Investigations of Dark Matter Using Cosmological Simulation

Thesis defense

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Johns Hopkins University

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Background of Dark Matter

Why Dark Matter?

- Explain the rotation curve of spiral galaxy (Historically).

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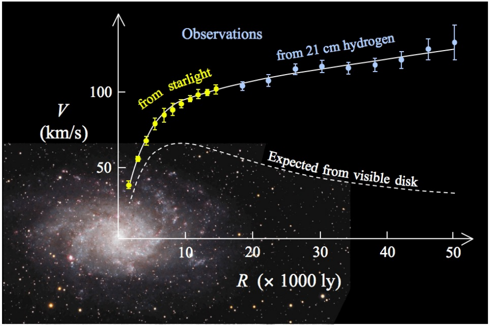

Figure 1: M33 rotation curve (Corbelli et al, 00).

Why Dark Matter?

- Explain the rotation curve of spiral galaxy (Historically).

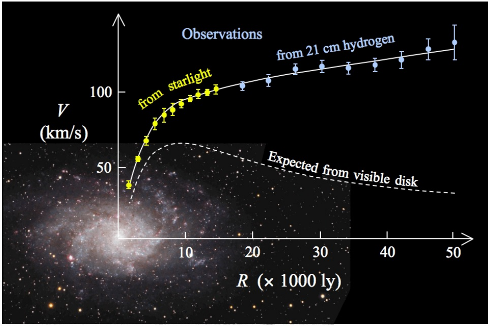

Figure 1: M33 rotation curve (Corbelli et al, 00).

Implication:

- Large portion of the matter content is invisible.

Other Evidences

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- x-ray observation + gravitational lensing.

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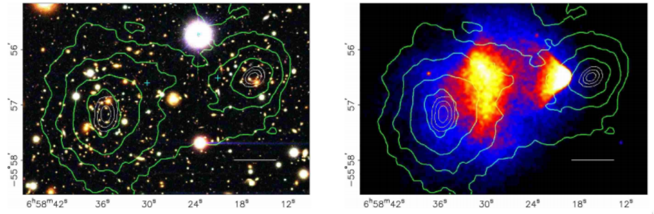

Figure 2: Bullet Cluster (Clowe et al, 06)

Other Evidences

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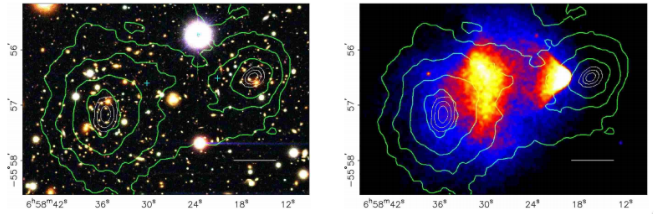

Figure 2: Bullet Cluster (Clowe et al, 06)

Larger scales also need Dark Matter.

Other Evidences

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- Cosmic Microwave Background (CMB).

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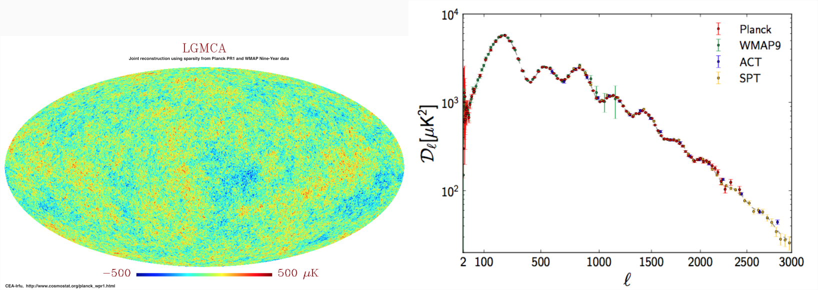

Figure 3: CMB and power spectrum.

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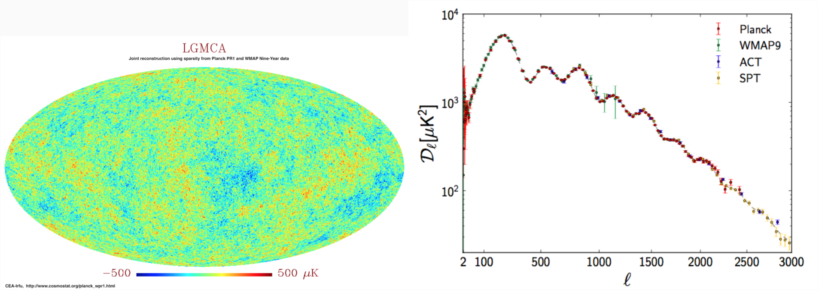

Figure 3: CMB and power spectrum.

The alternating peak heights require Dark Matter as well.

Large Scale Structure

Large Scale Structure

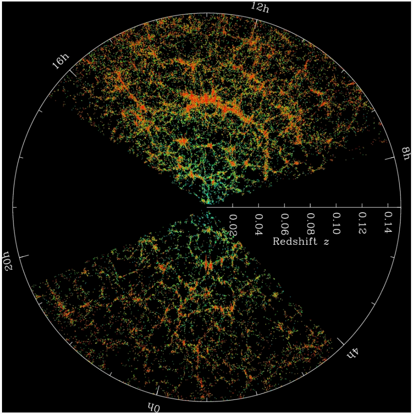

Figure 4: SDSS: Large Scale Structure.

Large Scale Structure Formation

Large Scale Structure Formation

- ΛCDM model: so far the most successful model.

