Axions, Majorana Neutrino Masses and implications for the dark sector of the Universe

Nick E. Mavromatos
King’s College London

Workshop on the Standard Model and Beyond
September 2 - 10, 2017
• **PART I:** Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions

• **PART II – Astrophysical Implications:** $\Lambda_{CDM}$ fits very well Astrophysical Data for **Universe** at **Large scales**

• **BUT:** @ GALACTIC SCALES, DWARF GALAXIES) – DISCREPANCY between $\Lambda_{CDM}$-based simulations and observations – “small scale Cosmology crisis” – problems (i) Core-cusp problem, (ii) The missing satellites problem (iii) Too-Big-to-fail problem

• **Self-Interacting Dark matter (SIDM)** as a solution (on top of astrophysical ones) ?

• **PART III:** Right-Handed (50 keV mass) neutrinos with massive vector self-interactions as a concrete SIDM model & consequences for galactic structure

---

NEM & Pilaftsis

Arguelles, NEM, Rueda, Ruffini
JCAP 1604 (2016) no.04, 038
• **PART I:** Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions

• **PART II – Astrophysical Implications:** $\Lambda$CDM fits very well Astrophysical Data for **Universe** at **Large scales**

• **BUT:** @ GALACTIC SCALES, DWARF GALAXIES) – DISCREPANCY between $\Lambda$CDM-based simulations and observations – “**small scale Cosmology crisis**” – **problems** (i) Core-cusp problem, (ii) The missing satellites problem (iii) Too-Big-to-fail problem

• **Self-Interacting Dark matter (SIDM)** as a solution (on top of astrophysical ones) ?

• **PART III:** Right-Handed (50 keV mass) neutrinos with massive vector self-interactions as a concrete SIDM model & consequences for galactic structure
PART I: Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions

Anomalies, Kalb-Ramond Axions and Gravity
Basic String-Inspired Effective Field theory

PART II – Astrophysical Implications: $\Lambda$CDM fits very well
Astrophysical Data for Universe at Large scales

BUT: @ GALACTIC SCALES, DWARF GALAXIES) – DISCREPANCY between $\Lambda$CDM-based simulations and observations – “small scale Cosmology crisis” – problems
(i) Core-cusp problem, (ii) The missing satellites problem
(iii) Too-Big-to-fail problem

Self-Interacting Dark matter (SIDM) as a solution (on top of astrophysical ones)?

PART III: Right-Handed (50 keV mass) neutrinos with massive vector self-interactions as a concrete SIDM model & consequences for galactic structure

Arguelles, NEM, Rueda, Ruffini
JCAP 1604 (2016) no.04, 038
• **PART I:** Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions

• **PART II – Astrophysical Implications:** $\Lambda$CDM fits very well
  Astrophysical Data for Universe at Large scales

• **BUT:** @ GALACTIC SCALES, DWARF GALAXIES) – DISCREPANCY between $\Lambda$CDM-based simulations and observations – “small scale Cosmology crisis” – problems (i) Core-cusp problem, (ii) The missing satellites problem, (iii) Too-Big-to-fail problem

• Self-Interacting Dark matter (SIDM) as a solution (on top of astrophysical ones)?

• **PART III:** Right-Handed (50 keV mass) neutrinos with massive vector self-interactions as a concrete SIDM model & consequences for galactic structure.
Will argue that:

(i) resolution of **Galactic core-halo structure** problems of $\Lambda$CDM simulations vs observations + core-cusp and other problems of small-scale cosmology
``crisis’’ can be provided by **self-interacting Right-handed (Majorana) neutrinos with masses, m, at least 47 keV**

(ii) From a particle physics perspective of $\nu$ MSM, **with Higgs portal communication to standard model sector**, cosmological constraints imply masses of lightest of RH neutrinos, m, **at most 50 keV**

So combination of these (diverse) constraints imply narrow window

\[
47 \text{ keV } c^{-2} \leq m \leq 50 \text{ keV } c^{-2}
\]

**PART III:** Right-Handed (50 keV mass) neutrinos with massive vector self-interactions as a concrete SIDM model & consequences for galactic structure

Arguelles, NEM, Rueda, Ruffini
JCAP 1604 (2016) no.04, 038
PART I
Right-Handed Neutrino
Majorana Mass generation (beyond seesaw)
& the role of Axions...
ANOMALOUS GENERATION OF RIGHT-HANDED MAJORANA NEUTRINO MASSES THROUGH TORSIONFUL QUANTUM GRAVITY UV complete string models?

NEM & Pilaftsis 2012
PRD 86, 124038
arXiv:1209.6387
String Theories with Antisymmetric Tensor Backgrounds

Massless Gravitational multiplet of (closed) strings: spin 0 scalar (dilaton)
spin 2 traceless symmetric rank 2 tensor (graviton)
spin 1 antisymmetric rank 2 tensor

**KALB-RAMOND FIELD**

\[ B_{\mu \nu} = - B_{\nu \mu} \]

Effective field theories (low energy scale \( E << M_s \)) ``gauge'' invariant

\[ B_{\mu \nu} \rightarrow B_{\mu \nu} + \partial_{[\mu} \theta(x)_{\nu]} \]

Depend only on field strength:

\[ H_{\mu \nu \rho} = \partial_{[\mu} B_{\nu \rho]} \]

**Bianchi identity:**

\[ \partial_{[\sigma} H_{\mu \nu \rho]} = 0 \rightarrow d \star H = 0 \]
ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

\[ S^{(4)} = \int d^4 x \sqrt{-g} \left( \frac{1}{2\kappa^2} R - \frac{1}{6} H_{\mu\nu\rho} H^{\mu\nu\rho} \right) \]

\[ = \int d^4 x \sqrt{-g} \left( \frac{1}{2\kappa^2} \bar{R} \right) \]

\[ \bar{\Gamma}_{\nu\rho}^{\mu} = \Gamma_{\nu\rho}^{\mu} + \frac{\kappa}{\sqrt{3}} H_{\nu\rho}^{\mu} \neq \bar{\Gamma}_{\rho\nu}^{\mu} \]

Contorsion
ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

\[ S^{(4)} = \int d^4x \sqrt{-g} \left( \frac{1}{2\kappa^2} R - \frac{1}{6} H_{\mu\nu\rho} H^{\mu\nu\rho} \right) \]

\[ = \int d^4x \sqrt{-g} \left( \frac{1}{2\kappa^2} \bar{R} \right) \]

\[ \bar{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}} H^\mu_{\nu\rho} \neq \bar{\Gamma}^\mu_{\rho\nu} \]

IN 4-DIM DEFINE DUAL OF H AS:

\[ -3 \sqrt{2} \partial_\sigma b = \sqrt{-g} \epsilon_{\mu\nu\rho\sigma} H^{\mu\nu\rho} \]

b(x) = Pseudoscalar (Kalb-Ramond (KR) axion)
FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

\[ S_\psi = \frac{i}{2} \int d^4 x \sqrt{-g} \left( \bar{\psi} \gamma^\mu \overline{D}_\mu \psi - (\overline{D}_\mu \bar{\psi}) \gamma^\mu \psi \right) \]

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

\[ \overline{D}_a = \partial_a - \frac{i}{4} \overline{\omega}_{bca} \sigma^{bc} \]

\[ \overline{\omega}_{ab\mu} = \omega_{ab\mu} + K_{ab\mu} \]

contorsion

\[ K_{abc} = \frac{1}{2} \left( T_{cab} - T_{abc} - T_{bca} \right) \]

Non-trivial contributions to \( B^\mu \)

\[ B^d = \epsilon^{abcd} e_{b\lambda} \left( \partial_a e^\lambda_c + \Gamma^\lambda_{\alpha\mu} e^\alpha_c e^{\mu}_a \right) \]

\[ H_{cab} \]

\[ \overline{\Gamma}_{\nu\rho}^\mu = \Gamma_{\nu\rho}^\mu + \frac{\kappa}{\sqrt{3}} H_{\nu\rho}^\mu \]
FERMIIONS COUPLE TO H–TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

\[ S_\psi = \frac{i}{2} \int d^4 x \sqrt{-g} \left( \bar{\psi} \gamma^\mu \overline{D}_\mu \psi - (\overline{D}_\mu \bar{\psi}) \gamma^\mu \psi \right) \]

