Hunting **Axions** with Nuclear Spin Precession

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What's an axion?

- **Short answer:** A light, weakly-interacting, neutral, pseudo-scalar boson, added to the SM as a solution to the *strong CP problem.*
  - Dark matter candidate!
  - 100% effective on grease

- **Long answer:** Let's talk about strong CP...

You will get tired of these jokes if you see a lot of axion talks

The strong CP problem

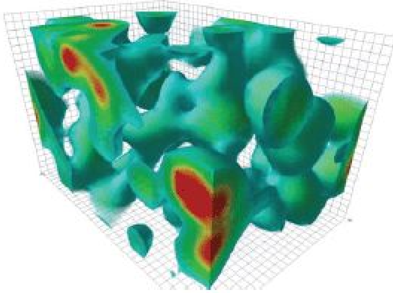
- The “naïve” QCD Lagrangian looks like

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{2}G^a_{\mu\nu}G^{\mu\nu a}$$

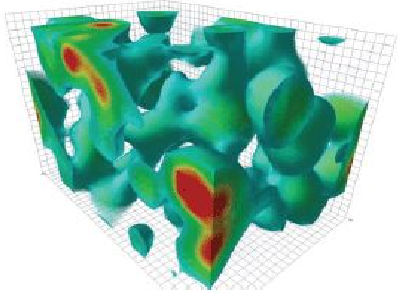
- Conserves CP, in agreement with observations

- **Problem:** QCD’s nontrivial vacuum structure is predicted to introduce large CP-violating effects

  ...which have never been seen!



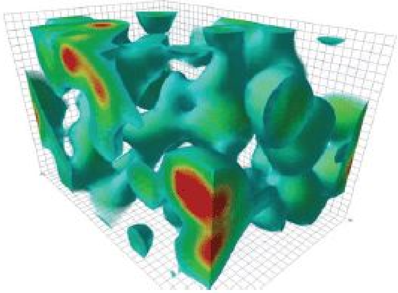
The QCD vacuum



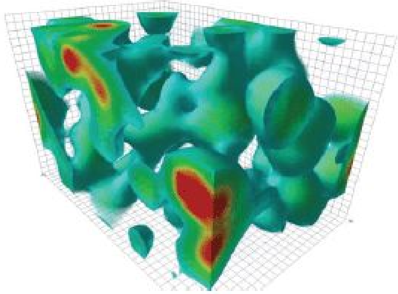
- QCD vacuum is degenerate; for any “angle” θ, there is a perfectly good vacuum state:

$$|\theta\rangle = \sum_n e^{-in\theta} |n\rangle$$

- The $|n>$ are topologically nontrivial gauge configurations
  - Imagine pure gluon fields “winding” around space once, twice, etc…
  - Discovered by ‘t Hooft in the context of *instantons*
  - Totally invisible in perturbation theory



QCD vacuum, cont'd



- When these "instantons" are included in the path integral, the result is equivalent to adding a term to the "effective" Lagrangian,

$$\Delta\mathcal{L} = \theta\frac{g^2}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{\mu\nu a}$$ where $$\widetilde{G}^{\mu\nu a} \equiv \epsilon^{\mu\nu\rho\sigma}G^a_{\rho\sigma}$$

- This violates CP, like an **E·B** term for EM!
- But that's not all, folks! Let's go back to the fermion mass term…

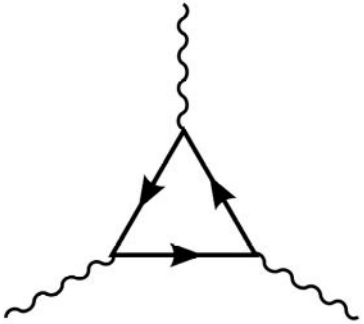
The fermion mass matrix

- Our "naïve" Lagrangian assumed that the fermion fields had been rotated to give a *real* mass matrix
- In general, the mass matrix may be complex, including a chiral phase *θ'*:

$$m\bar{\psi}\psi \rightarrow m\bar{\psi}e^{i\theta'\gamma_5}\psi$$

- We can perform a chiral rotation to get rid of *θ'*

  … but due to triangle diagrams (see: axial anomaly), this introduces a term



$$\Delta\mathcal{L} = \theta' \frac{g^2}{32\pi^2} G^a_{\mu\nu} \widetilde{G}^{\mu\nu a}$$

Look familiar?

