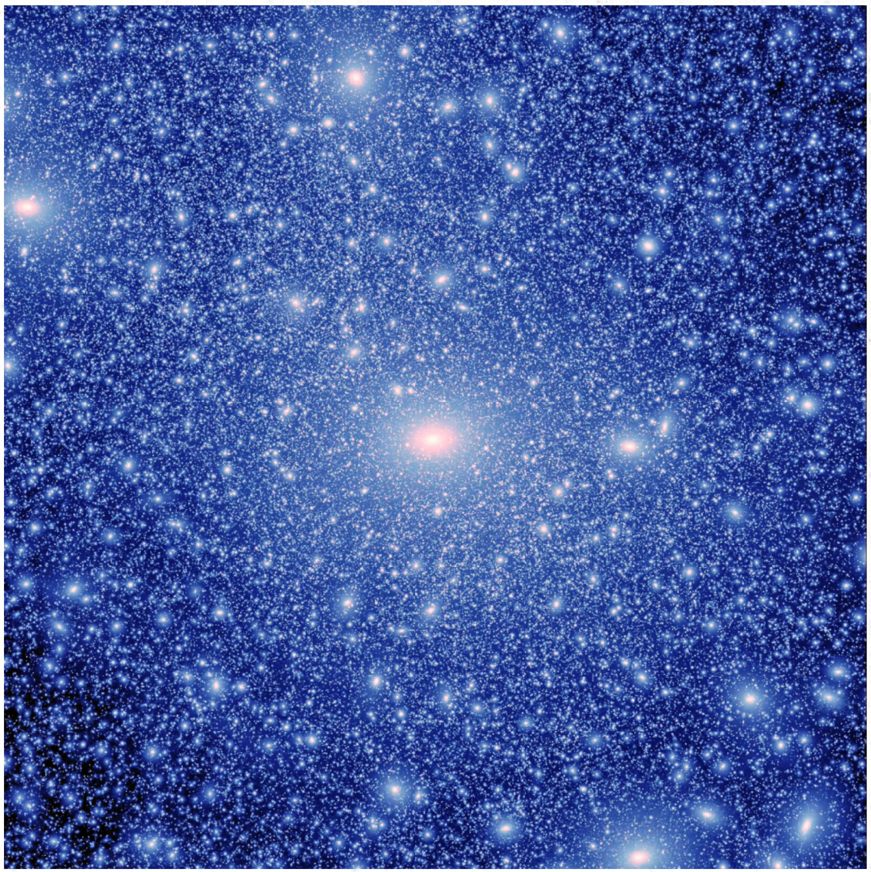
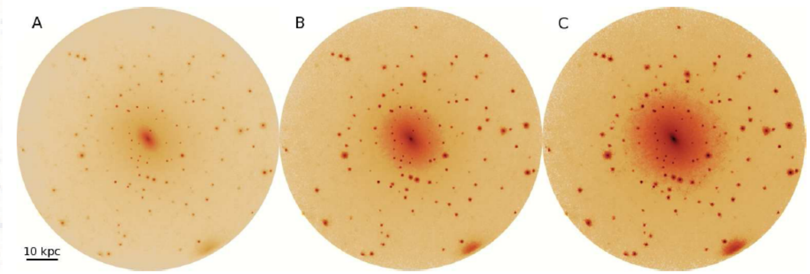
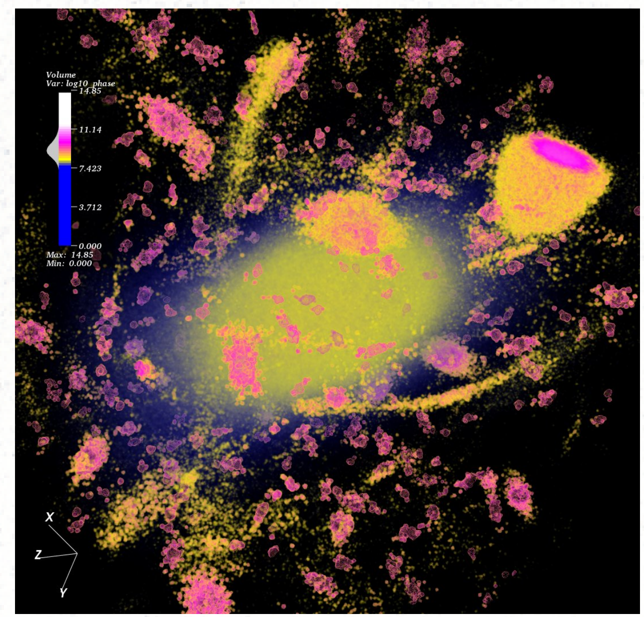
Implications of Galactic dark matter substructure on detection efforts

Michael Kuhlen, UC Berkeley





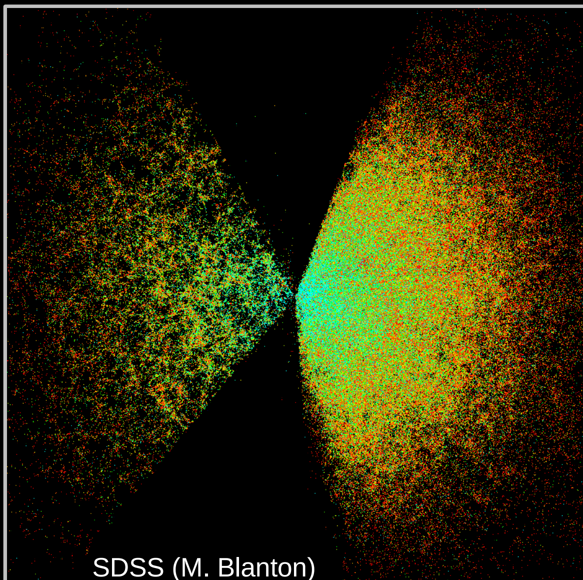


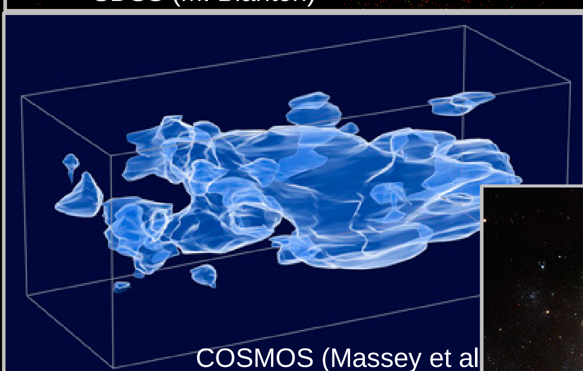
The Via Lactea collaboration

(P. Madau, J. Diemand, M. Zemp, B. Moore, J. Stadel, D. Potter, V. Rashkov)

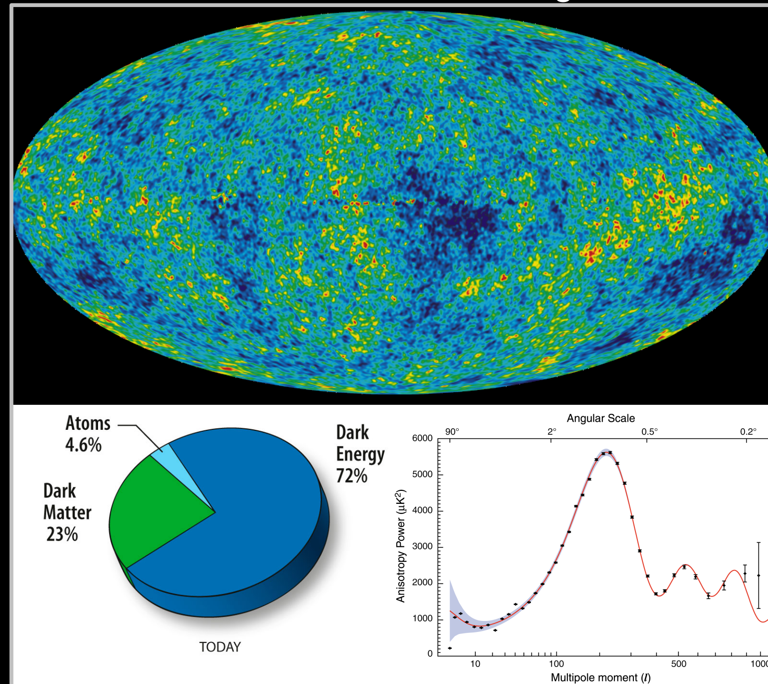
There's evidence for dark matter on many scales...

Large Scale Structure

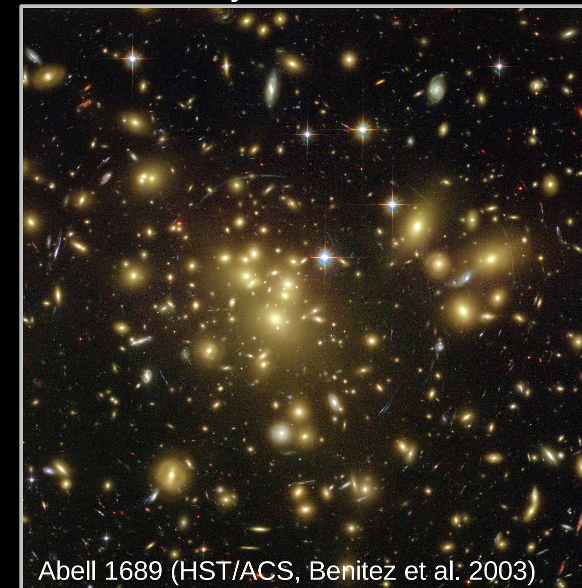

SDSS (M. Blanton)

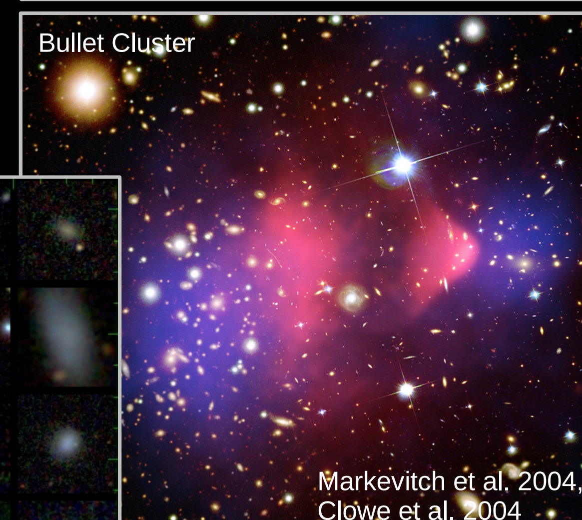

COSMOS (Massey et al

Cosmic Microwave Background



Galaxy Clusters

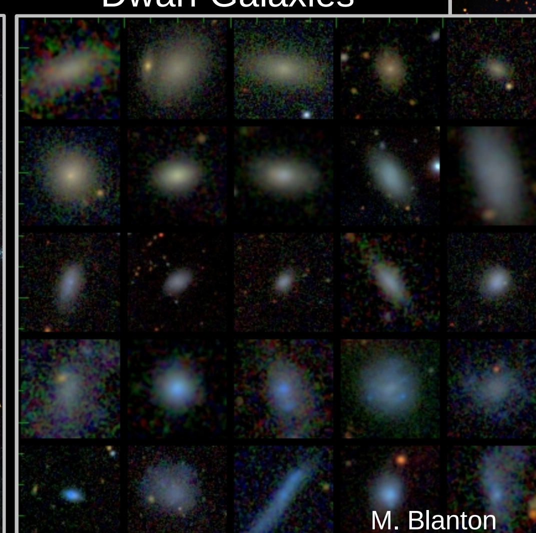

Abell 1689 (HST/ACS, Benitez et al. 2003)


