Neutrinos in cosmology

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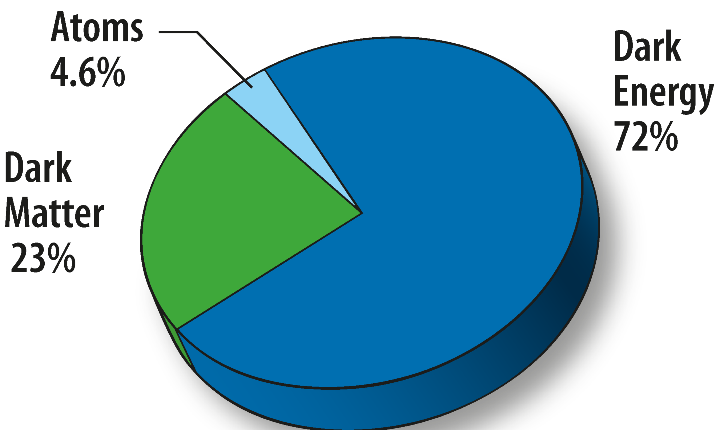
The University of New South Wales

DESY theory workshop “Bright ideas for a dark universe”, September 21 – 24, 2021

Concordance ΛCDM…

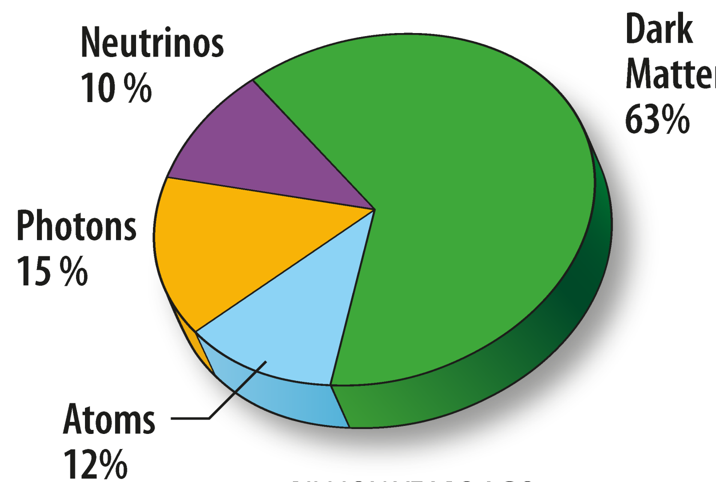
- The simplest model consistent with most observations.



TODAY

+ flat spatial geometry and initial conditions consistent with single-field inflation

Neutrino-to-photon energy density ratio fixed by SM physics



13.7 BILLION YEARS AGO

(Universe 380,000 years old)

The cosmic neutrino background...

- Neutrino decoupling at $T \sim O(1)$ MeV. ← Fixed by weak interactions
- After e^+e^- annihilation ($T \sim 0.5$ MeV)
  - **FD distribution with temperature**: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$ ← Assuming $T_{\rm dec} \gg m_e$
  - **Energy density** per flavour: $\rho_\nu = \frac{7}{8}\frac{\pi^2}{15} T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$ ← $\frac{3\rho_\nu}{\rho_\gamma} \sim 0.68$

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- If massive, then at $T \ll m_\nu$: $\rho_\nu = m_\nu n_\gamma$ ⇒ $\Omega_\nu h^2 = \sum \frac{m_\nu}{94 \text{ eV}}$
  - **Energy density in neutrino dark matter:**

$$0.1\% < \Omega_\nu < 7\%$$

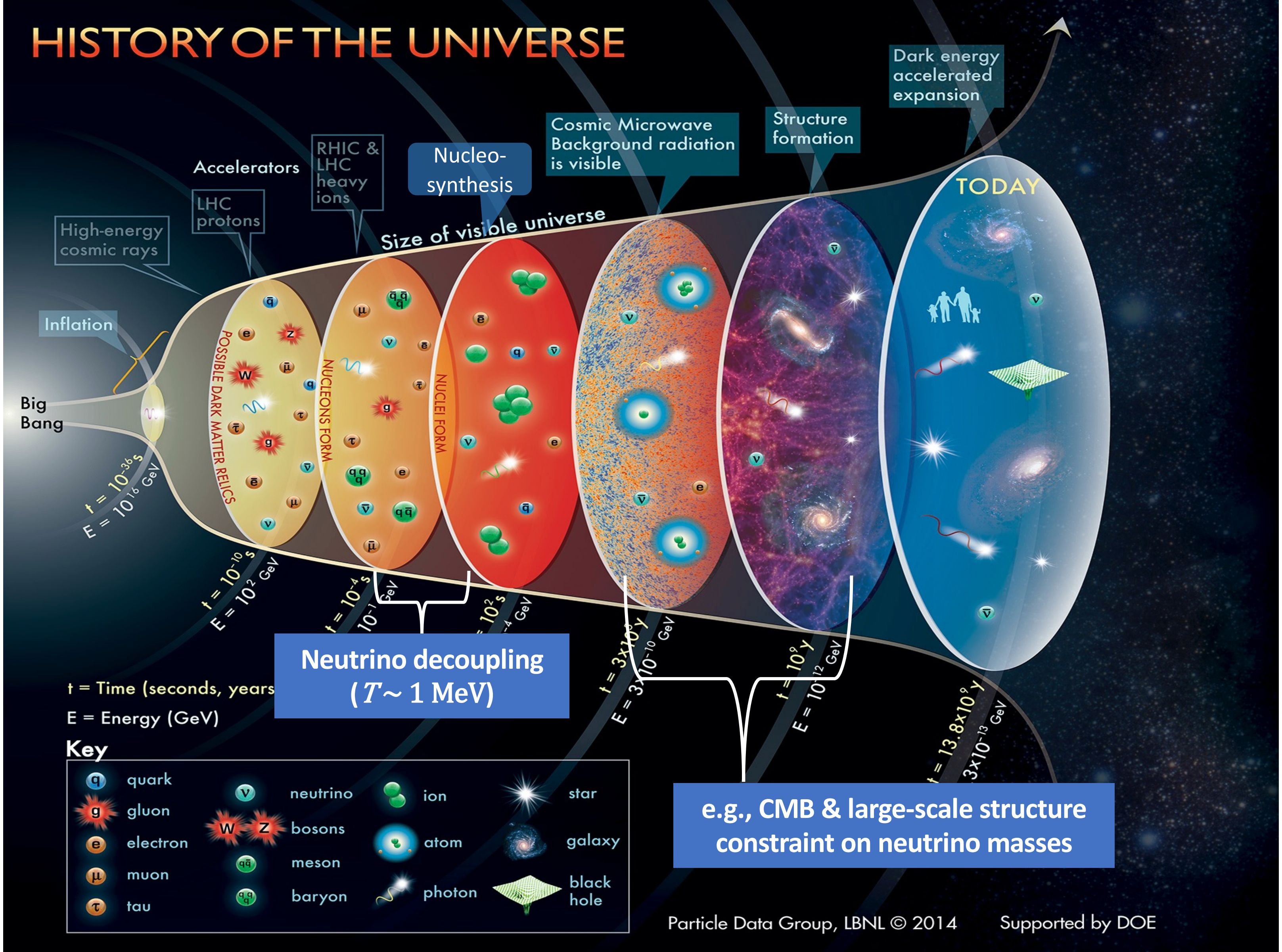
From neutrino oscillations → lower bound:

$$\min \sum m_\nu = 0.06 \text{ eV}$$

From KATRIN → upper bound:

