A Survey of Direct DM Searches

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Dark Matter in Collision Workshop

UC Davis April 12, 2012

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?**
  - **0.34 GeV/cm^3 : Bahcall et al, Astrophys. J. 265 (1983) 730.**
  - **0.23 GeV/cm^3 : R. R. Caldwell and J. P. Ostriker, Astrophys. J. 251 (1981) 61.**
  - **0.34 - 0.73 GeV/cm^3 : E. I. Gates et al., Astrophys. J. 449 (1995), L123.**
  - **0.2 - 0.8 GeV/cm^3 : L. Bergstrom et al, Astropart. Phys. 9 (1998), 137.**

BIGGEST astrophysical uncertainty! **Usually assumed to be 0.3 g/cm^3**

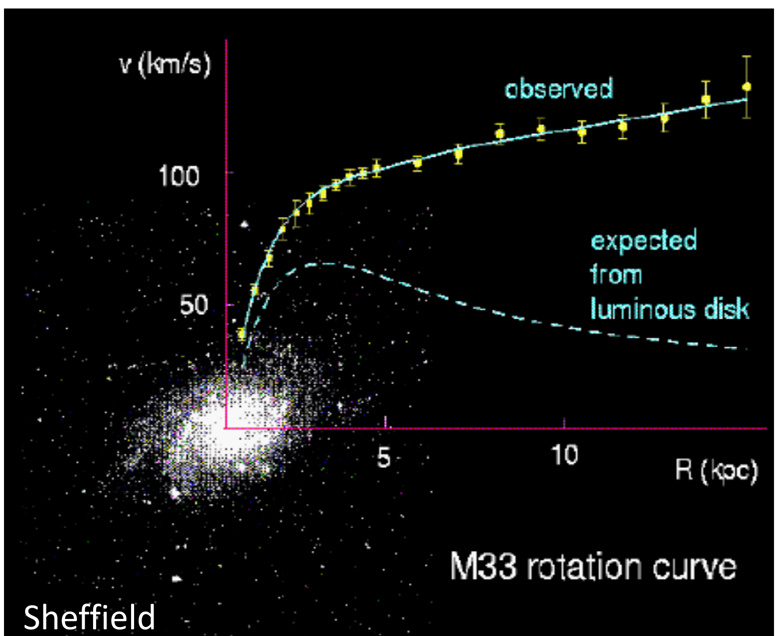
Astrophysical Uncertainties

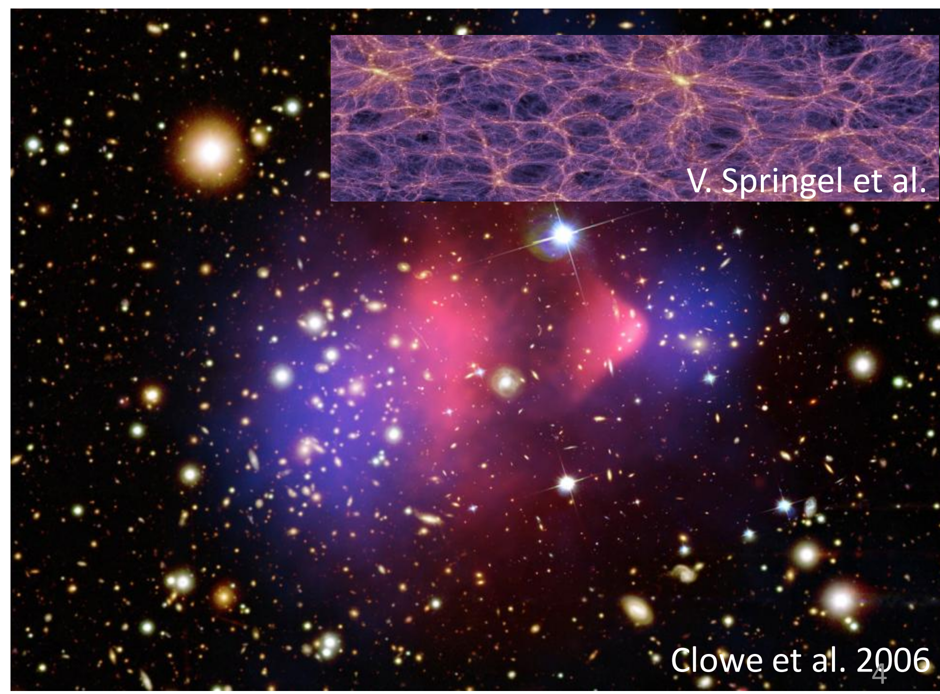
- **Energy density (and since the WIMP mass is unknown, the number density is unknown)**
  - **If WIMP mass is 100 GeV, then it's 3 WIMPs/liter**
- **What about the WIMP velocity distribution?**
  - **Mean velocity of 200-what km/s? Finite galactic escape velocity of ~600 km/s?**
  - **Deviations from 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%**

-Kamionkowski and Kinkhabwala, Phys. Rev. D 57, 3256 (1998).

What *is* certain? (Unless MOND…)

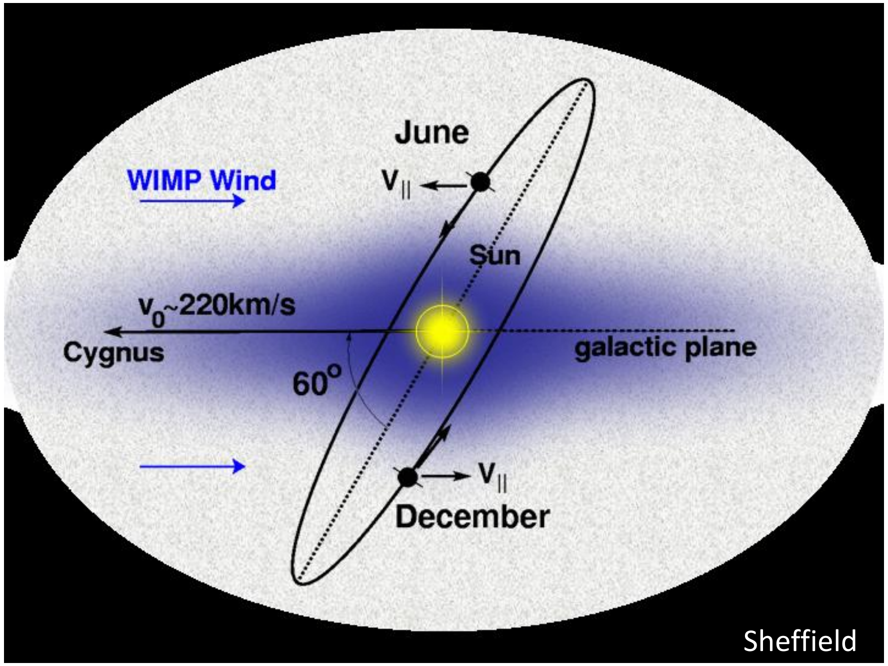
- **Not a SM particle (none have all right traits), and is thermal relic**
- **Wealth of indirect evidence but conclusive direct detection elusive**
- **Galactic rotation curves exhibit unexpected behavior consistently**
- **Gravitational lensing studies concur with the rotation curves**
- **CMB favors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

