Direct Dark Matter Detection: Overview and Principles

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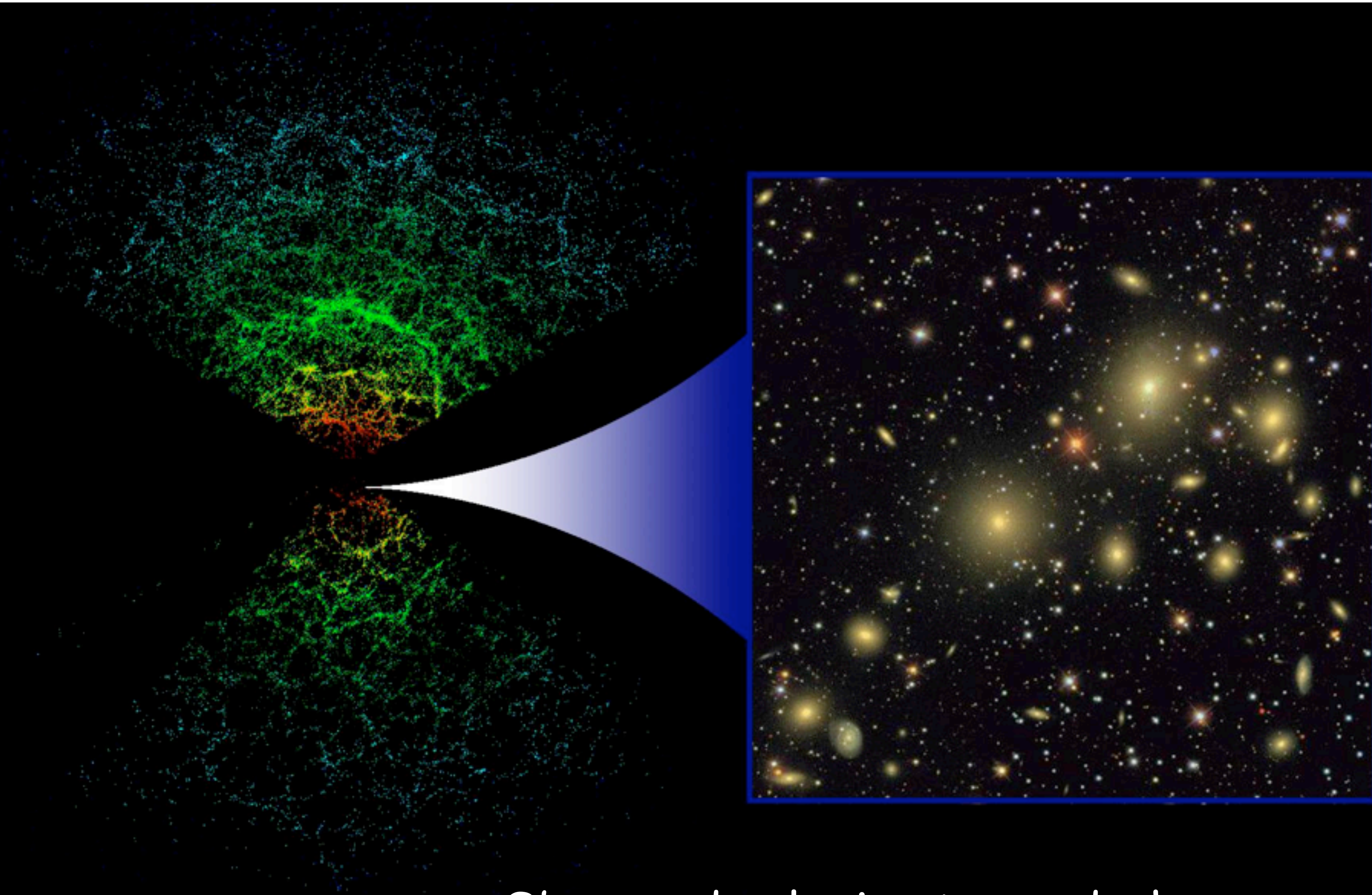
Stanford University

6th Patras Workshop on Axions, WIMPs, and WISPs
Zurich University, 5-9 July 2010

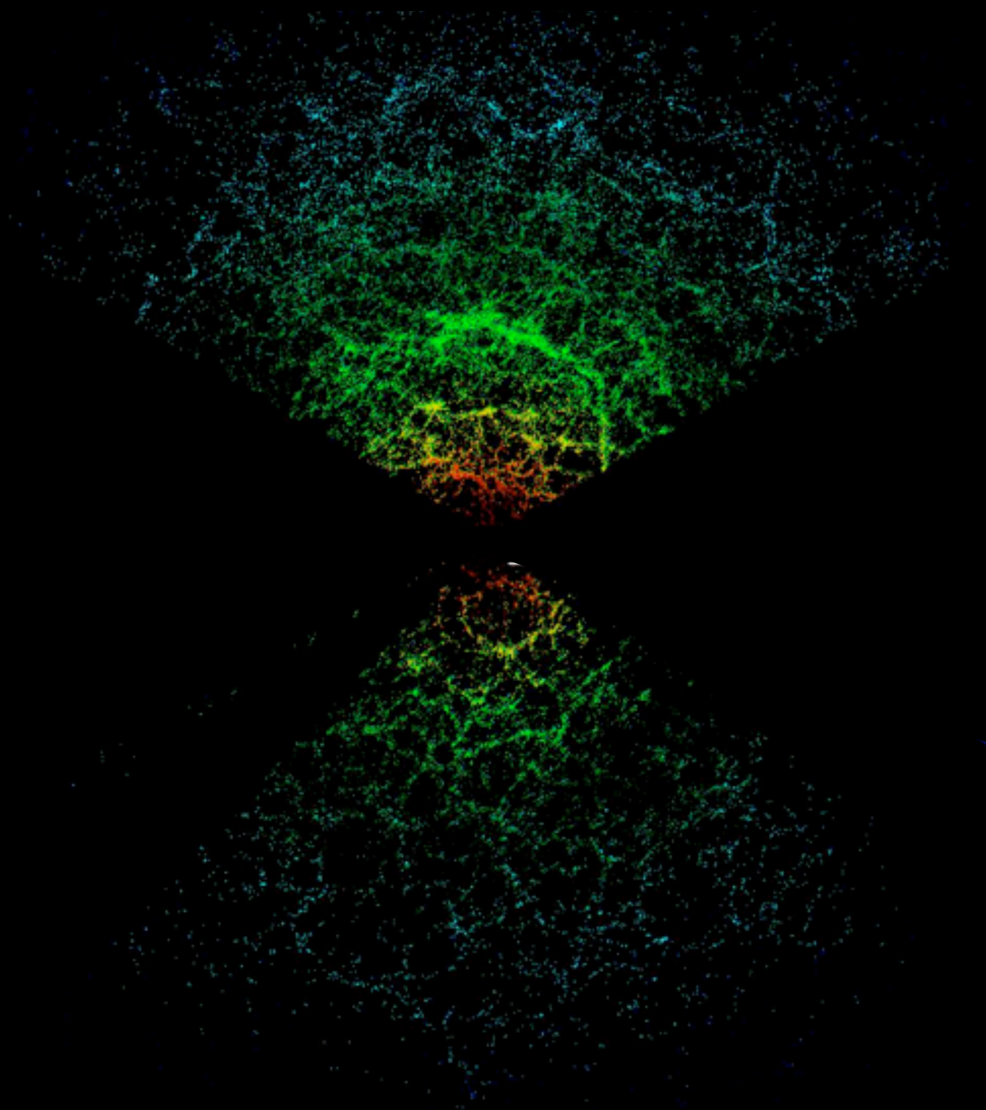


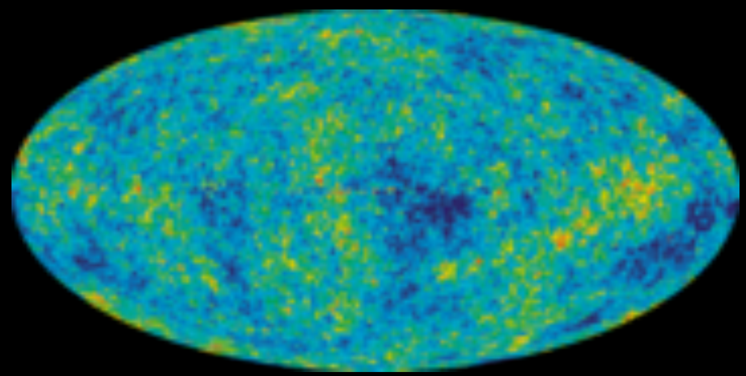
Observed galaxies trace dark matter distribution in the Universe

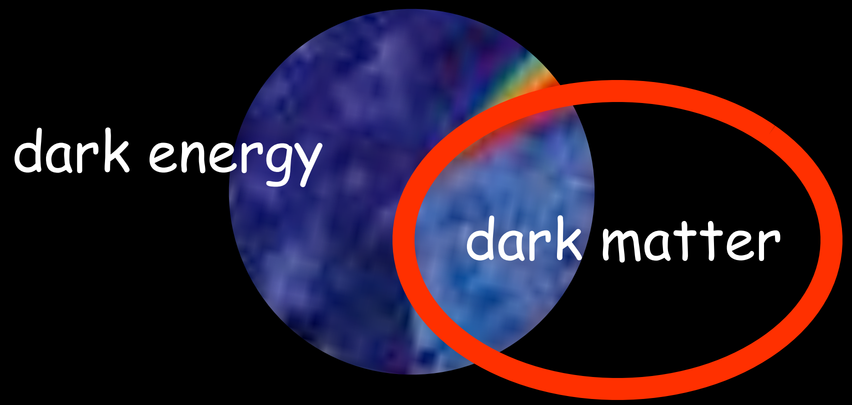
Sloan Digital Sky Survey

LSS + CMB + SNIa + Clusters indicate:

- Scale-invariant and adiabatic spectrum of initial density fluctuations
- Universe is dominated by dark energy and cold dark matter





