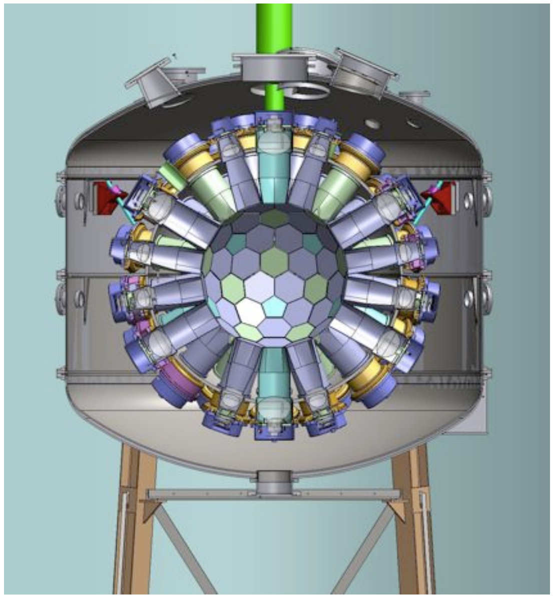
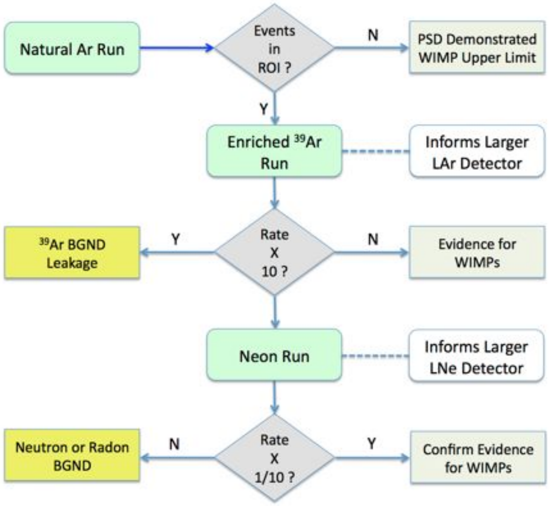
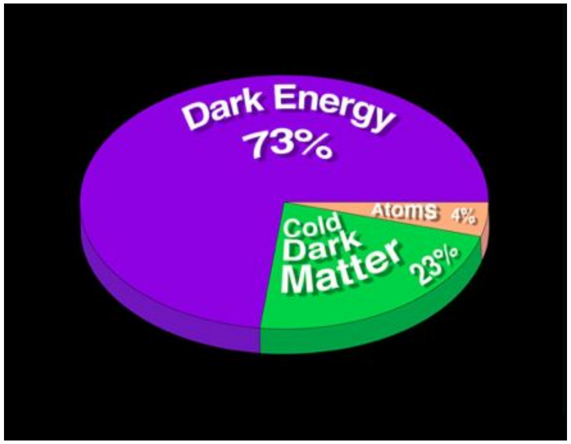
# CLEAN Detection of Dark Matter & Low-Energy Neutrinos