Summing up strong CP

- In the end, we have two *independent* sources of strong CP violation:
  - Vacuum angle θ (from QCD)
  - Mass matrix chiral phase θ' (from Higgs mech.)
- Their sum gives effective CPV parameter $\bar{\theta}$
- We expect a $\bar{\theta}$ of order 1; anything else would be "unnatural"
- What do we actually observe…?

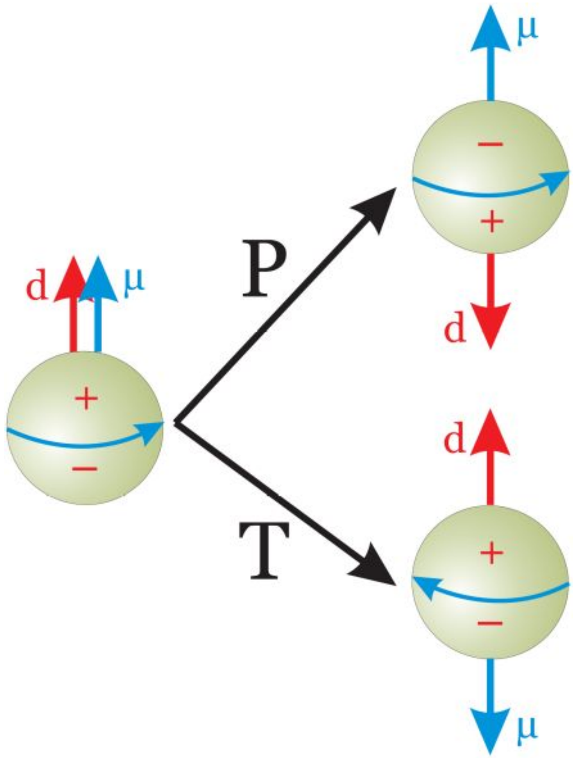
$\bar{\theta}$ is really tiny!

- $\bar{\theta}$ term induces an electric dipole moment in the neutron
- RAL-Sussex-ILL experiment:

  $d_n < 3.0 \times 10^{-26}\ e$ cm   (90% CL)
- This implies:

  $\bar{\theta} < 10^{-10}$

- **Why is $\bar{\theta}$ so small?**
  This is the strong CP problem!



Note: If at least one quark were massless, $\bar{\theta}$ would be unobservable, but this case has long been ruled out!

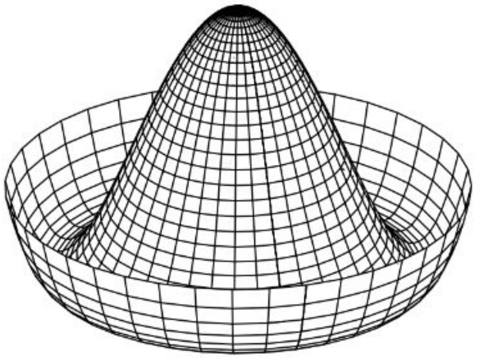
Peccei-Quinn to the rescue!

- The favored solution (by far)
- Roughly speaking, promote $\bar{\theta}$ to a dynamical field…

  ...whose potential leads to a VEV of zero. No CPV!
- Let's jog through the details...

Acts oppositely on right- and left-handed fields

The magic of $U(1)_{PQ}$



- PQ says: Add *chiral* global symmetry $U(1)_{PQ}$

  Depending on model, assign $U(1)_{PQ}$ charges to some scalars (typically two Higgs doublets), plus some/all SM/BSM fermions

