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

KING'S College LONDON

Nick E. Mavromatos

King's College London

Workshop on the Standard Model and Beyond

September 2 - 10, 2017

E I S A

European Institute for Sciences and Their Applications


Corfu Summer Institute

17th Hellenic School and Workshops on Elementary Particle Physics and Gravity

Corfu, Greece 2017

OUTLINE

- **PART I**: **Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions**

NEM & Pilaftsis
Phys.Rev. D86
(2012) 124038

- **PART II – Astrophysical Implications**: **ΛCDM** fits very well Astrophysical Data for **Universe** at **Large scales**
- BUT: @ GALACTIC SCALES, DWARF GALAXIES) – **DISCREPANCY between ΛCDM-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

OUTLINE

- **PART I**: **Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions**

NEM & Pilaftsis
Phys.Rev. D86
(2012) 124038

- **PART II – Astrophysical Implications: ΛCDM** fits very well Astrophysical Data for **Universe** at **Large scales**
- BUT: @ GALACTIC SCALES, DWARF GALAXIES) – **DISCREPANCY between ΛCDM-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

OUTLINE

- **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

NEM & Pilaftsis
Phys.Rev. D86
(2012) 124038

- **PART II – Astrophysical Implications**: **ΛCDM** fits very well Astrophysical Data for **Universe** at **Large scales**
- BUT: @ GALACTIC SCALES, DWARF GALAXIES) – DISCREPANCY between ΛCDM-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

OUTLINE

- **PART I: Mechanism (beyond seesaw) for right-handed neutrino mass generation through Axion-Right-handed Neutrino Interactions**

NEM & Pilaftsis
Phys.Rev. D86
(2012) 124038

- **PART II – Astrophysical Implications: ΛCDM** fits very well Astrophysical Data for **Universe** at **Large scales**
- BUT: @ GALACTIC SCALES, DWARF GALAXIES) – **DISCREPANCY between ΛCDM-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

OUTLINE

Will argue that:

(i) resolution of **Galactic core-halo structure** problems of ΛCDM 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 ν 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

$$\boxed{47\ \text{keV}\ c^{-2} \leq m \leq 50\ \text{keV}\ c^{-2}}$$

- **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 symemtric rank 2 tensor (graviton)
spin 1 asntisymmetric rank 2 tensor

KALB-RAMOND FIELD $B_{\mu\nu} = -B_{\nu\mu}$

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

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

Depend only on field strength : $H_{\mu\nu\rho} = \partial_{[\mu}B_{\nu\rho]}$

Bianchi identity : $\boxed{\partial_{[\sigma}H_{\mu\nu\rho]} = 0 \to d \star \mathbf{H} = 0}$

ROLE OF H-FIELD AS TORSION

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

4-DIM
PART

$$
\begin{aligned}
S^{(4)} &= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big) \\
&= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big)
\end{aligned}
$$

$$
\overline{\Gamma}^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho} \neq \overline{\Gamma}^{\mu}_{\rho\nu}
$$

Contorsion

ROLE OF H-FIELD AS TORSION – AXION FIELD

EFFECTIVE GRAVITATIONAL ACTION IN STRING LOW-ENERGY LIMIT

$$\boxed{\sim \frac{1}{2}\partial^\mu b\,\partial_\mu b}$$

4-DIM PART

$$\begin{aligned} S^{(4)} &= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}R - \frac{1}{6}H_{\mu\nu\rho}\,H^{\mu\nu\rho}\Big) \\ &= \int d^4x\sqrt{-g}\Big(\frac{1}{2\kappa^2}\overline{R}\ \Big) \end{aligned}$$

$$\overline{\Gamma}^{\mu}_{\nu\rho} = \Gamma^{\mu}_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^{\mu}_{\nu\rho} \neq \overline{\Gamma}^{\mu}_{\rho\nu}$$

IN 4-DIM DEFINE DUAL OF H AS :

$$\boxed{-3\sqrt{2}\partial_\sigma b = \sqrt{-g}\,\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}}$$

b(x) **= Pseudoscalar**
(Kalb-Ramond (KR) axion)

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu\overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

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

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

contorsion

$$K_{abc} = \frac{1}{2}\Big(T_{cab} - T_{abc} - T_{bca}\Big)$$

$$H_{cab}$$

Non-trivial contributions to $\boldsymbol{B^\mu}$

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

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

FERMIONS COUPLE TO H –TORSION VIA GRAVITATIONAL COVARIANT DERIVATIVE

$$S_\psi = \frac{i}{2}\int d^4x\sqrt{-g}\Big(\overline{\psi}\gamma^\mu \overline{\mathcal{D}}_\mu\psi - (\overline{\mathcal{D}}_\mu\overline{\psi})\gamma^\mu\psi\Big)$$

TORSIONFUL CONNECTION, FIRST-ORDER FORMALISM

$$\boxed{S_\psi \ni \int d^4x\overline{\psi}\gamma^a\gamma^5 B_a\psi}$$

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

contorsion

$$K_{abc} = \frac{1}{2}\Big(T_{cab} - T_{abc} - T_{bca}\Big)$$

$$H_{cab}$$

$$B^d \sim \epsilon^{abcd}H_{bca}$$

Non-trivial contributions to ***B***$^\mu$

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

$$\overline{\Gamma}^\mu_{\nu\rho} = \Gamma^\mu_{\nu\rho} + \frac{\kappa}{\sqrt{3}}H^\mu_{\nu\rho} \neq \overline{\Gamma}^\mu_{\rho\nu}$$

Fermionic Field Theories with H-Torsion
EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

Fermions:

$$S_\psi \ni -\frac{3}{4}\int d^4\sqrt{-g}\, S_\mu \bar{\psi}\gamma^\mu\gamma^5\psi = -\frac{3}{4}\int S \wedge {}^\star J^5$$

+ standard Dirac terms without torsion

$$\mathbf{S} = {}^\star\mathbf{T}$$

$$S_d = \frac{1}{3!}\epsilon^{abc}{}_d T_{abc}$$

$$T_{abc} \to H_{cab} = \epsilon_{cabd}\,\partial^d b$$

Bianchi identity

$$\mathrm{d}\,{}^\star\mathbf{S} = 0$$

classical

conserved
``torsion " charge

$$Q = \int {}^\star\mathbf{S}$$

Postulate conservation at quantum level by adding counterterms

Implement $\mathrm{d}\,{}^\star\mathbf{S} = 0$ via $\delta(d\,{}^\star\mathbf{S})$ constraint
→ lagrange multiplier in Path integral → b-field

Fermionic Field Theories with H-Torsion
EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

Fermions:

$$S_\psi \ni -\frac{3}{4}\int d^4\sqrt{-g}\, S_\mu \bar{\psi}\gamma^\mu\gamma^5\psi = -\frac{3}{4}\int S \wedge {}^\star J^5$$

+ standard Dirac terms without torsion

$$\mathbf{S} = {}^\star\mathbf{T}$$

$$S_d = \frac{1}{3!}\epsilon^{abc}{}_d T_{abc}$$

$$T_{abc} \to H_{cab} = \epsilon_{cabd}\,\partial^d b$$

Bianchi identity

$$\boxed{\mathrm{d}\,{}^\star\mathbf{S} = 0}$$

classical

conserved
``torsion " charge

$$Q = \int {}^\star\mathbf{S}$$

Postulate conservation at quantum level by adding counterterms

Implement $\mathrm{d}\,{}^\star\mathbf{S} = 0$ via $\delta(d\,{}^\star\mathbf{S})$ constraint
→ lagrange multiplier in Path integral → b-field

$$
\int D\mathbf{S}\, Db \,\exp\Big[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \Big(\frac{3}{2\kappa^2}\Big)^{1/2} b\, d^\star\mathbf{S}\Big]
$$

$$
= \int Db \,\exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge{}^\star\mathbf{J}^5\Big]
$$

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

$$
f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}}
$$

$$\int D\mathbf{S}\, Db\, \exp\left[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \left(\frac{3}{2\kappa^2}\right)^{1/2} b\, d^\star\mathbf{S}\right]$$

$$= \int Db\, \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5\wedge{}^\star\mathbf{J}^5\right]$$

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

$$f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}}$$

$$\int D\mathbf{S}\, Db \exp\left[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge{}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge{}^\star\mathbf{J}^5 + \left(\frac{3}{2\kappa^2}\right)^{1/2} b\, d{}^\star\mathbf{S}\right]$$

$$= \int Db \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge{}^\star\mathrm{d}b + \frac{1}{f_b}\boxed{\mathrm{d}b\wedge}{}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5 \overset{\star}{\wedge}\mathbf{J}^5\right]$$

partial integrate

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

$$f_b = (3\kappa^2/8)^{-1/2} = \frac{M_P}{\sqrt{3\pi}}$$

$$\int DS\, Db\, \exp\Big[i \int \frac{3}{4\kappa^2}\mathbf{S}\wedge {}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge {}^\star\mathbf{J}^5 + \Big(\frac{3}{2\kappa^2}\Big)^{1/2} b\, d{}^\star\mathbf{S}\Big]$$

$$= \int Db\, \exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge {}^\star\mathrm{d}b + \frac{1}{f_b}\boxed{\mathrm{d}b\wedge} {}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5 \overset{\star}{\wedge}\mathbf{J}^5\Big]$$

partial integrate

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

$$\begin{aligned}\nabla_\mu J^{5\mu} &= \frac{e^2}{8\pi^2}F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{192\pi^2}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma}\\ &\equiv G(\mathbf{A},\omega)\,.\end{aligned}$$

Hence, effective action of torsion-full QED

$$\int Db\, \exp\Big[-i\int \frac{1}{2}\mathrm{d}b\wedge {}^\star\mathrm{d}b - \frac{1}{f_b}bG(\mathbf{A},\omega) + \frac{1}{2f_b^2}\mathbf{J}^5 \overset{\star}{\wedge}\mathbf{J}^5\Big].$$

$$\int D\mathbf{S}\, Db\, \exp\left[i\int \frac{3}{4\kappa^2}\mathbf{S}\wedge {}^\star\mathbf{S} - \frac{3}{4}\mathbf{S}\wedge {}^\star\mathbf{J}^5 + \left(\frac{3}{2\kappa^2}\right)^{1/2} b\, d{}^\star\mathbf{S}\right]$$

$$= \int Db\, \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge {}^\star\mathrm{d}b + \frac{1}{f_b}\mathrm{d}b\wedge {}^\star\mathbf{J}^5 + \frac{1}{2f_b^2}\mathbf{J}^5 \wedge {}^\star\mathbf{J}^5\right]$$

partial integrate

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

$$\nabla_\mu J^{5\mu} = \frac{e^2}{8\pi^2}F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{192\pi^2}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma}$$
$$\equiv G(\mathbf{A},\omega)\ .$$

$$\boxed{bR\widetilde{R} - bF\widetilde{F}}$$

coupling

Hence, effective action of torsion-full QED

$$\int Db\, \exp\left[-i\int \frac{1}{2}\mathrm{d}b\wedge {}^\star\mathrm{d}b - \frac{1}{f_b}bG(\mathbf{A},\omega) + \frac{1}{2f_b^2}\mathbf{J}^5 \wedge {}^\star\mathbf{J}^5\right] .$$

Fermionic Field Theories with H-Torsion
EFFECTIVE ACTION AFTER INTEGRATING OUT QUANTUM TORSION FLUCTUATIONS

$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b}R^{\mu\nu\rho\sigma}\,\widetilde{R}_{\mu\nu\rho\sigma} + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} \; +$$

+ Standard Model terms for fermions

SHIFT SYMMETRY b(x) → b(x) + c

$c\,R^{\mu\nu\rho\sigma}\,\widetilde{R}_{\mu\nu\rho\sigma}$ and $c\,F^{\mu\nu}\,\widetilde{F}_{\mu\nu}$ total derivatives

Mavromatos, Pilaftsis arXiv: 1209.6387

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)

$$
\begin{aligned}
\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[&\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} \\
&+\frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \gamma(\partial_\mu b)\,(\partial^\mu a) + \frac{1}{2}(\partial_\mu a)^2 \\
&-y_a i a\left(\overline{\psi}_R^{\,C}\psi_R - \overline{\psi}_R\psi_R^{\,C}\right)\Big]\,,
\end{aligned}
$$

Mavromatos, Pilaftsis arXiv: 1209.6387

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)

$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \gamma(\partial_\mu b)\,(\partial^\mu a) + \frac{1}{2}(\partial_\mu a)^2 - y_a i a\left(\overline{\psi}_R^{\ C}\psi_R - \overline{\psi}_R\psi_R^{\ C}\right)\Big]\,,$$

Mavromatos, Pilaftsis arXiv: 1209.6387

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)

$$\mathcal{S} = \int d^4x \sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b)^2 + \frac{b(x)}{192\pi^2 f_b} R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} + \frac{1}{2f_b^2} J^5_\mu J^{5\mu} + \gamma(\partial_\mu b)\,(\partial^\mu a) + \frac{1}{2}(\partial_\mu a)^2 - y_a i a\left(\overline{\psi}_R^{\ C}\psi_R - \overline{\psi}_R \psi_R^{\ C}\right)\Big]\,,$$

Yukawa

right-handed neutrino fields

Field redefinition

$$b(x) \to b'(x) \equiv b(x) + \gamma a(x)$$

so, effective action becomes

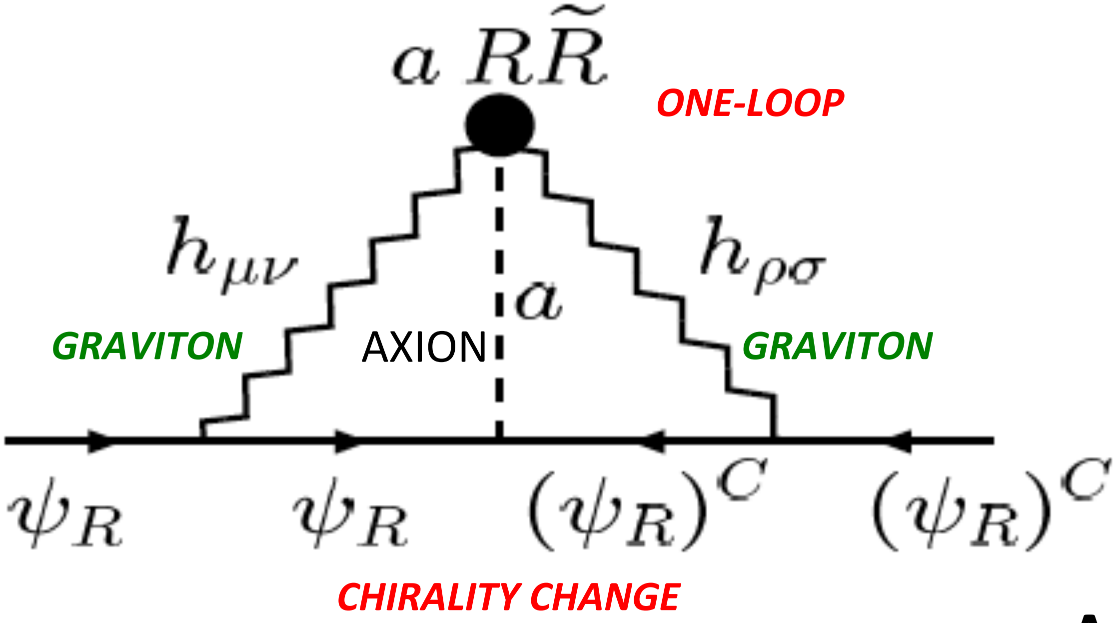
$$\mathcal{S} = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu b')^2 + \frac{1}{2}\left(1-\gamma^2\right)(\partial_\mu a)^2 + \frac{1}{2f_b^2}J^5_\mu J^{5\mu} + \frac{b'(x)-\gamma a(x)}{192\pi^2 f_b}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - y_a i a\left(\overline{\psi}_R^{\,C}\psi_R - \overline{\psi}_R\psi_R^{C}\right)\Big]\,.$$

must have $|\gamma| < 1$ ***otherwise axion field a(x) appears as a ghost → canonically normalised kinetic terms***

$$\mathcal{S}_a = \int d^4x\sqrt{-g}\,\Big[\frac{1}{2}(\partial_\mu a)^2 - \frac{\gamma a(x)}{192\pi^2 f_b\sqrt{1-\gamma^2}}R^{\mu\nu\rho\sigma}\widetilde{R}_{\mu\nu\rho\sigma} - \frac{i y_a}{\sqrt{1-\gamma^2}}\,a\left(\overline{\psi}_R^{\,C}\psi_R - \overline{\psi}_R\psi_R^{C}\right) + \frac{1}{2f_b^2}J^5_\mu J^{5\mu}\Big]\,.$$

CHIRALITY CHANGE

THREE-LOOP ANOMALOUS FERMION MASS TERMS



Λ = UV cutoff

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

SOME NUMBERS

$\Lambda = 10^{17}$ GeV

$\gamma = 0.1$

M_R is at the TeV for $y_a = 10^{-3}$

$\Lambda = 10^{16}$ GeV

$M_R \sim 16$ keV,

$y_a = \gamma = 10^{-3}$

SOME NUMBERS

$$\Lambda = 10^{17}\ \text{GeV}$$

$$\gamma = 0.1$$

M_R is at the TeV for $y_a = 10^{-3}$

$$\Lambda = 10^{16}\ \text{GeV}$$

$$M_R \sim 16\ \text{keV},$$

$$y_a = \gamma = 10^{-3}$$

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

$$\Lambda = 10^{17}\ \mathrm{GeV}$$

$$\gamma = 0.1$$

M_R is at the TeV

for $y_a = 10^{-3}$

$$\Lambda = 10^{16}\ \mathrm{GeV}$$

$M_R \sim 16\ \mathrm{keV}$,

$$y_a = \gamma = 10^{-3}$$

May be (discrete) **symmetry** reasons (*cf* **Leontaris-Vlachos approach**) force **two** of the heavier **RH neutrinos** to be **degenerate** → 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

Arvanitaki, Dimopoulos *et al*.