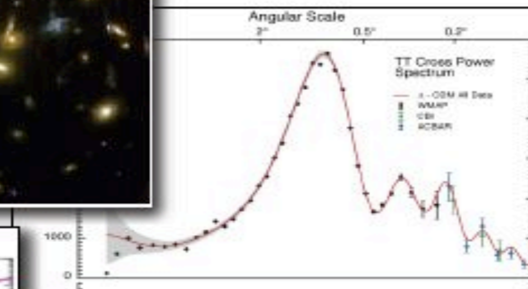




## SNOLAB Workshop

**August 21, 2013**
**SNOLAB**

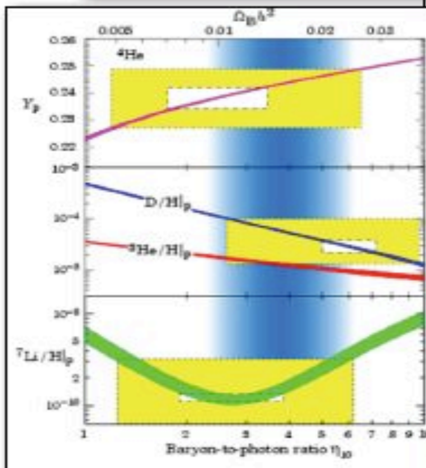

**Andrew Hime**
**Physics Division, MS H803**
**Los Alamos National Laboratory**
**Los Alamos, NM 87545**

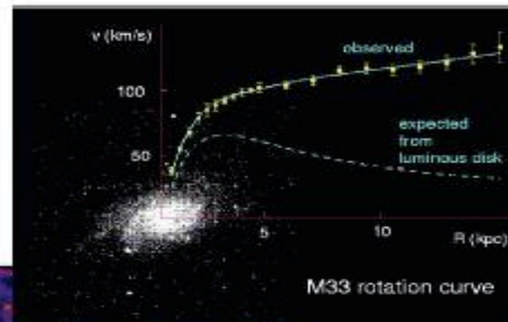
Gravitational Lensing




CMB

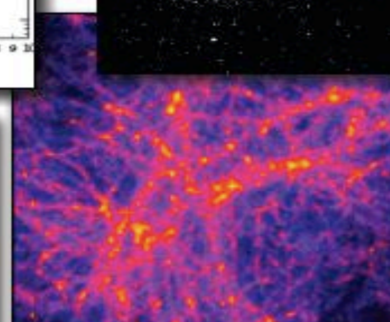
BBN
Light Element
Abundances



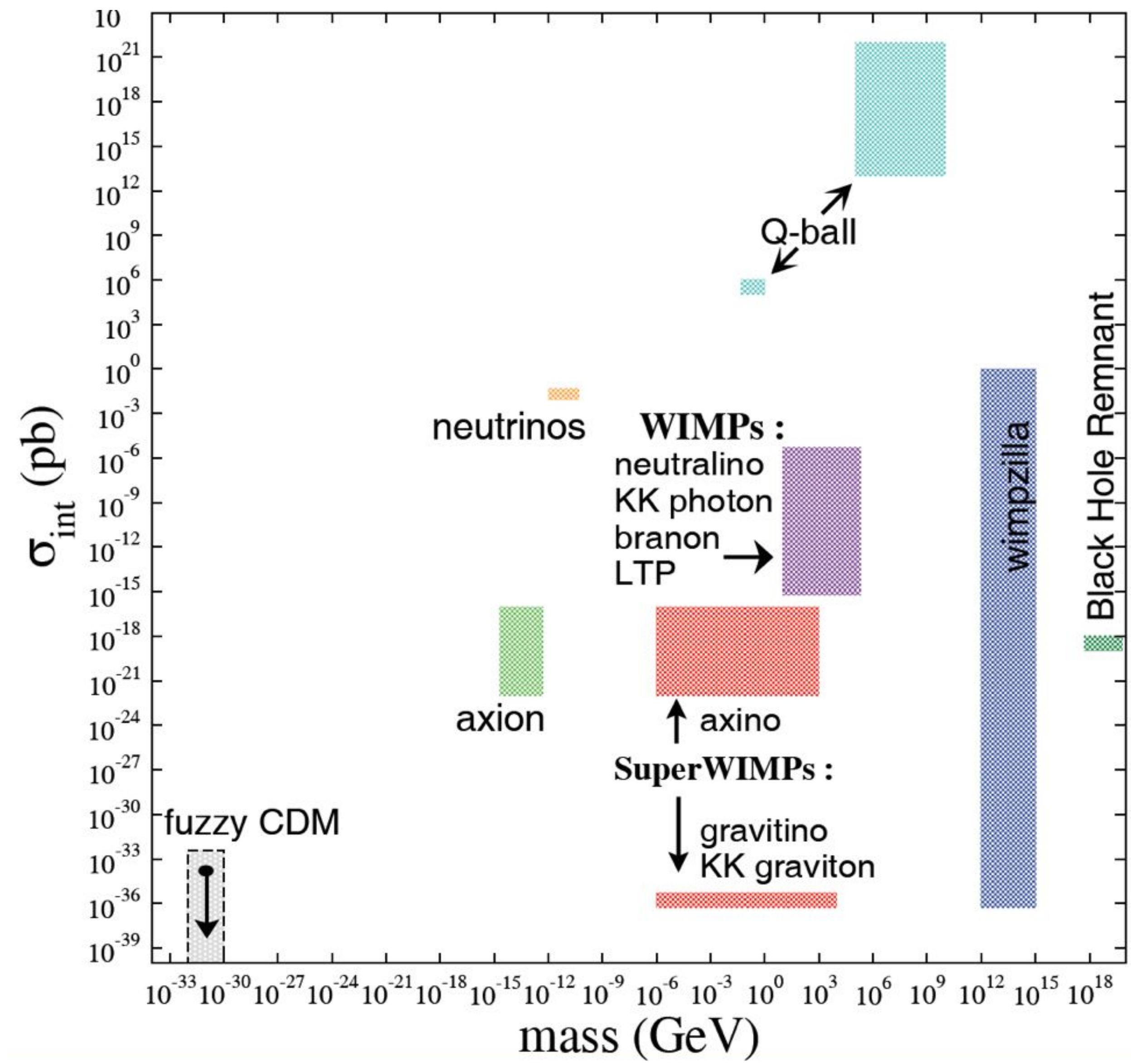



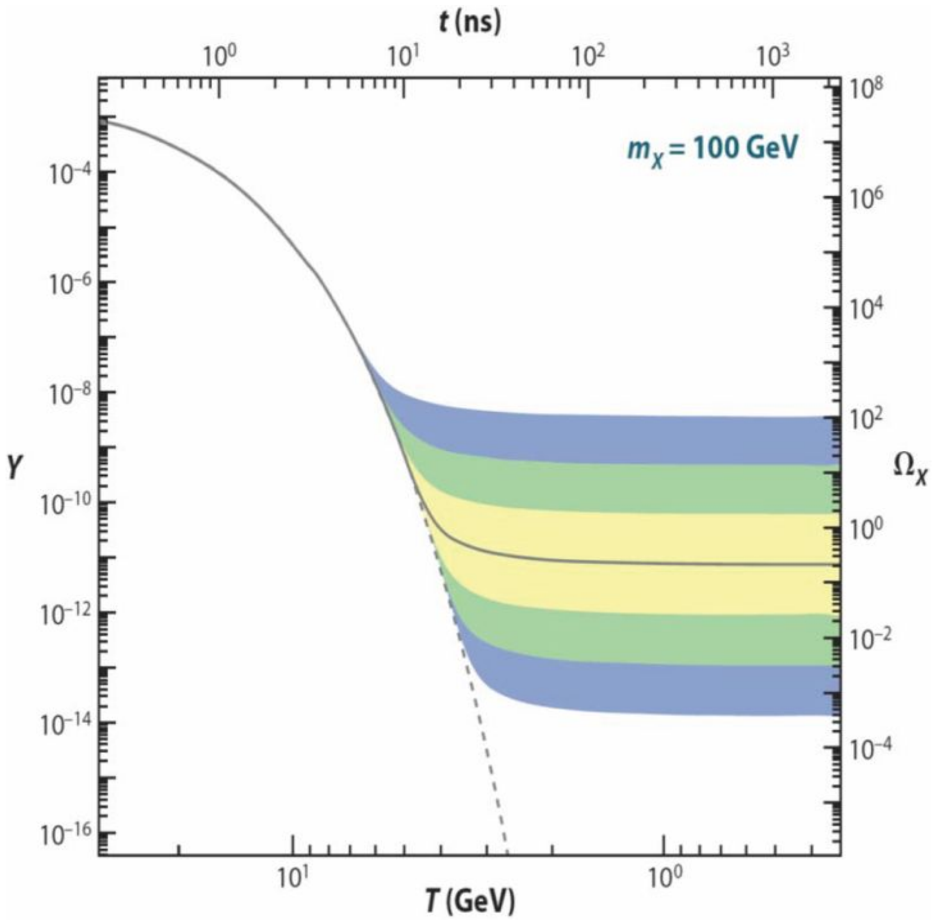

Galactic
Rotation Curves

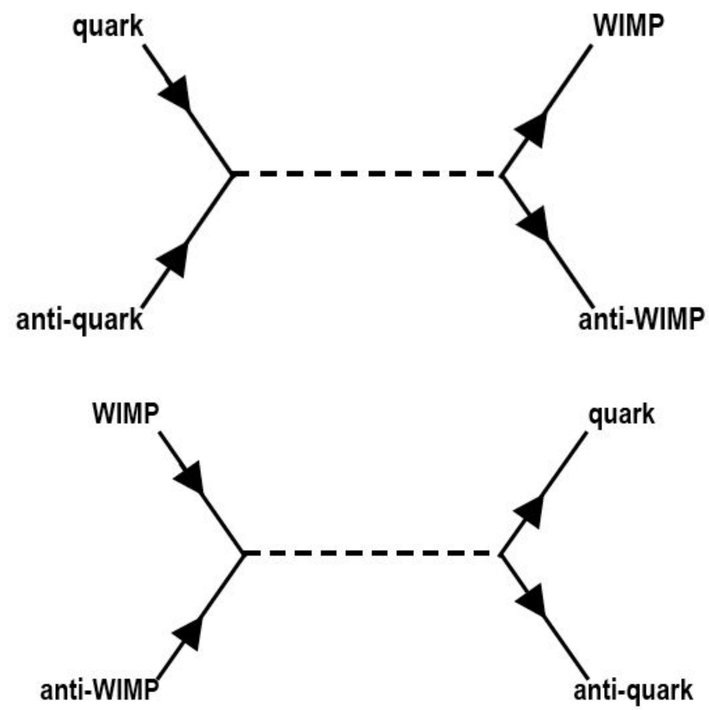
Bullet
Cluster

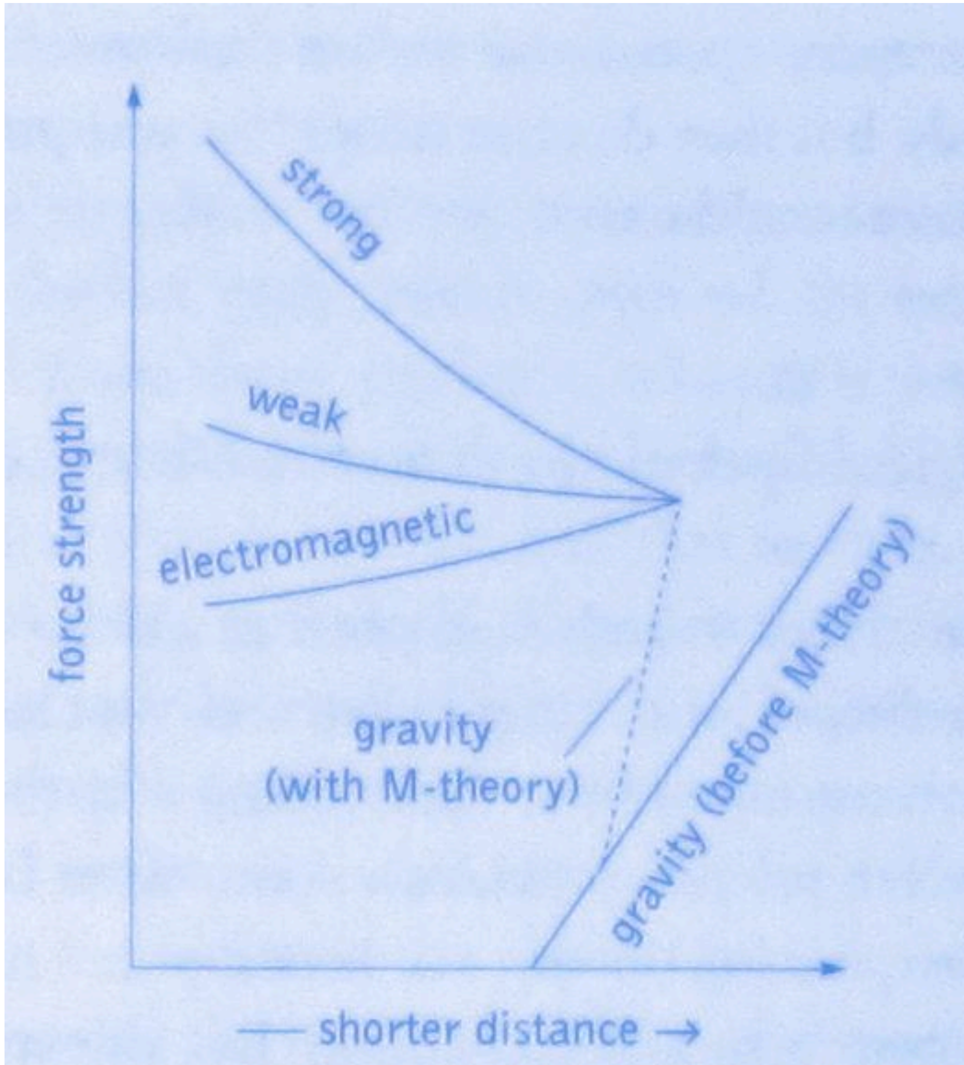


Large-Scale
Structure

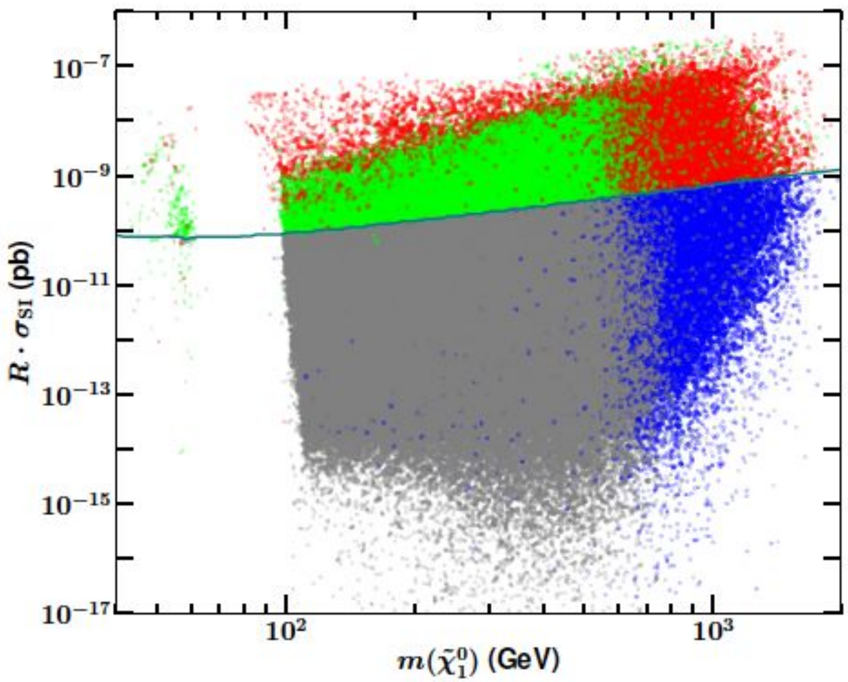

Q-ball
neutrinos
WIMPs :
neutralino
KK photon
branon
LTP
wimpzilla
Black Hole Remnant
axion
axino
SuperWIMPs :
gravitino
KK graviton
fuzzy CDM
$\sigma_{int}$ (pb)
mass (GeV)

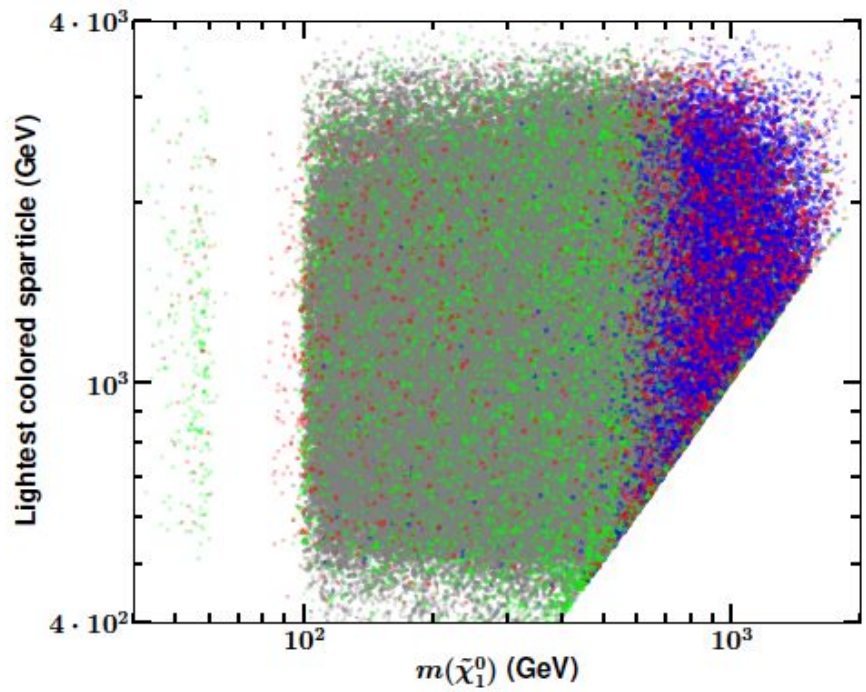

t (ns)
10^0
10^1
10^2
10^3
10^8
10^6
10^4
10^2
10^0
10^-2
10^-4
m_χ = 100 GeV
10^-4
10^-6
10^-8
Y
10^-10
10^-12
10^-14
10^-16
Ω_χ
10^1
10^0
T (GeV)


quark
WIMP
anti-quark
anti-WIMP
WIMP
quark
anti-WIMP
anti-quark

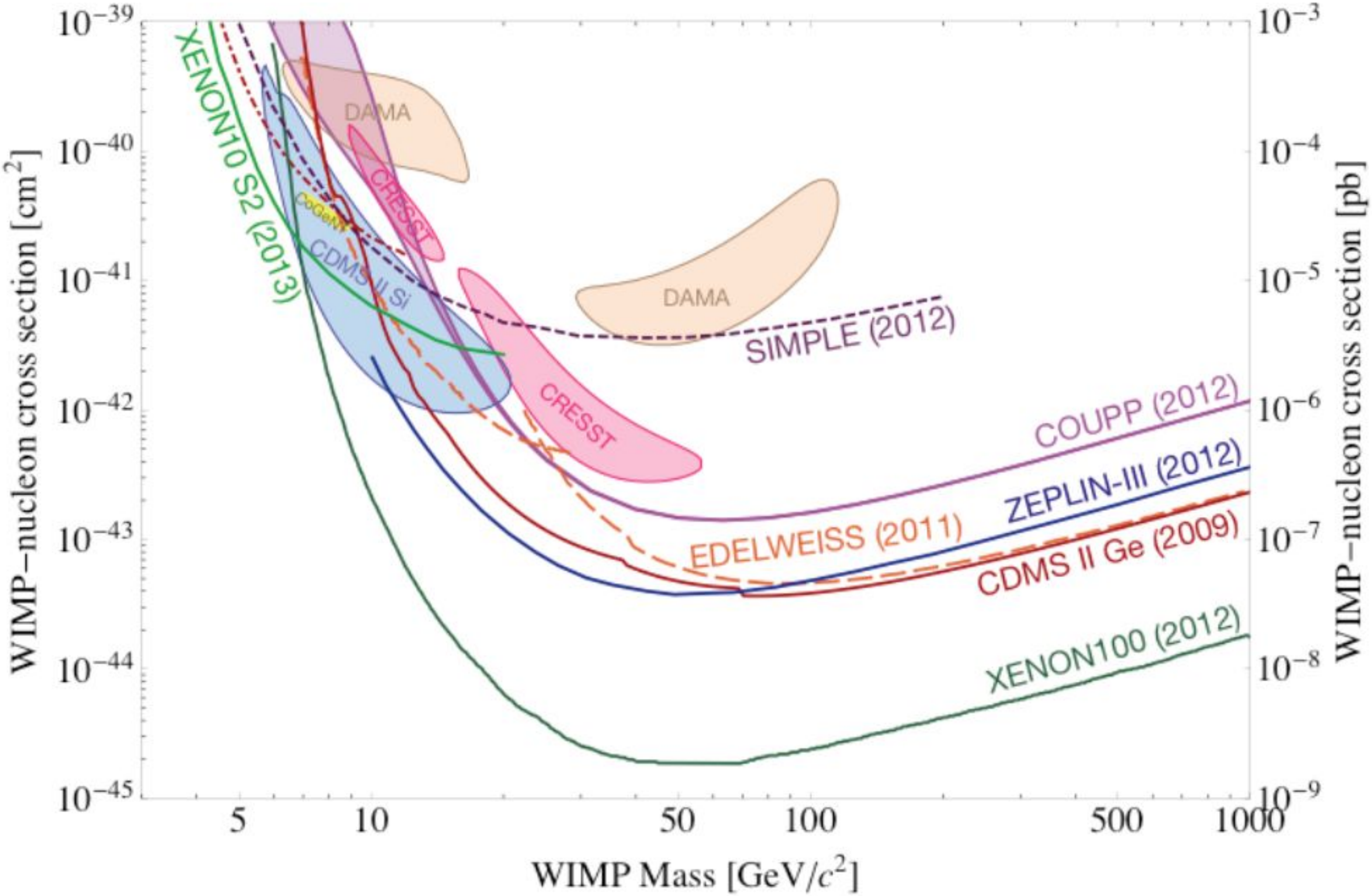

strong
weak
electromagnetic
force strength
gravity
(with M-theory)
gravity (before M-theory)
— shorter distance →

Dark Matter in the Coming Decade – Complementary Paths to Discovery
arXiv:1305.1605




Scans of MSSM-space: direct detection (green)
indirect (blue)
grey (LHC upgrade)


WIMP−nucleon cross section [cm$^2$]
WIMP−nucleon cross section [pb]
WIMP Mass [GeV/$c^2$]
XENON10 S2 (2013)
DAMA
CRESST
CoGeNT
CDMS II Si
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
EDELWEISS (2011)
CDMS II Ge (2009)
XENON100 (2012)

# Conclusions

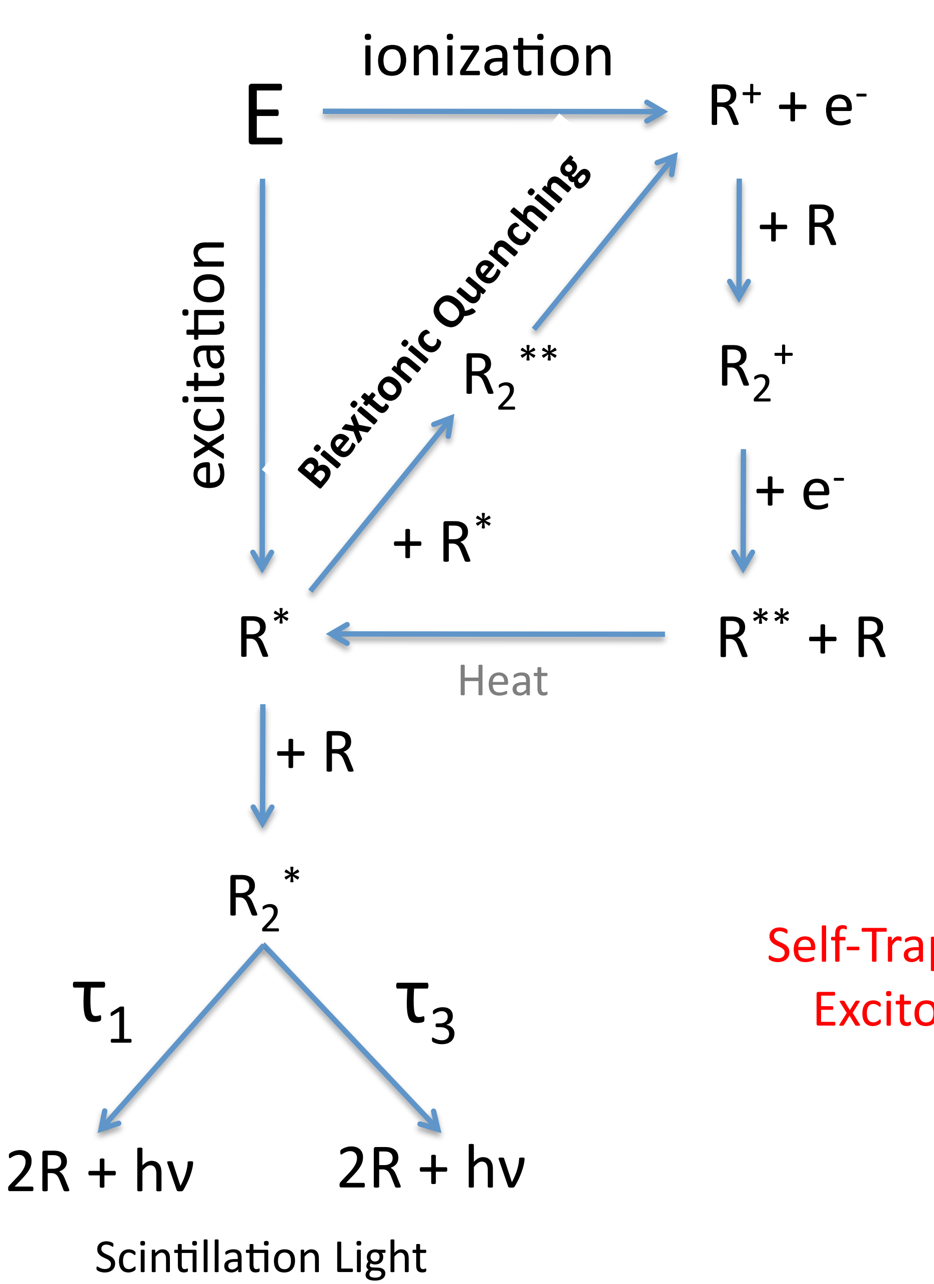
° We likely need to get to very large (> 10 tonne) target masses whilst maintaining ever smaller levels of radioactive background (<0.1 events/tonne/year) to discover WIMP dark matter.

