# Detection of Axions

Stanford Linear Accelerator Center
International Symposium on the Delelopment of Detectors …
April 4, 2006

QuickTime™ and a TIFF (Uncompressed) decompres are needed to see this picture.

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**University of Washington & Lawrence Livermore Lab**

# Properties of the axion

- The Axion is a light pseudoscalar resulting from the Peccei-Quinn mechanism to enforce strong-CP conservation
- $f_a$, the SSB scale of PQ-symmetry, is the one important parameter in the theory

### Mass and Couplings

$$m_a \sim 6\ \mu eV \cdot \left(\frac{10^{12}\ GeV}{f_a}\right)$$

Generically, all couplings

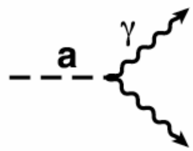
$$g_{aii} \propto \frac{1}{f_a}$$

### Cosmological Abundance

$$\Omega_a \sim \left(\frac{5\ \mu eV}{m_a}\right)^{7/6}$$

(Vacuum misalignment mechanism)

### Coupling to Photons




$$g_{a\gamma\gamma} = \frac{\alpha g_\gamma}{\pi f_a};\ g_\gamma = \begin{cases} 0.97\ \text{KSVZ} \\ -0.36\ \text{DFSZ} \end{cases}$$

### Axion Mass 'Window'

$10^{-(5\ \text{to}\ 6)}\ eV < m_a < 10^{-(2\ \text{to}\ 3)}\ eV$

(Overclosure) (SN1987a)

With lower end of window preferred if $\Omega_{CDM} \sim 1$

# Axions and dark matter

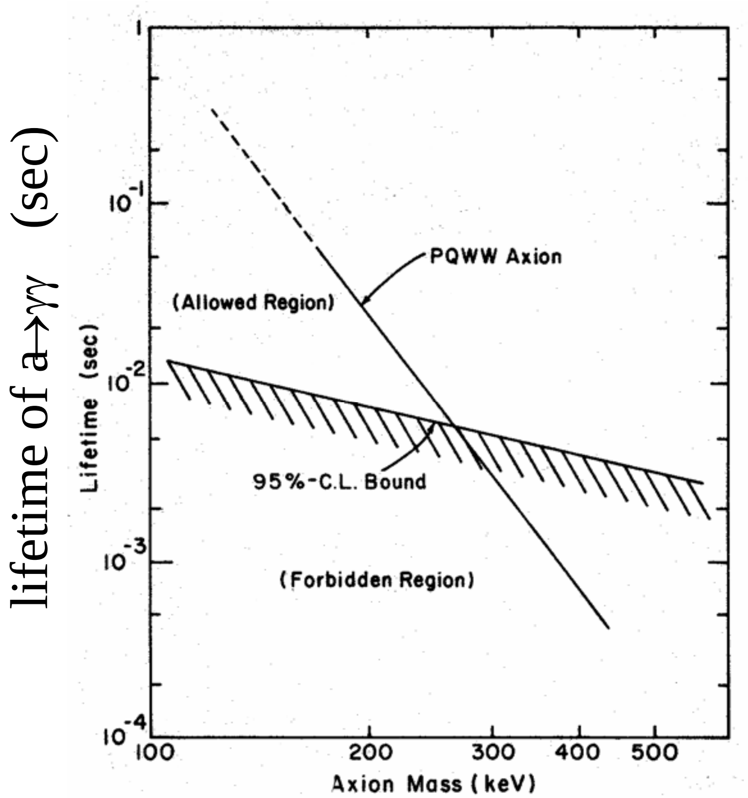
**Some properties of dark matter:**
Almost no interactions with normal matter and radiation (“dark…”);
Gravitational interactions (“…matter”);
Cold (slow-moving in the early universe);
If particles are low mass, it’s bosonic (to stuff enough into rich clusters).

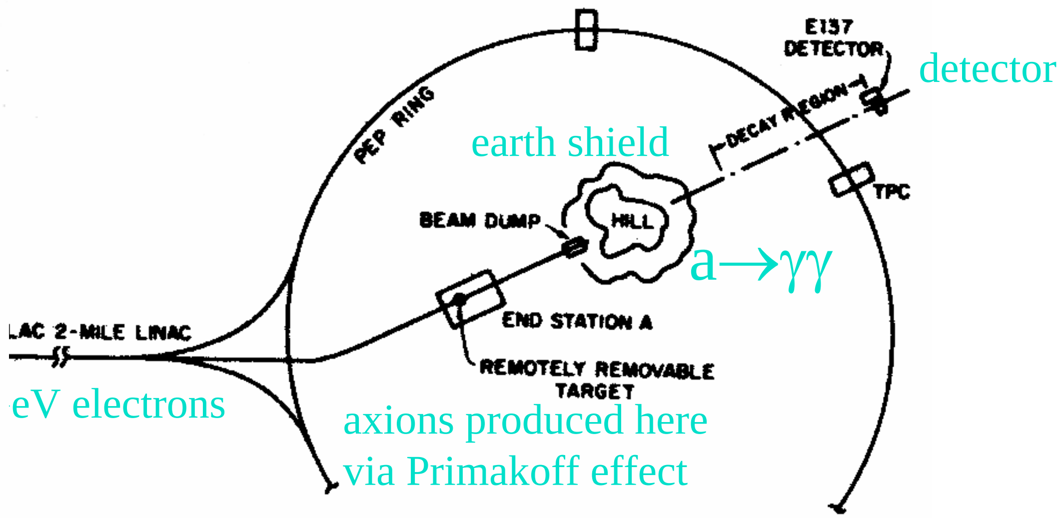
**Dark matter properties are those of a low-mass axion:**
**Low mass axions are an ideal dark matter candidate:**
**“Axions: the thinking persons dark-matter candidate”,**
**Michael Turner.**

Plus…
The axion mass is constrained to 1 or 2 orders-of-magnitude;
Some axion couplings are constrained to 1 order-of-magnitude;
The axion is doubly-well motivated…it solves 2 problems (Occam’s razor).

# Example of laboratory search:
# A heavy axion (a new $\pi^0$-like thing) is excluded

For example: SLAC E137 (Bjorken et al.)

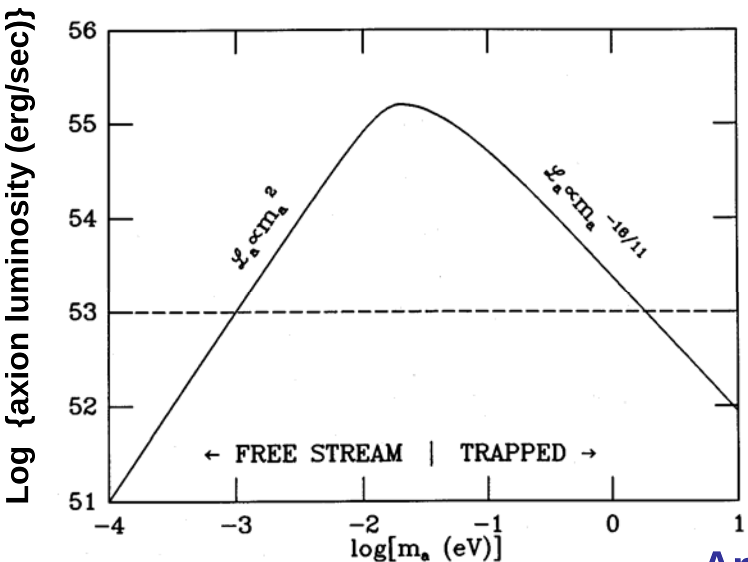



**$f_{PQ}$ must be considerably greater than the weak scale**

# Example of astrophysical bound: The axion mass is very small small

## The most sensitive bound: neutrinos from SN1987A




**Supernova in the LMC.**
**Neutrinos are trapped and diffuse out over timescales of around 10 seconds.**

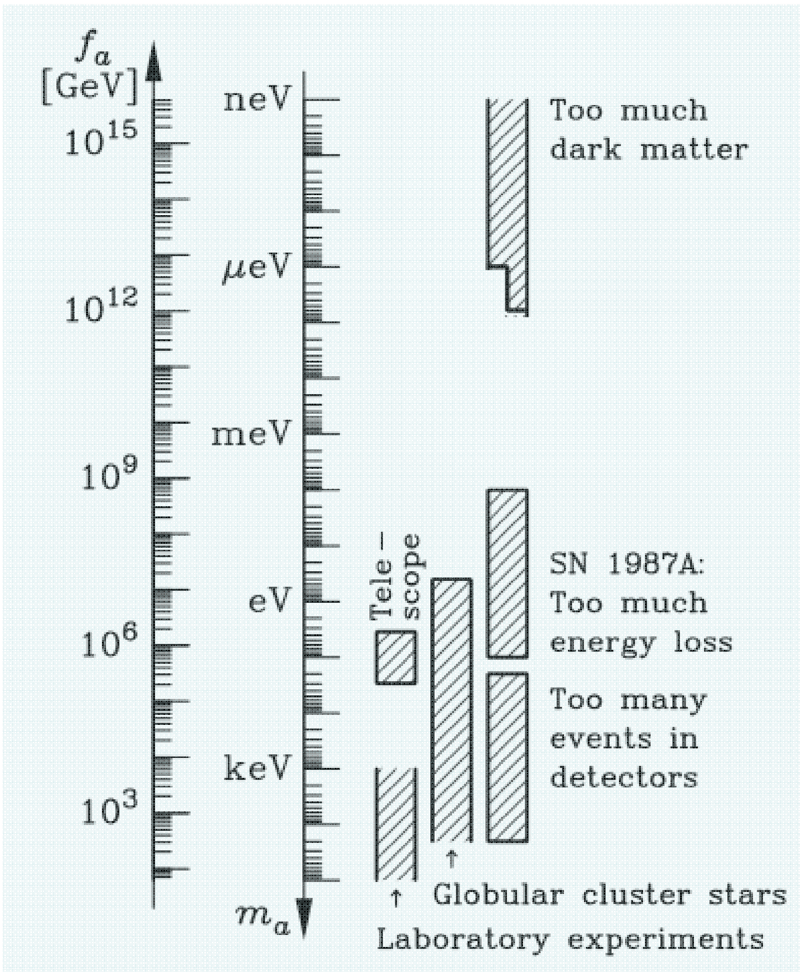
**Kamiokande and IMB together recorded 19 neutrinos from SN1987A.**

**An axion of mass between $10^{-3}$ and 2 eV would take so much energy out that...**

**the length of the explosion would be observably forshortened.**

**Overall summary: Astrophysics (stellar evolution and SN1987A), cosmology, and laboratory experiments leave the invisible CDM axion window $10^{-6} < m_a < 10^{-3}$ eV (with large uncertainties)**

# Present bounded window of allowed axion masses




Very light axions forbidden:
else too much dark matter

⇐Dark matter range:“axion window”
very hard to detect
“invisible axions”

Heavy axions forbidden:
else new pion-like particle

This assumes “standard” cosmology

# Axion search strategies: two main approaches

Produce then detect axions

versus

Detect cosmic axions

Doesn't require a substantial local halo axion density.

Since axions are cosmologically produced, they are necessarily in halos. (Infall argument.)

Produce and detect: very low rates since it's a product of 2 small couplings.

