Neutrino Cosmology

ORIGINS Excellence Cluster

COSMIC WISPERS CA21106

MAX-PLANCK-INSTITUT FÜR PHYSIK

SFB 1258 Neutrinos Dark Matter Messengers

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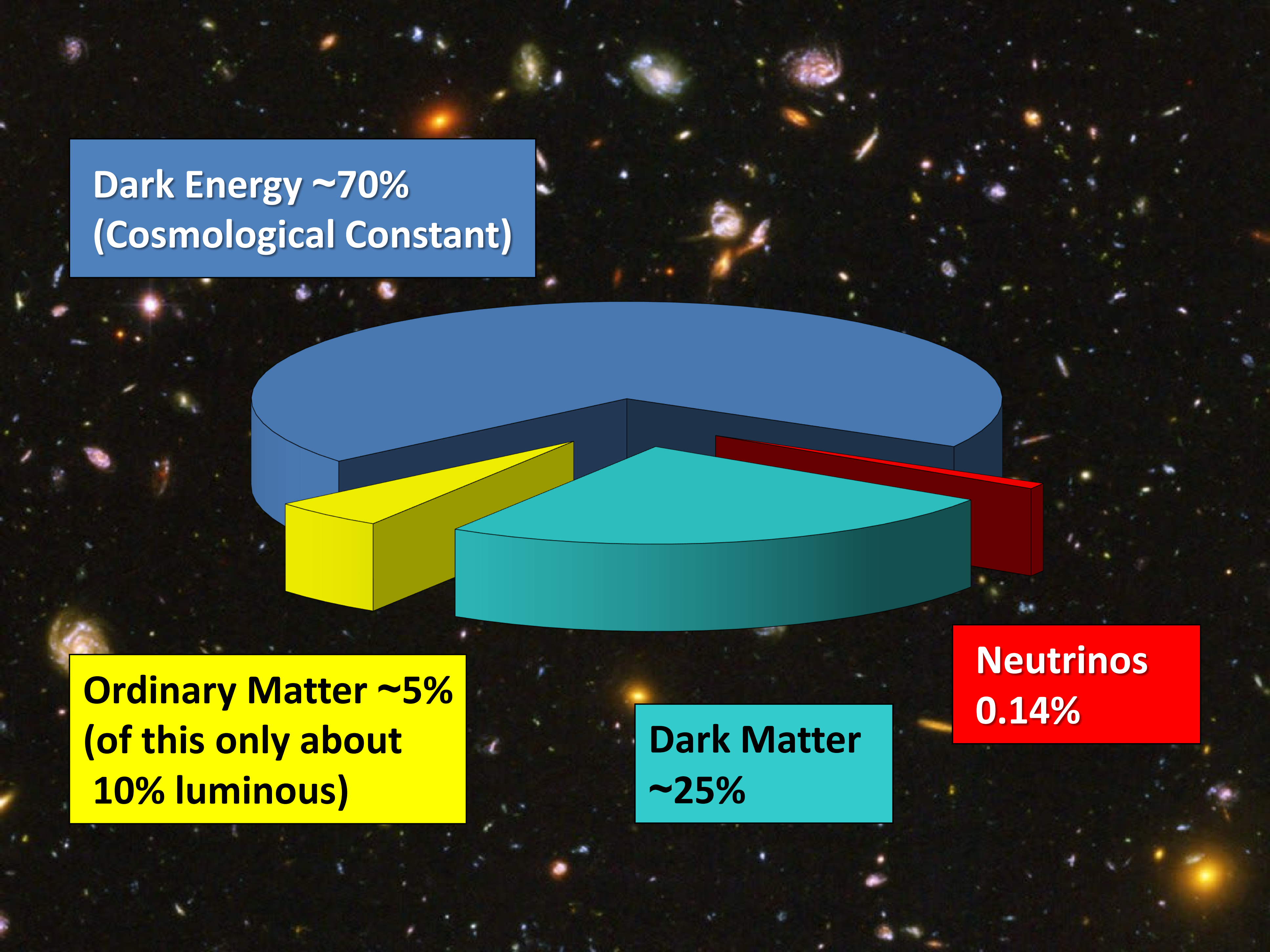

Dark Energy ~70%
(Cosmological Constant)
Ordinary Matter ~5%
(of this only about
10% luminous)
Dark Matter
~25%
Neutrinos
0.14%

- How Many Neutrinos?
  (Dark radiation/sterile neutrinos?)

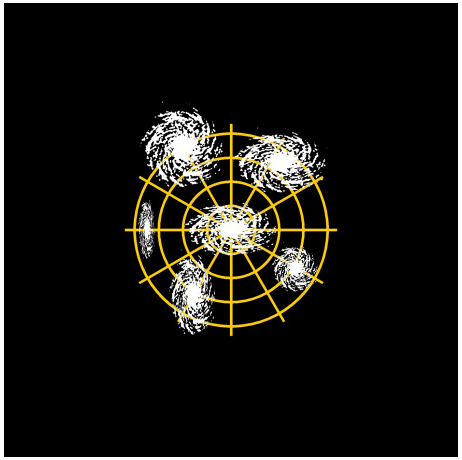
- Absolute mass determination and limits

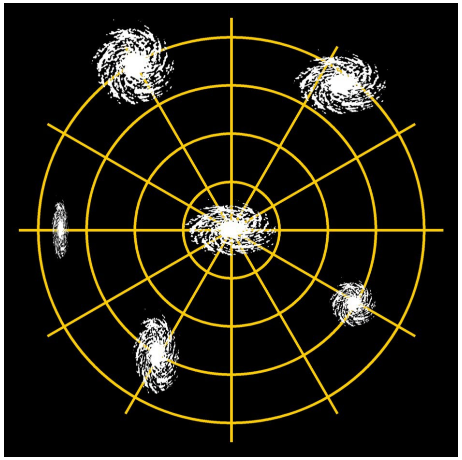
- Big Bang Nucleosynthesis – BBN
  (Origin of light elements)

- Leptogenesis
  (Origin of Matter Abundance)

Cosmic Expansion

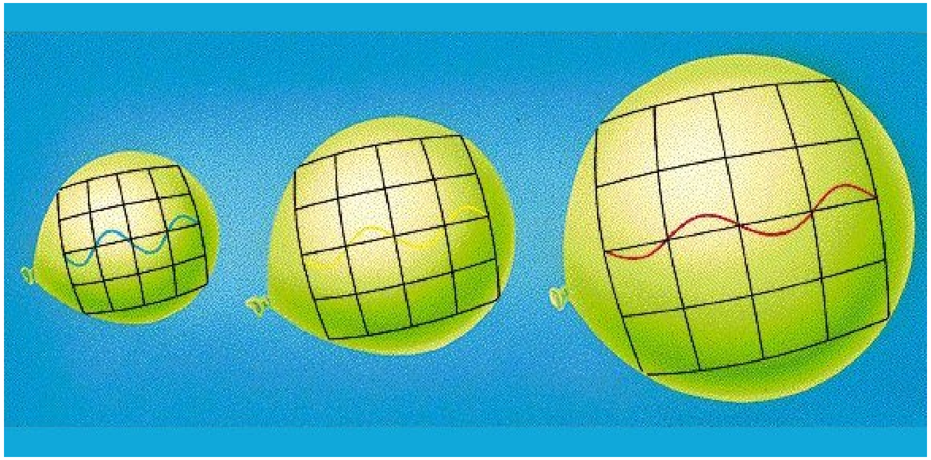
Cosmic Scale Factor





- Space between galaxies grows
- Galaxies (stars, people) stay the same
  (dominated by local gravity
  or by electromagnetic forces)
- Cosmic scale factor today: $a = 1$

Cosmic Redshift



- Wavelength of light is "stretched"
- Suffers redshift $z + 1 = \frac{\lambda_{\text{today}}}{\lambda_{\text{then}}}$
- Redshift today: $z = 0$

$$z + 1 = \frac{\lambda_{\text{today}}}{\lambda_{\text{then}}} = \frac{a_{\text{today}}}{a_{\text{then}}}$$

Friedmann Equation

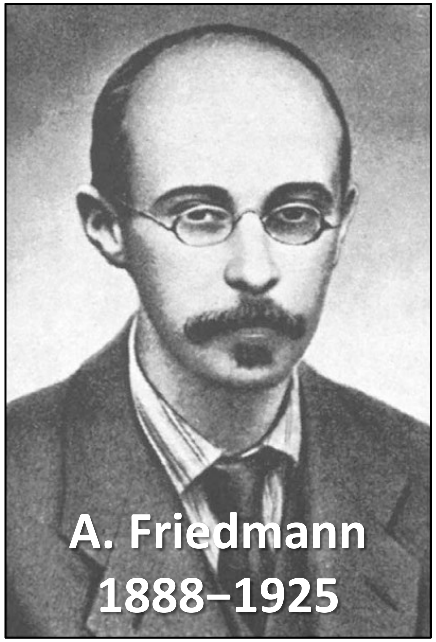
Evolution of cosmic scale factor a, for flat geometry

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_\mathrm{N} \rho$$

Unique relation between expansion rate and gravitating density

$$\rho = \frac{3H^2}{8\pi G_\mathrm{N}} = \frac{3}{8\pi}(H m_\mathrm{Pl})^2$$

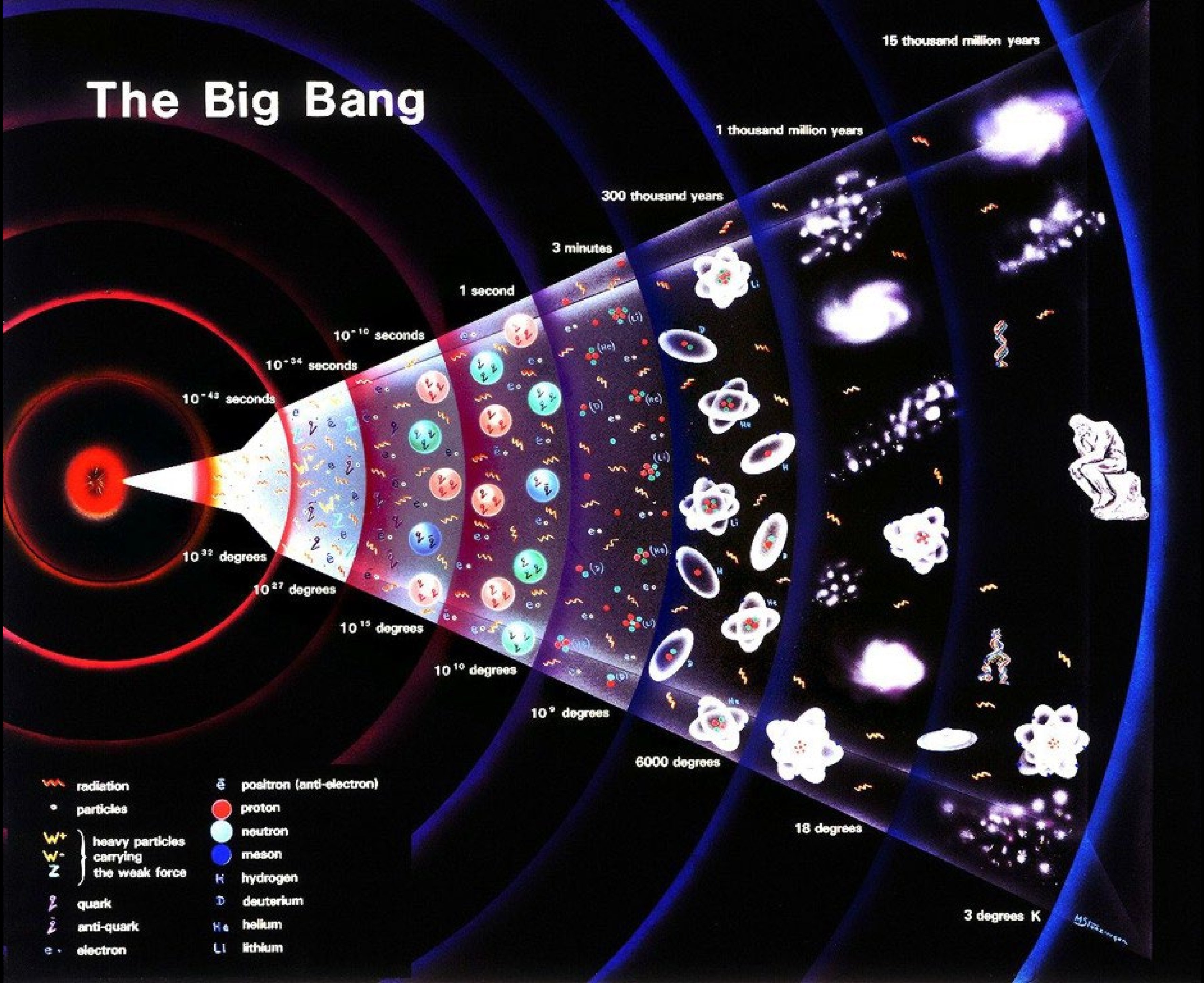
Planck mass $1.221 \times 10^{19}\ \mathrm{GeV}$



With the present-day Hubble parameter $H_0 = 67.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$

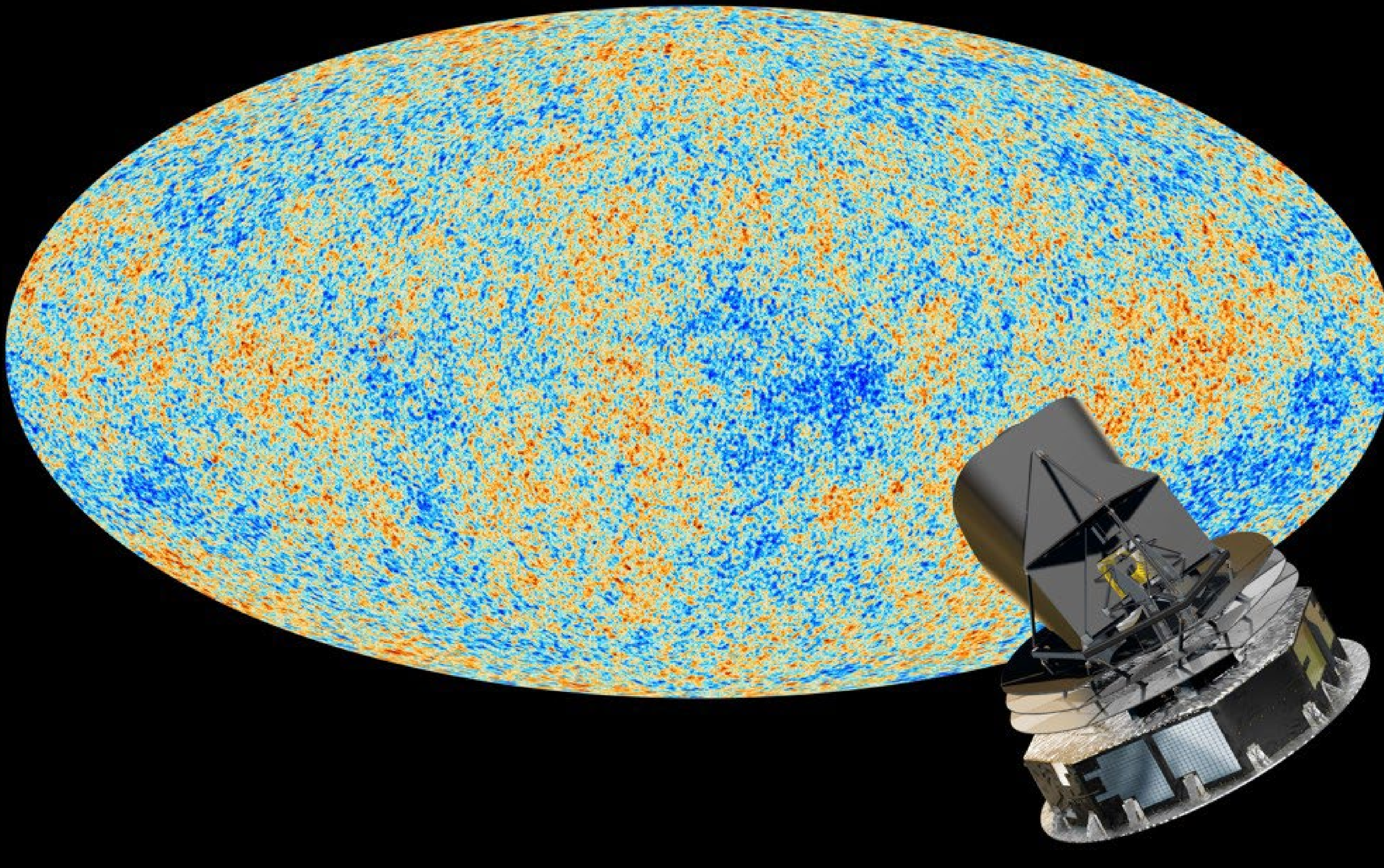
$$\rho = 0.85 \times 10^{-29}\mathrm{g\ cm^{-3}} = 4.8\ \mathrm{GeV\ m^{-3}} = (2.5\ \mathrm{meV})^4$$

Most of this in the form of “dark energy”



The Big Bang
15 thousand million years
1 thousand million years
300 thousand years
3 minutes
1 second
10^-10 seconds
10^-34 seconds
10^-43 seconds
10^32 degrees
10^27 degrees
10^15 degrees
10^10 degrees
10^9 degrees
6000 degrees
18 degrees
3 degrees K
radiation
particles
W+ W- Z heavy particles carrying the weak force
quark
anti-quark
e electron
positron (anti-electron)
proton
neutron
meson
H hydrogen
D deuterium
He helium
Li lithium

Cosmic Microwave Background (Planck 2013)



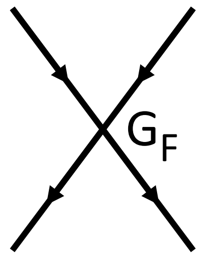
The Cosmic Neutrino Sea

Neutrino Thermal Equilibrium

Neutrino reaction rate

Examples for neutrino processes

$$e^+ + e^- \leftrightarrow \overline{\nu} + \nu$$
$$\overline{\nu} + \nu \leftrightarrow \overline{\nu} + \nu$$
$$\nu + e^\pm \leftrightarrow \nu + e^\pm$$



Dimensional analysis of reaction rate in a thermal medium for $T \ll m_{W,Z}$

$$\Gamma \sim G_F^2 T^5$$

Cosmic expansion rate

Friedmann equation (flat universe)

$$H^2 = \frac{8\pi}{3} \frac{\rho}{m_{Pl}^2} \qquad \left(G_N = \frac{1}{m_{Pl}^2}\right)$$

Radiation dominates

$$\rho \sim T^4$$

Expansion rate

$$H \sim \frac{T^2}{m_{Pl}}$$

Condition for thermal equilibrium: $\Gamma > H$

$$T > \left(m_{Pl} G_F^2\right)^{-1/3} \sim \left[10^{19}\text{GeV}\left(10^{-5}\text{GeV}^{-2}\right)^2\right]^{-1/3} = 1\ \text{MeV}$$

Neutrinos are in thermal equilibrium for $T \gtrsim 1$ MeV corresponding to $t \lesssim 1$ sec

Thermal Radiations

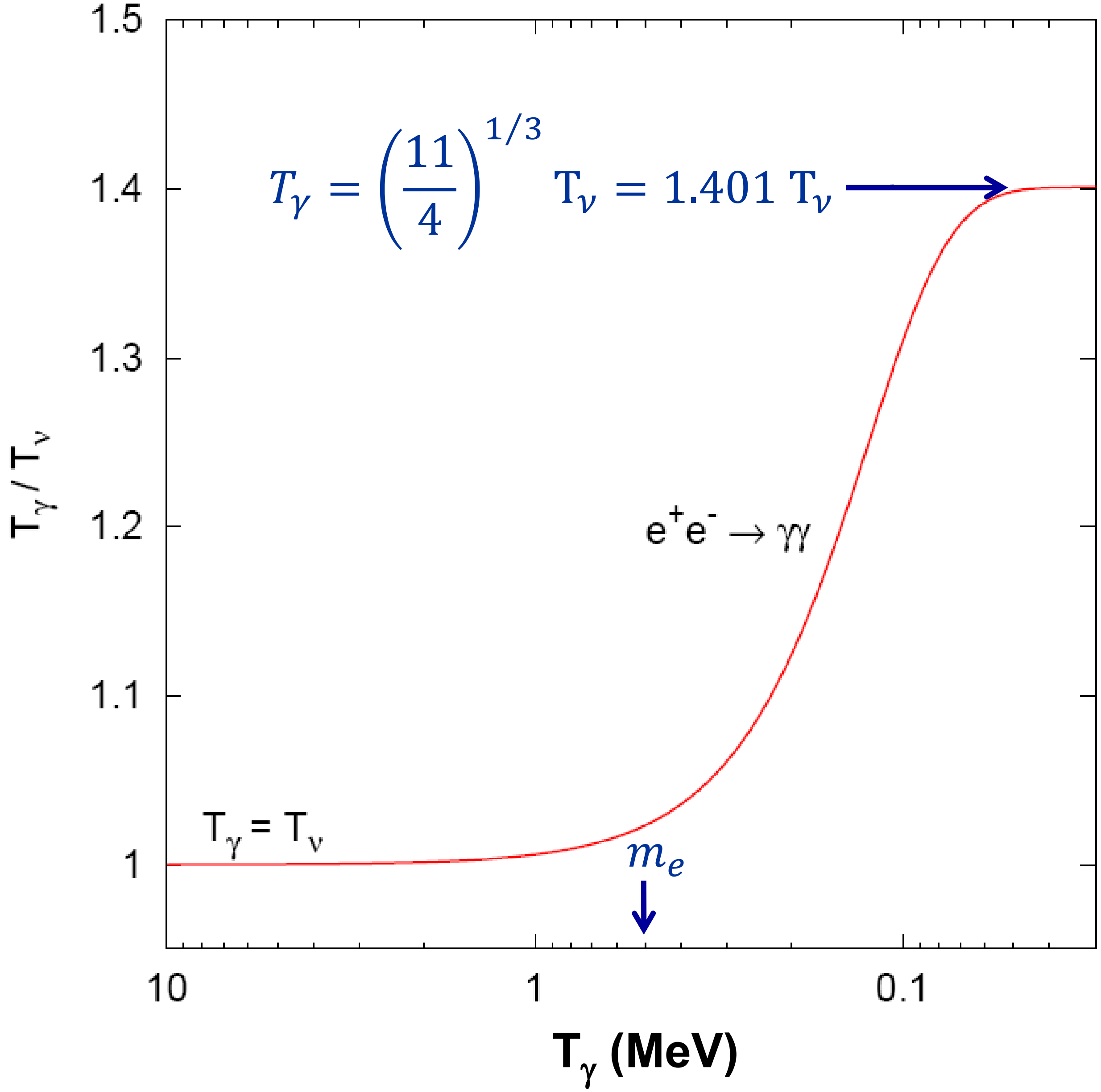
	General	Bosons	Fermions
Number density n	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{1}{e^{E_p/T}\pm 1}$	$g_B \frac{\zeta_3}{\pi^2} T^3$	$\frac{3}{4}\, g_F \frac{\zeta_3}{\pi^2} T^3$
Energy density ρ	$g\int \frac{d^3\boldsymbol{p}}{(2\pi)^3}\frac{E_{\boldsymbol{p}}}{e^{E_p/T}\pm 1}$	$g_B \frac{\pi^2}{30} T^4$	$\frac{7}{8}\, g_F \frac{\pi^2}{30} T^4$
Pressure p	$\frac{\rho}{3}$		
Entropy density s	$\frac{\rho+p}{T}=\frac{4}{3}\,\frac{\rho}{T}$	$g_B \frac{2\pi^2}{45} T^3$	$\frac{7}{8}\, g_F \frac{2\pi^2}{45} T^3$

Riemann Zeta Function
$\zeta_3 = 1.2020569 \ldots$

Present-Day Neutrino Density

Neutrino decoupling (freeze out)	$H \sim \Gamma$ $T \approx 2.4\ \mathrm{MeV}$ (electron flavor) $T \approx 3.7\ \mathrm{MeV}$ (other flavors)
Redshift of Fermi-Dirac distribution ("nothing changes at freeze-out")	$\frac{dn_{\nu\bar\nu}}{dE} = \frac{1}{\pi^2}\frac{E^2}{e^{E/T}+1}$ Temperature scales with redshift $T_\nu = T_\gamma \propto (z+1)$
Electron-positron annihilation beginning at T ≈ m_e = 0.511 MeV	• QED plasma is "strongly" coupled • Stays in thermal equilibrium (adiabatic process) • Entropy of e^+e^- transfered to photons $\left.\underbrace{g_* T_\gamma^3}_{2+\frac{7}{8}4=\frac{11}{2}}\right\vert_{\text{before}} = \left.\underbrace{g_* T_\gamma^3}_{2}\right\vert_{\text{after}} \Bigg\}\ \left.T_\gamma^3\right\vert_{\text{before}} = \frac{\mathbf{4}}{\mathbf{11}} \left.T_\gamma^3\right\vert_{\text{after}}$
Redshift of neutrino and photon thermal distributions so that today we have	$n_{\nu\bar\nu}(1\ \text{flavor}) = \frac{4}{11}\times\frac{3}{4}\times n_\gamma = \frac{3}{11}n_\gamma \approx 112\ \mathrm{cm}^{-3}$ $T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.95\ \mathrm{K}$ for massless neutrinos

Photon Heating by Electron-Positron Annihilation



Cosmic radiation density after e^+e^- annihilation

Radiation density for $N_\nu = 3$ standard neutrino flavors

$$\rho_{\mathrm{rad}} = \rho_\gamma + \rho_\nu = \frac{\pi^2}{15}\left(T_\gamma^4 + N_\nu \frac{7}{8}\, T_\nu^4\right) = \left[1 + \mathbf{N}_{\boldsymbol{\nu}} \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma$$

Cosmic radiation density is expressed in terms of
"effective number of thermally excited neutrino species" N_{eff}

$$\rho_{\mathrm{rad}} = \left[1 + \mathbf{N}_{\mathbf{eff}}\, \frac{7}{8}\left(\frac{4}{11}\right)^{4/3}\right]\rho_\gamma = [1 + \mathbf{N}_{\mathbf{eff}}\ 0.2271]\rho_\gamma$$

N_{eff} is a measure for the radiation density, not necessarily related to neutrinos

Residual neutrino heating by e^+e^- annihilation and corrections for plasma effects and neutrino flavor oscillations implies

$N_{\mathrm{eff}} = 3.0440(2)$ Standard value

$$\rho_{\mathrm{rad}} = (1 + 0.6918 + 0.2271\ \Delta\mathrm{N}_{\mathrm{eff}})\ \rho_\gamma$$

Of course, the number of known neutrino species ν_e, ν_μ, ν_τ is exactly 3

Precision Calculations of Neff

$$N_{\text{eff}} = 3.0440(2)$$

Standard-model corrections to $N_{\text{eff}}^{\text{SM}}$	Leading 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	-0.006
$\mathcal{O}(e^3)$ FTQED correction to the QED EoS	-0.001
Flavour oscillations	$+0.0005$
Type (a) FTQED corrections (thermal mass) to the weak rates	$\lesssim 10^{-4}$
Type (d) FTQED corrections (fermion loop) to the weak rates	$\lesssim 10^{-5}$
$\mathcal{O}(e^4)$ FTQED correction to the QED EoS	3.5×10^{-6}
Electron/positron chemical decoupling	$\sim -10^{-7}$

Sources of uncertainty	
Numerical solution by `FortEPiaNO`	± 0.0001
Input solar neutrino mixing angle θ_{12}	± 0.0001

Drewes et al., https://arxiv.org/abs/2411.14091

Measured Cosmic Radiation Density

J. Lesgourgues & L. Verde, Neutrinos in Cosmology, in: Review of Particle Properties, https://pdg.lbl.gov/2024/reviews/rpp2024-rev-neutrinos-in-cosmology.pdf

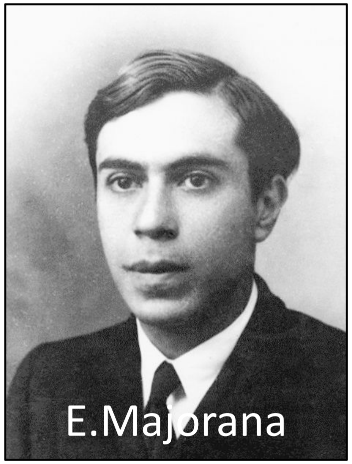
	Model	$N_{\rm eff}$	Ref.
CMB alone			
Pl18[TT,TE,EE+lowE]	ΛCDM+$N_{\rm eff}$	$2.92^{+0.36}_{-0.37}$ (95%CL)	[24]
CMB + background evolution + LSS			
Pl18[TT,TE,EE+lowE+lensing] + BAO	ΛCDM+$N_{\rm eff}$	$2.99^{+0.34}_{-0.33}$ (95%CL)	[24]
”	” +5-params.	$2.85^{+0.23}_{-0.23}$ (68%CL)	[25]

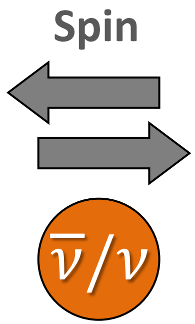
[24] Planck 2018, https://arxiv.org/abs/1807.06209

Constraints on Neutrino Physics from DESI DR2 BAO and DR1 Full Shape
https://arxiv.org/abs/2503.14744

DESI DR2 BAO + CMB	ΛCDM + Neff	$3.23^{+0.35}_{-0.34}$ (95% CL)

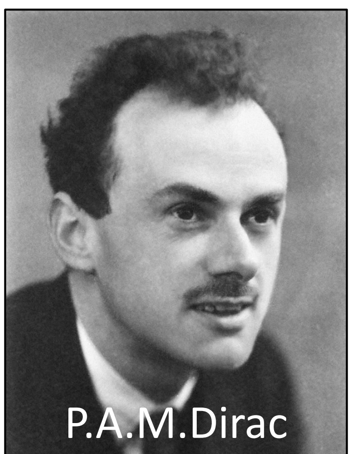
Two or four components?