Bullet Cluster
Markevitch et al. 2004, Clowe et al. 2004

Galaxies

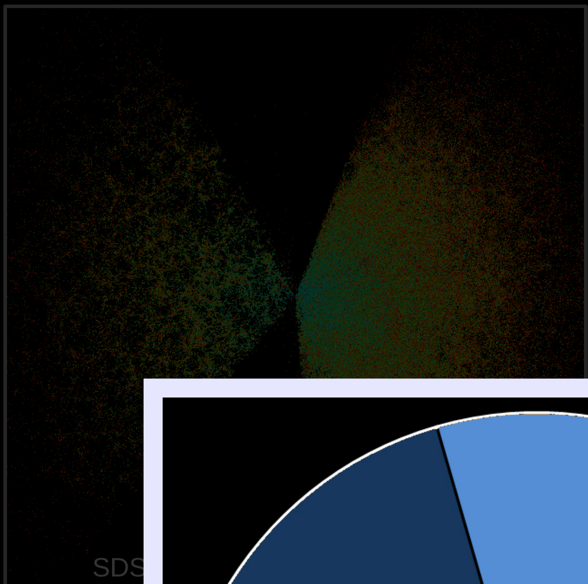

M101 (HST; Kuntz et al. 2006)

Dwarf Galaxies

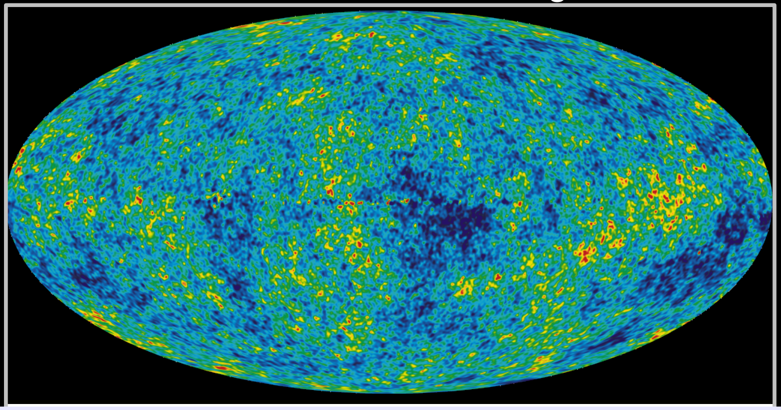

M. Blanton

There's evidence for dark matter on many scales...

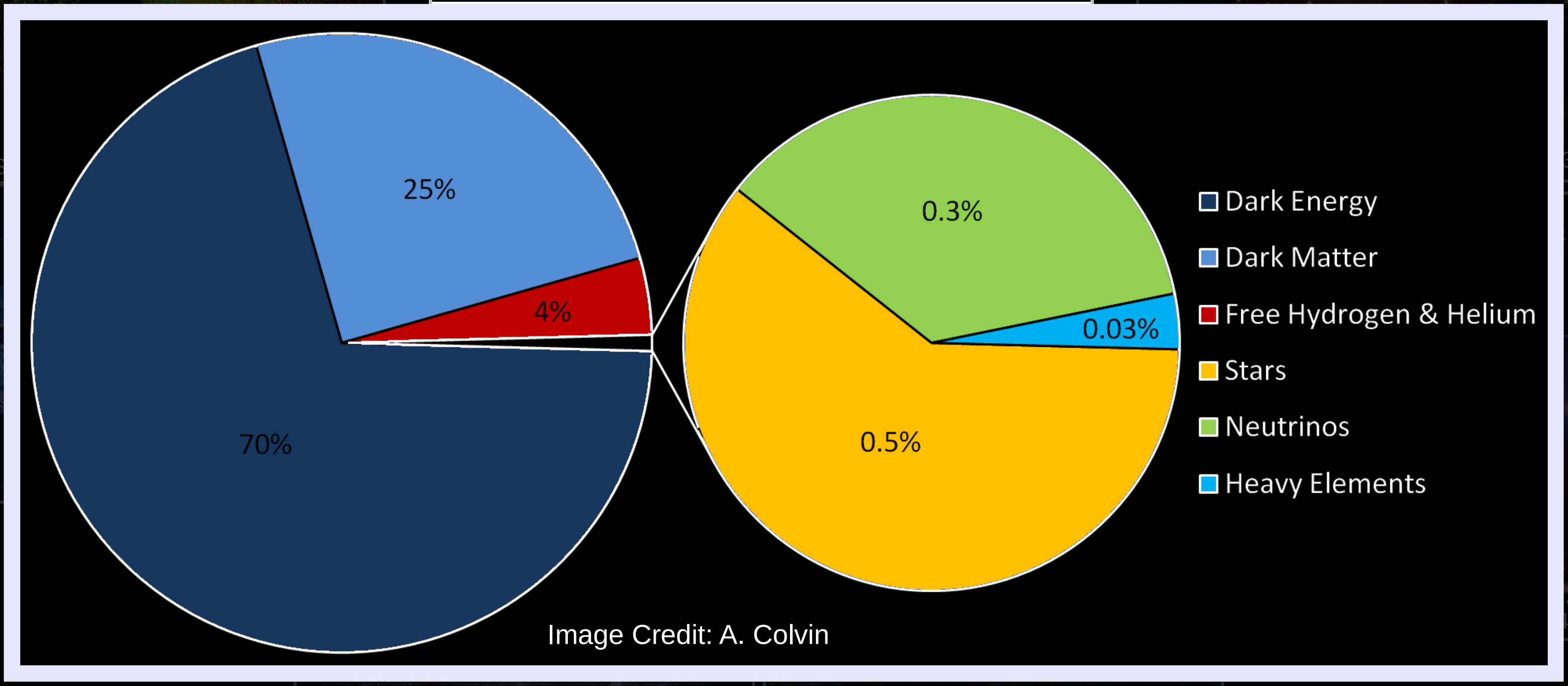
Large Scale Structure

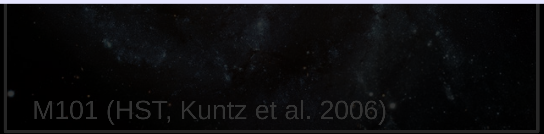


Cosmic Microwave Background

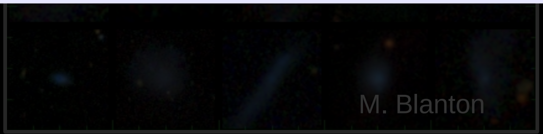


Galaxy Clusters





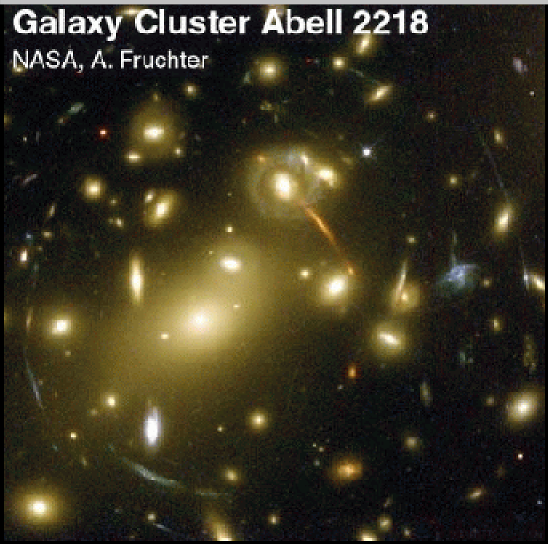
M101 (HST; Kuntz et al. 2006)

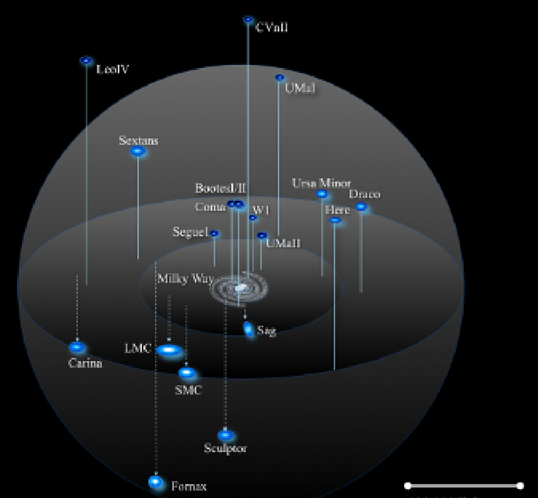


M. Blanton

How can we learn more about dark matter?

