Halo simulations with baryons and direct detection of dark matter

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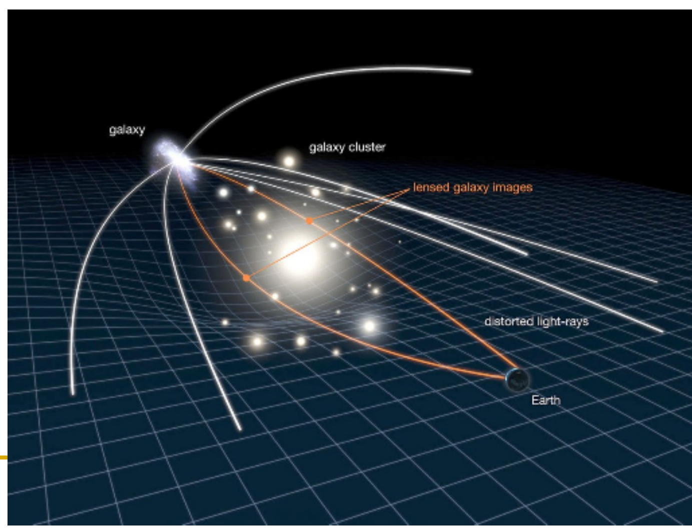
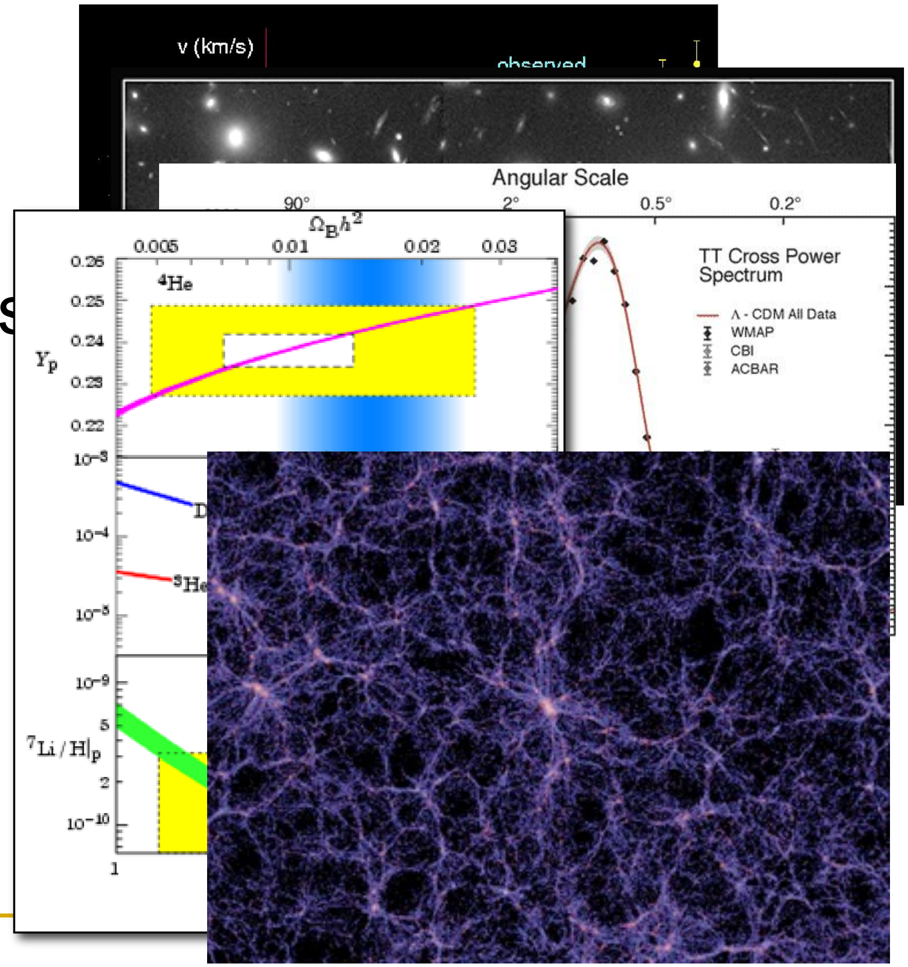
UCLA Dark Matter 2016

With Chris Savage, Monica Valluri, Katie Freese, Greg Stinson, Jeremy Bailin: arXiv:1601.04725

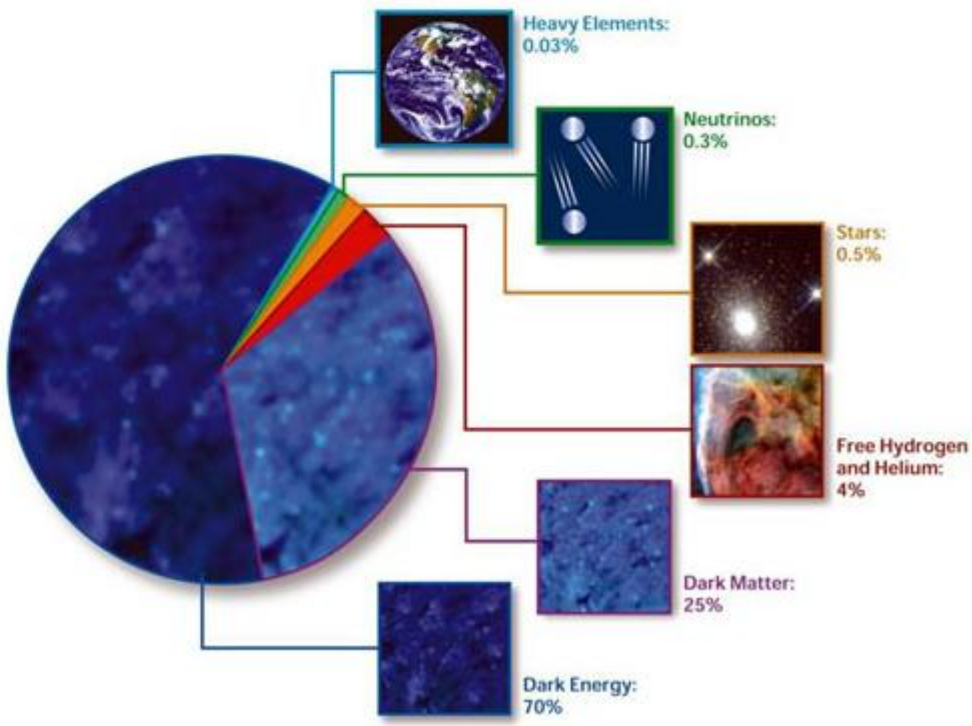
Evidence for Dark Matter

- Rotation Curves
- Gravitational Lensing
- CMB Power Spectrum
- Big Bang Nucleosynthesis
- Large Scale Structure



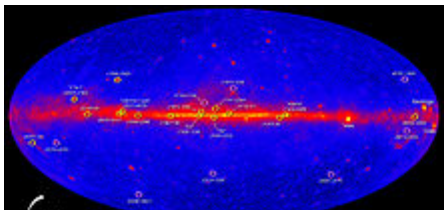


ΛCDM Model

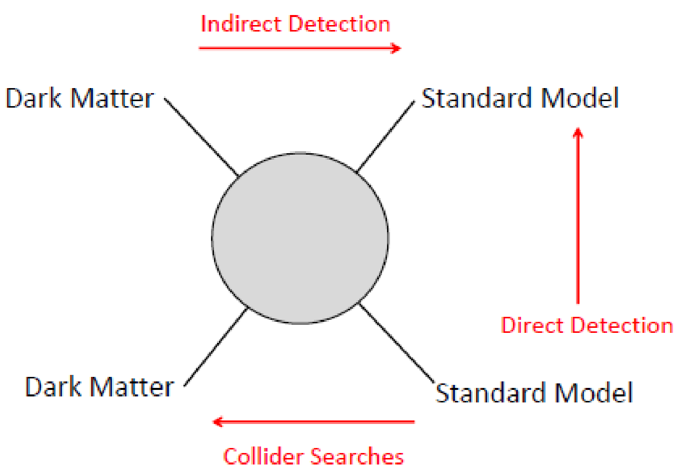


Rocky Kolb argues that this should also be the distribution of funding in the sciences

How are we searching for dark matter?

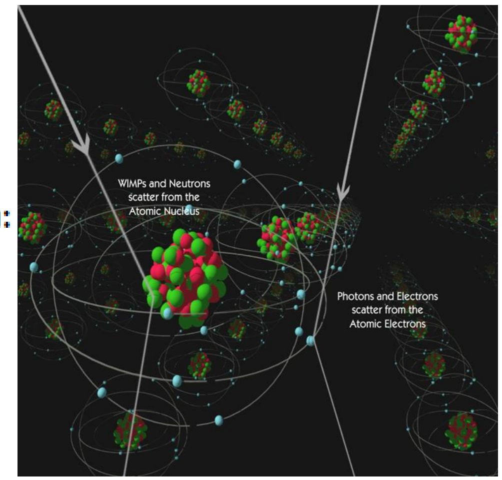


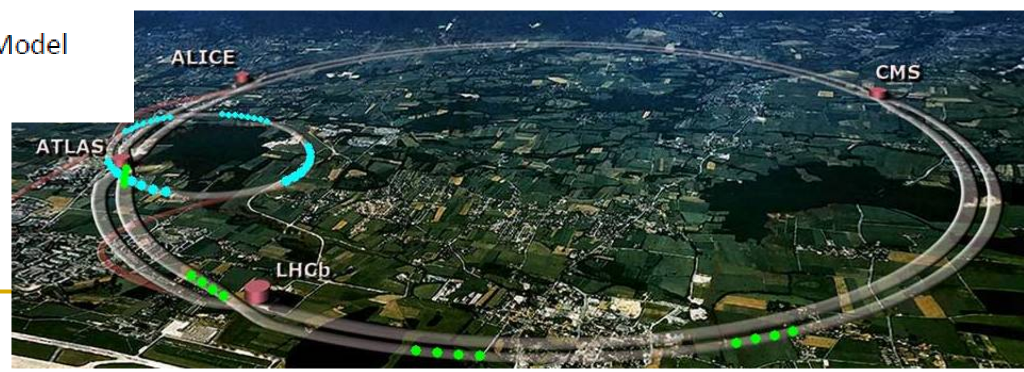
Indirect detection:
AMS2, PAMELA, Fermi-LAT



LEP
LHC
Tevatron

Direct detection:
CDMS
CoGeNT
COUPP
CRESST
DAMA
XENON
.....





