The quest for dark matter

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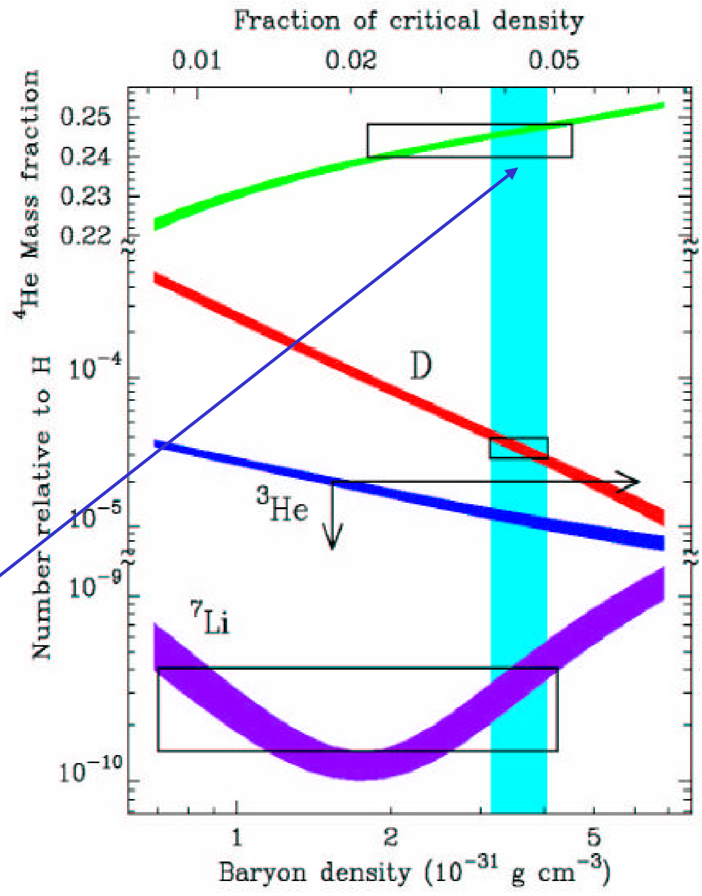
Summary

- One of the most exciting cosmological results is the now solid experimental evidence of a cosmic concordance, $\Omega_o = 1.02 \pm 0.02$ of a mixture of about 2:1 between dark energy and matter,
- These results are to be compared with the also firmly established Big Bang Nucleo Synthesis, $\Omega_{BBN} = 0.044 \pm 0.004$, i.e. ordinary hadronic matter is only a few % of Ω_o.
- There is therefore strong, direct cosmological support for a so-far unknown non hadronic matter $\Omega_M - \Omega_{BNN} \tilde{} \; 0.226 \pm 0.06$
- The experimental detection in the laboratory of a such new form of dark matter is an extremely exciting programme.
- Demonstrating experimentally in the laboratory that the dominant matter of the Universe is not the one of which we are made of will be a result of immense significance.

Ordinary matter from BB Nucleo-Synthesis (baryons)

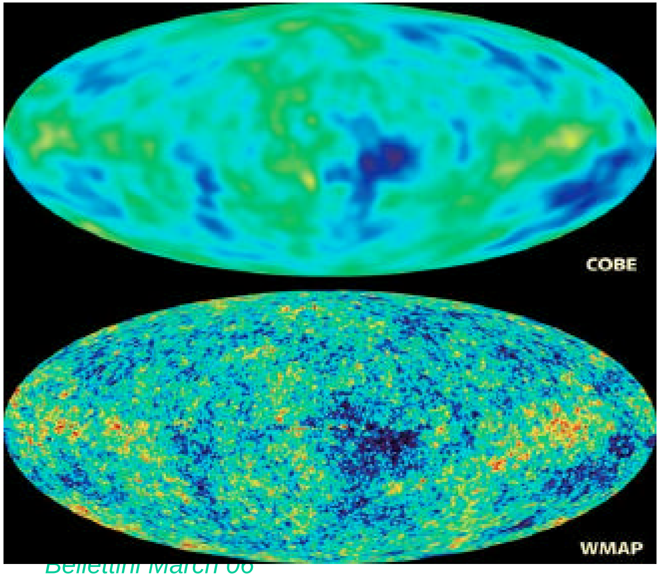
- Big-Bang Nucleosynthesis depends sensitively on the baryon/photon ratio,
- Since we know how many photons there are, we can constrain the baryon density.
- [Burles, Nollett & Turner]

$\Omega_{BBN} = 0.044 \pm 0.004$

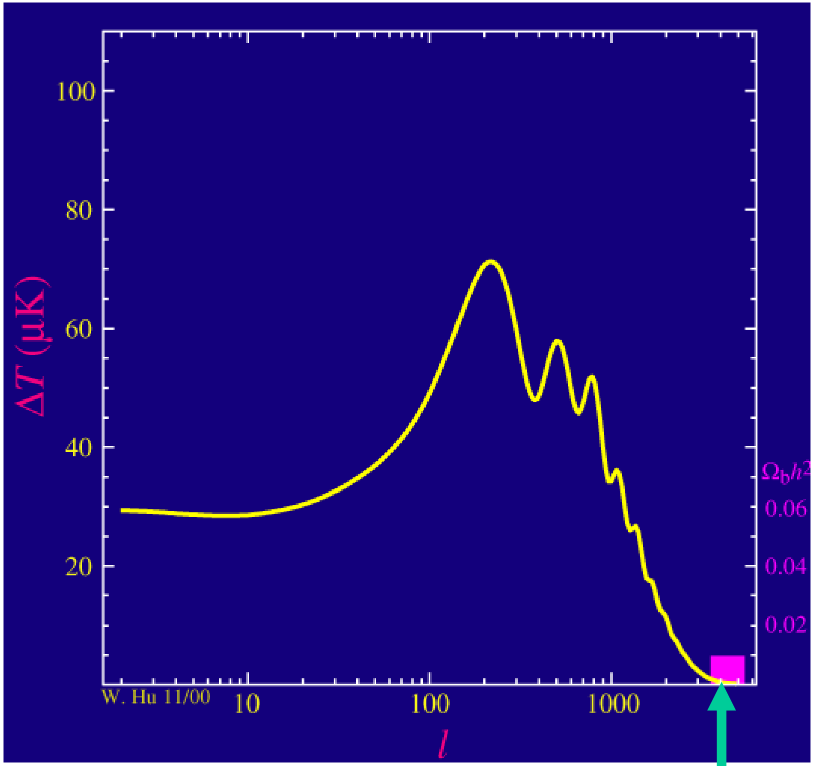


Baryons in the WMASS Power Spectrum

- The odd numbered acoustic peaks in the power spectrum are enhanced in amplitude over the even numbered ones as we increase the baryon density of the universe.



Baryon Density: $\Omega_b h^2 = 0.024 \pm 0.001$

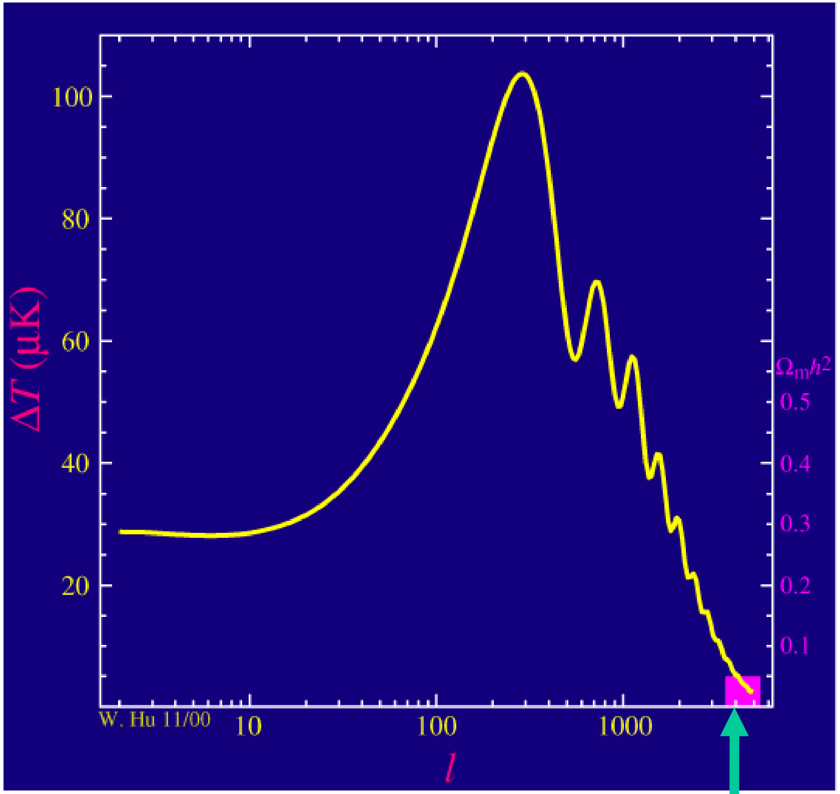


Baryon density

Overall Matter in the WMASS Power Spectrum

Matter Density : $\Omega_m h^2 = 0.14 \pm 0.02$

- Raising the overall matter density reduces the overall amplitude of the peaks
- Lowering the overall matter density eliminates the baryon loading effect so that a high third peak is an indication of dark matter.
- With three peaks, its effects are distinct from the one due to baryons



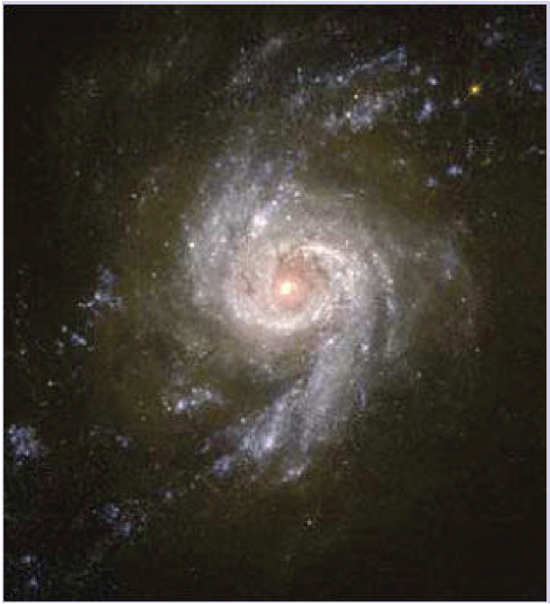
Matter density

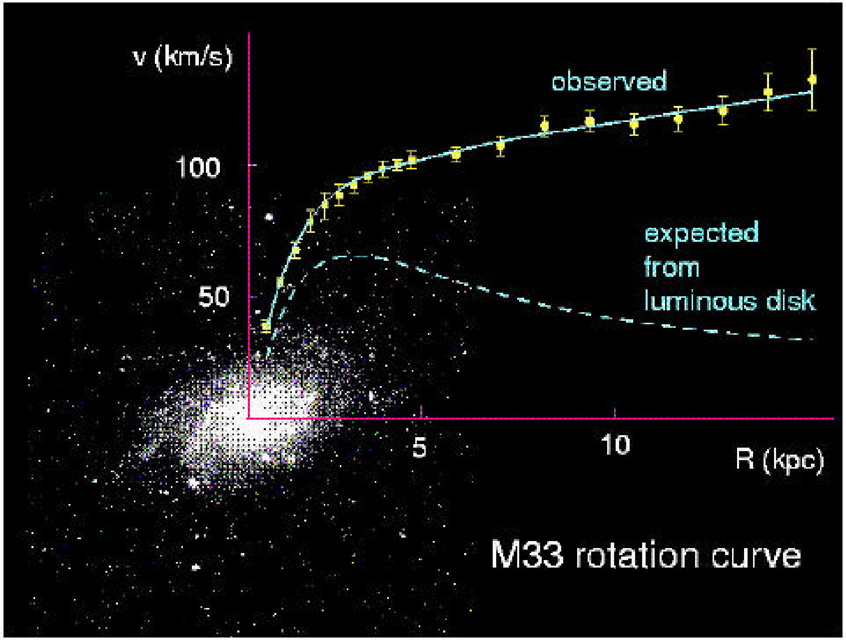
WMASS results

Parameter	Value
Baryon Density	$\Omega_b h^2 = 0.024 \pm 0.001$
Matter Density	$\Omega_m h^2 = 0.14 \pm 0.02$
Hubble Constant	$h = 0.72 \pm 0.05$
Baryon Density/Critical Density	$\Omega_b = 0.044 \pm 0.004$
Matter Density/Critical Density	$\Omega_m = 0.27 \pm 0.04$
Age of the Universe	$t_o = 13.7 \pm 0.2$

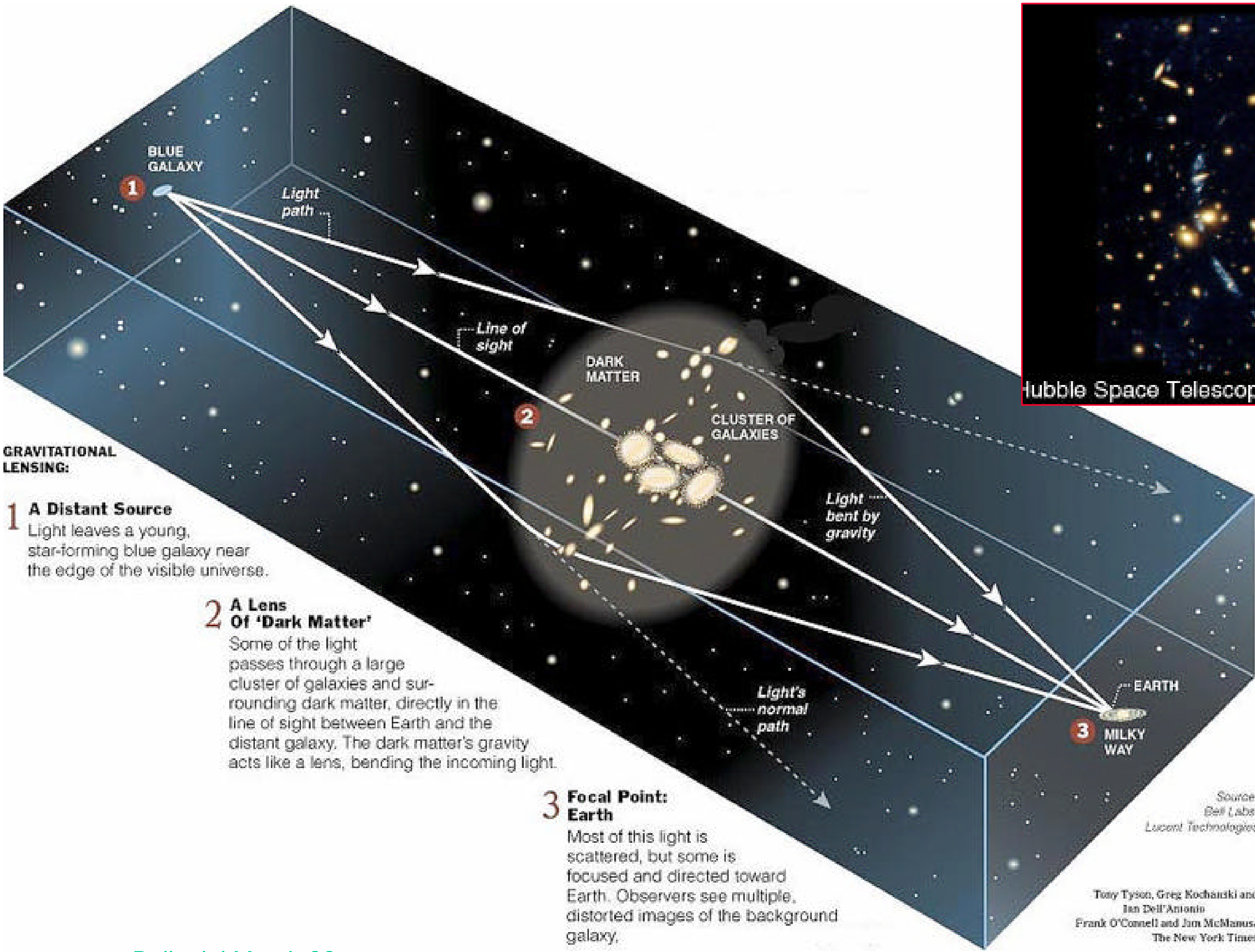
Galactic rotation curves

- Doppler measurements in spiral galaxies.
  - Observe: v(r)
  - if v is constant, then: M ~ r
  - Needs "dark matter"