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

\[ S_\psi \equiv \int d^4 x \bar{\psi} \gamma^a \gamma^5 B_a \psi \]

\[ B^d \sim \epsilon^{abcd} H_{bca} \]

\[ K_{abc} = \frac{1}{2} \left( T_{cab} - T_{abc} - T_{bca} \right) \]

\[ \bar{\omega}_{ab\mu} = \omega_{ab\mu} + K_{ab\mu} \]

contorsion

Non-trivial contributions to \( B^\mu \)

\[ B^d = \epsilon^{abcd} e_b \lambda \left( \partial_a e_c^\lambda + \Gamma_\alpha^\lambda e_c^\alpha e_\lambda^\alpha \right) \]
Fermionic Field Theories with H-Torsion

EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

Fermions:

\[ S_\psi \equiv -\frac{3}{4} \int d^4 \sqrt{-g} S_\mu \overline{\psi} \gamma^\mu \gamma^5 \psi = \frac{3}{4} \int S \wedge *J^5 \]

+ standard Dirac terms without torsion

\[ S = *T \]

\[ S_d = \frac{1}{3!} \epsilon^{abc} d T_{abc} \]

\[ T_{abc} \rightarrow H_{cab} = \epsilon_{cabd} \partial^d b \]

Bianchi identity

\[ d *S = 0 \]

classical

Postulate conservation at quantum level by adding counterterms

Implement \delta(d *S) \rightarrow \text{lagrange multiplier} in Path integral \rightarrow \text{b-field}
Fermionic Field Theories with H-Torsion

**EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS**

Fermions:

\[
S_{\psi} \equiv -\frac{3}{4} \int d^4 \sqrt{-g} \, S_{\mu} \overline{\psi} \gamma^\mu \gamma^5 \psi = -\frac{3}{4} \int S \wedge *J^5
\]

+ standard Dirac terms without torsion

\[S = *T\]

\[S_d = \frac{1}{3!} \epsilon^{abc} d T_{abc}\]

\[T_{abc} \rightarrow H_{cab} = \epsilon_{cabd} \partial^d b\]

**Bianchi identity**

\[d *S = 0\]

Conserved "torsion" charge

\[Q = \int *S\]

Postulate conservation at quantum level by adding counterterms

Implement \(d *S = 0\) via \(\delta(d *S)\) constraint

\(\rightarrow\) lagrange multiplier in Path integral \(\rightarrow\) b-field
\[ \int D\mathbf{S} \, D\mathbf{b} \, \exp \left[ i \int \frac{3}{4\kappa^2} \mathbf{S} \wedge \star \mathbf{S} - \frac{3}{4} \mathbf{S} \wedge \star \mathbf{J}^5 + \left( \frac{3}{2\kappa^2} \right)^{1/2} b \, d^* \mathbf{S} \right] \]

\[ = \int D\mathbf{b} \, \exp \left[ -i \int \frac{1}{2} \mathbf{db} \wedge \star \mathbf{db} + \frac{1}{f_b} \mathbf{db} \wedge \star \mathbf{J}^5 + \frac{1}{2f_b^2} \mathbf{J}^5 \wedge \star \mathbf{J}^5 \right] . \]

multiplier field \( \Phi(x) \equiv (3/\kappa^2)^{1/2} b(x) \).

\[ f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}} \]
\[
\int DS \, Db \exp \left[ i \int \frac{3}{4\kappa^2} S \wedge {}^*S - \frac{3}{4} S \wedge {}^*J^5 + \left( \frac{3}{2\kappa^2} \right)^{1/2} b \, d^*S \right] \\
= \int Db \exp \left[ -i \int \frac{1}{2} db \wedge {}^*db + \frac{1}{f_b} db \wedge {}^*J^5 + \frac{1}{2 f_b^2} J^5 \wedge {}^*J^5 \right].
\]

**multiplier field** \( \Phi(x) \equiv (3/\kappa^2)^{1/2} b(x). \)

\[
f_b = \left( \frac{3\kappa^2}{8} \right)^{-1/2} = \frac{M_P}{\sqrt{3\pi}}
\]
\[
\int D\Sigma \, D\Phi \exp \left[ i \int \frac{3}{4\kappa^2} \mathbf{S} \wedge \ast \mathbf{S} - \frac{3}{4} \mathbf{S} \wedge \ast \mathbf{J}^5 + \left( \frac{3}{2\kappa^2} \right)^{1/2} b \, d\mathbf{S} \right]
\]

\[
= \int D\Phi \exp \left[ -i \int \frac{1}{2} db \wedge \ast db + \frac{1}{f_b} db \wedge \ast \mathbf{J}^5 + \frac{1}{2f_b^2} \mathbf{J}^5 \wedge \mathbf{J}^5 \right]
\]

multiplier field \( \Phi(x) \equiv (3/\kappa^2)^{1/2} b(x) \).

\[ f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}} \]
\[ \int DS \, Db \, \exp \left[ i \int \frac{3}{4 \kappa^2} S \wedge *S - \frac{3}{4} S \wedge *J^5 + \left( \frac{3}{2 \kappa^2} \right)^{1/2} b \, d^*S \right] \]

\[ = \int Db \, \exp \left[ -i \int \frac{1}{2} db \wedge *db + \frac{1}{f_b} \, db \wedge *J^5 + \frac{1}{2 f_b^2} \, J^5 \wedge \star J^5 \right] \]

Use chiral anomaly equation (one-loop) in curved space-time:

\[ \nabla_\mu J^{5\mu} = \frac{e^2}{8 \pi^2} F_{\mu\nu} \tilde{F}_{\mu\nu} - \frac{1}{192 \pi^2} R_{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \]

\[ \equiv \, G(A, \omega) . \]

Hence, effective action of torsion-full QED

\[ \int Db \, \exp \left[ -i \int \frac{1}{2} db \wedge *db - \frac{1}{f_b} b G(A, \omega) + \frac{1}{2 f_b^2} J^5 \wedge \star J^5 \right] . \]
Use chiral anomaly equation (one-loop) in curved space-time:

\[ \nabla_\mu J^{5\mu} = \frac{e^2}{8\pi^2} F^{\mu\nu} \tilde{F}_{\mu\nu} - \frac{1}{192\pi^2} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \]

\[ \equiv G(A, \omega) . \]

Hence, effective action of torsion-full QED

\[ \int D\pi D\bar{\pi} \exp \left[ -i \int \frac{1}{2} d\pi \wedge \ast d\pi - \frac{1}{f_b} b G(A, \omega) + \frac{1}{2 f_b^2} J^5 \wedge J^5 \right] \]
Fermionic Field Theories with H-Torsion
EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

\[
S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \right] + \frac{1}{2f_b^2} J^5_\mu J^{5\mu} + \text{Standard Model terms for fermions}
\]

\textit{SHIFT SYMMETRY} \quad b(x) \rightarrow b(x) + c

\begin{align*}
c R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \quad \text{and} \quad c F^{\mu\nu} \tilde{F}_{\mu\nu}
\end{align*}

total derivatives
ANOMALOUS MAJORANA NEUTRINO MASS TERMS from QUANTUM TORSION

OUR SCENARIO Break such shift symmetry by coupling first $b(x)$ to another pseudoscalar field such as QCD axion $a(x)$ (or e.g. other string axions)

\[
S = \int d^4 x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \\
+ \frac{1}{2f_b^2} J_\mu^5 J_5^{\mu} + \gamma (\partial_\mu b) (\partial^\mu a) + \frac{1}{2} (\partial_\mu a)^2 \\
- y_{aia} \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) \right],
\]
ANOMALOUS MAJORANA NEUTRINO MASS TERMS from QUANTUM TORSION

