DARK MATTER COLLOQUIUM
(MODERATOR ALEX KUSENKO)

EVIDENCE FOR DARK MATTER AND DARK MATTER CANDIDATES (MANOJ KAPLINGHAT)

DIRECT AND INDIRECT SEARCHES FOR DARK MATTER (DAN MCKINSEY AND JIM BUCKLEY)

PUTTING IT ALL TOGETHER: INFORMATION FROM COLLIDERS, SPACE AND UNDERGROUND (TIM TAIT)

DISCUSSION OF SOME TOUGH QUESTIONS (SPEAKERS ABOVE AND LIANTAO WANG)

OPEN DISCUSSION
Evidence from astronomy points to the presence of dark matter on kilo-parsec to horizon scales. **This evidence is summarized in the next few slides.**

There is no stable, massive and neutral particle in the standard model that could be the dark matter.

If dark matter is a new particle (which necessarily implies physics beyond the standard model), then the cosmological predictions match the large scale structure data beautifully.

Models of new physics (such as Supersymmetry) typically have in their spectrum a new particle that could be the dark matter.
Our knowledge of this dark sector is purely gravitational at present. In order to understand this sector we need to answer many questions, including:

How many particles make up the dark matter? What are their masses and spins? How do they couple to the standard model and to other dark sector particles?

It is essential to attack the dark matter questions from multiple angles: colliders, direct searches, indirect searches and astrophysics. The short talks in this colloquium will serve to illustrate this using concrete examples.
Local measurement of dark matter density

- Oort (1932) used motion of stars out of the plane of the disk to estimate the total amount of matter, including dark matter, locally.
  
  J. H. Oort, Bulletin of the Astronomical Institutes of the Netherlands, Vol. 6, p.249 (1932)

- Most recent estimate gets local dark matter density 0.3+/-0.1 Gev/cc
  
Total mass of Andromeda and Milky Way from their relative motion

* Andromeda and Milky Way have turned around from the Hubble flow and are headed for collision. Kahn and Woltjer (1959) used this to bound the total mass of the local group from below.


* Recent measurements show sum of virial masses of milky way and andromeda is $3.2 \times 10^{12} \text{ M}_{\text{sun}}$ with 20% error. Stars and gas ~10% of this mass.

Dark matter in the satellites of the Milky Way

Rotation speed and dark matter in galaxies

* The plateau in rotation speed as the distance from the center increases is the evidence for dark matter in spiral galaxies. The fact that spiral galaxies don’t show a decline in rotation speed became widely accepted in the early 80’s.


* To the right, velocity field and rotation curve of F583-1; this galaxy is 32 Mpc away and has low surface brightness (dark matter dominates).
Dark matter in clusters of galaxies

Zwicky (1937) used the velocity dispersion of galaxies in Coma to infer the dark matter

Clusters have a lot of gas, which can be inferred from X-ray and mm wavelength measurements. This allows us to measure the gravitational potential and hence the total mass as well as gas mass.

Clustering therefore light up at X-ray wavelengths as luminous, continuous, spatially extended sources.

For reviews of the principles underlying X-ray observations of clusters see, e.g., Sarazin

heating it to virial temperatures of $10^8$–10$^9$K.

This gas is very difficult to observe. Within galaxy clusters, however, gravity squeezes the gas, heating it to virial temperatures of $10^8$ K.

For reviews of the principles underlying X-ray observations of clusters see, e.g., Sarazin

heating it to virial temperatures of $10^8$ K.

3.1.1. X-ray observations. For reviews of the principles underlying X-ray observations of clusters see, e.g., Sarazin

In this section we review briefly the physics underlying multiwavelength observations of galaxy clusters

3.1. Multiwavelength Measurements of Galaxy Clusters

3. OBSERVATIONAL TECHNIQUES

led to cosmological constraints. We discuss techniques used to measure the masses of clusters and

In this section we review briefly the physics underlying multiwavelength observations of galaxy clusters

In this section we review briefly the physics underlying multiwavelength observations of galaxy clusters


A2667

Lensung measures total mass.

Bullet cluster

Markevitch et al, Clowe et al. (2004)
Great match to data on cosmological scales (CMB) down to scales of order Mega-parsec (Galaxies)

Blue: data (SDSS, 2dFGRS)
Red: Millennium simulation

Correlation function at z~0.5 (about 5 Gyr ago)

Cosmic Microwave Background and the cosmological density of dark matter

- Lower matter density leads to larger change of the gravitational potential wells, which boosts peak heights.
- *Higher baryon density increases* odd peak heights.
- $\Omega_{\text{Dark Matter}} h^2 = 0.12$ to about 2% where expansion rate today is $100h$ km/s/Mpc.

