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Connecting neutrinos with light dark matter candidates

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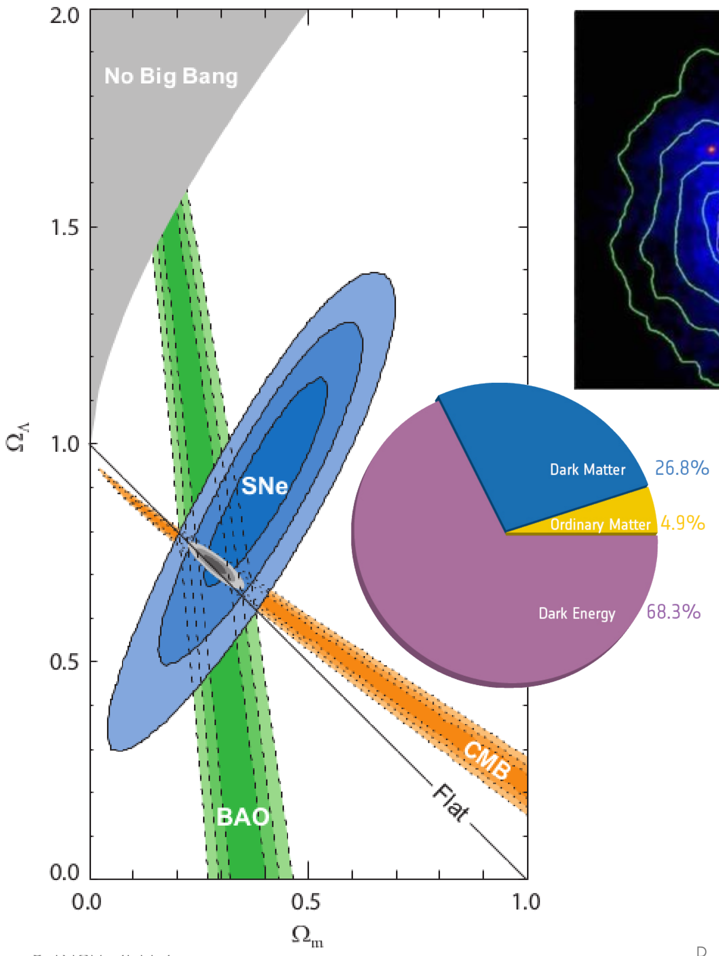
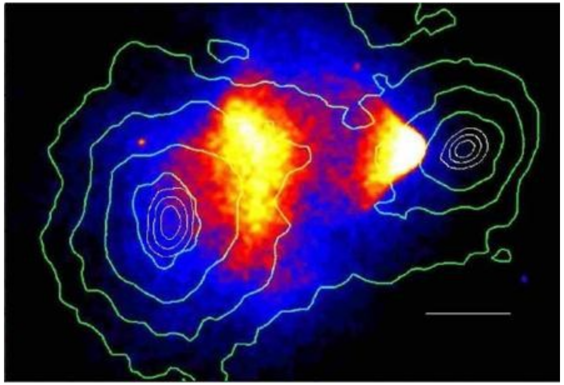
Dark Matter Days 2017 – CIFFU BUAP

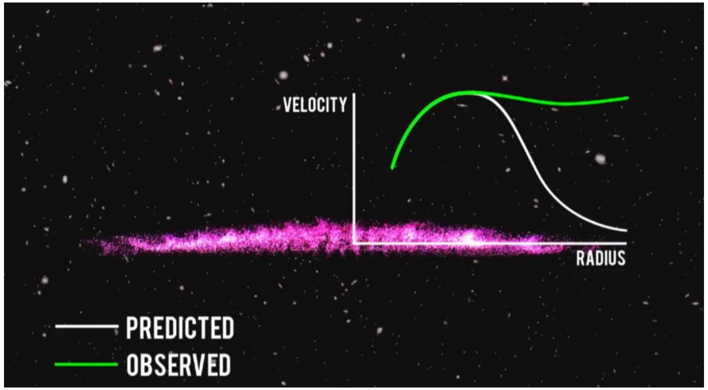
Outline


Dark Matter
Neutrinos
DM and Neutrino masses
DM and Neutrino oscillations
Final words

Dark Matter





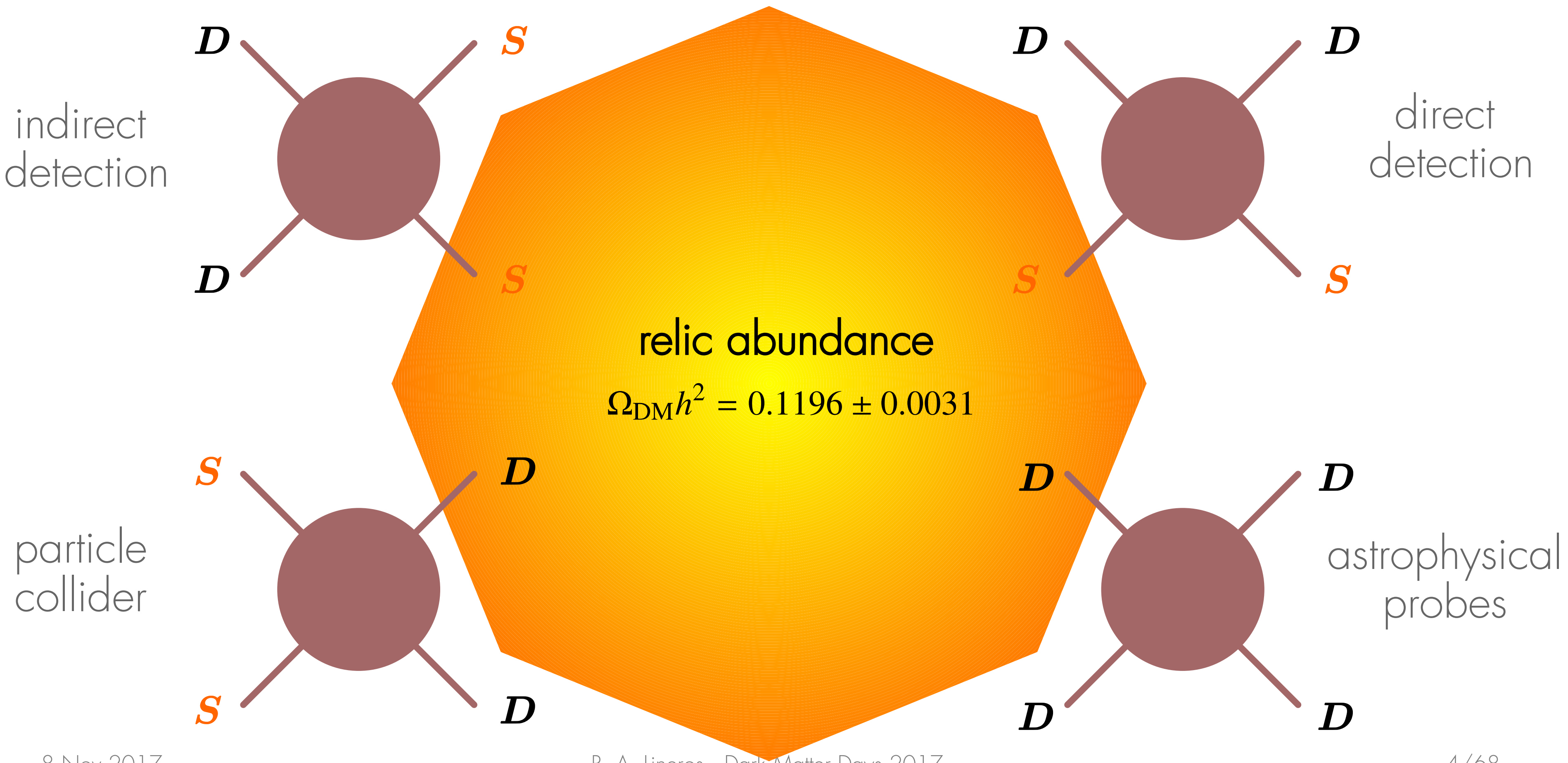


Observations support Dark Matter

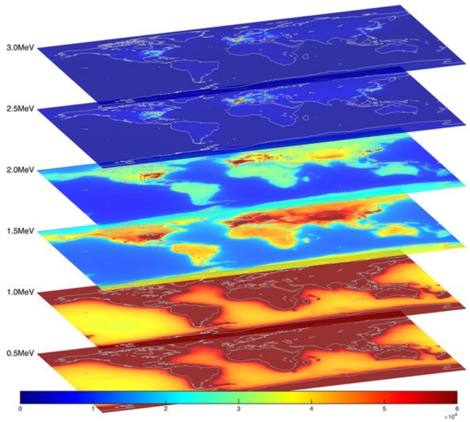
- Dynamics of clusters and galaxies
- Structure formation
- CMB anisotropies
- Baryon Acoustic Oscillation

$$\Omega_{\rm DM} h^2 = 0.1196 \pm 0.0031$$

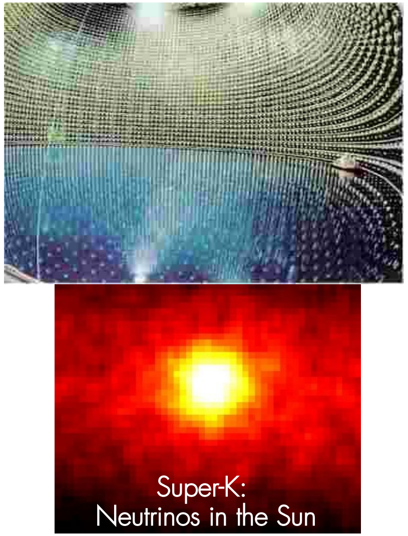
Dark Matter Searches



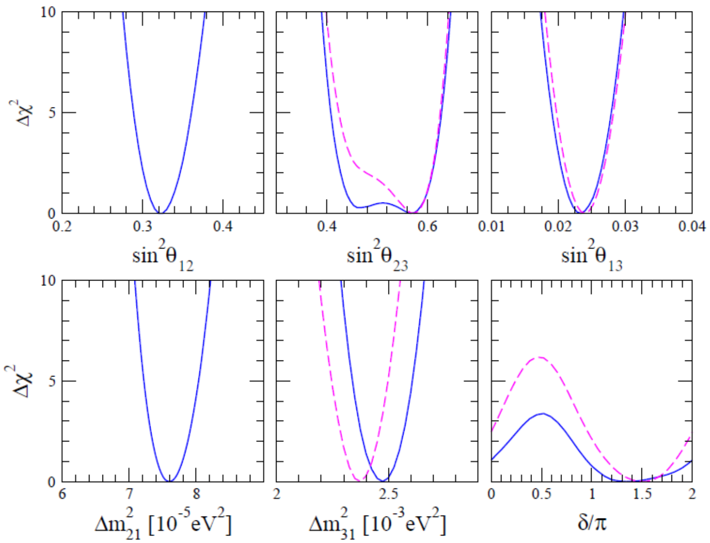
Neutrinos



AGM2015: Antineutrino Global Map 2015



Forero, Tortola and Valle PRD 90 (2014) 093006



The SM predicts zero neutrino mass

Beyond SM physics is required to explain mass spectrum and mixing angles

Example 1

(light) Dark Matter candidate and neutrino masses

Neutrino mass mechanisms

A large fraction of the models uses the 5-dim Weinberg operator to generate majorana neutrino masses

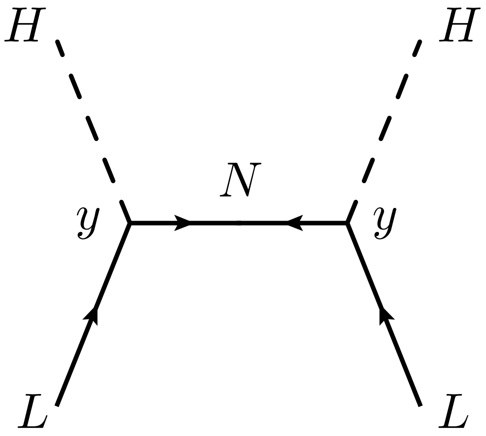
$$\mathcal{O}_{5ij} \propto (L_i H)^T (L_j H)$$

This operator breaks lepton number in 2 units

Neutrino mass mechanisms

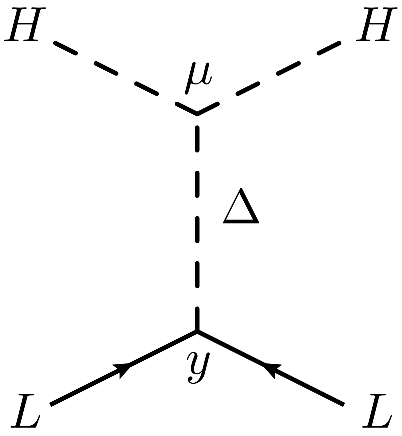
The commonly known schemes are see-saw mechanisms

Type-I



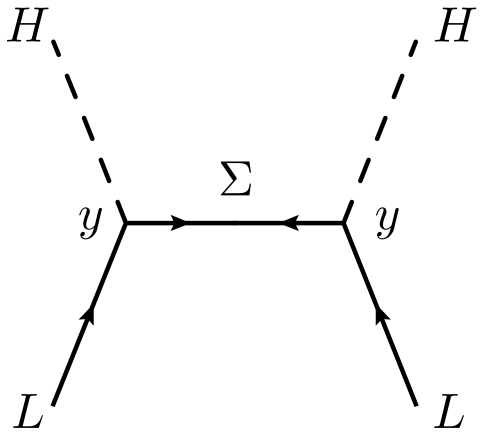
$$m_\nu \propto \frac{v^2 y^2}{M_N}$$

Type-II



$$m_\nu \propto \frac{v^2 y \mu}{M_\Delta^2}$$

Type-III



$$m_\nu \propto \frac{v^2 y^2}{M_\Sigma}$$

Neutrino mass mechanisms

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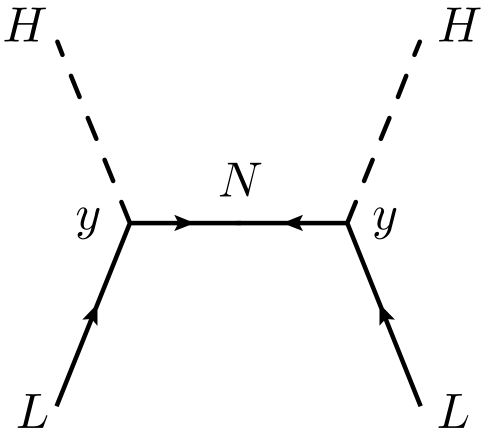

