P599 Seminar, April 9, 2014

Development of a New Paradigm for Direct Dark Matter Detection

Jason Rose / UTK

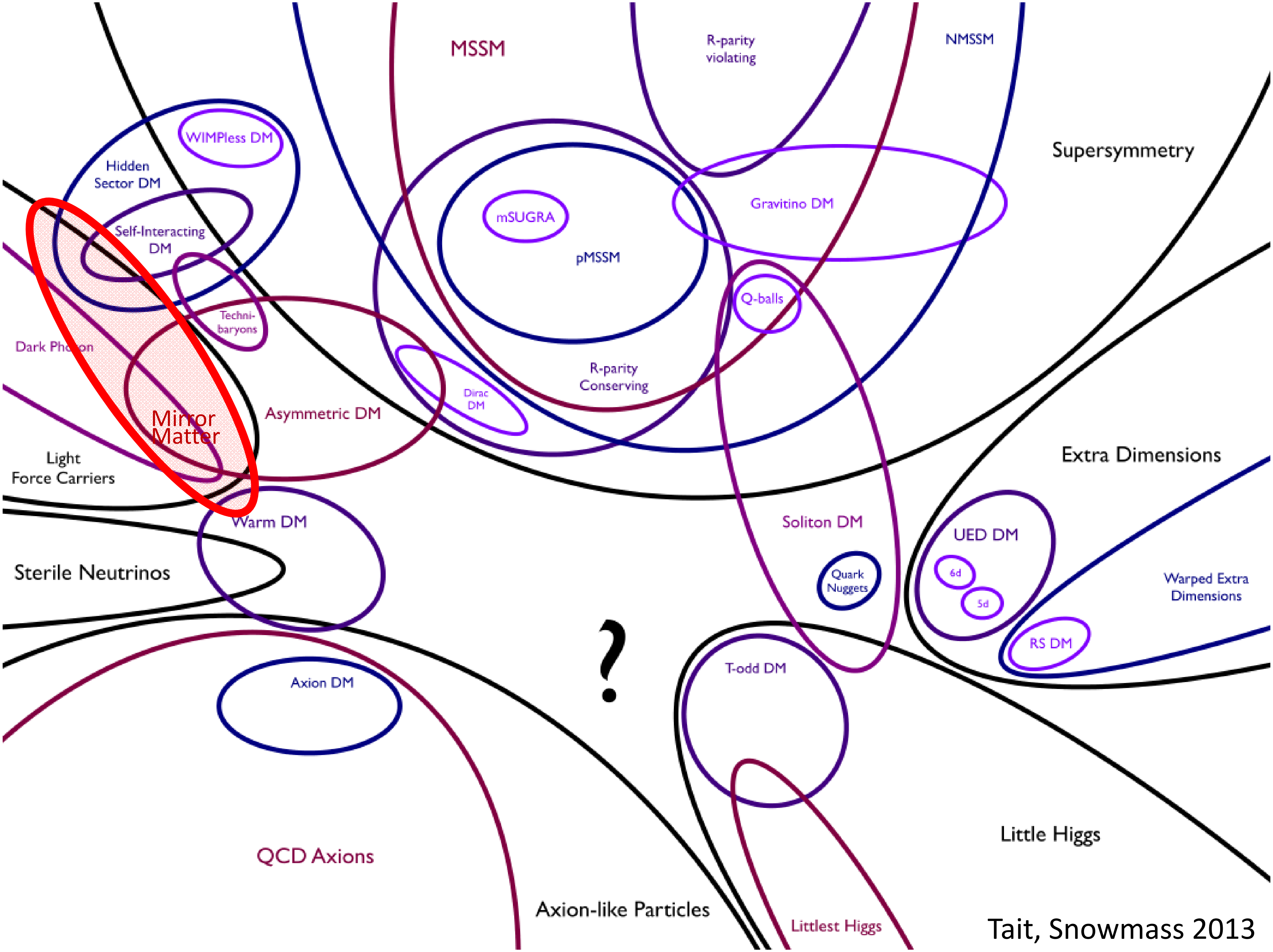
(working with Dr. Kamyshkov)

Dark Matter Recap

- Evidence:
  - Galactic Rotation Curves
  - Gravitational Lensing
  - Cosmic Microwave Background
  - Collisions of galactic clusters
  - And more…

Dark Matter Recap

- Characteristics
  - Conclusively observed only indirectly by gravitational interaction with baryonic matter
  - Outnumbers baryonic matter 5 to 1
  - Important component of structure formation
  - Composed of WIMPs (weakly interacting massive particles)
  - But we don’t actually know what it is