Large Scale Structure Formation

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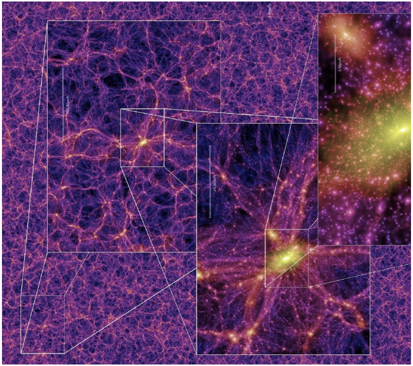


Figure 5: Millenium Simulation.

- ΛCDM model: so far the most successful model.

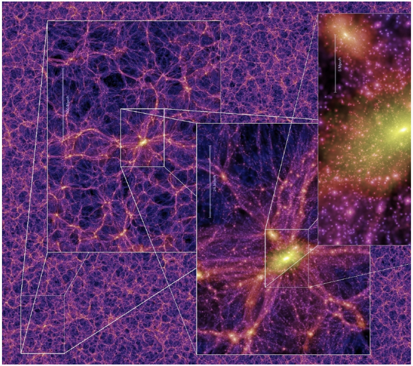


Figure 5: Millenium Simulation.

Structure formed by gravity.

Universe Content

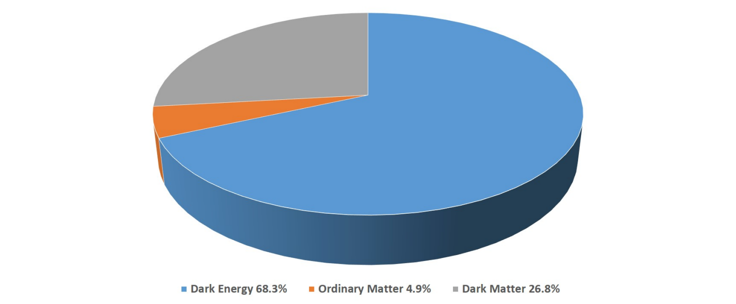
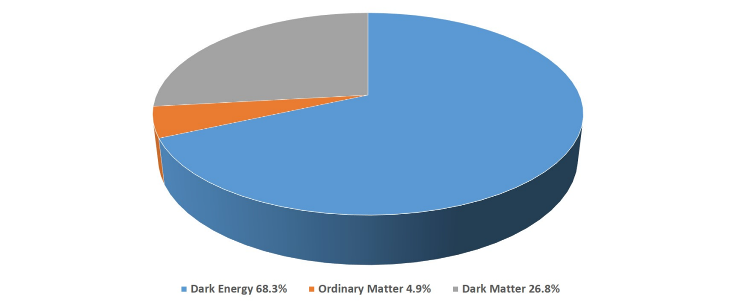


Figure 6: Universe Energy Content: Plank Data.

Universe Content



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$\geq 95\%$ of the universe is invisible.

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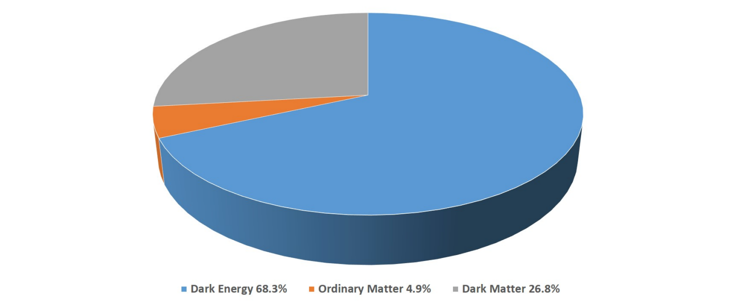

Figure 6: Universe Energy Content: Plank Data.

$\geq 95\%$ of the universe is invisible. Dark Matter is about 85% of all the matter in the universe.

Candidates for Dark Matter

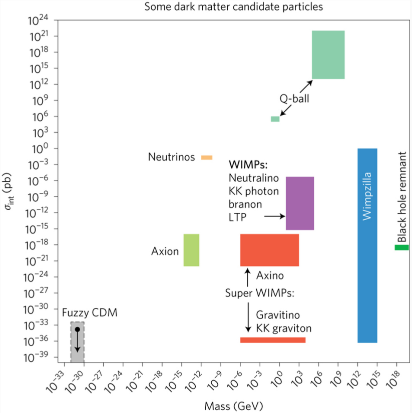

Figure 7: Dark Matter Candidates

Candidates for Dark Matter

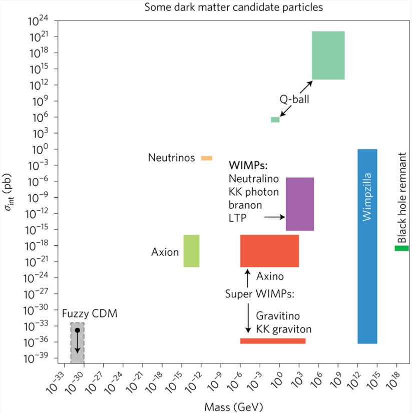

Figure 7: Dark Matter Candidates

Almost 100 orders of magnitude in mass.

