Particle physics-cosmology connections

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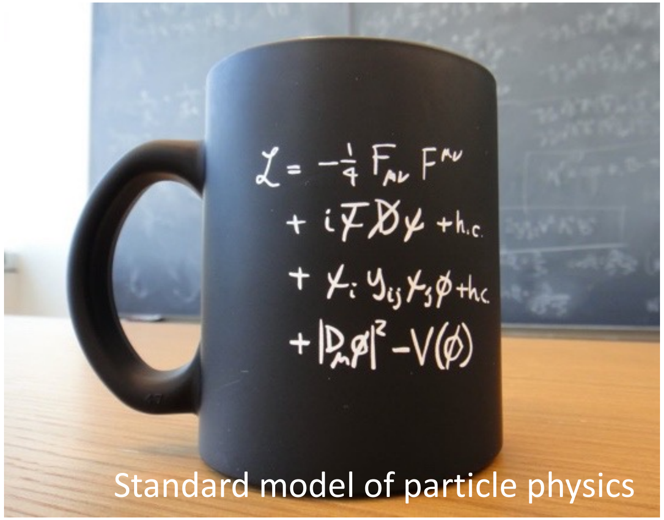
Cosmology from home, July 4 – 15, 2022

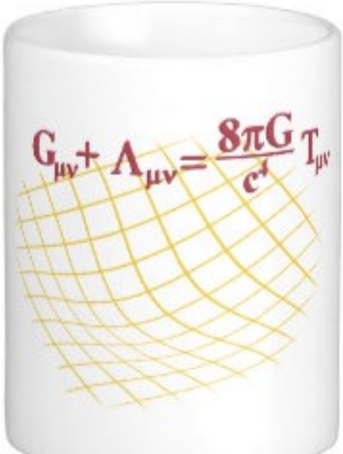
An unlikely partnership?

Particle physics = interactions of fundamental building blocks of nature on the smallest scales

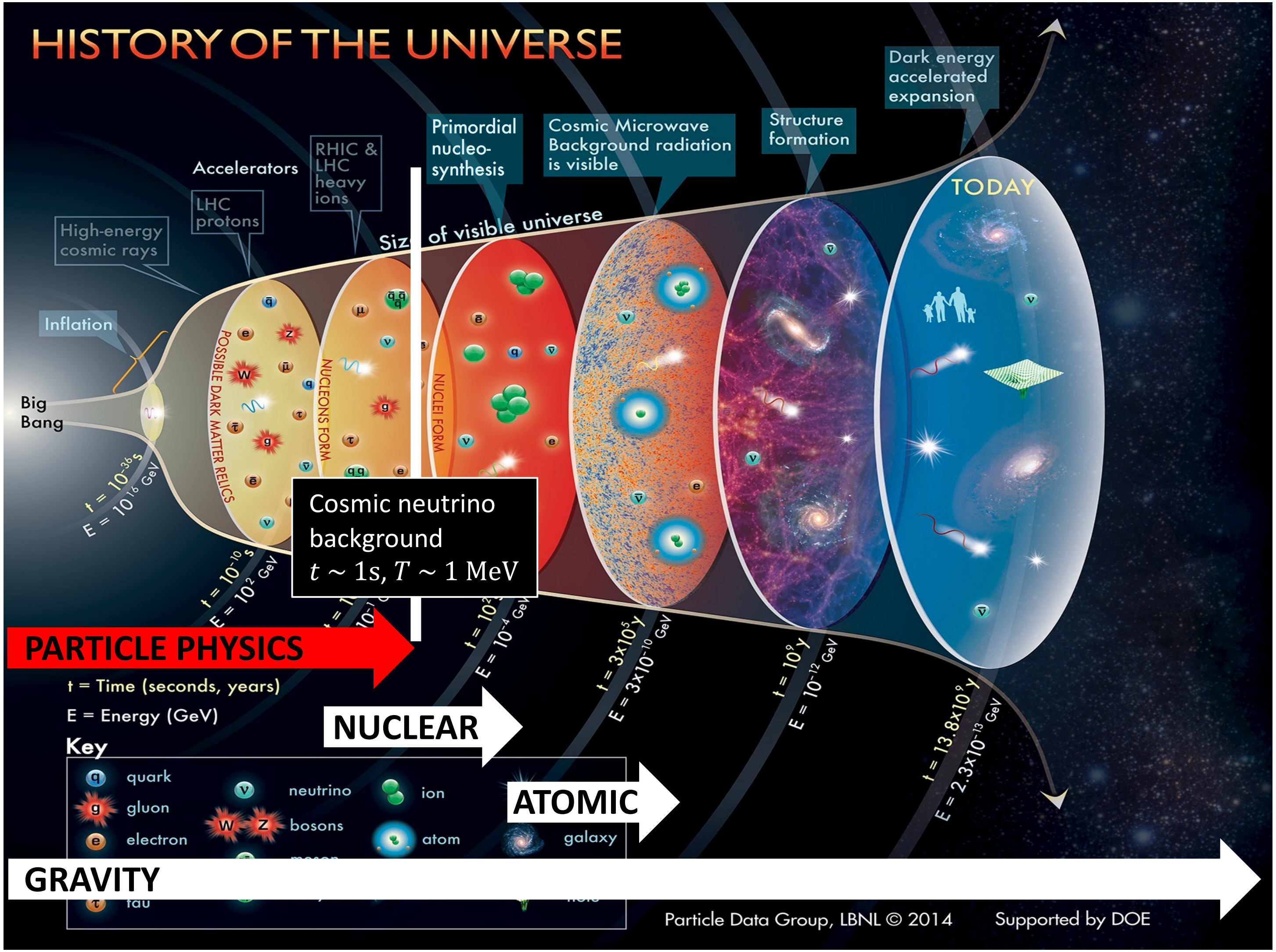
Cosmology = gravitation on the largest observable scales



Standard model of particle physics



General relativity



Cosmic neutrino background
$t \sim 1\text{s}, T \sim 1\text{ MeV}$

PARTICLE PHYSICS

NUCLEAR

ATOMIC

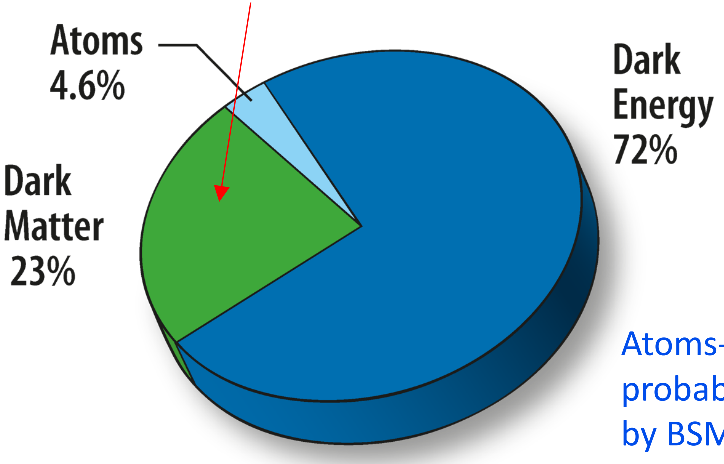
GRAVITY

Concordance ΛCDM…

SM = Standard Model of particle physics
BSM = Beyond the Standard Model

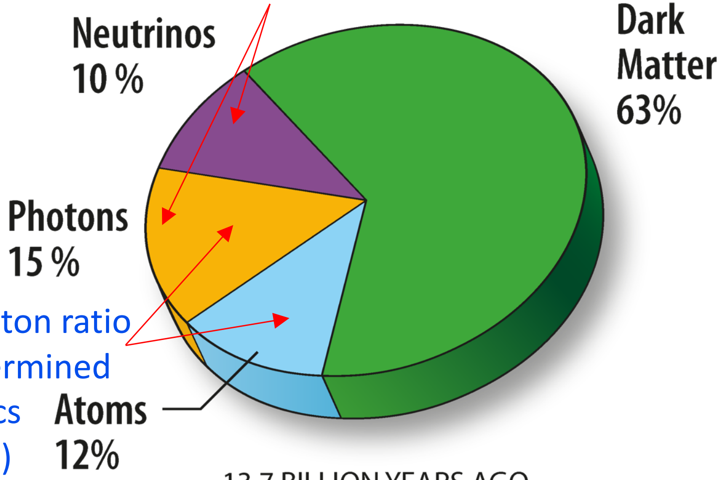
The simplest model consistent with most observations.

DM is probably a BSM particle relic



TODAY

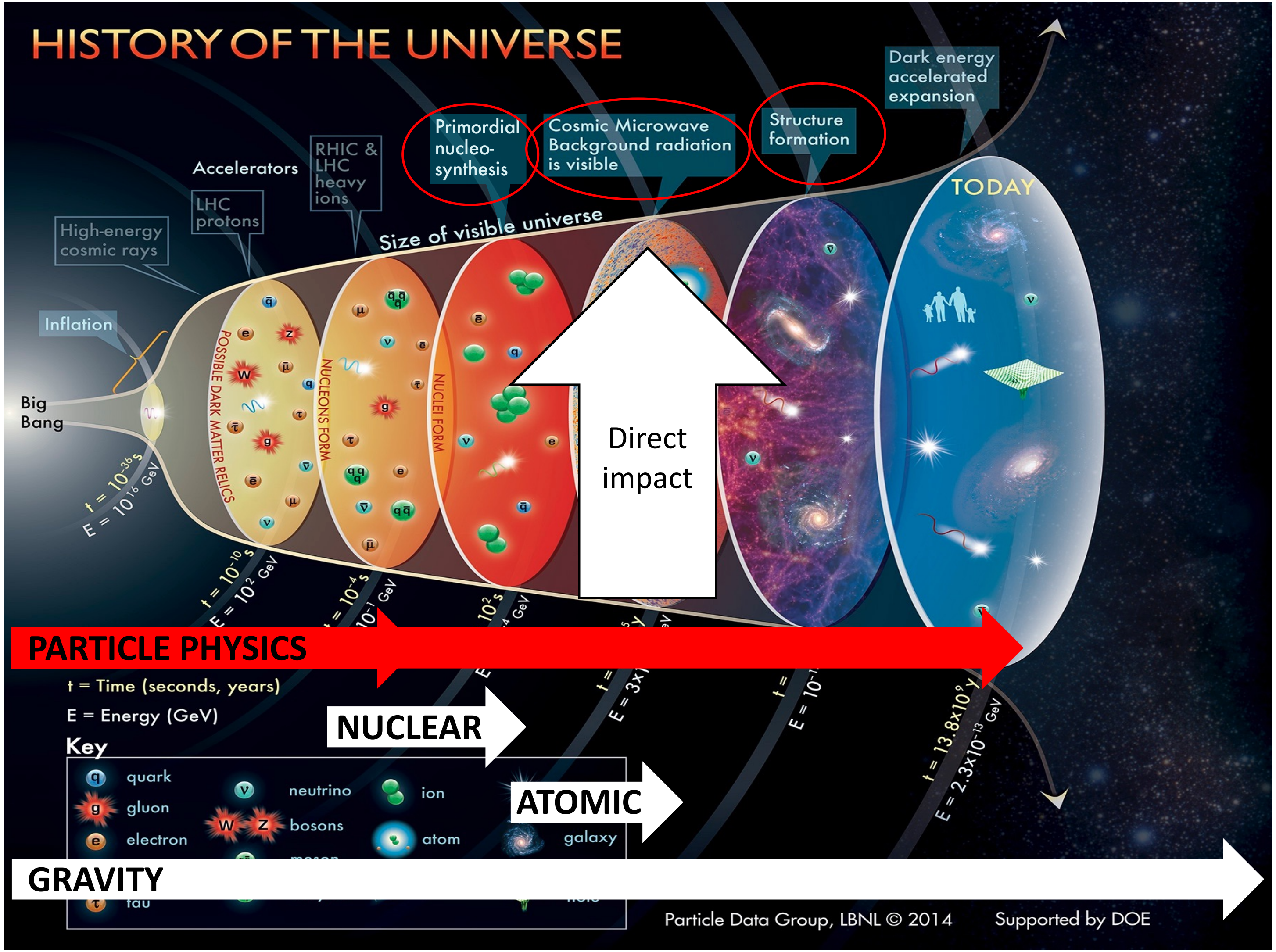
Neutrino-to-photon energy density ratio fixed by SM particle physics



Atoms-to-photon ratio probably determined by BSM physics (baryogenesis)

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

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



Direct impact

PARTICLE PHYSICS

NUCLEAR

ATOMIC

GRAVITY

Plan…

- **Particle physics in the very early universe**
  - Light thermal relics and N_{eff}

- **Particle physics in the not-so-early universe**
  - CMB constraints on the invisible neutrino decay and the neutrino lifetime

There are many more topics under these categories: neutrino-dark matter interaction, dark matter annihilation and decay, neutrino self-interaction, etc.