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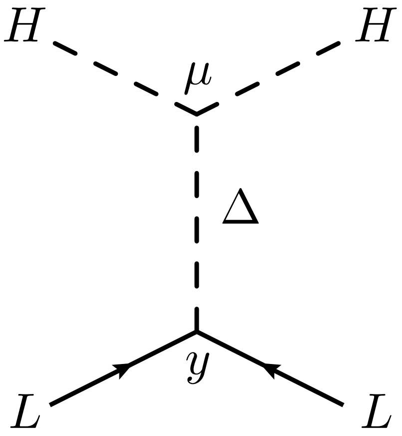
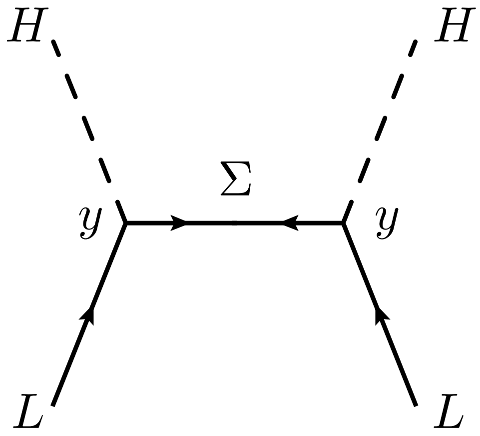
Type-II



$$m_\nu \propto \frac{v^2 y \mu}{M_\Delta^2}$$

Type-III

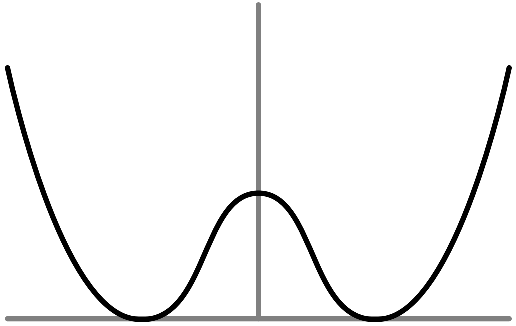


$$m_\nu \propto \frac{v^2 y^2}{M_\Sigma}$$

Enters the Majoron

The Type-I seesaw can be generated by the spontaneous breaking of the $\mathrm{U}(1)$ lepton number symmetry

$$S = \frac{v_S + \sigma + iJ}{\sqrt{2}}$$



$$\mathcal{L} \supset -y_L \overline{L} H N^c - \frac{y_S}{2} S \overline{N^c} N + h.c.$$

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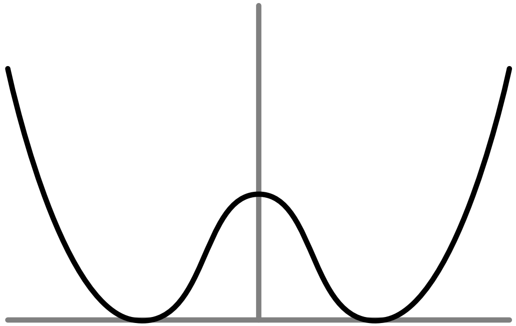

$$\mathcal{L} \supset -y_L \overline{L} H N^c - \frac{y_S}{2} S \overline{N^c} N + h.c.$$

-1 0 1 2 -1 -1

Enters the Majoron

$$m_D = \frac{y_L v_H}{\sqrt{2}}$$

$$M_N = \frac{y_S v_S}{\sqrt{2}}$$

After the SSB, we get the Type-I seesaw

$$\mathcal{L} \supset -m_D \bar{\nu}_\mathrm{L} N^c - \frac{M_N}{2} \overline{N^c} N + h.c.$$

and 2 scalars: σ and J

$$m_\sigma \simeq v_S \qquad m_J = 0$$

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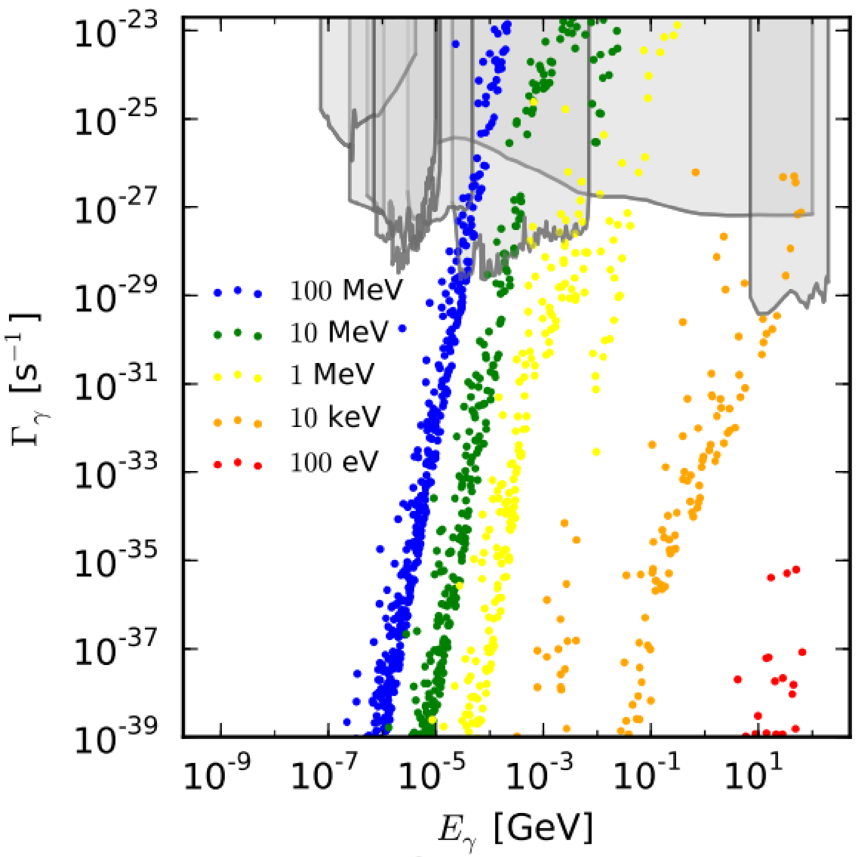
$$\mathcal{L} \supset -m_D \bar{\nu}_{\rm L} N^c - \frac{M_N}{2} \overline{N^c} N + h.c.$$

and 2 scalars: σ and J ⟵ DM candidate

$$m_\sigma \simeq v_S \qquad m_J = 0$$

Majoron as DM (pros)

- Neutral
- Weakly coupled to the SM
- Long lived



Details in arxiv: 1406.0004

$$\Gamma_{J\to\nu\nu} = \frac{m_J}{32\pi}\frac{\sum_i (m_i^\nu)^2}{2v_1^2} \qquad \Gamma_{J\to\gamma\gamma} = \frac{\alpha^2 m_J^3}{64\pi^3}\left|\sum_f N_f Q_f^2 \frac{2v_3^2}{v_2^2 v_1}(-2T_3^f)\frac{m_J^2}{12 m_f^2}\right|^2$$

Majoron as DM (cons)

$$m_J = 0 \quad !!!!$$

… but global symmetries are not protected under gravity effects

Therefore

$$m_J \neq 0$$

… and the majoron DM is just a pseudo Nambu-Goldstone boson

Majoron as DM (our proposal)

ArXiv:1703.03416

What defines a majoron DM?

- It is a (pseudo)scalar
- It is part of the neutrino mass mechanism
- Its signature is the decay into neutrinos
- It is massive

Inverse seesaw

The standard inverse seesaw

$$\mu \ll m_D \ll M$$

$$\mathcal{L} = -\frac{1}{2} n_L^T C \mathcal{M} n_L + h.c.$$

$$n_L^T = (\nu_L, N_1^c, N_2)$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Inverse seesaw

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$$\mu \ll m_D \ll M$$

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$$n_L^T = (\nu_L, N_1^c, N_2)$$

$$\mathcal{M} = \begin{pmatrix} 0 & m_D & 0 \\ m_D^T & 0 & M \\ 0 & M^T & \mu \end{pmatrix}$$

Lepton number violating term

Inverse seesaw

The standard inverse seesaw

$$\mu \ll m_D \ll M$$

Active neutrinos

$$m_\nu = \left(\frac{m_D}{M}\right)^2 \mu$$

Heavy neutrinos

$$m_{N'} = M - \frac{m_D^2}{M} + \frac{\mu}{2}$$

$$m_N = M - \frac{m_D^2}{M} - \frac{\mu}{2}$$

Inverse seesaw

The standard inverse seesaw $\mu \ll m_D \ll M$

Some numerology:

$$M \sim 100\,\mathrm{TeV} \quad m_D \sim 10\,\mathrm{GeV} \quad \mu \sim 10\,\mathrm{MeV}$$

$$m_\nu \sim 0.1\,\mathrm{eV}$$

$$\alpha = \frac{\mu}{M} \sim 10^{-7}$$

Spontaneous Inverse seesaw

To generate the inverse seesaw scheme we need to add 2 complex scalars

$$\mathcal{L} = -y_L \bar{L} H N_1^c - y_S S^\dagger \overline{N_2} N_1^c - \frac{y_X}{2} X^\dagger \overline{N_2^c} N_2 + h.c.$$

$$m_D = \frac{y_L v_h}{\sqrt{2}}, \; M = \frac{y_S v_S}{\sqrt{2}}, \text{and } \mu = \frac{y_X v_X}{\sqrt{2}}$$

Spontaneous Inverse seesaw

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$$\mathcal{L} = -y_L \bar{L} H N_1^c - y_S S^\dagger \overline{N_2} N_1^c - \frac{y_X}{2} X^\dagger \overline{N_2^c} N_2 + h.c.$$

$$v_S > 50 \text{ TeV} \qquad v_X > 5 \text{ MeV}$$

Spontaneous Inverse seesaw

But the charge assignments do not follow the typical one of the ISS

	L	N_1	N_2	S	X
$SU(2)_L$	2	1	1	1	1
$U(1)_Y$	1/2	0	0	0	0
$U(1)_l$	1	-1	x	$1-x$	$2x$

$$x = 3/5$$

$$\mathcal{L} = -y_L \bar{L} H N_1^c - y_S S^\dagger \overline{N_2} N_1^c - \frac{y_X}{2} X^\dagger \overline{N_2^c} N_2 + h.c.$$

Scalar potential

The assignment fixes the potential

$$\omega = \frac{v_X}{v_S}$$

$$V_{\rm scalar} = V_{XS} + V_{HXS} + V_I$$

$$V_I = \lambda_{\rm cp} e^{i\delta} X S^{\dagger 3} + h.c.$$

$$S = \frac{v_S e^{i\theta} + \sigma_S + i\chi_S}{\sqrt{2}} \qquad X = \frac{v_X e^{i\tau} + \sigma_X + i\chi_X}{\sqrt{2}}$$

The tadpole equations relate the CP phases: $\tau = 3\theta - \delta - \pi$

Mass spectrum

$$\omega = \frac{v_X}{v_S}$$

Now we have 5 spin-0 fields: 4 related to L breaking
1 related to EW breaking

ζ_1 ζ_2 ζ_3 ζ_4 ζ_5

ζ_5 → higgs-like

ζ_1 → Massless

ζ_2 →

$$M_J^2 = \frac{v_S^2}{2\omega}\lambda_{\rm cp}(1+9\omega^2)$$

ζ_3, ζ_4 → Heavy scalars

$$M^2_{\zeta_{3,4}} \sim \mathcal{O}(v_S^2)$$

Majoron DM stability

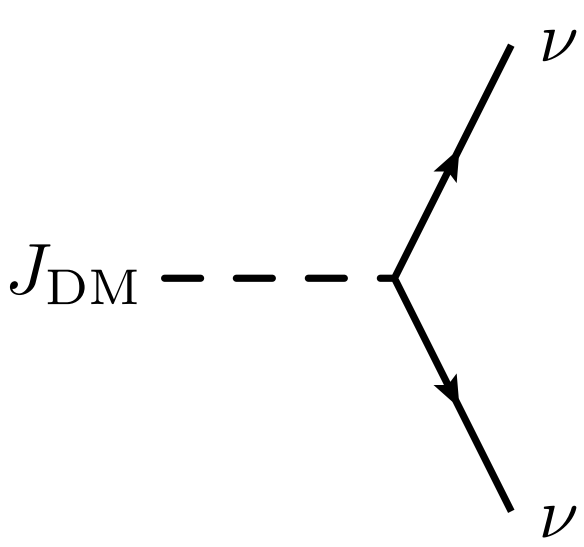
The only candidate is the lightest massive scalar i.e. $\zeta_2 = J_{\rm DM}$

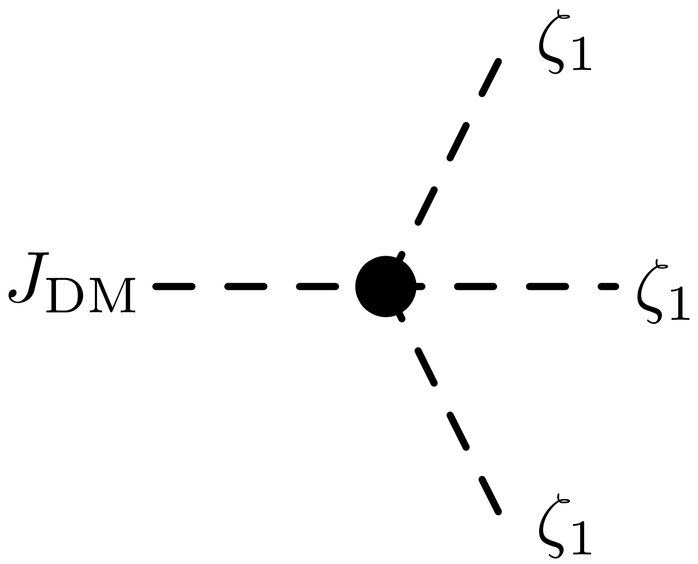
We still has to satisfy the stability condition:

$$\Gamma_{\rm DM} < 10^{-52}\,{\rm GeV}$$

Decay modes

There are potentially dangerous decay modes:





Decay into neutrinos

$$\alpha = \frac{\mu}{M} \sim 10^{-7}$$

The decay rate vanishes for:

