# Axion searches

P. Sikivie (CERN & U. of Florida)

Seminaire a trois
-- premier mouvement --

Saclay, May 30, 2006

# Outline

- introduction
- axion cosmology
- dark matter axion detection
- the Axion Dark Matter eXperiment
- solar axion searches
- laser experiments

# The Strong CP Problem

$$L_{\mathrm{QCD}} = \;\ldots + \theta \frac{g^2}{32\pi^2} G^a{}_{\mu\nu} \tilde{G}^{a\mu\nu}$$

Because the strong interactions conserve P and CP, . $\theta \leq 10^{-10}$

The Standard Model does not provide a reason for $\theta$ to be so tiny,

but a relatively small modification of the model does provide a reason …

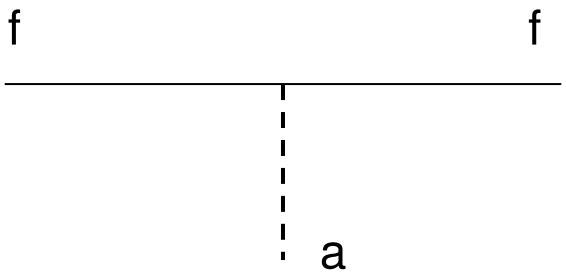
If a $\mathrm{U}_{\mathrm{PQ}}(1)$ symmetry is assumed,

$$L = \ldots + \frac{a}{f_a}\frac{g^2}{32\pi^2} G^a{}_{\mu\nu}\tilde{G}^{a\mu\nu} + \frac{1}{2}\partial_\mu a\,\partial^\mu a + \ldots$$

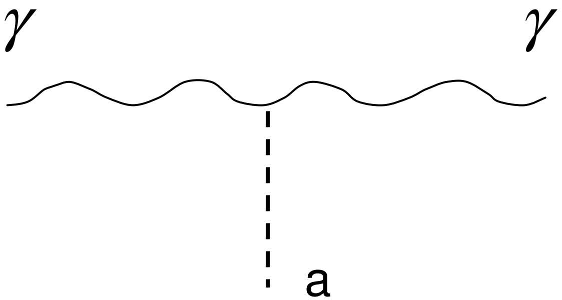
$\theta = \dfrac{a}{f_a}$ relaxes to zero,

and a light neutral pseudoscalar particle is predicted: the axion.

$$m_a \simeq 6\ \text{eV}\ \frac{10^6\ \text{GeV}}{f_a}$$



$$L_{a\bar{f}f} = i\, g_f\, \frac{a}{f_a}\, \overline{f}\, \gamma_5\, f$$

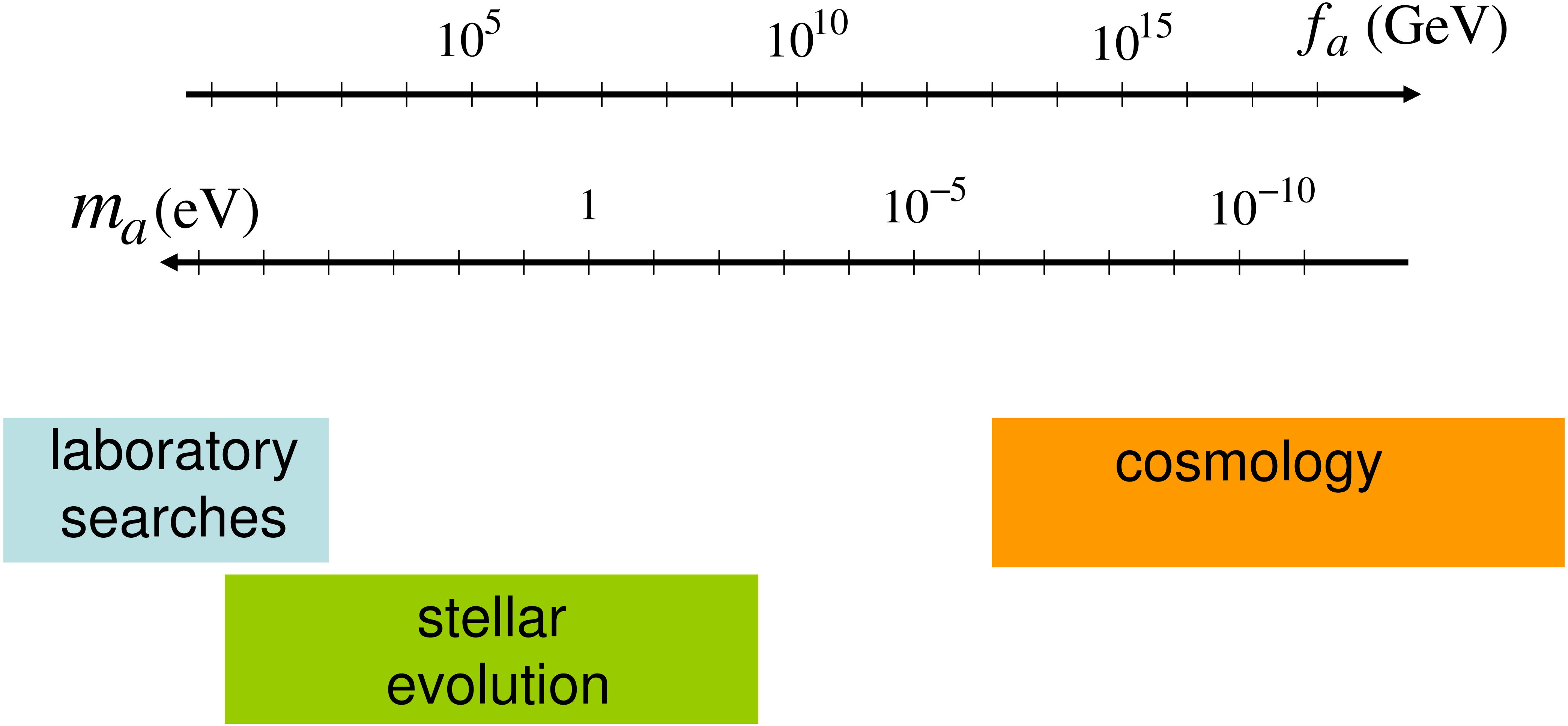


$$L_{a\gamma\gamma} = g_\gamma\, \frac{\alpha}{\pi}\, \frac{a}{f_a}\, \vec{E} \cdot \vec{B}$$

$g_\gamma$ = 0.97 in KSVZ model
0.36 in DFSZ model

□ means $\cong$

# The remaining axion window



laboratory searches

stellar evolution

cosmology

# Axions are cold dark matter

Density

$$\Omega_a \approx \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)^{\frac{7}{6}}$$

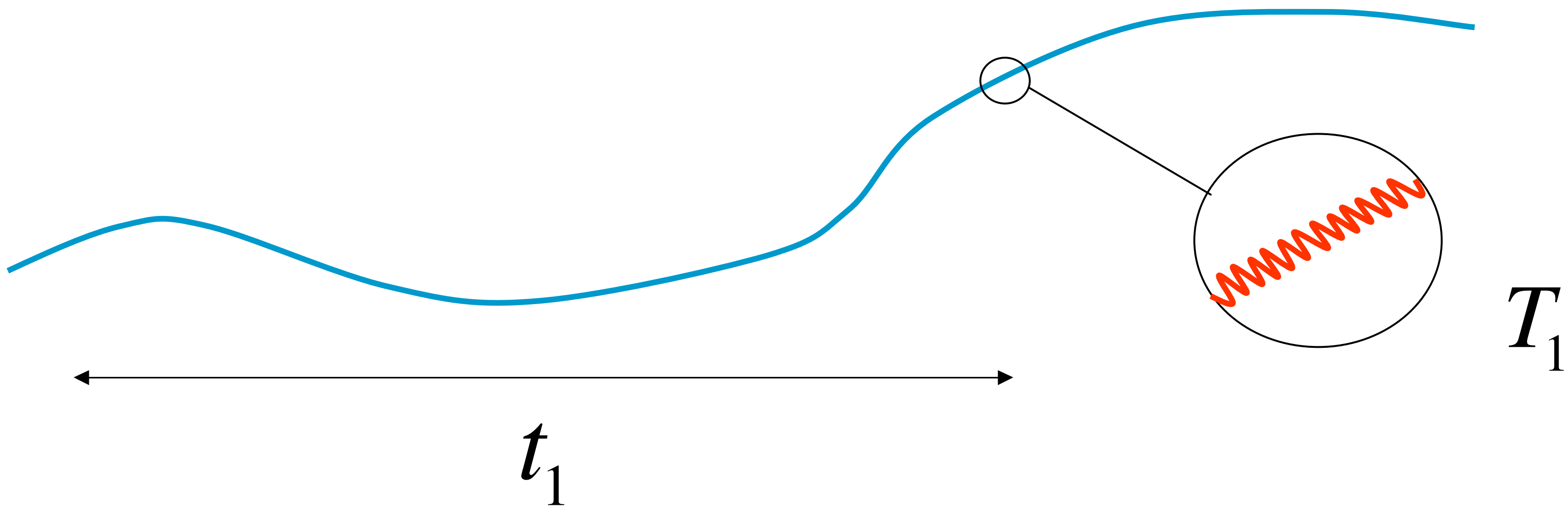
Velocity dispersion

$$\delta \mathrm{v}_a\left(t_0\right) \square\ 3 \cdot 10^{-17}\, c \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)^{\frac{5}{6}}$$

Effective temperature

$$T_{a,\,\mathrm{eff}}\left(t_0\right) \square\ 10^{-34}\,\mathrm{K} \left(\frac{10^{-5}\,\mathrm{eV}}{m_a}\right)^{\frac{2}{3}}$$

# There are two axion populations: hot and cold.

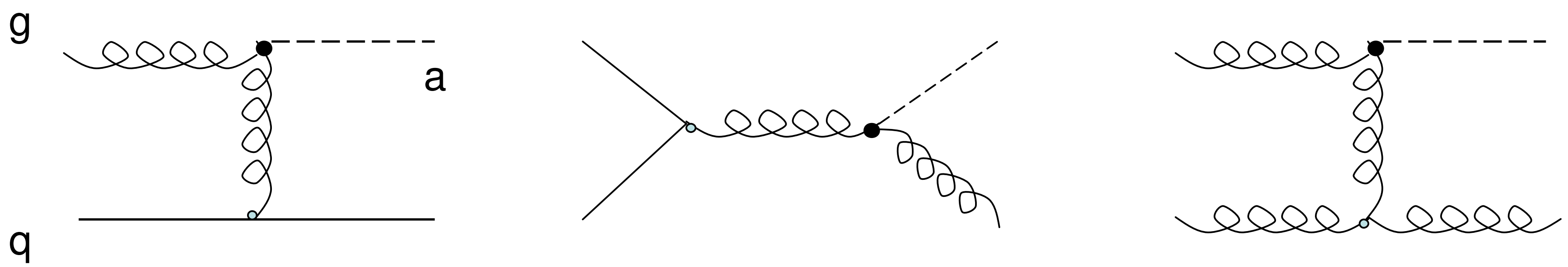


When the axion mass turns on, at QCD time,

$T_1 \sim 1\ \mathrm{GeV}$  $t_1 \sim 2 \cdot 10^{-7}\ \mathrm{sec}$

$$p_a(t_1) = \frac{1}{t_1} \sim 3 \cdot 10^{-9}\ \mathrm{eV}$$

# Thermal axions



these processes imply an axion decoupling temperature

$$T_D \simeq 3 \cdot 10^{11}\ \mathrm{GeV} \left( \frac{f_a}{10^{12}\ \mathrm{GeV}} \right)^2$$

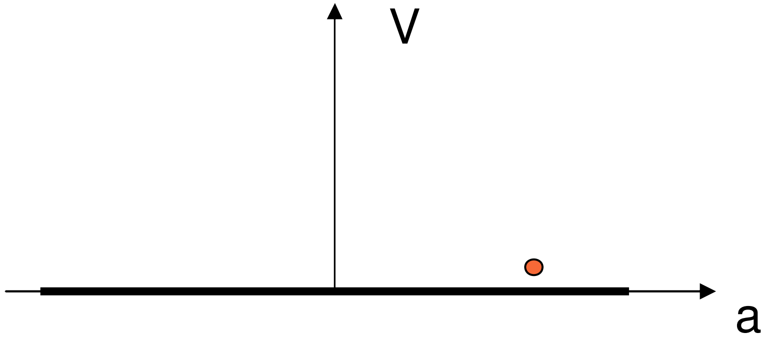
E. Masso
R. Rota
G. Zsembinszki

thermal axion
temperature today:

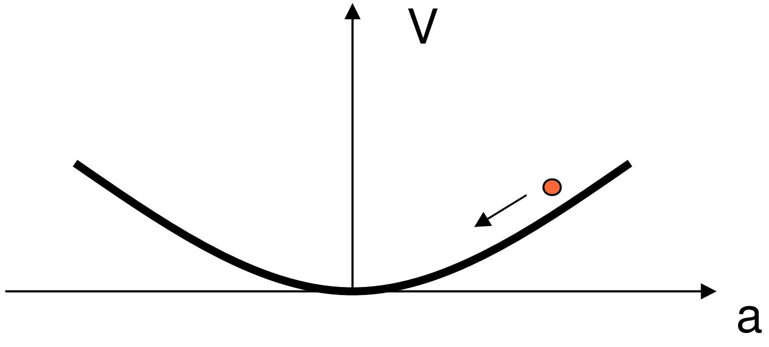
$$T_a(t_0) = 0.908\ \mathrm{K} \left( \frac{106.75}{N_D} \right)^{\frac{1}{3}}$$

$N_D$ = effective number of thermal degrees of freedom at axion decoupling

# Axion production by vacuum realignment



$T \geq 1\,\mathrm{GeV}$



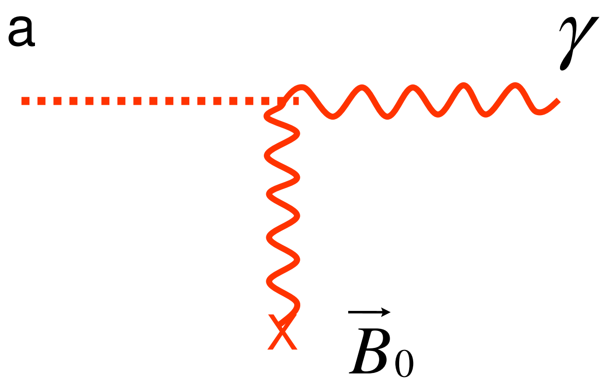
$T \leq 1\,\mathrm{GeV}$

$$n_a(t_1) \square \frac{1}{2} m_a(t_1)\, a(t_1)^2 \square \frac{1}{2t_1} f_a{}^2\, \alpha(t_1)^2$$

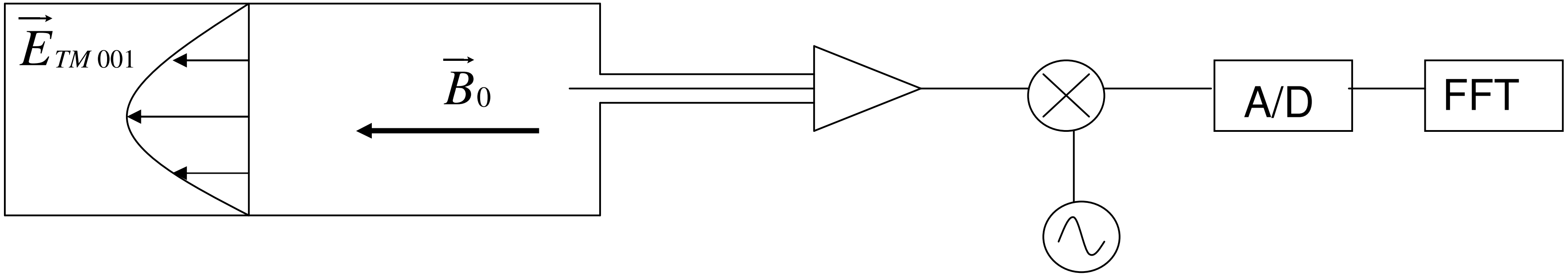
initial
misalignment
angle

$$\rho_a(t_0) \square m_a\, n_a(t_1) \left( \frac{R_1}{R_0} \right)^3 \propto m_a{}^{-\frac{7}{6}}$$

# Axion dark matter is detectable

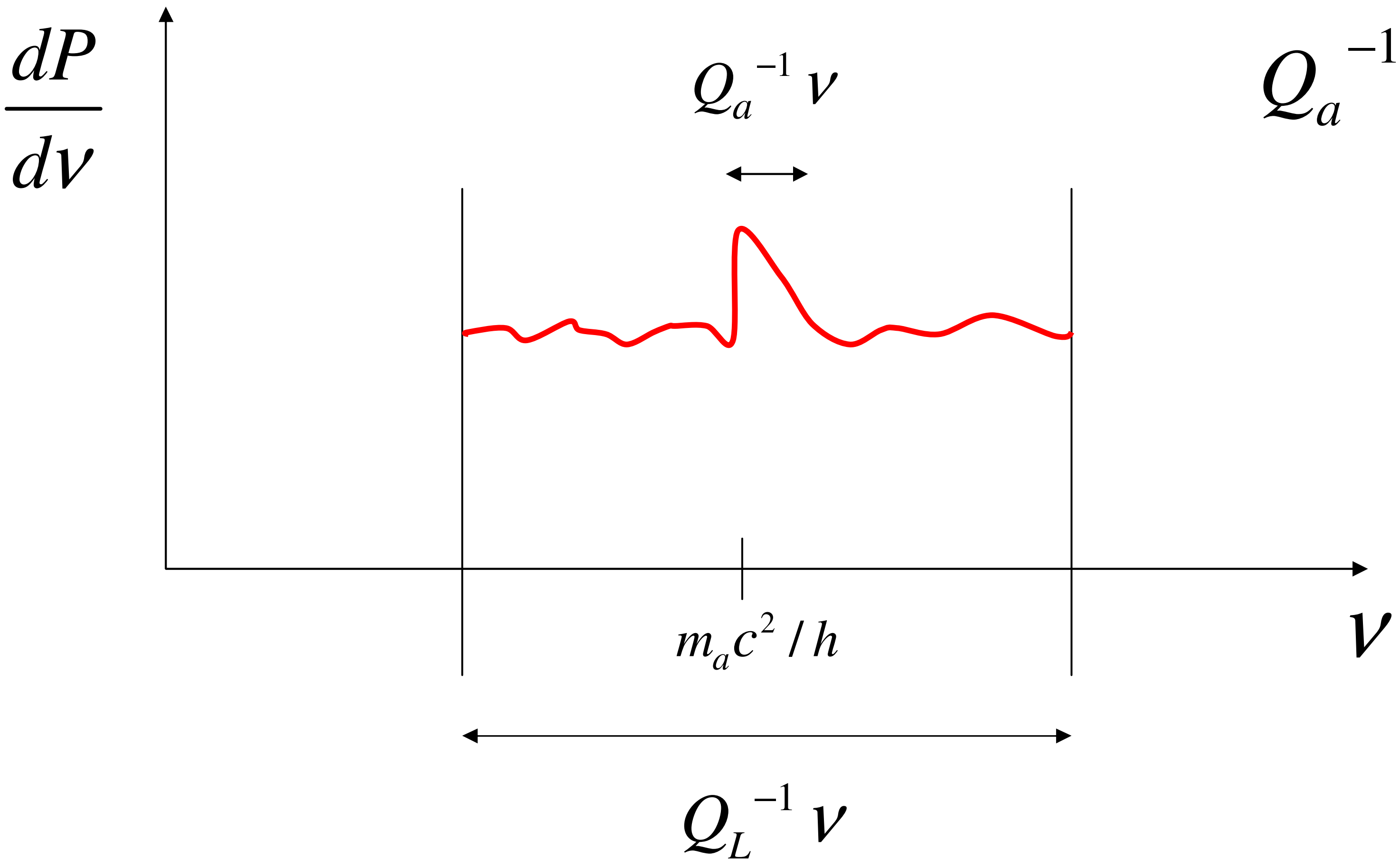


$$L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B}$$



$$h\nu = m_a c^2 \left(1 + \frac{1}{2}\beta^2\right)$$

$$\beta = \frac{\mathrm{v}}{c} \sim 10^{-3}$$



$$Q_a^{-1} \approx 10^{-6}$$

# $a \to \gamma$

## conversion power on resonance

$$P = \left(\frac{\alpha g_\gamma}{\pi f_a}\right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L$$

$$= 2 \cdot 10^{-22}\ \text{Watt} \left(\frac{V}{500\ \text{liter}}\right)\left(\frac{B_0}{7\ \text{Tesla}}\right)^2 \left(\frac{C}{0.4}\right)$$

$$\left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{\rho_a}{5 \cdot 10^{-25}\ \text{gr/cm}^3}\right)\left(\frac{m_a c^2}{h\ \text{GHz}}\right)\left(\frac{Q_L}{10^5}\right)$$

