Nuclear Recoil Techniques for the Detection of Dark Matter

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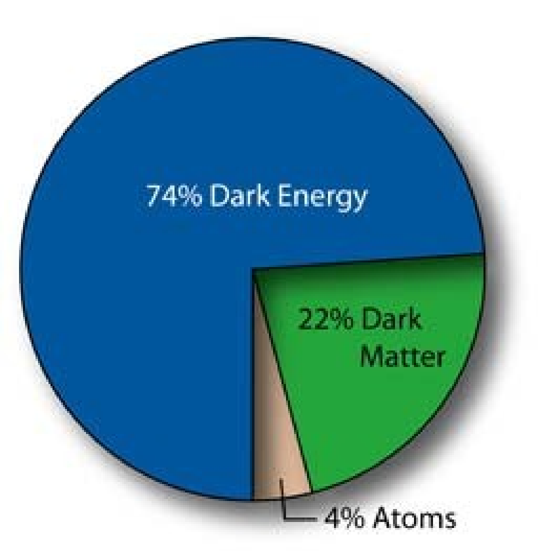
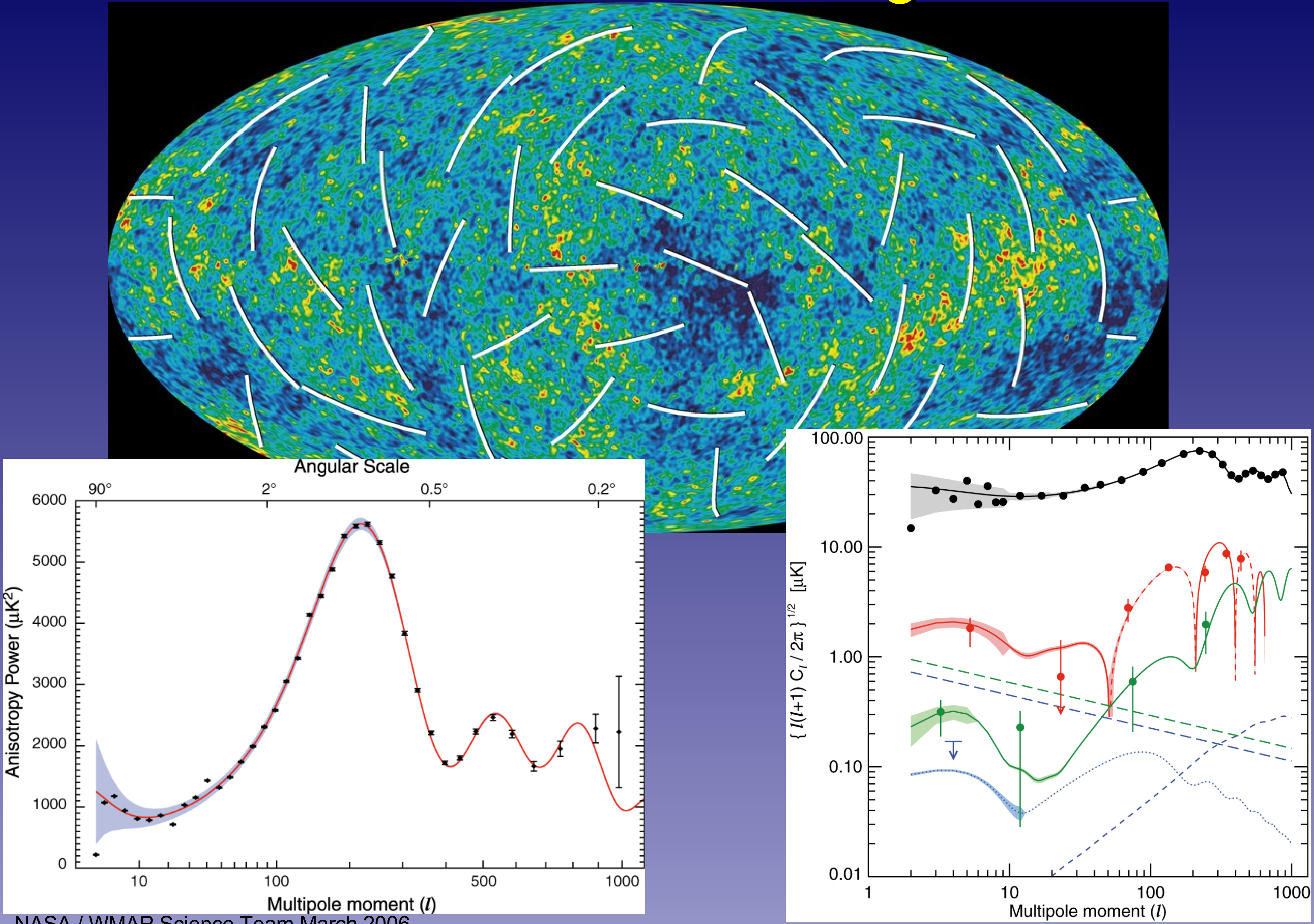
The Cosmic Recipe

Astrophysical observations reveal a dark universe.

- Cosmic Microwave Background.
  - → Geometry of the universe.
  - → Uniformity of the universe at age 380,000 yr.
- Supernovae as standard light beacons.
  - → Expansion history of the universe.
- Galaxy surveys and simulations of structure formation.
  - → Large scale structure.
  - → Early structure formation.
    - ▪ Early appearance of first stars (reionization).
    - ▪ Early appearance of quasars and galaxies.
- Big Bang Nucleosynthesis and light element abundances observed in the early universe.
  - → Limit on baryon density.
- More ...



Cosmic Microwave Background

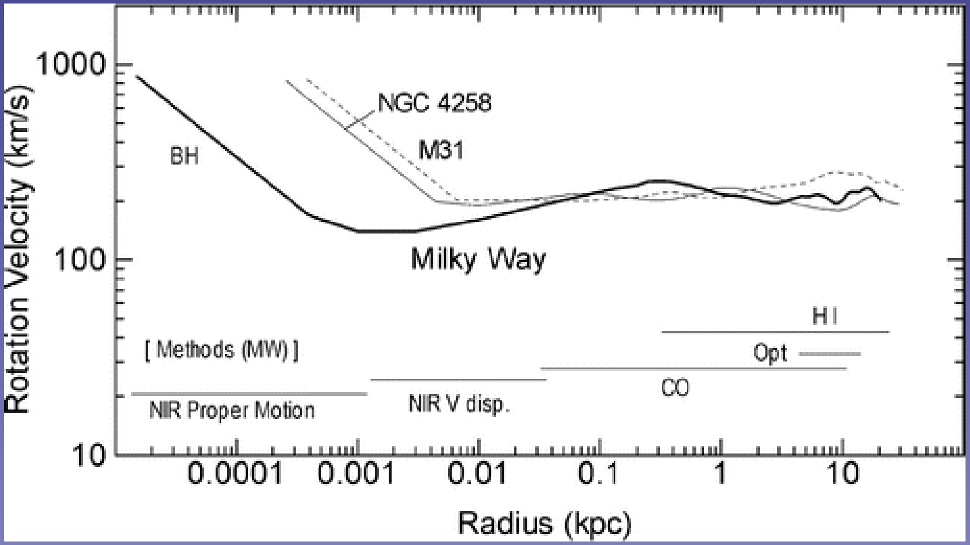


NASA / WMAP Science Team March 2006

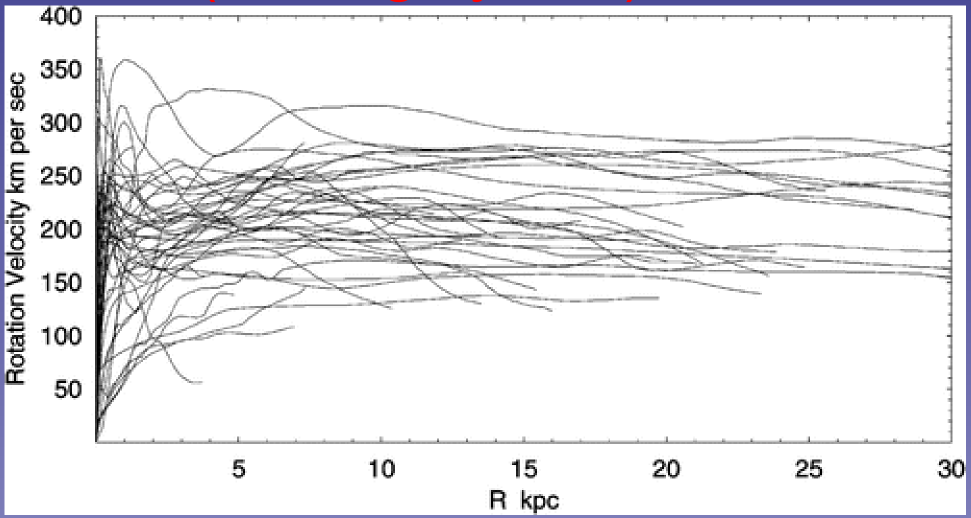
Evidence for Dark Matter in Spiral Galaxies

- Rotation curves (orbital velocity as a function of galactocentric radius) remain flat well beyond the edge of the visible disk in spiral galaxies.
- $v(R) = \sqrt{G\,M(R)/R}$
  $v(R) \approx const \;\Rightarrow\; M(R) \propto R$

Scale: ~10^{21} m
(~10^{5} lightyears)



Rotation curve of the Milky Way
(Sofue & Rubin ARAA 2001)

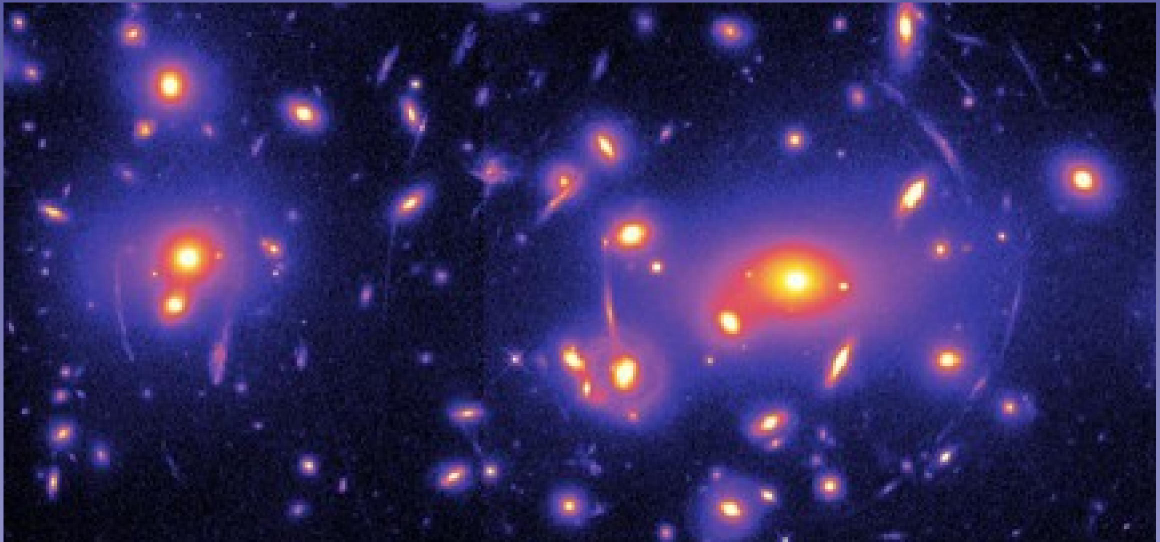


Rotation curves of nearby galaxies
(Sofue & Rubin ARAA 2001)

Evidence for Dark Matter in Galaxy Clusters

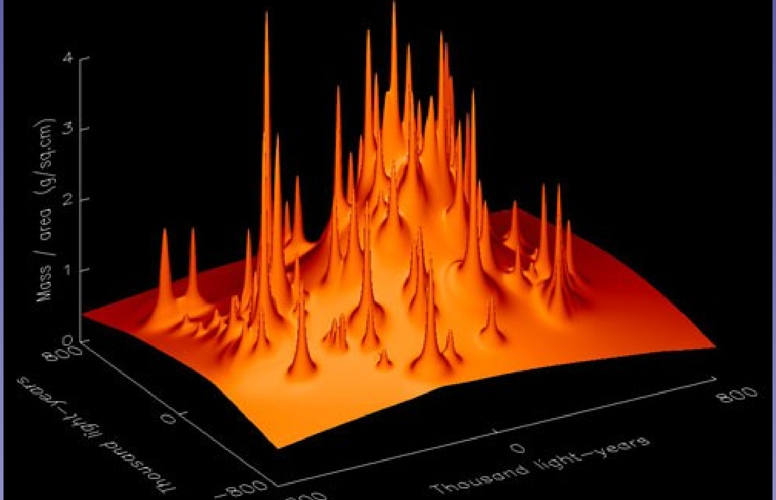
- Orbital velocities of galaxies exceed escape velocity estimated from visible mass in galaxies (Zwicky 1933).
- X-ray gas: pressure too great for visible mass. Traces gravitational potential.
- Gravitational lensing: measures total mass distribution in galaxy clusters.

NOAO/Kitt Peak: Uson, Dale
NASA/CXC/IoA: Allen et al.



W. Couch, R. Ellis, NASA

Scale: ~10^{22} m
(~10^{6} lightyears)



G. Kochanski, I. Dell'Antonio, T. Tyson, 2002

Evidence for Non-Baryonic Cold DM

Definition: $\Omega_i = \rho_i / \rho_c$

ρ_i: mass density of component i

$\rho_c = (1.9 \times 10^{-29})\ h^2\ \mathrm{cm}^{-3}$
critical density

$h = H_0 / 100\ (\mathrm{km/s})\ \mathrm{Mpc}^{-1}$: Today's
Hubble parameter.

