Experimental Searches for Dark Matter

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Caltech
DPF2009
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Overview

• Why Dark Matter?
• The Particle Dark Matter Zoo
• Specific candidates and search techniques, with editorial selection
  • Sterile Neutrinos
  • Axions
  • WIMPs
Why Dark Matter?

• A host of astronomical and cosmological observations indicate:
  • Total energy density = critical density $\rho_{\text{crit}}$ needed for spatially flat universe (within errors)
  • The bulk is in the form of dark energy, a fluid that has negative pressure (causes the universe’s expansion to accelerate) and does not clump gravitationally, $\Omega_{\text{DE}} = \rho_{\text{DE}}/\rho_{\text{crit}} = 0.73\pm0.03$
  • Most of the matter is in the form of dark matter, matter that interacts gravitationally but not electromagnetically, $\Omega_{\text{DM}} = \rho_{\text{DM}}/\rho_{\text{crit}} = 0.20\pm0.03$
  • The remainder is in the form of baryons, $\Omega_{\text{B}} = \rho_{\text{B}}/\rho_{\text{crit}} = 0.042\pm0.004$ (though much of this has not yet been directly observed!)
Required Dark Matter Characteristics

- Dark matter must be:
  - Cold/warm (not hot):
    - nonrelativistic at matter-radiation equality \( z \sim 3500 \) to seed LSS. \( M < \text{keV} \) (e.g., \( \nu \)) too hot.
  - Nonbaryonic
    - Light element abundances + Big Bang Nucleosynthesis measure baryon density: too low.
    - Baryonic matter could not collapse until recombination \( (z \sim 1100) \): too late to seed LSS
  - Locally, we know
    - density \( \sim 0.1-0.7 \text{ GeV/cm}^3 \):
      - \( \sim 1 \text{ proton/3 cm}^3, \sim 1 \text{ WIMP/coffee cup} \)
    - velocity: simplest assumption is Maxwell-Boltzmann distribution with \( \sigma_v \approx 270 \text{ km/s} \) (recently increased based on VLBA maser measurements!)
The Particle Dark Matter Zoo

- **Neutrinos**
  - only massive (sterile) neutrinos can be cold or warm. Low-mass neutrinos make hot dark matter.

- **Axions**
  - Form as Bose condensate in early universe: cold in spite of low mass

- **Weakly Interacting Massive Particles (WIMPs)**
  - new massive (~100 GeV) particle with electroweak scale interactions with normal matter
  - SUSY neutralino
  - Lightest Kaluza-Klein particle in universal extra dimensions

- **Less compelling candidates:**
  - SUSY gravitinos (SuperWIMPs) and axinos
  - WIMPzillas, SIMPzillas, primordial black holes, Q-balls, strange quark nuggets, mirror particles, CHArged Massive Particles (CHAMPs), self interacting dark matter, D-matter, cryptons, brane world dark matter...
Massive Sterile Neutrinos

• **keV sterile neutrino**
  • acts as warm dark matter: cold enough to form structure correctly, hot enough to fix some cosmological quandaries
  • Produced in early universe by oscillations of active neutrinos (Dodelson-Widrow (DW) mechanism)
  • Decays to (M/2) photons via SM penguin diagrams

• **Limits**
  • overclosure
  • x-ray emission from decays
    • bounds will improve with future X-ray satellites (Astro-H and IXO): sensitivity limited by energy resolution
  • Lyman-α forest: too light a neutrino is too hot, washing out small-scale structure
    • Bounds may improve with better understanding of systematics in measurements and simulations
  • pulsar kicks: asymmetry in scattering of neutrinos off magnetic-field-polarized electrons and nucleons results in asymmetric neutrino emission
    • improvements perhaps with better modeling of supernovae
Axions

**Particle-Physics Motivation**

CP conservation in QCD by Peccei-Quinn mechanism

\[ \rightarrow \text{Axions } a \sim \pi^0 \]

\[ m_{\pi} f_{\pi} \approx m_a f_a \]

For \( f_a >> f_{\pi} \) axions are “invisible” and very light

**Solar and Stellar Axions**

Axions thermally produced in stars, e.g. by Primakoff production

- Limits from avoiding excessive energy drain
- Search for solar axions (CAST)

