Results for Dark Matter direct detection and their interpretation

LPSC, Grenoble, 8 Sept 2011

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Introduction

Direct detection: present status

XENON100 results

Hints for a DM signal?

DAMA/LIBRA

CoGeNT

CRESST-II

Constraints from CDMS and XENON

Alternative particle physics

Spin-dependent scattering

Inelastic scattering

General iso-spin dependence

Conclusion

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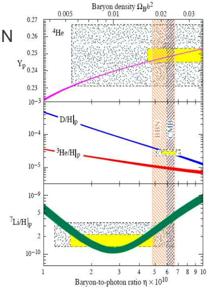
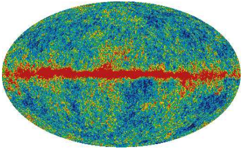
What is the Universe made of?

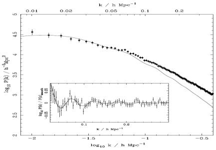
BBN



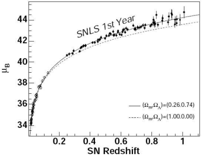
CMB (WMAP)



BAO



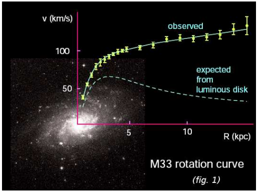
SN 1a



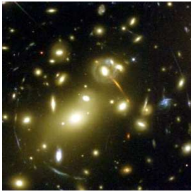
WMAP 7yr + BAO + H_0: $\Omega_{\rm CDM} = 0.229 \pm 0.015$

The scale of galaxies and clusters of galaxies

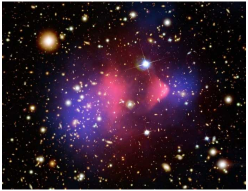
- rotation curves



- gravitational lensing



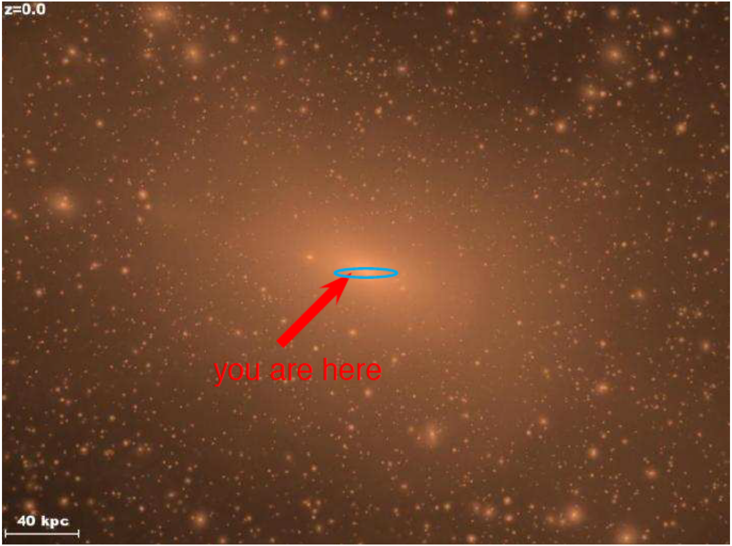
- bullet clusters



- virial theorem applied to galaxies and clusters
- X-rays from clusters of galaxies

$\Rightarrow$ Many independent observations are consistent with the hypothesis that the dominating gravitating component of the Universe cannot be the matter we know.

Dark Matter in a Milkyway-like Galaxy



Via Lactea N-body DM simulation Diemand, Kuhlen, Madau, astro-ph/0611370

Local Dark Matter density

"standard halo model":

local DM density: $\rho_\chi \approx 0.389 \pm 0.025\,\mathrm{GeV\,cm^{-3}}$ Catena, Ullio, 0907.0018

Maxwellian velocity distribution (in halo rest frame)

$$f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

with $\bar{v} \simeq 220$ km/s and $v_{\rm esc} \simeq 600$ km/s

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$\Rightarrow$ local DM flux: $\phi_\chi \sim 10^5\,\mathrm{cm^{-2}s^{-1}} \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)\left(\frac{\rho_\chi}{0.4\,\mathrm{GeV\,cm^{-3}}}\right)$

Does DM have an interaction with us beyond gravity?

$\Rightarrow$ the WIMP hypothesis: relic density of DM is set by the annihilation cross section $\chi\chi \to$ SM SM Lee, Weinberg, 1977; Bernstein, Brown, Feinberg, 1985; Scherrer, Turner, 1986

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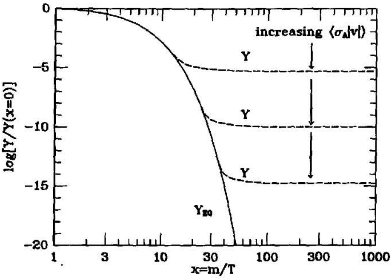
thermal freeze-out:

$$\Omega_\chi h^2 \simeq \frac{10^{-37}\mathrm{cm}^2}{\langle \sigma_{\mathrm{annih}} v \rangle}$$

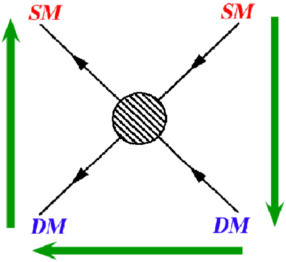
$$\Omega_\chi h^2|_{\mathrm{WMAP}} = 0.1126 \pm 0.0036$$



s-wave annihilations of a particle χ due to mediator ϕ:

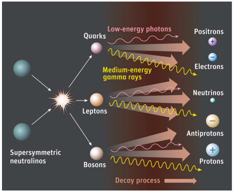
$$\langle \sigma_{\mathrm{annih}} v \rangle \sim \frac{g^4}{2\pi} \frac{m_\chi^2}{m_\phi^4} \simeq 6 \times 10^{-37}\mathrm{cm}^2\, g^4 \left(\frac{m_\chi}{100\,\mathrm{GeV}}\right)^2 \left(\frac{m_\phi}{1\,\mathrm{TeV}}\right)^{-4}$$

Testing the WIMP hypothesis

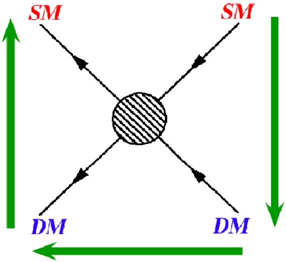


Testing the WIMP hypothesis

indirect detection



PAMELA, FERMI, AMS-II, IceCube, HESS, ...



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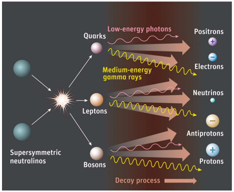

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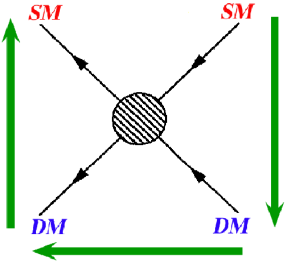
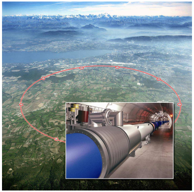


colliders



LHC at CERN

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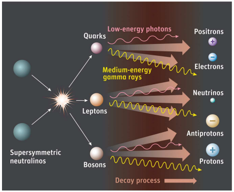

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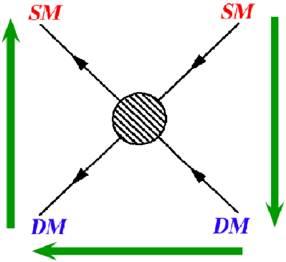

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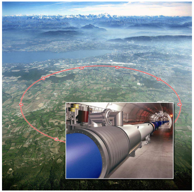
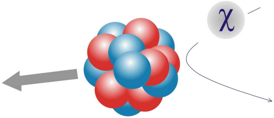


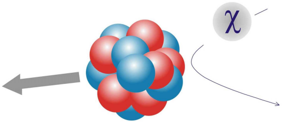
LHC at CERN

direct detection



DM direct detection

assuming DM has non-gravitational interactions (“WIMP”)
look for recoil of DM-nucleus scattering M. Goodman, E. Witten, PRD 1985



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Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

DM direct detection

colliding a $\sim$ 100 GeV DM particle with a $\sim$ 100 GeV nucleus
DM velocity: $v \sim 10^{-3}$c $\Rightarrow$ non-relativistic

$$\text{recoil energy:} \quad E_R = \frac{2\mu^2 v^2}{m_A} \cos^2\theta_{\text{lab}} \sim 10\,\mathrm{keV}$$

cnts / keV recoil energy E_R:

$$\frac{dN}{dE_R}(t) \propto \frac{\rho_\chi}{m_\chi} \int_{v>v_{\min}} d^3v \, \frac{d\sigma}{dE_R} \, v \, f_\oplus(\vec{v}, t)$$