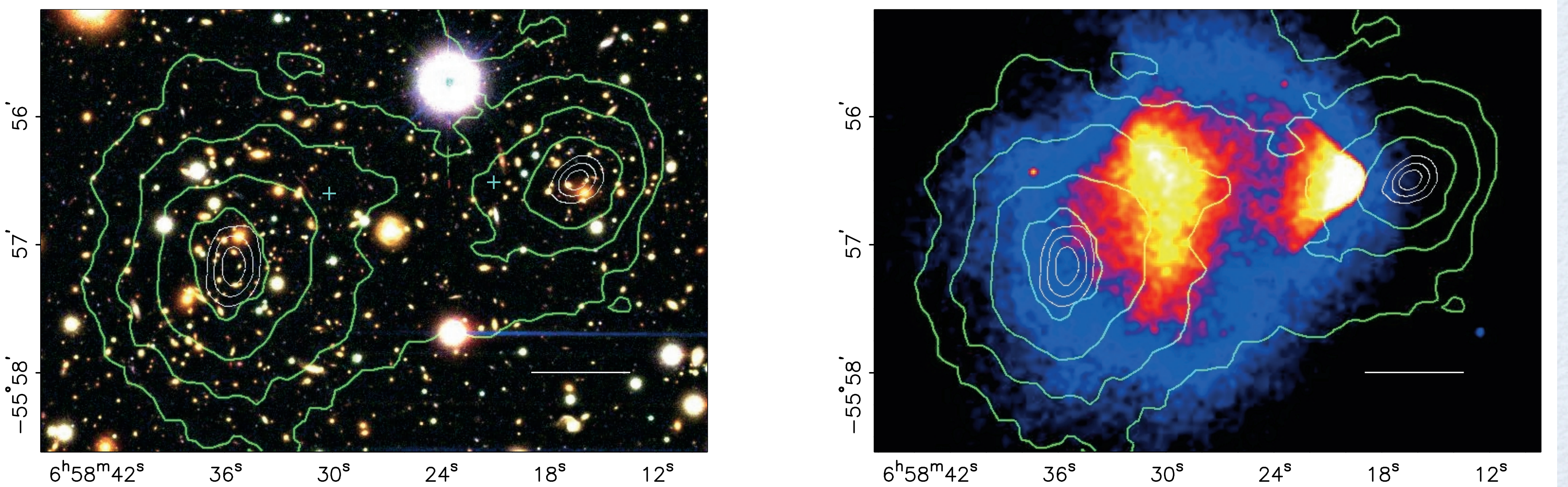


'Direct Proof' of Dark Matter

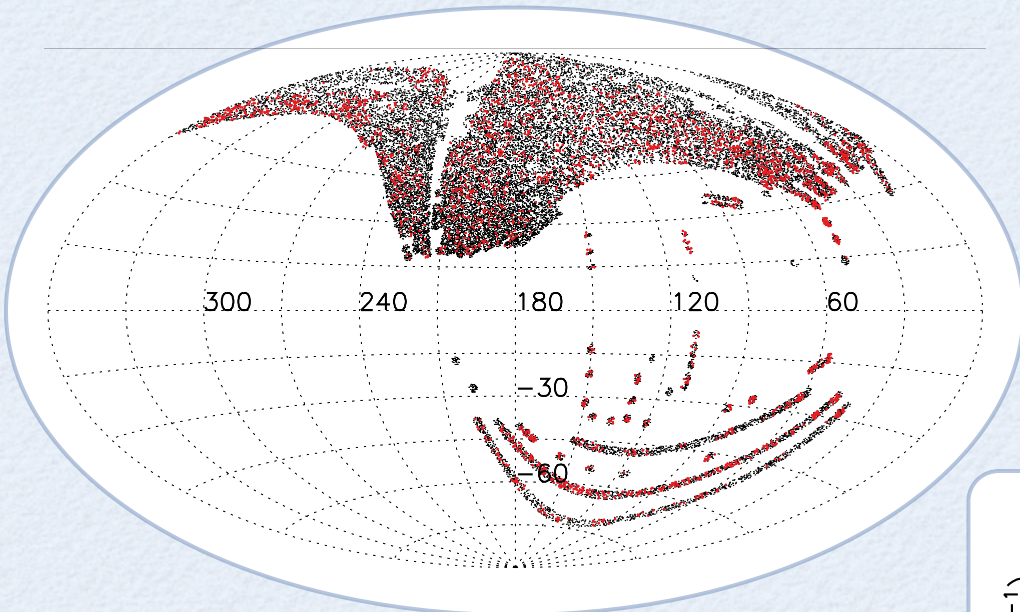
A DIRECT EMPIRICAL PROOF OF THE EXISTENCE OF DARK MATTER[1]

Douglas Clowe,[2] Maruša Bradač,[3] Anthony H. Gonzalez,[4] Maxim Markevitch,[5,6]
Scott W. Randall,[5] Christine Jones,[5] and Dennis Zaritsky[2]

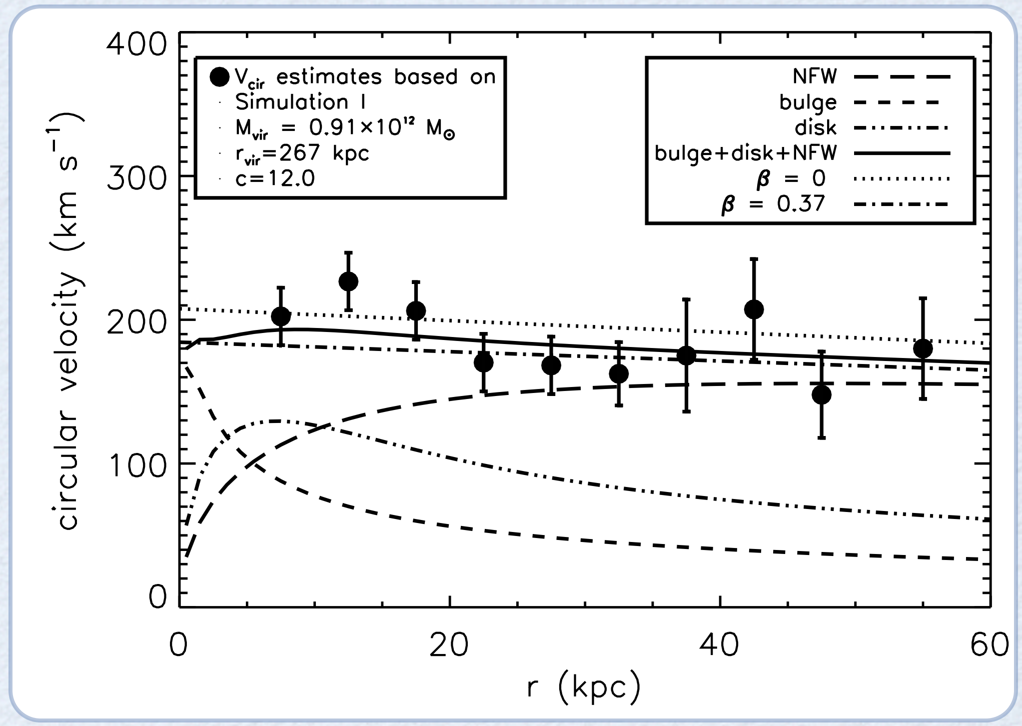
Received 2006 June 6; accepted 2006 August 3; published 2006 August 30



<u>The</u> Milky Way Dark Matter Halo



Xue et al. 2008 use a population of 2000 BHB stars out to 60 kpc

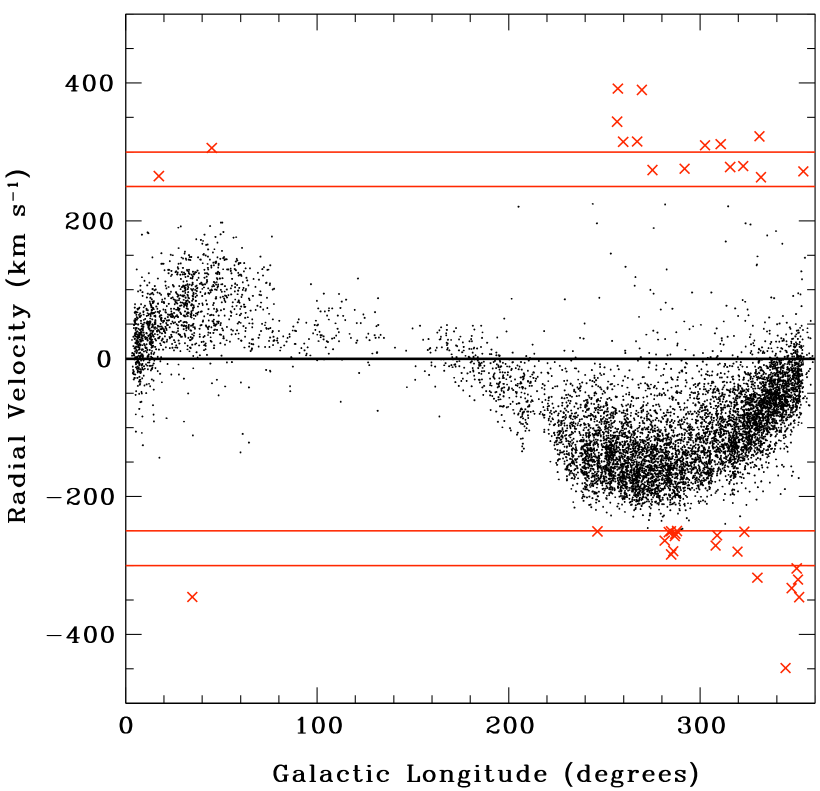


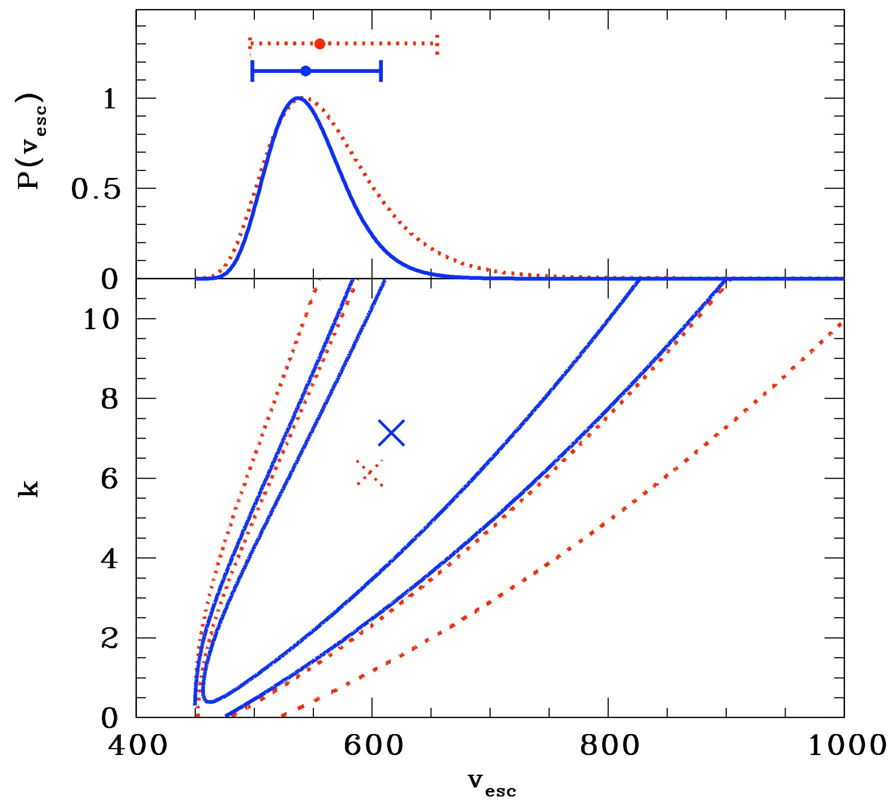
Mass estimates broadly consistent with those that use satellite dynamics (Frenk & White 1981, Little & Tremaine 1987, Kochanek 1996, Evans & Wilkinson 1999, Li & White 2008)

Solar neighborhood high velocity stars

$$f(|\mathbf{v}|\,|\,v_{\rm esc},k) \propto (v_{\rm esc}-|\mathbf{v}|)^k, \quad |\mathbf{v}|<v_{\rm esc}$$

$$f(|\mathbf{v}|\,|\,v_{\rm esc},k) = 0, \quad |\mathbf{v}| \geqslant v_{\rm esc},$$



