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Relic neutrinos: clustering and consequences for direct detection

Featuring "Milky Way" & friends

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Horizon 2020
European Union funding
for Research & Innovation

1 ***Introduction***

- Neutrinos and early Universe
- Relic neutrino capture

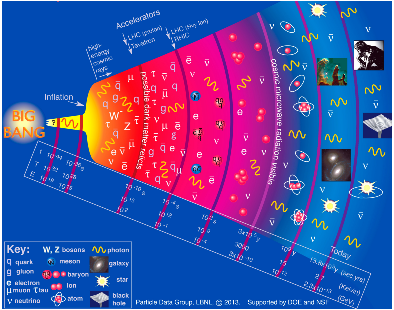
2 ***Neutrino clustering***

- Milky Way parameterization
- Results from the Milky Way

3 ***Beyond the Milky Way***

4 ***Direct detection of relic neutrinos***

5 ***Conclusions***



Three Neutrino Oscillations

Analogous to CKM mixing for quarks: [Pontecorvo, 1968] [Maki, Nakagawa, Sakata, 1962]

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

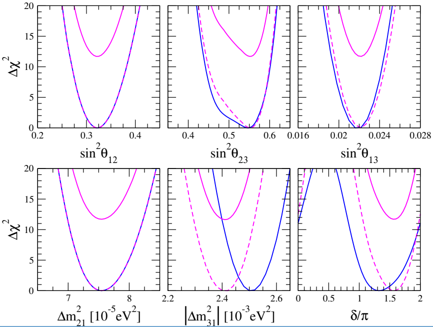
ν_α flavour eigenstates, $U_{\alpha k}$ PMNS mixing matrix, ν_k mass eigenstates.

Current knowledge of the 3 active ν mixing: [de Salas et al. (2018)]

$\Delta m^2_{ji} = m^2_j - m^2_i$, θ_{ij} mixing angles
NO: Normal Ordering, $m_1 < m_2 < m_3$
IO: Inverted Ordering, $m_3 < m_1 < m_2$

$$\begin{aligned}
\Delta m^2_{21} &= (7.55^{+0.20}_{-0.16}) \cdot 10^{-5}\ \mathrm{eV}^2 \\
|\Delta m^2_{31}| &= (2.50 \pm 0.03) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{NO}) \\
&= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3}\ \mathrm{eV}^2\ (\mathrm{IO})
\end{aligned}$$

$$\begin{aligned}
\sin^2(\theta_{12}) &= 0.320^{+0.020}_{-0.016} \\
\sin^2(\theta_{13}) &= 0.0216^{+0.008}_{-0.007}\ (\mathrm{NO}) \\
&= 0.0222^{+0.007}_{-0.008}\ (\mathrm{IO}) \\
\sin^2(\theta_{23}) &= 0.547^{+0.020}_{-0.030}\ (\mathrm{NO}) \\
&= 0.551^{+0.018}_{-0.030}\ (\mathrm{IO})
\end{aligned}$$



First hints for $\delta_{CP} \simeq 3/2\pi$

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see also: http://globalfit.astroparticles.es

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$$= (2.42^{+0.03}_{-0.04}) \cdot 10^{-3} \ldots$$

$\sin^2(\theta_{12})$ ...

$\sin^2(\theta_{13})$ ... $^{+0.008}_{-0.007}$ (NO)

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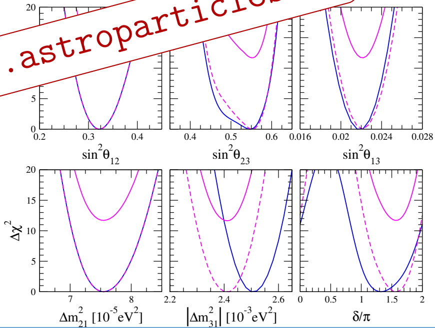
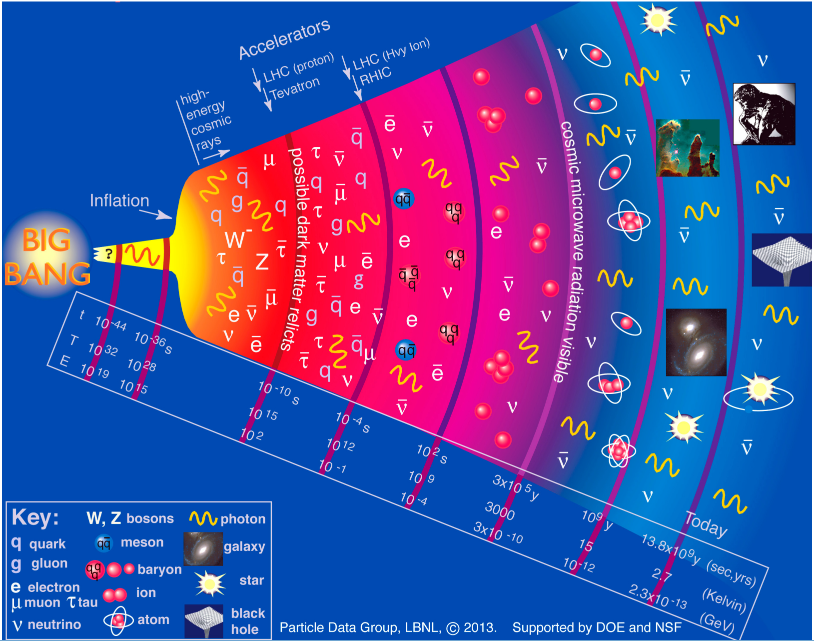


History of the universe



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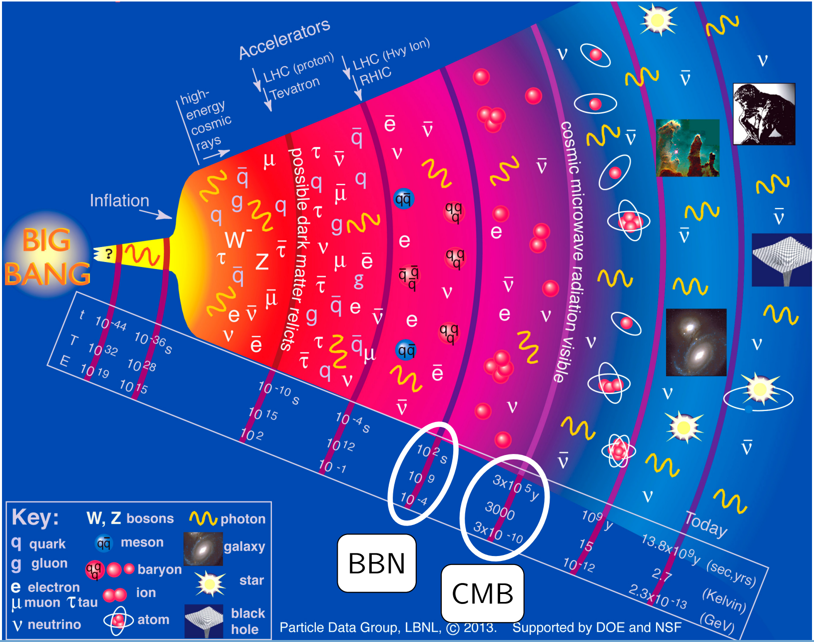