Direct Detection Methods

Direct Detection Methods

- Two Major Experimental Designs

Direct Detection Methods

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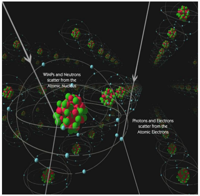

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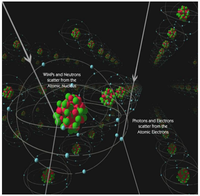

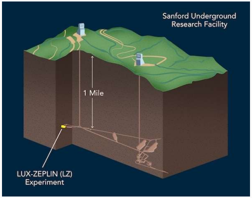

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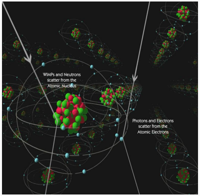

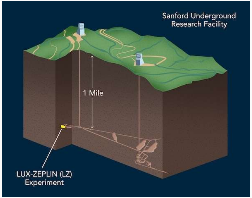

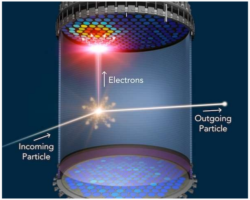

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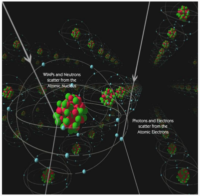

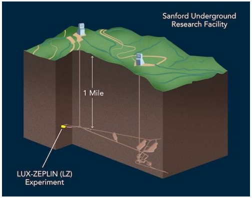

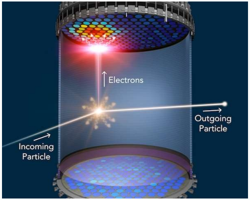

Figure 8: Nucleon Recoil Reaction: LUX, 10 tons of liquid xenon.

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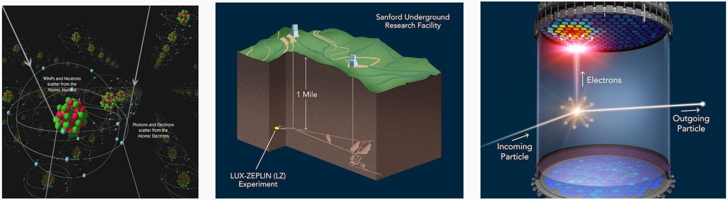

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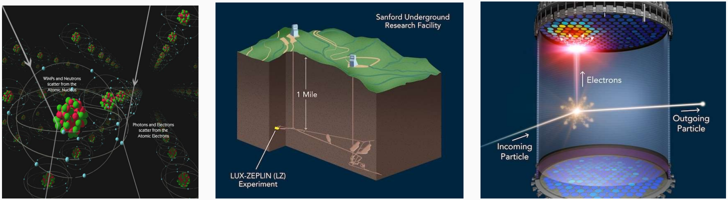

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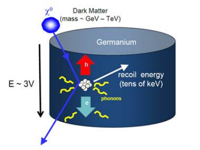

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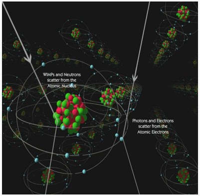

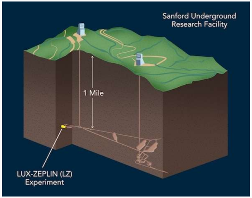

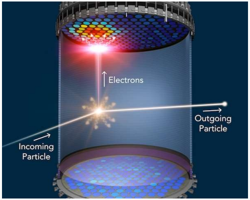

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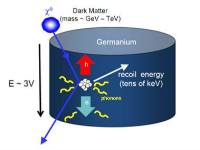

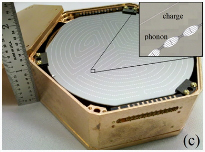

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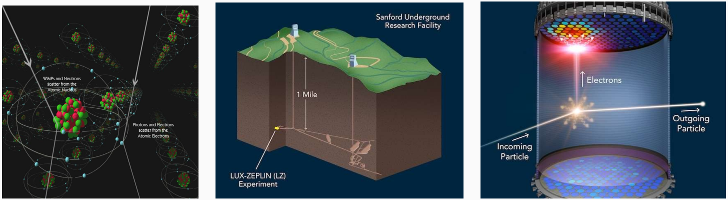

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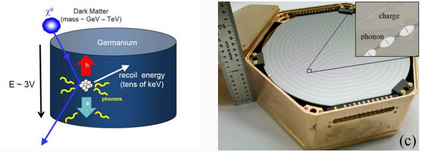
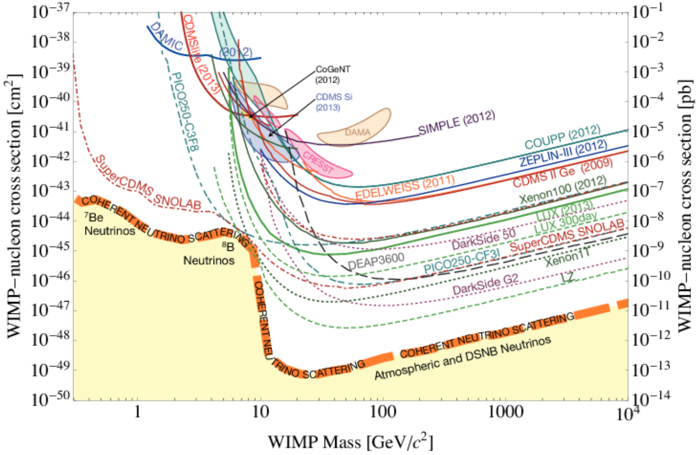


Figure 9: Cryogenic Dark Matter Search (CDMS)