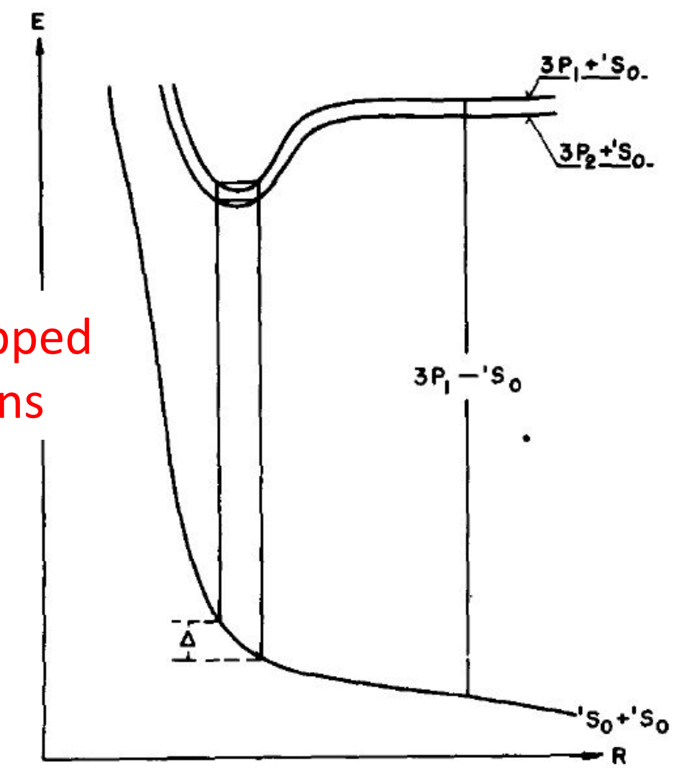
° Intrinsic neutrino backgrounds limit how far existing technologies can go (eg. elastic scattering of pp-solar neutrinos limit LXe to $\sim 10^{-47}$ $cm^2$). Pulse-shape discrimination in LAr avoids this problem.

° Target exchange from LAr to LNe *in the same detector* might prove vital in verifying a WIMP discovery.

° LNe might be the only viable means to provide a precision measurement of the *pp*-solar neutrino flux and thus $\theta_{12}$.

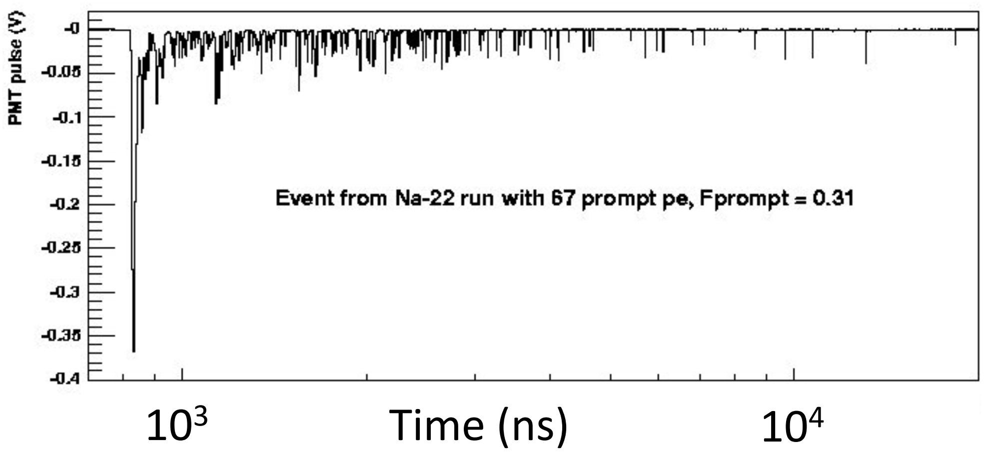
° A massive, single-phase detector capable of target exchange between LAr and LNe could achieve all of the above.

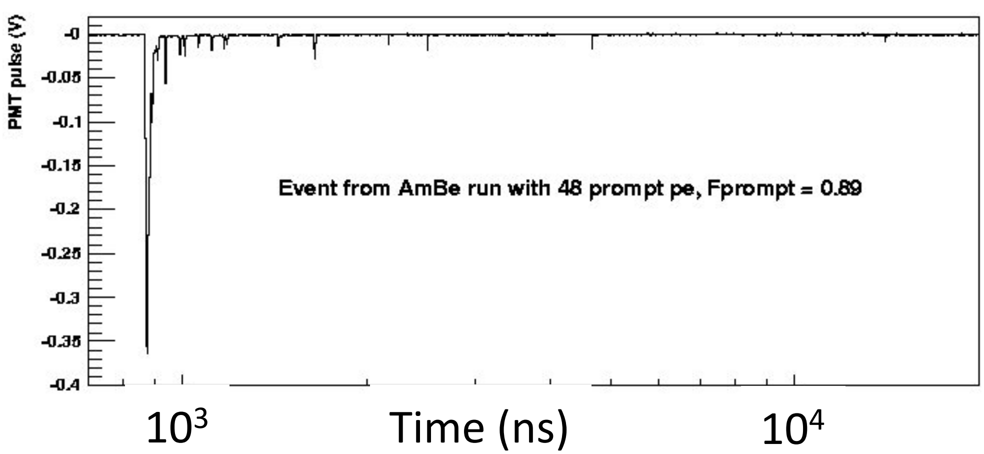

ionization
E
$R^+ + e^-$
Escape Electrons
excitation
Biexitonic Quenching
$R_2^{**}$
+ R
$R_2^+$
+ $e^-$
Recombination
+ $R^*$
$R^*$
$R^{**}$ + R
Heat
+ R
$R_2^*$
$\tau_1$
$\tau_3$
2R + hν
2R + hν
Scintillation Light
Self-Trapped
Excitons


E
$^3P_1 + ^1S_0$
$^3P_2 + ^1S_0$
$^3P_1 - ^1S_0$
Δ
$^1S_0 + ^1S_0$
R

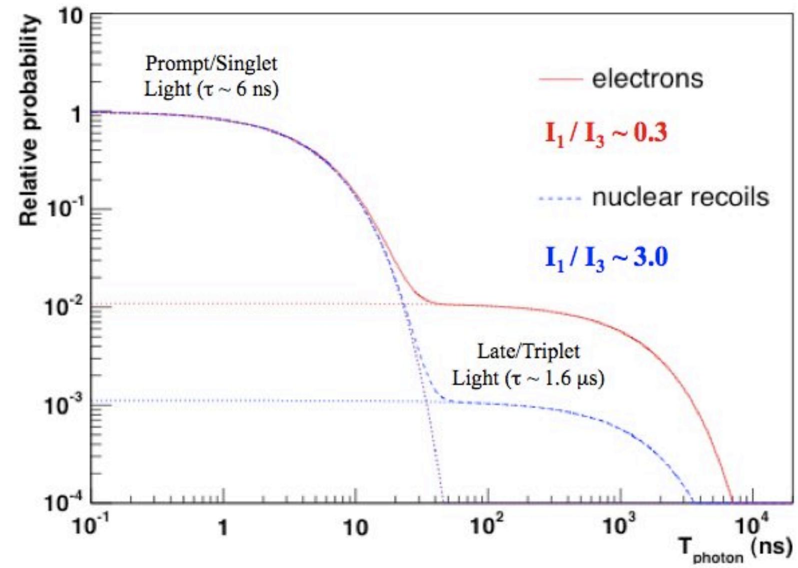
## Pulse-Shape Discrimination in LAr

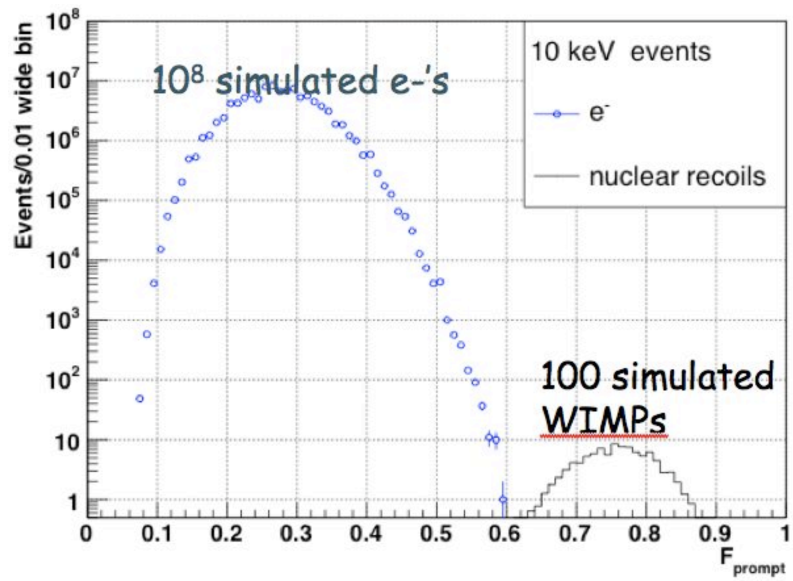
Example Pulses from DEAP-0



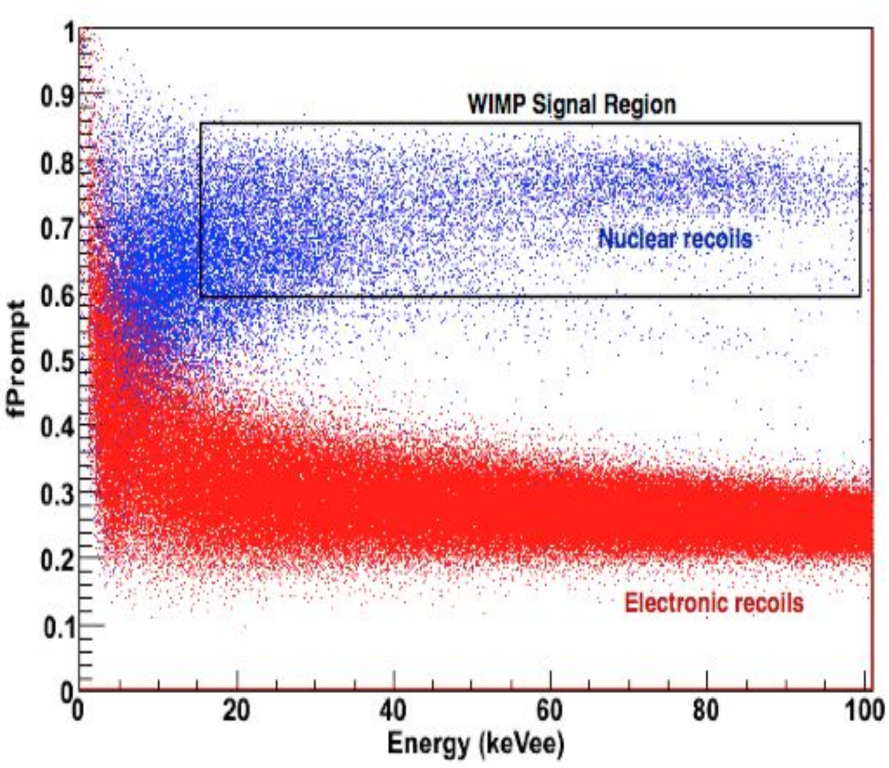

M.G. Boulay and A. Hime
Astroparticle Physics **25**, 179 (2006)



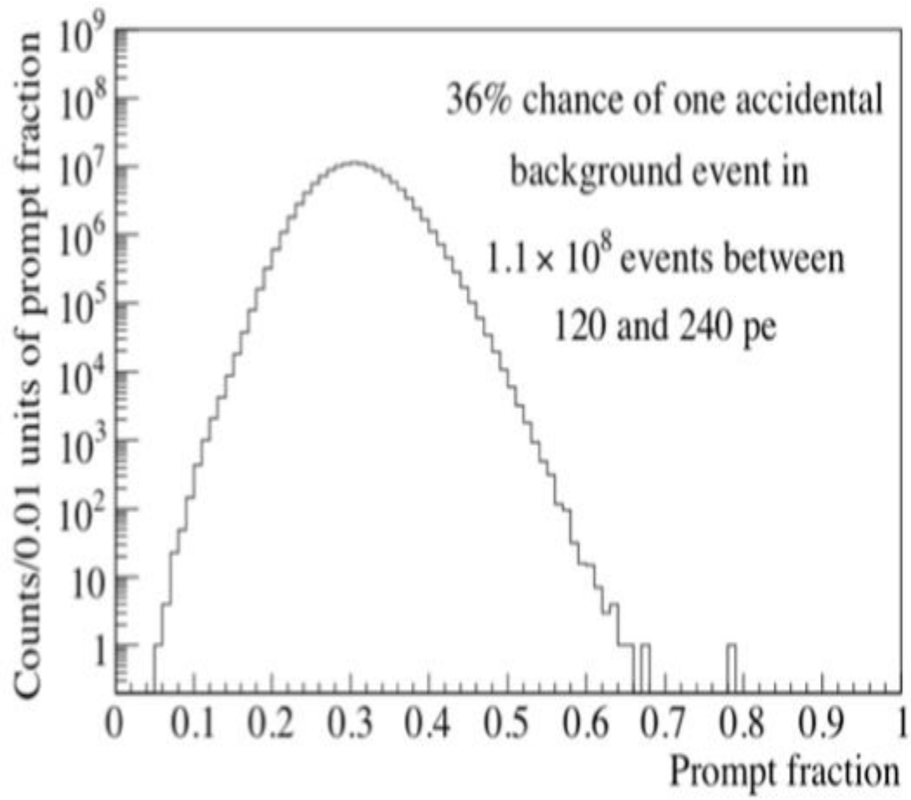
# Experimental Measurements of PSD in LAr