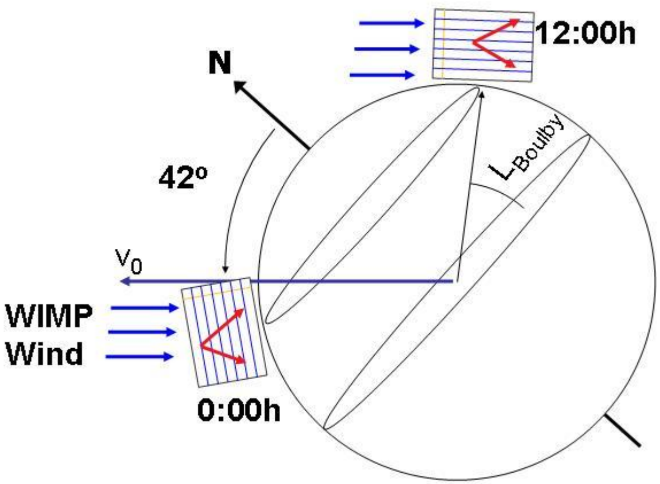




Annual and Daily WIMP Modulations

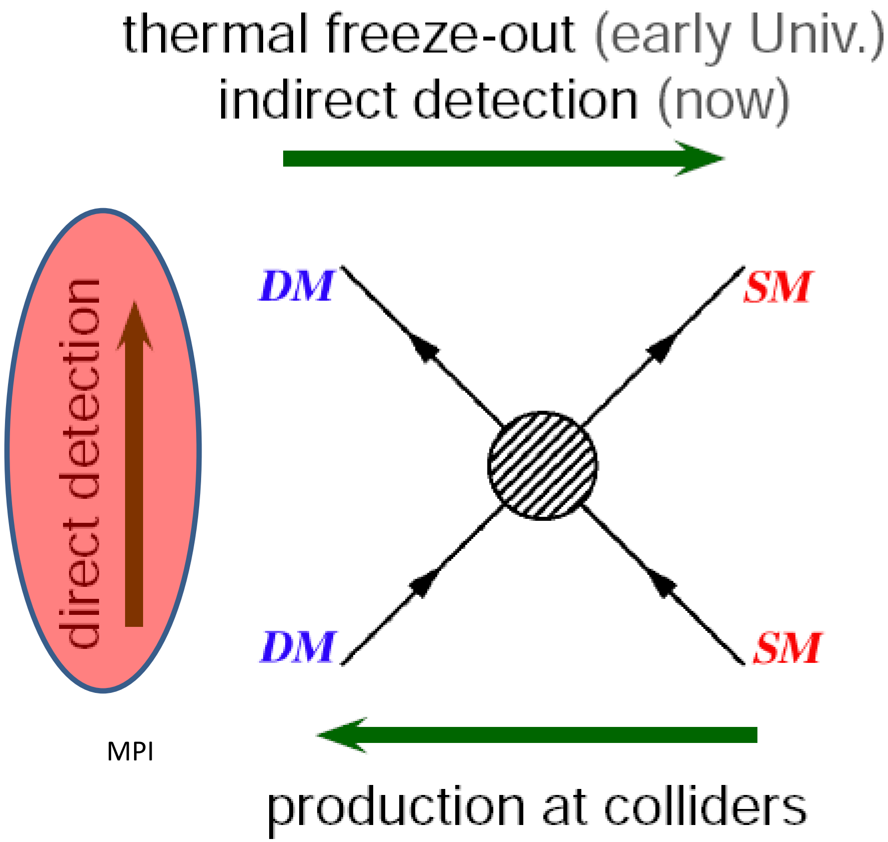
- **A WIMP detection signal should vary over the course of the year as Earth revolves around the Sun, which is traversing the galaxy**
- **There is also a daily variation caused by the rotation of the Earth (though this is a much smaller effect), and a preferred direction**
- **Experiments which capitalize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