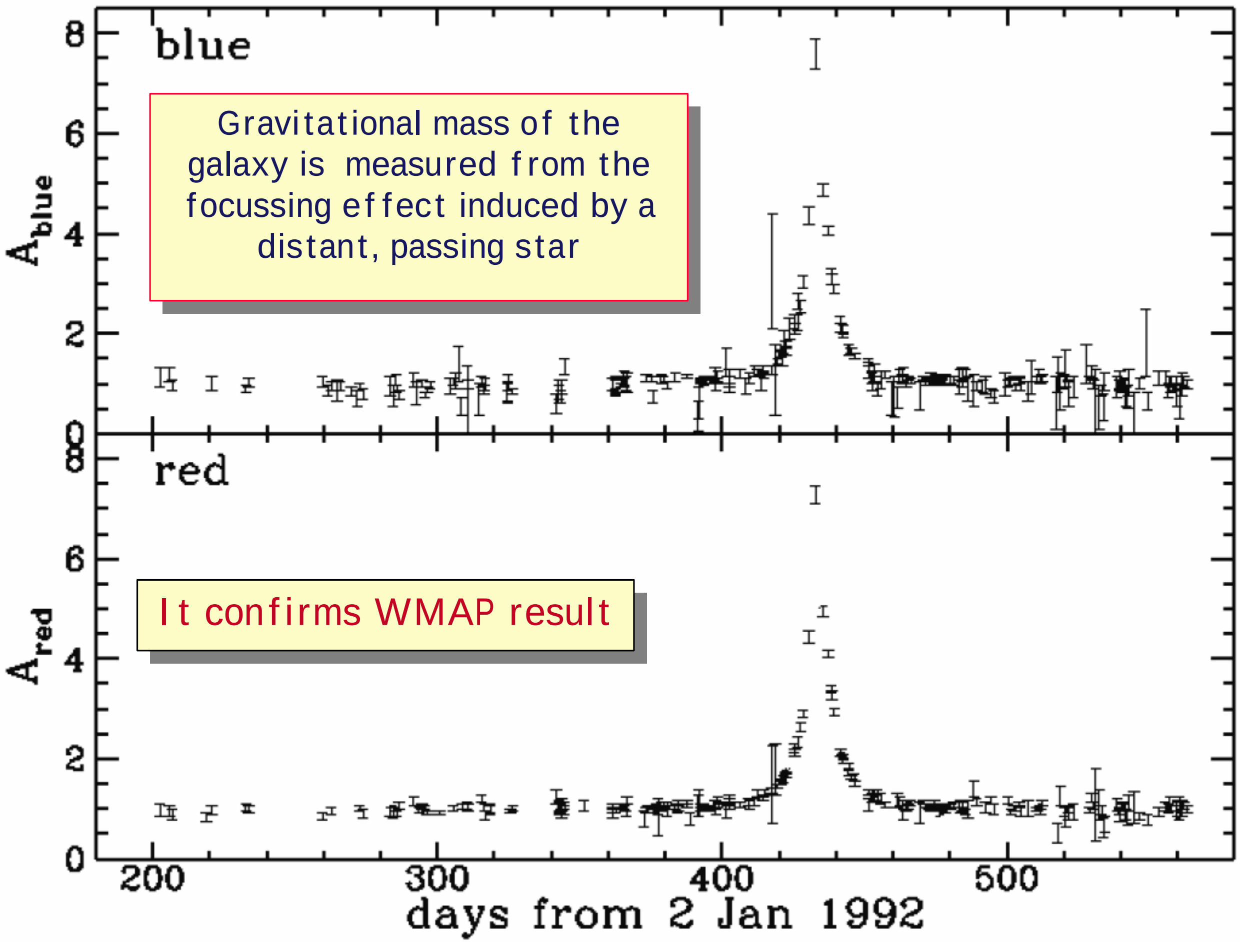


Gravitational Lensing



Hubble Space Telescope image of a cluster of galaxies.

Gravitational lensing



Gravitational mass of the galaxy is measured from the focussing effect induced by a distant, passing star

It confirms WMAP result

Open questions

- Matter: 27%, of which: Baryons: < 5%, Neutrinos: <0.5%
- Energy: 73%

- Dark energy and dark matter have both a common origin or are they two completely unrelated phenomena ?
- Is each of them describable as classical (gravitational) or as quantum mechanical phenomenon ?
- Cold dark matter is well detected gravitationally: *but does it have other interactions, in particular an electro-weak coupling to ordinary matter?*
- If it has electro-weak properties, how can it be so (very) massive and so stable as to have *survived without decay for at least 13.7 billion years* ?

Ω_Λ ? 0: a huge Pandora box

- The energy density Λ is not larger than the critical cosmological density Ω_o ˜ 1, and thus *incredibly small by particle physics standards*.
- This is a profound mystery, since we expect that all sorts of *vacuum energies* contribute to the effective cosmological constant. In particular the quantum aspects are very serious, since they predict invariably values for Λ-term which are up to very *many tens of order of magnitude* larger than the experimental value. How can we reconcile such huge difference ?
- A second puzzle: since vacuum energy constitutes the missing 2/3 of the *present* Universe, we are confronted with a *cosmic coincidence problem*.
- The vacuum energy density is constant in time, while the matter density decreases as the Universe expands. It would surprising that the two would be comparable just at about the present time, while their ratio was tiny in the early Universe and would become very large in the future.

Origin of dark matter

- This has been the Wild, Wild West of particle physics: *axions, warm gravitinos, neutralinos, Kaluza-Klein particles, Q balls, wimpzillas, superWIMPs, self-interacting particles, self-annihilating particles, fuzzy dark matter,...*
- Masses and interaction strengths span many orders of magnitude, but in all cases we expect new particles with electroweak symmetry breaking,
- Particle physics provides an attractive solution to CDM: long lived or stable neutral particles:
  - Neutrino (but mass ~ 30 eV !)
  - Axion (mass ~ 10^{-5} eV)
  - SUSY Neutralino (mass > 50 GeV)
- Axion and SUSY neutralino are the most promising particle dark matter candidates, but they both await to be discovered !

Standard Model and beyond

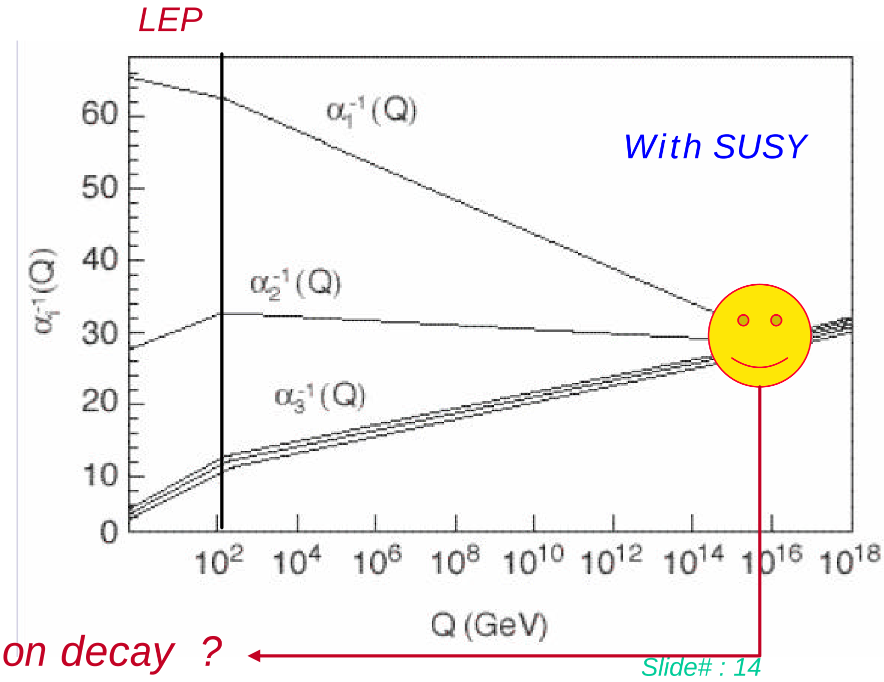
- Some of the most relevant questions for the future of Elementary particles are related to the completion of the Standard model and of its extensions.
- Central to the Standard Model is the experimental search of the Higgs boson, for which a very strong circumstantial evidence for a relatively low mass comes from the remarkable findings of LEP and of SLAC.
- However the shear experimental existence of an Higgs particle has very profound consequences, *provided it is truly elementary*.
- [We remark that in other scenarios the Higgs may rather be "composite", requiring however some kind of new particles]
- Indeed, in the case of an elementary Higgs, while fermion masses are "protected", the Higgs causes *quadratically divergent effects due to higher order corrections.*
- This would move its physical mass near to the presumed limit of validity of quantum mechanics, well above the range of any conceivable collider.

Cancellations ?

- In order to "protect" the Higgs mass, we may assume an extremely precise *graph cancellation* in order to compensate for the residual divergence of the "known" fermions.
- SUSY is indeed capable of ensuring such a cancellation, provided that for each and every ordinary particle, a SUSY partner is present compensating each other.

- An observation of a low physical mass of Higgs particle may imply that the mass range of the SUSY partners must be not too far away.

Running coupling constants are modified above SUSY threshold, and the three main interactions converge to a common Grand Unified Theory at about 10^{16} GeV

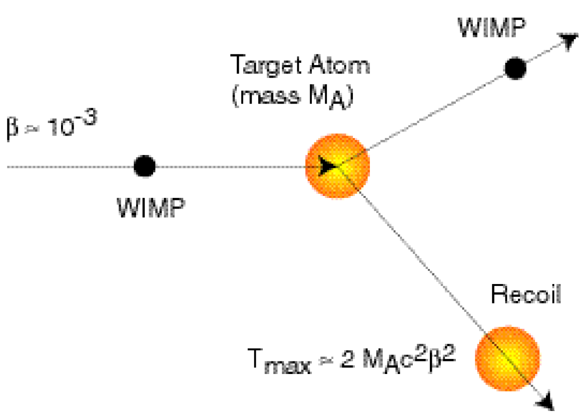


SUSY also as the source of non-baryonic matter ?

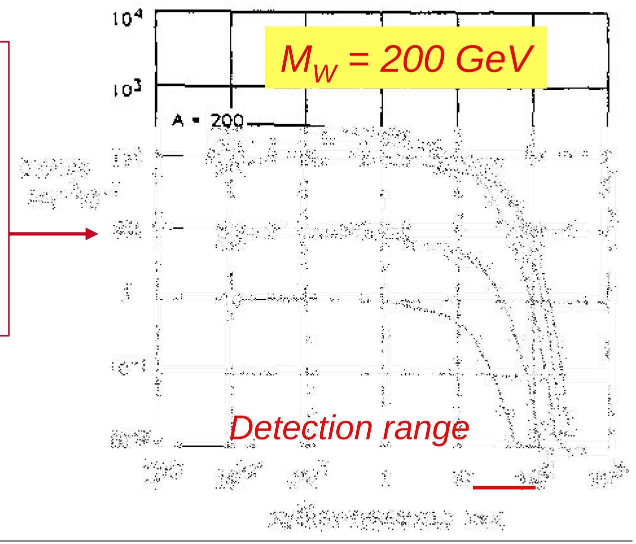
- A discovery of a “low mass” *elementary* Higgs may become an important hint to the existence of an extremely rich realm of new physics, *a real blessing for colliders*.
- Such a doubling of known elementary particles, will be a result of gigantic magnitude.
- However in order to be also the origin of dark mass, the lowest lying neutral SUSY particle must be able to survive the 13.7 billion years of the Universe The lifetime of an otherwise fully “permitted” SUSY particle decay is typically ~10^{-18} sec !
- We need to postulate some strictly conserved quantum number (R-symmetry) capable of an almost absolute conservation, with a forbidness factor well in excess of $4x10^{+17} / 10^{-18} = 4x10^{35}$!!!
- The relation between dark matter and SUSY matter is far from being immediate: however the fact that such SUSY particles may also eventually account for the non baryonic dark matter is therefore either *a big coincidence or a big hint*.

Direct relic DM detection underground

- *Lest we become overconfident, we should remember that nature has many options for particle generated dark matter, some of which less rich, but also less "wasteful" than with SUSY.*
- Therefore in parallel with the searches for new particles with colliders, a search for relic decays of non-baryonic origin is an important, complementary task which must be *carried out in parallel with LHC*.
- The overwhelming argument to pursue a search for dark matter should be the assumption that dark matter has indeed *electro-weak couplings with ordinary matter* (it behaves like a heavy neutrino).