Planck Collaboration, eprint arXiv:1303.5076
Consistency of different cosmological measures of the matter density

The different measures of matter density from growth of clusters, fraction of gas in clusters, CMB, Supernova distances and Baryon acoustic oscillation all agree on a value for the matter density that is close to 25% of the critical density of the universe, which is about 6 times the density in baryons.

Motivations to search for a dark matter particle

* Observed large-scale structure reproduced by a model in which all of the dark matter is a cold collision-less particle.

* Models of new physics (such as Supersymmetry) have in their spectrum a new particle that could be the dark matter.

* These dark matter candidates can be produced in quantities that are comparable to the measured cosmological density of dark matter. We consider a few such examples next.
Production through early universe freeze-out

\begin{align*}
\langle \sigma_{\text{ann}} v \rangle &= \pi \left( \frac{\alpha}{0.025} \right)^2 \left( \frac{\text{TeV}}{m_X} \right)^2 2.3 \times 10^{-26} \frac{\text{cm}^3}{\text{s}} \\
\text{Example: Mass } &\sim 300 \text{ GeV, Freeze out } \sim 10 \text{ GeV (10 nano-second) }
\end{align*}

Candidates

WIMP (SUSY neutralino, KK dark matter, ...): masses typically weak-scale (~100 GeV and larger) but could be smaller in non-minimal versions of SUSY.

WIMPless (LSP in hidden sector): masses could be much lower than weak-scale.

Phenomenological models with a light force carrier (hidden sector dark matter): masses in GeV-TeV range
Axions are pseudo-Goldstone bosons of a spontaneously broken global symmetry. A well-motivated example is the QCD axion in the Peccei-Quinn solution to the strong CP problem. It could be produced via a misalignment mechanism and could be all of the dark matter. It has been suggested that axions could form Bose-Einstein condensates in galaxies.

Right-handed or sterile neutrinos are motivated by the observation of non-zero neutrino masses, and for certain range of masses (1-100 keV), they may be dark matter. In a class of models (below), the mixing with active neutrinos and a significant lepton asymmetry determines the relic density.

Asymmetric dark matter posits that the abundance of dark matter is set by the particle-antiparticle asymmetry in the dark sector.

Annihilation cross section must be larger than the thermal relic cross section.

If the asymmetry in baryons is linked to the asymmetry in dark matter, then the dark matter masses must be \( \sim 10 \) GeV.

In simple models of asymmetric dark matter, there are fairly generic predictions for the scattering cross section with nucleons that also allow for dark matter self-interaction cross section which affects galaxies on observable scales.
Tough Question CF17: Is cold non-interacting dark matter in good agreement with observations of structure on all scales?

There are many puzzling aspects of structure formation on galactic and sub-galactic scales. Among these puzzles, one that is often discussed is the core-cusp issue or the related issue of densities that are lower than simple predictions for a variety of galaxies. An example is shown to the right.
Tough Question CF17: Is cold non-interacting dark matter in good agreement with observations of structure on all scales?

There are many puzzling aspects of structure formation on galactic and sub-galactic scales. Among these puzzles, one that is often discussed is the core-cusp issue or the related issue of densities that are lower than simple predictions for a variety of galaxies. An example is shown to the right.
Tough Question CF17: Is cold non-interacting dark matter in good agreement with observations of structure on all scales?

There are many puzzling aspects of structure formation on galactic and sub-galactic scales. Among these puzzles, one that is often discussed is the core-cusp issue or the related issue of densities that are lower than simple predictions for a variety of galaxies. An example is shown to the right.

Linear rise in rotation speed => \( \sqrt{\frac{M}{R}} \sim r \) or \( M \sim r^3 \) => density is constant, in conflict with the simplest predictions of cold dark matter.
Tough Question CF17: Is cold non-interacting dark matter in good agreement with observations of structure on all scales?

There are many puzzling aspects of structure formation on galactic and sub-galactic scales. Among these puzzles, one that is often discussed is the core-cusp issue or the related issue of densities that are lower than simple predictions for a variety of galaxies. An example is shown to the right.

