DIRECT SEARCHES OF DARK MATTER

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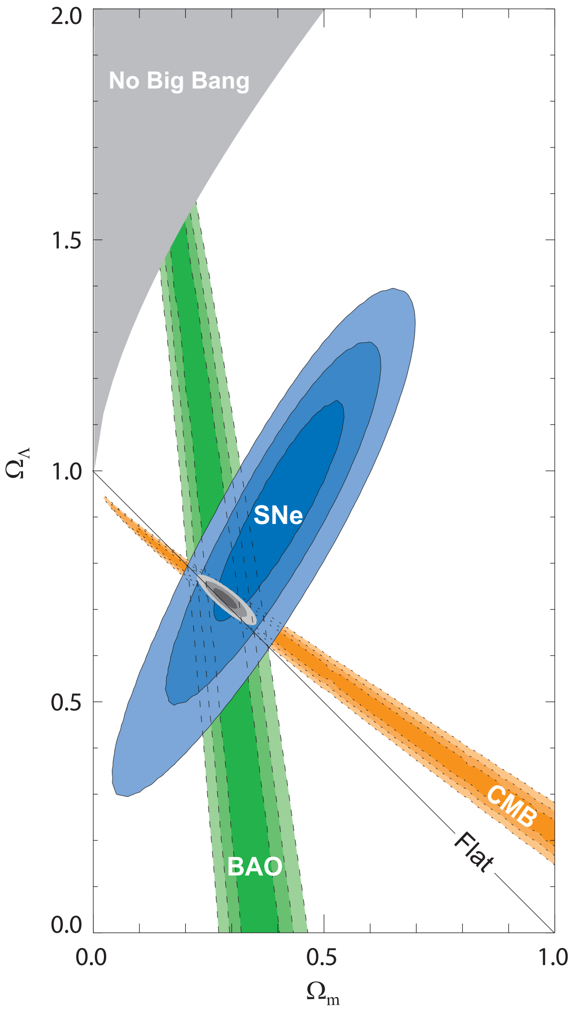
Pheno 09, May 12, 2009

Dark Matter: We know a lot!

- We know its abundance in the Universe (23%)
- We know most is not baryonic
- We know DM exists (no modified gravity explains the Bullet Cluster!)
- We know most of it is not in MACHOS (thus $m_{DM} < 10^{-7} M_{\odot}$)
- We know is it NOT explained by the Standard Model of EP

Concordance cosmology

Fig. from M. Kowalski et al 2008



$$\Omega = \rho/\rho_c \qquad \rho_c \simeq 5\ \mathrm{keV/cm^3}$$

68.3%, 95.4%, 99.7%CL constraints on Ω_M and Ω_Λ obtained from Cosmic Background Radiation Anisotropy CMB (orange), Baryon Acoustic Oscillations BAO (green), and the Union Compilation of 307 Type Ia supernovae (SNe Ia) (blue); $\Omega_m = 0.285^{+0.020}_{-0.019}$(stat)$^{+0.011}_{-0.011}$(sys) assuming DE is a cosmological constant

WMAP5, BAO, SN: E. Komatsu, et al., 2009

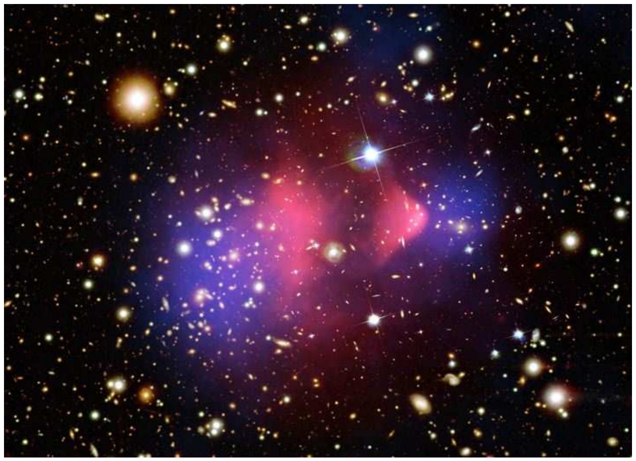
$\Omega_\Lambda = 0.721 \pm 0.015$, $\Omega_m = 0.279 \pm 0.015$,

where Ω_m is:

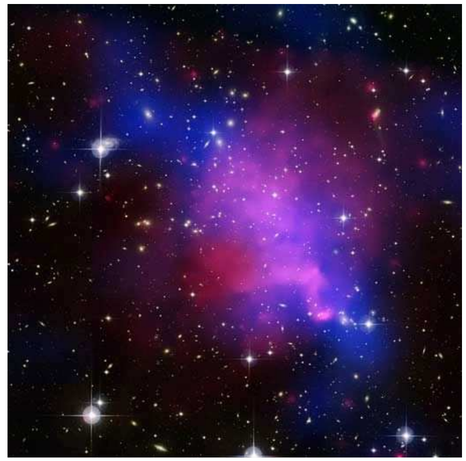
$\Omega_b = 0.0462 \pm 0.0015$, $\Omega_{DM} = 0.233 \pm 0.0013$

Dark Matter exists!

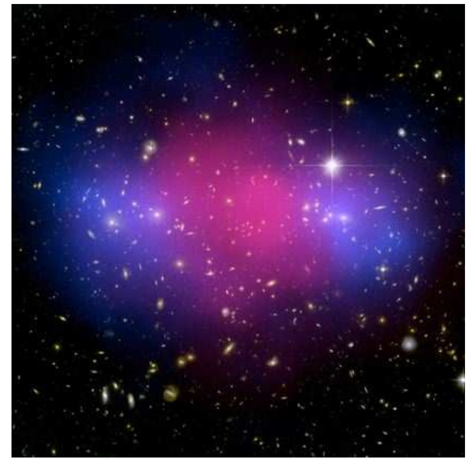
"bullet cluster" August 2006



"train wreck" August 2007



"baby-bullet" August 2008



The visible mass, hot gas detected by Chandra in X-rays (pink), is not where the mass of the cluster seen through gravitational lensing (blue) is.

New bound on DM self-interaction: $\sigma/m < 0.7$cm^2/g=1.3 barn/GeV, S.Randall et al. 2008-arXiv 0704.0261 (Spergel Steinhardt -2000 range was 0.5 to 6 cm^2/g)

Most of the Dark Matter: is cold or warm namely is non-relativistic or semi-relativistic at galaxy formation ($T \simeq 1\text{keV}$)

No CDM or WDM in the SM!

(active-ν are HDM)

But many in extensions of the SM!

Warm dark matter:

- sterile neutrino, gravitino, non-thermal neutralino...

Cold dark matter:

- WIMPs (LSP or variants LKP, LZP, LTP), axion, WIMPZILLAs, solitons (Q-balls)...

New physics at the EW scale?

Expected because of Spontaneous Symmetry Breaking arguments (totally independently of the DM issue)

Naturalness implies above $\Lambda_{SM} \approx \mathrm{O(TeV)}$ cancellations in corrections to m_{Higgs} due to a new theory....

- supersymmetry (with or without a composite Higgs boson)
- technicolor (walking or top assisted TC)
- large extra spatial dimension (possibly warped)
- "Little Higgs" model (Higgs is a pseudo-Goldstone boson)

which provides main potential discoveries at the LHC and DM candidates...mostly WIMPs: LSP, Lightest Technibaryon, LKP (Lightest KK Particle) or LZP (in Warped SO(10) with Z3 model), LTP (the Lightest T-odd heavy photon in Little Higgs with T-parity)...

New physics to explain DM?

May be different...., for example Arkani-Hamed, Finkbeiner, Slatyer and Weiner 0810.0713

"A Theory of DM" WIMP, with 500-800 GeV mass, has an exited state with mass difference 0.1 to 1 MeV, is charged under a broken hidden gauge symmetry G_{dark} with a boson ϕ lighter than 1GeV, explaining:

- the INTEGRAL data with "exciting" (XDM)
- the ATIC (now not found by Fermi!) and PAMELA data
- the WMAP Haze and the EGRET excess (now not found by Fermi!)
- the DAMA signal with "inelastic" (IDM)

Attests to the ingenuity of theorists to explain everything.....

Made to fit DM-not to solve the EW hierarchy.... and provides signatures for the LHC: many lepton jets with GeV invariant masses expected...Arkani-Hamed, Weiner 0810.0714 [hep-ph]

Physics beyond the SM

is required by Dark Matter,

and expected at the EW scale,

and both physics may or

may not be related!

Thus LHC and DM searches are

independent and complementary.

WIMPs as Dark Matter

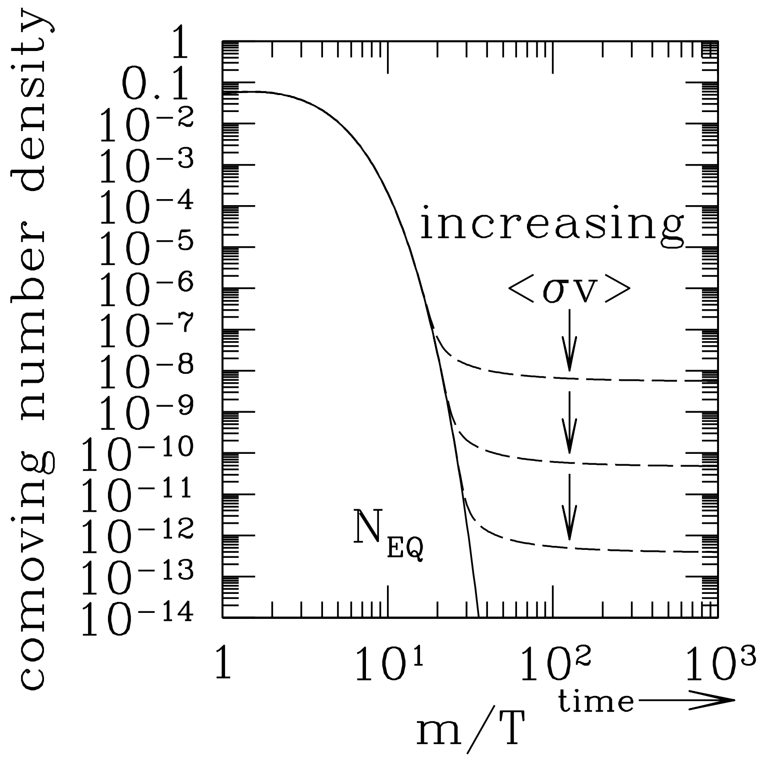
WIMPs are the earliest relics, from the pre-BBN era of the Universe, from which we have no data! So we must make assumptions... the standard ones are:

Standard calculations: start at $T > T_{f.o.} \simeq m/20$

- WIMPs reach thermal equilibrium while radiation dominates
- Chemical decoupling when $\Gamma_{\rm ann} = \langle \sigma v \rangle \, n \leq H$,
- No entropy change in matter+radiation

$$\Omega h^2 \approx \frac{2 \times 10^{-10} {\rm GeV}^{-2}}{\langle \sigma v \rangle}$$

Weak σ for $\Omega \sim 1$!