Direct Detection Methods



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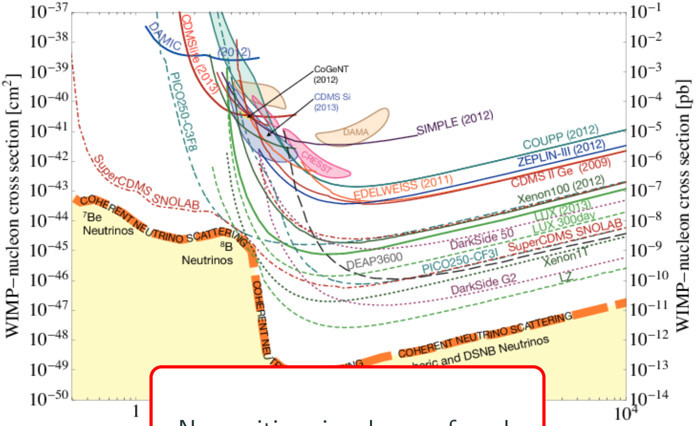
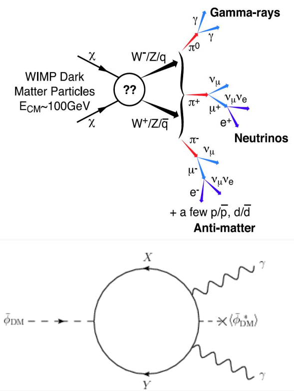


No positive signals ever found.

Figure 9: Cryogenic Dark Matter Search (CDMS)

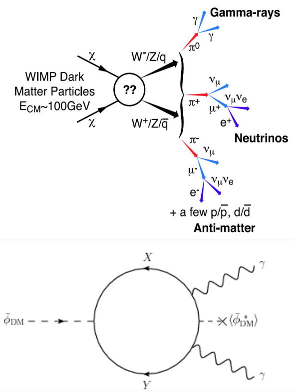
Indirect Detection

Indirect Detection



(a) Dark Matter Decay and Annihilation

Indirect Detection



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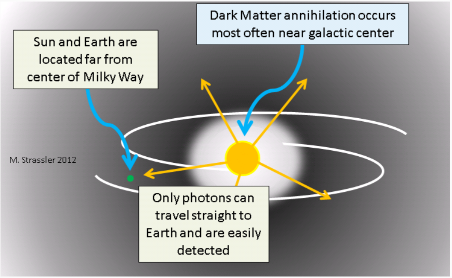


(b) Indirect Detection

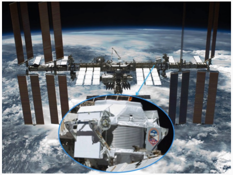
Indirect Detection Results

Indirect Detection Results

(a) Fermi-LAT

Indirect Detection Results

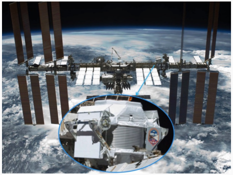
(a) Fermi-LAT



(b) AMS

Indirect Detection Results

(a) Fermi-LAT

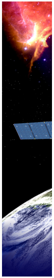


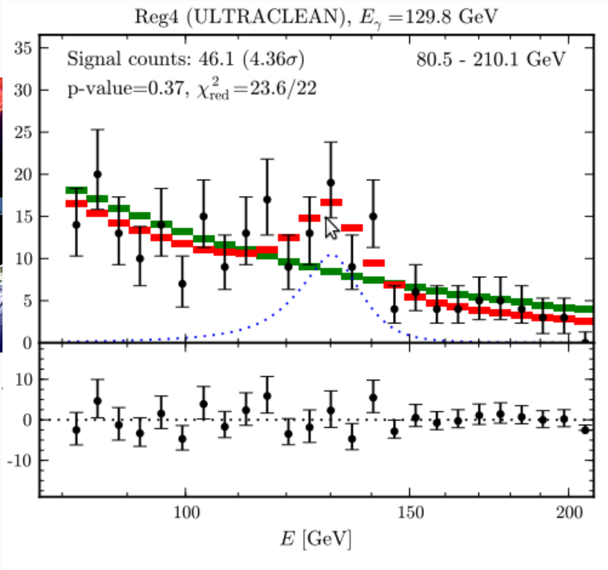
(b) AMS

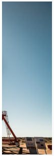
(c) HESS

Figure 11: Gamma-Ray and Particle Detectors

Indirect Detection Results



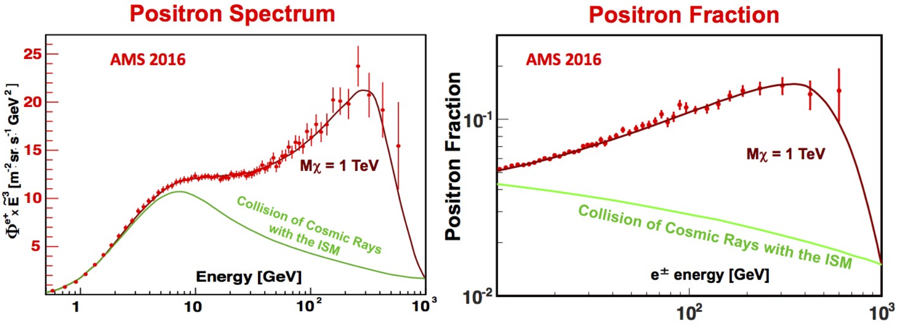




Weniger 2012

Indirect Detection Results

AMS collaborations.



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Indirect Detection Results

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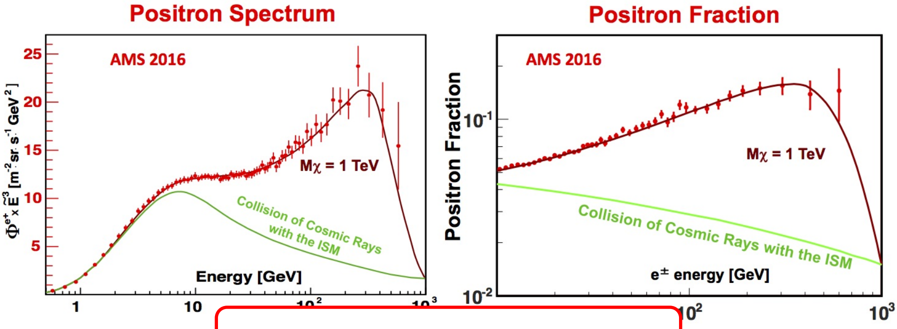


Prossible signals, but not convincing.

