# Dark Matter searches with liquid noble elements

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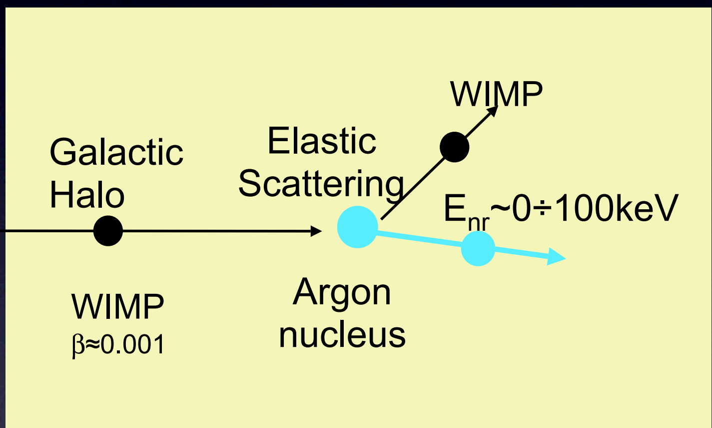
# Why (Liquid) noble gases ?

- Liquid noble gases for Direct Dark Matter Searches (≡DDMS)
  - Well-known "noble" elements with extensive experience as detector medium, in particular in case of Argon & Xenon
  - Response to radiation understood (although some experimental puzzles remain at very small energies)
  - Scintillation via atomic excimer states → nuclear recoil discrimination achieved (S2/S1 and/or PSD)
  - High yields → keV thresholds achievable
  - Provide self-shielding → reduce external backgrounds
  - Very high levels of purity achieved → long drift of ionization
  - Operate as TPC → position resolution → fiducial volume
  - Imaging TPC → background topology (Compton, n-scatter)
  - Scalable detectors → "ton"-scale to reach cross-section at few $10^{-45}$ cm$^2$
- Not covered in this talk:
  - High-pressure gaseous chambers → SIGN, HPGS

# The signal: WIMP elastic scatters

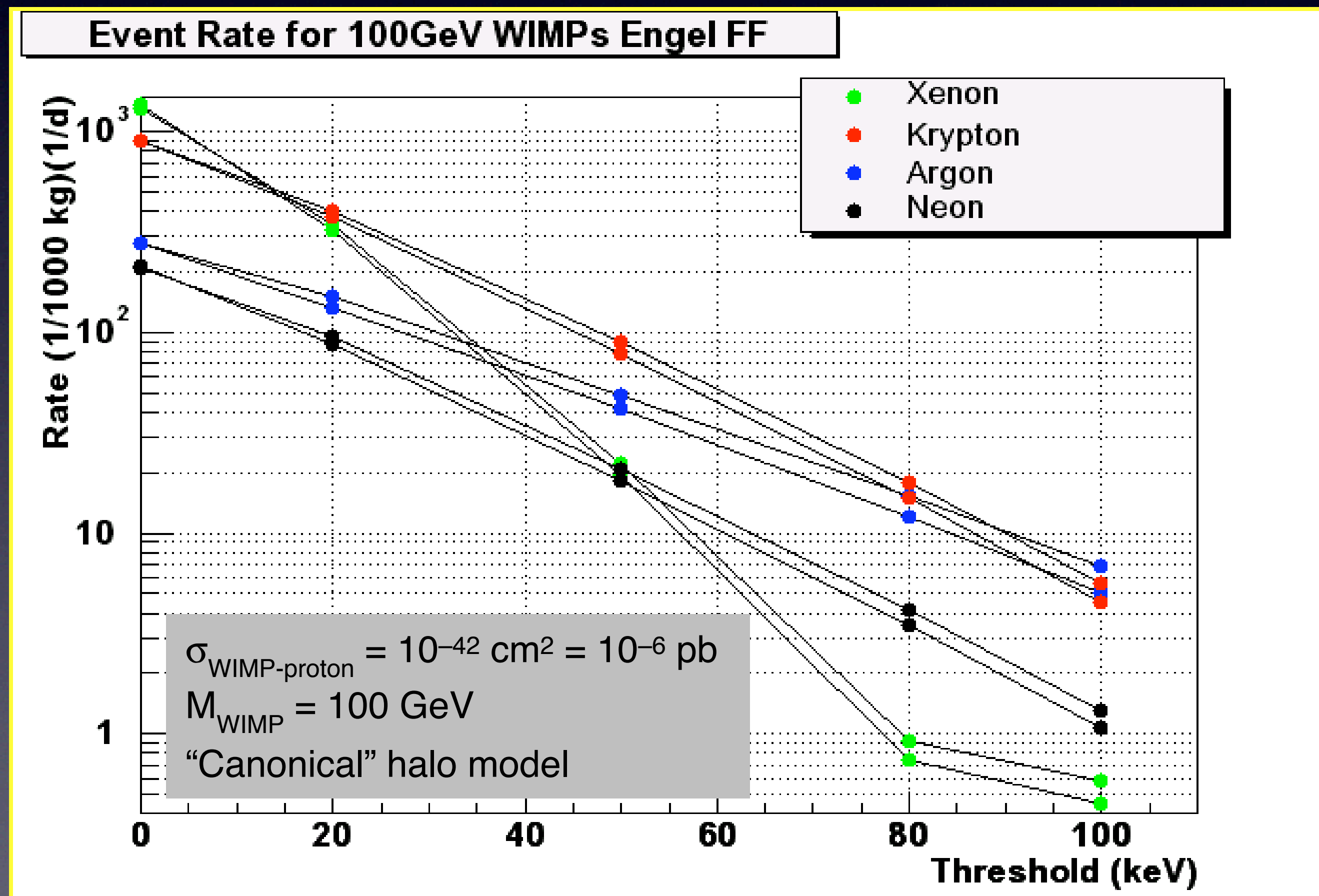
- Consider coherent elastic scatter from a nucleus in a terrestrial experiment

$$\frac{dR}{dE_{nr}} \propto S\left(E_{nr}\right)\times\left[F^2\left(q^2 = 2M_{WIMP}E_{nr}\right)\right]\times I \approx e^{-E_{nr}/E_0}F^2 I$$



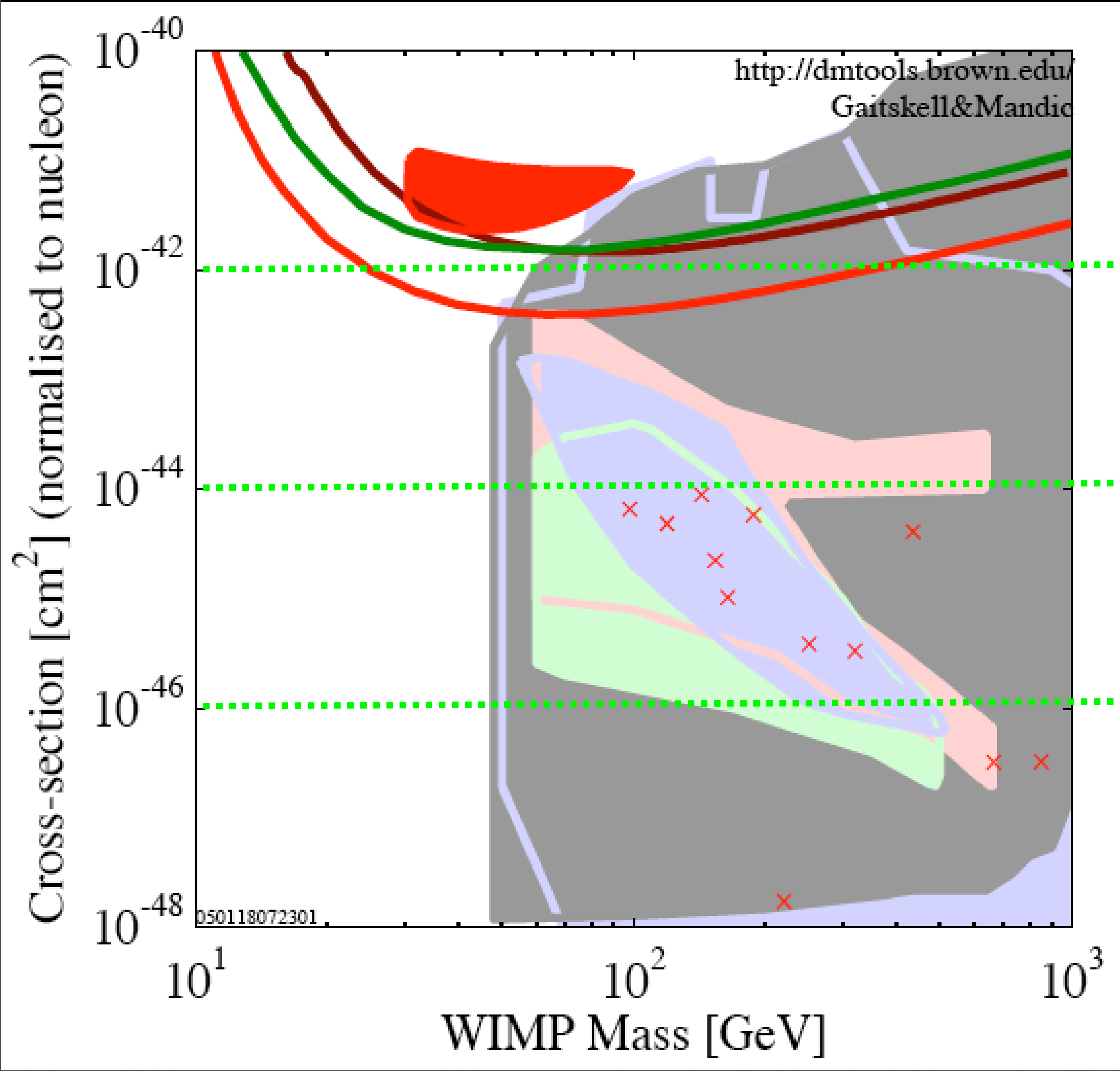

- $E_{nr}$ = nuclear recoil kinetic energy
- S = spectral function, depends on halo model, masses, velocities, ...
- F = nuclear form factor
- I = non-relativistic scalar (SI) & axial (SD) interaction

Event rate above recoil energy threshold per day and per 1000 kg target of Xe/Kr/Ar/Ne



# Estimated event rates

E.g. LAr




With recoil energy threshold ≈ 30 keVr

≈ 100 events/ton/day

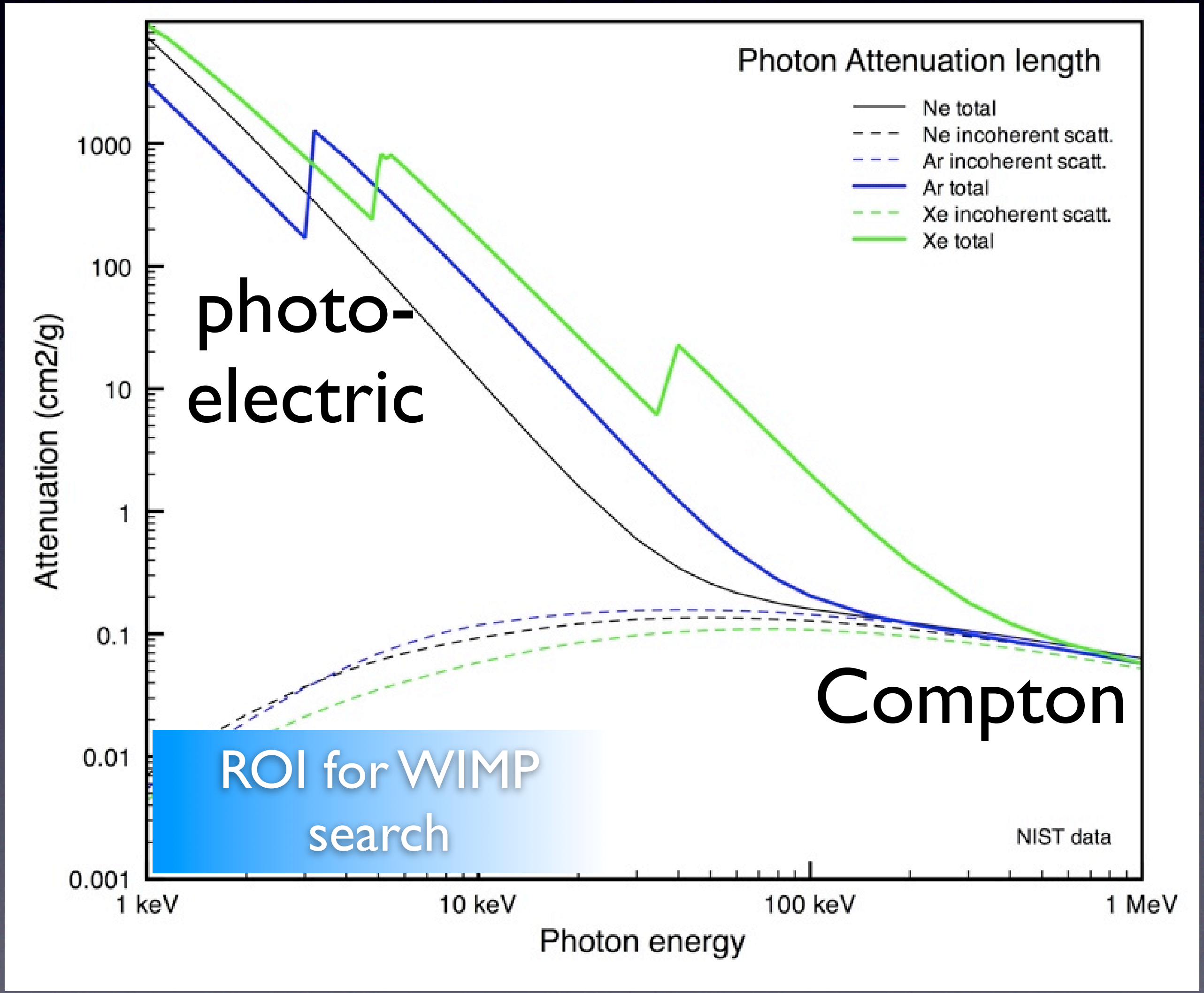
≈ 1 event/ton/day

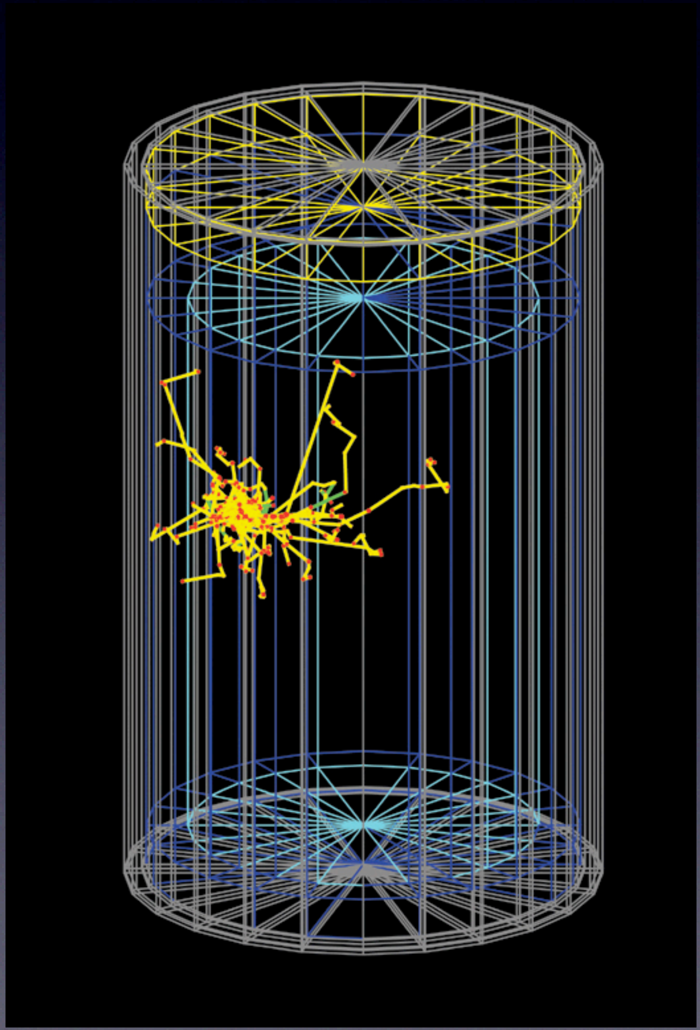
≈ 0.01 events/ton/day

Rare event...

# External gamma background

- Photons in ROI for WIMP rapidly absorbed by photo-electric process
- Compton process source of low energy deposits within fiducial volume
- However, often results in multiple scatters within active volume

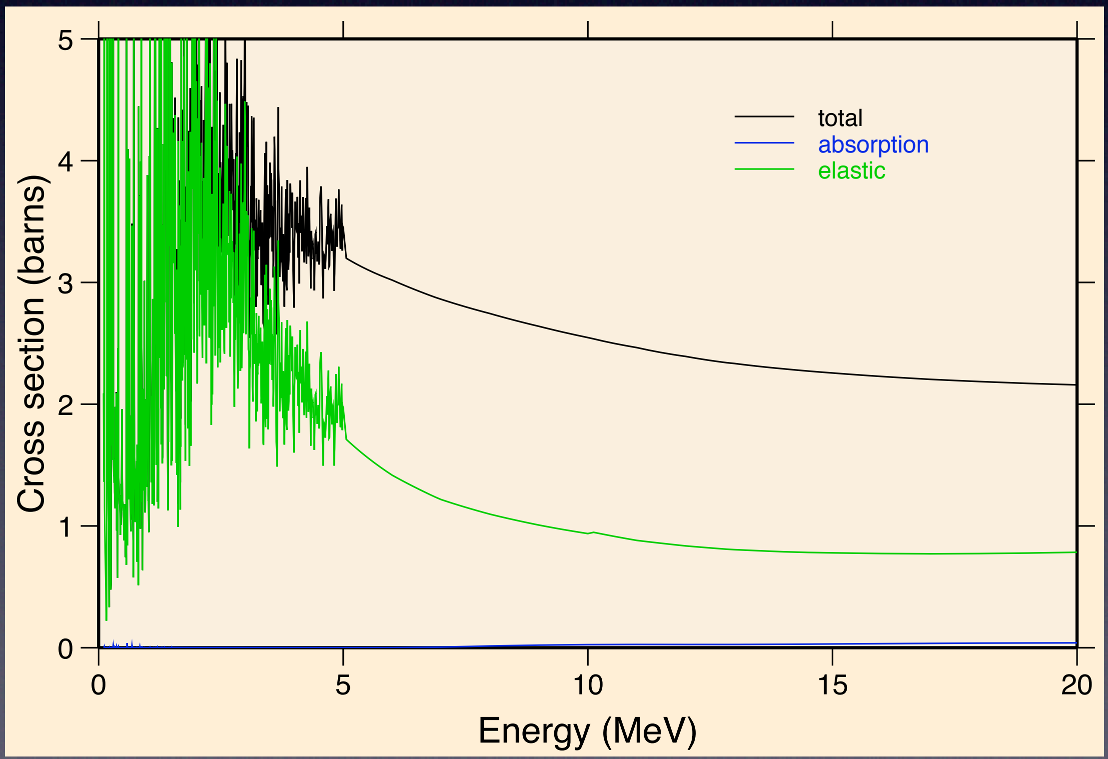


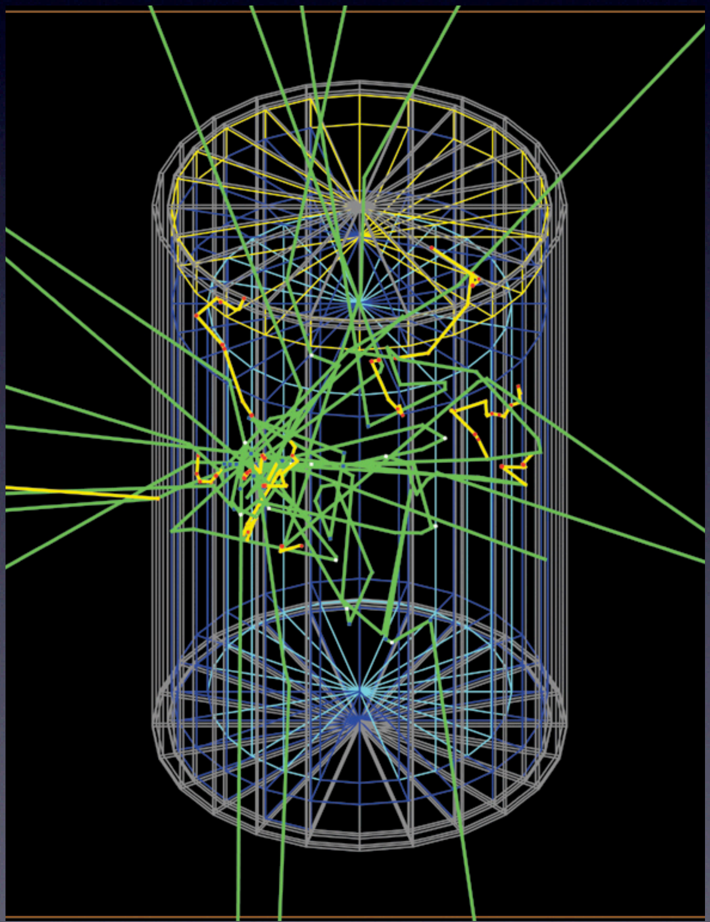



# Irreducible neutron background

- Irreducible genuine nuclear recoils (NR) are produced by fast neutrons elastically scattering off target nuclei
- Reverse argument: assume WIMP elastic interaction looks exactly like neutron elastic scattering → calibration of NR. However, neutron is strongly interacting ➠ high probability for multiple-scatters within target volume.

