Direct Dark Matter Searches with WARP
-
Discovery of Underground Source or Argon depleted in ^{39}Ar

Cristiano Galbiati
Princeton University
-
FNAL
Batavia, IL
October 1, 2006

Direct Dark Matter Detection: Very Exciting Moment

WIMP Dark Matter well supported by independent cosmological arguments, CMB and astrophysical observations, SUSY models

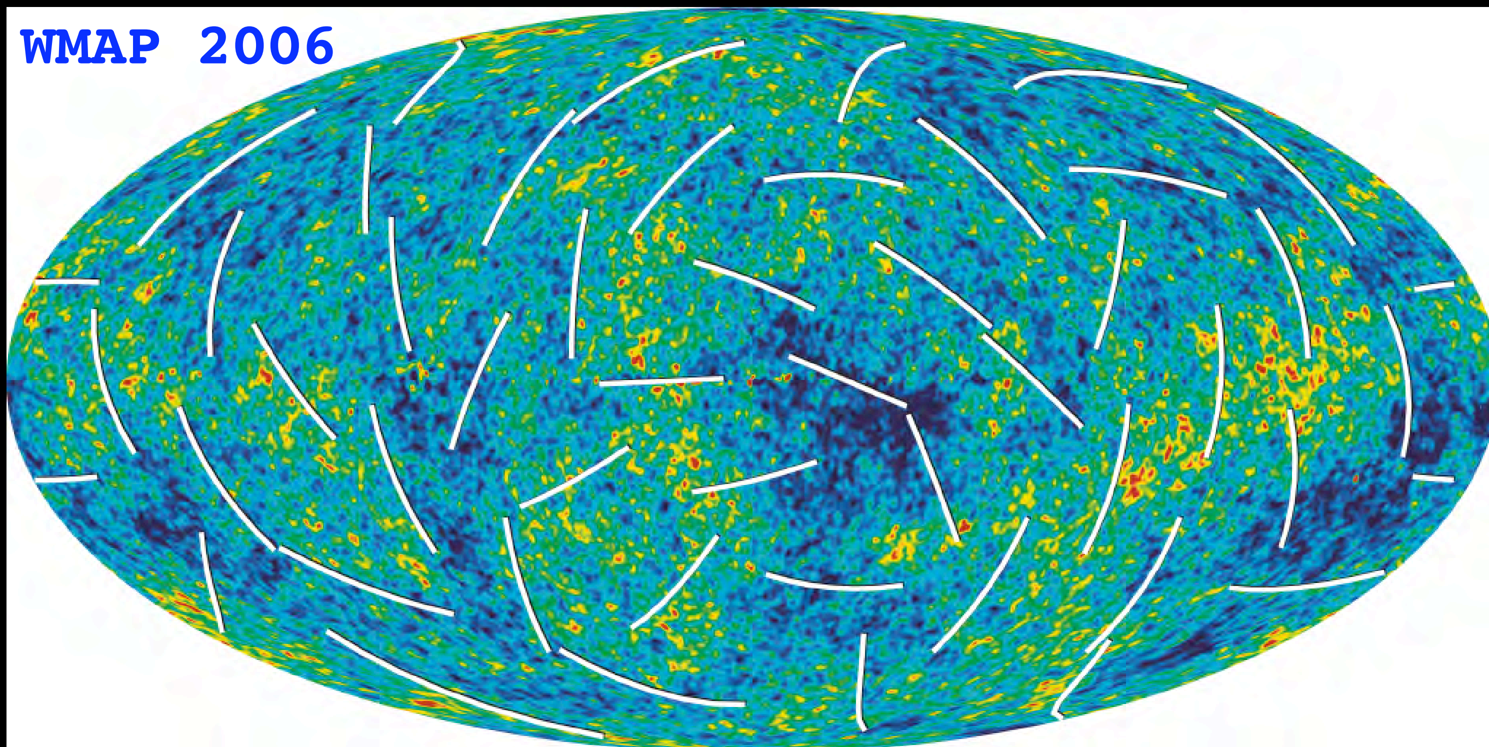
Very High Discovery Potential

Field set and ready for a "quantum leap" in sensitivity (many orders of magnitude) thanks to liquified noble gas detectors

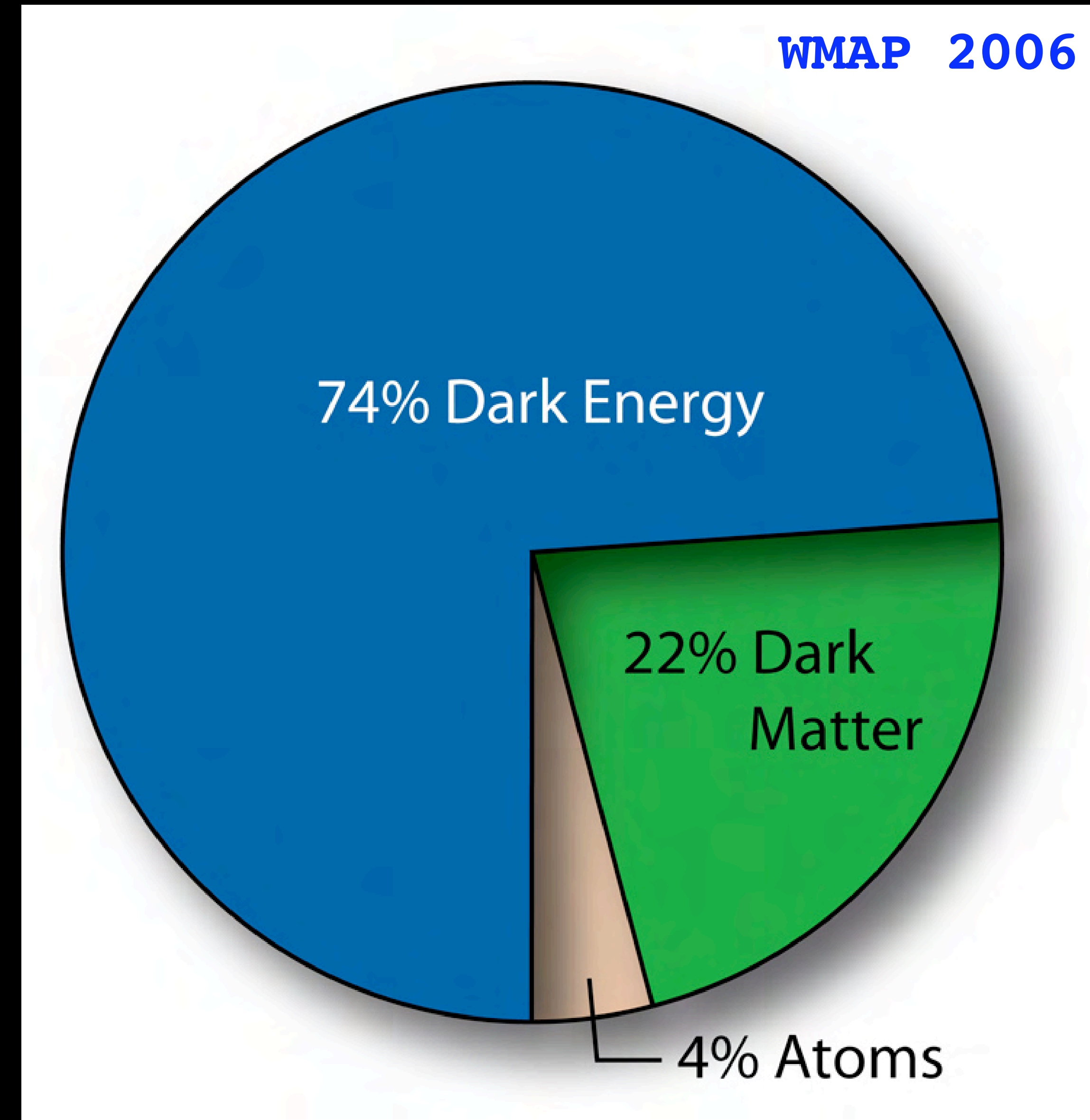
liquified noble gas detector to be scale by x100 - x1000 soon!

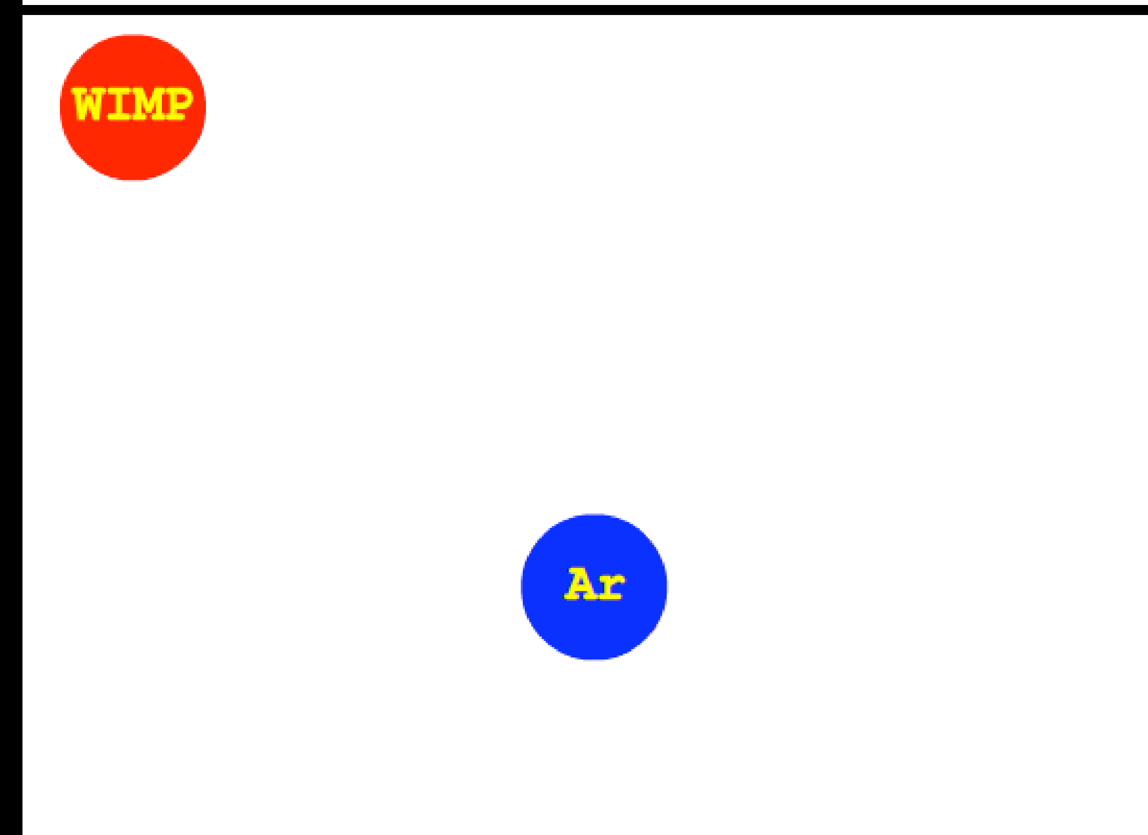
Exciting developments in particle, atomic physics and and significant improvements detector technology

Dark Matter



- Dark Matter comprises 22% of Universe
- Intriguing Hypothesis: Weakly Interacting, Massive Particles (WIMPs)
- Predicted by SUSY theories (neutralinos etc.)
- How to detect WIMPs?





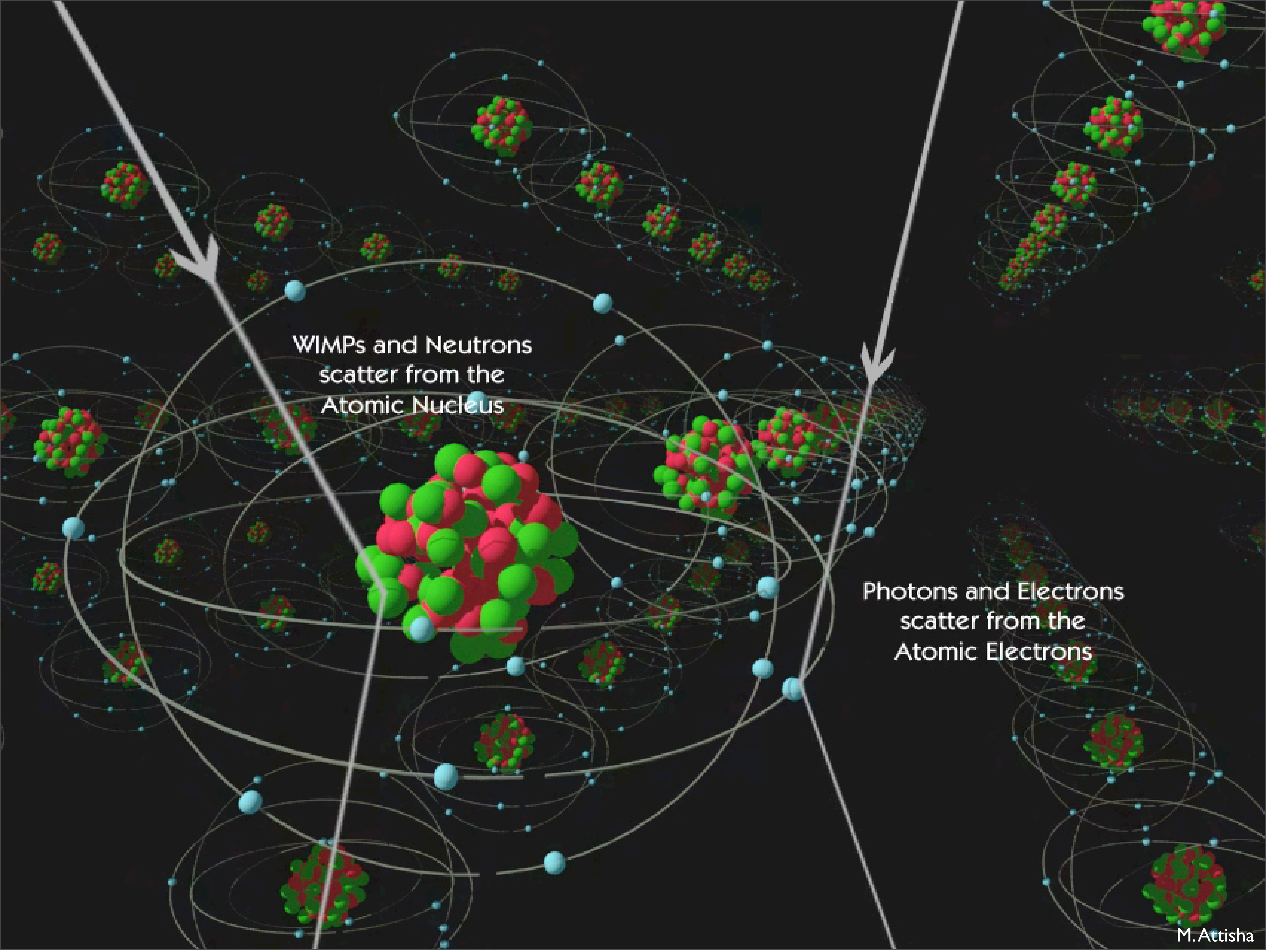
WIMP Coherent Scattering

The highest sensitivity is obtained by exploiting elastic neutral-current scattering of nuclei by WIMPs. The idea was originally proposed by Drukier and Stodolski to detect solar and reactos neutrinos [PRD **30**, 2295, 1985)].