microCLEAN

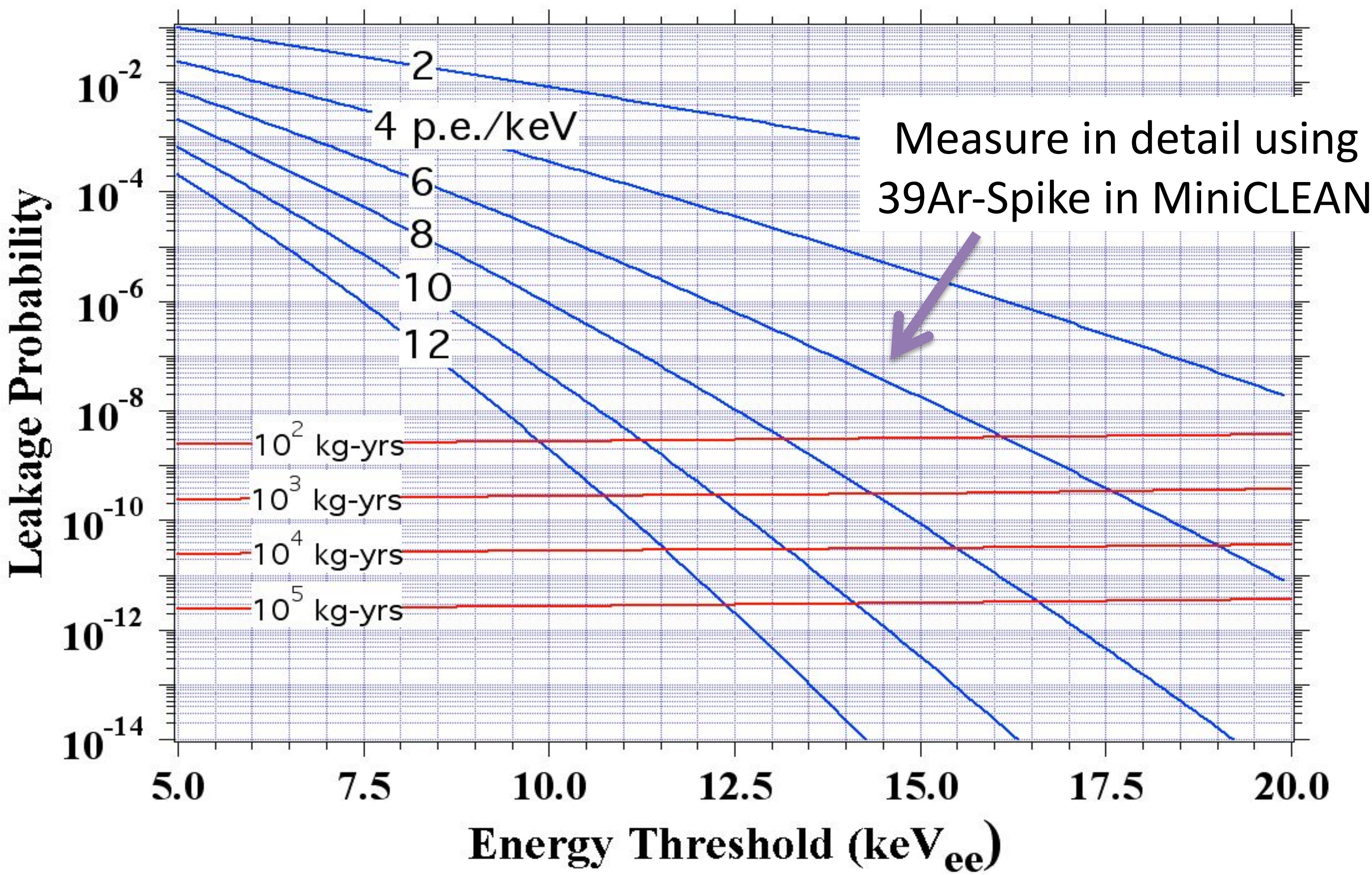



Phys. Rev. C**78**, 035801 (2008)

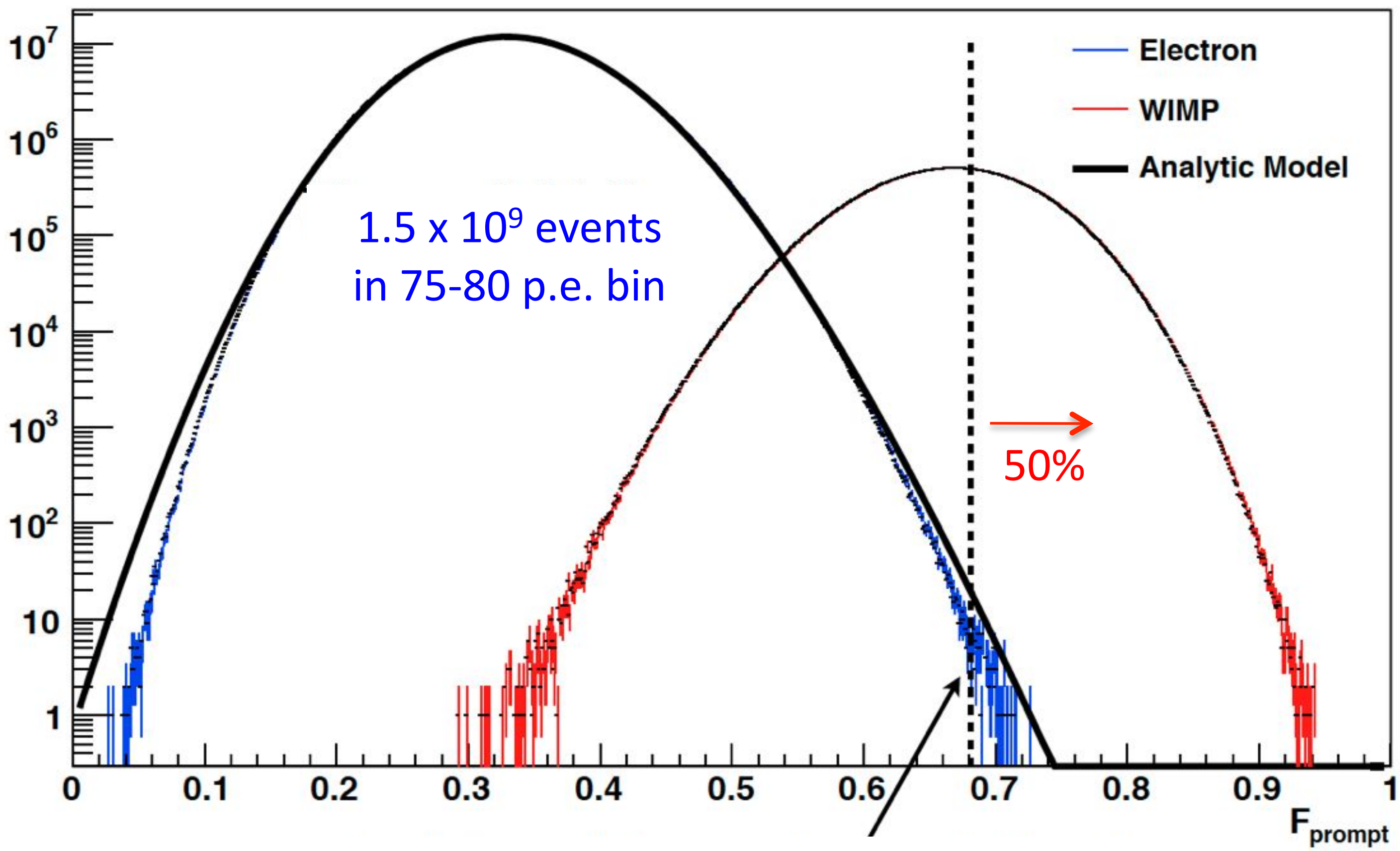
DEAP-1




arXiv:0904.2903 (2009)
TAUP - 2011

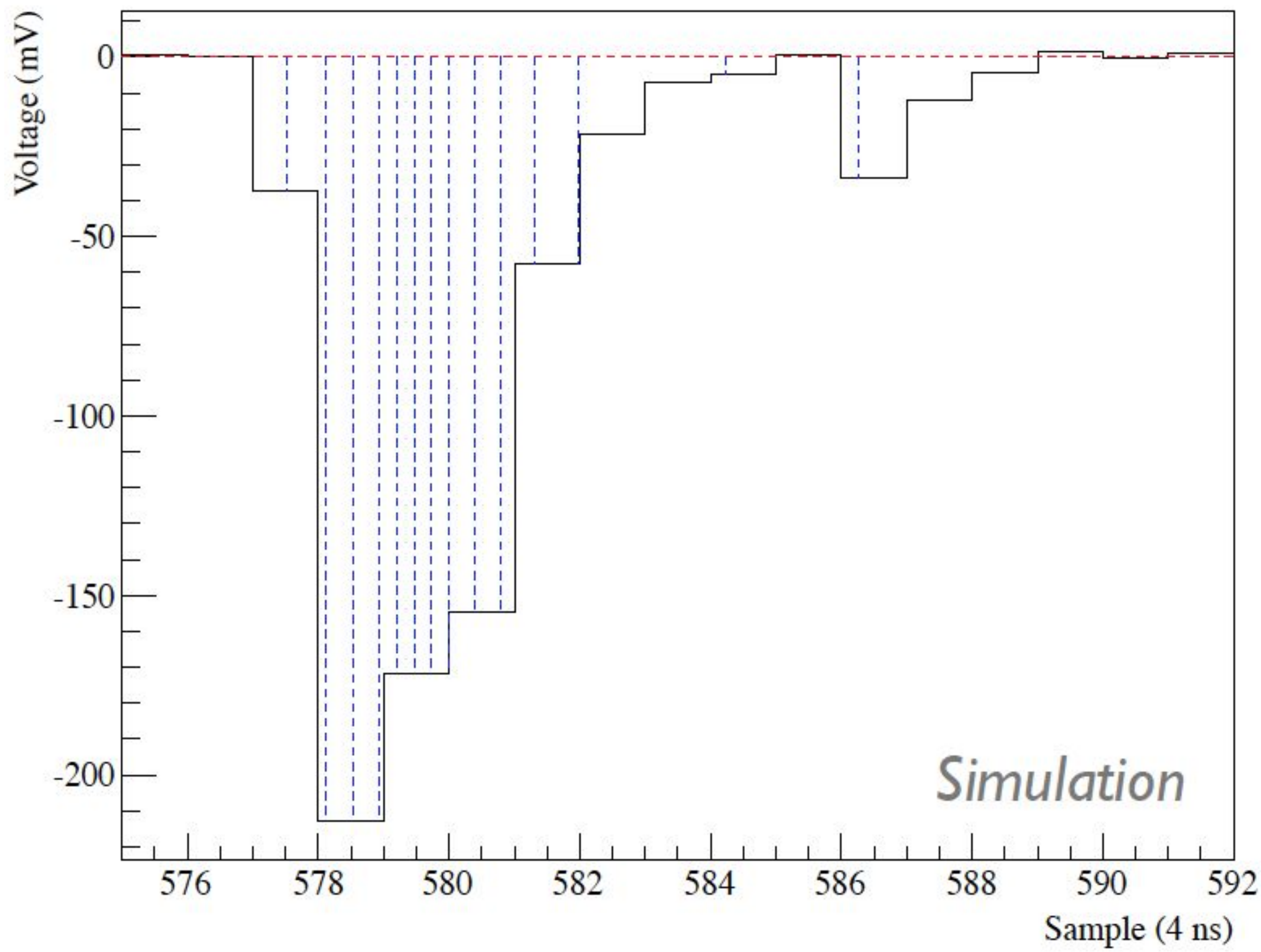

Measure in detail using
39Ar-Spike in MiniCLEAN
2
4 p.e./keV
6
8
10
12
10^2 kg-yrs
10^3 kg-yrs
10^4 kg-yrs
10^5 kg-yrs
Leakage Probability
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Energy Threshold (keV_ee)

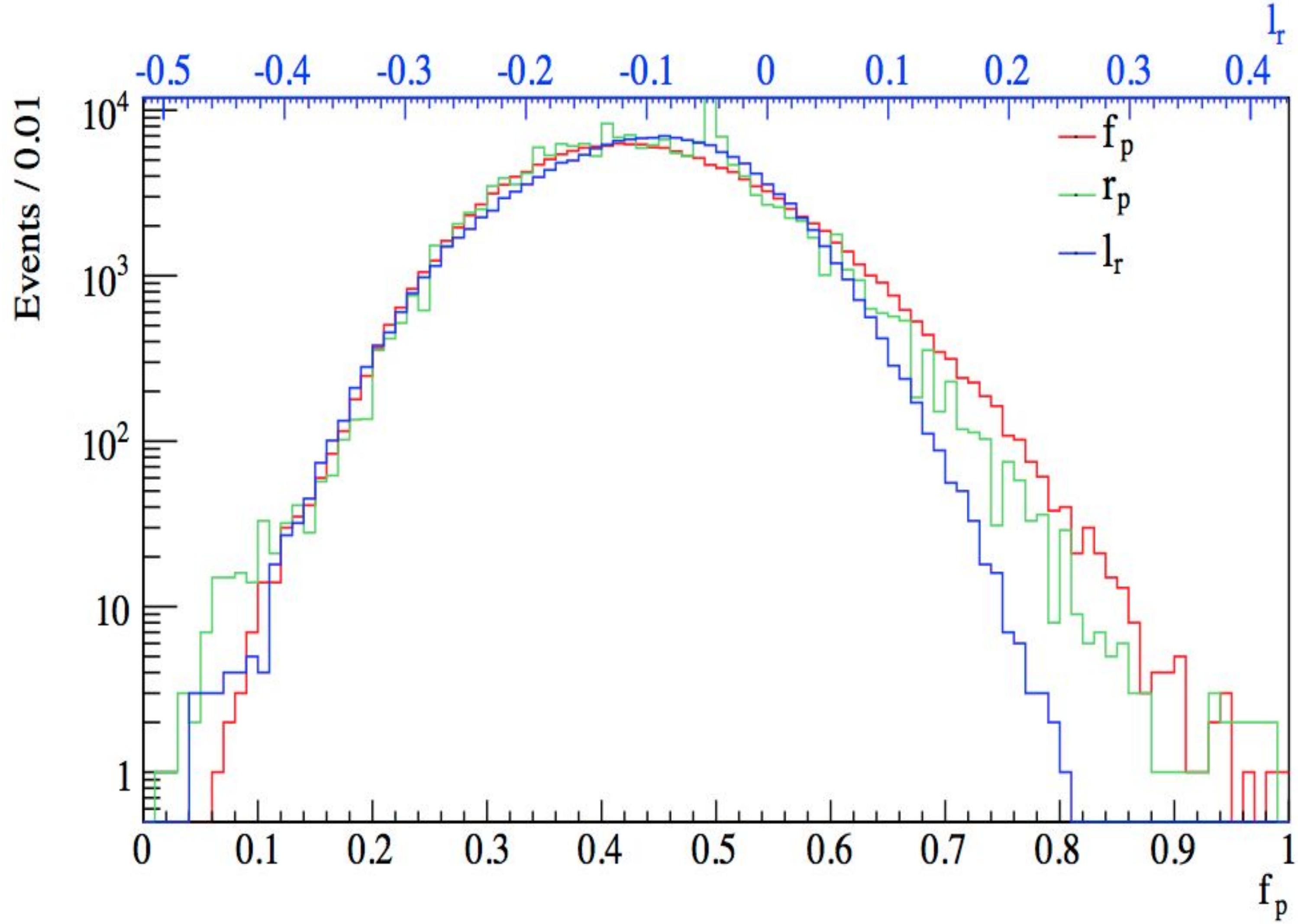
# Extrapolating $^{39}$Ar Leakage is Challenging




*Analytic model overestimates leakage by ~ x10*

With a likelihood of particle type based on photon arrival times, we can do much better than simple "$F_{prompt}$".




