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Relic neutrinos, direct detection and clustering in the Milky Way

Based on arxiv:1706.09850, in collaboration with
P. F. de Salas, J. Lesgourgues, S. Pastor

13/09/2017 - Meeting on Fundamental Cosmology - CEFCA, Teruel (ES)

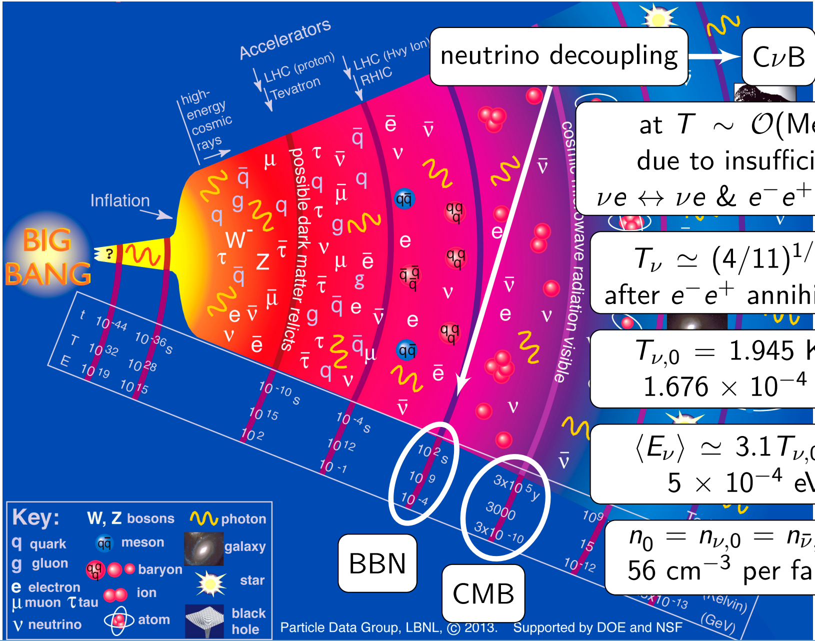
1. Cosmic neutrino background
    - Neutrinos in the early universe
    - Direct detection of relic neutrinos
    - PTOLEMY

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

4. Conclusions

History of the universe



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neutrino decoupling → CνB

at $T \sim \mathcal{O}(\text{MeV})$ due to insufficient $\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

$T_\nu \simeq (4/11)^{1/3} T_\gamma$ after $e^- e^+$ annihilation

$T_{\nu,0} = 1.945$ K $\simeq 1.676 \times 10^{-4}$ eV

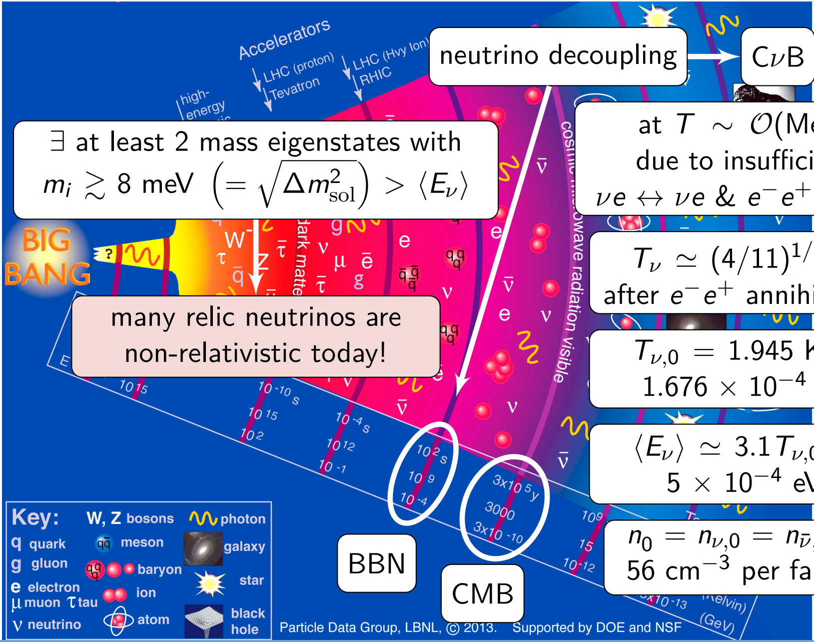
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq 5 \times 10^{-4}$ eV