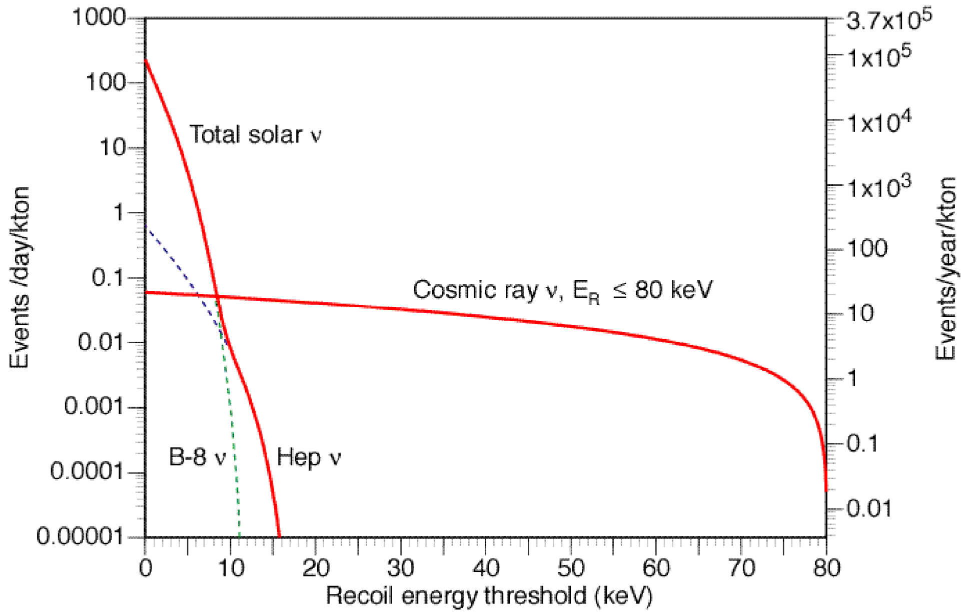


Coherent neutrino-like Xsect, is taken for purpose of illustration



Main backgrounds

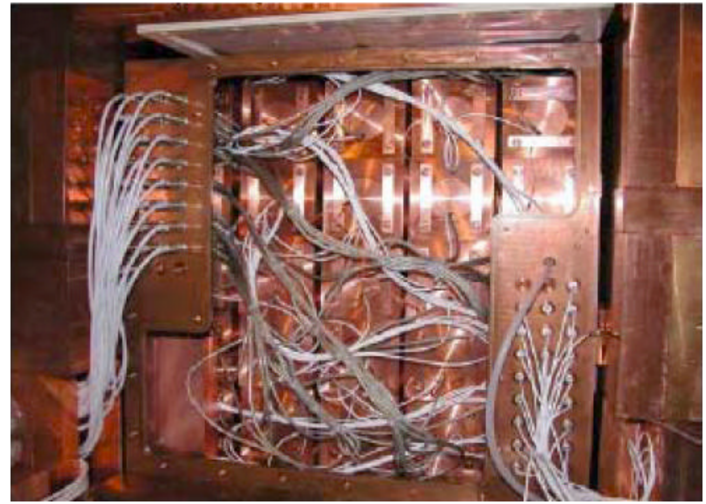
- The flux from DM is known, once we assume we know its elementary mass. It is typically of the order of 10^6 p/cm^2/s.
- Although very large, it is negligibly small compared to solar neutrinos which are 10^{12} p/cm^2/s.
- NC induced nuclear recoils due to neutrinos produce an irreducible background.
- The more abundant CC events are removed by the signature of the detector.
- ν-background leaves open a wide window for a WIMP search

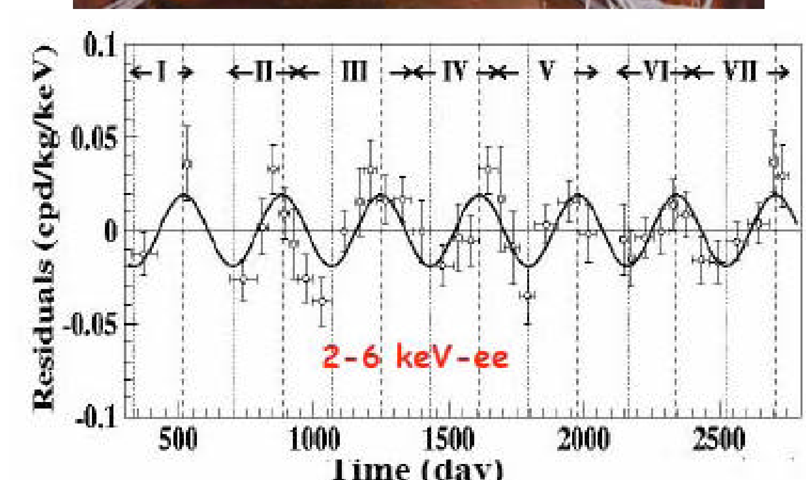


- The main background to fight against is due *to residual neutrons* which may mimic a WIMP recoil signal (active shielding and WIMP directionality)

The DAMA Experiment

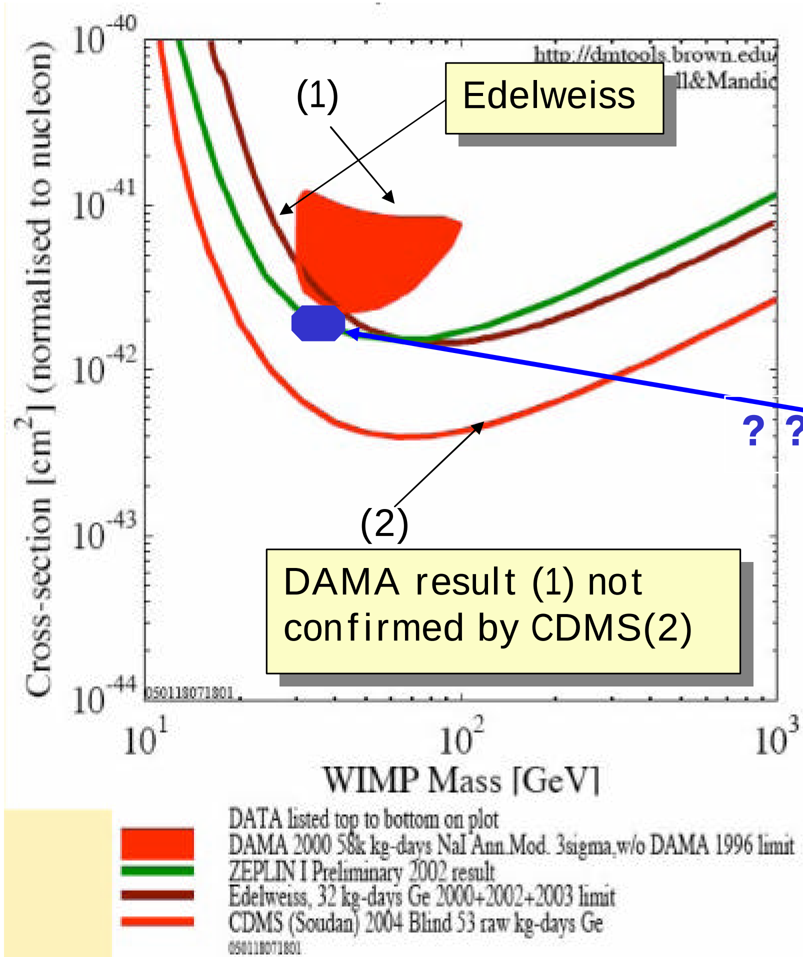
- The experiment has been running since 1996
- Located at Gran Sasso (3.8 km w.e.). Made of low activity NaI scintillators (9 x 9.7 kg), expecting a modulation of ~ 2% in absence of background.
- Claimed a model independent evidence for WIMP in the galactic halo.
- Parameters are M ~ (52^{+10}_{-8}) GeV, $\sigma_{\chi\text{-}p} = (7.2 \pm 0.4) \times 10^{-6}$ pb
- Analysis is perhaps opaque (raw spectrum, cuts, calibrations)
- Total exposure 1.07×10^5 kg day

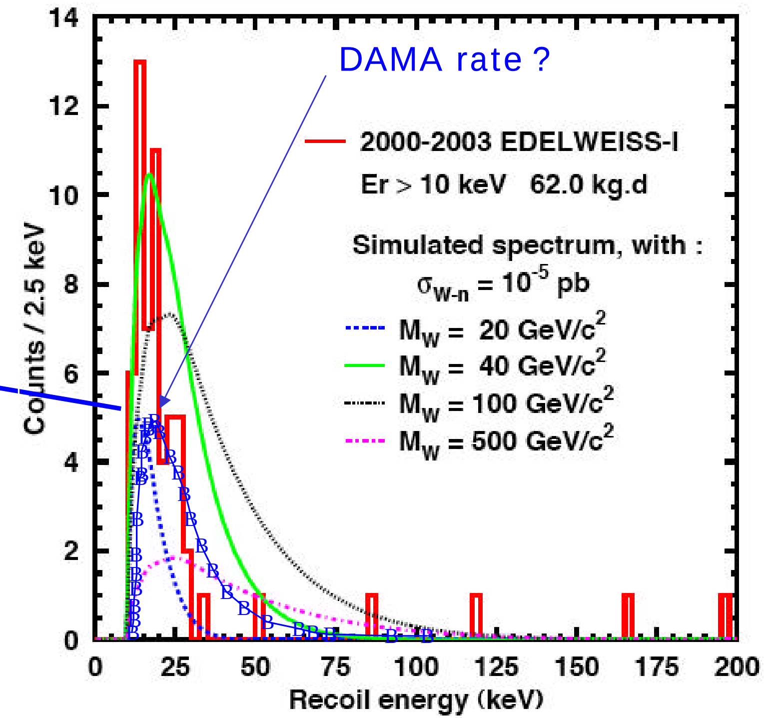




Yearly time variation: ± 0.02 ev/kg/keV day; ~ 0.1 ev/kg day

Experimental results





Unknown effect, probably neutrons, occurring with a spectrum not widely different from the one predicted by a WIMP cross section of about 5×10^{-6} pb (DAMA like)

First Runs at Soudan

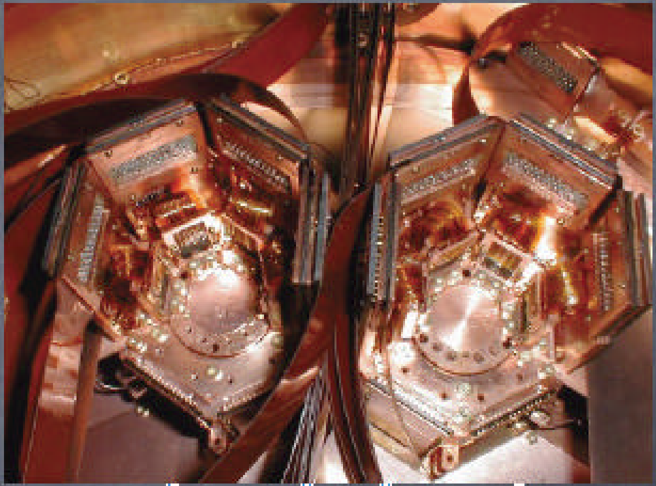
October 2003 - January 2004

one tower = 4 Ge and 2 Si detectors

22 kg d Ge exposure (10-100 keV recoil)

first results in 2004

PRL 93 (2004), PRD 72 (2005)



March 2004 - August 2004

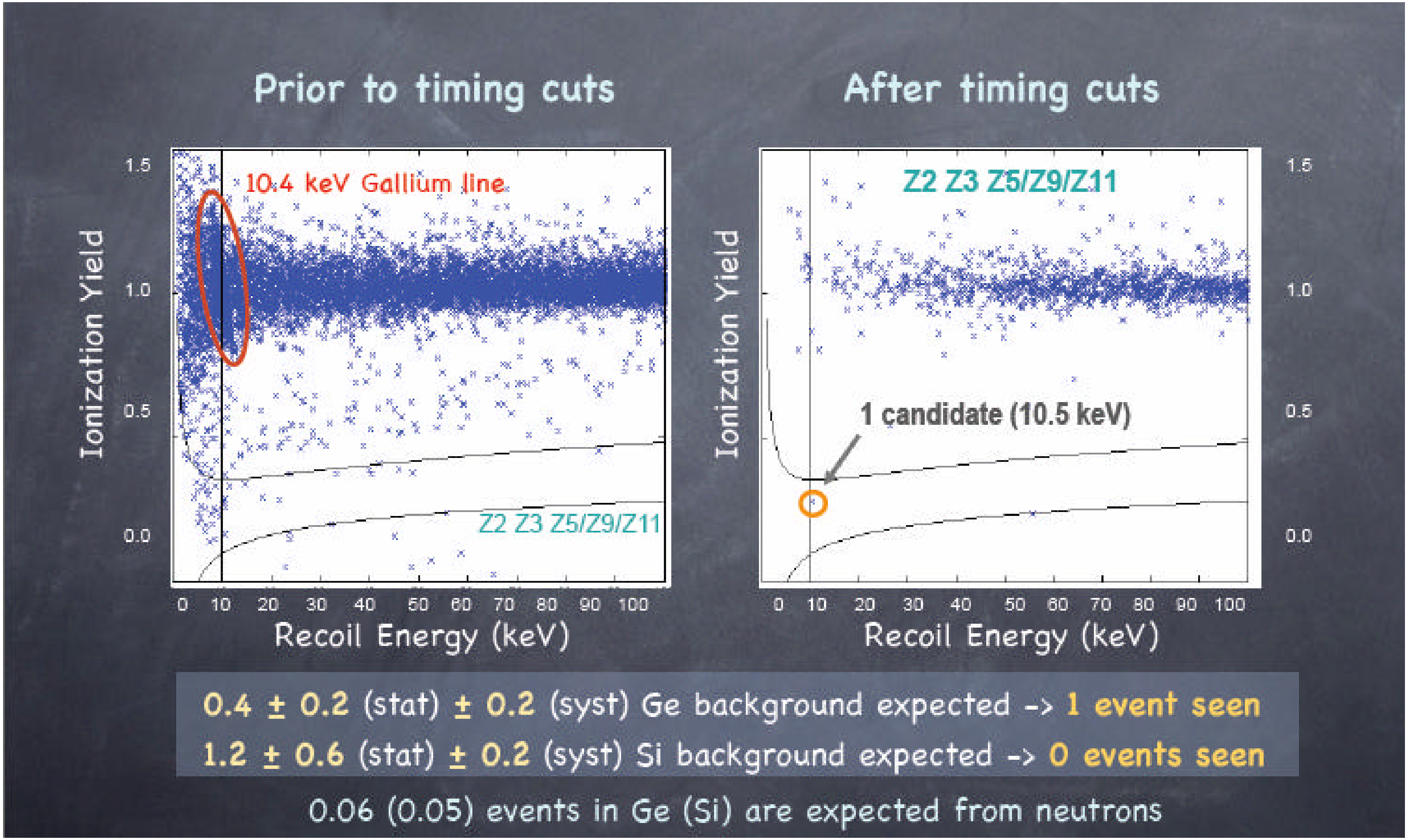
two towers = 6 Ge and 6 Si detectors

38 kg d Ge exposure (10 -100 keV recoil)