Events / 0.01
$10^4$
$10^3$
$10^2$
10
1
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
$f_p$
-0.5
-0.4
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
0.4
$l_r$
$f_p$
$r_p$
$l_r$

# Three Noble Liquids

| Parameter | LNe | LAr | LXe |
|---|---|---|---|
| Light Yield | 25 photons/keV | 40 photons/keV | 42 photons/keV |
| Prompt Time Constant | 2.2 ns | 6 ns | 2.2 ns |
| Late Time Constant | 16 μs | 1.6 μs | 21 ns |
| Peak Wavelength | 77 nm | 128 nm | 174 nm |
| Rayleigh Scattering Length | 60 cm | 90 cm | 30 cm |
| Density ($g/cm^3$) | 1.20 | 1.40 | 2.95 |
| Boiling Point (K) | 27.1 | 87.3 | 165.1 |
| Electron Drift Velocity at 1kV/cm | 2 cm/s | $2 \times 10^5$ cm/s | $2 \times 10^5$ cm/s |

# Three Noble Liquids

**Single-Phase** → MiniCLEAN, CLEAN (LNe/LAr) · DEAP-3600 (LAr) · XMASS (LXe)

| Parameter | LNe | LAr | LXe |
|---|---|---|---|
| Light Yield | 25 photons/keV | 40 photons/keV | 42 photons/keV |
| Prompt Time Constant | 2.2 ns | 6 ns | 2.2 ns |
| Late Time Constant | 16 μs | 1.6 μs | 21 ns |
| Peak Wavelength | 77 nm | 128 nm | 174 nm |
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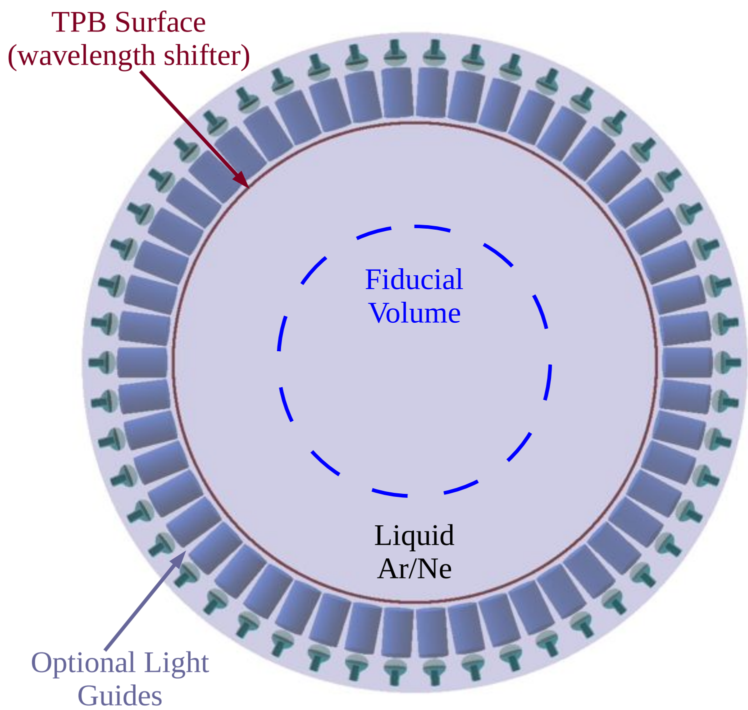
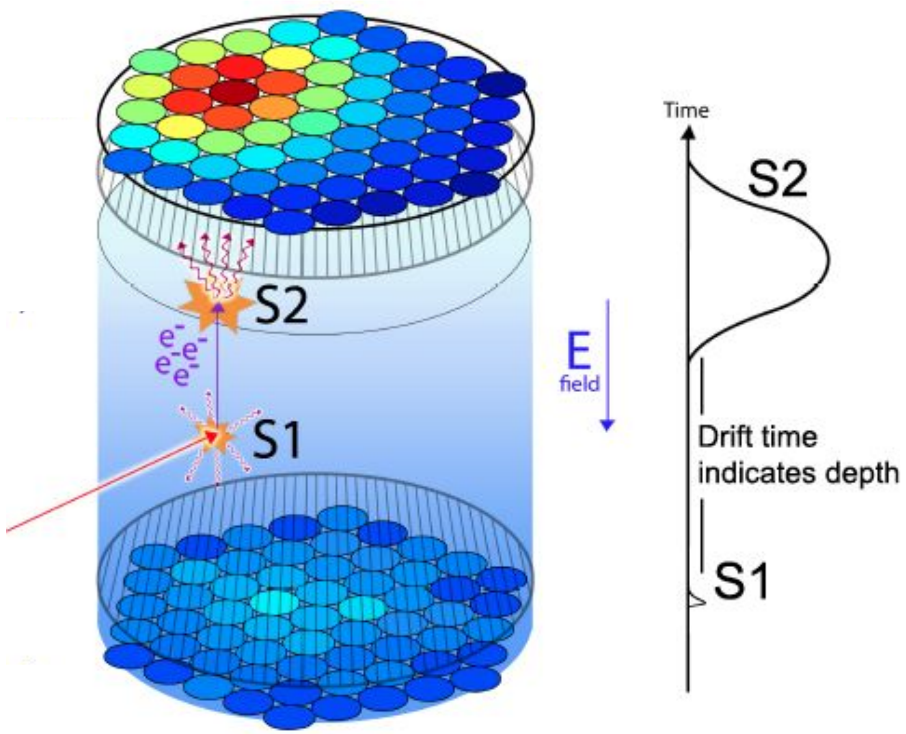
| Density ($g/cm^3$) | 1.20 | 1.40 | 2.95 |
| Boiling Point (K) | 27.1 | 87.3 | 165.1 |
| Electron Drift Velocity at 1kV/cm | 2 cm/s | $2 \times 10^5$ cm/s | $2 \times 10^5$ cm/s |