- I only picked these because I happen to have thought about them lately. But complementarity with terrestrial searches is also a motivating factor.

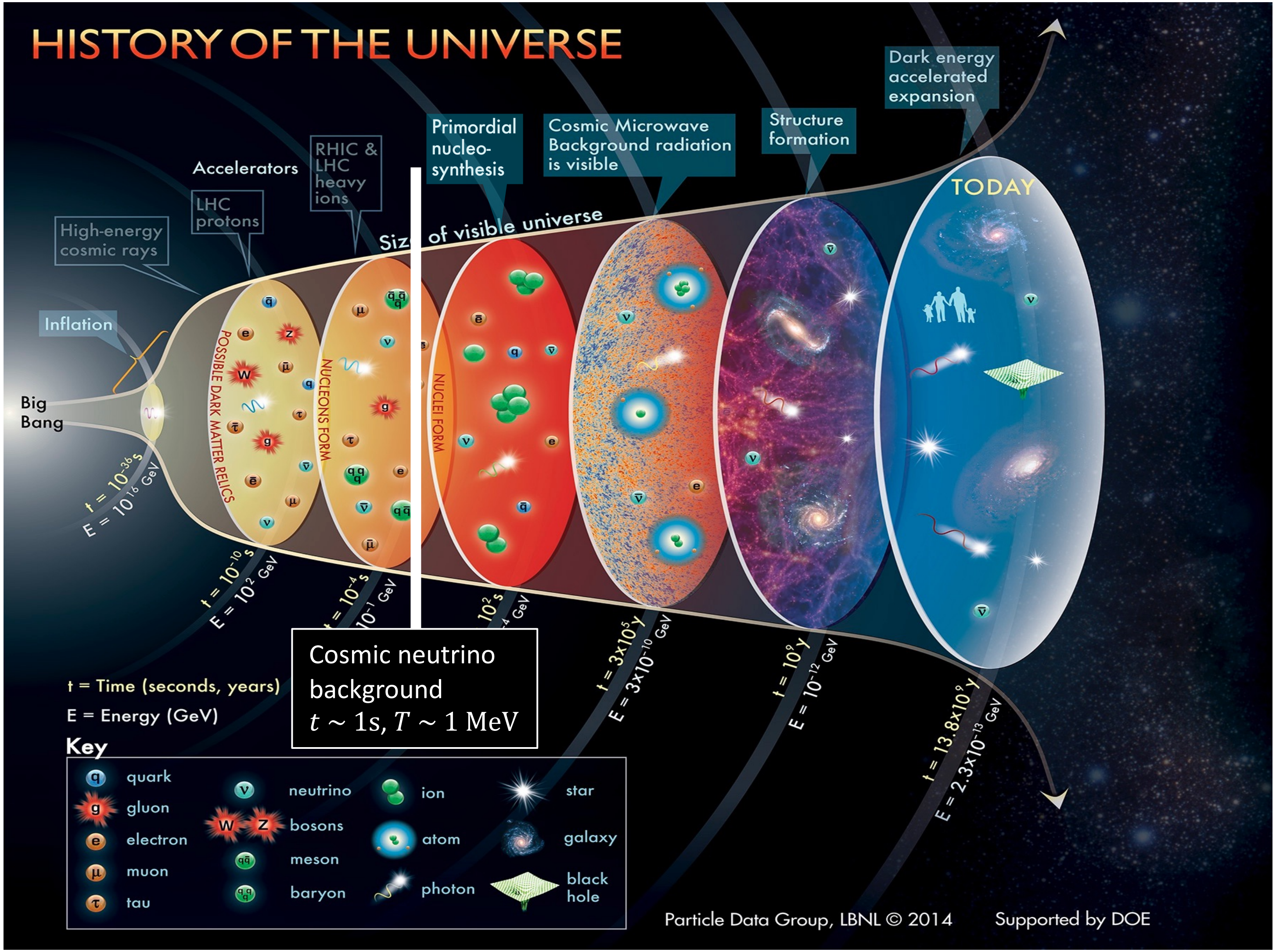
I. Light thermal relics and N_{eff}…

What’s a light thermal relic...

Any light (~sub-eV mass), feebly-interacting particle species produced via number-changing inelastic scattering processes with the Standard Model bath in the early universe.

- **Scattering** = relic inherits temperature of the SM bath (or thereabouts)
- **Feebly-interacting** = production stops at $t \lesssim 1s$, comoving number density freezes
- **Sub-eV masses** = behaves like radiation when production stops, and will not subsequently overclose the universe

The prime Standard Model example of a light thermal relic is the cosmic neutrino background.



Particle Data Group, LBNL © 2014 Supported by DOE

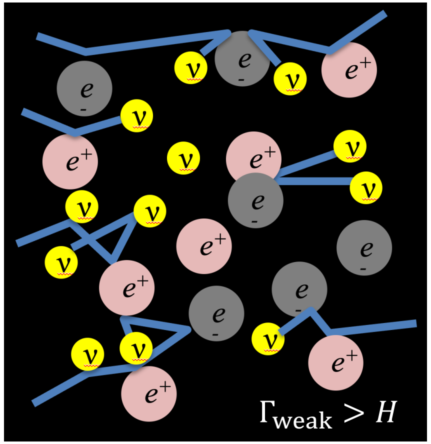
Cosmic neutrino background
$t \sim 1\text{s}, T \sim 1\ \text{MeV}$

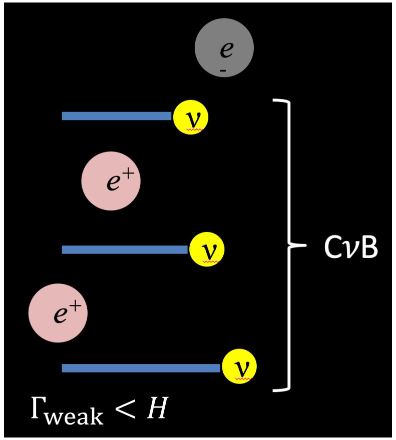
Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

Expansion rate: $H \sim M_{\text{pl}}^{-2} T^2$

Formation of the CνB…

The CνB is formed when neutrinos decouple from the cosmic plasma.



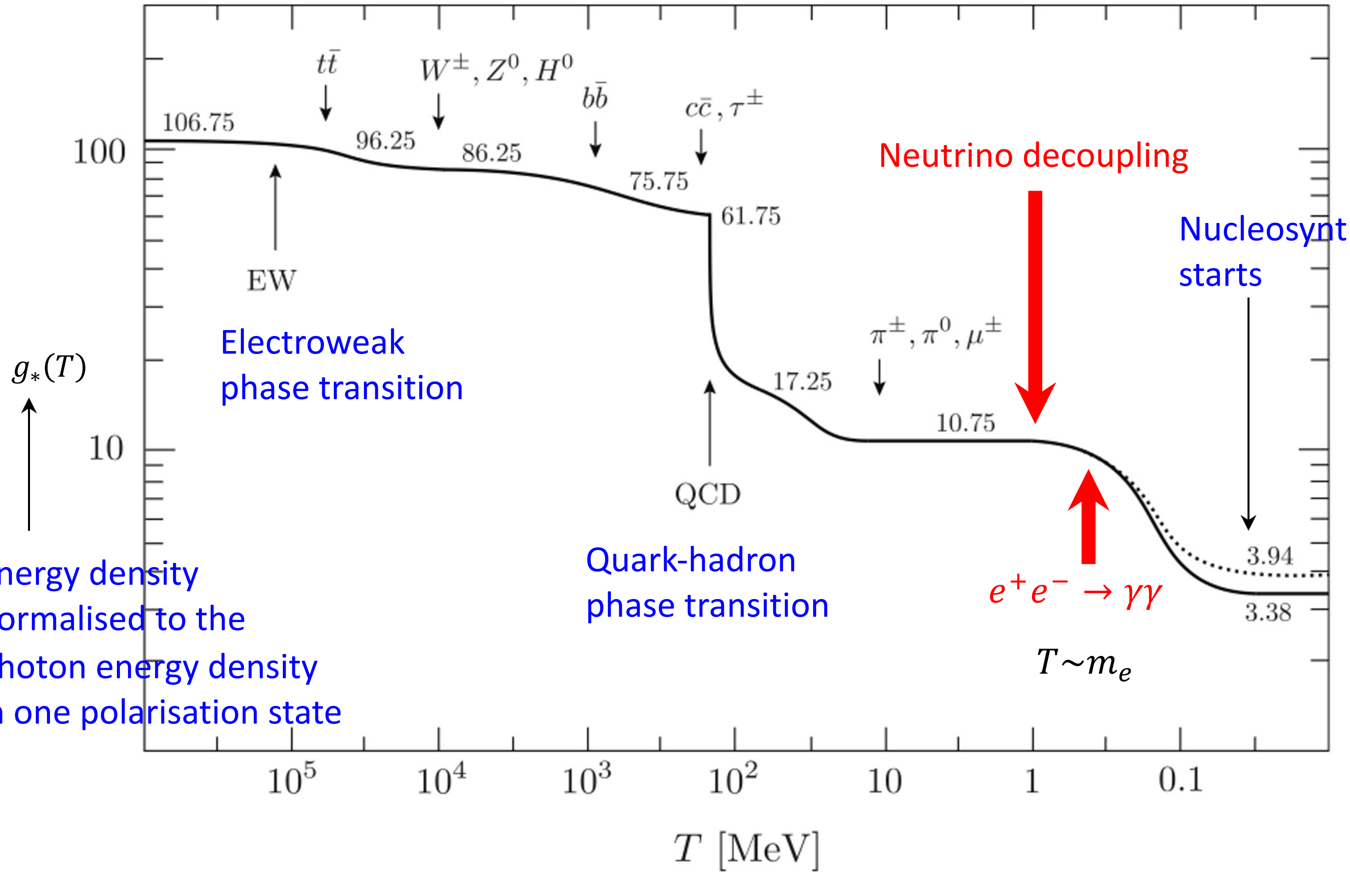


Neutrinos "free-stream" to infinity.

