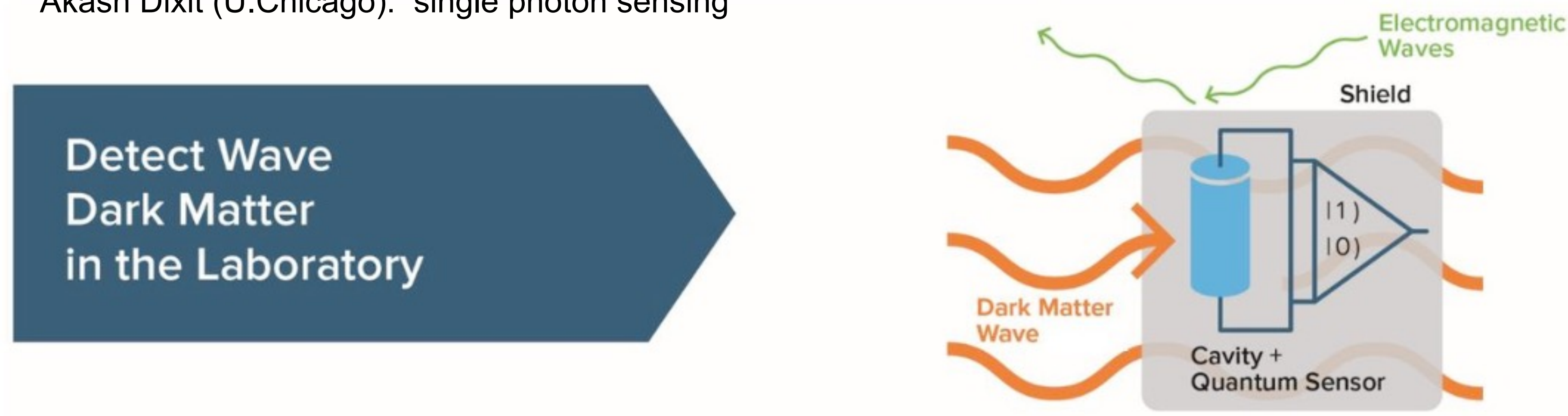
Clever Quantum Tricks for Detecting Dark Matter Waves

Aaron S. Chou (Fermilab)
QSFP School

Tutorials (repeated today and Thursday):
Chelsea Bartram (U.Washington): axion experimental techniques
Samantha Lewis (Fermilab): axions and microwave cavities
Akash Dixit (U.Chicago): single photon sensing



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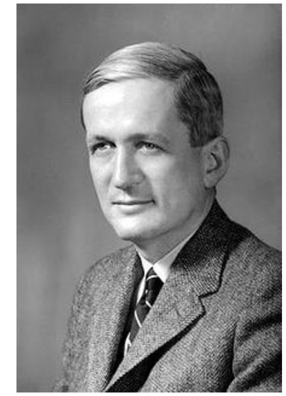
Plan for lectures

(30 minutes each)

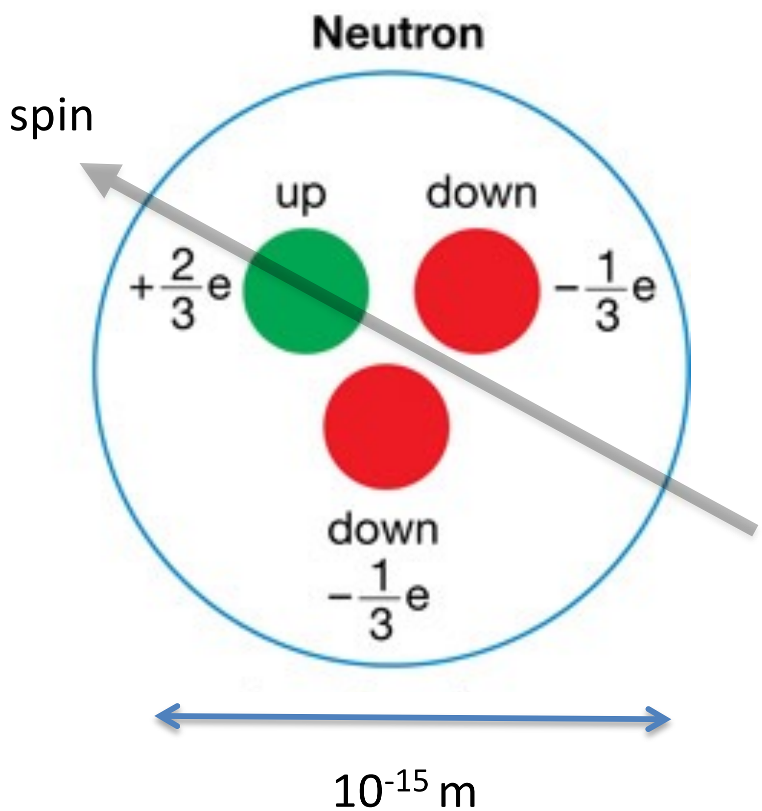
- Dark matter waves, the strong-CP problem and axions
- Axion haloscopes and the Standard Quantum Limit on noise
- Quantum optics and quantum non-demolition measurements
- Stimulated emission using non-classical state preparation
- Single photon detection and Micro-calorimetry

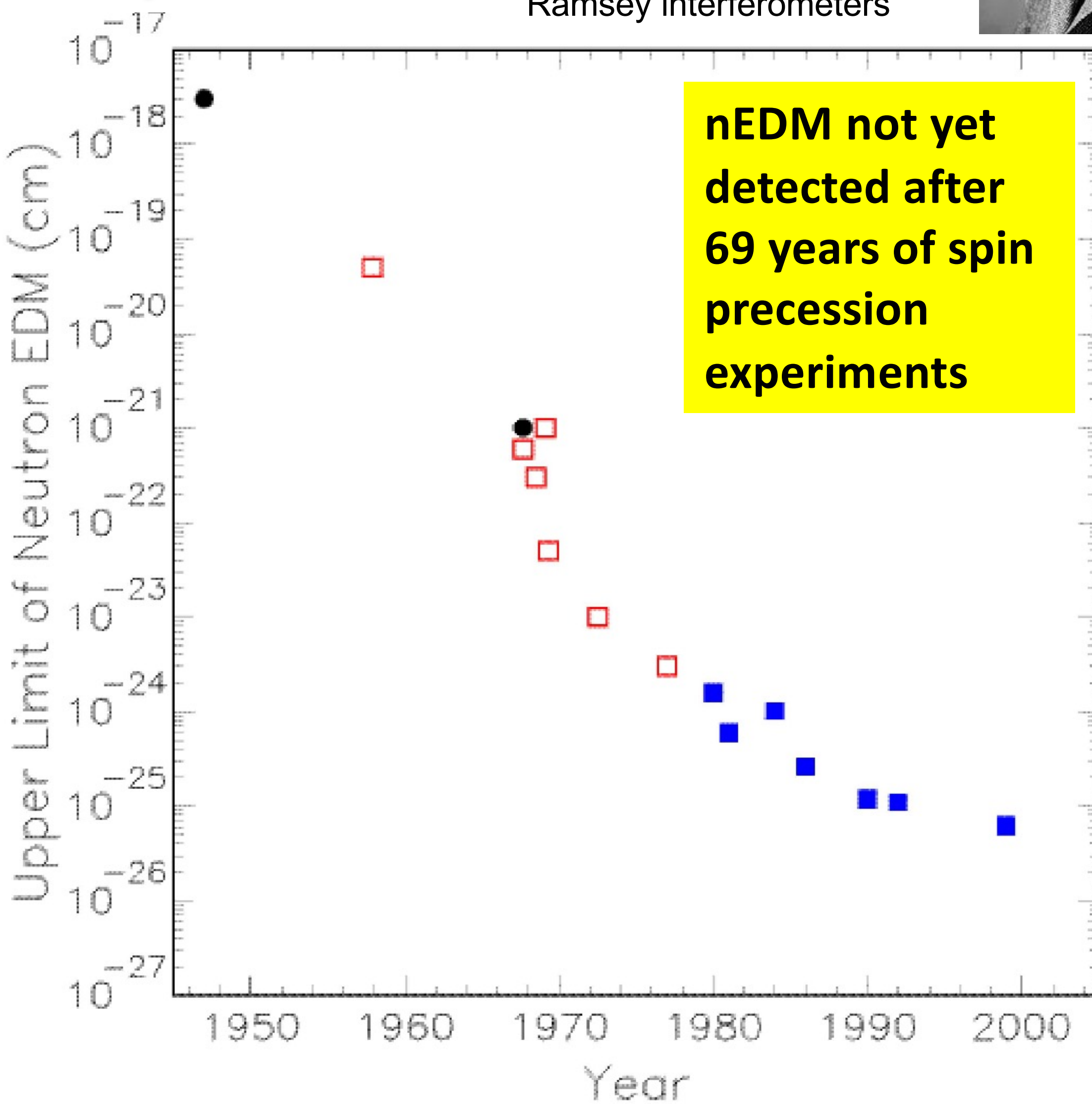
QCD axion motivated by the Strong-CP Problem:
Why is the neutron electric dipole moment so small?

Norman Ramsey
Nobel Prize 1989.
Neutrino oscillation expts are
"Ramsey interferometers"



Naive estimate gives
nEDM ≈ 10^{-16} e-cm





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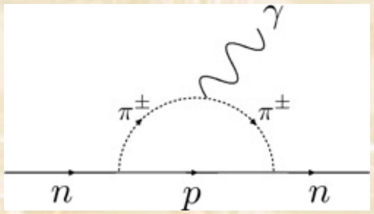
The CP Problem of Strong Interactions



Characterizes degenerate QCD ground state (Θ vacuum)

Phase of Quark Mass Matrix

Standard QCD Lagrangian contains a CP violating term

$$L_{CP} = -\frac{\alpha_s}{8\pi}\underbrace{(\Theta - \arg\det M_q)}_{0\le\overline{\Theta}\le 2\pi}\,\mathrm{Tr}\,\tilde{G}_{\mu\nu}G^{\mu\nu}$$

Induces a neutron electric dipole moment (EDM) much in excess of experimental limits

$$d_n \approx \overline{\Theta}\,10^{-16}\,e\,cm \approx \frac{\overline{\Theta}}{10^2}\mu_n < 3\times 10^{-26}\,e\,cm$$