**Cosmology**

In spite of small mass, axions are born non-relativistically (“non-thermal relics”)

\[ \rightarrow \text{Cold dark matter candidate } m_a \sim 1-1000 \mu\text{eV} \]

**Search for Axion Dark Matter**

Microwave resonator (1 GHz = 4 \( \mu \text{eV} \))

Primakoff conversion

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Axion Direct Search Techniques

Cosmologically interesting: provides appropriate $\Omega_{\text{DM}}$, $m_a = 1 \ \mu\text{eV}$ to 1 meV

- Microwave cavity conversion
  - $1 \ \text{GHz} = 4 \ \mu\text{eV}$: use high-Q tunable cavity in high B field; when $f_0 = m_a$, excess power
  - Detection: RF amplifier + Fourier transform power spectrum, excited Rydberg atom photodetection
  - Can cover $\sim 1 \ \mu\text{eV}$ to 100 $\mu\text{eV}$; cavities become too small $> 100 \ \mu\text{eV}$
  - With $\mu$wave SQUID amplifier and colder cavity, will test full KSVZ-DFSZ range

Figure 4: Exclusion region reported from the microwave cavity experiments RBF and UF [75] and ADMX [76]. A local dark-matter density of $450 \ \text{MeV} \ \text{cm}^{-3}$ is assumed. [78]. The ADMX experiment is currently undergoing commissioning of an upgrade that replaces the microwave HFET amplifiers by near quantum-limited low-noise dc SQUID amplifiers [79], allowing a significant improvement in the experiment sensitivity. A Rydberg atom single-photon detector [80] can in principle evade the standard quantum limit [81] for coherent detection, thus achieving very good sensitivity. Efforts are underway to incorporate Rydberg atom systems in RF cavity axion searches [82].

Conclusions: Experimental, astrophysical, and cosmological limits have been refined and indicate that axions, if they exist, are likely very light, $m_A < \sim 10 \ \text{meV}$, suggesting that axions are a non-negligible fraction of the cosmic CDM. The upgraded versions of the ADMX experiment will ultimately cover the range $1$–$100 \ \mu\text{eV}$ with a sensitivity allowing one to detect axions, unless the local DM density is unexpectedly small or the axion–photon coupling anomalously weak. Other.
Axion Direct Search Techniques

Cosmologically interesting: provides appropriate $\Omega_{\text{DM}}$, $m_a = 1 \, \mu\text{eV}$ to $1 \, \text{meV}$

- **Decays**
  - $a \rightarrow 2\gamma$, $E_\gamma = m_a/2$ spectral line
  - Old and more recent searches done at optical wavelengths, excluded DFSZ and KSVZ axion models
  - Improvements in radio receivers may enable searches in mm/cm-wave regime where cavity expts are more difficult ($100 \, \mu\text{eV} - 1 \, \text{meV}$), but not easy w/o enhancement by $B$!

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Grin et al (2007)

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Axion Direct Search Techniques

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- Solar axions
  - Photons convert to axions via Primakoff process in sun; $\sim$keV thermal kinetic energy
  - Axion-conversion telescopes sensitive to $\sim$1 eV axions; too massive to be CDM, could be HDM (though $\ll \Omega_{\text{DM}}$)
- Higher masses probed by Bragg scattering searches
- Beginning to probe DFSZ and KSVZ models

after G. Raffelt

Experiments: CAST

Tele scope: Hot dark matter limits (a-\pi-coupling)

Globular clusters (a-\gamma-coupling)

Too many events

Too much energy loss

SN 1987A (a-N-coupling)

Cosmologically Interesting
Axion Direct Search Techniques

Cosmologically interesting: provides appropriate $\Omega_{\text{DM}}$, $m_a = 1 \mu\text{eV}$ to $1 \text{meV}$

- Other laboratory searches
  - $\gamma \rightarrow a \rightarrow \gamma$ in B field; relatively poor sensitivity bec. two vertices; very far away from plausible models
    - Shining light thru walls. Will be more sensitive w/high Q optical cavities in future.
    - B-induced polarization rotation;
      PVLAS polarization rotation signal has disappeared in second measurement
    - B-induced birefringence
  - Torsion pendulum (Eot-Wash group)
    - Axions mediate a P and T violating force between electrons and nucleons
    - Look for violations of $1/r^2$
WIMPs

• A WIMP $\delta$ is like a massive neutrino: produced when $T \gg m_{\delta}$ via pair annihilation/creation. Reaction maintains thermal equilibrium.

