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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)

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

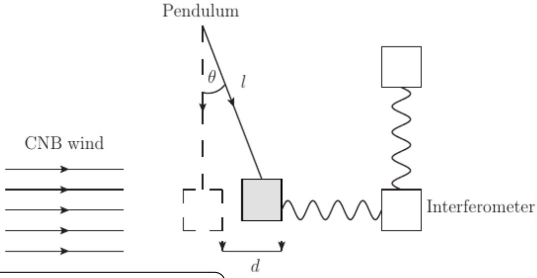
Direct detection - proposed methods - at interferometers

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

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 $\longrightarrow$ a process without energy threshold is necessary

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

[Cocco et al., 2009]

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

(e^- from inner level)

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

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

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

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 $\longrightarrow$ a process without energy threshold is necessary

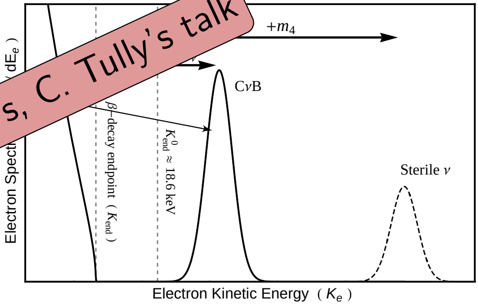
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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 $\nu +^3 \mathrm{H} \to ^3 \mathrm{He} + e^-$)

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)

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

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

(without clustering)

Dirac:

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

Majorana:

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

$$\Gamma^{M}_{\mathrm{C}\nu\mathrm{B}} = 2\Gamma^{D}_{\mathrm{C}\nu\mathrm{B}}$$

PTOLEMY

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ehnancement from ν clustering in the galaxy?

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

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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

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

$f_c(m_i) = n_i / n_{i,0}$ 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 $\rho_{\rm matter}(z) = \rho_{\rm DM}(z) + \rho_{\rm baryon}(z)$

Assumptions:

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

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

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

Reweighting neutrinos

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ϕ independent of relic neutrinos

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

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

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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

NFW profile: | Einasto (EIN) profile:

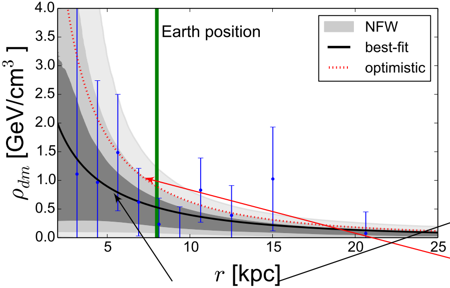
$$\mathcal{N}_{\rm NFW}\left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma} = \rho_{\rm DM}(r) = \mathcal{N}_{\rm Ein}\exp\left\{-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha}-1\right)\right\}$$

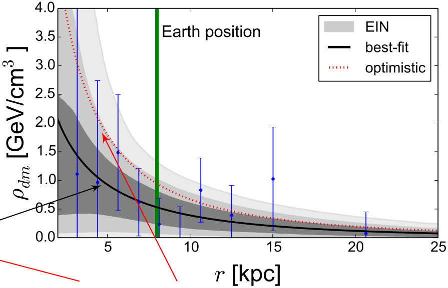
normalization

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

parameters

$\mathcal{N}_{\rm NFW}$, r_s, γ | $\mathcal{N}_{\rm Ein}$, r_s, α





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]

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

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

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

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

$\tilde\rho_{\rm DM}$ 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

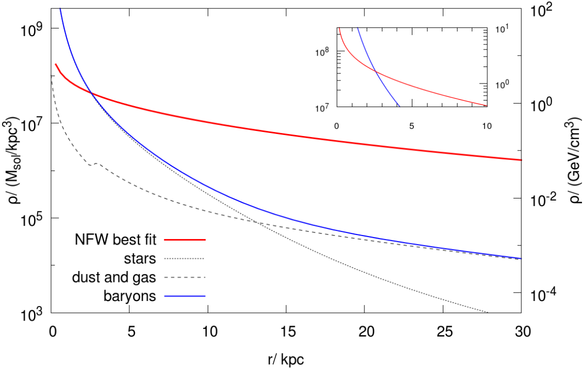
Complex problem: how to model baryon content of a galaxy?

