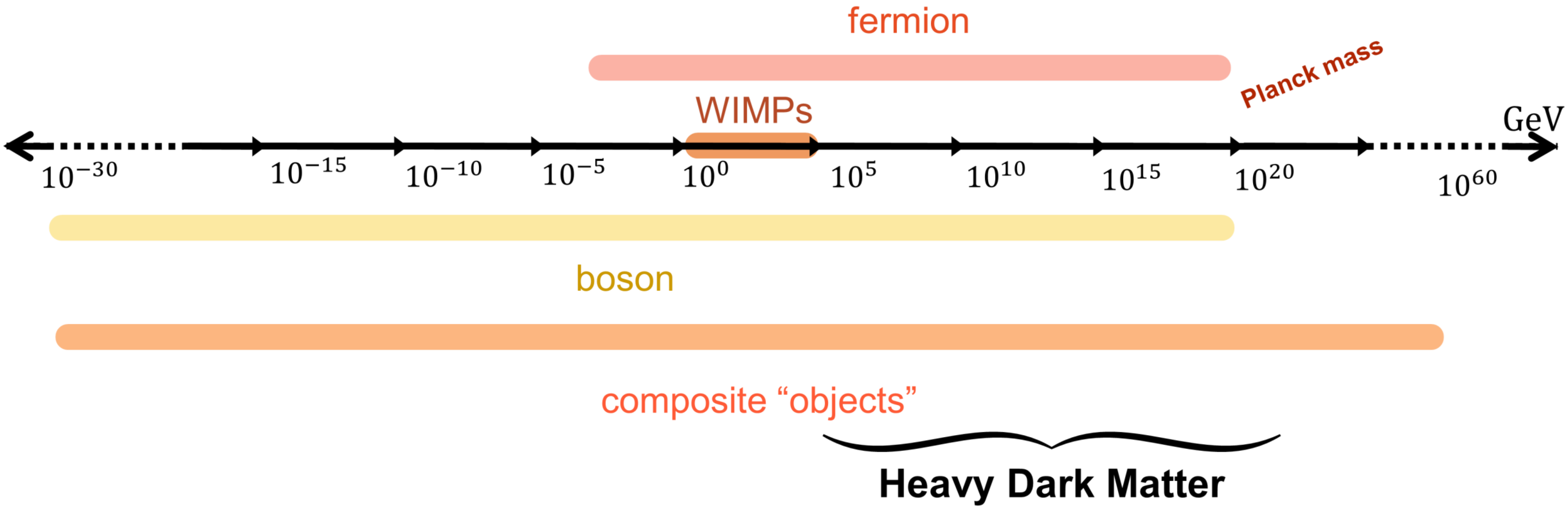
High Mass Dark Matter Searches With the High Speed LMC

ANDREW BUCHANAN

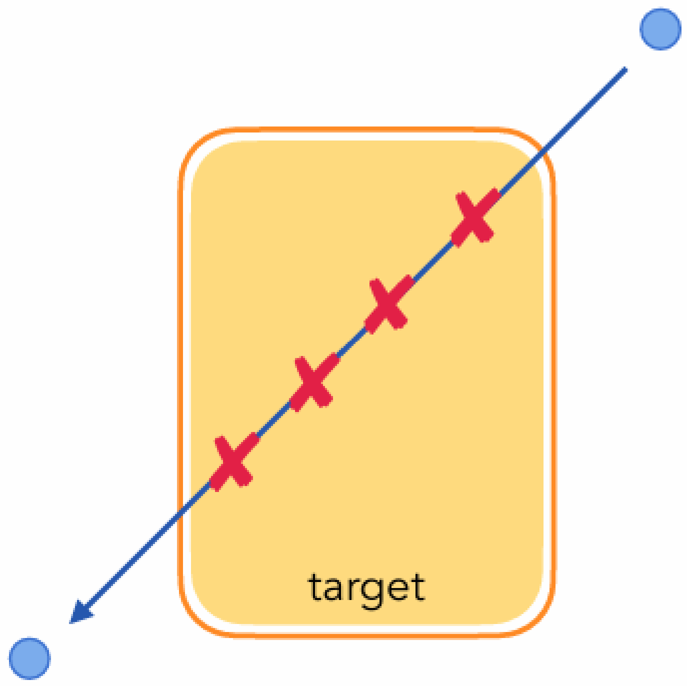
Heavy Dark Matter



Boukhtouchen '24

Why Heavy Dark Matter?

- Low number density
- Hard to see (that's why we haven't seen it!)
- Unconstrained even at high cross sections ($\sigma_{\chi,A} \lessapprox 10^{-8}\text{cm}^2$ at $m_\chi \sim m_{\text{PL}}$)
- Multiple scatters
- Want to minimize overburden!
- Much heavier than backgrounds
- Presents a unique frontier for direct dark matter searches



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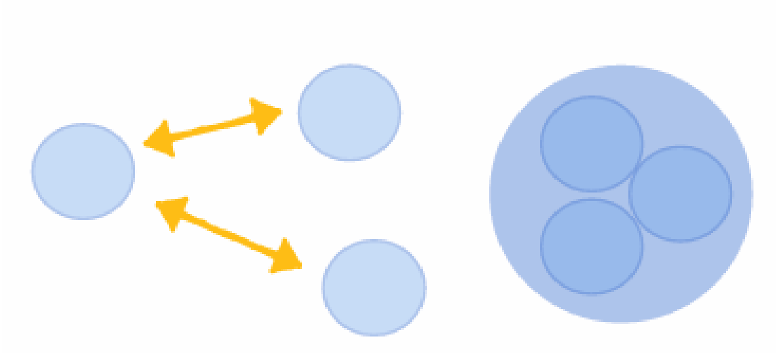
How Can Heavy Dark Matter Form?

Dark Nucleosynthesis



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How Can Heavy Dark Matter Form?

Production from False Vacuum Bubbles

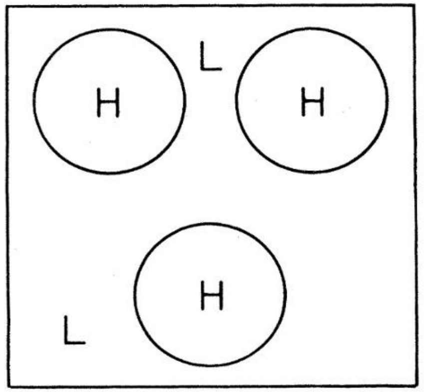
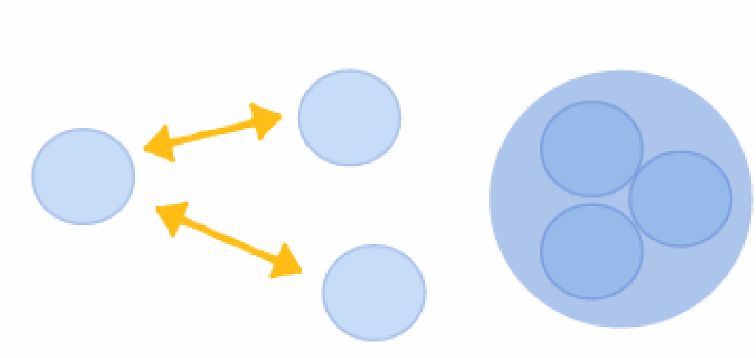


FIG. 3. Isolated shrinking bubbles of the high-temperature phase.

Witten ‘84

Dark Nucleosynthesis



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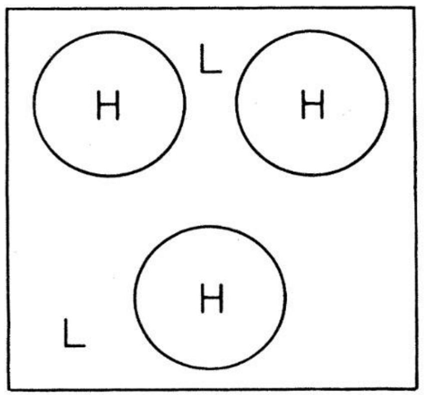

FIG. 3. Isolated shrinking bubbles of the high-temperature phase.

