Cosmic Axion Spin Precession Experiment (CASPEr)

Surjeet Rajendran,
Stanford

with

Dmitry Budker,
Peter Graham,
Micah Ledbetter,
Alex Sushkov

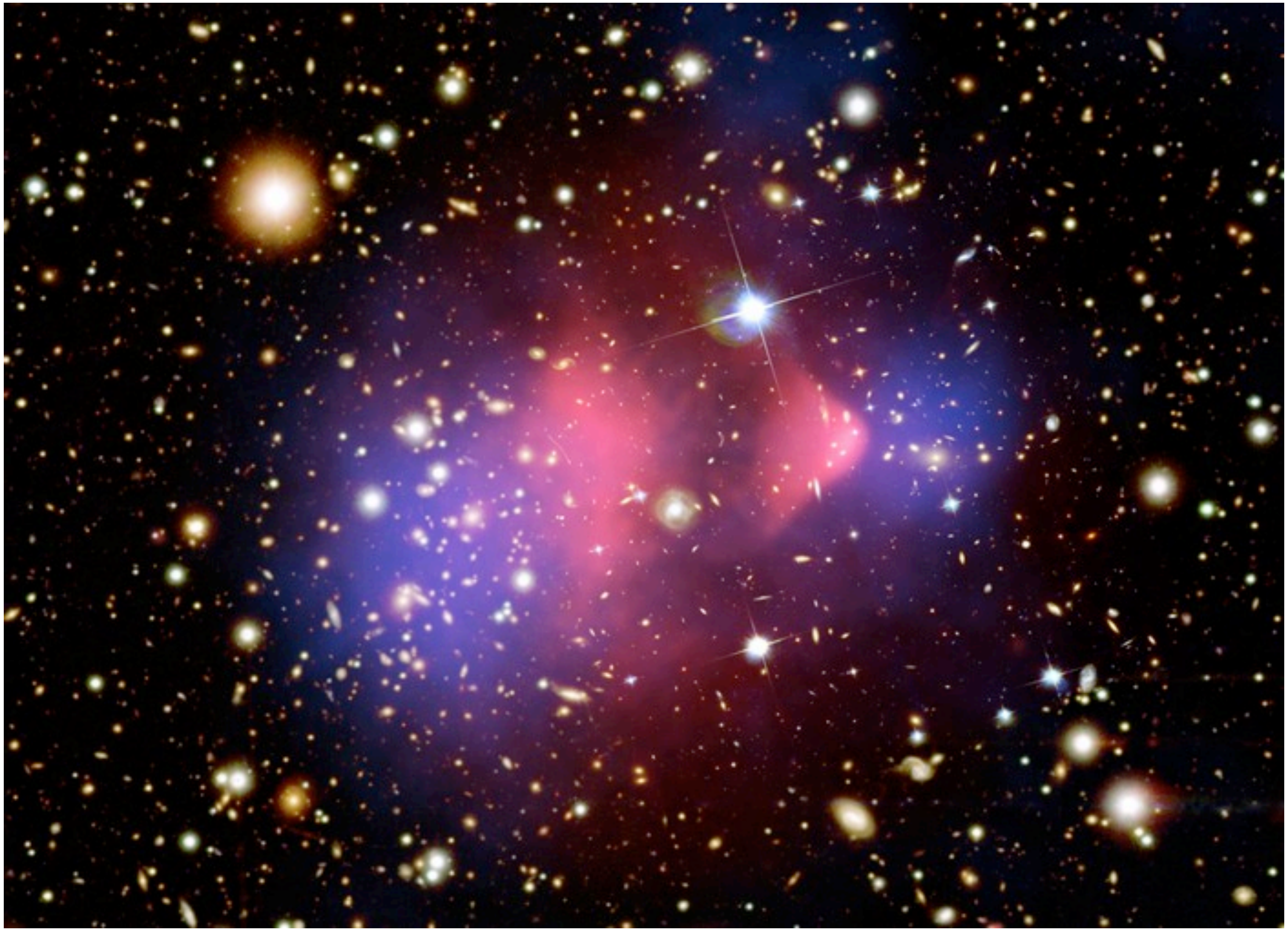
Based On:

D. Budker et.al.,
arXiv:1306.6089

P.W. Graham and S.R.,
PRD 88 (2013) 035023,
(arXiv:1306.6088)

P.W. Graham and S.R,
PRD 84 (2011) 055013
(arXiv:1101.2691)

Particle Dark Matter



Non-gravitational interactions

Detect these interactions?

Dark Matter Candidates

WIMP

M ~ 100 GeV.

Weak interactions.

e.g. Neutralino.

(Goodman and Witten, 1985)

Ultra-light scalars

Derivative coupling.

Ultra-high energy physics.

e.g. Axions

Light fermions

M ~ keV.

High energy physics.

e.g. Gravitino.

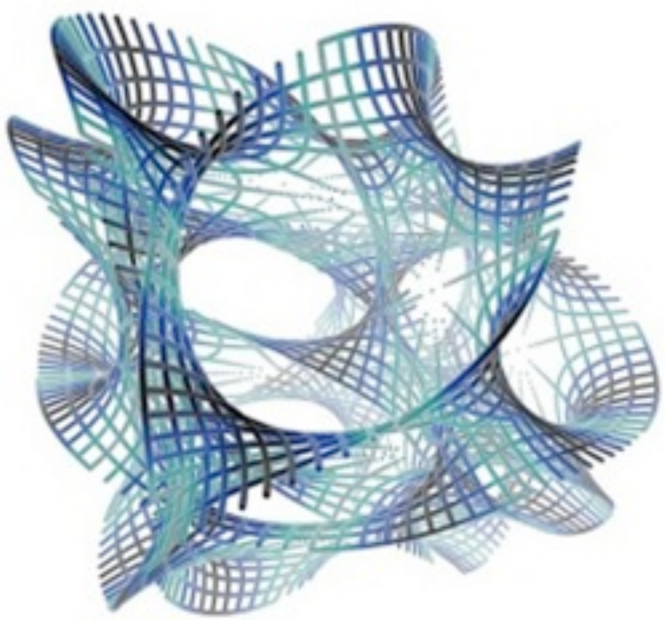
Axions and WIMPs are the best motivated cold dark matter candidates

Axions From High Energy Physics

Easy to generate axions from high energy theories

have a global symmetry broken at a high scale f_a

string theory or extra dimensions naturally
create axions from non-trivial topology



naturally gives large $f_a \sim$ GUT (10^{16} GeV) or Planck (10^{19} GeV) scales

The QCD Axion

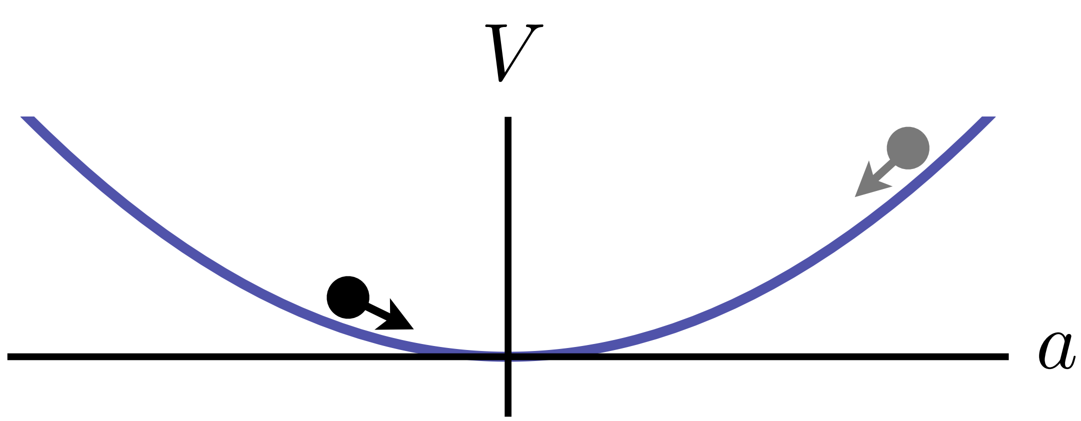
Strong CP problem:

$\mathcal{L} \supset \theta\, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\, \mathrm{cm}$

measurements $\Rightarrow$ $\theta \lesssim 3 \times 10^{-10}$

the axion is a simple solution:

$$\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G} \quad \text{with} \quad m_a \sim \frac{(200\ \mathrm{MeV})^2}{f_a} \sim \mathrm{MHz}\left(\frac{10^{16}\ \mathrm{GeV}}{f_a}\right)$$



$$a(t) \sim a_0 \cos\left(m_a t\right)$$

cosmic expansion reduces amplitude a_0

this field has momentum = 0 $\Rightarrow$ it is non-relativistic matter

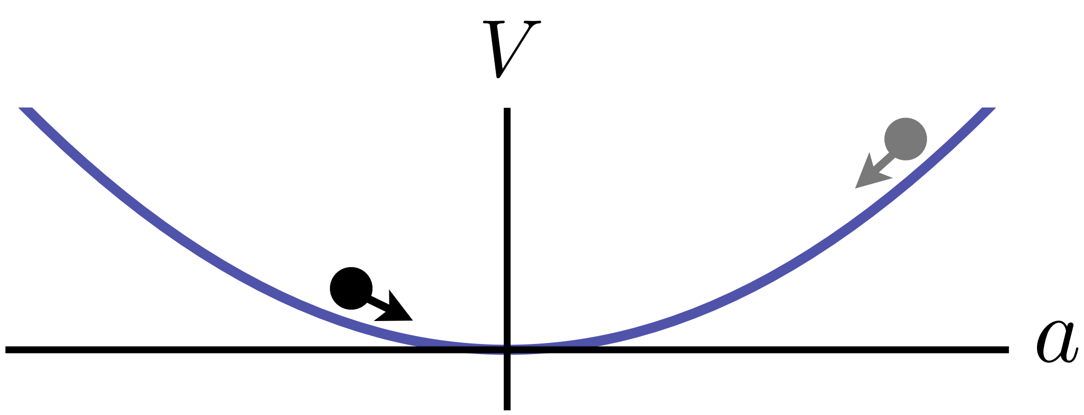
the axion is a good cold dark matter candidate

(J. Preskill et.al. 1982)

Cosmic Axions

misalignment production:

after inflation axion is a constant field, mass turns on at $T \sim \Lambda_{QCD}$ then axion oscillates



$$a(t) \sim a_0 \cos(m_a t)$$

Preskill, Wise & Wilczek, Abott & Sikivie, Dine & Fischler (1983)

axion easily produces correct abundance $\rho = \rho_{\rm DM}$

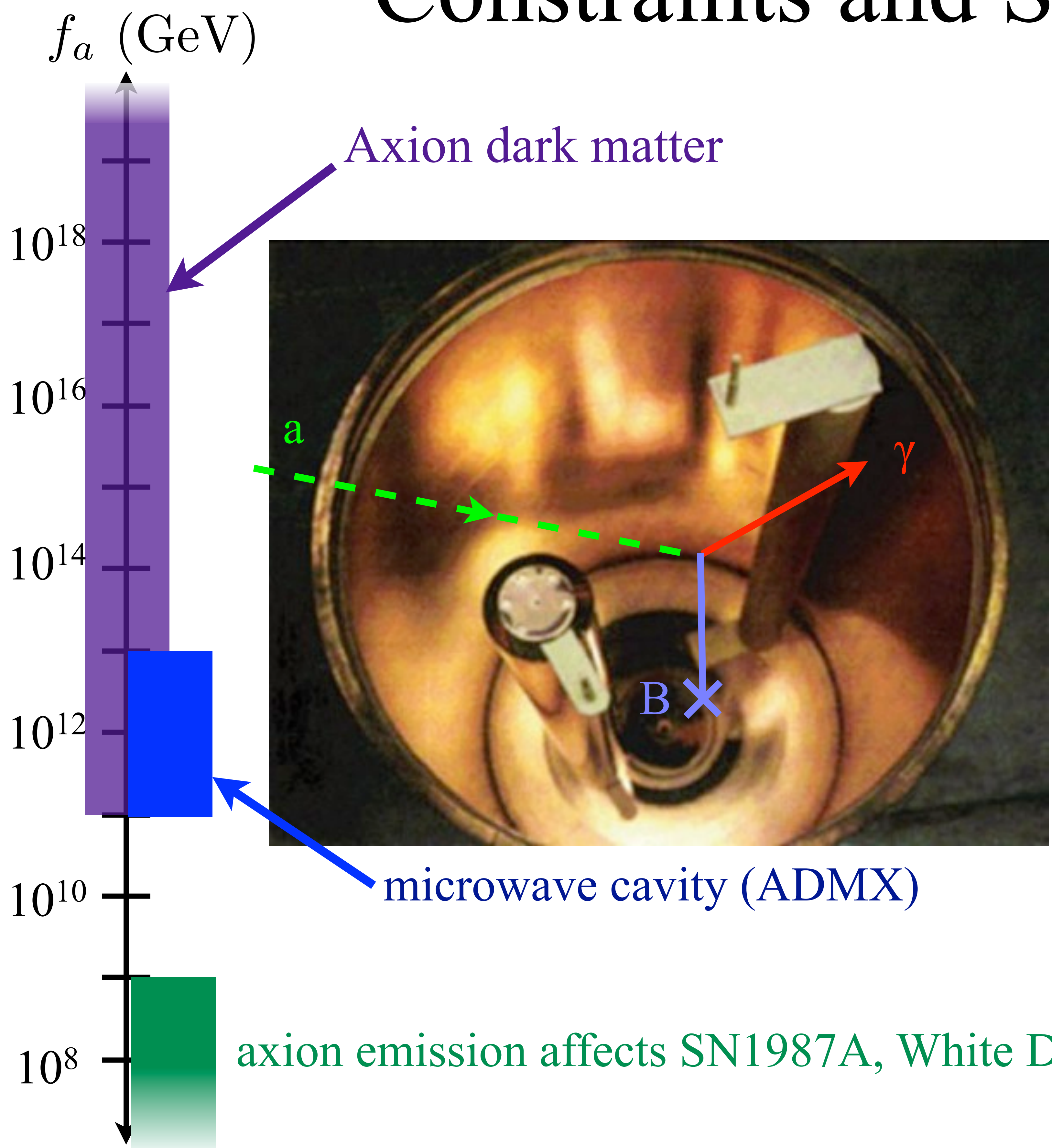
requires $\left(\frac{a_i}{f_a}\right)\sqrt{\frac{f_a}{M_{\rm Pl}}} \sim 10^{-3.5}$ late time entropy production eases this

e.g. $\frac{f_a}{M_{\rm Pl}} \sim 10^{-7}$ $\frac{a_i}{f_a} \sim 1$ or $\frac{f_a}{M_{\rm Pl}} \sim 10^{-3}$ $\frac{a_i}{f_a} \sim 10^{-2}$

inflationary cosmology does not prefer flat prior in Θ_i over flat in f_a

all f_a in DM range (all axion masses ≲ meV) equally reasonable

Constraints and Searches



Searches based on:

$$\mathcal{L} \supset \frac{a}{f_a} F\widetilde{F} = \frac{a}{f_a} \vec{E} \cdot \vec{B}$$

axion-photon conversion

$$\sigma_{a\to\gamma} \propto \frac{1}{f_a^2}$$

size of cavity increases with f_a

$$\text{signal} \propto \frac{1}{f_a^4}$$

axion emission affects SN1987A, White Dwarfs, other astrophysical objects

How to search for high f_a axions?

