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European Commission
Horizon 2020
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for Research & Innovation

Relic neutrinos: clustering and consequences for direct detection

Featuring "Milky Way" & friends

EPS-HEP 2019, Ghent (BE), 10–17/07/2019

1 Introduction

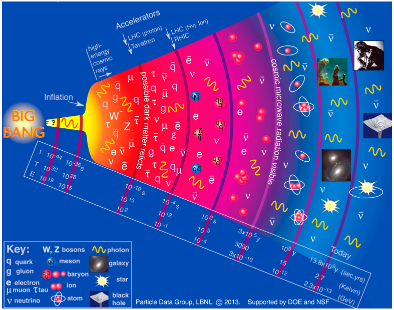
- Neutrinos and early Universe
- Relic neutrino capture

2 Neutrino clustering

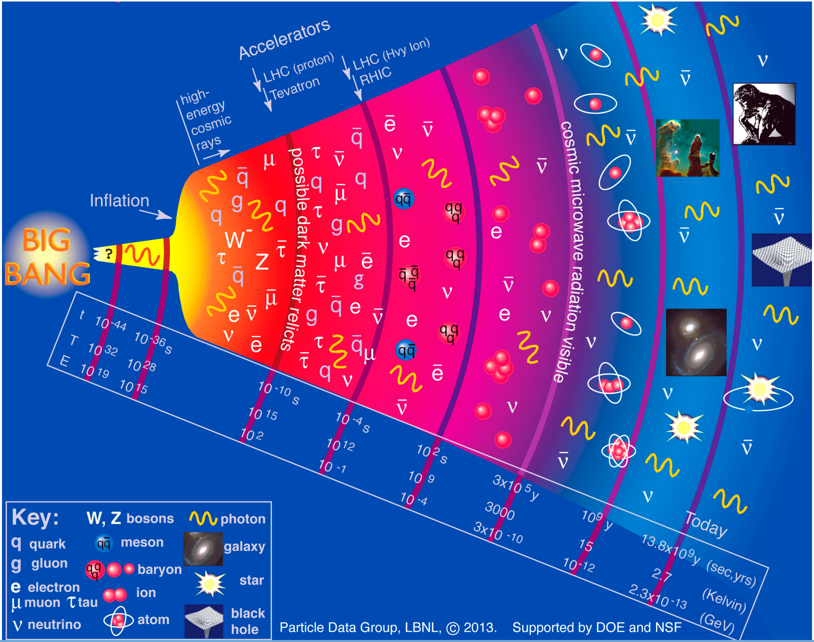
- Theory
- Results from the Milky Way
- Beyond the Milky Way

3 Direct detection of relic neutrinos

4 Conclusions



History of the universe



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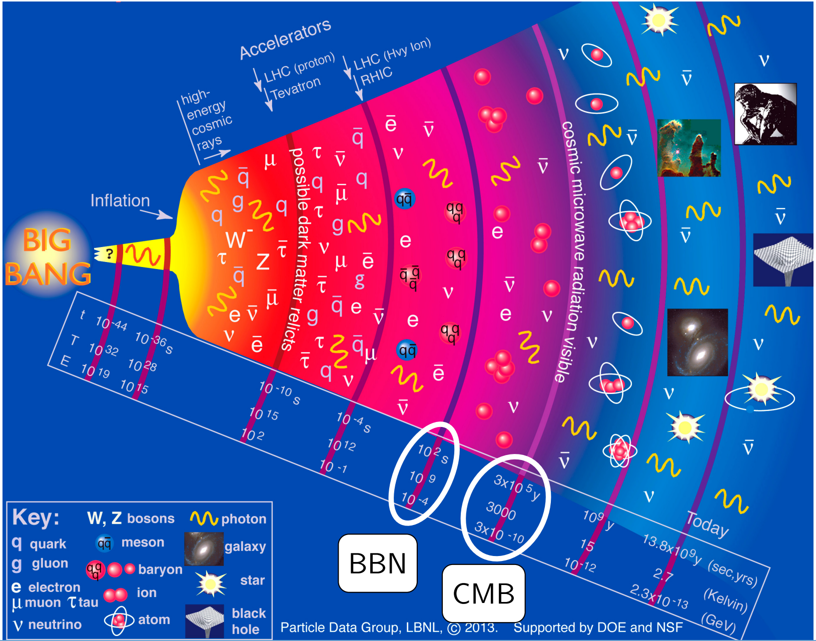