Direct Detection Experiments

$$\frac{dR}{dE_R} = N_T \frac{\rho_{DM}}{m_{DM}} \int_{|\vec{v}|>v_{\rm min}} d^3v \, v f(\vec{v}, \vec{v_e}) \frac{d\sigma}{dE_R}$$

$$v_{\rm min} = \sqrt{E_R m_N / 2\mu^2},$$

Defined by kinematics

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2} \frac{\sigma_n}{\mu_n^2} \frac{[f_p Z + f_n (A-Z)]^2}{f_n^2} F^2(q)$$

Spin-Independent
Elastic Scattering

Signal in a detector needs inputs from
astrophysics, particle physics, and nuclear physics

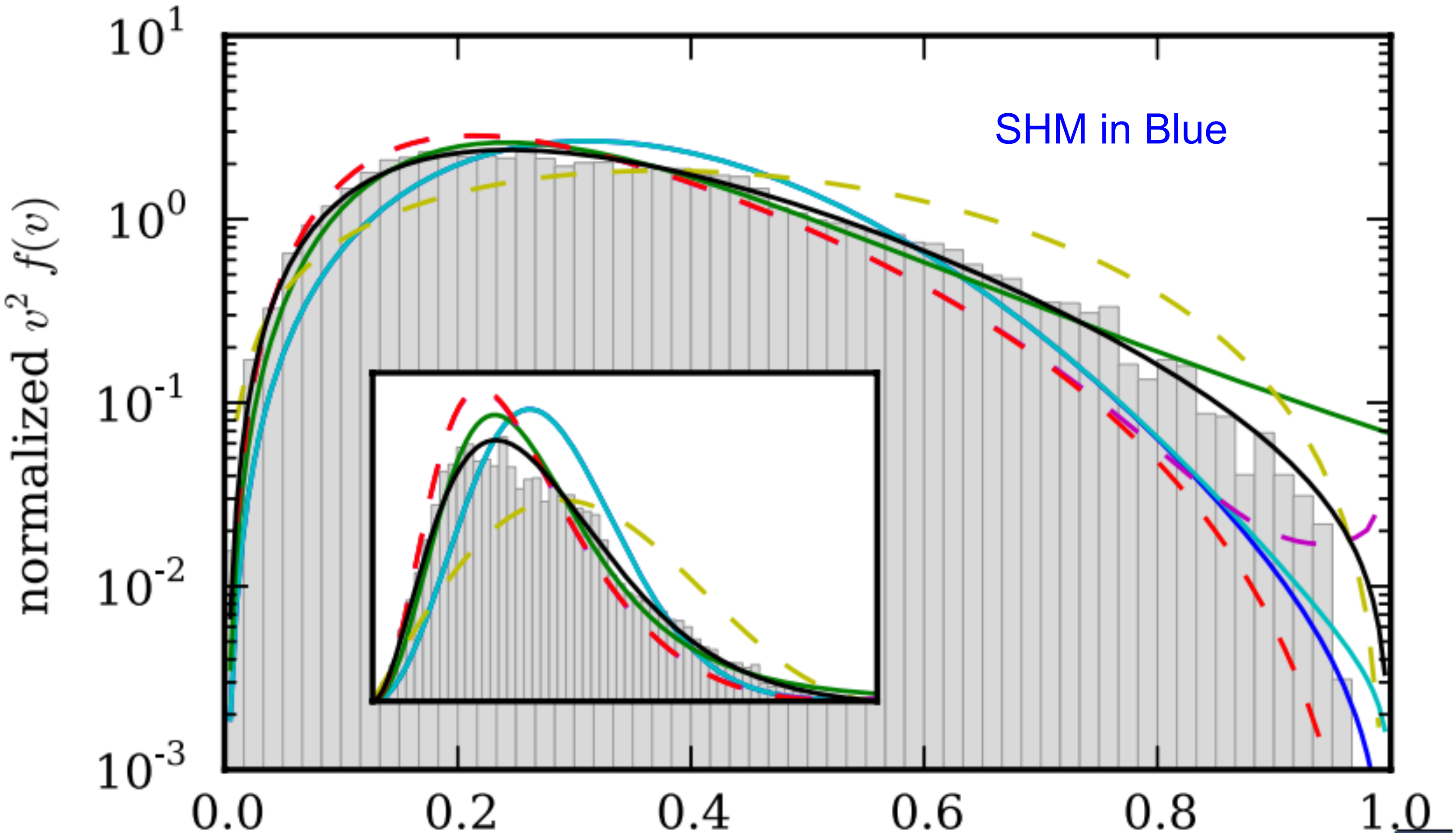
The Standard Halo Model (SHM)

$$f_{\mathrm{MB}}(\mathbf{v}) = \begin{cases} \frac{1}{N_{\mathrm{esc}}} \left(\pi v_0^2\right)^{-3/2} e^{-\mathbf{v}^2/v_0^2}, & \text{for } |\mathbf{v}| < v_{\mathrm{esc}} \\ 0, & \text{otherwise,} \end{cases} \qquad N_{\mathrm{esc}} = \mathrm{erf}(z) - \frac{2}{\sqrt{\pi}} z e^{-z^2}$$

- The SHM assumes an isothermal spherical dark matter distribution
  - Maxwell-Boltzmann distribution
  - dispersion velocity equal to the (circular) disk rotation speed in the solar neighborhood.
  - inferred strictly from the mass distribution and not the actual particle velocities.
- This is the fiducial halo model overwhelmingly assumed in the community for the purposes of dark matter direct detection phenomenology.
- Belief among community that this SHM cannot be trusted as it does not adequately account for the complicated gravitational collapse and merger history of actual galaxies.
- As alternatives, some have studied anisotropic velocity distributions and others have found alternative analytic fits that were thought to better match the true distribution, particularly at the high-velocity tail
- These alternatives to the SHM were motivated in part by results of dark matter only N-body simulations of structure formation


Many different dark matter only
simulations of galaxy formation exist

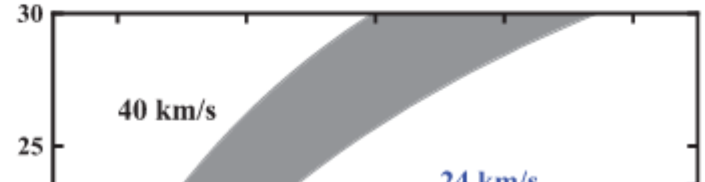
How Does the SHM compare to the dark matter only N-body simulations?

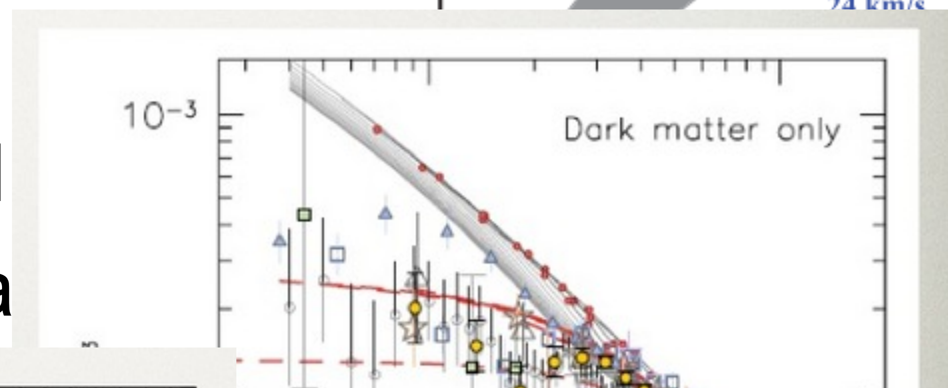


THE ASTROPHYSICAL JOURNAL, 764:35 (6pp), 2013 February 10

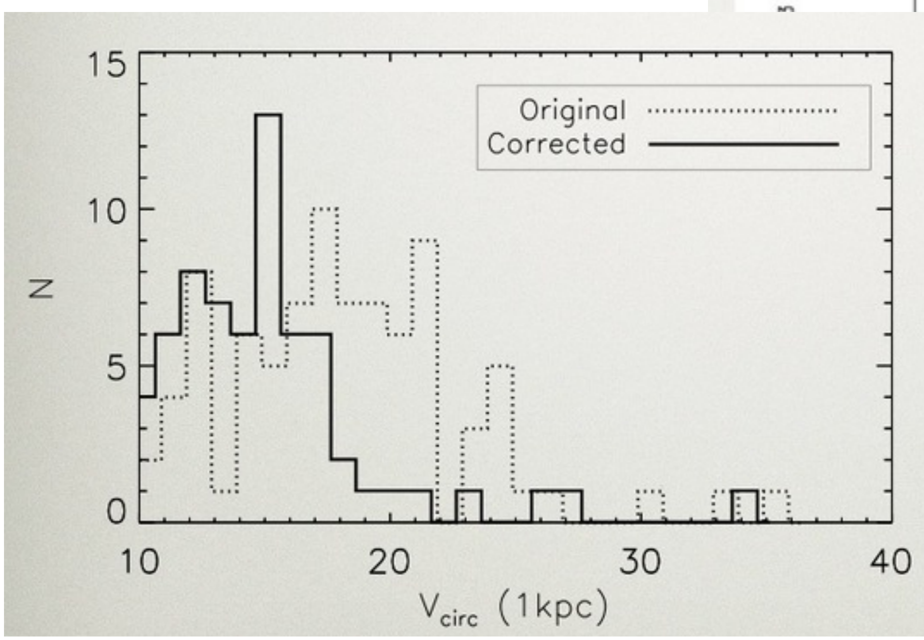
Small Scale Problems With CDM

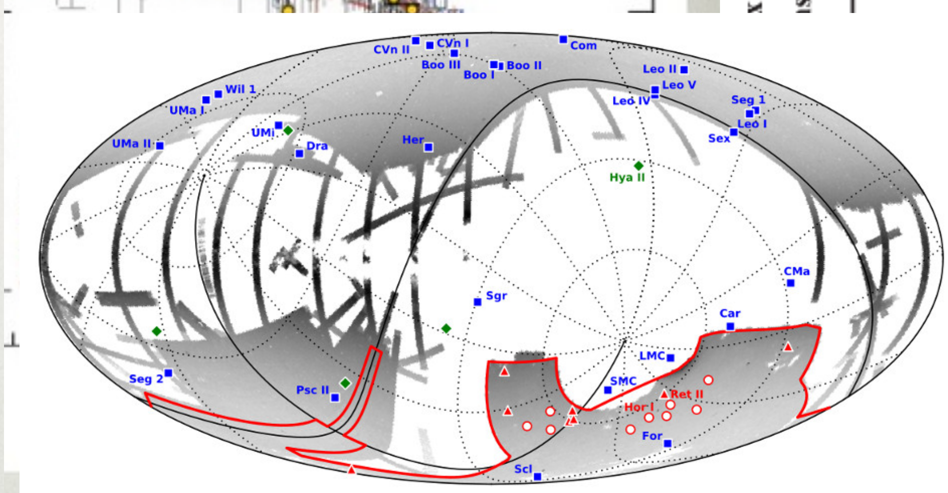
- Bulgeless Disk Galaxies
- Core/Cusp
- Too Big To Fail
- The Missing Sa



