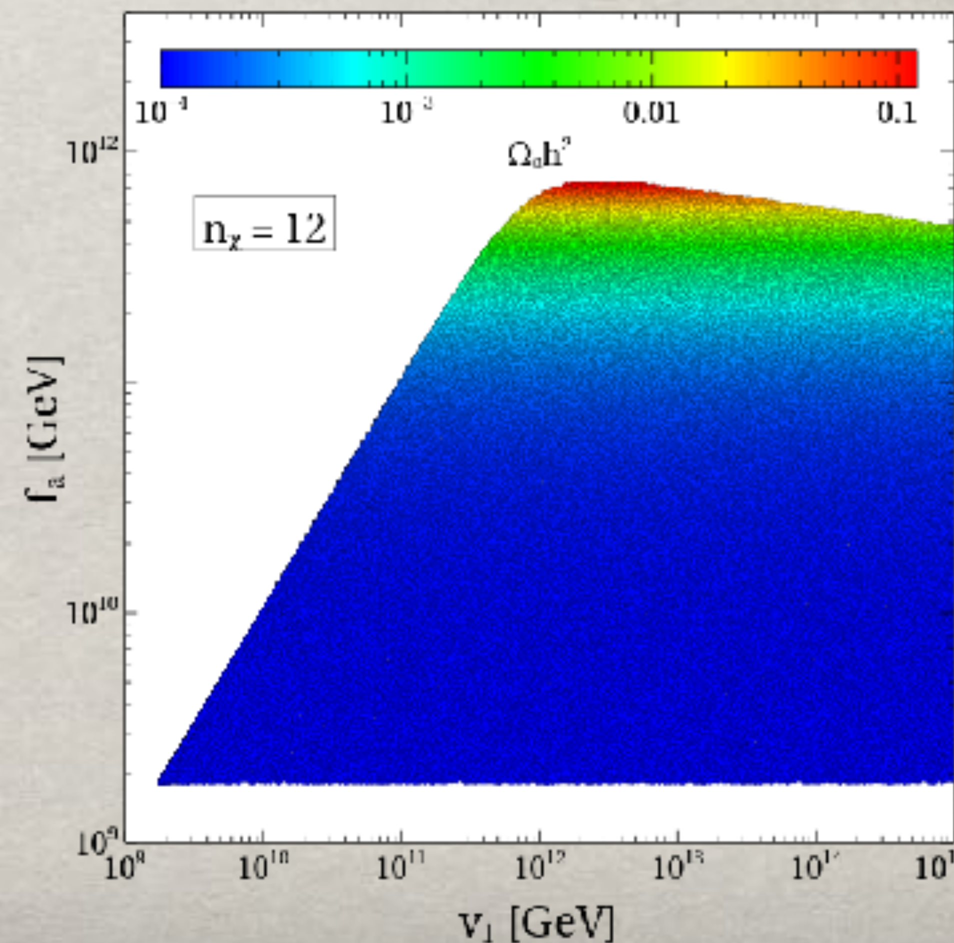
$$m_a = \Lambda_{QCD}^2 / f_a \sim 6 \times 10^{-5}\mathrm{eV} \left(\frac{f_a}{10^{11}\mathrm{GeV}} \right)^{-1}$$

Can the axion be DM ?

The gravitational mass is much smaller than the QCD mass, so the axion remains practically massless in the early Universe before the QCD phase transition and is produced as usual via misalignment, but often the energy density is too low:

[LC & S. Khan 2022]





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 !

