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Neutrino clustering in the Milky Way

Based on arxiv:170(6|7).[0-9]{5}
In collaboration with P. F. de Salas,
J. Lesgourgues, S. Pastor

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1. Cosmic neutrino background and neutrino clustering
    - Neutrinos in the early universe
    - PTOLEMY
    - Neutrino clustering
2. Matter distributions in the Milky Way
    - Dark Matter
    - Baryons
3. The local neutrino overdensity
    - Results for (nearly) minimal neutrino masses
    - Results for non-minimal neutrino masses: 150 meV
4. Conclusions

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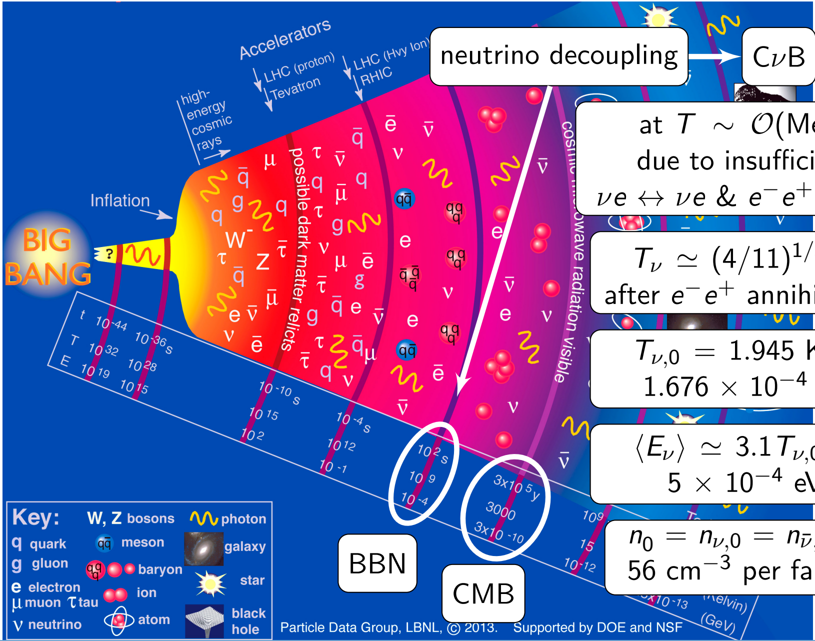
History of the universe



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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 $\simeq$
1.676×10^{-4} eV

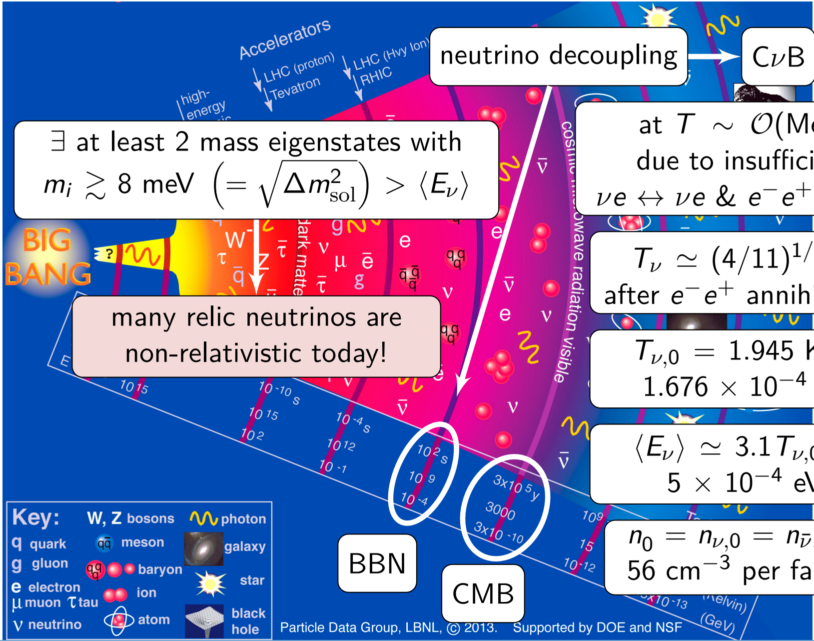
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq$
5×10^{-4} eV

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

BBN

CMB

History of the universe



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

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many relic neutrinos are
non-relativistic today!