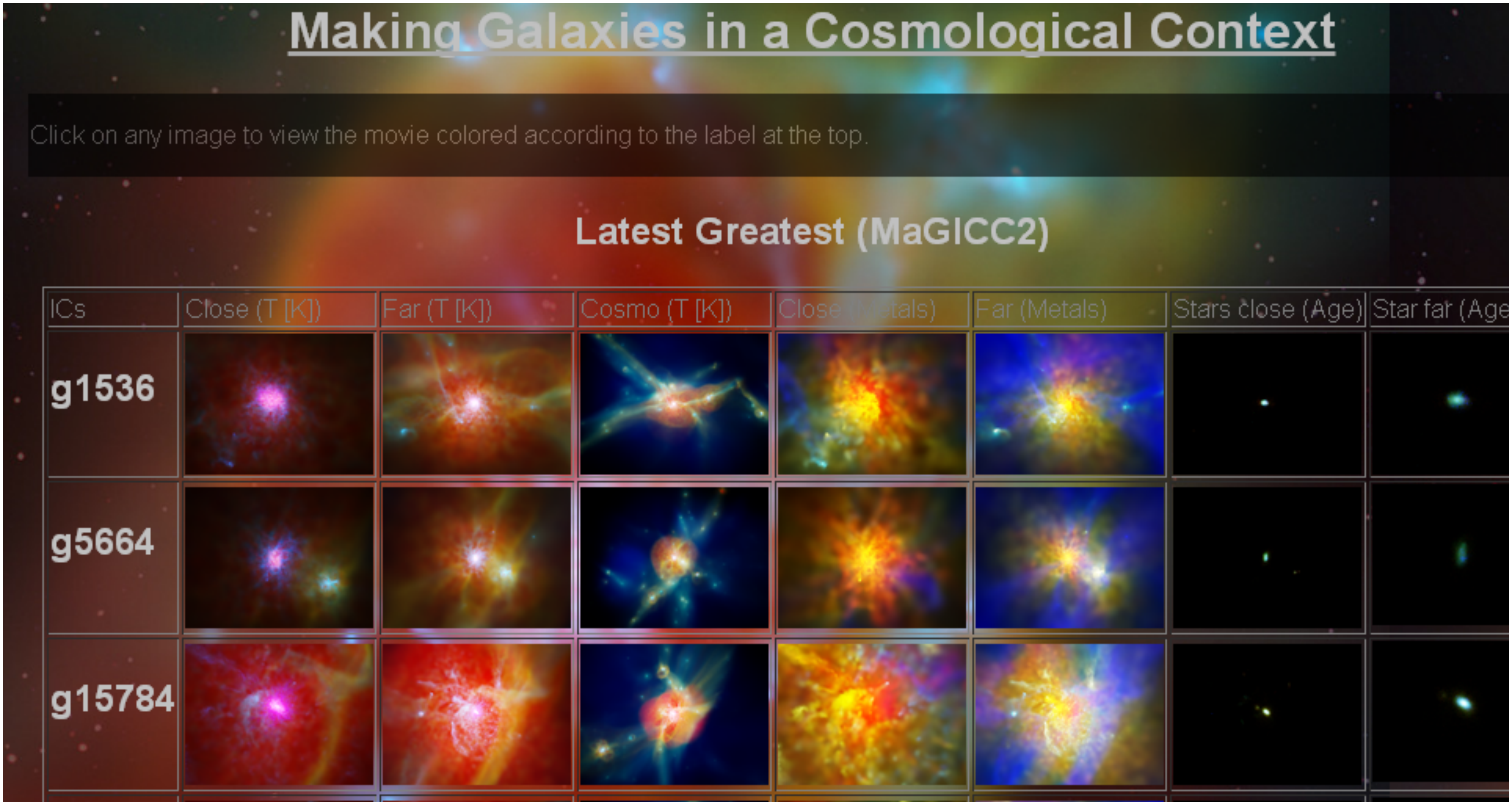


Oh et al., 2011, AJ, 142, 24





MaGICC Simulations



McMaster Unbiased Galaxy Simulations

- The MUGS project is a set of high-resolution galaxy formation simulations of isolated ~L* galaxies performed using the hydrodynamics (SPH) plus N-body code GASOLINE.

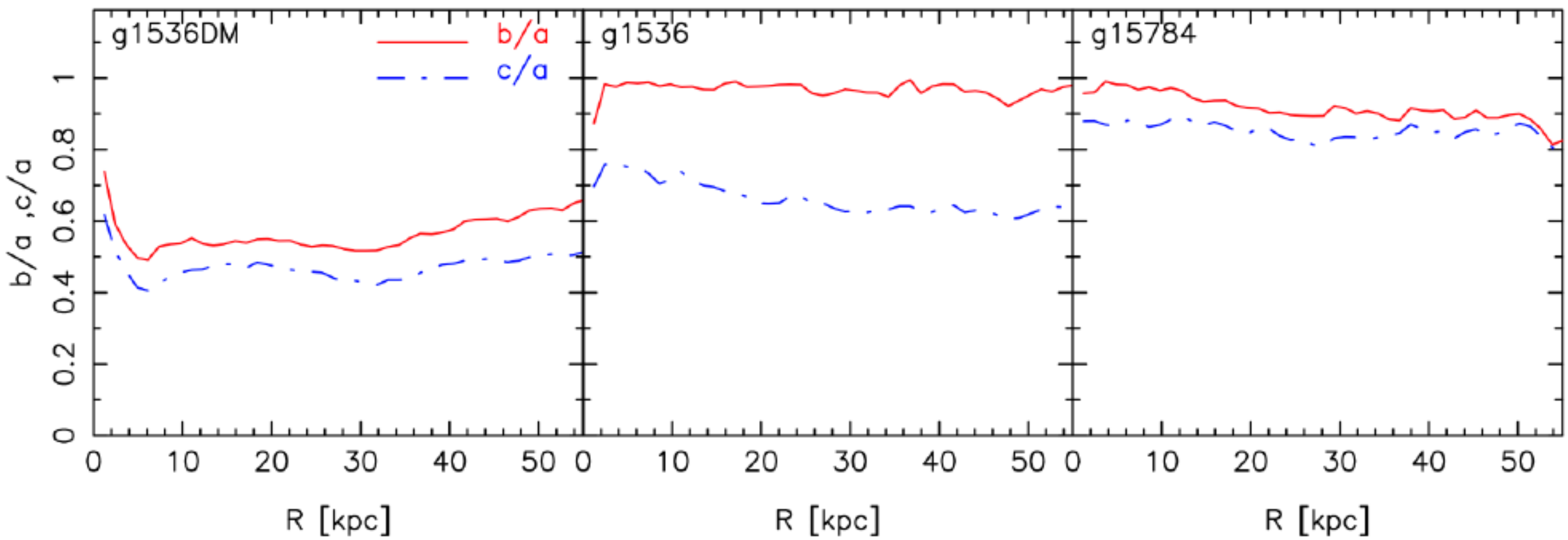
- The simulations include a treatment of low temperature metal cooling, UV background radiation, star formation, and physically motivated stellar feedback.

- The regions to resimulate at high resolution are chosen randomly from halos of mass 5×10^{11} to 2×10^{12} Msun without regards to merger history or spin parameter; this lack of selection bias enables us to directly compare not only the mean properties of the resulting galaxies, but also their full distribution.

