The Detection Challenge of the Cosmic Neutrino Background and Other Relics

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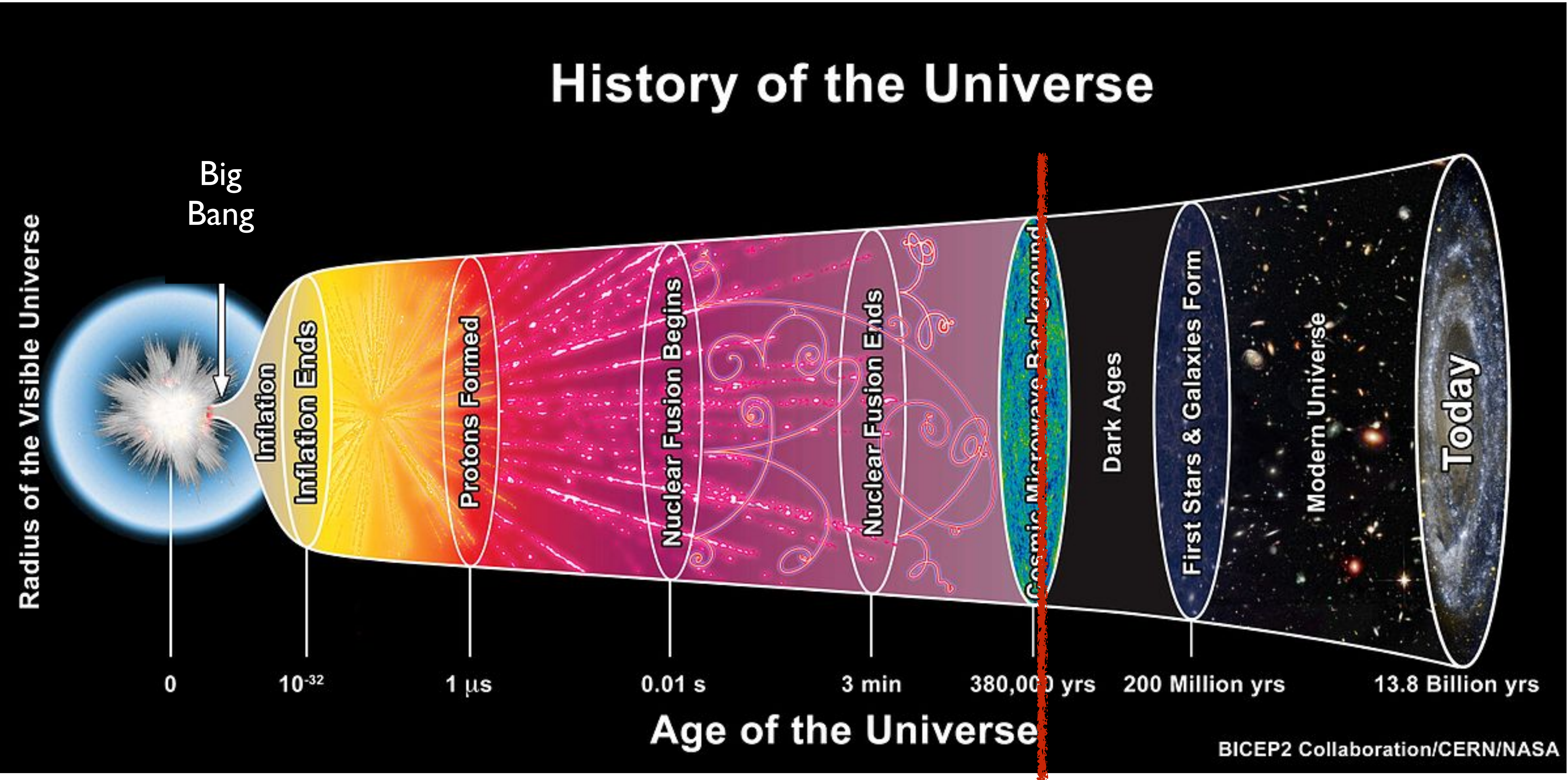
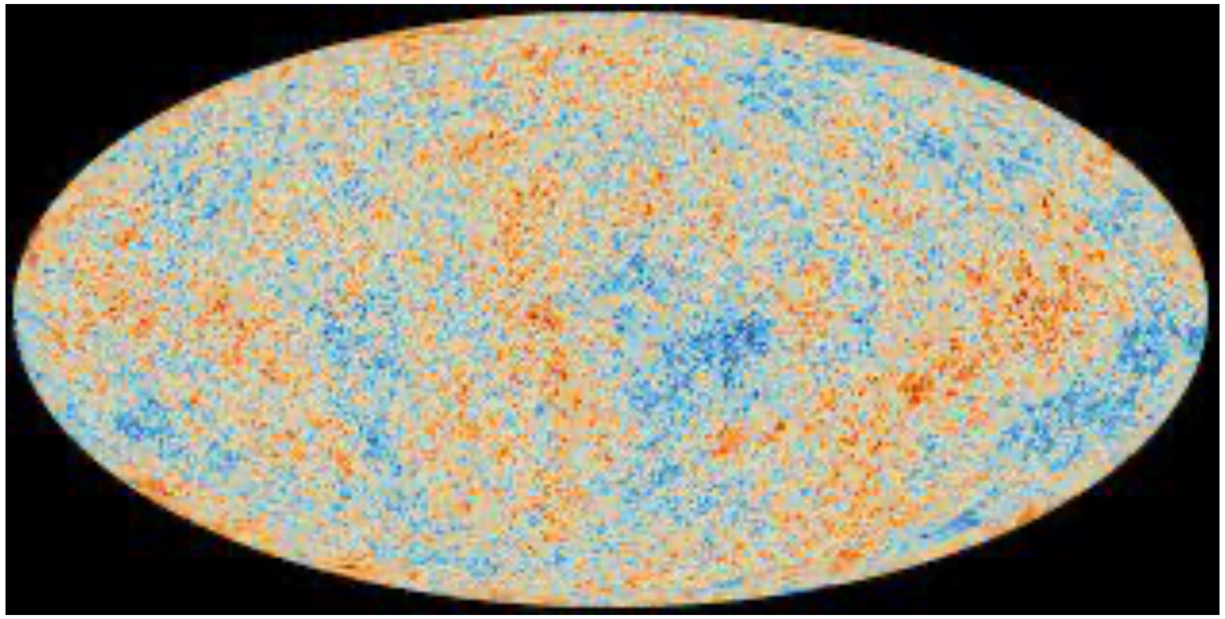
A Brief History of the Universe



The Cosmic Microwave Background

The Cosmic Microwave Background (CMB)