Above $T \sim 1$ MeV, even the Weak Interaction occurs efficiently enough to allow neutrinos to scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium.

Below $T \sim 1$ MeV, expansion dilutes plasma, and reduces interaction rate: the universe becomes transparent to neutrinos.

g_* for the **Standard Model of particle physics:**



Electroweak
phase transition

Quark-hadron
phase transition

Neutrino decoupling

Nucleosynthesis
starts

$e^+e^- \rightarrow \gamma\gamma$

$T \sim m_e$

Energy density
normalised to the
photon energy density
in one polarisation state

What's left?

Mainly
- Photons
- Neutrinos

Small numbers* of
- Electrons
- Nucleons
- Nuclei

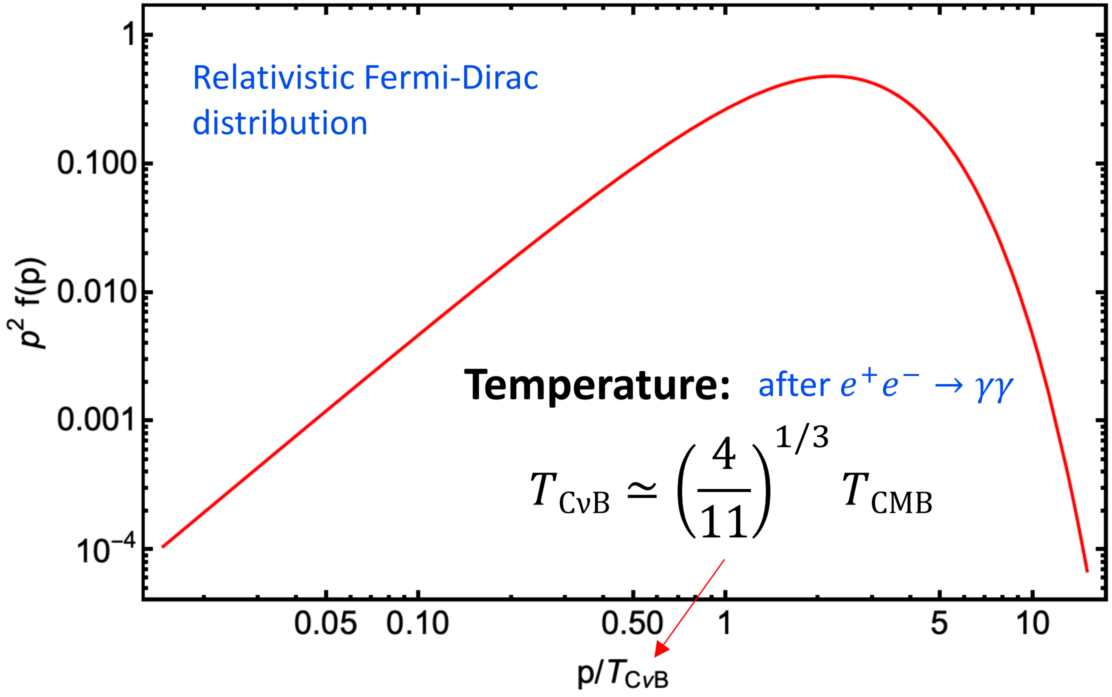
* Small means
$< 10^{-9} n_\gamma$

Photon temperature

Time

The cosmic neutrino background…

Standard model predictions



Relativistic Fermi-Dirac distribution

Temperature: after $e^+e^- \to \gamma\gamma$

$$T_{C\nu B} \simeq \left(\frac{4}{11}\right)^{1/3} T_{CMB}$$

Number density: Per family of neutrinos +antineutrinos

$$n_{C\nu B} \simeq 110\ \mathrm{cm}^{-3}$$

Energy density: Per family

- Relativistic (if $T_{C\nu B} \gg m_\nu$):

$$\rho_{C\nu B} \simeq \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} \rho_{CMB} \simeq 0.227\rho_{CMB}$$

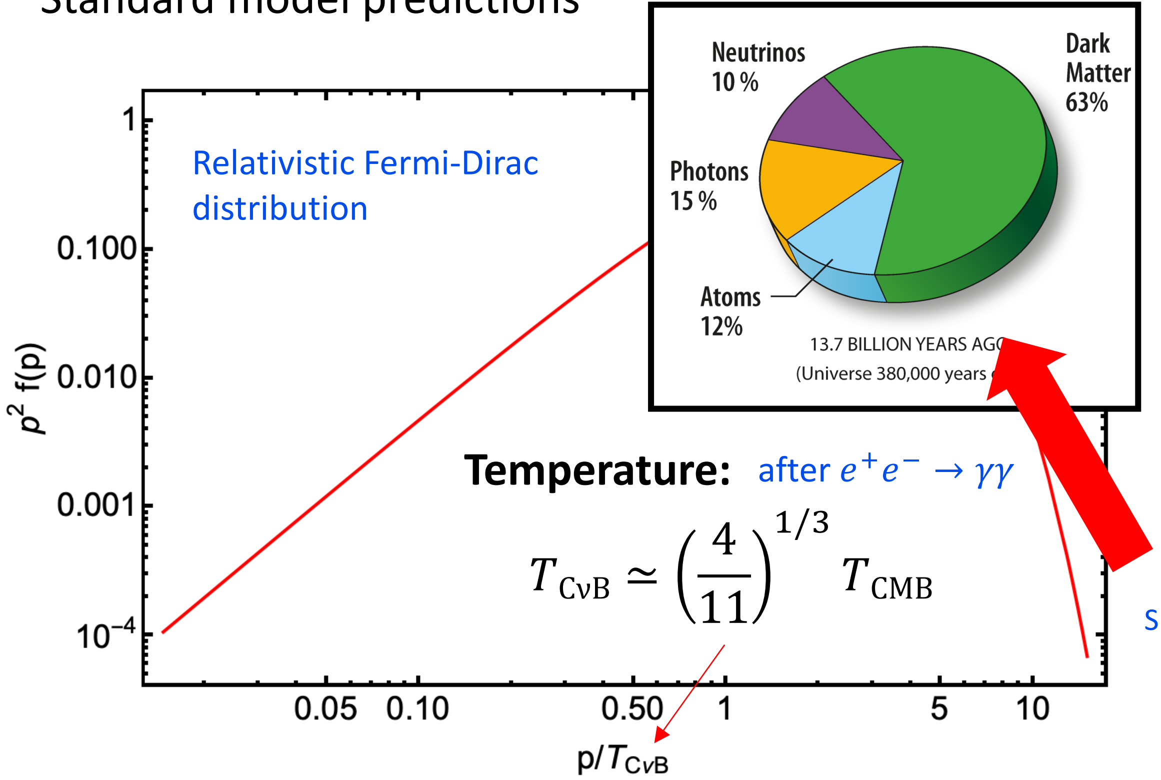
- Non-rel (if $T_{C\nu B} \ll m_\nu$):

$$\Omega_{C\nu B} \simeq \frac{m_\nu}{93\ h^2\ \mathrm{eV}}$$

Neutrino (hot) dark matter;
basis for cosmological neutrino mass bounds

The cosmic neutrino background…

Standard model predictions



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Sum over all SM families:

$$\Rightarrow \sum_{\nu_e,\nu_\mu,\nu_\tau,} \rho_{C\nu B} \simeq 3\times 0.227\ \rho_{\text{CMB}}$$

$$\simeq 0.68\ \rho_{\text{CMB}}$$

Neutrino-to-photon energy density ratio…

In fact, the Standard Model neutrino-to-photon energy density ratio can be calculated very precisely.

- Usually goes under the name of **SM effective number of neutrinos $N_{\mathrm{eff}}^{\mathrm{SM}}$**:

$$\rho_{\mathrm{CMB}} + \sum_{\nu_e,\nu_\mu,\nu_\tau,} \rho_{\mathrm{C\nu B}} = \left[1 + N_{\mathrm{eff}}^{\mathrm{SM}} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right] \rho_{\mathrm{CMB}}$$

$N_{\mathrm{eff}}^{\mathrm{SM}} = 3 +$ percent-level corrections for

- Non-instantaneous neutrino decoupling
- Non-relativistic electron gas across neutrino decoupling
- Finite-temperature QED effects in the photon/electron plasma
- Neutrino flavour oscillations

Energy density in one thermalised species of massless fermions with 2 internal d.o.f. and temperature

$$T = \left(\frac{4}{11}\right)^{1/3} T_{\mathrm{CMB}}$$

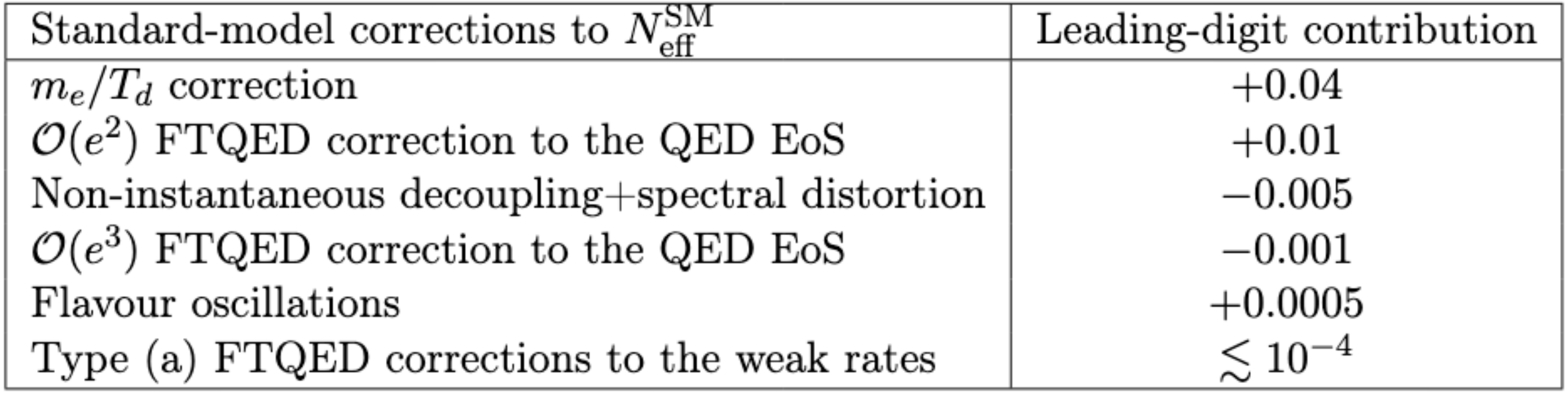
Precision $N_{\text{eff}}^{\text{SM}}$ ...

