Underground searches for Dark Matter

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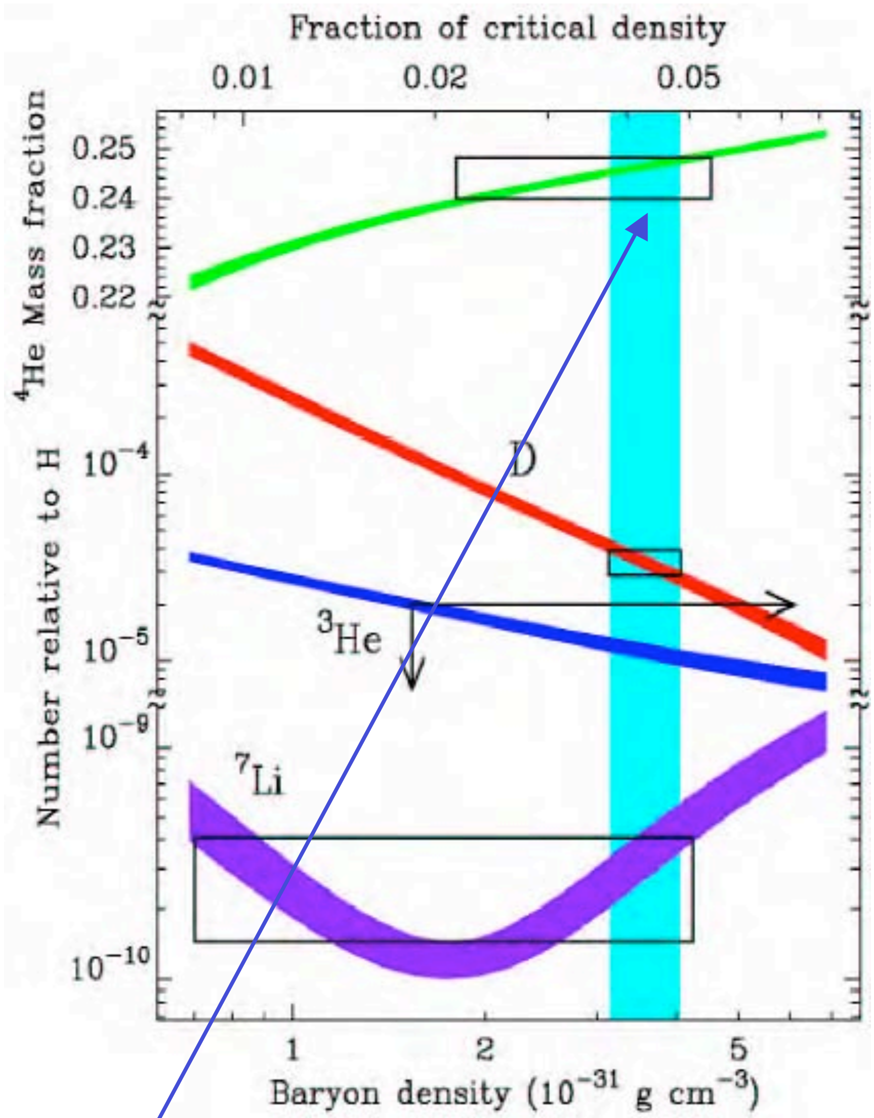
Ordinary matter from BB Nucleo-Synthesis (baryons)

- Big–Bang Nucleosynthesis is a combined result of nuclear physics and of observational astronomy.
- It depends sensitively on the baryon/photon ratio.
- Since we know how many photons there are, we can constrain the baryon density.
- Over-all agreement of relic concentration of nuclear elements
- [Burles, Nollett & Turner]

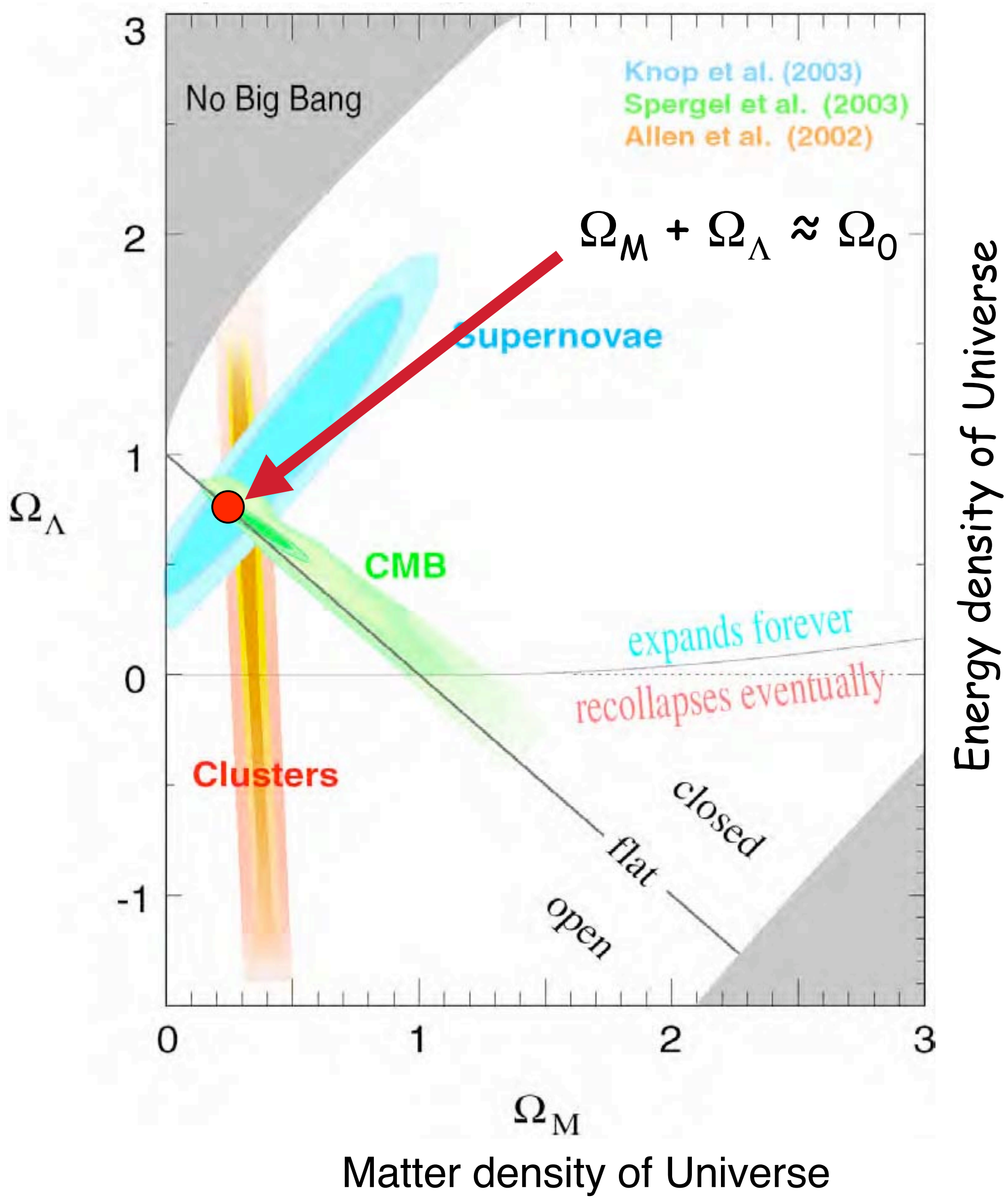


Ω_{BBN} = 0.044 ± 0.004

Cosmology: a few established facts

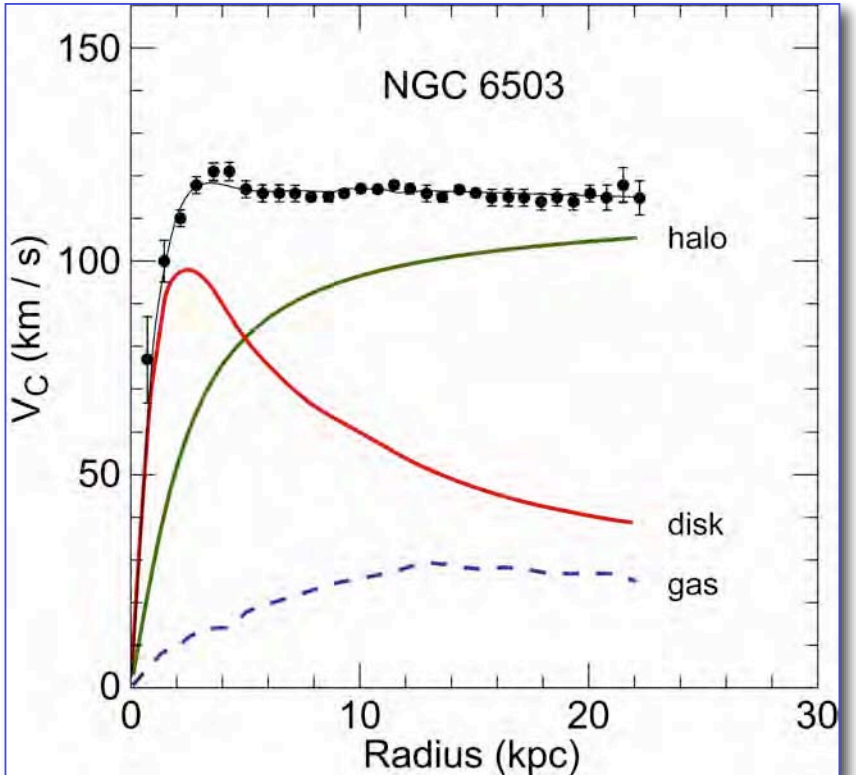
- BBN is firmly set to Ω_{BBN} = 0.044 ± 0.004
- Need for Dark, non baryonic matter, since

  $\Omega_M - \Omega_{BNN} \approx 0.226 \pm 0.06$!
- What is the origin of such a difference ?
- Neutrino's contribution insufficient ($0.0005 < \Omega\, h^2 < 0.0076$)
- Cold dark matter hypothesis preferred by cosmological considerations
- But Cold + Warm dark matters not excluded

