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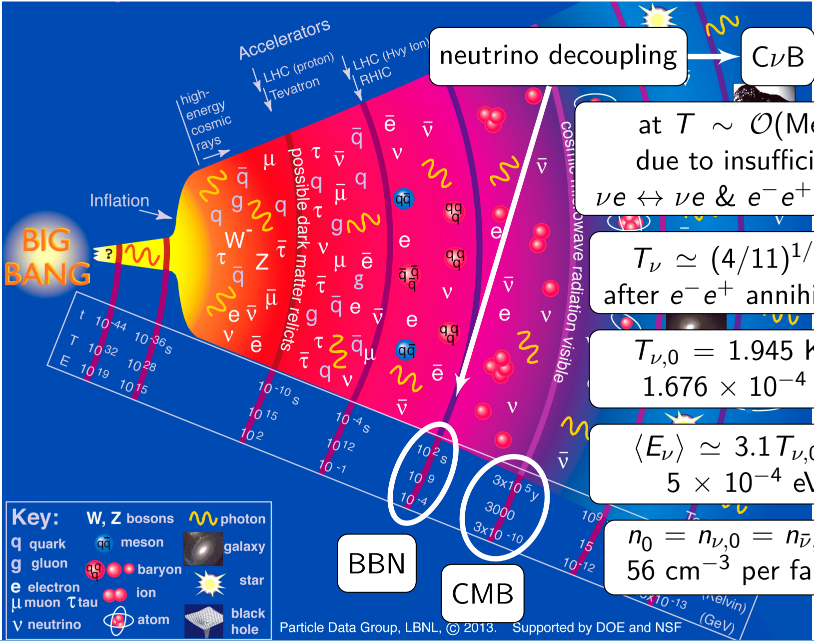
Relic neutrinos, direct detection and clustering in the Milky Way

With a focus on the PTOLEMY proposal

21/12/2017 - Seminar at the Physics Department - Torino (IT)

History of the universe



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

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

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

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

BBN

CMB

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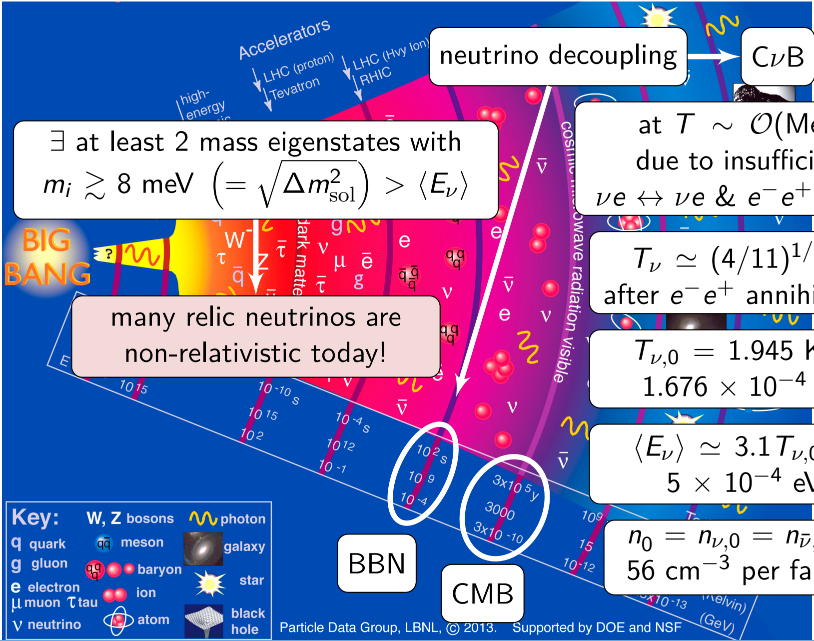

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$\exists$ at least 2 mass eigenstates with $m_i \gtrsim 8$ meV $\left(= \sqrt{\Delta m^2_{\text{sol}}}\right) > \langle E_\nu \rangle$

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:

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

$\bar{\nu}_L,\ n(\bar{\nu}_L) \simeq 0$

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

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

NOTE: free-streaming conserves helicity, not chirality!

because neutrinos are massive and become non-relativistic during expansion

Dirac:

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

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

only left-helical!

Majorana:

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

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

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!

Cosmological mass bounds

Cosmology can constrain also $M_\nu = \sum m_\nu$

standard

based on ΛCDM model

[Planck Collaboration 2015, AA594 (2016) A13]

95%
$M_\nu < 0.72$ eV (PlanckTT+lowP)
$M_\nu < 0.21$ eV (+BAO)
$M_\nu < 0.49$ eV (PlanckTTTEEE+lowP)
$M_\nu < 0.17$ eV (+BAO)

see also:

[Vagnozzi et al., PRD96 (2017) 123503]

[Planck Collaboration 2016, AA596 (2016) A107]

95%
$M_\nu < 0.59$ eV (PlanckTT+SimLow)
$M_\nu < 0.17$ eV (+BAO)
$M_\nu < 0.34$ eV (PlanckTTTEEE+SimLow)
$M_\nu < 0.14$ eV (+BAO)

(SimLow not public yet)

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Modified gravity?

