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Horizon 2020
European Union funding
for Research & Innovation

Cosmological relic neutrinos, from A to Z

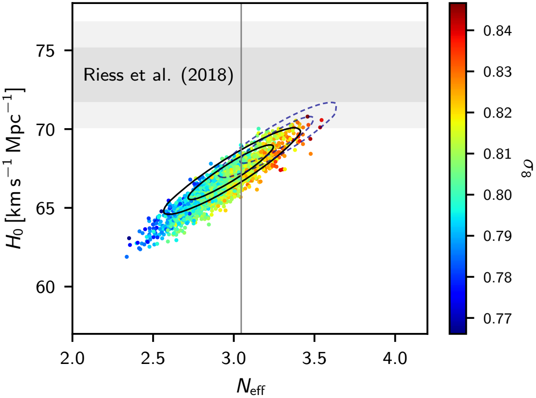
INT-20-1a, Seattle (USA/WA), 30/01/2020

A Active neutrinos

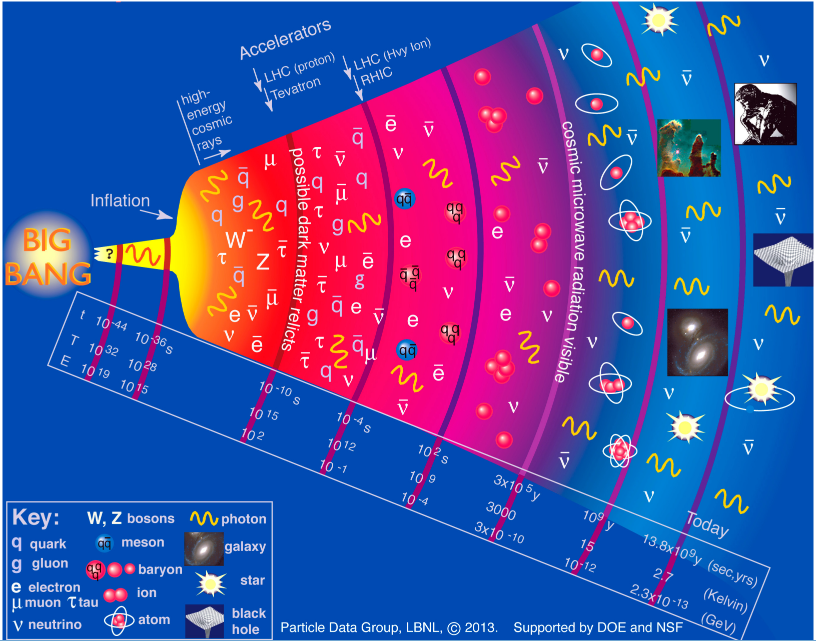
Spoiler: “Sterile” will come later

Based on:

- Planck 2018
- Mangano+ 2005
- de Salas+ 2016
- in preparation (1)



History of the universe



Particle Data Group, LBNL, © 2013. Supported by DOE and NSF

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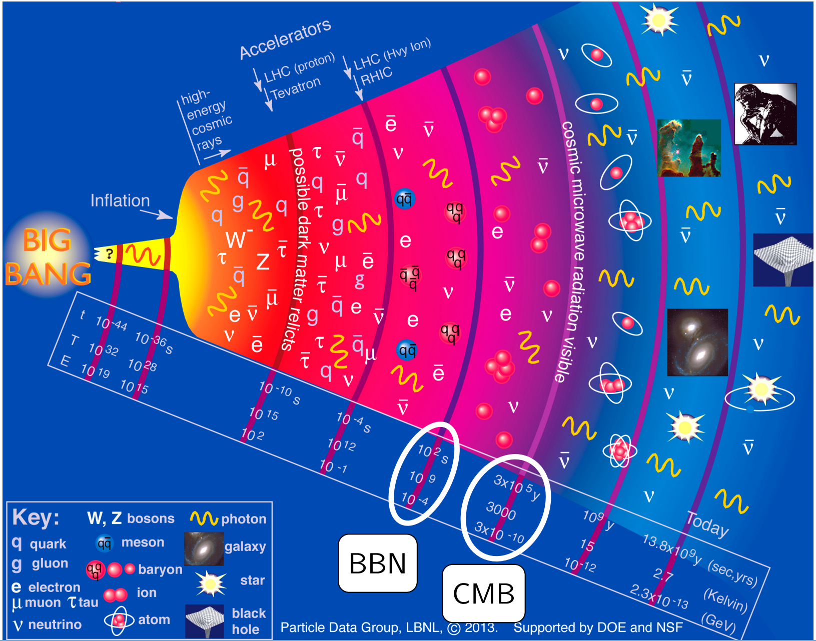

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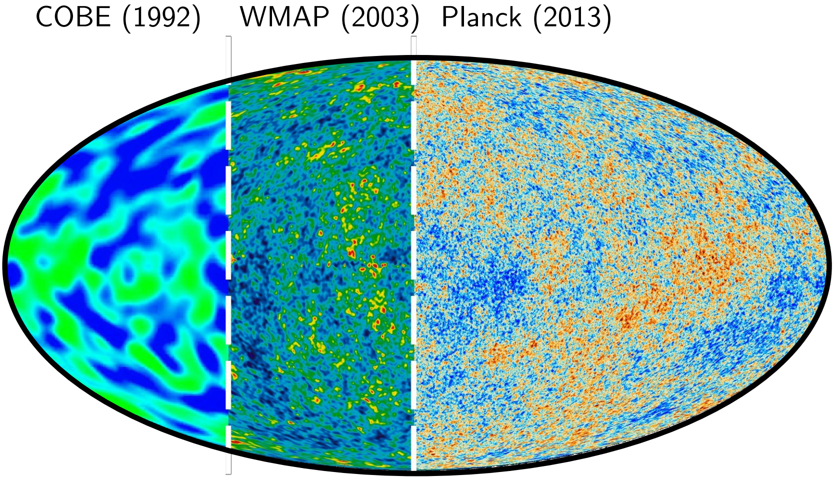
The oldest picture of the Universe

The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years



Big Bang Nucleosynthesis (BBN)

BBN: production of light nuclei at $t \sim 1\mathrm{s}$ to $t \sim \mathcal{O}(10^2)\mathrm{s}$

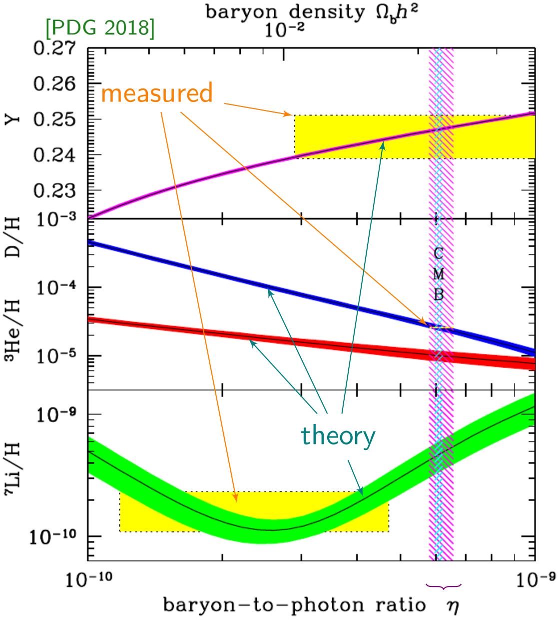
temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out

much earlier than CMB!

strong probe for physics
before the CMB

e.g. neutrinos!

ν affect
universe expansion
and
reaction rates $(\nu_e/\bar{\nu}_e)$
at BBN time. . .



[PDG 2018]

BBN concordance

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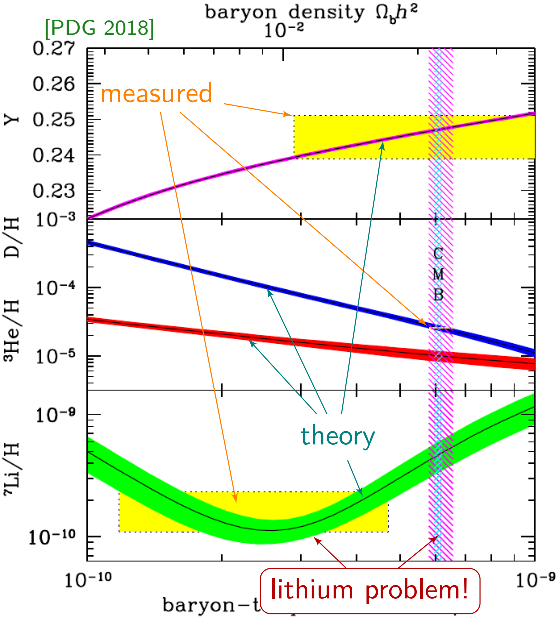


[PDG 2018]

measured

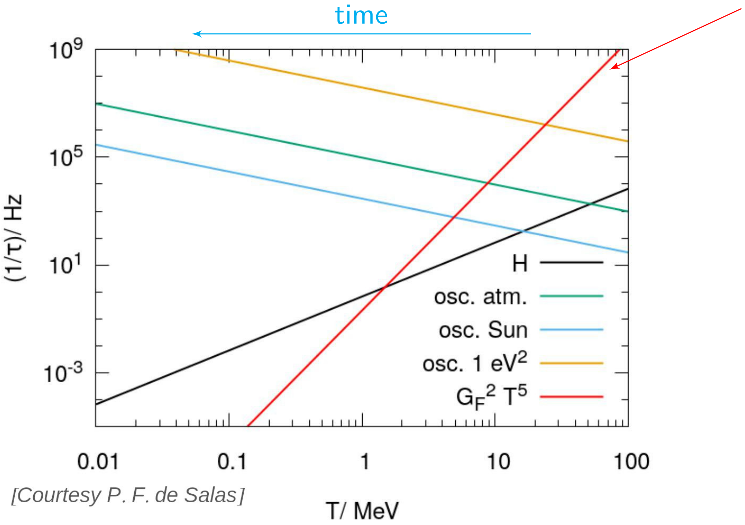
theory

lithium problem!

