Experimental Particle Astrophysics

Low energy particles from the Universe

Nigel Smith
Rutherford Appleton Laboratory, UK

- MACHOs
  - **Jean-Francois Glicenstein**
- A large scale search for dark matter axions
  - **Karl A. van Bibber**
- Dark matter detection
  - **Neil J.C. Spooner**
- Recent results from AMANDA
  - **Douglas F. Cowen**
- Neutralino relic densities
  - **Manuel Drees**
- Constraints on supersymmetric dark matter from LEP
  - **Keith A. Olive**
- Neutralino-proton cross section
  - **Richard Arnowitt**
- Results from AMS
  - **Vitaly Choutko**

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WIMPs
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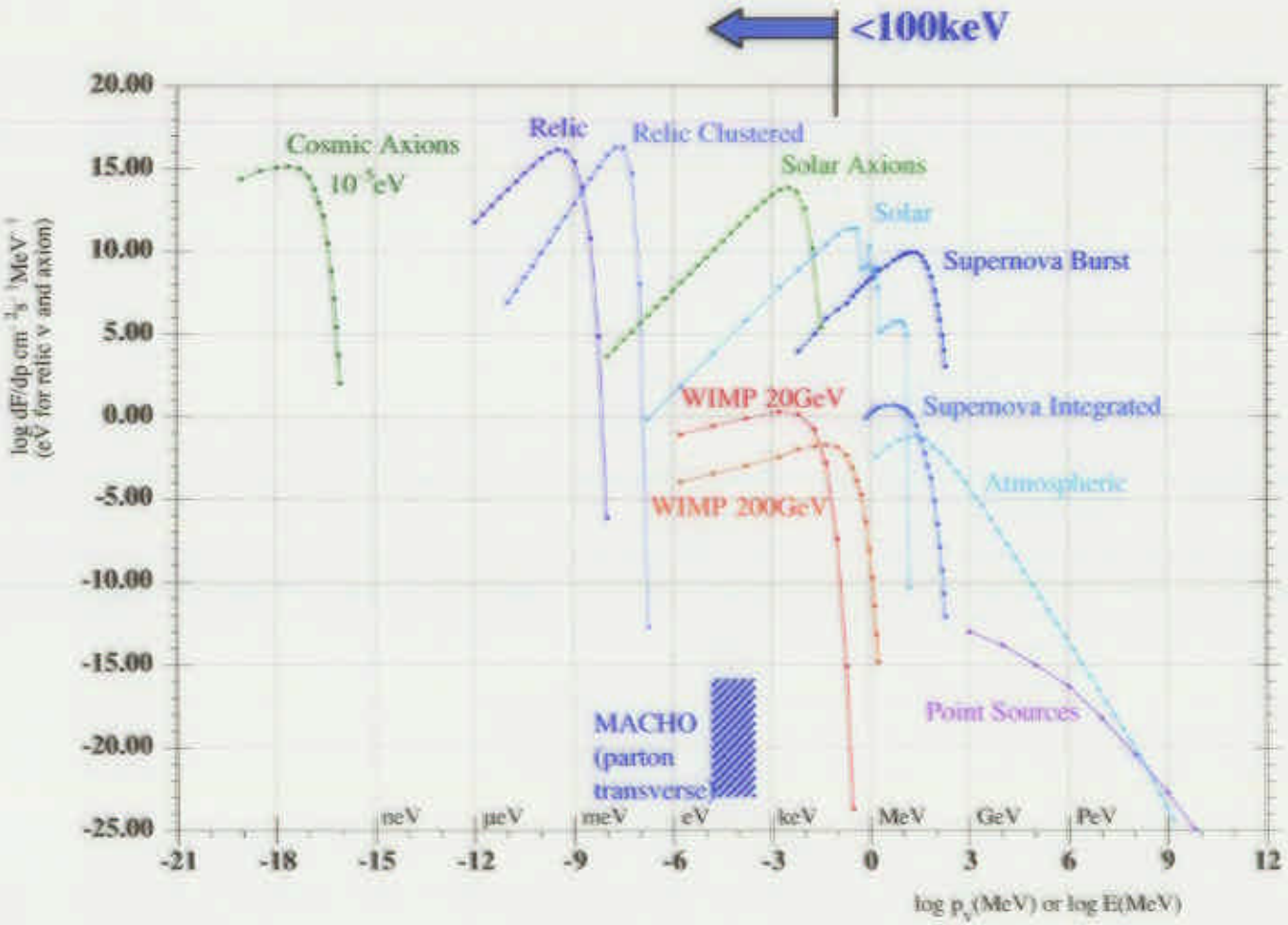
Definition



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Talk Overview

- Contributions
- Definition
- (Invisible) Low Energy Particles from the Universe
  - Astronomical Indicators for dark matter
  - MACHOs
  - Axions
  - WIMPs
    - Direct searches
    - Indirect searches
- Summary

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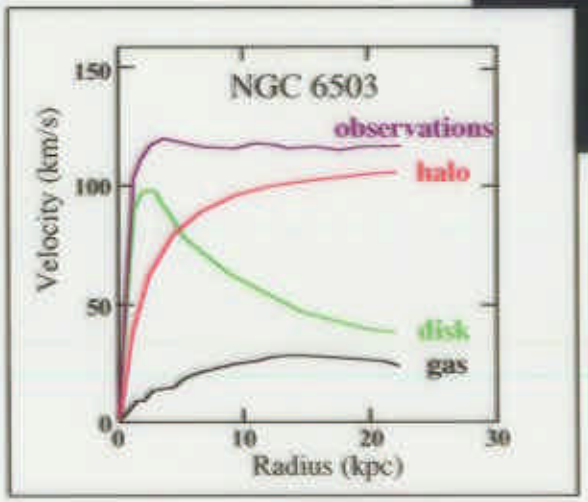
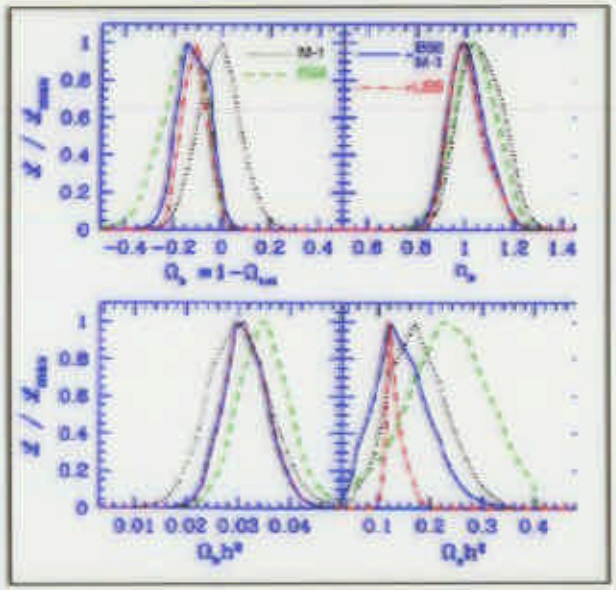
Astronomical Observations

- Scale 10kpc
- Doppler->v_t
- Halo to 200kpc?
  - Violates BBN?





A Jaffe

- CMBR
  - Boomerang/Maxima
  - +LSS +SN1a
- Ω_t~1.0; $\Omega_b h^2$~0.03; Ω_{cdm}~0.14;

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MACHOs

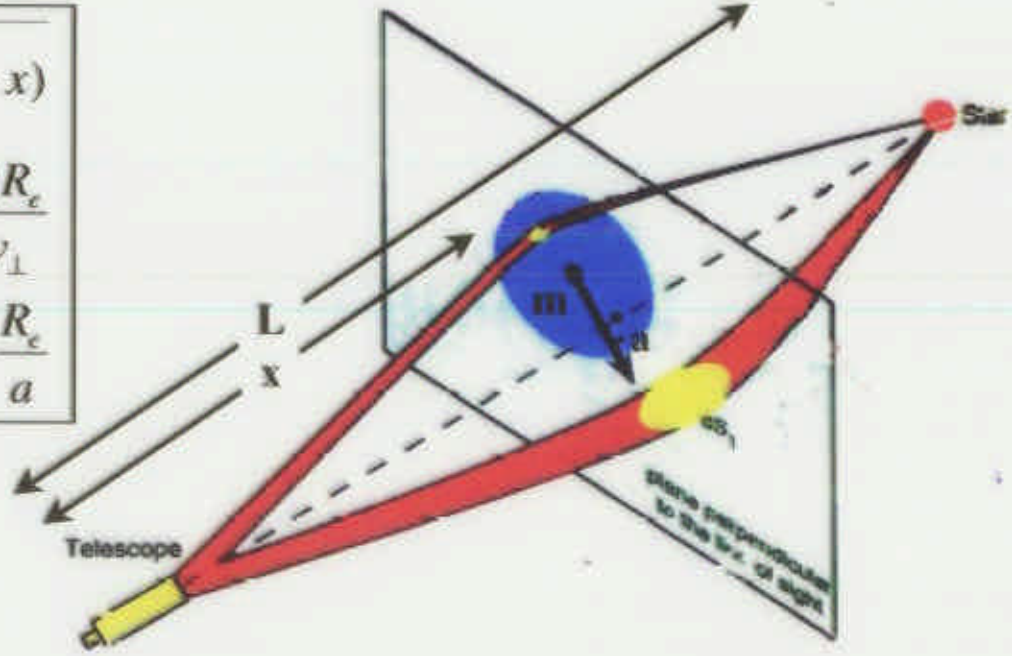
- Baryonic Dark Matter: Massive Astronomical Compact Halo Objects
- Use μLensing in LMC/SMC/GC: MACHO, EROS, ….
  - Optical depth, $\tau \sim 5\times10^{-7}$: require tens millions stars
  - Achromatic, one off, symmetrical
- Measure transit time, amplification

$$R_e = 2\sqrt{\frac{Gm}{L}x(L-x)}$$

$$\Delta t = \frac{2R_e}{v_\perp}$$

$$A \sim \frac{R_e}{a}$$

Degeneracy in mass/distance (for point source/lens)