Tait, Snowmass 2013

Detection Categories

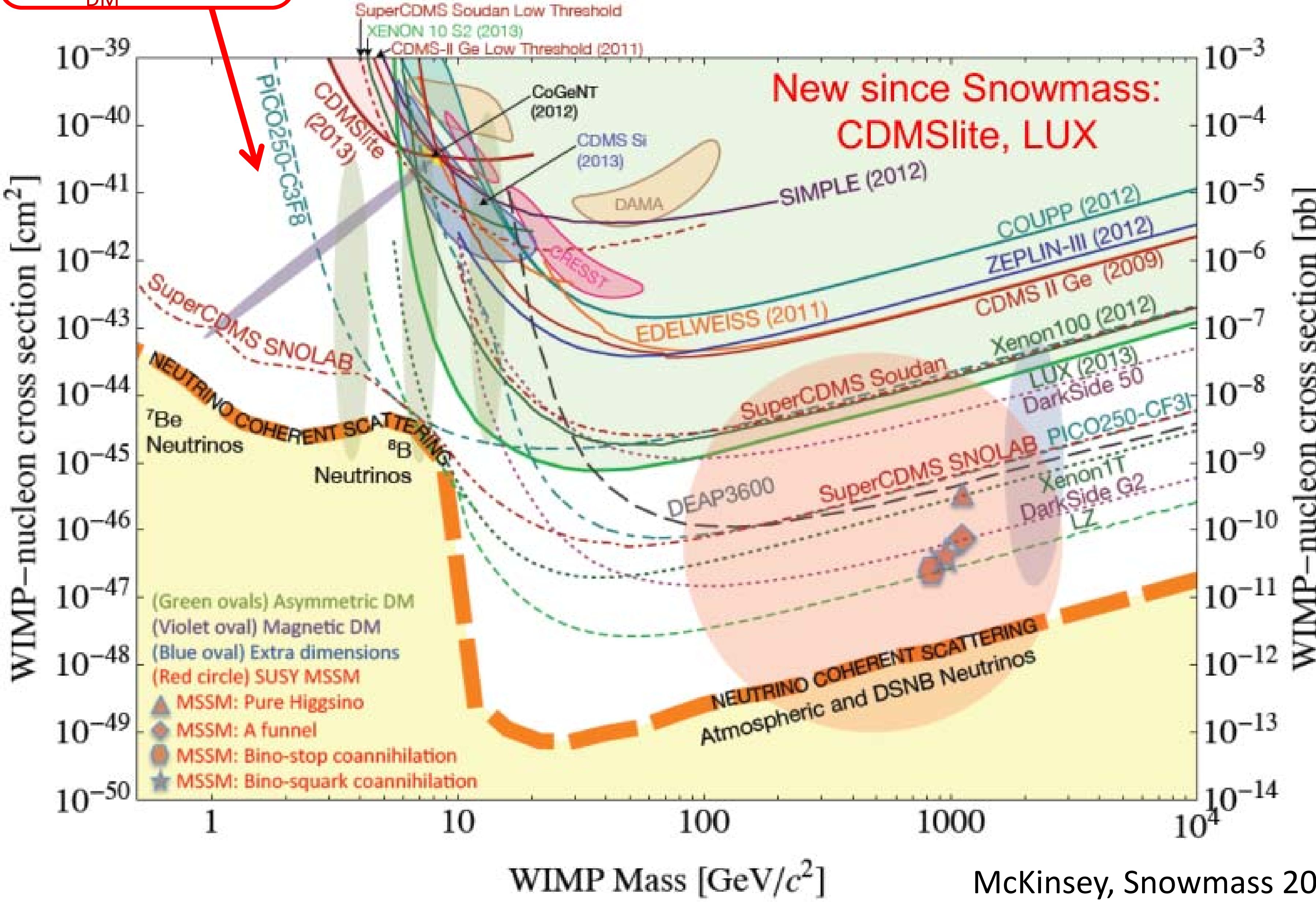
- Indirect Detection
  - Interactions with standard model particles through annihilations and decays
- Accelerators
  - Search for energy and momentum violation
  - No luck yet
- Direct Detection
  - Our field

Existing Direct Detection Approach

- Dark matter is a single type of particle (LSP neutralino) which is heavy (~100 GeV/c^2) and not self-interacting
- Possibility of weak interaction with baryonic matter through unknown forces (assumed)
- Unknown parameters: M_{DM} and cross-section
- Method used:
  - Look for small recoil energy with small cross-section (large M_T)
  - Rule out background or electronic noise (atmospheric, solar, reactor, and geo neutrinos; neutrons)
  - Build detector with optimal material ($M_T = M_{DM}$)