Sheffield

Dark Matter Detection Strategies

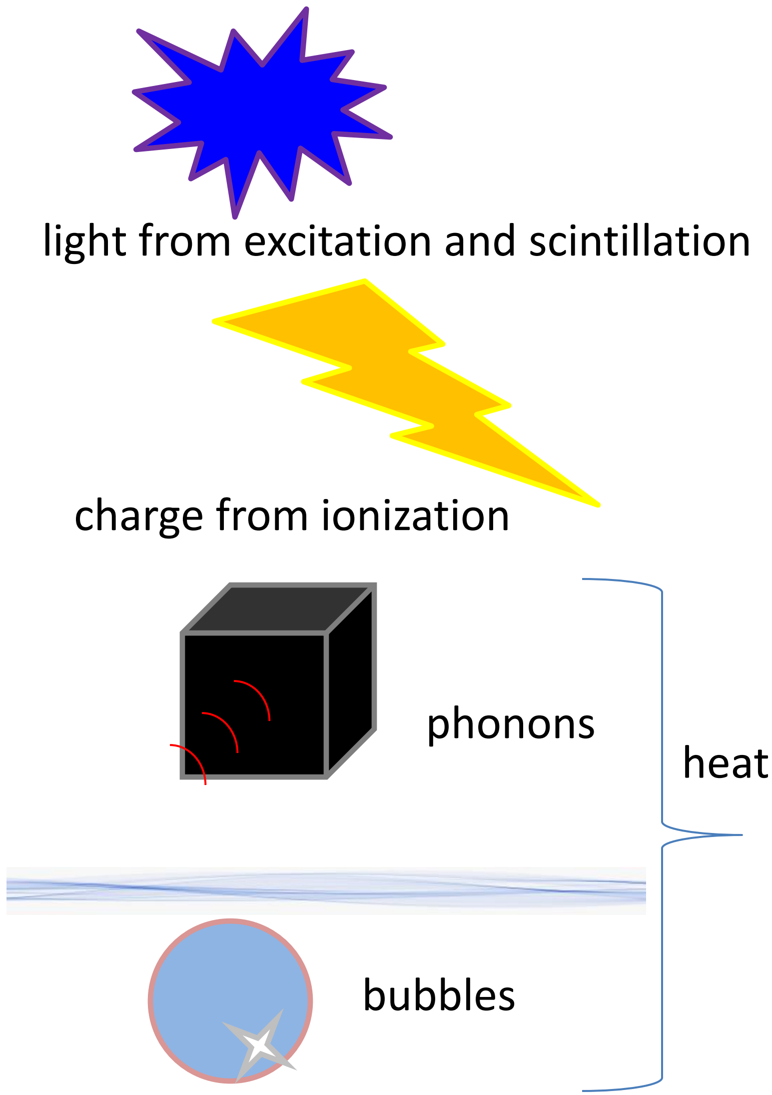


- **Indirect detection of WIMP self-annihilation into Standard Model particles, like gammas or neutrinos**
- **Direct detection via nuclear recoils: WIMPs interacting with the nuclei of a detector**
- **Production of WIMPs from the high-energy collisions of particle colliders – LATER!**
- **Multiple 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_3I, CF_3Br, C_3F_8, C_4F_{10}, C_2ClF_5 (cameras and/or piezos detect bubbles)**



Experiments of the World

- Ionization + Phonons (Ge)
  - CDMS-I-**II**, *SuperCDMS, GEODM*
  - EDELWEISS-I-**II**-*III* (I also Al_2O_3), *EURECA*
  - *CDEX, GENIUS-TF, GENIUS,* **IGEX-DM**, *GEDEON*, HDMS, Heidelburg-Moscow, COSME
- Phonons Alone
  - ROSEBUD (Al_2O_3)
- Ionization/Charge
  - **CoGeNT**, *C-4*, **TEXONO** (Ge)
  - **DMTPC***ino**, **NEWAGE** (CF_4)
  - DRIFT-I-**IId**-*III* (CS_2/CF_4 gas)
  - **MIMAC** ($^3He + CF_4$ gas)
  - **DAMIC** (CCDs) *light too
- Bubbles (BC or SDD/BD)
  - COUPP 2,**4**,15,**60**,*500* kg (CF_3I)
  - **PICASSO** (C_4F_{10})
  - SIMPLE Phase I, **II** (C_2ClF_5)

COLD (cryogenic) experiments are in BLUE

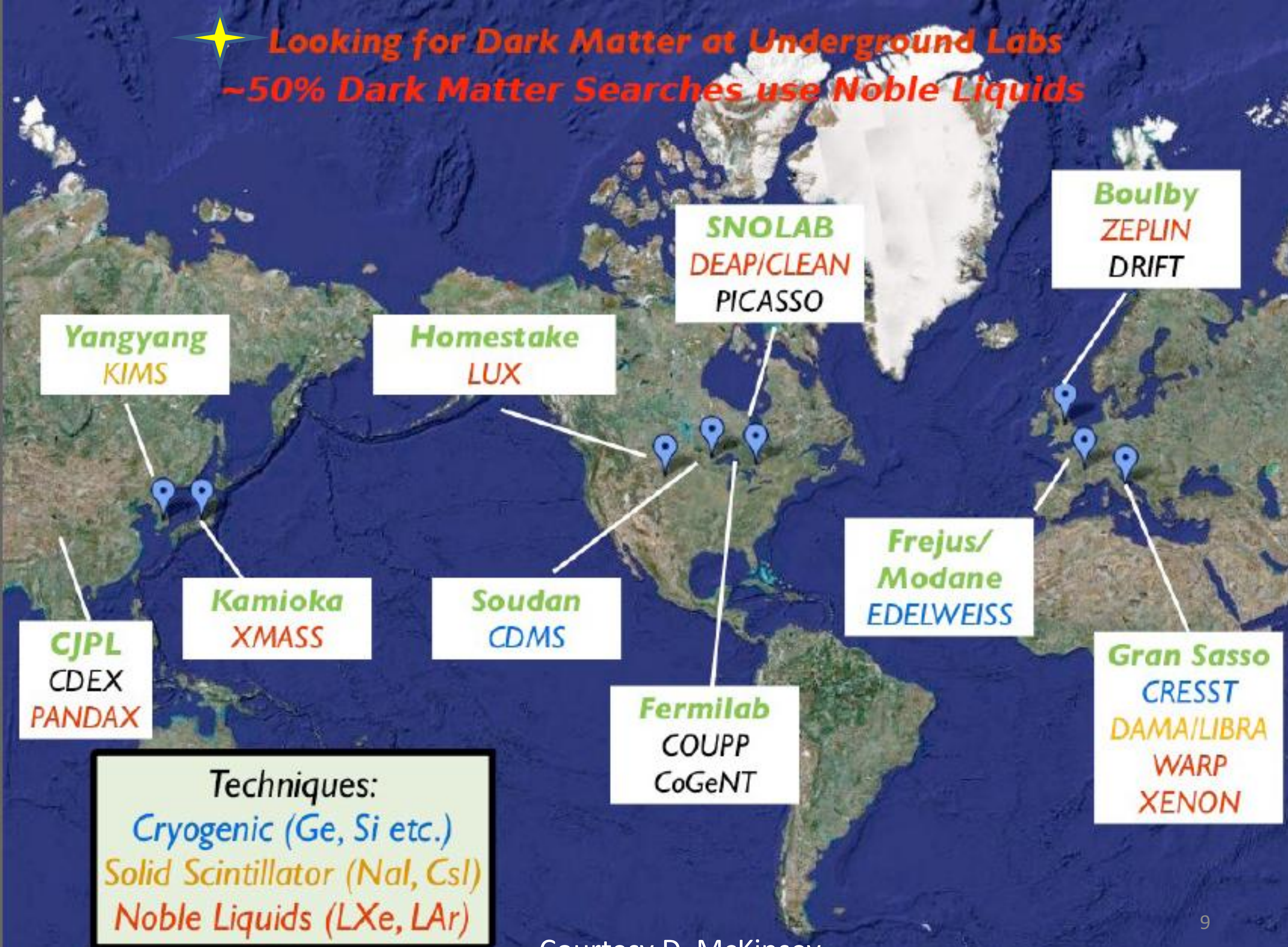
HOT (superheated liquid) experiments are in RED