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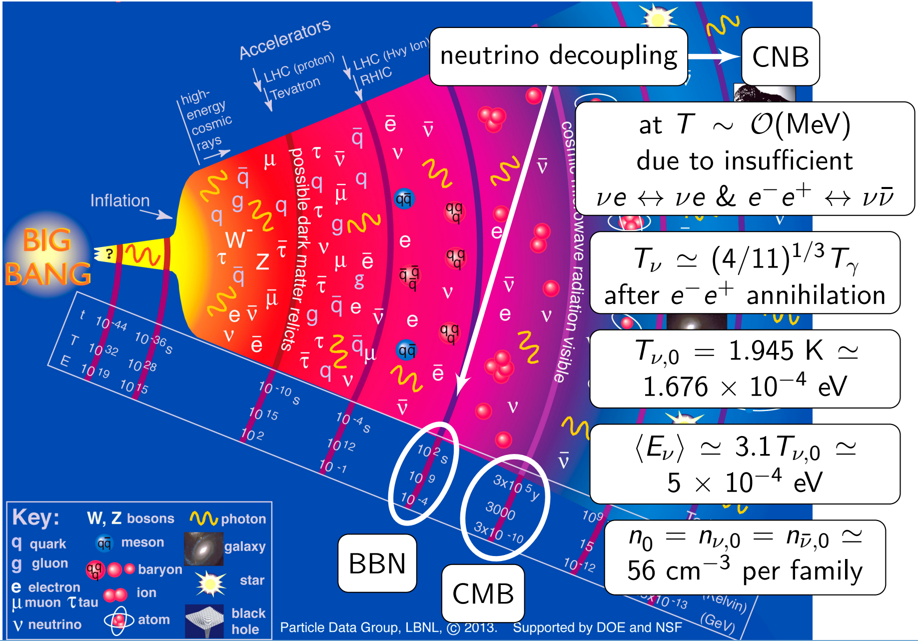


neutrino decoupling → CNB

at $T \sim \mathcal{O}(\mathrm{MeV})$
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

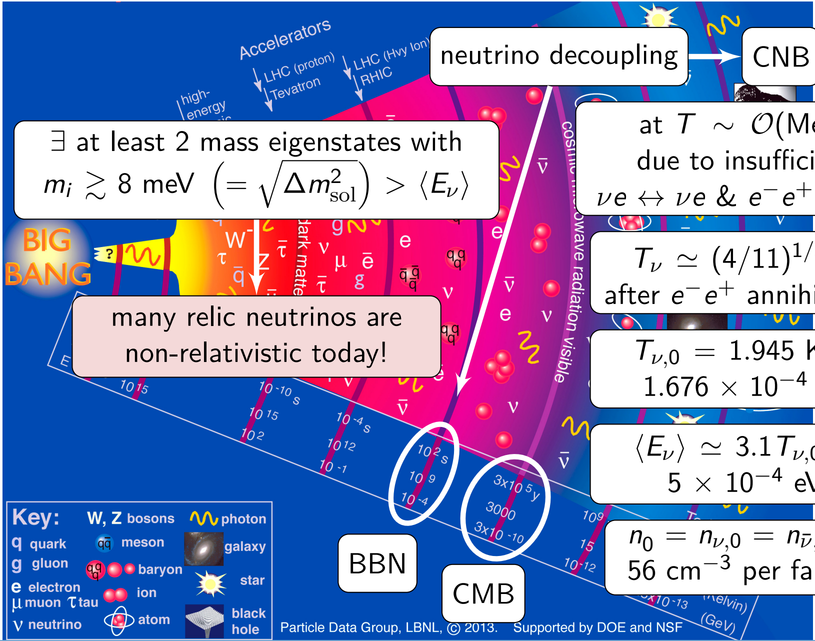
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq$
5×10^{-4} eV

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

BBN

CMB

History of the universe



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

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

many relic neutrinos are non-relativistic today!

BBN

CMB

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: $N_{\rm eff} \simeq 3.0 \pm 0.2$ [Planck 2018]
Indirect probe of cosmic neutrino background!

$\gg 10\sigma$!