## search rate for s/n = 4

$$\frac{df}{dt} = \frac{1.2\ \text{GHz}}{\text{year}} \left(\frac{P}{2 \cdot 10^{-22}\ \text{Watt}}\right)^2 \left(\frac{3\,K}{T_n}\right)^2$$

# ADMX Collaboration

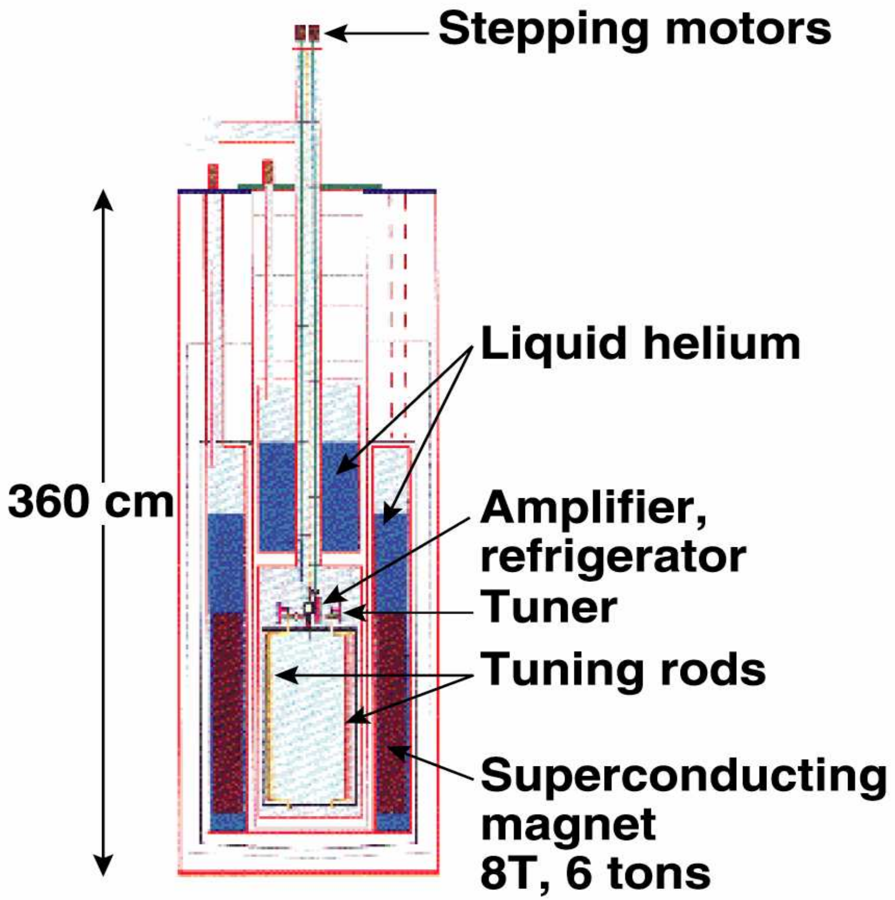
LLNL: S. Asztalos, C. Hagmann, D. Kinion,
L.J Rosenberg, K. van Bibber, D. Yu

U of Florida: L. Duffy, P. Sikivie, D. Tanner

NRAO: R. Bradley

# Axion Dark Matter eXperiment

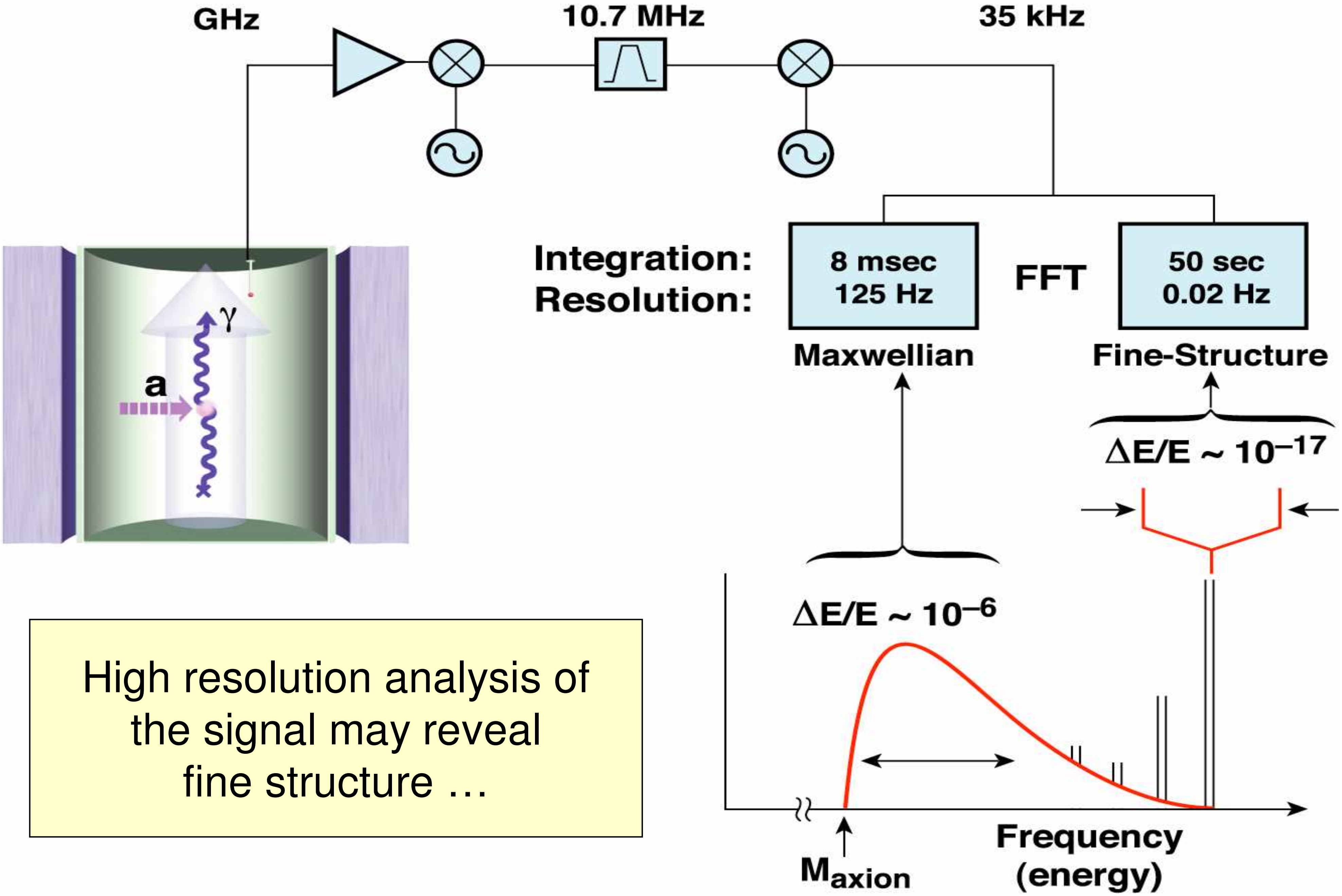
**Magnet with Insert (side view)**



**Pumped LHe → T ~ 1.5 k**

**Magnet**

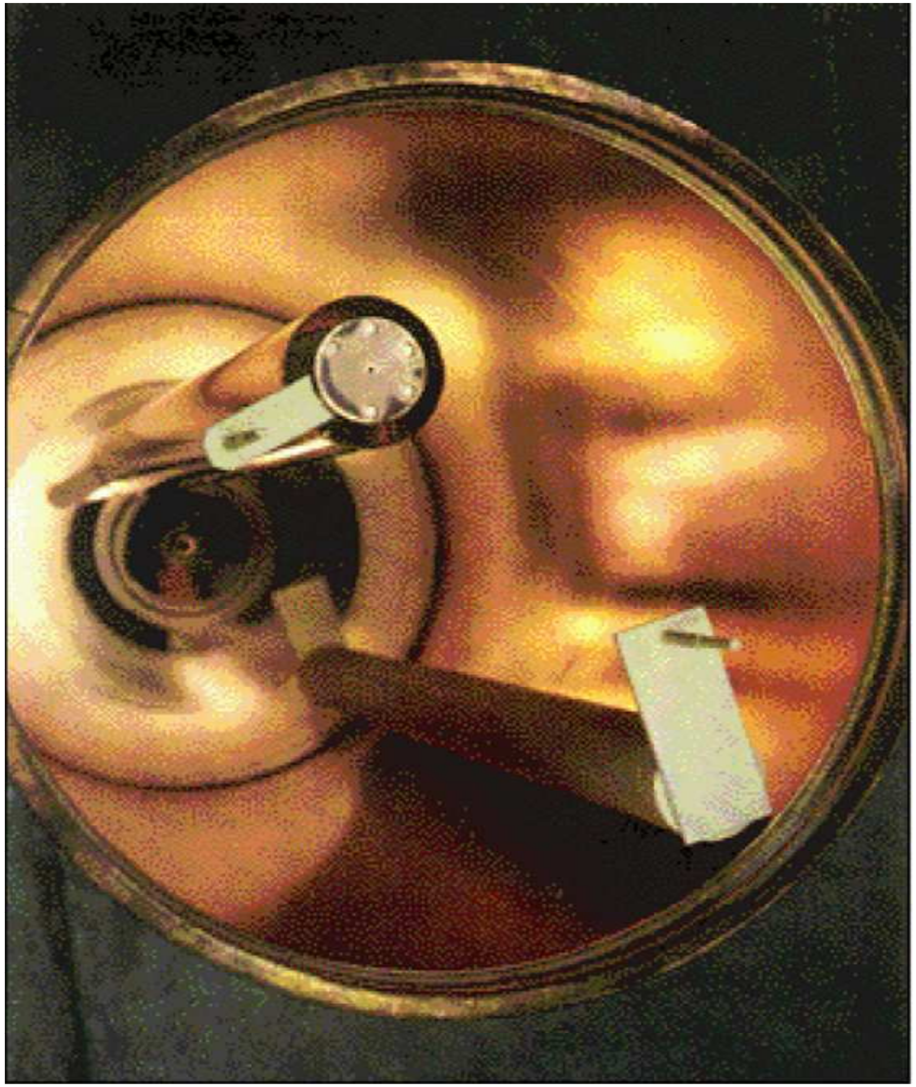
**8 T, 1 m × 60 cm ∅**



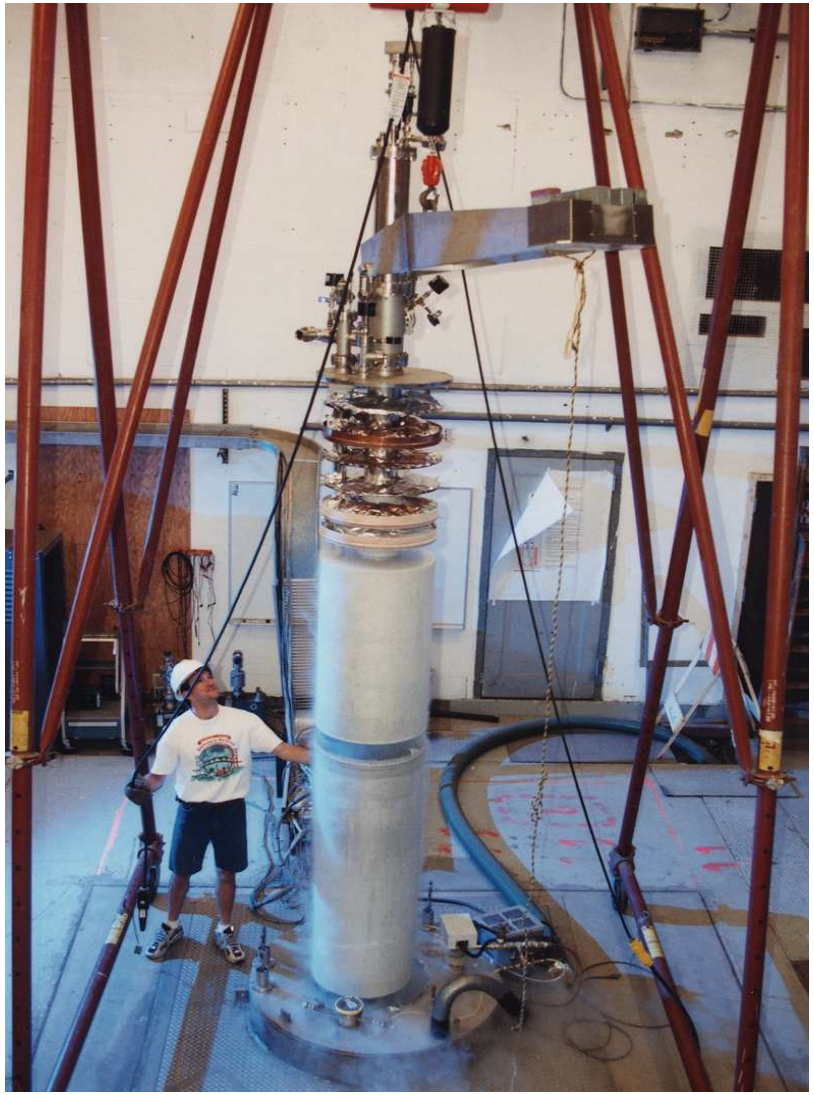
High resolution analysis of
the signal may reveal
fine structure …