A Different Operator For Axion Detection

So how can we detect high f_a axions?

Strong CP problem: $\mathcal{L} \supset \theta\, G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \theta\, e\,\text{cm}$

the axion: $\mathcal{L} \supset \frac{a}{f_a} G\widetilde{G}$ creates a nucleon EDM $d \sim 3 \times 10^{-16}\, \frac{a}{f_a}\, e\,\text{cm}$

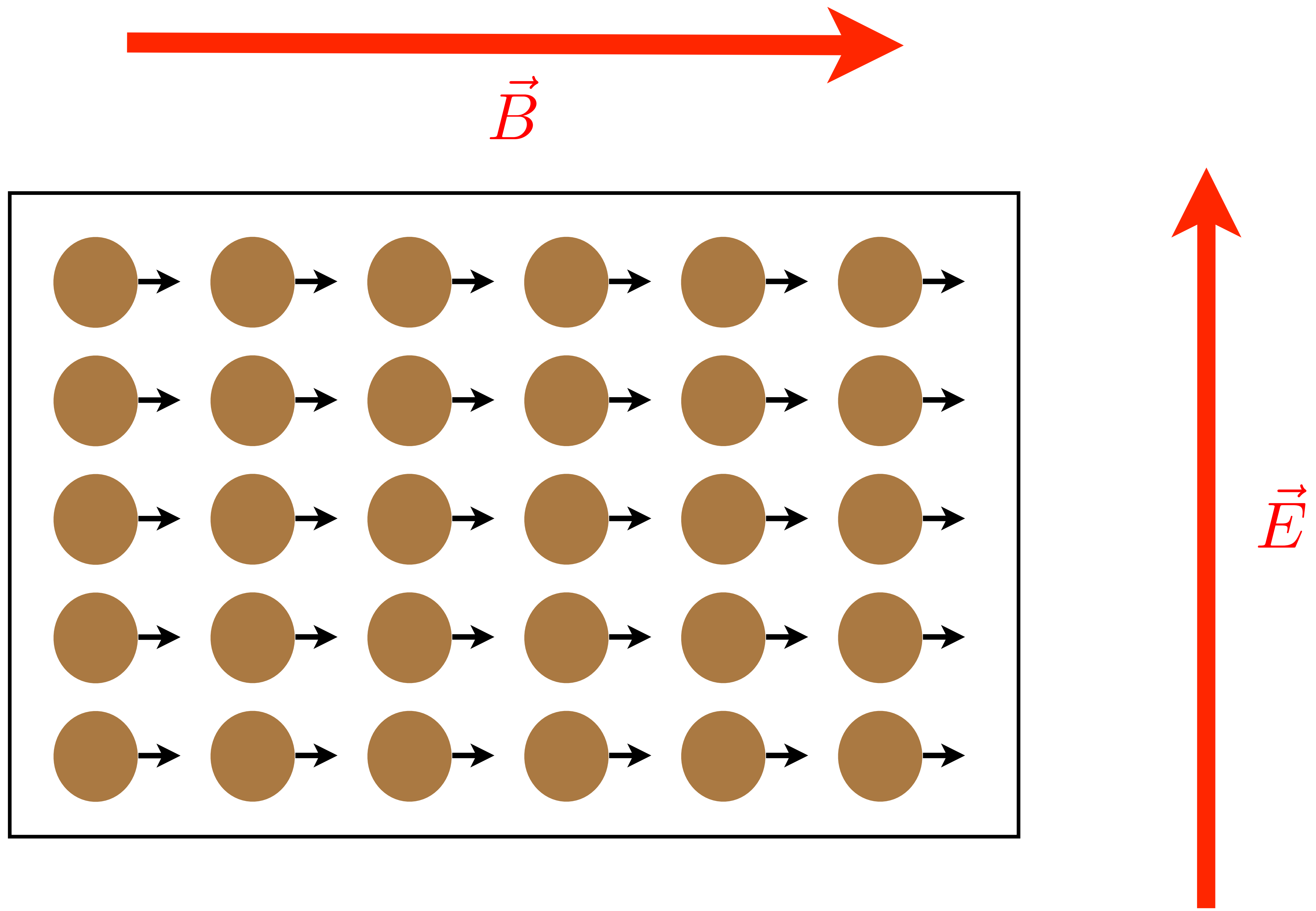
$$a(t) \sim a_0 \cos\left(m_a t\right) \quad \text{with} \quad m_a \sim \frac{\left(200\ \text{MeV}\right)^2}{f_a} \sim \text{MHz} \left(\frac{10^{16}\ \text{GeV}}{f_a}\right)$$

axion dark matter $\rho_{\text{DM}} \sim m_a^2 a^2 \sim \left(200\text{MeV}\right)^4 \left(\frac{a}{f_a}\right)^2 \sim 0.3\, \frac{\text{GeV}}{\text{cm}^3}$

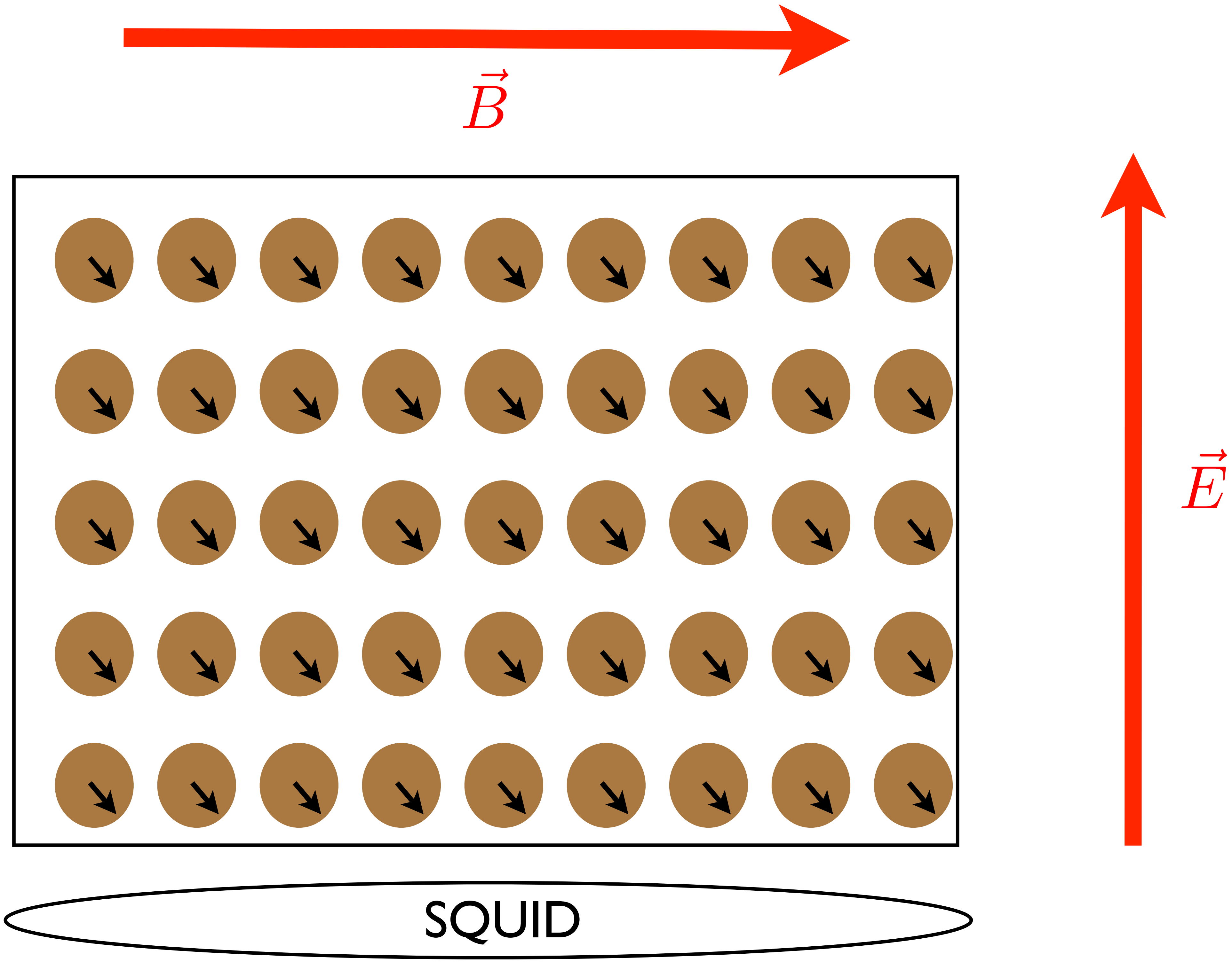
so today: $\left(\frac{a}{f_a}\right) \sim 3 \times 10^{-19}$ independent of f_a

