Getting the most out of dark matter observations and experiments

Annika Peter
Caltech
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Lines of Evidence for Dark Matter

From Bertone et al. 2005
With data from
Begeman et al. 1991

Wayne Hu’s website

Bullet Cluster
Clowe et al. 2006

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What is Dark Matter?

• Astrophysical (not favored)
• Particle physics:
  – WIMPs (weakly interacting massive particles): neutralinos, Kaluza-Klein photons
  – SuperWIMPs: gravitinos
  – Sterile neutrinos
  – Axions
  – Hidden sector particles
  – Self-interacting dark matter
  – ...
How to Nail Down Dark Matter

• Collider
• Direct detection
• Indirect detection via annihilation/interaction/decay products
• “Gravitational probes”
How to Nail Down Dark Matter

- Collider
- **Direct detection**
- Indirect detection via annihilation/interaction/decay products
- “Gravitational probes”
Direct Detection

Recoil spectrum depends on the WIMP mass, cross sections, local phase space density, target nucleus.

Some experiments will have directional sensitivity, too.
How to Nail Down Dark Matter

• Collider
• Direct detection
• Indirect detection via annihilation/decay products
  – E.g., gamma-rays, neutrinos, anti-particles from annihilation.
• “Gravitational probes”
How to Nail Down Dark Matter

• Collider
• Direct detection
• Indirect detection via annihilation/interaction/decay products
• “Gravitational probes”
  – Lensing
  – Dwarf galaxy satellite kinematics
  – Rotation curves
How to Nail Down Dark Matter

- Collider
- Direct detection
- Indirect detection via annihilation/interaction/decay products
- “Gravitational probes”

These probes depend on “astrophysical” dark matter, but there are a LOT of uncertainties in interpreting potential signals related to galaxy evolution.
Astrophysical Complications

• Dark matter response to baryonic physics
  – Dark matter-only simulations show definite predictions for $\rho(r)$
  – No consensus on what happens when baryons are added—see papers by Romano-Diaz, Gnedin, Abadi, Blumenethal, Scannapieco, for a diversity of views. What drives changes?
  – Additional macroscopic structures (“dark disk”; Read et al. 2009, Purcell et al. 2009)?
Astrophysical Complications

• Substructure
  – How much is there? Down to what scales? (Quite complicated even for vanilla WIMPs due to hierarchical structure formation, small-scale interactions with baryons.)
  – Tidal debris: stream density on mpc scales? How long do the structures survive before being phase-mixed?
Two Approaches

• There are essentially two approaches to understanding these astrophysical uncertainties:
  – Better modeling.
  – Treat the astrophysical uncertainties on par with the particle physics uncertainties, try to extract both from data.
Two Approaches: A Detailed Example

- Application: direct detection experiments and v telescopes, to model and empirically determine the local dark-matter distribution function $f(r, v)$.
- Where does $f(r, v)$ come in?
  - Direct detection experiments:
    \[
    \frac{dR}{dQ} \propto \int_{v_{cut}}^{v_{esc}} d^3 v f(r, v) v \frac{d\sigma}{dQ}, \quad v_{cut} = \sqrt{\frac{m_A Q}{2\mu^2}}
    \]
  - Indirect detection of neutrinos from WIMP annihilation in Solar System bodies (primarily Sun + Earth):
    \[
    C = \sum_A \int_{v_{fin} < v_{esc}(r)} d^3 v d^3 v_A d^3 v f_A(r, v_A) f(r, v) v \sigma
    \]
    \[
    \Gamma = 0.5 \int d^3 r n^2(r) \langle \sigma v \rangle
    \]
Two Approaches: A Detailed Example

• **Modeling:**
  – Dark matter bound to the Solar System.

• **Data mining:**
  – Determining the local Galactic dark matter velocity distribution from data as well as the WIMP mass and elastic scattering cross sections
Case Study for Better Modeling: WIMPs Bound to the Solar System

- Elastic scattering off nuclei in the Sun. (see Menon et al., Nussinov et al. 2009 for inelastic case)
- Gravitational three-body interactions with planets.
Why Better Modeling?