# ADMX hardware

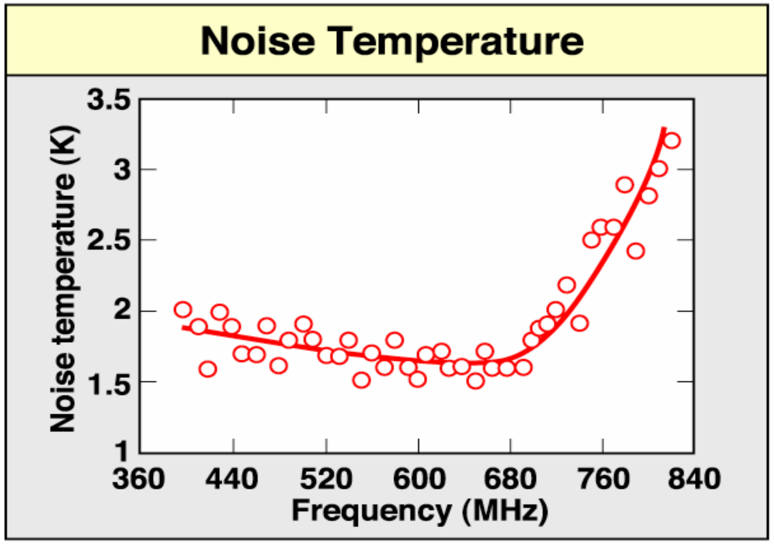
high Q cavity

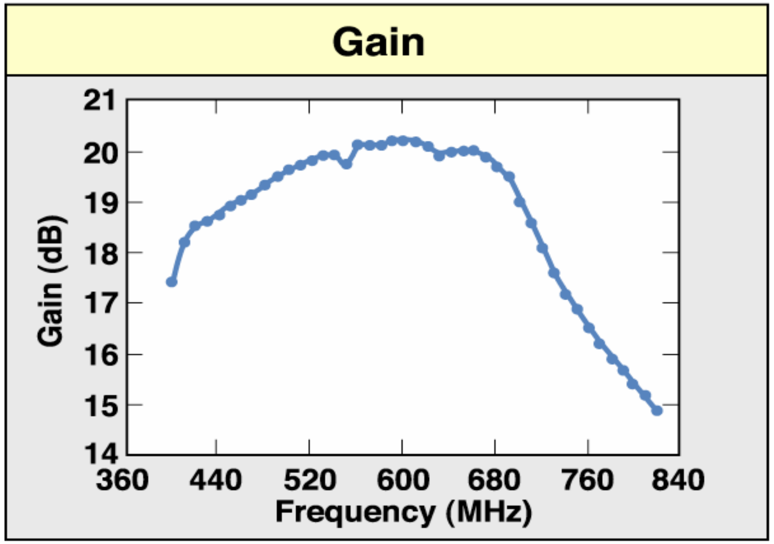


experimental insert



# ADMX hemt amplifiers


Noise Temperature

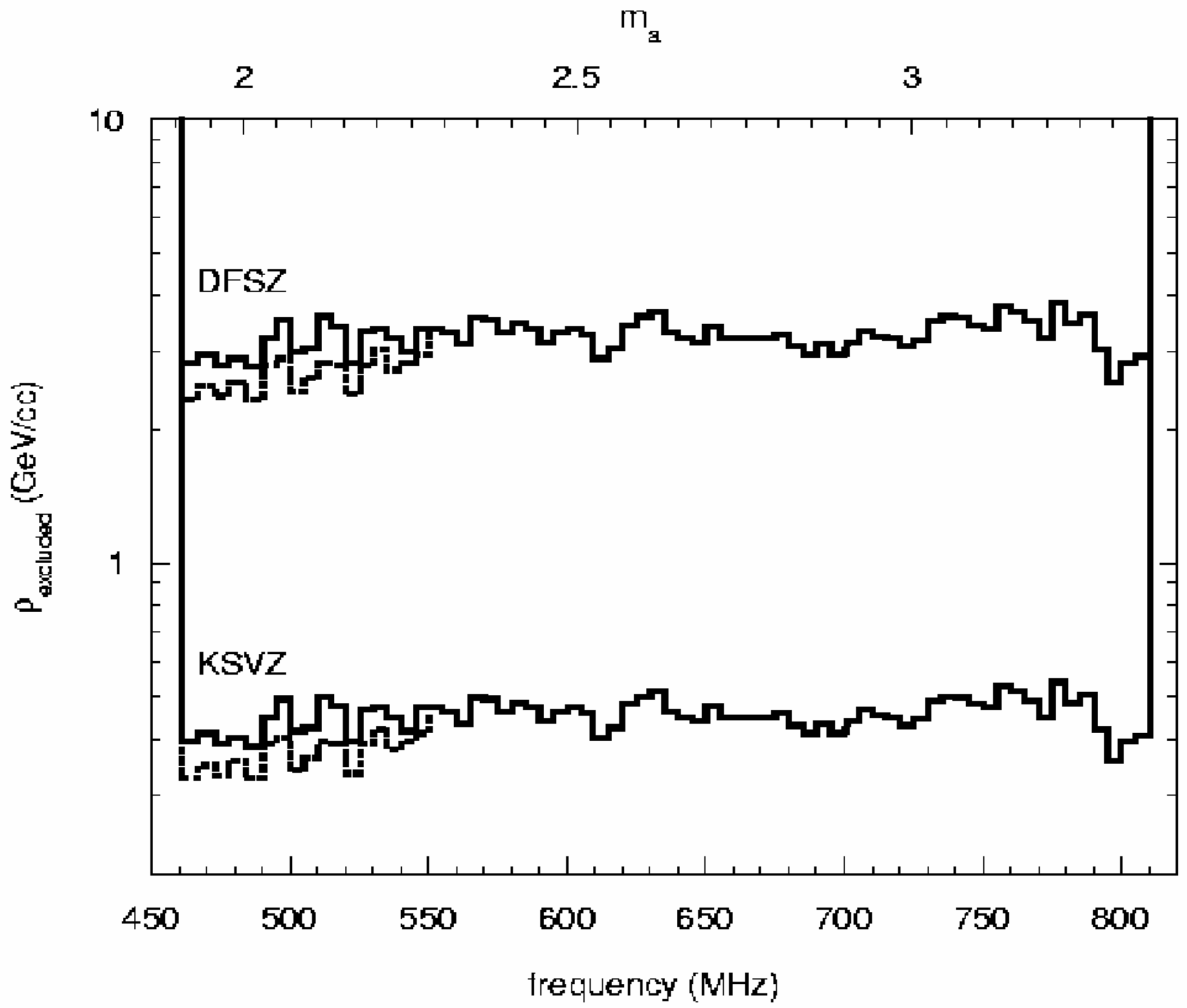

Gain

- **Currently HFET amplifiers (Heterojunction Field-Effect Transistor)**
  - **A.k.a. HEMT™ (High Electron Mobility Transistor)**
  - **Workhorse of radio astronomy, military communications, etc.**
- **Best to date $T_N \gtrsim 1$ K**
  - **Independent of T**
  - **Works in magnetic field**

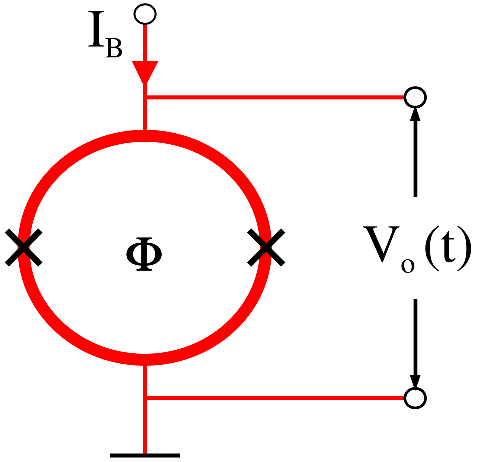
**But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!**

**A quantum-limited amplifier would both give us definitive sensitivity, *and* dramatically speed up the search!**

# ADMX MedRes limits

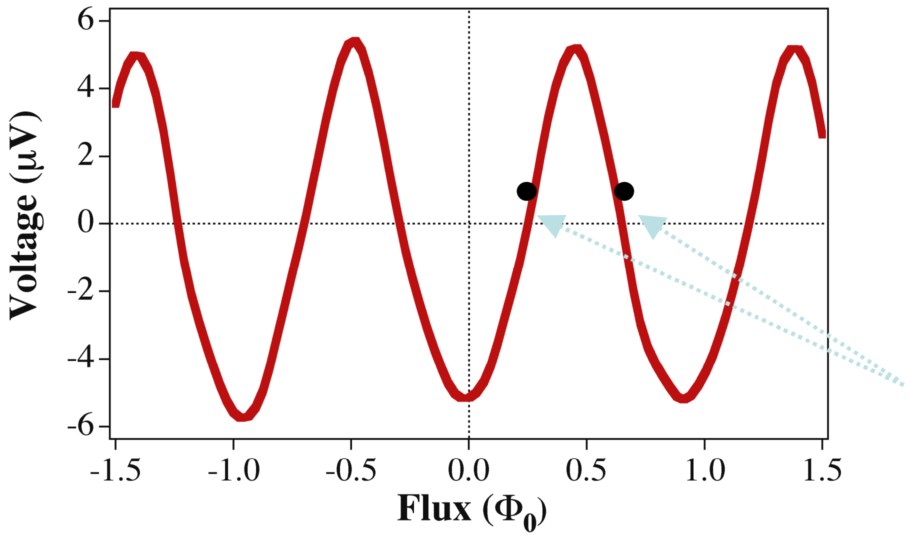


# Upgrade with SQUID Amplifiers



The basic SQUID amplifier is a flux-to-voltage transducer

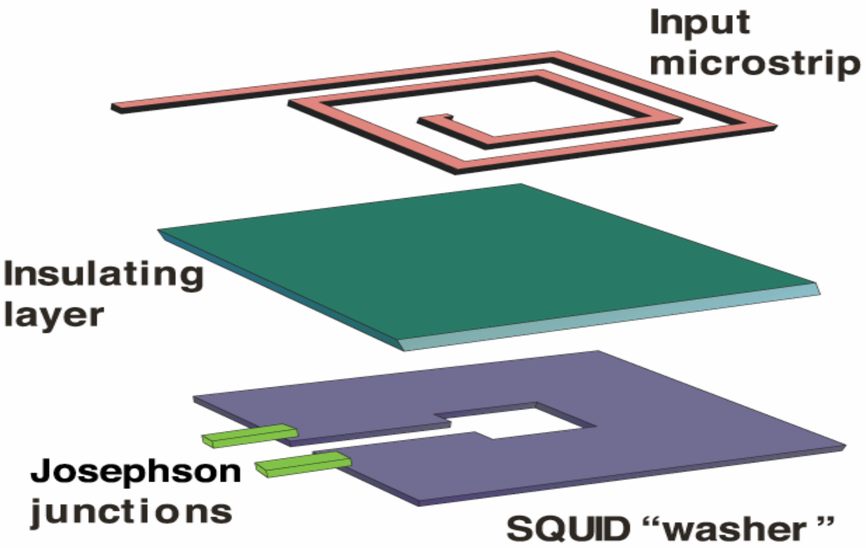
SQUID noise arises from Nyquist noise in shunt resistance
    scales linearly with T

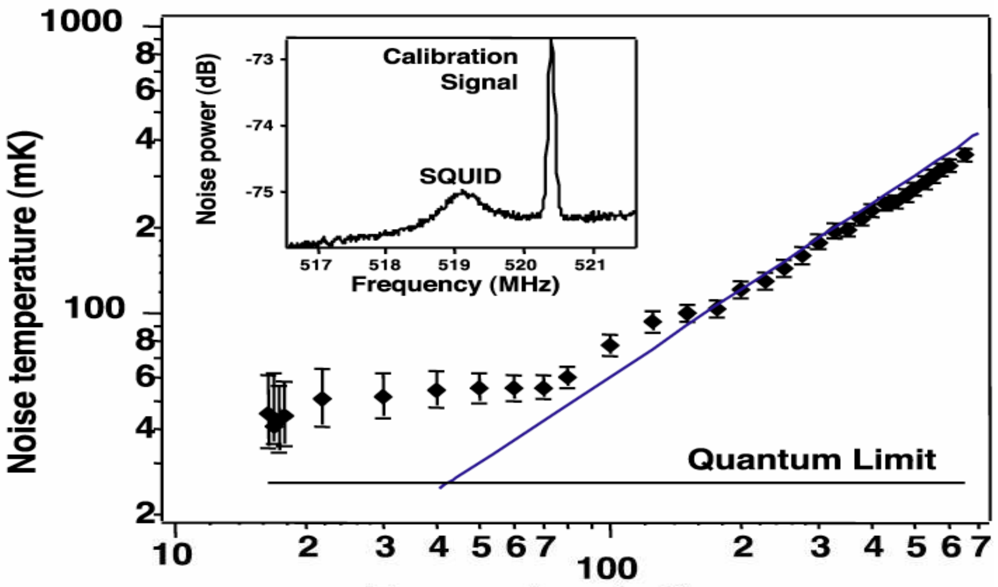


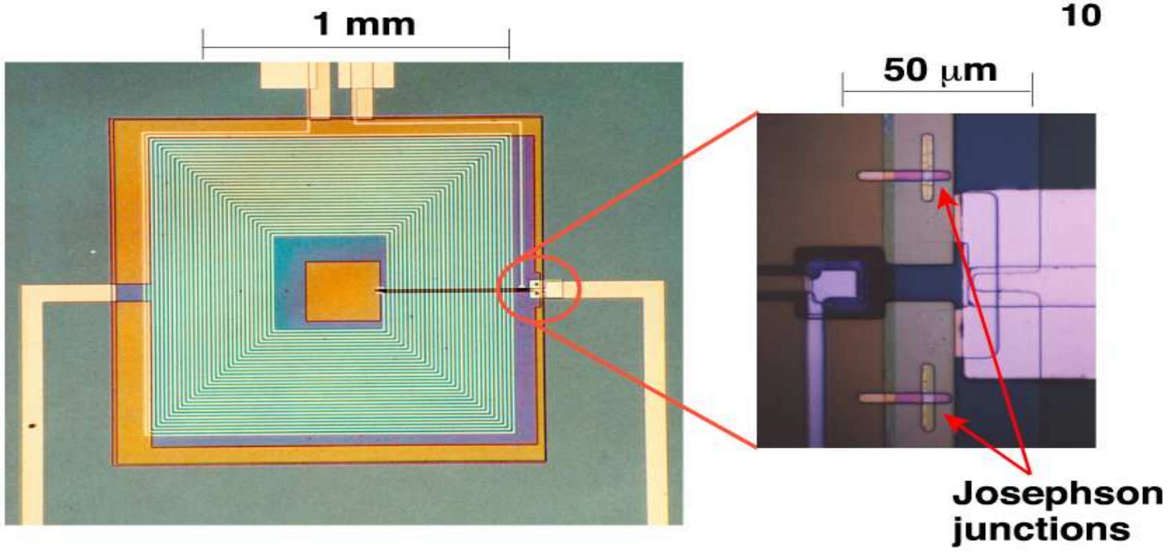
However, SQUIDs of conventional design are poor amplifiers above 100 MHz (parasitic couplings).

Flux-bias to here

# ADMX Upgrade: replace HEMTs (2 K) with SQUIDs (50 mK)





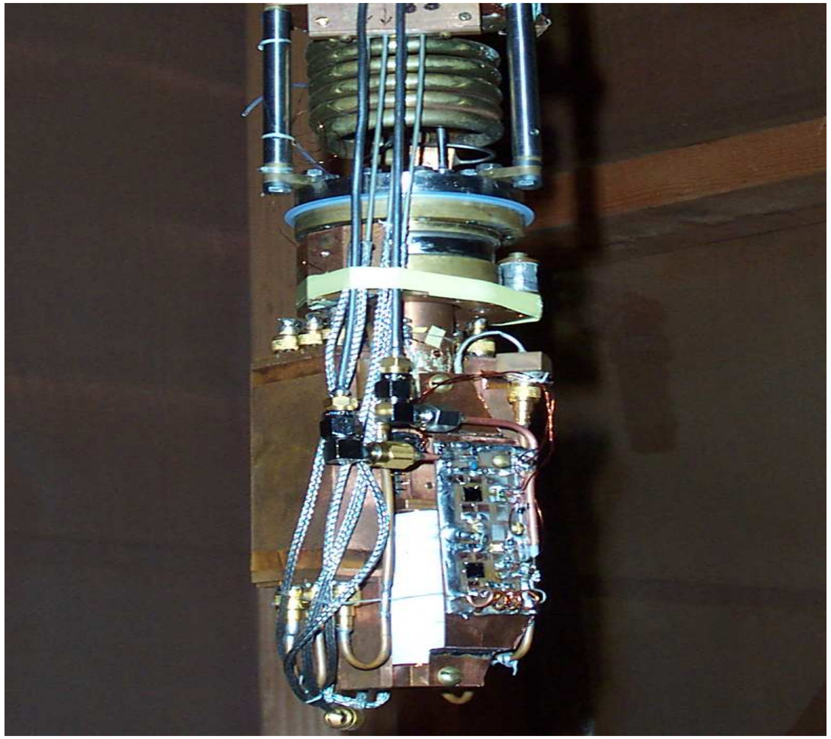


(J. Clarke *et al.*, U.C. Berkeley)

In phase II of the upgrade, the experiment is cooled with a dilution refrigerator.

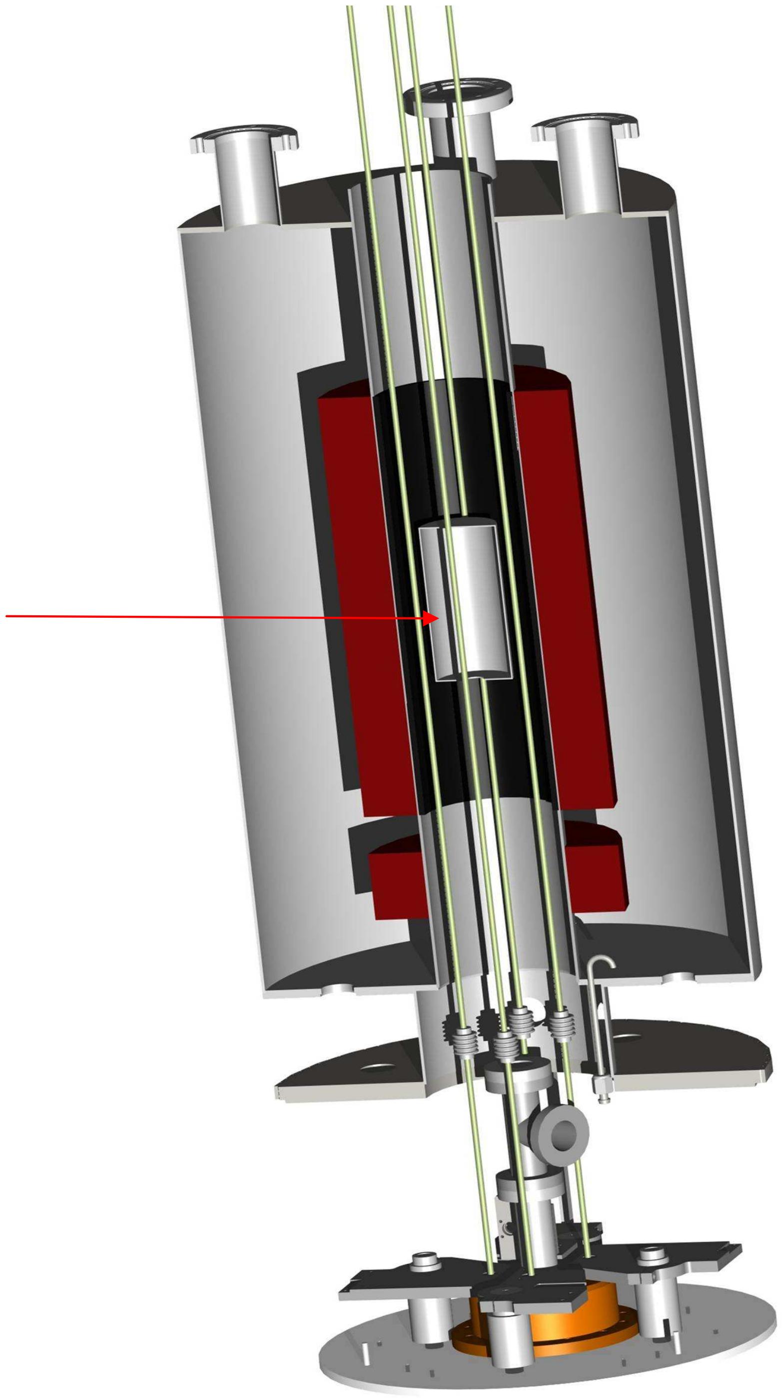
# SQUIDs packaged into amplifiers

SQUIDs mounted on fridge



Darin Kinion

The magnetic field needs to be cancelled at the location of the SQUID.