• If interaction rates high enough, comoving density drops as $\exp(-m_{\delta}/T)$ as $T$ drops below $m_{\delta}$: annihilation continues, production becomes suppressed.

• But, weakly interacting $\rightarrow$ will “freeze out” before total annihilation if

$$H > \Gamma_{ann} \sim \frac{n_{\delta}}{\langle \sigma_{ann} v \rangle}$$

i.e., if annihilation too slow to keep up with Hubble expansion

• Leaves a relic abundance:

$$\Omega_{\delta} h^2 \approx \frac{10^{-27}}{\langle \sigma_{ann} v \rangle_{fr}} \text{cm}^3 \text{s}^{-1}$$

$\rightarrow$ if $m_{\delta}$ and $\sigma_{ann}$ determined by new weak-scale physics, then $\Omega_{\delta}$ is $O(1)$

• LSP in R-parity conserving SUSY is an ideal WIMP: weak-scale cross-section, neutral, stable. But WIMPs are not SUSY-specific!
Supersymmetric WIMPs

- SUSY lightest superpartner w/ R-parity cons. is WIMP(-like)

- Neutralino LSP \( \delta \)
  - mixture of bino, wino, higgsinos; spin 1/2 Majorana particle

- Allowed regions
  - bulk: \( \delta \) annih. via t-channel slepton exchange, light \( h \), high \( \text{BR}(b \rightarrow s \gamma) \) and \( (g-2)_\mu \); good DD rates
  - stau coann: \( \delta \) and stau nearly degenerate, enhances annihilation, low DD rates
  - focus point: less fine-tuning of REWSB, \( \delta \) acquires higgsino component, increases annihilation to \( W, Z \), good DD rates
  - A-funnel: at high tan \( \beta \), resonant s-channel annihilation via A, low DD rates

- Gravitino LSP: nondetection interesting!

\[ \chi^2 \text{ of fit to } \text{BR}(b \rightarrow s \gamma), \mu \text{on } g-2, \text{ and relic density} \]

\( m_{\text{SUGRA}} \) with \( \tan \beta = 54, A_0 = 0, \mu > 0 \)

\[ m_{h} = 114.1 \text{GeV} \]

LEP2 excluded

SuperCDMS

CDMSII

predictions!
Universal Extra Dimensions WIMPs

- Kaluza-Klein tower of partners due to curled-up extra dimension of radius $R$
  - $n =$ quantum number for extra dimension, $m_n^2 \sim n^2/R^2$
  - momentum cons. in extra dim. $\implies$ exact cons. of KK particles (KK parity)
  - KK parity $P_{KK} = (-1)^n$ implies lightest KK partner ($n = 1$) is stable
- $B^{(1)}$, $n = 1$ partner of B gauge boson, is lightest KK partner in simple cases
- Cross-section on quarks depends on fractional mass difference between $B^{(1)}$ and 1st KK partner of quarks, $q^{(1)}$
Astrophysical Detection and Colliders

- Astro searches will limit $\sigma_{\text{scatt}}$ and $\sigma_{\text{annih}}$ as colliders push up in mass
- Astro searches test whether collider DM candidate is stable and measures $\sigma_{\text{scatt}}$ and $\sigma_{\text{annih}}$
- Hopefully we will narrow down the parameter space together.

Figure 3: mSUGRA, $A_0=0$, $\tan\beta=45$, $\mu<0$

Legend:
- $\Phi(p^\pm) = 3 \times 10^{-7}$ GeV$^{-1}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$
- $(S/B)_{e^+} = 0.01$
- $\Phi(\gamma) = 10^{-10}$ cm$^{-2}$ s$^{-1}$
- $\Phi_{\text{sun}}(\mu) = 40$ km$^{-2}$ yr$^{-1}$
- $m_h = 114.4$ GeV
- $\Phi_{\text{earth}}(\mu) = 40$ km$^{-2}$ yr$^{-1}$
- $\sigma(\tilde{\chi}_1^0) = 10^{-9}$ pb
- $0 < \Omega h^2 < 0.129$
Indirect Searches

• In many places, the WIMP density becomes large enough for annihilation to occur in spite of low cross sections: galactic haloes/cores, Sun, Earth