[Barreira et al., 2014]:

νGalileon

68%
$M_\nu = 0.98 \pm 0.24$ eV (CMB)
$M_\nu = 0.65 \pm 0.11$ eV (CMB+BAO)

[Bellomo et al., 2016]:

95%
Horndeski scalar-tensor
$M_\nu < 0.76$ eV

[Dirian, 2017]:

68%
nonlocal gravity
$M_\nu = 0.21 \pm 0.08$ eV

[Peirone et al, 2017]:

68%
Covariant Galileon
$M_\nu = 0.8 \pm 0.1$ eV

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

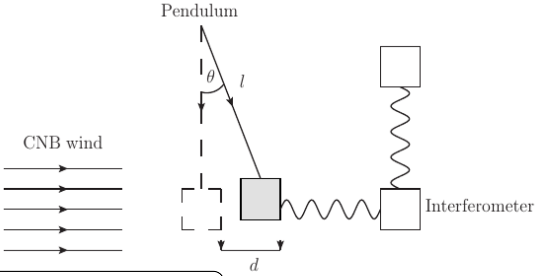
Direct detection - proposed methods - at interferometers

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

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

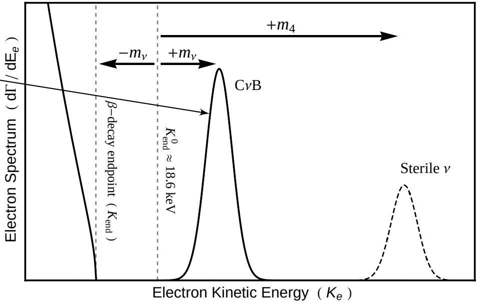
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

Main background: β decay $n \to p + e^- + \bar{\nu}$!

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

only with a lot of material

need a very good energy resolution



What material?

[Cocco et al., JCAP 06 (2007) 015]

best element has highest $\sigma_{\rm NCB}(v_\nu/c) \cdot t_{1/2}$

to minimize contamination from β decay background

Isotope	Decay	Q_β (keV)	Half-life (s)	$\sigma_{\rm NCB}(v_\nu/c)$ (10^{-41} cm^2)
^{3}H	β^-	18.591	3.8878×10^8	7.84×10^{-4}
^{63}Ni	β^-	66.945	3.1588×10^9	1.38×10^{-6}
^{93}Zr	β^-	60.63	4.952×10^{13}	2.39×10^{-10}
^{106}Ru	β^-	39.4	3.2278×10^7	5.88×10^{-4}
^{107}Pd	β^-	33	2.0512×10^{14}	2.58×10^{-10}
^{187}Re	β^-	2.64	1.3727×10^{18}	4.32×10^{-11}
^{11}C	β^+	960.2	1.226×10^3	4.66×10^{-3}
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^{18}F	β^+	633.5	6.809×10^3	2.63×10^{-3}
^{22}Na	β^+	545.6	9.07×10^7	3.04×10^{-7}
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^{3}H better because the cross section ($\rightarrow$ event rate) is higher

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 of atomic ^{3}H

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

(must distinguish CνB events from β-decay ones)

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

N_T number of ^{3}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

Dirac: (without clustering) Majorana:

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

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PTOLEMY

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Majorana:

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ehnancement from ν clustering in the galaxy?

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Status of PTOLEMY

[Cocco et al., 2007] theoretical basis for the experiment

[Betts et al., arxiv:1307.4738] first proposal – Princeton based

Sept 2017: first Letter of Intent (LoI) submitted to LNGS

11–12 Dec '17: "Kick-off meeting of the PTOLEMY project", at LNGS
`https://agenda.infn.it/conferenceDisplay.py?ovw=True&confId=14222`

→ summary of current status

→ reunite interested people from different communities

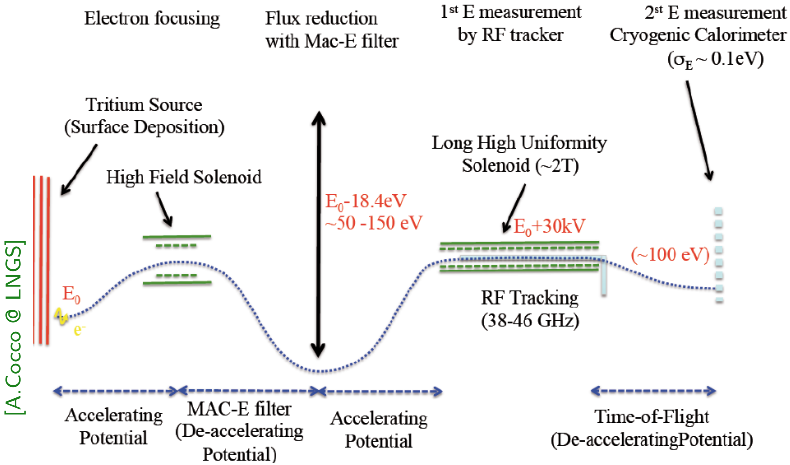
→ Extended LoI expected for April 2018 (LNGS scientific committee meeting)