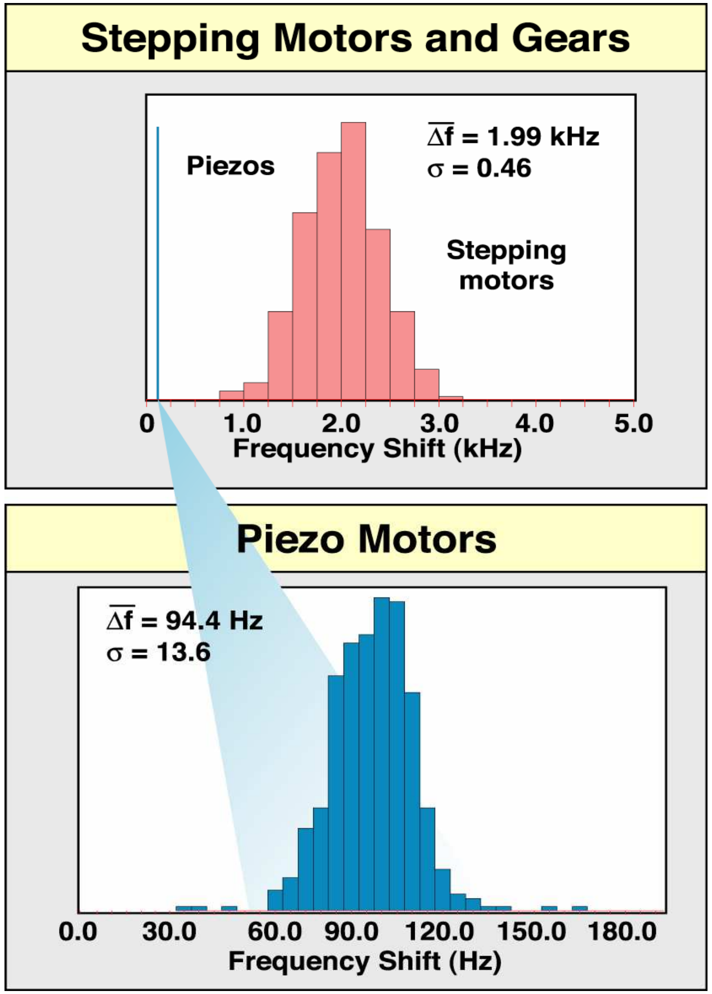


From outwards-in:

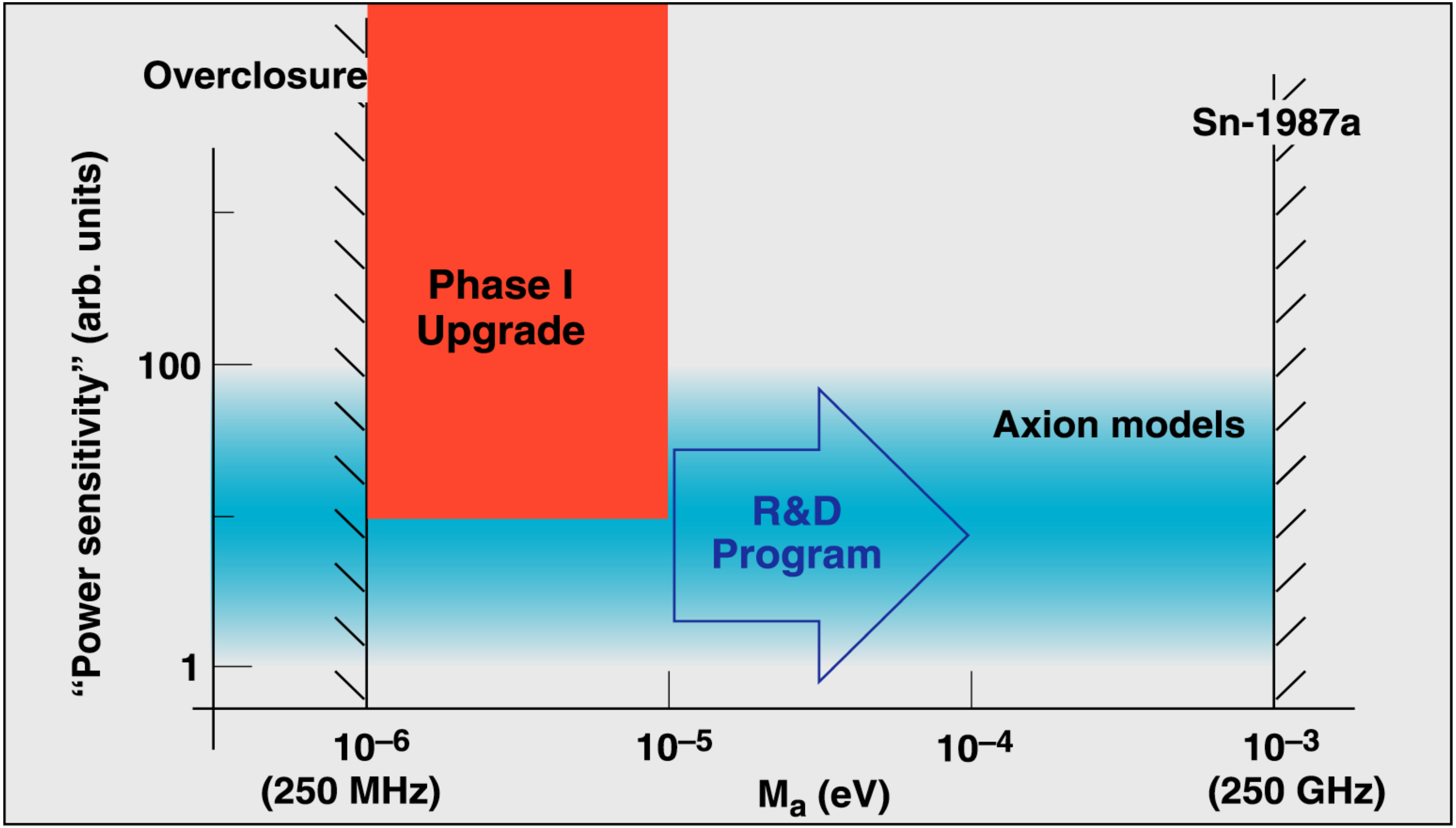
Iron shield
Cryoperm (mumetal) shields
Superconducting shields
SQUID amplifier package
SQUIDs

The upgrade will be sensitive to the more pessimistically-coupled axions even if they are a minority fraction of the dark-matter halo.

# 4 cavity array – engineering run

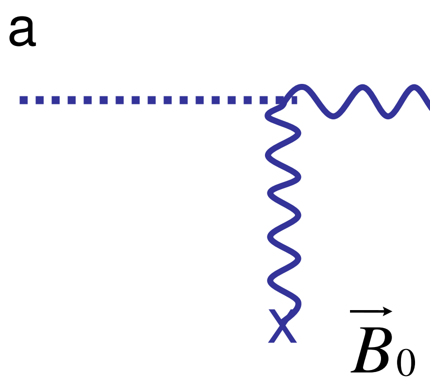


**Piezo motors have low power dissipation, work at low temperatures and high magnetic fields**



- **Phase I will incorporate SQUIDs for the first time**
- **The physical temperature will remain T = 1.3 K, but the system noise temperature will be $T_S \sim 1.5$ K**

# Axion to photon conversion in a magnetic field



in vacuum probability

$$p(a \longleftrightarrow \gamma) = \left(\frac{\alpha \; g_\gamma}{\pi \; f_a}\right)^2 \mathrm{B}_0{}^2 \left(\frac{\sin \frac{q_z L}{2}}{q_z}\right)^2$$

with $$q_z = \frac{m_a{}^2 - \omega_{\mathrm{pl}}{}^2}{2E_a}$$

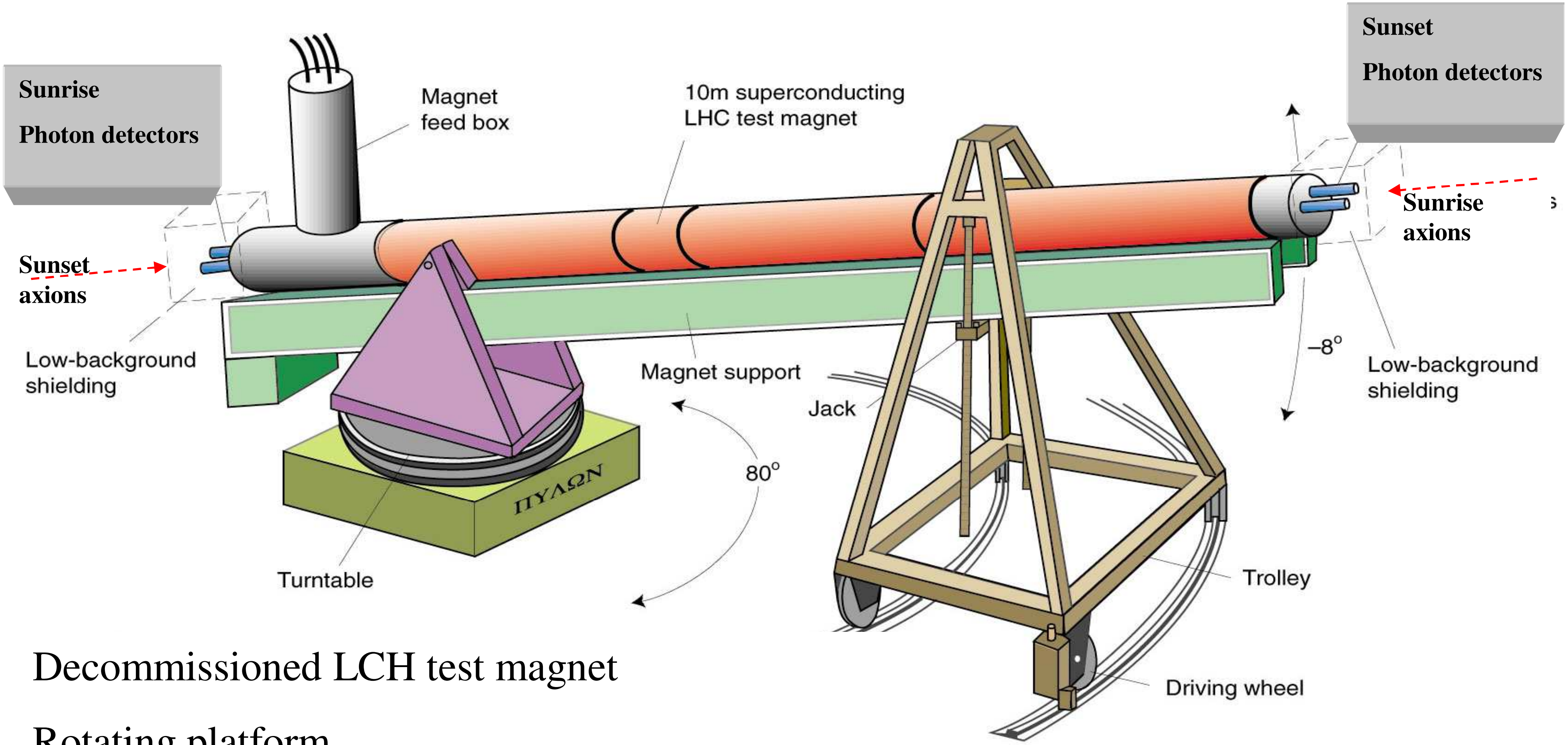
Theory

- P. S. '83
- L. Maiani, R. Petronzio and E. Zavattini '86
- K. van Bibber et al. '87
- G. Raffelt and L. Stodolsky, '88
- K. van Bibber et al. '89

Experiment

- D. Lazarus et al. '92
- R. Cameron et al. '93
- S. Moriyama et al. '98, Y. Inoue et al. '02
- K. Zioutas et al. 04
- E. Zavattini et al. 05

# Cern Axion Solar Telescope



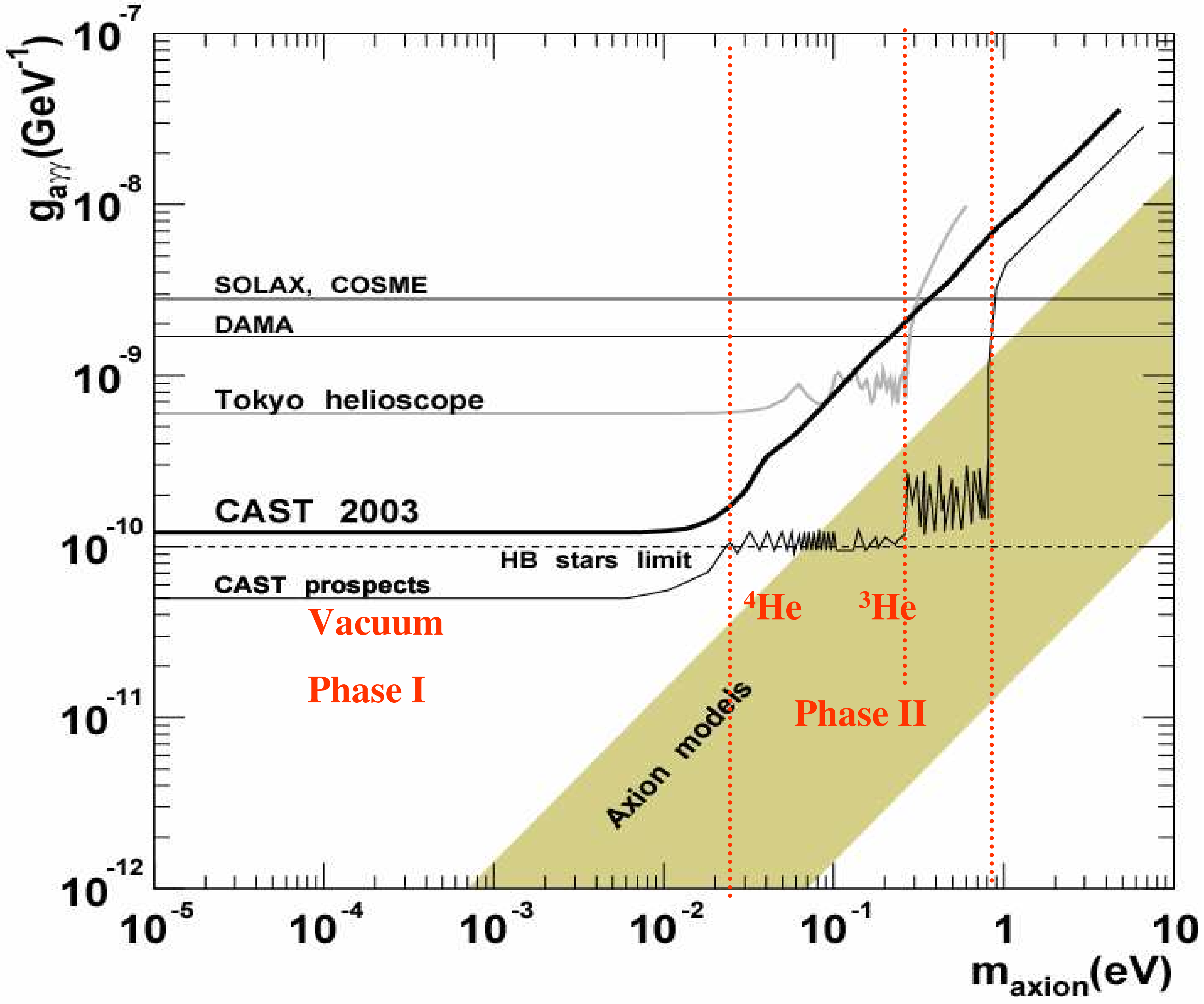
Decommissioned LCH test magnet

Rotating platform

3 X-ray detectors

X-ray Focusing Device

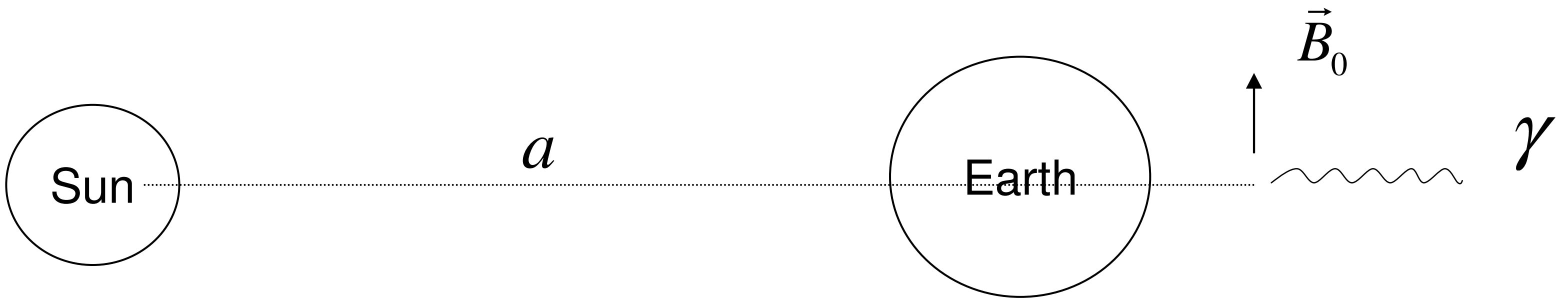

DIPOLE PROTOTYPE
CAST
ANSALDO OIE
EUROPAMETALLI – LMI
E. ZANON


$g_{a\gamma\gamma}$ (GeV$^{-1}$)
$10^{-7}$
$10^{-8}$
$10^{-9}$
$10^{-10}$
$10^{-11}$
$10^{-12}$
SOLAX, COSME
DAMA
Tokyo helioscope
CAST 2003
HB stars limit
CAST prospects
Axion models
Vacuum
Phase I
$^4$He
$^3$He
Phase II
$10^{-5}$
$10^{-4}$
$10^{-3}$
$10^{-2}$
$10^{-1}$
1
10
$m_{axion}$(eV)

# Detecting solar axions using Earth's magnetic field

by H. Davoudiasl and P. Huber

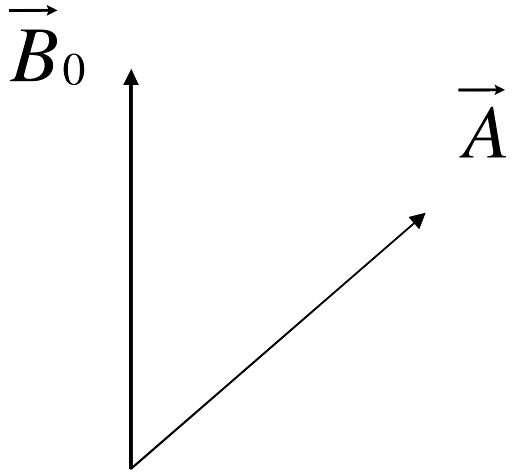
hep-ph/0509293



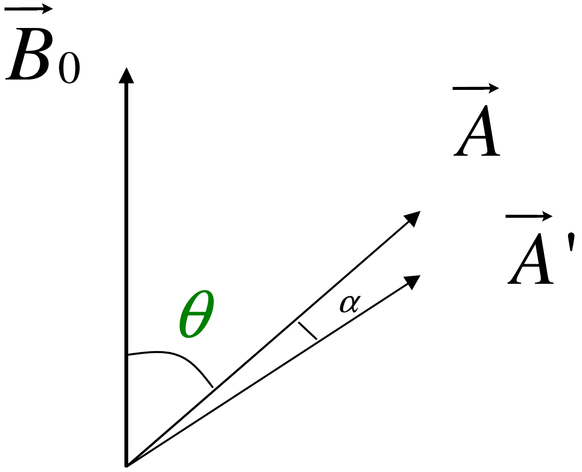
For axion masses $m_a \leq 10^{-4}\,\mathrm{eV}$, a low-Earth-orbit x-ray detector with an effective area of $10^4\,\mathrm{cm}^2$, pointed at the solar core, can probe down to $M_a \sim 10^{11}\,\mathrm{GeV}$, in one year.