$\overline{\Theta} \lesssim 10^{-10}$ **Why so small?**

Slide from G. Raffelt

The 1977 Peccei-Quinn solution to the strong-CP problem

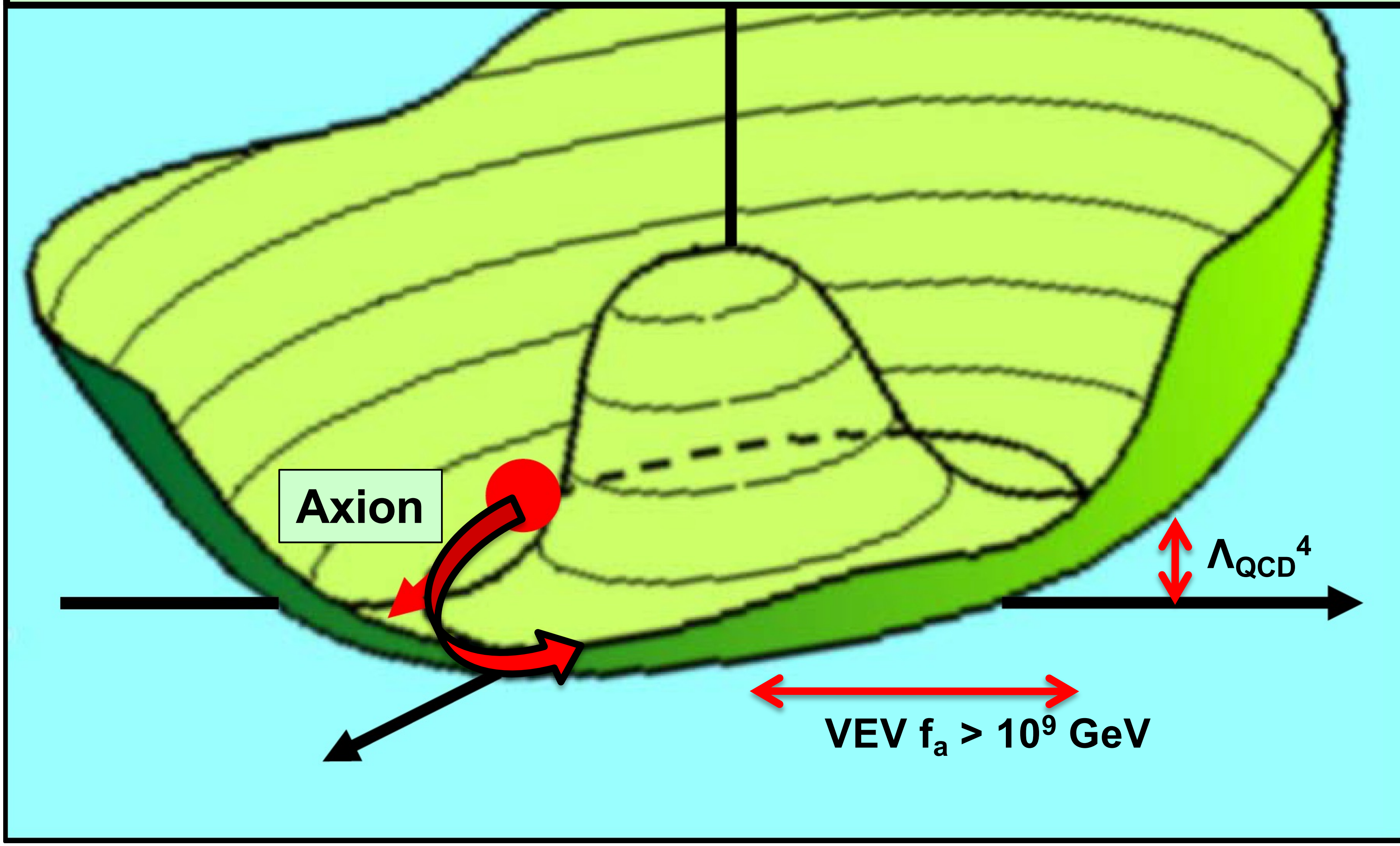
Dirac Medal (2000)

- Promote theta to become a new **dynamical** scalar field which has a two-gluon coupling. (dynamical = can vary in space and time)

- Think like an electrical engineer: Use this field in a cosmological feedback loop to dynamically zero out any pre-existing CP-violating phase angles.

Natural potential energy function

$$V(A) = -f_a^2 A^2 + \frac{\lambda}{4!} A^4 + \left(\frac{g^2}{32\pi^2} \arg(A) - \frac{\alpha_s}{8\pi} \left(\theta_{QCD} + \theta_{quark} \right) \right) \langle G\tilde{G} \rangle$$



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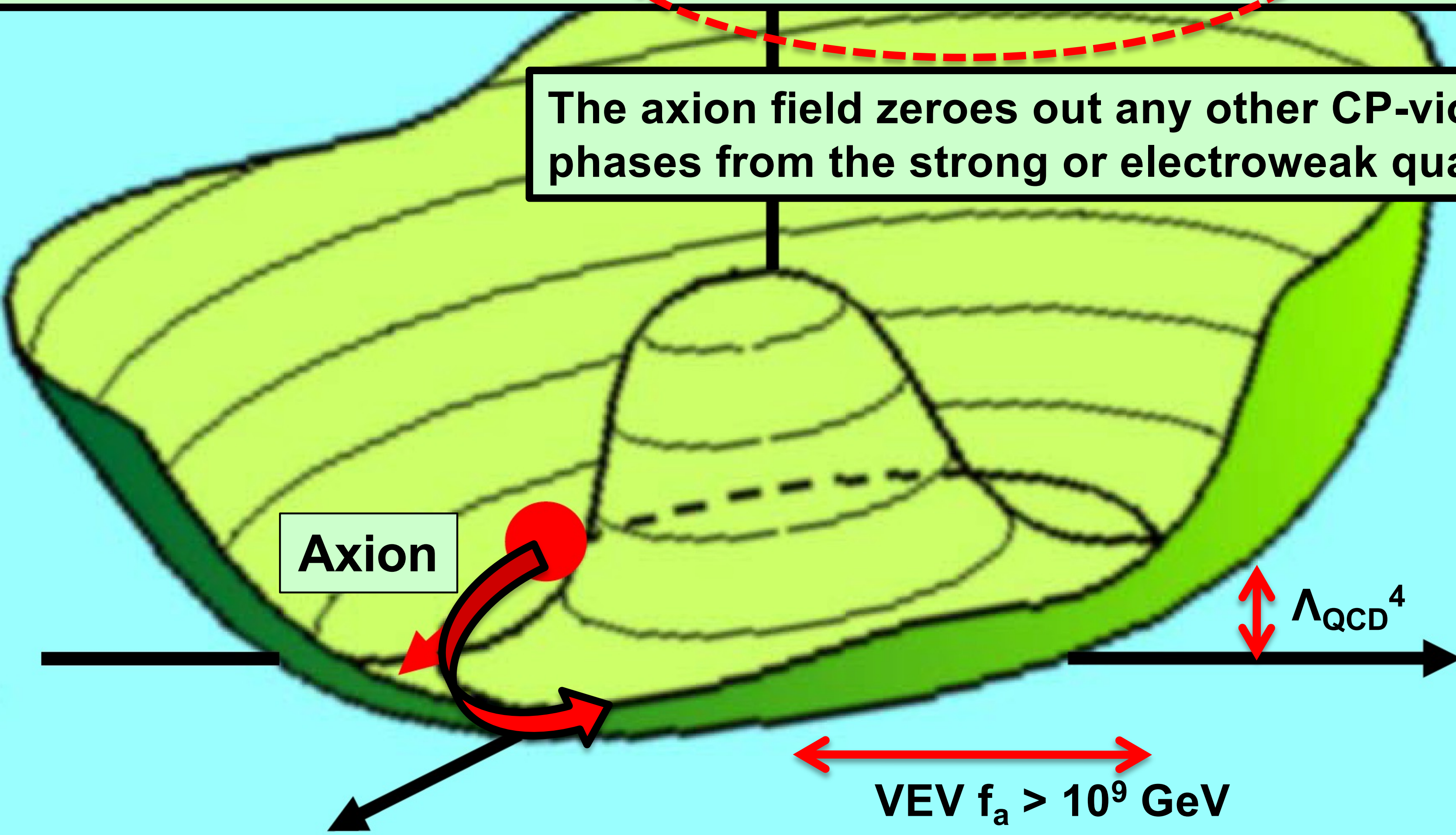
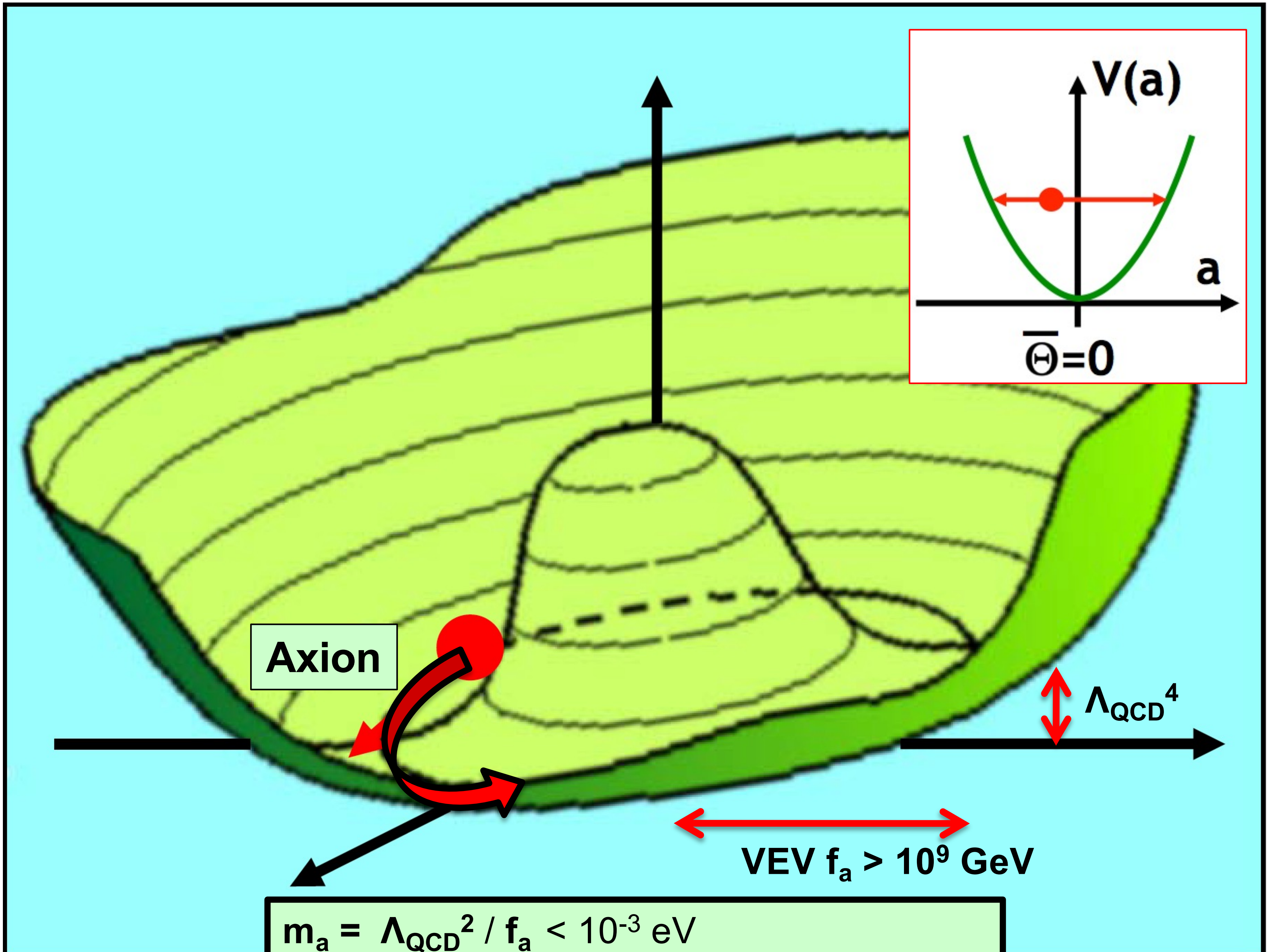
The axion field zeroes out any other CP-violating phases from the strong or electroweak quark sector.