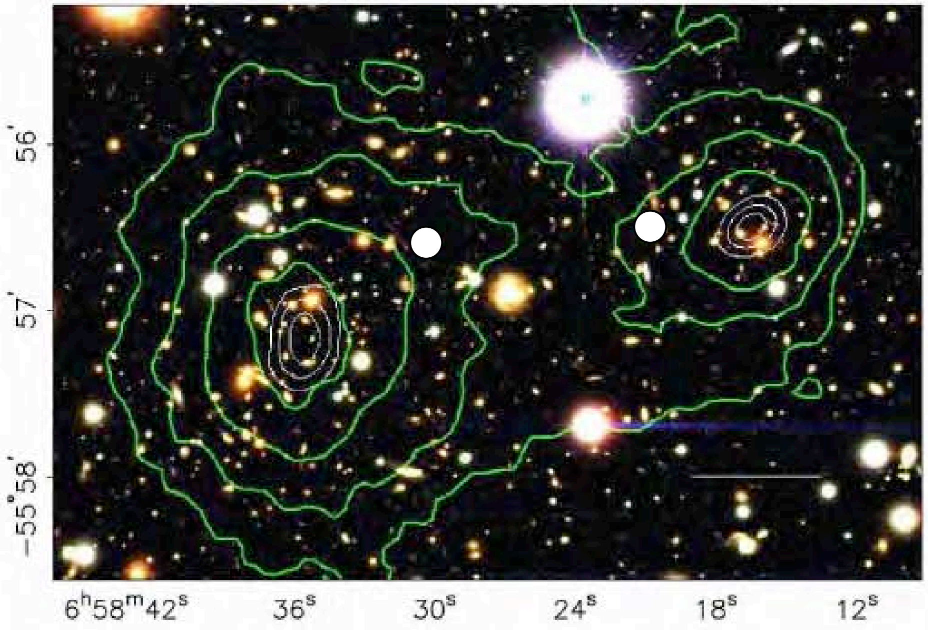


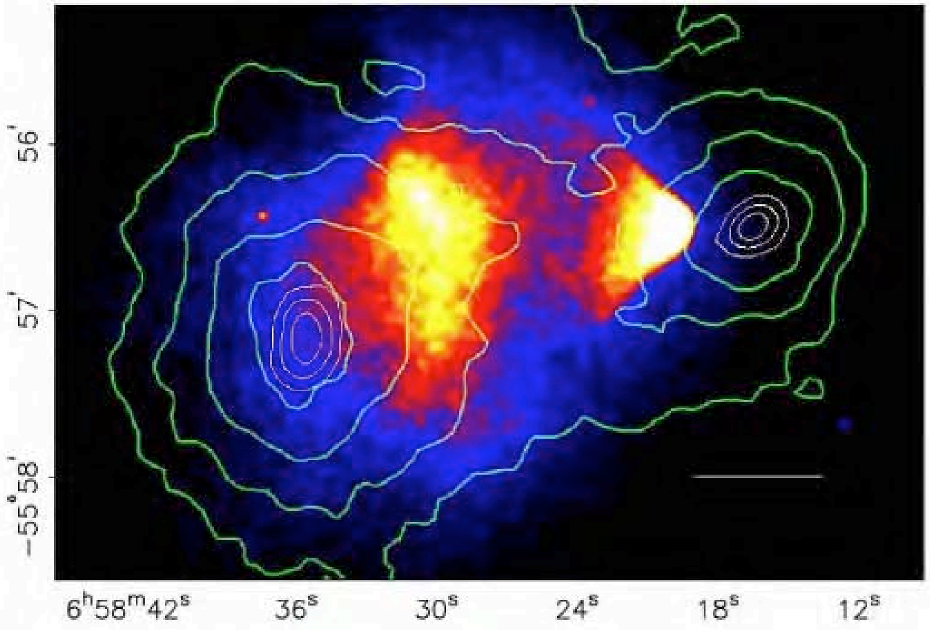
Exprimental evidence for dark matter:Galactic rotation curves

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



Experimental evidence for DM : Lensing of cluster merger





- Shown in green contours in both panels are the weak lensing reconstruction with the outer contour level at κ = 0.16 and increasing in steps of 0.07. The white contours show the errors on the positions of the κ peaks and correspond to 68:3%, 95:5%, and 99:7% confidence levels. The white o show the location of the centers of the masses of the plasma clouds.
- The gravitational potential does not trace the plasma distribution, the dominant baryonic mass component, and thus proves that the majority of the matter in the system is unseen.

Clowe, Bradac et al.

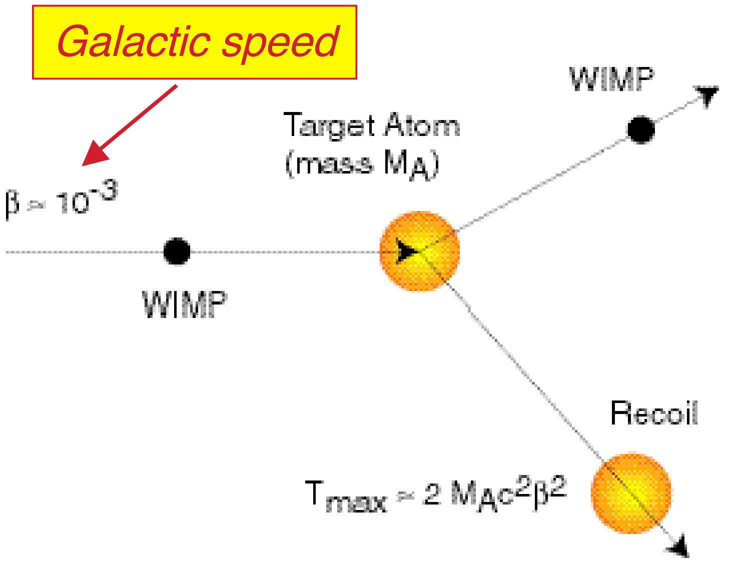
Dark Matter Candidates ?

- Despite the impressive amount of astrophysical evidence, the exact nature of Dark Matter is still unknown.
- All present evidence *is now limited to gravitational effects*. The main question is that if other types of interactions may be also connected to DM. A key question is the presence of a *electro-weak coupling to ordinary matter*.
- Elementary particle physics provides a number of possible candidates in the form of long lived, Weakly Interacting Massive Particles (WIMPs).
- Good bets are, at the moment, the lightest SUSY particle (the Neutralino) and the Axion.

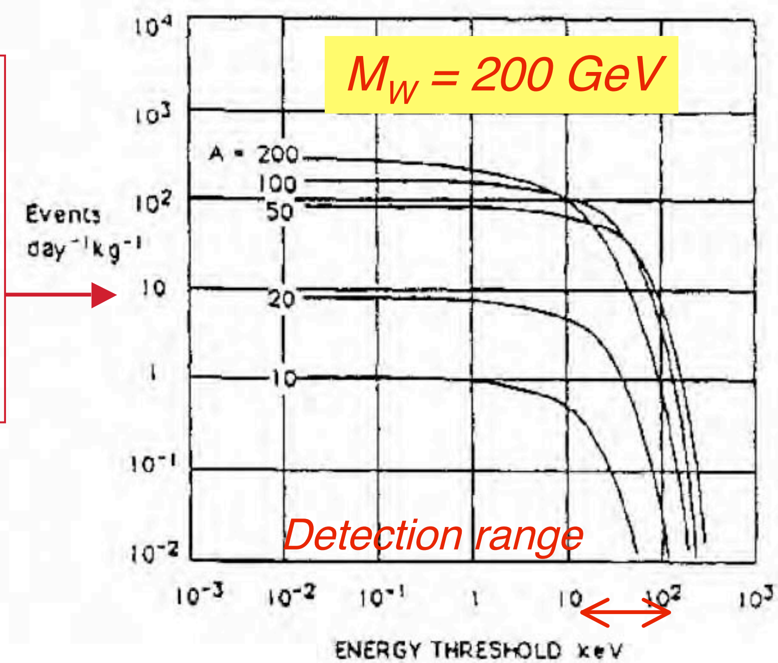
- Kaluza-Klein DM inUED
- Kaluza-Klein DM in RS
- **Axion**
- Axino
- Gravitino
- Photino
- SM Neutrino
- Sterile Neutrino
- Sneutrino
- Light DM
- Little Higgs DM
- Wimpzillas
- Q-balls
- Mirror Matter
- Champs (charged DM)
- D-matter
- Cryptons
- Self-interacting
- Superweakly interacting
- Braneworls DM
- Heavy neutrino
- **NEUTRALINO**
- Messenger States in GMSB
- Branons
- Chaplygin Gas
- Split SUSY
- Primordial Black Holes

WIMP as the source of non-baryonic matter ?

- A first, most relevant question is if DM, besides gravitational effects also couples quantum-mechanically with electroweak interactions. If this is so at some level one might expect collisions in the laboratory between DM and ordinary particles, like for instance the so called WIMP particles.