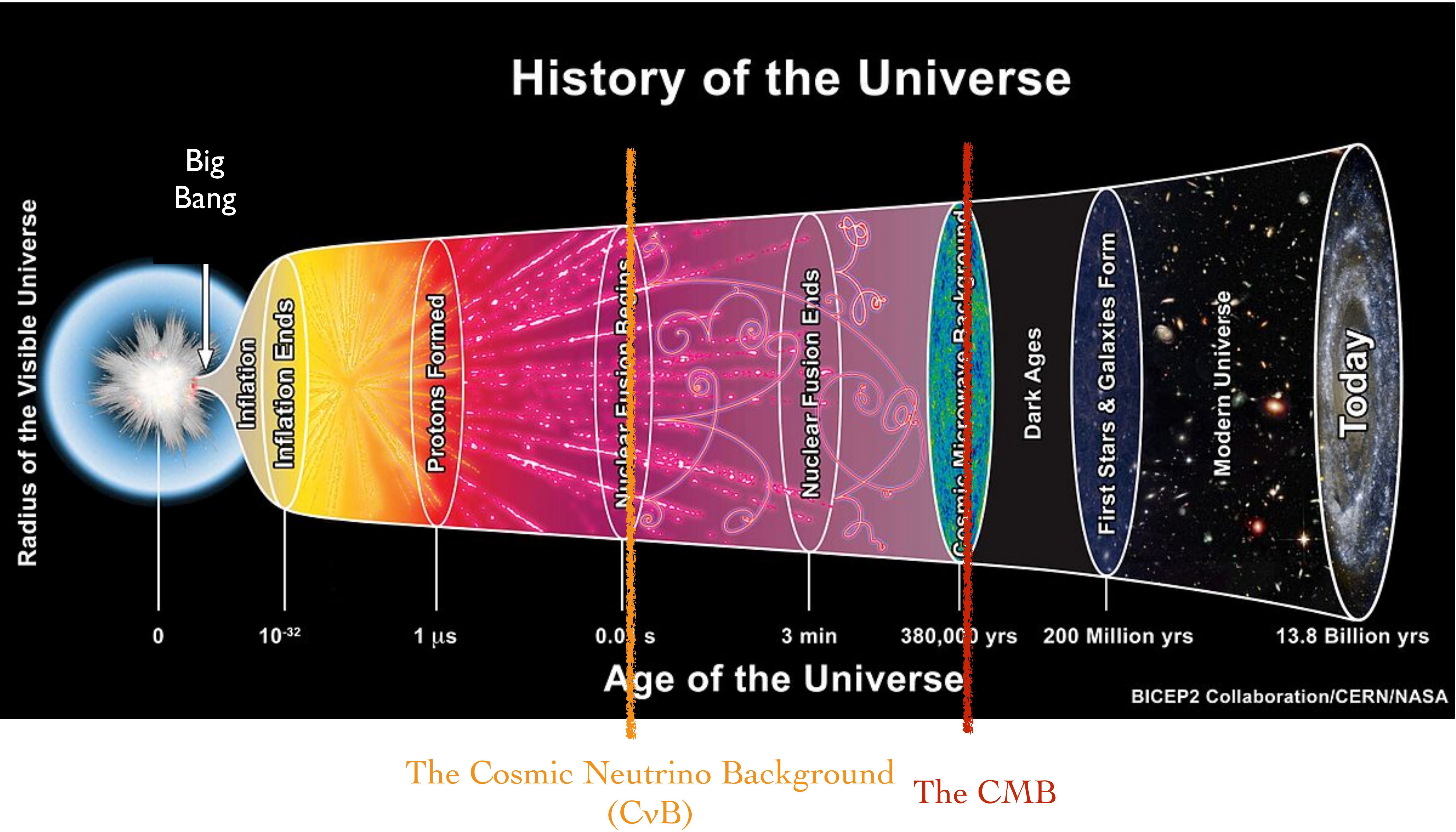


- Time when atoms formed and the universe became transparent to light

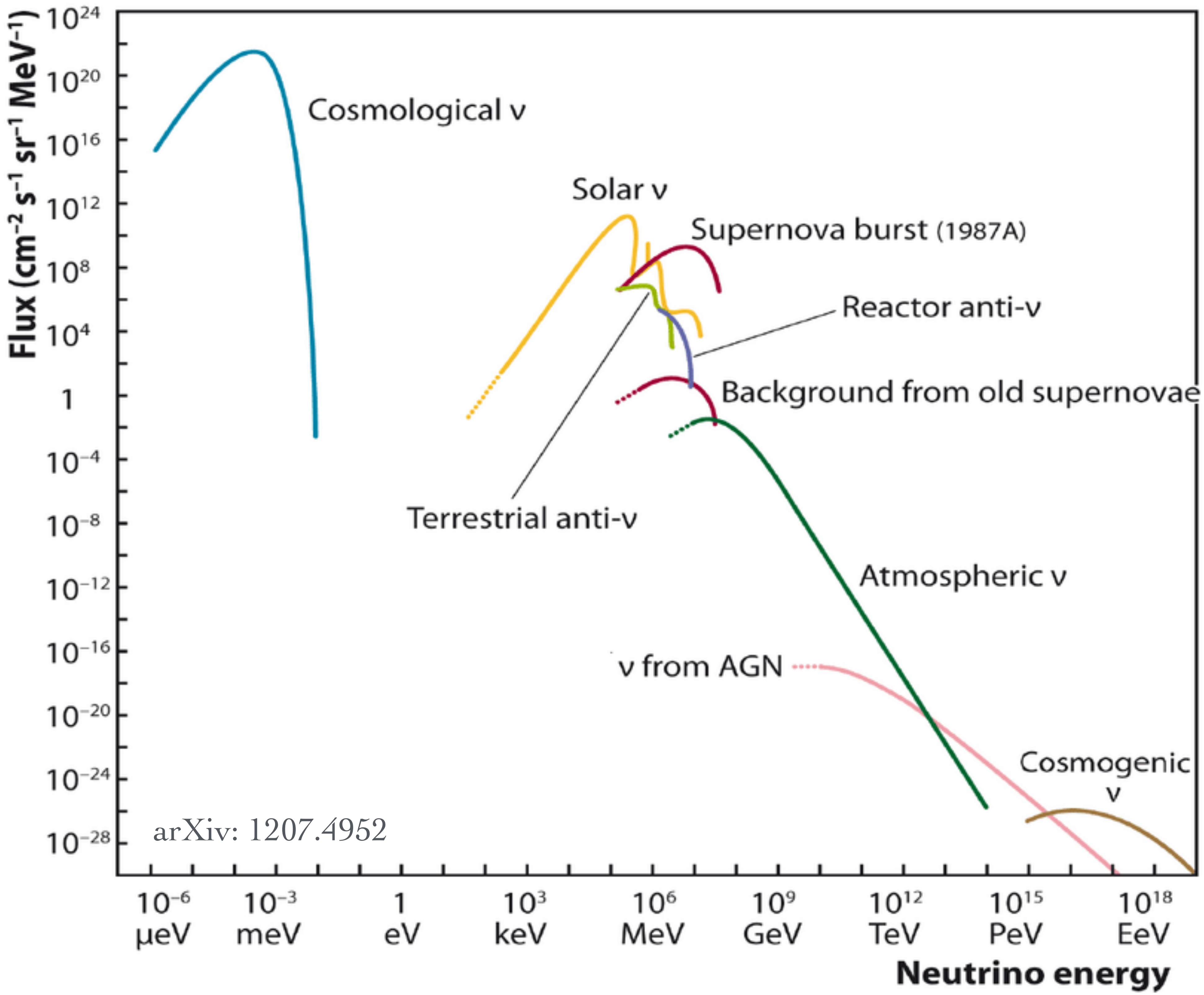
- The Universe was 400,000 years-old at the time

- Allowed to measure the composition of the Universe to 1%

A Brief History of the Universe



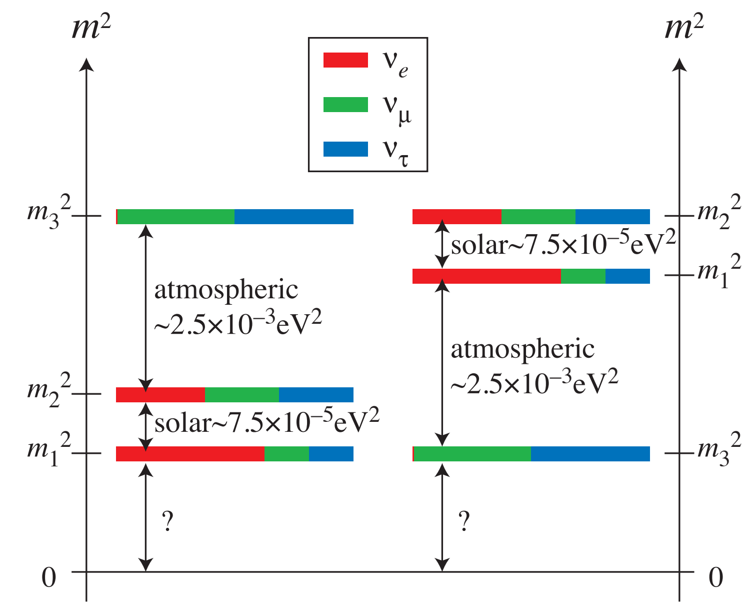
Neutrino sources



The Cosmic Neutrino Background (CνB)

- Relic neutrinos from the pre-BBN era $\tau_{\text{universe}} \sim 0.1$ sec

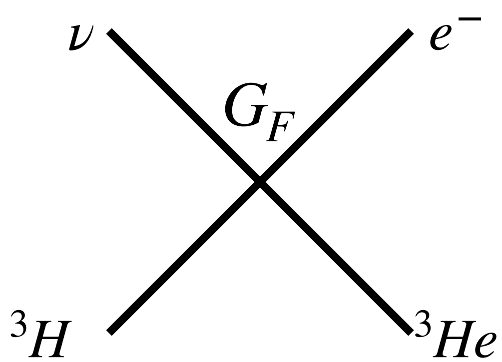
- They follow a Fermi-Dirac distribution with:
  - $\langle p_\nu \rangle = 6 \times 10^{-4}$ eV
  - $\langle E_\nu \rangle = 1.6 \times 10^{-6} \text{ eV} \left(\frac{0.1 \text{ eV}}{m_\nu} \right)$
  - $\langle \lambda_\nu \rangle = 2.1$ mm
  - $n_\nu = 56$ cm^{-3} per mass eigenstate (total of 3) , per helicity mode



Why is the CνB important?

- Probes physics at a time much earlier than the CMB
- An entire sector of the Standard Model: 3 flavors and *7* parameters
- Are neutrinos their own antiparticle? (Dirac vs Majorana)
- Using non-relativistic particles for 3D tomography of the Universe

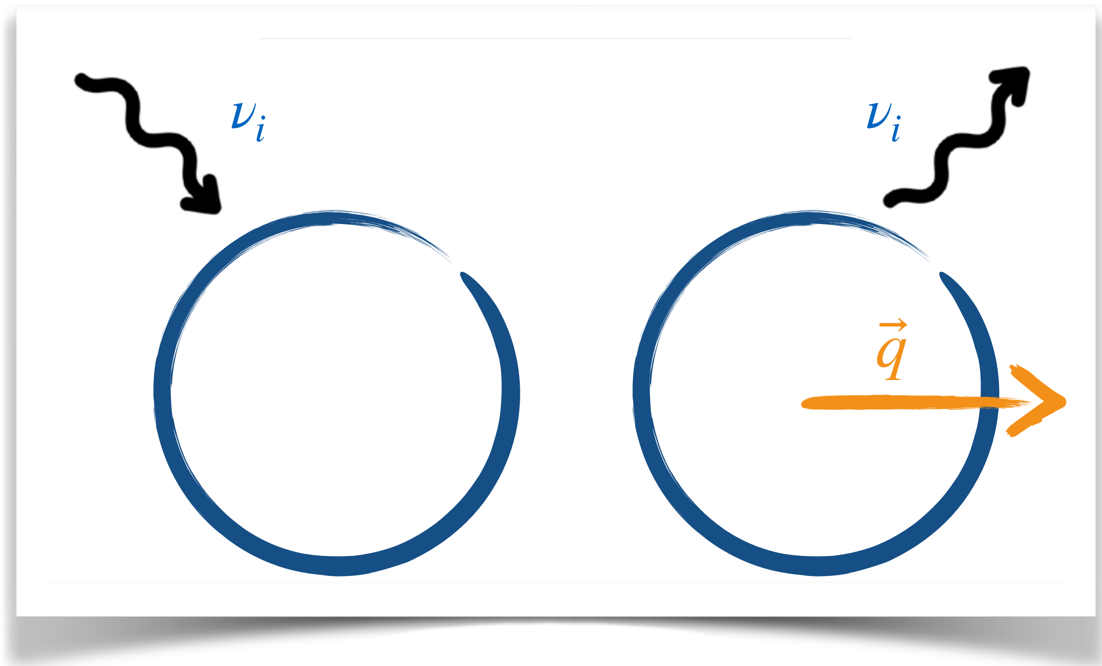
Why is the CνB hard to detect?