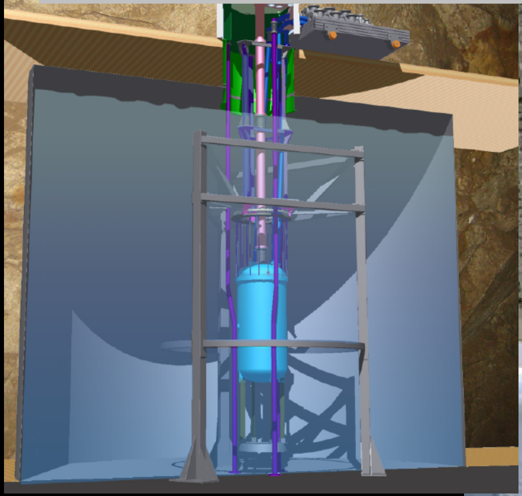
More Astronomical Observations

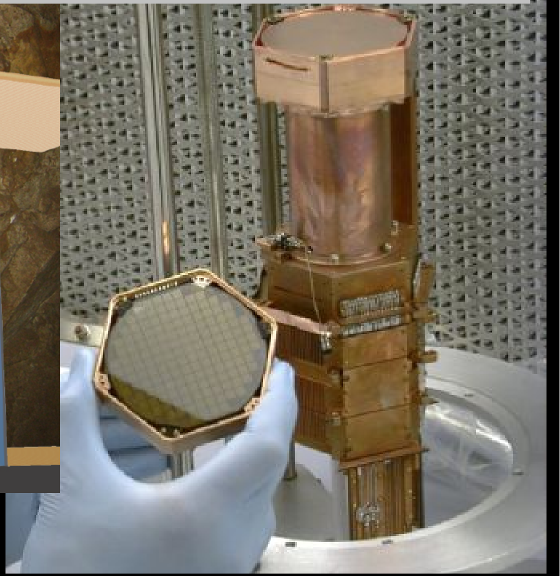




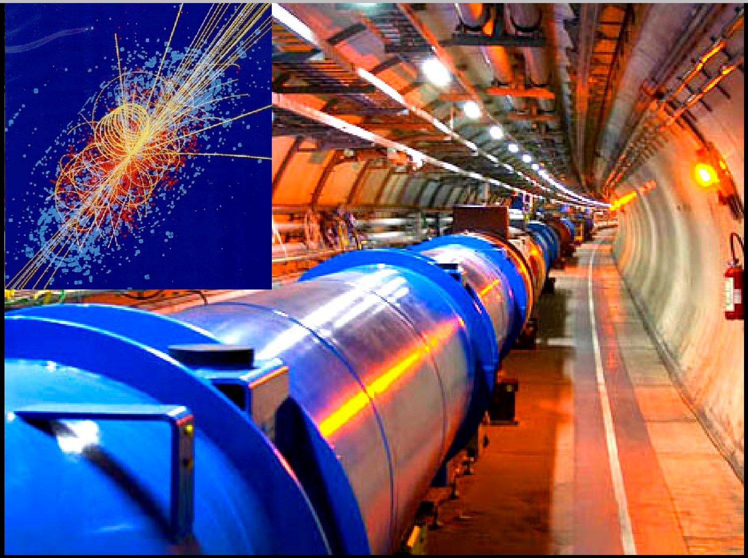
Bullock, Geha & Powell

Direct Detection Experiments





LHC might produce WIMPs!



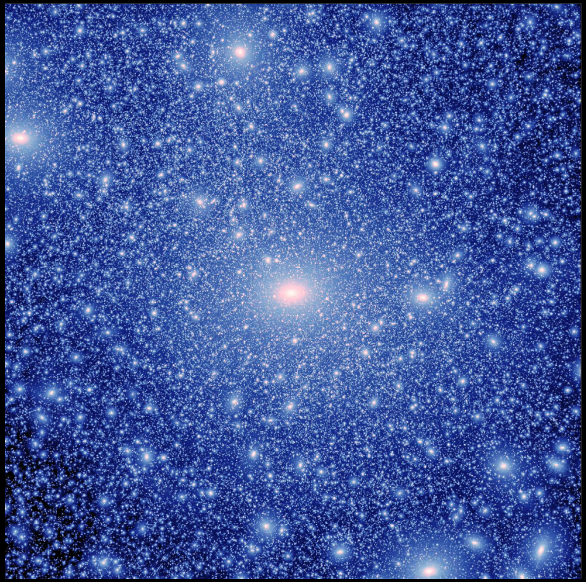
Indirect Detection

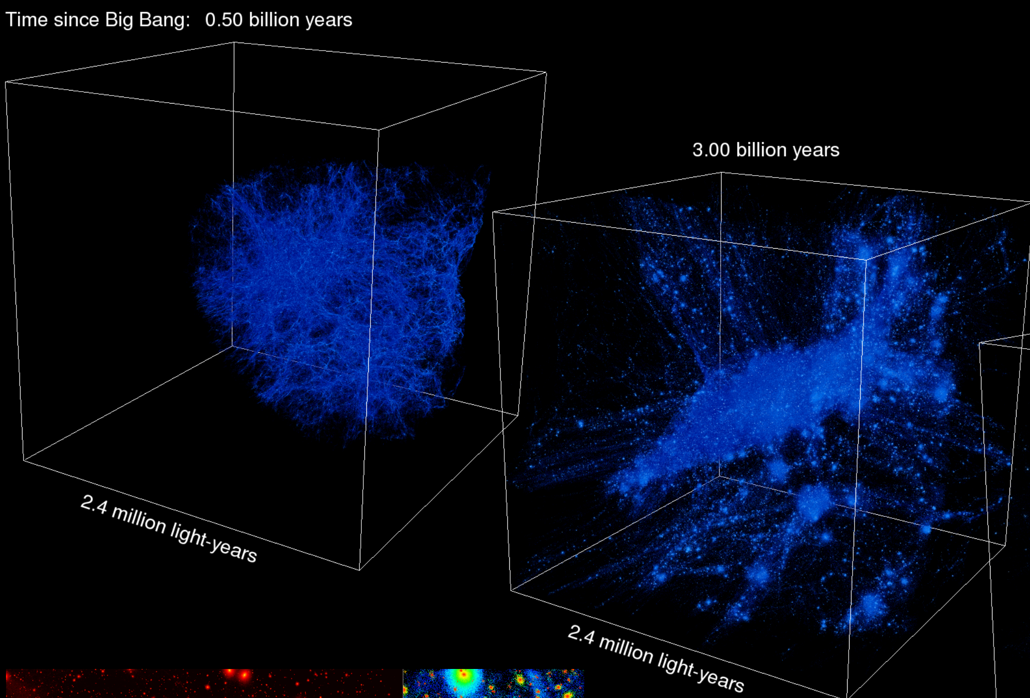
PAMELA satellite

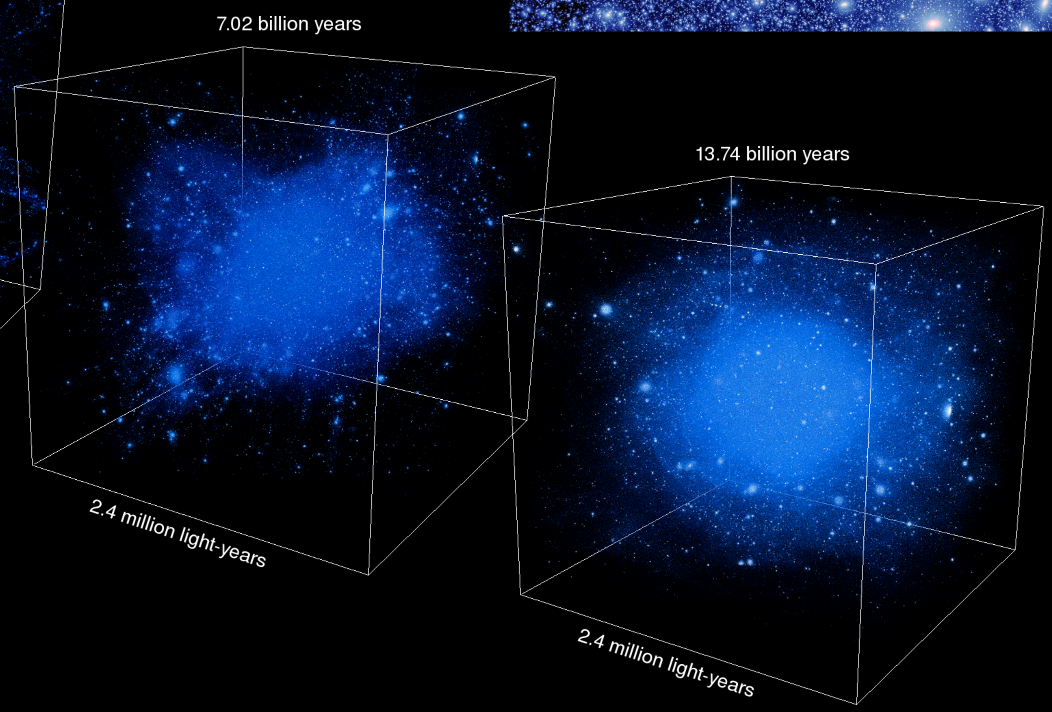
Atmospheric Cerenkov Telescopes

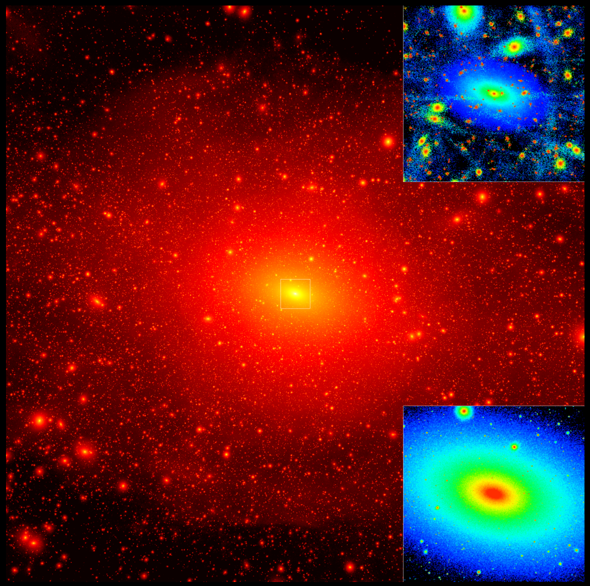
The Via Lactea Project

GHALO
Stadel et al. (2009)
2.1 billion particles, 1,000 $M_{\odot}$









VIA LACTEA II
Diemand, Kuhlen et al. 2008
1.1 billion particles, 4,000 $M_{\odot}$