Past experiments are normal font.

Present experiments are in **bold**.

Future ones are in *italics*.

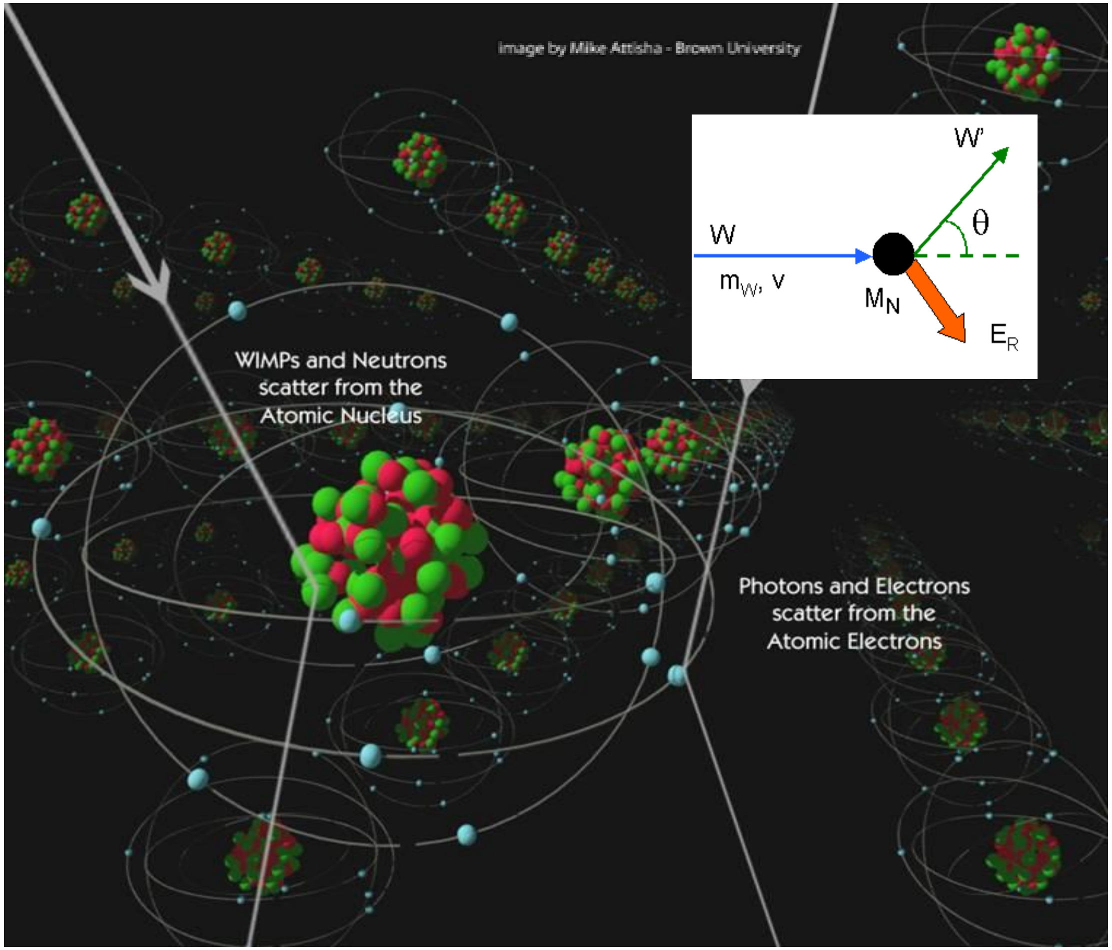
- Noble Scintillation
  - ZEPLIN I/UK-DMC (Xe)
  - **DEAP/CLEAN** (Ar, Ne)
  - **XMASS** (Xe)
  - ICARUS (Ar)
- Scintillation + Ionization
  - **LUX**, *LZS, LZD* (Xe)
  - XENON10-**100**-*1T* (Xe)
  - ZEPLIN-II-**III** (Xe)
  - **DarkSide** (Ar)
  - *MAX, DARWIN* (Ar, Xe)
  - *PANDA-X I-II* (Xe)
  - **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** ($CaWO_4$)



Courtesy D. McKinsey

What is the signal from a WIMP?

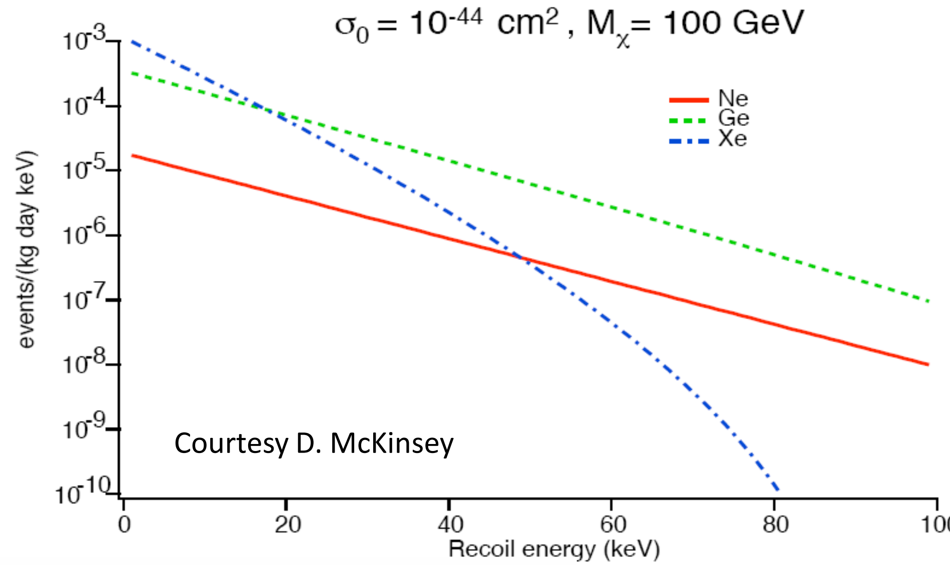
- **In the leading theories, WIMPs preferentially interact with the nuclei of a given target (intermediary varies)**
- **Depending on target material, the resulting nuclear recoil may lead to scintillation/light, ionization, a phase change, phonons/heat, or a combination**
- **Interactions rare, so looking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