Present and Future of Direct DM Search

No limits established for M_{DM} < 6 GeV

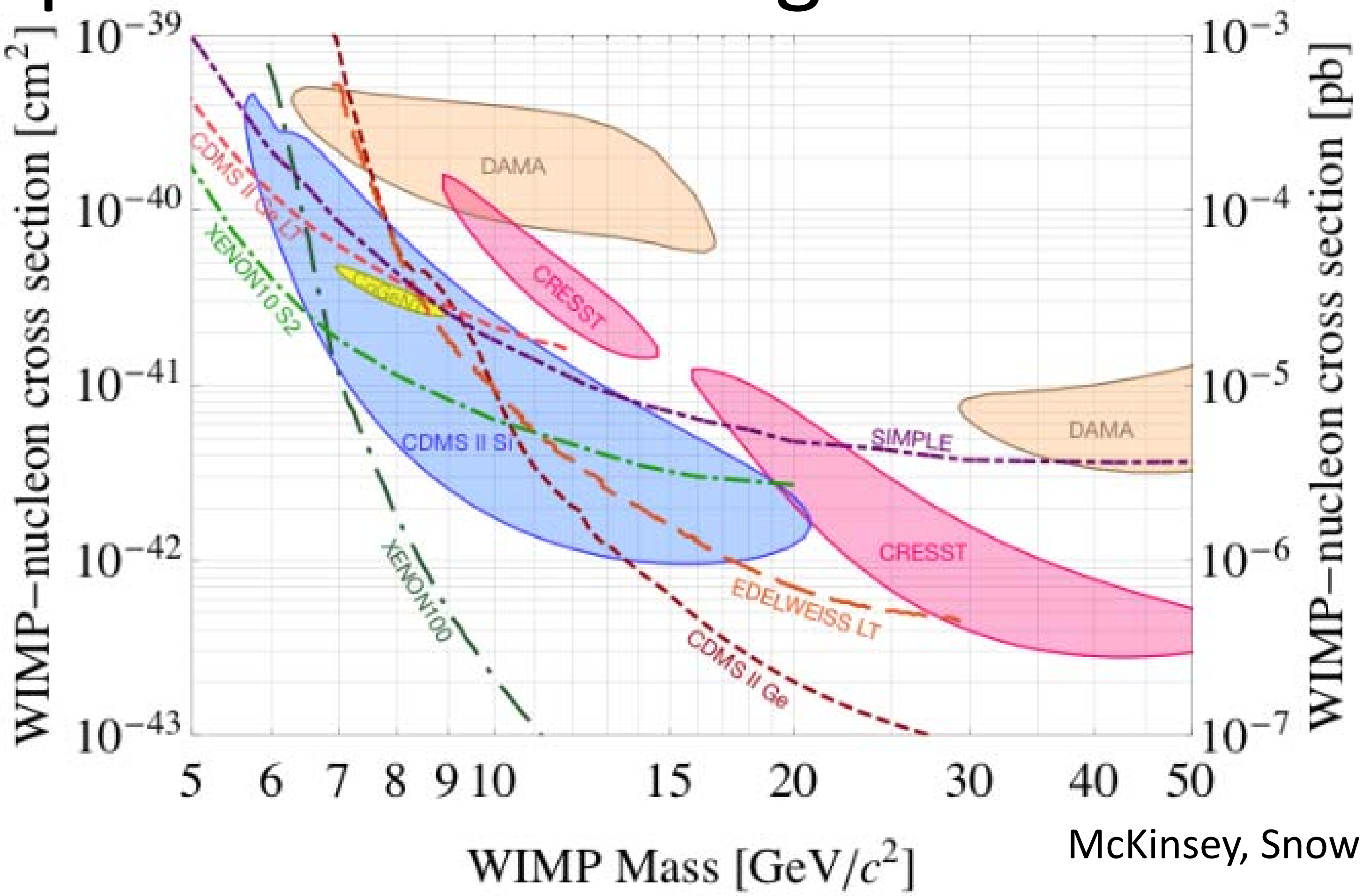


McKinsey, Snowmass 2013

The Supersymmetric Dream

- No positive results in expected supersymmetric mass range from direct detection experiments
- No positive results from LHC
- Searching for heavier masses at smaller cross sections is expensive due to large detector mass
- Regardless, many research collaborations still pursue supersymmetry and are well-funded for large detectors

Experiments Claiming DM Detection



McKinsey, Snowmass 2013

- The results say to look for the low-mass WIMP
- These experiments have low mass target nuclei and low thresholds

Dark Matter Search Results Using the Silicon Detectors of CDMS II

R. Agnese,[18] Z. Ahmed,[1] A.J. Anderson,[4] S. Arrenberg,[20] D. Balakishiyeva,[18] R. Basu Thakur,[2] D.A. Bauer,[2] J. Billard,[4] A. Borgland,[8] D. Brandt,[8] P.L. Brink,[8] T. Bruch,[20] R. Bunker,[11] B. Cabrera,[10] D.O. Caldwell,[15] D.G. Cerdeno,[13] H. Chagani,[19] J. Cooley,[9] B. Cornell,[1] C.H. Crewdson,[6] P. Cushman,[19] M. Daal,[14] F. Dejongh,[2] E. Do Couto E Silva,[8] T. Doughty,[14] L. Esteban,[13] S. Fallows,[19] E. Figueroa-Feliciano,[4] J. Filippini,[1] J. Fox,[6] M. Fritts,[19] G.L. Godfrey,[8] S.R. Golwala,[1] J. Hall,[5] R.H. Harris,[12] S.A. Hertel,[4] T. Hofer,[19] D. Holmgren,[2] L. Hsu,[2] M.E. Huber,[16] A. Jastram,[12] O. Kamaev,[6] B. Kara,[9] M.H. Kelsey,[8] A. Kennedy,[19] P. Kim,[8] M. Kiveni,[11] K. Koch,[19] M. Kos,[11] S.W. Leman,[4] B. Loer,[2] E. Lopez Asamar,[13] R. Mahapatra,[12] V. Mandic,[19] C. Martinez,[6] K.A. McCarthy,[4] N. Mirabolfathi,[14] R.A. Moffatt,[10] D.C. Moore,[1] P. Nadeau,[6] R.H. Nelson,[1] K. Page,[6] R. Partridge,[8] M. Pepin,[19] A. Phipps,[14] K. Prasad,[12] M. Pyle,[14] H. Qiu,[9] W. Rau,[6] P. Redl,[10] A. Reisetter,[17] Y. Ricci,[6] T. Saab,[18] B. Sadoulet,[14,3] J. Sander,[12] K. Schneck,[8] R.W. Schnee,[11] S. Scorza,[9] B. Serfass,[14] B. Shank,[10] D. Speller,[14] K.M. Sundqvist,[14] A.N. Villano,[19] B. Welliver,[18] D.H. Wright,[8] S. Yellin,[10] J.J. Yen,[10] J. Yoo,[2] B.A. Young,[7] and J. Zhang[19]
(CDMS Collaboration)