These puzzles provide good motivation for considering non-WIMP dark matter candidates.

Linear rise in rotation speed $\Rightarrow \sqrt{\text{mass}/\text{radius}} \sim r$ or $\text{mass} \sim r^3 \Rightarrow$ density is constant, in conflict with the simplest predictions of cold dark matter.
Tough Question CF17: Is cold non-interacting dark matter in good agreement with observations of structure on all scales?

There are many puzzling aspects of structure formation on galactic and sub-galactic scales. Among these puzzles, one that is often discussed is the core-cusp issue or the related issue of densities that are lower than simple predictions for a variety of galaxies. An example is shown to the right.

These puzzles provide good motivation for considering non-WIMP dark matter candidates.

In the last couple of years, cosmological simulations including baryons have reached the point where they can start to address this issue. Continued advances in computing are essential to this area. *Keep your ears open for progress on this front of galactic puzzles.*
Tough Question CF16: What are the prospects for determining the temperature of dark matter or self-interactions in the dark sector from astrophysics?

WIMP and axion dark matter are categorized as **cold non-interacting** dark matter.

The dominant form of dark matter could be **warm** (e.g., sterile neutrino, weak-scale gravitinos)

The dominant form of dark matter could have **large self-interactions** (e.g., hidden sector with light force carrier, asymmetric dark matter).
Tough Question CF16: What are the prospects for determining the temperature of dark matter or self-interactions in the dark sector from astrophysics?

WIMP and axion dark matter are categorized as **cold non-interacting** dark matter.

The dominant form of dark matter could be **warm** (e.g., sterile neutrino, weak-scale gravitinos).

The dominant form of dark matter could have **large self-interactions** (e.g., hidden sector with light force carrier, asymmetric dark matter).

**Prospects**

In the last few years, there has been great progress in simulating realistic galaxies with star formation. There has also been an explosion of high quality, high resolution data capable of peering closer than ever before into the centers of the least luminous galaxies to the brightest clusters of galaxies.

The puzzles have not vanished and it is reasonable to hope that further progress in numerical simulations and observations will sharpen or finally solve these puzzles.
If the dominant form of dark matter is warm or strongly self-interacting, does this mean that the SUSY framework is wrong?

No.

However, $\Omega_{\text{Neutralino}} \ll \Omega_{\text{Observed DM}}$, which is entirely natural. SUSY provides motivation for weak-scale cross sections but there is no strong argument to assert that $\Omega_{\text{Neutralino}} = \Omega_{\text{Observed DM}}$.

It should also be noted that examples of warm or self-interacting dark matter within the SUSY framework exist.
Direct Dark Matter Detection

Dan McKinsey
Yale University
July 29, 2013
WIMP Direct Detection

Look for anomalous nuclear recoils in a low-background detector.

\[ R = N \rho \sigma <v> \]

From \(<v> = 220 \text{ km/s}\), get order of 10 keV deposited

Requirements:
• Low radioactivity
• Low energy threshold
• Gamma ray rejection
• Scalability
Predicted nuclear recoil spectra from WIMP-nucleus scattering

Isothermal halo

$\nu_0 = 220 \text{ km/s}, \nu_E = 240 \text{ km/s},$

$\nu_{\text{esc}} = 600 \text{ km/s}, \rho_0 = 0.3 \text{ GeV/c}^2/\text{cm}^3$

$M_X = 100 \text{ GeV/c}^2$

$\sigma_{X,\text{Si}} = 10^{-9} \text{ pb} \left(10^{-45} \text{ cm}^2\right)$

V. Chepel and H. Araujo,

JINST 8, R04001 (2013).

D. McKinsey  Direct Detection
Background sources and shielding in a typical dark matter experiment.

Need sensitivity of better than 1 event/100kg/year
WIMP Direct Detection Technologies

• Cryogenic Ge detectors (CDMS, Edelweiss, CRESST): Excellent background rejection, low threshold and good energy resolution.

• Threshold detectors (COUPP, SIMPLE, PICASSO): Ultimate electron recoil rejection, inexpensive, easy to change target material for both SI and SD sensitivity.

• Single-phase LAr, LXe (DEAP, CLEAN, XMASS): Simple and relatively inexpensive per tonne, pulse-shape discrimination and self-shielding.
WIMP Direct Detection Technologies

• Dual-phase Ar (DarkSide, ArDM): Excellent electron recoil rejection, position resolution.