RH neutrino Dark Matter

Neutrino as FIMP DM

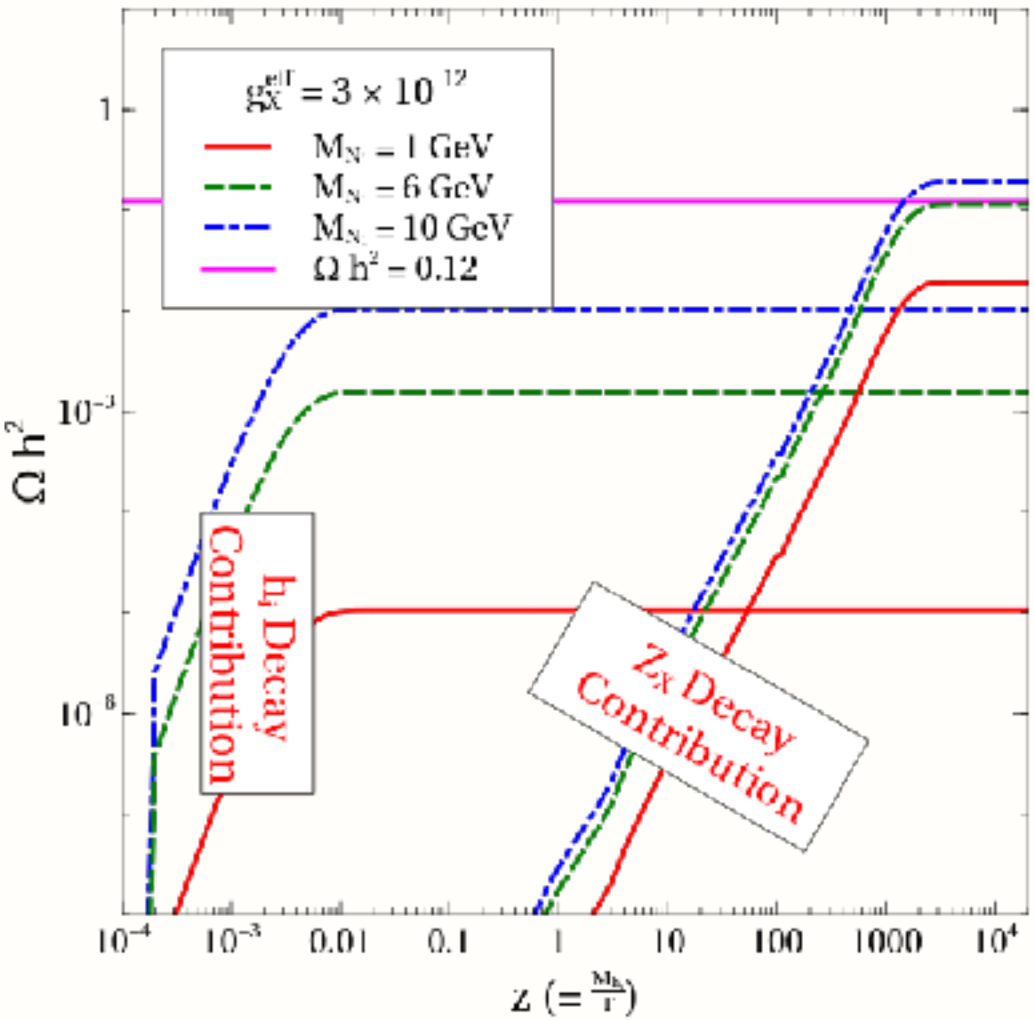
In the parameter range where the axion density is too low, another DM candidate is needed… One of the RH neutrinos can play this role thanks to the special U(1) charges and Z_2 symmetry ! The other two RH neutrinos instead realise the light neutrino masses via the seesaw mechanism.