Neutron cross-section on Ar40



# Basic liquid medium properties

| Medium/ Property | BP @ 1atm | Density liquid g/cm$^3$ | W (eV) $Q_0$=E/W | electron mobility (cm$^2$/Vs) | $W_\gamma$ (eV) | Scintillation wavelength (nm) | Lifetime of scintillation slow component | Long-lived metastable isotope |
|---|---|---|---|---|---|---|---|---|
| He | 4.2K | 0.13 | 25.6 | low | 45.5 | 80 | >>ms | no |
| Ne ≈$60/kg | 27.1K | 1.21 | 21.7 | low | 33.3 | 85 need WLS | 15μs | no |
| Ar ≈$1/kg | 87.3K | 1.40 | 23.8 | 400 | 25.0 | 128 need WLS or $MgF_2$ | 1.6μs | $^{39}Ar$ $^{42}Ar$ |
| Kr | 119.8K | 2.41 | 20.4 | 1200 | 40.0 | 150 | 0.09μs | $^{81}Kr$ $^{85}Kr$ |
| Xe ≈$800/kg | 165.0K | 3.06 | 15.6 | 2200 | 21.7 | 175 quartz window | 0.03μs | $^{136}Xe$ |

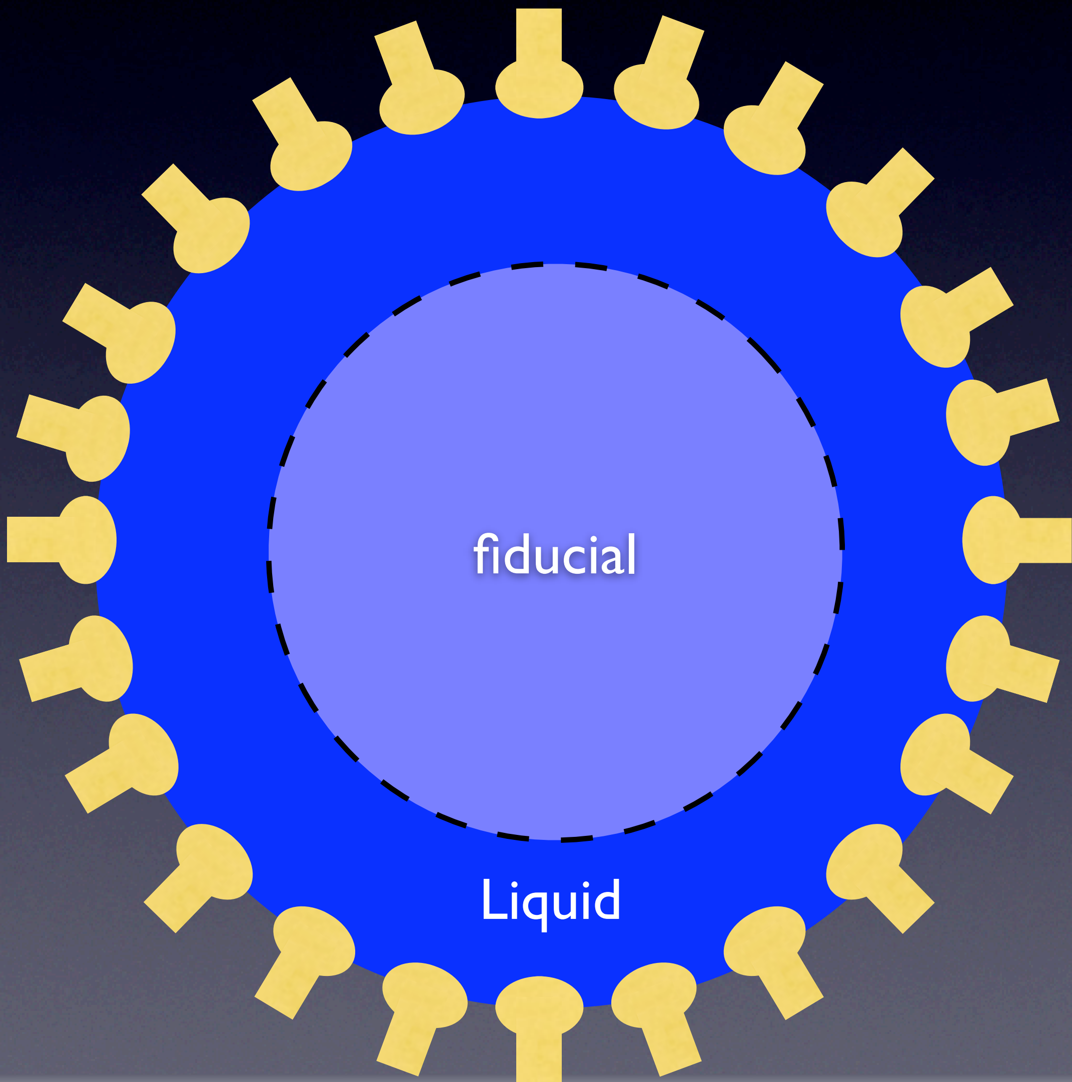
ionization

scintillation

# Two basic detector concepts

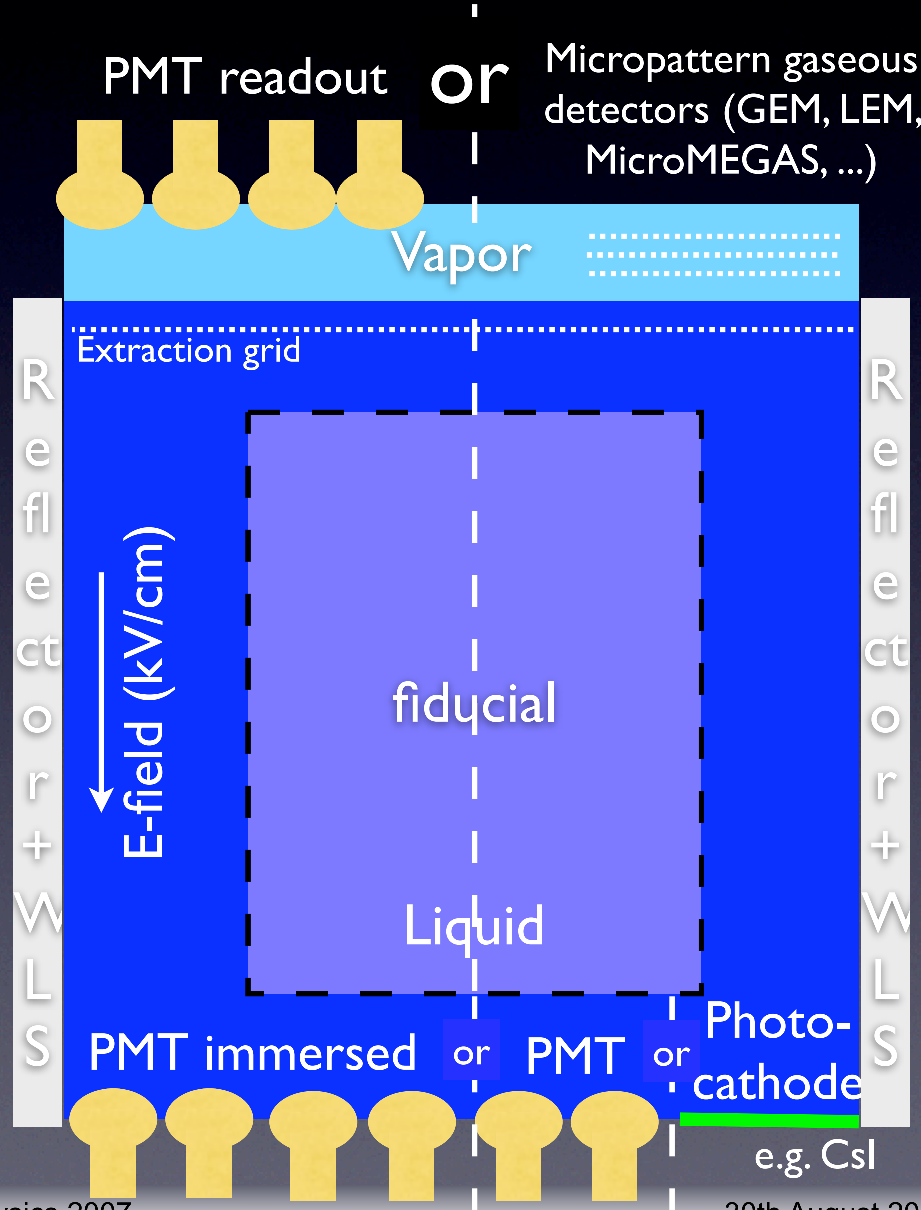
## Single phase:

No drift (E=0)




## Double phase:

Ionization $e^-$ drift ($E\neq0$)



# Two basic detector concepts

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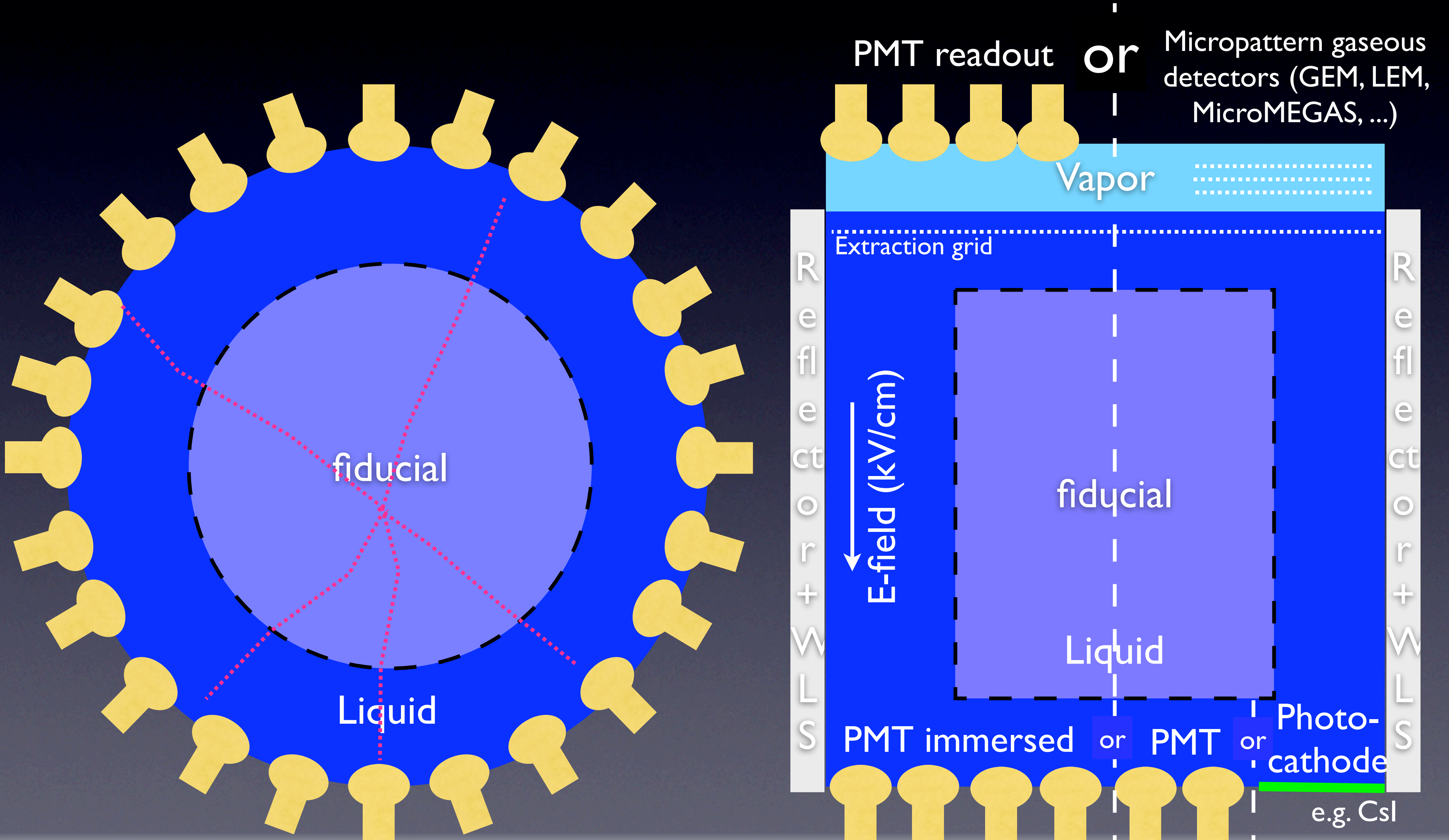
|---|---|
| No drift (E=0) | Ionization $e^-$ drift ($E \neq 0$) |



# Two basic detector concepts

<u>Single phase:</u>
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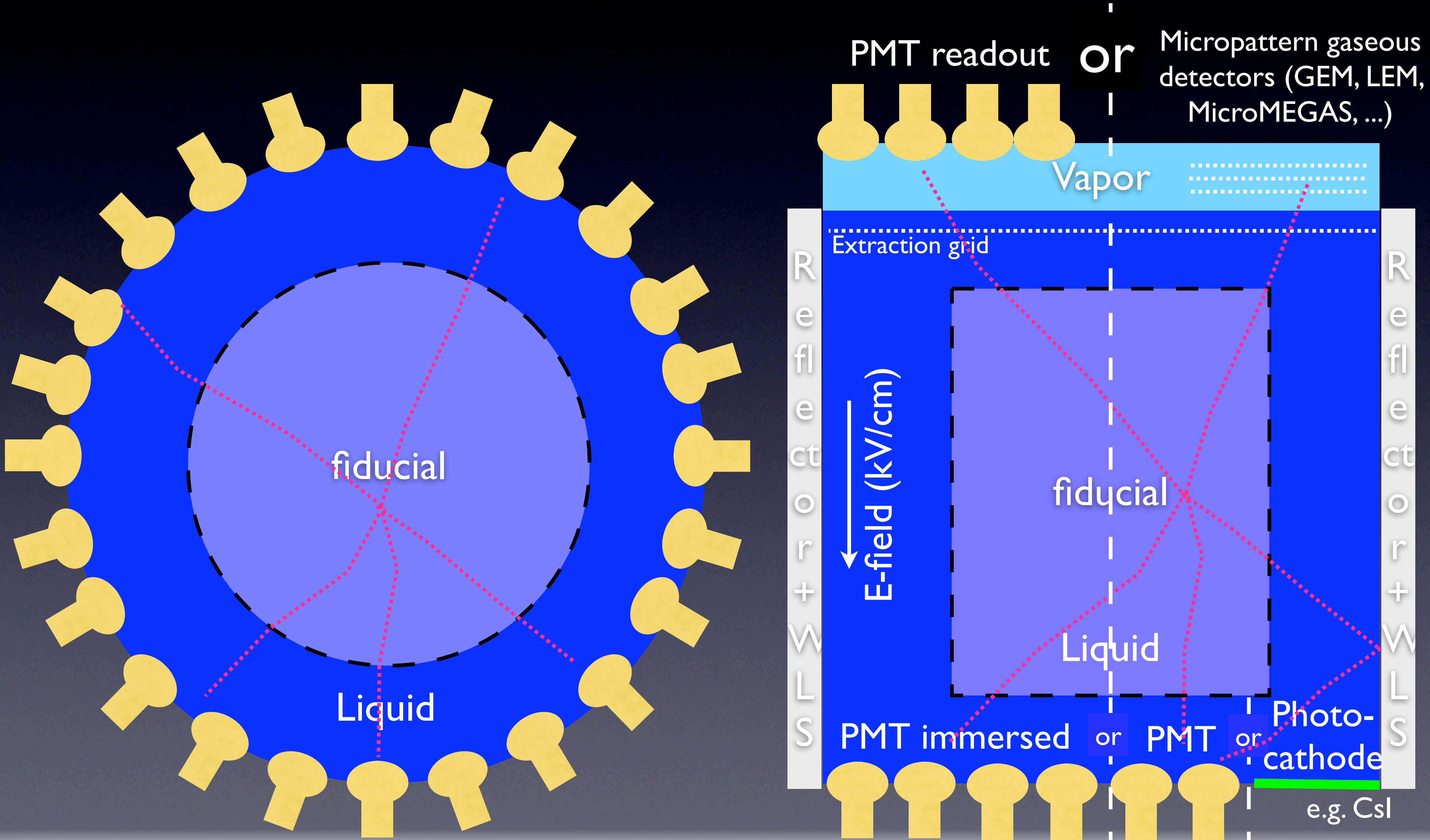
<u>Double phase:</u>
Ionization e⁻ drift (E≠0)



