

Prospects for relic neutrino detection using nuclear spin experiments

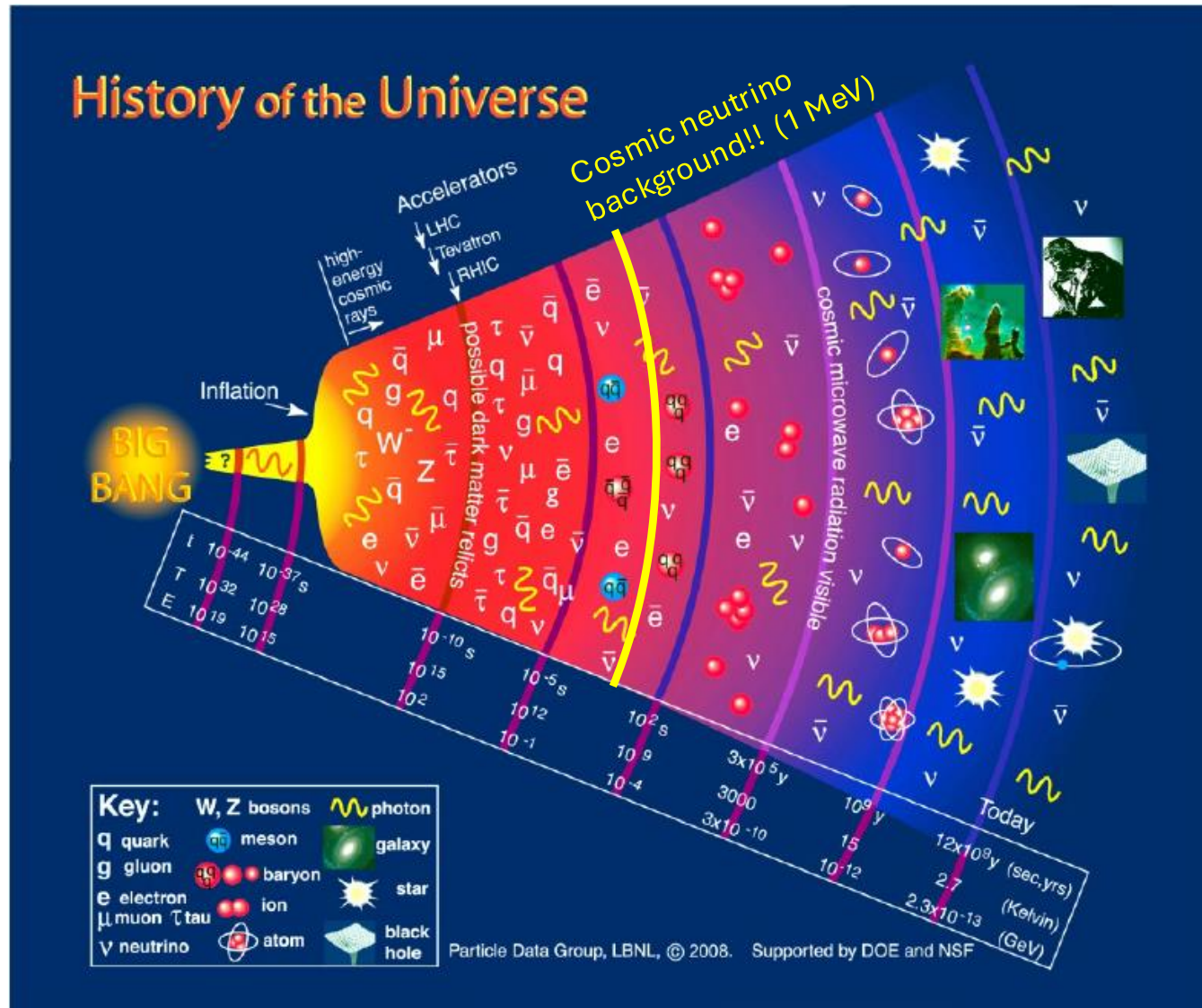
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1. Cosmic neutrino background



- Cosmic Microwave Background detected!
- Cosmic Neutrino Background **NOT** detected!

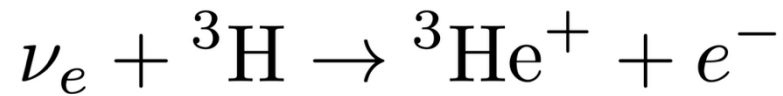
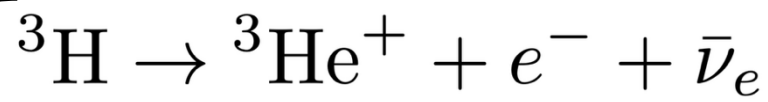
- Why?
 - Very weak interaction $\mathcal{O}(G_F^2) \sim 10^{-10} \text{ GeV}^{-4}$
 - Low energy $\langle p_\nu \rangle \approx 5.3 \times 10^{-4} \text{ eV}$

- Interesting?
 - Window into very early Universe!
 - Neutrino properties (effective number, masses, Majorana)
 - Cosmic structure