Weinberg (1962)

- Relic Neutrino $+^3 H \rightarrow {}^3He + e^-$
    - Rate of ~10/year for 100 gr of tritium at leading direct detection concept experiment PTOLEMY

Why is the CνB hard to detect?



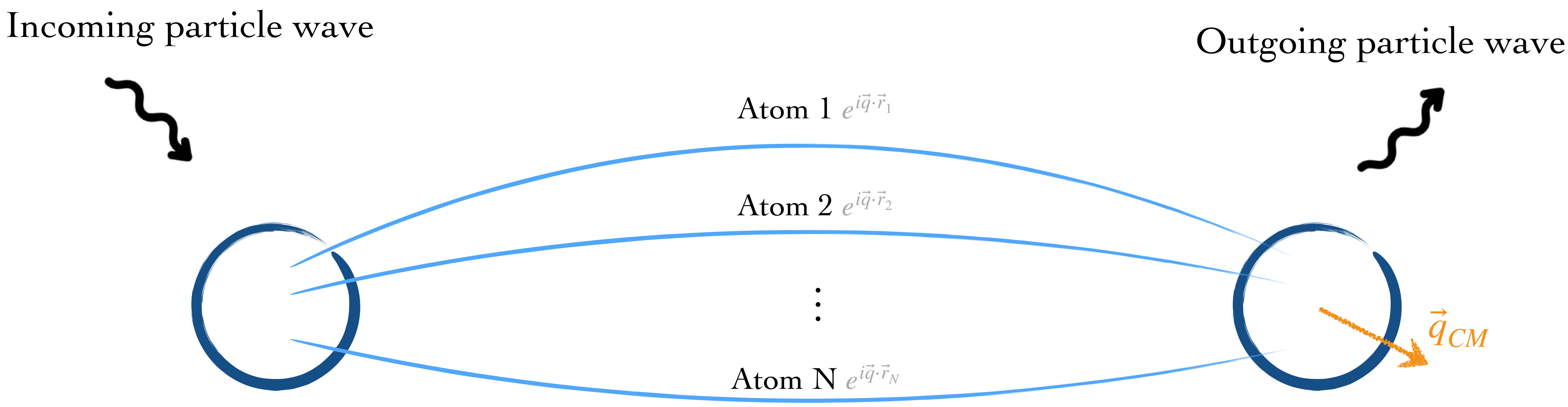
Smith & Lewin (1983), …

- Coherent elastic scattering from an extended object, with momentum transfer $\mathcal{O}(\langle p_\nu \rangle)$
    - 2/day on a mm size object

Why is the CNB hard to detect?

- Besides coherent elastic scattering, are there inelastic processes that are enhanced by N^2 ?

How does elastic scattering give you N^2?

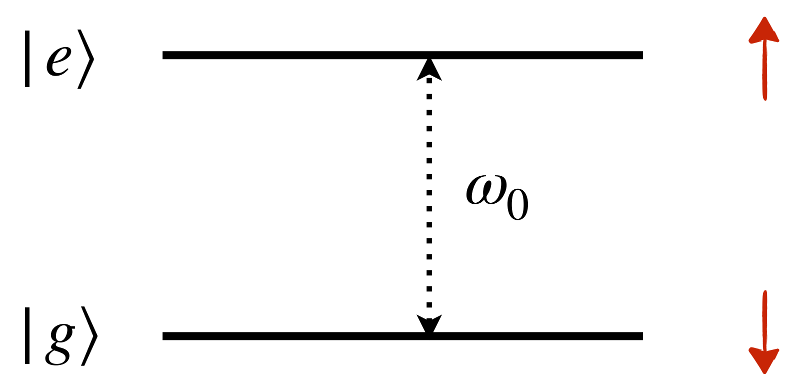


- For small enough momentum transfer, there are N paths all leading to the same final state
  - Scattering amplitude $\propto N$
  - Scattering rate $\propto N^2$
  - Momentum transfer $q_{CM} \sim 5 \times 10^{-6}$ eV
  - Energy transfer $E_{CM} \sim 10^{-49}$ eV

For $R = 10$ cm

Understanding N^2 scalings in inelastic scattering

- A target made of N two-level "atoms": nuclear and atomic transitions, spins in magnetic field, etc…

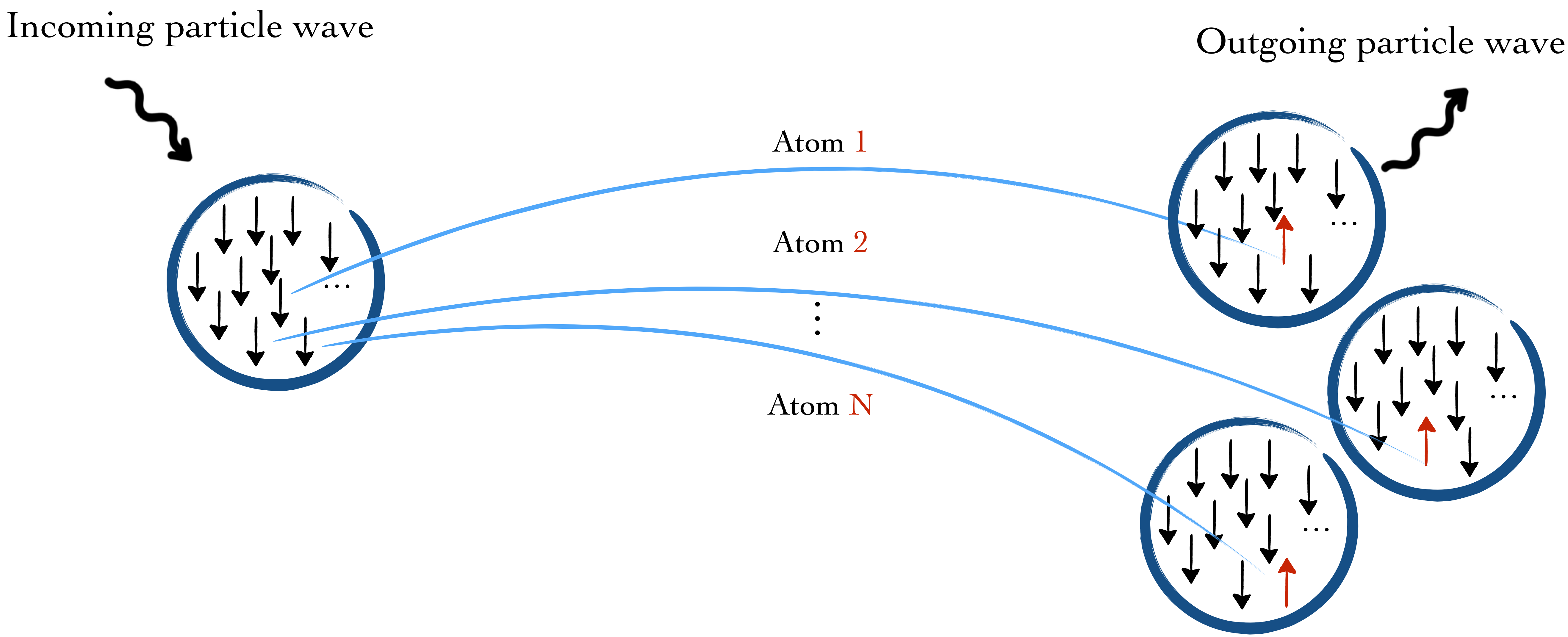


- Two extreme possibilities:
  - All atoms in the ground state $\prod |\downarrow\rangle$
  - All atoms in an equal superposition of ground and excited:

$$\prod\left(\frac{1}{\sqrt{2}}(|\downarrow\rangle + |\uparrow\rangle)\right) = \prod |\rightarrow\rangle \equiv \text{Product state}$$

Why does inelastic scattering normally $\propto N$?