the axion gives all nucleons a rapidly oscillating EDM independent of f_a

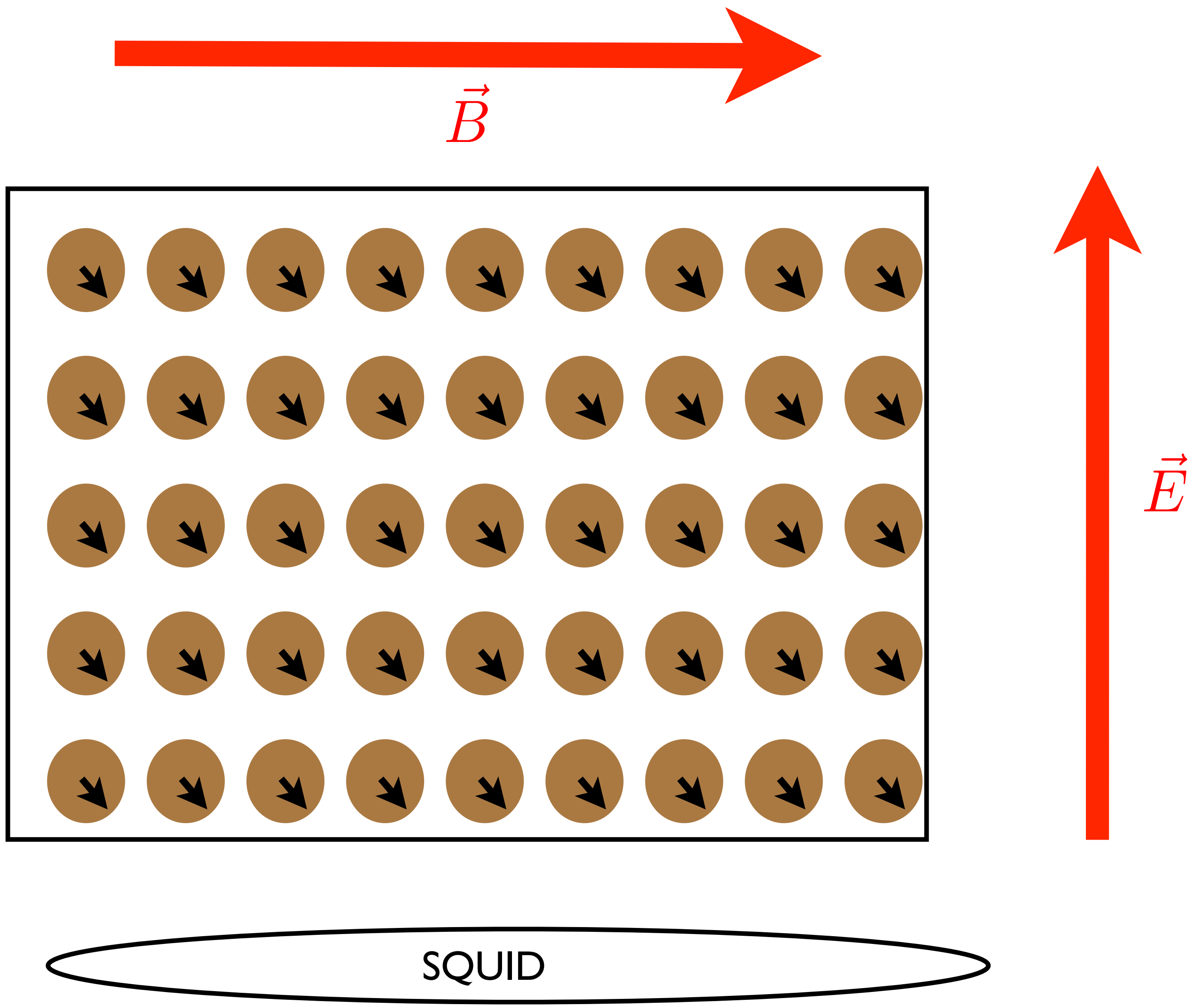
Setup



Setup



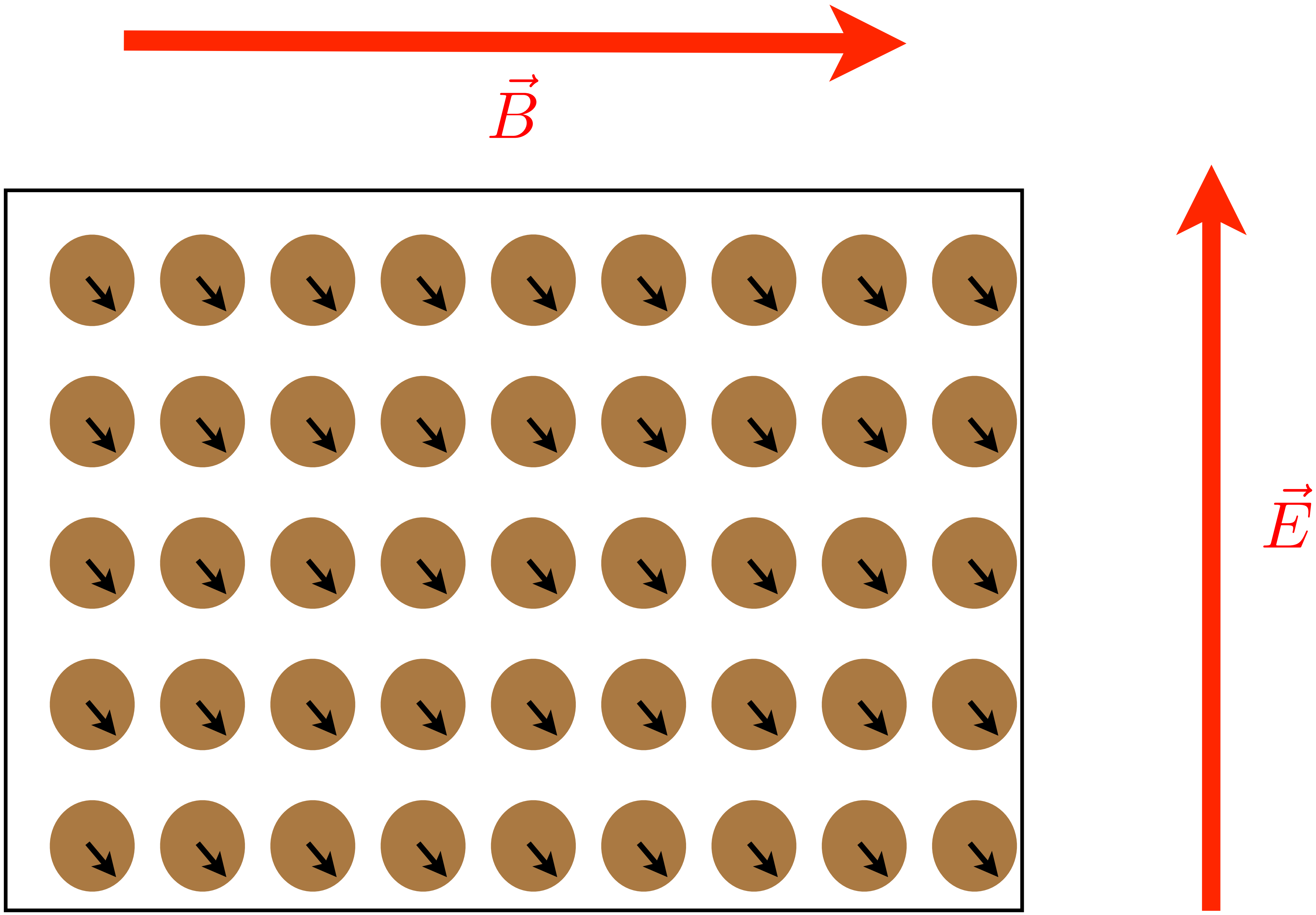
Outline



1. Signal
2. Parameters
3. Sensitivities
4. Conclusions

Signal

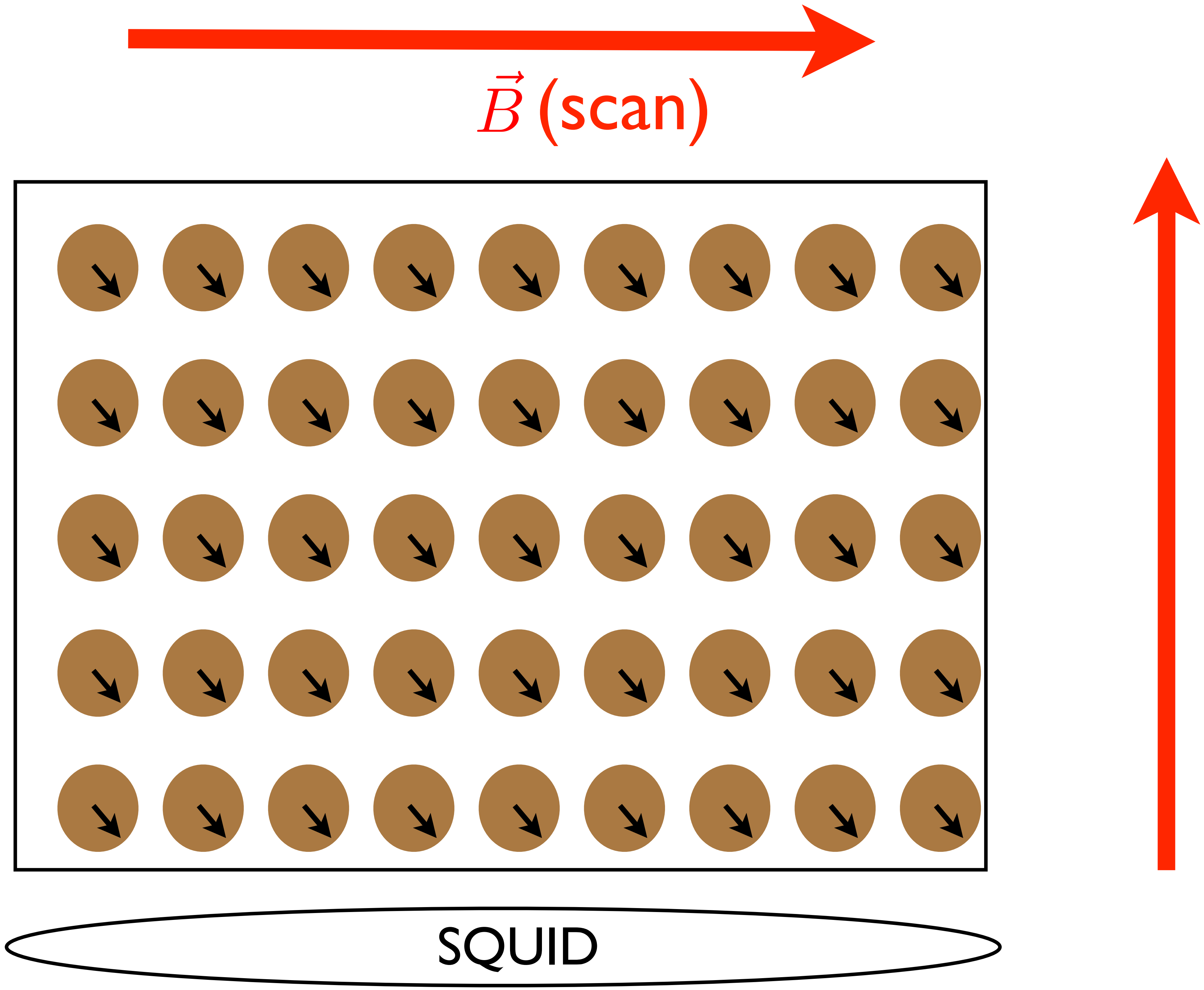
Solid State Precision Magnetometry



$$\delta\theta \sim \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right)t\right) \sin\left(2\mu_N B t\right)$$

Resonant Rabi oscillations

Solid State Precision Magnetometry



$$\delta B \sim n\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right)t\right) \sin\left(2\mu_N B t\right)$$

Rough Estimate

$$\delta B \sim n p \mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N B t\right)$$

$$n \sim \frac{10^{22}}{\text{cm}^3}$$

$$\mu_N \sim \frac{e}{\text{GeV}}$$

$$d_N \sim 10^{-34} \text{ e-cm}$$

$$p \sim \mathcal{O}\left(1\right)$$

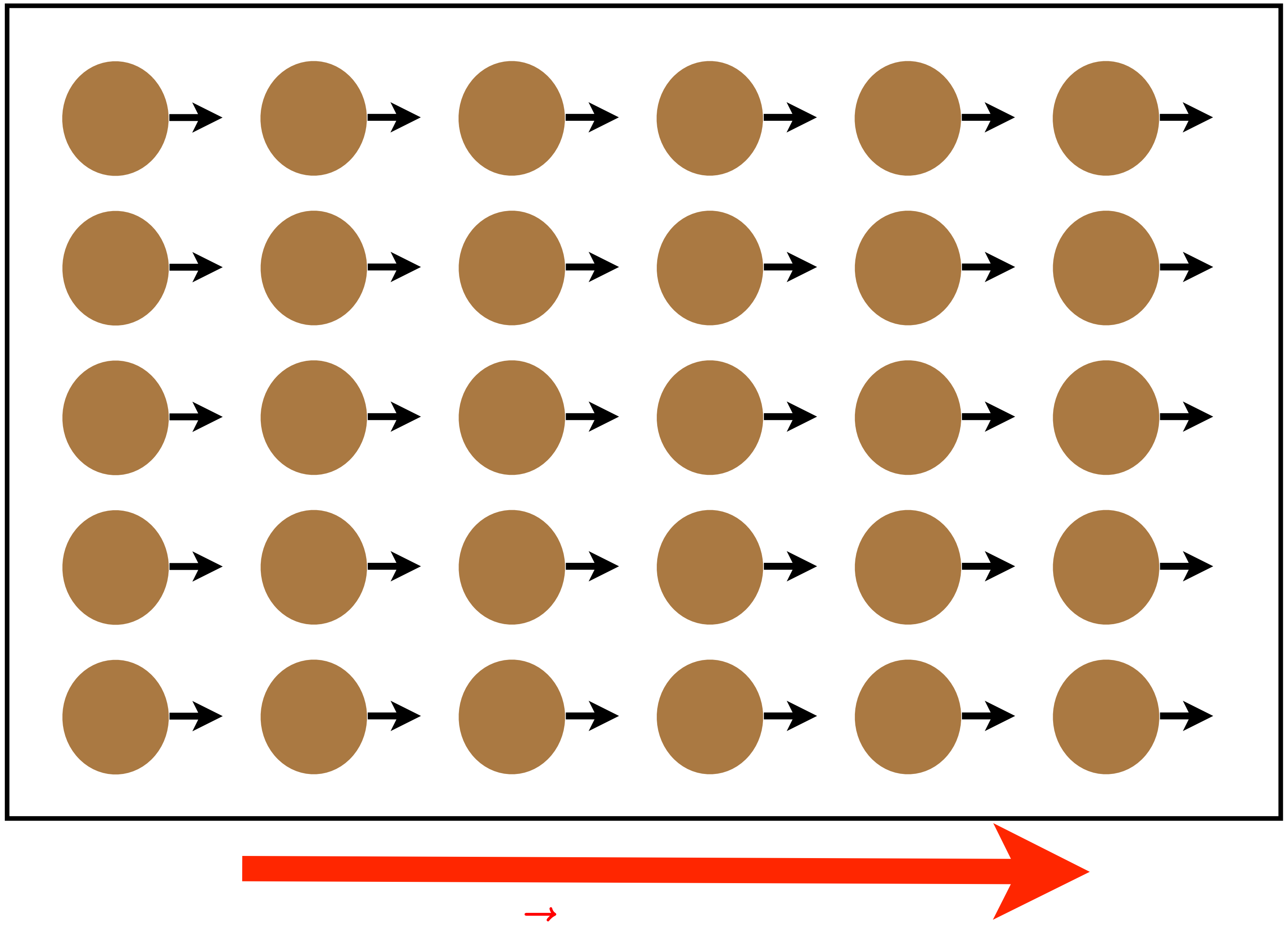
$$E_{\text{eff}} \sim 10^6 \frac{\text{V}}{\text{cm}}$$

$$\left(\mu_N B - m_a\right)^{-1} \sim \left(10^{-6} m_a\right)^{-1} \sim t \sim 1 \text{ s} \left(\frac{f_a}{10^{16}\text{GeV}}\right)$$

$$\delta B \sim 10^{-2} \text{ fT}$$

Parameters

Nuclear Polarization (p)