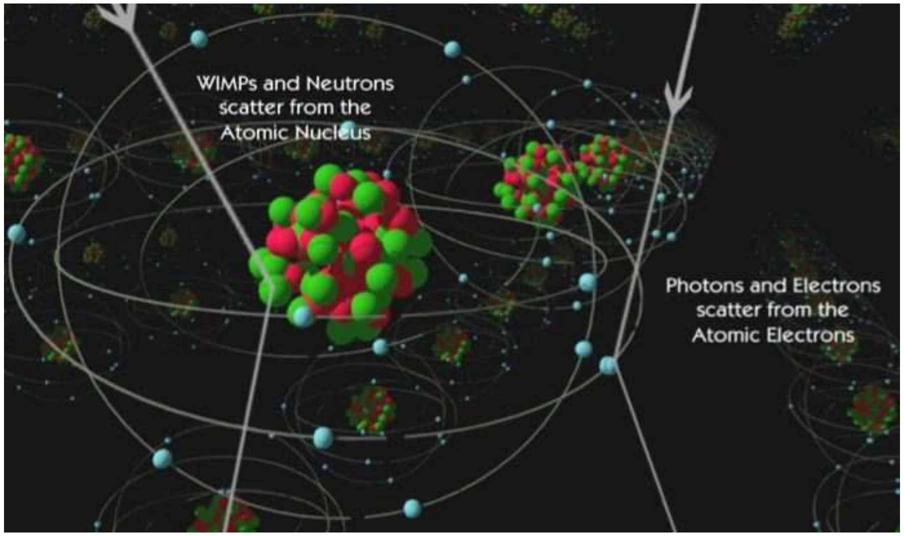


WIMP DM searches:

- **Indirect Detection**- looks for WIMP annihilation products
(Talk of Dan Hooper)

- **Direct Detection**- looks for energy deposited within detector
Signature: same σ and m $+$ annual modulation and/or recoil direction, seen by different experiments with different nuclei

Direct DM Searches:



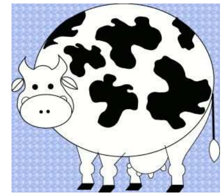
- Small $E_{\rm Recoil} \leq 50$ keV
- Rate: depends on WIMP mass, cross section, dark halo model, nuclear form factors...
- Single hits: single scatters, uniform through volume of detector
- Annual flux modulation (few % effect)
- Diurnal modulation (requires measuring the recoil direction)

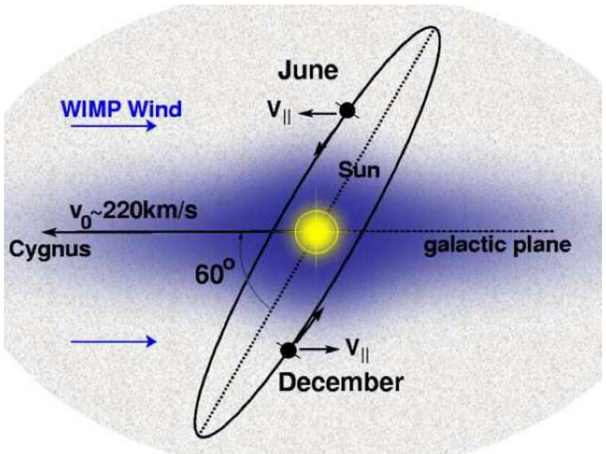
Event rate: events/(kg of detector)/(keV of recoil energy)

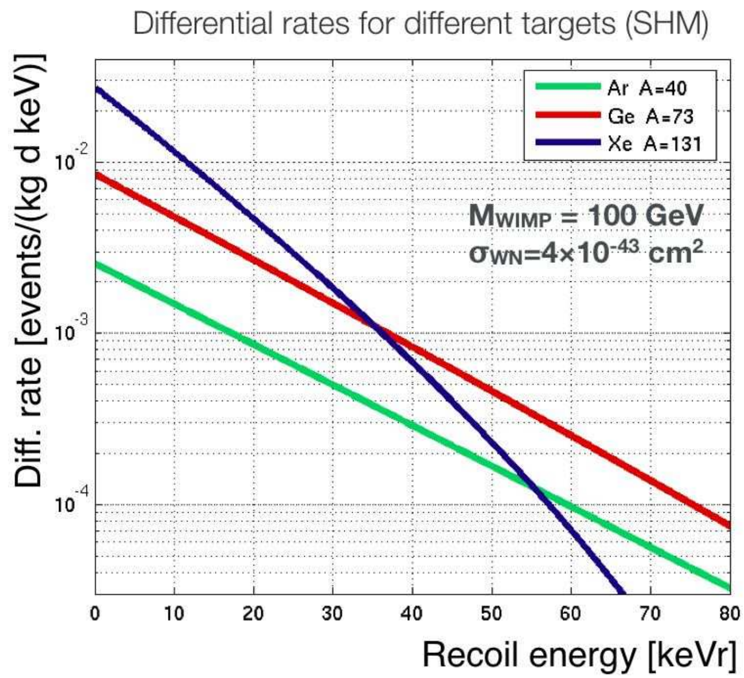
$$\frac{dR}{dE} = \int \frac{N_T}{M_T} \times \frac{d\sigma}{dE} \times n v f(\mathbf{v},t) d^3v$$
$$= \frac{\rho\sigma(q)}{2m\mu^2} \int_{v>v_{\rm min}} \frac{f(\mathbf{v},t)}{v} d^3v$$

- For elastic scattering: $v_{\rm min} = \sqrt{ME/2\mu^2}$
-μ is the reduced WIMP-nucleus mass $\mu = mM/(m+M)$
- ρ local, $f(\mathbf{v},t)$ depend on dark halo model
- spin-independent $\sigma(q)= \sigma_0 F^2(q)$, $\sigma_0 = A^2(\mu^2/\mu_{\rm p}^2)\sigma_{\rm p}$ for $f_p = f_n$

- spin-dependent $\sigma(q) = \frac{32\mu^2 G_F^2}{2J+1}\left[\langle S_{\rm pp}\rangle {a_{\rm p}}^2 + \langle S_{\rm pn}\rangle a_{\rm p} a_{\rm n} \langle S_{\rm nn}\rangle {a_{\rm n}}^2\right]$

Standard Halo Model (SHM) The  of halo models



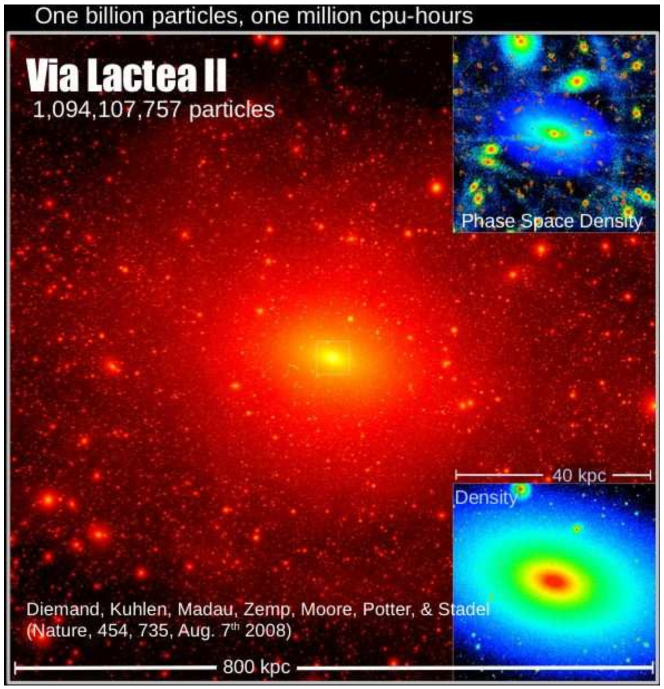


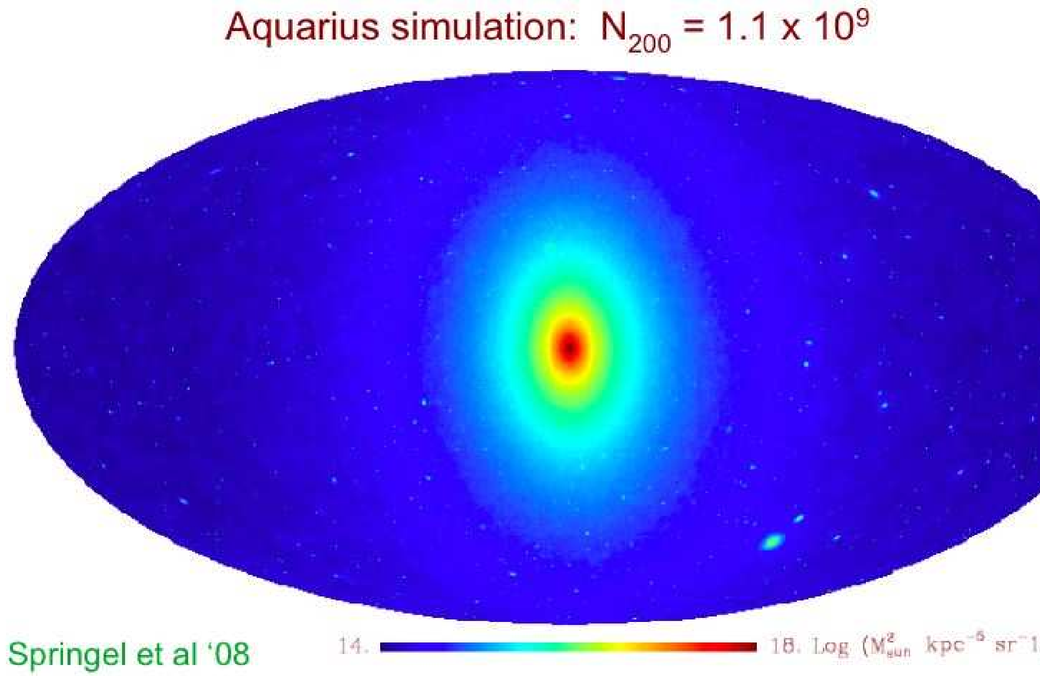
$\rho_{SHM} = 0.3$ GeV/cm^3 ($\times$ 1/2 - 2)

Maxwellian $\vec{v}$ distribution
at rest with the Galaxy
v_d =220 km/s, v_{esc} = 500 - 650 km/s

Local ρ and velocity could be very different if the Earth is within a DM clump or stream or if there is a "Dark Disk" . Simulations advancing fast, but cannot tell...

State of the art non-linear N-body simulations No baryons!

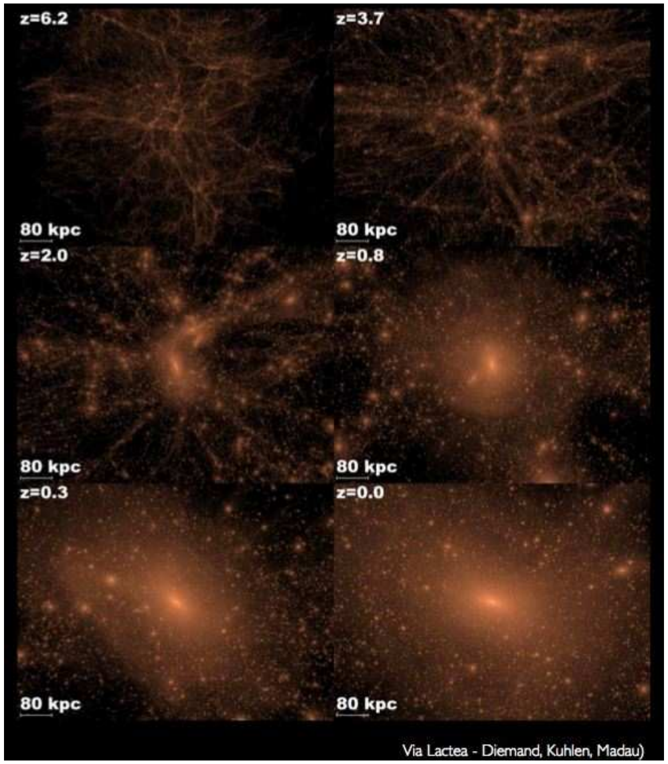




Dark halo substructure:

Haloes grow hierarchically incorporating lumps and tidal streams from earlier phases of structure formation.