$$m_e \equiv \left(\sum_i |U_{ei}|^2 m_i^2\right)^{1/2} < 1.1 \text{ eV}$$

Aker et al. [KATRIN] 2019


HISTORY OF THE UNIVERSE
Dark energy accelerated expansion
Structure formation
Cosmic Microwave Background radiation is visible
Nucleo-synthesis
RHIC & LHC heavy ions
Accelerators
LHC protons
High-energy cosmic rays
Inflation
Big Bang
Size of visible universe
TODAY
POSSIBLE DARK MATTER RELICS
NUCLEONS FORM
NUCLEI FORM
t = 10^-36 s
E = 10^16 GeV
t = 10^-10 s
E = 10^2 GeV
t = 10^-4 s
t = 10^2 s
t = 3x10^5 y
E = 3x10^-10 GeV
t = 10^9 y
E = 10^-12 GeV
t = 13.8x10^9 y
3x10^-13 GeV
Neutrino decoupling
(T ~ 1 MeV)
e.g., CMB & large-scale structure constraint on neutrino masses
t = Time (seconds, years)
E = Energy (GeV)
Key
quark
gluon
electron
muon
tau
neutrino
bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

This talk…

- **“Standard” neutrinos in cosmology**

  I. New precision calculation of the SM effective number of neutrinos, $N_{\mathrm{eff}}^{\mathrm{SM}}$

- **“Non-standard” neutrinos in cosmology**

  II. Non-standard neutrino interactions

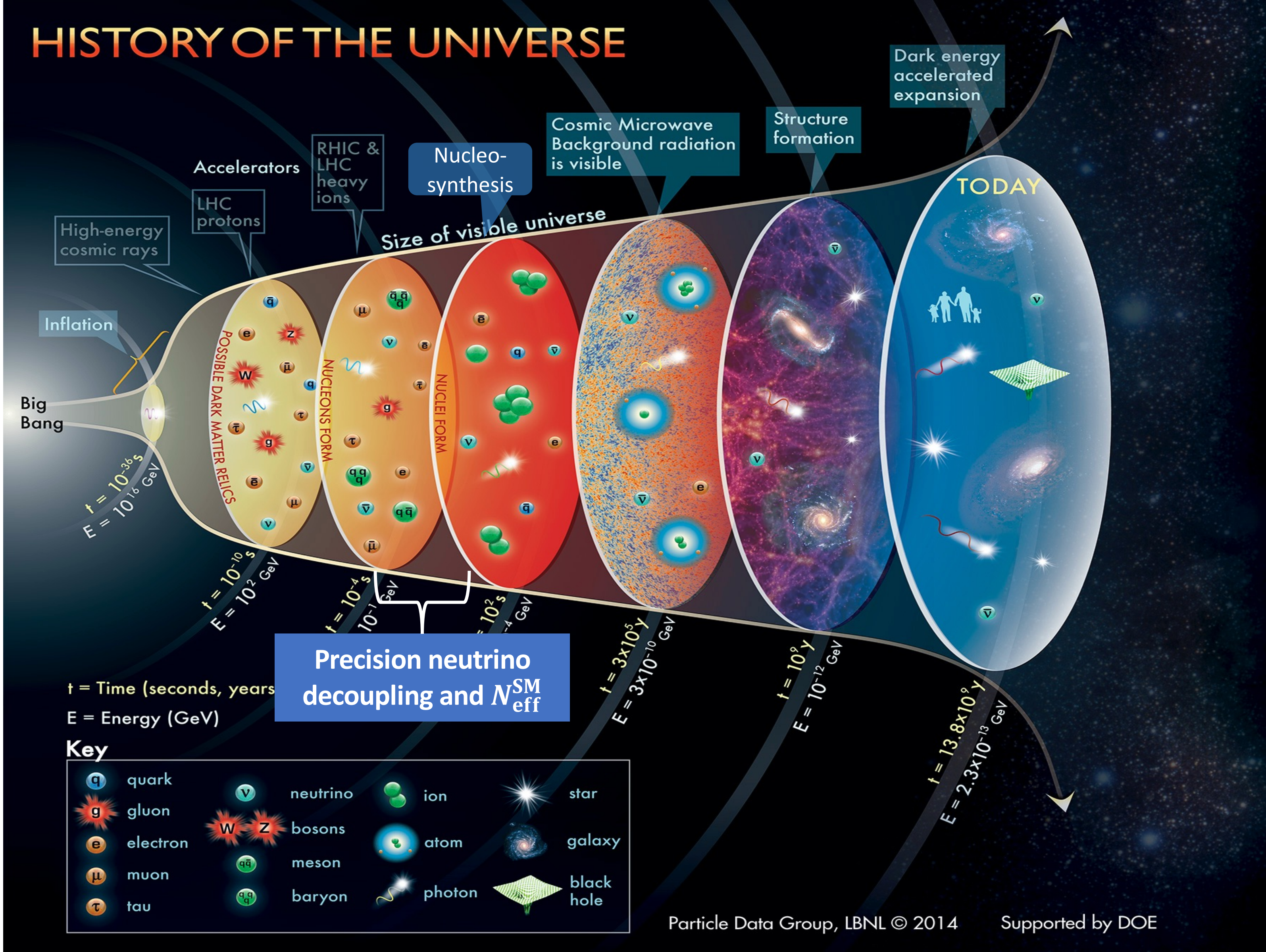
  - Revised bound on the neutrino lifetime
  - Neutrino self-interaction and the Hubble tension

- An unashamed advertisement of the works of my students and postdocs (and collaborators) in the past few years.

Gabriela Barenboim, Jack Bennett, Celine Boehm, Gilles Buldgen, Joe Chen, Pablo de Salas, Marco Drewes, Stefano Gariazzo, Steen Hannestad, Olga Mena, Isabel Oldengott, Sergio Pastor, Cornelius Rampf, Julia Stadler, Thomas Tram, Amol Upadhye

I. A new precision calculation of the standard model $N_{\text{eff}}^{\text{SM}}$ …

Bennett, Buldgen, Drewes & Y^{3}W, *JCAP* 03 (2020) 003, *JCAP* 03 (2021) A01 (addendum)
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y^{3}W, *JCAP* 04 (2021) 073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Precision neutrino decoupling and $N_{\rm eff}^{\rm SM}$
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photon
star
galaxy
black hole
Particle Data Group, LBNL © 2014
Supported by DOE

The CνB: some small tweaks...

- Neutrino decoupling at $T \sim O(1)$ MeV. ← Fixed by weak interactions
- After e^+e^- annihilation ($T \sim 0.5$ MeV)
  - **FD distribution with temperature**: $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma$
  - **Energy density** per flavour: $\rho_\nu = \frac{7}{8}\frac{\pi^2}{15}T_\nu^4 = \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\rho_\gamma$

This is not a very good approximation.