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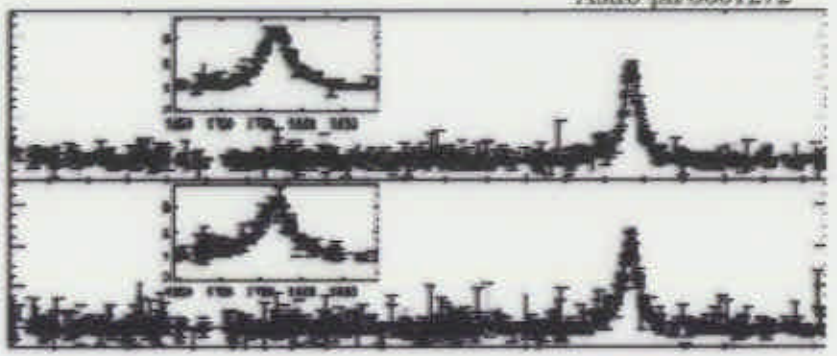
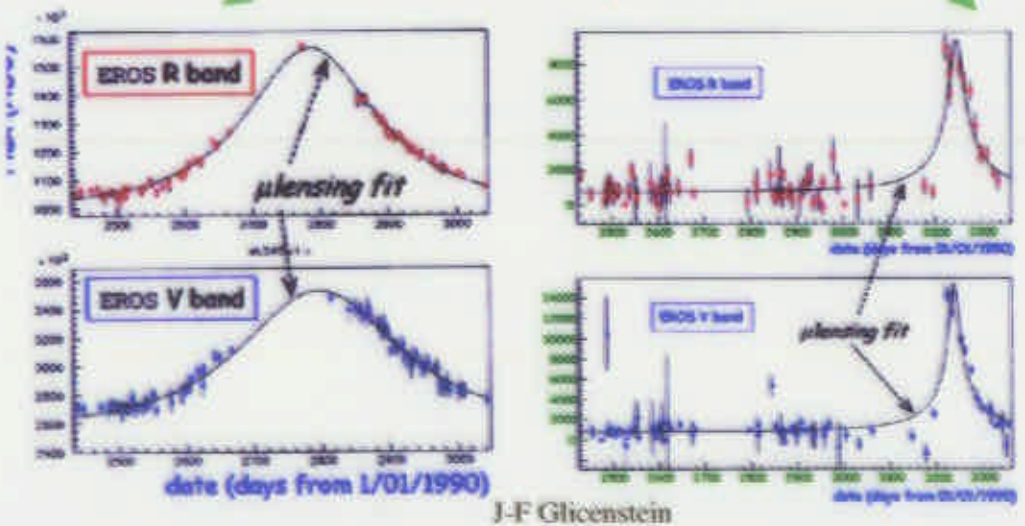
μLensing Signal and Background

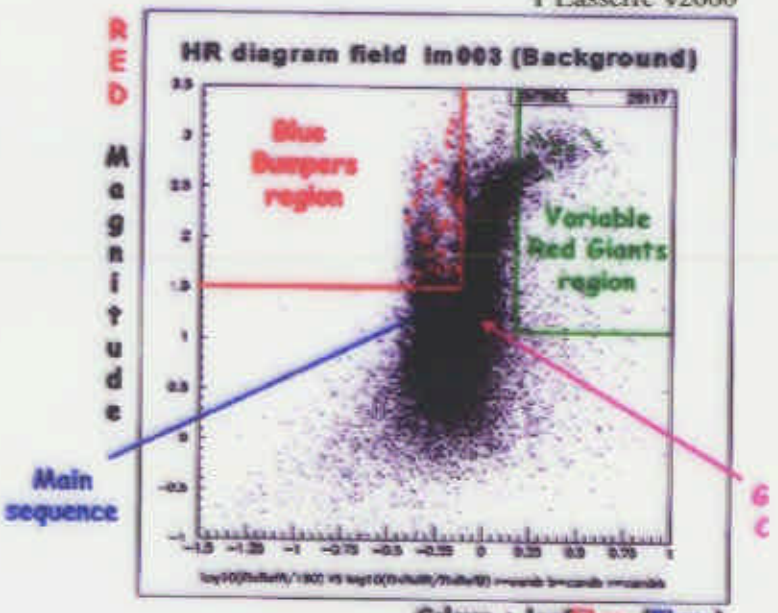
- MACHO Event
- "Blue Bumpers"
  - Chromatic (R~1.2V)
  - Low magnification
- Variable stars/novae
  - Asymmetric
  - ~5 expected/data set

Astro-ph/0001272





T Lasserre v2000



J-F Glicenstein

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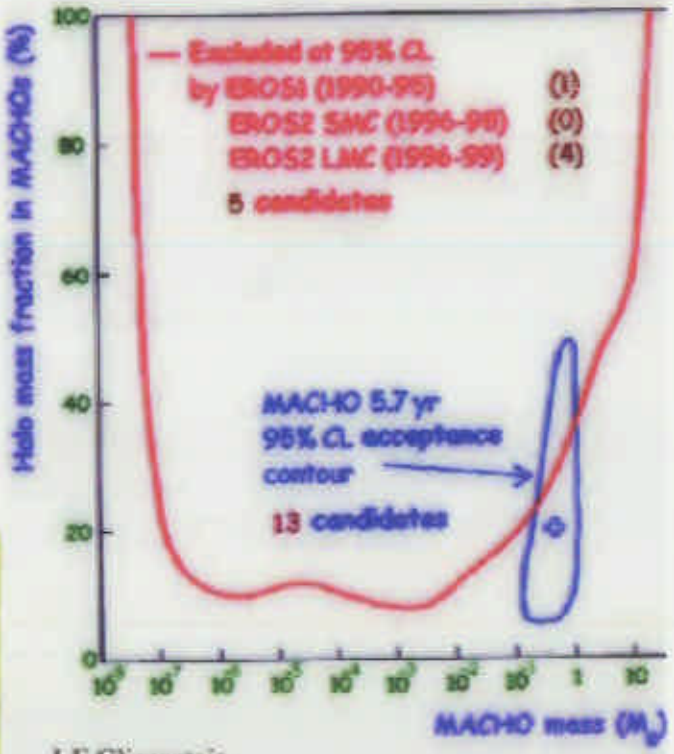
μLensing Results

- Possible candidates
  - White dwarf stars?
    - Ibata ApJ 2000 f_h~10%
    - EROS - exclude @95%cl
  - Self lensing?
    - Binaries seen
  - Primordial black holes, ..

	EROS2 LMC	EROS2 SMC	EROS1 LMC	MACHO LMC
# stars (million)	25.5	5.3	4.1	10.7
area (sq. degrees)	39 (64)	9.	27.	15.
analyzed exposure time (yr)	3.	2.	3.	5.7
efficiency (@50 days)	15%	18%	12%	40% (50%)
candidates	4	1(0)	2(1)	13(17)
expected (full halo 0.5 Mo)	26.	6(4)	2.4	55.
expected (20% halo 0.5 Mo)	5.2	1.2(0.8)	0.5	11.
expected (all data, 20% halo)	10.4	3.6	0.5	15.