We report results of a search for Weakly Interacting Massive Particles (WIMPs) with the silicon detectors of the CDMS II experiment. A blind analysis of 140.2 kg-days of data revealed three WIMP-candidate events with an expected total background of 0.7 events. The probability that the known backgrounds would produce three or more events in the signal region is 5.4%. A profile likelihood ratio test of the three events that includes the measured recoil energies gives a 0.19% probability for the known-background-only hypothesis when tested against the alternative WIMP+background hypothesis. The highest likelihood occurs for a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9×10^{-41} cm^2.

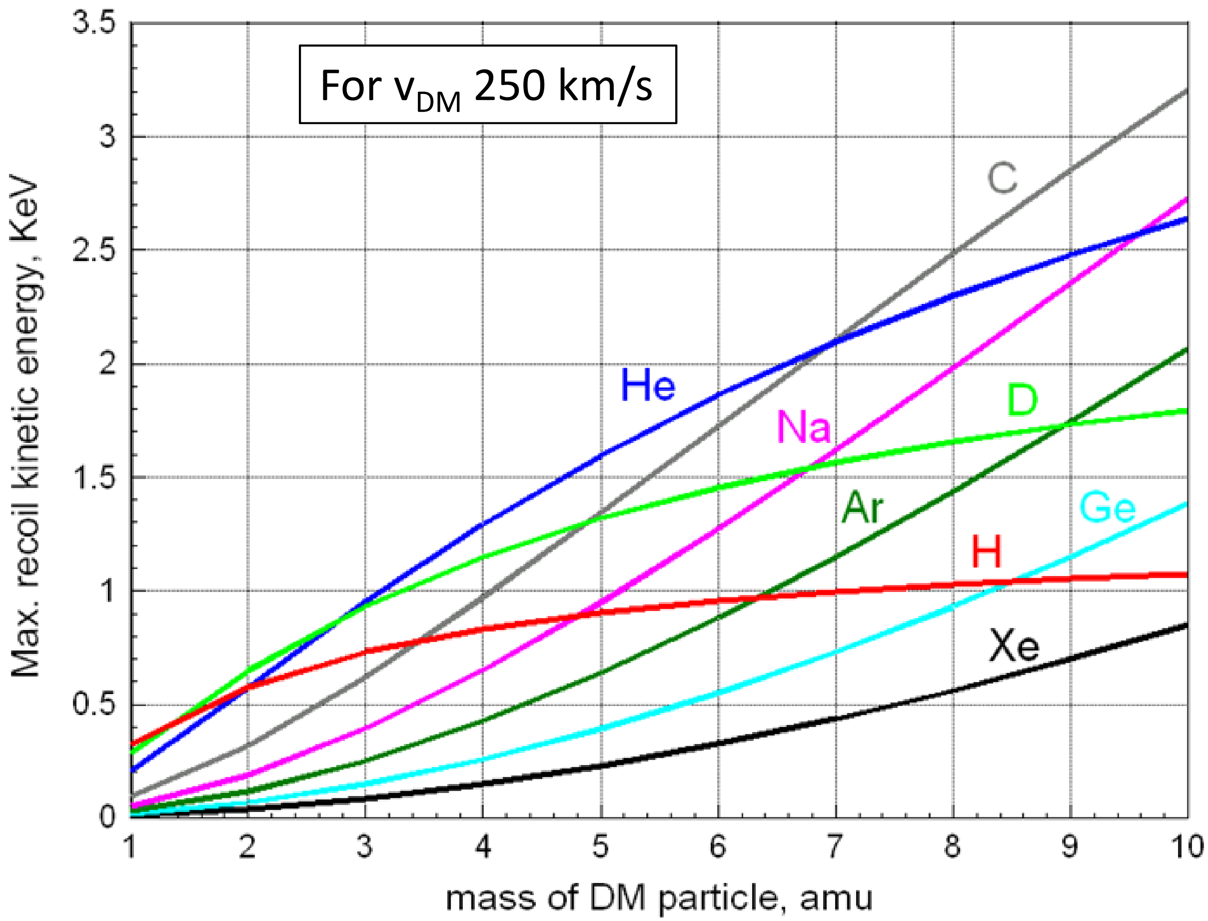
arXiv:1304.4279v2 [hep-ex] 4 May 2013

Why low masses are not detectable?

