Prospects for relic neutrino detection with NMR experiment

PRD 113 (2026) 4, 043061 [arxiv:2508.20357 [hep-ph]]

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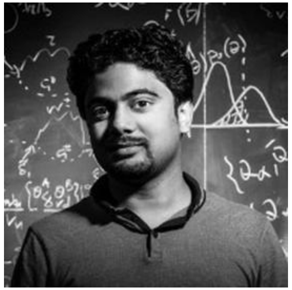


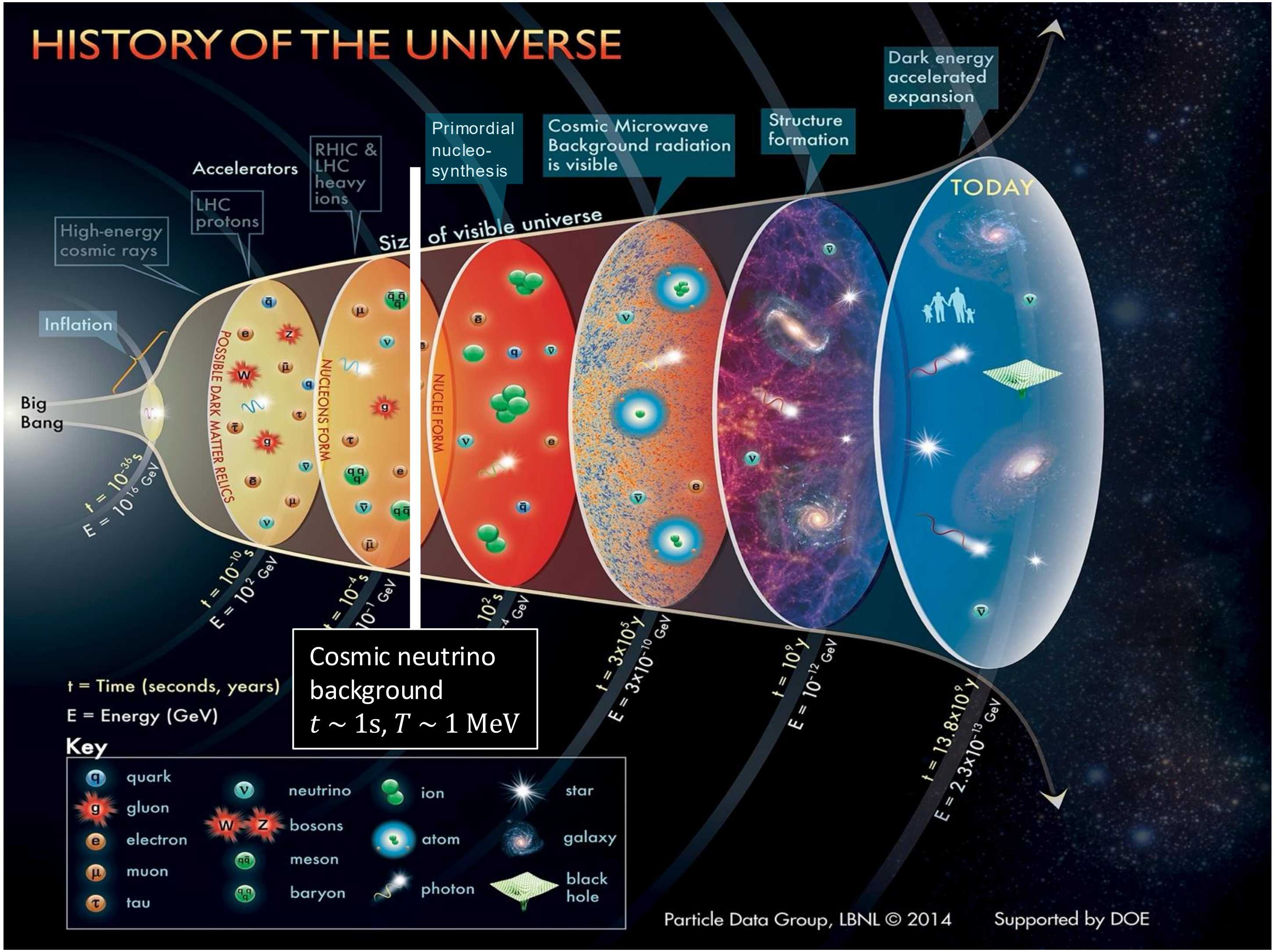
Dipan Sengupta

Rencontres de Moriond (Electroweak Interactions & Unified Theories), March 15-22, 2026

And in the last 5 minutes:

Status of neutrinos in cosmology

I alone bear full responsibility for this part…



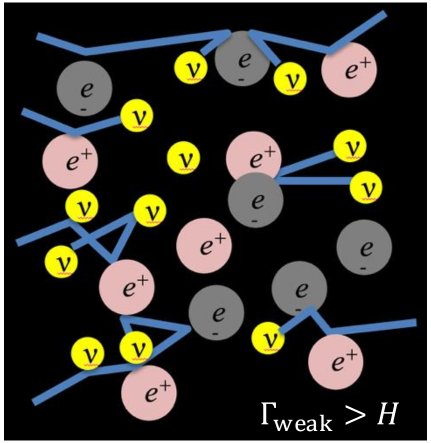
Cosmic neutrino background
$t \sim 1\text{s}, T \sim 1\ \text{MeV}$

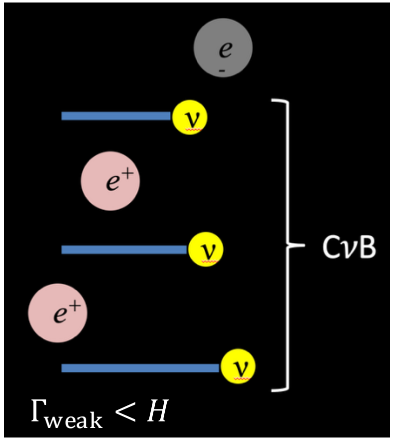
Formation of the CνB…

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.



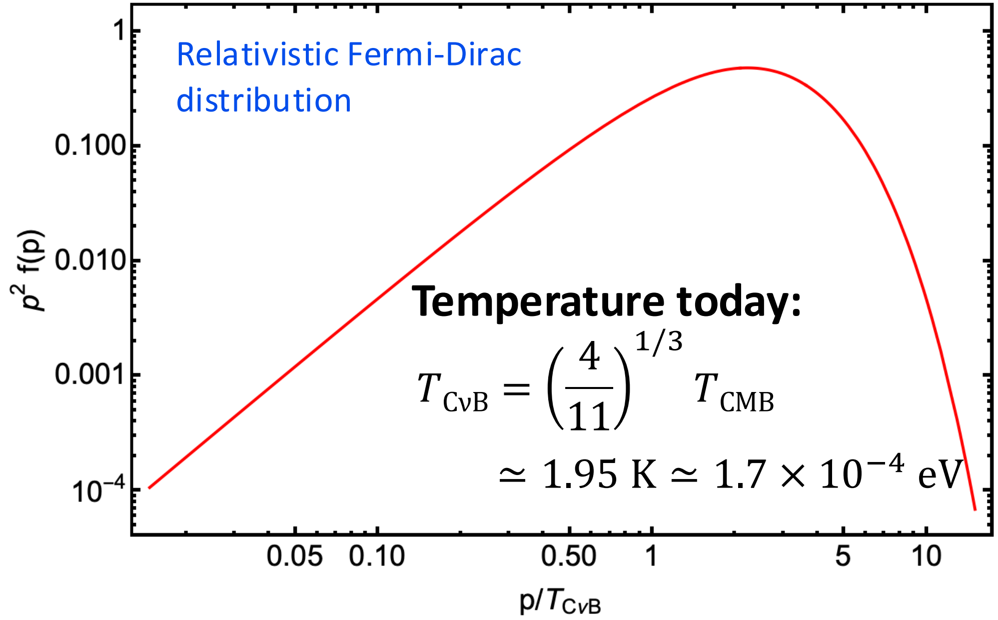


Neutrinos "free-stream" to infinity.

