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Relic neutrinos: clustering and consequences for direct detection

Featuring "Milky Way" & friends

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

1 ***Introduction***

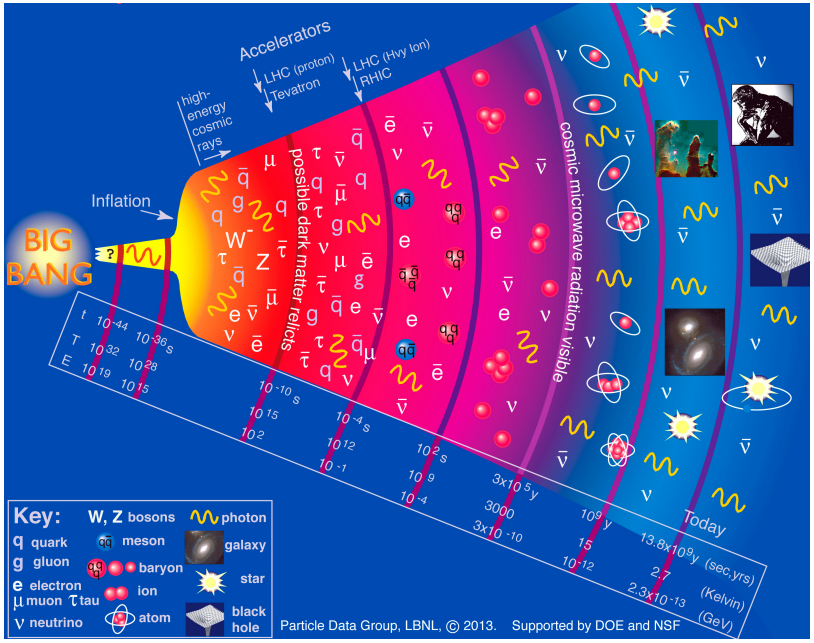
- Neutrinos and early Universe
- Relic neutrino capture

2 ***Neutrino clustering***

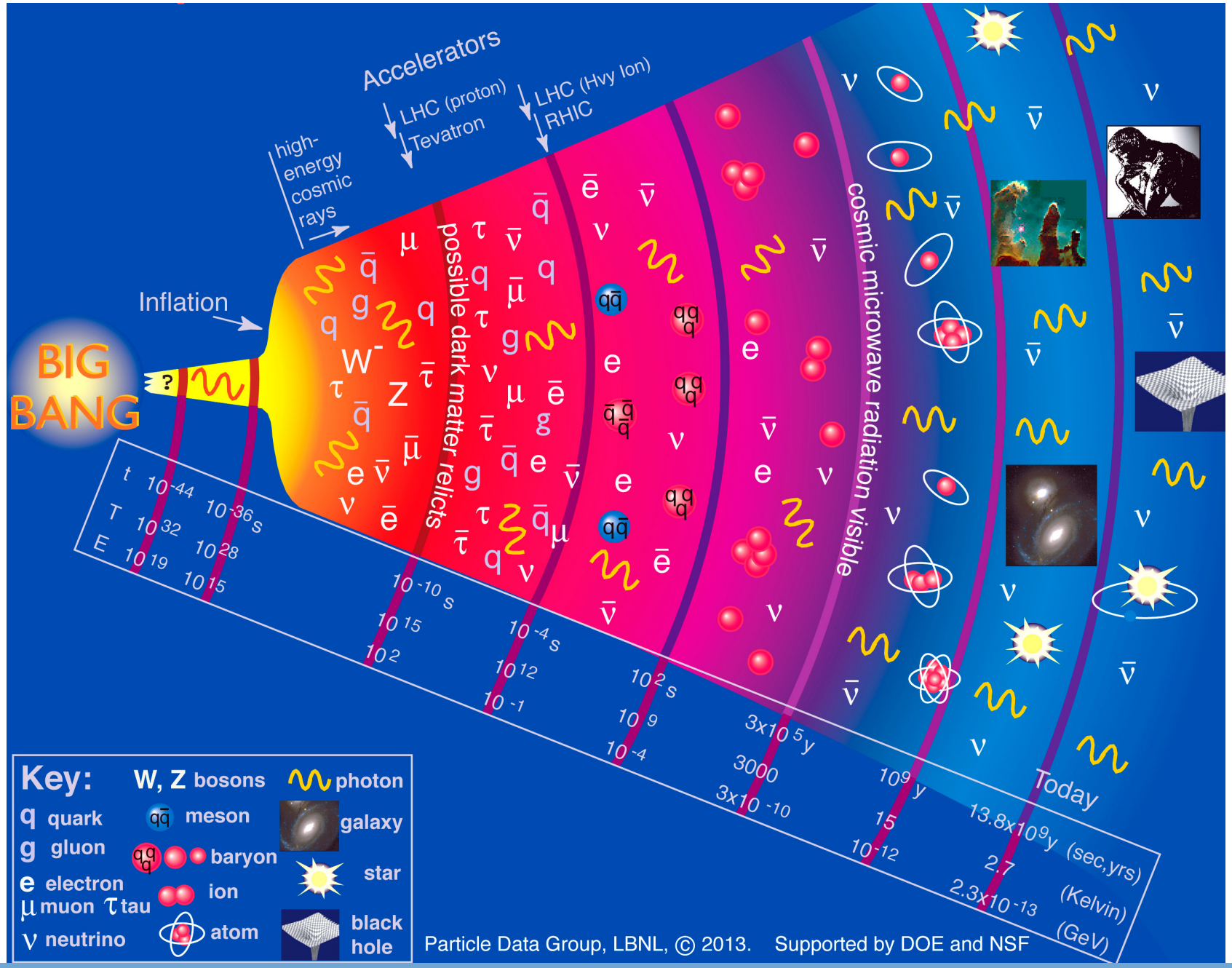
- Theory
- Results from the Milky Way
- Beyond the Milky Way

3 ***Direct detection of relic neutrinos***

4 ***Conclusions***



History of the universe



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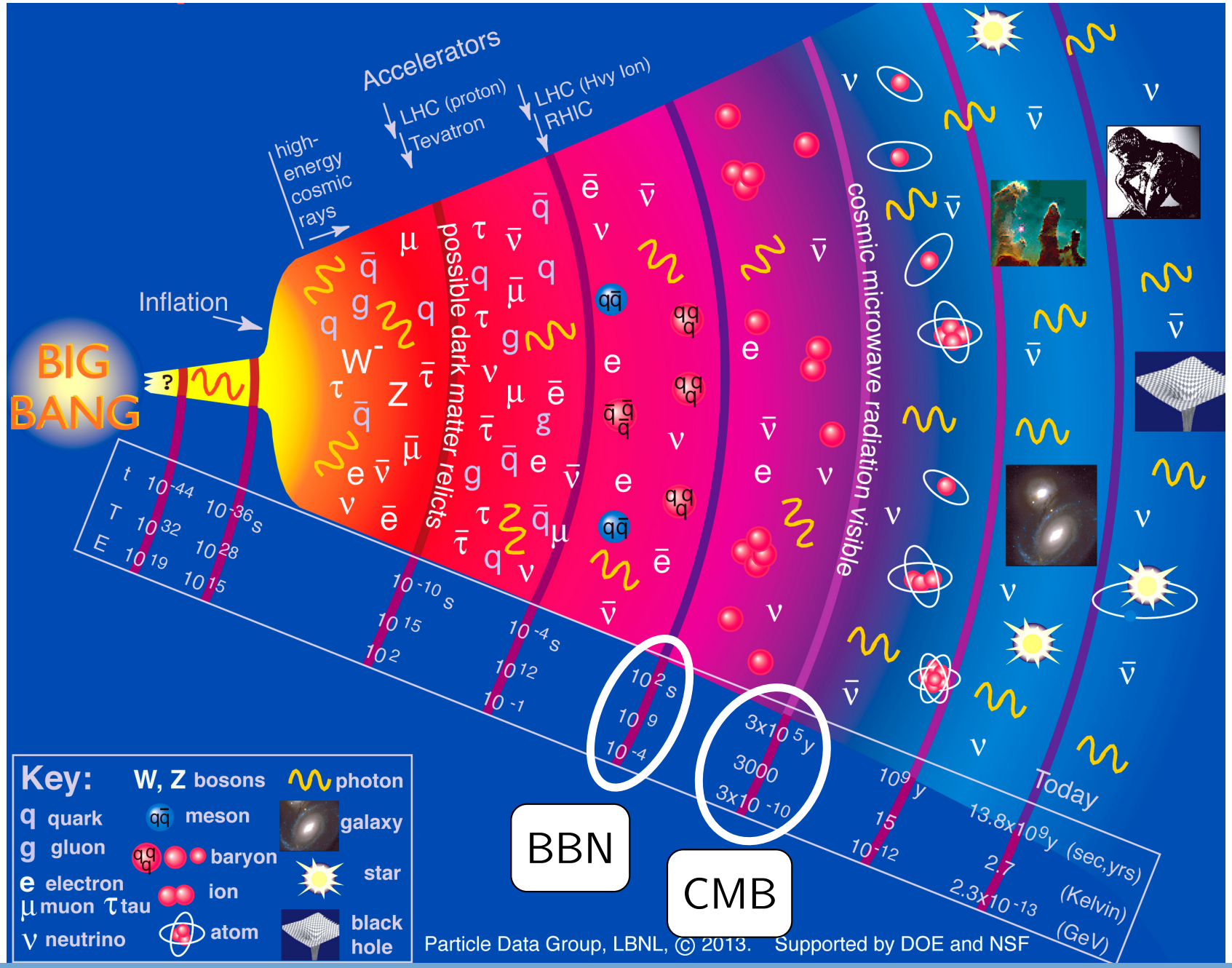

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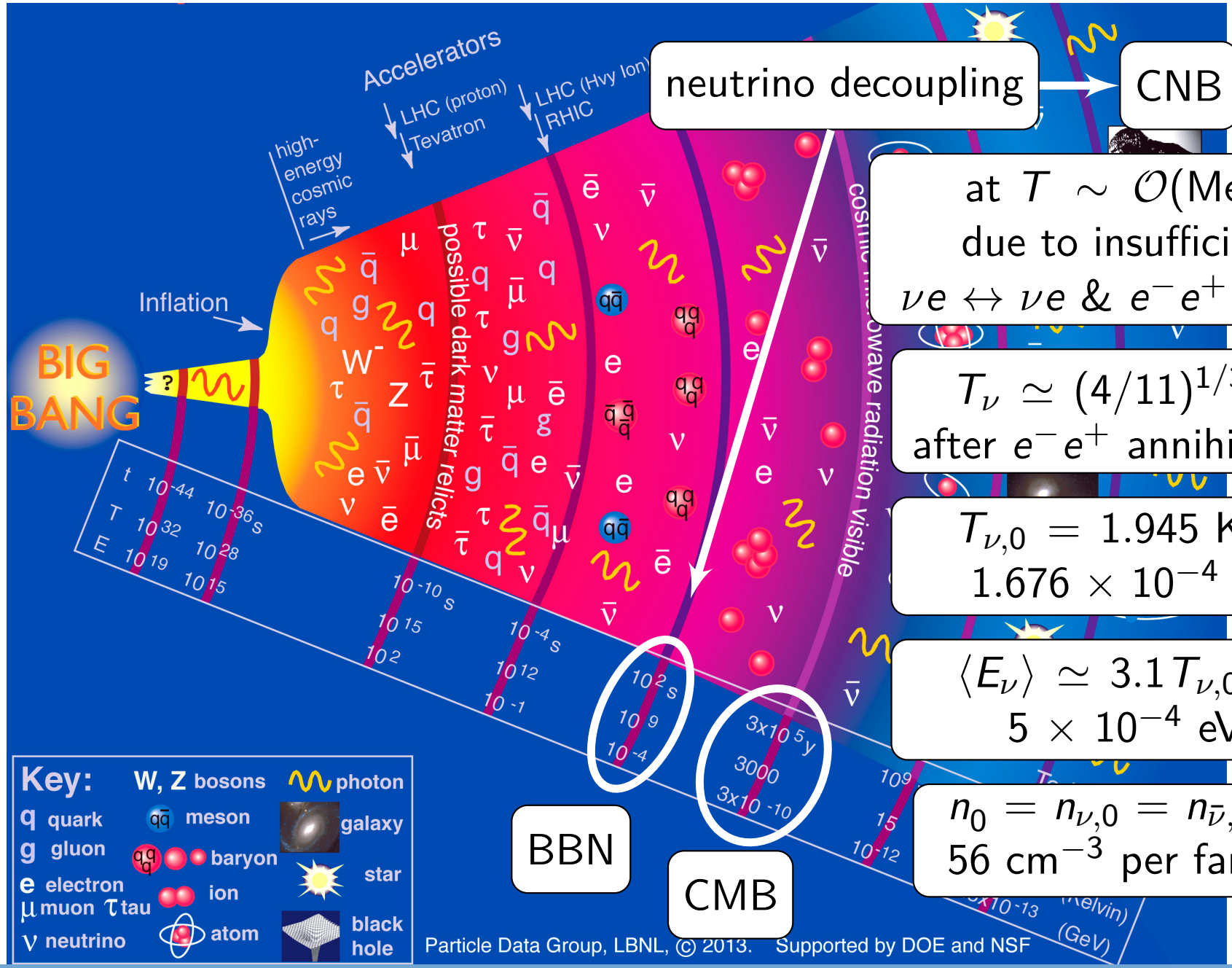


neutrino decoupling → CNB

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

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

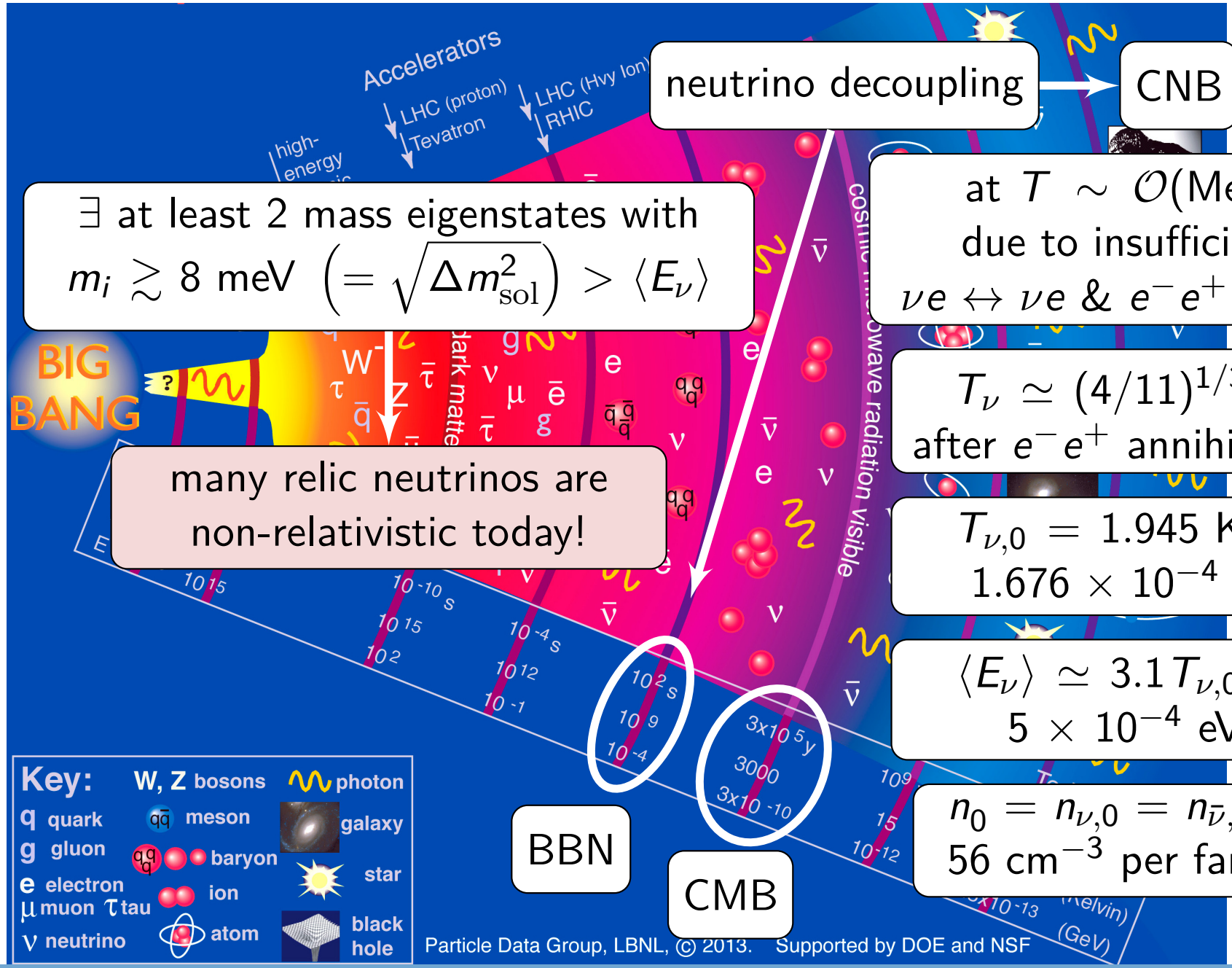
$\langle E_\nu \rangle \simeq 3.1\, T_{\nu,0} \simeq$
5×10^{-4} eV

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

BBN

CMB

History of the universe



neutrino decoupling → CNB

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

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

many relic neutrinos are non-relativistic today!