$$E_{max} = E_{kin} \cdot \frac{4M_T M_{DM}}{(M_T + M_{DM})^2}$$

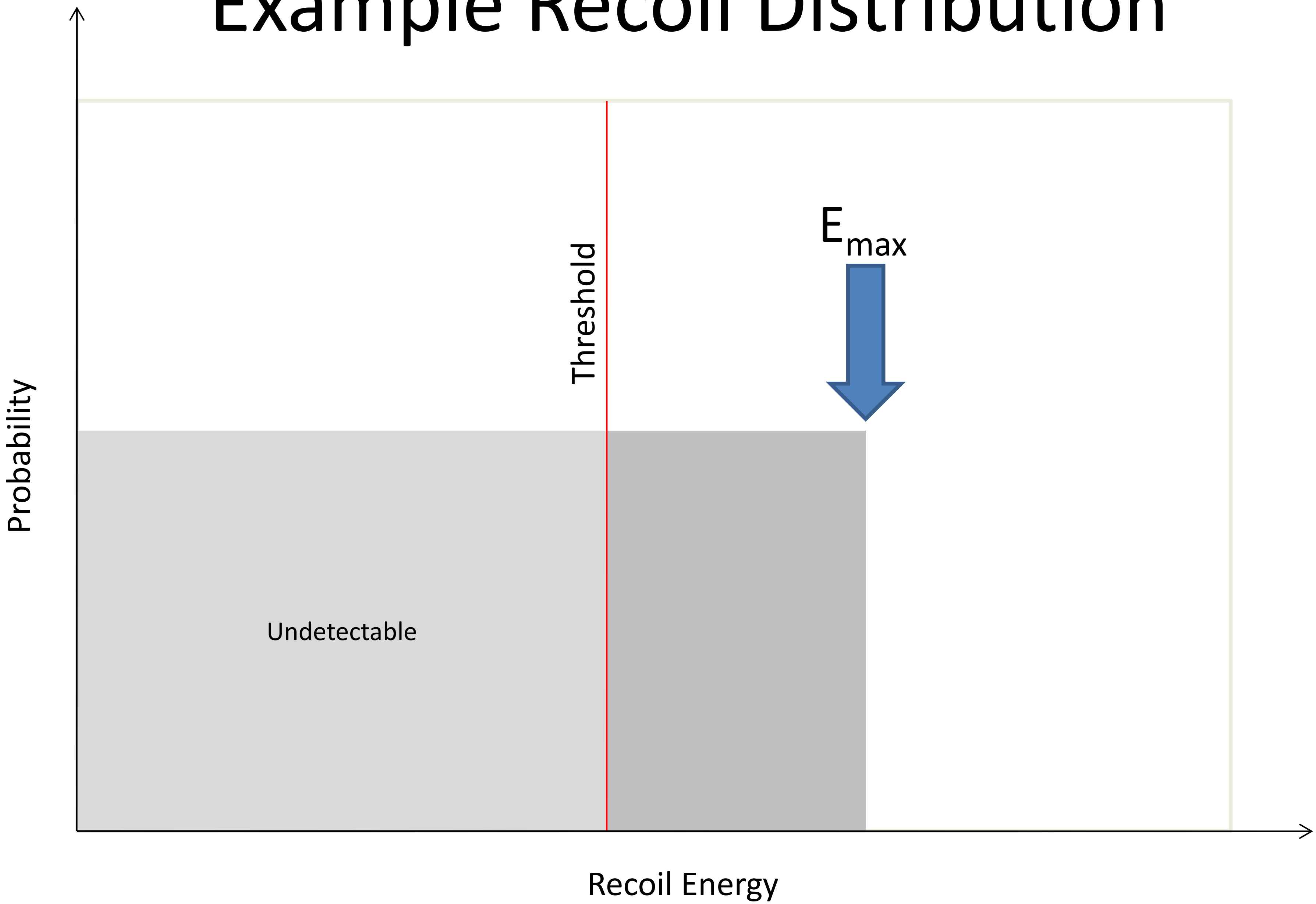
CDMS-Si
7 keV

DAMA-Na
2 keV



Yuri Kamyshkov

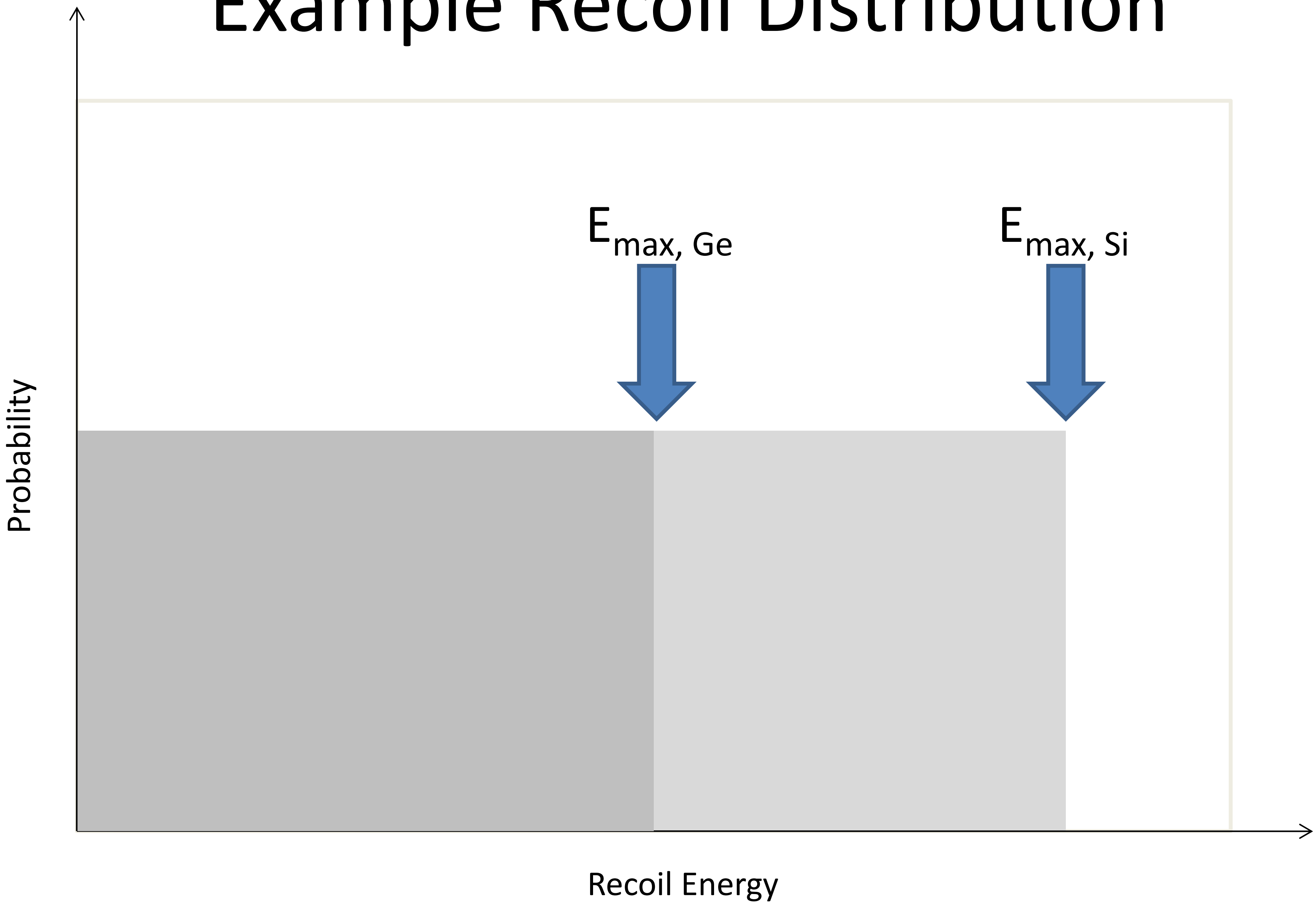
Example Recoil Distribution



Example Recoil Distribution

- For a WIMP mass of 8.5 GeV/c^2 and v_{DM} = 200 km/s, E_{kin} = 1.89 keV
- For a detector made of germanium (A = 72), E_{max} = .81648 keV in this case
- For a detector made of silicon (A = 28), E_{max} = 1.395 keV
- This is a 70.9% increase in E_{max}

Example Recoil Distribution



Our Research

- There is no alternative paradigm to SUSY direct dark matter detection
- The concept of mirror matter (co-developed with Z. Berezhiani) includes:
  - Multiple species of atoms and nuclei with similar interactions as ordinary matter (self-interacting)
  - Abundances: 25% mirror hydrogen, 74% mirror helium, 1% mirror metals by mass
  - Resides in gas clouds similar to baryonic clouds in galaxy where it thermalizes because of self-interaction
  - Interacts with ordinary matter through a weak, unknown force beyond the standard model
  - Average local density of dark matter is .48 GeV/cm^3
  - Nobody but us pursuing these ideas, as far as we know