BBN

CMB

CνB: Dirac vs Majorana

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

Dirac neutrinos		Majorana neutrinos	
active:	sterile:	active:	sterile:
$\nu_L,\ n(\nu_L) = n_0$	$\nu_R,\ n(\nu_R) \simeq 0$	$\nu_L,\ n(\nu_L) = n_0$	$N_L,\ n(N_L) = 0$
$\bar\nu_R,\ n(\bar\nu_R) = n_0$	$\bar\nu_L,\ n(\bar\nu_L) \simeq 0$	$\nu_R,\ n(\nu_R) = n_0$	$N_R,\ n(N_R) = 0$

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

NOTE: free-streaming conserves helicity, not chirality!

because neutrinos are massive and become non-relativistic during expansion

Dirac		Majorana	
$n(\nu_{h_L}) = n_0$	$n(\nu_{h_R}) \simeq 0$	$n(\nu_{h_L}) = n_0$	$n(N_{h_L}) = 0$
$n(\bar\nu_{h_R}) = n_0$	$n(\bar\nu_{h_L}) \simeq 0$	$n(\nu_{h_R}) = n_0$	$n(N_{h_R}) = 0$
only left-helical!		both left and right-helical	

<ins>if not completely free-streaming, helicities can be flipped</ins>

$\Rightarrow$ 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:

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

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 of CνB neutrinos

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

At least two CνB neutrinos over three are non-relativistic now!

How to detect non-relativistic neutrinos?

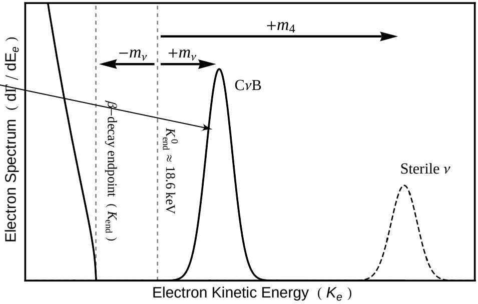
a process without energy threshold is necessary

[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

(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)

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

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

(without clustering)

Dirac:

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

Majorana:

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

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

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ehnancement from ν clustering in the galaxy?

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

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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:170(6|7).[0-9]{5}]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

$f_c(m_i)$ 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]

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Dark matter: profiles today

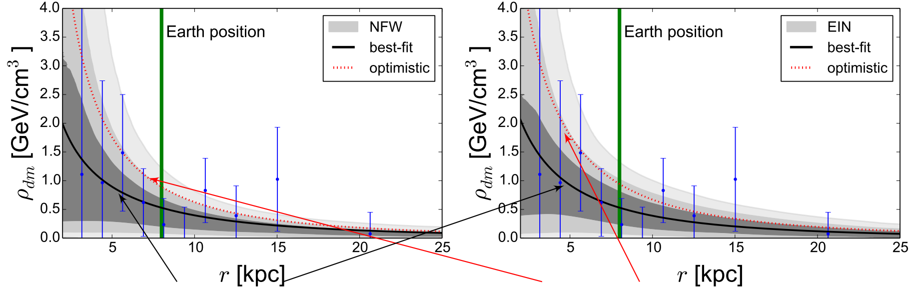
[arxiv:170(6|7).[0-9]{5}]

NFW profile: **Einasto (EIN) profile:**

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

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

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



Best-fit profiles optimistic: close to 2σ upper limits

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

DM: Time evolution of the profiles

[arxiv:170(6|7).[0-9]{5}]

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

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

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

↓

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

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

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

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

$\tilde\rho_{\rm DM}$ 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

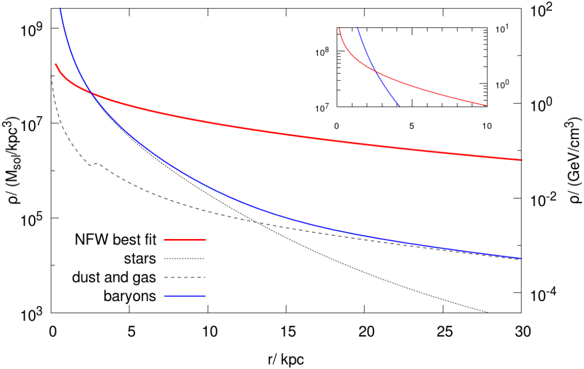
Complex problem: how to model baryon content of a galaxy?

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

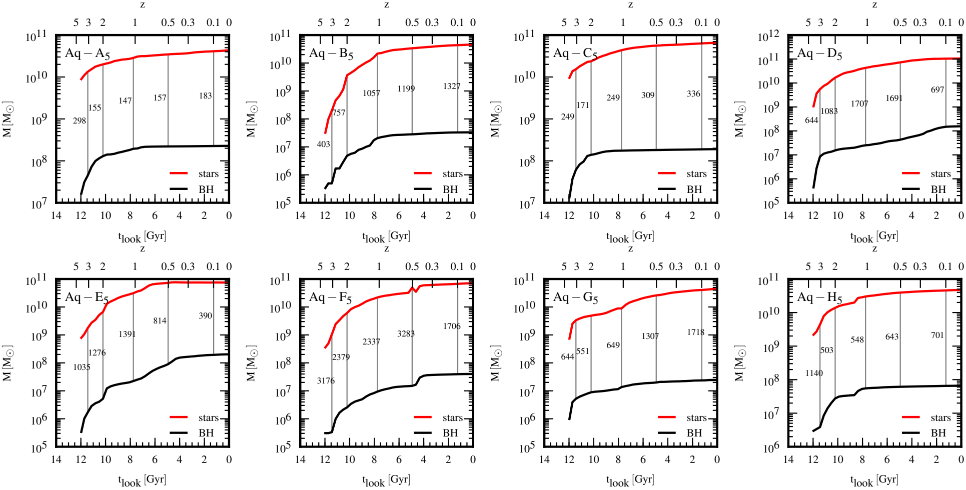
baryon evolution with redshift?

