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Neutrino clustering in the Milky Way

Based on arxiv:1706.09850

*In collaboration with P. F. de Salas,
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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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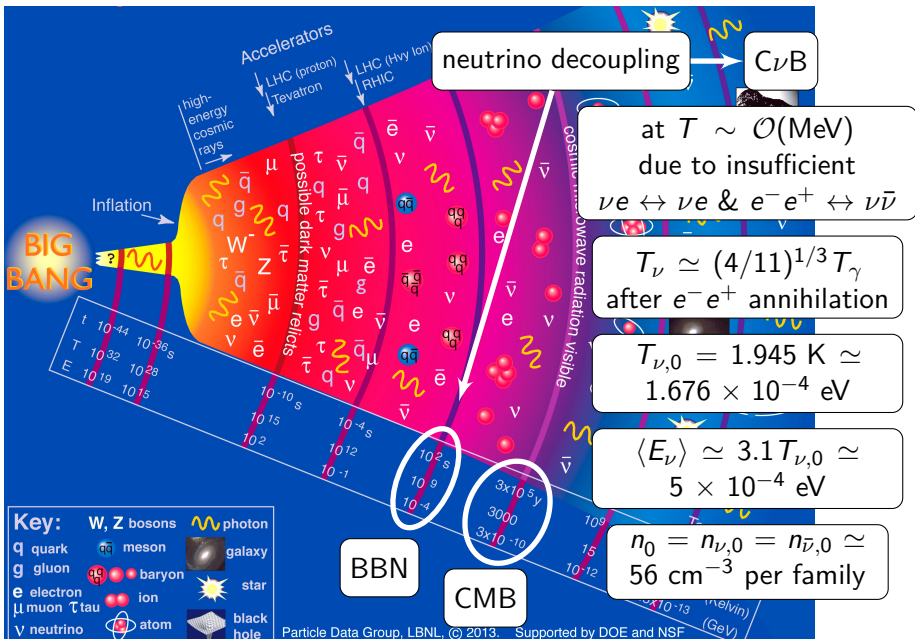
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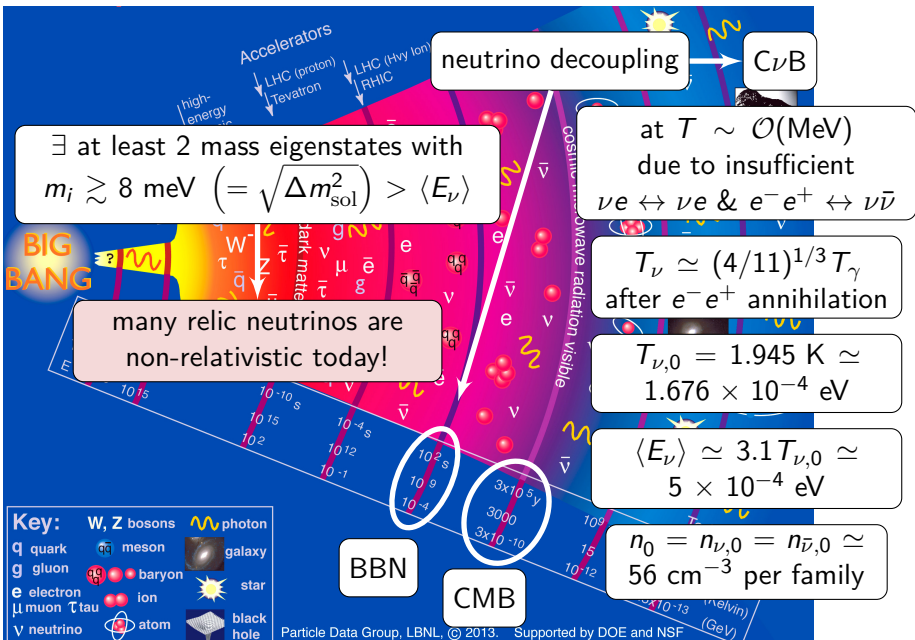
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4 Conclusions

History of the universe



History of the universe



$C\nu B$: Dirac vs Majorana

Dirac neutrinos

active:

sterile:

$$\nu_L, n(\nu_L) = n_0 \quad \nu_R, n(\nu_R) \simeq 0$$

$$\bar{\nu}_R, n(\bar{\nu}_R) = n_0 \quad \bar{\nu}_L, n(\bar{\nu}_L) \simeq 0$$

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

Majorana neutrinos

active:

sterile:

$$\nu_L, n(\nu_L) = n_0 \quad N_L, n(N_L) = 0$$

$$\nu_R, n(\nu_R) = n_0 \quad N_R, n(N_R) = 0$$

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

NOTE: free-streaming conserves helicity, not chirality!

because neutrinos are massive and become non-relativistic during expansion

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

$$n(\bar{\nu}_{h_R}) = n_0 \quad n(\bar{\nu}_{h_L}) \simeq 0$$

only left-helical!