- Let $U(1)_{PQ}$ be spont. broken at a high scale f_a

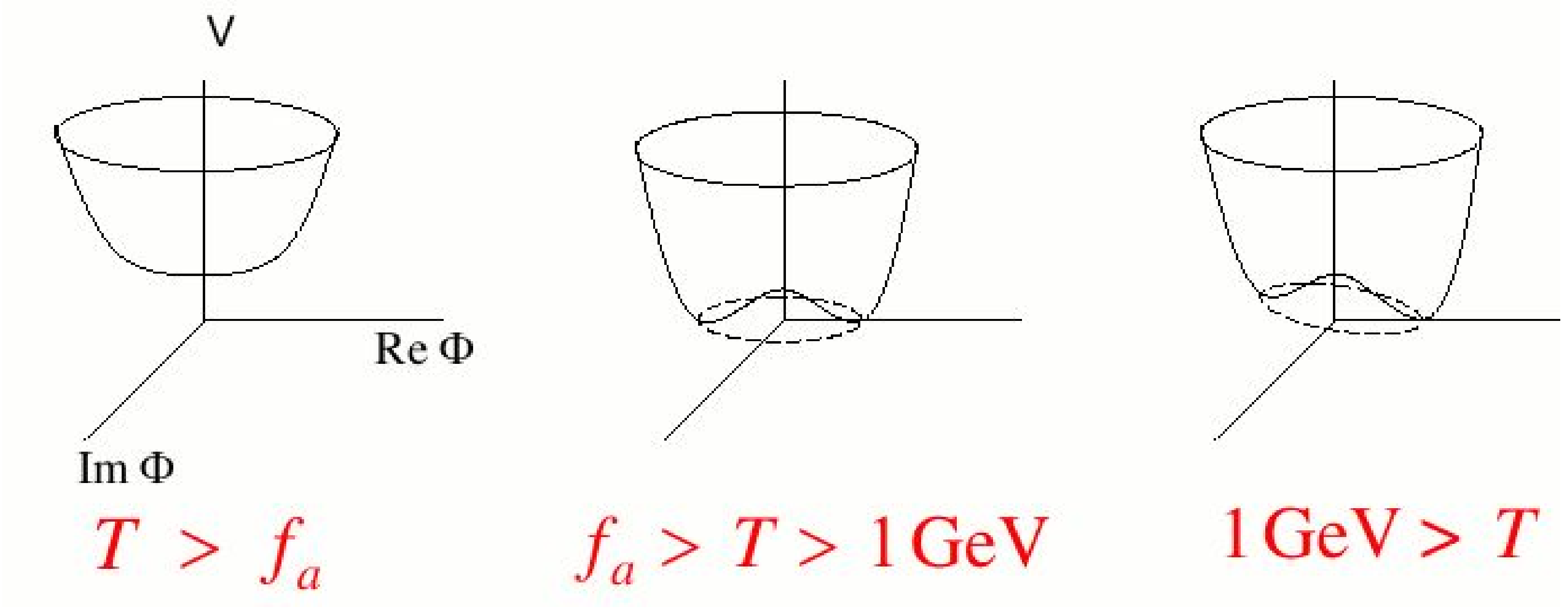
  Get a massless Nambu-Goldstone boson *a*: Axion!

- Due to QCD triangle diagrams, we get a familiar-looking term:

$$\Delta\mathcal{L} = -\frac{a}{f_a}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\widetilde{G}^{\mu\nu a}$$

$U(1)_{PQ}$ cont'd

- $U(1)_{PQ}$ will be explicitly broken by QCD instantons
  - "Tilts" axion potential, giving axion a mass ~ $(f_\pi/f_a)\, m_\pi$
  - **The effective potential happens to be minimized when $a = f_a\bar{\theta}$.** CP violation disappears!