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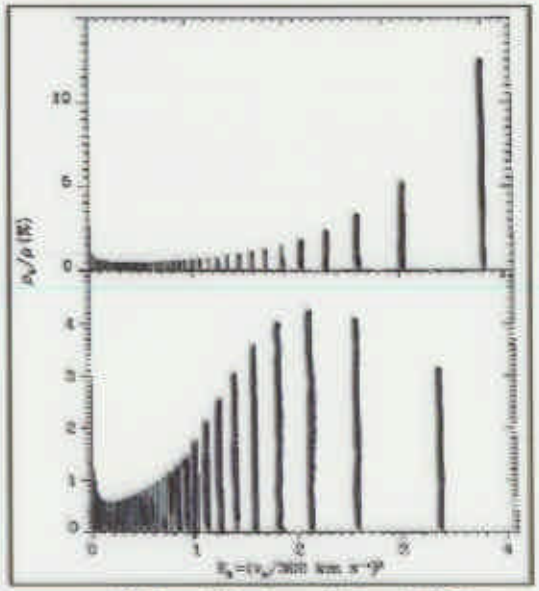
Axions

- Strong CP Problem
  - QCD expect P, T, CP violation: edm of neutron too small
  - Axion: Goldstone boson from PQ mechanism
    - DFSZ: l
    - KSZV: q

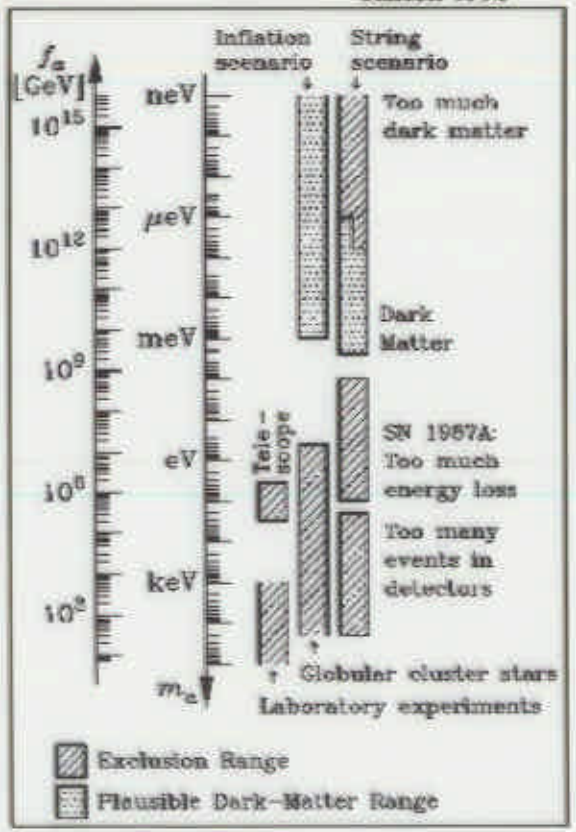
$$m_a \approx 6\mu eV\left(\frac{10^{21}\,eV}{f_{PQ}}\right)$$



Sikive, Tkachev, Wang 1995

- Cosmological axions
  - Vacuum misalignment
  - String decays
- Mass limits
  - Overclosure
  - SN1987a

Raffelt 1996



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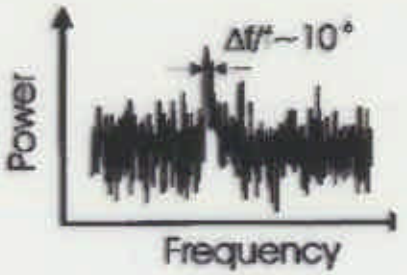
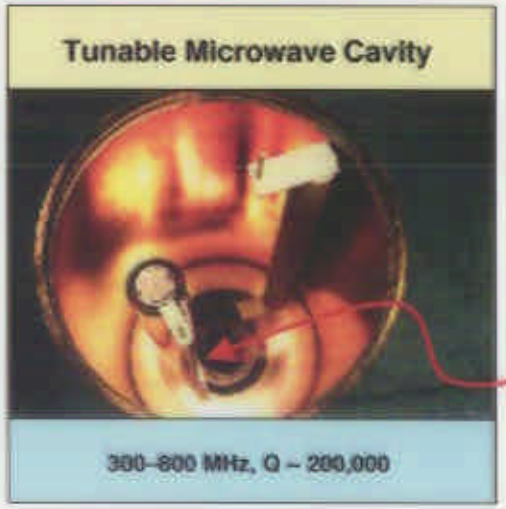
Axion Detection

- Primakoff conversion to μwave photon in B-field
  - Scan frequencies: reproducible, B scalable
- US Large Scale Axion Search
  - Currently HEMT amplifiers (T_{eff}~1.5K)
  - Developing 'in-line' SQUIDS (T_{eff}~50mK)
- Kyoto CARRACK
  - Rydberg atom detector (T_{cavity}~10mK)





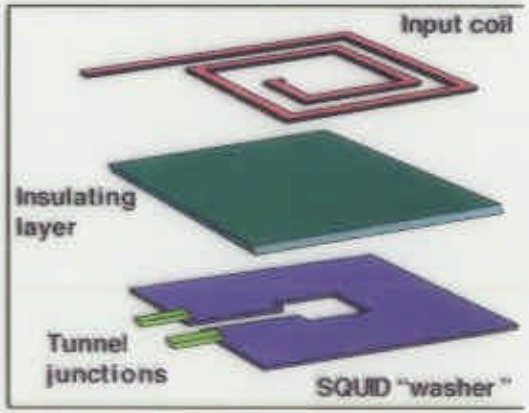
KA van Bibber

Dielectric Tuning Rods

hep-ph/9908445

$$[\text{ axion }] \overset{B_0}{\Longleftrightarrow} [\text{ photon }] \begin{matrix} \rightarrow n' \\ \updownarrow \\ \rightarrow n \end{matrix} [\text{ atom }]$$

Optical pump & Selective field ionisation



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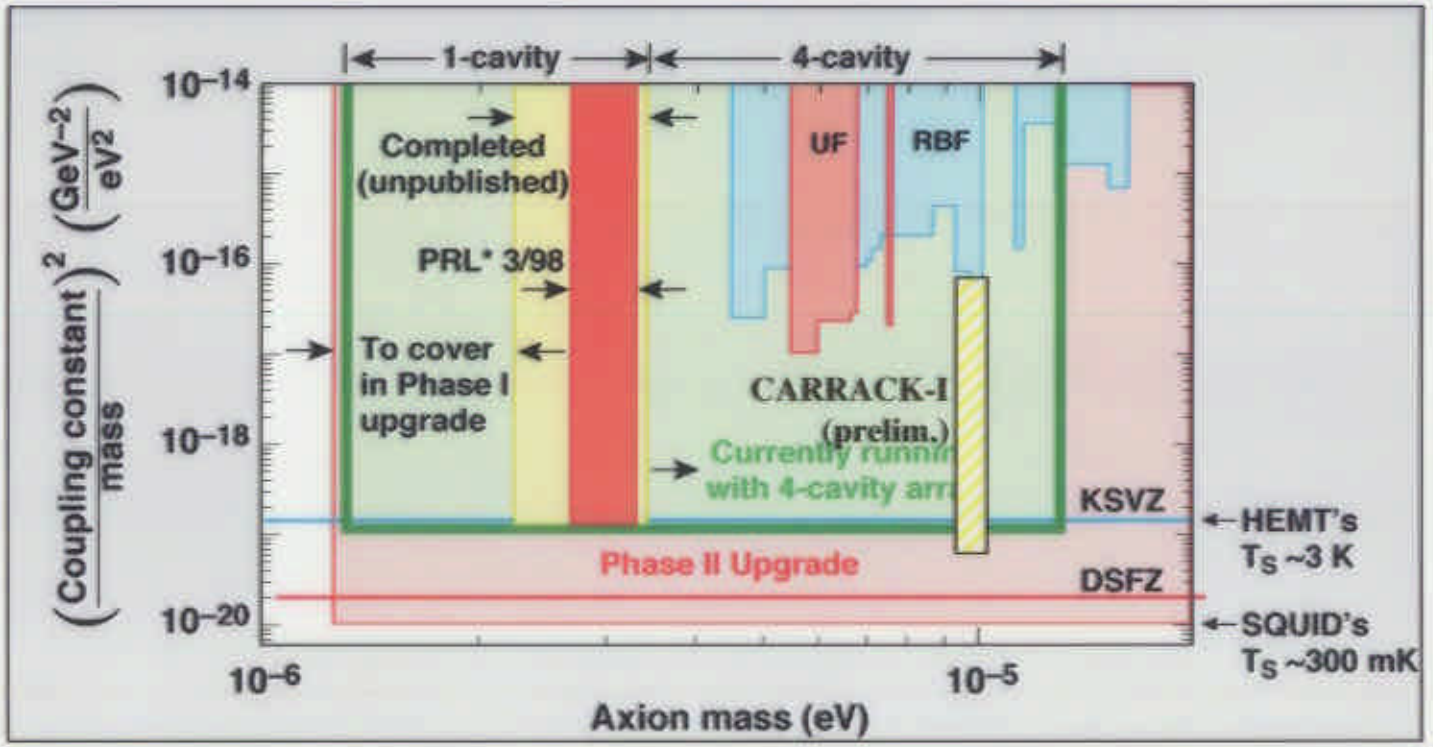
Axion Limits



- Phase I Upgrade: SQUIDs at 1.3 K will allow us run at KSVZ 4 times faster than with HEMTS
- Phase II Upgrade: SQUIDs at 200 mK will give us sensitivity to DFSZ axions even if they only constitute 50% of the halo