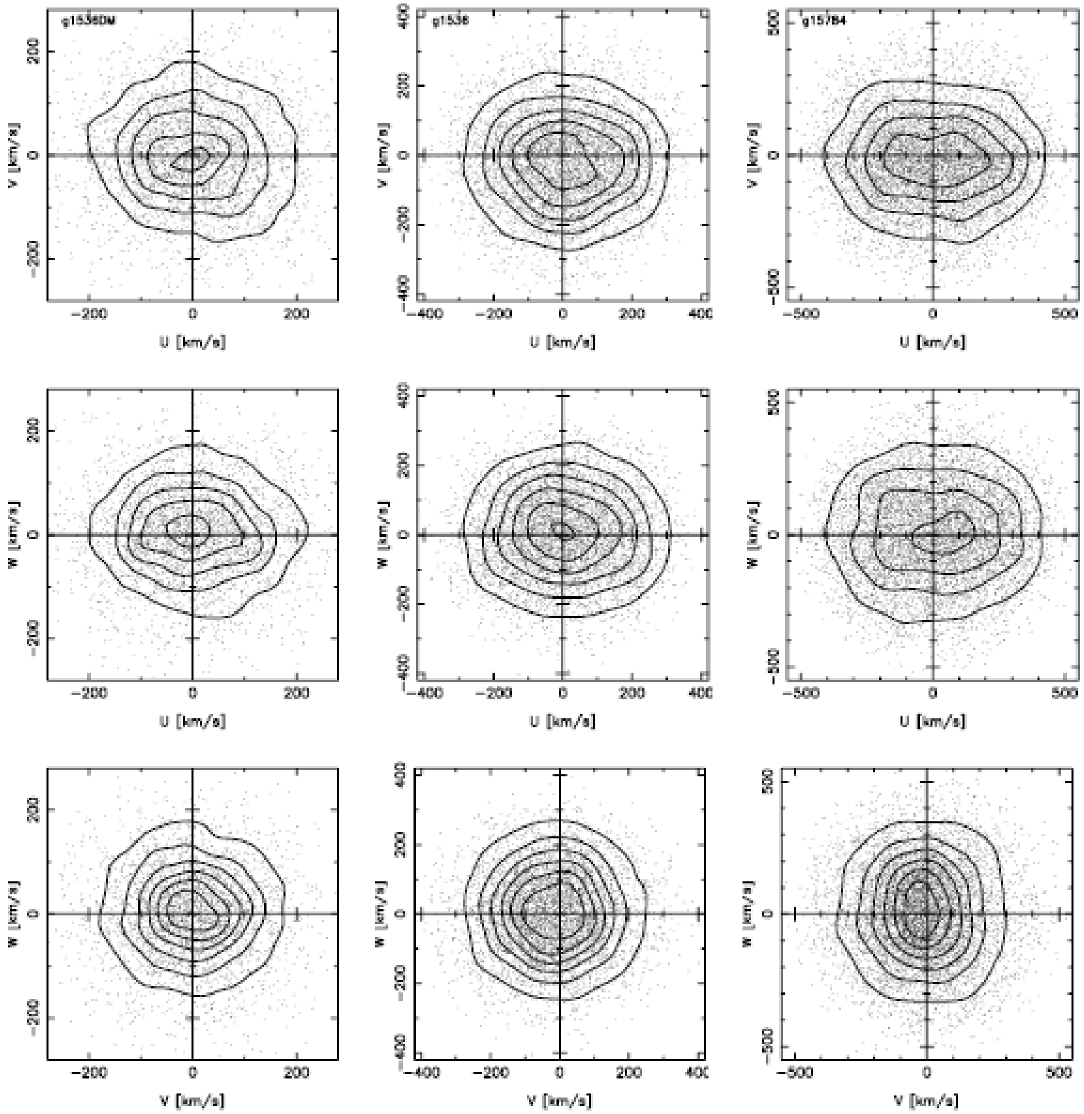
The Galaxies We Have Used

	g1536DM (DM-only)	**g1536** (DM+baryons)	**g15784** (DM+baryons)
Simulation			
Virial Mass [$M_\odot$]	7.48×10^{11}	5.84×10^{11}	1.50×10^{12}
Virial Radius [kpc]	260	143	328
DM particle mass [$M_\odot$]	1.33×10^{6}	1.11×10^{6}	1.11×10^{6}
Circular velocity (at $R = 8$ kpc) [km/s]	108	187	273
Torus ($r_1 = 8$ kpc, $r_2 = 2$ kpc)			
Number of DM particles	3085	4849	6541
Average DM density [GeV/cm^3]	0.270	0.346	0.493
Average velocity (U,V,W) [km/s]	$(0.0, 5.3, -0.5)$	$(2.7, 21.6, 2.3)$	$(0.9, 18.5, 3.4)$
Velocity s.d. (σ_U,σ_V,σ_W) [km/s]	$(109, 95, 90)$	$(144, 128, 121)$	$(205, 166, 177)$
RMS speed [km/s]	$98\sqrt{3}$	$133\sqrt{3}$	$184\sqrt{3}$
Maximum speed [km/s]	359	454	600.

Halo Shapes



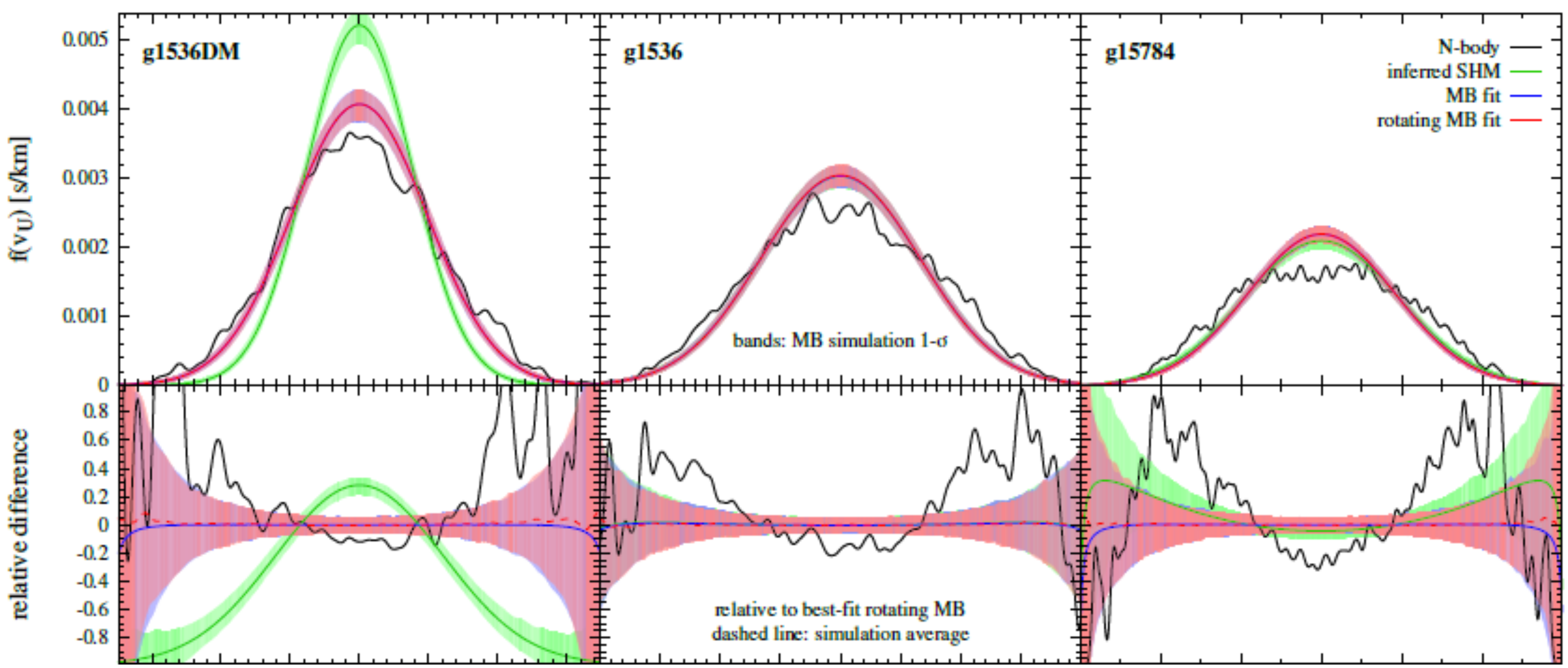
The Velocity Ellipsoids



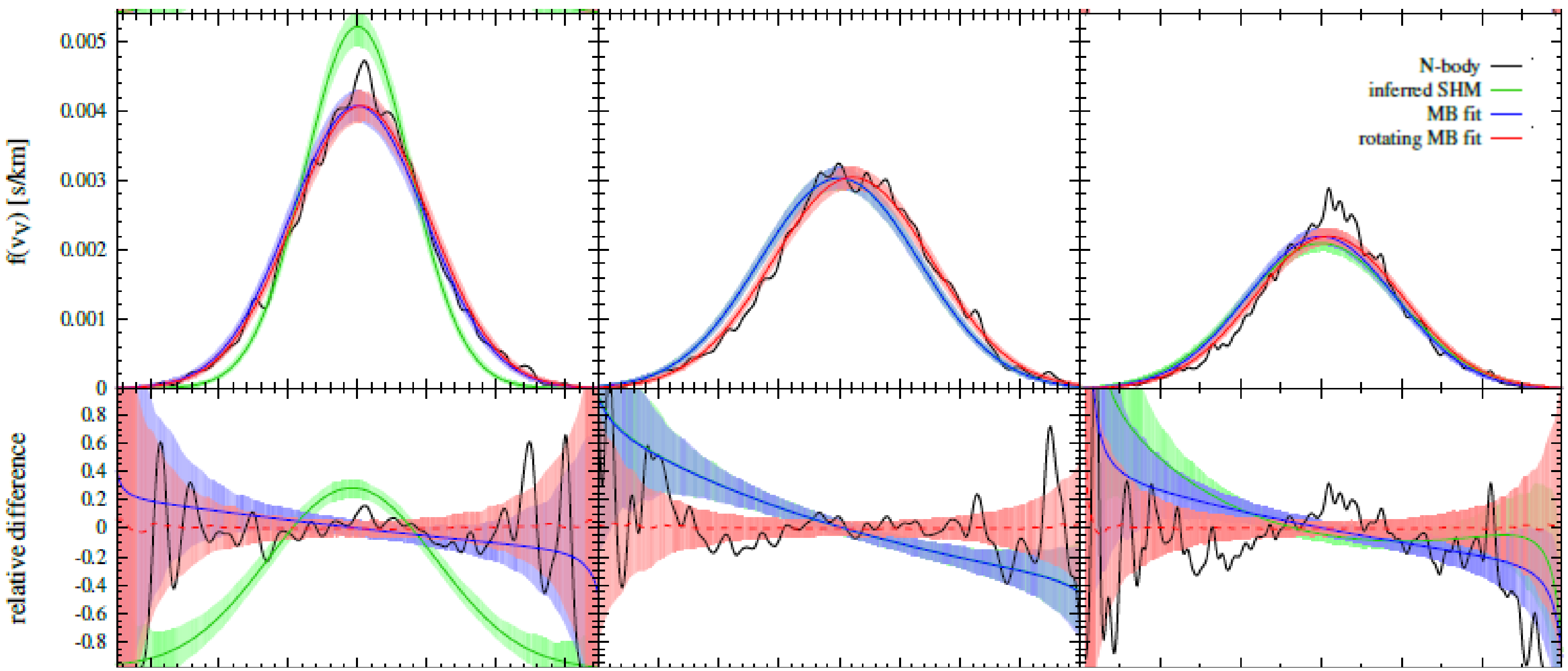
The Models for the Velocity Distributions

	g1536DM	g1536	g15784
Standard Halo Model			
$v_0 (= v_{\rm rot})$ [km/s]	108	187	273
$v_{\rm esc}$ [km/s]	359	454	600.
Best-fit Maxwell-Boltzmann			
v_0 [km/s]	139	187	260.
$v_{\rm esc}$ [km/s]	359	454	600.
Best-fit Maxwell-Boltzmann (rotating)			
v_0 [km/s]	139	186	259
$v_{\rm esc}$ [km/s]	363	465	602.
$\mathbf{v}_{\rm MB}$ [km/s]	(0,5.3,0)	(0,21.6,0)	(0,18.5,0)