Bennett, Buldgen, Drewes & Y^{3}W 2020;
Bennett, Buldgen, de Salas, Drewes, Gariazzo, Pastor & Y^{3}W 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} :

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



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	$\lesssim 10^{-4}$

Bennett et al. 2021

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

Bennett, Buldgen, Drewes & Y^3W 2020;
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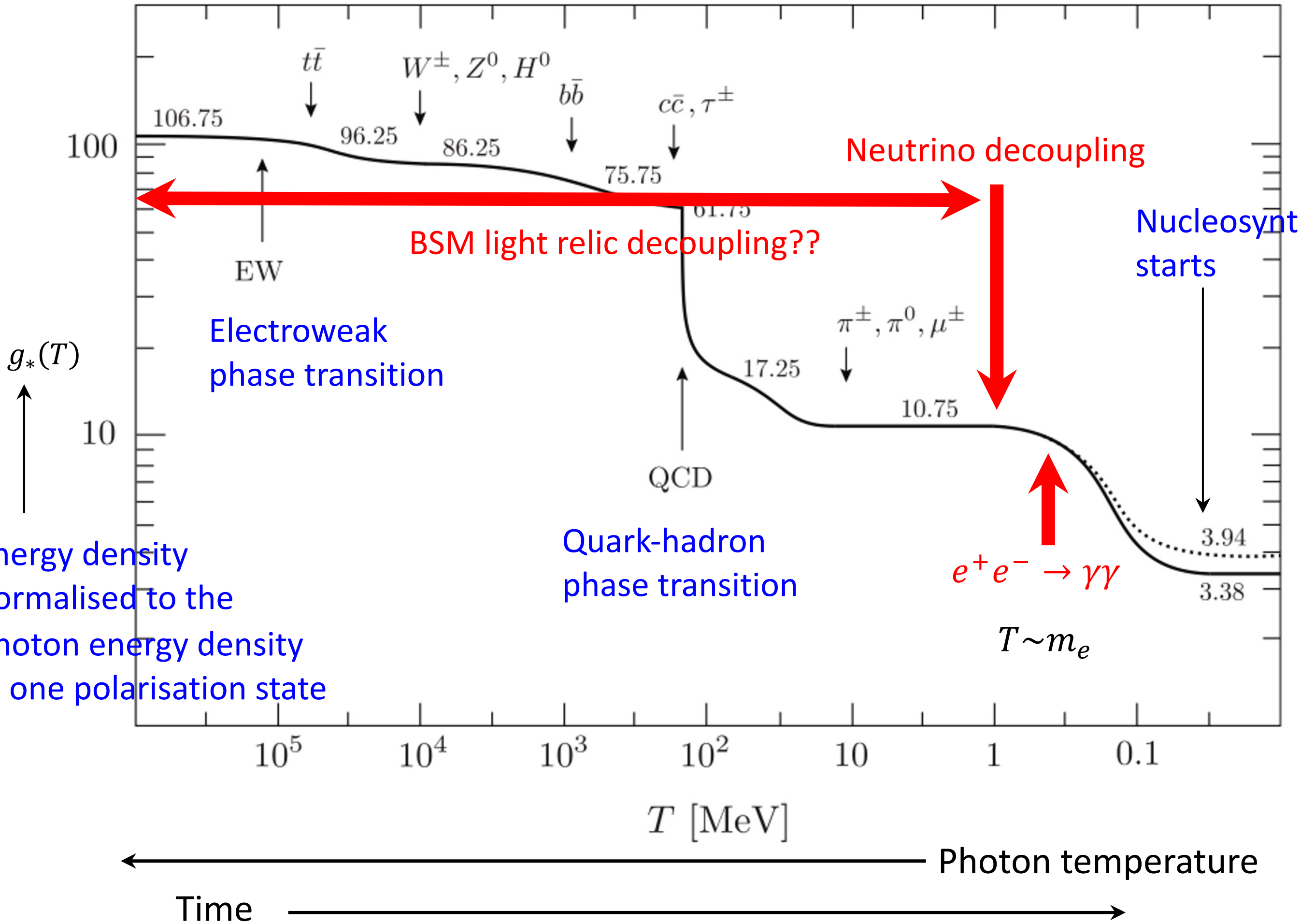
The **most precise to-date** computation of the Standard-Model N_{eff} :

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

- 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:
        - Half due to numerics, half from experimental uncertainty in the solar neutrino mixing angle
- Already implemented in the stock version of `CLASS`

Ia. From SM neutrinos to BSM light relics…

g_* for the **Standard Model of particle physics:**



Neutrino decoupling

BSM light relic decoupling??

Nucleosynthesis starts

Electroweak phase transition

Quark-hadron phase transition

$e^+e^- \to \gamma\gamma$

$T \sim m_e$

Energy density normalised to the photon energy density in one polarisation state

Photon temperature

Time

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Small numbers* of
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* Small means $< 10^{-9} n_\gamma$

Extending N_{eff} to light BSM thermal relics…

Any light (~sub-eV mass), feebly-interacting particle species produced by scattering in the early universe will **look sort of like a neutrino** as far as cosmology is concerned.

- E.g., light sterile neutrinos, thermal axions, …

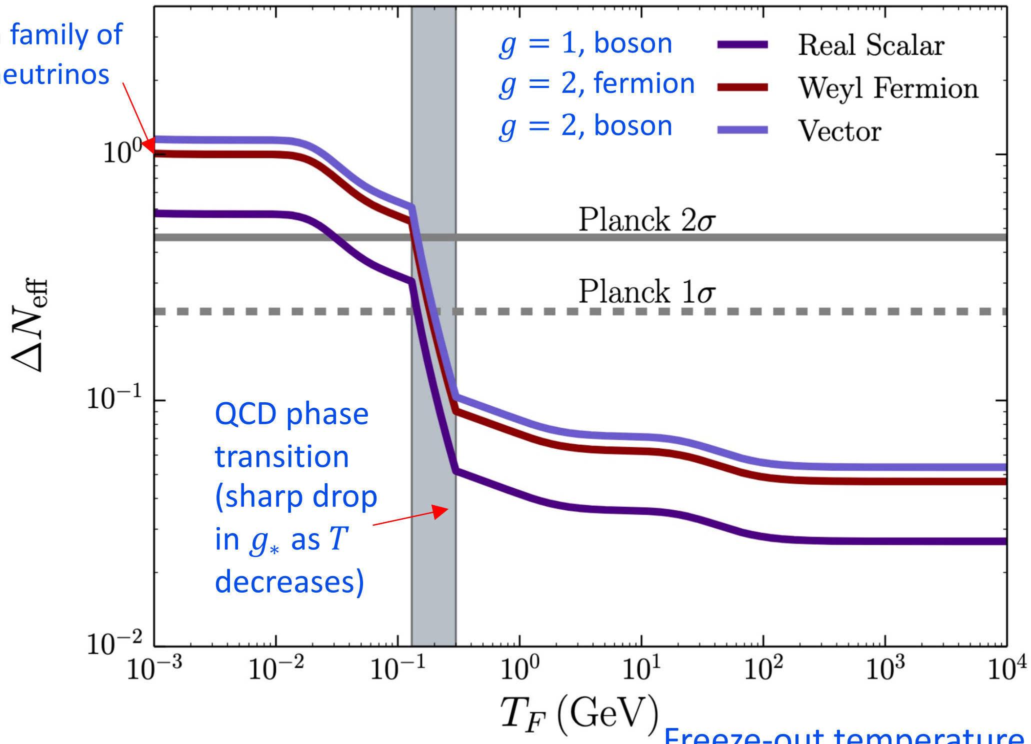
- At leading order, these **light thermal relics** add to the SM neutrino energy density as if $N_{\text{eff}} \gtrsim 3$.

→ Re-interpret N_{eff} as the early-time non-photon radiation content:

$$\rho_{\text{CMB}} + \sum_{\nu_e,\nu_\mu,\nu_\tau,} \rho_{\text{C}\nu\text{B}} + \rho_{\text{other}} = \left[1 + N_{\text{eff}} \times \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right] \rho_{\text{CMB}}$$

$$N_{\text{eff}} = N_{\text{eff}}^{\text{SM}} + \Delta N_{\text{eff}}$$

ΔN_{eff} from generic particle freeze-out…



Extra family of SM neutrinos

QCD phase transition (sharp drop in g_* as T decreases)

Freeze-out temperature

Abazajian et al., CMB-S4 Science book, 2016

New, light particles that freeze-out while ultra-relativistic will contribute:

$$\Delta N_{\text{eff}} = \frac{g}{2}\left(\frac{43/4}{g_*(T_F)}\right)^{4/3}$$ Fermion

Internal d.o.f.

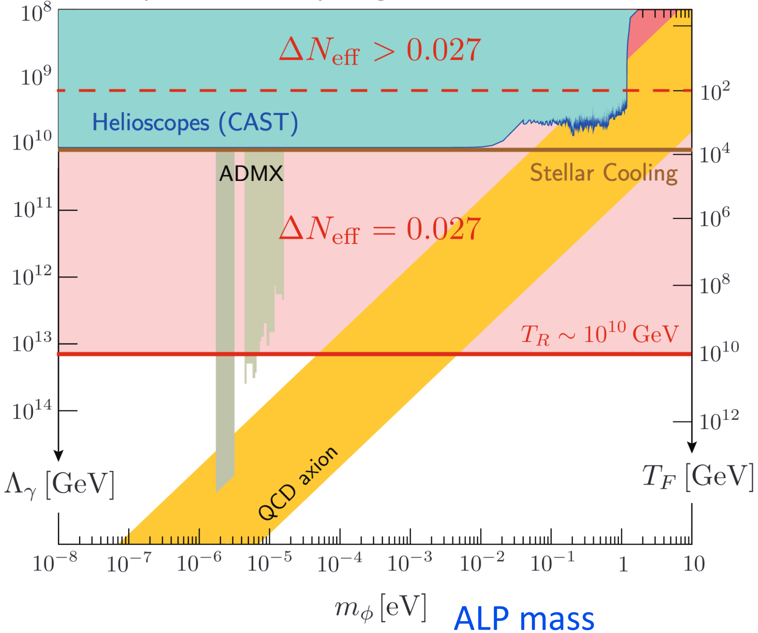
$$\Delta N_{\text{eff}} = \frac{4g}{7}\left(\frac{43/4}{g_*(T_F)}\right)^{4/3}$$ Boson

- Exactly analogous to neutrino decoupling, except for different quantum statistics, g and $g_*(T_F)$.

Some examples of BSM ΔN_{eff}: 1/2

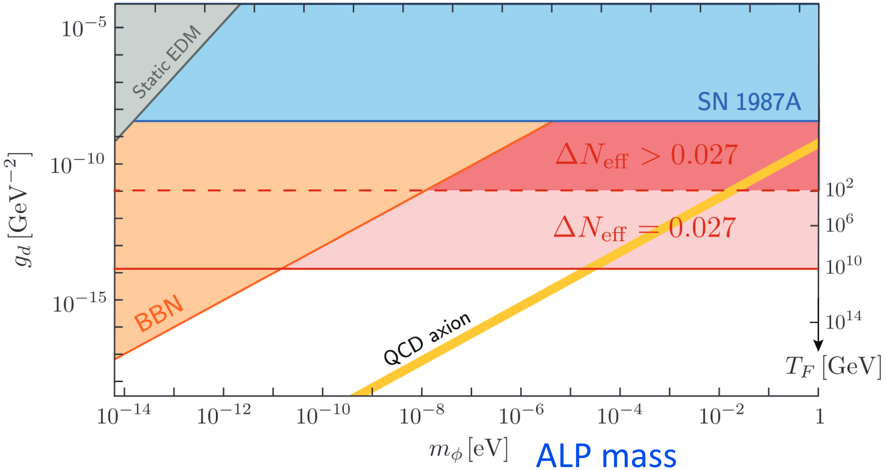
Thermal axion-like particles (ALPs) from freeze-out.