Weniger 2012

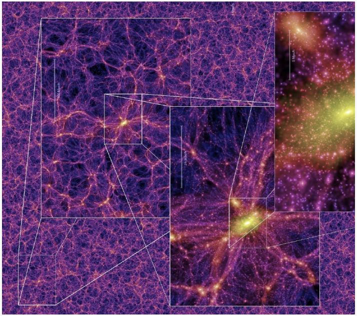
Cosmological Simulation

Why Simulation?

- Gravitational interaction – Highly non-linear;;
- Tests cosmological models;
- Guidance for detection experiments.

Simulation Method

- N-Body simulation;
- Pure-Dark Matter (usually large scale);
- With Baryons (usually galactic scale);



(a) Large Scale Cosmological Simulation: Millenium Run

(b) Via Lactea II simulation.

- The resolution increases exponentially over time.

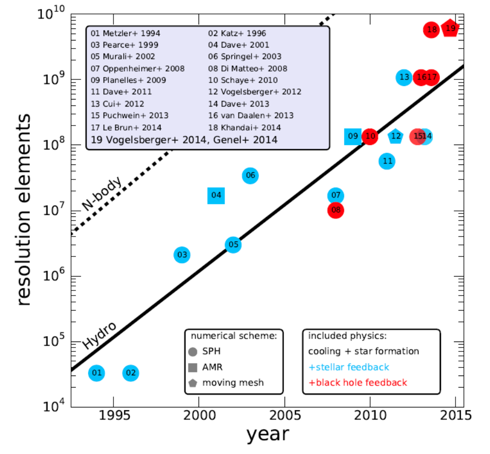


Figure 13: The exponential increase of simulation resolution[1].

[1] Image Source: http://www.illustris-project.org/

Dark Matter Radiation

Motivation: Fermi-LAT

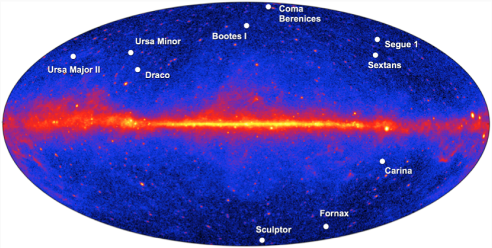
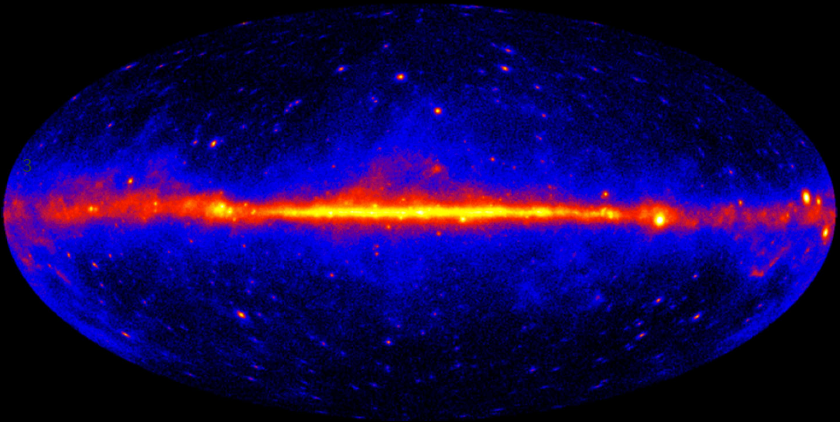


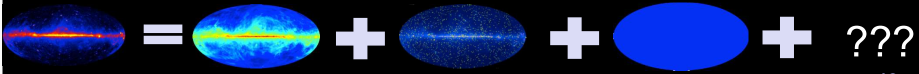
Figure 14: Fermi-LAT Gamma-Ray Observations.[2]

- Extremely Complicated Model GAPROP

[2]Image from Fermi-LAT collaborations

Searching for Dark Matter in the Gamma-ray Sky

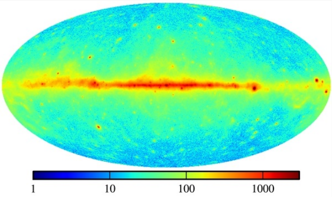




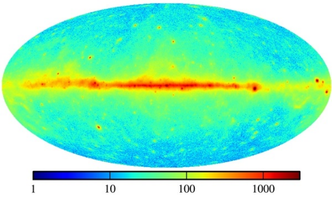
GeV Sky | Galactic | Point Sources | Isotropic

[3] Adapted form Matthew Wood's slide.

Residue Map of Fermi-LAT



(a) Observation.



(b) Simulation.

Figure 15: Fermi-LAT Gamma-Ray Observations.

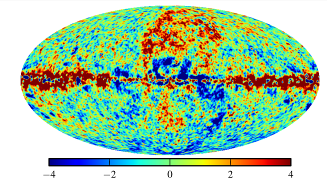


Figure 16: The Residue [Ackermann et al 2012].