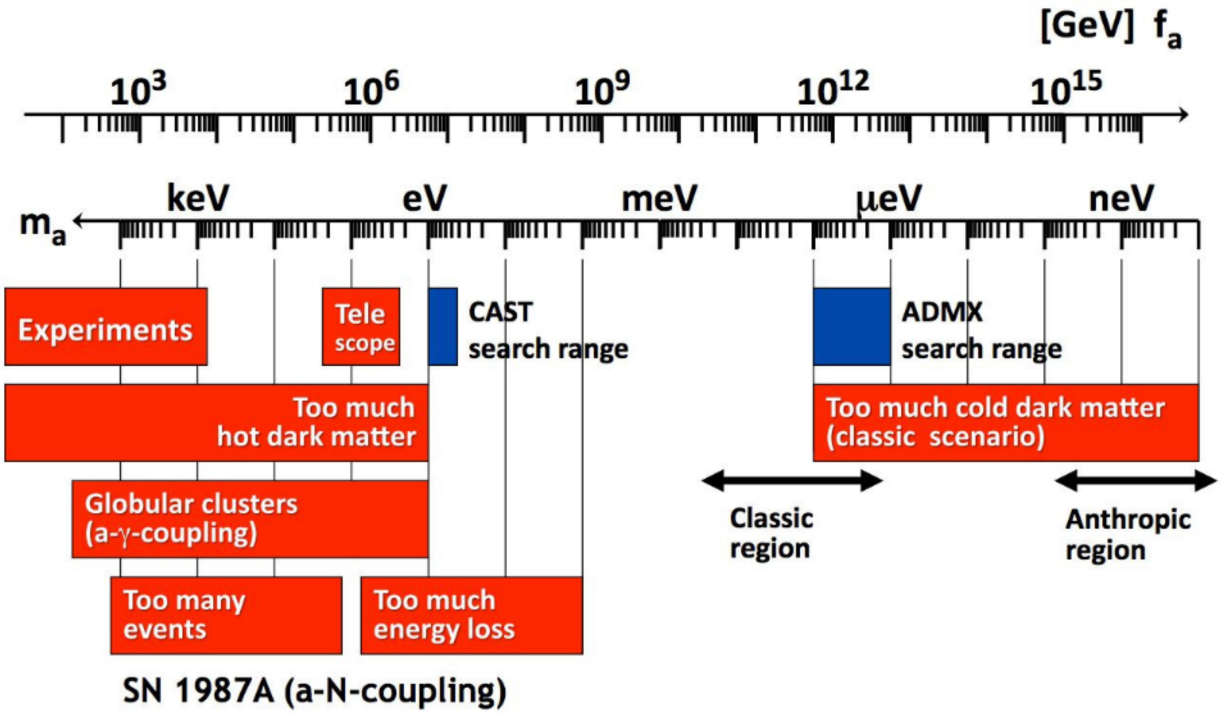
Recap

- QCD vacuum structure → large CP violation
- Neutron EDM measurements constrain CPV parameter $\bar{\theta}$ to be unnaturally small ($< 10^{-10}$)
- Peccei-Quinn: Add global $U(1)_{PQ}$ symmetry, break it at high energies, get Goldstone boson = axion
- Axion-gluon coupling (from triangle diagrams) violates CP just like $\bar{\theta}$
- QCD instantons give axion a mass and a potential which is minimized when $\bar{\theta}$ is canceled
- Voila! Now, **what about the axion's properties?**

Axion mass bounds

- Above 10 meV excluded by SN1987A
- Below 10 μeV ($f_a > 10^{12}$ GeV) in tension with *some* cosmological models (too much DM)

But if we relax the models' assumptions, we're driven to consider f_a up to Planck scale (10^{19} GeV, m_a ~ peV)



Generally, the lighter the axion, the larger its share of the dark matter pie.

Vijay will hopefully go into more detail! ☺

Axion couplings

- Three interaction terms in Lagrangian:

$$\frac{a}{f_a} F_{\mu\nu}\tilde{F}^{\mu\nu}, \qquad \frac{a}{f_a} G_{\mu\nu}\tilde{G}^{\mu\nu}, \qquad \frac{\partial_\mu a}{f_a} \bar{\Psi}_f \gamma^\mu \gamma_5 \Psi_f.$$

Triangle diagrams — Spontaneous symmetry breaking

- Traditional experiments have used the first coupling (axion-photon conversion)