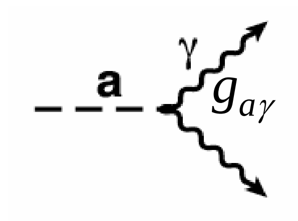
Detect: 1 factor of a small Coupling.

e.g., searches for solar axions (see following talk)

e.g., "RF-cavity" experiments

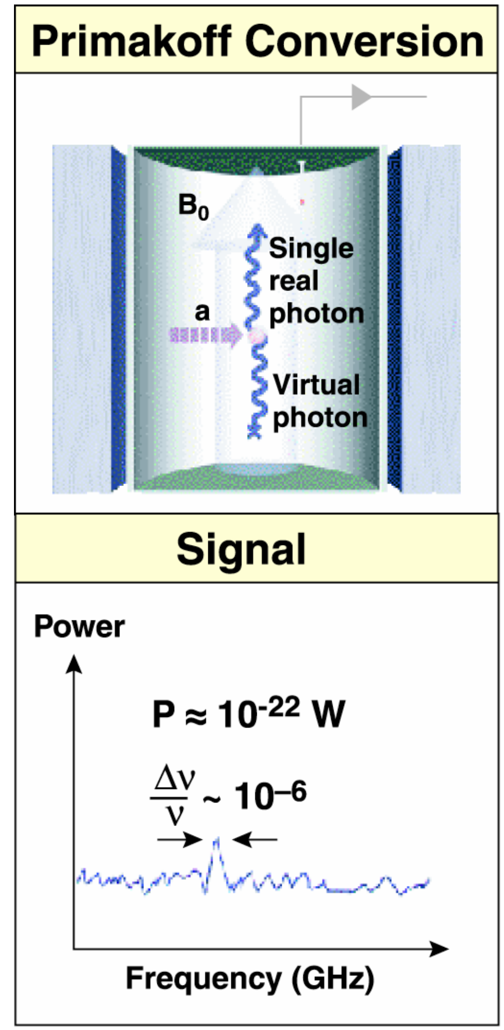
# RF cavity experiments…the most sensitive: Axion and electromagnetic fields exchange energy

The axion-photon coupling…




…is a source in Maxwell’s Equations

$$\frac{\partial(\mathbf{E}^2/2)}{\partial t} - \mathbf{E}\cdot(\nabla\times\mathbf{B}) = g_{a\gamma}\,\dot{a}(\mathbf{E}\cdot\mathbf{B})$$

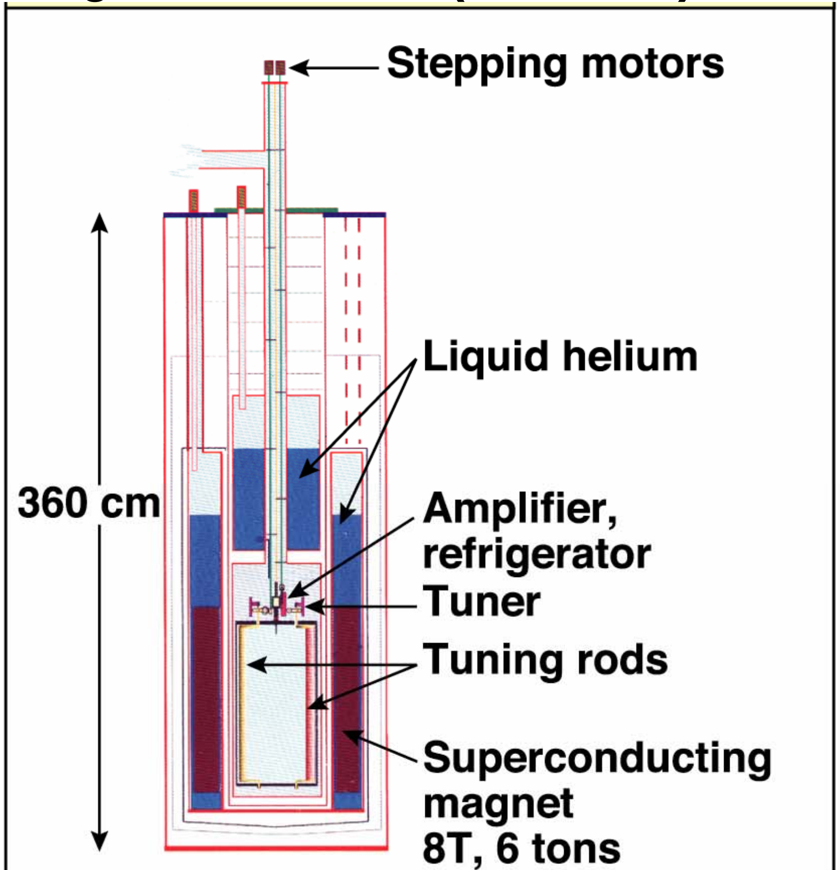



So imposing a strong external magnetic field B allows the axion field to pump energy into the cavity.

# ADMX: Axion Dark-Matter eXperiment

*U of Washington, LLNL, University of Florida, UC Berkeley, National Radio Astronomy Observatory*