Can the solar system be within a DM lump or a stream?
"Via- Lactea II" simulations: "lots of subhalos and tidal streams down to 8kp"
"fewer subhaloes in inner regions (but more concentrated)"



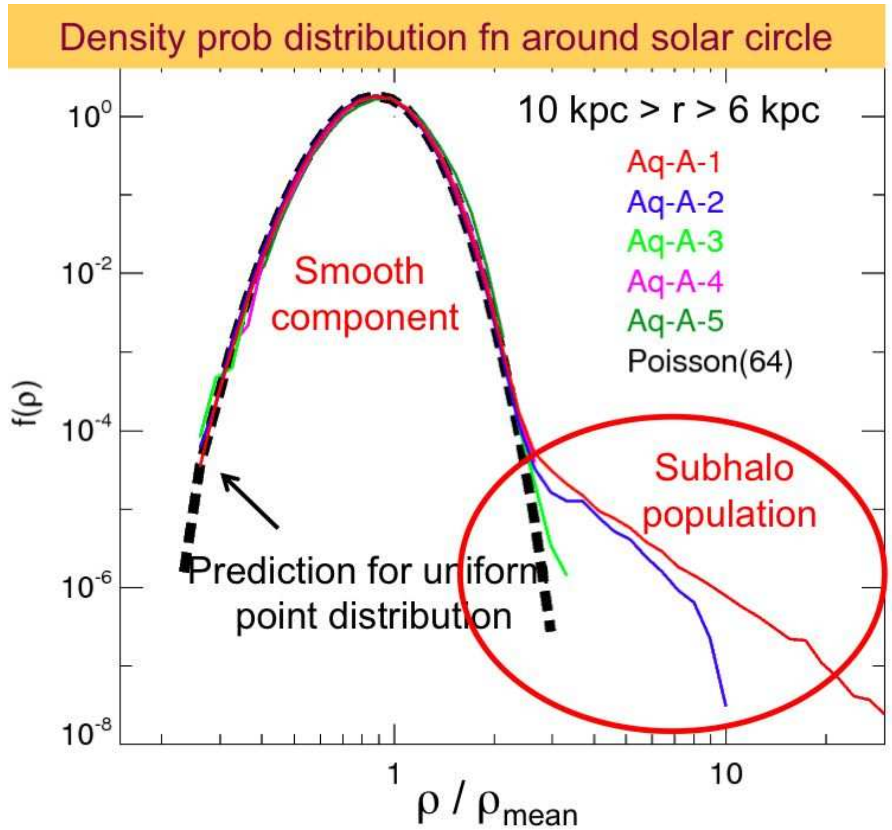
Kuhlen Diemand Madau arXiv:0805.4416

Dark halo substructure: VIRGO Collaboration-Aquarius Programme

Most subhaloes are at large distances from the galactic center, far from the Sun. Subhaloes are more effectively destroyed near the center

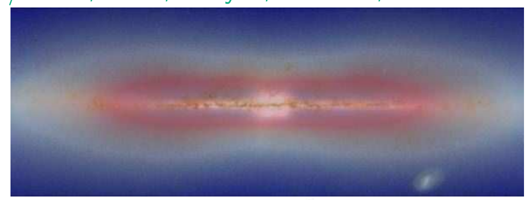
The chance of a random point close to the Sun lying in a substructure is $< 10^{-4}$

Local v distribution smooth (no streams) but differs from Gaussian due to the detailed assembly history of the halo (rates may deviate by 10%)



Vogelsberger et al. 0812.0362 [astro-ph]

Dark Disk: Read, Lake, Agertz, Debattista MNRA 389, 8/2008;Read, Mayer, Brooks, Governato, Lake 0902.0009



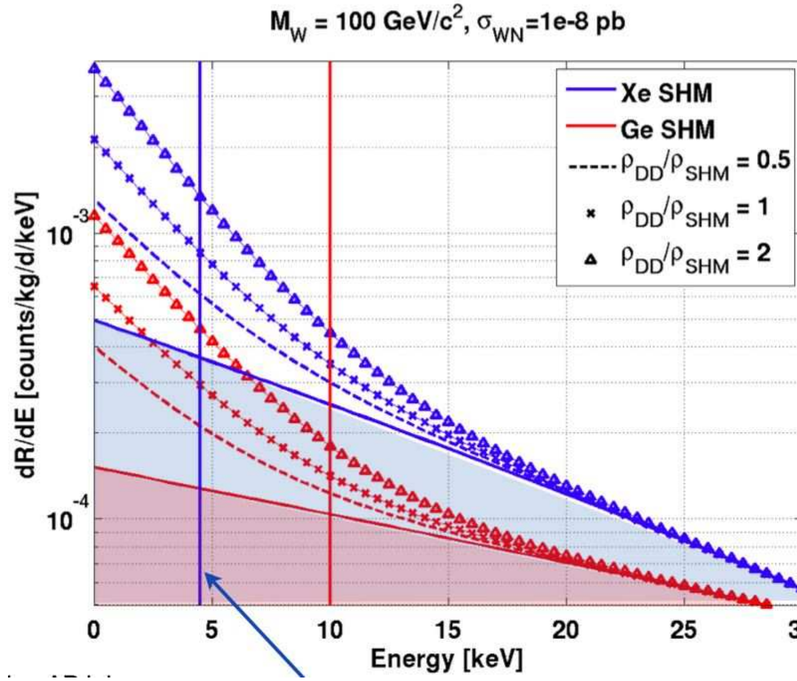
Read et al include baryons in simulations: "A stellar/gas disc, already in place at high redshift, causes merging satellites to be dragged preferentially towards the disc plane where they are torn apart by tides."

Dark Disk: equilibrium structure

$\rho_D \leq 2 \times \rho_{SHM}$

$v_{lag} \simeq 50$ km/s with respect to Sun

$v_{disp} \simeq 50$ km/s



Threshold of XENON 10

Bruch, Read, Baudis, Lake Ap.J.696:920-923,2009 and arXiv:0811.4172

Direct DM Searches: Many experiments!

- **Single Channel Techniques:**

  -Ionization (Ge, Si, CdTe): IGEX, HDMS, GENIUS, TEXONO, CoGeNT

  -Scintillation (NaI, Xe, Ar, Ne, CsI): DAMA (2 keVee), NAID, DEAP, CLEAN, XMASS, KIMS

  -Phonons (Ge, Si, Al_2O_3, TeO_2): CRESST-I (0.6 keV), Cuoricino, CUORE (5 keV)

  -Threshold detectors: PICASSO (bubbles of C_4F_10),
  COUPP (superheated bubble chamber)

- **Hybrid detector techniques for discrimination:**

  -Ionization + Phonons (Ge, Si): CDMS, SuperCDMS, EDELWEISS, EURECA

  -Ionization + Scintillation(Xe, Ar, Ne): XENON, LUX, ZEPLIN, WARP, ArDM, XAX

  -Scintillation+Phonons ($CaWO_4$, Al_2O_3): CREST-II

- **Very promising: (Liquid) Noble-Gas Detectors** act as their own veto, up-scalable to multi tonnes

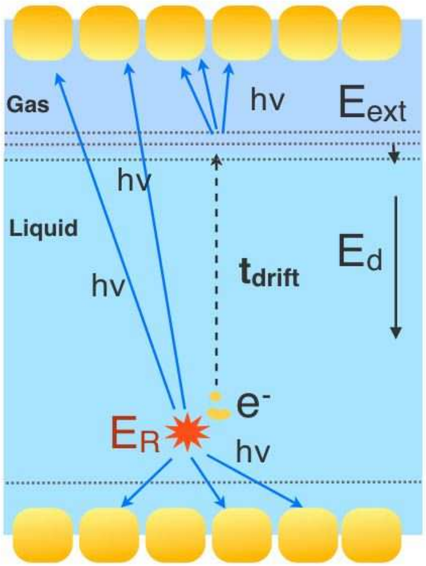
Noble Liquid detectors:

- Single-Phase: Scintillation

  -XMASS - Xe (Japan, Kamioka)
  -DEAP/CLEAN - Ar/Ne (US/Canada, SNOLab)

- Two-phase liquid and gas: Scintillation and ionization
  Both seen as light pulses (one delayed)

  -XENON - Xe (US/Switzerland/Germany/France/
  Portugal/Italy/Japan/China, LNGS)
  -WARP - Ar (Italy/US, LNGS)
  -ZEPLIN - Xe (UK/US, Boulby)
  -LUX - Xe (US/UK, Sanford Lab- later DUSEL)
  -ArDM - Ar (Switzerland/Spain/UK, Canfranc)

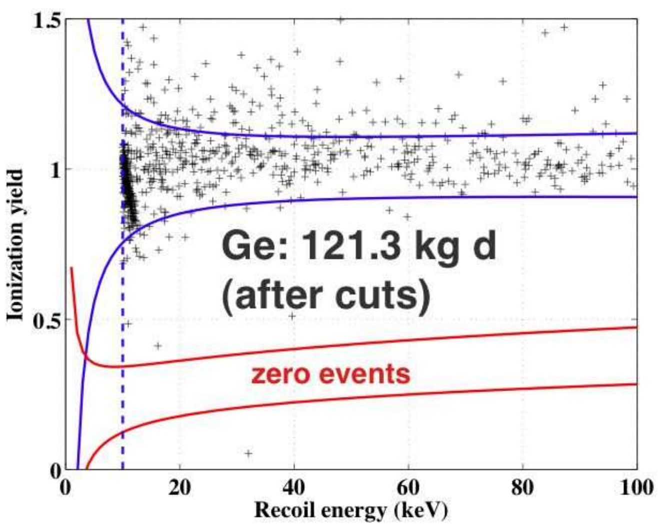


CDMS at the Soudan Mine:

30 Ge (4.75 kg) and Si (1.1 kg) ZIPs in 5 towers

Rejection: ionization-phonons and timing to discriminate surface vs bulk events

Future: Super CDMS with 16 kg Ge



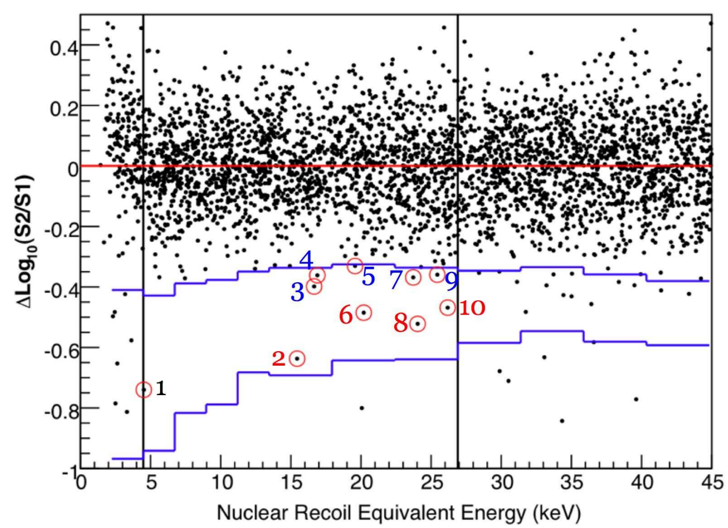
XENON 10 at Gran Sasso:

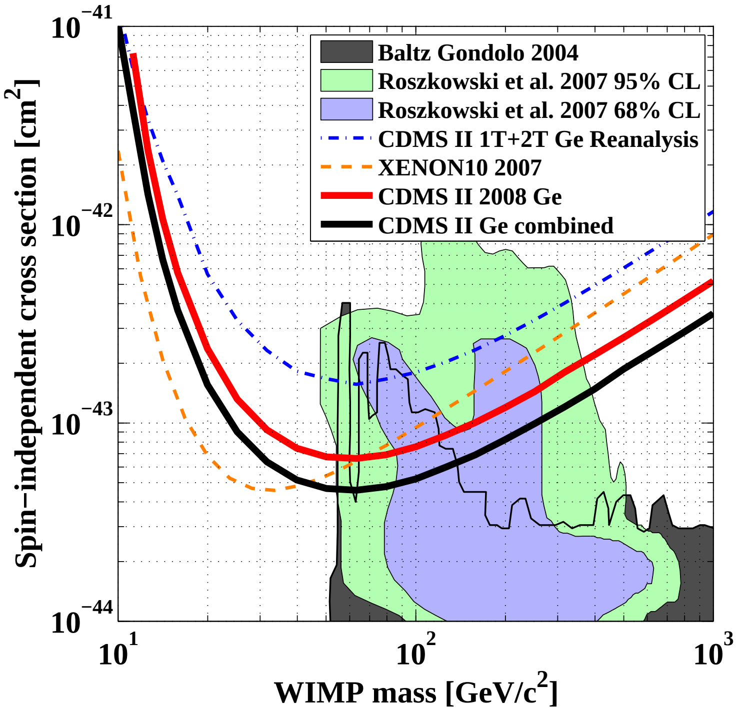
22 kg of L Xe (15 kg in active volume), 136 kg day