Dark Matter Annihilation

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- Weakly Interacting Massive Particles (WIMP);

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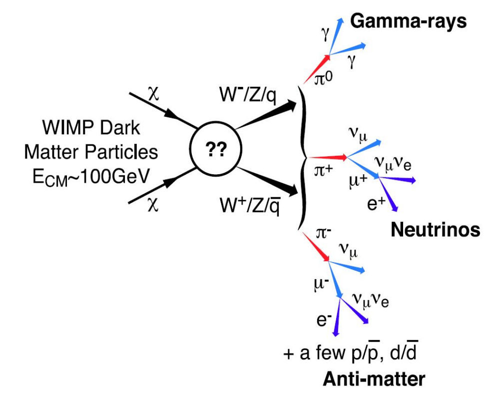

Figure 17: Dark Matter Annihilation.

Dark Matter Annihilation

Observation:

$$\Psi_\gamma^a(\theta, \phi) = P_a \int_{l.o.s.} \langle \sigma v \rangle \rho(\mathbf{r})^2 dr$$

Dark Matter Annihilation

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Dark Matter Annihilation

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P_a: particle physics factor.

- Unknown P_a: study the astrophysical factor

$$J_a(\theta, \phi) = \int_{l.o.s.} \rho(\mathbf{r})^2 dr.$$

- Method – Simulation.

Dark Matter Decay

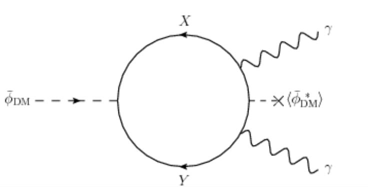
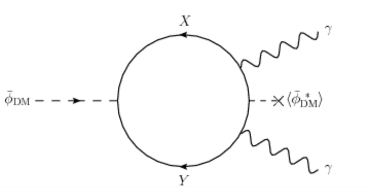


Figure 18: Possible Decay Channel.

Dark Matter Decay



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$$\Psi^{d}_{\gamma}(\theta,\phi) = P_d \int_{l.o.s.} \rho(\mathbf{r})dr.$$

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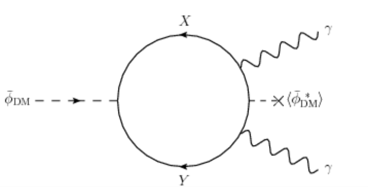

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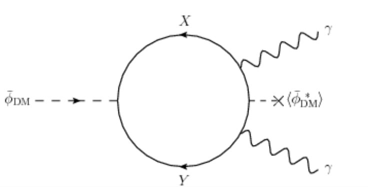

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- Method – Simulation.

Method of Study

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- Use N-body simulation to provide the astrophysical factor J; – Via Lactea II simulation.

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- Use N-body simulation to provide the astrophysical factor J; – Via Lactea II simulation.
- Include other corrections to J:

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- 1.1×10^9 particles, each of mass 4100 $M_\odot$;
- Milky-Way-Sized Host Halo;
- We use 4×10^8 particles within $r_{200} = 402$ kpc.

Integration of dark matter annihilation

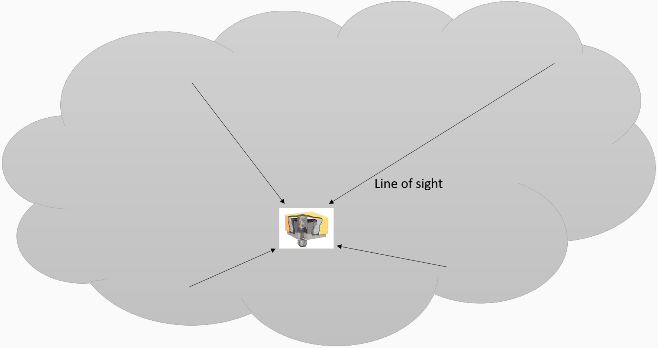

Figure 19: The observation of DM radiation.

Simulated Allsky Maps

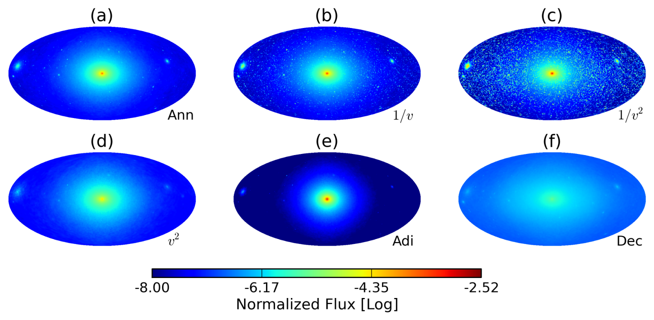

Figure 20: Simulated Observations

Sommerfeld Enhancement

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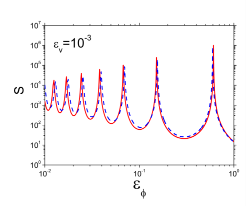

Figure 21: Sommerfeld Enhancement ($\varepsilon_\phi = \frac{v}{\alpha_X}$, Feng et al 10).

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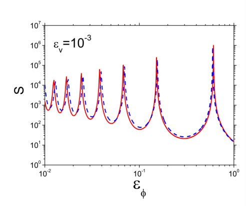

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General case: $S \propto \frac{1}{v_{rel}}$; Resonance $S \propto \frac{1}{v_{rel}^2}$.