OUR SCENARIO: Break such shift symmetry by coupling first $b(x)$ to another pseudoscalar field such as QCD axion $a(x)$ (or e.g. other string axions)

$$S = \int d^4 x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R_{\mu\nu\rho\sigma} \tilde{R}^{\mu\nu\rho\sigma} \right. $$

$$+ \frac{1}{2 f_b^2} J_\mu^5 J^{5\mu} + \gamma (\partial_\mu b) (\partial^\mu a) + \frac{1}{2} (\partial_\mu a)^2$$

$$\left. - y_{\alpha i} a \left( \bar{\psi}_R^\alpha \psi_R - \bar{\psi}_R \psi_R^C \right) \right] ,$$
ANOMALOUS MAJORANA NEUTRINO MASS TERMS from QUANTUM TORSION

OUR SCENARIO Break such shift symmetry by coupling first $b(x)$ to another pseudoscalar field such as QCD axion $a(x)$ (or e.g. other string axions)

$$S = \int d^4 x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} ight. \\
\left. + \frac{1}{2f_b^2} J_\mu^5 J_5^{5\mu} + \gamma (\partial_\mu b)(\partial^\mu a) + \frac{1}{2} (\partial_\mu a)^2 \right.$$

$$- y_{\alpha\beta} \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) ,$$

Yukawa right-handed neutrino fields
Field redefinition

\[ b(x) \rightarrow b'(x) \equiv b(x) + \gamma a(x) \]

so, effective action becomes

\[
S = \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu b')^2 + \frac{1}{2} \left( 1 - \gamma^2 \right) (\partial_\mu a)^2 \\
+ \frac{1}{2f_b^2} J_\mu^5 J_5^\mu + \frac{b'(x) - \gamma a(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \\
- y_\alpha i a \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) \right].
\]

must have \(|\gamma| < 1\)

otherwise axion field \(a(x)\) appears as a ghost \(\rightarrow\) canonically normalised kinetic terms

\[
S_a = \int d^4x \sqrt{-g} \left[ \frac{1}{2} (\partial_\mu a)^2 - \frac{\gamma a(x)}{192\pi^2 f_b \sqrt{1 - \gamma^2}} R^{\mu\nu\rho\sigma} \tilde{R}_{\mu\nu\rho\sigma} \\
- \frac{i y_\alpha}{\sqrt{1 - \gamma^2}} a \left( \bar{\psi}_R^C \psi_R - \bar{\psi}_R \psi_R^C \right) + \frac{1}{2f_b^2} J_\mu^5 J_5^\mu \right].
\]

CHIRALITY CHANGE
THREE-LOOP ANOMALOUS FERMION MASS TERMS

\[ \Lambda = \text{UV cutoff} \]

\[ M_R \sim \frac{1}{(16\pi^2)^2} \frac{y_a \gamma \kappa^4 \Lambda^6}{192\pi^2 f_b (1 - \gamma^2)} = \frac{\sqrt{3} y_a \gamma \kappa^5 \Lambda^6}{49152\sqrt{8} \pi^4 (1 - \gamma^2)} \]
SOME NUMBERS

\[ \Lambda = 10^{17} \text{ GeV} \]
\[ \gamma = 0.1 \]

\[ \Lambda = 10^{16} \text{ GeV} \]

\[ M_R \approx 16 \text{ keV}, \quad y_a = \gamma = 10^{-3} \]

\[ M_R \text{ is at the TeV for } y_a = 10^{-3} \]
SOME NUMBERS

\[ \Lambda = 10^{17} \text{ GeV} \]

\[ \gamma = 0.1 \]

\[ \Lambda = 10^{16} \text{ GeV} \]

\[ M_R \text{ is at the TeV for } y_a = 10^{-3} \]

\[ M_R \sim 16 \text{ keV, } \]

\[ y_a = \gamma = 10^{-3} \]

INTERESTING

WARM DARK MATTER REGIME

Appropriate Hierarchy for the other two massive Right-handed neutrinos for Leptogenesis-Baryogenesis & Dark matter constraints can be arranged by choosing Yukawa couplings
Some numbers

\[ \Lambda = 10^{17} \text{ GeV} \]
\[ \gamma = 0.1 \]
\[ \Lambda = 10^{16} \text{ GeV} \]
\[ M_R \text{ is at the TeV for } y_a = 10^{-3} \]
\[ M_R \sim 16 \text{ keV}, \]
\[ y_a = \gamma = 10^{-3} \]

May be (discrete) symmetry reasons (cf. Leontaris-Vlachos approach) force two of the heavier RH neutrinos to be degenerate \( \rightarrow \) dictate patterns for the axion-RH-neutrino Yukawa couplings \( y_a \)

Interesting Warm Dark Matter Regime

Appropriate Hierarchy for the other two massive Right-handed neutrinos for Leptogenesis-Baryogenesis & Dark matter constraints can be arranged by choosing Yukawa couplings
FINITENESS OF THE MASS

MULTI-AXION SCENARIOS (e.g. string axiverse)

\[ S_{a}^{\text{kin}} = \int d^{4}x \sqrt{-g} \left[ \frac{1}{2} \sum_{i=1}^{n} \left( (\partial_{\mu}a_{i})^{2} - M_{i}^{2} \right) + \gamma (\partial_{\mu}b)(\partial^{\mu}a_{1}) \right. \]
\[ \left. - \frac{1}{2} \sum_{i=1}^{n-1} \delta M_{i,i+1}^{2} a_{i}a_{i+1} \right] \]

\[ \delta M_{i,i+1}^{2} < M_{i}M_{i+1} \]

positive mass spectrum for all axions

simplifying all mixing equals

\[ M_{R} \sim \frac{\sqrt{3}y_{a}\gamma \kappa^{5} \Lambda^{6-2n}(\delta M_{a}^{2})^{n}}{49152 \sqrt{8} \pi^{4}(1 - \gamma^{2})} \quad n \leq 3 \]

\[ M_{R} \sim \frac{\sqrt{3}y_{a}\gamma \kappa^{5}(\delta M_{a}^{2})^{3}}{49152 \sqrt{8} \pi^{4}(1 - \gamma^{2})} \frac{(\delta M_{a}^{2})^{n-3}}{(M_{a}^{2})^{n-3}} \quad n > 3 \]
MULTI-AXION SCENARIOS (e.g. string axiverse)

\[
S_{a}^{\text{kin}} = \int d^4x \sqrt{-g} \left[ \frac{1}{2} \sum_{i=1}^{n} \left( (\partial_{\mu}a_i)^2 - M_i^2 \right) + \gamma (\partial_{\mu}b)(\partial^{\mu}a_1) \right. \\
\left. - \frac{1}{2} \sum_{i=1}^{n-1} \delta M_{i,i+1}^2 a_i a_{i+1} \right]
\]

\[\delta M_{i,i+1}^2 < M_i M_{i+1}\]

positive mass spectrum for all axions

simplifying all mixing equals

\[
M_R \sim \frac{\sqrt{3} y_a \gamma \kappa^5 \Lambda^{6-2n} (\delta M_a^2)^n}{49152 \sqrt{8} \pi^4 (1 - \gamma^2)}
\]

\[n \leq 3\]

\[
M_R \sim \frac{\sqrt{3} y_a \gamma \kappa^5 (\delta M_a^2)^3}{49152 \sqrt{8} \pi^4 (1 - \gamma^2)} \frac{(\delta M_a^2)^{n-3}}{(M_a^2)^{n-3}}
\]

\[n > 3\]

\[M_R : \text{UV finite for } n=3 \text{ @ 2-loop independent of axion mass}\]
FINITENESS OF THE MASS

MULTI-AXION SCENARIOS (e.g. string axiverse)

\[
S_{a}^{\text{kin}} = \int d^{4}x \sqrt{g} \left[ 1 + \sum_{i}^{n} \left( \frac{(\partial_{\mu} a_{i})^{2}}{M^{2}} + \gamma(\partial_{\mu} b)(\partial^{\mu} a_{i}) \right) \right]
\]