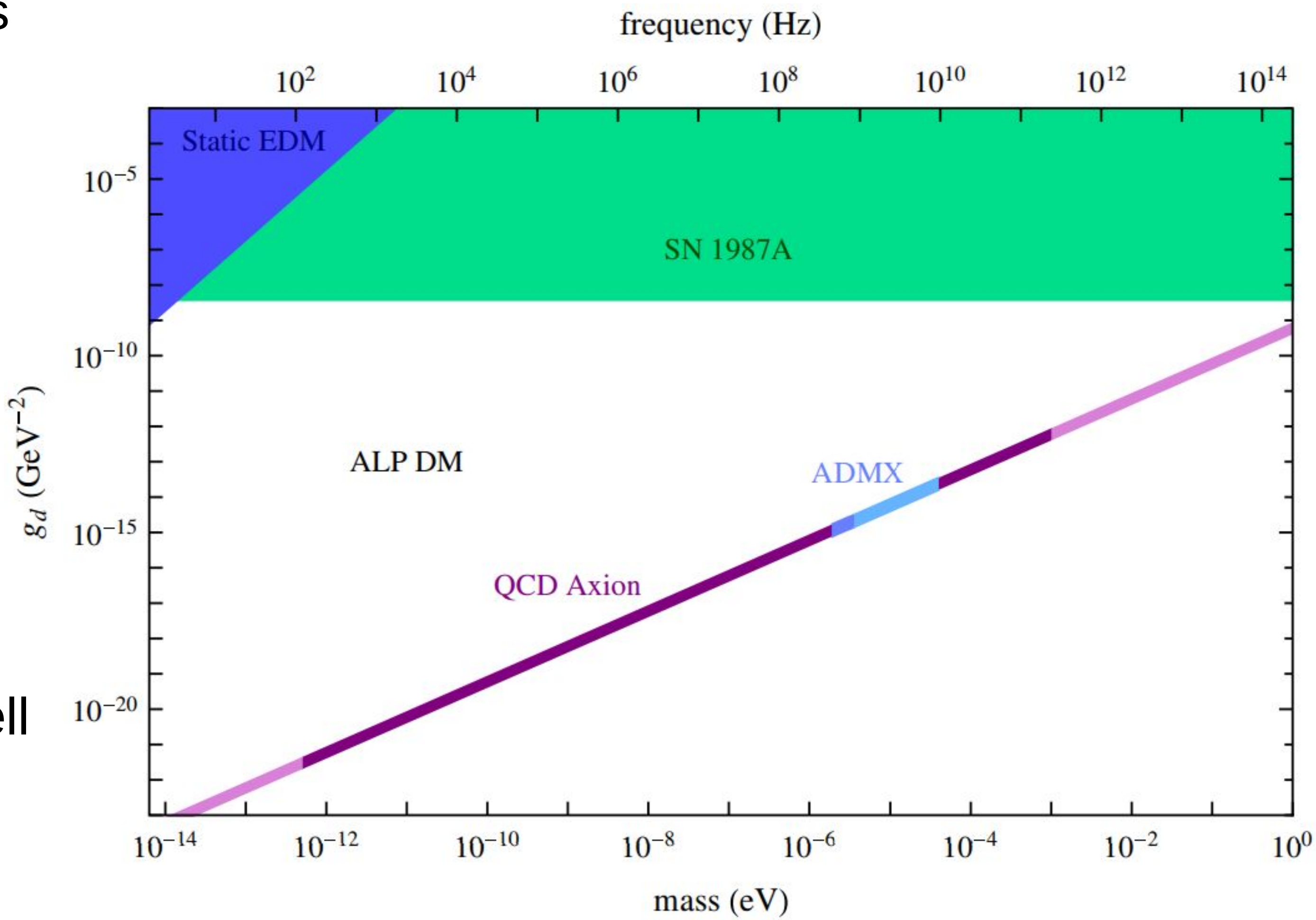
  Sensitivity goes like f_a^{-2} or worse – lots of trouble pushing below 1 μeV. (Also, cavity expt's too small.)

- We'll be focusing on techniques that use the 2nd and 3rd couplings

  Potential to reach much lower in mass!

QCD axions vs. axion-like particles

- QCD axion isn't the only possible light, weakly interacting pseudoscalar
- String theory predicts vacua with various other *axion-like particles* (ALPs)
- QCD axion has well-defined relationship between mass and coupling; not so for ALPs
- I'll be discussing techniques that can measure ALPs as well as QCD axions



Axions as a classical field

- Again, m_a is expected to be in peV - µeV range

  Corresponding frequencies: kHz - GHz

- Low frequency, high occupation number…

  We can treat the axion as a coherent classical field!

- Instead of looking for extremely rare single-particle scattering/conversion events…

  We can look for much larger effects caused by the whole field!

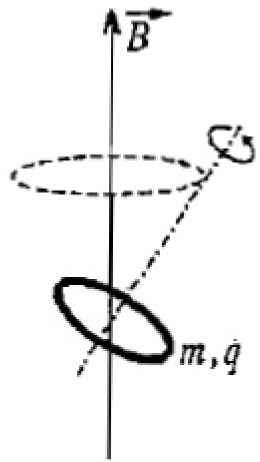
- Using de Broglie wavelength, can calculate coherence time/length:

  Result: (1 s, 1000 km) x (MHz / m_a), 300 km.

- Momentum (DM flow!) encoded in spatial gradient of field

New “NMR” detection scheme

- Rajendran *et al.* have proposed a novel type of axion search
- Basic idea:
  - Magnetize a sample of nuclei
  - Oscillating axion field can induce various moments in particles (EDM, axial moment, …)
  - Induced moments will cause spin precession → oscillating magnetization of sample
  - When applied **B** hits resonance (axion mass), get a “big” signal. Read out with sensitive magnetometer (SQUID, SERF, ...)