BBN concordance

Neutrinos in the early Universe

before BBN: neutrinos coupled to plasma ($\nu_\alpha\bar{\nu}_\alpha \leftrightarrow e^+e^-$, $\nu e \leftrightarrow \nu e$)



[Courtesy P. F. de Salas]

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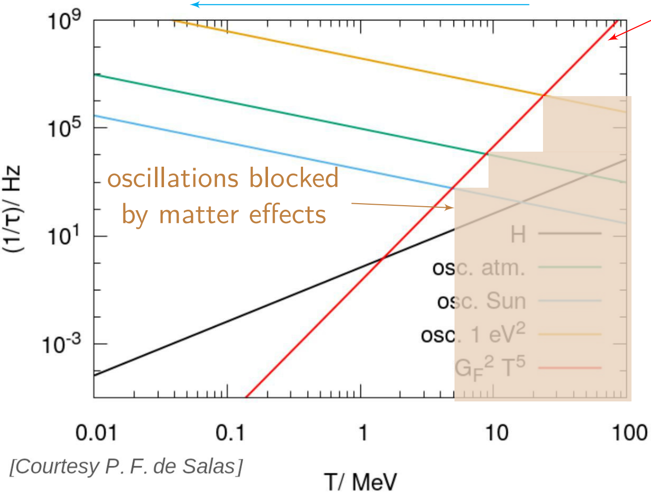

oscillations blocked by matter effects

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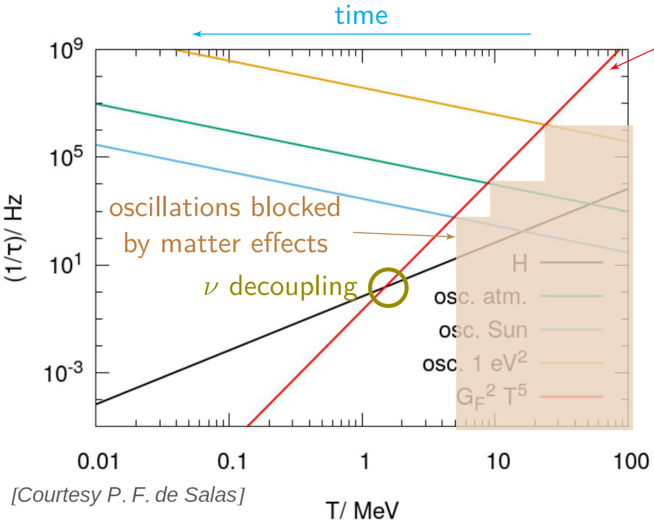

oscillations blocked by matter effects

ν decoupling

[Courtesy P. F. de Salas]

ν decouple mostly before $e^+e^- \to \gamma\gamma$ annihilation!

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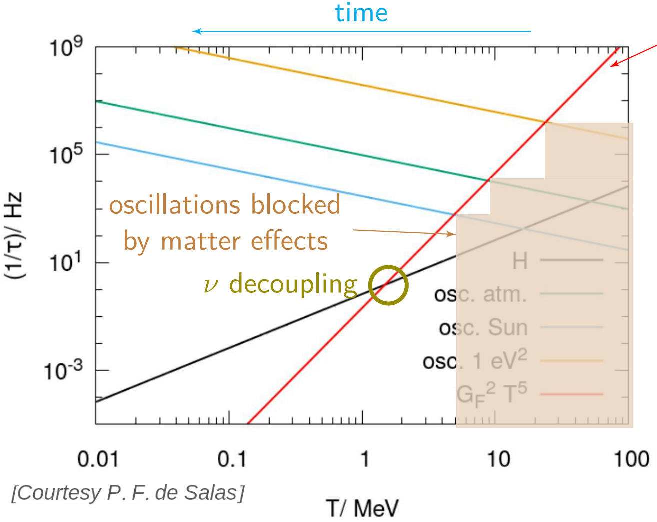

[Courtesy P. F. de Salas]

$T_\nu \simeq (4/11)^{1/3}\, T_\gamma$ after $e^+ e^- \to \gamma\gamma$

f_ν: frozen Fermi-Dirac distribution

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

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

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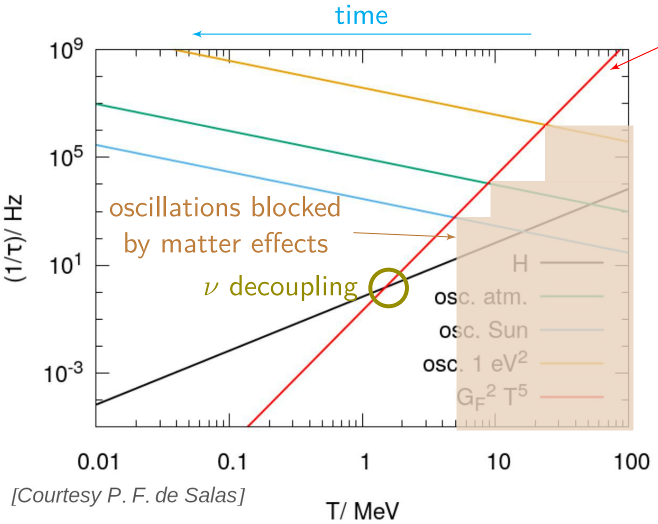
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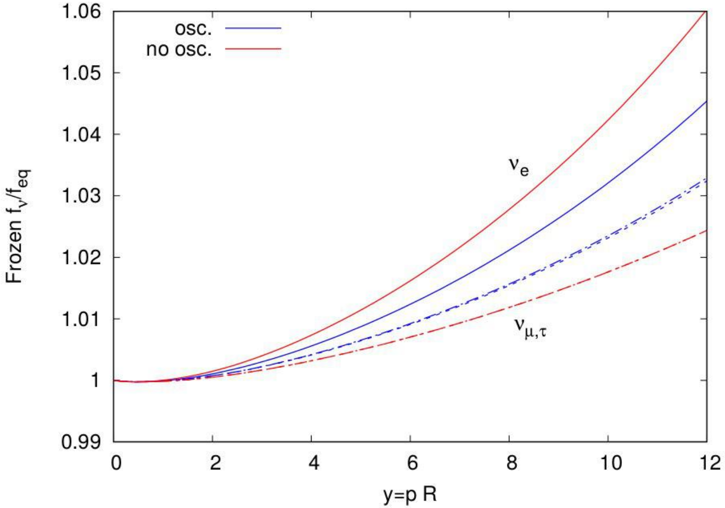
actually, the decoupling T is momentum dependent! → distortions to equilibrium f_ν!

Neutrino momentum distribution and N_{eff}

[deSalas+, 2016]

Distortion of the momentum distribution (f_{eq}: Fermi-Dirac)

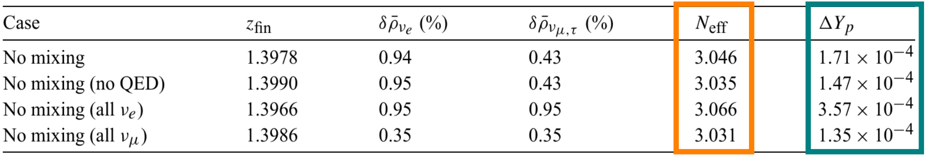


Neutrino momentum distribution and N_{eff}

$$N_{\text{eff}} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{\rho_\nu}{\rho_\gamma} = \frac{8}{7}\left(\frac{11}{4}\right)^{4/3}\frac{1}{\rho_\gamma}\sum_i g_i \int \frac{d^3p}{(2\pi)^3} E(p)\, f_{\nu,i}(p)$$

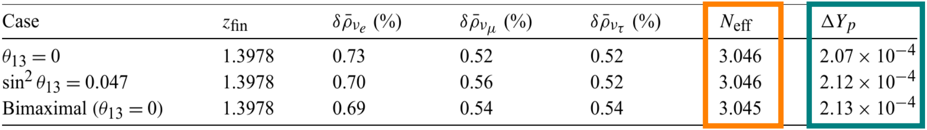
[Mangano+, 2005]

two-neutrino approximation:



Case	z_{fin}	$\delta\bar{\rho}_{\nu_e}$ (%)	$\delta\bar{\rho}_{\nu_{\mu,\tau}}$ (%)	N_{eff}	ΔY_p
No mixing	1.3978	0.94	0.43	3.046	1.71×10^{-4}
No mixing (no QED)	1.3990	0.95	0.43	3.035	1.47×10^{-4}
No mixing (all ν_e)	1.3966	0.95	0.95	3.066	3.57×10^{-4}
No mixing (all ν_μ)	1.3986	0.35	0.35	3.031	1.35×10^{-4}

full three-neutrino results (with oscillations):



Case	z_{fin}	$\delta\bar{\rho}_{\nu_e}$ (%)	$\delta\bar{\rho}_{\nu_\mu}$ (%)	$\delta\bar{\rho}_{\nu_\tau}$ (%)	N_{eff}	ΔY_p
$\theta_{13} = 0$	1.3978	0.73	0.52	0.52	3.046	2.07×10^{-4}
$\sin^2\theta_{13} = 0.047$	1.3978	0.70	0.56	0.52	3.046	2.12×10^{-4}
Bimaximal ($\theta_{13} = 0$)	1.3978	0.69	0.54	0.54	3.045	2.13×10^{-4}

How precise is $N_{\mathrm{eff}} = 3.04\ldots$?