$$(L_{a\gamma\gamma} = \frac{1}{M_a}\, a\, \vec{E}\cdot\vec{B})$$

# Linearly polarized light in a constant magnetic field



# Rotation



$$A'_{//} = A_{//}\,(1 - \frac{1}{2}p - i\psi)$$

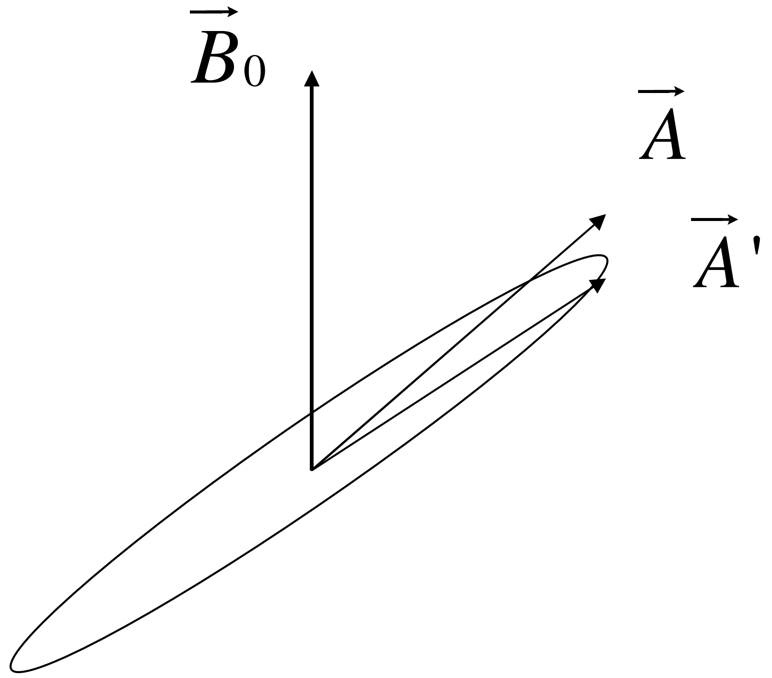
$$A'_{\perp} = A_{\perp}$$

$$p = 4\frac{B_0{}^2\omega^2}{M_a{}^2 m_a{}^4}\sin^2\left(\frac{m_a{}^2 L}{4\omega}\right)$$

$$\frac{\alpha g_{\gamma}}{\pi f_a} = g_{a\gamma\gamma} = \frac{1}{M_a}$$

$$\alpha = -\frac{1}{4}p\sin(2\theta)$$

# Rotation and Ellipticity



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$$A'_{\perp} = A_{\perp}$$

$$p = 4\frac{B_0{}^2\omega^2}{M_a{}^2 m_a{}^4}\sin^2\left(\frac{m_a{}^2 L}{4\omega}\right)$$

$$\psi = 2\frac{B_0{}^2\omega^2}{M_a{}^2 m_a{}^4}\left[\frac{m_a{}^2 L}{2\omega} - \sin\left(\frac{m_a{}^2 L}{2\omega}\right)\right]$$

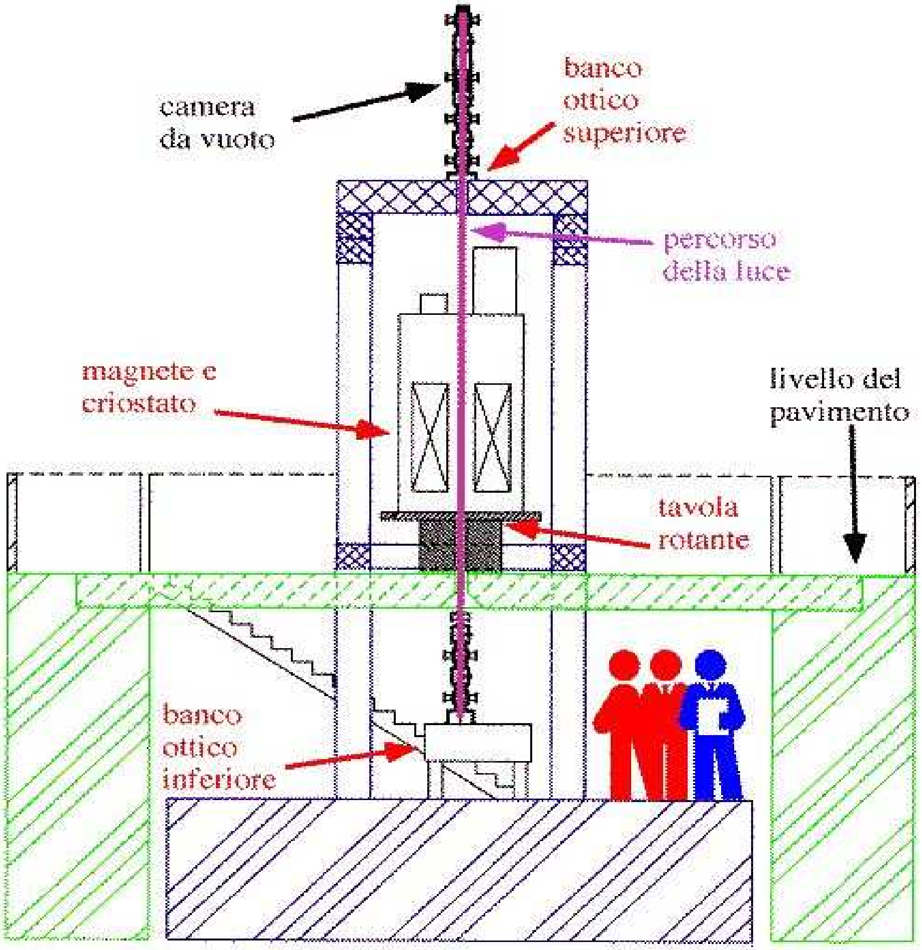
$$\frac{\alpha g_\gamma}{\pi f_a} = g_{a\gamma\gamma} = \frac{1}{M_a}$$

# Experimental observation of optical rotation generated in vacuum by a magnetic field

by E. Zavattini et al. (the PVLAS collaboration)
hep-ex/0507107

the average measured optical rotation is
$(3.9 \pm 0.5)\ 10^{-12}$ rad/pass
through a 5 T, 1 m long magnet

# PVLAS


camera
da vuoto
banco
ottico
superiore
percorso
della luce
magnete e
criostato
livello del
pavimento
tavola
rotante
banco
ottico
inferiore

# The PVLAS result can be interpreted in terms of an axion-like particle b

$$L_{b\gamma\gamma} = \frac{1}{M_b} b\, \vec{E} \cdot \vec{B}$$

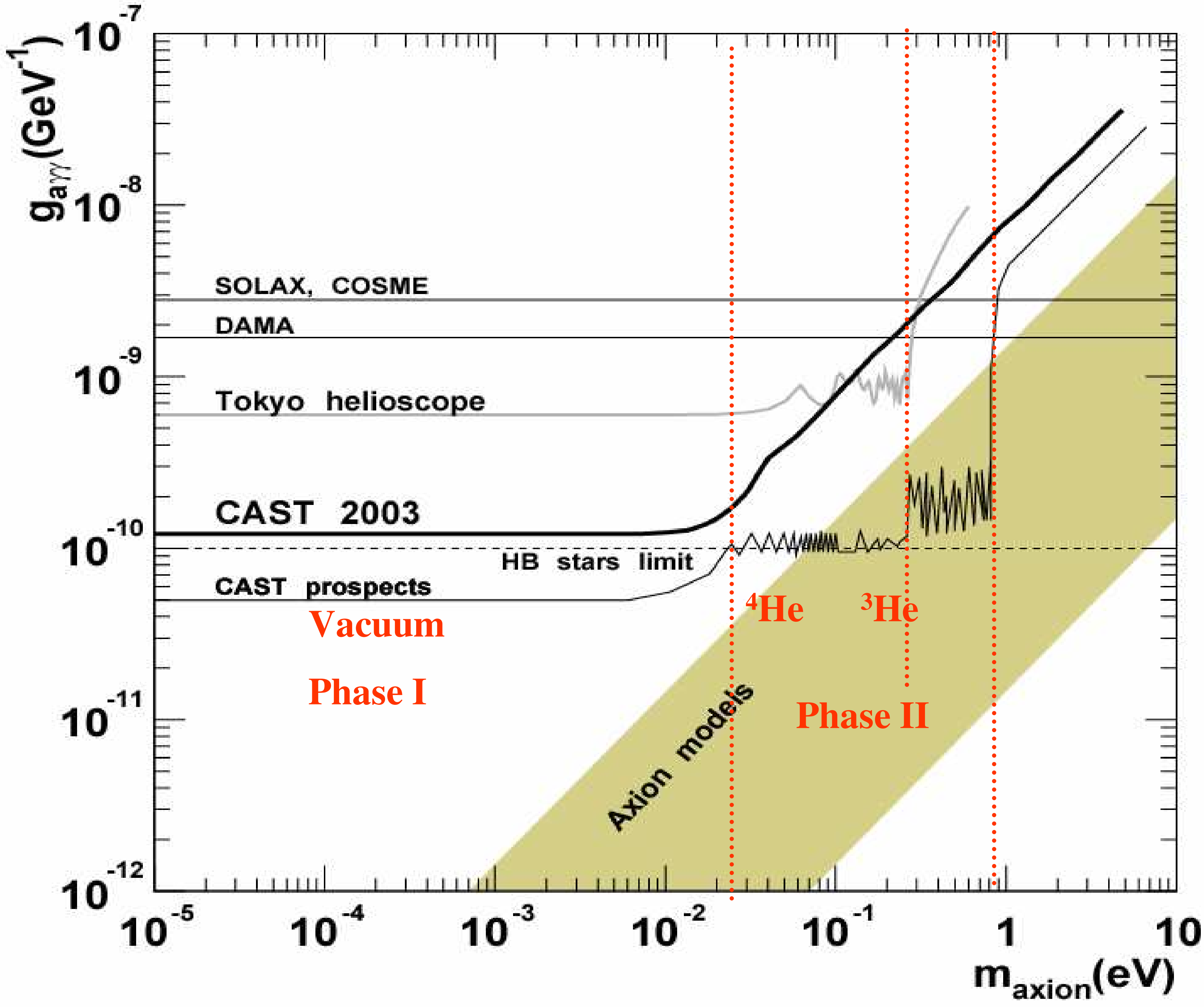
$$1 \cdot 10^5 \text{ GeV} \leq M_b \leq 6 \cdot 10^6 \text{ GeV}$$

$$0.7 \text{ meV} \leq m_b \leq 2 \text{ meV}$$

inconsistent with solar axion searches, stellar evolution

descrepancy may be avoided in some models

E. Masso and J. Redondo, hep-ph/0504202



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SOLAX, COSME
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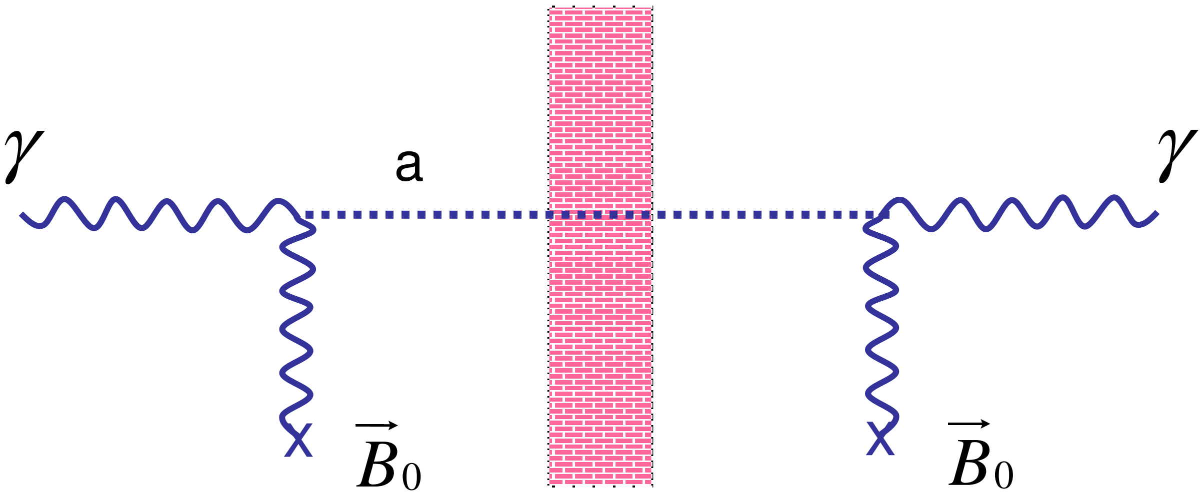
Axion models
Vacuum
Phase I
$^4$He
$^3$He
Phase II

# Shining light through walls



K. van Bibber
et al. ‘87

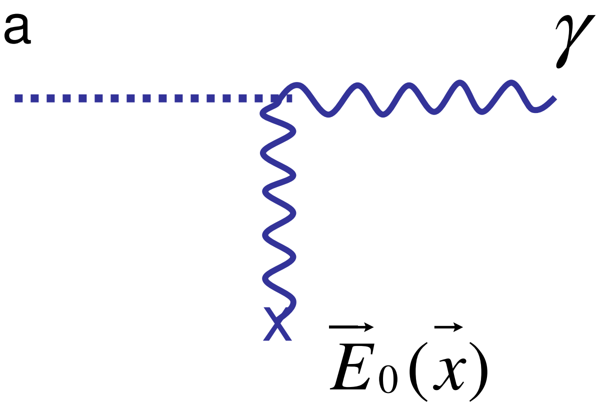
A. Ringwald ‘03

R. Rabadan,
A. Ringwald and
C. Sigurdson ‘05

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

P. Pugnat et al. ‘05

# Primakoff conversion of solar axions in crystals on Earth



Solax, Cosme ’98

Ge

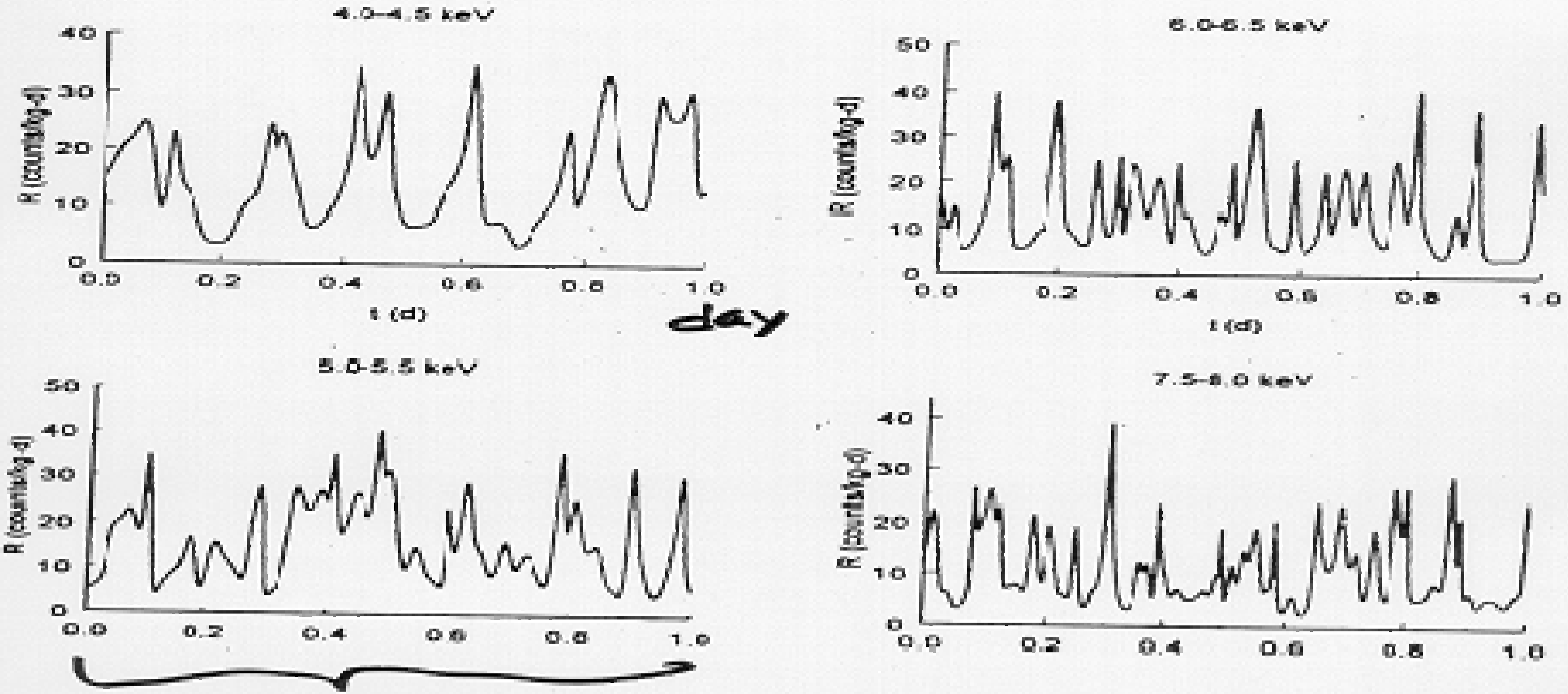
DAMA ‘01

NaI (100 kg)

