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Direct detection, PTOLEMY and the clustering of relic neutrinos

Based on JCAP 09 (2017) 034, in collaboration with P. F. de Salas, J. Lesgourgues, S. Pastor

11/12/2017 - PTOLEMY Kick-off meeting - LNGS, Assergi (IT)

1. Direct detection of cosmic neutrino background
    - Proposed methods
    - PTOLEMY
2. Relic neutrino clustering in the Milky Way
    - N-one-body simulations
    - Dark Matter in the MW
    - Baryons in the MW
3. The local neutrino overdensity
    - Results for (nearly) minimal neutrino masses
    - Results for non-minimal neutrino masses: 150 meV
    - Beyond the Milky Way
4. Beyond the standard: light sterile neutrinos
5. Conclusions

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Direct detection - proposed methods - Stodolsky effect

How to directly detect non-relativistic neutrinos?

Stodolsky effect

[Stodolsky, 1974][Duda et al., 2001]

(only if there is lepton asymmetry)

energy splitting of e^- spin states due to coherent scattering with relic neutrinos

↓

torque on e^- in lab rest frame

↓

use a ferromagnet to build detector

↓

measure torque with a torsion balance

expected $a_\nu \simeq \mathcal{O}(10^{-26})$ cm/s^2 ⟷ $a_{\rm exp} \simeq \mathcal{O}(10^{-12})$ cm/s^2

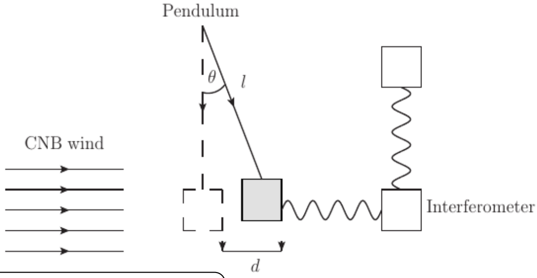
Direct detection - proposed methods - at interferometers

How to directly detect non-relativistic neutrinos?

At interferometers

[Domcke et al., 2017]

coherent scattering of relic ν on a pendulum $\longrightarrow$ measure oscillations at interferometers



expected
$10^{-33} \lesssim a_\nu/(\text{cm/s}^2) \lesssim 10^{-27}$ $\longleftrightarrow$ $a_{\text{LIGO/Virgo}} \simeq 10^{-16}\ \text{cm/s}^2$

Direct detection - proposed methods - Capture (I)

How to directly detect non-relativistic neutrinos?

Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today → a process without energy threshold is necessary

(anti)neutrino capture on electron-capture-decaying nuclei

[Cocco et al., 2009]

electron capture (EC): $e^- + A^+ \rightarrow \nu_e + B^*$

(e^- from inner level)

$$\boxed{\bar{\nu}_e + A \rightarrow B^- + e^+}$$

must have very specific Q value in order to avoid EC background and have no threshold

$$\boxed{\bar{\nu}_e + e^- + A^+ \rightarrow B}$$

specific energy conditions required

but Q value depends on ionization fraction!

process useful only “if specific conditions on the Q-value are met or significant improvements on ion storage rings are achieved”

A viable method - Capture (II)

[Long et al., JCAP 08 (2014) 038]

How to directly detect non-relativistic neutrinos?

Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today → a process without energy threshold is necessary

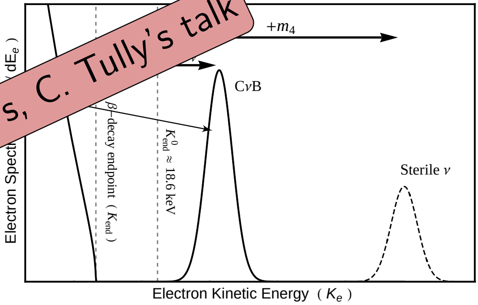
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \rightarrow p + e^-$

signal is a peak at $2m_\nu$ above β–decay endpoint

only with a lot of mate

need a very goo esolution

see G. Mangano's, C. Tully's talk



Good candidate: tritium

[Cocco et al., 2007]

(low $Q-$value) + (good availability of ^{3}H) + (high cross section of $\nu +^3 \mathrm{H} \rightarrow ^3 \mathrm{He} + e^-$)

PTOLEMY

[Long et al., JCAP 08 (2014) 038]
[Betts et al., arxiv:1307.4738]

PonTecorvo Observatory for Light, Early-universe, Massive-neutrino Yield (PTOLEMY)

expected resol

this is the reason of this meeting

→ built only for CνB

omic tritium

can probe $m_\nu \simeq 1.4\Delta \simeq 0.14$ eV

(must distinguish CνB
events from β-decay ones)

$$\boxed{\Gamma_{\mathrm{C}\nu\mathrm{B}} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})]\, N_T\, \bar\sigma} \quad \sim \mathcal{O}(10)\ \mathrm{yr}^{-1}$$