WMAP + galaxy surveys + supernovae + BBN:

Total density: $\Omega_{Total} = 1.02 \pm 0.02$

Dark energy: $\Omega_\Lambda = 0.73 \pm 0.04$

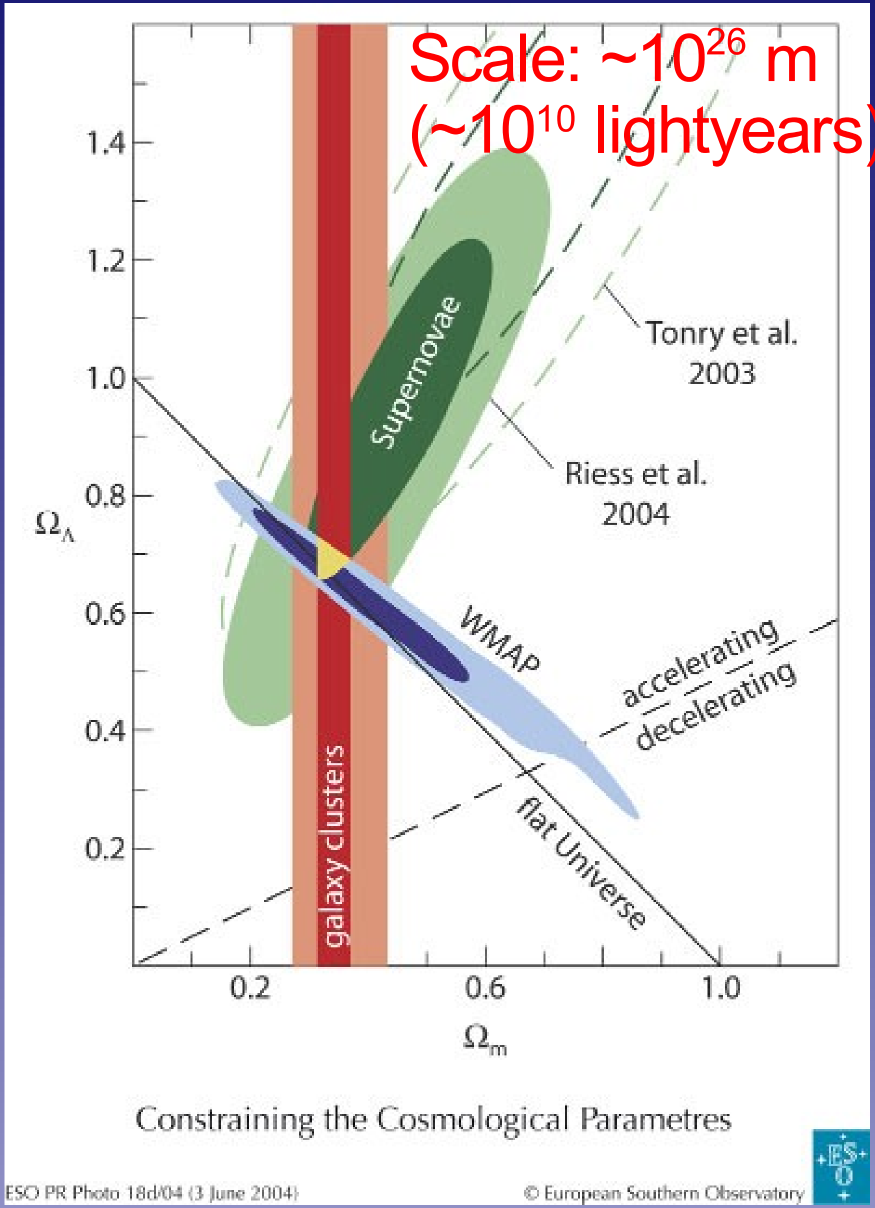
Matter density: $\Omega_m = 0.27 \pm 0.04$

Baryon density: $\Omega_b = 0.044 \pm 0.004$

Neutrinos (HDM): $\Omega_\nu < \sim 0.015$

Non-baryonic Cold Dark Matter:

$\Omega_d = \Omega_m - \Omega_b = 0.22$



Scale: ~10^{26} m
(~10^{10} lightyears)

Constraining the Cosmological Parametres

ESO PR Photo 18d/04 (3 June 2004)

© European Southern Observatory

Non-Baryonic DM Candidates

- Neutrinos (hot DM – small contribution to DM)
- Axions (see following talks)
- Weakly Interacting Massive Particles "WIMPs"
  - → In particular SUSY WIMPs, called Neutralinos (this talk)
- ... and many more (some other talk)

WIMPs: SUSY & Others

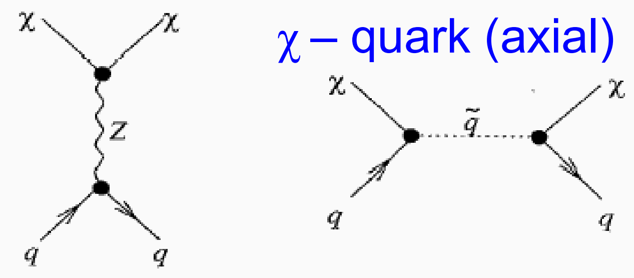
- The Standard Model is incomplete.
- Supersymmetry is one of the favored symmetries arising from “Physics beyond the Standard Model”.
- It postulates a symmetry (broken at low energies) between fermions and bosons, such that each fermion (boson) in the Standard Model has a bosonic (fermionic) supersymmetric counterpart, called a supersymmetric particle or “sparticle”.
- So there should be squarks, selectrons, etc.
- The partners of gauge bosons are called “gauginos”.
- SUSY was *not* invented to explain DM but it provides a natural DM candidate if the lightest supersymmetric particle (LSP) is stable (or has sufficiently long lifetime to have survived since the Big Bang). The mass eigenstate of the LSP is called neutralino.
- Unified Extra Dimensions can provide a viable DM candidate as well. This can be probed with 1 ton-scale DM detectors.

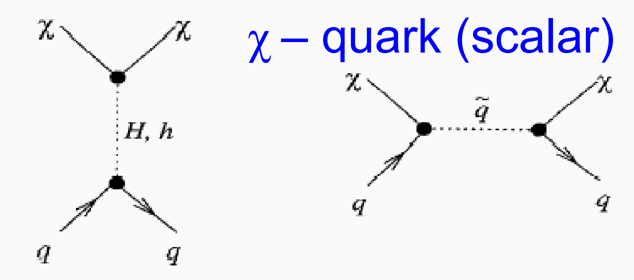
How to Detect DM
"Indirect" Observation

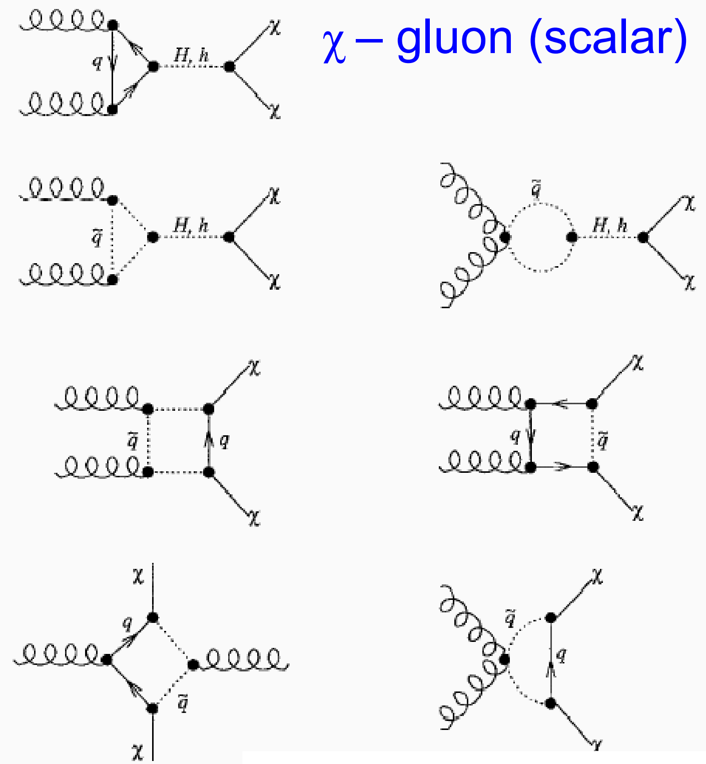
- DM Annihilation
  - → $\propto n_X^2 \Rightarrow$ look at places of enhanced DM density, e.g., Galactic Center
- Potential Signatures:
  - → High-energy (sub-GeV/GeV) continuum gamma-rays (EGRET,GLAST)
  - → Continuum gamma-rays at even higher energies: ground-based imaging air shower Cherencov telescopes (H.E.S.S., Veritas, Cangoroo, Magic, ...)
  - → (Very) high-energy gamma-ray lines
  - → 511 keV gamma-ray line (INTEGRAL?)
  - → High-energy neutrinos (escape even denser regions, e.g. center of the Sun)
  - → etc.

How to Detect DM
“Direct” Observation

- Elastic scattering of neutralinos χ off of nuclei A.
- Compute cross sections χ – quark and χ – gluon with various SUSY models. Large uncertainties! Parameter space constrained by accelerator and direct search experiments.
  - spin-dependent: coupling of spins of nucleus and neutralino $\propto$ J (J+1)
  - spin-independent: coupling to mass of nucleus ~A^2


χ – quark (axial)


χ – quark (scalar)

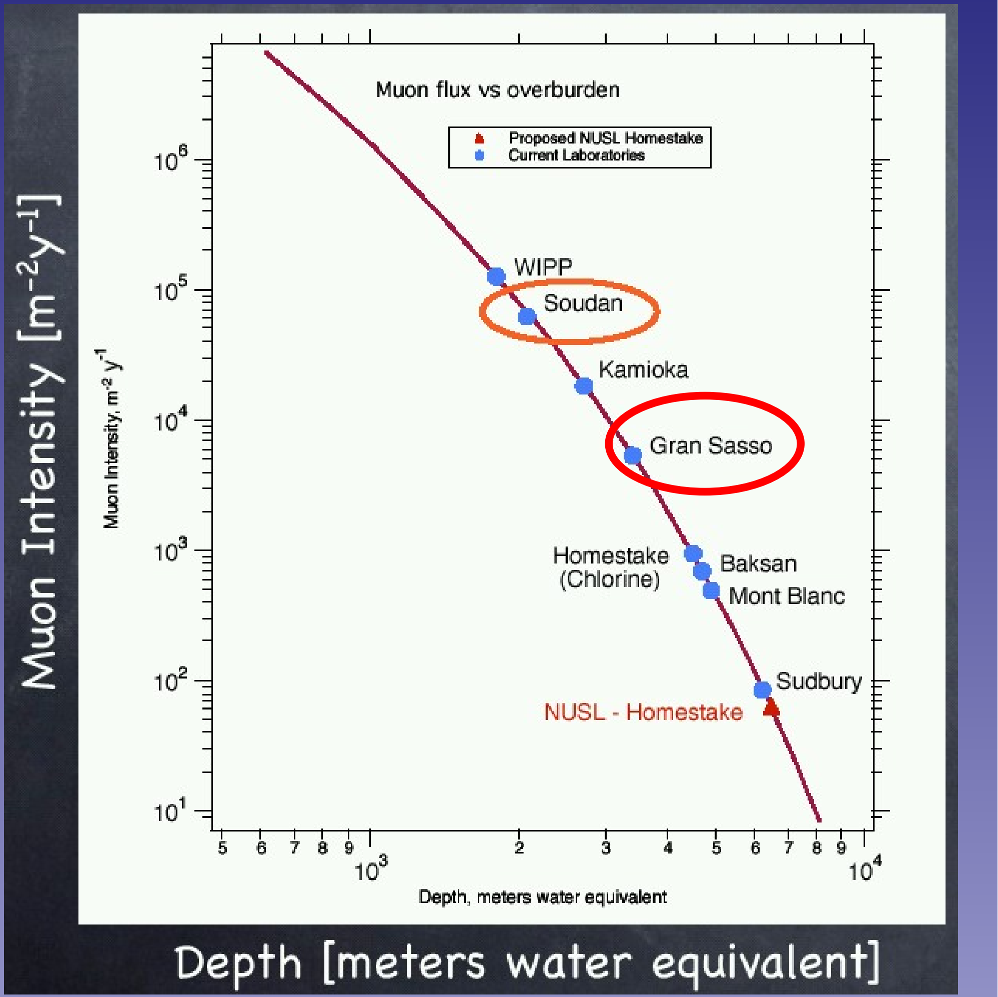

χ – gluon (scalar)

Jungmann et al. '96 Phys.Rep.

- Distribution of nucleons within nucleus (nuclear form factor).
- Large nuclei gain due to A^2 factor, but lose at higher momentum transfer due to coherence loss (form factor).

Fighting the Background

- Cross-sections are *very* small.
  Current limit (spin-indep.) ~O (10^{-43} cm^2) (or 10^{-7} pb)
- Without background,
  sensitivity ∝ (mass × exposure time)$^{-1}$
- With background subtraction ∝ (M t)$^{-1/2}$
- Backgrounds:
  - Gamma-rays & beta decays: ~100 events/kg/day
    - need efficient β and γ background discrimination
    - shielding (low-activity lead, water, noble liquids (active), liquid nitrogen, ...)
  - Neutrons from (α, n) reactions in rock: ~ 1 event/kg/day (LNGS)
    - Neutron moderator (polyethylene, paraffin, ...)
  - Neutrons from CR muons: depends on depth.



DETECTOR OVERVIEW (1)

There are *many* detector concepts for direct DM search that are at various stages of fruition:

- Past experiments that have produced results.
- Currently active experiments, taking data and producing results.
- Experiments that will soon take data.
- Experiments that are being developed in the lab.
- Funded detector concepts.
- Unfunded detector concepts.
- This crazy idea after some red wine last night ...

I can only present a small selection. Apologies if I skipped your favorite!

For a review see R. Gaitskell, 2004, Annu. Rev. Nucl. Part. Sci. and recent DM workshops (TAUP 2005, UCLA Dark 2006, etc.).