ALP-photon coupling



ALP mass

ALP-gluon



ALP mass

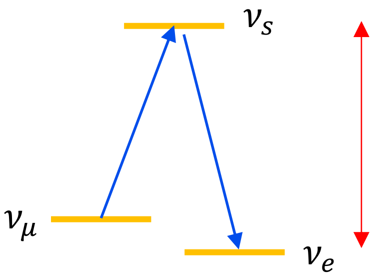
Baumann, Green & Wallisch 2016

Also QCD axions in Giarè et al, 2022;
D’Eramo et al. 2021, 2022; etc.

Some examples of BSM ΔN_{eff}… 2/2

Light sterile neutrinos: solution to the short-baseline anomalies in neutrino oscillation experiments (LSND, MiniBooNE and reactor).

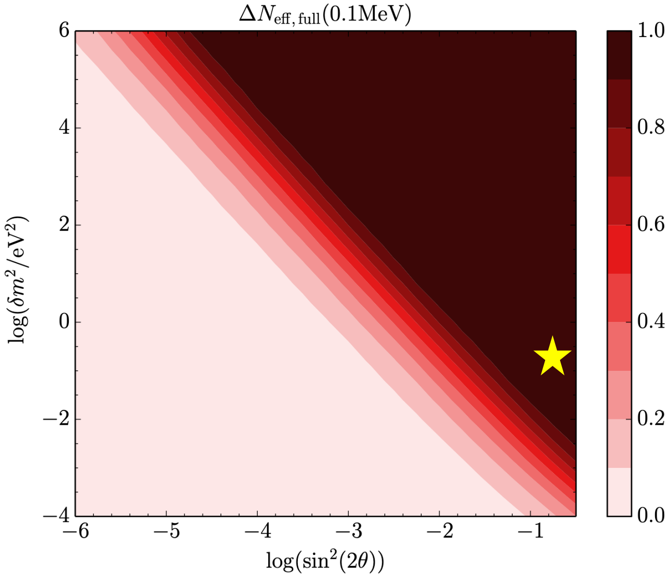
- Solution requires effective oscillation parameters:



$$\delta m^2 \sim 1\ \mathrm{eV}^2$$

$$\sin^2 2\theta_{es} \sim \sin^2 2\theta_{s\mu} \sim 0.1$$

→ $\Delta N_{\mathrm{eff}} \sim 1$ looks inevitable…

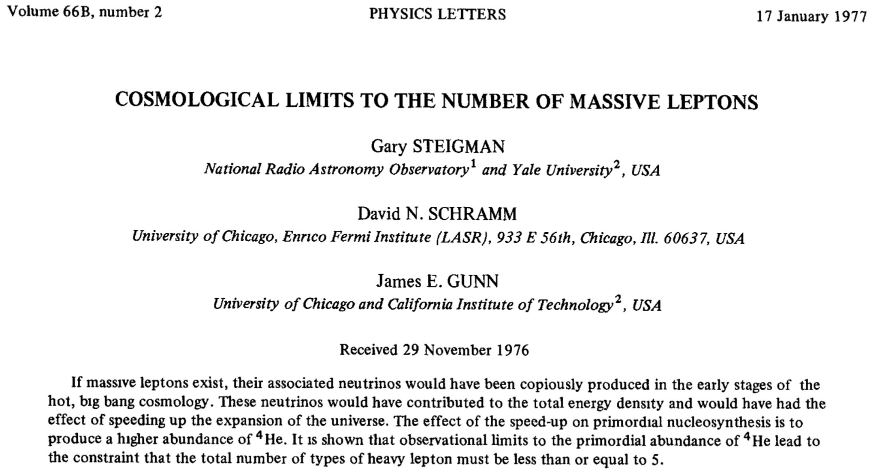


Hannestad, Hansen, Tram & Wong 2015
Also Gariazzo, de Salas & Pastor 2019; Hagstotz et al. 2020; Hannestad, Hansen & Tram 2013; etc.

- Parameter space will be further tested by the Fermilab Short Baseline Neutrino program.

Nucleosynthesis & N_{eff}…

Constraining N_{eff} with the primordial elemental abundances has a long history.



Volume 66B, number 2 PHYSICS LETTERS 17 January 1977

COSMOLOGICAL LIMITS TO THE NUMBER OF MASSIVE LEPTONS

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National Radio Astronomy Observatory[1] *and Yale University*[2], *USA*

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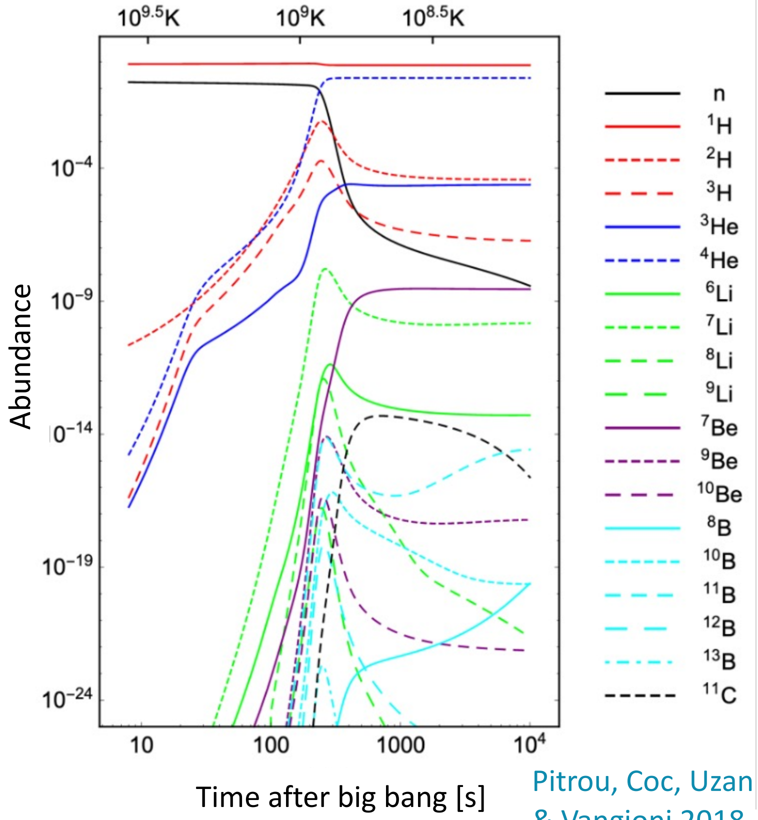
James E. GUNN
University of Chicago and California Institute of Technology[2], *USA*

Received 29 November 1976

If massive leptons exist, their associated neutrinos would have been copiously produced in the early stages of the hot, big bang cosmology. These neutrinos would have contributed to the total energy density and would have had the effect of speeding up the expansion of the universe. The effect of the speed-up on primordial nucleosynthesis is to produce a higher abundance of ^{4}He. It is shown that observational limits to the primordial abundance of ^{4}He lead to the constraint that the total number of types of heavy lepton must be less than or equal to 5.

$$\boxed{N_{\text{eff}} < 5}$$



Pitrou, Coc, Uzan & Vangioni 2018

How much of these elements is produced depends on how fast the universe expands.

Nucleosynthesis & N_{eff}…

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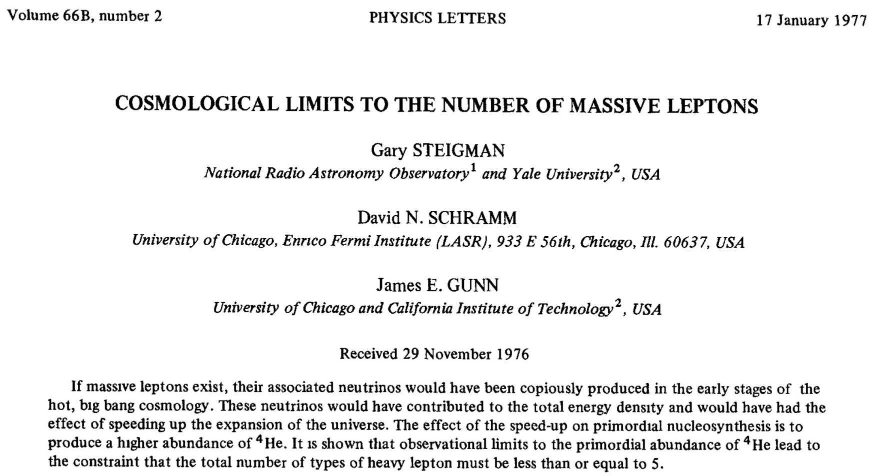

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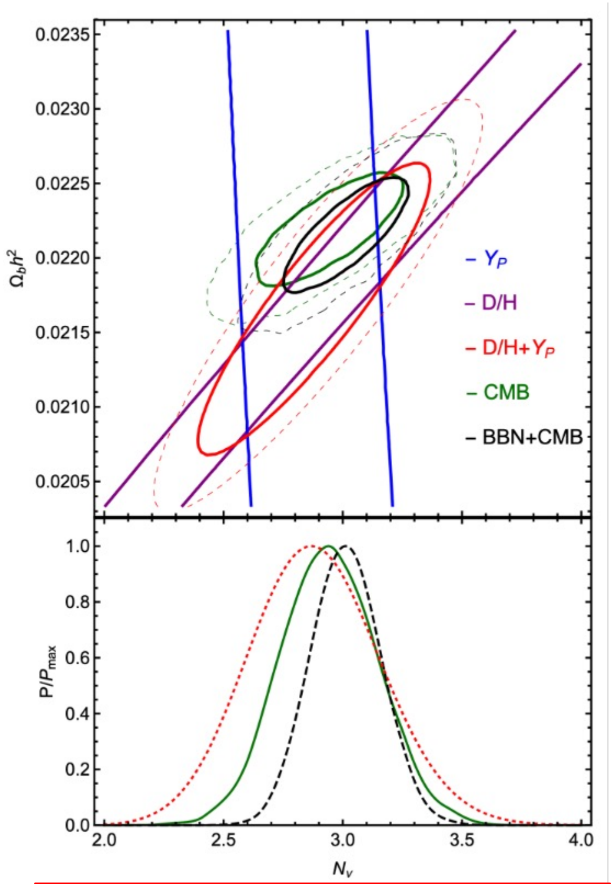


$$\boxed{N_{\text{eff}} = 2.88 \pm 0.27 \ (68\% \ \text{CL})}$$

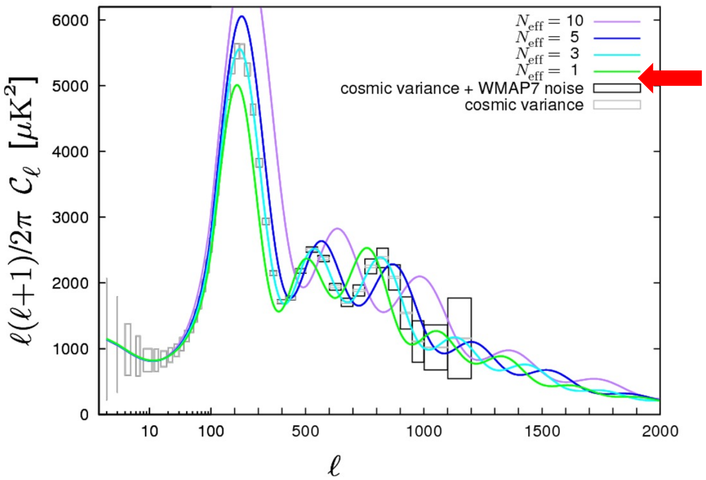
Pitrou, Coc, Uzan & Vangioni 2018

CMB anisotropies & $N_{\rm eff}$...