**Magnet with insert (side view)**



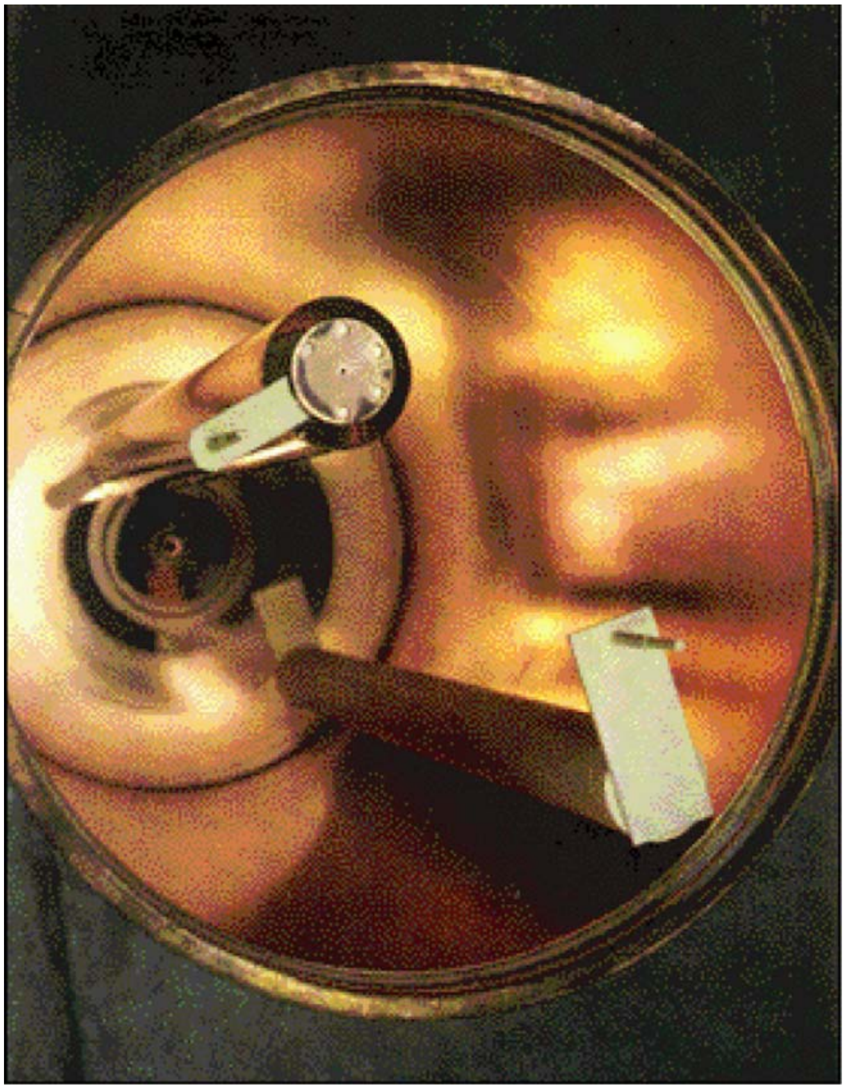

Pumped LHe → T ~ 1.5 k

**Magnet arrives**

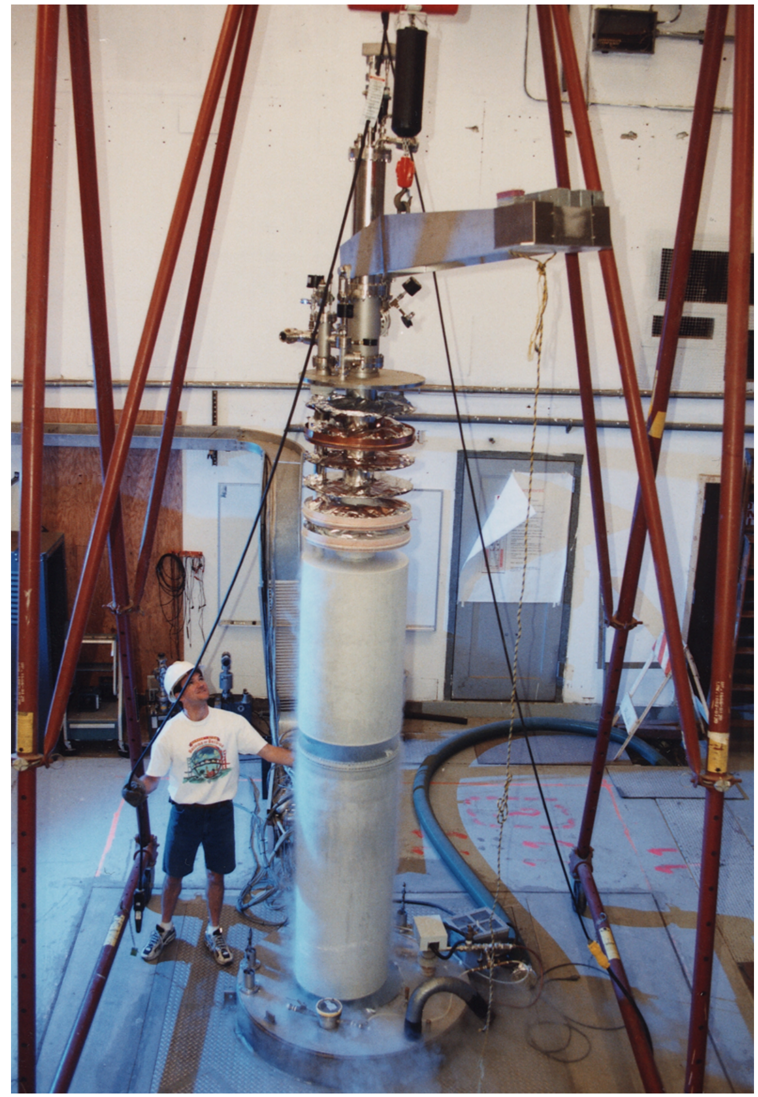
8 T, 1 m × 60 cm ∅

# ADMX hardware

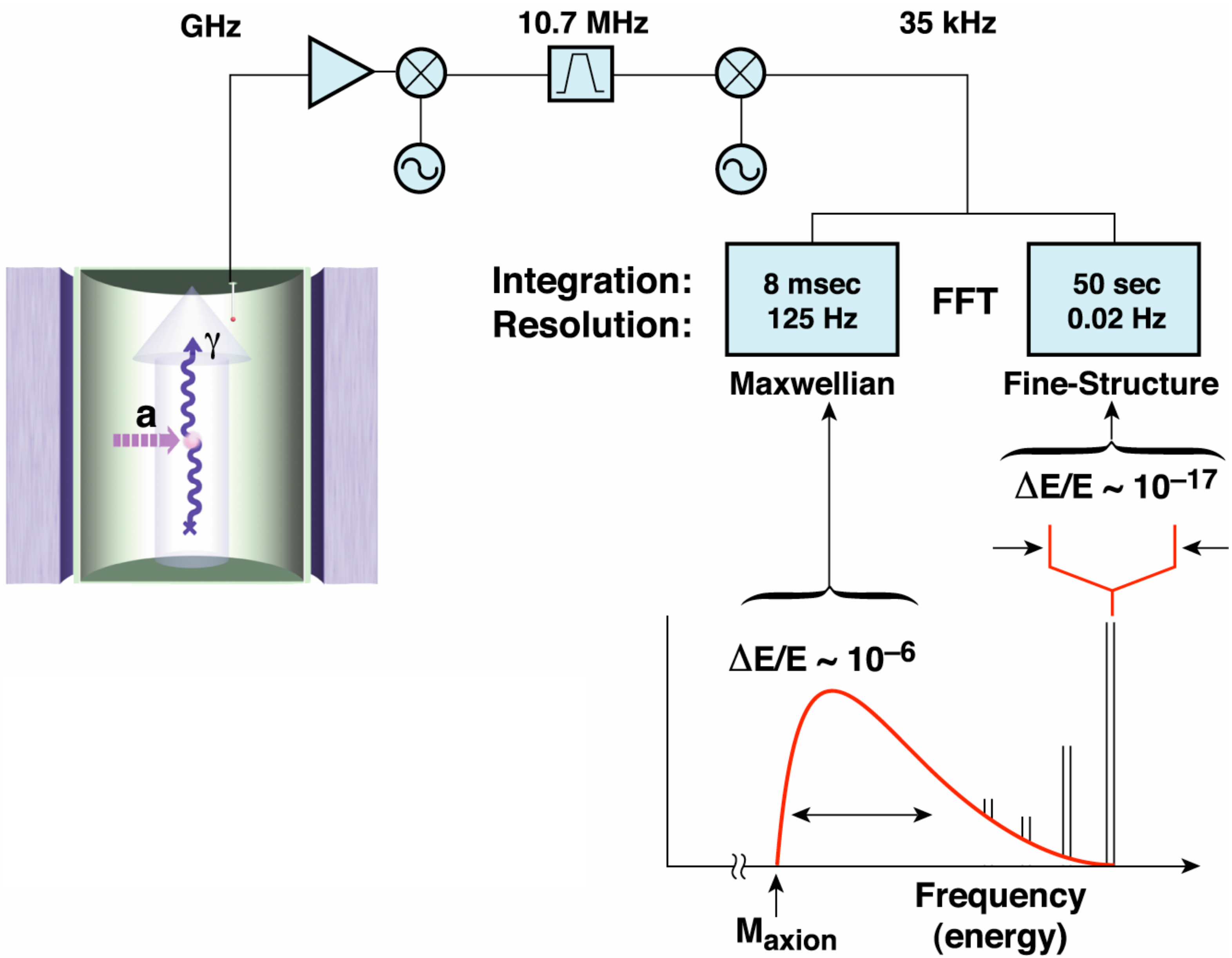
high-Q cavity



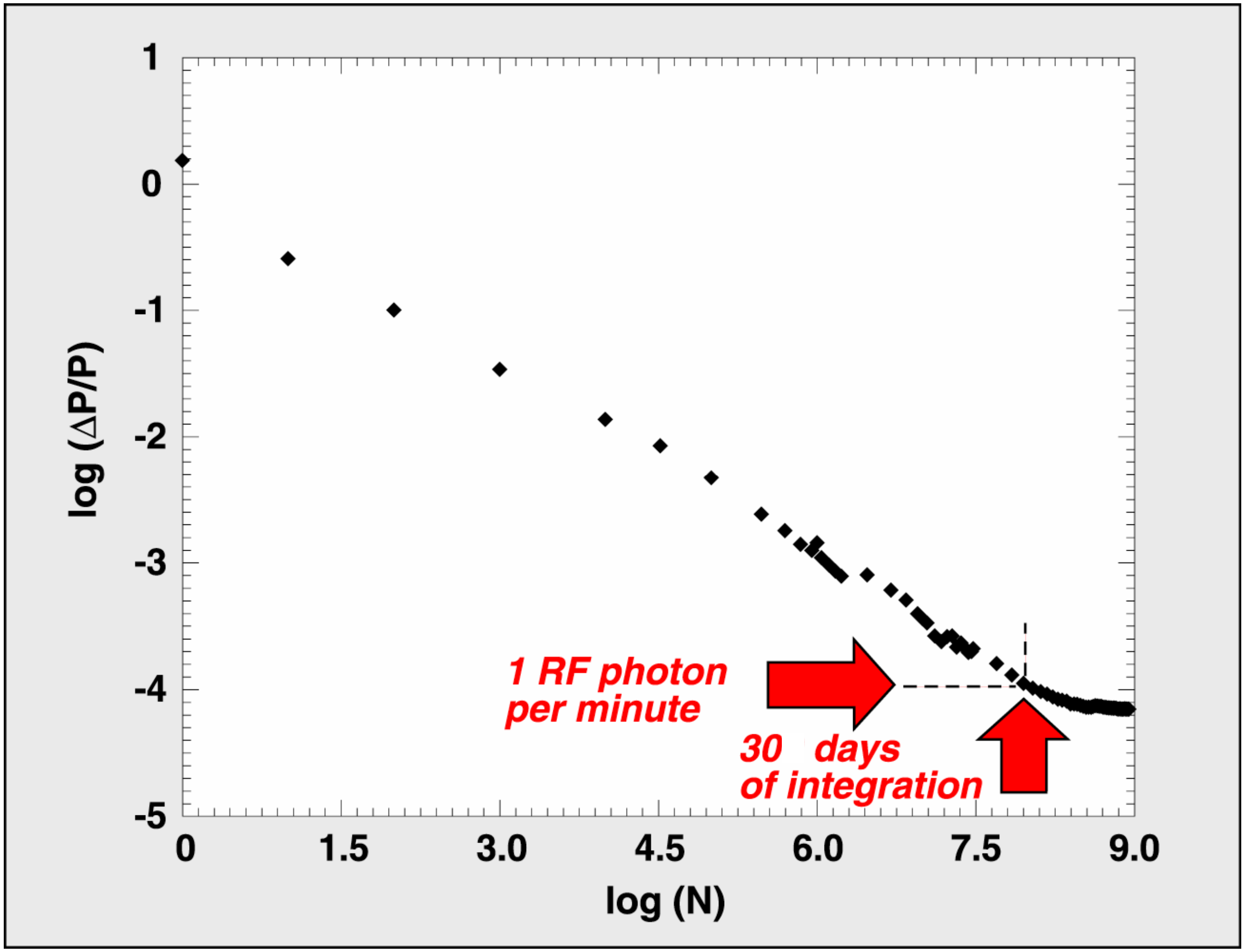
experiment insert



# The axion receiver

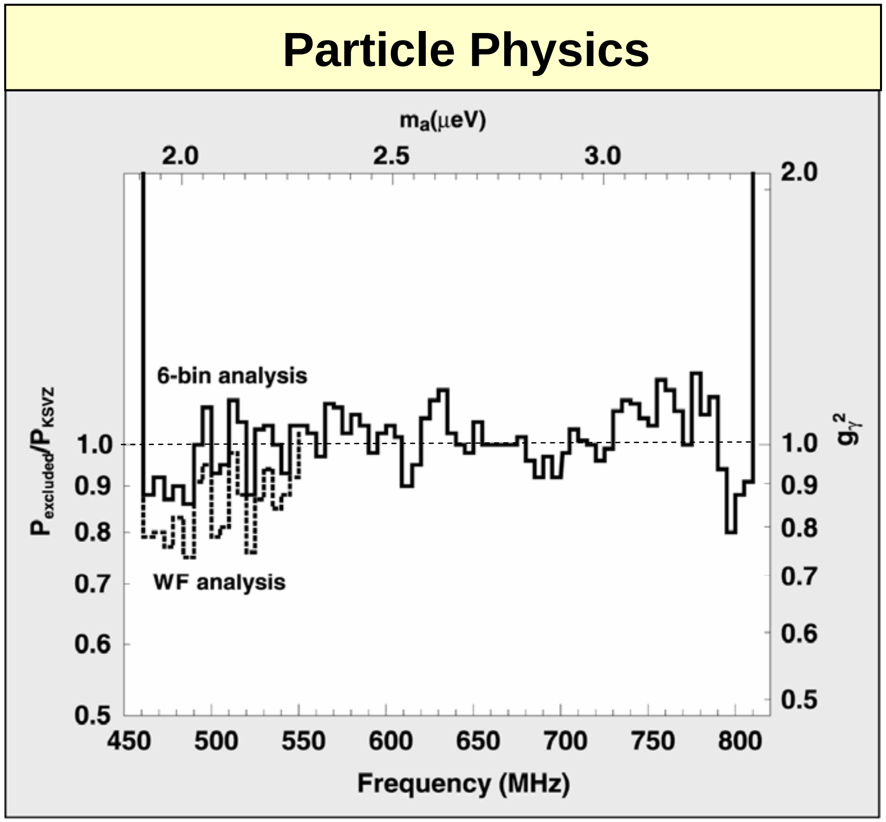


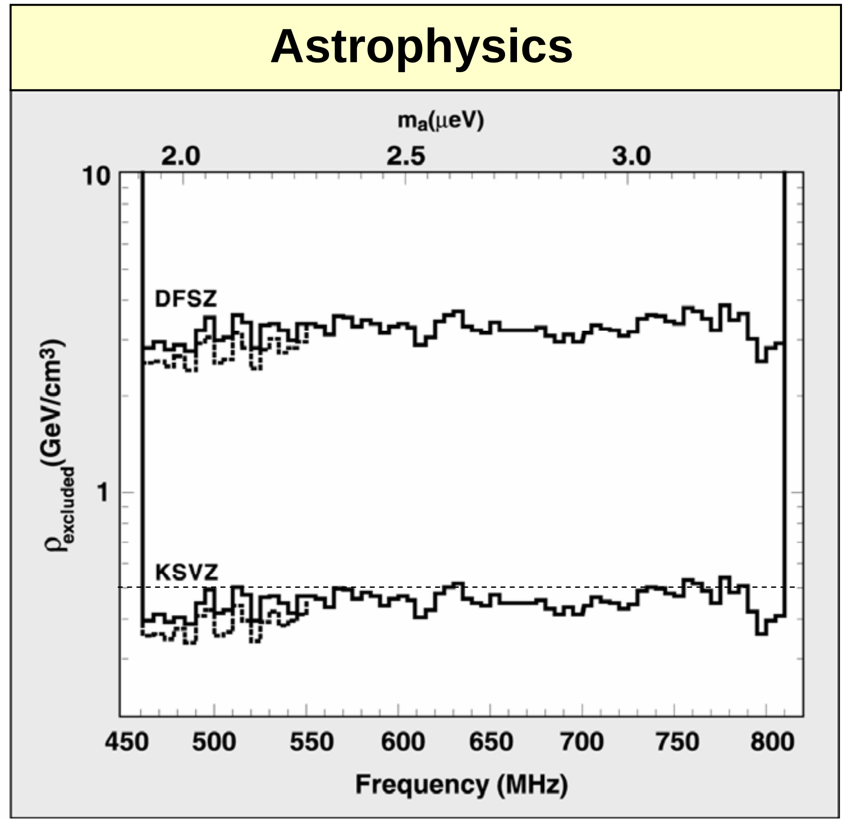
# The world's quietest radio receiver




**Systematics-limited for signals of $10^{-26}$ W**
**$\sim 10^{-3}$ of DFSZ axion power (1/100 yoctoWatt).**

# Some recent published data

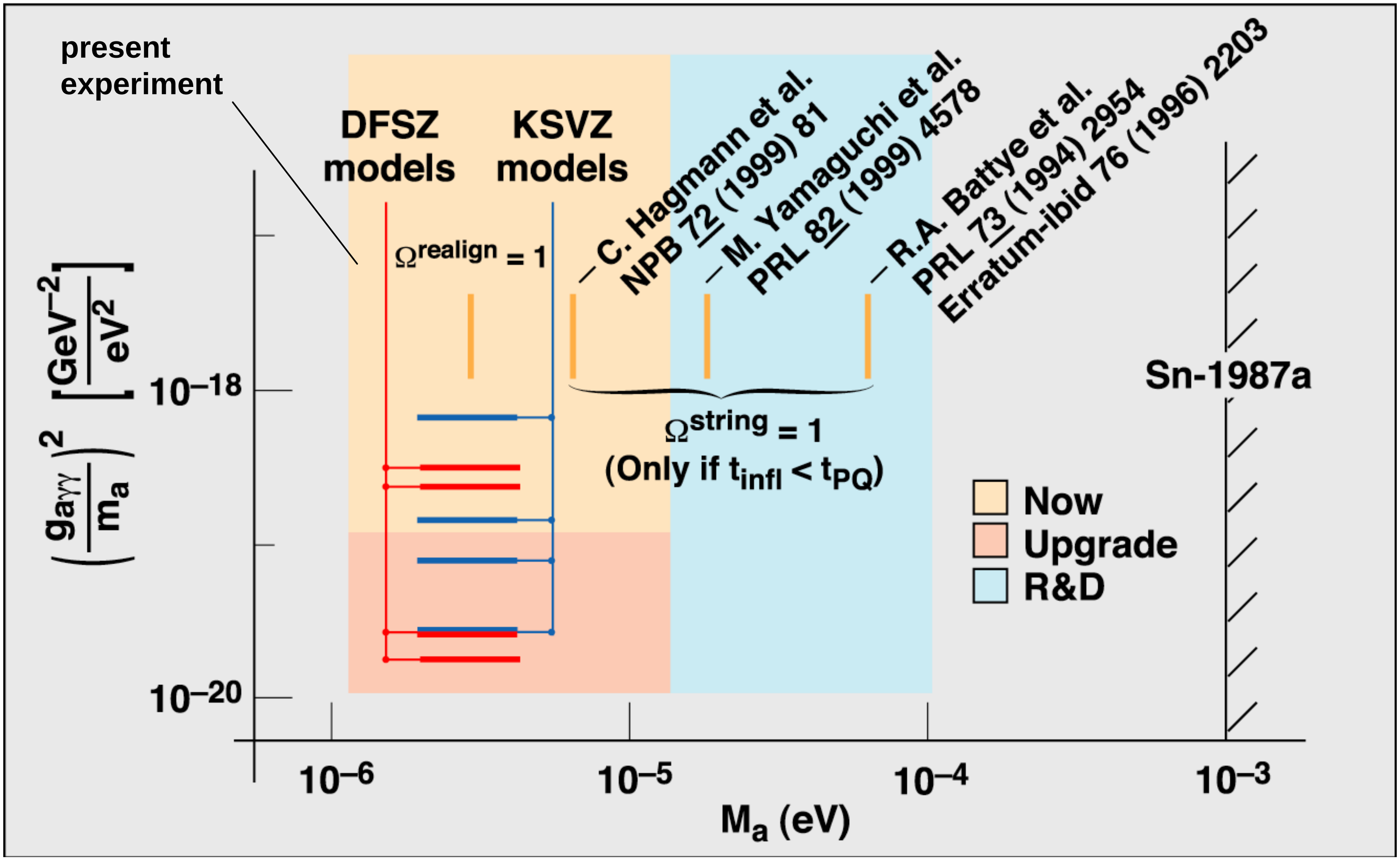



Ap.J

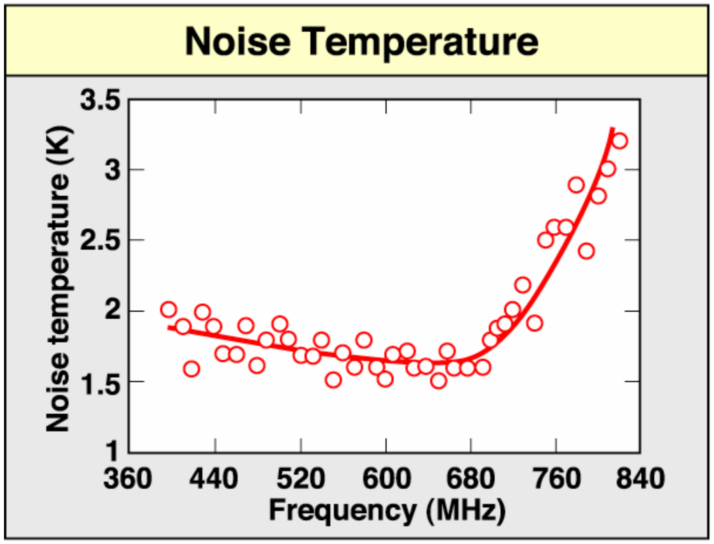
**These are interesting regimes of particle and astrophysics: probe realistic axion couplings and halo densities**

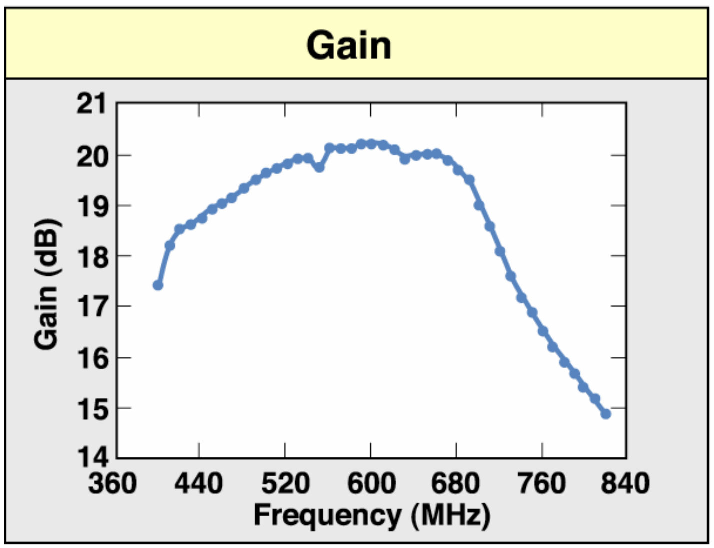