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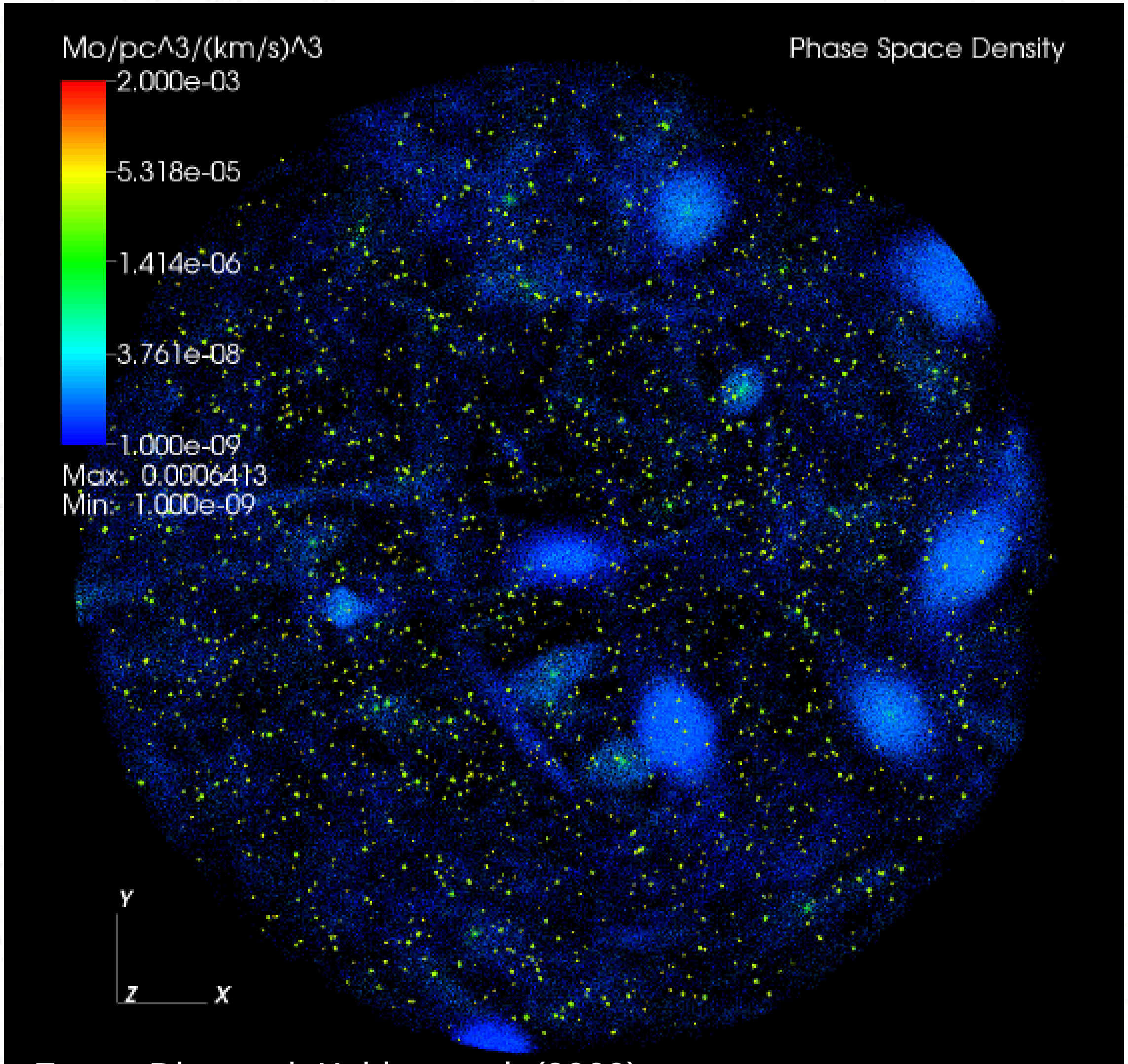
Summary of Numerical Results: Substructure

Velocity Space Substructure

When viewed in **phase-space-density**, many additional unbound substructures become apparent: dark matter tidal streams from disrupted subhalos.

Direct counterparts to the stellar streams from disrupted satellites (e.g. SDSS Field of Streams).

In the future will there be a Missing Streams Problem?

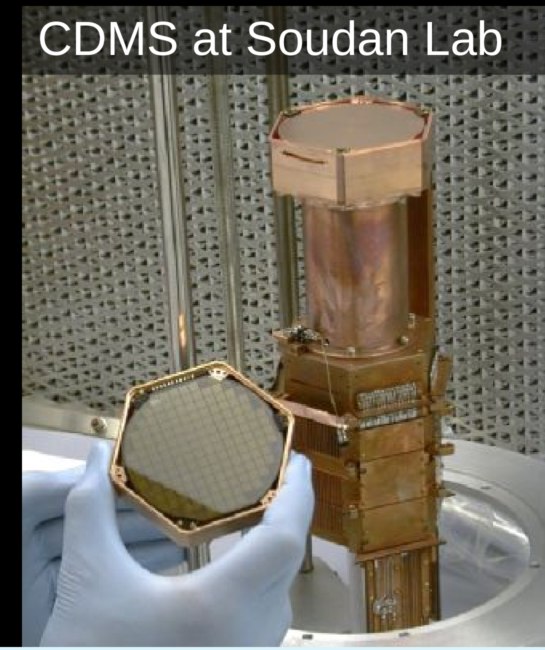


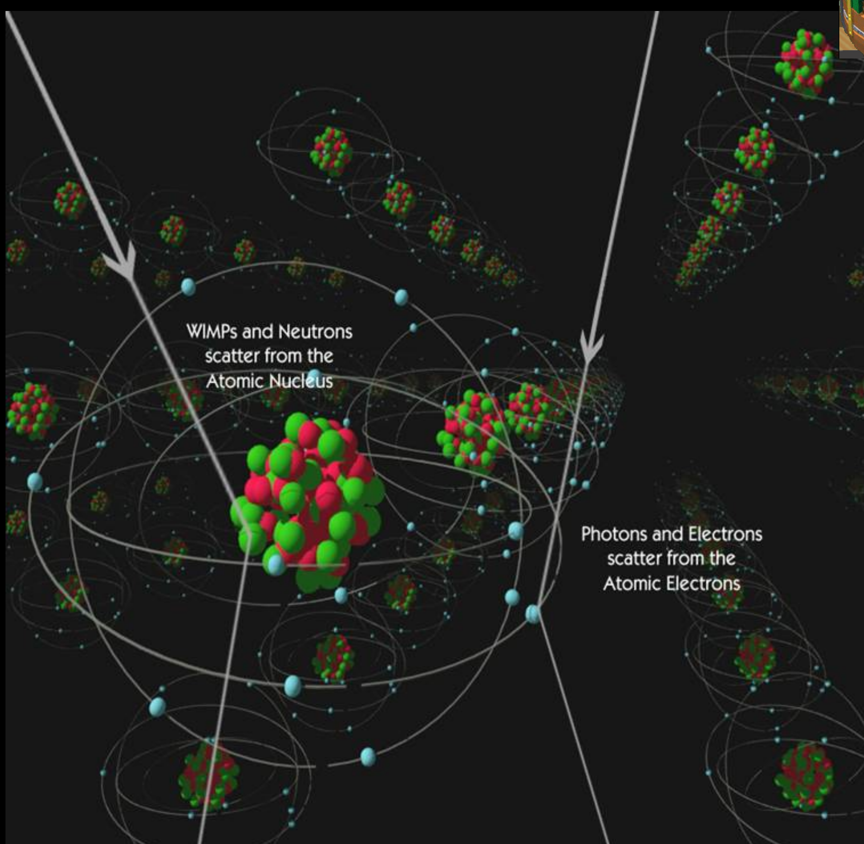
Zemp, Diemand, Kuhlen et al. (2009)

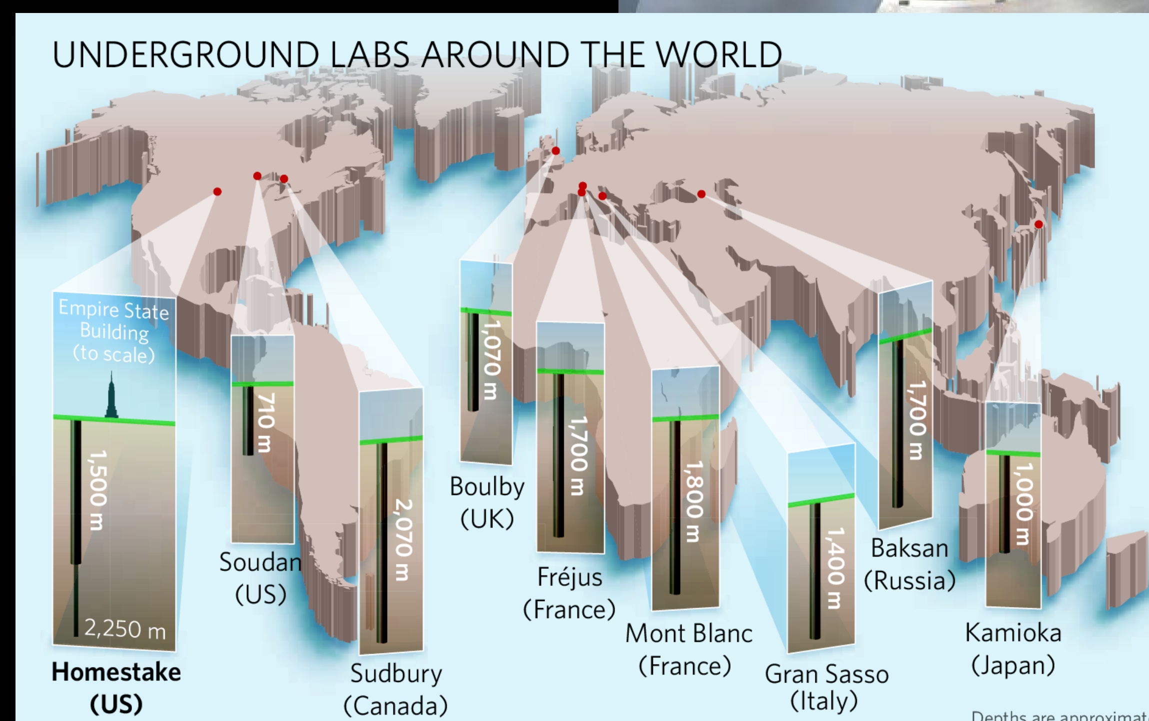
Direct Detection: Dark Matter in the Laboratory

Direct Detection aims to detect the weak signals (ionization, scintillations, vibrations) from dark matter particles scattering off target nuclei.

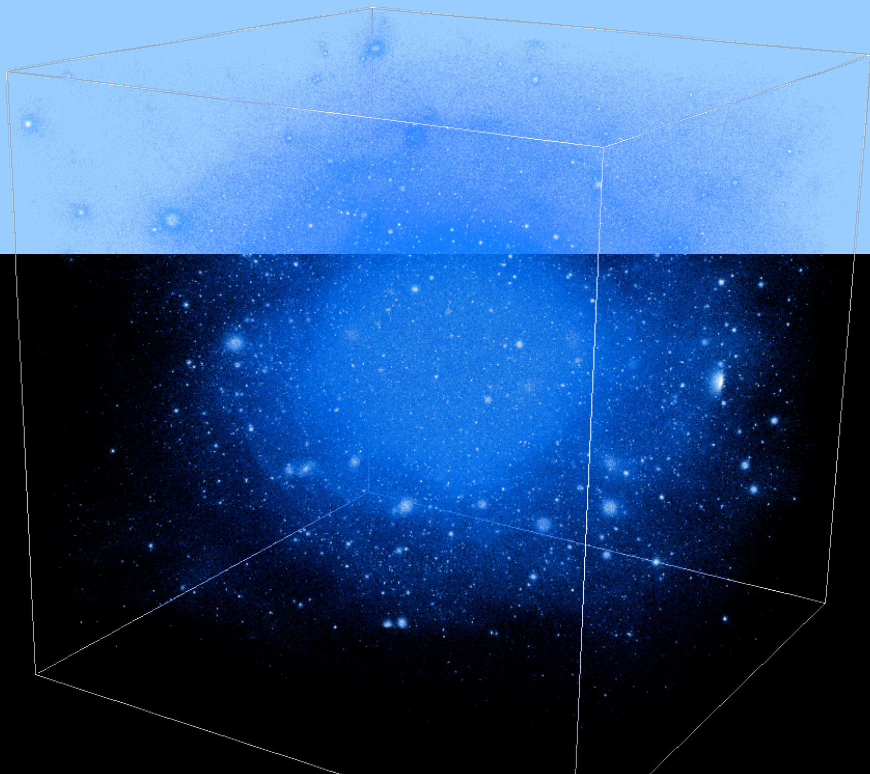
In order to reduce background from cosmic rays, these experiment are located deep underground, shielded by 1000's of meters of rock.