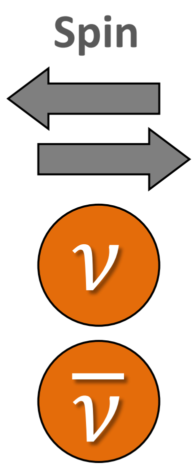




Two states (Majorana neutrino)

- Neutral spin ½ fermion
- No "charge" distinguishing particle from antiparticle
- No magnetic moment
- Relativistically acts as ν or $\bar{\nu}$ depending on helicity



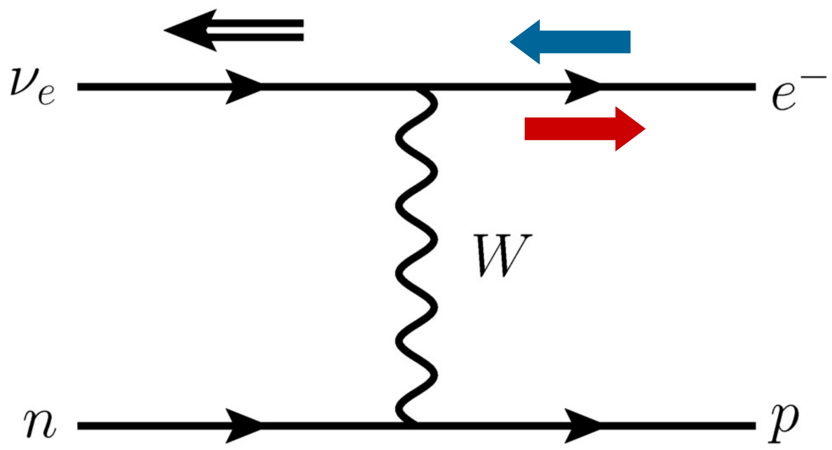


Four states (Dirac neutrino)

- Neutral spin ½ fermion
- Lepton number distinguishes particle from antiparticle
- Non-zero magnetic moment
- Relativistically is active or sterile depending on helicity

Role of Mass

Massless, left-handed neutrino with $E \gg m_e$

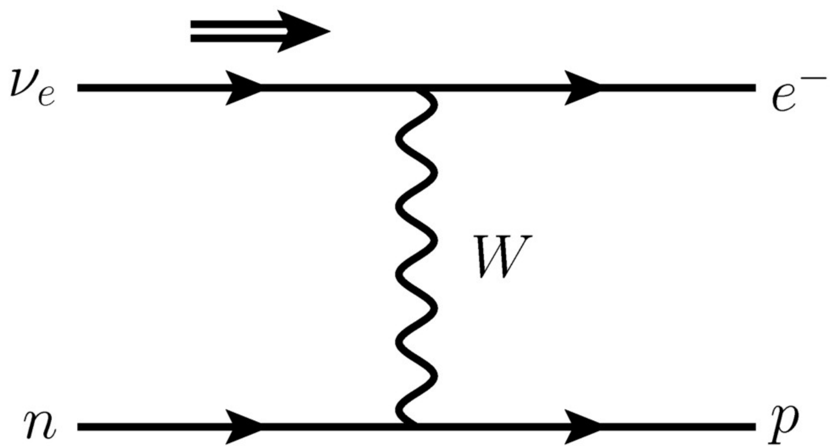


Relativistic electron is strongly, but not perfectly polarized

"Wrong" helicity state with probability $\sim (m_e/E)^2$

Right-handed neutrino with small mass $E \gg m_\nu$

Rate smaller by $\sim (m_\nu/E)^2$



Neutrino Thermal Equilibrium for Dirac Neutrinos

Neutrino reaction rate

Examples for neutrino processes

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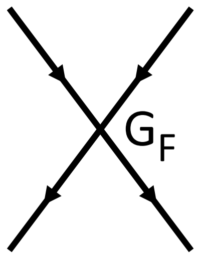
$$\overline{\nu} + \nu \leftrightarrow \overline{\nu} + \nu$$
$$\nu + e^\pm \leftrightarrow \nu + e^\pm$$



Dimensional analysis of reaction rate in a thermal medium for $T \ll m_{W,Z}$

$$\Gamma \sim G_{\rm F}^2 T^5 \times (m_\nu / T)^2$$

Cosmic expansion rate

Friedmann equation (flat universe)

$$\mathrm{H}^2 = \frac{8\pi}{3}\frac{\rho}{m_{\rm Pl}^2} \qquad \left(G_{\rm N} = \frac{1}{m_{\rm Pl}^2}\right)$$

Radiation dominates

$$\rho \sim T^4$$

Expansion rate

$$\mathrm{H} \sim \frac{T^2}{m_{\rm Pl}}$$

Condition for thermal equilibrium: $\Gamma > H$

$$m_\nu > G_{\rm F}^{-1} (m_{\rm Pl} T)^{-1/2}$$

To avoid excessive dilution at quark-hadron phase transition: $T < T_{\rm QCD} \sim 170~\mathrm{MeV}$

$$m_\nu > 60~\mathrm{keV}$$

For eV-scale Dirac neutrinos, r.h. helicity degrees not thermally excited

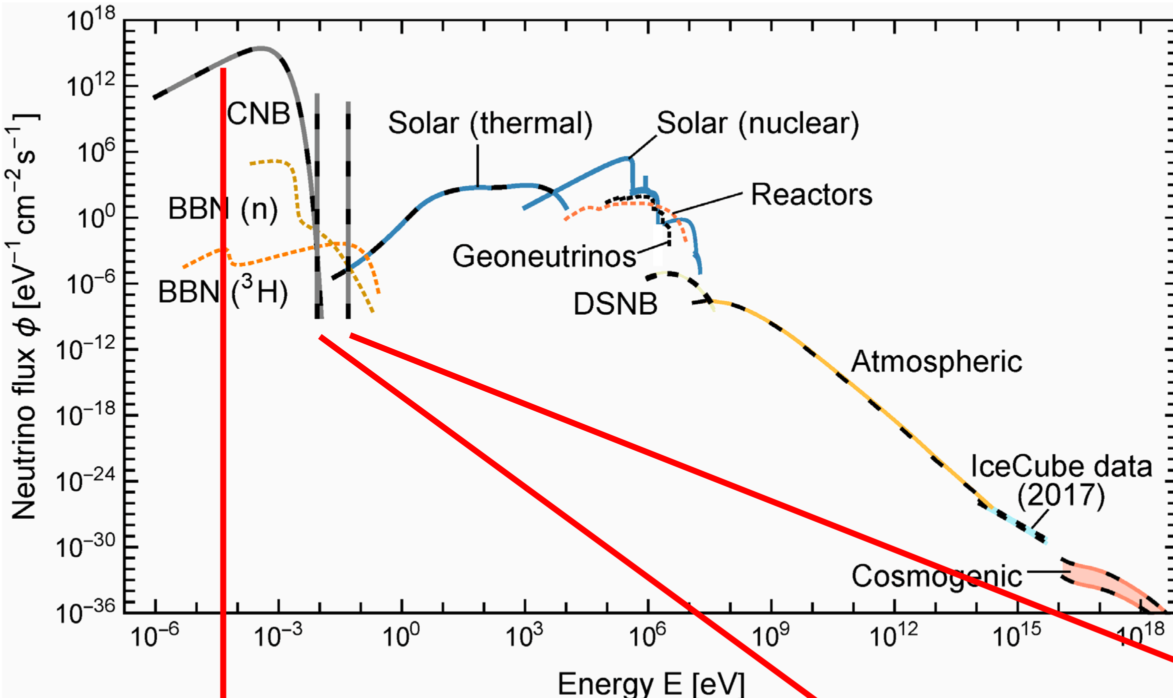
Present-Day Neutrino Distribution

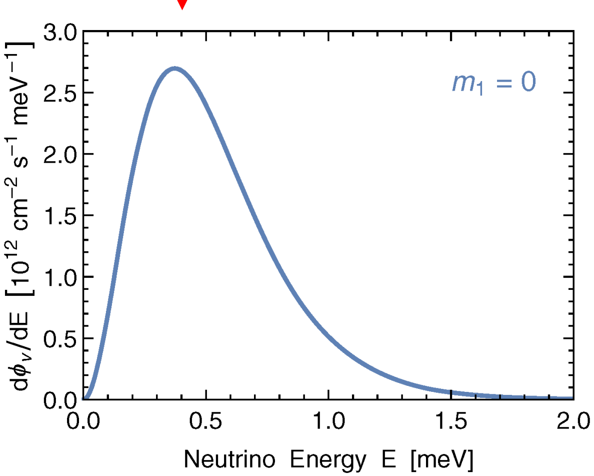
Minimal neutrino masses from oscillation experiments	<u>Normal</u> $m_3 \gtrsim 50$ meV $m_2 \gtrsim 8$ meV $m_1 \geq 0$	<u>Inverted</u> $m_1 \approx m_2 \gtrsim 50$ meV $m_3 \geq 0$
Temperature of massless cosmic background neutrinos	T = 1.95 K = 0.17 meV	
Cosmic redshift of **momenta** (not energies)	$\frac{dn_{\nu\bar{\nu}}}{dp} = \frac{1}{\pi^2}\frac{p^2}{e^{p/T}+1}$	Not a thermal distribution unless $T \gg m$
Average velocity for $m \gg T$	$\langle v \rangle \approx \frac{3T}{m}$	
Normal hierarchy neutrinos	$\langle v_3 \rangle < 1 \times 10^{-2} c$	$\langle v_2 \rangle < 6 \times 10^{-2} c$

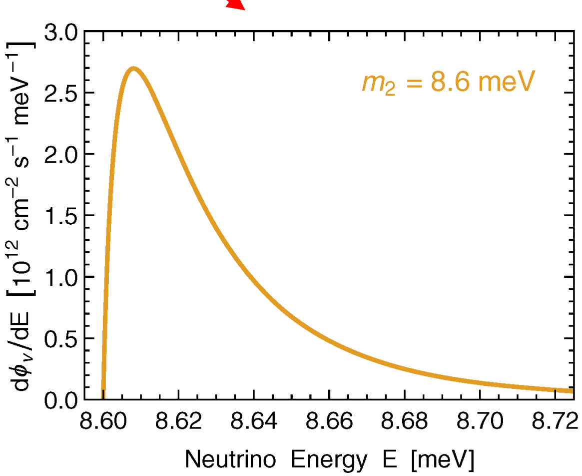
Nonrelativistic, but too fast to be trapped in galaxies $v \sim 10^{-3} c$

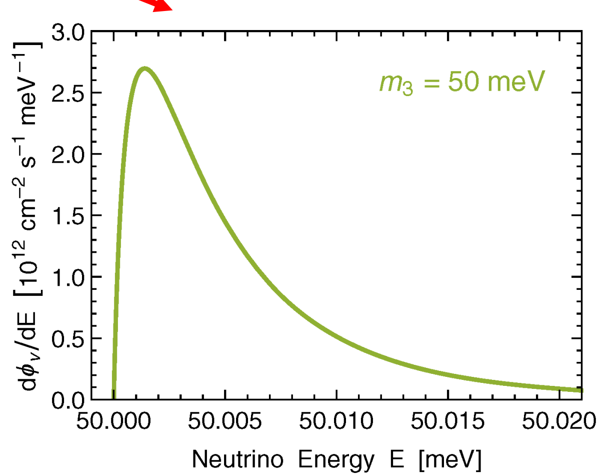
Primordial Neutrino Spectrum at Earth

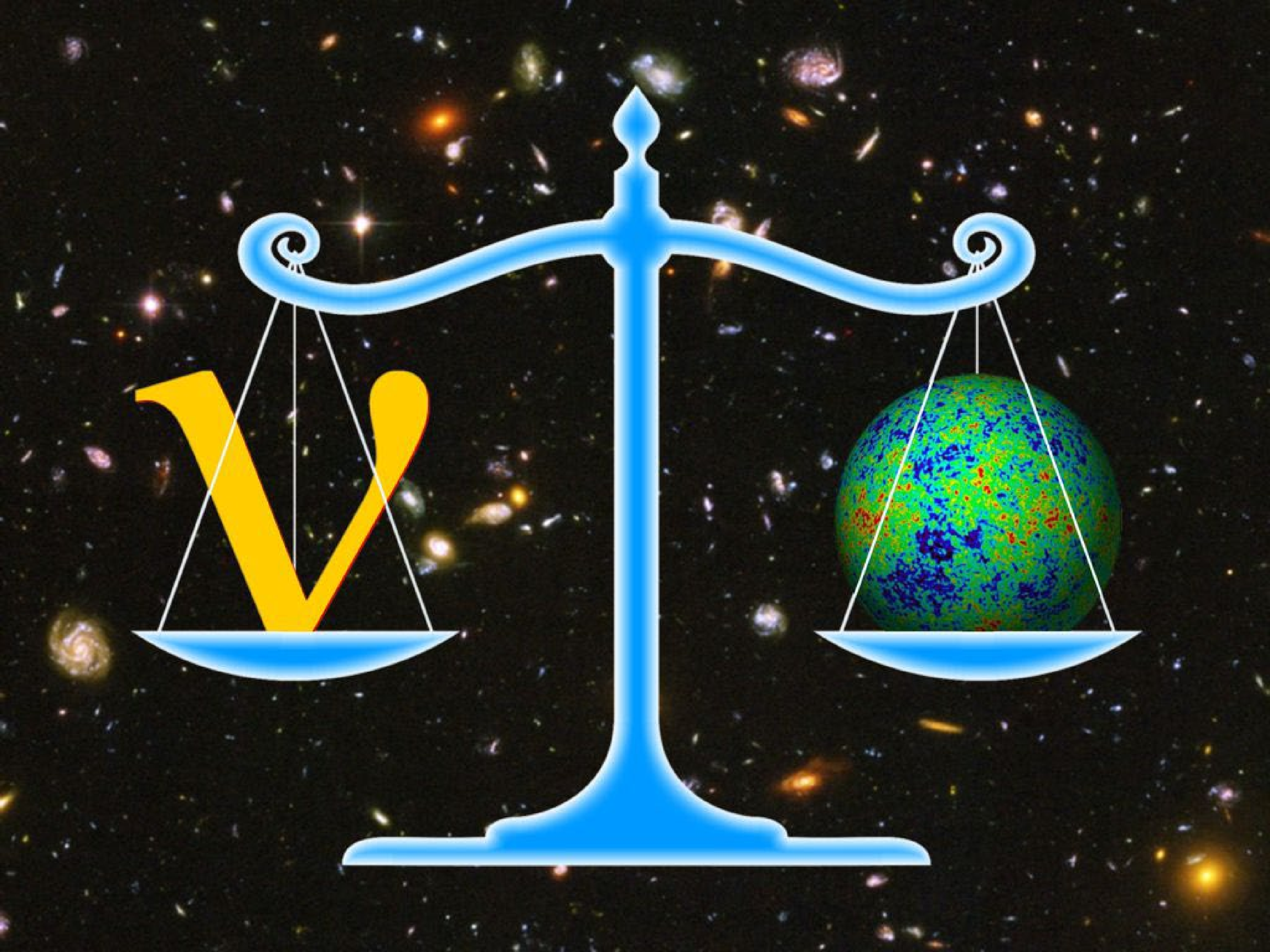
Vitagliano, Tamborra & Raffelt, arXiv:1910.11878











What is wrong with neutrino dark matter?

Galactic Phase Space ("Tremaine-Gunn-Limit")

Maximum mass density of a degenerate Fermi gas

$$\rho_{\rm max} = m_\nu \underbrace{\frac{p_{\rm max}^3}{3\pi^2}}_{n_{\rm max}} = \frac{m_\nu \left(m_\nu v_{\rm escape}\right)^3}{3\pi^2}$$

Spiral galaxies

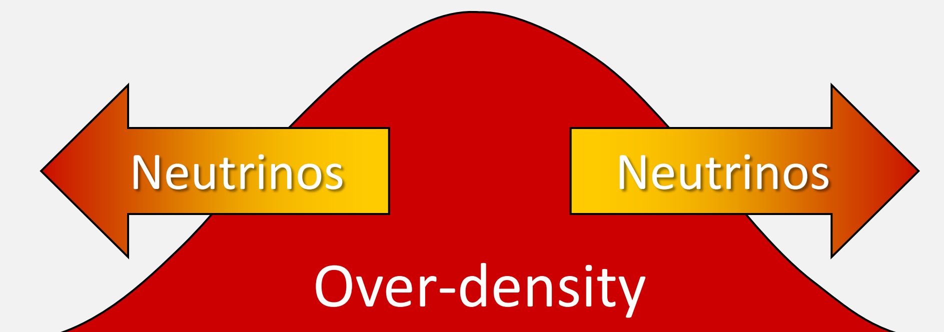
m_ν > 20–40 eV

Dwarf galaxies

m_ν > 100–200 eV

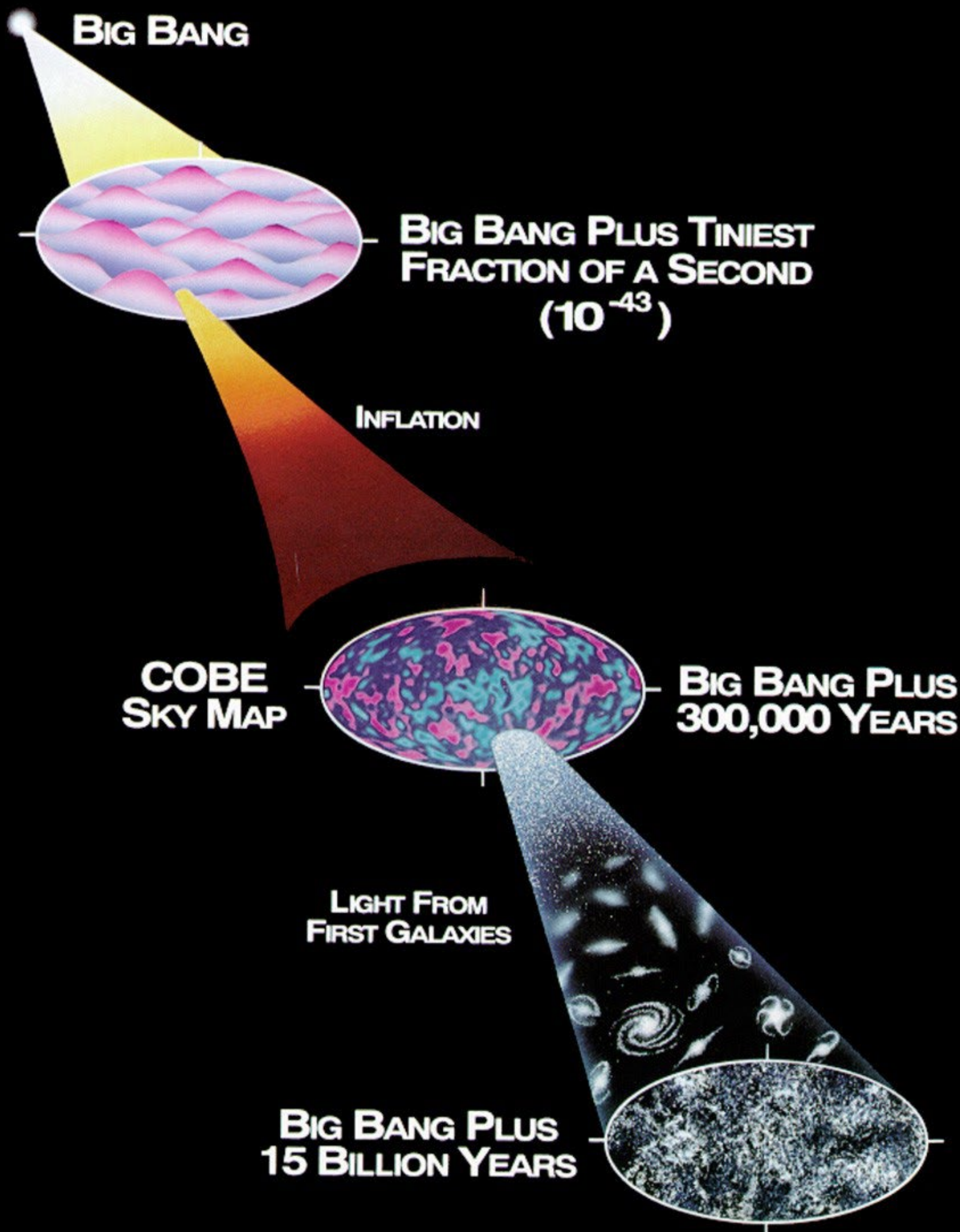
Neutrino Free Streaming (Collisionless Phase Mixing)

- At $T < 1$ MeV neutrino scattering in early universe is ineffective
- Stream freely until non-relativistic
- Wash out density contrasts on small scales



- Neutrinos are "Hot Dark Matter"
- Ruled out by structure formation

Structure Formation in the Universe



Early phase of exponential expansion (Inflationary epoch)

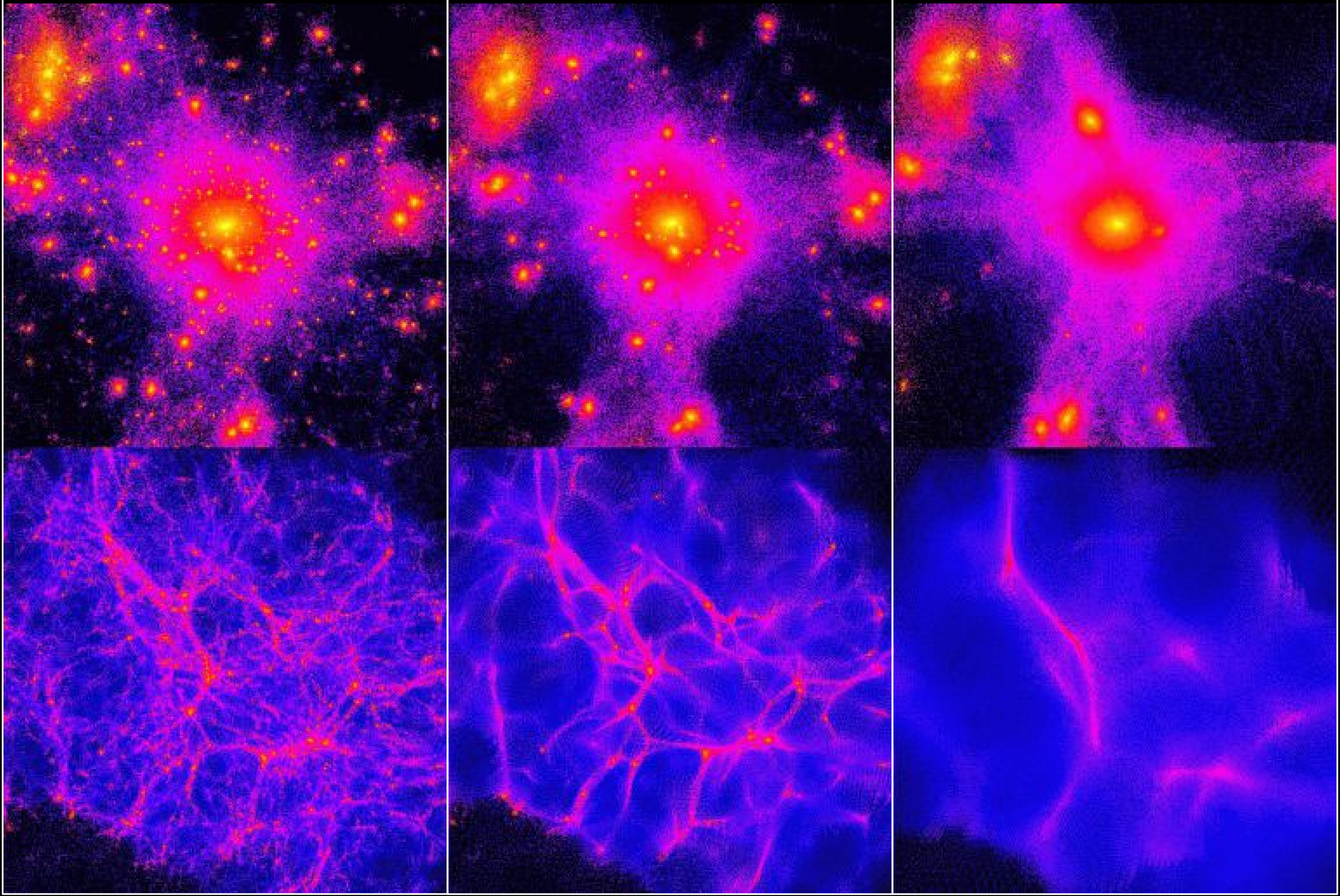
Zero-point fluctuations of quantum fields are stretched and frozen

Structure grows by gravitational instability

Cosmic density fluctuations are frozen quantum fluctuations

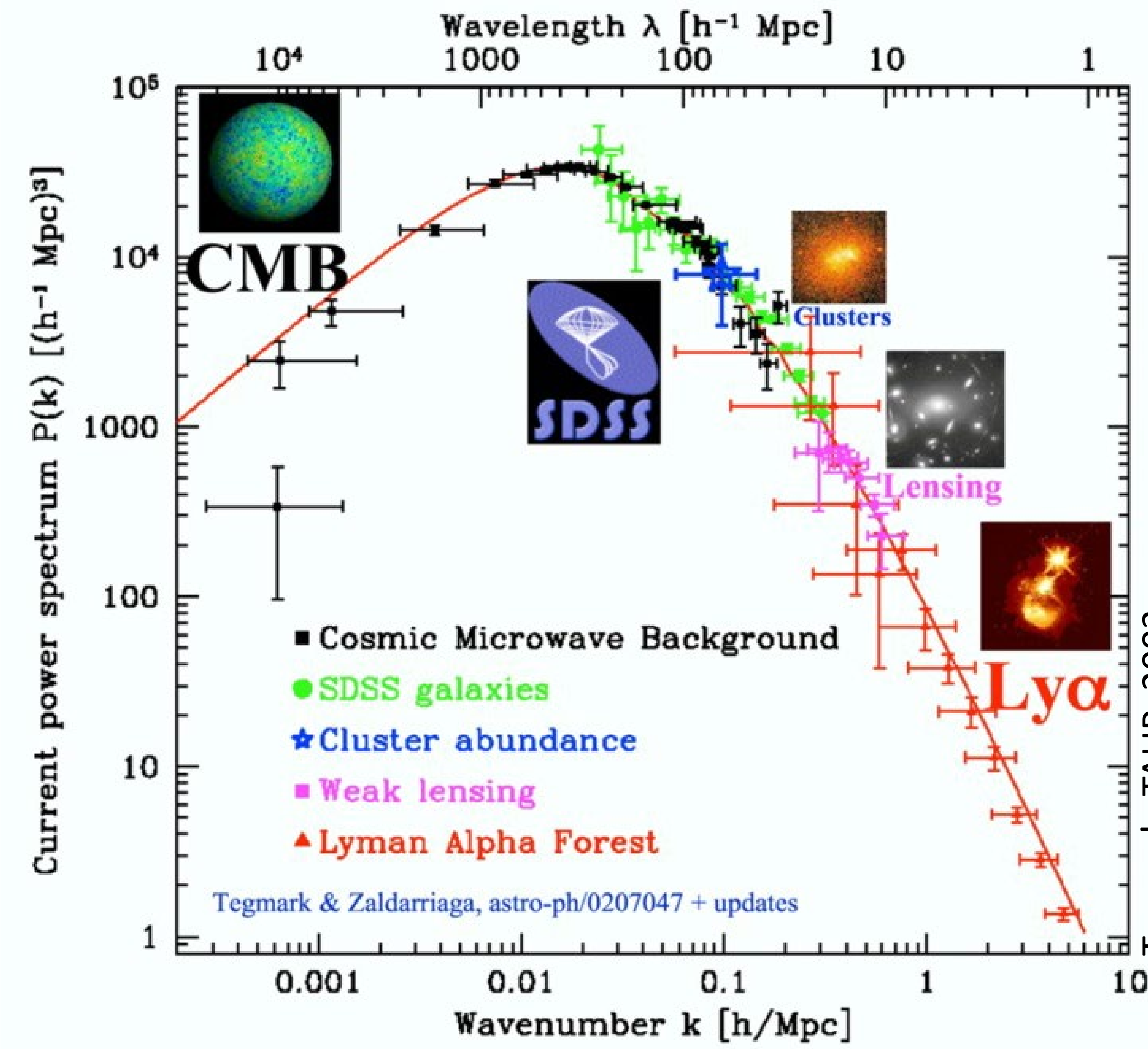
Structures for Cold, Warm and Hot Dark Matter

CDM	**WDM**	**HDM**
Small-scale structure pronounced	Small-scale structure damped	Small-scale structure erased



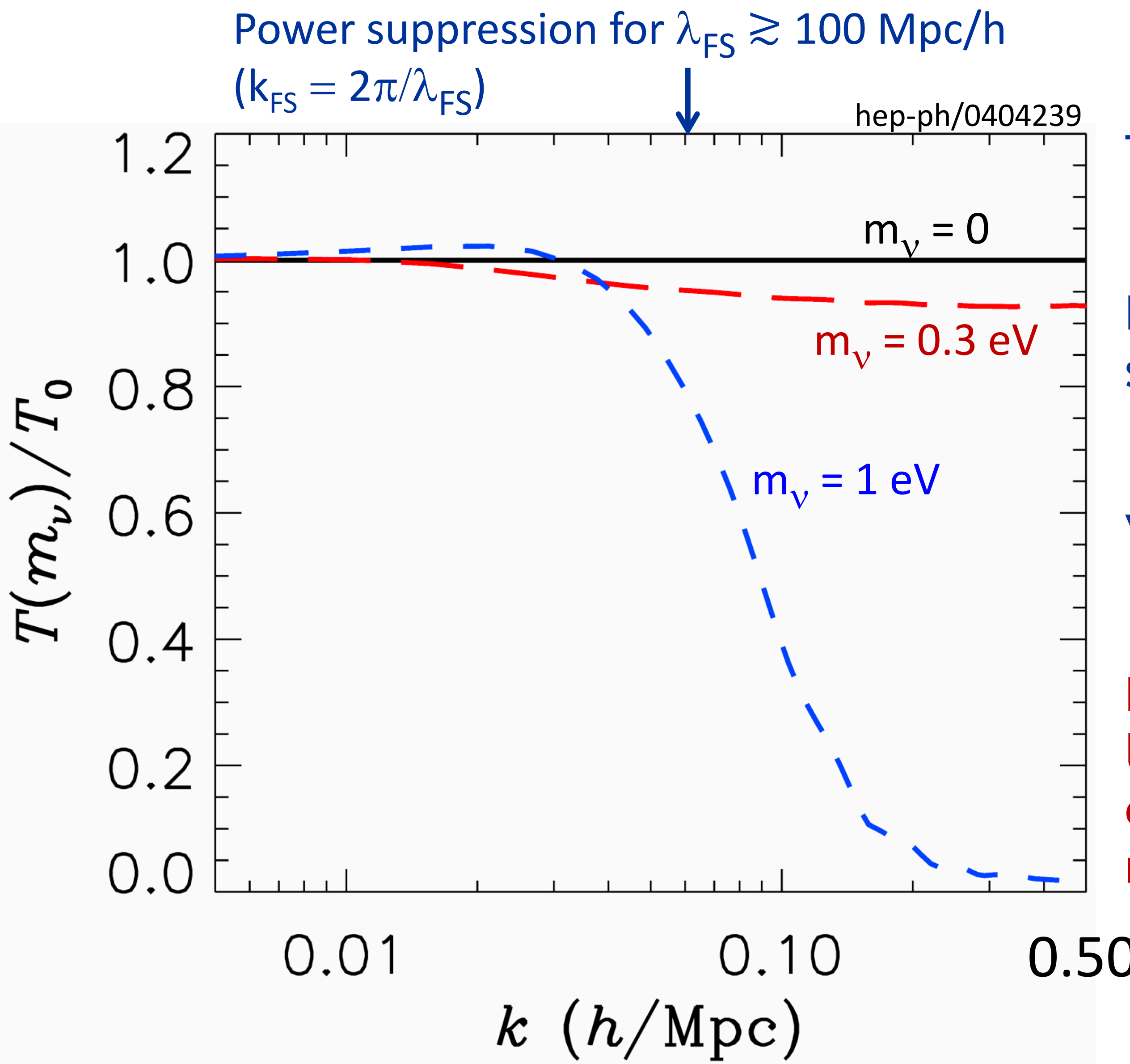
CTAC, University of Zurich, http://www.ctac.uzh.ch/gallery/

Power Spectrum of Cosmic Density Fluctuations



Tegmark, TAUP 2003

Neutrino Free Streaming: Transfer Function



Transfer function

$P(k) = T(k)\, P_0(k)$

Effect of neutrino free streaming on small scales

$T(k) = 1 - 8\, \Omega_\nu/\Omega_M$

valid for $8\Omega_\nu/\Omega_M \ll 1$

Power suppression much larger (factor 8) than corresponds to neutrino mass fraction!