$E_a =$ few keV

Bragg scattering on crystal lattice

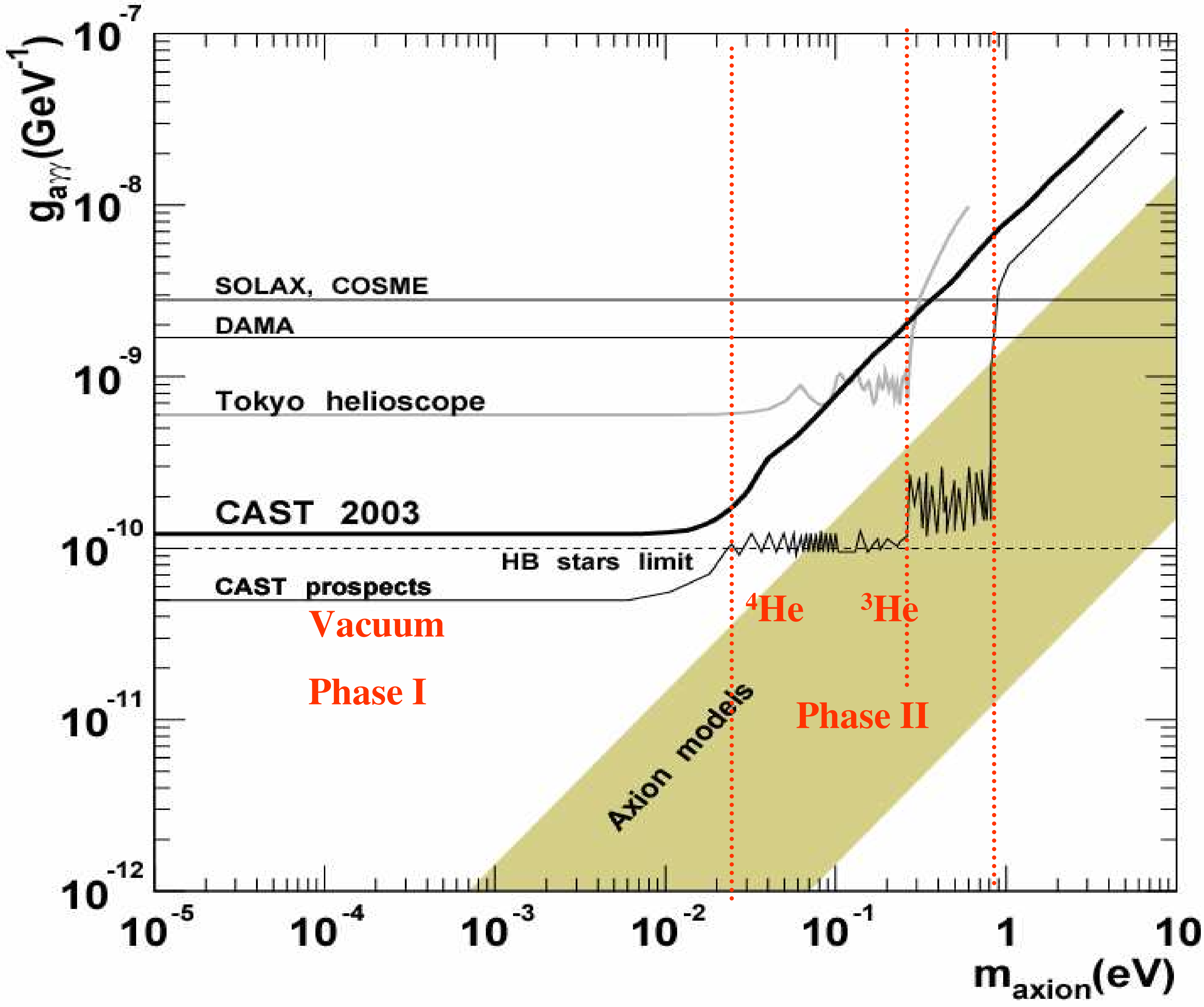
# Ge



day

1 day

Changes every day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$m_{axion}$(eV)
SOLAX, COSME
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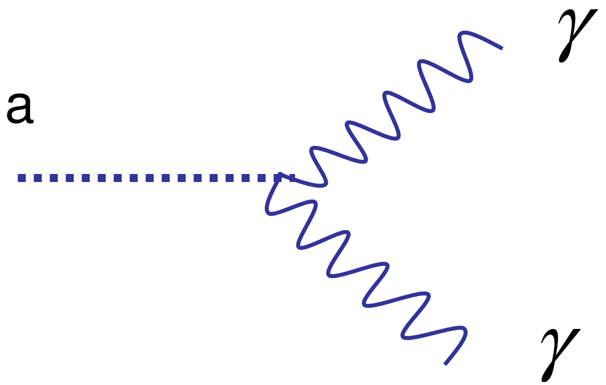
Axion models
Vacuum
Phase I
$^4$He
$^3$He
Phase II

# Telescope search for cosmic axions



M.S. Bershady, M.T.Ressell and M.S. Turner ’90

galaxy clusters

3 – 8  eV

B.D. Blout et al. ‘02

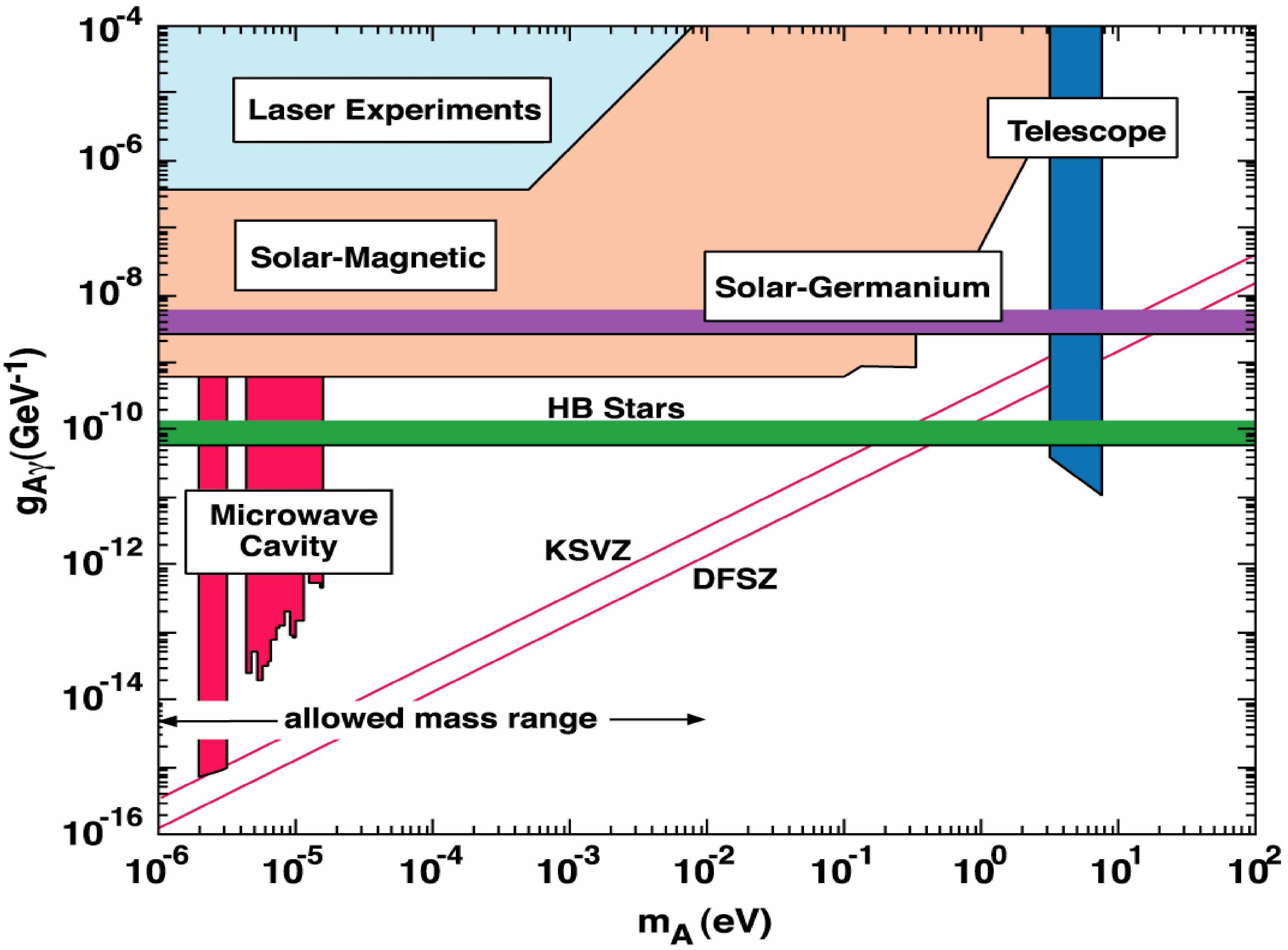
nearby dwarf galaxies

298 – 363  $\mu$eV

$$g_{a\gamma\gamma} < 1.0 \cdot 10^{-9}\ \mathrm{GeV}^{-1}$$

$$E_\gamma = \frac{m_a}{2}$$

$$\Gamma(a \to 2\gamma) = \frac{1}{0.67 \cdot 10^{25}\ \mathrm{sec}} \left(\frac{m_a}{\mathrm{eV}}\right)^5 \left(\frac{g_\gamma}{0.36}\right)^2$$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allowed mass range
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$10^{-1}$
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# Macroscopic forces mediated by axions

$$L_{a\bar{f}f} = g_f \frac{m_f}{f_a} a \bar{f} \left( i\gamma_5 + \theta_f \right) f$$

forces coupled to
the f spin density

background of
magnetic forces

forces coupled to
the f number density

$$\vartheta_f \square 10^{-17}$$

Theory:

J. Moody and
F. Wilczek ’84

Experiment:

A. Youdin et al. ’96
W.-T. Ni et al. ‘96

# Conclusions

Axions solve the strong CP problem and are a cold dark matter candidate.

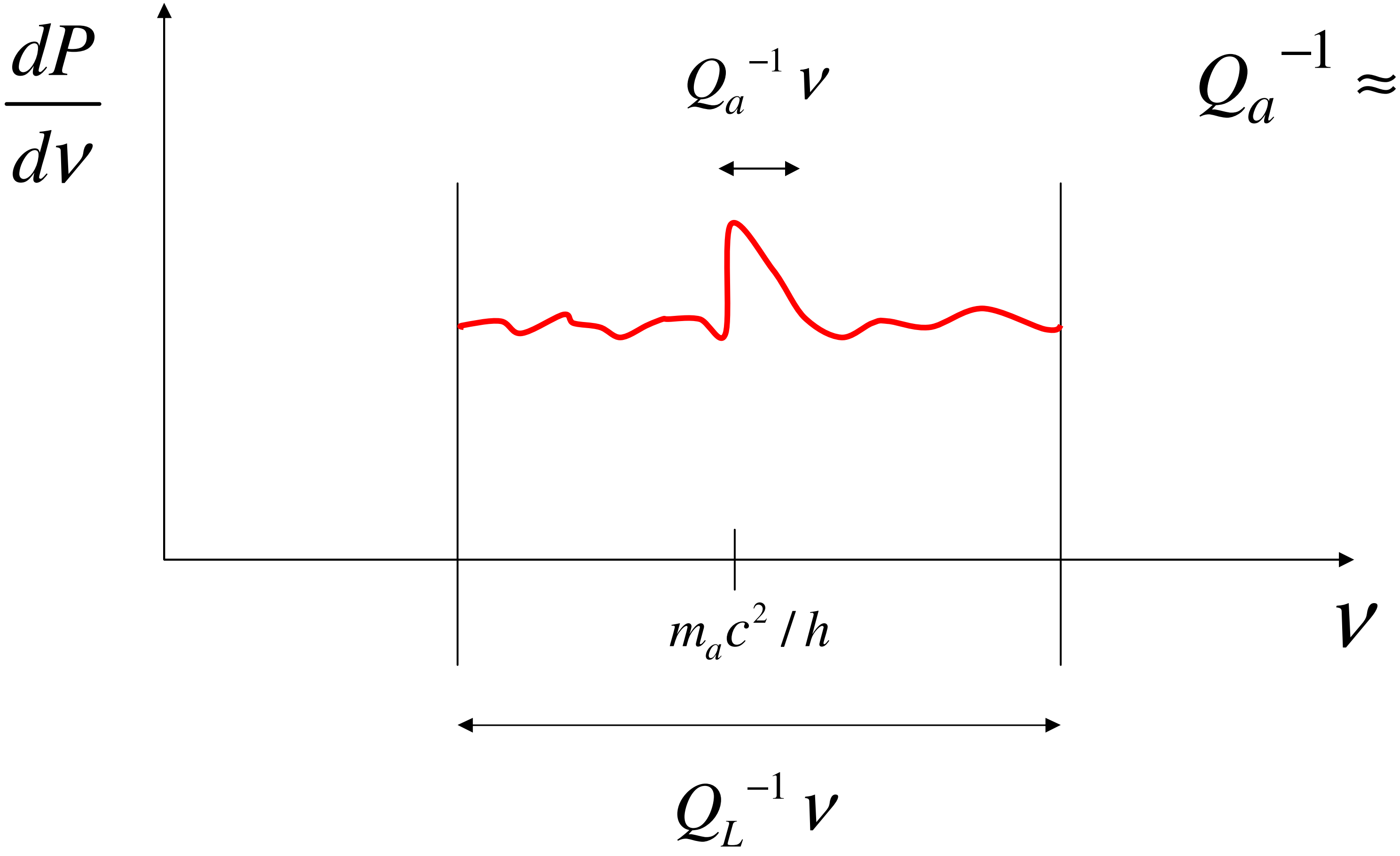
Axions haven't been found yet.

If axions exist, they are present on Earth as dark matter and emitted by the Sun.

If an axion signal is found, it will provide a rich trove of information on the structure of the Milky Way halo, and/or the Solar interior.

$$h\nu = m_a c^2 \left(1 + \frac{1}{2}\beta^2\right)$$

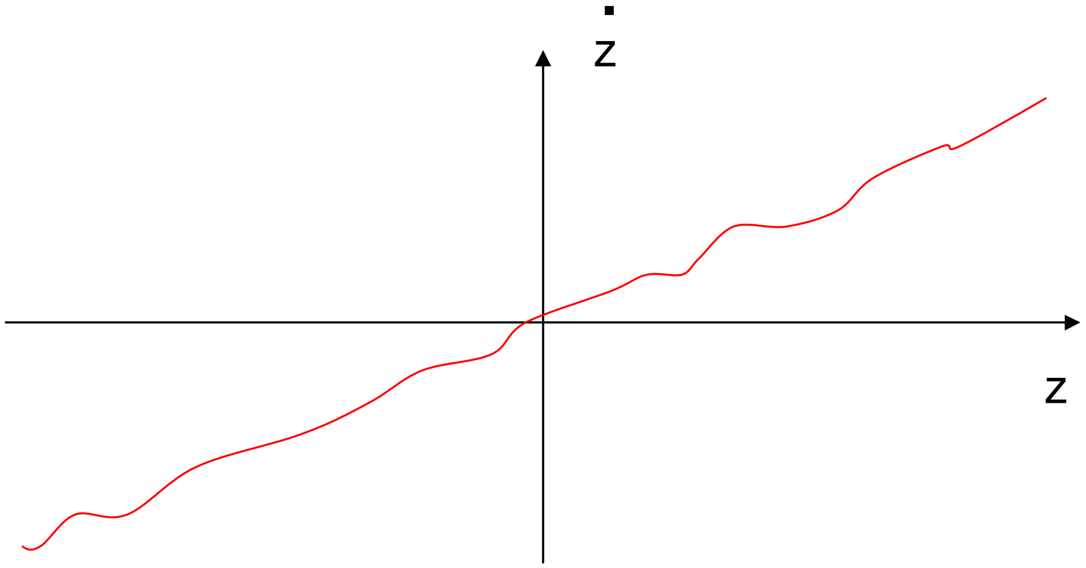
$$\beta = \frac{v}{c} \sim 10^{-3}$$



$$Q_a^{-1} \approx 10^{-6}$$

# The cold dark matter particles lie on a 3-dimensional sheet in 6-dimensional phase space

the physical density is the projection of the phase space sheet onto position space



$$\vec{v}\,(\vec{r},t) = H(t)\,\vec{r} + \Delta\,\vec{v}\,(\vec{r},t)$$

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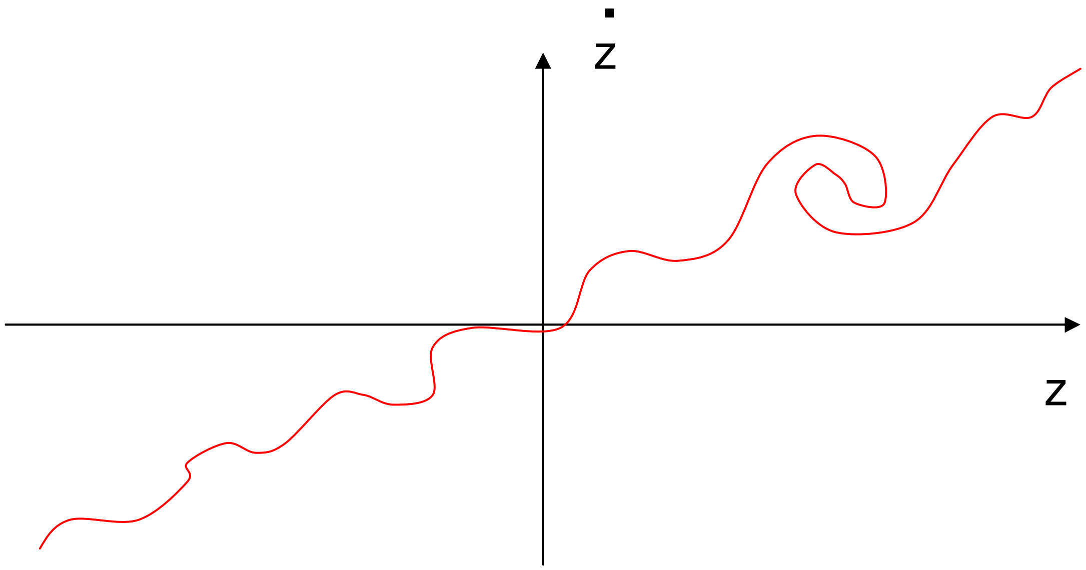


$$\vec{v}\,(\vec{r},t) = H(t)\,\vec{r} + \Delta\,\vec{v}\,(\vec{r},t)$$

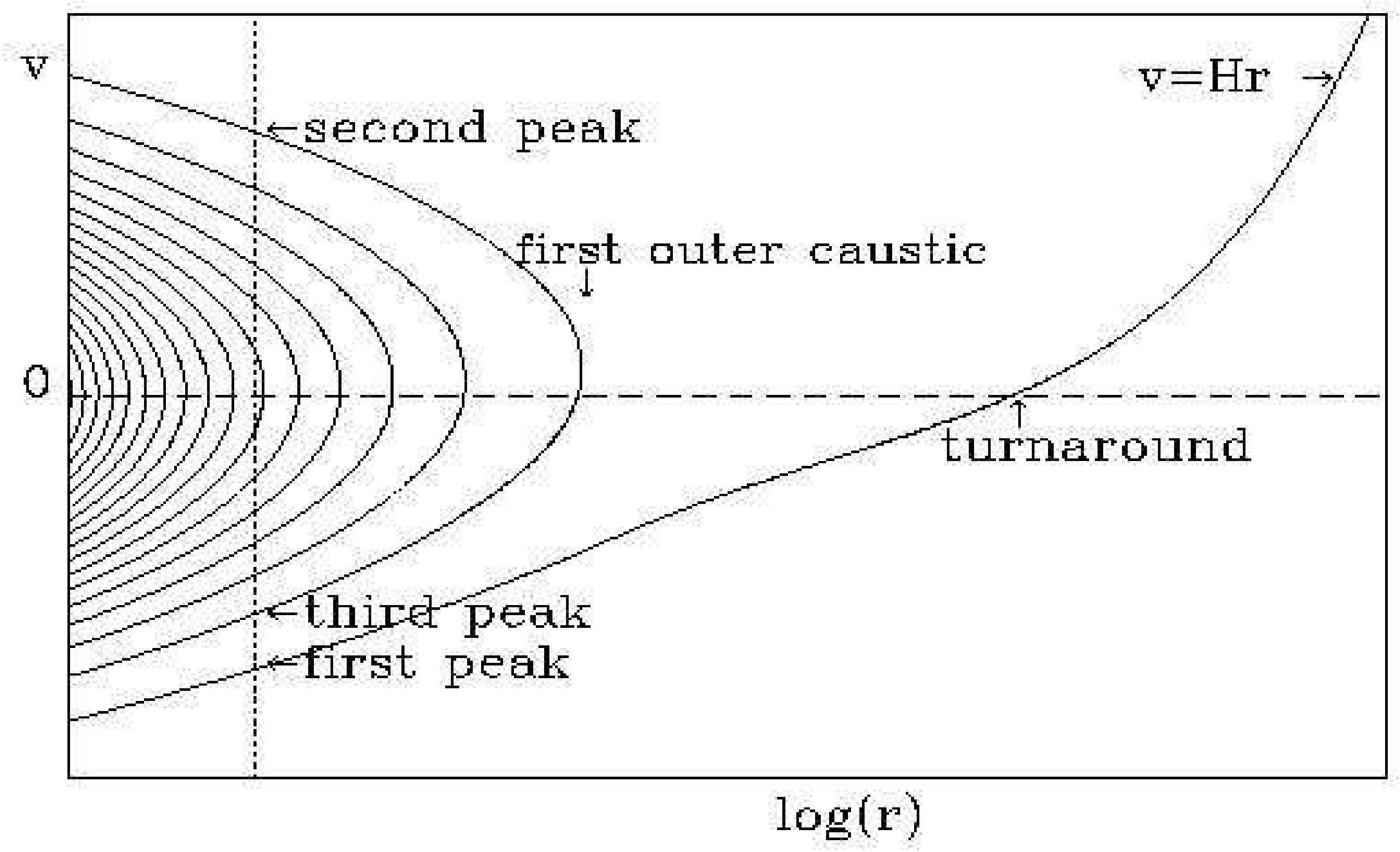
# Implications:

1. At every point in physical space, the distribution of velocities is discrete, each velocity corresponding to a particular flow

   at that location.