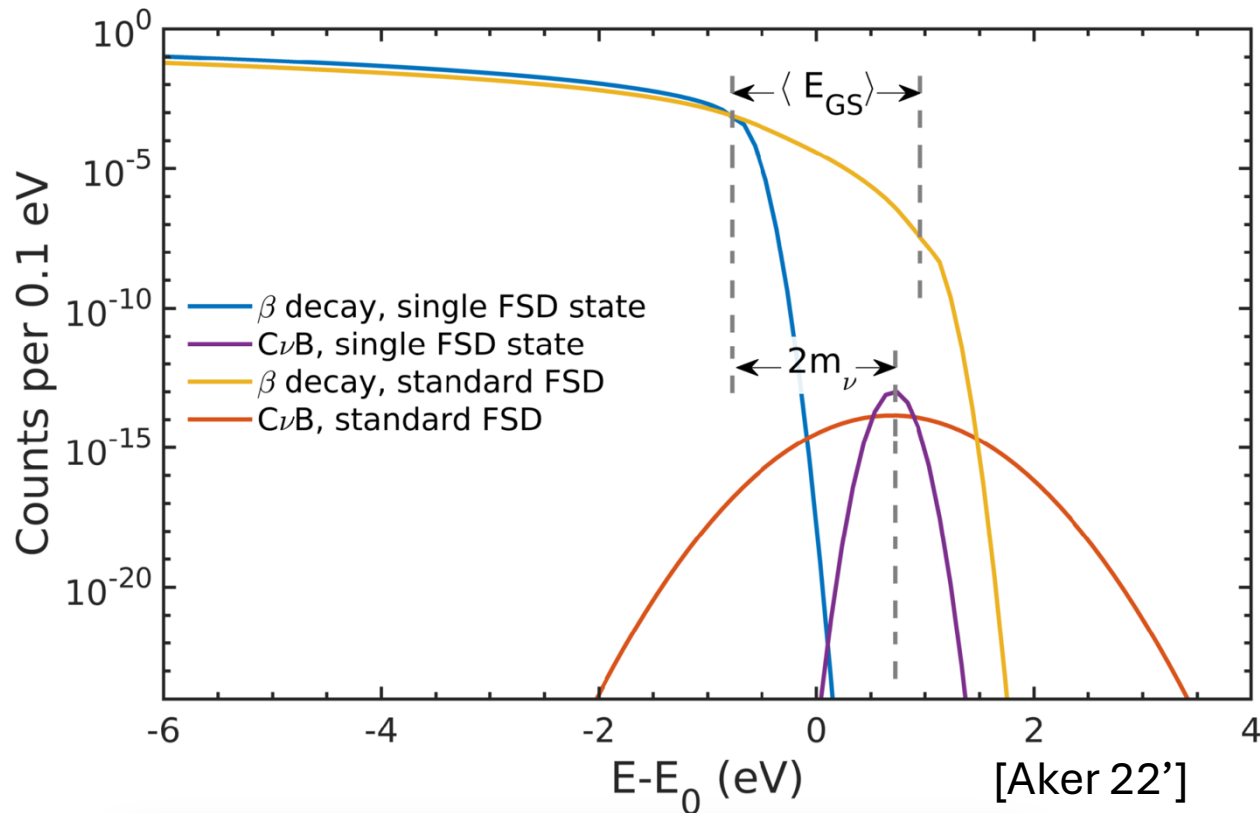
- **KATRIN** is the “**biggest**” experimental effort



- Tritium

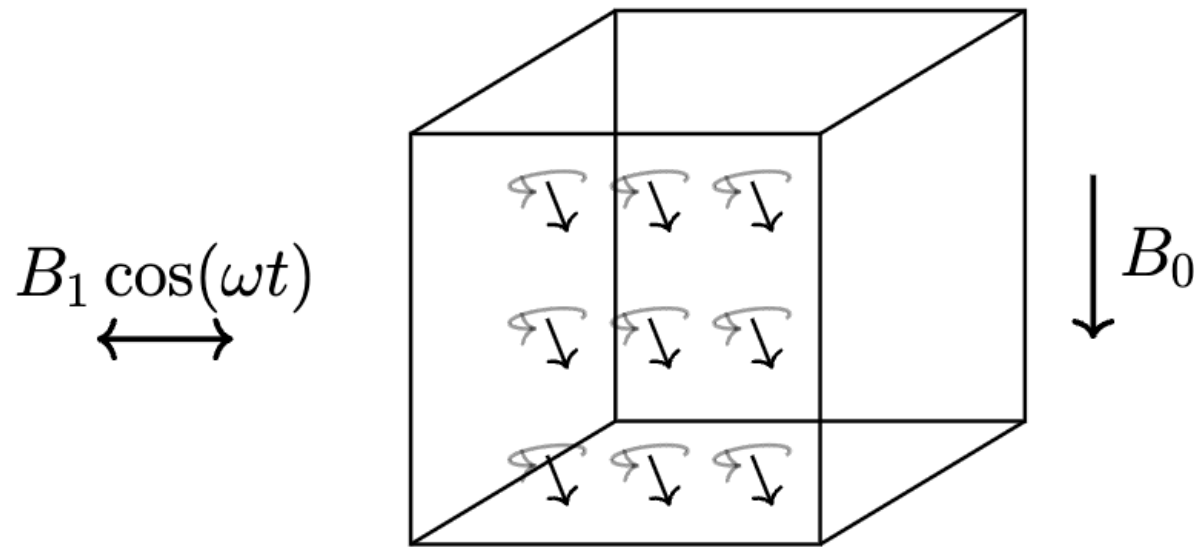


[Weinberg 62']



- **Best constraint** $\delta_\nu = \frac{n_\nu}{\bar{n}_\nu} \leq 10^{11}$ (95% C.L.)
- **Can nuclear spin systems do better?**