N_T number of $^3\mathrm{H}$ nuclei in a sample of mass M_T $\bar\sigma \simeq 3.834 \times 10^{-45}$ cm^2 n_i number density of neutrino i

Dirac: (without clustering) Majorana:

$$\Gamma^D_{\mathrm{C}\nu\mathrm{B}} = \sum_{i=1}^{3} |U_{ei}|^2 \left[2\left(\frac{n_0}{2}\right)\right] N_T\, \bar\sigma \simeq 4\ \mathrm{yr}^{-1}$$

$$\Gamma^M_{\mathrm{C}\nu\mathrm{B}} = \sum_{i=1}^{3} |U_{ei}|^2 \left[2\,(n_0)\right] N_T\, \bar\sigma \simeq 8\ \mathrm{yr}^{-1}$$

$$\boxed{\Gamma^M_{\mathrm{C}\nu\mathrm{B}} = 2\Gamma^D_{\mathrm{C}\nu\mathrm{B}}}$$

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ehnancement from ν clustering in the galaxy?

$$\Gamma_{\text{C}\nu\text{B}} = \sum_{i=1}^{3} |U_{ei}|^2 [n_i(\nu_{h_R}) + n_i(\nu_{h_L})]\, N_T\, \bar\sigma \qquad \sim \mathcal{O}(10)\ \text{yr}^{-1}$$

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ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →
$$\boxed{\Gamma_{\mathrm{C}\nu\mathrm{B}} = \sum_{i=1}^{3} |U_{ei}|^2 \, f_c(m_i) \, [n_{i,0}(\nu_{h_R}) + n_{i,0}(\nu_{h_L})] \, N_T \, \bar{\sigma}}$$

$f_c(m_i) = n_i / n_{i,0}$ clustering factor ⟶ How to compute it?

Idea from [Ringwald & Wong, 2004] ⟶ **N-one-body= N × single ν simulations**

→ each ν evolved from initial conditions at $z = 3$

→ spherical symmetry, coordinates $(r,\ \theta,\ p_r,\ l)$

→ need $\rho_{\mathrm{matter}}(z) = \rho_{\mathrm{DM}}(z) + \rho_{\mathrm{baryon}}(z)$

Assumptions:

- νs are independent
- only gravitational interactions
- νs do not influence matter evolution ($\rho_\nu \ll \rho_{\mathrm{DM}}$)

how many νs is “N”?

→ must sample all possible r, p_r, l

→ must include all possible νs that reach the MW (fastest ones may come from several (up to $\mathcal{O}(100)$) Mpc!)

given N ν:

→ weigh each neutrinos

→ reconstruct final density profile with kernel method from [Merritt&Tremblay, 1994]

Reweighting neutrinos

[Zhang&Zhang, arxiv:1712.01153]

Hamilton equations for neutrino motion in a plane:

$$\boxed{\frac{dr}{d\tau} = \frac{p_r}{am_\nu}, \qquad \frac{dp_r}{d\tau} = \frac{\ell^2}{am_\nu r^3} - am_\nu \frac{\partial\phi}{\partial r}}$$

$\tau = dt/a$ conformal time – $a = 1/(1+z)$ scale factor – z redshift – ϕ gravitational potential

$p_r = am_\nu \dot{r}$, $\ell = am_\nu r^2 \dot{\theta}$ coniugate momenta of r, θ

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spherical sym: ℓ conserved

ϕ independent of relic neutrinos

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spherical sym: ℓ conserved

ϕ independent of relic neutrinos

define normalized quantities $u_r \equiv p_r/m_\nu$, $u_\theta \equiv \ell/m_\nu$

$$\boxed{\frac{dr}{dz} = -\frac{u_r}{da/dt}, \qquad \frac{du_r}{dz} = -\frac{1}{da/dt}\left(\frac{u_\theta^2}{r^3} - a^2\frac{\partial \phi}{\partial r}\right)}$$

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Now do one N-one-body simulation, sampling the N νs using (r, u_r, u_θ)!

At the end, compute weights and profiles using several m_ν!