Sommerfeld Enhancement

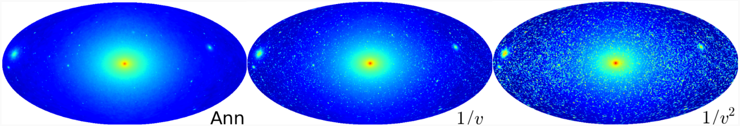

Figure 22: Sommerfeld Enhancement v.s. pure annihilation

Sommerfeld Enhancement

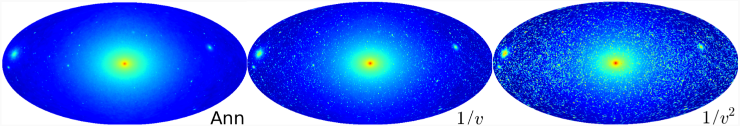

Figure 22: Sommerfeld Enhancement v.s. pure annihilation

The subhalos light up.

p-wave Annihilation

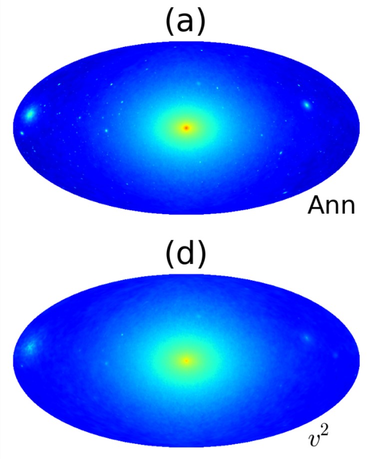

Figure 23: P-wave annihilation v.s. pure annihilation

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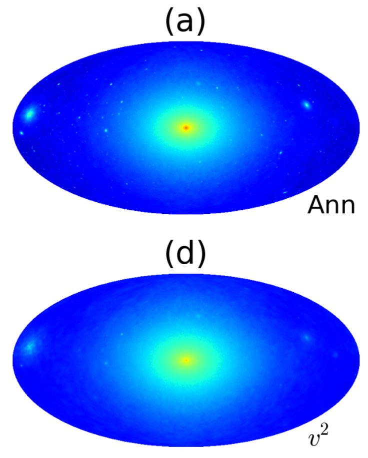

Figure 23: P-wave annihilation v.s. pure annihilation

e.g. Neutralino (s-wave is suppressed due to conservation laws):

$$\langle \sigma v \rangle \propto v_{rel}^2.$$

Adiabatic Contraction

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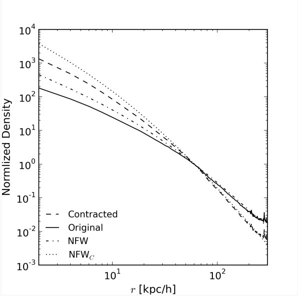

Figure 24: Density profiles of the main halo.

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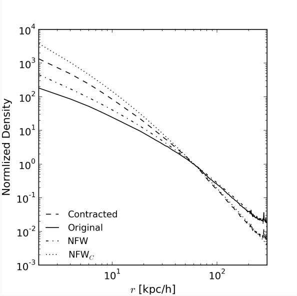

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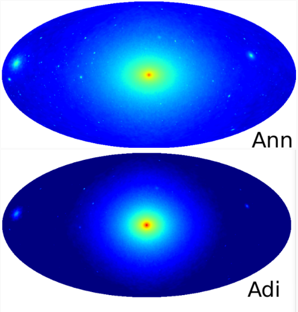

Figure 25: Pure annihilation v.s. adiabatic contraction.

Comparison With Fermi-LAT

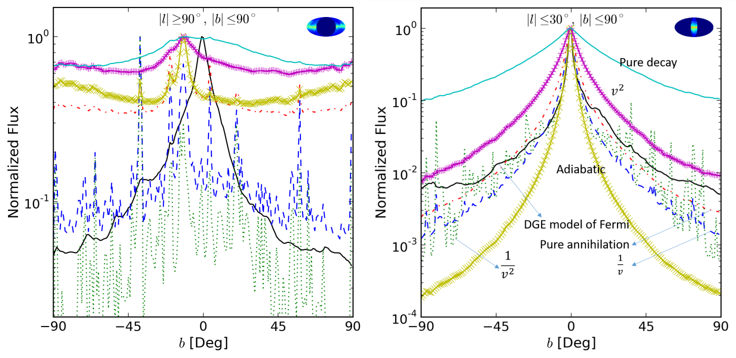

Figure 26: Angular profiles of radiation maps.

Summarize of This Project

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- Subhalos can dominate the radiation if Sommerfeld enhancement exists;
- p-wave only radiation smooths out substructures;
- No spectral signatures are considered – possible future projects.

Density Profile of Voids: An Indicator of the Warmth of Dark Matter

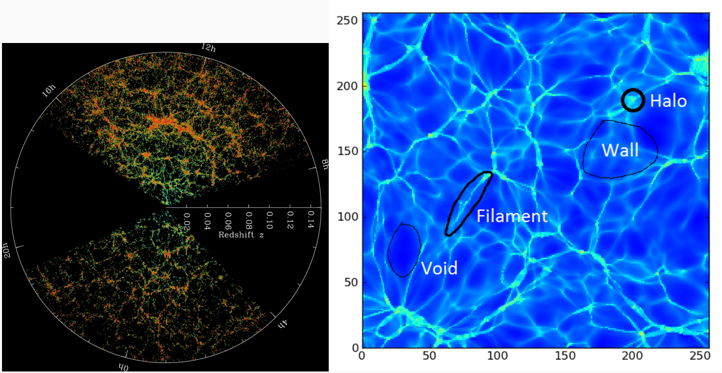

Figure 27: Large scale structure of the universe.

