A Survey of Direct DM Searches

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What do we really know about DM?

• Not much: more questions than there are answers

• Is the dark matter comprised of …?
  – WIMPs, axions, axinos, WIMPzillas? LSP? LKKP?
  – Supersymmetric (MSSM, NMSSM, CMSSM?) or Kaluza-Klein WIMP? Pseudo-scalar boson? Something else?

• What is the shape/density profile of the DM halo of our own galaxy (or that of a generic galaxy)?
  – Spherical, elliptical? How elliptical? Einasto profile?

• What is the mean local energy density?
  – 0.2 - 0.8 GeV/cm$^3$: L. Bergstrom et al, Astropart. Phys. 9 (1998), 137.
Astrophysical Uncertainties

• Energy density (and since the WIMP mass is unknown, the number density is unknown)
  – If WIMP mass is 100 GeV, then it’s 3 WIMPs/liter

• What about the WIMP velocity distribution?
  – Mean velocity of 200-what km/s? Finite galactic escape velocity of ~600 km/s?
  – Deviations from spherical isothermal model only change event rates by ~10% for velocity distributions compatible with models of galactic formation

• Maximum WIMP rotational rate could affect the event rate in a detector by ~30%

What is certain? (Unless MOND...)

- Not a SM particle (none have all right traits), and is thermal relic
- Wealth of indirect evidence but conclusive direct detection elusive
- Galactic rotation curves exhibit unexpected behavior consistently
- Gravitational lensing studies concur with the rotation curves
- CMB favors model with ~25% energy content non-baryonic particles
- Large-scale structure simulations indicate DM is rarely interacting and non-relativistic/heavy
Annual and Daily WIMP Modulations

- A WIMP detection signal should vary over the course of the year as Earth revolves around the Sun, which is traversing the galaxy.
- There is also a daily variation caused by the rotation of the Earth (though this is a much smaller effect), and a preferred direction.
- Experiments which capitalize upon these effects are DAMA and DM-TPC. A periodic or directional signal helps avoid backgrounds.
Dark Matter Detection Strategies

- Indirect detection of WIMP self-annihilation into Standard Model particles, like gammas or neutrinos
- Direct detection via nuclear recoils: WIMPs interacting with the nuclei of a detector
- Production of WIMPs from the high-energy collisions of particle colliders – LATER!
- Multiple detections by different methods good for solidifying a discovery.

The scope of this talk will be direct detection alone.
Different Direct Detection Methods

• Atoms or molecules can be excited by recoiling nuclei (or electrons), and they can produce scintillation light upon de-excitation detectable by PMTs, QUPIDs, APDs, etc. as a voltage signal
  – Liquid/gas scintillators: Xe, Ar, Ne (noble)
  – Solid scintillators: NaI, CsI, CaWO$_4$, LiF, CaF$_2$

• Electrons may be fully ionized instead of just being excited, and free charge is collected in an electric field. Used in:
  – Xe à la XENON (in combination with light)
  – Ge à la CDMS (in combination with phonons)

• Nuclear or electron recoil can also cause lattice vibration (phonons) read by bolometers/calorimeters: Ge, Si, CaWO$_4$

• Recoiling species can boil superheated liquid: CF$_3$I, CF$_3$Br, C$_3$F$_8$, C$_4$F$_{10}$, C$_2$ClF$_5$
  (cameras and/or piezos detect bubbles)
<table>
<thead>
<tr>
<th>Experiments of the World</th>
<th>COLD (cryogenic) experiments are in BLUE</th>
<th>HOT (superheated liquid) experiments are in RED</th>
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<tr>
<td>Past experiments are normal font.</td>
<td>Present experiments are in bold.</td>
<td>Future ones are in italics.</td>
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- **Noble Scintillation**
  - ZEPLIN I/UK-DMC (Xe)
  - DEAP/CLEAN (Ar, Ne)
  - XMASS (Xe)
  - ICARUS (Ar)

- **Scintillation + Ionization**
  - LUX, LZS, LZD (Xe)
  - XENON10-100-1T (Xe)
  - ZEPLIN-II-III (Xe)
  - DarkSide (Ar)
  - MAX, DARWIN (Ar, Xe)
  - PANDA-X I-II (Xe)
  - WArP, ArDM (Ar)