# The parameter space




**Present Sensitivity in the heart of the axion parameter space**

# R&D: Microwave amplifiers



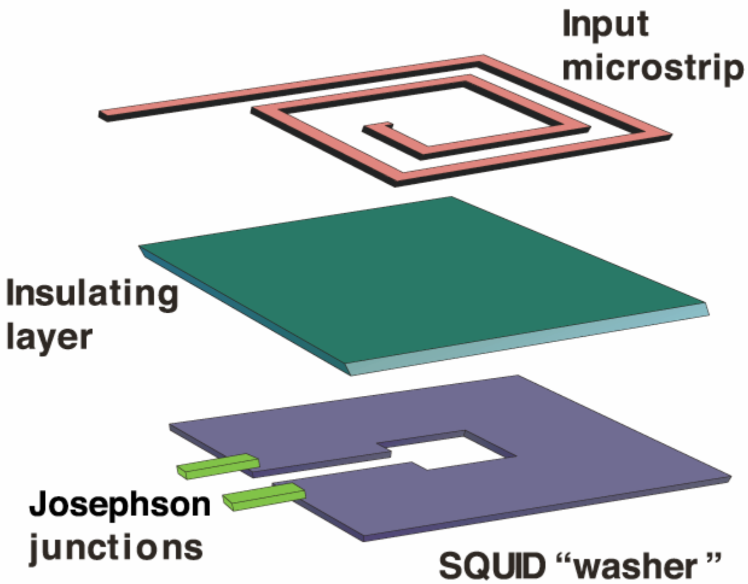



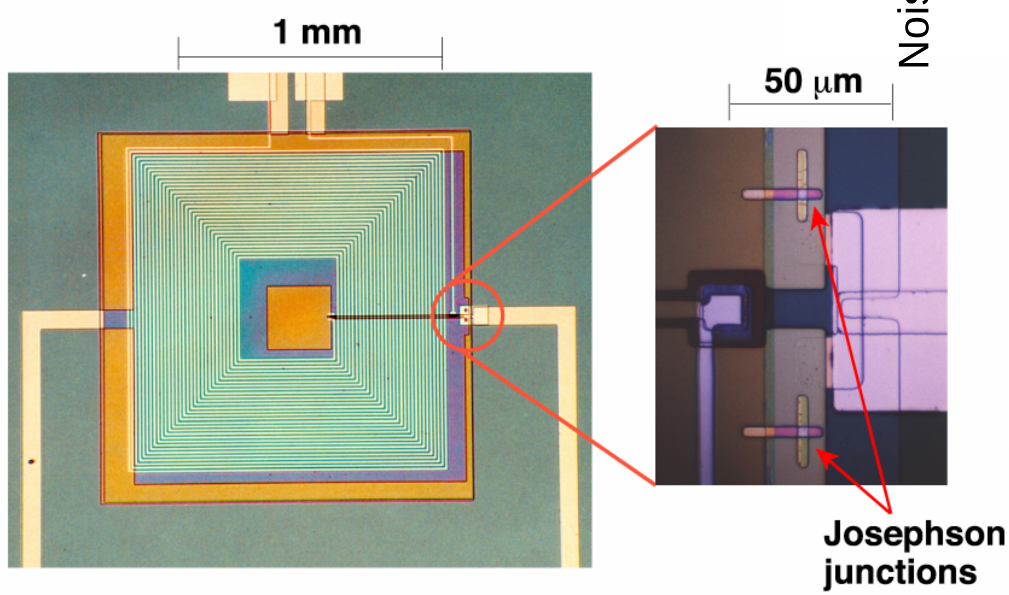

- **Currently HFET amplifiers (Heterojunction Field-Effect Transistor)**
  - **A.k.a. HEMT™ (High Electron Mobility Transistor)**
  - **Workhorse of radio astronomy, military communications, etc.**
- **Best to date $T_N \gtrsim 1$ K**

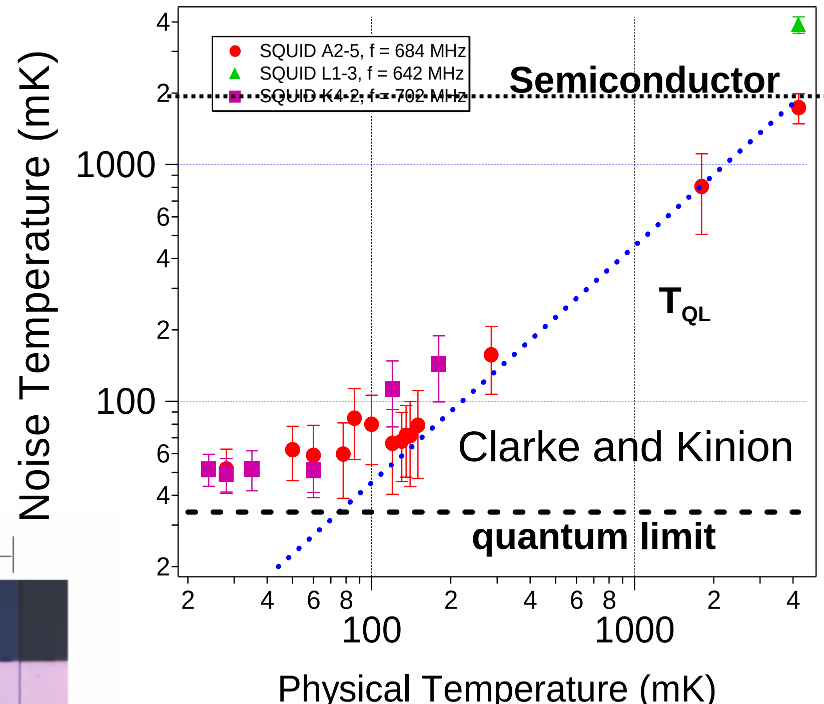
**But the quantum limit $T_Q \sim h\nu/k$ at 500 MHz is only ~ 25 mK!**

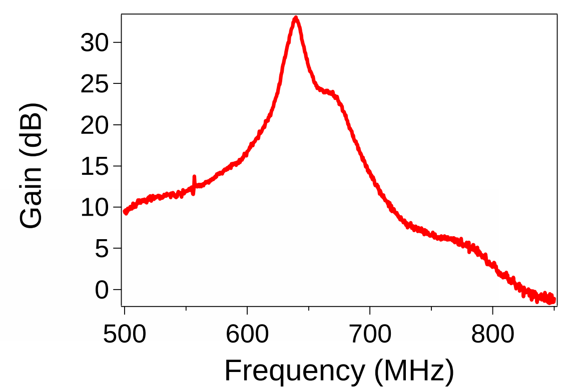
**A quantum-limited amplifier would both give us definitive sensitivity, *and* dramatically speed up the search!**