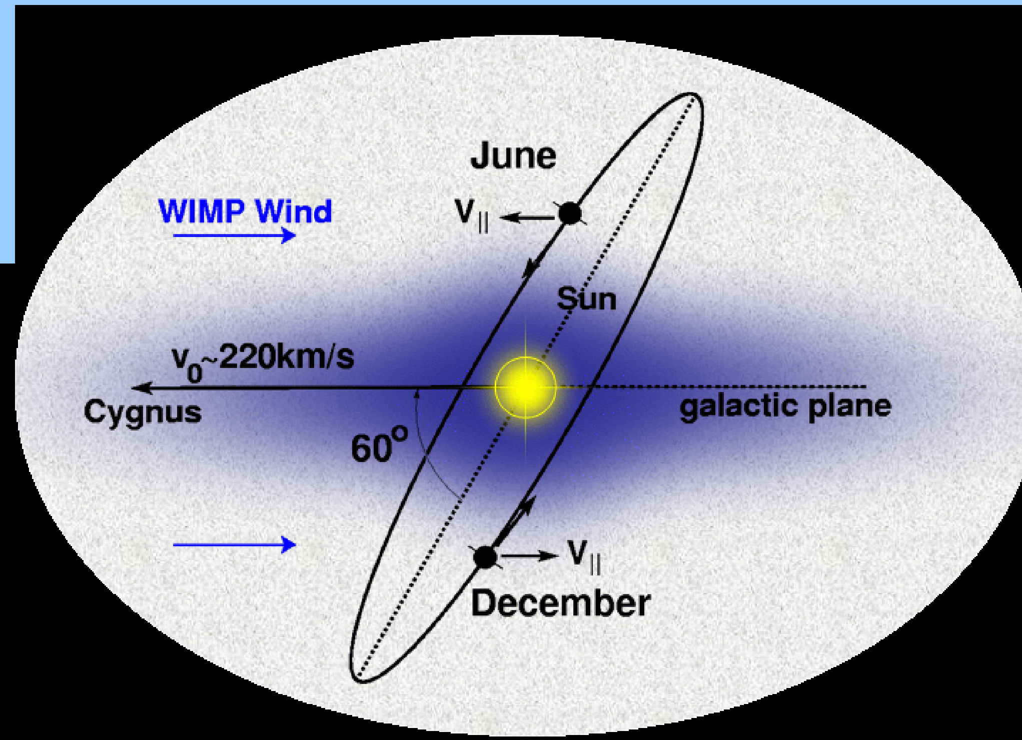






Direct Detection: Dark Matter in the Laboratory





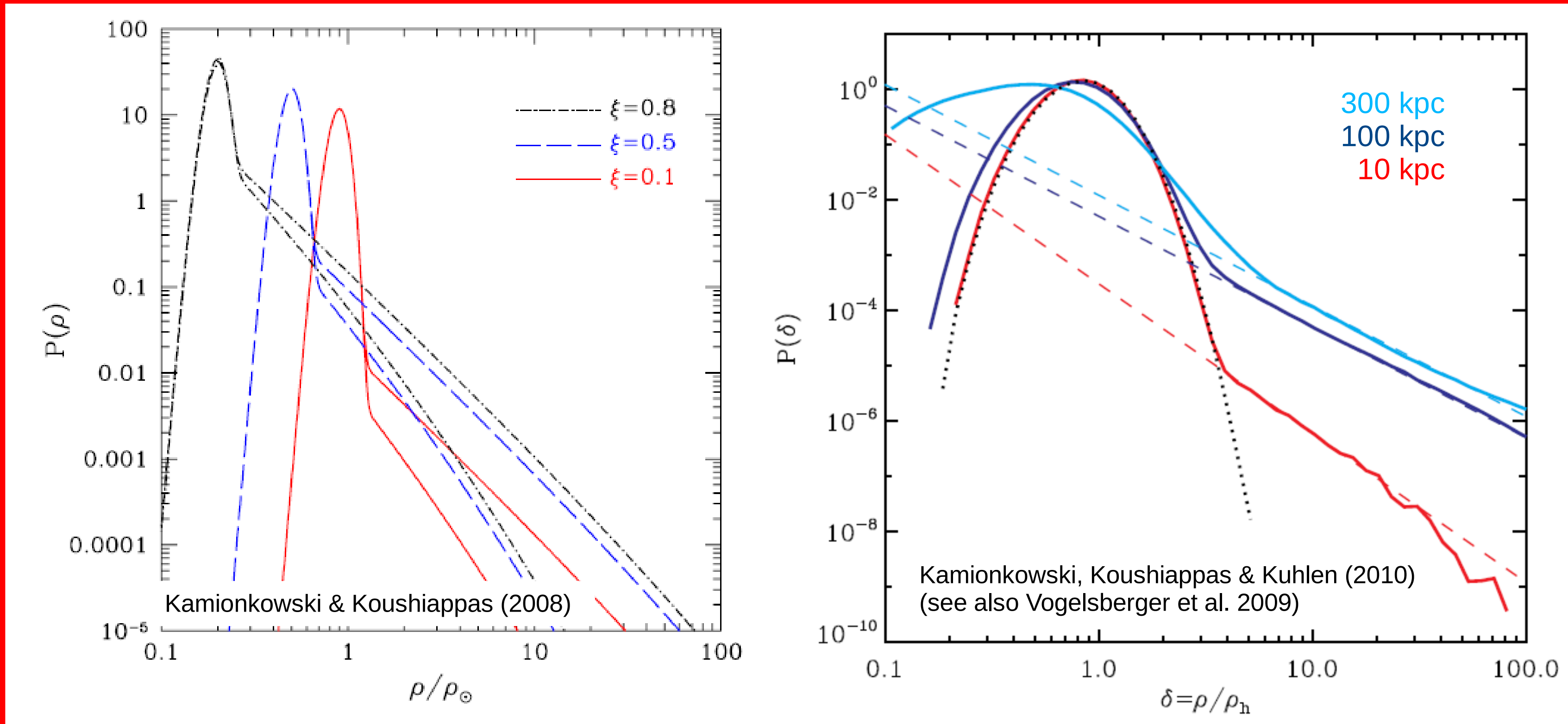
The scattering event rate (events/recoil energy) is given by:

$$\frac{dR}{dE_R} = N_T M_N \frac{\rho_\chi \sigma_n}{2 m_\chi \mu_{ne}^2} \frac{(f_p Z + f_n (A - Z))^2}{f_n^2} F^2[E_R] \int_{\beta_{min}}^{\infty} \frac{f(v)}{v} dv$$

This depends on the local DM density ρ_χ and the velocity distribution function f(v).

A typical assumption is ρ_χ=0.3 GeV/cm^3 and f(v) a Maxwellian with v_p = 220 km/s truncated at an escape speed of 500-600 km/s.

Direct Detection: Dark Matter in the Laboratory



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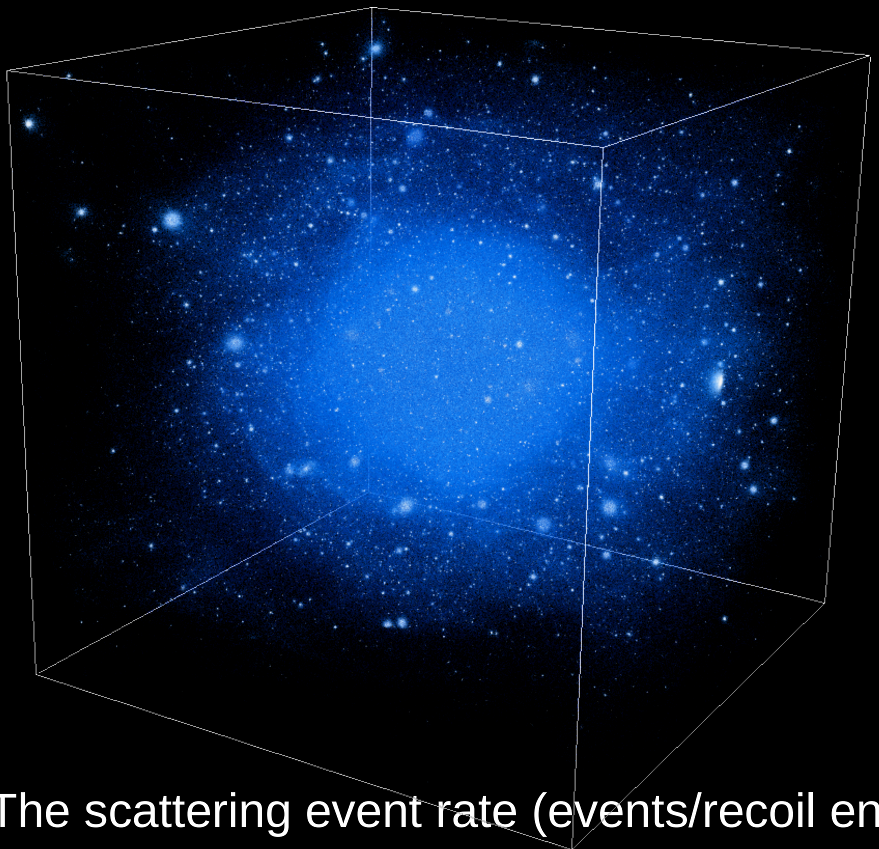