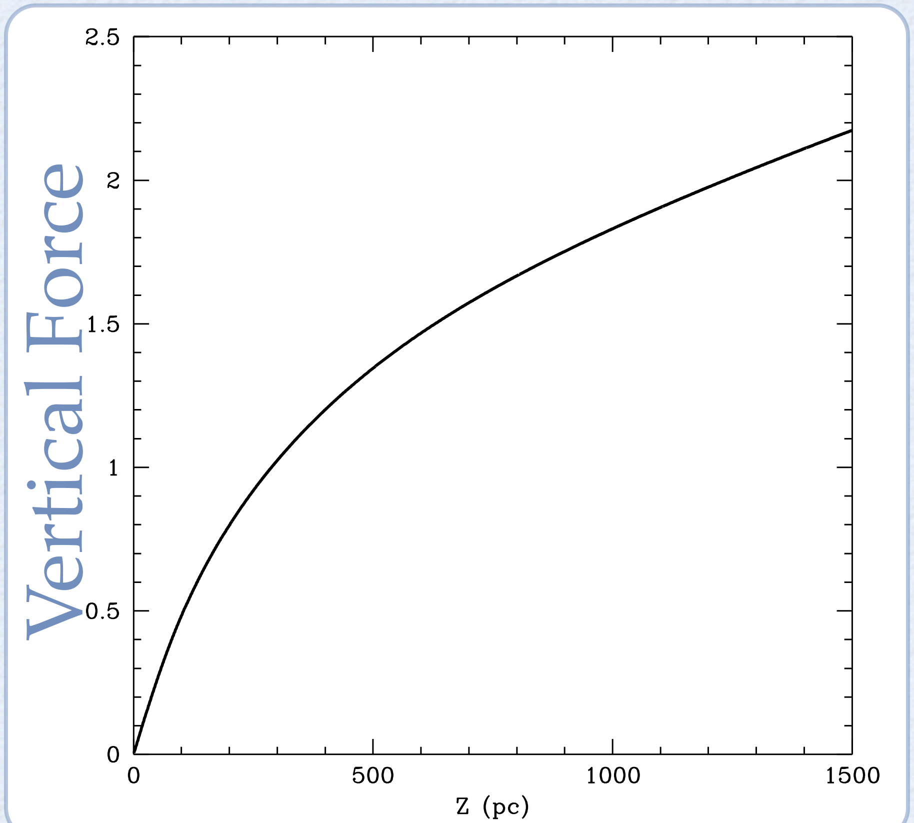


Escape Velocity

Smith et al.,

Mon.Not.Roy.Astron.Soc. 379:755-772,2007

Dark Matter in Galactic Disk



Dynamical matter

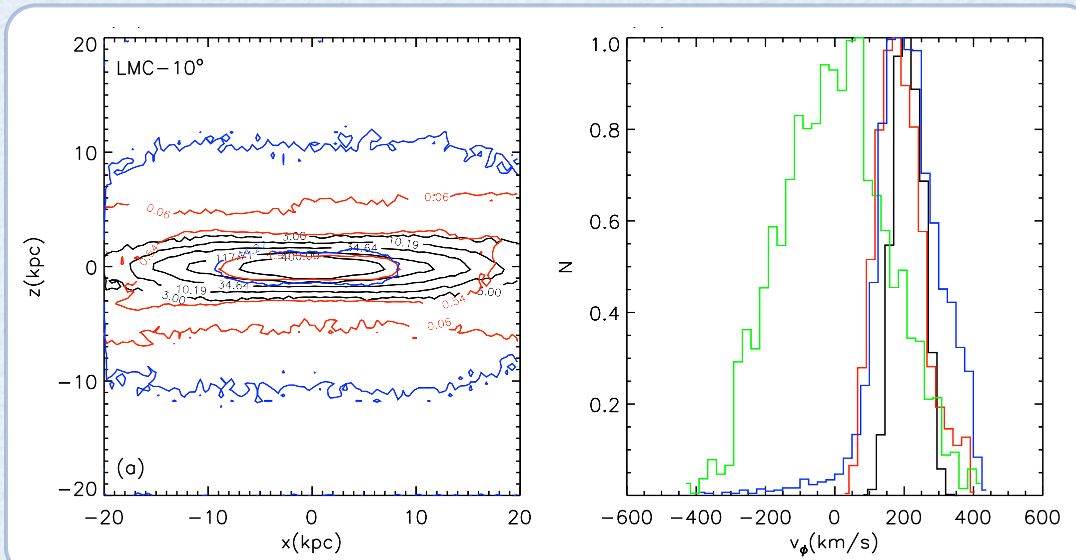
$56 \pm 6\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$

Visible matter

$53\,\mathrm{M}_{\odot}\,\mathrm{pc}^{-2}$

Constrains contribution from a ``dark matter disk"

Read, Bruch, et al. 2009



Oort, 1930

Bahcall 80's-90's

Kuijken & Gilmore 1991

Holmberg & Flynn 2004

'Direct Detection' of Dark Matter

...Quasar microlensing

The direct detection of non-baryonic dark matter in the Galaxy?

M. R. S. Hawkins

Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ

2 citations

...surveys of halo stars

Direct Detection of Galactic Halo Dark Matter

B. R. Oppenheimer,[1]* N. C. Hambly,[2] A. P. Digby,[2] S. T. Hodgkin,[3] D. Saumon[4]

100+ citations

'Direct Detection' of Dark Matter

...substructure lensing

DIRECT DETECTION OF COLD DARK MATTER SUBSTRUCTURE

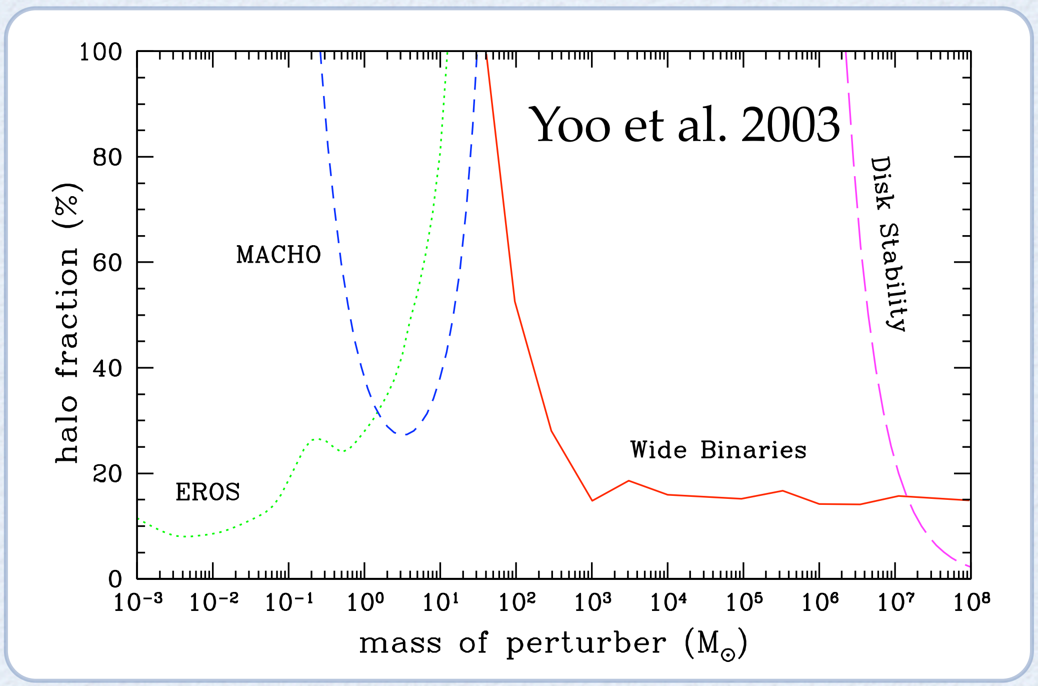
N. DALAL[1] AND C. S. KOCHANEK[2]

Received 2001 November 20; accepted 2002 February 18

...halo microlensing

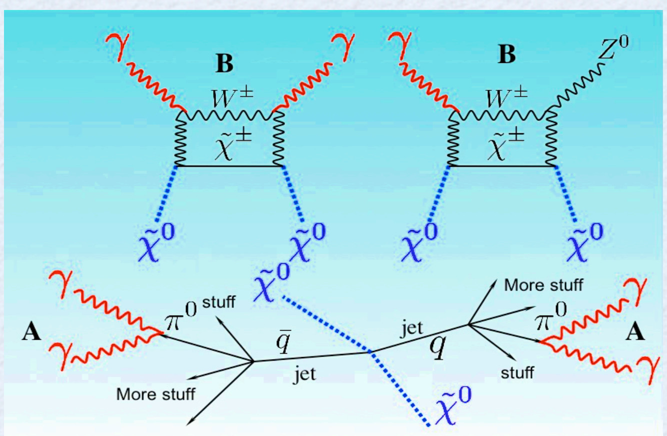
Experimental Limits on the Dark Matter Halo of the Galaxy from Gravitational Microlensing

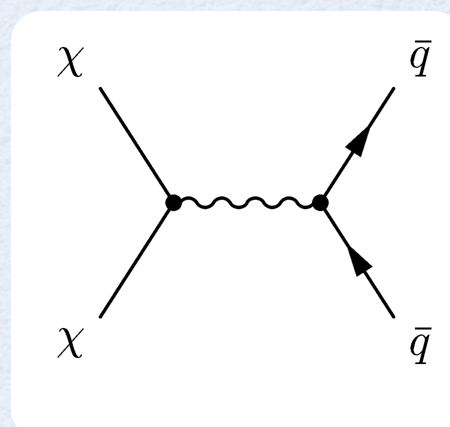
C. Alcock,[1,2] R. A. Allsman,[3] T. S. Axelrod,[1,4] D. P. Bennett,[1,2] K. H. Cook,[1,2] K. C. Freeman,[4] K. Griest,[2,5] J. A. Guern,[2,5] M. J. Lehner,[2,5] S. L. Marshall,[2,6] H.-S. Park,[1] S. Perlmutter,[2] B. A. Peterson,[4] M. R. Pratt,[2,6] P. J. Quinn,[4] A. W. Rodgers,[4] C. W. Stubbs,[2,6,7] and W. Sutherland[2,8]



Case for Weak Scale Dark Matter

- Low baryon density (BBN)
- CMB and large-scale structure dissipation-less matter component
- Standard Model extensions pick out weak scale for new physics
- Particles with weak-scale annihilation cross section have relic abundance near the critical density
- Simplest model assumption (e.g. 'crossing symmetry') imply a WIMP-quark cross section ~10^{-36} cm^2





WIMP Detection Basics

- mass density of Galactic WIMPs is approx. 0.3 GeV/cm^3.
- WIMPs move around Galaxy with a speed of about 10^{-3}c
- Assuming a WIMP mass of 50 GeV/c^2, the kinetic energy is ~ 50 keV
- WIMP mean free path ~ 10^7 km
- WIMP interaction rate in 1 kg of Ge ~ 1/10^5 s^{-1}

CDMS talk,

D. Balakishiyeva

WIMP Interactions

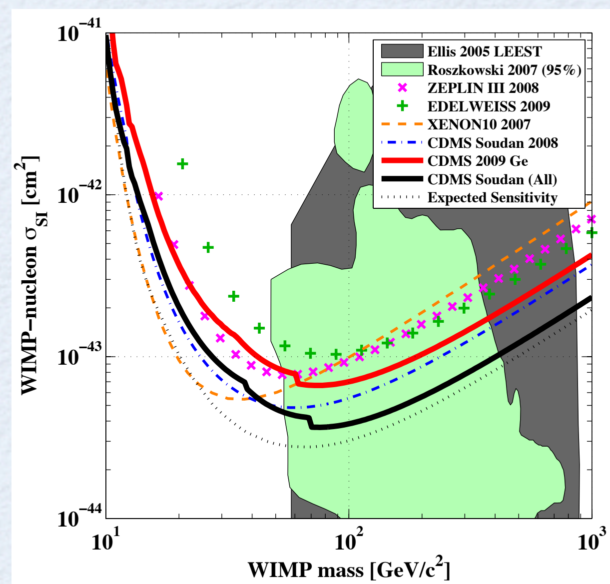
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