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

$$\mathcal{S}_a^{\rm kin} = \int d^4x \sqrt{-g}\left[\frac{1}{2}\sum_{i=1}^{n}\Big((\partial_\mu a_i)^2 - M_i^2\Big) + \gamma(\partial_\mu b)(\partial^\mu a_1) - \frac{1}{2}\sum_{i=1}^{n-1}\delta M_{i,i+1}^2\, a_i a_{i+1}\right];$$

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

positive mass spectrum for all axions

simplifying all mixing equals

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

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

FINITENESS OF THE MASS

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

$$\mathcal{S}_a^{\rm kin} = \int d^4x\,\sqrt{-g}\left[\frac{1}{2}\sum_{i=1}^{n}\Big((\partial_\mu a_i)^2 - M_i^2\Big) + \gamma(\partial_\mu b)(\partial^\mu a_1)\right.$$
$$\left. -\frac{1}{2}\sum_{i=1}^{n-1}\delta M_{i,i+1}^2\, a_i a_{i+1}\right];$$

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

positive mass spectrum
for all axions

simplifying all mixing equals

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

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

M_R: UV finite for n=3 @ 2-loop independent of axion mass

FINITENESS OF THE MASS

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

$$\mathcal{S}_a^{\rm kin} = \int d^4x\,\sqrt{-g}\,\Big[1 \sum^{n}\Big((\partial\, a)^2 \quad M^2\Big) + \gamma(\partial_\mu b)(\partial^\mu a_1)$$

Three RH neutrinos
Three axions
Three generations

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

positive mass spectrum
for all axions

simplifying all mixing equals

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

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

M_R : UV finite for n=3 @ 2-loop independent of axion mass

PART II

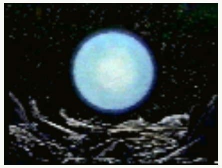
Implications for the Dark Sector–
Astro/Cosmological Phenomenology

THE DARK SECTOR OF THE UNIVERSE

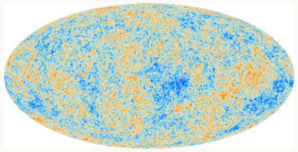
http://www.cosmos.esa.int/web/planck/publications#Planck2015

Observations from:

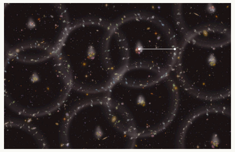
Supernovae Ia



CMB

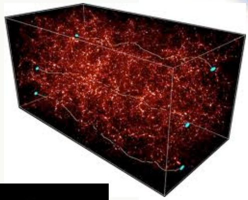


Baryon Acoustic Oscillations

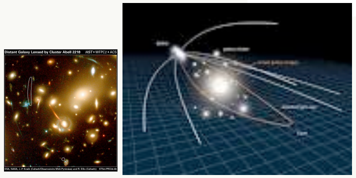


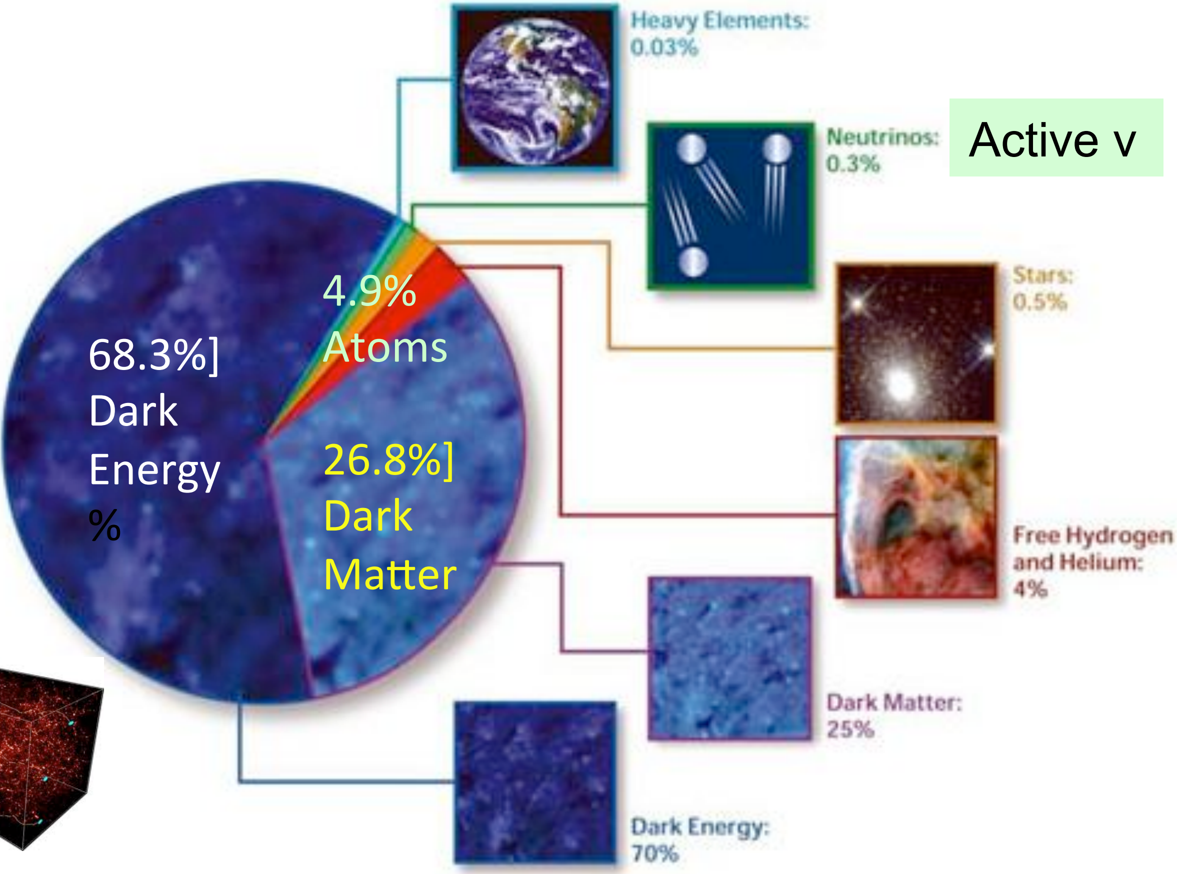
Galaxy Surveys

Structure Formation data



Strong & Weak lensing





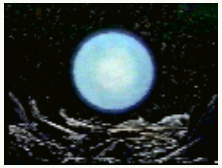
Active ν

THE DARK SECTOR OF THE UNIVERSE

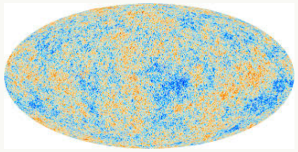
http://www.cosmos.esa.int/web/planck/publications#Pl 15

Observations from:

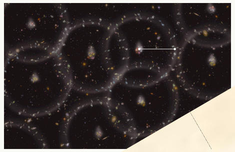
Supernovae Ia



CMB

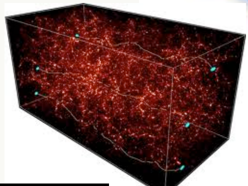


Baryon Acoustic Oscillations

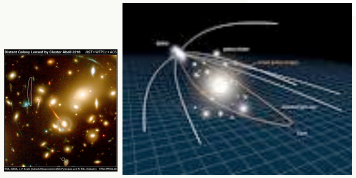


Galaxy Surveys

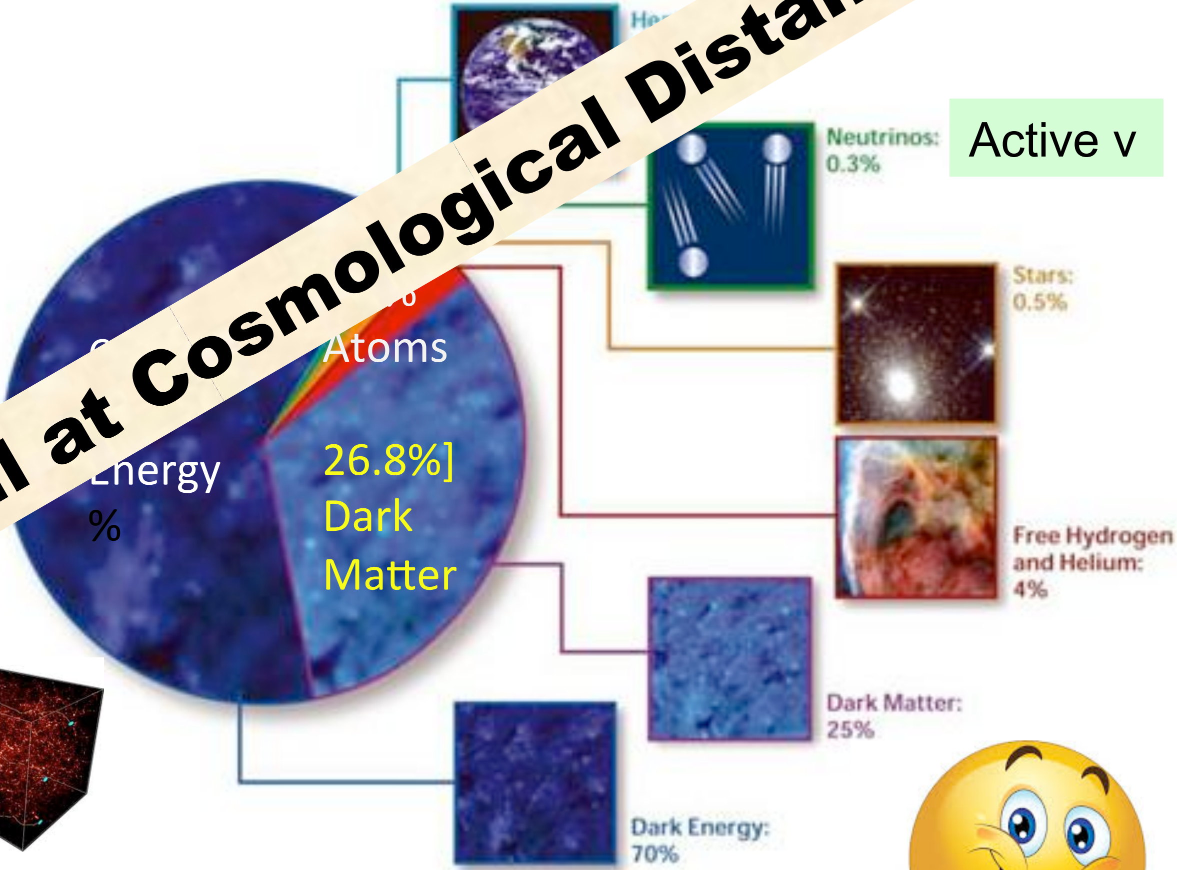
Stru ation data



St ng & Weak lensing



ΛCDM fits them all at Cosmological Distances



But.....there are still open **issues** with the **ΛCDM** framework **@ small (galactic) scales**

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

PART IIb

Small-scale Cosmology "crisis"

Collisionless ΛCDM - based N-body simulations

$\neq$

galactic scale observations
especially Dwarf Galaxy structure

The 3-Problems of Galactic-Scale-Cosmology (GSC)

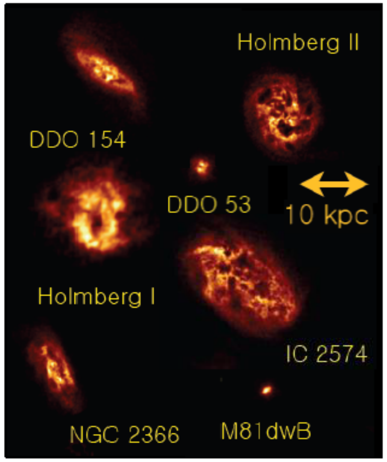
(i) The Core-Cusp problem (or cuspy-halo problem):

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***”).

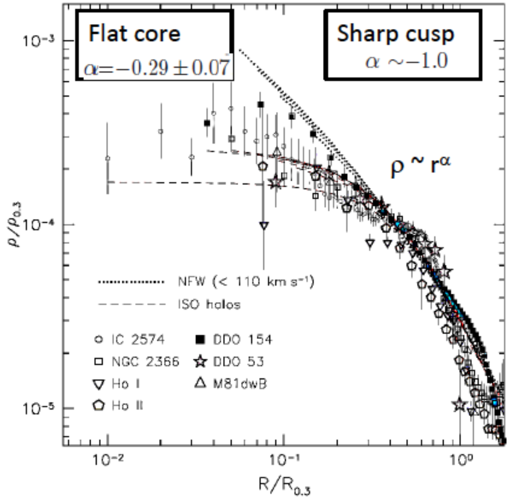
B. Moore (1994)
J.G. de Blok [arXiv:0910.3538]
Se-Heon Oh *et al.* ,
Astrophys. J. 149 (6), 96 (2015).

1. Cores in dwarfs outside MW halo

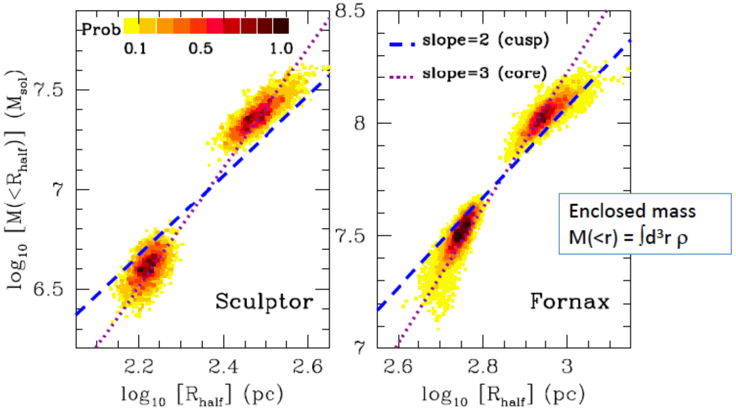
Moore (1994), Flores & Primack (1994), ...