$n_0 = n_{\nu,0} = n_{\bar{\nu},0} \simeq 56$ cm^{-3} per family

BBN

CMB

History of the universe



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$56\ \mathrm{cm}^{-3}$ per family

∃ at least 2 mass eigenstates with
$m_i \gtrsim 8\ \mathrm{meV} \left(= \sqrt{\Delta m^2_{\mathrm{sol}}}\right) > \langle E_\nu \rangle$

many relic neutrinos are
non-relativistic today!

BBN

CMB

CνB: Dirac vs Majorana

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

Dirac neutrinos

active:

$\nu_L,\ n(\nu_L) = n_0$

$\bar\nu_R,\ n(\bar\nu_R) = n_0$

sterile:

$\nu_R,\ n(\nu_R) \simeq 0$

$\bar\nu_L,\ n(\bar\nu_L) \simeq 0$

Majorana neutrinos

active:

$\nu_L,\ n(\nu_L) = n_0$

$\nu_R,\ n(\nu_R) = n_0$

sterile:

$N_L,\ n(N_L) = 0$

$N_R,\ n(N_R) = 0$

total: $n_{C\nu B} \simeq 6n_0$ $\longleftrightarrow$ total: $n_{C\nu B} \simeq 6n_0$

NOTE: free-streaming conserves helicity, not chirality!

because neutrinos are massive and become non-relativistic during expansion

$n(\nu_{h_L}) = n_0 \qquad n(\nu_{h_R}) \simeq 0$

$n(\bar\nu_{h_R}) = n_0 \qquad n(\bar\nu_{h_L}) \simeq 0$

only left-helical!

$n(\nu_{h_L}) = n_0 \qquad n(N_{h_L}) = 0$

$n(\nu_{h_R}) = n_0 \qquad n(N_{h_R}) = 0$

both left and right-helical

if not completely free-streaming, helicities can be flipped

$\Rightarrow$ mix of helicities: $n(\nu_{h_L}) = n(\bar\nu_{h_R}) = n(\nu_{h_R}) = n(\bar\nu_{h_L}) = n_0/2$

no change for Majorana

Relic neutrinos in cosmology: $N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\rm eff}\right]\rho_\gamma = [1 + 0.2271 N_{\rm eff}]\,\rho_\gamma$$

ρ_γ photon energy density, 7/8 is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

- $N_{\rm eff} \to$ all the radiation contribution not given by photons
- $N_{\rm eff} \simeq 1$ correspond to a single family of active neutrino, in equilibrium in the early Universe
- Active neutrinos:
  $N_{\rm eff} = 3.046$ [Mangano et al., 2005] (damping factors approximations) $\sim$
  $N_{\rm eff} = 3.045$ [de Salas et al., 2016] (full collision terms)
  due to not instantaneous decoupling for the neutrinos
- $+$ Non Standard Interactions: $3.040 < N_{\rm eff} < 3.059$ [de Salas et al., 2016]

Observations: $N_{\rm eff} \simeq 3.04 \pm 0.2$ [Planck 2015]
Indirect probe of cosmic neutrino background!

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?

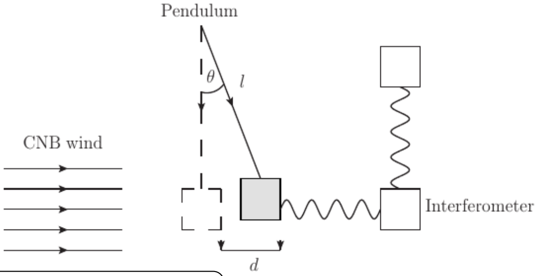
At interferometers

[Domcke et al., 2017]

coherent scattering of
relic ν on a pendulum

⟶

measure oscillations
at interferometers



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

⟷

$a_{\text{LIGO/Virgo}} \simeq 10^{-16}\ \text{cm/s}^2$

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?