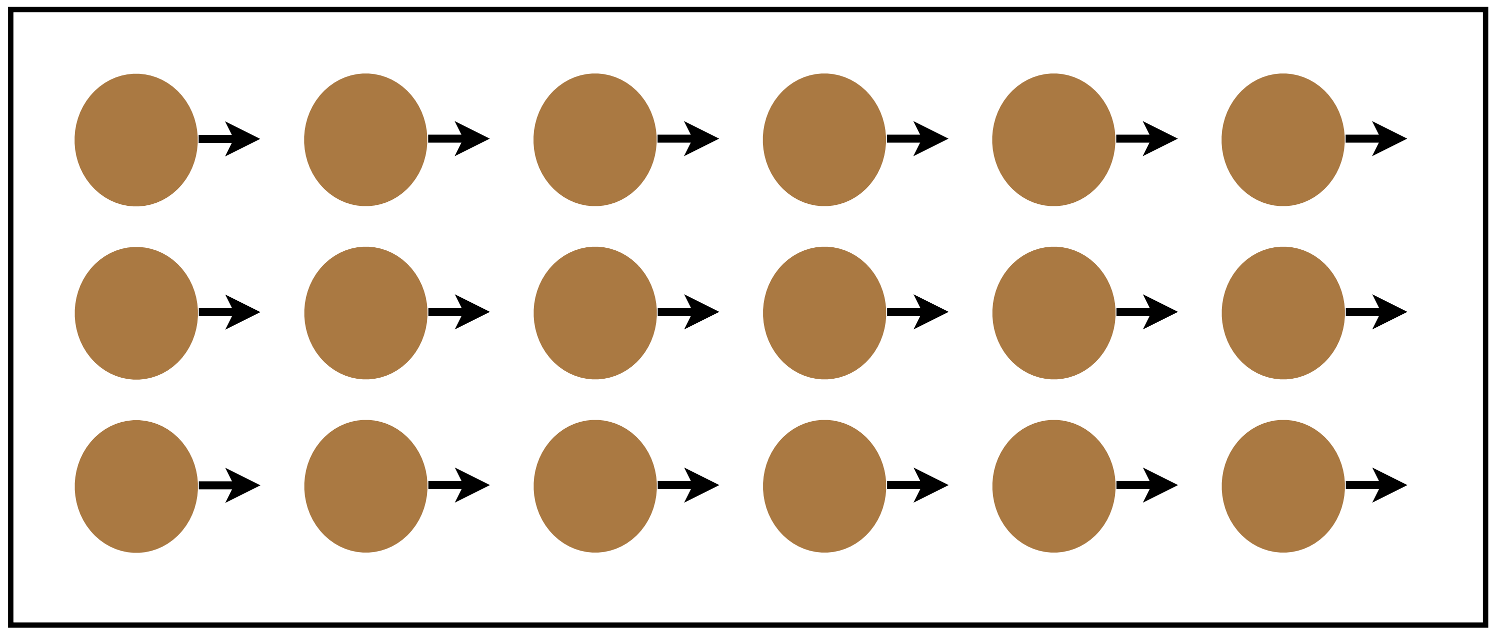
$\vec{B}_0 \sim 10\ \mathrm{T}$

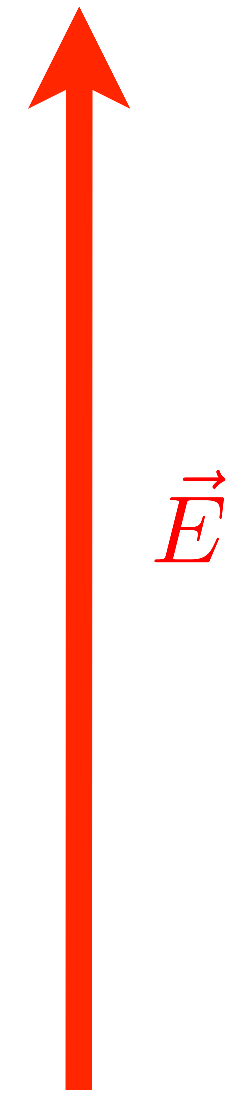
$\theta_0 \sim 4\ \mathrm{K}$

$p \sim \mathcal{O}(1)\ \ \text{for}\ T_1 \sim 3\ \text{hrs}$

Optical pumping
p ~ 0.9 in Liquid Xe, Diamond

Effective Electric Field





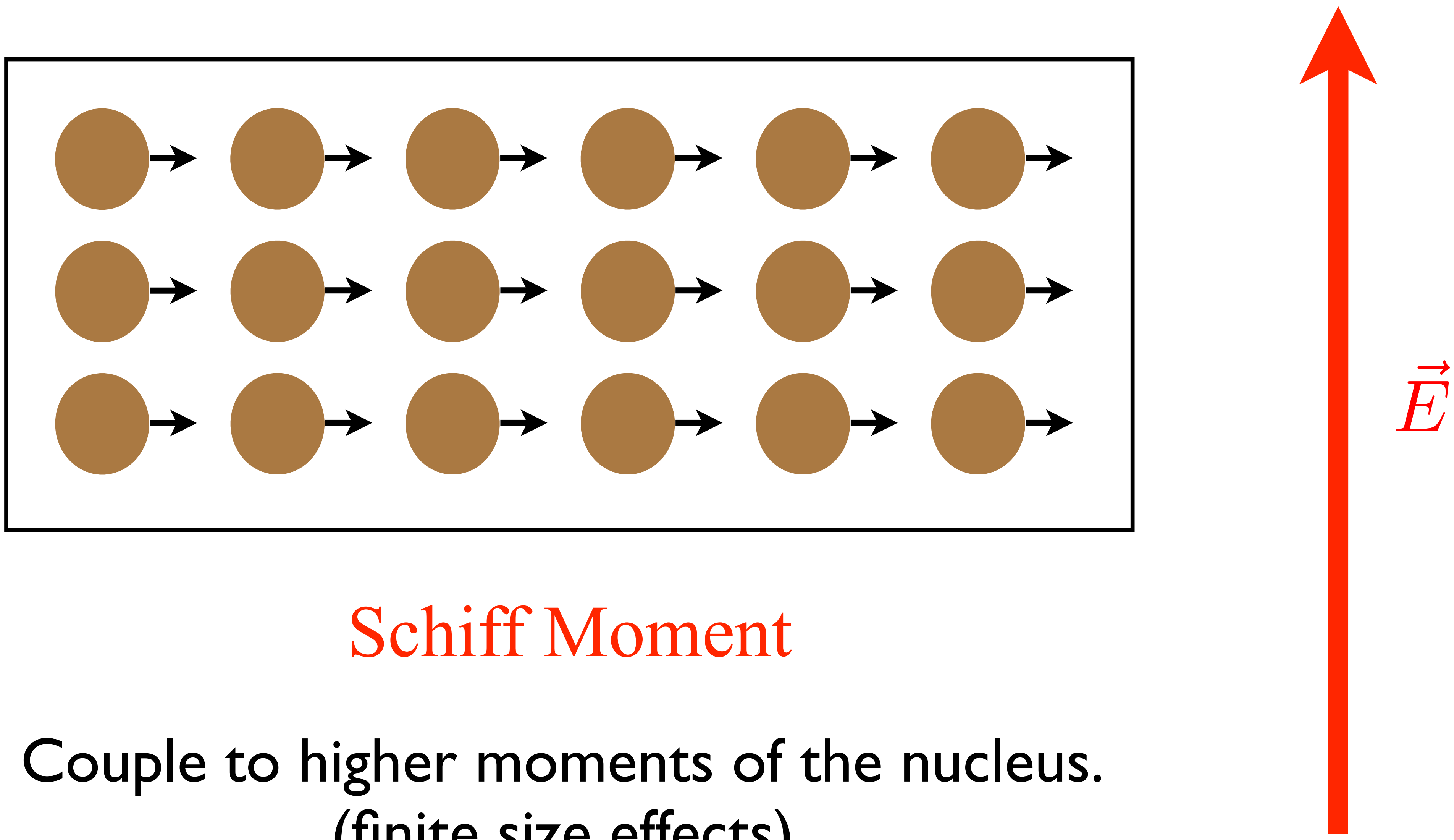
Schiff's Theorem

$$\text{Equilibrium} \implies \langle \vec{F}_N \rangle = 0$$

Only electrostatic forces on nucleus.

$$\langle \vec{E}_N \rangle = 0$$

Effective Electric Field



Schiff Moment

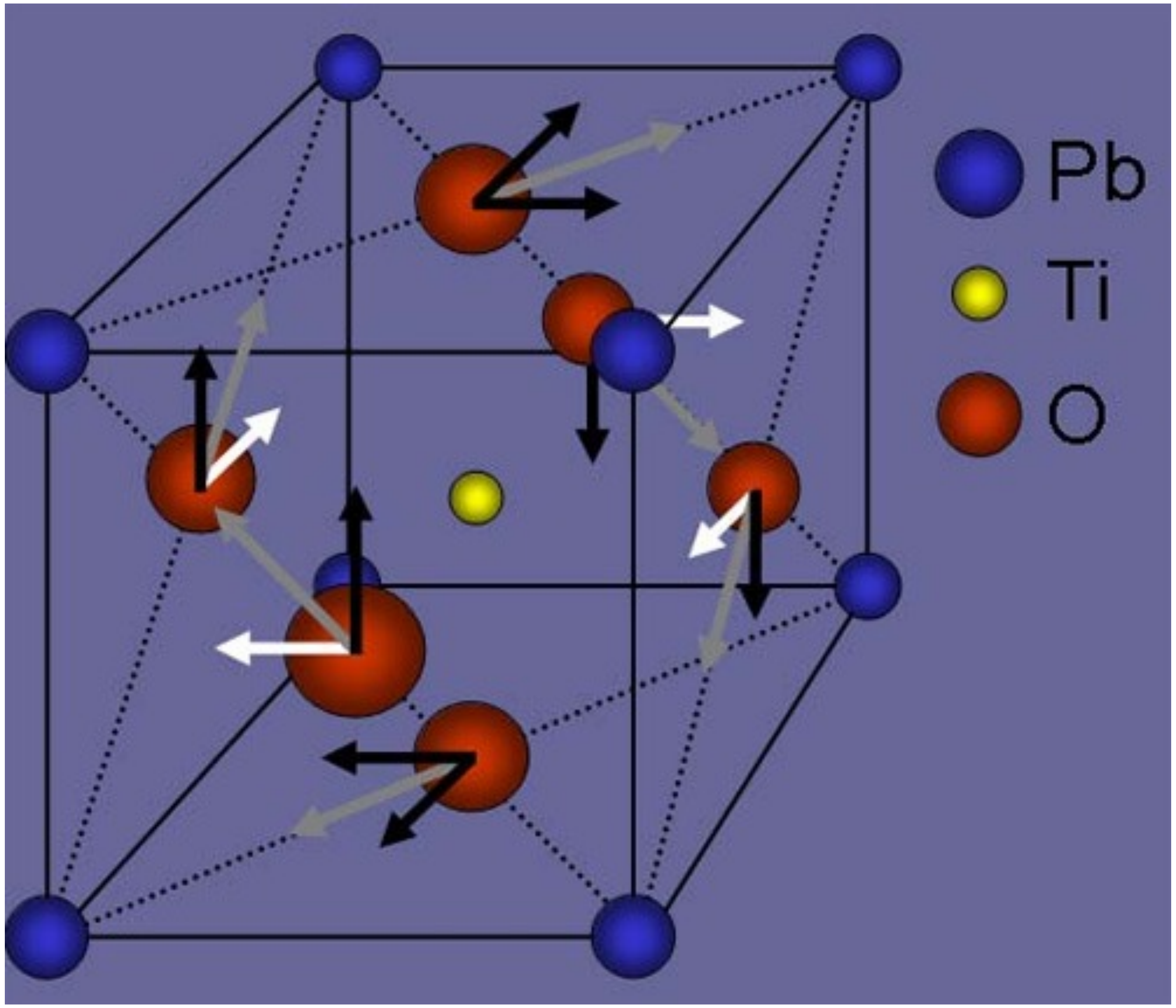
Couple to higher moments of the nucleus.
(finite size effects)

$$E_{\text{eff}} \sim \left(10^{-9} Z^3\right) E_N$$

Use high Z nucleus (Pb, Hg)

$$E_{\text{eff}} \sim \left(10^{-3}\right) E_N$$

Polar Crystal



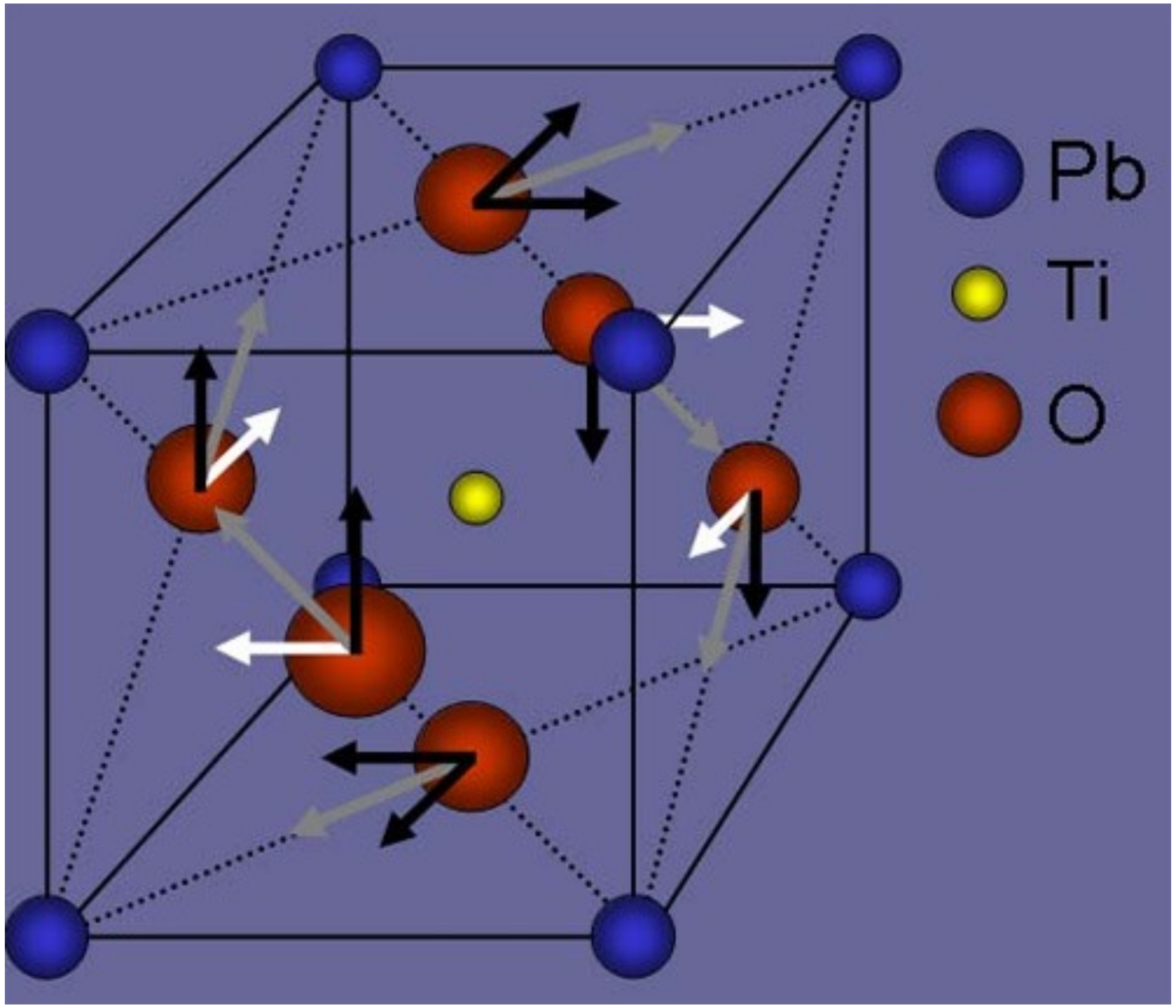
Lead Titanate

Pb displaced from axis of symmetry, large internal field.

$$E_{\text{eff}} \sim 10^6 \, \frac{\text{V}}{\text{cm}}$$

O. Sushkov et.al.,
PRA 72, 034501(2005)

Polar Crystal



$$E_{\text{eff}} \sim 10^6 \, \frac{\text{V}}{\text{cm}}$$

Field reversal not needed. Ferroelectric not needed.

Larger (~few) fields may exist in other polar crystals.

Interrogation Time (t)

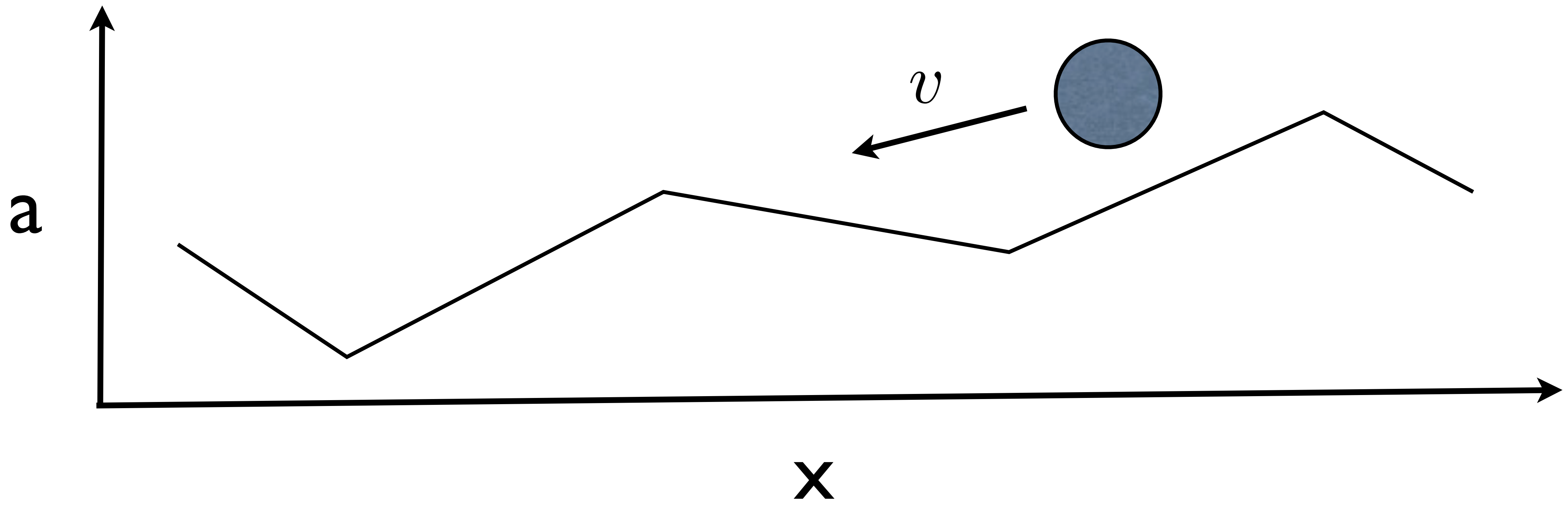
$$\delta B \sim np\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N B t\right)$$

Temporal coherence of the dark matter axion field.