Hou, Keisler, Knox, Millea & Reichardt 2013

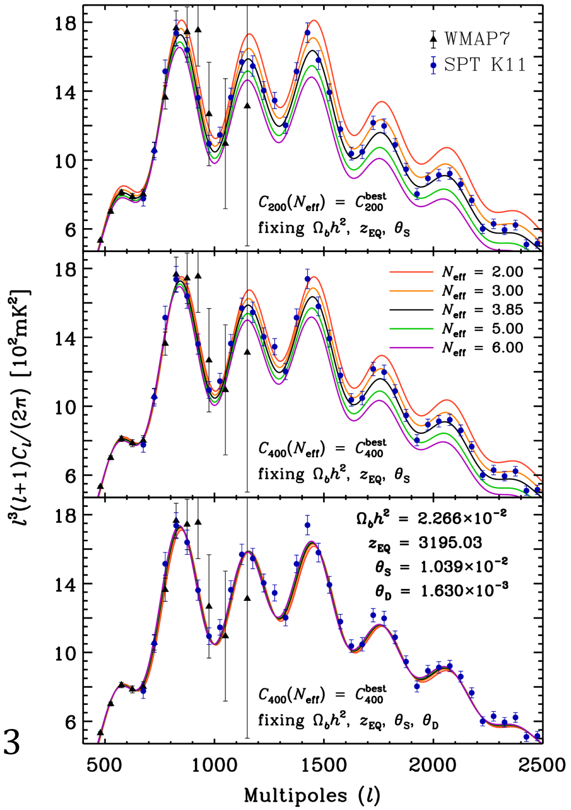
$N_{\rm eff}$ also affects the expansion rate at recombination.

- Observable in the CMB temperature power spectrum



"Naïve" signature

"Irreducible" signature is in the CMB damping tail



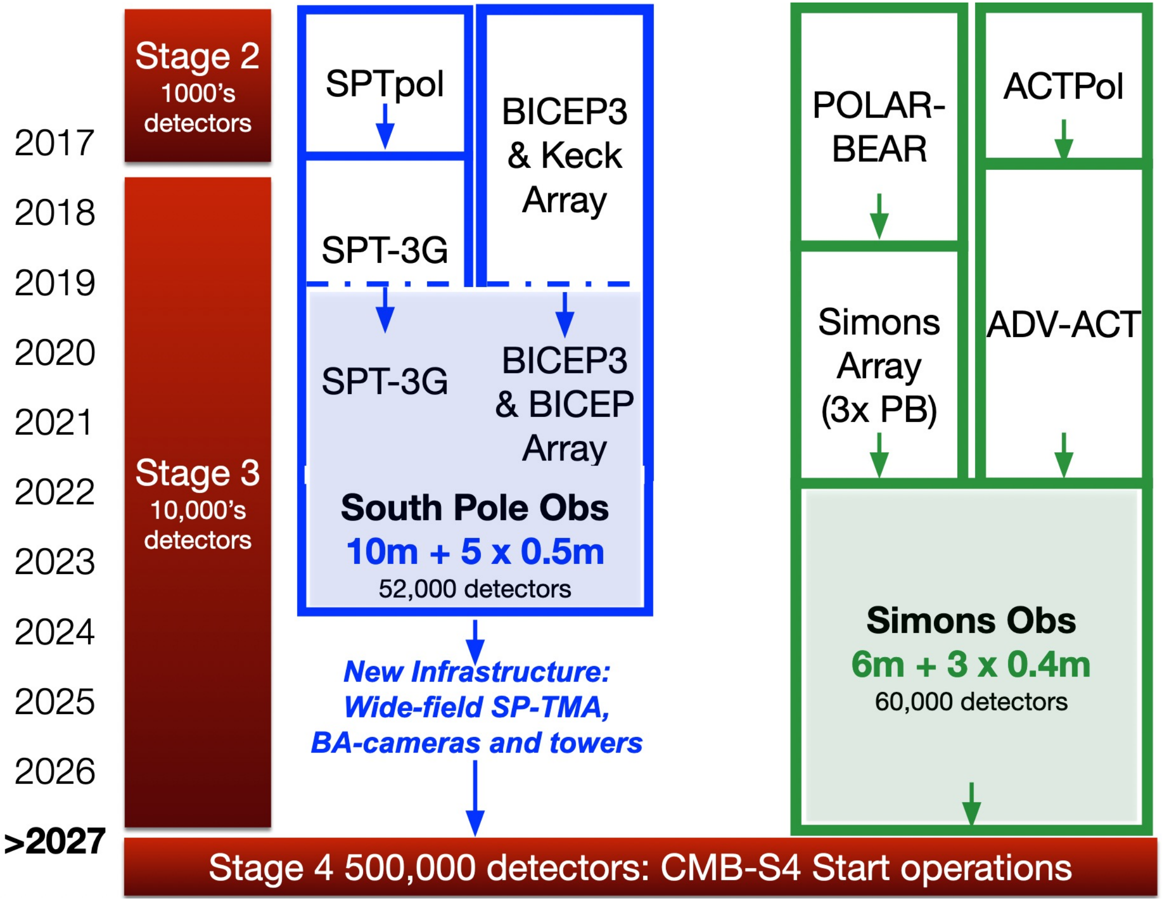
Planck TTTEEE +lowE+lensing+BAO; 7-parameters

$$\boxed{N_{\rm eff} = 2.99 \pm 0.34\ (95\%\ \rm CL)}$$

Aghanim et al. [Planck] 2021

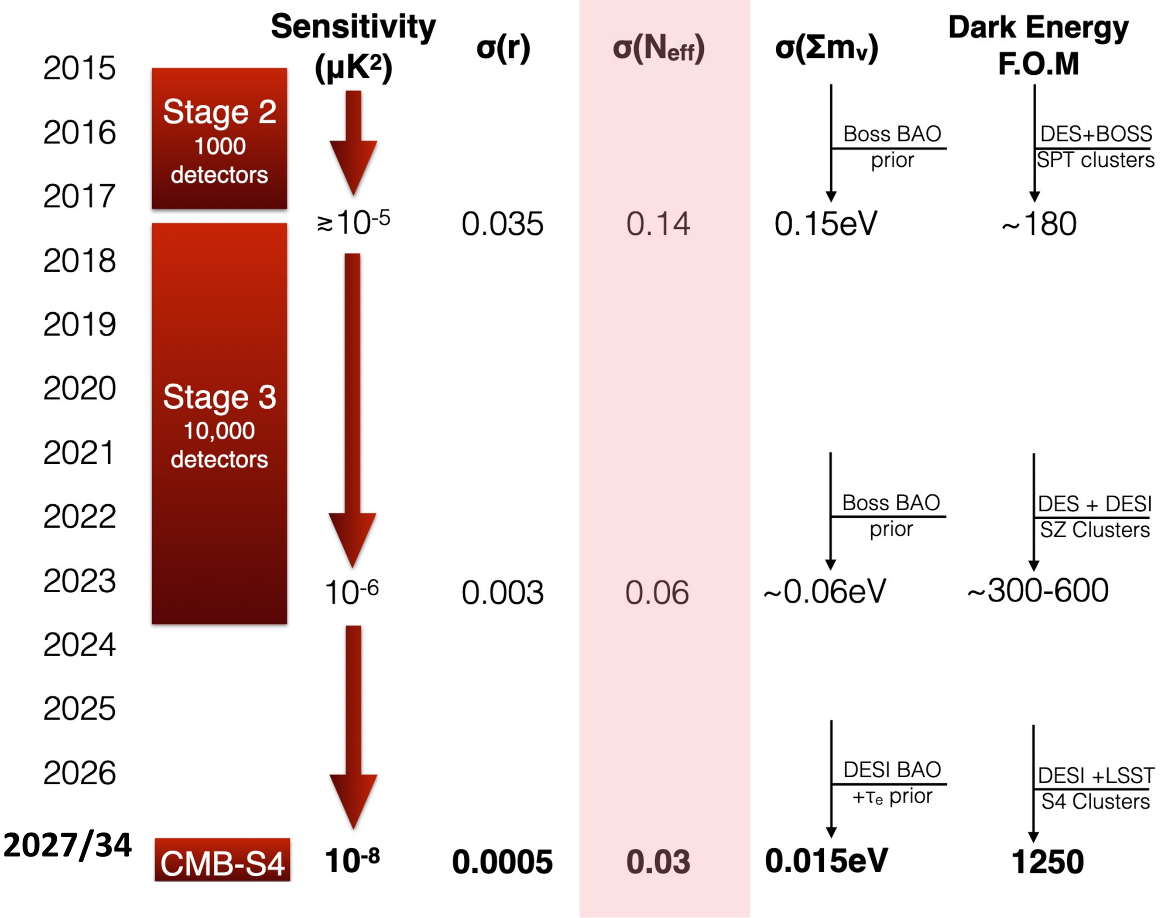
Remarkably consistent with Standard Model prediction $N_{\rm eff} \approx 3$

What to expect in the future?



John Carlstrom

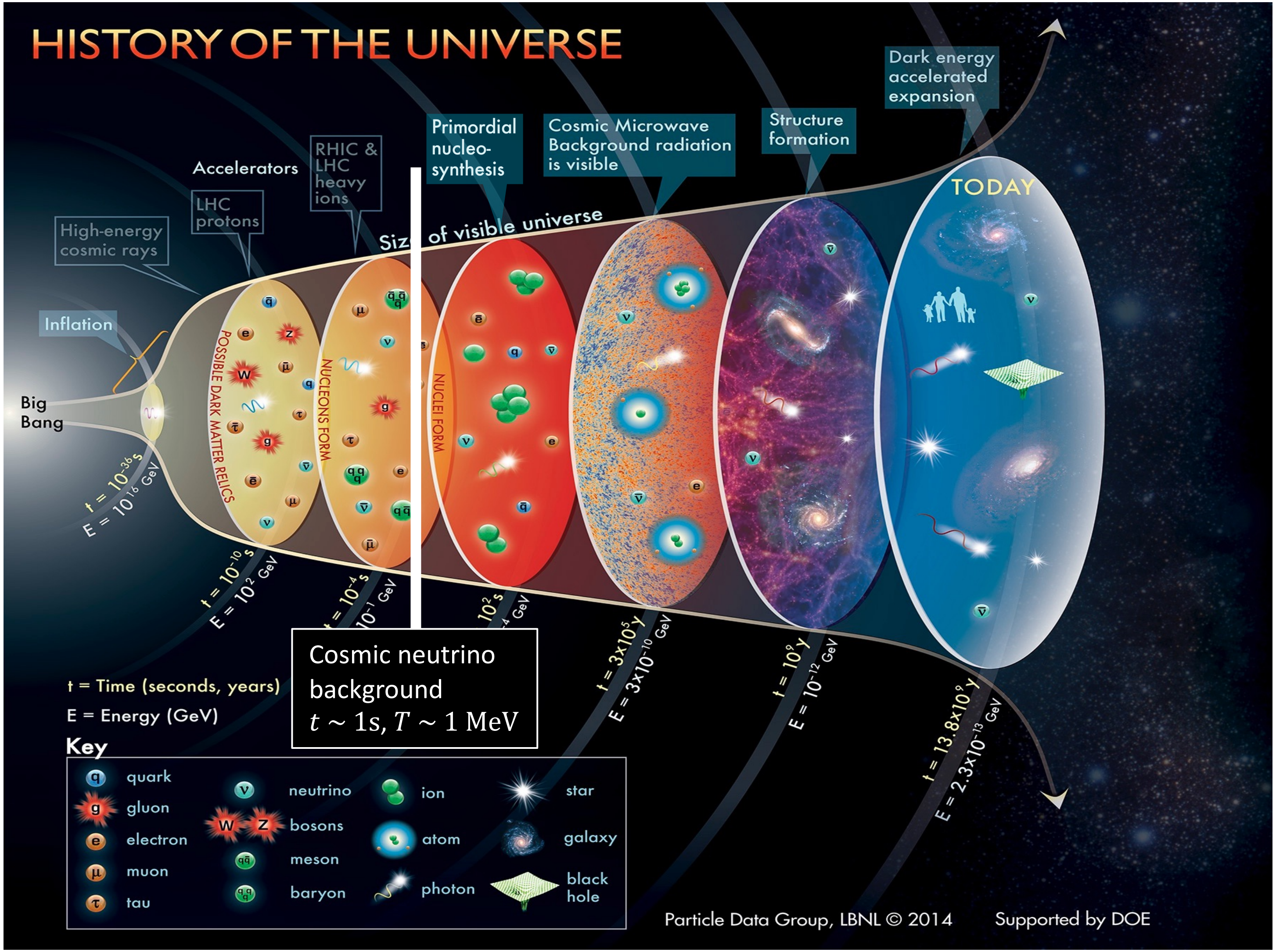
What to expect in the future?