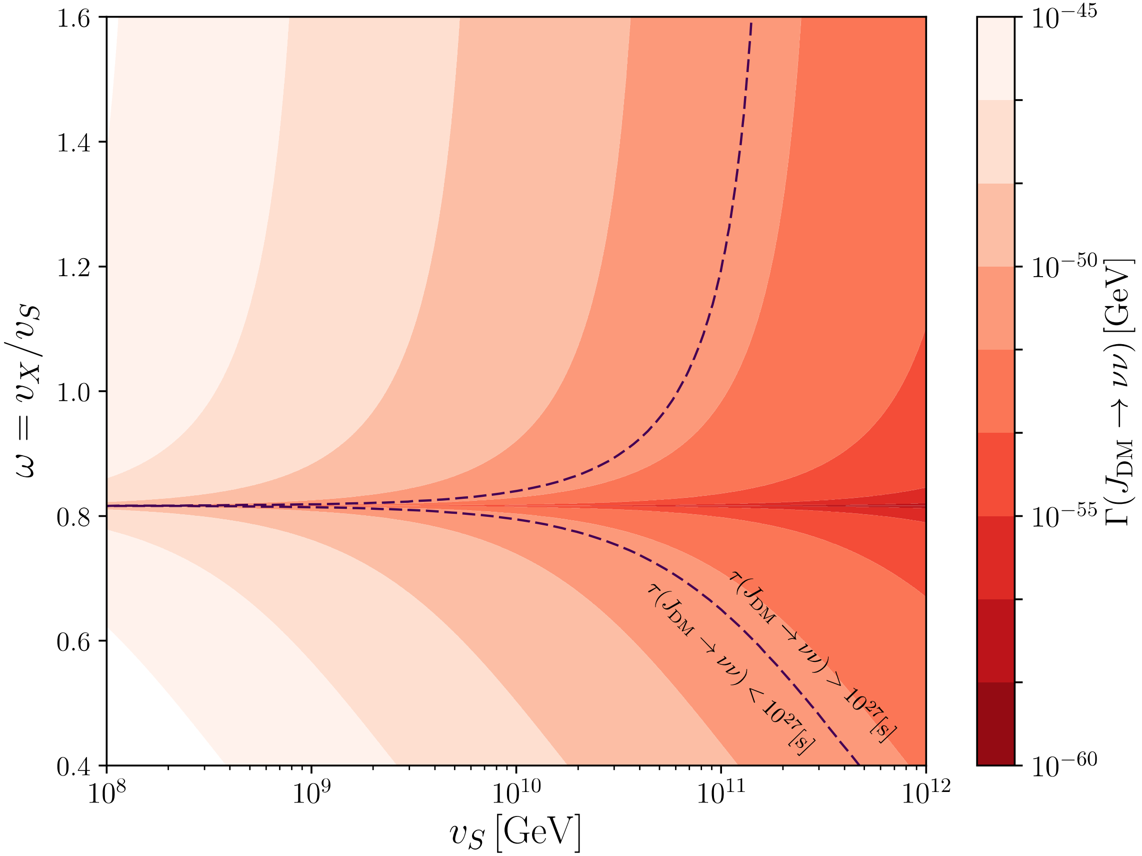
$$\omega_0 = \sqrt{2/3}$$

$$\Gamma_\nu = \Gamma_{0\nu}(\omega_0)\, 4\alpha^2$$

$$\Gamma_{0\nu}(\omega_0) \simeq 10^{-40}\,\mathrm{GeV}\left(\frac{m_\nu}{0.1\,\mathrm{eV}}\right)^2\left(\frac{M_J}{1\,\mathrm{keV}}\right)\left(\frac{v_S}{100\,\mathrm{TeV}}\right)^{-2}$$

Decay into neutrinos

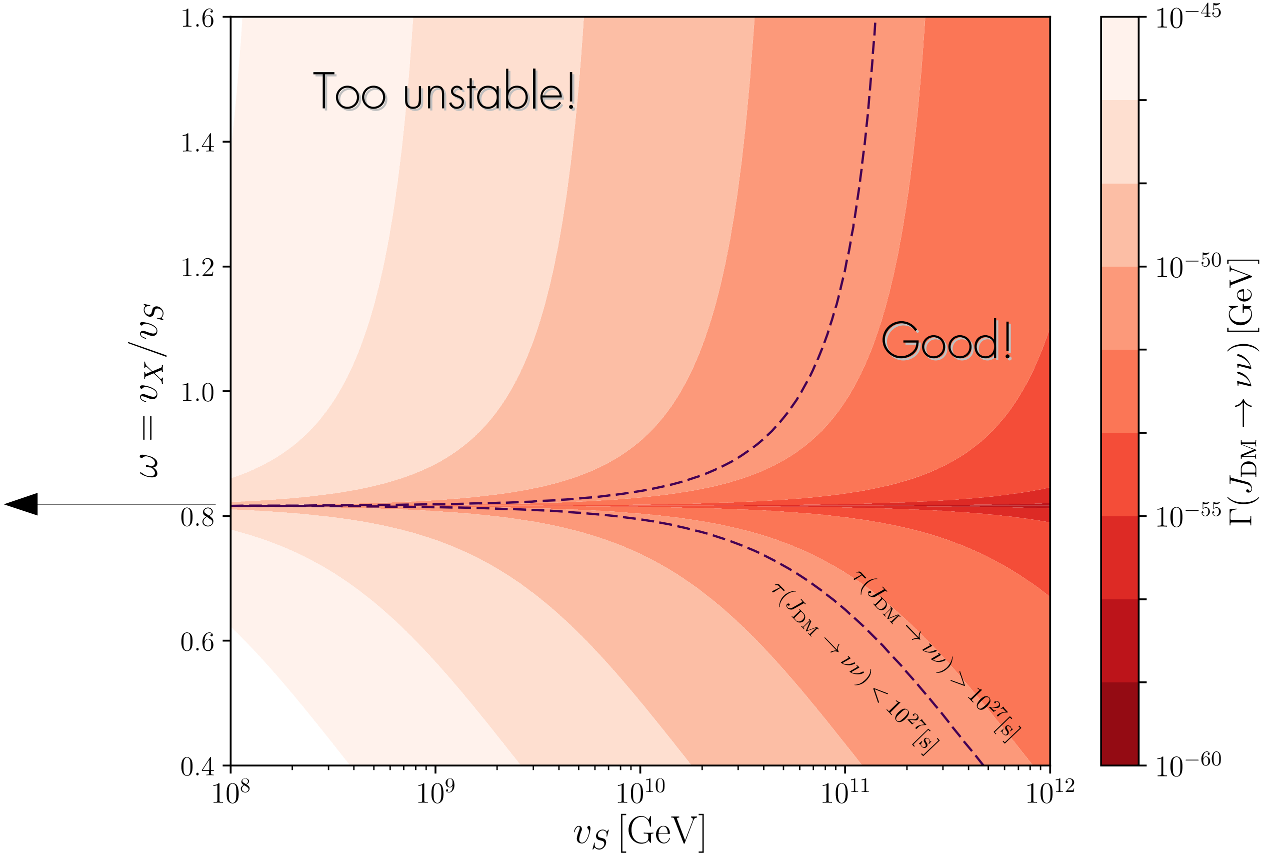
$$J_{\mathrm{DM}} \to \nu\nu$$



Decay into neutrinos

$$J_{\rm DM} \to \nu\nu$$

$$\omega = \sqrt{\frac{2}{3}}$$



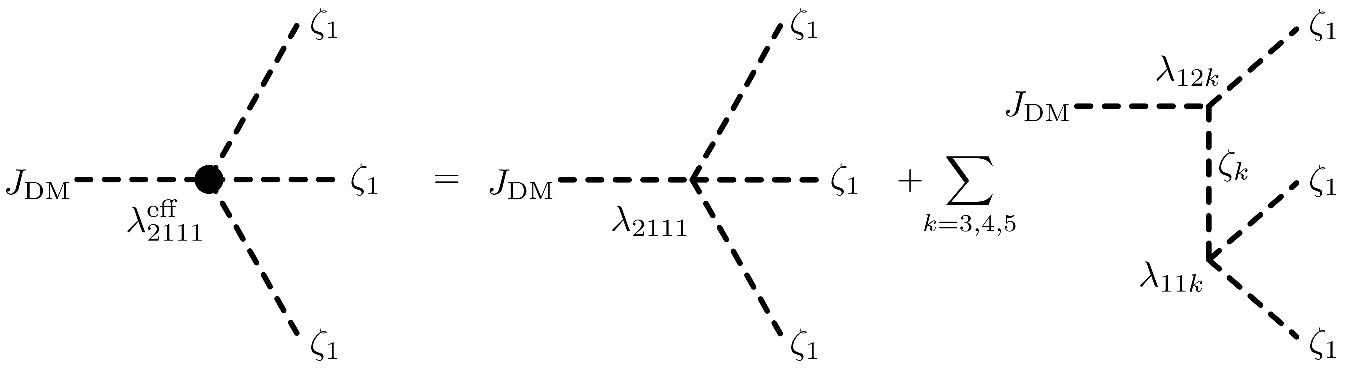
Stability thanks to vev alignment

Decay into scalars

$$J_{\rm DM} \to \zeta's$$

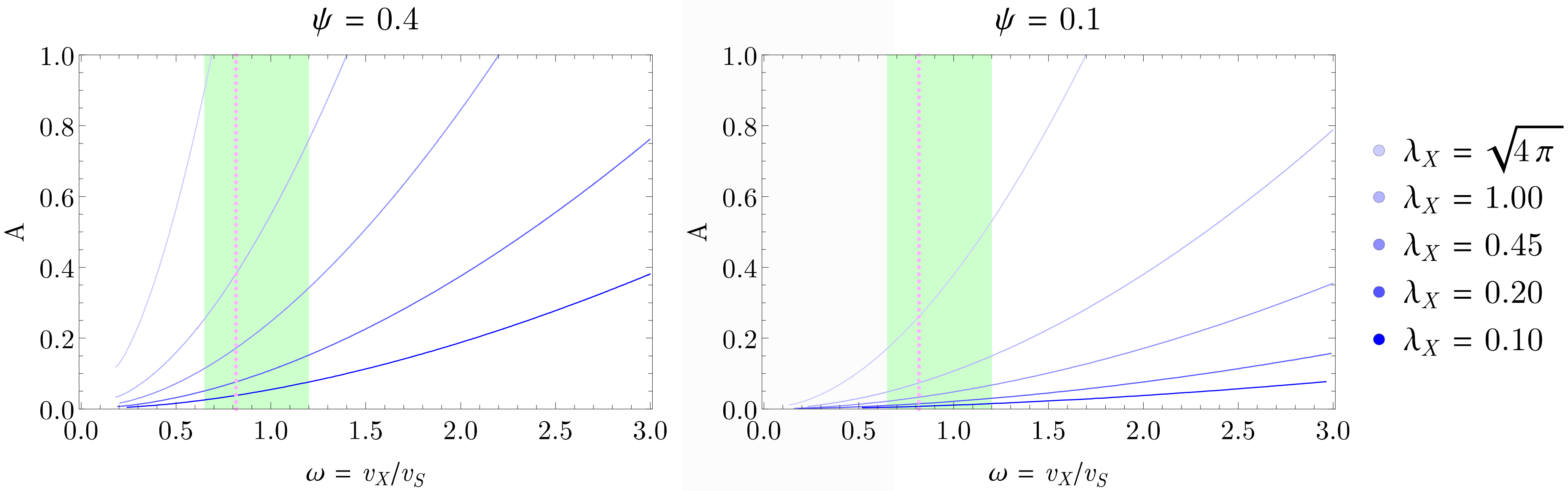
Without a protective symmetry, this channel is not suppressed

However we can find the parameter space where the mode vanishes



Decay into scalars

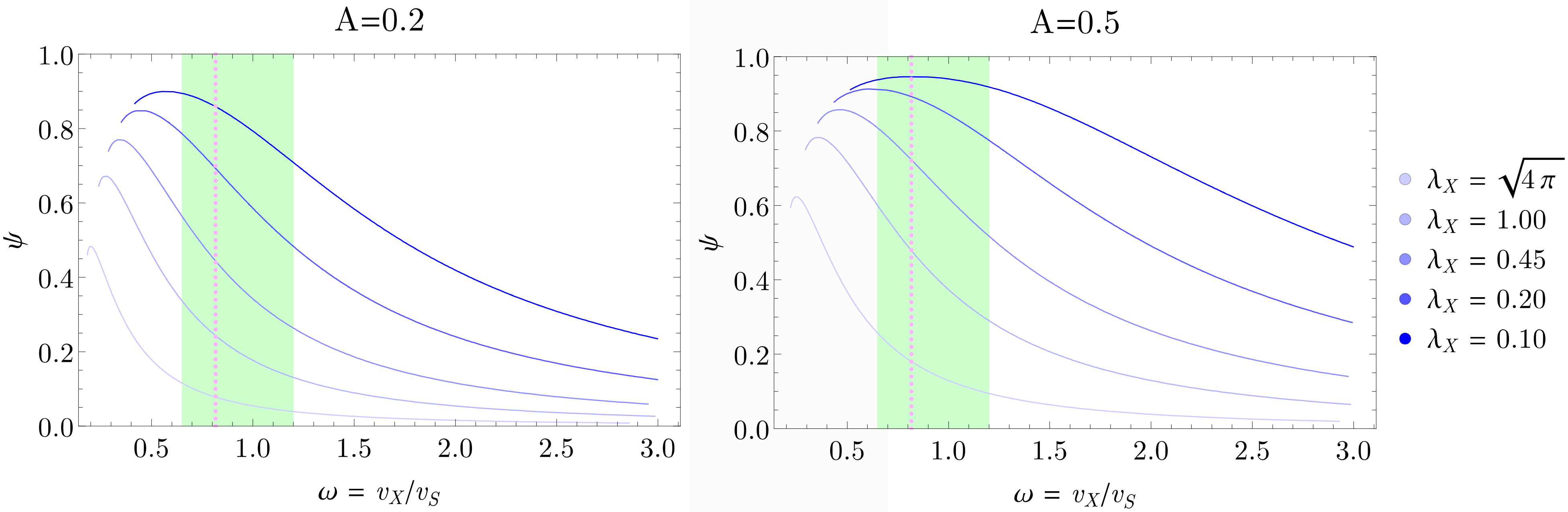
$J_{\rm DM} \to \zeta' {\rm s}$



The interplay of different diagrams allows to vanish the decay mode

Decay into scalars

$$J_{\rm DM} \to \zeta' \rm s$$



There is a whole volume that satisfy this condition

Conclusions (of this part)