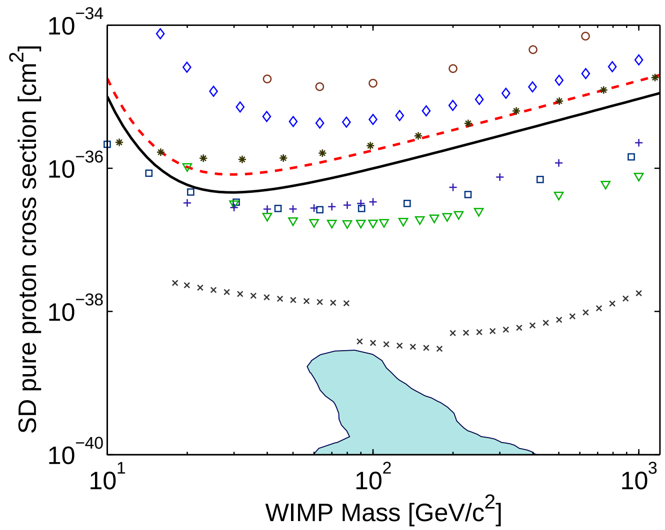
Rejection: Prompt scintillation light (S1) - prop. light from charge drifted into gas phase (S2)

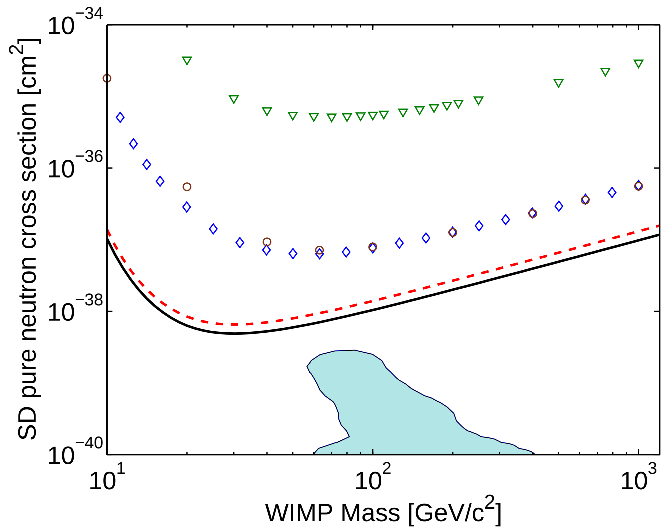
Future: Xenon 100 (100 kg active) + “Ugrade”

(2-12 keVee = 4.5-27 keVr- 1800 events- in red 50%acceptance)









Best SI: CDMS Feb/08, m > 30 GeV

CDMS (diamonds), ZEPLIN-II (circles), KIMS (triangles), NAIAD (squares), PICASSO (stars), COUPP (pluses) and SuperK (crosses)

Best SD n-only:XENON-10 May/08

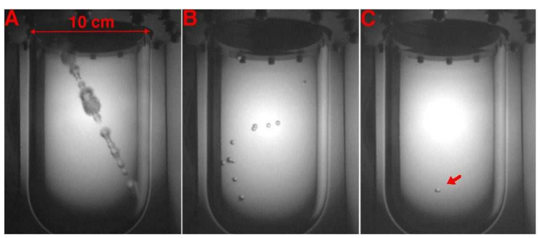
Best SD p-only bound:

COUPP at FNAL

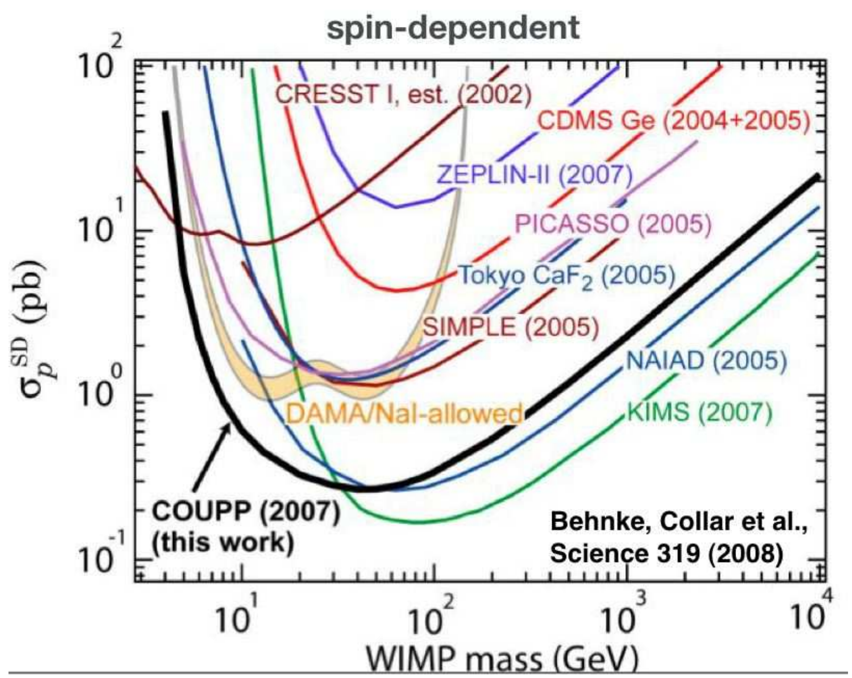
1.5 kg of CF_3I, room-temperature bubble chamber (60 Kg detector under construction)

WIMP: single bubble,

n: multiple bubbles



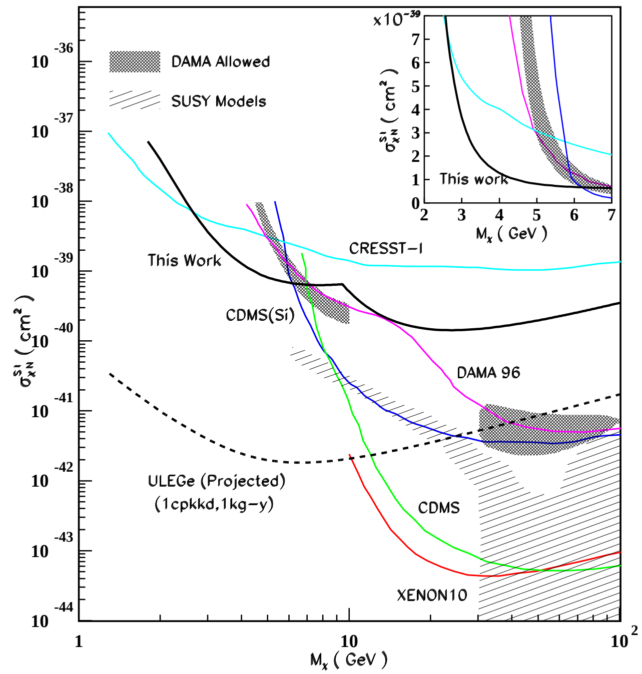
and KIMS in Korea 4× 6kg CsI(Tl)-237d

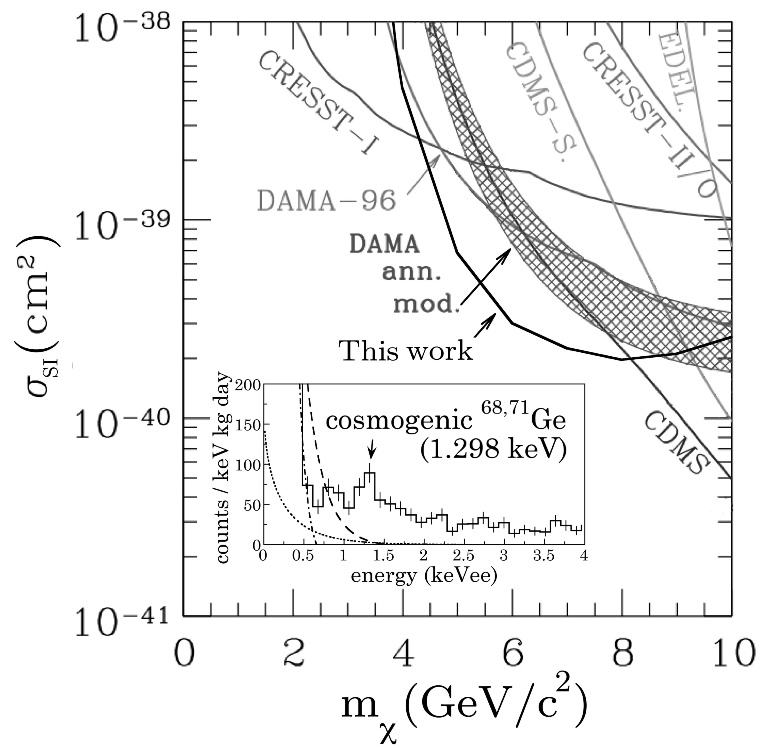


Low Threshold:
TEXONO (4× 5 g of Ge) and CoGent (500g of PPC Ge)

PRD79:061101,2009

PRL101:251301,2008, Erratum-ibid.102:109903,2009





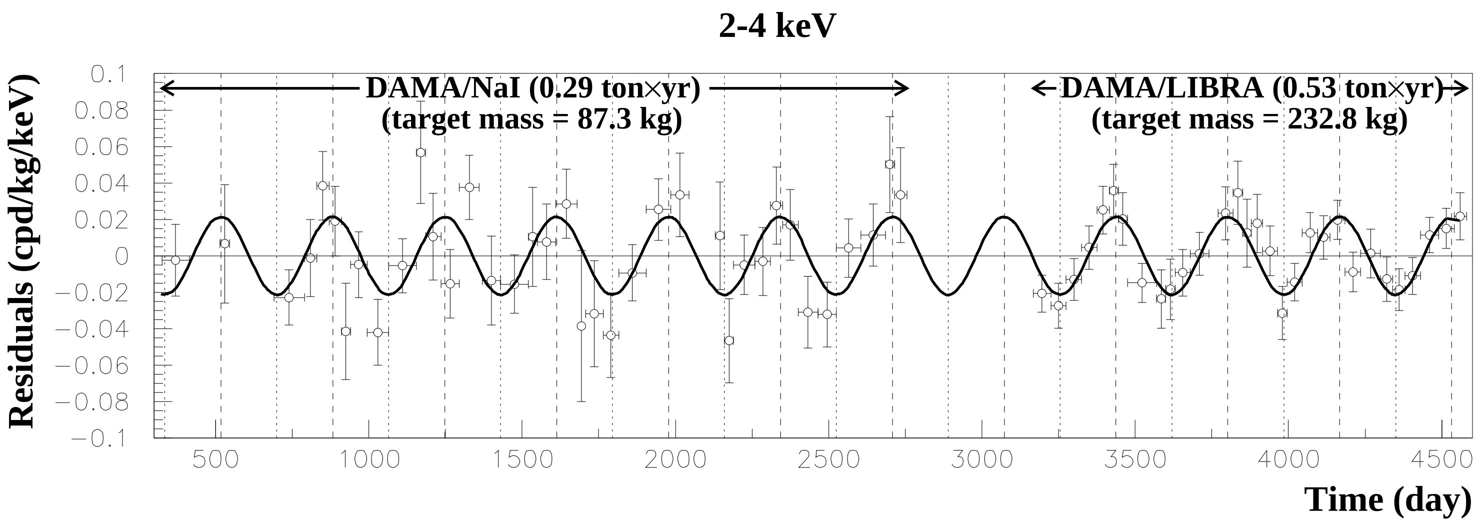
DAMA/LIBRA

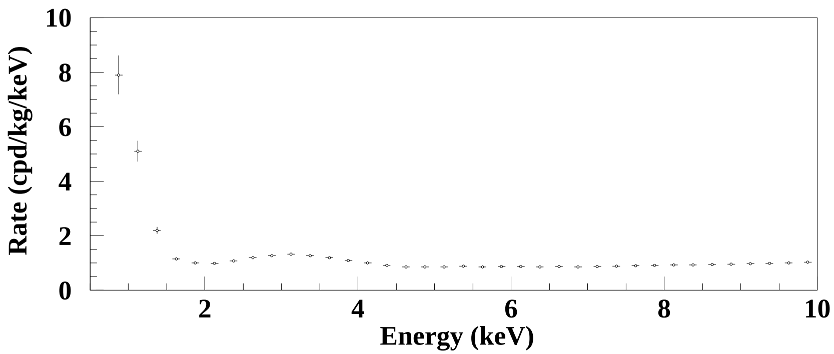
- The DAMA collaboration, has found an annual modulation in its data compatible with the signal expected from dark matter particles bound to our galactic halo-which has been confirmed by DAMA/LIBRA in Apr/2008
- All other experiments have not found any signal from WIMPs
- Are these results compatible?