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WIMP Direct Detection

M Drees, KA Olive, R Arnowitt

- WIMPs
  - MSSM, R parity $\chi = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_b^0 + N_{14}\tilde{H}_t^0$
  - χ - lightest supersymmetric particle (LSP)
    - gaugino preffered (Bino)
- Elastic recoils from target nucleii
  - Few keV signal, Backgrounds: e-recoils, neutrons
- WIMP Mass
  - $m_\chi > 50$ GeV from chargino mass bound (except low tan β)
  - $m_\chi < 300$ GeV (bino) from MSSM unless χ t^- degenerate
  - $m_\chi < 600$ GeV (bino) from CMSSM
- WIMP-proton cross section
  - ($\mu<0$) $\sigma_{\chi p} > 10^{-9}$ pb
  - ($\mu>0$) $\sigma_{\chi p} > 10^{-10}$ pb (although can get to 10^{-12} pb)

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Detection Techniques

- Germanium bolometers
- Cryogenic temperature bolometers
- Ge/Si ionisation/thermal discrimination
- NaI scintillation time constant discrimination
- Xe liquid/gas scintillation + scintillation/ionisation
- Xe gas TPC directional
- $CaWO_2$scintillation/phonon
- Superconducting granule
- Superheated droplet detectors
- Superfluid ^3He

WIMP Searches

NJC Spooner

USC-PNL-Zaragoza	Homestake	Ge	
Neuchatel-Caltech-PSI	St. Gottard	Ge	
UCSB-UCB-LBL		Si, Ge	
HDMS (Heidelberg-Moscow)	Gran Sasso	Ge	ion
GENIUS (Heidelberg)		Ge	
TANDAR-USC-PNL-Zaragoza	Sierra Grande	Ge	
GEDEON (MOZA collaboration)	Canfranc	Ge	
UKDMC (IC-Sheffield-RAL)	Boulby	Na, I	
NAIAD (UKDMC)	Boulby	Na, I	
DAMA (Rome)	Gran Sasso	Na, I	
ELEGANTS	Kamioka	Na, I	
SACLAY	Frejus	Na, I	
USC-PNL-Zaragoza	Canfranc	Na, I	
ANAIS (Zaragoza)	Canfranc	Na, I	scint
DAMA (Rome)	Gran Sasso	Ca, F	
ELEGANTS VI (Osaka, Otho)	Oto-Cosmo	Ca, F	
CASPAR (Sheffield)	Boulby	Ca, F (C,H)	
DAMA (Rome)	Gran Sasso	Xe	
ZEPLIN I (UKDMC)	Boulby	Xe	
ZEPLIN II (UK-UCLA-Torino)	Boulby	Xe	
DRIFT (UK-UCSD-Oxy-Temple)	Boulby	Xe, Ar	gas
SIMPLE (Paris VII-Lisbon)	Paris	freon	sdd
Montreal Droplet Detector	Montreal	freon	
CRESST-I (MPI-TUM-Oxford)	Gran Sasso	sapphire	
CUORCINO(Italy-US collab)	Gran Sasso	TeO_2	bol
CUORE (Italy-US collab)	Gran Sasso	TeO_2	
ROSEBUD (IAS-IAP-Zaragoza)	Canfranc	sapphire	
PASS (UBC-Bayreuth)	UBC	In/Sn	
ORPHEUS(Bern)	Bern	Sn	ssg
SALOPARD(Lisbon-Paris-Zaragoza)	Canfranc	Sn	
CDMS-I (US collaboration)	Stanford	Ge, Si	
CDMS-II (US collaboration)	Soudan	Ge, Si	ion/
EDELWEISS-I (French collab)	Frejus	Ge	therm
EDELWEISS-I (French collab)	Frejus	Ge	
CRESST-II (MPI-TUM-Oxford)	Gran Sasso	$CaWO_2$	

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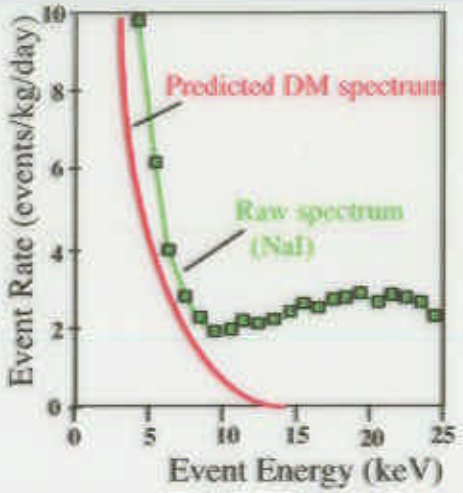
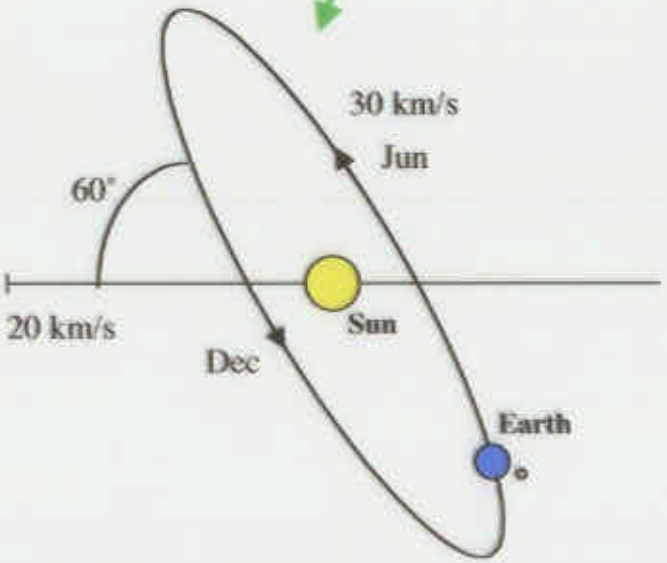
Signal Identification

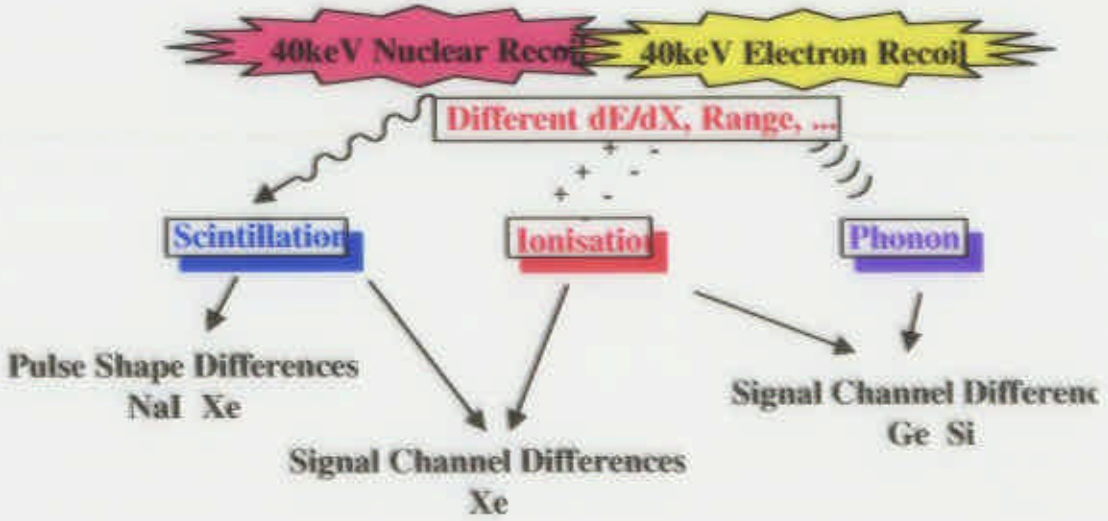
- Underlying spectrum

$$\frac{dR}{dE_R} = \frac{R_0}{E_0 r} \exp\left(-\frac{E_R}{E_0 r}\right)$$

- Nuclear recoil disrimination
- Directional signal
  - Annual modulation
  - Direct correlation