first results in 2005

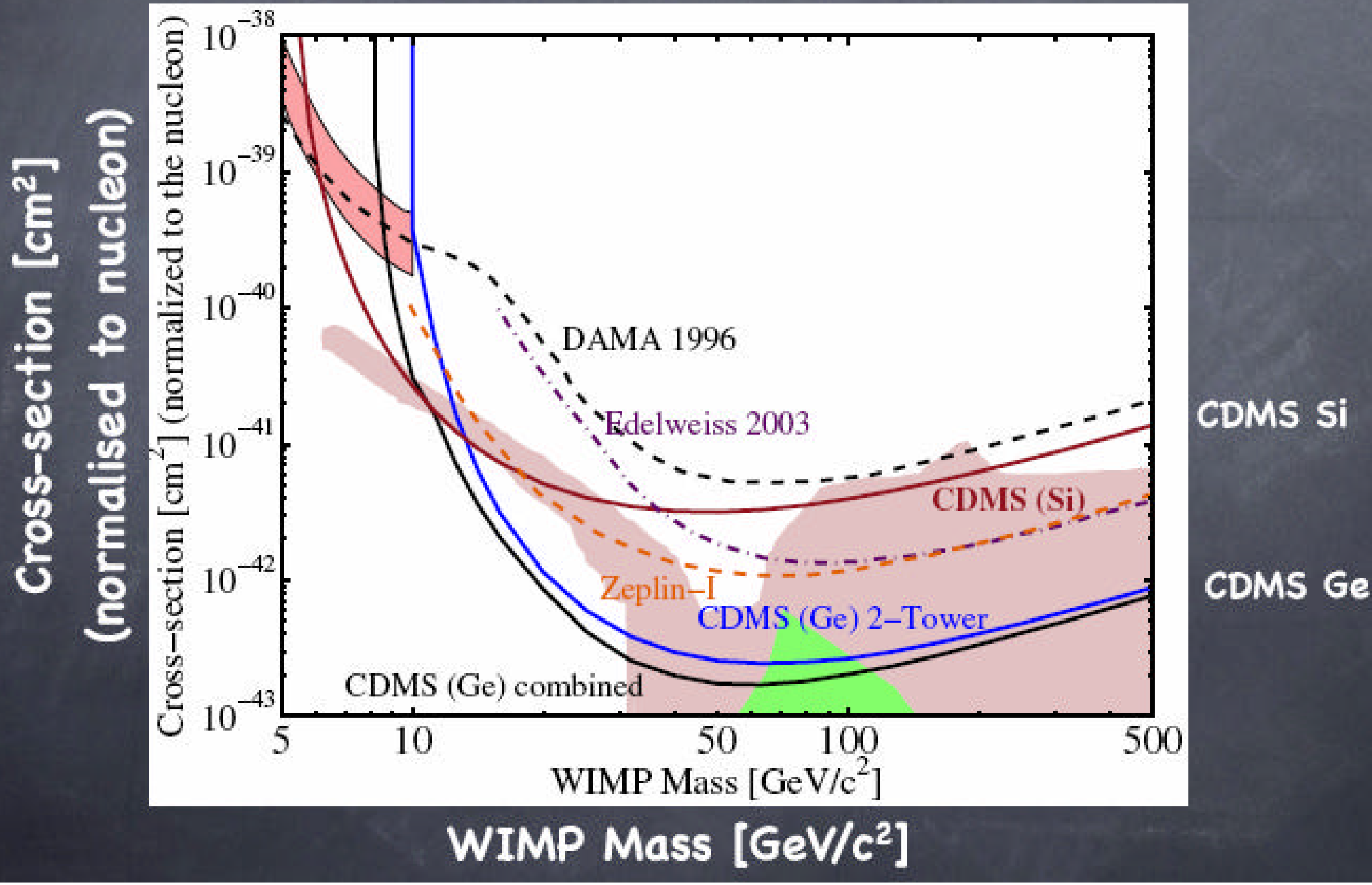
Phys. Rev. Lett. 96 (2006)

CDMS-Results



Spin-Independent WIMP Limits (90%CL) and SUSY Predictions

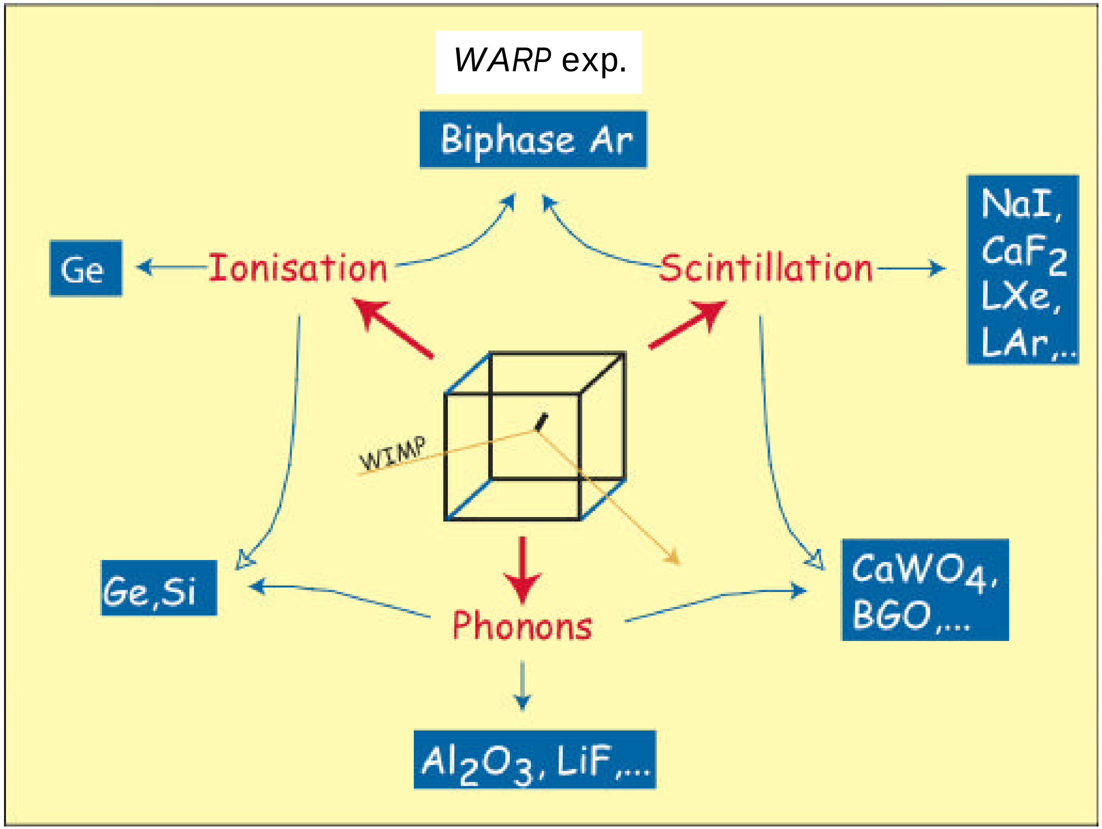
Phys. Rev. Lett. 96 (2006)



Methods of direct detection

- Earlier experiments identify in a well shielded, underground laboratory (LNGS) the presence of a very small seasonal variation in the otherwise very huge background due to ordinary, low energy (=6 keV) electron-like events. Such a tiny variation is interpreted as due to the WIMP signal. (DAMA)
- More recent experiments (CDMS and EDELWEISS) , in order to detect directly a WIMP signal above background make use of a very low temperature (12-50 milliK) Ge target, in which the slow thermal energy of the recoiling WIMP associated atom is detected by an electric signal sensitive to the *phonons* (local heating) of the recoil.
- These detectors are capable of a good discrimination but they suffer from the very low integrated mass sensitivity: 32 kg x day for EDELWEISS(Frejus) AND 38 kg x day for CDMS(Soudan).
- A new kind of detector, ultimately capable of many tens of tons of sensitive mass has been developed based on the use of a ultra-pure Noble liquid (earlier Xenon, now Argon) at standard temperature with the simultaneous detection of the *scintillation and ionisation* signals in order to identify, *with an adequate selectivity*, a WIMP recoil signal from ordinary backgrounds.

Methods of direct detection of WIMPS



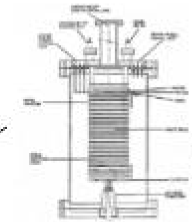
DAMA

ZEPLIN
XENON

EDELWEISS
CDMS

CRESST

The path to larger liquid Argon detectors



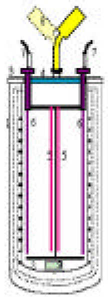
24 cm drift wires chamber

CERN 1

1987: First LAr TPC. Proof of principle. Measurements of TPC performances.

2

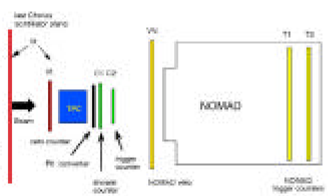
3 ton prototype



1991-1995: First demonstration of the LAr TPC on large masses. Measurement of the TPC performances. TMG doping.

CERN

Laboratory work



50 litres prototype
1.4 m drift chamber

CERN

3

1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m3 industrial prototype

1999-2000: Test of final industrial solutions for the wire chamber mechanics and readout electronics.

T600 detector

2001: First T600 module

5

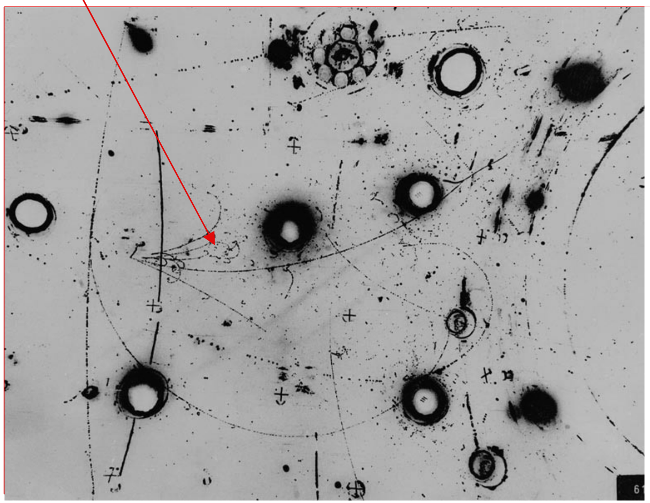
Cooperation with industry

Thirty years of progress........

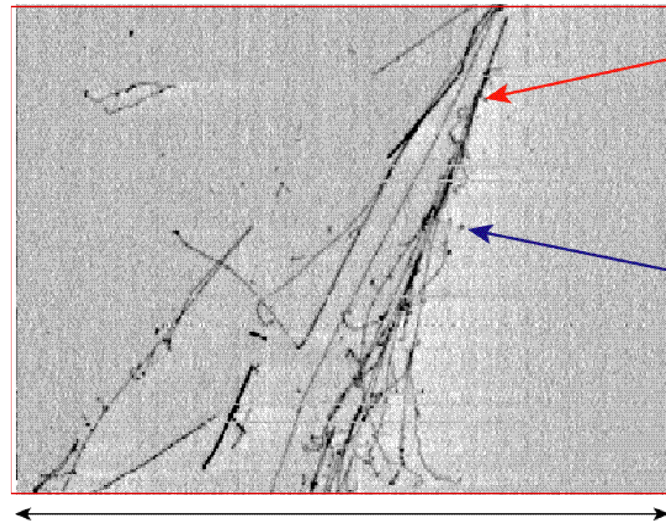
LAr is a cheap liquid (~1CHF/litre), vastly produced by industry

Bubble diameter ~ 3 mm (diffraction limited)

Gargamelle bubble chamber



ICARUS electronic chamber



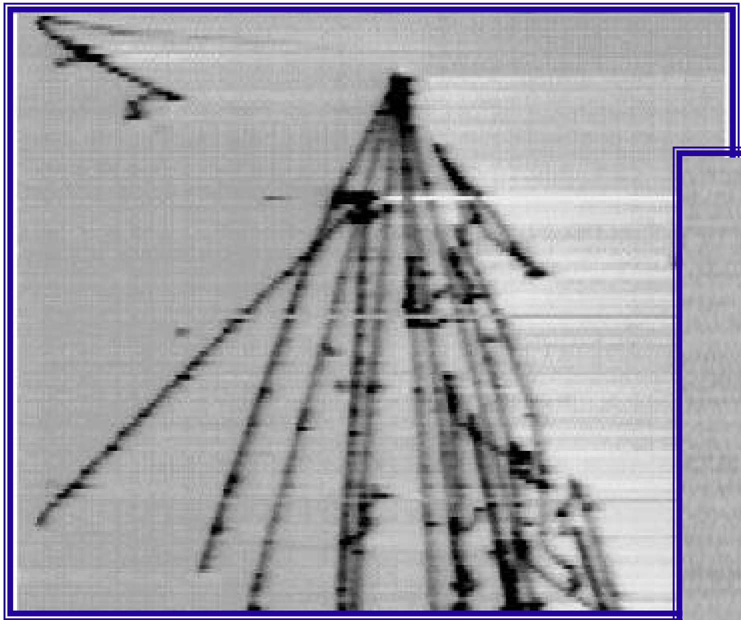
"Bubble" size ≈ 3 x 3 x 0.2 mm^3

Energy deposition measured for each point

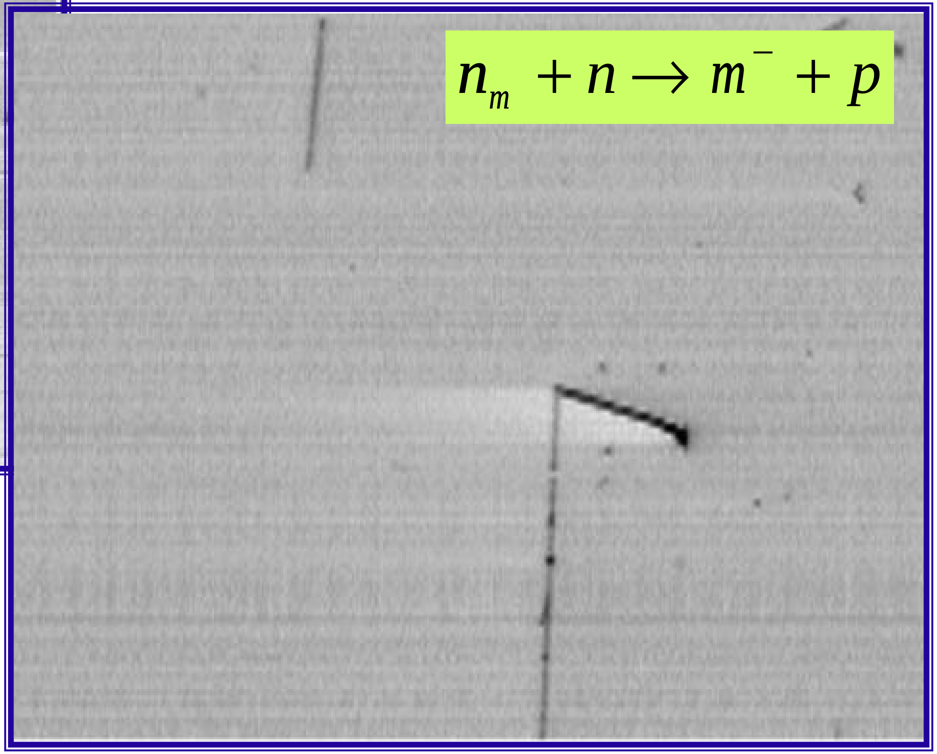
Medium	*Heavy freon*	
Sensitive mass	3.0	ton
Density	1.5	g/cm^3
Radiation length	11.0	cm
Collision length	49.5	cm
dE/dx	2.3	MeV/cm

Medium	*Liquid Argon*	
Sensitive mass	Many ktons	
Density	1.4	g/cm^3
Radiation length	14.0	cm
Collision length	54.8	cm
dE/dx	2.1	MeV/cm

50 liter prototype in CERN West Area neutrino beam



$$n_{m} + X \rightarrow m^{-} + many \quad prongs$$



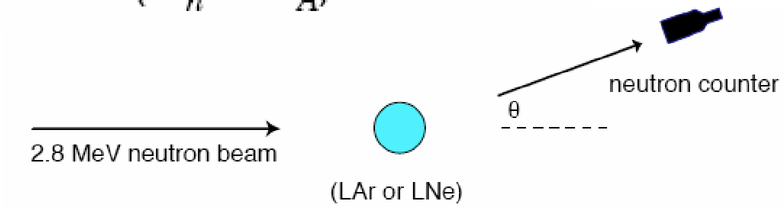
$$n_{m} + n \rightarrow m^{-} + p$$

Why search of WIMP with LAr ?