The rate of exciting a single atom

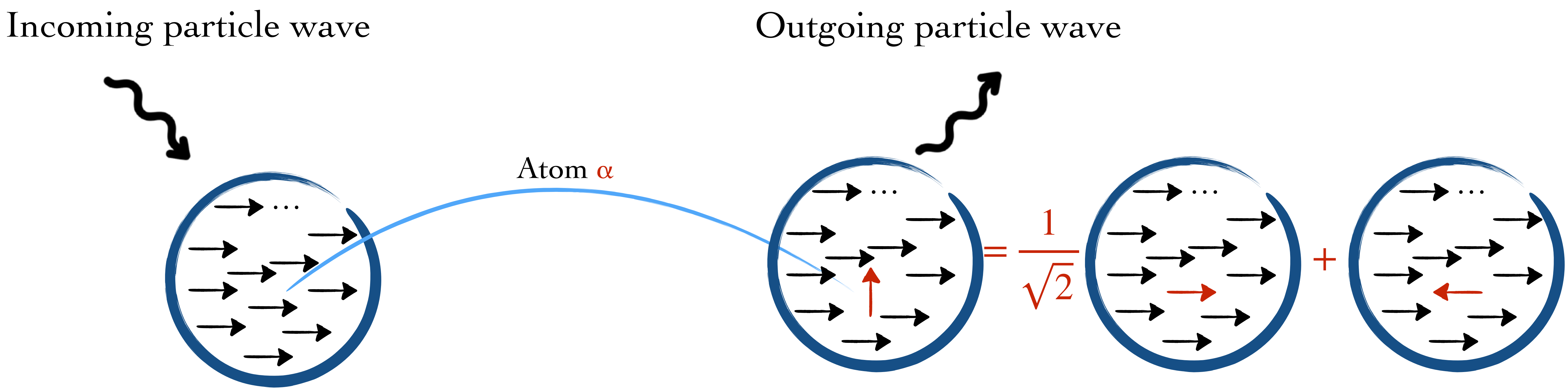


- N atoms all in the ground state $\Rightarrow$ N distinct orthogonal final states
  - Scattering amplitude $\propto 1$
  - Scattering rate $\propto N$
  - Momentum transfer $q \sim 5 \times 10^{-6}$ eV
  - Energy transfer $E \sim \omega_0 \gg 10^{-49}$ eV

For $R = 10$ cm

When does inelastic scattering $\propto N^2$?

AA, S. Dimopoulos, M. Galanis (2024)

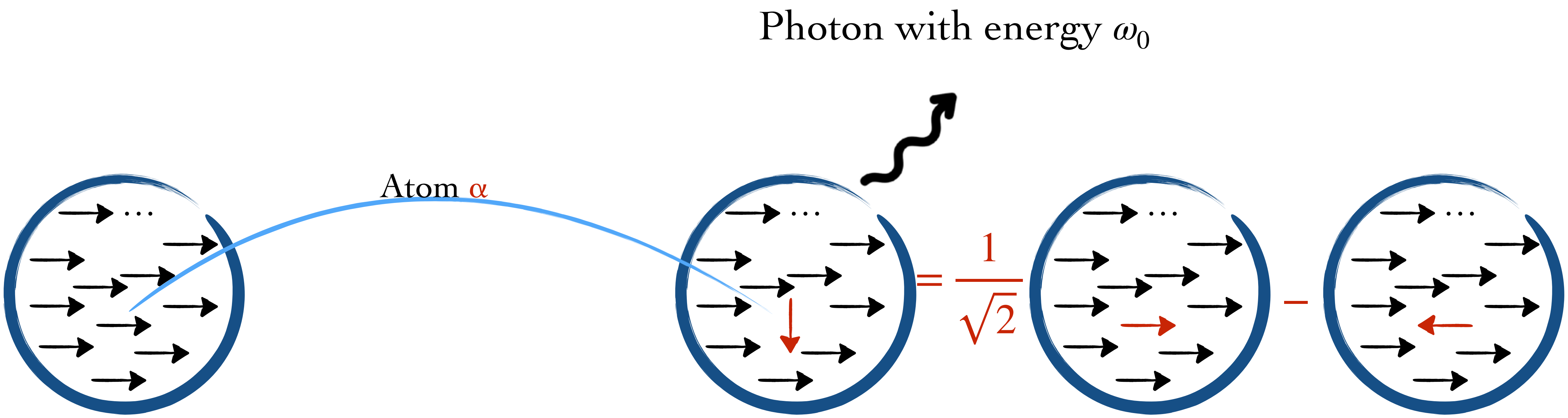


$$|\uparrow\rangle = \frac{1}{\sqrt{2}}\left(|\rightarrow\rangle + |\leftarrow\rangle\right)$$

- N atoms in an equal superposition of ground and excited, therefore there are $\sim \frac{N}{2}$ indistinguishable final states
  - Scattering amplitude $\propto N$
  - Scattering rate $\propto N^2$
  - Energy transfer still large, $E = \omega_0$

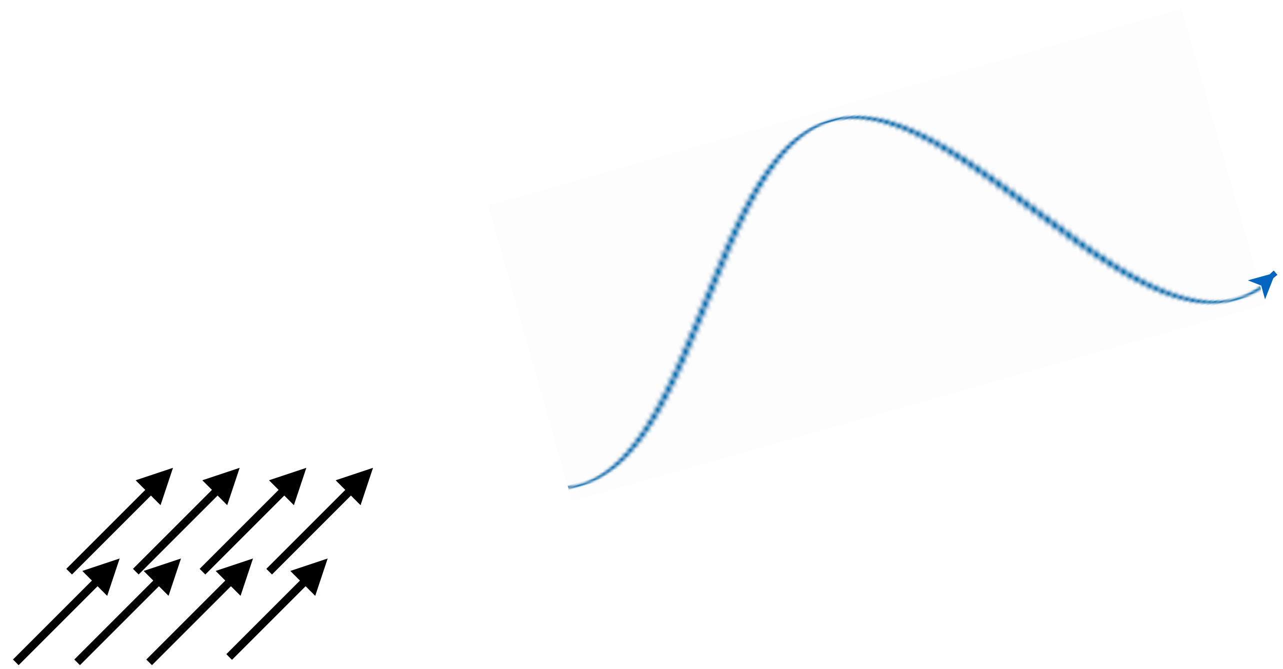
Analogous to Dicke Superradiance

Dicke Superradiance (1954)



- Atoms in an equal superposition of ground and excited emitting photons, produce $\frac{N}{2}$ indistinguishable states
  - Amplitude $\propto N$
  - Photon emission rate $\propto N^2$
  - Similar effects in stimulated absorption and emission

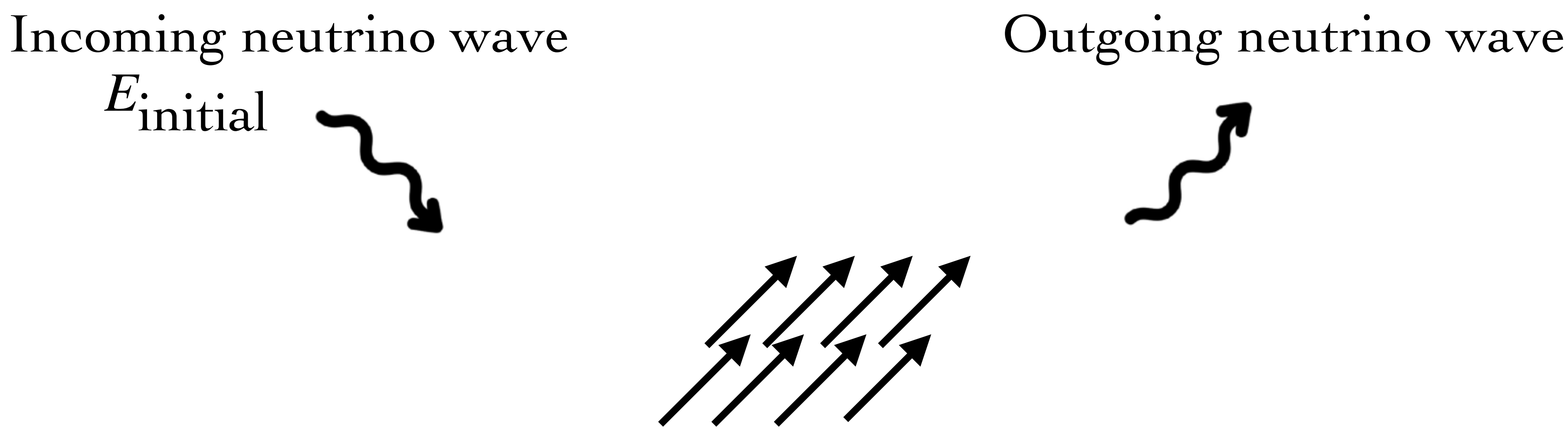
Coherence in emission and absorption of light