PTOLEMY pipeline

scope of PTOLEMY:

measure electron spectrum near ^{3}H β-decay endpoint

(same as neutrino mass experiments as KATRIN)



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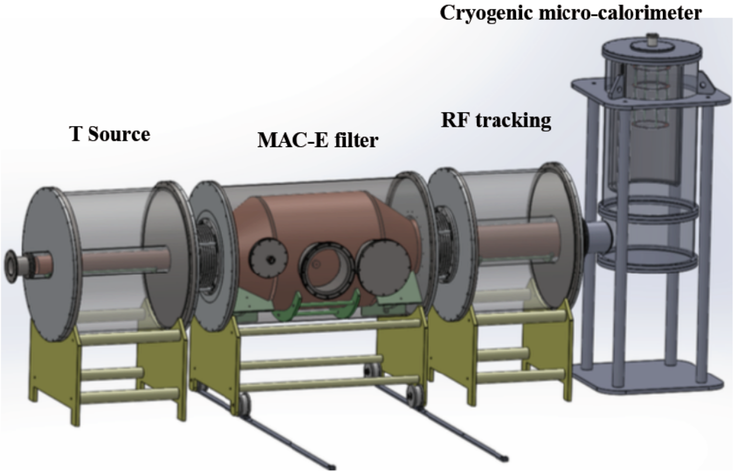

[A.Cocco @ LNGS]

The source - graphene

source of ^{3}H in gas form (KATRIN-like) has column density $\sim 1\,\mu$g cm^{-2}
source tube is 10 m for $\sim \mathcal{O}(100)$ μg of ^{3}H

not practical solution for required 100 g of ^{3}H!

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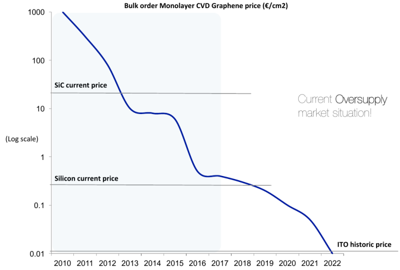
partially existing technology: hydrogenated graphene

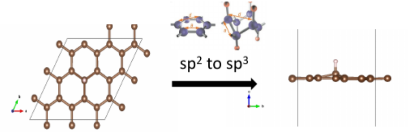
layers

Graphene layers are cheap
(commercial use in displays)

hydrogenation under study
at Princeton



[A.Zurutuza @ LNGS]



[F.Zhao @ LNGS]

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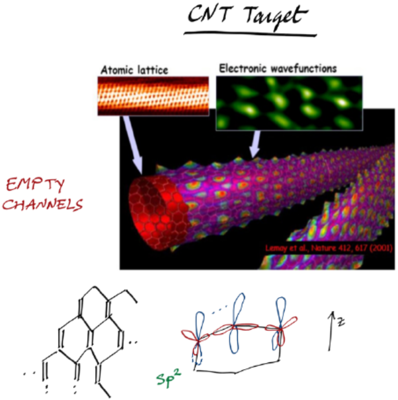
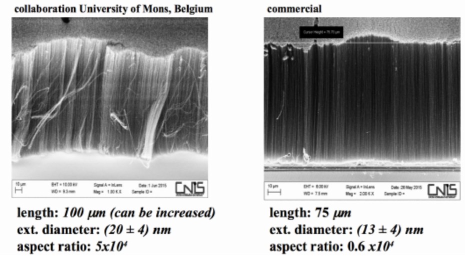
nanotubes



[G.Cavoto @ LNGS]

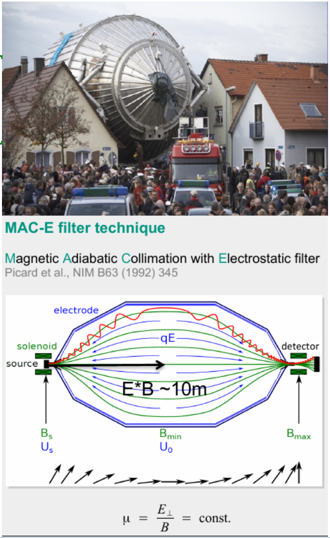


MAC-E filter

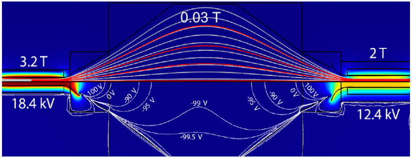
Background flux is too high for microcalorimeter. Must be reduced!