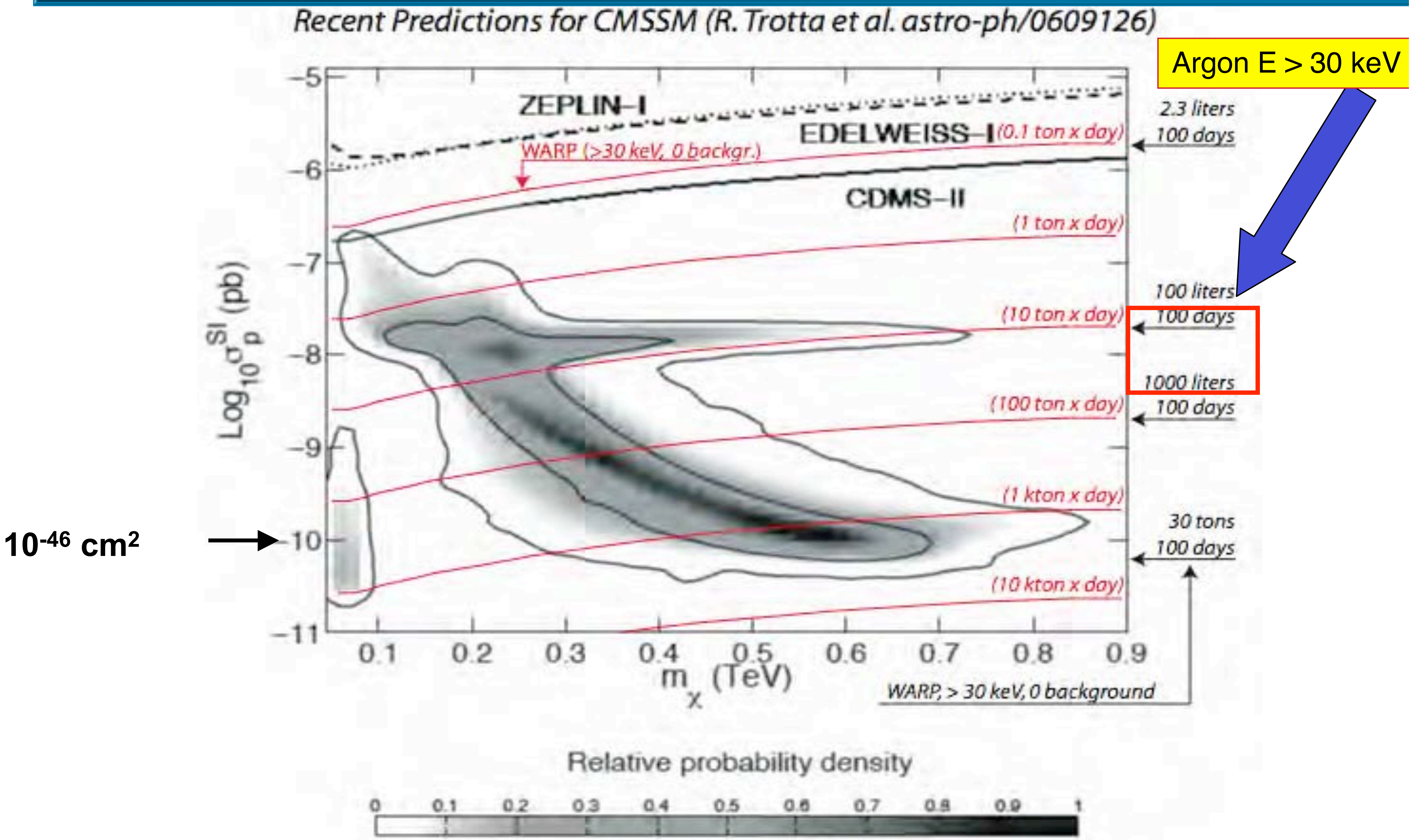


Coherent neutrino-like Xsect, is taken for purpose of illustration



- Lest we become overconfident, we should remember that nature has many options for particle generated dark matter, some of which less rich than with SUSY.
- With sufficiently sensitive searches we may confirm or exclude the electroweak coupling. *Indeed DM may be an exclusive realm of gravitation.*

Predictions of relic Susy/WIMP



Choice of the Target

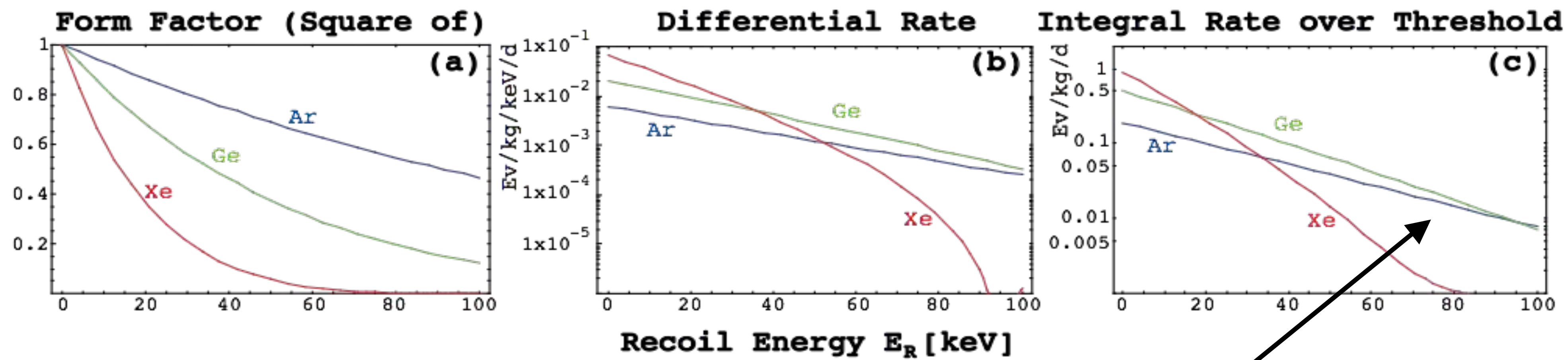
Direct WIMP detection is based on the identification of nuclear recoils from elastic WIMP-nucleus interactions

$$\frac{dR}{dE} = R_0 \cdot S(E) \cdot F^2(E) \cdot I$$

Spectral Function

Nuclear Form Factor

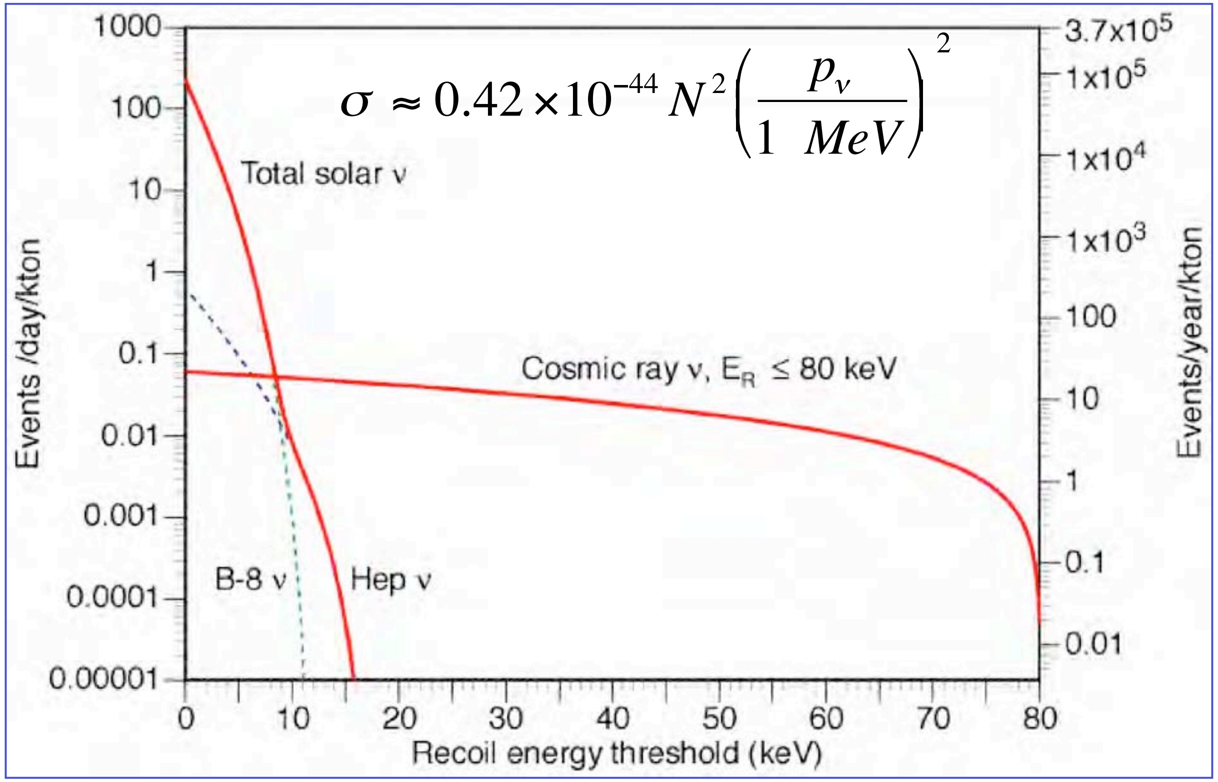
Spin-dependent Term



- Increase of interaction rate due to coherence ($\propto A^2$) is typically compensated, at increasing recoil energies, by the form factor.
- For energy thresholds in the range 20 ÷ 30 keV the integral rate for most commonly used targets is very similar.
- For WIMP masses > 100 GeV low A targets retain a significant rate of "gold plated" events with recoil energy > 60 keV.

Neutrino-induced nuclear recoils

- Neutral current induced nuclear recoils due to solar and cosmic ray neutrinos produce an irreducible background.
- The more abundant electron related neutrino events are removed by the signature of the detector
- For cosmic ray neutrinos, which exhibit an essentially flat recoil energy distribution, an upper limit $E_R < 80$ keV has been introduced.



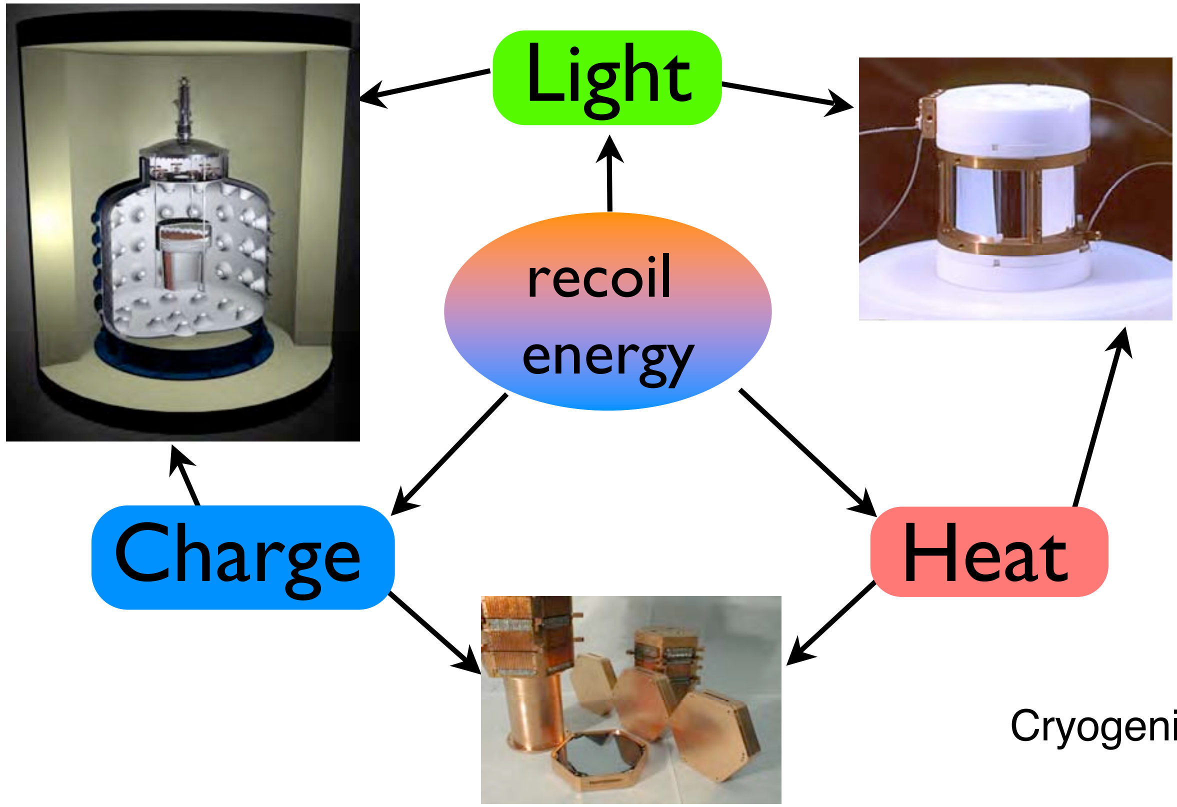
- The Argon neutrino background within 30 keV $\le E_R \le$ 80 keV is $\approx$ 0.033 ev/kton/day, just below the parameter independent WIMP limit, > 0.1 ev/kton/day.
- Therefore the neutrino background leaves open a wide rate window over which a search for a WIMP signal may be experimentally conducted.