- **Solid scintillators**
  - DAMA/LIBRA, Modane, NaIAD, DM-ICE, ELEGANT V (NaI)
  - KIMS (CsI)
  - Nokogiriyama (LiF)
  - Tokyo Kamioka (CaF$_2$)

- **Scintillation + Phonons**
  - CRESST-I-II (CaWO$_4^8$)

- **Ionization + Phonons (Ge)**
  - CDMS-I-II, SuperCDMS, GEODM
  - EDELWEISS-I-II-III (I also Al$_2$O$_3$), EURECA
  - CDEX, GENIUS-TF, GENIUS, IGEX-DM, GEDEON, HDMS, Heidelberg-Moscow, COSME

- **Phonons Alone**
  - ROSEBUD (Al$_2$O$_3$)

- **Ionization/Charge**
  - CoGeNT, C-4, TEXONO (Ge)
  - DMTPCino *, NEWAGE (CF$_4$)
  - DRIFT-I-IIId-III (CS$_2$/CF$_4$ gas)
  - MIMAC ($^3$He + CF$_4$ gas)
  - DAMIC (CCDs) *light too

- **Bubbles (BC or SDD/BD)**
  - COUPP 2,4,15,60,500 kg (CF$_3$I)
  - PICASSO (C$_4$F$_{10}$)
  - SIMPLE Phase I, II (C$_2$ClF$_5$)
Looking for Dark Matter at Underground Labs
~50% Dark Matter Searches use Noble Liquids

Techniques:
- Cryogenic (Ge, Si etc.)
- Solid Scintillator (NaI, CsI)
- Noble Liquids (LXe, LAr)

Courtesy D. McKinsey
What is the signal from a WIMP?

- In the leading theories, WIMPs preferentially interact with the nuclei of a given target (intermediary varies)
- Depending on target material, the resulting nuclear recoil may lead to scintillation/light, ionization, a phase change, phonons/heat, or a combination
- Interactions rare, so looking only for a single scatter in a detector, so need: Mass $\times$ Time

Depending on the precise WIMP model and the target substrate, the WIMP may interact with matter as rarely once per ton-year! Current limits are about two orders of magnitude away: $O(1000) \text{ kg-days exposure}$
Recoil Spectra for Different Materials

- **Model-independent***: we are just looking at a scattering cross section and a mass and doing the simple kinematics.

- Arguments rage about which material is best: depends on your threshold (plus more ...)

\[ \sigma_0 = 10^{-44} \text{ cm}^2, \ M_x = 100 \text{ GeV} \]

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**WIMP-nucleon SI cross-section of 1 pb and a 1,000 GeV WIMP.**

Energetic recoil becomes increasingly improbable.

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*Not astrophysics-independent*
Different Coupling Types

- **Spin-independent (scalar):** most sought after by experiments
  - WIMP interacts coherently with an entire nucleus
  - Cross section scales roughly as $A^2$, so the bigger the nucleus the better, in general
  - Energetic recoils suffer from form factor penalty, damaging above bonus
  \[ \sigma_T(q=0) = A^4 \frac{(M_n + M_\chi)^2}{(AM_n + M_\chi)^2} \sigma_n \]

- **Spin-dependent (axial-vector):** harder to use
  - WIMP interacts with individual nucleons, and may interact differently with protons and neutrons
  - The cross-section depends heavily upon nucleus selected, with $^{19}\text{F}$ being the best for SD(p) interactions (Behnke et al. 2011)
  - Form factor becomes significantly more complicated

\[
F^2(qr_n) = S(q)/S | S(q) = a_0^2 S_{00}(q) + a_1^2 S_{11}(q) + a_0 a_1 S_{01}(q)
\]

(All equations from Lewin and Smith.)
Experimental Backgrounds

- **Neutrons**: Go bump in the night just like WIMPs. Can be remediated by cutting multiple scatter events and by aggressively fiducializing your detector volume, if it is self-shielding, and by simulating all of the neutrons sources you can think of.

- **Alphas**: Can also produce nuclear recoil like WIMPs. Alpha events near detector walls can be removed from data by good fiducialization. However, \((\alpha, n)\) events remain a problem (above).