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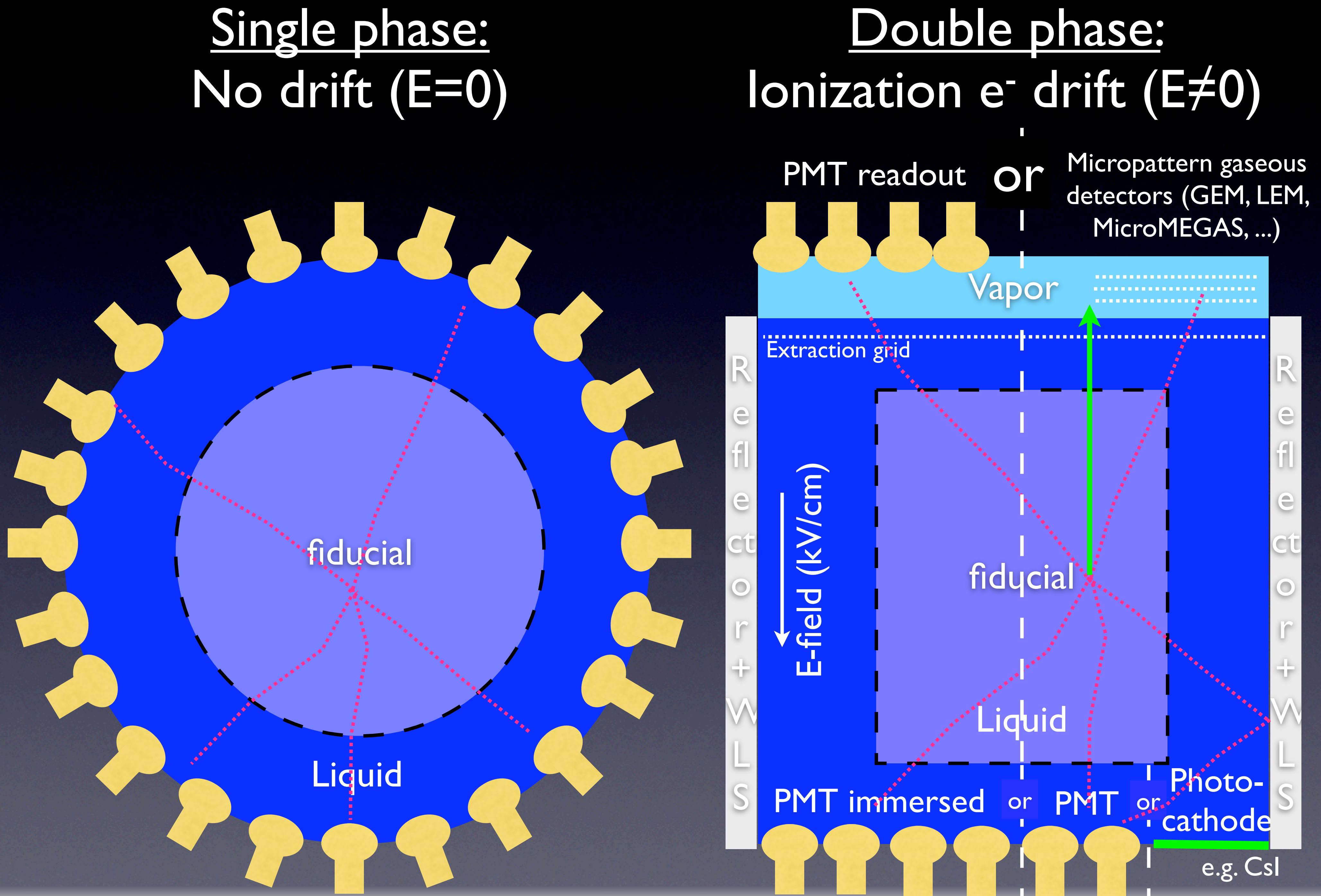

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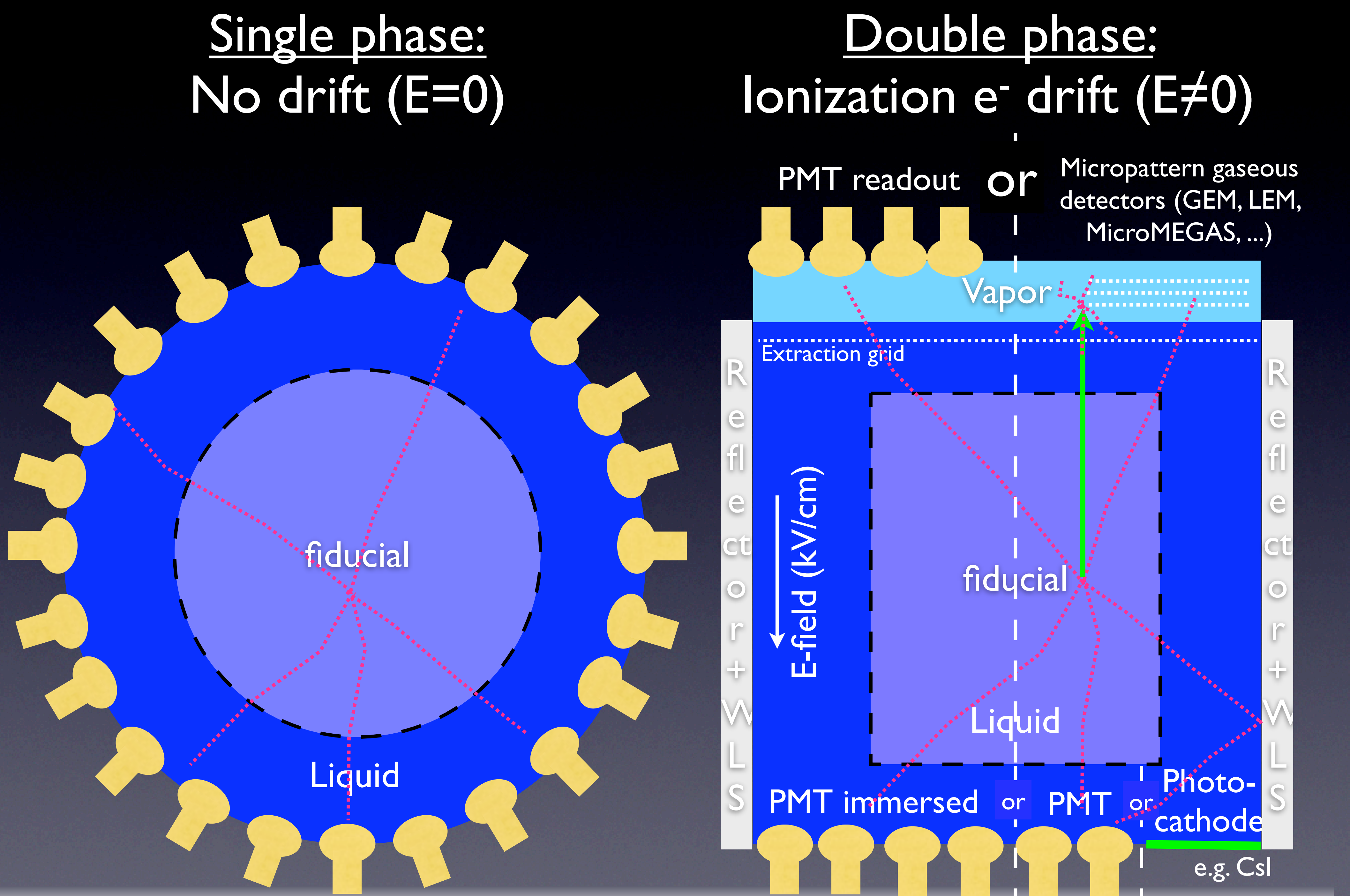

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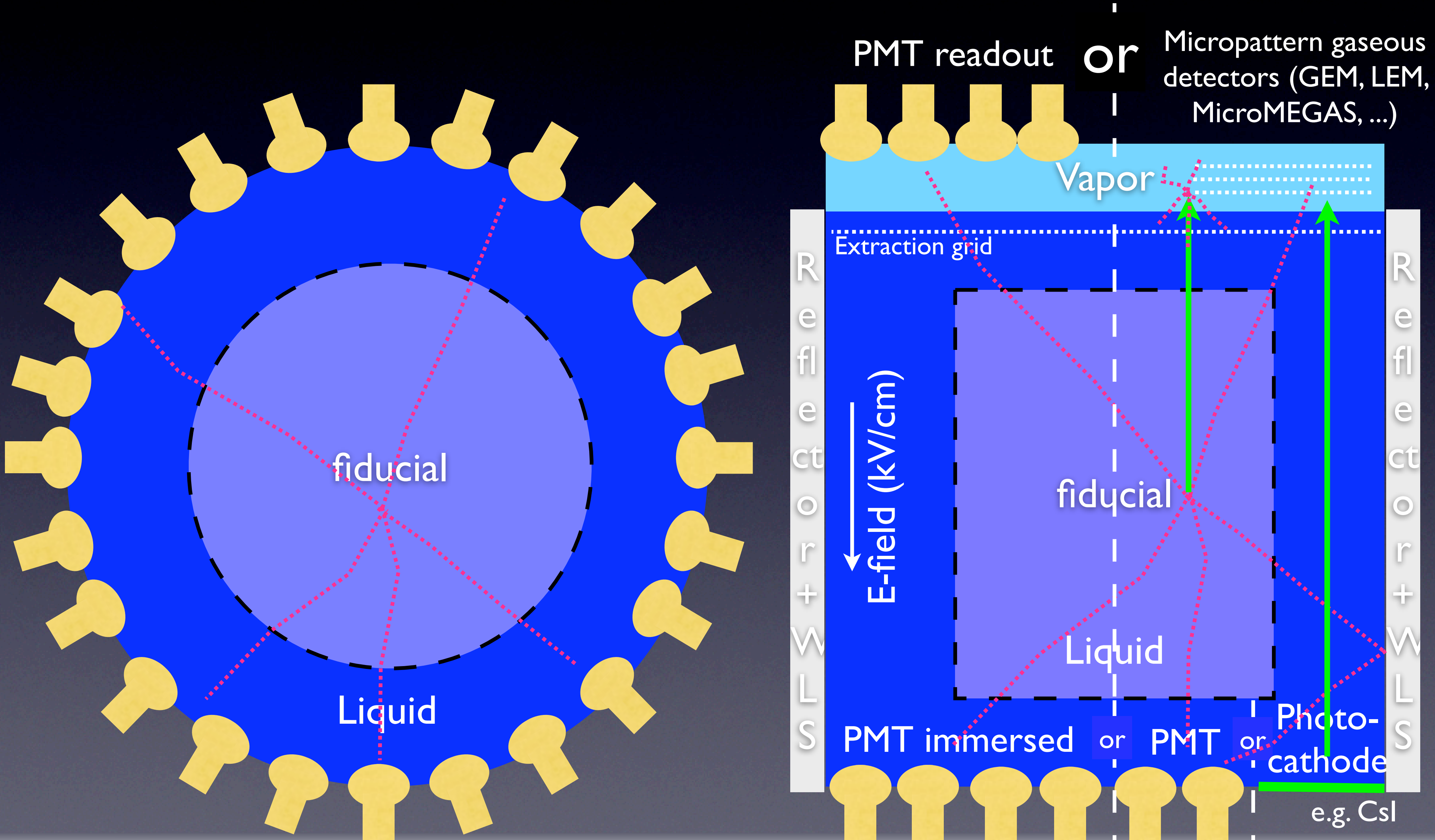

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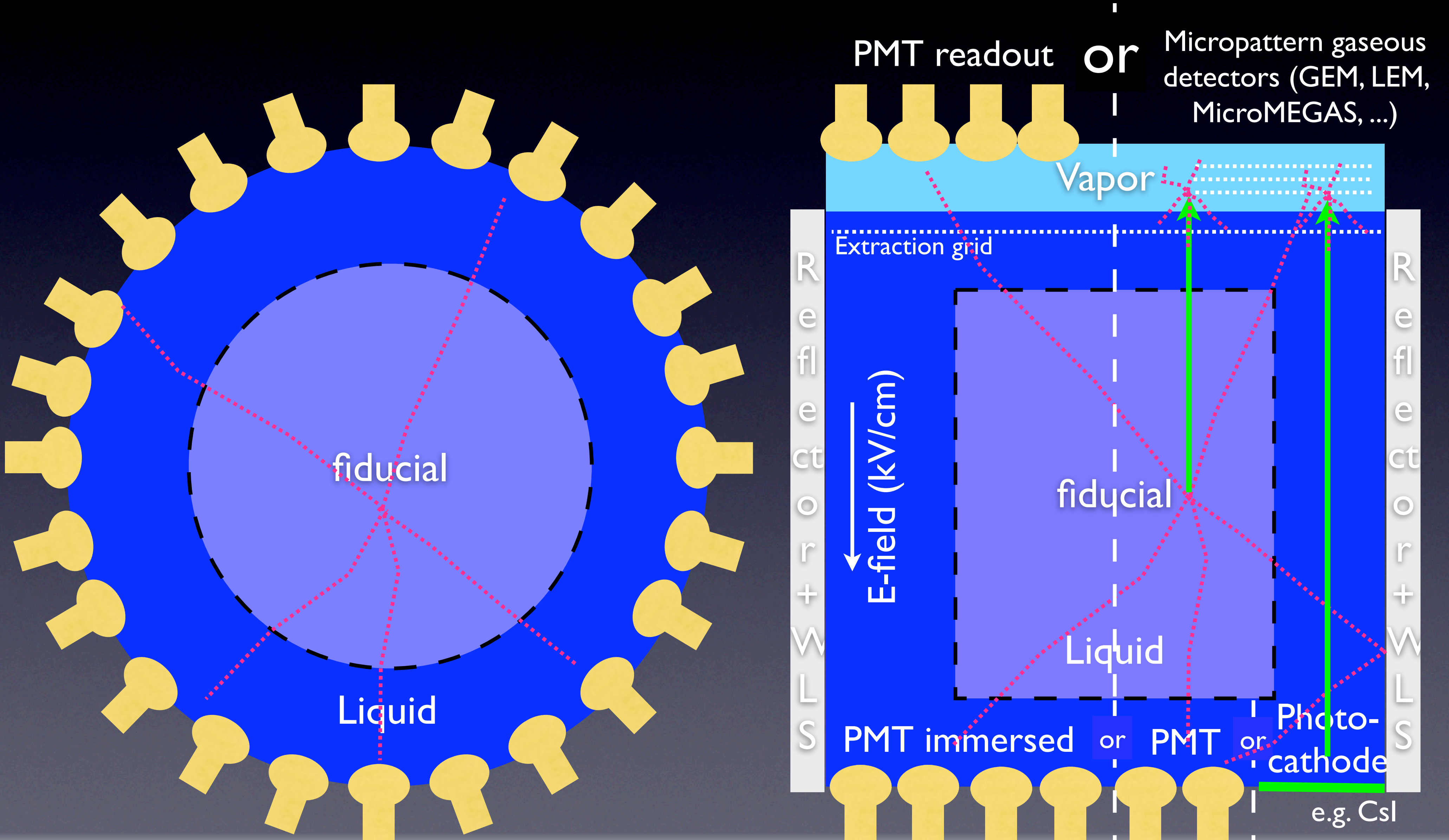
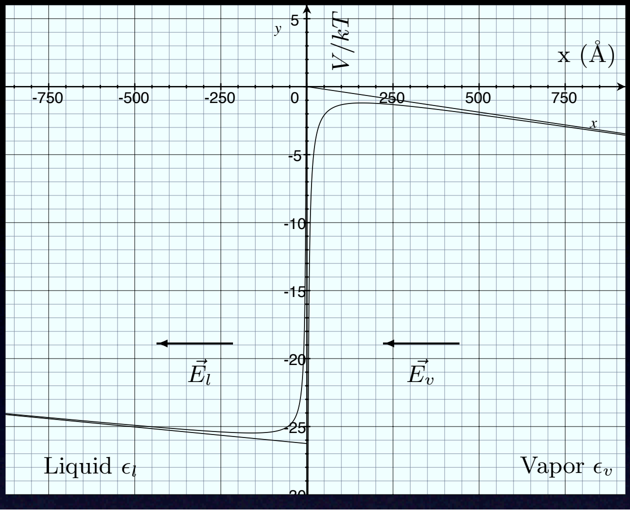


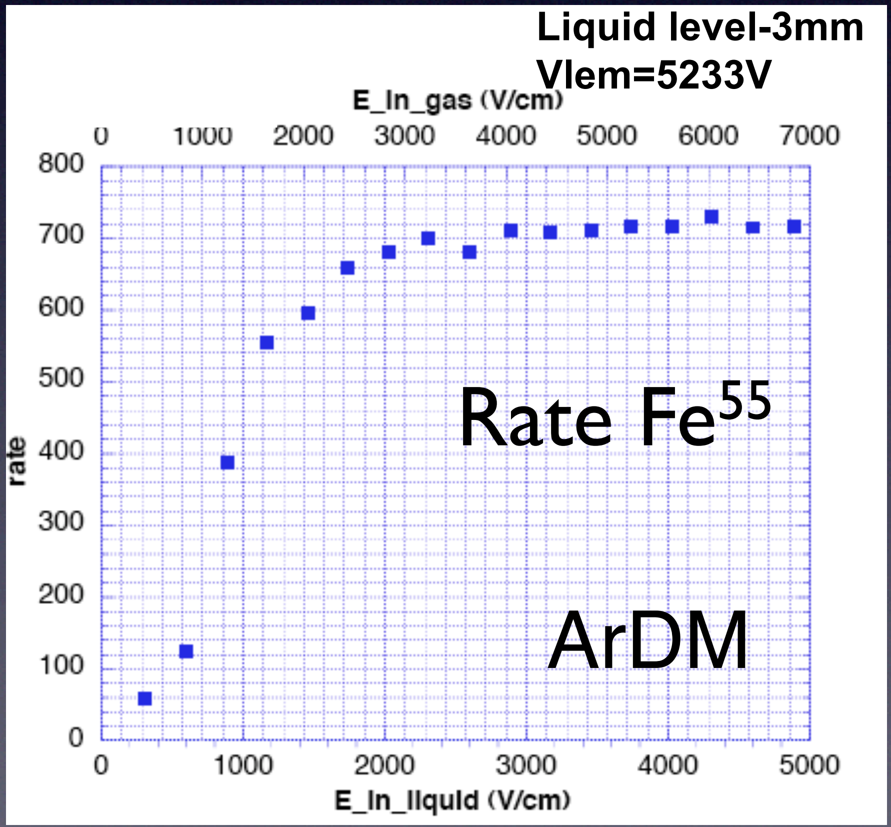
# Electron extraction in double phase

- Based on the extraction of the quasi-free electrons from liquid into vapor phase (B.A. Dolgoshein et al., Sov. J. Part. Nucl. 4 (1973) 70. )
- Classical potential barrier at interface of two media with different dielectric constants >> kT
- Time to traverse the barrier given by Shottky model of electric-field-enhanced thermionic emission

Measured extraction rate plateau from LAr as a function of electric field
➟ ≈3kV/cm for fast (μs) extraction
Similar situation in LXe

Classical potential as a function of distance from interface



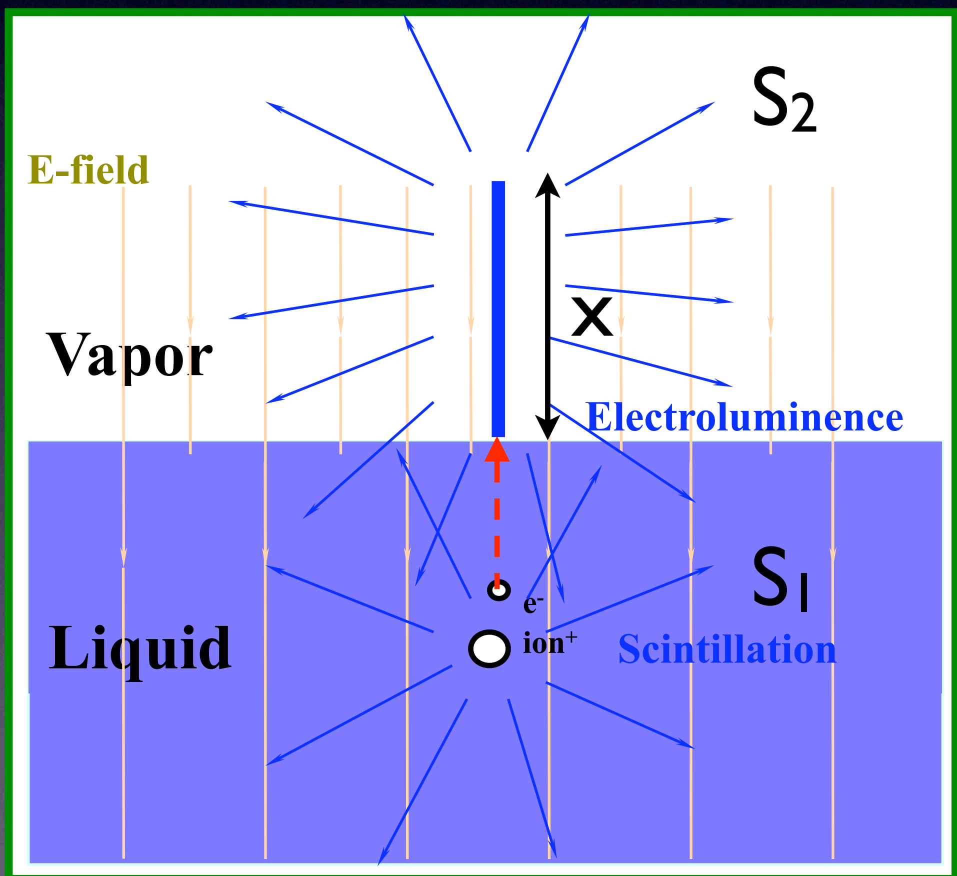
# Proportional light: $S_1$ & $S_2$ signals