  Yes for light usual WIMPs...

  and also for inelastically scattering WIMPs (IDM)...

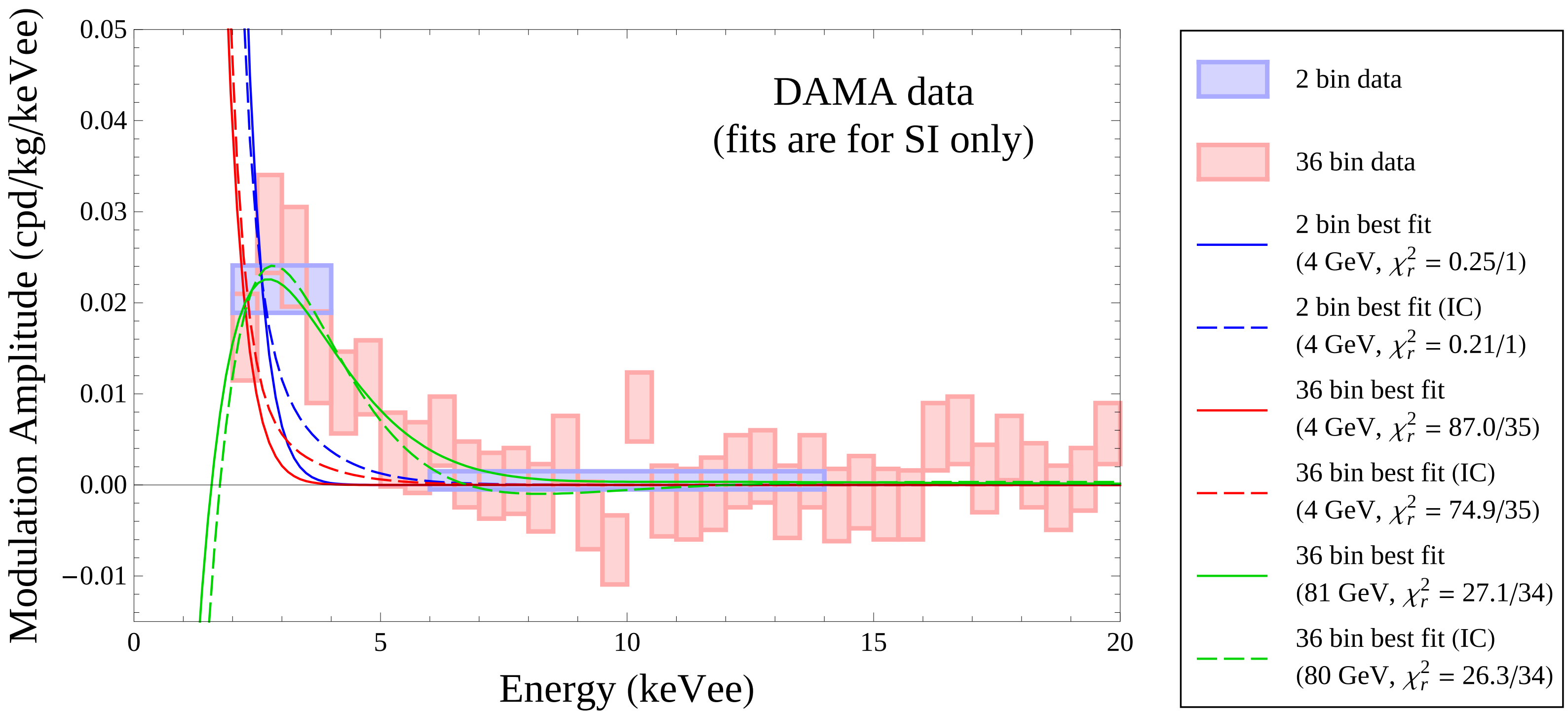
DAMA/LIBRA 25 NaI (Tl) crystal of 9.5 kg each, 4y in LIBRA (11 years total), 0.83 ton $\times$ year, 8.2σ modulation signal.





Rate

DAMA data in 2 bins, DAMA/LIBRA in 36 bins Savage,Gelmini, Gondolo and Freese 0808.3607 [astro-ph].



Many papers studied compatibility:

F. Petriello and K. M. Zurek, "DAMA and WIMP dark matter," [arXiv:0806.3989 [hep-ph]].

A. Bottino F. Donato, N. Fornengo and S. Scopel, "Interpreting the recent results on direct search for dark matter particles in terms of relic neutralino," arXiv:0806.4099 [hep-ph];

S. Chang, A. Pierce and N. Weiner, "Using the Energy Spectrum at DAMA/LIBRA to Probe Light Dark Matter," arXiv:0808.0196 [hep-ph];

M. Fairbairn and T. Schwetz, "Spin-independent elastic WIMP scattering and the DAMA annual modulation signal," arXiv:0808.0704 [hep-ph].

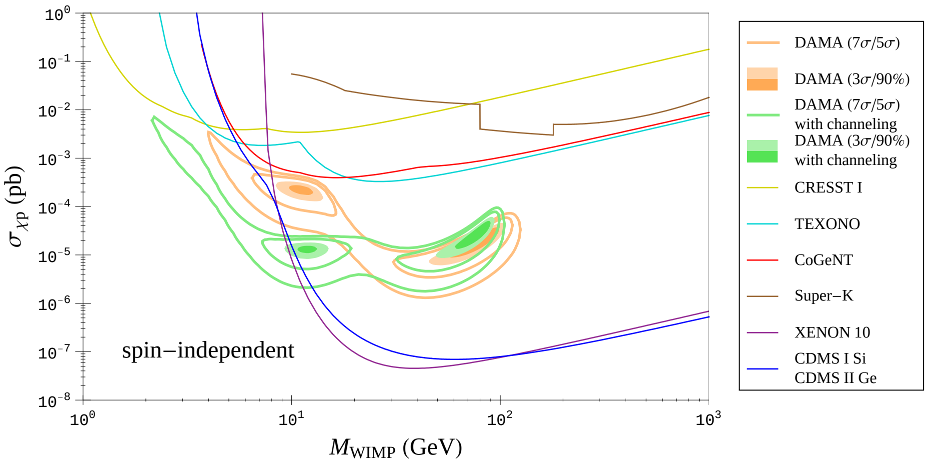
D. Hooper, F. Petriello, K. M. Zurek and M. Kamionkowski, "The New DAMA Dark-Matter Window and Energetic-Neutrino Searches," arXiv:0808.2464 [hep-ph].

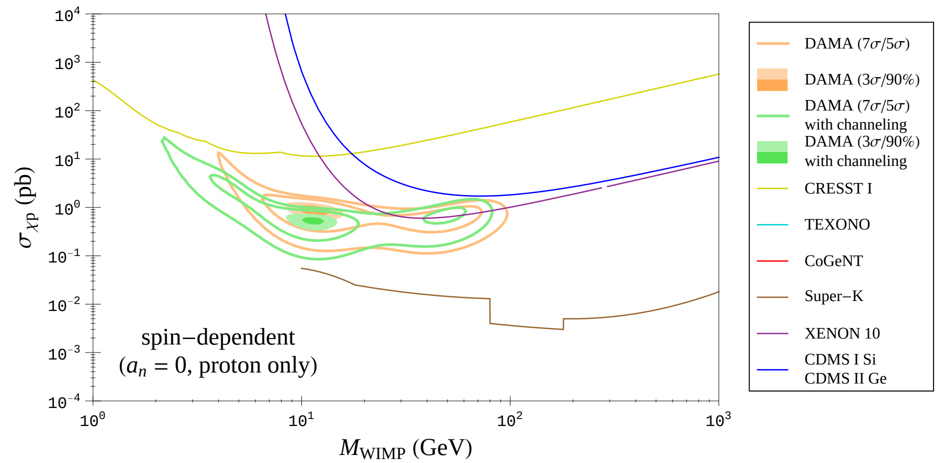
C. Savage, G. Gelmini, P. Gondolo and K. Freese, "Compatibility of DAMA/LIBRA dark matter detection with other searches," arXiv:0808.3607 [astro-ph].

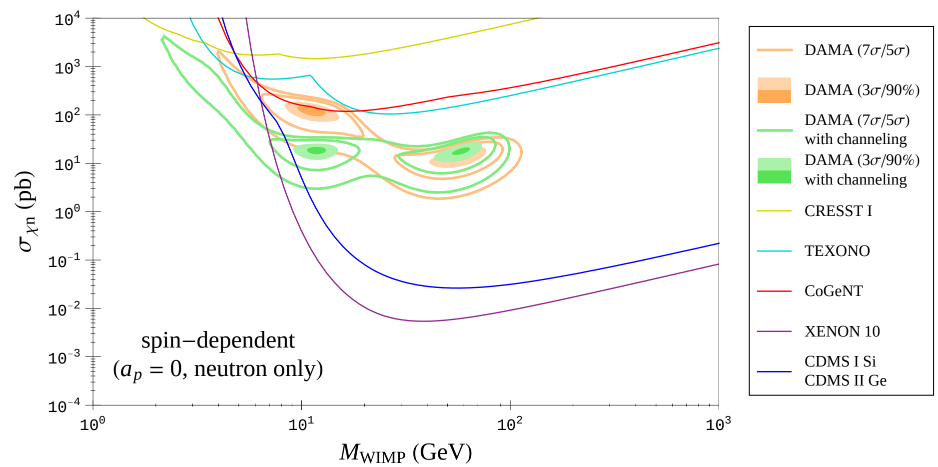
S. Chang, G. D. Kribs, D. Tucker-Smith and N. Weiner, "Inelastic Dark Matter in Light of DAMA/LIBRA," arXiv:0807.2250 [hep-ph]... and more...