Cosmological Neutrino Mass Limits (8/2023)

Table 26.2: Summary of $\sum m_\nu$ constraints.

	Model	95% CL (eV)	Ref.
CMB alone			
Pl18[TT+lowE]	ΛCDM+$\sum m_\nu$	< 0.54	[24]
Pl18[TT,TE,EE+lowE]	ΛCDM+$\sum m_\nu$	< 0.26	[24]
CMB + probes of background evolution			
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$	< 0.13	[49]
Pl18[TT,TE,EE+lowE] + BAO	ΛCDM+$\sum m_\nu$+5 params.	< 0.515	[25]
CMB + LSS			
Pl18[TT+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.44	[24]
Pl18[TT,TE,EE+lowE+lensing]	ΛCDM+$\sum m_\nu$	< 0.24	[24]
Pl18[TT,TE,EE+lowE]+ ACT[lensing]	ΛCDM+$\sum m_\nu$	< 0.12	[50]
CMB + probes of background evolution + LSS			
Pl18[TT,TE,EE+lowE] + BAO + RSD	ΛCDM+$\sum m_\nu$	< 0.10	[49]
Pl18[TT,TE,EE+lowE+lensing] + BAO + RSD + Shape	ΛCDM+$\sum m_\nu$	< 0.082	[51]
Pl18[TT+lowE+lensing] + BAO + Lyman-α	ΛCDM+$\sum m_\nu$	< 0.087	[52]
Pl18[TT,TE,EE+lowE] + BAO + RSD + SN + DES-Y1	ΛCDM+$\sum m_\nu$	< 0.12	[49]
Pl18[TT,TE,EE+lowE] + BAO + RSD + SN + DES-Y3	ΛCDM+$\sum m_\nu$	< 0.13	[53]

[24] Planck 2018, https://arxiv.org/abs/1807.06209

J. Lesgourgues & L. Verde, Neutrinos in Cosmology, in: Review of Particle Properties,
https://pdg.lbl.gov/2024/reviews/rpp2024-rev-neutrinos-in-cosmology.pdf

DESI (Dark Energy Spectroscopic Instrument)

Image Wikipedia

See also DESI at https://www.desi.lbl.gov

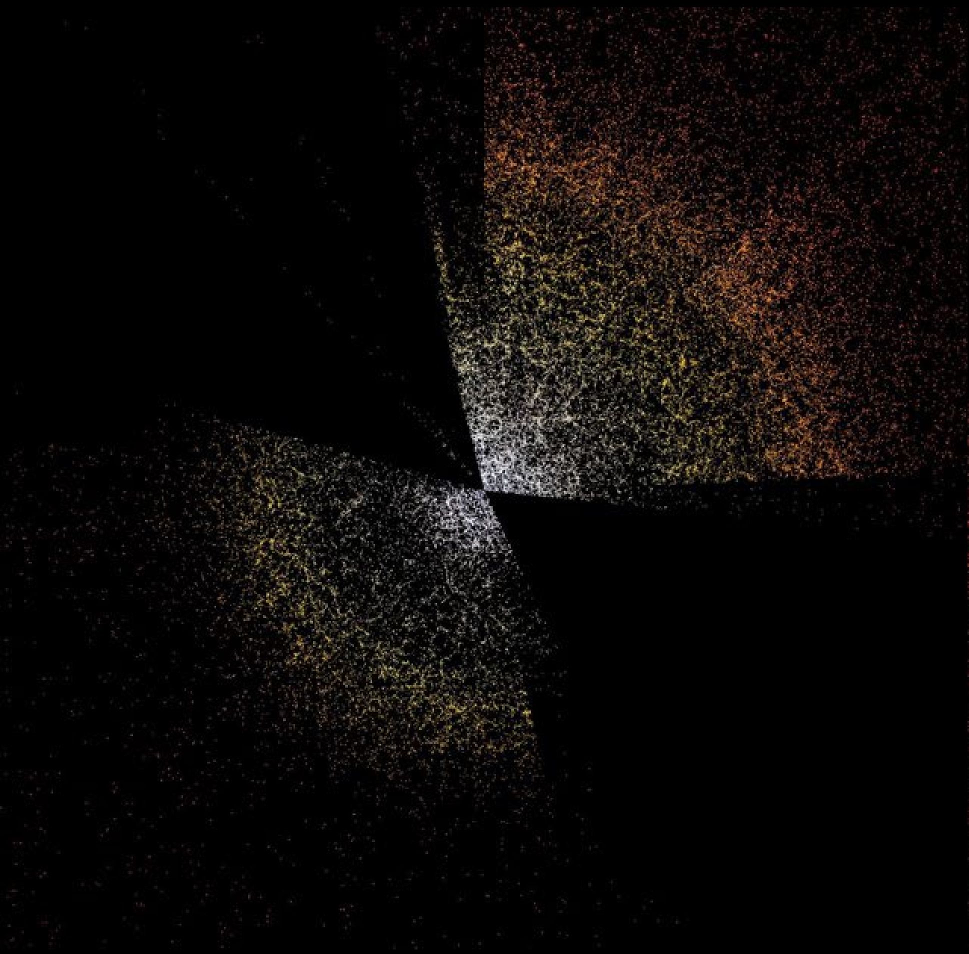
DESI installed on the Mayall 4-meter Telescope at Kitt Peak Observatory, Arizona

- Produce largest 3D map of the universe (20 million galaxies, quasars and stars)
- Main purpose: Precise expansion history (Is dark energy evolving?)
- Data Release 2 (3 years data) March 2025
- Tension (around 3σ) with ΛCDM
- Or formally best-fit "negative" $\sum m_\nu$

https://arxiv.org/abs/2503.14738

https://arxiv.org/abs/2503.14744

Sloan Digital Sky Survey (SDSS)



DESI (First 7 months)

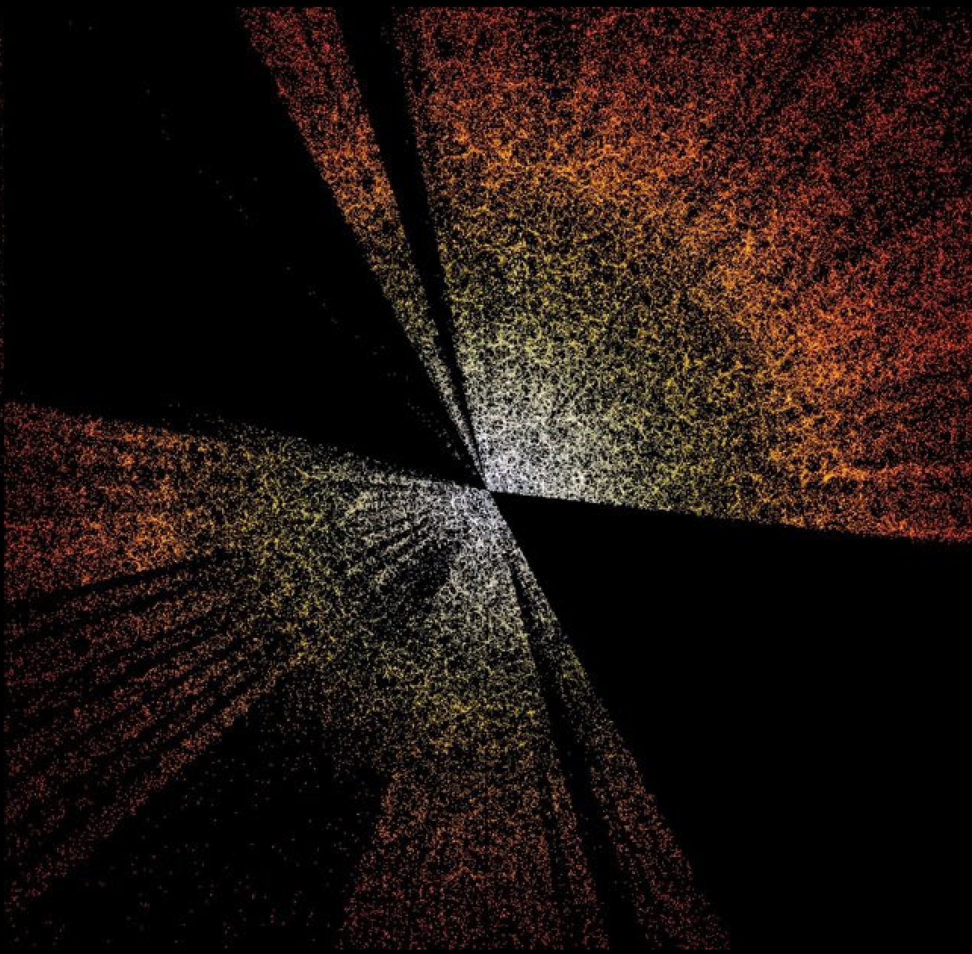


Image Wikipedia

Transfer Function with Massive Neutrinos

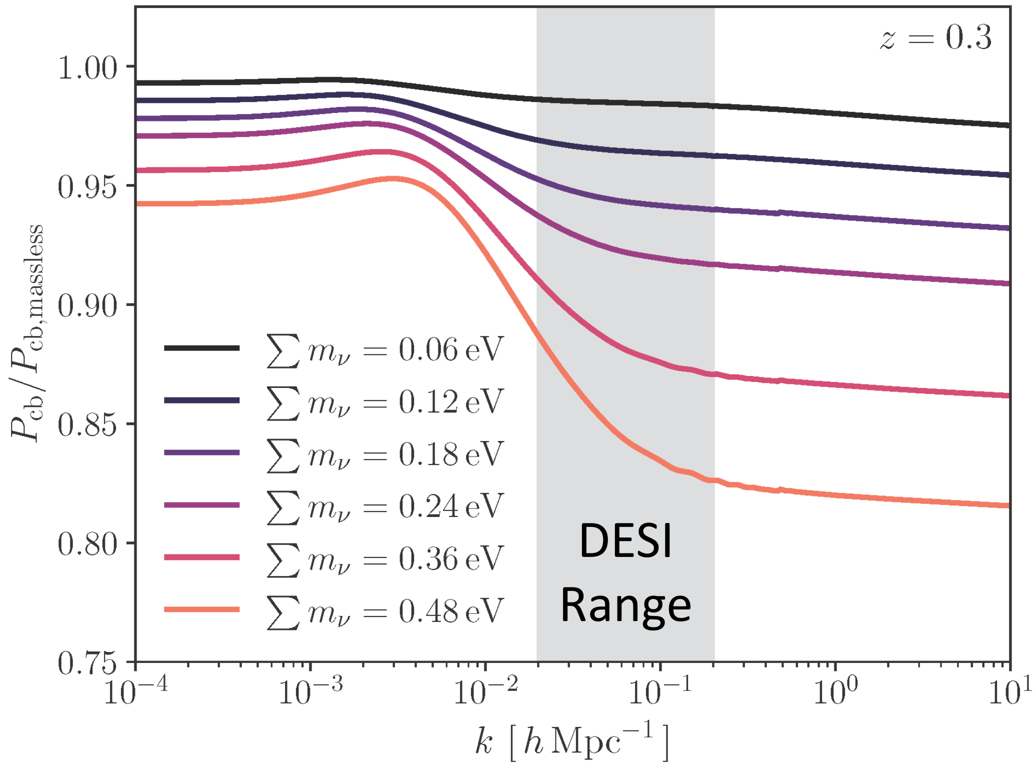


FIG. 2. The neutrino effect at $z = 0.3$ on the linear power spectrum of cold dark matter and baryons, $P_{\rm cb}(k)$, compared to the massless case, for fixed cosmological parameters, $(h, \omega_{\rm b}, \omega_{\rm cdm}, A_{\rm s}, n_{\rm s}, \tau)$. The range of scales used in the DESI full-shape power spectrum analysis is shown as a gray band.

Constraints on Neutrino Physics from DESI DR2 BAO and DR1 Full Shape
https://arxiv.org/abs/2503.14744

DESI Best Fit for Effective Neutrino Masses

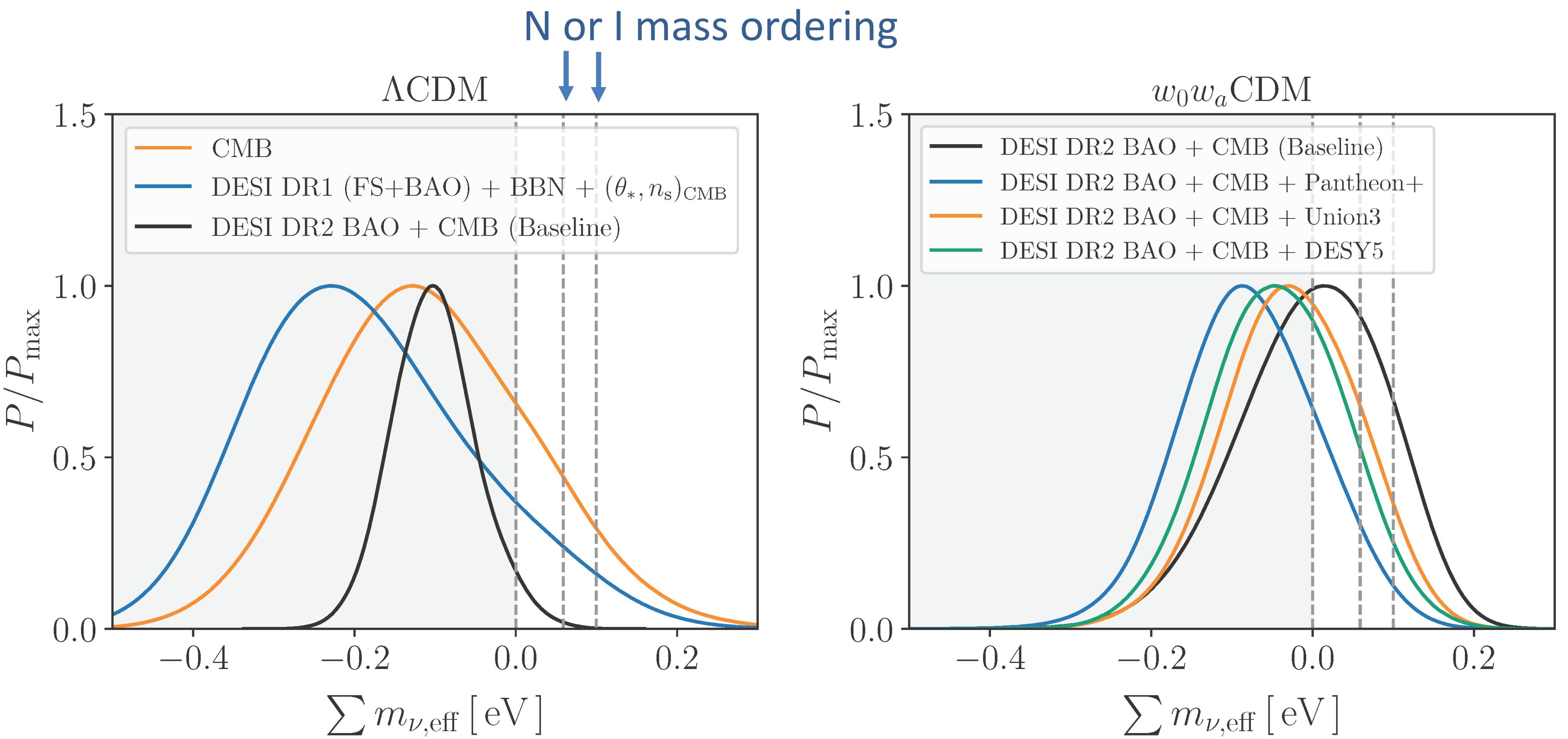
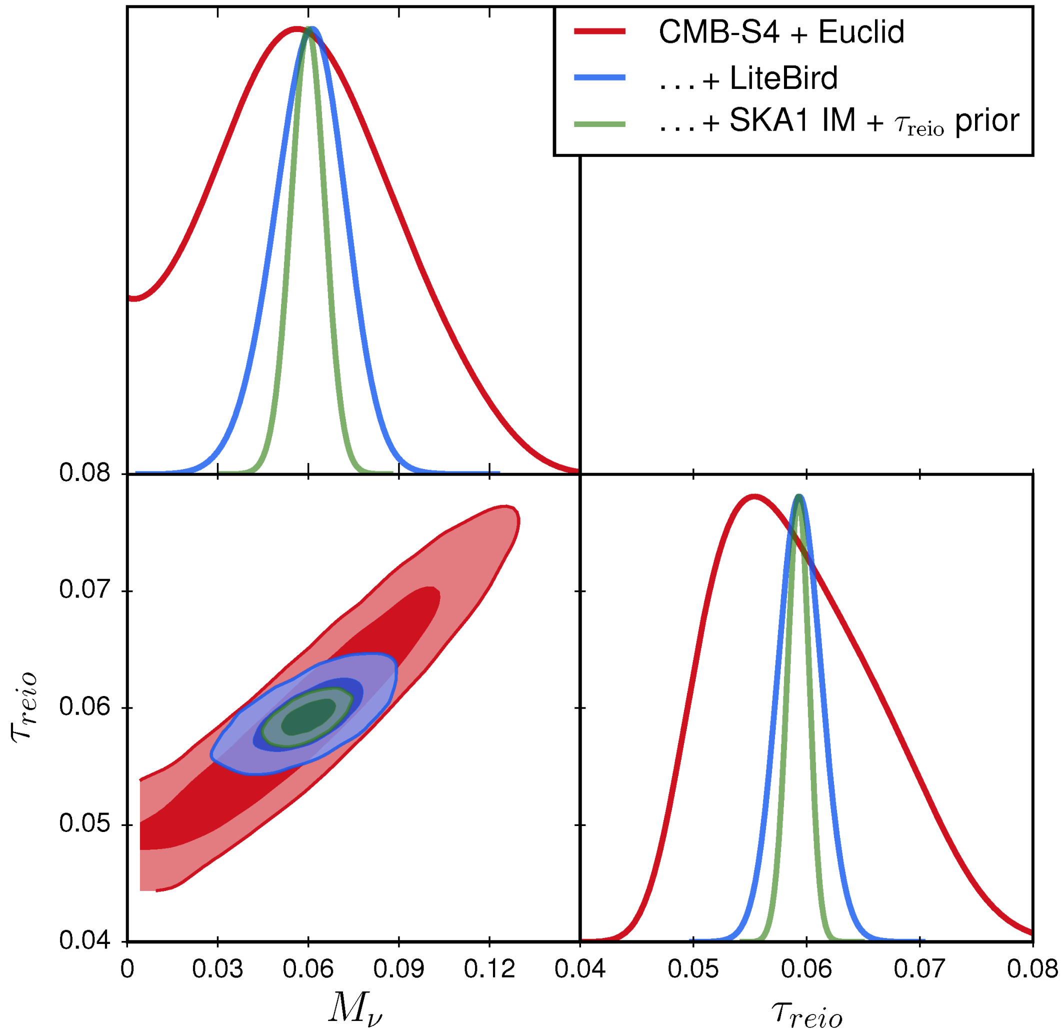
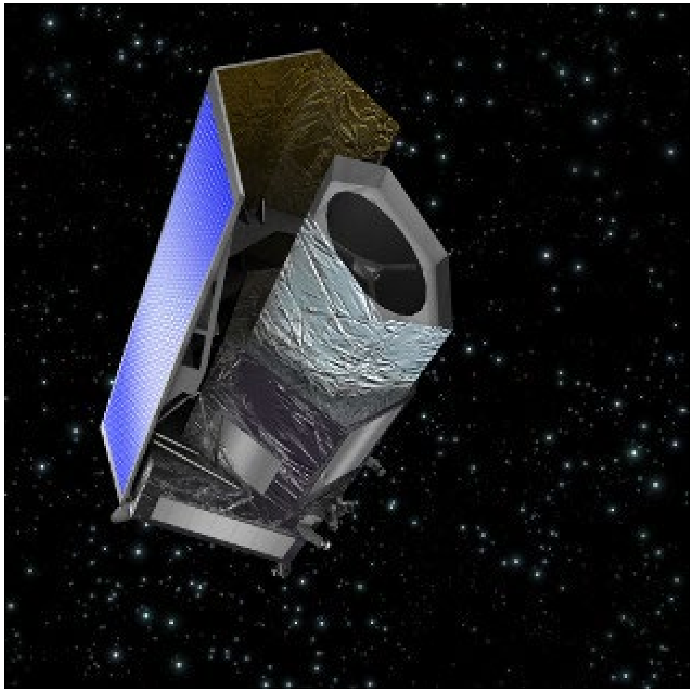


FIG. 11. Left: marginalized constraints on the effective neutrino mass parameter, $\sum m_{\nu,\rm eff}$, in the ΛCDM model, from the CMB, from a full-shape power spectrum analysis of DESI DR1 (including BBN and CMB priors on $\Omega_b h^2, \theta_*$, and n_s), and from the combination of DR2 BAO and CMB. All three combinations prefer negative values, but the tension with the lower bounds from neutrino oscillations (the second and third vertical dashed lines) is only significant for DESI + CMB. Right: the same for the $w_0 w_a$CDM model, using DESI DR2 BAO and CMB data, combined with three different SNe Ia datasets as indicated.

Constraints on Neutrino Physics from DESI DR2 BAO and DR1 Full Shape
https://arxiv.org/abs/2503.14744

Future Cosmological Neutrino Mass Sensitivity





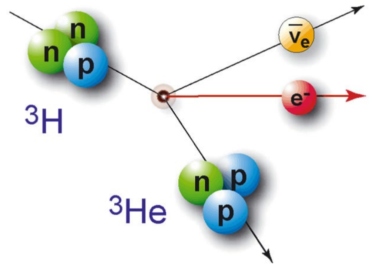
ESA's Euclid satellite
Launched on 1 Juli 2023
Precision measurement of the universe out to redshift of 2

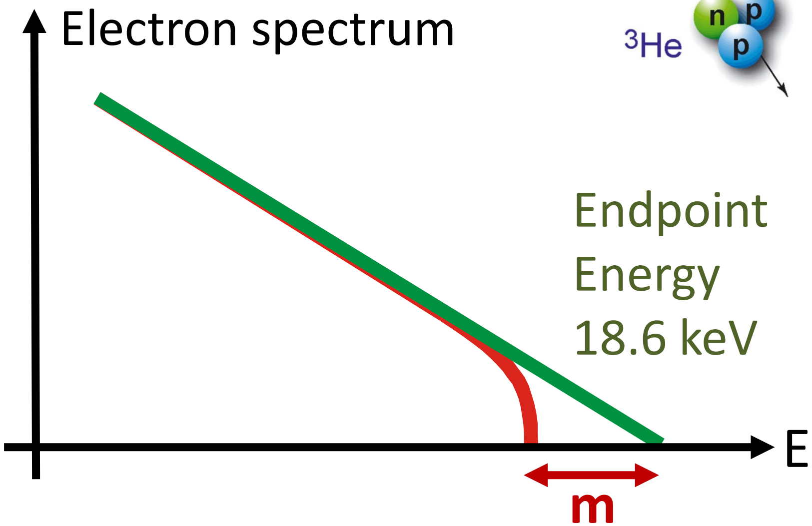
Brinckmann+, https://arxiv.org/abs/1808.05955

"Weighing" Neutrinos with KATRIN

Tritium β decay

$$^3\mathrm{H} \to {}^3\mathrm{He} + e^- + \overline{\nu}_e$$

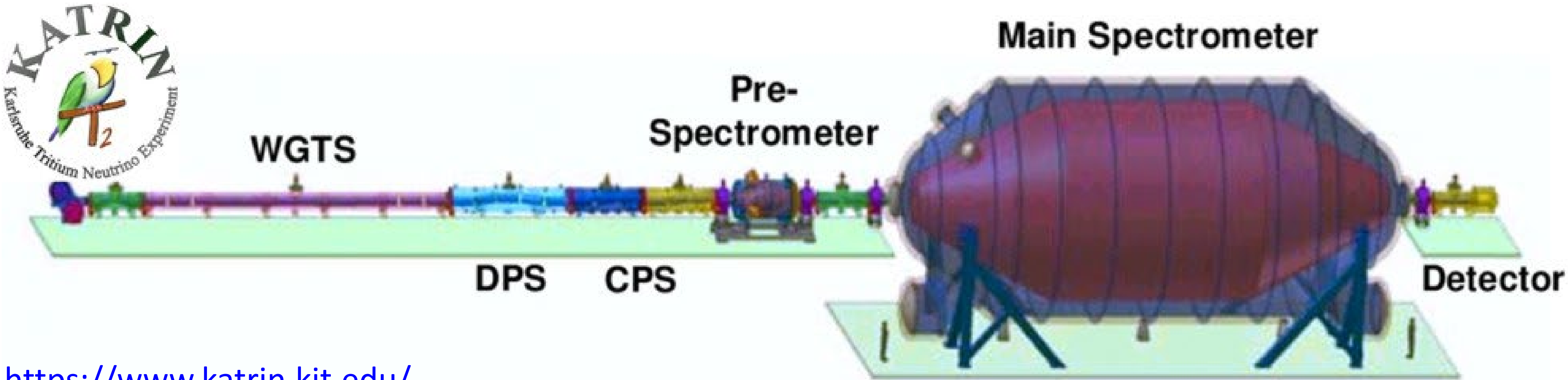




- Sensitive to common mass scale m for all flavors because of small mass differences from oscillations
- Data taking began in mid 2018
- Latest constraint

  m < 0.45 eV (90% CL)

  [Science 388 (2025) 180–185]
- Can reach 0.3 eV (2025–2026)



https://www.katrin.kit.edu/

Cosmic Neutrino Capture in Tritium Beta Decay

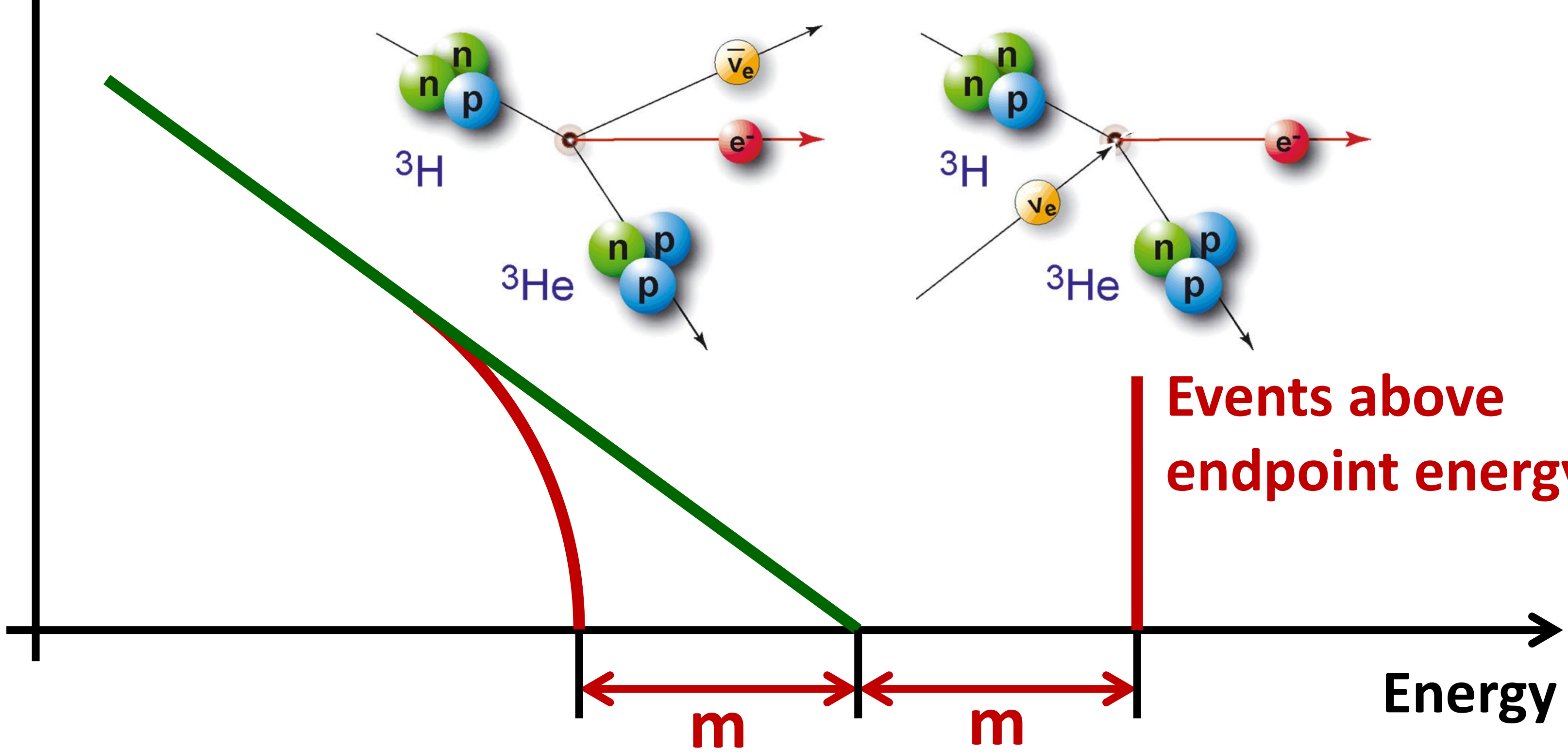
Electron spectrum

Tritium β decay

$$^{3}\mathrm{H} \to {}^{3}\mathrm{He} + \bar{\nu}_e + e^-$$

Tritium inverse β decay capturing cosmic neutrinos

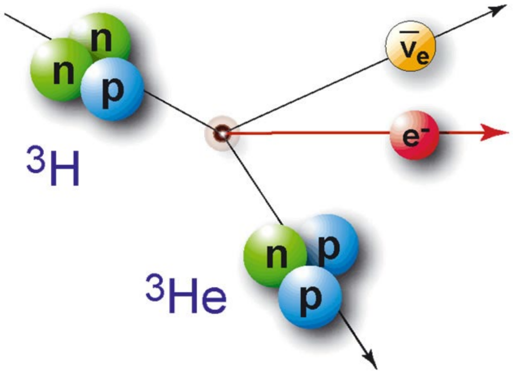
$$\nu_e + {}^{3}\mathrm{H} \to {}^{3}\mathrm{He} + e^-$$



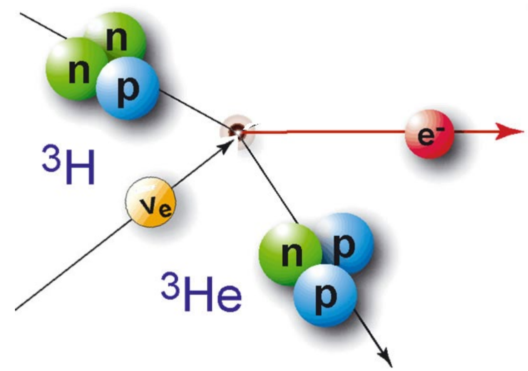
PTOLEMY

[Ptolemy project](#) (Chris Tully et al.)