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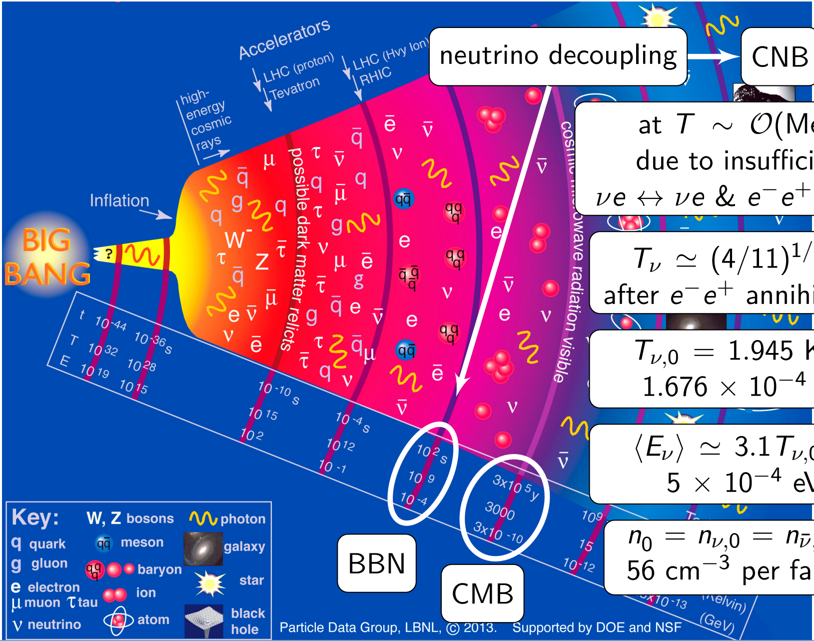

neutrino decoupling → CNB

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 $\simeq 1.676 \times 10^{-4}$ eV

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

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

BBN

CMB

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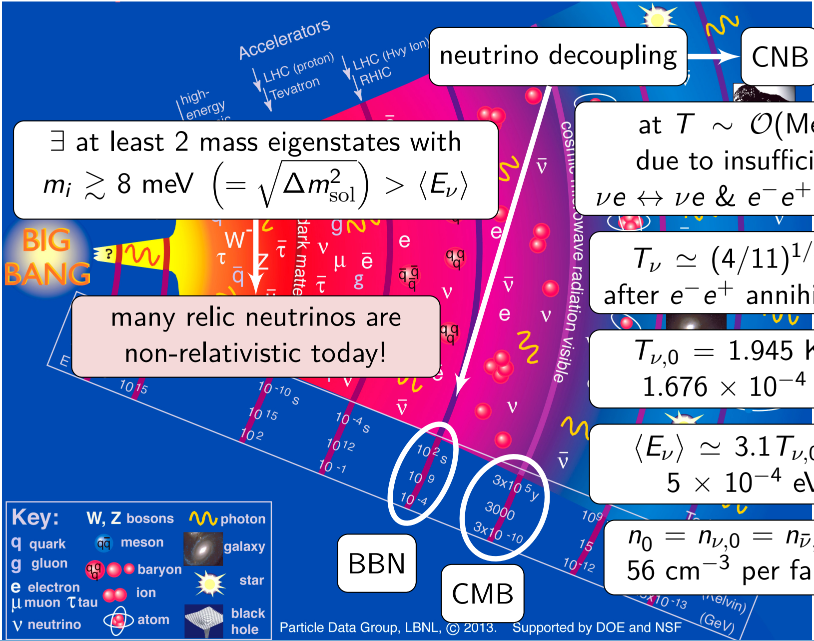

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$\exists$ at least 2 mass eigenstates with
$m_i \gtrsim 8$ meV $\left(= \sqrt{\Delta m^2_{\text{sol}}}\right) > \langle E_\nu \rangle$

many relic neutrinos are
non-relativistic today!

BBN

CMB

Relic neutrinos in cosmology: N_{eff}

Radiation energy density ρ_r in the early Universe:

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

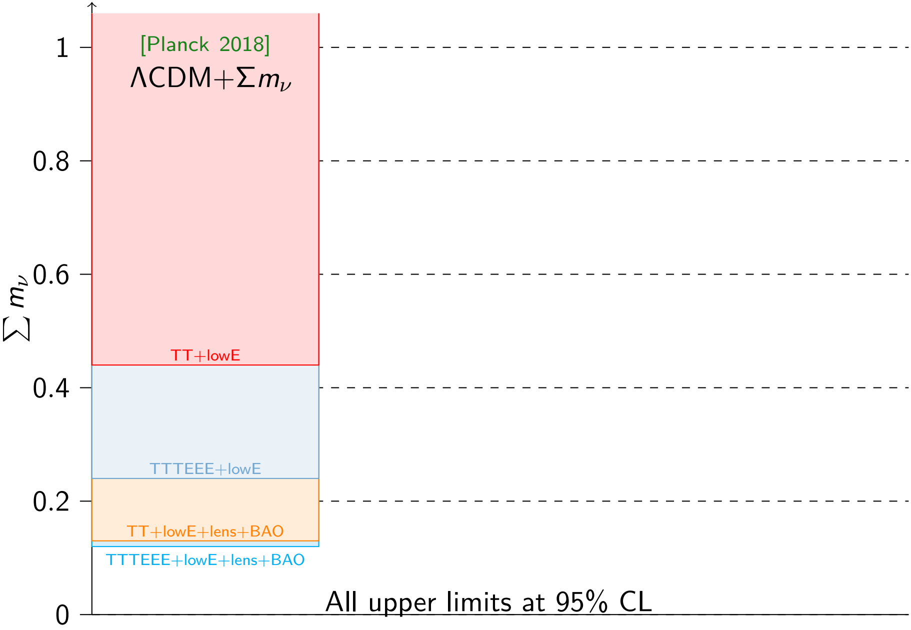
ρ_γ photon energy density, $7/8$ is for fermions, $(4/11)^{4/3}$ due to photon reheating after neutrino decoupling

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

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

$\gg 10\sigma$!

Cosmological neutrino mass bounds



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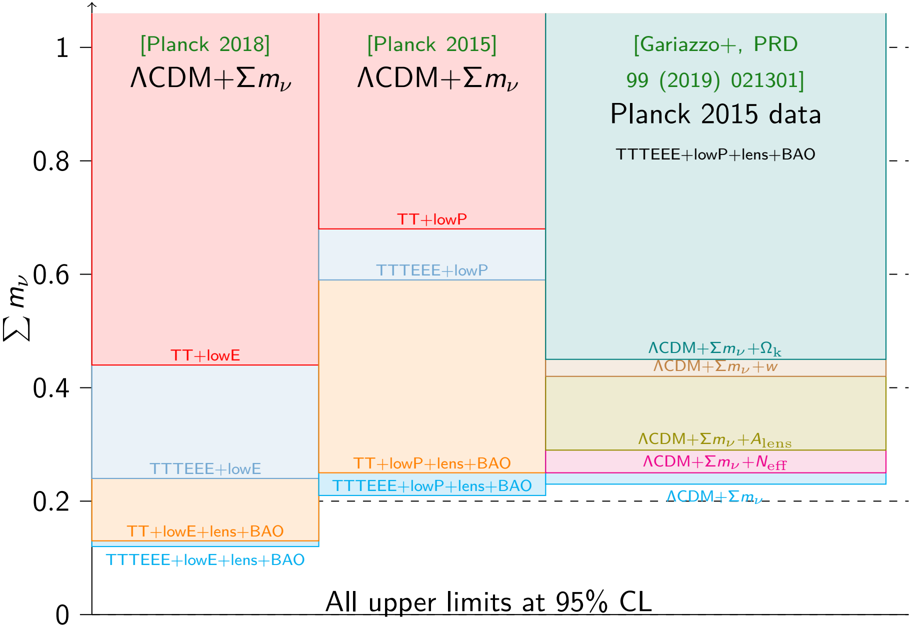