- The spontaneous inverse seesaw provides a well suited majoron DM candidate
- Our majoron DM is phenomenologically equivalent to the PNGB
- The vev alignment has a relevent role in the DM stability

Example 2

Dark Matter interaction with neutrinos

Neutrino oscillations

Flavor and mass eigenstates do not coincide $|\nu_\alpha\rangle = \sum_k U^*_{\alpha k}|\nu_k\rangle$

Mass eigenstates evolve according to:

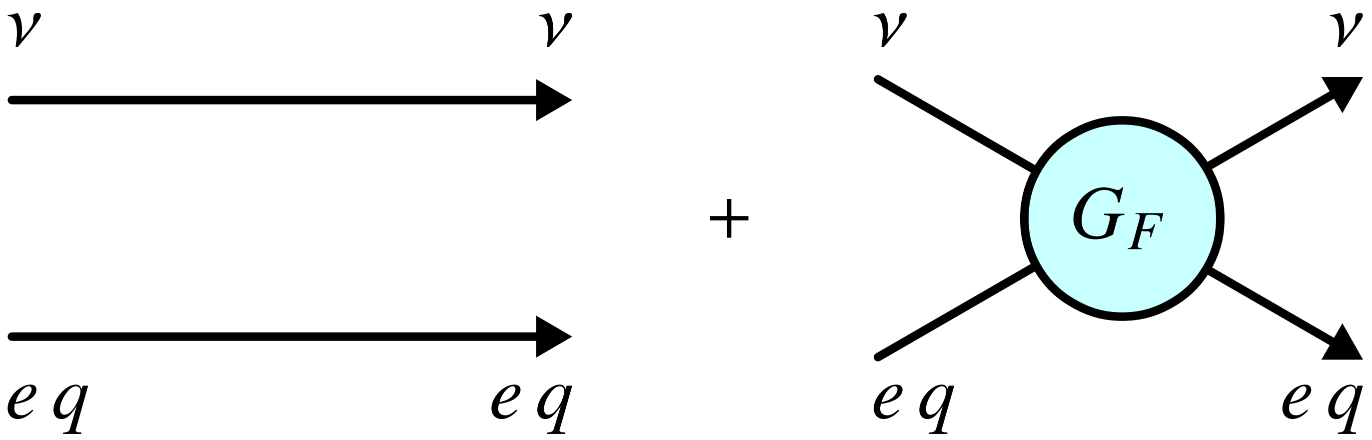
$$i\frac{\partial \Psi}{\partial t} = \mathcal{H}\,\Psi$$

$$\mathcal{H}_{\rm vac} = \frac{1}{2E}\,U \begin{pmatrix} 0 & 0 & 0 \\ 0 & \Delta m^2_{21} & 0 \\ 0 & 0 & \Delta m^2_{31} \end{pmatrix} U^\dagger$$

The final ν flavor depends on: Initial state, Source distance, Neutrino energy

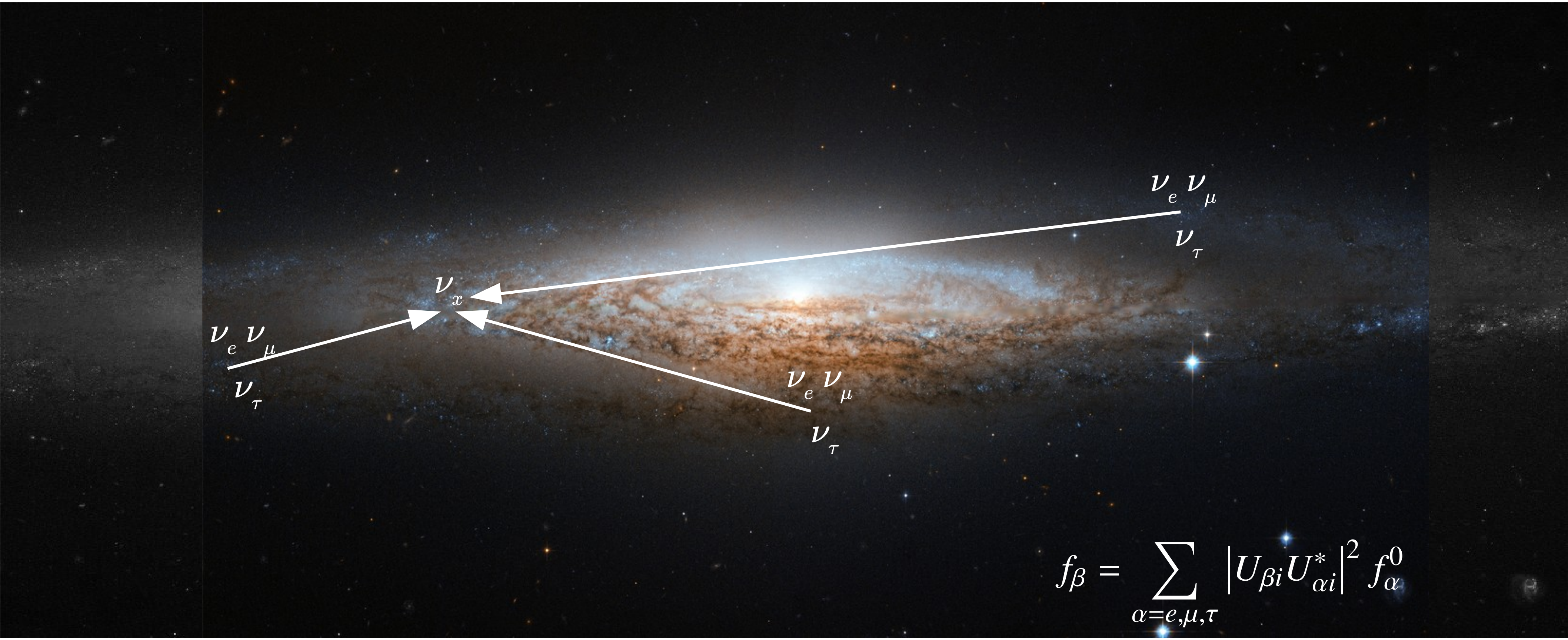
Matter effects (a.k.a. MSW effect)

The interaction with a medium modifies the oscillation patterns w.r.t. vacuum



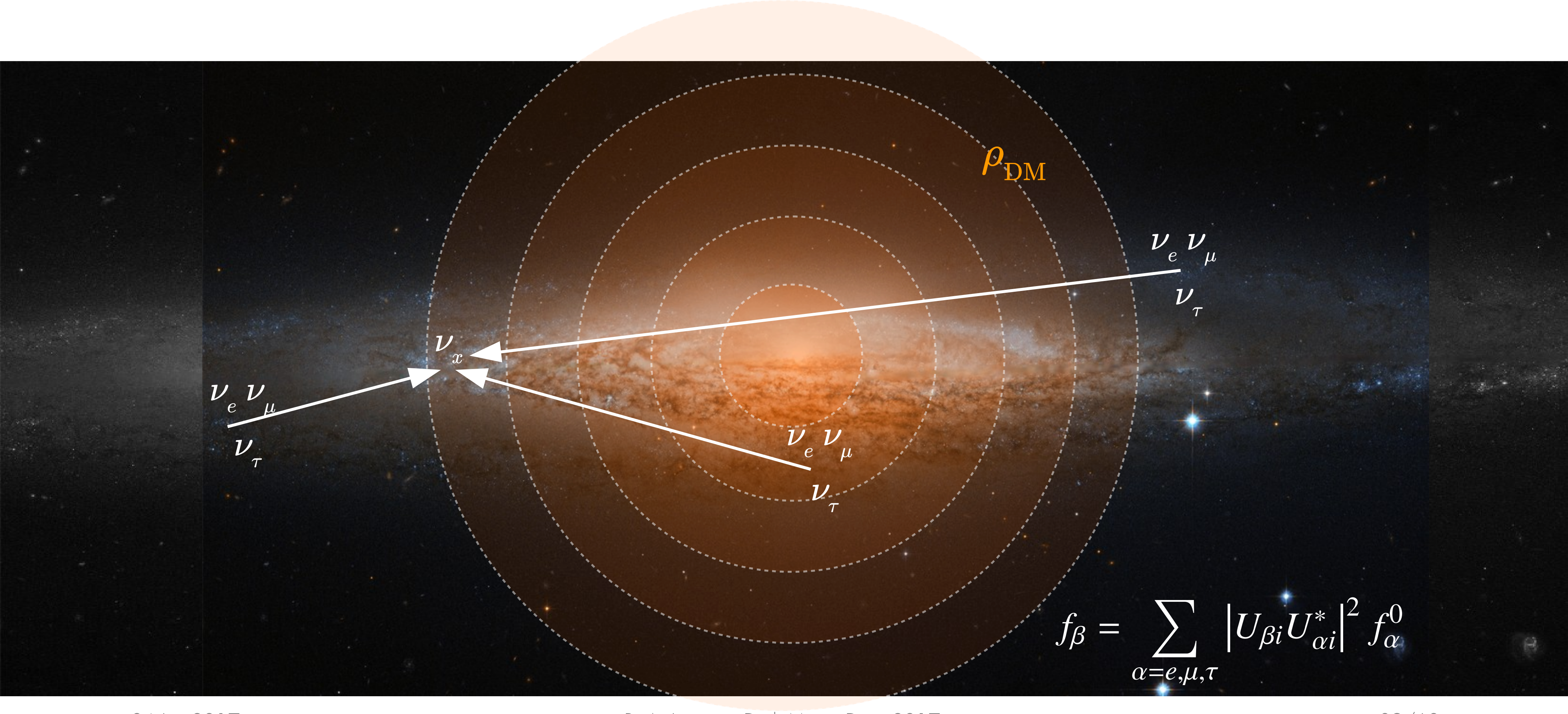
$$\mathcal{H}_{\rm tot} = \mathcal{H}_{\rm vac} + \mathcal{V}$$

Dark Matter effects



$$f_\beta = \sum_{\alpha=e,\mu,\tau} \left|U_{\beta i} U^*_{\alpha i}\right|^2 f^0_\alpha$$

Dark Matter effects



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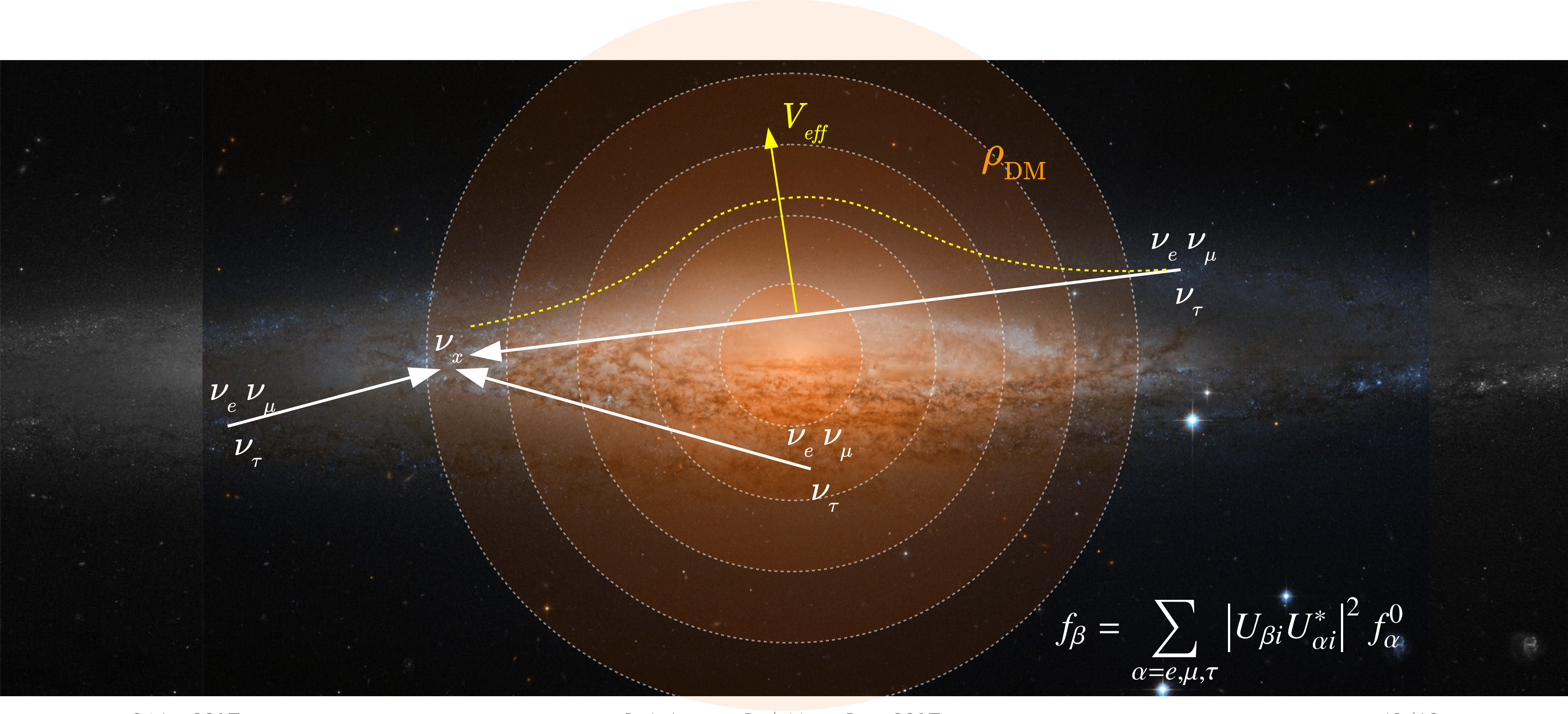
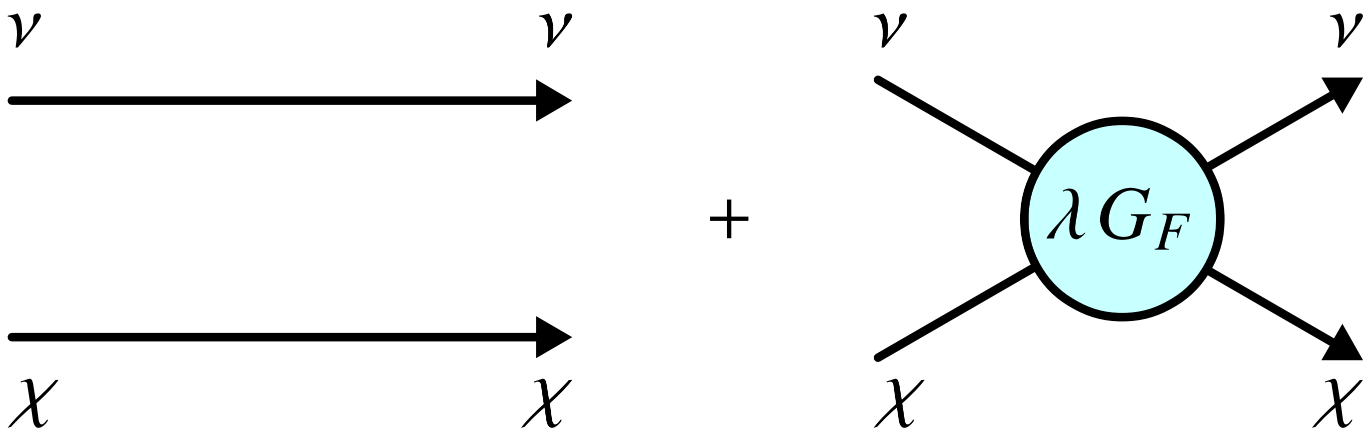