Discrimination Methods

Nuclear Recoils (Neutrons, WIMPs) vs.
Electron Recoils (gammas, betas)

ZEPLIN
XMASS
XENON
ArDM
WARP

Liquid Argon, Xenon



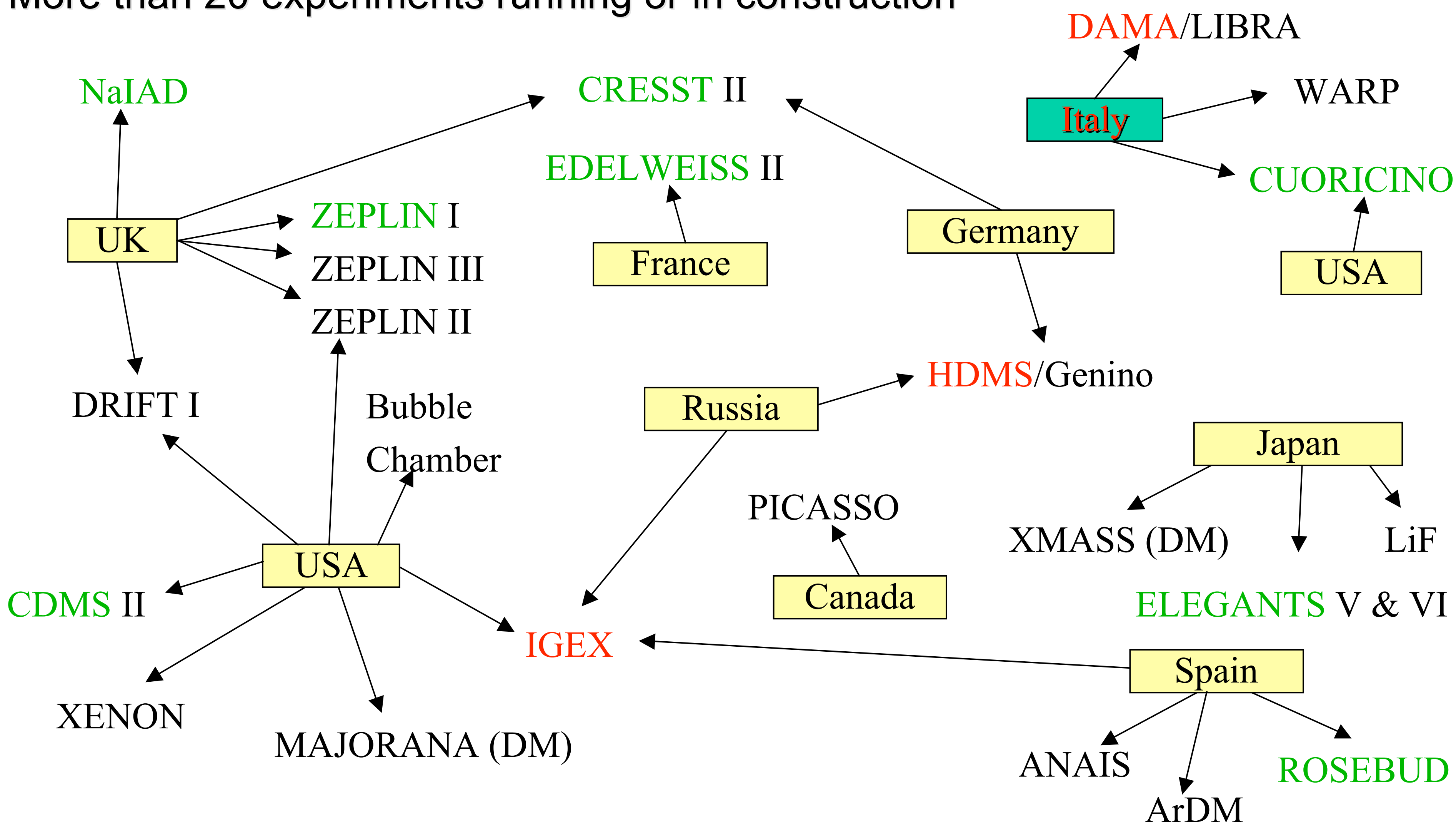
CRESST

Cryogenic, 30 milli-K

CDMS, EDELWEISS

Competition

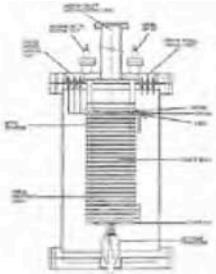
More than 20 experiments running or in construction



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 ($\lesssim$ 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.

Twenty years of development of ultra-pure cryogenic liquids



24 cm drift wires chamber

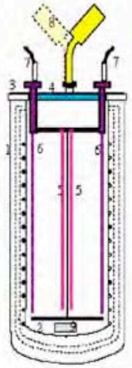
CERN 1

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

Equivalent Oxygen contamination ≈ 100 pptrillion

2

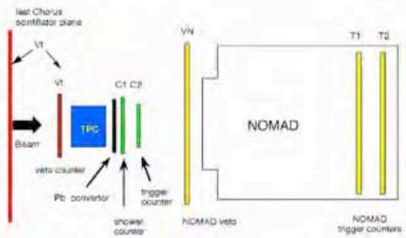
3 ton prototype



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

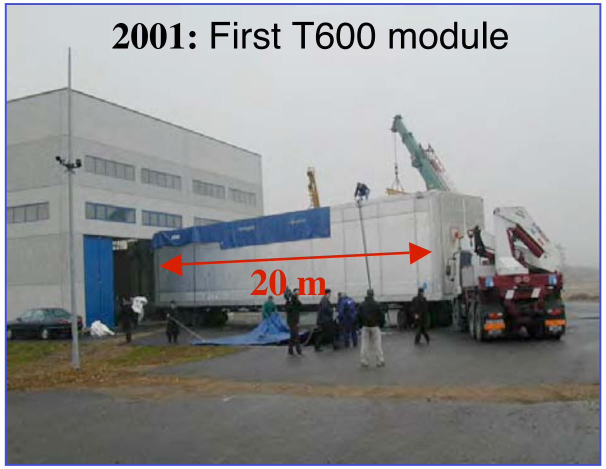
1997-1999: Neutrino beam events measurements. Readout electronics optimization. MLPB development and study. 1.4 m drift test.

4

10 m3 industrial prototype

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

T600 detector



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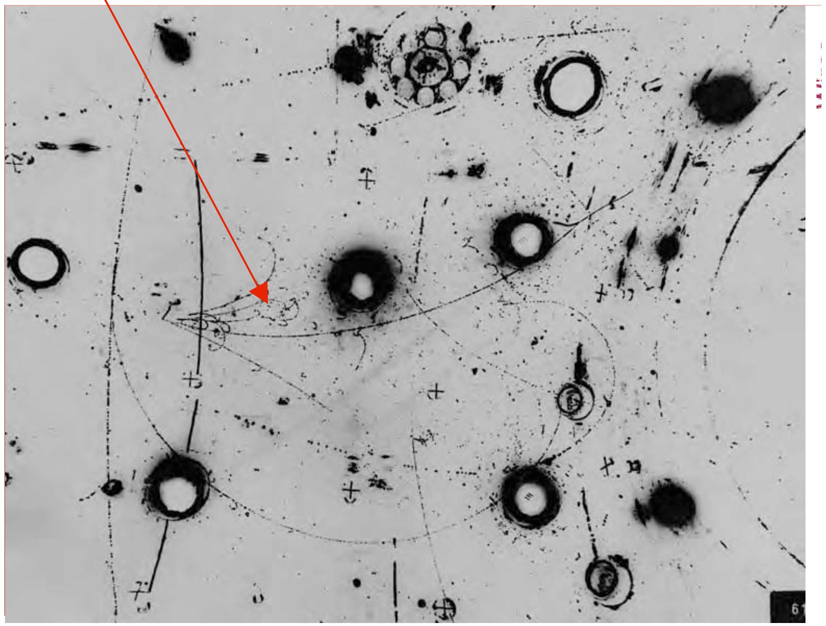
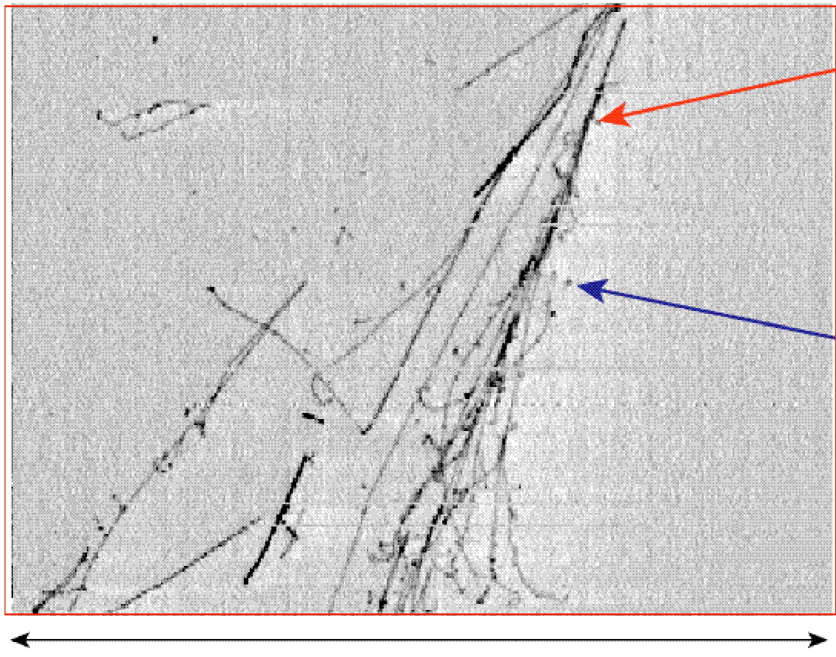
Cooperation with industry