Witten '84

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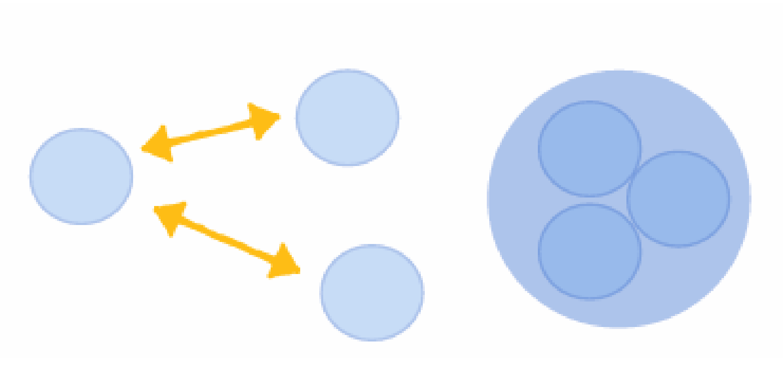

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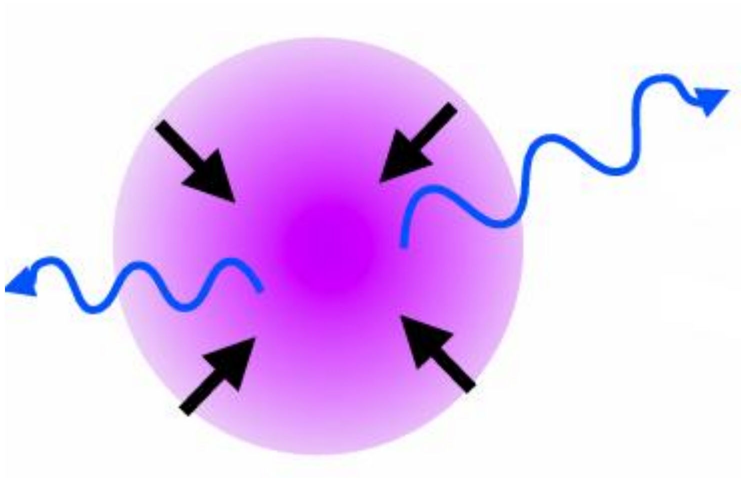
Dissipative Processes



Bramante et al '24

Heavy DM Interactions with Nuclei

PER-NUCLEON

- Realistic for large loosely-bound composite DM
- Each DM constituent interacts coherently with whole nucleus

$$\sigma_{\chi A} = A^2 \frac{\mu_{\chi A}^2}{\mu_{\chi n}^2} \sigma_{\chi n}$$

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$$\sigma_{\chi A} = A^2 \frac{\mu_{\chi A}^2}{\mu_{\chi n}^2} \sigma_{\chi n}$$

CONTACT

- Realistic for large single particles or tightly-bound composite DM
- DM interacts with each nuclei with the same strength

$$\sigma_{\chi A} = \sigma_C$$

Heavy DM and the High Velocity Tail

$$\frac{dE}{dx} = -\frac{2E}{m_\chi}\sum_{A\in M}\frac{\mu_{\chi A}^2}{m_A}n_A\sigma_{\chi A}$$

- For multiple scatters, energy deposition is proportional to initial energy $\propto v_0^2$

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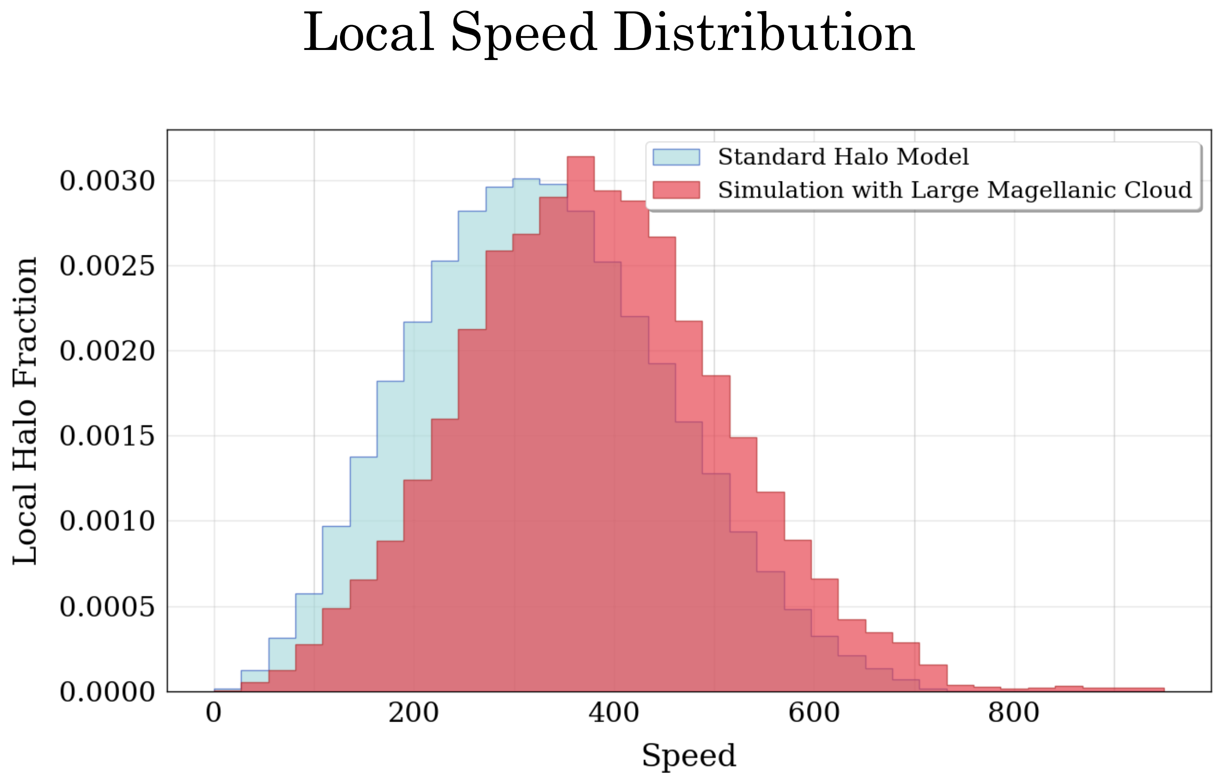
- For multiple scatters, energy deposition is proportional to initial energy $\propto v_0^2$
- Highly sensitive to high velocity tail of local DM Halo
- Standard Halo Model is cutoff at $v_{esc} = 503$ km/s
- Any other sources of high-speed dark matter?

The Large Magellanic Cloud

- Satellite galaxy of Milky Way with its own halo
- Use simulated velocities of MW LMC analogues from Auriga cosmological simulations



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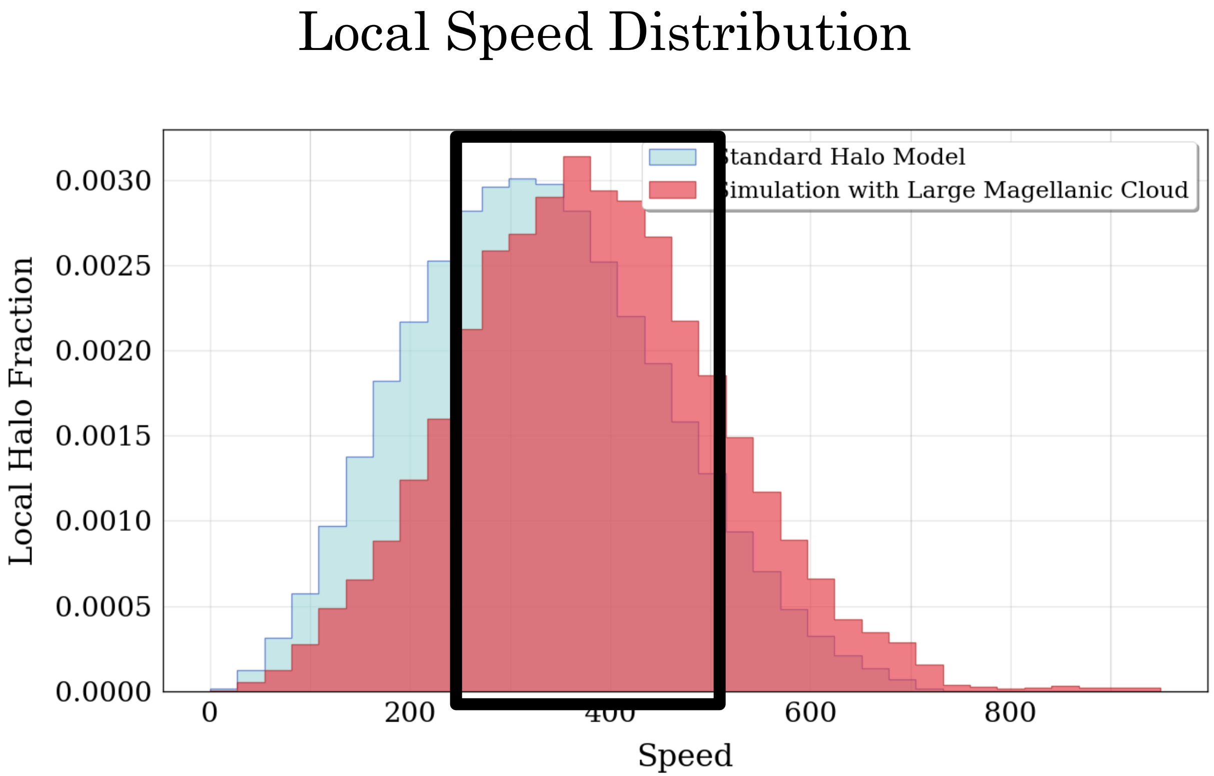