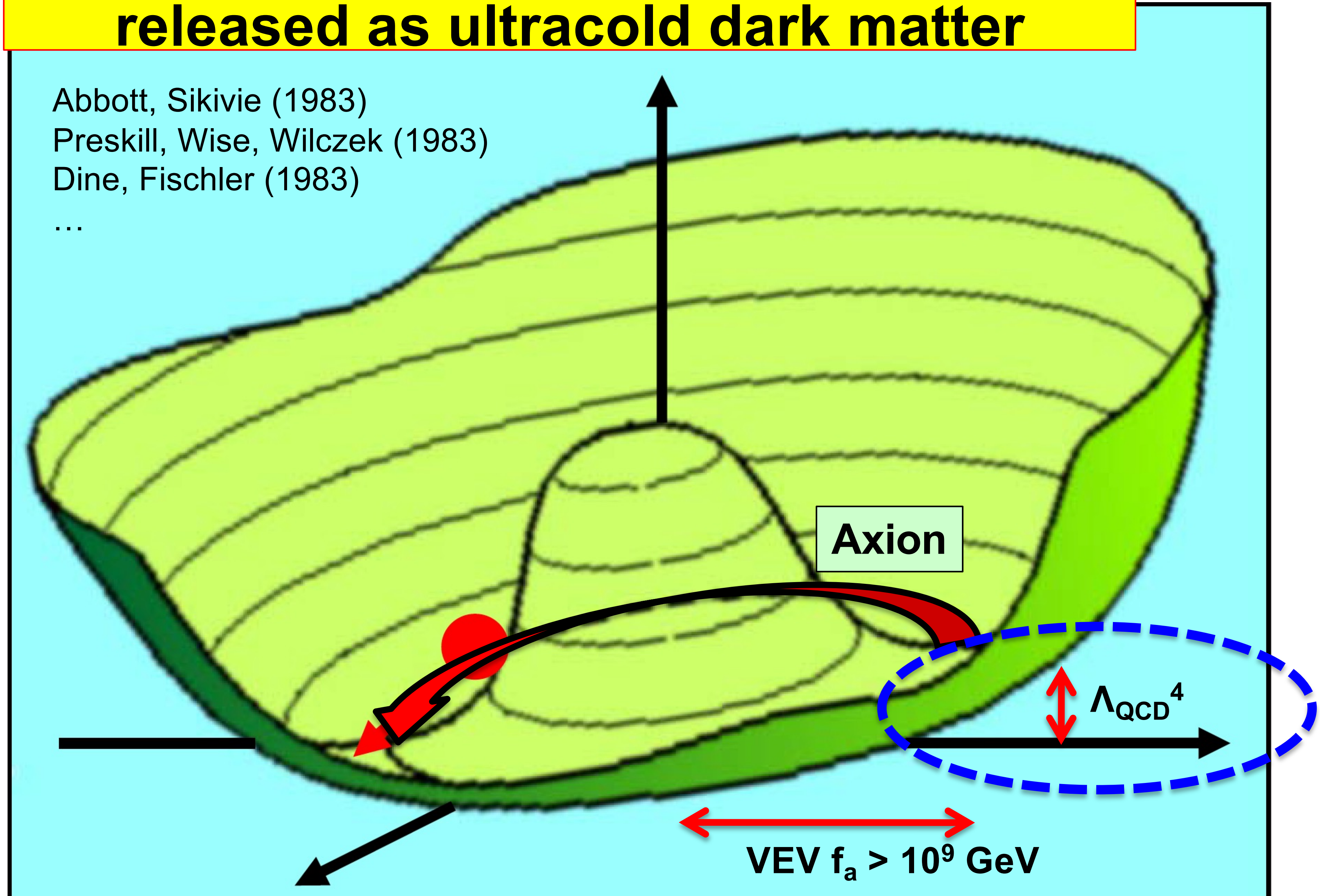
The neutron EDM vanishes, solving the **strong CP fine-tuning problem**.

Axion mass = harmonic oscillator frequency



$m_a = \Lambda_{QCD}{}^2 / f_a < 10^{-3}$ eV
Single parameter model for axions

The initial potential energy density is released as ultracold dark matter



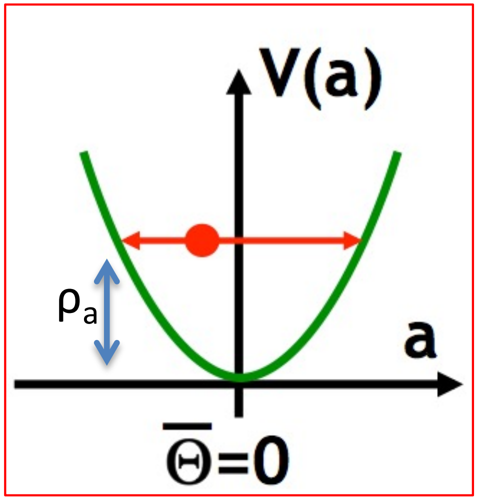
The initial azimuthal angle $\boldsymbol{\theta_0}$, determines the available potential energy to be released. **$O(1)\times\Lambda_{QCD}^4$** of potential energy density is converted into **dark matter**.

Axion dark matter = waves of oscillating θ_{CP}

Locally coherent oscillation of the QCD θ angle about its CP-conserving minimum:

$$\theta(x,t) = \theta_{\max} e^{i(kx - m_a t)}$$

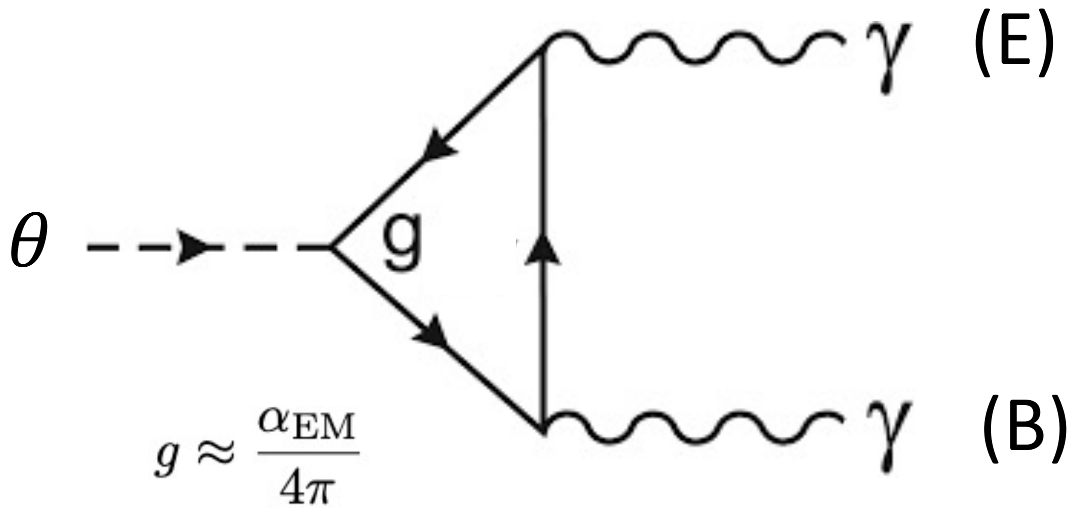
where $\theta_{\max} = \sqrt{\frac{2\rho_a}{\Lambda^4_{\mathrm{QCD}}}} \approx 3.7 \times 10^{-19} \mathrm{radians}$



DM oscillations partially undo the Peccei-Quinn mechanism by enabling the coherent field to climb out of the potential minimum. **Signal strength depends only on local dark matter density, and is independent of DM mass and phase transition scale f_a**

Phenomenology based on a classically oscillating CP-violating angle which:

- **Rotates B-fields into E-fields**
- **Creates AC nucleon EDMs**
- **Creates AC torques on fermion spins**



Bucket of dark matter is dumped into the red-shifting photon bath at time $1/H \approx 1/m_a$

Non-DM density redshifting away →

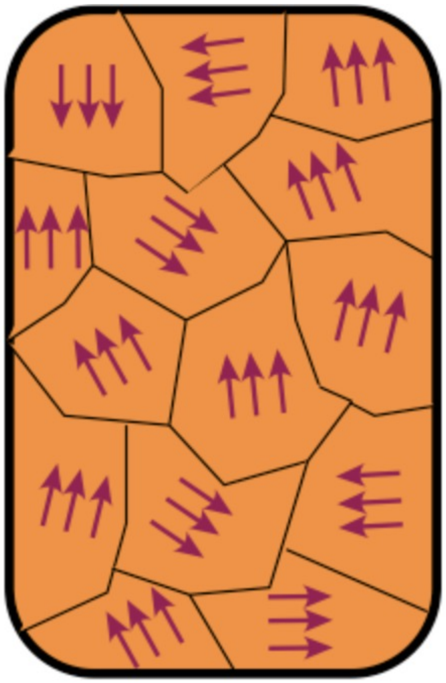
Global warming

For a bucket filled to the level **$\langle \sin^2 \theta_0 \rangle \times \chi$** of fish,
dumping it too late creates an improper balance of fish/water.

If you are going to procrastinate and dump it late, you better not have too many fish in that bucket since there is not a lot of water left!

→ **Small m_a requires small $\langle \sin^2 \theta_0 \rangle$ to avoid overproducing dark matter.**

Fullness of bucket depends on whether the axion phase transition happens before or after cosmic inflation