Three **RH neutrinos**
Three **axions**
Three **generations**

positive mass spectrum for all axions

\[
\delta M_{i,i+1}^{2} < M_{i}M_{i+1}
\]

simplifying all mixing equals

\[
M_{R} \sim \frac{\sqrt{3} y_{a} \gamma \kappa^{5} \Lambda^{6-2n}(\delta M_{a}^{2})^{n}}{49152 \sqrt{8} \pi^{4}(1 - \gamma^{2})} \quad n \leq 3
\]

\[
M_{R} \sim \frac{\sqrt{3} y_{a} \gamma \kappa^{5}(\delta M_{a}^{2})^{3}}{49152 \sqrt{8} \pi^{4}(1 - \gamma^{2})} \frac{(\delta M_{a}^{2})^{n-3}}{(M_{a}^{2})^{n-3}} \quad n > 3
\]

\(M_{R} \): UV finite for \(n=3\) @ 2-loop independent of axion mass
PART II
Implications for the Dark Sector–Astro/Cosmological Phenomenology
THE DARK SECTOR OF THE UNIVERSE

Observations from:

- Supernovae Ia
- CMB
- Baryon Acoustic Oscillations
- Galaxy Surveys
- Structure Formation data
- Strong & Weak lensing

http://www.cosmos.esa.int/web/planck/publications#Planck2015
THE DARK SECTOR OF THE UNIVERSE

Observations from:
- Supernovae Ia
- CMB
- Baryon Acoustic Oscillations
- Galaxy Surveys
- Structure Formation data
- Strong & Weak lensing

http://www.cosmos.esa.int/web/planck/publications#Planck-2015

Active $\nu$

ACDM fits them all at cosmological distances
But.....there are still open issues with the $Λ$CDM framework @ small (galactic) scales

What are they? and what do sterile neutrinos have to do with them???
PART IIb

Small-scale Cosmology “crisis”

Collisionless $\Lambda$CDM - based N-body simulations $\neq$

galactic scale observations especially Dwarf Galaxy structure
The 3-Problems of Galactic-Scale-Cosmology (GSC)

(i) The Core-Cusp problem (or cuspy-halo problem):

Nearly all simulations form dark matter halos which have *cuspy dark matter* distributions, with the density increasing steeply at small radii; on the contrary, *the rotation curves* of most of the observed *dwarf galaxies* indicate flat central density profiles ("cores").

**1. Cores in dwarfs outside MW halo**

**1. Cores in MW dwarf spheroidals**

B. Moore (1994)
J.G. de Blok [arXiv:0910.3538]
(ii) The missing satellite problem (or, dwarf galaxy problem)

Although there seem to be **enough observed normal-sized galaxies** to account for such a distribution, **the number of dwarf galaxies** is orders of magnitude **lower than** that expected from the simulations. E.g. there were observed to be around 38 dwarf galaxies in the Local Group, and only around 11 orbiting the Milky Way, yet one **dark matter simulation** predicted around 500 Milky Way dwarf satellites.

E. Polisensky and M. Ricotti, PR D83, 043506 (2011)

Weinberg et al. 2013, arXiv:1306.0913
(ii) The missing satellite (dwarves) problem

Missing Satellite Problem (MSP)
A quantitative comparison of # satellites at r < 400 kpc.

Klypin et al. 1999

CDM

$\Lambda$CDM

MW/M31

simulated

Observed

$v < 40 \text{ km / sec}
(M < 10^{10} M_\odot)$
discrepancy apparent

$\nu_{\text{circ}} = \sqrt{GM/R_{\text{vir}}} \sim 10 \left( \frac{M}{10^8 M_\odot} \right)^{1/3} \left( \frac{1+z}{4} \right)^{1/2} \text{ km s}^{-1}$
(iii) The Too-Big-to-Fail Problem

$\Lambda$CDM simulations predict that the most massive subhaloes of the Milky Way are too dense to host any of its brightest satellites, with luminosity higher than $10^5$ the luminosity of the Sun.  

(Models that are based on simulations predict much larger rotational velocities than the observed ones)

Rotational velocities $\rightarrow$ measure of enclosed mass $\rightarrow$ $\Lambda$CDM predicted satellites are too massive (too big).)


Central density of most massive subhaloes (left) **too high** to host dwarf galaxies of MW (right)
(iii) The too-big-to-fail Problem

Continuous curve: rotation curve of typical largest sub-halo of the Milky Way as simulated by collisionless $\Lambda$CDM

Data points pertain to observed circular velocities of the largest subhaloes of the Milky Way at their half-light radii

\[ v_{\text{rot}}^2(r) = \frac{GM(<r)}{r} \]

Astrophysical explanations

The missing satellite problem:

(i) Smaller halos do exist but only a few of them end up becoming visible (have not been able to attract enough baryonic matter to create a visible dwarf) (cf. Keck observations (2007) of eight newly discovered ultrafaint Milky Way dwarf satellites) showed that six were almost exclusively composed of DM, around 99.9% (with a mass-to-light ratio of about 1000) – Such ultra-faint dwarfs substantially alleviate the discrepancy, but there are still discrepancies by a factor of about four too few dwarves over a significant range of masses.

(ii) Galaxy formation in low-mass dark matter halos is strongly suppressed after re-ionization → simulated circular velocity function of CDM subhalos in approximate agreement with the observed circular velocity function of Milky Way satellite galaxies.

(iii) Dwarves tend to be merged into or tidally stripped apart by larger galaxies due to complex interactions. This tidal stripping has been part of the problem in identifying dwarf galaxies in first place, which is difficult due to their low surface brightness and high diffusion so that they are virtually unnoticeable.
Astrophysical explanations

(iv) **(Baryonic) Feedback** plays an important role: complex processes by means of which star formation and matter accretion onto black holes deposit energy in the surrounding environments of galaxies.

Various types of feedback:

- **Radiative**: photoionization, radiation pressure
  - *(stellar, or from accretion disk of a supermassive BH (AGN))*

- **Mechanical**: supernovae explosions, cosmic ray exerted pressure

Possible to explain **Missing satellite problem** with **Baryonic (not well understood) physics feedback**.
Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations needed?

All of the above problems seem that **cannot be entirely solved** by conventional **Astrophysics** explanations
- discrepancies still remain **moreover:** case by case studies
Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations needed?

All of the above problems seem that cannot be entirely solved by conventional Astrophysics explanations – discrepancies still remain moreover: case by case studies

CHANGE THE $\Lambda$CDM $\rightarrow$
Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that cannot be entirely solved by conventional Astrophysics explanations – discrepancies still remain moreover: case by case studies

CHANGE THE $\Lambda$CDM $\rightarrow$

(i) Exotic mechanisms of Early Universe imply suppressed density fluctuations at subgalactic scales (e.g. models with broken scale invariance during inflation, but somewhat lacking clear microscopic motivation from particle physics)

Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that cannot be entirely solved by conventional Astrophysics explanations – discrepancies still remain moreover: case by case studies

CHANGE THE Λ CDM →

(ii) modify gravity models (no DM except neutrinos) Milgrom, Bekenstein (TeVeS)

\[ f \left( \frac{|\vec{a}|}{a_0} \right) \vec{a} = -\vec{\nabla} \Phi_N \]

\[ f(x) = \frac{2x}{1 + (2 - \alpha)x + \sqrt{(1-x)^2 + 4x}}; \]

\[ a_0 \approx 1.2 \times 10^{-10} \text{ m s}^{-2} \]

Modified Gravitational acceleration @ galactic scales
Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that **cannot be entirely solved** by **conventional Astrophysics** explanations

- discrepancies still remain **moreover:** case by case studies

**CHANGE THE $\Lambda$CDM $\rightarrow$**

(ii) modify gravity models (no DM except neutrinos)  
Milgrom, Bekenstein (TeVeS)

$\rightarrow$ lensing problematic (bullet cluster or other merging galaxies, offer observational support for DM)
Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that **cannot be entirely solved** by conventional Astrophysics explanations
– discrepancies still remain moreover: case by case studies

CHANGE THE \( \Lambda \) CDM →

(ii) modify gravity models (no DM except neutrinos)
→ lensing problematic (bullet cluster or other merging galaxies, offer observational support for DM)
Towards a Solution of the 3-Problems of Galactic-Scale-Cosmology (GSC)