Dark matter: profiles today

[JCAP 09 (2017) 034]

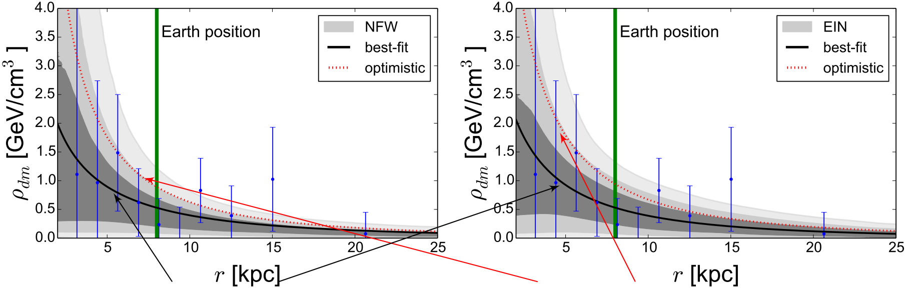
NFW profile:

Einasto (EIN) profile:

$$\mathcal{N}_{\rm NFW}\left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma} = \boxed{\rho_{\rm DM}(r)} = \mathcal{N}_{\rm Ein}\exp\left\{-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha}-1\right)\right\}$$

$\mathcal{N}_{\rm NFW} = 2^{3-\gamma}\rho_{\rm NFW}(r_s)$ normalization $\mathcal{N}_{\rm Ein} = \rho_{\rm Ein}(r_s)$

$\mathcal{N}_{\rm NFW},\ r_s,\ \gamma$ parameters $\mathcal{N}_{\rm Ein},\ r_s,\ \alpha$



Best-fit profiles

optimistic: close to 2σ upper limits

fit of data points from [Pato & Iocco, 2015]

DM: Time evolution of the profiles

[JCAP 09 (2017) 034]

profile evolution from universe expansion

$$\begin{cases} \rho_{\rm cr}(z) = \frac{3}{8\pi G} H^2(z) \\ F_{\rm cr}(z) = \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} \\ H^2(z) = H_0^2\, F_{\rm cr}(z) \\ \rho_{\rm cr}(z) = F_{\rm cr}(z) \times \rho_{\rm cr}(z=0) \end{cases}$$

$$M_{\rm vir} = \frac{4\pi}{3}\Delta_{\rm vir}(z)\rho_{\rm cr}(z)a^3 r^3_{\rm vir}(z)$$

(constant in time)

virial radious $r_{\rm vir}$

radius of sphere containing $M_{\rm vir}$, average density $\Delta_{\rm vir}(z) \times \rho_{\rm cr}(z)$

but $\rho_{\rm DM} = \rho_{\rm DM}(r;\, r_s, \mathcal{N}, [\gamma|\alpha])$

relation between r_s and $r_{\rm vir}$?

↓

from N-body [Dutton et al., 2014]

$$r_{\rm vir}(M_{\rm vir}, z) = \left(\frac{3M_{\rm vir}}{4\pi\rho_{{\rm cr},0}\,\Omega_{m,0}}\right)^{1/3} \left(\frac{\Omega_m(z)}{\Delta_{\rm vir}(z)F_{\rm cr}(z)}\right)^{1/3}$$

$$\Delta_{\rm vir}(z) = \begin{cases} 200 & \text{for EIN,} \\ 18\pi^2 + 82\lambda(z) - 39\lambda(z)^2 & \text{for NFW.} \end{cases}$$

$$\lambda(z) = \Omega_m(z) - 1$$

final expression $\Longrightarrow$ $\boxed{\rho_{\rm DM}(r,z) = N(z)\,\tilde{\rho}_{\rm DM}(r, r_s(z))}$

$\tilde{\rho}_{\rm DM}$ depends on redshift only through r_s

$a = 1/(1+z)$, $h = H_0/(100\ {\rm Km\ s^{-1}\ Mpc^{-1}})$ – $h = 0.6727$, $\Omega_{m,0} = 0.3156$, $\Omega_{\Lambda,0} = 0.6844$ [Planck Collaboration, 2015]

Baryons: the complexity of a structure

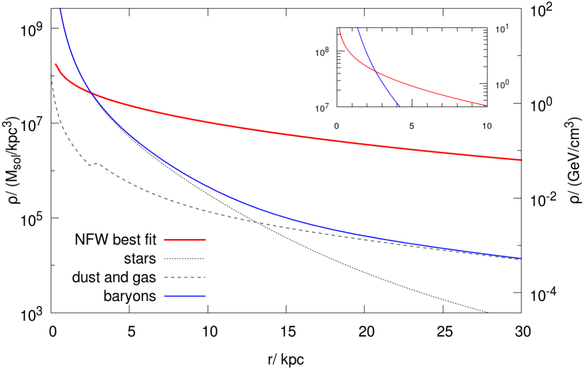
Complex problem: how to model baryon content of a galaxy?