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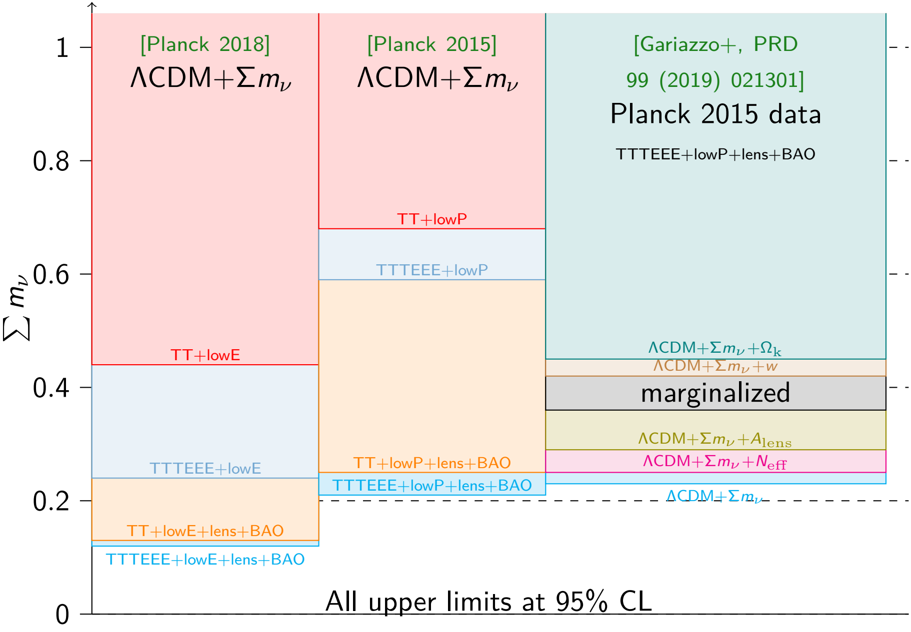


Relic neutrino capture

[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 $\longrightarrow$ a process without energy threshold is necessary

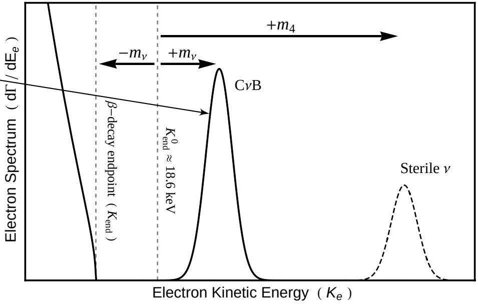
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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



PTOLEMY

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

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

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

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

N_T number of ^{3}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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ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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

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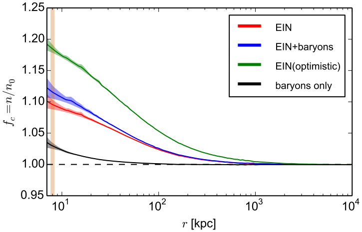

EIN
EIN+baryons
EIN(optimistic)
baryons only
$f_c = n/n_0$
r [kpc]
1.25
1.20
1.15
1.10
1.05
1.00
0.95
10^1
10^2
10^3
10^4

ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

clustering →

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

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

Assumptions:

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

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]

Dark matter: profiles today

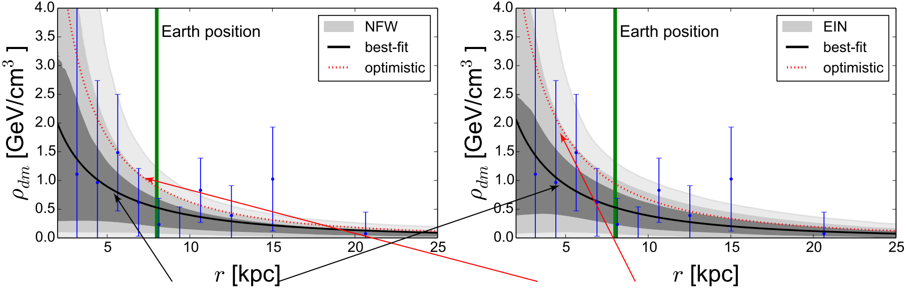
[JCAP 09 (2017) 034]

(γ)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

[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

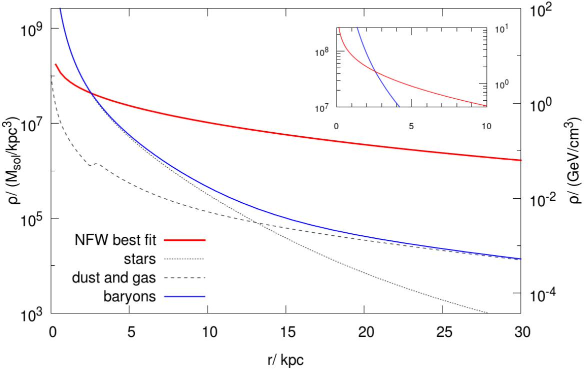
Complex problem: how to model baryon content of a galaxy?

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

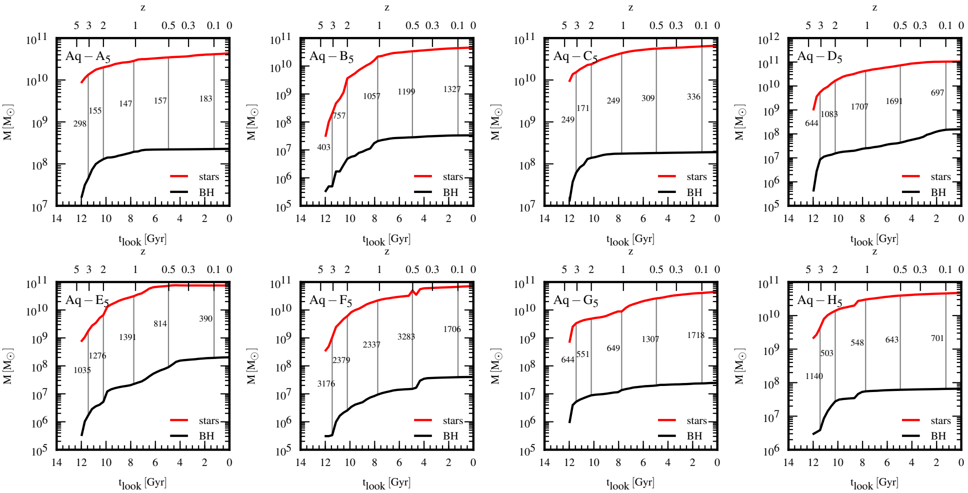
baryon evolution with redshift?

from [Marinacci et al., 2013]

results of full N-body simulations

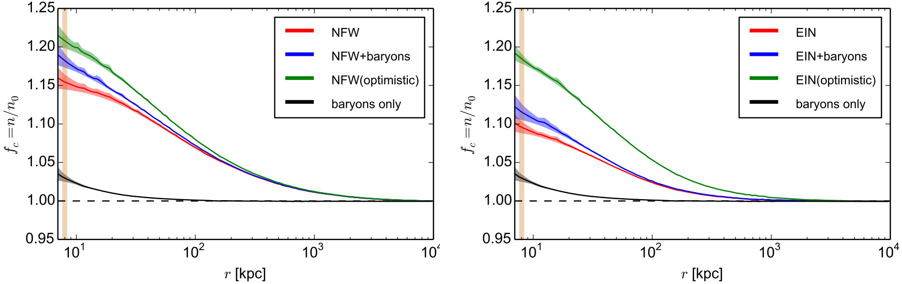
$\mathcal{N}_{\rm bar}(z)$ from $M(z)$

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



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

[JCAP 09 (2017) 034]



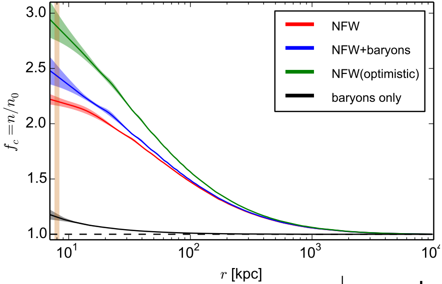
masses	ordering	matter halo	overdensity f_c: $f_1 \simeq f_2$	overdensity f_c: f_3	$\Gamma_{\rm tot}$ (yr^{-1})
any	any	any	no clustering		4.06
$m_3 = 60$ meV	NO	NFW(+bar)	~ 1	1.15 (1.18)	4.07 (4.08)
		NFW optimistic		1.21	4.08
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)
		EIN optimistic		1.18	4.08
$m_1 \simeq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