• Annihilation products:
  • fermion pairs (via Z, A, sfermion exchange), though note helicity suppression for SUSY neutralino WIMPs, which are Majorana
  • gluons, which hadronize
  • Z, W, Higgs, which decay to fermions
  • neutrinos (direct production at exactly $m_\delta/2$, continuum from decays of other products)
  • photons (via 2nd-order diagrams only, at $m_\delta/2$, continuum from decays of other products)
  • stable hadrons and antihadrons (from hadronization of antiquarks)
  • synchrotron emission (resulting from electron products near the galactic center spiraling in the mG magnetic field)

• Caveats
  • Very dependent on modeling of dark matter density, esp. its clumpiness
WIMPs pair-annihilate to stable, SM particles
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S. Profumo
WIMPs pair-annihilate to stable, SM particles

Supersymmetric neutralinos

Bosons

Leptons

Quarks

Low-energy photons

Medium-energy gamma rays

Decay process

Positrons

Electrons

Neutrinos

Antiprotons

Protons

Gamma Rays
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Neutrinos

- WIMPs suffer energy loss via elastic scattering with p and n in Sun
  - density at galactic center, elsewhere in halo not large enough
  - density predictions pretty solid
- WIMPs annihilate to neutrinos, yielding continuum signal:
  - Directly produced neutrinos lose energy as they leave sun
  - Much bigger phase space for neutrinos from decay of other annihilation products
- Search for $\nu_\mu$ via upward-going $\mu$ in $\nu$ telescopes such as IceCube, Antares
  - Sensitive to SUSY-relevant mass range, $\gtrsim 100$ GeV
  - To first order, sensitivity of neutrino searches and direct detection are proportional because both scale with nucleon-scattering cross-section
Gamma Rays

- **Two types of instruments**
  - GLAST: satellite mission with large silicon strip tracker + CsI calorimeter, sensitive up to few x 100 GeV
  - Air Cerenkov Telescopes (ACTs): ground-based telescope collecting Cerenkov light from gamma-ray air showers; E > tens of GeV → few GeV (future km² array)
    - (Ground-based air-shower arrays, E > 1 TeV)

- **Requires large clumping factors**
  - \( J \sim \left< \rho^2 \right> / \left< \rho \right>^2 \sim 1000 \) possible in galaxies depending on density profile
  - Astro bgnnds problematic

- **Current limits**
  - HESS GC limit not useful yet
  - HESS Sagittarius dwarf, Whipple M15, Ursa Minor, Draco limits begin to be interesting, but requires modeling to calculate \( J \)
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Antimatter

- Positrons:
  - Measure dE/dx and rigidity, ID those too light to be CR and w/wrong sign to be electrons
    - key experimental issue: misidentification of p as e^+. Need 10^3-10^4 rejection.
  - HEAT balloon payload (mid-1990s) saw a bump in e^+/e^- consistent with WIMP annihilation
  - PAMELA satellite (launched 2006) has confirmed rise in positron fraction
  - ATIC, PPB-BETS balloons saw bump in total electron flux, not seen by Fermi
  - PEBS balloon will measure fraction to much better precision up to 200 GeV
  - See Aaron Pierce’s talk for scientific interpretation

![Graph showing positron fraction vs energy](image-url)
Antimatter

- **Antiprotons**
  - Previous experiments measurements have been fully consistent with expected spectrum
  - PAMELA has improved precision greatly
  - No sign of signal from vanilla WIMP consistent with positron excess
  - See A. Pierce’s talk
• **Antimatter**

  - **Antideuterons**
    - Antideuteron production possible during hadronization of annihilation products
    - Expected flux at earth far exceeds backgrounds from cosmic ray spallation; a very different regime than positron and antiproton searches (Donato, Baer and Profumo)
  - **GAPS**
    - Detects antideuterons by capture: Antideuteron slows to stop in detector, forms atom; antideuteron atom deexcites via X-rays and Auger electrons; annihilation into pions
    - Challenging! 200 kg of Si(Li) wafers target (~5000 4” wafers), coincidence demo’d in beam test; test flight 2009, Antarctic long-duration balloon 2013, perhaps 100-day ULDB
Direct Detection: Signature