Long list of previous works. . . always less than 3ν mixing

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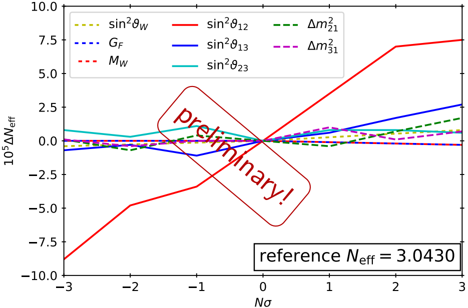
further terms should be negligible

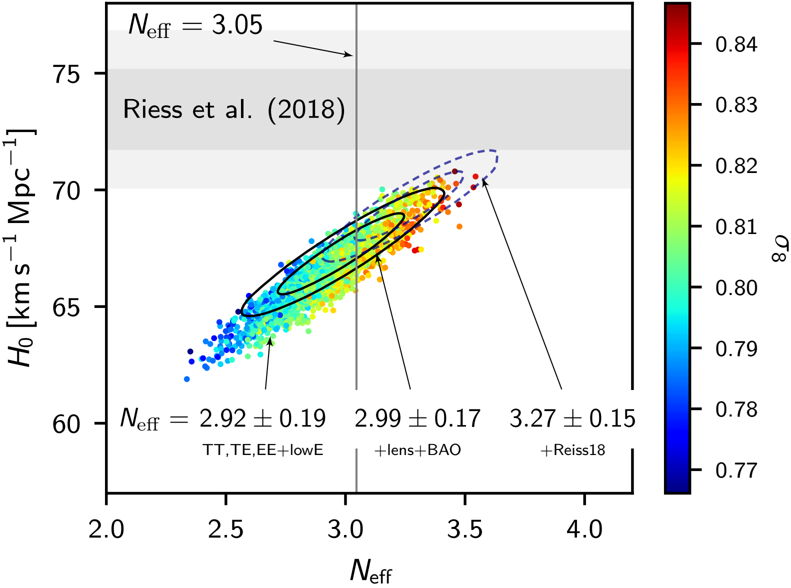
[in preparation]:
uncertainty from neutrino mixing and other parameters?

$\Delta N_{\rm eff} \simeq 10^{-4}$ at most



N_{eff} and CMB

[Planck Collaboration, 2018]



$N_{\rm eff}$ and BBN

BBN: production of light nuclei
at $t \sim 1$s to $t \sim \mathcal{O}(10^2)$s

temperature $T_{fr} \simeq 1$ MeV
from nucleon freeze-out:

$$\Gamma_{n\leftrightarrow p} \sim G_F^2 T^5 \;=\; H \sim \sqrt{g_\star G_N}\, T^2$$

$$\downarrow$$

$$\boxed{T_{fr} \simeq (g_\star G_N / G_F^4)^{1/6}}$$

enters
$n/p = \exp(-Q/T_{fr})$
which controls element abundances

$\boxed{g_\star \text{ depends on } N_{\rm eff}}$

$$\downarrow$$

abundances depend on $N_{\rm eff}$

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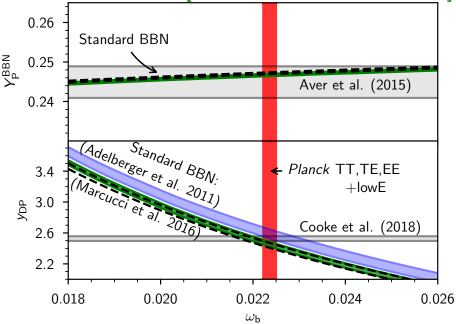

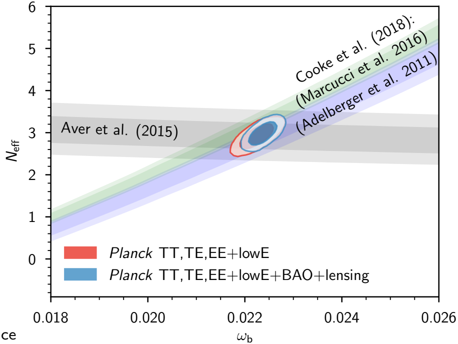

G_F Fermi constant
G_N Newton constant
n, p: neutron, proton density number
$Q = 1.293$ MeV neutron–proton mass difference

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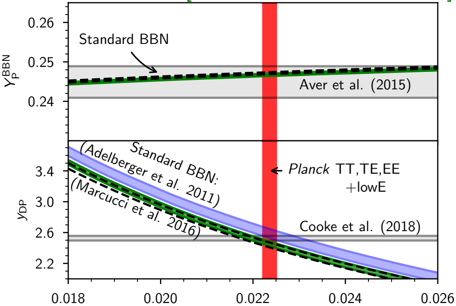
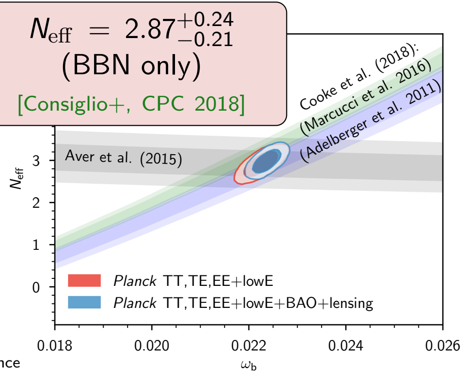


$N_{\rm eff} = 2.87^{+0.24}_{-0.21}$
(BBN only)
[Consiglio+, CPC 2018]



G_F Fermi constant
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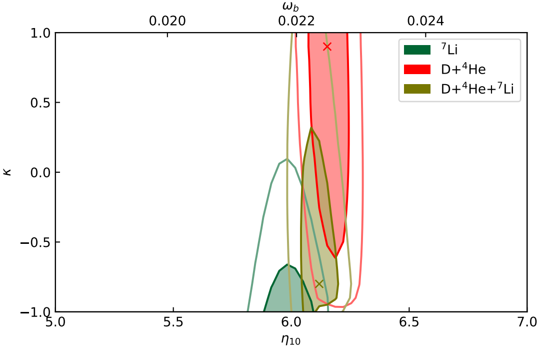
B Bosonic neutrinos

(?!? what?)

Based on:

- JCAP 03 (2018) 050



Motivation

Neutrinos are fermions $\longrightarrow$ they obey Fermi-Dirac statistics

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Do they obey Fermi-Dirac statistics?

No experimental confirmation of spin-statistics theorem for neutrinos!

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Can we find violations of the Pauli exclusion principle?

electrons

no violations for atomic electrons

e.g. look for anomalous X-rays from atomic decays

[Goldhaber&Scharff-Goldhaber, 1948]

[Fischbach&Kirsten&Schaeffer, 1968]

[Reines&Sobel, 1974]

...

nucleons

no violations for protons/neutrons

e.g. look for anomalous star (Sun) dynamics or transitions in nuclei

[Plaga, 1989]

[Miljanić+, 1990]

[Borexino, 2004]

...

see detailed discussion in [Dolgov&Smirnov, PLB 2005]

The neutrino case

important: since spin-statistics relation confirmed for electrons, difficult to imagine large deviation for neutrinos

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$A \to A' + 2\bar{\nu} + 2e^-$ or $A \to A' + 2\nu + 2e^+$

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Fermi-Bose parameter κ_ν [Dolgov+, JCAP 2005]

$$\boxed{f_\nu(E) = \frac{1}{\exp(E/T) + \kappa_\nu}}$$

"mixed" distribution!

$$\mathrm{BE} \leftarrow \kappa_\nu = -1 \xleftrightarrow[\mathrm{MB}]{\kappa_\nu = 0} \kappa_\nu = +1 \rightarrow \mathrm{FD}$$

[Barabash+, NPB 2007]: $\kappa_\nu \gtrsim -0.2$

100% violation excluded [Barabash+, NPB 2007],
but still 50% admixture of bosonic component allowed

Constraints on κ_ν from BBN

[de Salas, SG+, JCAP 03 (2018) 050]

what can cosmology say about κ_ν?

different $f_\nu(p)$ affects BBN!

statistics factor becomes $(1-\kappa_\nu f_\nu)$

$(1+f_\nu)$ → Bose enhancement,

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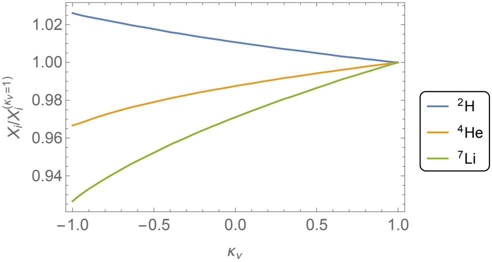
change of n/p ratio at BBN

[Dolgov+, JCAP 2005]

less He, more D, less Li



deviation from $\kappa_\nu = 1$ obtained with a modified version of `PArthENoPE`

[Consiglio+, CPC 2018]