# John Clarke et al.:
# Quantum-limited gigahertz SQUID amplifiers

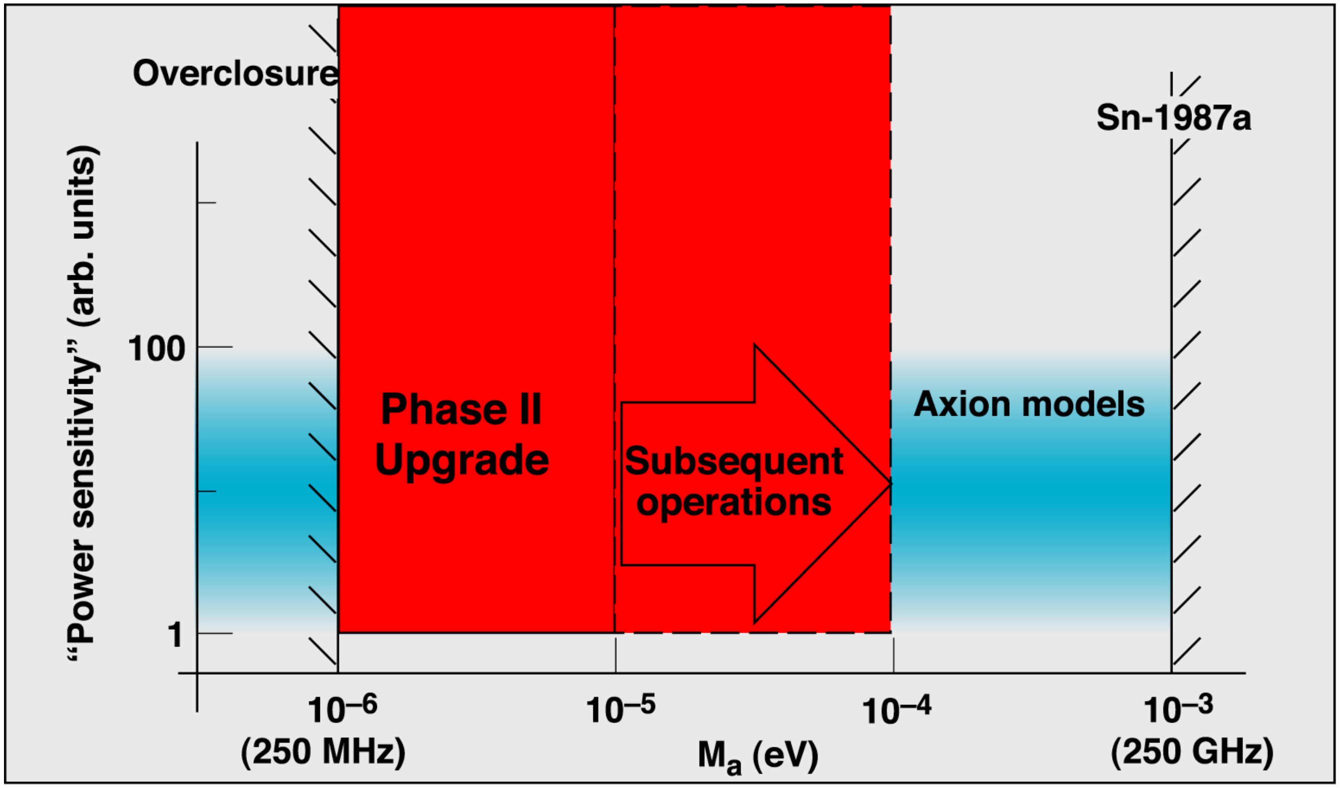


# The ADMX SQUID-upgrade target sensitivity




**Definitive sensitivity over lowest decade in mass (where dark matter axions would likely be)**

**Plus operations into second decade of mass (where unusual axions might be)**

# New thread: Non-classical photon states

Single microwave-photon detection: a RF-photon phototube

For any detector of electromagnetic radiation, there's a number-of-quanta, phase-of-radiation uncertainty relation:

$$\Delta n \cdot \Delta\phi \geq 1$$

If you don't measure the electromagnetic phase $\phi$,
you can measure the number of quanta $n$ to arbitrarily high precision.
(We do this all the time in the optical with photomultiplier tubes.)

A "phototube" for microwave photons can evade the standard quantum limit of phase-sensitive detectors.

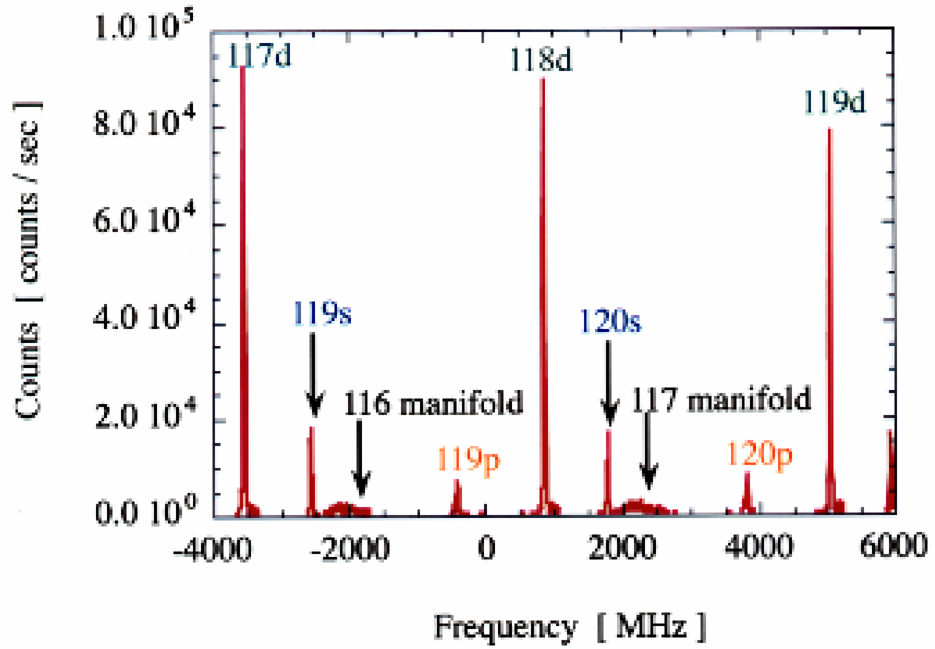
# RF Phototube: Rydberg-atom microwave-photon detection

Rydberg atoms are alkali metals in high states of excitation

Small energy difference between n and n+1 levels
$\Delta W_n \sim 1/n^3$
$\Delta W_{100} \approx 7$ GHz

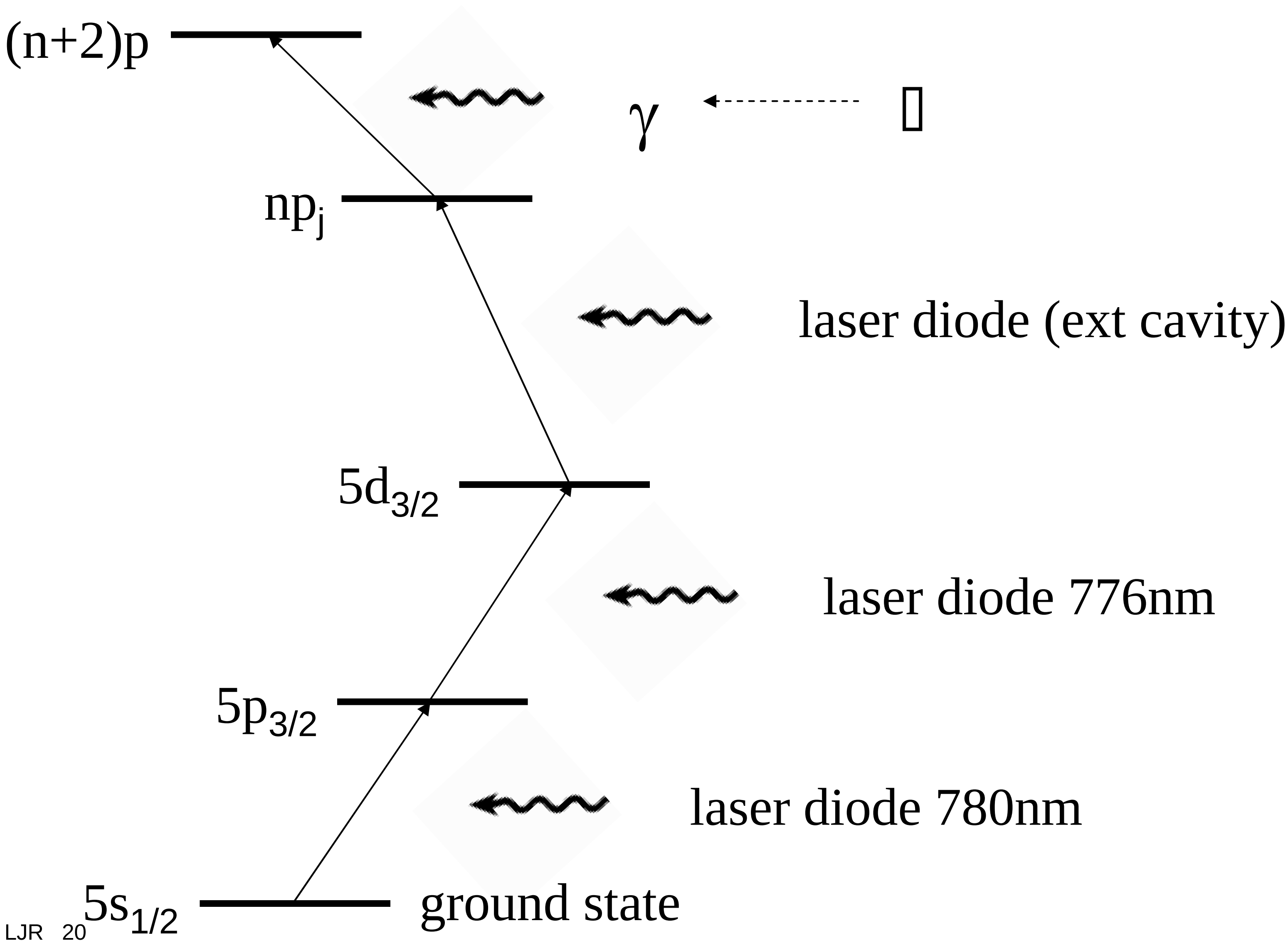
Large E1 transition between
n and n+1 levels
$\langle n+1|er|n\rangle \sim n^2$, $\Gamma_n \sim n^4$
$\Gamma_{100} \approx 3\times10^4$/sec