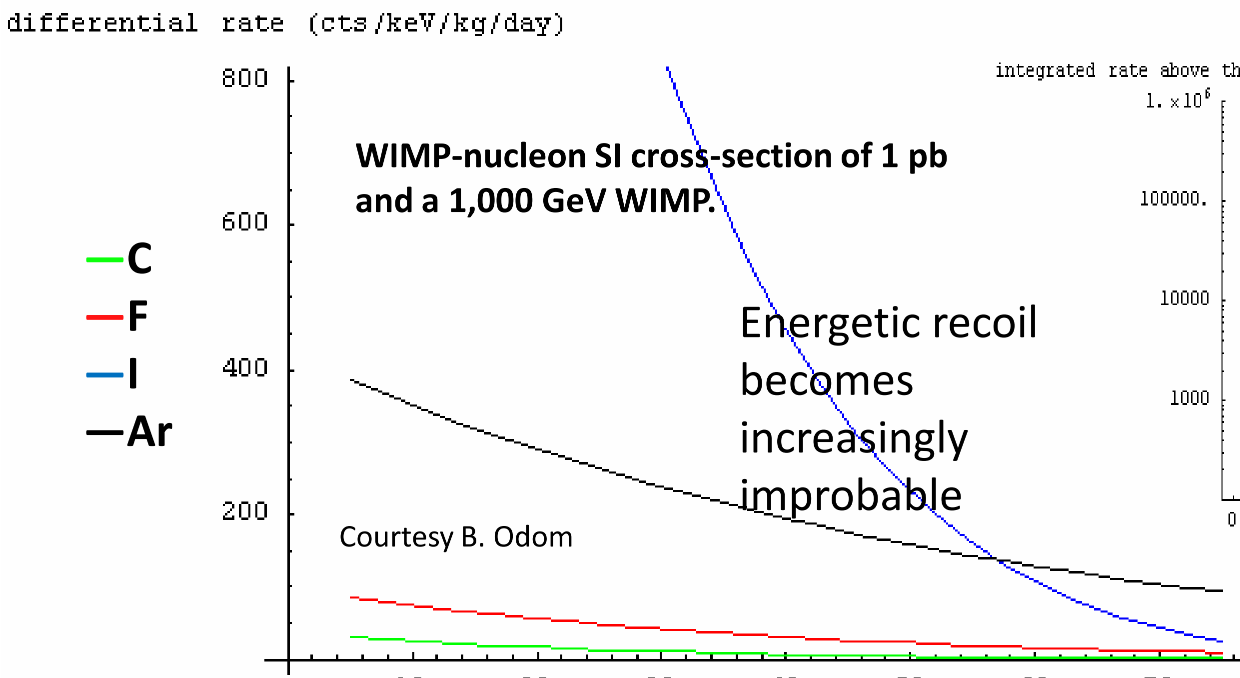


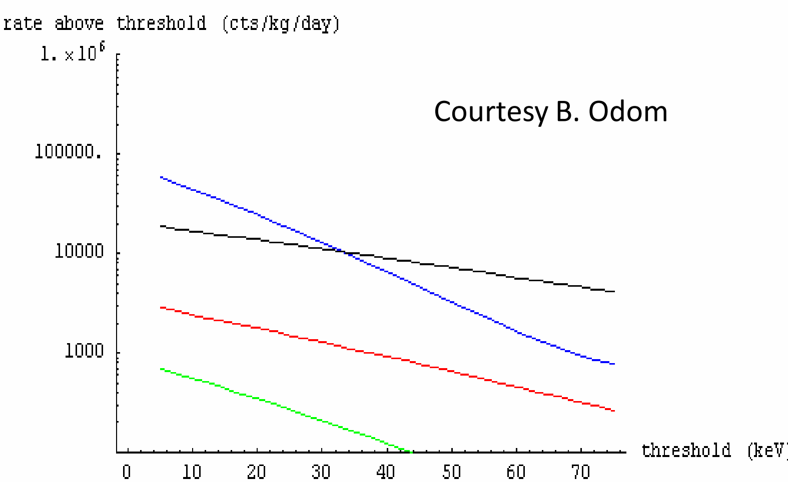
Depending on the precise WIMP model and the target substrate, the WIMP may interact with matter as rarely once per ton-year! Current limits are about two orders of magnitude away: O(1000) kg-days exposure

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 …)**







*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**

Consider per A^2

$$\sigma_T(q=0) = A^4 \frac{(M_n + M_\chi)^2}{(AM_n + M_\chi)^2} \sigma_n$$

  - **Energetic recoils suffer from form factor penalty damaging above bonus**

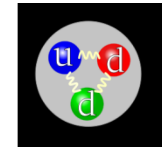
$$\sigma_T(q) = \sigma_T(q=0) F^2(q), \quad F(q) = \frac{3 j_1(qR_0)}{qR_0} e^{-\frac{(qs)^2}{2}}$$

- **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}F being the best for SD(p) interactions (Behnke et al. 2011)**
  - **Form factor becomes significantly more complicated**

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

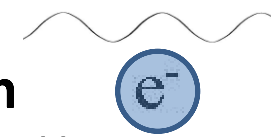
(All equations from Lewin and Smith.)

