The Search for Weakly Interacting Massive Particle Dark Matter
Science motivations and strategies

Is dark matter made of particles?
What physics?
Complementarity of experimental approaches

Two paradigms
Weak scale WIMP ($\approx 100\,\text{GeV}$): how this business started!
A Dark Sector (low mass?, structure?): emerging ideas!

Experimental strategy for Direct Detection
Very low rate, small energy deposition, need for nuclear recoil
Complementarity of approaches:
Noble Liquids may be more natural at high masses
Low temperature detectors are essential if we want to explore low mass WIMP
Thanks to APS
Particularly honored because Pief was one of the important mentors of my youth!
Very happy to share this prize with Blas Cabrera

Coordinated talks
Dark Matter: A Central Cosmology Question

A surprising but consistent picture

The nature of dark matter is a central problem of cosmology!

≠ baryons
≠ light neutrinos

Is it made of particles produced in the early universe?

If yes: evidence for physics beyond standard model!
Tev scale or totally different origin?
4 Complementary Approaches

**Cosmological Observations**
- Planck
- Keck telescopes

**Dark Matter**
- Galactic Halo (simulation)

**WIMP production on Earth**
- VERITAS, also HESS, Magic + IceCube (v)

**WIMP annihilation in the cosmos**
- Fermi/GLAST

**WIMP scattering on Earth:** e.g. CDMS, Xenon 100, etc.
Two Paradigms

Weak scale WIMPs $\leq$ hierarchy problem

Dark Matter Hidden Sector: no necessarily weak scale
Weak Scale WIMP paradigm

Fantastic success of Standard Model but unstable
Why is h, W and Z at \( \approx 100 \, M_p \)?
Need for new physics at that scale
supersymmetry
additional dimensions, global symmetries
In order to prevent the proton to decay, a new quantum number
=> Stable particles: Neutralino
Lowest Kaluza Klein excitation, little Higgs

A remarkable concidence

Particles in thermal equilibrium
+ decoupling when nonrelativistic
Freeze out when annihilation rate \( \approx \) expansion rate

\[
\Rightarrow \Omega x h^2 = \frac{3 \cdot 10^{-27} \, \text{cm}^3 / s}{\langle \sigma_A v \rangle} \Rightarrow \sigma_A \approx \frac{\alpha^2}{M_{EW}^2}
\]

Cosmology points to W&Z scale
Inversely standard particle model requires new physics at this scale
=> significant amount of dark matter

Weakly Interacting Massive Particles
Dark Matter could be due to TeV scale physics
Weak scale WIMP: How It All Started!

My subjective impression of key steps

**Dark Matter**
B Lee and S. Weinberg 1977 annihilation rate -> density
Article of Silk and Srednicki, 1984 annihilation in gamma rays

**Low temperature detectors -> neutrinos**
Drukier and Stodolsky Dec 1984
Cabrera, Krauss, Wilzcek, Dec 1984

**Goodman and Witten Jan 1985**
Direct detection is possible!

**Ionization and Nuclear recoil recognition**
Nuclear recoils will ionize! (Marv Cohen -> Lindhardt) ≈ 1986
Germanium (Avignone, Caldwell) 1987-88
excluded Z0
Importance of nuclear recoil (CDMS) 1989
Low pressure TPC (Tao, ≈ 1990)
DAMA (Bernabei) 1990-2000
Liquid Xenon (Elena Aprile) 1998-2002
An Active Field

Credit: Joerg Jaeckel

Direct Detection
An expanding community

US ≈ 270 physicists ≈ 70% FTE
≈ 40% of world
Direct Detection

**CMSSM≈mSUGRA Focal point region**

No threshold for Direct Detection

Xe 100 (2012)

LHC Monojets

\[(\bar{\chi}\gamma_\mu\gamma_5\chi)(\bar{q}\gamma_\mu\gamma_5q)\]

APS 2013 W.K.H Panofsky Prize
No Missing Energy at the LHC

\( \text{mSUGRA} \approx \text{CMSSM 4 parameter + sign} \)