ρ_χ DM energy density, default: 0.3 GeV cm^{-3}
$v_{\min}$: minimal DM velocity required to produce recoil energy E_R

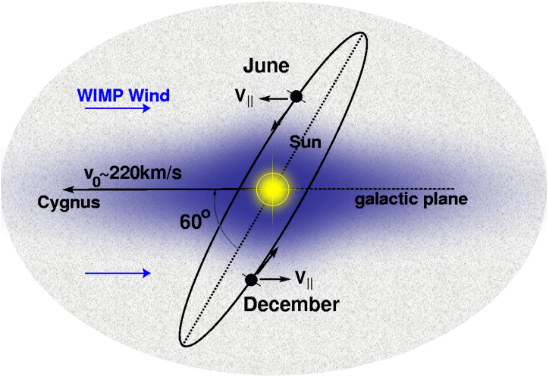
DM velocity distribution

$$f_\oplus(\vec{v}, t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

$\bar{v} \simeq 220\,\mathrm{km/s}$ $\quad v_{\rm esc} \simeq 550\,\mathrm{km/s}$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



DM nucleon scattering cross section

assume effective interaction of DM with SM $\Rightarrow$ Example: fermionic DM

$$\mathcal{L}_{\rm eff} = \frac{1}{\Lambda^2}\,(\bar\chi\Gamma_{\rm dark}\chi)\,(\bar\psi\Gamma_{\rm vis}\psi)$$

	S	P	V	A	T	AT
$\Gamma_{\rm dark,vis}$	γ_0	$\gamma_0\gamma_5$	γ_μ	$\gamma_\mu\gamma_5$	$\sigma_{\mu\nu}$	$\sigma_{\mu\nu}\gamma_5$

calculate $\langle N|\bar\psi\Gamma_{\rm vis}\psi|N\rangle \Rightarrow$

match to nucleus level (form factors) $\Rightarrow$

non-rel limit of DM current

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non-rel limit of DM current

- $(S\otimes S), (V\otimes V)$: spin-independent $\Rightarrow$ A^2 enhancement
- $(A\otimes A), (T\otimes T)$: spin-dependent $\Rightarrow$ unpaired n or p
- other combinations are suppressed by $\mathcal{O}(q^2/m_N^2, v^2) \sim 10^{-6}$

e.g., A. Kurylov, M. Kamionkowski, hep-ph/0307185

applies also for scalar/vector DM

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Conclusion

- many exps. running and setting relevant limits:

  CDMS (Ge, Si), CoGeNT (Ge), COUPP (CF_3I), CRESST ($CaWO_4$), DAMA (NaI), Edelweiss (Ge), KIMS (CsI), PICASSO (F), SIMPLE (C_2ClF_5), TEXONO (Ge), XENON (Xe), ZEPLIN (Xe),. . .

  appologizes for the ones I forgot

different target materials and different techniques used

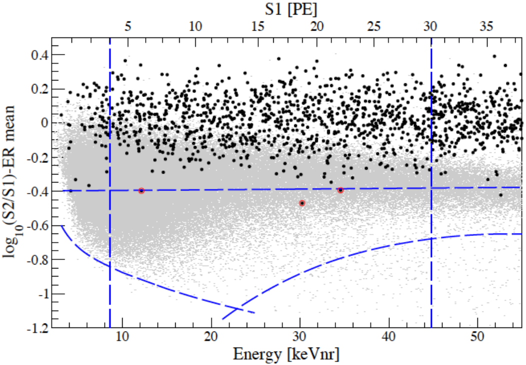
XENON100

2 phase (gas/liquid) Xenon detector @ Gran Sasso

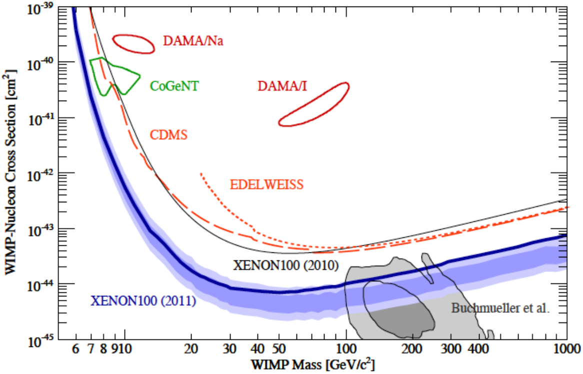
S1: prompt scintillation signal, S2: delayed ionization signal

48 kg fid., 100.9 days (Jan to June 2010) 1104.2549

3 events observed, 1.8 ± 0.6 background expectation



XENON100 limit on spin-indep. interactions



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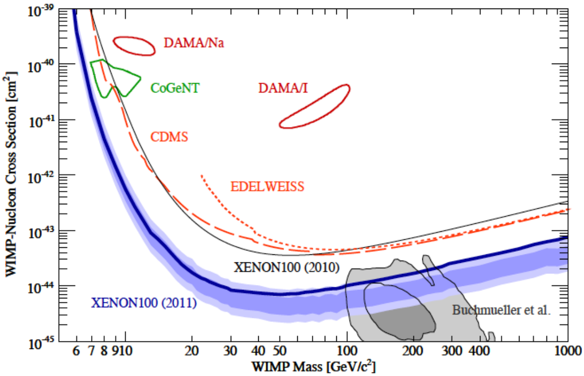
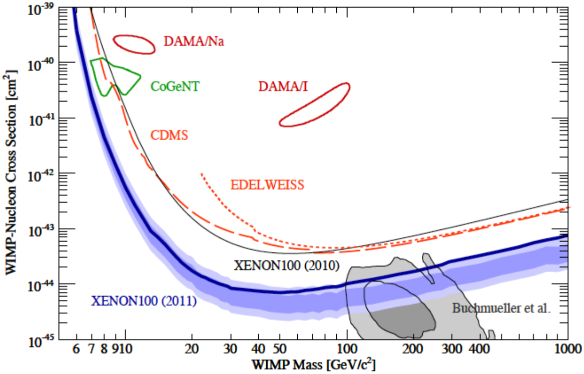


SI cross section: $\sigma_p \sim \frac{G_{\rm eff}^2 m_p^2}{\pi}$

Z_0 mediated interaction: $\sigma_p \sim \lambda_{\chi Z}^2 \frac{G_F^2 m_p^2}{\pi} \sim 10^{-38}\,{\rm cm}^2\,\lambda_{\chi Z}^2$

"heavy Dirac neutrino" is excuded as DM by many orders of magnitude

XENON100 limit on spin-indep. interactions



SI cross section: $\sigma_p \sim \frac{G_{\rm eff}^2 m_p^2}{\pi}$

Higgs mediated interaction: $\sigma_p \sim 10^{-44}\,\mathrm{cm}^2 \left(\frac{\lambda_\chi}{0.1}\right)^2 \left(\frac{115\,\mathrm{GeV}}{m_H}\right)^4$

implications of $\sigma_{\rm scat} \lesssim 10^{-44}{\rm cm}^2$ for the WIMP argument

$$\Omega_\chi h^2 \simeq \frac{10^{-37}{\rm cm}^2}{\langle \sigma_{\rm annih} v \rangle} = 0.1126 \pm 0.0036$$

assume a Higgs mediated interaction:

$$\mathcal{L} = \lambda_\chi H_1 \bar\chi\chi + y_q \bar q_L H_2 q_R + h.c. \quad \rightarrow \quad \langle \sigma_{\rm ann} v \rangle \approx \frac{3 m_\chi^2 \lambda_\chi^2 y_q^2 \langle v^2 \rangle}{8\pi (4 m_\chi^2 - m_H^2)^2}$$

$\Rightarrow$ for $m_\chi = 50$ GeV, $m_H = 115$ GeV, $\lambda_\chi = 0.1$: $\langle \sigma_{bb} v \rangle \approx 10^{-38}{\rm cm}^2$

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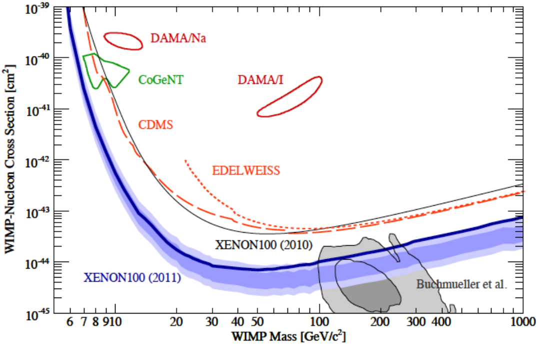
need mechanism to enhance annihilation cross section:

- go to the s-channel resonance $2m_\chi \approx m_{\rm mediator}$
- additional annihilation channels ($W^\pm$, light mediator particles,...)
- co-annihilations
- ...