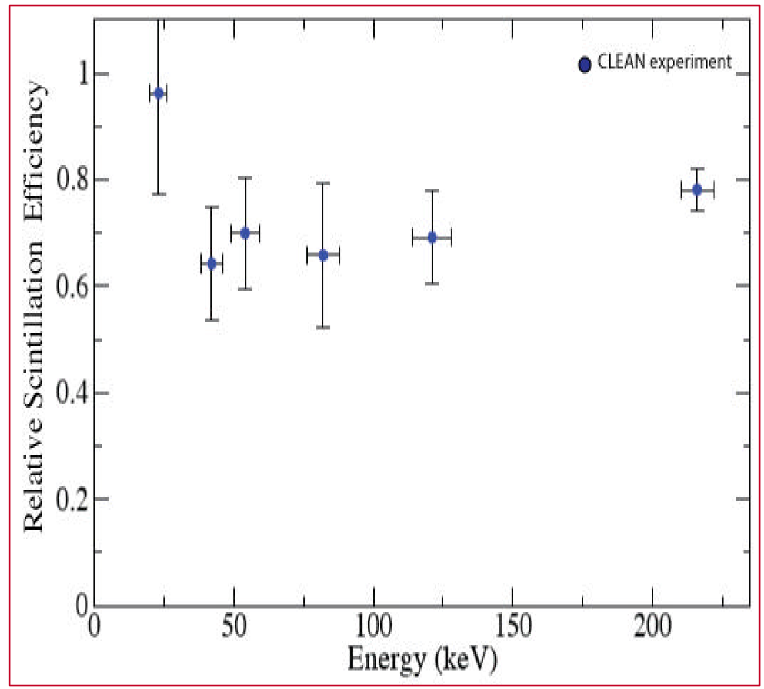
- Cryogenic Noble gases permit simultaneous detection of both ionisation and scintillation
- Why Argon ?
  - The largest scintillation yield for signal from recoils from WIMPS
  - Two components of scintillation yield, $\tau_{singlet}$ = 7ns and τ_{riplet} = 1.8 μs, vastly different for fast and slow recoils.
  - Strong recombination of ionisation effect due to columnar charge density. Electrons drifted away are transmitted from liquid to gas and multiplied by a grid to produce delayed signal.
  - Low cost and easy availability of truly large volumes.
  - Possibility of an integrated active anticoincidence and an effective neutron shield

Scintillation yield of slow recoils (WIMP-like)

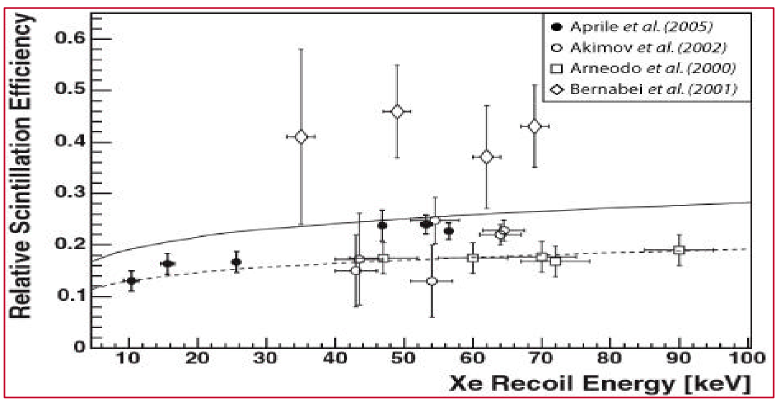
$$E_A = E_n \frac{2M_n M_A}{(M_n + M_A)^2}(1 - \cos\theta)$$



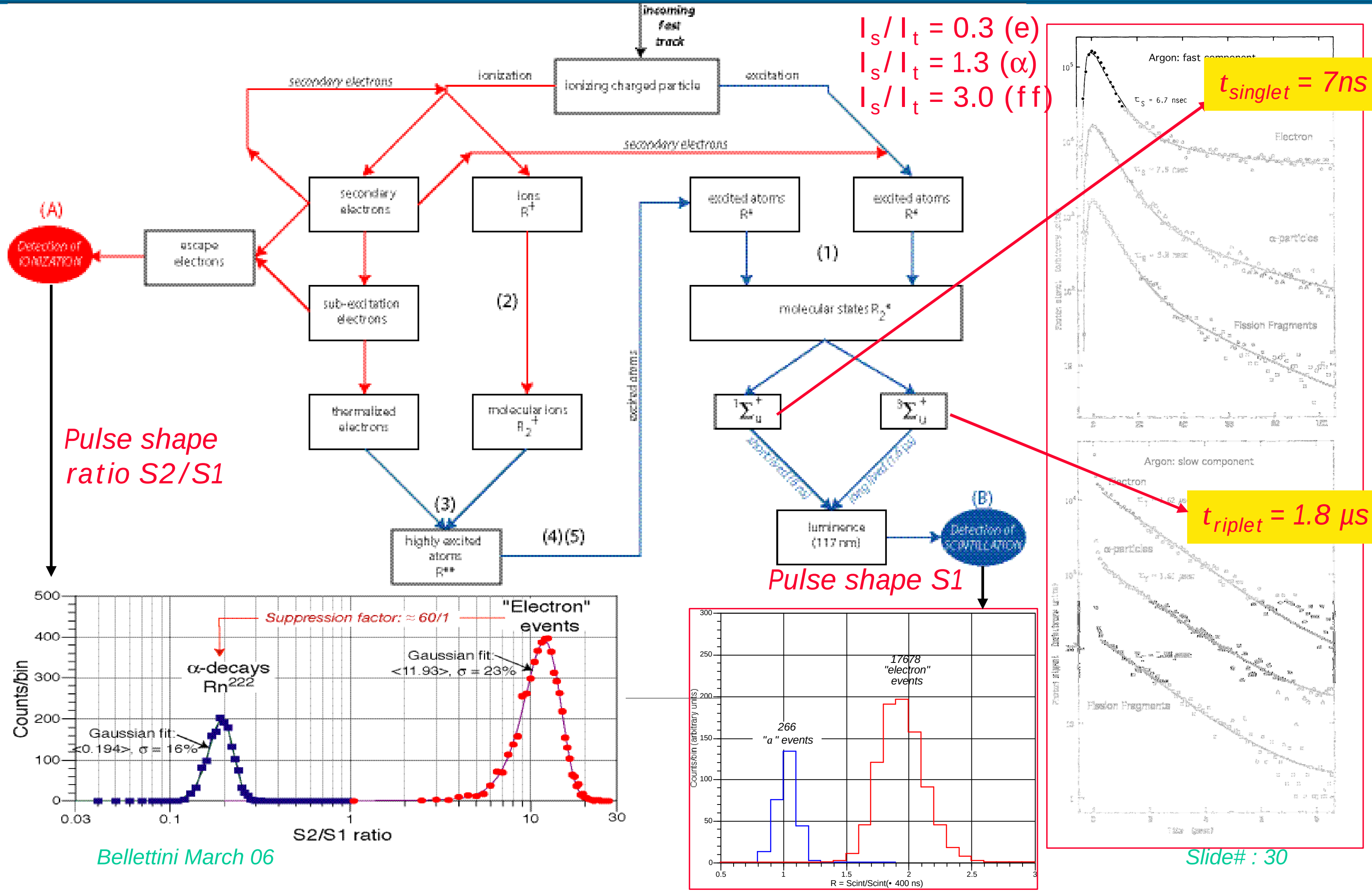
Ar recoils in LAr



Xe recoils in LXe



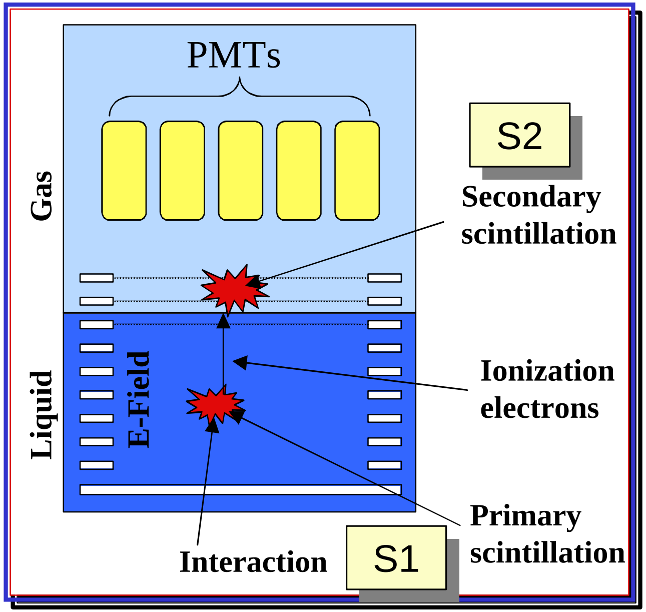
The case of Argon: two main selection criteria



The WARP experiment

- **Two simultaneous criteria to discriminate potential WIMP recoils from backgrounds**:
  1. Simultaneous detection of **prompt scintillation (S1) and drift time-delayed ionization (S2)** in LAr, after electron extraction in gas and local multiplication:
     - pulse height ratio S2/S1 is strongly dependent from columnar recombination of ionizing tracks.
     - 3D reconstruction of the event from drift time and PMT localization of centroid of S2 within 1 cm^3.
  2. **Pulse shape discrimination of primary scintillation**:
     - wide separation in rise times between fast (~ 10 ns) and slow (~ 1.6 μs) components of the emitted UV light. This is an unique feature of Argon.
- Scintillation yield is ~ 2 phel. / keV_{ion} and the detection WIMP threshold is ~ 15 ÷ 20 keV_{ion}

Double Phase Argon Chamber



Recoil-like event
Slow component ~ 10 %

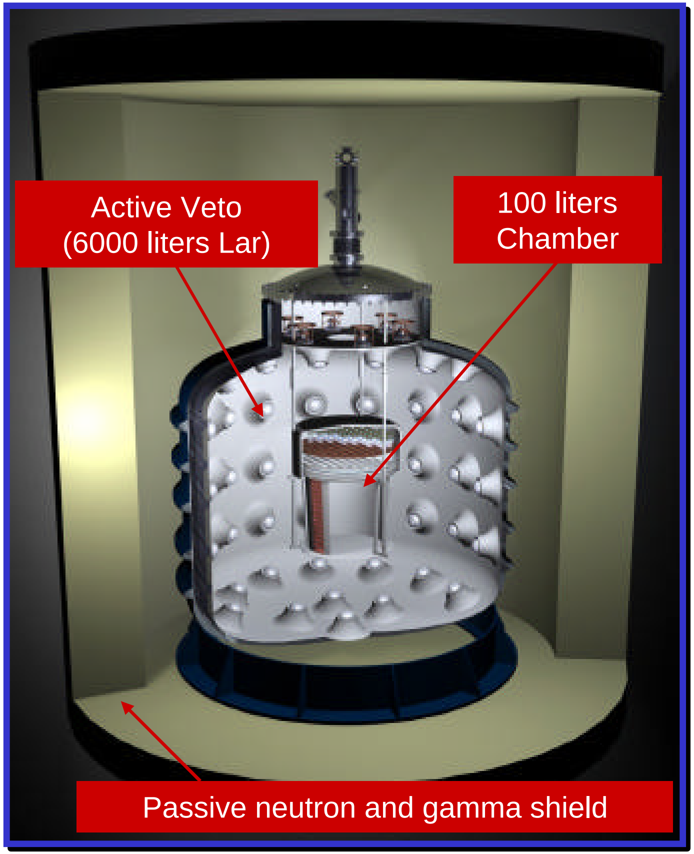
g-like event
Slow component ~ 70 %

The need for a new technology

- The WARP experiment is intended to search for WIMP recoils in LAr with 140 kg fiducial volume and a threshold of < 20 KeV_{ion}.
- A unique feature of this experiment is that the active volume is tightly surrounded by a ~ 8 ton, 4 p active anticoincidence, also of LAr, in order to veto not only β and γ, but especially entering and exiting neutrons with a recoil threshold as low as ~ 30 keV.
- In order to perfect the technology, a small 2.3 Liters prototype is now operational in the LNGS.
- The local radioactivity background has been intentionally left at a high level (~ 5 c/s) in order to demonstrate an achieved extremely high rejection capability within a reasonable time.
- The 100 liters detector will be then further purified, in order to reach such a demonstrated rejection capability against spurious events and a correspondingly larger mass.

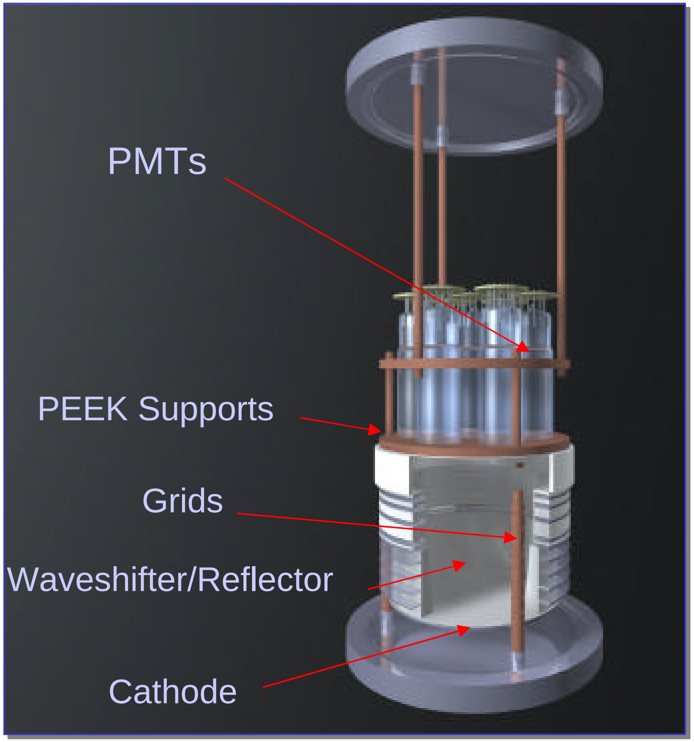
The projected detector

- Sensitive volume = 100 liters (140 kg).
  - 3-D event localization by means of:
    - Drift time recording (vertical axis);
    - Centroid of PM's secondary signal amplitudes (horizontal plane).
- 4π active VETO system:
  - tags and measures the neutron-induced background with an ID-factor ˜ 99.99 %;
- In construction since the end of 2004; deployment in LNGS hall B will start in March 2006.
- Operational by second half of 2006.
- Designed also to host a 1 ton detector.