Experimental Backgrounds

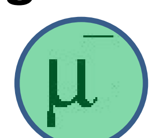


- **<u>Neutrons</u>: Go bump in the night just like WIMPs. Can be remediated by cutting multiple scatter events and by aggressively fiducializing your detector volume, if it is self-shielding, and by simulating all of the neutrons sources you can think of.**
- **<u>Alphas</u>: Can also produce nuclear recoil like WIMPs. Alpha events near detector walls can be removed from data by good fiducialization. However, (α,n) events remain a problem (above).**

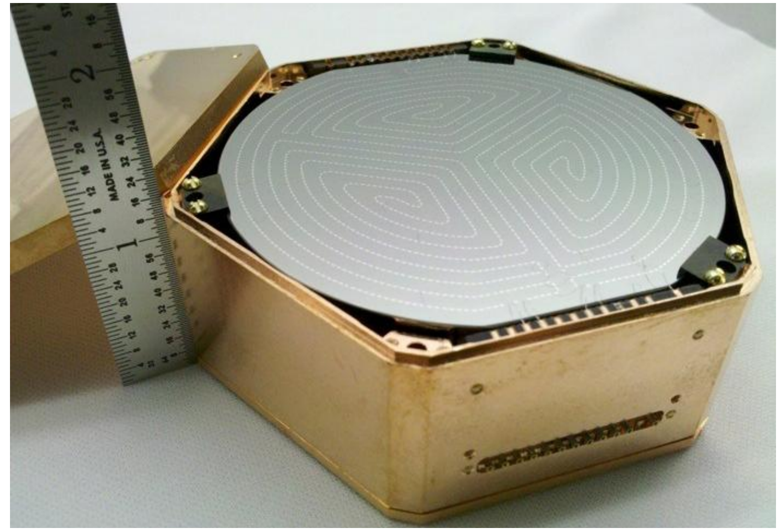
- **<u>Gammas and electrons</u>: Not a problem if your detector is insensitive to electron recoil, or can discriminate between electron and nuclear recoils well (between 1 part in 10^3-10^{11} level discrimination/acceptance achieved with current technologies)**



- **<u>Muons</u>: 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



Photos courtesy of CDMS and SuperCDMS collaborations.

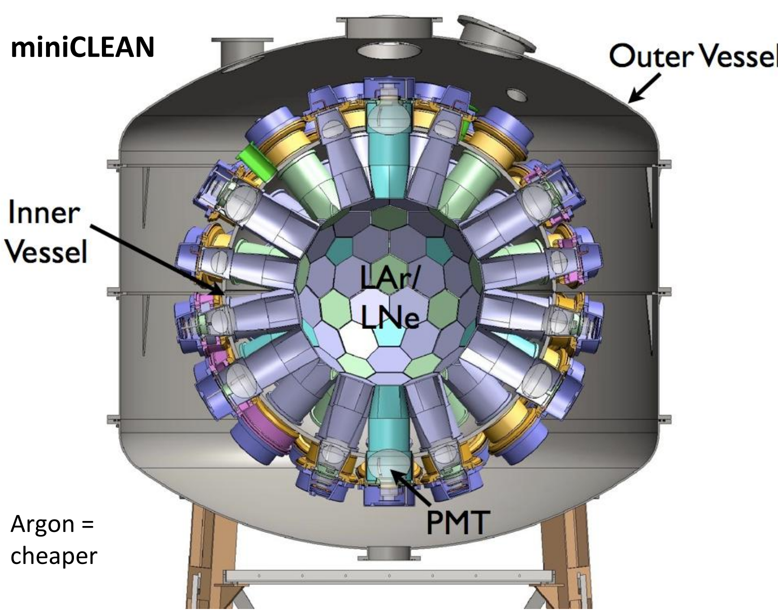
- **CDMS, Edelweiss (+others) use cryogenic Ge detectors**
- **CDMS-II ionization charge readout: divided Al electrode**
- **Phonon readout: TES (transition edge sensor), a resistor which goes superconducting (sharp sigmoid transition)**
  - **Four deployed per detector, with sub-ms-timescale signals**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