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

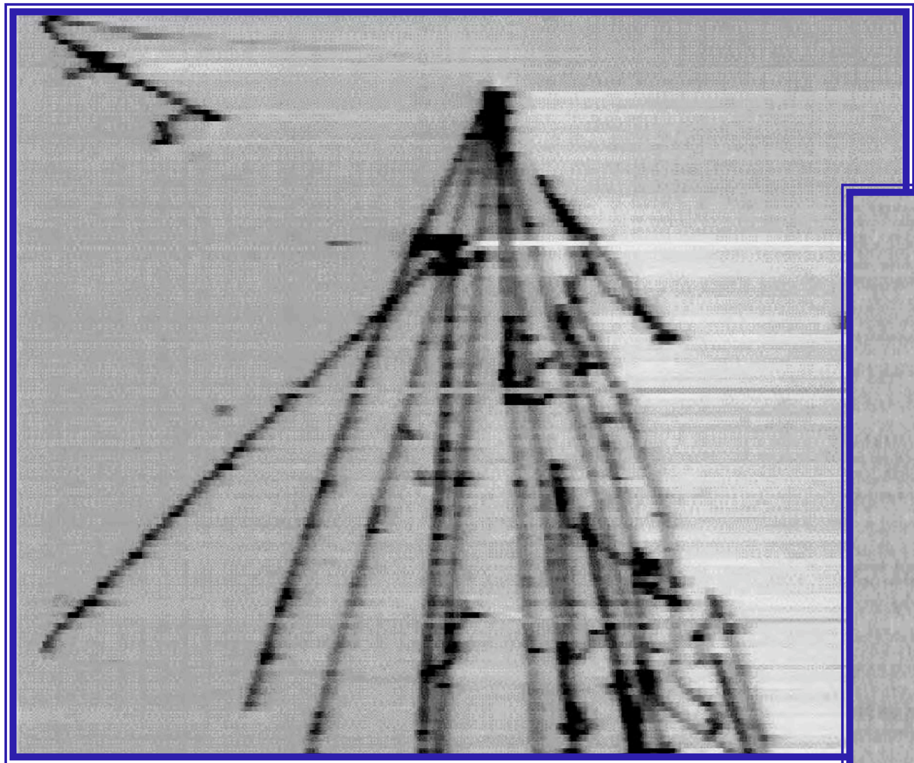
LAr is a cheap liquid (≈1CHF/litre), vastly produced by industry

Bubble diameter ≈ 3 mm (diffraction limited)

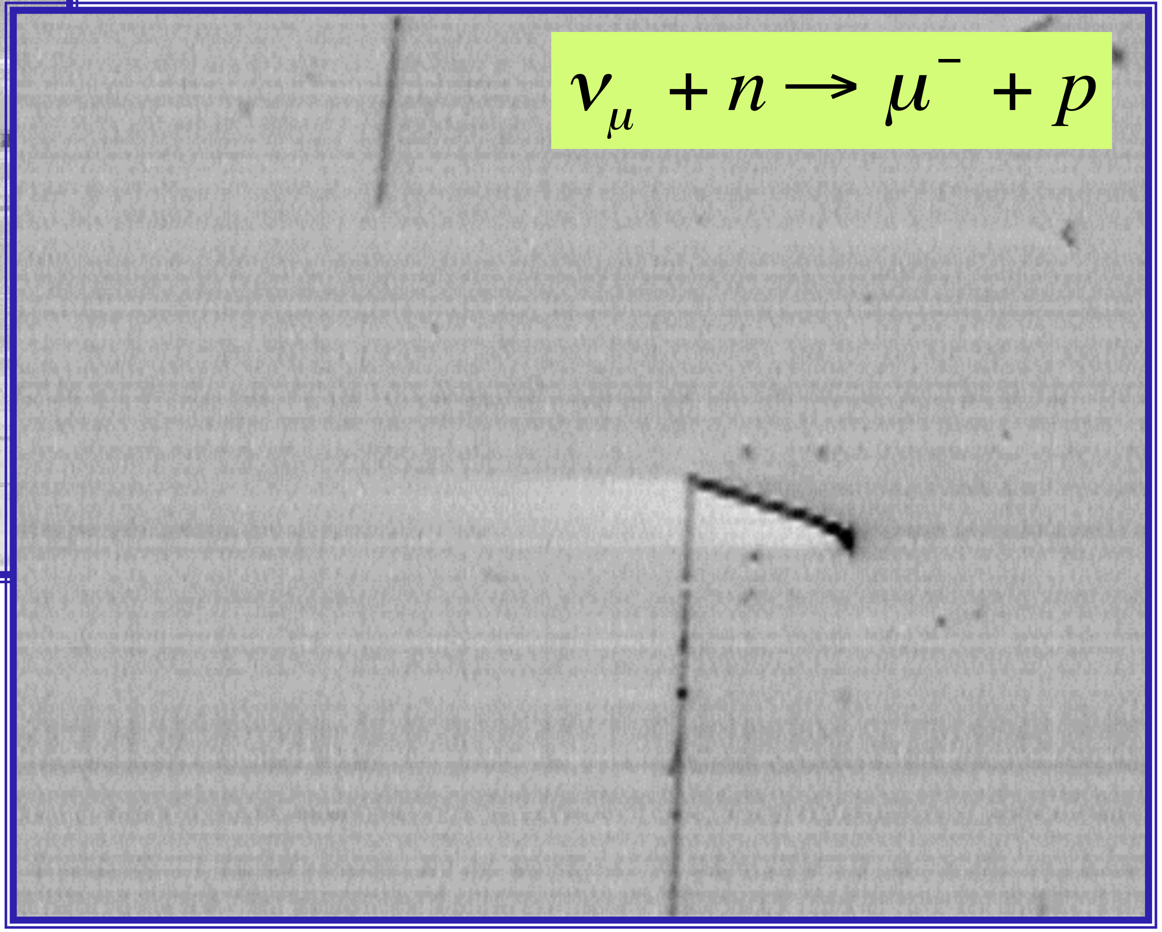
Gargamelle bubble chamber	*ICARUS electronic chamber*
	

Medium	*Heavy freon*			Medium	*Liquid Argon*	
Sensitive mass	3.0	ton		Sensitive mass	Many ktons	
Density	1.5	g/cm^3		Density	1.4	g/cm^3
Radiation length	11.0	cm		Radiation length	14.0	cm
Collision length	49.5	cm		Collision length	54.8	cm
dE/dx	2.3	MeV/cm		dE/dx	2.1	MeV/cm

50 liter prototype in CERN West Area neutrino beam



$$\nu_\mu + X \rightarrow \mu^- + many\ \ prongs$$



WArP Collaboration

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Why searching WIMP's with LAr ?

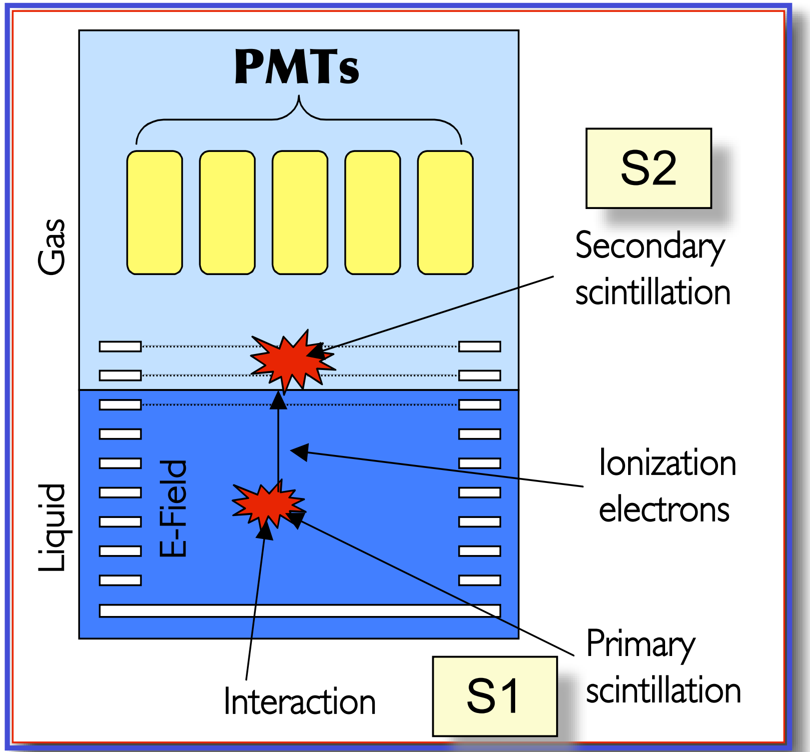
- Cryogenic Noble liquids or gases permit simultaneous detection of both ionisation and scintillation
- Why liquid Argon ?
  - ⇨ The largest scintillation yield for signal from slow ($\beta \approx 10^{-3}$) recoils from WIMPS
  - ⇨ Two components of scintillation yield, $\tau_{singlet}$ = 7ns and τ_{riplet} = 1.6 μs, different relative intensities for fast and slow recoils.
  - ⇨ Strong recombination of ionisation effect due to columnar charge density. Electrons drifted away may be transmitted from liquid to gas and multiplied to produce delayed signal.
  - ⇨ Low cost and easy availability of truly large volumes.
  - ⇨ Possibility of an integrated active anticoincidence and an effective neutron shield
- Xenon and Neon are candidates, but →
- Ar is contaminated by Ar-39 (≈1 bq/kg) and it may need isotopic separation

	Singlet Lifetime (ns)	Triplet Lifetime (ns)
Ne	$< 18.2 \pm 0.2$	14900 ± 300
Ar	7.0 ± 1.0	1600 ± 100
Xe	4.3 ± 0.6	22.0 ± 2.0

The WARP experiment

- **<u>Two simultaneous criteria</u> 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 ($\approx$ 10 ns) and slow ($\approx$ 1.6 μs) components of the emitted UV light. This is an unique feature of Argon.
- Scintillation yield is $\approx$ 3-4 phel. / keV_{ion} and the detection WIMP threshold is $\approx 20 \div 30$ keV_{ion}