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↓

change of n/p ratio at BBN

[Dolgov+, JCAP 2005]

less He, more D, less Li

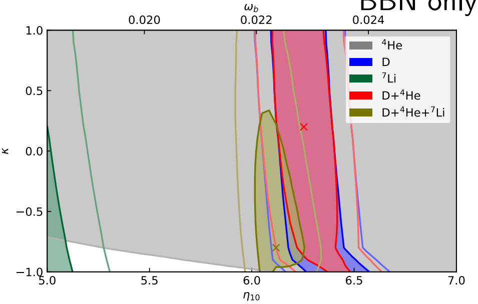
He or D alone cannot constrain κ_ν

Li problem drives ω_b down

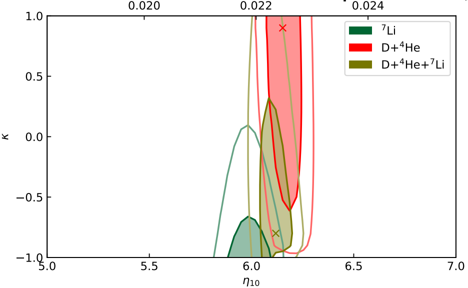
and κ_ν to -1

also when prior on ω_b is included

BBN only



CMB prior on ω_b



Neutrino densities and κ_ν

[de Salas, SG+, JCAP 03 (2018) 050]

$$\boxed{f_\nu(E) = \frac{1}{\exp(E/T) + \kappa_\nu}}$$

κ_ν affects
background evolution:

$$\rho_\nu^{\rm rel} \simeq \frac{g_\nu}{2\pi^2}\int_0^\infty dp\, p^3\, f_\nu(p)$$

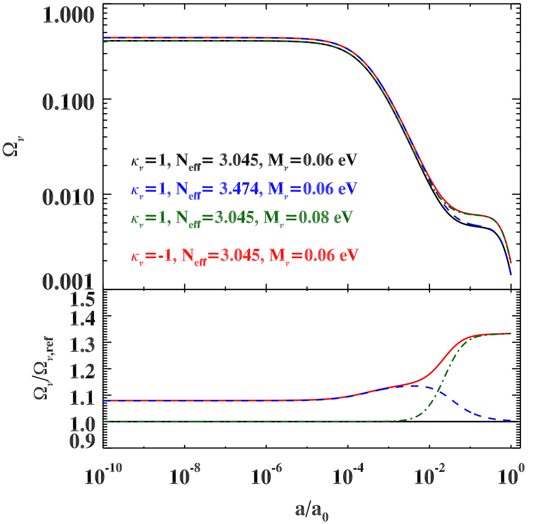
bosons:
$\frac{\pi^2}{30} g_i\, T^4$

fermions:
$\frac{7}{8}\frac{\pi^2}{30} g_i\, T^4$

$$\rho_\nu^{\rm nr} \simeq m_\nu \frac{g_\nu}{2\pi^2}\int_0^\infty dp\, p^2\, f_\nu(p)$$

bosons:
$\frac{\zeta(3)}{\pi^2} m_\nu g_i\, T^3$

fermions:
$\frac{3}{4}\frac{\zeta(3)}{\pi^2} m_\nu g_i\, T^3$



changing κ_ν “mimics” altering $N_{\rm eff}$ or Σm_ν (at late or early times)

$$\boxed{\text{partial degeneracies with } N_{\rm eff} \text{ and } \Sigma m_\nu}$$

CMB/BAO constraints on κ_ν

[de Salas, SG+, JCAP 03 (2018) 050]

need to cover κ_ν–Σm_ν degeneracy:
vary both!

degeneracy affects
mostly CMB only bounds

with BAO, bound on Σm_ν is stronger

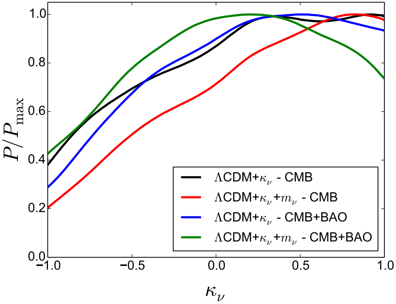
adding radiation (through κ_ν) and Ω_Λ alters H_0 and compensates a bit the larger mass

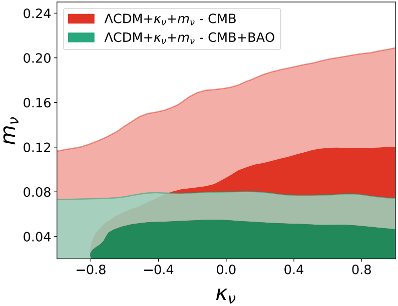
bounds: $\kappa_\nu \gtrsim -0.1$ at 68%

$-1 \leq \kappa_\nu \leq 1$ at 95%

$\kappa_\nu = -1$ corresponds to
$N_{\rm eff} \simeq 3.47$ at early times

inside Planck 2σ region!
reasonably it's not excluded

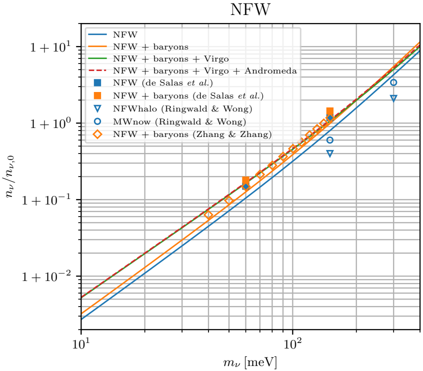




C Clustering in the local Universe

Based on:

- JCAP 09 (2017) 034
- arxiv:1910.13388



ν clustering with N-one-body simulations

Relic neutrinos are slow! [$c_\nu \sim 160(1+z)(1\text{ eV}/m_\nu)$ km s^{-1}]

Can be trapped in the gravitational potential of the Milky Way and neighbours

$f_c(m_i) = n_i/n_{i,0}$ 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!)

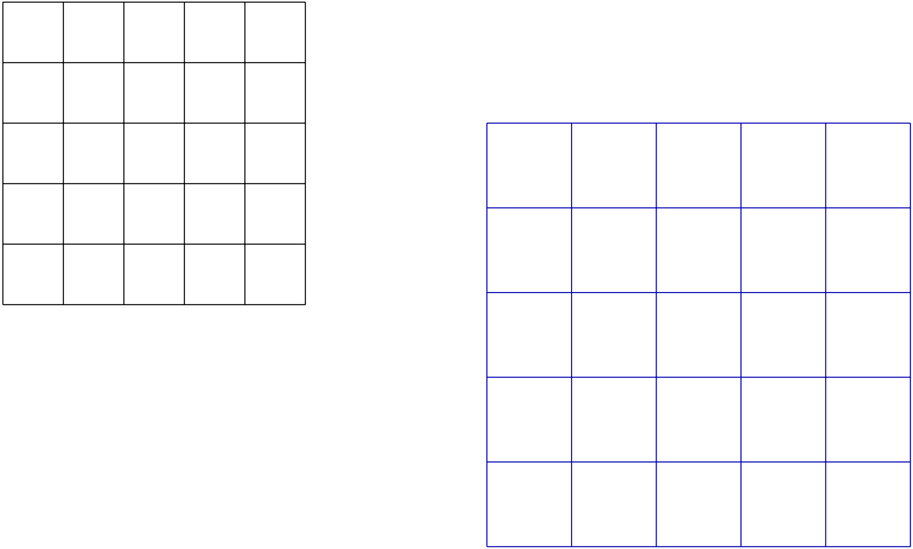
given N ν:

→ weigh each neutrinos

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

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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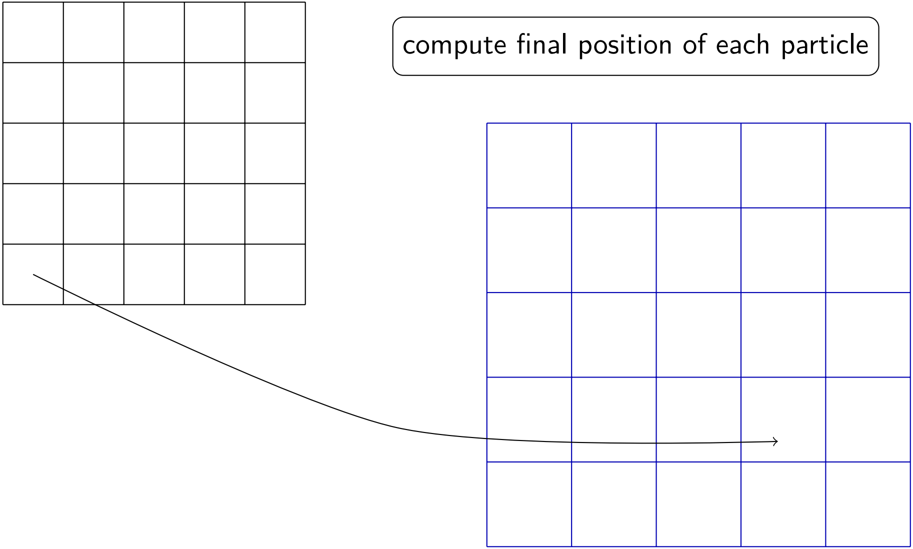

compute final position of each particle

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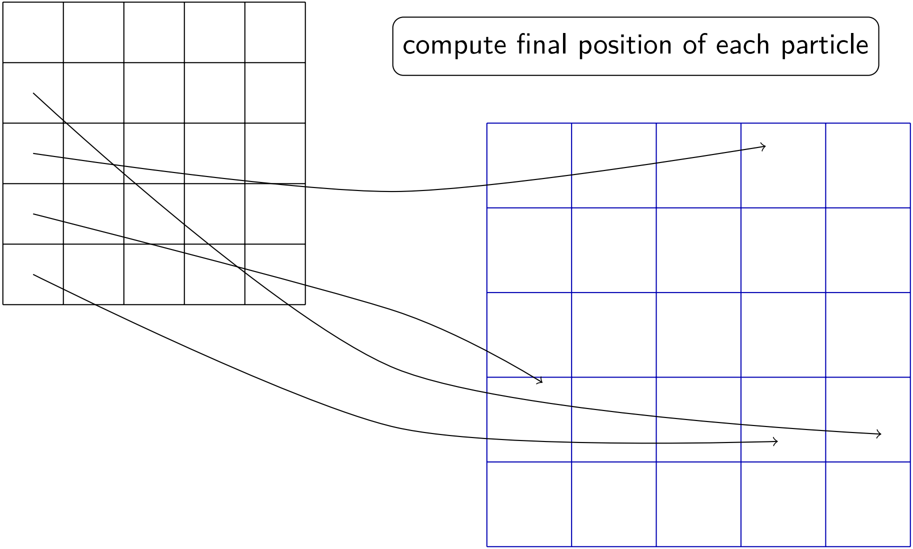