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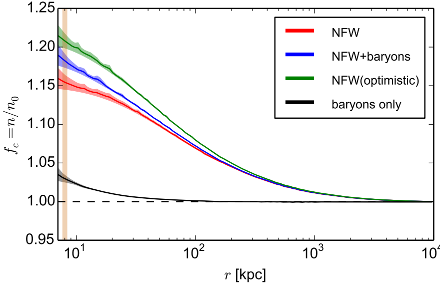
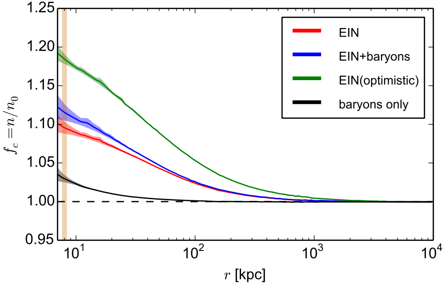
Overdensity when $m_{\text{heaviest}} \simeq 60$ meV

[arxiv:170(6|7).[0-9]{5}]





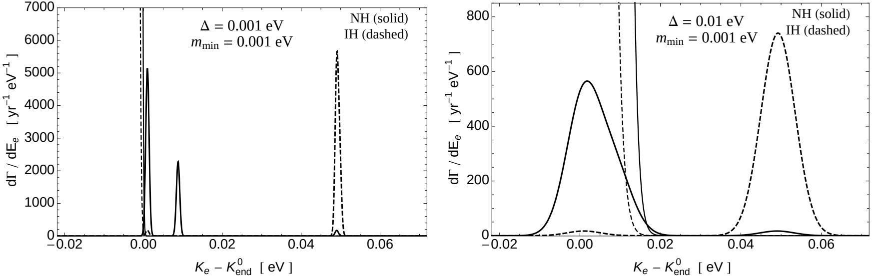
masses	ordering	matter halo	overdensity f_c		Γ^D_{tot} (yr^{-1})	Γ^M_{tot} (yr^{-1})
			$f_1 \simeq f_2$	f_3		
any	any	any	no clustering		4.06	8.12
$m_3 = 60$ meV	NO	NFW(+bar)	$\sim$1	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	4.08	8.16
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)	8.14 (8.14)
		EIN optimistic		1.18	4.08	8.15
$m_1 \simeq m_2 = 60$ meV	IO	NFW(+bar)	1.15 (1.18)	$\sim$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 $\Gamma_{C\nu B} = \sum_{i=1}^{3} |U_{ei}|^2 \, f_i \, [n_i(\nu_{h_R}) + n_i(\nu_{h_L})] \, N_T \, \bar{\sigma}$

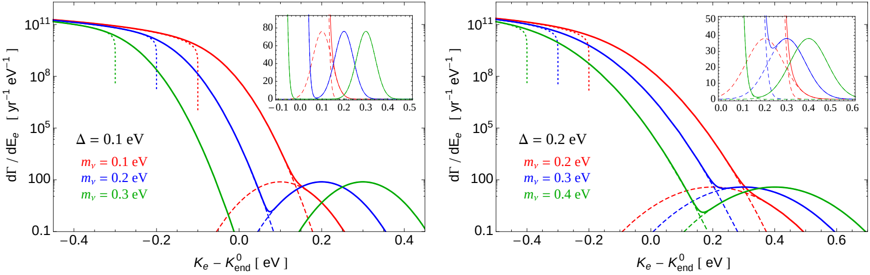
Energy resolution and event rate

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

Hierarchical:



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



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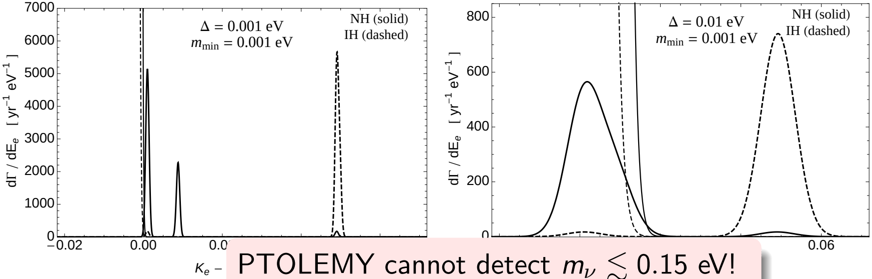
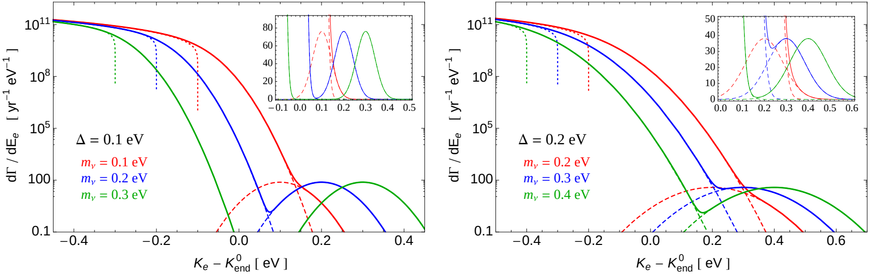


PTOLEMY cannot detect $m_\nu \lesssim 0.15$ eV!

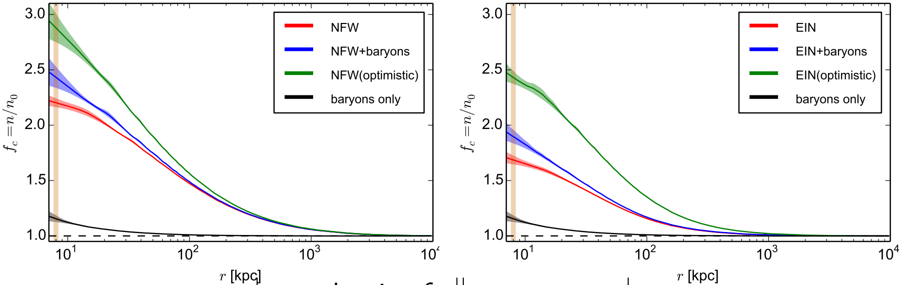
Degenerate: (solid: measured, dotted: ideal with $\Delta = 0$)



Overdensity when $m_\nu \simeq 150$ meV

[arxiv:170(6|7).[0-9]{5}]

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

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Conclusions

- Cosmic Neutrino Background (CνB) predicted but not detected:
  - only $N_{\rm eff} \simeq 3.04$ 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
    - $\rightarrow$ ν capture on β-decaying nuclei
    - $\rightarrow$ 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 ?)

5 Backup slides

Additional clustering due to other galaxies

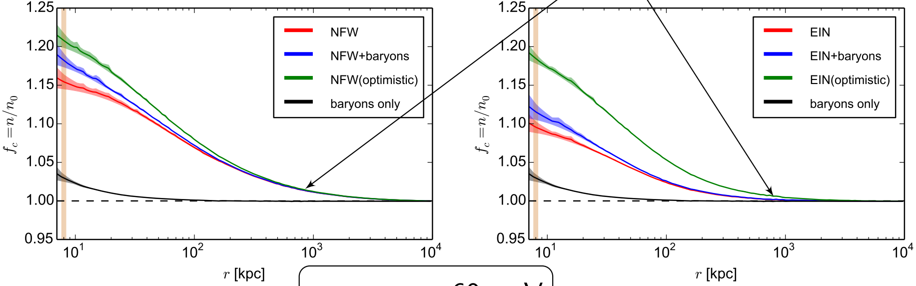
nearest galaxies: various MW satellites

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

nearest big galaxy:

Andromeda → f_c increased of $\lesssim 0.03$

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



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

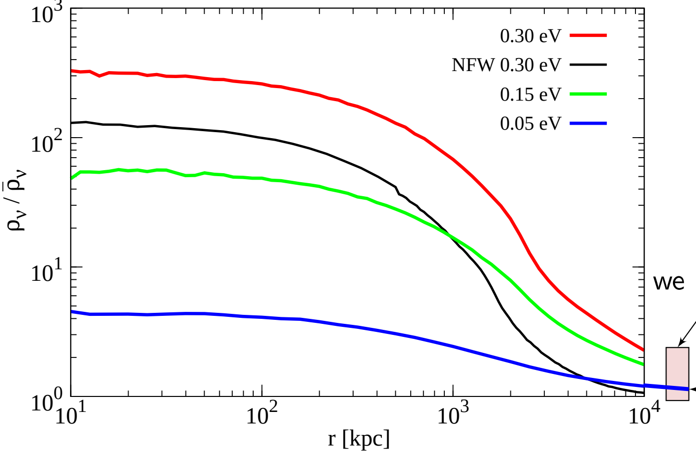
(halo is less diffuse for higher ν masses)

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]