Long life time
$\tau_n \sim n^3$
$\tau_{100} \approx 1$ msec

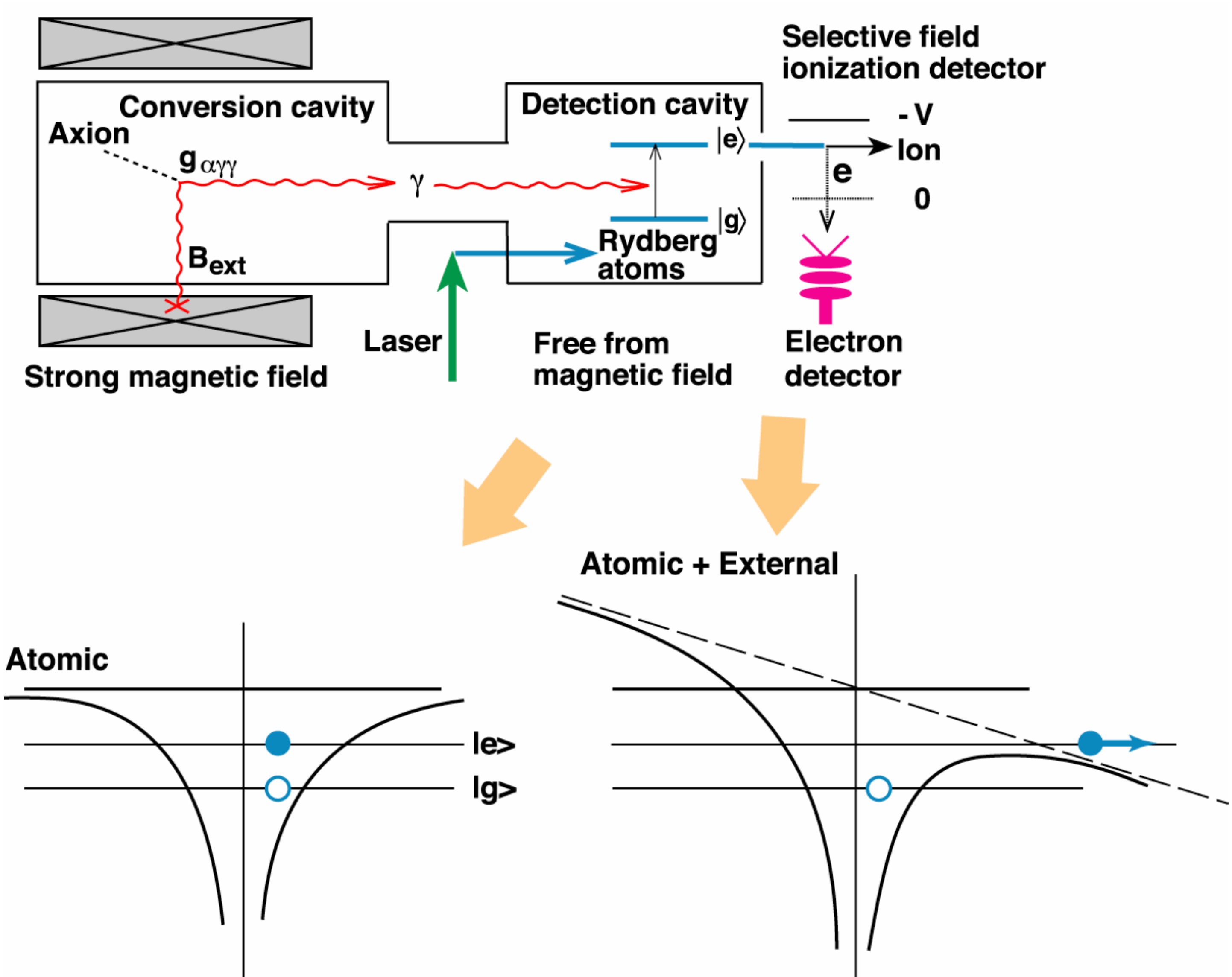


# Preparing the Rydberg state

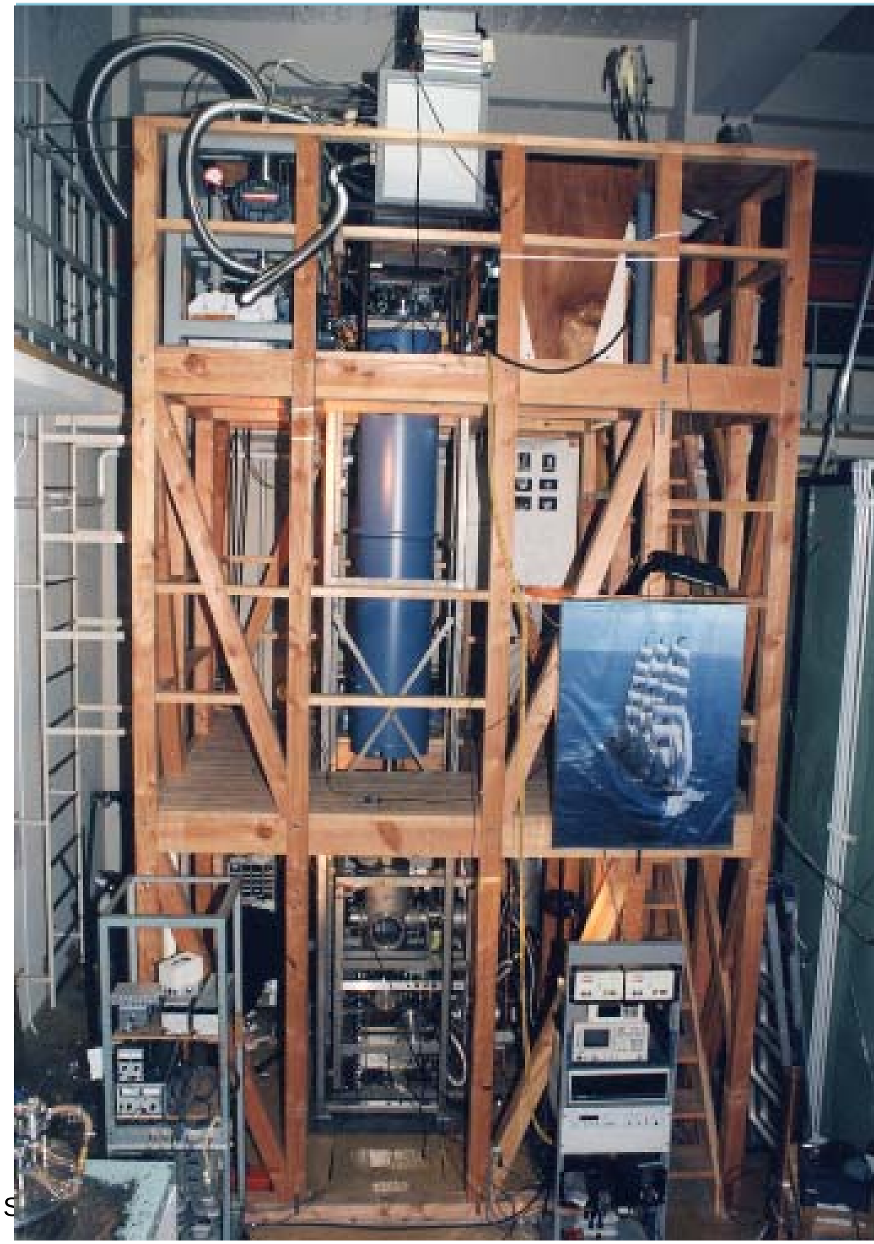
Laser diodes make this semi-practical

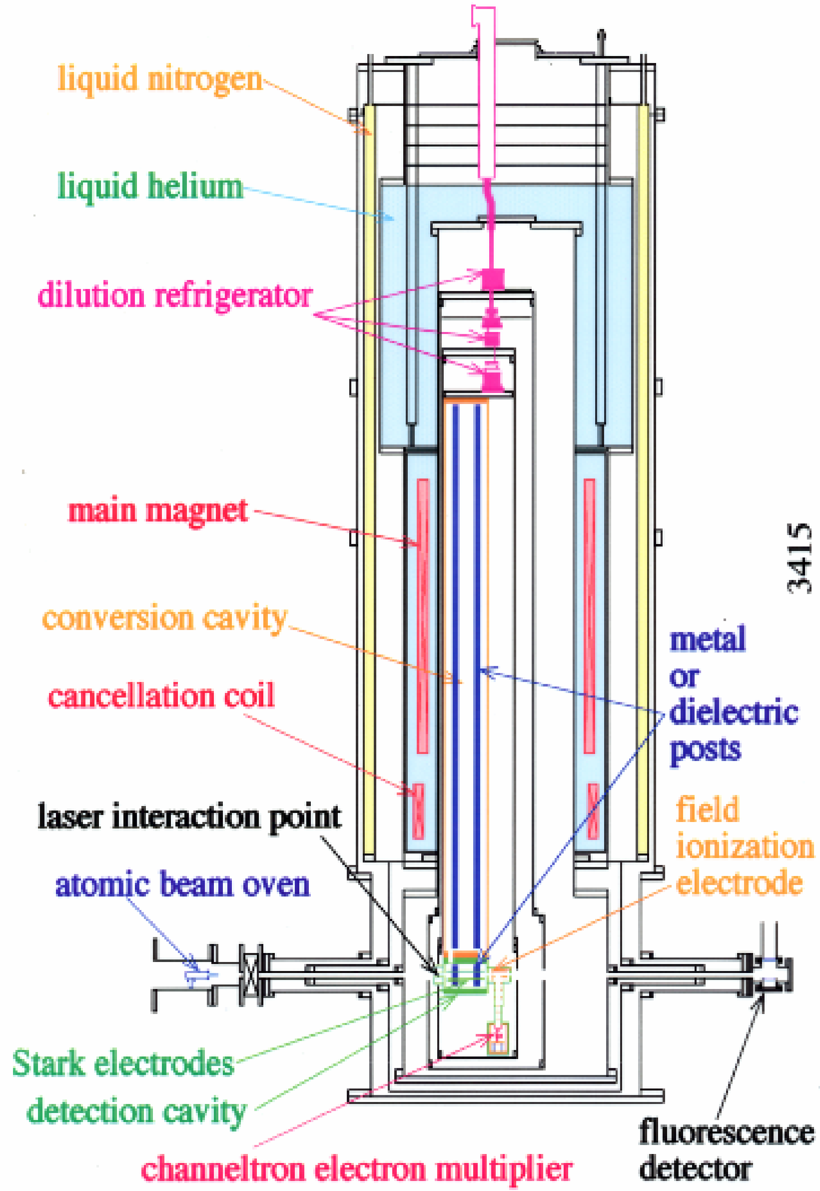


# Principle of Rydberg-atom-based axion detector

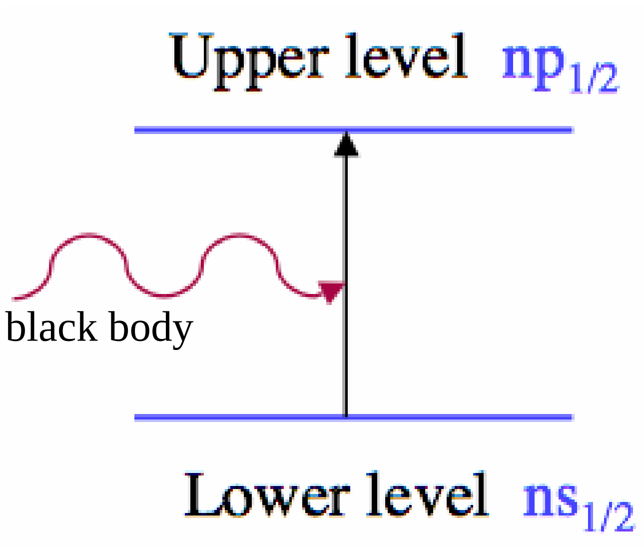


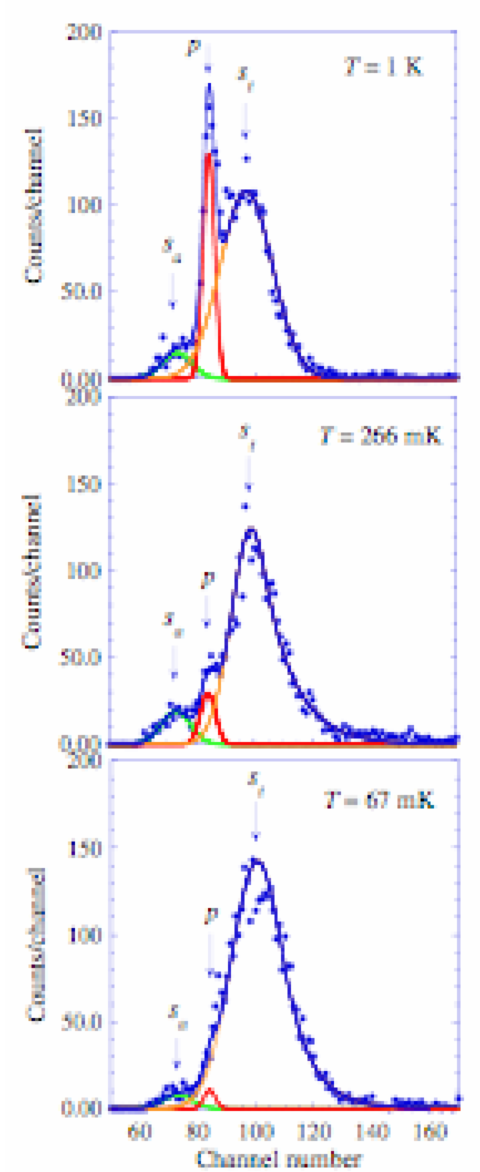
# CARRACK: Cosmic Axion Research with Rydberg Atoms in resonant Cavities in Kyoto





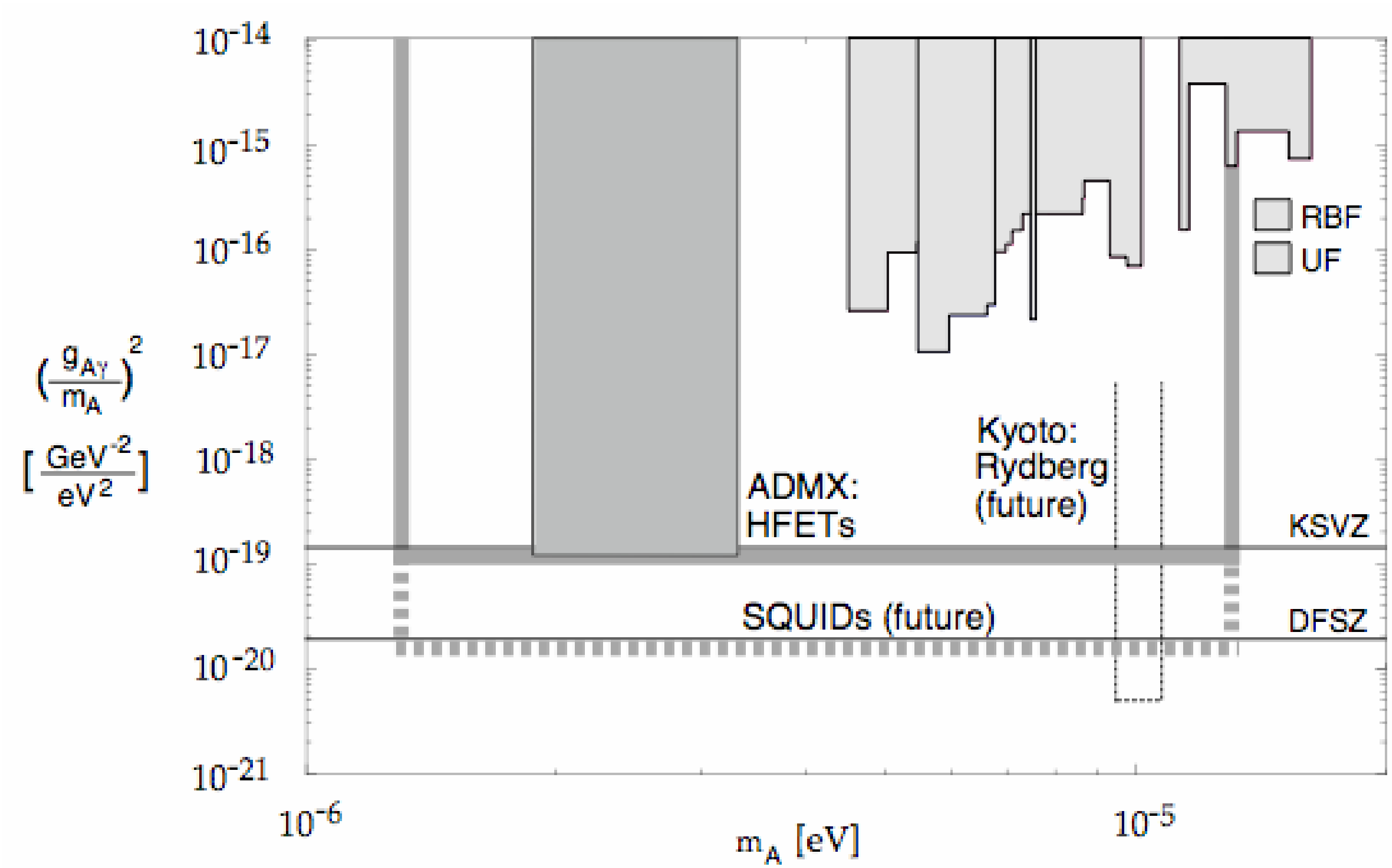
# Ionization spectra: detection of single black-body photons