2.1 Nuclear Magnetic Resonance (NMR)

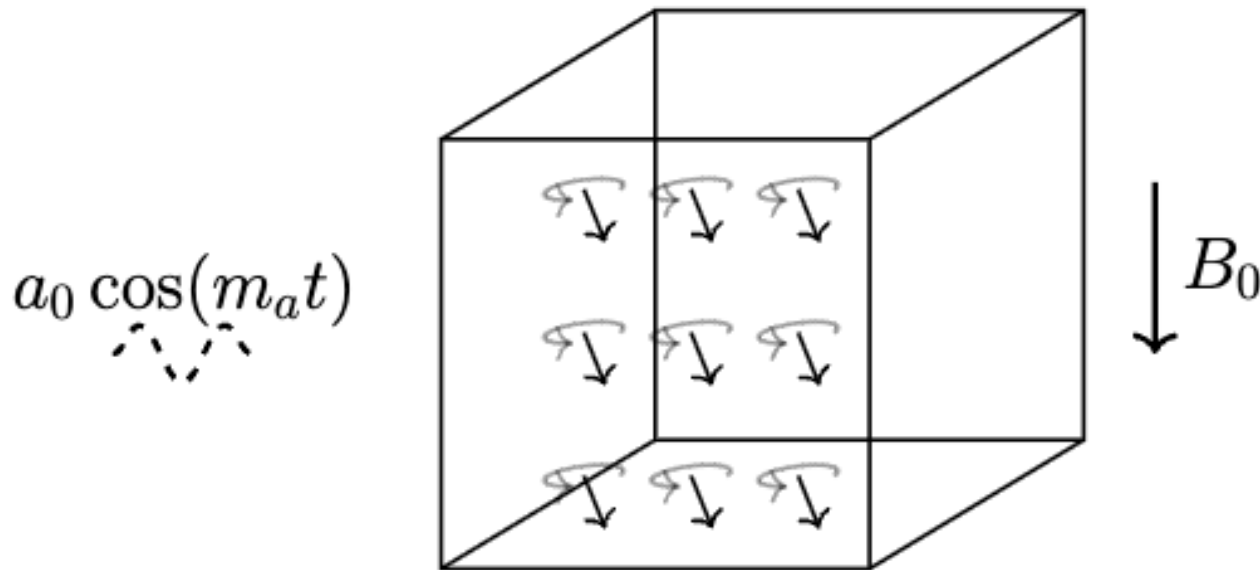


- RF pulse with resonant frequency
- Nuclear spins precess if $\omega = \gamma B_0$
- Oscillating transverse magnetization can be measured (magnetometer)

- Do spins precess forever? **NO!**
- **T1** {
 - **Relaxation**
 - Loss of resonance intensity
 - Spins exchange energy with surroundings
 - System relaxes to thermal equilibrium (spins tend to align again)
- **T2** {
 - **Dephasing**
 - Spin-spin interaction
 - Field inhomogeneities

Normally $T2 < T1$

2.2 NMR axion dark matter (CASPEr experiment) [Kimball 07']



- High occupation number ➡ Coherent classical field
- Axion can interact with nuclear spins
- NMR where axion “acts” as magnetic field B1
- Scan B_0 till resonance is found! $\gamma B_0 = m_a$

2.3 NMR cosmic neutrinos

- Stodolski effect

[Stodolski 75',
Shergold 23']

- Shift in energy levels

$$\Delta E \sim G_F \beta_{\text{Earth}} (n_\nu - n_{\bar{\nu}})$$

- Can lead to precession
- Very small to be measured!!

$$G_F \beta_{\text{Earth}} n_\nu \sim 10^{-39} \text{ eV}$$

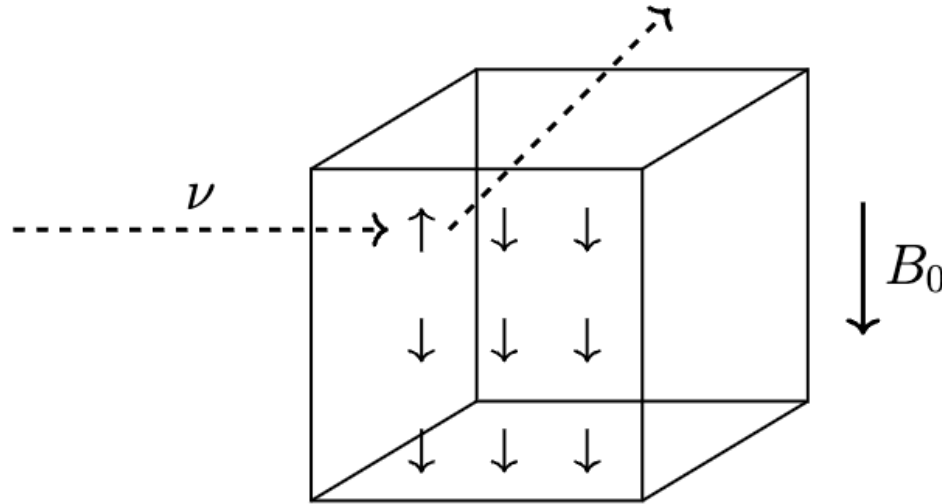
- Big asymmetry not expected!

- Different strategy



Looking into neutrino
induced noise

- Different picture!



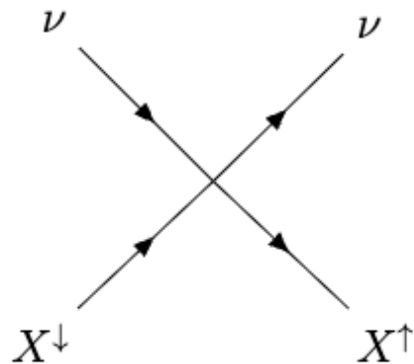
- B_0 + neutrino background
- Neutrinos can flip spins
- Investigate how the magnetization changes over time [Arvanitaki 24']