Material limitations.

Axion Coherence

How large can t be?



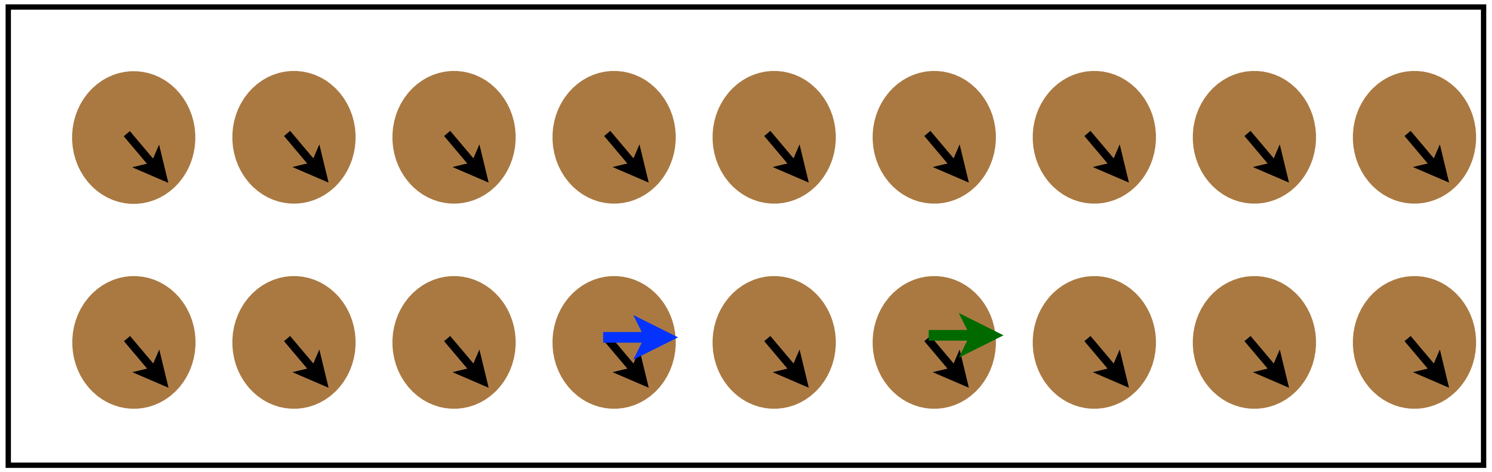
Spatial Homogeneity of the field?

Classical field a(x) with velocity v $\sim 10^{-3}$

$$\Longrightarrow \frac{\nabla a}{a} \sim m_a\, v$$

$$t \sim \frac{1}{m_a\, v^2} = 1\ \mathrm{s} \left(\frac{f_a}{10^{16}\ \mathrm{GeV}}\right)$$

Coherence of Transverse Magnetization



$$B(x_1) \neq B(x_2)$$

Local variations in Larmor frequency leads to dephasing.

(T_2)

Spin-Spin Interactions

$T_2 \sim 1 \text{ ms}$

Dynamic Decoupling

40 s in Si, 1300 s in Liquid Xe

$T_2^{\text{eff}} \sim 1 \text{ s}$

Recap

$$\delta B \sim n p \mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N B t\right)$$

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$$\mu_N \sim \frac{e}{\mathrm{GeV}}$$

$$d_N \sim 10^{-34}\ \text{e-cm}$$

$$p \sim \mathcal{O}\left(1\right)$$

(e.g. optical pumping)

$$E_{\mathrm{eff}} \sim 10^6 \frac{\mathrm{V}}{\mathrm{cm}}$$

(e.g. polar crystal)

$$\left(\mu_N B - m_a\right)^{-1} \sim \left(10^{-6} m_a\right)^{-1} \sim t \sim 1\ \mathrm{s}\left(\frac{f_a}{10^{16}\,\mathrm{GeV}}\right)$$

(dynamic decoupling and m_a < MHz)

$$\delta B \sim 10^{-2}\ \mathrm{fT}$$

Sensitivities

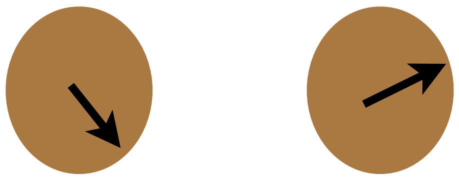
Noise

1. Magnetization Noise

2. Magnetometer Noise

3. Integration Time

Magnetization Noise
(Spin Projection)



Each spin has random initial transverse projection.

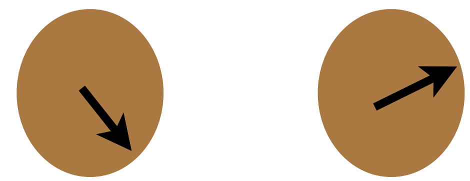
Needs time variation for it to be noise.

$$M_n(\omega) \sim \frac{\mu_N}{r^3}\sqrt{nr^3}\langle S_{\mathrm{rms}}(\omega)\rangle \sim \mu_N\sqrt{\frac{n}{V}}\langle S_{\mathrm{rms}}(\omega)\rangle$$

$$S^2_{\mathrm{rms}}(\omega) \approx \frac{1}{8}\left(\frac{T_2}{1+T_2^2(\omega-2\mu_N B)^2}\right)$$

M. Braun and J. Konig, PRB 75, 085310 (2007)

Magnetization Noise
(Spin Projection)



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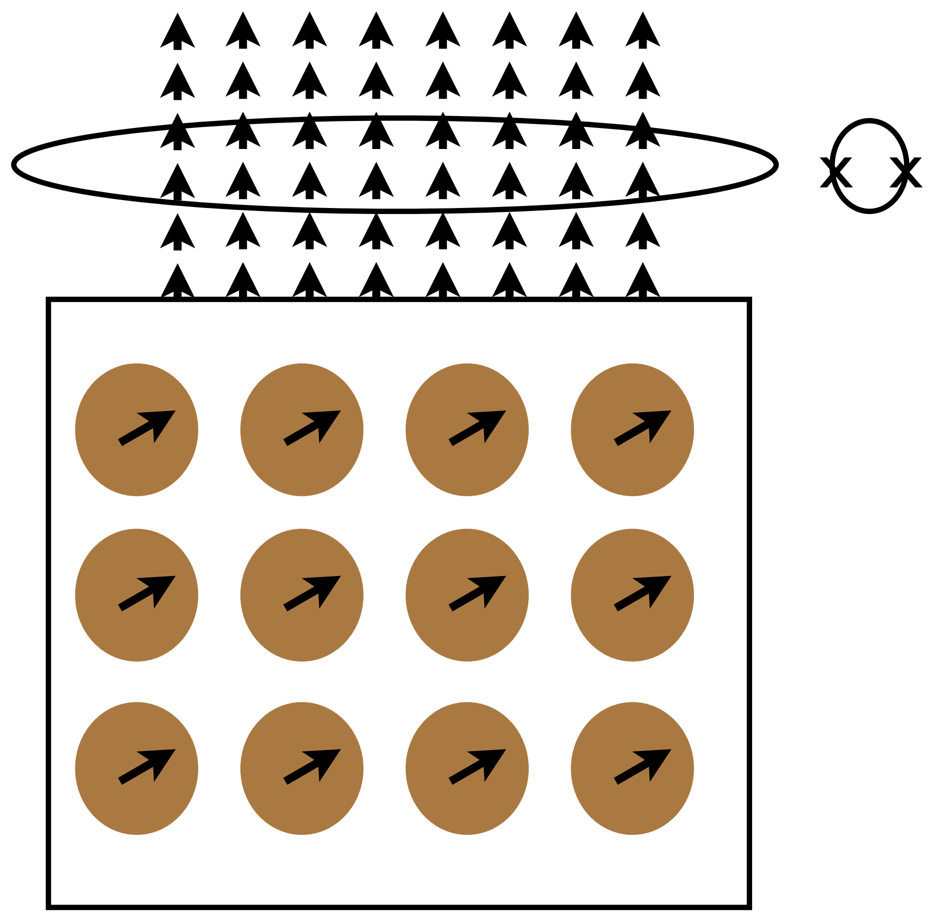
$$S^2_{\mathrm{rms}}(\omega) \approx \frac{1}{8}\left(\frac{T_2}{1+T_2^2(\omega-2\mu_N B)^2}\right)$$

Intuition

$$\omega \gg 2\mu_N B \implies S_{\mathrm{rms}} \sim \sqrt{\frac{1}{T_2\omega}}\sqrt{\frac{1}{\omega}}$$

$$(\omega - 2\mu_N B) \approx \frac{1}{T_2} \implies S_{\mathrm{rms}} \propto \sqrt{T_2}\ \text{(resonantly enhanced)}$$

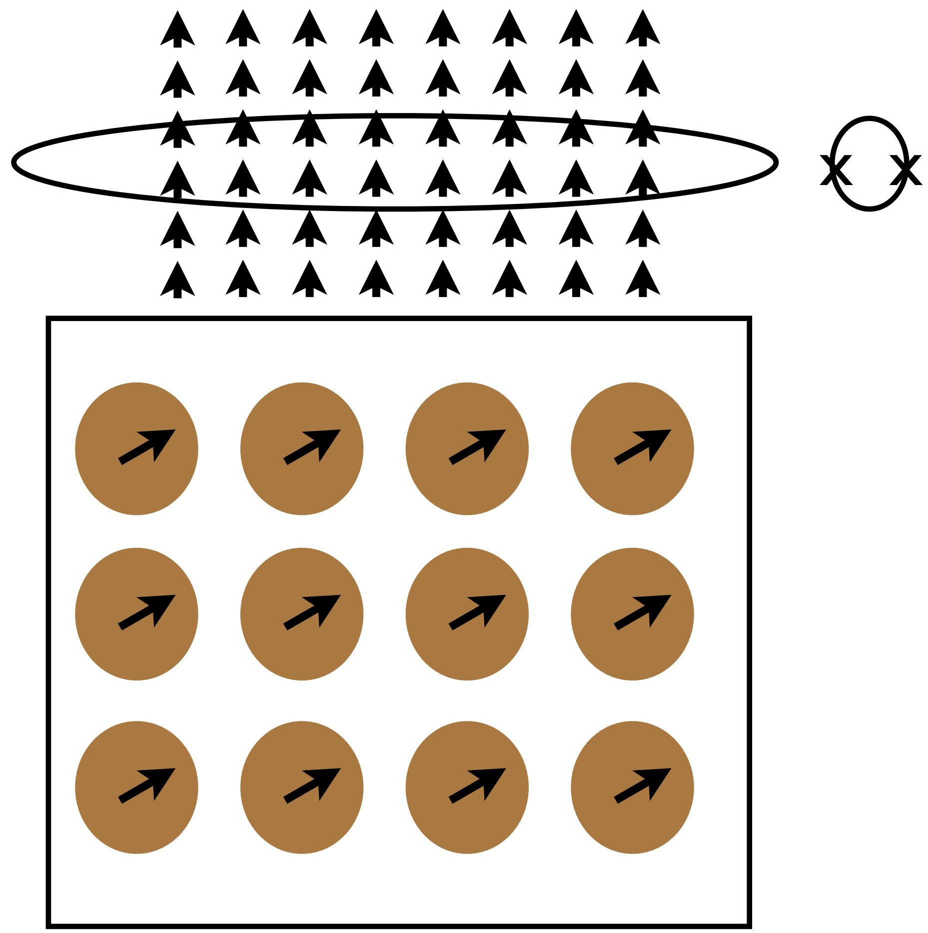
Magnetometer Noise
(SQUID)



SQUID measures magnetic flux.

More flux with more volume.

Magnetometer Noise (SQUID)



Typical Parameters

$$\phi_n \sim 10^{-21}\,\frac{\mathrm{Wb}}{\sqrt{\mathrm{Hz}}}\ \text{(at 4 K)}$$

$$L_i \sim 500\ \mathrm{nH} \qquad M \sim 10\ \mathrm{nH} \qquad r \sim 10\ \mathrm{cm}$$

$$B \sim 0.1\,\frac{\mathrm{fT}}{\sqrt{\mathrm{Hz}}}$$

Integration Time

$$\delta B \sim np\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N B t\right)$$

Signal to Noise Scaling

$$t \lessapprox \min\left(t_a, T_2\right) \propto t^{\frac{3}{2}}$$

Signal builds linearly. Noise integrates down.

$$T_2 \lessapprox t \lessapprox t_a \propto \sqrt{t}$$

Signal limited by T_2. Noise integrates down.

$$t \gtrapprox t_a \propto t^{\frac{1}{4}}$$

Signal looks like excess noise.

$$\sqrt{\rho_n^2 + \rho_a^2} \approxeq \rho_n + \frac{1}{2}\frac{\rho_a^2}{\rho_n} \sim \frac{\rho_n}{\sqrt{t}} + \frac{\rho_a^2}{2\rho_n}$$

Integration Time

$$\delta B \sim np\mu_N \frac{d_N E}{2\mu_N B - m_a} \sin\left(\left(2\mu_N B - m_a\right) t\right) \sin\left(2\mu_N Bt\right)$$

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Signal limited by T_2. Noise integrates down.