e.g. [Pato et al., 2015]:
70 different baryonic models

7 models for the bulge
×
5 for the disc
×
2 for the gas

[Misiriotis et al., 2006]:
5 independent
components

- warm dust
- cold dust
- stars
- atomic *H* gas
- molecular *H* gas



our case: [Misiriotis et al., 2006], spherically symmetrized

Baryons: redshift evolution

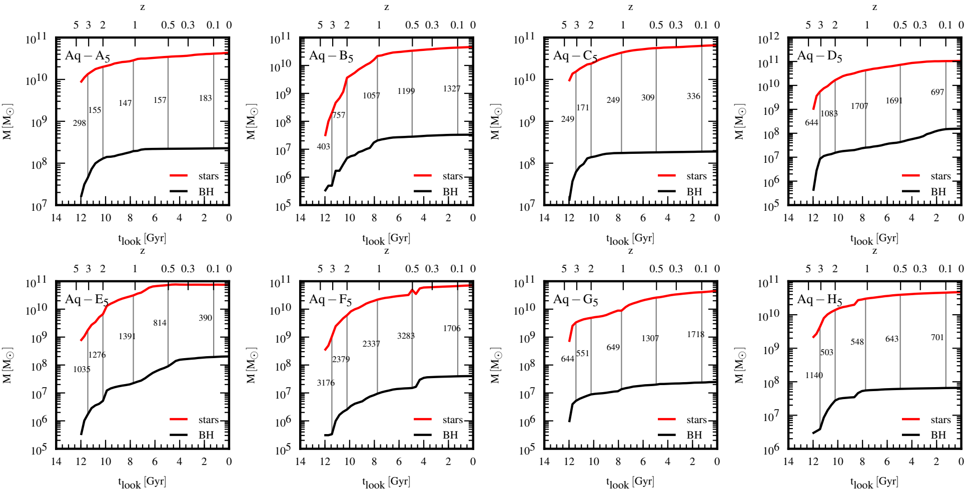
baryon evolution with redshift?

from [Marinacci et al., 2013]

results of full N-body simulations

$\mathcal{N}_{\rm bar}(z)$ from $M(z)$

mean of 8 simulations ↔ based on Aquarius simulation: $M_{\rm Aq} \simeq M_{\rm MW}$



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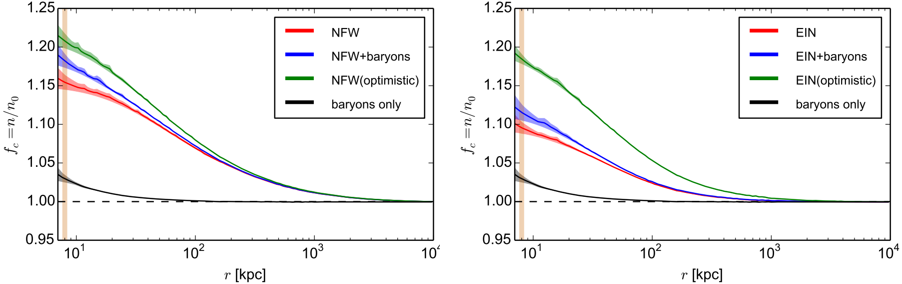
Overdensity when $m_{\rm heaviest} \simeq 60$ meV

[JCAP 09 (2017) 034]



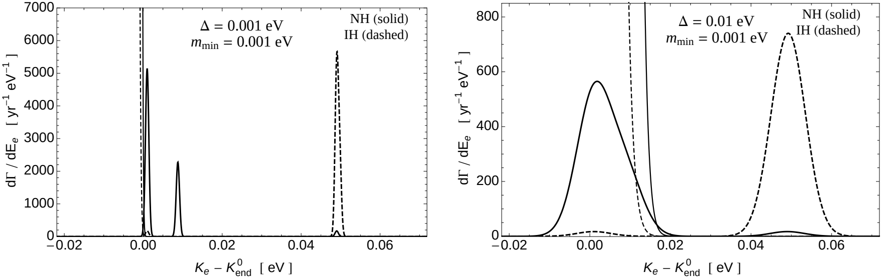
masses	ordering	matter halo	overdensity f_c		$\Gamma^D_{\rm tot}$ (yr^{-1})	$\Gamma^M_{\rm tot}$ (yr^{-1})
			$f_1 \simeq f_2$	f_3		
any	any	any	no clustering		4.06	8.12
$m_3 = 60$ meV	NO	NFW(+bar)	~1	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	4.08	8.16
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)	8.14 (8.14)
		EIN optimistic		1.18	4.08	8.15
$m_1 \simeq m_2 = 60$ meV	IO	NFW(+bar)	1.15 (1.18)	~1	4.66 (4.78)	9.31 (9.55)
		NFW optimistic	1.21		4.89	9.77
		EIN(+bar)	1.09 (1.12)		4.42 (4.54)	8.84 (9.07)
		EIN optimistic	1.18		4.78	9.55

ordering dependence from $\Gamma_{C\nu B} = \sum_{i=1}^{3} |U_{ei}|^2 \, f_i \, [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] \, N_T \, \bar{\sigma}$