Double Phase Argon Chamber

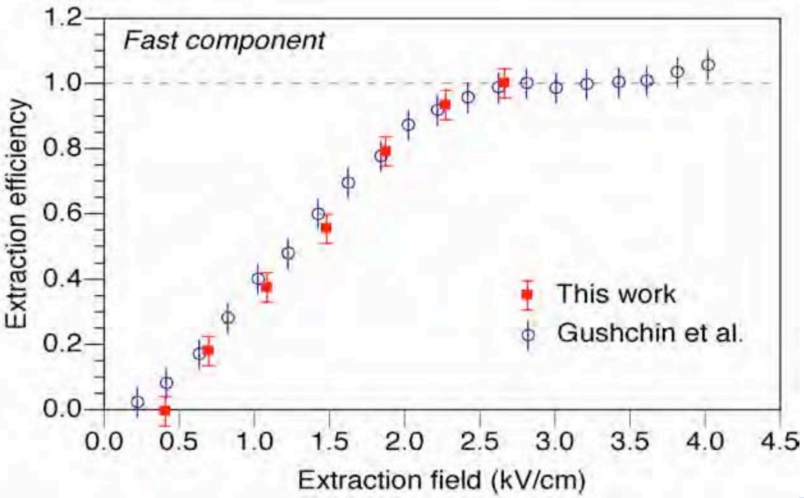


Recoil-like event
Slow component ≈ 10 %

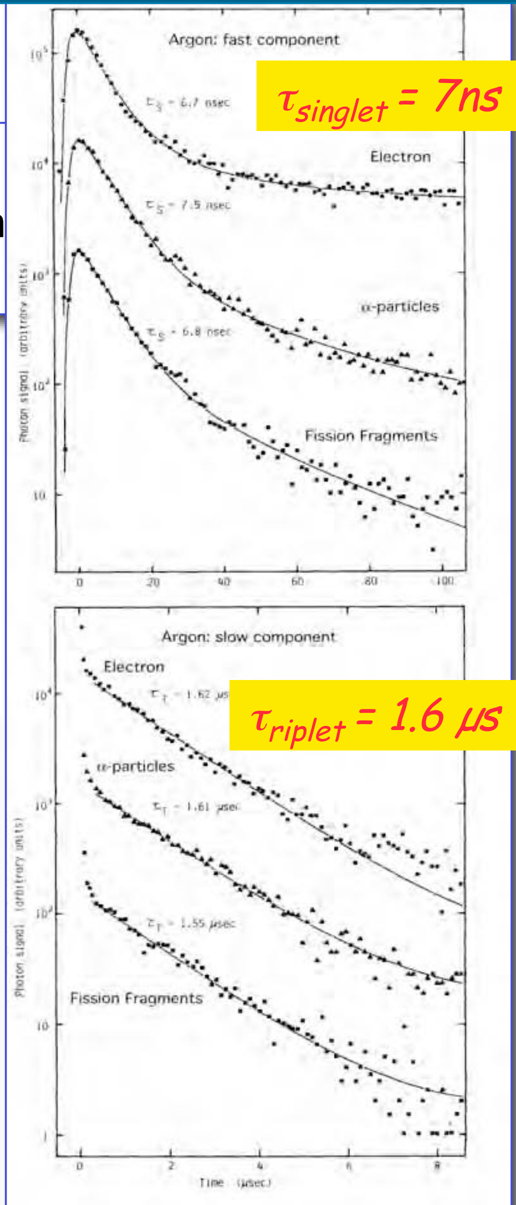
γ-like event
Slow component ≈ 70 %

Basic Technical Elements

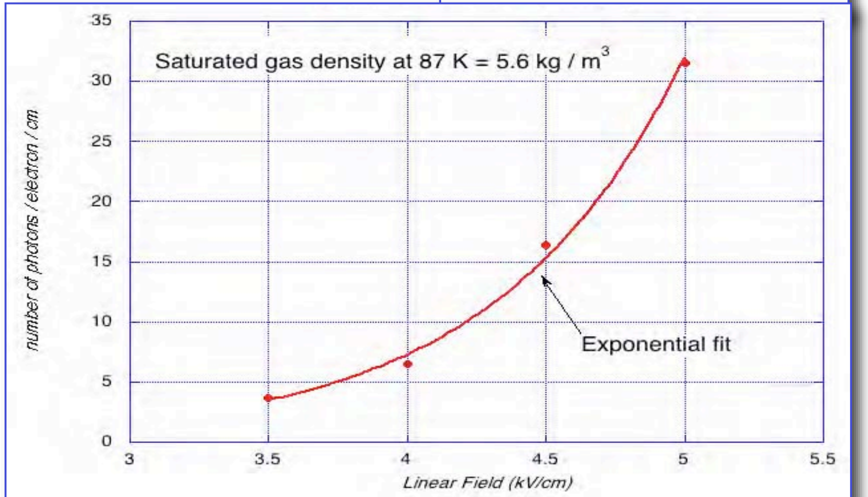
Electrons extraction from liquid to gas



Primary Scintillation in LAr

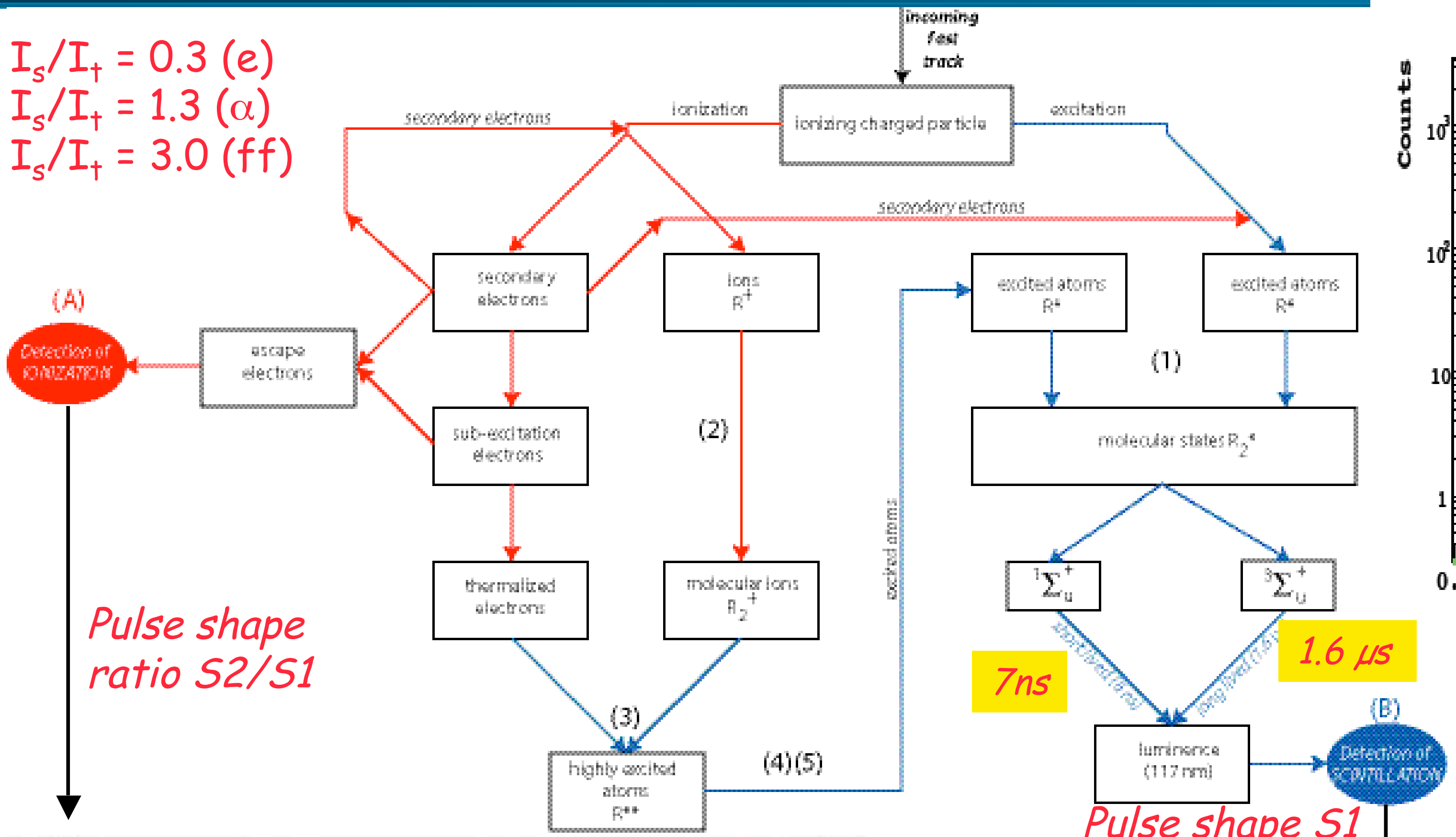


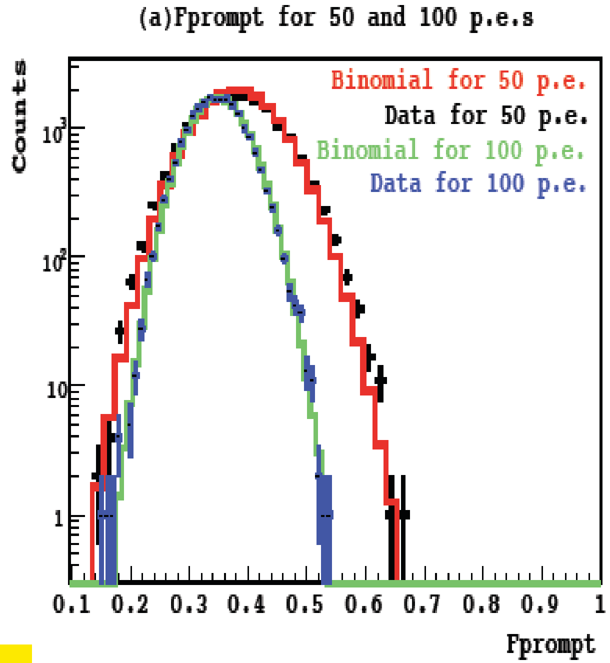
Secondary Light Production

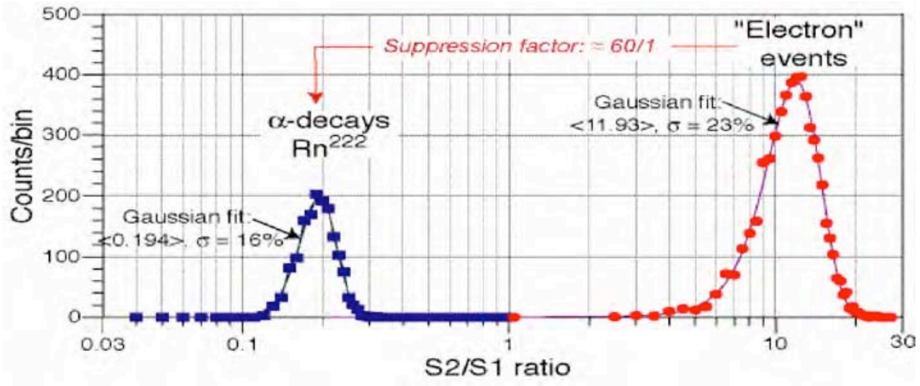


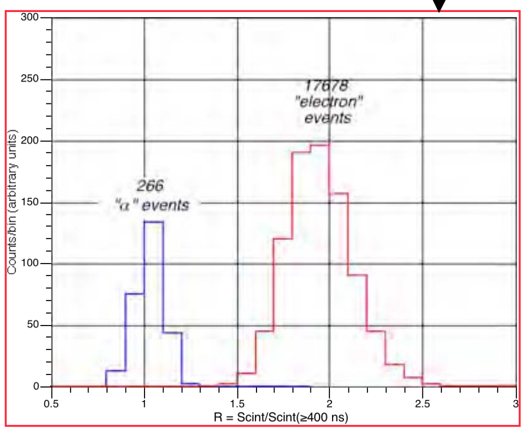
The case of Argon: two main selection criteria