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

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

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

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Relic neutrinos in cosmology: $N_{\rm eff}$

Radiation energy density ρ_r in the early Universe:

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

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

- $N_{\rm eff} \to$ 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: $N_{\rm eff} \simeq 3.0 \pm 0.2$ [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 $\longrightarrow$ a process without energy threshold is necessary

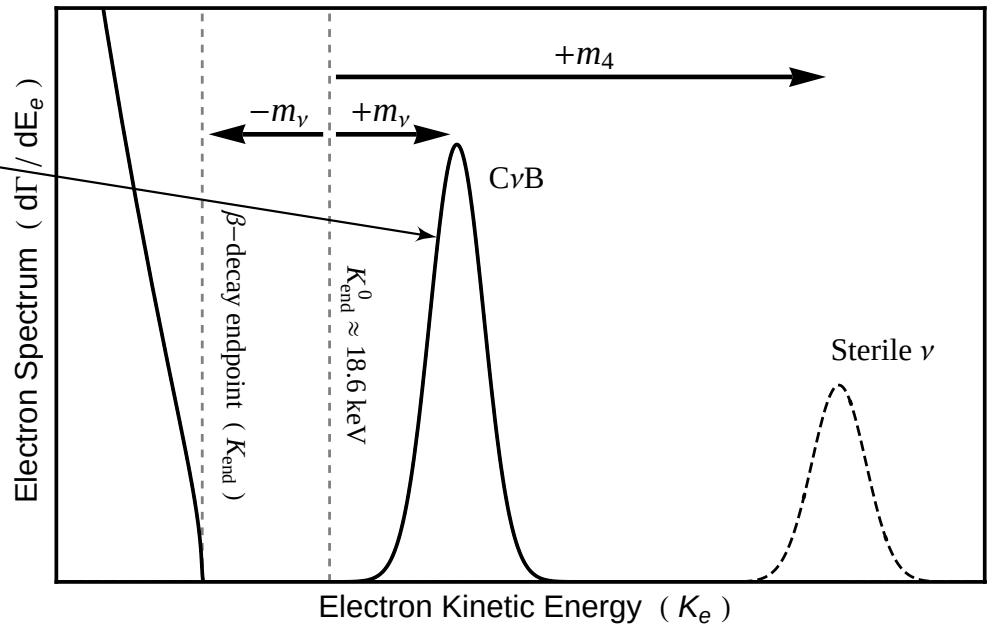
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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]
[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

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

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

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

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

(without clustering)

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ehnancement from ν clustering in the galaxy?

ehnancement from other effects?

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

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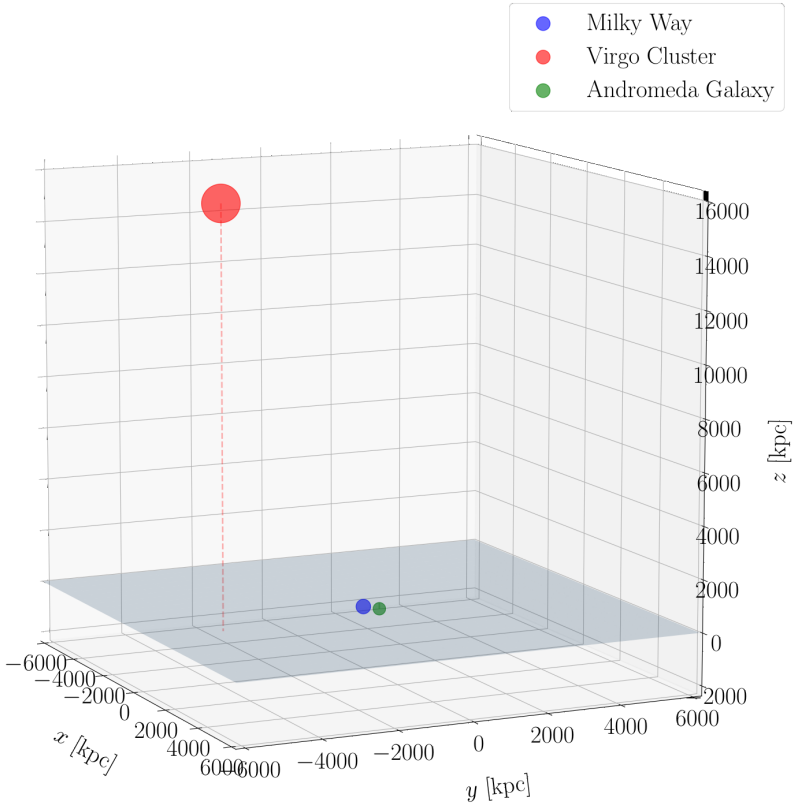


ν clustering with N-one-body simulations

[JCAP 09 (2017) 034]

Milky Way (MW) matter attracts neutrinos!

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

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

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

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

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

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

Assumptions:

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

how many νs is "N"?

$\rightarrow$ must sample all possible r, p_r, l

$\rightarrow$ must include all possible νs that reach the MW (fastest ones may come from several (up to $\mathcal{O}(100)$) Mpc!)

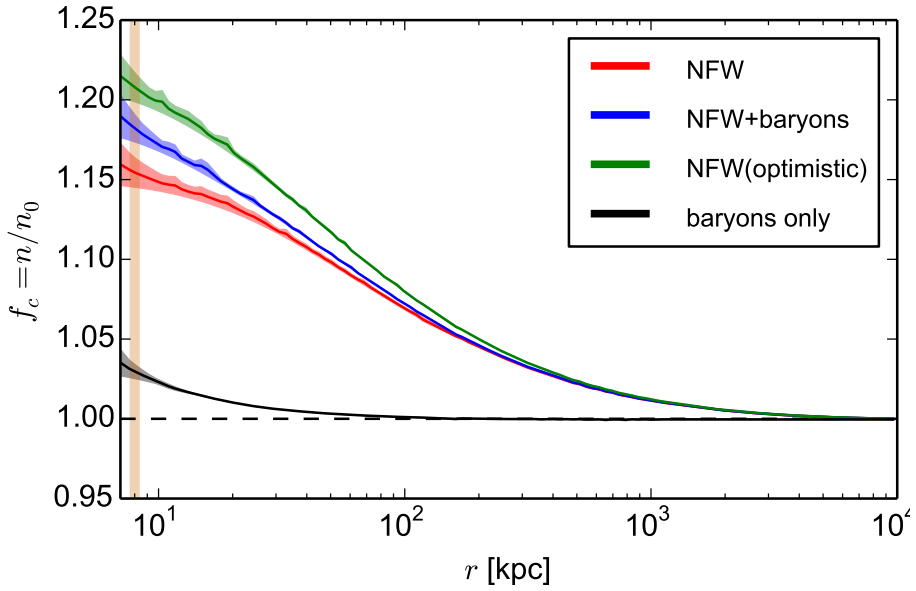
given N ν:

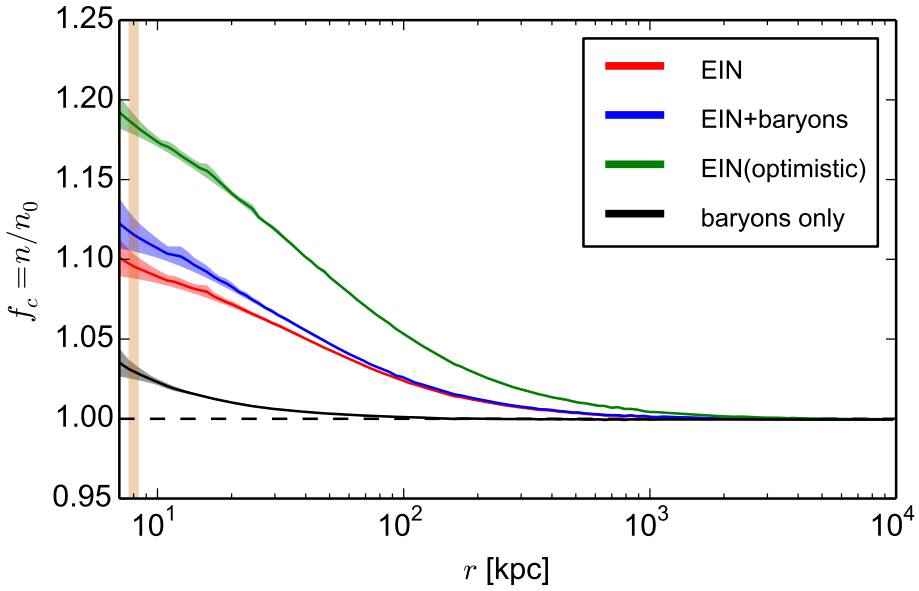
$\rightarrow$ weigh each neutrinos

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

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

[JCAP 09 (2017) 034]





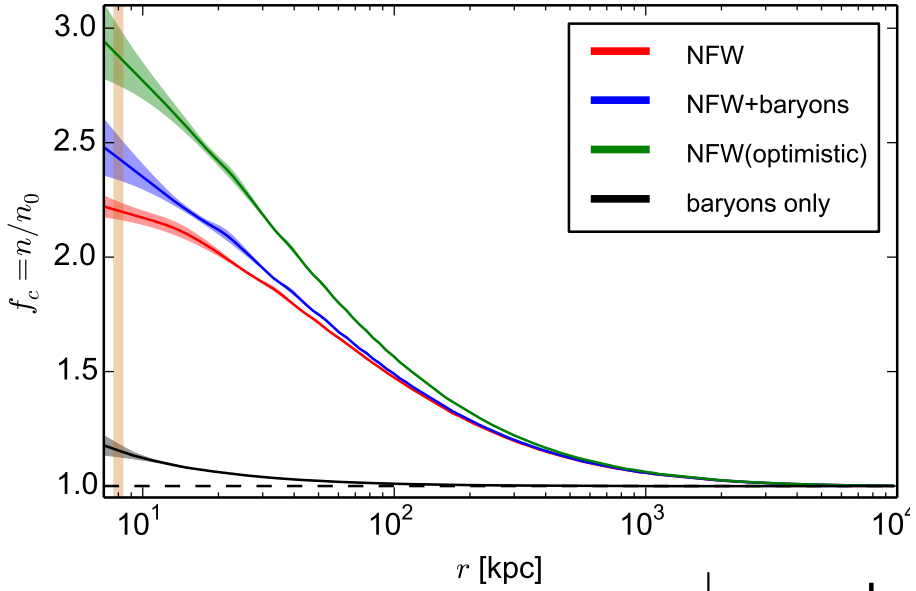
masses	ordering	matter halo	overdensity f_c		$\Gamma_{\rm tot}$ (yr^{-1})
			$f_1 \simeq f_2$	f_3	
any	any	any	no clustering		4.06
$m_3 = 60$ meV	NO	NFW(+bar)	$\sim$1	1.15 (1.18)	4.07 (4.08)
		NFW optimistic		1.21	4.08
		EIN(+bar)		1.09 (1.12)	4.07 (4.07)
		EIN optimistic		1.18	4.08
$m_1 \simeq m_2 =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

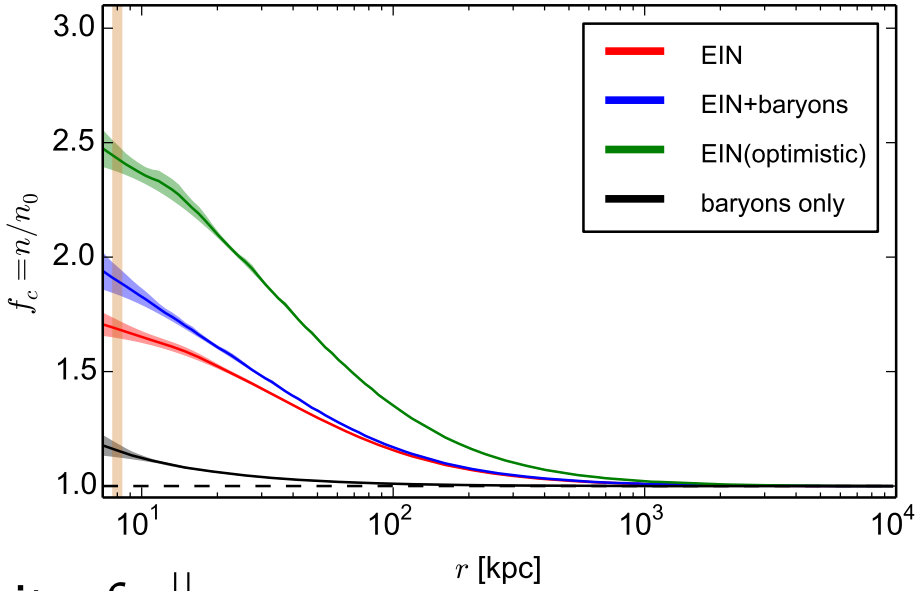
ordering dependence from $\Gamma_{\rm CNB} = \sum_{i=1}^{3} |U_{ei}|^2 f_i \left[n_i(\nu_{h_R}) + n_i(\nu_{h_L})\right] N_T \bar{\sigma}$

Overdensity when $m_\nu \simeq 150$ meV

[JCAP 09 (2017) 034]