Assuming $T_{\text{dec}} \gg m_e$

Distortions from non-instantaneous decoupling

Finite-temperature corrections to the QED equation of state

- Lump all corrections into the **effective number of neutrino** parameter:

$$\sum \rho_\nu = N_{\text{eff}} \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma = (3 + \delta N_{\text{eff}})\, \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

3 families

%-level SM corrections

→ Precision $N_{\text{eff}}^{\text{SM}}$

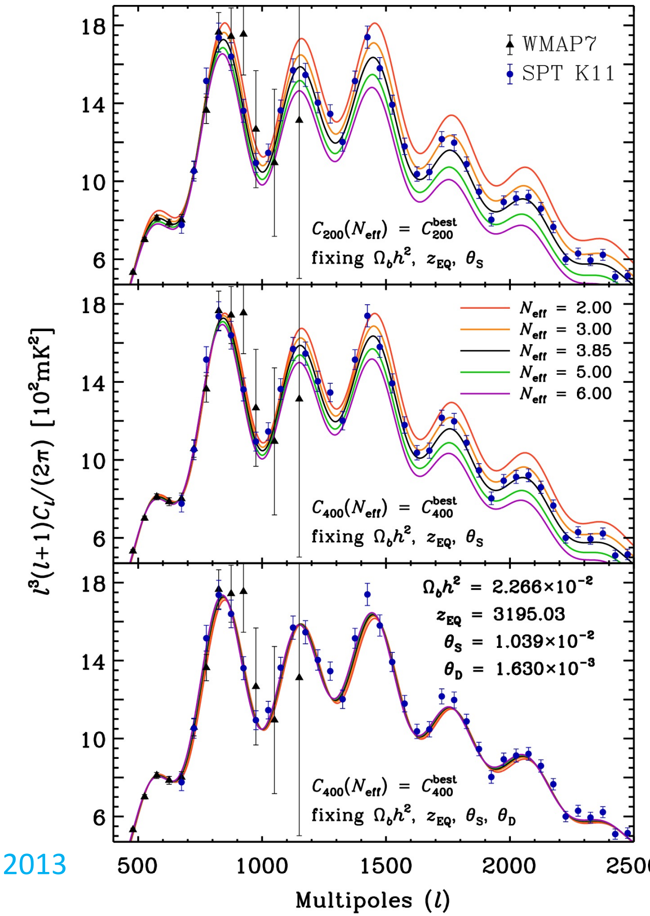
Why bother with precision $N_{\text{eff}}^{\text{SM}}$? 1/2

- Varying N_{eff} impacts directly on matter-radiation equality and the expansion rate at recombination.

  → Observable effects in the CMB anisotropies

  - Planck-era signature primarily in the **CMB damping tail**

  - An observed $N_{\text{eff}} > N_{\text{eff}}^{\text{SM}}$ indicates an excess of non-photon radiation and could be **a sign of new physics**.



Hou, Keisler, Knox, Millea & Reichardt 2013

Why bother with precision $N_{\rm eff}^{\rm SM}$? 2/2

- **Current cosmological constraints**:

ΛCDM+Neff 7-parameter fit	Planck 2018 (95%)	Planck2015 (95%)
TT+lowE	$\mathbf{3.00^{+0.57}_{-0.53}}$	3.13±0.64
+lensing+BAO	$\mathbf{3.11^{+0.44}_{-0.43}}$	n/a
TT+lowE+TE+EE	$\mathbf{2.92^{+0.36}_{-0.37}}$	2.99±0.40
+lensing+BAO	$\mathbf{2.99^{+0.34}_{-0.33}}$	n/a

- **Future 1σ sensitivity** (CMB-S4): $\sigma(N_{\rm eff})\sim 0.02 - 0.04$

Aghanim [PLANCK] 2018
Ade [PLANCK] 2015

→ This motivates us to pursue $N_{\rm eff}^{\rm SM}$ to the next significant digit.

Precision $N_{\text{eff}}^{\text{SM}}$ …

Bennett, Buldgen, Drewes & Y^3W 2020;
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y^3W 2021;
Froustey, Pitrou & Volpe, 2020

See also Akita & Yamaguchi 2020; Hansen, Shalgar & Tamborra 2021; Escudero 2020 for related works

- The **most precise to-date** computation of the standard model N_{eff} :

$$N_{\text{eff}}^{\text{SM}} = 3.0440 \pm 0.0002$$

- Two independent calculations: same physics but using **independent numerical implementations** by two independent groups
  - Central values agree to **five significant digits**
  - Broadly consistent uncertainty assessment

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- **What goes into it**:
  - Neutrino decoupling tracked with Quantum Kinetic Equations, including
    - In-medium 3-flavour oscillations — Sigl & Raffelt 1993; McKeller & Thomson 1994
    - All 2 → 2 neutrino-neutrino and neutrino-electron weak interactions
    - Full momentum dependence plus quantum statistics implemented in `FortEPiaNO` — Gariazzo, de Salas & Pastor 2019
  - Finite-temperature QED correction to
    - Equation of state of photon-electron plasma
    - Weak scattering rates (thermal masses only; other corrections yet to be determined although expected to be inconsequential)

Precision $N_{\text{eff}}^{\text{SM}}$ ...

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Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y^3W 2021;
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- The **most precise to-date** computation of the standard model N_{eff} :

$$N_{\text{eff}}^{\text{SM}} = 3.0440 \pm 0.0002$$

- **Compare with older values**:

$$N_{\text{eff}}^{\text{SM}} = 3.046 \pm 0.002$$ Mangano et al. 2005

$$N_{\text{eff}}^{\text{SM}} = 3.045 \pm 0.001$$ de Salas & Pastor 2015

At face value:

- The new central value, while broadly consistent with older calculations, tends to the low end; **more later**
- Factor of 5 improvement in the uncertainty; primarily due to better numerical implementation

Precision $N_{\mathrm{eff}}^{\mathrm{SM}}$ …

Bennett, Buldgen, Drewes & Y^{3}W 2020;
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y^{3}W 2021;
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Beneath the surface, new calculations contain **new elements**:

- NLO finite-temperature QED corrections to the plasma EOS
- EW running of weak couplings
- Full implementation of neutrino-neutrino scattering

Precision $N_{\text{eff}}^{\text{SM}}$ …

Bennett, Buldgen, Drewes & Y^{3}W 2020;
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y^{3}W 2021;
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	Standard-model corrections to $N_{\text{eff}}^{\text{SM}}$	Leading-digit contribution
	m_e/T_d correction	$+0.04$
	$\mathcal{O}(e^2)$ FTQED correction to the QED EoS	$+0.01$
	Non-instantaneous decoupling+spectral distortion	-0.005
*	$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
	Flavour oscillations	$+0.0005$
	Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$

* Previously neglected correction: main cause of the central value shift   Bennett et al. 2020

Bennett, Buldgen, Drewes & Y[3]W 2020;
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y[3]W 2021;
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Precision $N_{\mathrm{eff}}^{\mathrm{SM}}$ ...