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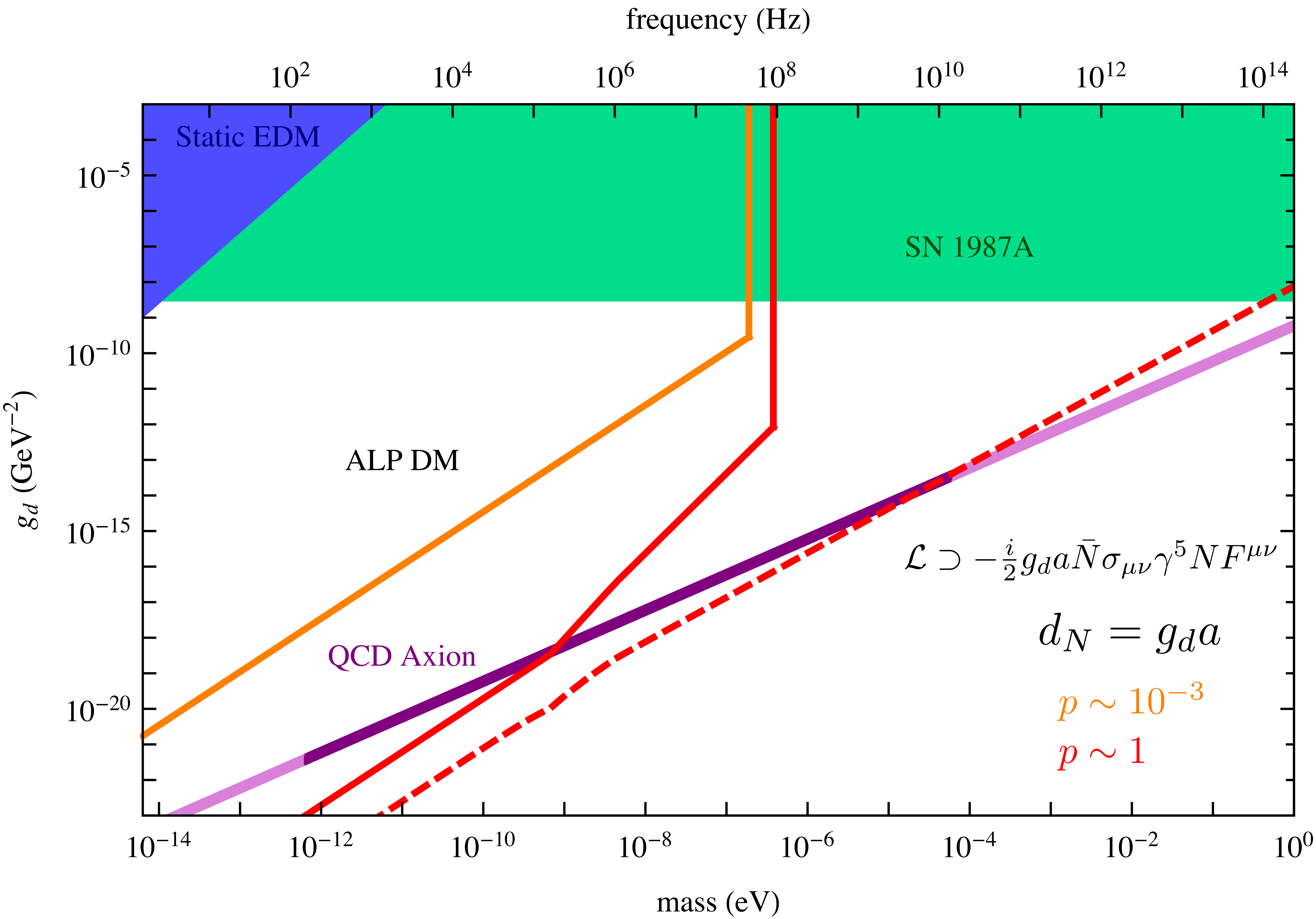
Signal looks like excess noise.

Limited by time needed to scan over the full band.

Projected Sensitivity in Lead Titanate

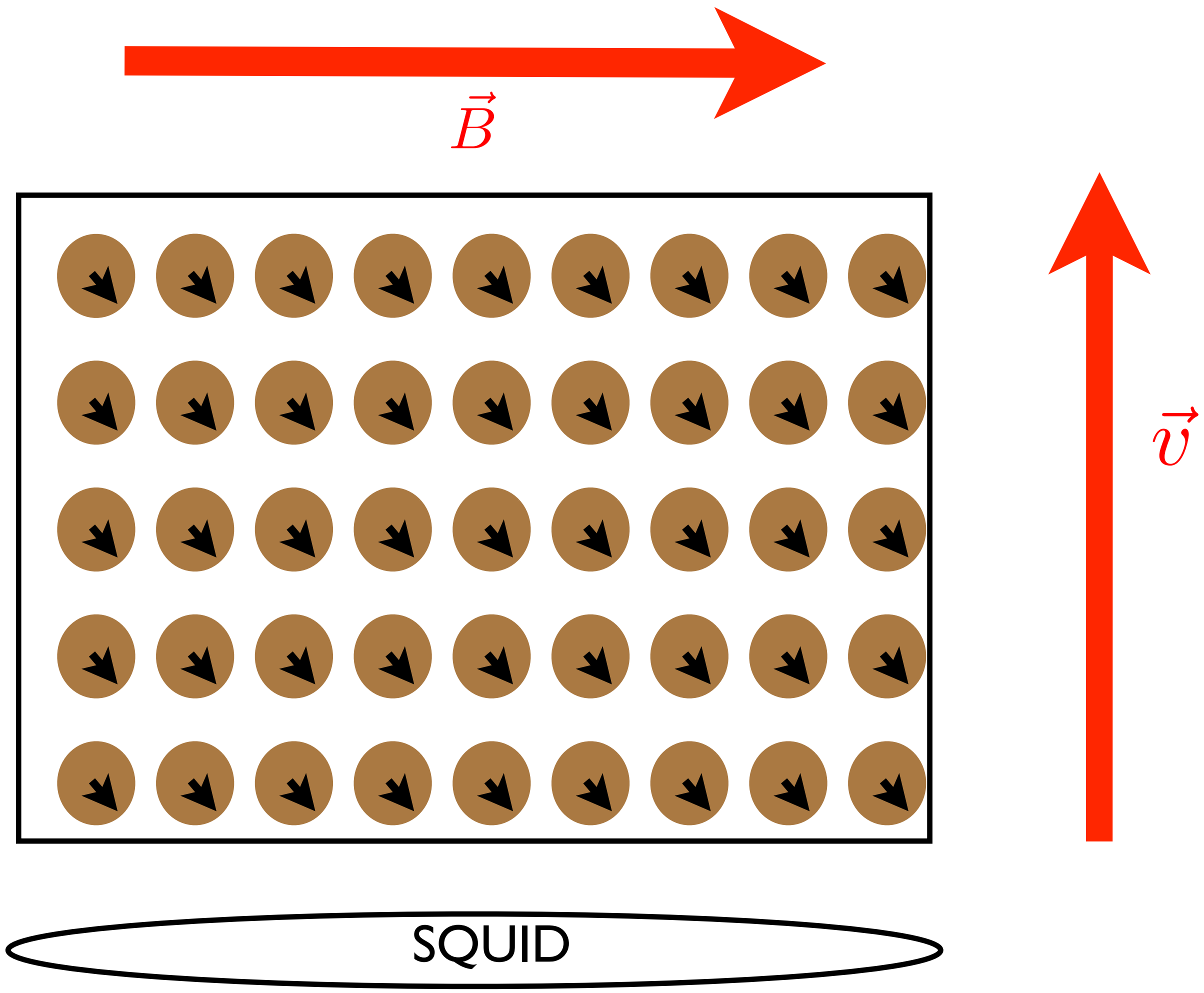


$$\delta B = 0.1 \frac{\text{fT}}{\sqrt{\text{Hz}}},\ n = \frac{10^{22}}{\text{cm}^3},\ V = 1000\ \text{cm}^3,\ T_2 = 1\ \text{s}$$

Another Operator

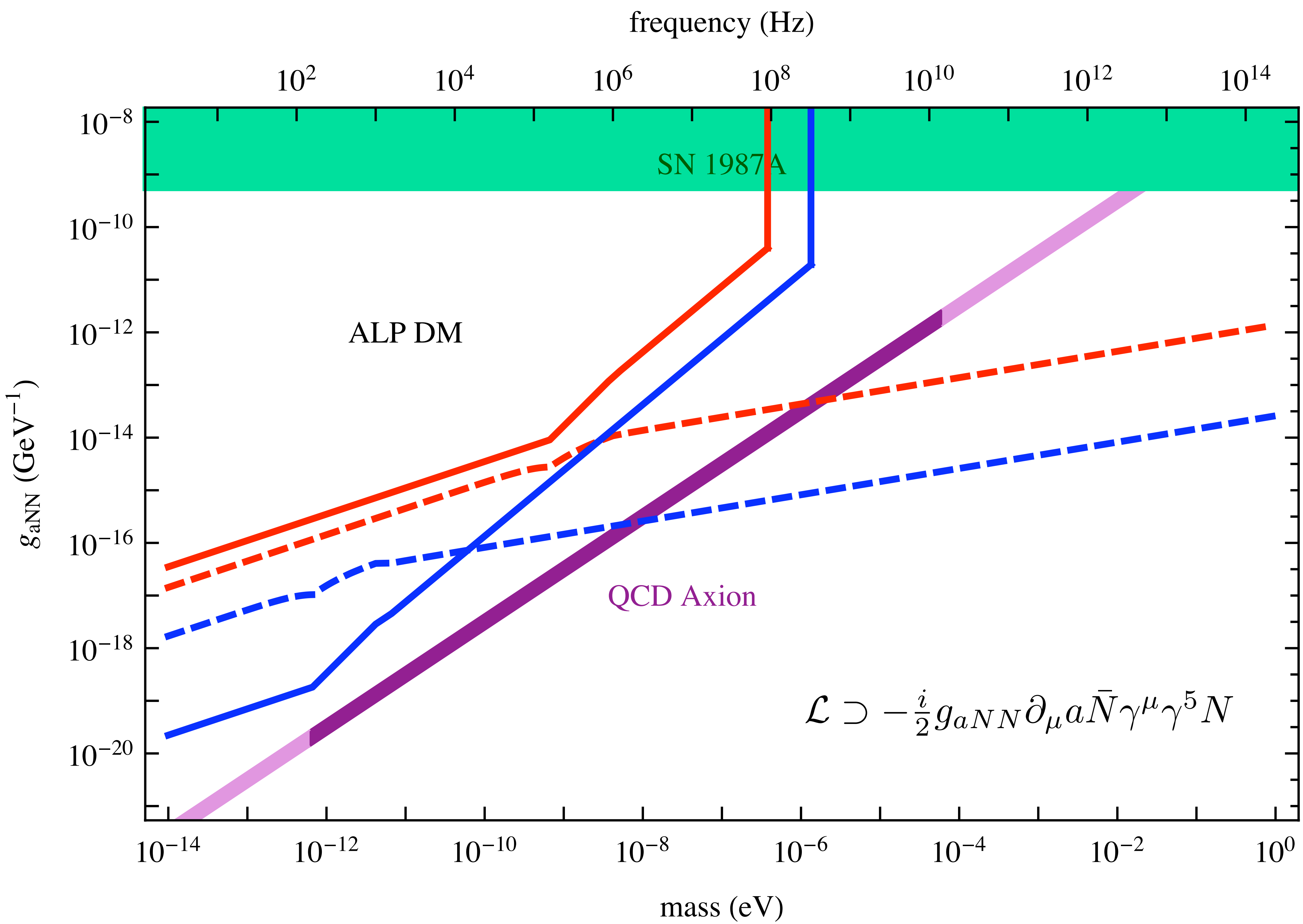
$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{\psi} \gamma^\mu \gamma_5 \psi$$

$$H \supset \frac{a}{f_a} m_a \vec{v}.\vec{S}$$

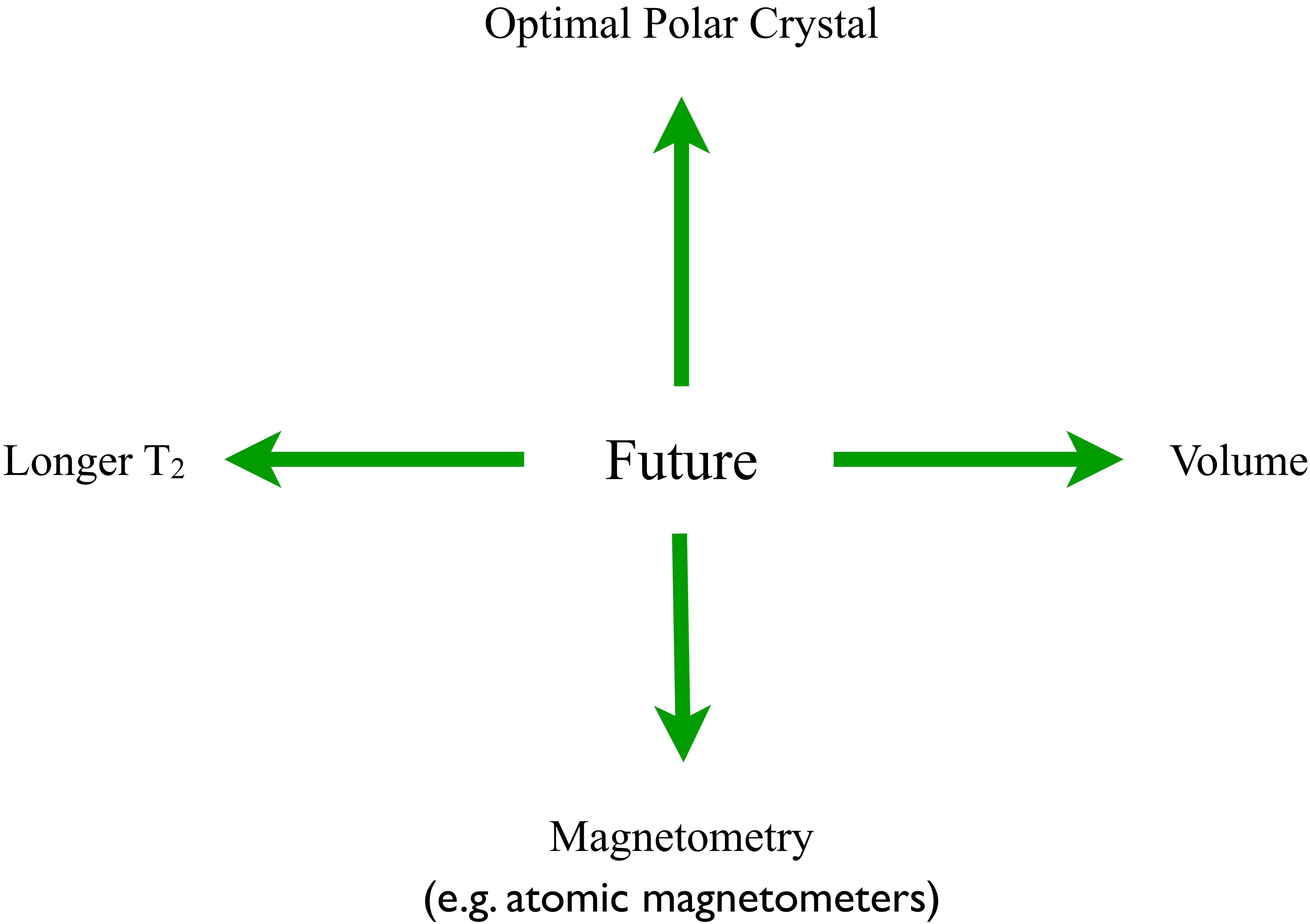


Can use Xe, He...