Savage,Gelmini, Gondolo, Freese JCAP 0904:010,2009

36 bins (likelihood ratio 4 param. fits

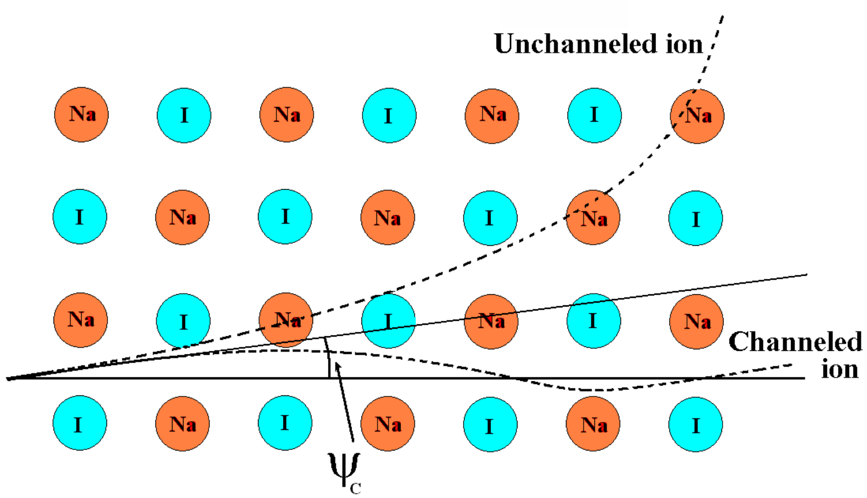


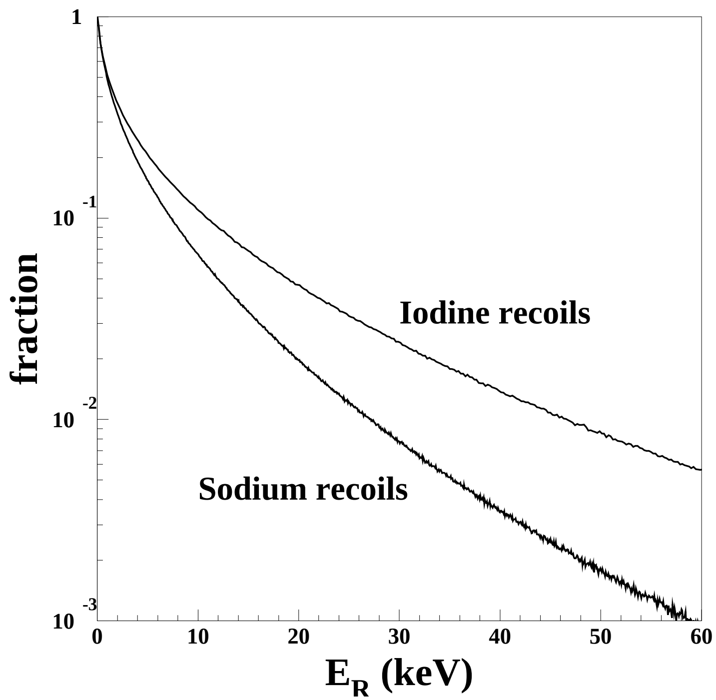




Channeling effect: very important for light WIMPs

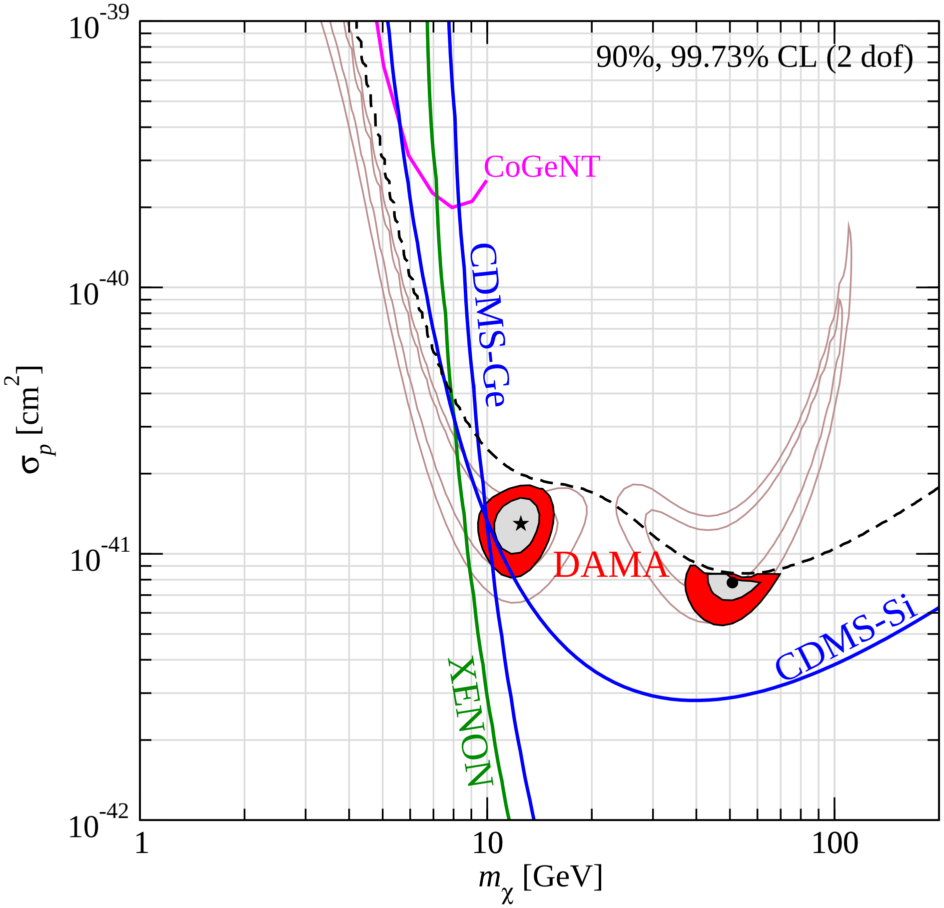
When ions move along crystal axes and planes penetrate longer and give their energy to electrons, so $Q = 1$ instead of $Q_I = 0.09$ and $Q_{Na} = 0.3$ (Drobyshevki, 07; DAMA- Eur. Phys. J. C 53, 205-2313, 2008)





Light usual WIMPs Figure from Fairbairn and Schwetz 08

With channeling, light usual WIMPs, 7 to 10 GeV are still a possible explanation (in conflict with CDMS and XENON at the 2-3σ level)

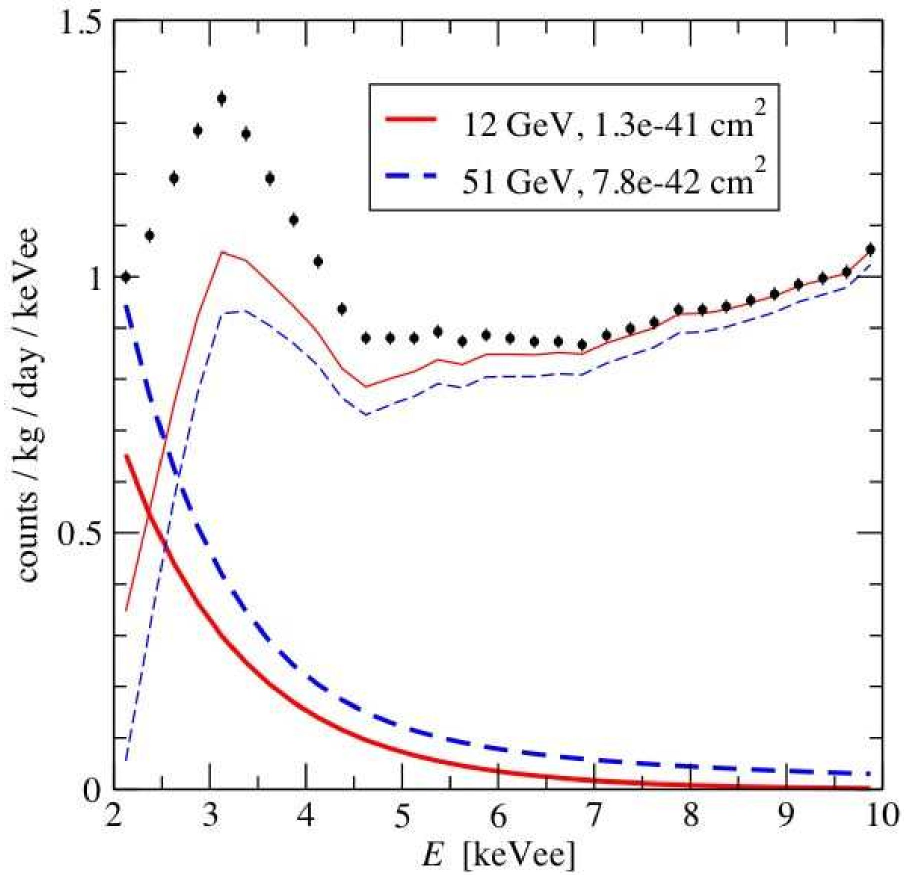


Problem with DAMA/Libra background? fig from Schwetz

Background falls sharply at low E
for elastic scattering WIMP's
and this is hard to fit according to
G. Gerbier and A. Lemrani 07
(Saclay) and

V. Kudryavtsev, M. Robinson and
N. Spooner 09 (Sheffield)

who tried to analyse the
backgrounds (above 10 keV
DAMA/LIBRA only gave data for
two crystals)



Other possibilities to explain the DAMA signal:

- Very tuned DM stream (aligned with Sun motion-3% of local density) marginal solution appears for 2 to 4 GeV WIMP (very unlikely)

- Light keV mass DM particles which interact only with e?

- MeV and above mass DM particles which interact with e-bound to nuclei (not at rest)?

- Inelastic DM scattering?

Inelastic DM (IDM)

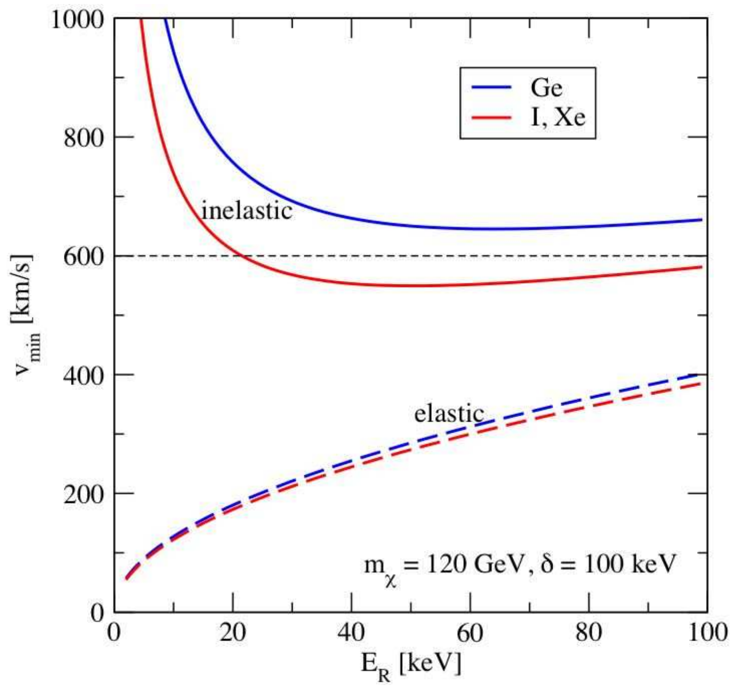
Tucker-Smith, Weiner 01 and 04; Chang, Kribs, Tucker-Smith, Weiner 08; March-Russel, McCabe, McCullough 08; Cui, Morrisey, Poland, Randall 09

In addition to the DM state χ with mass m_χ there is an excited state χ^*

$$m_\chi - m_{\chi^*} = \delta \simeq 100\text{keV}$$

Inelastic scattering $\chi + N \to \chi^* + N$ dominates over elastic.

Inelastic DM (fig from T. Schwetz)

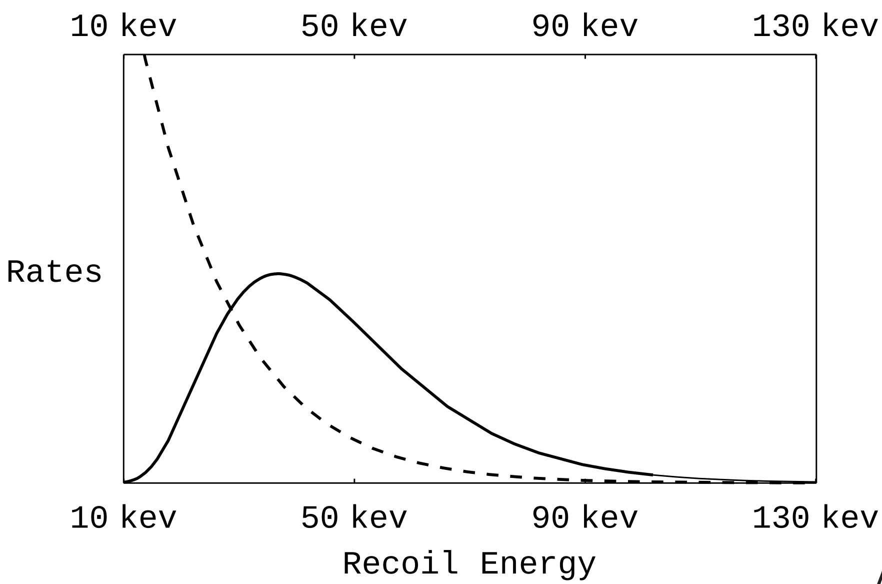


$$v_{min}^{inel} = \sqrt{\frac{ME_R}{2\mu^2}} + \frac{\delta}{\sqrt{2ME_R}}$$

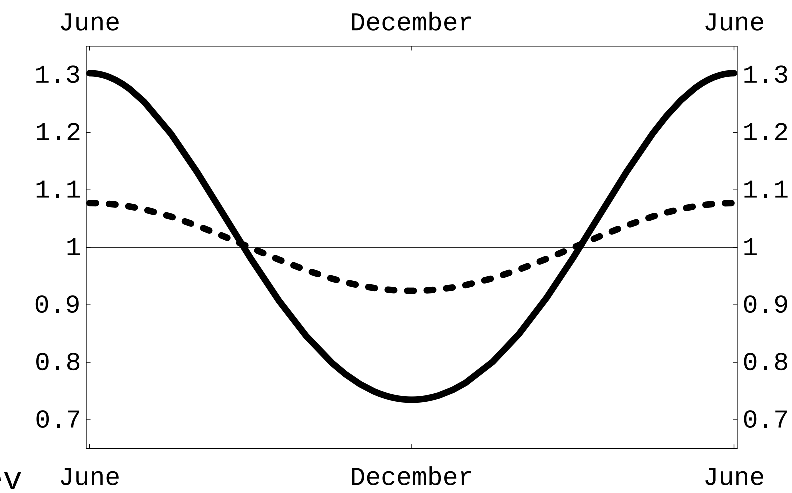
$$v_{min}^{el} = \sqrt{\frac{ME_R}{2\mu^2}}$$

Only high-velocity DM particles have enough energy to up-scatter, and v_{min}^{inel} decreases with increasing target mass M, thus targets with high mass are favored (better I than Ge...). Notice no low E_R events.