- The **most precise to-date** computation of the standard model N_{eff} :

$$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.0440 \pm 0.0002$$

- **Uncertainty estimate:**
  - ~ 0.0001 from numerical errors (discretisation artefacts in numerical solutions of the QKEs)
  - ~ 0.0001 from experimental uncertainty in the solar mixing angle:

$$\sin^2\theta_{12} = (3.18 \pm 0.16)\times 10^{-1}$$

de Salas et al. 2021
Esteban et al. 2020

Take-home message: Part I…

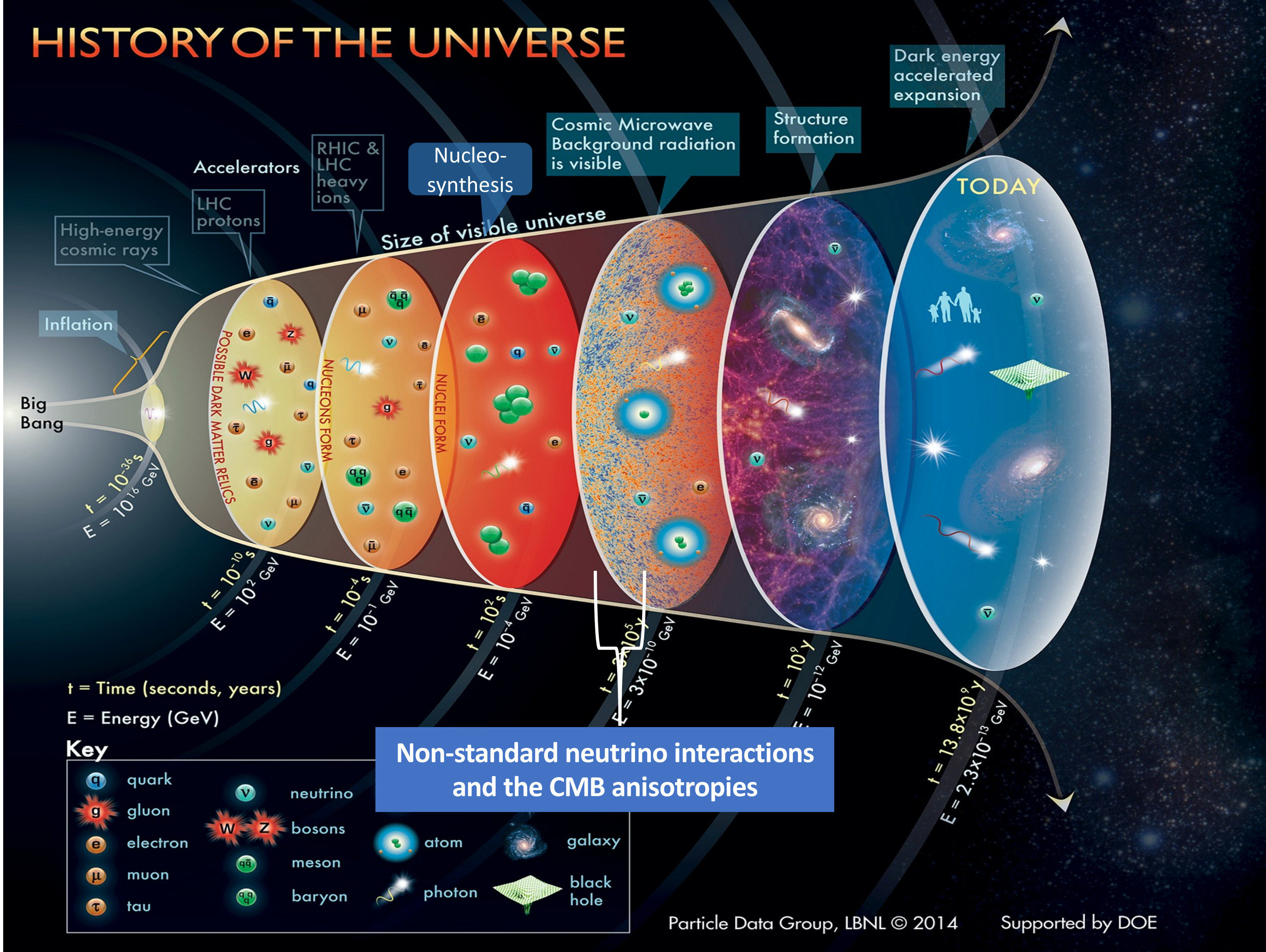
- A most precise to-date determination of the standard model effective number of neutrinos:

$$N_{\mathrm{eff}}^{\mathrm{SM}} = 3.0440 \pm 0.0002$$

- Already adopted as **default value** in the latest release of `CLASS`.
- **Uncertainty**: part numerical errors in the solution of the QKEs, part due to experimental uncertainty in the solar mixing angle $\sin^2\theta_{12}$
- **Remains to be determined**: corrections from certain types of thermal loop corrections to the weak rates. Watch this space!

II. Cosmological implications of non-standard neutrino interactions…

Oldengott, Rampf & Y^3W, *JCAP* 04 (2015) 016
Oldengott, Tram, Rampf & Y^3W, *JCAP* 11 (2017) 027
Mosbech, Boehm, Hannestad, Mena, Stadler & Y^3W, *JCAP* 03 (2021) 066
Barenboim, Chen, Hannestad, Oldengett, Tram & Y^3W, *JCAP* 03 (2021) 087

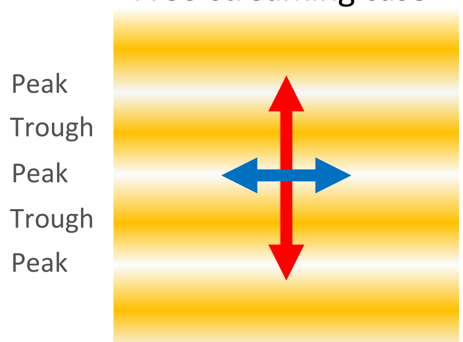


Non-standard neutrino interactions and the CMB anisotropies

Neutrino interactions and the CMB… 1/2

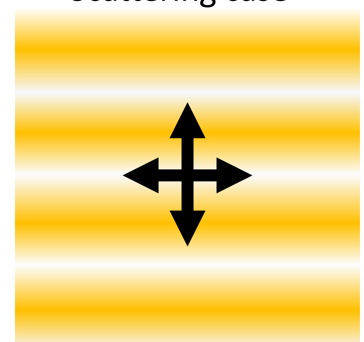
- After neutrino decoupling, standard neutrinos free-stream.
  - **Free-streaming** in a spatially inhomogeneous background induces **shear stress**.
  - Conversely, **scattering tends to isotropise** a phase space element.

Free-streaming case



Sinusoidal gravitational potential

Scattering case

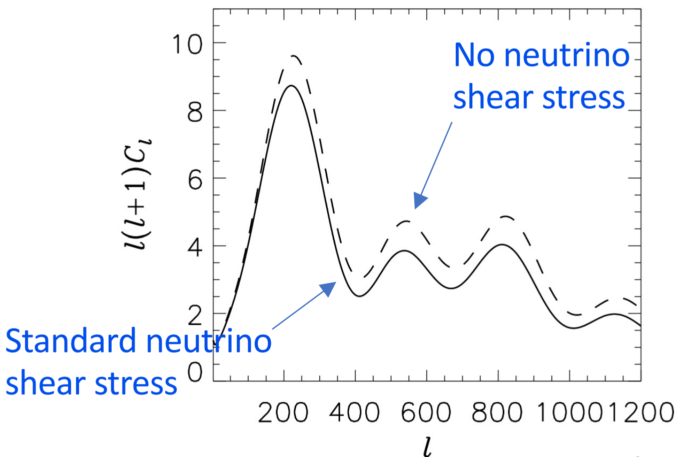


Scattering transfers momentum and wipes out shear

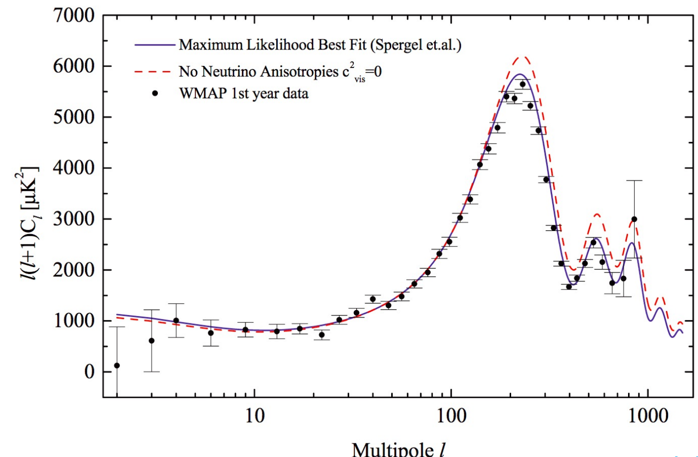
- Observable consequences in the CMB, when neutrinos are ultra-relativistic and form a substantial fraction of universe's energy density.