- Cross section: $$\frac{d\sigma}{dE_R} = \frac{m_N}{2\mu_N^2 v^2}\left[\sigma_0^{SI} F_{SI}^2(E_R) + \sigma_0^{SD} F_{SD}^2(E_R)\right]$$
- Spin-Independent (SI) $$\mathcal{L} \supset \alpha_q^s \bar{\chi}\chi\bar{q}q + \alpha_q^V \bar{\chi}\gamma_\mu\chi\bar{q}\gamma^\mu q$$
- Spin-dependent (SD) $$\mathcal{L} \supset \alpha_q^A \left(\bar{\chi}\gamma^\mu\gamma_5\chi\right)\left(\bar{q}\gamma_\mu\gamma_5 q\right)$$

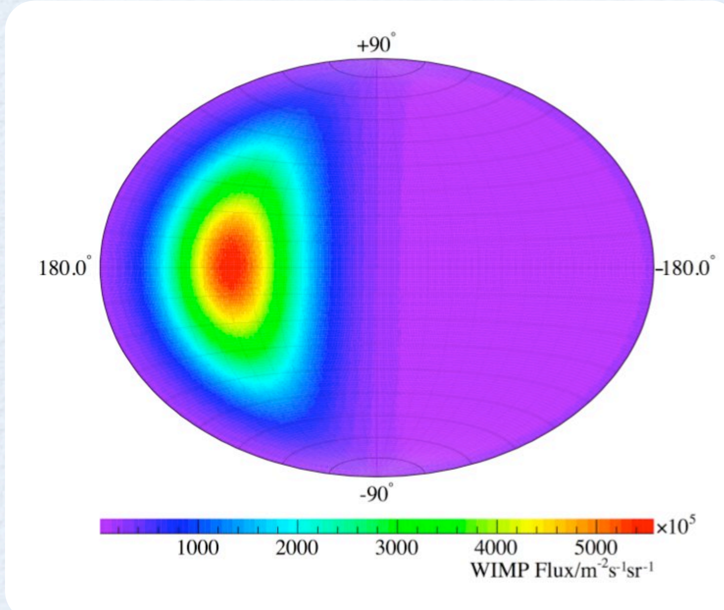
Energy spectrum at detector

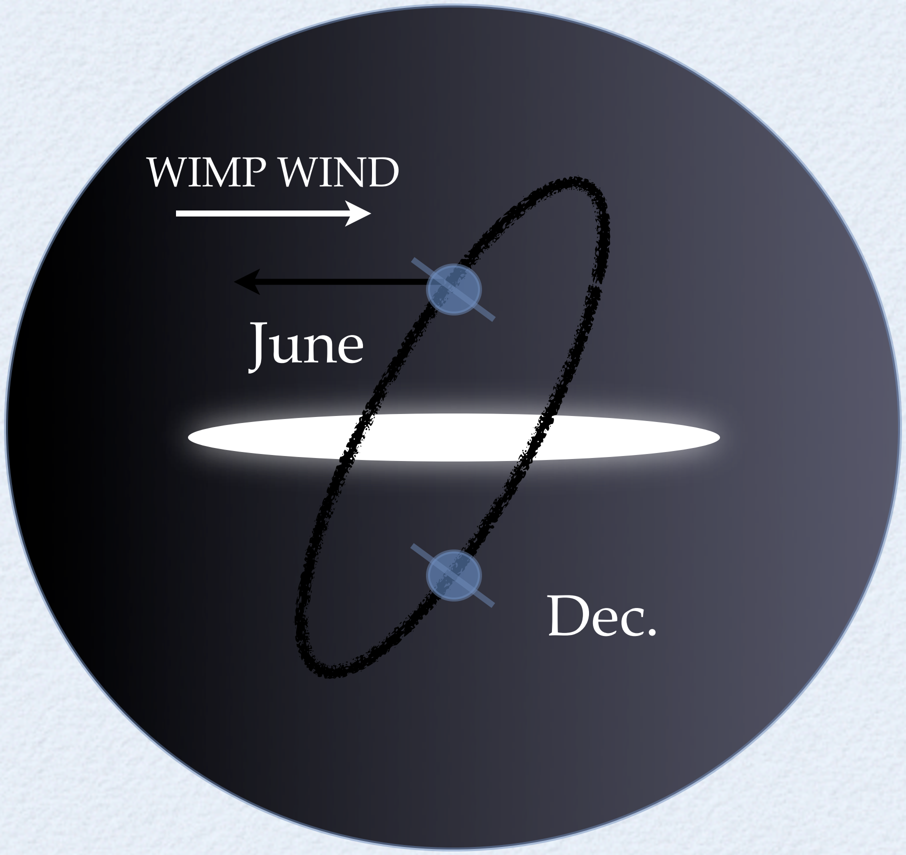
$$\frac{dR}{dE_R} = \frac{N_T m_N \rho_\chi}{2m_\chi\mu^2}\sigma(q^2)\int_{v_{min}}^{\infty}\frac{f(v)}{v}dv.$$

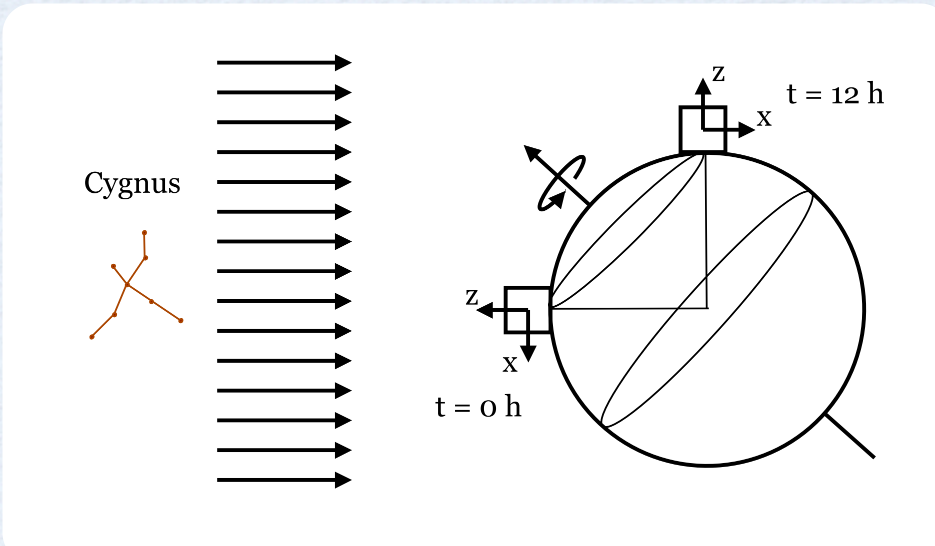


Time-dependent direct detection

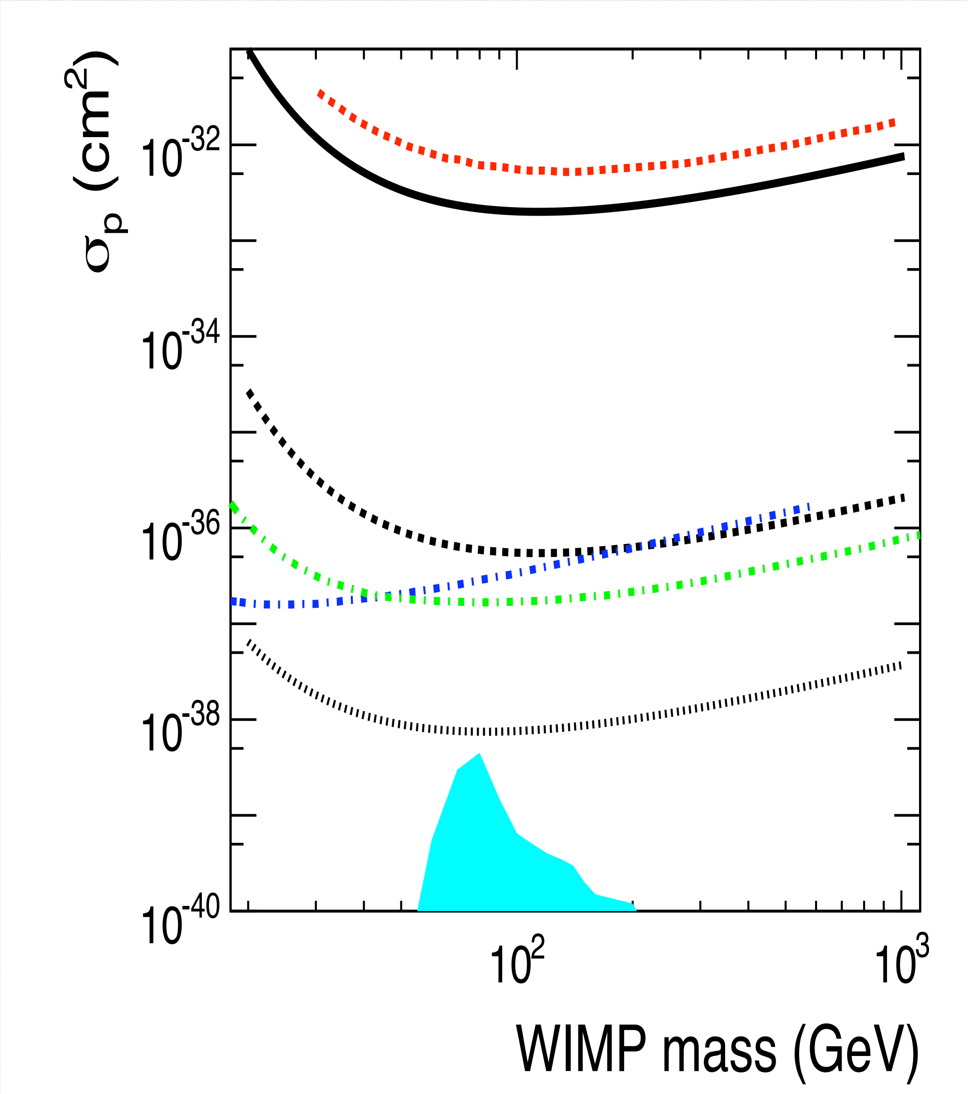
- Annual modulation (Drukier, Freese, Spergel, 1986)
- Directional detection (Spergel, 1988)







New directional limits



DMTPC: arXiv:1006.2928

See Drift talk, D. Walker

Dark Matter 'Detections': Modern perspective

...Annual Modulation

First results from DAMA/LIBRA and the combined results with DAMA/NaI

the several requirements of this DM signature. Thus, the presence of Dark Matter particles in the galactic halo is supported also by DAMA/LIBRA and, considering the former DAMA/NaI and the present DAMA/LIBRA data all together (total exposure 0.82 ton×yr), the presence of Dark Matter particles in the galactic halo is supported at 8.2 σ C.L..

[246 citations]

...Recoil spectrum (`heavy')

Dark Matter Search Results from the CDMS II Experiment

interacting massive particle (WIMP) dark matter. The final exposure of our low-temperature germanium particle detectors at the Soudan Underground Laboratory yielded two candidate events, with an expected background of 0.9 ± 0.2 events. This is not statistically significant evidence for a WIMP signal. The combined CDMS II data place the strongest constraints on the WIMP-nucleon spin-independent scattering cross section for a wide range of WIMP masses and exclude new parameter space in inelastic dark matter models.

[132 citations]

...Recoil spectrum (`light')

Results from a Search for Light-Mass Dark Matter with a P-type Point Contact Germanium Detector

number of cosmogenic peaks can be observed for the first time. We discuss several possible causes for an irreducible excess of bulk-like events below 3 keVee, including a dark matter candidate common to the DAMA/LIBRA annual modulation effect, the hint of a signal in CDMS, and phenomenological predictions. Improved constraints are placed on a cosmological origin for the DAMA/LIBRA effect.