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



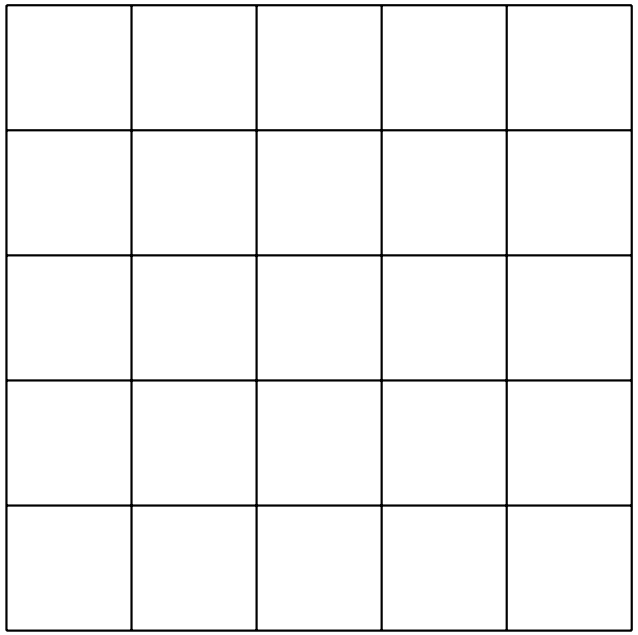


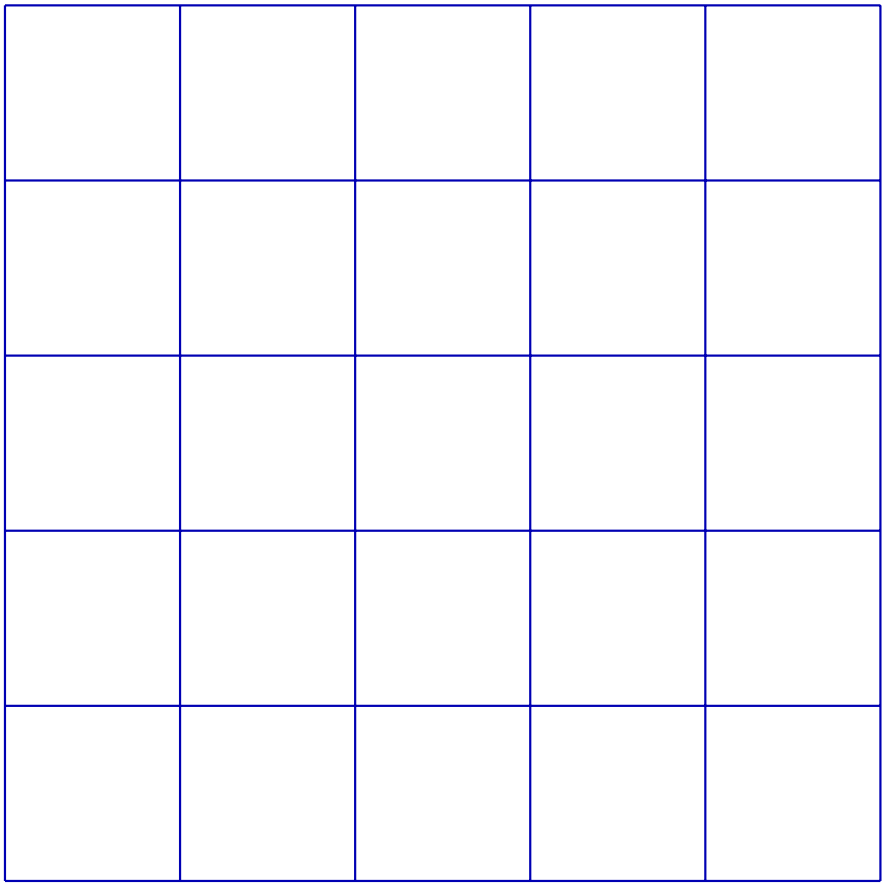
matter halo	overdensity f_c $f_1 \simeq f_2 \simeq f_3$	$\Gamma_{\rm tot}$ (yr^{-1})
any	no clustering	4.06
NFW(+bar)	2.18 (2.44)	8.8 (9.9)
NFW optimistic	2.88	11.7
EIN(+bar)	1.68 (1.87)	6.8 (7.6)
EIN optimistic	2.43	9.9

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

Forward-tracking and back-tracking

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

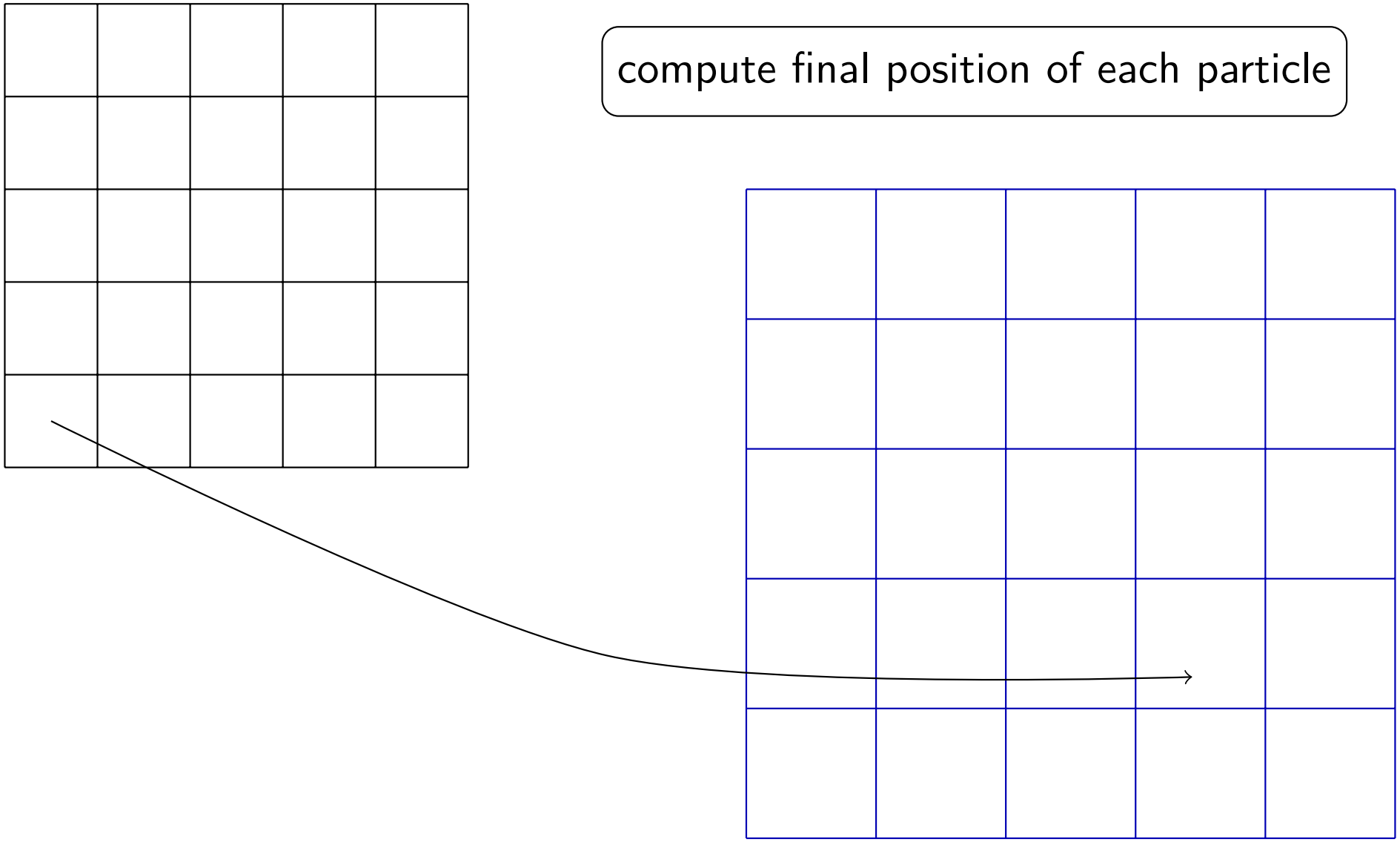




final phase space, $z = 0$

Forward-tracking and back-tracking

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



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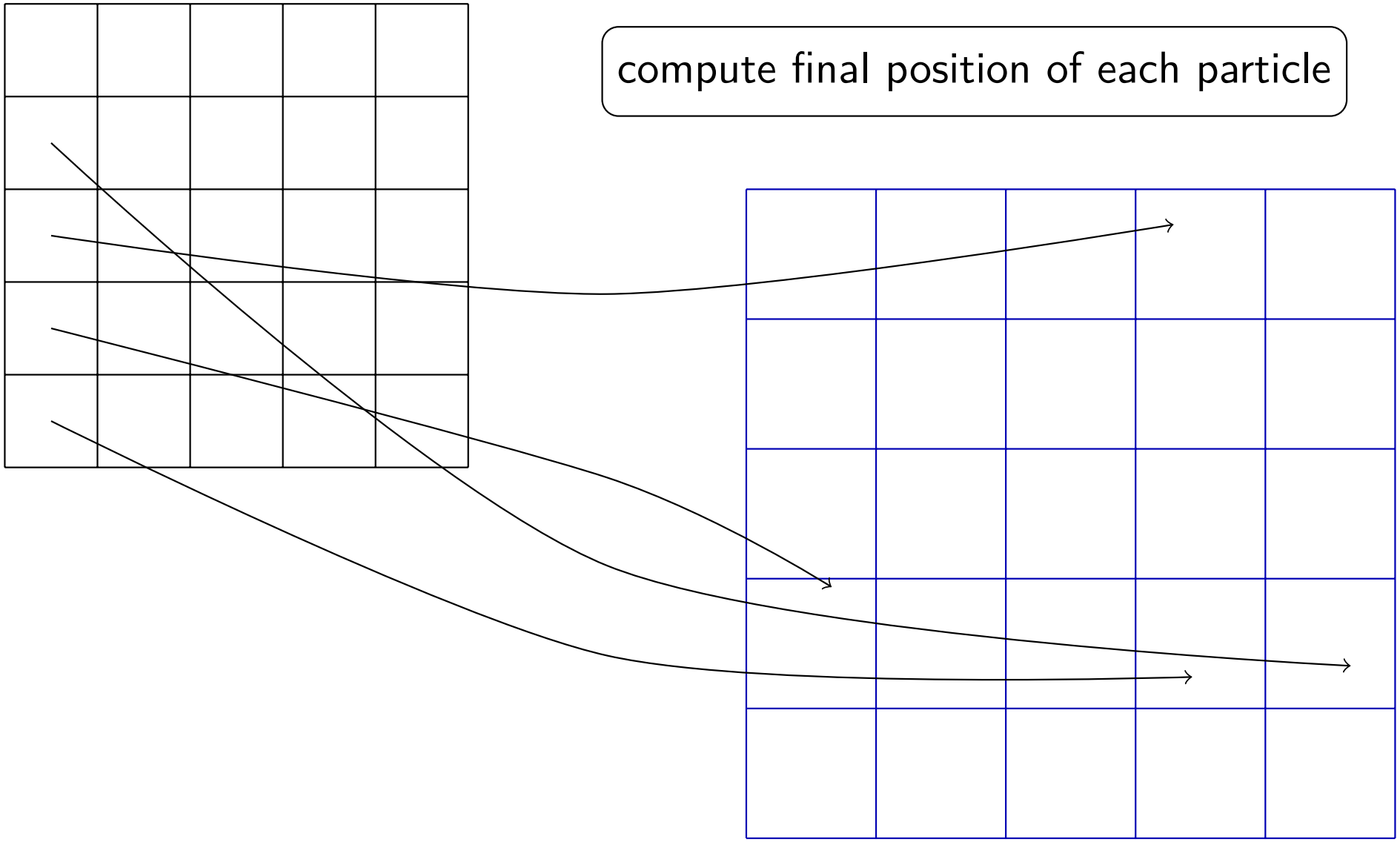

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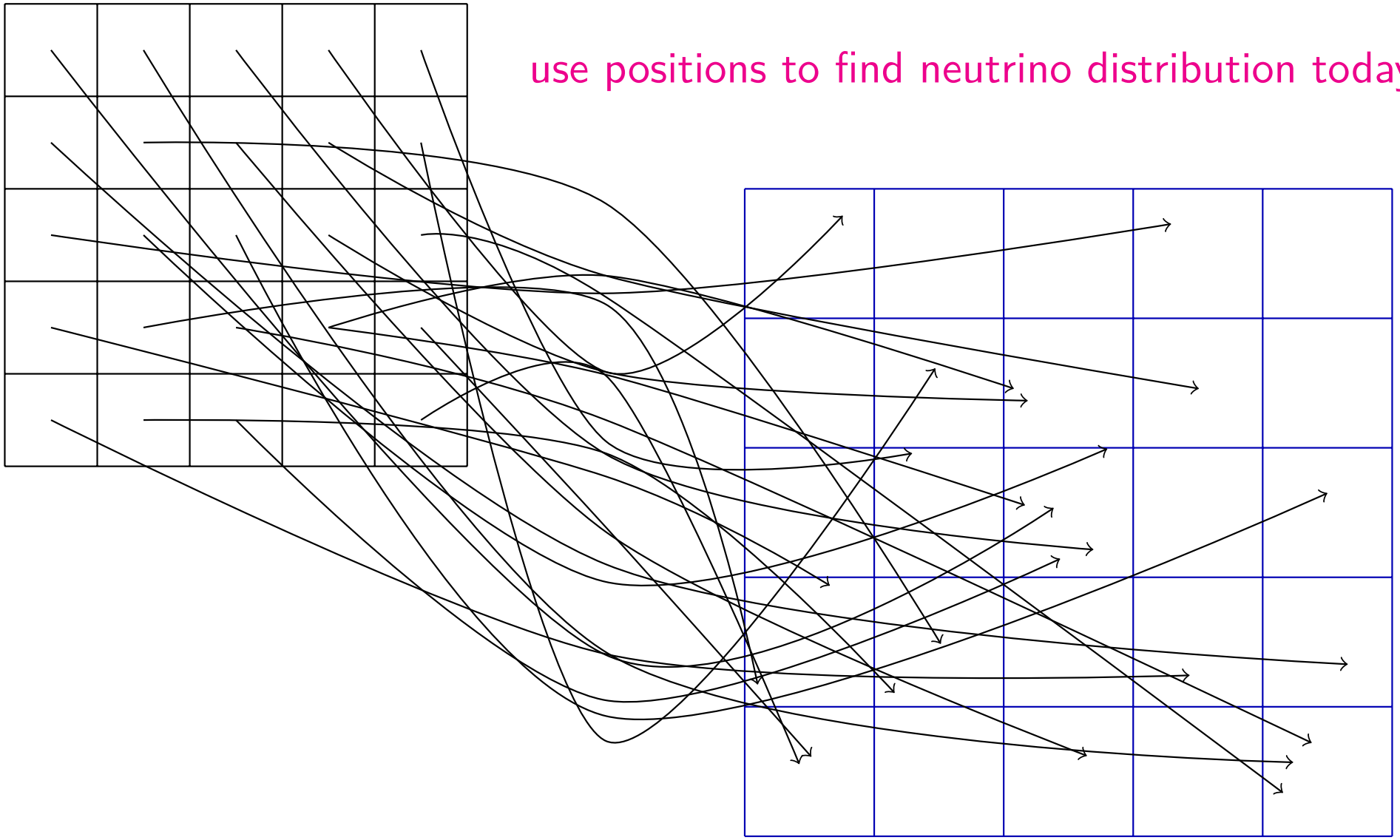
Forward-tracking and back-tracking