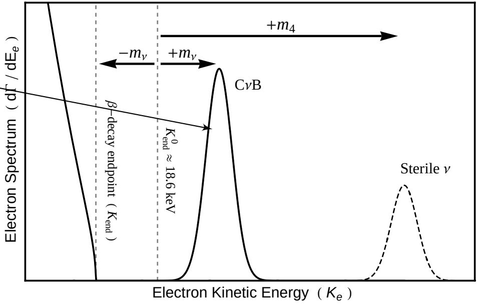
Remember that $\langle E_\nu \rangle \simeq \mathcal{O}(10^{-4})$ eV today → a process without energy threshold is necessary

[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 material

need a very good energy resolution



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]

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

expected resolution $\Delta \simeq 0.1$ eV

built only for CνB

$M_T = 100$ g atomic tritium

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

(must distinguish CνB events from β-decay ones)

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

N_T number of ^3H 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:

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

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

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

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ehnancement from ν clustering in the galaxy?

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

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

ν clustering with N-one-body simulations

[arxiv:1706.09850]

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, θ, 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]

Dark matter: profiles today

[arxiv:1706.09850]

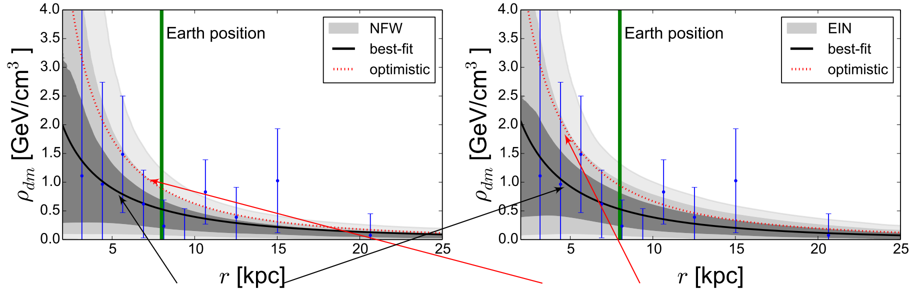
NFW profile:

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

profile evolution from universe expansion

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

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

← (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

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

Baryons: the complexity of a structure

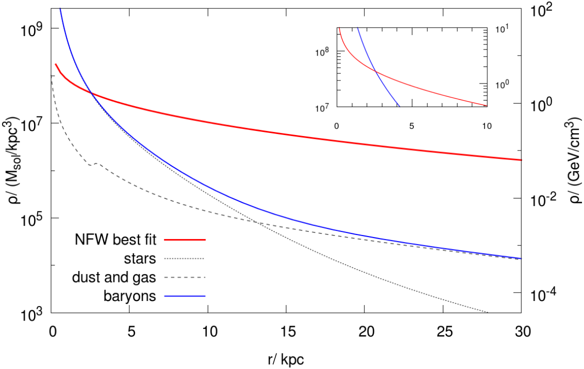
Complex problem: how to model baryon content of a galaxy?

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

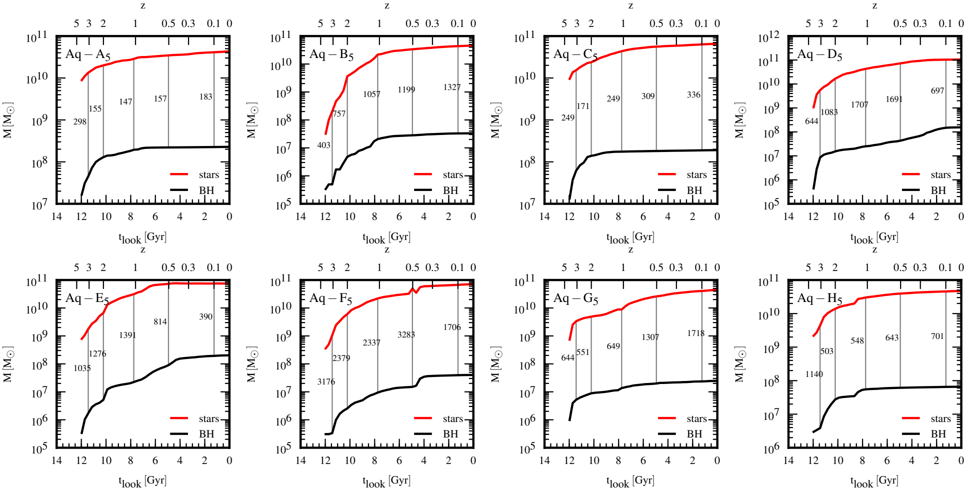
baryon evolution with redshift?