XENON100 limit on spin-indep. interactions



- XENON100 is probing an exciting region of parameter space, motivated by the argument of DM thermal freeze-out
- if no signal is found within 1-2 orders of magnitude in σ the WIMP hypothesis will come under pressure, and one should start to think about alternatives ("secluded" models, non-thermal DM production, non-WIMP candidates, . . .)

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- a few experiments report "hints" for WIMP interactions:

  DAMA, CoGeNT, CRESST

  $\Rightarrow$ WIMPs (SI) in the low-mass ($\sim$10 GeV) region?
  $\Rightarrow$ or maybe something more exotic
  $\Rightarrow$ or have nothing to do with DM at all

- Severe constraints from CDMS and XENON10/100

Comments on $\sim$ 10 GeV WIMPs

"conventional" WIMP has $\sim$ 100 GeV
light WIMP must not couple to Z^0 (LEP)

- Scalar singlet DM: add scalar singlet to the SM with Z_2 symmetry,
  Silveira, Zee, 85; McDonald 94; Burgess, Pospelov, Veldhuis, 00; He, Li, Li, Tandean, Tsai, 09; Andreas, Arina, Hambye, Ling, Tytgat, 1003.2595;...

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\partial_\nu S \partial^\nu S - \frac{1}{2}\mu^2 S^2 - \frac{1}{2}\lambda_1 S^4 - \lambda_2 S^2 \phi^\dagger \phi$$

  communication with the SM via the "Higgs portal" λ_2
  relic abundance obtained for $m_S \sim 10$ GeV with right cross section

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- MSSM neutralino:
  LEP Z^0 invis width OK by making it mostly bino, but have to depart from CMSSM to make it light $\Rightarrow$ non-universal gaugino masses

  e.g., Bottino, Donato, Fornengo, Scopel, 02,03,07,08,09; Hooper, Plehn, 02; Belanger, Boudjema, Cottrant, Pukhov, Rosier-Lees, 03; Asano, Matsumoto, Senami, Sugiyama, 09; Hisano, Nakayama, Yamanaka, 09; Kuflik, Pierce, Zurek, 1003.0682; Feldman, Liu, Nath, 1003.0437; Albornoz, Belanger, Boehm, Pukhov, Silk, 1009.4380; Fornengo, Scopel, Bottino, 1011.4743; Calibbi, Ota, Takanishi, 1104.1134

  $B_s \to \mu^+\mu^-$, Tevatron light Higgs searches, B, K decays
  fine-tuned region allows $m_\chi \sim 10$ GeV $\to$ tested soon

- NMSSM (singlino component)

  e.g., Gunion, Hooper, McElrath, hep-ph/0509024; Bae, Kim, Shin, 1005.5131; Das, Ellwanger, 1007.1151; Belikov, Gunion, Hooper, Tait, 1009.0549; Gunion, Belikov, Hooper, 1009.2555; Draper, Liu, Wagner, Wang, Zhang, 1009.3963; Albornoz, Belanger, Boehm, Pukhov, Silk, 1009.4380; Kappl, Ratz, Winkler, 1010.0553

- sneutrino: MSSM + ν_R

  Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner, 00; Belanger, Kakizaki, Park, Kraml, Pukhov, 1008.0580

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  Arkani-Hamed, Hall, Murayama, Tucker-Smith, Weiner, 00; Belanger, Kakizaki, Park, Kraml, Pukhov, 1008.0580

Comments on ~ 10 GeV WIMPs

- Asymmetric Dark Matter: Nussinov, 1985; Barr, Chivukula, Farhi, 1990; Barr, 1991; Kaplan, 1992; Kaplan, Luty, Zurek, 0901.4117; An, Chen, Mohapatra, Zhang, 0911.4463; Shelton, Zurek, 1008.1997; Davoudiasl, Morrissey, Sigurdson, Tulin, 1008.2399; Haba, Matsumoto, 1008.2487; McDonald, 1009.3227; Chun, 1009.0983; Buckley, Randall, 1009.0270; Gu, Lindner, Sarkar, Zhang, 1009.2690; Blennow, Dasgupta, Fernandez-Martinez, Rius, 1009.3159; Allahverdi, Dutta, Sinha, 1011.1286 Falkowski, Ruderman, Volansky, 1101.4936; Haba, Matsumoto, Sato, 1101.5679; Graesser, Shoemaker, Vecchi, 1103.2771; Frandsen, Sarkar, Schmidt-Hoberg, 1103.4350; McDermott, Yu, Zurek, 1103.5472; Kouvaris, Tinyakov, 1104.0382; Buckley, 1104.1429;...

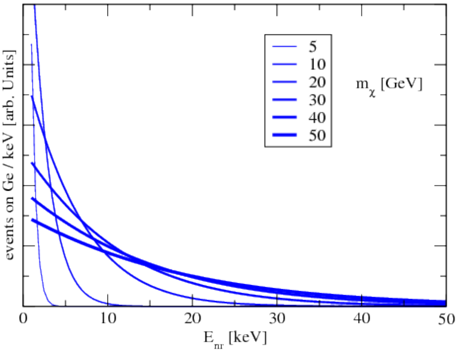
$$\frac{\Omega_{DM}}{\Omega_B} = \frac{n_{DM}}{n_B}\frac{m_{DM}}{m_p} \simeq 5$$

DM carries some quantum number; invoke common mechanism for baryon and DM genesis: $n_{\rm DM} \sim n_B \quad \Rightarrow \quad m_{\rm DM} \sim m_p$

Event spectrum

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi}\,\frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2}\int_{v>v_{\min}(E_R)} d^3v\,\frac{f_\oplus(\vec{v},t)}{v}$$

$v_{\min} = \frac{m_\chi + M}{m_\chi}\sqrt{\frac{E_R}{2M}}$: minimal DM velocity needed for recoil energy E_R



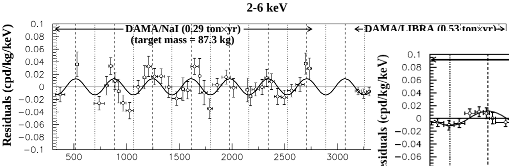
$m_\chi \ll M$:

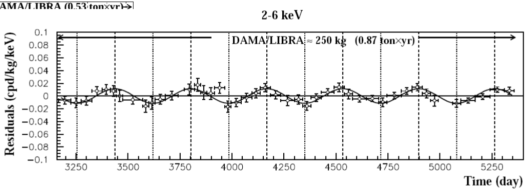
$$v_{\min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

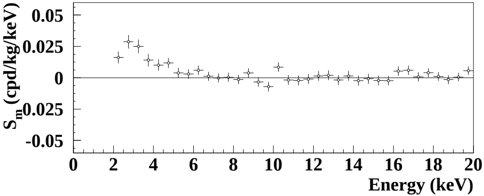
spectrum gets shifted to low energies for low WIMP masses
$\Rightarrow$ energy threshold is crucial

DAMA/LIBRA annual modulation signal

Scintillation light in NaI detector, 1.17 t yr exposure (13 yrs)
~ 1 cnts/d/kg/keV $\quad\rightarrow\quad \sim 4\times 10^5$ events/keV in DAMA/LIBRA
$\sim 8.9\sigma$ evidence for an annual modulation of the count rate with maximum at day 146 ± 7 (June 2nd: 152) Bernabei et al., 0804.2741, 1002.1028

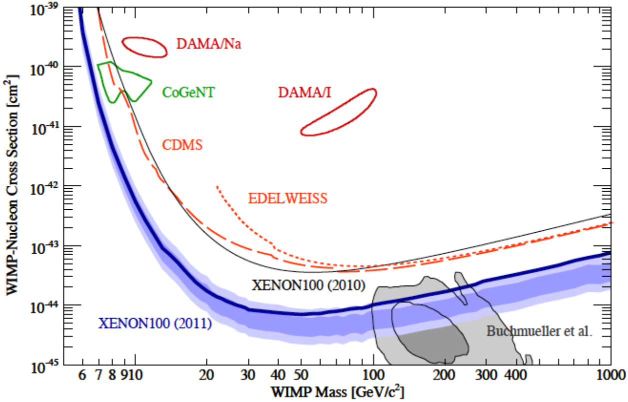






energy shape of modulation is important for constraining params
Chang, Pierce, Weiner, 0808.0196
Fairbairn, TS, 0808.0704

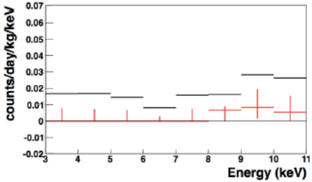
DAMA/LIBRA annual modulation signal



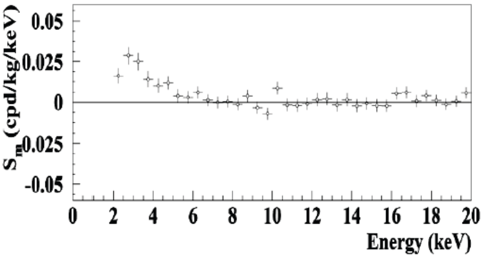
KIMS results challenge DAMA NEW!