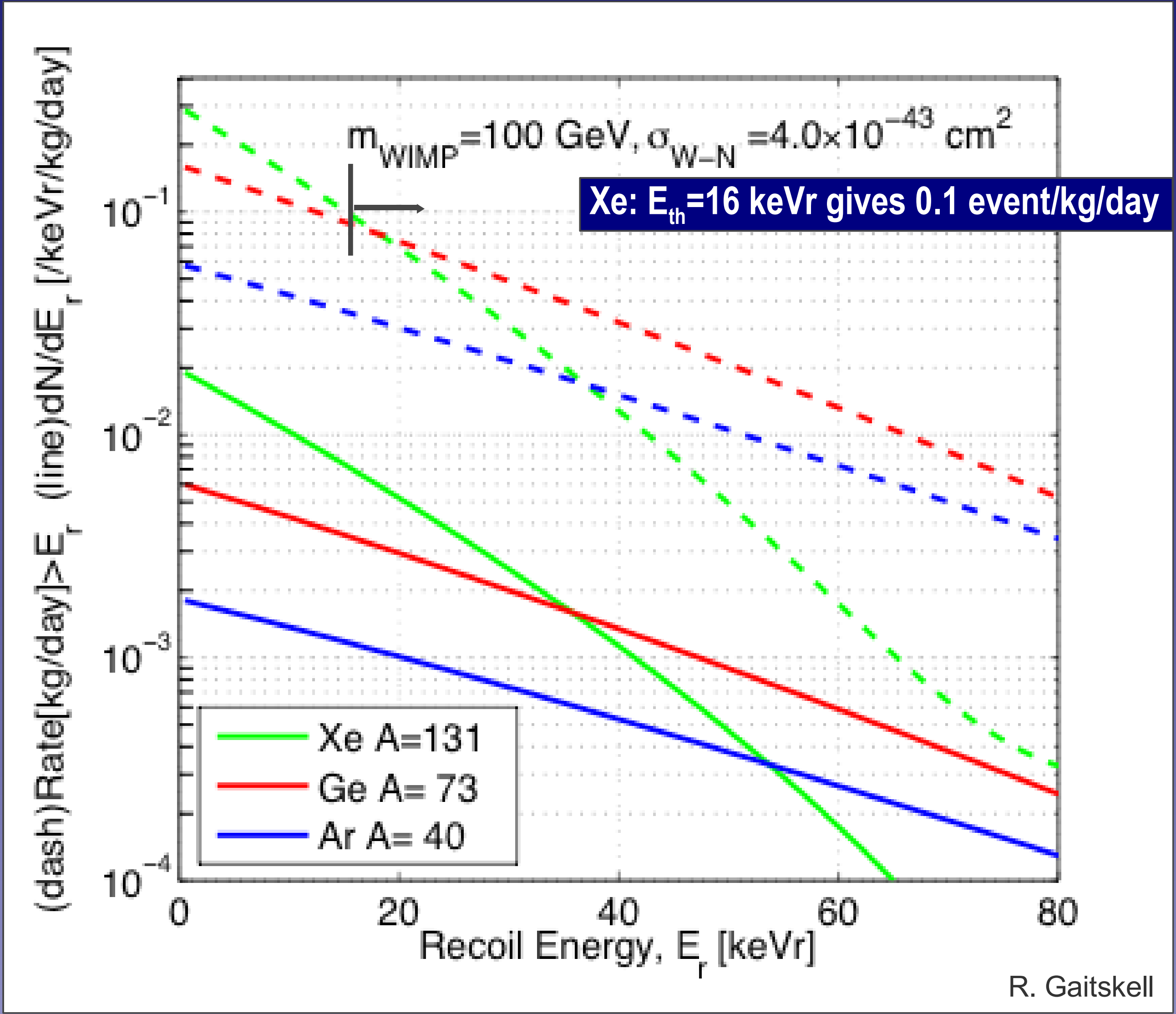
DETECTOR OVERVIEW (2)

Classify detectors by detection (physics) channels.

Some use more than one feature of a given physics channel (e.g., scintillation: amplitude and pulse shape).

- Single channel: ionization (Ge).
- Single channel: scintillation (NaI, LXe).
- Single channel: phonons.
- Two channels: any combination of the above.
  - → Ionization & Phonons: cryogenic Ge & Si detectors
  - → Scintillation & Phonons: cryogenic $CaWO_4$
  - → Ionization & Scintillation: liquid noble elements LXe, LAr, ...
- Tracking gas detectors (DRIFT).
- Other: e.g., bubble chamber.

WIMP Energy Spectra for Different Detector Materials



R. Gaitskell

Xe rate enhanced by high A, but low threshold necessary to avoid form factor suppression.

Single Channel Detectors: Scintillation

- Low-activity NaI(Tl) crystals: DAMA/LIBRA, NAIAD, ANAIS, ...
- With or without pulse-shape discrimination between nuclear and electronic recoils.
- LXe scintillation detector: XMASS

DAMA NaI Array

(Il Nuovo Cim. A112 (1999) 545-575 EPJC18(2000)283,Riv. N. Cim. 26 n.1 (2003)1-73) IJMPD13(2004)2127

Main Features of DAMA/NaI

- **Reduced standard contaminants** (e.g. U/Th of order of ppt) by material selection and growth/handling protocols.
- **PMTs:** Each crystal coupled - through 10cm long tetrasil-B light guides acting as optical windows - to 2 low background EMI9265B53/FL (special development) 3" diameter PMTs working in coincidence.
- **Detectors** inside a sealed Cu box maintained in HP Nitrogen atmosphere in slight overpressure
- **Very low radioactive shields:** 10 cm of Cu, 15 cm of Pb + shield from neutrons: Cd foils + polyethylene/paraffin+ ~ 1 m concrete moderator largely surrounding the set-up
- **Installation sealed:** A plexiglas box encloses the whole shield and is also maintained in HP Nitrogen atmosphere in slight overpressure. Walls, floor, etc. of inner installation sealed by Supronyl (2×10-11 cm^2/s permeability).Three levels of sealing.
- **Installation in air conditioning** + huge heat capacity of shield
- **Calibration** using the upper glove-box (equipped with compensation chamber) in HP Nitrogen atmosphere in slight overpressure calibration → in the same running conditions as the production runs.
- **Energy and threshold:** Each PMT works at single photoelectron level. Energy threshold: 2 keV (from X-ray and Compton electron calibrations in the keV range and from the features of the noise rejection and efficiencies). Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy
- **Pulse shape** recorded over 3250 ns by Transient Digitizers.
- **Monitoring and alarm system** continuously operating by self-controlled computer processes.

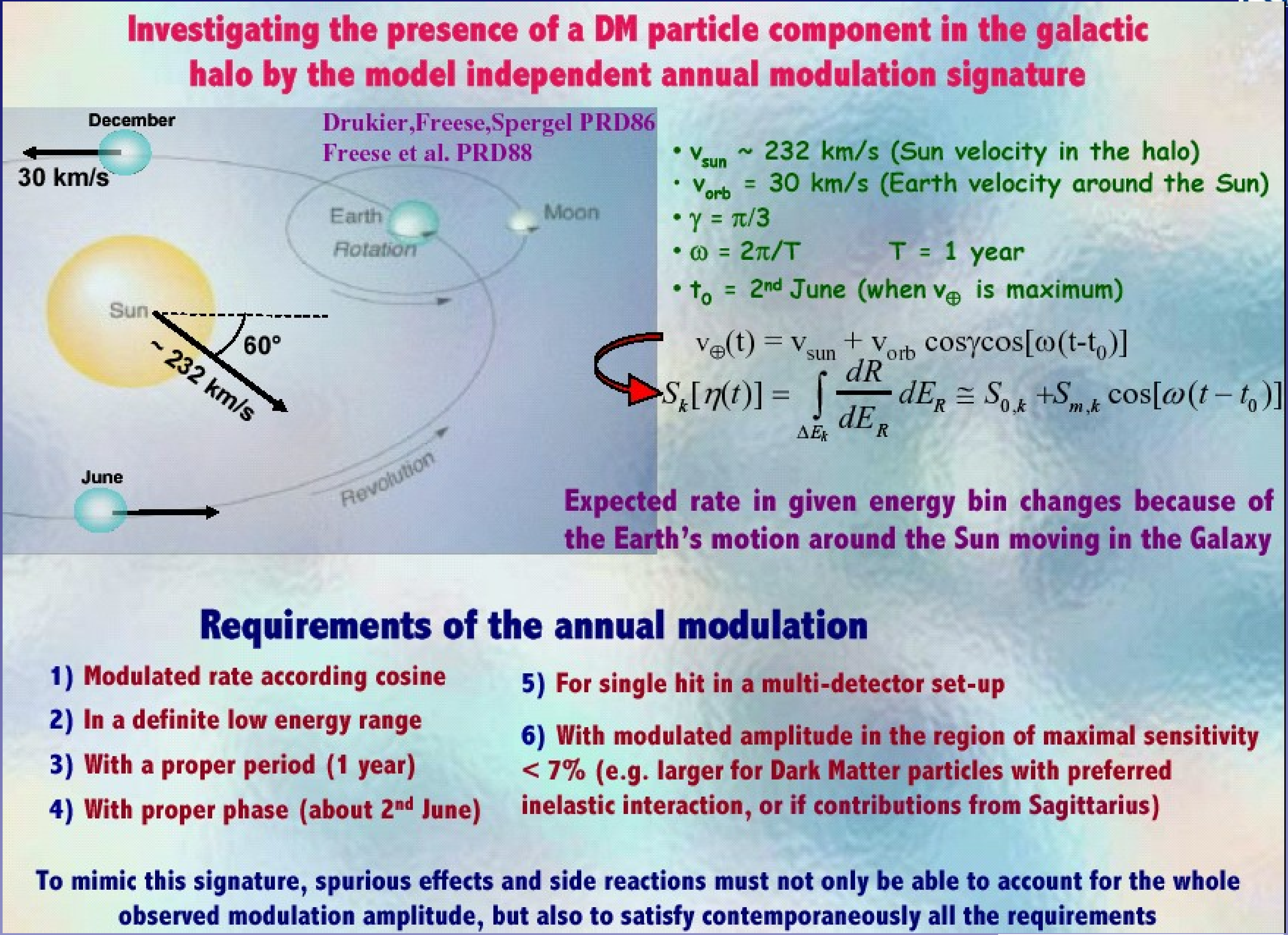
+ electronics and DAQ fully renewed in summer 2000

Main procedures of the DAMA data taking for the DMp annual modulation signature

- **data taking of each annual cycle** starts from autumn/winter (when $\cos\omega(t-t_0)\approx 0$) toward summer (maximum expected).
- **routine calibrations** for energy scale determination, for acceptance windows efficiencies by means of radioactive sources each ~ 10 days collecting typically ~10^5 evts/keV/detector + intrinsic calibration from ^{210}Pb (~ 7 days periods) + periodical Compton calibrations, etc.
- **continuous on-line monitoring of all the running parameters** with automatic alarm to operator if any out of allowed range.

A. Incicchitti, TAUP 2005

DAMA Annual Modulation Signal



Investigating the presence of a DM particle component in the galactic halo by the model independent annual modulation signature

Drukier,Freese,Spergel PRD86
Freese et al. PRD88

- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R}\, dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because of the Earth's motion around the Sun moving in the Galaxy

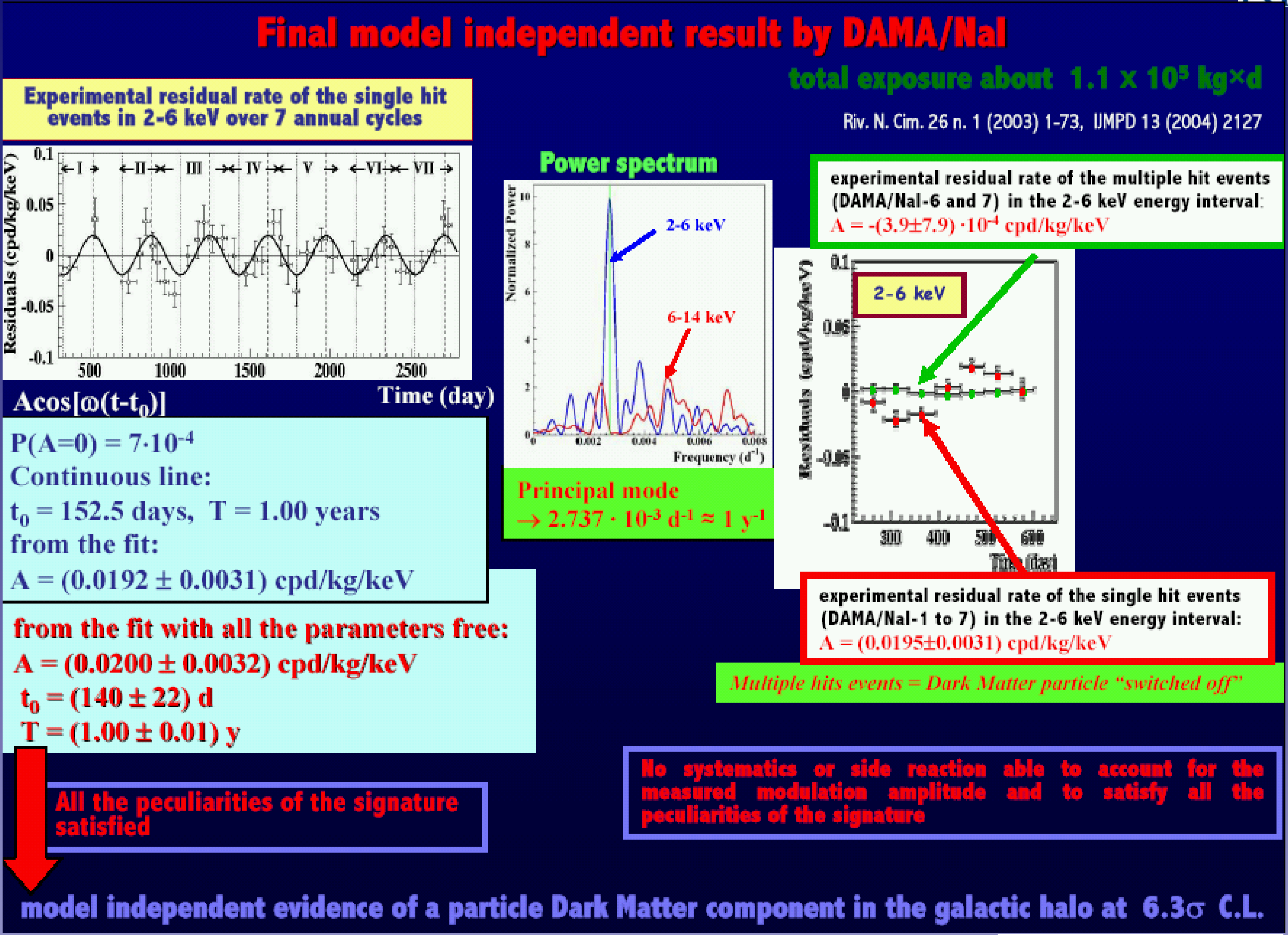
Requirements of the annual modulation

1) Modulated rate according cosine
2) In a definite low energy range
3) With a proper period (1 year)
4) With proper phase (about 2nd June)
5) For single hit in a multi-detector set-up
6) With modulated amplitude in the region of maximal sensitivity < 7% (e.g. larger for Dark Matter particles with preferred inelastic interaction, or if contributions from Sagittarius)

To mimic this signature, spurious effects and side reactions must not only be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

A. Incicchitti, TAUP 2005

DAMA Annual Modulation Signal



Final model independent result by DAMA/NaI

total exposure about 1.1 x 10^5 kg×d

Riv. N. Cim. 26 n. 1 (2003) 1-73, IJMPD 13 (2004) 2127

Experimental residual rate of the single hit events in 2-6 keV over 7 annual cycles

$A\cos[\omega(t-t_0)]$

$P(A=0) = 7 \cdot 10^{-4}$

Continuous line:

t_0 = 152.5 days, T = 1.00 years

from the fit:

A = (0.0192 ± 0.0031) cpd/kg/keV

Power spectrum

Principal mode

→ $2.737 \cdot 10^{-3}\ d^{-1} \approx 1\ y^{-1}$

experimental residual rate of the multiple hit events (DAMA/NaI-6 and 7) in the 2-6 keV energy interval:

$A = -(3.9\pm7.9) \cdot 10^{-4}$ cpd/kg/keV

experimental residual rate of the single hit events (DAMA/NaI-1 to 7) in the 2-6 keV energy interval:

$A = (0.0195\pm0.0031)$ cpd/kg/keV

Multiple hits events = Dark Matter particle "switched off"

from the fit with all the parameters free:

A = (0.0200 ± 0.0032) cpd/kg/keV

t_0 = (140 ± 22) d

T = (1.00 ± 0.01) y

All the peculiarities of the signature satisfied

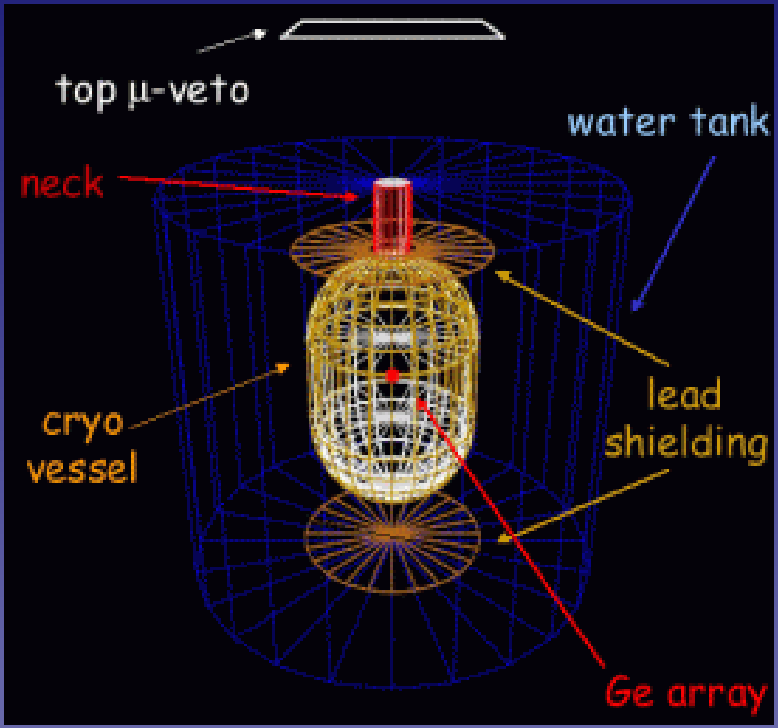
No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

model independent evidence of a particle Dark Matter component in the galactic halo at 6.3σ C.L.

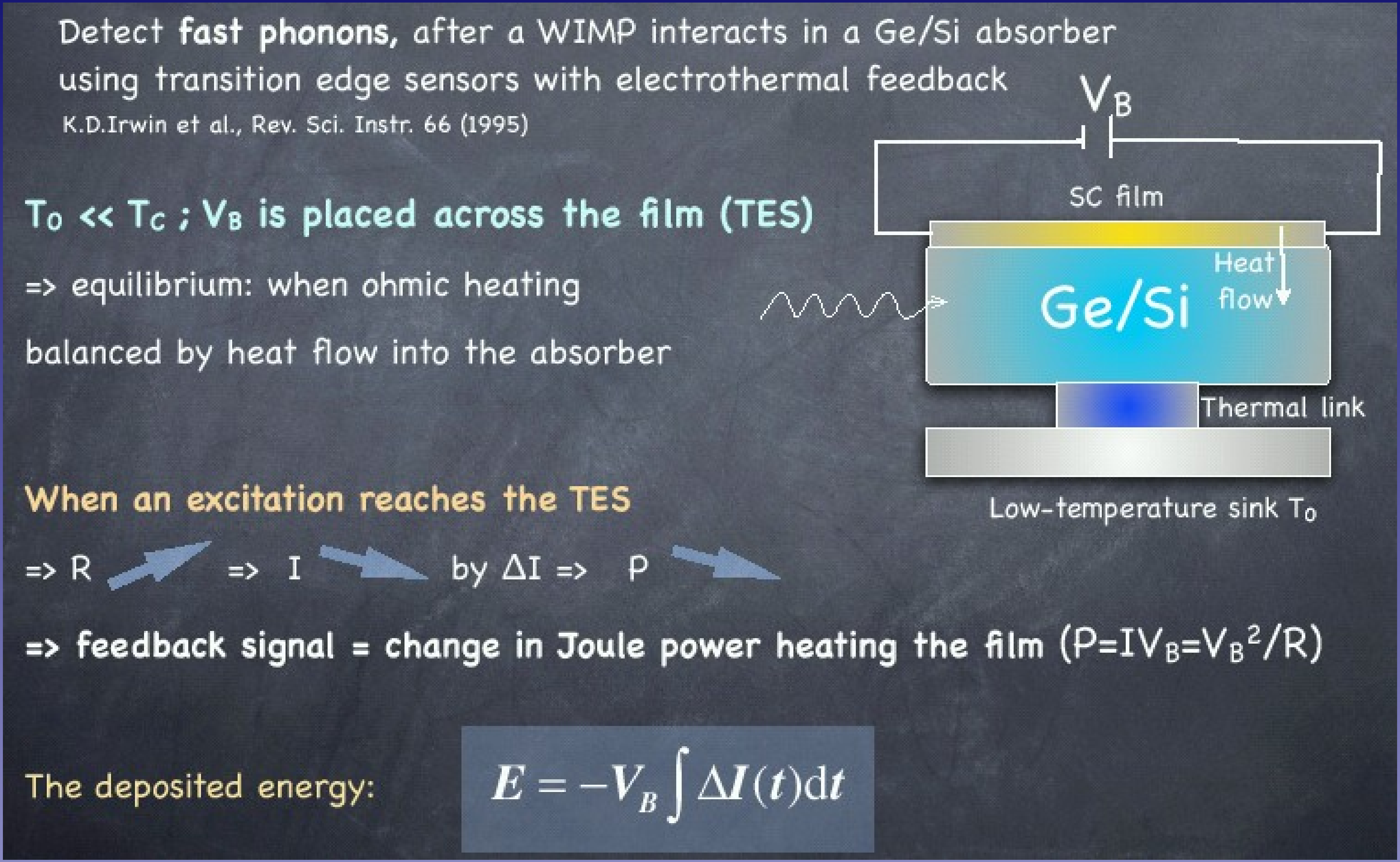
A. Incicchitti, TAUP 2005

Single Channel Detectors: Ionization

- HPGe.
- Mostly ν-less double beta decay searches. Isotopically enriched ^{76}Ge. (Majorana, GERDA)
- Shielding, e.g. with liquid N_2
- With large mass (~500 kg) and low background also sensitive to DM, looking for annual modulation.



Ionization & Fast Phonons
CDMS II



Detect **fast phonons**, after a WIMP interacts in a Ge/Si absorber using transition edge sensors with electrothermal feedback

K.D.Irwin et al., Rev. Sci. Instr. 66 (1995)

$T_0 \ll T_C$; V_B is placed across the film (TES)

=> equilibrium: when ohmic heating balanced by heat flow into the absorber

When an excitation reaches the TES

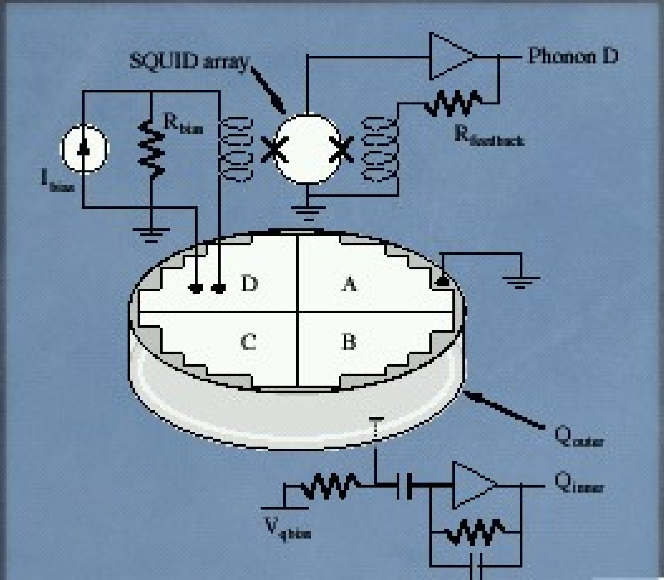
=> R $\nearrow$ => I $\searrow$ by ΔI => P $\searrow$

=> **feedback signal = change in Joule power heating the film** ($P=IV_B=V_B^2/R$)

The deposited energy: $E=-V_B\int \Delta I(t)\,\mathrm{d}t$

L. Baudis DM 2006

CDMS II - Detectors

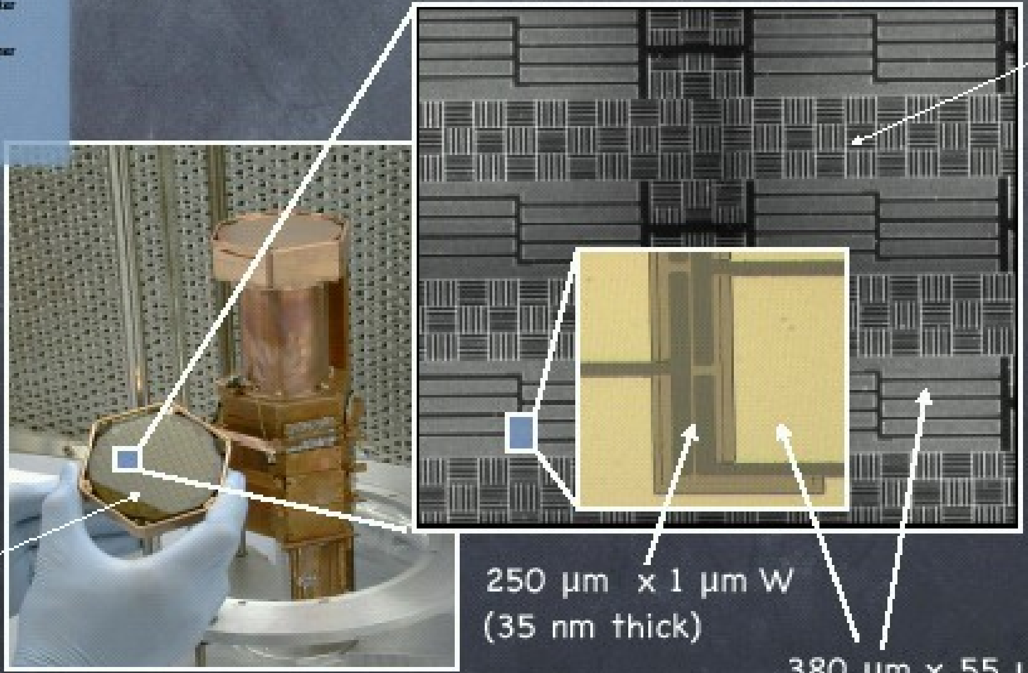


Absorbers:

250 g Ge or 100 g Si crystal
1 cm thick x 7.5 cm diameter

T-sensor:

photolithographic
patterned thin Al+W films



passive
tungsten
grid

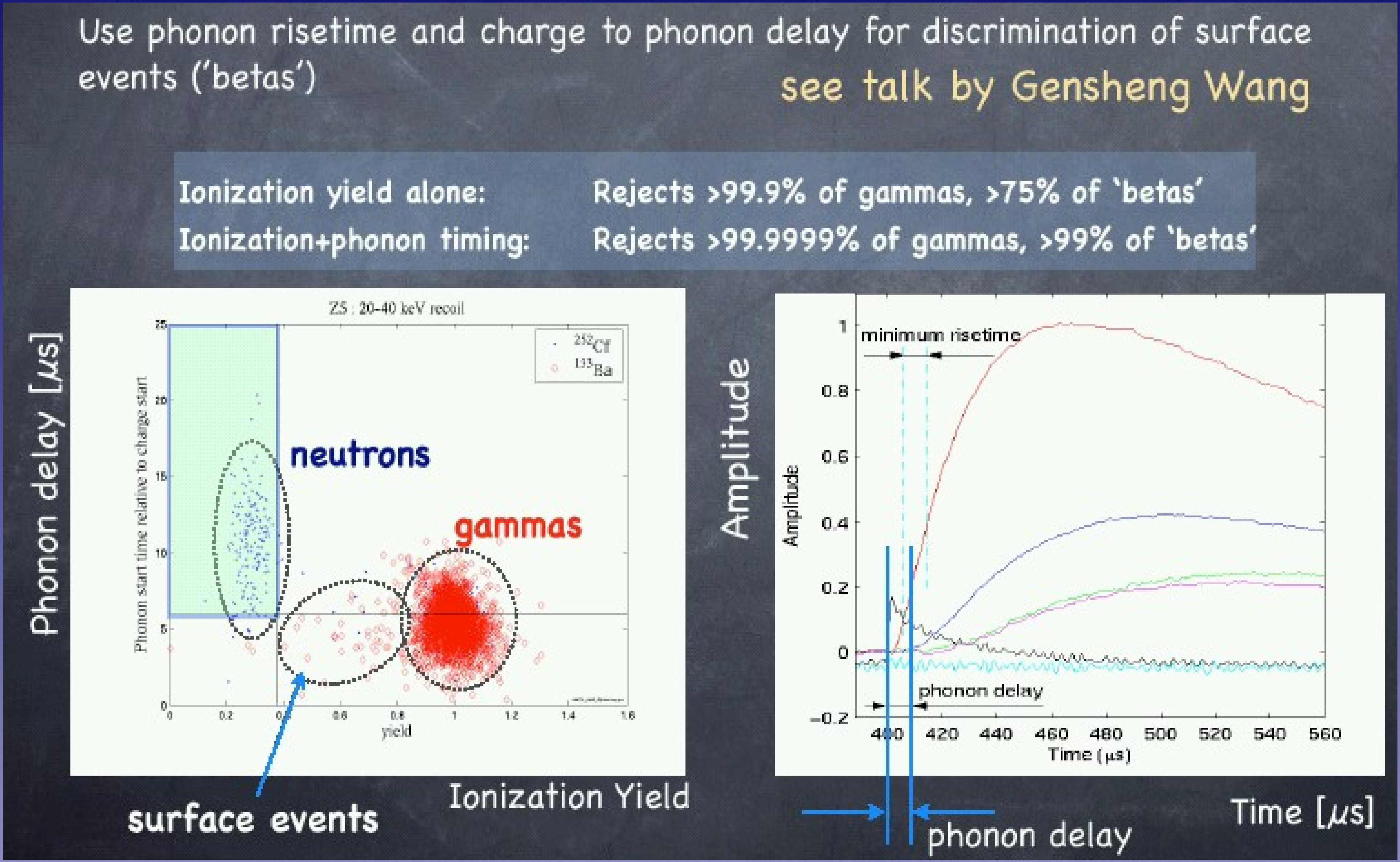
4144 QETs
(4x1036)