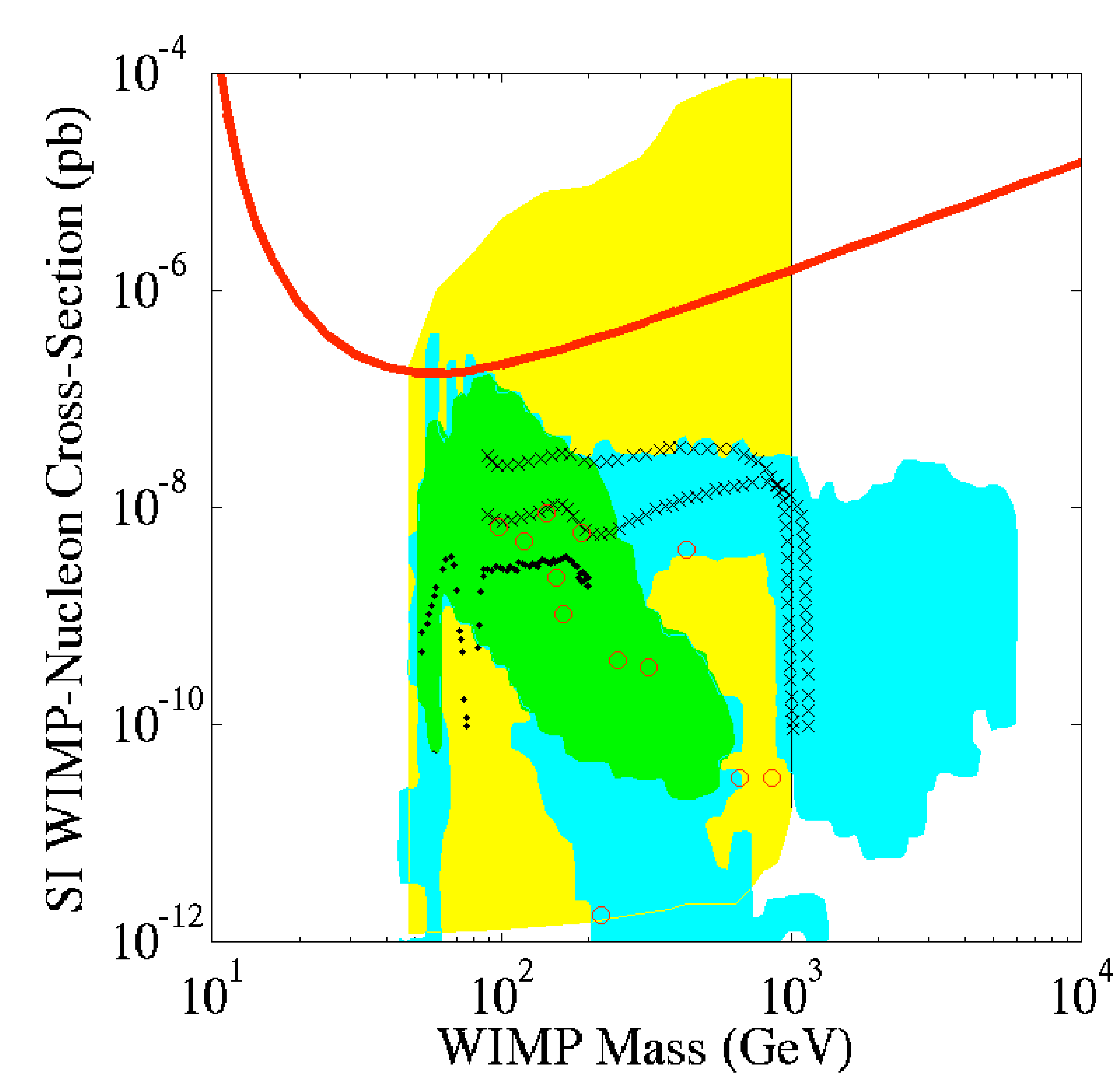
Sensitivity to hypothetic WIMPs detailed by Goodman and Witten [PRD **31**, 3059 (1985)].

Halo particle of mass *m* (100 GeV), velocity *v* = 300 km/s on nucleus of mass *M* (100 GeV):

$p = 2mv$ (max possible value)
$\lambda = hbar/p = hbar/(2mv) =$
$= (197 \text{ MeV fm } c^{-1})/(2 \times 100 \text{ GeV } c^{-2} \times 10^{-3}\, c) \sim \text{fm}$
$R_A = 1.0 \times A^{1/3}$ fm
$E_{kin} = (2mv)^2/2M \sim 2mv^2 =$
$= (2 \times 100 \text{ GeV } c^{-2} \times 10^{-3}\, c)^2 = 200$ keV


WIMPs and Neutrons
scatter from the
Atomic Nucleus
Photons and Electrons
scatter from the
Atomic Electrons
M. Attisha

Supersymmetry Reach



Current CDMS II limit
PRL 96, 011302 (2006)
(~20 attobarn^{-1})

Kim et al. 2002
yellow (MSSM scan)

Baltz & Gondolo 2004
cyan (mSUGRA)
green (with g-2 constraints)

Battaglia et al. 2004
red circles (post-LEP benchmark points)

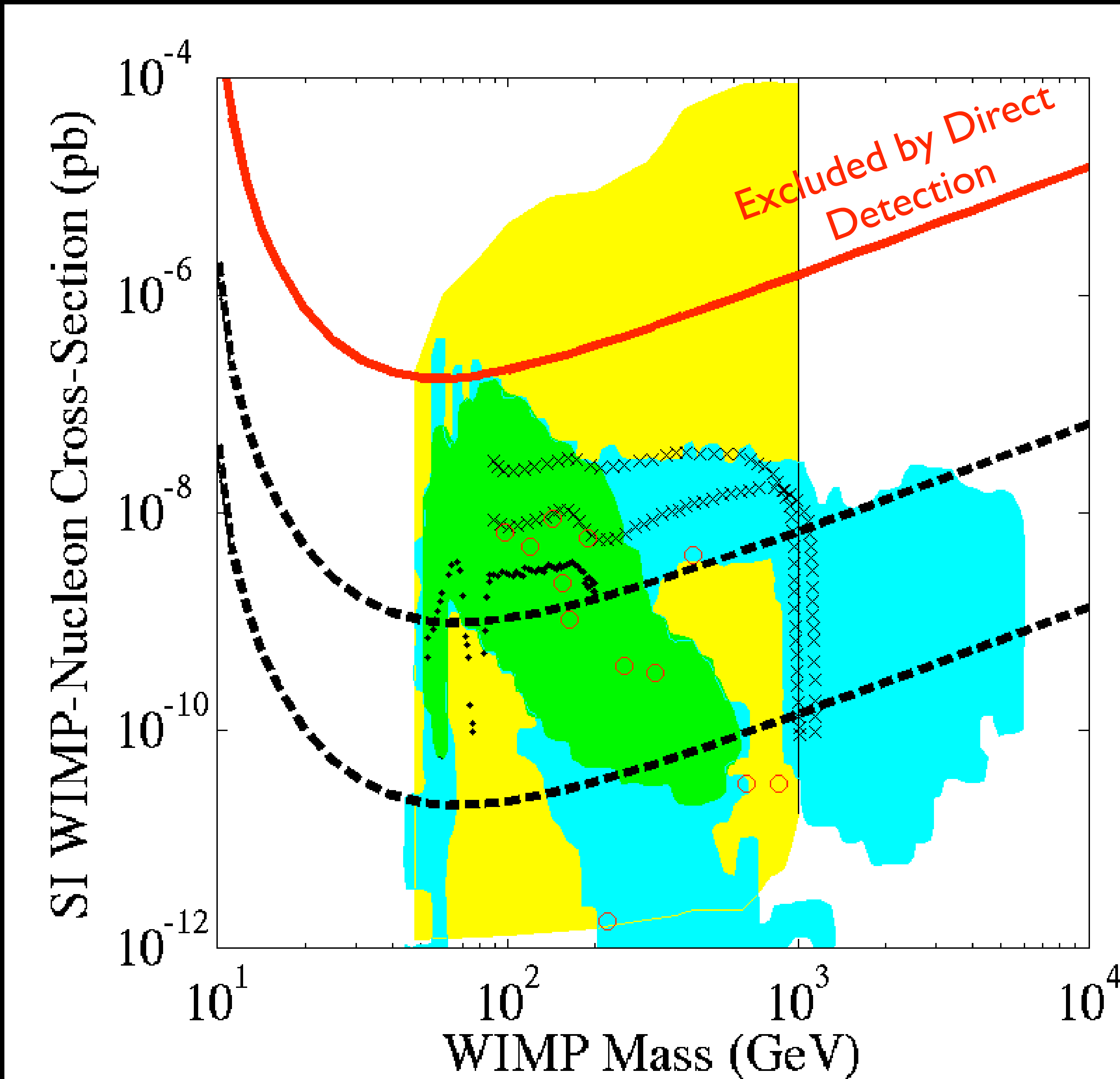
Guidice & Romanino 2004
black crosses (split SUSY)

Pierce 2004
black dots (split SUSY)

Many model frameworks
10^{-8}-10^{-10} pb

R. Schnee

Supersymmetry Reach



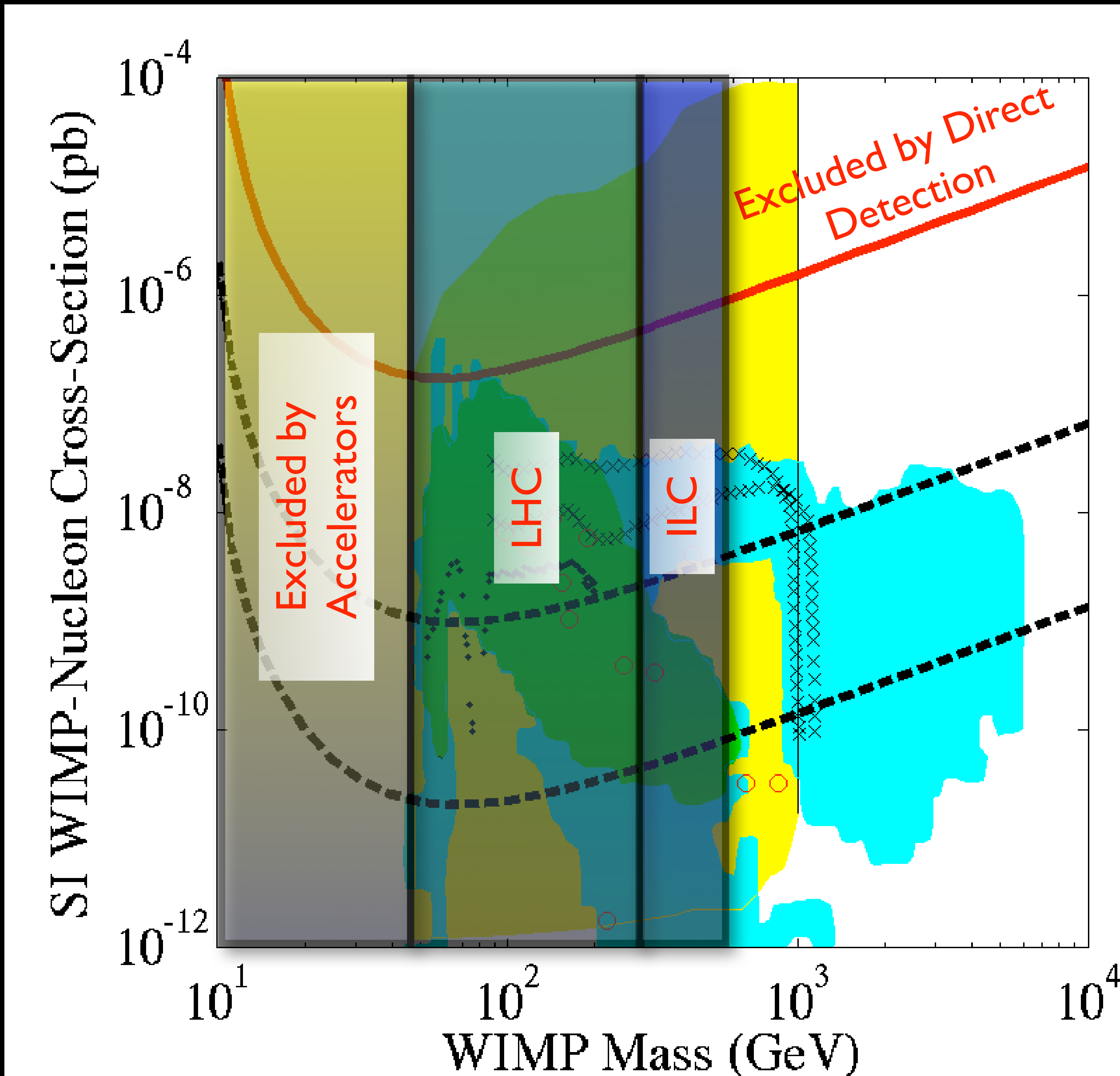
Current CDMS II limit
PRL 96, 011302 (2006)
(~20 attobarn^{-1})