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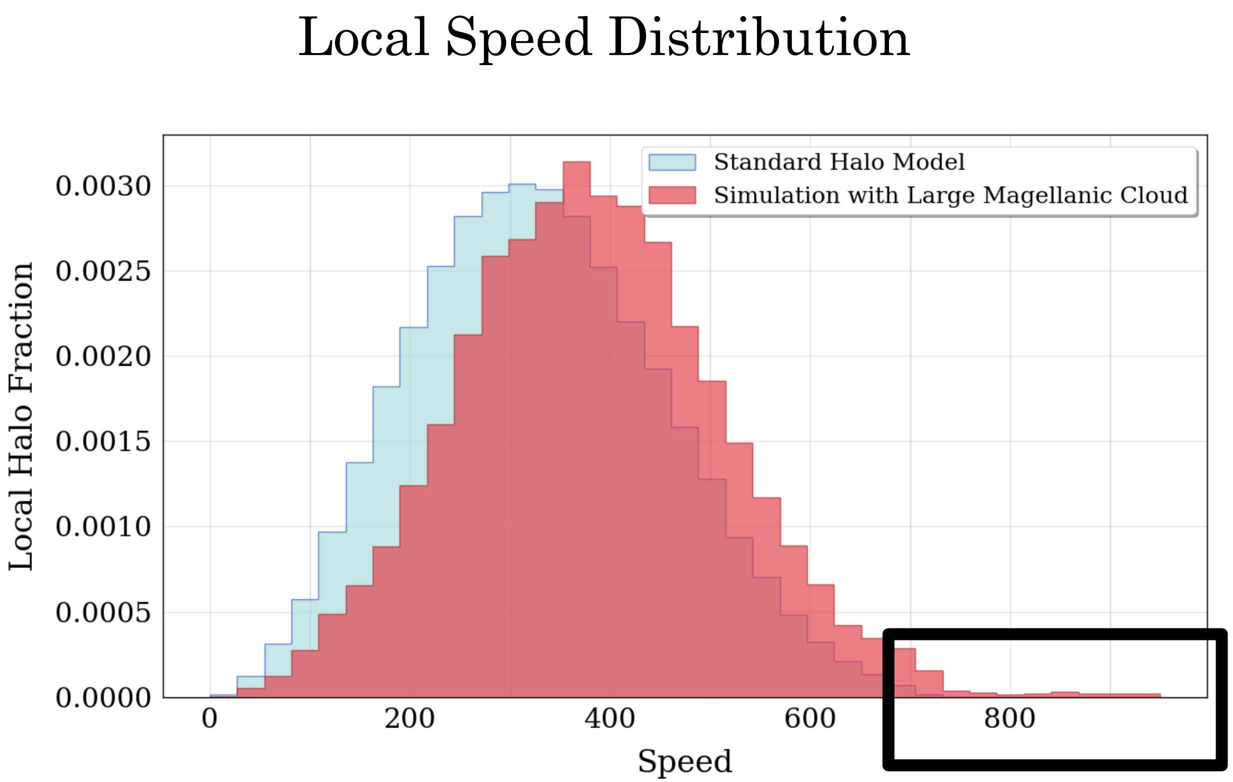
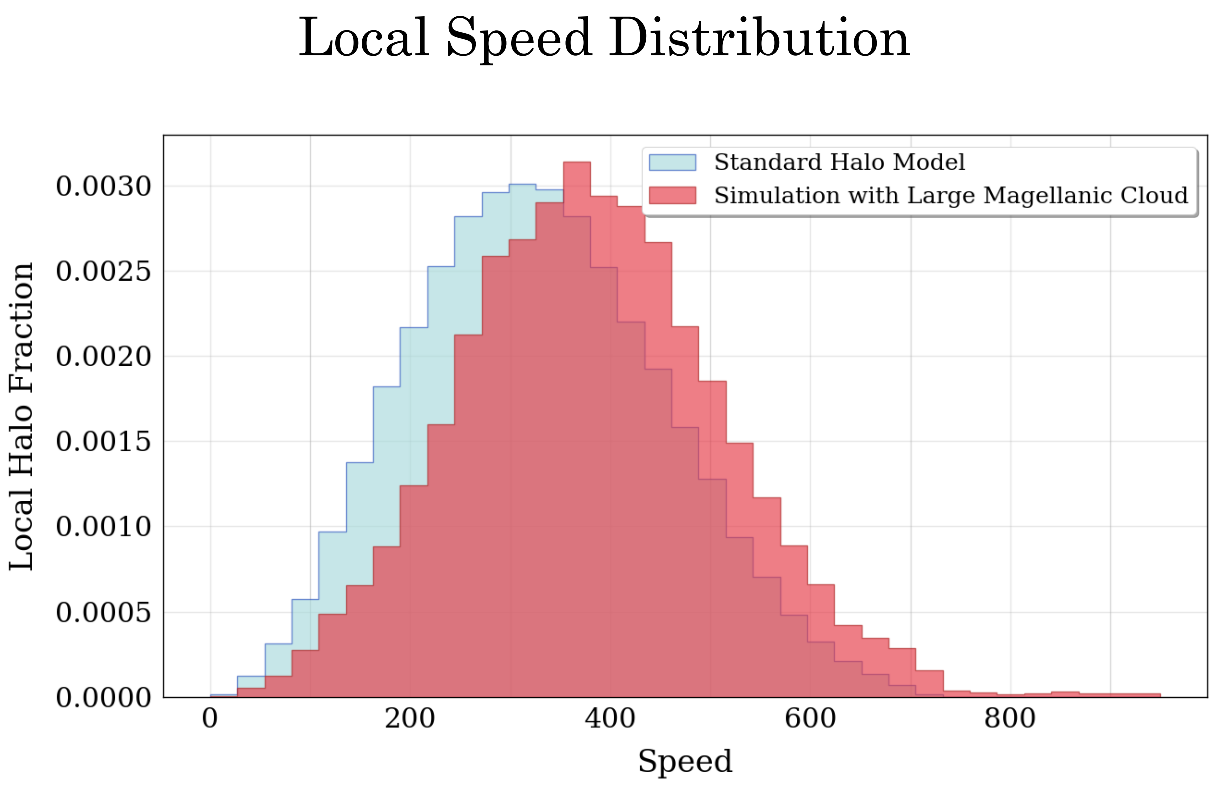
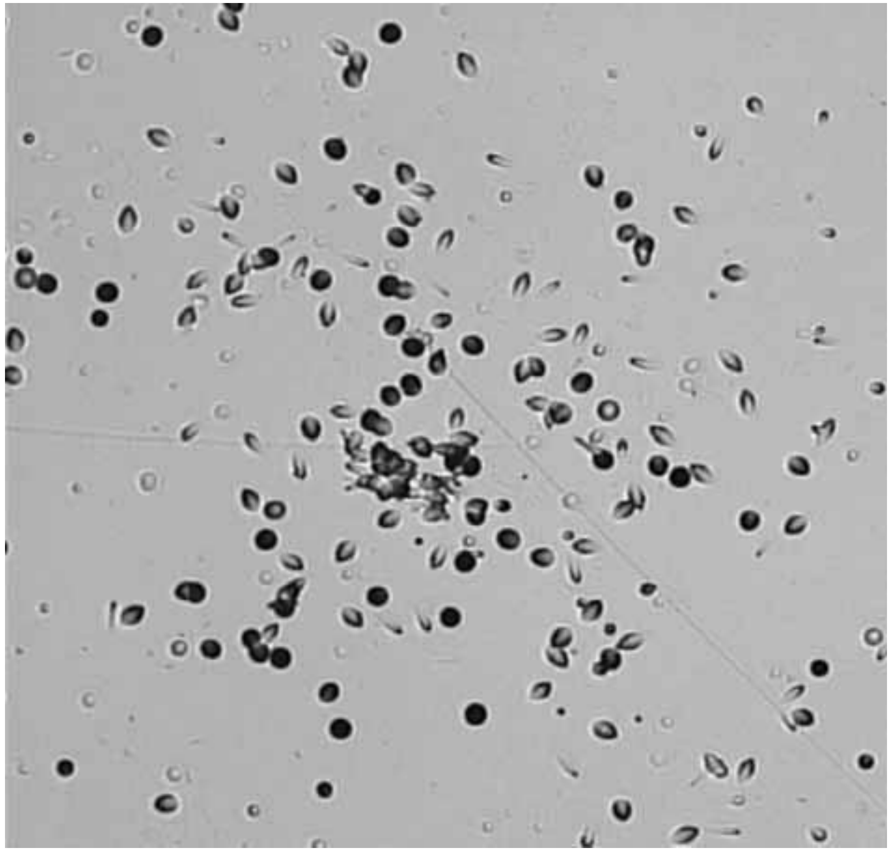