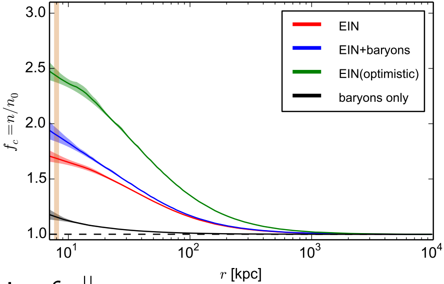
ordering dependence from $\Gamma_{\rm CNB} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \left[n_i(\nu_{h_R}) + n_i(\nu_{h_L})\right] N_T \bar{\sigma}$

Overdensity when $m_\nu \simeq 150$ meV

[JCAP 09 (2017) 034]

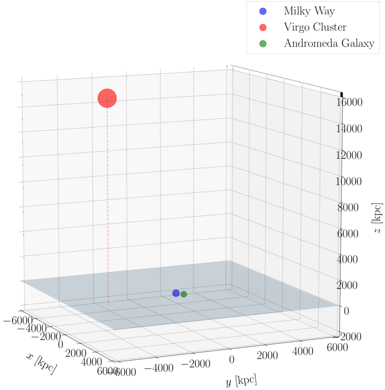
$\Longrightarrow$ minimal mass detectable by PTOLEMY if $\Delta \simeq$ 100–150 meV





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



Milky Way
Virgo Cluster
Andromeda Galaxy
x [kpc]
y [kpc]
z [kpc]

Additional clustering due to other galaxies

[JCAP 09 (2017) 034]

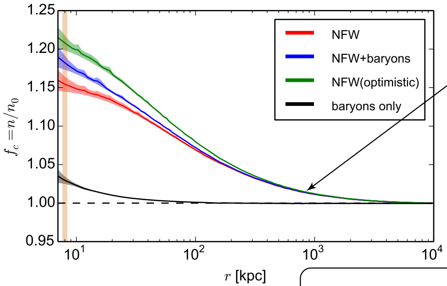
nearest galaxies: various MW satellites

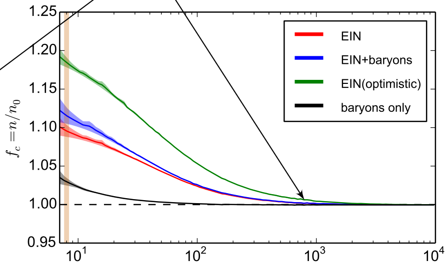
with $M_{\rm sat} \ll M_{\rm MW}$ ⟶ negligibly small ν halo

nearest big galaxy:

Andromeda

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





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

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[JCAP 09 (2017) 034]

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

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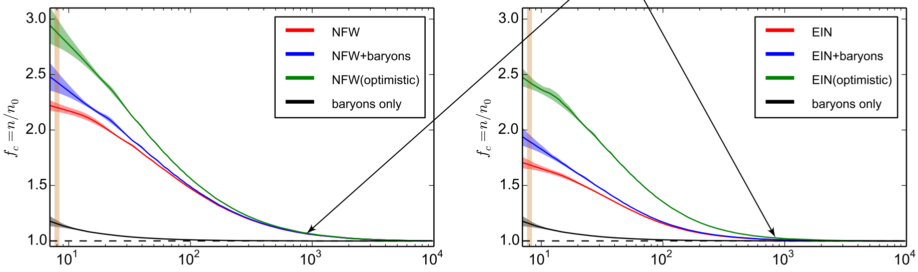


$m_\nu \simeq 150$ meV → f_c increased of $\lesssim 0.1$

(halo is less diffuse for higher ν masses)

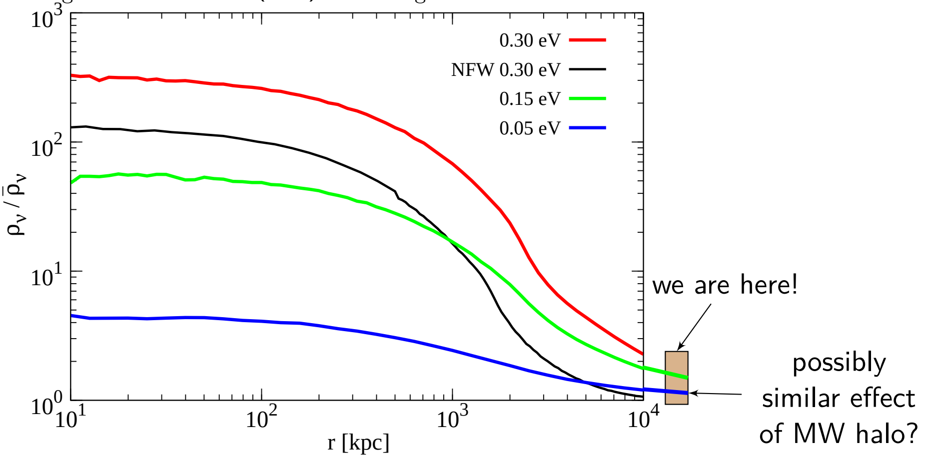
Additional clustering due to Virgo cluster

[JCAP 09 (2017) 034]

nearest galaxy cluster:

Virgo cluster → very wide ν halo, may reach Earth

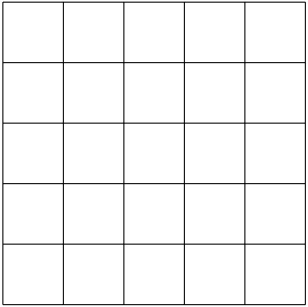
$M_{\mathrm{Virgo}} = M_{\mathrm{MW}} \times \mathcal{O}(10^3)$ — $d_{\mathrm{Virgo}} \simeq 16$ Mpc

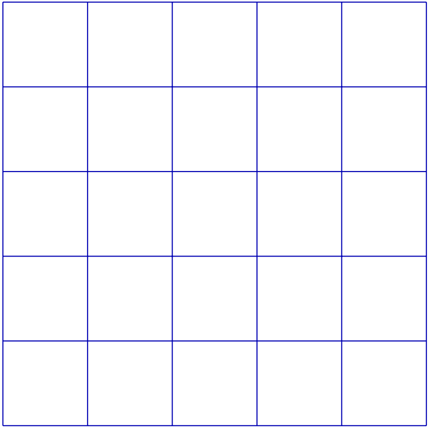


[Villaescusa-Navarro et al., JCAP 1106 (2011) 027]