• Dual-phase Xe (XENON, LUX, Panda-X): Suitable target for both SI and SD, low energy threshold, excellent position resolution, self-shielding.

• Scintillating crystals (DAMA/LIBRA, KIMS): Annual modulation with large target mass.

• Ionization detectors (CoGeNT, DAMIC): Very low energy threshold, good energy resolution.
WIMP Directional Detectors
(DRIFT, DMTPC, D^3, MIMAC, NEWAGE, NEXT/Osprey)

In the long run, directional detection will allow one to map out the velocity distribution of the dark matter in the galactic halo, and could serve as an important input to modeling of the detailed formation history and dynamics of the galaxy.
This field has seen tremendous progress over the past 25 years.

Evolution of the $\sigma_{SI}$ for a 50 GeV/$c^2$ WIMP
... and this progress is expected to continue.

Evolution of the $\sigma_{SI}$ for a 50 GeV/$c^2$ WIMP

D. McKinsey  Direct Detection
Current limits
The resolution of these conflicts can only be achieved by observations with lower background, lower threshold, and higher discrimination detectors to either confirm or reject hints in the same target nuclei and then correlate with the magnitude of such signals in other targets. This will require improvement of existing detectors or development of new techniques.
Existing and projected spin-independent cross-section limits

WIMP–nucleon cross section [cm$^2$]

WIMP Mass [GeV/$c^2$]

- DAMA
- CoGeNT
- CDMS Si (2013)
- Soudan CDMS-lite 170 eVee
- SuperCDMS Soudan Low Threshold
- SuperCDMS SNOLAB Low Threshold
- EDELWEISS (2011)
- CDMS II Ge (2009)
- Xenon100 (2012)
- DarkSide 50
- LUX
- SuperCDMS Soudan
- DarkSide G2
- Xenon1T
- LZ

D. McKinsey  Direct Detection
Spin-dependent cross-section limits

In spin-dependent coupling, the WIMP interacts with the free spin of the target, typically parameterized as a neutron- or proton-spin dependent cross-section.
Axion Detection

Dark matter axions may be converted into photons in a high magnetic field. ADMX (a resonant cavity axion detector) is sensitive to axions in the mass range 1 µeV to 100 µeV. Ongoing R&D to push to higher mass (higher frequency cavities).
Axion detection: existing limits and future projections
Indirect Detection Experiments
Jim Buckley
for the CF2 working group

\[ 10^{-17} \]

\[ 10^{-15} \]

\[ 10^{-13} \]

\[ 10^{-11} \]

\[ 10^{-9} \]

\[ 10^{-7} \]

\[ 10^{-5} \]

\[ XENON1T \]

Survives DD, ID, and LHC
Excluded by LHC but not DD or ID
Excluded by DD and ID
Excluded by ID but not DD
Excluded by DD but not ID

M. Cahill-Rowley, R. Cotta, A. Drlica-Wagner, S. Funk, J. Hewett, A. Ismail, T. Rizzo and M. Wood (SLAC and Irvine Particle Theory groups)
DM relic abundance: \( \Omega_X \approx \frac{0.1}{h^2} \left( \frac{3 \times 10^{-26} \text{cm}^3\text{sec}^{-1}}{\langle \sigma v \rangle} \right) \)

- The same interactions of WIMPs with standard model particles in the early universe (holding WIMPs in thermal equilibrium) imply interactions in the current universe.

- While the cross-section for a specific interaction (e.g., scattering off a nucleon) or annihilation channel is indirectly related to this decoupling cross section, almost all annihilation channels produce photons and the total annihilation rate to photons is closely related to the decoupling cross section: \( \sim n_X^2 \langle \sigma v \rangle \)

* Gamma-ray production by annihilation in the present universe is closely related to the decoupling cross section in the early universe with a natural scale \( \langle \sigma v \rangle \approx 3 \times 10^{-26} \text{cm}^3\text{sec}^{-1} \)
Indirect Detection

Fermi, VERITAS, Super-K, ICECUBE, PAMELA, AMS

$\gamma$, $\nu$, $e^-$, $e^+$, $p$, $\bar{p}$
Gamma Rays from DM Annihilation

\[ E_\gamma \Phi_\gamma(\theta) \approx 10^{-10} \left( E_{\gamma, \text{TeV}} \frac{dN}{dE_{\gamma, \text{TeV}}} \right) \left( \frac{\langle \sigma v \rangle}{10^{-26} \text{cm}^3 \text{s}^{-1}} \right) \left( \frac{100 \text{ GeV}}{M_\chi} \right)^2 J(\theta) \text{ erg cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \]