- The proportional light produced in the gas (vapor) phase is a measure of the charge drifted to the interface and extracted from the liquid.
- S1 & S2 signals are detected by the same set of photodetectors

$$G_\gamma \approx \alpha\left(E/p - \varepsilon_{thresh}\right)\cdot x \cdot p$$

E=field, $\varepsilon_{thresh}$=threshold field, p=equiv. pressure, x=path, α=constant

$$\alpha_{LXe} = 70\ \gamma / kV \qquad \varepsilon_{thresh}^{LXe} = 1.3 kV / cm / atm$$

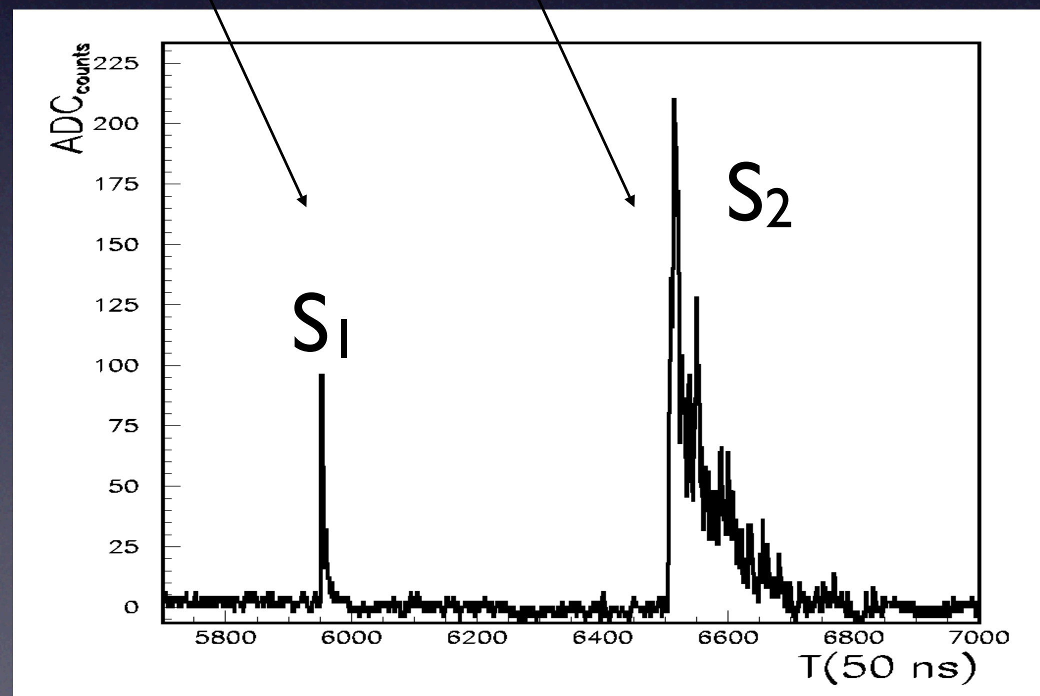



**Scintillation SC is a result of:**

**1. Direct excitation**

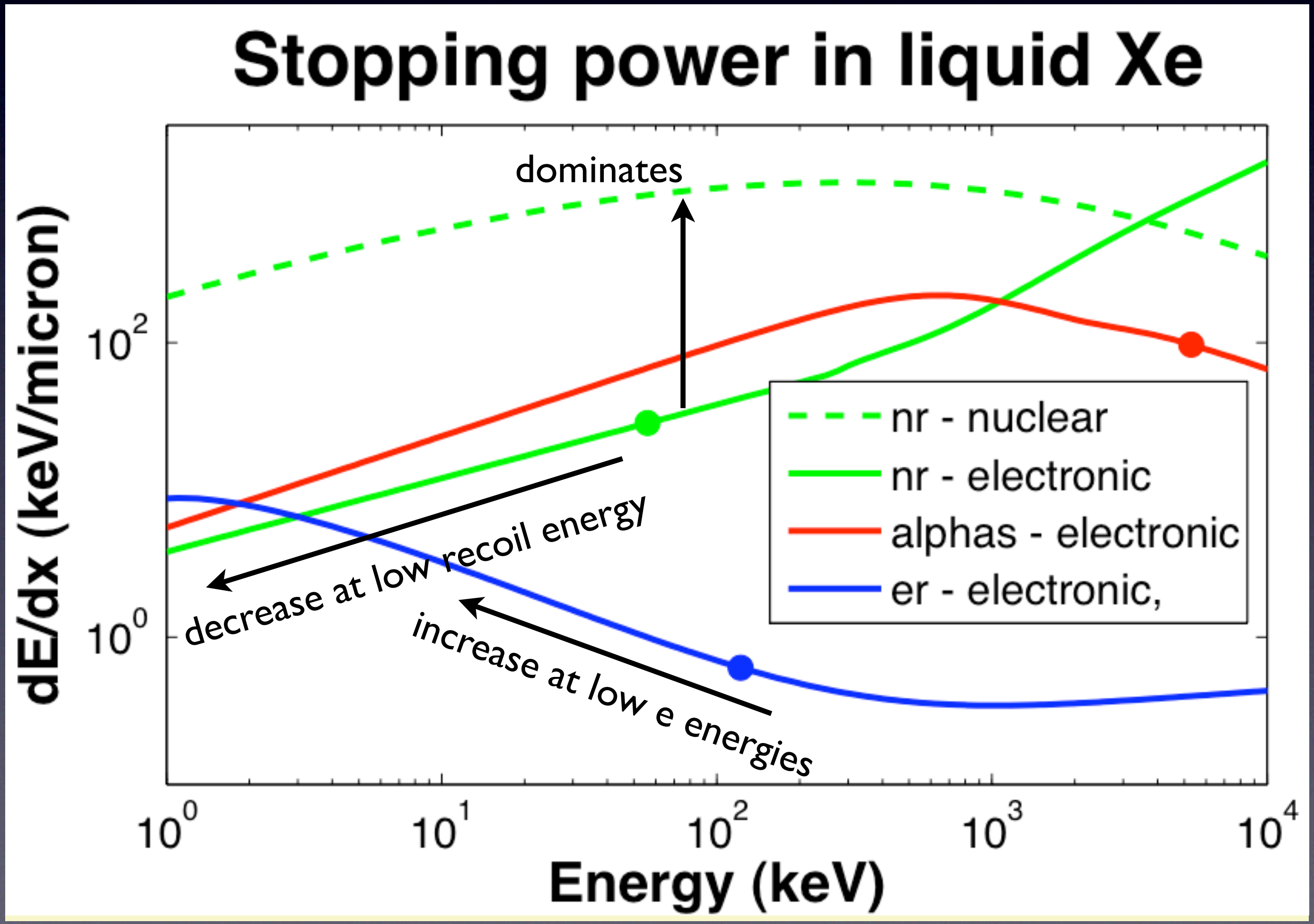
**2. Recombination**

**Electroluminescence EL (proportional scintillation) is a result of electron acceleration in the gas**



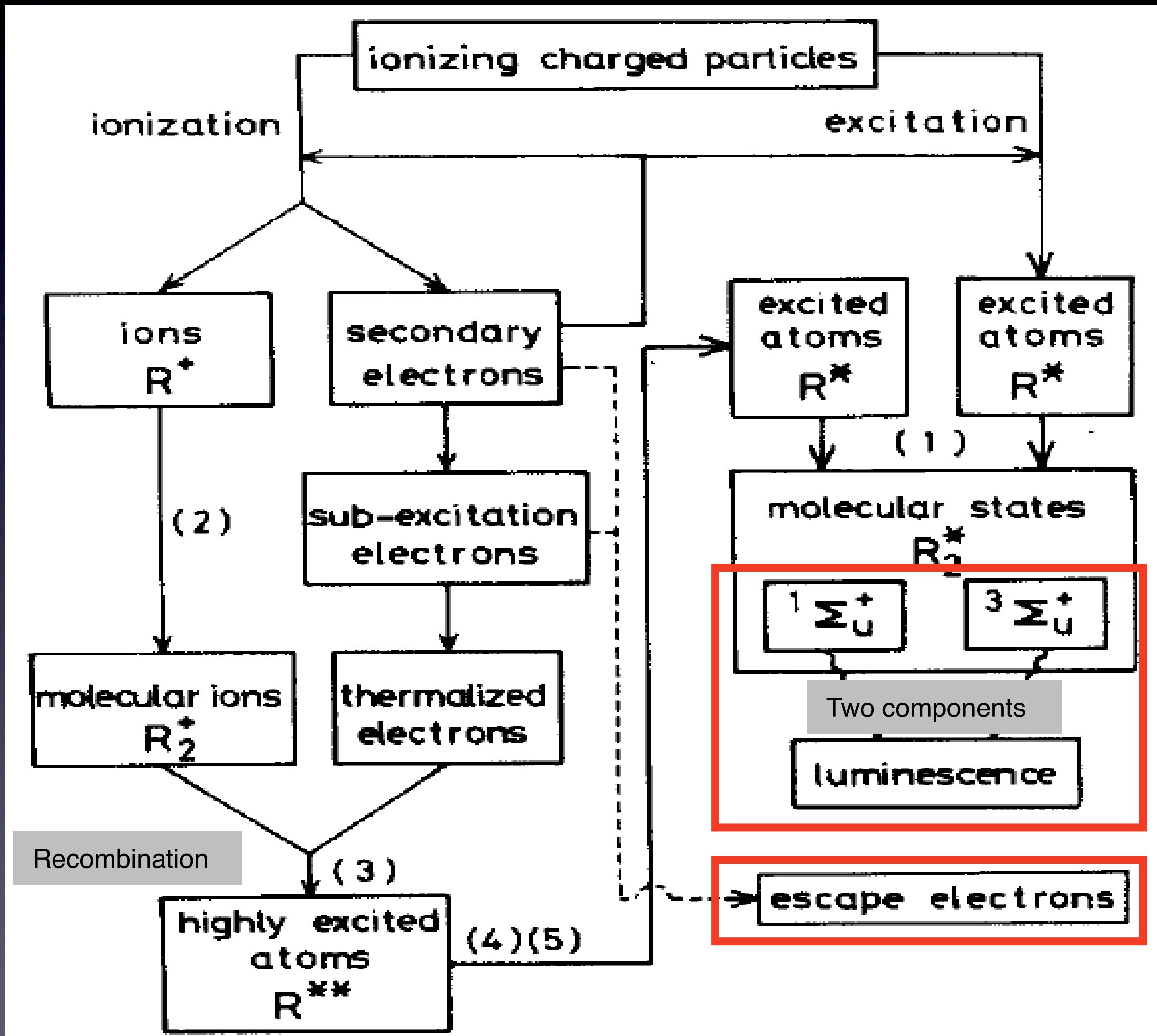
# Basic microscopic processes in medium

- Interaction of slow ions with matter given by Lindhard theory (1963)
- When ionizing particle enters medium, electronic and nuclear stopping take place. For slow ions, nuclear stopping starts to dominate.
- Stopping power calculation take into account charge state of slow ion (dressing up of ion with electrons determined by Z and velocity)



# Basic microscopic processes in medium

- Electronic stopping of ionizing particles (mip, e, α, fast ions, FF, ...) leading to scintillation and electron-ion pair production has been experimentally and theoretically studied for LAr & LXe for several decades.



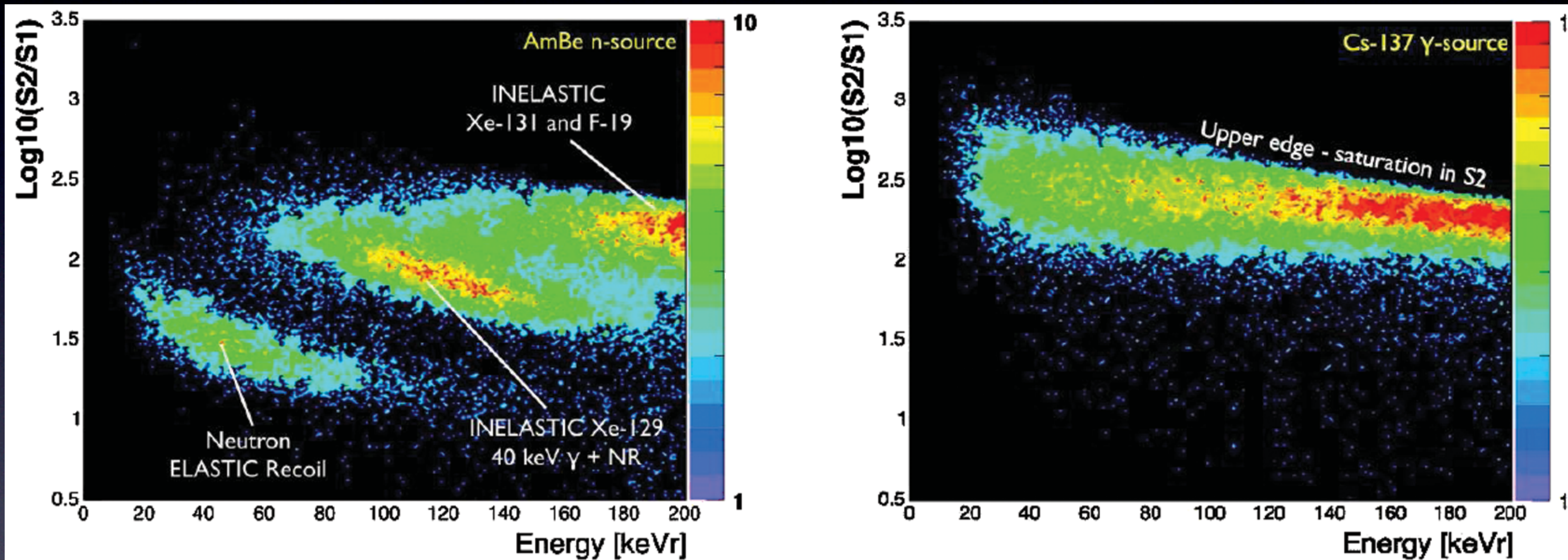

M. Suzuki et al., NIM 192 (1982) 565

- Columnar recombination decreases the secondary electron yield at the favor of scintillation photons. It is affected by an external drift field $E_{drift}$.
- For slow moving ions, nuclear stopping becomes important. This energy does not lead to scintillation or ionization → "nuclear quenching factor" $q_{nc}$
- Scintillation quenching (e.g. by biexcitonic collisions) also occurs in the high ionization density "core" → "electronic quenching factor" $q_{el}$

# Xenon response to ER & NR

PRL 97, 081302 (2006)

- Microscopic behavior leads to different ratio of scintillation to ionization for faster electron and slow ion tracks → S2/S1 discrimination




*The first unambiguous demonstration of the capability of dual-phase xenon detectors to discriminate between electron and nuclear recoils down to 20 keVr*

Measurements on S2/S1 discrimination between α and γ were already reported in P. Benetti et al., Nucl. Instr. and Meth. A 327 (1993) 203.

# Nuclear recoil scintillation efficiency

$$E_{nr} = \frac{S_1}{L_y \Im_{eff}} \frac{S_{er}}{S_{nr}}$$

Phys.Rev.Lett.97:081302,2006

$S_1$ = signal in #pe

$L_y$ = Light yield of ER for calibration γ (eg. 122keV)

$L_{eff}$ = relative scintillation efficiency relative of NR relative to ER at zero electric field

$S_{er}$ = quenching of ER due to electric field

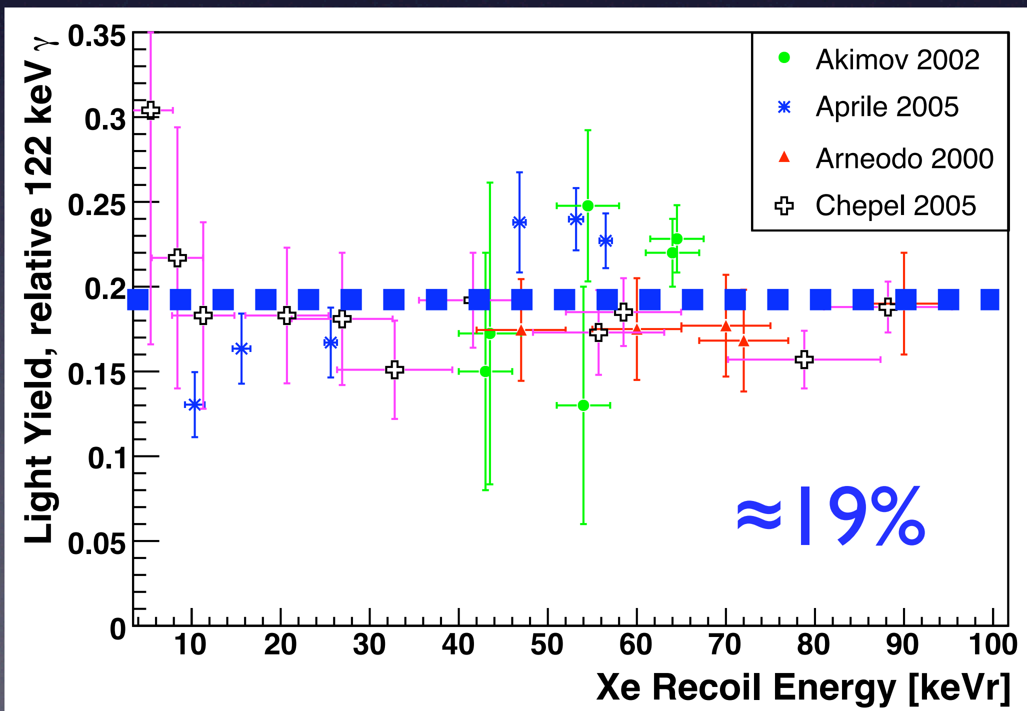
$S_{nr}$ = quenching of NR due to electric field

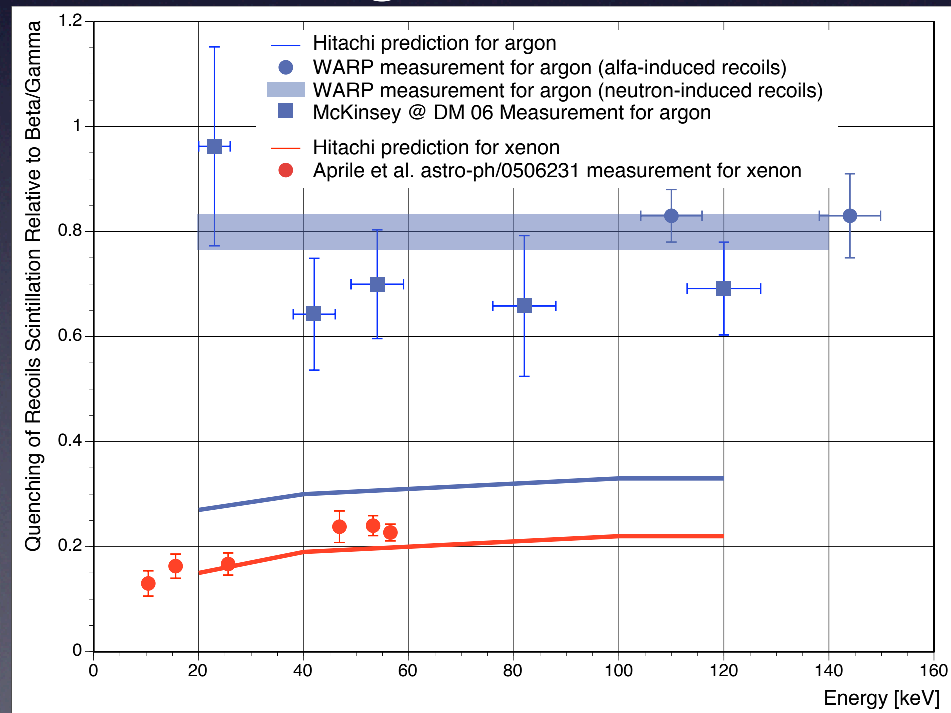
Measured with n-beam scattered at defined angle:

$$E_{nr} \approx E_n \frac{2 m_n M_{Ar/Xe}}{\left(m_n + M_{Ar/Xe}\right)^2}\left(1 - \cos\theta\right)$$