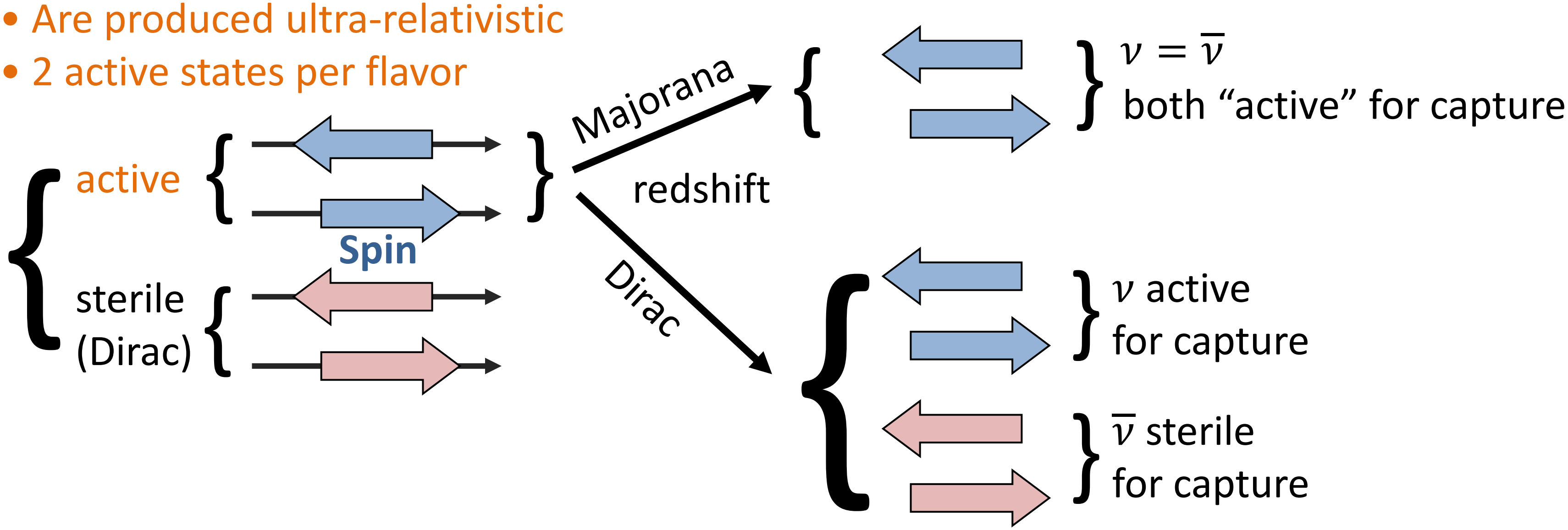
Dirac vs. Majorana Neutrinos



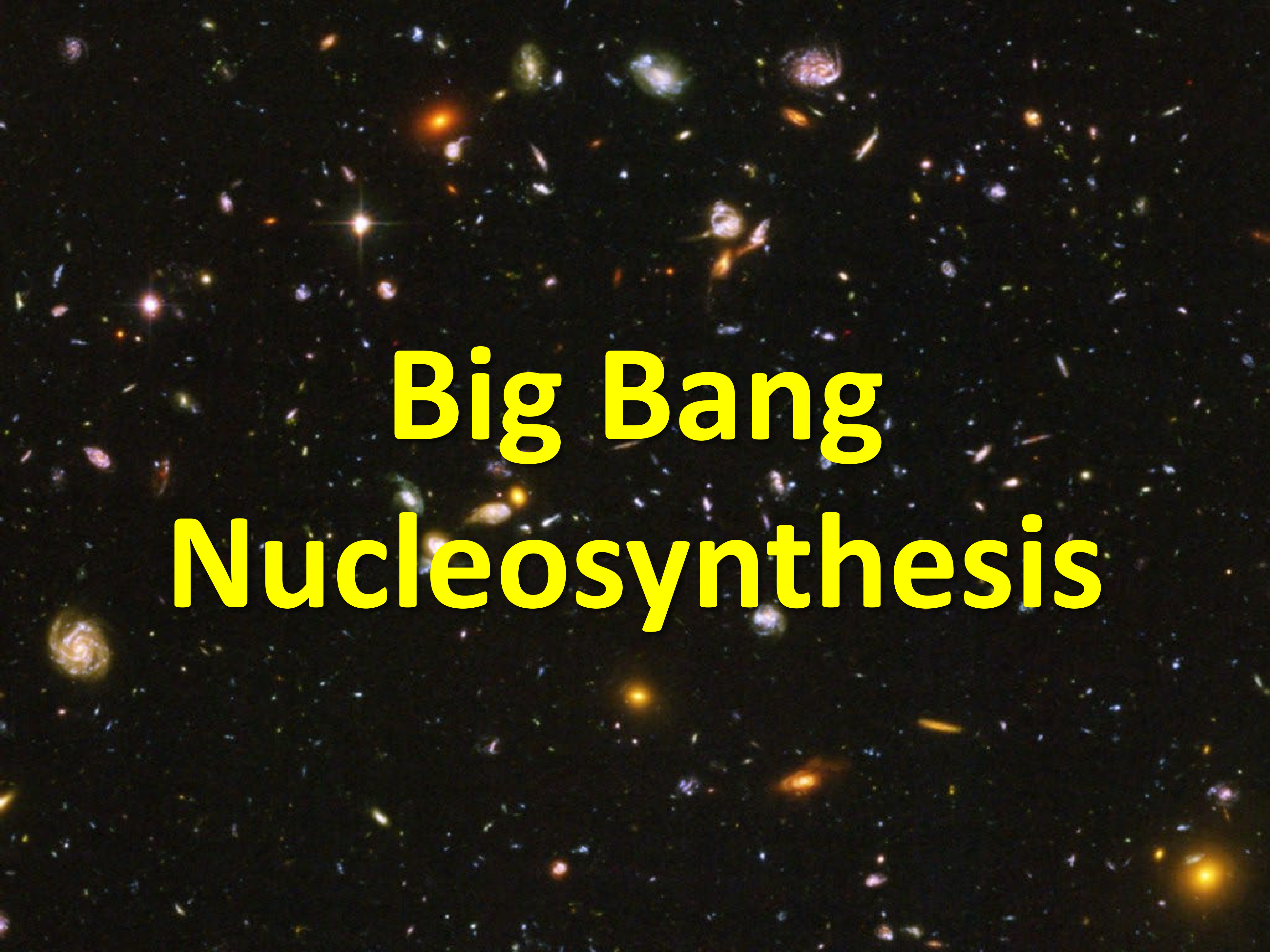
Mass in tritium decay
and ν capture purely kinematical:
No Dirac/Majorana difference



Cosmic background neutrinos:
- Are produced ultra-relativistic
- 2 active states per flavor

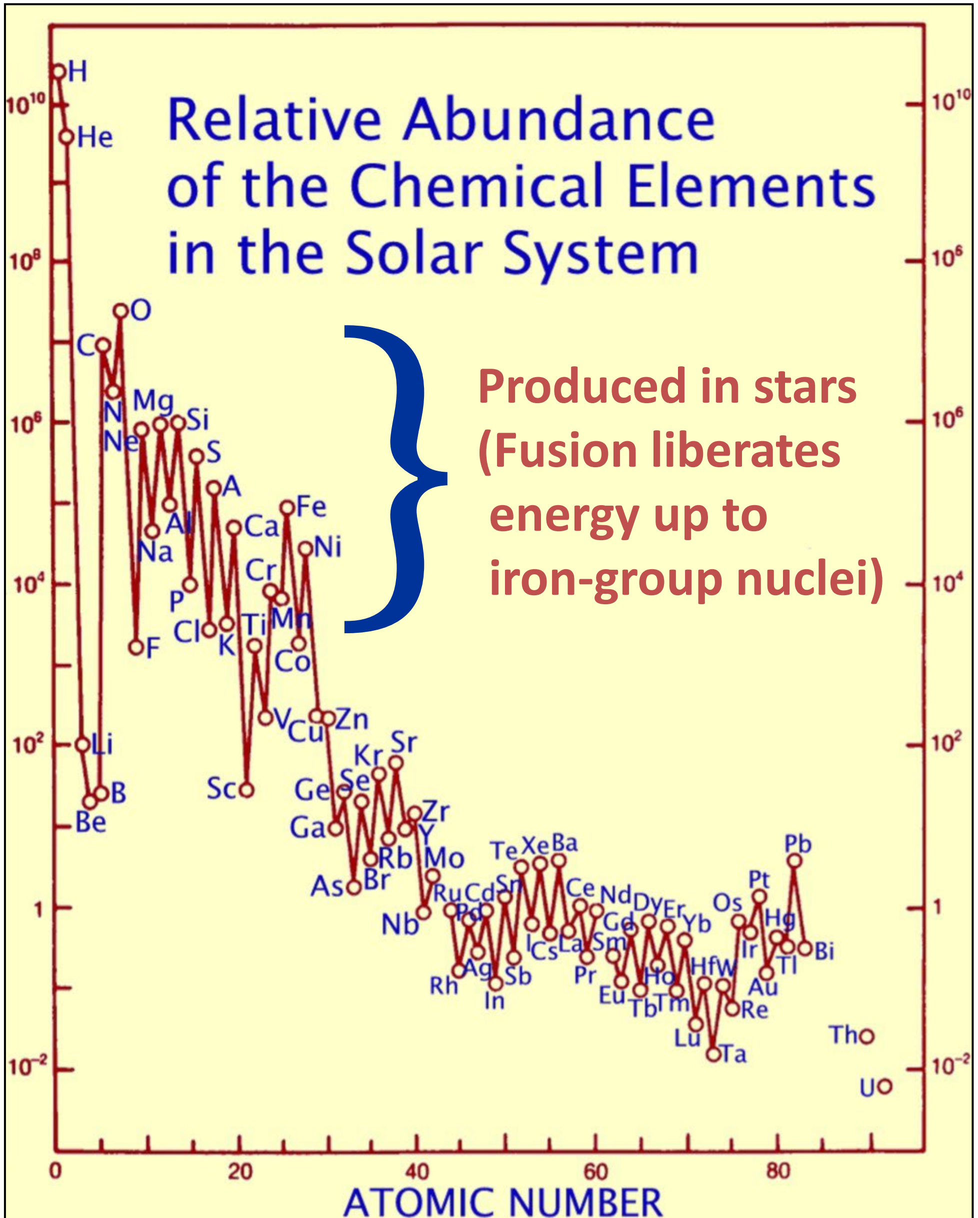


For Majorana neutrinos twice the capture rate!
- Long, Lunardini & Sabancilar, arXiv:1405.7654
- Hernandez-Molinero, Jimenez & Peña-Garay, arXiv:2205.00808



Big Bang Nucleosynthesis

Origin of Elements



- **Mass fraction of helium ~ 25% everywhere in the universe**
- **Most of it not produced in stars (far too little star light from liberated energy)**
- **Big-bang nucleosynthesis (BBN) is a pillar of modern cosmology**
- **Neutrinos play a crucial role**

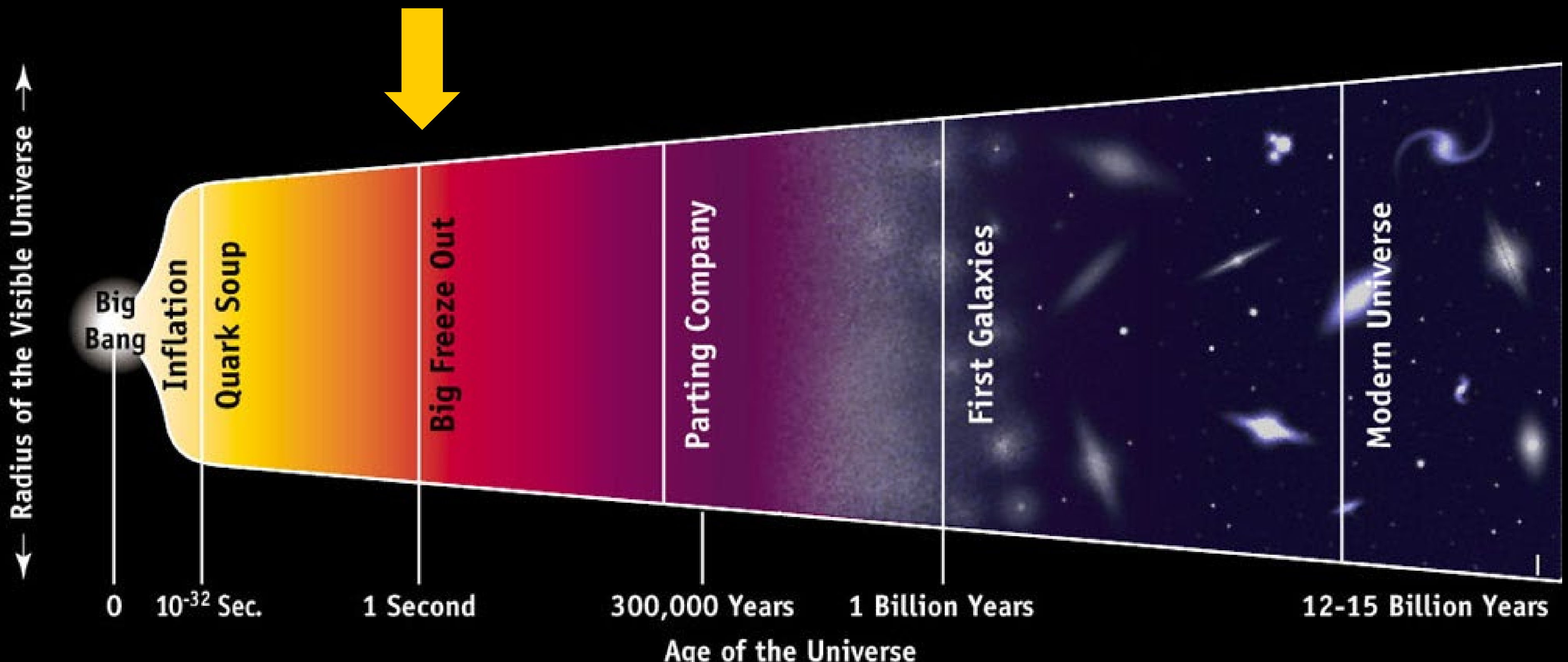
Where, When, and What?

Epoch: 1 sec – 3 minutes

Temperature: 1 MeV – 30 keV

Constituents: Photons, neutrinos, e^+e^-

Baryon density: $0.07\ \mathrm{g\ cm^{-3}}$ (at 1 sec)



Alpher's PhD work

PHYSICAL REVIEW VOLUME 73, NUMBER 7 APRIL 1, 1948

Letters to the Editor

PUBLICATION of brief reports of important discoveries in physics may be secured by addressing them to this department. The closing date for this department is five weeks prior to the date of issue. No proof will be sent to the authors. The Board of Editors does not hold itself responsible for the opinions expressed by the correspondents. Communications should not exceed 600 words in length.

The Origin of Chemical Elements

R. A. ALPHER*
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
AND
H. BETHE
Cornell University, Ithaca, New York
AND
G. GAMOW
The George Washington University, Washington, D. C.
February 18, 1948

AS pointed out by one of us,[1] various nuclear species must have originated not as the result of an equilibrium corresponding to a certain temperature and density, but rather as a consequence of a continuous building-up process arrested by a rapid expansion and cooling of the primordial matter. According to this picture, we must imagine the early stage of matter as a highly compressed neutron gas (overheated neutral nuclear fluid) which started decaying into protons and electrons when the gas pressure fell down as the result of universal expansion. The radiative capture of the still remaining neutrons by the newly formed protons must have led first to the formation of deuterium nuclei, and the subsequent neutron captures resulted in the building up of heavier and heavier nuclei. It must be remembered that, due to the comparatively short time allowed for this process,[1] the building up of heavier nuclei must have proceeded just above the upper fringe of the stable elements (short-lived Fermi elements), and the present frequency distribution of various atomic species was attained only somewhat later as the result of adjustment of their electric charges by β-decay.

Thus the observed slope of the abundance curve must not be related to the temperature of the original neutron gas, but rather to the time period permitted by the expansion process. Also, the individual abundances of various nuclear species must depend not so much on their intrinsic stabilities (mass defects) as on the values of their neutron capture cross sections. The equations governing such a building-up process apparently can be written in the form:

$$\frac{dn_i}{dt} = f(t)(\sigma_{i-1}n_{i-1} - \sigma_i n_i) \quad i = 1, 2, \cdots 238, \qquad (1)$$

where n_i and σ_i are the relative numbers and capture cross sections for the nuclei of atomic weight i, and where $f(t)$ is a factor characterizing the decrease of the density with time.

We may remark at first that the building-up process was apparently completed when the temperature of the neutron gas was still rather high, since otherwise the observed abundances would have been strongly affected by the resonances in the region of the slow neutrons. According to Hughes,[2] the neutron capture cross sections of various elements (for neutron energies of about 1 Mev) increase exponentially with atomic number halfway up the periodic system, remaining approximately constant for heavier elements.

Using these cross sections, one finds by integrating Eqs. (1) as shown in Fig. 1 that the relative abundances of various nuclear species decrease rapidly for the lighter elements and remain approximately constant for the elements heavier than silver. In order to fit the calculated curve with the observed abundances[3] it is necessary to assume the integral of $\rho_n dt$ during the building-up period is equal to 5×10^4 g sec./cm³.

On the other hand, according to the relativistic theory of the expanding universe[4] the density dependence on time is given by $\rho \cong 10^6/t^2$. Since the integral of this expression diverges at $t=0$, it is necessary to assume that the building-up process began at a certain time t_0, satisfying the relation:

$$\int_{t_0}^{\infty} (10^6/t^2)dt \cong 5\times10^4, \qquad (2)$$

which gives us $t_0 \cong 20$ sec. and $\rho_0 \cong 2.5\times10^5$ g sec./cm³. This result may have two meanings: (a) for the higher densities existing prior to that time the temperature of the neutron gas was so high that no aggregation was taking place, (b) the density of the universe never exceeded the value 2.5×10^5 g sec./cm³ which can possibly be understood if we

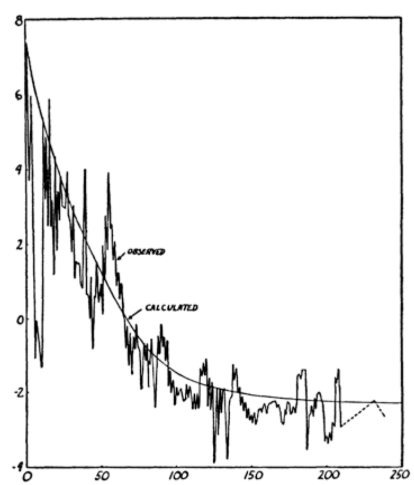
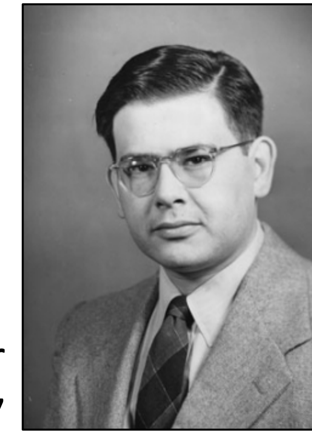


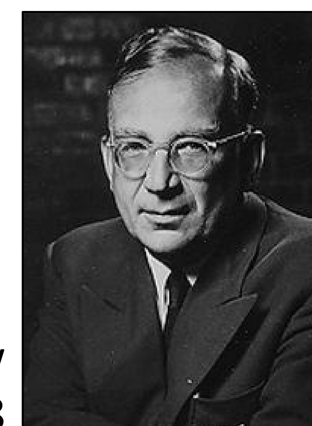
FIG. 1.
Log of relative abundance
Atomic weight



Ralph Alpher
1921–2007

Bethe included
as a joke ($\alpha\beta\gamma$)

Hans Bethe
1906–2005



George Gamow
1904–1968

This cartoon, published in the Washington Post (April 16, 1948), was inspired by a statement in Alpher's dissertation to the effect that the period of nucleosynthesis in the early universe lasted about 5 minutes. © The Herb Block Foundation.

Helium Synthesis – Three Easy Steps

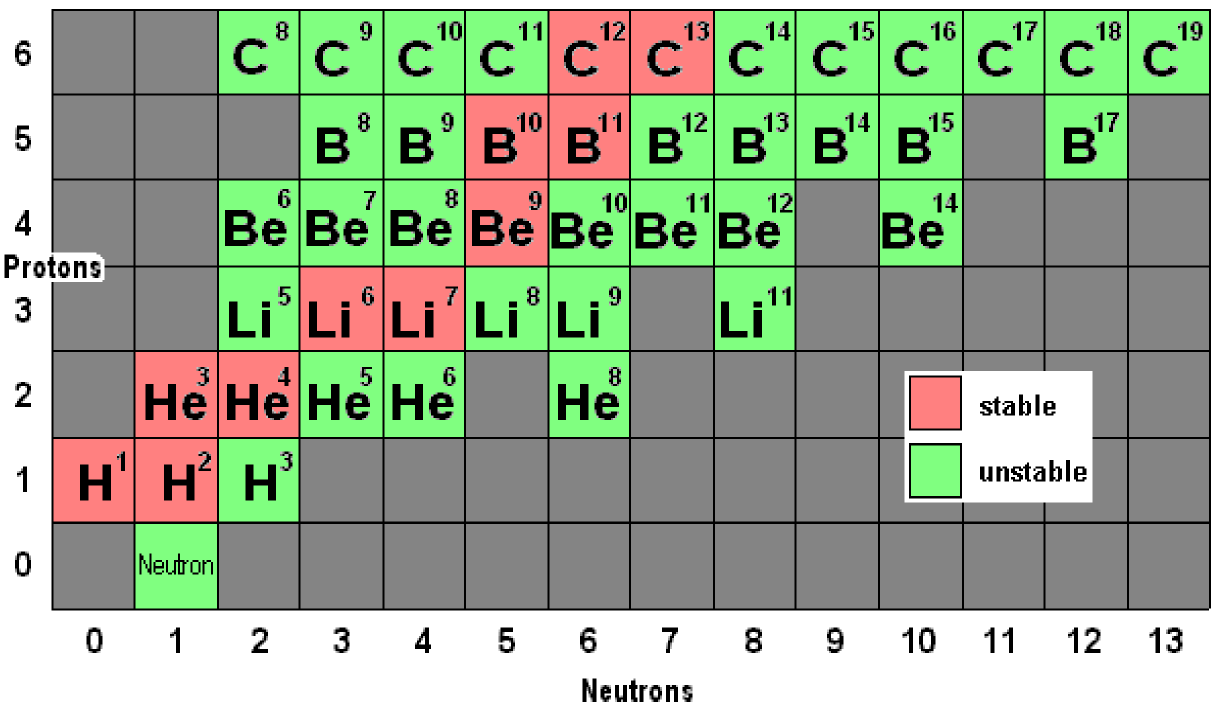
t (sec)	T (MeV)			
		β equilibrium	$p + e^- \leftrightarrow n + \nu_e$ $p + \overline{\nu}_e \leftrightarrow n + e^+$	$\frac{n}{p} = \exp\left(-\frac{m_n - m_p}{T}\right) \approx 1$ $m_n - m_p = 1.293~\mathrm{MeV}$
1	1	β freeze-out	$\frac{n}{p} \approx \frac{1}{6}$	β rates fall below expansion rate H
		• Neutron decay • Nuclear statist. equilibrium	$n_n \propto \exp\left(-\frac{t}{\tau_n}\right)$ $\tau_n \approx 880~\mathrm{sec}$	$2\mathrm{p} + 2\mathrm{n} \leftrightarrow {}^4\mathrm{He} + \gamma$ Helium suppressed by large entropy
100	0.1	Neutrons freeze in helium	$\frac{n}{p} \approx \frac{1}{7}$	Helium mass fraction $Y_P \approx 25\%$
		Thermonuclear reaction chains	Production and destruction of traces of D, ^{3}He, ^{6}Li, ^{7}Li, ^{7}Be	
10^4	0.01	All done		

Why do nuclei form so late?

- Thermal equilibrium → all nuclei present
- Binding energies much larger than MeV, so why are they still dissociated at weak-interaction freeze-out? Why not everything in iron?
- Basic answer: High-entropy environment with $\sim 10^9$ photons per baryon

$$Nn + Zp \leftrightarrow (A, Z) + \text{photons}$$

High-E tail of photon distribution enough to keep nuclei dissociated



	B (MeV)	B/A (MeV)
D	2.23	1.1
^{3}H	6.92	2.3
^{3}He	7.72	2.6
^{4}He	28.30	7.1
^{6}Li	31.99	5.3
^{7}Li	39.25	5.6
^{7}Be	37.60	5.4
^{12}C	92.2	7.7

Predicting the Cosmic Microwave Background

Nature 162 (1948) 774–775

Evolution of the Universe

IN checking the results presented by Gamow in his recent article on "The Evolution of the Universe" [*Nature* of October 30, p. 680], we found that his expression for matter-density suffers from the following errors: (1) an error of not taking into account the magnetic moments in Eq. (7) for the capture cross-section, (2) an error in estimating the value of α by integrating the equations for deuteron formation (the use of an electronic analogue computer leads to $\alpha = 1$), and (3) an arithmetical error in evaluating ρ_0 from Eq. (9). In addition, the coefficient in Eq. (3) is 1·52 rather than 2·14. Correcting for these errors, we find

$$\rho_{\text{mat.}} = \frac{4{\cdot}83 \times 10^{-4}}{t^{3/2}}.$$

The condensation-mass obtained from this corrected density comes out not much different from Gamow's original estimate. However, the intersection point $\rho_{\text{mat.}} = \rho_{\text{rad.}}$ occurs at $t = 8{\cdot}6 \times 10^{17}$ sec. $\cong 3 \times 10^{10}$ years (that is, about ten times the present age of the universe). This indicates that, in finding the intersection, one should not neglect the curvature term in the general equation of the expanding universe. In other words, the formation of condensations must have taken place when the expansion was becoming linear with time.

Accordingly, we have integrated analytically the exact expression[1]:

$$\frac{dl}{dt} = \left[\frac{8\pi G}{3}\left(\frac{aT^4}{c^2} + \rho_{\text{mat.}}\right)l^2 - \frac{c^2 l_0^2}{R_0^2}\right]^{1/2},$$

with $T \propto 1/l$ and $R_0 = 1{\cdot}9 \times 10^9 \sqrt{-1}$ light-years. The integrated values of $\rho_{\text{mat.}}$ and $\rho_{\text{rad.}}$ intersect at a reasonable time, namely, $3{\cdot}5 \times 10^{14}$ sec. $\cong 10^7$ years, and the masses and radii of condensations at this time become, according to the Jeans' criterion, $M_c = 3{\cdot}8 \times 10^7$ sun masses, and $R_c = 1{\cdot}1 \times 10^3$ light-years. The temperature of the gas at the time of condensation was 600° K., and the temperature in the universe at the present time is found to be about 5° K.

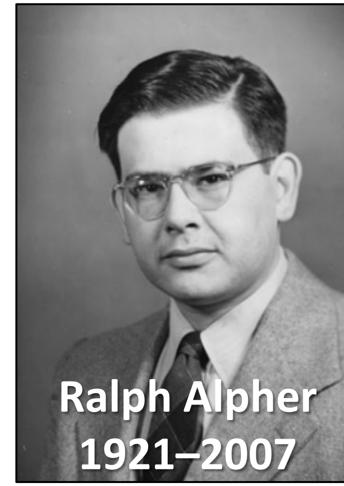
We hope to publish the details of these calculations in the near future.

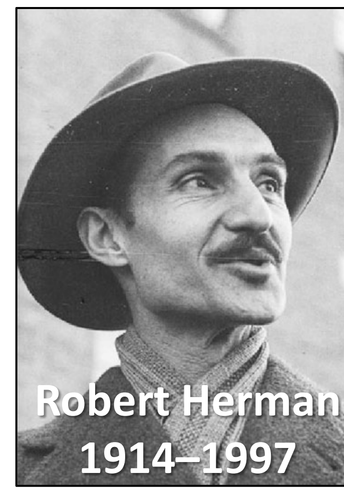
Our thanks are due to Dr. G. Gamow for the proposal of the topic and his constant encouragement during the process of error-hunting. We wish also to thank Dr. J. W. Follin, jun., for his kindness in performing the integrations required for the determination of α, on a Reeves Analogue Computer. The work described in this letter was supported by the United States Navy, Bureau of Ordnance, under Contract NOrd-7386.

RALPH A. ALPHER
ROBERT HERMAN

Applied Physics Laboratory,
Johns Hopkins University,
Silver Spring, Maryland.
Oct. 25.

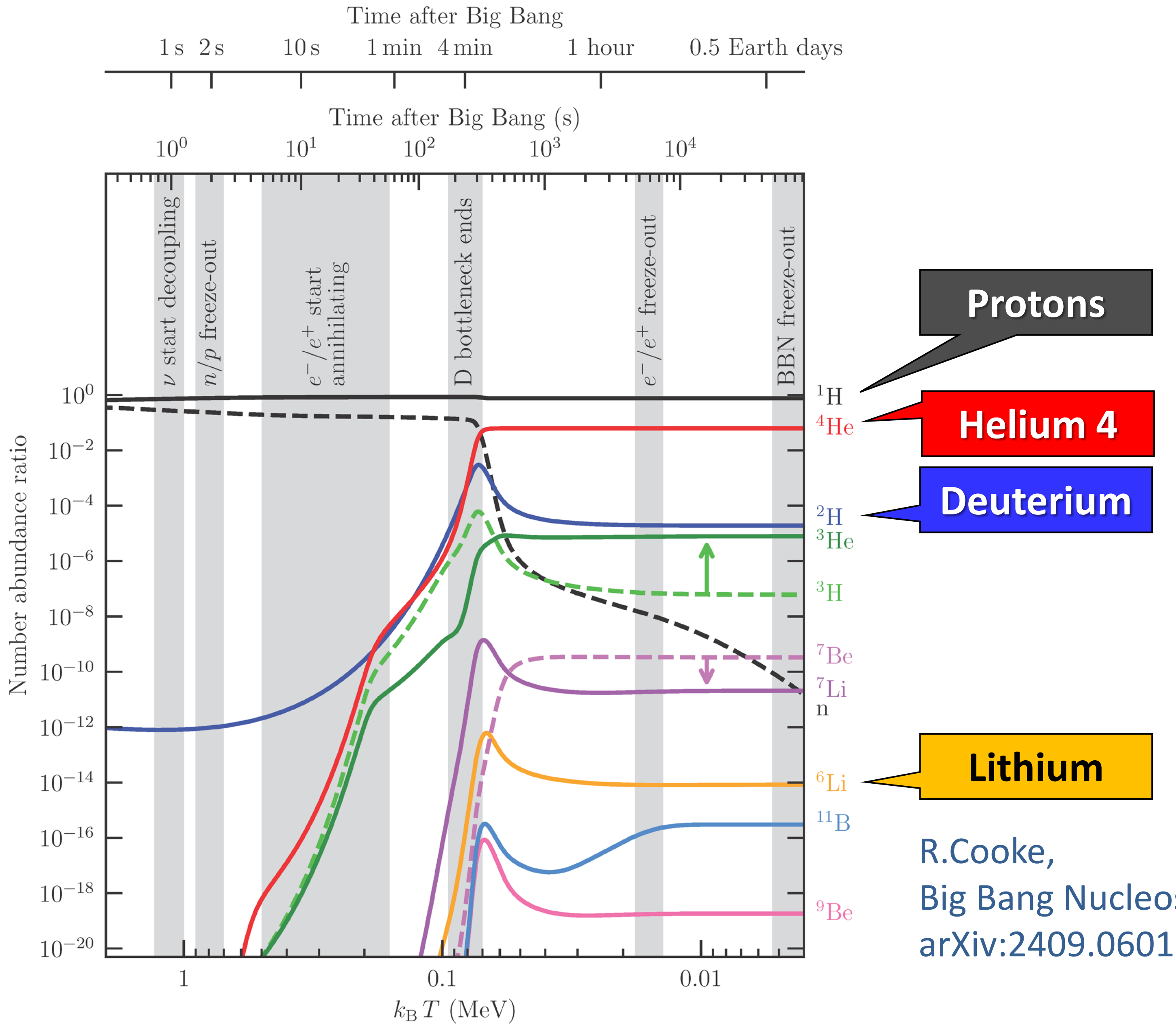
[1] Gamow, G., *Phys. Rev.*, **70**, 572 (1946).