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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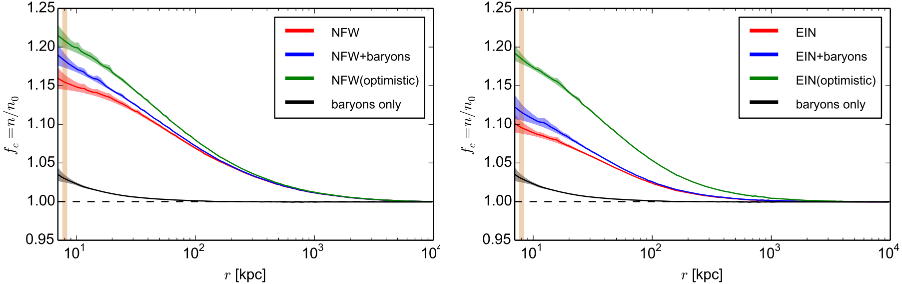
4. Conclusions

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

[arxiv:1706.09850]



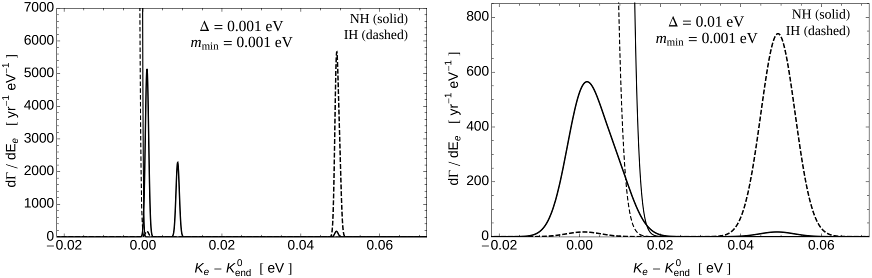
masses	ordering	matter halo	overdensity f_c		$\Gamma^D_{\rm tot}$ (yr^{-1})	$\Gamma^M_{\rm tot}$ (yr^{-1})
			$f_1 \simeq f_2$	f_3		
any	any	any	no clustering		4.06	8.12
$m_3 = 60$ meV	NO	NFW(+bar)	∼1	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	4.08	8.16
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)	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 $\Gamma_{C\nu B} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \, [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] \, N_T \, \bar{\sigma}$

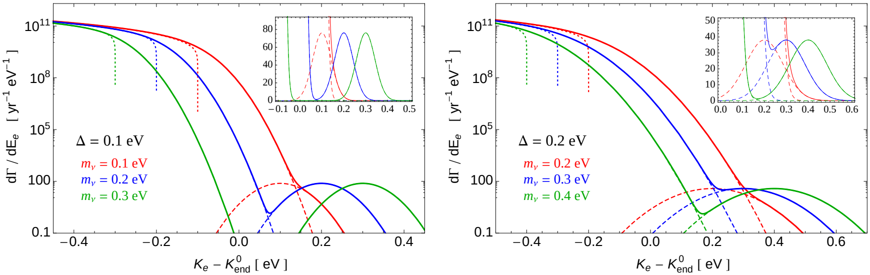
Energy resolution and event rate

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

Hierarchical:



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



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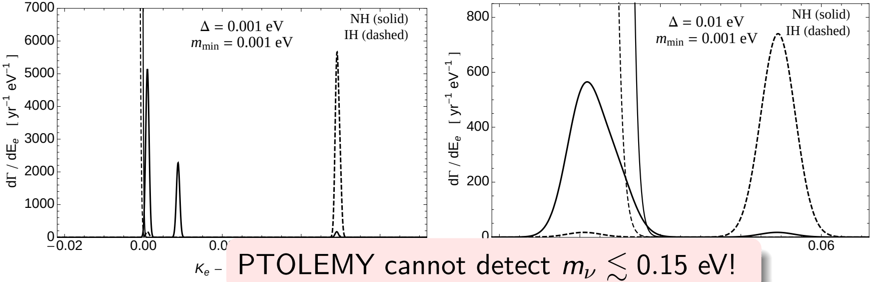
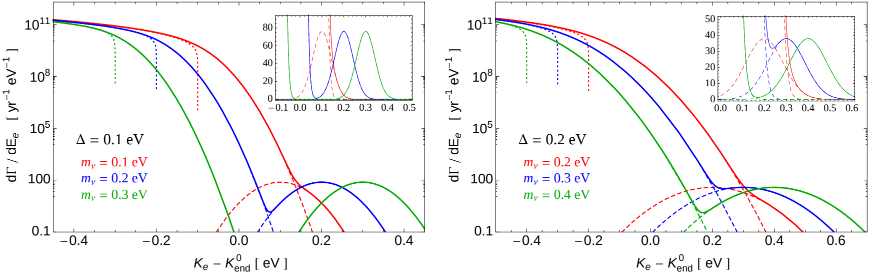


PTOLEMY cannot detect $m_\nu \lesssim 0.15$ eV!

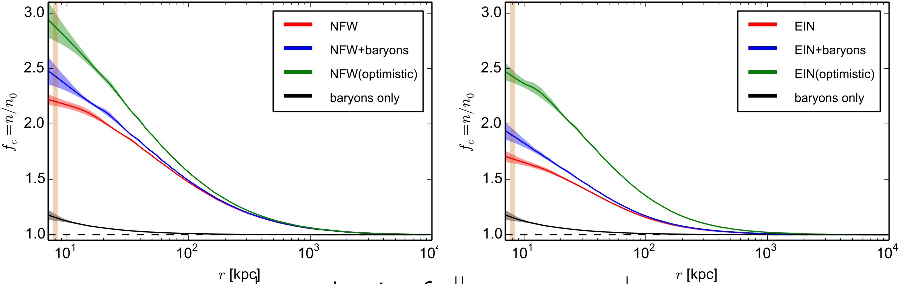
Degenerate: (solid: measured, dotted: ideal with $\Delta = 0$)



Overdensity when $m_\nu \simeq 150$ meV

[arxiv:1706.09850]

$\Longrightarrow$ 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: $m_1 \simeq m_2 \simeq m_3 \Longrightarrow f_1 \simeq f_2 \simeq f_3$

Conclusions

- Cosmic Neutrino Background (CνB) predicted but not detected:
  - only $N_{\mathrm{eff}} \simeq 3.04$ as indirect probe
  - must detect scattering of *non-relativistic* neutrinos!
- massive ν can cluster in the local matter distribution
  - *N*-one-body method: follow *N* single neutrinos in the Milky Way
  - requires knowledge of matter (DM, baryons) profiles and their evolution
- to detect relic neutrinos:
  - process without threshold required
    - → ν capture on β-decaying nuclei
    - → PTOLEMY proposal with 100g of tritium
  - very good energy resolution Δ is necessary to probe $m_\nu \gtrsim 1.4\Delta$
- *for non-minimal ν masses*, PTOLEMY can:
  - detect relic neutrinos (for the first time ✓)
  - study non-relativistic neutrinos (for the first time ✓)
  - probe the neutrino clustering (for the first time ✓)
    - constrain the matter profile of our galaxy
  - measure the absolute neutrino masses (for the first time ?)
  - test Dirac/Majorana nature (for the first time ?)
- and also detect relic sterile neutrinos (if any ?)