Relic neutrino capture

[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

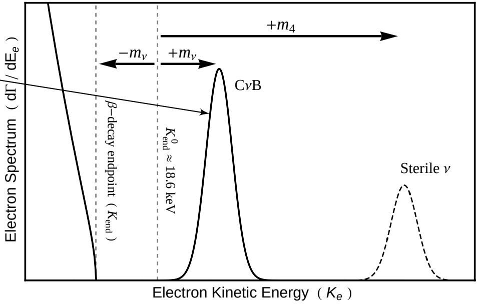
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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



PTOLEMY

[Long et al., JCAP 08 (2014) 038]
[Betts et al., arxiv:1307.4738]
[PTOLEMY LoI, arxiv:1808.01892]

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

expected resolution $\Delta \simeq 0.1$ eV**?**
0.05 eV**?**

built mainly for CNB

can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

$M_T = 100$ g of atomic ^{3}H

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

N_T number of $^3\mathrm{H}$ 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)

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built mainly for CNB

can probe $m_\nu \simeq 1.4\Delta \simeq 0.1$ eV

$M_T = 100$ g of atomic ^{3}H

ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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

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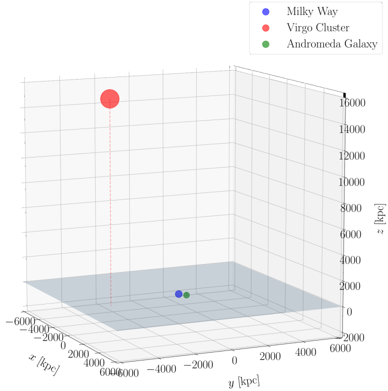


ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

$f_c(m_i) = n_i/n_{i,0}$ 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 $(r,\ \theta,\ p_r,\ l)$

→ 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!)

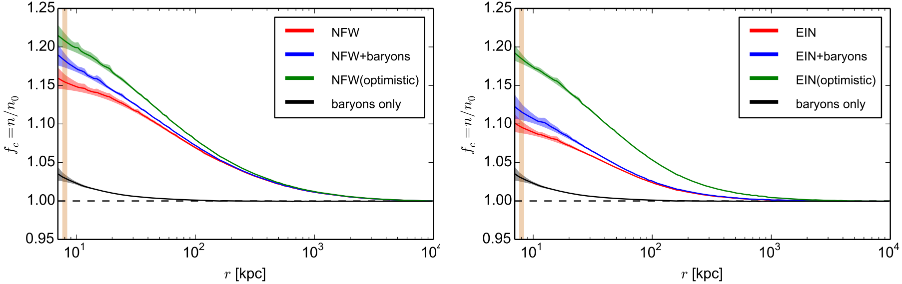
given N ν:

→ weigh each neutrinos

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

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

[JCAP 09 (2017) 034]



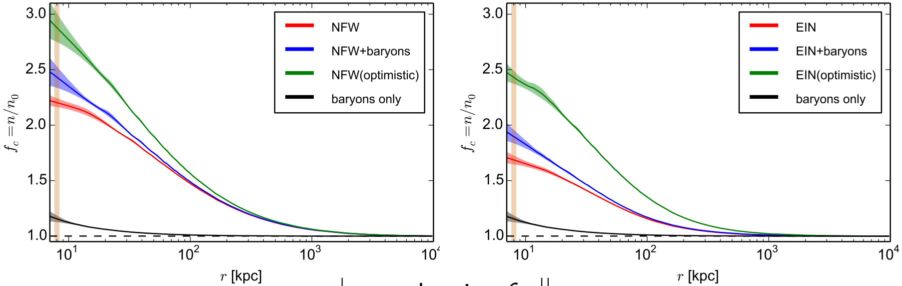
masses	ordering	matter halo	overdensity f_c		$\Gamma_{\rm tot}$ (yr^{-1})
			$f_1 \simeq f_2$	f_3	
any	any	any	no clustering		4.06
$m_3 = 60$ meV	NO	NFW(+bar) NFW optimistic EIN(+bar) EIN optimistic	∼1	1.15 (1.18) 1.21 1.09 (1.12) 1.18	4.07 (4.08) 4.08 4.07 (4.07) 4.08
$m_1 \simeq m_2 = 60$ meV	IO	NFW(+bar) NFW optimistic EIN(+bar) EIN optimistic	1.15 (1.18) 1.21 1.09 (1.12) 1.18	∼1	4.66 (4.78) 4.89 4.42 (4.54) 4.78