25 kg of Ge or Xe
100 kg Ar

1000 kg of Ge or Xe
4000 kg of Ar

R. Schnee

Supersymmetry Reach



Current CDMS II limit
PRL 96, 011302 (2006)
(~20 attobarn^{-1})

25 kg of Ge or Xe
100 kg Ar

1000 kg of Ge or Xe
4000 kg of Ar

Direct detection is cross-section limited, sensitive to TeV WIMPs

Colliders are mass limited

R. Schnee

WARP Collaboration

INFN and Università degli Studi di Pavia
P. Benetti, E. Calligarich, M. Cambiaghi, L. Grandi,
C. Montanari, A. Rappoldi, G.L. Raselli, M. Roncadelli,
M. Rossella, C. Rubbia, C. Vignoli

INFN and Università degli Studi di Napoli
F. Carbonara, A. Cocco, G. Fiorillo, G. Mangano

INFN Laboratori Nazionali del Gran Sasso
R. Acciarri, F. Cavanna, F. Di Pompeo, N. Ferrari,
A. Ianni, O. Palamara, L. Pandola

Princeton University
A. Burgers, F. Calaprice, A. Chavarria, C. Galbiati,
B. Loer, A. Nelson, R. Saldanha

IFJ PAN Krakow
A.M. Szelc

INFN and Università degli Studi di Padova
B. Baibussinov, S. Centro, M.B. Ceolin,
G. Meng, F. Pietropaolo, S. Ventura

WARP: the Motivation

WARP: the Motivation

- TARGET: Atomic number 40
  No loss of coherence at intermediate energies
  Complete retention of gold plated events (60-120 keV)

WARP: the Motivation

- TARGET: Atomic number 40
  No loss of coherence at intermediate energies
  Complete retention of gold plated events (60-120 keV)

- WIMP CANDIDATES IDENTIFICATION: Highest discrimination between nuclear recoils and beta/gamma-like background
  ^{39}Ar, 1 Bq/kg → need $3x10^8$ rejection against betas (for 140 kg detector)
  WARP Collaboration, Benetti *et al.*, astro-ph/0603131

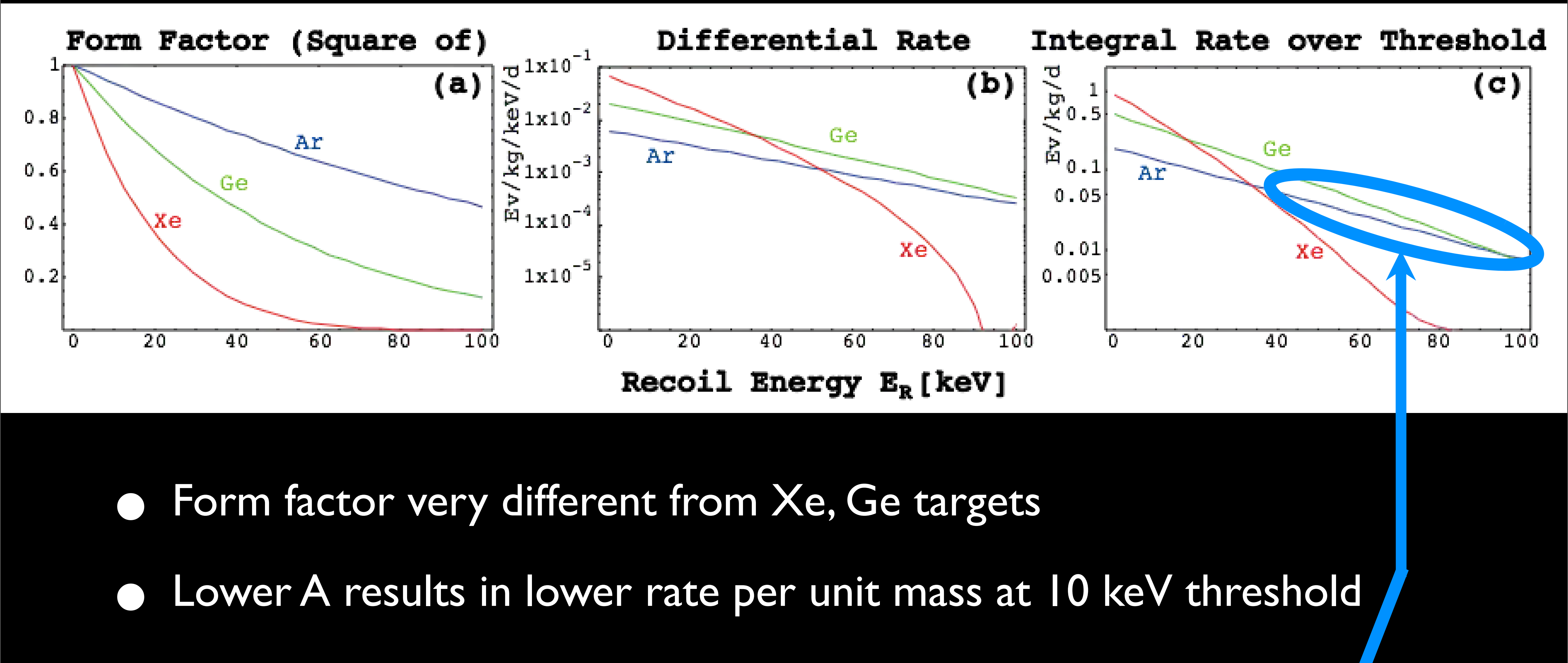
WARP: the Motivation

- TARGET: Atomic number 40
  No loss of coherence at intermediate energies
  Complete retention of gold plated events (60-120 keV)

- WIMP CANDIDATES IDENTIFICATION: Highest discrimination between nuclear recoils and beta/gamma-like background
  ^{39}Ar, 1 Bq/kg → need 3×10^{8} rejection against betas (for 140 kg detector)
  WARP Collaboration, Benetti *et al.*, astro-ph/0603131

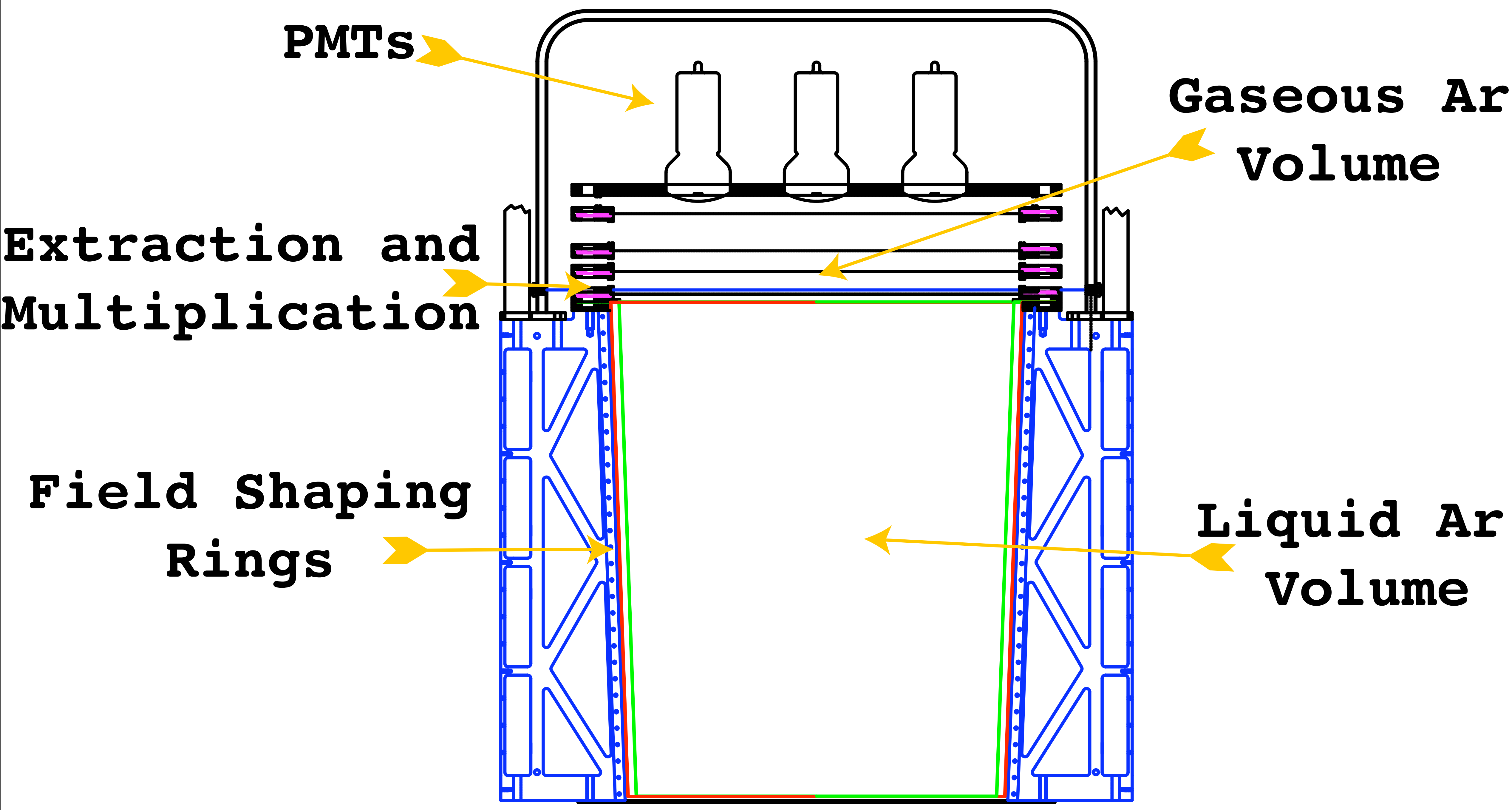
- Spin 0 for ^{40}Ar:
  Sensitive only to spin-independent interactions

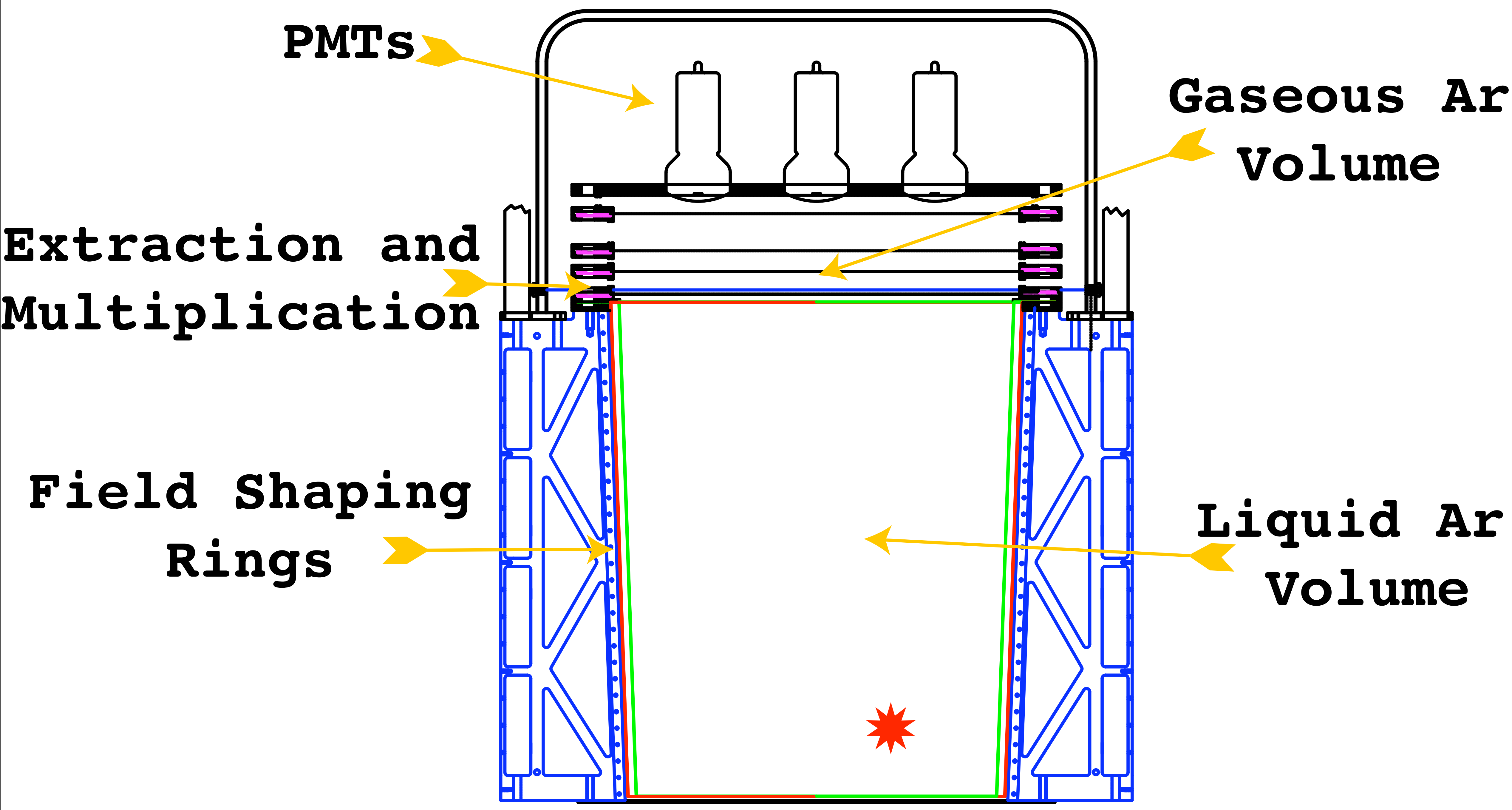
WARP: the Target



- Form factor very different from Xe, Ge targets
- Lower A results in lower rate per unit mass at 10 keV threshold
- For M_X>100 GeV, "Gold Plated" events (>60 keV) still abundant!
- Can run with a significantly higher threshold than other experiments and be very competitive