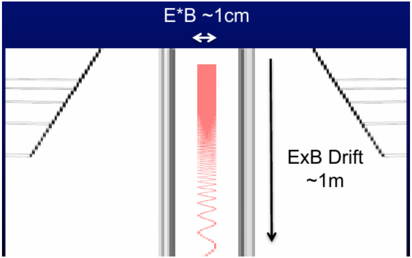
Magnetic Adiabatic Collimation with Electrostatic filter

[KATRIN]



[PTOLEMY]: $E \times B$ filter
(must enter in GS labs)





[C.Tully @ LNGS]

RF tracking

first energy determination with

RadioFrequency trigger, using
Cyclotron Radiation Emission Spectroscopy (CRES)

see also [Project 8, arxiv:1703.02037]

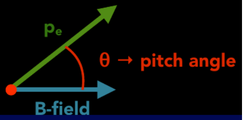
[C.Tully @ LNGS]

Larmor formula

$$P(\gamma,\theta) = \frac{1}{4\pi\varepsilon_0}\frac{2}{3}\frac{q^4B^2}{m_e^2}(\gamma^2-1)\sin^2\theta$$

Emitted power

- 1.1 fW for 18 keV e⁻ at 90°



PTOLEMY ExB Filter is a natural harmonic trap
- B field is dropping adiabatically as the electrons drift radially
- Drift velocity has to be adjusted so that number of bounces is roughly ~20,000 per FFT/Trigger decision

RF tracking

first energy determination with

RadioFrequency trigger, using
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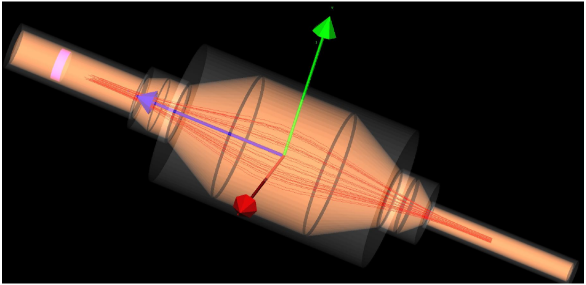
see also [Project 8, arxiv:1703.02037]

can RF antenna be integrated in the MAC-E filter?



GEANT-4 simulation

[A.Cocco @ LNGS]

Final energy determination with TES

Final energy determination needs $\sigma_E \simeq 0.1$ eV or less!

Microcalorimetry with Transition-Edge Sensors

TES: "*A microcalorimeter*
made by a superconducting film
operated in the temperature region
between the normal and the superconducting state"

↙ difficult readout

↘ difficult temperature control

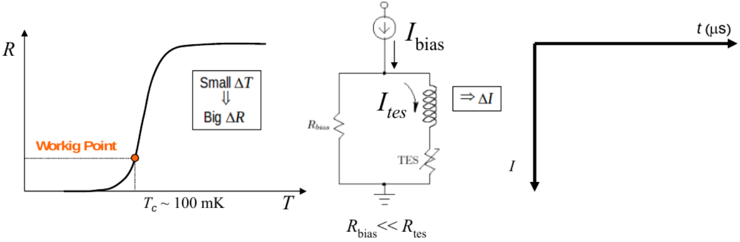
Torino contributing through INRIM facilities
Nanoscience and Materials division

Final energy determination with TES

Final energy determination needs $\sigma_E \simeq 0.1$ eV or less!

Microcalorimetry with Transition-Edge Sensors

[M.Ratjeri (INRIM) @ LNGS]



Final energy determination with TES

Final energy determination needs $\sigma_E \simeq 0.1$ eV or less!

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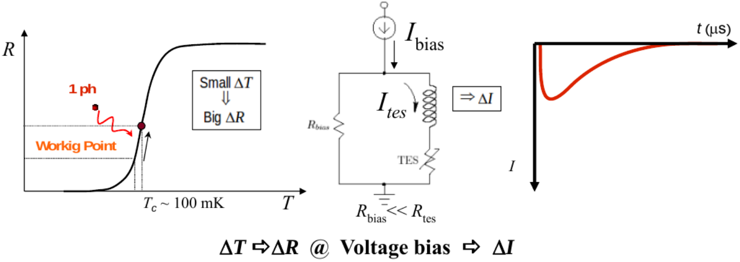

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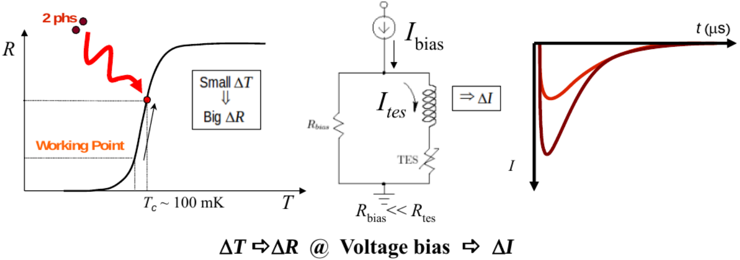