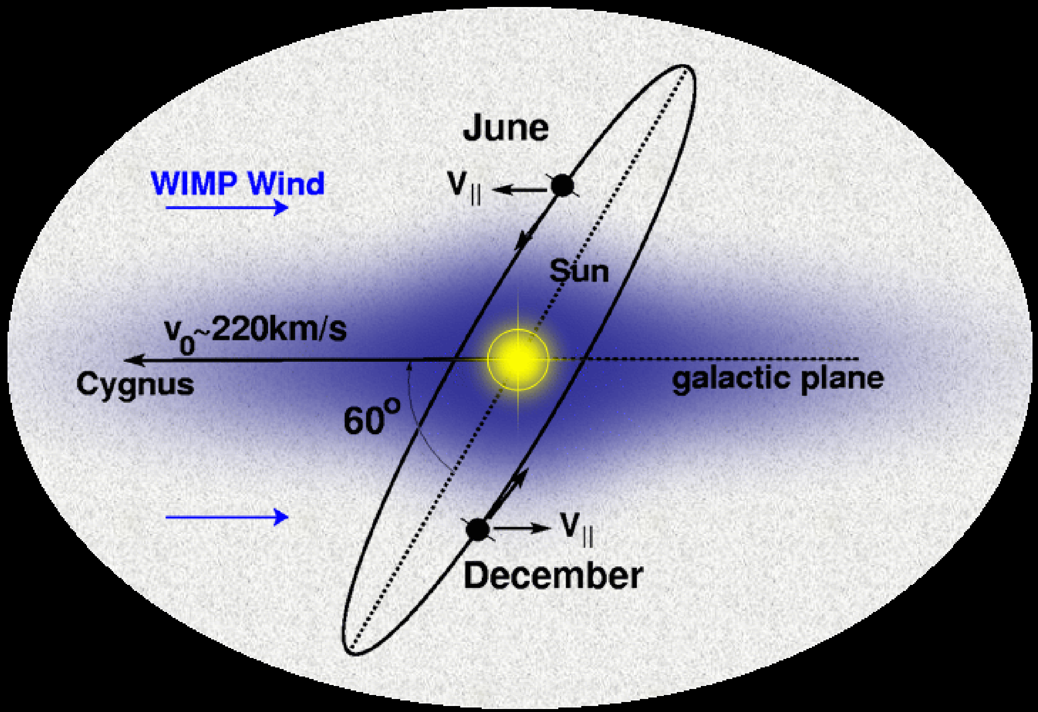

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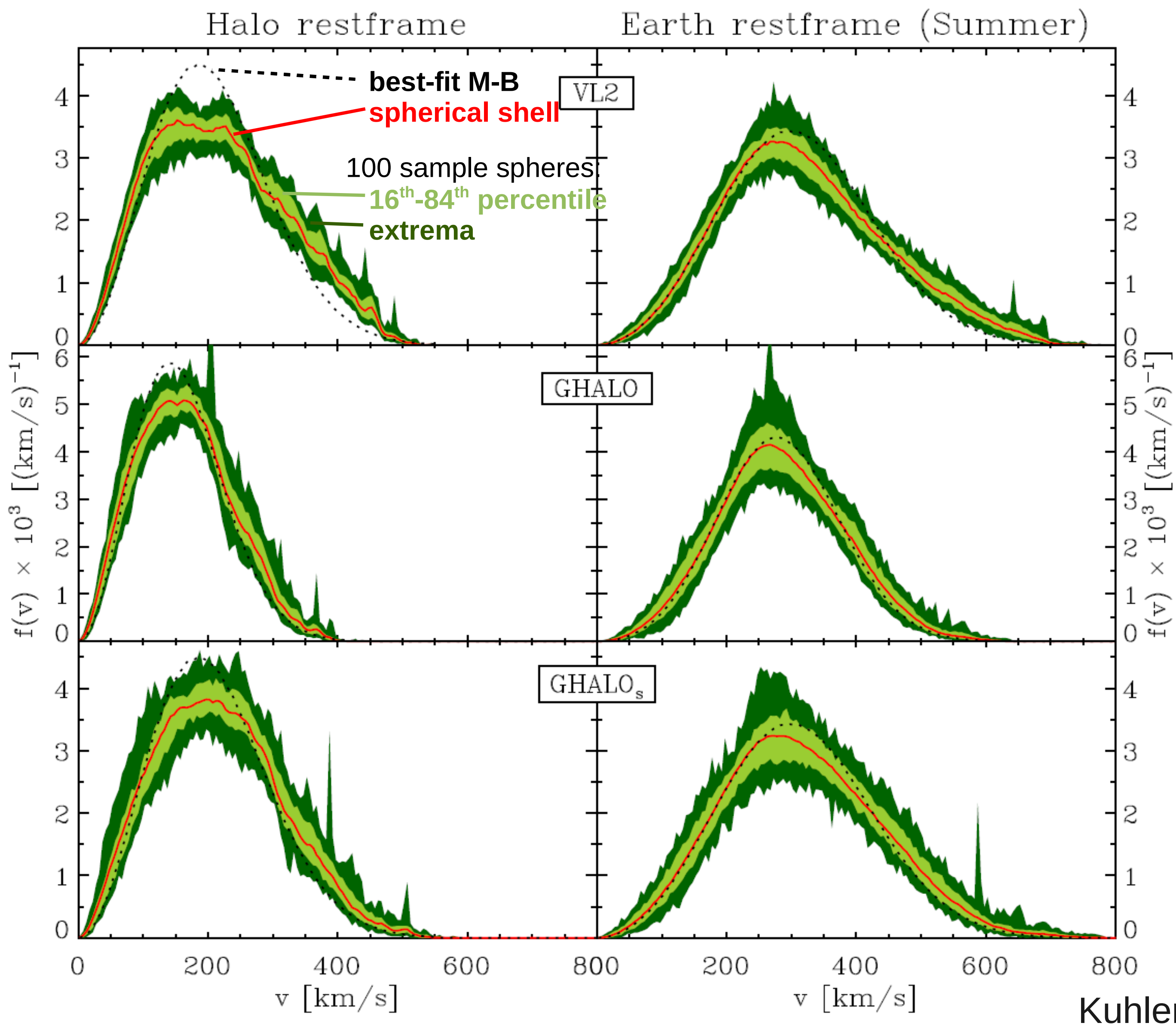
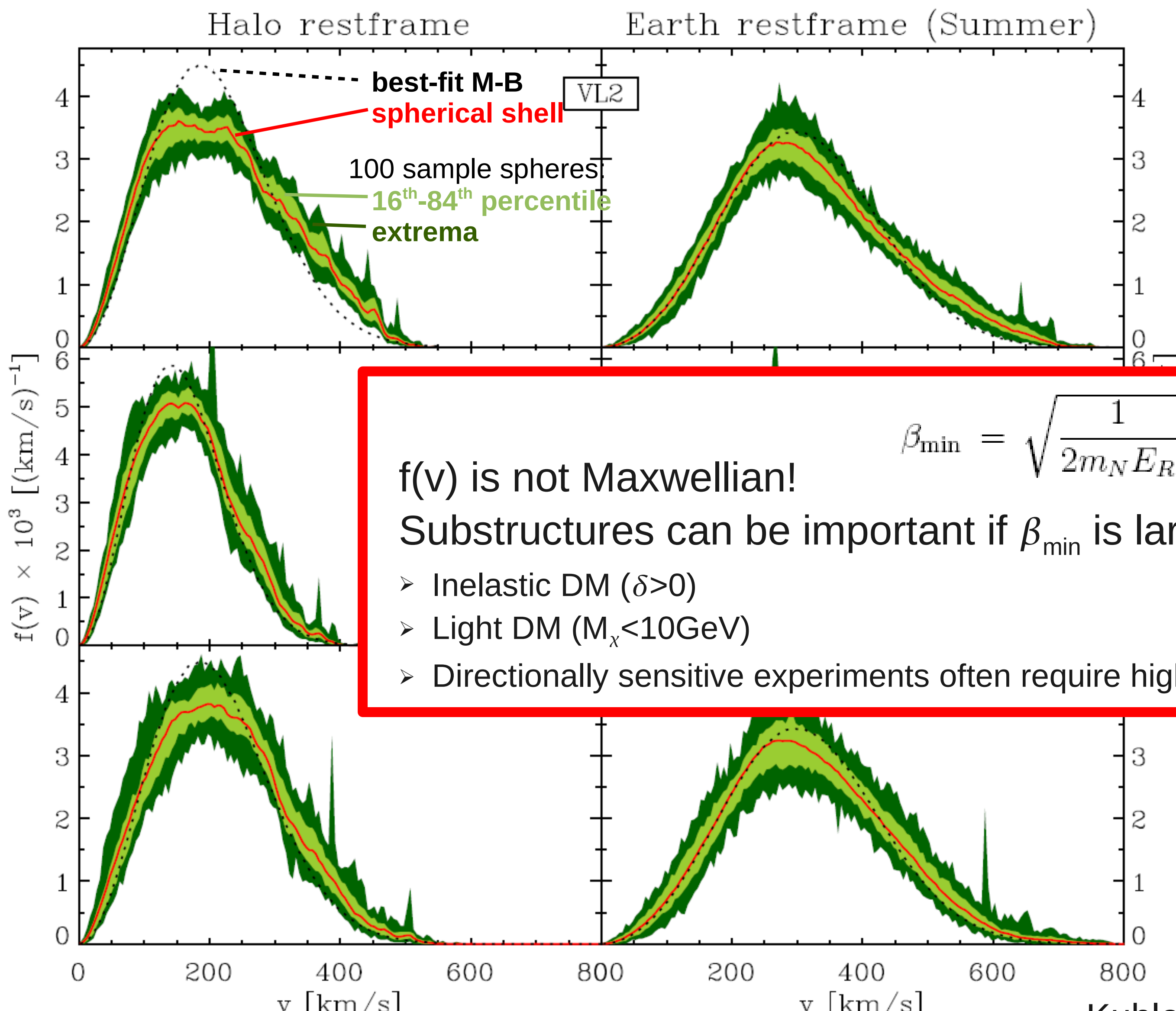
Velocity Space Substructure



Kuhlen et al. (2010)

See also: Hansen et al. (2005), Vogelsberger et al. (2009)

Velocity Space Substructure



f(v) is not Maxwellian!

$$\beta_{\min} = \sqrt{\frac{1}{2 m_N E_R}} \left(\frac{m_N E_R}{\mu} + \delta \right)$$

Substructures can be important if β_{min} is large.

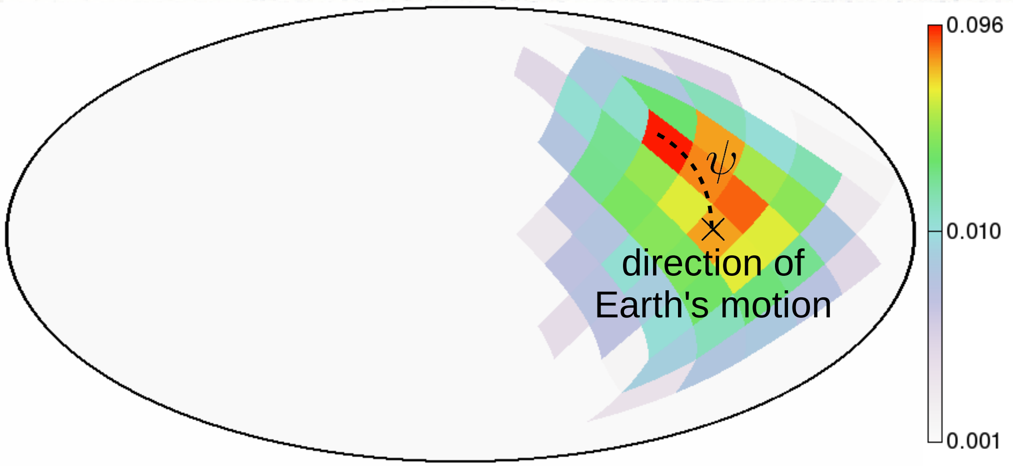
- Inelastic DM (δ>0)
- Light DM (M_χ<10GeV)
- Directionally sensitive experiments often require high E_{recoil}, large β_{min}.