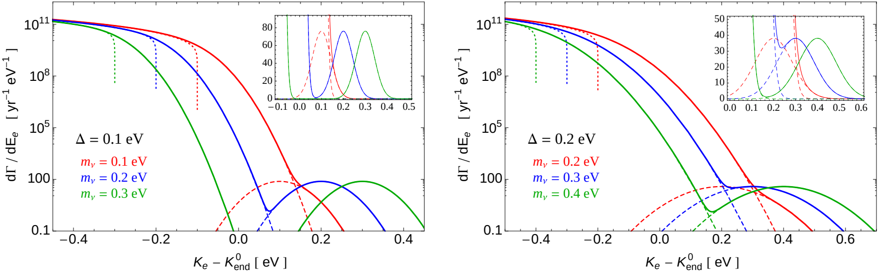
Energy resolution and event rate

[Long et al., JCAP 08 (2014) 038]

Hierarchical:



Degenerate: (solid: measured, dotted: ideal with $\Delta = 0$)



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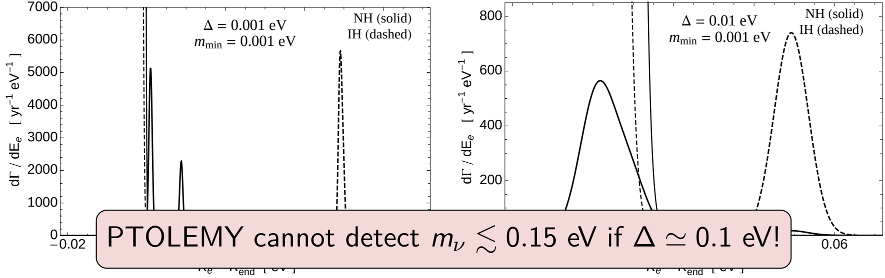
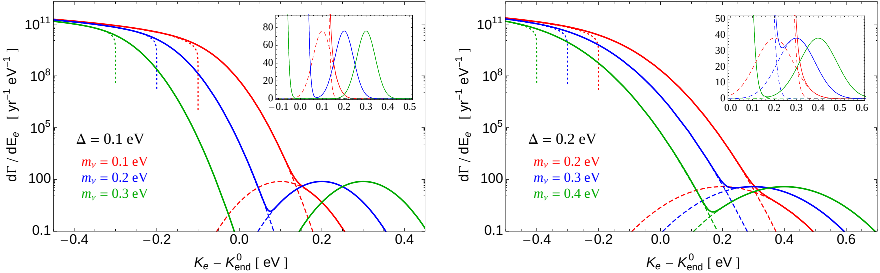


PTOLEMY cannot detect $m_\nu \lesssim 0.15$ eV if $\Delta \simeq 0.1$ eV!

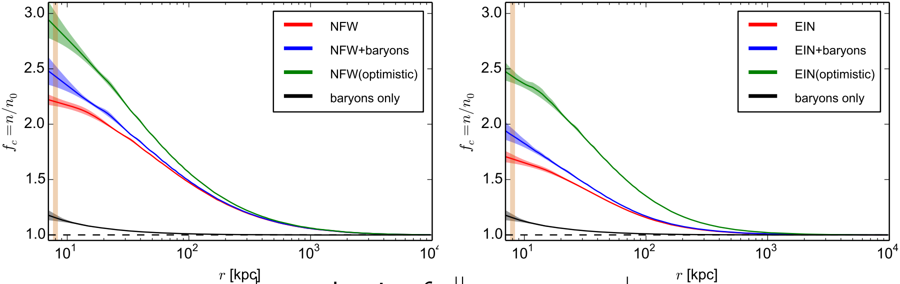
Degenerate: (solid: measured, dotted: ideal with $\Delta = 0$)



Overdensity when $m_\nu \simeq 150$ meV

[JCAP 09 (2017) 034]