		Sensitivity (μK^2)	$\sigma(r)$	$\sigma(N_{eff})$	$\sigma(\Sigma m_\nu)$	Dark Energy F.O.M
2015 2016 2017	Stage 2 1000 detectors	$\gtrsim 10^{-5}$	0.035	0.14	Boss BAO prior 0.15eV	DES+BOSS SPT clusters ~180
2018 2019 2020 2021 2022 2023	Stage 3 10,000 detectors	10^{-6}	0.003	0.06	Boss BAO prior ~0.06eV	DES + DESI SZ Clusters ~300-600
2024 2025 2026						
2027/34	CMB-S4	**10^{-8}**	**0.0005**	**0.03**	DESI BAO +τ_e prior **0.015eV**	DESI +LSST S4 Clusters **1250**

John Carlstrom

II. CMB constraints on invisible neutrino decay and the neutrino lifetime…



Cosmic neutrino background
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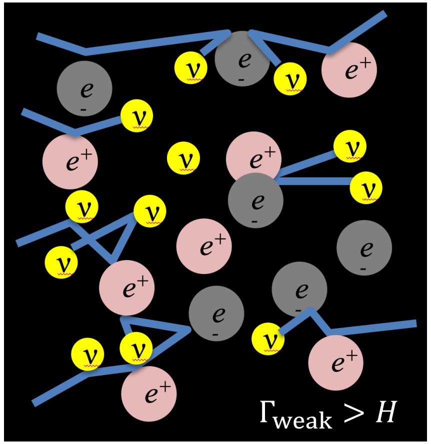
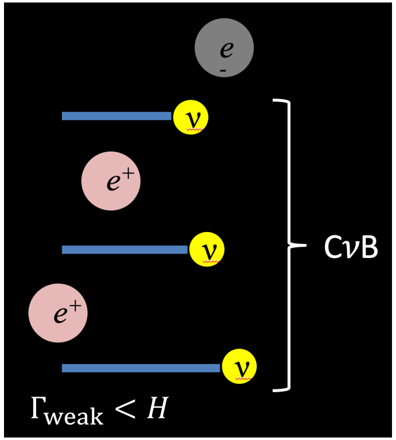
Formation of the CνB…

Interaction rate: $\Gamma_{\text{weak}} \sim G_F^2 T^5$

Expansion rate: $H \sim M_{\text{pl}}^{-2} T^2$

The CνB is formed when neutrinos decouple from the cosmic plasma.





Neutrinos "free-stream" to infinity.

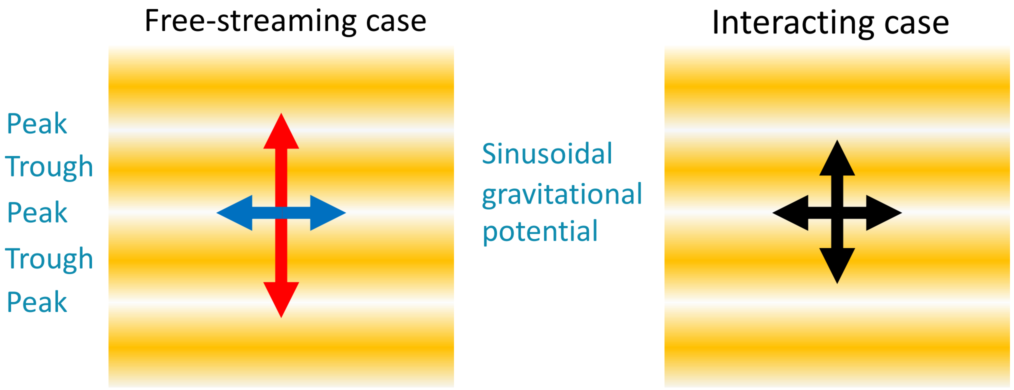
Above $T \sim 1\ \mathrm{MeV}$, even the Weak Interaction occurs efficiently enough to allow neutrinos to scatter off e^+e^- and other neutrinos, and attain thermodynamic equilibrium.

Below $T \sim 1\ \mathrm{MeV}$, expansion dilutes plasma, and reduces interaction rate: the universe becomes transparent to neutrinos.

Neutrino free-streaming…

Standard Model neutrinos free-stream.

- Free-streaming in a spatially inhomogeneous background induces shear stress (or momentum anisotropy).
- Conversely, interactions transfer momentum and, if sufficiently efficient, can wipe to out shear stress.



Free-streaming case

Interacting case

Peak

Trough

Peak

Trough

Peak

Sinusoidal gravitational potential

Scattering transfers momentum and wipes out shear

Neutrino free-streaming & the metric…

Neutrino shear stress (or lack thereof) leaves distinct imprints on the spacetime metric perturbations.

Scale factor

Conformal Newtonian gauge

$$\mathrm{d}s^2 = a^2(\tau)[-(1+2\psi)\mathrm{d}\tau^2 + (1-2\phi)\mathrm{d}x^i\mathrm{d}x_i]$$

where $$k^2(\phi - \psi) = 12\pi G a^2(\bar{\rho} + \bar{P})\sigma$$

Mean energy density & pressure

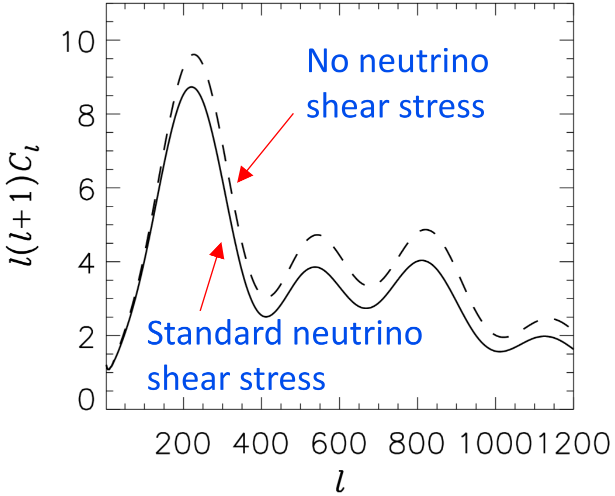
Shear stress

In ΛCDM, mainly from ultra-relativistic neutrinos and photons.

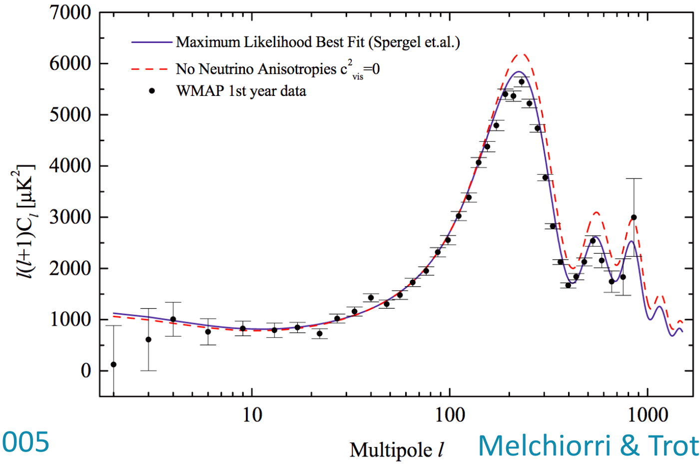
- Changes to $(\phi - \psi)$ affect the evolution of CMB perturbations and are observable in the **CMB TT power spectrum**.
- Good probe of neutrino interactions around CMB formation times $(t \sim 400\ \mathrm{kyr})$ when the CνB still constitutes a substantial fraction of the relativistic energy density.

Neutrino free-streaming & the CMB…

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



Hannestad 2005



Melchiorri & Trotta 2005

- The trickly part is, how do you translate this preference to constraints on the fundamental parameters of a non-standard neutrino interaction?

→ What is the isotropisation timescale given an interaction?

Isotropisation timescale…

Given an interaction Lagrangian, the isotropisation timescale is calculable.

- Write down the Boltzmann equation:

$$P^\mu \frac{\partial f_i}{\partial x^\mu} - \Gamma^\nu_{\rho\sigma} P^\rho P^\sigma \frac{\partial f_i}{\partial P^\nu} = \frac{1}{2} \left(\prod_j^N \int g_j \frac{\mathrm{d}^3\mathbf{n}_j}{(2\pi)^3 2E_j(\mathbf{n}_j)} \right) \left(\prod_k^M \int g_k \frac{\mathrm{d}^3\mathbf{n}_k}{(2\pi)^3 2E_k(\mathbf{n}_k)} \right)$$

$$\times\, (2\pi)^4\, \delta_D^{(4)} \left(p + \sum_j^N n_j - \sum_k^M n'_k \right) \, |\mathcal{M}_{i+j_1+\cdots+j_N \leftrightarrow k_1+\cdots+k_M}|^2$$

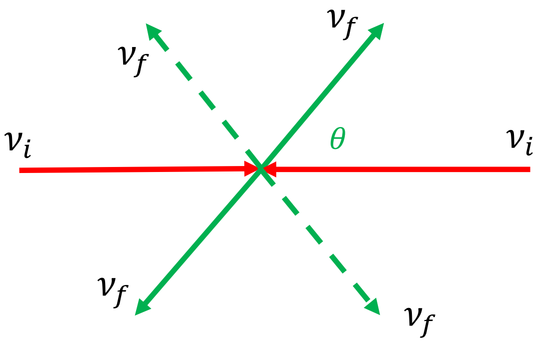
$$\times\, [f_{k_1} \cdots f_{k_N} (1 \pm f_i)(1 \pm f_{j_1}) \cdots (1 \pm f_{j_N}) - f_i f_{j_1} \cdots f_{j_N} (1 \pm f_{k_1}) \cdots (1 \pm f_{k_M})]$$

- Decompose in a Legendre series
- The damping rate of the quadrupole ($\ell = 2$) moment is the **isotropisation rate**.