Microscopic Physics explanations

All of the above problems seem that cannot be entirely solved by conventional Astrophysics explanations – discrepancies still remain moreover: case by case studies

CHANGE THE Λ CDM →

(ii) modify gravity models (no DM except neutrinos) → lensing problematic (bullet cluster or other merging galaxies, offer observational support for DM)

(iii) CHANGE the DM properties → include self interactions or assume more than one dominant species ... with non-trivial role in galactic structure for our talk
Self-Interacting Dark Matter (SIDM) & small-scale Cosmology

Early pioneering works in implementing SIDM in N-body simulations

D. N. Spergel and P. J. Steinhardt, PRL 84, 3760 (2000)

Figure of merit: (total) cross section per unit DM particle mass

$$\frac{\sigma}{m}$$

Early days: 10 GeV $c^{-2} \geq m \geq 1$ MeV $c^{-2}$
in DM haloes with densities $10^{-2} M_\odot / pc^3$

$$\frac{\sigma}{m} \sim 0.1 - 100 \text{ cm}^2 / \text{g}$$

would imply observational effects in the inner haloes
Self-Interacting Dark Matter (SIDM) & small-scale Cosmology

Large Scale Structure: roughly the same

Individual galaxies: more cored & spherical in SIDM models

Self-Interacting Dark Matter (SIDM) & small-scale Cosmology

Early pioneering works in implementing SIDM in N-body simulations

D. N. Spergel and P. J. Steinhardt, PRL 84, 3760 (2000)

Figure of merit: (total) cross section per unit DM particle mass

\[ \frac{\sigma}{m} \]

Early days: \(10 \text{ GeV } c^{-2} \geq m \geq 1 \text{ MeV } c^{-2}\)
in DM haloes with densities \(10^{-2} M_\odot/\text{pc}^3\)

\[ \frac{\sigma}{m} \sim 0.1 - 100 \text{ cm}^2/\text{g} \]

would imply observational effects in the inner haloes

=1 barn/GeV consistent with all current constraints of GSC
CONSTRAINTS ARE LIMITED

Solves cosmology's "small scale crisis"

Clowe+ 2004
Mertens+ 2011
Bradac+ 2008

Dark matter self-interaction cross section, $\sigma_{DM}$ [cm$^2$/g]
CONSTRAINTS ARE LIMITED

Solves cosmology's "small scale crisis"

Clowe+ 2004

Mertens+ 2011

Bradac+ 2008

Dark matter self-interaction cross section, $\sigma_{DM} \text{[cm}^2\text{/g]}$
Compare with typical WIMPs, cross section in e.g. in SUSY models \( \sigma / m \approx 10^{-22} \text{ barn/GeV} \)
30 MERGING GALAXY CLUSTERS

Harvey, Massey, Kitching, Taylor, Titley
Self-Interacting Dark Matter (SIDM) & small-scale Cosmology

Harvey, Massey, Kitching, Taylor, Titley
In Right-handed neutrino WDM:
(i) mass of O(50) keV,
(ii) self-interactions stronger than the weak force, $10^8 G_F$
(iii) massive $\sim 10^4$ keV exchange vector is OK for core-galaxy structure

Arguelles, NEM, Ruffini, Rueda, JCAP (2016)
PART III
Self-Interacting Right-Handed Neutrino Warm Dark matter & galactic core-halo structures
A concrete model for SIDM – Right-handed keV Neutrinos with vector interactions

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

- Assume minimal extension of the Standard Model (non-supersymmetric) with right-handed neutrinos (RHN) self interacting via massive vector exchange interactions in the dark sector.

- Use models of particle physics, e.g. $\nu$ MSM (Shaposhnikov et al.) with three RHN, but augment them with these self-interactions.

- Among the lightest of the RHN (quasi stable $\rightarrow$ DM).

- Consistency of the halo-core profile of dwarf galaxies in Milky Way or large Elliptical $\rightarrow$ mass of lightest RHN in $O(10)$ keV (WDM) $\leftarrow$ Cosmological constraints of $\nu$ MSM.

Two different approaches yield similar range for WDM mass!
A concrete model for SIDM –
Right-handed keV Neutrinos with vector interactions

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

• Assume minimal extension of the Standard Model (non-supersymmetric) with right-handed neutrinos (RHN) self-interacting via massive vector exchange interactions in the dark sector

• Use models of particle physics, e.g. νMSM (Shaposhnikov et al.) with three RHN, but augment them with these self-interactions among the lightest of the RHN (quasi stable \(\rightarrow\) DM)

• Consistency of the halo-core profile of dwarf galaxies in Milky Way or large Elliptical \(\rightarrow\) mass of lightest RHN in \(O(10)\) keV (WDM) \(\leftarrow\) Cosmological constraints of \(\nu\) MSM

Moreover…..
DM may consist of more than one dominant species!

Two different approaches yield similar range for WDM mass!
SM Extension with N extra right-handed neutrinos

\[ L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \phi - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.} \]

SM Extension with N extra right-handed neutrinos

\[
L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \phi - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}
\]

Right-handed Massive \textbf{Majorana} neutrinos

Leptons

\[
L_\alpha = \begin{pmatrix} \nu_\alpha \\ \alpha^- \end{pmatrix}, \quad \alpha = e, \mu, \tau
\]
SM Extension with N extra right-handed neutrinos

\[ L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.} \]

**Higgs scalar SU(2)**

**Dual:** \[ \tilde{\phi}_i = \epsilon_{ij} \phi^*_j. \]
SM Extension with N extra right-handed neutrinos

$$\nu_{MSM}$$

Asaka, Blanchet, Boyarski, Ruchayskiy, Shaposhnikov

$$L = L_{SM} + \bar{N}_I i \partial_{\mu} \gamma^{\mu} N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$

Yukawa couplings
Matrix ($l=1,2,3$)

$$F = \tilde{K}_L f_d \tilde{K}_R^\dagger$$

$$f_d = \text{diag}(f_1, f_2, f_3), \quad \tilde{K}_L = K_L P_\alpha, \quad \tilde{K}_R^\dagger = K_R^\dagger P_\beta$$

$$P_\alpha = \text{diag}(e^{i\alpha_2}, e^{i\alpha_2}, 1), \quad P_\beta = \text{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

Mixing

$$K_L = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{L23} & s_{L23} \\ 0 & -s_{L23} & c_{L23} \end{pmatrix} \begin{pmatrix} c_{L13} & 0 & s_{L13} e^{-i\delta_L} \\ 0 & 1 & 0 \\ -s_{L13} e^{i\delta_L} & 0 & c_{L13} \end{pmatrix} \begin{pmatrix} c_{L12} & s_{L12} & 0 \\ -s_{L12} & c_{L12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$$c_{Li,j} = \cos(\theta_{Li,j}) \text{ and } s_{Li,j} = \sin(\theta_{Li,j})$$
SM Extension with N extra right-handed neutrinos

\[ L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \phi - \frac{M_I}{2} \bar{N}_I^c N_I + h.c. \]

Yukawa couplings
Matrix \((l=1, \ldots, N=2\text{ or }3)\)

For Constraints (compiled v oscillation data) on (light) sterile neutrinos cf.: Giunti, Hernandez, …
N=1 excluded by data

Model with 2 or 3 singlet fermions works well in reproducing Baryon Asymmetry and is consistent with Experimental Data on neutrino oscillations

Model with N=3 also works fine, and in fact it allows one of the Majorana fermions to almost decouple from the rest of the SM fields, thus providing candidates for light (keV region of mass) sterile neutrino Dark Matter.
SM Extension with N extra right-handed neutrinos

$$\nu_{\text{MSM}}$$

Asaka, Blanchet, Boyarski, Ruchayskiy, Shaposhnikov

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \phi - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$

For Constraints (compiled $\nu$ oscillation data) on (light) sterile neutrinos cf.: Giunti, Hernandez, …

$N=1$ excluded by data

Yukawa couplings
Matrix ($I=1, \ldots, N=2$ or $3$)

Model with 2 or 3 singlet fermions works well in reproducing Baryon Asymmetry and is consistent with Experimental Data on neutrino oscillations