THINGS (dwarf galaxy survey) - Oh et al. (2011)



1. Cores in MW dwarf spheroidals



Stellar subpopulations (metal-rich & metal-poor) as “test masses” in gravitational potential

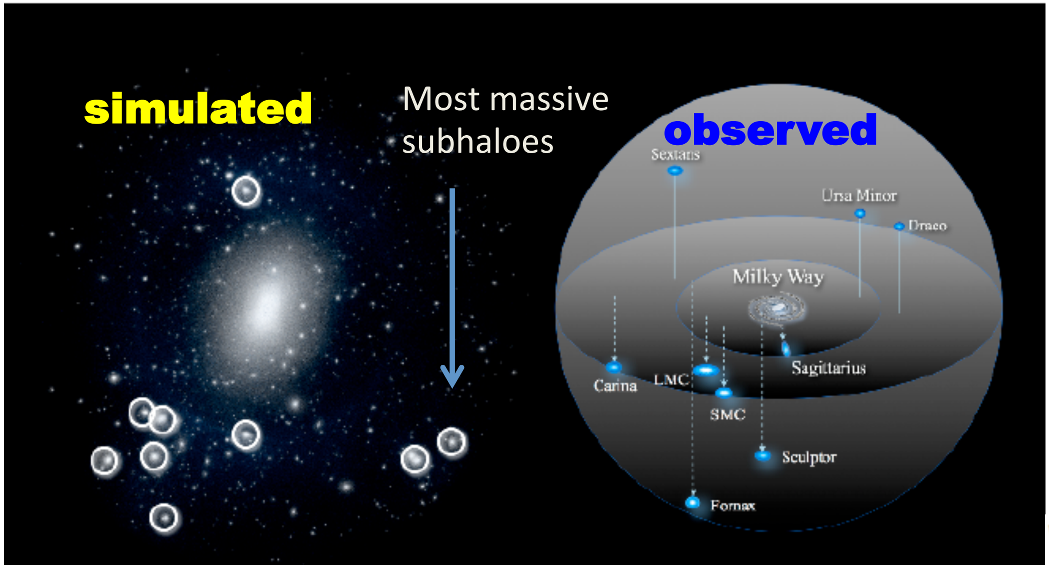
Walker & Penarrubia (2011)

The 3-Problems of Galactic-Scale-Cosmology (GSC)

(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**



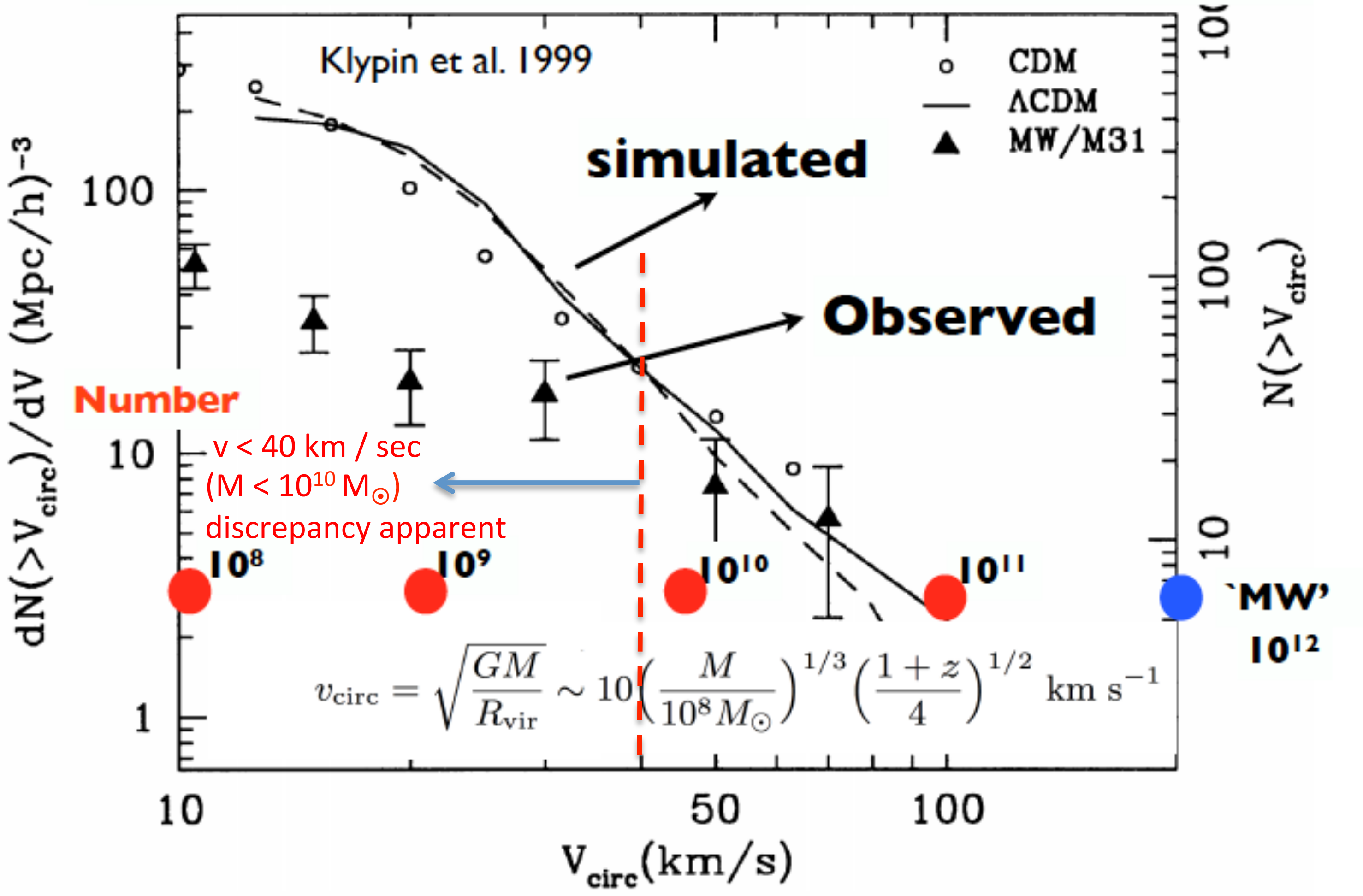
Weinberg et al. 2013, arXiv:1306.0913

B. Moore *et al.*, Astrophys. J. 524 , L19 (1999)
A. Klypin, *et al.*,Astrophys. J. 522, 82 (1999)
E. Polisensky and M. Ricotti, PR D83, 043506 (2011)

(ii) The missing satellite (dwarves) problem

Missing Satellite Problem (MSP)

A quantitative comparison of # satellites at r < 400 kpc.



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

$$v_{\rm circ} = \sqrt{\frac{GM}{R_{\rm vir}}} \sim 10\left(\frac{M}{10^8 M_\odot}\right)^{1/3}\left(\frac{1+z}{4}\right)^{1/2} \,\text{km s}^{-1}$$

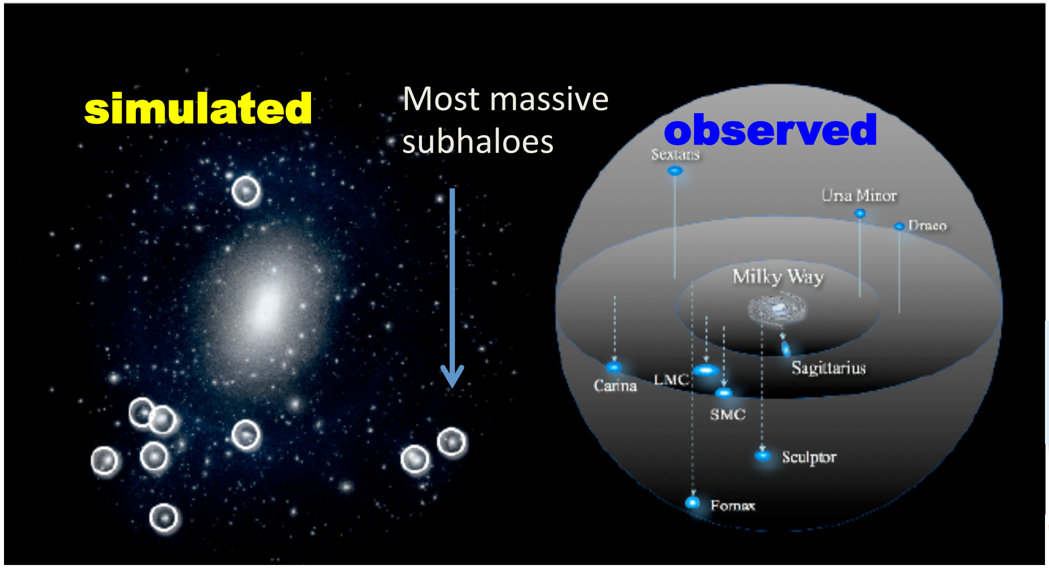
The 3-Problems of Galactic-Scale-Cosmology (GSC)

(iii) The Too-Big-to-Fail Problem

ΛCDM 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 → measure of enclosed mass → ΛCDM predicted satellites are too massive (too big).)

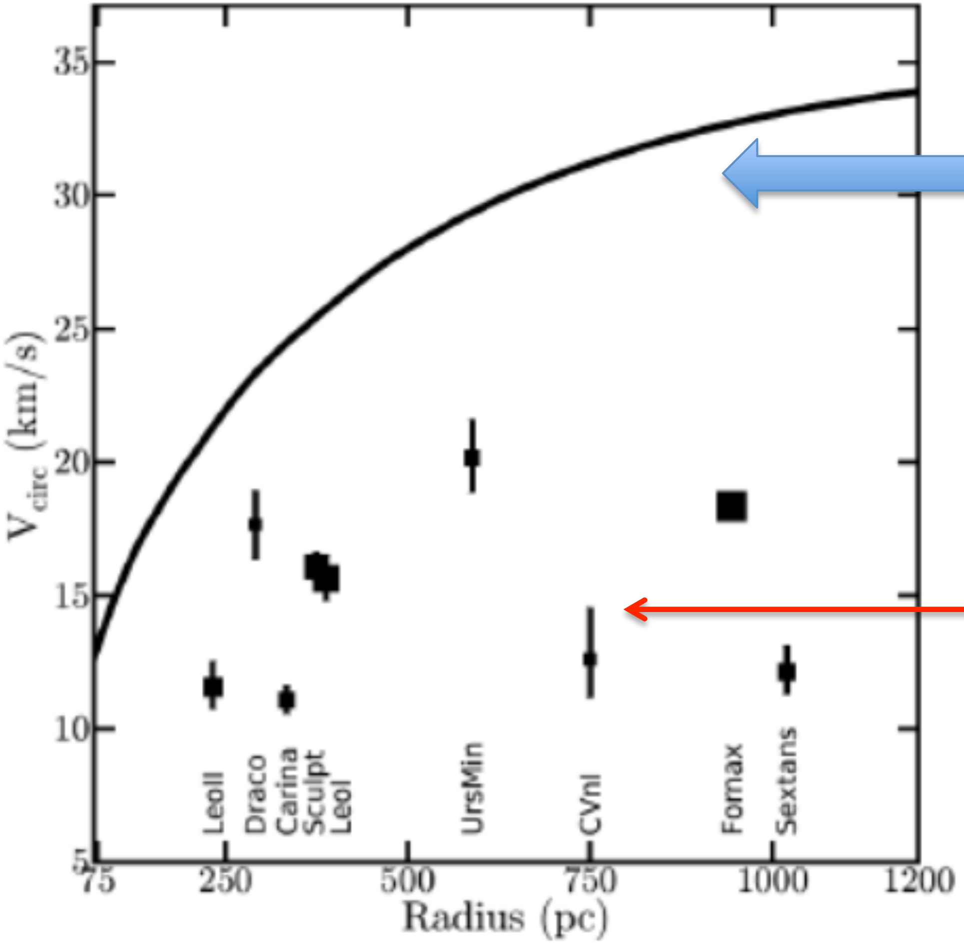


M. Boylan-Kolchin, J.S. Bullock & M. Kaplinghat,
MNRAS 415, L11 (2011);
***ibid.* 422, 1203 (2012)**

Central density of most massive subhaloes (left) too high to host dwarf galaxies of MW (right)

Weinberg et al. 2013, arXiv:1306.0913

(iii) The too-big-to-fail Problem



Continuous curve: rotation curve of typical largest sub-halo of the Milky Way as **simulated by collisionless ΛCDM**

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

$$v_{\rm rot}^2(r) = r\left|\frac{\partial\Phi(r)}{\partial r}\right| = \frac{GM(<r)}{r}$$

M. Boylan-Kolchin, J.S. Bullock & M. Kaplinghat, MNRAS 415, L11 (2011); *ibid.* 422, 1203 (2012)

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

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 signicant range of masses.

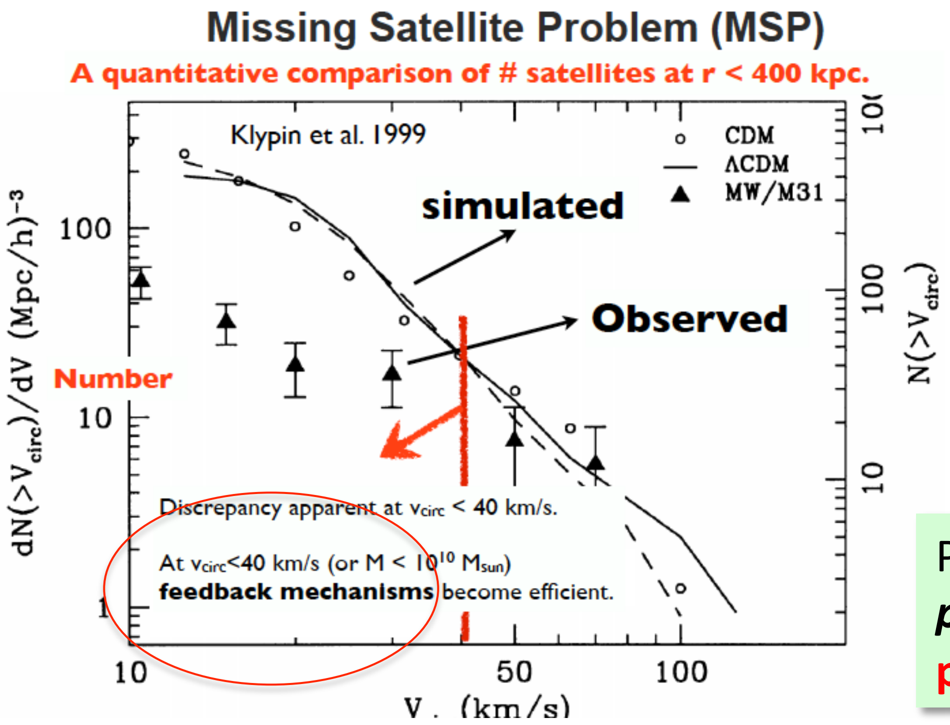
(ii) Galaxy formation in low-mass dark matter halos is **strongly suppressed after re-ionization** → simulated circular velocity function of CDM subhalos in approximate agreement with the observed circular velocity function of Milky Way satellite galaxies.

(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**.

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

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



Missing Satellite Problem (MSP)

A quantitative comparison of # satellites at r < 400 kpc.

Discrepancy apparent at $v_{circ} < 40$ km/s.

At $v_{circ} < 40$ km/s (or $M < 10^{10}\ M_{sun}$) **feedback mechanisms** become efficient.

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 ΛCDM →

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 ΛCDM →

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

Kamionkowski, Liddle astro-ph/9911103; **Yokohama**, astro-ph/0009127; **Zentner, Bullock**, astro-ph/0205216; **Ashoorioon, Krause**, hep-th/0607001; **Kobayashi, Takahashi**, arXiv:1011.3988, ...