Review of Select Technologies: Noble

XMASS

Xenon = expensive, but dense

miniCLEAN

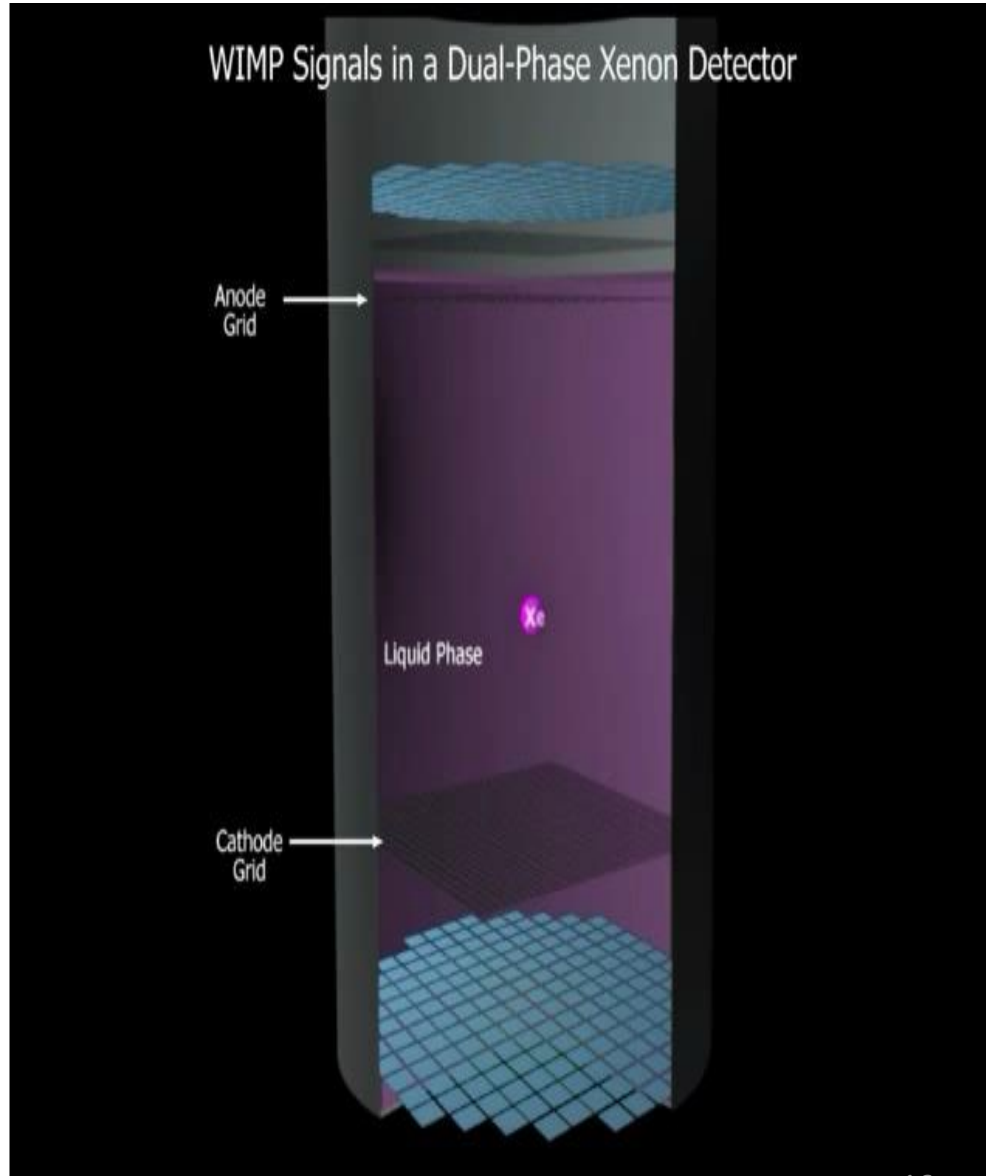


Argon = cheaper

- **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**



LUX

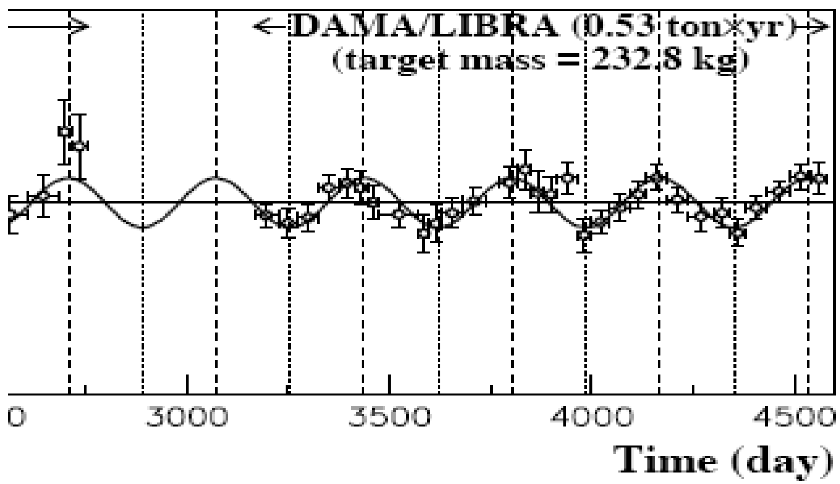
Review of Select Technologies: BC

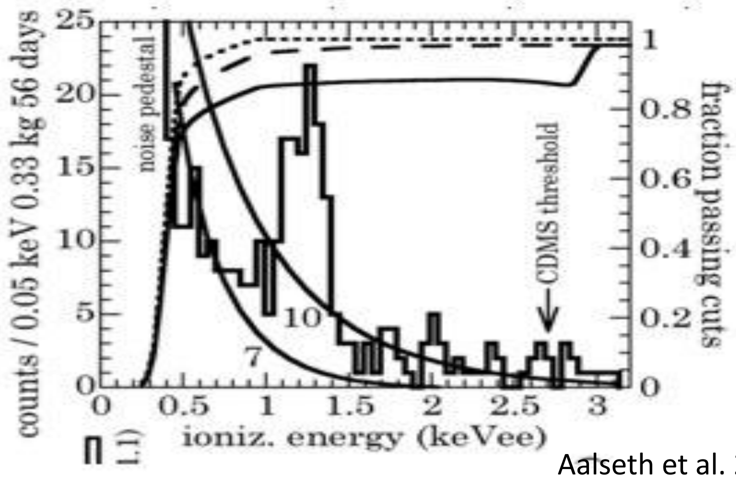
- **Bubble chamber: metastable fluid, liquid phase, below vapor pressure**
- **Individual nucleations induced by high-dE/dx nuclear recoils detected**
- **Reapplication of old HEP technique**
- **Scalable, with target swappable**
- **CF_3I good for SD, SI WIMP coupling**
- **Dual thresholds (energy, stopping power), functions of temperature + pressure, lead to β, γ insensitivity**
- **Excellent acoustic alpha rejection, due to difference in proto-bubbles. Listen to neutron ( ) and an α ( )**
- **Temperature fixed at 30-40^{o}C, and a piston used to control pressure**

COUPP

Controversial Detection Claims/Hints

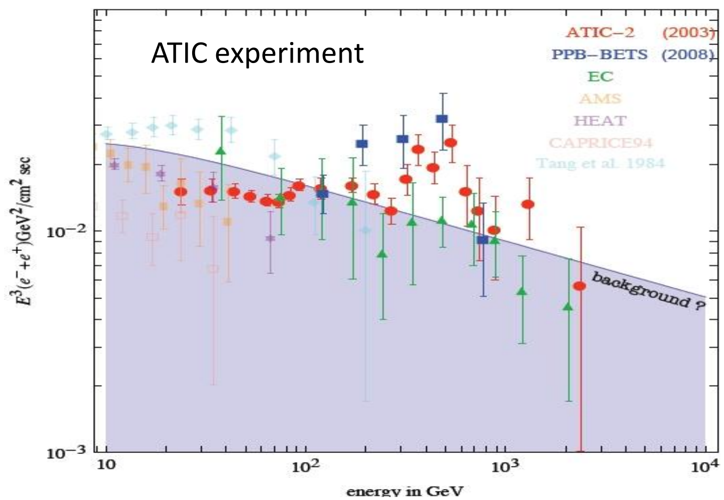
- **Direct: DAMA/LIBRA, CoGeNT, CRESST**