[44 citations]

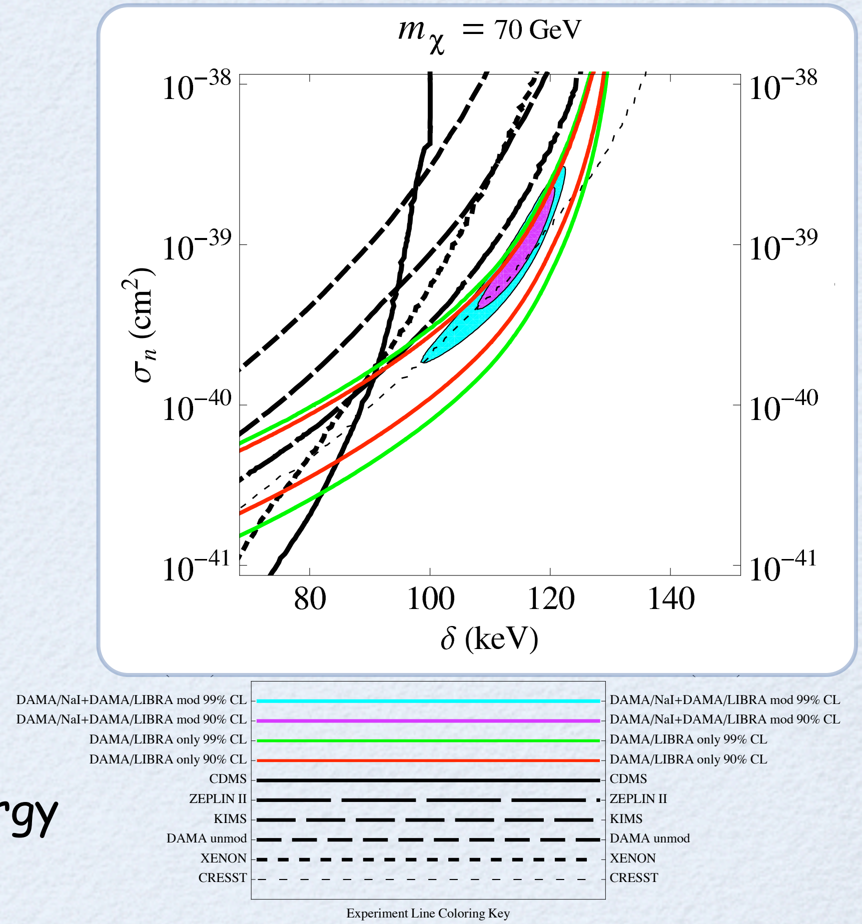
Inelastic dark matter

e.g. Chang et al., arXiv:0807.2250

- In addition to dark matter, excited state with mass greater by 100 keV
- Elastic scatterings suppressed compared to inelastic
- Larger minimum velocity to scatter

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

- Heavy targets favored over light targets
- Modulation signal can be significantly enhanced
- Elimination or suppression of events at low energy



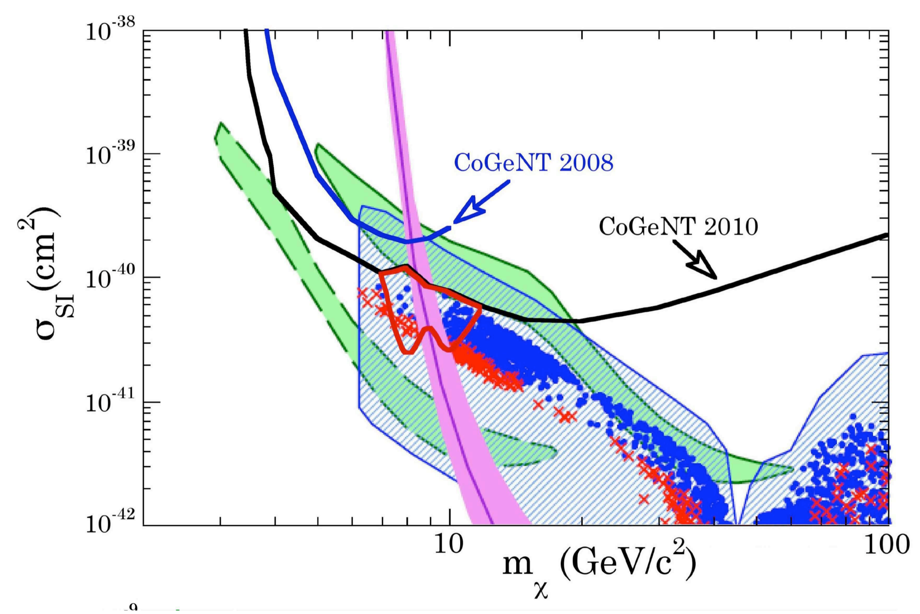
Light WIMPs: A CoGeNT Interpretation?

- Difficult to reconcile with other evidences for light WIMPs (Chang et al., arXiv:1004.0697)

- In contrast to previous studies (Fitzpatrick et al., arXiv:1003:0014)

- Non-standard models, with backgrounds, may explain data

$$\sigma_{\rm SI}(q^2) = \frac{4G_F^2\mu^2}{\pi}\left[Zf_p + (A-Z)f_n\right]^2 F^2(q^2)$$

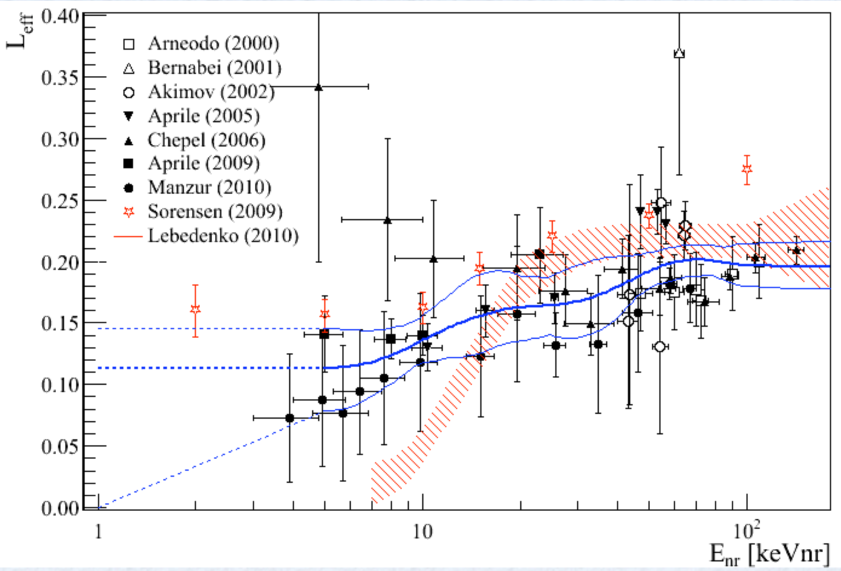


CoGeNT collaboration 2010

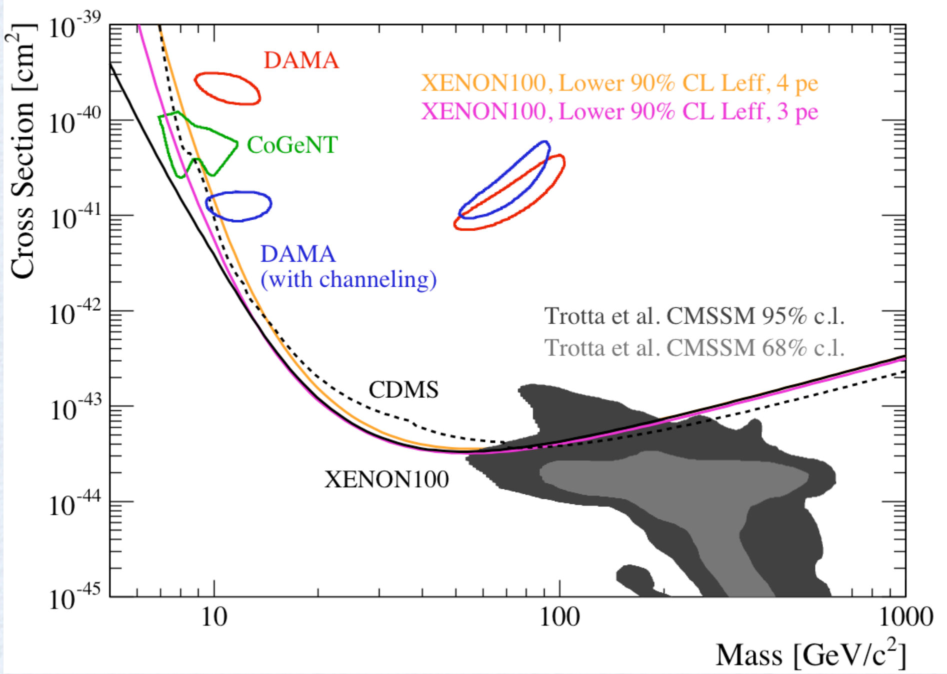
Low mass WIMPs?

- Leff dependence of limits at low mass?