Power of the emitted light grows like the N^2 as long as all precessing dipoles are within the wavelength

Coherence in inelastic scattering processes

AA, S. Dimopoulos, M. Galanis (2024)

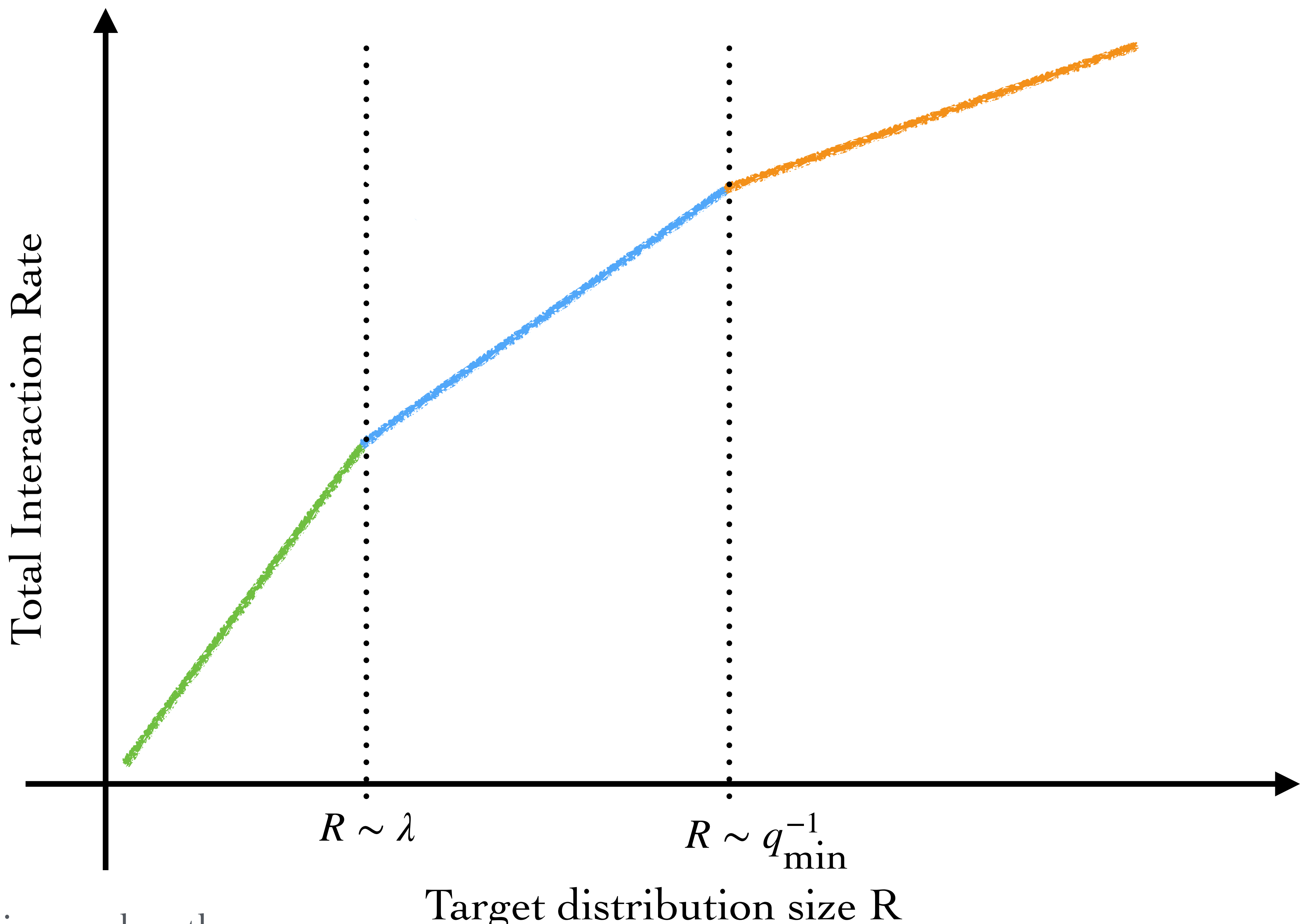


- Spin-Spin interaction results in a time-dependent potential
  $H \sim \frac{G_F}{\sqrt{2}} \delta^{(3)}(\vec{x}_\nu - \vec{x}_S) N \; \vec{\sigma}_\nu \cdot \vec{\sigma}_S \cos(\omega t)$

- Scattered outgoing neutrino energies $E_{\text{initial}} \pm \omega$ and scattering rate scales like N^2

Superradiant scattering from a target of size R

Scattering form factor: $\left|\sum_{\alpha=1}^{N} e^{i\vec{q}\cdot\vec{r}_a}\right|^2$



λ: particle deBroglie wavelength

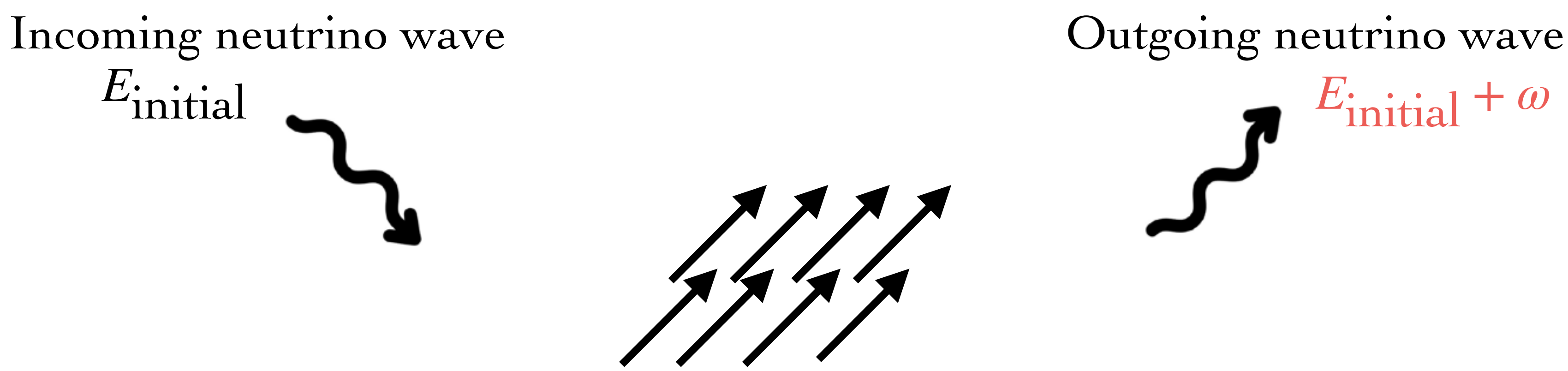
$q_{\rm min}$: Minimum momentum transfer set by energy conservation

Outline

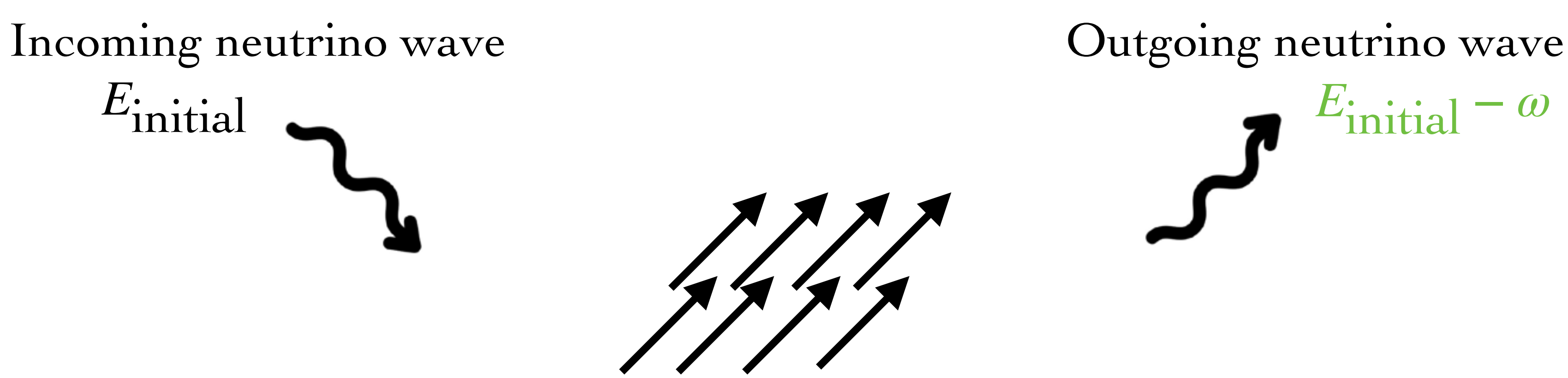
- Superradiant interactions: Inelastic processes with N^2 rates
- Sample superradiant interaction rate calculations
    - Cosmic Neutrino Background super-scattering
    - Axion and Dark Photon Dark Matter super-absorption and super-emission
- Towards measuring the total interaction rate