See also Alpher & Herman, Reflections on Early Work on Big Bang Cosmology
Physics Today, August 1988, pp 24–34

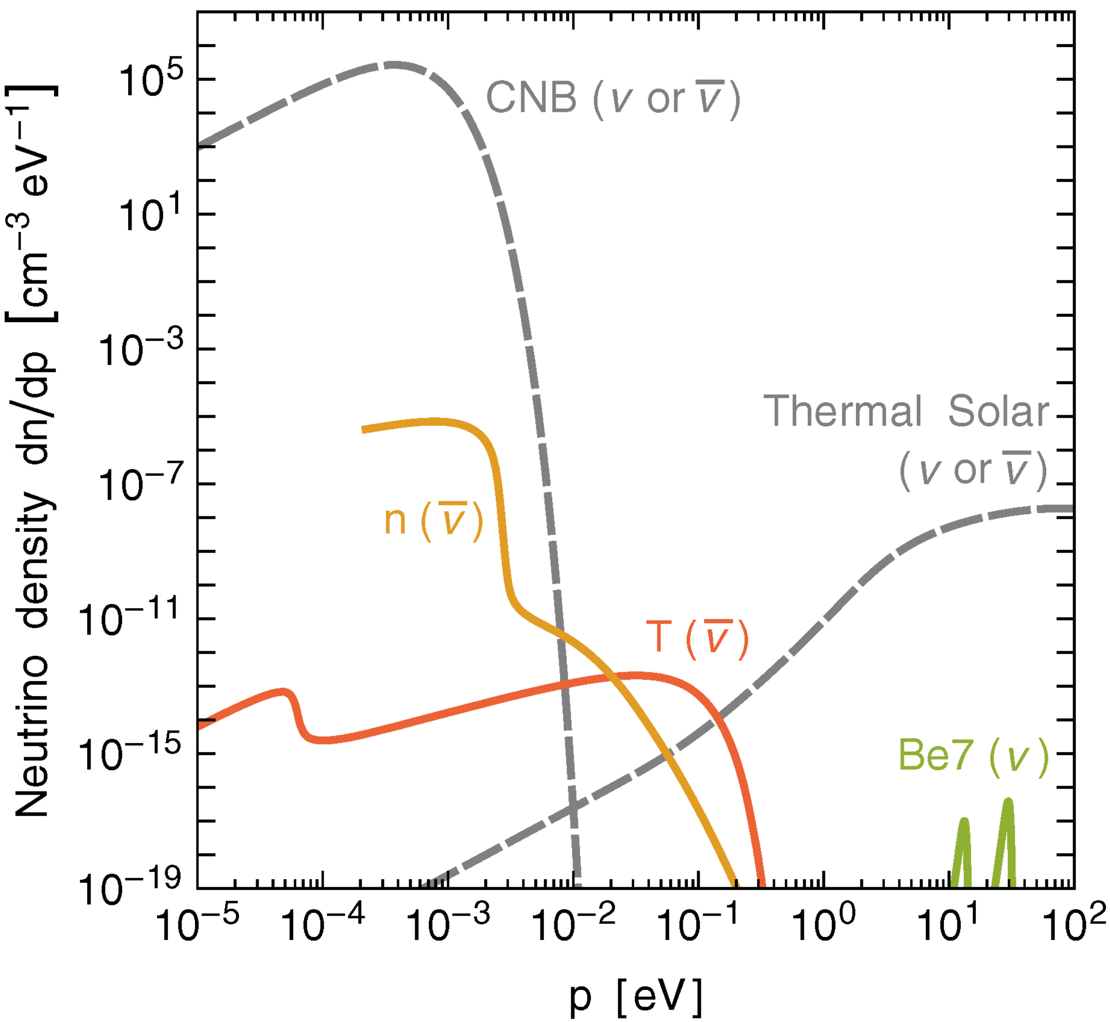
Formation of Light Elements



R.Cooke,
Big Bang Nucleosynthesis
arXiv:2409.06015

Neutrinos from Decay of Light BBN Nuclei

Vitagliano et al., arXiv:1910.11878



Khatri & Sunyaev
arXiv:1009.3932

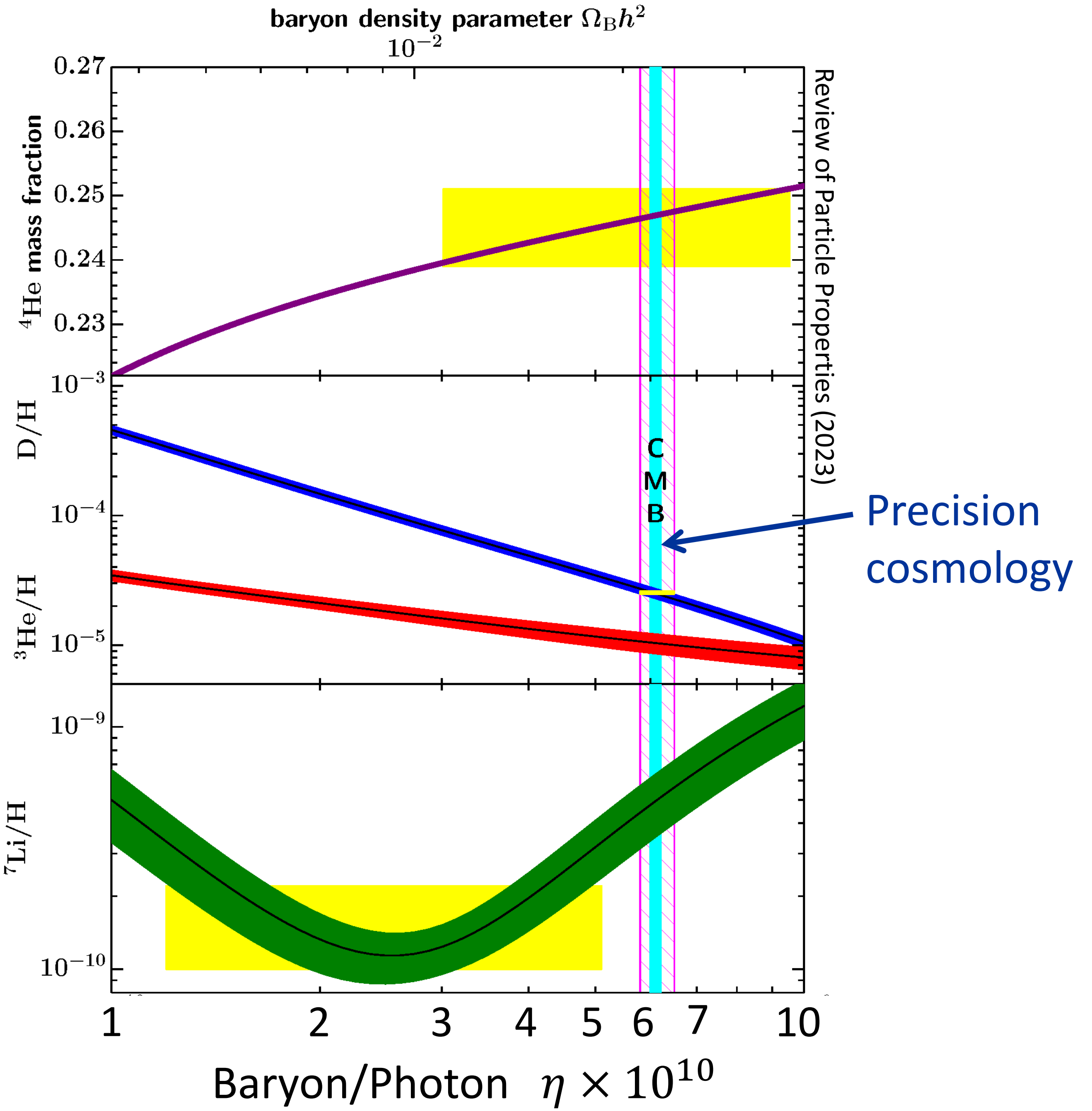
Ivanchik & Yurchenko
arXiv:1809.03349

BBN Theory vs Observations

- He-4 and H-2 (deuterium) main reliable probes
- Come mostly from BBN

Primordial He-3 difficult to measure, heavily processed

Lithium processed in stars, but discrepancy hard to explain. Unresolved “Lithium problem”



Neutrino Impact on BBN

- **Radiation density ρ**

  Determines expansion rate $H^2 = \frac{8\pi}{3} G_{\rm N} \rho$

  Faster expansion $\to$ less time for neutron decay $\to$ more He

  $Y_P \approx 0.2485 + 0.013\,\Delta N_{\rm eff}$

  Historically first way to "count flavors"

  Still of interest for sterile neutrinos

- **Chemical potential μ_{ν_e} modifies β equilibrium**

  $\frac{n}{p} = \exp\left(-\frac{m_n - m_p}{T} - \frac{\mu_{\nu_e}}{T}\right)$

  Modifies frozen neutron abundance

  Bounds on ν_e-$\overline{\nu}_e$ asymmetry

  (But probably very small, similar to matter-antimatter)

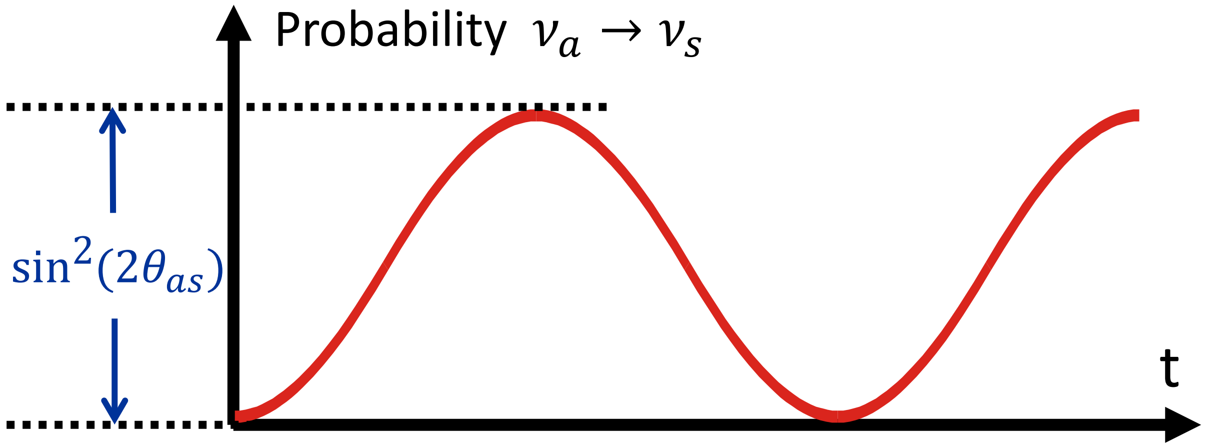
Sterile Neutrino Oscillations

Sterile (right-handed) neutrinos ν_s may exist
Not the Dirac partner of ordinary (active) neutrino $\nu_a = \nu_e, \nu_\mu$, or ν_τ
(White Papers arXiv:1204.5379, 1602.04816, 2203.07323)

- Unknown mass m_s
- Unknown mixing angles with ordinary neutrinos Θ_{es}, $\Theta_{\mu s}$, and $\Theta_{\tau s}$
- Some experimental "anomalies" explained by ν_s
- Experimental constraints imply that mixing angle must be small

Production in the early universe?

- Naïve average population $\langle p_{\nu_a \to \nu_s} \rangle = \frac{1}{2}\sin^2(2\theta_{as}) \ll 1$ (ignoring matter effects)



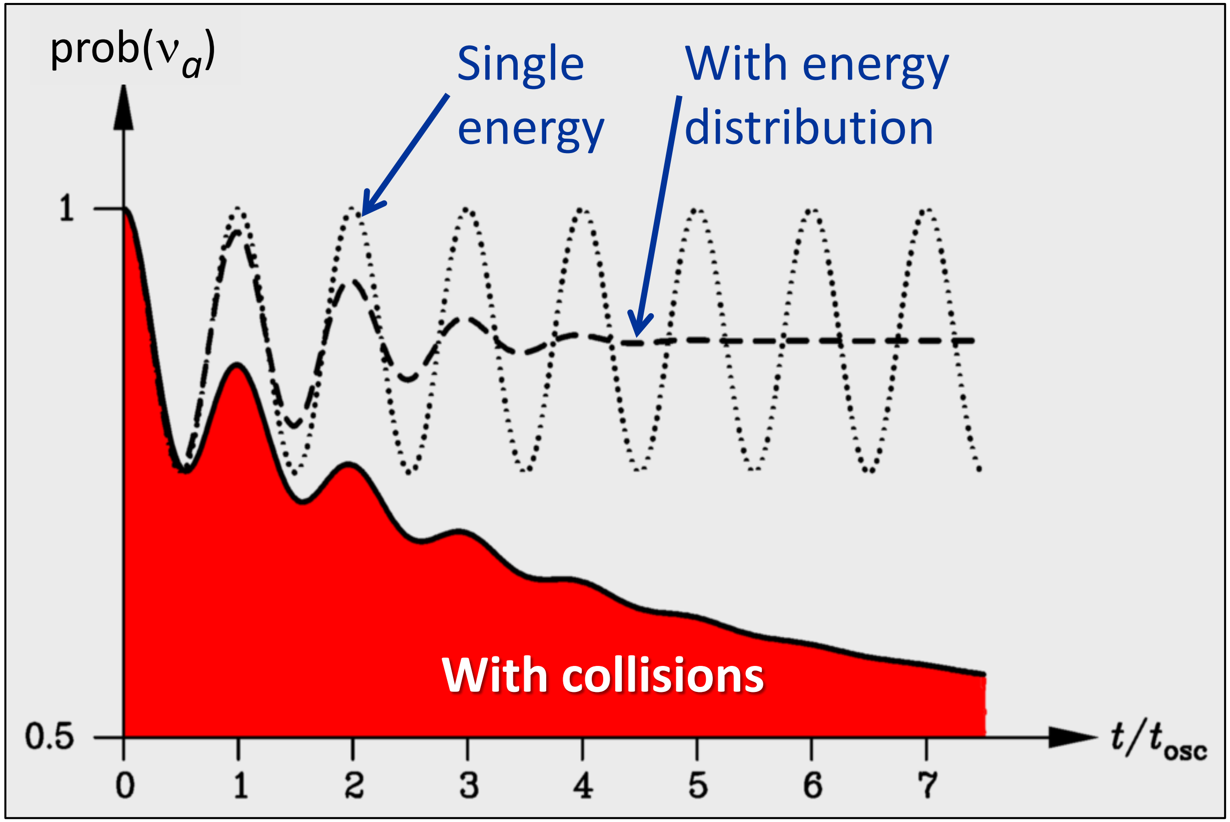
Flavor Relaxation in a Medium

Active neutrinos suffer collisions in a medium (rate Γ), but not ν_s

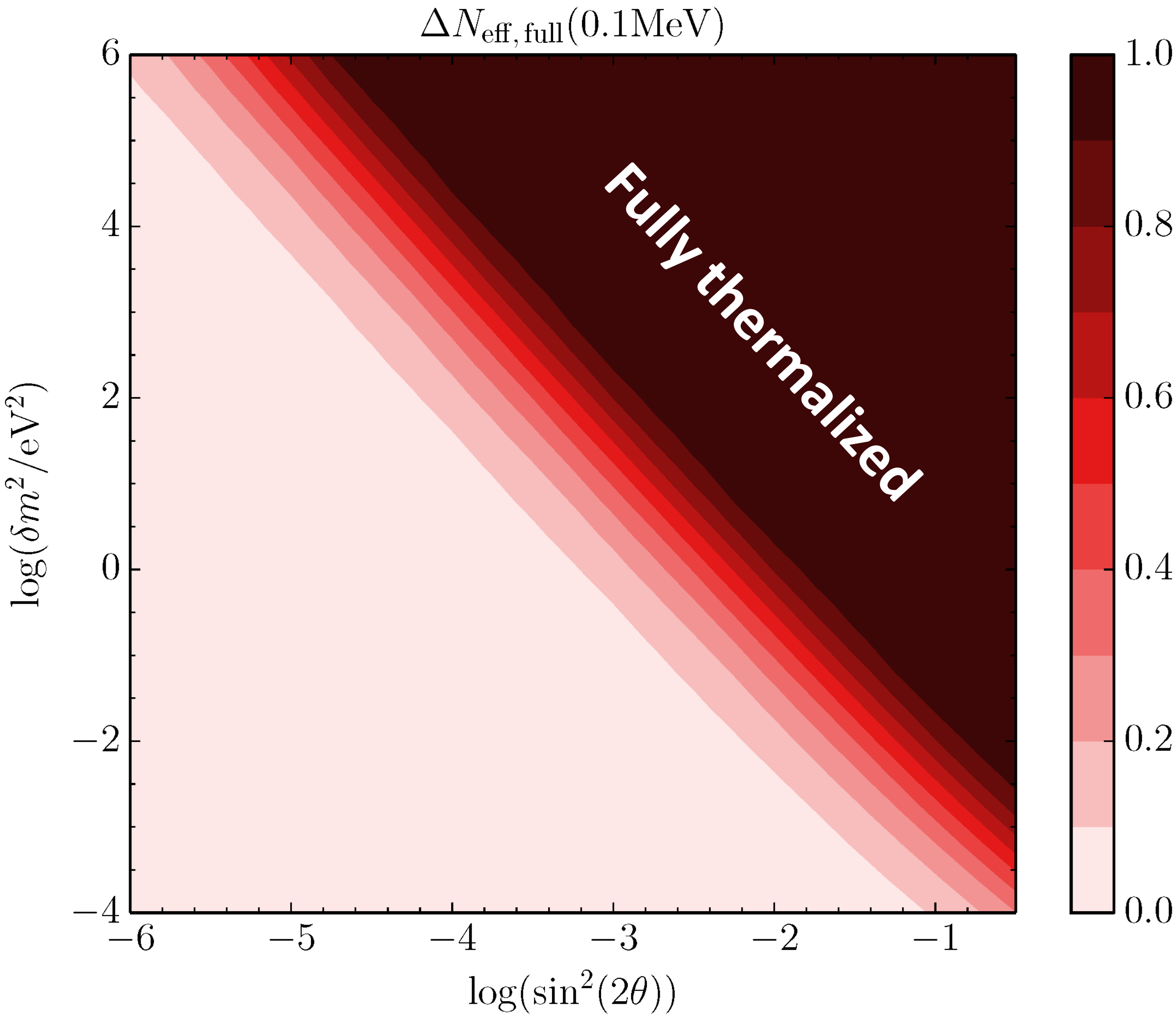
- Mixed state "collapses" to ν_a or ν_s
- Flavor content is "measured" by the medium at intervals $\tau \sim \Gamma^{-1}$
- Oscillations begin again
- Average oscillation probability $^1/_2\,\sin^2(2\Theta)$

Flavor conversion rate

$$\frac{1}{2}\sin^2(2\Theta)\ \Gamma$$



Parameters for Thermalisation



Hannestad, Hansen, Tram & Wong, arXiv:1506.05266

BBN and Neutrino Chemical Potentials

Expansion rate effect (all flavors)

Energy density in one neutrino flavor with degeneracy parameter $\xi = \eta/T$

$$\rho_{\nu\overline{\nu}} = \frac{7\pi^2}{120}\,T_\nu^4\left[1+\underbrace{\frac{30}{7}\left(\frac{\xi}{\pi}\right)^2+\frac{15}{7}\left(\frac{\xi}{\pi}\right)^4}_{\Delta N_{\rm eff}}\right]$$

Beta equilibrium effect for electron flavor

$n+\nu_e \leftrightarrow p+e^-$

Helium abundance essentially fixed by n/p ratio at beta freeze-out

$$\frac{n}{p} = e^{-(m_n-m_p)/T_{\rm F}-\xi_{\nu_e}}$$

Effect on helium equivalent to

$$\Delta N_{\rm eff} \sim -18\,\xi_{\nu_e}$$

- ν_e beta effect can compensate expansion-rate effect of $\nu_{\mu,\tau}$
- Naively, no significant BBN limit on neutrino number density
- However, flavor oscillations equalize chemical potentials before BBN

Chemical Potentials and Flavor Oscillations

Flavor mixing
(neutrino oscillations)

Flavor lepton numbers
not conserved

Only one common neutrino
chemical potential

Stringent ξ_{ν_e} limit
applies to all flavors
$|\xi_{\nu_{e,\mu,\tau}}| < 0.07$

Extra neutrino density
$\Delta N_{eff} < 0.0064$

Cosmic neutrino density
close to standard value

Flavor equilibrium before n/p freeze out assured because all mixing angles not small

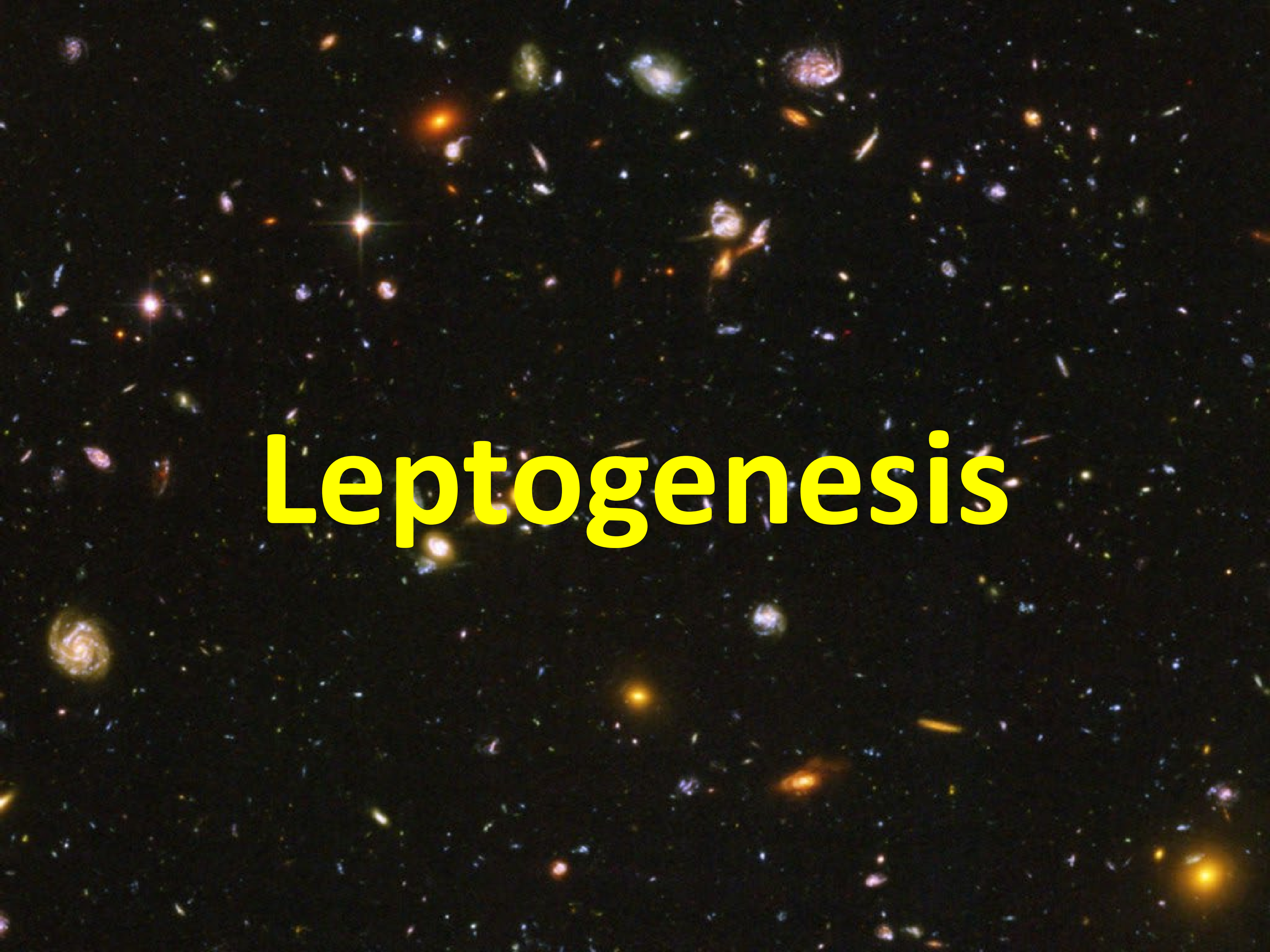
Our knowledge of the cosmic neutrino density depends on measured oscillation parameters!

arXiv:hep-ph/0012056 , hep-ph/0201287,
astro-ph/0203442, hep-ph/0203180,
arXiv:0808.3137, 1011.0916, 1110.4335
Most recently
Froustey & Pitrou, arXiv:2405.06509

BBN Summary

- BBN accounts well for He and D abundance
- Lithium remains in tension
- Large neutrino asymmetries not possible
- Cosmic neutrino background exists
  with roughly the predicted abundance
- Agrees well with CMB and LSS data
- BBN remains valuable probe for BSM physics,
  dark matter decay, or similar

Leptogenesis



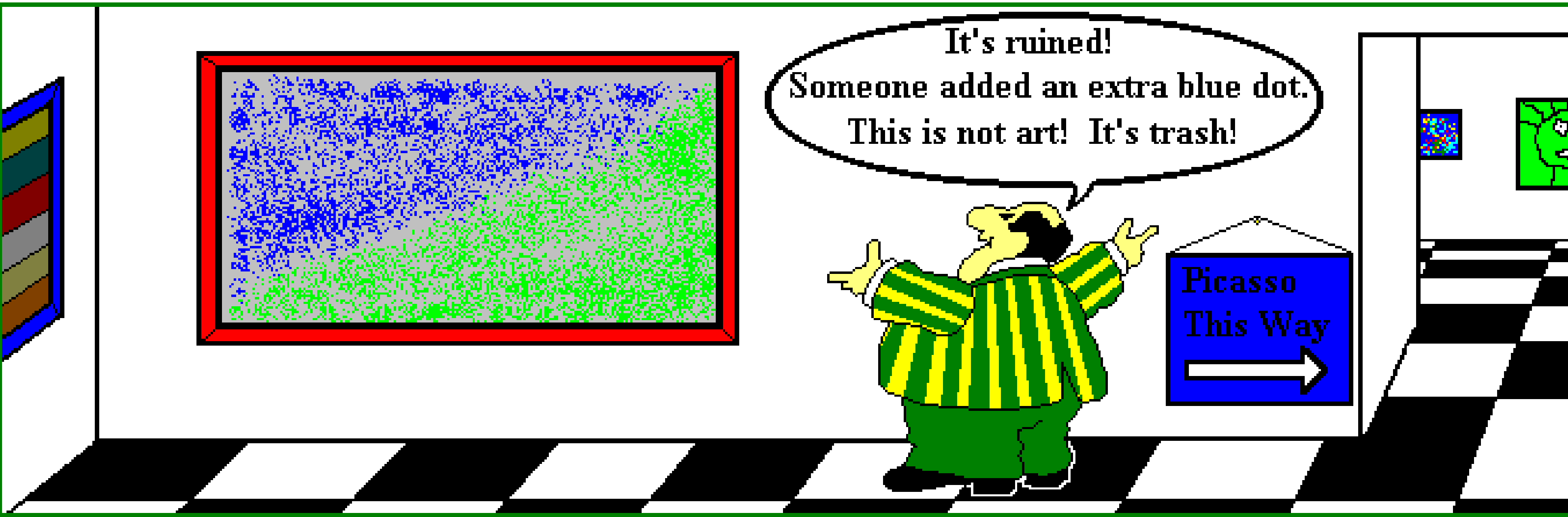
- More matter than anti-matter in the universe (BAU – Baryon Asymmetry of the Universe)
- Not from initial conditions (inflationary universe)
- Should be generated by physical process: “Baryogenesis”
- Requires an absolute difference between matter and anti-matter in laws of physics

Cosmic Matter-Antimatter Asymmetry

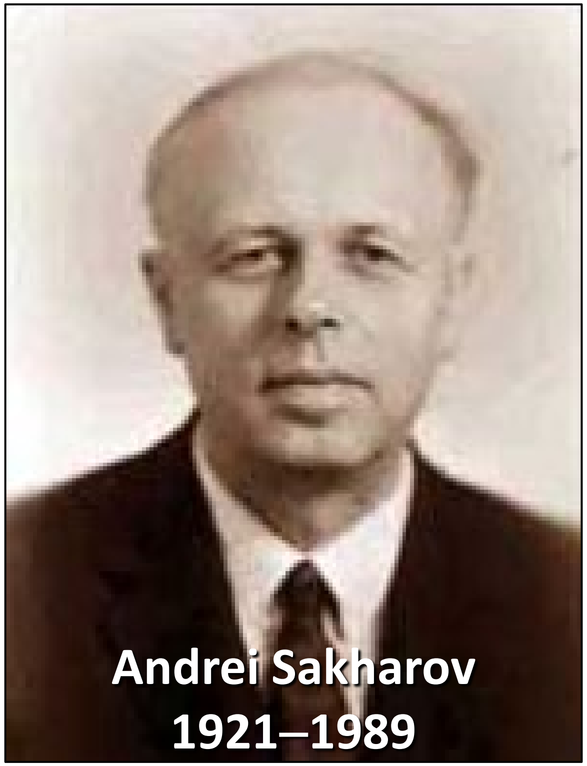
- No substantial regions of antimatter in the universe (gamma rays!)
- Baryon densiy relative to CMB photons today

$$\eta_B = \frac{n_B}{n_\gamma} = (6.12 \pm 0.04) \times 10^{-10}$$

- Universe electrically neutral ($n_p \simeq n_e$), but how much L in neutrinos? (for Majorana neutrinos L not even defined)
- Matter-antimatter asymmetry $\simeq$ Baryon asymmetry
- Hot early universe: 1 extra quark per 10^9 thermal quark-antiquark pairs



Baryogenesis in the Early Universe



Sakharov conditions for creating the Baryon Asymmetry of the Universe (BAU)
- C and CP violation
- Baryon number violation
- Deviation from thermal equilibrium

JETP Lett. 5 (1967) 24

Particle-physics standard model
- Violates C and CP
- Violates B and L by EW sphaleron effects (B – L conserved)
- Expanding universe provides deviation from thermal equilibrium

However, electroweak baryogenesis not quantitatively possible within Standard Model (not enough CP violation)

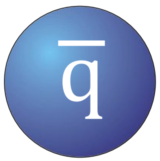
→ Cosmic matter/antimatter asymmetry requires new physics

A.Riotto & M.Trodden: Recent progress in baryogenesis, Ann. Rev. Nucl. Part. Sci. 49 (1999) 35 arXiv:hep-ph/9901362 • D.Bödeker & W.Buchmüller: Baryogenesis from the weak scale to the grand unification scale, Rev. Mod. Phys. 93 (2021) 3 arXiv:2009.07294

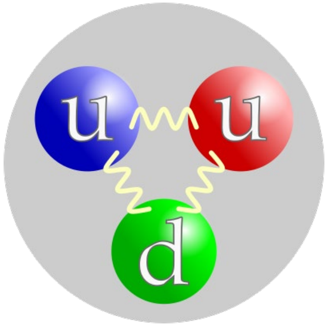
Baryon & Lepton Number

Baryon number (B)

$+\frac{1}{3}$ quarks

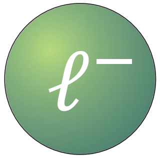


$-\frac{1}{3}$ antiquarks

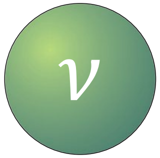


$+1$ proton etc.