Ferromagnetic spin domains

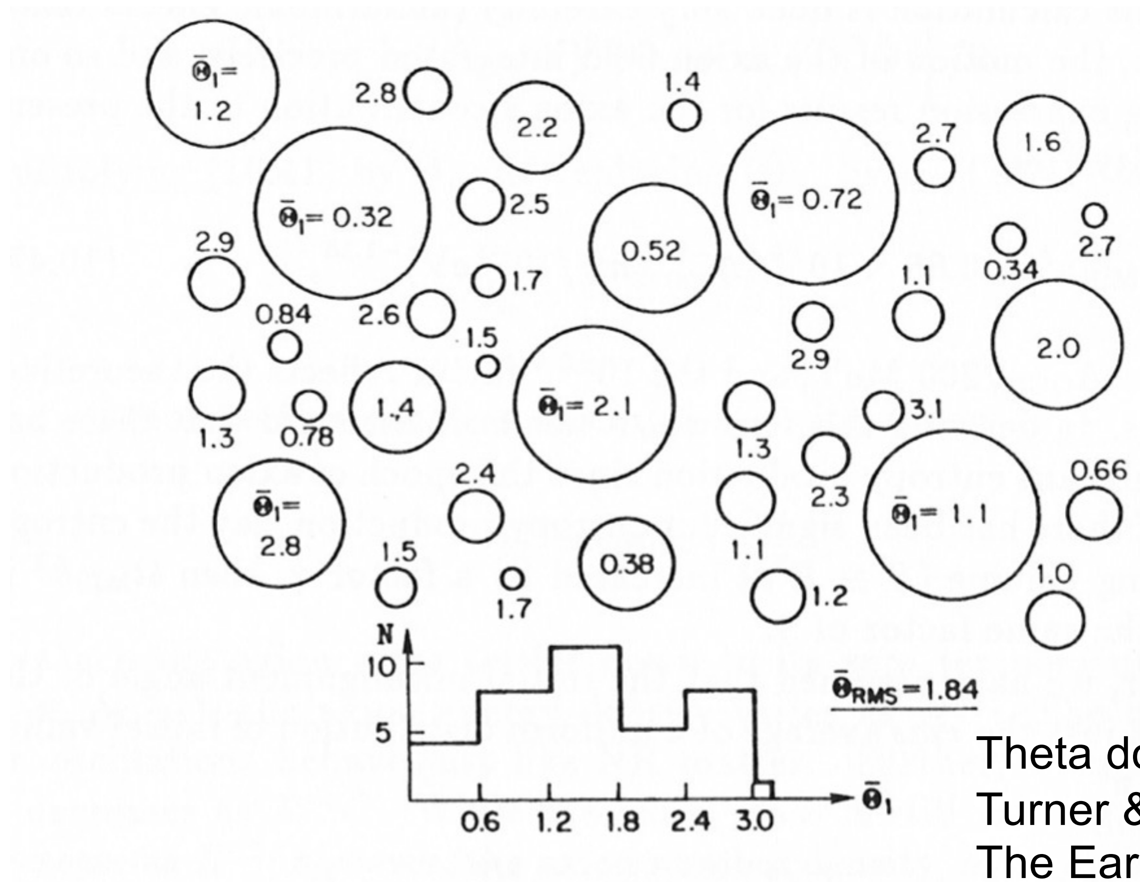
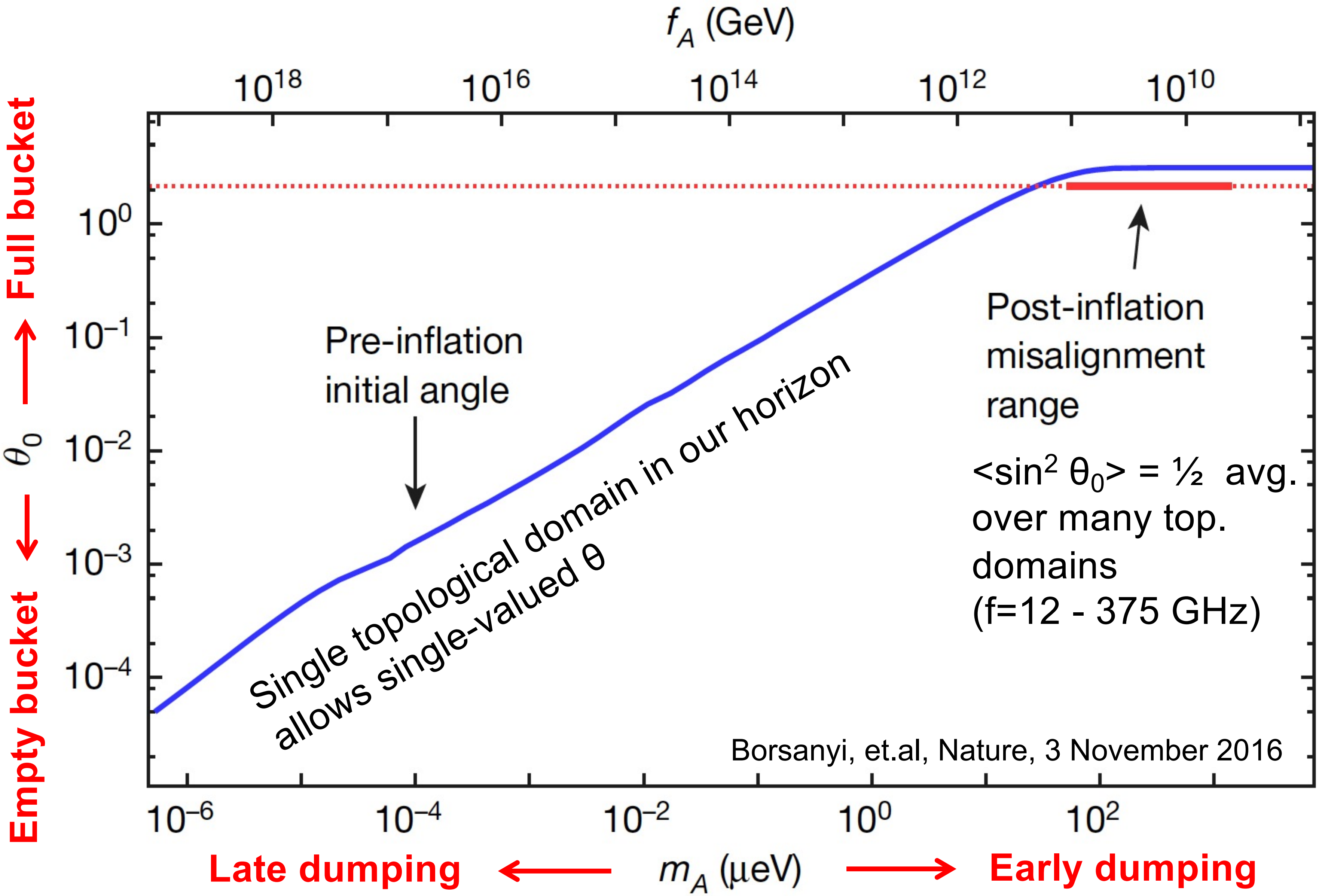


Fig. 10.9: Distribution of $|\bar{\Theta}_1|$ in an inflationary Universe.

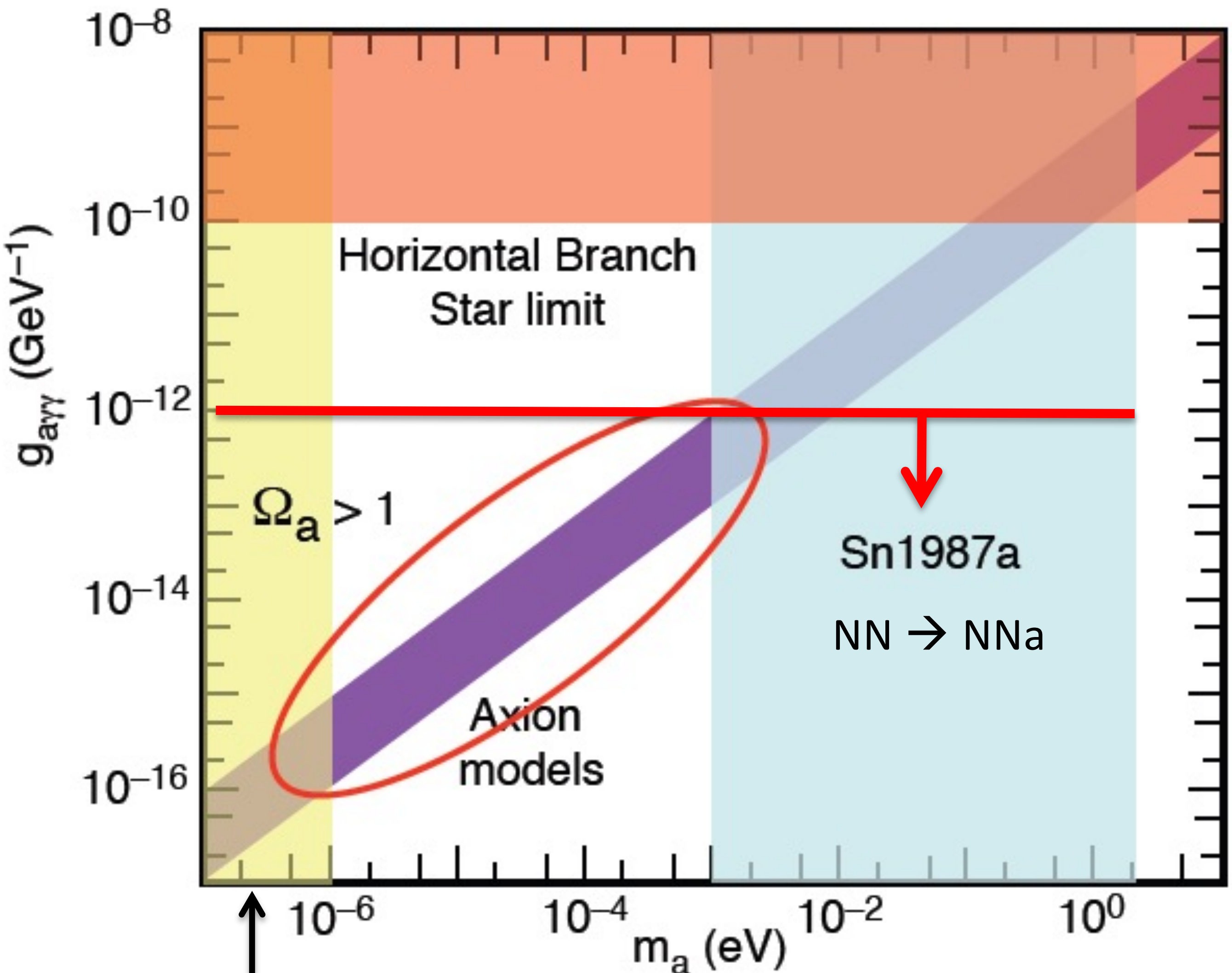
Theta domains,
Turner & Kolb
The Early Universe

- If axion phase transition occurs **pre-inflation**, bubbles are inflated, and we live in a single bubble which by chance can have θ<1.
- If axion phase transition occurs **post-inflation**, many bubbles are contained within our horizon, and so we get average value $\langle \sin^2\theta \rangle \times \Lambda_{QCD}^4$ of dark matter.

New lattice result gives dividing line at $m_a \approx 50$ μeV between pre- vs post-inflationary axion phase transition



The classic axion window



$$\Omega_a \approx \left(\frac{6\,\mu\text{eV}}{m_a}\right)^{\frac{7}{6}}$$

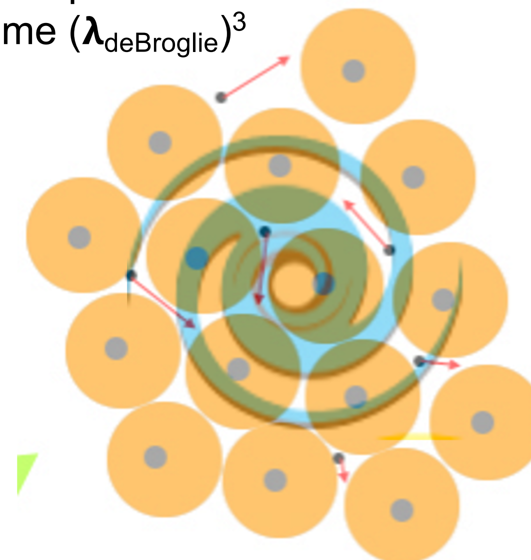
or even more due to cosmic string decay.

PQ model + local energy conservation **guarantees** the existence
of dark matter axions in the last place we haven't looked!

Disfavored by "naturalness." Requires small initial θ to avoid DM overproduction.

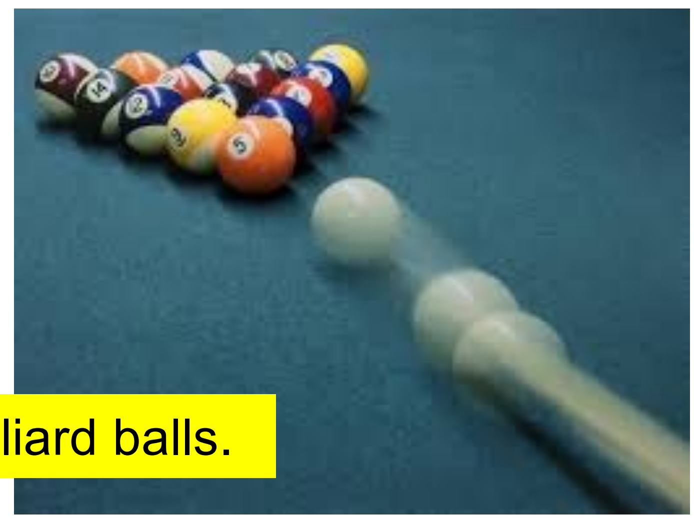
Low mass dark matter generically takes the form of classical bosonic sine waves

Fermions: 1 DM particle per mode volume ($\lambda_{deBroglie}$)^3



For **mass < 70 eV**, Pauli exclusion principle causes dark matter clumps to swell up to be larger than the size of the smallest dwarf galaxies. (Randall, Scholtz, Unwin 2017)

→ If lower mass, dark matter must be coherent bosonic sine waves with **macroscopic mode occupation number >>1**



Not billiard balls.