The 2.3 liters chamber

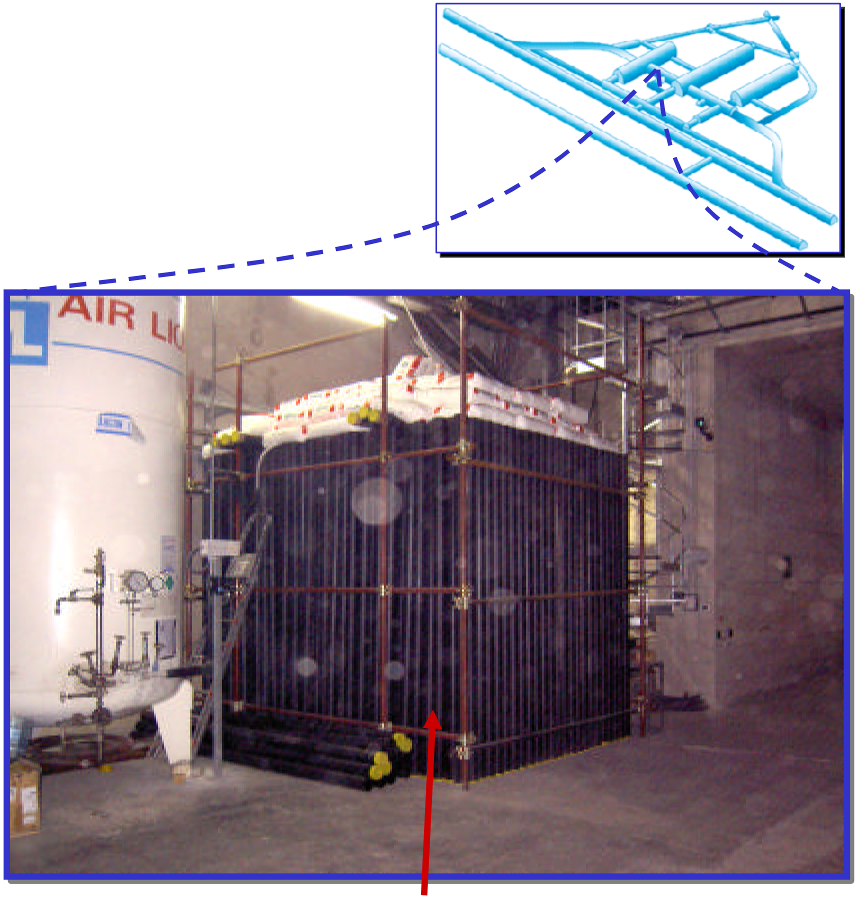
- The 2.3 liters prototype is equipped with seven 2” PMs made of low background materials and designed to work at LAr temperature.
- Scaled version of the 100 liters detector, with field-shaping electrodes and gas to liquid extraction and acceleration grids.
- Equipment contained in a high-vacuum tight container immersed into an external, refrigerating, liquid argon bath.
- LAr Purity kept stable by means of argon recirculation:
  - continuous and stable operation during several months.



Schematic view of the 2.3 liters chamber

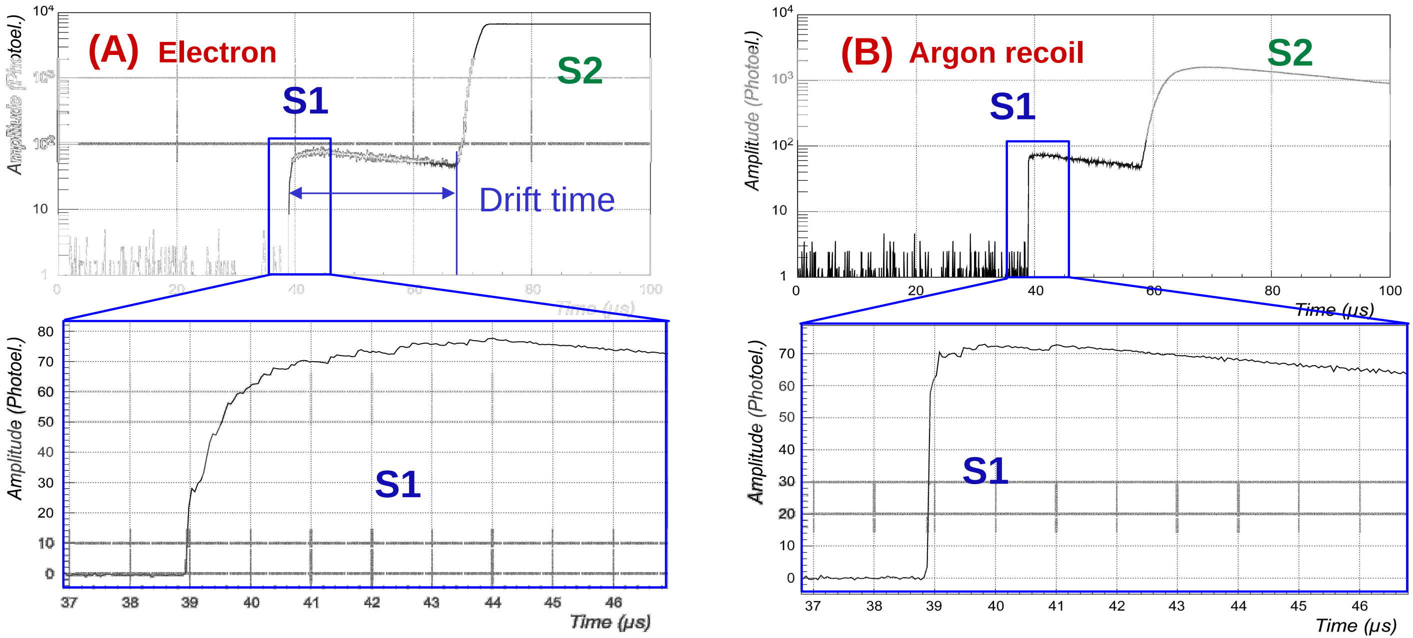
2.3 liters chamber at LNGS

- After the technical R&D performed in Pavia laboratories the chamber is installed in LNGS for a detailed study of environmental backgrounds.
- Start operation: May 2004
- Environmental gamma and neutron background measurements.
- Data taking with gamma and neutron shields since August 2005.



External lead (10 cm) + Polyethylene (60 cm) shield

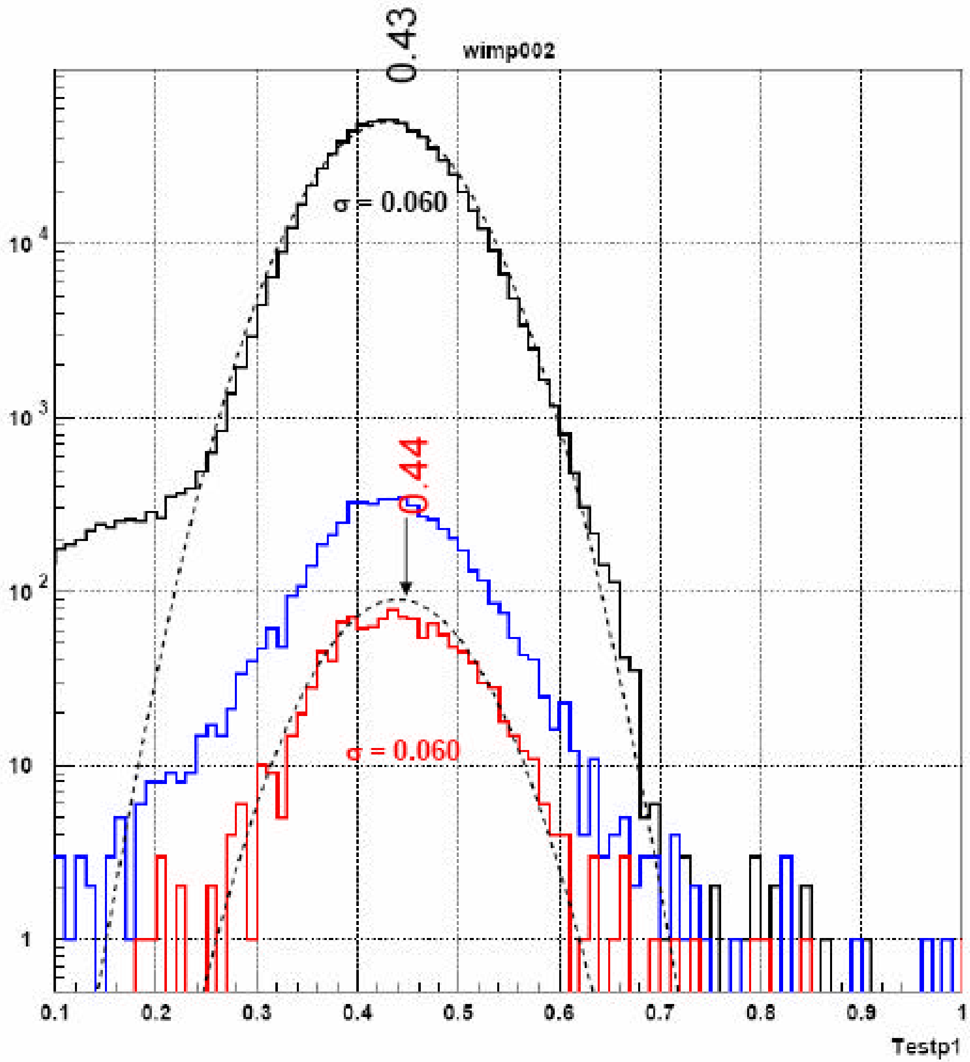
Shapes of recorded PMT's signals



- ➔ **S1** = primary (prompt) scintillation signal
- ➔ **S2** = secondary (delayed) scintillation signal (proportional to ionization)

- **Minimum ionising particles**: high S2/S1 ratio (~100) + slow S1 signal.
- a **particles and nuclear recoils (R-like events)**: low (<30) S2/S1 + fast S1.

Selezione eventi regione 50 keV<E<100 keV



Run 2017-2097
Tempo vivo:11.4 days

Nero: 779143 eventi
(Non saturati)

Blu: 5822 eventi
0.3<S2/S1<30

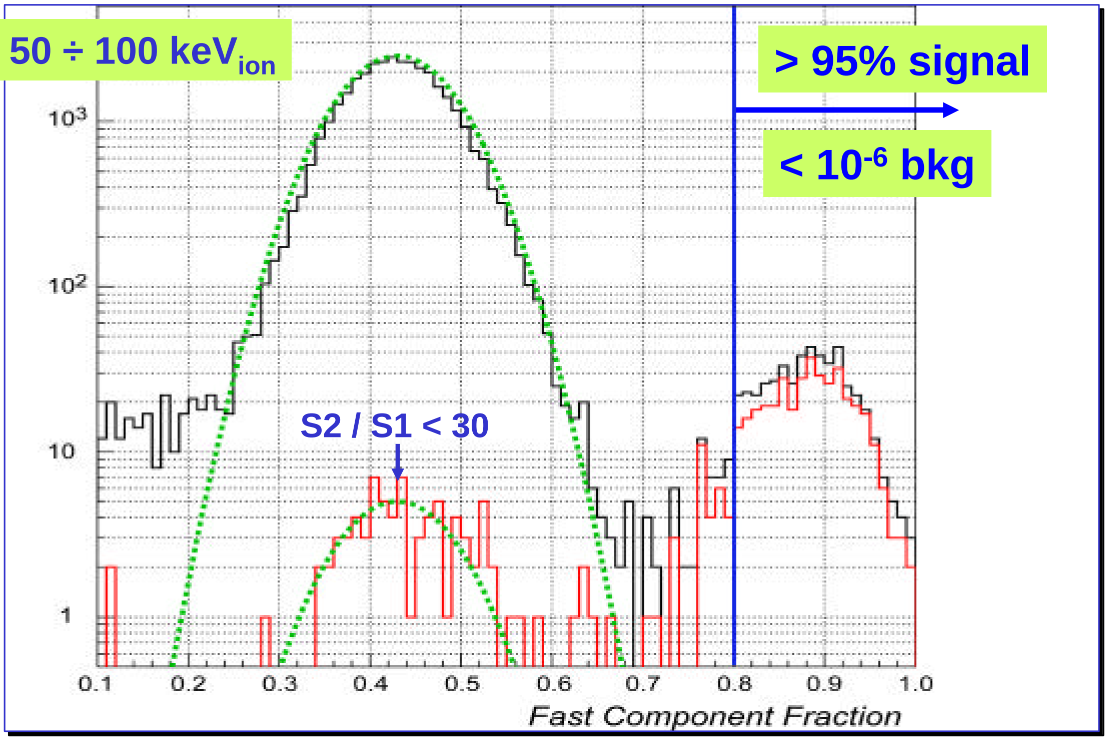
Rosso: 1389 eventi
Regione 1-hit

Eventi fast (Tp>0.8) nella regione 1-hit: 2 eventi

Dopo vis. Scanning: 0 eventi

Same, but with neutron recoils

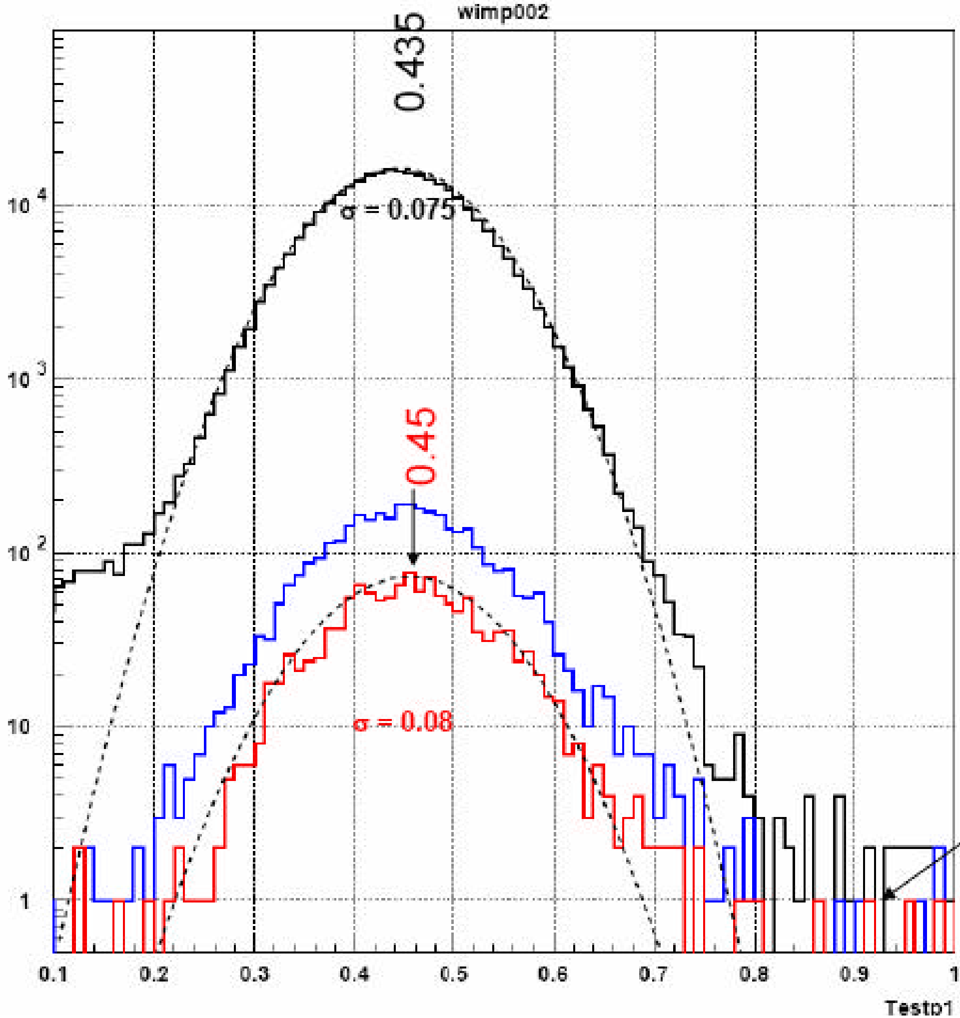
Recoil Energy 50 ÷ 100 keV$_{ion}$



The two methods, combined, give **an effective identification power in excess of 1 recoil-like event in 10^8 gamma-like events.**