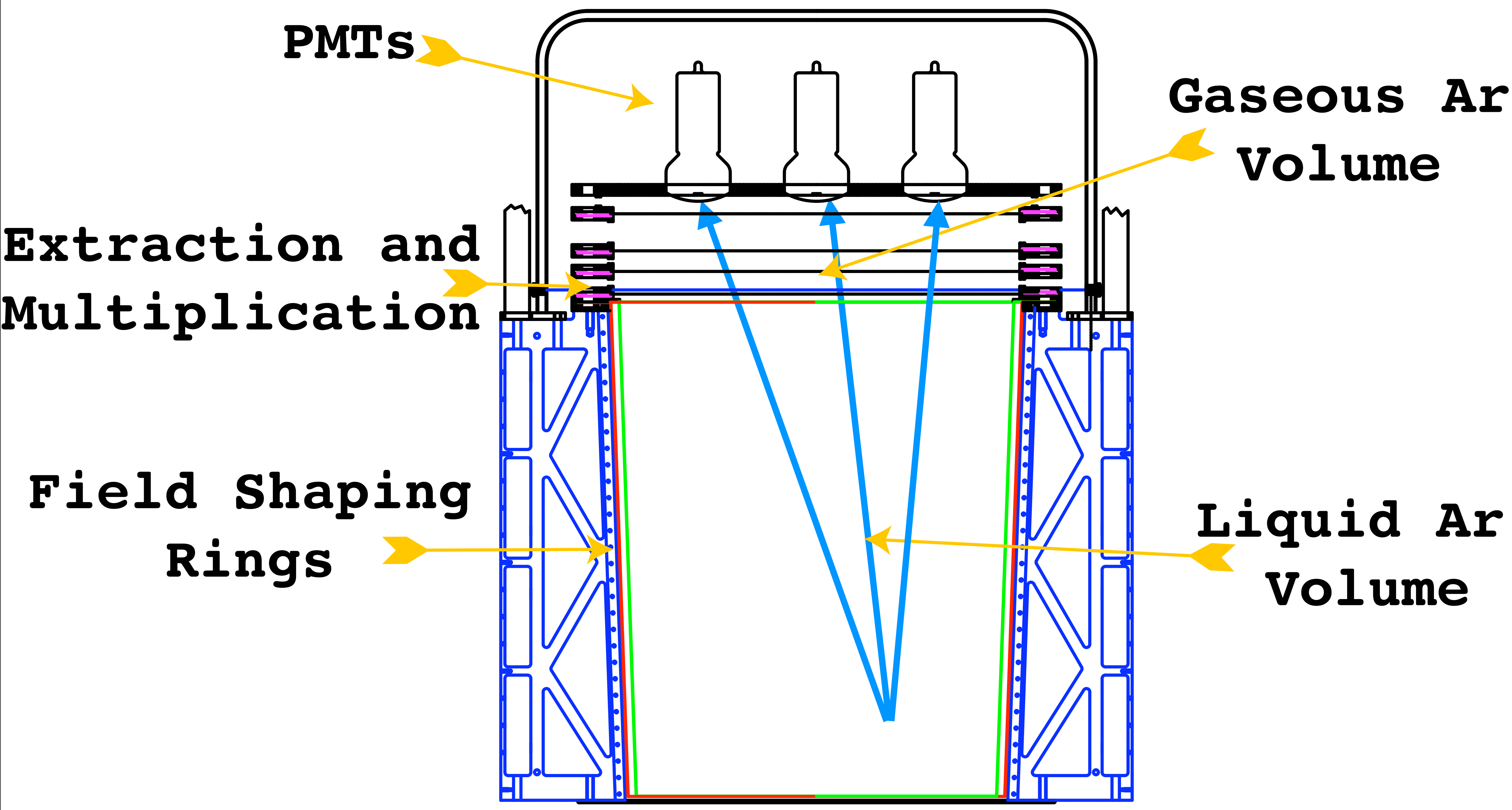
Two-Phase Argon Drift Chamber



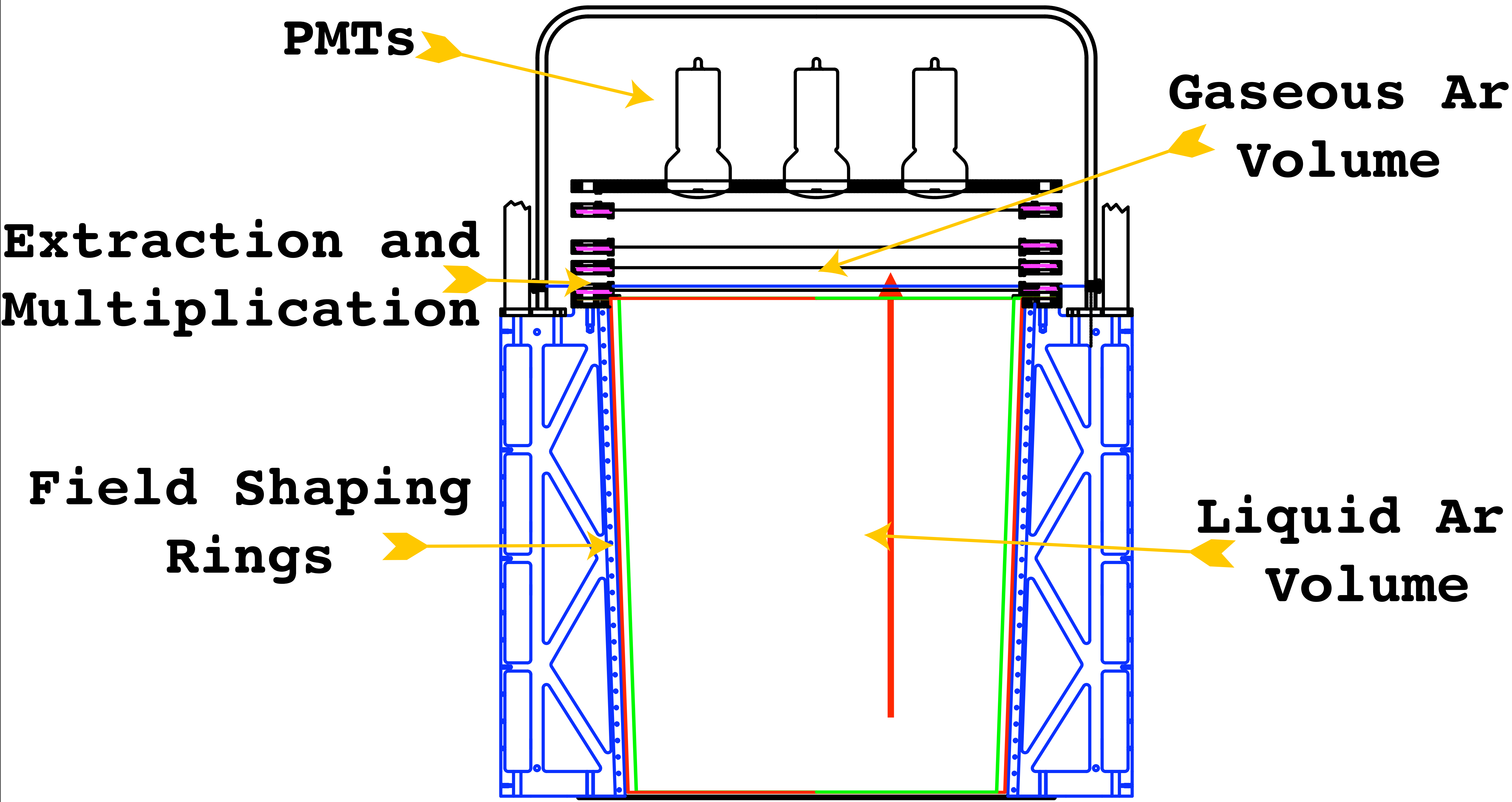


Energy Deposit

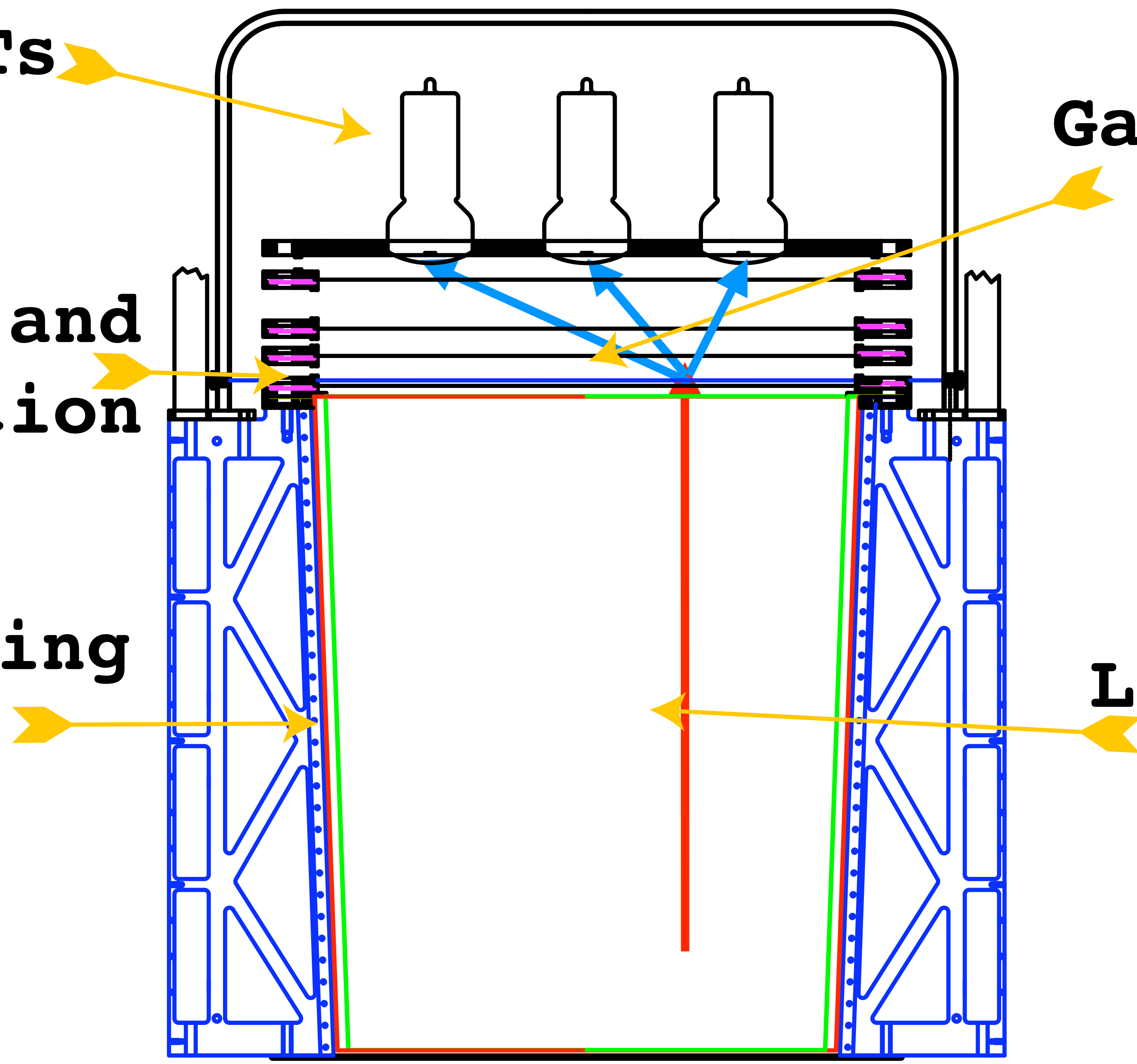
Primary Scintillation Photons (S1)



Electrons Surviving Recombination Drift Towards Anode



Multiplication in Gas
Secondary Scintillation Photons (S2)



The WARP Technology

Highest discrimination of minimum ionizing events, in favor of potential WIMP recoils, with three simultaneous and independent criteria:

- Pulse shape discrimination of primary scintillation (S1) based on the very large difference in decay times between fast (≈ 7 ns) and slow (1.6 μs) components of the emitted UV light

  Minimum ionizing: slow/fast ~ 3/1

  Nuclear recoils: slow/fast ~ 1/3

  Hitachi *et al.*, Phys. Rev. B **27**, 5279 (1983)

  Theoretical Identification Power exceeds 10^8 for > 60 photoelectrons

  Boulay & Hime astro-ph/0411358

- Both prompt scintillation (S1) and drift time-delayed ionization (S2) are simultaneously detected with a pulse ratio strongly dependent from recombination of ionizing tracks.