Particle Physics Input

\[ J(\theta) = \frac{1}{8.5 \text{ kpc}} \left( \frac{1}{0.3 \text{ GeV/cm}^3} \right)^2 \int_{\text{line of sight}} \rho^2(l) dl(\theta) \]

Astrophysics/Cosmology Input

\[ \rho^2(l) = \text{Line-of-sight integral of } \rho^2 \text{ for a Milky-Way-like halo in the VL Lactea II } \Lambda CDM \text{ N-body simulations (Kuhlen et al.)} \]
ACT DM Constraints

**HESS**

**VERITAS**

**GC Limits**

- Einasto (this work)
- NFW (this work)
- Sgr Dwarf
- Willman 1
- Ursa Minor
- Draco

**Segue Dwarf Galaxy Limits**

- $XX \rightarrow W^+W^-$
- $XX \rightarrow W^+W^-$, Sommerfeld

(Aharonian et al. for the HESS collaboration, PRL 106, 1301) (Aliu et al. for the VERITAS collaboration, PRD 85, 062001)
Theoretical developments outlined above have significantly improved the determinations of the J_l values of the dSphs since the time when they were first determined over a decade ago. Baltz et al. have developed a maximum likelihood method to determine J_l values from stellar kinematical and photometric data using the likelihood in Equation...}

\[ J_l = \frac{1}{2} \int \rho(r) \, v(r)^2 \, dr \]  

where \( \rho(r) \) is the dark matter density profile, \( v(r) \) is the stellar velocity dispersion, and the integral is evaluated over the entire volume of the dSph. This is the region within which the integrated density and the integrated density squared are the best constrained from the kinematic data set. Thus, the assumption of a core or a cusp for the density profile does not significantly affect the gamma-ray flux predictions for the Fermi-LAT. As discussed more below, however, for instruments with better angular resolution than the Fermi-LAT, the assumption of a core or the cusp is much more relevant.
A CTA-like instrument with ~60 Mid-sized telescopes has the sensitivity to probe the natural cross section for WIMP annihilation from 100 GeV to 10 TeV - But this requires a US contribution.
CTA-US

Snowmass 2013                                                CF2: Indirect Detection                                      James Buckley

SC-MST (Dual Mirror)  DC-MST (Single Mirror)

0.1°  0.03°

0.1% Crab Nebula  Fermi (3 yr, Extragalactic)

Hybrid-1 SC-MST  Hybrid-1 DC-MST

Fermi (3yr)  ~2-3x improvement in core energy range from US contribution

Hybrid-1 (50 hr)  Prod-1 Array I (50 hr)

Prod-1 Array I

6 LSTs  18 MSTs  56 SSTs

Hybrid-1

61 MSTs


Fermi (3yr)

CTA: Point-Source Sensitivity

CTA: Angular Resolution

~2-3x improvement in core energy range from US contribution

1 km

100 GeV  1 TeV

SLAC Cosmic Fronter Workshop

SLAC Cosmic Frontier Workshop
HAWC

Differential Sensitivity per Quarter Decade

Energy [GeV]

10^1 10^2 10^3 10^4 10^5

Sensitivity E^2 dN/dE [erg cm^{-2} s^{-1}]

10^{-13} 10^{-12} 10^{-11} 10^{-10} 10^{-9}

VERITAS 50 hr
Whipple 50 hr
HAWC-100 1 yr
H.E.S.S. 50 hr
HAWC-300 1 yr
CASA-MA
Fermi 5 yr
HAWC-300 5 yr

0.1 ×
0.01 ×
Future Neutrino Detectors

- The cosmic ray muon background (around $10^6$ times the atmospheric neutrino rate)
- Overburden of 2.1 km water-equivalent is substantial, but not as large as at deep underground labs
- However, top and outer layers of IceCube provide an active veto shield for DeepCore
- ~40 horizontal layers of modules above; 3 rings of strings on all sides
- Effective veto-free depth much greater
- Can use to distinguish atmospheric from atmospheric or cosmological (access to the Southern Hemisphere sky!)
- Vetoing algorithms surpass the required $10^6$ level of background rejection

**MICA Conceptual Detector**

- $\chi_{\text{GeV}}$
- $10^{-4}$ to $10^{-3}$
- $10^{-2}$ to $10^{-1}$
- $10^{0}$ to $10^{1}$

*Future Neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of discovery of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.*
Positron Results

• Pamela results on positron excess are now confirmation by Fermi (using geomagnetic field) and AMS result.
• Signal may also be explained by some cosmic-ray propagation models, or by astrophysical sources such as pulsars.
• A DM interpretation requires a combined astrophysical/particle physics boost of 100 or more.