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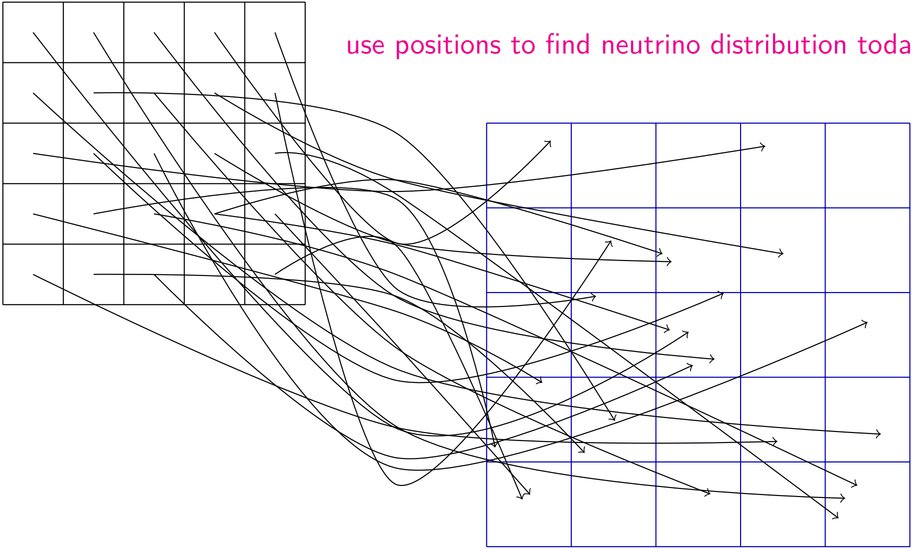

use positions to find neutrino distribution today

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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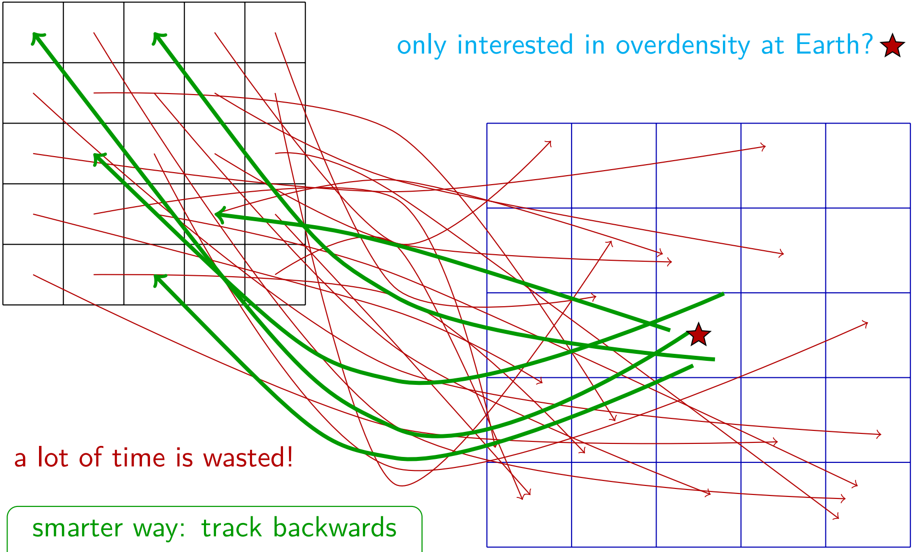

only interested in overdensity at Earth? ★

a lot of time is wasted!

smarter way: track backwards
only interesting particles!

final phase space, $z = 0$

Advantages of tracking back

[JCAP 01 (2020) 015]

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

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[JCAP 01 (2020) 015]

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

[JCAP 01 (2020) 015]

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

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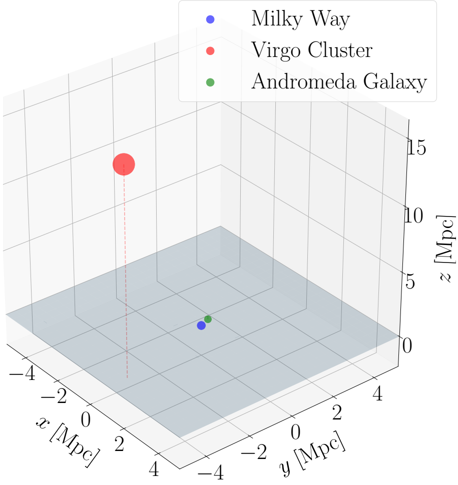
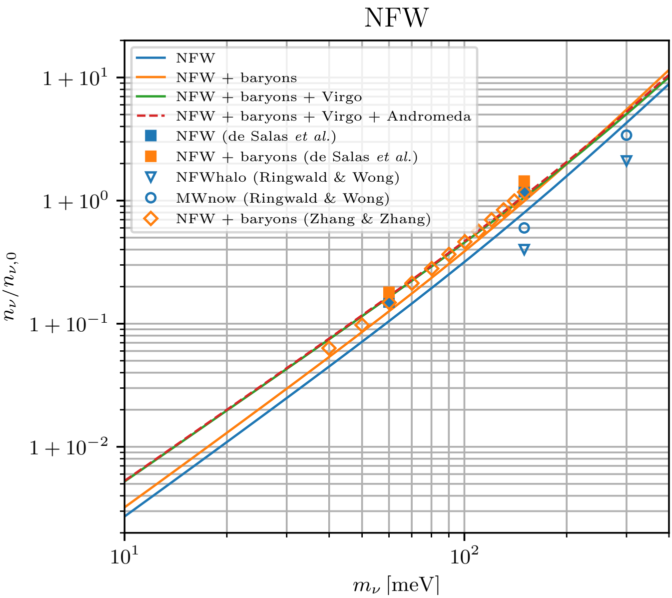


Clustering results with back-tracking

In comparison with previous results:



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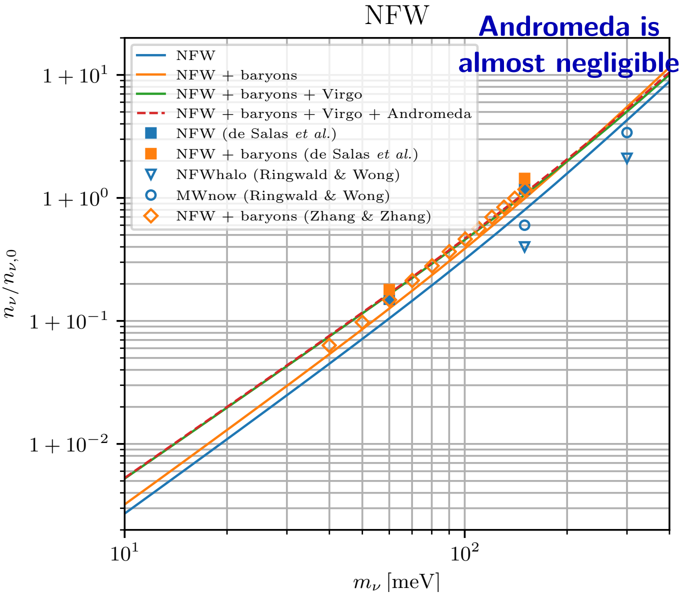

Andromeda is almost negligible

Clustering results with back-tracking

[JCAP 01 (2020) 015]

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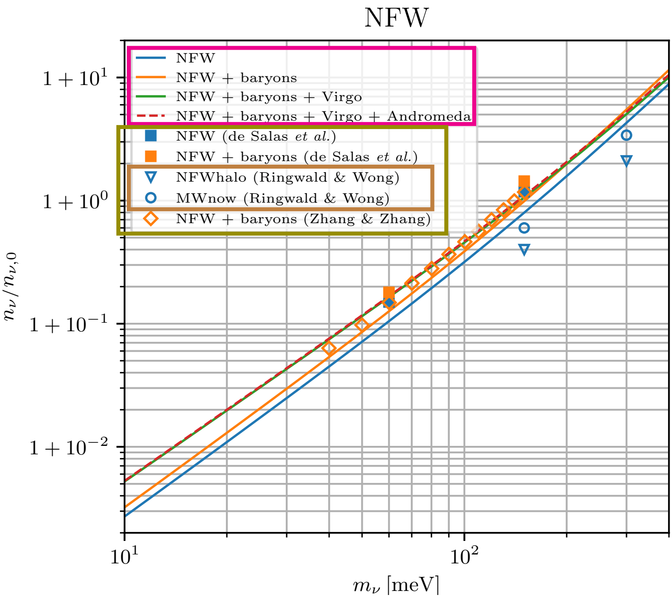

Warning: NFW is not the same for all the cases!