Forward-tracking and back-tracking

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

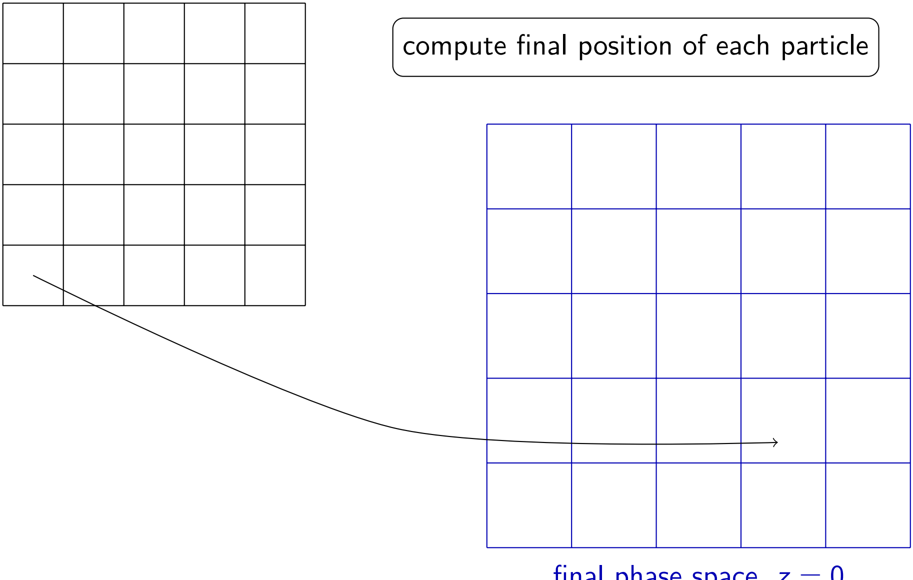




final phase space, $z = 0$

Forward-tracking and back-tracking

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



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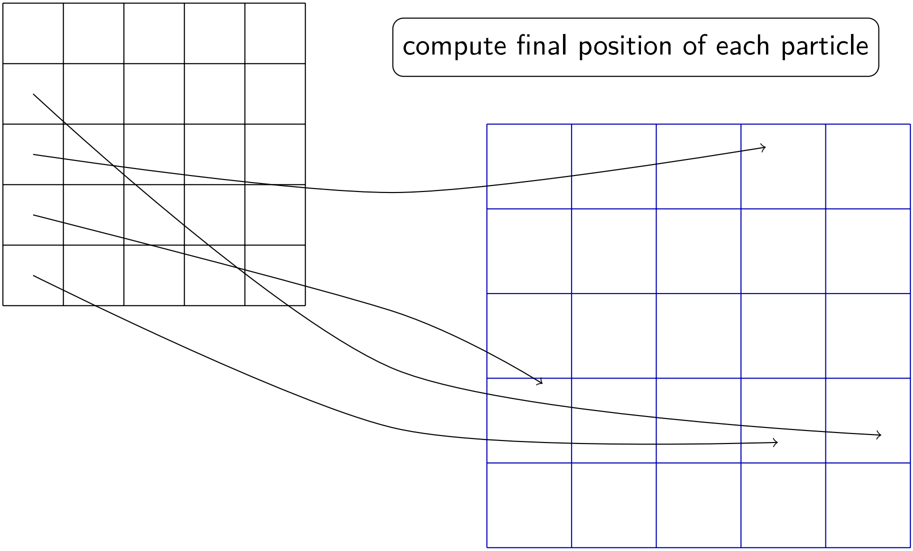

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Forward-tracking and back-tracking

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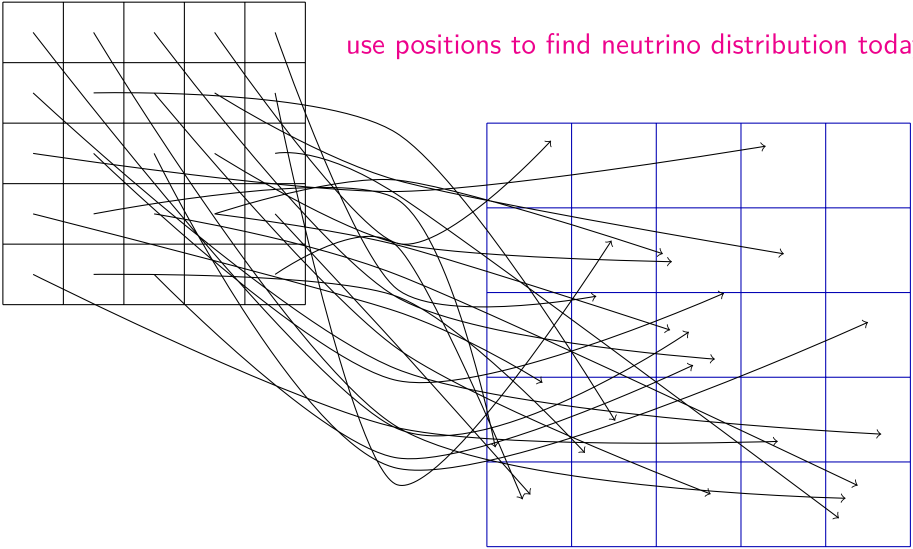

use positions to find neutrino distribution today

final phase space, $z = 0$

Forward-tracking and back-tracking

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only interested in overdensity at Earth? ★

a lot of time is wasted!

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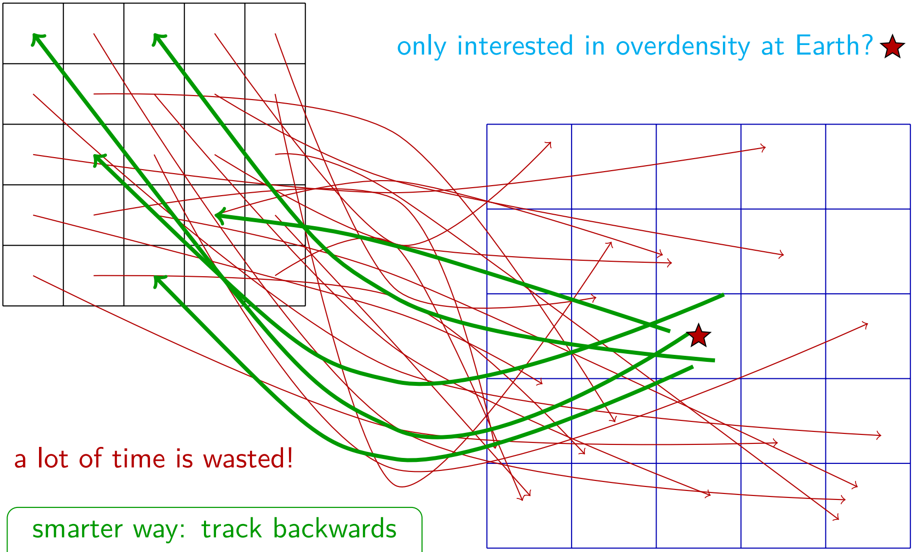

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smarter way: track backwards only interesting particles!

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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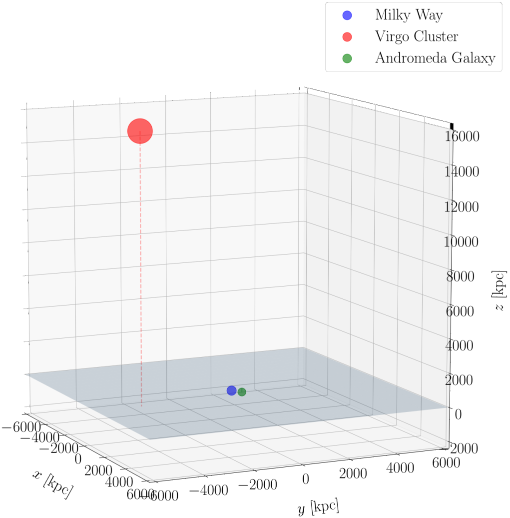
Second advantage: no need to use spherical symmetry!

Forward-tracking	Back-tracking
initial conditions need to sample 1D for position + 2D for momentum when using spherical symmetry	"Initial" conditions only described by 3D in momentum
with full grid would require 3+3 dimensions!	(position is fixed, apart for checks)
Impossible to relax spherical symmetry!	can do the calculation with any astrophysical setup

Advantages of tracking back

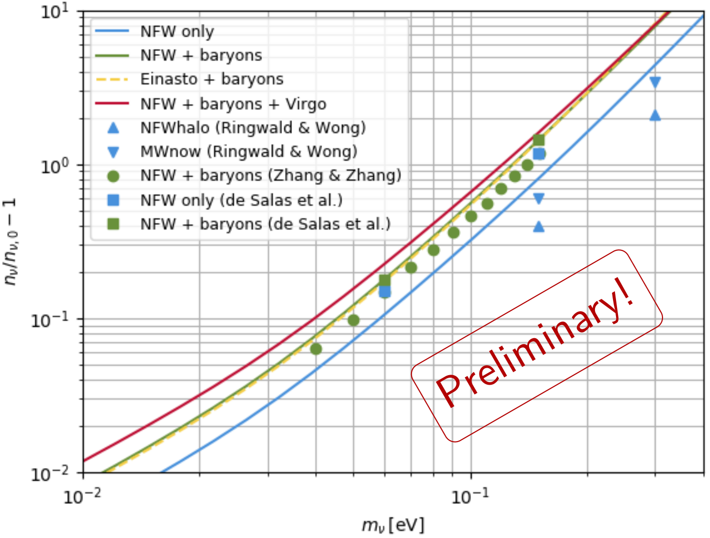
First advantage is in computational terms: much less points to compute

Second advantage: no need to use spherical symmetry!