Neutrino interactions and the CMB… 2/2

- That CMB prefers neutrino shear stress to no shear stress is well known.



Hannestad 2005

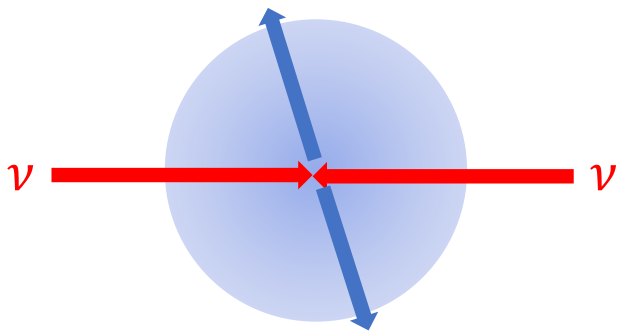


Trotta & Melchiorri 2005

- The tricky part is how to translate this preference to constraints on the **fundamental parameters** of a non-standard neutrino interaction
  → What is the **isotropisation or transport rate**?

Transport rate from scattering… 1/2

- **2 → 2 neutrino-neutrino scattering**: The final state particles are equally likely to be emitted in any direction.
  → It takes one scattering event to transfer momentum by 90 degrees.



$$\Gamma_{\text{transport}} \sim \Gamma_{\text{scattering}}$$

$$\sim G_{\text{eff}}^2 T^5 \quad \text{4-Fermi}$$

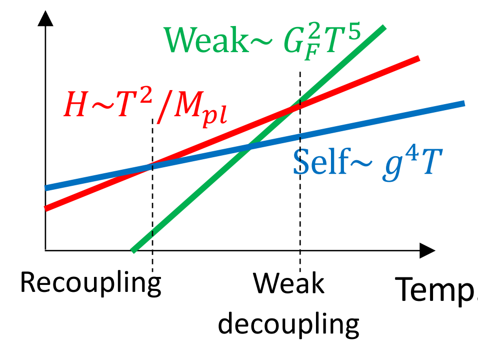
$$\sim g^4 T \quad \text{Light mediator}$$

- 4-Fermi is a decoupling scenario

Cyr-Racine & Sigurdson 2014; Oldengott, Rampf & Y[3]W 2015; Lancaster, et al. 2017; Oldengott, Tram, Rampf & Y[3]W 2017; Kreisch, Cyr-Racine & Dore 2019

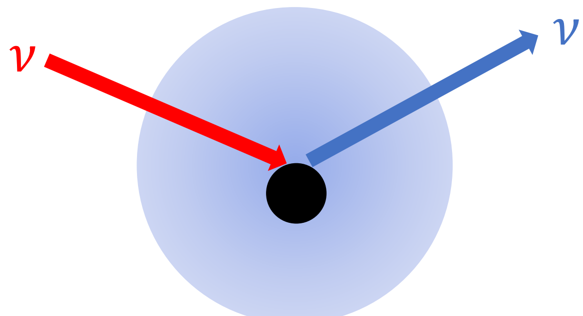
- Light mediator is a recoupling scenario

Forastieri, Lattanzi & Natoli 2015



Transport rate from scattering…

- A variation: **neutrino scattering on cold dark matter** → Again, it takes one scattering event to transfer neutrino momentum by 90 degrees.



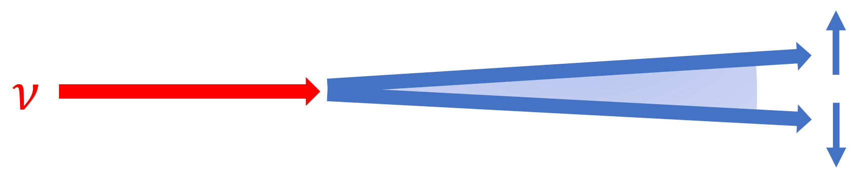
$$\Gamma_{\mathrm{transport}} \sim \Gamma_{\mathrm{scattering}}$$

Wilkinson, Boehm & Lesgourgues 2015
Mosbech, Boehm, Hannestad, Mena, Stadler & Y^3W 2021

- Also has non-trivial consequences for the dark matter perturbations, particularly on very small scales; so phenomenologically not exactly the same as neutrino self-interaction.

Transport rate from relativistic decay…

- **Relativistic 1 → 2 decay to massless** particles (and inverse decay) has an opening angle $\sim m_\nu/E$ (mass and energy of the decaying particle).



One power from Lorentz boost;
Two powers from opening angle

$$\Gamma_{\text{transport}}^{\text{old}} \sim \left(\frac{m_\nu}{E}\right)^3 \Gamma_{\text{decay}}^{\text{rest}}$$

Hannestad & Raffelt 2005

- Old estimate neglected **momentum conservation**: Only the transverse momentum (suppressed by m_ν/E) can be transported.
  - Revised transport rate as two extra powers of m_ν/E.

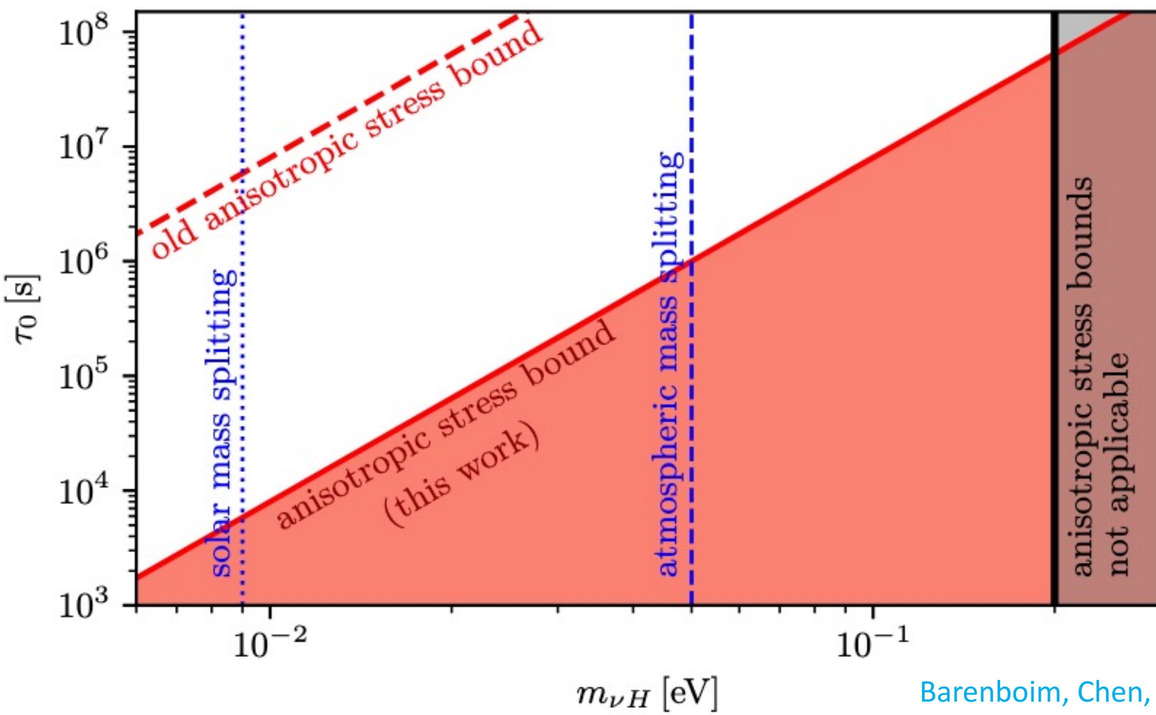
$$\Gamma_{\text{transport}}^{\text{new}} \sim \left(\frac{m_\nu}{E}\right)^5 \Gamma_{\text{decay}}^{\text{rest}}$$