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

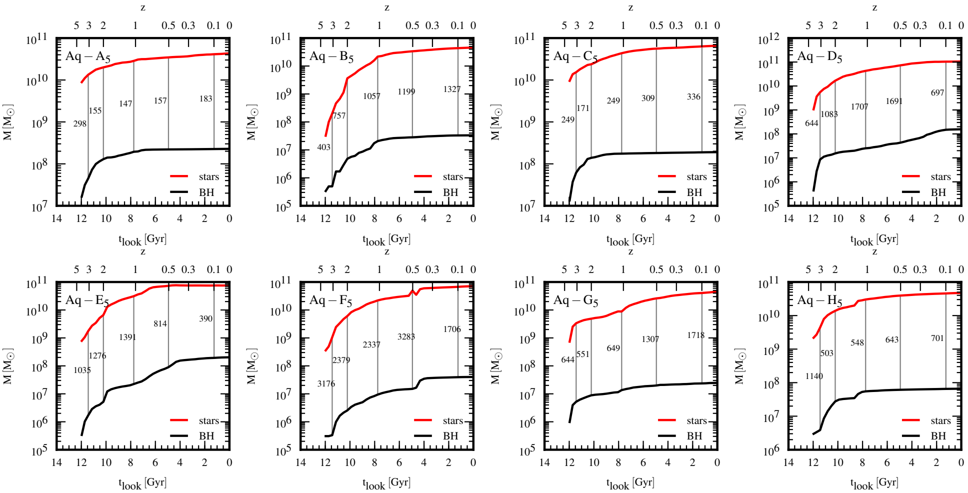
baryon evolution with redshift?

from [Marinacci et al., 2013]

results of full N-body simulations

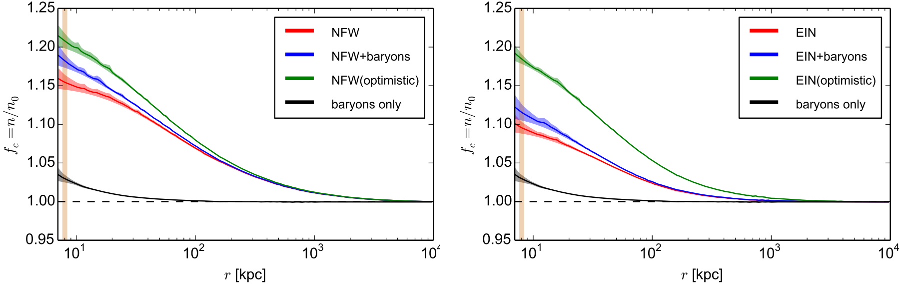
$\mathcal{N}_{\rm bar}(z)$ from $M(z)$

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



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

[JCAP 09 (2017) 034]



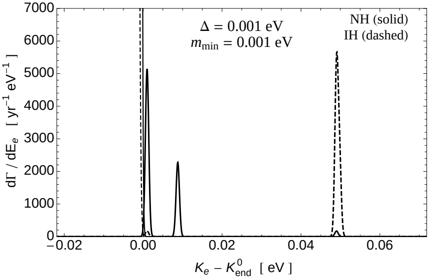
masses	ordering	matter halo	overdensity f_c: $f_1 \simeq f_2$	overdensity f_c: f_3	Γ^D_{tot} (yr^{-1})	Γ^M_{tot} (yr^{-1})
any	any	any	no clustering		4.06	8.12
$m_3 = 60$ meV	NO	NFW(+bar)	∼1	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	4.08	8.16
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)	8.14 (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

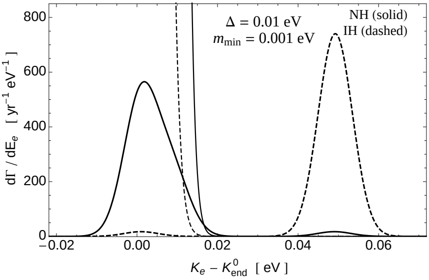
ordering dependence from $\Gamma_{C\nu B} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \left[n_i(\nu_{h_R}) + n_i(\nu_{h_L})\right] N_T \bar{\sigma}$

Energy resolution and event rate

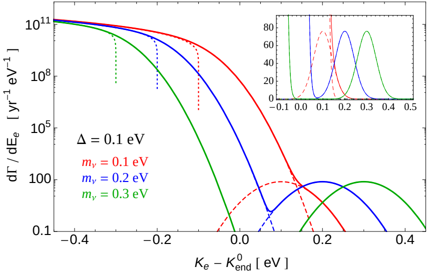
[Long et al., JCAP 08 (2014) 038]