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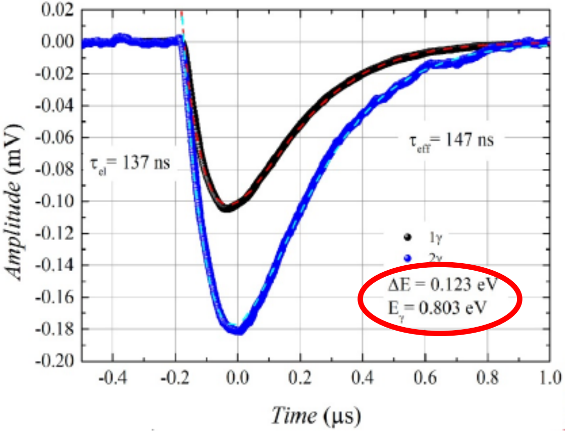
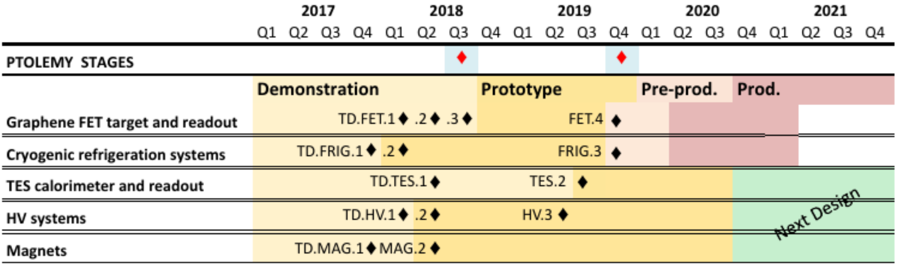


PTOLEMY Milestones

(Depending on fundings...)



[Sept '17 LoI]

ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

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

Idea from [Ringwald & Wong, 2004] ⟶ N-one-body= N $\times$ 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]

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

Reweighting neutrinos

[Zhang&Zhang, arxiv:1712.01153]

Hamilton equations for neutrino motion in a plane:

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

$\tau = dt/a$ 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 $u_r \equiv p_r/m_\nu$, $u_\theta \equiv \ell/m_\nu$

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

Reweighting neutrinos

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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:**

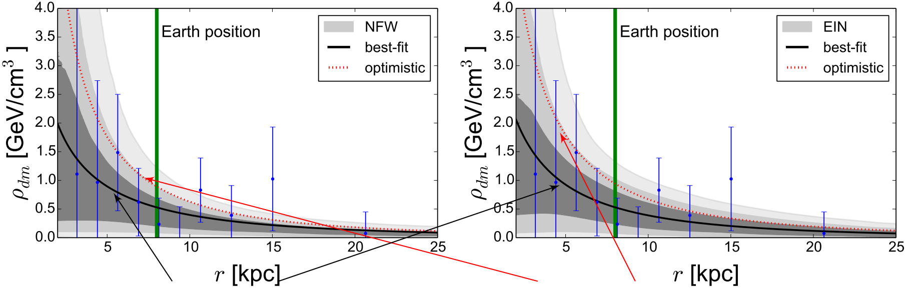
$$\mathcal{N}_{\rm NFW}\left(\frac{r}{r_s}\right)^{-\gamma}\left(1+\frac{r}{r_s}\right)^{-3+\gamma} = \boxed{\rho_{\rm DM}(r)} = \mathcal{N}_{\rm Ein}\exp\left\{-\frac{2}{\alpha}\left(\left(\frac{r}{r_s}\right)^{\alpha}-1\right)\right\}$$

normalization:

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

parameters:

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



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

$\tilde\rho_{\rm DM}$ 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

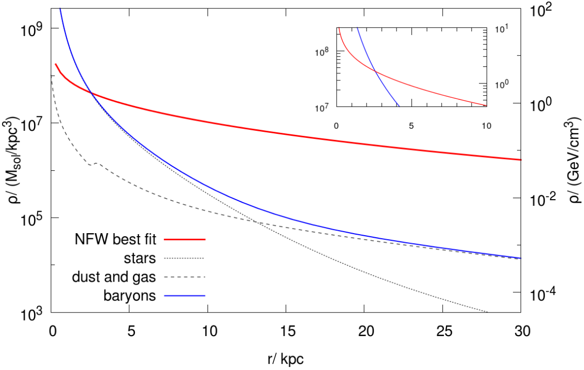
Complex problem: how to model baryon content of a galaxy?

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

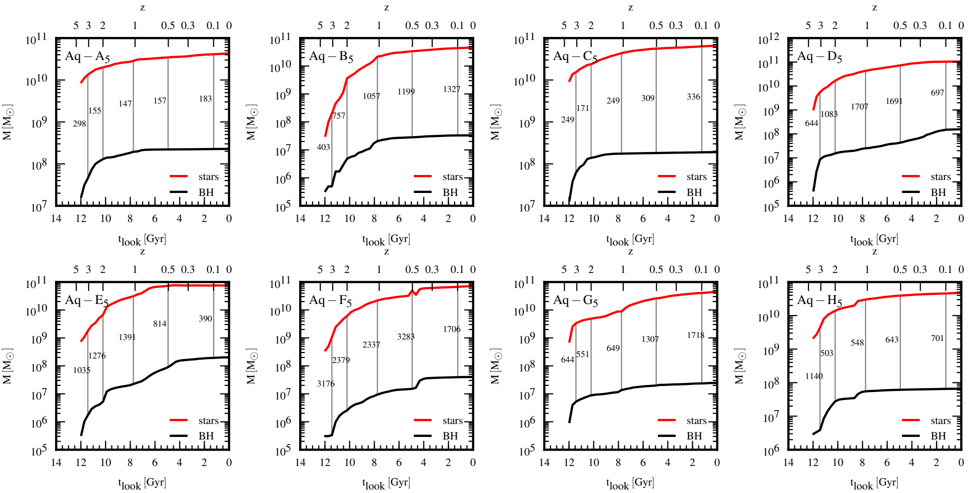
baryon evolution with redshift?