3.1 Neutrino-Spin interaction

- 4-Fermi effective interaction

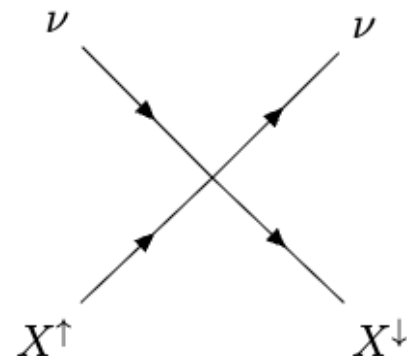
$$\mathcal{L} \supset - \sum_f \frac{G_F}{\sqrt{2}} \bar{X} \gamma^\mu (g_V^f - g_A^f \gamma^5) X \bar{\nu}_f \gamma_\mu (1 - \gamma^5) \nu_f$$

$$H = \Sigma_- J_- + \Sigma_+ J_+$$



Excitation γ_+

<

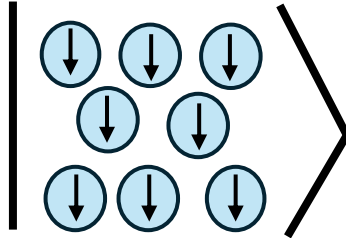


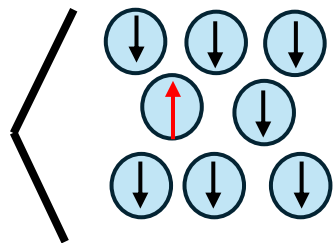
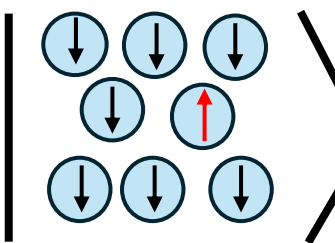
De-excitation γ_-

Rates very suppressed!! $\gamma_- \sim 10^{-48} \text{ Hz}$

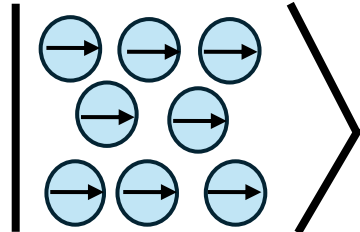
3.2 Coherent inelastic scattering

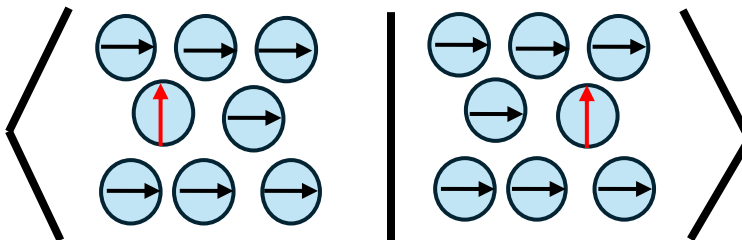
$$\Gamma \sim \sum_f |\langle f | H | i \rangle|^2$$

- Ground state $|G\rangle = \prod |\downarrow\rangle$ 

  $= 0$

$$\Gamma \sim N$$

- Product state $|P\rangle = \prod \frac{1}{\sqrt{2}} (|\uparrow\rangle + |\downarrow\rangle)$ 

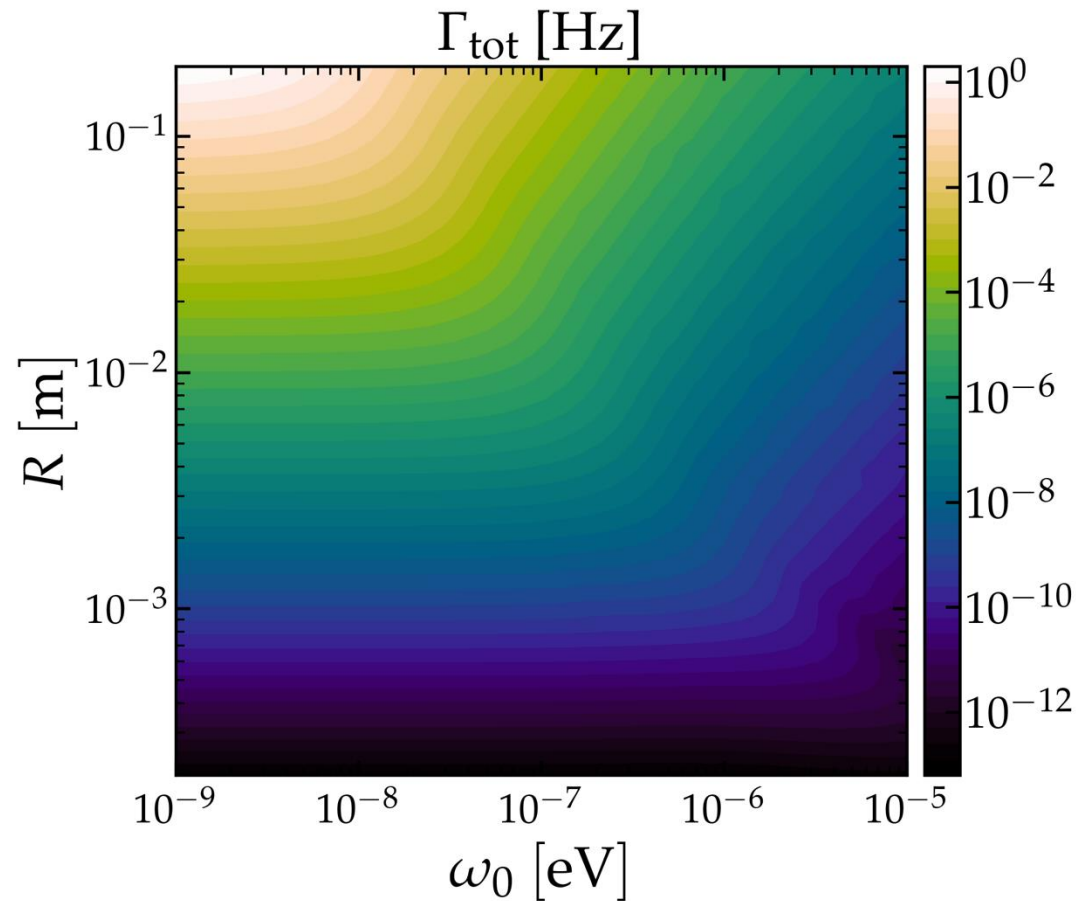
 $= 1/2$

- Product state + low momentum transfer $qR \ll 1$



Enhancement! $\Gamma \sim \frac{N^2}{4}$

3.3 Total rates



- Large rates!
- This treatment is too simplistic!