Collar & McKinsey 2010, Savage et al. arXiv:1006.0972



XENON100 Collaboration

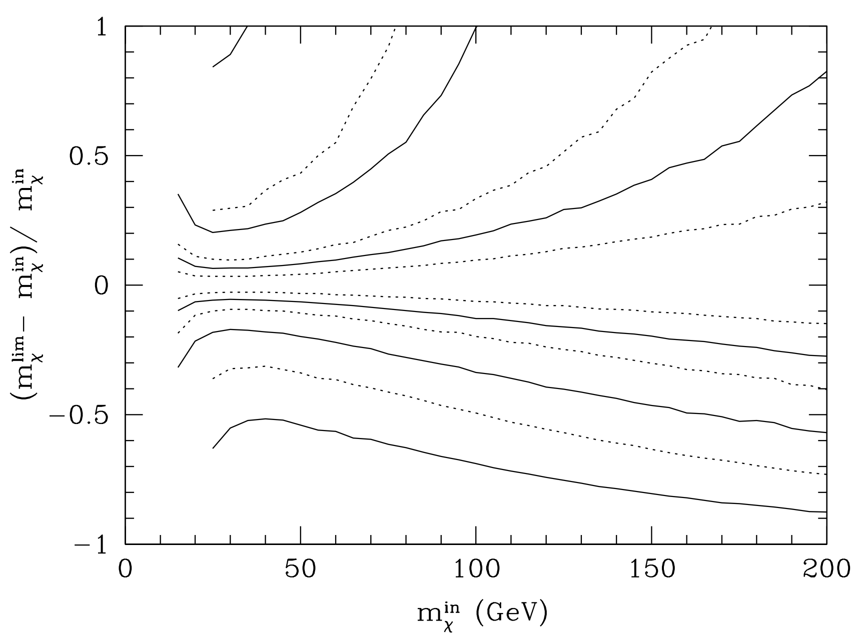


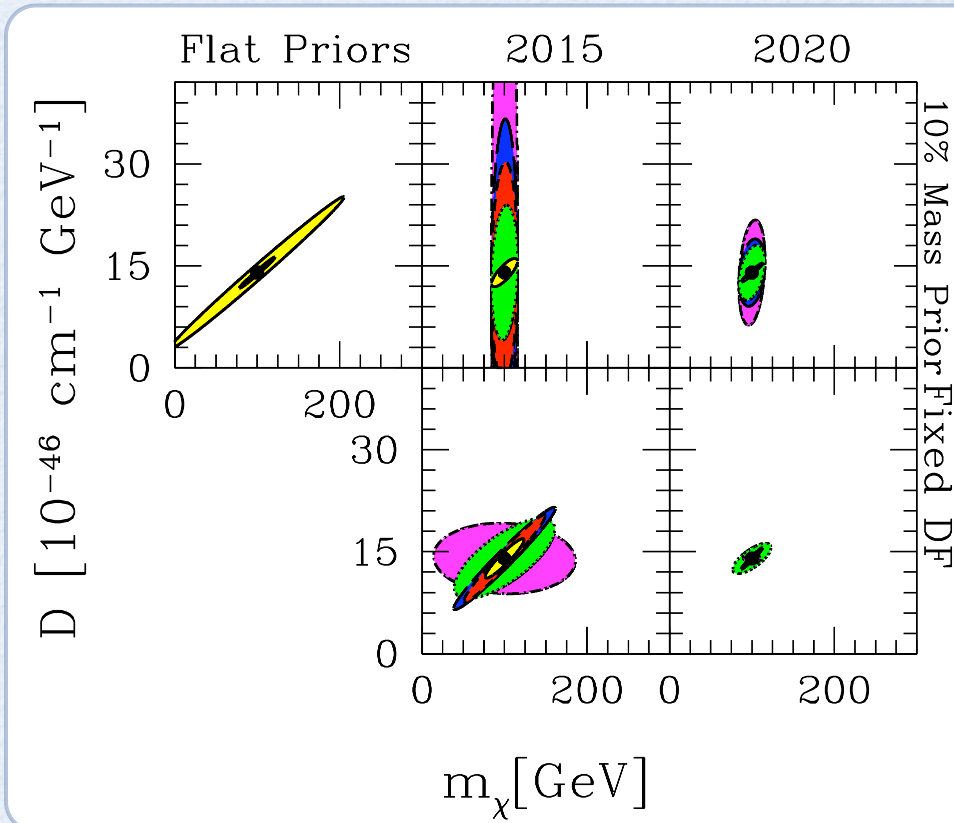
Talk today,
U. Oberlack

Extracting particle physics

Extracting particle physics

- marginalize over particle parameters for fixed halo model





Anne Green, **JCAP 0807:005,2008**

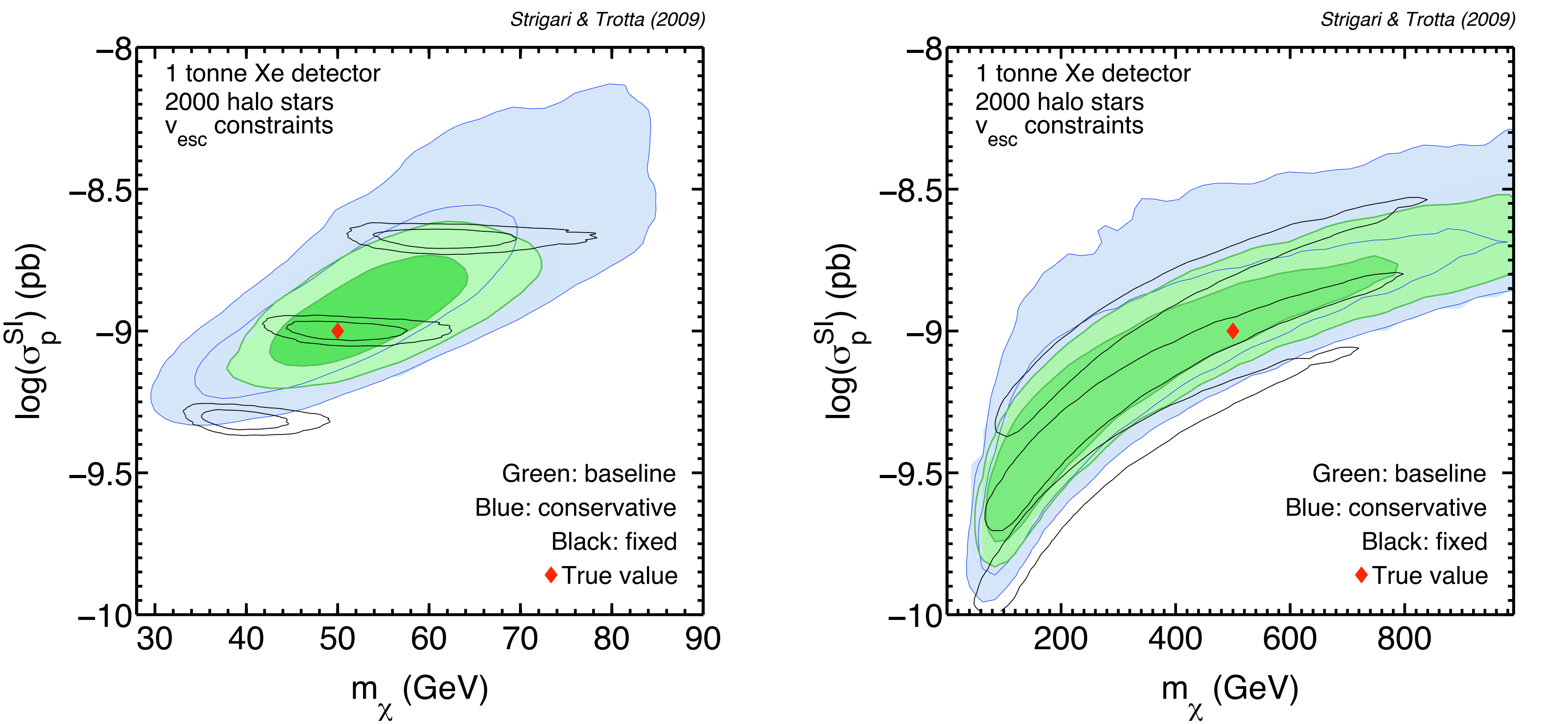
Shan, arXiv:0903.4320 [hep-ph]

Bernal et al, **JCAP 0901:046,2009**

A. Peter, arXiv:0910.4765v1

Projected Constraints for future detectors

- MW halo modeling included in constraints projected for future detectors

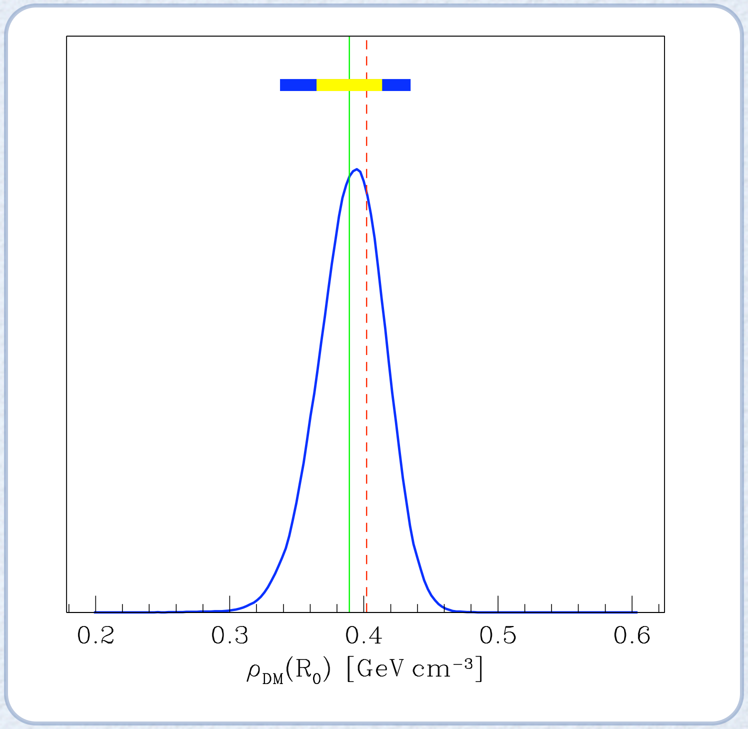


Approx. 300 (100) events for 50 (500) GeV WIMP

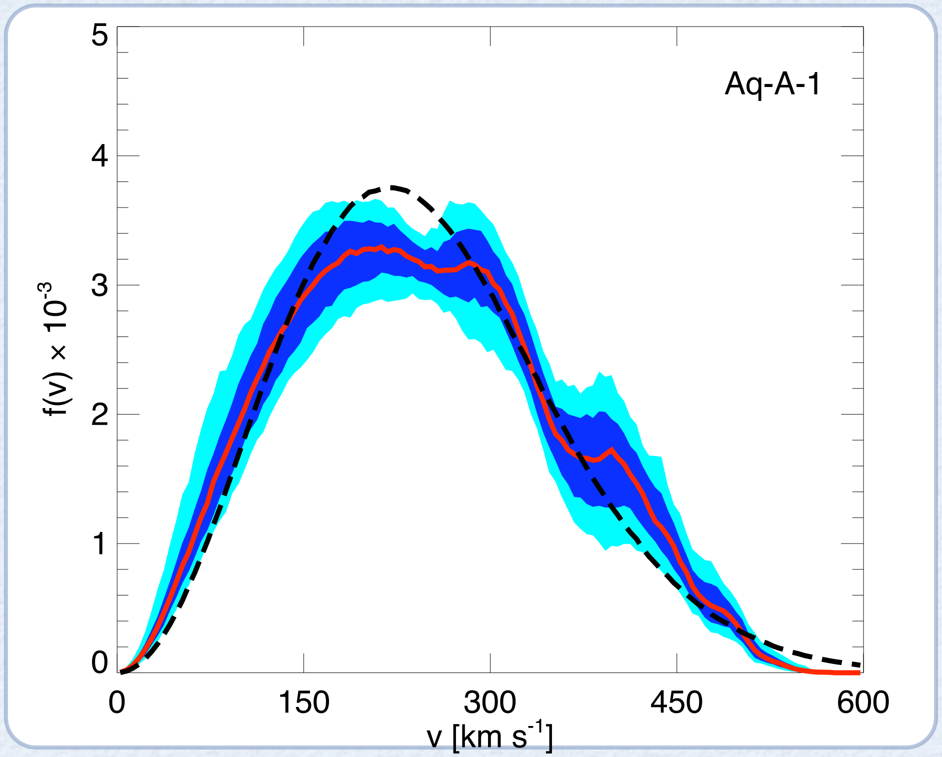
Astrophysical systematics

Very recent studies: astrophysical systematics

- Catena & Ullio 2009: MCMC; local density strongly peaked at 0.4 GeV cm^{-3} (See previous work: Dehnen & Binney 1998; Widrow, Pym, & Dubinski 2008)
- Weber & de Boer 2009: Correlations of local density with halo scalelength weaken constraints
- Ling et al. 2009: Milky Way halo with baryons; velocity distribution more platykurtic than DM-only simulations. High velocity tail suppressed.
- Pato et al. 2010: disk orientation in numerical simulations