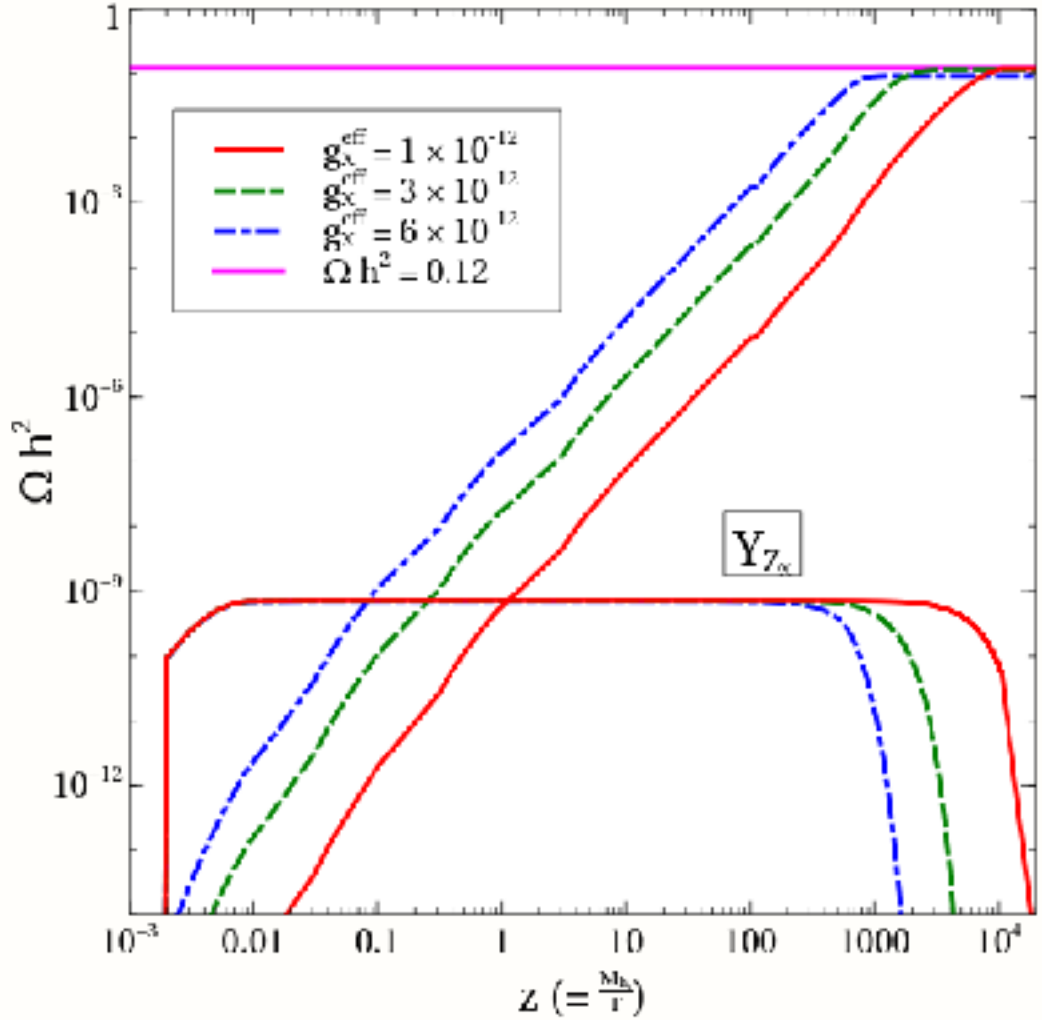
$$\mathcal{L}_{N_1} = \frac{i}{2}\bar{N}_1\gamma^\mu \left(\partial_\mu - i\, g_X^{eff} Z_X\right) N_1 + y_{11}\bar{N}_1^c N_1 \frac{\phi_1^\dagger \phi_2}{M_{Pl}} + h.c.$$

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!
Kind of SuperFIMP production… Z_X then at TeV scale !