$\Longrightarrow$ minimal mass detectable by PTOLEMY if $\Delta \simeq$ 100–150 meV



matter halo	overdensity f_c $f_1 \simeq f_2 \simeq f_3$	$\Gamma^D_{\rm tot}$ (yr^{-1})	$\Gamma^M_{\rm tot}$ (yr^{-1})
any	no clustering	4.06	8.12
NFW(+bar)	2.18 (2.44)	8.8 (9.9)	17.7 (19.8)
NFW optimistic	2.88	11.7	23.4
EIN(+bar)	1.68 (1.87)	6.8 (7.6)	13.6 (15.1)
EIN optimistic	2.43	9.9	19.7

no ordering dependence: $m_1 \simeq m_2 \simeq m_3 \Longrightarrow f_1 \simeq f_2 \simeq f_3$

Additional clustering due to other galaxies

[JCAP 09 (2017) 034]

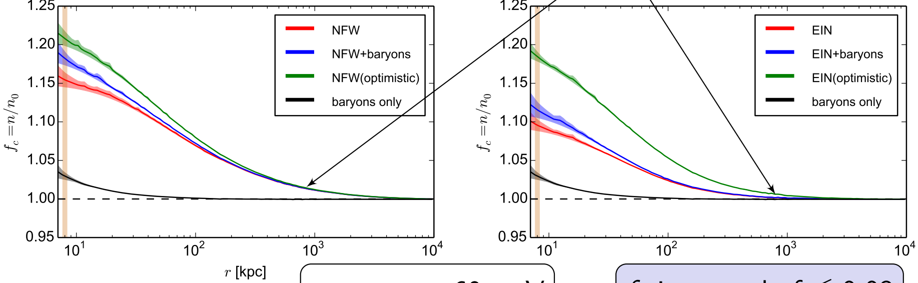
nearest galaxies: various MW satellites

with $M_{\rm sat} \ll M_{\rm MW}$ ⟶ negligibly small ν halo

nearest big galaxy:

Andromeda

$M_{\rm Andromeda} = M_{\rm MW} \times \mathcal{O}(1)$ — $d_{\rm Andromeda} \simeq 800$ kpc



$m_{\rm heaviest} \simeq 60$ meV ⟶ f_c increased of $\lesssim 0.03$

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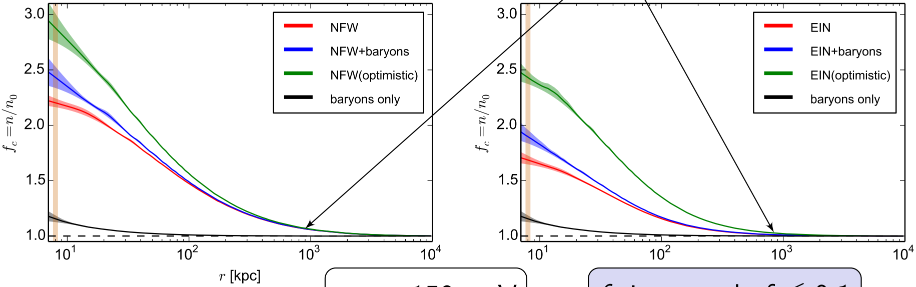
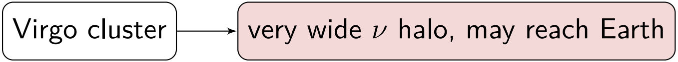


$m_\nu \simeq 150$ meV ⟶ f_c increased of $\lesssim 0.1$

(halo is less diffuse for higher ν masses)

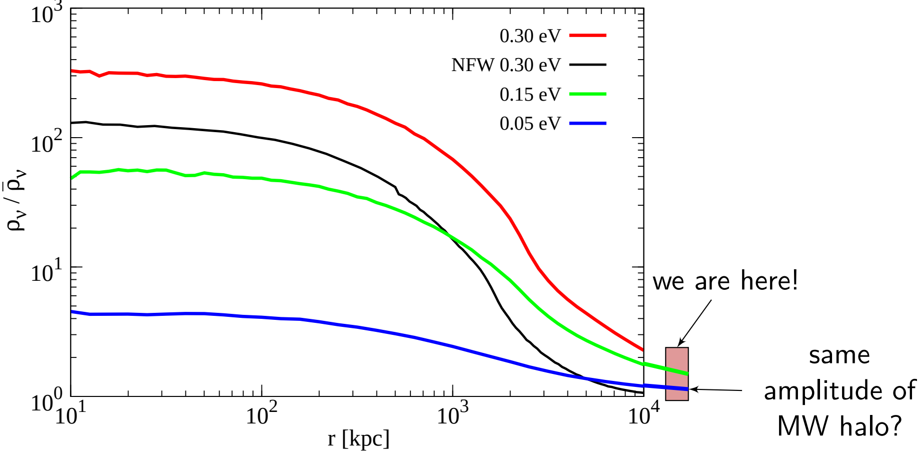
Additional clustering due to Virgo cluster

nearest galaxy cluster:



Virgo cluster → very wide ν halo, may reach Earth

$M_{\rm Virgo} = M_{\rm MW} \times \mathcal{O}(10^3)$ — $d_{\rm Virgo} \simeq 16$ Mpc



we are here!

same amplitude of MW halo?