Model with $N=3$ also works fine, and in fact it allows one of the Majorana fermions to almost **decouple** from the rest of the SM fields, thus providing candidates for **light** (keV region of mass) sterile neutrino **Dark Matter.**
SM Extension with N extra right-handed neutrinos

$$\nu_{\nu} \text{MSM}$$

$$L = L_{SM} + \bar{N}_I i \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \phi - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$

Majorana masses to (2 or 3) active (light) neutrinos via **seesaw**

Yukawa couplings Matrix (N=2 or 3)

**NB:** Upon Symmetry Breaking $\langle \Phi \rangle = v \neq 0 \rightarrow$ Dirac mass term

$$M_D = F_{\alpha I} v$$

$$v = \langle \phi \rangle \sim 175 \text{ GeV}$$

$$M_D \ll M_I$$

$$m_\nu = -M_D \frac{1}{M_I} [M_D]^T$$

Minkowski, Fugujita, Yanagida, Lazarides, Shafi, Wetterich, Sechter, Valle, Mohapatra, Senjanovic, ...
Light Neutrino Masses through see saw

\[ L = L_{SM} + \bar{N}_I i \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.} \]

mass of lightest of \( N_i \) by agreement with Cosmological data

\[ m_\nu = -M_D \frac{1}{M_I} [M_D]^T, \]

\[ M_D = F_{\alpha I} \nu \]

\[ \nu = \langle \phi \rangle \sim 175 \text{ GeV} \]

\[ M_D \ll M_I \]
Light Neutrino Masses through see saw

\[
L = L_{SM} + \bar{N}_I i \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + h.c.
\]

\[
m_\nu = -M_D \frac{1}{M_I} [M_D]^T .
\]

\[M_D = F_{\alpha I} \nu \]

\[\nu = \langle \phi \rangle \sim 175 \text{ GeV} \quad M_D \ll M_I \]

\[F_{\alpha_1} \approx 10^{-10} \Rightarrow m_\nu^2 \approx 10^{-3} \text{ eV}^2 \]
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

\[ N \rightarrow H \nu \rightarrow \gamma \]

\[ M_1 = O(10) \text{ keV} \]
More than one sterile neutrino needed to reproduce Observed oscillations

$v$MSM

Boyarski, Ruchayskiy, Shaposhnikov...

Constraints on two heavy degenerate singlet neutrinos

$N_1$ DM production estimation in Early Universe must take into account its interactions with $N_{2,3}$ heavy neutrinos
More than one sterile neutrino needed to reproduce Observed oscillations

\[ \nu_{MSM} \]

Boyarski, Ruchayskiy, Shaposhnikov...

Constraints on two heavy degenerate singlet neutrinos

\[ N_1 \] DM production estimation in Early Universe must take into account its interactions with \[ N_{2,3} \] heavy neutrinos

\[ \text{Increased CPV} \]

Pilaftsis, Underwood...
This talk: restrict mass of $N_1$ by agreement with observed galactic core-halo structure in SIDM versions of the model

$$L = L_{SM} + \bar{N}_I i \partial_\mu \gamma^\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + h.c.$$  

Light Neutrino Masses through see saw

$$m_\nu = -M_D \frac{1}{M_I} [M_D]^T \nu$$

$$M_D = F_{\alpha I} \nu$$

$$\nu = \langle \phi \rangle \sim 175 \text{ GeV} \quad M_D \ll M_I$$

$$F_{\alpha 1} \approx 10^{-10} \Rightarrow m_\nu^2 \approx 10^{-3} \text{ eV}^2$$
Light Neutrino Masses through see saw

\[ L = L_{SM} + \bar{N}_I i \gamma^\mu \partial_\mu N_I - F_{\alpha I} \bar{L}_\alpha N_I \tilde{\phi} - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.} \]

This talk: restrict mass of \( N_1 \) by agreement with observed galactic core-halo structure in SIDM versions of the model

\[ m_\nu = -M_D \frac{1}{M_I} [M_D]^T, \]

\[ M_D = F_{\alpha I} v \]

\[ v = \langle \phi \rangle \sim 175 \text{ GeV} \]

\[ M_D \ll M_I \]

\[ F_{\alpha 1} \approx 10^{10} \Rightarrow m_\nu^2 \approx 10^{-3} \text{ eV}^2 \]

Ignore in front of strong self-interactions for our purposes
Right-handed keV Neutrinos with vector self-interactions & galactic structure

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)

Place the νMSM in curved space time

$$g_{\mu\nu} = \text{diag}(e^\nu, -e^\lambda, -r^2, -r^2 \sin^2 \varphi)$$

$$\nu = \nu(r), \lambda = \lambda(r)$$

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{NR_1} + \mathcal{L}_V + \mathcal{L}_I$$

$$\mathcal{L}_{GR} = -\frac{R}{16\pi G}, \quad \mathcal{L}_{NR_1} = i \overline{N}_{R_1} \gamma^\mu \nabla_\mu N_{R_1} - \frac{1}{2} m \overline{N} c_{R_1} N_{R_1},$$

$$\mathcal{L}_V = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_v^2 V_\mu V^\mu, \quad \mathcal{L}_I = -g_V V_\mu J_V^\mu = -g_V V_\mu \overline{N}_{R_1} \gamma^\mu N_{R_1}$$

$$\nabla_\mu = \partial_\mu - \frac{i}{8} \omega^a_\mu [\gamma_a, \gamma_b]$$

Classical fields (eqs of motion) satisfy detailed thermodynamic equilibrium conditions in a galaxy at a temperature $T < O(keV)$.
Right-handed keV Neutrinos with vector self-interactions & galactic structure

Place the νMSM in **curved space time**

\[ g_{\mu\nu} = \text{diag}(e^\nu, -e^\lambda, -r^2, -r^2 \sin^2 \varphi) \]

$v = v(r)$ \quad $\lambda = \lambda(r)$

\[ \mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{NR_1} + \mathcal{L}_V + \mathcal{L}_I \]

\[ \mathcal{L}_{GR} = -\frac{R}{16\pi G}, \quad \mathcal{L}_{NR_1} = i \overline{N}_{R_1} \gamma^\mu \nabla_\mu N_{R_1} - \frac{1}{2} m \overline{N}_{c R_1} N_{R_1}, \]

\[ \mathcal{L}_V = -\frac{1}{4} V_{\mu\nu} V^{\mu\nu} + \frac{1}{2} m_V^2 V_\mu V^\mu, \quad \mathcal{L}_I = -g_V V_\mu J^\mu_{V} = -g_V V_\mu \overline{N}_{R_1} \gamma^\mu N_{R_1} \]

\[ \nabla_\mu = \partial_\mu - \frac{i}{8} \omega^a_\mu [\gamma_a, \gamma_b] \]

Classical fields (eqs of motion) satisfy detailed thermodynamic equilibrium conditions in a galaxy at a temperature $T < O(\text{keV})$
Right-handed keV Neutrinos with vector self-interactions & galactic structure

**Measure of Strength of self Interactions**

\[ C_V \equiv \frac{g_V^2}{m_V^2} \]

\[ C_V(r) = \begin{cases} 
C_0 & \text{at } r < r_m \text{ when } \lambda_B/l > 1 \\
0 & \text{at } r \geq r_m \text{ when } \lambda_B/l < 1 
\end{cases} \]

Effective interactions in galactic medium

\[ r_m = \text{core-halo matching point} = r_c + \delta r \]

Core radius

Inter-particle mean distance \( l \)

At temperature \( T \)

De-Broglie wavelength \( \lambda_B = \frac{\hbar}{\sqrt{2\pi mk_BT}} \)
**Right-handed keV Neutrinos with vector self-interactions & galactic structure**