Projected Sensitivity



$$\delta B = 0.1 \frac{\text{fT}}{\sqrt{\text{Hz}}},\ n = \frac{10^{22}}{\text{cm}^3},\ V = 1000\ \text{cm}^3,\ T_2 = 1\ \text{s}$$


Optimal Polar Crystal
Longer T_2
Future
Volume
Magnetometry
(e.g. atomic magnetometers)

Conclusions

Morals

1. Model independent, non-derivative coupling. Phase measurement. Moderate scaling with f_a.

2. Signal $\propto \sqrt{\rho}$, can search for small component of dark matter.

3. A/C signal. Resonant boost. Noise amelioration.

4. Signal verification using dependence on electric field and spatial coherence of the axion. Help reject technical noise.

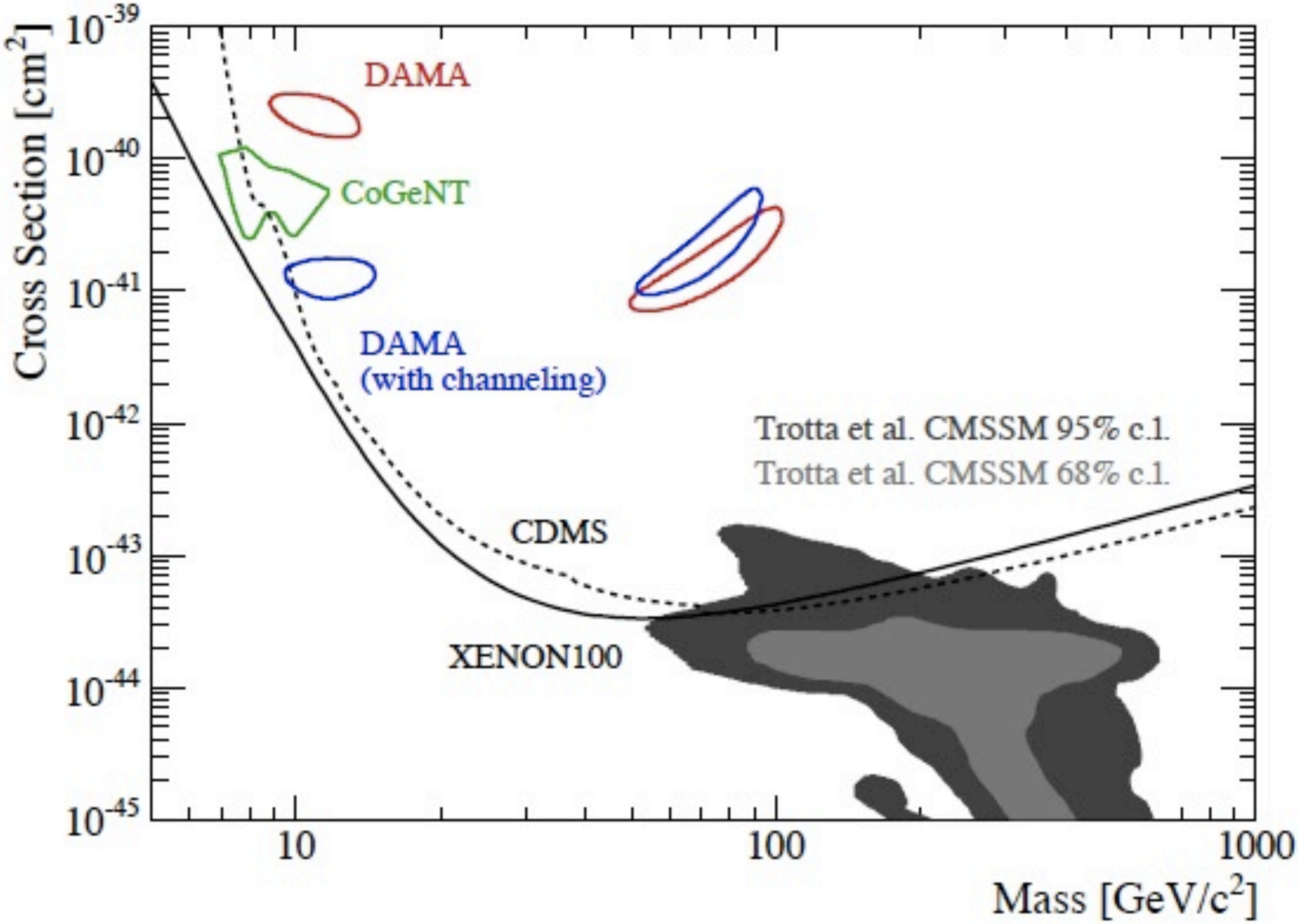
5. Scan over wide bandwidth by changing magnetic field.

6. Scalable. Complements solid state EDM efforts.

WIMP Detection

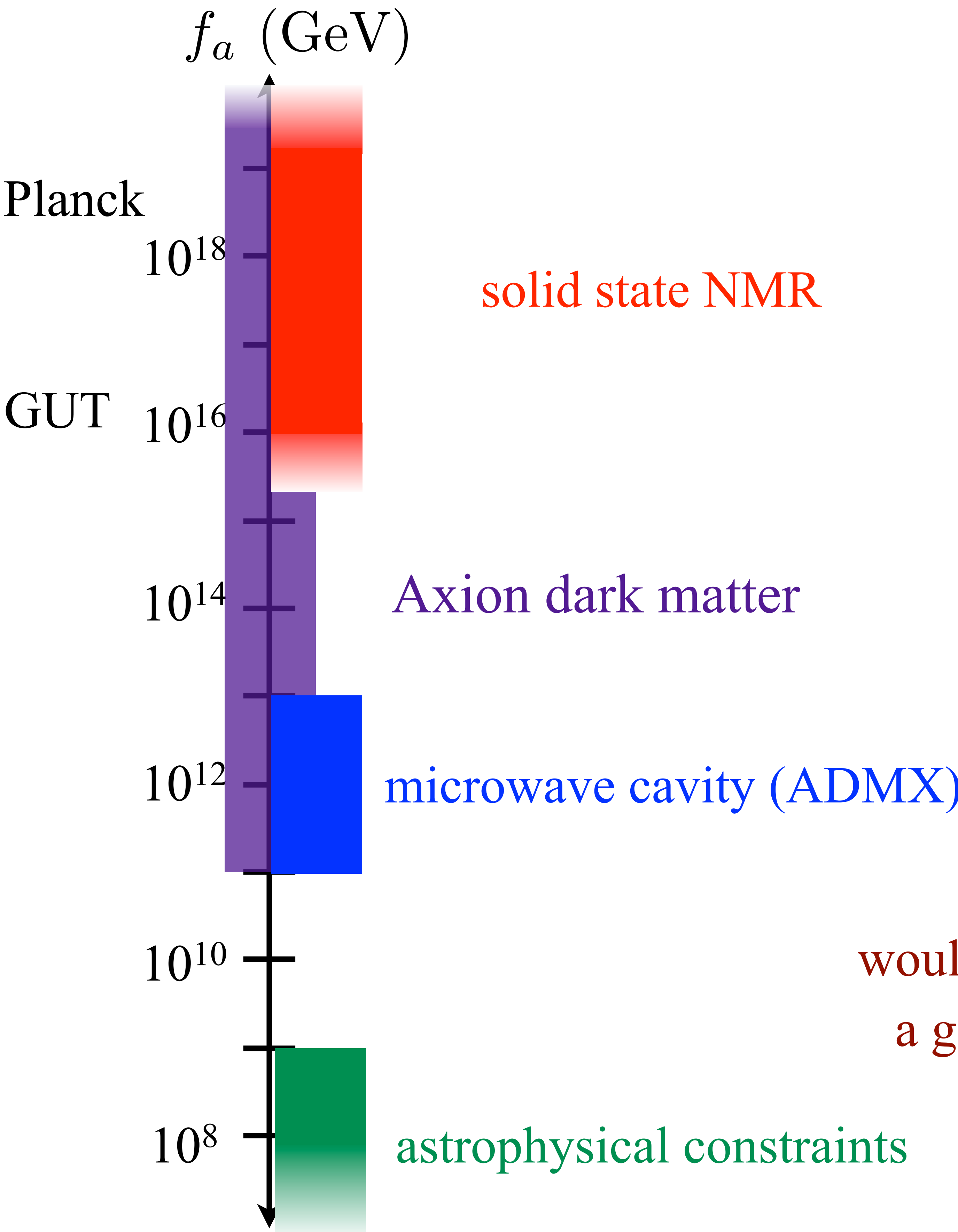
Goodman and Witten, 1985 : $\sigma_{\chi N} \sim 10^{-38}\ \mathrm{cm}^2$

Today



Axions deserve similar effort.

Solid State Axion Searches



can most easily search in kHz - MHz frequencies ➙ high f_a

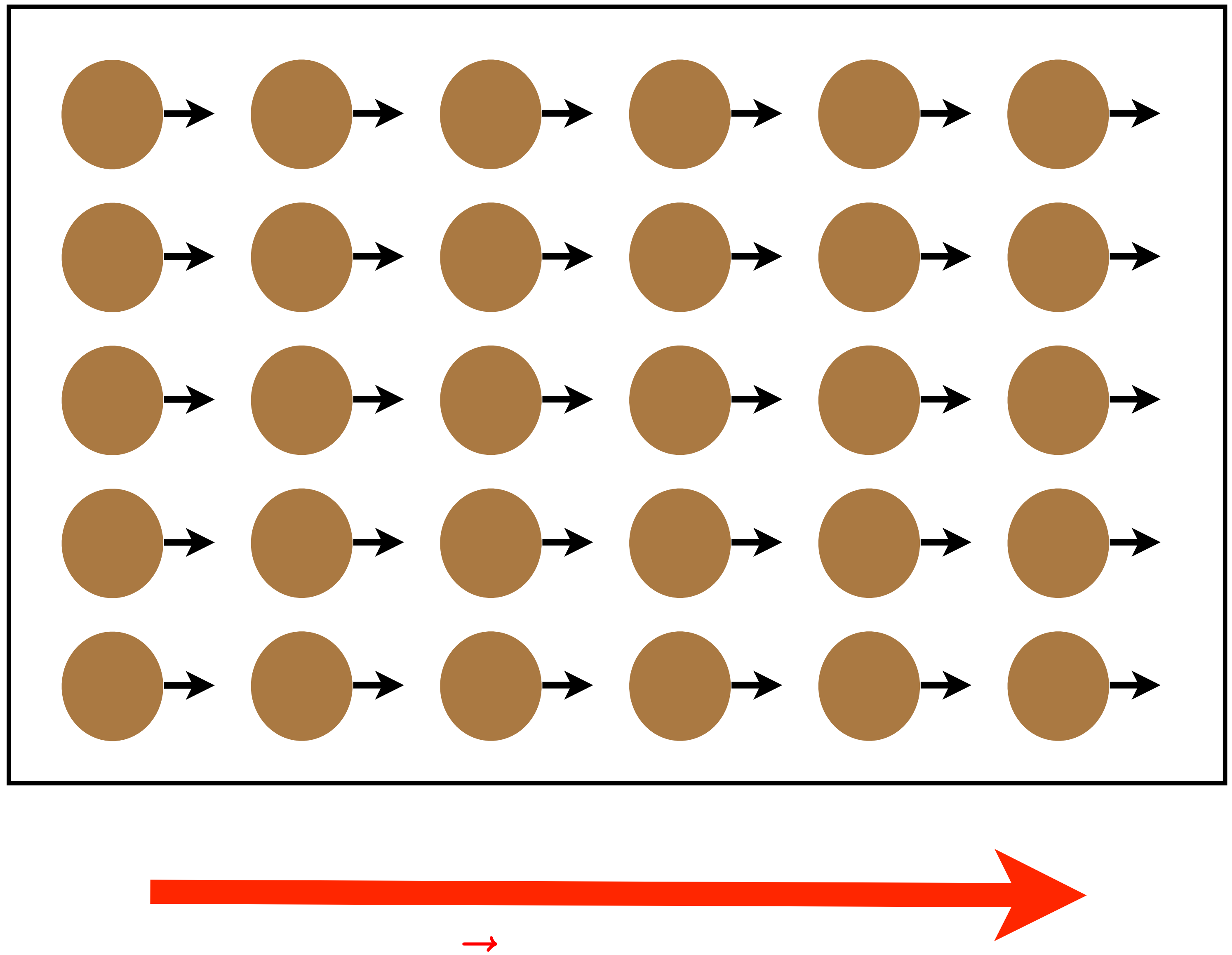
technological challenges, similar to early stages of WIMP detection

axion dark matter is very well-motivated, no other way to search for at high f_a

would be both the discovery of dark matter and a glimpse into physics at very high energies

Backup

Nuclear Polarization (p)