Dark Matter effects

The interaction with DM might modify the oscillation patterns w.r.t. vacuum



$$\mathcal{H}_{\rm tot} = \mathcal{H}_{\rm vac} + \mathcal{V}$$

Dark Matter effects

We parameterized the effective potential using a "weak interaction" form:

$$\mathcal{V}_{\alpha\beta} = \lambda_{\alpha\beta} \, G_F \, N_\chi$$

But also spatial dependency:

$$\mathcal{V}_{\alpha\beta} = \mathcal{V}^{\oplus}_{\alpha\beta} \times f_{\mathrm{DM}}(r)$$

Dark Matter effects

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$$\mathcal{V}_{\alpha\beta} = \lambda_{\alpha\beta} \, G_F \, N_\chi$$

But also spatial dependency:

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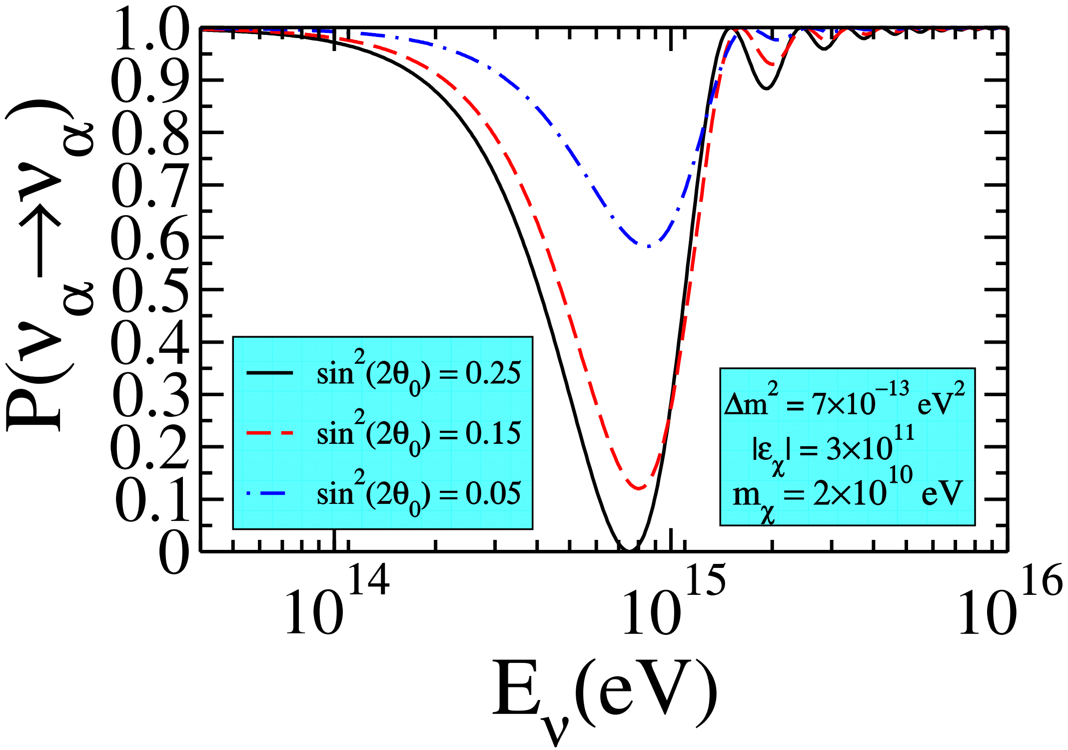
Dark Matter effects (1+1) neutrinos

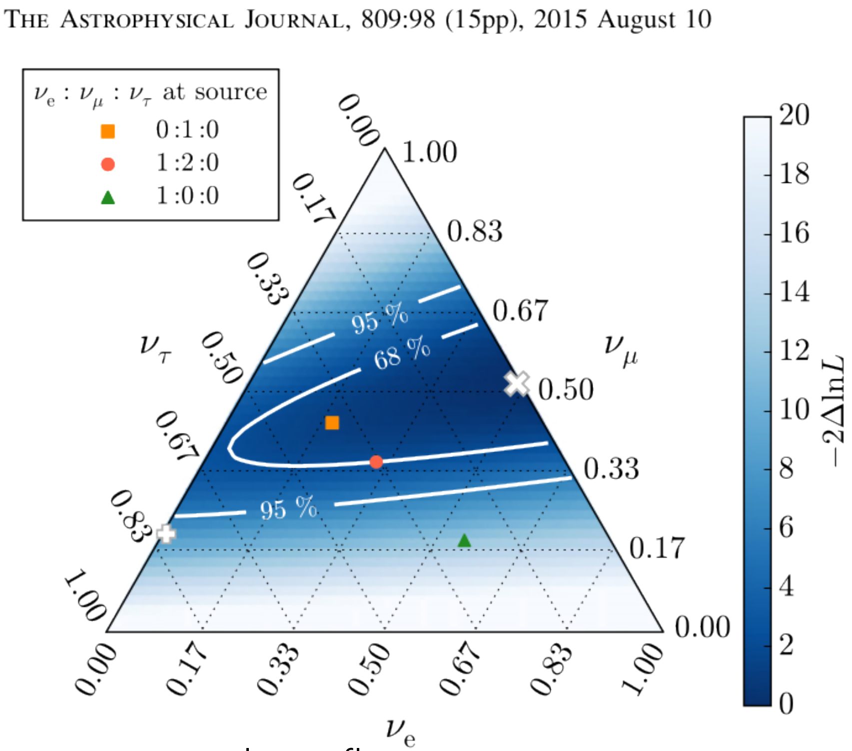
The effect in the neutrino oscillation due to DM was studied showing that resonances maybe important



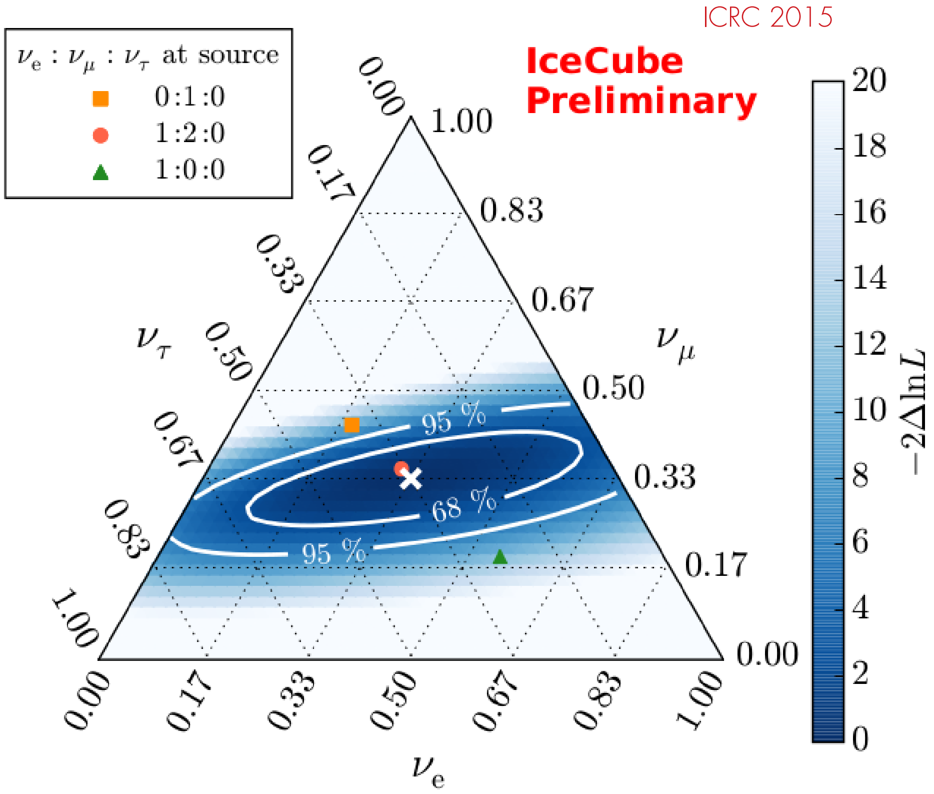
Miranda, Moura, Parada. Phys. Lett. B 744 (2015) 55

Mixing angle and mass splitting are free

Flavor composition in IceCube



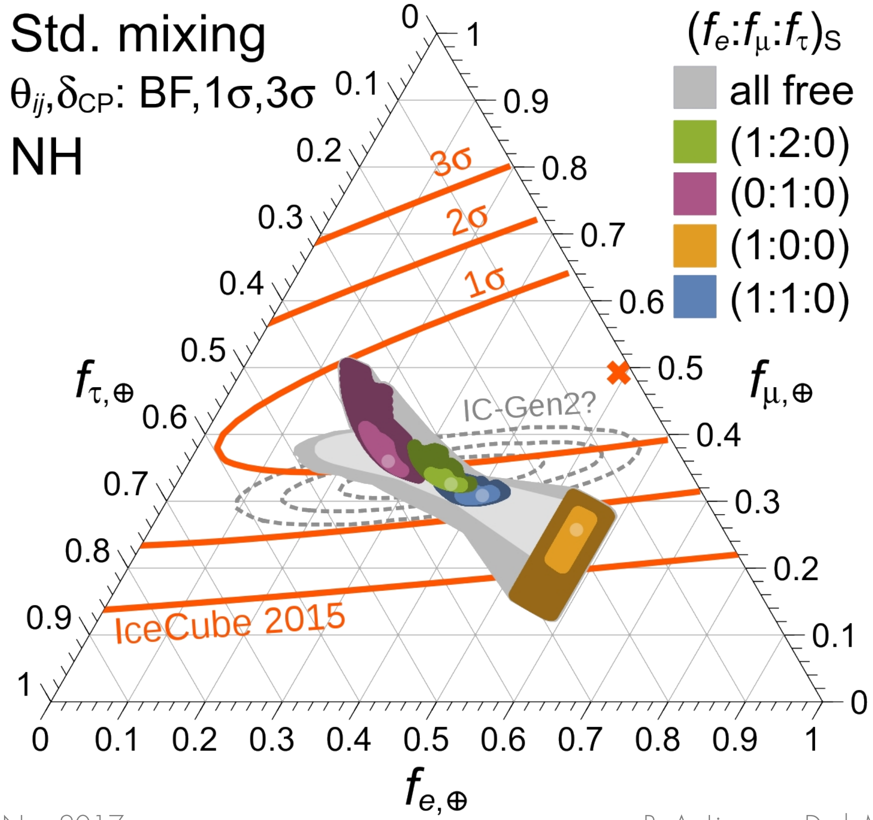
Latest result on flavor composition

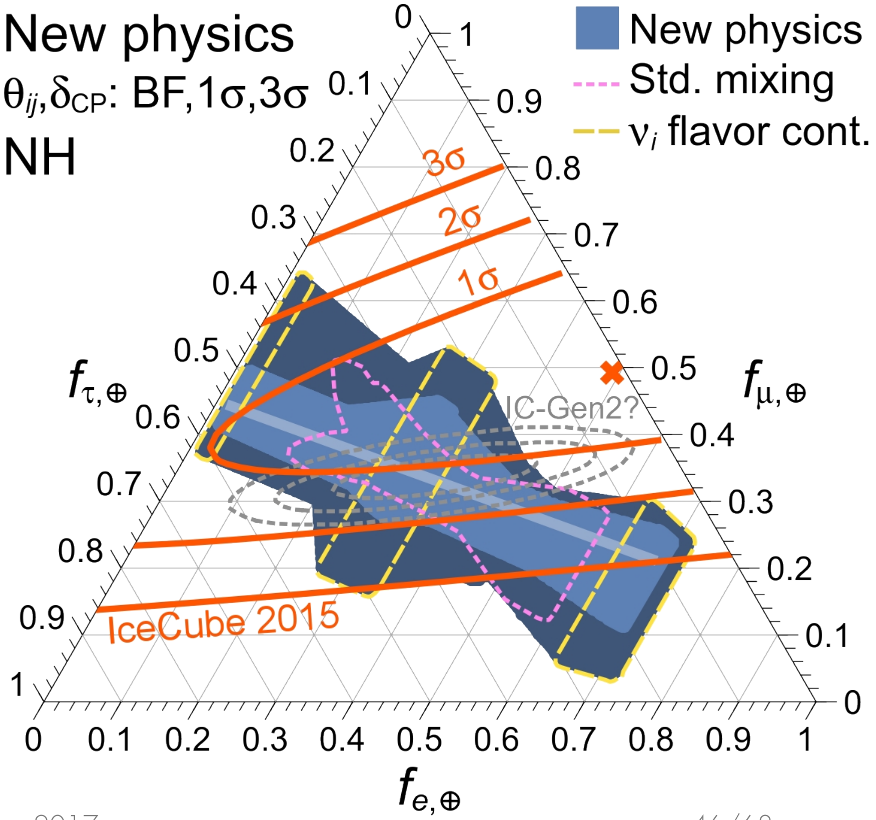


Sensitivity after 10 years

What we expect?