- WIMPs collected in spherical isothermal halo: ideal gas with gravity, \( kT = \langle mv^2/2 \rangle, \sqrt{\langle v^2 \rangle} \approx 220 \text{ km/s} \)
- WIMPs elastically scatter off quarks in target nuclei, producing nuclear recoils, with \( \sigma_q \delta \) related to \( \sigma_{\text{ann}} \) (same diagrams: via Z, h, H, and squarks)
- Energy spectrum of recoils is exponential, \( \langle E_R \rangle \sim 50 \text{ keV} \), depends on WIMP and target masses: Boltzmann distribution (spherical isothermal halo) + NR s-wave scattering

\[
E_0 = \frac{2 m_\delta^2 m_N}{(m_\delta + m_N)^2} v_0^2 \approx \frac{m_N}{10^6} \approx 50 \text{ keV}
\]

- Amplitude of recoil energy spectrum, i.e. event rate, normalized by \( \sigma_n \delta \), local WIMP number density, and nucleus-dependent \( A^2 F^2(E_R) \):

\[
\frac{dR}{dE_R} \propto \frac{n_\delta \sigma_n \delta}{E_0} \exp \left( -\frac{E_R}{E_0} \right) A^2 F^2(E_R)
\]

- At low \( E_R \), scattering is coherent and \( \propto A^2 \). Coherence lost at larger \( E_R \) via form factor \( F^2(E_R) \)
Scattering Cross Sections

• In general, a Lorentz-invariant Lagrangian $L$ has $S, P, V, A$ interactions
• WIMP can be fermion, boson, or scalar
• In non-relativistic limit, reduces to two cases
  • Scalar interaction, scales as $A^2$ because deBroglie wavelength is large
    \[
    \sigma_{SI} = \frac{m_N^2}{4\pi(m_\chi + m_N)^2} \left[ Z f_p + (A - Z) f_n \right]^2
    \]
    $f_p$ and $f_n$ are effective couplings to $p$ and $n$, equal in most theories under consideration
  • Spin-spin interaction couples to net nuclear spin $J_N$
    \[
    \sigma_{SD} = \frac{32 G_F^2}{\pi} \frac{m_\chi^2 m_N^2}{(m_\chi + m_N)^2} \frac{J_N + 1}{J_N} \left( a_p \langle S_p \rangle + a_n \langle S_n \rangle \right)^2
    \]
    $\langle S_p \rangle$, $\langle S_n \rangle$ are total proton and neutron spin contributions
    $a_p$ and $a_n$ are couplings to $p$ and $n$
WIMP Direct Searches

• Fundamental goal: See a very small WIMP signal in presence of many other particles interacting in detectors (photons, electrons, alpha particles, neutrons)

• Many different techniques:
  • Reduce backgrounds
    • (HDMS, IGEX), CoGeNT: Ge γ spectrometers
    • XMASS: single-phase LXe
  • Reduce backgrounds + annual modulation
    • DAMA: NaI scintillator; KIMS: CsI scintillator
  • Statistical nuclear recoil discrimination
    • DAMA, UKDMC: pulse-shape analysis in NaI, LXe
  • Event-by-event nuclear recoil discrimination
    • phonons + ionization/scintillation: CDMS, EDELWEISS, CRESST, ROSEBUD
    • Liquid Nobles: direct electronic excitation + ionization: XENON, ZEPLIN, LUX, WArP, ArDM, DEAP/CLEAN, etc.
    • Superheated droplets: bgnd-insensitive threshold detectors; SIMPLE, PICASSO
  • Diurnal modulation
    • DRIFT, DMTPC

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Nuclear Recoil Discrimination

**Signal**

- Nuclear Recoils
- Dense Energy Deposition
- $E_r$
- $\nu/c \approx 10^{-3}$
- Neutrons same, but $\sigma \approx 10^{20}$ higher; must shield

**Background**

- Electron Recoils
- Sparse Energy Deposition
- $E_r$
- $\nu/c \approx 0.3$

**Density/Sparsity: Basis of Discrimination**
Annual Modulation

- WIMP wind ~ isotropic in halo frame, $v_{\text{rms}} \sim 270$ km/s
- Sun travels through this cloud at 270 km/s
- Earth adds or subtracts 15 km/s ($= 30 \text{ km/s} \times \cos 60^\circ$) to solar velocity
- Expect $\pm$ 1-few % modulation in rate, energy deposition, depending on target and threshold
- DAMA/LIBRA: clear modulation; is it a WIMP?
- KIMS Korean CsI scintillator experiment aiming to test
Diurnal Modulation