<table>
<thead>
<tr>
<th>sterile ν mass</th>
<th>Milky Way ($M_c = 4.4 \times 10^6 M_\odot$)</th>
<th>Elliptical ($M_c^{cr} = 2.3 \times 10^8 M_\odot$)</th>
<th>Large Elliptical ($M_c = 1.8 \times 10^9 M_\odot$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m$ (keV)</td>
<td>$\overline{C}_0$</td>
<td>$\theta_0$</td>
<td>$\beta_0$</td>
</tr>
<tr>
<td>47</td>
<td>2</td>
<td>$3.70 \times 10^3$</td>
<td>$1.065 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$10^{14}$</td>
<td>$3.63 \times 10^3$</td>
<td>$1.065 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$10^{16}$</td>
<td>$2.8 \times 10^3$</td>
<td>$1.065 \times 10^{-7}$</td>
</tr>
<tr>
<td>350</td>
<td>1</td>
<td>$2.40 \times 10^6$ (†)</td>
<td>$1.431 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$10^{14}$</td>
<td>$1.27 \times 10^5$</td>
<td>$1.104 \times 10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$4.5 \times 10^{18}$</td>
<td>$1.7 \times 10^1$</td>
<td>$1.065 \times 10^{-7}$</td>
</tr>
</tbody>
</table>

\[ \beta \equiv \frac{k_B T}{m} = \beta_0 e^{(\nu_0 - \nu(r))/2} \]
\[ \theta \equiv \frac{\mu}{(k_B T)} \]

at the core ($\beta_0, \theta_0$)

**No solution for gravitational collapse**
Right-handed keV Neutrinos with vector self-interactions & galactic structure

<table>
<thead>
<tr>
<th>$m$ (keV)</th>
<th>$\overline{C}_0$</th>
<th>$\theta_0$</th>
<th>$\beta_0$</th>
<th>$r_c$ (pc)</th>
<th>$\delta r$ (pc)</th>
<th>$\theta(r_m)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>2</td>
<td>$3.70 \times 10^3$</td>
<td>$1.065 \times 10^{-7}$</td>
<td>$6.2 \times 10^{-4}$</td>
<td>$2.1 \times 10^{-4}$</td>
<td>-29.3</td>
</tr>
<tr>
<td></td>
<td>$10^{14}$</td>
<td>$3.63 \times 10^3$</td>
<td>$1.065 \times 10^{-7}$</td>
<td>$6.2 \times 10^{-4}$</td>
<td>$2.2 \times 10^{-4}$</td>
<td>-29.3</td>
</tr>
<tr>
<td></td>
<td>$10^{16}$</td>
<td>$2.8 \times 10^3$</td>
<td>$1.065 \times 10^{-7}$</td>
<td>$6.3 \times 10^{-4}$</td>
<td>$2.4 \times 10^{-4}$</td>
<td>-29.3</td>
</tr>
<tr>
<td>350</td>
<td>1</td>
<td>$2.40 \times 10^6$ (†)</td>
<td>$1.431 \times 10^{-7}$</td>
<td>$1.3 \times 10^{-6}$</td>
<td>$6.7 \times 10^{-7}$</td>
<td>-37.3</td>
</tr>
<tr>
<td></td>
<td>$10^{14}$</td>
<td>$1.27 \times 10^5$</td>
<td>$1.104 \times 10^{-7}$</td>
<td>$5.9 \times 10^{-6}$</td>
<td>$9.4 \times 10^{-7}$</td>
<td>-37.3</td>
</tr>
<tr>
<td></td>
<td>$4.5 \times 10^{18}$</td>
<td>$1.7 \times 10^1$</td>
<td>$1.065 \times 10^{-7}$</td>
<td>$5.9 \times 10^{-4}$</td>
<td>$2.0 \times 10^{-4}$</td>
<td>-37.3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_c$ (Elliptical)</th>
<th>$M_c^{cr}$ = $2.3 \times 10^8 M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>$2$</td>
</tr>
<tr>
<td></td>
<td>$10^{14}$</td>
</tr>
<tr>
<td></td>
<td>$10^{16}$</td>
</tr>
<tr>
<td></td>
<td>$1.76 \times 10^5$ (†)</td>
</tr>
<tr>
<td></td>
<td>$5.8 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$1.5 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$1.7 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$1.4 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$1.3 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$7.9 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$1.4 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$3.0 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$3.9 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$4.8 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$7.0 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
<tr>
<td></td>
<td>$-31.8$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$M_c$ (Large Elliptical)</th>
<th>$M_c$ = $1.8 \times 10^9 M_\odot$</th>
</tr>
</thead>
<tbody>
<tr>
<td>47</td>
<td>$10^{16}$</td>
</tr>
<tr>
<td></td>
<td>$1.02 \times 10^4$</td>
</tr>
<tr>
<td></td>
<td>$3.0 \times 10^{-6}$</td>
</tr>
<tr>
<td></td>
<td>$3.8 \times 10^{-4}$</td>
</tr>
<tr>
<td></td>
<td>$1.8 \times 10^{-5}$</td>
</tr>
<tr>
<td></td>
<td>$-32.8$</td>
</tr>
</tbody>
</table>

$\beta \equiv k_B T/m = \beta_0 e^{(\nu_0-\nu(r))/2}$

$\theta \equiv \mu/(k_B T)$

at the core ($\beta_0, \theta_0$)

Allowed WDM mass range

$47$ keV $c^{-2} \leq m \leq 350$ keV $c^{-2}$
Right-handed keV Neutrinos with vector self-interactions & galactic structure

If mixing with observable sector is non zero ($\nu_{\text{MSM}}$) → narrow window of allowed WDM mass!

$47 \text{ keV c}^{-2} \leq m \leq 50 \text{ keV c}^{-2}$
Interactions make inner Core more compact and increase central degeneracy compared to non-interacting case.

Non interacting right-handed neutrino case with $m = O(10)$ keV


Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)
Provide natural resolution of Core-Cusp Problem because the density profiles based on fermionic (as RH neutrinos) phase-space distributions develop always an extended plateau on halo scales, resembling Burkert or cored Einasto profiles.

Moreover, as the right-handed neutrino DM mass is `colder' by a few keV ($m \approx 47 \text{ keV } c^{-2}$) compared to most of the WDM models available in the literature, our model does not suffer from standard WDM problems, associated with the `too warm' nature of the particles involved.
N-N Cross sections under massive vector exchange (perturbation theory $g_V < 1$ OK)

$$\sigma_{core}^{tot} \approx \frac{(g_V/m_V)^4}{4^3 \pi} \frac{29m^2}{(p^2/m^2 \ll 1)}$$

Hidden sector vector interactions -> Much stronger than weak interactions in visible sector

$$\overline{C}_V = \left( \frac{g_V}{m_V} \right)^2 G_F^{-1}$$

$$\overline{C}_V \in (2.6 \times 10^8, 7 \times 10^8)$$

to resolve issues of small-scale cosmology crisis

$$m_V \lesssim 3 \times 10^4 \text{ keV}$$

Arguelles, NEM, Rueda, Ruffini, JCAP 1604, 038 (2016)
Conclusions - Outlook - so far

- At galactic scales $\Lambda$CDM model suffers from discrepancies with observations regarding the core-cusp, missing satellite, and too big to fail problems of small-scale Cosmology "crisis" ...

- To remedie this, self interactions among DM have been introduced with relatively strong cross sections per unit dark matter mass $\sigma/m$:

  \[
  0.1 \leq \frac{\sigma_{\text{SIDM}}}{m} \leq 0.47
  \]

- We have considered the role of the lightest of the right-handed neutrinos in vMSM extensions of the standard model, and added appropriately strong vector interactions in the dark sector among the neutrinos to increase inner degeneracy and inner core region in dwarf satellites of the Milky Way or Large elliptical galaxies. For interaction strengths $10^8 \text{ G_F}$, WDM mass = 47-50 keV, & vector mass < $10^4$ keV, we can resolve the three small-scale Cosmology problems.

- The RH neutrino WDM, which solves core-halo structure in galaxies, may co-exist with other CDM DM species to search for it in particle physics and neutrino oscillation experiments.
Conclusions – Outlook

• At galactic scales $\Lambda$CDM model suffers from discrepancies with observations regarding the core-cusp, missing satellite, and too big to fail problems of small-scale Cosmology “crisis” ...