New dark sector force carrier giving a Sommerfeld enhancement, hadronic channels kinematically inaccessible (e.g., Arkani-Hamed, Finkbeiner, Slatyer and Weiner, 1999, PRD 79, 015014)
Radio Synchrotron and gamma-ray IC limits for Pamela scenario (Bertone, Cirelli, Strumia and Taoso, arXiv:0811.2744v3). Note: Radio bounds are sensitive to assumptions about B-fields and diffusion, may be optimistic.

- Pamela excess implies a large radio synchrotron and inverse Compton signal, and a boost in secondary gammas from the GC that are not observed.
Astrophysical Constraints

- When the magnetic field and diffusion are understood, radio constraints on DM can be important.
- Electrons up-scatter CMB photons, producing a measurable X-ray signal and DM constraints.

Radio Constraints on Galaxy Cluster (A2199)

X-Ray (NuSTAR) constraints on Fornax cluster compared with Fermi gamma-ray constraints

Comparison of NuSTAR and Fermi

Jeltema & Profumo 2011

Planned X-ray telescopes will have (at best) similar sensitivity to Fermi to low mass WIMPs.

Predictions for a long NuSTAR observation of the Fornax Cluster

Radio Constraints on Galaxy Cluster (A2199)

Fornax (NO substructures)

bb annihilation final state

1 Ms

WIMP Mass [GeV]
Sterile Neutrinos

If sterile neutrinos make up 100% of dark matter (any cosmology), lower bounds on the mass vary depending on cosmological production scenario.


- Pulsar kicks (allowed)
- Excluded by X-rays if sterile neutrinos make up 100% of dark matter (any cosmology)

Snowmass 2013  CF2: Indirect Detection  James Buckley
**Novel approach for antideuteron identification**

- antideuteron slows down and stops in material
- large chance for creation of an excited exotic atom ($E_{\text{kin}} \sim E_f$)
- deexcitation:
  - fast ionisation of bound electrons (Auger) → complete depletion of bound electrons
  - Hydrogen-like exotic atom (nucleus+antideuteron) deexcites via **characteristic X-ray transitions**
- nucleus-antideuteron annihilation: **pions and protons**
- exotic atomic physics understood (tested in KEK 2004/5 testbeam)

---

**GAPS**

Ph. von Doetinchem  
GAPS  
March 13 - p6
CF2 Key Findings

• CTA, with the U.S. enhancement, would provide a powerful new tool for searching for WIMP dark matter. The angular distribution would determine the distribution of dark matter in halos, and the universal spectrum would be imprinted with information about the mass and annihilation channels needed to ID the WIMP.

• Future Neutrino experiments like the PINGU enhancement to IceCube/DeepCore offer the possibility of a smoking-gun signal (high energy neutrinos from the sun), and may provide some of the best constraints on spin dependent cross sections.

• Other astrophysical constraints such as low-frequency radio (synchrotron from electrons) or X-rays (inverse Compton scattering by electrons, sterile neutrino decay) can provide very powerful tests for DM annihilation for certain annihilation channels and provide constraints on decaying dark matter.

• Detailed theoretical studies with PMSSM, contact operators, realistic halo models are resulting in quantitative estimates of sensitivity, showing the complementary reach of different techniques.

\[ \Omega_{\text{DM}} h^2 > 0.1 \]
Assembling a Theory of Dark Matter

Tim M.P. Tait
University of California, Irvine

Snowmass
July 29, 2013
What is Dark Matter?
The Dark Matter Questionnaire

- Mass
- Spin
- Stable?
  - Yes
  - No

Couplings:
- Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons?
- Leptons?

Thermal Relic?
- Yes
- No
Ultimately, we need to fill out the questionnaire experimentally. But as we try to relate the results of experiments to one another and unravel the deeper theoretical underpinning, we need at least some kind of theoretical framework in which to cast our progress.