2. At some locations in physical space, where the number of flows changes, there is a caustic, i.e. the density of dark matter is very high there.

# Phase space structure of spherically symmetric halos



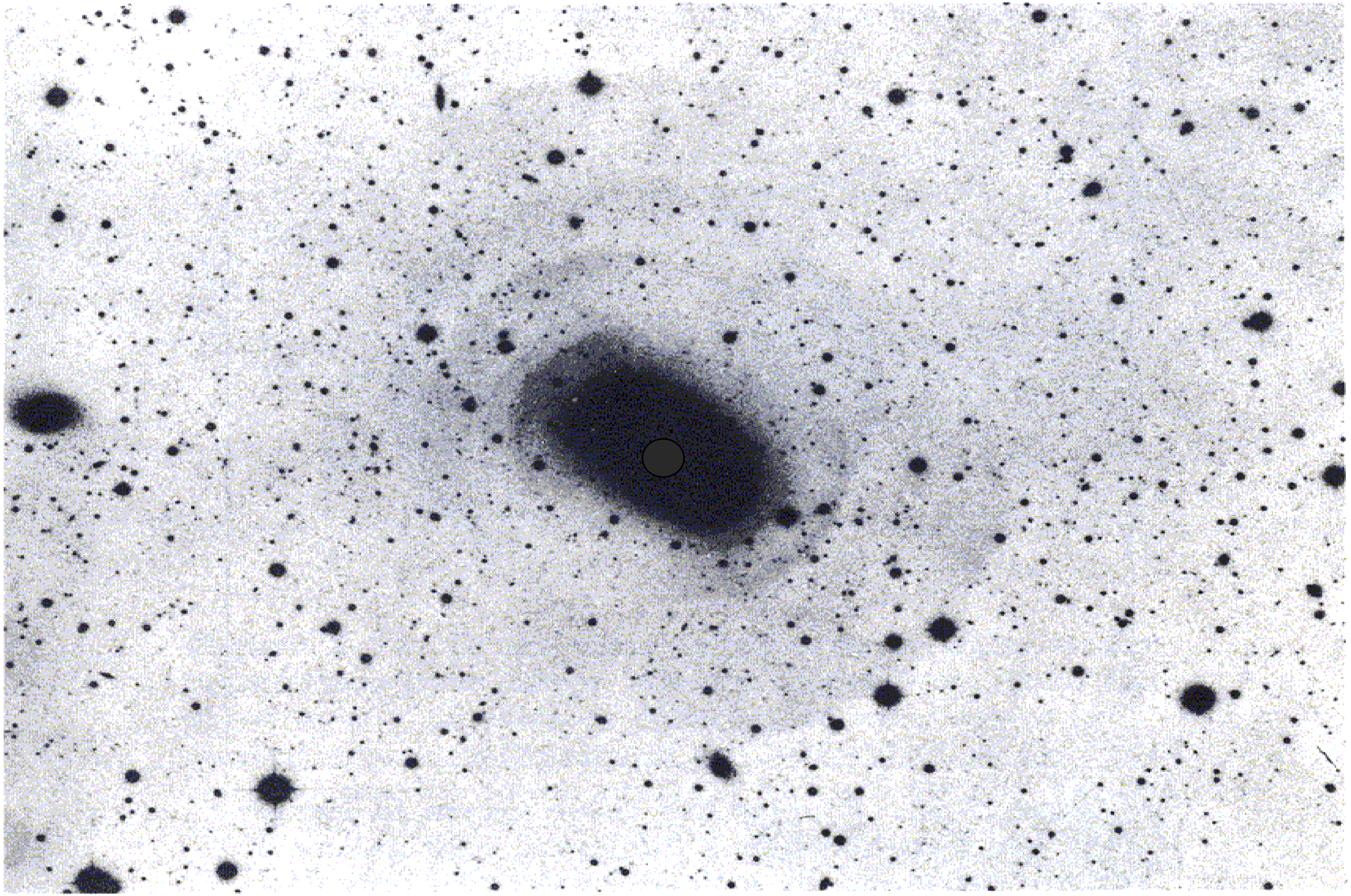


**Figure 7-22.** The giant elliptical galaxy NGC 3923 is surrounded by faint ripples of brightness. Courtesy of D. F. Malin and the Anglo-Australian Telescope Board.

(from Binney and Tremaine’s book)

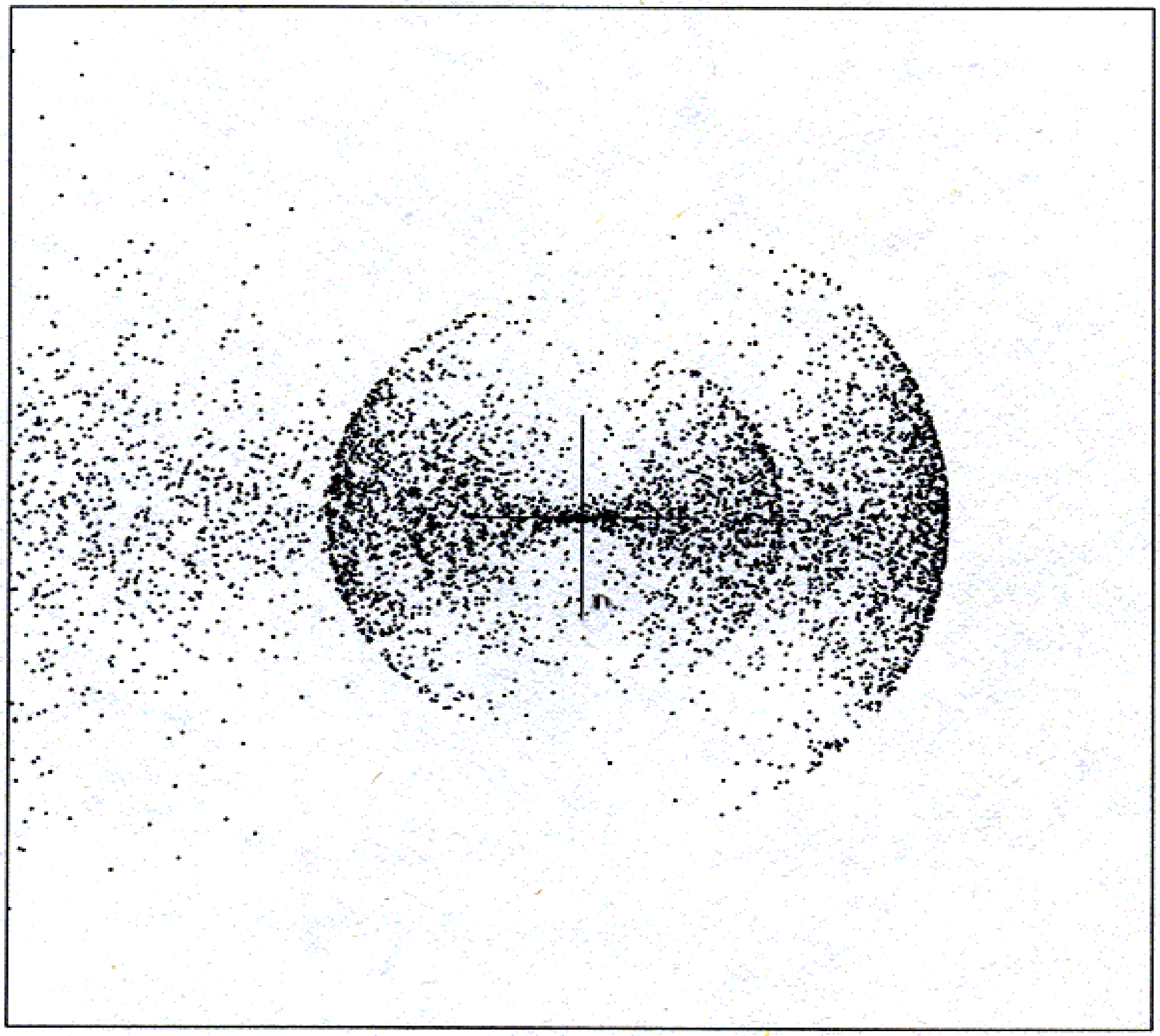
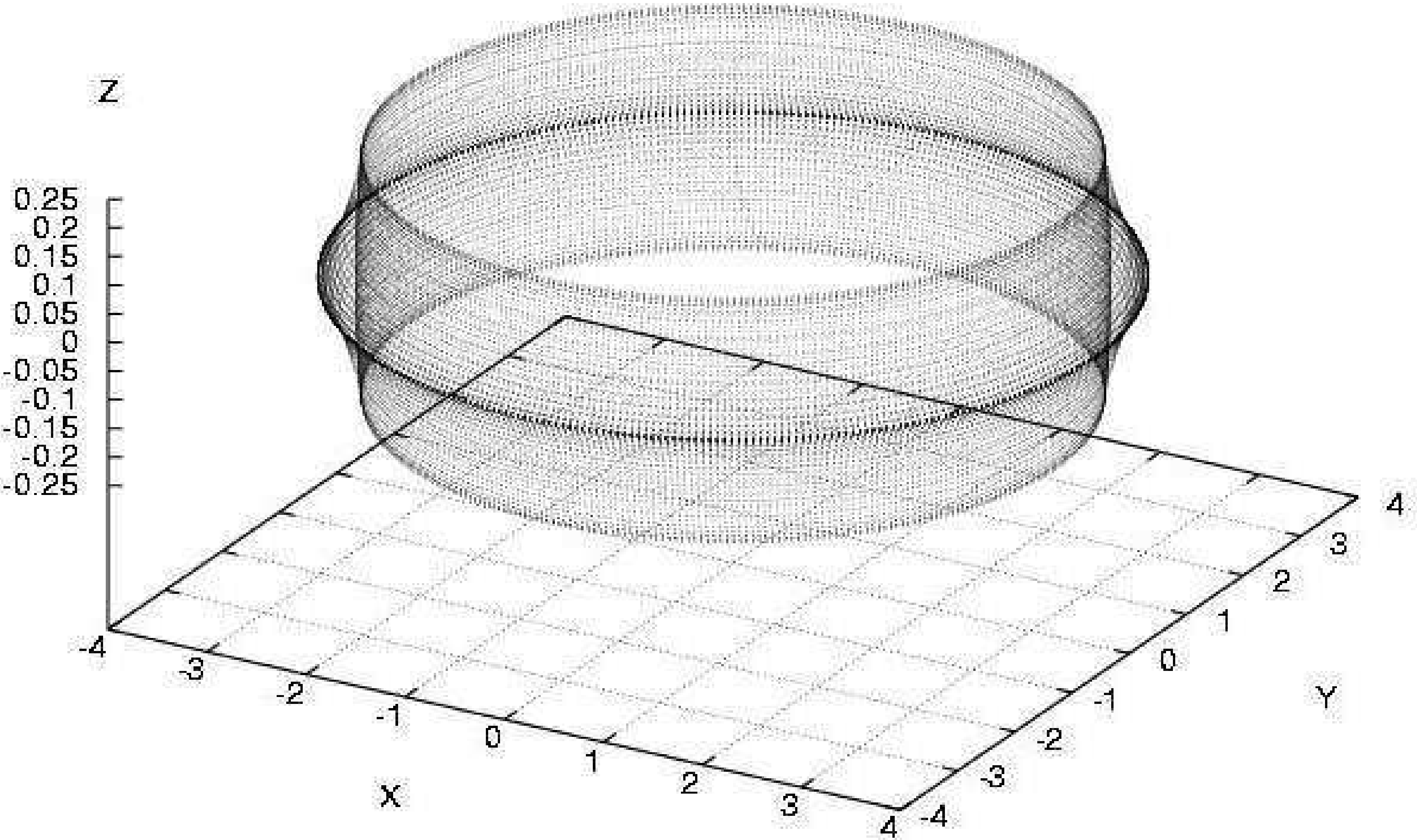
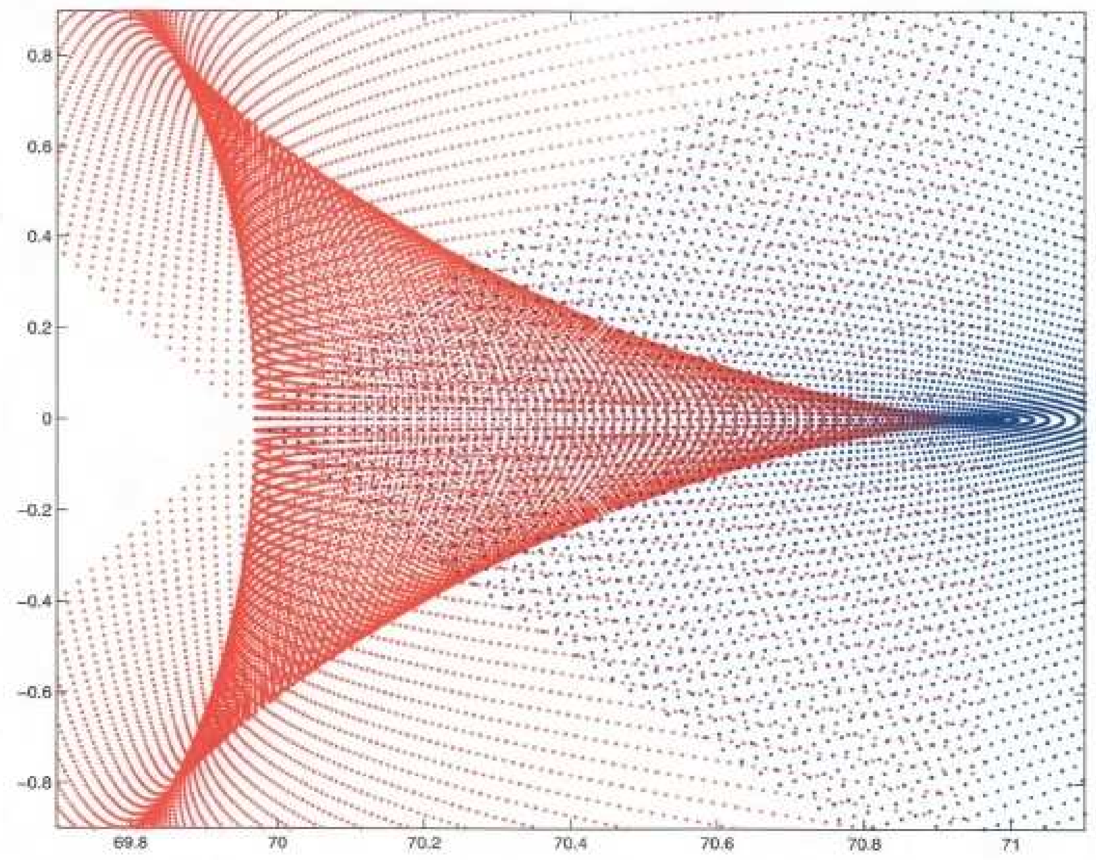


**Figure 7-23.** Ripples like those shown in Figure 7-22 are formed when a numerical disk galaxy is tidally disrupted by a fixed galaxy-like potential. (See Hernquist & Quinn 1987.)

simulation by Arvind Natarajan



# The caustic ring  cross-section



$D_{-4}$

an elliptic umbilic catastrophe

# The Big Flow

- density $d_5 \approx 1.7\ 10^{-24}\ \text{gr/cm}^3$

previous estimates of the total local halo density range from 0.5 to 0.75 $10^{-24}$ $\text{gr/cm}^3$

- velocity $\vec{v}_5^{\pm} \cong (470\ \hat{\phi} \pm 100\ \hat{r})\ \text{km/s}$

$\hat{\phi}$ in the direction of galactic rotation
$\hat{r}$ in the direction away from the galactic center