250 µm x 1 µm W
(35 nm thick)

380 µm x 55 µm Al fins
(300 nm thick)

L. Baudis DM 2006

CDMS II – Background Discrimination



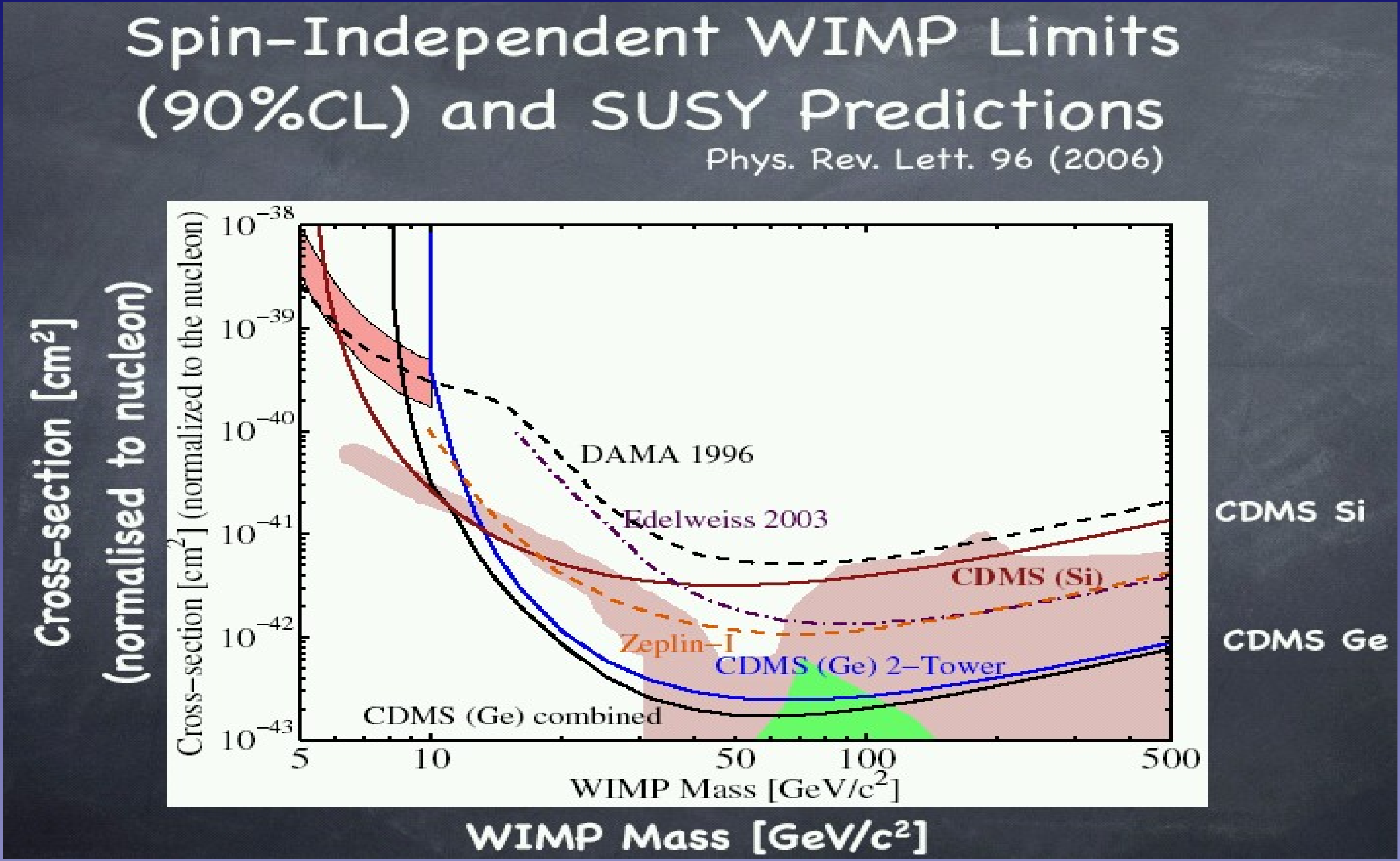
Use phonon risetime and charge to phonon delay for discrimination of surface events ('betas')

see talk by Gensheng Wang

Ionization yield alone:	**Rejects >99.9% of gammas, >75% of 'betas'**
Ionization+phonon timing:	**Rejects >99.9999% of gammas, >99% of 'betas'**

L. Baudis DM 2006

CDMS II – Currently the Lowest Limits



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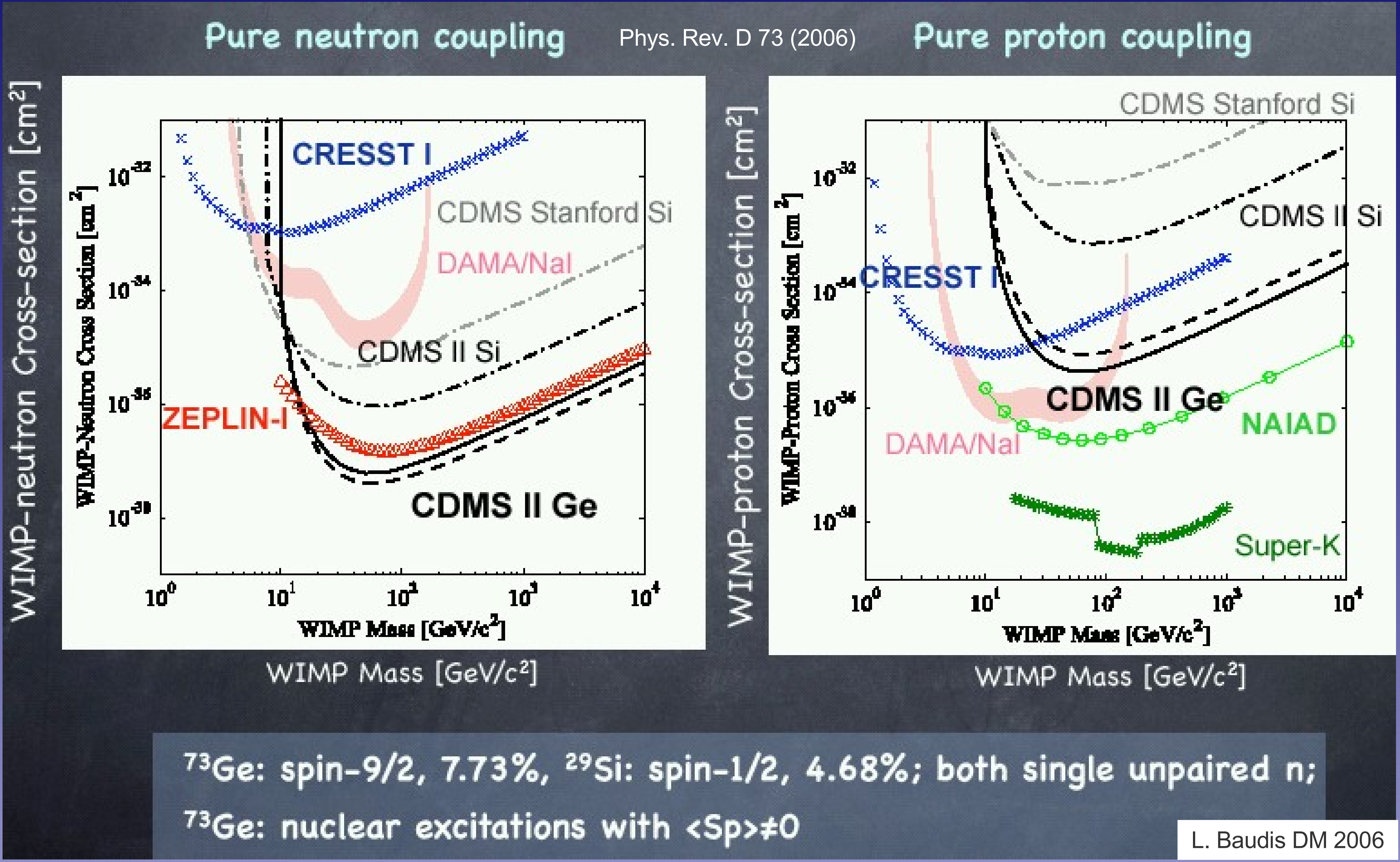
CDMS II – Spin-Dependent Limits



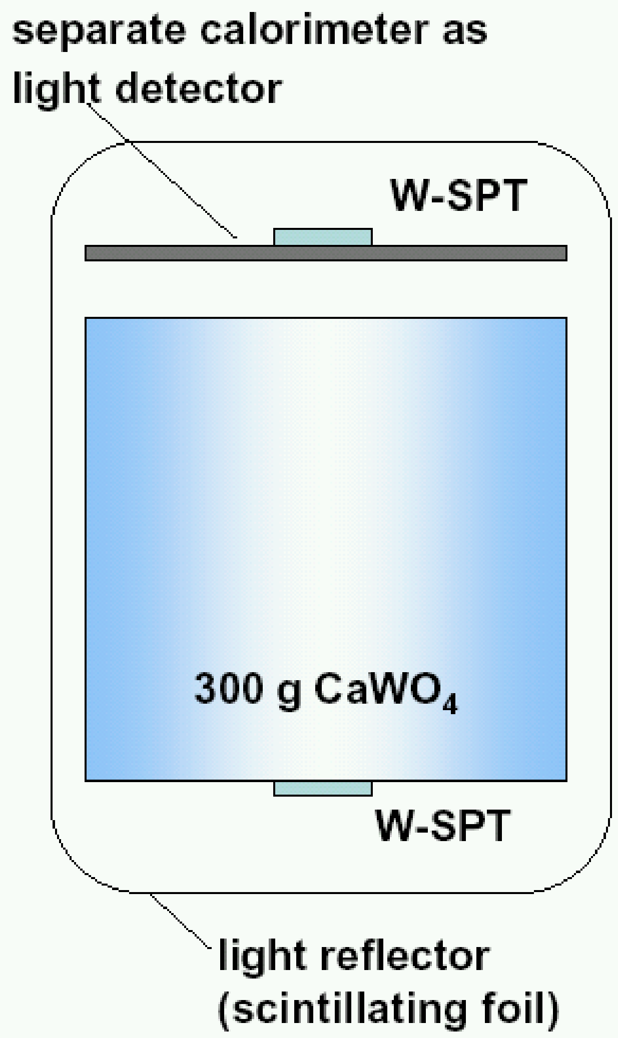
^{73}Ge: spin-9/2, 7.73%, ^{29}Si: spin-1/2, 4.68%; both single unpaired n;

^{73}Ge: nuclear excitations with <Sp>≠0

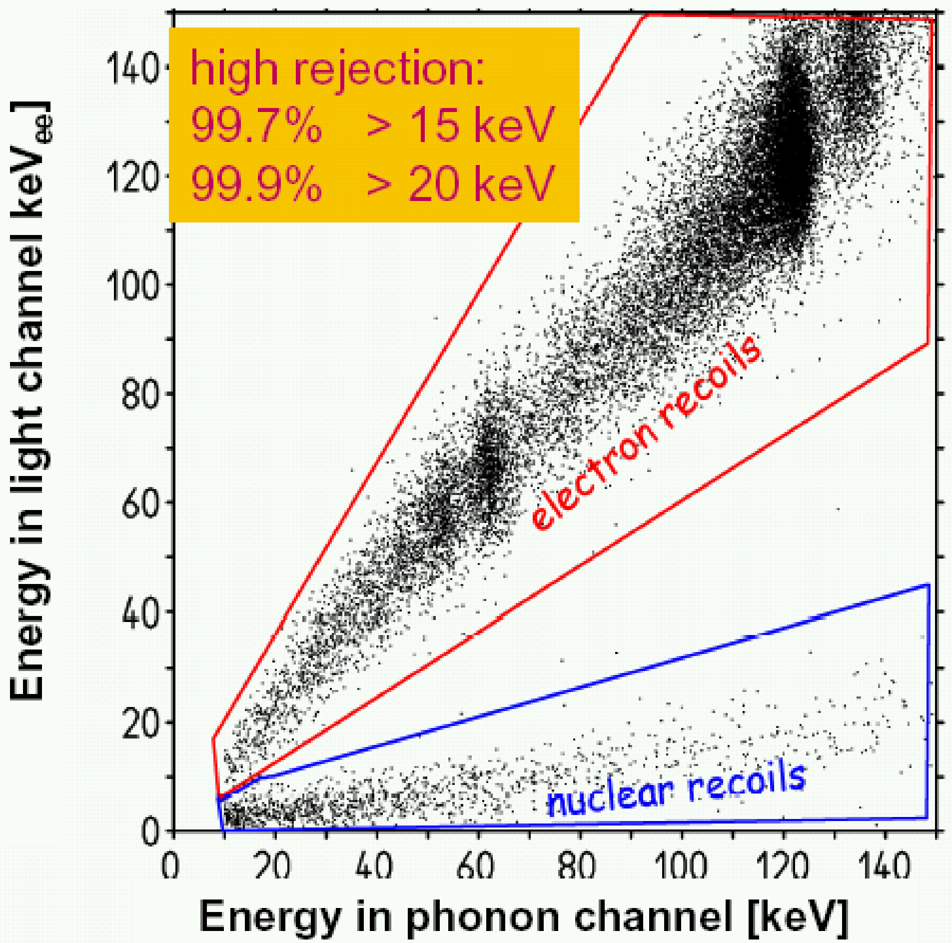
L. Baudis DM 2006

Scintillation & Thermal Phonons
CRESST II

Discrimination of nuclear recoils from radioactive backgrounds (electron recoils) by simultaneous measurement of phonons and scintillation light