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 ΛCDM →

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

$$f\left(\frac{|\vec{a}|}{a_0}\right)\vec{a} = -\vec{\nabla}\Phi_{\rm N}$$

simplest models

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

$a_0 \approx 1.2 \times 10^{-10}$ m s^{-2} **Modified Gravitational acceleration @ galactic scales**

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

Microscopic Physics explanations

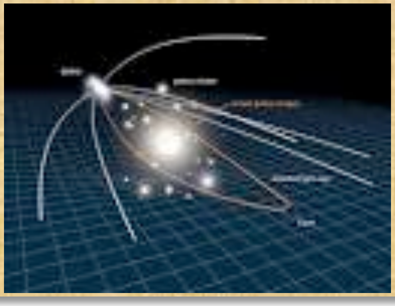
All of the above problems seem that **cannot be entirely solved** by conventional Astrophysics explanations

- discrepancies still remain moreover: case by case studies

CHANGE THE ΛCDM →

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

→ 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 ΛCDM →

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

for our talk

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 ΛCDM →

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

for our talk

(iii) CHANGE the DM properties → include self interactions or assume more than one dominant species

... with non-trivial role in galactic structure

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

σ/m

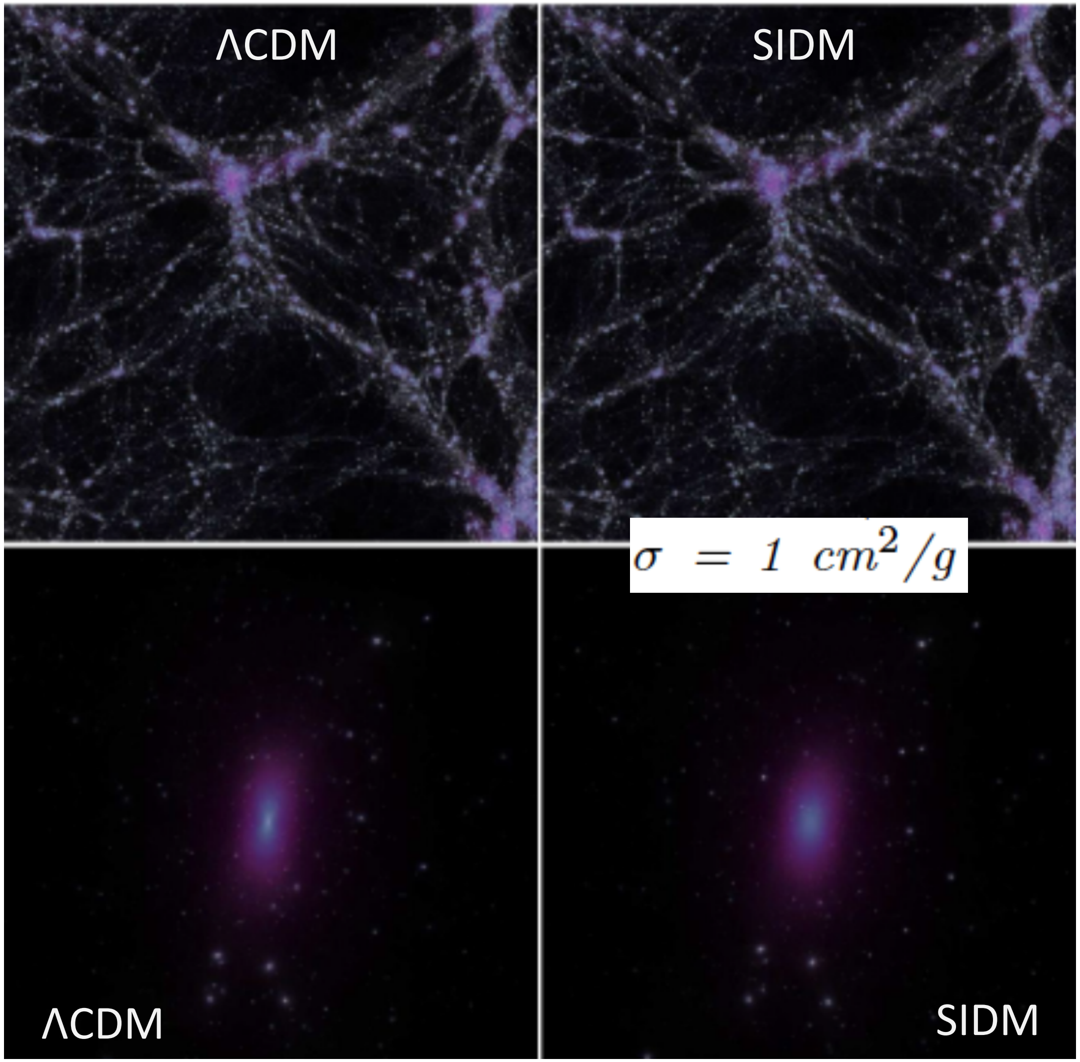
Early days: 10 GeV $c^{-2} \geq m \geq 1$ MeV c^{-2}

in DM haloes with densities $10^{-2} M_\odot/\mathrm{pc}^3$

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

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

M Rocha *et al.* MNRAS 430, 81 (2013)

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

$$\boldsymbol{\sigma/m}$$

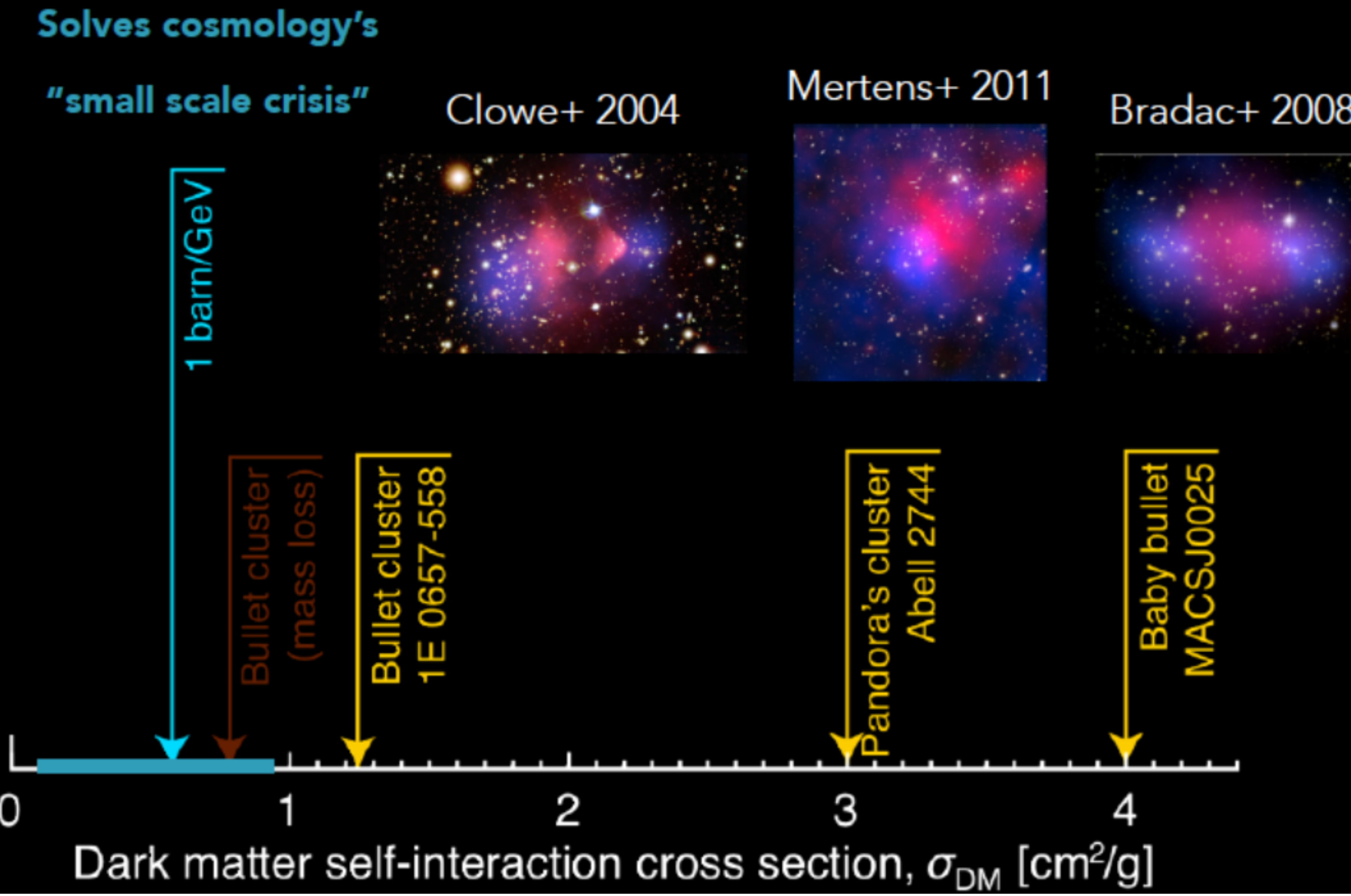
Early days: 10 GeV $c^{-2} \geq m \geq 1$ MeV c^{-2}
in DM haloes with densities $10^{-2} M_\odot/\mathrm{pc}^3$

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

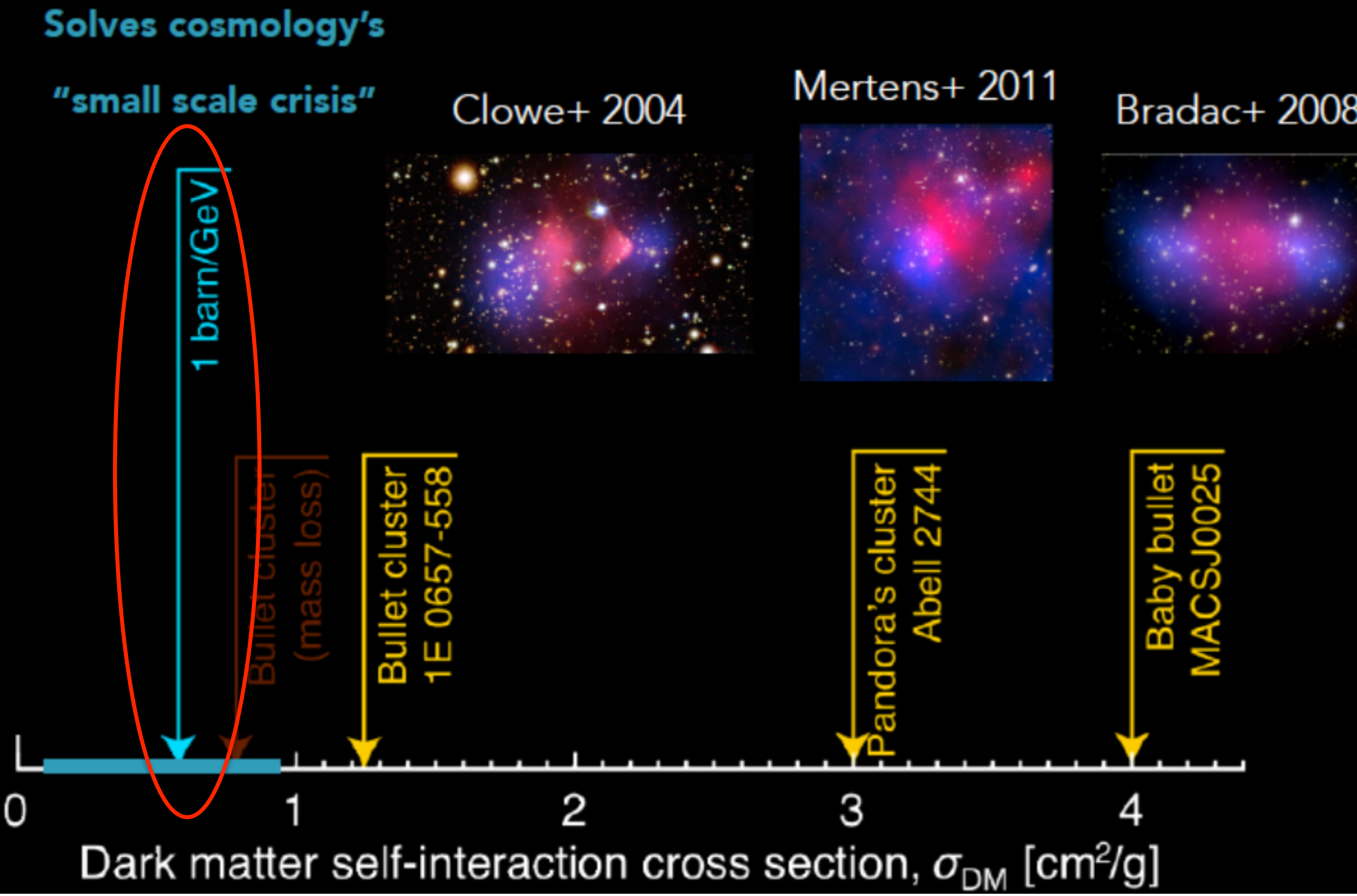
=1 barn/GeV
consistent with all current constraints of GSC

would imply observational effects in the inner haloes

CONSTRAINTS ARE LIMITED

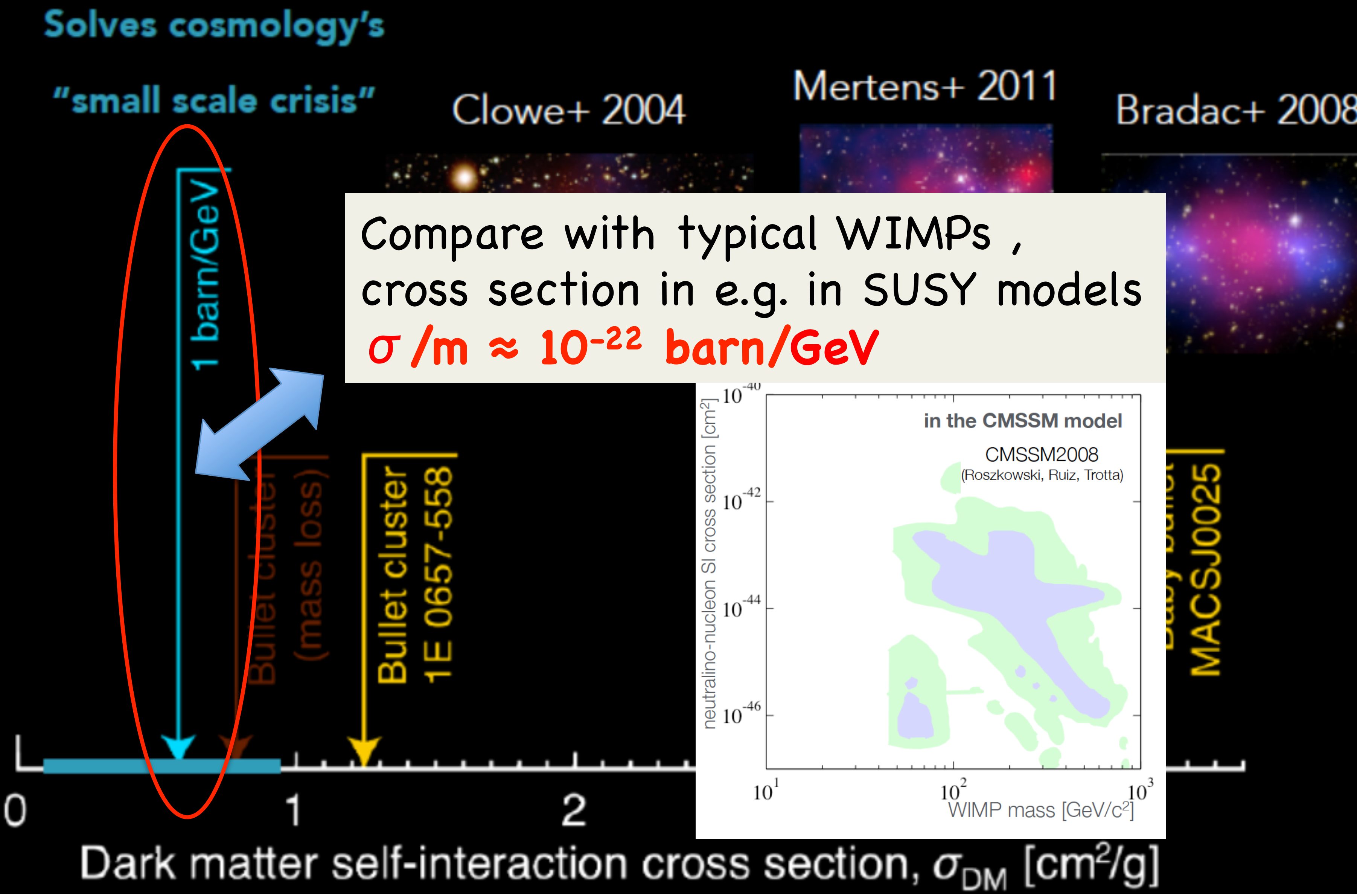


CONSTRAINTS ARE LIMITED



Solves cosmology's "small scale crisis"