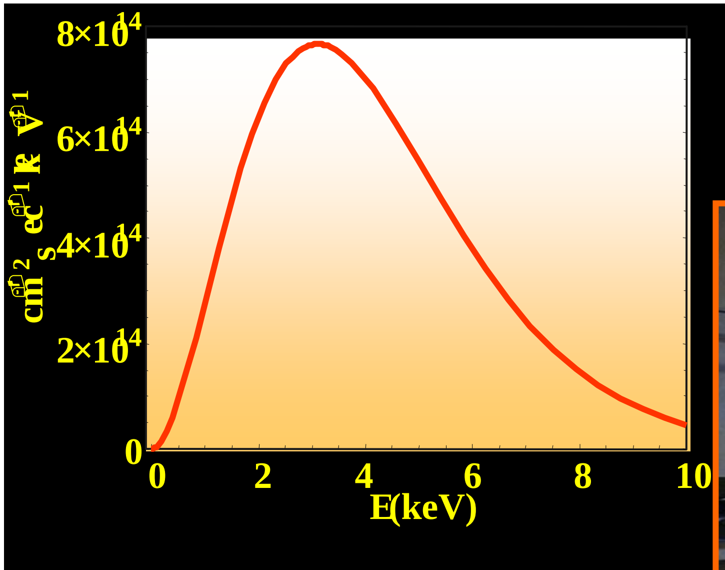




Tada et al., Phys.Lett.A

# CARRACK target sensitivity

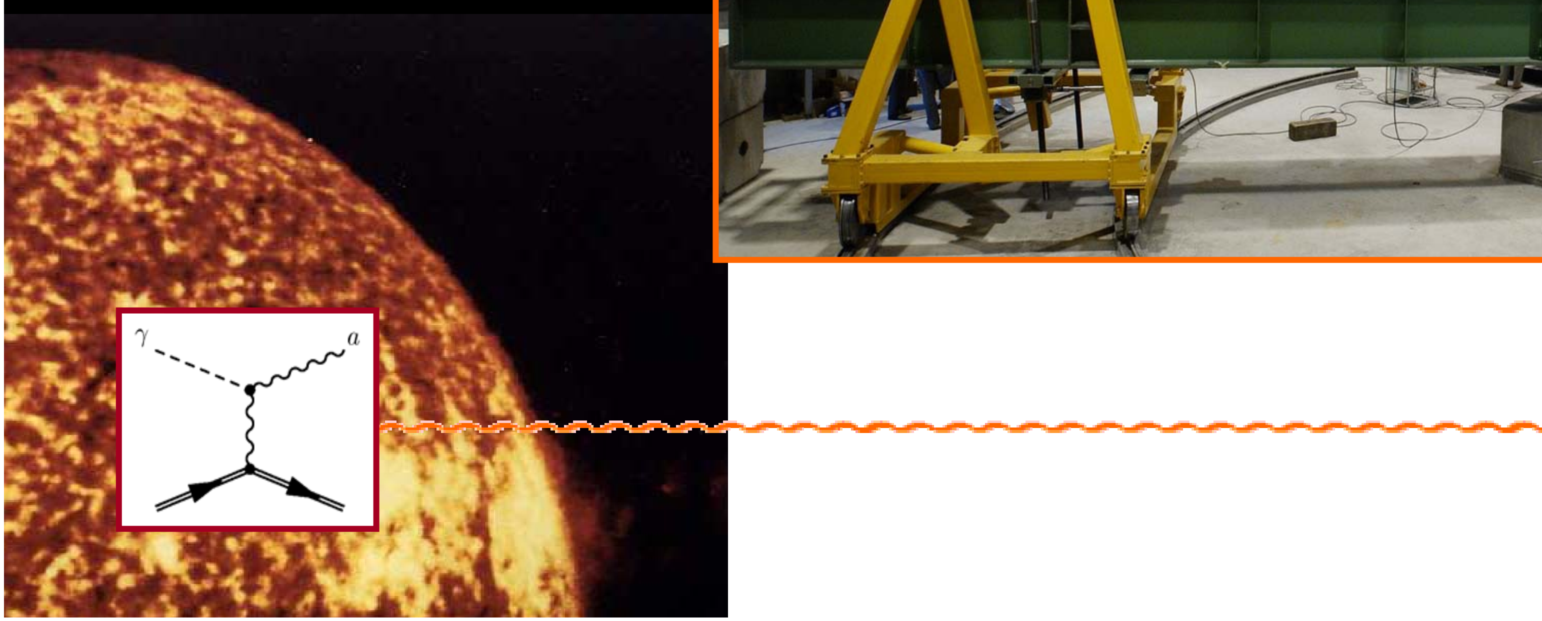


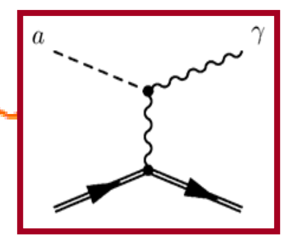
# CAST: CERN Axion Solar Telescope.
# Searching for axions produced in the Sun.




Axions from the sun…

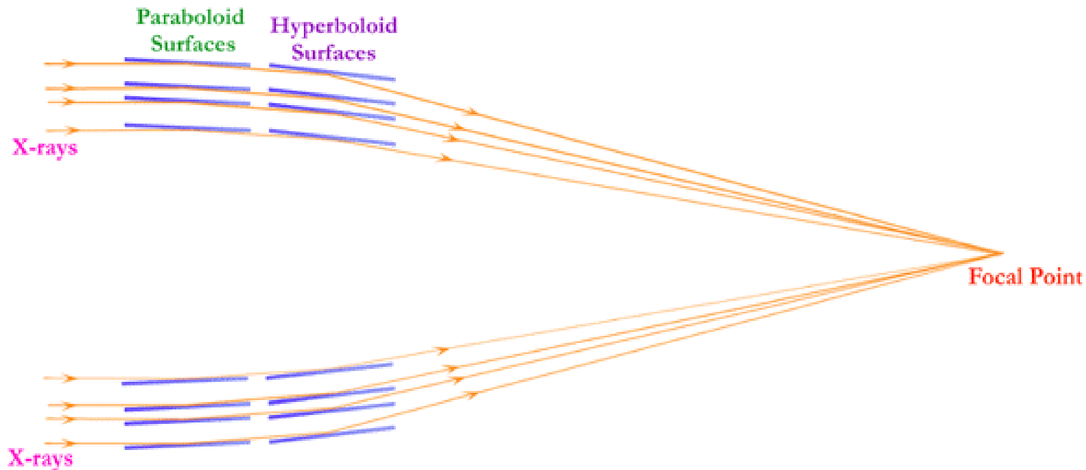
…become x-rays inside a LHC dipole magnet