$I_s/I_t = 0.3$ (e)
$I_s/I_t = 1.3$ (α)
$I_s/I_t = 3.0$ (ff)





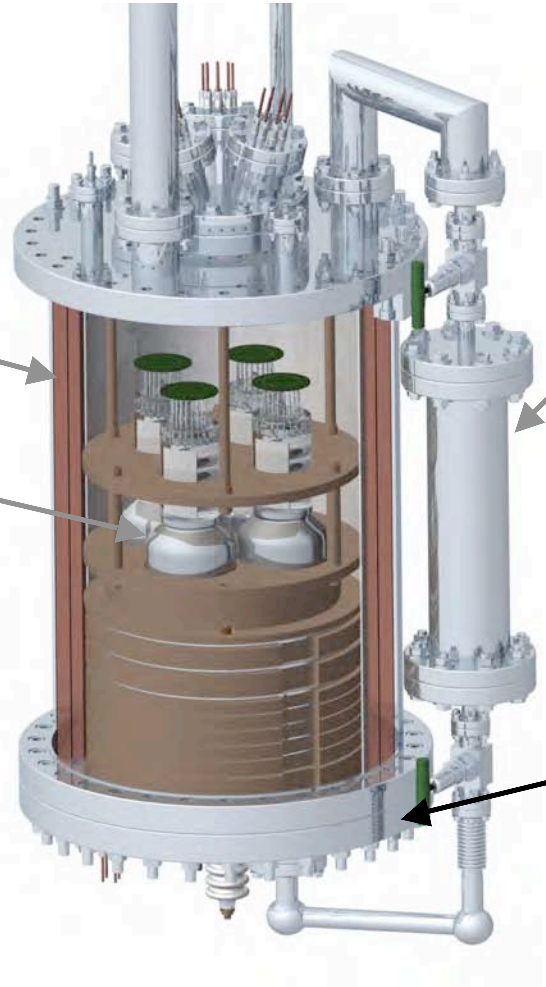




Experimental comparison of short/tot electrons F_{prompt} for 2.3 litre chamber

Rejection power better than ≈ 3 10^{-7} for nuclear recoils

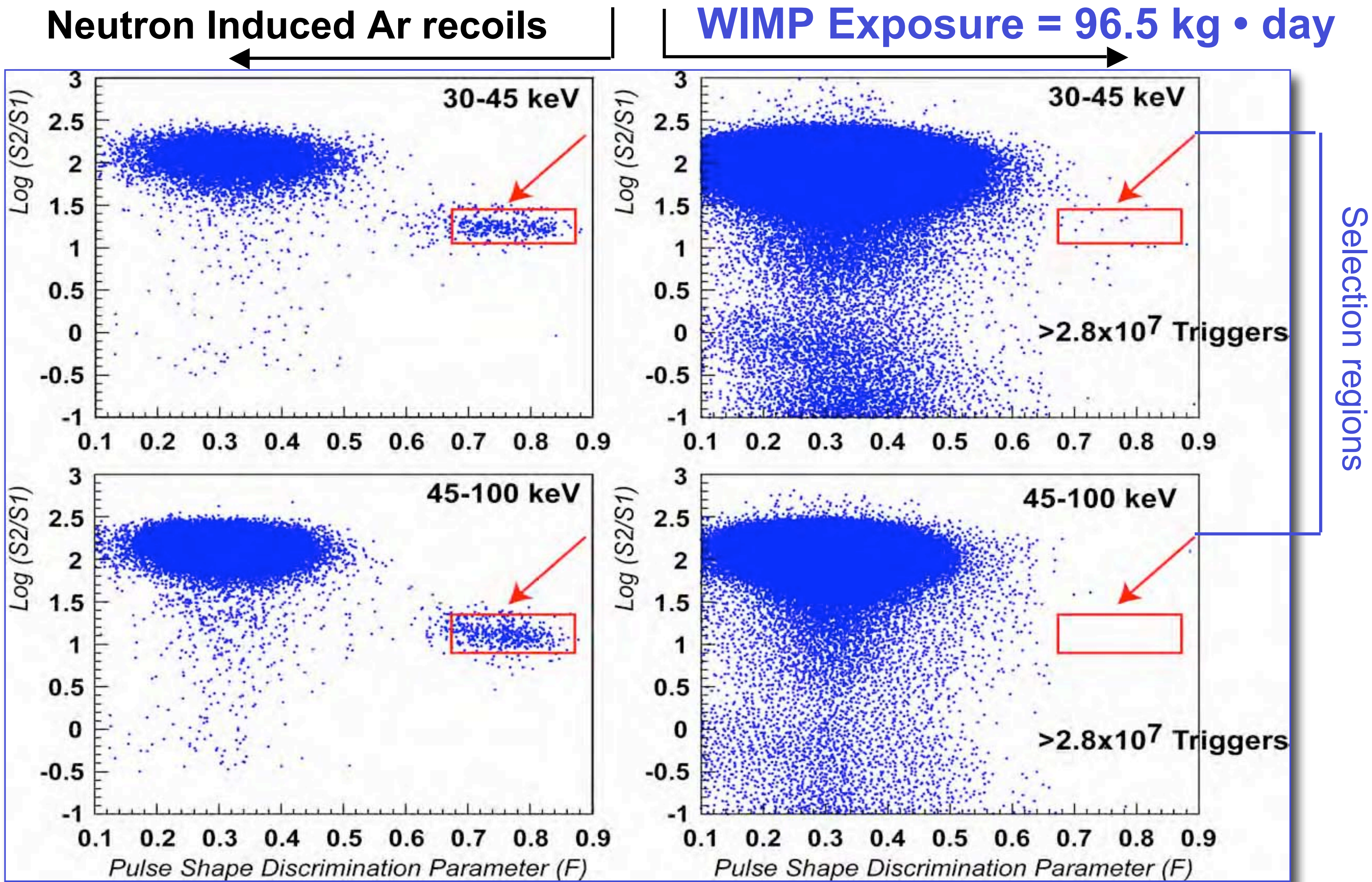
Present 2.3 litres small test chamber



residual rate ≤ 2 Hz

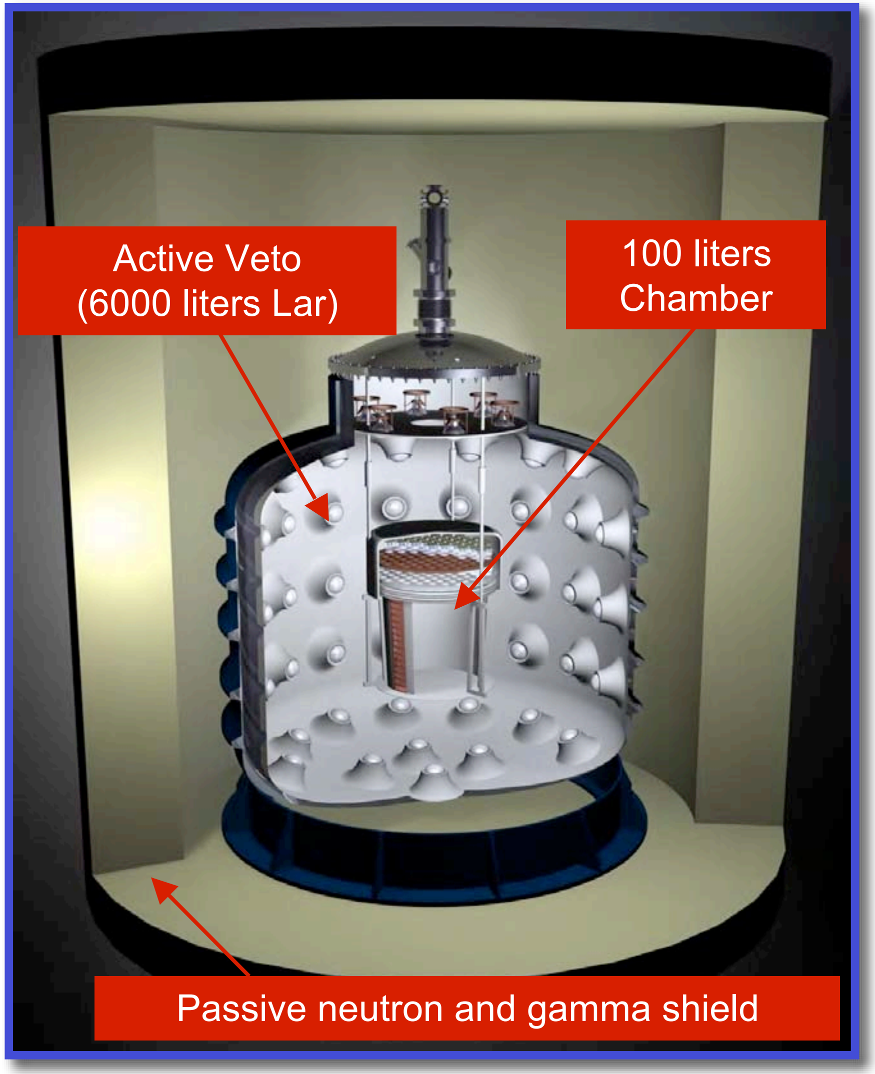
Identifying WIMP Candidates with 2.3 litre chamber

Rejection power better than ≈ 3 10^{-7} for electron recoils



The 100 litre 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 2007.
- Operational by second half of 2008.
- Ultimate sensitivity -> cross sections up to 10^{-8} pb on proton equivalent.
- Designed also to host a 1 ton detector.