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

Overdensity when $m_\nu \simeq 150$ meV

[JCAP 09 (2017) 034]

$\Longrightarrow$ minimal mass detectable by PTOLEMY if $\Delta \simeq 100$–150 meV

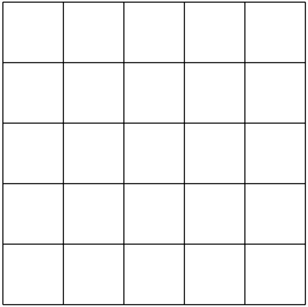


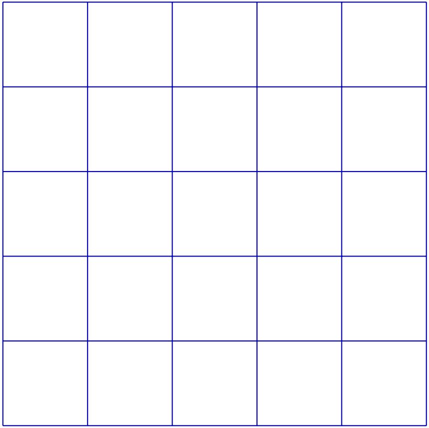
matter halo	overdensity f_c $f_1 \simeq f_2 \simeq f_3$	$\Gamma_{\rm tot}$ (yr^{-1})
any	no clustering	4.06
NFW(+bar)	2.18 (2.44)	8.8 (9.9)
NFW optimistic	2.88	11.7
EIN(+bar)	1.68 (1.87)	6.8 (7.6)
EIN optimistic	2.43	9.9

no ordering dependence: $m_1 \simeq m_2 \simeq m_3 \Longrightarrow f_1 \simeq f_2 \simeq f_3$

Forward-tracking and back-tracking

initial phase space, $z = 4 \longrightarrow$ homogeneous Fermi-Dirac distribution





final phase space, $z = 0$

Forward-tracking and back-tracking

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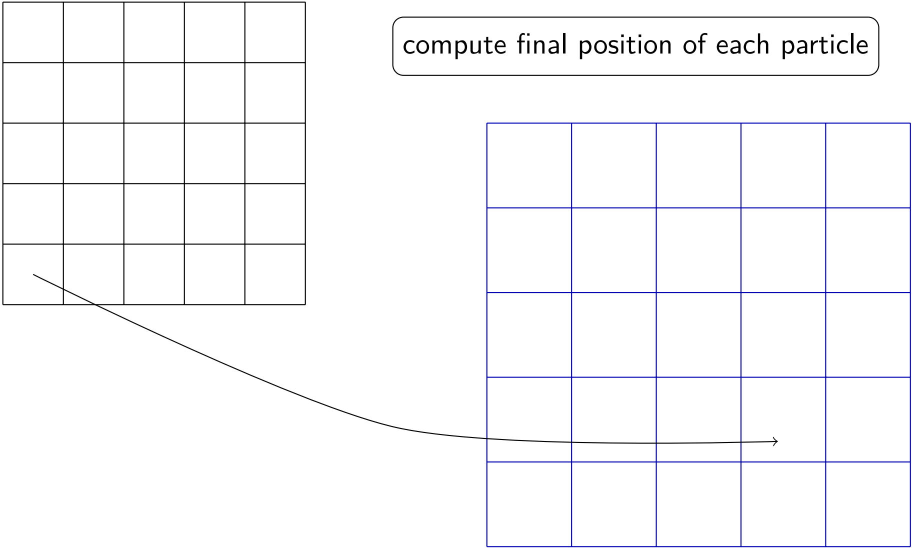