The Large Magellanic Cloud

- Satellite galaxy of Milky Way with its own halo
- Use simulated velocities of MW LMC analogues from Auriga cosmological simulations
- Shifts peak of speed distribution
- Increases high speed tail
- Can improve heavy DM bounds with strong velocity dependence
- Use plastic etch detectors as a case study



Plastic Etch Detectors



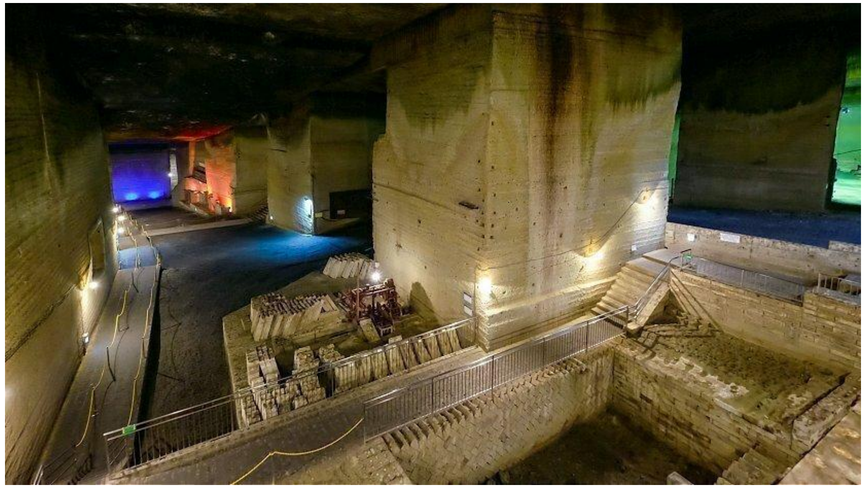
El-Badry et al ‘07

- Detector made of thin sheets of plastic
- Particle passing through the detector damages molecular bonds
- Damage becomes visible after an acid wash
- ~0.3 GeV/cm energy threshold
- Only very massive particles puncture completely through
- Cheap, easy, and discriminable background!

Plastic Etch Experiments

OHYA QUARRY

- Search for magnetic monopoles at the Ohya underground mine north of Tokyo in the 1990s



Ohya History Museum

Plastic Etch Experiments

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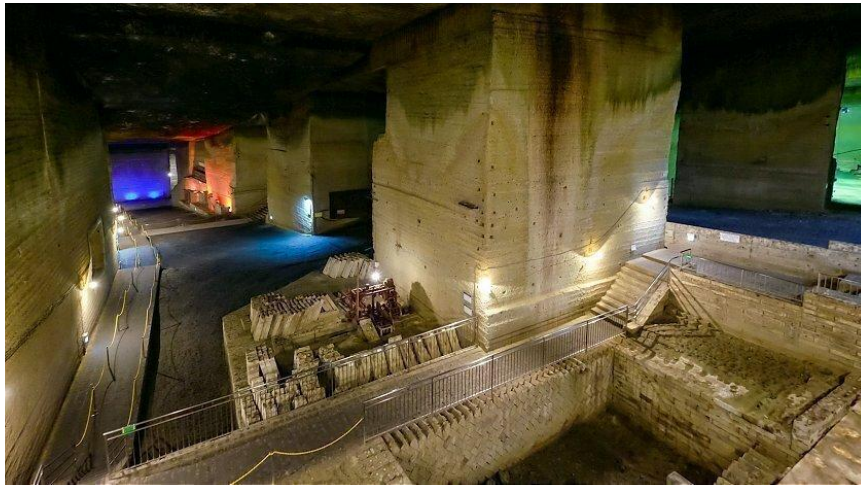


Ohya History Museum

SKYLAB

- Search for highly charged cosmic rays (Z > 60) at Skylab, the ISS predecessor in the 1970s

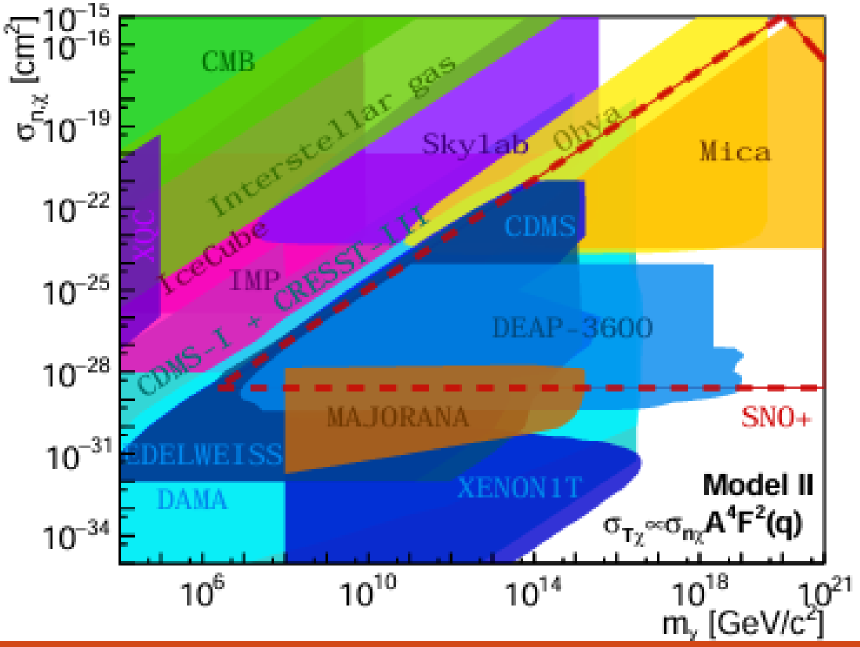
NASA

Both detected nothing above background.

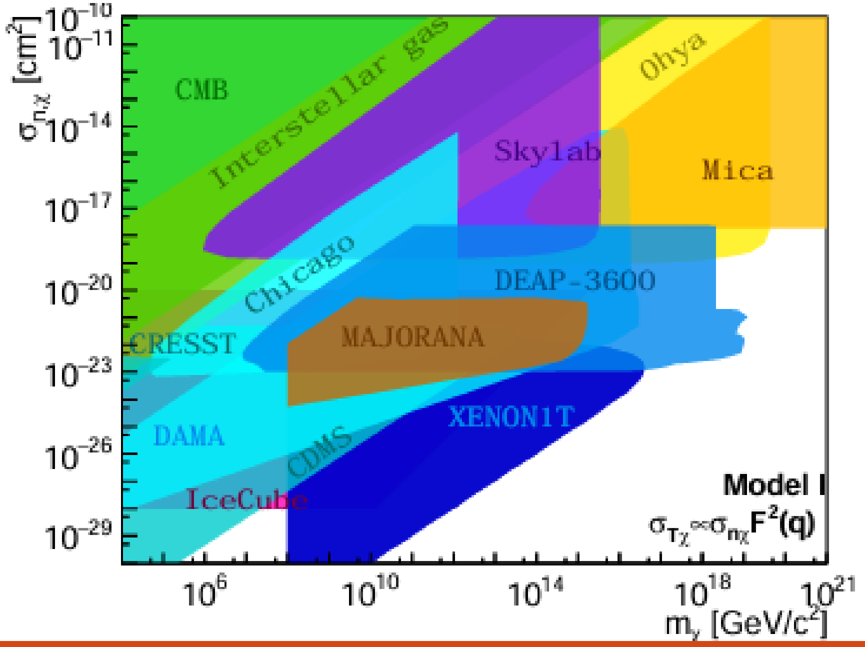
Existing Bounds

- In 2020, my colleagues used the Skylab and Ohya data to derive heavy DM bounds for contact and per-nucleon interactions (hep-ph 2012.13406)
- Useful test case for the effect of LMC