from [Marinacci et al., 2013]

results of full N-body simulations

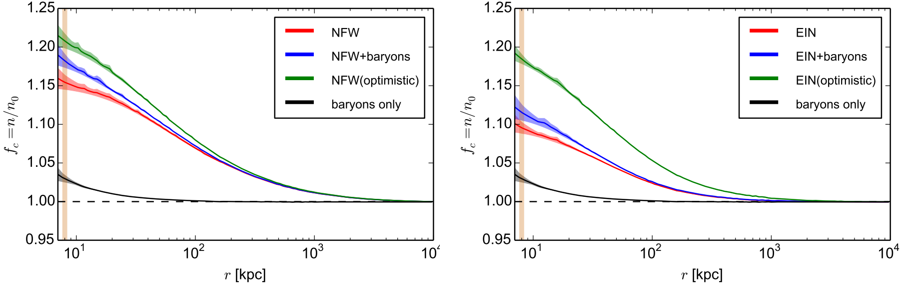
$\mathcal{N}_{\rm bar}(z)$ from $M(z)$

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]



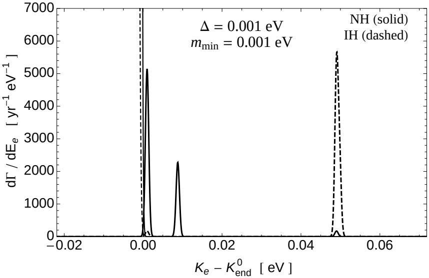
masses	ordering	matter halo	overdensity f_c $f_1 \simeq f_2$	f_3	Γ^D_{tot} (yr^{-1})	Γ^M_{tot} (yr^{-1})
any	any	any	no clustering		4.06	8.12
$m_3 = 60$ meV	NO	NFW(+bar)	$\sim$1	1.15 (1.18)	4.07 (4.08)	8.15 (8.15)
		NFW optimistic		1.21	4.08	8.16
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)	8.14 (8.14)
		EIN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

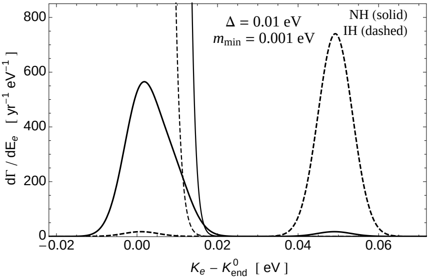
ordering dependence from $\Gamma_{\text{C}\nu\text{B}} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \left[n_i(\nu_{h_R}) + n_i(\nu_{h_L})\right] N_T \bar{\sigma}$

Energy resolution and event rate

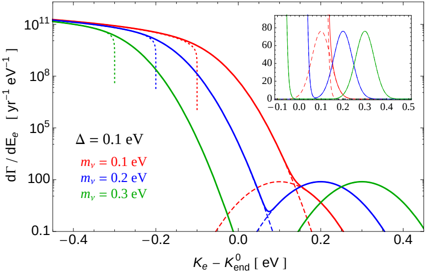
[Long et al., JCAP 08 (2014) 038]

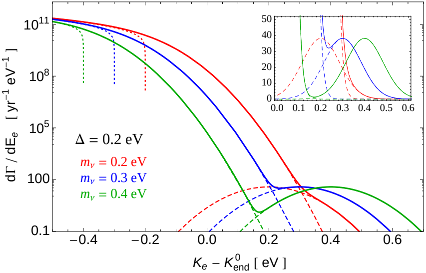
Hierarchical:





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





Energy resolution and event rate

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

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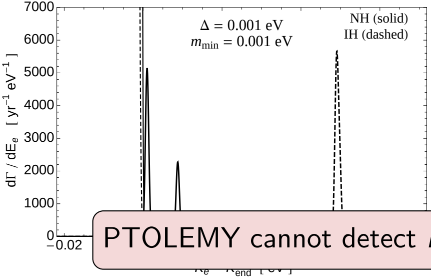
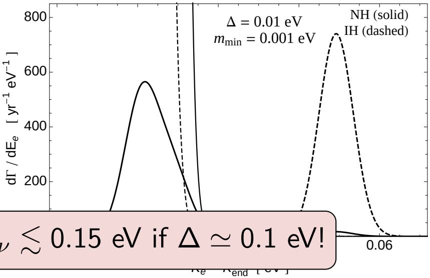
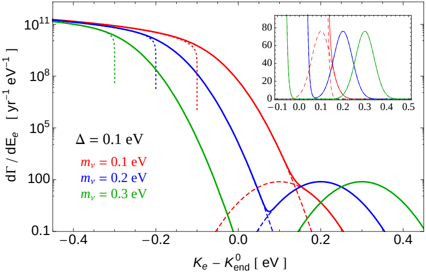
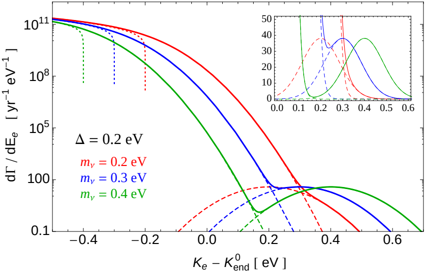




PTOLEMY cannot detect $m_\nu \lesssim 0.15$ eV if $\Delta \simeq 0.1$ eV!

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

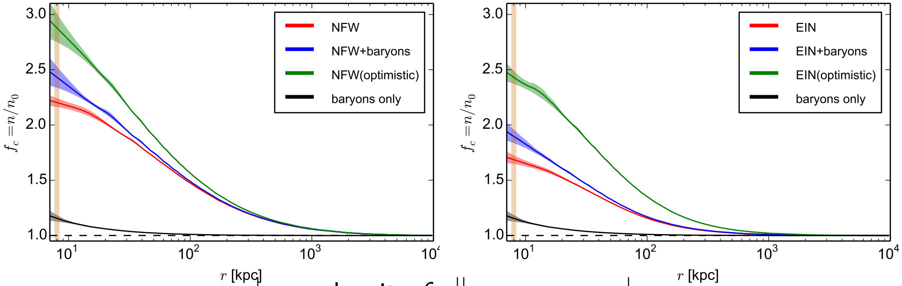




Overdensity when $m_\nu \simeq 150$ meV

[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

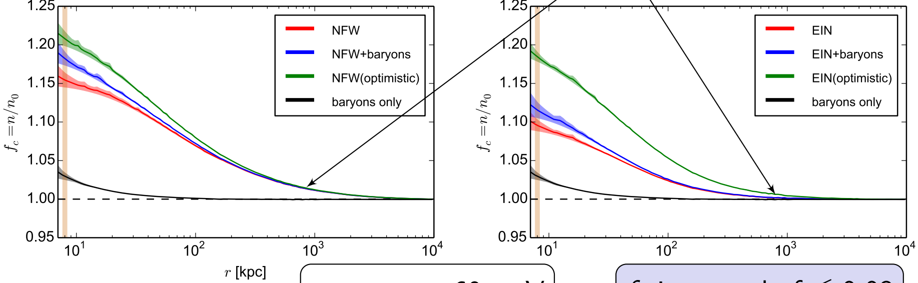
nearest galaxies: various MW satellites

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

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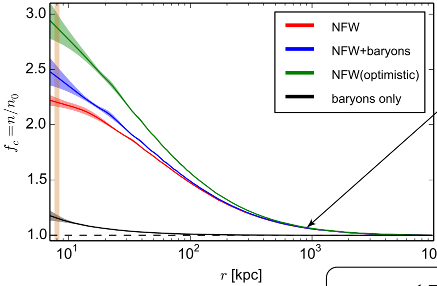
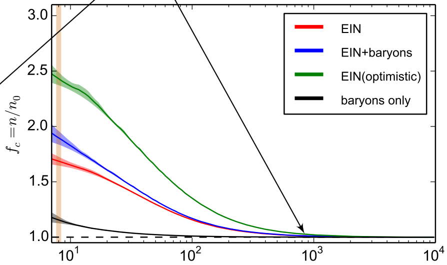




$m_\nu \simeq 150$ meV ⟶ f_c increased of $\lesssim 0.1$

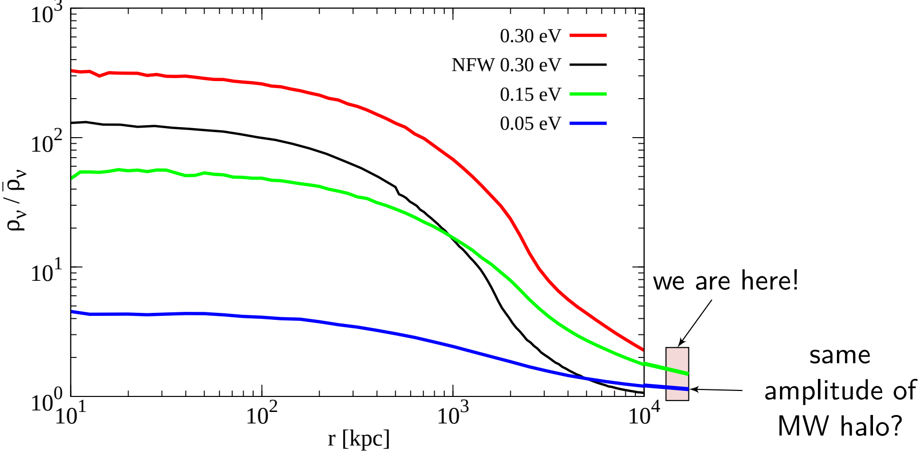
(halo is less diffuse for higher ν masses)