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

use positions to find neutrino distribution today



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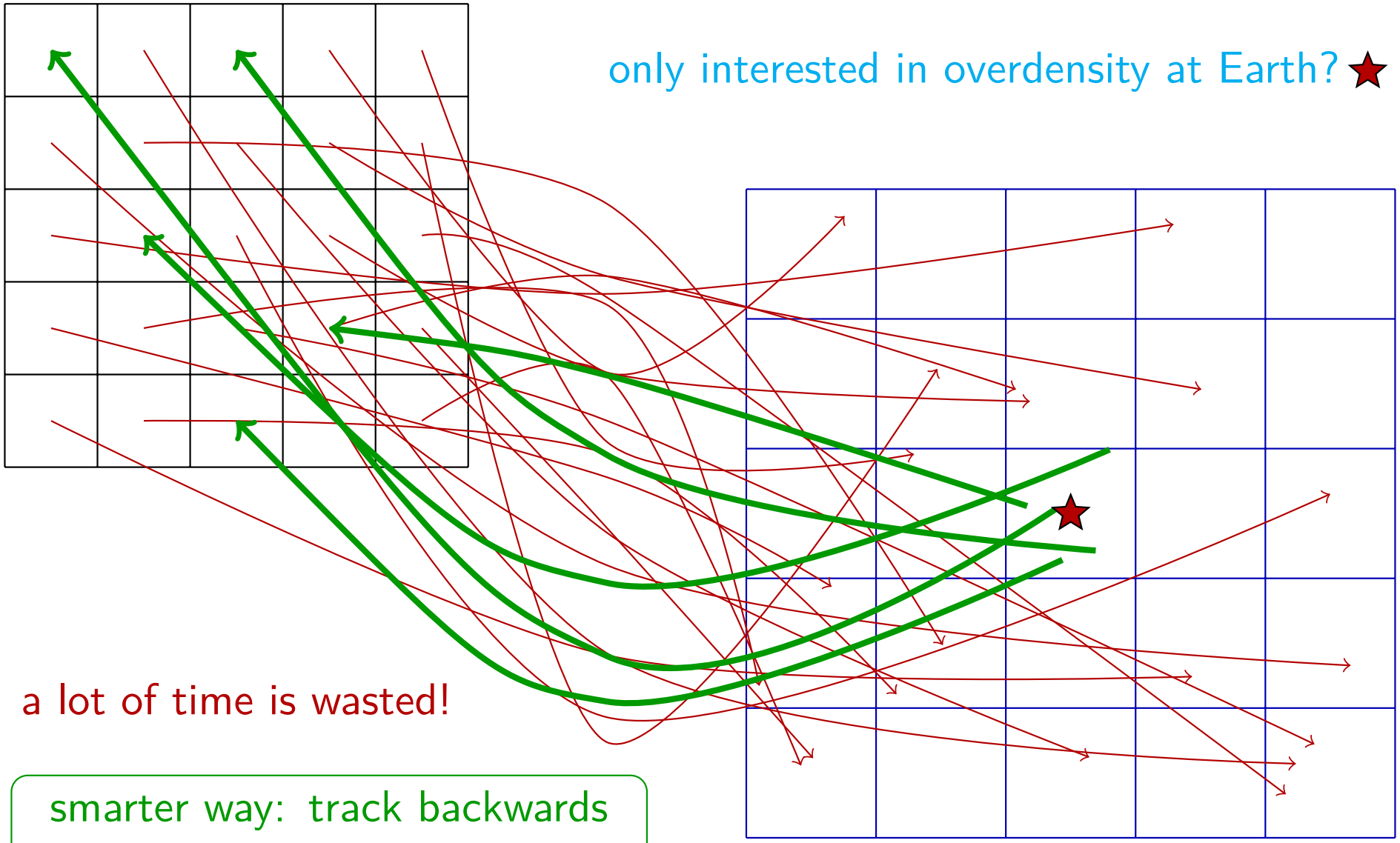

smarter way: track backwards
only interesting particles!

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

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

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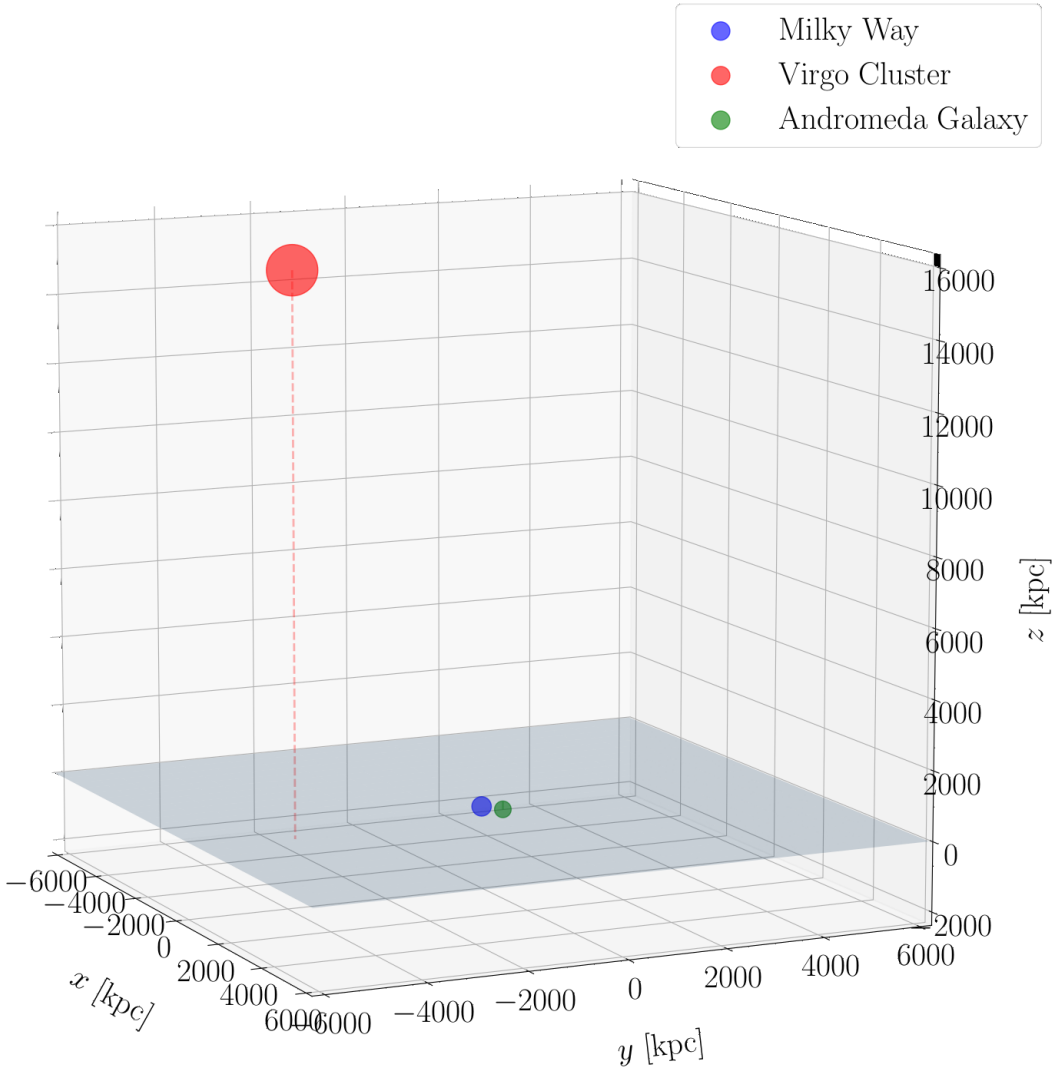
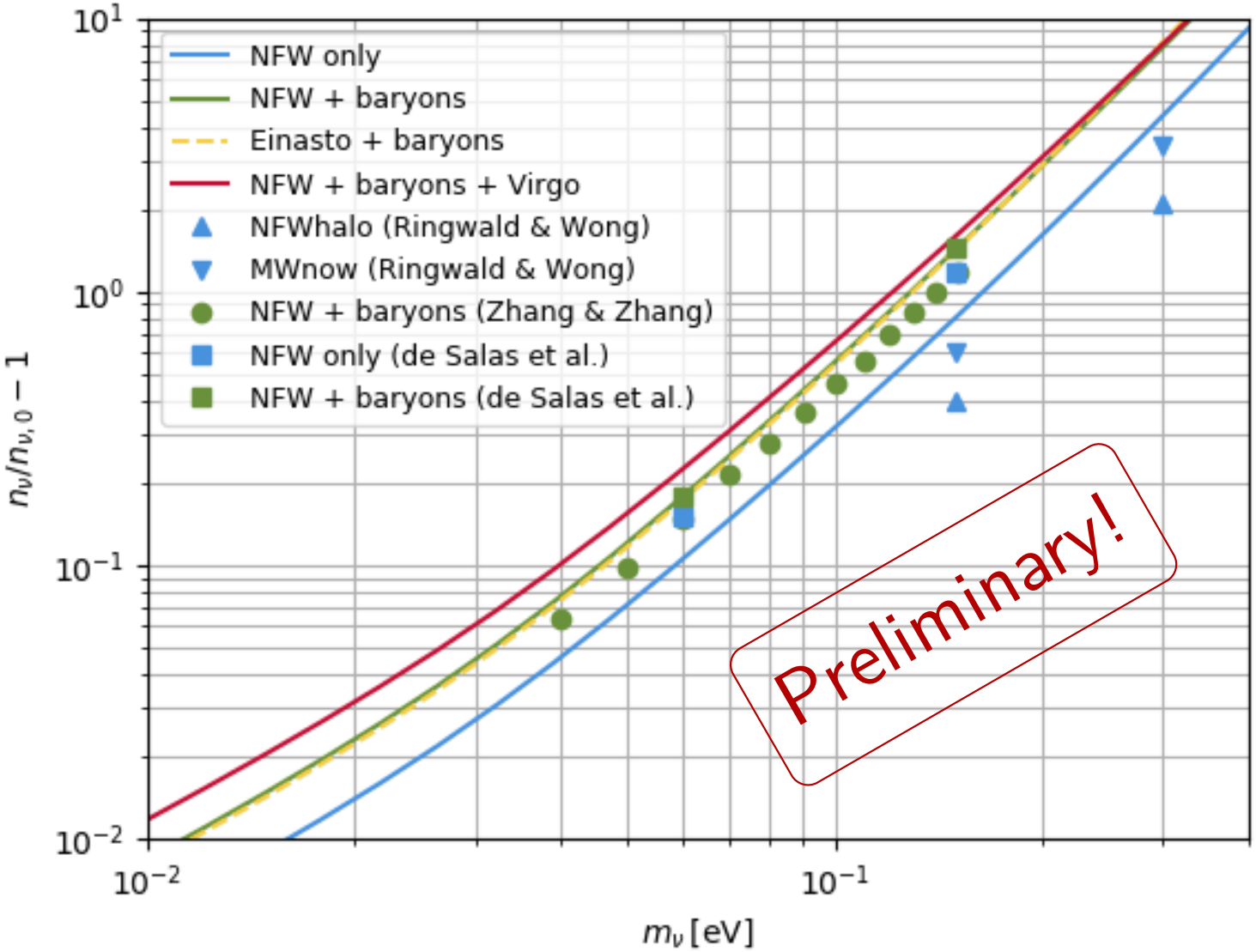
Second advantage: no need to use spherical symmetry!



Preliminary results with back-tracking

[SG+, in preparation]

In comparison with previous results:



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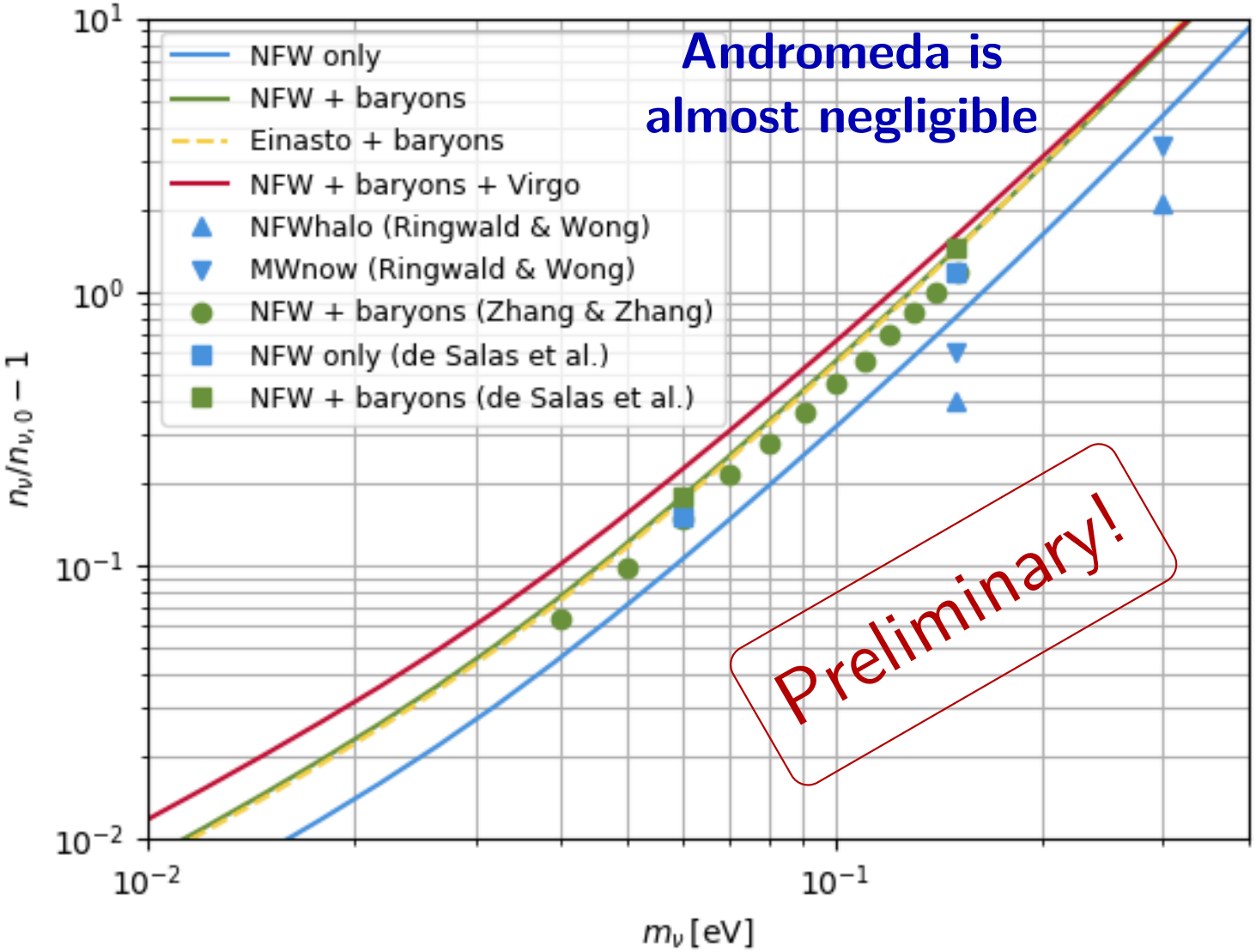

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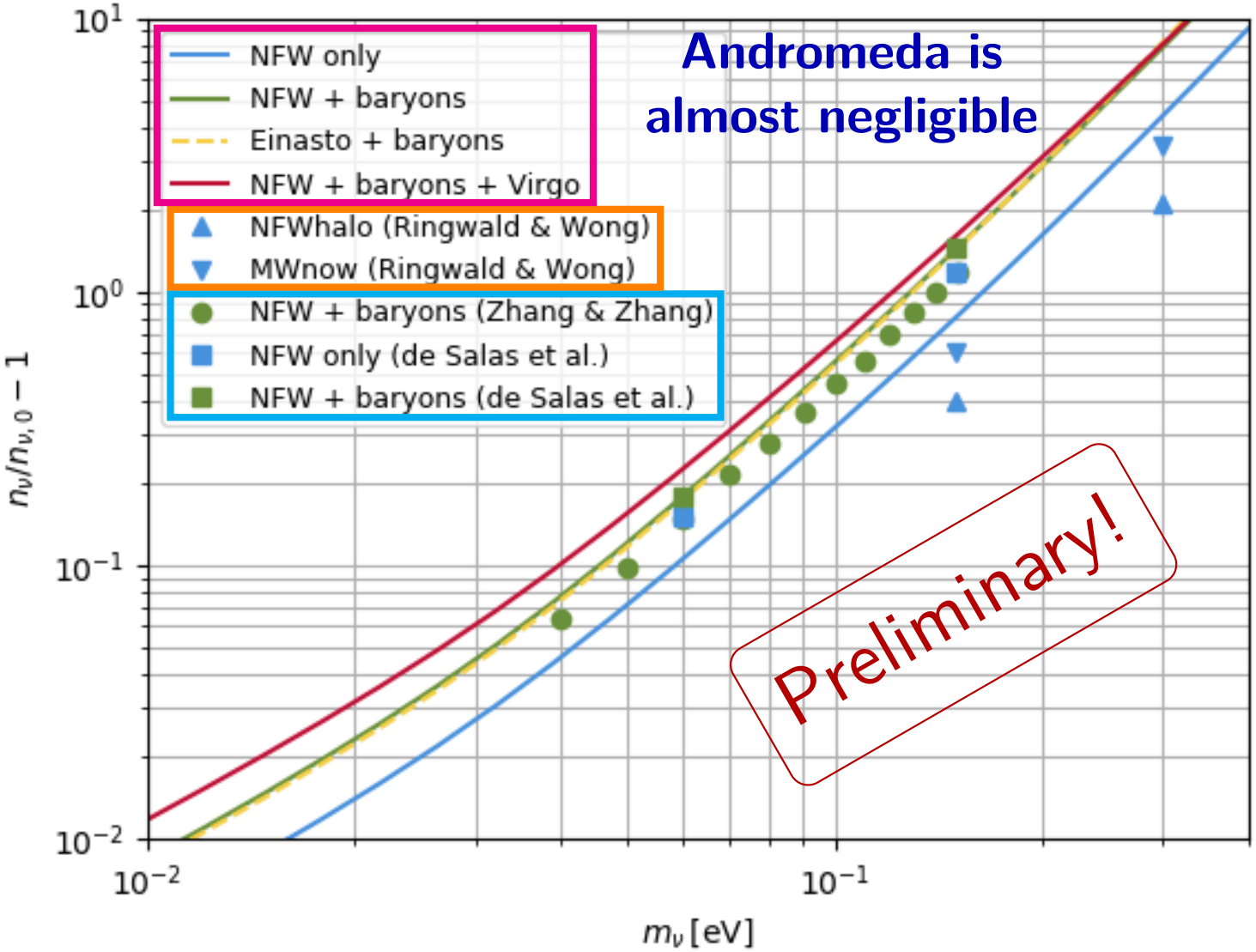

Warning: NFW is not the same for all the cases!