4. An open quantum system

- Does the rate change over time?
- What role do T_1 and T_2 play?
- What happens for more realistic initial states?

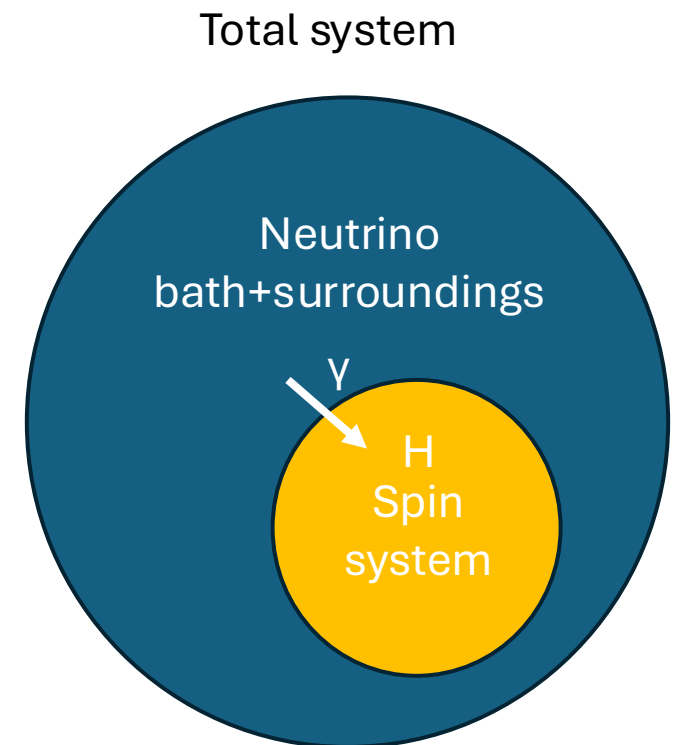


Lindblad Equation

$$\frac{d\rho_S}{dt} = -i[H, \rho_S] + \frac{1}{2} \sum_k \gamma_k \mathcal{D}_{\mathcal{O}_k}[\rho_S(t)]$$

$$\mathcal{D}_{\mathcal{O}}[\rho_S(t)] = \mathcal{O}\rho_S\mathcal{O}^\dagger - \frac{1}{2}\{\mathcal{O}^\dagger\mathcal{O}\rho_S\} \quad [\text{Lindblad 76'}]$$

- Focuses only on the dynamics of the spin system
- Can include coherent neutrino scattering
- Can model relaxation and dephasing via local interactions
- Can account for different initial states



4.1 Coherent observables

- Lindblad equation can be solved perturbatively (with only neutrinos)

$$\langle J_z \rangle_{|P\rangle} \approx -\frac{N^2}{4}(\gamma_- - \gamma_+)t$$

- Energy exchange with neutrinos
- Measure magnetization z axis

$$\langle J_x^2 \rangle_{|G\rangle} \approx \frac{N}{4} + 2\gamma_+ N^2 t$$

- Neutrinos induce noise
- Measure variance magnetization x axis

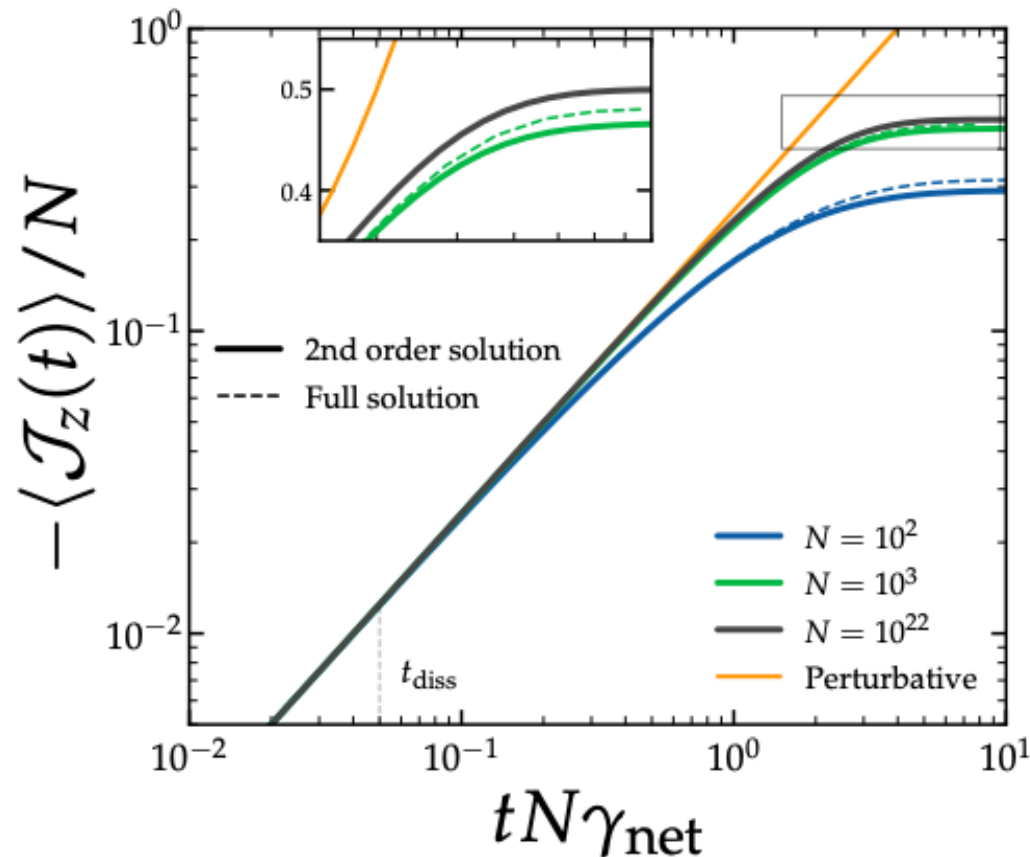
$$\Delta J_x = \sqrt{\langle J_x^2 \rangle}$$

How good is the perturbative solution?