Inelastic DM Tucker-Smith, Weiner 04 $m_\chi = 50\text{GeV}, \delta = 100\text{keV}$



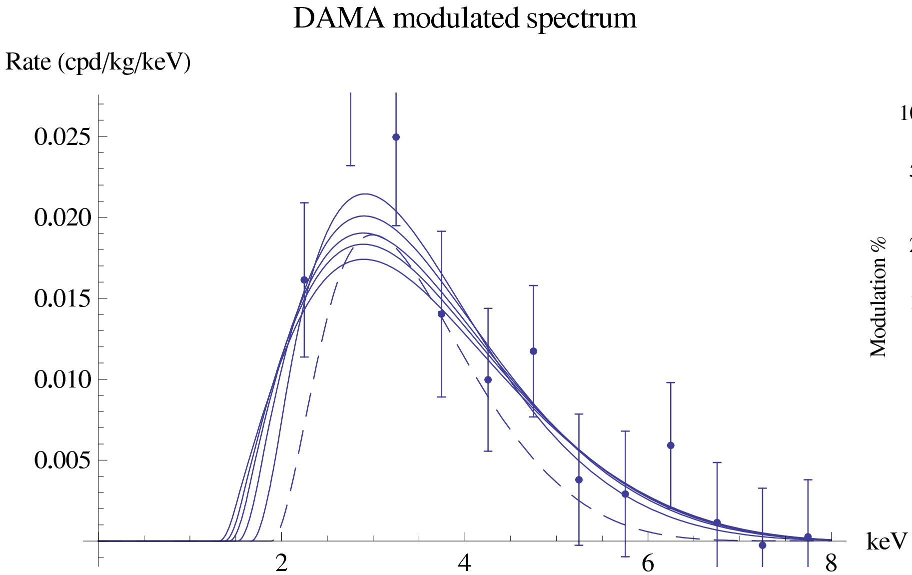
Spectrum in Ge



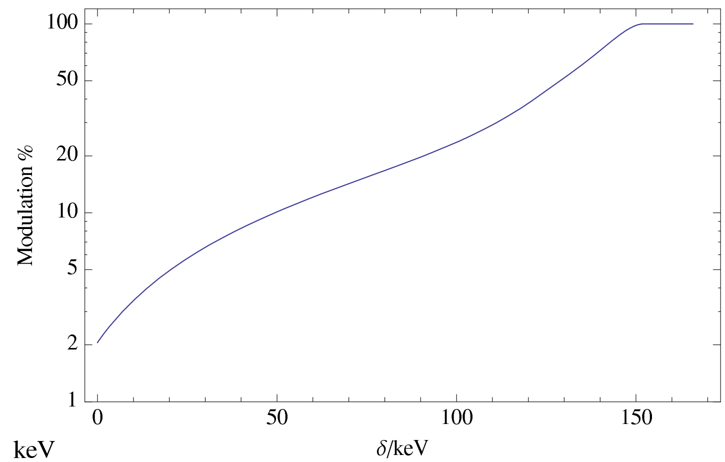
Annual modulation: elastic (dashed) and inelastic (solid)

Leads to very different spectrum (no low E_R events) The modulation of the signal is enhanced (the number of WIMPs changes more rapidly at high v)

Inelastic DM Chang, Kribs, Tucker-Smith, Weiner 08 $m_\chi = 50\text{GeV}$, $\delta = 100\text{keV}$



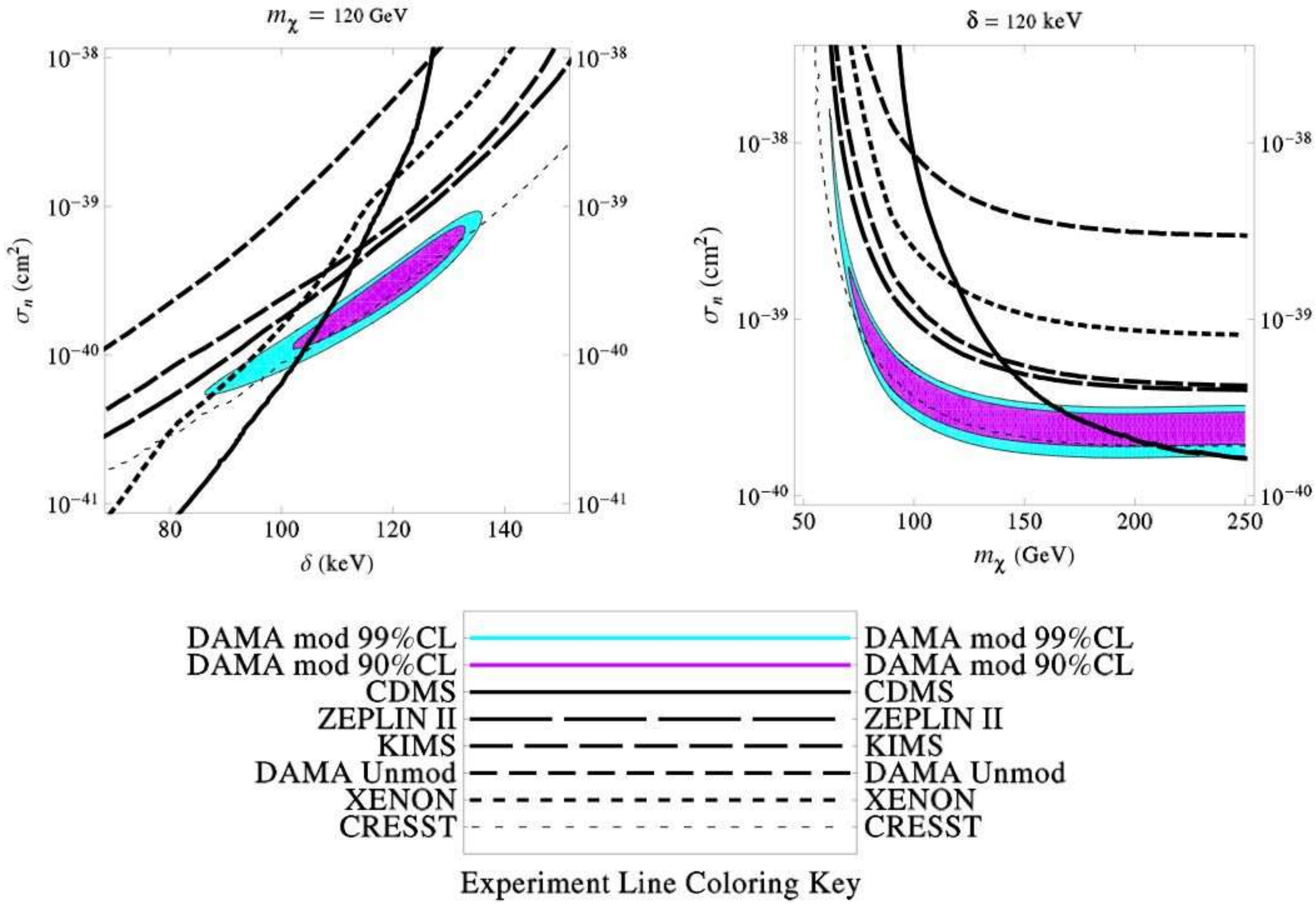
DAMA, benchmarks, $v_{esc} = 500\text{km/s}$



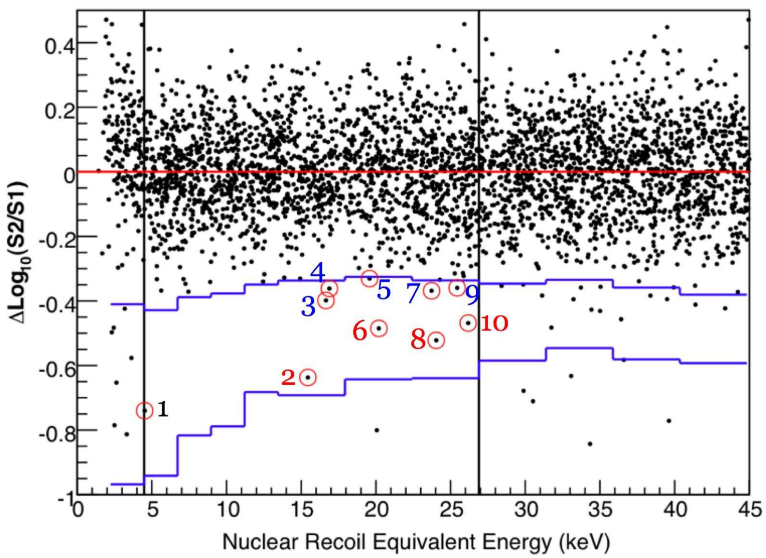
Modulated fraction, $m_\chi = 100\text{GeV}$.

A spectrum with no low E_R events and larger modulation (as δ increases) fit well the DAMA/LIBRA data

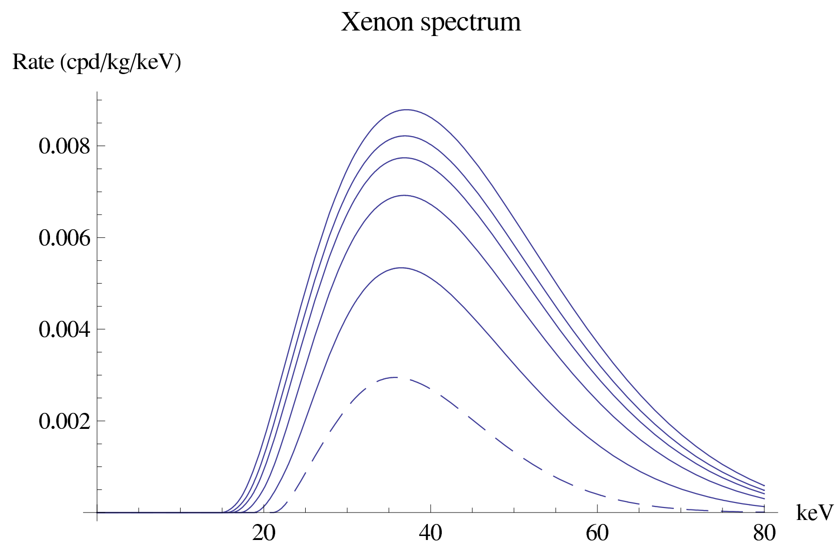
IDM Chang, Kribs, Tucker-Smith, Weiner 08