Useful simplification but easy to eliminate

\[ \tan(\beta) = 10, A_0 = 0 \text{ GeV}, \mu > 0, m_1 = 173.2 \text{ GeV} \]

Natural supersymmetry

Do only what you really need to solve the hierarchy problem:

light s-top

Much more open

But other problems (m_h, B_s \rightarrow \gamma)

Simplified models \( \rightarrow 600 \text{ GeV} \)

\( \text{mSUGRA} \approx \text{out except FP} \)

but SUSY parameter space still very much open although \( \rightarrow \) larger mass
Dark Matter Annihilation (Fermi)

No clear signal
Presentation in terms of $b\bar{b}$, $\tau\bar{\tau}$, $WW$ channels is simple
But realistic model is a mix $\rightarrow$ less-restrictive limits:

No strong limit on low mass

---

Comparison with Ground-based Telescopes ($b\bar{b}$)

Dwarfs

Extragalactic Background

Galactic Halo

cf Alex Drlica-Wagner
Different Paradigm: Dark Sector

What if there were a hidden dark sector?
In contact with ordinary sector at high temperature.
Now shielded from ordinary sector
  e.g., preventing production of low mass WIMP at accelerators.

Three examples

Asymmetric Dark Matter (e.g., K. Zurek)
What if dark sector was also asymmetric between dark matter and anti-dark matter?
Reasonable to have $\approx$ same asymmetry
if $M_{DM}=6*M_p$ we get $\Omega_{DM}\approx 6*\Omega_b$ as observed
but no idea about cross section, no indirect

WIMP-less DM (e.g., Feng Kumar)
MSSM breaking through gauge mediation in SUSY breaking sector+ Hidden sectors
  $\Rightarrow$ Naturally $\langle \sigma v \rangle \approx \frac{g_x^4}{m_x^2} \approx \frac{g_{EW}^4}{m_Z^2}$ but $m_x \neq m_Z$

  Thermal relic with WIMP-less miracle

Dark Photon (e.g., Arkani-Ahmed, Finkbeiner, Weiner)
Light mediator -> interesting phenomenology: excited stated, Sommerfeld enhancement etc..
Fundamental Motivations?

Weak: Make sense of a confused experimental situation

Just having more parameters to play with, to fit experiments which are probably plagued by misunderstood backgrounds, systematics, calibration and astrophysics problems

Stronger: Natural in many theoretical models

e.g., String theory inspired
Non necessarily related to weak scale

Hopefully: establish by solid observations

Current candidates

Serious failure of LCDM in dwarf galaxies
Astrophysics
Or fundamental physics? e.g. self interacting

Direct detection signals at low energy????

Fermi-Glast GeV excess: unlikely that can distinguish from astrophysics
Pamela,Fermi,AMS positron excess: difficult to distinguish from astrophysics
Fermi-Glast 135 GeV gamma line in Fermi Glast if confirmed
(no continuum -> internl structure of dark sector )
Dwarf Spheroidals

2 distinct but related problems

1) The number of satellites
   but we keep discovering small ones
   Not enough large mass
   satellites: “Too big to fail problem”
   Frenk et al.
   Bullock et al.

2) The density profile: NFW or core?
   Basic degeneracy between velocity
   anisotropy and density profile
   Walker and Penarrubia: break the
degeneracy for Fornax and
Sculptor with two populations of
stars -> Core!

Is it astrophysics or particle physics?
Extremely efficient ejection of baryons by repetition of SNs
Or strongly interacting dark matter => would point to dark sector

\[ \sigma \approx 0.1 \left( \frac{g}{cm^2} \right)^{-1} \approx 0.18 \text{ barns/ (GeV/c}^2 \right) \] (Bullock's group)
Low WIMP Mass Region (DD)

Trying to make sense of the various claims

- CoGeNT evolving (surface events): no more claim
- CRESST likely $^{206}\text{Pb}$
- CDMS Ge interpreted by Collar/Fields:
  - Our only comment so far similar effect in multiples

Claims for Very large modulations

- CDMS does not see modulation (but needs to go below 5 keV if possible)
- Statistical significance of CoGeNT marginal (2.8 sigma) $\Rightarrow$ more statistics.
- Malbeck does not see a modulation
- Control of systematics is essential
New result for CDMS on Si
K. McCarthy yesterday

Analysis favors a WIMP region of interest $\approx 3\sigma$
- Most likely value at 8.6 GeV WIMP mass with $1.9 \times 10^{-41}$ cm$^2$ cross section
- Consistent with earlier CDMS Ge and Si limits
- Also consistent with a WIMP interpretation of the COGENT experiment
- In tension with limits from Xenon 10, Xenon 100 experiments

Data are insufficient to claim discovery of a WIMP signal, but does warrant further investigation
How do we check?