• Direct detection: Damour & Krauss (1999) claim secular resonances can enhance the signal by $O(1)$ at low $Q$. Shape of the direct detection curve used to find $m_X$ (e.g., Green 2008).
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- Neutrinos from the Earth
Neutrinos from Celestial Bodies

Process

Initial Trajectory
Earth
Scattered Trajectory

Capturability

\(\bullet\) unbound

\(\bigcirc\) bound

\(\text{Speed [km/s]}\)

\(\text{Mass [GeV]}\)
Why Better Modeling?

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• Neutrinos from the Earth
• Neutrinos from the Sun
ν’s from the Sun in IceCube

Abbasi et al. 2009

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New Estimates (Peter 2009a,c)  
PR D 79, 103531 + 103533

• Simulations of orbits in a Sun + Jupiter solar system:
  – $\sim 1.5 \times 10^6$ orbits of WIMPs initially scattered onto bound orbits by elastic scattering in the Sun.
  – $\sim 10^{10}$ orbits of WIMPs that might be gravitationally captured ($\sim 3 \times 10^5$ were captured for at least 10 orbits)
Effects on Direct Detection

- Small!
Estimate of $\nu$'s from Earth: Also Small

(Peter 2009a,c)

Using the seven-parameter phenomenological MSSM model in DarkSUSY (Gondolo et al. 2004). Only through-going events. Contained events may boost the event rate for $m_\chi < 300$ GeV by $\leq \times 10$ depending on branching ratios.
ν’s from the Sun: WIMP Thermalization Times
(Peter 2009b, PR D 79, 103532)

• Three types of behaviors:
  – a < 1.5 AU: the typical time between scatters goes as $t \sim \frac{P_\chi}{\tau}$
  – 1.5 AU < a < 2.6 AU (half Jupiter’s semi-major axis): the time between scatters goes as $t \sim 300 \frac{P_\chi}{\tau}$ (due to interactions between the Kozai and mean-motion resonances)
  – a > 2.6 AU (Jupiter-crossing): ejected on timescales of \~ Myr unless the timescale for rescattering in the Sun is shorter than the angular momentum diffusion timescale.

• The distribution of initial a is skewed higher for higher WIMP masses.

• It takes more scatters to thermalize a heavier WIMP.
Suppression of the Annihilation Rate
(Standard Halo Model)
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(Standard Halo Model)

If $m_\chi > 1$ TeV and $\sigma_p^{SD} \lesssim 10^{-38}$ cm$^2$, $\Gamma$ will be heavily suppressed.
Summary So Far

• The distribution function of WIMPs bound to the Solar System at the position of the Earth is small.
  – Essentially no impact on direct detection rates.
  – Flux of $\nu$’s from WIMP annihilation in the Earth is too small to be detected with IceCube.

• **Major Effect:** Gravitational interactions with planets may severely depress the annihilation rate of WIMPs in the Sun if $m_{\chi} \geq 1$ TeV.

• Caveat: Simulations in a simple Solar System.

• Caveat: Halo model.
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Case Study for Extracting Astrophysics of WIMPs from Data: local $f(r,v)$

- $f(r, v) = \rho \chi g(v)$.

- Usual smooth halo assumptions:
  - $\rho \sim r^{-2}$ and a completely phase-mixed, static system. Assuming an isotropic velocity ellipsoid and spherical symmetry, $\sigma = v_\odot/\sqrt{2}$.