Theory of dark matter halos

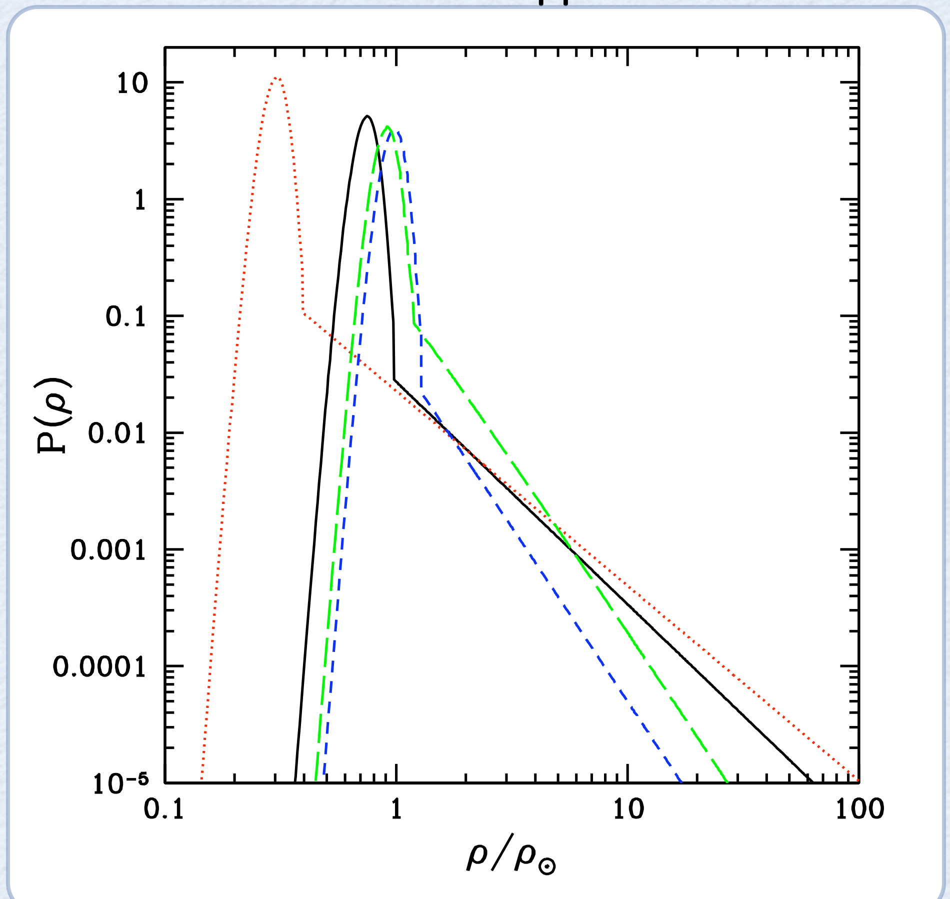


Measured distribution of speeds near solar circle implies 10% variation relative to multivariate gaussian fit

Vogelsberger et al., MNRAS 2009

Including substructure, local density probably not less than 1/2 the canonical value

Kamionkowski & Koushiappas 2008



Distribution function modeling: Milky Way

Distribution function is the sum of disk, bulge, and halo components

$$f\left(\mathcal{E},\, L_z,\, E_z\right) \;=\; f_{\rm disk}\left(\mathcal{E},\, L_z,\, E_z\right) \;+\; f_{\rm bulge}\left(\mathcal{E}\right) \;+\; f_{\rm halo}\left(\mathcal{E}\right)$$

Solve poisson equation for each component and sum to get the total potential

$$f_i\left(\mathcal{E}\right) = \frac{1}{\sqrt{8}\pi^2}\int_0^{\mathcal{E}} \frac{d^2\tilde{\rho}_i}{d\Psi_{\rm total}^2}\frac{d\Psi_{\rm total}}{\sqrt{\mathcal{E}-\Psi_{\rm total}}}$$

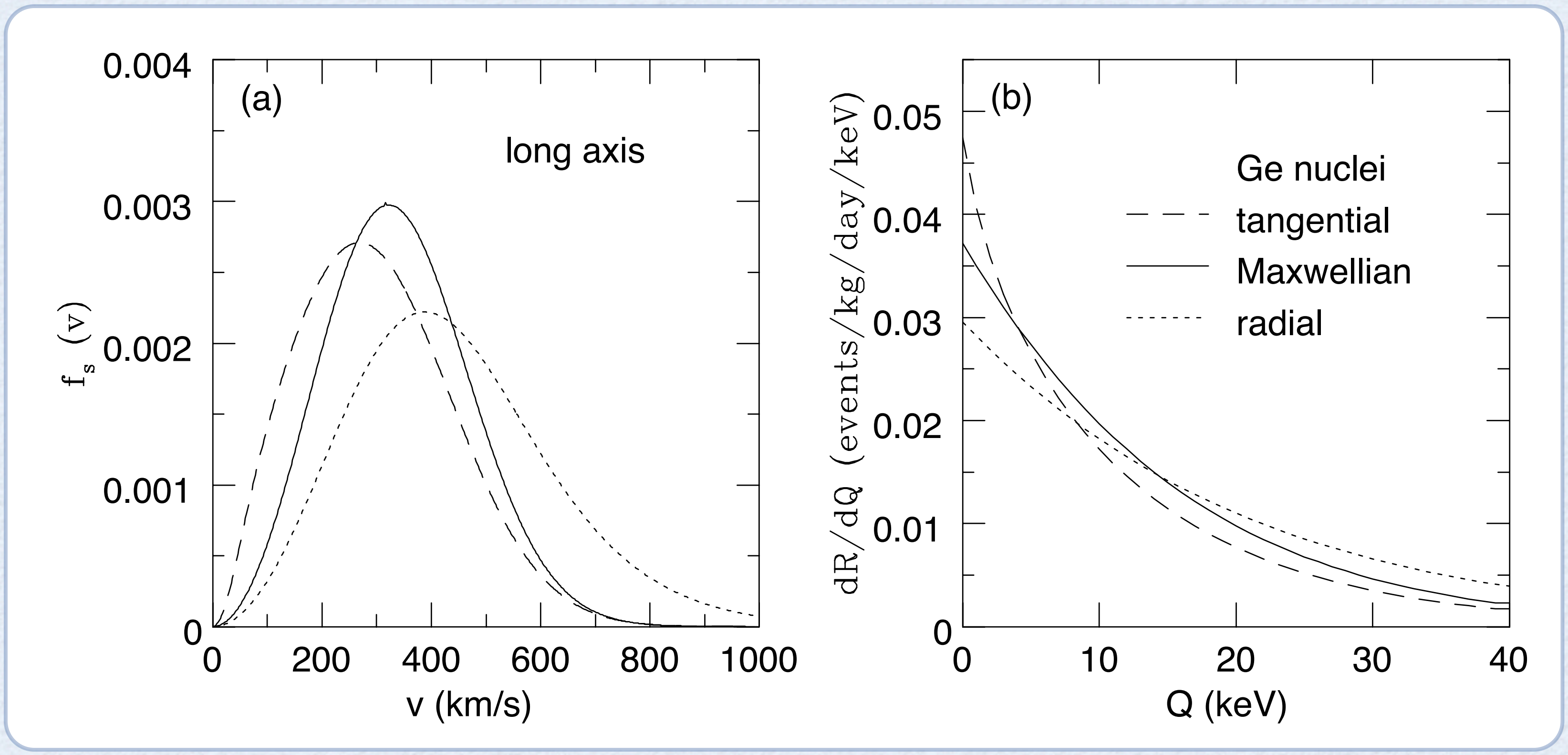
Can assume a spherical expansion for the disk potential

$$\phi_{\rm disk} = -GM_{\rm disk}(1 - e^{-r/b_{\rm disk}})/r$$

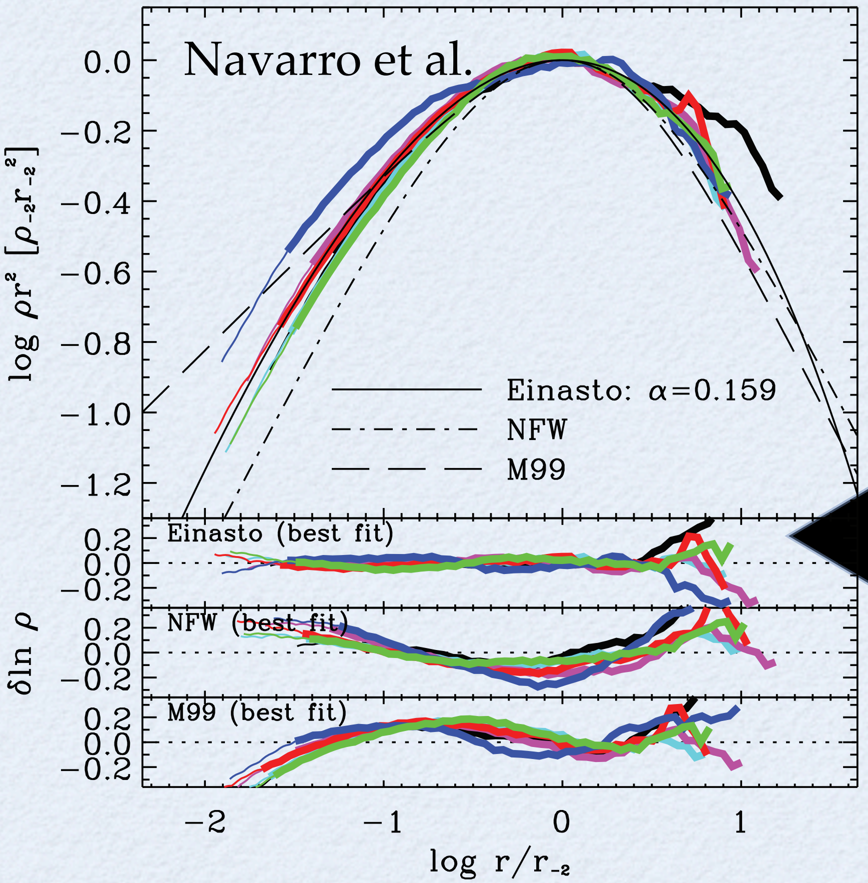
Stability requires integrand to be a monotonic function of energy

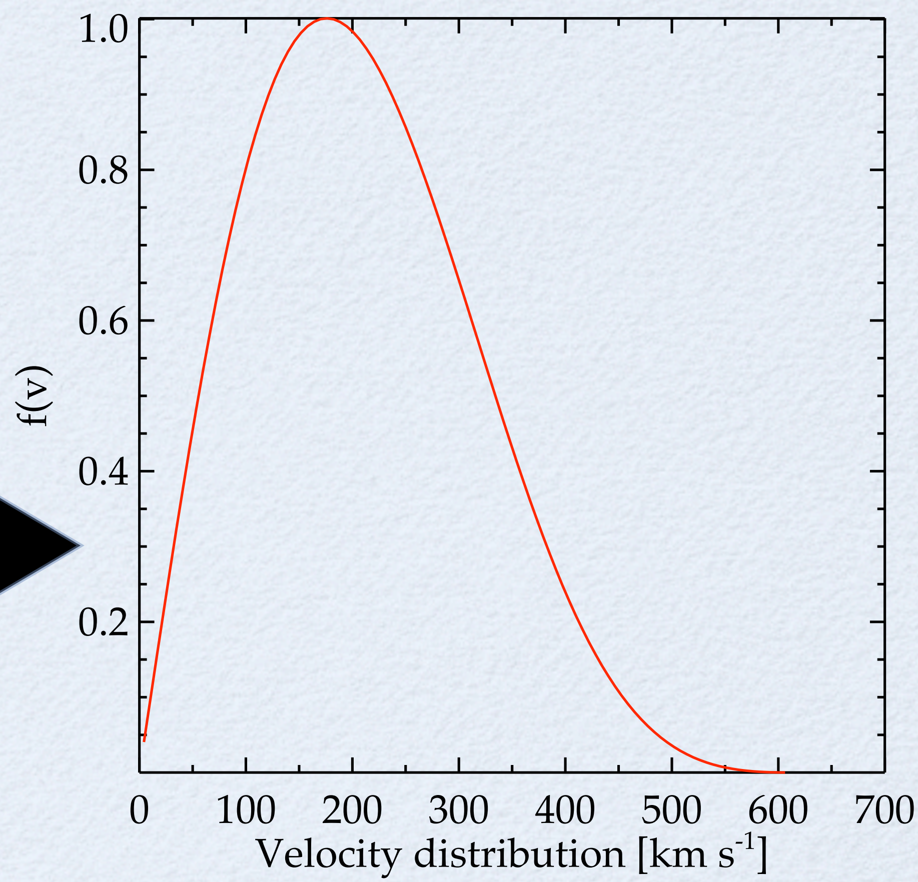
Milky Way distribution function: Earlier studies