Lepton number (L)



$+1$ charged leptons



$+1$ Dirac neutrino

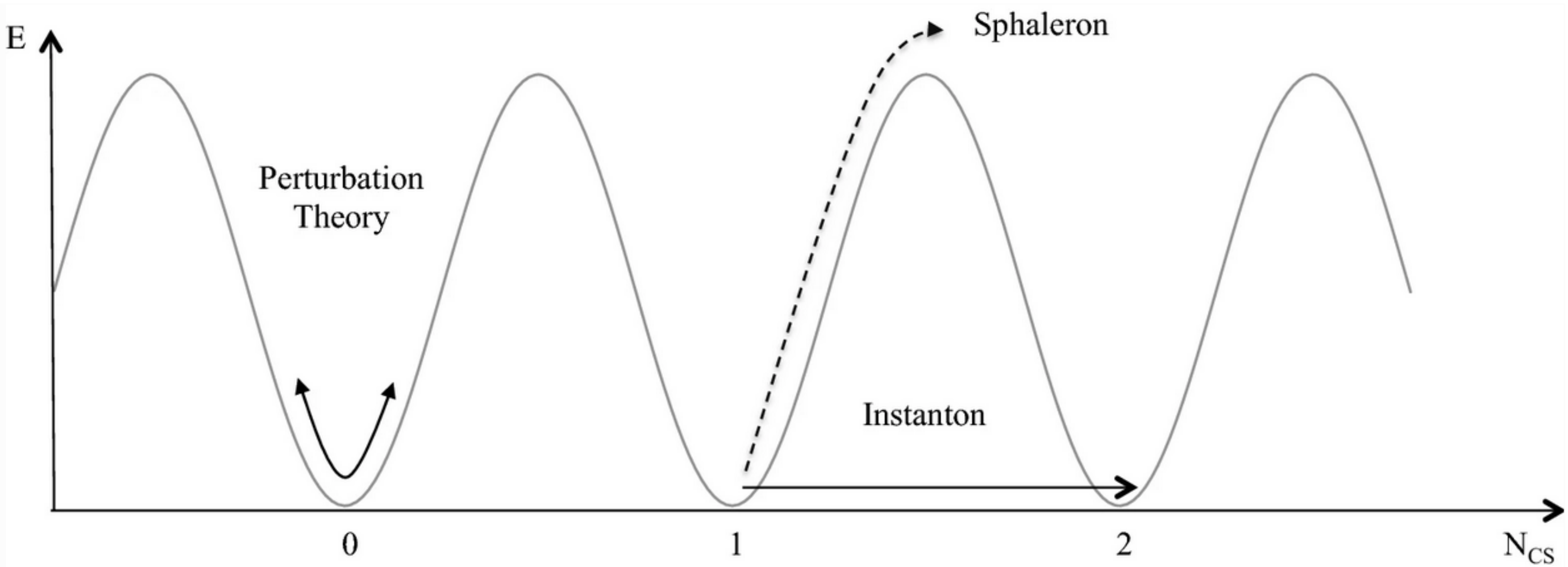
- Accidentally conserved in Standard Model
  (No fundamental symmetry, not a “conserved charge”
  but no normal process that violates B or L)
- Violation never observed

Violation expected

- Baryon-lepton unification (Grand unification of all forces)
- Generate matter-antimatter asymmetry in the universe (“baryogenesis”)
- Small neutrino masses motivate Majorana nature (see-saw mechanism)

B and L Violation in the Standard Model

- Ground state (vacuum) not unique in electroweak standard model (non-Abelian)
- Different topologies (winding number N_{CS})
- B and L perturbatively conserved
- Tunneling (instantons) violates B and L (“chiral anomaly”)
- Sphaleron (unstable classical solution at maximum, elongated blob of energy)
  $E_S \simeq \frac{m_W}{\alpha_W} \simeq 10\ \mathrm{TeV}$ size $m_W^{-1} \simeq 10^{-2}\ \mathrm{fm}$
- Decays into many baryons and leptons



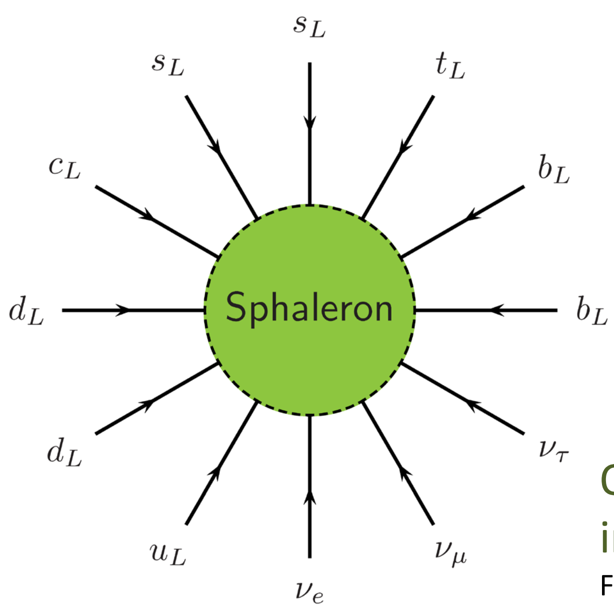
Winding number of gauge-field topology

Figure from https://arxiv.org/abs/2012.09120

Sphalerons in the Early Universe

Sphaleron process: $\Delta(B-L) = 0$

$$\underbrace{\Delta(B+L)}_{\text{Change of fermion number}} = 2N_{\text{fam}} \times \Delta N_{\text{CS}} = 6 \quad \text{(for } \Delta N_{\text{CS}} = 1\text{)}$$



One of the 12 sphaleron processes that are in thermal equilibrium in the early universe

Figure from arXiv:hep-ph/0406014

Early universe:
- Sphalerons in thermal equilibrium for $T >$ few 100 GeV
- Pre-existing $B + L$ erased

Kuz'min, Rubakov & Shaposhnikov: On anomalous electroweak baryon-number non-conservation in the early universe, Phys. Lett. B 155 (1985) 36 (thousands of citations)

See Saw Mechanism for Neutrino Mass

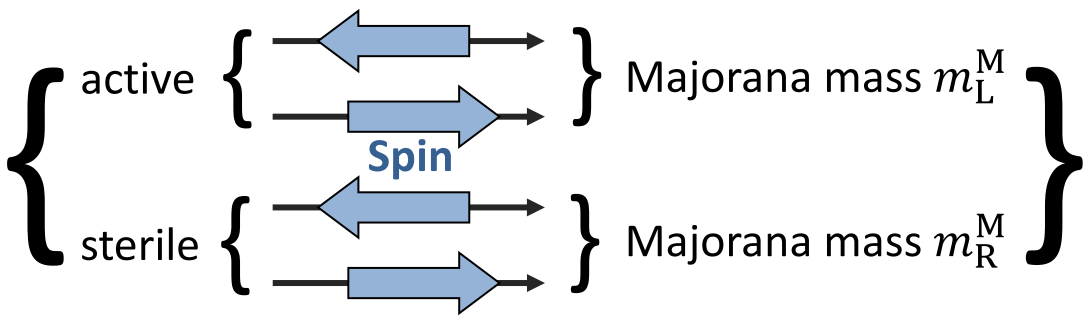
Mass terms on the Lagrangian level

$$\mathcal{L}_{\rm mass} = -\,\overline{\nu}_{\rm L} m^{\rm D} N_{\rm R} - \tfrac{1}{2}\,\overline{\nu}_{\rm L} m^{\rm M}_{\rm L} (\nu_{\rm L})^c - \tfrac{1}{2}\,\overline{(N_{\rm R})^c} m^{\rm M}_{\rm R} N_{\rm R} + {\rm h.c.}$$

Dirac mass term couples L with R fields

Majorana mass terms couple only L with L and R with R fields

Dirac mass $m^{\rm D}$ combines them to a single Dirac neutrino



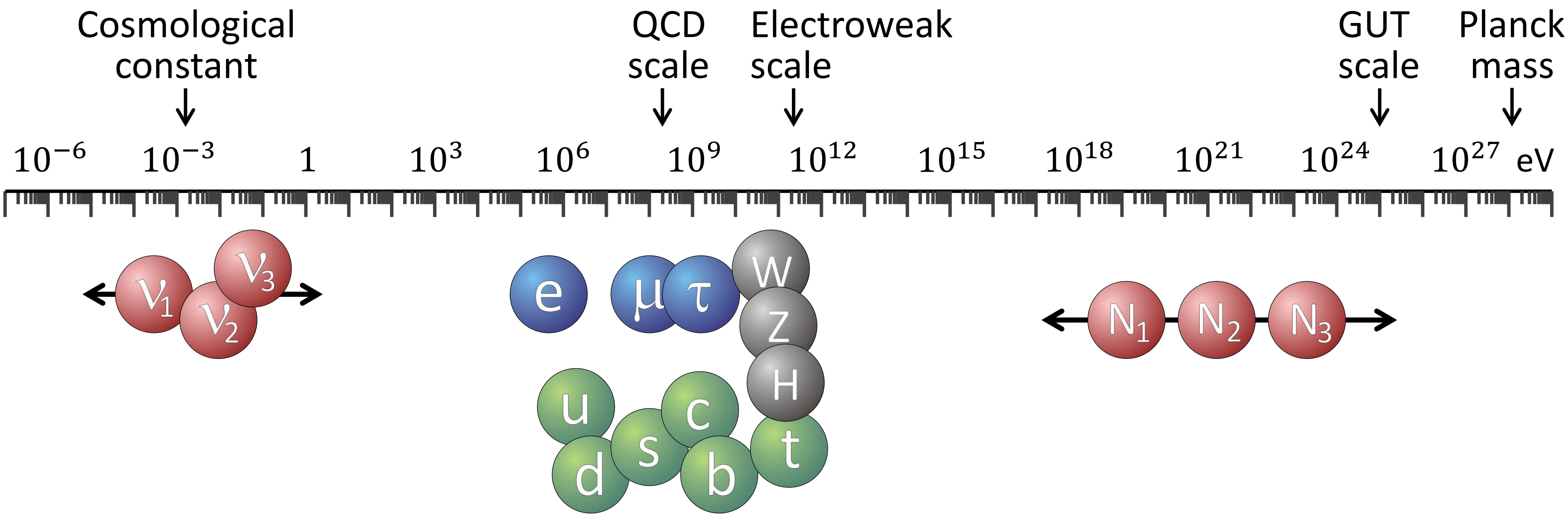
Dirac mass $m^{\rm D}$ mixes them to form two modified Majorana neutrinos

Assume $m^{\rm M}_{\rm L} = 0$ (no Majorana mass for active neutrino)
and $M_{\rm R} \equiv m^{\rm M}_{\rm R} \gg m^{\rm D} \equiv m_{\rm D}$ (Dirac mass a small perturbation)

$$\mathcal{L}_{\rm mass} \simeq \begin{pmatrix} \overline{\nu}_{\rm L} \\ \overline{N}_{\rm R} \end{pmatrix} \begin{pmatrix} 0 & m_{\rm D} \\ m_{\rm D} & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu_{\rm L} \\ N_{\rm R} \end{pmatrix} \xrightarrow[m_{\rm D} \ll M_{\rm R}]{\text{diagonalize}} \simeq \begin{pmatrix} \overline{\nu}_{\rm L}' \\ \overline{N}_{\rm R}' \end{pmatrix} \begin{pmatrix} m_{\rm D}^2/M_{\rm R} & 0 \\ 0 & M_{\rm R} \end{pmatrix} \begin{pmatrix} \nu_L' \\ N_R' \end{pmatrix}$$

Light neutrino $\nu' = \nu + \theta N \simeq \nu$ with **Majorana mass $m_\nu \simeq m_{\rm D}^2/M_{\rm R}$**

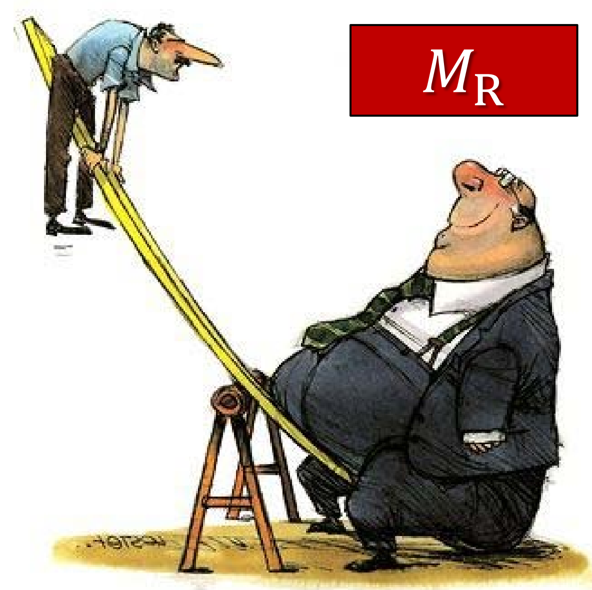
See-Saw Model for Neutrino Masses



$m_\nu = m_\mathrm{D}^2/M_\mathrm{R}$

m_D

M_R



$$\mathbf{M_R = m_D^2/m_\nu \simeq 10^{14}GeV \simeq M_{GUT}}$$

100 GeV 100 meV

BARYOGENESIS WITHOUT GRAND UNIFICATION

M FUKUGITA

Research Institute for Fundamental Physics, Kyoto University, Kyoto 606, Japan

and

T YANAGIDA

Institute of Physics, College of General Education, Tohoku University, Sendai 980, Japan and Deutsches Elektronen-Synchrotron DESY, D-2000 Hamburg, Fed Rep Germany

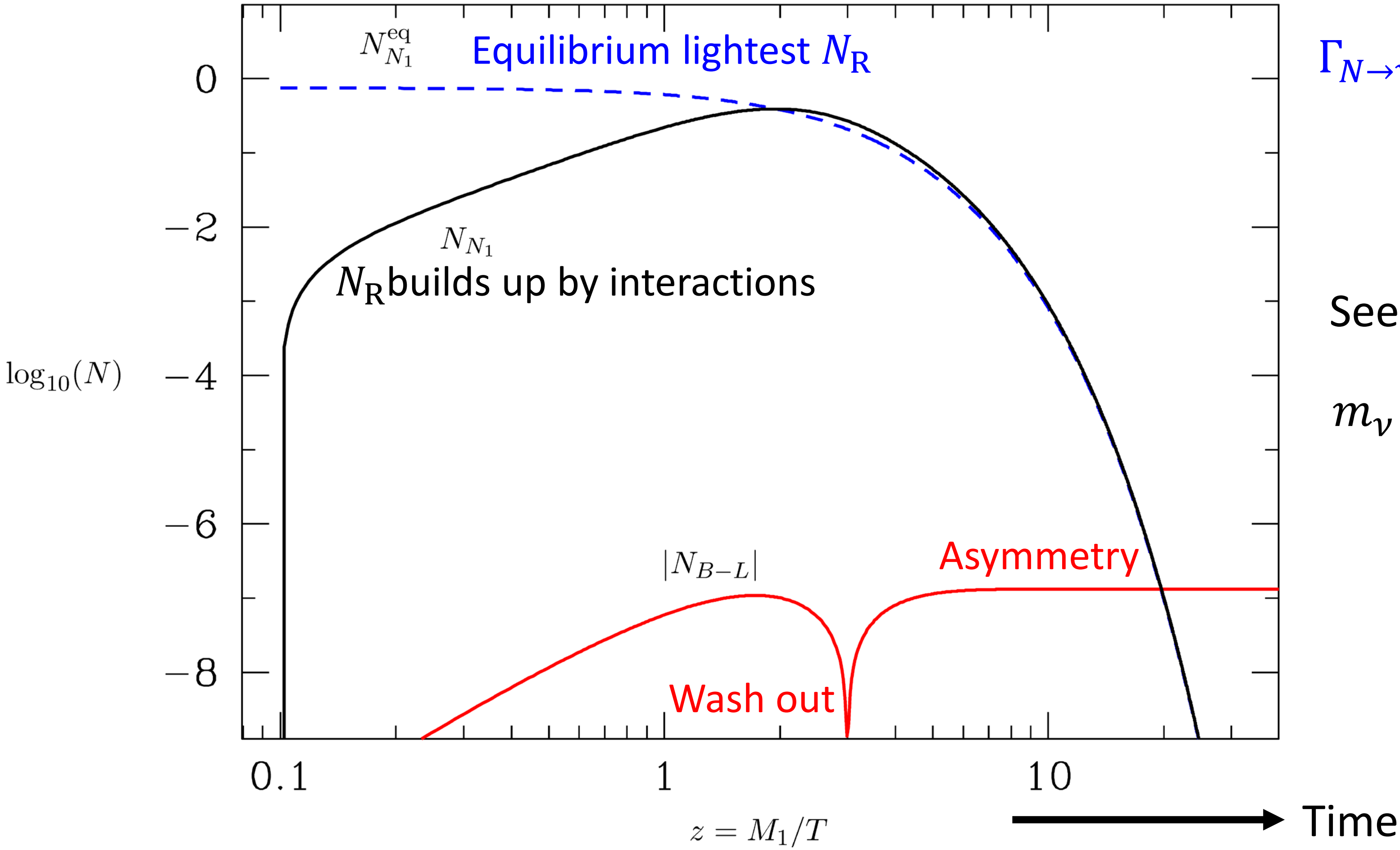
Received 8 March 1986

A mechanism is pointed out to generate cosmological baryon number excess without resorting to grand unified theories The lepton number excess originating from Majorana mass terms may transform into the baryon number excess through the unsuppressed baryon number violation of electroweak processes at high temperatures

- Heavy Majorana decay $N_R \to \ell_L + \overline{\phi}$ (standard Higgs) and $N_R \to \overline{\ell_L} + \phi$ } Different rates from CP violating phase in N_R mass matrix
- Reprocessed to B by sphalerons
- "To achieve this, however, all neutrino mass matrix elements (Majorana mass) should be **smaller than ~0.1 eV.** If the double beta decay experiment would observe a Majorana mass greater than this value, this scenario fails."

Leptogenesis by Out-of-Equilibrium Decay

[arXiv:hep-ph/0406014](https://arxiv.org/abs/hep-ph/0406014)



$$\Gamma_{N\to\nu+\phi} = \frac{y_\nu^2 M_R}{8\pi} = \frac{m_\nu M_R^2}{8\pi\,\langle\phi\rangle^2}$$

See-saw mass

$$m_\nu = \frac{y_\nu^2\,\langle\phi\rangle^2}{M_R}$$

Optimal window for neutrino Majorana masses

$$\mathbf{1 < m_i < 100\ meV}$$

Bödeker & Buchmüller: Baryogenesis from the weak scale to the grand unification scale
Rev. Mod. Phys. 93 (2021) 3 [arXiv:2009.07294](https://arxiv.org/abs/2009.07294)

BARYOGENESIS WITHOUT GRAND UNIFICATION

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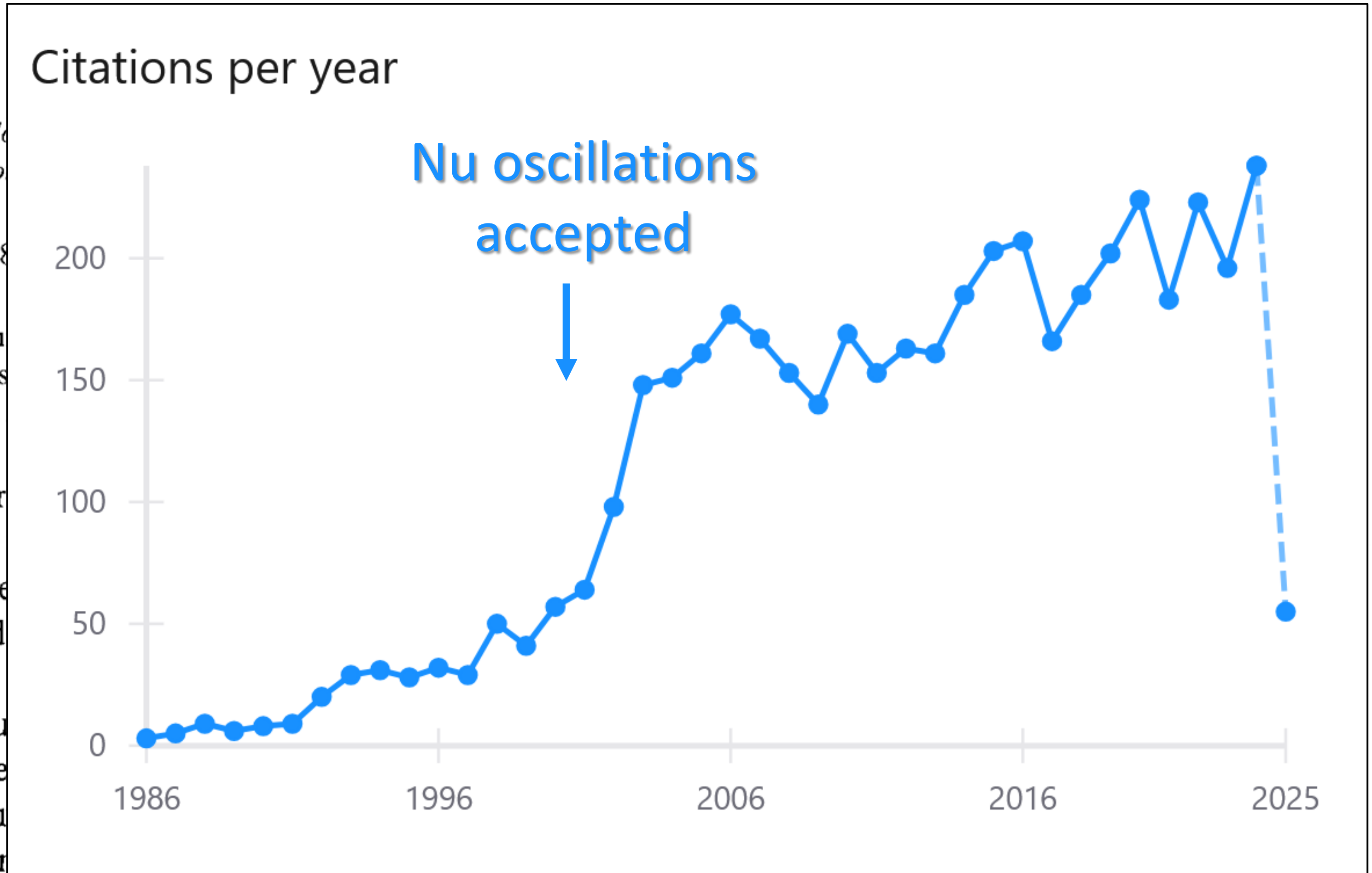
Institute of Physics, C
and Deutsches Elektro

Received 8 March 198

A mechanism is poi
lepton number excess
unsuppressed baryon

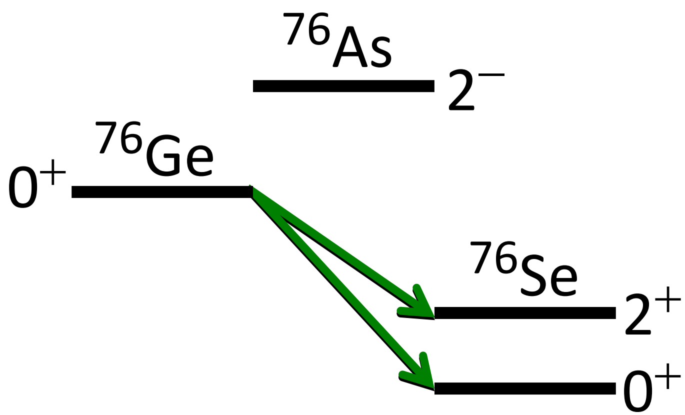


The current view ascr
cal baryon excess to the
violation process in the
[1,2]. The grand unified
teractions is regarded as
count for this baryon nu
can give the correct orde
entropy ratio. If the Uni
epoch after the baryoger
baryon numbers are diluted by a huge factor. The reheating after the inflation is unlikely to raise the

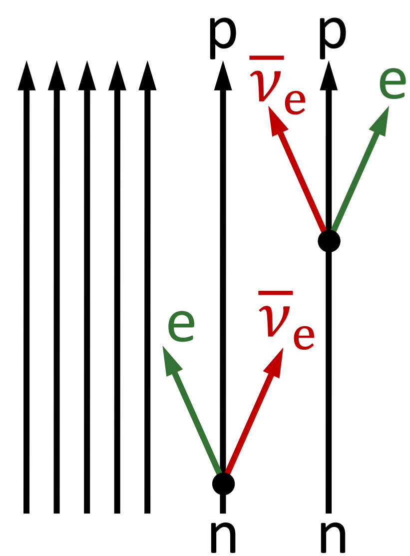
baryon number violation process, if it is supplemented by a lepton number generation at an earlier epoch.

Neutrinoless ββ Decay

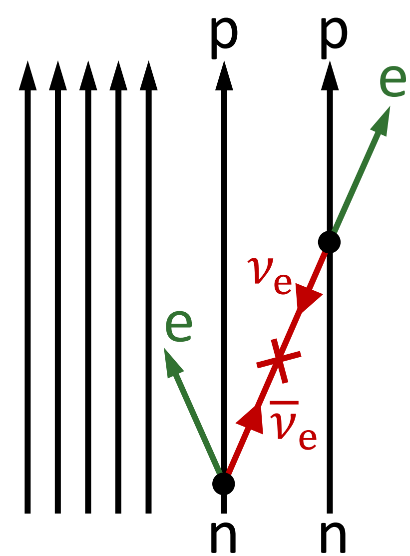
Some nuclei decay only by the ββ mode, eg Ge-76



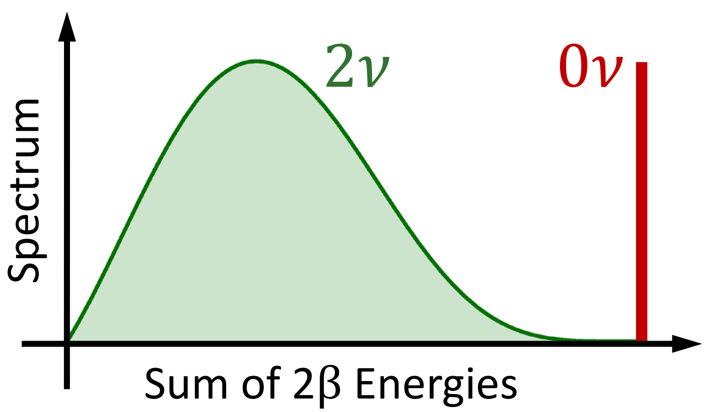
Half life ~ 2×10^{21} yr



Standard 2ν mode



0ν mode, enabled by Majorana mass



Measured quantity

$$m_{ee} = \left| \sum_{i=1}^{N} U_{ei}^2\, m_i \right|$$

Best limits from ^{136}Xe and ^{76}Ge

m_{ee} < 86 meV

[arXiv:2503.07752]

SEPTEMBER 15, 1935 PHYSICAL REVIEW VOLUME 48

Maria Goeppert-Mayer 1906–1972

Double Beta-Disintegration

$2\nu 2\beta$

M. Goeppert-Mayer, *The Johns Hopkins University*

(Received May 20, 1935)

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

SULLA SIMMETRIA TRA PARTICELLE E ANTIPARTICELLE

$0\nu 2\beta$

Nuovo Cim. 14 (1937) 322

Nota di Giulio Racah

Florence Univ.

Sunto. - *Si mostra che la simmetria tra particelle e antiparticelle porta alcune modificazioni formali nella teoria di* Fermi *sulla radioattività* β, *e che l'identità fisica tra neutrini ed antineutrini porta direttamente alla teoria di* E. Majorana.

Giulio Racah 1909–1965

DECEMBER 15, 1939 PHYSICAL REVIEW VOLUME 56

$0\nu 2\beta$

Wendell Hinkle Furry 1907–1984

On Transition Probabilities in Double Beta-Disintegration

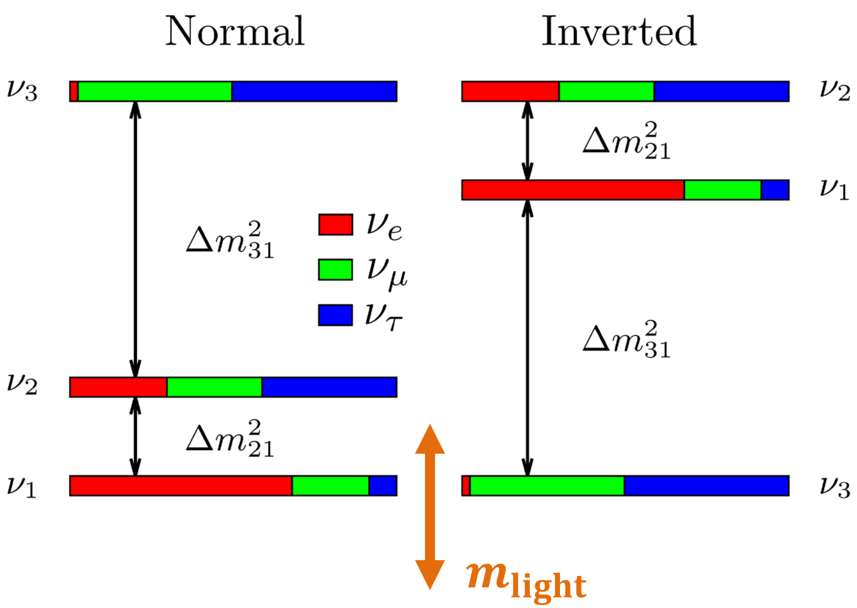
W. H. Furry

Physics Research Laboratory, Harvard University, Cambridge, Massachusetts

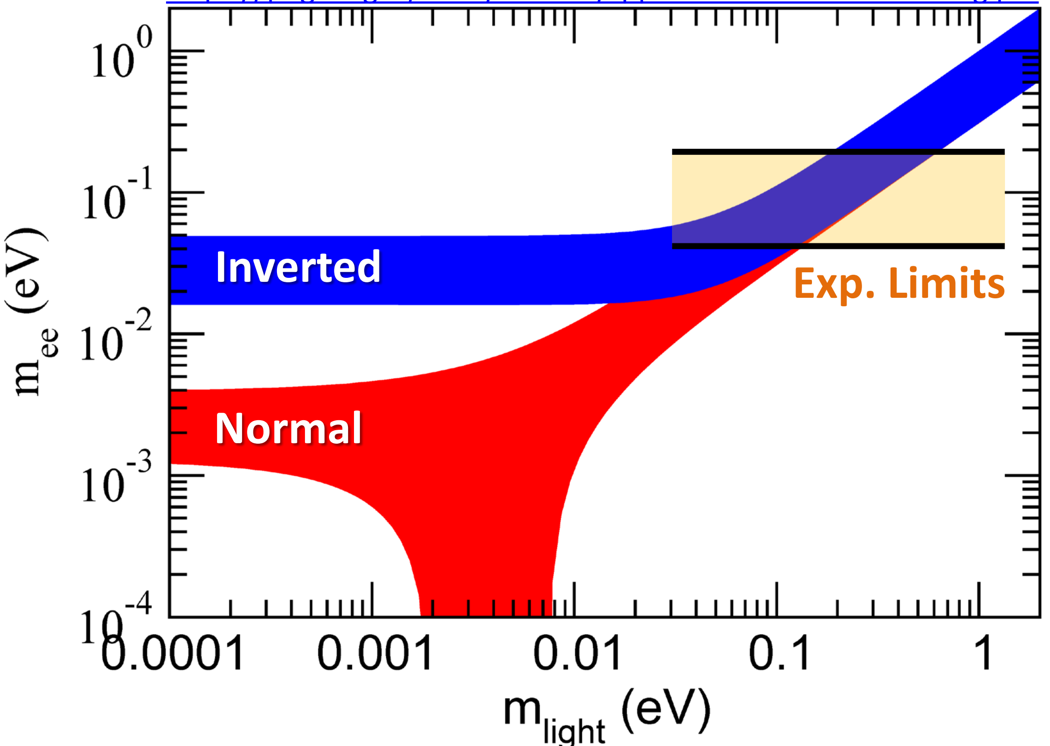
(Received October 16, 1939)

The phenomenon of double β-disintegration is one for which there is a marked difference between the results of Majorana's symmetrical theory of the neutrino and those of the original Dirac-Fermi theory. In the older theory double β-disintegration involves the emission of four particles, two electrons (or positrons) and two antineutrinos (or neutrinos), and the probability of disintegration is extremely small. In the Majorana theory only two particles—the electrons or positrons—have to be emitted, and the transition probability is much larger. Approximate values of this probability are calculated on the Majorana theory for the various Fermi and Konopinski-Uhlenbeck expressions for the interaction energy. The selection rules are derived, and are found in all cases to allow transitions with $\Delta i = \pm 1,0$. The results obtained with the Majorana theory indicate that it is not at all certain that double β-disintegration can never be observed. Indeed, if in this theory the interaction expression were of Konopinski-Uhlenbeck type this process would be quite likely to have a bearing on the abundances of isotopes and on the occurrence of observed long-lived radioactivities. If it is of Fermi type this could be so only if the mass difference were fairly large ($\epsilon \gtrsim 20$, $\Delta M \gtrsim 0.01$ unit).