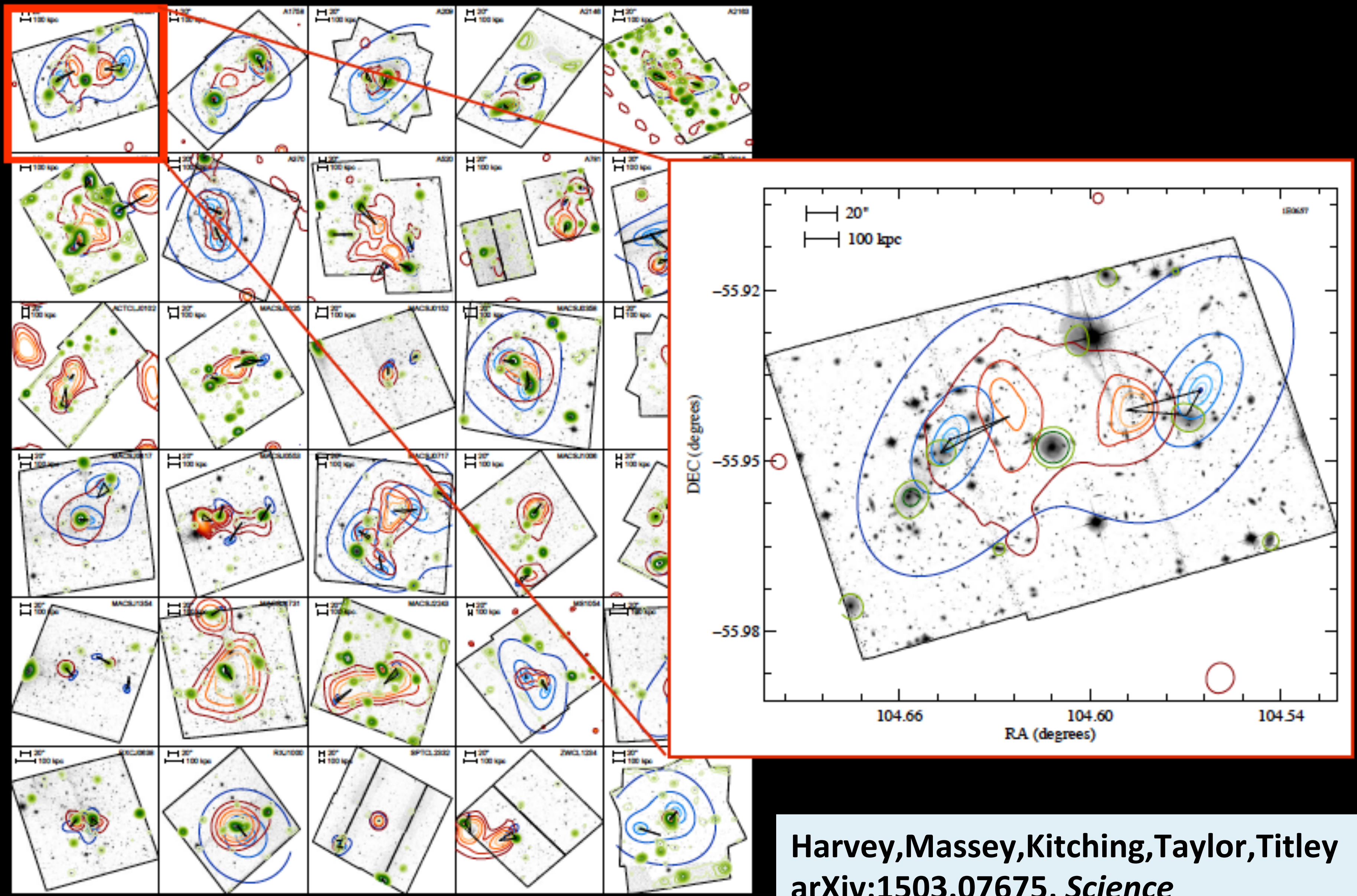
CONSTRAINTS ARE LIMITED



Compare with typical WIMPs , cross section in e.g. in SUSY models

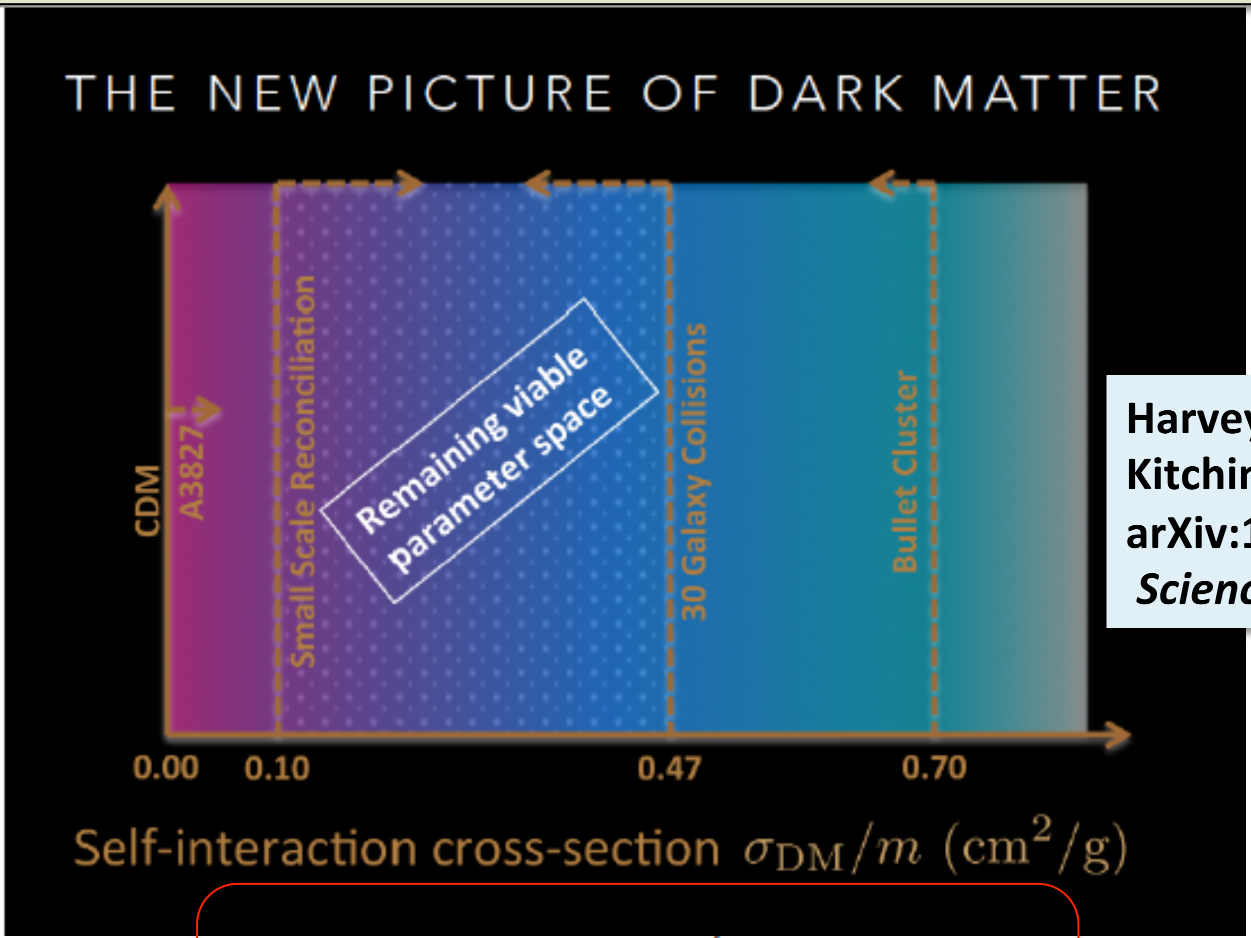
σ /m ≈ 10^{-22} barn/GeV

30 MERGING GALAXY CLUSTERS



Harvey,Massey,Kitching,Taylor,Titley
arXiv:1503.07675, *Science*

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

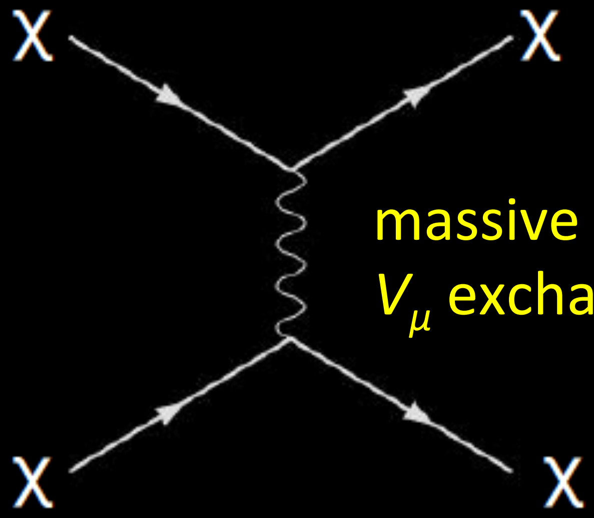


Harvey,Massey, Kitching,Taylor,Titley arXiv:1503.07675, ***Science***

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

OBSERVABLE MANIFESTATION OF SELF-INTERACTIONS IN COLLIDING CLUSTERS

χ = Right-handed neutrino



massive vector
V_μ exchange

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 ~ 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. ν **MSM** (**Shaposhnikov *et al*.**) with three RHN, but augment them with these self-interactions
- among the lightest of the RHN (**quasi stable → DM**)

- Consistency of the **halo-core profile** of dwarf galaxies in Milky Way or large Elliptical → **mass** of lightest RHN in **O(10) keV (WDM)** ← **Cosmological constraints** of ν 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, R… 04, 038 (2016)

- Assume **minimal extension** … **(non-supersymmetric)** … s **(RHN)** **self interacting** vi… **interactions** in…
- Use m… g. ν **MSM** (S… ee RHN, … ese self-interactions
- … the RHN (**quasi stable → DM**)
- C… of the **halo-core profile** of dwarf galaxies in M… Way or large Elliptical → **mass** of lightest RHN in **O(10) keV (WDM)** ← **Cosmological constraints** of ν MSM

Two different approaches yield similar range for WDM mass!

Moreover…..

DM may consist of more than one dominant species !

SM Extension with N extra right-handed neutrinos

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

Minkowski, Fukugita, Yanagida,
Mohapatra, Senjanovic, Lazarides, Shafi, Wetterich,
Sechter, Valle, Paschos, Hill, Luty,
Vergados, de Gouvea…, Liao, Nelson,
Buchmuller, Anisimov, di Bari…, Akhmedov, Rubakov,
Smirnov, Davidson, Giudice, Notari, Raidal,
Riotto, Strumia, Pilaftsis, Underwood,
Asaka, Blanchet, Shaposhnikov, Boyarski, Ruchayskiy…
Hernandez, Giunti...

SM Extension with N extra right-handed neutrinos

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

Right-handed Massive **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

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

Higgs scalar SU(2)
Dual: $\tilde{\phi}_i = \epsilon_{ij}\phi_j^*.$

SM Extension with N extra right-handed neutrinos

$\nu\mathrm{MSM}$ **Asaka, Blanchet, Boyarski, Ruchayskiy, Shaposhnikov**

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

Yukawa couplings
Matrix (*I=1,2,*3)

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

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

$$P_\alpha = \mathrm{diag}(e^{i\alpha_1}, e^{i\alpha_2}, 1)\,, \quad P_\beta = \mathrm{diag}(e^{i\beta_1}, e^{i\beta_2}, 1)$$

Majorana phases

Mixing

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

$c_{Lij} = \cos(\theta_{Lij})$ and $s_{Lij} = \sin(\theta_{Lij})$.

SM Extension with N extra right-handed neutrinos

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

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

Yukawa couplings
Matrix *(I=* 1, …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

νMSM **Asaka, Blanchet, Boyarski, Ruchayskiy, Shaposhnikov**

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

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

Yukawa couplings
Matrix *(I=* 1, …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

$$\nu\mathrm{MSM}$$

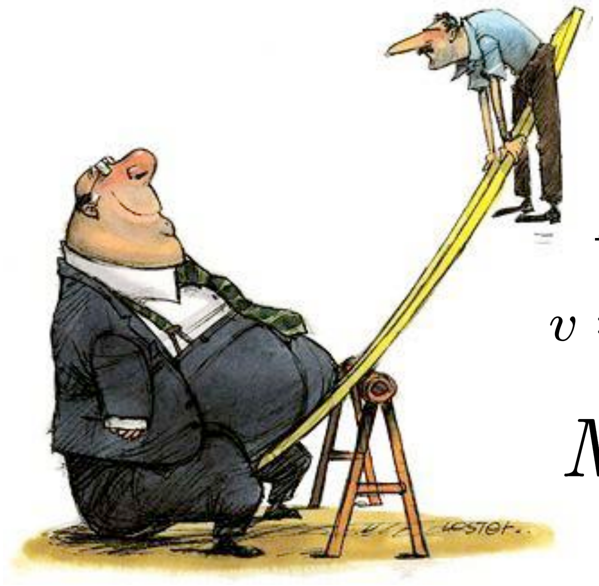
$$L = L_{SM} + \bar{N}_I i\partial_\mu\gamma^\mu N_I - F_{\alpha I}\,\bar{L}_\alpha N_I\tilde{\phi} - \frac{M_I}{2}\,\bar{N}_I^c N_I + \mathrm{h.c.}$$

Yukawa couplings Matrix (N=2 or 3)

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

Minkowski, Fugujita, Yanagida, Lazarides, Shafi, Wetterich, Sechter, Valle, Mohapatra, Senjanovic, ...