- WIMPs directional in terrestrial frame
- Direction of WIMP wind varies diurnally due to Earth’s rotation
- Recoiling nucleus will preserve some directionality
- Large modulation (~ DC signal) possible in theory
- Backgrounds will be unmodulated

Figures courtesy of J. Battat
Cryogenic Dark Matter Search (CDMS)

- NR discrimination via total recoil energy + ionization + phonon timing/position:
  - phonon signal provides total recoil energy (athermal phonon sensor using tungsten transition-edge sensors attached to aluminum phonon absorbers)
  - ionization signal depends on density of deposition, ionization yield ~ 1/3 for NRs in Ge
    - Collected using H-a-Si electrodes to minimize dead-layer effects
  - detectors close-packed with no intervening material: detectors see other clean detectors, not outside radiation sources
  - radial segmentation of electrode enables rejection of events at outer edge of detector
  - Also: CRESST, EDELWEISS, ROSEBUD (no time to discuss here)
• Dead layer and athermal phonons
  • tens of μm deep “dead layer” due to loss of hot charges into “wrong” electrode before drift field takes over
  • athermal phonon sensor provides rejection: phonon signal rising edge provides 2-d imaging and sensitivity to z position; latter provides rejection of ionization dead-layer events

• Background rejection (15-45 keV, 50-70% acceptance)
  • in CDMS II:
    2 x 10^{-6} misid of gamma events
    2 x 10^{-3} misid of surface electron events
  • SuperCDMS:
    1 x 10^{-7} for gammas,
    2.5 x 10^{-4} for surface electrons

• Final CDMS II results expected late summer/early fall; see Oleg Kamaev talk for status update in PAC II, Tuesday 2pm
SuperCDMS

- **SuperCDMS Soudan:**
  - 1 cm → 2.5 cm thickness (0.25 kg → 0.65 kg)
  - New phonon sensor design reduces surface event misid
  - New understanding that cosmogenic neutron bgnd much lower than previously expected (2000 mwe)
  - 16 kg total: 5 x 10^{-45} cm^2 reach at end of 2011, likely limited by apparatus background
  - Production of first 8 kg funded, proposal for second 8 kg and running submitted Oct 2008

- **Breaking news (LTD13)**
  - new electrode design ID’s surface events with < 3 x 10^{-4} misid in three independent ways; Need underground demo to demonstrate (3 x 10^{-4})^3
  - EDELWEISS has similar results (one method, better limit on misid bec of underground demo)

- **Enables:**
  - **SuperCDMS SNOLAB**
    - 100 kg mass; reach of 3 x 10^{-46} cm^2
  - **DUSEL Germanium Observatory for DM (GEODM)**
    - 1.5 T mass, reach of 2 x 10^{-47} cm^2
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Noble Liquids/Gases

- **Method:**
  - Ionization and direct excitation paths have different populations for nuclear and electron recoils
  - *Independently,* different paths populate fast singlet and slow triplet states differently

- **Implementations:**
  - LXE: observe scintillation and drift e-
  - LNE: observe slow and fast scintillation
  - LAr, GXe: both

<table>
<thead>
<tr>
<th></th>
<th>Liquid density (g/cc)</th>
<th>Boiling point at 1 bar (K)</th>
<th>Electron mobility (cm²/Vs)</th>
<th>Scintillation wavelength (nm)</th>
<th>Scintillation yield (photons/MeV)</th>
<th>Long-lived radioactive isotopes</th>
<th>Triplet molecule lifetime (µs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHe</td>
<td>0.145</td>
<td>4.2</td>
<td>low</td>
<td>80</td>
<td>19,000</td>
<td>none</td>
<td>13,000,000</td>
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<tr>
<td>LNe</td>
<td>1.2</td>
<td>27.1</td>
<td>low</td>
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<td>30,000</td>
<td>none</td>
<td>15</td>
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<tr>
<td>LAr</td>
<td>1.4</td>
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<td>400</td>
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D. McKinsey

N. Smith

DPF2009/Experimental Searches for Dark Matter
Sunil Golwala
Noble Liquids/Gases

- **Method:**
  - ionization and direct excitation paths have different populations for nuclear and electron recoils
  - *independently,* different paths populate fast singlet and slow triplet states differently