What could the theory be? No lack of possibilities...
Spectrum of Theory Space

Effective Field Theories

Less Complete
- Contact Interactions
- Dipole Interactions

Simplified Models
- Higgs portal
- “Squarks”

UV Complete Models
- Z’
- dark photon
- UED
- MSSM
- mSUGRA
- Little Higgs

Contact Interactions

Dipole Interactions

Higgs portal

“Squarks”

Z’

dark photon

UED

MSSM

mSUGRA

Little Higgs

More Complete
The Most Complete Theory

- On the “complete” end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM’ parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1 ton only, CTA only, both Xenon and CTA, or can’t be discovered.
- It is clear that just based on which experiments see a signal, and which don’t, that there could be (potentially soon) suggestions of favored parameter space(s) from data.

Cahill-Rowley et al, 1305.6921

On the “complete” end of the spectrum is our favorite theory: the MSSM.

Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.

This plot shows a scan of the `pMSSM’ parameter space in the plane of the WIMP mass versus the SI cross section.

The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1 ton only, CTA only, both Xenon and CTA, or can’t be discovered.

It is clear that just based on which experiments see a signal, and which don’t, that there could be (potentially soon) suggestions of favored parameter space(s) from data.
The Most Complete Theory

- On the “complete” end of the spectrum is our favorite theory: the MSSM.
- Reasonable phenomenological models have ~20 parameters, leading to rich and varied visions for dark matter.
- This plot shows a scan of the `pMSSM' parameter space in the plane of the WIMP mass versus the SI cross section.
- The colors indicate which (near) future experiments can detect this model: LHC only, Xenon 1 ton only, CTA only, both Xenon and CTA, or can’t be discovered.
- It is clear that just based on which experiments see a signal, and which don’t, that there could be (potentially soon) suggestions of favored parameter space(s) from data.
Moving away from complete theories, we come to simplified models. These contain the dark matter, and some of the particles which allow it to talk to the SM, but are not meant to be complete pictures.

As a simple example, we can look at a theory where the dark matter is a Dirac fermion which interacts with a quark and a (colored) scalar mediating particle.

There are three parameters: the DM mass, the mediator mass, and the coupling $g$.

These are like the particles of the MSSM, but with subtle differences in their properties and more freedom in their interactions.

Just like the MSSM was one example of a complete theory, this is only one example of a “partially complete” one.
Simplified Models

- Moving away from complete theories, we come to simplified models.
- These contain the dark matter, and some of the particles which allow it to talk to the SM, but are not meant to be complete pictures.
- As a simple example, we can look at a theory where the dark matter is a fermion which interacts with a quasi-real (colored) scalar mediating particle.
- There are three parameters: the DM mass, the mediator mass, and the coupling $g$.
- These are like the particles of the MSSM, but with subtle differences in their properties, and the interactions.
- Just like the MSSM was one example of a ‘‘partially complete’’ one.
In the limit where the mediating particles are heavy compared to all energies of interest, we are left with a theory containing the SM, the dark matter, and nothing else.

The residual effects of the mediators are left behind as what look like non-renormalizable interactions between DM and the SM.

These are the simplest and least complete description of dark matter we can imagine.

For any particular choice of interaction type, there are two parameters: the DM mass and the strength of that interaction.
In the limit where the mediating particles are heavy compared to all energies of interest, we are left with a theory containing the SM, the dark matter, and nothing else.

The residual effects of the mediators are left behind as what look like non-renormalizable interactions between DM and the SM.

These are the simplest and least complete description of dark matter we can imagine.

For any particular choice of interaction type, there are two parameters: the DM mass and the strength of that interaction.
since high energy collisions readily produce light dark matter particles with large momenta.

Heavy nuclei. This region of low mass is precisely where collider production of dark matter is easiest, direct searches for dark matter are very powerful for masses around 100 GeV, but have difficulty that the searches are complementary to each other in terms of being sensitive to interactions with dark matter searches that are sensitive to interactions with quarks and gluons, or leptons. It is clear which, however, could not account for all of the dark matter (within this model framework), and above channels still waiting to be observed. Finally, if an experiment were to observe a cross section that the corresponding relic density is too large, and therefore there are important annihilation below channels into quarks, gluons, and leptons, and the production rate of dark matter at colliders.

rate of both spin-dependent and spin-independent direct scattering, the annihilation cross section

account for all of the dark matter in the Universe. If the discovery potential for an experiment with annihilation cross section normalized to the value

below the dark matter relic density, the reach of any experiment is thus equivalent to a fraction of the

annihilation cross section into a particular channel. Since the annihilation cross section predicts strengths for a given dark matter mass. Therefore, they are all implicitly putting a bound on the

FIG. 2: Dark matter discovery prospects in the (1305.1605, 1707.0810)

For non-thermal WIMPs, e.g. asymmetric DM, the annihilation cross-section does not have a naturally preferred value, but the plots in Fig. 2 are still meaningful.