Selezione eventi regione 30 keV<E<50 keV

Run 2017-2097
Tempo vivo:11.4 days



Nero: 310786 events
(Non saturati)

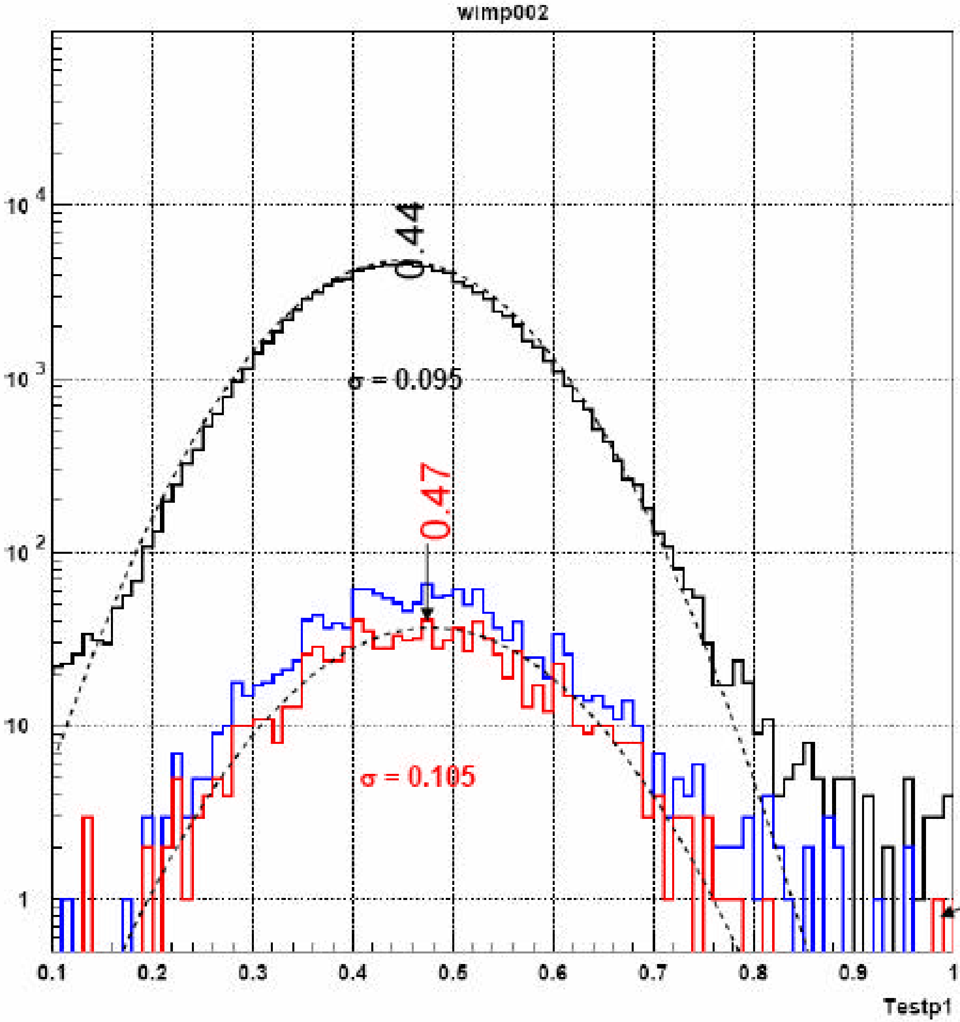
Blu: 3825 events
0.3<S2/S1<30

Rosso:1546 events
1-hit region

Eventi fast (Tp>0.8) nella regione 1-hit: 5 eventi

Dopo visual Scanning: 1 evento (Evento 1)

Selezione eventi regione 20 keV<E<30 keV



Run 2017-2097
Tempo vivo:11.4 days

Nero: 113335 events
(Non saturati)

Blu: 1643 events
0.3<S2/S1<30

Rosso: 1090 events
1-hit region

Eventi fast (Tp>0.8) nella regione 1-hit: 2 eventi

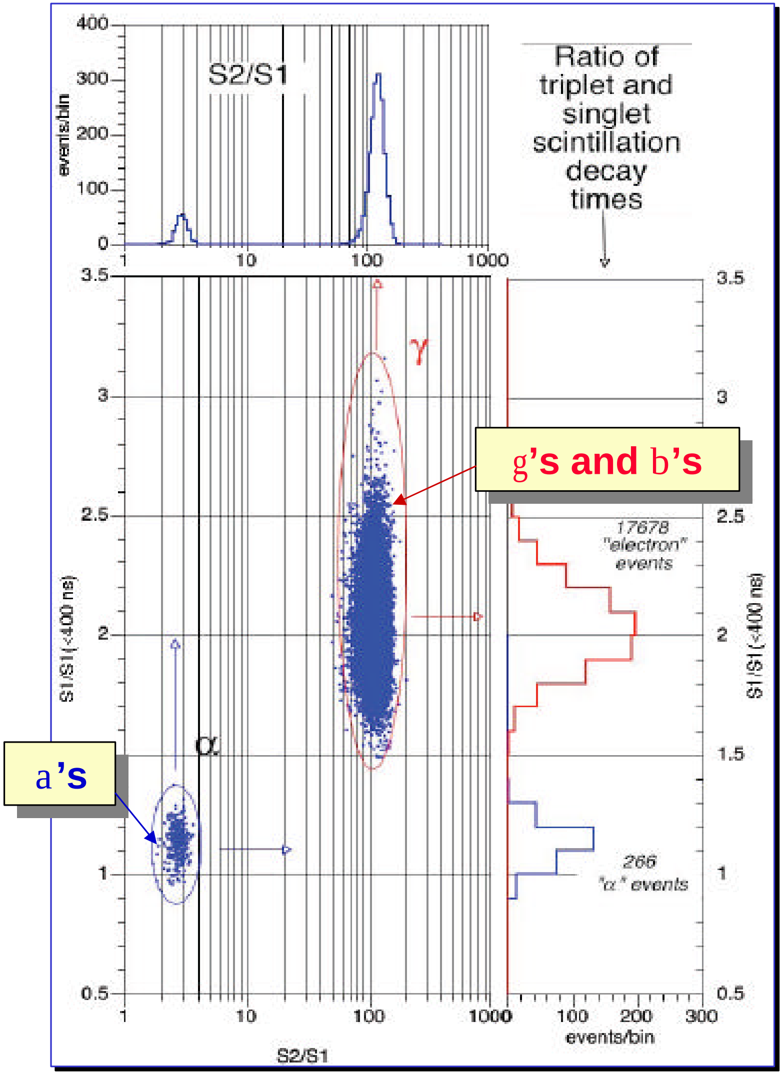
Dopo vis. Scanning: 1 evento (Evento 3)

Spontaneous α-decay events from Rn chain

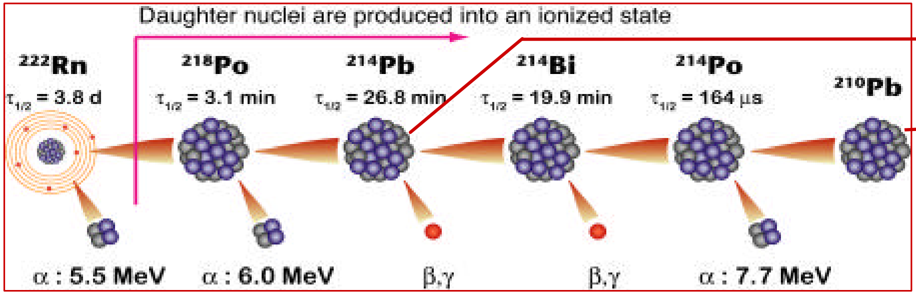
Combined selection based on S2/S1 ratio and rise time of primary scintillation

No event outside the two circled regions

Complete agreement up to an observed level of ˜ 1/20000
➔➔➔
↙ extrapolated combined rejection < $1/10^8$



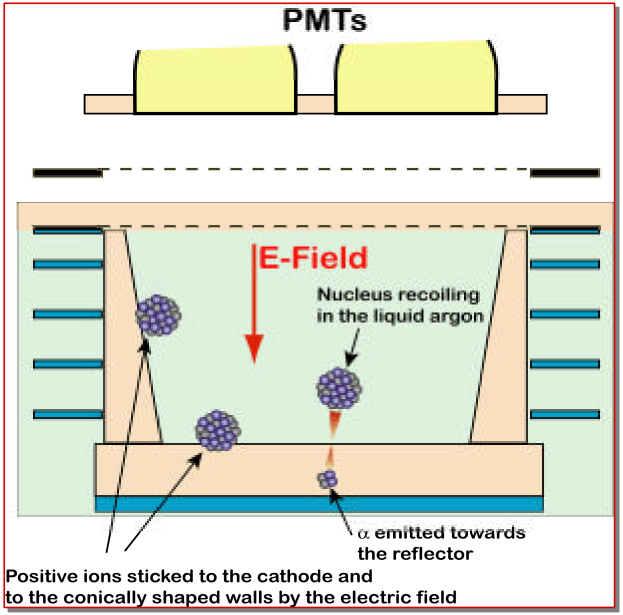
Nuclear recoils from cathode to LAr

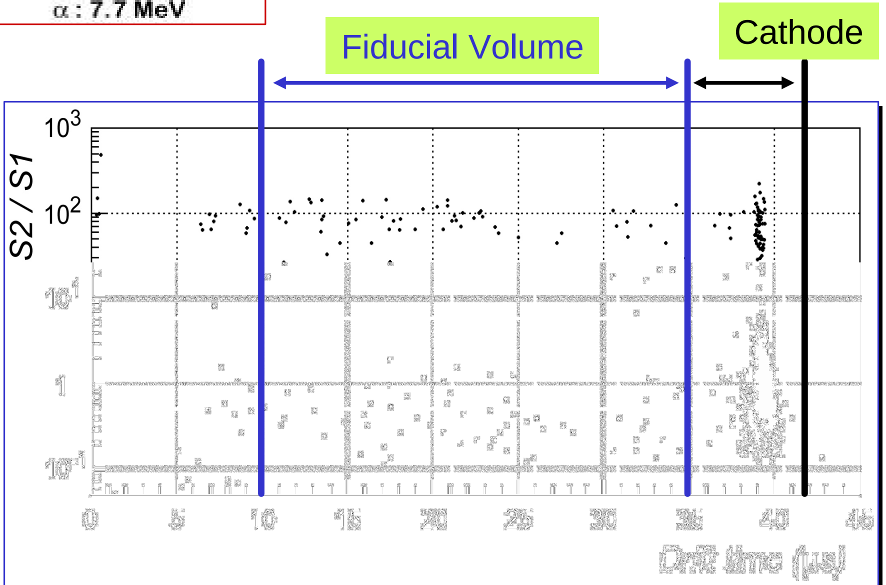


Recoil energy = 110 keV

Recoil energy = 144 keV

^{222}Rn Decay Chain



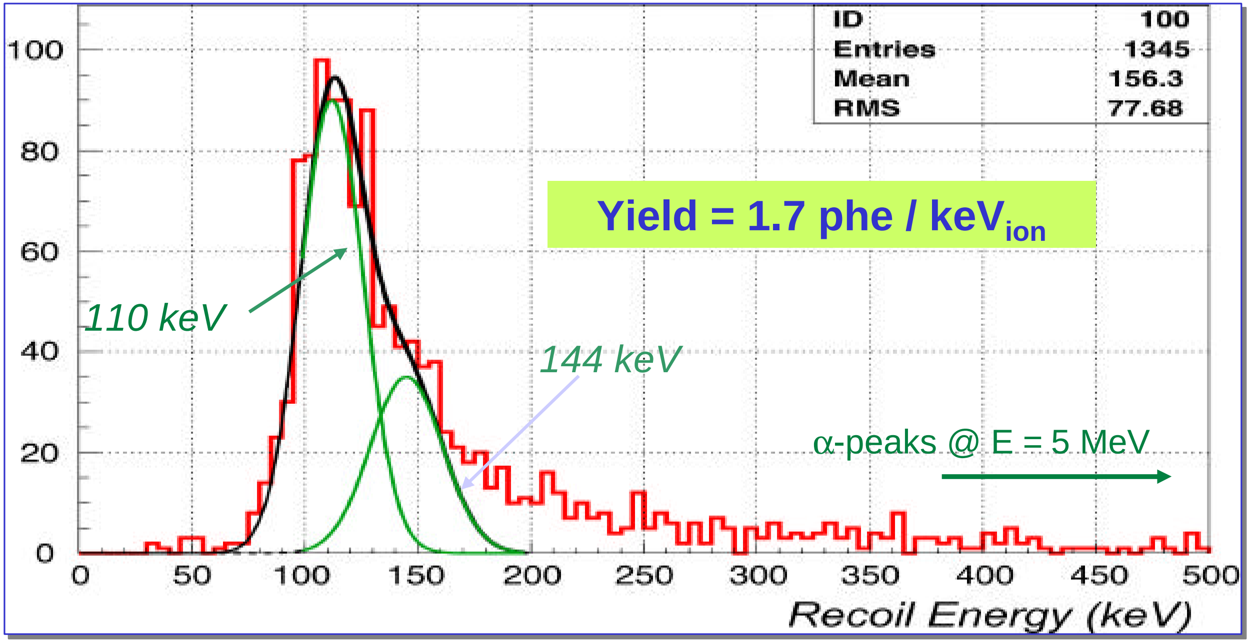


Events with fast primary signal only

Observed ion recoil energy spectrum

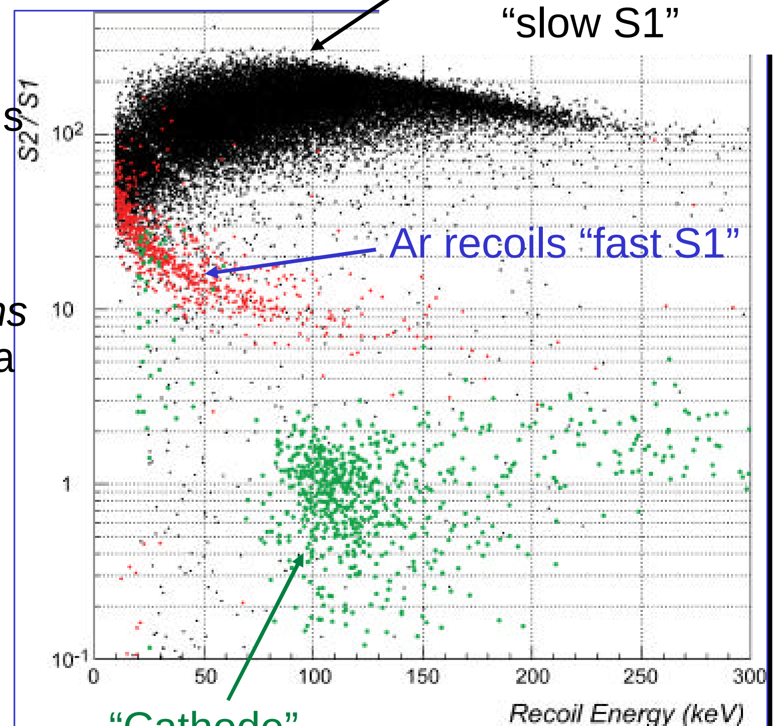
Monoenergetic ion recoils from unstable ^{222}Rn daughters kept by the chamber walls allow a continuous calibration signal (two lines: 110 keV and 140 keV in a known relative ratio)