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

[Ringwald&Wong, 2004] uses old parameters

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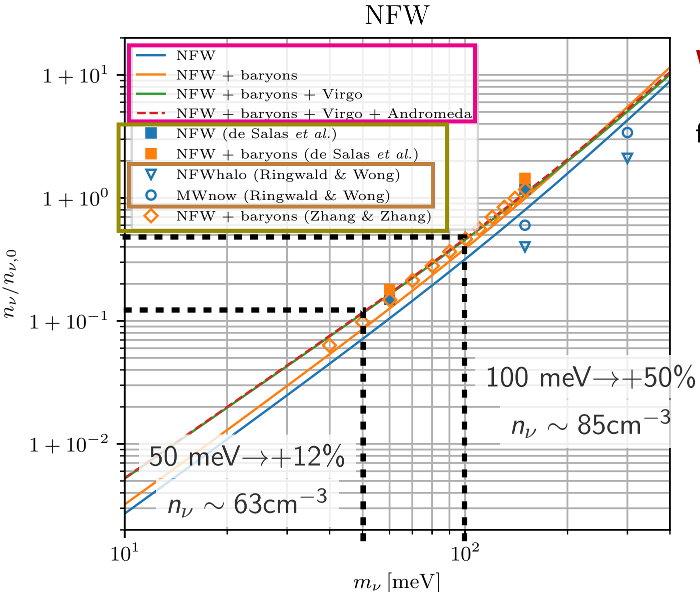

100 meV→+50%

$n_\nu \sim 85\text{cm}^{-3}$

50 meV→+12%

$n_\nu \sim 63\text{cm}^{-3}$

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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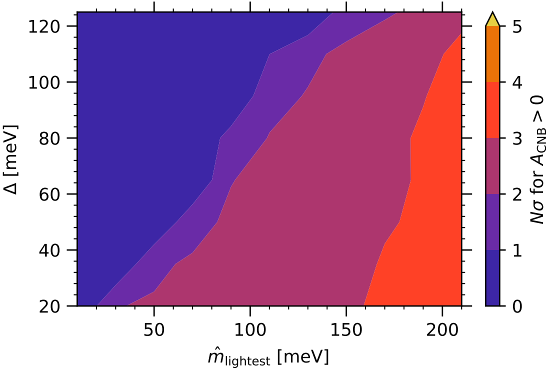
D Direct Detection

i.e. currently science-fiction, but in few years...

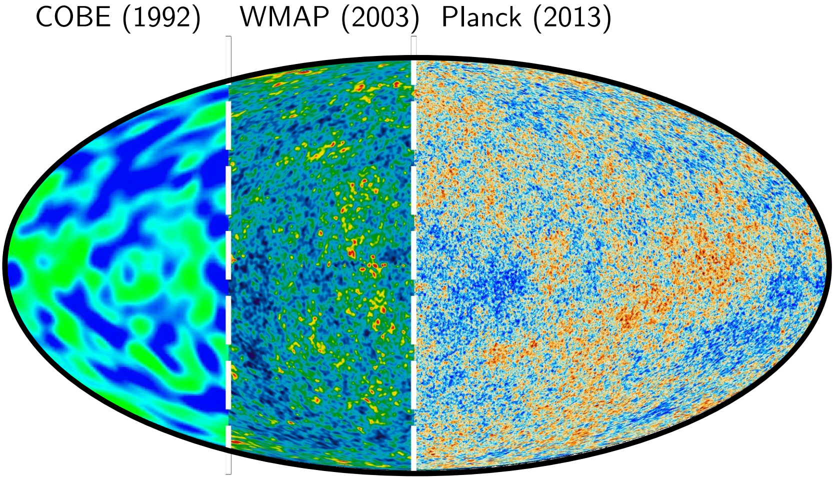
Based on:

- arxiv:1808.01892
- JCAP 07 (2019) 047



The oldest picture of the Universe

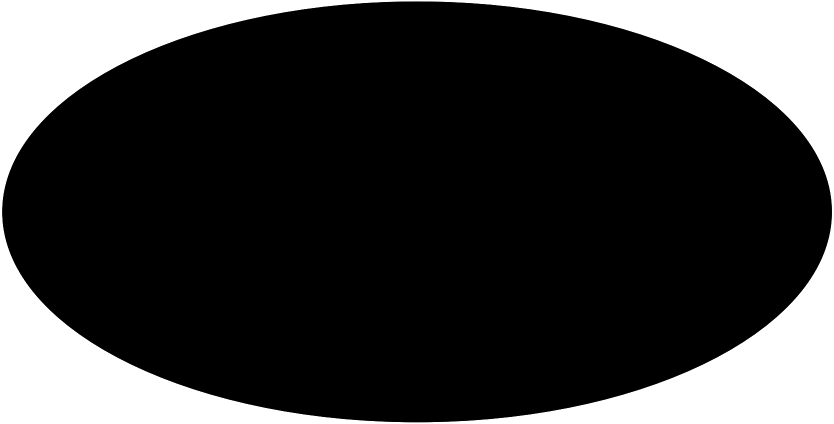
The Cosmic Microwave Background, generated at $t \simeq 4 \times 10^5$ years



The oldest picture of the Universe

The Cosmic Neutrino Background, generated at $t \simeq 1$ s

$\ldots \rightarrow 2019 \rightarrow \ldots$



How to capture relic neutrinos?

[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

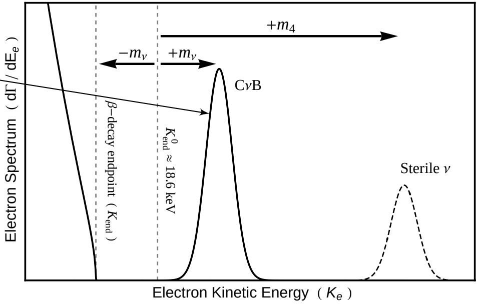
[Weinberg, 1962]: neutrino capture in β–decaying nuclei $\nu + n \to p + e^-$

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



β and Neutrino Capture spectra

[PTOLEMY, JCAP 07 (2019) 047]

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

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

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

$\bar\sigma$ 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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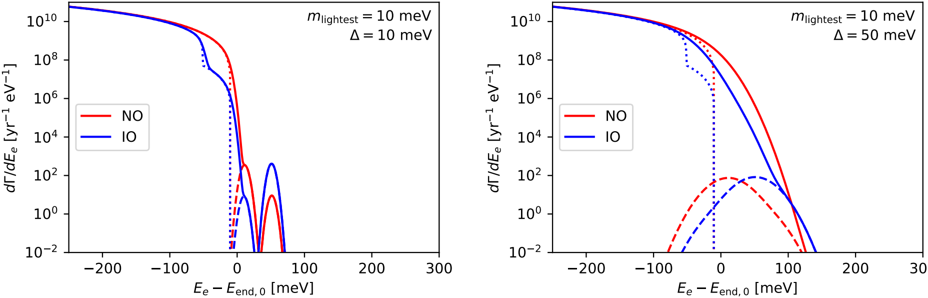

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PTOLEMY

[PTOLEMY LoI, arxiv:1808.01892]

Pontecorvo Tritium 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}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?

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Detection of the relic neutrinos

[PTOLEMY, JCAP 07 (2019) 047]

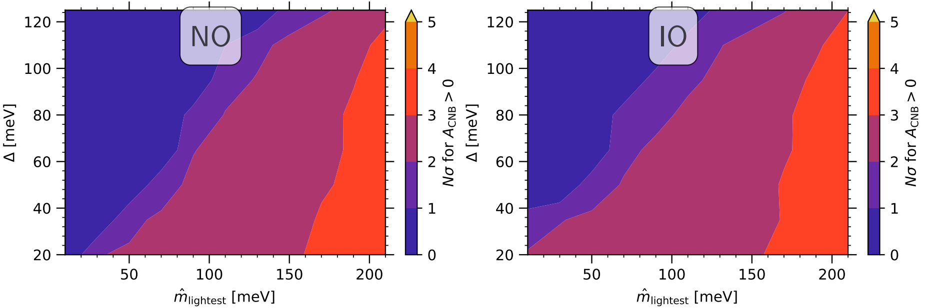
using the definition:

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

if $\boldsymbol{A_{\rm CNB}} > 0$ 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



E-R

(skipping. . .)

seriously, I cannot go
through the entire alphabet in 30 minutes!