Above $T \sim 1$ 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.

Standard-model predictions of the CνB…



Relativistic Fermi-Dirac distribution

Temperature today:

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

$$\simeq 1.95\ \mathrm{K} \simeq 1.7 \times 10^{-4}\ \mathrm{eV}$$

Number density:

Per family of neutrinos +antineutrinos

$$n_{\nu,i} \simeq 110\ \mathrm{cm}^{-3}$$

Energy density:

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

$$\rho_{\nu,i} \simeq \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} \rho_\gamma$$

This ratio can be calculated to 10^{-4} precision

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

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

$$\Omega_{\nu,i} \simeq \frac{m_{\nu,i}}{93\ h^2\ \mathrm{eV}}$$

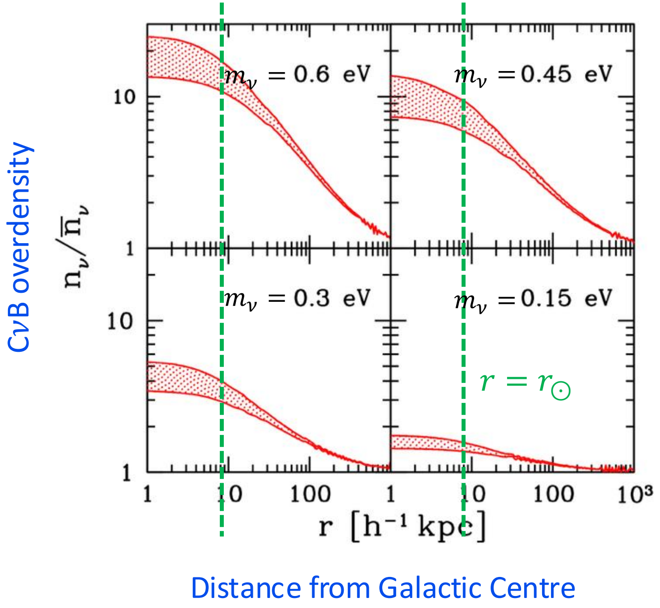
Neutrino (hot) dark matter

→ cosmological neutrino mass bounds →

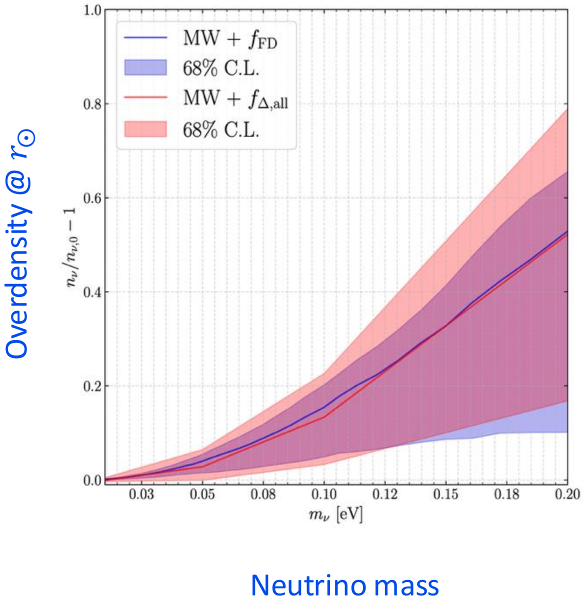
CνB in the solar neighbourhood…

Gravitational clustering enhances CνB density around cosmic structures.

- At $r_\odot \sim 10$ kpc from the Galactic Centre, expect $O(0.1-1)$ overdensity for allowed neutrino masses.



Ringwald & Y^3W 2004

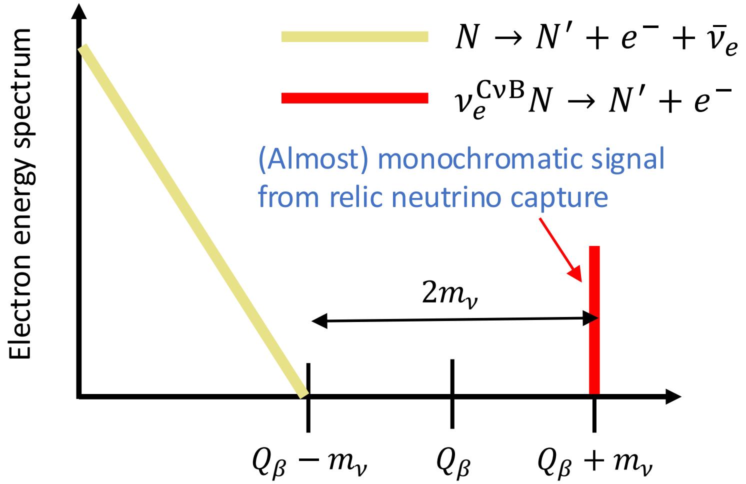


Zimmer, Abellán & Ando 2024

“Direct” detection of the CνB…

“Direct” in the sense of scattering-based experiment in a laboratory.

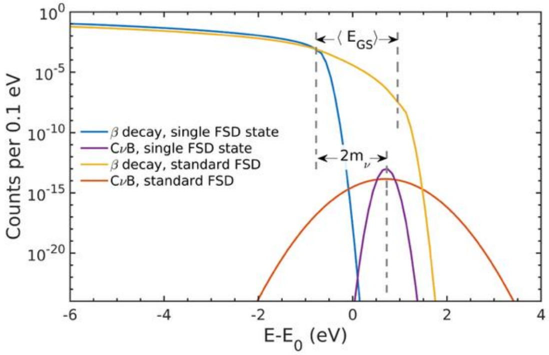
- Has not happened yet, though many ideas have been proposed.
- **Best terrestrial bound** on the local CνB overdensity δ_ν comes from KATRIN based on neutrino capture by a β-decaying nucleus. Weinberg 1962



$N \to N' + e^- + \bar{\nu}_e$

$\nu_e^{\mathrm{C\nu B}} N \to N' + e^-$

(Almost) monochromatic signal from relic neutrino capture



$$\boxed{\delta_\nu \lesssim 10^{11}\ (95\%\ \mathrm{C.L.})}$$

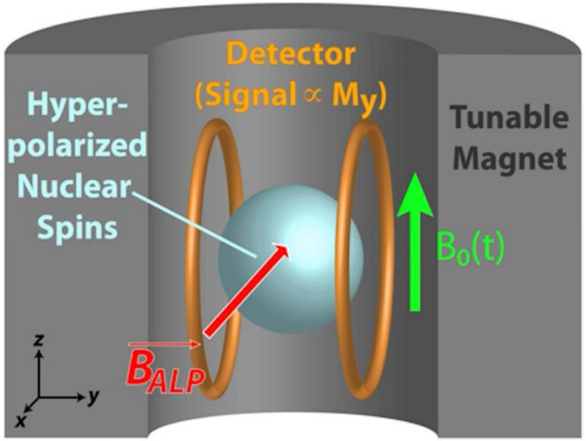
Aker et al. [KATRIN] 2022;
Based on first 2 science runs

Projected final sensitivity: $\delta_\nu \lesssim 10^{10}\ (90\%\ \mathrm{C.L.})$

CνB with NMR experiments (this talk)…

… falls in the direct detection category.