compute final position of each particle

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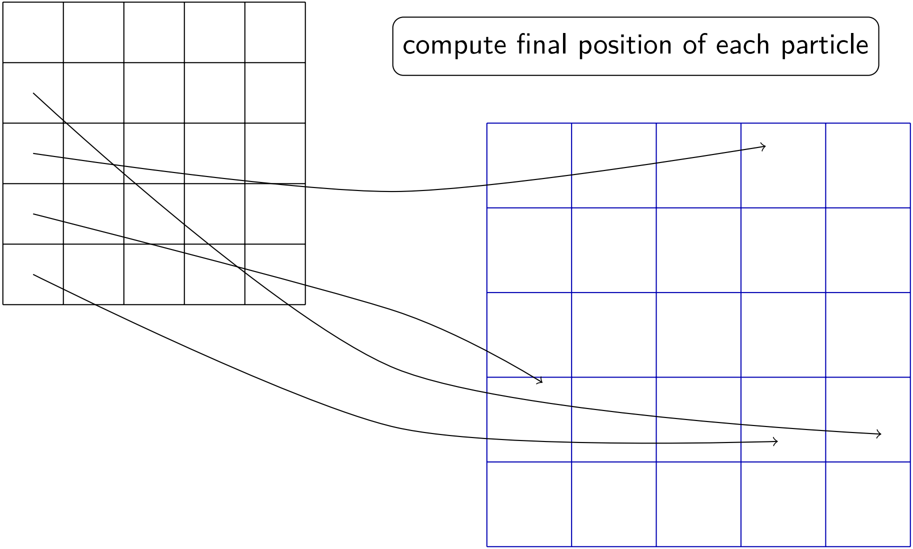

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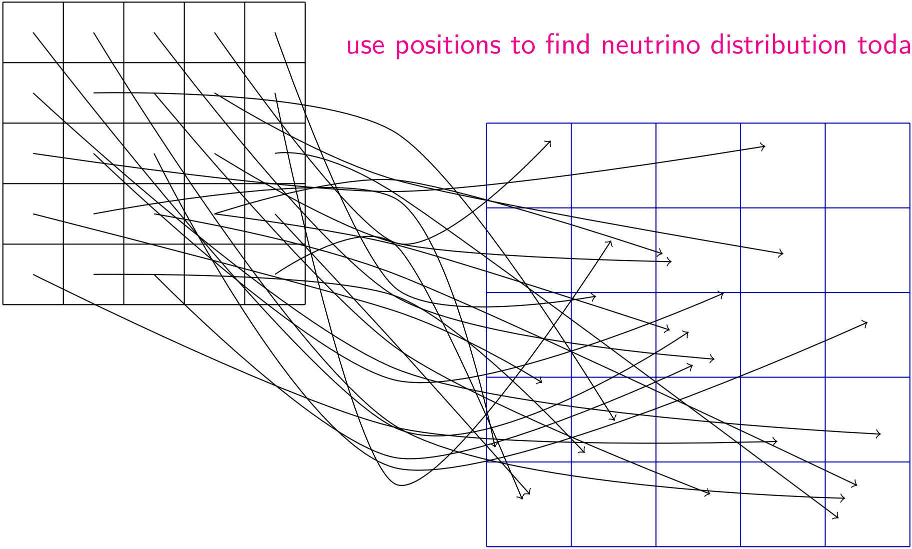

use positions to find neutrino distribution today

final phase space, $z = 0$

Forward-tracking and back-tracking

initial phase space, $z = 4 \longrightarrow$ homogeneous Fermi-Dirac distribution

only interested in overdensity at Earth? ★

a lot of time is wasted!

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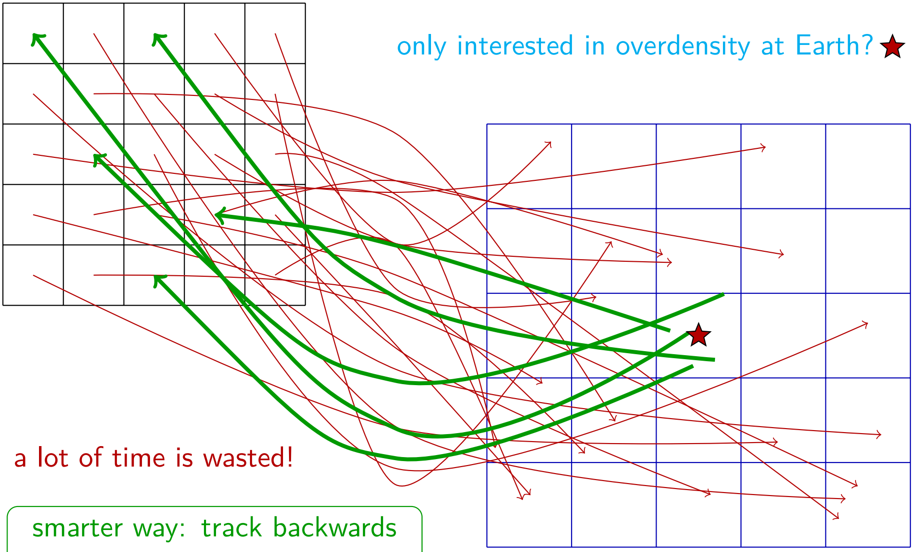

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smarter way: track backwards
only interesting particles!

final phase space, $z = 0$

Advantages of tracking back

[SG+, in preparation]

First advantage is in computational terms: much less points to compute

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First advantage is in computational terms: much less points to compute

Second advantage: no need to use spherical symmetry!