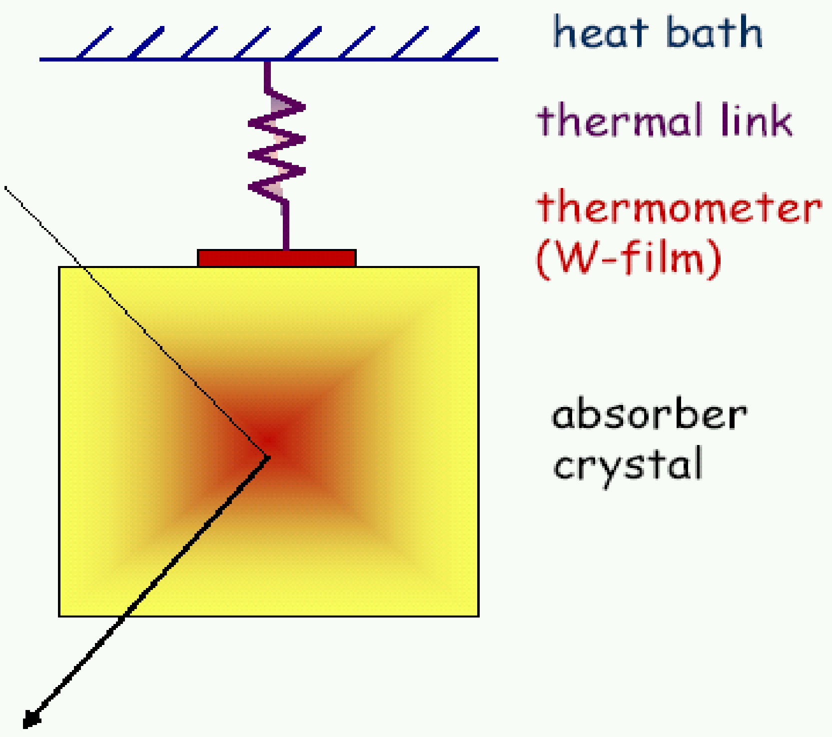
proof of principle



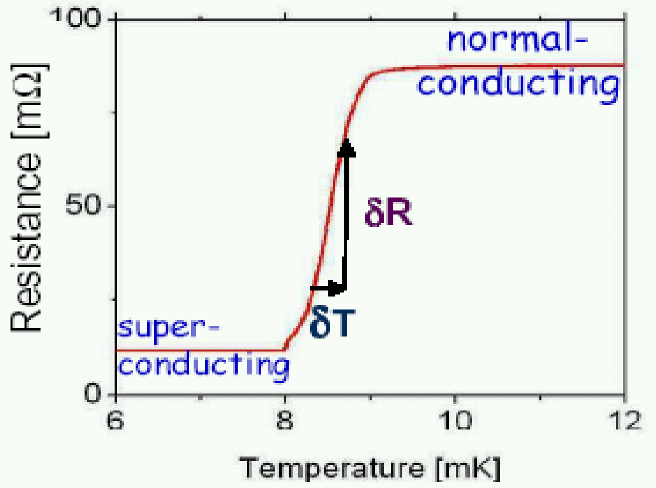
high rejection:
99.7% > 15 keV
99.9% > 20 keV

H. Kraus, DM 2006

Thermal Phonon Measurement CRESST (II)

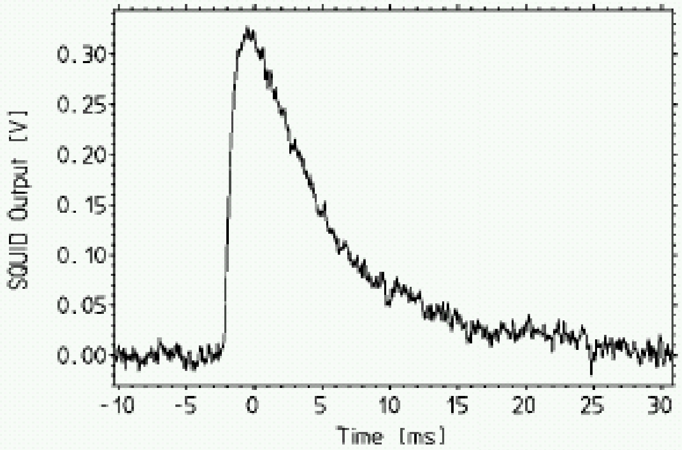


Particle interaction in absorber creates a temperature rise in thermometer which is proportional to energy deposit in absorber



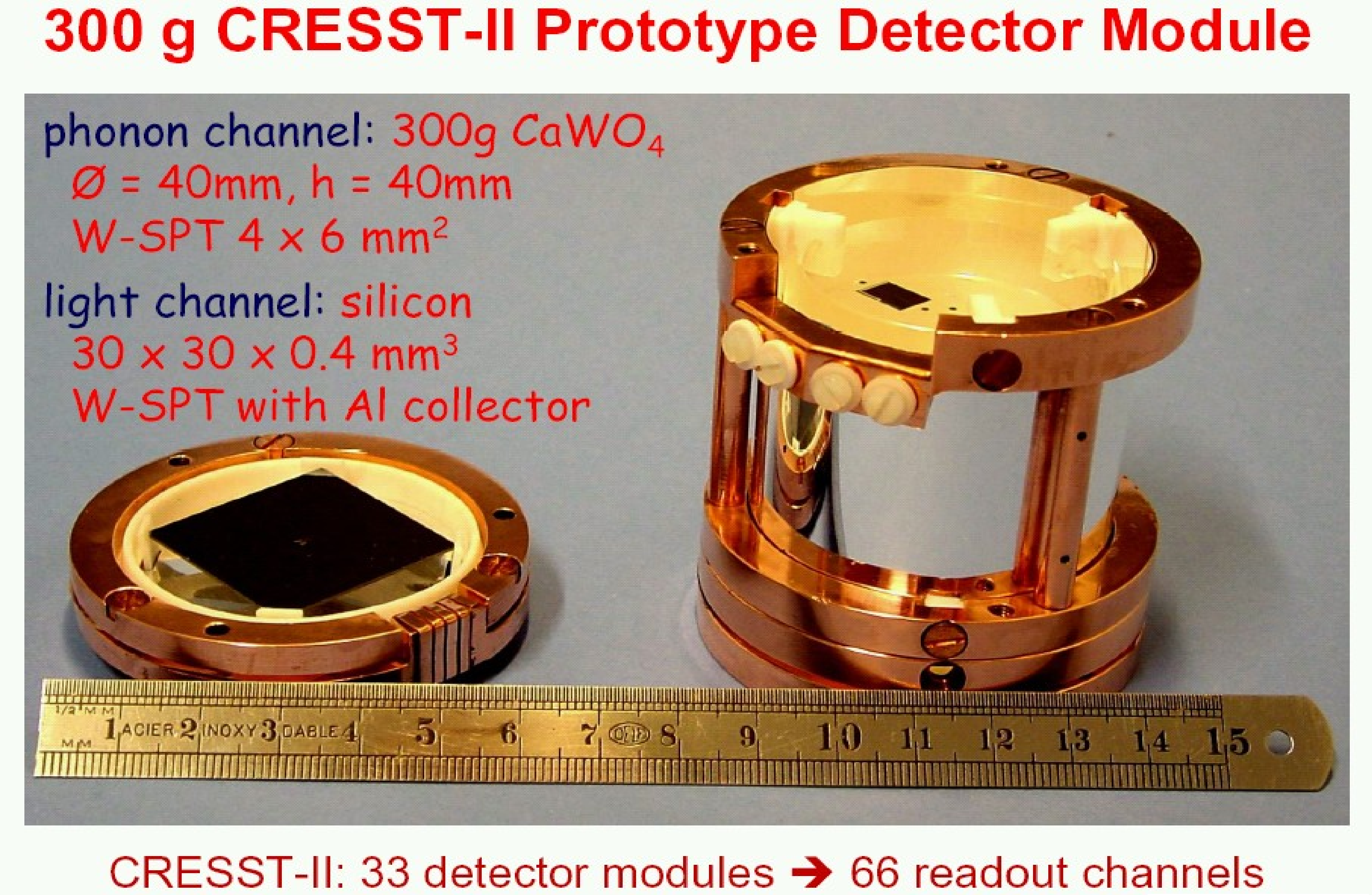
Width of transition: ~1mK
Signals: few μ K
Stablity: ~ μ K

Signal pulse (~6keV)



H. Kraus, DM 2006

CRESST II Prototype



300 g CRESST-II Prototype Detector Module

phonon channel: 300g $CaWO_4$
Ø = 40mm, h = 40mm
W-SPT 4 x 6 mm^2

light channel: silicon
30 x 30 x 0.4 mm^3
W-SPT with Al collector

CRESST-II: 33 detector modules ➔ 66 readout channels

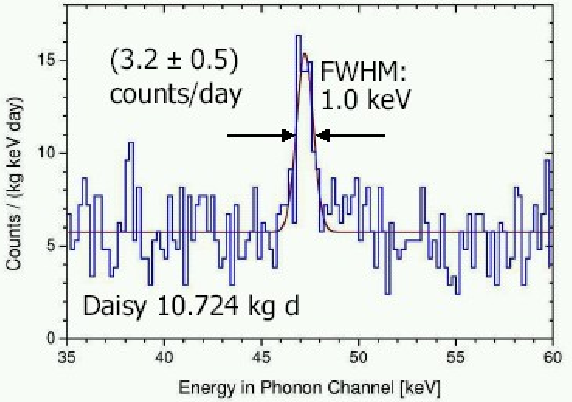
H. Kraus, DM 2006

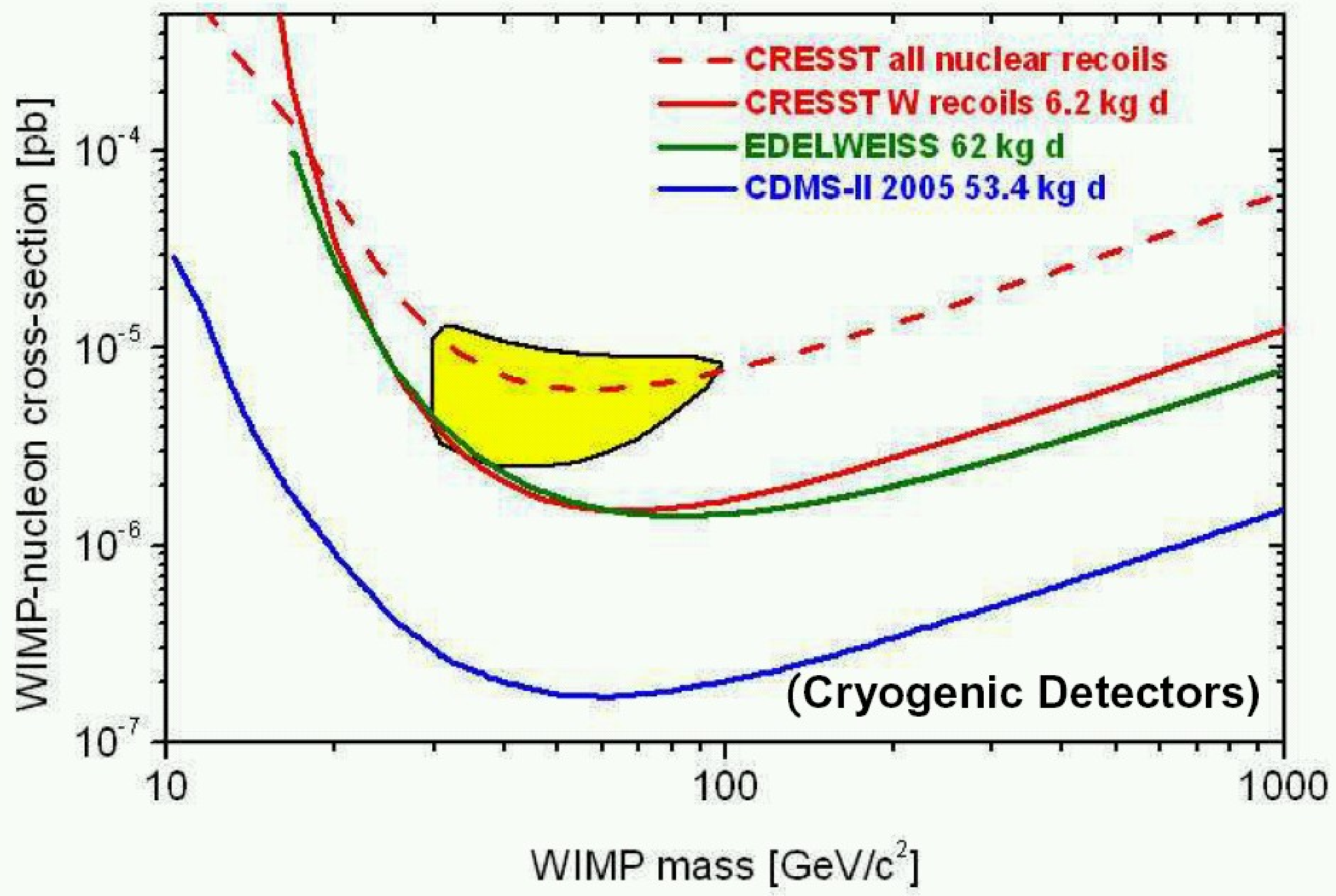
CRESST Performance & Limits

Energy Resolution of Phonon Detector:

γ : 1.0 keV @ 46.5 keV

α : 6.7 keV @ 2.3 MeV

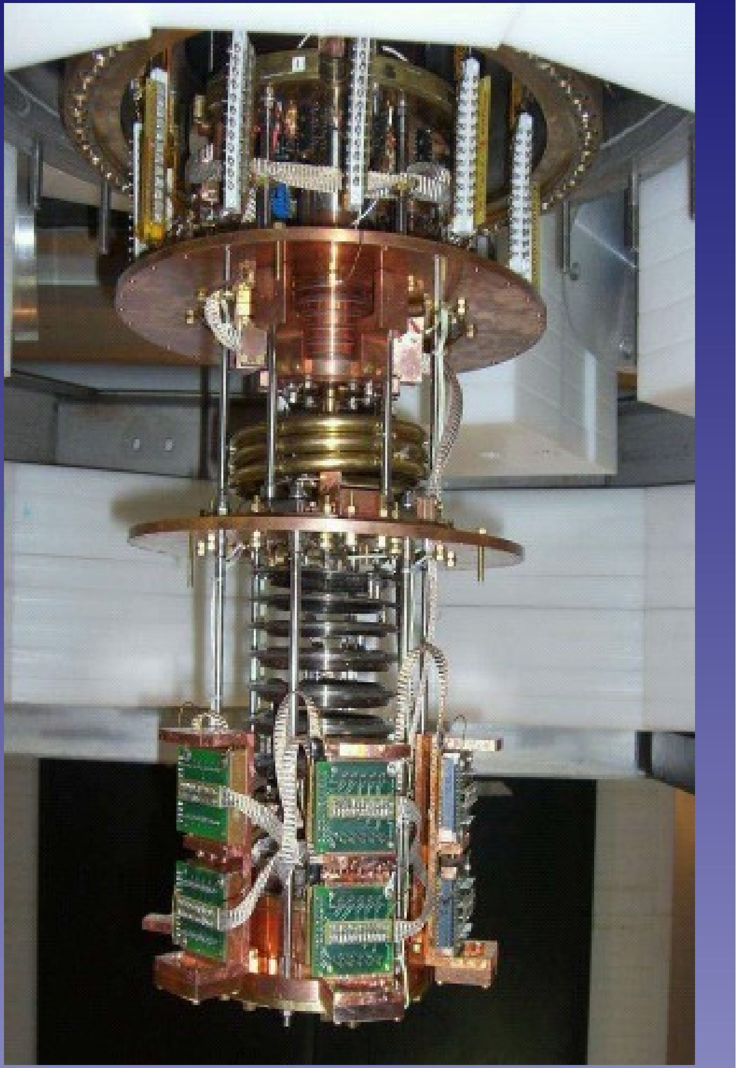




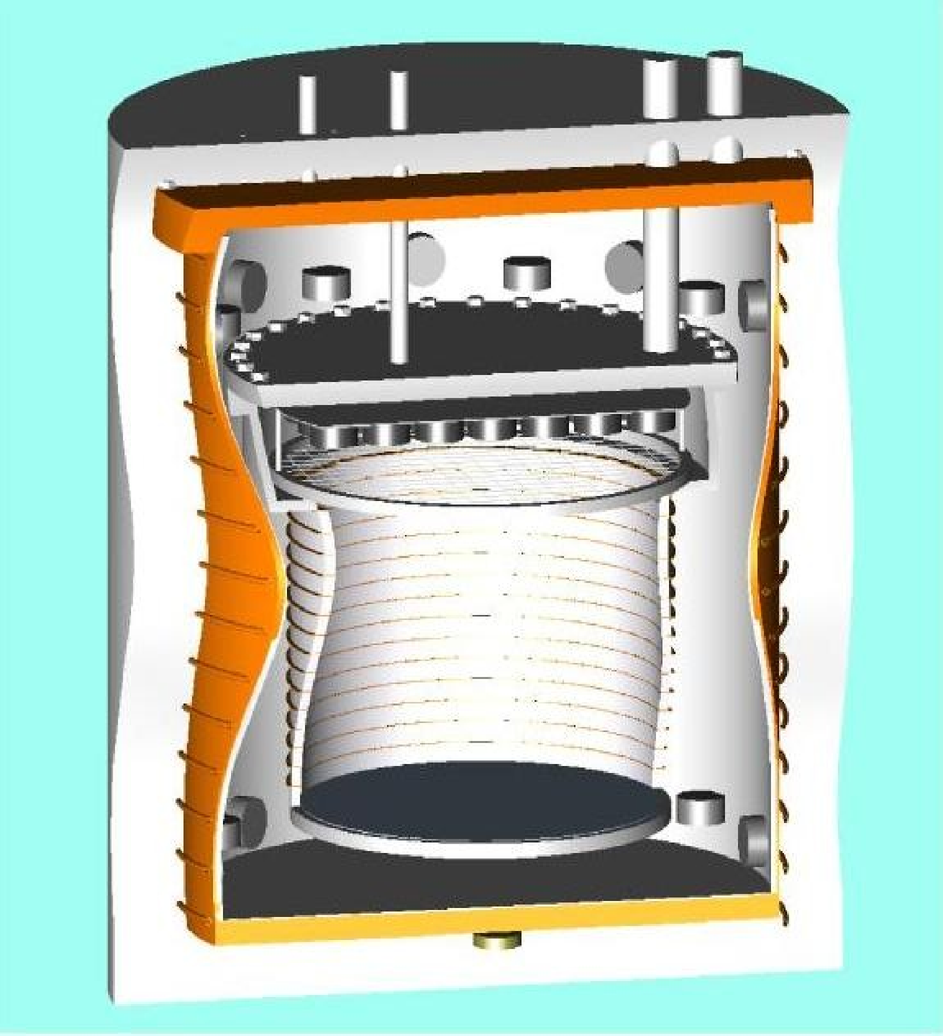
H. Kraus, DM 2006

CRESST II Status

- Two CRESST II prototype detectors have been operated for two months.
- Discrimination threshold (βγ) well below 10 keV.
- Type of recoiling nucleus identified above 12 keV.
- Upgrade to 66 readout channels (10 kg target), installation of neutron shield and muon veto complete.
- Restart in summer 2006.
- CRESST-II is aiming for a sensitvity of ~ 10^{-8} pb (~factor 10 improvement over current limits).



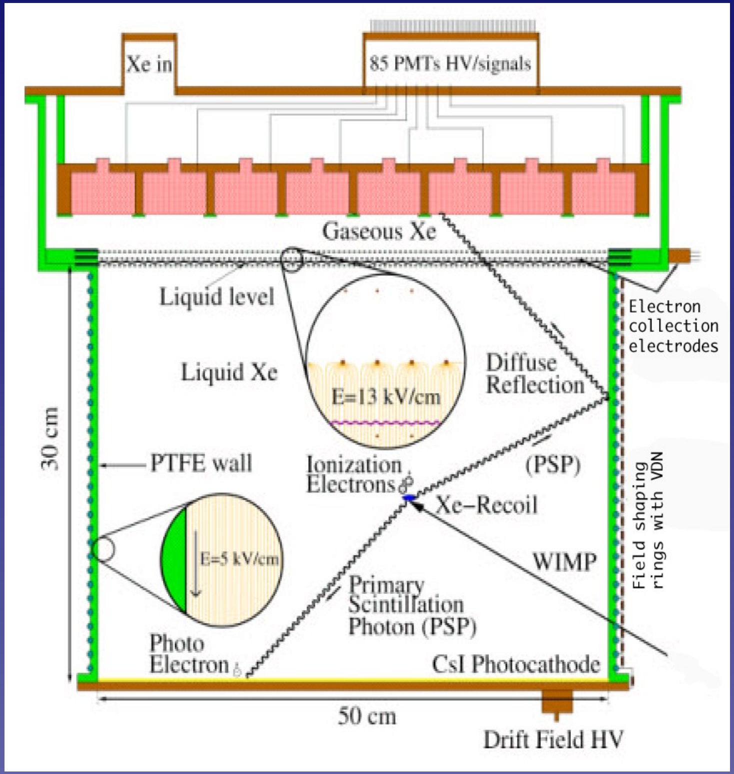
Two-Channel – Ionization & Scintillation LXe – XENON

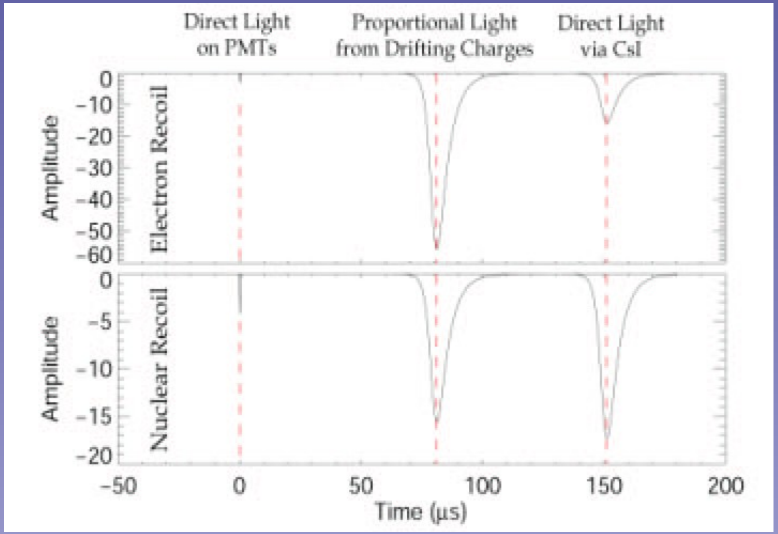


- Goal XENON1T
  1 ton active Xe distributed in an array of ten 3D position sensitive dual-phase (liquid/gas) XeTPCs, actively shielded by a LXe veto.
- Simultaneous detection of ionization and scintillation for event-by-event discrimination of nuclear recoils from electron recoils (>99.5%) down to 16 keVr.
- XENON funded by NSF and DOE.
- Roadmap:
  - R&D started 2001
  - XENON-3 lab. prototype 2005
  - XENON-10 first DM detector now
  - XENON-100 design later in 2006

XENON: A TPC for Dark Matter Search

- Wimp interaction in dense liquid volume (~3 g/cm^3).
- Detection of primary scintillation light (S1) with PMTs.
  (Option being studied: CsI).
- Extraction of charges in gas phase at ~10 kV/cm.
- Proportional scintillation converts charge signal in strong light signal (S2).
- 3D position measurement:
  - X/Y: from S2 signal, resolution O(few mm).
  - Z: from electron drift time (<~1 mm).





XENON R&D: Ionization and Scintillation Yields from Nuclear Recoils in LXe

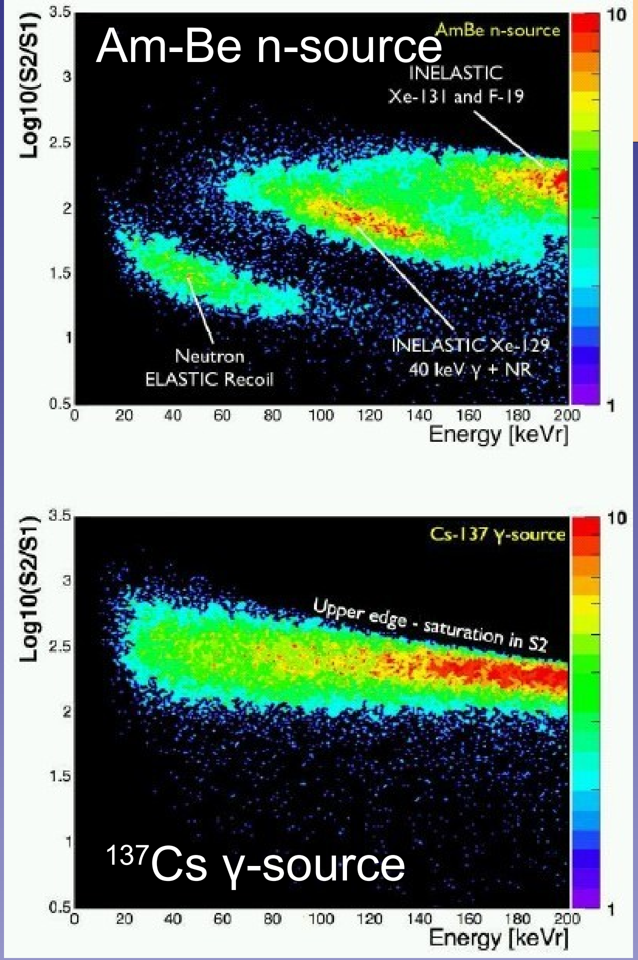
- Relative scintillation and ionization efficiency for nuclear recoils compared to other interactions:

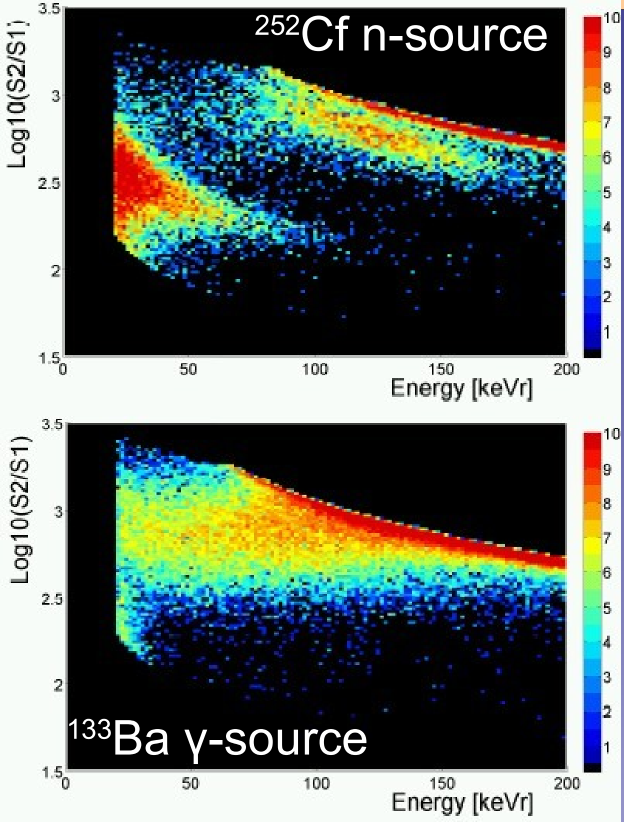
$E_r = E_e / L_{eff} \cdot S_e / S_r$

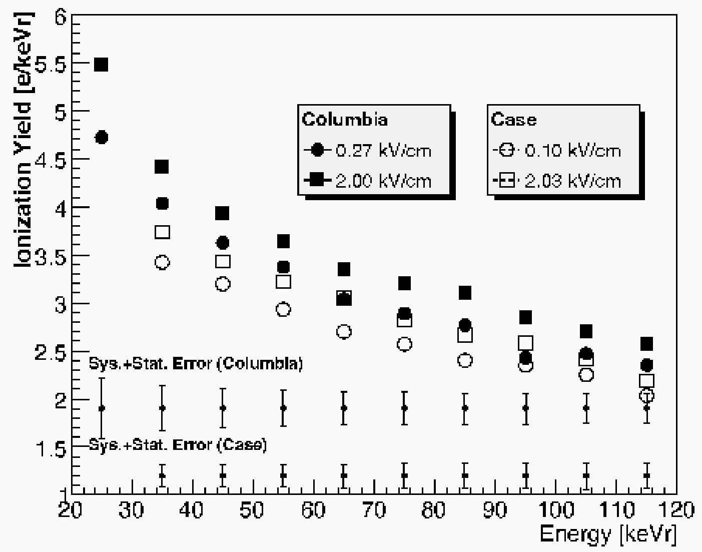
E_e: linear electron recoil scale

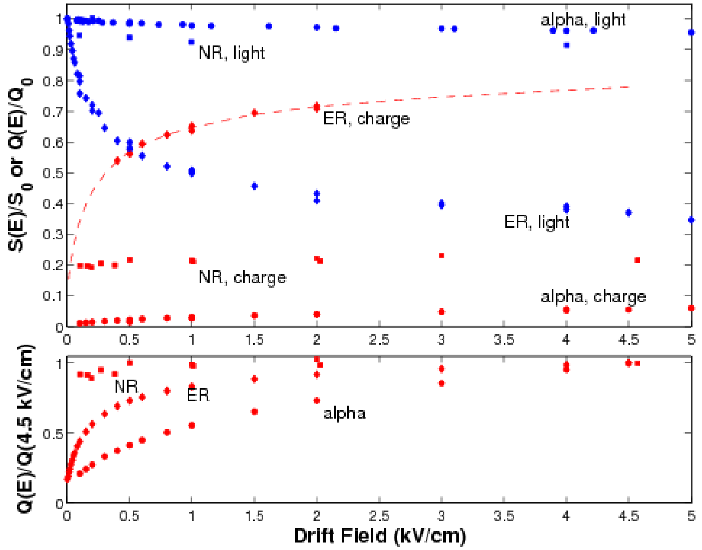
L_{eff}: effective Lindhard factor (zero field)