NB: Upon Symmetry Breaking
<Φ> = v ≠ 0 → Dirac mass term



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

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

$$M_D \ll M_I$$

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

mass of lightest of N_I
by agreement
with Cosmological data

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

Light Neutrino Masses through see saw

$$\boxed{m_\nu = -M^D \frac{1}{M_I} [M^D]^T .}$$

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

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

$$M_D \ll M_I$$

$N \rightarrow H\,\nu$

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

Light Neutrino Masses through see saw

$$m_\nu = -M^D \frac{1}{M_I}[M^D]^T\,.$$

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

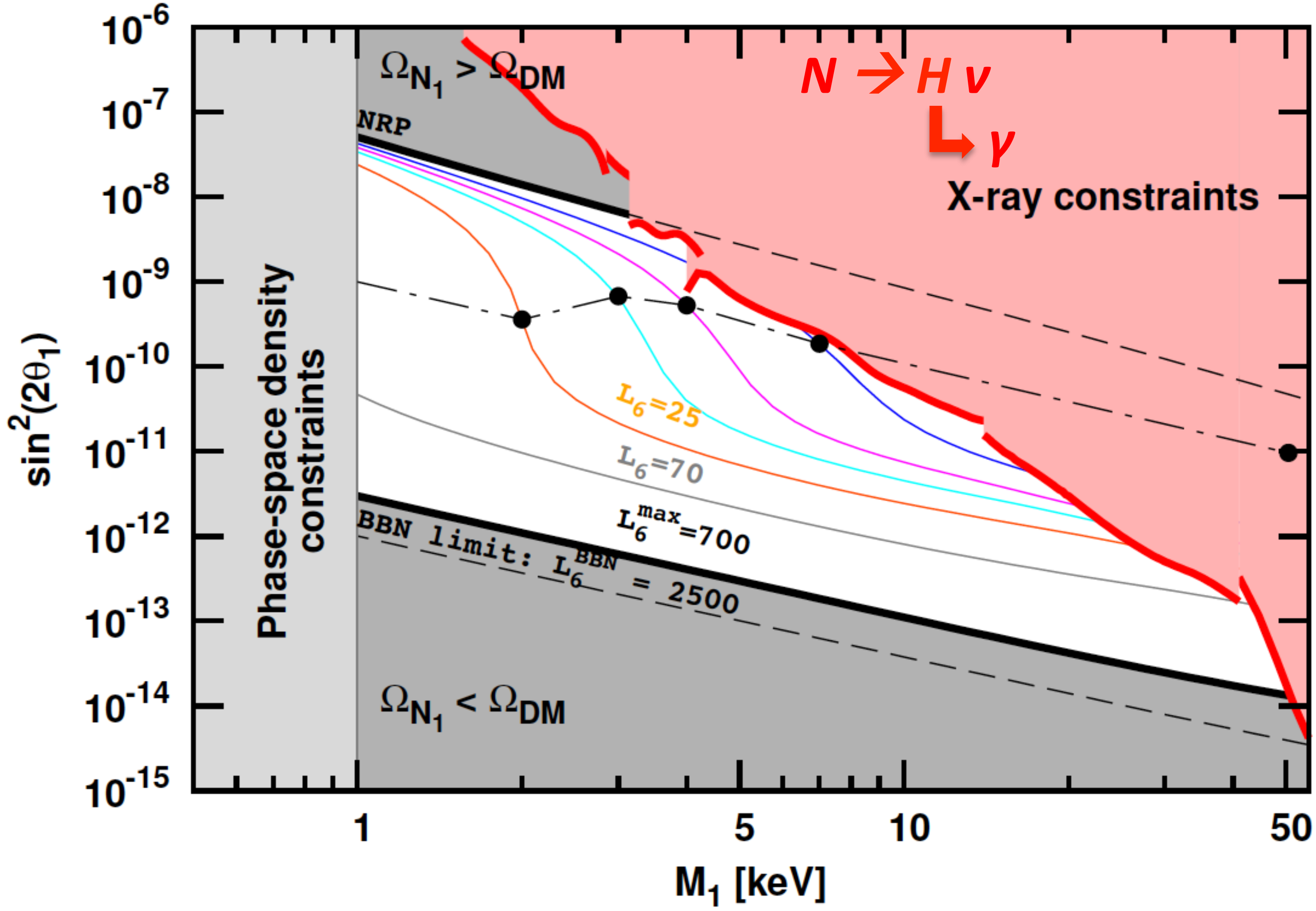
$$v = \langle\phi\rangle \sim 175\ \text{GeV} \qquad M_D \ll M_I$$

$F_{\alpha 1} \approx 10^{-10} \rightarrow m_\nu^2 \approx 10^{-3}\,\text{eV}^2$

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

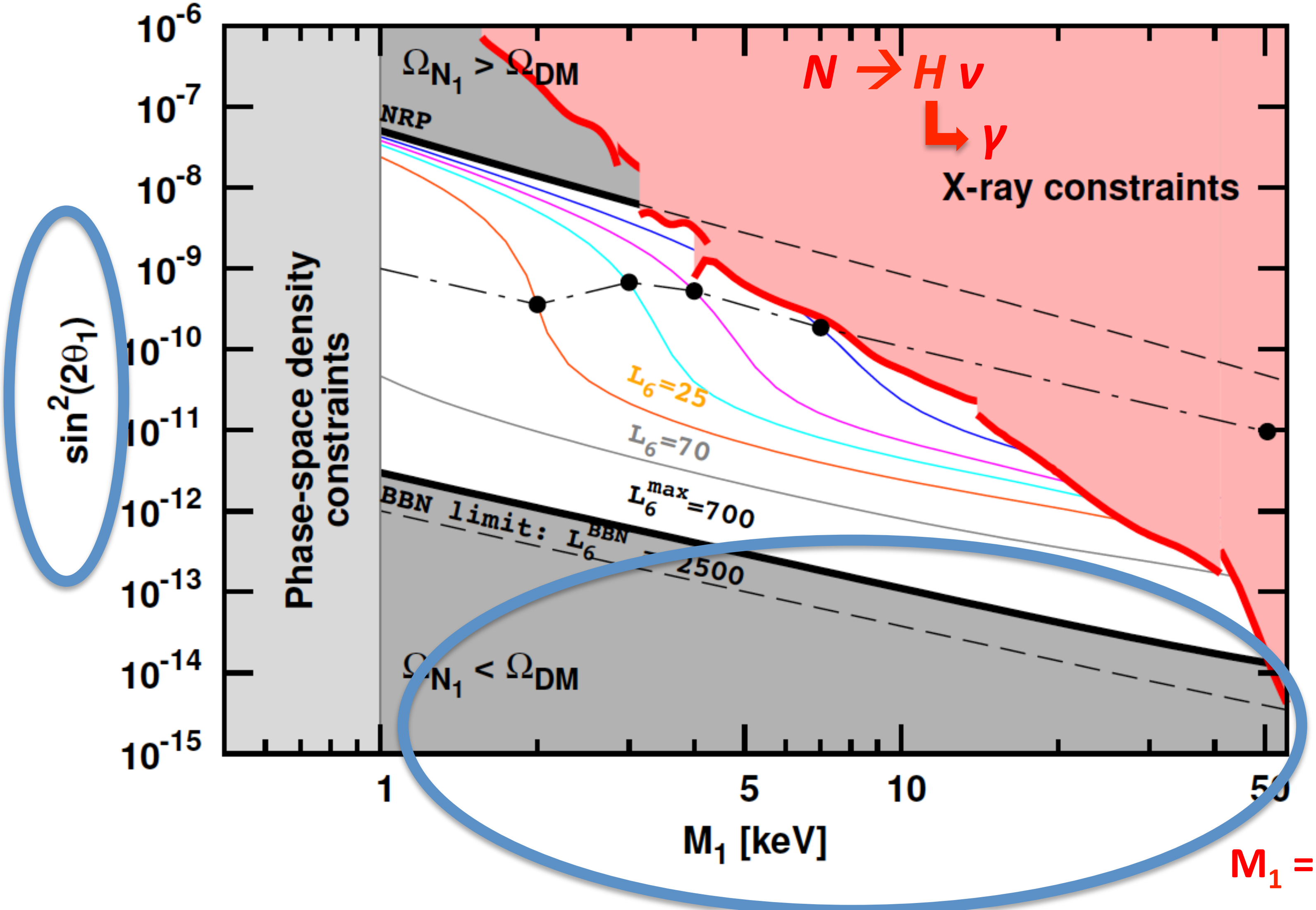
MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS



νMSM

Boyarski, Ruchayskiy, Shaposhnikov…

MODEL CONSISTENT WITH BBN, STRUCTURE FORMATION DATA IN THE UNIVERSE & ALL OTHER ASTROPHYSICAL CONSTRAINTS

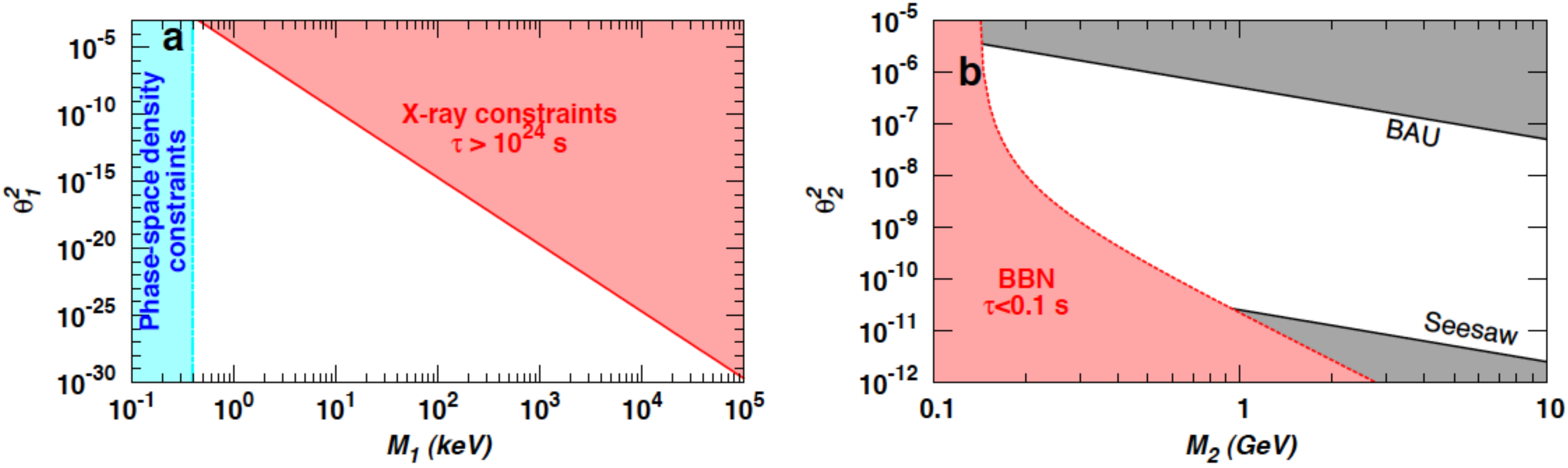


M_1 = O(10) keV

More than one sterile neutrino needed to reproduce Observed oscillations

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…



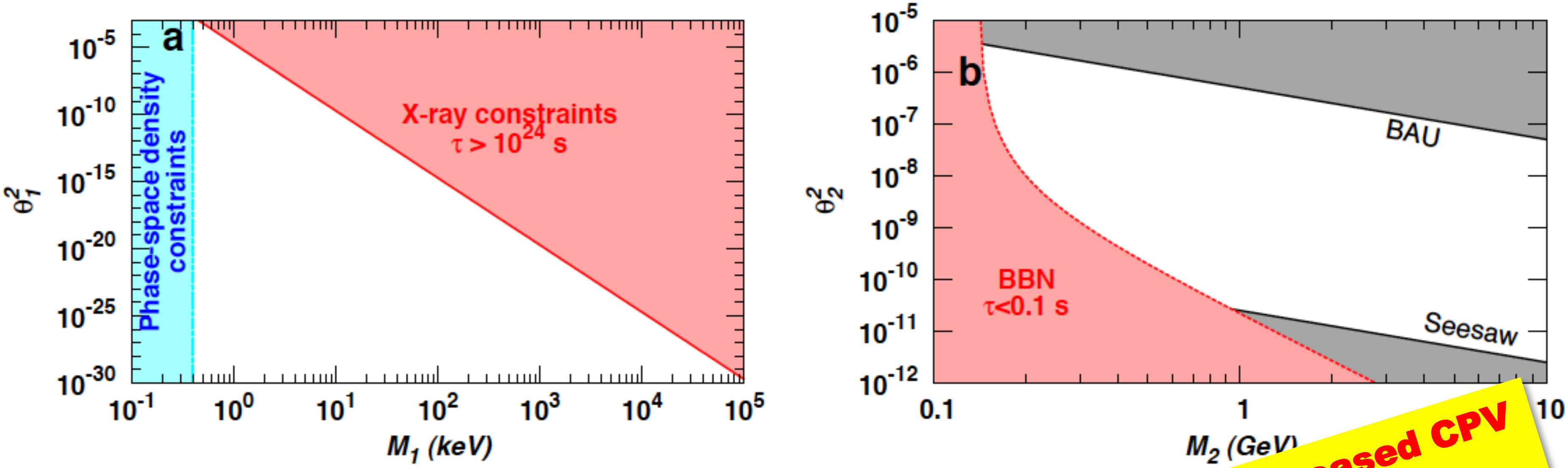
Constraints on two heavy degenerate singlet neutrinos

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

νMSM

Boyarski, Ruchayskiy, Shaposhnikov…



Constraints on two heavy degenerate singlet neutrinos

Increased CPV
Pilaftsis,
Underwood…

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

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

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

Light Neutrino Masses through see saw

$$m_\nu = -M^D \frac{1}{M_I}[M^D]^T \, .$$

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

$$v = \langle\phi\rangle \sim 175 \text{ GeV} \qquad M_D \ll M_I$$

$F_{\alpha 1} \approx 10^{-10}$ → $m_\nu^2 \approx 10^{-3}\,\text{eV}^2$

kingvector.blogspot.com

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

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

Light Neutrino Masses through see saw

$$m_\nu = -M^D \frac{1}{M_I} [M^D]^T .$$

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

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

$$M_D \ll M_I$$

~~$F_{\alpha 1} \approx 10^{-10}$~~ → $m_\nu^2 \approx 10^{-3}\ \mathrm{eV}^2$

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

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

ν=ν(r) λ = λ(r)

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{N_{R\,1}} + \mathcal{L}_V + \mathcal{L}_I$$

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

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

$$\nabla_{\mu} = \partial_{\mu} - \tfrac{i}{8}\,\omega_{\mu}^{ab}[\gamma_a, \gamma_b]$$

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

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

Place the νMSM in **curved space time** $g_{\mu\nu} = \mathrm{diag}(e^{\nu}, -e^{\lambda}, -r^2, -r^2 \sin^2\varphi)$

ν=ν(r) λ = λ(r)

$$\mathcal{L} = \mathcal{L}_{GR} + \mathcal{L}_{N_{R1}} + \mathcal{L}_V + \boxed{\mathcal{L}_I}$$

$$\mathcal{L}_{GR} = -\frac{R}{16\pi G}, \; \mathcal{L}_{N_{R1}} = i\,\overline{N}_{R1}\gamma^{\mu}\nabla_{\mu}N_{R1} - \frac{1}{2}m\,\overline{N^c}_{R1}N_{R1},$$

$$\mathcal{L}_V = -\frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_V^2 V_{\mu}V^{\mu}, \; \boxed{\mathcal{L}_I = -g_V V_{\mu}J_V^{\mu} = -g_V V_{\mu}\overline{N}_{R1}\gamma^{\mu}N_{R1}}$$

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

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

Measure of Strength of self Interactions

$$\boxed{C_V \equiv g_V^2 / m_V^2}$$

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

effective interactions in galactic medium

r_m = core-halo matching point = **r_c** + δr

core radius

inter-particle mean distance l

at temperature T

de-Broglie wavelength $\lambda_B = \frac{\hbar}{\sqrt{2\pi m k_B T}}$

Right-handed keV Neutrinos with vector self-interactions & galactic structure

sterile ν mass

Milky Way ($M_c = 4.4 \times 10^6 M_\odot$)

m (keV)	$\overline{C}_0$	θ_0	β_0	r_c (pc)	δr (pc)	$\theta(r_m)$
47	2	3.70×10^3	1.065×10^{-7}	6.2×10^{-4}	2.1×10^{-4}	-29.3
	10^{14}	3.63×10^3	1.065×10^{-7}	6.2×10^{-4}	2.2×10^{-4}	-29.3
	10^{16}	2.8×10^3	1.065×10^{-7}	6.3×10^{-4}	2.4×10^{-4}	-29.3
350	1	2.40×10^6 (†)	1.431×10^{-7}	1.3×10^{-6}	6.7×10^{-7}	-37.3
	10^{14}	1.27×10^5	1.104×10^{-7}	5.9×10^{-6}	9.4×10^{-7}	-37.3
	4.5×10^{18}	1.7×10^1	1.065×10^{-7}	5.9×10^{-4}	2.0×10^{-4}	-37.3
Elliptical ($M_c^{cr} = 2.3 \times 10^8 M_\odot$)						
47	2	1.76×10^5 (†)	1.7×10^{-6}	7.9×10^{-5}	3.9×10^{-5}	-31.8
	10^{14}	5.8×10^4	1.4×10^{-6}	1.4×10^{-4}	4.8×10^{-5}	-31.8
	10^{16}	1.5×10^4	1.3×10^{-6}	3.0×10^{-4}	7.0×10^{-5}	-31.8
Large Elliptical ($M_c = 1.8 \times 10^9 M_\odot$)						
47	10^{16}	1.02×10^4	3.0×10^{-6}	3.8×10^{-4}	1.8×10^{-5}	-32.8