Per-Nucleon



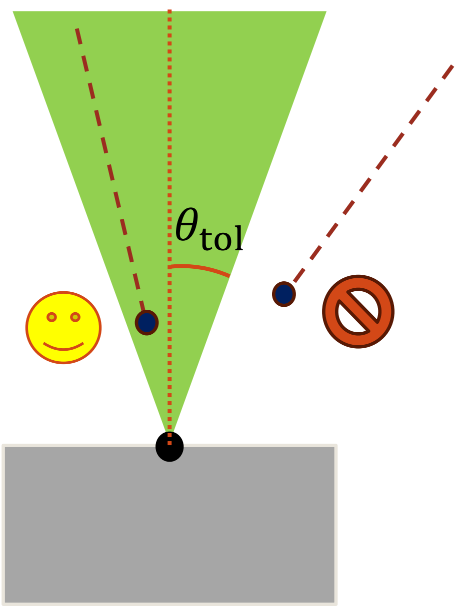
Contact



Snowmass2021

Directionality Matters

- Detector is planar and has acceptance angle θ_{tol}



$\theta_{\text{ohya}} = 18°$ $\theta_{\text{skylab}} = 60°$

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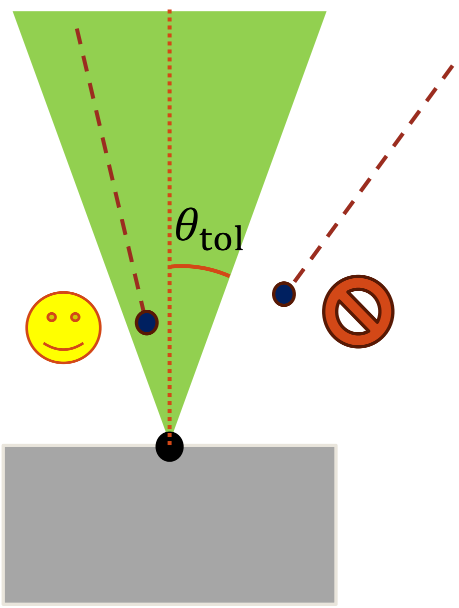
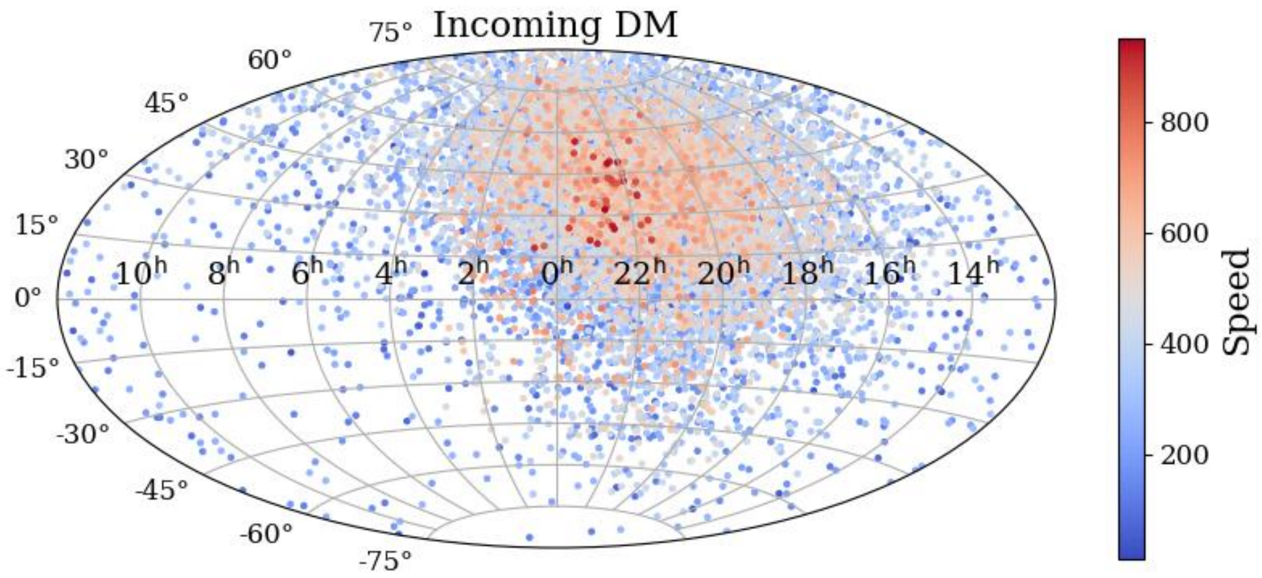


$\theta_{\text{ohya}} = 18°$ $\theta_{\text{skylab}} = 60°$

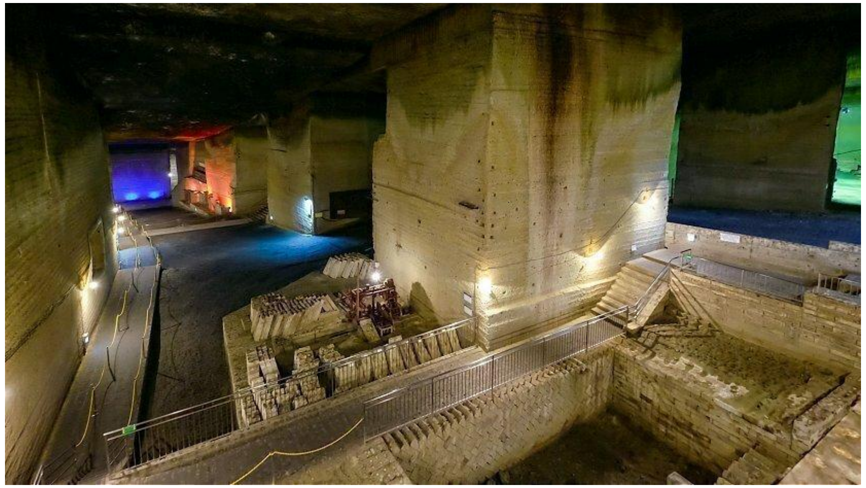
- DM Wind from Sun's motion
- LMC's effects are concentrated in a small region of the sky



Dealing with Detector Orientation

OHYA

- Daily oscillation in orientation with respect to solar system frame
- $T = 2.1$ yrs
- Average over sidereal day



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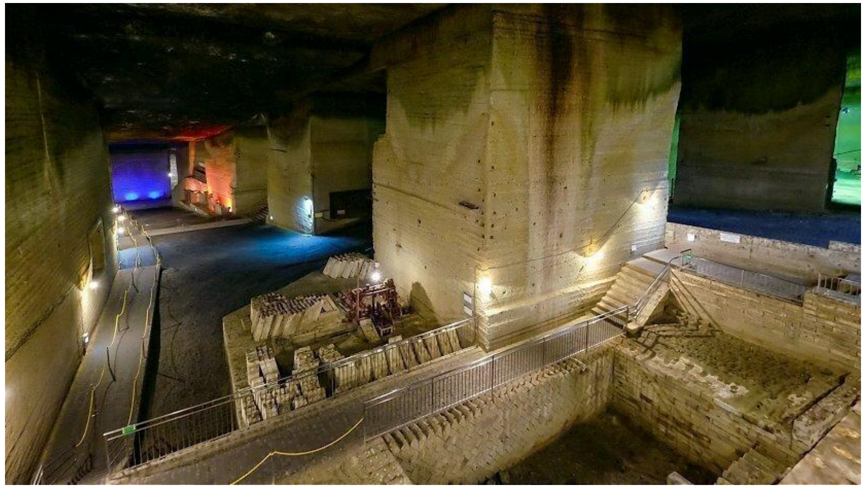
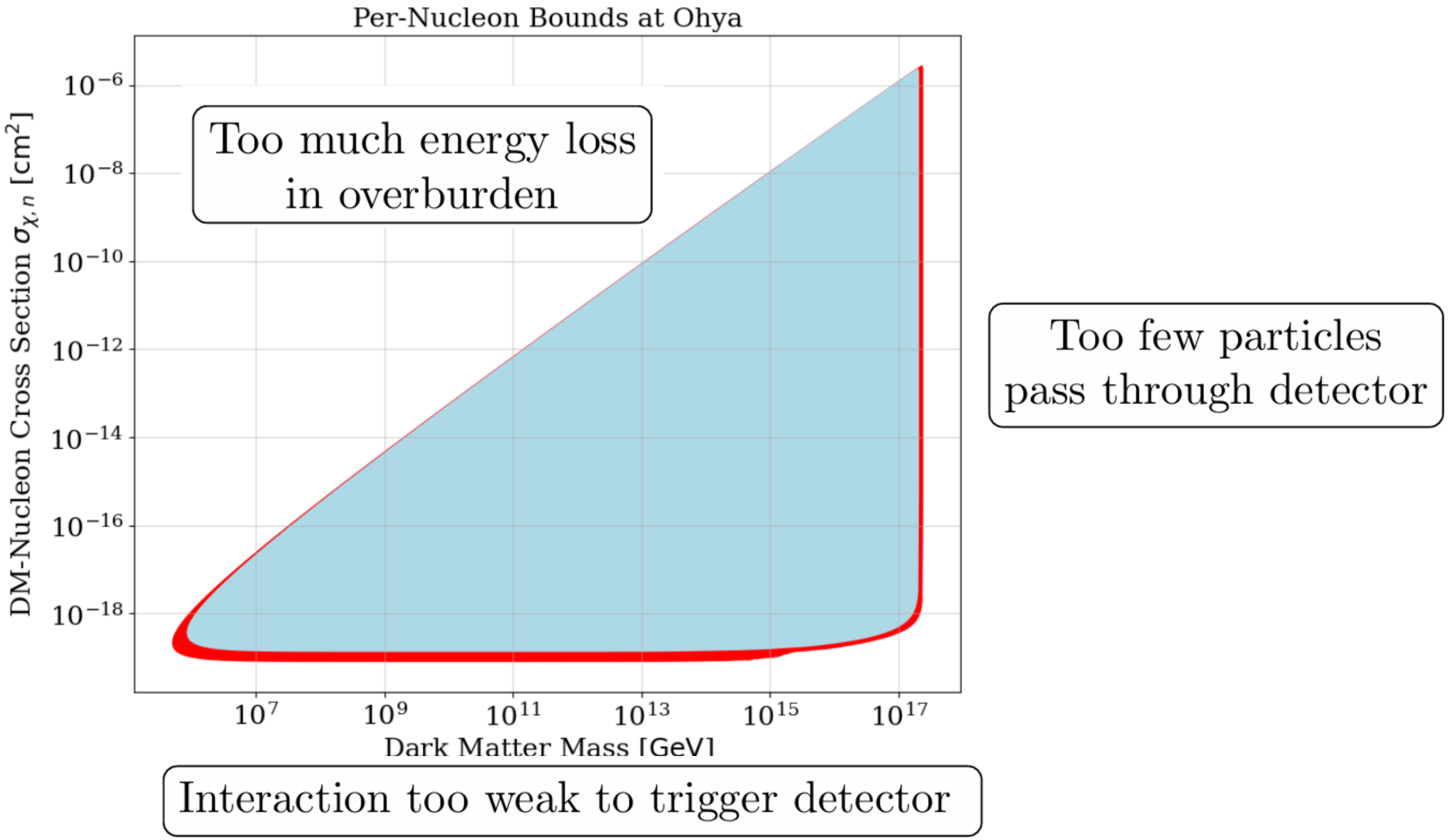