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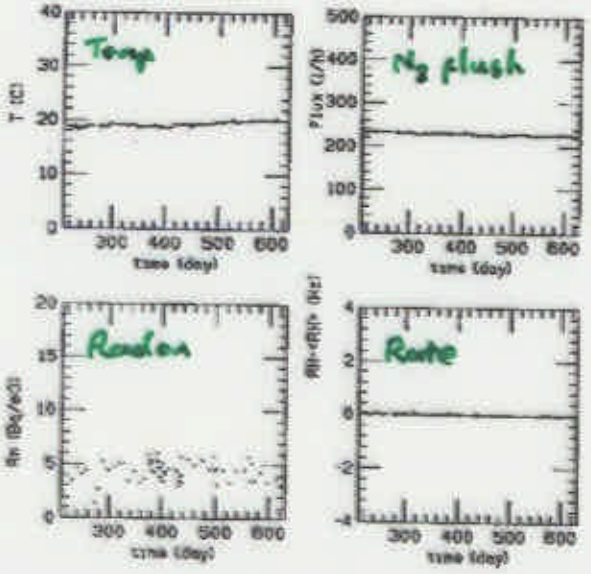
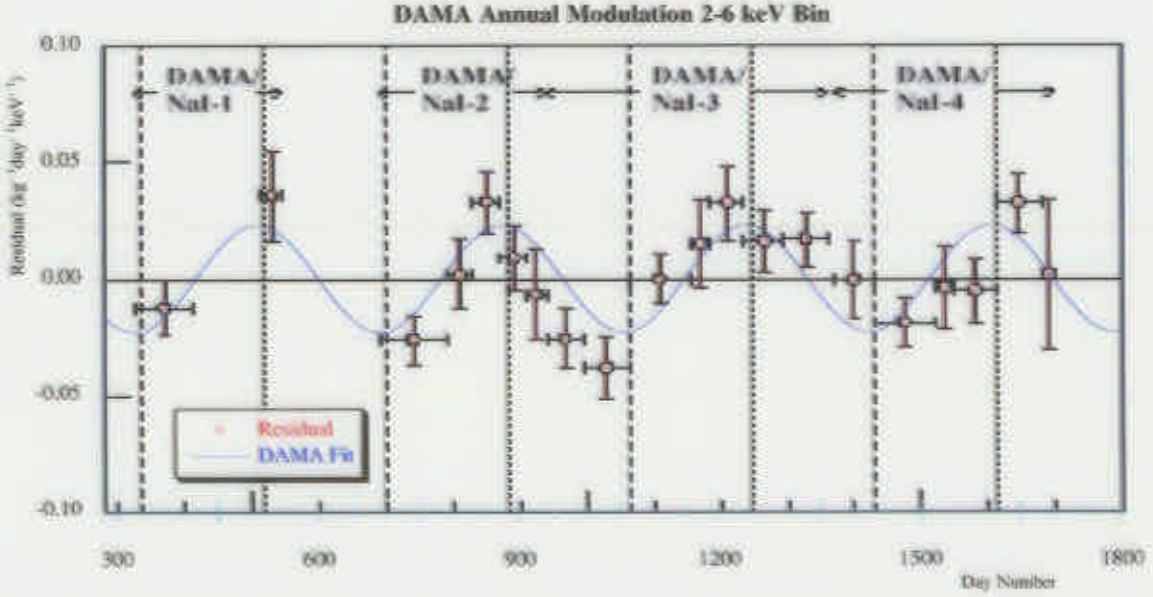
DAMA Annual Modulation Result

INFN/AE-00/01

- NaI @ Gran Sasso: 9 x 9.7kg crystals.
  - Annual modulation few % of signal
- High energy (>90keV) no modulation, rate $\sigma = 0.1\%$
- No recoil discrimination
  - PMT noise rejection

Energy (keV)	S0 (/kg/day)	Sm (/kg/day)
2-3	0.54	0.023
3-4	0.21	0.013
4-5	0.08	0.007
5-6	0.03	0.003





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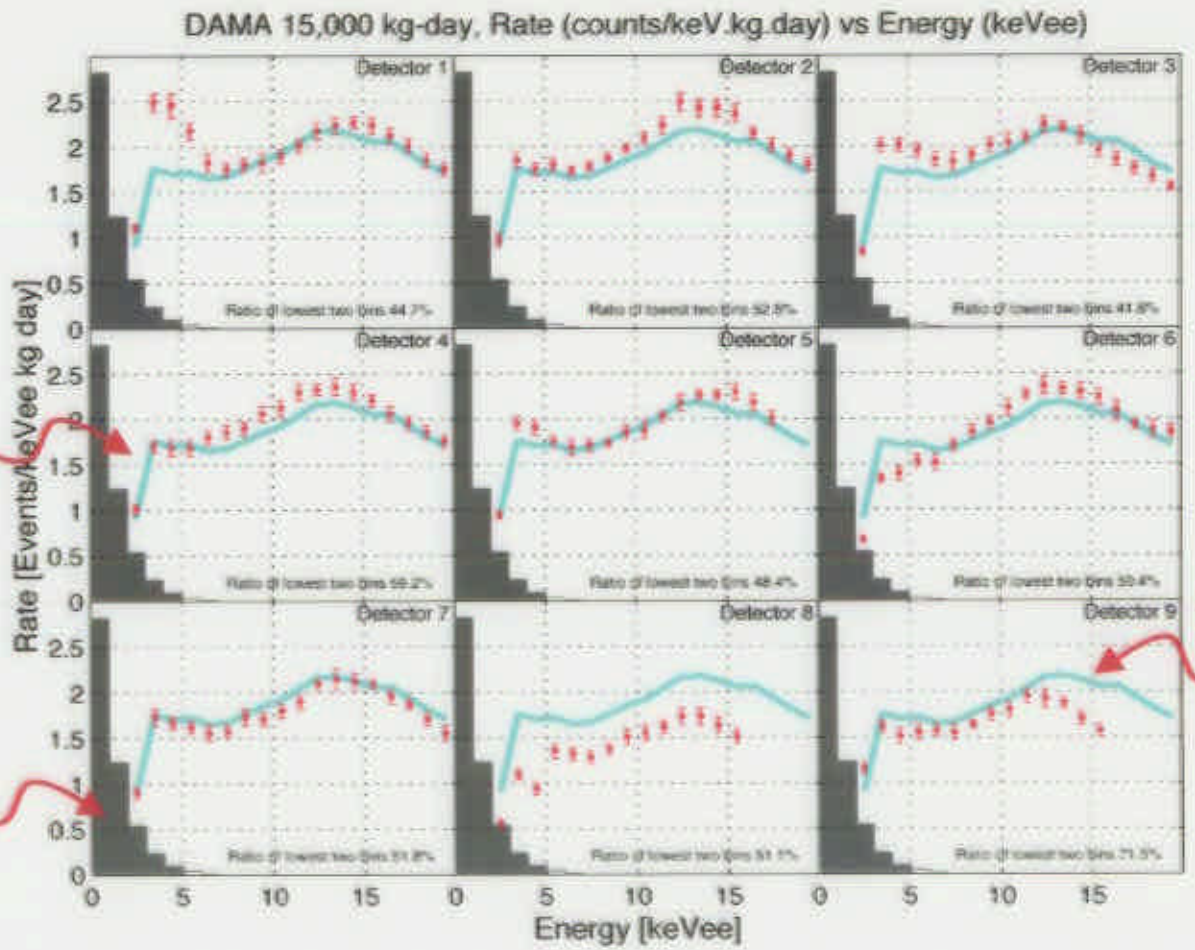
DAMA 1-2 Rates (replotted)

Gaitskell 1999



Modulation in Low energy bins - threshold fluctuation?

Expected WIMP Recoil spectrum

Average over all crystals

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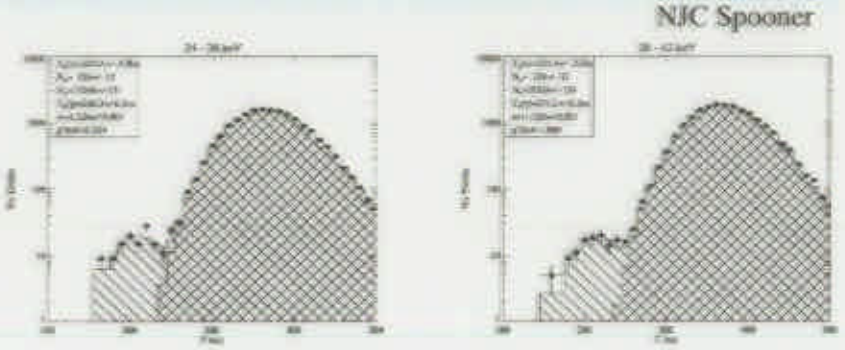
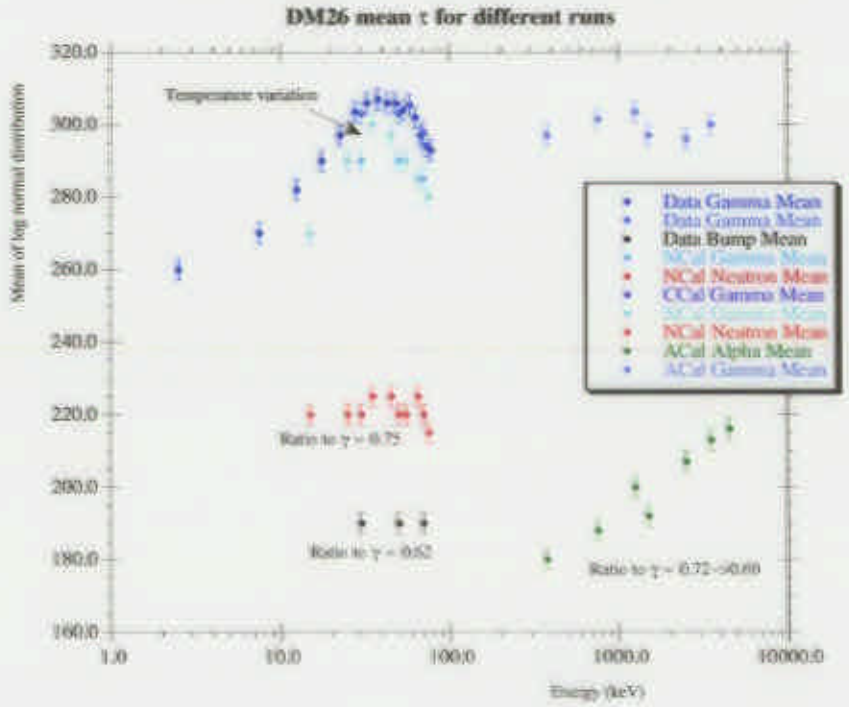
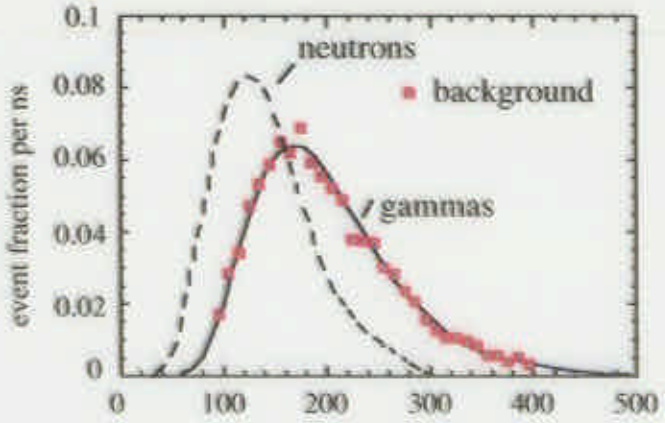
UKDMC + Saclay NaI Results