**Still to be done with CDMS II**
- Investigation of possible systematics, unsuspected background
- Ge+Si consistent likelihood analysis
- Low energy Si analysis in same style as Ge

**SuperCDMS Soudan**
- CDMS Lite 23eV rms
- Low threshold

Si towers?

**SuperCDMS SNOLAB**
- Lower noise in phonons and Ionization <-R&D
- Si towers?
Compatibility of Low Mass WIMP with LHC

LHC Monojets in effective contact operator
Probably means that if indeed there is light dark matter it does not couple to gluons (in most models it does not).
Experimental Strategy

2 directions
1. Improve sensitivity at large mass
2. Improve sensitivity at small mass
2 frontiers: 1. High Mass Frontier

Get as many events as possible
with no background
=> convincing signal, enough statistics to do physics
Weak scale WIMP: natural scale if Higgs exchange $10^{-45} - 10^{-46} \text{ cm}^2/\text{nucleon}$
+ push as down as possible if no signal
  The smaller, the more fine tuned...
  $\approx 10^{-48} \text{ cm}^2/\text{nucleon}$: irreducible background from atmospheric coherent neutrino scattering

What technology?
Noble liquids most natural if they can control their background
=> several tons (e.g., LZ 7 tons)
However Xe requires a factor 3000 improvement to get $10^{-48} \text{ cm}^2/\text{nucleon}$

But low temperature detectors can play a useful role for Weak scale WIMP:
  Current CDMS proposal 200kg $\rightarrow 10^{-46} \text{ cm}^2/\text{nucleon}$
  Needed background rejection demonstrated within a factor of 2.
  Complementary: very different backgrounds and detection mechanism

Need a diversity of target
  e.g., isospin dependence (J. Kumar)
2 frontiers: 2. Low Mass Frontier

Need excellent signal to noise

Energy deposition goes as square of the WIMP mass

\[ E_d = \frac{2M_\chi^2 M_N}{(M_\chi + M_N)^2} v^2 (1 - \cos \theta^*) \approx \frac{2M_\chi^2}{M_N} v^2 (1 - \cos \theta^*) \text{ for } M_\chi << M_N \]

What technology?

Low temperature detectors are most natural because of their large S/N

Best: improved phonons and ionization (see next slide)

Giving up rejection, you can go to very low threshold with luke phonons

but then background limited

Xenon with S2 only (Sorensen) could also be useful, but

No rejection: will have to rely on self shielding

Fiducialization difficult (no t0-> can we use diffusion?)

Few 100eV/ electron?

Single electron background from surface would have to be corrected

Both would need careful calibration of energy scale
Importance of Discrimination

How far can we go?

Gamma level 1/210 CDMS, beta 200kg
Phonon energy: $\approx Tc^3 \sigma = 180 \text{ eV} \rightarrow \sigma = 10 \text{ eV}$
Ionization: FET->HEMT $\sigma = 300 \text{ eV} \rightarrow \sigma = 150 \text{ eV} + \text{noise environment}$

More optimistic!

Ionization: $\sigma = 300 \text{ eV} \rightarrow \sigma = 150 \text{ eV} + \text{noise environment}$
not baseline!!

Likelihood sensitivity
Estimate by M. Pyle
Preliminary!

We may be even able to detect coherent scattering of $^8\text{B}$ solar neutrino!
L. Strigari
Important physics signal (30kg/yr) + sensitivity demonstration (if no Si)

WIMP Sensitivity
CoGeNT - Kelso
Si
CRESST
DAMA
Majorana Demonstrator
CDMS II 2013
SuperCDMS Soudan
Conclusions

WIMPs: ≥ Two paradigms

- Weak scale
- Dark Sector

Phenomenology (e.g., dependence on the target nucleus) may be more complex than for the “vanilla” WIMP scenarios.