SKYLAB

- No record of Skylab's motion through sky (I tried!)
- Must assume random orientation over time
- Average over all orientations
- Reasonable since $\theta_{\text{tol}} = 60°$

Halo Model vs Halo + LMC



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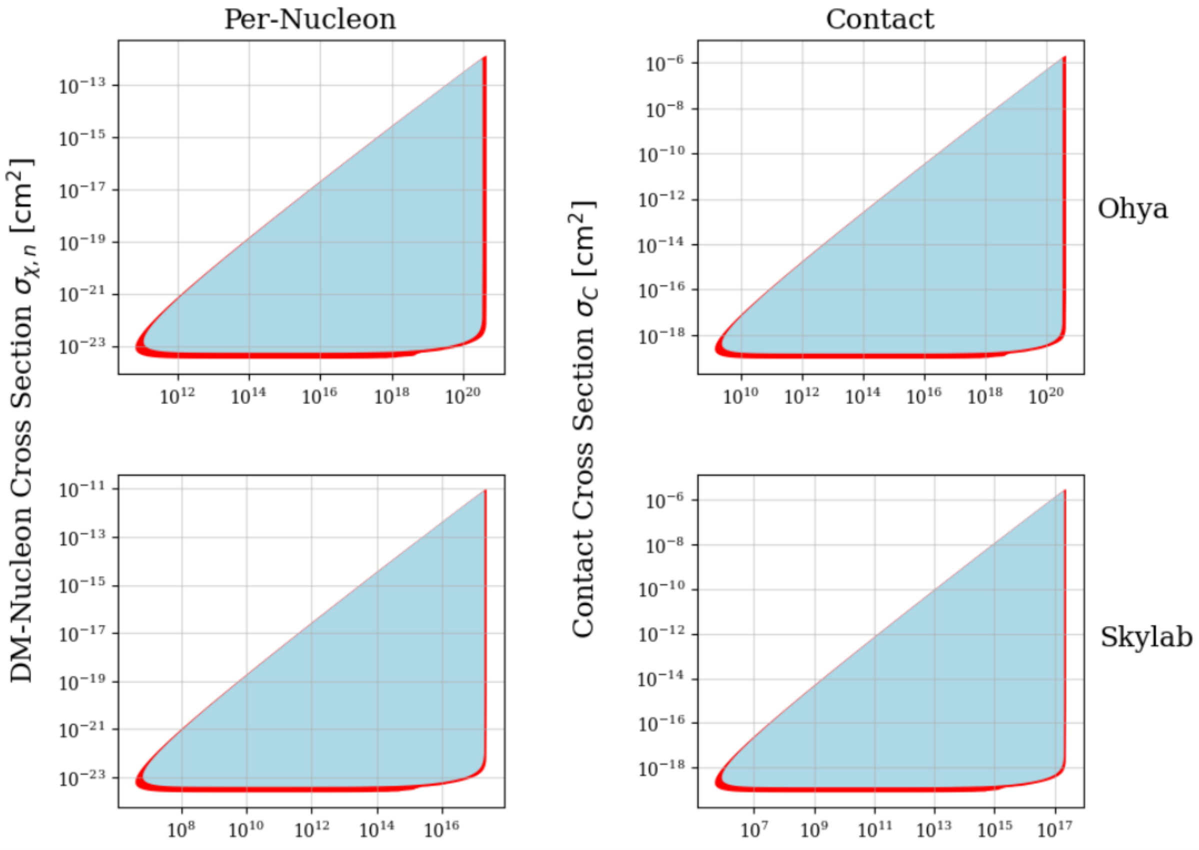
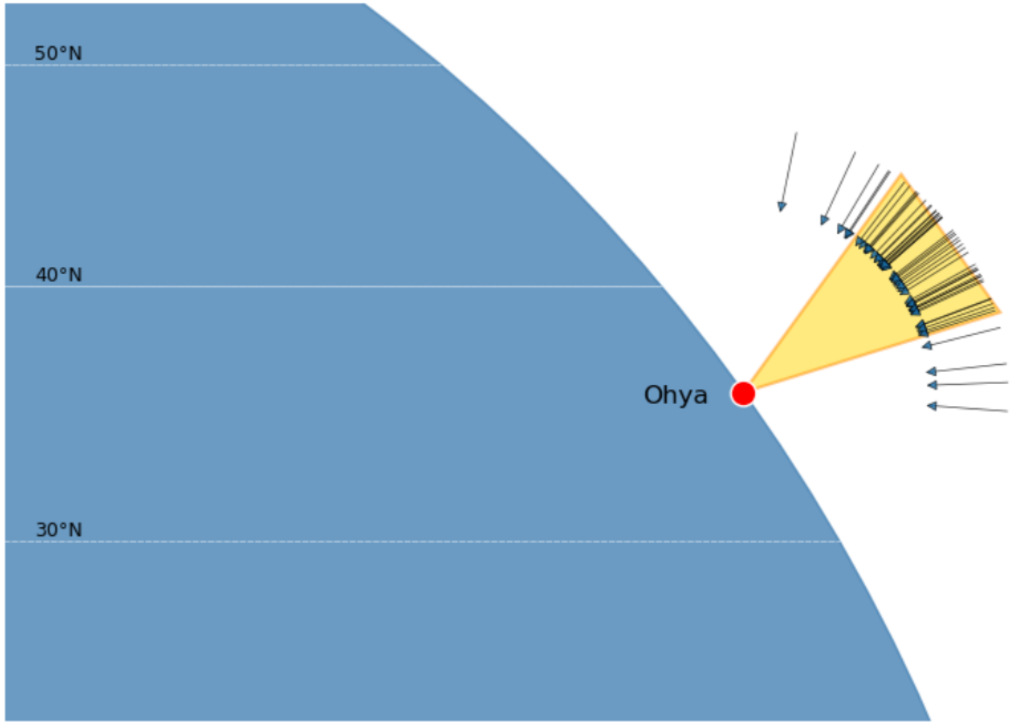


Catching the LMC Wind

- Ohya was well-positioned to catch many of the faster particles even with $\theta_{\mathrm{tol}} = 18°$
- Detector on the southern hemisphere would see a smaller flux
- In future, one can catch more at latitude ≈ 30 - 40° N