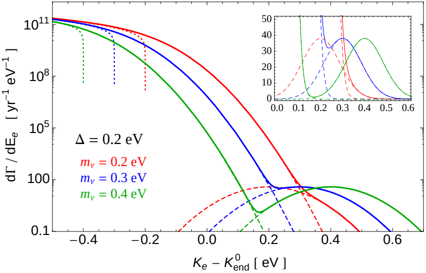
Hierarchical:





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





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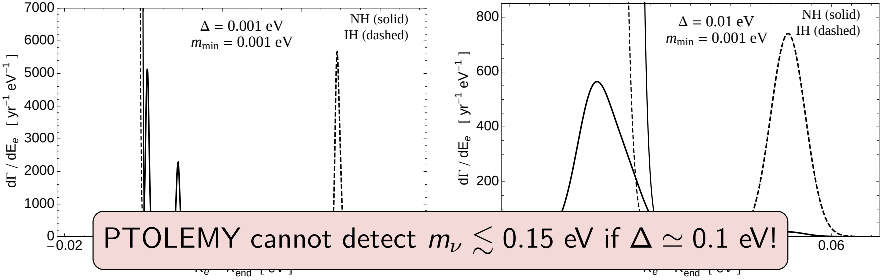
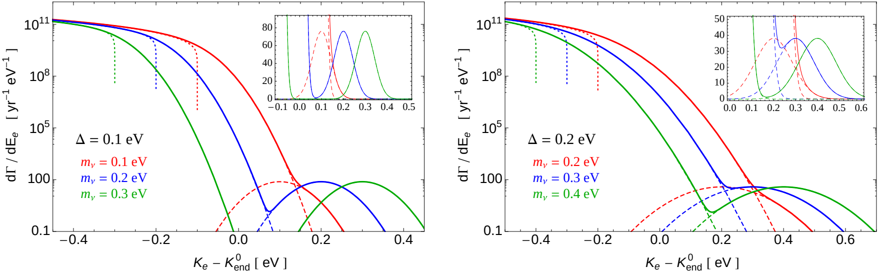


PTOLEMY cannot detect $m_\nu \lesssim 0.15$ eV if $\Delta \simeq 0.1$ eV!

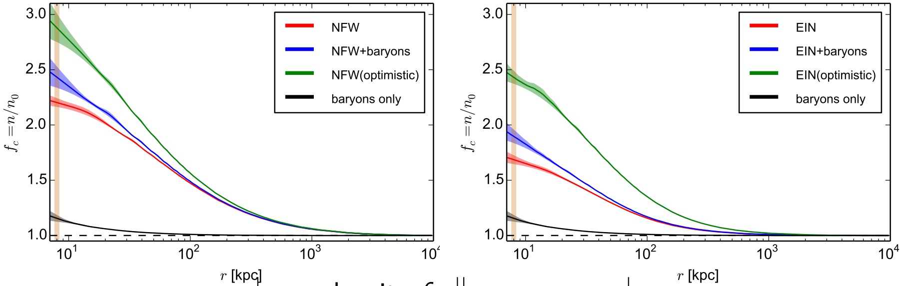
Degenerate: (solid: measured, dotted: ideal with $\Delta = 0$)



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

[JCAP 09 (2017) 034]

Additional clustering due to other galaxies

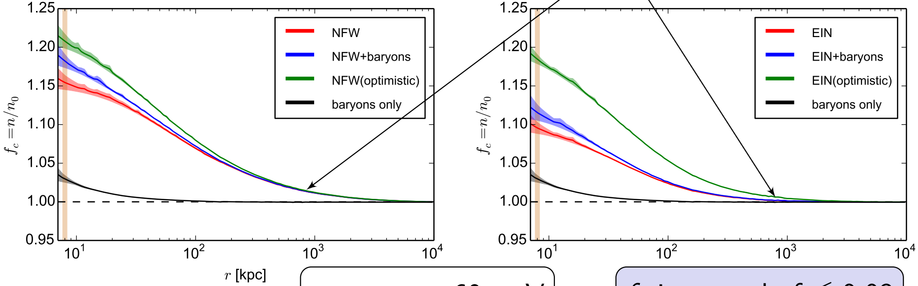
nearest galaxies: various MW satellites

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

nearest big galaxy:

Andromeda

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



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

Additional clustering due to other galaxies

[JCAP 09 (2017) 034]

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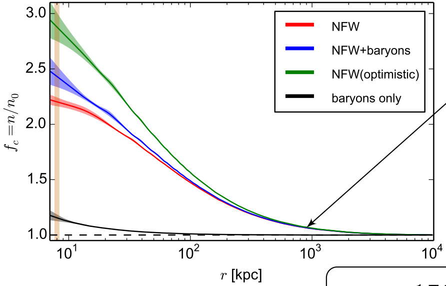
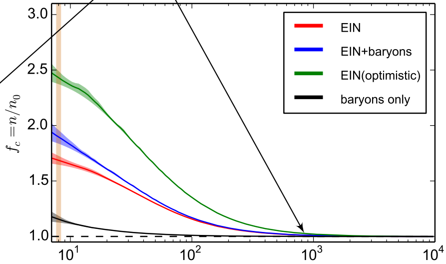




$m_\nu \simeq 150$ meV ⟶ f_c increased of $\lesssim 0.1$

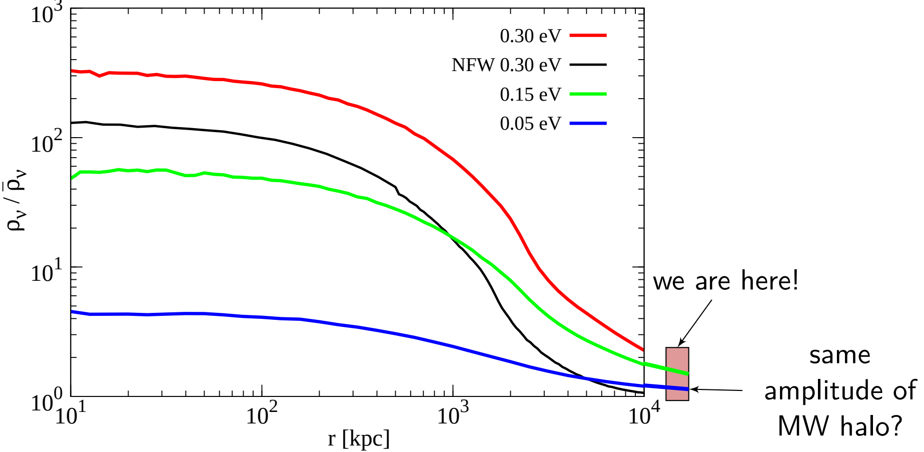
(halo is less diffuse for higher ν masses)

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



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

Short Baseline (SBL) anomaly

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

Problem: anomalies in SBL experiments ⇒ { errors in flux calculations? / deviations from 3-ν description? }

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

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

See also [SG et al., 2017]

3+1 Neutrino Model

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

$\downarrow$

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

$\downarrow$

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

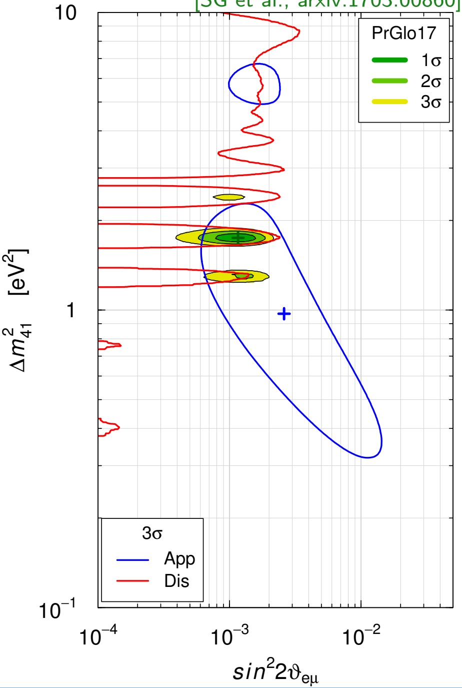
$$\nu_\alpha = \sum_{k=1}^{3+1} U_{\alpha k}\nu_k \quad (\alpha = e, \mu, \tau, s)$$

ν_s is mainly ν_4:
$$m_s \simeq m_4 \simeq \sqrt{\Delta m^2_{41}} \simeq \sqrt{\Delta m^2_{\rm SBL}}$$

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

can ν_4 thermalize in the early Universe through oscillations?