Coherent inelastic scattering of the CNB

For $m_\nu = 0.1$ eV and $\omega_0 \leq \frac{v_\nu}{R}$



- Neutrino - spin de-excitation scattering rate $\sim 0.2\ \text{Hz} \dfrac{n^2}{(3 \times 10^{22}\ cm^{-3})^2} \dfrac{R^4}{(10\ \text{cm})^4}$

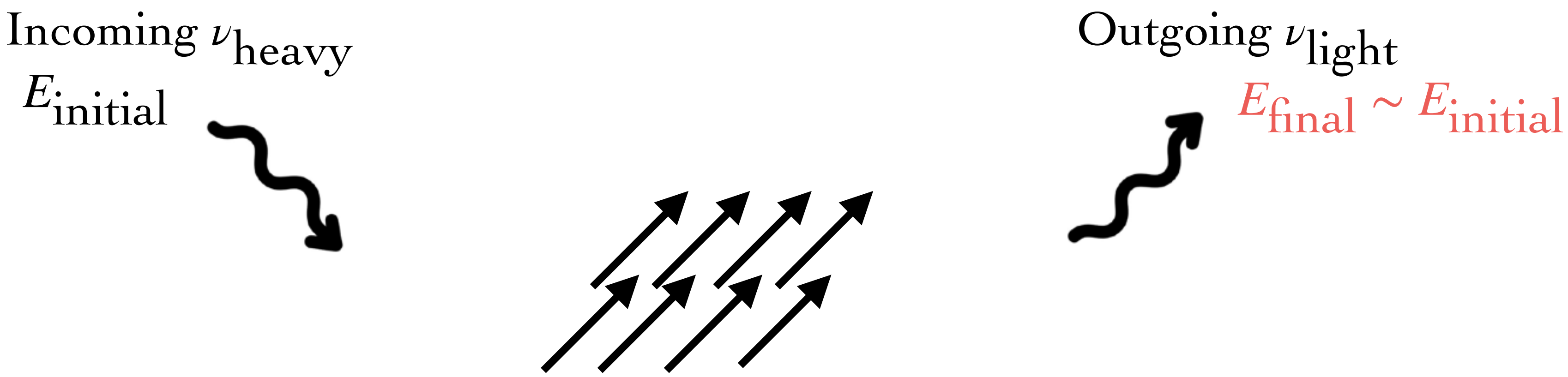


- Neutrino - spin excitation scattering rate $\sim \left(0.2\ \text{Hz} - 0.001\ \text{Hz} \dfrac{10\ \text{cm}}{R}\right) \dfrac{n^2}{(3 \times 10^{22}\ cm^{-3})^2} \dfrac{R^4}{(10\ \text{cm})^4}$

Incoherent part: 10^{-22} **Hz**$\dfrac{n}{3 \times 10^{22}\ \mathbf{cm}^{-3}} \dfrac{R^3}{(10\ \mathbf{cm})^3}$

Coherent inelastic scattering of the CNB

For $m_\nu = 0.1$ eV



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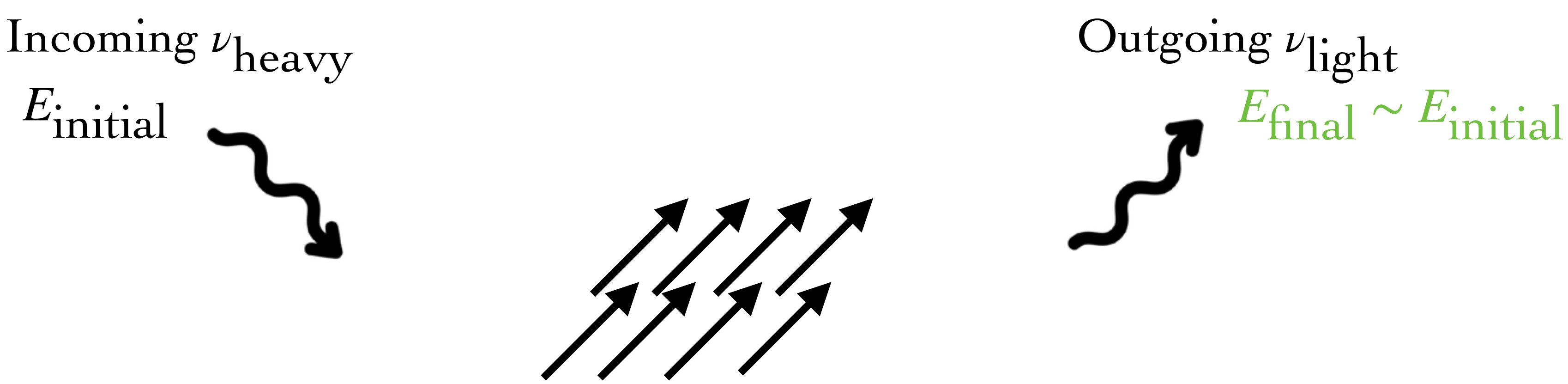
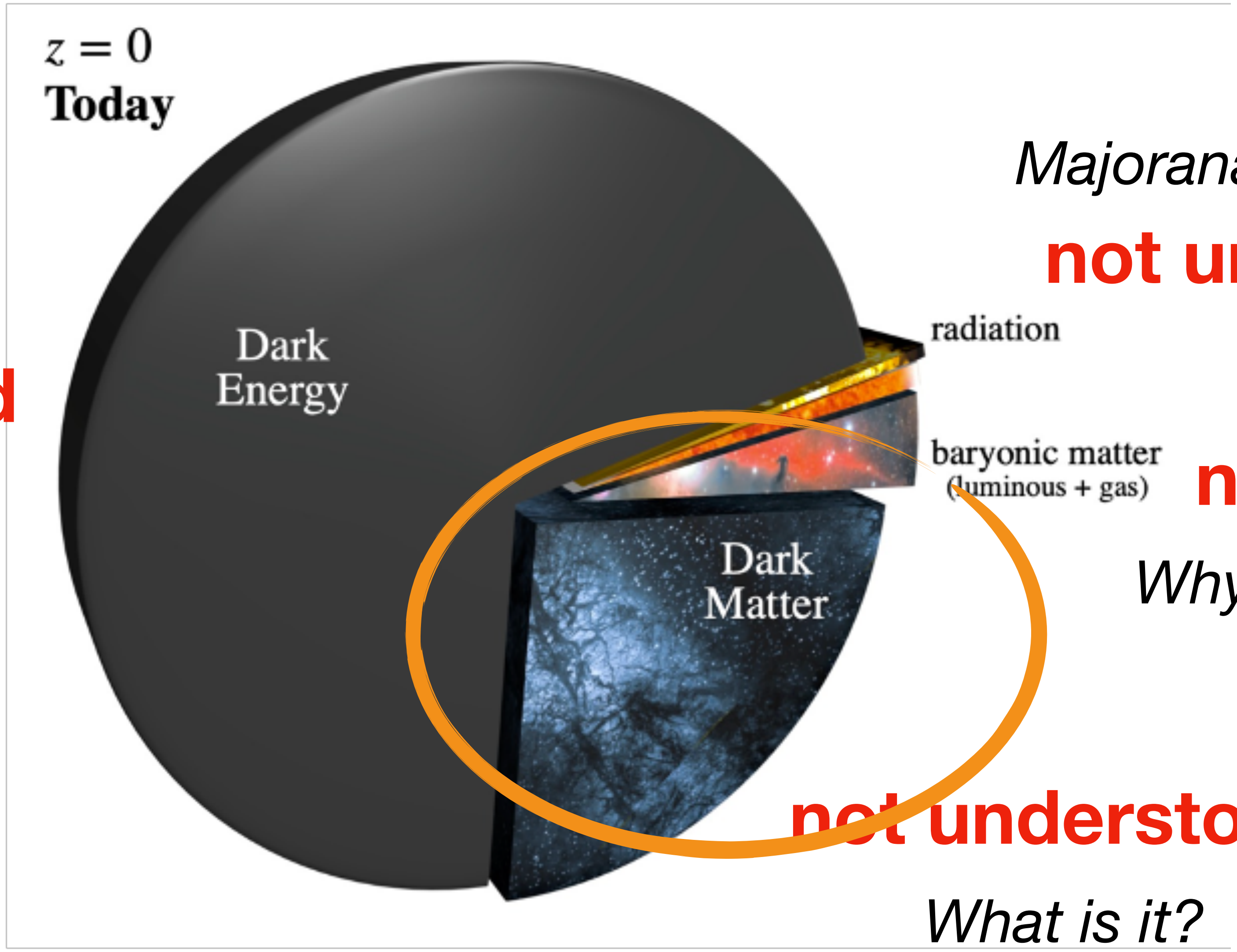


- Neutrino - spin excitation scattering rate $\sim \left(0.2 \text{ Hz} \pm 0.001 \text{ Hz} \dfrac{10 \text{ cm}}{R}\right) \dfrac{n^2}{(3 \times 10^{22}\ cm^{-3})^2} \dfrac{R^4}{(10 \text{ cm})^4}$

$$\omega_0 \approx m_{\text{heavy}} - m_{\text{light}} \mp \frac{v_\nu}{R}$$

Inventory of the universe



Majorana or Dirac neutrinos?

not understood

not understood

Is it a constant?
Why so small?

not understood

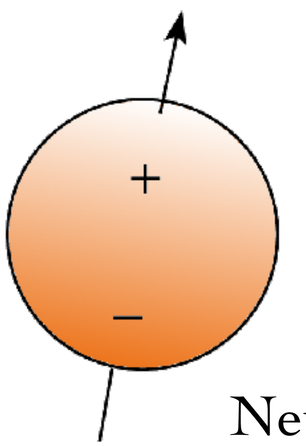
Why is there more matter than antimatter?

not understood

What is it?