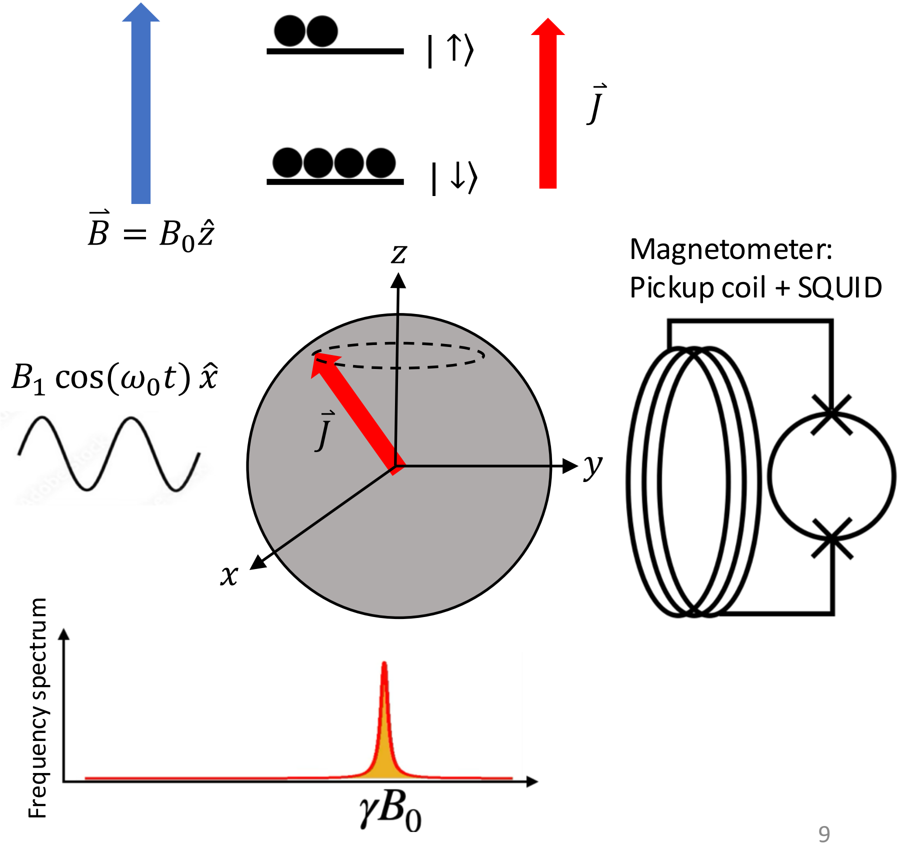
- Exploiting recent efforts in using quantum sensing for fundamental physics.
- Particularly existing and/or planned spin experiments for **axion/axion-like particle detection**, e.g., CASPEr.



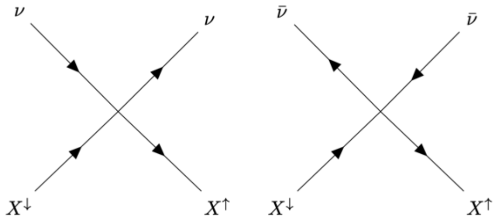
D. Budker

Basics of nuclear magnetic resonance…

- Ensemble of spin-1/2 in an external B field; energy splitting $\Delta E = \gamma B_0$.
- A **net magnetisation** develops (thermal or other means).
- Apply **transverse RF** with frequency ω_0 matching ΔE.
  - **Pulsed NMR** (e.g., MRI): apply RF over some time to coherently tilt magnetisation vector to desired angle → vector precesses at frequency ω_0.
  - Continuous wave (basis for ALP detection) → Rabi oscillations at frequency $\omega_1 = \gamma B_1$.
- **Magnetometer** detects precessing magnetisation.



Relic neutrino-spin interaction…



Since the CνB is everywhere, **interaction** of the spin ensemble with relic neutrinos can cause spin flips, e.g., $\nu + X^{\uparrow} \rightarrow \nu + X^{\downarrow}$.

- In our non-relativistic system, this inelastic scattering for a **single spin** is described by a Hamiltonian:

Precession

Interaction

$$H^{(1/2)} = H_S^{(1/2)} + H_{\text{int}}^{(1/2)}$$
$$= \omega_0 J_z + \Sigma_z J_z + \Sigma_- J_- + \Sigma_+ J_+$$

Spin lowering and raising operators

Fermi's constant

$$\Sigma_{\pm} = \sum_i \frac{G_F}{\sqrt{2}} g_A \bar{\nu}_i (\gamma^1 \mp i\gamma^2)(1 - \gamma^5)\nu_i$$

Axial-vector coupling of the unpaired nucleon in the nucleus

- **Single-spin interaction rates**:

De-excitation (i.e., flip down) rate: $\gamma_- \simeq 1.1 \times 10^{-48}\ \text{Hz}$

De-excitation minus excitation rate: $\gamma_{\text{net}} = \gamma_- - \gamma_+ \simeq 6 \times 10^{-51}\ \text{Hz}$

Assuming ^{129}Xe, $\omega_0 \sim 10^{-8}$eV, $\sum m_\nu = 0.15$ eV normal ordering

That's one net flip every 5×10^{19} years for one mole of spins…

Collective neutrino-spin interactions… 1/5

But CνB is **very cold** and has a typical momentum $p_\nu \sim 3T_{\mathrm{C}\nu\mathrm{B}} \sim 27\ \mathrm{cm}^{-1}$.

- **Collective spin flips** over a macroscopic ensemble of N spins may be possible.

Arvanitaki, Dimopoulos & Galanis 2025

- **Total excitation and de-excitation rate** of the ensemble

Rate at which the net magnetisation of the ensemble increases or decreases by one unit of ω_0.

$$\Gamma_\pm \sim \gamma_\pm F_\pm(\vec{p}_{\mathrm{in}} - \vec{p}_{\mathrm{out}})$$

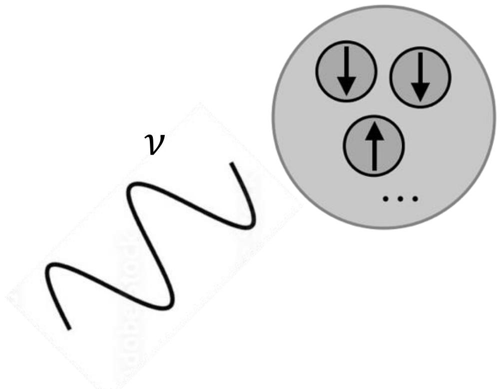
Schematic expression only!

Single-spin rate

Form factor

$$\boxed{F_\pm(\vec{p}\,' - \vec{p}) \equiv \sum_{\mathrm{f_{spin}}} \left| \langle \mathrm{f_{spin}} | \sum_{\alpha}^{N} J_\pm^\alpha e^{-\mathrm{i}(\vec{p}\,'-\vec{p})\cdot\vec{x}_\alpha} | \mathrm{i_{spin}} \rangle \right|^2}$$

α = spin label



- $F_\pm(\vec{p}_{\mathrm{in}} - \vec{p}_{\mathrm{out}})$ and hence $\Gamma_\pm$ may scale as N^2 **under the right conditions**.