1. Drift time from cathode
2. Fast S1 signal timing shape
3. S2/S1 < 30



The observation of the S2/S1 ratio

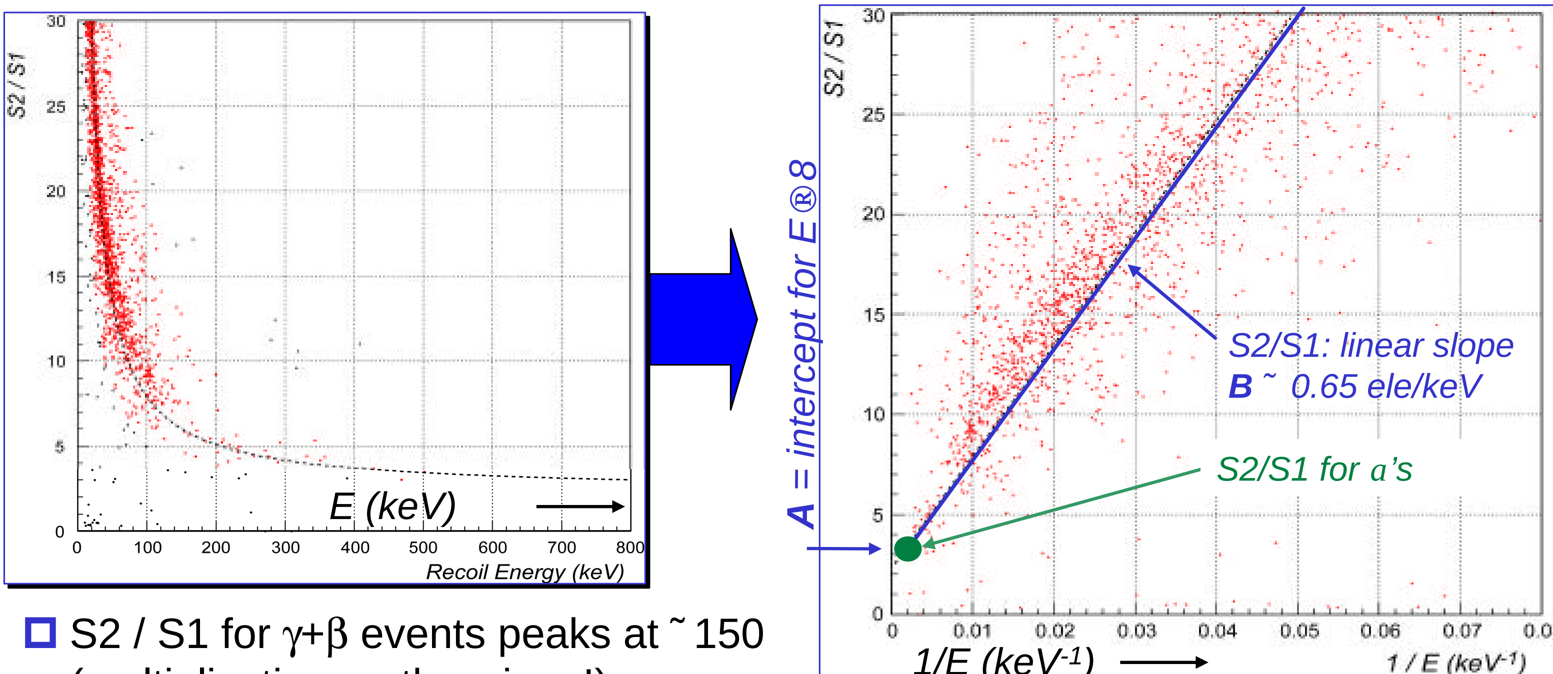
- The separation between minimum and heavy ionizing tracks is relatively straightforward, based on the fast (˜ 10 ns) and slow (˜ 1.6 μs) components of the LAr scintillation decay pulse of S1.
- *<u>But</u>* the S2 pulse, *i.e. the secondary, multiplied number of surviving electrons after drift and extraction to gas*, has a much more complex structure, which has to be elucidated in more detail.
- The ratio S2/S1 for heavy ionizing tracks, as signalled by "fast S1", *is found to be <u>dependent on energy</u>* E_{ion}



Trigger threshold ˜ 5 keV_{ion}

$S2/S1 = A + B/E_{ion}$

Energy deposition of S2/S1 for “fast S1” -neutron recoils



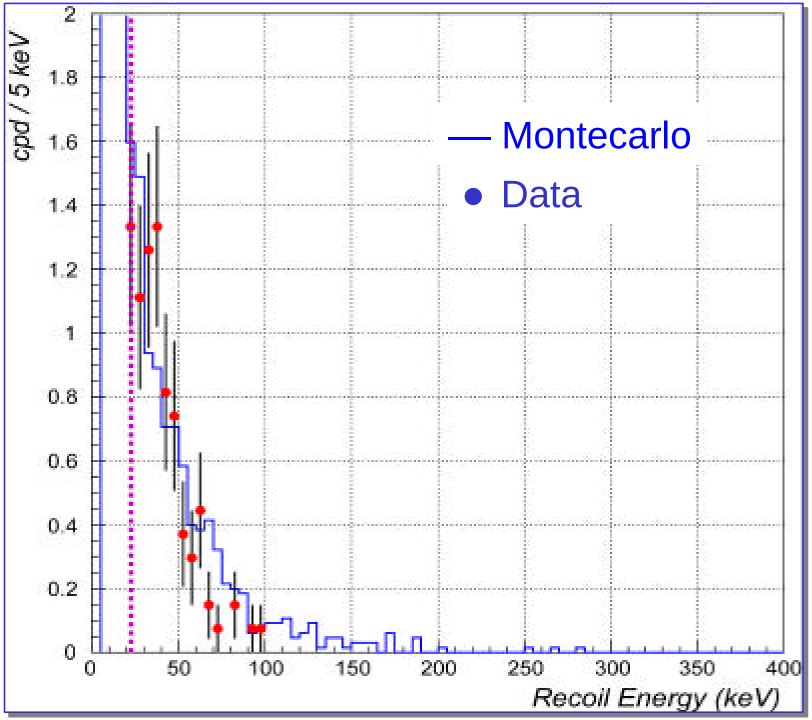
- S2 / S1 for γ+β events peaks at ˜150 (multiplication on the wires !)
- S2 is a linear function of S1: constant term (A) ˜ 160 electrons, and a proportionality constant (B) ˜ 0.65 electrons / keV.
- **S2/S1 point for a-particles consistent with indicated extrapolation**

Neutrons from HallB with no shielding

- Data were taken in the underground location during June/July 2005, but *without neutron shielding*.
- live-time = 14 days (~ 28 kg • day)
- Total triggers = 6.82 x 10^6
- Trigger threshold = 10 keV.
- Threshold for data selection = 22 keV (recoil energy).
- Selected events in the n-induced recoils window = 111 events

↙~ 8 events / day

R-like events in the fiducial volume



Early candidates with full shield

~7 x 10^6 events

Run 2017 – 2097
Dal 3/2/06 al 17/2/06
Tempo vivo totale 11.4 giorni

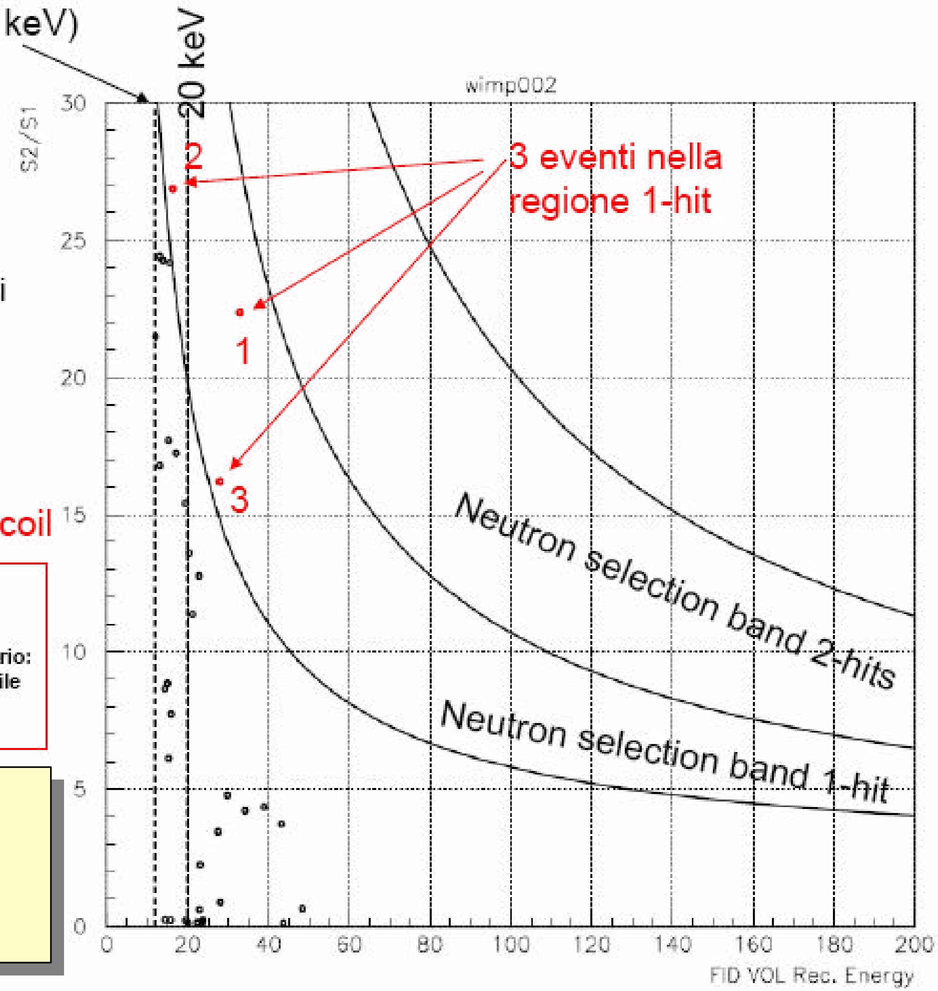
Total live time
22 day x kg

Selezione eventi di Ar-recoil

- Entro Volume fiduciale 10<tdrift<35 µs
- primario fast (tp>0.8)
- s2/s1<30
- scanning visuale sulla forma del primario: selezione di eventi con forma compatibile con gli eventi osservati con la sorgente di n (slides 20-21)

Expected CR induced neutron background ?
~ 1-3 events (no anti)

20 phe (12 keV)

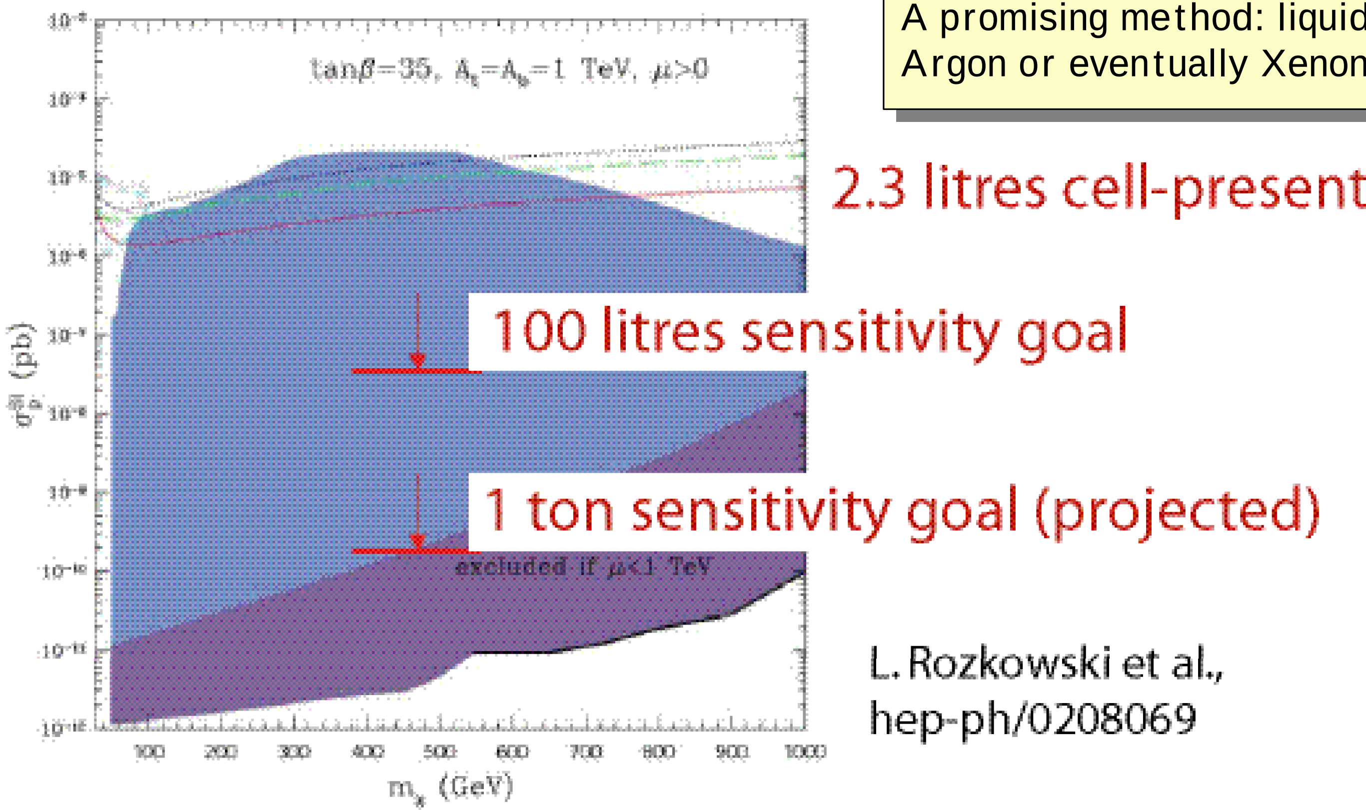


Conclusions

- With the help of a double signal discrimination, WARP has achieved the most advanced and best performing method for (WIMP-induced) recoil identification.
- A combined identification power in excess of 1 Argon recoil event in 10^8 (gamma + beta) induced events has been observed.
- Heavy ion recoils(^{222}Rn daughters) have been used to determine the ion recoil scintillation yield in LAr and provide a “on line” energy calibration.
- Data taking has just started. An exposure of 22.4 kg x day has been recently accumulated with the 2.3 liters prototype operating with gamma and neutron shields. Fiducial volume is about 2 kg.
- *Preliminary indications give 3 events detected in the Ar recoil region above 15 keV. Their origin is being investigated with better statistics.*
- A [50 x] larger LAr detector based on this double signal technology — but with an active 4p neutron shield (also LAr) — is under construction and should come into in operation by 2006.
- It should provide an almost complete recognition of background neutrons and conclusively decide if this is the origin of the observed events.

Comparing DM with SUSY predictions (LHC)

A promising method: liquid Argon or eventually Xenon



These experiments are already capable to sample the SUSY models at a level compatible with future accelerators constraints, such as CERN's LHC collider.