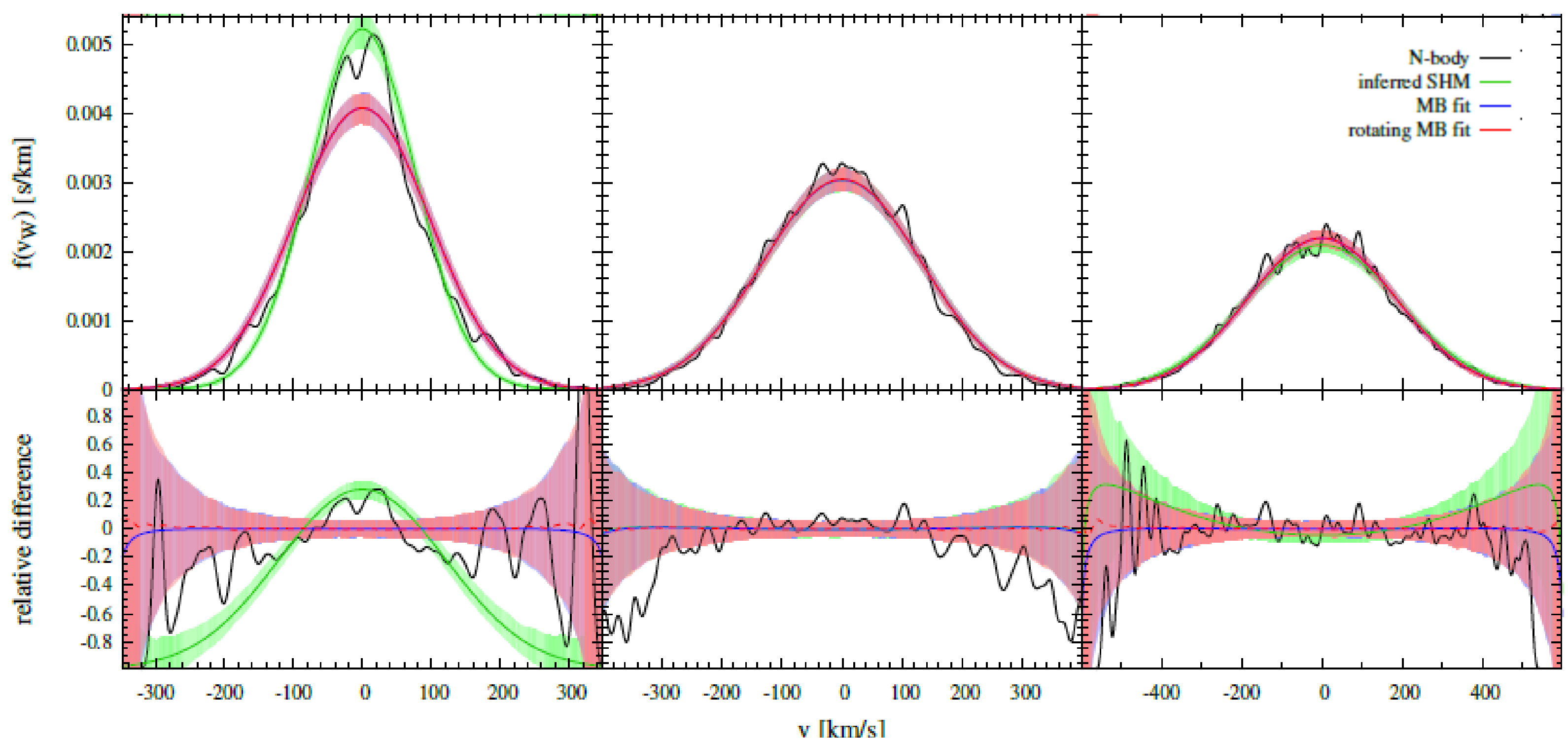
Results for the velocity component in the direction towards the Galactic center



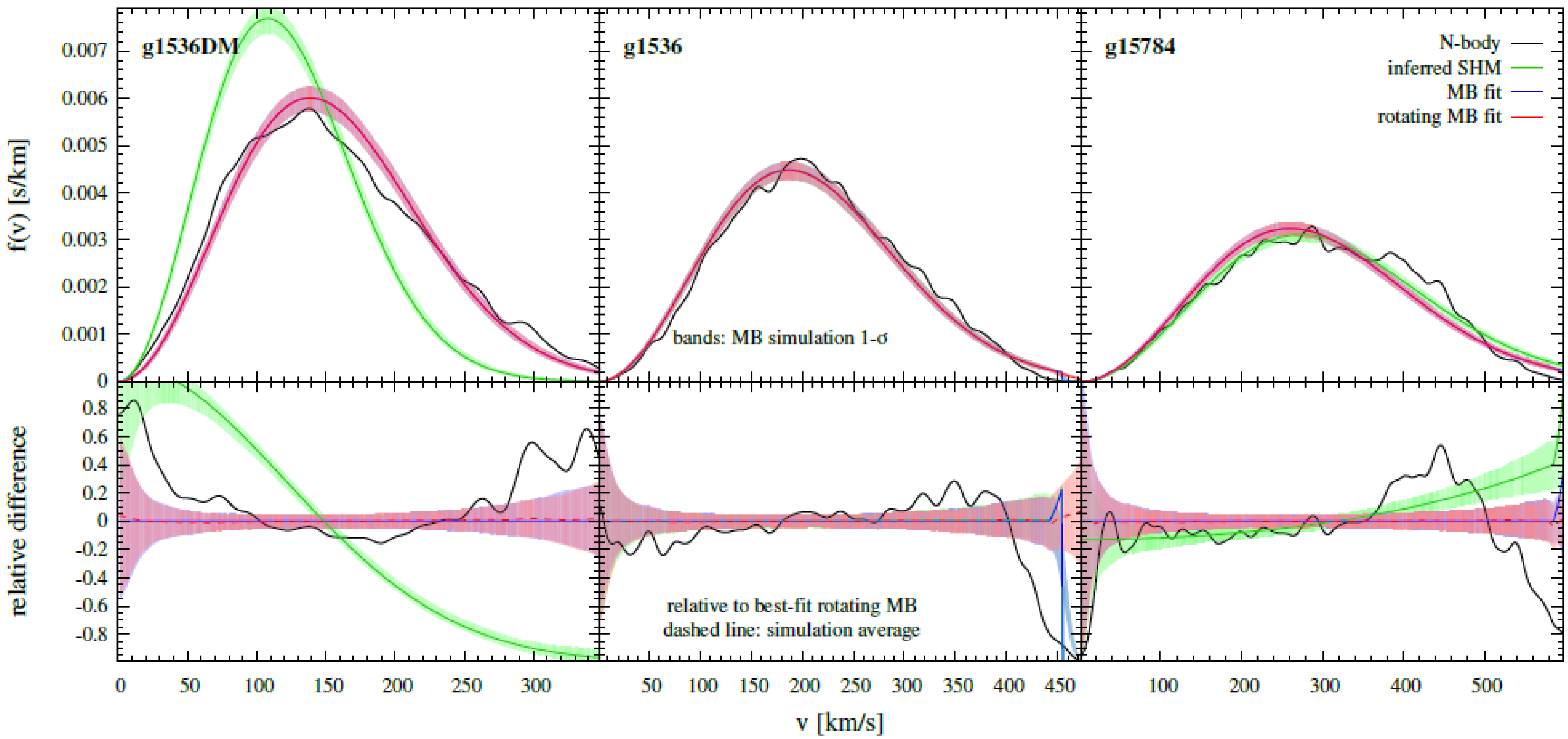
Results for the velocity component in the direction of the bulk rotation



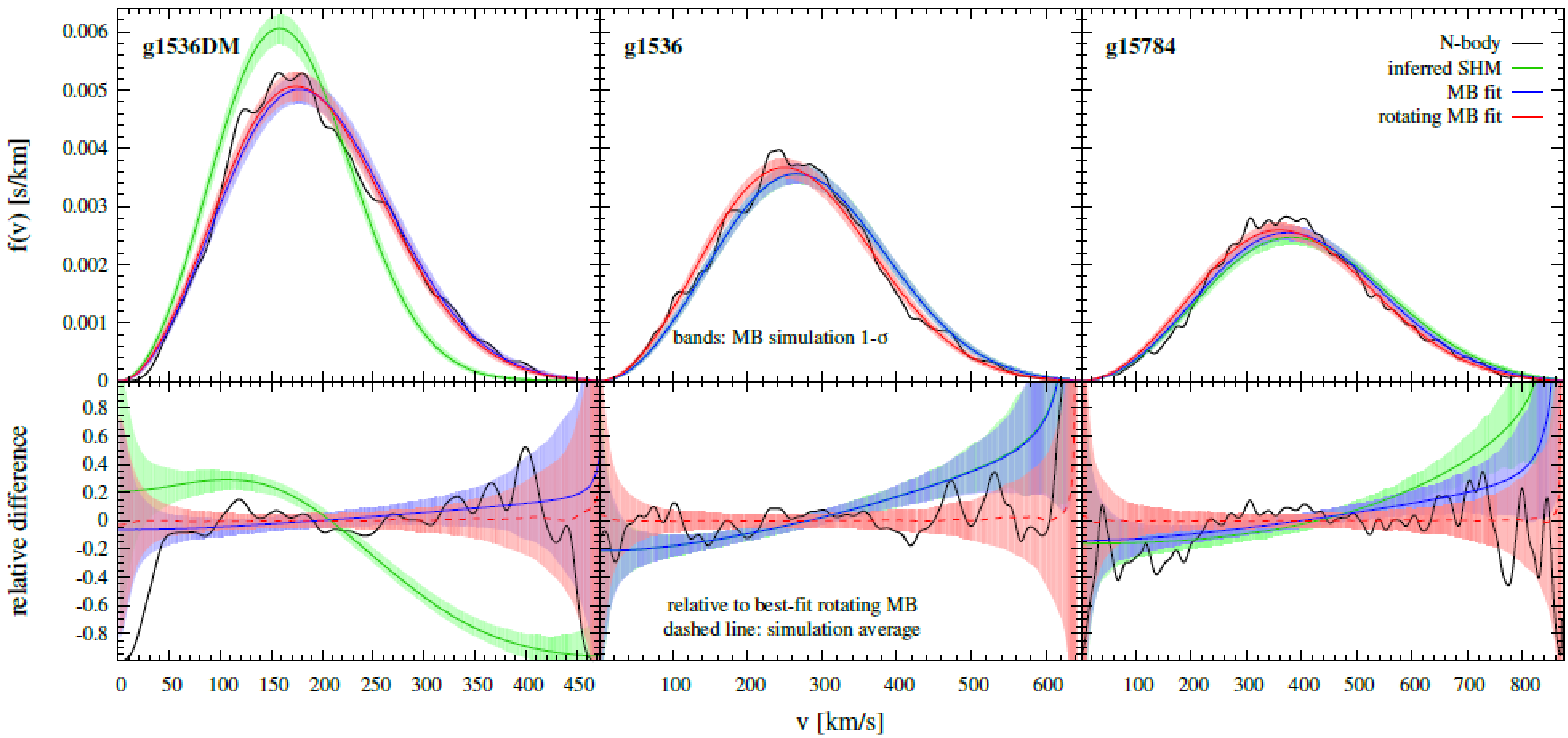
Results for the velocity component out of the Galactic plane