IDM benchmarks, $v_{esc} = 500\text{km/s}$ Chang, Kribs, Tucker-Smith, Weiner 08



XENON-data



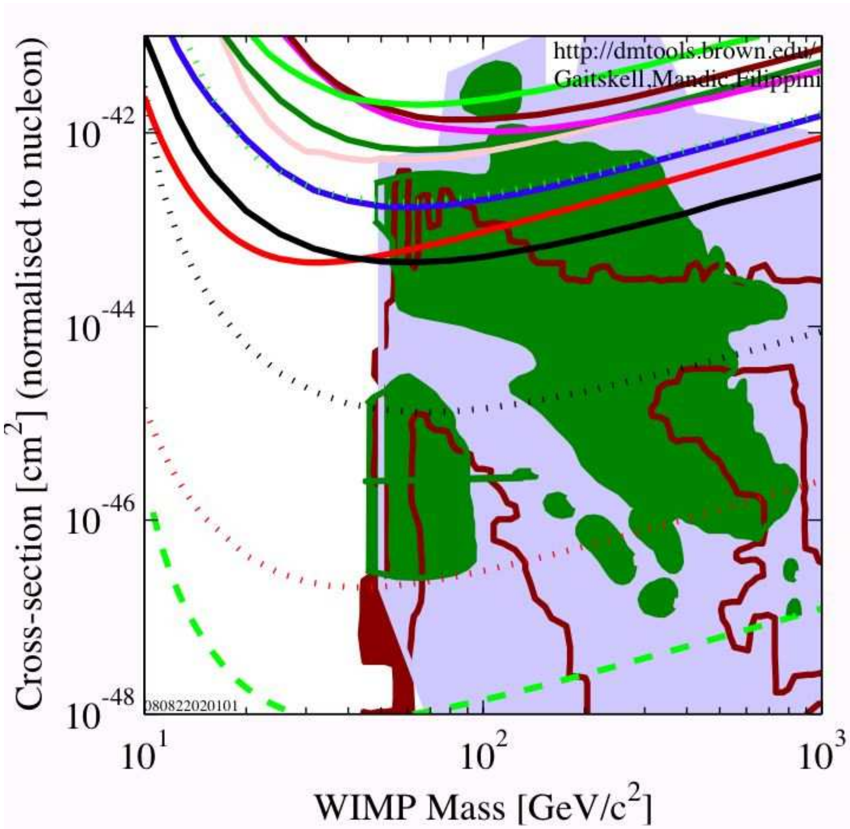
XENON- expected spectrum

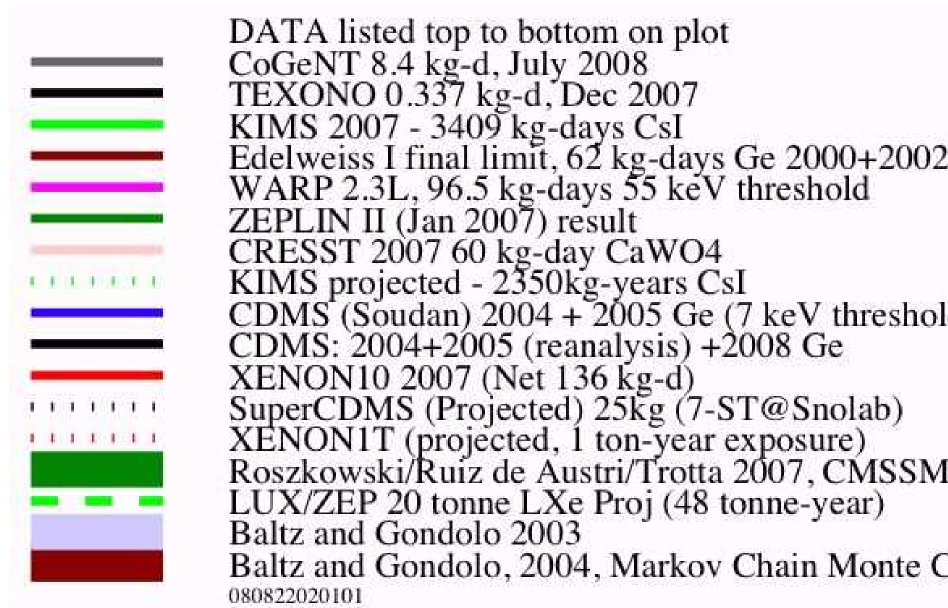
-Different spectra: IDM events expected at higher energy. Xenon, Zeplin, CRESST, may have already seen DM events and taken then for background!

IDM: fixed relative even rates for Ge, Xe, I, and W should test this explanation for the DAMA signal Chang, Kribs, Tucker-Smith, Weiner 08

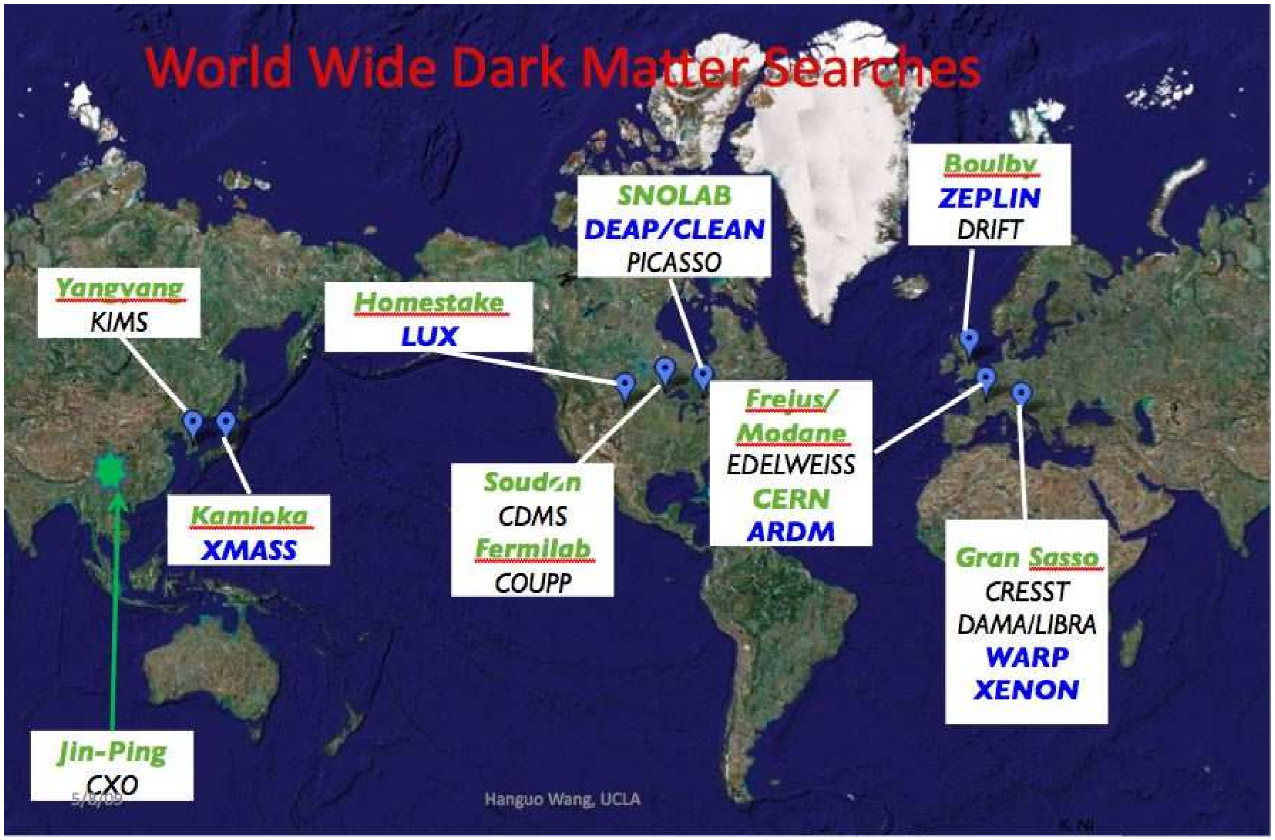
#	m_χ (GeV)	σ_n (10^{-40} cm^2)	δ (keV)	DAMA 2-6 keVee (10^{-2} dru)	XENON 4.5-45 keV (counts)	CDMS 10-100 keV (counts)	ZEPLIN 5-20 keVee (counts)	KIMS 3-8 keVee (10^{-2} dru)	CRESST 12-60 keV (counts)	
expt				1.31 ± 0.16	24 (31.6)	2 (5.3)	29 (37.2)	5.65 ± 3.27	6 (10.5)	obs. # events
1	70	11.85	119	0.93	1.39	0	8.81	0.77	8.92	pred. # events
2	90	5.75	123	1.25	5.52	0	14.87	1.62	9.38	
3	120	3.63	125	1.24	9.06	0.26	18.61	2.27	9.64	
4	150	2.92	126	1.21	11.17	1.19	20.55	2.63	9.82	
5	180	2.67	126	1.18	12.46	2.22	21.69	2.85	9.93	
6	250	2.62	127	1.14	14.01	3.95	23.03	3.12	10.02	

Outlook


http://dmtools.brown.edu/
Gaitskell,Mandic,Filippini
Cross-section [cm^2] (normalised to nucleon)
10^{-42}
10^{-44}
10^{-46}
10^{-48}
080822020101
10^{1}
10^{2}
10^{3}
WIMP Mass [GeV/c^2]


DATA listed top to bottom on plot
CoGeNT 8.4 kg-d, July 2008
TEXONO 0.337 kg-d, Dec 2007
KIMS 2007 - 3409 kg-days CsI
Edelweiss I final limit, 62 kg-days Ge 2000+2002+
WARP 2.3L, 96.5 kg-days 55 keV threshold
ZEPLIN II (Jan 2007) result
CRESST 2007 60 kg-day CaWO4
KIMS projected - 2350kg-years CsI
CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold
CDMS: 2004+2005 (reanalysis) +2008 Ge
XENON10 2007 (Net 136 kg-d)
SuperCDMS (Projected) 25kg (7-ST@Snolab)
XENON1T (projected, 1 ton-year exposure)
Roszkowski/Ruiz de Austri/Trotta 2007, CMSSM
LUX/ZEP 20 tonne LXe Proj (48 tonne-year)
Baltz and Gondolo 2003
Baltz and Gondolo, 2004, Markov Chain Monte Ca
080822020101

Direct DM Searches: Many experiments!



Direct DM Searches: New lab at Jin-Ping, Sichuan Province China- to be built before the end of the year- $12 \times 12 \times$ 50 m^3- THE DEEPEST!

Depth comparison of underground labs

实验室 Lab Name	国家 Country	实际深度（等效水深）【单位：千米】 Depth and (w.e)	条件
Soudan	美国 (US)	0.7 (2.0)	矿井 (Mine)
Kamioka	日本 (Japan)	1.0 (2.7)	矿井 (Mine)
Boulby	英国 (UK)	1.1 (2.8)	矿井 (Mine)
Gran Sasso (LNGS)	意大利 (Italy)	1.4 (3.1)	隧道
Homestake	美国 (US)	1.5 (4.2)	矿井 (Mine)
Modane (LSM)	法国 (France)	1.7 (4.2)	隧道
Snolab	加拿大 (Canada)	2.0 (6.0)	矿井 (Mine)
锦屏山地下实验室 (JPUL)	中国 (China)	2.5 (6.2)	隧道

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Outlook: plenty of direct detection data to come!

In the near future:

- Xenon 100 and Upgrade at Gran Sasso: almost finished 100 kg fiducial mass
- SuperCDMS at Soudan: 16 kg of Ge
- WARP at Gran Sasso: 3.2 kg L Ar prototype-140 kg under construction
- EDELWEISS at LSM (Modane-Frejus): 10 kg NbSi Ge
- LUX for DUSEL: 50 kg L Xe tested at CWRU -300 L Xe (100 kg fiducial)
- ArDM at CERN: 1 ton L Ar TPC/Calorimeter prototype
- COUPP at FNAL: 60kg module under construction
- KIMS at Yangynag Undeground Lab-Korea: in 2008 12$\times$ 6kg CsI(Tl) crystals (before 4)
- CRESST at Gran Sasso: 10 kg of 33 $CaWO_4$

-XMASS at Kamioka: 3kg fiducial of Xe- 100 kg next step?

For DAMA/LIBRA: - DAMA/LIBRA is reducing its threshold to 1 keVee

A signal in another detector with other techniques is needed to confirm a DM discovery: XENON, KIMS, CRESST II, can test IDM, and these + COUPP, TEXONO can test light WIMPs - KIMS (100 kg CsI) should in a few years reproduce the statistics of DAMA?

Further away:
- Directional detectors: gas TPC (DRIFT at Boulby; DM-TPC for DUSEL)
- Tonne to multi-tonne detectors: SuperCDMS 1t?, WARP 1t?, XENON 1t?, EURECA?, XMASS?, XAX?

And there is also the LHC and indirect detection searches....