- What happens when one relaxes assumptions about the Galactic dark matter?
Strigari & Trotta 2009

• 1 ton Xe experiment along with hypothetical kinematics of 2000 halo stars (to constrain the halo).
• Spherical symmetry.
• Baseline: Fix stellar disk and bulge, fix inner and outer slopes of the dark matter density profile, marginalize over dark matter halo parameters (scale density, scale radius, constant velocity anisotropy).
• Conservative: Marginalize over other halo parameters and the disk parameters, too. Keep bulge fixed.
Additional Complications

• Macroscopic:
  – Even if the dark matter density profile is well constrained from stellar kinematics, the velocity distribution is NOT.
  – Dark disk
The Halo is Not Alone: The Dark Disk

- Simulations that include baryons show that the stellar disk drags satellites into the disk plane, where they dissolve.
- This yields a DARK DISK with properties similar to the stellar disk generated by these satellites.
- The dark disk properties are extremely sensitive to the merger history of the Galaxy.
- Typically, speeds wrt to the solar system are MUCH smaller—much easier to capture.

(Read et al. 2008, 2009; Purcell et al. 2009)
The Dark Disk & $\nu$'s in the Earth


Free space phase density

Phase space density from my simulations

halo
disk

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Additional Complications

• Macroscopic:
  – What is the halo $f(r, v)$ in simulations with baryons?
  – Dark disk

• Microscopic:
  – Are we passing through clumps? (Not likely: see Kamionkowski & Koushiappas)
  – Tidal streams: What is the local stream density on mpc scales? How long till streams phase mix? As far as I know, no one has really looked at this (although it has been looked at on ~kpc scales by, e.g., Vogelsberger et al.)
How to Deal with $f(r, v)$

• Imagine a world in which WIMPs have been detected (definitively) in at least one direct detection experiment.

• My approach: estimate how well one can extract the WIMP mass and elastic scattering cross sections as well as $f(r, v)$ using two new ideas:
  – no (rather, flat) priors on velocity parameters or $\rho_X$.
  – combining data sets.

• NB: Direct detection experiments and neutrino telescopes are the ONLY ways to learn about the dark matter velocity distribution.
Test of Principle (Peter 2009d, arXiv:0910:4765)

- Use large, directionally-insensitive, energy-sensitive, “background-free” direct detection experiments. Models of multiple experiments—forecasting for 2015, 2020 (approx.)
- Fisher matrix analysis
- Single dark matter species
- Single macro/microscopic WIMP component with Gaussian velocity distribution. Assume a Gaussian velocity with 1-d dispersion $v_{\text{rms}}$, isotropic velocities, and lagging the Earth by $v_{\text{lag}}$. 

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Standard Halo Model & Particle Physics

\[ m_{\chi} = 100 \text{ GeV}, \quad \sigma_{p}^{\text{SI}} = 10^{-44} \text{ cm}^2 \]

\[ \rho_{\chi} = 0.3 \text{ GeV cm}^{-3}, \quad v_{\text{lag}} = 220 \text{ km/s}, \quad v_{\text{rms}} = 155 \text{ km/s} \]

\[ A \sim \sigma_{p}^{\text{SI}} \rho_{\chi} \]

2015-era experiments: WArP, SuperCDMS, LUX, XENON1T

2020-era experiments: 10 ton liquid argon, 20 ton xenon, 1 ton germanium
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Stream with $v_{\text{lag}} = 400 \text{ km/s}$, $v_{\text{rms}} = 30 \text{ km/s}$
Dark Matter Astrophysics from Data: The Future

• Local velocity distribution:
  1. Fold in neutrino telescopes (energy/direction sensitive to mass, normalization to velocities, mass, cross sections).
  2. Fold in other types of direct detection experiments.
  3. Experiment with multiple velocity components.
  4. Try to reconstruct the velocity information non-parametrically.
  5. Hope that better simulations of disk galaxies come along so that it will be possible to compare the derived velocity distribution with simulations.

• Other:
  – Extend this type of forecasting for other observations and experiments.
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• Future:
  – First step: more local $f(r, v)$ data analysis.
  – Move beyond WIMP-specific experiments, figure out how different types of data compliment each other, do some forecasting.
  – Will the astrophysics of dark matter yield insights into galaxy evolution?