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

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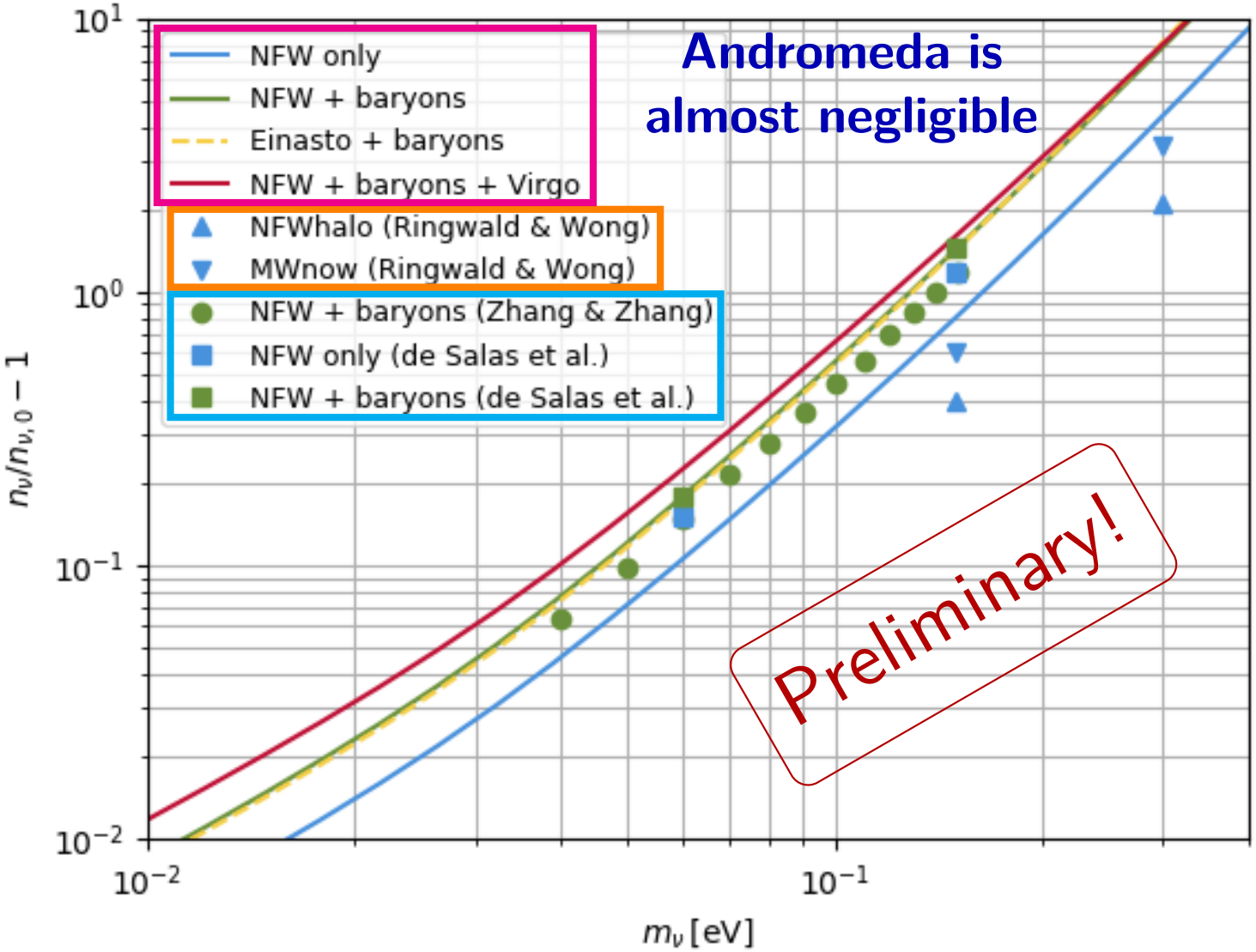

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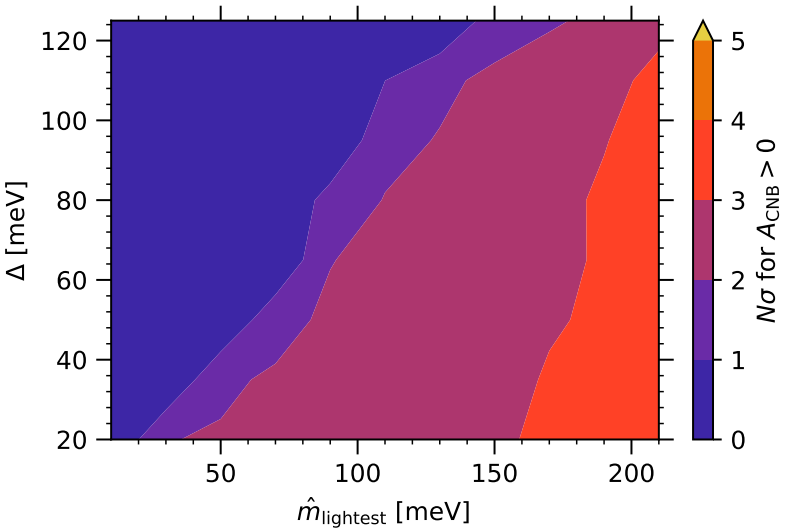
many checks are missing: distance of Virgo, Sun position, more on DM, ...



β and Neutrino Capture spectra

[PTOLEMY, arxiv:1902.05508]

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

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

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

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

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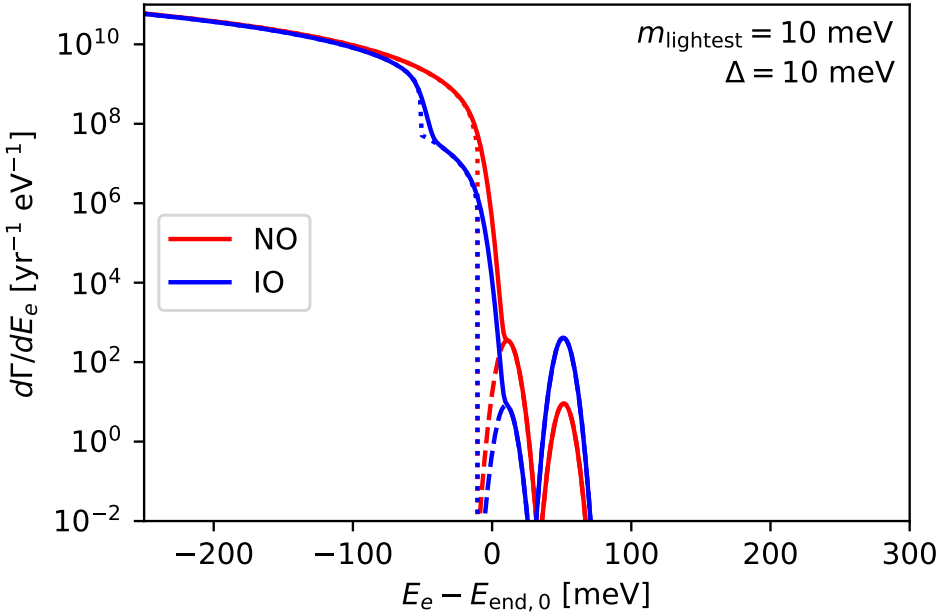
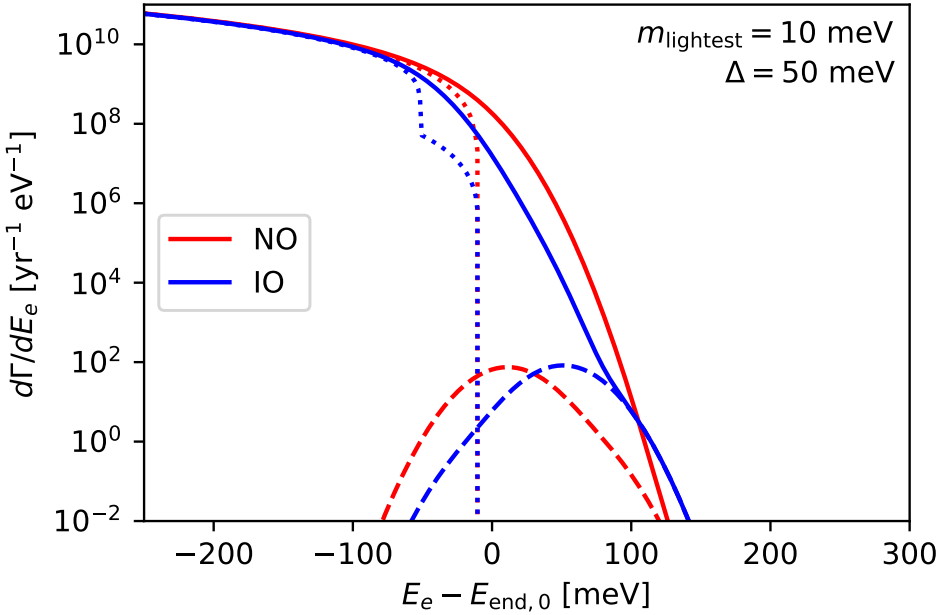




$\bar{\sigma}$ cross section, N_T number of tritium atoms in the source (PTOLEMY: 100 g), $E_{\rm end}$ endpoint, $\sigma = \Delta/\sqrt{8\ln 2}$ standard deviation

Detection of the relic neutrinos

[PTOLEMY, arxiv:1902.05508]

using the definition:

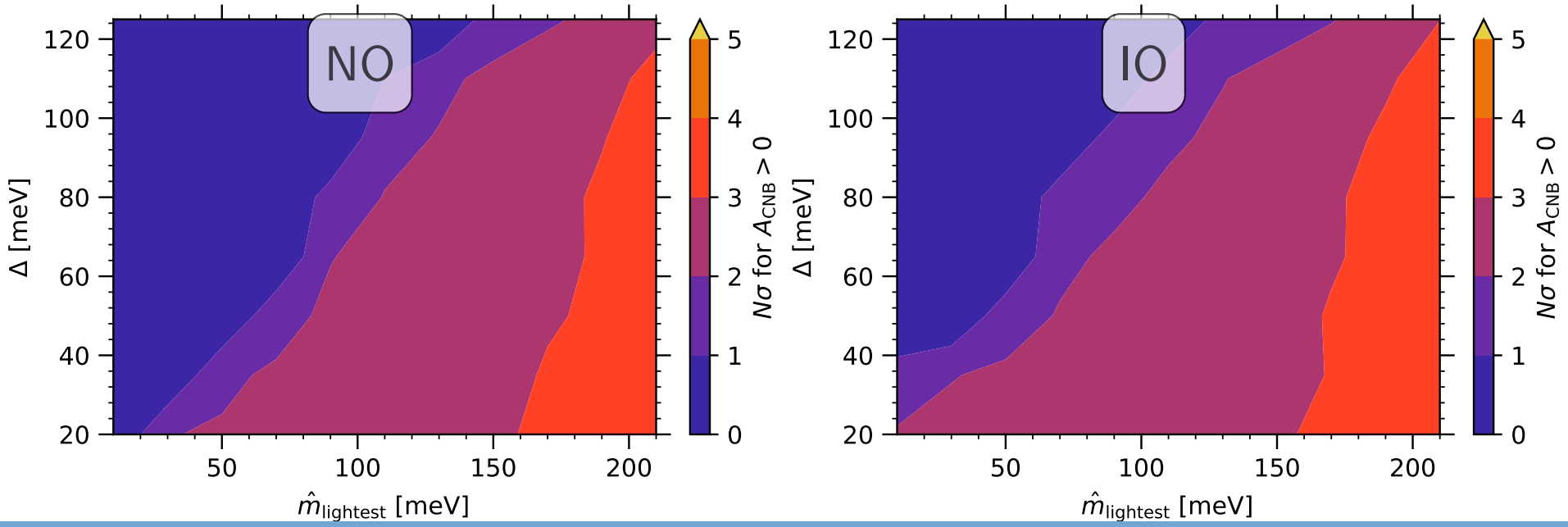
$$N^i_{\rm th}(\boldsymbol{\theta}) = A_\beta N^i_\beta(\hat{E}_{end} + \Delta E_{end}, m_i, U) + \boldsymbol{A}_{\mathbf{CNB}} N^i_{\rm CNB}(\hat{E}_{end} + \Delta E_{end}, m_i, U) + N_b$$

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



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,
and also nearby galaxies/clusters!

4 Clustering cannot increase detection chances,
but we could constrain the composition of the
astrophysical environment using the event rate!

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Thank you for the attention!