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

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

at the core (β_0, θ_0)

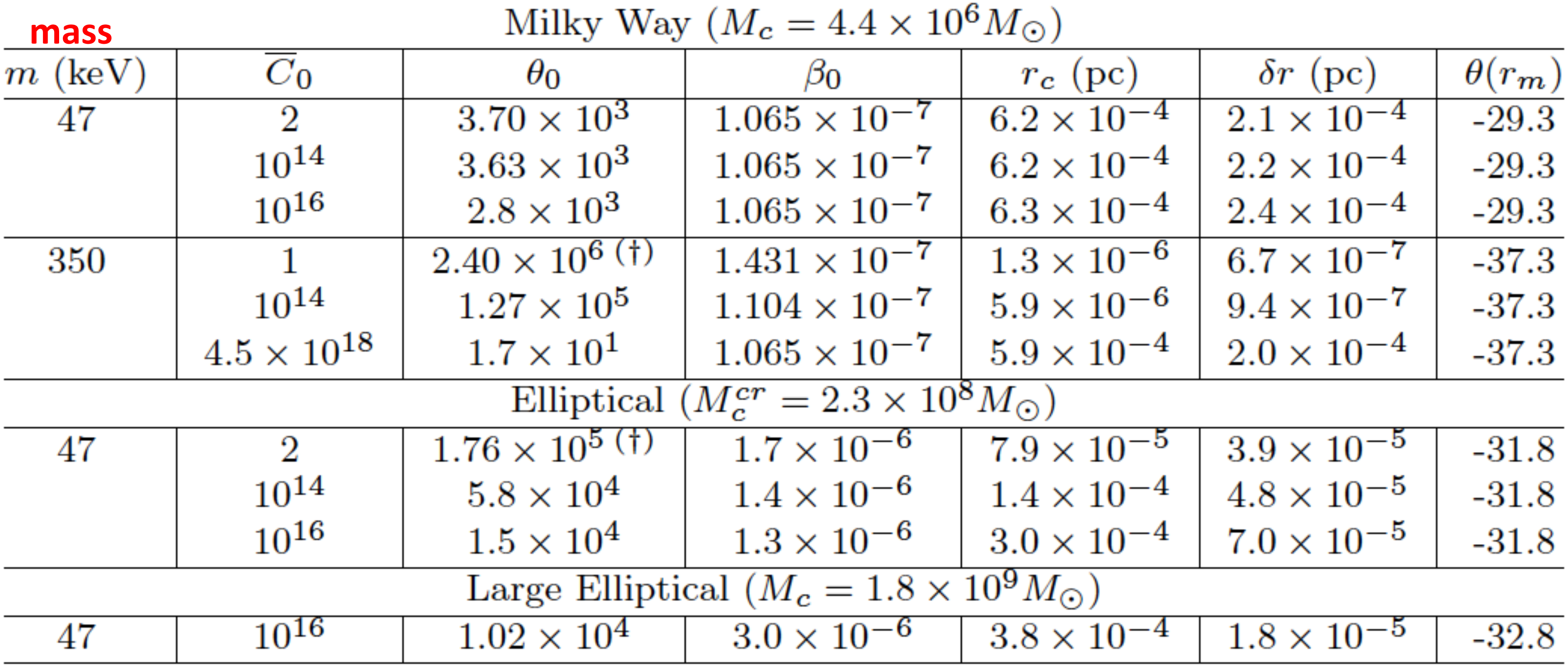
No solution for

$m < 47$ keV$/c^2$

gravitational collapse → $m > 350$ keV$/c^2$

Right-handed keV Neutrinos with vector self-interactions & galactic structure

sterile ν mass



Milky Way ($M_c = 4.4 \times 10^6 M_\odot$)

m (keV)	$\overline{C}_0$	θ_0	β_0	r_c (pc)	δr (pc)	$\theta(r_m)$
47	2	3.70×10^3	1.065×10^{-7}	6.2×10^{-4}	2.1×10^{-4}	-29.3
	10^{14}	3.63×10^3	1.065×10^{-7}	6.2×10^{-4}	2.2×10^{-4}	-29.3
	10^{16}	2.8×10^3	1.065×10^{-7}	6.3×10^{-4}	2.4×10^{-4}	-29.3
350	1	2.40×10^6 (†)	1.431×10^{-7}	1.3×10^{-6}	6.7×10^{-7}	-37.3
	10^{14}	1.27×10^5	1.104×10^{-7}	5.9×10^{-6}	9.4×10^{-7}	-37.3
	4.5×10^{18}	1.7×10^1	1.065×10^{-7}	5.9×10^{-4}	2.0×10^{-4}	-37.3

Elliptical ($M_c^{cr} = 2.3 \times 10^8 M_\odot$)

m (keV)	$\overline{C}_0$	θ_0	β_0	r_c (pc)	δr (pc)	$\theta(r_m)$
47	2	1.76×10^5 (†)	1.7×10^{-6}	7.9×10^{-5}	3.9×10^{-5}	-31.8
	10^{14}	5.8×10^4	1.4×10^{-6}	1.4×10^{-4}	4.8×10^{-5}	-31.8
	10^{16}	1.5×10^4	1.3×10^{-6}	3.0×10^{-4}	7.0×10^{-5}	-31.8

Large Elliptical ($M_c = 1.8 \times 10^9 M_\odot$)

m (keV)	$\overline{C}_0$	θ_0	β_0	r_c (pc)	δr (pc)	$\theta(r_m)$
47	10^{16}	1.02×10^4	3.0×10^{-6}	3.8×10^{-4}	1.8×10^{-5}	-32.8

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

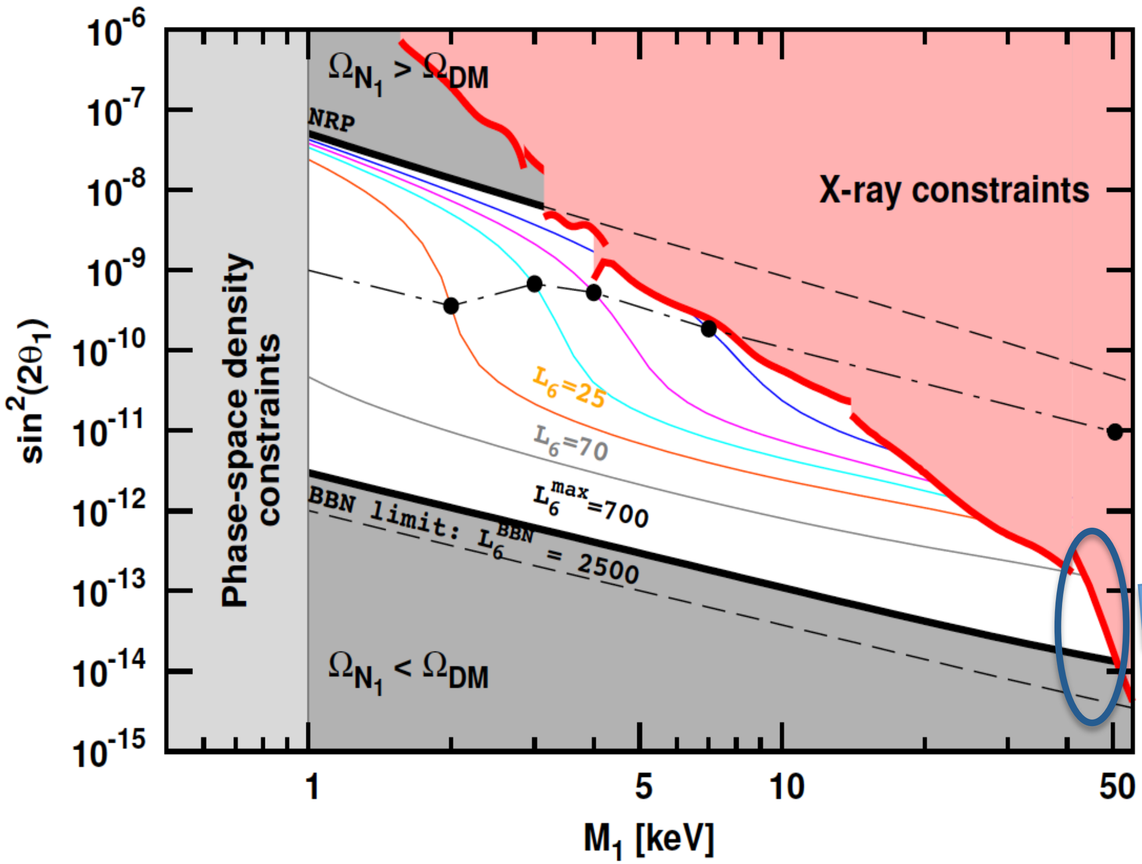
$$\theta \equiv \mu/(k_B T)$$

at the core (β_0, θ_0)

Allowed WDM mass range

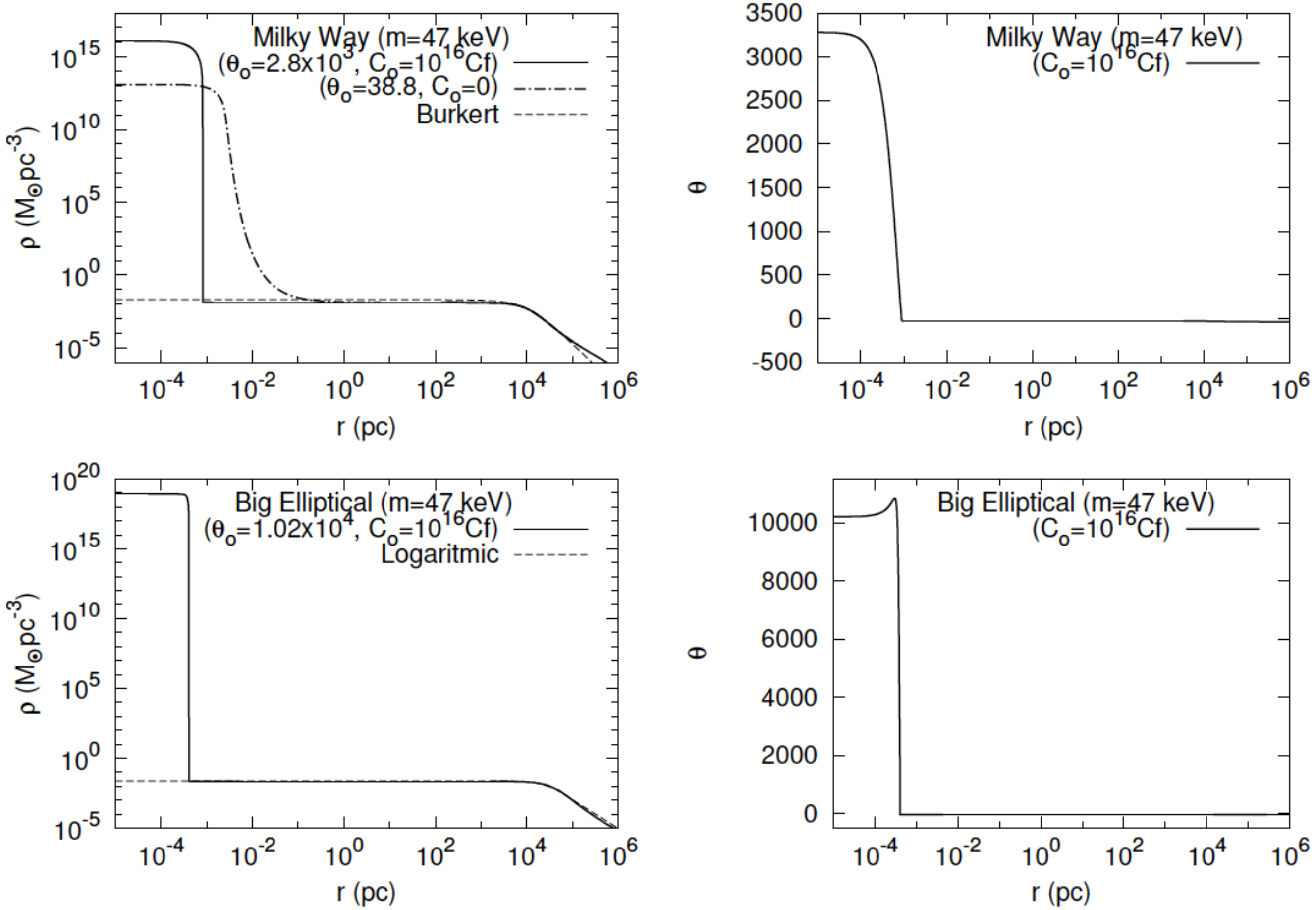
47 keV c^{-2} ≤ m ≤ 350 keV c^{-2}

Right-handed keV Neutrinos with vector self-interactions & galactic structure



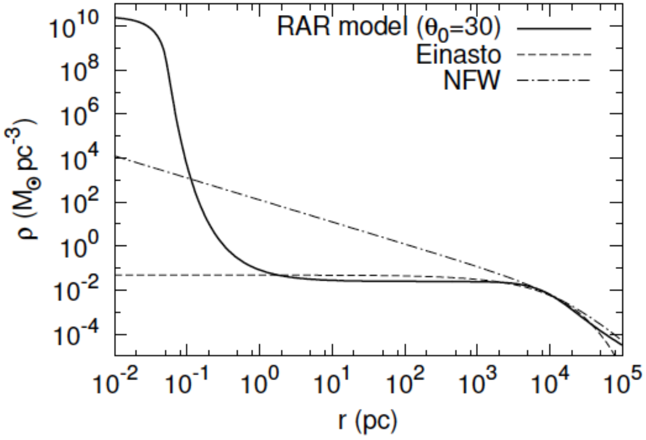
If **mixing** with observable sector is **non zero** (νMSM)
→ **narrow window of allowed WDM mass!**

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



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

Interactions make inner Core more compact and increase central degeneracy compared to non-interacting case



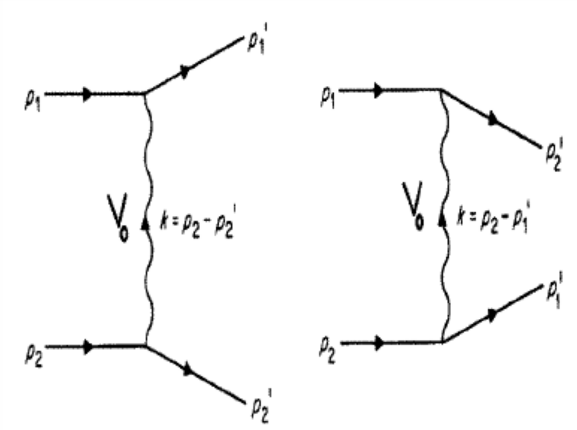
Non interacting right-handed neutrino case with m = O(10) keV

Ruffini, Arguelles, Rueda, MNRAS (2015)

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 ≈ 47 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)

$$m \in (47, 350)\ \mathrm{keV}$$

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

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

$$\overline{C}_V = \left(\frac{g_V}{m_V}\right)^2 G_F^{-1} \Rightarrow \boxed{\overline{C}_V \in (2.6 \times 10^8, 7 \times 10^8)}$$

to resolve issues of small-scale cosmology crisis

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

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

Conclusions-Outlook – so far

- At galactic scales **ΛCDM 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 σ/m :

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

- We have considered the role of **the lightest of the right-handed neutrinos in νMSM** extensions of the standard model, and **added appropriately strong vector interactions** in the dark sector among the neutrinos → **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** → **search** for it in **particle physics** and neutrino **oscillation** experiments

Conclusions – Outlook

- At galactic scales ΛCDM 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 σ/m :

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

- We have considered the role of the lightest of the right-handed neutrinos in νMSM extensions of the standard model, and added appropriately strong vector interactions in the dark sector among the neutrinos → 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 → **search** for it in particle physics and neutrino oscillation experiments (eg **SHiP**) ...