Nuclear electric dipole moment

- Axion-gluon coupling $\frac{a}{f_a} G\tilde{G}$ can induce nuclear EDM:

$$\mathcal{L} \ni -\frac{i}{2} g_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$

- The resulting dipole moment d_n is given by

$$d_n^{\mathrm{QCD}} \approx 2.4 \times 10^{-16} \frac{a}{f_a} \; e \cdot \mathrm{cm}$$

- Assuming axion composes all of DM, we can calculate a, and we finally get

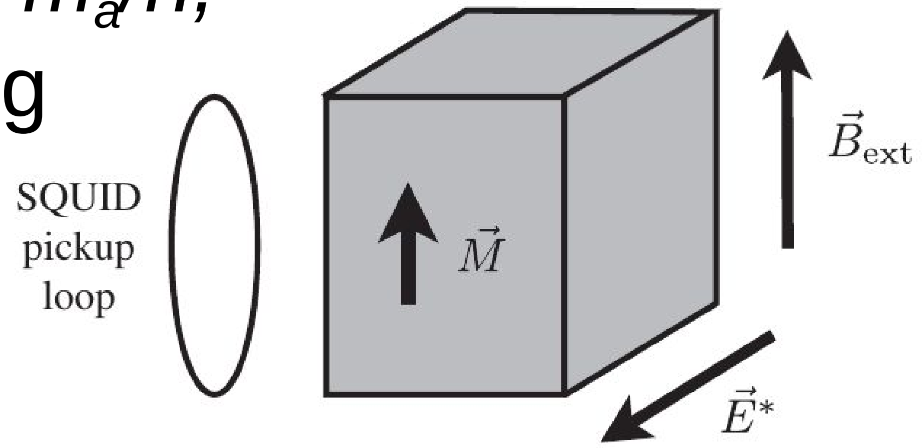
$$d_n^{\mathrm{QCD}} \approx (9 \times 10^{-35} \; e \cdot \mathrm{cm}) \cos(m_a t)$$

- The amplitude is independent of m_a!

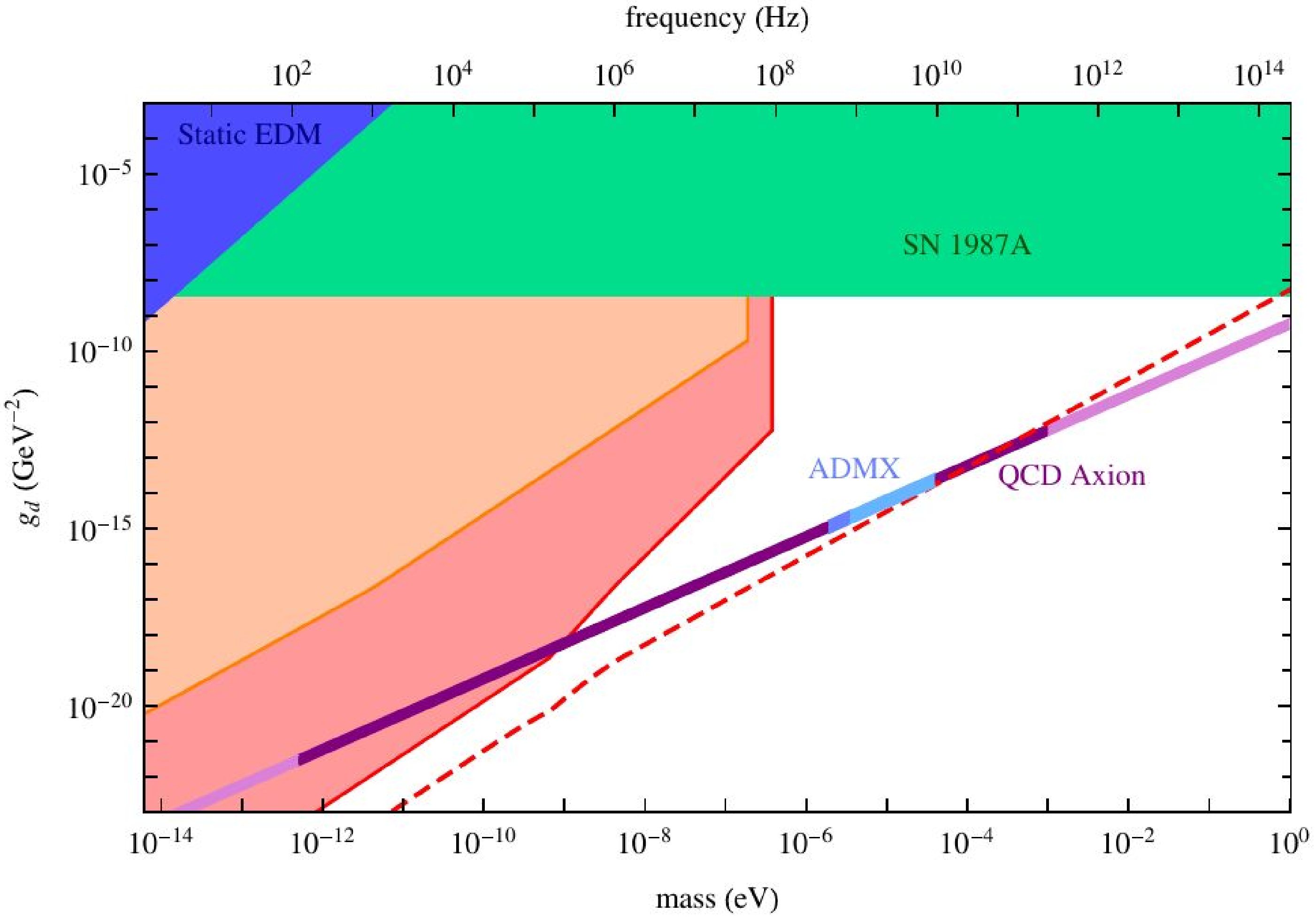
  ...unlike in axion-photon experiments, which lose much sensitivity for m_a < μeV