[Villaescusa-Navarro et al., JCAP 1106 (2011) 027]

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Short Baseline (SBL) anomaly

[SG et al., JPG 43 (2016) 033001]

Problem: anomalies in SBL experiments ⇒ $\begin{cases}\text{errors in flux calculations?}\\ \text{deviations from 3-}\nu\text{ description?}\end{cases}$

A short review:

LSND search for $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.4 \div 1.5$ m/MeV. Observed a 3.8σ excess of $\bar{\nu}_e$ events [Aguilar et al., 2001]

Reactor re-evaluation of the expected anti-neutrino flux ⇒ disappearance of $\bar{\nu}_e$ events compared to predictions ($\sim 3\sigma$) with $L < 100$ m [Azabajan et al, 2012]

Gallium calibration of GALLEX and SAGE Gallium solar neutrino experiments give a 2.7σ anomaly (disappearance of ν_e) [Giunti, Laveder, 2011]

MiniBooNE (inconclusive) search for $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$, with $L/E = 0.2 \div 2.6$ m/MeV. No ν_e excess detected, but $\bar{\nu}_e$ excess observed at 2.8σ [MiniBooNE Collaboration, 2013]

Possible explanation:

Additional squared mass difference

$$\Delta m^2_{\text{SBL}} \simeq 1\ \text{eV}^2$$

See also [SG et al., 2017]

3+1 Neutrino Model

new $\Delta m^2_{\mathrm{SBL}} \Rightarrow$ 4 neutrinos!

↓

ν_4 with $m_4 \simeq 1$ eV,
no weak interactions

↓

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k} \nu_k \quad (\alpha = e, \mu, \tau, s)$$

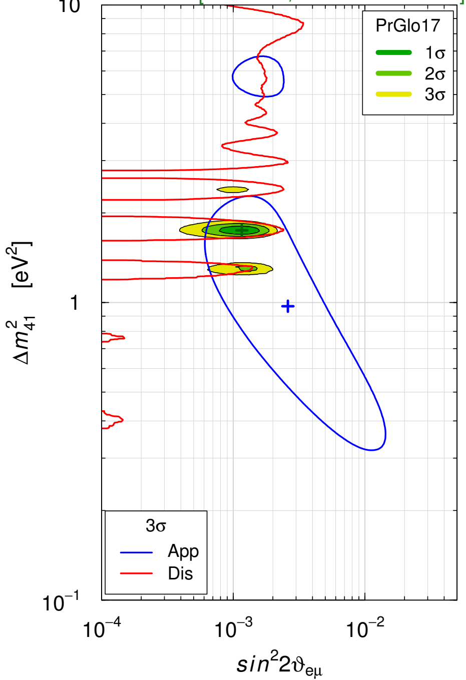
ν_s is mainly ν_4:

$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\mathrm{SBL}}}$$

assuming $m_4 \gg m_i$ $(i = 1, 2, 3)$

can ν_4 thermalize in the early Universe through oscillations?

[SG et al., arxiv:1703.00860]

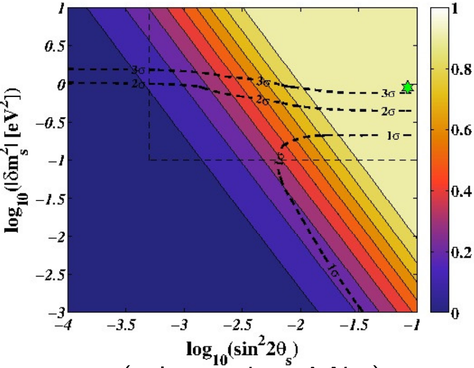


LSν thermalization

Using SBL best-fit parameters for the LSν (Δm^2_{41}, θ_s):

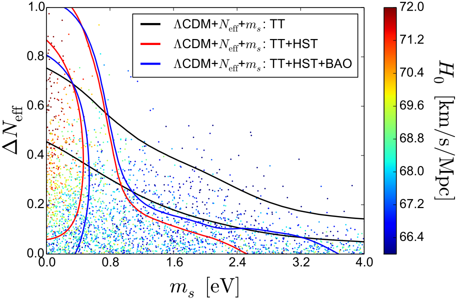
[Hannestad et al., JCAP 1207 (2012) 025]

[Archidiacono, SG et al., JCAP 08 (2016) 067]



(colors coding ΔN_{eff})

but cosmological fits give:



$\Delta N_{\mathrm{eff}} = 1$ disfavoured!