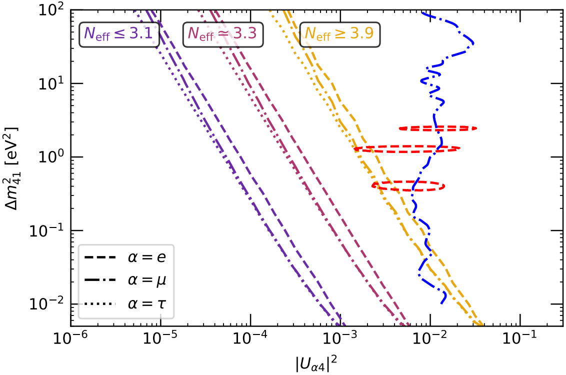
S

(Light) Sterile neutrinos

let's pretend they exist

Based on:

- JCAP 07 (2019) 014
- in preparation (2)



Sterile neutrino in the early universe

[SG+, JCAP 07 (2019) 014]

Four neutrinos ⟶ new oscillations in the early Universe

sterile $\Longrightarrow$ no weak/em interactions in the thermal plasma

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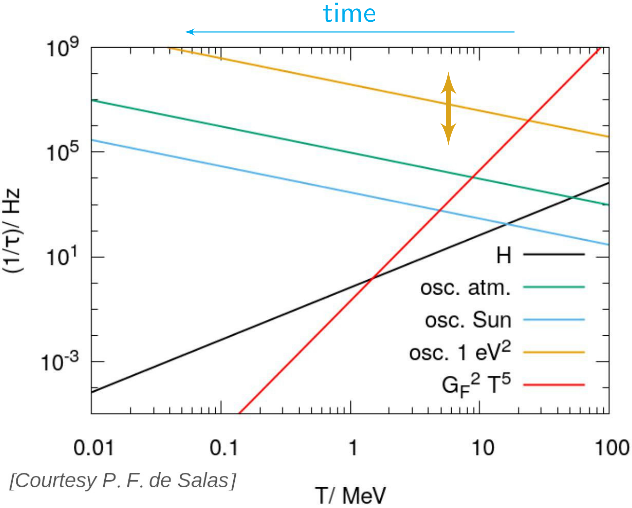

[Courtesy P. F. de Salas]

beginning of oscillations depends on Δm^2_{41}

later oscillations

$\Downarrow$

less time before ν decoupling!

Sterile neutrino in the early universe

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Four neutrinos $\longrightarrow$ new oscillations in the early Universe

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when are they enough to allow full equilibrium of active-sterile states?

$$0 \longleftarrow \Delta N_{\mathrm{eff}} = N_{\mathrm{eff}}^{4\nu} - N_{\mathrm{eff}}^{3\nu} \longrightarrow \simeq 1$$

no sterile production

active&sterile in equilibrium

$$\frac{\Delta m^2_{as}}{\mathrm{eV}^2} \sin^4\left(2\vartheta_{as}\right) \simeq 10^{-5} \ln^2\left(1 - \Delta N_{\mathrm{eff}}\right) \qquad \text{(1+1 approx.)}$$

[Dolgov&Villante, 2004]

e.g.: $\Delta m^2_{as} = 1\ \mathrm{eV}^2$, $\sin^2\left(2\vartheta_{as}\right) \simeq 10^{-3} \Longrightarrow \Delta N_{\mathrm{eff}} \simeq 1$

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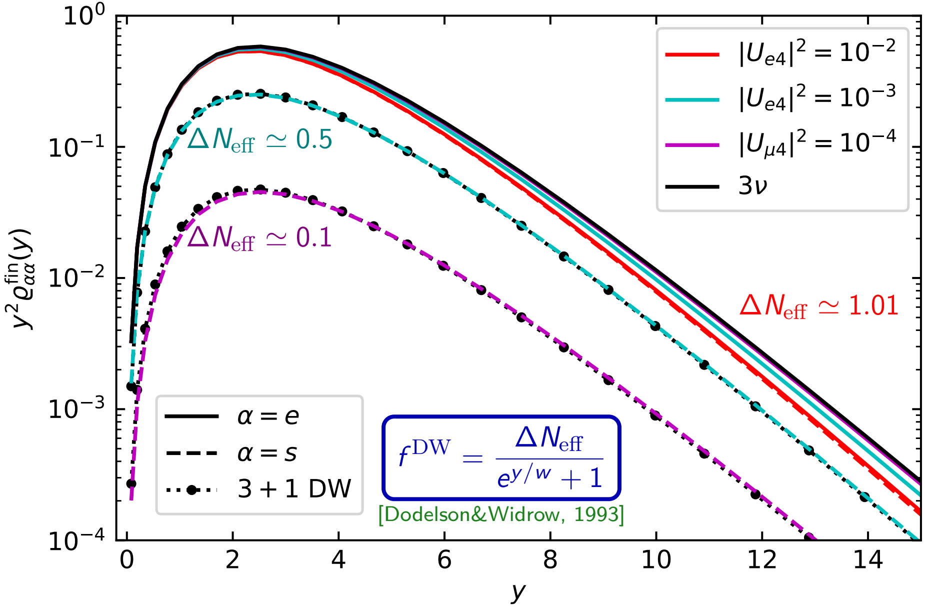
Full calculation: use numerical code!

`FORTran-Evolved PrimordIAl Neutrino Oscillations`
`(FortEPiaNO)`
`https://bitbucket.org/ahep_cosmo/fortepiano`

Momentum distributions

[SG+, JCAP 07 (2019) 014]

$\Delta m^2_{41} = 1.29\ \mathrm{eV}^2$, other $|U_{\beta 4}|^2 = 0$, $\Delta N_\mathrm{eff} = N_\mathrm{eff} - N_\mathrm{eff}^\mathrm{active}$



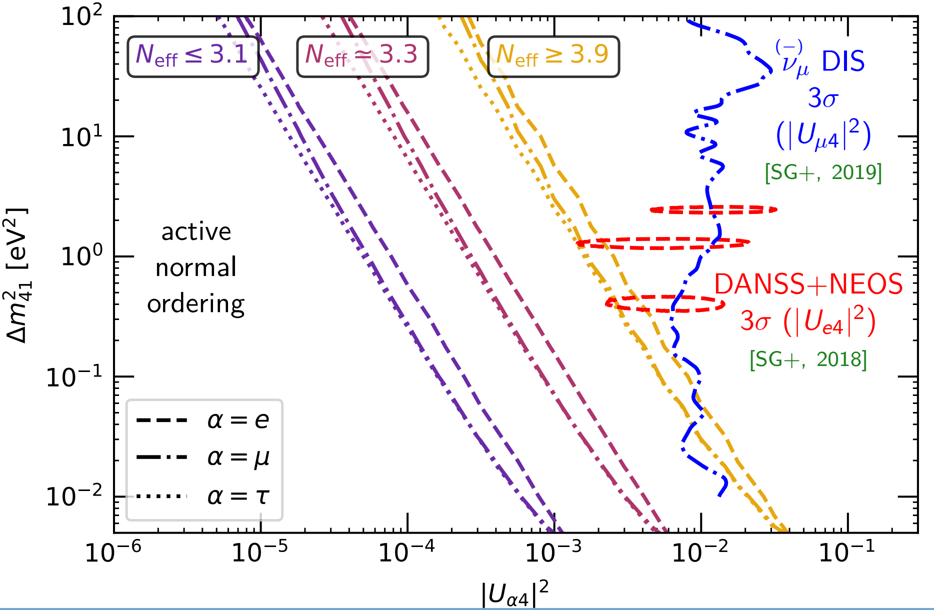
$$\boxed{f^\mathrm{DW} = \frac{\Delta N_\mathrm{eff}}{e^{y/w}+1}}$$

[Dodelson&Widrow, 1993]

$N_{\rm eff}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

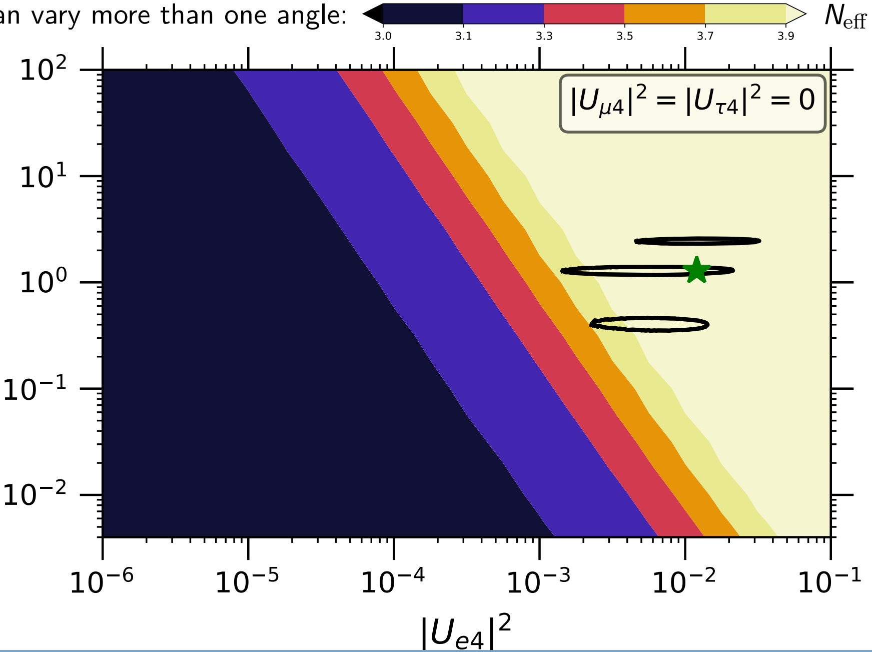
Only vary one angle and fix two to zero: do they have the same effect?