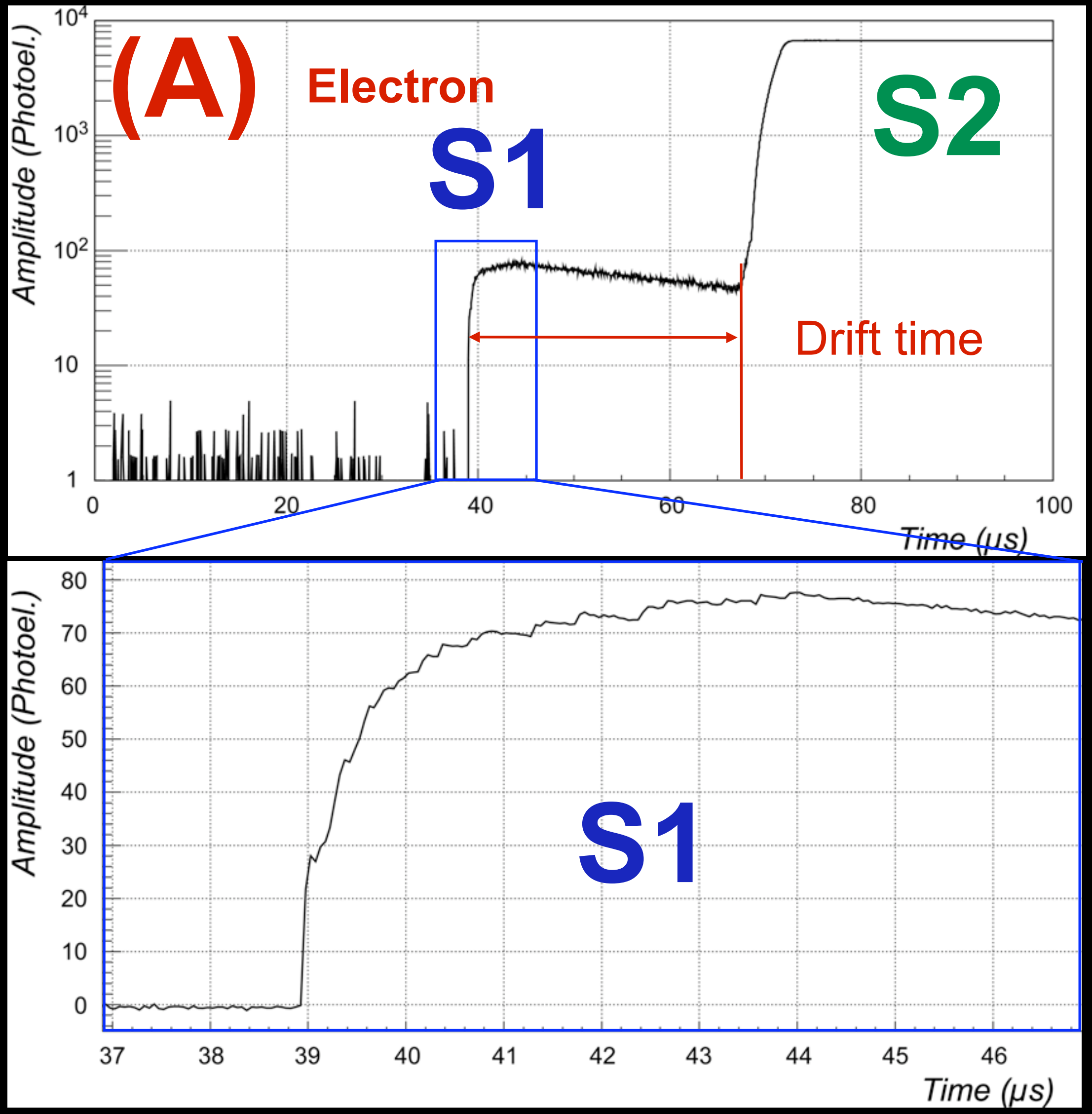
  Rejection ~ 10^2-10^3

  P. Benetti *et al.*, NIM A **332**, 395 (1993)

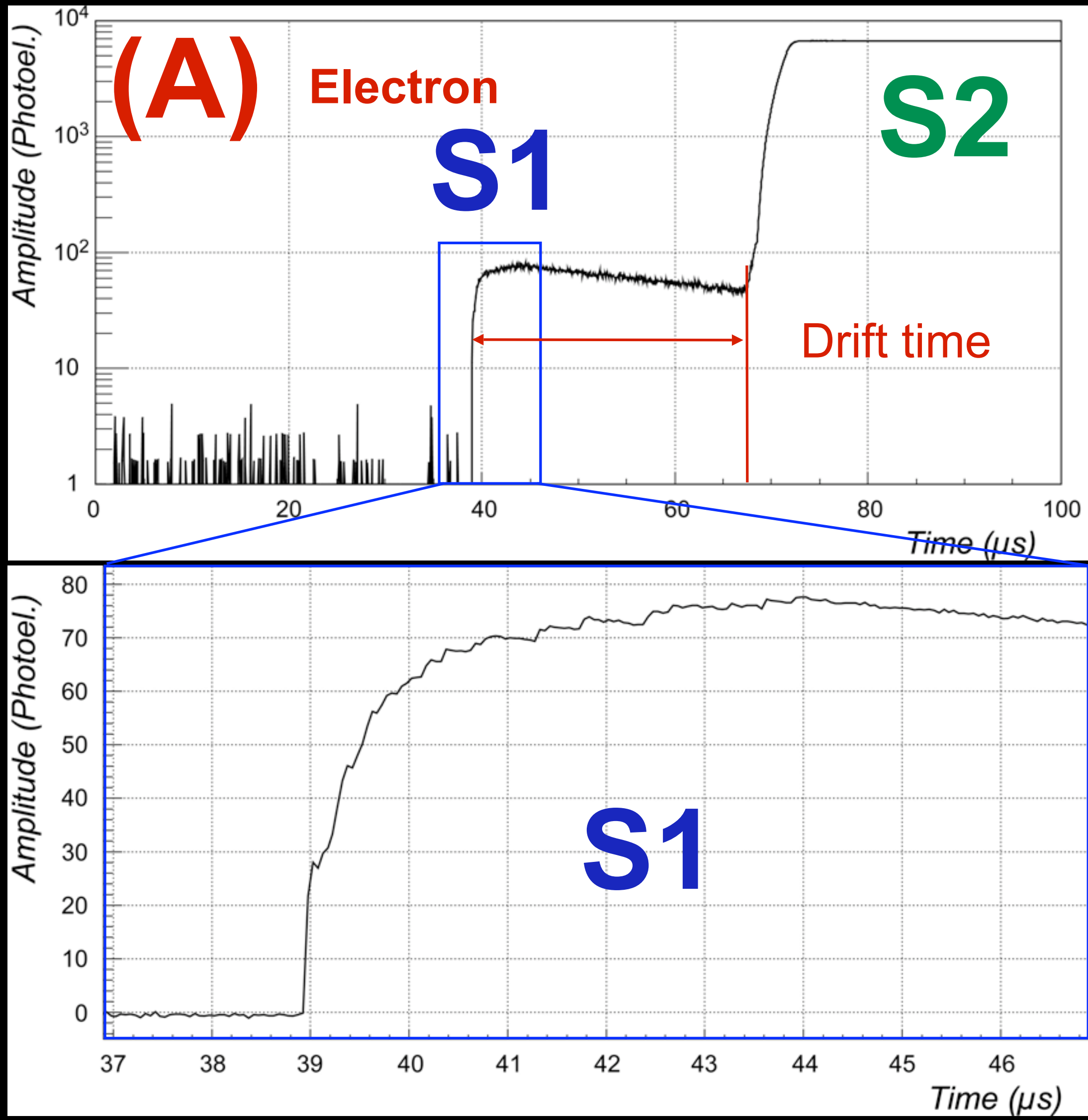
- Precise determination of events location in 3D: 5 mm x-y, 1 mm z
  - Additional Rejection for multiple neutron recoils and γ background

First Two Discrimination Methods

First Two Discrimination Methods



First Two Discrimination Methods



Events are characterized by:

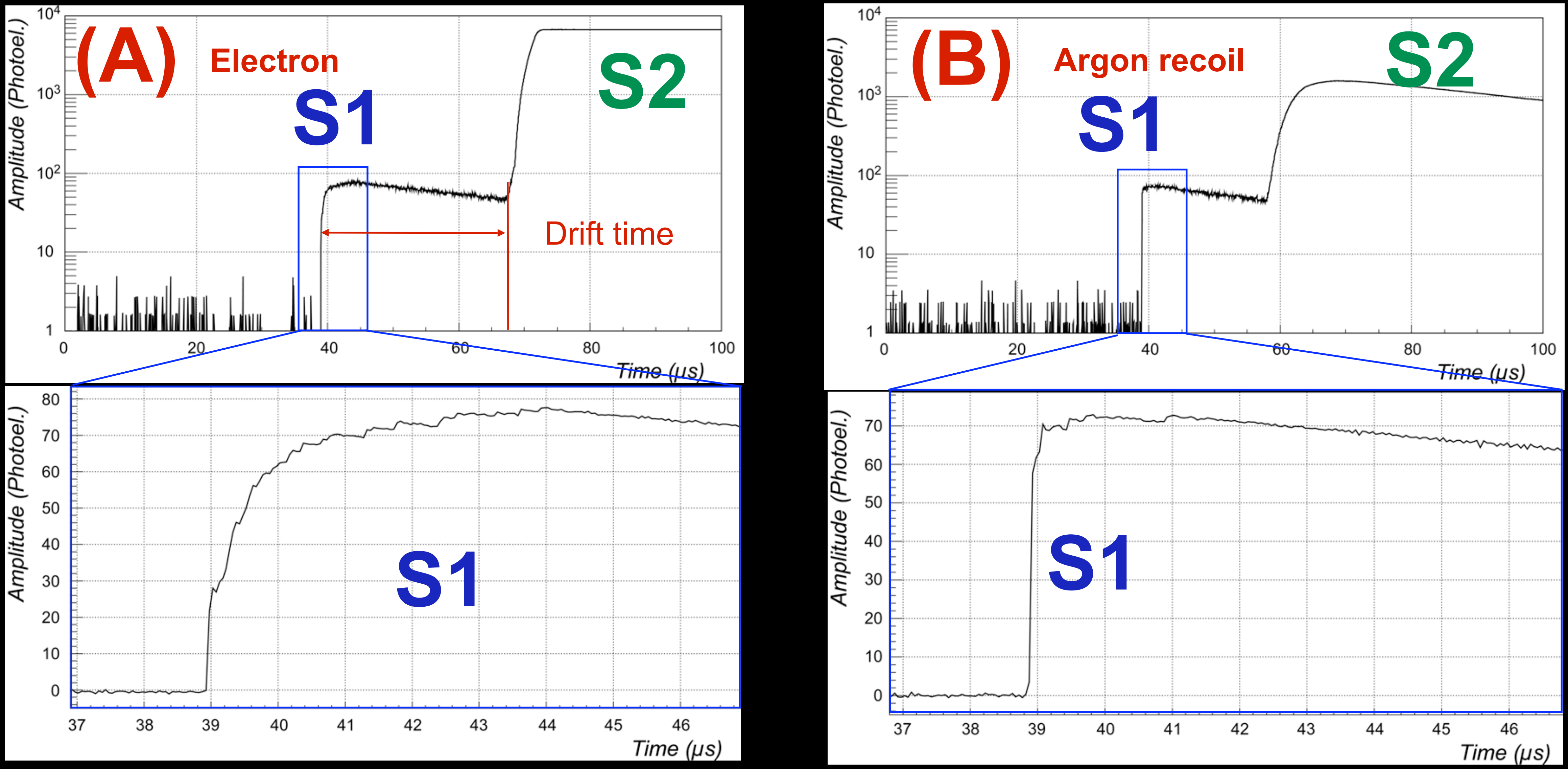
the ratio S2/S1 between the primary (S1) and secondary (S2)

the rising time of the S1 signal

Minimum ionizing particles: high S2/S1 ratio (~100) and by slow S1 signal

Alfa particles and Ar recoils: low (<5) S2/S1 ratio and fast S1 signal

First Two Discrimination Methods



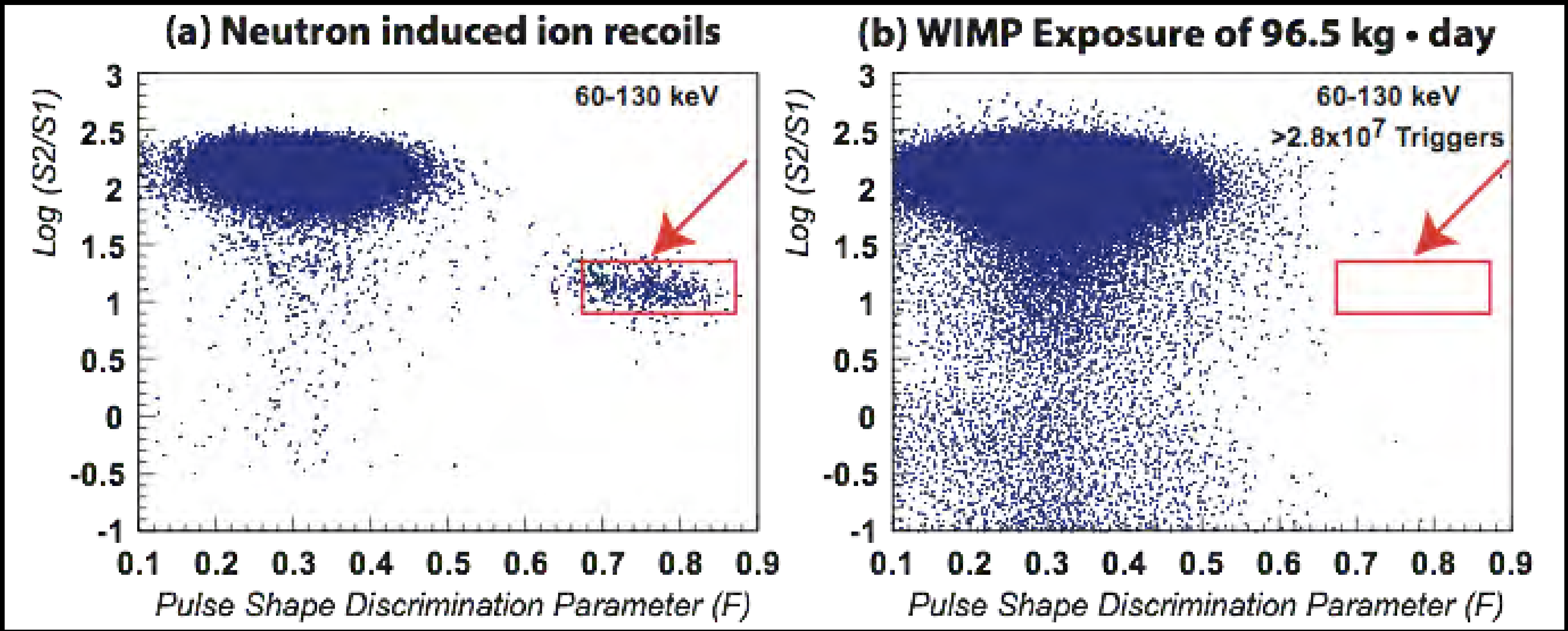
Events are characterized by:

- the ratio S2/S1 between the primary (S1) and secondary (S2)
- the rising time of the S1 signal

Minimum ionizing particles: high S2/S1 ratio (~100) and by slow S1 signal

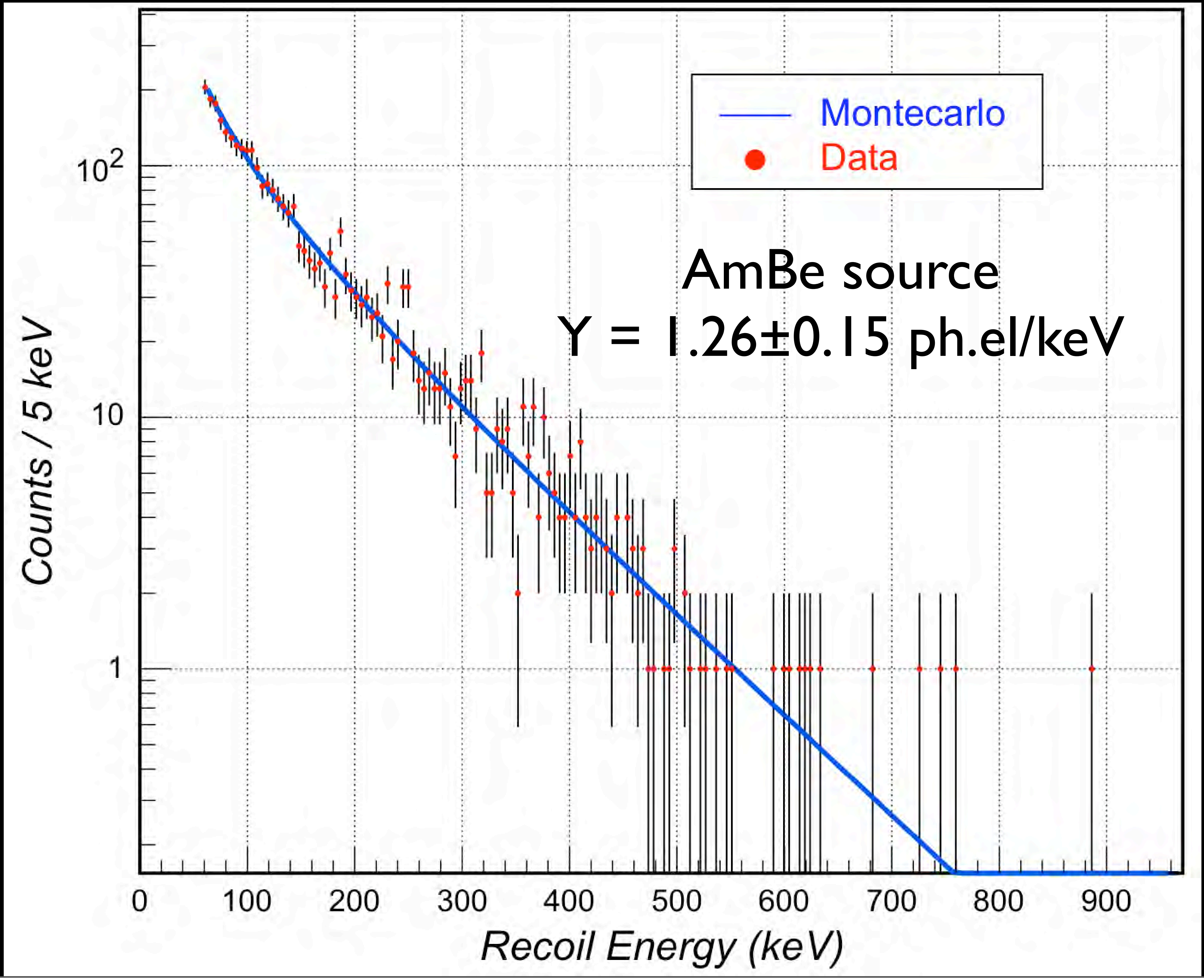
Alfa particles and Ar recoils: low (<5) S2/S1 ratio and fast S1 signal

First Dark Matter Results

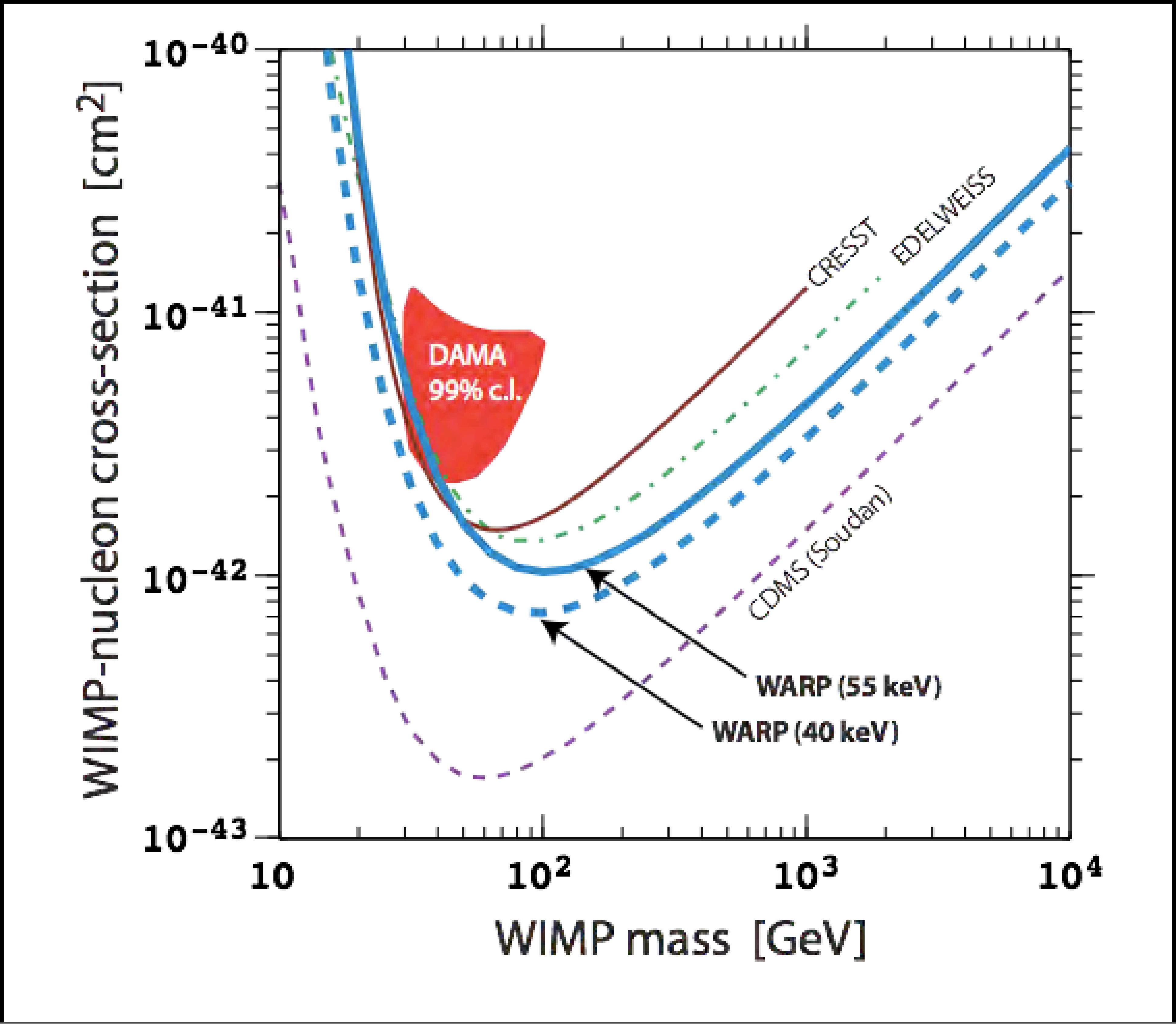


Selected events in the n-induced single recoils window during the WIMP search run: None

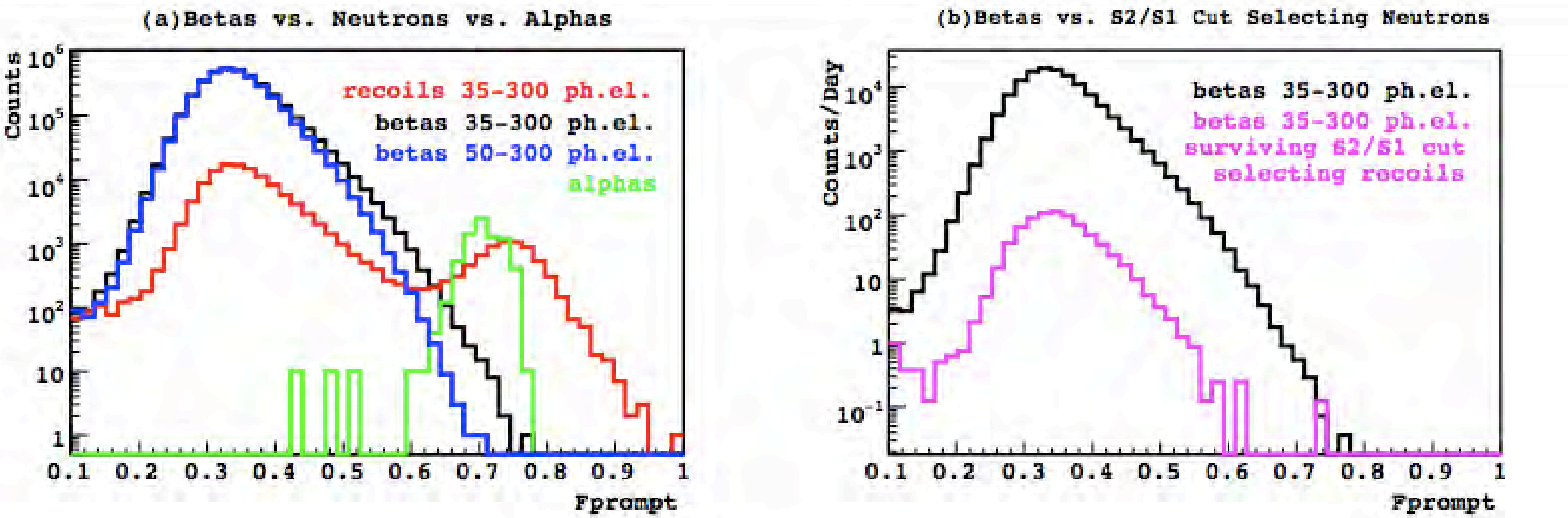
Energy Calibration



First Dark Matter Results



Most Recent Results on Discrimination



After recent electronics upgrade, pulse shape discrimination between m.i.p. and nuclear recoils better than $3x10^{-7}$

Shape of distribution does not change by applying S2/S1 cut. Two discriminations seemingly independent.

WARP 140-kg Detector

The WARP 140-kg detector to be installed and commissioned at LNGS

140 kg active target, to reach into 10^{-45} cm^2 and cover critical part of SUSY parameter space

Complete neutron shield!

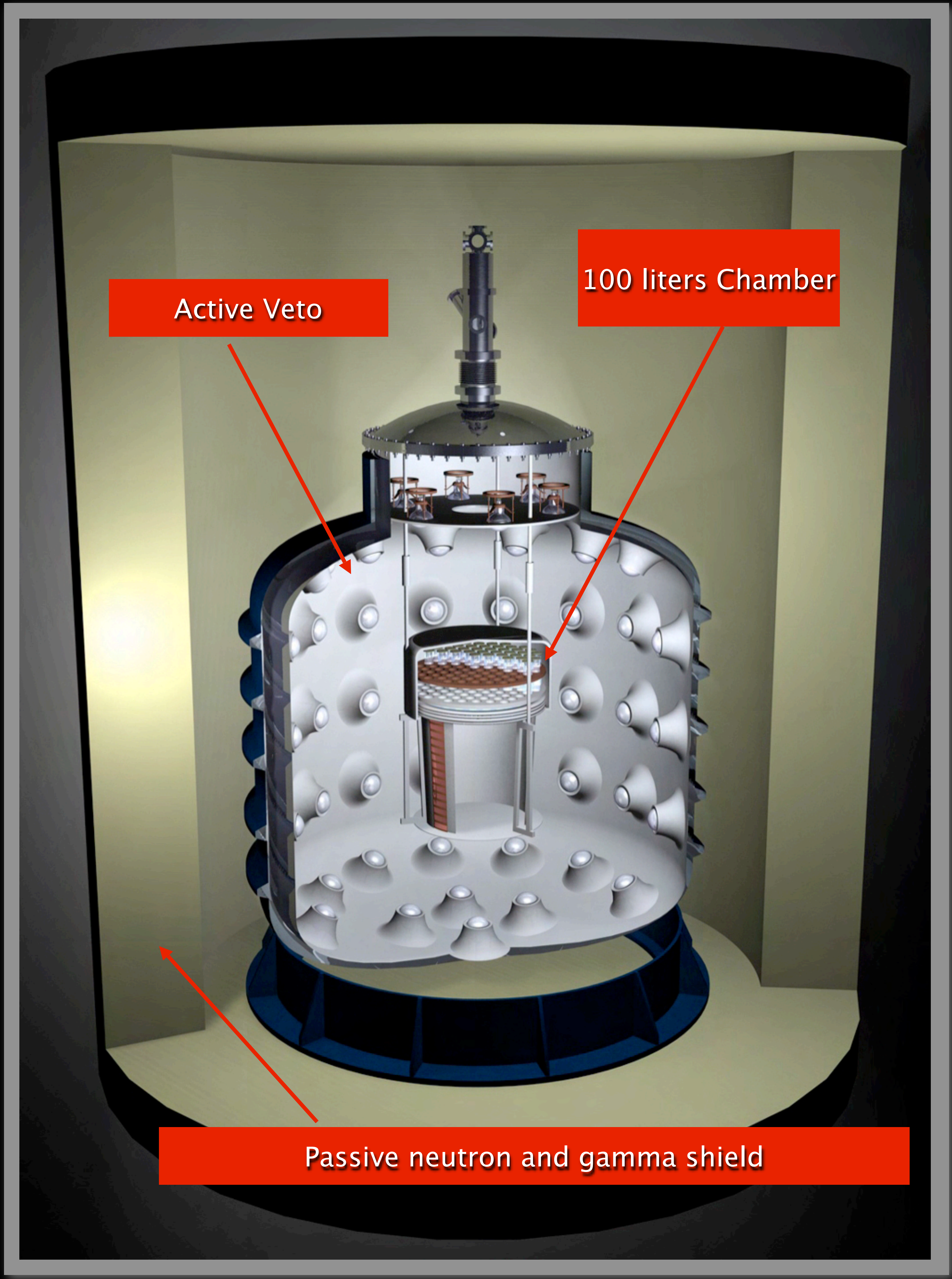
4π active neutron veto (9 tons Liquid Argon, 300 PMTs)