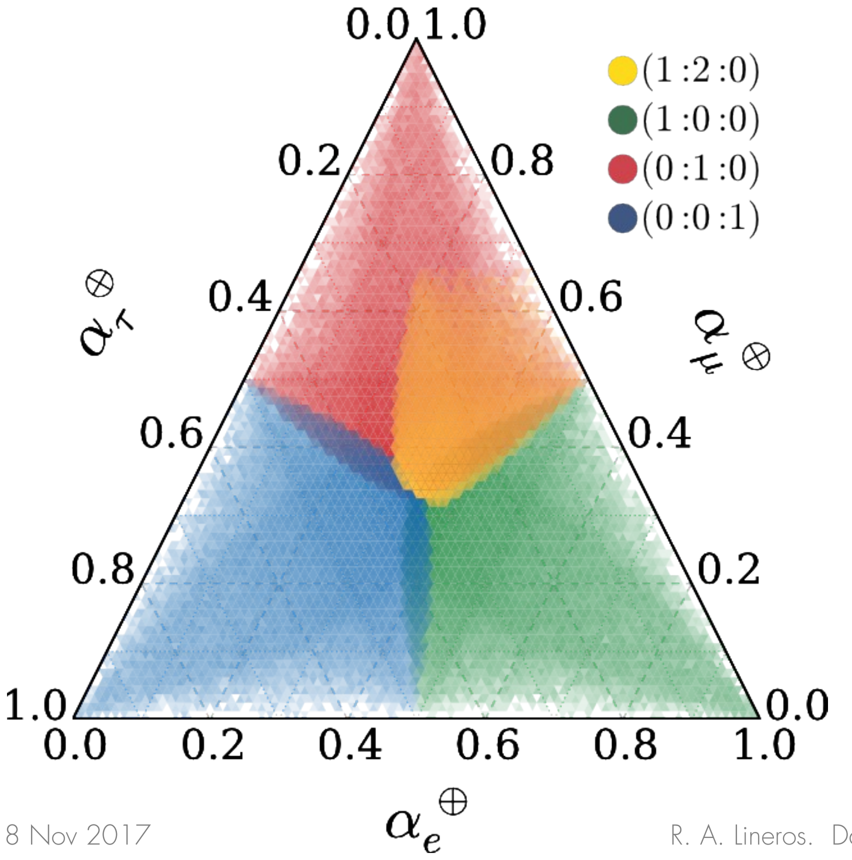
M. Bustamante et al. PRL 115, 161302 (2015)





Effects from New Physics

Argüelles et at. PRL 115, 161303 (2015)

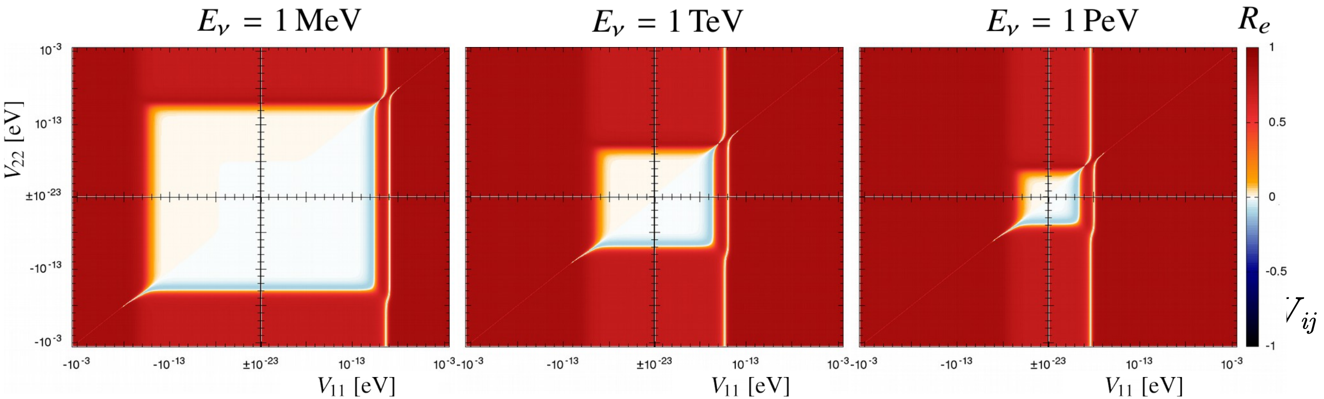


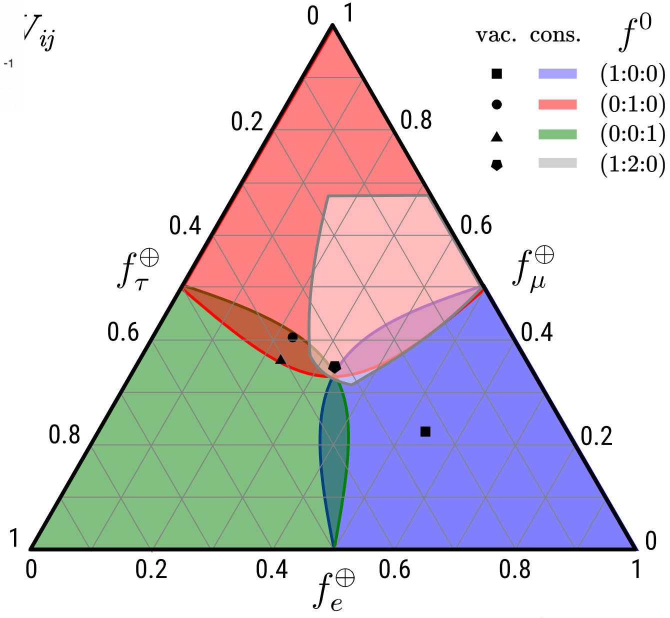
Sources of New Physics:

- Space torsion
- CPT - Lorentz violation

All NP effects are homogeneous in space

Composition in a homogeneous halo





Homogeneous DM distribution can mimic New Physics effects

Higher ν-energy, smaller potential are accessible

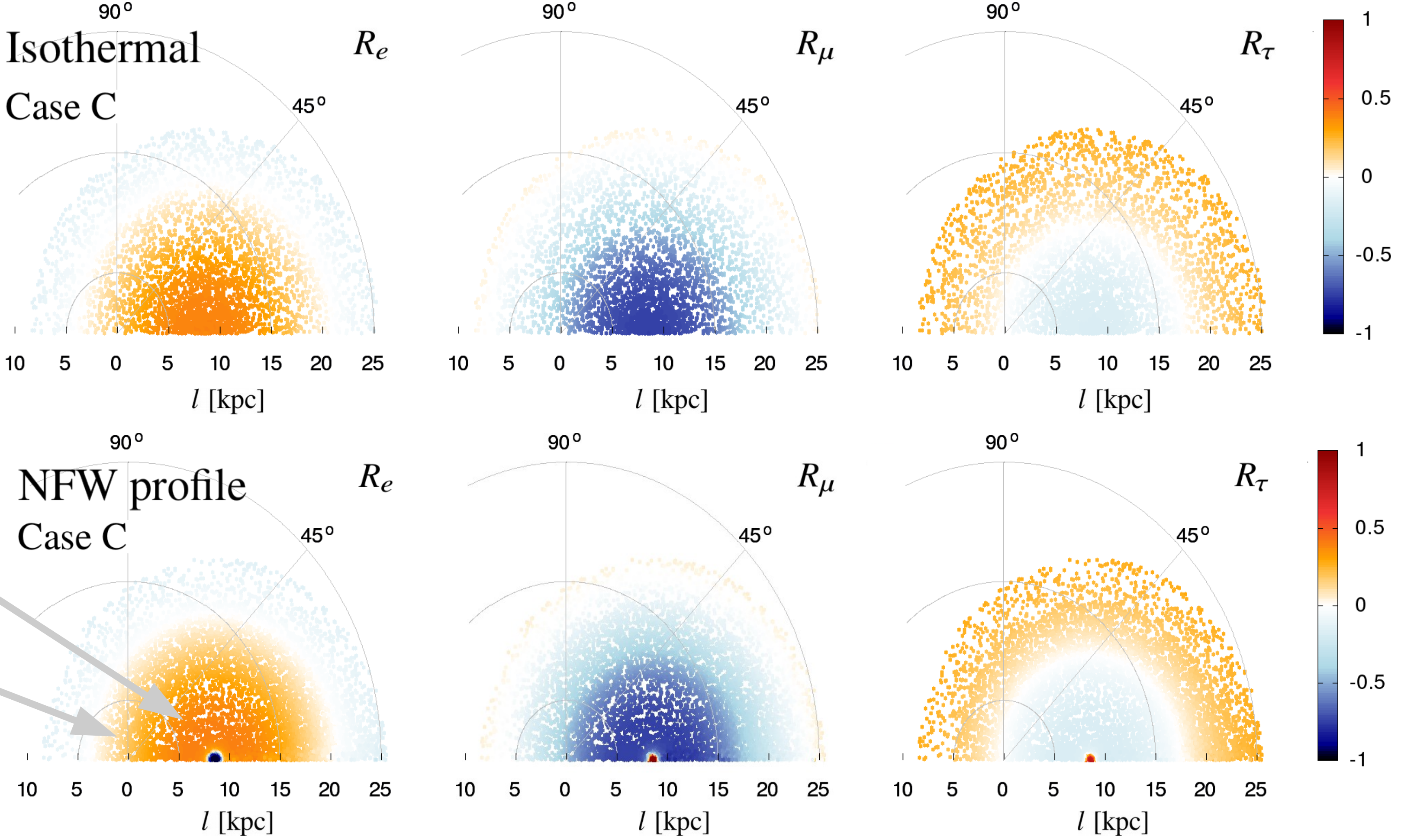
Spatial dependence

$$\mathcal{V}_{\alpha\beta} = \mathcal{V}^{\oplus}_{\alpha\beta} \times f_{\rm DM}(r)$$