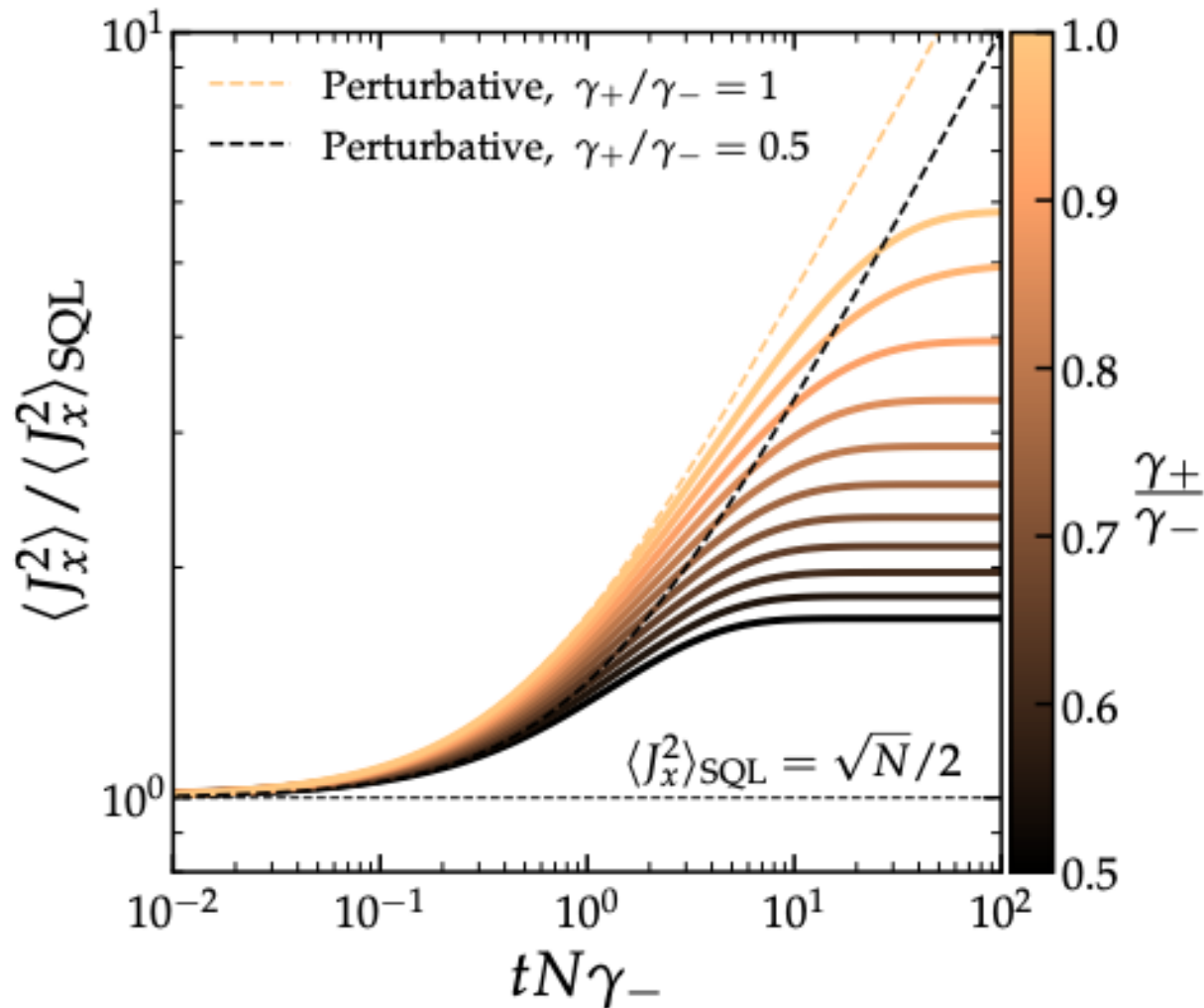
- OpenNu
 - Solves Lindblad for coherent effects
 - Reasonable for $N \sim 10000$
- Qutip
 - Solves Lindblad for coherent+local interactions
 - Reasonable for $N \sim 100$

[Shammah 17']
- Second-order approximation
 - System differential equations for expected values of observables
 - Coherent+local interactions
 - Not limited by N

Let's start by considering only the neutrinos



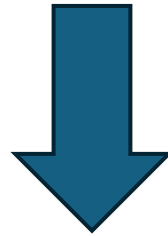
- Perturbative solution valid for $t \lesssim 1/(N\gamma_{\text{net}})$
- Coherence also lost after same time
- Second-order very good approximation!!