Kuhlen et al. (2010)

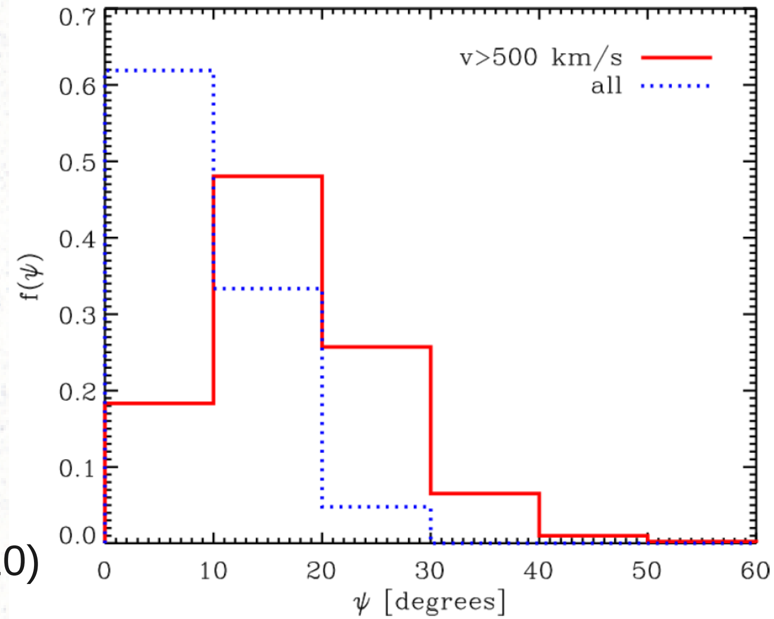
See also: Hansen et al. (2005), Vogelsberger et al. (2009)

Substructure Relevance for Direct Detection

Sample Sphere #004 (containing a subhalo)



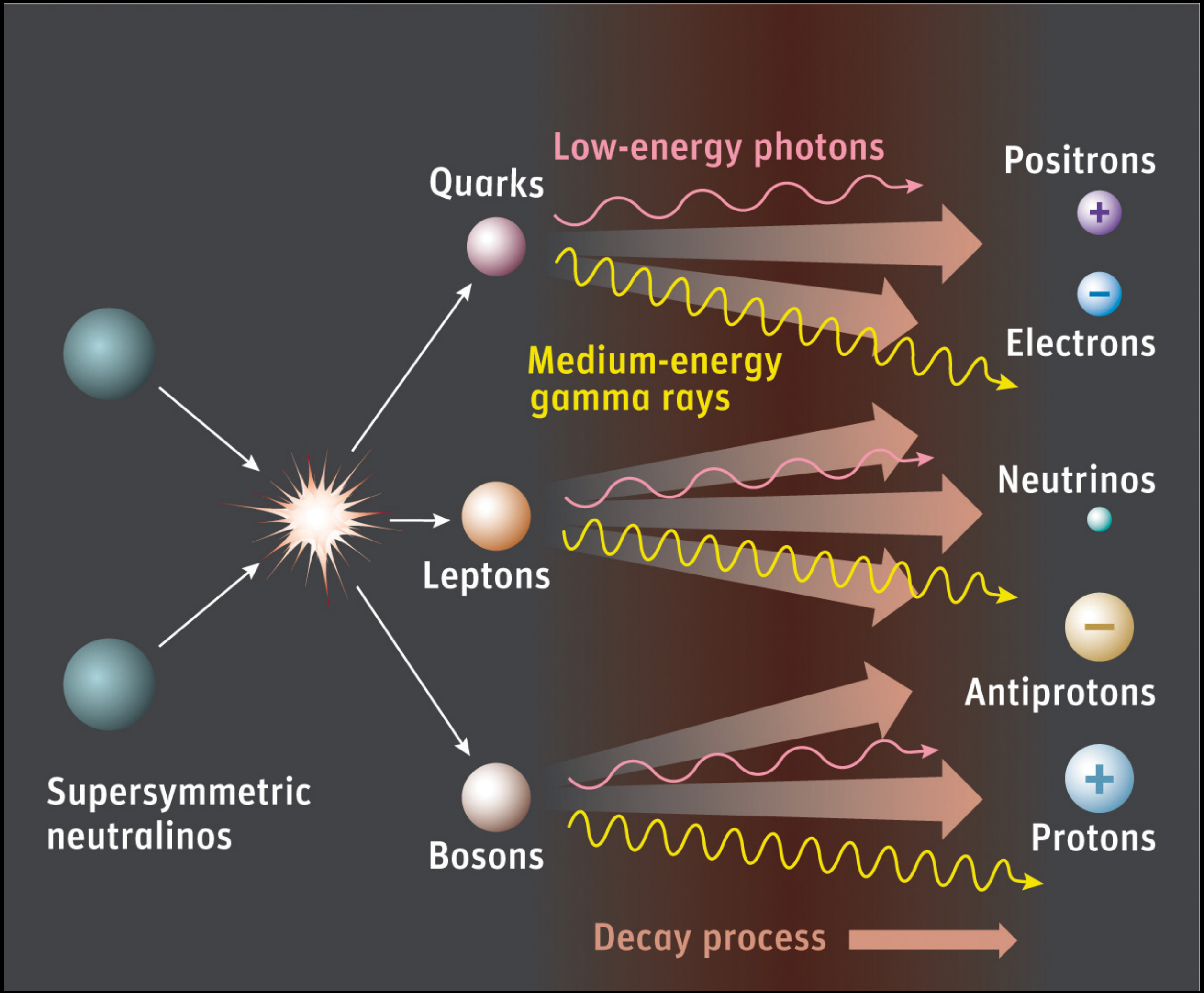
Kuhlen et al. (2010)



At v_{min}=500 km/s the hotspot is more than 10° away from the direction of Earth's motion in ~80% of all cases!

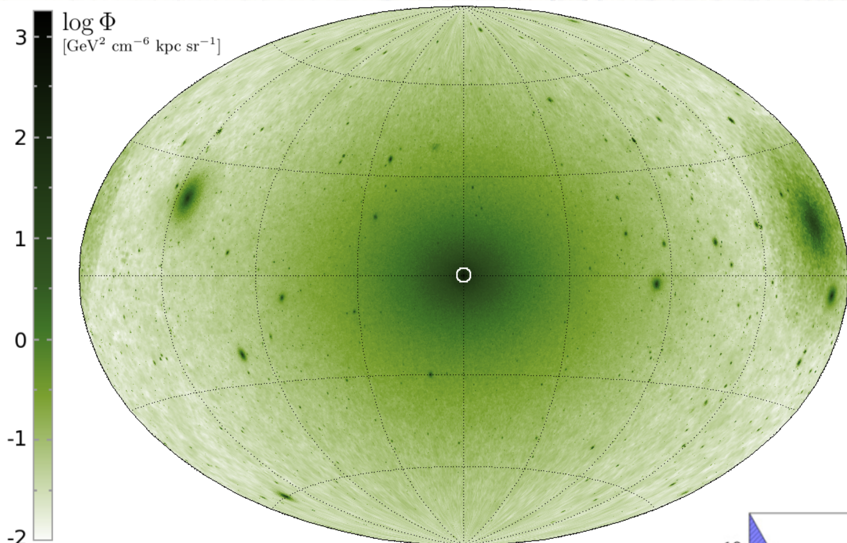
Indirect Detection: Dark Matter Annihilation

The goal of **Indirect Detection** is to measure the products (gamma rays, positrons, neutrinos) of the annihilation of dark matter particles in regions of high dark matter density.



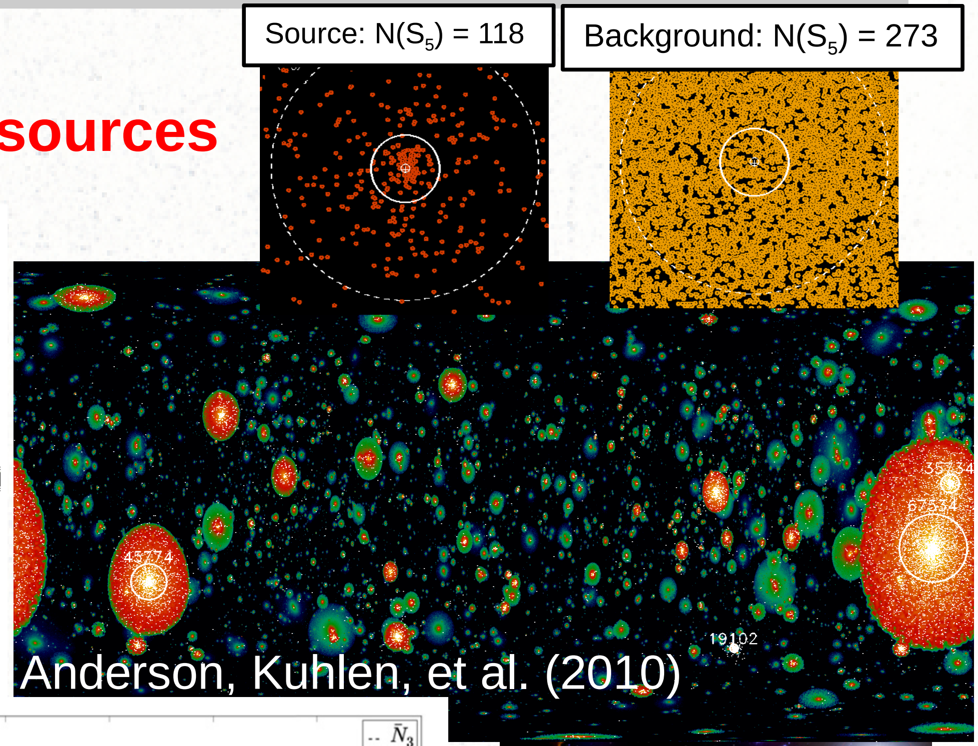
DM Substructure and Indirect Detection

Subhalos as DM annihilation sources

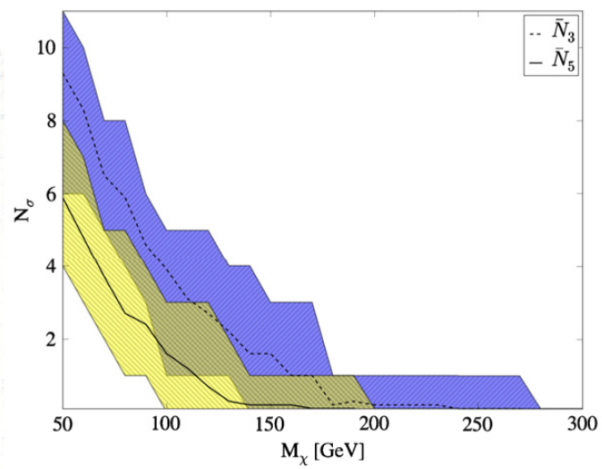


Kuhlen et al. (2008)

$$\Phi \propto \int \rho^2 d\ell$$

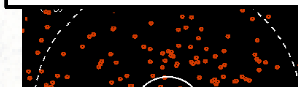


Anderson, Kuhlen, et al. (2010)