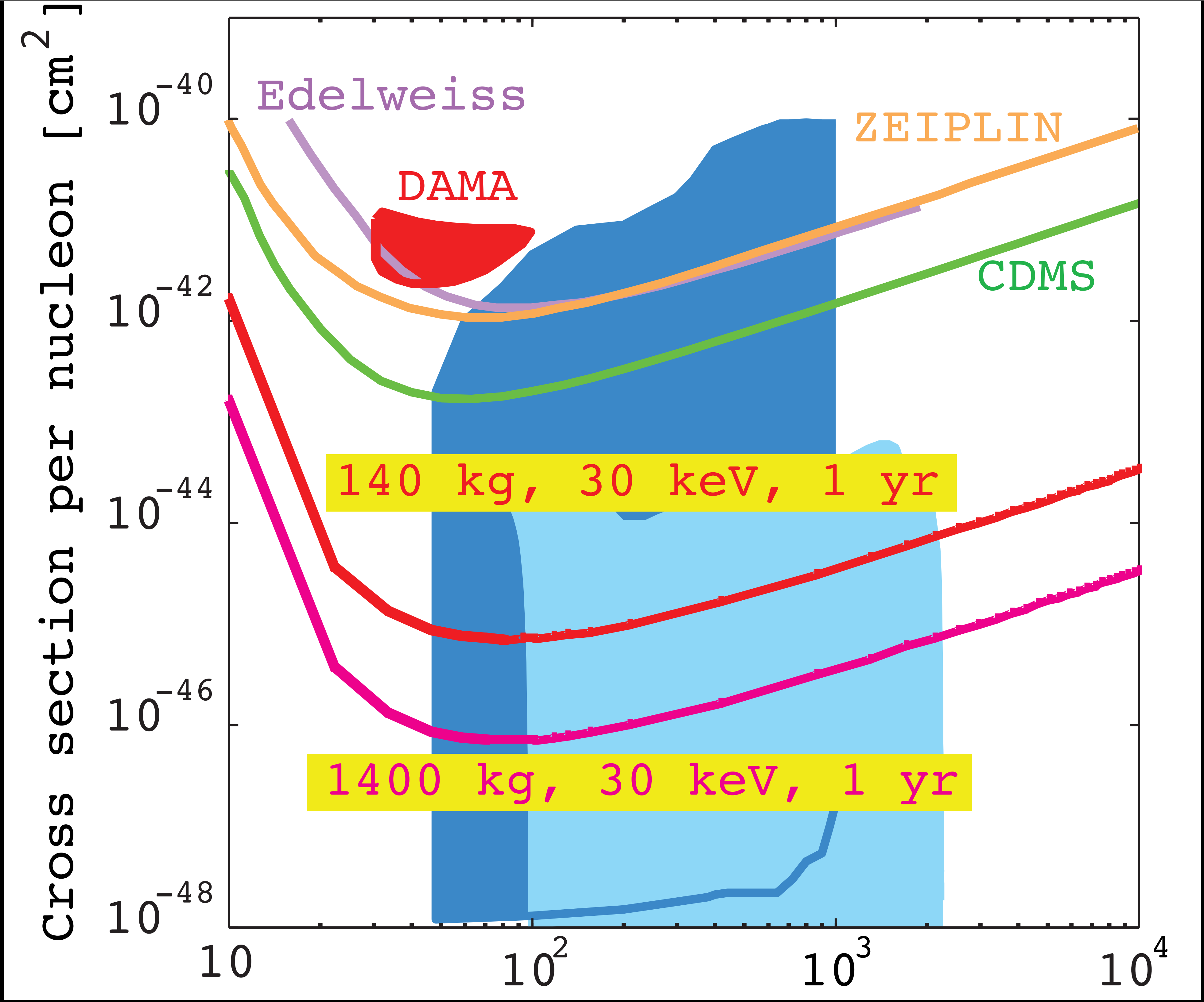
3D Event localization and definition of fiducial volume for surface background rejection

Detector designed for positive confirmation of a possible WIMP discovery

Active control on nuclide-recoil background, owing to unique feature (LAr active veto)

Cryostat designed to allocate a possible 1400 kg detector



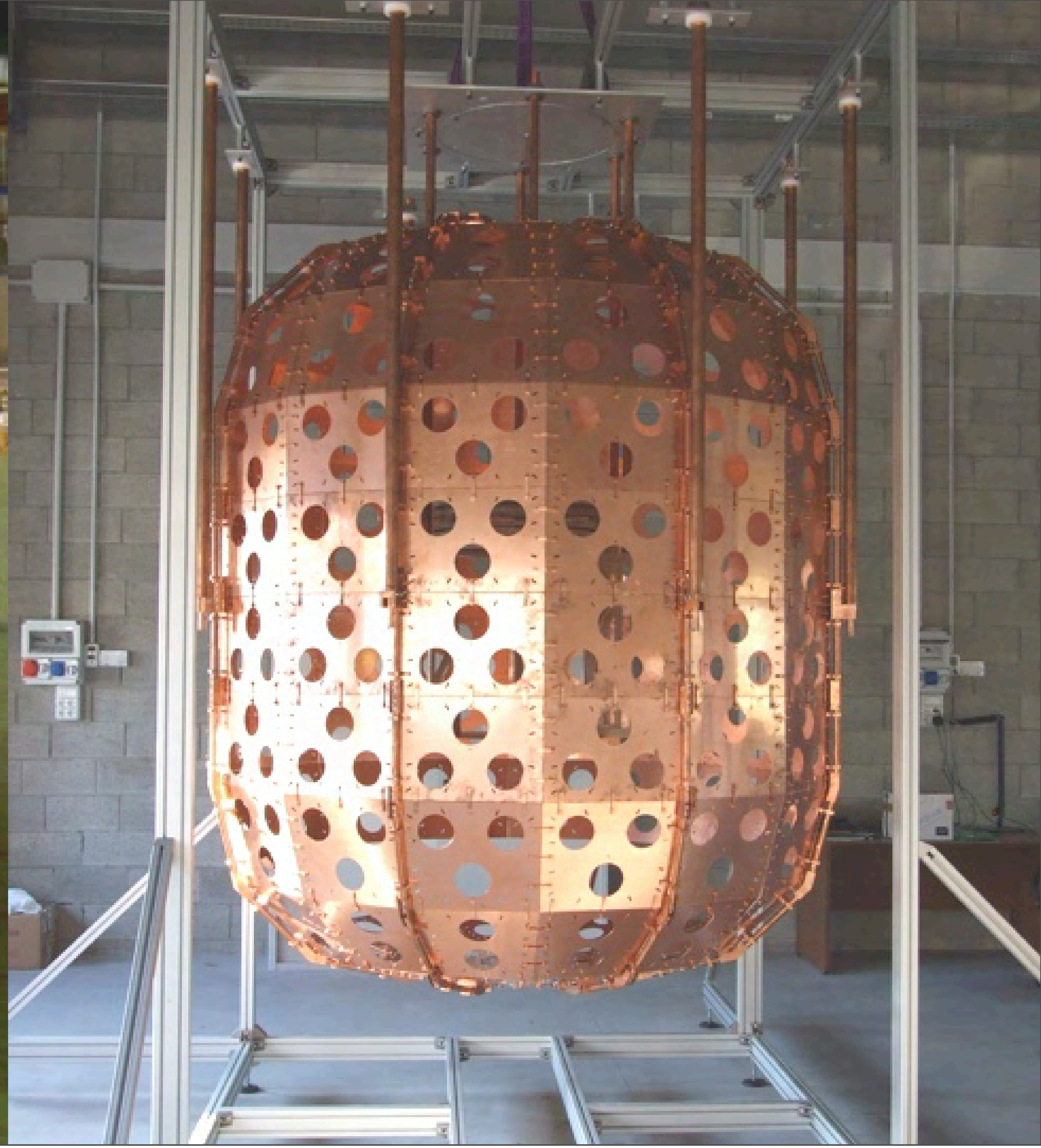


One year, 140 kg, null measurement, 30 keV threshold

One year, 1400 kg, null measurement, 30 keV threshold

WARP Update
Cryostat for 140-kg detector in Hall B
Operating 2008

WARP Update
Cryostat for
140-kg detector
in Hall B
Operating 2008



Discovery of underground reservoir of argon with low level of ^{39}Ar

FNAL - October 1 2007

Cristiano Galbiati, on behalf of …

Discovery of underground argon with low level of radioactive ^{39}Ar and possible applications to WIMP dark matter detectors

D. Acosta-Kane,[1] R. Acciarri,[2] O. Amaize,[1] M. Antonello,[2] B. Baibussinov,[3] M. Baldo Ceolin,[3] C. J. Ballentine,[4] R. Bansal,[5] L. Basgall,[6] A. Bazarko,[7] P. Benetti,[8] J. Benziger,[9] A. Burgers,[1] F. Calaprice,[1] E. Calligarich,[8] M. Cambiaghi,[8] N. Canci,[2] F. Carbonara,[10] M. Cassidy,[11] F. Cavanna,[2] S. Centro,[3] A. Chavarria,[1] D. Cheng,[1] A. G. Cocco,[10] P. Collon,[12] F. Dalnoki-Veress,[1] E. de Haas,[1] F. Di Pompeo,[2] G. Fiorillo,[10] F. Fitch,[13] V. Gallo,[10] C. Galbiati,[1,*] M. Gaull,[1] S. Gazzana,[14] L. Grandi,[14] A. Goretti,[1] R. Highfill,[6] T. Highfill,[6] T. Hohman,[1] Al. Ianni,[14] An. Ianni,[1] A. LaCava,[15] M. Laubenstein,[14] H. Y. Lee,[16] M. Leung,[1] B. Loer,[1] H. H. Loosli,[17] B. Lyons,[1] D. Marks,[1] K. McCarty,[1] G. Meng,[3] C. Montanari,[8] S. Mukhopadhyay,[18] A. Nelson,[1] O. Palamara,[14] L. Pandola,[14] R. C. Pardo,[16] F. Pietropaolo,[3] T. Pivonka,[6] A. Pocar,[19] R. Purtschert,[17,†] A. Rappoldi,[8] G. Raselli,[8] K. E. Rehm,[16] F. Resnati,[20] D. Robertson,[12] M. Roncadelli,[8] M. Rossella,[8] C. Rubbia,[14] J. Ruderman,[1] R. Saldanha,[1] C. Schmitt,[12] R. Scott,[16] E. Segreto,[14] A. Shirley,[21] A. M. Szelc,[22,2] R. Tartaglia,[14] T. Tesileanu,[1] S. Ventura,[3] C. Vignoli,[8] C. Visnjic,[1] R. Vondrasek,[16] and A. Yushkov[14]

[1] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*

Why is underground argon desirable?

- Radioactive ^{39}Ar produced by cosmic rays in atmosphere
  - decays betas, $Q = 565$ keV, $t_{1/2} = 269$ years
- In atmospheric argon:
  - $^{39}Ar/Ar$ ratio 8×10^{-16}
  - specific activity 1 Bq/kq
- Limits size and sensitivity of argon detectors

Why is underground argon desirable?

