**Talks Outline**

Finding order in chaos... Talk is centered on experiments

**LECTURE 1**
Dark matter in the universe ... and near us.

A tour of the experiments, including ...

WIMP searches via their recoil on laboratory targets
Annual modulation and the DAMA claim
The return of bubble chambers
Recoil-direction detectors

**LECTURE 2**
Noble-liquid detectors
Deep cryogenic detectors

WIMP searches: the big picture

Axion searches
What’s an axion, anyway?
Selected searches:
  via 5th force
  Photon regeneration and optical rotation
  Solar-axion searches
  RF-cavity

Axion searches: the big picture

Scenarios of dark-matter discovery

“Stupid humans. You will never find it.”
Klaatu, The Day the Earth Stood Still
The sobering thought from the last lecture:
solar-neutrino background
Moving on: Noble-liquid detectors

\[ m_W = 100 \text{ GeV}, \sigma = 3.6 \times 10^{-42} \text{ cm} \]

“XENON 10”
Noble-liquid: “XENON” detector series

Cartoon of PMT pulses

<table>
<thead>
<tr>
<th></th>
<th>Primary Light Direct on PMT</th>
<th>Secondary Light From Drifting Charges</th>
<th>Primary Light via CsI Photocathode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma - Ray</td>
<td></td>
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<tr>
<td>WIMP</td>
<td></td>
<td></td>
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<tr>
<td>( t_0 )</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( t_i )</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>( t_{\text{max}} )</td>
<td></td>
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</tbody>
</table>
The “Xenon I0” detector

- 22 kg of liquid xenon
  - 15 kg active volume
  - 20 cm diameter
  - 15 cm drift

- 12 kV cathode
  - \(E_{\text{drift}} = 0.73 \text{ kV/cm}\)
  - \(E_{\text{gas}} = \sim 9 \text{ kV/cm (S2)}\)

- Liquid Xe maintained at \(T=180 \text{ K and } P=2.2 \text{ atm.}\)
  - Cooling: Pulse Tube Refrigerator (PTR), 90W, coupled via cold finger (LN\(_2\) for emergency)
Noble-liquid: XENON series: recoil ionization yield
Noble-liquid: XENON 10: results

Spin-independent

Spin-dependent

(NO BKG SUBTRACTION)
8.8 x 10^{-44} cm^2 at 100 GeV
4.5 x 10^{-44} cm^2 at 30 GeV

Constrained Minimal Supersymmetric Model

(NO BKG SUBTRACTION)
6 x 10^{-39} cm^2 at 30 GeV
Noble-liquid: XENON series: future

**The past** (2005 - 2007)

**The current** (2007-2010)

**The future** (2010-2014)

**XENON10**
Achieved (2007) $\sigma_{SI}=8.8 \times 10^{-44}$ cm$^2$

**XENON100**
Projected (2009) $\sigma_{SI}\sim 2 \times 10^{-45}$ cm$^2$

**XENON1T**
Projected (2014) $\sigma_{SI}\sim 10^{-47}$ cm$^2$
Noble-liquid: ZEPLIN series

ZEPLIN I

Target = 3.1kg liquid Xenon in Cu vessel

Viewed by 3 PMTs in turrets.

Surrounded by Compton veto to reduce backgrounds from PMTs and outside.
ZEPLIN I: Results

ZEPLIN-I operated from 2001-2004

Results from 91 day live-time, 290kg-days exposure
ZEPLIN II: Two-Phase LXe

**ZEPLIN-II.**
30Kg Dual-Phase detector
Ran until 2006

**ZEPLIN-III.**
Bigger & better: See next slides.
Noble-liquid: other liquids: LNe is light, LAr is radioactive

LAr/LNe detectors

39Ar \rightarrow 39K + e^- + n

\[ t_{1/2} = 269 \text{ yr, } E_{\text{max}} = 565 \text{ keV} \]

Produced in atmosphere by cosmic rays:

\[ n + ^{40}\text{Ar} \rightarrow ^{39}\text{Ar} + 2n \]

Abundance: \( 8 \times 10^{-16} \)

Decay rate \( \sim 1 \text{ Hz/kg} \).

Need factor of \( 10^8 \) suppression.

Isotopic separation?