**Dual-Phase** → DarkSide (LAr) · ZEPLIN, XENON, LUX (LXe)

**Single-Phase**
**LNe / LAr**

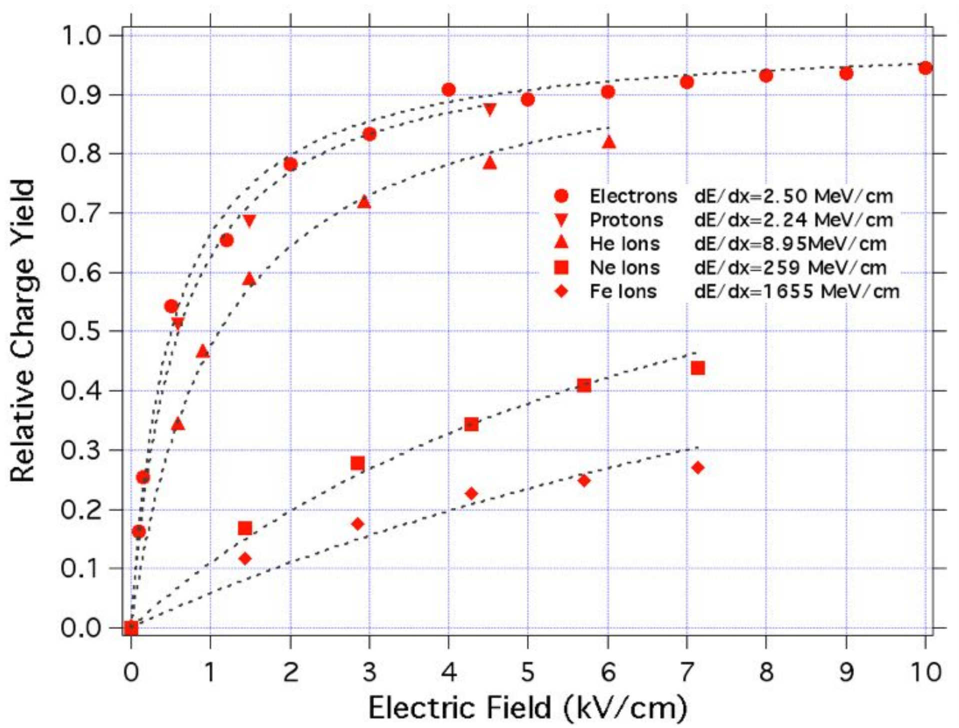


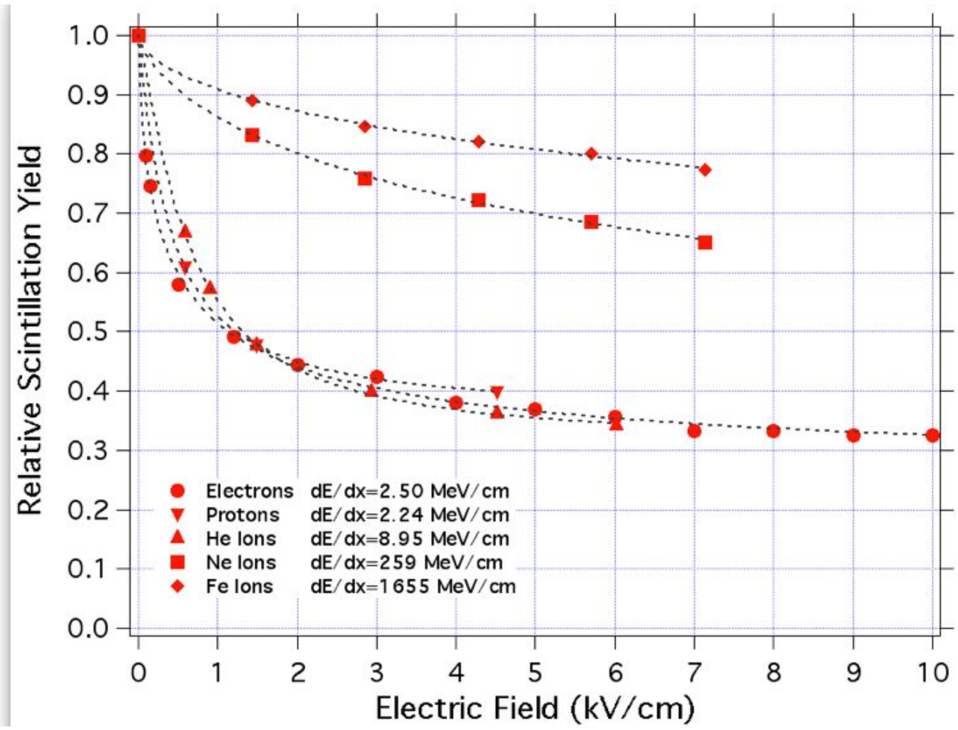

**Dual-Phase**
**LAr / LXe**

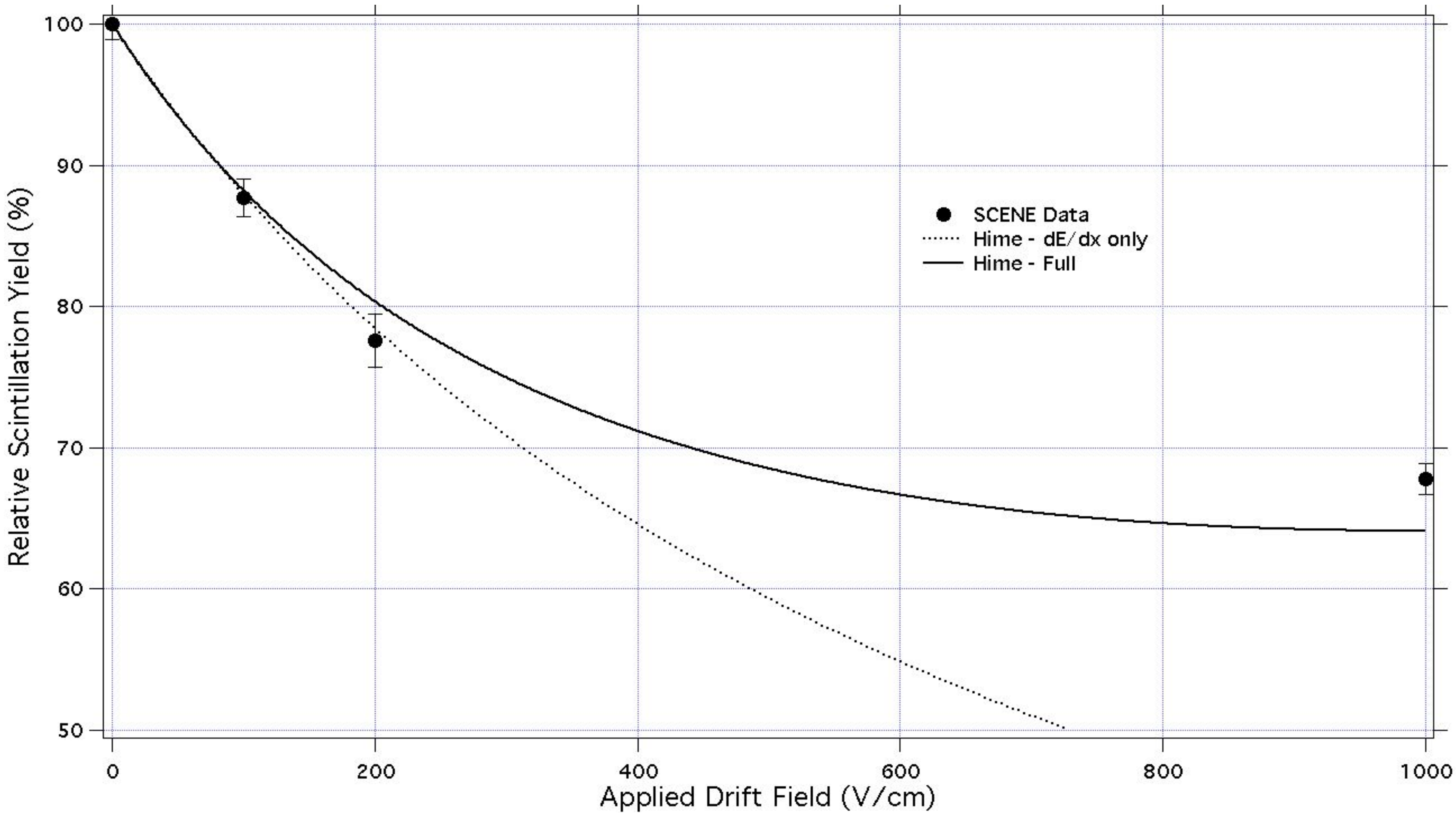


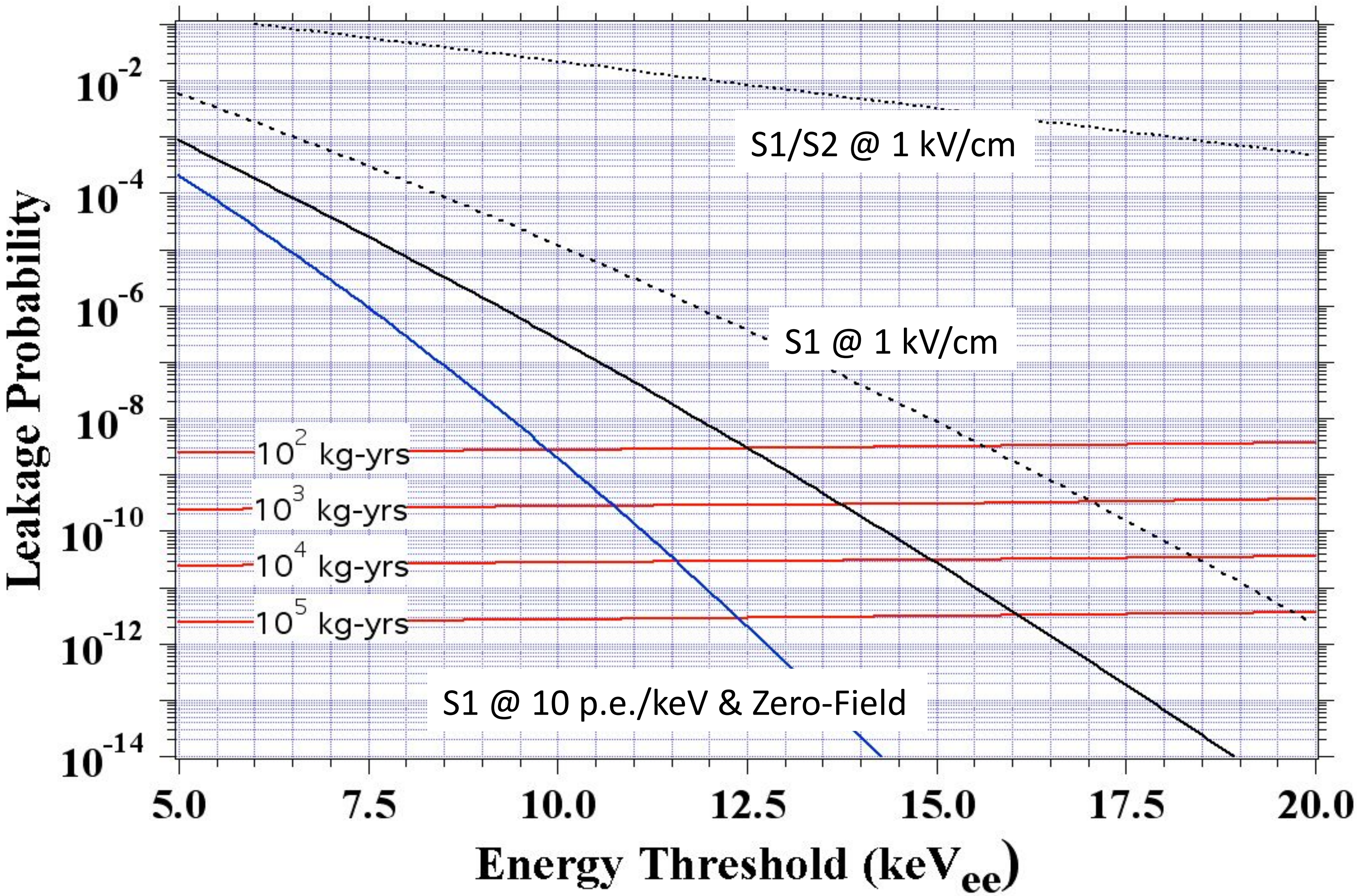

D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025.
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

# Charge & Scintillation Yield in LAr

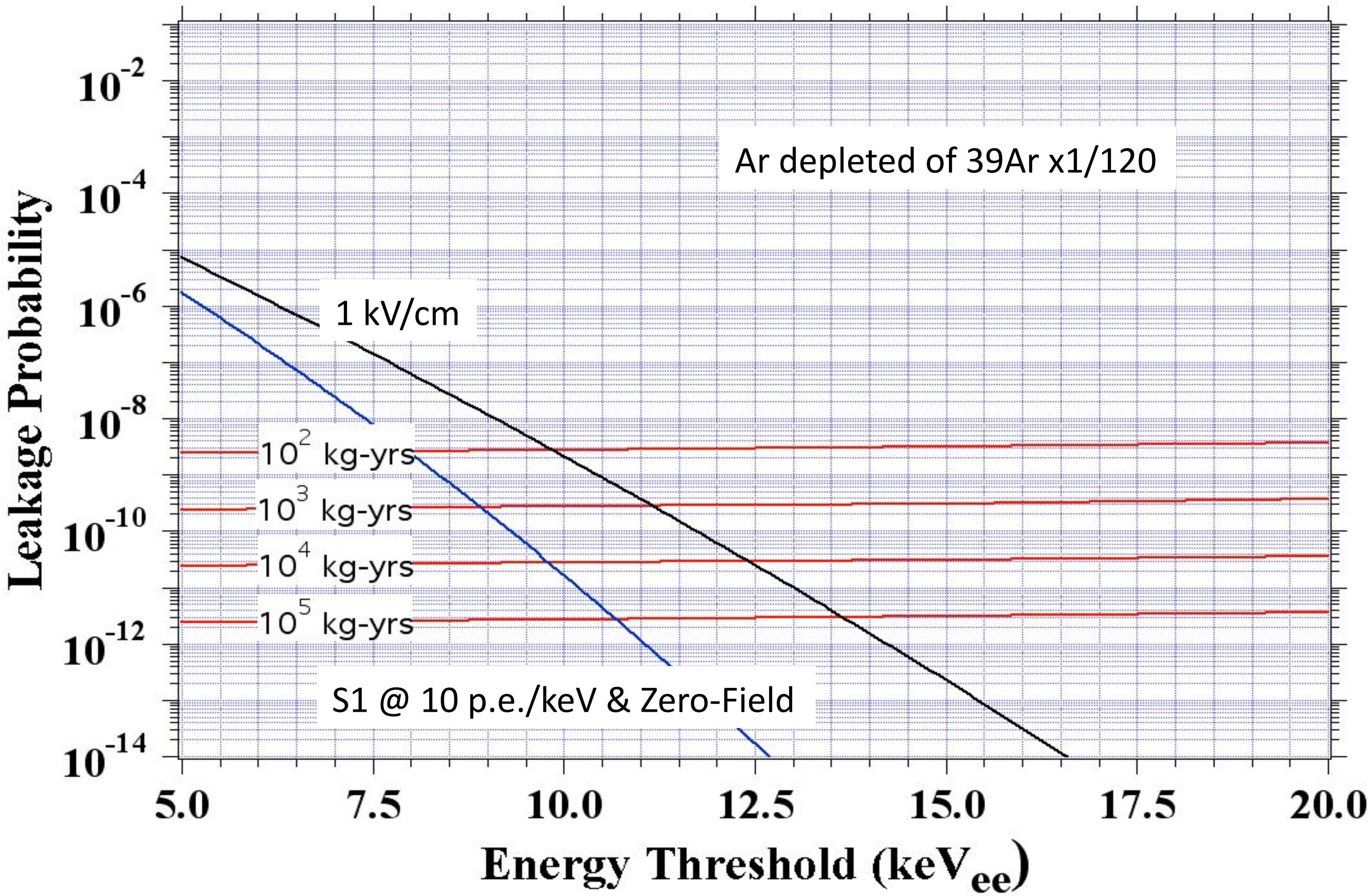



SCENE Data
Hime - dE/dx only
Hime - Full
Relative Scintillation Yield (%)
Applied Drift Field (V/cm)
100
90
80
70
60
50
0
200
400
600
800
1000



Leakage Probability
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
S1/S2 @ 1 kV/cm
S1 @ 1 kV/cm
10^2 kg-yrs
10^3 kg-yrs
10^4 kg-yrs
10^5 kg-yrs
S1 @ 10 p.e./keV & Zero-Field
5.0
7.5
10.0
12.5
15.0
17.5
20.0
Energy Threshold (keV_ee)

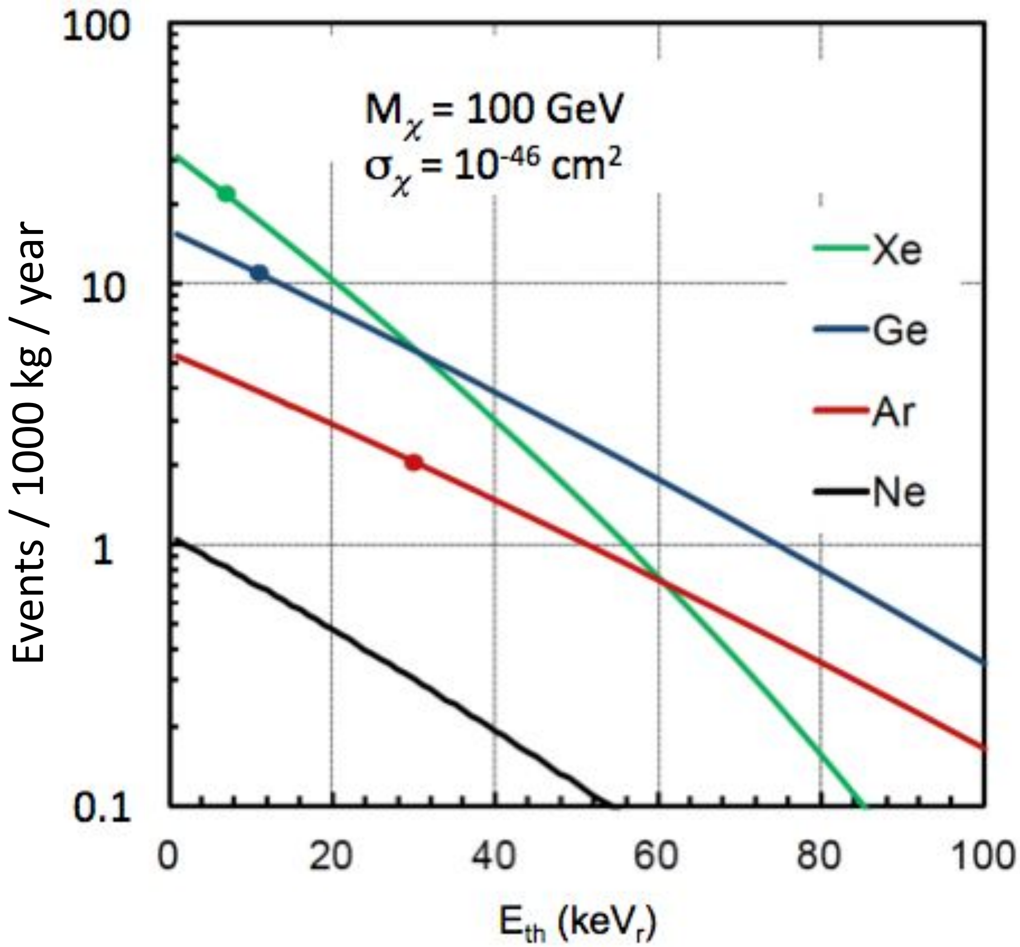


Ar depleted of 39Ar x1/120
1 kV/cm
10^2 kg-yrs
10^3 kg-yrs
10^4 kg-yrs
10^5 kg-yrs
S1 @ 10 p.e./keV & Zero-Field
Leakage Probability
Energy Threshold (keV_ee)
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
5.0
7.5
10.0
12.5
15.0
17.5
20.0

# MiniCLEAN – Photon Budget

| Parameter | Value | Light Yield p.e. / keVee | Note |
|---|---|---|---|
| **Scintillation Yield (photons/keVee)** | 46.2±5.2 | | |
| **PMT Efficiency** | 19±2 % | 8.8±1.3 | R5912-02MOD |
| **TPB Coverage** | 93.4 | 8.2±1.2 | Viewing 500 kg Target |
| **TPB Re-Emission Efficiency** | 1.2±0.1 | 9.8±1.5 | 128 nm |
| **Absorption in TPB** | 2 to 19 % | 7.9 to 9.8 | |
| **Absorption in Acrylic** | 11.3 % | 7.0 to 8.7 | Attenuation Length is ~1 m at 400 nm |
| **Absorption in Light Guide** | 12.3 % | 6.1 to 7.6 | Reflectivity is 98% at 420 nm |
| **Resulting Light Yield** | | **6.1 to 7.6** | |

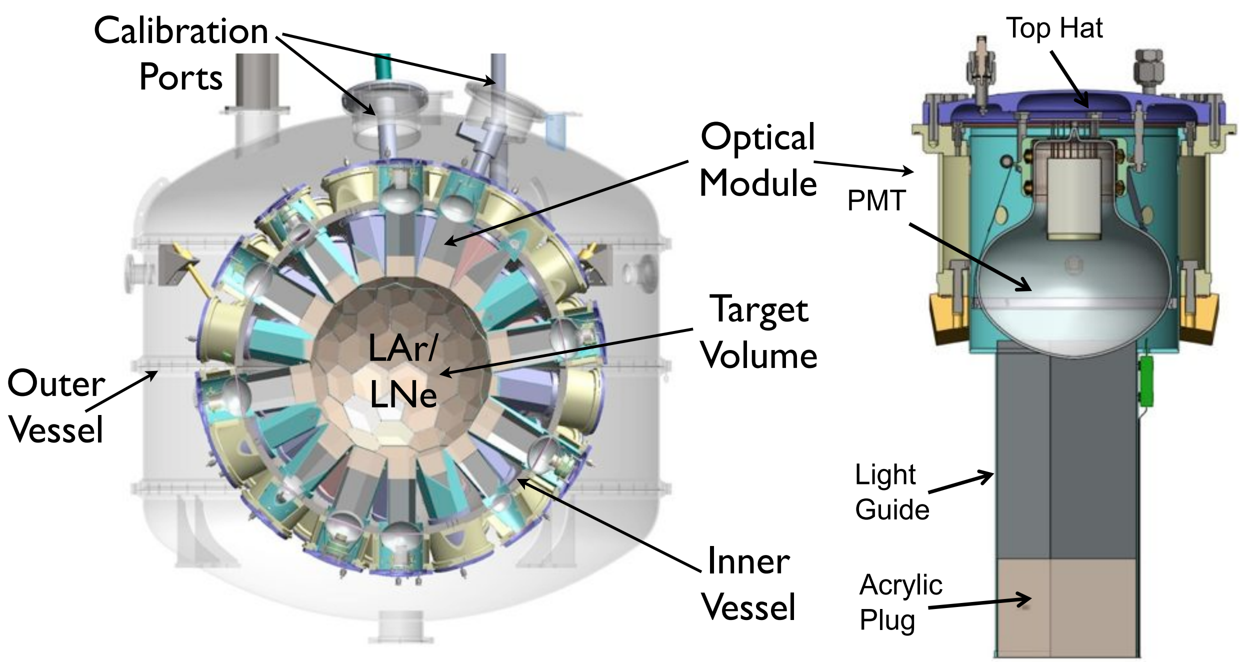
| Parameter | Value MiniCLEAN | Light Yield p.e. / keVee | Value CLEAN | Light Yield p.e. / keVee |
|---|---|---|---|---|
| **Target Mass** | 500 kg | | 50000 kg | |
| **Scintillation Yield (photons/keVee)** | 46.2±5.2 | | 46.2±5.2 | |
| **PMT Efficiency** | 19±2 % | 8.8±1.3 | 31±2 % | 14.3±1.6 |
| **TPB Coverage** | 93.4 | 8.2±1.2 | 93.4 | 13.4±1.2 |
| **TPB Re-Emission Efficiency** | 1.2±0.1 | 9.8±1.5 | 1.2±0.1 | 16.0±1.5 |
| **Absorption in TPB** | 19 % | 7.9 | 19 % | 13.0 |
| **Absorption in Acrylic** | 11.3 % | 7.0 | --- | 13.0 |
| **Absorption in Light Guide** | 12.3 % | **6.1** | < 2 % | **12.7** |