5 *Milky Way parameterization*

6 *PTOLEMY*

Dark matter: profiles today

[JCAP 09 (2017) 034]

(γ)NFW profile:

Einasto (EIN) profile:

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

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

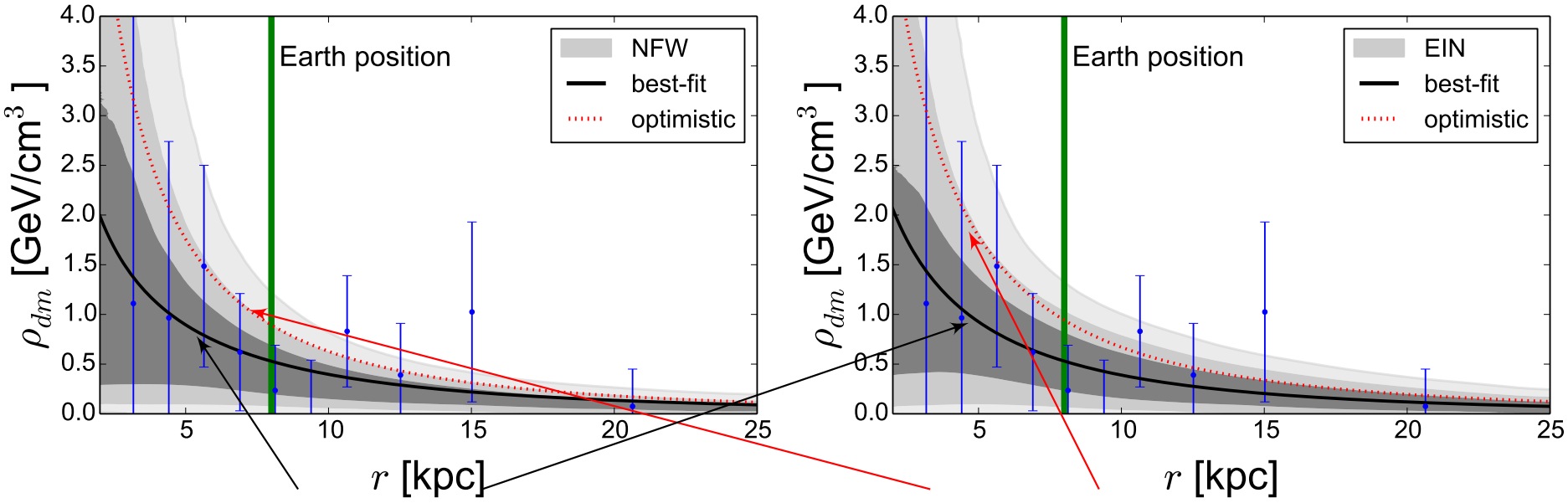
normalization

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

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

parameters

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



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

$$\begin{cases} \rho_{\rm cr}(z) = \frac{3}{8\pi G} H^2(z) \\ F_{\rm cr}(z) = \Omega_{m,0}(1+z)^3 + \Omega_{\Lambda,0} \\ H^2(z) = H_0^2\, F_{\rm cr}(z) \\ \rho_{\rm cr}(z) = F_{\rm cr}(z) \times \rho_{\rm cr}(z=0) \end{cases}$$

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

(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 $r_{\rm vir}$?

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

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

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

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

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

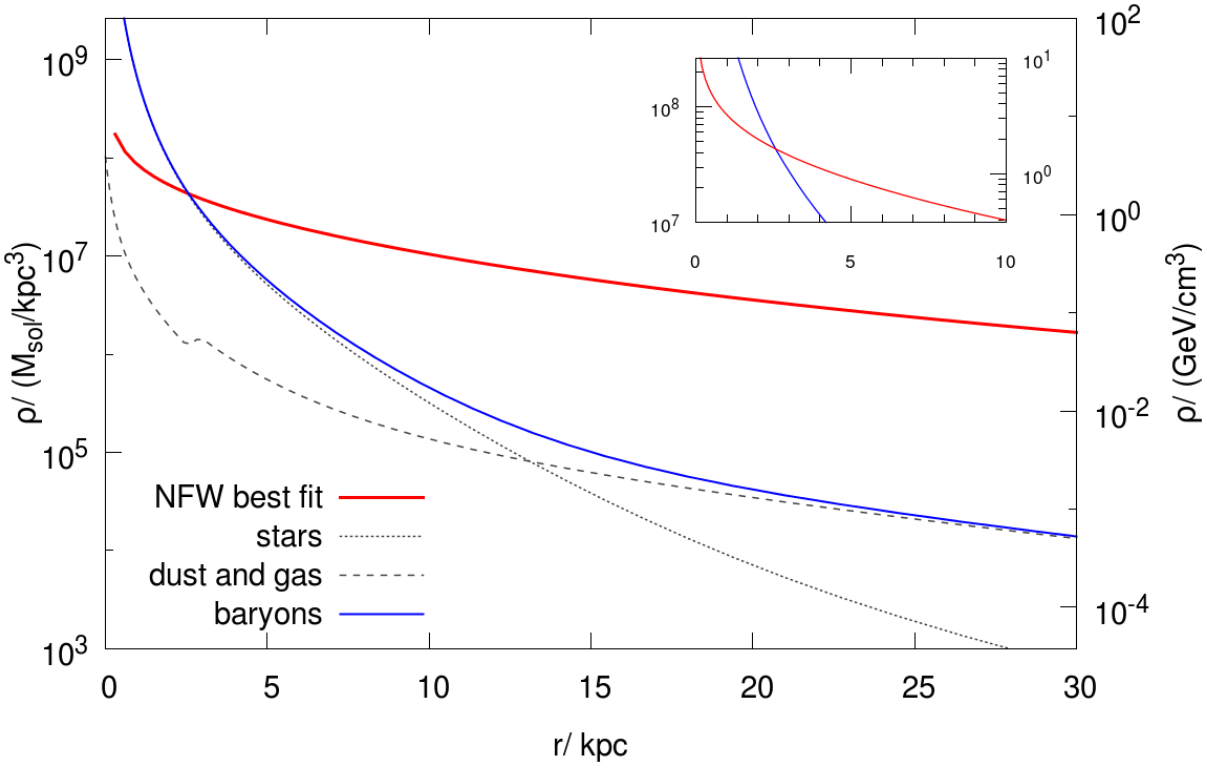
Complex problem: how to model baryon content of a galaxy?

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

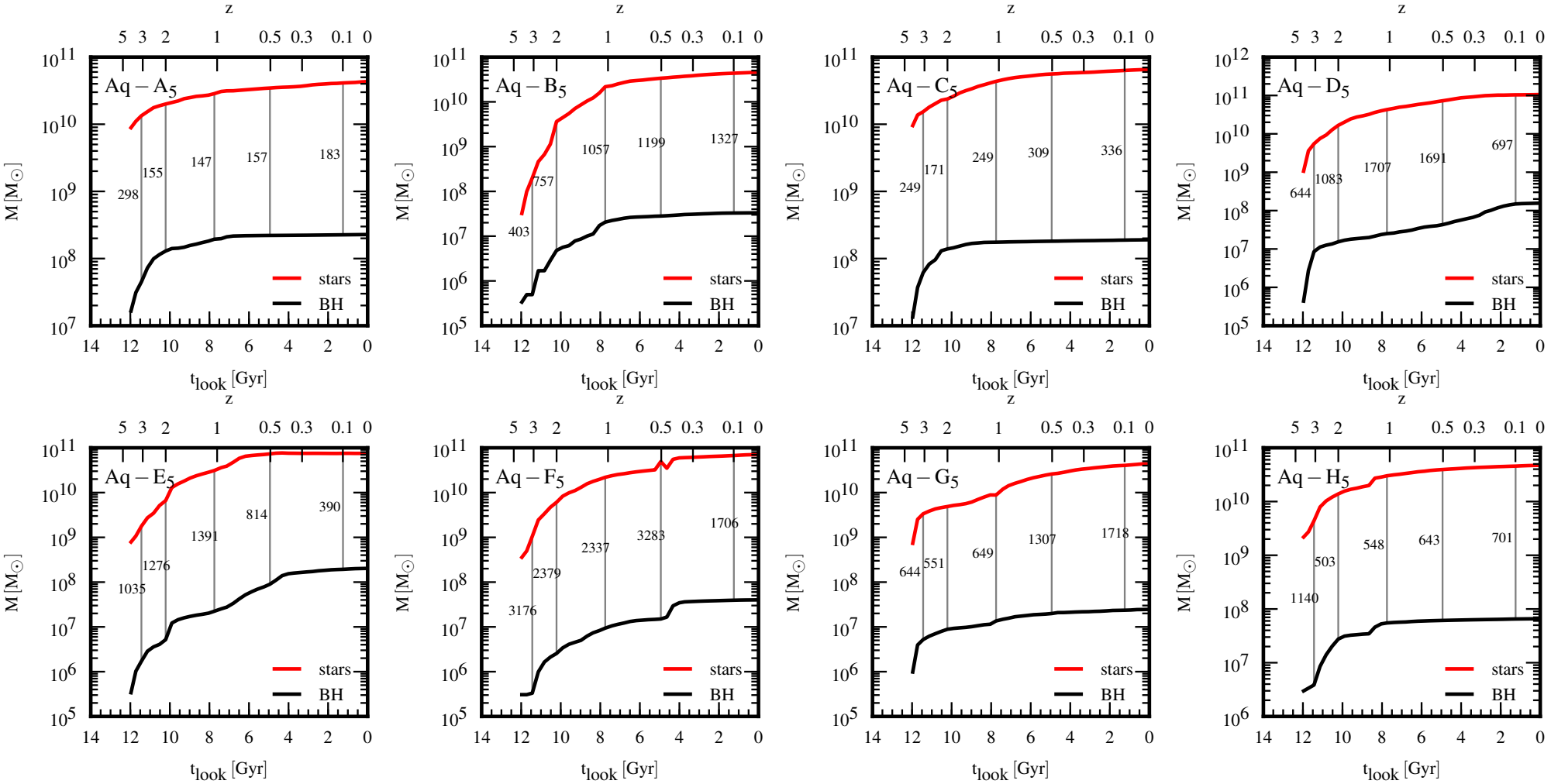
baryon evolution with redshift?

from [Marinacci et al., 2013]

results of full N-body simulations

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

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



5 *Milky Way parameterization*

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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simulated experimental spectrum: $N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) = N^i_t \pm \sqrt{N^i_t}$

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repeat for theory spectrum, free **amplitudes** and **endpoint position**:

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

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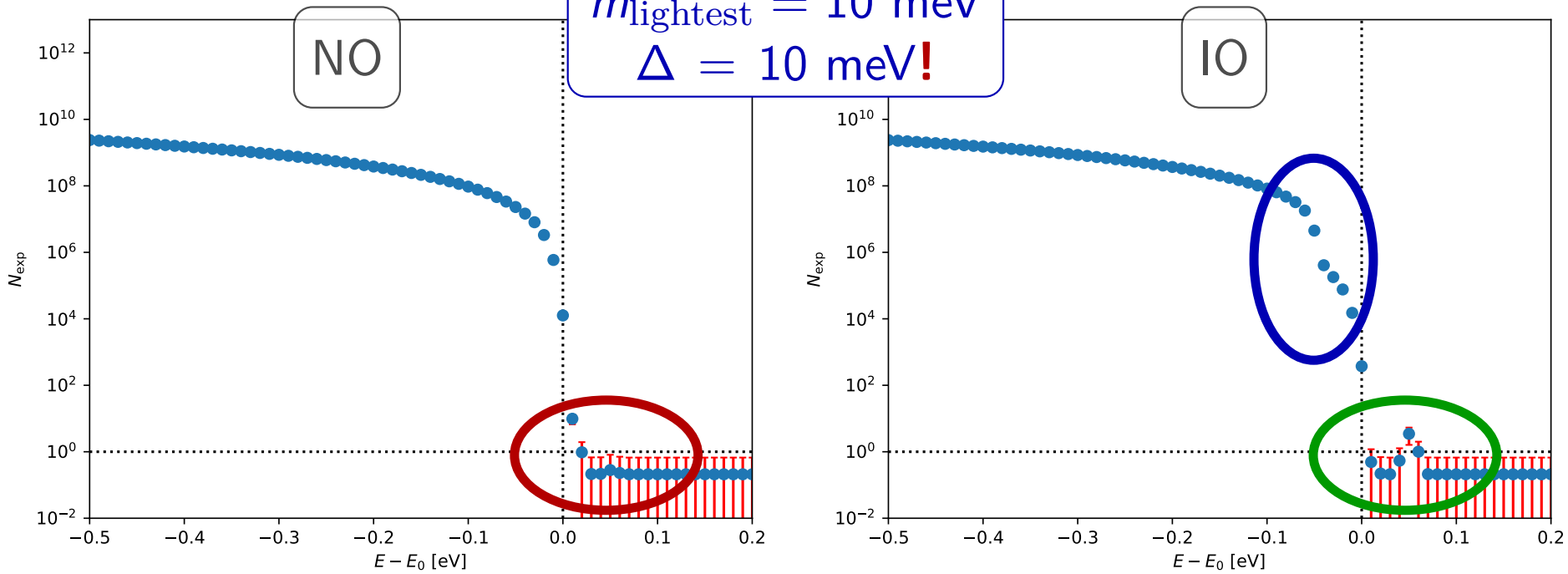
fit $\longrightarrow$ $\chi^2(\boldsymbol{\theta}) = \sum_i \left(\frac{N^i_{\rm exp}(\hat{E}_{\rm end}, \hat{m}_i, \hat{U}) - N^i_{\rm th}(\boldsymbol{\theta})}{\sqrt{N^i_t}} \right)^2$ or $\log \mathcal{L} = -\frac{\chi^2}{2}$

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

Simulations - II

no random noise?

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

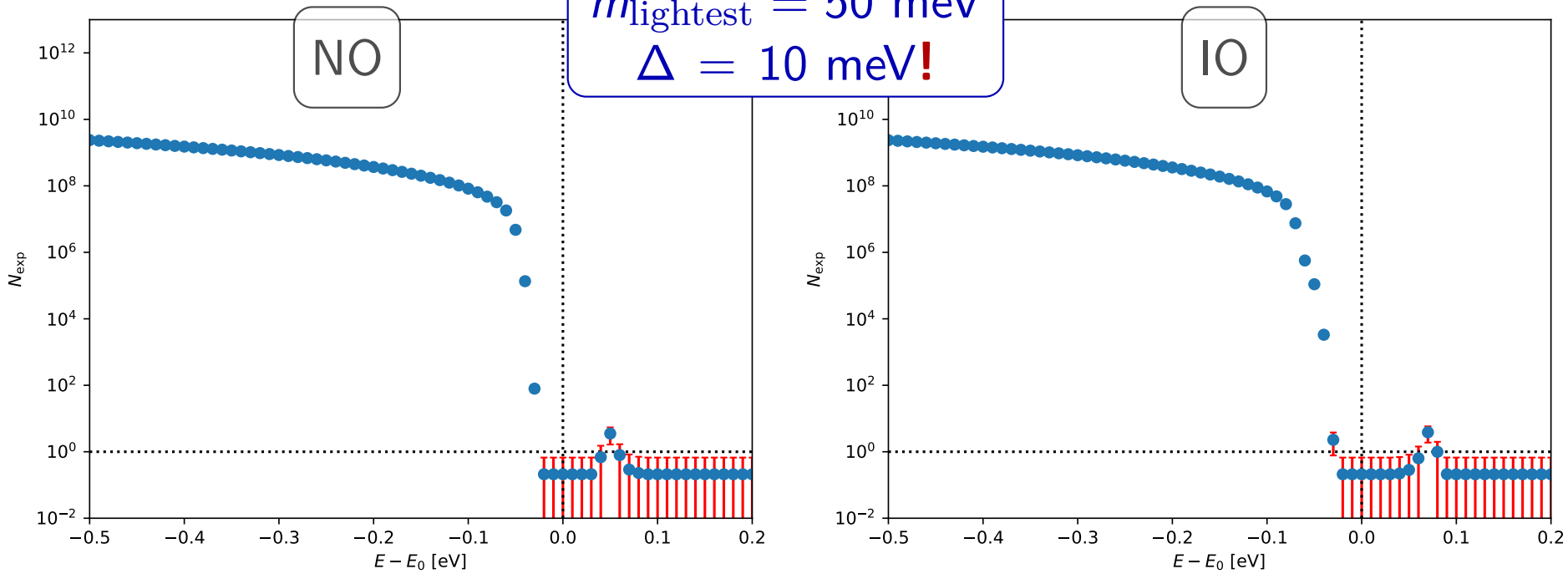


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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