→ Naïvely, **thousands** of events per year for one mole of spins.

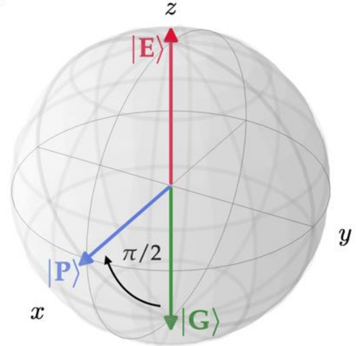
Collective neutrino-spin interaction… 2/5

Two conditions must be satisfied for coherent enhancement:

1. **Small momentum transfer** $q \equiv |\vec{p}_{\text{in}} - \vec{p}_{\text{out}}|$ relative to the inverse spatial separation between spins.
2. **Non-orthogonal** initial and final states.

$$F_\pm(\vec{p}\,' - \vec{p}) \equiv \sum_{\text{f}_{\text{spin}}} \left| \langle \text{f}_{\text{spin}} | \sum_{\alpha}^{N} J_\pm^\alpha e^{-\text{i}(\vec{p}\,'-\vec{p})\cdot\vec{x}_\alpha} |\text{i}_{\text{spin}}\rangle \right|^2$$

Example 1: The initial state is the ground state. $|\text{i}_{\text{spin}}\rangle = |\downarrow_1, \downarrow_2, \cdots, \downarrow_\gamma, \cdots, \downarrow_N\rangle$



$$F_+^G(\vec{p}\,' - \vec{p}) = N$$

$$F_-^G(\vec{p}\,' - \vec{p}) = 0$$

Orthogonal initial and final state;
No coherent enhancement even if q is small.

Collective neutrino-spin interaction… 3/5

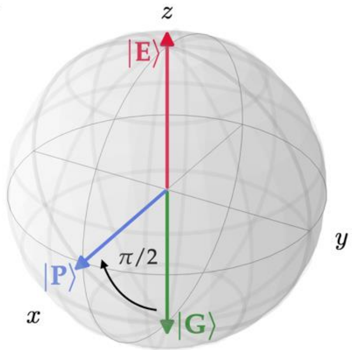
Two conditions must be satisfied for coherent enhancement:

1. **Small momentum transfer** $q \equiv |\vec{p}_{\text{in}} - \vec{p}_{\text{out}}|$ relative to the inverse spatial separation between spins.
2. **Non-orthogonal** initial and final states.

$$F_{\pm}(\vec{p}\,' - \vec{p}) \equiv \sum_{\mathrm{f_{spin}}} \left| \langle \mathrm{f_{spin}} | \sum_{\alpha}^{N} J_{\pm}^{\alpha} e^{-\mathrm{i}(\vec{p}\,'-\vec{p})\cdot\vec{x}_\alpha} | \mathrm{i_{spin}} \rangle \right|^2$$

$$|\rightarrow\rangle \equiv (|\uparrow\rangle + |\downarrow\rangle)/\sqrt{2}$$

Example 2: The initial state is the product state. $|\mathrm{i_{spin}}\rangle = |\rightarrow_1, \rightarrow_2, \cdots, \rightarrow_\gamma, \cdots, \rightarrow_N\rangle$



$$F_{\pm}^{P}(\vec{p}\,' - \vec{p}) = \frac{N}{2} + \frac{1}{4} \sum_{\alpha, \beta \neq \alpha} e^{-\mathrm{i}(\vec{p}\,'-\vec{p})\cdot(\vec{x}_\alpha - \vec{x}_\beta)}$$

Spherical sample of radius R

$$= \frac{N}{2} + \frac{N^2}{4} \frac{9}{|\vec{p}\,' - \vec{p}|^2 R^2} \left| j_1 \left(|\vec{p}\,' - \vec{p}| R \right) \right|^2$$

➡ Non-orthogonal initial and final states; Coherent enhancement if $qR \ll 1$.

Collective neutrino-spin interaction… 4/5

In the **coherent regime**, the total excitation and de-excitation rates of the ensemble are:

Number of spins

Spin sample size

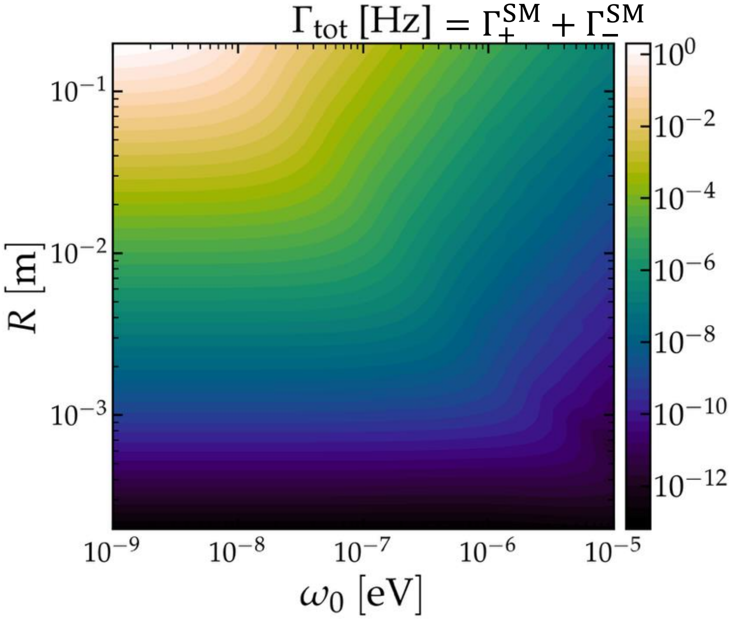
$$\Gamma_{\pm} \approx \frac{N^2}{16 p_\nu^2 R^2} \gamma_{\pm}$$

CνB momentum

Single-spin rate

- For a standard CνB, this evaluates to:

$$\Gamma_{\pm}^{\mathrm{SM}} \simeq 1.2 \times 10^{-6}\ \mathrm{Hz} \left(\frac{R}{1\ \mathrm{cm}} \right)^4$$



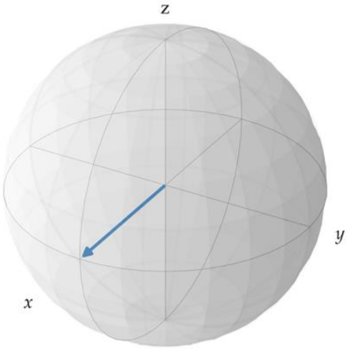
Assuming ^{129}Xe, $\omega_0 \sim 10^{-8}$eV, $\sum m_\nu = 0.15$ eV normal ordering

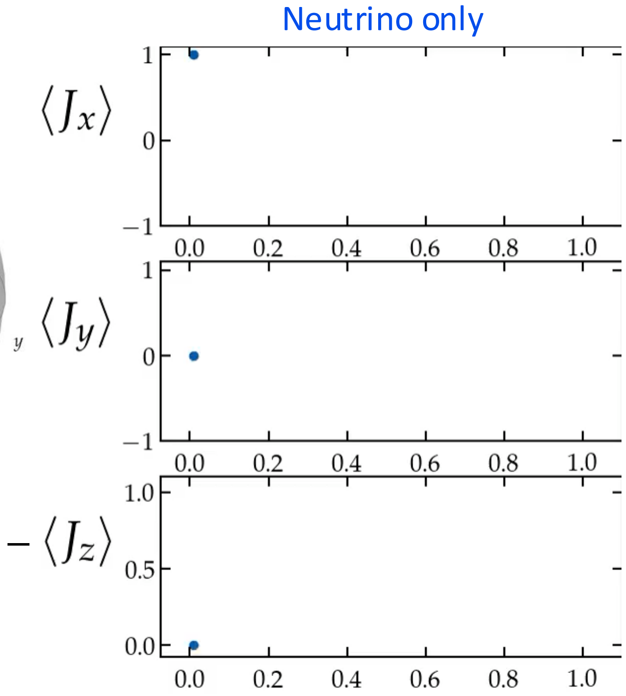
Collective neutrino-spin interaction… 5/5

What should we see in an ensemble of precessing spins?