Underground Ar? Maybe 5% of above-ground 39Ar
Noble-liquid: More future LXe

**LUX**
350kg dual phase detector.
Installation at DUSEL

**ZEPLIN-III.**
12kg dual phase detector.
Bigger electric field.
Full installation @ Boulby 2009
Noble-liquid: Far future “LZ20”: sub zepto-barn

- LUX-Zeplin Collaboration: 20 Tonnes liquid Xe detector
- Estimated Schedule for Construction and Operation: 2012 and 2015
Deep Cryogenic Detectors: principle

WIMP scatters; recoil energy appears as phonons (heat) and ionization.
Deep Cryogenic Detectors: Refrigeration

Phonon signals require dilution-refrigerator temperatures.

Dilution refrigerator: 10-25mK
Maybe 10 µWatt of cooling power at 25mK

XENON10 has maybe 1kWatt of cooling power

So what? Gravity bars (tons) are cooled to 25mK. But that’s basically two suspensions and one channel.
CDMS: These experiments need to be cold, but …

Soudan mine entrance
CDMS: The Cryogenic Dark Matter Search

Si and Ge “pucks.

Phonon (heating) and ionization recorded

Separate nuclear-recoil and EM events

L. Baudis
CDMS: ZIP-a very sophisticated detector

Highly segmented (TES) W-Al and W film phonon sensor with SQUID readout (self biasing)

Mildly segmented “Conventional” charge readout
CDMS: Event localization

L. Baudis
CDMS II: Current experiment

In the Soudan mine
In the “icebox”: 5 towers of Si and Ge ZIPs

L. Baudis
CDMS II: Data

Based on 3.75 kg Ge ZIPs: 121 kg-d
CRESST I and II

Initially: Sapphire with W films, 260 g pucks. Sensitive to lower mass WIMPS.

Next phase CREEST II:
33+ CaWO4 crystals, 10 kg
Preliminary run:
CRESST results
EDELWEISS

Arrays of Ge detectors
Dilution-refrigerator cooling
320g “pucks”
2000-2003
32 kg-days exposure
Modane underground laboratory

200 g “interdigit detector” modifies surface E field
NbSi film sees athermal surface events
EDELWEISS results
Deep Cryogenic: Overview of results

Spin-independent cross section (normalized to nucleons)

WIMP-nucleon σ_{SI} [cm^2]

Spin-dependent

WIMP Mass [GeV/c^2]

Laura Baudis, University of Zurich, ENTApP DM Workshop, February 3, 2009
Deep cryogenic Experiments: Future

CRESST at LNGS
10 kg array of 33 CaWO₄ detectors
new 66 SQUID channel array
- new limit from operating 2 detectors (48 kg d) published in 2008, arXiv:0809.1829v1
- new run in progress

EDELWEISS at LSM
10 kg (30 modules) of NTD and NbSi Ge detectors in new cryostat
- new charge electrodes
- 100 kg d under analysis
- data taking in progress

CDMS/SuperCDMS at Soudan
CDMS-II run 129 in progress
SuperCDMS detectors (1” thick ZIPs, each 650 g of Ge) have been tested
Installation of first SuperTower at Soudan in spring 2009
Goal: $5 \times 10^{-45} \text{ cm}^2$ with 16 kg Ge
Deep cryogenic Experiments: more future

EDELWEISS plus CRESST
100kg-1ton
1000+ detectors
dilution-refrigerator cooling
sensitivity to $10^{-8}$ pb
SuperCDMS: near-term at Soudan plans

Replace CDMS II detectors with SuperCDMS detectors
0.25 kg Ge/0.1 kg Si --> 0.64 kg Ge
Each new tower has 5 Ge detectors => ~3 kg mass
Each also has two Ge endcap veto detectors
  Improves ability to reject backgrounds from nearby materials
First ‘Supertower’ due in March 2009
  Will bring Ge mass to 6 kg
Remaining 4 supertowers in early 2010
  Total deployed Ge mass will be 15 kg
Two year run will yield x3 sensitivity improvement over the best that CDMS II will produce (x10 better than currently published).

D.Bauer Dec2008
SuperCDMS: SNOLAB

Science goals
  Increase sensitivity by x50 (compared with current published)
  Reach WIMP-nucleon cross section of $10^{-46}$ cm$^2$

Technical goals
  6” diameter ZIPs
  “Kinetic Inductance Phonon Sensors”
  Increase detector mass in stages up to 100 kg by 2012
  Stay background free
    Challenge to deal with existing backgrounds at Soudan
    New setup needed at SNOLAB to reduce neutron background
Deep cryogenic versus noble liquid detectors

Deep cryogenic:
Serious development started in late 1980’s
Very expensive scaling…expensive target, dilution refrigerator
Challenging to purify
Challenging to operate (stability, etc.)
Best limits at higher WIMP masses

Noble liquid:
Serious development started in late 1990’s
Less expensive scaling…Xe
Less challenging to purify
Less challenging to operate
Best limits at lower WIMP masses

Noble liquid detectors therefore became competitive quickly

Which is “better”? Depends on the backgrounds and background rejection. Can’t predict at the moment.
WIMP detectors: big picture

It’s the wild west: Lots of detectors and many groups.