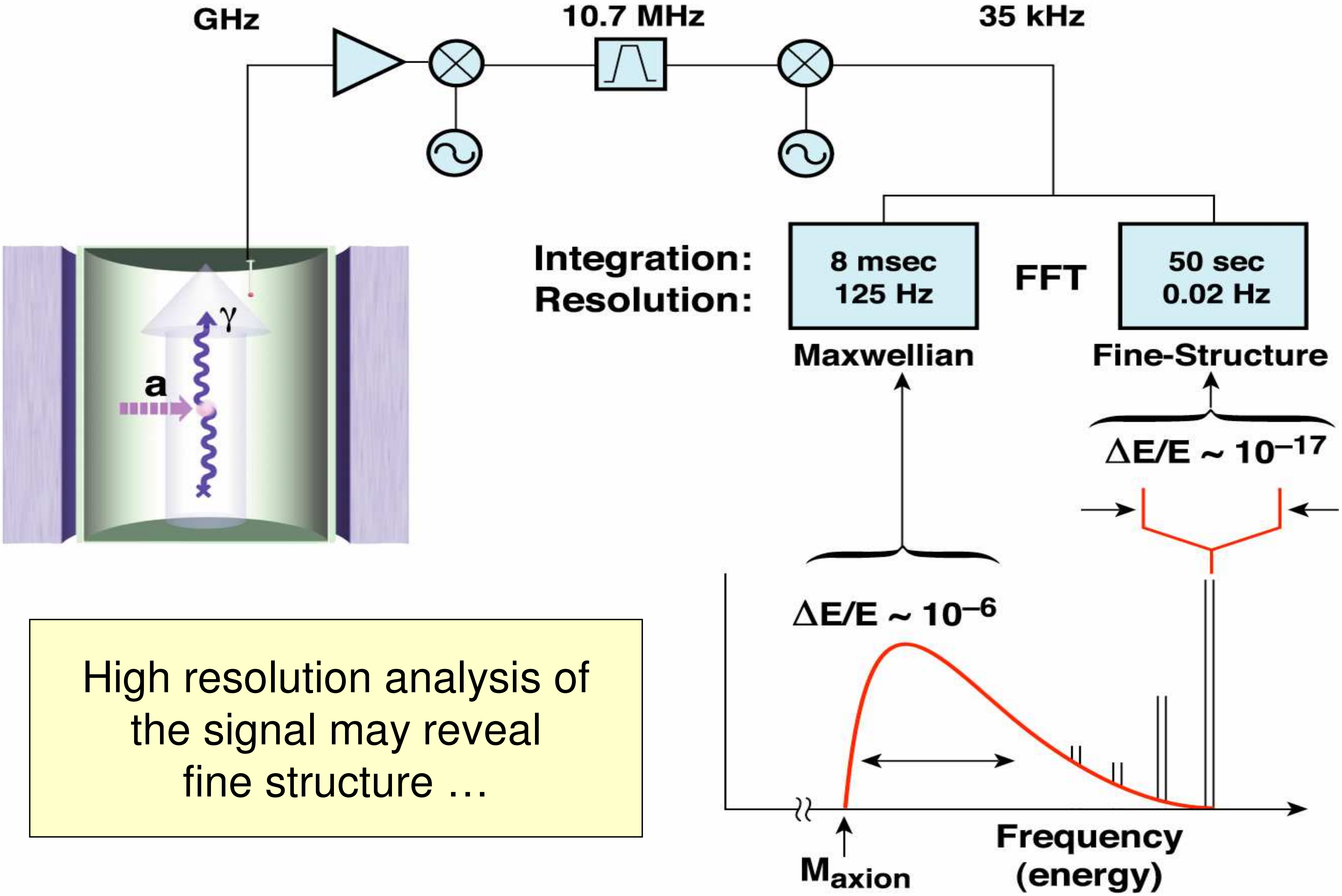
- velocity dispersion $\delta v_5 < 50\ \text{m/s}$

# Experimental implications

- for dark matter axion searches
 - peaks in the energy spectrum of microwave photons from $a \rightarrow \gamma$ conversion in the cavity detector
 - high resolution analysis of the signal yields a more sensitive search (with L. Duffy and ADMX collab.)

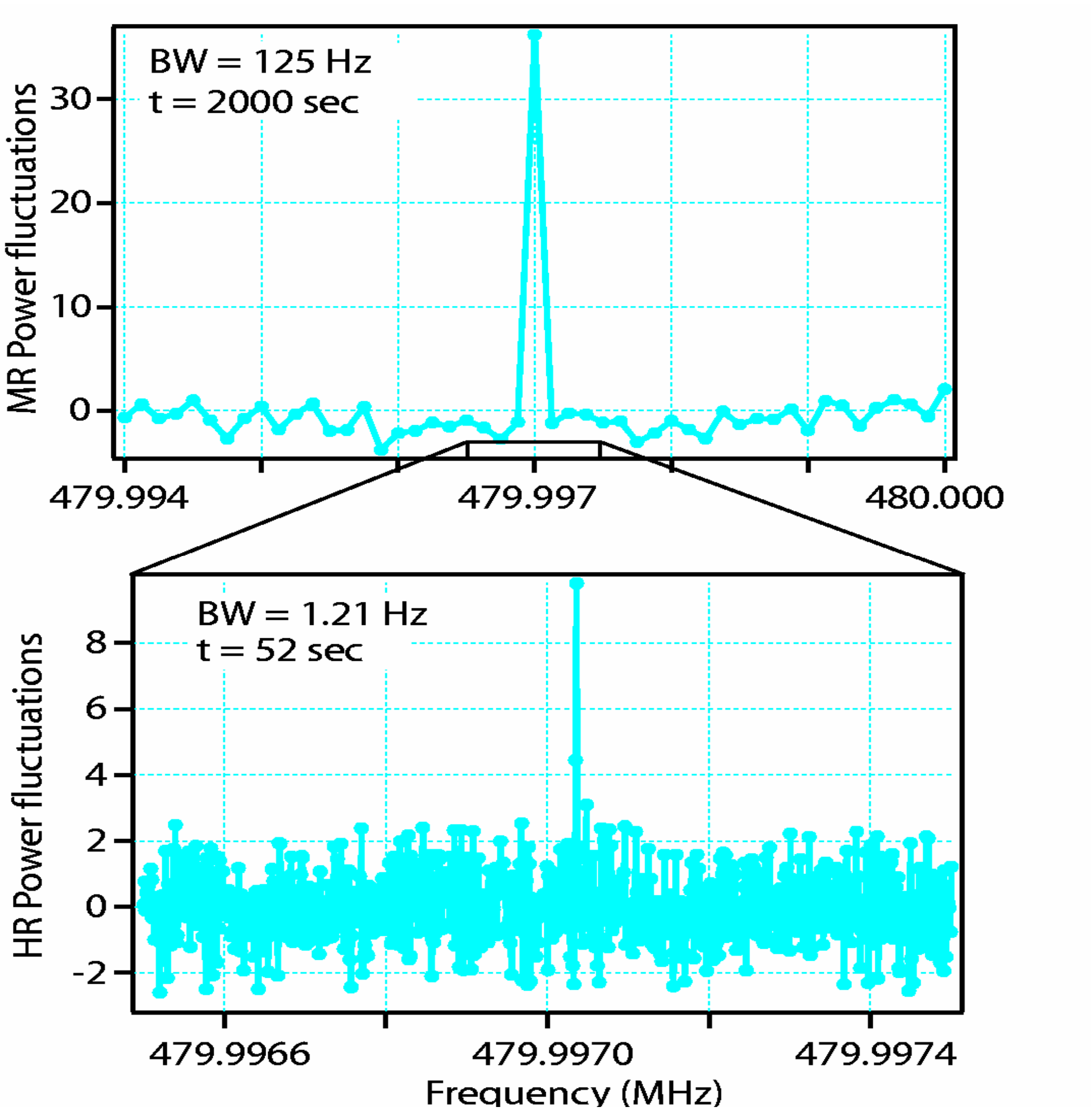
- for dark matter WIMP searches
 - plateaux in the recoil energy spectrum from elastic WIMP collisions with target nuclei
 - the flux is largest around December

(Vergados; Green; Gelmini and Gondolo; Ling, Wick &PS)



High resolution analysis of
the signal may reveal
fine structure …

# an environmental peak, as seen

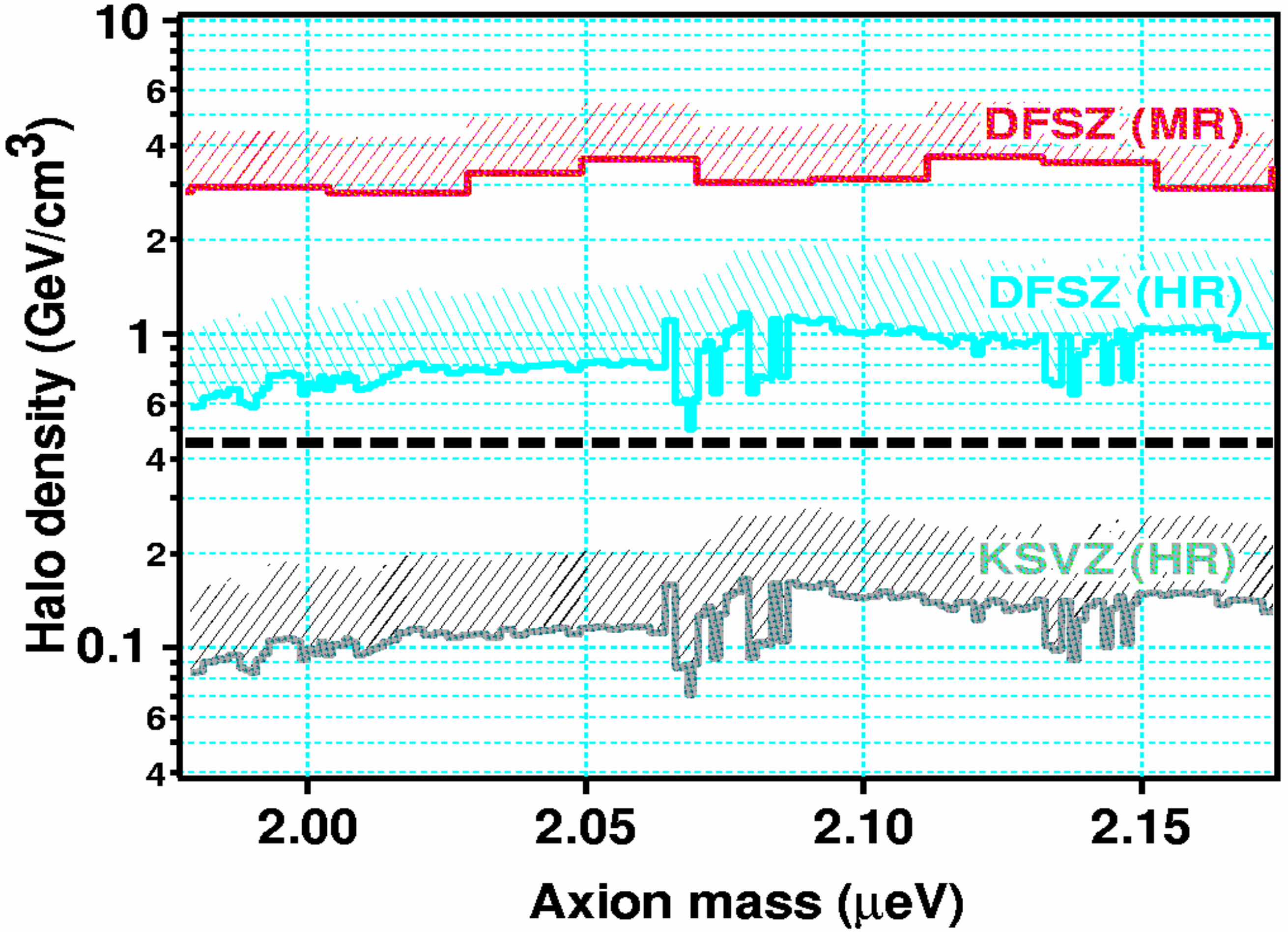


in the
medium

and

high
resolution
channels

# ADMX limit using high resolution (HR) channel



for $\delta v \leq 12\ \mathrm{m/s} \left( \frac{300\ \mathrm{km/s}}{v} \right)$

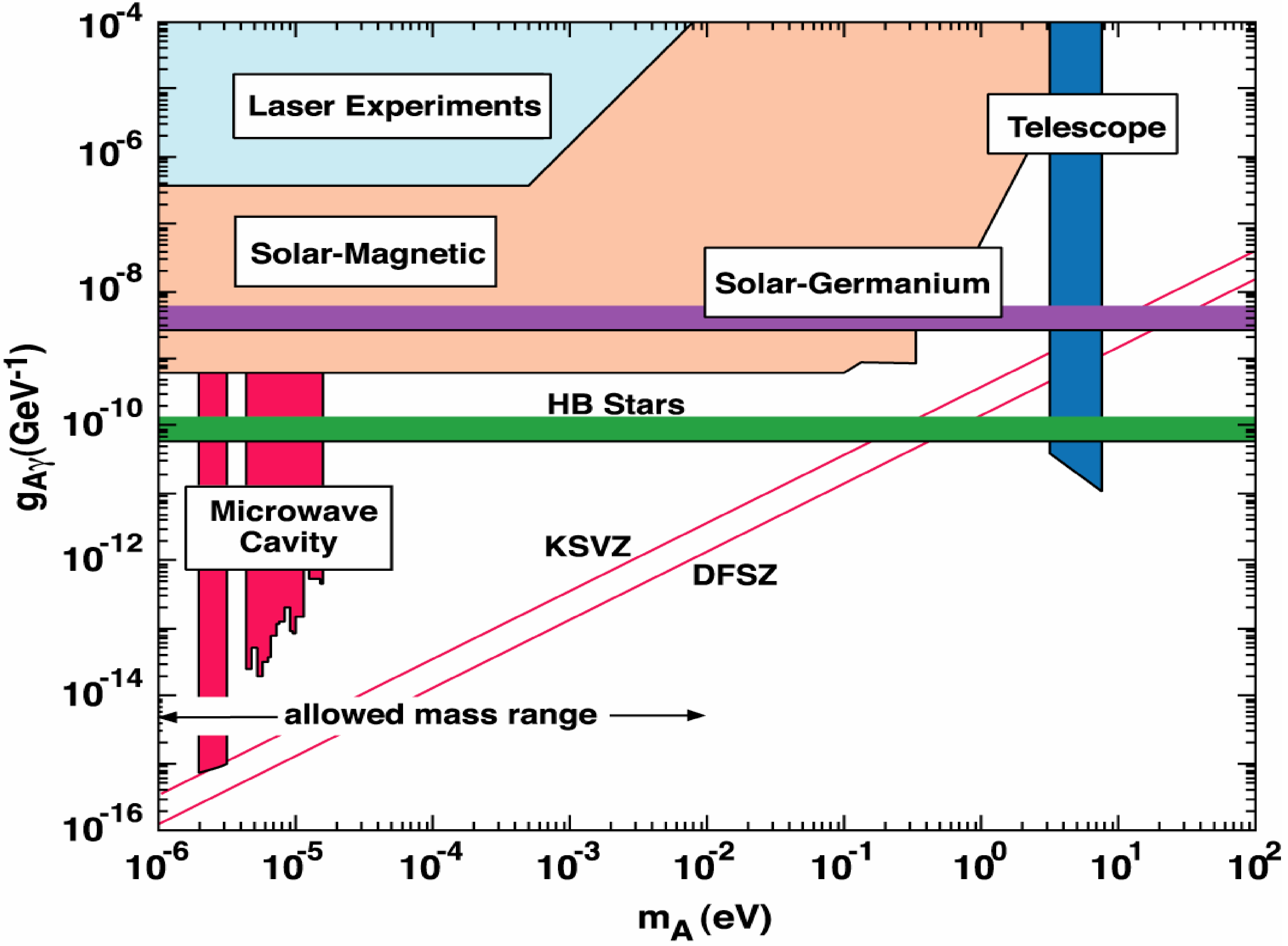
# Conclusions

Axions remain a viable cold dark matter candidate.

The upgraded ADMX will be able to find axions at even a fraction of the halo density.

Remaining challenge:  widen the searchable axion mass range.

If an axion signal is found, it will provide a rich trove of information on the structure of the Milky Way halo.



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$10^{2}$
$m_A$ (eV)

- the number of flows at our location in the Milky Way halo is of order 100
- small subhalos from hierarchical structure formation produce an effective velocity dispersion

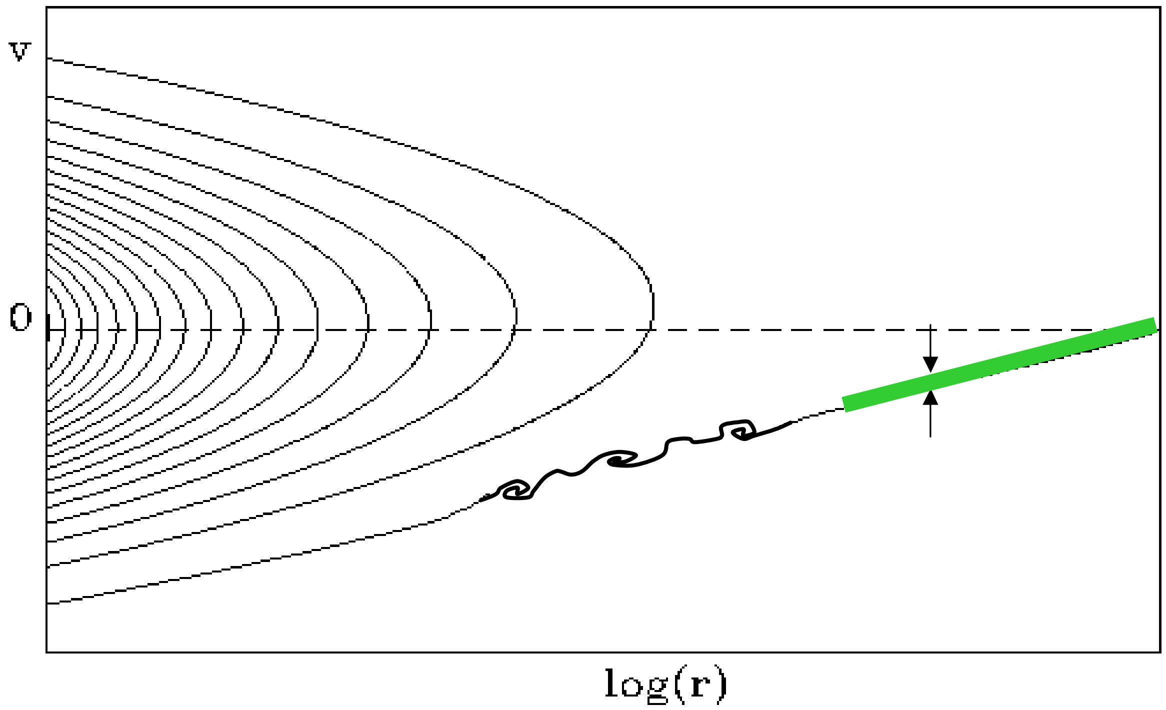
$$\delta v_{\mathrm{eff}} \leq 30\,\mathrm{km/s}$$

but do not destroy the sheet structure in phase space

- the known inhomogeneities in the distribution of matter are insufficient to diffuse the flows by gravitational scattering
- present N-body simulations do not have enough particles to resolve the flows and caustics

(see however: Stiff and Widrow, Bertschinger and Shirokov)

# Hierarchical clustering introduces effective velocity dispersion



$\delta v_{eff}$

$$\delta v_{eff} \leq 30\,\mathrm{km/s}$$