CsI detector, puse shape for NR discrimination, 24524 kg days exposure

KIMS Nuclear recoil event rate



DAMA Modulation amplitude rate



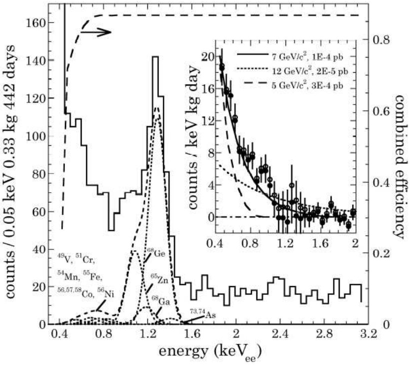
KIMS 3.6-5.8 keV **DAMA 2-4 keV** 0.0183 ± 0.0022

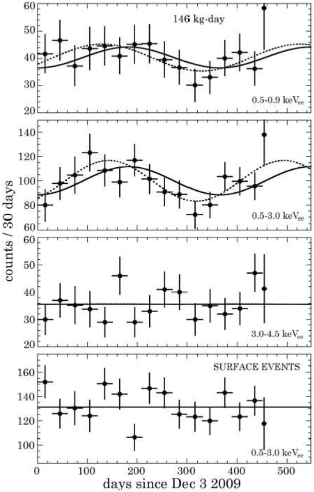
< 0.0098 counts/kg/day/keV (90% C.L.)

Modulation cannot be bigger than 100% !
→Iodine recoil cannot explain both KIMS and DAMA even with enhanced modulation such as iDM models

CoGeNT: exponential event excess and hint for modulation

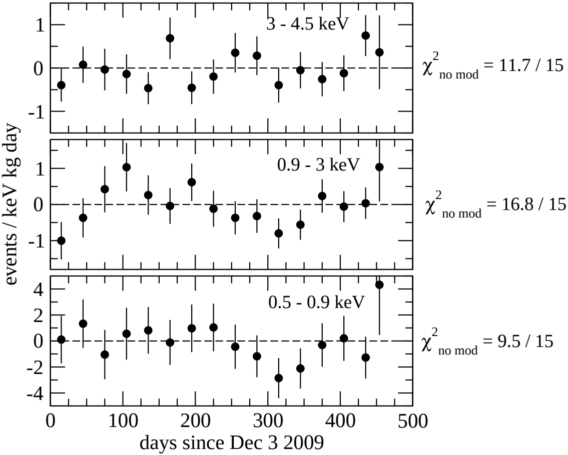
Germanium detector with very low threshold of 0.4 keVee $\approx$ 1.9 keV$_{nr}$





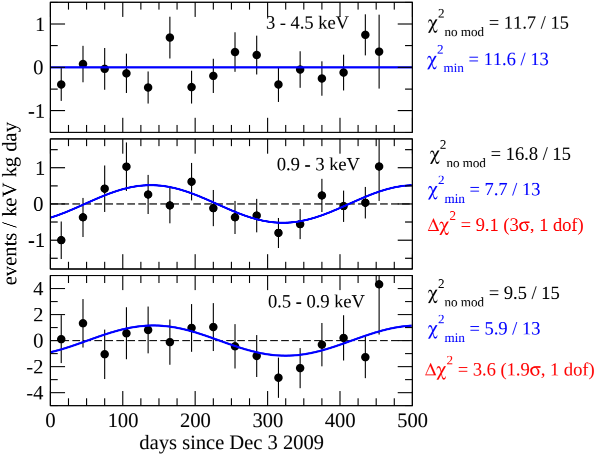
Aalseth et al, 1106.0650

Annual modulation in CoGeNT



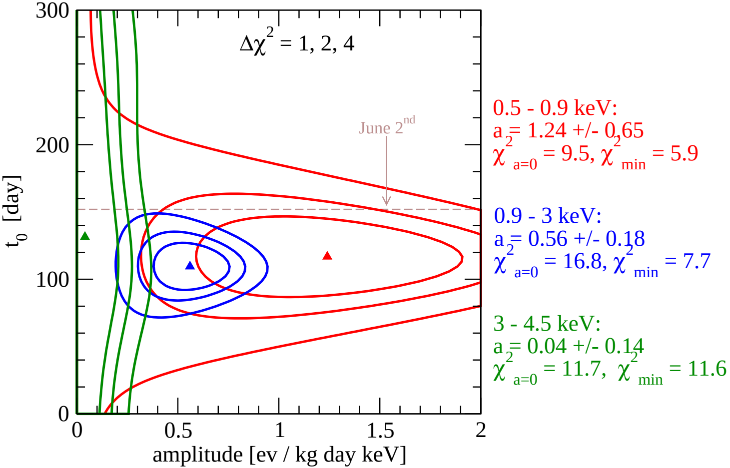
$0.5 - 3$ keV: $\chi^2_{\text{no mod}} = 20/15$ (17%)

Annual modulation in CoGeNT

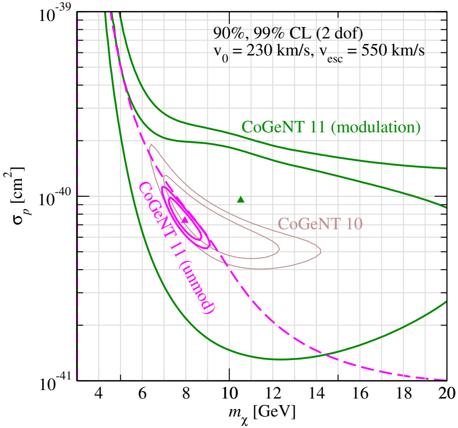


$0.5 - 3$ keV: 2.8σ preference for modulation Aalseth et al, 1106.0650

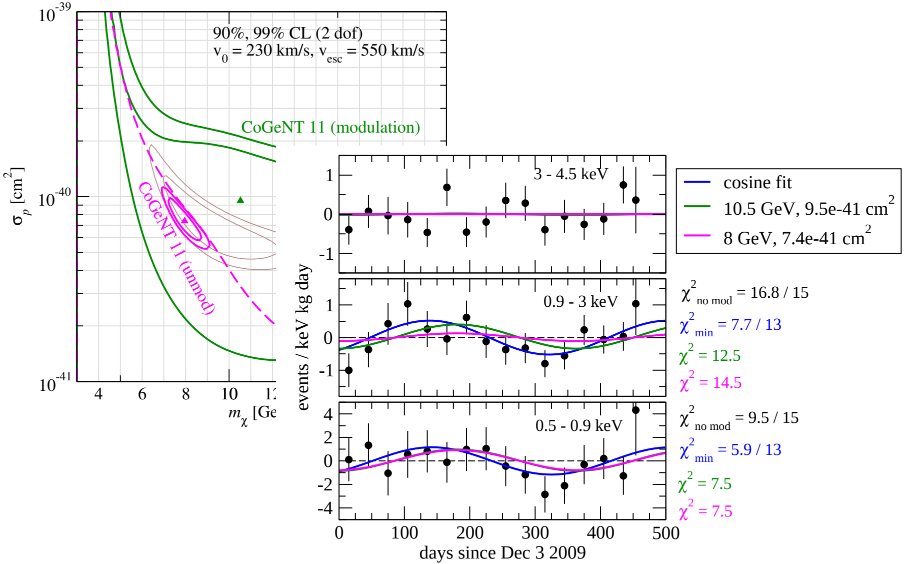
Annual modulation in CoGeNT



Fitting CoGeNT with elastic SI scattering

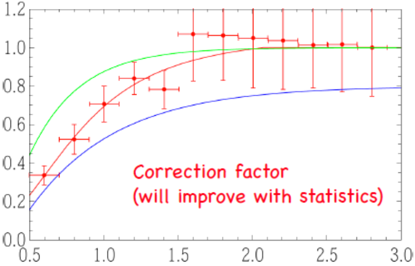


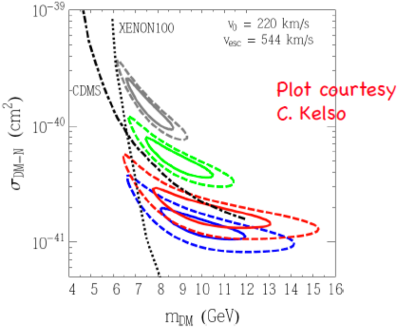
Fitting CoGeNT with elastic SI scattering