$N_{\rm eff}$ and the new mixing parameters

[SG+, JCAP 07 (2019) 014]

We can vary more than one angle:



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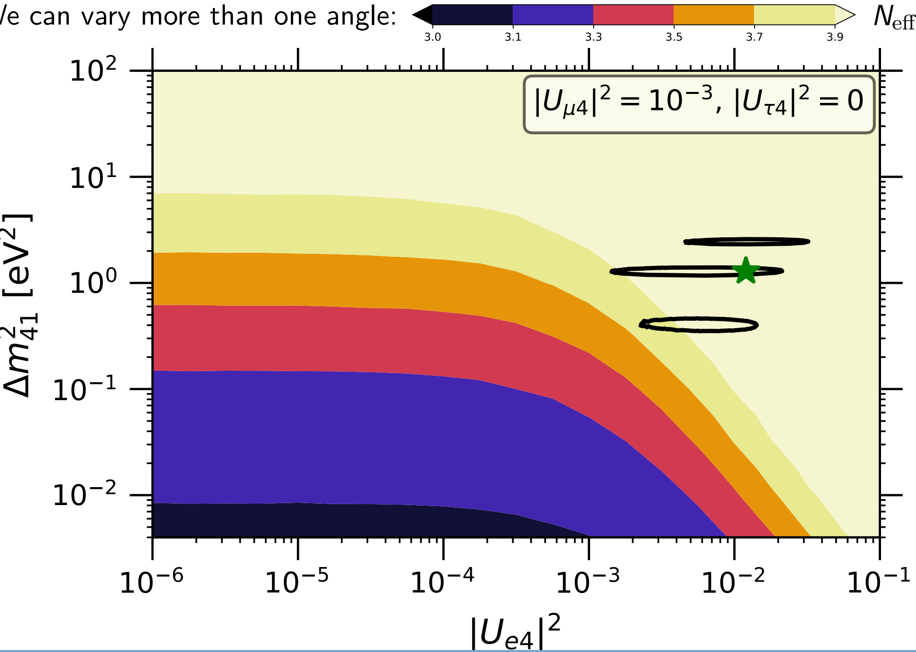

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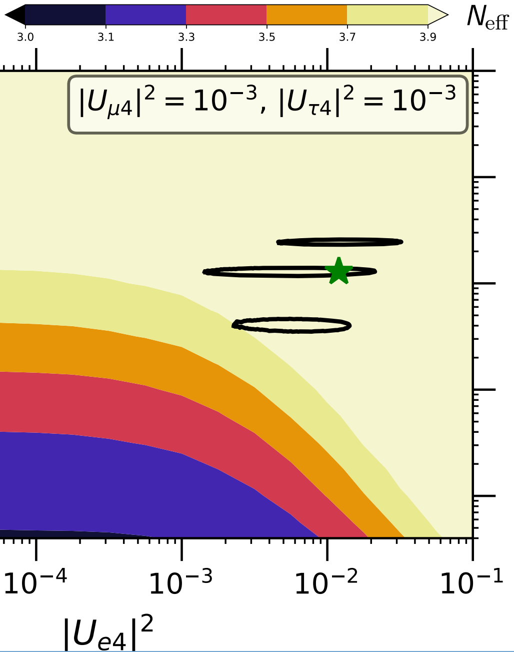
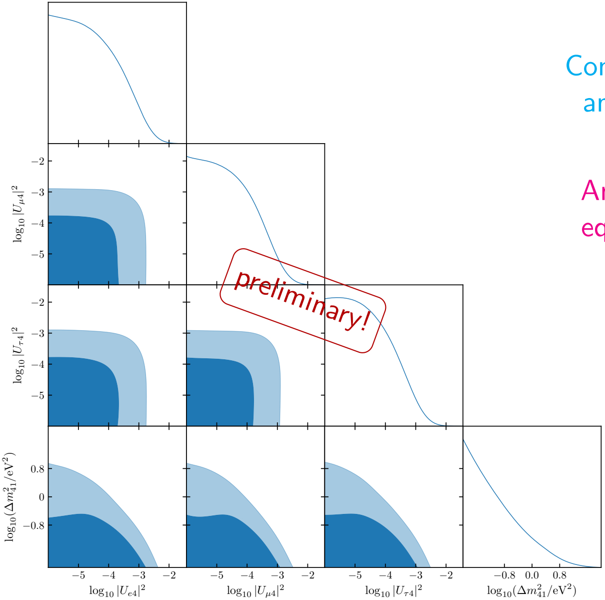


Cosmological constraints on $|U_{\alpha 4}|^2$

[in preparation]

Use multi-angle results from `FortEPiaNO` to derive constraints on $|U_{\alpha 4}|^2$:



Constraints come from $N_{\rm eff}$ and late-time density Ω_s

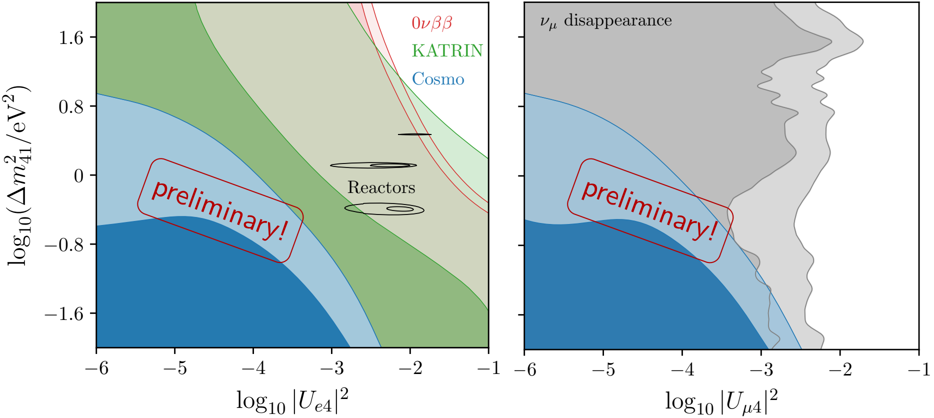
Angles $|U_{\alpha 4}|^2$ are almost equivalent for cosmology

Comparing constraints

[in preparation]

Cosmological constraints are stronger than most other probes

But much more model dependent (as all the cosmological constraints)!



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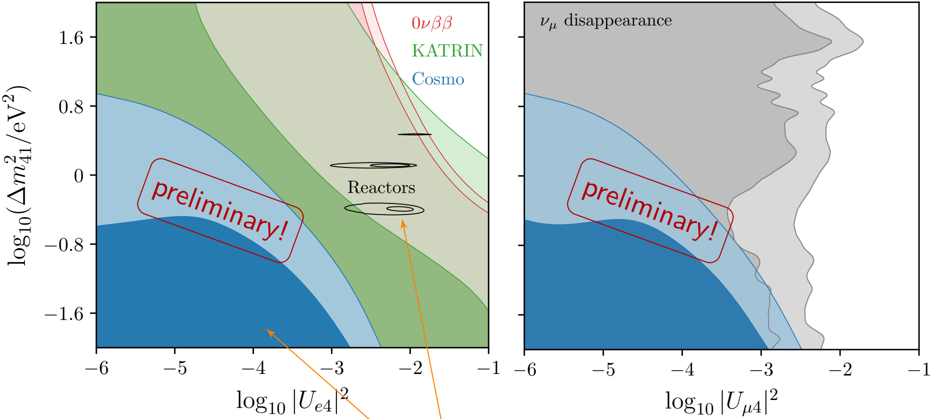
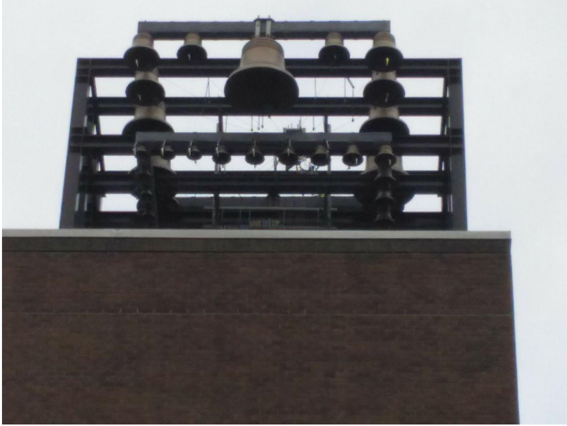


Warning: tension between reactor experiments and CMB bounds!

Z

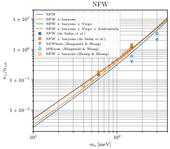
Conclusions

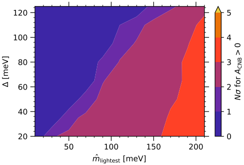
almost there!



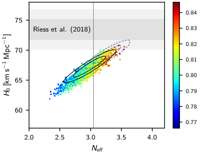
What do we learn from relic neutrinos?

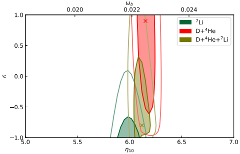
D Direct detection - wonderful opportunities for the future



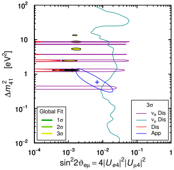


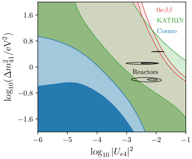
I Indirect probes - what we have now, it's a lot and it will improve





N New physics - beyond the corner? neutrinos will help us find it!





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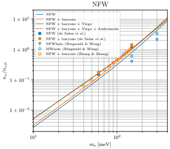

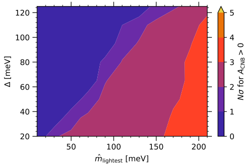

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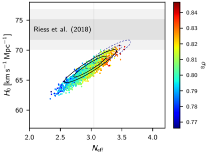

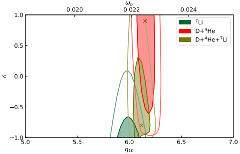

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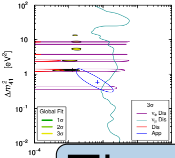

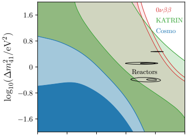

Thank you!