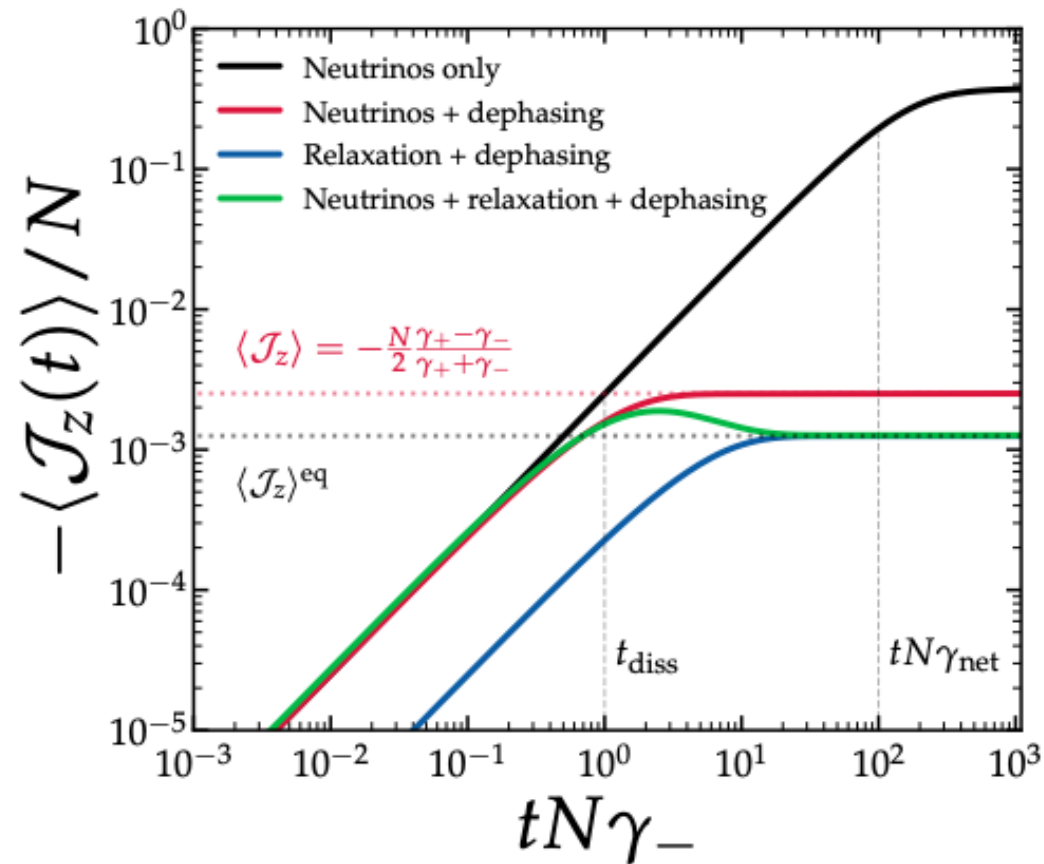
- Perturbative solution valid for $t \lesssim 1/(N\gamma_{\text{net}})$
- Coherent effect lost after same time since system far from $|G\rangle$

4.2 Relaxation and dephasing

- Energy exchange with surroundings induce relaxation
- Field inhomogeneities and spin-spin interactions induce dephasing
- Can be modeled with local interactions



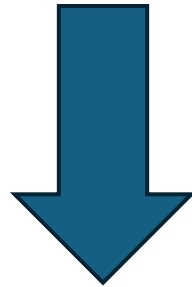
- Solve equation numerically including local interactions



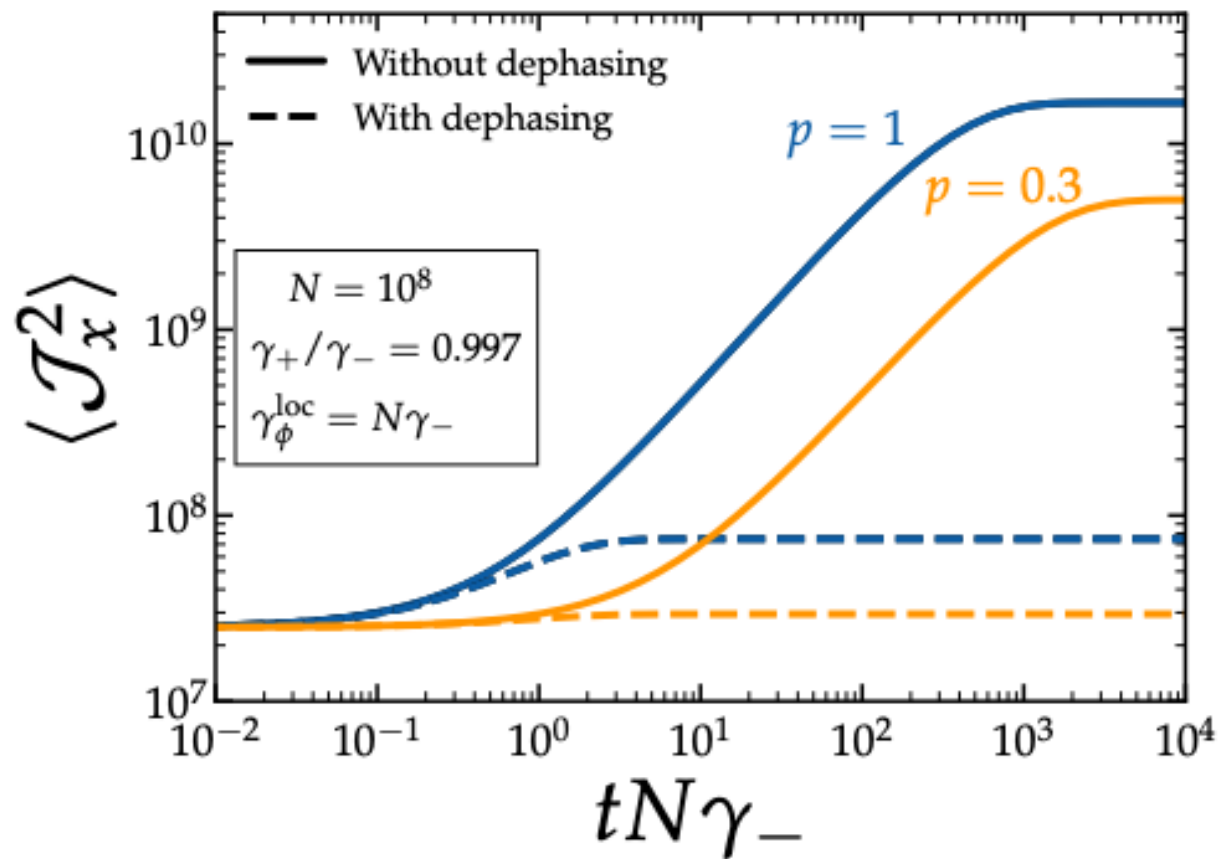
- System driven to thermal equilibrium
- Coherent effects lost after $t_{\text{diss}} = T_2$!