Need coherent wave detector.

Ultracold low mass dark = classical wave

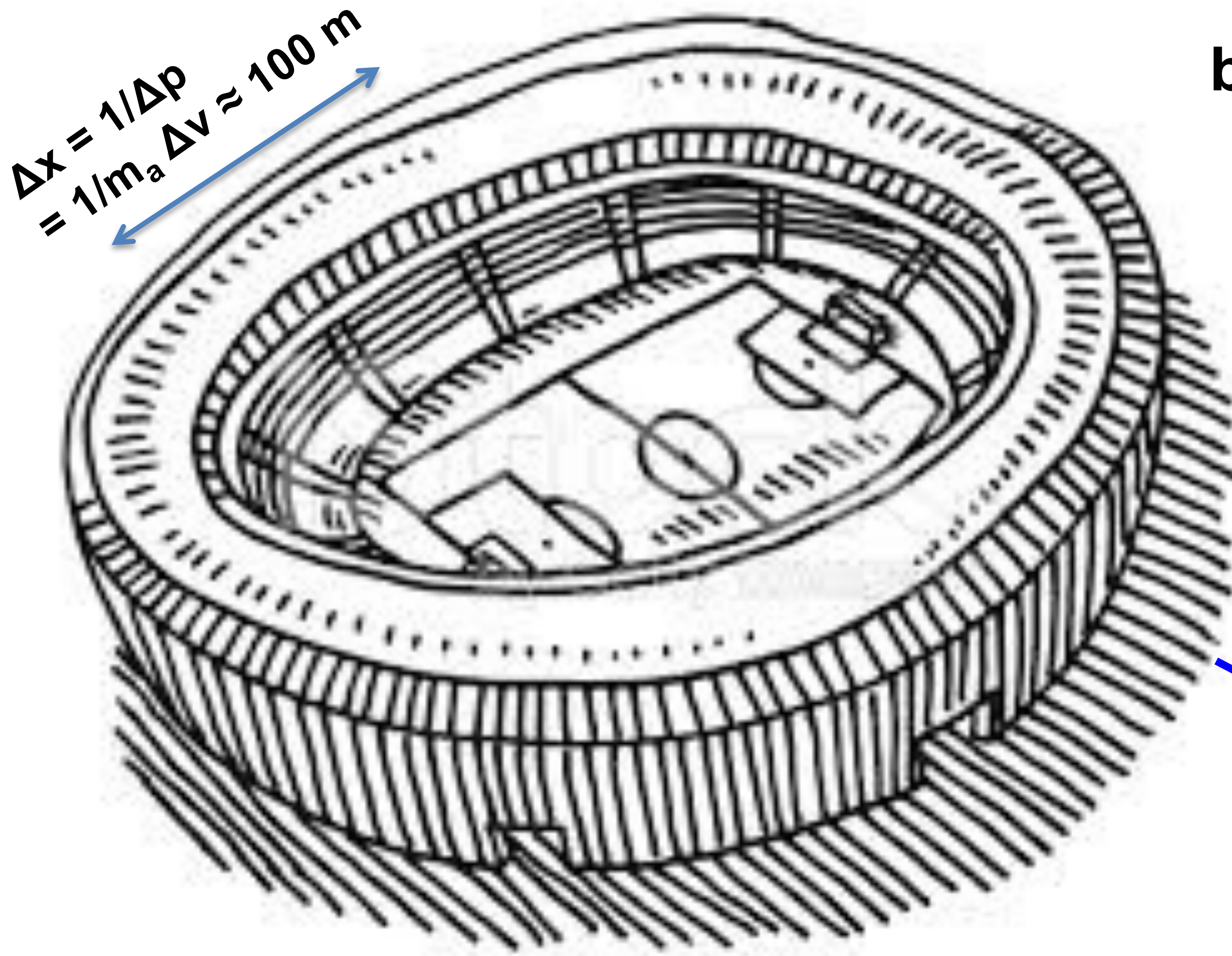
Described by a **Glauber** coherent state with properties similar to a modern laser.

Huge number density 10^{14}/cc,
Linewidth ≈ kHz

$$a \approx \frac{\sqrt{2\rho_a}}{m_a} e^{i(\vec{k}\cdot\vec{x} - m_a t + \phi)}$$

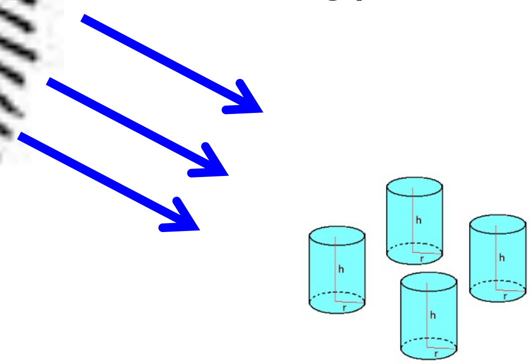
$$|\vec{A}| \approx \frac{\sqrt{Z_0 P_{\text{laser}}/\text{Area}}}{\omega} e^{i(\vec{k}\cdot\vec{x} - \omega t + \phi)}$$

e.g. 10^{-5} eV = GHz dark matter



Non-relativistic bosonic DM is like a slow CW laser with $f=m_a/2\pi$

$v \approx \Delta v \approx 300$ km/s (galactic escape velocity)



Football stadium-sized regions of coherently oscillating **classical sine waves** slowly drifting through detectors. Mean DM occupation number **$N>10^{22}$ per mode.**

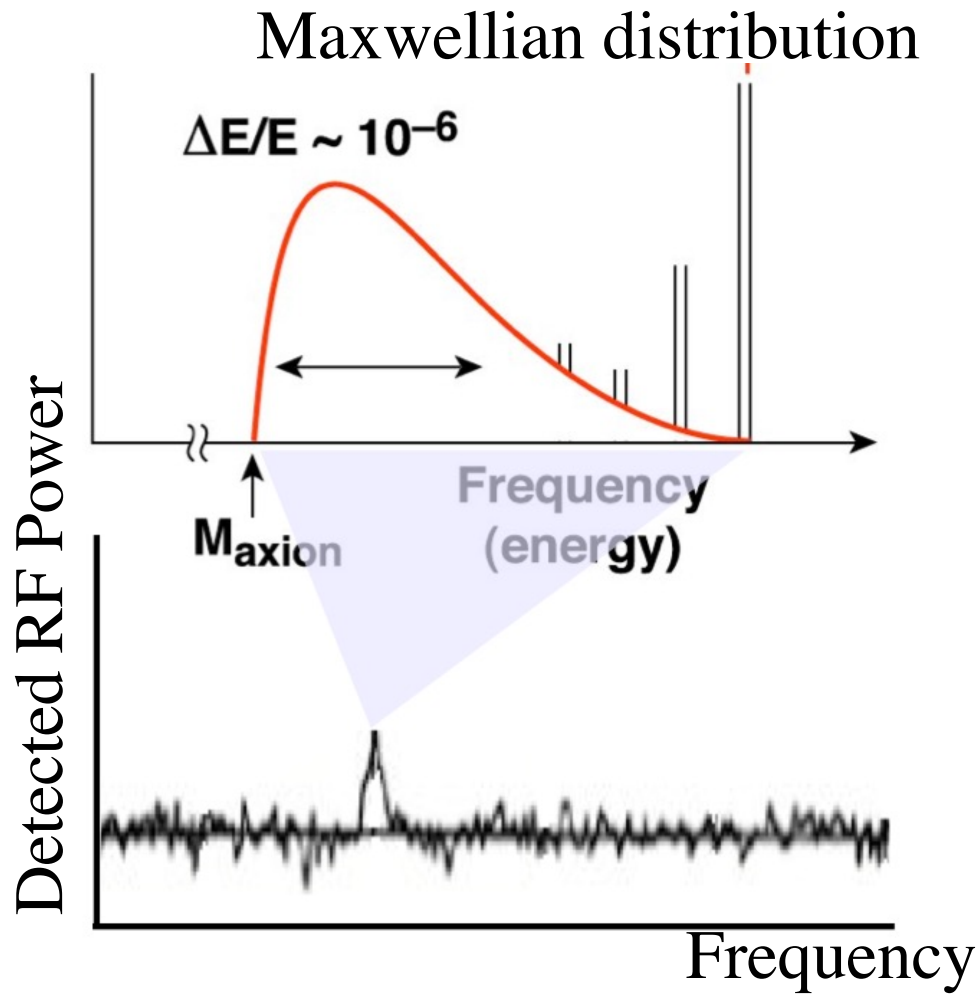
Accumulate oscillatory signals in various kinds of laboratory oscillators which are weakly coupled to the DM wave

Axion energy is kinetically broadened by virial velocity

Non-relativistic DM:
$v \sim \Delta v \sim 10^{-3}$ c
(galactic escape velocity)

Kinetic energy = $\frac{1}{2} m_a v^2$
$\Delta E = m_a v \Delta v$
$E_{rest} = m_a c^2$

$\Delta E/E = v \Delta v / c^2 \sim 10^{-6}$



Very narrowband line, but can reconfirm signal in minutes once found.

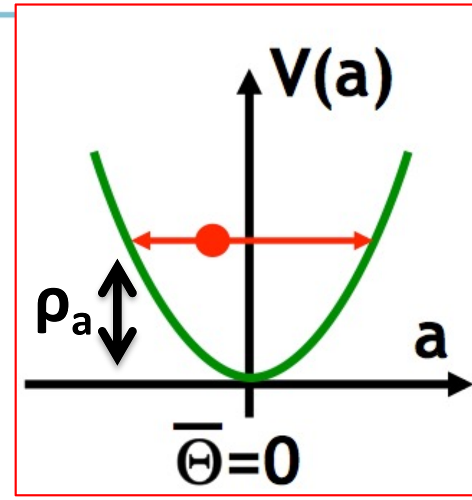
Most of search time spent slowly stepping through frequency space, one frequency tuning at a time.