- Evens, Carollo, de Zeeuw 2000: Triaxial halo models
- Kamionkowski and Kinkhabwala 1998: small changes in distribution function for models normalized to circular velocity
- Ullio and Kamionkowski 2000: Anisotropic models considered in



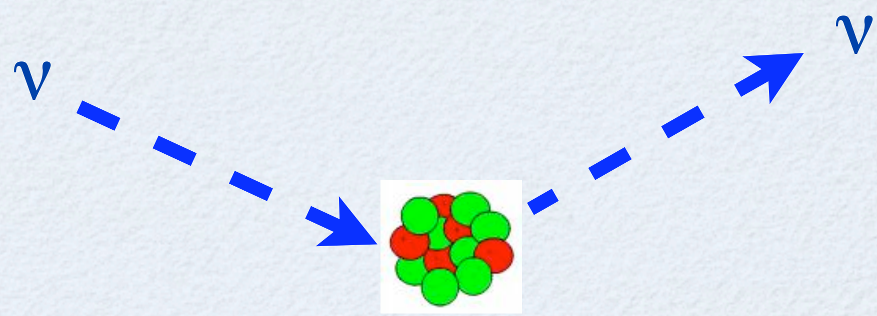
Milky Way halo modeling





- Applications to Inelastic dark matter (in prep.)

Neutrino Coherent Scattering



Cross Section: $\sigma \sim G_f^2\, Q_w^2\, E_\nu^2\, F(Q^2)^2$

Weak charge: $Q_w^2 = N - (1 - 4\sin^2\theta_w)Z$

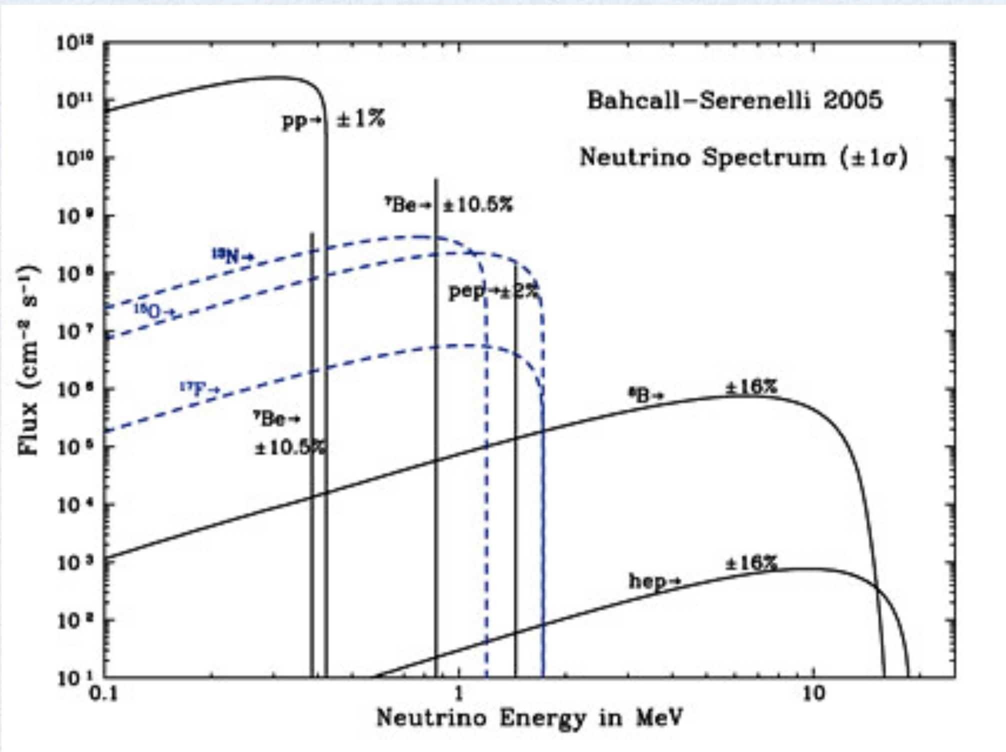
Coherence condition: [three-momentum] x [nuclear radius] ≤ 1

Implies sensitivity to neutrinos ~ 10 MeV

Fundamental prediction of the Standard Model, but not yet detected

Freedman 1974 PRD, Tubbs & Schramm 1975

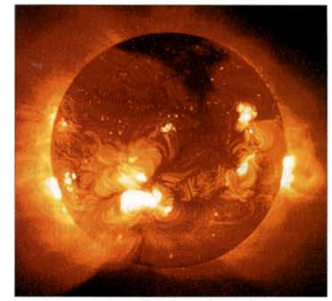
Astrophysical Neutrinos



$^8B \rightarrow {}^7Be^* + e^+ + \nu_e$

$^3He + p \rightarrow {}^4He + e^+ + \nu_e$

Solar Neutrinos



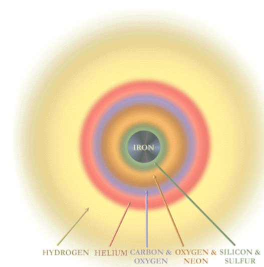
$$\pi^{\pm} \rightarrow \quad \mu^{\pm} \quad + \nu_\mu(\overline{\nu}_\mu)$$

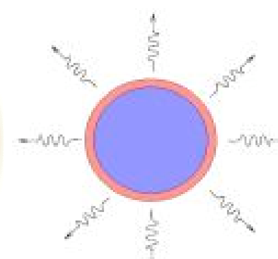
$$\searrow$$

ATM Neutrinos

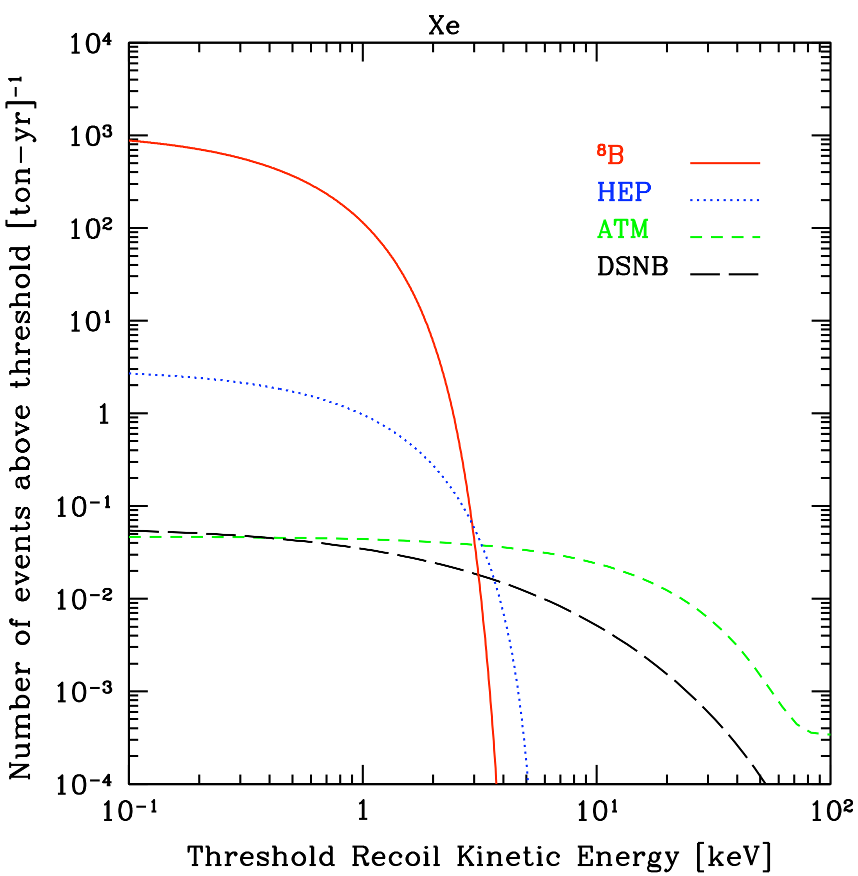
$$e^{\pm} + \nu_e(\overline{\nu}_e) + \overline{\nu}_\mu(\nu_\mu)$$

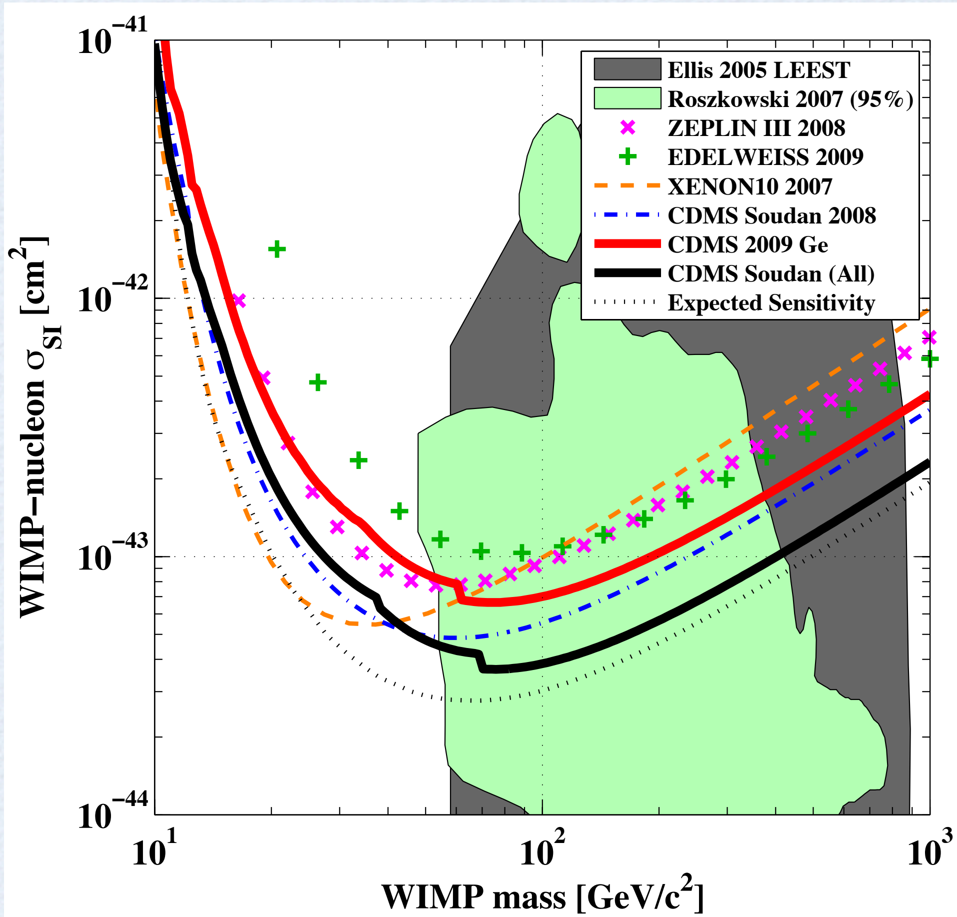
SN Neutrinos





Neutrinos and limits of direct detection





Monroe and Fisher PRD 2008

Strigari, NJP 2009

10^{-48} Neutrino backgrounds

Upcoming decade in Dark Matter