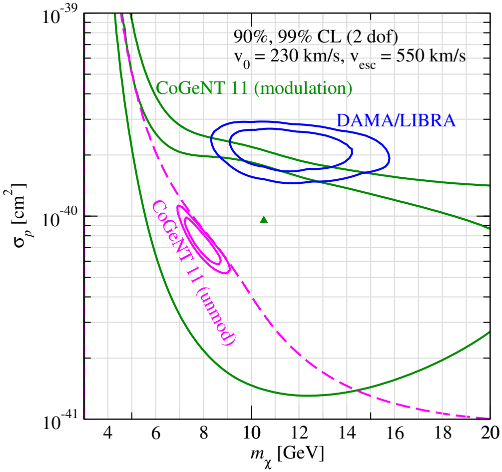
CoGeNT surface event rejection near threshold?

preliminary J. Collar @ TAUP 2011





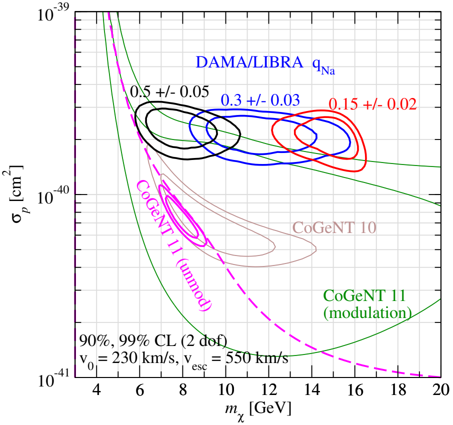
CoGeNT and DAMA not quite consistent...

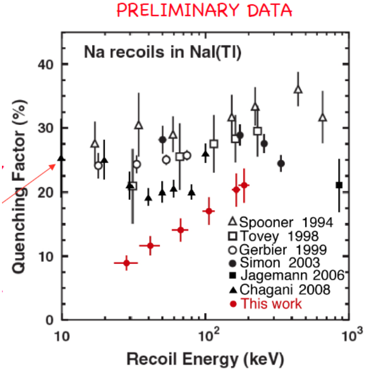


Can we make CoGeNT and DAMA consistent?

Hooper, Collar, Hall, McKinsey, 1007.1005; Hooper, Kelso, 1106.1066

How well do we know the quenching factor of Na?

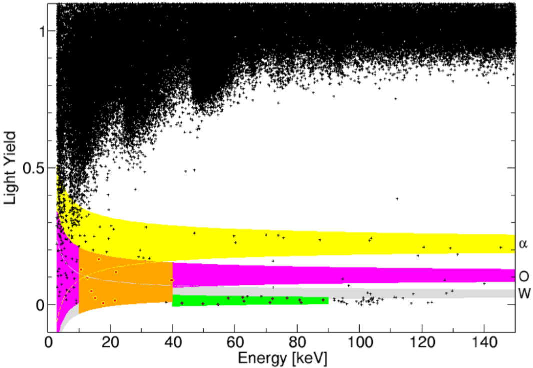


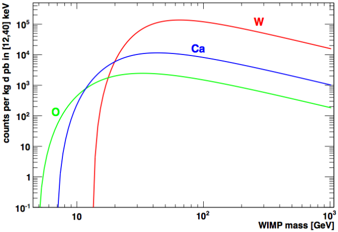


J. Collar @ TAUP 2011

CRESST-II NEW!

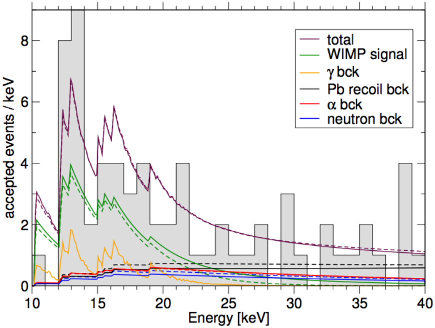
$CaWO_4$ target, 8 detectors, 730 kg d TAUP 2011, 1109.0702

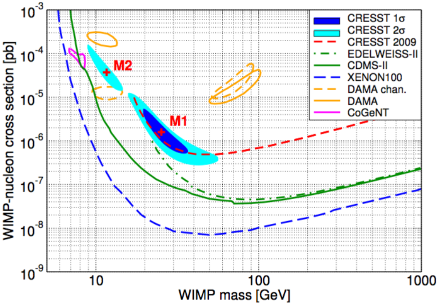




backgrounds: e/γ : 8, α : ~ 11, neutrons: ~ 7, Pb: ~ 15
observe 67 events: likelihood fit gives ~ 29 signal events at more than 4σ

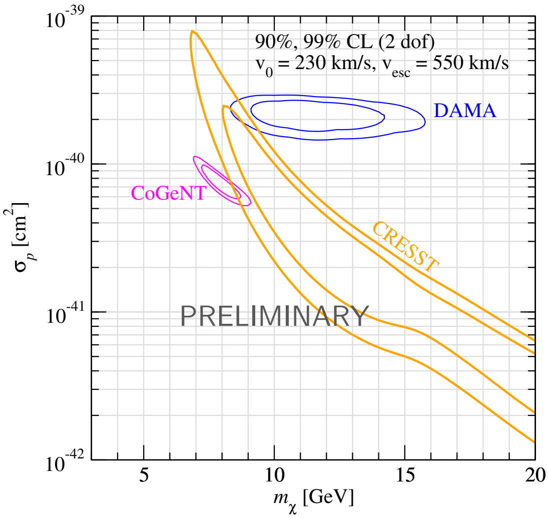
CRESST-II TAUP 2011, 1109.0702



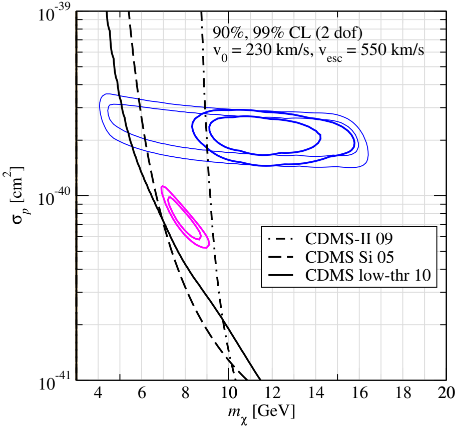


M1: $m_\chi = 25.3$ GeV, significance: 4.7σ (signal: 69% W, 25% Ca, 7% O)
M2: $m_\chi = 11.6$ GeV, significance: 4.2σ (signal: 52% O, 48% Ca)

The low-mass hints

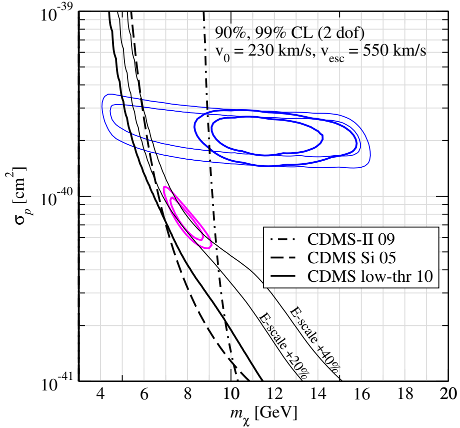


CDMS constraints



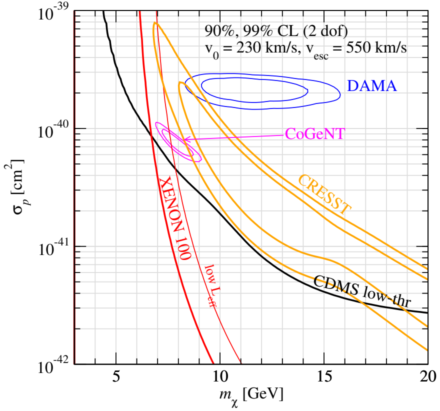
- CDMS data on Si astro-ph/0509259: 12 kg day, 7 keV threshold
- low-threshold analysis of Soudan Ge data (2006–08) 1011.2482
  do not insist on full NR/electr discrimination →
  accept some background →
  lower threshold to 2 keV

CDMS constraints



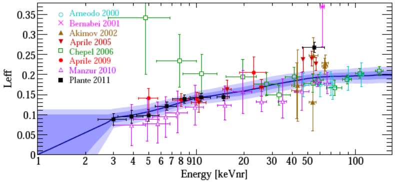
energy scale uncertainty in CDMS low-thr?