$S_x(|\vec{E}|)$: scintillation loss due to recombination suppression





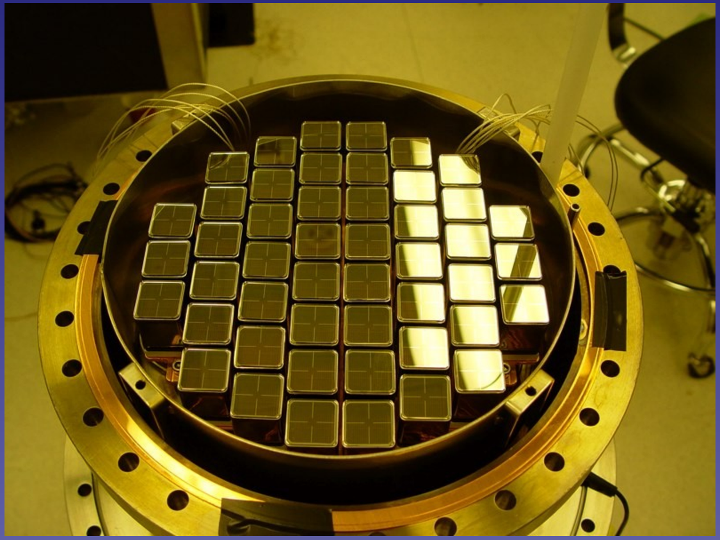


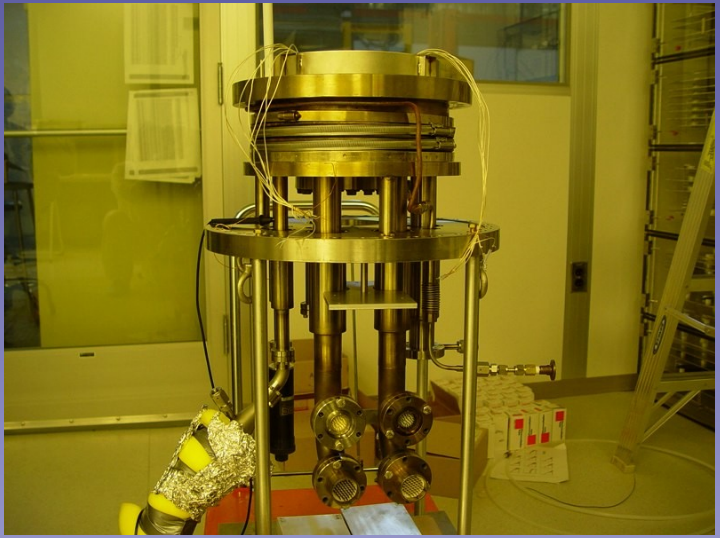


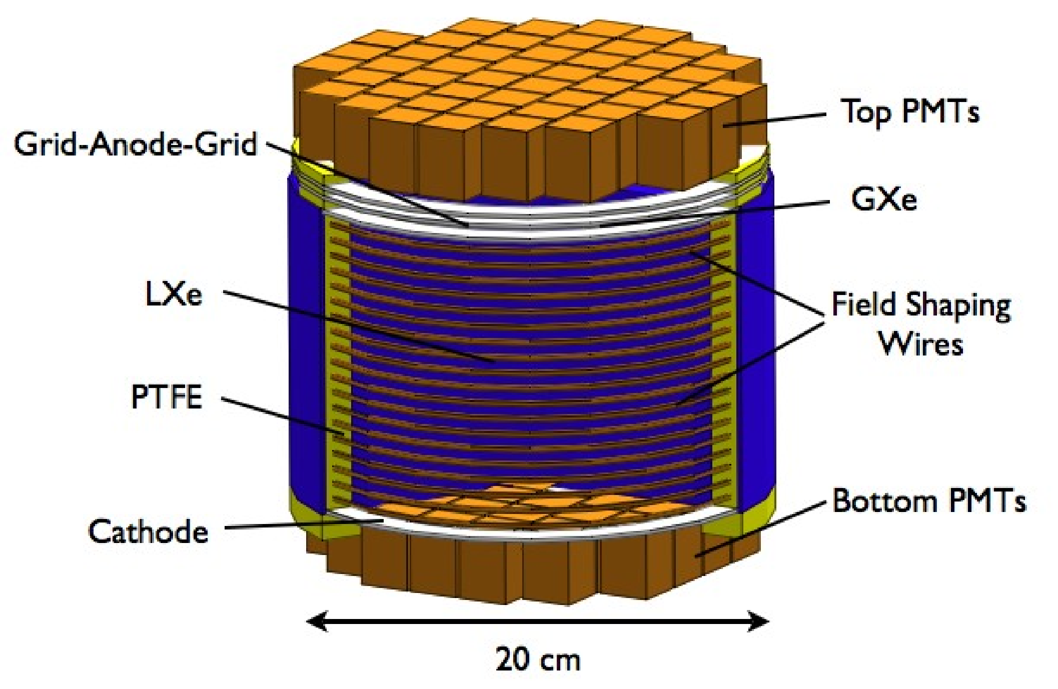
Aprile et al. 2006, astro-ph/0601552

XENON-10 Detector now at LNGS

- XENON10 now installed and being tested at LNGS (Gran Sasso, Italy)
- Expect first DM search run June – August 2006



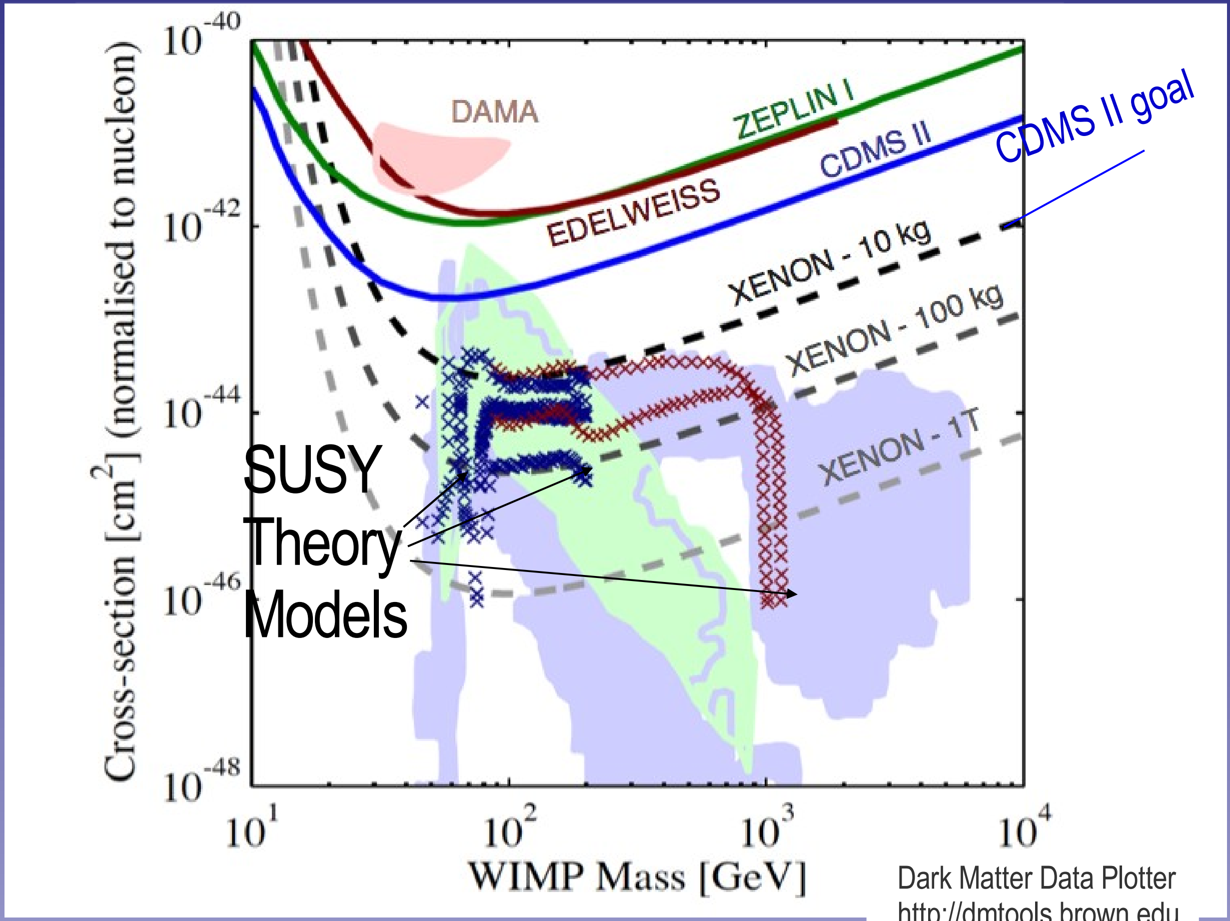




- 48 PMTs on top, 41 on bottom inside LXe
- 20 cm diameter, 15 cm drift length
- 14 kg LXe

Dark Matter Existing Limits and Goals

XENON10 - Sensitivity curve corresponds to ~2 dm evts /10 kg / month
Equivalent CDMSII Goal for mass >100 GeV
(Latest 2005 CDMSII result is x10 above this level)
With only 30 live-days x 10 kg fiducial - Zero events - would reach XENON10 sensitivity goal (90% CL), but we would like to do physics!
XENON100 ~2 dm evts / 100 kg / month
XENON1T ~1 dm evts / 1 ton / month

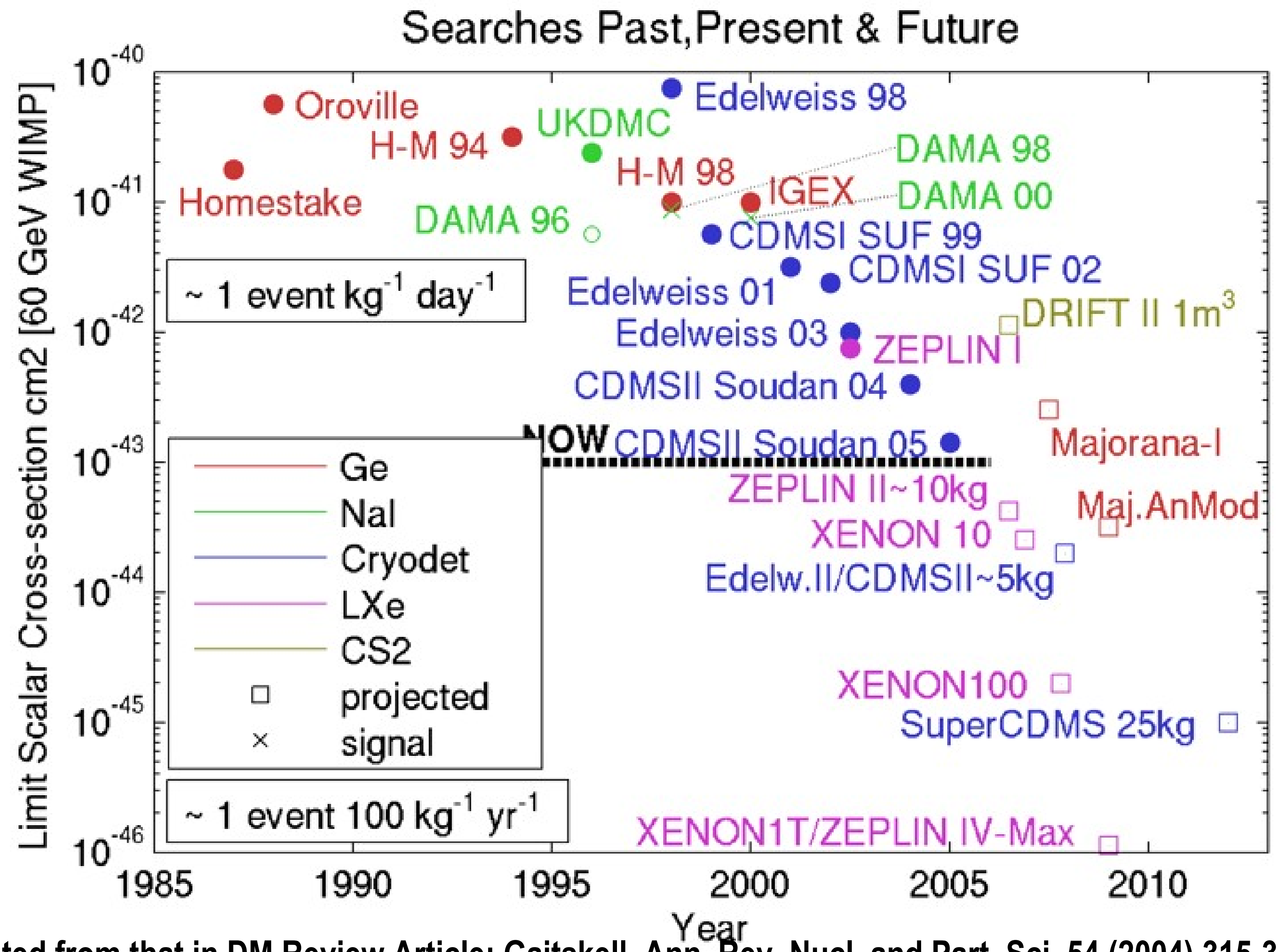


Dark Matter Data Plotter
http://dmtools.brown.edu

SOME SUSY MODELS

- [blue] T. Baltz and P. Gondolo, Markov Chain Monte Carlos. JHEP 0410 (2004) 052, (hep-ph/0407039)
- [green] J. Ellis et al. CMSSM, Phys.Rev. D71 (2005) 095007, (hep-ph/0502001)
- [red crosses] G.F. Guidice and A. Romanino, Nucl.Phys. B699 (2004) 65; Erratum-ibid. B706 (2005) 65, (hep-ph/0406088)
- [blue crosses] A. Pierce, Finely Tuned MSSM, Phys.Rev. D70 (2004) 075006, (hep-ph/0406144)

DM Direct Search Progress Over Time (2006)



Plot updated from that in DM Review Article: Gaitskell, Ann. Rev. Nucl. and Part. Sci. 54 (2004) 315-359

Summary & Outlook

- A vigorous experimental effort is producing improvements in direct DM search at a rapid pace.
- New technologies have been developed and detectors are coming online.
- New detectors comprise various different technologies with presumably different systematics – good cross-checks to be expected.
- Scalability of liquid noble detectors promises possible ton-scale detectors ~ by the end of the decade.
- Timeline of new DM direct search detectors is compatible with LHC (2007), and indirect searches e.g. by GLAST (2007).
- *Exciting times in DM search – stay tuned!*

BACKUP SLIDES

How to Detect DM
DM Creation with Accelerators

Two Channel - Ionization & Phonons
Edelweiss

Two Channel – Ionization & Scintillation LAr - WARP

Two-Channel – Ionization & Scintillation LXe – ZEPLIN II

Two-Channel – Ionization & Scintillation LXe – ZEPLIN III