Here’s some themes:

Low background requirement limits the number of players. This technology is hard to master, and you have to go deep underground.

It will be hard to have a convincing result without discrimination of WIMP versus background recoils.

The next generation of detectors are at the $100M level; There will only be a couple: maybe one liquid, and one Ge.

In my opinion, theory gives little guidance as the the recoil cross sections.

The discovery potential of these searches by themselves is poor: search space is very big

Keep your eye on DAMA and the LHC.
Switching gears: Searching for Dark-Matter Axions

Outline

Basic axion properties

Selected searches:
(see, e.g., parallel sessions for more …)
5th force searches
Photon regeneration and optical rotation
Solar axion searches
RF cavity (dark-matter axions)

Overall status of axion searches
Axions and axion-like particles

e.g.,

Majoron (from lepton-number breaking… neutrino masses)

Familon (from family-symmetry breaking)

Dilaton (low-energy state in string theory)

Axion (removes CP violation in strong interactions)

Axions are well-motivated and their phenomenology is well-understood
QCD and CP violation

1973: QCD... a gauge theory of color. QCD theory respected the observed conservation of C, P and CP.

1975: QCD + “instantons” ⇒ QCD is expected to be hugely CP-violating. “The Strong-CP Problem”

QCD on the lattice:
CP-violating instantons in a slice of spacetime (sort of)
Properties of the axion

The axion is a light pseudoscalar resulting from the broken “Peccei-Quinn” symmetry to enforce Strong CP conservation. $f_a$, the SSB scale the PQ symmetry breaking, is the one important parameter of the theory.

<table>
<thead>
<tr>
<th>Mass and Couplings</th>
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</thead>
<tbody>
<tr>
<td>m_a \sim 6 \mu eV \cdot \left(\frac{10^{12} \text{ GeV}}{f_a}\right)</td>
</tr>
<tr>
<td>Generically, all couplings $g_{aii} \propto \frac{1}{f_a}$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cosmological Abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_a \sim \left(\frac{5 \mu eV}{m_a}\right)^{7/6}$</td>
</tr>
<tr>
<td>(Vacuum misalignment mechanism)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Axion Mass ‘Window’</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-(5 \text{ to } 6)} \text{ eV} &lt; m_a &lt; 10^{-(2 \text{ to } 3)} \text{ eV}$</td>
</tr>
<tr>
<td>(Overclosure) (SN1987a)</td>
</tr>
<tr>
<td>With lower end of window preferred if $\Omega_{\text{CDM}} \sim 1$</td>
</tr>
</tbody>
</table>
More on axion masses and couplings

The axion is a light cousin of $\pi^0$: $J^{\pi} = 0^-$

$m_a, g_{aii} \propto f_a^{-1} \implies g_{a\gamma\gamma} \propto m_a$

$\Omega_a \propto f_a^{7/6} \implies m_a > 1 \mu eV$

Sn1987a $\nu$ pulse precludes $\text{NN} \rightarrow \text{NNa}$ for $m_a \sim 10^{-(3-0)}$ eV

Red giant evolution precludes $g_{a\gamma\gamma} > 10^{-10}$ GeV$^{-1}$

Good news – Parameter space is bounded
Bad news – All couplings are *extraordinarily* weak
Remember: Wilczek on axions and dark matter

“…I'm much more optimistic about the dark matter problem. Here we have the unusual situation that two good ideas exist – which, according to William of Occam (the razor guy), is one too many.

“The symmetry of the standard model can be enhanced, and some of its aesthetic shortcomings can be overcome, if we extend it to a larger theory. Two proposed extensions, logically independent of one another, are particularly specific and compelling.