Forward-tracking

initial conditions need to sample
1D for position + 2D for momentum
when using spherical symmetry

with full grid would require 3+3 dimensions!

Impossible to relax
spherical symmetry!

Back-tracking

"Initial" conditions only described
by 3D in momentum

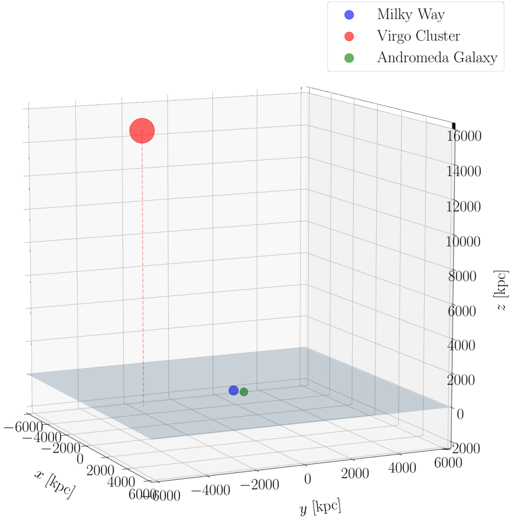
(position is fixed, apart for checks)

can do the calculation with
any astrophysical setup

Advantages of tracking back

First advantage is in computational terms: much less points to compute

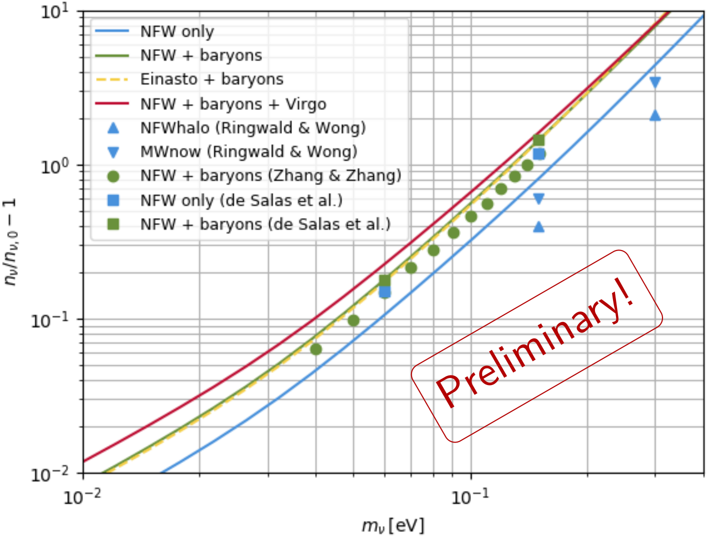
Second advantage: no need to use spherical symmetry!



Preliminary results with back-tracking

[SG+, in preparation]

In comparison with previous results:



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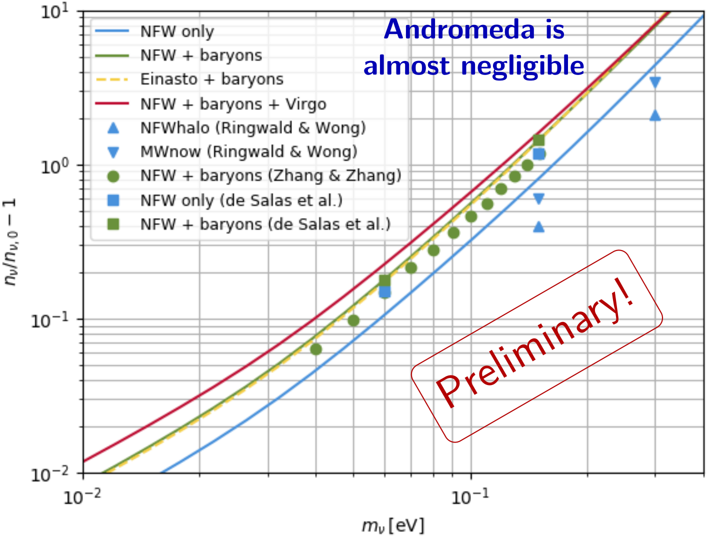