Other good DM candidates: axions and possibly sterile neutrinos

Fascinating time

4 prong approach=>
complementary coverage
constrain theory speculations

No convincing result so far
But both paradigms still in good shape

Strategy for Direct Detection

Several technologies with complementary capabilities

2 frontiers

- high WIMP mass: natural region of noble liquids (background control)
- low WIMP mass: S/N of low temperature (target mass cost)

Different susceptibility to background, energy scale uncertainties
Enough sensitivity overlap to have at least a second experiment able to cross-check any claim.
Several targets => physics, large target masses-> astrophysics
Last but not least

The SuperCDMS Collaboration

California Institute of Technology
Queen's University
Southern Methodist University
Texas A&M University
University of California, Berkeley
University of Evansville
Fermi National Accelerator Laboratory
Santa Clara University
Stanford University
Universidad Autónoma de Madrid
Pacific Northwest National Laboratory
University of Florida
Massachusetts Institute of Technology
SLAC / Kavli Institute for Particle Astrophysics and Cosmology
Syracuse University
University of British Columbia
University of Colorado, Denver
University of Minnesota
Additional Material
Is it a signal?
- incompatible with other experiments (New: KIMs)
- Saturates single rate
- => Unphysically large modulation

If true important!

Can it be instrumental?
- Unstability in threshold: modulation appears smaller in LIBRA than in DAMA?
- Delayed pulses from muons (not neutrons, but defects): problems single rate + phase

Awkward to the community: What to do?
- Lower threshold: LIBRA has changed Phototubes to high QE + background model
- Experiment by other groups: DM-Ice, ANAIS, KIMS, Princeton
Monojets/Monophotons
Tim Tait et al, Paddy Fox et al:
Effective theory with various operators
But: Physical interpretation?
limits of formalism(e.g., $E \ll M$)
Complementarity Direct-Indirect

pMSSM model scan (19-dimensional scan of the MSSM) shown in gray
red = models which the LAT may be sensitive to over a 10 year mission
Anomalies

- LSND antineutrino
- MiniBoone

Antineutrinos now similar to neutrinos
twice as much statistic
less fluctuation up in high energy

Now compatible with LSND
3.6 sigma

Deficit of reactor antineutrinos
Sage-Galley
Tension with $\mu$ disappearance
We need probably $\geq 2$ sterile neutrinos

Note: Karmen excludes large $DM^2$

Not keV neutrino! Best fit $\approx 1\ \text{eV}$

Compatibility with cosmology???

Ignarra Oct 12

LSND 90% CL
LSND 99% CL

$68\%\ \text{CL}$
$90\%\ \text{CL}$
$95\%\ \text{CL}$
$99\%\ \text{CL}$
3 directions

- Cosmological axions with RF cavities
- Solar axions
- Light-through the wall experiments
What about the Galactic Center?

2 independent analysis
Hooper, Linden
Abazadjian, Klapinghat

More or less agree on conclusions
Could be dark matter annihilation: spatial shape, cross section, spectrum
But could be Millisecond Pulsars
or Cosmic rays interaction

How will we ever know whether astrophysics or Particle Physics?
Better spectrum
Higher spatial resolution? Gamma 400?

Same type of remarks about TeV positron excess
Fermi 135 GeV Gamma Line?

Very few events \(\approx 15\)
+ Fundamental difficulty: how do we determine the number of trials

Can it be instrumental?
  A priori smooth efficiency (MC) but
  Use the limb as efficiency calibrator: 30 events; large error bars
  “Signal” appears toward the limb and the sun (Daniel Whiteson)
  Can it be due to change of reconstruction algorithm in this energy region?

What could it be if it is real?
Not ordinary WIMP (large cross section/absence of continuum)
Dark Sector with light mediator or more generally structure (Weiner et al.)
Decay of heavy right handed neutrino (Bergstrom)