4.3 Polarization

- Coherence strongly depends on the initial state
- Experimentally $|G\rangle$ $|P\rangle$ can not be perfectly prepared



Solve equation numerically for more realistic
initial states



- Small polarization limits the signal

5. Experimental protocol

- Prepare system close to $|P\rangle$ and measure z magnetization as signal
- Noise sources
 - Magnetometer noise (SQUID)
 - Intrinsic quantum noise (Spin Projection Noise)



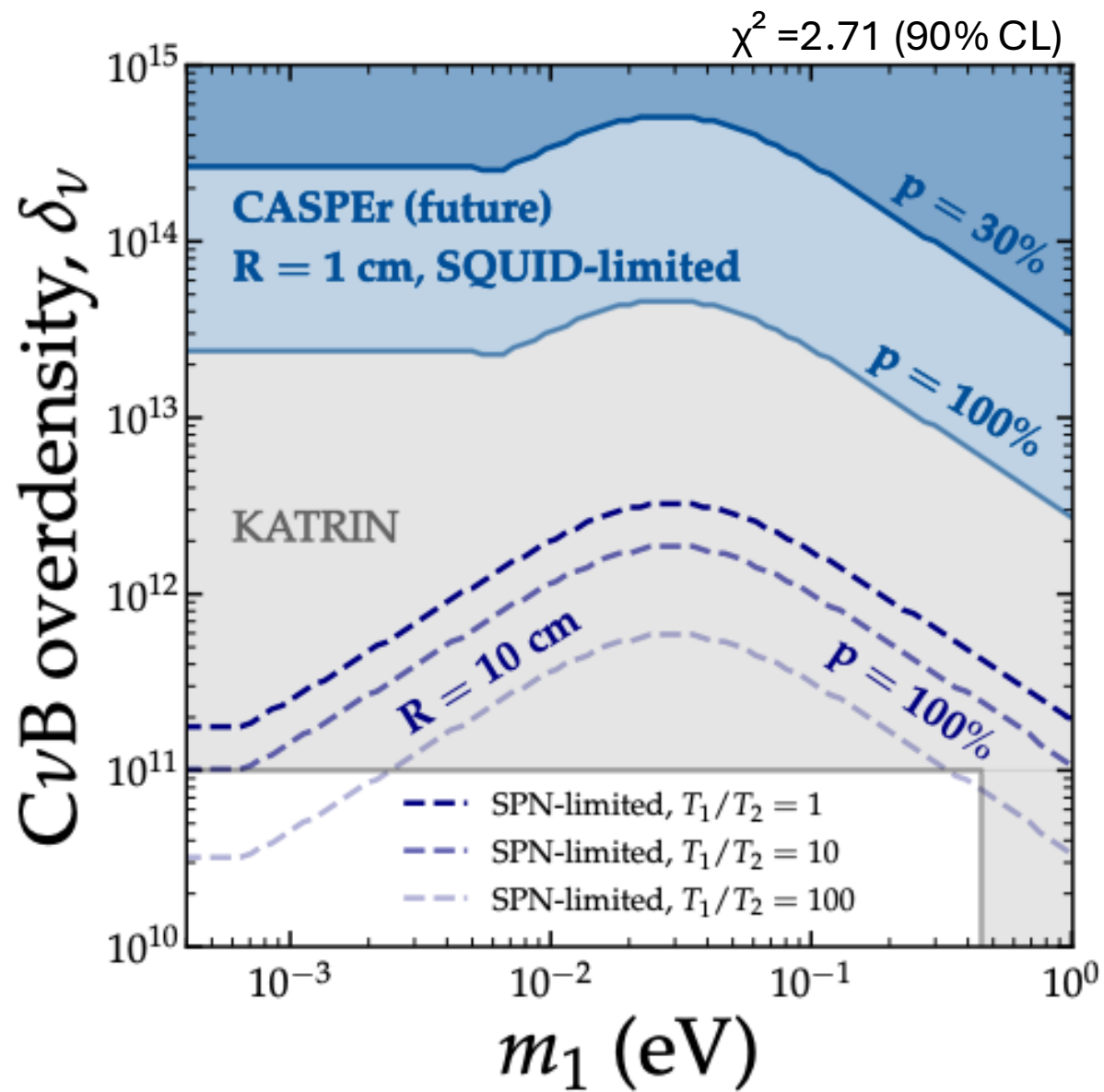
Signal far below noise!

5.1 Projected constraint

- Maximum neutrino overdensity compatible with the noise



- χ^2 test
 - Generate mock magnetization data (without neutrinos)
 - Compute χ^2 with varying neutrino overdensity
 - Set χ^2 threshold for allowed range



6. Summary

- Cosmic neutrinos can interact coherently with nuclear spins
- Local dephasing and limited polarization suppress coherent observable signals
- Direct detection with current NMR technology beyond reach but very competitive constraints!

Thank you for listening!

Questions?