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

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

See also [SG et al., 2017]

3+1 Neutrino Model

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

↓

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

↓

light sterile neutrino (LSν)

3 (active) + 1 (sterile) mixing:

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

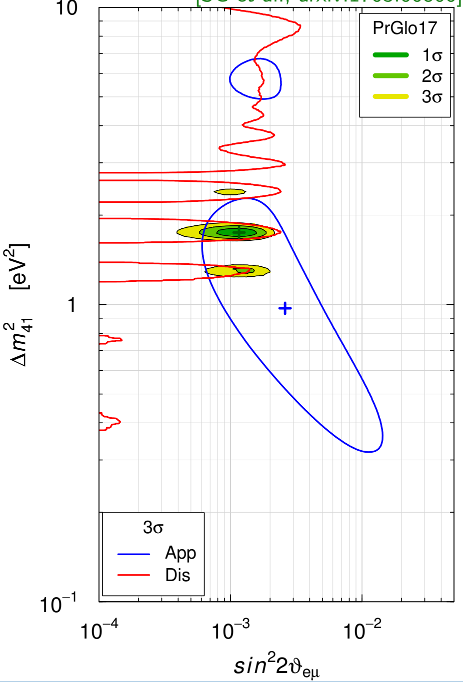
ν_s is mainly ν_4:

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

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

can ν_4 thermalize in the early Universe through oscillations?

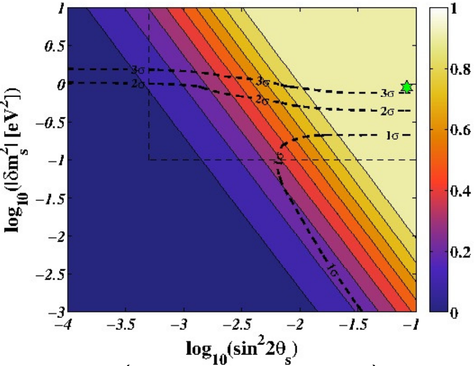
[SG et al., arxiv:1703.00860]



LSν thermalization

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

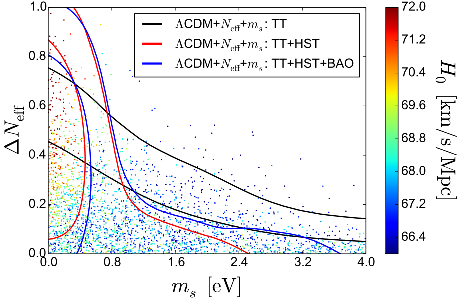
[Hannestad et al., JCAP 1207 (2012) 025]



(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

We assume possible incomplete thermalization

(due to some unknown new physics)

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

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

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

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

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

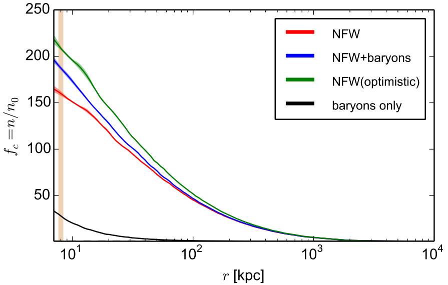
$$\Gamma_4^{M(D)} \simeq |U_{e4}|^2\,\Delta N_{\mathrm{eff}}\,f_c(m_4)\,\Gamma_{\mathrm{C\nu B}}^{M(D)}$$

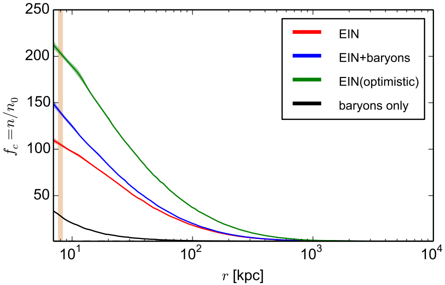
(from global fit [SG et al., 2017]: $m_4 \simeq 1.3$ eV, $|U_{e4}|^2 \simeq 0.02$)

Overdensity of a sterile neutrino

[JCAP 09 (2017) 034]

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

Conclusions

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amazing neutrino science with direct detection
of relic neutrinos (with PTOLEMY?)
[non-relativistic regime, masses, ordering?, Majorana/Dirac, MW content, ...]

2

event rate enhancement due
to clustering in the Milky Way:
+0–20% for $m_{\rm heaviest} \simeq 60$ meV (ordering!)
+70–200% for $m_\nu \simeq 150$ meV

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

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possible detection thanks to large clustering

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Thank you for the attention!