## Several Xenon meas'ments

## Blue: Argon, Red: Xenon



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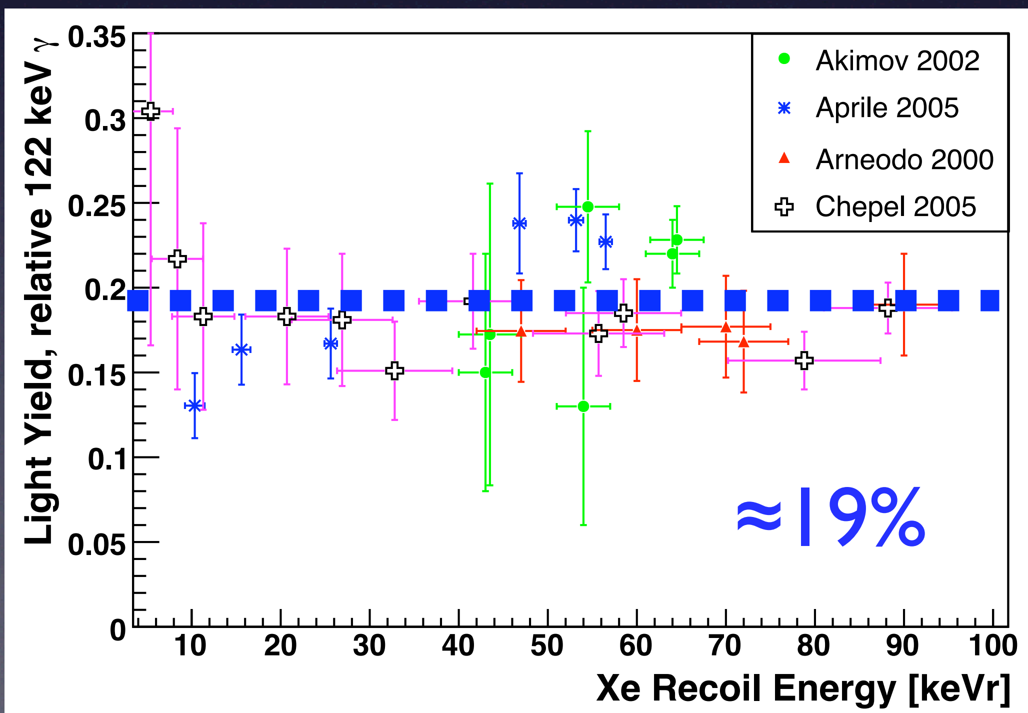


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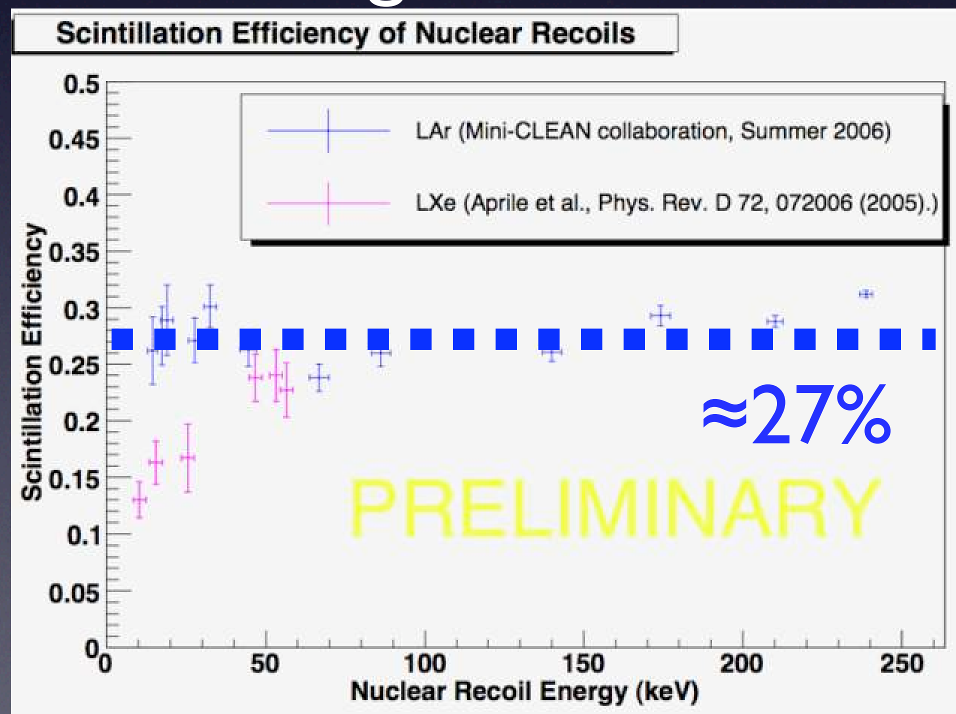
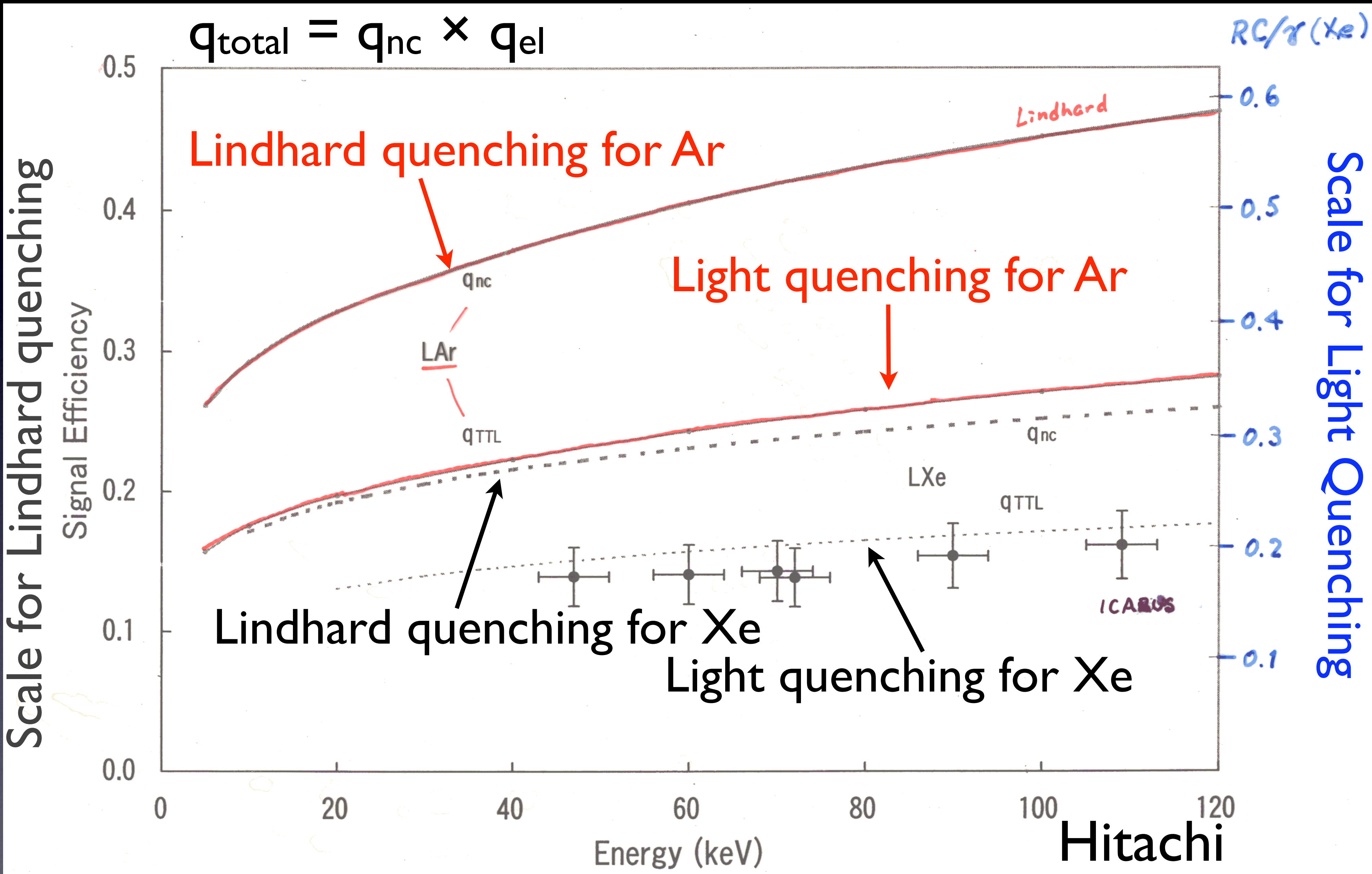


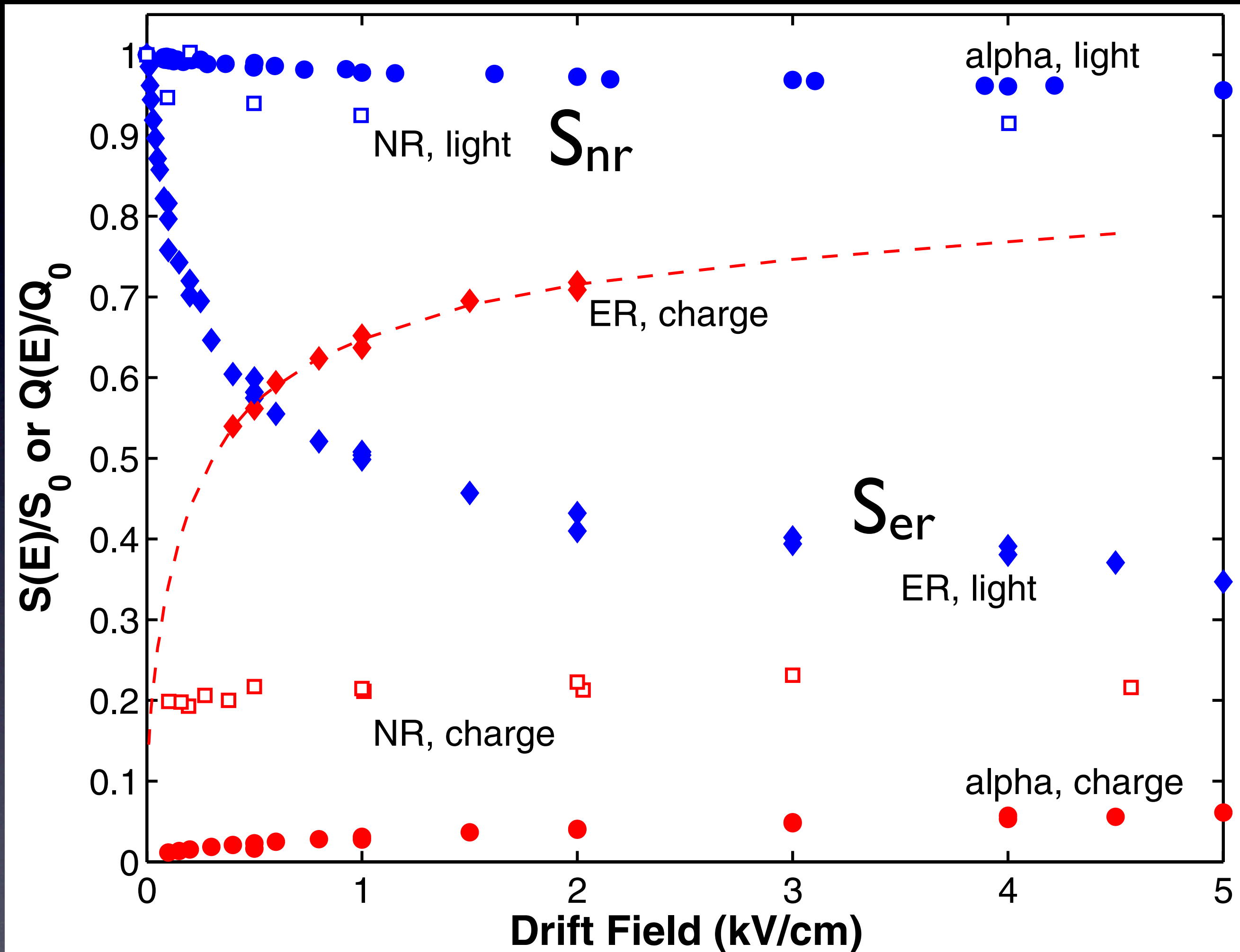
# Nuclear recoil scintillation efficiency



# Quenching due to electric field

PRL 97, 081302 (2006)

Xenon




$$E_{nr} = \frac{S_1}{L_y \mathfrak{I}_{eff}} \frac{S_{er}}{S_{nr}}$$

$L_{eff} \approx$ Lindhard theory

e.g. E=1 kV/cm

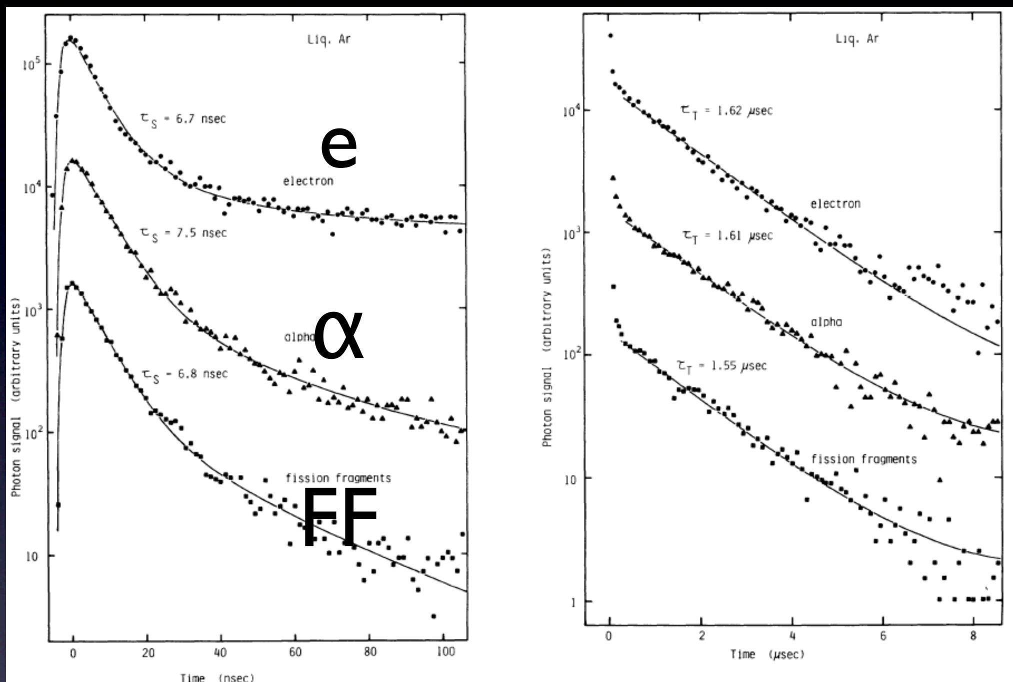
$S_{er} \approx 0.5$

$S_{nr} \approx 0.93$

Results indicate that stopping power is not only determining quenching. The *a priori* surprising differing behavior between α and NR is explained in terms of "track geometry"; small E-dependence for NR is not fully understood.

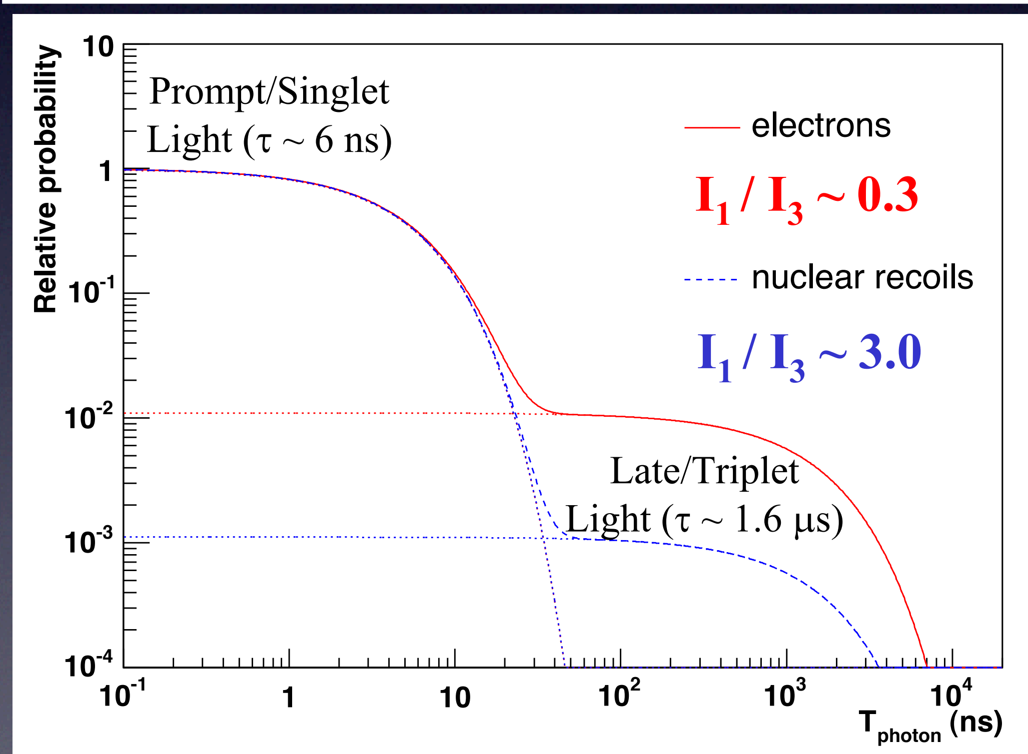
# Time dependence of scintillation

- Observed quenching of triplet (slow) component in high density ionization core (Hitachi et al., Phys. Rev. B 27, 5279 (1983))




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

| Medium/ Property | Wavelength (nm) | Lifetime of slow component |
|---|---|---|
| Ne | 85 | 15μs |
| Ar | 128 | 1.6μs |
| Xe | 175 | 0.03μs |




Boulay & Hime, Astrop. Phys. 25, 179 (2006)

Theoretical rejection
1:$10^8$ for 60 phe

# Several on-going projects

| Medium/Technique | Single phase (Liquid only) Detect scintillation | Double phase (Liquid + Vapor) Detect scintillation +ionization |
|---|---|---|
| Neon | CLEAN | |
| Argon | DEAP / CLEAN | WARP<br>ArDM(*) |
| Xenon | ZEPLIN-I<br>XMASS | ZEPLIN-II/III<br>XENON-10/50<br>LUX |

All detectors use PMTs

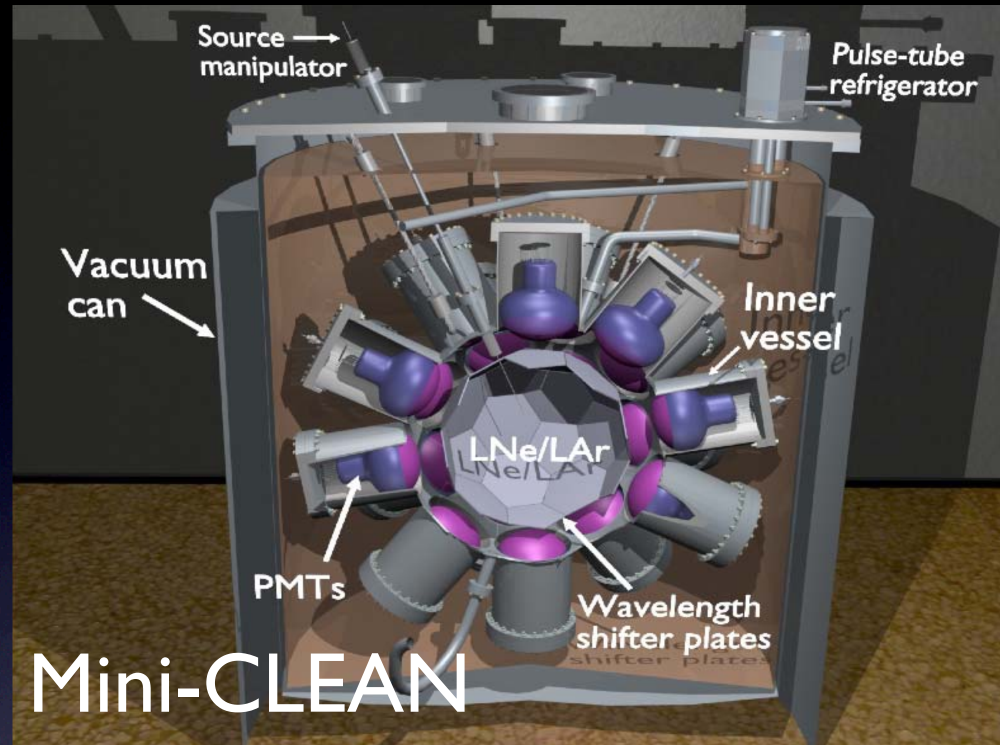
(*) ArDM detects primary scintillation with PMTs & ionization with LEM