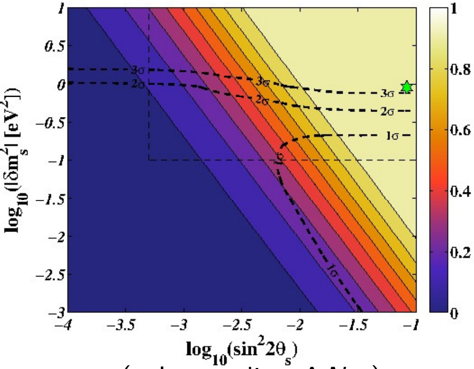
[SG et al., arxiv:1703.00860]



LSν thermalization

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

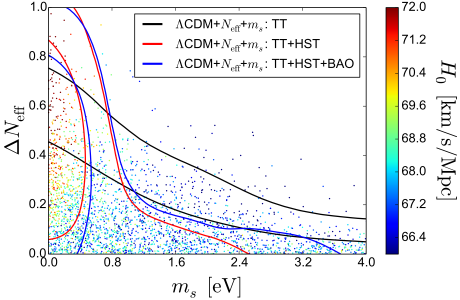
[Hannestad et al., JCAP 1207 (2012) 025]



(colors coding $\Delta N_{\rm eff}$)

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

but cosmological fits give:



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

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

[to be precise: $\Delta N_{\rm eff}$ 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)

→

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

↓

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

↙

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

↓

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

($f_c(m_4)$ is independent of $\Delta N_{\rm eff}$)

↓

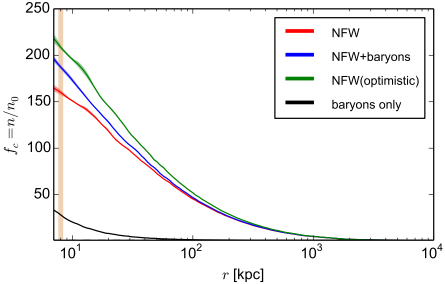
$$\Gamma_4^{M(D)} \simeq |U_{e4}|^2\,\Delta N_{\rm eff}\, f_c(m_4)\,\Gamma_{\rm C\nu B}^{M(D)}$$

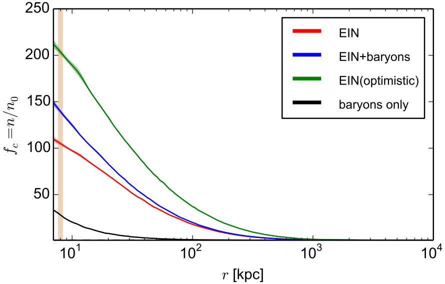
(from global fit [SG et al., 2017]: $m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$)

Overdensity of a sterile neutrino

[JCAP 09 (2017) 034]

$$\Gamma_4^{M(D)} \simeq \Delta N_{\rm eff}\,|U_{e4}|^2\, f_c(m_4)\,\Gamma_{\rm C\nu B}^{M(D)} \qquad m_4 \simeq 1.3 \text{ eV},\ |U_{e4}|^2 \simeq 0.02$$





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 1.0	2.6 (3.0) 13.0 (15.2)	5.2 (6.1) 26.0 (30.4)
NFW optimistic	208.6	0.2 1.0	3.4 16.9	6.8 33.9
EIN(+bar)	105.1 (139.5)	0.2 1.0	1.7 (2.3) 8.5 (11.3)	3.4 (4.5) 17.1 (22.7)
EIN optimistic	203.5	0.2 1.0	3.3 16.5	6.6 33.0

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)

Conclusions

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direct detection event rate depends on
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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