Signal strength is independent of m_a, f_a

Locally coherent oscillation of the QCD θ angle about its CP-conserving minimum:

$$\theta(x,t) = \theta_{\max} e^{i(kx - m_a t)}$$

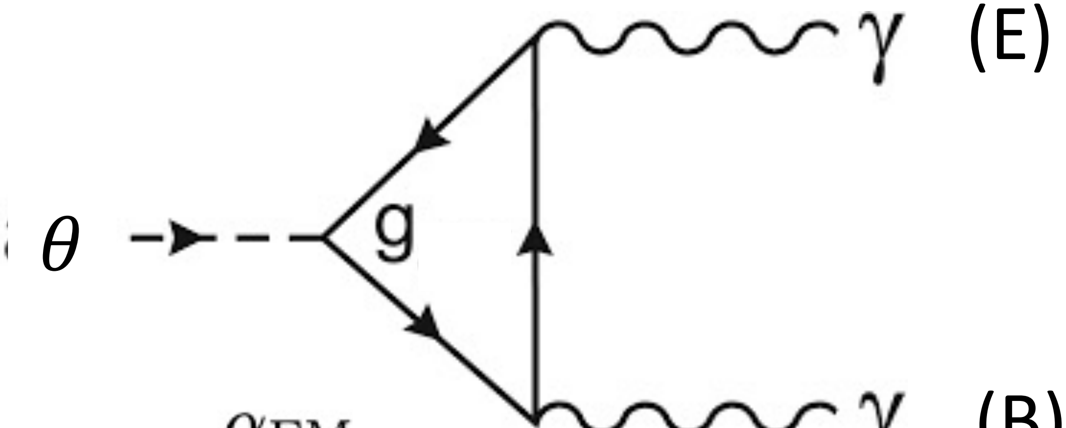
where $\theta_{\max} = \sqrt{\frac{2\rho_a}{\Lambda^4_{\mathrm{QCD}}}} \approx 3.7 \times 10^{-19} \mathrm{radians}$



DM oscillations partially undo the Peccei-Quinn mechanism by enabling the coherent field to climb out of the potential minimum.

Wave amplitude and hence signal strength depends only on local dark matter density ρ_a !

Experimental goal:
Determine frequency of the signal and hence the axion mass



$$g \approx \frac{\alpha_{\mathrm{EM}}}{4\pi}$$

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The Dark Matter Haloscope:
Classical axion wave drives RF cavity mode

Pierre Sikivie,
Sakurai Prize 2019

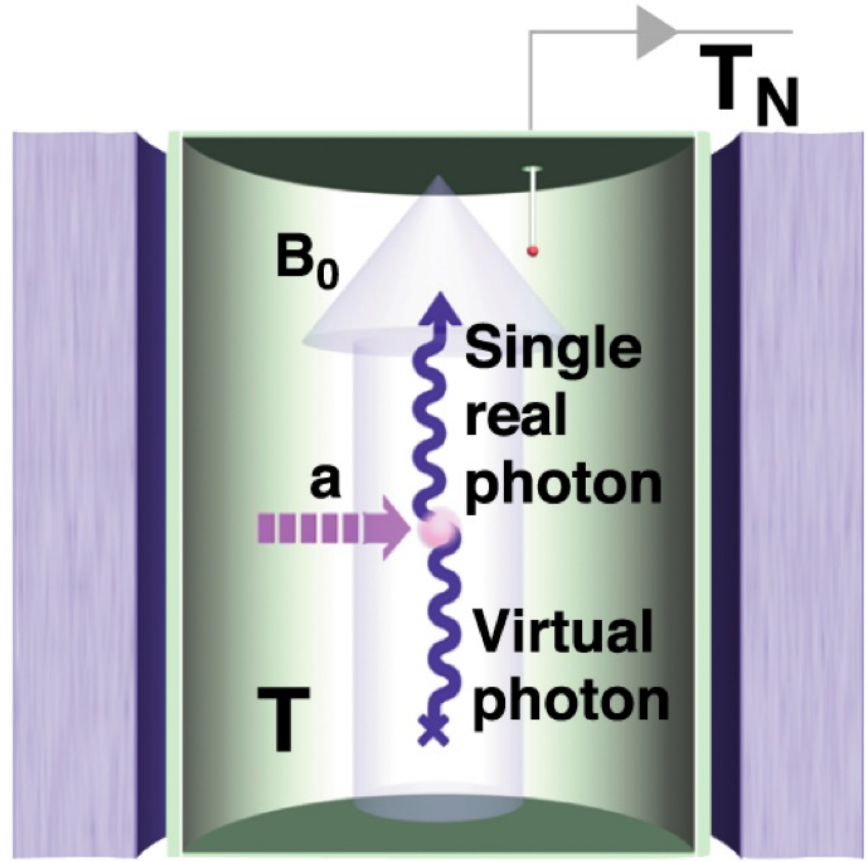
- In a constant background B_0 field, the oscillating axion field acts as an exotic, space-filling current source

$$\vec{J}_a(t) = -g\theta\vec{B}_0 m_a e^{i m_a t}$$

which drives E&M via Faraday's law:

$$\vec{\nabla} \times \vec{H}_r - \frac{d\vec{D}_r}{dt} = \vec{J}_a$$

- Periodic cavity boundary conditions extend the coherent interaction time **(cavity size ≈ 1/m$_a$) →** the exotic current excites standing-wave RF fields.

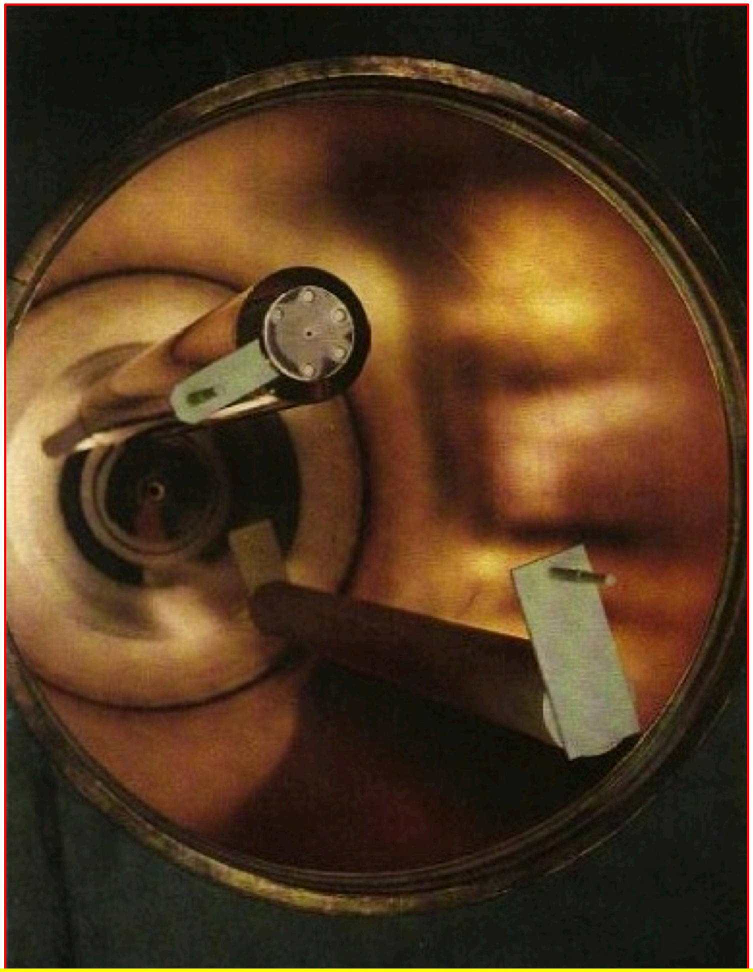


A spatially-uniform cavity mode can **optimally** extract power from the dark matter wave

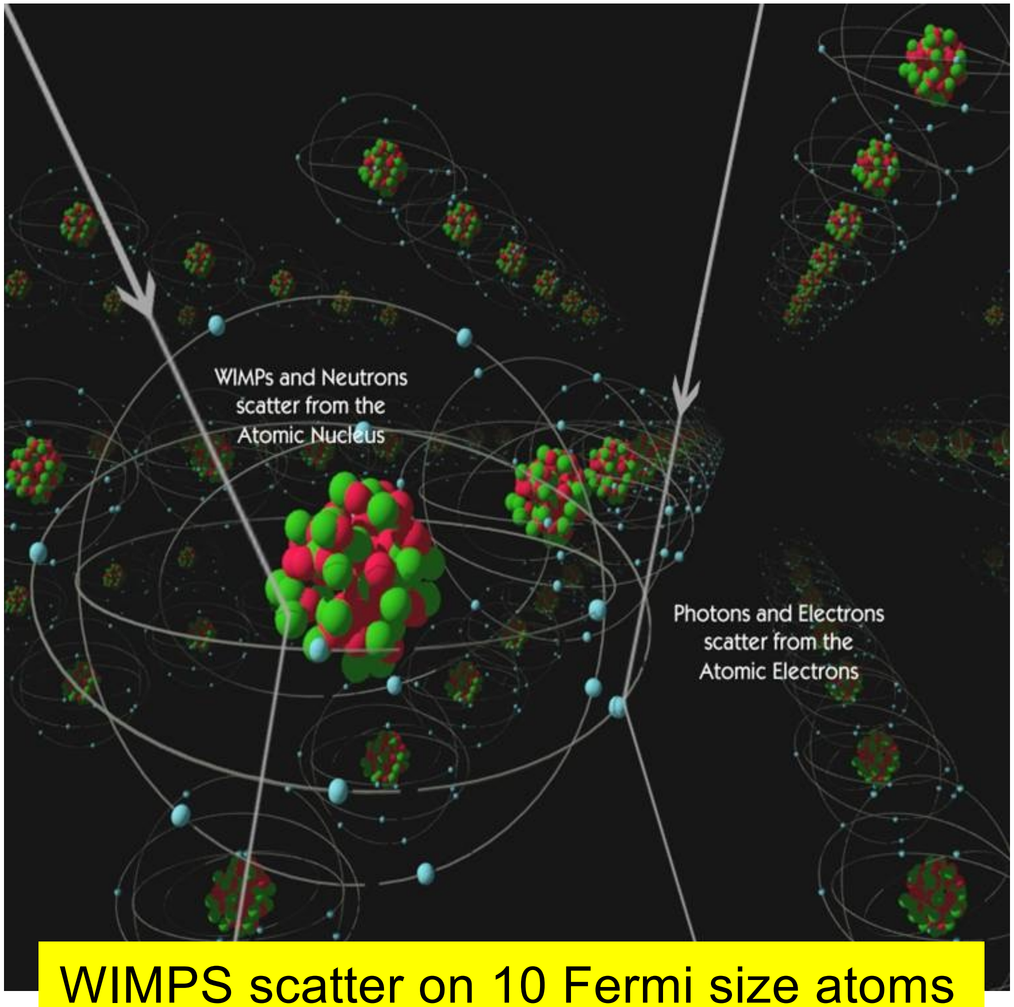
$$P_a(t) = \int \vec{J}_a(t) \cdot \vec{E}_r(t)\, dV$$

Axions vs WIMPs:

Resonant scattering requires size of scattering target = 1/(momentum transfer)