Components of our Model

(Mostly) Known

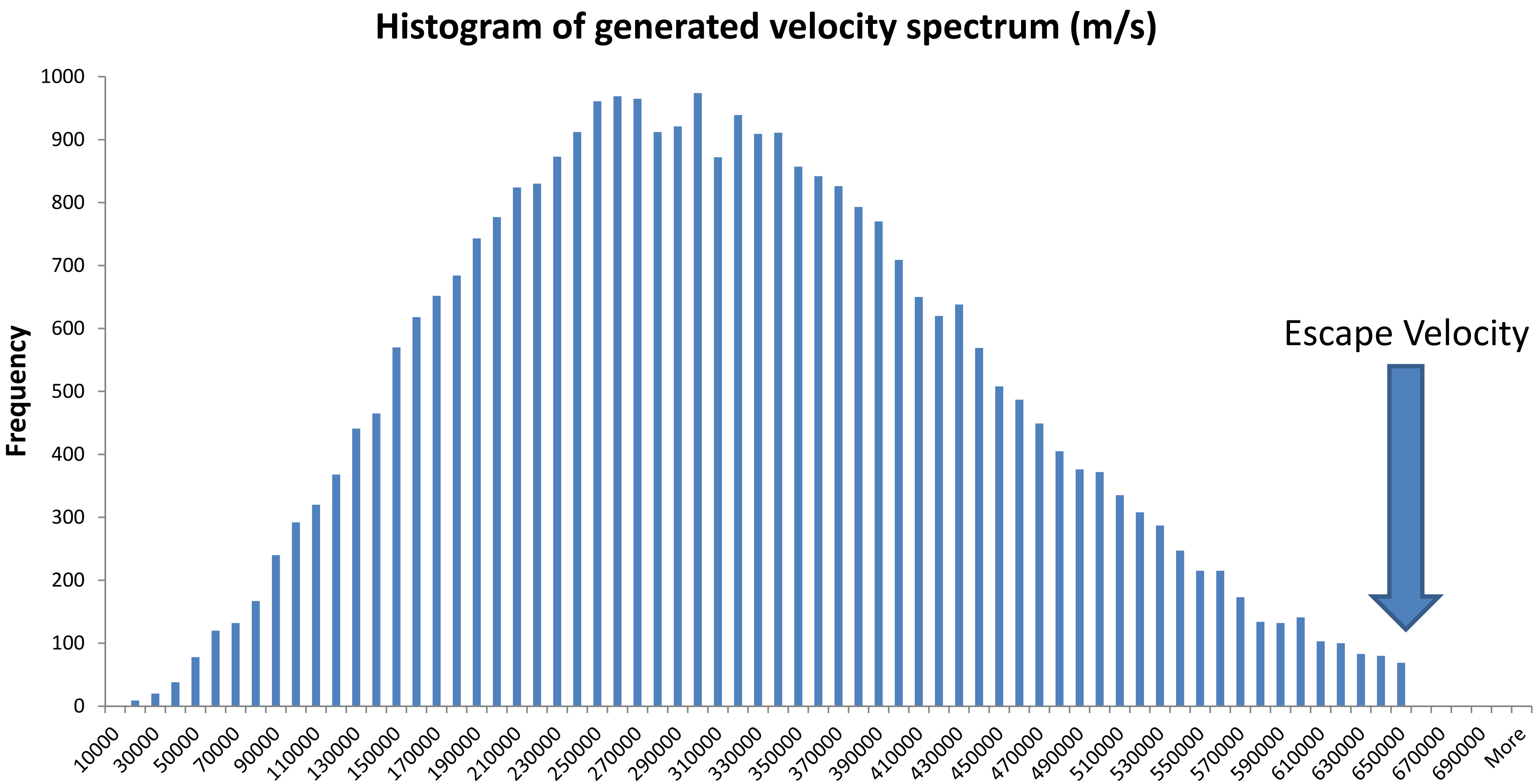
- Detector mass, density, dimensions, and runtime
- Amount of events detected
- Combined motion of Earth
  - Revolution, local standard of rest, peculiar solar system motion
- Galactic escape velocity
- Average density of dark matter

Provided by model

- WIMP composition
- WIMP masses
- Local density and temperature of fast DM
- Relative speed of DM
  - Jets, debris sheets, rotation velocity, rotation angle

Unknown

- Cross-sections
- Interacting force



Characteristics:

- Mirror gas cloud temperature of 20 MK (parameter)
- Cloud is moving with velocity $\vec{v}$ (parameter) relative to solar system
- Velocity of solar system + Earth $(\vec{v}_S = 230 \pm 30\ \mathrm{km/s})$