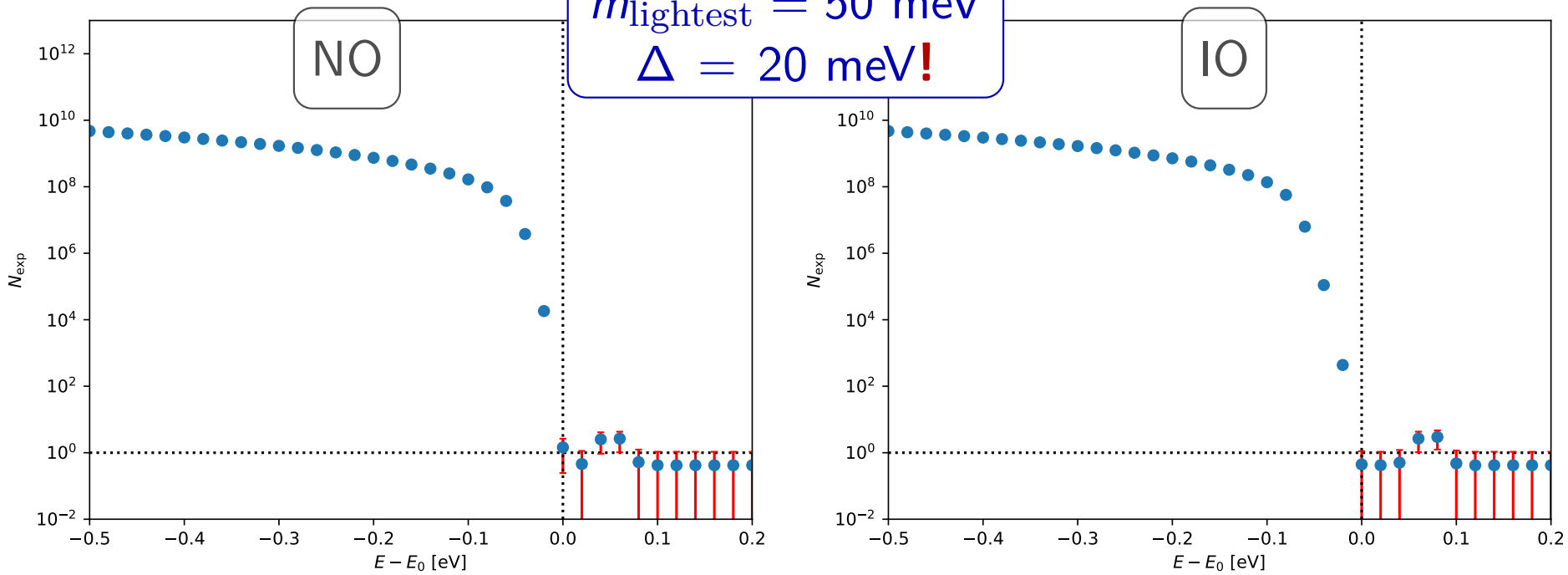


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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



1 year of observation with 100 g of T source

Simulations - II

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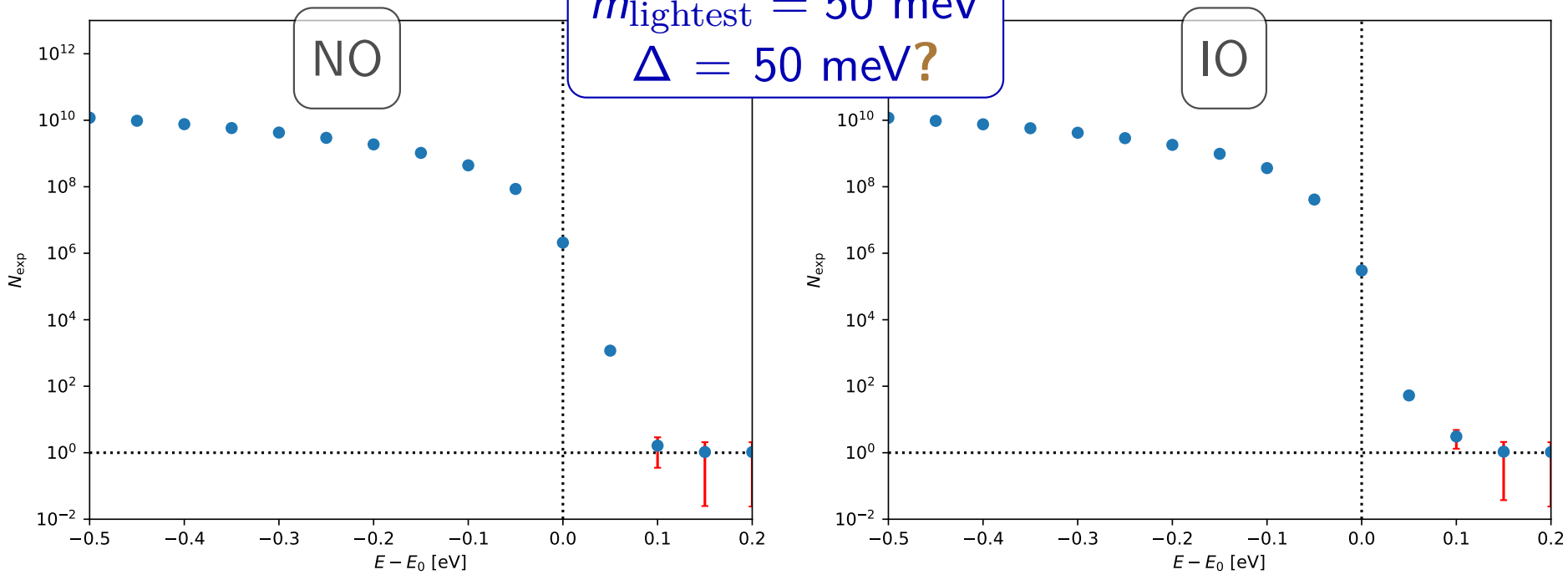
$m_{\text{lightest}} = 50$ meV
$\Delta = 50$ meV?

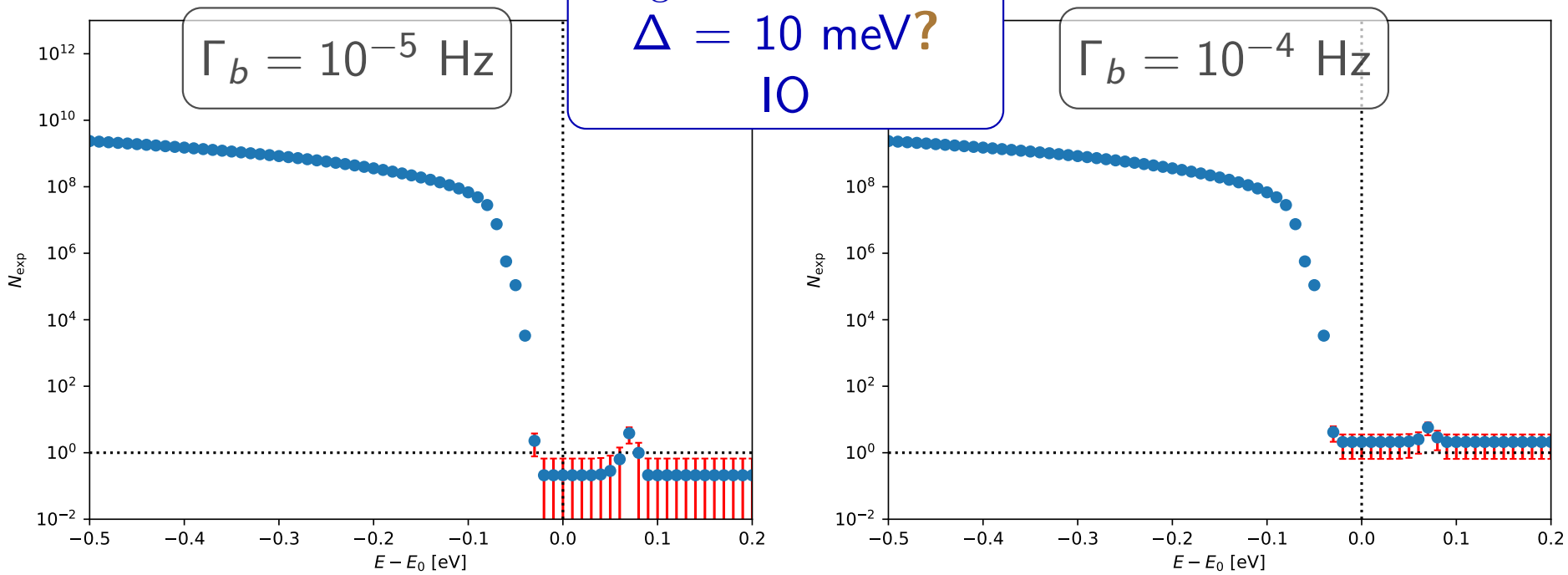


1 year of observation with 100 g of T source

Simulations - II

no random noise?

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

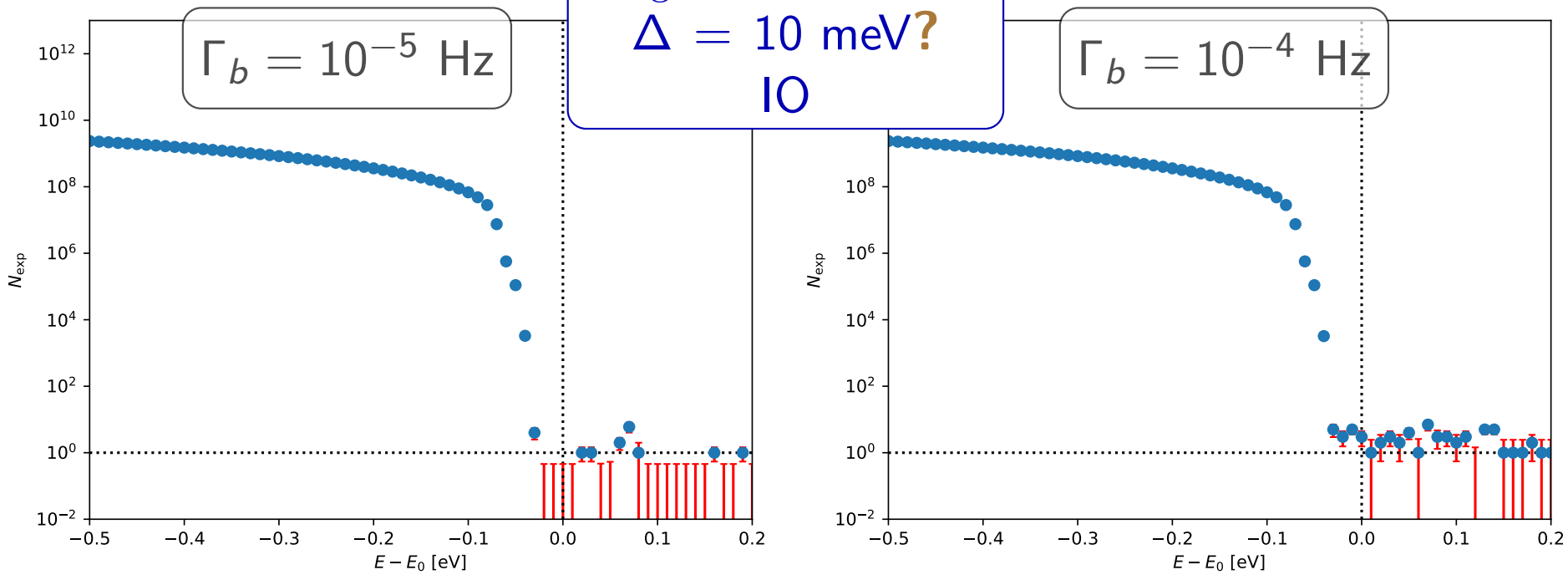


1 year of observation with 100 g of T source

Simulations - II

with random noise!

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



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_{lightest}

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

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

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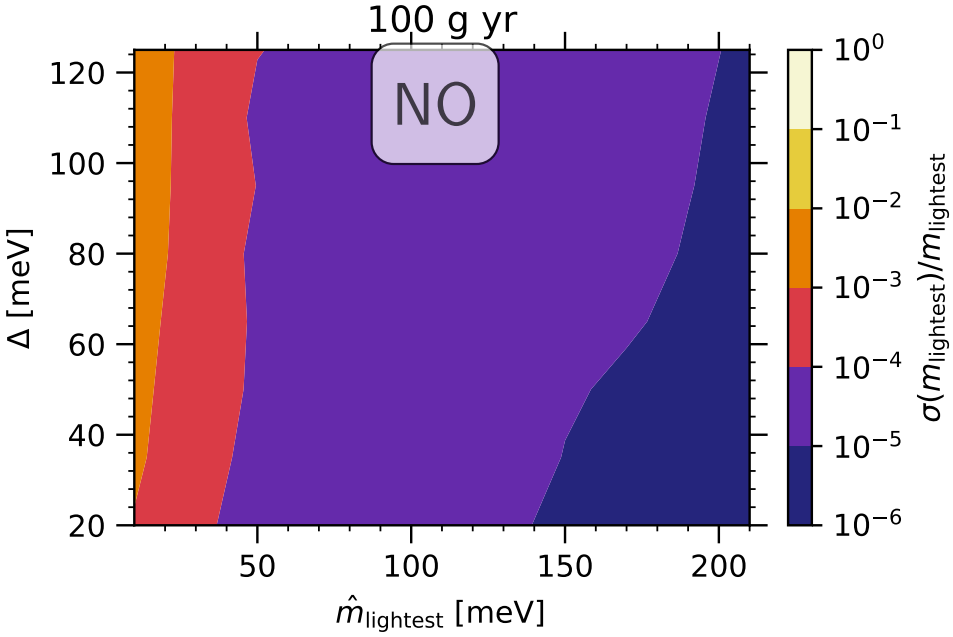