- Population of events
  - Too fast for neutrons
- Seen in many crystals
  - Different manufactur
  - Different aspect ratio
  - Different history
- Saclay events
  - Ex-DAMA crystals







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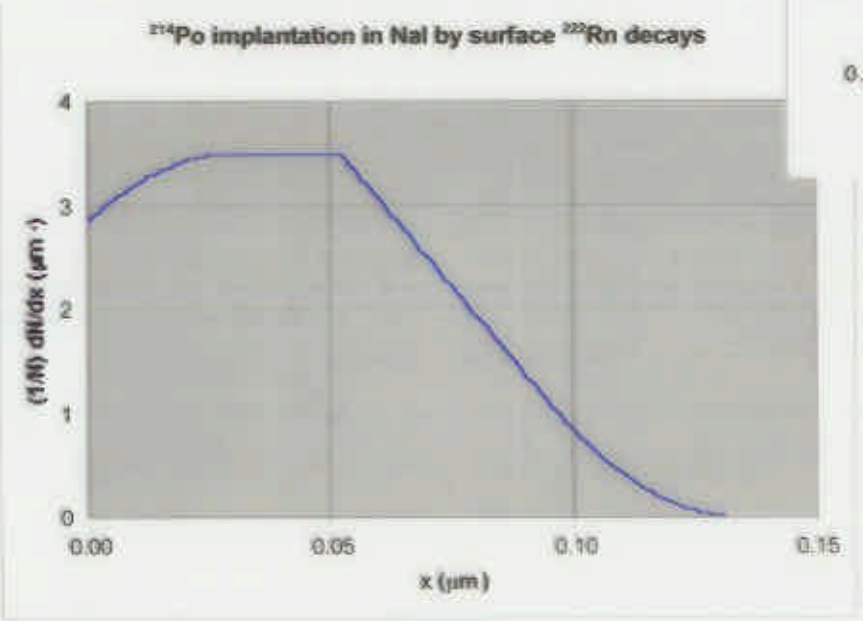
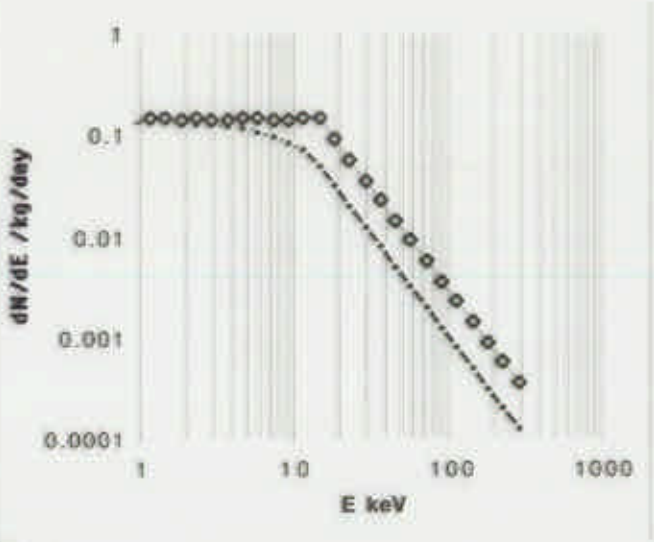
Surface α?

- Outgoing α events
  - Radon implantation?
  - Surface contamination?
- Supported by recent surface treatment results





- $^{222}Rn \rightarrow {}^{218}Po + \alpha$;
- $^{218}Po \rightarrow {}^{214}Pb + \alpha$;
- $^{214}Pb \rightarrow {}^{214}Bi + \beta + \nu\,(+\gamma)$;
- $^{214}Bi \rightarrow {}^{214}Po + \beta + \nu\,(+\gamma)$;
- $^{214}Po \rightarrow {}^{210}Pb + \alpha$;
- $^{210}Pb \rightarrow {}^{210}Bi + \beta + \nu\,(+\gamma)$;
- $^{210}Bi \rightarrow {}^{210}Po + \beta + \nu\,(+\gamma)$;
- $^{210}Po \rightarrow {}^{206}Pb + \alpha$;

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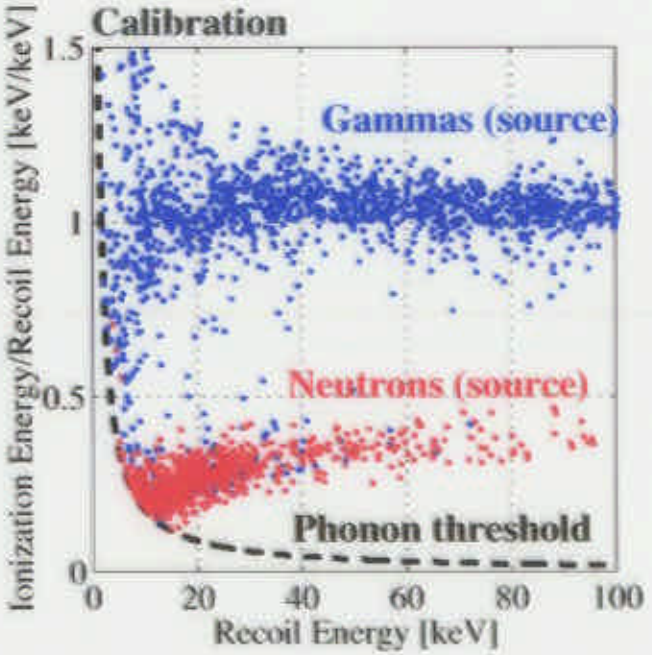
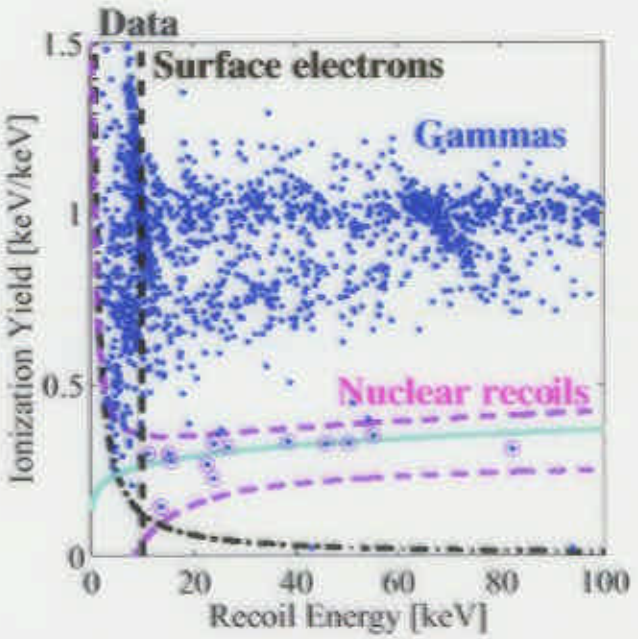
CDMS Results

Astro-ph/0002471

- Thermal/ionisation Ge/Si detectors
- Ge: 10.6 kg-day, 13 nuclear recoils, 4 multiple scatters
- Si: 1.6 kg-day, 4 nuclear recoils