First-principles derivation in

Barenboim, Chen, Hannestad, Oldengott, Tram & Y³W 2021

New CMB constraint on the neutrino lifetime…

- Revised transport rate → **weaker bound on the neutrino lifetime**



$$\tau_0^{\mathrm{old}} \geq 10^{-9}\,\mathrm{s}\left(\frac{m_\nu}{50\ \mathrm{meV}}\right)^3$$

$$\tau_0^{\mathrm{new}} \geq 10^{-6}\,\mathrm{s}\left(\frac{m_\nu}{50\ \mathrm{meV}}\right)^5$$

Barenboim, Chen, Hannestad, Oldengott, Tram & Y³W 2021

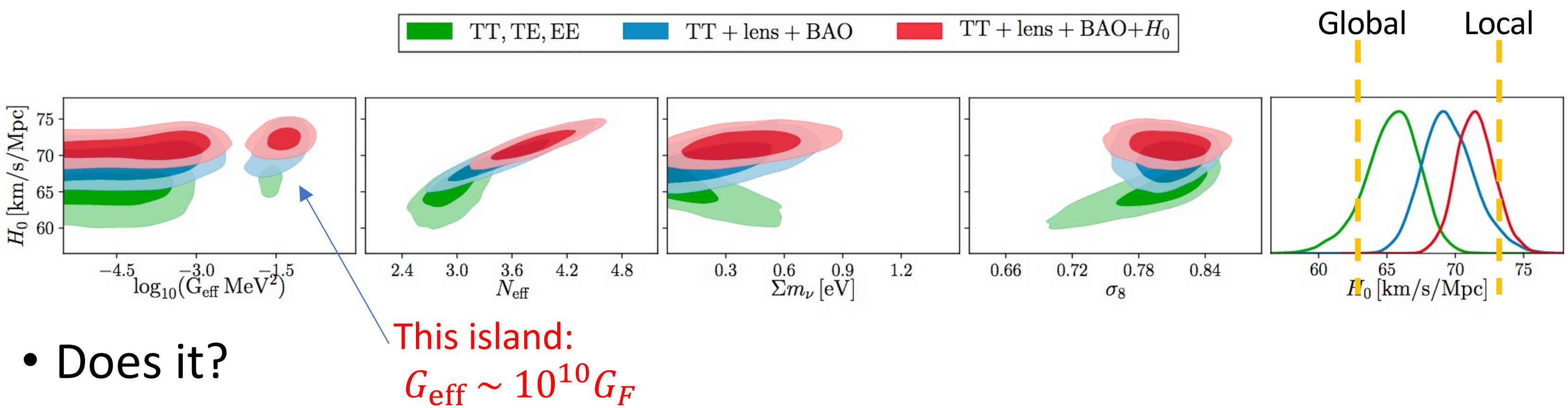
IIb. Shear stress loss and the H_0 tension…

Oldengott, Rampf & Y[3]W, *JCAP* 04 (2015) 016
Oldengott, Tram, Rampf & Y[3]W, *JCAP* 11 (2017) 027

Shear stress loss and the H_0 tension... 1/3

Kreisch, Cyr-Racine & Dore 2019

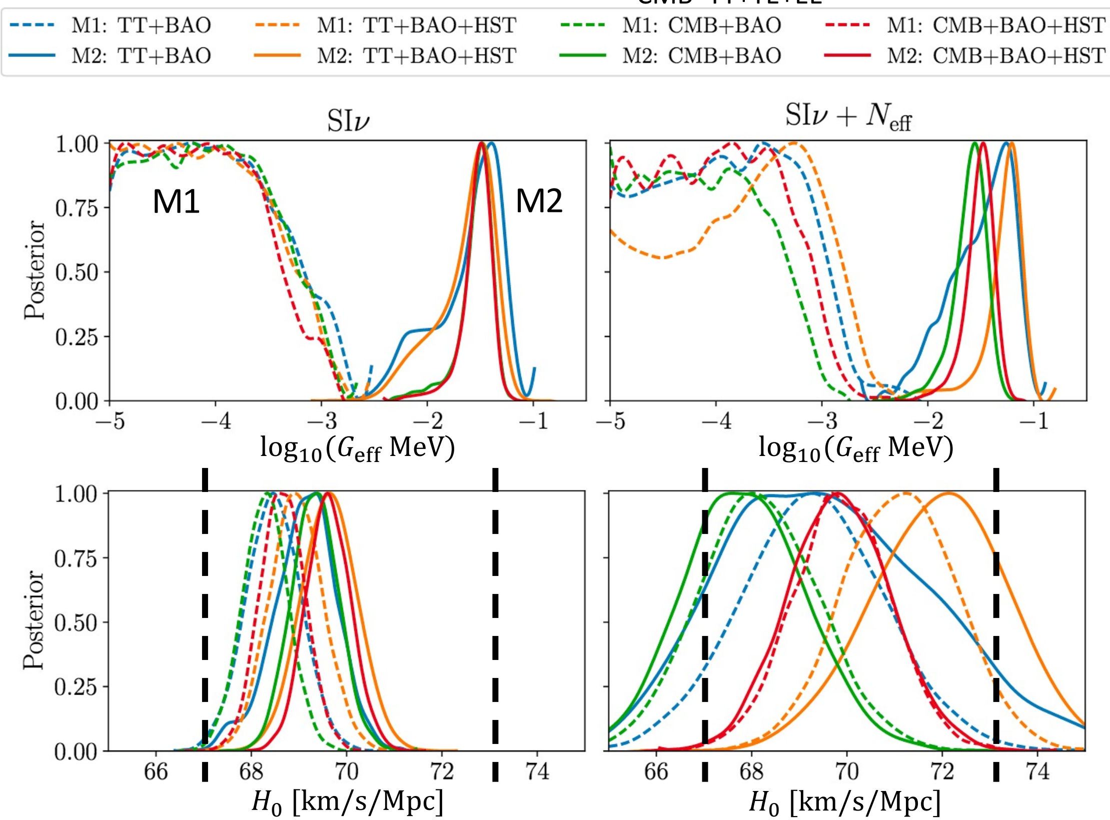
- Recent claim that shear stress loss due to neutrino self-interaction **alleviates the Hubble tension**.
  - **Local/late time**: Cepheid-calibrated SNIa (SH0ES) and strong-lensing time delays (H0liCOW); $H_0 = (73.5 \pm 1.4)$ km/s/Mpc
  - **Global/early time**: Statistical inference from CMB anisotropies (Planck), weak lensing, BAO; $H_0 = (67.4 \pm 0.5)$ km/s/Mpc



- Does it?