Why is the Electric Dipole Moment of the Neutron Small?

The Strong CP Problem and the QCD axion



Neutron
EDM

$$\frac{g_s^2}{32\pi^2}\theta_s \vec{E}_s \cdot \vec{B}_s$$

EDM ~ e fm θ_s

Experimental bound: $\theta_s < 10^{-10}$

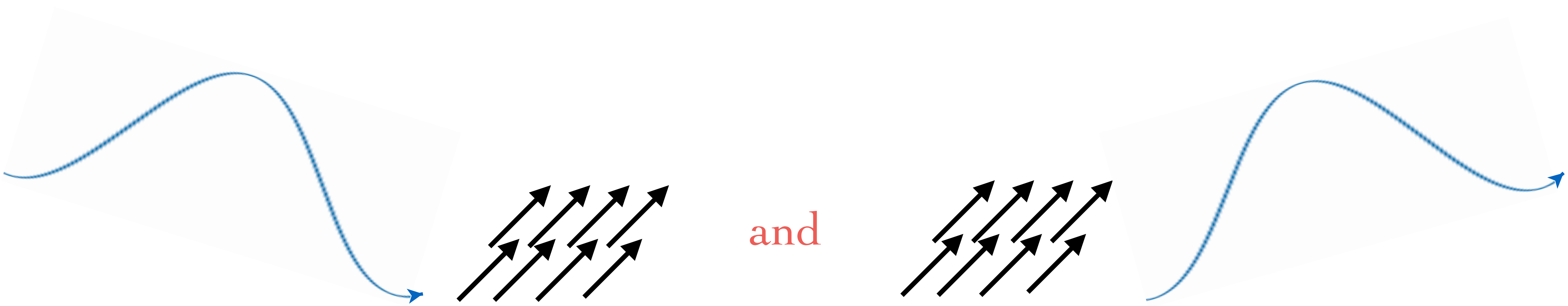
Solution:
θ_s ~a(x,t) is a dynamical field, an axion

Axion mass from QCD:

$$\mu_a \sim 6 \times 10^{-11}\ \text{eV}\ \frac{10^{17}\ \text{GeV}}{f_a} \sim (3\ \text{km})^{-1}\ \frac{10^{17}\ \text{GeV}}{\mathrm{f_a}}$$

f_a : axion decay constant

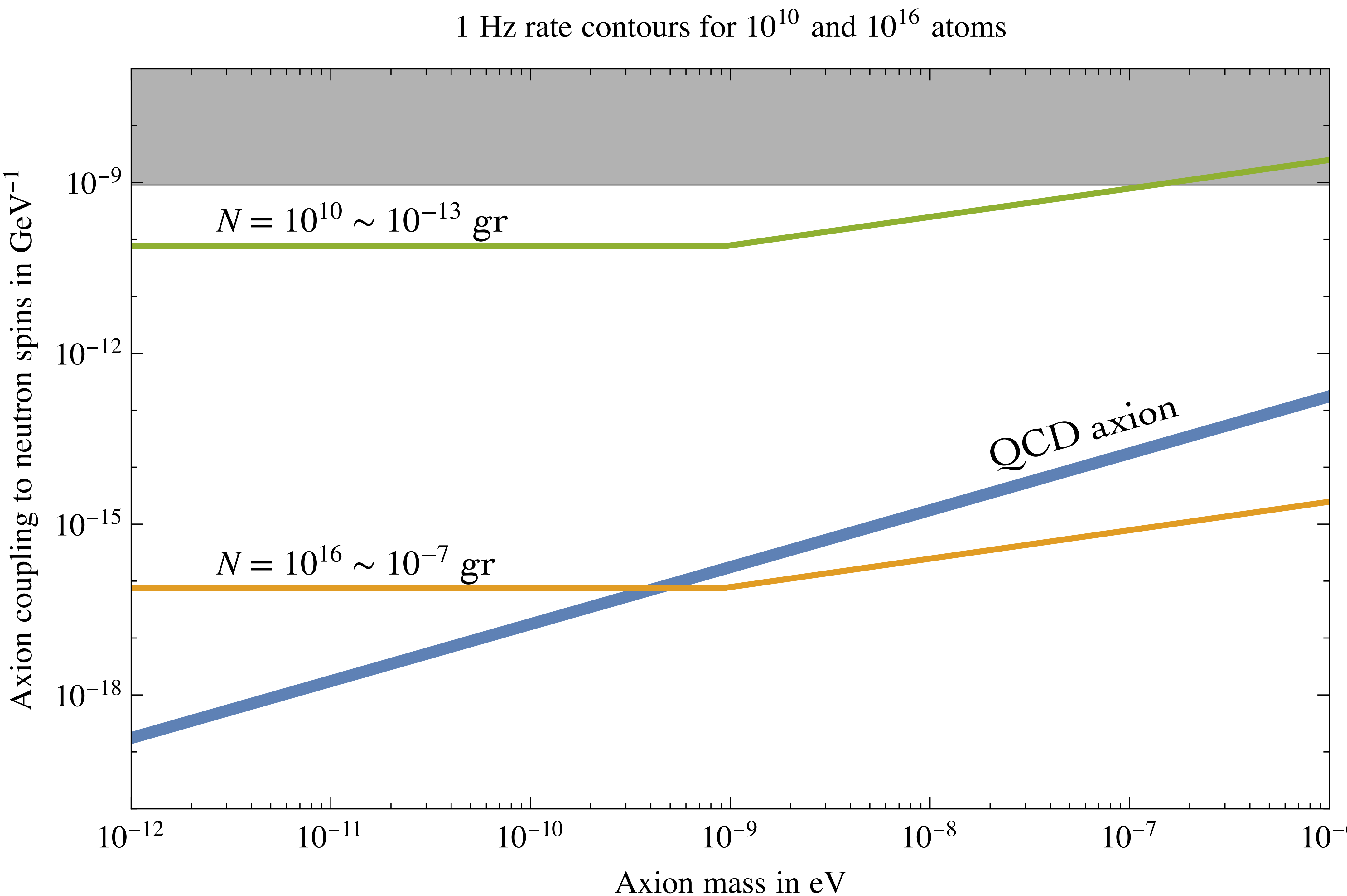
Stimulated emission and absorption of the QCD axion



Axions couple to spins: $\frac{\vec{\nabla} a}{f_a} \cdot \vec{\sigma}$

This not the same as the coupling Andreas presented yesterday

Axion DM superradiance and superabsorption



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- Sample superradiant interaction rate calculations
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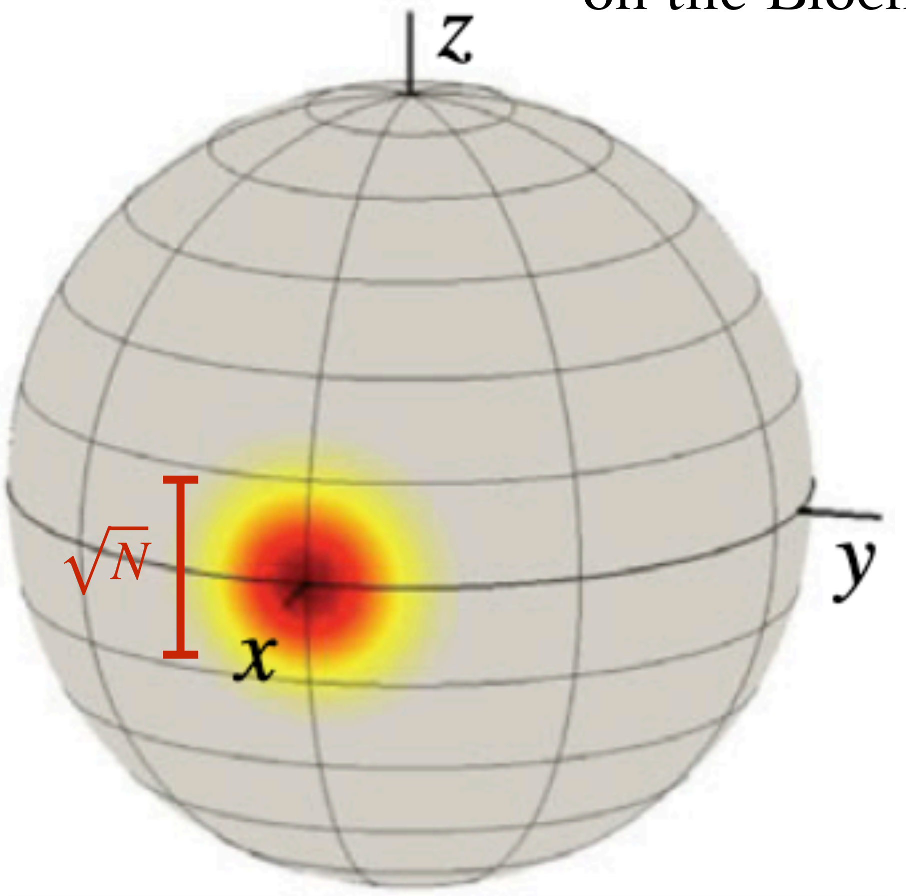
  - Solar, Reactor, and Bomb Neutrino super-scattering
- Towards measuring the total interaction rate

How would you measure the total N^2 rate?