$\mathcal{V}^{\oplus}_{11} = 40 \times 10^{-21}$ eV

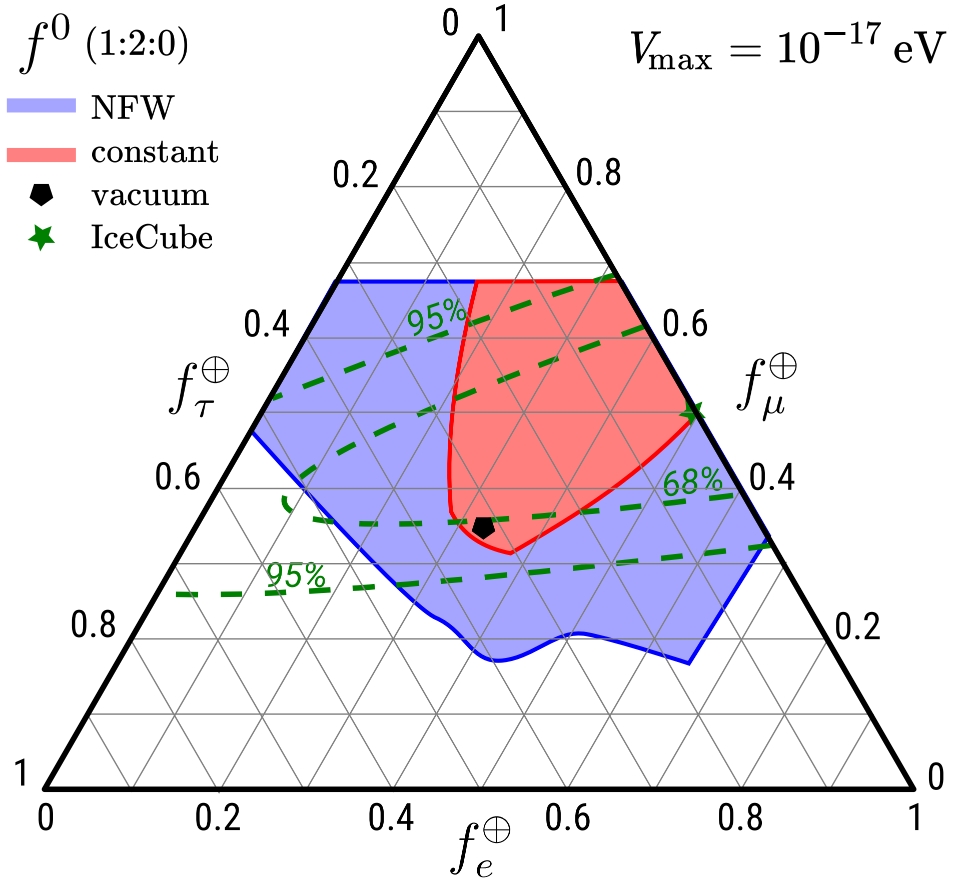
GC

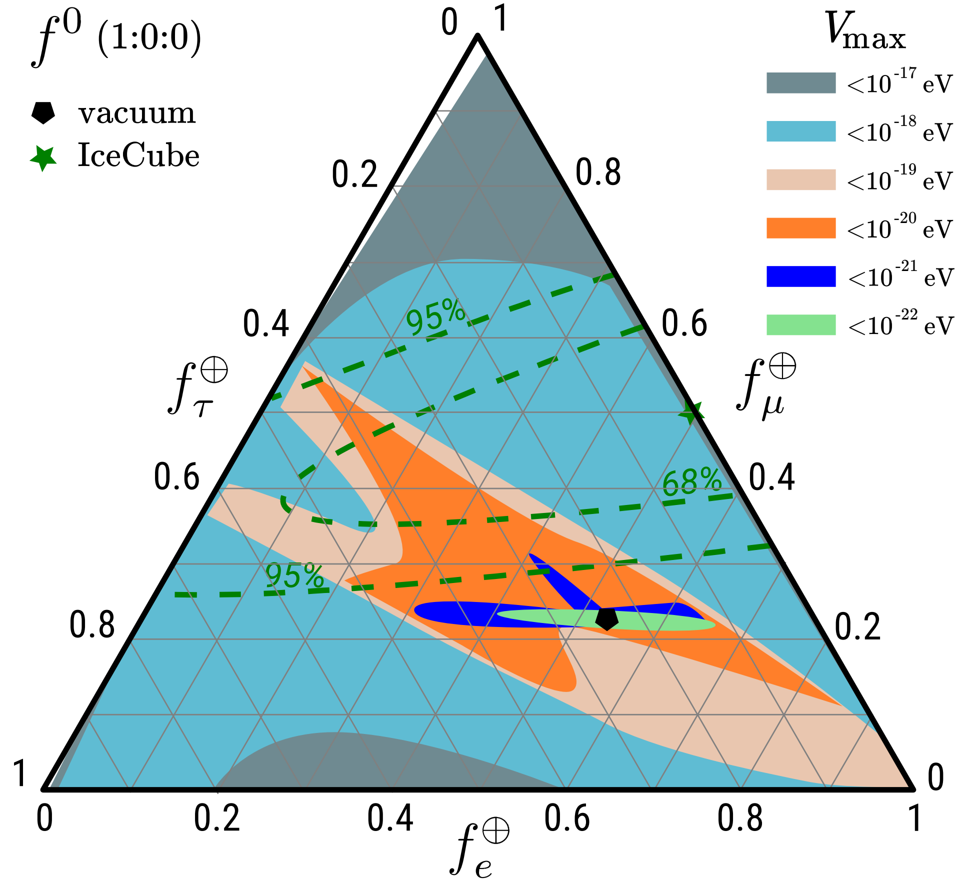
Sun



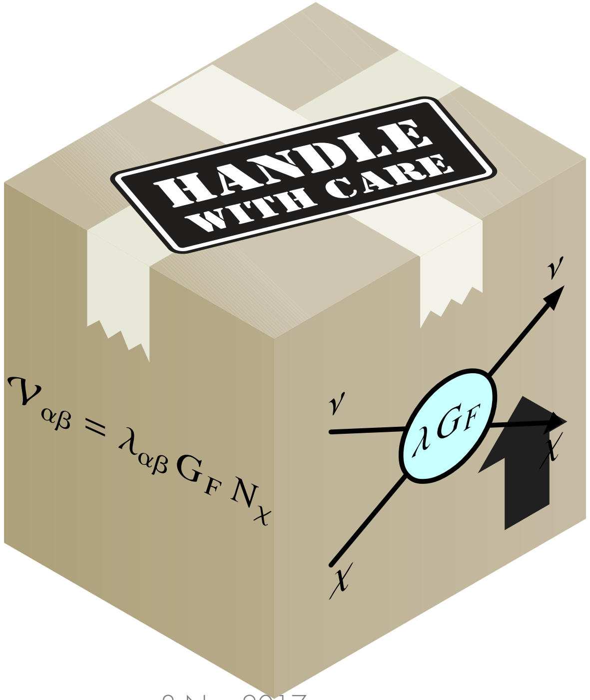
8 Nov 2017

Composition in a NFW halo

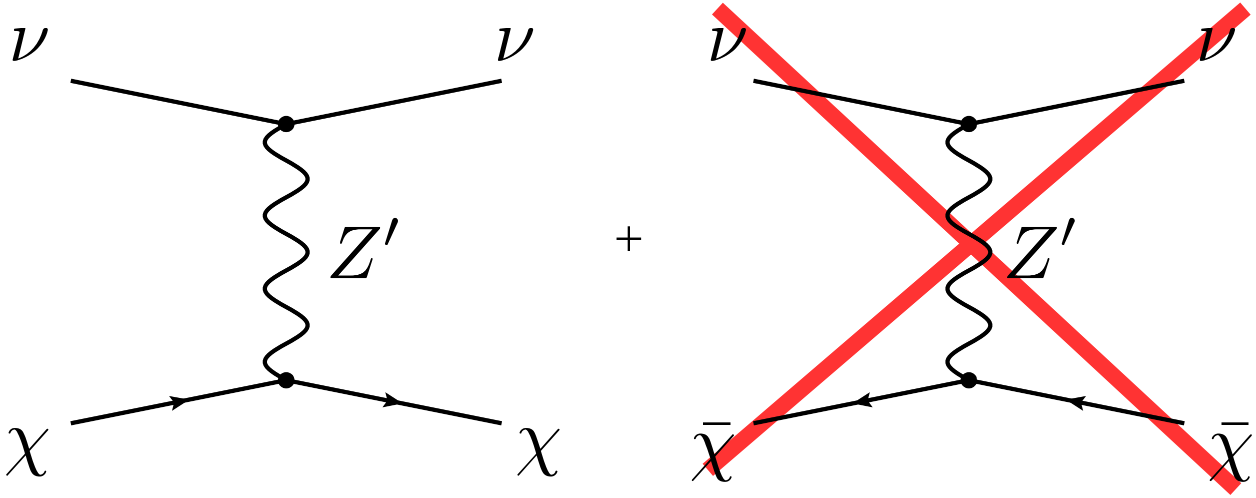




Particle physics interpretation

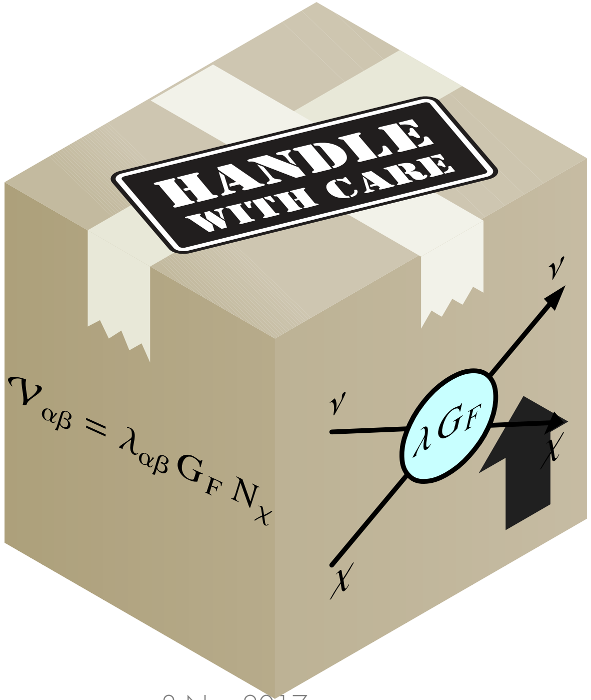


The simplest scenarios are models with asymmetric DM

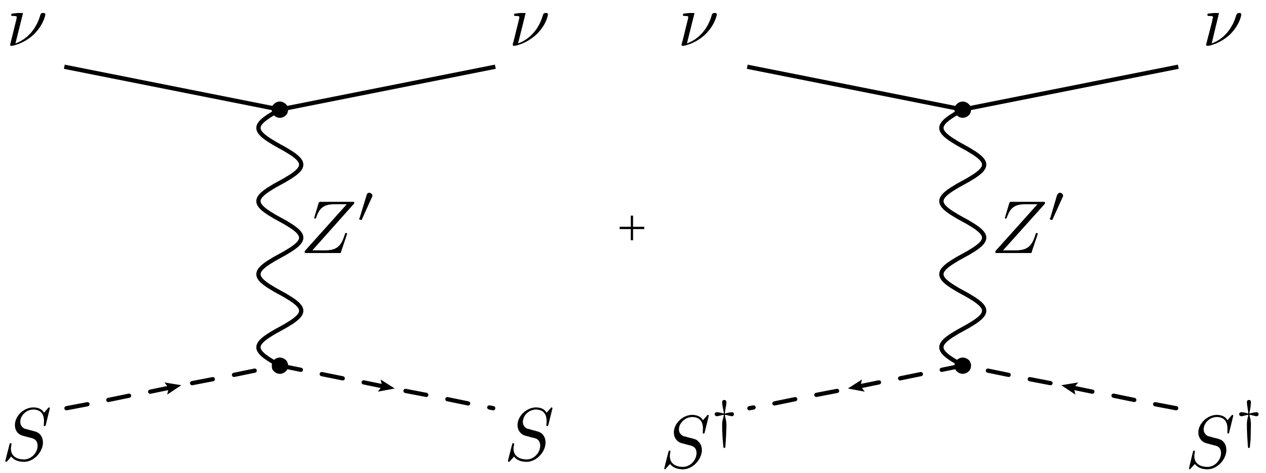


$$\mathcal{V}_{\alpha\beta} = \lambda_{\alpha\beta}\, G_F\, N_\chi$$

Particle physics interpretation



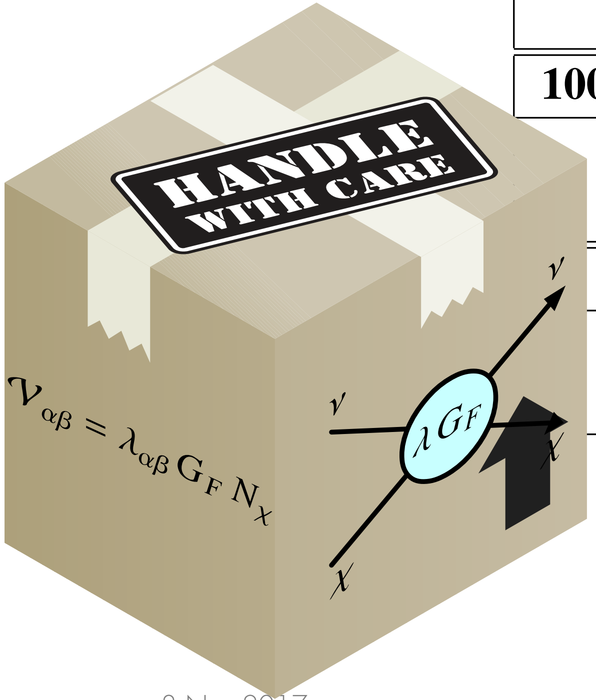
Or with scalar DM



$$\mathcal{V}_{\alpha\beta} = \lambda_{\alpha\beta}\, G_F\, N_\chi$$

Particle physics interpretation

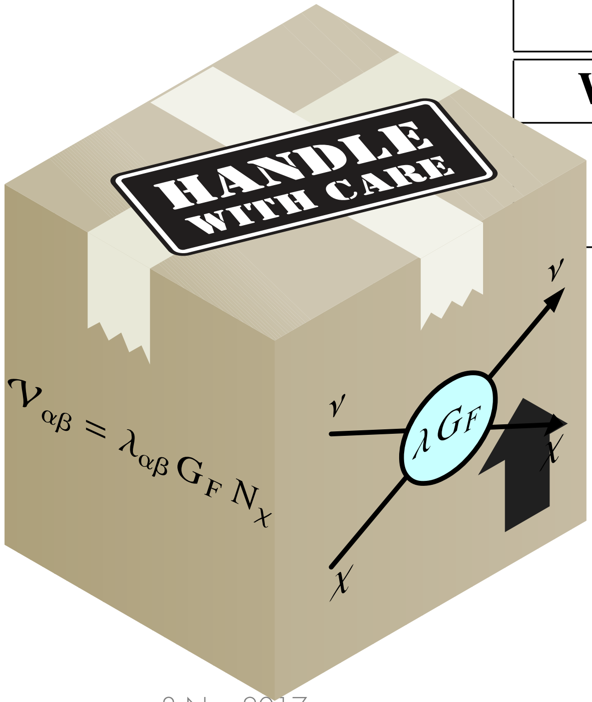
$V_{11}^{\oplus}$ [eV]	10^{-21}	10^{-19}	10^{-17}
Weak scale (a) assumptions:	$G'_F = G_F,\ \lambda_{11} = 1$		
$m_{\rm DM}$ [eV]	10^{-8}	10^{-10}	10^{-12}
l_ν [pc]	10^{-2}	10^{-4}	10^{-6}
100 GeV DM (a) assumptions:	$m_{\rm DM} = 100$ GeV, $l_\nu = 50$ kpc		
λ_{11}	10^{-7}	10^{-9}	10^{-11}
$m_{Z'}$ [eV]	10^{-2}	10^{-4}	10^{-6}
1 keV DM (a) assumptions:	$m_{\rm DM} = 1$ keV, $l_\nu = 50$ kpc		
λ_{11}	10^{-7}	10^{-9}	10^{-11}
$m_{Z'}$ [eV]	10^{2}	1	10^{-2}



One can try to explain the effective potential in terms of particle physics scales

Particle physics interpretation

$V_{11}^{\oplus}$ [eV]	10^{-21}	10^{-19}	10^{-17}
Weak scale (a) assumptions:	$G'_F = G_F,\ \lambda_{11} = 1$		
$m_{\rm DM}$ [eV]	10^{-8}	10^{-10}	10^{-12}
l_ν [pc]	10^{-2}	10^{-4}	10^{-6}
Weak scale (b) assumptions:	$G'_F = G_F,\ l_\nu = 50$ kpc		
λ_{11}	10^{-7}	10^{-9}	10^{-11}
$m_{\rm DM}$ [eV]	10^{-15}	10^{-19}	10^{-23}



Assuming weak scale couplings and mediators DM has to be extremely light. Fuzzy DM, Bose-Einstein DM?

For λ=1, the mean free path is sub-pc :-(

Particle physics interpretation

$V_{11}^{\oplus}$ [eV]	10^{-21}	10^{-19}	10^{-17}
100 GeV DM (a) assumptions:	$m_{\rm DM} = 100$ GeV, $l_\nu = 50$ kpc		
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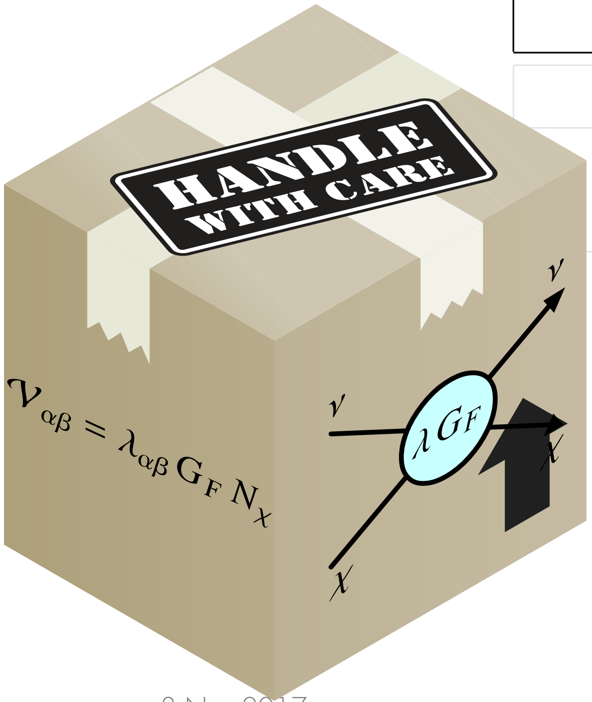