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

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

both left and right-helical

if not completely free-streaming, helicities can be flipped

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

no change for Majorana

Radiation energy density ρ_r in the early Universe:

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

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

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

Observations: $N_{\text{eff}} \simeq 3.04 \pm 0.2$ [Planck 2015]

Indirect probe of cosmic neutrino background!

At least two $C\nu B$ neutrinos over three are non-relativistic now!

How to detect non-relativistic neutrinos?

a process without energy threshold is necessary

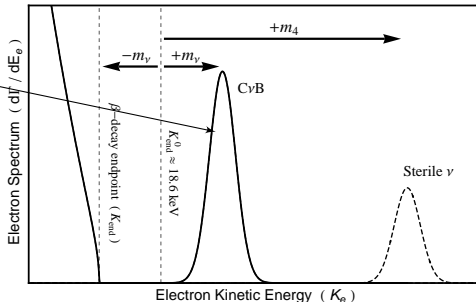
[Weinberg, 1962]: neutrino capture in β -decaying nuclei $\nu + n \rightarrow p + e^-$

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 ${}^3\text{H}$) + (high cross section of $\nu + {}^3\text{H} \rightarrow {}^3\text{He} + e^-$)

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

expected resolution $\Delta \simeq 0.1$ eVbuilt only for $C\nu B$ $M_T = 100$ g atomic tritiumcan probe $m_\nu \simeq 1.4\Delta \simeq 0.14$ eV(must distinguish $C\nu B$
events from β -decay ones)

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

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

Dirac:

(without clustering)

Majorana:

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

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

$$\Gamma_{C\nu B}^M = 2\Gamma_{C\nu B}^D$$

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

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Dirac: (without clustering) Majorana:

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ν clustering with N-one-body simulations

Milky Way (MW) matter attracts neutrinos!

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

$f_c(m_i)$ clustering factor \rightarrow How to compute it?

Idea from [Ringwald & Wong, 2004] \rightarrow **N-one-body** = $N \times$ single ν simulations

\rightarrow each ν evolved from initial conditions at $z = 3$

\rightarrow spherical symmetry, coordinates (r, θ, p_r, l)

\rightarrow need $\rho_{\text{matter}}(z) = \rho_{\text{DM}}(z) + \rho_{\text{baryon}}(z)$

Assumptions:

ν s are independent

only gravitational interactions

ν s do not influence matter evolution

$(\rho_\nu \ll \rho_{\text{DM}})$

how many ν s is "N"?

\rightarrow must sample all possible r, p_r, l

\rightarrow must include all possible ν s that reach the MW

(fastest ones may come from
several (up to $\mathcal{O}(100)$) Mpc!)

given $N \nu$:

\rightarrow weigh each neutrinos

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

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Dark matter: profiles today

NFW profile:

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

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

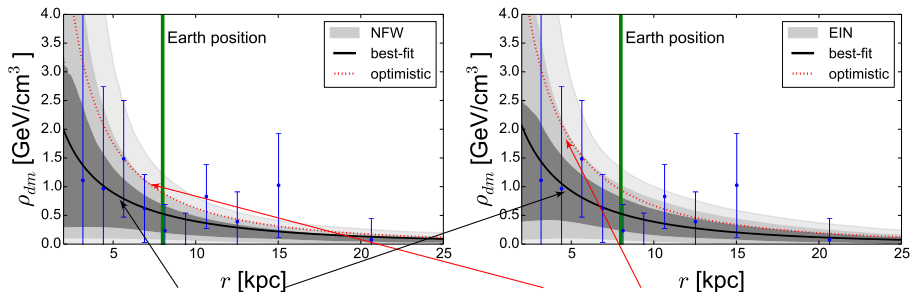
$$\mathcal{N}_{\text{NFW}}, r_s, \gamma$$

parameters

Einasto (EIN) profile:

$$\mathcal{N}_{\text{Ein}} = \rho_{\text{Ein}}(r_s)$$

$$\mathcal{N}_{\text{Ein}}, r_s, \alpha$$



Best-fit profiles

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

optimistic: close to 2σ upper limits

DM: Time evolution of the profiles

profile evolution from universe expansion

$$\rho_{\text{cr}}(z) = \frac{3}{8\pi G} H^2(z)$$

$$F_{\text{cr}}(z) = \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0}$$

$$H^2(z) = H_0^2 F_{\text{cr}}(z)$$

$$\rho_{\text{cr}}(z) = F_{\text{cr}}(z) \times \rho_{\text{cr}}(z=0)$$

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

(constant in time)

virial radius r_{vir} radius of sphere containing M_{vir} ,
average density $\Delta_{\text{vir}}(z) \times \rho_{\text{cr}}(z)$ but $\rho_{\text{DM}} = \rho_{\text{DM}}(r; r_s, \mathcal{N}, [\gamma|\alpha])$ relation between r_s and r_{vir} ?