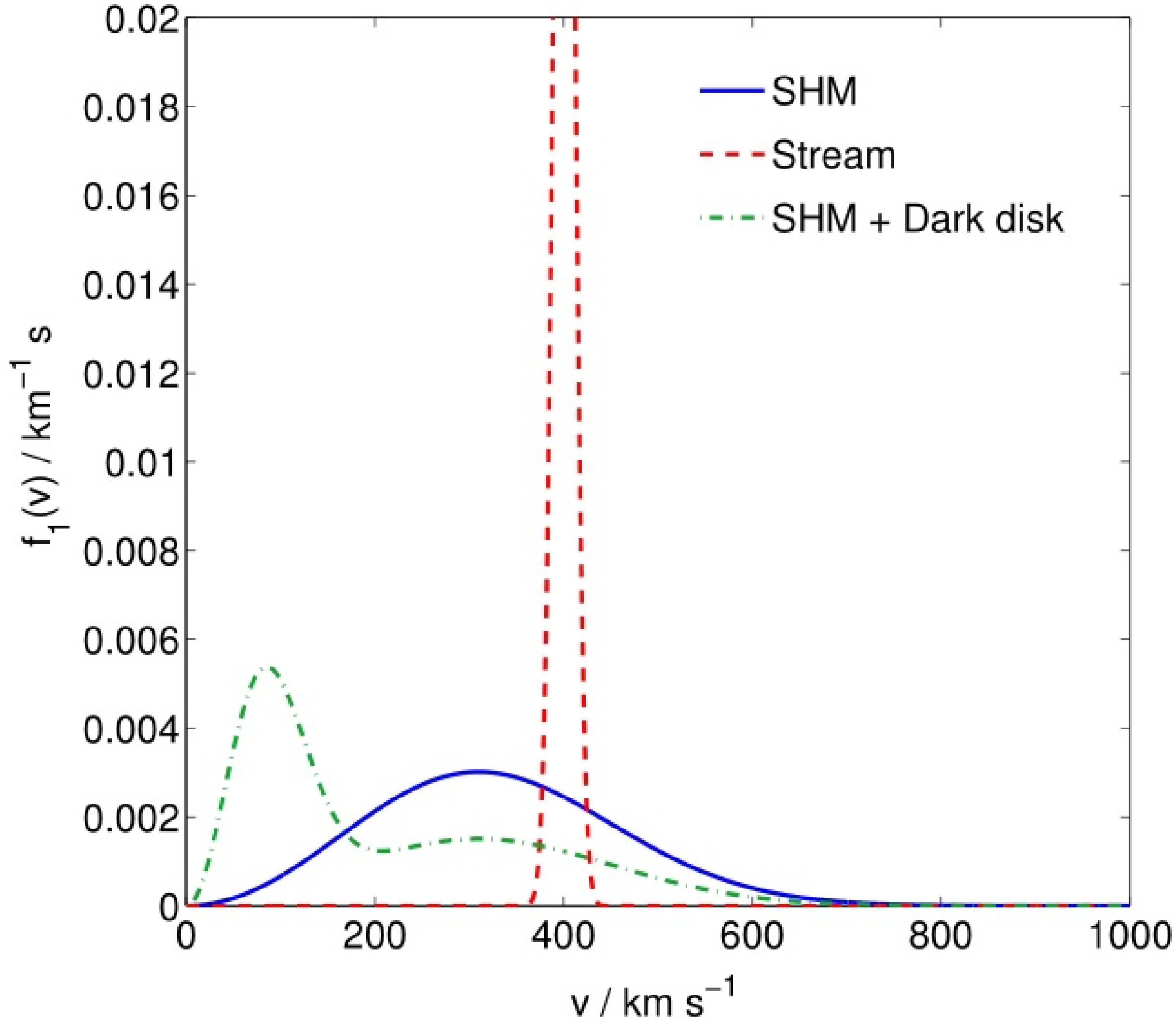
Feasibility of Cloud Types

Table 1: Components of the interstellar medium[2]

Component	Fractional Volume	Scale Height (pc)	Temperature (K)	Density (atoms/cm³)	State of hydrogen	Primary observational techniques
Molecular clouds	< 1%	80	10—20	10^2—10^6	molecular	Radio and infrared molecular emission and absorption lines
Cold Neutral Medium (CNM)	1—5%	100—300	50—100	20—50	neutral atomic	H I 21 cm line absorption
Warm Neutral Medium (WNM)	10—20%	300—400	6000—10000	0.2—0.5	neutral atomic	H I 21 cm line emission
Warm Ionized Medium (WIM)	20—50%	1000	8000	0.2—0.5	ionized	Hα emission and pulsar dispersion
H II regions	< 1%	70	8000	10^2—10^4	ionized	Hα emission and pulsar dispersion
Coronal gas Hot Ionized Medium (HIM)	30—70%	1000—3000	10^6—10^7	10^{-4}—10^{-2}	ionized (metals also highly ionized)	X-ray emission; absorption lines of highly ionized metals, primarily in the ultraviolet

Wikipedia, "Interstellar Medium"
K. Ferriere

Usual Velocity Distribution Models of DM



B. J. Kavanagh et al., arXiv:1308.6868v2

Interaction Overview

- Now that we have velocity…

$$\#\ \text{WIMP interactions} = \text{Flux} \cdot \text{P} \cdot \text{runtime} \cdot \text{Detector Area}$$

- Where integrated flux:

$$\text{Flux} = n_{DM} \cdot \int_0^{v_{esc}} f(v) \cdot v \cdot dv = n_{DM} \cdot \overline{v}$$

- And P = Probability of detection:

$$P = \sigma \cdot L \cdot n_T \qquad (\sigma = \sigma_{NN'} \cdot A_{DM}^2 \cdot A_T{}^2)$$

σ = WIMP-nucleus cross section $(\sigma_{NN'}$ is parameter$)$

L = Detector length

n_T = Detector number density

Interaction Overview

- We still must account for recoil spectrum and detector threshold:
- Check if recoil energy above threshold based on kinematics and scattering angle:

$$E_{recoil,lab} = E_{kin} \cdot r \cdot \frac{1 - \cos(\theta_{cms})}{2}$$

Where E_{kin} is the kinetic energy of the DM particle and the kinematic factor r:

$$r = 4 \cdot \frac{m_{DM} \cdot m_{Detec}}{(m_{DM} \cdot m_{Detec})^2}$$

Research Direction

- Within the mirror matter paradigm, we created a model of composition and velocity distribution of dark matter
- Our next step is to explain all positive and negative experimental observations for dark matter within the new paradigm
- Will it be possible to find parameters such as temperature , velocity, and cross-section that will explain these experiments' results?