No detector is using photocathode (e.g. CsI) method

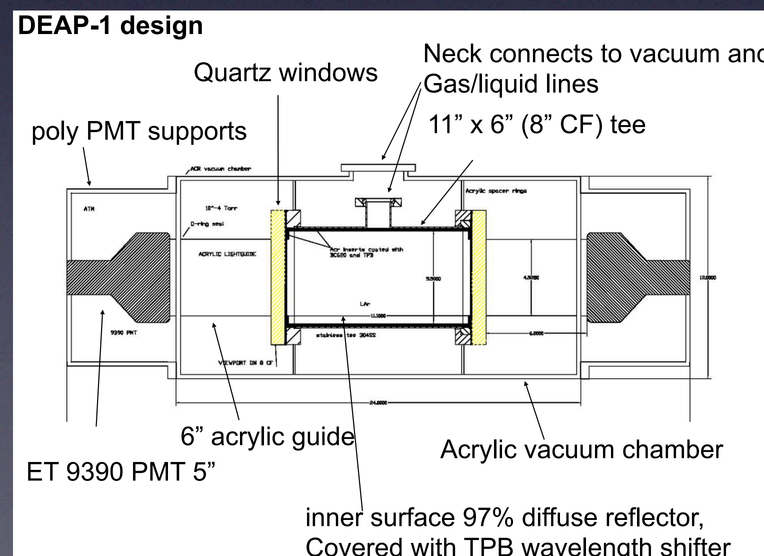
*See talks in parallel session (McKinsey, Kaufmann, Smith)*

# Single phase Ar: DEAP & CLEAN

- 100 kg miniCLEAN proposed
  - WIMP goal ≈ $5 \times 10^{-45}$ cm$^2$
  - Results reported with pico-CLEAN (0.2kg) & micro-CLEAN (4kg)
  - Exchange target for "beam off/on" measurement: $S_{Ar} \approx 5 \times S_{Ne}$ for $M_{WIMP}$=100 GeV and $B_{Ar} \approx B_{Ne}$

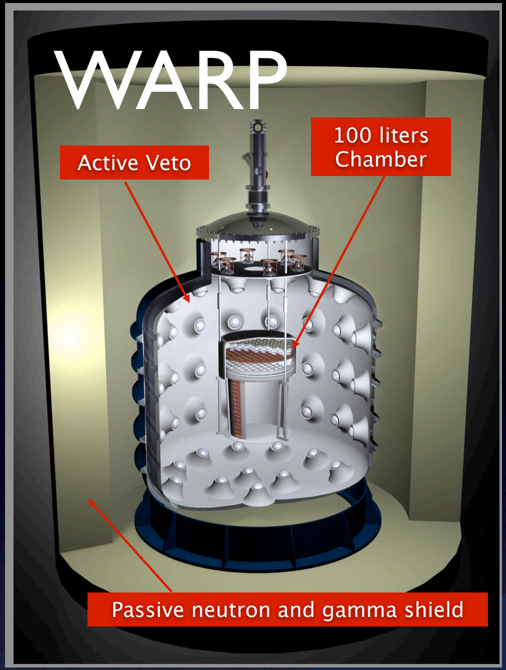



- DEAP (Dark matter Experiment with Argon and Pulse-shape-discrimination)
  - 7kg DEAP-1 being deployed at SNOLAB



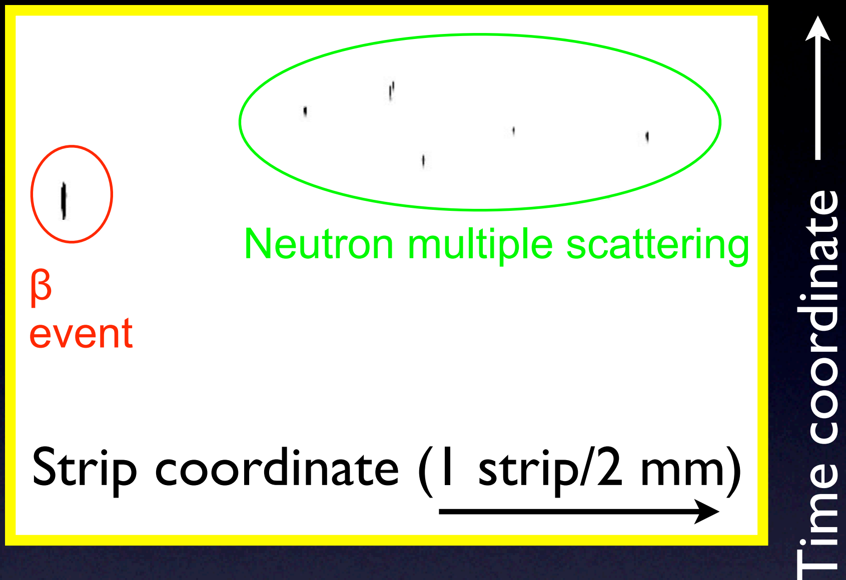
# Two phase Ar: WARP and ArDM

- PSD and S2/S1
- WARP
  - 2.3 lt prototype @ LNGS
  - Preliminary results reported
  - 140-kg detector with 800-kg LAr active veto under installation @ LNGS
- ArDM
  - LEMs for ionization readout
  - PMTs for primary scintillation
  - "Ton-scale" prototype in construction (surface test)

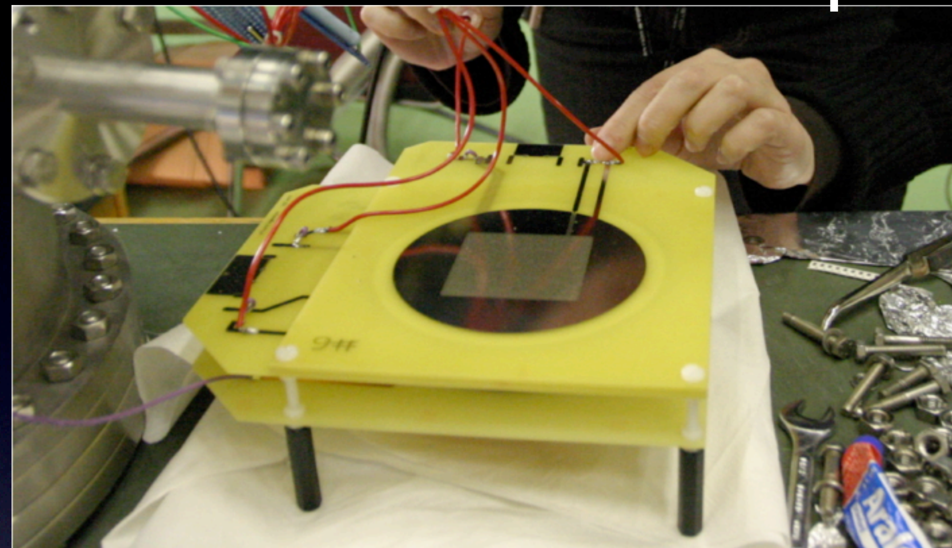


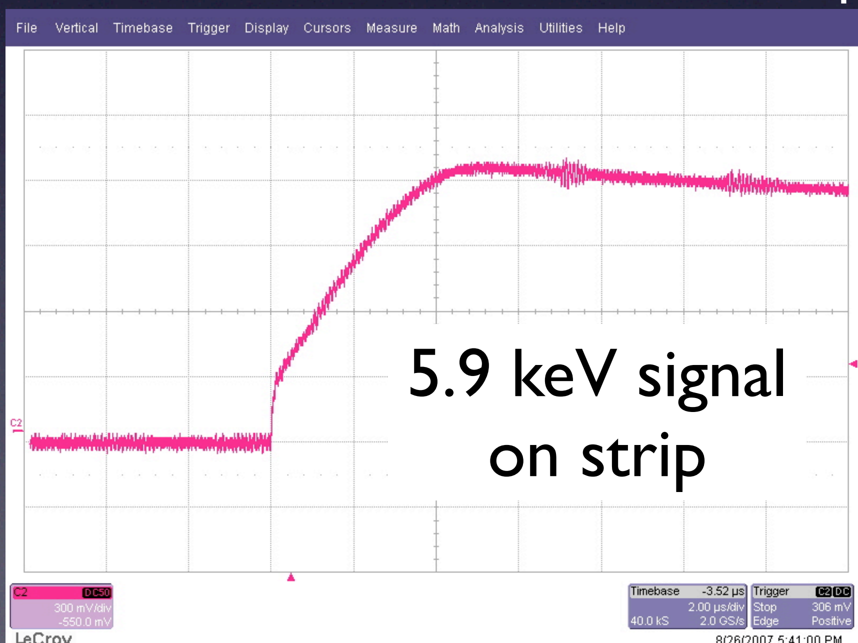

# ArDM: striped LEM readout

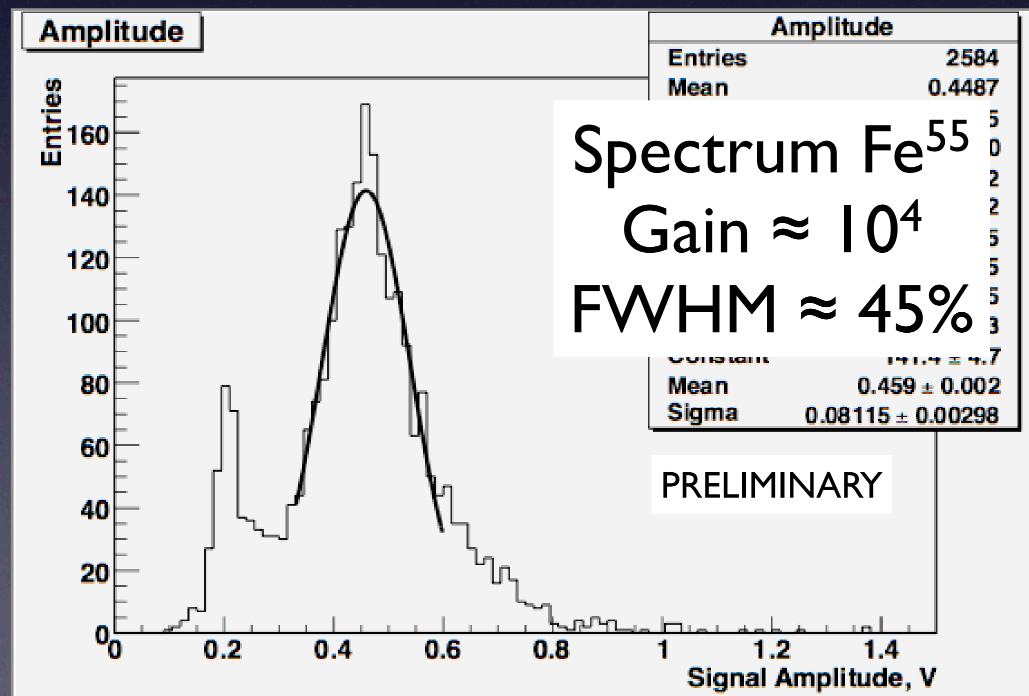
## Imaging TPC properties




## Results on R&D setup

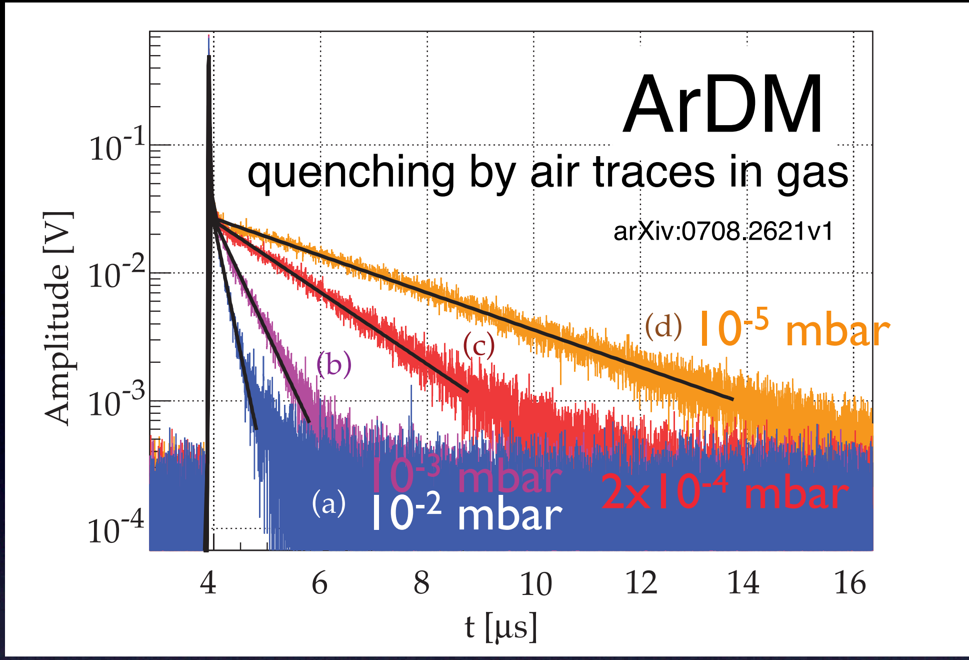


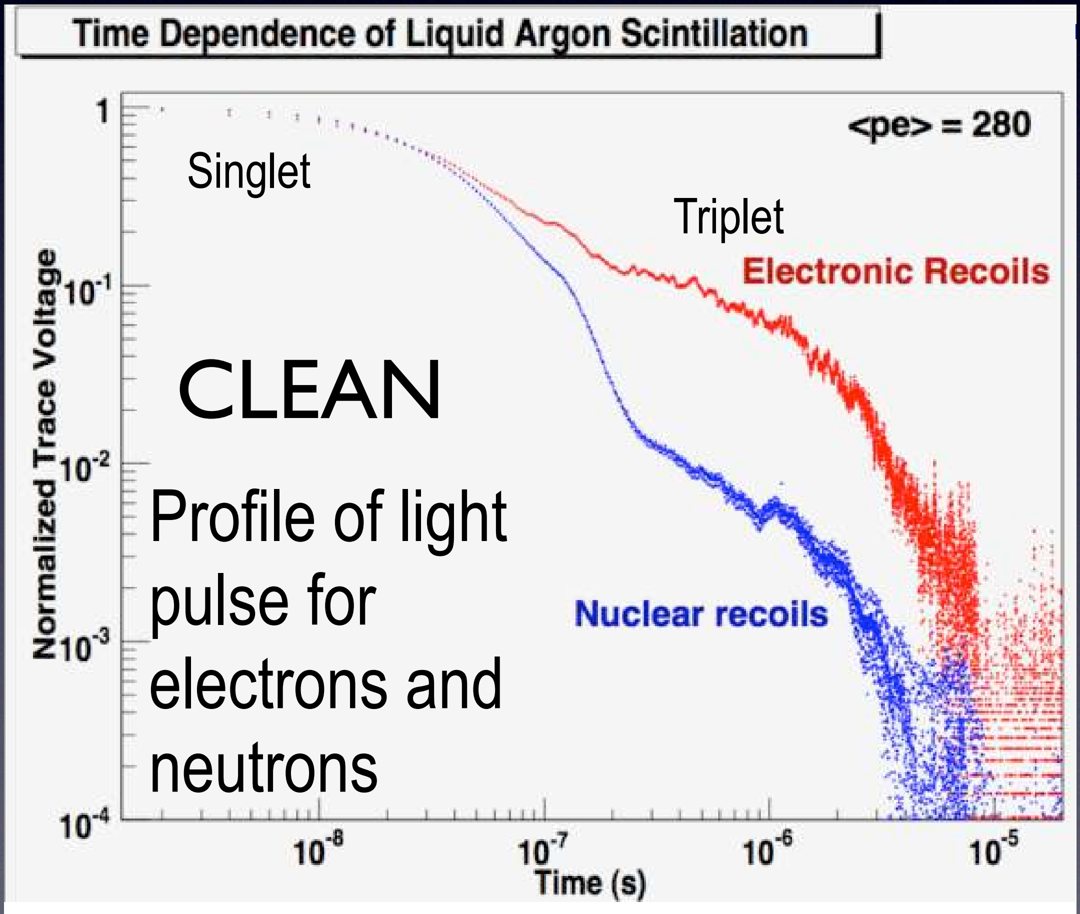


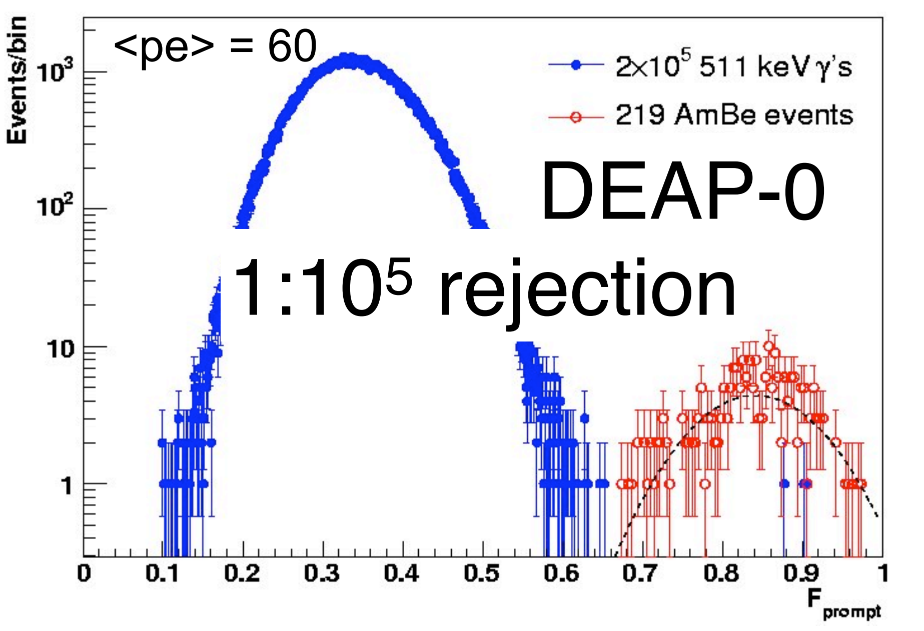



# Pulse shape discrimination (PSD)

- Exploit quenching of triplet (slow) component in high density ionization core
- Effective in LAr($\tau_{slow}$=1.6μs) & Ne ($\tau_{slow}$=15μs)
- Define $F_{prompt}$ ≡ fraction of "prompt" light