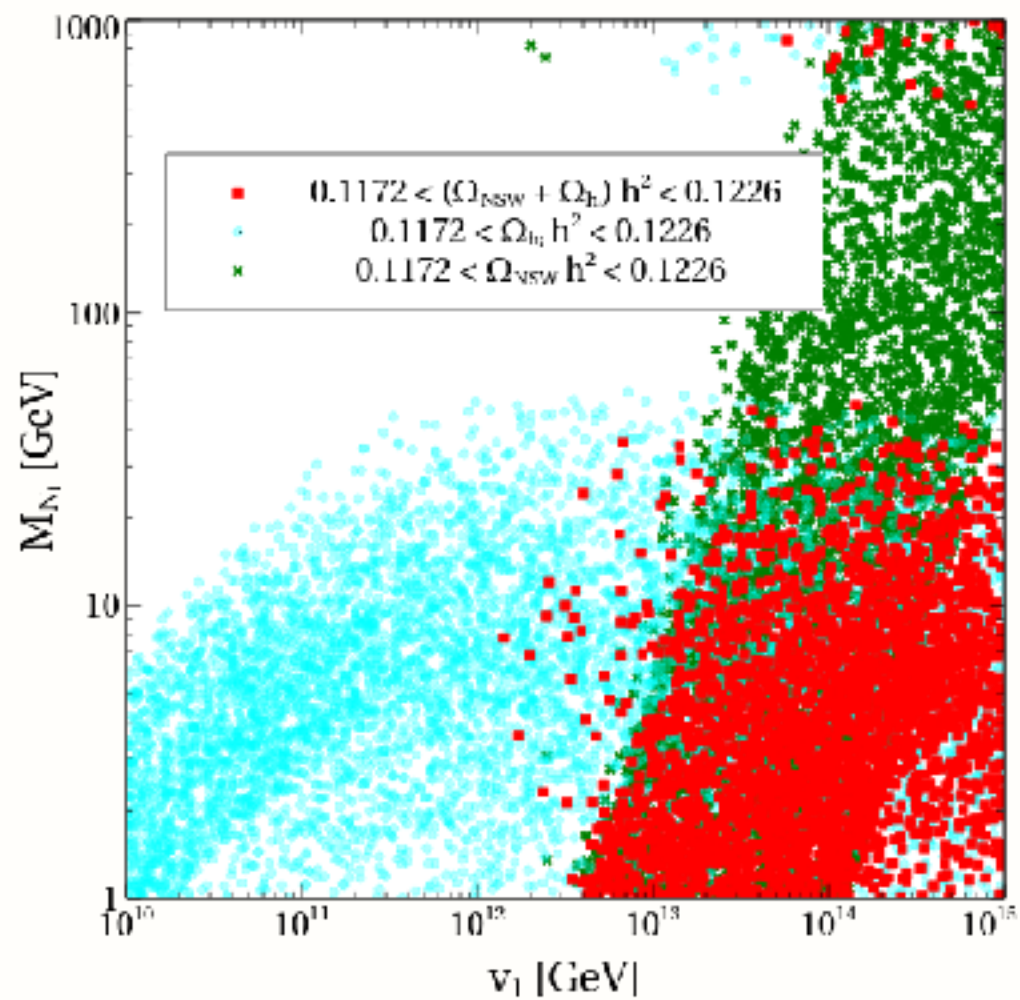


AXION PARAMETERS GIVE DM

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

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

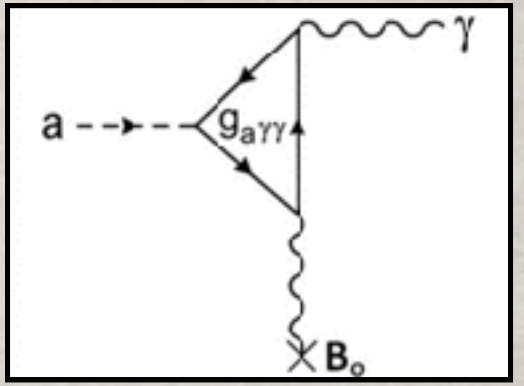
Also for the RH neutrinos as DM, the axion sector parameters determine the DM density as the mass and couplings contain the PQ breaking v.e.v.s and the BR the charges…



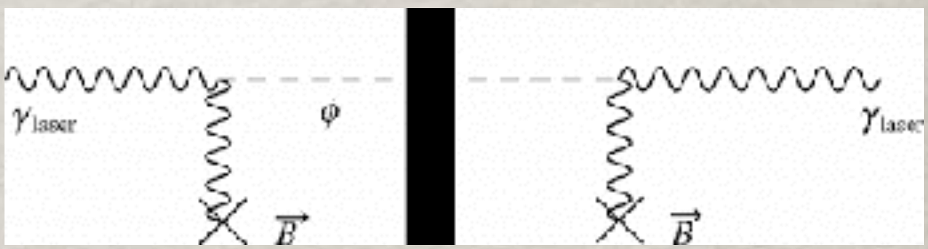
OUTLOOK

Photon couplings

Axions are searched for via their coupling to photons, as they can oscillate into real photons in a magnetic field:



Primakoff effect in presence of a classical magnetic field for axions



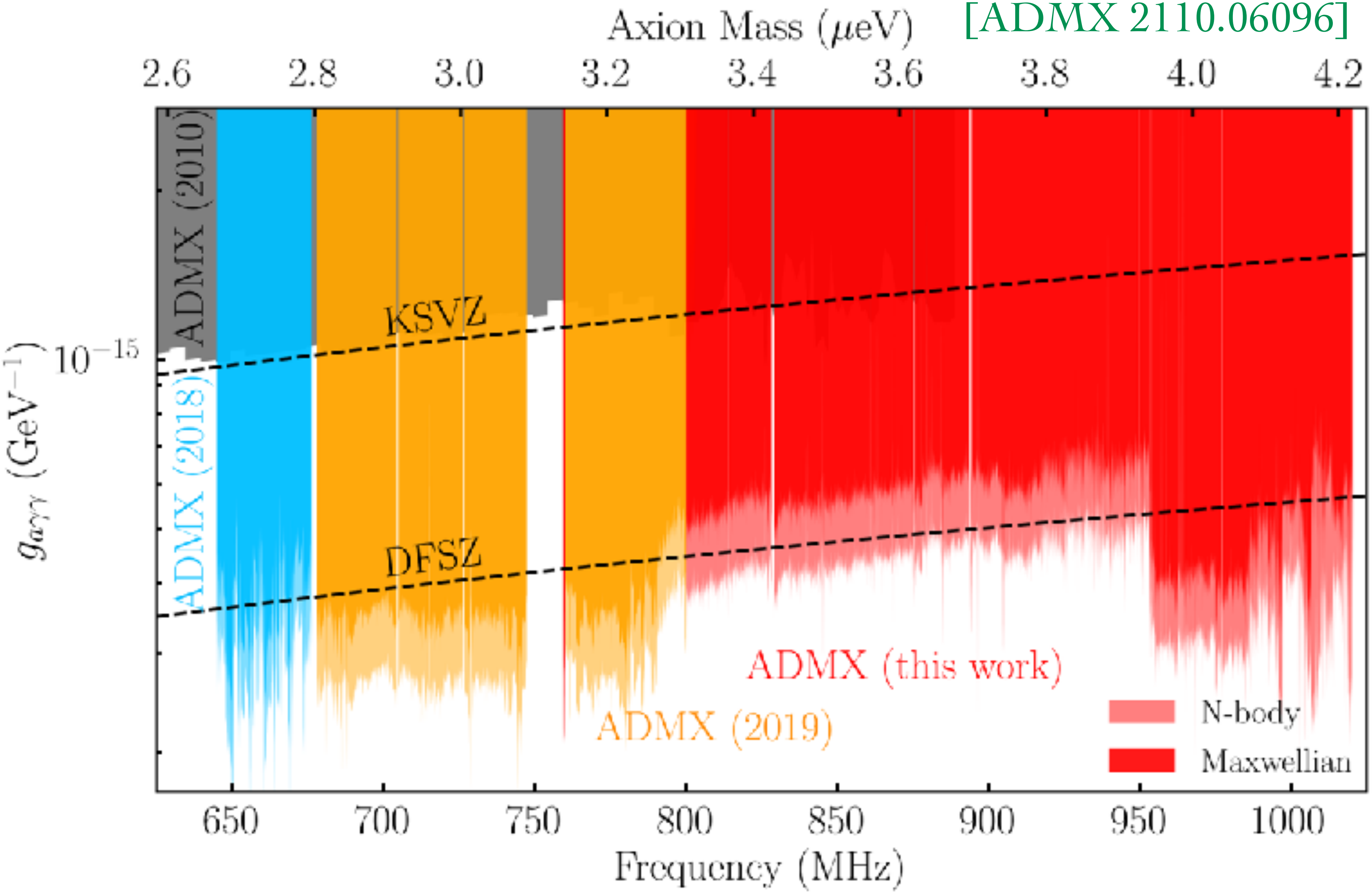
Birefringence effect,
light shining through the wall

In our case the axion is of the KSVZ type and so has no direct coupling to photons, apart those due to mixing with the pion

$$C_{A\gamma\gamma} = -\frac{e^2}{12\pi^2}\left(\frac{4m_d + m_u}{m_d + m_u}\right)$$

AXION DM SEARCHES

[ADMX 2110.06096]



Conclusions & Outlook

- The PQ solution for the strong CP problem relies on a global symmetry, not expected to survive gravity effects…, but it could just be an accidental symmetry and still suppress theta enough…
- Then the nEDMs arise from non-renormalisable operators and are not generically zero !
- We construct a model with the an additional U(1) and an axion field with an accidental PQ symmetry. The axion can be DM if there are many exotic quarks, otherwise the RH neutrino can be a FIMP
- Maybe also generate the BAU ?