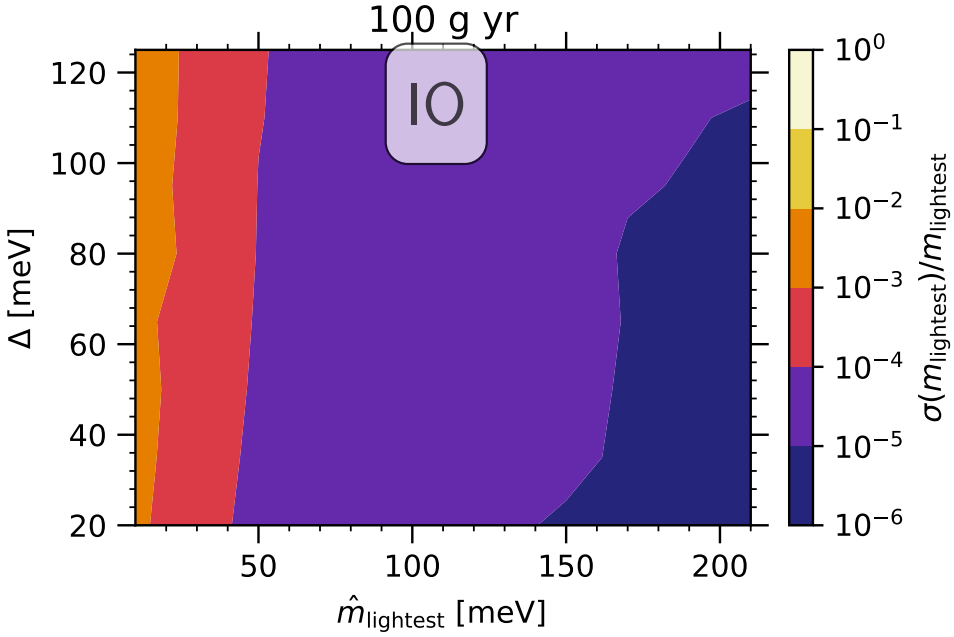

wonderful precision in determining the neutrino mass

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

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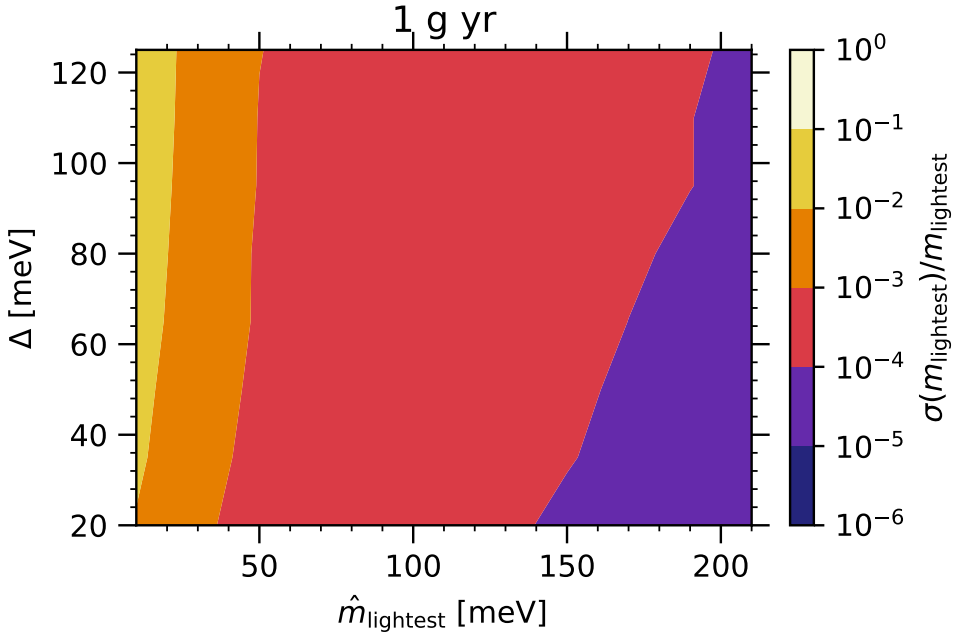

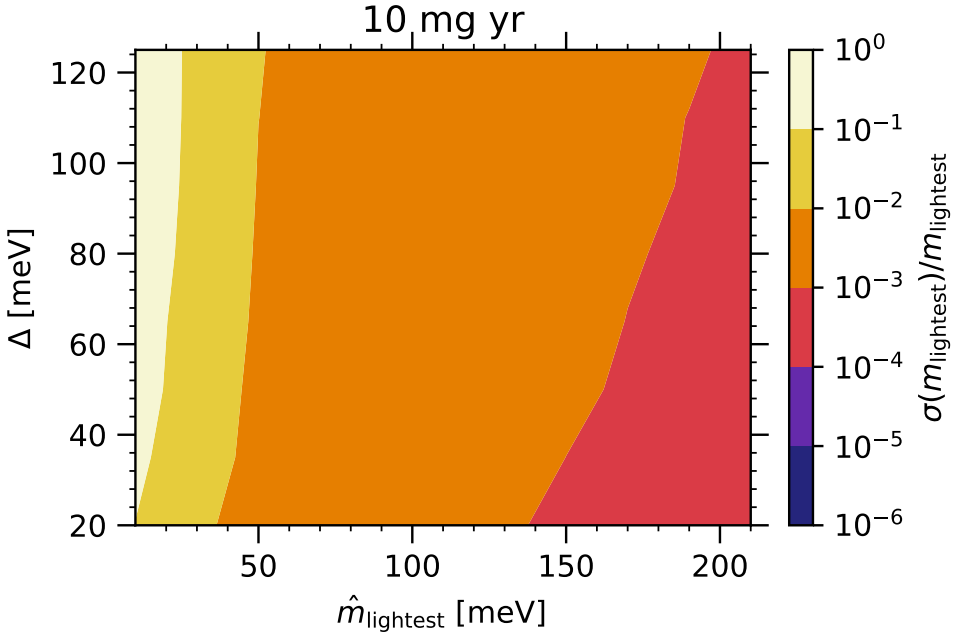

wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

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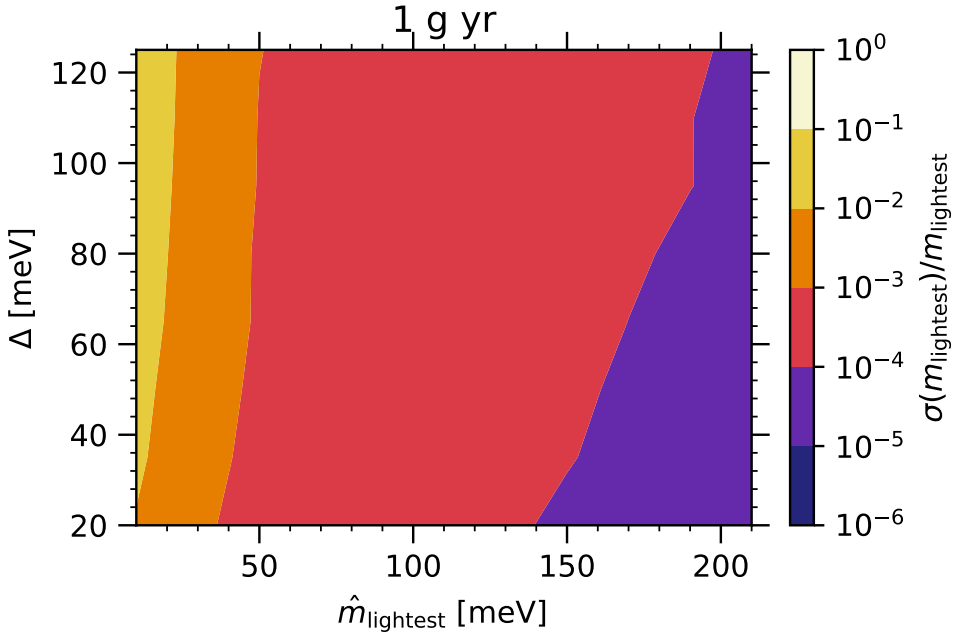

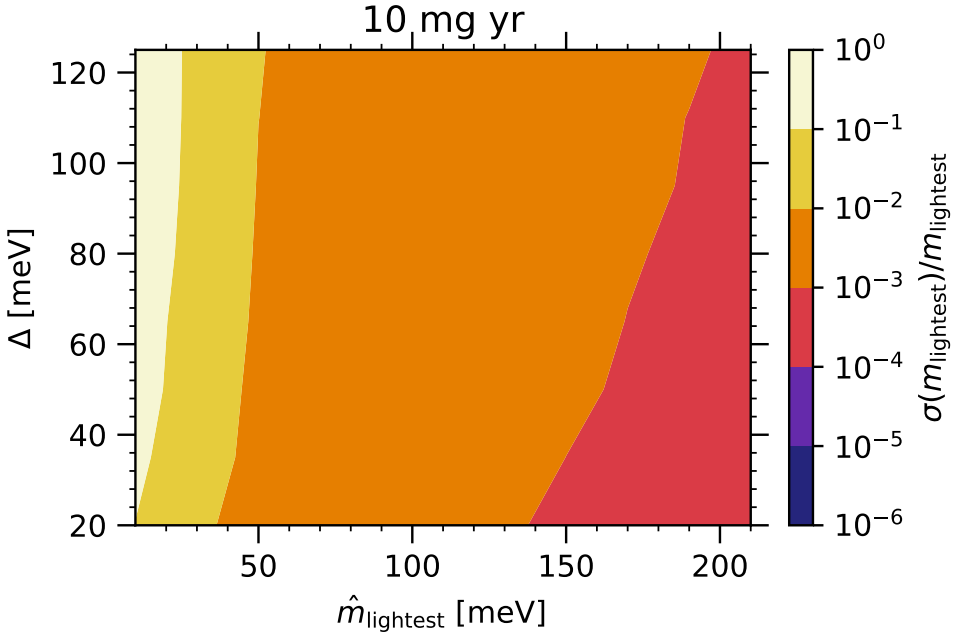

wonderful precision in determining the neutrino mass

(mass detection already with 10 mg of tritium!)

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

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

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

worse fit

better fit

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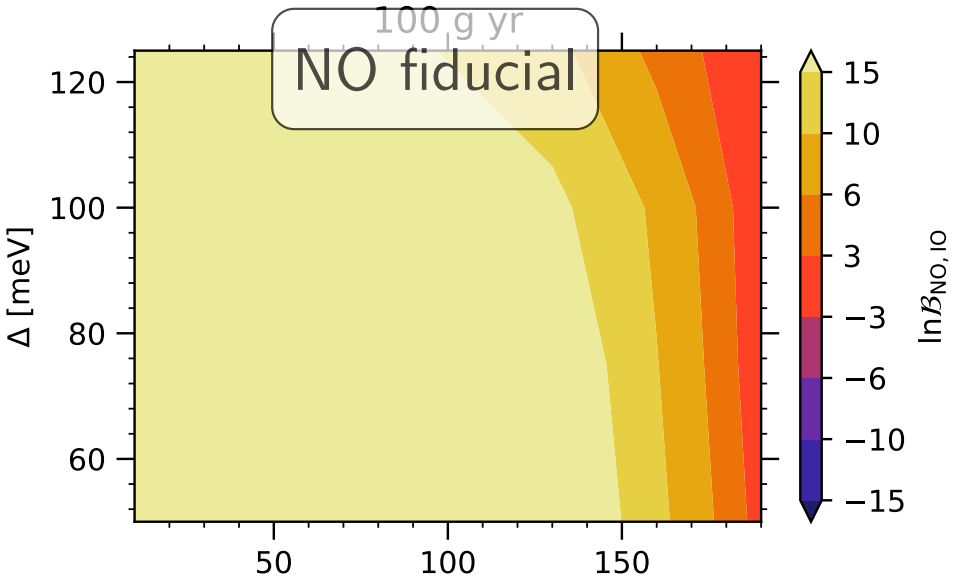
worse fit

better fit

statistical only!

(Bayesian) preference on m_{lightest} as a function of $\hat{m}_{\mathrm{lightest}}$, Δ



IO fiducial

always strong significance

Neutrino mass ordering

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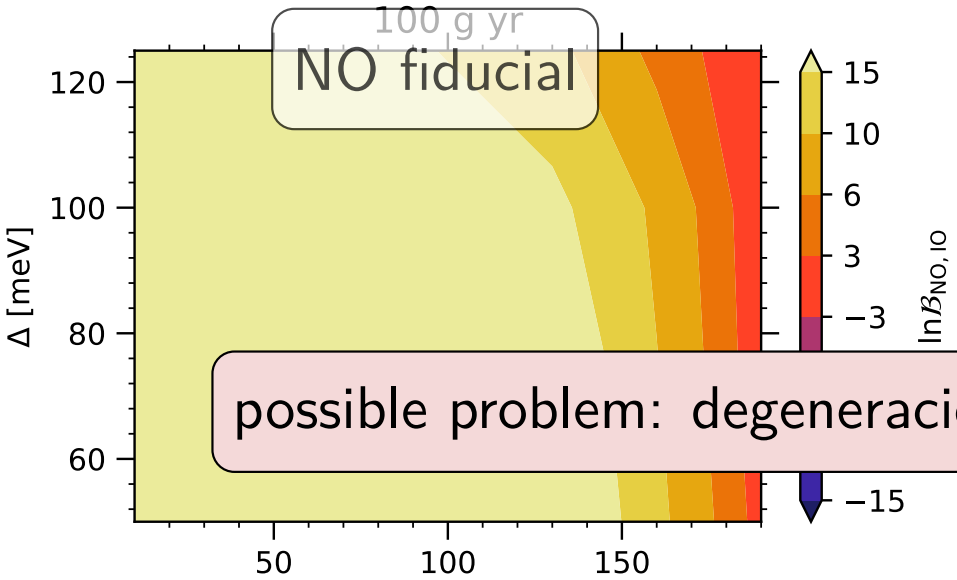


IO fiducial

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

Dirac and Majorana neutrinos

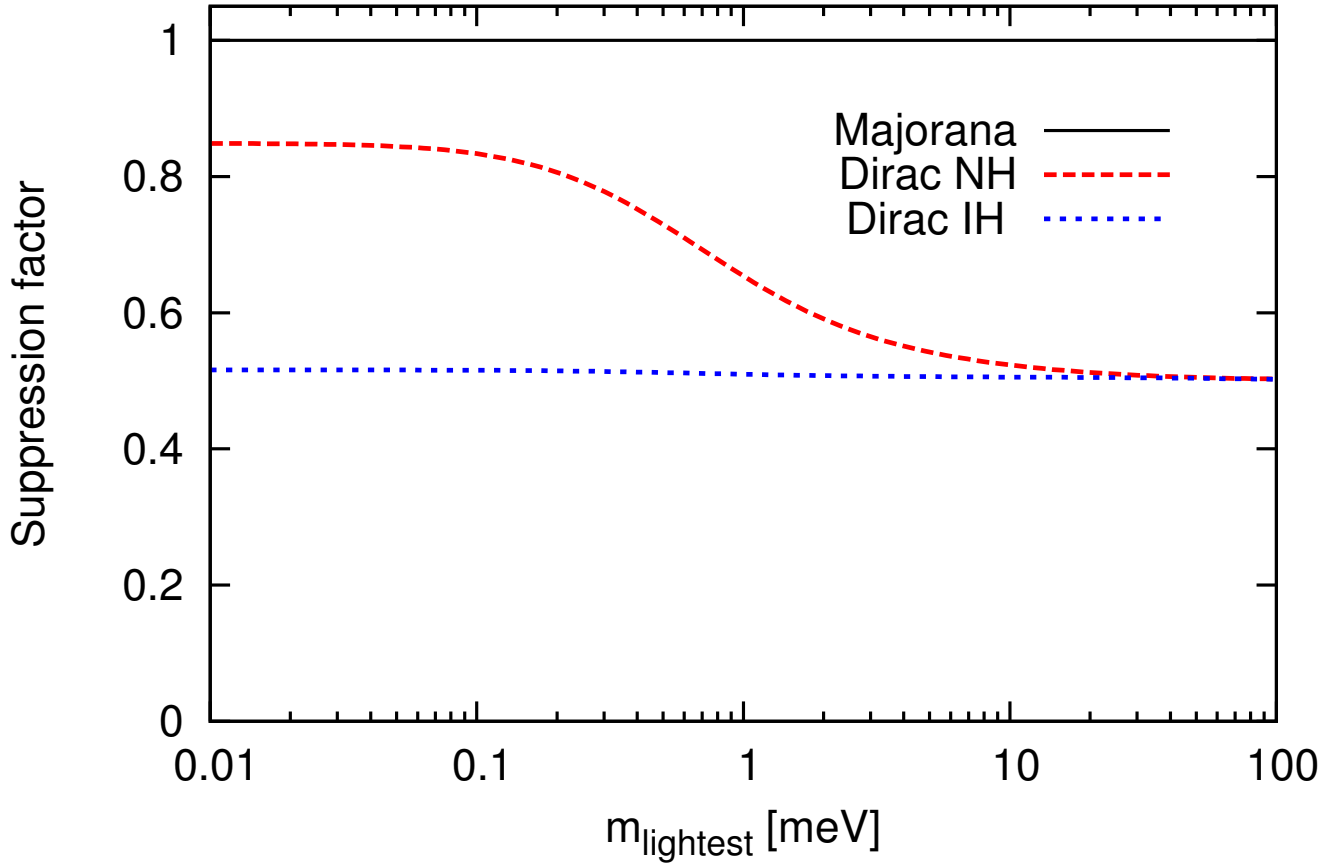
[Roulet+, JCAP 10 (2018) 049]

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**