ΔN_{eff} should be $\simeq 1$, but it is disfavoured! (new physics?)

[to be precise: ΔN_{eff} is slightly smaller at CMB decoupling, when the LSν starts to be non-relativistic]

Assumptions and useful equations

[JCAP 09 (2017) 034]

We assume possible incomplete thermalization

(due to some unknown new physics)

$$\boxed{f_4(p) = \frac{\Delta N_{\mathrm{eff}}}{e^{p/T_\nu}+1} = \Delta N_{\mathrm{eff}}\, f_{\mathrm{active}}(p)}$$

$$\Delta N_{\mathrm{eff}} = \left[\tfrac{1}{\pi^2}\int dp\; p^3 f_4(p)\right] \Big/ \left[\tfrac{7}{8}\tfrac{\pi^2}{15}\, {T_\nu}^4\right]$$

$$\bar{n}_4 = \frac{g_4}{(2\pi)^3}\int f_4(p)\, p^2\, dp = n_0\, \Delta N_{\mathrm{eff}}$$

$$\boxed{n_4 = n_0\, \Delta N_{\mathrm{eff}}\, f_c(m_4)}$$

($f_c(m_4)$ is independent of ΔN_{eff})

$$\boxed{\Gamma_4^{M(D)} \simeq |U_{e4}|^2\, \Delta N_{\mathrm{eff}}\, f_c(m_4)\, \Gamma_{\mathrm{C\nu B}}^{M(D)}}$$

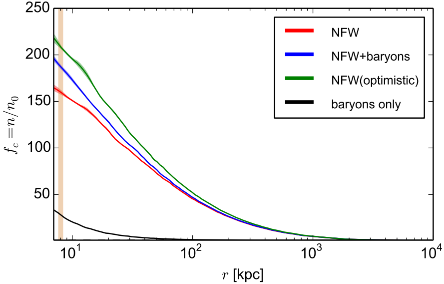
(from global fit [SG et al., 2017]: $m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$)

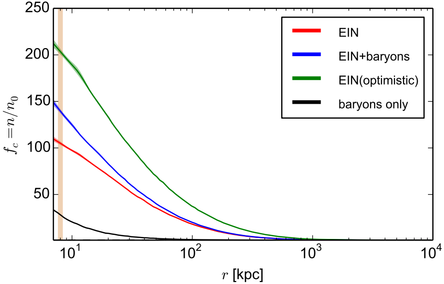
Overdensity of a sterile neutrino

[JCAP 09 (2017) 034]

$\Gamma_4^{M(D)} \simeq \Delta N_{\rm eff}\,|U_{e4}|^2\, f_c(m_4)\,\Gamma^{M(D)}_{\rm C\nu B}$

$m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$





matter halo	overdensity f_4	$\Delta N_{\rm eff}$	$\Gamma^D_{\rm tot}$ (yr^{-1})	$\Gamma^M_{\rm tot}$ (yr^{-1})
NFW(+bar)	159.9 (187.3)	0.2	2.6 (3.0)	5.2 (6.1)
		1.0	13.0 (15.2)	26.0 (30.4)
NFW optimistic	208.6	0.2	3.4	6.8
		1.0	16.9	33.9
EIN(+bar)	105.1 (139.5)	0.2	1.7 (2.3)	3.4 (4.5)
		1.0	8.5 (11.3)	17.1 (22.7)
EIN optimistic	203.5	0.2	3.3	6.6
		1.0	16.5	33.0

1. Direct detection of cosmic neutrino background
    - Proposed methods
    - PTOLEMY

2. Relic neutrino clustering in the Milky Way
    - N-one-body simulations
    - Dark Matter in the MW
    - Baryons in the MW

3. The local neutrino overdensity
    - Results for (nearly) minimal neutrino masses
    - Results for non-minimal neutrino masses: 150 meV
    - Beyond the Milky Way

4. Beyond the standard: light sterile neutrinos

5. Conclusions

Conclusions

1. direct detection event rate depends on clustering of relic neutrinos

2. event rate enhancement (*N*-one-body method) due to Milky Way of order
   $+0$–20% for $m_{\rm heaviest} \simeq 60$ meV (ordering!)
   $+70$–200% for $m_\nu \simeq 150$ meV

3. Considering the Milky Way is not enough!
   Virgo cluster may have strong effect
   (work in progress)

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Bonus

And if there is
a light sterile neutrino ($m_4 \simeq 1.3$ eV) **???**
possible detection thanks to large clustering

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Thank you for the attention!