- Starting from a coherent state (the product state in this example), collective neutrino-spin interaction drives the ensemble to the ground state in a time:

$$t_{C\nu \mathrm{B}} \sim \frac{1}{N\gamma_{\mathrm{net}}}$$



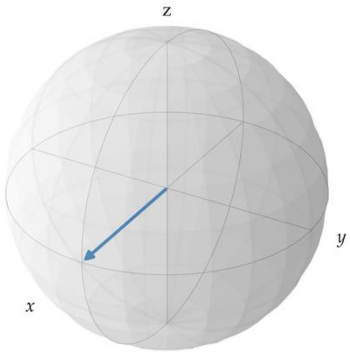


- **If we were in an ideal world**, this is what one should look for to detect the CνB. …. Except we're not…

Local interactions…

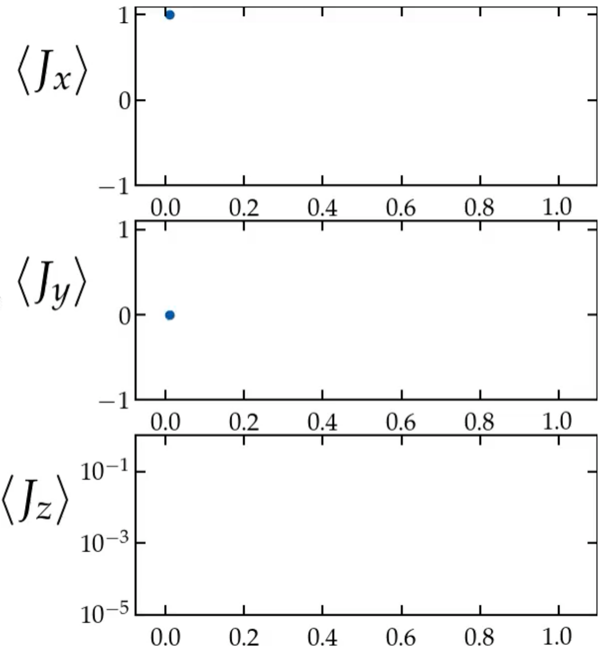
In reality, there are **other effects** that can also flip spins and do other damages to obscure the CνB signal.

- **Relaxation** due to local absorption + emission from, e.g., energy exchange of spins with lattice.
  - J_z relaxes to thermal expectation in a time T_1.
- **Dephasing** due to, e.g., spin-spin relaxation, inhomogeneous B field, etc.
  - Spins go out of phase with each other in a time $T_2 < T_1$.
  - Drives J_x and J_y to zero.



Coherent effects can only be seen at $t < T_2$

Dephasing+relaxation



T_2 at work

T_1 at work

Open quantum system framework...

We use a OQS framework to track the evolution of the spin ensemble under the combined effects of neutrino-spin and local interactions.

- Start with the total **density matrix** of system + bath $\rho = \rho_S \otimes \rho_B$, whose evolution is governed by the **von-Neumann equation**:

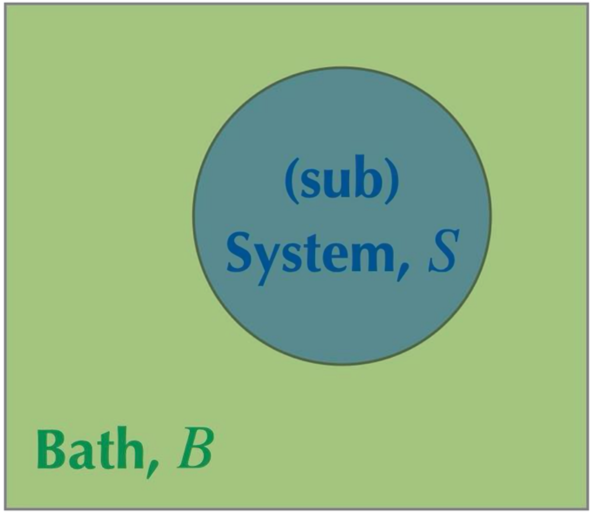
$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = -\mathrm{i}\,[H, \rho] \qquad H = H_S + H_B + H_{\text{int}}$$

- **Tracing out the bath** (and making some assumptions) yields an EoM for ρ_S:

Lindblad master equation

$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} = -\mathrm{i}[H^I_{\text{int}}, \rho_S] + \sum_k \gamma_k \mathcal{D}_{\mathcal{O}_k}[\rho_S(t)]$$

$$\mathcal{D}_{\mathcal{O}}[\rho_S(t)] = \mathcal{O}\rho_S\mathcal{O}^\dagger - \frac{1}{2}\{\mathcal{O}^\dagger\mathcal{O}, \rho_S\}$$



Lindblad master equation…

Assumptions:

- Interactions are (small w) **weak**.
- **Markovian** dynamics
- Secular approximation.

System density matrix

Interaction between system and bath

Interaction rate of the kth channel

$$\frac{\mathrm{d}\rho_S}{\mathrm{d}t} = -\mathrm{i}[H^I_{\mathrm{int}}, \rho_S] + \sum_k \gamma_k \mathcal{D}_{\mathcal{O}_k}[\rho_S(t)]$$

$$\mathcal{D}_{\mathcal{O}}[\rho_S(t)] = \mathcal{O}\rho_S\mathcal{O}^\dagger - \frac{1}{2}\{\mathcal{O}^\dagger\mathcal{O}, \rho_S\}$$

- Can account for both collective neutrino and local interactions simultaneously; just specify the **superoperator** $\mathcal{D}_{\mathcal{O}_k}$ and rate γ_k.

Collective de-excitation and excitation

$$\mathcal{D}_- = \mathcal{J}_-\rho_S\mathcal{J}_+ - \tfrac{1}{2}\{\mathcal{J}_+\mathcal{J}_-, \rho_S\}$$
$$\mathcal{D}_+ = \mathcal{J}_+\rho_S\mathcal{J}_- - \tfrac{1}{2}\{\mathcal{J}_-\mathcal{J}_+, \rho_S\}$$
$$\mathcal{J}_{\pm,z} = \textstyle\sum_\alpha J^\alpha_{\pm,z}$$

Local emission, absorption, and dephasing

$$\mathcal{D}^{\mathrm{loc}}_- = \textstyle\sum_\alpha (J^\alpha_-\rho_S J^\alpha_+ - \tfrac{1}{2}\{J^\alpha_+J^\alpha_-, \rho_S\})$$
$$\mathcal{D}^{\mathrm{loc}}_+ = \textstyle\sum_\alpha (J^\alpha_+\rho_S J^\alpha_- - \tfrac{1}{2}\{J^\alpha_-J^\alpha_+, \rho_S\})$$
$$\mathcal{D}^{\mathrm{loc}}_\phi = \textstyle\sum_\alpha (J^\alpha_z\rho_S J^\alpha_z - \tfrac{1}{2}\{(J^\alpha_z)^2, \rho_S\})$$

Solving the Lindblad master equation… 1/2

A **brute force solution** for $N = 10^{23}$ spins is impossible...