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

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

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

final expression \implies

$$\rho_{\text{DM}}(r, z) = N(z) \tilde{\rho}_{\text{DM}}(r, r_s(z))$$

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

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

Baryons: the complexity of a structure

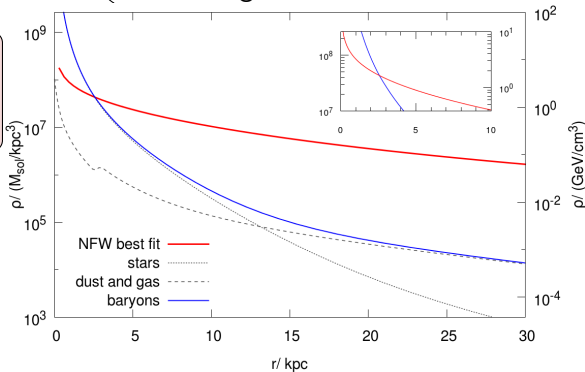
Complex problem: how to model baryon content of a galaxy?

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

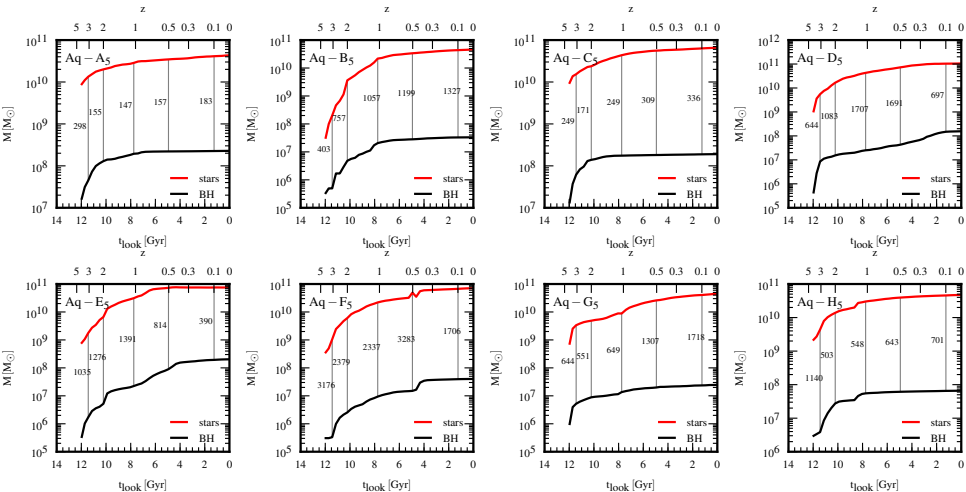
baryon evolution with redshift?

from [Marinacci et al., 2013]

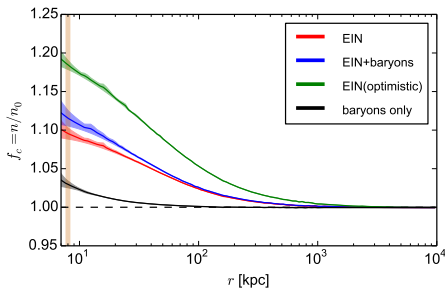
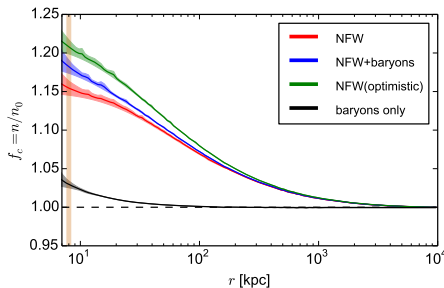
results of full N-body simulations