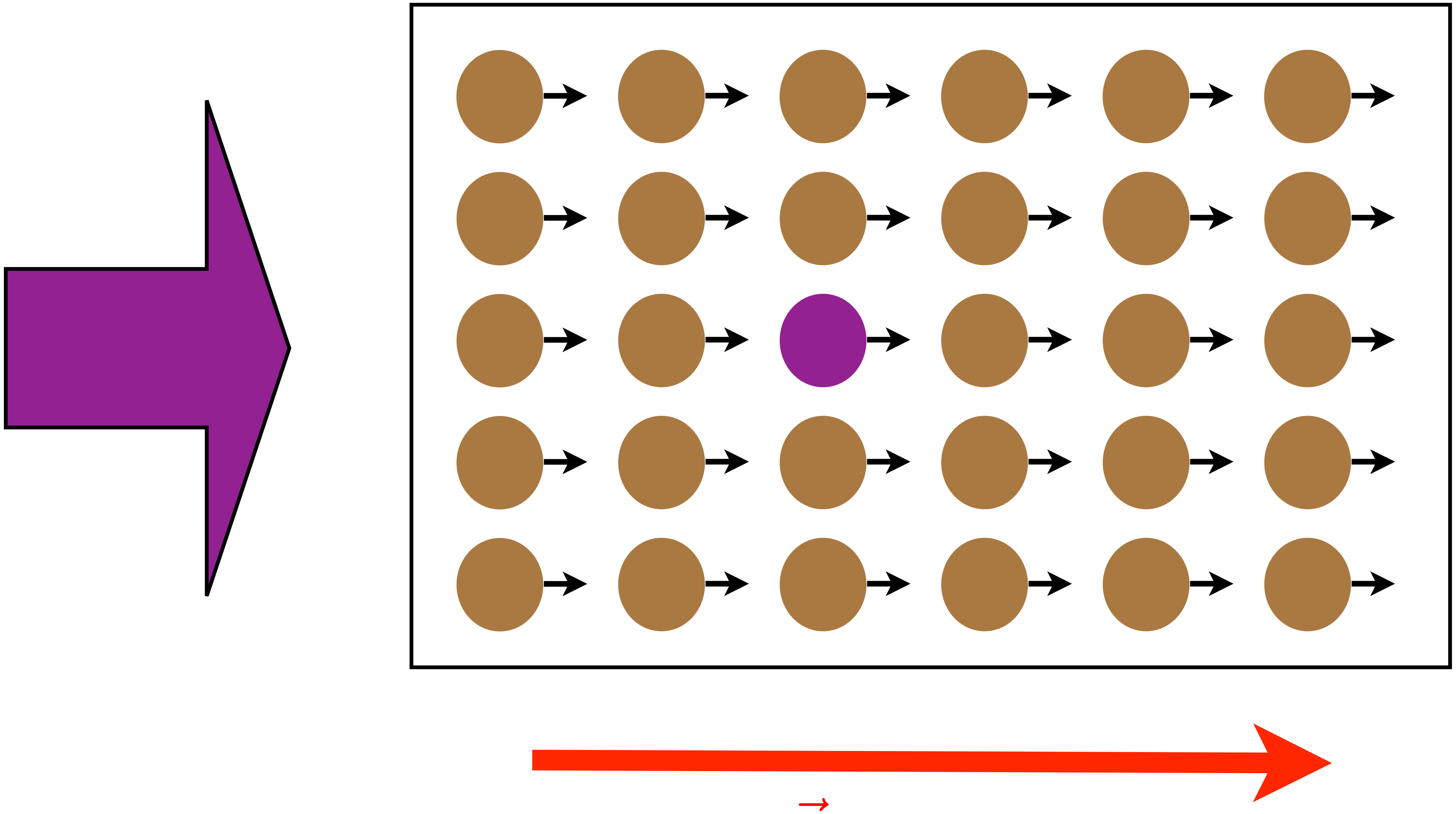


$\vec{B}_0 \sim 10$ T

$\theta_0 \sim 4$ K

$p \sim 10^{-3}$ in $T_1 \sim 3$ hrs

Optical Pumping



$$\vec{B}_0 \sim 10 \text{ T}$$

$$\theta_0 \sim 4 \text{ K}$$

Polarize impurity.

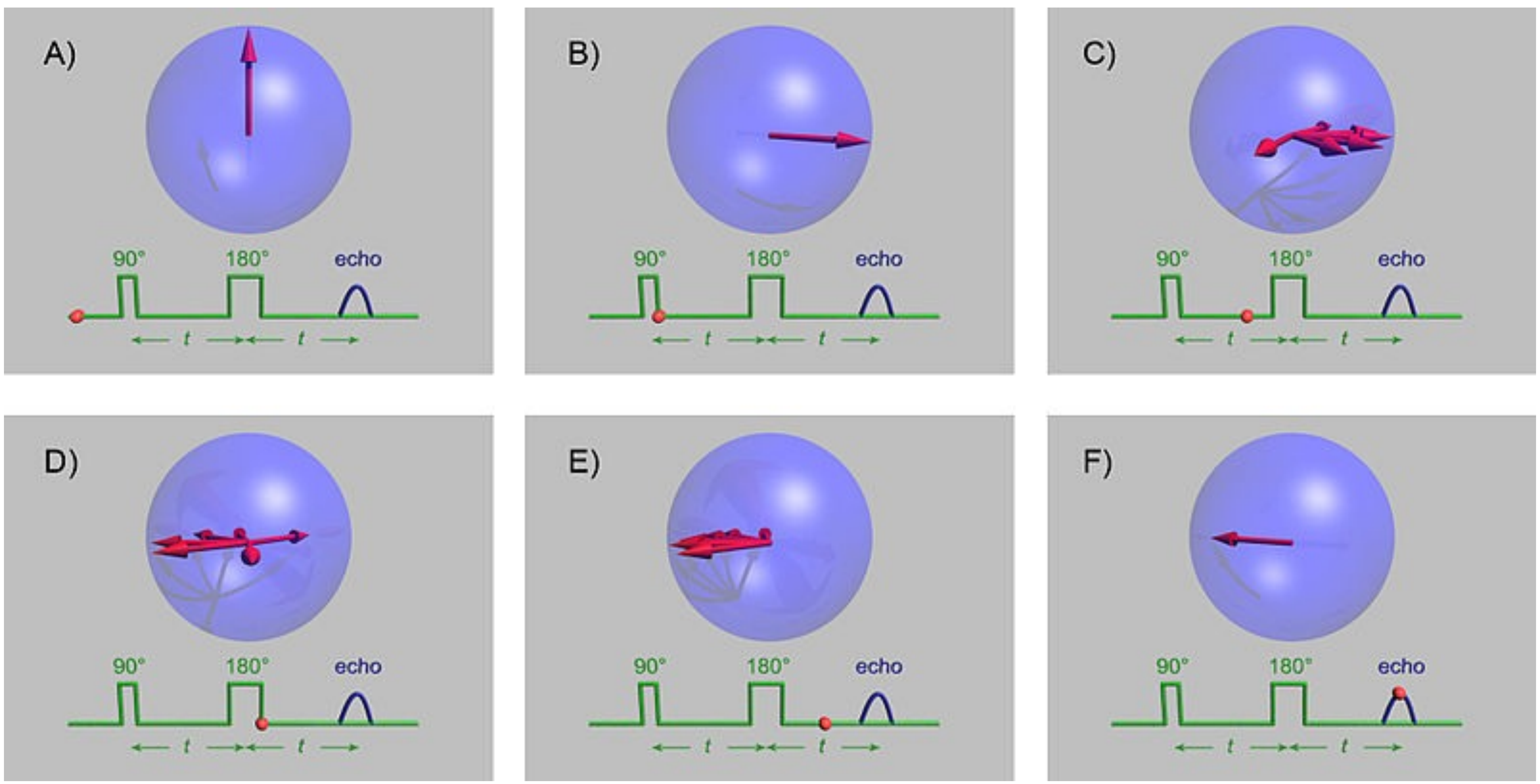
Transfer to nuclei through optical interactions.

Dynamic Decoupling

$$H\left(\vec{S}_i\right) = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \ldots$$

Refocus spins within T_2 through EM pulse sequences.

Hahn Echo



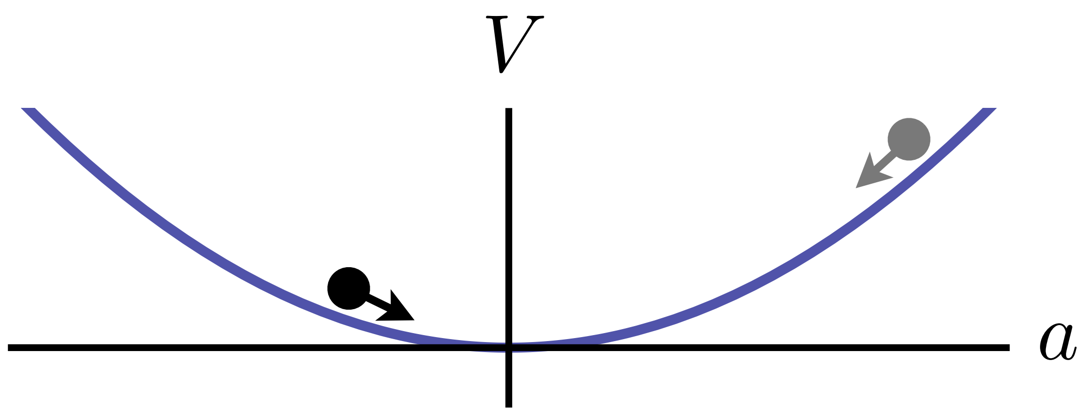
π rotation eliminates unknown but constant gradient.

Axion-like Particles (ALPs)

Broken global symmetry couples to Standard model through derivative interactions of the Goldstone boson.

Interactions: $\frac{\partial_\mu a}{f_a} \bar{\Psi} \gamma^\mu \gamma^5 \Psi, \; \frac{a}{f_a} F^{\mu\nu} \tilde{F}_{\mu\nu}$

Mass: m_a



$$a(t) \sim a_0 \cos(m_a t)$$

cosmic expansion reduces amplitude a_0

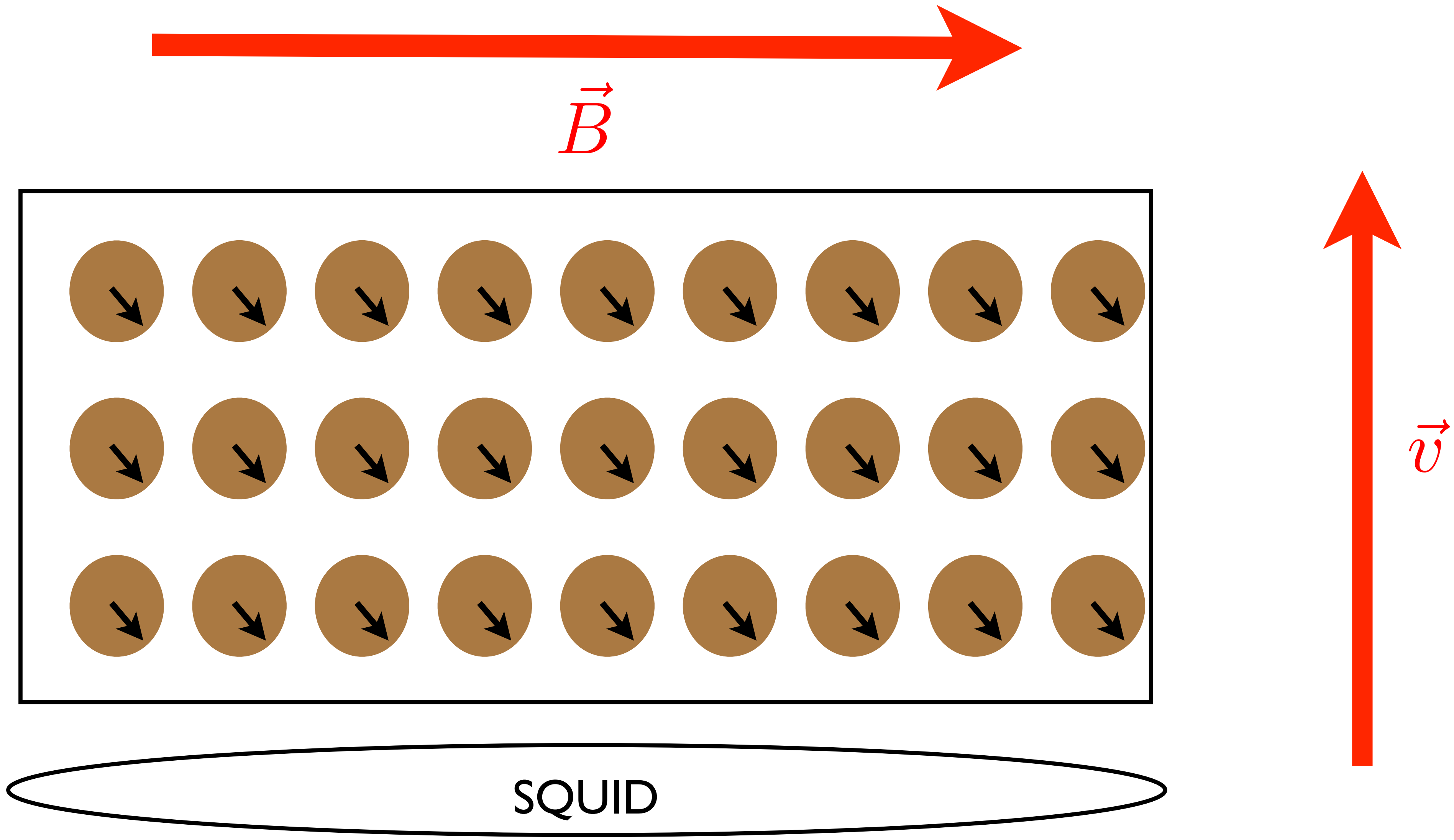
this field has momentum = 0 $\Rightarrow$ it is non-relativistic matter

Good cold dark matter candidate

Axion-like Particles

$$\mathcal{L} \supset \frac{\partial_\mu a}{f_a} \bar{N}\gamma^\mu\gamma^5 N \implies \frac{\langle a \rangle m_a}{f_a} \vec{v}.\vec{S_N}$$

Spin precession perpendicular to galactic dark matter wind.



Electric field/Schiff moment unimportant. Can use low Z.

Dynamic Decoupling

$$H\left(\vec{S}_i\right) = \alpha_0 + \alpha_1 t + \alpha_2 t^2 + \ldots$$

Refocus spins within T_2 through EM pulse sequences.

In principle, $T_2^{\text{eff}} \sim T_1 \sim$ hr

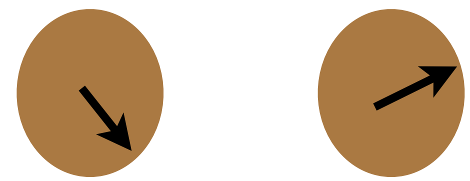
Demonstrated

(1) 40 s in ^{29}Si (Y. Dong et.al., PRL 100, 247601 (2008))

(2) 1300 s in Xe (M. Ledbetter and M. Romalis)

$$T_2^{\text{eff}} \sim 1 \text{ s}$$

Magnetization Noise
(Spin Projection)



$$M_n(\omega) \sim \frac{\mu_N}{r^3}\sqrt{nr^3}\langle S_{\rm rms}(\omega)\rangle \sim \mu_N\sqrt{\frac{n}{V}}\langle S_{\rm rms}(\omega)\rangle$$

$$\frac{dS}{dt} = -\frac{S}{T_2} + 2\mu_N B \times S$$

$$S^2_{\rm rms}(\omega) \approx \frac{1}{8}\left(\frac{T_2}{1+T_2^2(\omega-2\mu_N B)^2}\right)$$

M. Braun and J. Konig, PRB 75, 085310 (2007)