Measuring the EDM

- Apply $\mathbf{E}_{\mathbf{ext}}$ to material whose lattice structure produces strong internal **E***
- Magnetize material with $\mathbf{B}_{\mathbf{ext}} \perp \mathbf{E}^*$
- Spins will precess around $\mathbf{B}_{\mathbf{ext}}$ @ $f_{\text{Larmor}} = 2\mu B$
- EDM oscillates @ $f_{EDM} = m_a/h$, interacts with **E*,** causing add'l spin precession
- When $B = m_a/2\mu h$, **resonance!**



Sensitivity to oscillating EDM



Phase I: Current tech (optimize existing static EDM experiments). Probe ALPs but not QCD axion

Phase II: Combine improvements to existing tech, already shown in isolation but not together. Probe lighter QCD axions!

Red dashes: "Fundamental" limit from magnetization noise. Reachable with technology improvements. Fully covers QCD axion below ADMX range!

Axial nuclear moment

- Axion-fermion coupling gives rise to

$$\mathcal{L} \supset g_{\mathrm{aNN}}(\partial_\mu a)\bar{N}\gamma^\mu\gamma_5 N$$

- The derivative in *a* provides sensitivity to DM velocity – directional detection!

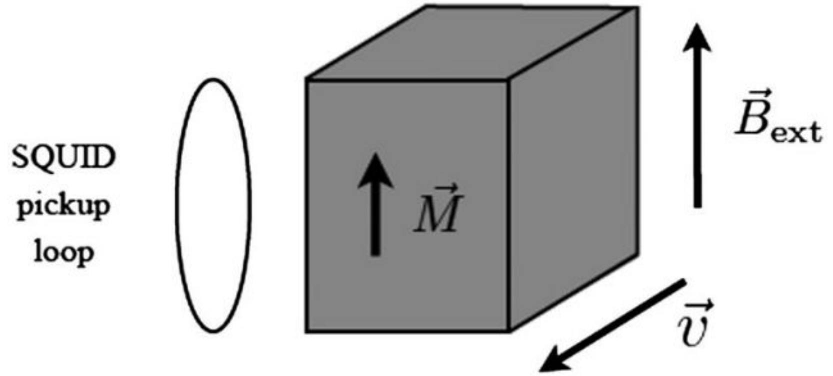
- In background *a* field (e.g. DM), non-relativistic limit gives