The speed distribution in the galactic frame

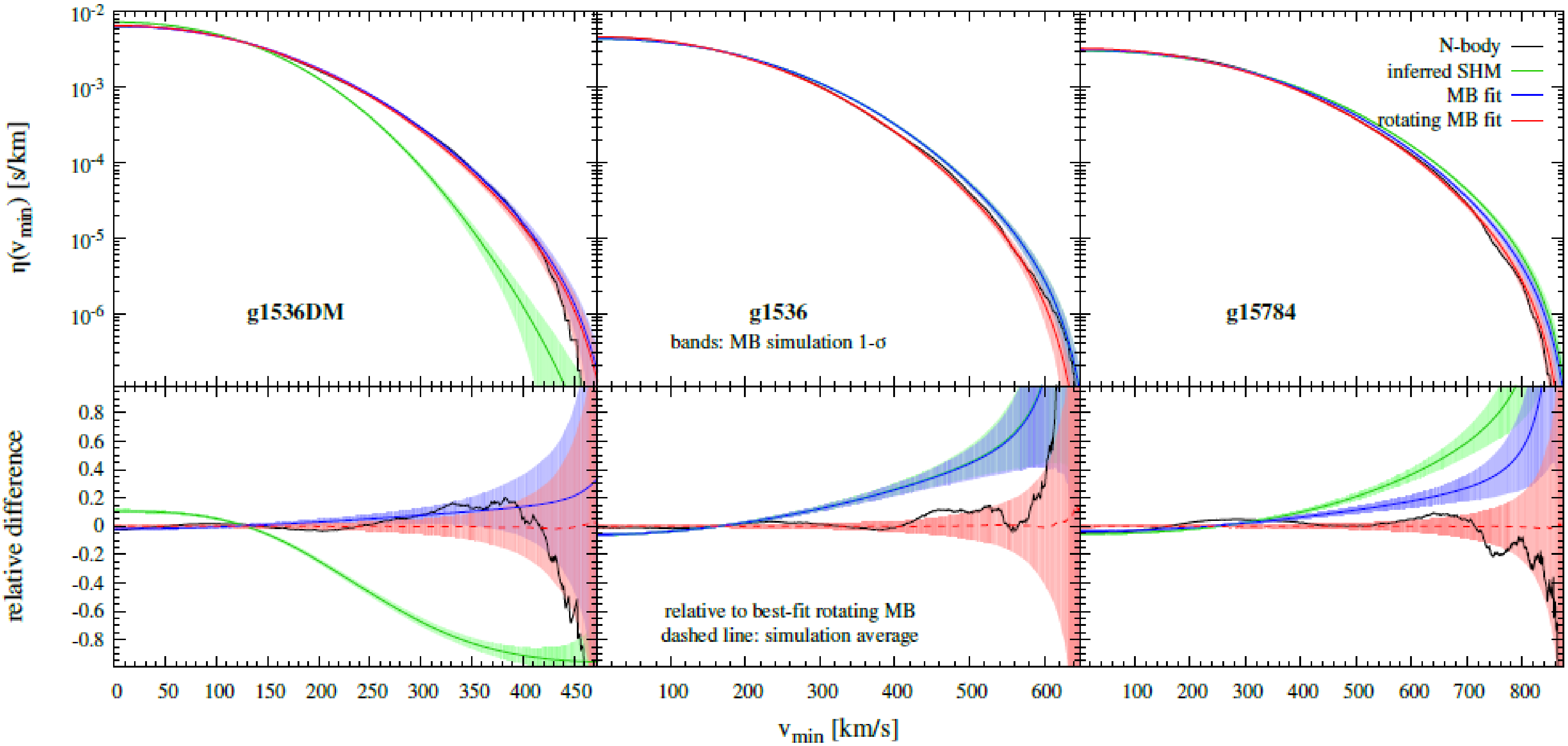


The speed distribution in the Earth's frame



The velocity integral

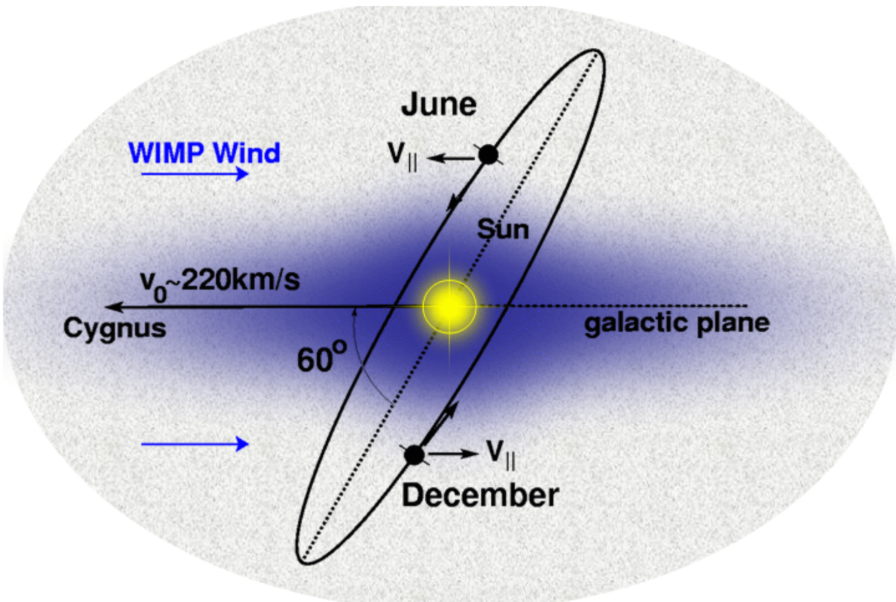
$$\frac{dR}{dE_R} = N_T \frac{\rho_{DM}}{m_{DM}} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma}{dE_R}$$



Dark Matter Should Have Annual Modulation

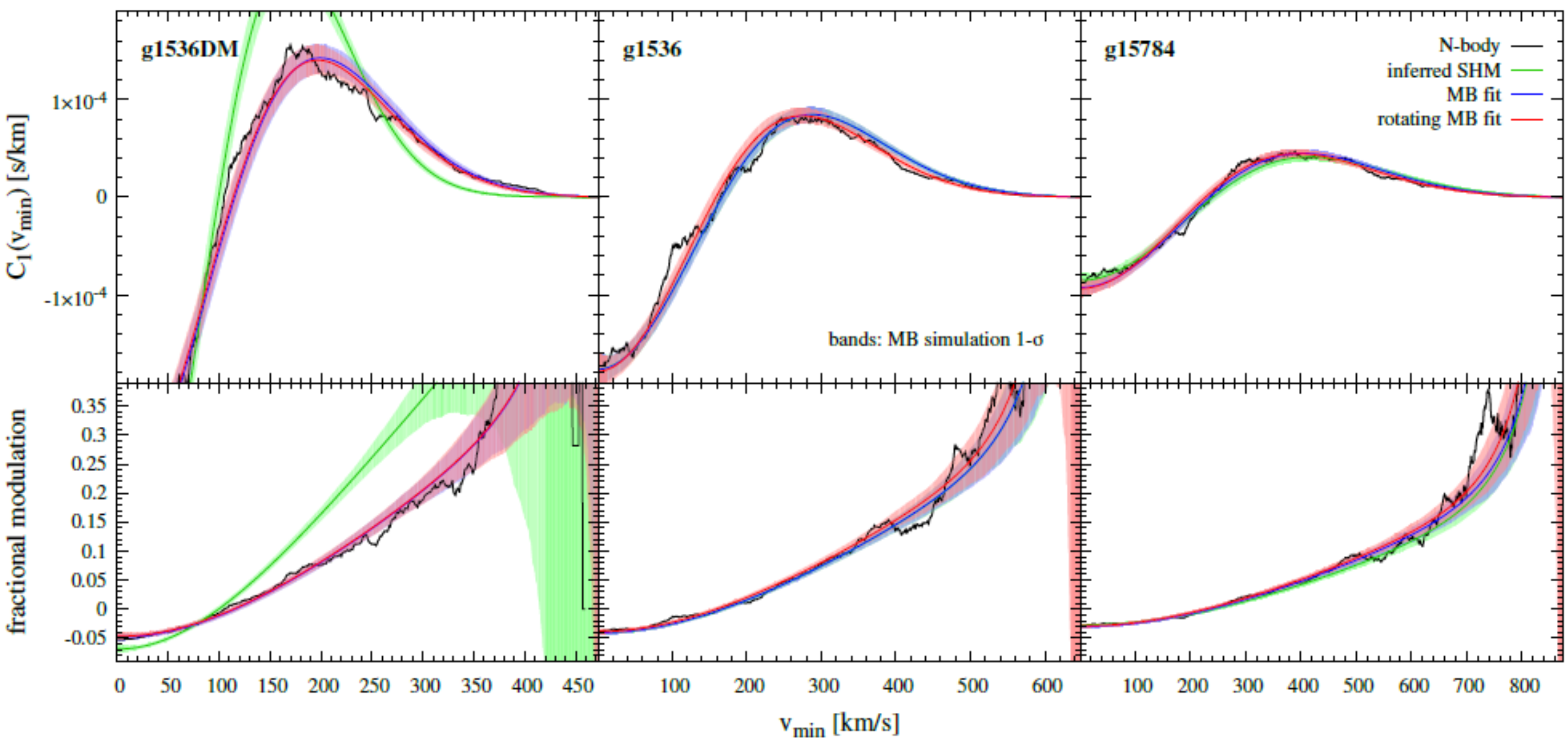
$$\frac{dR}{dE_R} = N_T \frac{\rho_{DM}}{m_{DM}} \int_{|\vec{v}|>v_{\min}} d^3v\, v\, f(\vec{v}, \vec{v_e}) \frac{d\sigma}{dE_R}$$

$$\eta(v_{\min}, t) = C_0(v_{\min}) + \sum_{n=1}^{\infty} C_n(v_{\min}) \cos n\omega(t-t_0) + \sum_{n=1}^{\infty} S_n(v_{\min}) \sin n\omega(t-t_0)$$