- **Implementations:**
  - LXe: observe scintillation and drift e-
  - LNe: observe slow and fast scintillation
  - LAr, GXe: both

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D. McKinsey
Liquid Xenon

- **XENON10 (Gran Sasso)**
  - First competitive LXe expt
  - 5.4 kg fiducial
  - Good light collection (5 pe/keV)
  - Good bgnds in in prototype
  - 2007 results limited by bgnd consistent with tail of EM into WIMP acceptance region
  - Cutting harder will reduce NR acceptance from 50%
  - Scale-up needed to reduce bgnd by self-shielding, need to maintain ionization and light collection efficiency

- **ZEPLIN III (Boulby)**
  - Similar idea, higher bgnds, less self-shielding
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![WIMP Search Data](Image)

- **99.0% rejection**
- **99.9% rejection**

**Primary Predicted Leakage in 58.6 Live–Days**

**Total: $7.0^{+2.1}_{-1.0}$ Events**

![Graph](Image)

- $\Delta \log_{10}(S_2/S_1)$
- Energy [keVee]
- 2 - 12 keVee
- 4.5 - 27 KeVr
Liquid Xenon

- **XENON100** (Gran Sasso)
  - upgrade of XENON10, 50 kg fiducial, 170 kg total
  - cold and operating since mid-2008, working on light yield and bgnd issues, physics running to begin by end 2009
  - XENON 100+: 100-kg fiducial w/QUPIDs

- **LUX** (Sanford/Homestake)
  - high-bgnd test cryostat for 60 kg LXe operational w/0.5 kg LXe at Case
  - Ti cryostat in fab
  - constructing surface lab
  - 4850 ft level dewatered, deploy to surface lab in Fall, 2009, underground in 2010?

- **XMASS**
  - single-phase: self-shielding only, shielding built, detector in process, commissioning ~start 2010
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**XENON100 Status: Light Yield**

- In April 09 we replaced a vacuum seal and reduced further detector outgas with bake-out and hot gas recirculation
- In May 09 we filled TPC again (current run-06): Light Yield 3.2 pe/keV for 662 keV
  - Equivalent to 4.5 pe/keV for 122 keV
  - With event position reconstruction we can now measure the S1 position dependence

3 pe/keV at 662 keV = 5 pe/keV at low energy
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Liquid Argon

- **WArP (Gran Sasso)**
  - 140-kg detector being commissioned inside passive water shield, active LAr shield

- **ArDM**
  - still in R&D phase, but 1-ton R&D detector constructed and filled, uses fewer larger PMTs, uses LEMs for ionization gain

- **DEAP/CLEAN (SNOLAB)**
  - single-phase Ar/Ne
  - miniCLEAN:
    - 150 kg fiducial, 500 kg total
  - hall at SNOLAB under construction
  - detector under construction
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Metastable Bubble Chamber Detectors

- **Bubble chamber**
  - Superheated liquid or gel + energy density effect: ER deposition density too small to nucleate bubbles
  - Excellent rejection of ERs: \( >10^{13} \) @ 10 keVr threshold (COUPP)

  ![Bubble Chamber Diagram](image)

  - Threshold detector, controlled by temperature & pressure.
  - Video and acoustic readout

- Assorted nuclei, spin-indep (I and Br) and spin-dep (F)

- In principle, inexpensive
Metastable Bubble Chamber Detectors

- **COUPP**
  - video readout
  - prior run of 2-kg at 300 mwe limited by $\alpha$ bgnd from vessel (edge events) and $\alpha$ events from radon emanation into bulk
  - 60 kg tested at surface, running underground at 300 mwe with water shield; want to demonstrated alpha bgnd at Borexino levels

- **PICASSO (SNOLAB)**
  - acoustic (piezo) readout
  - 14 kg-d from 0.12 kg provides new spin-dep constraints
  - 1.9 kg running since start 2009
  - demonstrated NR/$\alpha$ discrim. via acoustic pulse height
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Time Projection Chambers

• DMTPC
  • CF$_4$ gas: low diffusion, scintillates well
  • PMTs for trigger, z information
  • CCD images avalanche region to obtain energy, xy track orientation (good posn resolution with CCD, ~100 μm)
  • Excellent gamma/beta rejection based on track size
  • head/tail based on dE/dx: directionality!