Particles faster than 750 km/s



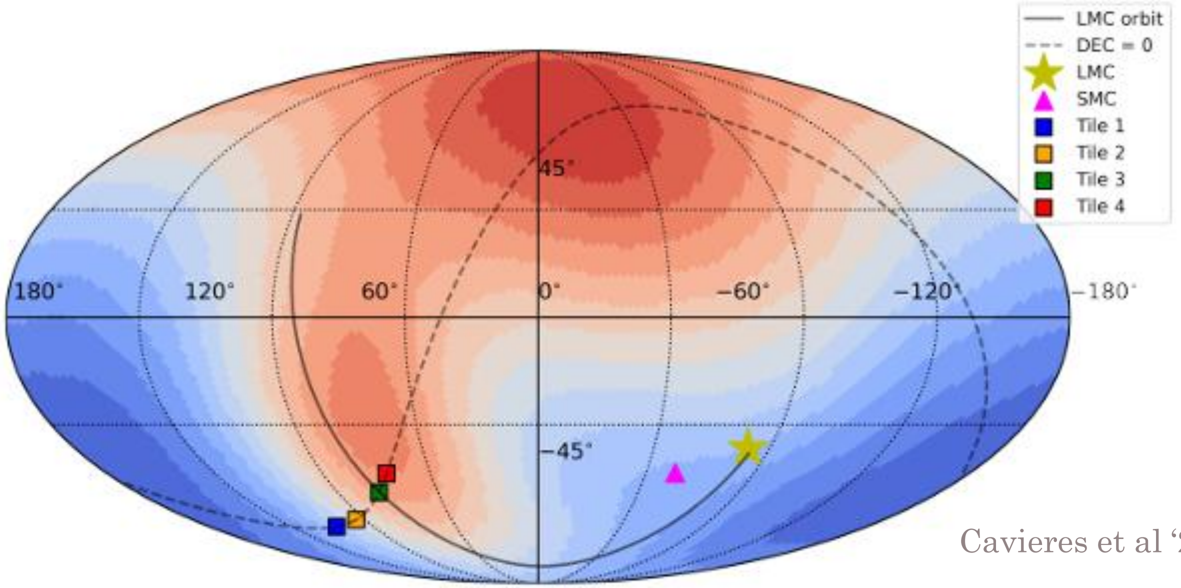
Conclusion

- Can improve bounds for heavy dark matter with fast dark matter due to the Large Magellanic Cloud
- Improvements can be applied straightforwardly to any multi-scattering heavy DM search
- Better bounds for free!
- Motivates more precise modelling of the effect of the LMC on the local dark matter distribution
- Choice of detector positioning can improve heavy DM detection prospects by a factor of 2!

Backup Slides

The LMC over Time

- LMC is in southern sky
- Incoming LMC DM is from northern direction
- Why?



Cavieres et al ‘25

Deriving The Bound

1. Simplify energy deposition rate

$$\frac{dE}{dx} = -\tilde{n}\sigma E$$

- $\tilde{n}$ depends on material + interaction type
- $\sigma = \sigma_C$ (contact) or $\sigma = \sigma_{\chi n}$ (per-nucleon)

2. No dark matter was observed. As a 90% confidence value, assume $N_c = -\ln(0.1) \approx 2.3$ events.
3. v_0 is the smallest speed above which N_c particles pass through the detector

$$N_c = N_{\geq v_0}(m_\chi)$$

4. Given a fixed m_χ, the bound on σ is

$$E'_{\rm th} \leq \frac{1}{2} m_\chi v_0^2 \tilde{n}_D \sigma \exp[-(x_D \tilde{n}_D + x_O \tilde{n}_O)\sigma]$$

- E'_{thr} - energy threshold per unit length,
- x_M, $\tilde{n}_M$ - length and ‘effective number density’ for overburden/detector

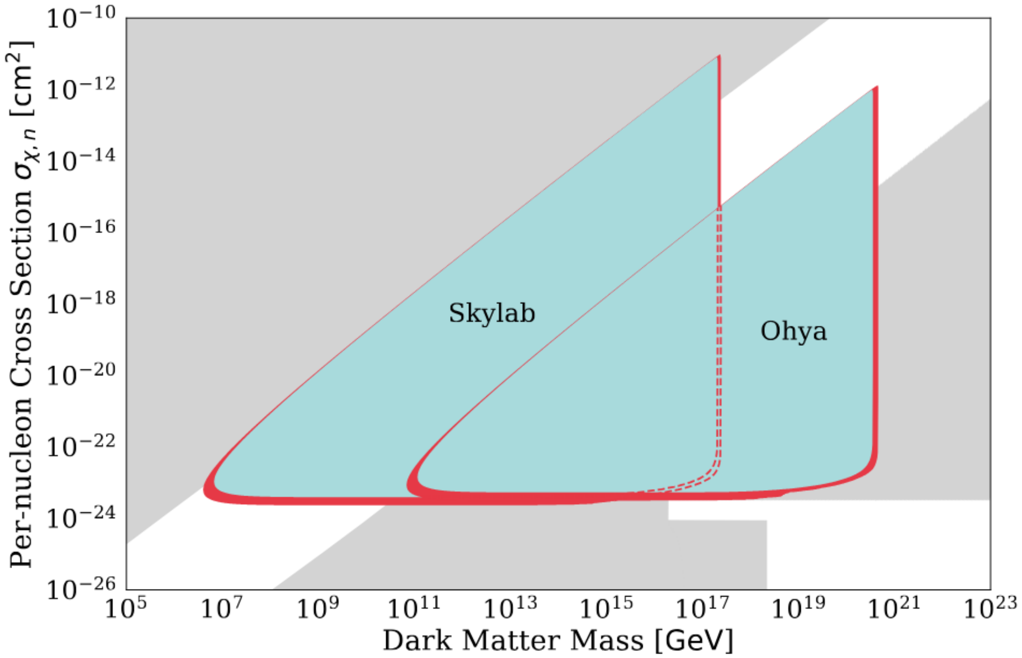
5. Solve in terms of Lambert-W function

$$\sigma_{\rm upper} = -\frac{1}{x_D \tilde{n}_D + x_O \tilde{n}_O} W_{-1}\left(-\frac{2(x_D \tilde{n}_D + x_O \tilde{n}_O)E'_{\rm th}}{\tilde{n}_D m_\chi v_0^2}\right)$$

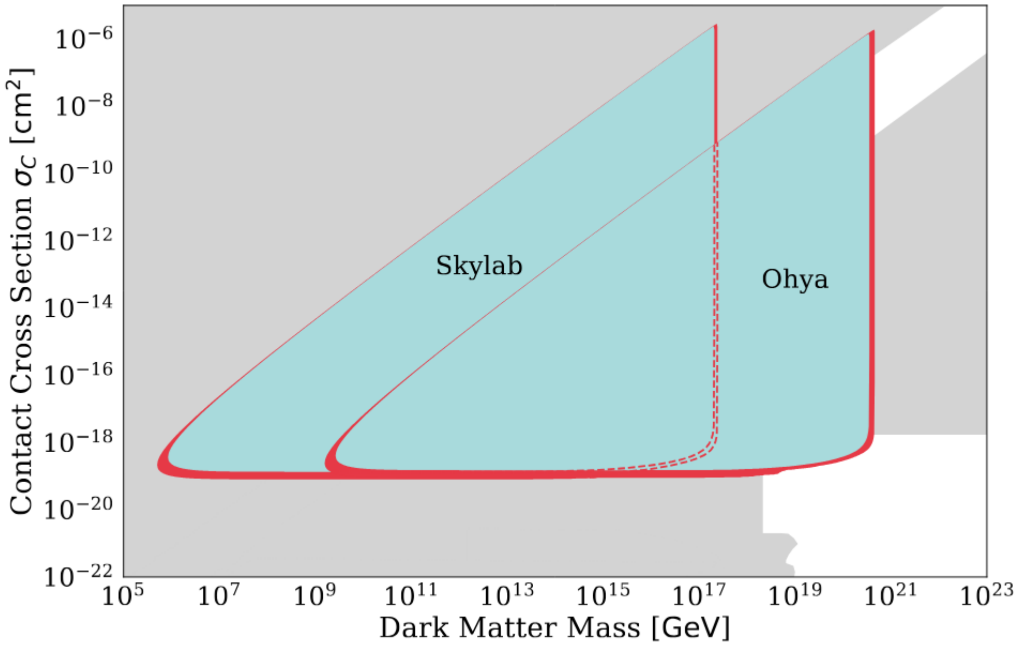
$$\sigma_{\rm lower} = -\frac{1}{x_D \tilde{n}_D + x_O \tilde{n}_O} W_{0}\left(-\frac{2(x_D \tilde{n}_D + x_O \tilde{n}_O)E'_{\rm th}}{\tilde{n}_D m_\chi v_0^2}\right)$$