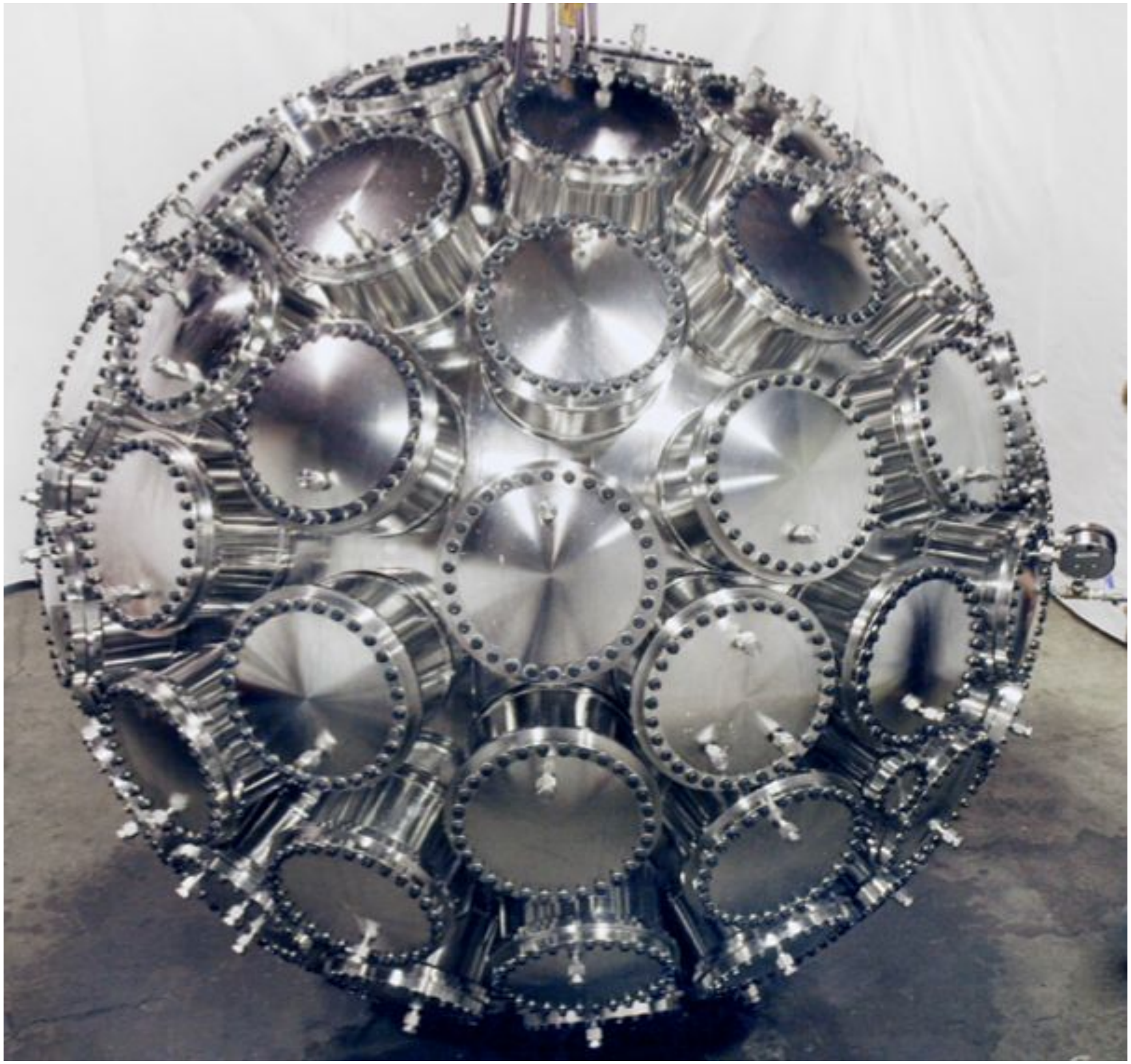



| *$E_{th}$* (keV$_r$) | *50 kt-yrs LAr events/yr @ $10^{-46}$ cm$^2$* |
|---|---|
| *50* keV$_r$ | *50* events |
| *30* keV$_r$ | *100* events |
| *20* keV$_r$ | *150* events |

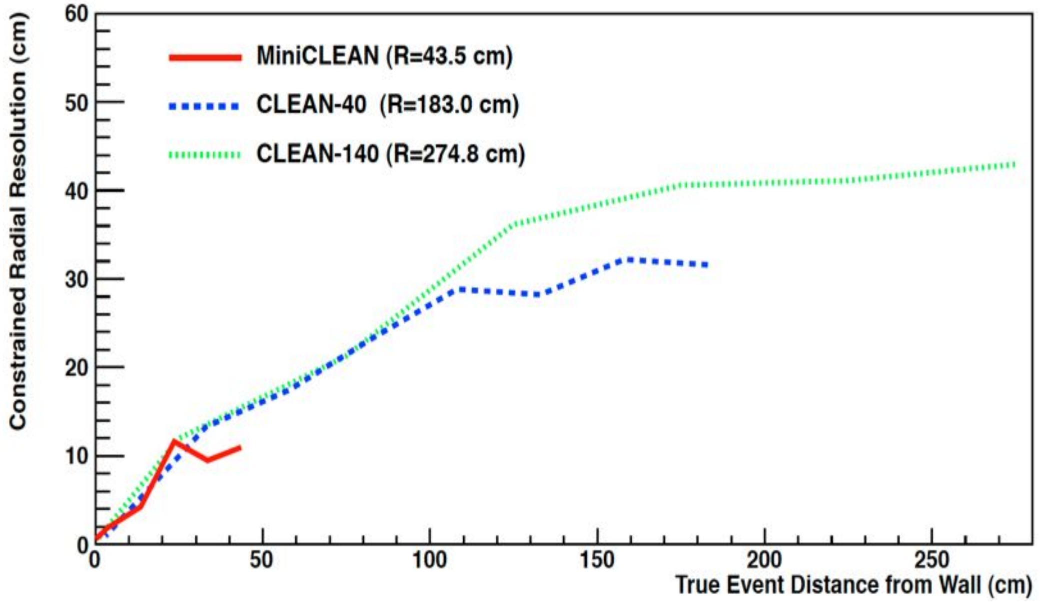
# MiniCLEAN Modular Design

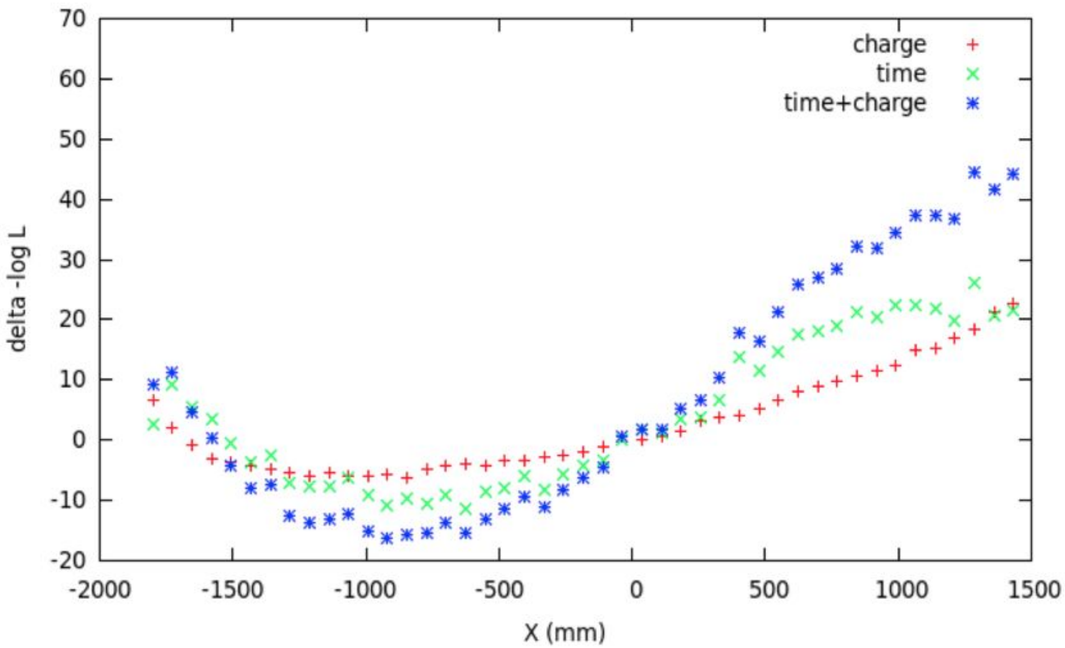
- 4π coverage to maximize light-yield at threshold …
  - 3D Position Reconstruction
  - Particle-ID via Pulse-shape discrimination
- Radon-reduced assembly …
- "Cold" design allows both LAr & LNe …
- No electric fields … PMTs only active component …
- Fast signals ($\tau_3$ = 1.6 μs) avoid pulse-pileup in LAr …