XENON bounds



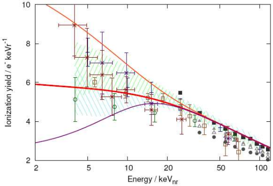
translate $S1$ [PE] into E_{nr} [keV]:

$$E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$$

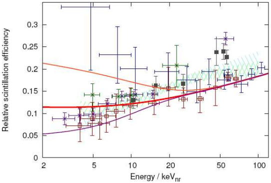


heated discussion: Collar, McKinsey, 1005.0838; XENON100, 1005.2615; Collar, McKinsey, 1005.2615; Savage et al., 1006.0972; Sorensen, 1007.3549; Collar, 1006.2031, 1106.0653

XENON bounds

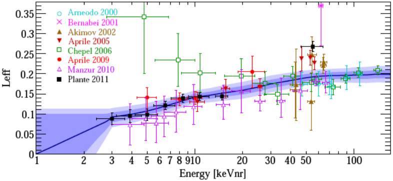


(a) The ionization yield



translate $S1$ [PE] into E_{nr} [keV]:

$$E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$$



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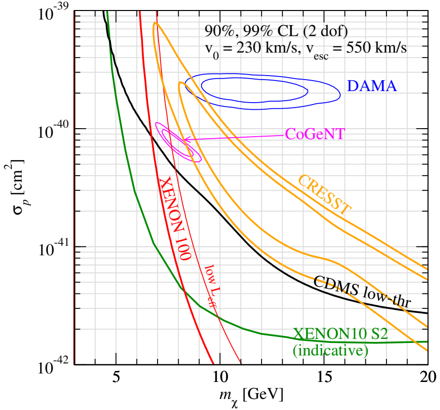
Bezrukov, Kahlhoefer, Lindner, 1011.3990

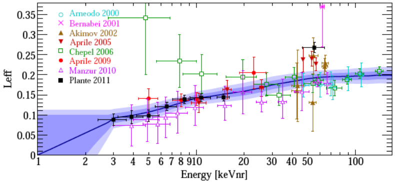
relation between ionization and scintillation suggest high L_{eff}.

XENON bounds



translate $S1$ [PE] into E_{nr} [keV]:

$$E_{nr} = \frac{S1}{L_{eff}(E_{nr})} \frac{1}{L_y} \frac{S_e}{S_n}$$



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S2 only analysis of XENON 10 data Sorensen @ iDM 2010; J. Angle et al. 1104.3088

energy scale from ionization signal (S2) $\rightarrow$ independent of L_{eff}

S2 energy scale determination criticized Collar, 1010.5187, 1106.0653; see also Sorensen @ TAUP11

How to reconcile?

- Experimental issues?
  $\sim$ 10 GeV region is experimentally challenging
  systematic uncertainties on quenching factors, energy scale, threshold effects, backgrounds... have to be understood and taken into account before making strong statements.

However, in order to get a consistent picture we need to assume that

- CDMS made a major calibration error (in Ge and Si),
- the XENON S2 analysis is completely wrong,
- there is a serious problem with L_{eff} in Xenon,
- major problem with Na quenching factor for DAMA,
- surface events in CoGeNT?

Modify astrophysics?

- changing $\bar{v}, v_{\rm esc}$ has little impact on consistency
- non-standard halos (asymmetric, DM streams, dark disc) may marginally improve but require extreem params

these statements hold for standard SI elastic scattering
in other models (e.g. inelastic scattering) the impact of astrophysics can be bigger

Outline

Introduction

Direct detection: present status
- XENON100 results

Hints for a DM signal?
- DAMA/LIBRA
- CoGeNT
- CRESST-II
- Constraints from CDMS and XENON

Alternative particle physics
- Spin-dependent scattering
- Inelastic scattering
- General iso-spin dependence

Conclusion

Let's depart from elastic SI scattering

- spin-dependent interaction
- inelastic DM Tucker-Smith, Weiner, hep-ph/0101138
- inelastic SD Kopp, Schwetz, Zupan, 0912.4264
- mirror DM R. Foot; An, Chen, Mohapatra, Nussinov, Zhang, 1004.3296
- leptophilic DM Fox, Poppitz, 0811.0399; Kopp, Niro, Schwetz, Zupan, 0907.3159
- form factor DM Feldstein, Fitzpatrick, Katz, 0908.2991
- momentum dep. DM Scattering Chang, Pierce, Weiner, 0908.3192
- resonant Dark Matter Bai, Fox, 0909.2900
- luminous Dark Matter Feldstein, Graham, Rajendran, 1008.1988
- electro-magnetic DM interactions Masso, Mohanty, Rao, 0906.1979; Chang, Weiner, Yavin, 1007.4200; Barger, Keung, Marfatia, 1007.4345; Fitzpatrick, Zurek, 1007.5325; Banks, Fortin, Thomas, 1007.5515
- iso-spin violating SI scattering Chang, Liu, Pierce, Weiner, Yavin, 1004.0697; Feng, Kumar, Marfatia, Sanford, 1102.4331; Frandsen et al., 1105.3734
- more to come

Spin-dependent scattering

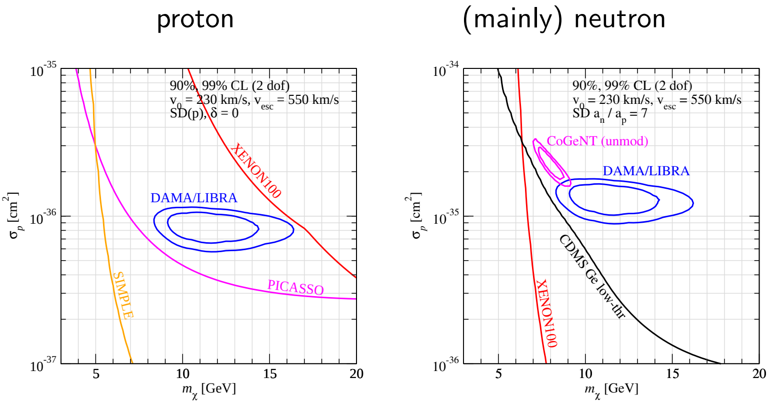
coupling mainly to an un-paired nucleon:

		neutron	proton
DAMA	$^{23}_{11}$Na	even	odd
DAMA, KIMS, COUPP	$^{127}_{53}$I	even	odd
SIMPLE	$^{35}_{17}$Cl, $^{37}_{17}$Cl	even	odd
XENON, ZEPLIN	$^{129}_{54}$Xe, $^{131}_{54}$Xe	odd	even
CDMS, CoGeNT	$^{73}_{32}$Ge	odd	even
PICASSO, COUPP, SIMPLE	$^{19}_{9}$F	even	odd
CRESST	$^{A}_{74}$W, $^{16}_{8}$O, $^{40}_{20}$Ca	even	even

coupling with proton promising for DAMA vs CDMS/XENON

BUT: severe bounds from COUPP, KIMS, PICASSO, SIMPLE

Spin-dependent scattering



Schwetz, Zupan, 1106.6241

Constraints from Tevatron (and LHC)

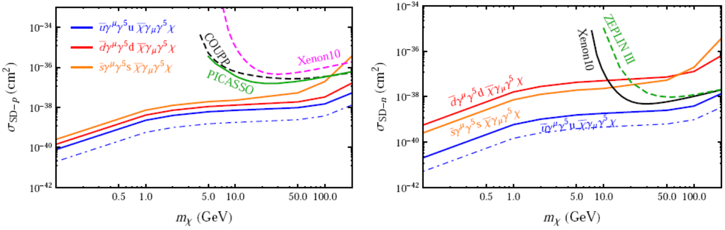
assume effective quark DM interaction:

$$\frac{\lambda^2}{\Lambda^2}(\bar{q}\gamma_5\gamma_\mu q)(\bar{\chi}\gamma_5\gamma^\mu\chi) \quad \Rightarrow \quad pp \rightarrow \bar{\chi}\chi + j$$

constraints from mono-jet searches at Tevatron

assume EFT is still valid at ∼TeV momentum transfer

e.g., Feng, Su, Takayama, hep-ph/0503117; Beltran et al., 1002.4137; Goodman et al., 1005.1286; ...