Preliminary results with back-tracking

In comparison with previous results:



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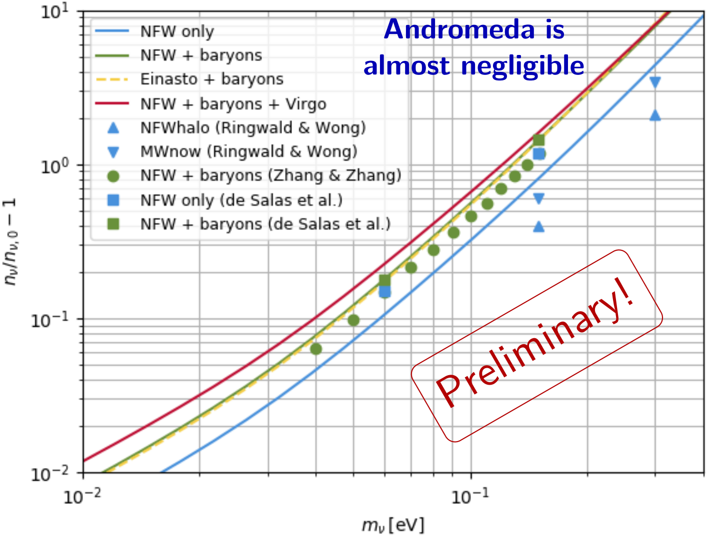

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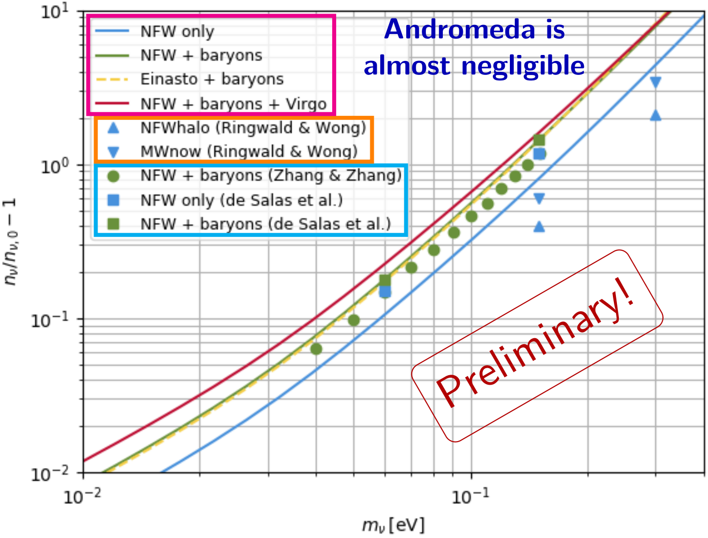

Warning: NFW is not the same for all the cases!

[de Salas+, 2017] and [Zhang², 2018] use $\gamma \neq 1$, now we have $\gamma = 1$

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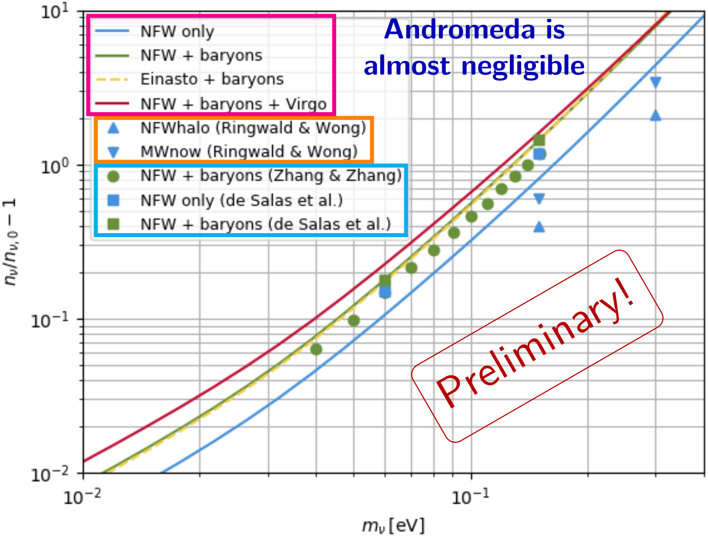

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[de Salas+, 2017] and [Zhang^2, 2018] use $\gamma \neq 1$, now we have $\gamma = 1$

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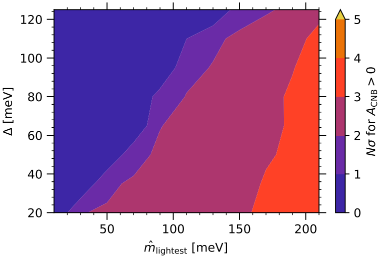
many checks are missing: distance of Virgo, Sun position, more on DM, ...


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

β and Neutrino Capture spectra

[PTOLEMY, arxiv:1902.05508]

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

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

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

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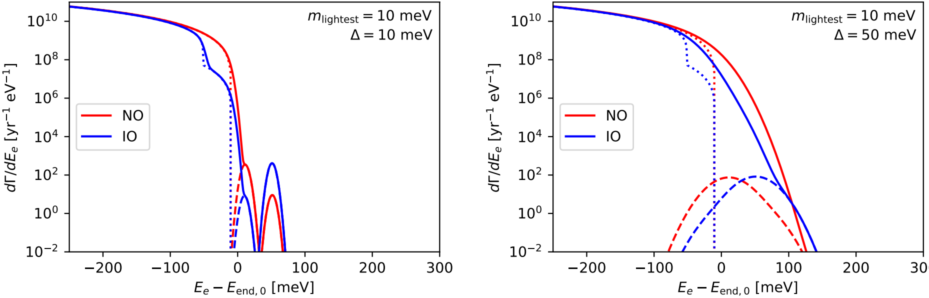

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Detection of the relic neutrinos

[PTOLEMY, arxiv:1902.05508]

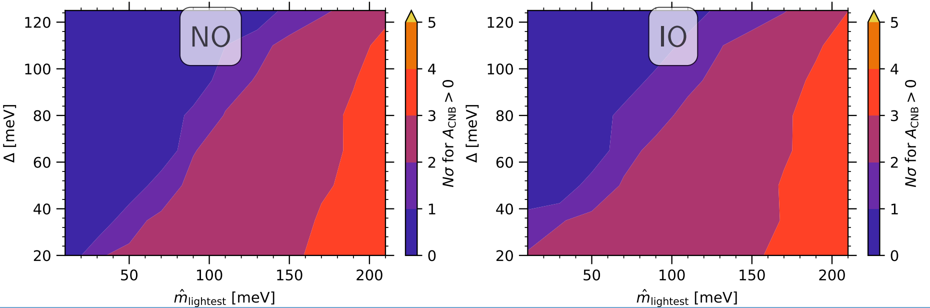
using the definition:

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

if $\boldsymbol{A}_{\rm \mathbf{CNB}} > 0$ 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



Dirac and Majorana neutrinos

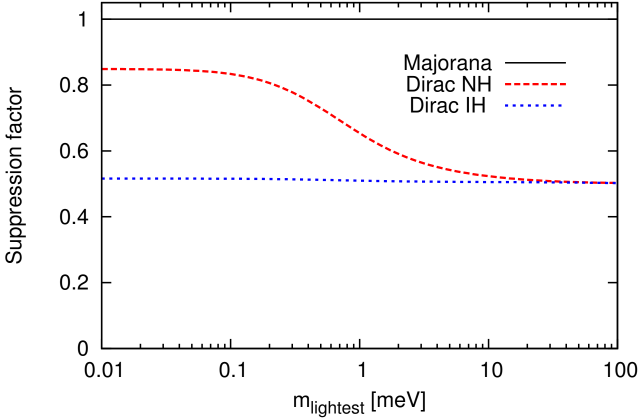
[Roulet+, JCAP 10 (2018) 049]

direct detection through $\nu_e + {}^3\mathrm{H} \longrightarrow e^- + {}^3\mathrm{He}$

only neutrinos with correct chirality can be detected!