- Net energy exchange for scattering appears as drift

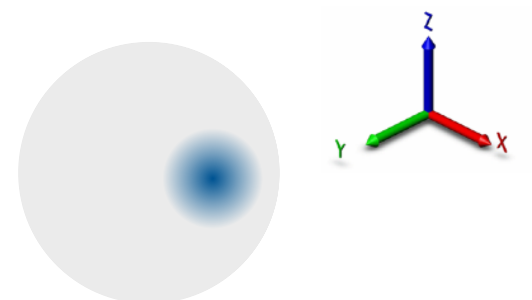
- Observables sensitive to the random walk/diffusion of the state vector on the Bloch sphere, ex. $\langle J_z^2 \rangle$

The product state on the Bloch sphere



Final Thoughts

- States that exhibit N^2 interaction rates



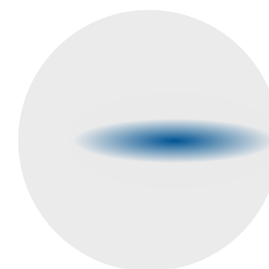
  - The product state
    - Easy to produce

  - The Dicke state $|\ell, m\rangle = |\frac{N}{2}, 0\rangle$

    - Robust against decoherence but much harder to prepare than the product state

Final Thoughts

- Best bet: a squeezed state

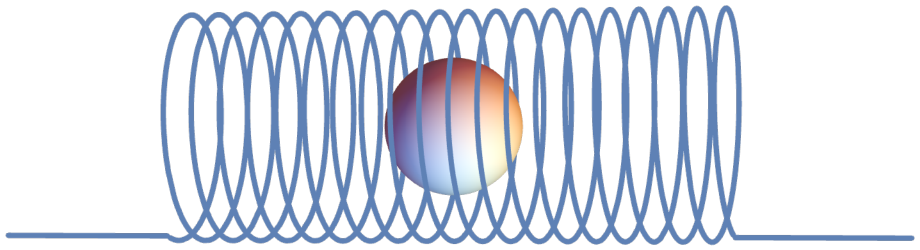


  - Somewhere in between a product state and a Dicke state
  - Preserves much of the good signal-to-noise ratio properties of the Dicke state

- Presently working on concrete protocol and experimental setup with S. Dimopoulos, M. Galanis, O. Hosten

Towards measuring coherent inelastic interactions

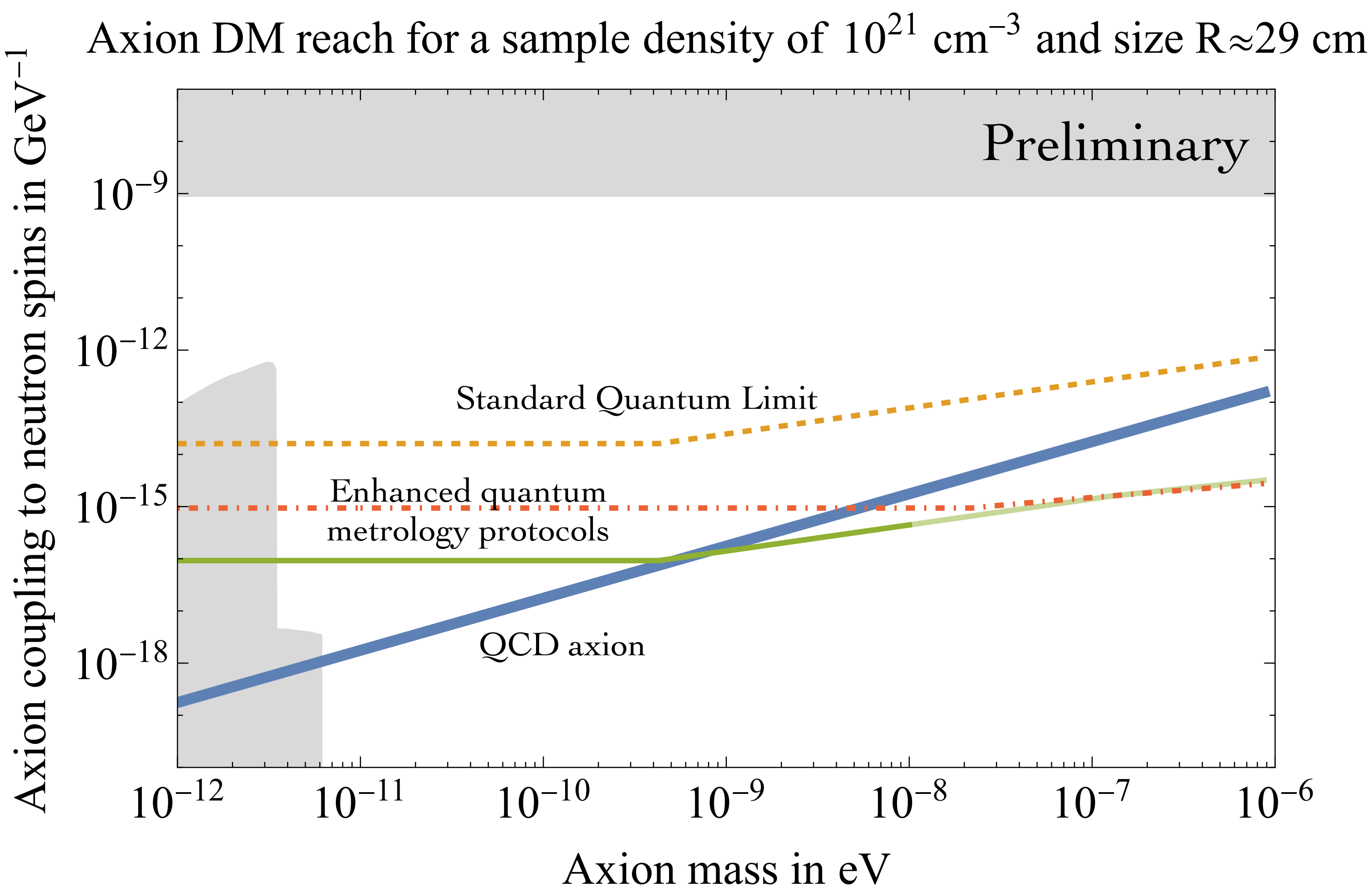
Nuclear spin polarized sphere coupled to an LC circuit



- Quantum optics techniques to reduce the spins quantum uncertainty

- QCD axion DM is now "easy" (Rate of a Hz corresponds to 10^{16} atoms instead of 10^{26} atoms for the CNB)

Reach for Axion Dark Matter



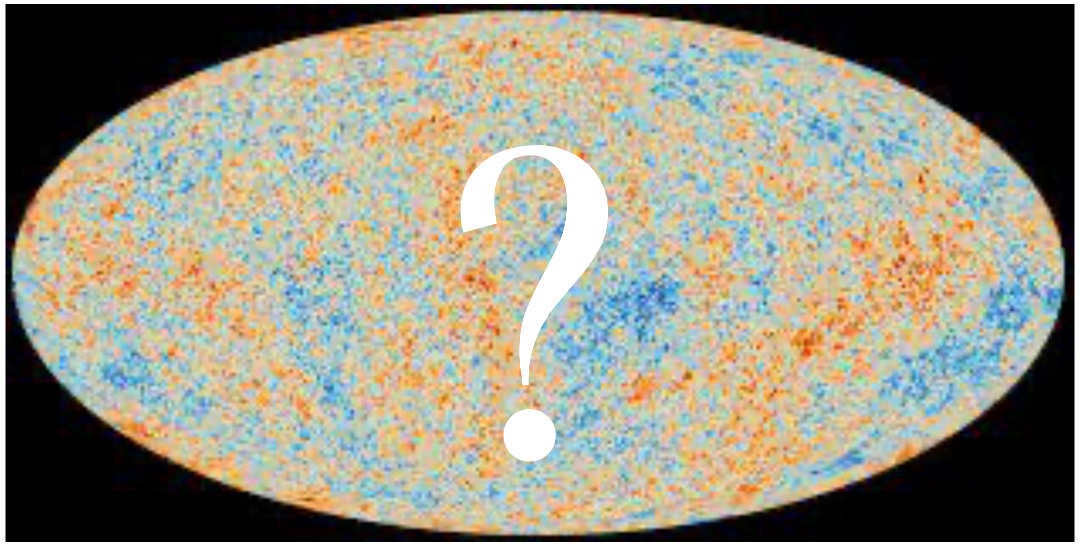
*For the CνB this matches the KATRIN

[With M. Galanis, O. Hosten and S. Dimopoulos]

Conclusions

- The Cosmic Neutrino Background is a long standing challenge
- Superradiant interactions can significantly boost interaction rates of cosmic relics like the CνB ($0.1\ Hz$ vs $10^{-22}\ Hz$)
- Axion searches could be a stepping stone
- There are observables that are depend on excitation and de-excitation rates, not just energy transfer
- This is just the beginning, but challenge remains

A Cosmic Neutrino Background Telescope?



How did the Universe looked like when it was less than 1 second old?…