• To remedy this, self interactions among DM have been introduced with relatively strong cross sections per unit dark matter mass $\sigma/m$:

$$0.1 \leq \frac{\sigma_{\text{SIDM}}/m}{\text{cm}^2\text{g}^{-1}} \leq 0.47$$

• We have considered the role of the lightest of the right-handed neutrinos in vMSM extensions of the standard model, and added appropriately strong vector interactions in the dark sector among the neutrinos $\rightarrow$ increase inner degeneracy and inner core region in dwarf satellites of the Milky Way or Large elliptical galaxies For interaction strengths $10^8$ G$_F$, WDM mass = 47-50 keV, & vector mass $< 10^4$ keV, we can resolve the three small-scale Cosmology problems.

• The RH neutrino WDM, which solves core-halo structure in galaxies, may co-exist with other CDM DM species $\rightarrow$ search for it in particle physics and neutrino oscillation experiments (eg SHiP) ...

SHiP
Search for Hidden Particles
Conclusions – Outlook

• At galactic scales $\Lambda$CDM model suffers from discrepancies with observations regarding the core-cusp, missing satellite, and too big to fail problems of small-scale Cosmology “crisis” ...

• To remedie this, self interactions among DM have been introduced with relatively strong cross sections per unit dark matter mass $\sigma/m$

\[
0.1 \leq \frac{\sigma_{\text{SIDM}}}{m_{\text{cm}^2 g^{-1}}} \leq 0.47
\]

• We have considered the role of the lightest of the right-handed neutrinos in vMSM extensions of the standard model, and added appropriately strong vector interactions in the dark sector among the neutrinos \( \rightarrow \) increase inner degeneracy and inner core region in dwarf satellites of the Milky Way or Large elliptical galaxies. For interaction strengths \( 10^8 \mbox{ G}_F \), WDM mass = 47-50 keV, & vector mass $< 10^4$ keV, we can resolve the three small-scale Cosmology problems.

• The RH neutrino WDM, which solves core-halo structure in galaxies, may co-exist with other CDM DM species \( \rightarrow \) coupling with axions may lead to Mass generation for Right Handed Neutrinos
THANK YOU !
SPARES
Dark Matter

DARK MATTER (DM): CURRENT EVIDENCE

Arguments in Favour

TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)

INDIRECT SEARCHES:
collider (LHC & beyond) searches photons, neutrinos,
matter-antimatter asymmetries (electron-positron, proton-antiproton)

Rotational Curves of galaxies, gravitational lensing growth of structure

Baryon-only Models, without Dark Matter
Dark Matter

DARK MATTER (DM):
CURRENT EVIDENCE
Arguments in Favour

TYPES OF DM:
hot, warm, cold

ASTROPHYSICAL CONSTRAINTS
(MODEL INDEPENDENT)

Rotational Curves of galaxies,
gravitational lensing
growth of structure

\[ \sum m_\nu < 0.23 \text{ eV} \]
\[ \Omega_\nu h^2 < 0.0025 \]
\[ \text{95\%, Planck TT+lowP+lensing+ext.} \]
Dark Matter

DARK MATTER (DM):
CURRENT EVIDENCE
Arguments in Favour

TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)

Distribution of dark haloes with mass $M > 10^5 M_\odot$

excludes Warm DM $m_{WDM} \leq 10$ keV!

Rotational Curves of galaxies, gravitational lensing, growth of structure

Re-ionization of the Universe @ redshift $z=20$
numerical N-body simulations based on warm & $\Lambda$CDM models

CDM

WDM

$WDM = 10$ keV

WMAP, Planck Coll 2015
Yoshida et al.
astro-ph/0303622
**DARK MATTER (DM):**

**CURRENT EVIDENCE**
Arguments in Favour

**TYPES OF DM:** hot, warm, cold

**ASTROPHYSICAL CONSTRAINTS**
(Model Independent)

**INDIRECT SEARCHES:**
collider (LHC & beyond) searches
photons, neutrinos,
matter-antimatter asymmetries
(electron-positron, proton-antiproton)

**Rotational Curves of galaxies,**
gravitational lensing,
growth of structure

**Compatible with all current data!**
$m \geq 100$ keV
$100$ keV $\leq m_{WDM} = m_{CDM}$
DARK MATTER (DM):
CURRENT EVIDENCE
Arguments in Favour

TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)

INDIRECT SEARCHES:
collider (LHC & beyond) searches
photons, neutrinos,
matter-antimatter asymmetries
(electron-positron, proton-antiproton)

THEORETICAL SCENARIOS

SUPERSYMMETRY neutralino

SUPERGRAVITY gravitino (if sufficiently light)

AXIONS (standard QCD or stringy)

STERILE NEUTRINOS
...

DARK MATTER (DM):
CURRENT EVIDENCE
Arguments in Favour
**Dark Matter**

*e.g. typical thermal WIMPs*

CMB-observations-compatible

DM relic abundance

$$\Omega_\chi \approx \frac{0.1 \text{ pb} \cdot \text{c}}{\langle \sigma(\chi \chi \rightarrow \text{SM} \nu) \rangle} \approx 0.22$$

occurs cross sections of weak-interactions type

$$\sigma(\chi \chi \rightarrow \text{SM} \nu)) \approx 3 \cdot 10^{-26} \text{ cm}^3 \text{ s}^{-1}$$

``WIMP miracle``

$$m_\chi \sim O(100 \text{ GeV – TeV})$$

**THEORETICAL SCENARIOS**

SUPERSYMMETRY *neutralino*

SUPERGRAVITY *gravitino* *(if sufficiently light)*

AXIONS *(standard QCD or stringy)*

STERILE NEUTRINOS

...
Predictions from supersymmetry \([10^{-8} \text{ pb} = 10^{-44} \text{ cm}^2]\):

\[
\sigma/m \approx 10^{-22} \text{ barn}/\text{GeV}
\]
Theoretical Model dependence in deriving bounds in experimental searches

But... None of these particles has been observed as yet...

\[ \Omega_c \approx \frac{0.1 \text{ pb} \cdot c}{\langle \sigma(\chi \chi \rightarrow \text{SM} \nu) \rangle} \approx 0.22 \]

\[ \sigma(\chi \chi \rightarrow \text{SM} \nu) \]

``WIMP miracle``

\[ m_{\chi} \sim O(100 \text{ GeV} - \text{TeV}) \]

**THEORETICAL SCENARIOS**

**SUPERSYMMETRY**

neutralino (if sufficiently light)

**SUPERGRAVITY**

gravitino

**AXIONS** (standard QCD or stringy)

**STERILE NEUTRINOS**

occurs cross sections of weak-interactions

*Arguments in favour of DM types:*

hot, warm, cold

**ASTROPHYSICAL CONSTRAINTS**

**INDIRECT SEARCHES:**

collider (LHC & beyond) searches

photons, neutrinos

MaLer-anMaLer asymmetries (electron-positron, proton-proton)

*``WIMP miracle``* typical thermal WIMPs

CMB-observations-compatible

DM relic abundance

The **``WIMP miracle``** occurs cross sections of weak-interactions

\[ \Omega_c \approx \frac{0.1 \text{ pb} \cdot c}{\langle \sigma(\chi \chi \rightarrow \text{SM} \nu) \rangle} \approx 0.22 \]

\[ \sigma(\chi \chi \rightarrow \text{SM} \nu) \]

\[ m_{\chi} \sim O(100 \text{ GeV} - \text{TeV}) \]
THEORETICAL SCENARIOS

SUPERSYMMETRY

neutralino

SUPERGRAVITY
grvitino (if sufficiently light)

AXIONS (standard QCD or stringy)

STERILE NEUTRINOS

THEORETICAL MODEL dependence

in deriving bounds in experimental searches

Moreover.....

DM may consist of more than one
dominant species!

This talk

DARK MATTER (DM):
CURRENT EVIDENCE

Arguments in Favour

TYPES OF DM: hot, warm

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)

INDIRECT SEARCHES: collider (LHC & beyond) searches
photons, neutrinos,
matter-antimatter asymmetries (electron-positron, proton-antiproton)