Shear stress loss and the H_0 tension… 2/3

CMB=TT+TE+EE



ΛCDM+self-interaction   ΛCDM+self-interaction+N_{eff}

Oldengott, Tram, Rampf & Y[3]W 2017

- Self-interaction alone does shift the inferred H_0 up (**left**).
- But need a large N_{eff} as well to substantially lift H_0 (**right**) because of well-known (N_{eff}, H_0)-degeneracy.
- Even then, TT+BAO and TT+TE+EE+BAO alone do not prefer a large H_0 (blue, green)
- TT+BAO only prefers high H_0 when combined with a local measurement HST (orange)
- Polarisation “kills” it anyway: TT+TE+EE+BAO fit settles in a **compromise region** (red).
- M1 (red dashed) & M2 (red solid) coincide on right → all gains in H_0 come from N_{eff} alone; self-interaction adds nothing substantial

Shear stress loss and the H_0 tension... 3/3

CMB=TT+TE+EE

ΛCDM+self-int		TT+BAO	TT+BAO+HST	CMB+BAO	CMB+BAO+HST
$\log_{10}(G_{\rm eff}\,\rm MeV)$	*M1*	< -2.7 (95%)	< -2.8 (95%)	< -2.8 (95%)	< -2.9 (95%)
	M2	$-1.6^{+0.5}_{-0.7}$	$-1.6^{+0.5}_{-0.6}$	$-1.5^{+0.3}_{-0.4}$	$-1.5^{+0.3}_{-0.3}$
H_0 [km/s/Mpc]	*M1*	$68.5^{+1.2}_{-1.2}$	$68.9^{+1.1}_{-1.1}$	$68.3^{+1.0}_{-1.0}$	$68.7^{+1.0}_{-1.0}$
	M2	$69.1^{+1.3}_{-1.5}$	$69.6^{+1.2}_{-1.2}$	$69.3^{+1.0}_{-1.0}$	$69.6^{+1.0}_{-0.9}$
$\chi^2_{M2} - \chi^2_{M1}$		4.5	2.9	3.4	0.9

ΛCDM+self-int+$N_{\rm eff}$		TT+BAO	TT+BAO+HST	CMB+BAO	CMB+BAO+HST
$\log_{10}(G_{\rm eff}\,\rm MeV)$	*M1*	< -2.3 (95%)	< -2.4 (95%)	< -2.9 (95%)	< -2.6 (95%)
	M2	$-1.5^{+0.5}_{-0.6}$	$-1.3^{+0.3}_{-0.6}$	$-1.6^{+0.3}_{-0.4}$	$-1.5^{+0.3}_{-0.3}$
$N_{\rm eff}$	*M1*	$3.2^{+0.5}_{-0.5}$	$3.4^{+0.4}_{-0.4}$	$3.0^{+0.4}_{-0.4}$	$3.3^{+0.3}_{-0.3}$
	M2	$3.1^{+0.8}_{-0.7}$	$3.5^{+0.5}_{-0.6}$	$2.8^{+0.4}_{-0.4}$	$3.1^{+0.3}_{-0.3}$
H_0 [km/s/Mpc]	*M1*	$69.3^{+3.1}_{-3.1}$	$71.1^{+2.4}_{-2.4}$	$68.2^{+2.6}_{-2.5}$	$69.9^{+2.1}_{-2.1}$
	M2	$69.6^{+4.5}_{-4.2}$	$71.9^{+2.9}_{-3.1}$	$67.9^{+2.6}_{-2.6}$	$69.8^{+2.2}_{-2.2}$
$\chi^2_{M2} - \chi^2_{M1}$		4.9	3.5	2.6	1.8

Oldengott, Tram, Rampf & Y[3]W 2017

Compare with ΛCDM+$N_{\rm eff}$ fit:

$$N_{\rm eff} = 3.27 \pm 0.3$$
$$H_0 = 69.32 \pm 1.9 \ \rm km/s/Mpc$$

TT+TE+EE+lowE+lensing +BAO+R18

Aghanim et al. 2018

It's $N_{\rm eff}$ doing the leg work; adding self-interaction too has no statistically significant effect.

Summary…

- I have presented:
  - A new precise calculation of the standard model $N_{\rm eff}$; the new value has already been implemented in the latest release of `CLASS`.
  - A revised cosmological limit on the neutrino lifetime based on a revised transport rate.

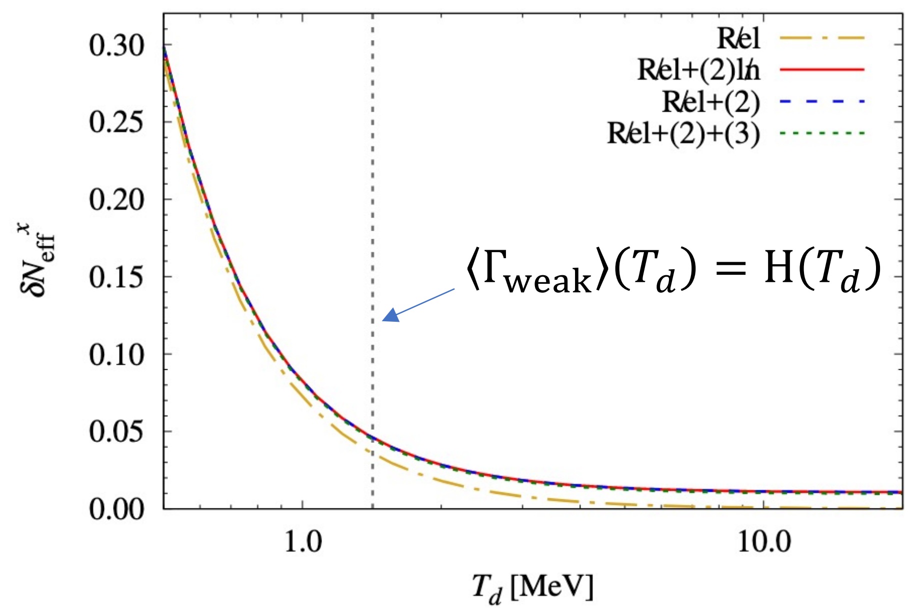
- Neutrino **self-interaction as a solution to the $\boldsymbol{H_0}$ tension** is doubtful.
  - Superficial agreement between local measurement and global inference of H_0 can be achieved only if you cherry-pick your data sets.
  - Check the free parameters of the fit: if $N_{\rm eff}$ is allowed to vary, then it’s just the $(N_{\rm eff}, H_0)$- degeneracy doing the legwork; self-interaction is a red herring.

Extra slides…

Standard-model corrections to $N_{\rm eff}^{\rm SM}$	Leading-digit contribution
m_e/T_d correction	$+0.04$
$\mathcal{O}(e^2)$ FTQED correction to the QED EoS	$+0.01$
Non-instantaneous decoupling+spectral distortion	-0.005
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
Flavour oscillations	$+0.0005$
Type (a) FTQED corrections to the weak rates	$\lesssim 10^{-4}$

Non-relativistic correction

- Dominant contribution
- Its size can be estimated from standard textbook entropy conservation arguments.