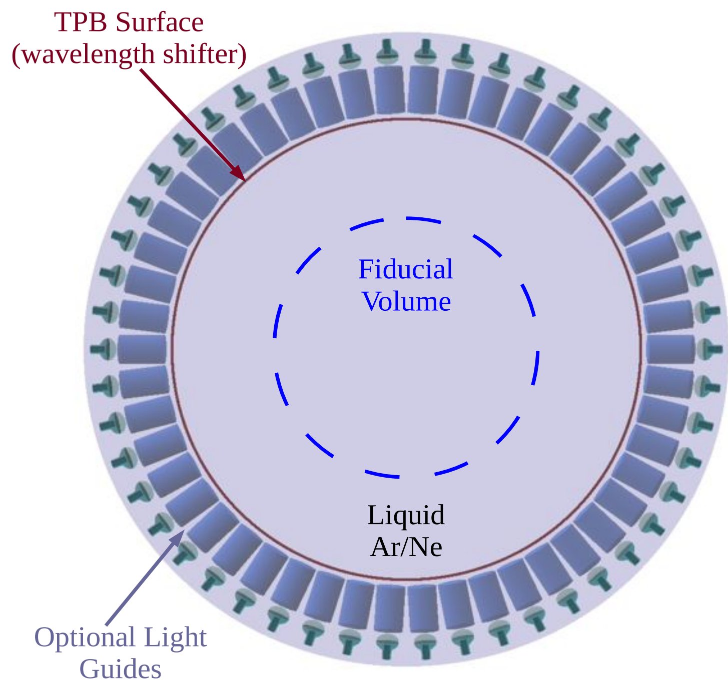




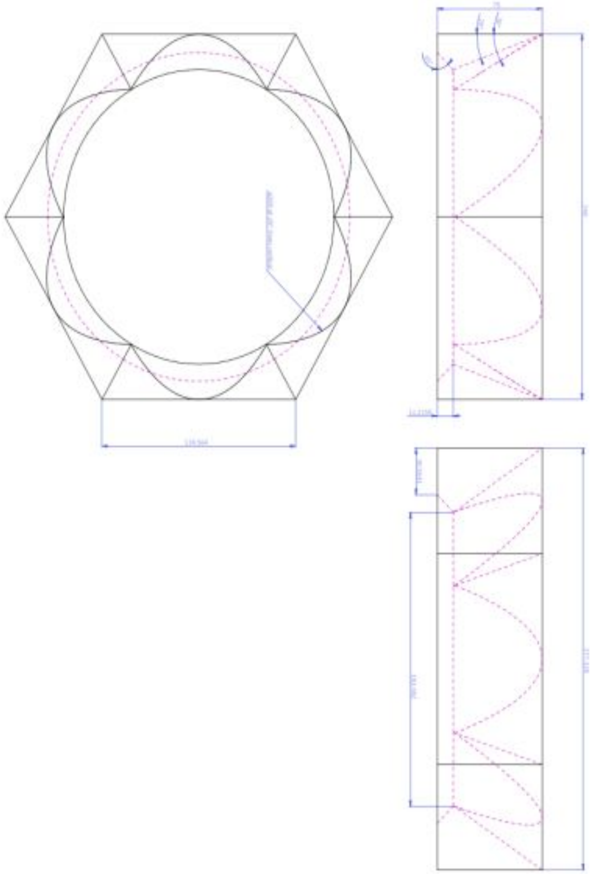
# Single-Phase Detector

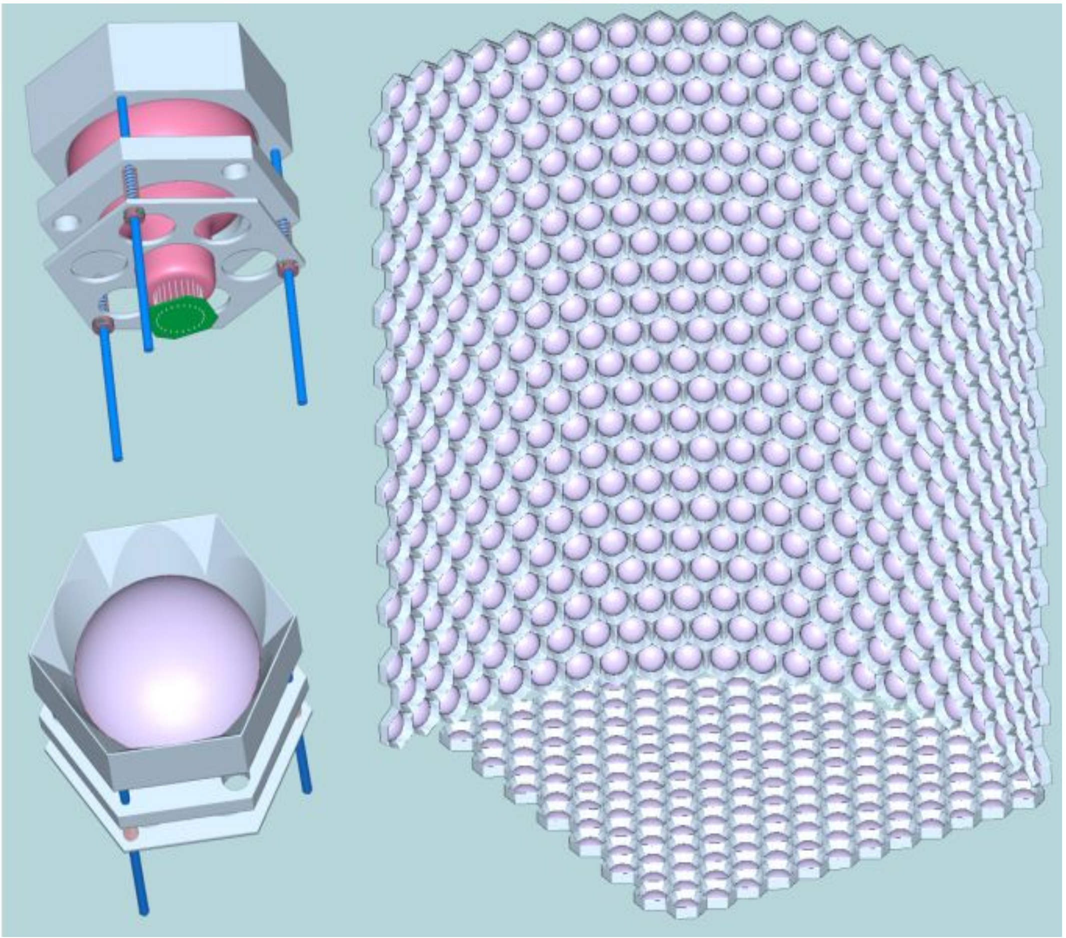


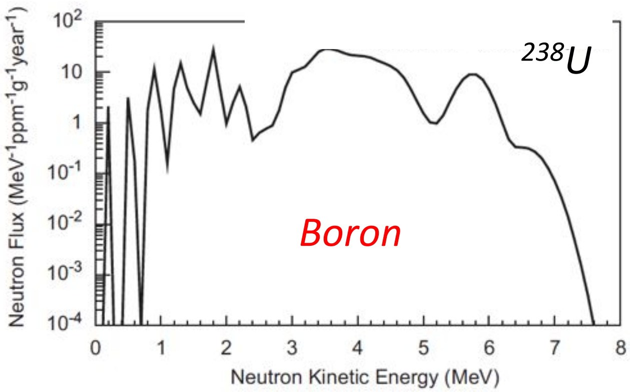



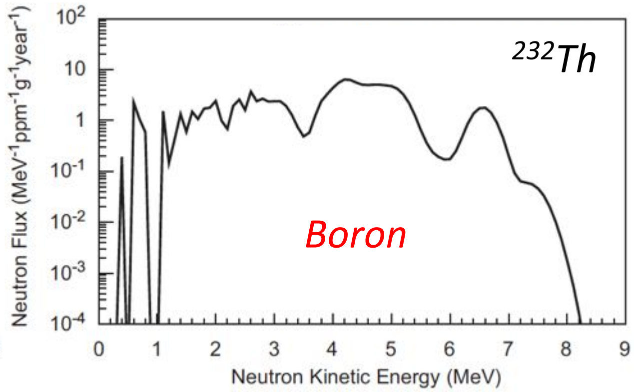
# Model for a 45 tonne CLEAN Detector

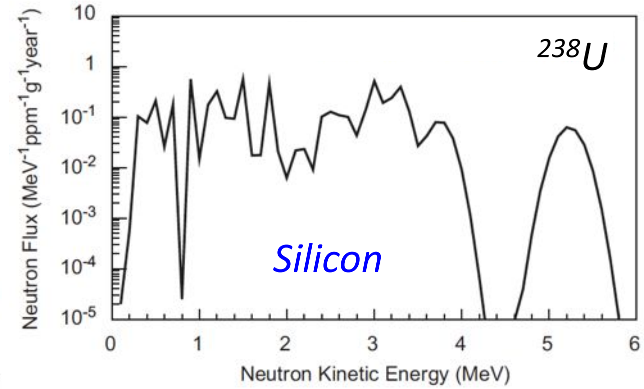


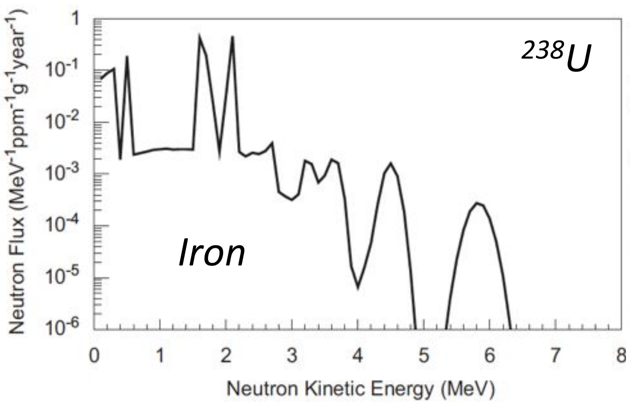


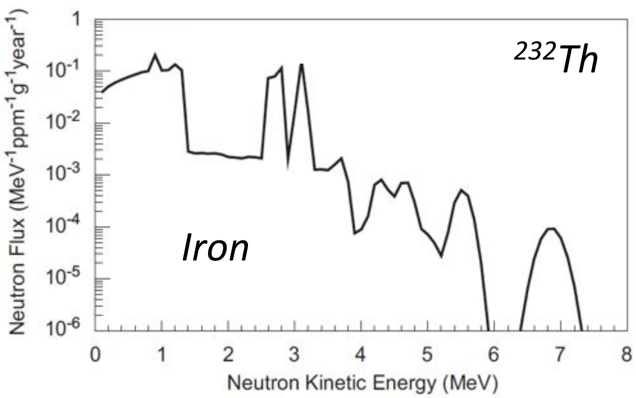
# (α,n) Yields



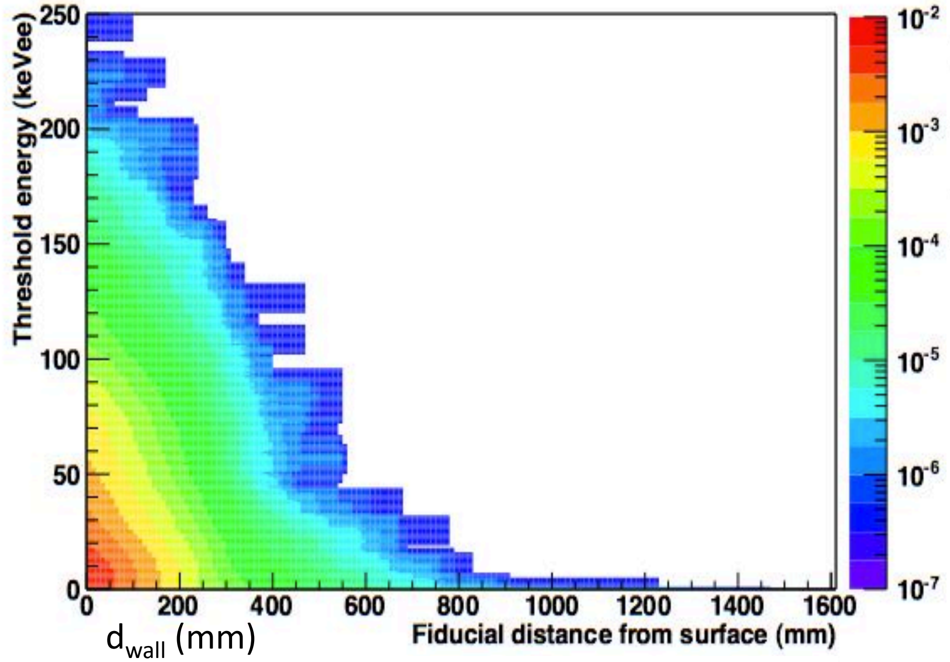



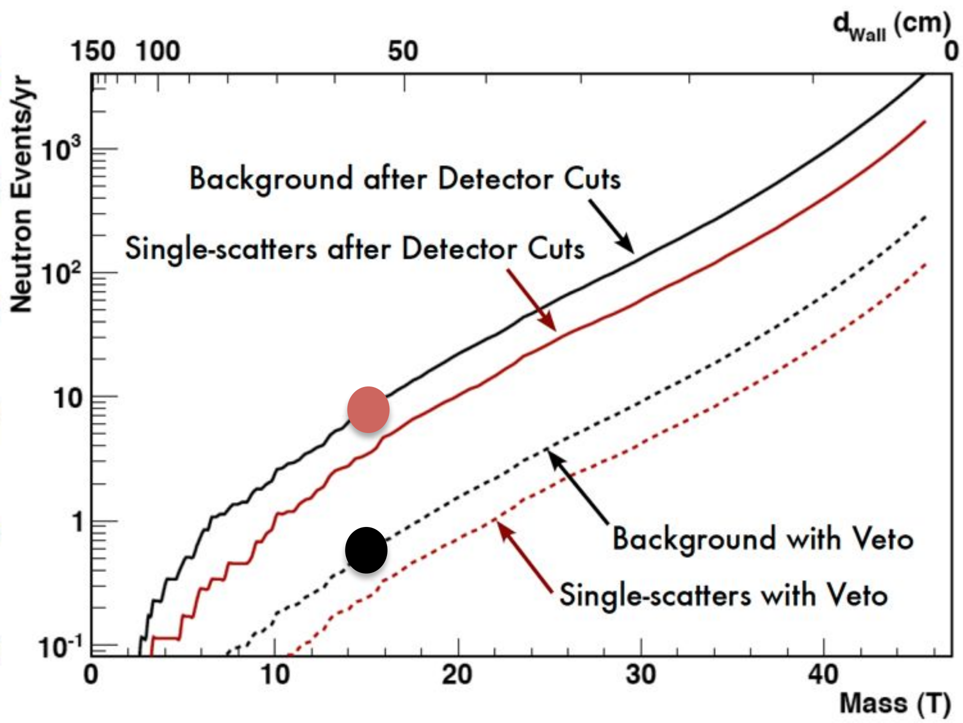

*Borated Silica Glass*

*Hamamatsu R5912-02MOD*

*D.-M. Mei, C. Zhang and A. Hime*
*NIM A**606**, 651 (2009)*

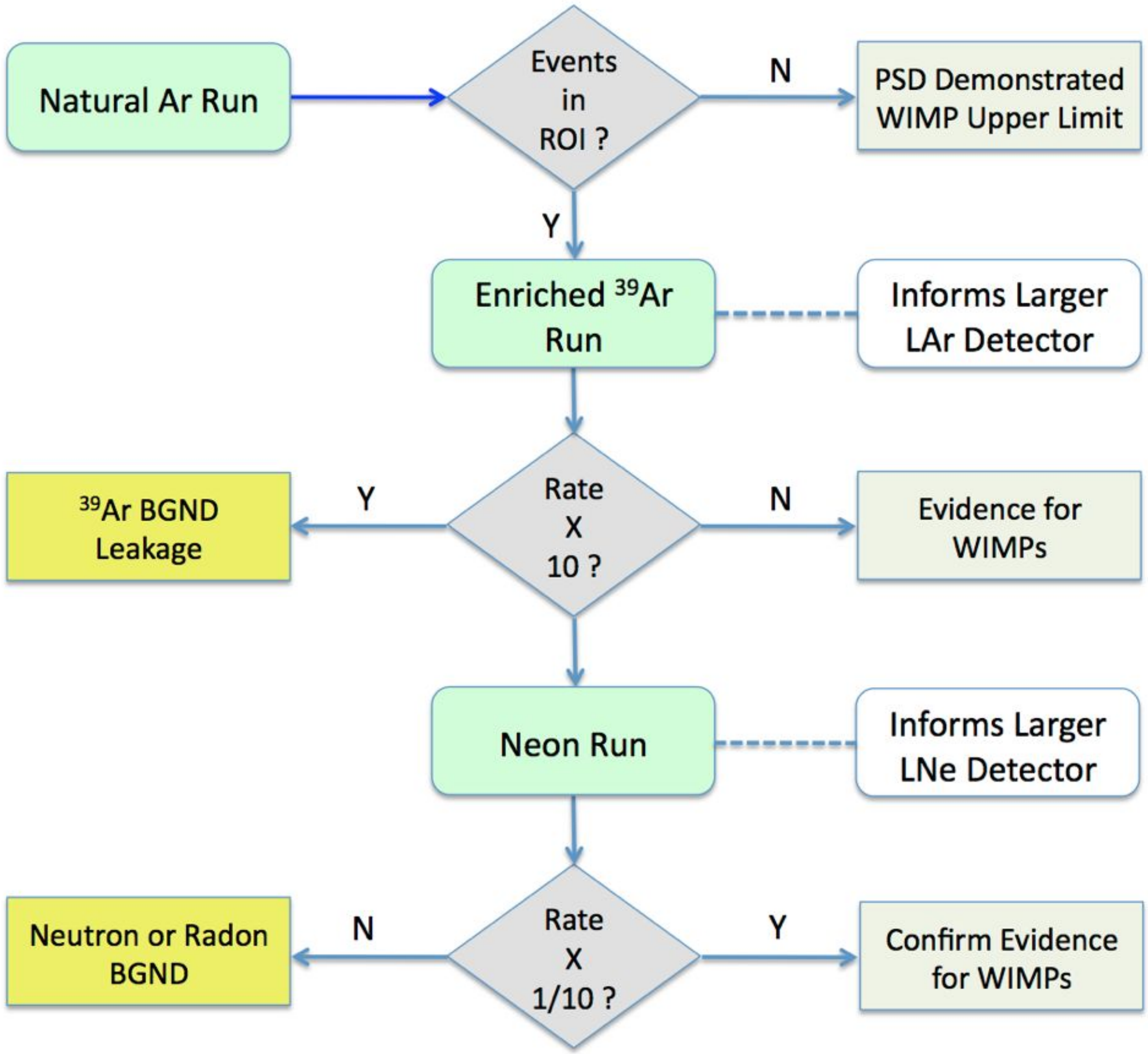
# Fast Neutrons in 45-tonne CLEAN




| Raw Yield | 499,000 yr$^{-1}$ | 1100 PMTs |
|---|---|---|
| Reconstructed | 386,997 yr$^{-1}$ | |
| Energy ROI | 10,424 yr$^{-1}$ | 12.5 – 25 keV$_{ee}$ |
| Fiducial Volume | 421 yr$^{-1}$ | $d_{wall}$ > 55 cm<br>M = 15,000 kg LAr |
| $F_{prompt}$ + Timing | 5.9 yr$^{-1}$ | |
| Active Veto | 0.53 yr$^{-1}$ | Irreducible BGND |

# $^{39}$Ar Spike & Target Exchange in CLEAN



Thank You

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