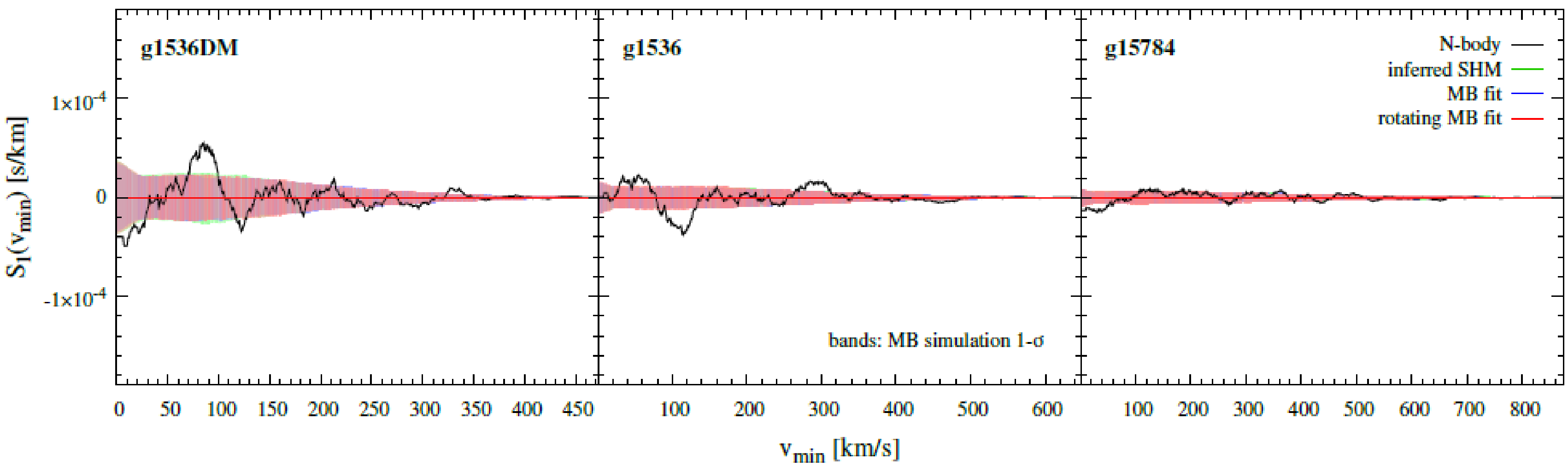
http://www.hep.shef.ac.uk/research/dm/intro.php

The Modulation Amplitude



The First Order Sine Component

- For isotropic dark matter distributions, this component should be approximately zero.

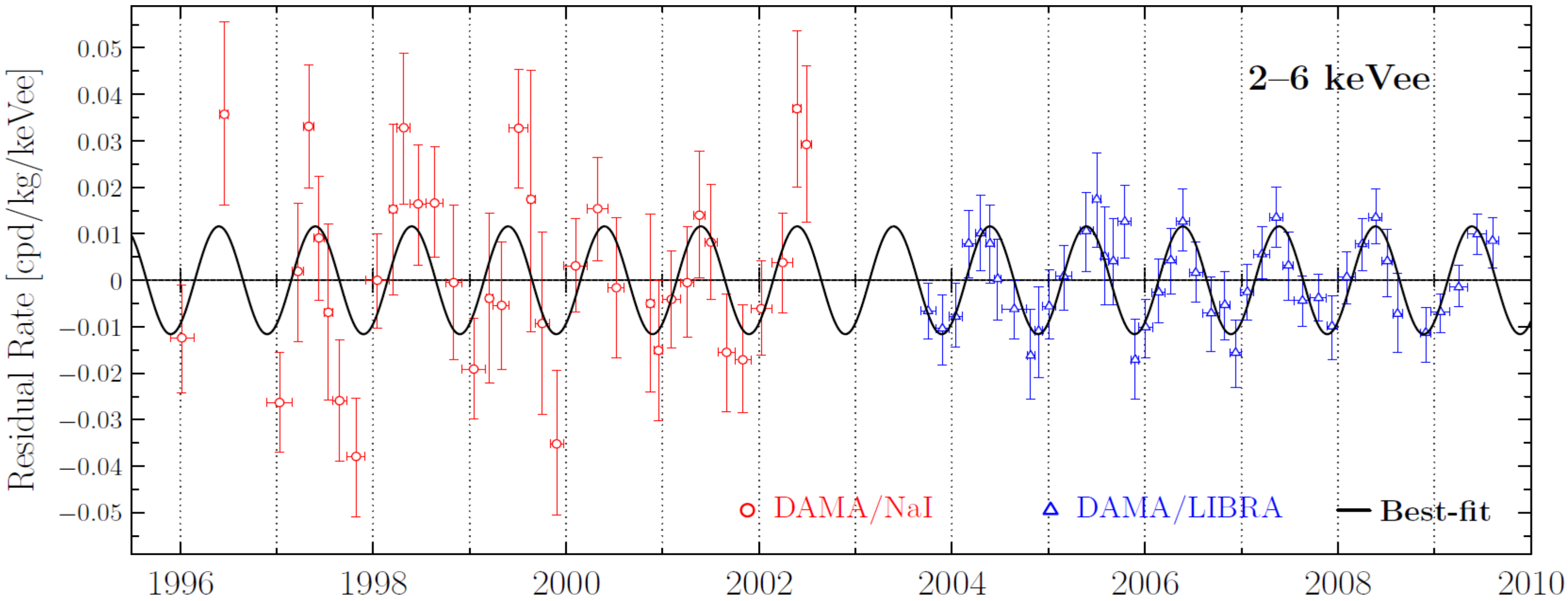


The million dollar question

- How would direct detection experimental results would be affected by the differences among the various halo models?

DAMA Results

- Modulation search using NaI crystals (scintillation only)
  - DAMA/NaI: 1996-2002 R. Bernabei *et al.*, Riv. Nuovo Cim. **26N1**, 1 (2003)
  - DAMA/LIBRA: 2003-2009 R. Bernabei *et al.*, Eur. Phys. J. **C67**, 039 (2010)

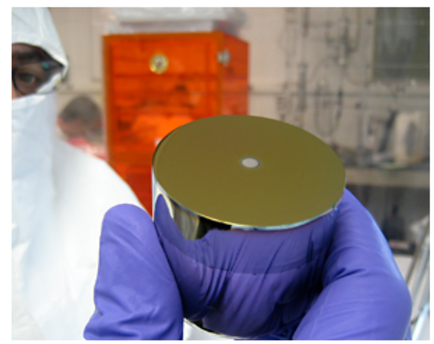


14 years, 1.33 ton years of exposure 9.3σ measurement of annual modulation

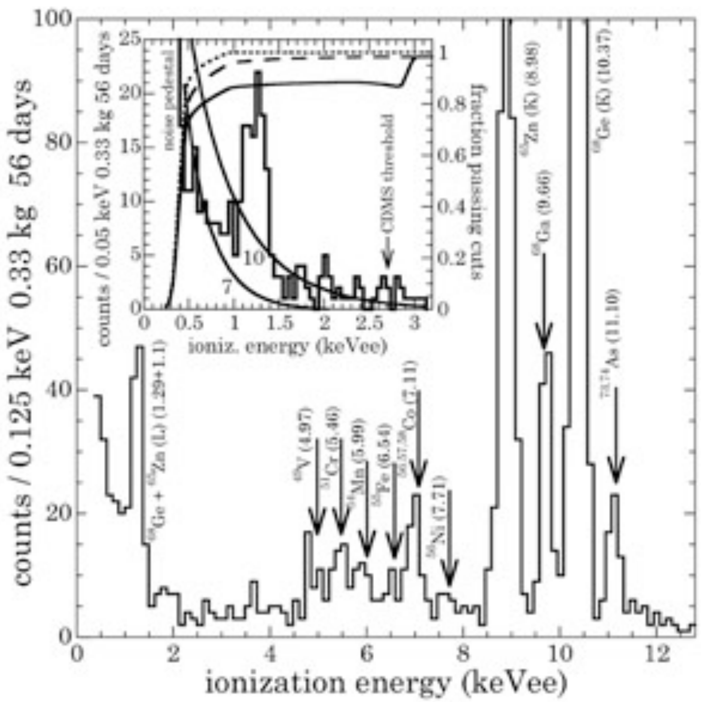
Lowering the DAMA threshold

The CoGeNT (Ge) detector

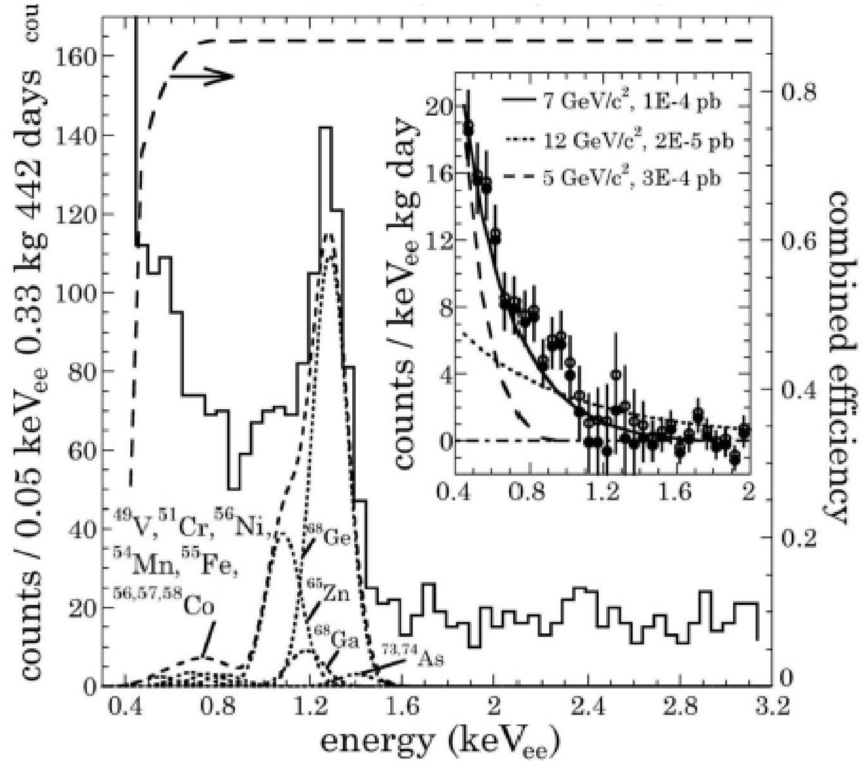
- Located in the Soudan Mine in Minnesota
- Low background and low energy threshold
- Uses ionization signal only with 0.33 kg fiducial mass
- Found an excess of events at low energy in first 56 day run (2010)
- Released 15 months of data (2011)
- Data is available by request