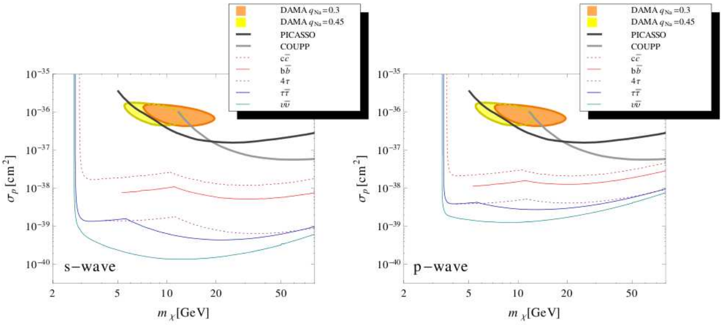


Bai, Fox, Harnik, 1005.3797

SD and constraints from neutrinos

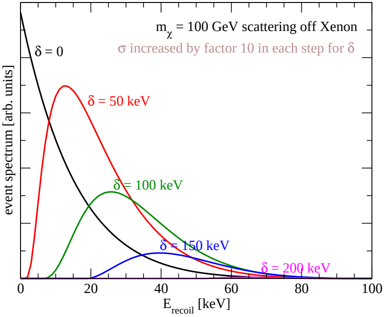
SD interactions on protons → large WIMP capture cross section in the sun
WIMPs may annihilate and produce high energy neutrinos → constraints from SuperKamiokande

In relation to light DM: e.g., Feng, Kumar, Learned, Strigari, 0808.4151; Andreas, Tytgat, Swillens, 0901.1750; Niro, Bottino, Fornengo, Scopel, 0909.2348; Hooper, Petriello, Zurek, Kamionkowski, 0808.2464



Kappl, Winkler, 1104.0679

Inelastic DM scattering Tucker-Smith, Weiner, 01

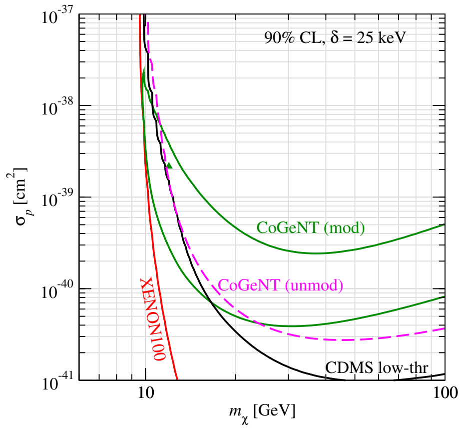


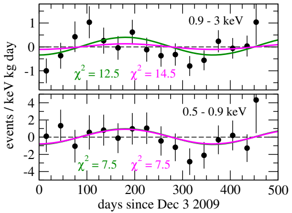
$$m_{\chi^*} - m_\chi = \delta \simeq 100\,\text{keV} \sim 10^{-6} m_\chi$$

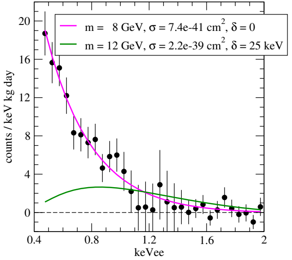
$$v_{\rm min}^{\rm inel} = \frac{1}{\sqrt{2ME_R}}\left(\frac{ME_R}{\mu_\chi} + \delta\right)$$

- sampling only high-velocity tail of velocity distribution
- no events at low recoil energies
- high mass targets favoured
- enhance modulation compared to unmodulated signal

iDM and CoGeNT modulation





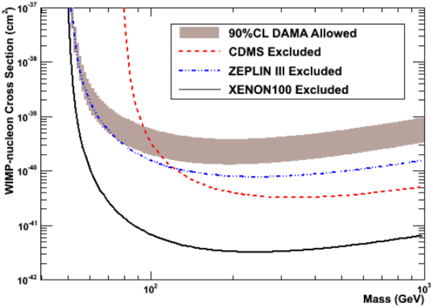


TS, Zupan, 1106.6241.

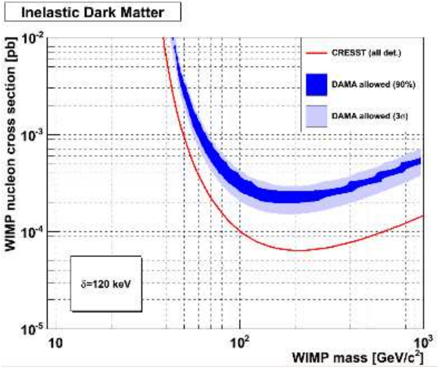
- make mod and unmod spectrum consistent but cannot explain rate
- XENON bound still severe

iDM and DAMA modulation

XENON100 1104.3121



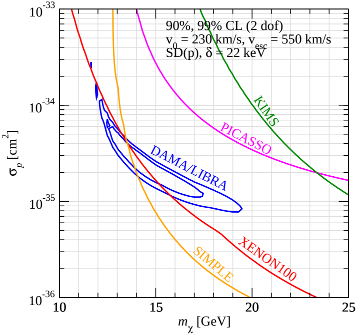
talk by W. Seidel @ IDM10, poster of J. Schmaller @ TAUP11

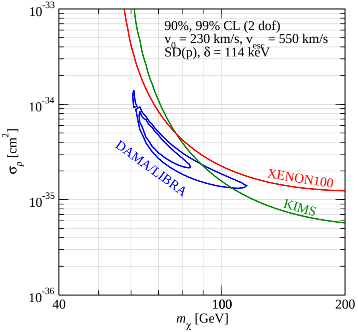


disfavored by XENON100, CRESST (tungsten), and KIMS

Inelastic spin-dependent scattering on protons

Kopp, Schwetz, Zupan, 0912.4264; Schwetz, Zupan, 1106.6241

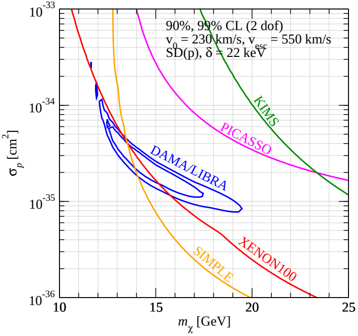


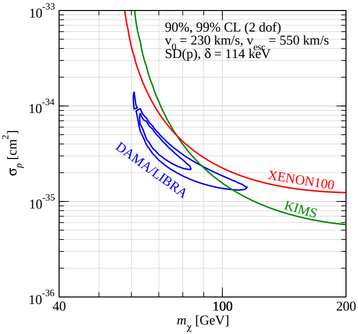


- SD coupling to proton gets rid of XENON/CDMS/CRESST bounds (no unpaired proton)
- inelastic scatt. gets rid of PICASSO/COUPP (light target)

Inelastic spin-dependent scattering on protons

Kopp, Schwetz, Zupan, 0912.4264; Schwetz, Zupan, 1106.6241





BUT:

- cannot explain CoGeNT/CRESST
- neutrinos from the sun (annih. into u, d, μ, e still OK) Shu, Yin, Zhu, 1001.1076
- probably mono-jet bounds from Tevatron apply
- new bounds from KIMS TAUP 2011 to be checked

iSD - toy model

Kopp, Schwetz, Zupan, 09: generalize idea of Tucker-Smith, Weiner, 01 to SD int.:
assume 4-Fermi interaction with $T \otimes T$ structure:

$$\mathcal{L}_{\rm int} = \frac{C_{\rm T}}{\Lambda^2}\left[\bar\psi \Sigma_{\mu\nu}\psi\right]\left[\bar q \Sigma^{\mu\nu} q\right], \qquad \Sigma^{\mu\nu} = i[\gamma^\mu, \gamma^\nu]/2$$

$\psi = (\eta, \xi^\dagger)$ with Dirac $m\bar\psi\psi$ and Majorana mass $(\delta_\eta \eta\eta + \delta_\xi \xi\xi)/2$
$\Rightarrow$ two Majorana fermions with masses $m \pm \delta$ ($\delta_\eta = \delta_\xi = \delta \ll m$):

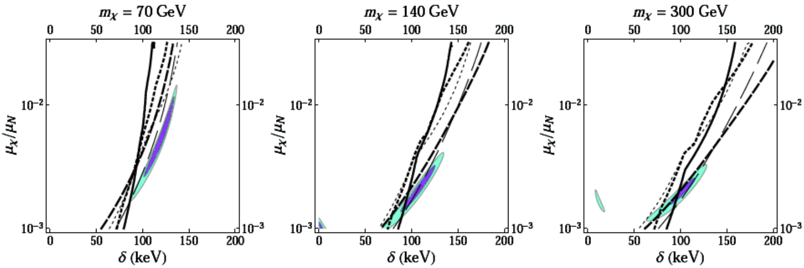
$$\chi_1 = i(\eta - \xi)/\sqrt{2}, \qquad \chi_2 = (\eta + \xi)/\sqrt{2}$$

$$\Rightarrow \quad \bar\psi \Sigma_{\mu\nu}\psi = -2i(\chi_2 \sigma_{\mu\nu}\chi_1 + \chi_2^\dagger \bar\sigma_{\mu\nu}\chi_1^\dagger),$$