Andromeda is almost negligible

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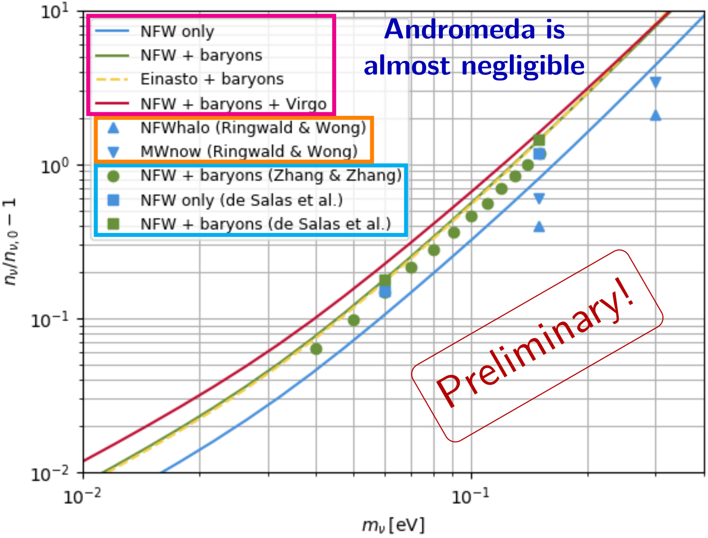

Warning: NFW is not the same for all the cases!

[de Salas+, 2017] and [Zhang^2, 2018] use $\gamma \neq 1$, now we have $\gamma = 1$

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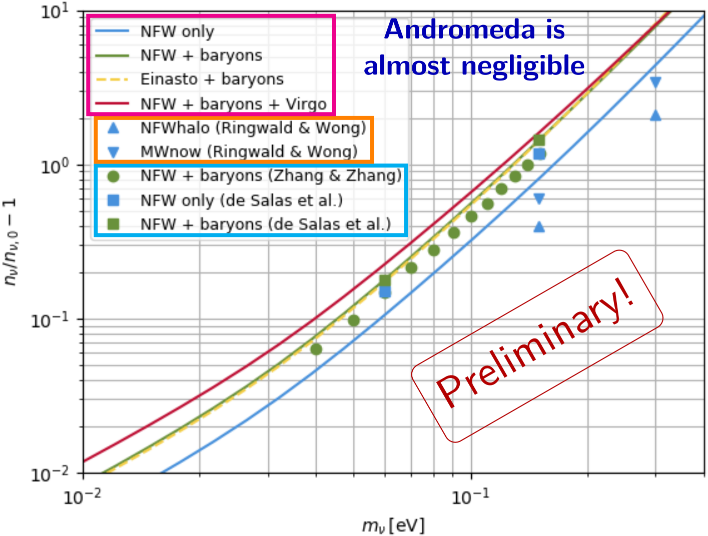

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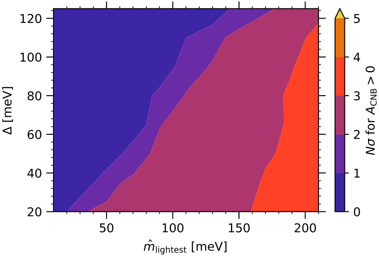
many checks are missing: distance of Virgo, Sun position, more on DM, . . .


Δ [meV]
120
100
80
60
40
20
50
100
150
200
$\hat{m}_{\rm lightest}$ [meV]
$N\sigma$ for $A_{\rm CNB} > 0$
0
1
2
3
4
5

β and Neutrino Capture spectra

[PTOLEMY, arxiv:1902.05508]

$$\boxed{\frac{d\widetilde{\Gamma}_{\mathrm{CNB}}}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\sum_{i=1}^{N_\nu} \bar{\sigma}\, N_T\, |U_{ei}|^2\, n_0\, f_c(m_i)\ \times e^{-\frac{[E_e-(E_{\mathrm{end}}+m_i+m_{\mathrm{lightest}})]^2}{2\sigma^2}}}$$

$$\frac{d\Gamma_\beta}{dE_e} = \frac{\bar{\sigma}}{\pi^2} N_T \sum_{i=1}^{N_\nu} |U_{ei}|^2 H(E_e, m_i)$$

$$\boxed{\frac{d\widetilde{\Gamma}_\beta}{dE_e}(E_e) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{+\infty} dx\, \frac{d\Gamma_\beta}{dE_e}(x)\, \exp\left[-\frac{(E_e-x)^2}{2\sigma^2}\right]}$$