- We use a **moments method** whereby we construct EoMs directly for the observables of interest and close the hierarchy using a closure condition.
- Works for **arbitrarily large** N.
- Method is also good for computing unequal-time correlations.

$$
\begin{aligned}
\frac{\mathrm{d}}{\mathrm{d}t}\langle\mathcal{J}_z\rangle &= \sum_{\pm} \pm\gamma_{\pm}\Big[\langle\mathcal{J}^2\rangle - \langle\mathcal{J}_z^2\rangle \mp \langle\mathcal{J}_z\rangle\Big] \\
&\quad + \sum_{\pm} \pm\gamma_{\pm}^{\mathrm{loc}}\left[\mp\langle\mathcal{J}_z\rangle + \frac{N}{2}\right], \\
\frac{\mathrm{d}}{\mathrm{d}t}\langle\mathcal{J}^2\rangle &= -\sum_{\pm} \gamma_{\pm}^{\mathrm{loc}}\Big[\langle\mathcal{J}^2\rangle + \langle\mathcal{J}_z^2\rangle \mp (N-1)\langle\mathcal{J}_z\rangle - N\Big] \\
&\quad - \gamma_{\phi}^{\mathrm{loc}}\left[\langle\mathcal{J}^2\rangle - \langle\mathcal{J}_z^2\rangle - \frac{N}{2}\right], \\
\frac{\mathrm{d}}{\mathrm{d}t}\langle\mathcal{J}_z^2\rangle &= \sum_{\pm} \gamma_{\pm}\Big[\langle\mathcal{J}^2\rangle - 3\langle\mathcal{J}_z^2\rangle \mp \langle\mathcal{J}_z\rangle \\
&\qquad \mp 2\langle\mathcal{J}_z\rangle\langle\mathcal{J}_z^2\rangle \pm 2\langle\mathcal{J}_z\rangle\langle\mathcal{J}^2\rangle\Big] \\
&\quad - \sum_{\pm} \gamma_{\pm}^{\mathrm{loc}}\left[2\langle\mathcal{J}_z^2\rangle \mp (N-1)\langle\mathcal{J}_z\rangle - \frac{N}{2}\right].
\end{aligned}
$$

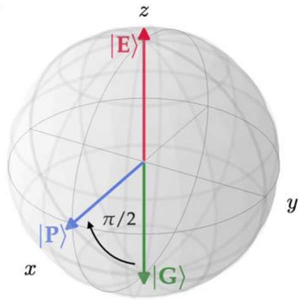
Solving the Lindblad master equation… 2/2

An illustrative example solution starting in the product state.

- Parameters in this example:

Neutrino interactions

$$\frac{\gamma_+}{\gamma_-} = 0.99$$



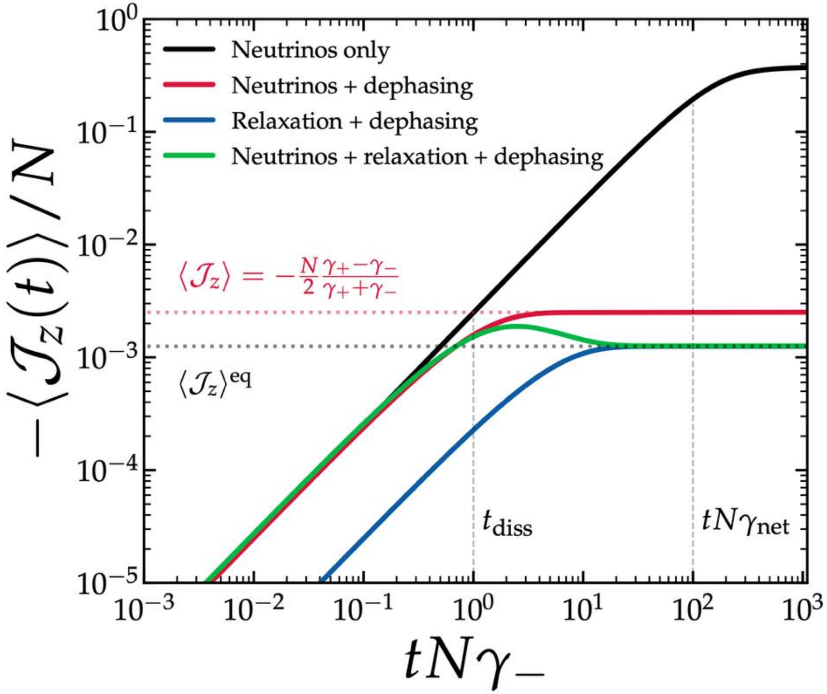
Local interactions

$$\frac{\gamma_+^{\mathrm{loc}}}{\gamma_-^{\mathrm{loc}}} = 0.995 \qquad \gamma_\phi^{\mathrm{loc}} = N\gamma_- \qquad N = 1000$$

$$T_1^{-1} = \gamma_+^{\mathrm{loc}} + \gamma_-^{\mathrm{loc}}$$

Local rates adjusted to match $T_1 = 10T_2$

$$T_2^{-1} = (\gamma_+^{\mathrm{loc}} + \gamma_-^{\mathrm{loc}} + \gamma_\phi^{\mathrm{loc}})/2$$

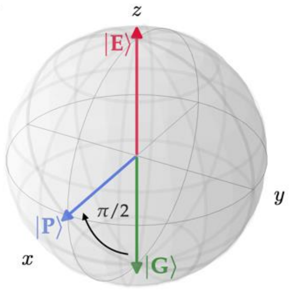


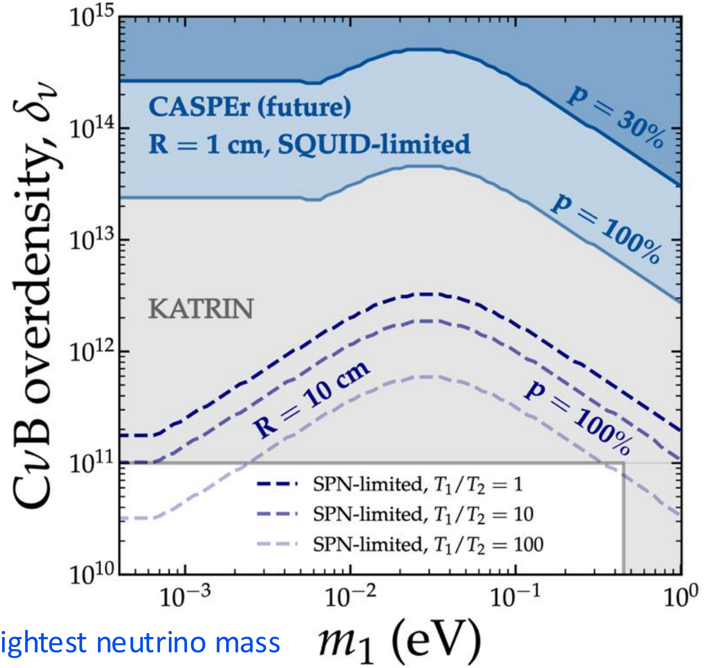
Forecast constraints on CνB overdensity.. 1/3

We consider an NMR experiment using liquid ^{129}Xe, as envisaged in **future stages of CASPEr**, following their experimental specifications. Walter et al. 2025

- $T_2 \sim 1000\ s$
- Instrumental noise; sampling frequency

- We assume the system is initially in the product state.
  - **Not** in CASPEr's future plans (they start in the ground state) but can be achieved by a π/2 pulse from the ground state.