- ^{39}Ar-depleted argon available via centrifugation or thermal diffusion, but expensive at the ton scale!
- ^{39}Ar production by cosmic rays strongly suppressed underground
- Shielding of hydrocarbons in deep underground reservoirs results in low cosmogenic ^{14}C, important for solar neutrino detection
  - Borexino just reported measurement of solar ^{7}Be neutrinos
  - Background from ^{14}C defeated through use of scintillator from petrochemicals

Necessary to pre-scan sources of interest for ^{39}Ar

- ^{39}Ar also produced underground by neutron activation, from fission and (α,n) neutrons
  - $^{39}K(n,p)^{39}Ar$
- ^{39}Ar content depends on local content of U, Th, and K, and on rock porosity
- In some groundwater samples $^{39}Ar/Ar$ ratio measured up to a factor 20× (2000%) of the atmospheric ratio
- Cannot rely on ^{39}Ar simply being low. Pre-scan of

Analytical techniques to measure ^{39}Ar

- Three main techniques:
  - Counting of argon gas in low-background proportional detectors
  - Accelerator Mass Spectrometry (AMS)
  - Counting of argon in low-background liquid-phase detectors

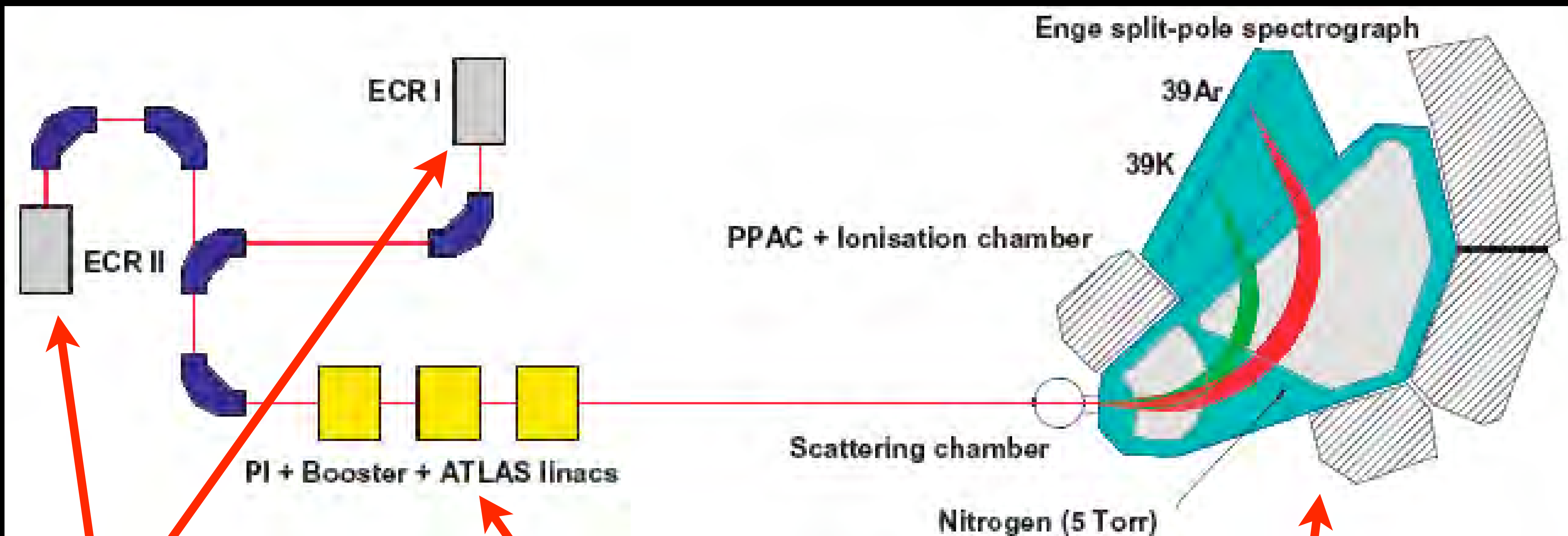
Counting of argon gas in low-background proportional counters

- First established (Loosli 1969) and still today standard method for ^{39}Ar determination
  - Collaborators Loosli and Purtschert run in Bern underground Lab dedicated facility for ^{39}Ar measurements since 1969
- Small samples (1-2 liters STP) of argon and limited depth (100 m.w.e.) required to measure ^{39}Ar at or below atmospheric level
- ^{39}Ar sensitivity limited by detector background. Detector background must be carefully characterized by measurement with reference argon gas depleted in ^{39}Ar
- Current limit on sensitivity at 5% of atmospheric level

Accelerator Mass Spectrometry (AMS)

- Requires special Electron Cyclotron Resonance (ECR) ion source to create positive ions in multiple (7+,8+) ionization states
- Combination of ECR source and ATLAS linear accelerator unique facility at Argonne National Labs
- In 2002 campaign, reached a sensitivity for $^{39}Ar/Ar$ equivalent to 5% of atmospheric level
- Most flexible tool: measurement requires few ml of

ATLAS at Argonne National Labs



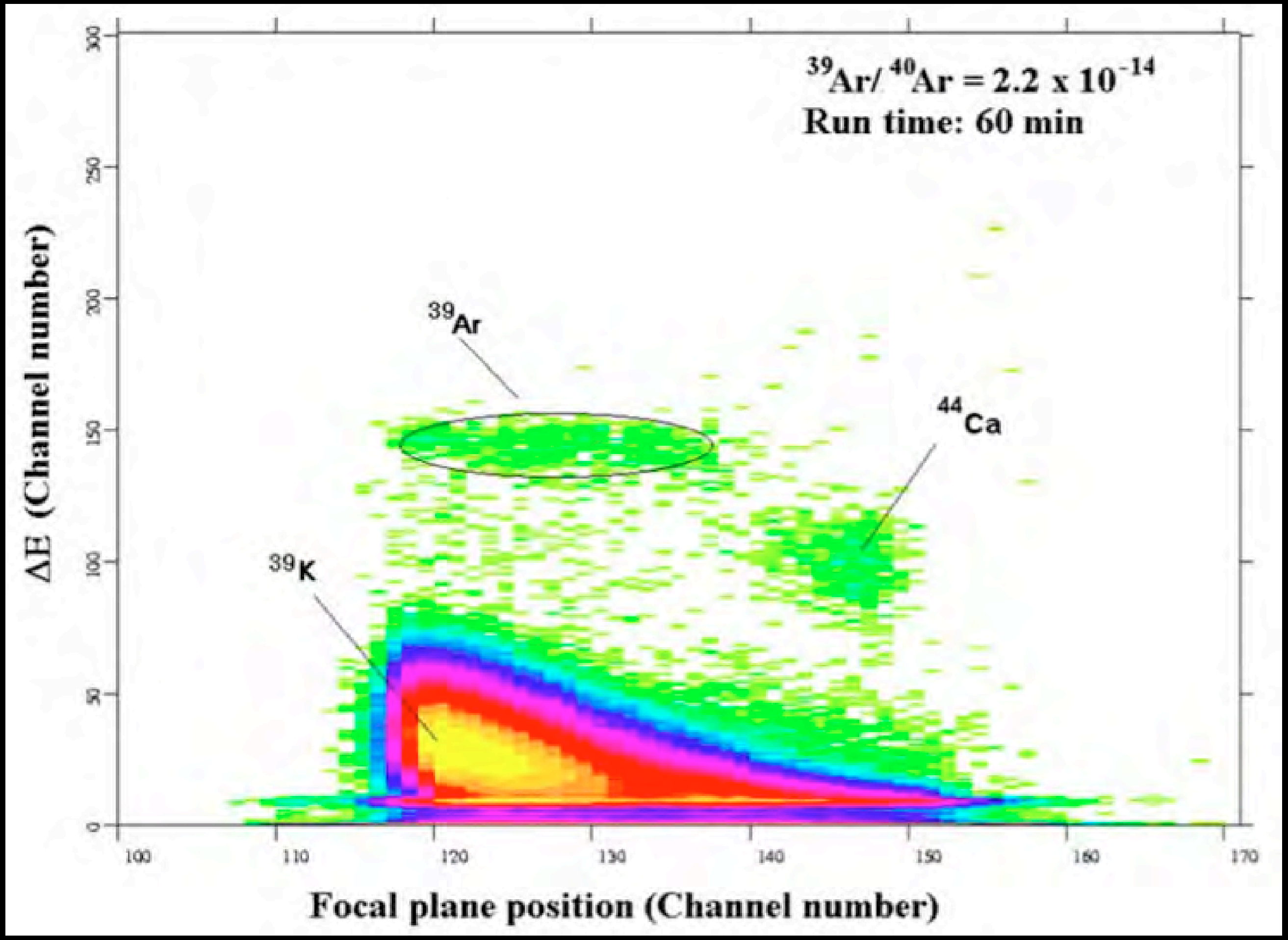
ECR Ion Sources

ATLAS Linear Accelerator

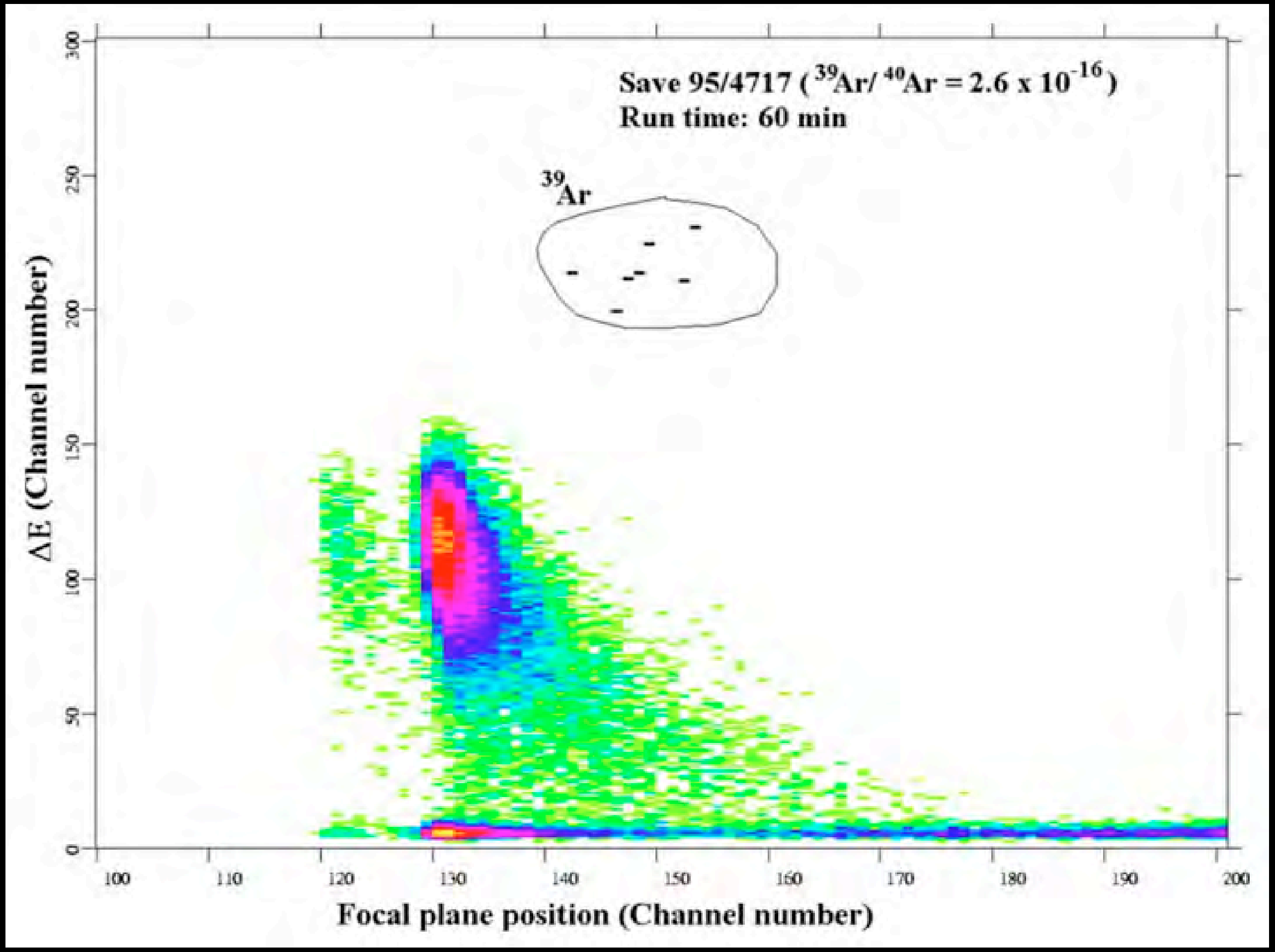
Spectrograph

AMS: 2002 Test

^{39}Ar-spiked argon at 3000% of atm. activity



Deep ocean argon at 30% of atm. activity



Sensitivity limited by presence of ^{39}K background from ion source walls, intrinsic to aluminum

AMS: 2007 Test

- 1 week run in June 2007, ECR source upgraded with addition of high purity aluminum liner
- Reduction of K background by factor 13
- Sensitivity potentially increased to 0.5% of atmospheric level
- Next step:
  Request of additional 2 weeks of time
  Measurement of large pool of samples at 0.5% atm. level

Counting in Liquid-phase detectors

- WARP 3.2-kg reached accuracy of 10% of atmospheric level
- Specially designed low background detector with 10-kg mass could reach below 0.1% of atmospheric level
- Requires first large batch of argon from underground reservoir

Sample Preparation

- Challenge: Ar in subsurface gases typically at few hundred ppm concentration. Needs large quantities with purity >50%
- 1+yr R&D program in Princeton run by graduate student Ben Loer, senior Daniel Marks, freshman Daniel Acosta-Kane
- Resulted in construction of two stages separation plant, deployable on the field
- Chromatographic plant removes strongly adsorbing components (methane, ethane, heavy hydrocarbons, nitrogen, carbon dioxyde)
- Cold trap removes helium, hydrogen
- Achieves production of argon samples with purity exceeding 80%

Discovery of low ^{39}Ar from underground reservoirs

	Count Rate [μBq]
Underground Ar	2036±43
^{39}Ar-Depleted Reference	2035±49
Atmospheric Ar	3625±77
(Under. Ar) - (Ref.)	1±65
(Atm. Ar) - (Ref.)	1589±91
$(^{39}Ar/Ar)_{und} / (^{39}Ar/Ar)_{atm}$	0.00 ±0.05

Submitted to Phys. Rev. Lett. on Aug 30, 2007

Conclusions

- Discovery of underground reservoir with argon low in radioactive ^{39}Ar! Depletion factor at least 20 relative to atmospheric argon
- No ^{39}Ar detection, represents only upper limit. Motivates development of new, more sensitive techniques
- Reservoir able to supply argon target for multi-ton WIMP/neutrino detector.
- Collaboration developing with industry infrastructure for massive collection and underground storage of depleted argon

The End