• DRIFT
  • negative ion TPC, e$^- +$ CS$_2$ → CS$_2^-$: drifting of heavy ion suppresses diffusion
  • 2 mm pitch anode + crossed MWPC grid give xyz imaging and energy
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- 1 m$^3$ detector in fabrication, will be run underground (WIPP)

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- 2 mm pitch anode + crossed MWPC grid give xyz imaging and energy
- Excellent gamma/beta rejection based on track size
- head/tail based on dE/dx: directionality!
- Multiple underground runs of 1 m$^3$ at Boulby mine (UK), still dealing with radon emanation and daughter issues
- Demonstrated CS$_2$-CF$_2$ mixtures for spin-dependent sensitivity
Spin Independent Limits

Cross-section [$cm^2$] (normalised to nucleon)

WIMP Mass [GeV/c²]

DAMA NaI (allowed @ 3σ):
- channeled Na (3σ)
- channeled I (3σ)
- unchanneled Na (3σ)
- unchanneled I (3σ)

- NAIAD (2005) NaI scint. + PSD

plot compiled by P. Cushman using Gaitskell, Mandic, and Filippini
http://dmtools.brown.edu

Trotta et al 2008, CMSSM Bayesian: 68% contour
Trotta et al 2008, CMSSM Bayesian: 95% contour
Baltz and Gondolo, 2004, Markov Chain Monte Carlos
Spin Dependent Limits: Pure Neutron Coupling

plot compiled by P. Cushman using Gaitskell, Mandic, and Filippini
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spin-dependent limits less sensitive because \( J(J+1) \) scaling (vs \( A^2 \)), but pure proton couplings approach SUSY!

Baltz and Gondolo, 2004, Markov Chain Monte Carlos

DPF2009/Experimental Searches for Dark Matter

Sunil Golwala
Spin Dependent Limits: Pure Proton Coupling

WIMP capture in Sun: scattering off $p$ results in capture, \(\sim\)model-independent

Bubble chambers and TPCs optimizing for SD to provide useful progress despite limited mass.

plot compiled by P. Cushman using Gaitskell, Mandic, and Filippini
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1\(\sigma\) \(\mu_{g-2}\) constraint
w/o 1\(\sigma\) \(\mu_{g-2}\) constraint

Baltz and Gondolo, 2004, Markov Chain Monte Carlos

CRESST I (est.) Al\(_2\)O\(_3\) ph.
ZEPLIN II (2007) LXe ioniz. + scint.
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WIMP Mass [GeV/c\(^2\)]

Cross-section [cm\(^2\)] (normalized to nucleon)

10\(^{-40}\) 10\(^{-38}\) 10\(^{-36}\) 10\(^{-34}\) 10\(^{-32}\)

10\(^{1}\) 10\(^{2}\) 10\(^{3}\)
Spin Dependent Limits: Pure Proton Coupling

- **CDMS II** (2005) Si ph. + ioniz.
- **CRESST I** (est.) AlO$_3$ ph.
- **ZEPLIN II** (2007) LXe ioniz. + scint.
- **SIMPLE** (2005) C$_2$ClF$_5$ bubble
- **Tokyo** (est.) CaF$_2$ scint.
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- **XENON10** (2008) LXe ioniz. + scint.
- **ZEPLIN III** (2009) LXe ioniz. + scint.
- **COUPP** (2008) CF$_3$I bubble

WIMP capture in Sun:
- Scattering off p results in capture, ~model-independent
- Bubble chambers and TPCs optimizing for SD to provide useful progress despite limited mass.
Spin-Dependent Limits

M = 50 GeV regions inside contours allowed at 90% CL

spin-dependent limits more model-dependent, \( \langle S_p \rangle, \langle S_n \rangle \)
calculated from nuclear model

from PICASSO (2009) using Gaitskell, Mandic, and Filippini
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\[ a_p \]
\[ a_n \]
The Future of Direct Searches

where the coming generation is aiming, $10^{-9}$-$10^{-8}$ pb

Many technologies under development promise $10^{-10}$ pb, but the devil is in the details!

DUSEL is coming: S4 engineering funding announcements soon, S5 proposals early 2010, DUSEL PDR late 2010, construction start 2013?