$$H_N \supset g_{\mathrm{aNN}} m_a a_0 \cos(m_a t)\vec{v}.\vec{\sigma}_N$$

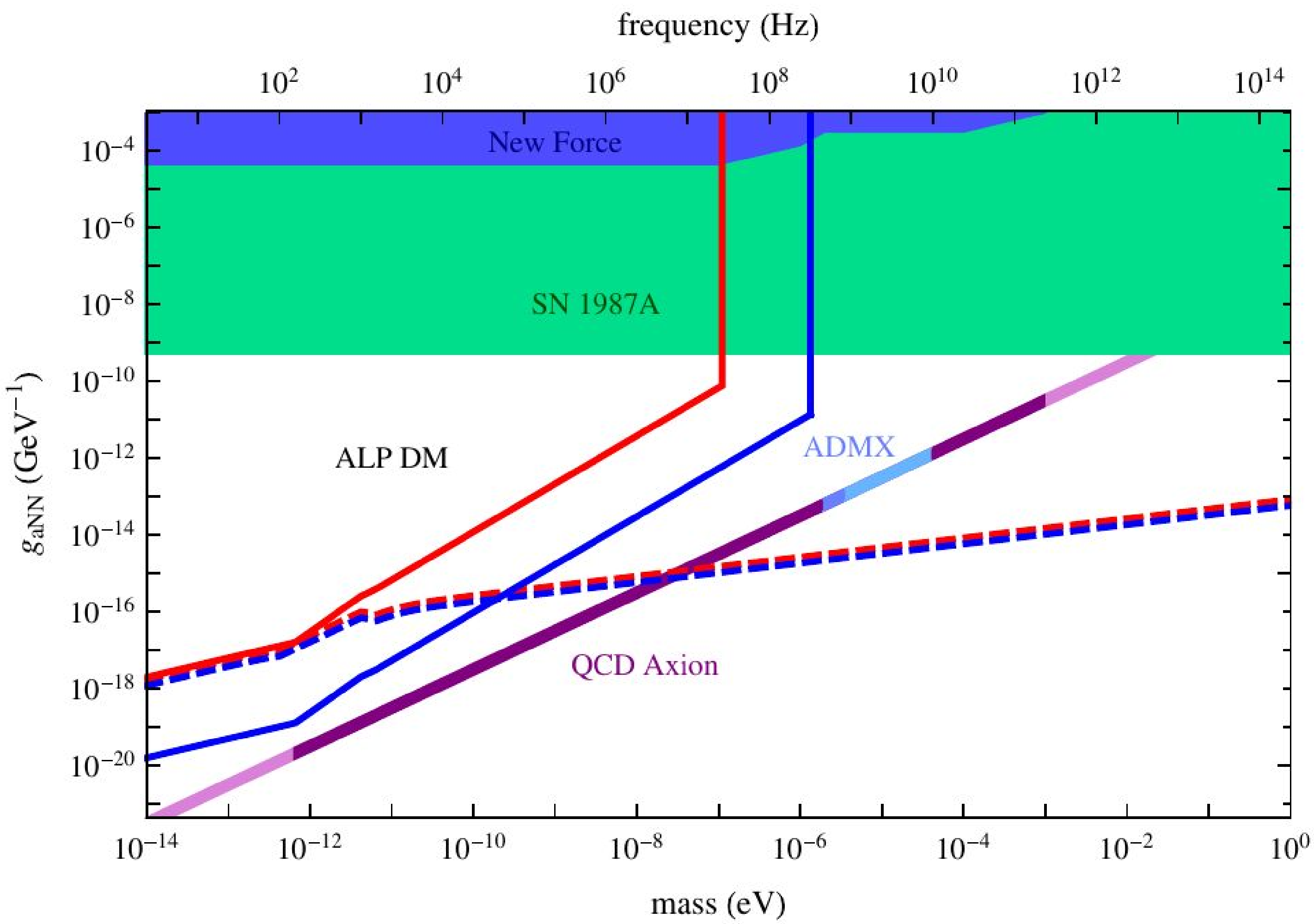
- This causes the nuclear spin to precess around the DM velocity vector!

Directional measurement

- Similar to EDM measurement, but no need for electric field
- Magnetize sample in direction orthogonal to $\mathbf{v}_{\mathrm{DM}}$
- Again, spins precess around $\mathbf{B}_{\mathbf{ext}}$ @ $f_{\mathrm{Larmor}} = 2\mu B$
- Time-varying axial moment leads to precession around $\mathbf{v}$ at $f = m_a/h$
- As before, $f = f_{\mathrm{Larmor}} \rightarrow$ **resonance!**



Directional measurement sensitivity



Red line: Sensitivity for preliminary experiment using Xe

Blue line: Same for H

Dashed lines: Limit from magnetization noise

We see that the QCD axion is unlikely to be probed with current tech. Masses in 0.1 to 1 μeV perhaps reachable in future.

Still, much ALP parameter space can be excluded, and any discovery would be **directional**

Conclusion

- Axions are a well-motivated solution to the strong CP problem
- Additional axion-like particles are motivated by string theory
- Axions and ALPs are leading candidates for dark matter, together with WIMPs
- Using modest-to-challenging improvements to *current technology*, NMR techniques can probe light axions down to the peV level
- **The first dark matter discovery may occur above ground!**

Thanks!

Now get back to your ROOT code