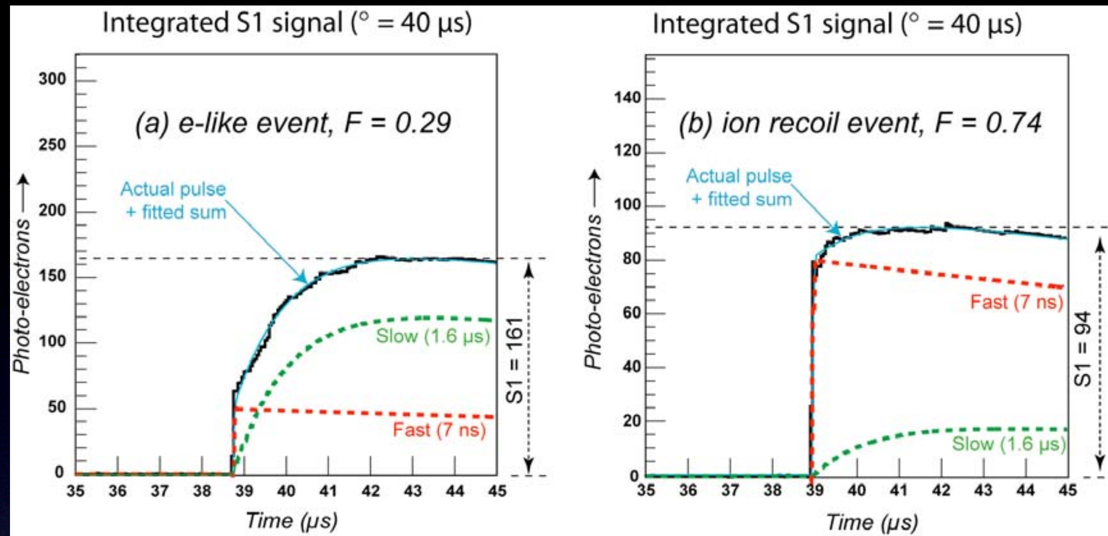



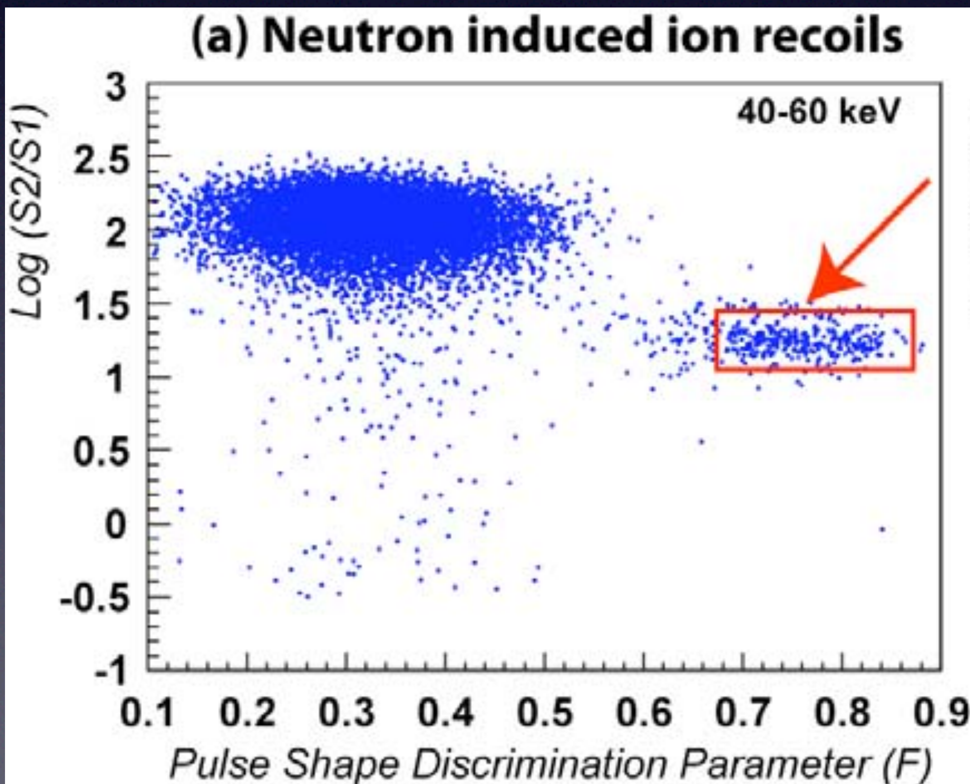



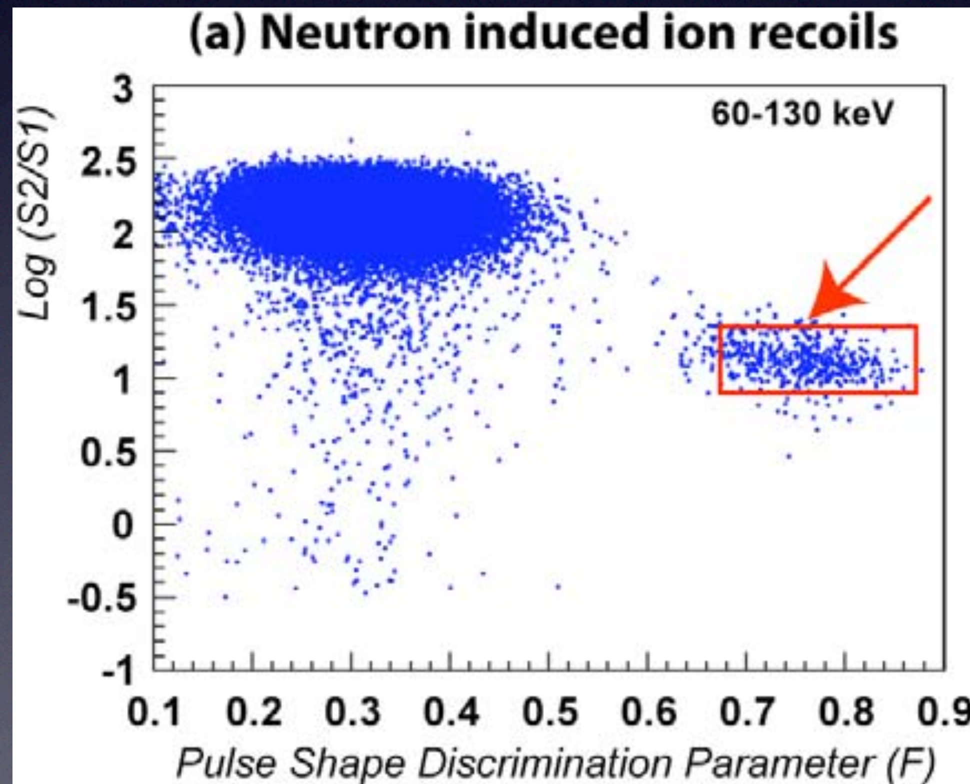

<pe> = 60 corresponds to 10 keV with 75% coverage

# WARP: combined S2/S1 & PSD

- Assume both effects uncorrelated and combine S2/S1 with PSD

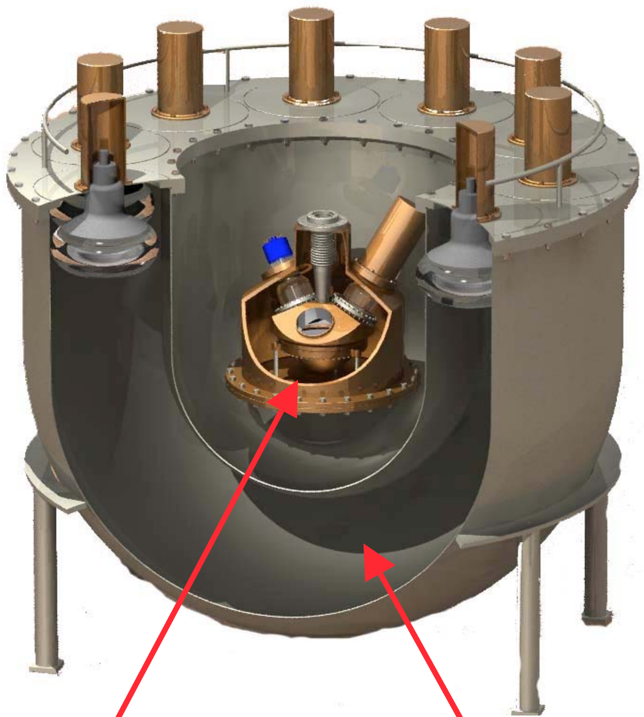


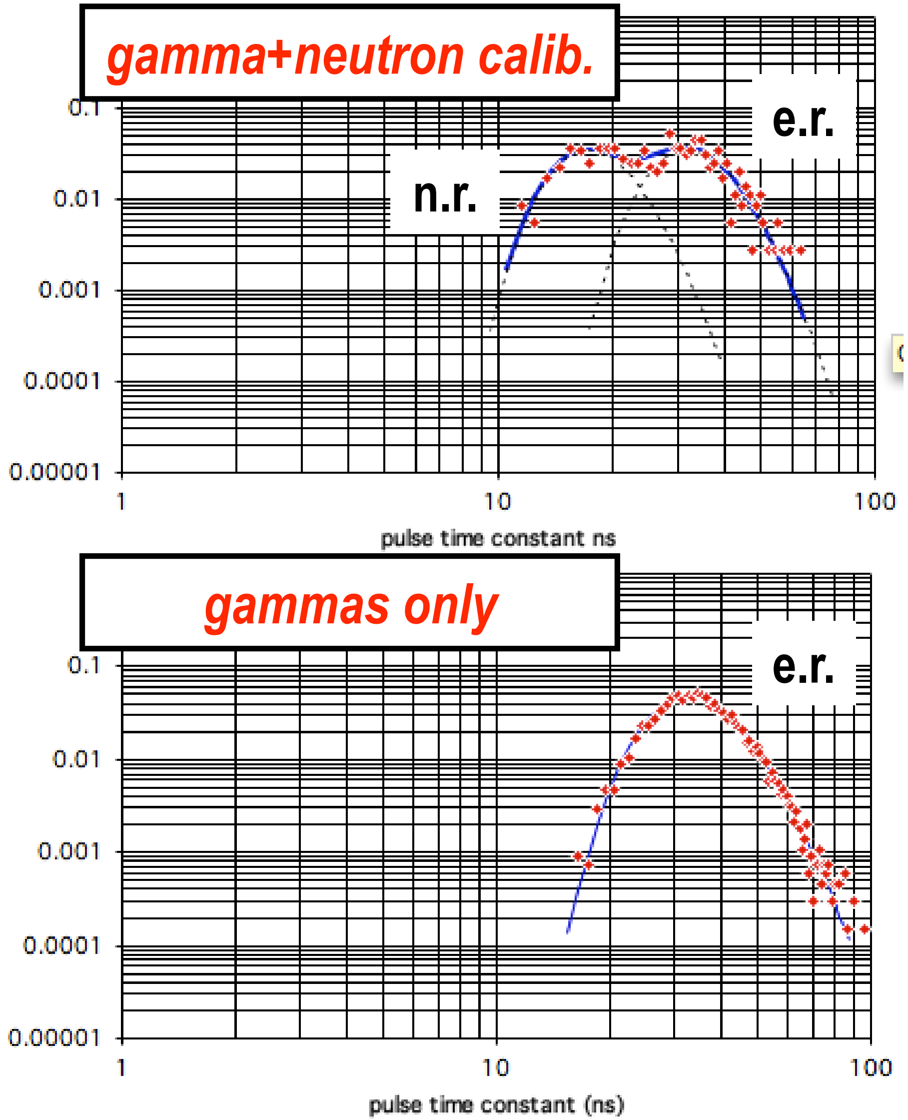



# Single phase Xenon: ZEPLIN-I

- Single-phase detector
  - Measure primary scintillation
  - Pulse shape discrimination

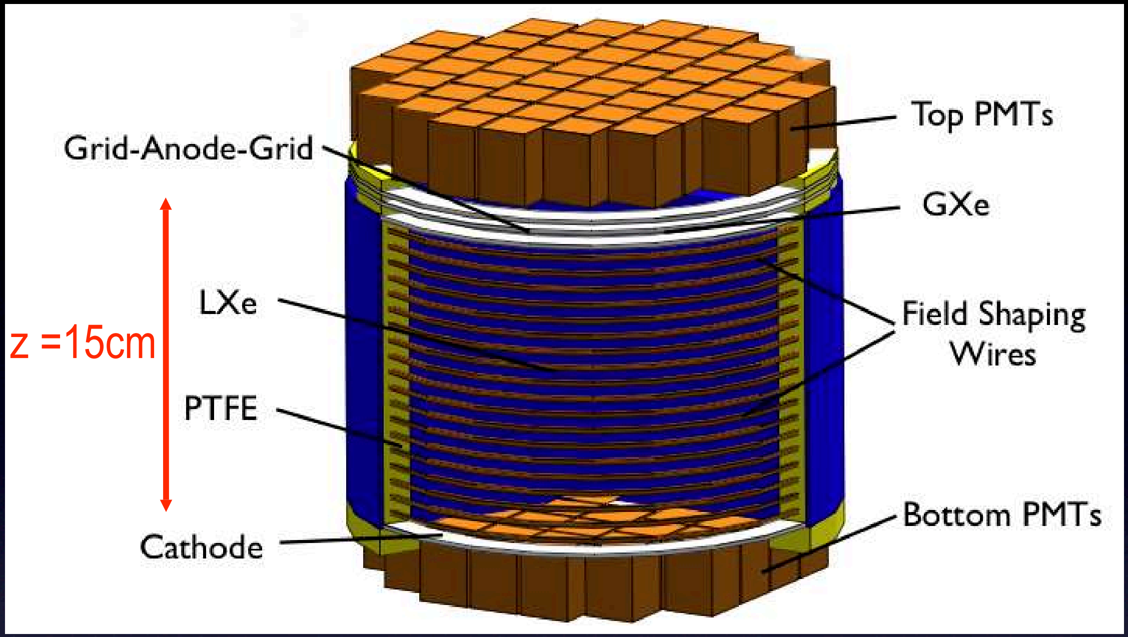


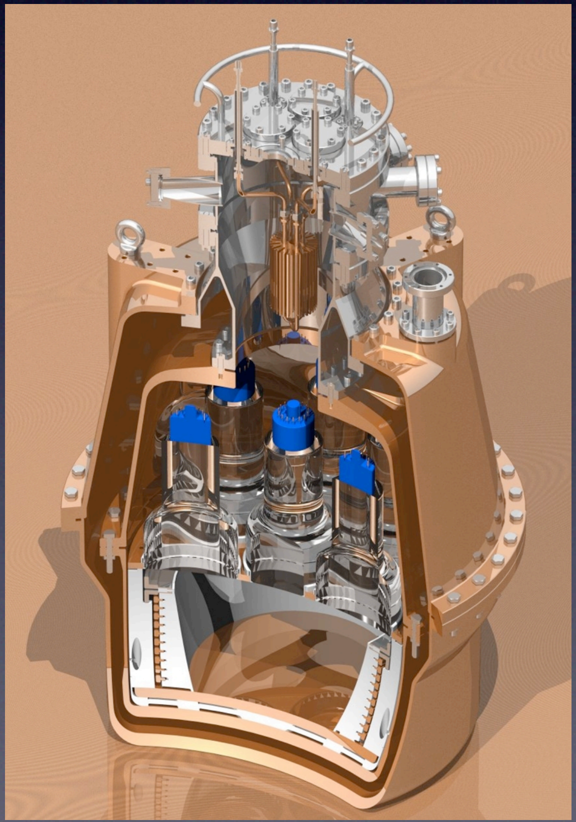




Pulse shape

# D. P. Xenon: ZEPLIN-II & XENON-10

- XENON-10: taking data @ LNGS
  - 15-kg target mass; 5.4kg fiducial
  - 89 low-bkg PMT



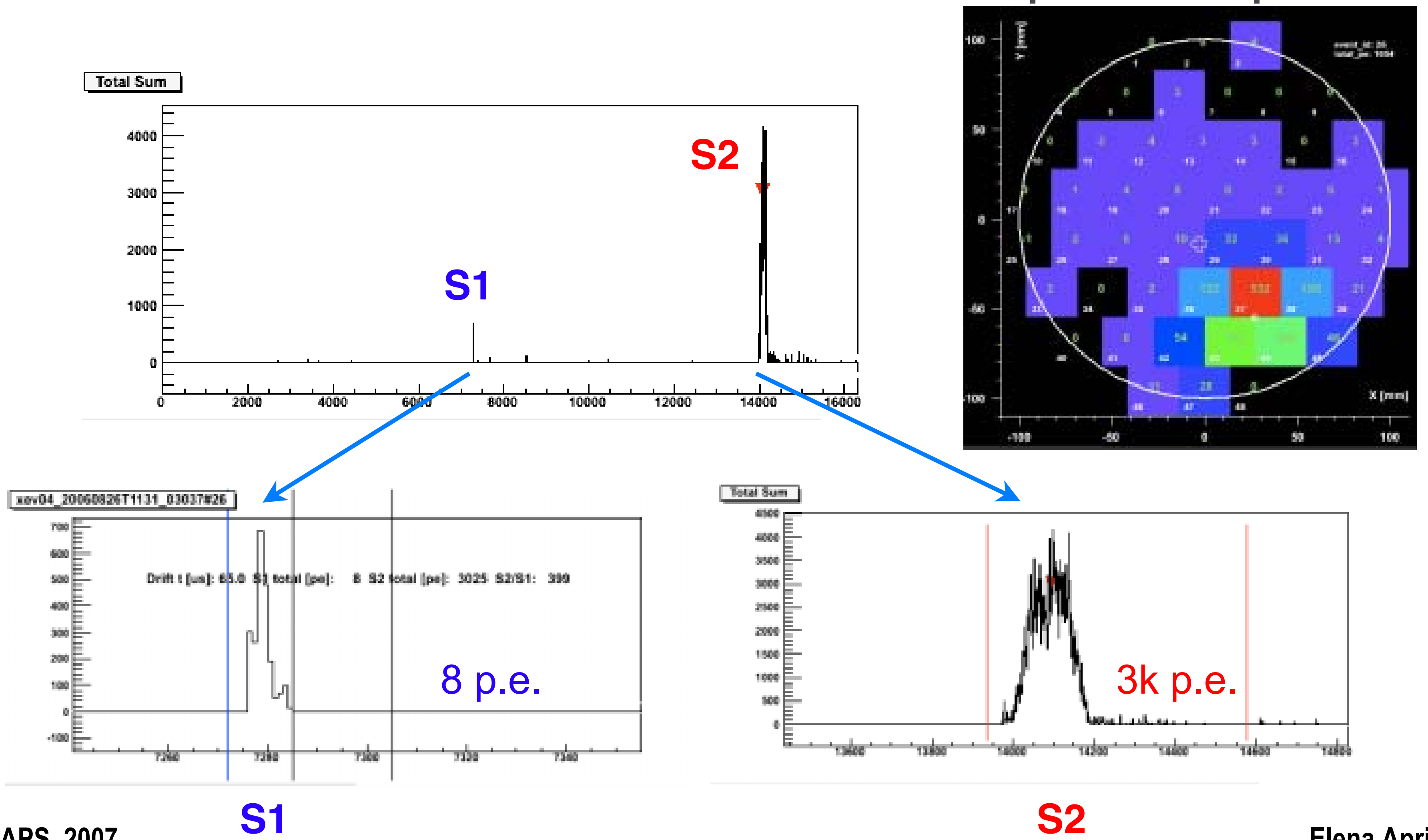



- ZEPLIN-II: taking data @ Boulby
  - 30-kg target mass; 7 kg fiducial
  - 7 PMT in gas phase