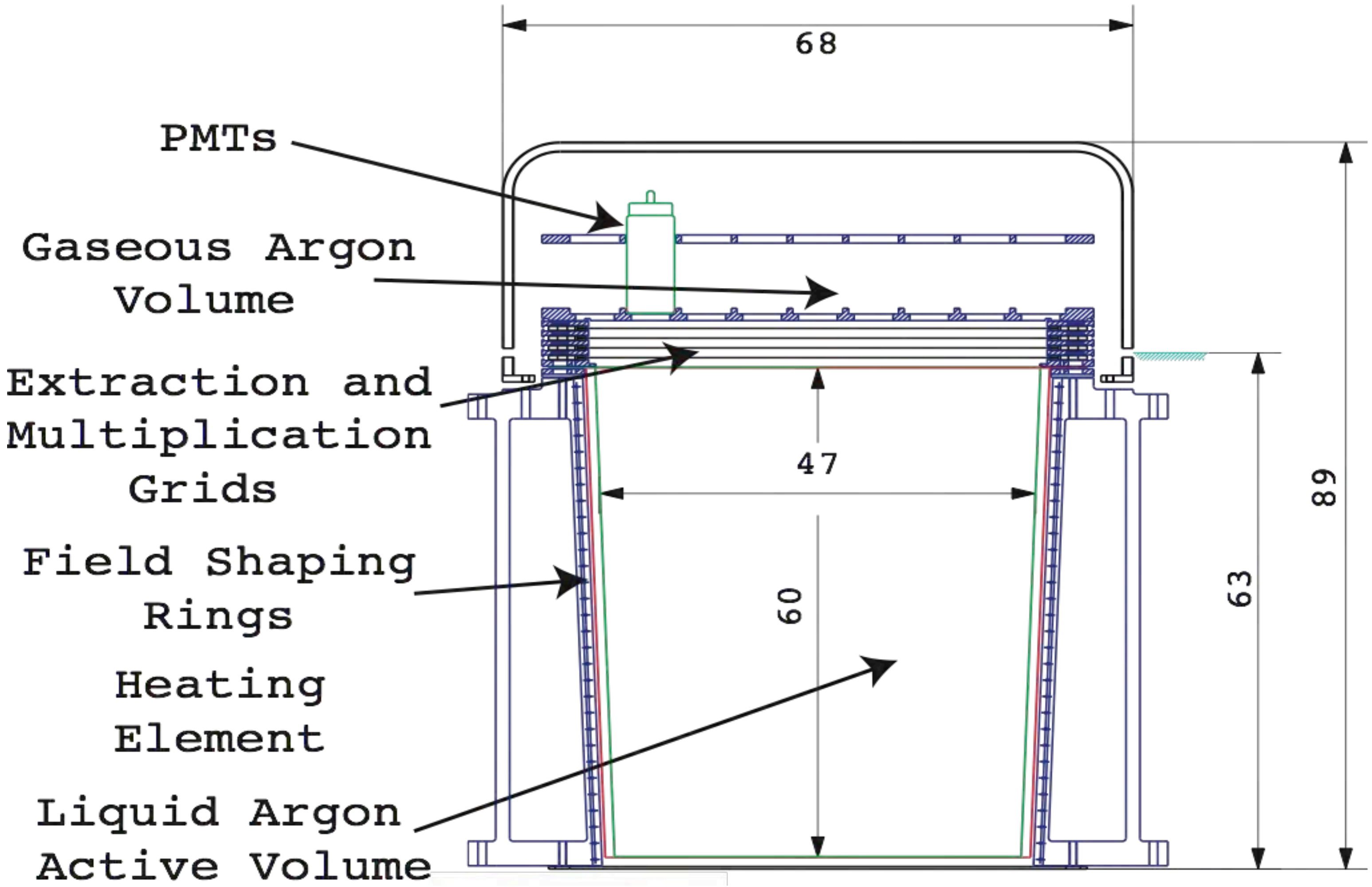


Main 100 liters cryostat (July 2007)

Main parameters of cryogenic system

Dewar Internal Height	380 cm
Dewar Internal Diameter	290 cm
Dewar Weight	12000 kg
LAr Volume	**26000 liters**
Insulation	Vacuum + SuperInsulation
Operating Pressure	1.5 bar abs
Operating Temperature	89 K
LAr Filling Speed	500 liters/hr
Nominal Gas Recirculation Rate	10 liters/hr
Maximum Gas Recirculation Rate	20 liters/hr
LAr Consumption Rate	10 liters/hr

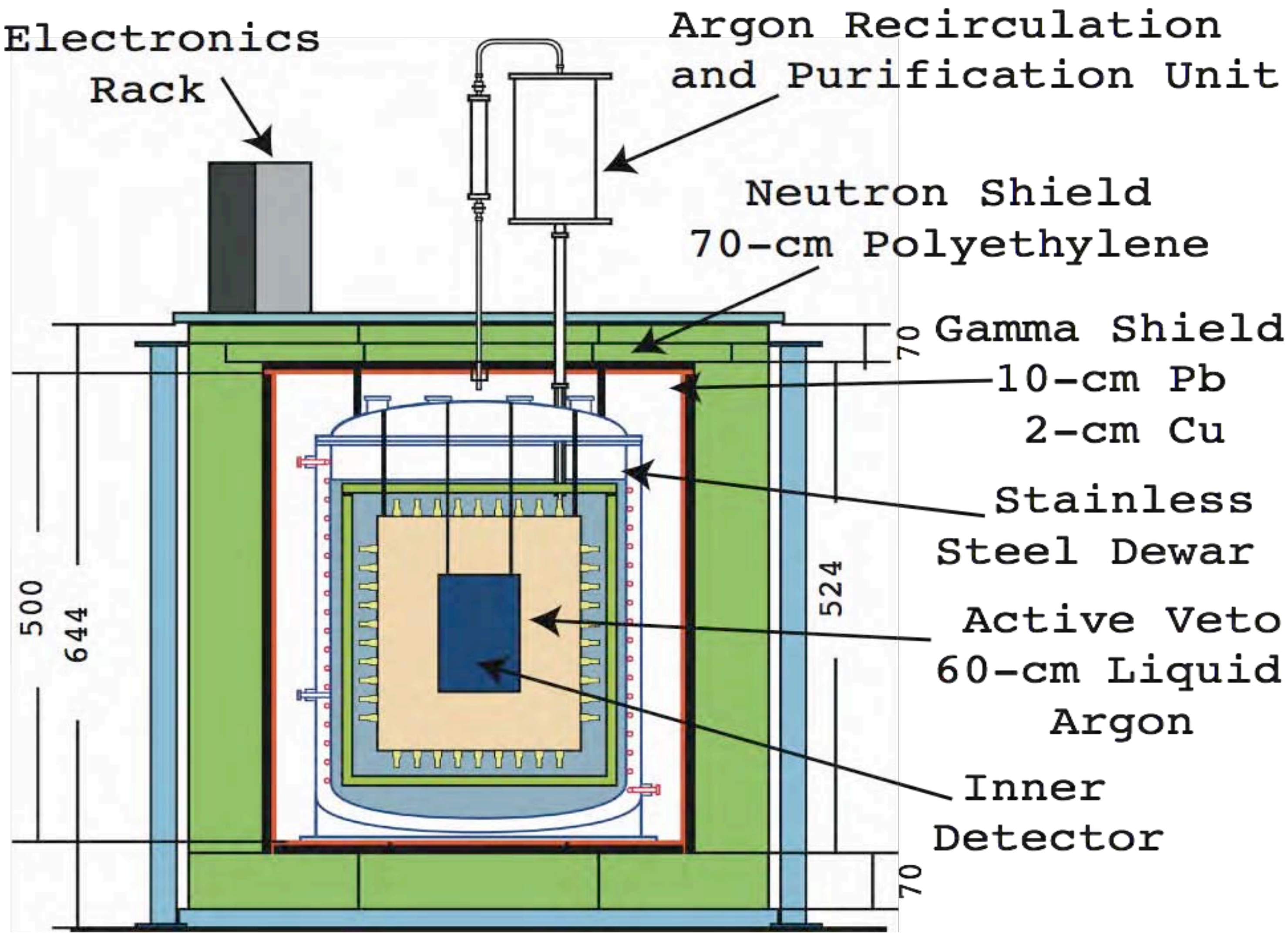
Inner vessel



Main parameters of Inner detector

External Heigth	89 cm
External Diameter	68 cm
Internal Heigth	60 cm
Maximum Internal Diameter	50 cm
Minimum Internal Diameter	46 cm
LAr Volume	**100 liters**
LAr Mass	140 kg
PMTs	41 x 3" ∅
Coverage	7%
Walls Reflectivity	94%
Light Yield	3-4 photoelectrons/keV
Trigger Threshold	$\lesssim$5 keV
Nominal Drift Field	1 kV/cm
Maximum Drift Field	1.5 kV/cm

Mechanical layout



Main parameters of active veto

External Heigth	260 cm
External Diameter	220 cm
Internal Heigth	220 cm
Internal Diameter	180 cm
Minimum LAr Thickness	60 cm
LAr Volume	5600 liters
LAr Mass	7850 kg
PMTs	400 x 3" ∅
Coverage	10%
Walls Reflectivity	94%
Light Yield	3 photoelectrons/keV
Threshold	8 keV

Conclusions

- Argon is proven to be an excellent candidate for WIMP Dark Matter Search.
- Multi-years effort firmly established technique to be also implemented, potentially, over very large scales (see ICARUS experience with 600 ton detector).
- Recoil Identification and Beta Rejection Power at unprecedented levels (for E < 100 keV).
  - ➥ Established within the 2.3-liter prototype program, intentionally designed as “high background detector”.
- 140-kg detector commissioned within 2008.
  - ➥ Will bring further upgrade on light yield. Background minimized.
- Big jump (x100) in sensitivity for WIMP Dark Matter Searches.
- The inner detector may be increased to 1.4 ton at a later stage
- Active neutron coincidence and bi-phase system with two independent and redundant criteria will offer ability to “certify” a possible WIMP discovery!
- S-WIMP : An ultimate new proposal for a detector with bi-phase of > 10 ton active mass and depleted Ar-39 under active preparation in order to explore cross sections up to 10^{-10} pb on proton equivalent.

Thank you !