SHiP
Search for Hidden Particles

Conclusions – Outlook

- At galactic scales **ΛCDM 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 σ/m :

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

- We have considered the role of **the lightest of the right-handed neutrinos in νMSM** extensions of the standard model, and **added appropriately strong vector interactions** in the dark sector among the neutrinos → **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** → coupling with **axions** may lead to **Mass generation for Right Handed Neutrinos**

THANK YOU !

SPARES

Dark Matter

DARK MATTER (DM):

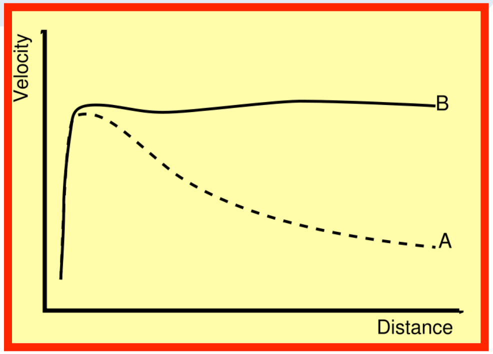
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,

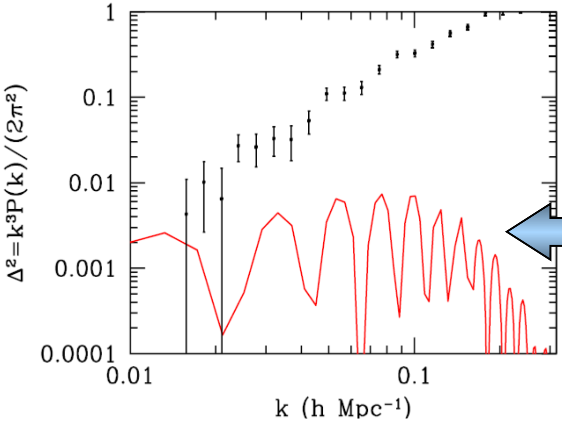
gravitational lensing

growth of structure



TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)



Baryon-only Models, without Dark Matter

INDIRECT SEARCHES:

collider (LHC & beyond) searches

photons, neutrinos,

matter-antimatter asymmetries

(electron-positron, proton-antiproton)

Dark Matter

DARK MATTER (DM):

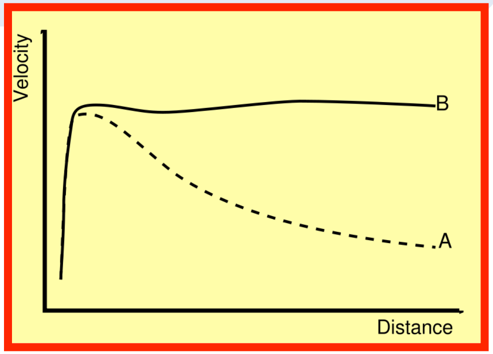
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,

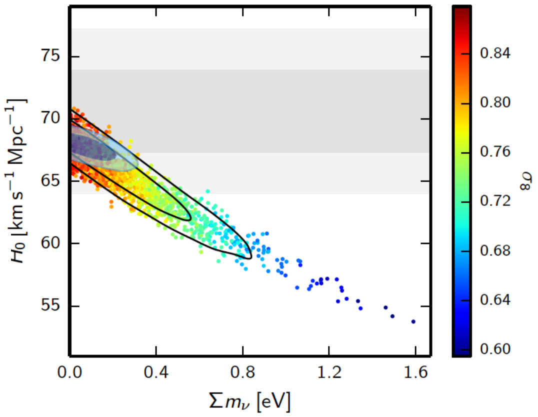
gravitational lensing

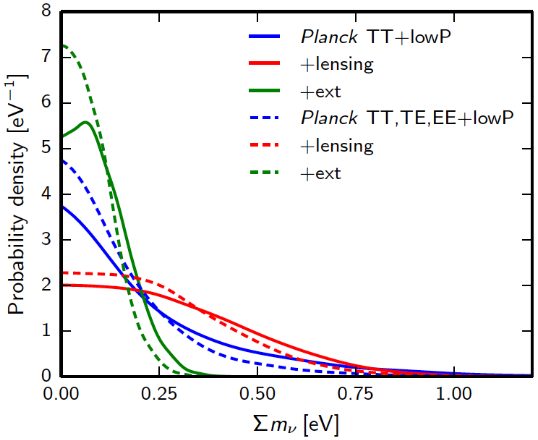
growth of structure



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

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)





$$\left.\begin{array}{l}\sum m_\nu < 0.23\ \mathrm{eV}\\ \Omega_\nu h^2 < 0.0025\end{array}\right\}\quad 95\%,\ \textit{Planck}\ \mathrm{TT{+}lowP{+}lensing{+}ext.}$$

Dark Matter

DARK MATTER (DM):

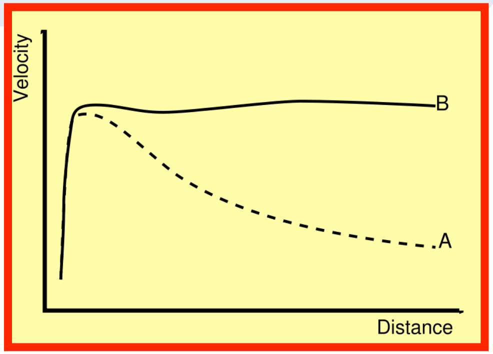
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,

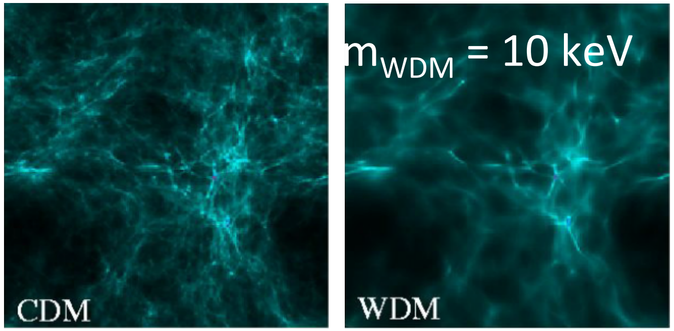
gravitational lensing

growth of structure



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

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)

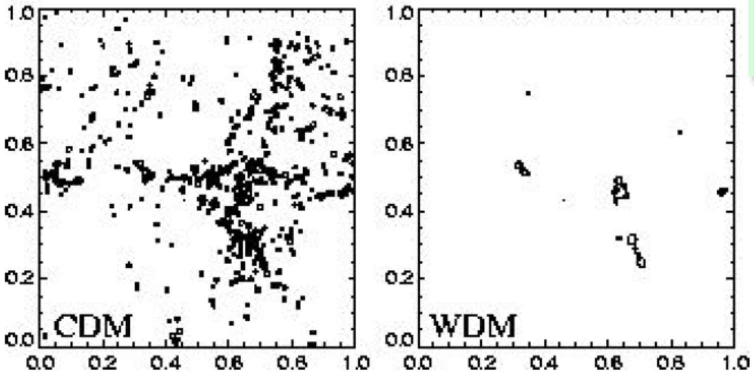


WMAP,

Planck Coll 2015

Yoshida *et al.*
astro-ph/0303622

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



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

Re-ionization of the Universe @ redshift z=20

numerical N-body simulations based on **warm** & **ΛCDM** models

Dark Matter

DARK MATTER (DM):

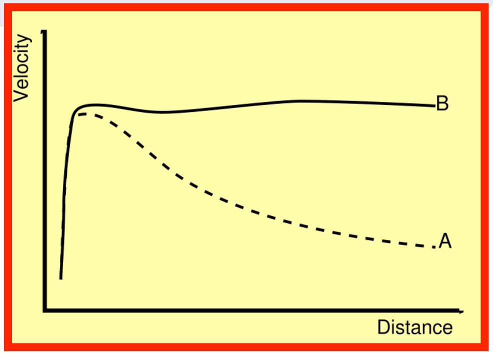
CURRENT EVIDENCE

Arguments in Favour

Rotational Curves of galaxies,

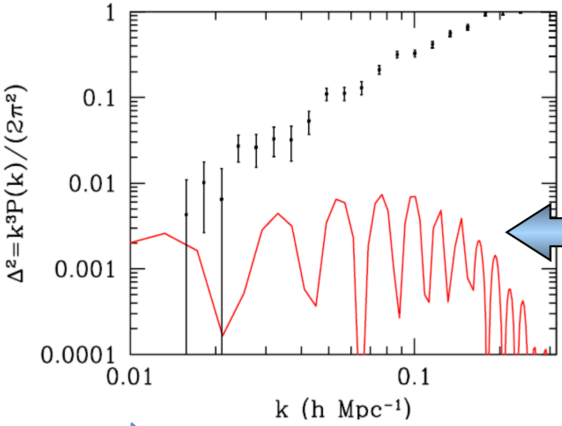
gravitational lensing

growth of structure



TYPES OF DM: hot, warm, cold

ASTROPHYSICAL CONSTRAINTS (MODEL INDEPENDENT)



Baryon-only Models, without Dark Matter

INDIRECT SEARCHES:

collider (LHC & beyond) searches

photons, neutrinos,

matter-antimatter asymmetries

(electron-positron, proton-antiproton)

Compatible with all current data !

m ≥ 100 keV

100 keV ≤ $m_{WDM} = m_{CDM}$

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)

THEORETICAL SCENARIOS

SUPERSYMMETRY ***neutralino***

SUPERGRAVITY ***gravitino*** **(*if sufficiently light*)**

AXIONS ***(standard QCD or stringy)***

STERILE NEUTRINOS

…

Dark Matter

e.g. typical thermal WIMPs
CMB-observations-compatible
DM relic abundance

$$\Omega_\chi \simeq \frac{0.1\,\mathrm{pb}\cdot \mathrm{c}}{\langle\sigma(\chi\chi \to \mathrm{SM}\, v\rangle} \simeq 0.22$$

occurs cross sections of
weak-interactions type

$$\sigma(\chi\chi \to \mathrm{SM}\, v\rangle) \simeq 3 \cdot 10^{-26} \mathrm{cm}^3\, \mathrm{s}^{-1}$$

``WIMP miracle"

$$m_\chi \sim O(100\ \mathrm{GeV} - \mathrm{TeV})$$

THEORETICAL SCENARIOS

SUPERSYMMETRY ***neutralino***

SUPERGRAVITY ***gravitino** (if sufficiently light)*

AXIONS ***(standard QCD or stringy)***

STERILE NEUTRINOS

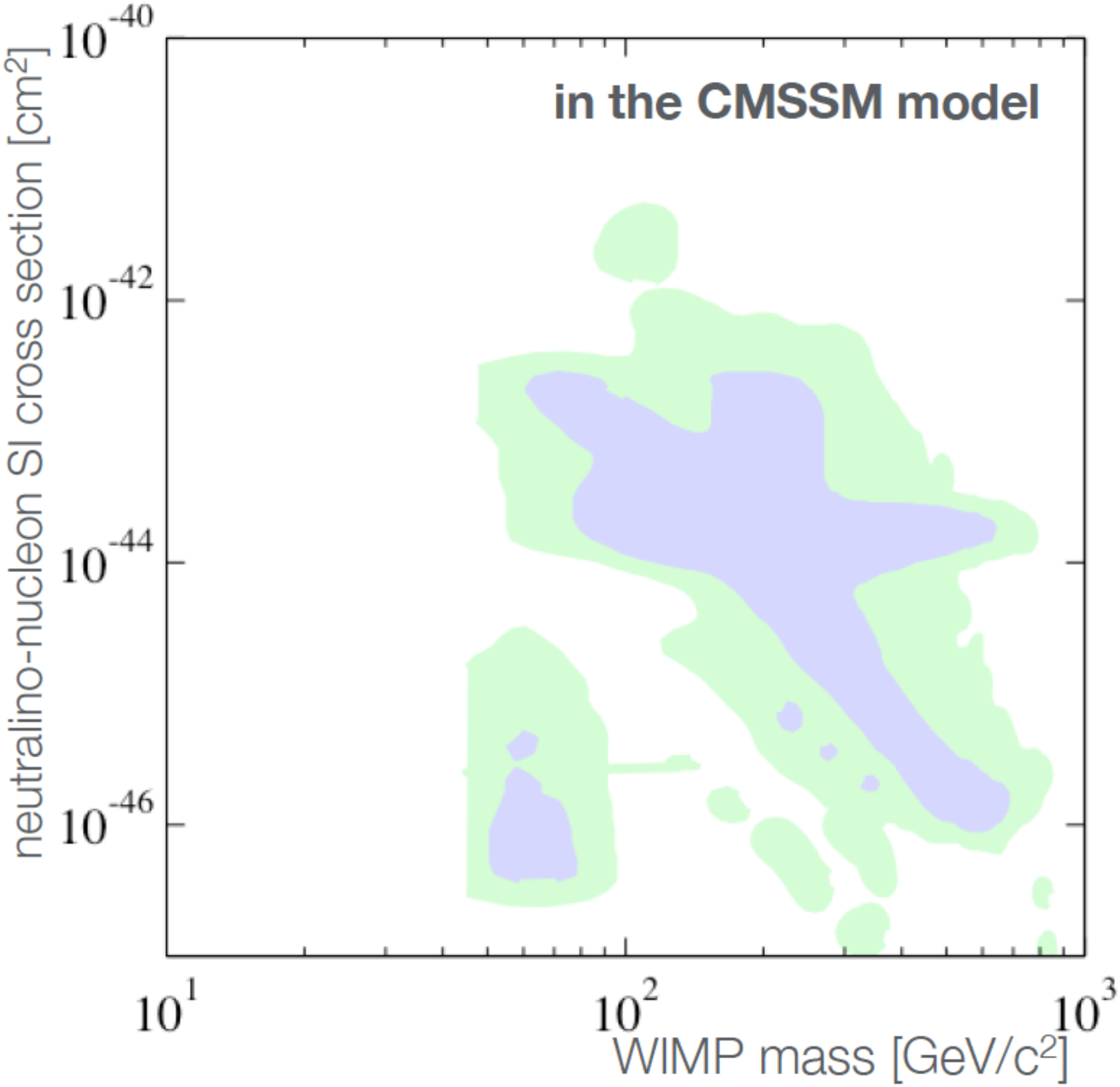
…

Theoretical Model dependence

in deriving bounds in experimental searches

- Predictions from supersymmetry [10^{-8} pb = 10^{-44} cm^2]:

$\sigma/m \approx 10^{-22}$ barn/GeV



CMSSM2008
(Roszkowski, Ruiz, Trotta)

Dark Matter

e.g. typical **thermal WIMPs**
CMB-observations-compatible
DM relic abundance

$$\Omega_\chi \simeq \frac{0.1\,\mathrm{pb}\cdot c}{\langle \sigma(\chi\chi \to \mathrm{SM}\, v)\rangle} \simeq 0.22$$

occurs cross sections o
weak-interaction

$\sigma(\chi\chi \to \mathrm{SM}$

``WIMP miracle”

$$m_\chi \sim O(100\ \mathrm{GeV} - \mathrm{TeV})$$

THEORETICAL SCEN

SUPE *lino*

ITY ***gravit***

ht)

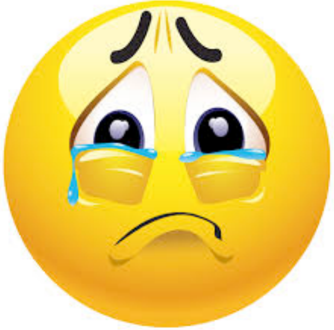
XIONS ***(standard QCD o***

STERILE NEUTRINOS

…

Theoretical Model dependence

in deriving bounds in experimental searches



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

Dark Matter

DARK MATTER (DM):

CURRENT EVIDENCE

Arguments in Favour

TYPES OF DM: hot, warm

ASTROPHYSICA

(MODEL I

INDIREC

collider (LH searches

photons, neu s,

matter-antimatter asymmetries

(electron-positron, proton-antiproton)

THEOR ARIOS

tralino

TY ***gravitino (if sufficiently light)***

ONS *(standard QCD or stringy)*

STERILE NEUTRINOS This talk

…

Theoretical Model dependence

in deriving bounds in experimental searches

Moreover…..

DM may consist of more than one dominant species !