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Cold Dark Matter v.s. Warm Dark Matter

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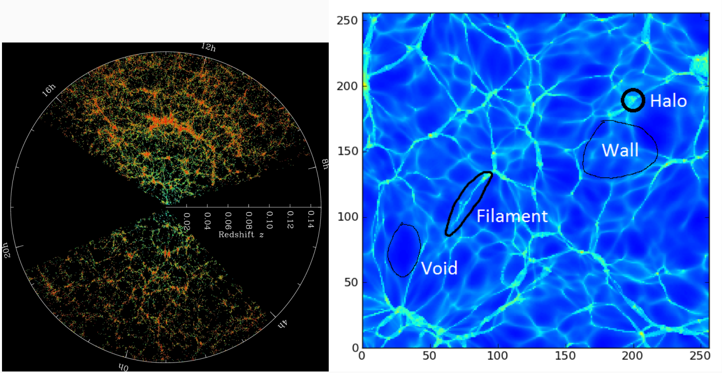

Figure 28: The void density profile – by observations.

Methods

Using simulations with different initialization.

$$T_{WDM} = T_{CDM}(k)\left[1 + (\alpha k)^2\right]^{-5.0}$$

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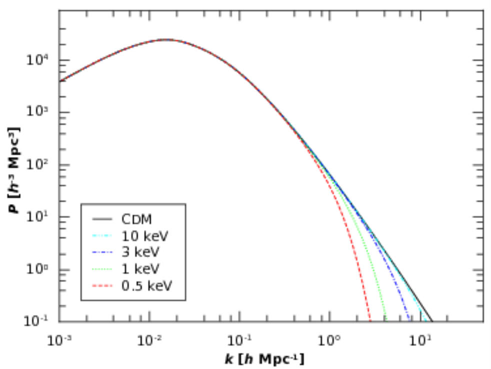

Figure 29: WDM linear spectrum with different cutoff scale (Dunstan et al, 11); $\alpha \propto M_{dm}^{-1.15}$

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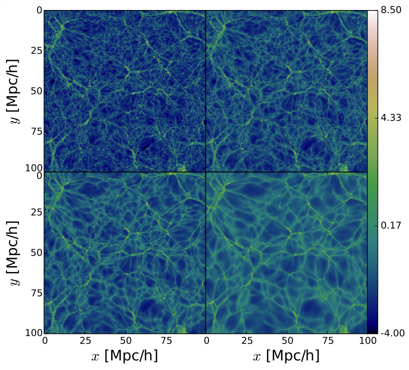

Figure 30: Density Field of WDM Simulations.

Void Density Profiles

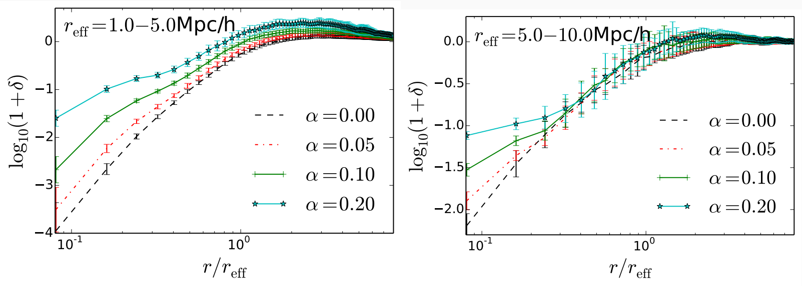

Figure 31: Density Profiles of Voids.

A Showcase for Numeric Tools

The Fast Annihilation/decay Integrator

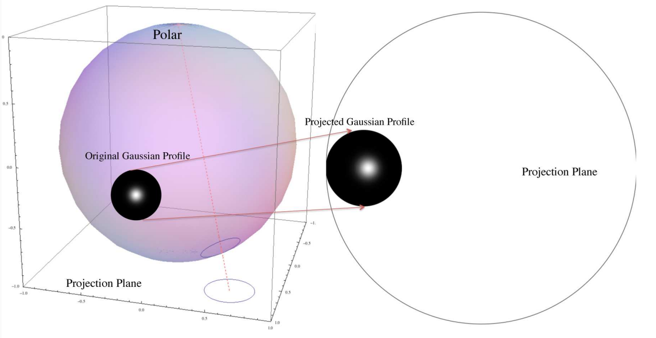

Figure 32: Stereographic projection enables fast GPU rendering for integration. Speedup: ≥ 1000.

The Fast Lagrangian Tessellation Density Estimator

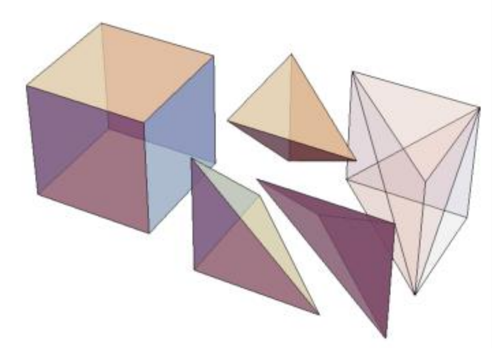

Figure 33: Tetrahedra Cut Enables GPU Rendering for Density Field. Speedup: ≥ 1000.

The Streaming Halo Finder

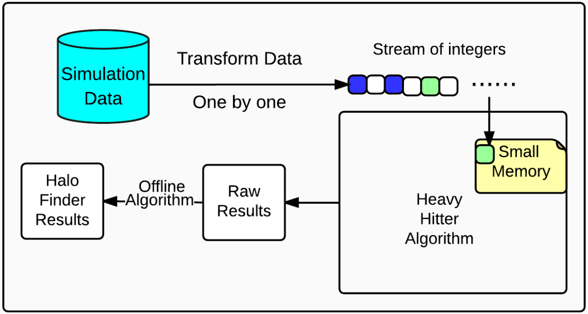

Figure 34: Streaming algorithm technique: linear time / log-space halo finder.

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Thank you!