Conclusions

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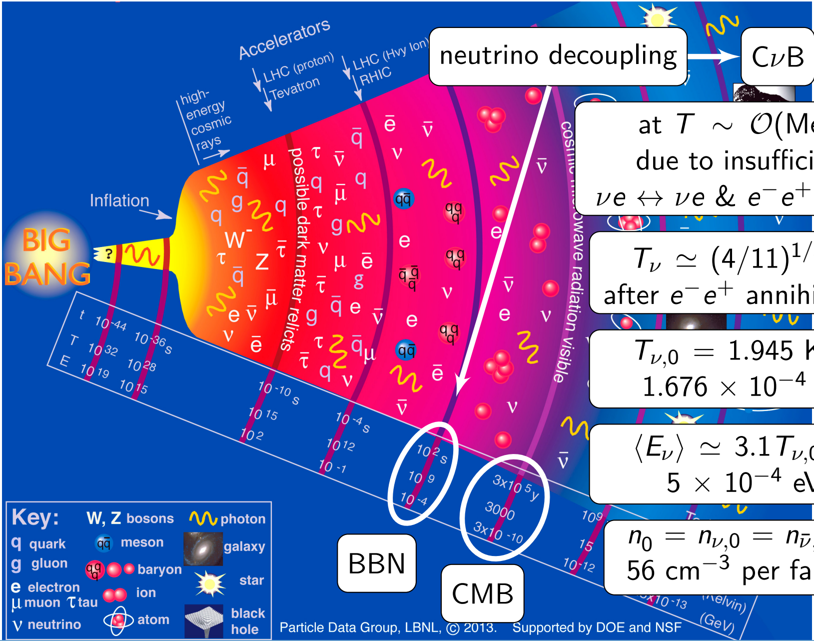
Thank you for the attention!

6 Backup slides

History of the universe



neutrino decoupling → $C\nu B$

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

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

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

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

BBN

CMB

History of the universe

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

many relic neutrinos are non-relativistic today!

neutrino decoupling → CνB

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$\nu e \leftrightarrow \nu e$ & $e^- e^+ \leftrightarrow \nu\bar{\nu}$

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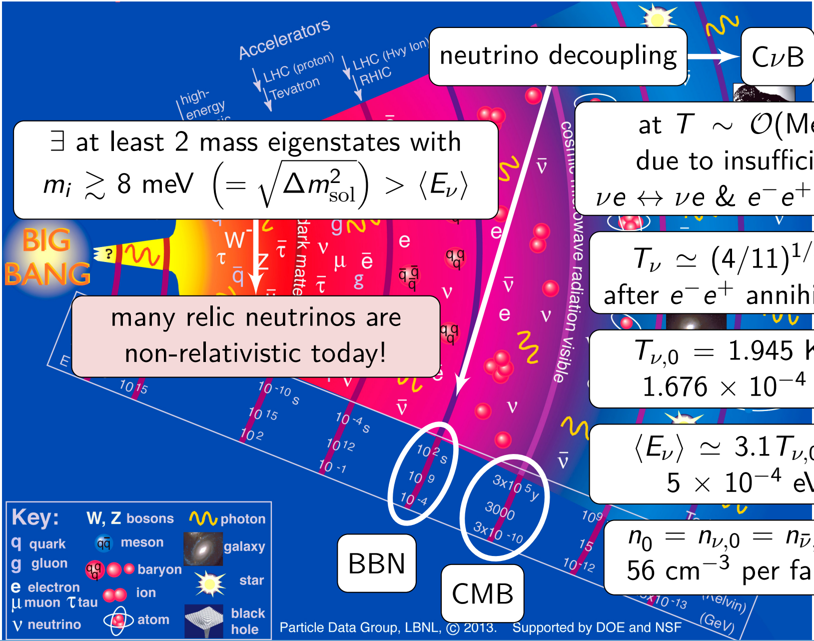

CνB: Dirac vs Majorana

[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: $n_{C\nu B} \simeq 6n_0$ ⟷ 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

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	

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

- $N_{\rm eff} \rightarrow$ 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!

Equations for the neutrino clustering

Lagrangian for a neutrino (m_ν) in a gravitational potential well $\phi(\mathbf{x},\tau)$:

$$L\left(r,\theta,\dot{r},\dot{\theta},\tau\right) \quad = \quad \frac{a}{2} m_\nu \left(\dot{r}^2 + r^2\dot{\theta}^2 - 2\,\phi(r,\tau)\right)$$

Hamiltonian: $H\left(r,\theta,p_r,l,\tau\right) \;=\; \frac{1}{2am_\nu}\left(p_r^2 + \frac{l^2}{r^2}\right) \;+\; am_\nu\phi(r,\tau)$

Canonical momenta: $p_r \;=\; \frac{\partial L}{\partial \dot{r}} \;=\; am_\nu \dot{r}, \qquad l \;=\; rp_\theta \;=\; \frac{\partial L}{\partial \dot{\theta}} \;=\; am_\nu r^2\dot{\theta}$