Effective Majorana Mass in $0\nu2\beta$ Decay



https://pdg.lbl.gov/2022/reviews/rpp2022-rev-neutrino-mixing.pdf

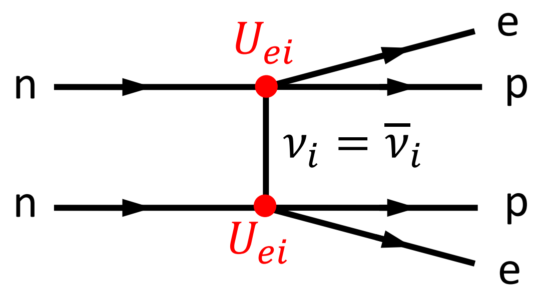


Majorana phases

Dirac phase

$$m_{ee} = \left| e^{i2\alpha_1} |U_{e1}|^2 m_1 + e^{i2\alpha_2} |U_{e2}|^2 m_2 + e^{i2\delta} |U_{e3}|^2 m_3 \right|$$

$c_{13}^2 c_{12}^2 \simeq 0.66$ $c_{13}^2 s_{12}^2 \simeq 0.32$ $s_{13}^2 \simeq 0.02$



Leptogenesis Summary

- See-saw model for small Majorana masses provides a generic way for BAU generation
- Preferred mass range < 100 meV
- Observing lepton-number violation (neutrinoless double beta decay) and leptonic CP violation (LBL oscillation) would provide strong support (not proof) for this scenario

Neutrino Mass Summary

Neutrino masses are in the sub-eV range

- Most restrictive limits from cosmology
- Should be seen “in the sky” in next round of precision data

Smallness suggests Majorana masses:

- Naturally explained by see-saw paradigm
- Requires new particles/fields
- Lepton number violation detectable in $0\nu2\beta$
- 1–100 meV mass range ideal for leptogenesis
- Corresponds to oscillation-implied range

Rather compelling package

Thank you!

ORIGINS Excellence Cluster

COSMIC WISPERS CA21106

MAX-PLANCK-INSTITUT FÜR PHYSIK

SFB 1258 | Neutrinos Dark Matter Messengers

Georg G. Raffelt, Max-Planck-Institut für Physik, Garching

Helium Mass Fraction from HII Regions

Extrapolation to zero metalicity in many HII regions

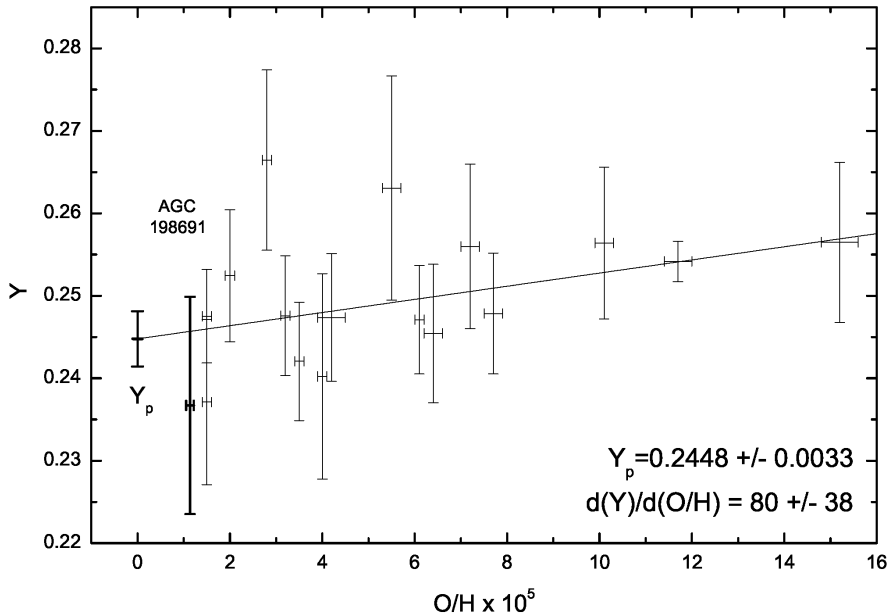


Figure 2. Helium abundance (mass fraction) versus oxygen to hydrogen ratio regression calculating the primordial helium abundance. The added point, AGC 198691, based on the analysis of this work, is shown as bold.

Aver et al., arXiv:2109.00178

Recent Y_p determinations (PDG Review on BBN 2023)

$Y_p(^4\mathrm{He})$	$\pm 1\sigma_{\mathrm{stat}}$	$\pm 1\sigma_{\mathrm{sys}}$	$\pm 1\sigma_{\mathrm{tot}}$	# systems	Ref
0.2453	0.0034			16	[54]
0.2451	0.0019	0.0018	0.0026	1	[55]
0.243	0.005			16	[56]
0.2462	0.0022			120	[57]
0.2436	0.0040			54	[58]
0.2448	0.0027	0.0018	0.0033	7	[59]
0.2448			0.0033	17	[60]

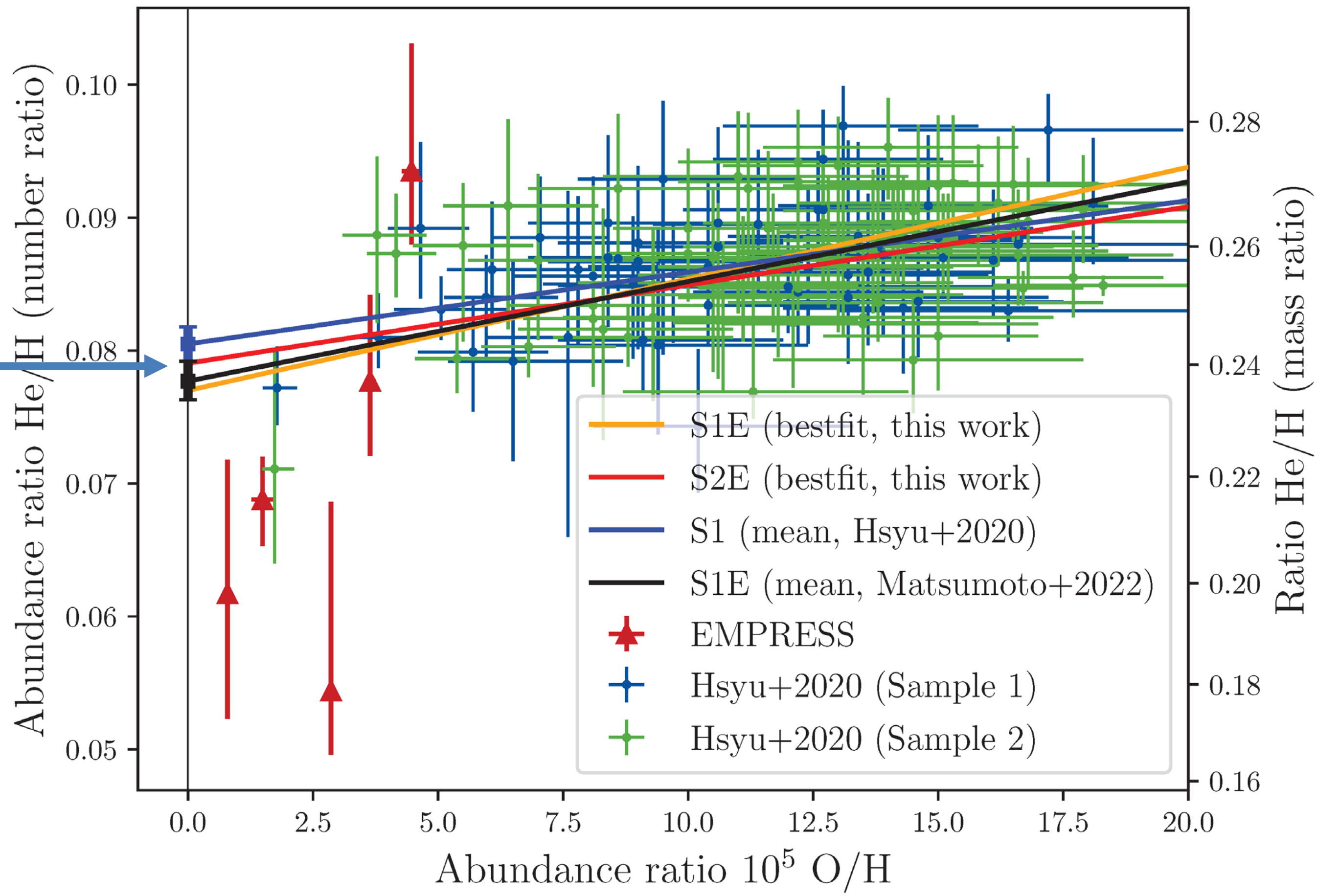
$$Y_\mathrm{P} = 0.245 \pm 0.003$$

Determination from metal-poor galaxies (EMPRESS arXiv:2203.09617)

$$Y_\mathrm{P} = 0.237 \pm 0.003$$

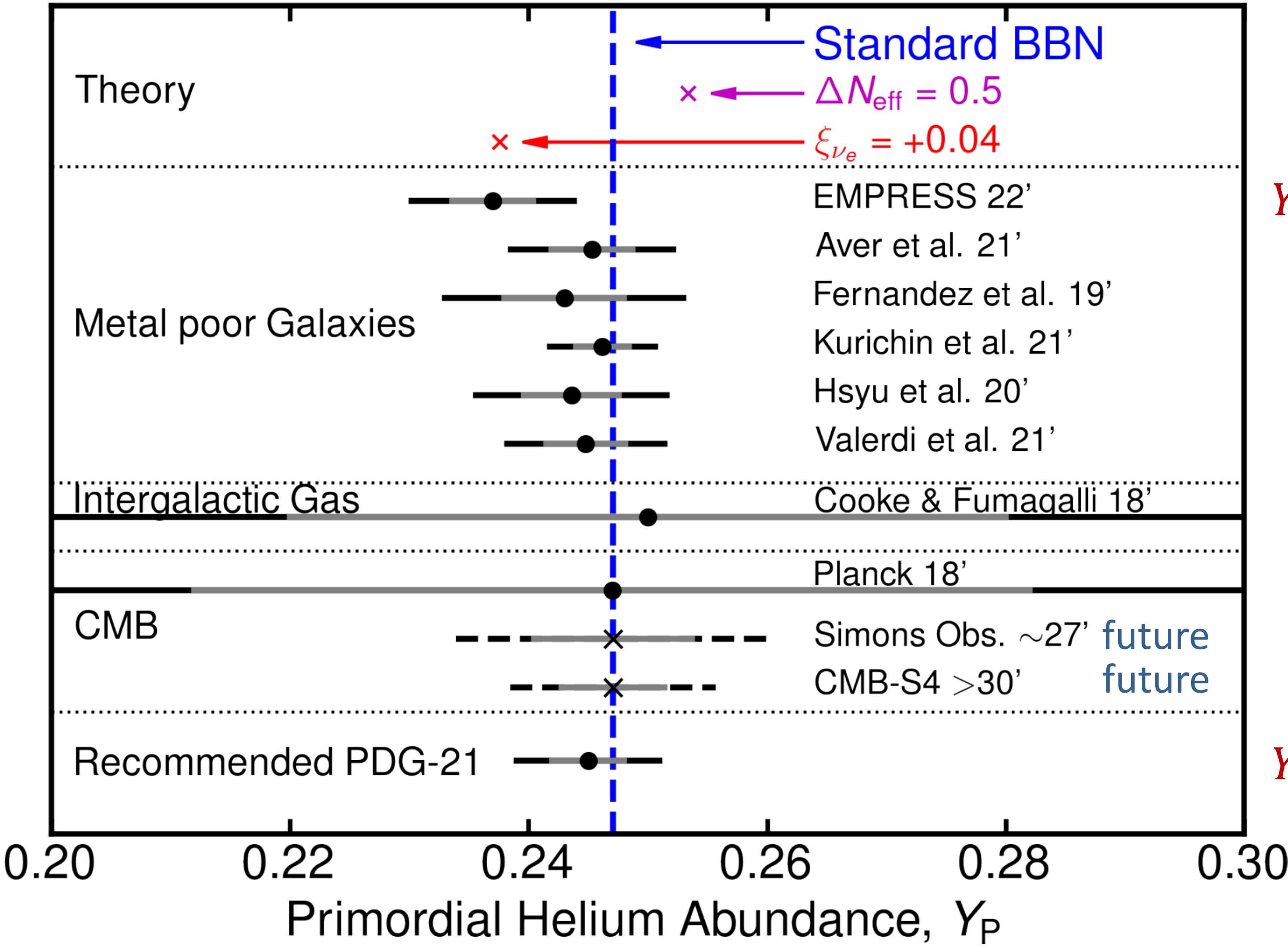
Extrapolations to Primordial He-4

Variation of zero-metallicity intercept



The CosmoVerse White Paper:
Addressing observational tensions in cosmology with systematics and fundamental physics
arXiv:2504.01669

Helium-4 Determinations



future

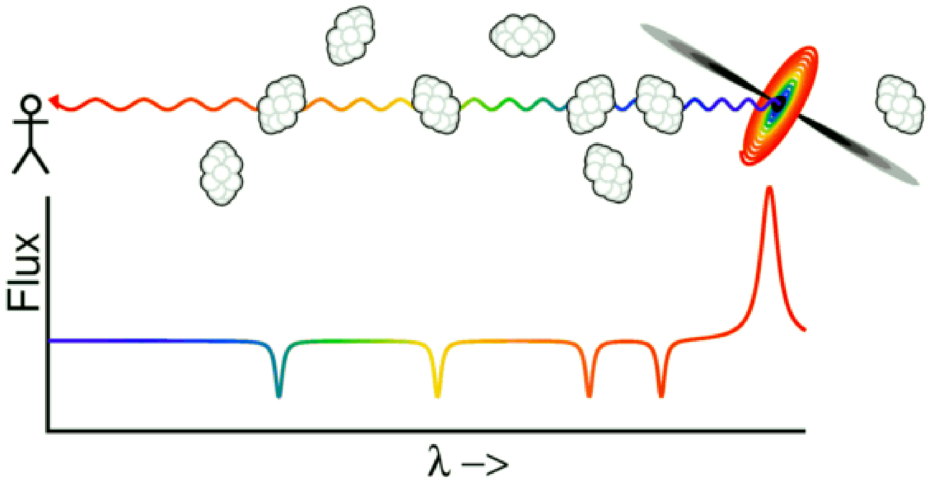
future

$Y_{\rm P} = 0.237 \pm 0.003$

$Y_{\rm P} = 0.245 \pm 0.003$

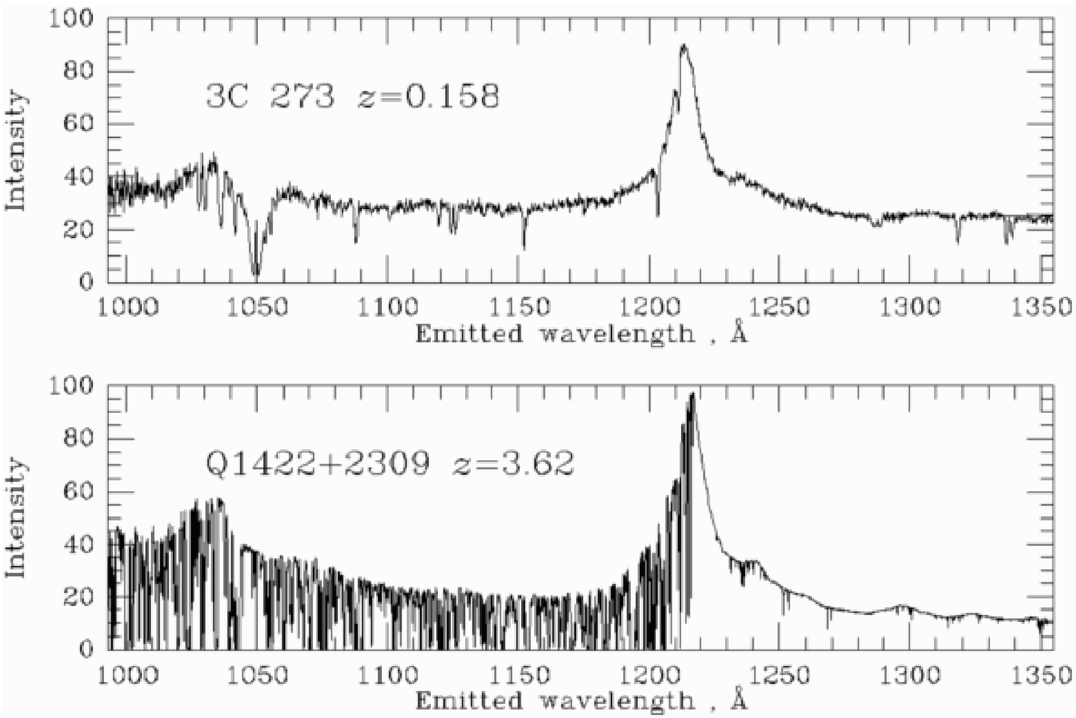
Escudero, Ibarra & Maura, arXiv:2208.03201

Lyman Alpha Forest



- Hydrogen clouds absorb from QSO continuum emission spectrum
- Absorption dips at Ly-α wavelengh corresponding to redshift

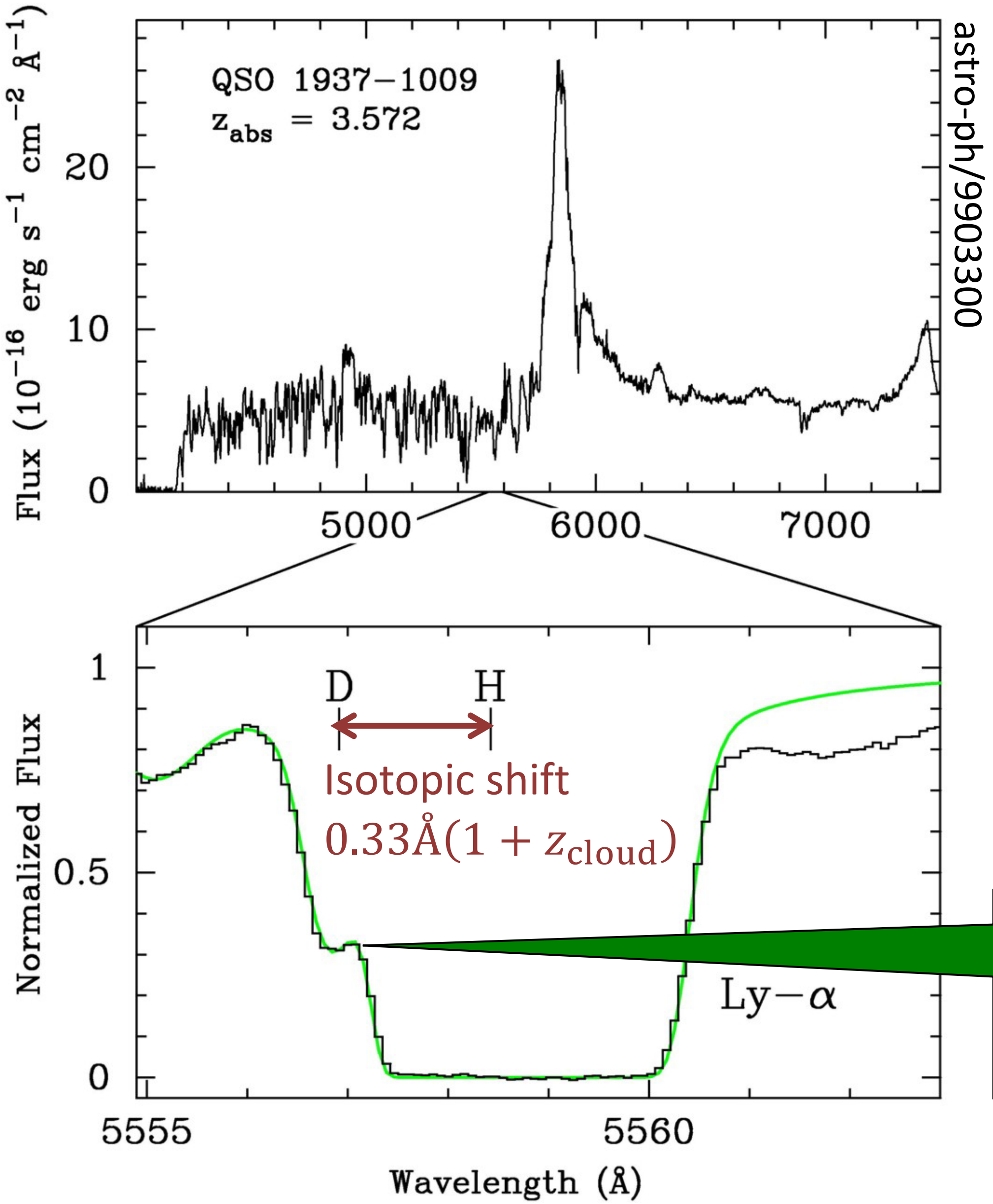
www.astro.ucla.edu/~wright/Lyman-alpha-forest.html



Examples for Lyman-α forest in low- and high-redshift quasars

http://www.astr.ua.edu/keel/agn/forest.gif

Measuring Primordial Deuterium



Hydrogen absorption spectrum of a background quasar in high-redshift hydrogen clouds

Deuterium Lyman-α in the flank of the saturated hydrogen Lyman-α line

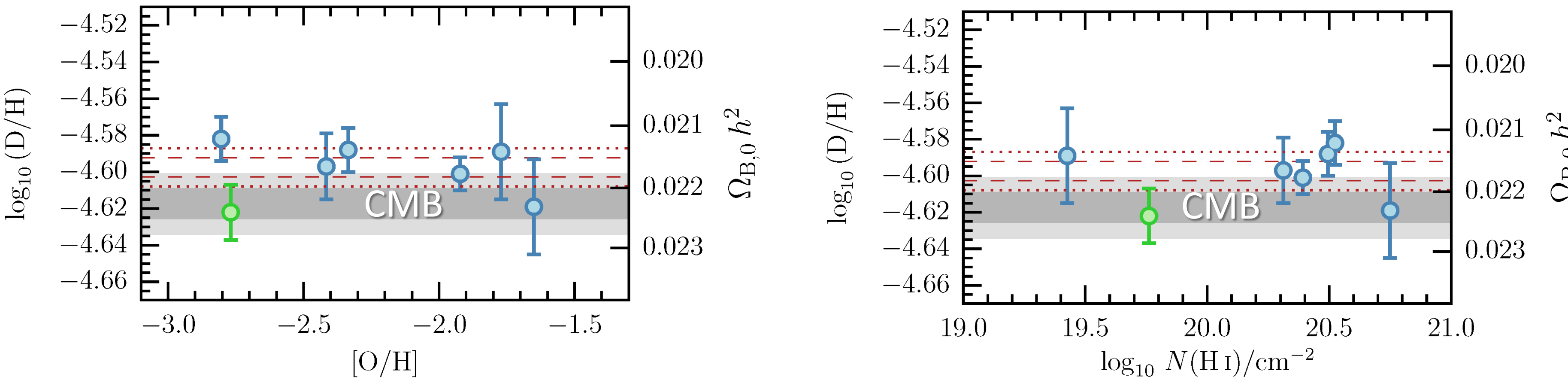


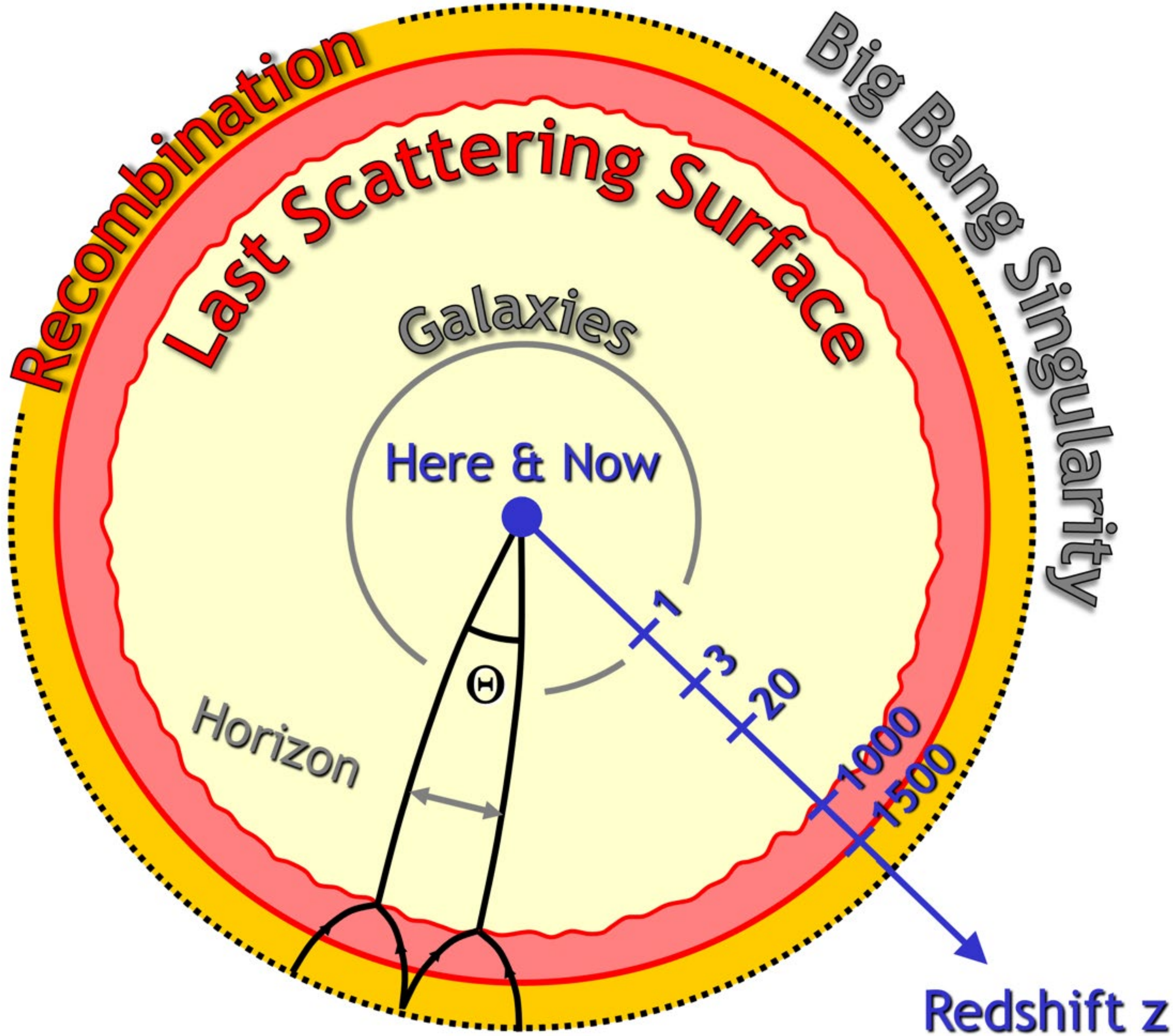
Figure 6. Our sample of seven high precision D/H measures is shown (symbols with error bars); the green symbol represents the new measure that we report here. The weighted mean value of these seven measures is shown by the red dashed and dotted lines, which represent the 68 and 95 per cent confidence levels, respectively. The left and right panels show the dependence of D/H on the oxygen abundance and neutral hydrogen column density, respectively. Assuming the Standard Model of cosmology and particle physics, the right vertical axis of each panel shows the conversion from D/H to the universal baryon density. This conversion uses the Marcucci et al. (2016) theoretical determination of the $d(p,\gamma)^3$He cross-section. The dark and light shaded bands correspond to the 68 and 95 per cent confidence bounds on the baryon density derived from the CMB (Planck Collaboration et al. 2015).