Comparison with Other Bounds

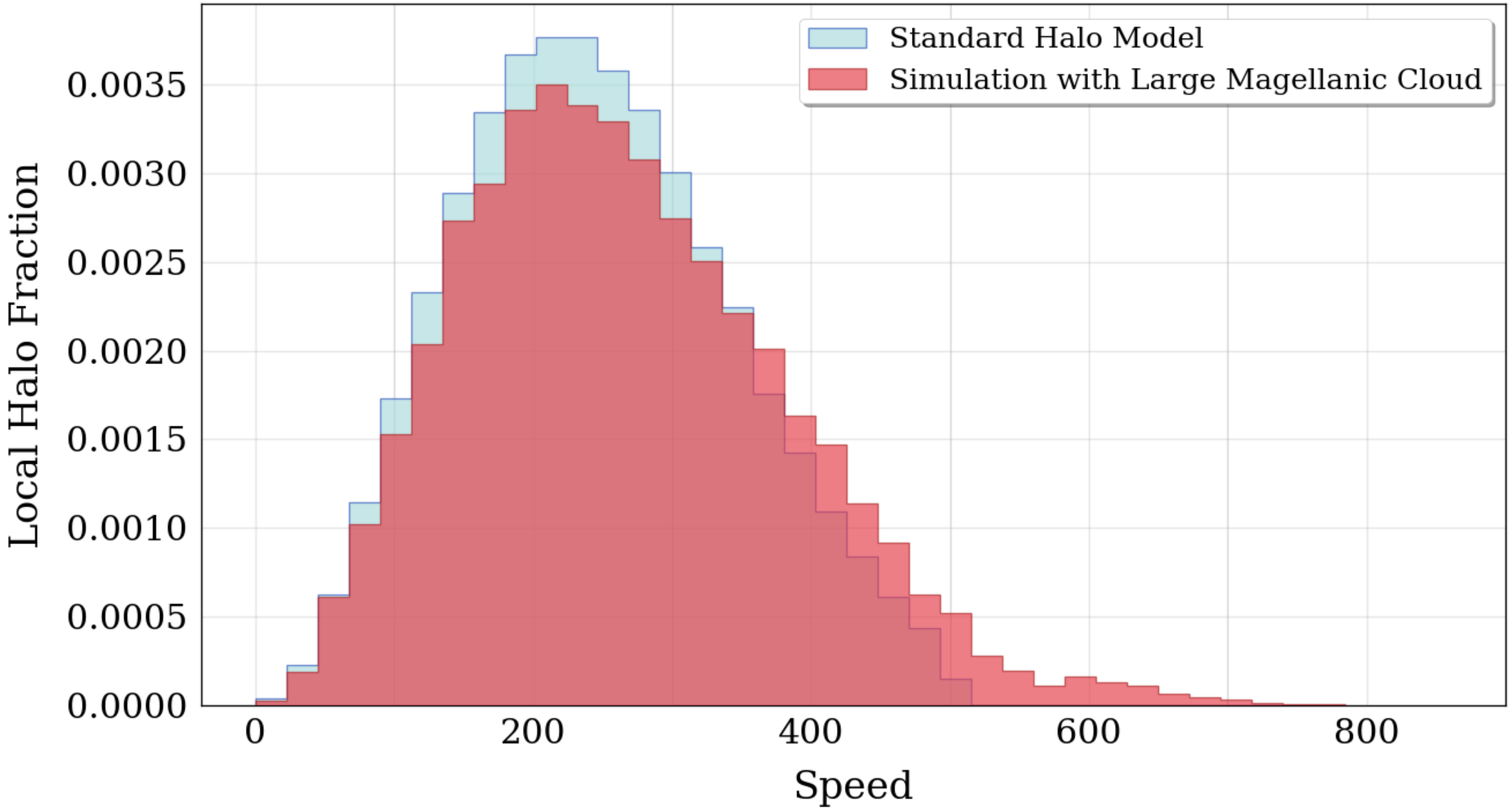
PER-NUCLEON



CONTACT



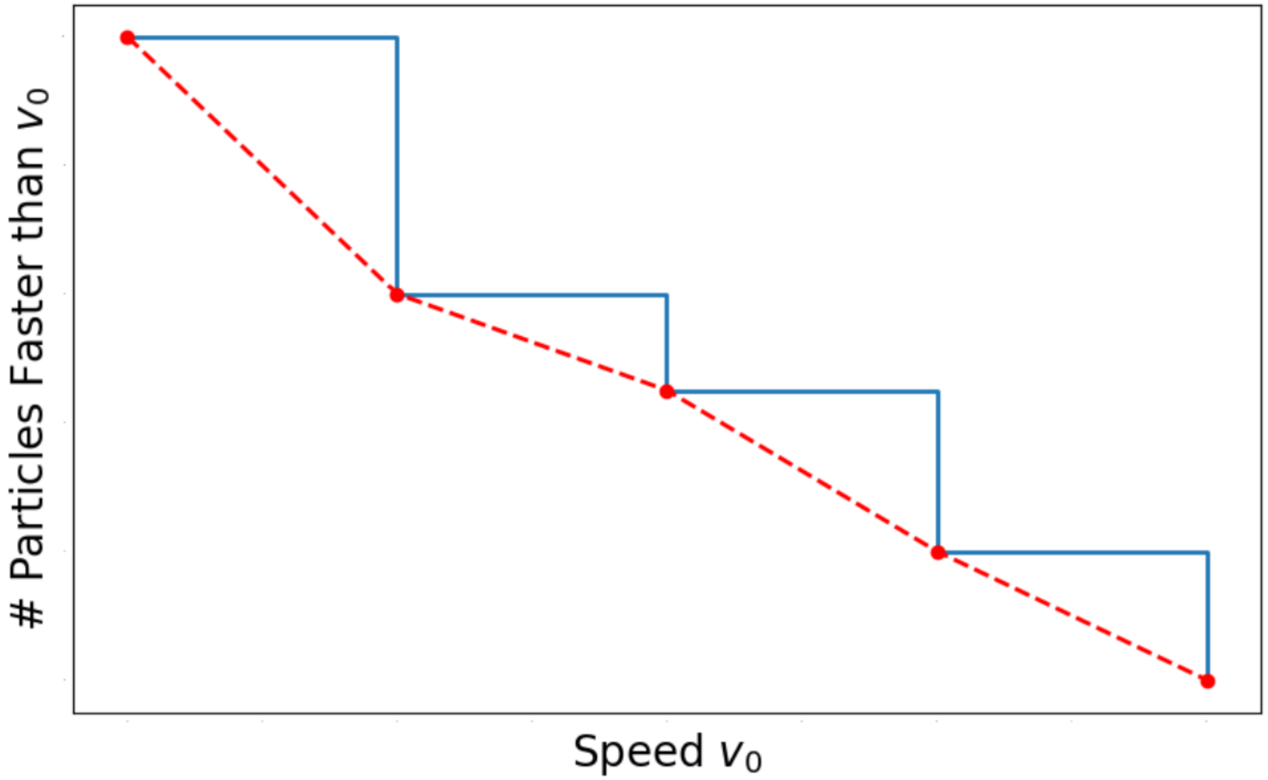
Galactic Speed Distribution



Handling Simulated Results

- Only ≈ 50 data points > 750 km/s in the simulation compared to ≈12600 total
- Robust statistics on the three-dimensional LMC velocity distribution not feasible
- Must interpolate number of particles between discrete data sets

$$N_{\geq v_0}(m_\chi) = \frac{AT\rho_\chi}{m_\chi} \int d^3\mathbf{v}\ f(\mathbf{v}) \left(-\frac{1}{T} \int_0^T dt\ \ \hat{n}(t) \cdot \mathbf{v}\ \epsilon(\hat{v}, t) \right)$$



Computing the Particle Number

- Rewrite flux through a planar detector above a speed v_0

$$N_{\geq v_0}(m_\chi) = \frac{AT\rho_\chi}{m_\chi} \int_{|\mathbf{v}|\geq v_0} d^3\mathbf{v}\ f(\mathbf{v}) \left(-\frac{1}{T} \int_0^T dt\ \ \hat{n}(t) \cdot \mathbf{v}\ \epsilon(\hat{v}, t) \right)$$

$f(\mathbf{v})$ – DM velocity distribution
A - Detector Area
T - Detector Time
ρ_χ - DM Density
m_χ - DM Mass
$\hat{n}$ - Detector Normal Vector
ϵ - Detector Efficiency

$$\epsilon(\hat{v}, t) = \begin{cases} 1 & \text{if } \hat{n}(t) \cdot \hat{v} \leq -\cos(\theta_{\text{tol}}) \\ 0 & \text{if } \hat{n}(t) \cdot \hat{v} > -\cos(\theta_{\text{tol}}) \end{cases}$$