Hamilton equations:

$$\frac{\partial H}{\partial p_r} = \frac{dr}{d\tau} = \frac{p_r}{am_\nu} \qquad \frac{\partial H}{\partial l} = \frac{d\theta}{d\tau} = \frac{l}{am_\nu r^2}$$

$$-\frac{\partial H}{\partial r} = \frac{dp_r}{d\tau} = \frac{l^2}{am_\nu r^3} - am_\nu\frac{\partial\phi}{\partial r} \qquad -\frac{\partial H}{\partial\theta} = \frac{dl}{d\tau} = 0$$

Gravitational potential: $\phi(r,\tau)$

Known from the Poisson equation $\nabla^2\phi \;=\; \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\phi}{\partial r}\right) \;=\; 4\pi G a^2 \rho_{\mathrm{matter}}\left(r,\tau\right)$

$$\frac{\partial\phi}{\partial r} \;=\; \frac{G}{ar^2} M_{\mathrm{matter}}(r,\tau), \qquad M_{\mathrm{matter}}(r,\tau) \;=\; 4\pi a^3 \int_0^r \rho_{\mathrm{matter}}(r',\tau) r'^2 dr'$$

Reconstruction of $n(r)$ from N-one-body neutrinos

[Merritt et al., 1994]
[Ringwald et al., 2004]

sample neutrino i starts in (r, p_r, p_T)

each ν is representative of a bin between $(r_a, p_{r,a}, p_{T,a})$ and $(r_b, p_{r,b}, p_{T,b})$

→ weight of the neutrino i: $w_i = \int_{(r,p_r,p_T)_a}^{(r,p_r,p_T)_b} \int_{\theta,\phi,\varphi} dN =$

$$w_i = 8\pi^2 T_{\nu,0}^3 \int_{r_a}^{r_b} r^2 dr \int_{y_a}^{y_b} f(y) y^2 dy \int_{\psi_a}^{\psi_b} \sin\psi d\psi$$

$f(y)$ Fermi-Dirac

(given that $p_r = p\cos\psi$, $p_T = p\sin\psi$ and $y = p/T_{\nu,0}$)

How to reconstruct the number density?

ν_i smeared around the surface of a sphere with radious r_i centered in $r = 0$,

gaussian kernel: $K(r, r_i, h) = \frac{1}{2(2\pi)^{3/2}} \frac{h^2}{r \cdot r_i} \left[e^{-(r-r_i)^2/2h^2} - e^{-(r+r_i)^2/2h^2}\right]$

$$n(r) = \sum_{i=1}^{N} \frac{w_i}{h^3} K(r, r_r, h)$$

h window width

Relating r_s and r_{vir}

$$\Delta_{\rm vir}(z) = \begin{cases} 200 & \text{for EIN,} \\ 18\pi^2 + 82\lambda(z) - 39\lambda(z)^2 & \text{for NFW.} \end{cases}$$
$$\lambda(z) = \Omega_m(z) - 1$$

$\longrightarrow$ from evolution of top-hat perturbation [Bryan et al., 1998]

$$M_{\rm vir} = \frac{4\pi}{3}\Delta_{\rm vir}(z)\rho_{\rm cr}(z)a^3 r^3_{\rm vir}(z) \longleftrightarrow M_{\rm vir} = 4\pi a^3 \int_0^{r_{\rm vir}(z)} \rho_{\rm DM}(r', z) r'^2 dr'$$

$\longrightarrow$ relation between $M_{\rm vir}$ and $r_{\rm vir}(0)$ $\longleftarrow$

$$c_{\rm vir}(M_{\rm vir}, z) \equiv r_{\rm vir}(z)/r_{\rm s}(z) \longrightarrow \text{relation between } r_{\rm vir}(z) \text{ and } r_{\rm s}(z)$$

$\longrightarrow$ from N-body simulations [Dutton et al., 2014]:

$$\begin{cases} \log_{10} c_{\rm vir}^{\rm average}(M_{\rm vir}, z) = a(z) + b(z)\log_{10}(M_{\rm vir}/[10^{12}h^{-1}M_\odot]) \\ + \\ c_{\rm vir}(M_{\rm vir}, z) = \beta \times c_{\rm vir}^{\rm average}(M_{\rm vir}, z) \text{ for each real object} \end{cases}$$

$\beta \simeq \mathcal{O}(1)$ from $M_{\rm vir}$, $r_{\rm vir}(0)$, $r_{\rm s}(0)$, $c_{\rm vir}^{\rm average}(M_{\rm vir}, 0)$

(computed for different the DM profiles)