R.J. Cooke, M. Pettini, C.C. Steidel,

One Percent Determination of the Primordial Deuterium Abundance

arXiv:1710.11129

Last Scattering Surface



Friedman-Robertson-Walker-Lemaître Cosmology

- On scales $\gtrsim$ 100 Mpc, space is maximally symmetric (homogeneous & isotropic)
- The corresponding Robertson-Walker metric is

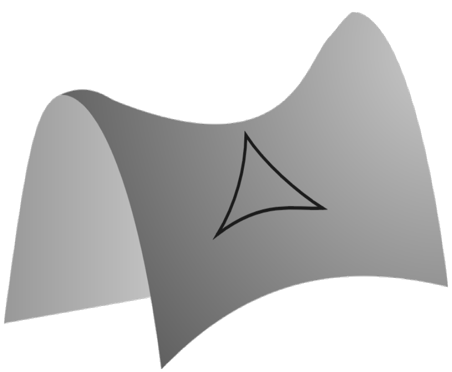
$$ds^2 = dt^2 - a^2(\mathrm{t})\left[\frac{dr^2}{1-kr^2} + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right)\right]$$

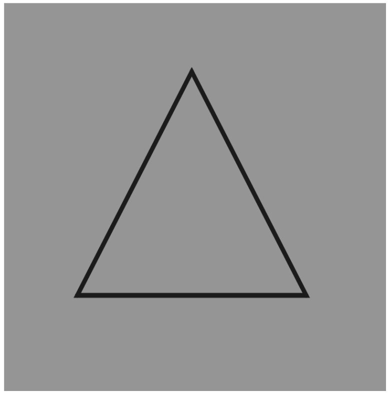
Clock time of co-moving observer

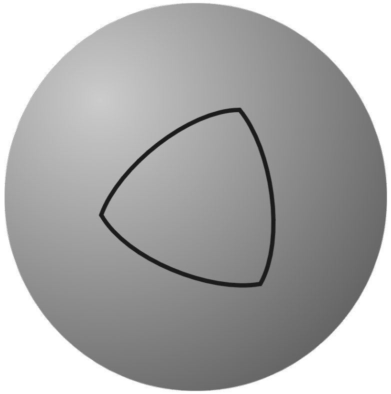
Cosmic scale factor

Curvature $k = 0, \pm 1$

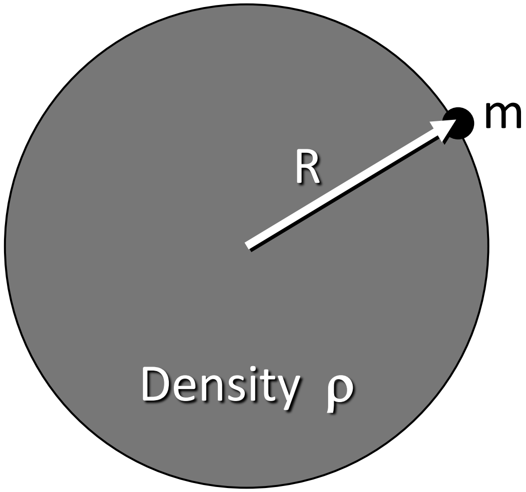
Co-moving spherical coordinates r is dimensionless


k = –1


k = 0


k = +1

Friedman Equation: Newtonian Derivation



- **Birkhoff's theorem:**
  Spherical symmetry implies that only the mass interior to a radius R is relevant for the motion of a test mass m at R

- **Energy conservation $V_{\rm pot} + V_{\rm kin} = \text{const}$**

$$-\frac{G_{\rm N}\frac{4\pi}{3}R^3\rho\, m}{R} + \frac{1}{2}\,\dot{R}^2 m = \text{const}$$

$$\Longrightarrow\quad \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}\,G_{\rm N}\rho + \frac{\text{const}}{R^2}$$

- **Rescale $R = a\,R_{\rm C}$ with cosmic scale factor a and $R_{\rm C}$ radius of curvature today**

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}G_{\rm N}\rho - \frac{k}{a^2 R_{\rm C}^2}$$

Friedman Equation

with $k = 0, \pm 1$

Critical Density and Density Parameter

- **Evolution of the cosmic scale factor $a(t)$ is governed by the Friedman Equation**

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3} G_\mathrm{N} \rho - \frac{k}{a^2 R_C^2}$$

- **In a flat universe ($k = 0$), the relationship between H and ρ is unique**

$$\rho_\mathrm{crit} = \frac{3H^2}{8\pi G_\mathrm{N}} = \frac{3}{8\pi} (H m_\mathrm{Pl})^2$$ **critical density**

Planck mass $1.221 \times 10^{19}\ \mathrm{GeV}$

- **Cosmic density always expressed in terms of density parameters**

$$\Omega = \frac{\rho}{\rho_\mathrm{crit}} = \frac{8\pi G_\mathrm{N} \rho}{3H^2}$$

- **With the present-day Hubble parameter $H_0 = 67.4\ \mathrm{km\ s^{-1}\ Mpc^{-1}}$ we have**

$$\rho_\mathrm{crit} = 0.85 \times 10^{-29} \mathrm{g\ cm^{-3}} = 4.8\ \mathrm{GeV\ m^{-3}} = (2.5\ \mathrm{meV})^4$$

Most of this in the form of "dark energy"

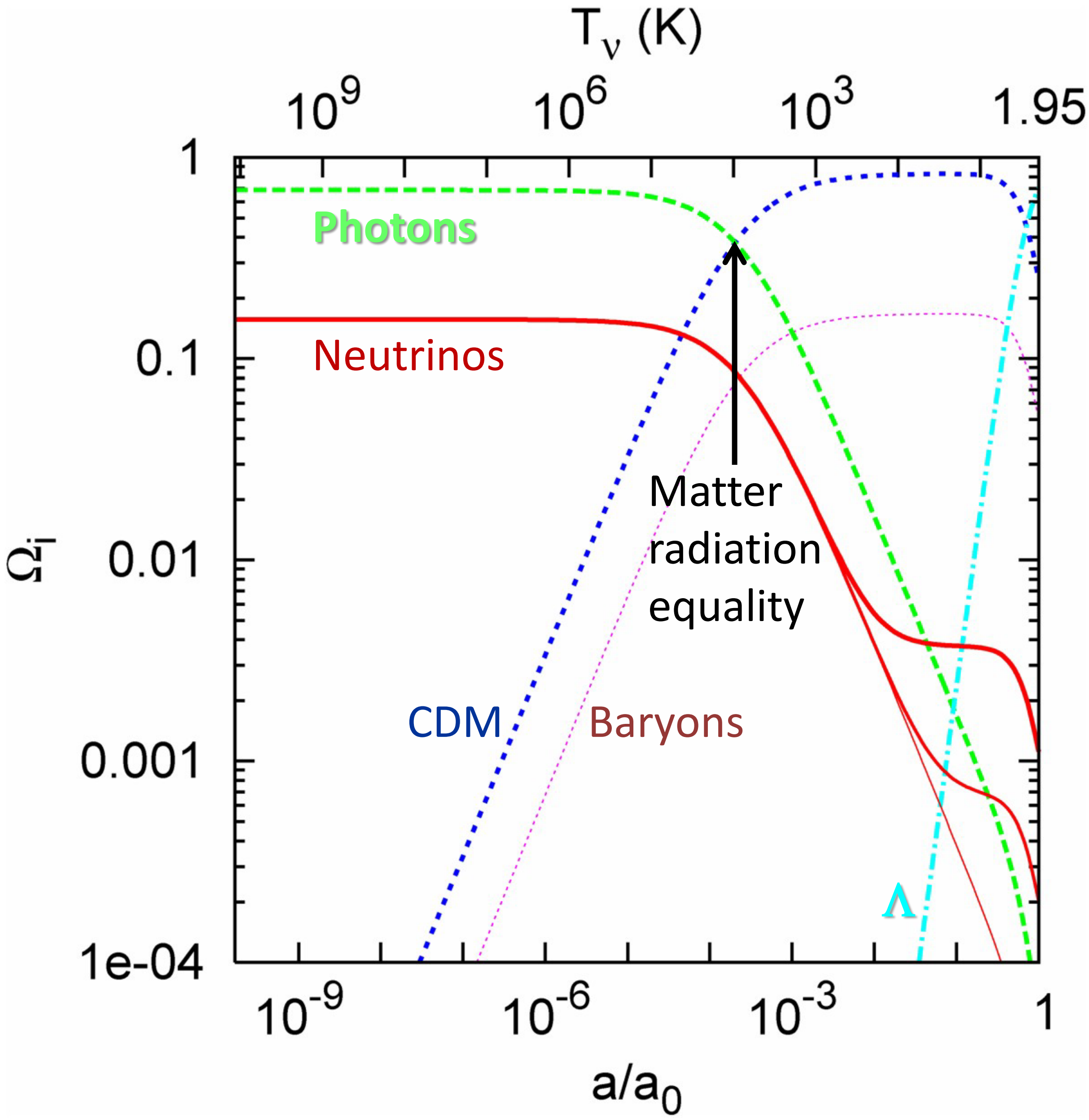
Generic Solutions of Friedman Equation

	Equation of state	Behavior of energy-density under cosmic expansion		Evolution of cosmic scale factor
Radiation	$p = \frac{\rho}{3}$	$\rho \propto a^{-4}$	Dilution of radiation and redshift of energy	$a(t) \propto t^{1/2}$
Matter	$p = 0$	$\rho \propto a^{-3}$	Dilution of matter	$a(t) \propto t^{2/3}$
Vacuum energy	$p = -\rho$	$\rho = \text{const}$	Vacuum energy not diluted by expansion	$a(t) \propto e^{\sqrt{\Lambda/3}\,t}$ $\Lambda = 8\pi G_\mathrm{N} \rho_\mathrm{vac}$

Energy-momentum tensor of a perfect fluid with density ρ and pressure p

$$\boldsymbol{T^{\mu\nu} = \begin{pmatrix} \rho & & & \\ & p & & \\ & & p & \\ & & & p \end{pmatrix}} \qquad \boldsymbol{T^{\mu\nu}_{\mathrm{vac}} = \rho\, g^{\mu\nu} \begin{pmatrix} \rho & & & \\ & -\rho & & \\ & & -\rho & \\ & & & -\rho \end{pmatrix}}$$

Evolution of Cosmic Density Components



Assumed neutrino masses

m_3 = 50 meV

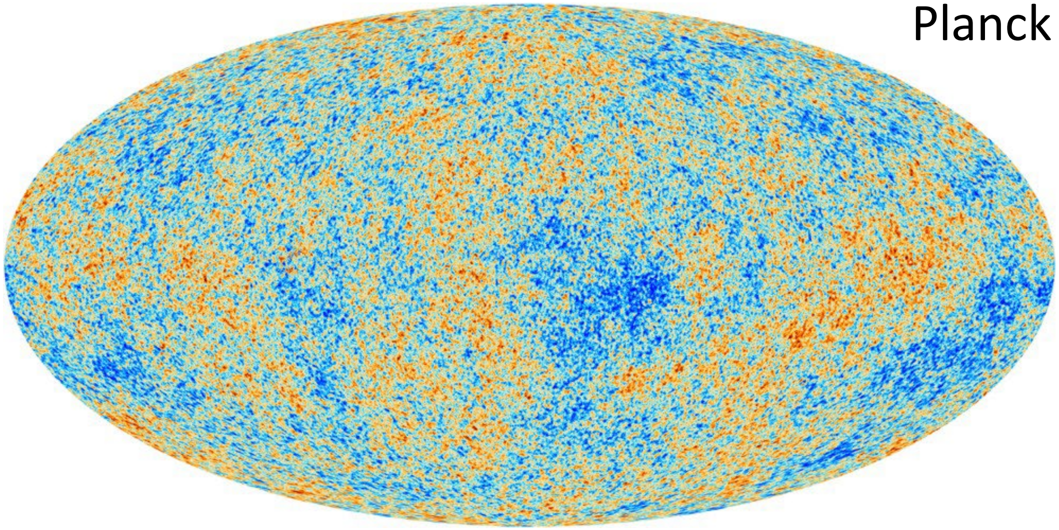
m_2 = 9 meV

m_1 = 0

Lesgourgues & Pastor
astro-ph/0603494

Power Spectrum of CMB Temperature Fluctuations

Sky map of CMBR temperature fluctuations



$$\Delta(\theta,\varphi) = \frac{T(\theta,\varphi) - \langle T \rangle}{\langle T \rangle}$$

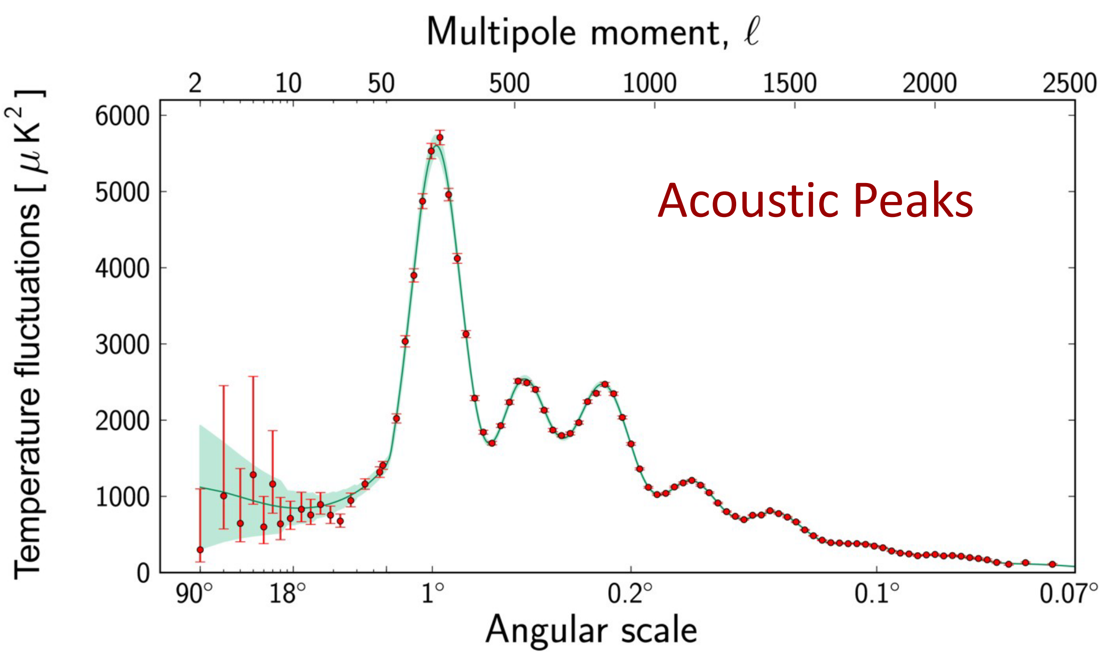
Multipole expansion

$$\Delta(\theta,\varphi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} Y_{\ell m}(\theta,\varphi)$$

Angular power spectrum

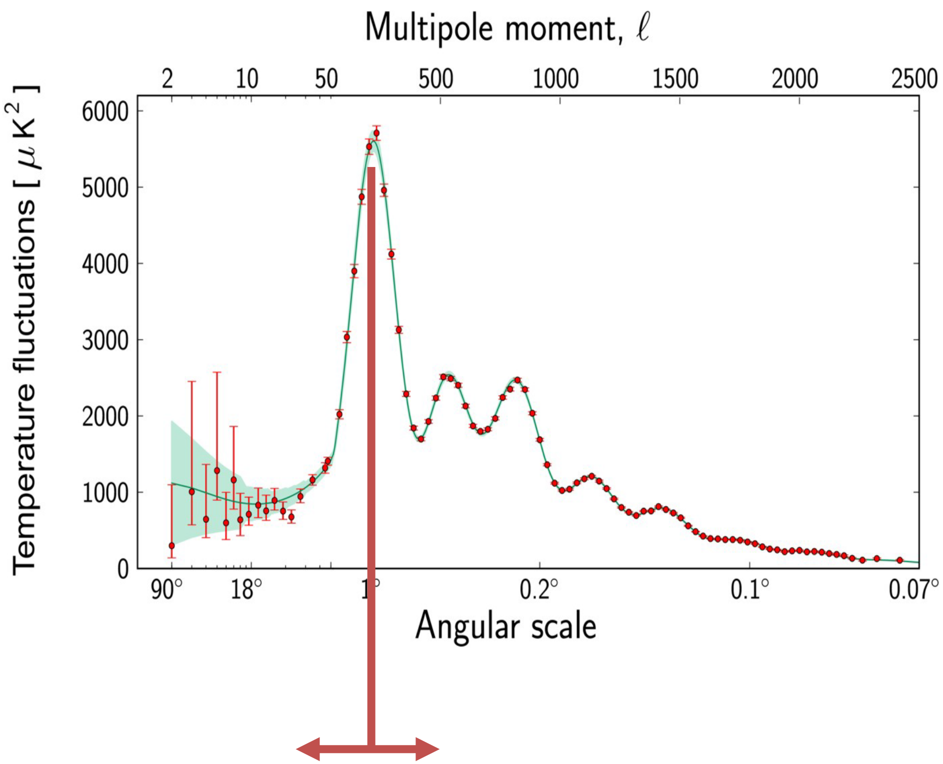
$$C_\ell = \langle a_{\ell m}^* a_{\ell m} \rangle$$

$$= \frac{1}{2\ell+1} \sum_{m=-\ell}^{\ell} a_{\ell m}^* a_{\ell m}$$



Provides “acoustic peaks” and a wealth of cosmological information

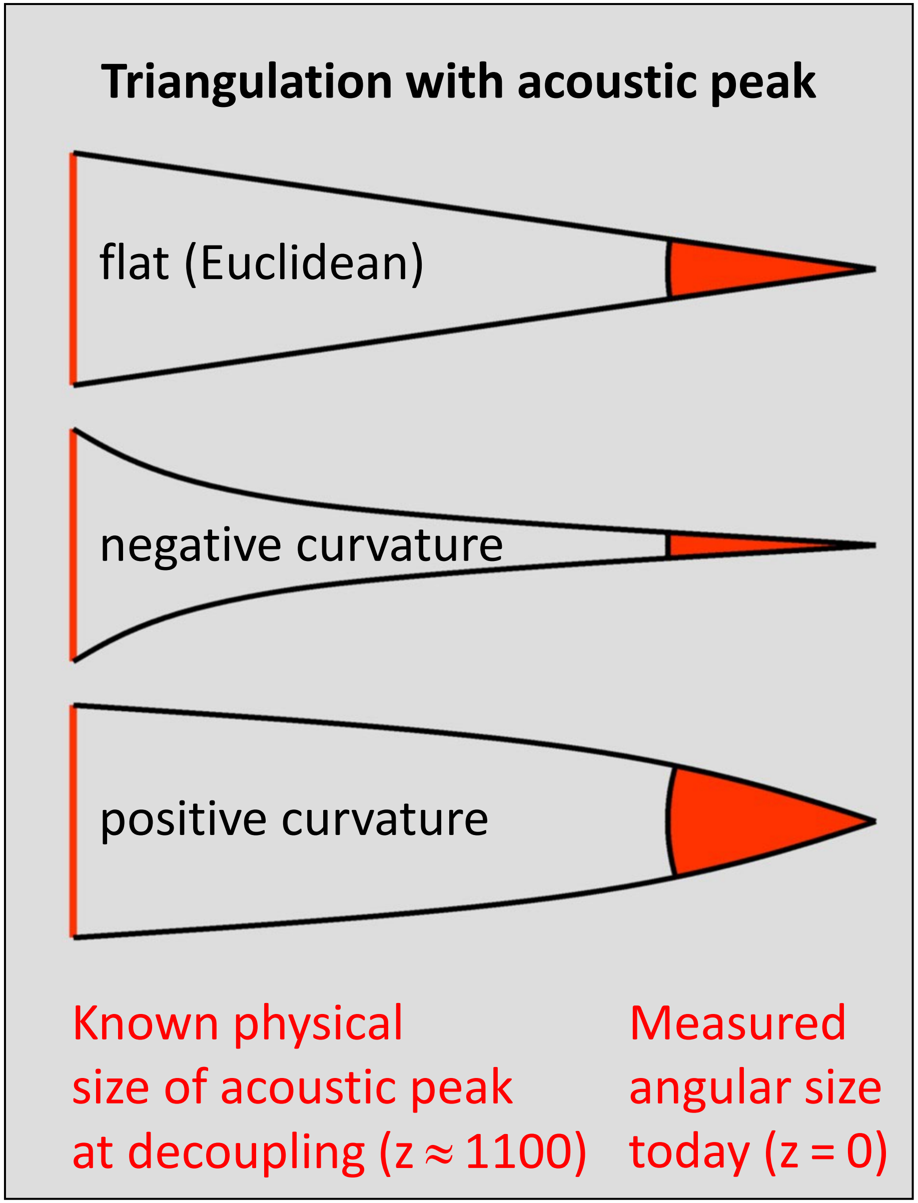
Flat Universe from CMBR Angular Fluctuations



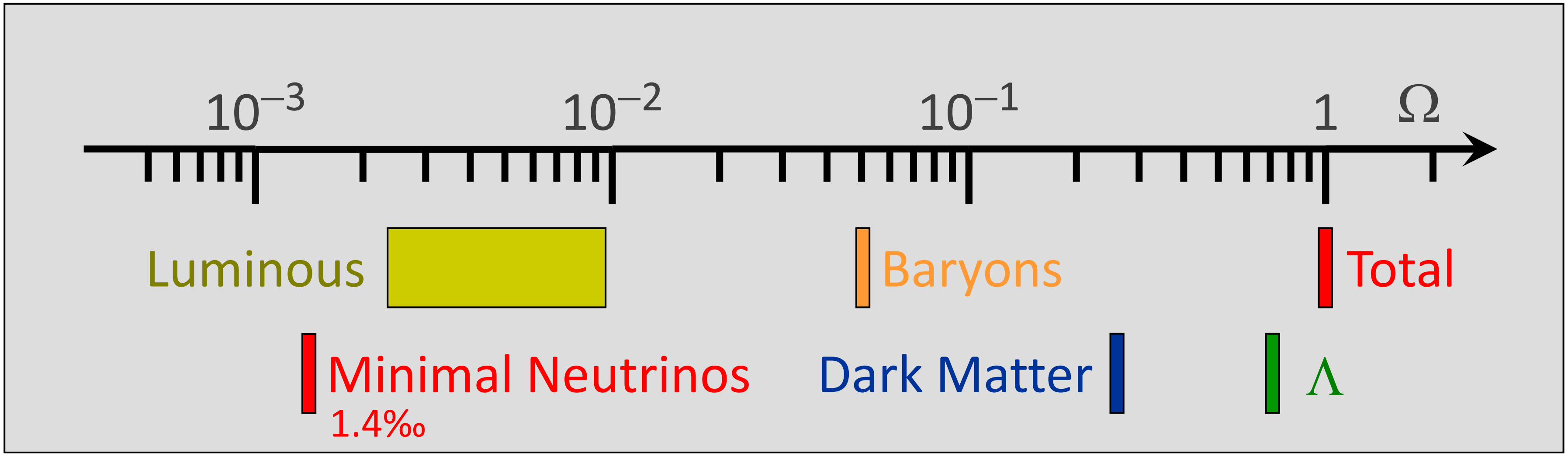
$$\Omega_{\rm tot} = 0.963^{+0.043}_{-0.049}$$ (CMB alone)

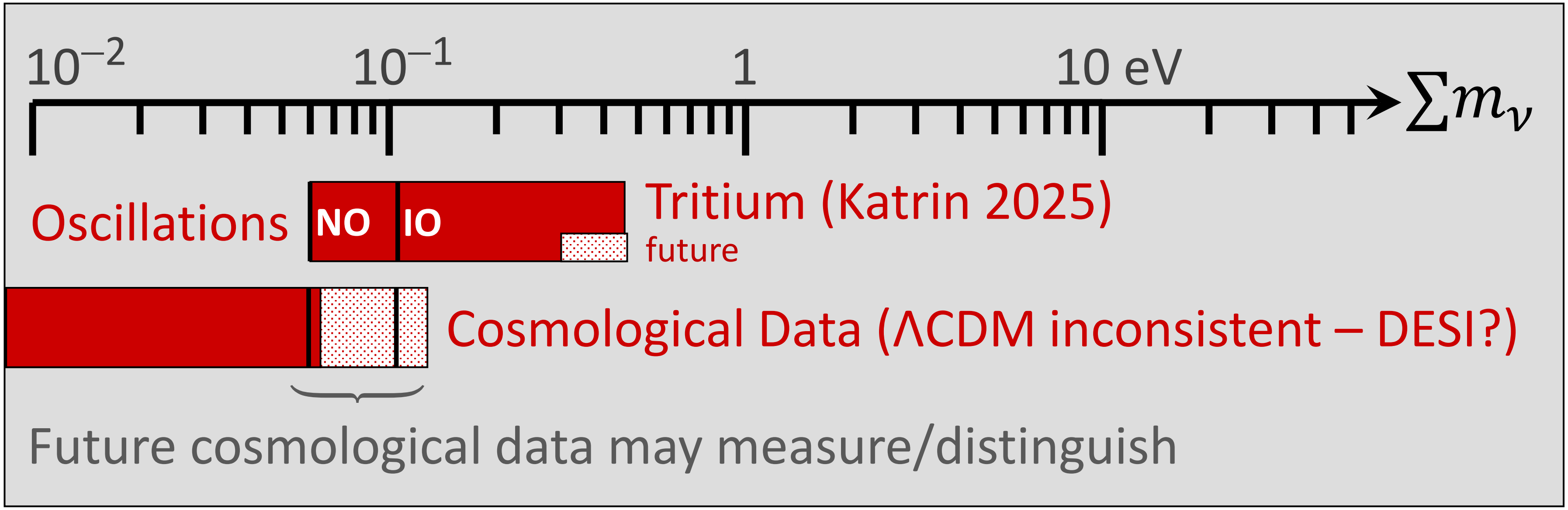
$$\Omega_{\rm tot} = 0.9995^{+0.0065}_{-0.0066}$$ (All data)

(95% ranges from Planck, arXiv:1303.5076)



Mass-Energy-Inventory of the Universe





CP Violation in Particle Physics

Discrete symmetries in particle physics

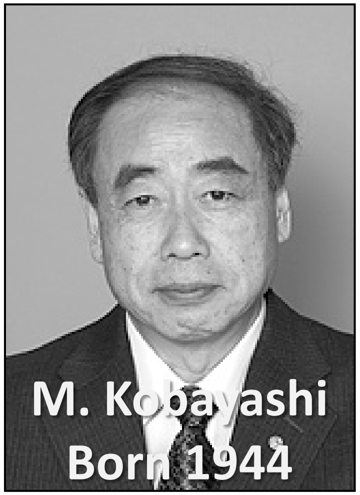
C – Charge conjugation, transforms particles to antiparticles
violated by weak interactions

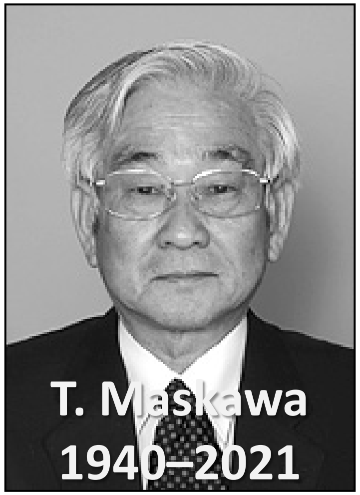
P – Parity, changes left-handedness to right-handedness
violated by weak interactions

T – Time reversal, changes direction of motion (forward to backward)

CPT – exactly conserved in quantum field theory

CP – conserved by all gauge interactions
violated by three-flavor quark mixing matrix



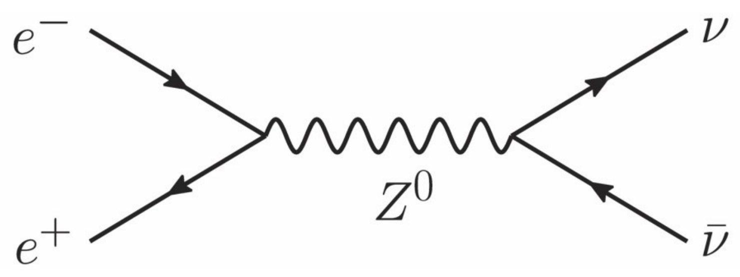


Physics Nobel Prize 2008

- All measured CP-violating effects derive from a single phase in the quark mass matrix (Kobayashi-Maskawa phase), i.e. from complex Yukawa couplings
- Cosmic matter-antimatter asymmetry requires new ingredients

Neutrino Counting in Particle Physics

Resonant Z-Boson production at LEP
(Electron-positron collider at CERN before LHC, in the same tunnel)



Or other final states

$q\bar{q}$, e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$

Measured properties

$$m_Z = (91.1876 \pm 0.0021)\ \mathrm{GeV}$$
$$\Gamma_{\mathrm{tot}} = (2.4952 \pm 0.0023)\ \mathrm{GeV}$$
$$\Gamma_{\mathrm{invis}} = (499.0 \pm 1.5)\ \mathrm{MeV}$$

Cross section follows resonance curve

$$\frac{d\sigma}{dE} \propto \frac{\Gamma/2}{(E - m_Z)^2 + (\Gamma/2)^2}$$

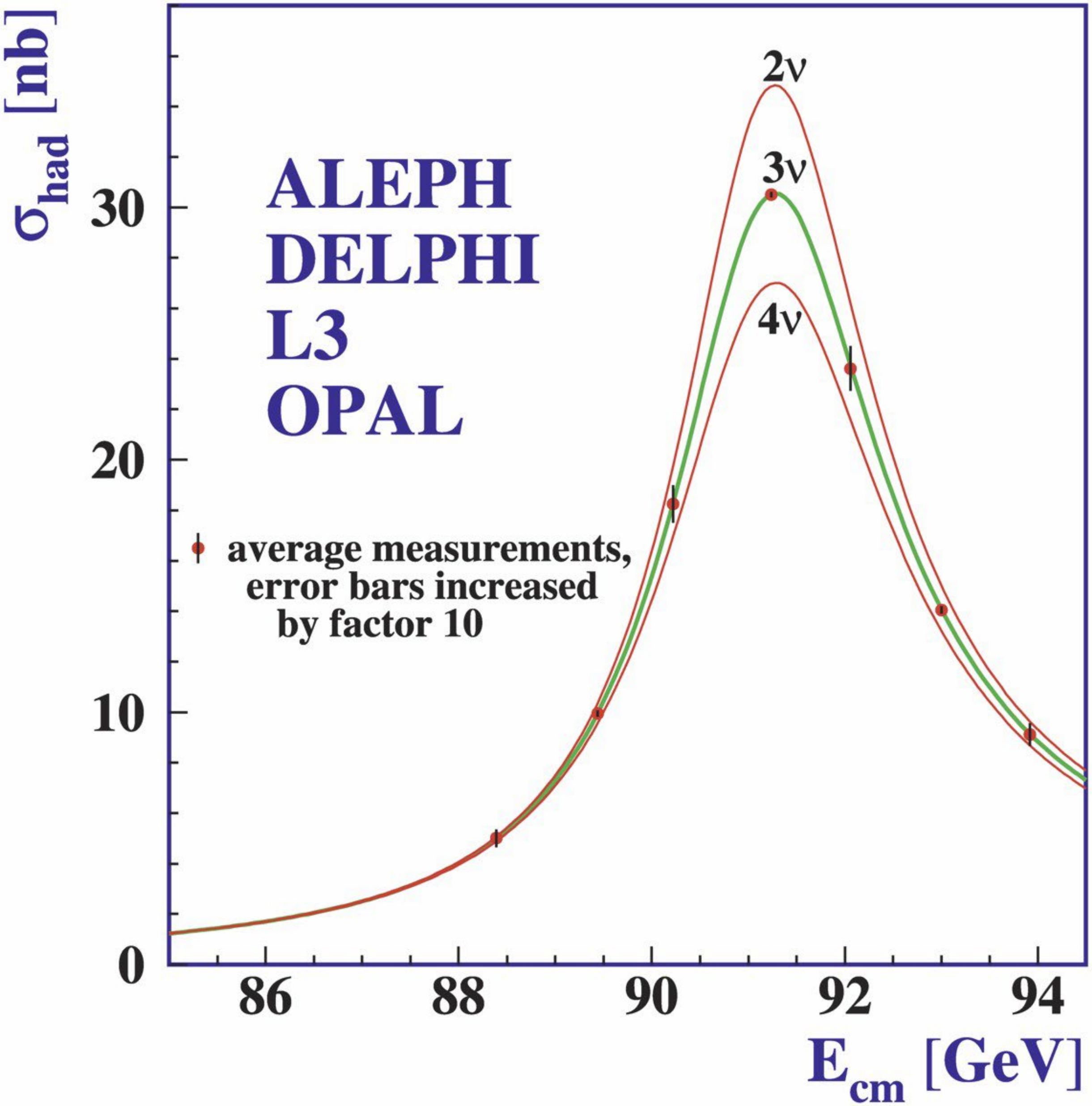
Contribution to Γ_{invis} of one standard neutrino family

$$\Gamma_{\nu\bar{\nu}} = 167.2\ \mathrm{MeV}$$

$$\frac{\Gamma_{\mathrm{invis}}}{\Gamma_{\nu\bar{\nu}}} = 2.984 \pm 0.008$$

No room for weakly interacting particles that couple to the Z unless m > $m_Z/2$
or strongly reduced coupling strength

Measured Z^0 Width at LEP (ca 1990)



Cosmological consequences:

- **Standard radiation density fixed**
- **No "trivial" weakly interacting dark matter particles**