non-relativistic **Majorana** case: ν and $\bar{\nu}$ cannot be distinguished!

expect more events for the **Majorana** than for Dirac case

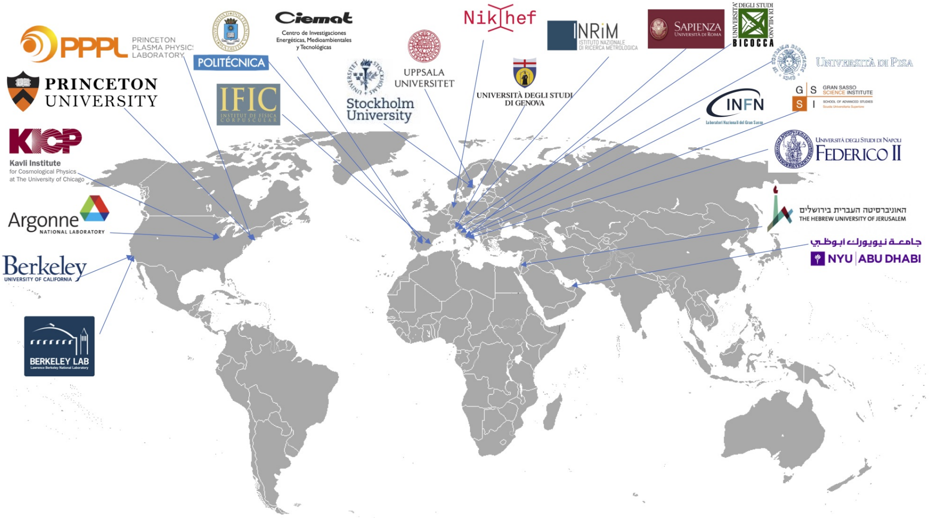


Dirac normal or inverted ordering differ because lighter ν_1 and ν_2 in NH are relativistic

↓

almost indistinguishable from **Majorana**

PTOLEMY collaboration



See talk by M. Messina on Thursday!

Conclusions

1. 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:
should also include nearby galaxies/clusters!

4. For smallest neutrino masses,
enhancement from local astrophysical environment
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Thank you for the attention!

6 PTOLEMY

Simulations - I

[PTOLEMY, arxiv:1902.05508]

Events in **bin** i, centered at E_i:

$$N^i_\beta = T \int_{E_i-\Delta/2}^{E_i+\Delta/2} \frac{d\widetilde{\Gamma}_\beta}{dE_e} dE_e \qquad N^i_{\rm CNB} = T \int_{E_i-\Delta/2}^{E_i+\Delta/2} \frac{d\widetilde{\Gamma}_{\rm CNB}}{dE_e} dE_e$$

fiducial number of events: $\hat{N}^i = N^i_\beta(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) + N^i_{\rm CNB}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$

add **background** $\hat{N}_b = \hat{\Gamma}_b T$
with $\hat{\Gamma}_b \simeq 10^{-5}$ Hz $\longrightarrow$ $\boxed{N^i_t = \hat{N}^i + \hat{N}_b}$

T exposure time – $(\hat{E}_{\rm end}, \hat{m}_i, \hat{U})$ fiducial endpoint energy, masses, mixing matrix – $\boldsymbol{\theta} = (A_\beta, N_b, \Delta E_{end}, A_{\rm CNB}, m_i, U)$

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fit $\longrightarrow$

$$\chi^2(\boldsymbol{\theta}) = \sum_i \left(\frac{N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) - N^i_{\rm th}(\boldsymbol{\theta})}{\sqrt{N^i_t}} \right)^2$$

or $\log \mathcal{L} = -\frac{\chi^2}{2}$

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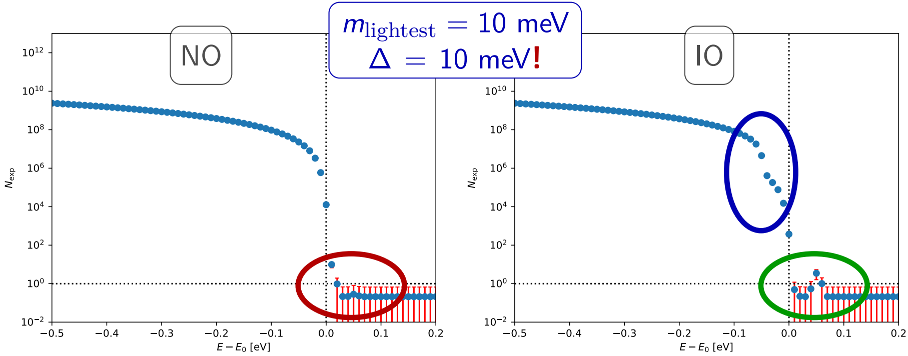
Simulations - II

no random noise?

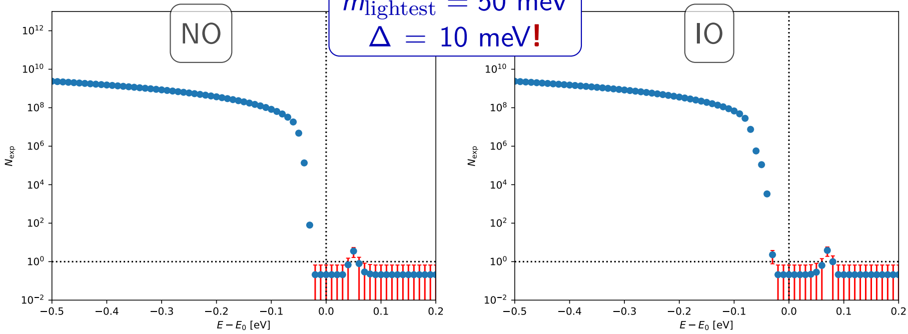


1 year of observation with 100 g of T source

Simulations - II

no random noise?

$m_{\text{lightest}} = 50$ meV
$\Delta = 10$ meV!



1 year of observation with 100 g of T source

Simulations - II

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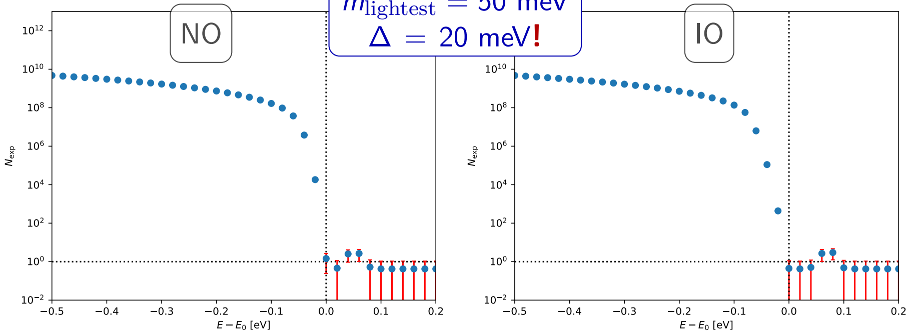
$m_{\rm lightest} = 50$ meV
$\Delta = 20$ meV!