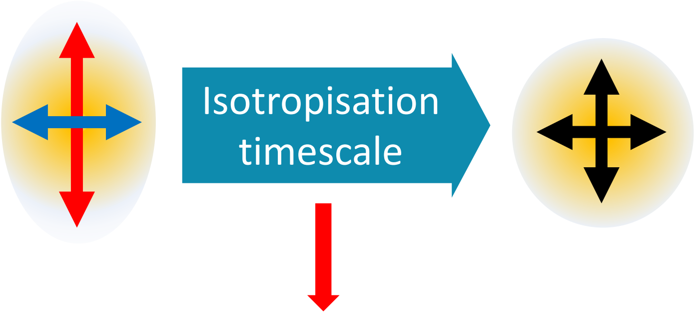
Tedious stuff, but this is really the only correct way to calculate these things, else you can get it very wrong…
However, the result can usually be understood in simple terms. → **Next slide**

Isotropisation from self-interaction…

Consider a 2-to-2 scattering event $\nu_i + \nu_i \rightarrow \nu_f + \nu_f$.



→ Particles in two head-on ν_i beams need only scatter once to transfer their momenta equally in all directions.



$$T_{\text{isotropise}} \sim 1/\Gamma_{\text{scattering}}$$

Scattering rate

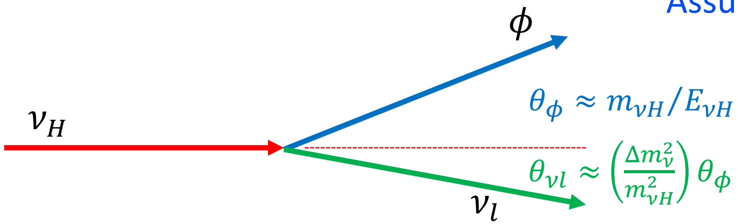
- The probability of ν_f emitted at any angle θ is the same for all $\theta \in [0, \pi]$.

Cyr-Racine & Sigurdson 2014; Oldengott, Rampf & Y^{3}W 2015;
Lancaster, Cyr-Racine, Knox & Pan 2017; Oldengott, Tram, Rampf & Y^{3}W 2017;
Kreisch, Cyr-Racine & Dore 2019; Forastieri et al. 2019; etc.

Isotropisation from relativistic (inverse) decay…

How long does it take $\nu_H \to \nu_l + \phi$ and its inverse process to wipe out momentum anisotropies? (Hint: it's not the rest-frame lifetime of ν_H.)

- In relativistic decay, the decay products are **beamed**.



Assuming a massless ϕ

$\theta_\phi \approx m_{\nu H}/E_{\nu H}$

$\theta_{\nu l} \approx \left(\frac{\Delta m_\nu^2}{m_{\nu H}^2}\right)\theta_\phi$

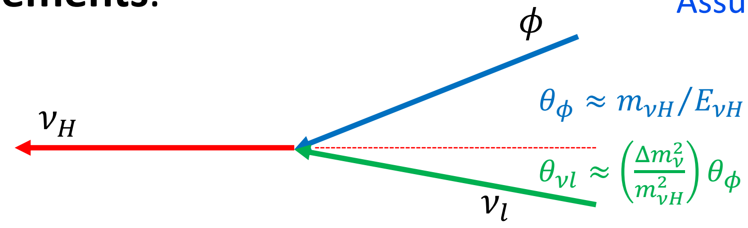
Barenboim, Chen, Hannestad, Oldengott, Tram & Y^{3}W 2021
Chen, Oldengott, Pierobon & Y^{3}W 2022

Isotropisation from relativistic (inverse) decay…

How long does it take $\nu_H \to \nu_l + \phi$ and its inverse process to wipe out momentum anisotropies? (Hint: it's not the rest-frame lifetime of ν_H.)

- In relativistic decay, the decay products are **beamed**.
- Inverse decay also only happens when the daughter particles meet **strict momentum/angular requirements**.

Assuming a massless ϕ



Rest-frame lifetime of ν_H

Boost

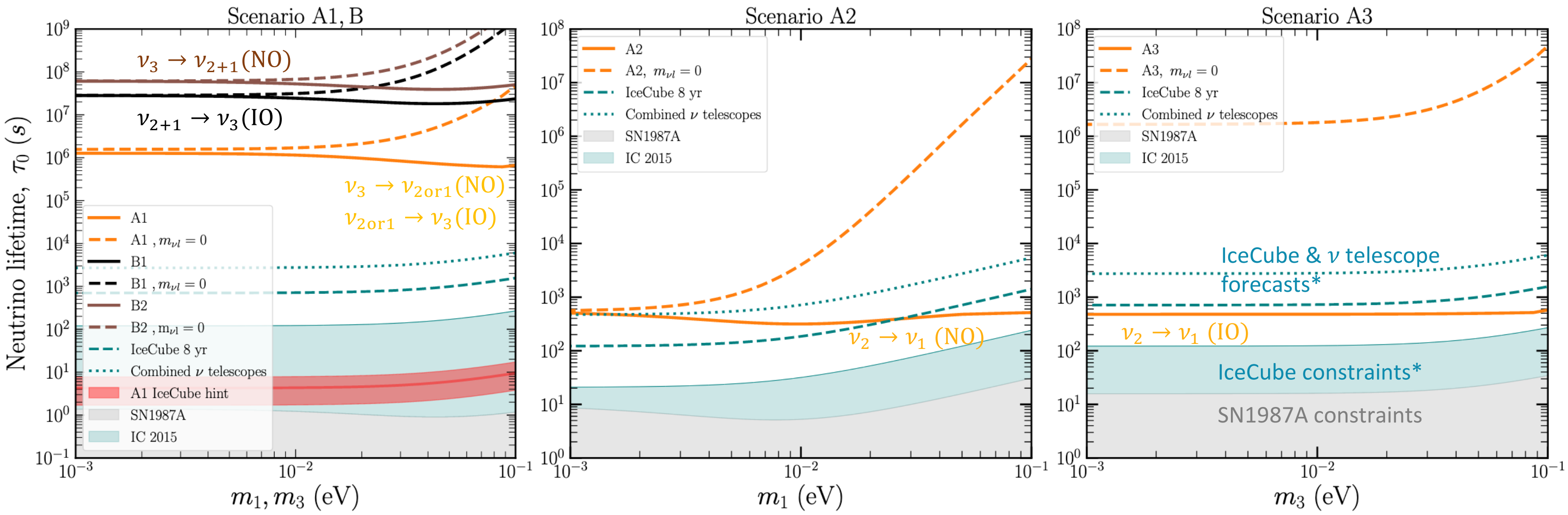
→ Isotropisation is a loooong process: $T_{\text{isotropise}} \sim (\theta_\phi \theta_{\nu l})^{-2}\, \gamma_{\nu H}\, \tau_{\text{rest}} \gtrsim 400\ \text{kyr}$

Barenboim, Chen, Hannestad, Oldengott, Tram & Y³W 2021
Chen, Oldengott, Pierobon & Y³W 2022

→ Lower bound on τ_{rest} as a function of $m_{\nu H}$ and $m_{\nu l}$.

CMB lower bounds on the neutrino lifetime…

Mass-spectrum consistent constraints on invisible neutrino decay $\nu_H \rightarrow \nu_l + \phi$.



Chen, Oldengott, Pierobon & Y^3W 2022

* IceCube constraints & forecasts from Song et al. 2021

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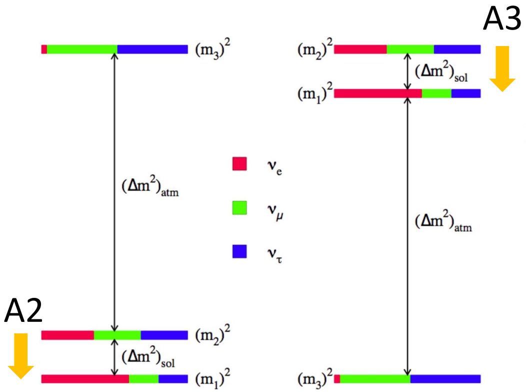
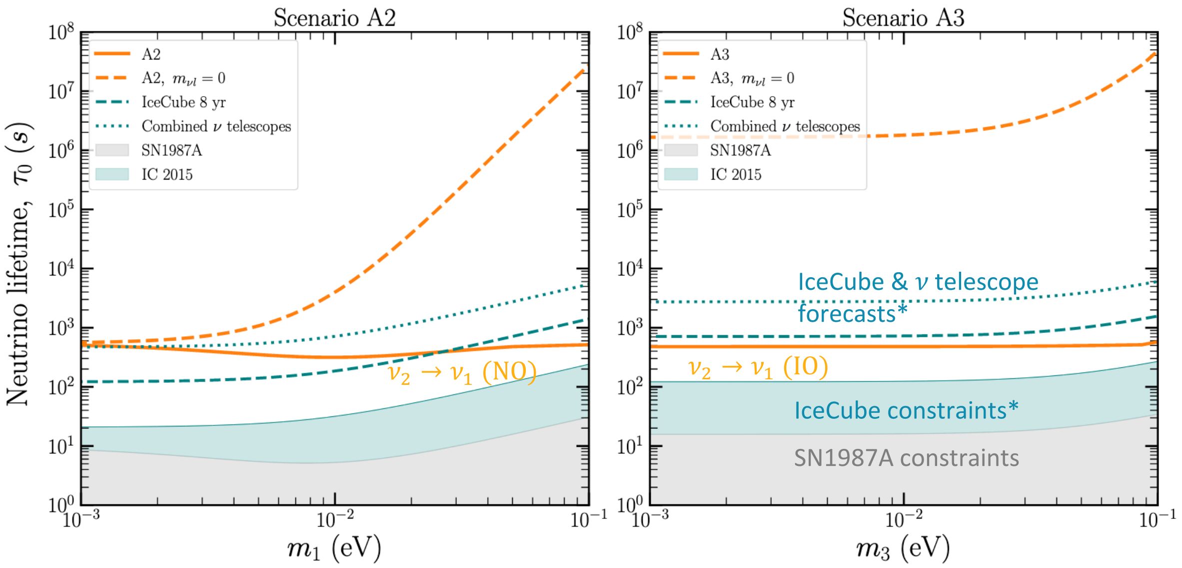


Normal mass ordering

Inverted mass ordering



Chen, Oldengott, Pierobon & Y³W 2022

- If $\nu_2 \rightarrow \nu_1 + \phi$, then neutrino telescopes and CMB probe the same parameter space.

* IceCube constraints & forecasts from Song et al. 2021

Summary…

Cosmology offers an interesting way to test Standard Model and Beyond-the-Standard-Model particle physics.

- In some cases, the same particle physics is also being probed or searched for at terrestrial experiments.
- Cosmological constraints on these scenarios from, e.g., BBN, CMB, etc., therefore provide an important cross-check on our understanding of both particle physics and cosmology.
- Here I have talked about
  - Light thermal relics (e.g., thermal ALPs, light sterile neutrinos)
  - Invisible neutrino decay and constraints on the neutrino lifetime