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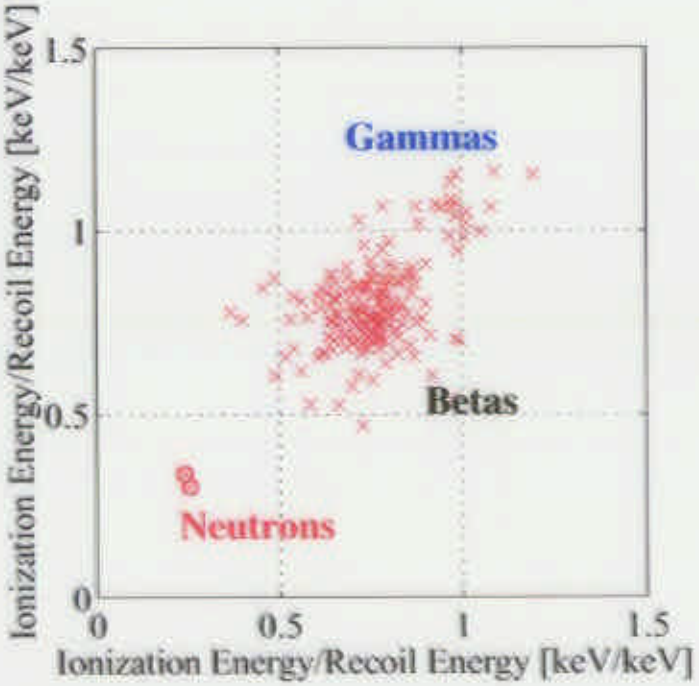
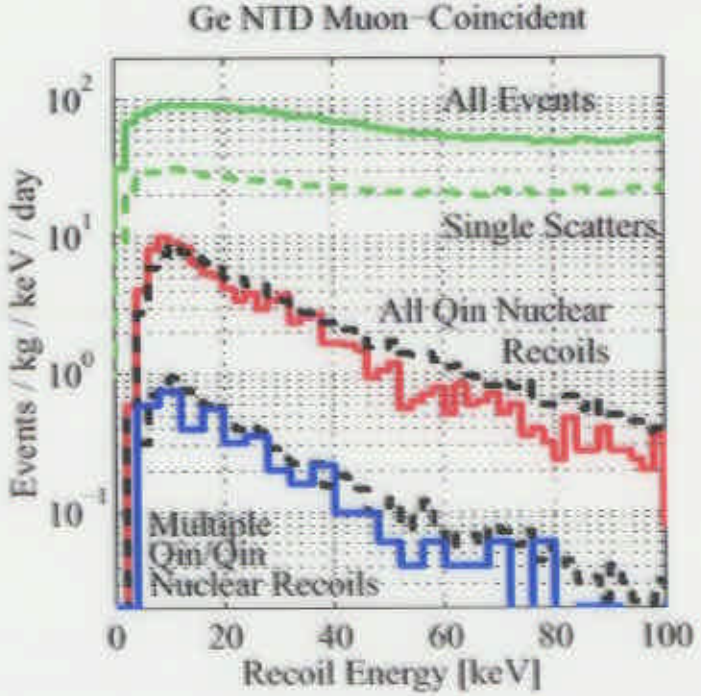
CDMS Observations

Astro-ph/0002471

- Multiple scattered events
  - High energy punch through neutrons
  - Surface electron contaminated B3-B4 combination: not betas
- Monte Carlo of vetoed events matches expectation





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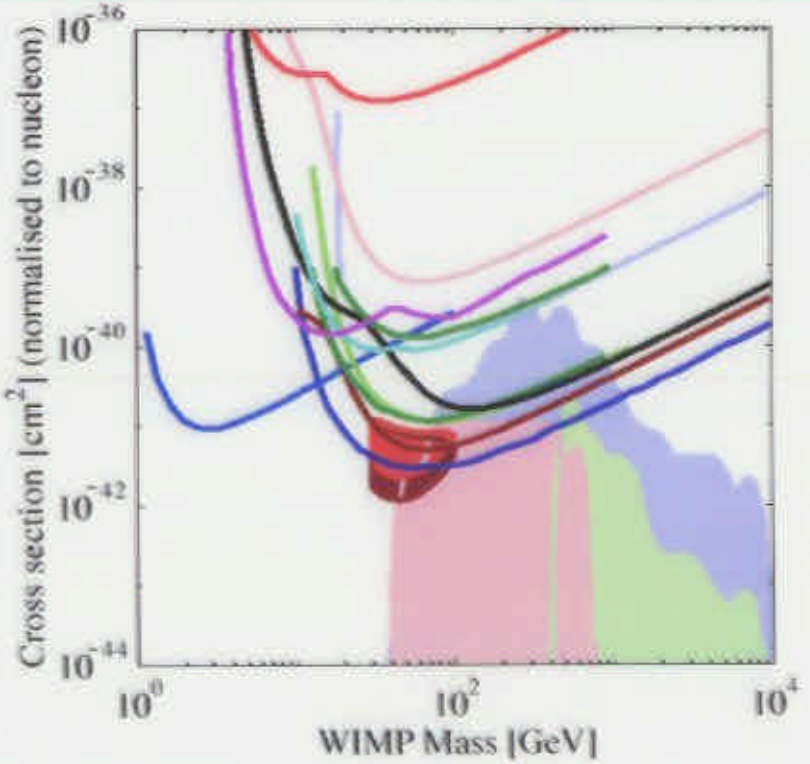
Direct Detection Limits

http://cdms.berkeley.edu/limitplots/
Gaitskell, Mandic

- Sensitivity ≈ 10^{-6} pb
  - DAMA: annual modulation of rate
  - CDMS: neutron background subtraction
  - UKDMC: 'anomalous' events preclude limit

DATA listed top to bottom on plot
Edelweiss Al2O3
Milan TeO2
ELEGANT spin indep. limit, OTO COSMO Observatory
Saclay exclusion limit
Modane NaI
MIBETA exclusion limit
UKDMC
IGEX exclusion limit
Heidelberg Moscow, 1998
CRESST exclusion limit, 25/02/00
DAMA 1996 Exclusion Region (90%CL)
CDMS Feb. 2000 ver. sub. to PRL
DAMA 2000 58k kg days NaI Ann.Mod. 3sigma w/o DAMA 1996 limit
DAMA 2000 58k kg days NaI Ann. Mod. 3sigma w/DAMA 1996
Gondolo et al. SUSY (Gaugino like Models)
Gondolo et al. SUSY (Higgsino like Models)
Gondolo et al. SUSY (Mixed Models)



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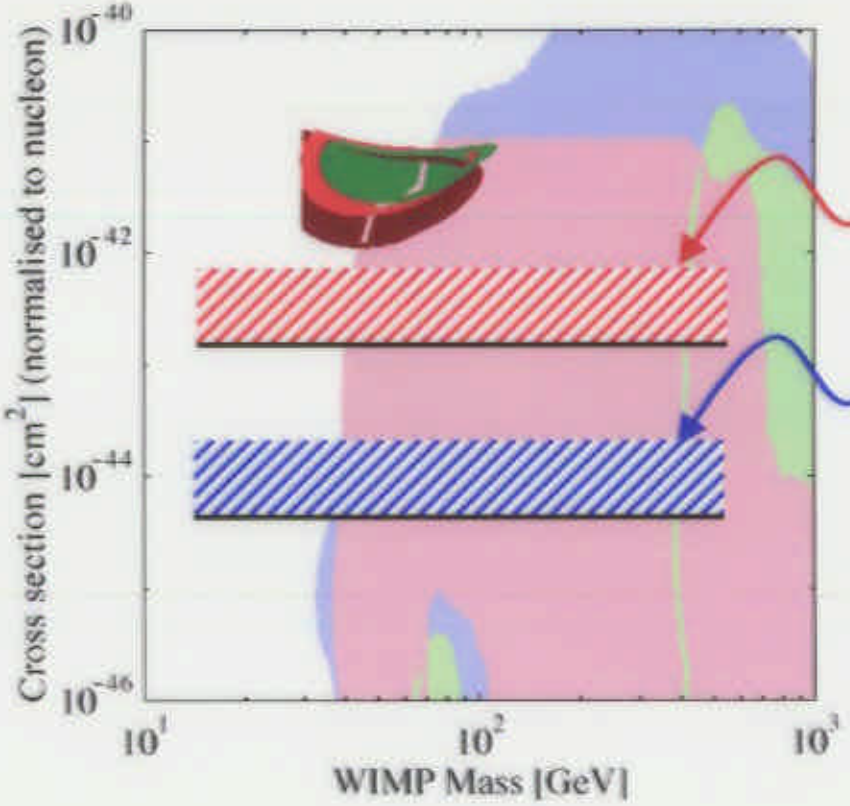
Future Techniques



Limits expected from current detectors: CDMS I, UK NaI, SIMPLE, CRESST, ZEPLIN, ...

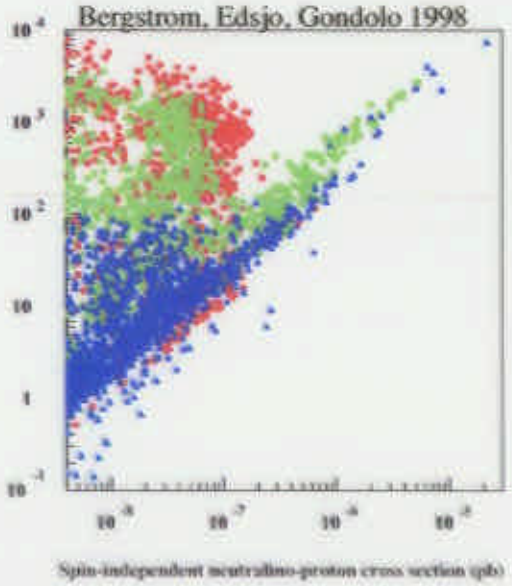
Limits expected from future detectors (known technology): CDMS II, GENIUS, Edelweiss, ZEPLIN, ...