“One incorporates a symmetry suggested by Roberto Peccei and Helen Quinn in 1977. Peccei-Quinn symmetry rounds out the logical structure of quantum chromodynamics by removing QCD's potential to support strong violation of time-reversal symmetry, which is not observed. This extension predicts the existence of a remarkable new kind of very light, feebly interacting particle: the axion. …
5th force searches: Goal distances less than 100 $\mu$m

Axions mediate matter-spin couplings

\[ V \sim (1/r) e^{-r/\lambda} \hat{\sigma} \cdot \hat{r} \]
The special role of axion-photon mixing in sensitive searches

\[ L_{\text{int}} = a g_{a \gamma \gamma} E \cdot B \]

P. Sikivie, PRL 51, 1415 (1983)
A class of search: Vacuum birefringence & dichroism

**Vacuum dichroism**

\[ \varepsilon \sim N \cdot (1/4 \, g B_0 L)^2 \quad (N = \text{number of passes}) \]

\[ \varepsilon = N \cdot (1/96) \cdot (g B_0 m_a)^2 \cdot L^3/\omega \]

**Vacuum birefringence**


INT-09jul09 LJ 43
Example: The PVLAS experiment (INFN Legnaro)

\[ M = \frac{1}{g_{\gamma\gamma}} \]

E. Zavattini et al., PRL 96 (2006) 110406

Y. Semertzidis et al., PRL 64 (1990) 2998
Recent PVLAS details & data

Rebuilt detector doesn’t find signal.

Their early value of $g_{\alpha\gamma\gamma}$ was ostensibly excluded already by 4 orders of magnitude, by CAST, and stellar evolution (stars would live only a few thousand years)

The allowed region is on the very fringe of the exclusion region of the earlier RBF polarization experiment, plus the photon regeneration experiment

Nevertheless, this renewed polarization-rotation experiments around the world, and much theoretical work
Photon regeneration ("shining light through walls")

Only measurement to date: 
\[ g < 6.7 \times 10^{-7} \text{ GeV}^{-1} \text{ for } m_a < 1 \text{ meV} \]

Several photon regeneration efforts around the world

Experiments in various phases of preparation or operation

<table>
<thead>
<tr>
<th>Name</th>
<th>Place</th>
<th>Magnet (field length)</th>
<th>Laser wavelength power</th>
<th>F$_{polux}$</th>
<th>Photon flux at detector</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS</td>
<td>DESY</td>
<td>5 T 4.21 m</td>
<td>1064 nm 20 kW</td>
<td>$10^{-19}$</td>
<td>10/pulse</td>
</tr>
<tr>
<td>BMV</td>
<td>LULI</td>
<td>11 T 0.26 m</td>
<td>1053 nm 500 W 4 pulses/day</td>
<td>$10^{-21}$</td>
<td>0.1/s</td>
</tr>
<tr>
<td>UPSS</td>
<td>Jefferson Laboratory</td>
<td>1.7 T 1.0 m</td>
<td>900 nm 10 kW</td>
<td>$10^{-22}$</td>
<td>0.1/s</td>
</tr>
<tr>
<td>OSQAR</td>
<td>CERN</td>
<td>9.5 T 1.0 m</td>
<td>540 nm 1 kW</td>
<td>$10^{-20}$</td>
<td>10/s</td>
</tr>
<tr>
<td>PVLAS</td>
<td>INFN Legnaro</td>
<td>9 T 3.3 m</td>
<td>1064 nm 50 W</td>
<td>$10^{-23}$</td>
<td>10/s</td>
</tr>
</tbody>
</table>

All of them would still be orders of magnitude away from CAST/HBS limits
Resonantly enhanced photon regeneration

Basic concept – encompass the production and regeneration magnet regions with Fabry-Perot optical cavities, actively locked in frequency

Sikivie et al. PRL (April 27, 2007)

\[
P^{\text{Resonant}}(\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\eta \eta'} \cdot P^{\text{Simple}}(\gamma \rightarrow a \rightarrow \gamma) = \frac{2}{\pi^2} FF' \cdot P^{\text{Simple}}(\gamma \rightarrow a \rightarrow \gamma)
\]

where \(\eta, \eta'\) are the mirror transmissivities & \(F, F'\) are the fineseses of the cavities

For \(\eta \sim 10^{(5-6)}\), the gain in rate is of order \(10^{(10-12)}\) and the limit in \(g_{\alpha\gamma\gamma}\) improves by \(10^{(2.5-3)}\)
Produced by a Primakoff interaction, with a mean energy of 4.2 keV

$T_{\text{central}} = 1.3$ keV, but plasma screening suppresses low energy part of spectrum (says G. Raffelt)

The total flux (for KSVZ axions) at the Earth is given by

$$\Phi_a = 7.44 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1} (m_a/1\text{eV})^2$$