Lightest neutrino mass (normal ordering)

Forecast constraints on CνB overdensity.. 2/3

We consider an NMR experiment using liquid ^{129}Xe, as envisaged in **future stages of CASPEr**, following their experimental specifications. Walter et al. 2025

- Our observable is the magnetisation in the z-direction $\langle J_z \rangle$.
- χ^2- analysis on **mock data**, where the fiducial model has **no** CνB signal.

$N_{\text{shots}} = 1000$

$$\chi^2(\delta_\nu) = N_{\text{shots}} \sum_{ij}^{n_t} d_i \left[C^{-1}\right]_{ij} d_j$$

Theory minus mock data

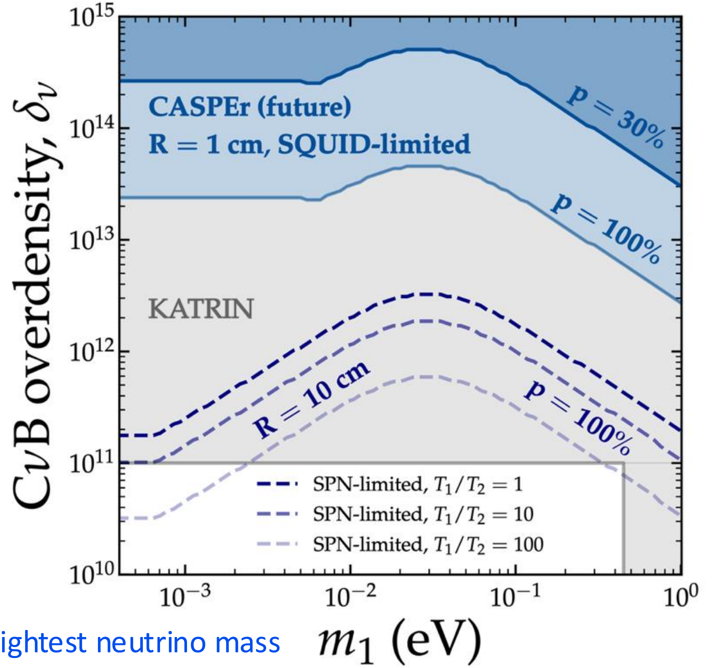
$$d_i \equiv \langle \mathcal{J}_z(t_i;\delta_\nu)\rangle_{|P\rangle} - \langle \hat{\mathcal{J}}_z(t_i)\rangle_{|P\rangle}$$

Covariance matrix

$$C_{ij} = C_{ij}^{\text{th}} + \sigma^2_{\text{SQUID}}\delta_{ij}$$

Spin projection noise + Unequal-time correlations

Instrumental noise



Lightest neutrino mass (normal ordering)

Forecast constraints on CνB overdensity.. 3/3

We consider an NMR experiment using liquid ^{129}Xe, as envisaged in **future stages of CASPEr**, following their experimental specifications. Walter et al. 2025

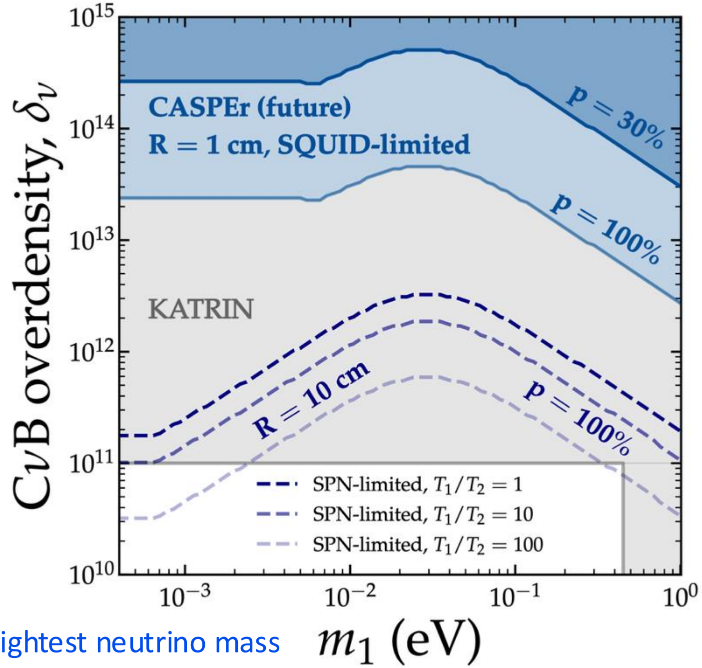
- A **hyperpolarised initial condition** (pre-$\pi/2$ pulse) is critical!

$p = 1$ corresponds to a pure ground state;
in general $0 < |p| < 1$.

$$\boxed{\delta_\nu^{\mathrm{CASPEr}} \lesssim 5.3 \times 10^{13} \left(\frac{0.5}{p}\right)^2}$$

- Cf thermal polarisation:

$$p = \tanh\left(\frac{\hbar\gamma B}{2k_B T}\right) \approx \frac{\hbar\gamma B}{2k_B T}$$
$$\simeq 10^{-3}\left(\frac{B}{10\ \mathrm{T}}\right)\left(\frac{4\,\mathrm{K}}{T}\right)$$



Conceivable

No instrumental noise + perfect polarisation

Lightest neutrino mass (normal ordering)

Take-home message so far…

CνB detection with NMR is **not** going to happen any time soon…

- Even setting competitive limits (e.g., better than what KATRIN can do) on the CνB overdensity represents a **significant experimental challenge**.
  - Reducing instrumental noise, achieving $O(1)$ polarisation, etc.
  - There may be other collective effects we did not describe…

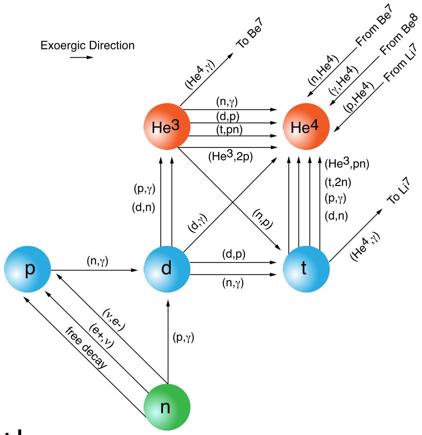
Now we switch gears…

Status of neutrinos in cosmology…

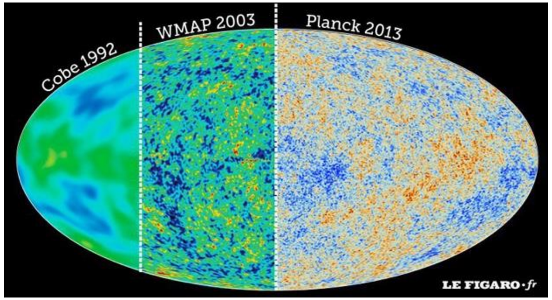
How else can we learn about the CνB?

Although we **cannot detect the CνB** in the lab yet, we can still exploit how it affects events that take place after its formation **to constrain its properties**.