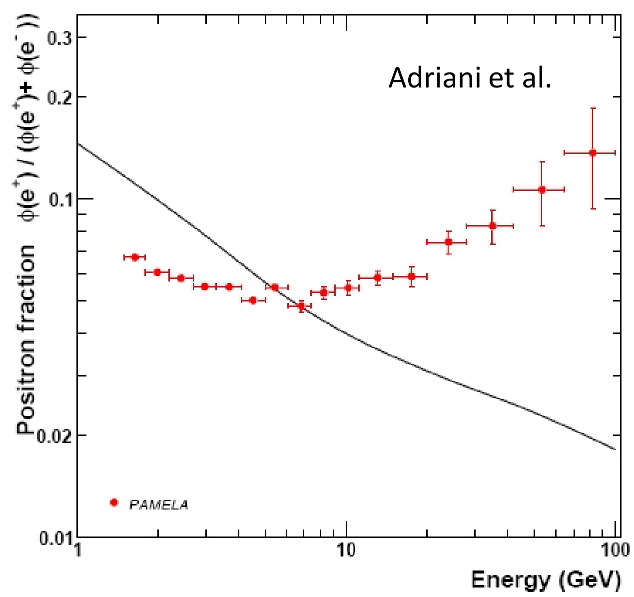




Aalseth et al. 2011

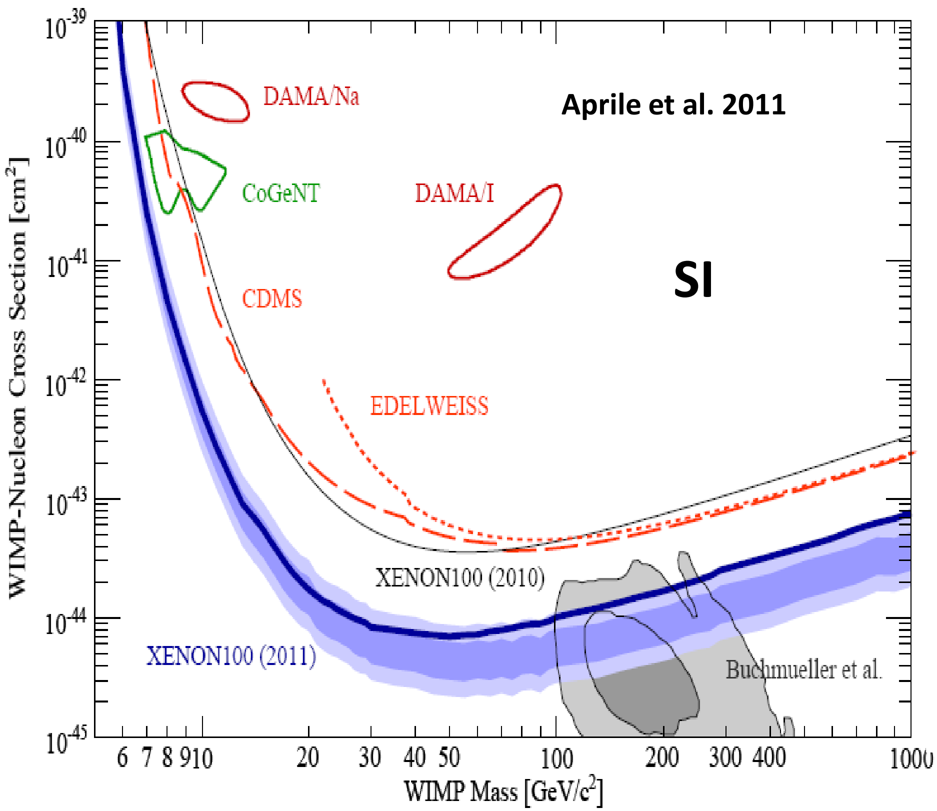
- **Indirect: ATIC, PAMELA**

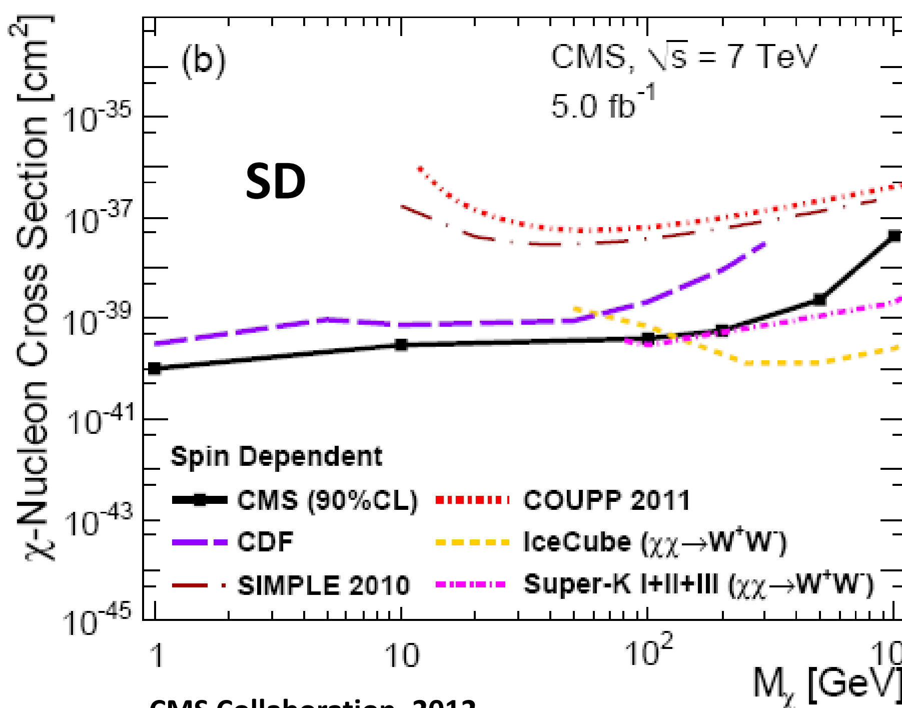




The Latest Dark Matter Limit Plots

- **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.**





CMS Collaboration, 2012

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.