- **Gammas and electrons**: Not a problem if your detector is insensitive to electron recoil, or can discriminate between electron and nuclear recoils well (between 1 part in \(10^3\) to \(10^{11}\) level discrimination/acceptance achieved with current technologies).

- **Muons**: Will induce neutrons in nearby material. Will also produce electron recoils. Can go deep underground to help avoid them. Can also tag them with a muon veto.
Review of Select Technologies: Ge

• CDMS, Edelweiss (+others) use cryogenic Ge detectors
• CDMS-II ionization charge readout: divided Al electrode
• Phonon readout: TES (transition edge sensor), a resistor which goes superconducting (sharp sigmoid transition)
  – Four deployed per detector, with sub-ms-timescale signals
  – Transition temperature of 50-100 mK, so detector very cold!
• Discriminate NR/ER with ratio of phonons/ionization

Photos courtesy of CDMS and SuperCDMS collaborations.
Review of Select Technologies: Noble

- Single-phase: spherical design to collect most light, and self-shield
- Transparent to own (UV) scintillation
  - Xe: 178 nm; Ar: 128 nm; Ne: 78 nm
- Pulse shape NR/ER discrimination utilizing a prompt light fraction difference caused by singlet/triplet de-excitation times and ratios
  - Xe: ~30 ns vs. ~3 ns (trip. vs. sing.)
  - Ar: ~1.6 µs vs. ~6 ns
  - Ne: ~15 µs vs. <10 ns (best!)
- Cryogenic, but not as cold as CDMS
  - Xe: 175 K, Ar: 87 K, Ne: 25 K
- Yields as high as 40-60 photons/keV at zero field (~0.1-0.2x less for NR)
Review of Select Technologies: Noble

- Two-phase detector, with non-zero electric field and ~1:1 cylindrical design, looking at 2 physics processes
  - Excitation => scintillation in the liquid (S1)
  - Ionization => more scintillation in liquid (e⁻’s recombine) or in the gas phase at top (S2)
- Energy gets lost to heat for nuclear recoils. Ratio of S2 (or Q) to S1 used for discrimination of NR vs. ER
- Time in between S1 and S2 signals gives you depth, while the S2 hitmap provides radial position information
Review of Select Technologies: BC

- Bubble chamber: metastable fluid, liquid phase, below vapor pressure
- Individual nucleations induced by high-dE/dx nuclear recoils detected
- Reapplication of old HEP technique
- Scalable, with target swappable
- CF$_3$I good for SD, SI WIMP coupling
- Dual thresholds (energy, stopping power), functions of temperature + pressure, lead to $\beta$, $\gamma$ insensitivity
- Excellent acoustic alpha rejection, due to difference in proto-bubbles. Listen to neutron (哞) and an $\alpha$ ( Organisation chart)
- Temperature fixed at 30-40$^\circ$C, and a piston used to control pressure
Controversial Detection Claims/Hints

- **Direct:** DAMA/LIBRA, CoGeNT, CRESST

- **Indirect:** ATIC, PAMELA

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Aatseth et al. 2011

Adriani et al.
The Latest Dark Matter Limit Plots

- All experiments report their result in terms of the ruled-out phase space on a plot of cross-section in pb or cm² vs. the mass in GeV
- SUSY, KK, etc. models are displayed as colored regions on the plots
- Experiments often show projected limits for better, future phases
- Exposures often quoted in kg-days, and limits represent 90% C.L.
Summary

• There’s a lot of non-direct evidence for dark matter, the WIMP is a good, generic dark matter candidate, and lots of theories can give you a natural WIMP, but astrophysical uncertainties abound
• There are three major ways to try and find it, and there has been a proliferation of direct detection experiments, which look for nuclear recoil, detected via light, charge, and heat, as a result of spin-independent or spin-dependent couplings to nucleons
• Neutrons and gammas are two of the most common backgrounds
• The direction detection experiments with the latest best limits are XENON100 and CDMS (SI) and COUPP and SIMPLE (SD)
• There are a few detection claims, and they are all hotly debated
• Experiments are ruling out large swaths of the parameter space, putting the squeeze on the models

Fin.