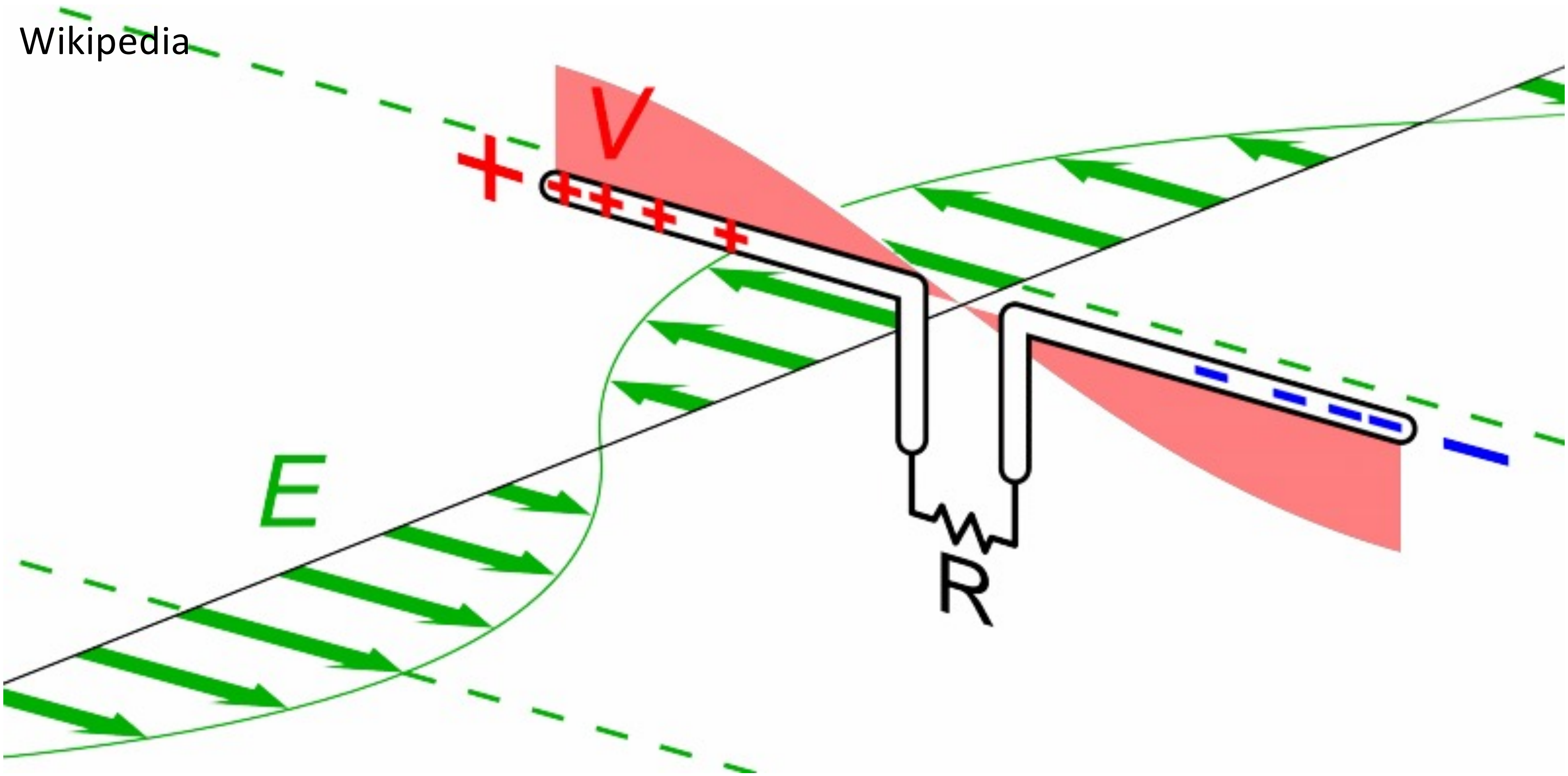
4 μeV mass axions scatter on 50cm size microwave cavities



WIMPS scatter on 10 Fermi size atoms

Match size of antenna to wavelength of signal

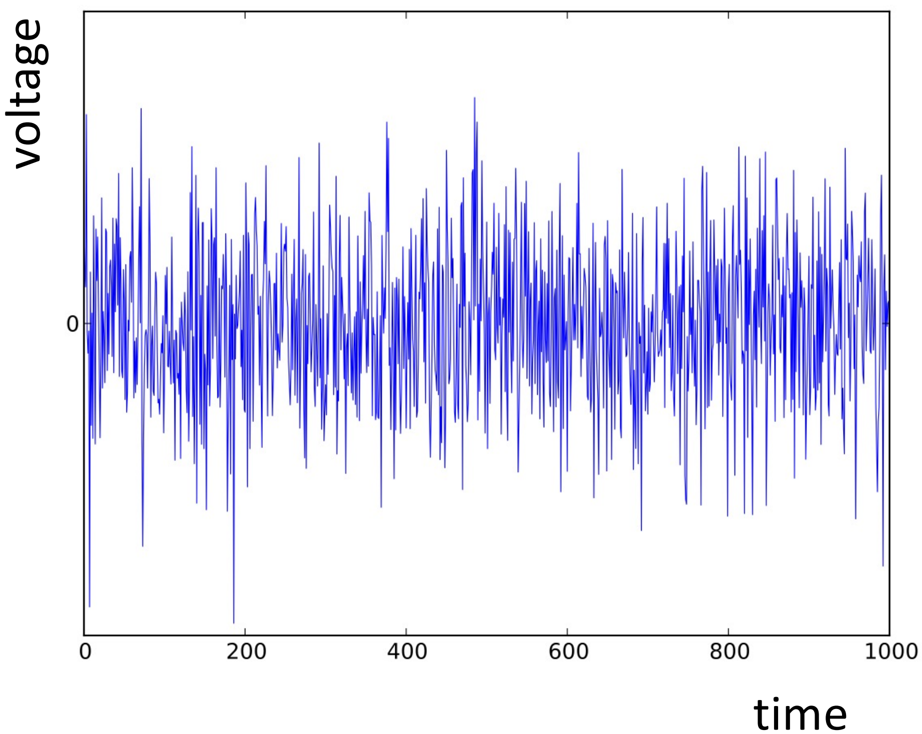
Wikipedia

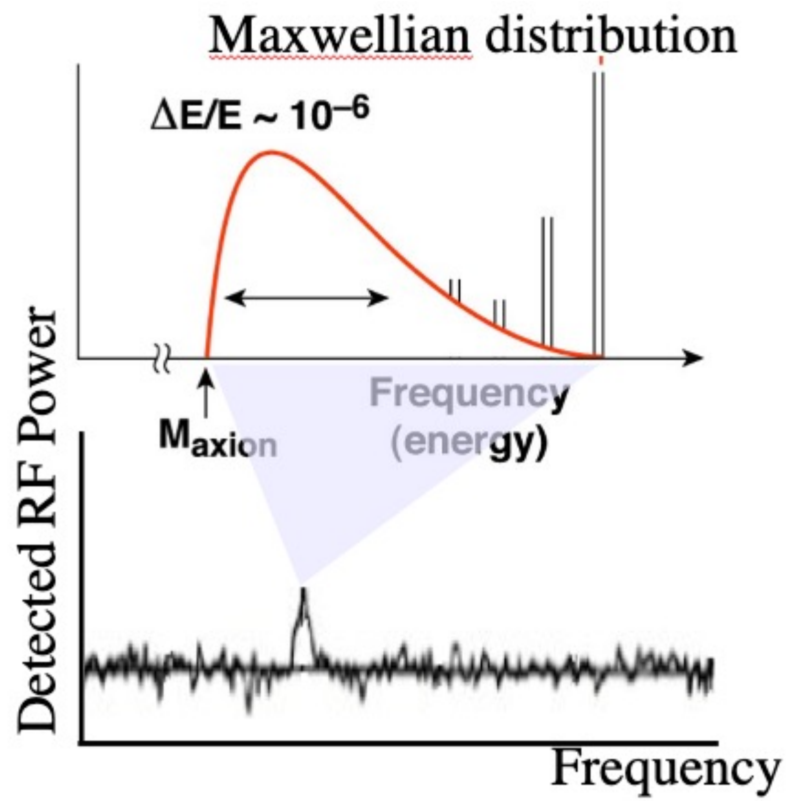


Wave mechanics: scattering matrix element is proportional to spatial Fourier transform of the scattering potential, with respect to the momentum transfer

Spectral analysis of output voltage time series

Discrete Fourier transform





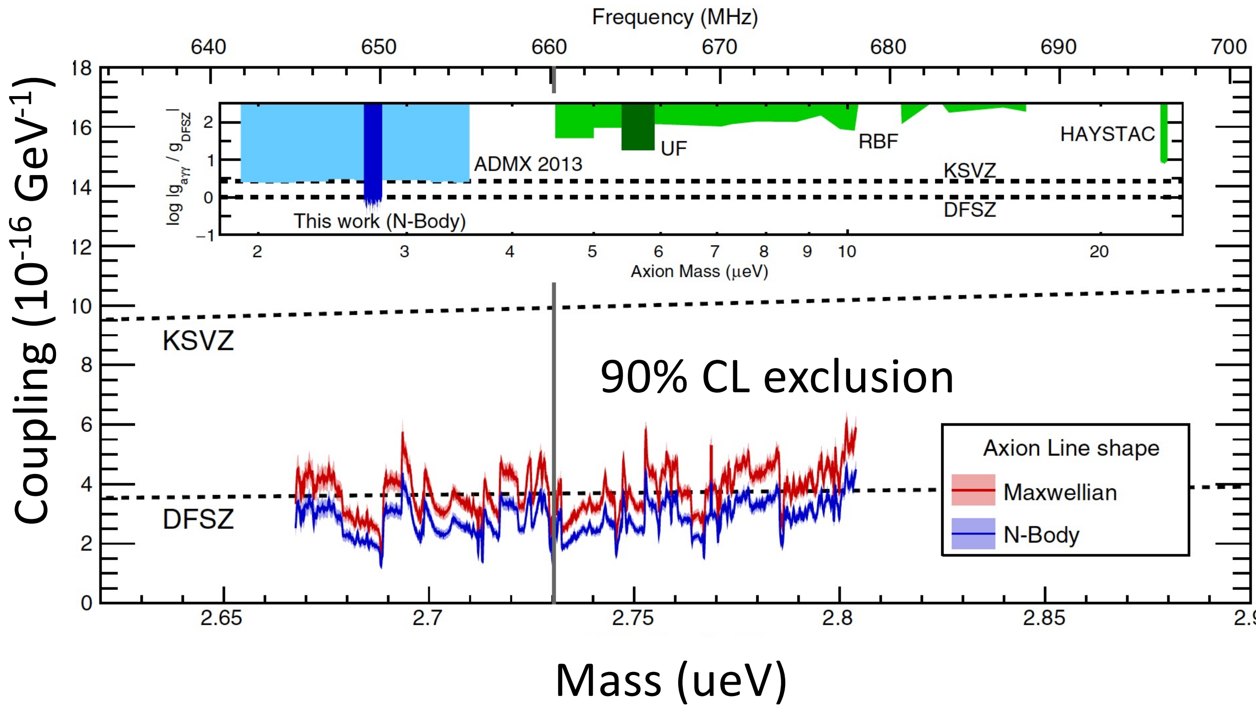
Digitization rate f_{dig} gives maximum resolvable "Nyquist" frequency $f_{dig}/2$.
Duration Δt of acquired time series gives frequency resolution $\Delta f = 1/2\Delta t$.

Dark matter signal = excess above white noise backgrounds.

2017: 30-year axion R&D program culminates in first sensitivity to DFSZ axions

PRL 120, 151301 (2018)

ADMX at U.Washington, FNAL = DOE lead lab



Operate an ultrasensitive radio in a cold, RF-shielded box to tune in to the axion broadcast.

Look for "spontaneous" emission from local axion dark matter into the empty cavity mode.