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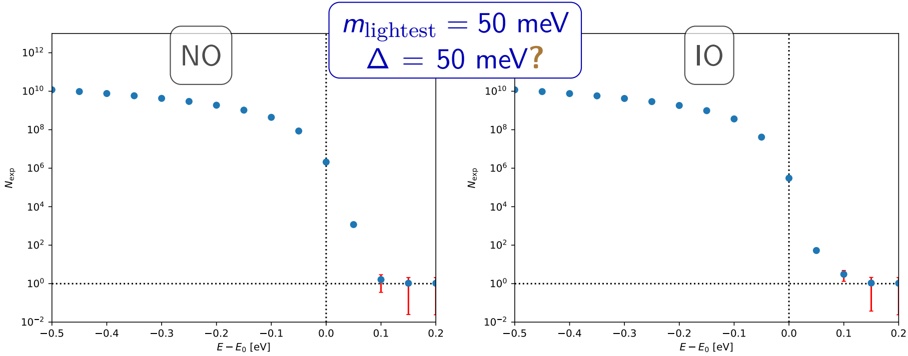

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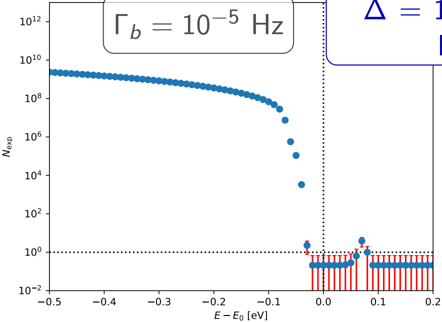
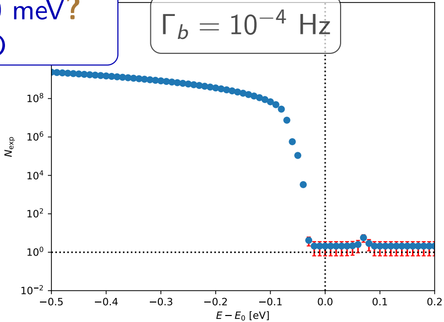
IO

$\Gamma_b = 10^{-5}$ Hz



$\Gamma_b = 10^{-4}$ Hz



1 year of observation with 100 g of T source

Simulations - II

with random noise!

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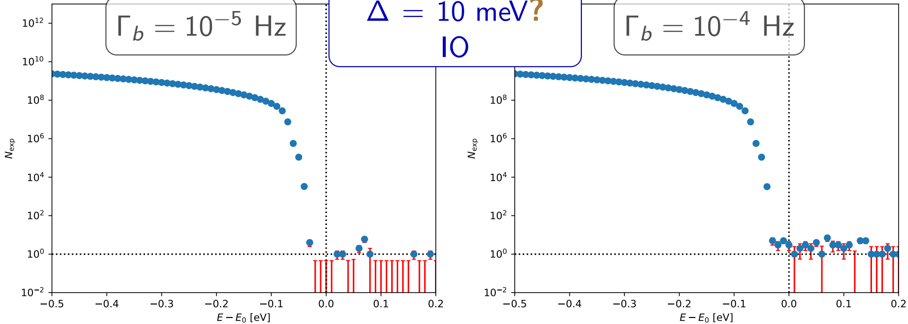
$\Delta = 10$ meV?
IO

$\Gamma_b = 10^{-5}$ Hz

$\Gamma_b = 10^{-4}$ Hz



things are more complicated in this way...low background needed!

1 year of observation with 100 g of T source

Perspectives for the mass determination [PTOLEMY, arxiv:1902.05508]

statistical only!

relative error on $m_{\rm lightest}$

as a function of $\hat{m}_{\rm lightest}$, Δ

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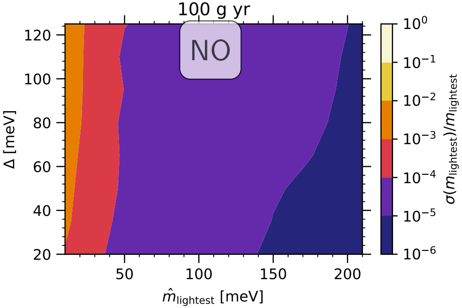

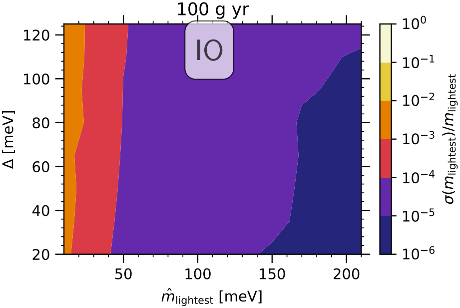

wonderful precision in determining the neutrino mass

(well, yes, with 100 g of tritium...)

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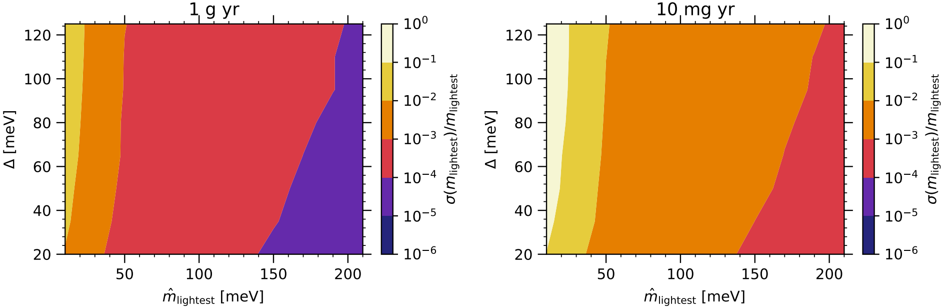

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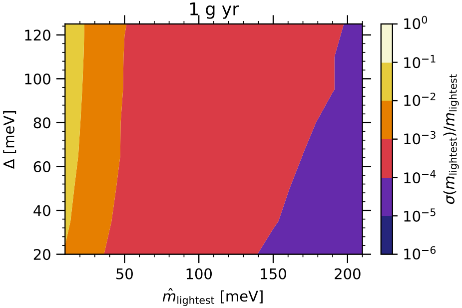

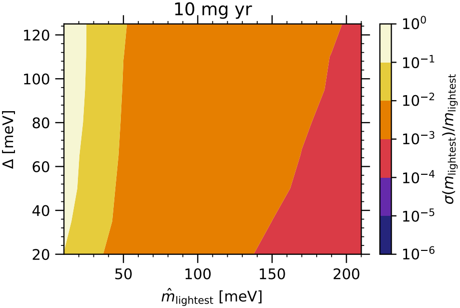

wonderful precision in determining the neutrino mass

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Δ has almost no impact

Neutrino mass ordering

[PTOLEMY, arxiv:1902.05508]

Bayesian method:

Fit fiducial ordering ($\widehat{\mathrm{NO}}$ or $\widehat{\mathrm{IO}}$) using both correct and wrong ordering

$\widehat{\mathrm{NO}}/\mathrm{NO}$ vs $\widehat{\mathrm{NO}}/\mathrm{IO}$

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worse fit

better fit

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(Bayesian) preference on m_{lightest}
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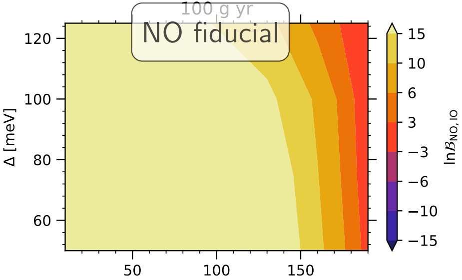

IO fiducial

always strong significance

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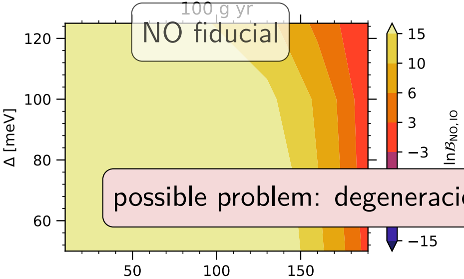

always strong significance

possible problem: degeneracies between m_{lightest} and Δm^2_{31}

Requirements for PTOLEMY discoveries

What do we need to discover…

	low Γ_b	extreme Δ	a lot of ^{3}H
… ν masses?	✗	✗	?
… ν mass ordering?	✗	?	?
… CNB direct detection?	✓	✓	✓

✓: strongly required

?: not so strongly required

✗: loosely required