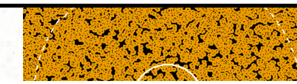


Selected Results: Astro-Particle Implications

Source: $N(S_5)$ = 118



Background: $N(S_5)$ = 273



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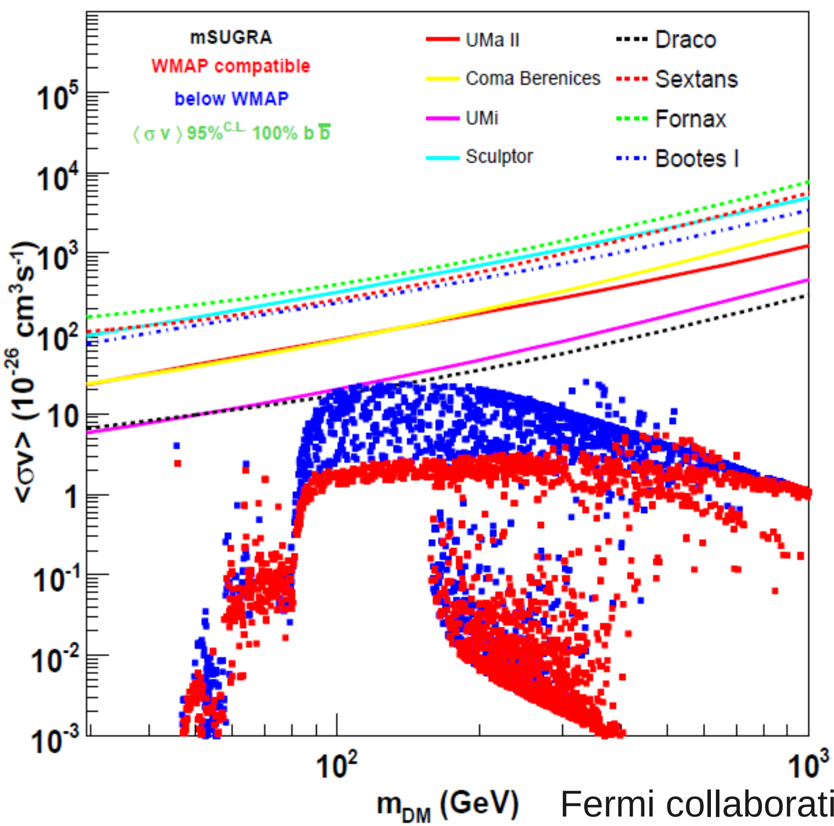
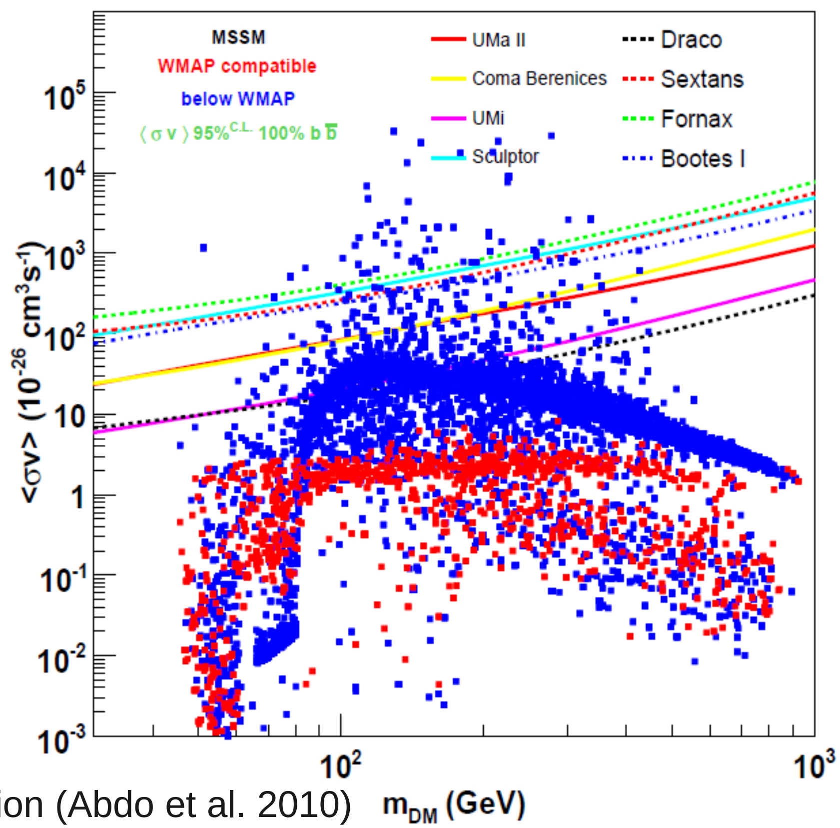
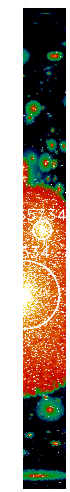
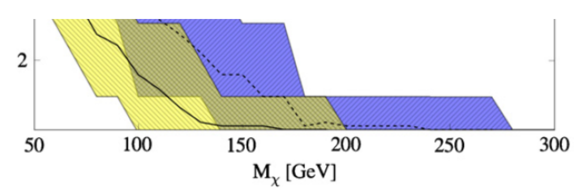


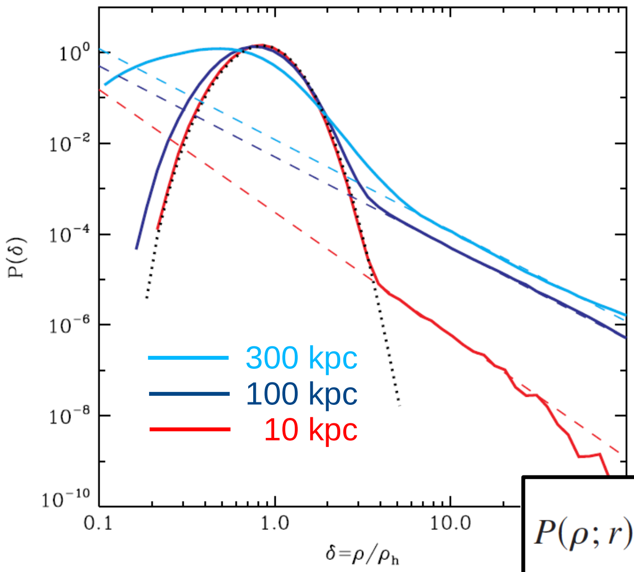


Fermi collaboration (Abdo et al. 2010)





Substructure Boost Factor



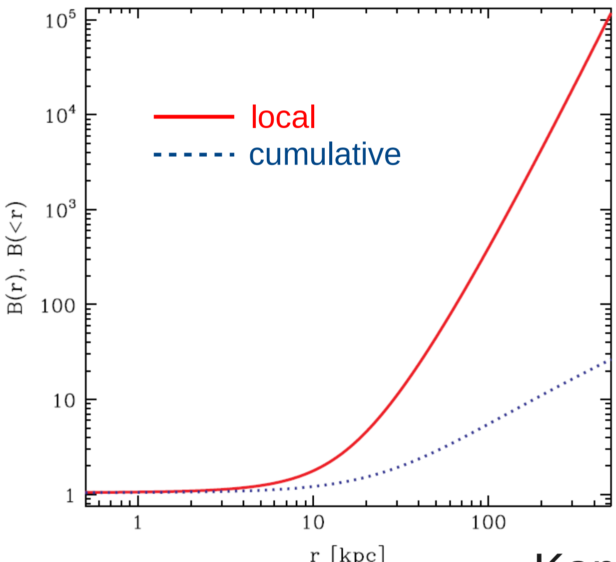
- The annihilation luminosity is potentially boosted by clumpy substructure:

$$\mathcal{L}_{\rm ann} \sim \langle \rho^2 \rangle \geq \langle \rho \rangle^2$$

- We measure the PDF of $\rho/\rho_{\rm host}$ in the simulation.
- It's fit well by a **log-normal** plus a **powerlaw** tail due to substructure.

$$P(\rho; r) = \frac{f_s}{\sqrt{2\pi\Delta^2}} \frac{1}{\rho} \exp\left\{-\frac{1}{2\Delta^2}\left[\ln\left(\frac{\rho}{\rho_h} e^{\Delta^2/2}\right)\right]^2\right\} + (1 - f_s) \frac{1+\alpha(r)}{\rho_h} \Theta(\rho - \rho_h) \left(\frac{\rho}{\rho_h}\right)^{-(2+\alpha)}$$

$$\alpha \approx 0.0 \pm 0.1 \qquad 1 - f_s(r) = 7 \times 10^{-3} \left(\frac{\bar{\rho}(r)}{\bar{\rho}(r = 100\ \rm kpc)}\right)^{-0.26}$$



- We can use this distribution to calculate a substructure boost factor as a function of radius

$$B(r) = \frac{\int \rho^2 dV}{\int [\bar{\rho}(r)]^2 dV} = \int_0^{\rho_{\rm max}} P(\rho, r) \frac{\rho^2}{[\bar{\rho}(r)]^2} d\rho,$$

$$= f_s e^{\Delta^2} + (1 - f_s) \frac{1+\alpha}{1-\alpha}\left[\left(\frac{\rho_{\rm max}}{\rho_h}\right)^{1-\alpha} - 1\right]$$

Kamionkowski, Koushiappas & Kuhlen (2010)

The Future – What's missing?

- Cosmic variance – we have 2 halos (Aquarius has 6 at lower resolution).
- Higher resolution – centers of subhalos barely resolved; needed for comparisons with dwarf galaxy kinematics.
- More detail in the phase-space structure at 8 kpc.
- **Baryonic physics!** But how? At what resolution?
- Different DM physics: “warm” DM, interacting DM, ...

Conclusions

- The number of subhalos resolved in the to-date largest simulations (Via Lactea II, GHALO, Aquarius) is ever increasing: >300,000 at latest count.
- The simulations indicate copious DM velocity substructure from subhalos and tidal streams. Corresponding stellar streams are being discovered: will there be a Missing Streams Problem?
- Velocity substructure in the DM distribution function might noticeably affect DM direct detection experiments, especially for DM models or experimental setups that are sensitive to high velocity DM particles: e.g. inelastic DM, light DM, directionally sensitive experiments.
- Individual subhalos are a tantalizing possible source for a DM annihilation signal.
- The annihilation boost factor from substructure depends on radius: at the GC or at the Sun it's not likely to be important, but integrated over the whole Galaxy it could be large.