Signal power level = 10^{-23} W

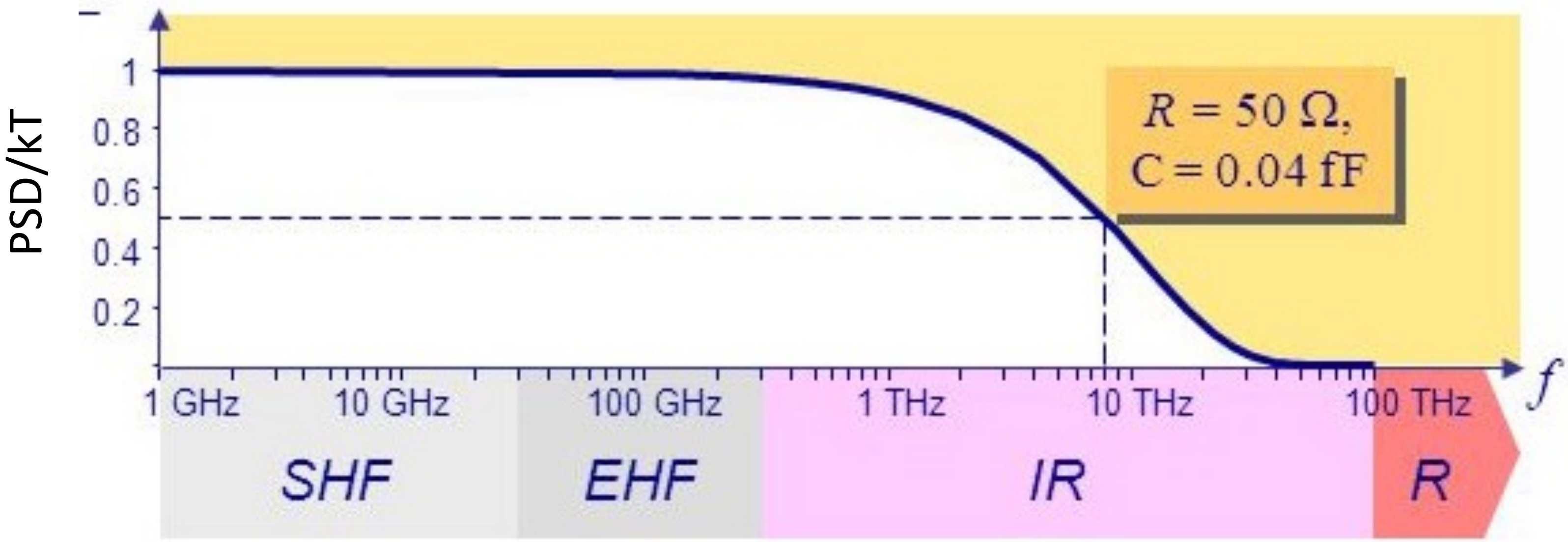
Need 15 minutes integration per radio tuning to beat thermal noise power at 500 mK.

How a theorist sees a spherical cow

How an experimentalist sees a spherical cow

Bose-Einstein occupancy of photon modes on a 1-dim transmission line, + zero point fluctuations:

$$n(\omega) = \frac{1}{2}\coth\frac{\hbar\omega}{2kT} = \frac{1}{e^{\hbar\omega/kT}-1} + \frac{1}{2}$$



Energy/mode = kT (½ kT for each quadrature).

Modes of linewidth Δf are defined by the integration time Δt = 1/(2 Δf) required to resolve these modes.

→ Thermal noise power emitted from each mode P = kT Δf.

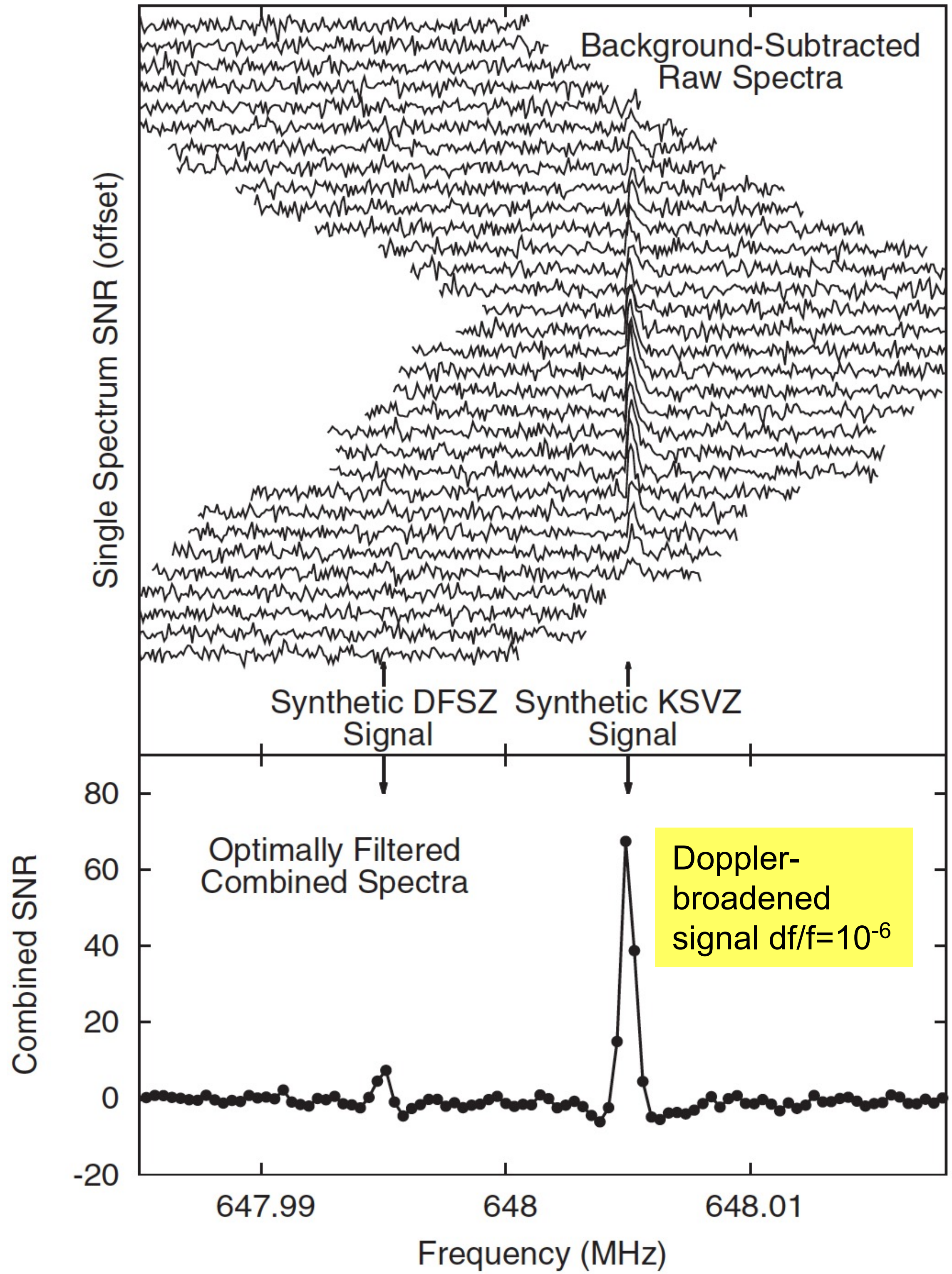
Detect small signal excesses by averaging away the noise over many power spectrum measurements

10^{-3} (for ADMX)

$$SNR = \frac{P_{\rm signal}}{\sqrt{2}kT\Delta f}\sqrt{2\Delta f t}$$

Require >10^6 averages!

Each measurement takes 10^{-3} s to resolve a kHz-wide bin.
→ 10^6 measurements takes 10^3 s = 15 minutes.



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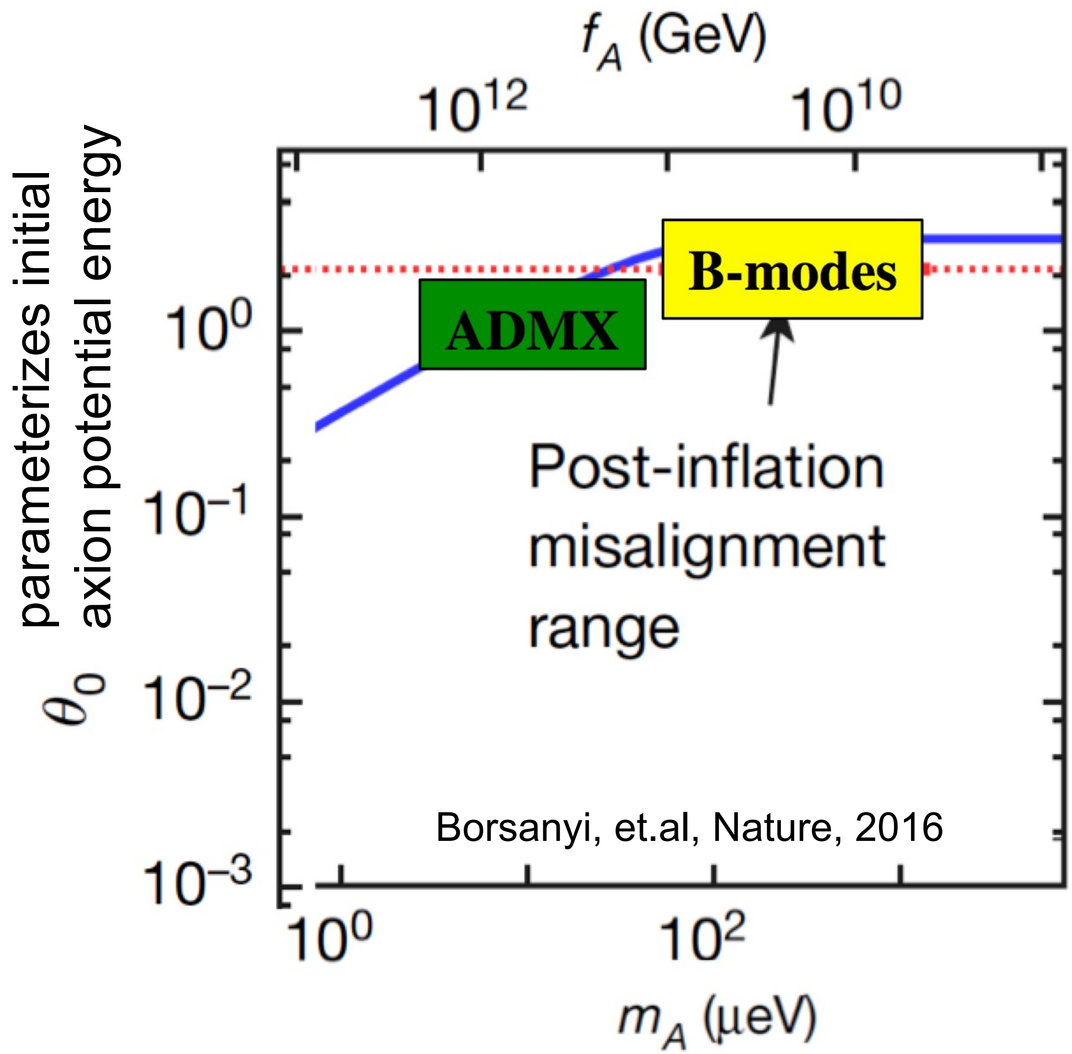
Targeting higher axion masses predicted in cosmological scenarios with *high energy scale* cosmic inflation

These simple inflation models also produce detectable primordial B-mode polarization patterns in the cosmic microwave background – science target for CMB-S4.



Higher axion mass allows early release of QCD vacuum energy. Avoids overproduction of dark matter.

What prevents us from immediately going to higher frequencies?

The predicted axion DM signal/noise ratio plummets as the axion mass increases → SQL readout is not scalable.