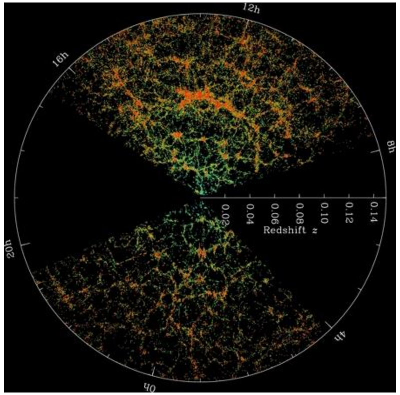
Light element abundances



CMB anisotropies



Large-scale matter distribution



Where the CνB shows up:

Expansion rate

Expansion rate
Free-streaming
Perturbation growth

Perturbation growth

What neutrino physics can we probe?

Neutrino properties that can be constrained by or inferred from precision cosmological observations include:

- **Absolute neutrino mass,** $\sum m_\nu$
- **Effective number of neutrinos,** N_{eff}
  - Deviations from SM prediction of $N_{\text{eff}} \approx 3$
  - e.g., test for the existence of light sterile states, dark radiation, etc,

“Standard” tests

- **Neutrino decay/lifetime,** τ_0
- **Non-standard neutrino interactions**
  - Self, neutrino-dark matter, neutrino-dark energy
  - …

More exotic, but of growing interest

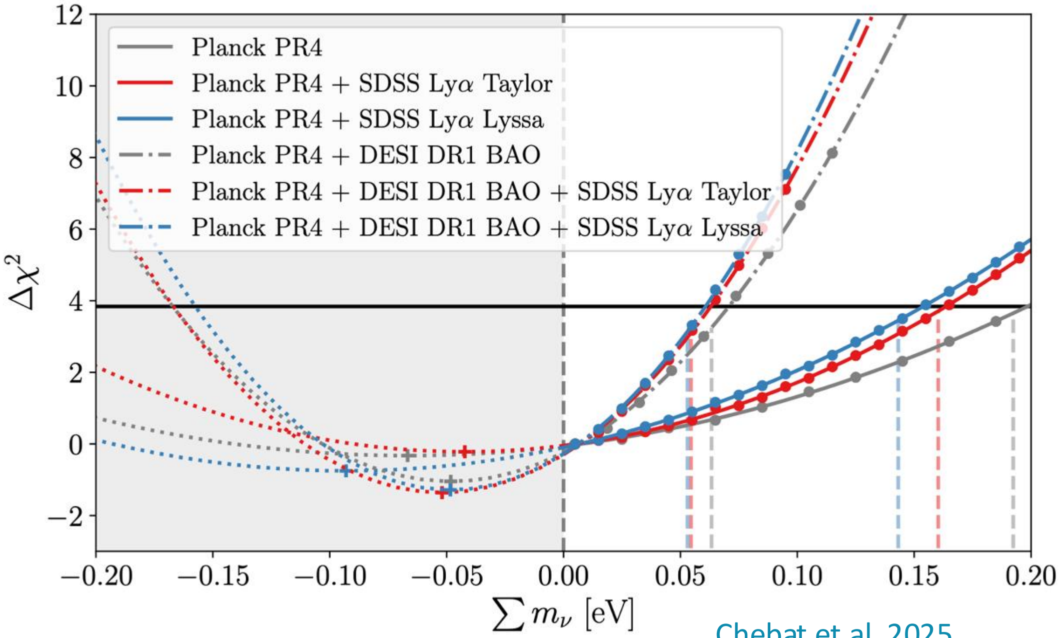
Cosmological neutrino mass bounds…

The combination of **DESI+Planck** appears to constrain the neutrino mass sum to an extremely tight $\sum m_\nu < 0.053\ \text{eV}\ (95\%)$ in a ΛCDM+Σm_ν fit.

Elbers et al [DESI]. 2025

- Bound is below the miniumum neutrino mass sum $\sum m_\nu = 0.06\ \text{eV}$ from neutrino oscillations.
- In fact, likelihood peaks in an **unphysical region**.
  - Seen in both Bayesian and frequentist analyses.
- **“Negative neutrino mass”**

Loverde & Weiner 2024;
Craig, Green, Meyers & Rajendran 2024;
Naredo-Tuero et al. 2024; Elbers et al. 2025



Chebat et al. 2025

Negative neutrino mass…

… is purely a phenomelogical description of the behaviours of the cosmological observables

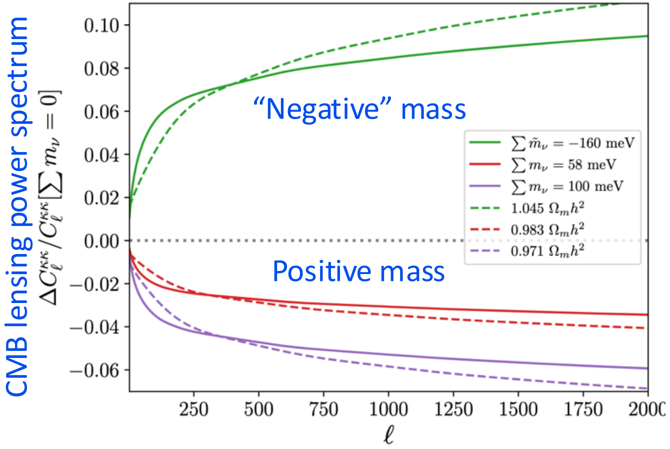
- **Excess power** in CMB lensing relative to ΛCDM prediction; can be mimicked if we **flip** the suppressed power due to positive m_ν to an enhancement due to a "negative mass".
  - Statistical significance: $(2.3-2.7)\sigma$

- True origin seems to lie in a **mismatch** in the preferred Ω_{m} between DESI & Planck:

$$\Omega_{\mathrm{m}}^{\mathrm{DESI}} < \Omega_m^{\mathrm{CMB}}$$

Elbers et al. 2025
LoVerde & Weiner 2024
Lynch & Knox 2025

  - Statistical significance: 2.3σ



Craig et al. 2024

Background expansion rate

$$h^2(z;\bar{m}_\nu) \equiv h^2(z;0) + \mathrm{sgn}(\bar{m}_\nu)\times \left(h^2(z;\Sigma m_\nu = |\bar{m}_\nu|) - h^2(z;0)\right)$$

Standard

Additional piece from negative neutrino mass

Negative neutrino mass… 2/2

Low statistical significance, but if you really want to play the game, there are non-standard physics scenarios that can reproduce these effects.

- Dynamical dark energy Elbers et al. 2025; Ahlen et al. [DESI] 2025
- Decaying dark matter Lynch & Knox 2025
- Decaying neutrinos Abellán 2026
- Suppressed growth rate Giare et al. 2025
- Modified recombination Lynch, Knox & Chluba 2024

⋮

- Or, more mundanely, unresolved systematics, or maybe the patch of universe we measure is a 2σ outlier?

Summary…

The **cosmic neutrino background** is a prediction of the standard hot big bang that is as fundamental as the CMB.

- **Direct CνB detection** in the laboratory remains out of reach.
- But we can still **infer its properties** by looking for its imprints on cosmological observables.
  - At face value, cosmological neutrino mass bounds are now getting very close to the minimum neutrino mass sum $\sum m_\nu = 0.06\ \mathrm{eV}$ established from neutrino oscillations.
  - **Minor discrepancies** between high-z and low-z obesrvations may be the root of some extraordinarily tight bounds on $\sum m_\nu$ reported in the literature.