- inelastic scattering for $\delta \neq 0$
- $T \otimes T$ leads to spin dependent scattering in the non-rel. limit

magnetic inelastic DM

observe that I, Cs, Na, F nuclei have very large effective MM
assume DM has MM: $\mathcal{L} = \frac{\mu_\chi}{2}\bar{\chi}^*\sigma_{\mu\nu}\chi F^{\mu\nu} + h.c.$



Chang, Weiner, Yavin, 1007.4200

- use large MM of iodine to enhance rate in DAMA
- inelast kinematics avoids florine constraints (light target)
- no explanation for CoGeNT/CRESST
- probably ruled out by KIMS results TAUP 2011

Generalized couplings to neutron and proton

SI scattering cross section $\propto [Zf_p + (A-Z)f_n]^2$
typically (iso-spin symmetry) one has $f_n \approx f_p \quad \Rightarrow \quad \mathrm{SI} \propto \sigma_p A^2$

consider quark operator $G_q \bar{q} q \bar{\chi}\chi \to$ eff. coupling to nucleon $N = p, n$:

$$f_N = \sum_q G_q \langle N|\bar{q}q|N\rangle$$

$$= \sum_{q=u,s,d} G_q \frac{m_N}{m_q} \xi_q^N + \frac{2}{27}\left(1 - \sum_{q=u,s,d} \xi_q^N\right) \sum_{q=c,b,t} G_q \frac{m_N}{m_q}$$

$$\xi_d^p \approx 0.033\,, \quad \xi_u^p \approx 0.023\,, \quad \xi_s^p \approx 0.26$$
$$\xi_d^n \approx 0.042\,, \quad \xi_u^n \approx 0.018\,, \quad \xi_s^n \approx 0.26$$

ex.: Higgs mediated interaction:

$G_q \propto m_q \Rightarrow$ dominated by s-quark and $f_n \approx f_p$

Generalized couplings to neutron and proton

allow for general couplings: Chang et al., 1004.0697; Feng, Kumar, Marfatia, Sanford, 1102.4331; Frandsen et al., 1105.3734; Nobile, Kouvaris, Sannino, 1105.5431

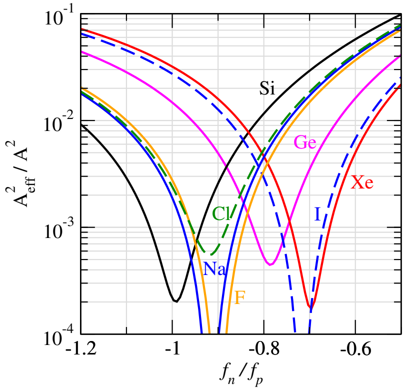
$$\text{SI} \propto \sigma_{\text{eff}} A_{\text{eff}}^2 \qquad \text{with}$$

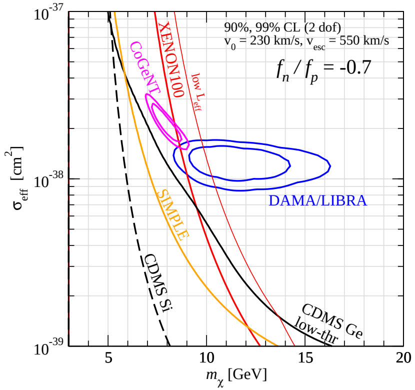
$$\sigma_{\text{eff}} \equiv \frac{\sigma_n + \sigma_p}{2}\,, \qquad \tan\theta \equiv f_n/f_p$$

$$A_{\text{eff}}^2 = 2 \sum_{i=\text{iso}} r_i [Z\cos\theta + (A_i - Z)\sin\theta]^2$$

for $f_n/f_p < 0$: cancellations $\Rightarrow$
can suppress rate for isotope if $f_n/f_p = -Z/(A-Z)$

Generalized couplings to neutron and proton

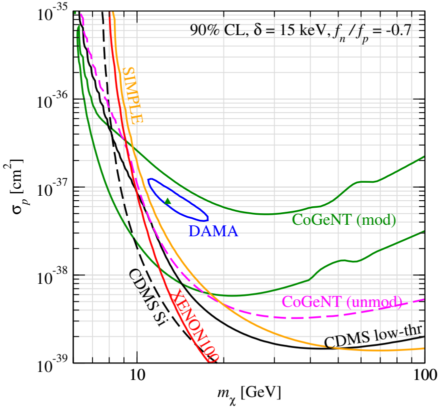


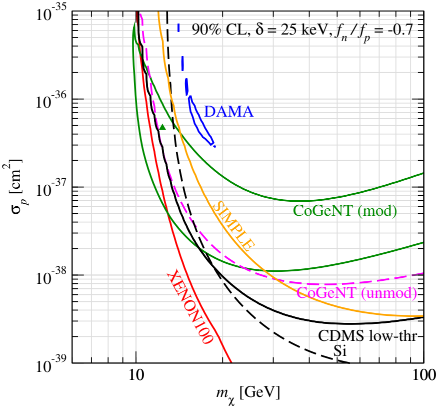


suppress Xe rate for $f_n/f_p \approx -0.7$, but enhanced rate for Si and F
constraint from CDMS low-threshold Ge analysis remains

Generalized couplings to neutron and proton + inelasticity

proposed to reconcile CoGeNT modulation and DAMA Frandsen et al., 1105.3734





TS, Zupan, 1106.6241

Outline

Introduction

Direct detection: present status
- XENON100 results

Hints for a DM signal?
- DAMA/LIBRA
- CoGeNT
- CRESST-II
- Constraints from CDMS and XENON

Alternative particle physics
- Spin-dependent scattering
- Inelastic scattering
- General iso-spin dependence

Conclusion

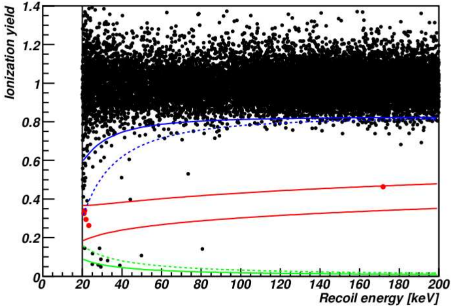
Conclusions

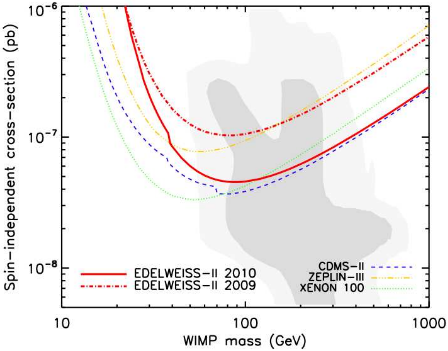
- Exciting times for direct detection
  we are probing a region motivated by the WIMP hypothesis
- Some hints for DM around 10 GeV $\Rightarrow$
  in tension with constraints, unclear situation
- Also exotic particle physics seems not to be able to fit all
  maybe we have not found the correct model yet?
- More data will tell!

Additional slides

Edelweiss

384 kg day Germanium exposure Armengaud et al, 1103.4070



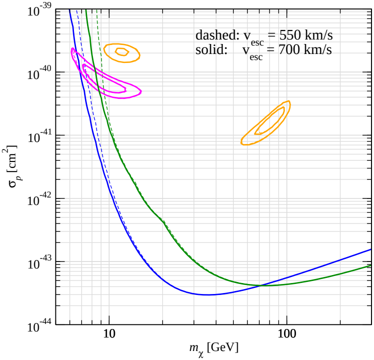


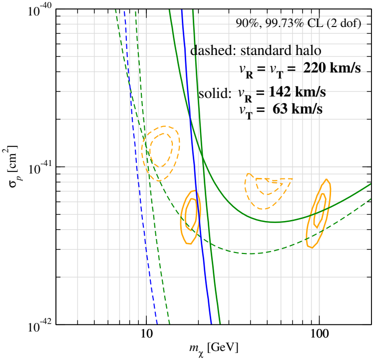
5 WIMP candidates observed

background expectation: $\lesssim 3$ events at 95% CL

Modify astrophysics?

changing $\bar{v}$, $v_{\rm esc}$ has little impact on consistency
non-standard halos (asymmetric, DM streams, dark disc)
may marginally improve but require extreem params





left: value of $v_{\rm esc}$ TS, 1011.5432; right: asymmetric velocity distr. Fairbairn, TS 0808.0704