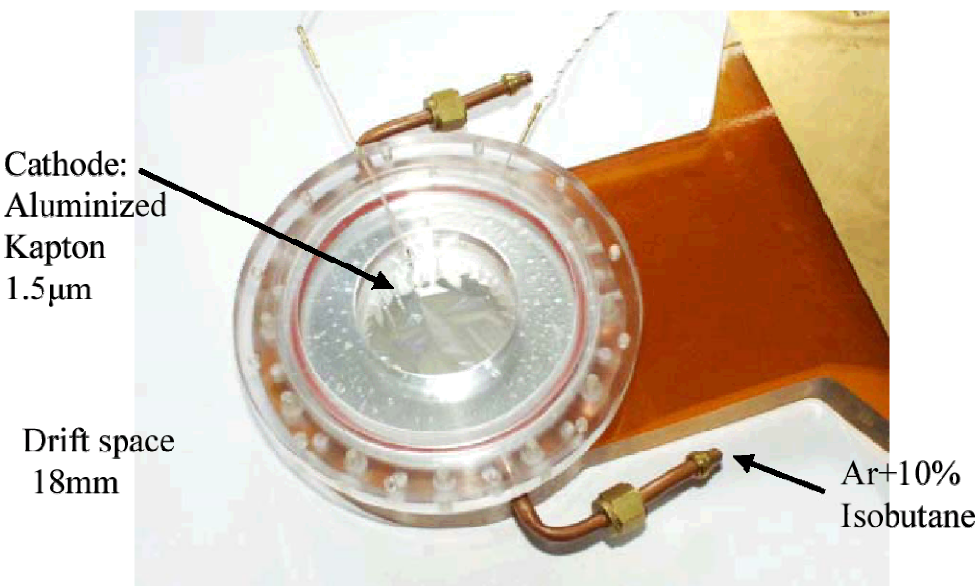



# CAST technology

Beautiful state-of-the-art x-ray detection borrowed from astrophysics

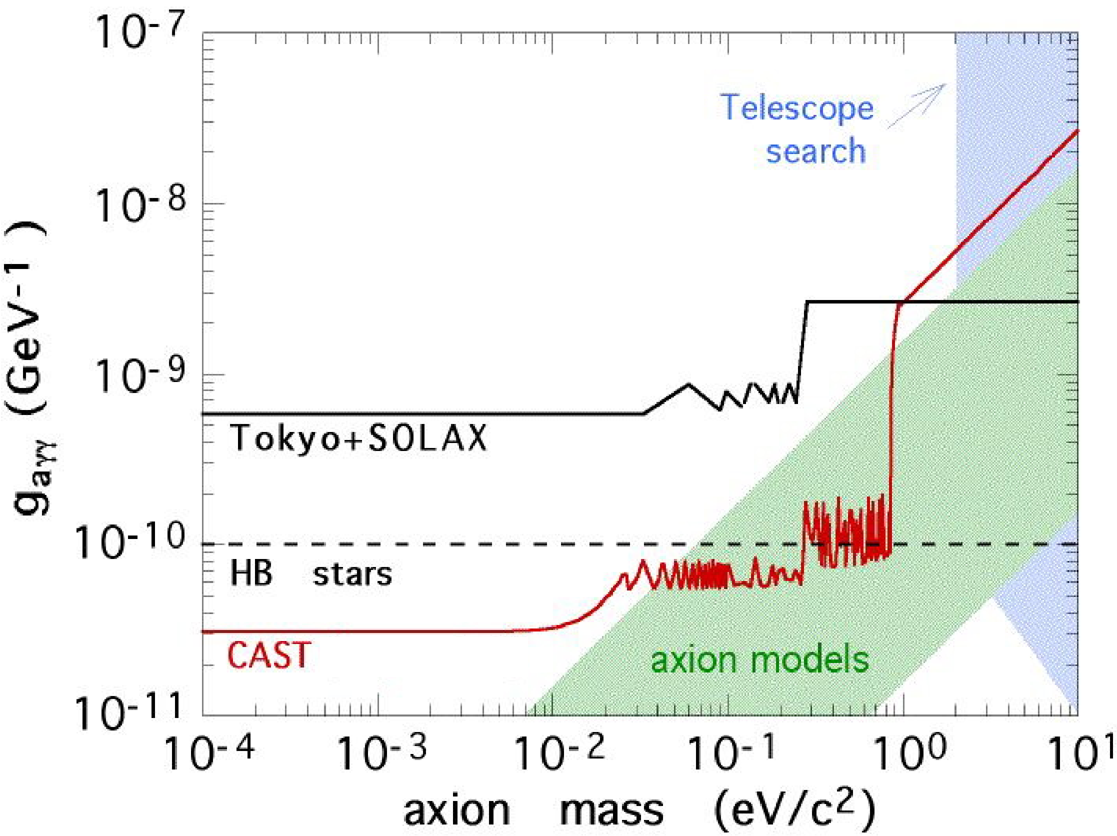



Grazing-incidence x-ray optics




Micromegas x-ray camera

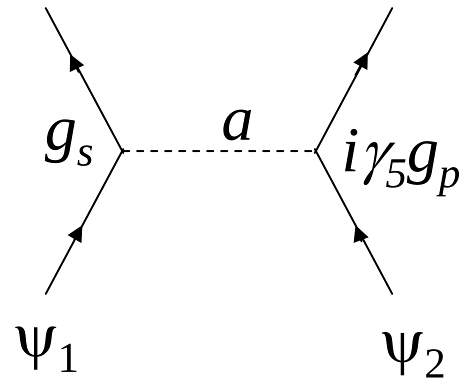
# CAST target search range



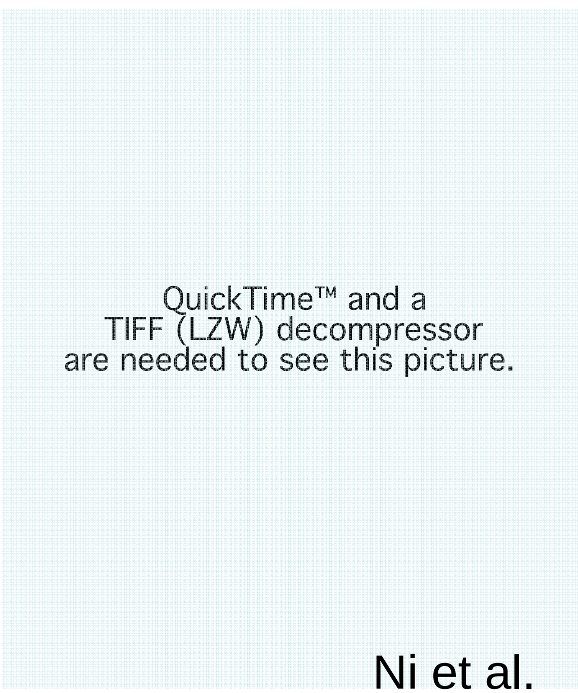

vary He gas pressure to
match dispersion relation

# $5^{th}$ force searches:
# Distances now less than 100 μm

Axions mediate matter-spin couplings

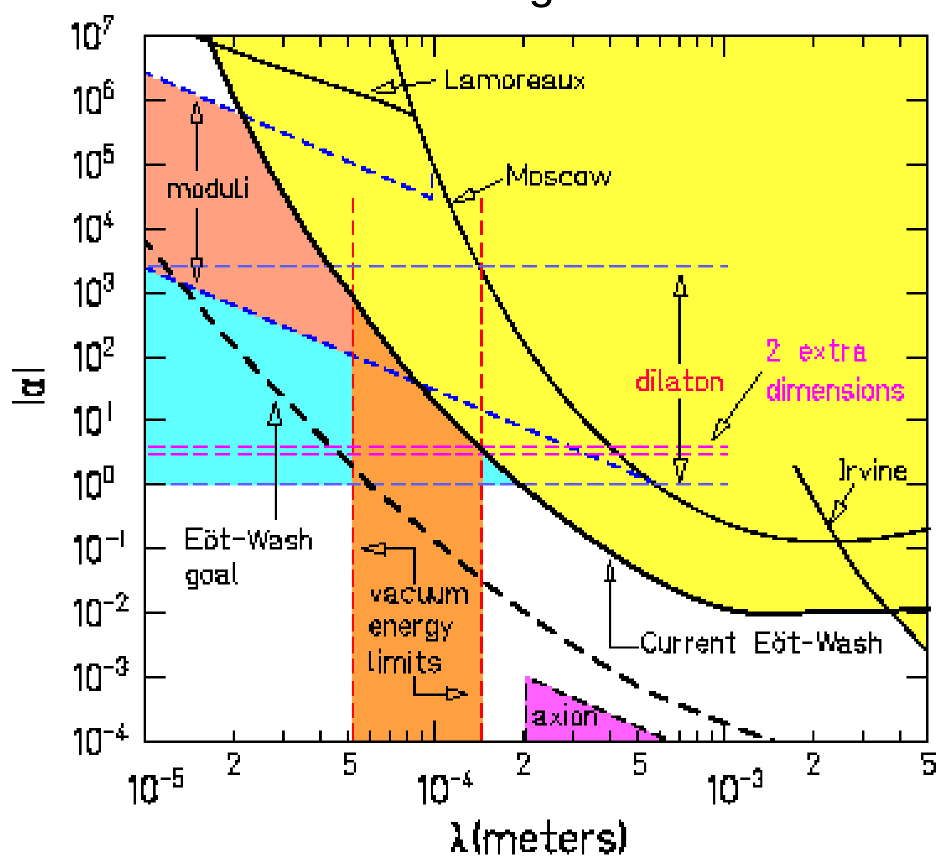



$V \sim (1/r)\, e^{-r/\lambda}$




Ni et al.

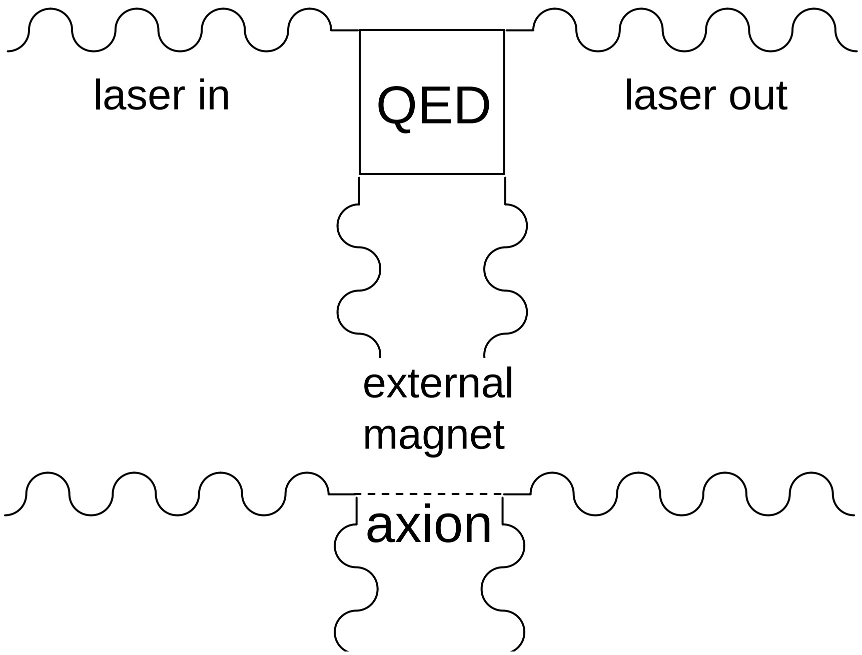
Adelberger et al.




Very challenging: everything has some magnetic susceptibility

# Laser searches: PVLAS

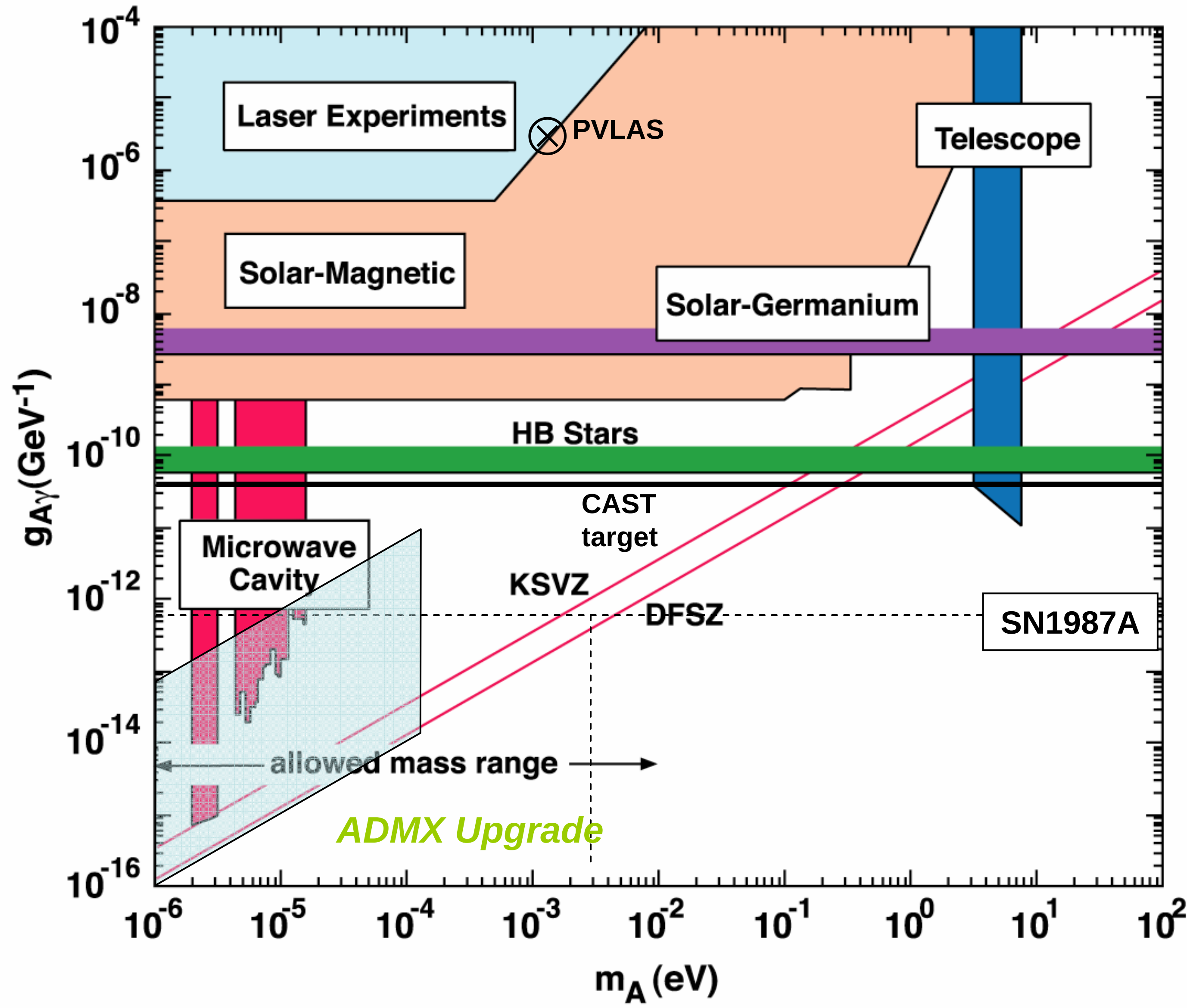
## Axions mediate anomalous vacuum birefrigence and dichroism




QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

PVLAS [PRL 96 (2006) 110406] reported anomalous polarization rotation of $10^{-12}$ per transit: corresponds to axion mass around 1 meV with coupling strength around $3\times10^{-6}$ GeV

# Overall status of axion hunting



# Conclusions

Current experiments are sensitive to realistic axion couplings and masses; they could see an axion at any time.

Upgrades to these experiments and new experiments are underway for definitive axion searches. These would be sensitive to even the more feeble axion couplings and would either detect or rule-out Peccei-Quinn axions with high confidence.

New cosmology…extra dimensions, etc., open the door to a much expanded set of non Peccei-Quinn axion masses and couplings.