$\bar{\sigma}$ cross section, N_T number of tritium atoms in the source (PTOLEMY: 100 g), E_{end} endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

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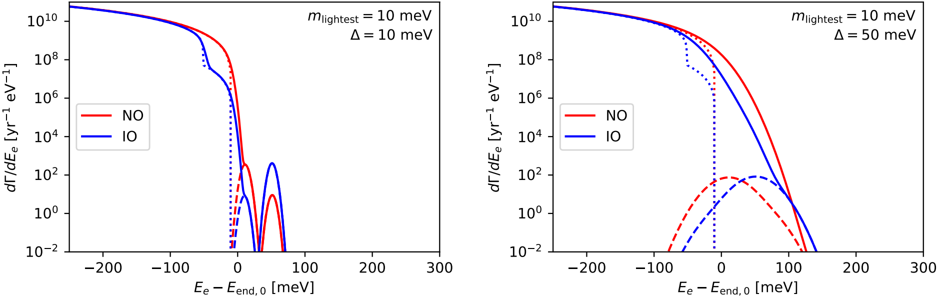

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Detection of the relic neutrinos

[PTOLEMY, arxiv:1902.05508]

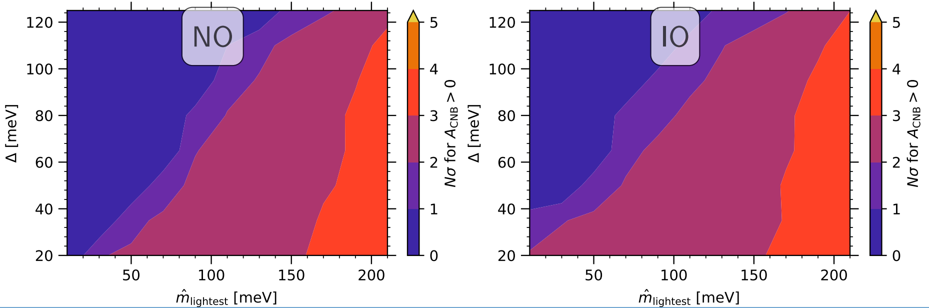
using the definition:

$$\boxed{N^i_{\rm th}(\boldsymbol{\theta}) = A_\beta N^i_\beta(\hat{E}_{end}+\Delta E_{end}, m_i, U) + \boldsymbol{A}_{\rm\bf CNB} N^i_{\rm CNB}(\hat{E}_{end}+\Delta E_{end}, m_i, U) + N_b}$$

if $\boldsymbol{A}_{\rm\bf CNB} > 0$ at $N\sigma$, direct detection of CNB accomplished at $N\sigma$

statistical only!

significance on $A_{\rm CNB} > 0$
as a function of $\hat{m}_{\rm lightest}$, Δ



Conclusions

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

2

But it will be a technological challenge!
(^{3}H amount, low background, energy resolution, . . .)

3

possible event rate enhancement
due to clustering in the Milky Way,
and also nearby galaxies/clusters**!**

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Clustering cannot increase detection chances,
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astrophysical environment using the event rate!

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Thank you for the attention!

Baryons: the complexity of a structure

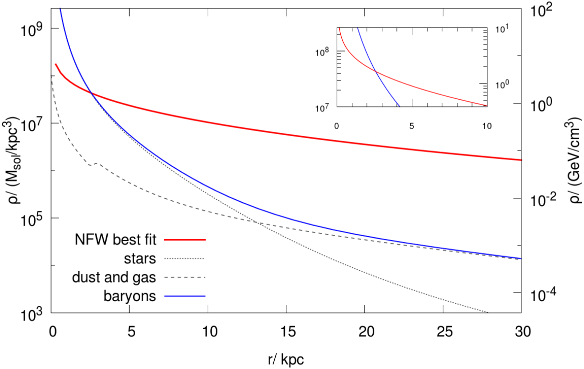
Complex problem: how to model baryon content of a galaxy?

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