In Fig. 2, we assemble the discovery potential and current bounds for several near-term dark

Each class of dark matter search outlined in Sec. III is sensitive to some range of the interaction

th different search strategies depends sensitively on the dark matter mass. For example,
LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.
A Possible Timeline

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

- Mass: 150 +/- 15 GeV
- Spin
- Stable?
- Couplings:
  - Gravity
  - Weak Interaction?
  - Higgs?
  - Quarks / Gluons
  - Leptons?
  - Thermal Relic?
A Possible Timeline

- **2013**: LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.
- **2014**: LUX sees a similar signal.
- **2015**: Fermi observes a faint gamma ray line at 150 GeV from the galactic center.
- **2016**: Two LHC experiments see a significant excess of leptons plus missing energy.
- **2017**: Xenon sees a similar signal.
- **2018**: Two LHC experiments see a significant excess of leptons plus missing energy.

**Properties of the Candidate DM Particle**

- **Mass**: 150 +/- 15 GeV
- **Spin**: 
- **Stable?**: 
- **Couplings**:
  - Gravity
  - Weak Interaction?
  - Higgs?
  - Quarks / Gluons
  - Leptons?
  - Thermal Relic?
A Possible Timeline

- **2013**: LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.
- **2014**: Fermi observes a faint gamma ray line at 150 GeV from the galactic center.
- **2015**: LHC experiments see a significant excess of leptons plus missing energy.
- **2016**: Neutrinos are seen coming from the Sun by IceCube.

### Potential DM Candidate

- **Mass**: 150 +/- 15 GeV
- **Spin**: > 0
- **Stable?**:
- **Couplings**:
  - Gravity
  - Weak Interaction?
  - Higgs?
  - Quarks / Gluons
  - Leptons
  - Thermal Relic?
A Possible Timeline

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Xenon sees a similar signal.

Two LHC experiments see a significant excess of leptons plus missing energy.

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

Mass: 150 +/- 15 GeV
Spin: > 0
Stable?
Couplings:
- Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons
- Leptons
- Thermal Relic?

Mass: 20 μeV
Spin: 0
Stable?
Couplings:
- Gravity
- Weak Interaction
- Higgs?
- Quarks / Gluons?
- Leptons?
- Thermal Relic?
LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Xenon sees a similar signal.

Two LHC experiments see a significant excess of leptons plus missing energy.

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

Mass: 150 +/- 0.1 GeV
Spin: > 0
Stable?
Couplings:
- Gravity
- Weak Interaction?
- Higgs?
- Quarks / Gluons
- Leptons
- Thermal Relic

Mass: 20 μeV
Spin: 0
Stable?
Couplings:
- Gravity
- Weak Interaction
- Higgs?
- Quarks / Gluons?
- Leptons?
- Thermal Relic?

Observation at a Higgs factory indicates that the interaction with leptons is too strong to saturate the relic density.
A Possible Timeline

LUX sees a handful of elastic scattering events consistent with a DM mass < 200 GeV.

Fermi observes a faint gamma ray line at 150 GeV from the galactic center.

Xenon sees a similar signal.

Two LHC experiments see a significant excess of leptons plus missing energy.

Neutrinos are seen coming from the Sun by IceCube.

A positive signal of axion conversion is observed at an upgraded ADMX.

A multi-pronged search strategy identifies a mixture of dark matter which is 50% classic WIMP and 50% axion.
Outlook

• Putting together a detailed particle description of dark matter will necessarily involve many experimental measurements.

• Important details such as the mass and spin will hopefully come along as part of that program.

• The three traditional pillars of dark matter searches: direct, indirect, and collider, naturally probe different parts of the space of DM-SM couplings.

• They are highly complementary to one another in terms of discovery potential.

• Together they can probe a large fraction of the space of interesting WIMP models in the near future.

• Input from all of them is likely to be necessary to reconstruct enough of the couplings to be able to firmly understand the dark matter relic density.

“Ωh^2 or bust!”