CoGeNT

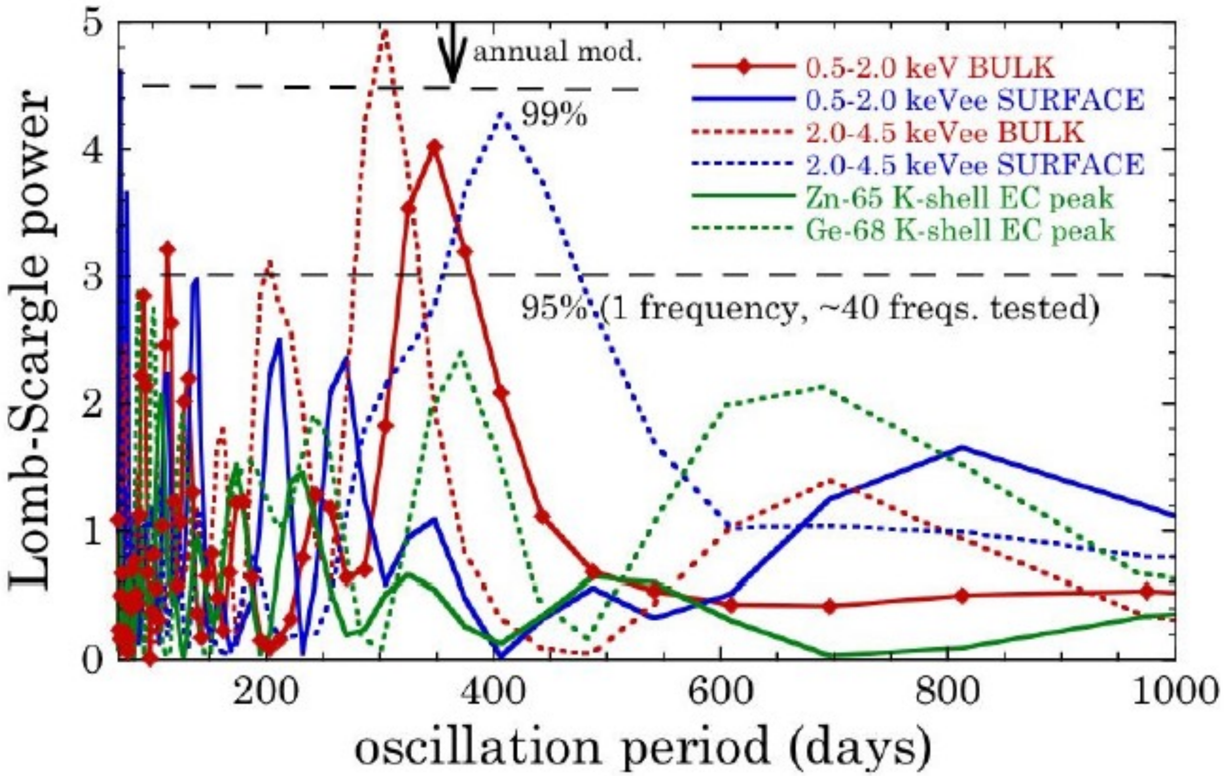


arXiv:1002.4703



arXiv:1106.0650

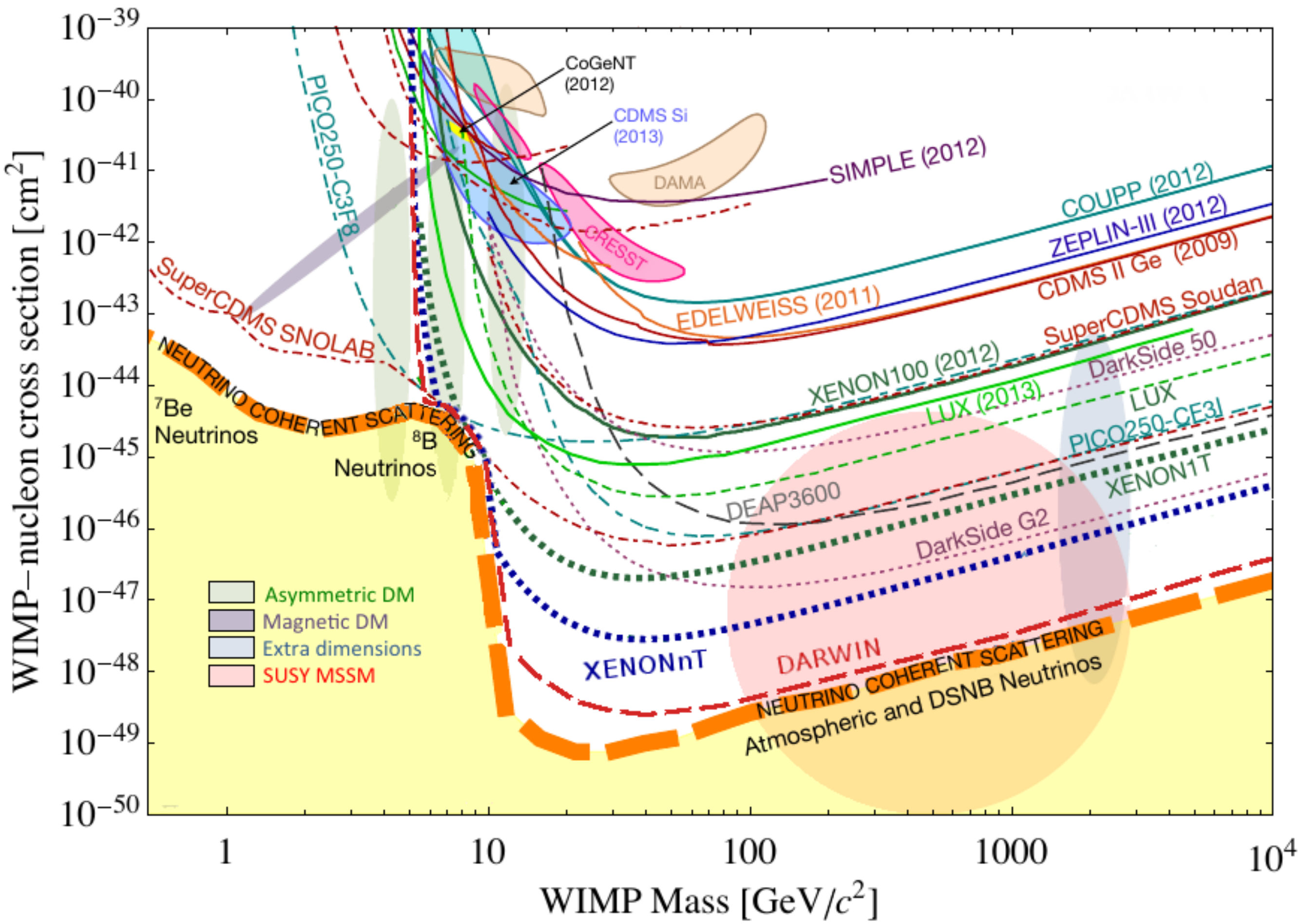
Annual Modulation in 3.5 years of data?



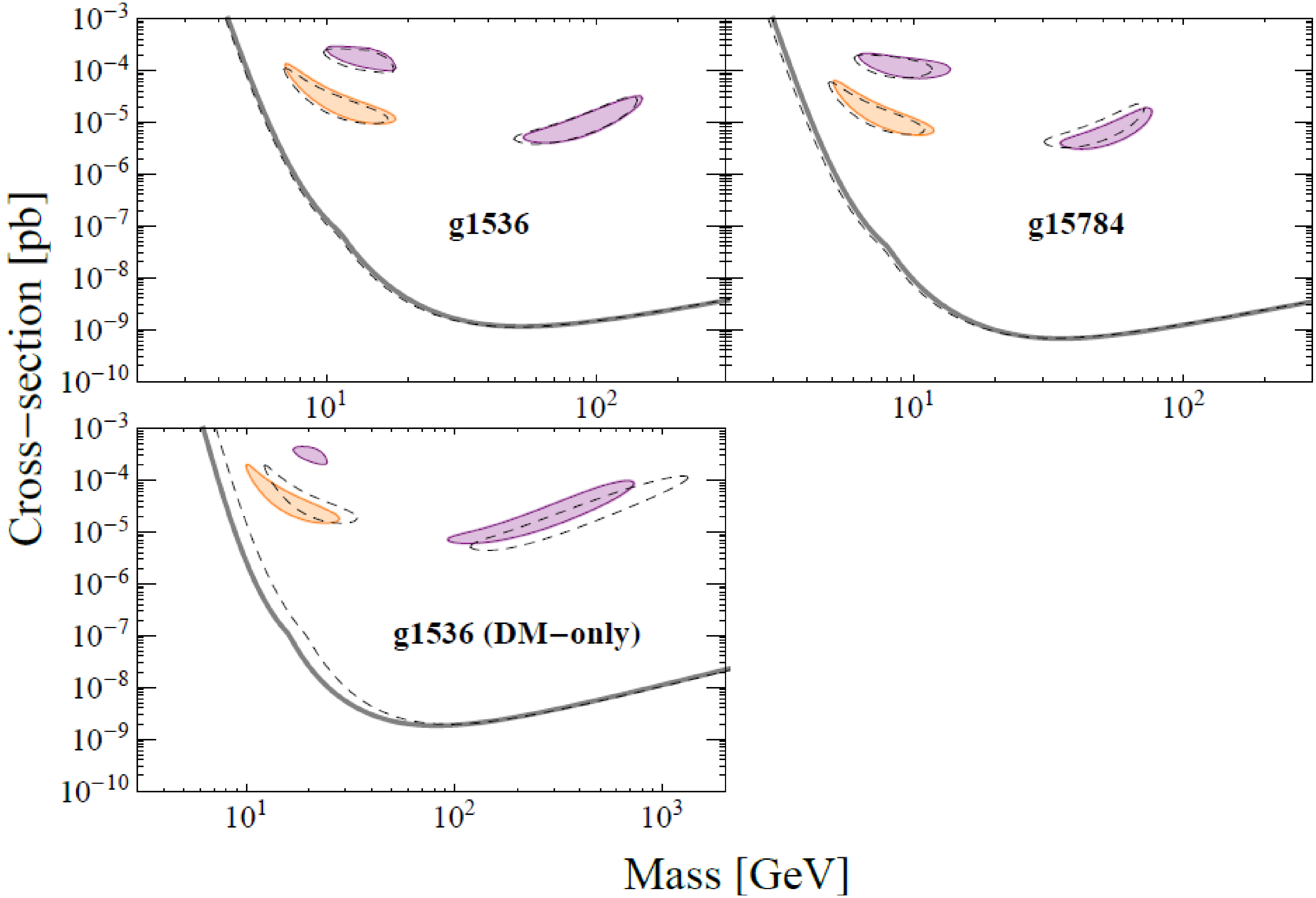
LUX: Currently Leading the Field

- 370 kg liquid xenon time-projection chamber
- ~1 mile under ground, in the Black Hills of South Dakota, USA

Present and Future of Direct Detection



Our Results



g1536
g15784
g1536 (DM−only)
Cross−section [pb]
Mass [GeV]
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{1}
10^{2}
10^{3}

Conclusions

- Maybe the SHM ain't so bad