100 GeV DM

sub-eV mediators, $g \sim \lambda^{1/2} = 10^{-3} - 10^{-6}$

$$\sigma_{\nu\chi} = 1.62 \times 10^{-23}\ (m_{\rm DM}/{\rm GeV})\,{\rm cm}^2$$

Particle physics interpretation

$V_{11}^{\oplus}$ [eV]	10^{-21}	10^{-19}	10^{-17}
100 GeV DM (a) assumptions:	$m_{\rm DM} = 100$ GeV, $l_\nu = 50$ kpc		
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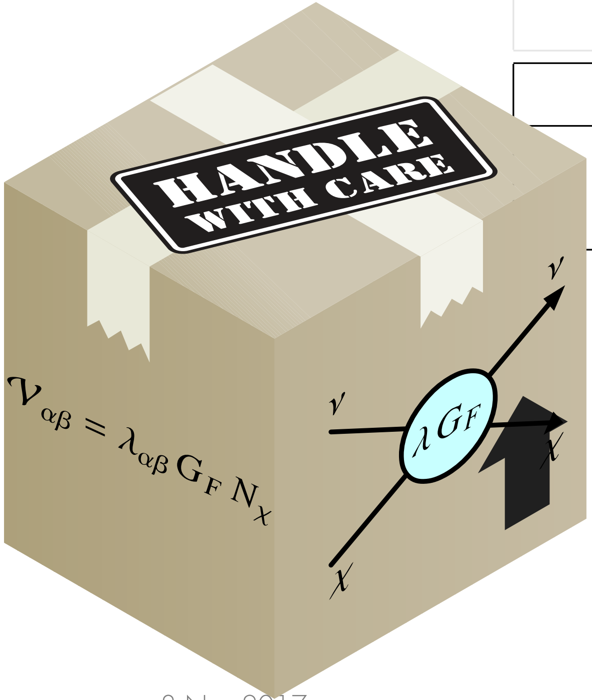
$m_{Z'}$ [eV]	10^{2}	1	10^{-2}



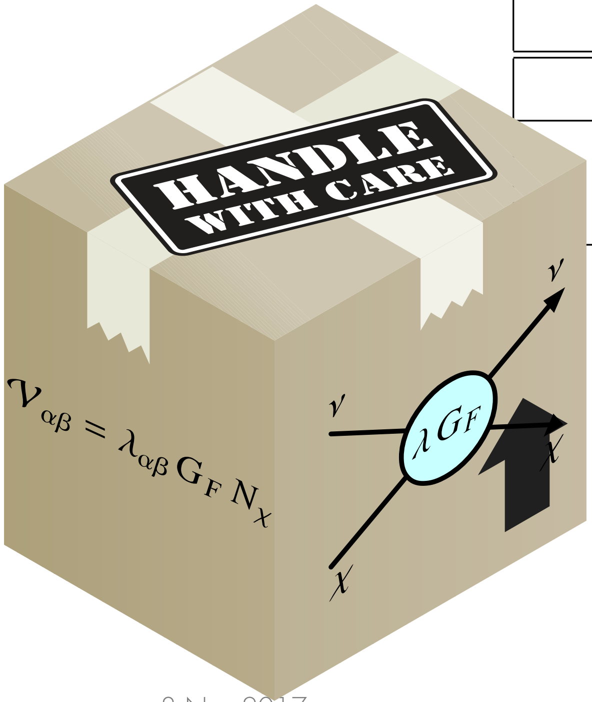
1 keV DM

eV mediators, $g \sim \lambda^{1/2} = 10^{-3} - 10^{-6}$

$$\sigma_{\nu\chi} = 1.62 \times 10^{-23}\ (m_{\rm DM}/{\rm GeV})\,{\rm cm}^2$$

Particle physics interpretation

$V_{11}^{\oplus}$ [eV]	10^{-21}	10^{-19}	10^{-17}
100 GeV DM (b) assumptions:	$m_{\rm DM} = 100$ GeV, $l_\nu = 10^6$ Gpc		
λ_{11}	10^{-17}	10^{-19}	10^{-21}
$m_{Z'}$ [eV]	10^{-7}	10^{-9}	10^{-11}
1 keV DM (b) assumptions:	$m_{\rm DM} = 1$ keV, $l_\nu = 10^6$ Gpc		
λ_{11}	10^{-17}	10^{-19}	10^{-21}
$m_{Z'}$ [eV]	10^{-3}	10^{-5}	10^{-7}



Assuming mean free path larger than the Observable Universe

Wilkinson et al. JCAP 1405 (2014) 011

$$\sigma_{\nu\chi} = 10^{-33}\ (m_{\rm DM}/{\rm GeV})\,{\rm cm}^2$$

@MeV!

Conclusions (of this part)

- Flavor composition might open a door to New-Physics effects
- Effects from the DM halo modify the oscillation pattern differently than in the homogeneous scenario
- (Hopefully) Correlation between flavor and arrival direction might serve as test of this hypothesis
- A particle physics explanation requires mediators lighter than eV

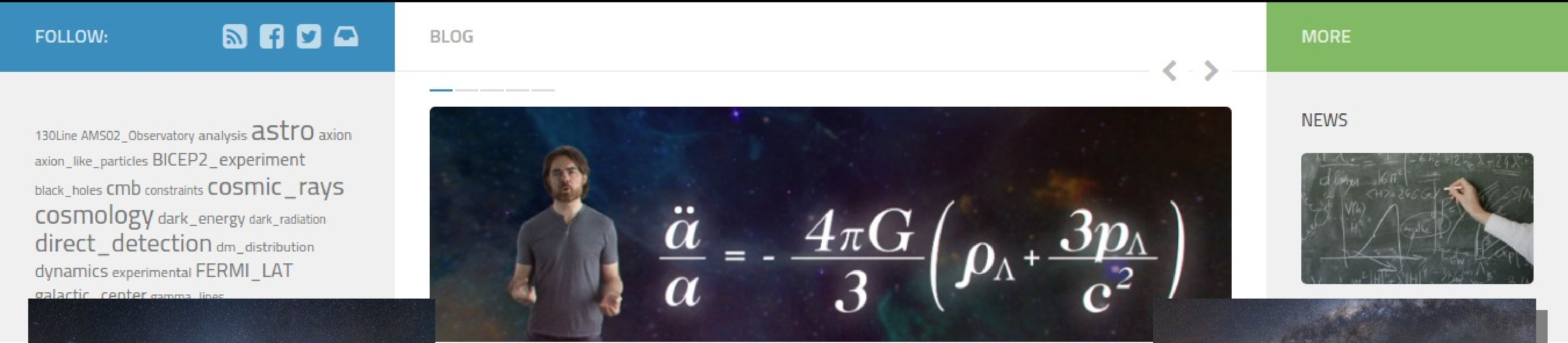
Final words

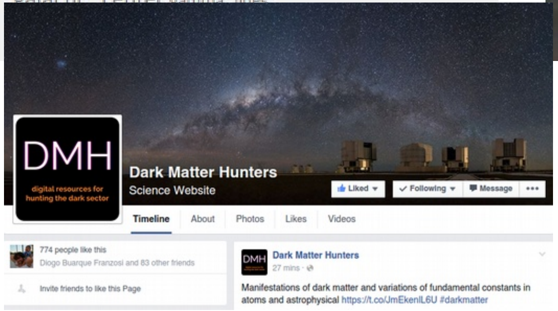
- Neutrinos observables and DM are keys to unveil New Physics
- DM candidates lighter than WIMPs can affect neutrino observables
- We need to propose new way to test «unobservable» DM candidates

Dark Matter Hunters

Digital resources for hunting the dark sector

dmhunters.org



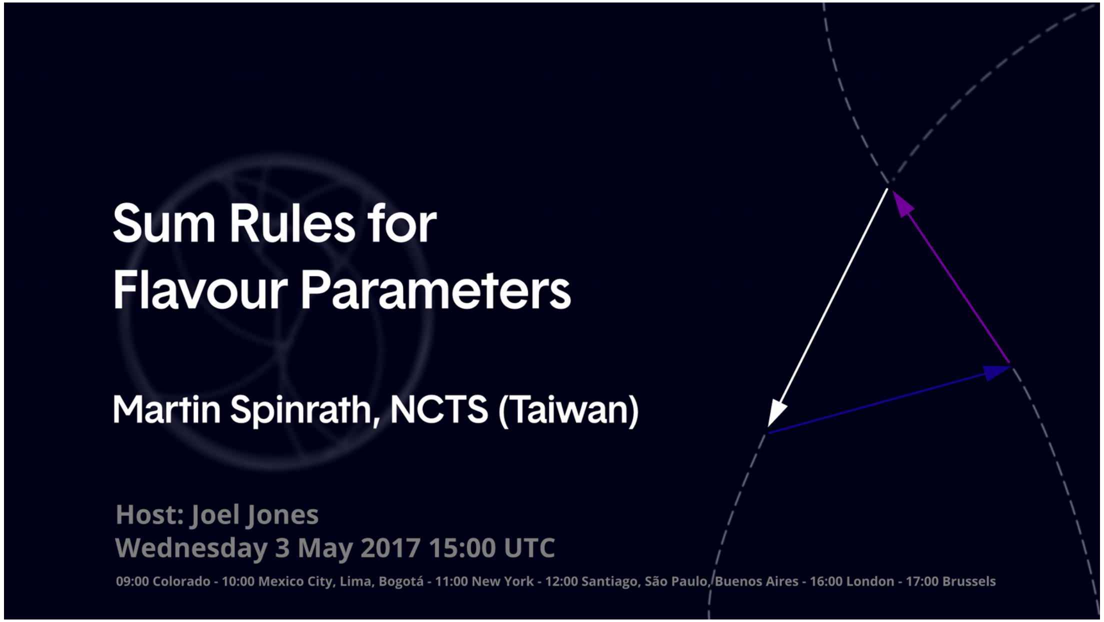


Daily digest of papers about

Dark Matter and related topics

lawphysics

Latin American Webinars on Physics



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lawphysics.wordpress.com

Thanks

Backup

Charge assignments

5 possible models

$$V_{\rm I} = \lambda_{\rm cp} e^{i\delta} X^m S^{\dagger n}$$

	L	N_1	N_2	S	X
$n=1$	1	-1	$1/7$	$6/7$	$2/7$
$n=2$	1	-1	$1/3$	$2/3$	$2/3$
$n=3$	1	-1	$3/5$	$2/5$	$6/5$

m+n = 4

m+n = 3

	L	N_1	N_2	S	X
$n=1$	1	-1	$1/5$	$4/5$	$2/5$
$n=2$	1	-1	$1/2$	$1/2$	1

The rest of the scalar potential

$$V_{SX} = -\mu_S^2 |S|^2 + \frac{\lambda_S}{4} |S|^4 - \mu_X^2 |X|^2 + \frac{\lambda_X}{4} |X|^4 + \lambda_5 |S|^2 |X|^2 + V_{\mathrm{I}}$$

$$V_{\mathrm{HSX}} = -\mu_H^2 H^\dagger H + \frac{\lambda_H}{4} (H^\dagger H)^2 + \lambda_{HS} |S|^2 H^\dagger H + \lambda_{HX} |X|^2 H^\dagger H$$

Mass spectrum

$$m_h^2 \simeq \frac{v_h^2}{2} \left\{ \frac{\lambda_H}{2} + 2 \left(\frac{\lambda_{HX}^2 \lambda_S + \lambda_{HS}^2 \lambda_X - 4\lambda_5 \lambda_{HS} \lambda_{HX}}{4\lambda_5^2 - \lambda_S \lambda_X} \right) \right\}$$

$$M_{\zeta_3}^2 \simeq \frac{v_S^2}{2} \left(\frac{-A + A\psi + 2\lambda_X \omega \psi}{2\psi} \right)$$

$$M_{\zeta_4}^2 \simeq \frac{v_S^2}{2} \left(\frac{A + A\psi + 2\lambda_X \omega \psi}{2\psi} \right)$$

$$\lambda_S = A + \lambda_X \omega^2$$

$$\lambda_5 = -A \left(\frac{\sqrt{1-\psi^2}}{4\,\omega\,\psi} \right)$$

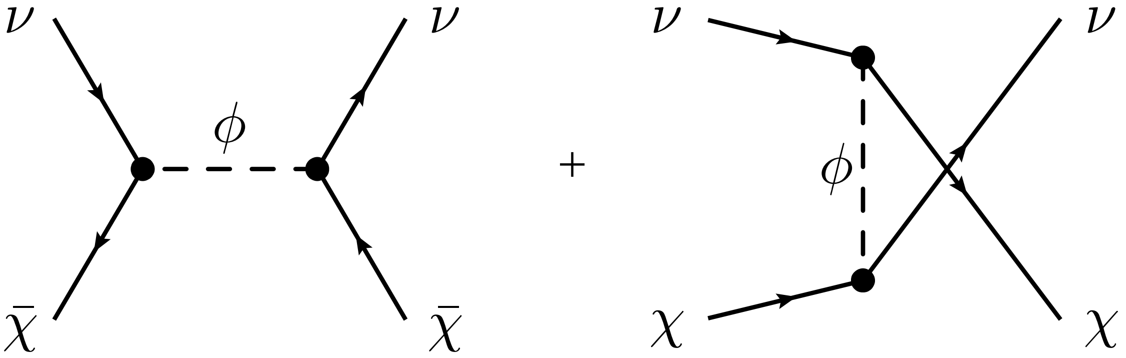
Numerology

Parameter	Value
M	100 TeV
μ	10 MeV
m_D	10 GeV
v_S	10^8 – 10^{12} GeV
ω	0.4 – 1.6

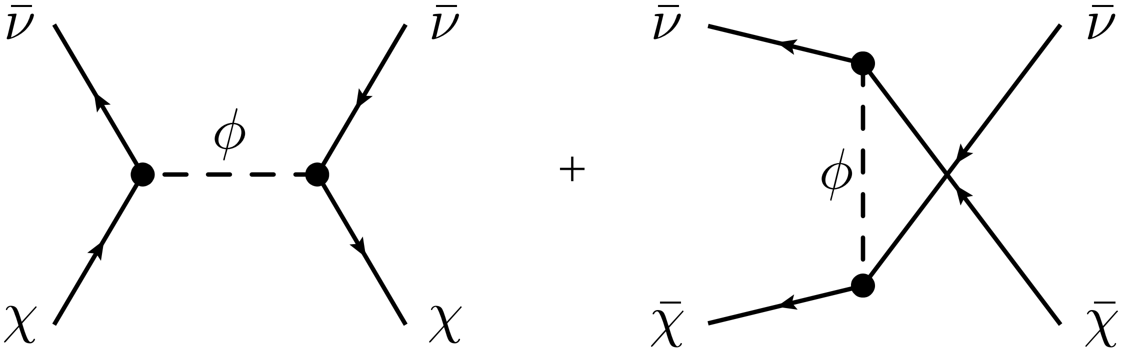
$$\lambda_{\rm cp} \simeq \frac{M_J^2}{v_S^2} < 10^{-22}$$

Dirac DM model

Neutrinos



Antineutrinos



No cancellation at first order due to diagrams are different