ZEPLIN-I

Contributions
Definition
Dark Matter
MACHOs
Axions
WIMPs
Direct
Indirect
Summary

WIMPs - Indirect Detection

- Annihilation in $\chi\chi \rightarrow WW, ZZ, \gamma\gamma, gg, \ldots \rightarrow e^+, \bar{p}, \gamma, \nu, \ldots$
  - Halo: positron, antiproton, gamma secondary decay products
    - Featureless spectrum, cosmic ray background
    - Distribution follows halo, not disk
  - Halo: mono-energetic gamma lines from loop processes
  - Earth, Sun, Galactic centre
    - High energy neutrinos



Signature	Experiment
Halo annihilation Positron, Antiproton Gamma Lines $\chi\chi \rightarrow Z\gamma$ $\chi\chi \rightarrow \gamma\gamma$	BESS, AMS, .. GLAST, VERITAS, MILAGRO,....
Earth, Sun, GC Neutrino	SuperK, Baksan, MACRO AMANDA, ANTARES, Baikal, ...

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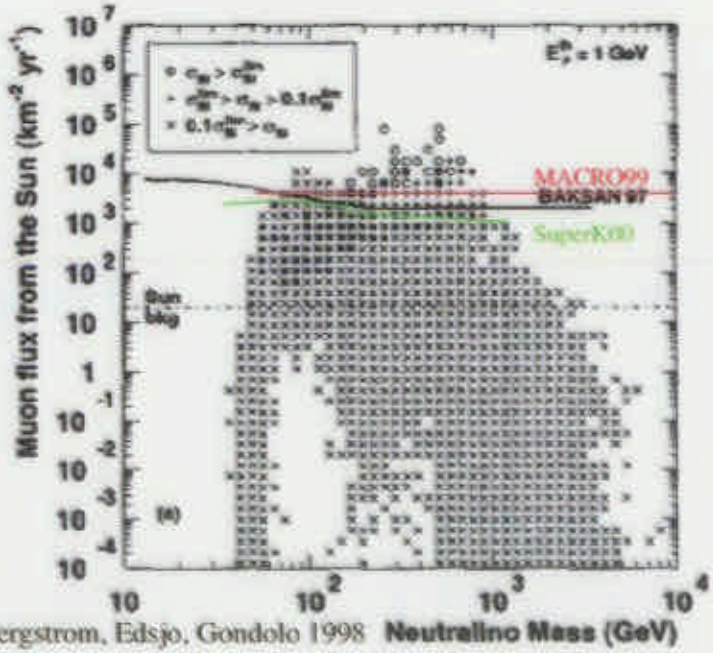
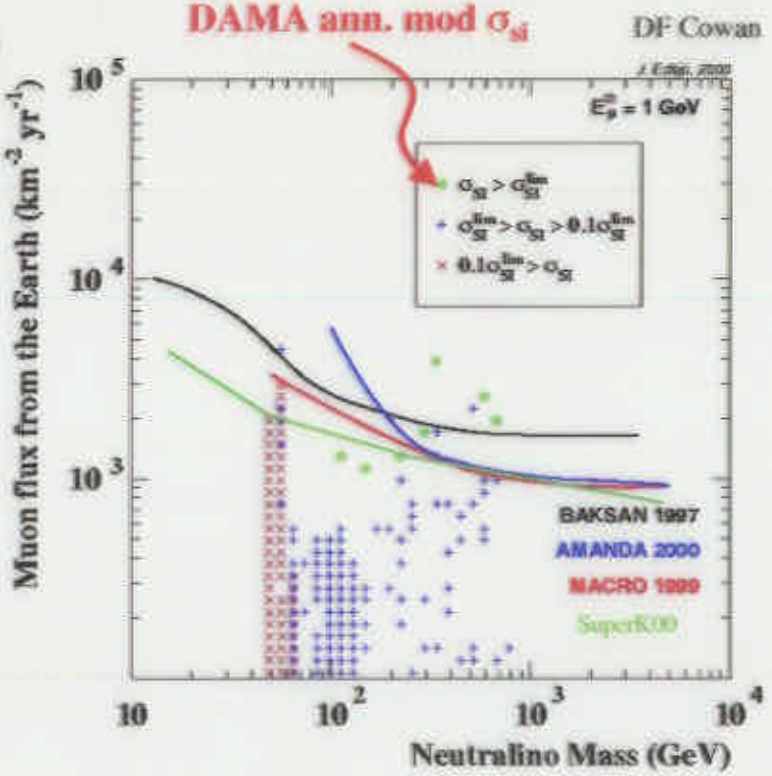
Indirect Searches - ν Results

- Search for muons (~30°)
  - AMANDA-B10
    - Vertical
  - SuperK Astro-ph/0007003
  - MACRO Astro-ph/9905021



Bergstrom, Edsjo, Gondolo 1998



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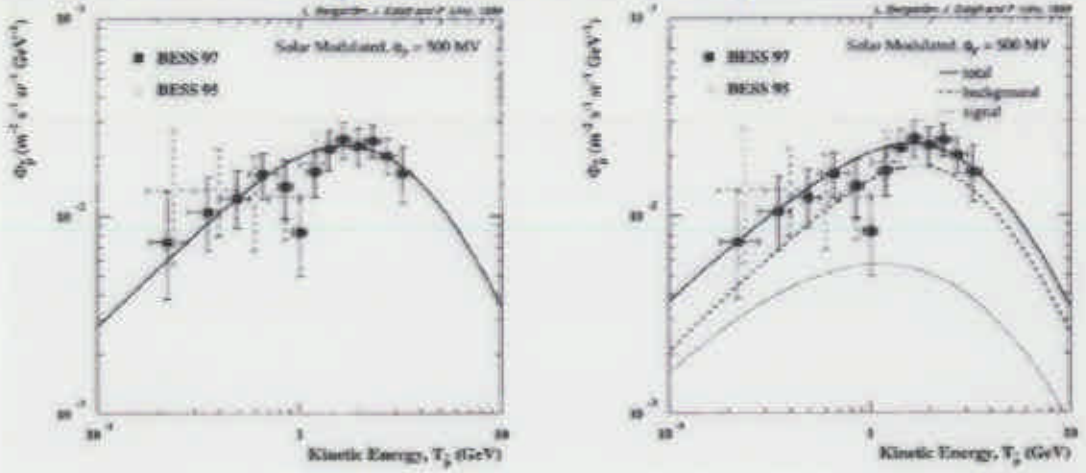
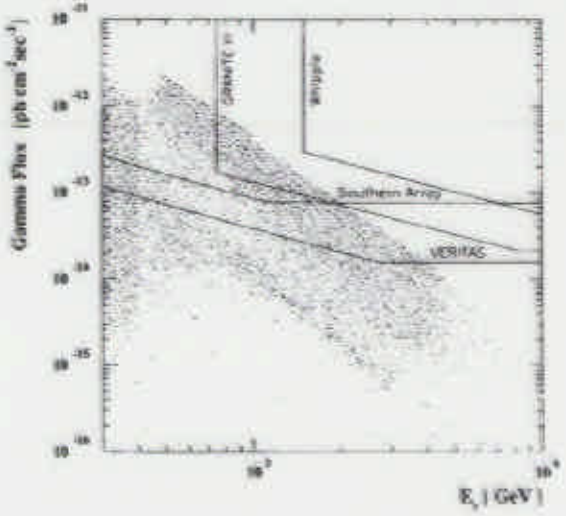
Indirect Searches - Halo

- BESS Antiproton fits c.r. spectrum OR composite
  - AMS...



Bergstrom, Edsjo, Ullio 1999

- Gamma line
  - New generation ACT
  - $10^5 m^2$ 50GeV
  - Model dependent



Bergstrom, Buckley, Ullio 1998

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Summary

- Low Energy Particles from the Universe
  - MACHOs ($\Omega_b h^2 \approx 0.03$)
    - Halo fraction ≤ 20% for mass≈0.5M_0
    - Composition under debate: white dwarf? More exotic?
  - Axions (10^{-6}eV < m_a < 10^{-2}eV)
    - KSVZ (hadronic) excluded for 2.10^{-6}eV < m_a < 3.10^{-6}eV
    - Upgrade (SQUID/4cavity/Rydberg atom) to exclude DFSZ
  - WIMPs ($10^{-9(\text{or } -12)}$ pb < $\sigma_{\chi p}$ < 10^{-6} pb, 50GeV < m_χ <600 GeV)
    - DAMA NaI annual modulation as objective
      - WIMP or fluctuating low energy noise?
    - UKDMC 'anomalous events' as surface alphas?
      - Seen in Saclay (DAMA) crystal
    - CDMS recoil limit (almost) excludes DAMA
      - Subtraction of neutron signal
    - Many more direct searches underway to reach ≈10^{-8}pb
    - Indirect ν searches reaching sensitivities to exclude models

Current sensitivity $\sigma_{\chi p} \approx 10^{-6}$ pb

- Particle Astrophysics has much to offer both fields