The dominant contribution is confined to the central 20% of the Sun’s radius
Principle of the solar-axion search experiment

\[ \Pi(a \leftrightarrow \gamma) = \frac{1}{4} (g_{a\gamma\gamma} B_0 L)^2 |F(q)|^2 \]

where

\[ F(q) = \frac{\sin(qL/2)}{(qL/2)} \quad , \quad F(0) = 1 \quad \text{and} \quad q = k_\gamma - k_a \approx m_a^2 / 2 \omega \]
Example: The CERN Axion Solar Telescope (CAST)

Prototype LHC dipole magnet, double bore, 50 tons, $L \sim 10\text{m}$, $B \sim 10\text{T}$

Tracks the Sun for 1.5 hours at dawn & 1.5 hours at dusk

Instrumented with: CCD with x-ray lens; Micromegas; TPC
CAST results and future

CAST has published results equaling the Horizontal Branch Star limit (Red Giant evolution)

They are pushing the mass limit up into the region of axion models, 0.1-1 eV

Plan: Fill the magnet bore with gas (e.g. helium), and tune the pressure

When the plasma frequency equals the axion mass, full coherence and conversion probability are restored:

$$\omega_p = (4\pi\alpha N_e / m_e)^{1/2} \equiv m_\gamma$$


They will go to higher $m_a$ with $^3$He, and a second x-ray optic

RF cavity axion-search experiments: Axion and electromagnetic fields exchange energy

The axion-photon coupling…

...is a source in Maxwell’s Equations

\[
\frac{\partial \left( E^2 / 2 \right)}{\partial t} - \mathbf{E} \cdot (\nabla \times \mathbf{B}) = g_{a\gamma} \dot{a} (\mathbf{E} \cdot \mathbf{B})
\]

So imposing a strong external magnetic field $\mathbf{B}$ allows the axion field to pump energy into the cavity.
RF cavity: How to detect dark-matter axions

- The conversion is resonant, i.e. the frequency must equal the mass + K. E.

- The total system noise temperature $T_S = T + T_N$ is the critical factor
  - Present experiment with HEMT amplifiers: $T \sim T_N \sim 3$ K

Important to lower $T_S$

<table>
<thead>
<tr>
<th>Signal</th>
<th>Scaling Laws</th>
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<tbody>
<tr>
<td>Power</td>
<td>$\frac{dv}{dt} \propto B^4 V^2 \cdot \frac{1}{T_S^2}$</td>
</tr>
<tr>
<td>$\Delta v / v \sim 10^{-6}$</td>
<td>$g^2 \gamma \propto \left( B^2 V \cdot \frac{1}{T_S} \right)^{-1}$</td>
</tr>
</tbody>
</table>

For fixed model $g^2$ | For fixed scan rate $\frac{dv}{dt}$ |
ADMX: Axion Dark-Matter eXperiment

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

Magnet with insert (side view)

- Stepping motors
- Liquid helium
- Amplifier, refrigerator
- Tuner
- Tuning rods
- Superconducting magnet
- 8T, 6 tons

Pumped LHe → T ~ 1.5 k

Magnet arrives

8 T, 1 m × 60 cm ø
ADMX hardware

high-Q cavity

experiment insert
The axion receiver

Integration:
Resolution:

8 msec
125 Hz
Maxwellian

FFT
50 sec
0.02 Hz
Fine-Structure
\( \Delta E/E \sim 10^{-17} \)

\( \Delta E/E \sim 10^{-6} \)

Maxion
Frequency (energy)
The world’s quietest radio receiver

Systematics-limited for signals of $10^{-26}$ W
$\sim 10^{-3}$ of DFSZ axion power (1/100 yoctoWatt).
These are interesting regimes of particle and astrophysics: probe realistic axion couplings and halo densities
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.
Quantum-limited gigahertz SQUID amplifiers

An old idea from antenna design ("shunt detuned frequency") applied to quantum electronics.
SQUID commissioning

calibration
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)
Overall status of axion hunting
Conclusions:
Two of many scenarios for direct dark-matter detection

Axion dark-matter:
If it’s the “usual” Peccei-Quinn type (“QCD axion”)
then ADMX will either find it or exclude it at high confidence.
This effort has a 5-year horizon.

and/or

WIMP dark-matter:
If it’s the usual SUSY dark-matter, then
via missing-energy signature in LHC: estimate neutralino mass.
Focus direct-detection experiments to that mass: observe recoils.
This combined effort has a 10-year horizon.

and/or

I may have it completely wrong …