Bennett, Buldgen, Drewes & Y[3]W 2020

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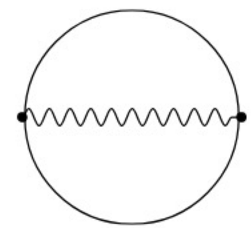
Finite-temperature corrections to the QED equation of state

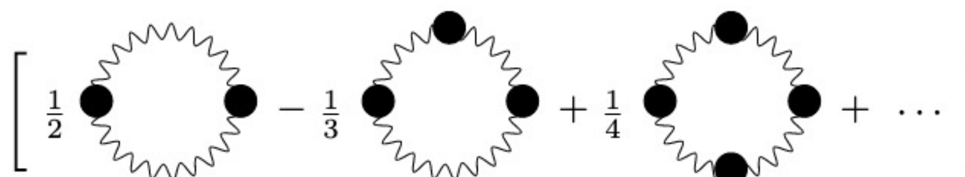
- At $T \geq m_e$, the $\gamma e^+ e^-$ plasma is no longer an ideal gas.
  - Evolution of plasma energy density and pressure modified by FTQED corrections to the partition function.

$\ln Z^{(2)} = -\frac{1}{2}$



$O(e^2)$

$O(e^3)$ $\ln Z^{(3)} = \frac{1}{2}$



e.g., Kapusta textbook

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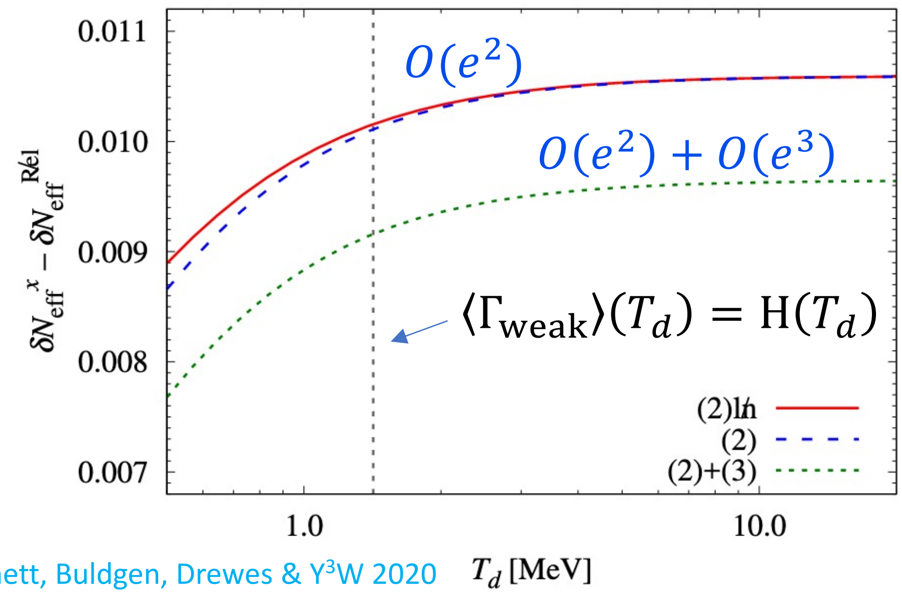

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Non-instantaneous decoupling + neutrino oscillations

- Higher-energy neutrinos stay coupled to the QED plasma for longer.
- Oscillations mix ν_e and $\nu_{\mu,\tau}$ (the latter has no CC coupling to e^+e^-).
- Tracked by the quantum kinetic equations (QKEs): Sigl & Raffelt 1993; McKellar & Thomson 1994

Neutrino density matrix

Weak collisions (non-unitary evolution) from $\nu e \leftrightarrow \nu e$ and $\nu\nu \leftrightarrow \nu\nu$ scattering

$$\frac{\partial \rho}{\partial t} = -i[H,\rho] + I[\rho]$$

Oscillation Hamiltonian incl. matter effects

- Publicly available solver package: `FortEPiaNO` Gariazzo, de Salas & Pastor 2019

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Oscillations not a big effect on N_{eff} when $\nu\nu \leftrightarrow \nu\nu$ scattering is switched on.

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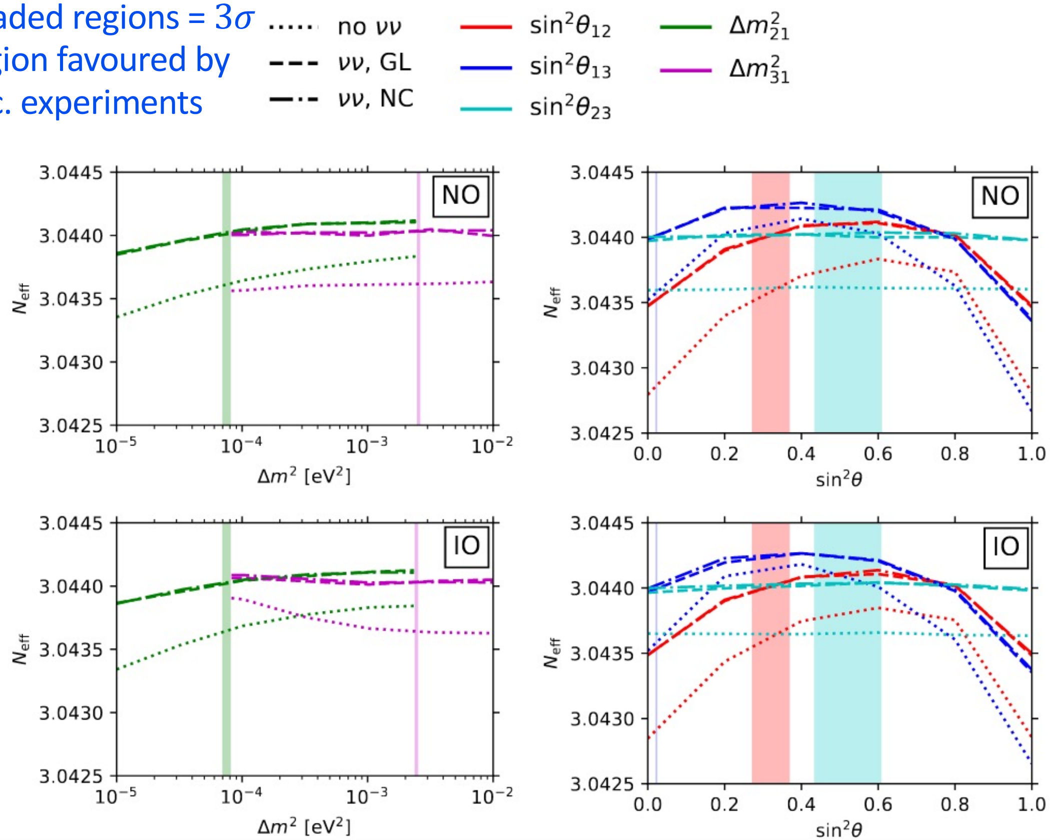
New in 2020/2021 precision calculations

- Publicly available solver package: `FortEPiaNO` Gariazzo, de Salas & Pastor 2019

- However, **uncertainties in the neutrino oscillation parameters** do account for a large chunk of the theoretical uncertainty in $N_{\rm eff}^{\rm SM}$.

Shaded regions = 3σ region favoured by osc. experiments



$$N_{\rm eff}^{\rm SM} = 3.0440 \pm 0.0002$$

- Negligible effects from varying Δm^2_{21} and Δm^2_{31}.
- Of the mixing angles, only $\sin^2\theta_{12}$ leads to an $O(0.0001)$ change in $N_{\rm eff}^{\rm SM}$ within the 3σ exp. allowed region.
- Remaining $O(0.0001)$ = error from numerical solution of QKEs.

Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y[3]W 2020

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Smaller than current uncertainty due to numerical solution of the QKEs.

FTQED corrections to the weak rates

- At $T \geq m_e$, expect in-medium QED corrections to the weak interaction rates.
  - Type (a) = thermal mass electron mass; included in calculation.
  - Type (b) to (d) corrections currently under investigation.