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

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



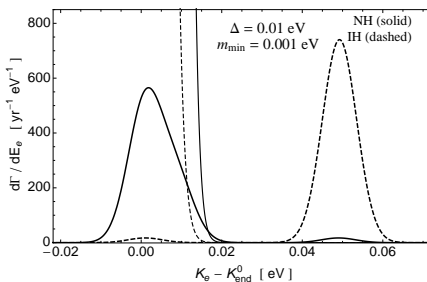
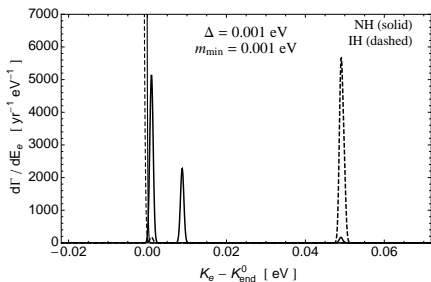
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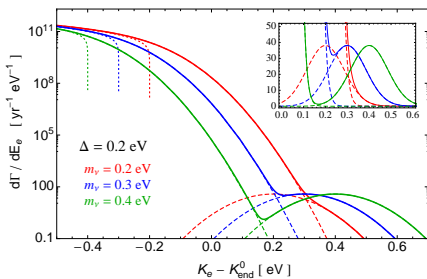
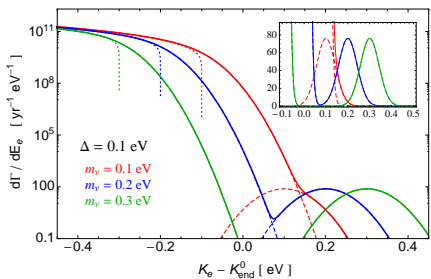
masses	ordering	matter halo	overdensity f_c		$\Gamma_{\text{tot}}^D \text{ (yr}^{-1}\text{)}$	$\Gamma_{\text{tot}}^M \text{ (yr}^{-1}\text{)}$
			$f_1 \simeq f_2$	f_3		
any	any	any	no clustering		4.06	8.12
$m_3 = 60 \text{ meV}$	NO	NFW(+bar)	~ 1	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	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
$m_1 \simeq m_2 = 60 \text{ meV}$	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 $\Gamma_{\text{C}\nu\text{B}} = \sum_{i=1}^3 |U_{ei}|^2 f_i [n_i(\nu_{hR}) + n_i(\nu_{hL})] N_T \bar{\sigma}$

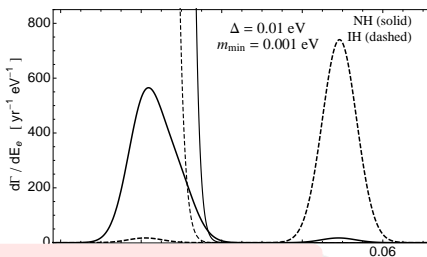
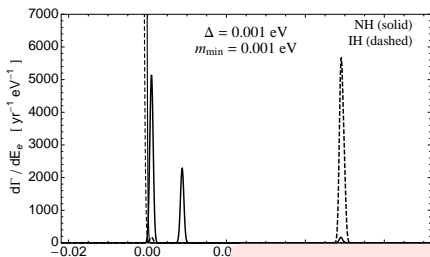
Hierarchical:



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

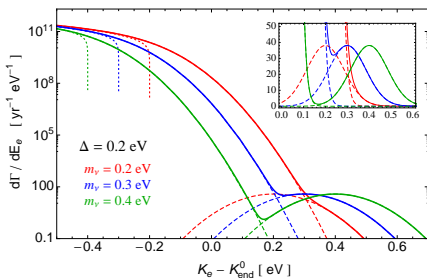
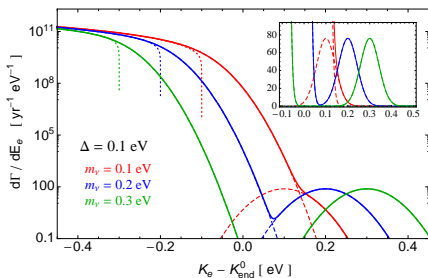


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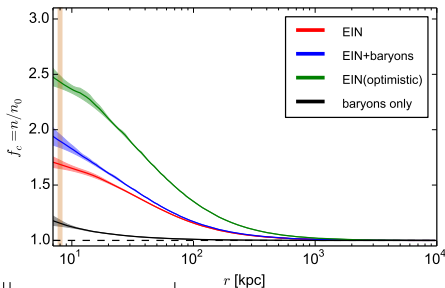
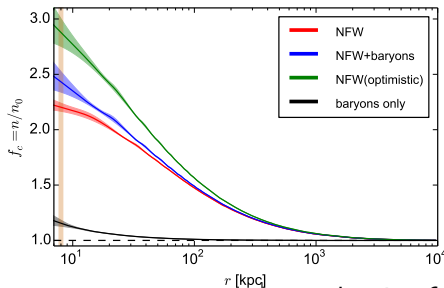


PTOLEMY cannot detect $m_\nu \lesssim 0.15 \text{ eV}$!

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



\Rightarrow minimal mass detectable by PTOLEMY if $\Delta \simeq 100\text{--}150$ meV



matter halo	overdensity f_c $f_1 \simeq f_2 \simeq f_3$	Γ_{tot}^D (yr $^{-1}$)	Γ_{tot}^M (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: $m_1 \simeq m_2 \simeq m_3 \Rightarrow f_1 \simeq f_2 \simeq f_3$

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Conclusions

- Cosmic Neutrino Background (C ν B) predicted but not detected:
 - only $N_{\text{eff}} \simeq 3.04$ 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 ?)