# Typical XENON10 Low-Energy Event

4 $keV_{ee}$ event; S1: 8 p.e => 2 p.e./keV

Hit pattern of top PMTs

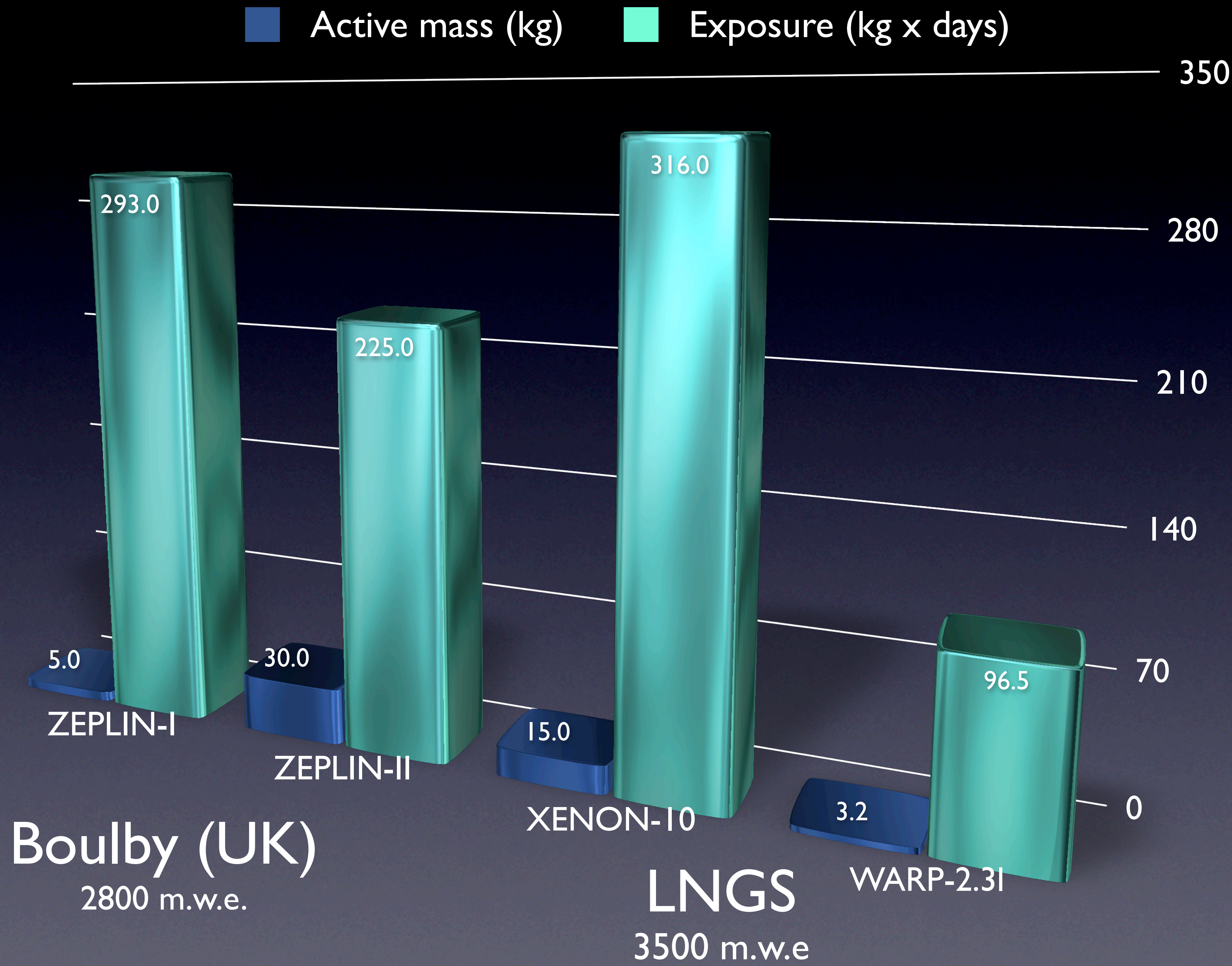



APS_2007

Elena Aprile

# WIMP search results

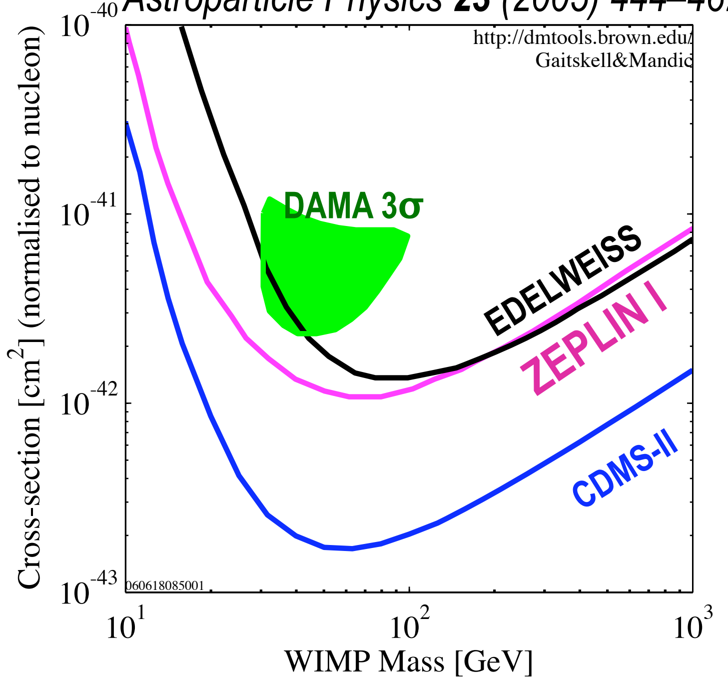
# WIMP data collected

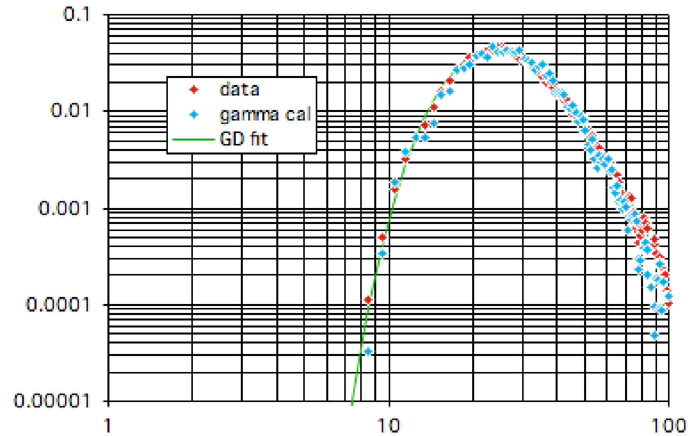


# ZEPLIN-I: First limit in noble liquids

- **230 kg-days in 3.1-kg fiducial mass**
  - **Gamma calibration data from contemporaneous veto events**
  - **Systematics dominated — no in situ neutron calibration**
    - **Trouble recondensing target**
    - **Reliance on surface-lab calibrations**
- **Some controversy...**
  - **Published critique of systematics** (A. Benoit *et al.*, *Phys. Lett.* ***B637*** *(2006) 156-160*)
    - **challenges assumptions of event populations used to limit excess nuclear recoils**
  - **Formal response in preparation**
- **Program evolved to 2-channel technique...**

*Astroparticle Physics* ***23*** *(2005) 444–462*



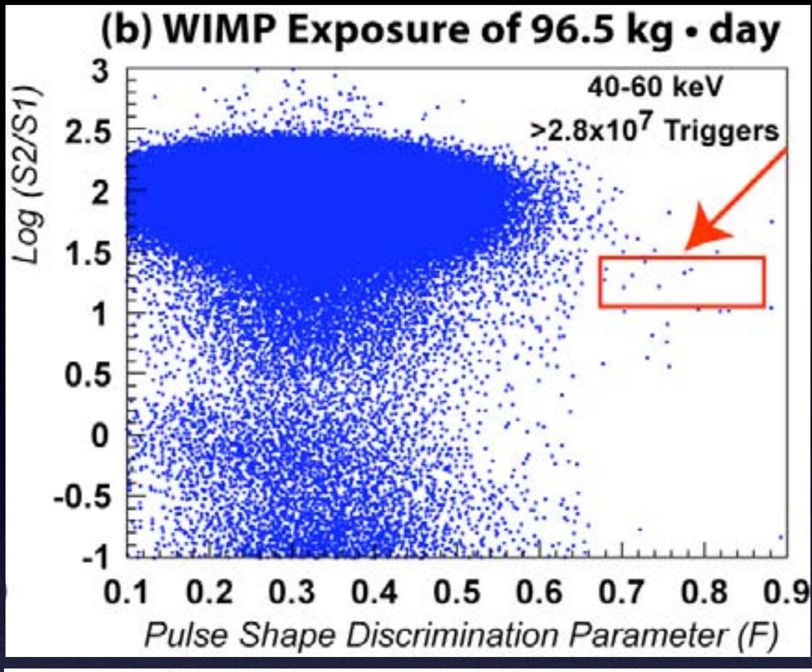



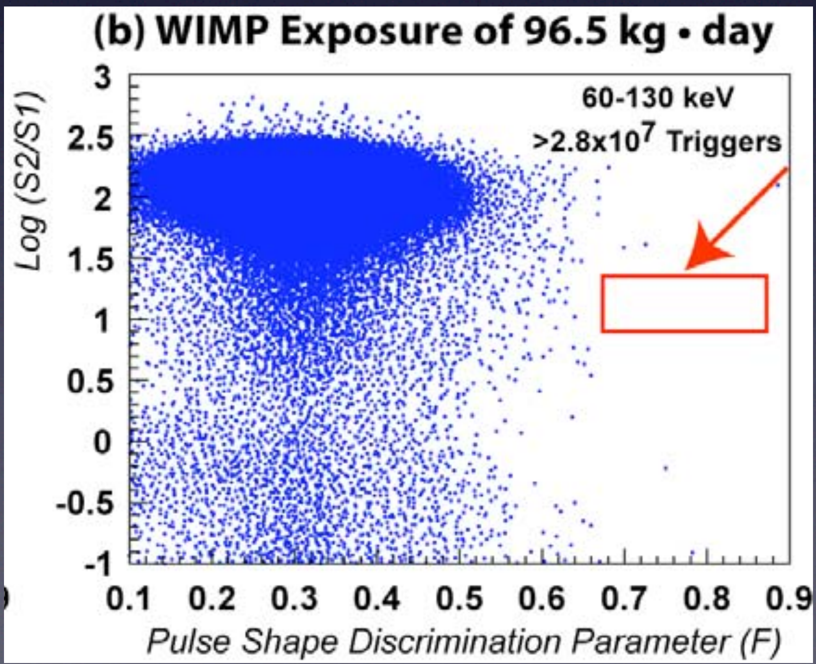

**Pulse shape**

Dan Akerib SSI 2007

# WARP initial result

astro-ph/0701286



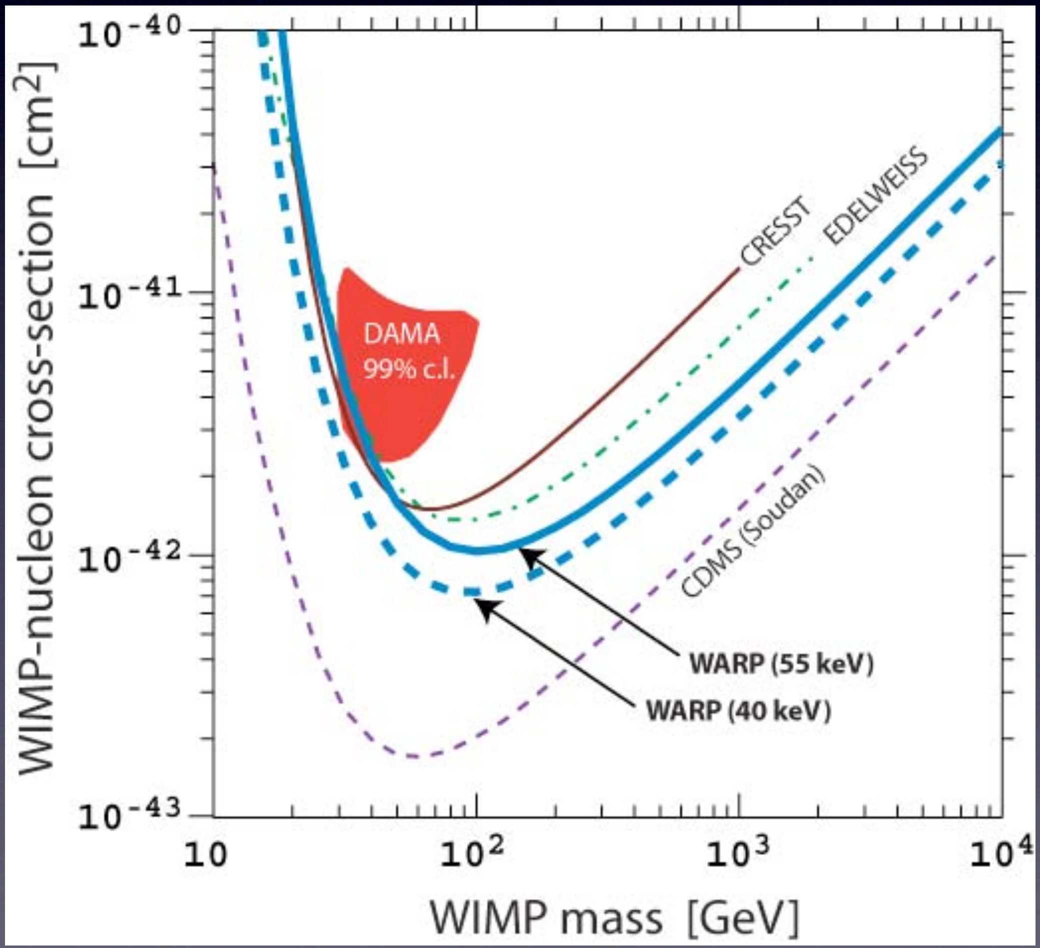




Not blind analysis (a posteriori cut at 55 keV)

8 events in 40-60 keV

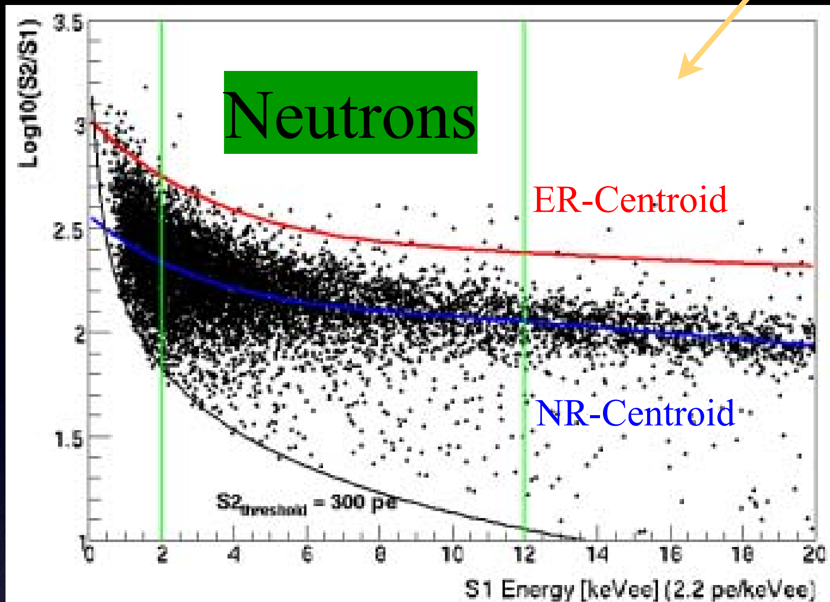
No events in 60-130 keV

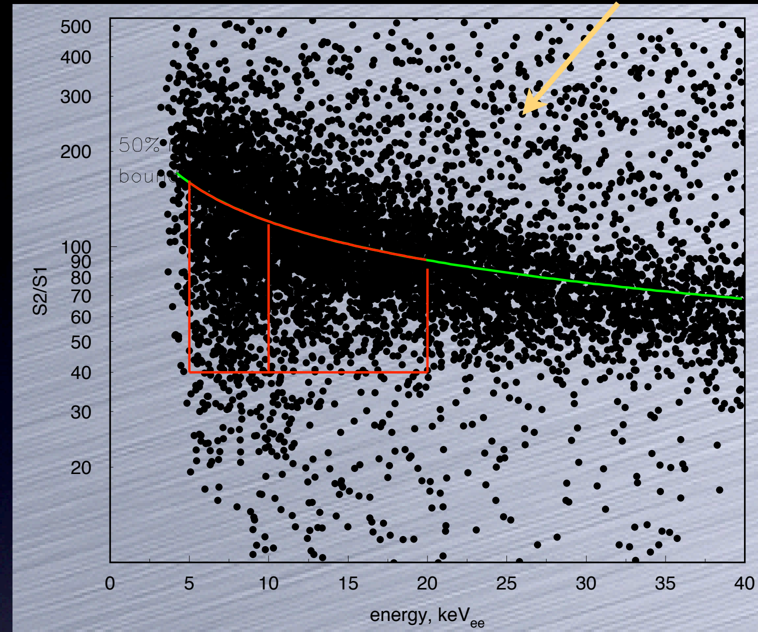
- ➪ Solve nuclear quenching issue...
- ➪ New data run with improved electronics...
- ➪ New data with isotopically $^{39}$Ar-depleted argon...



# In-situ: Xenon-10 vs ZEPLIN-II

AmBe

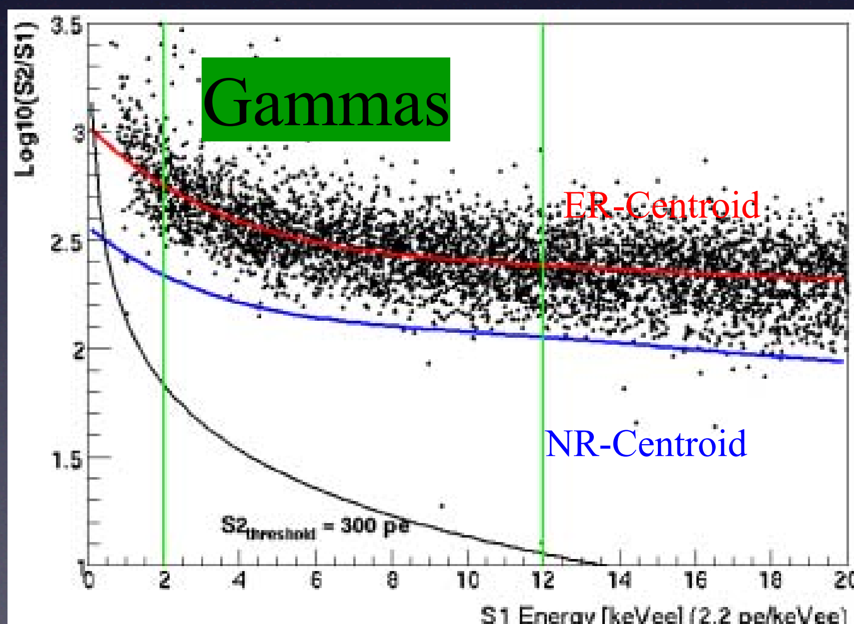


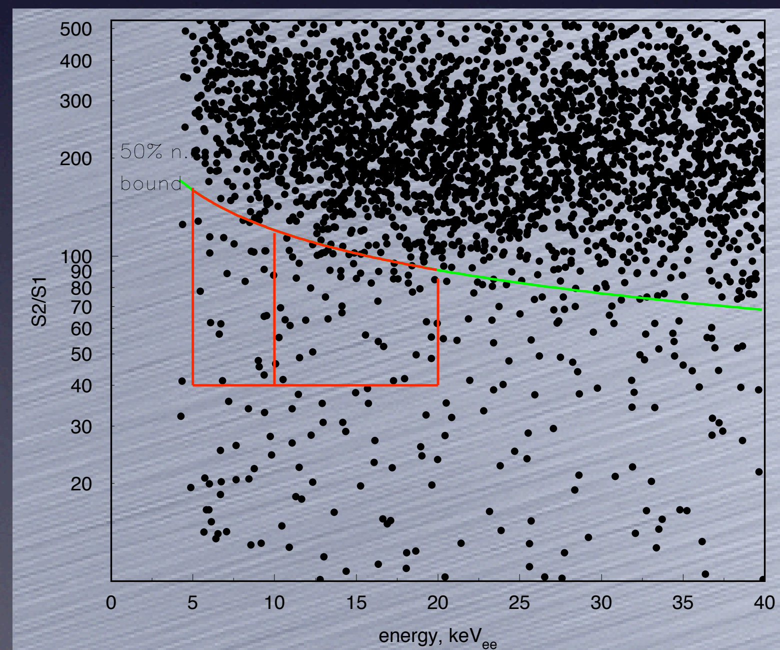




AmBe

$Cs^{137}$

2.2phe/keV




$Co^{60}$

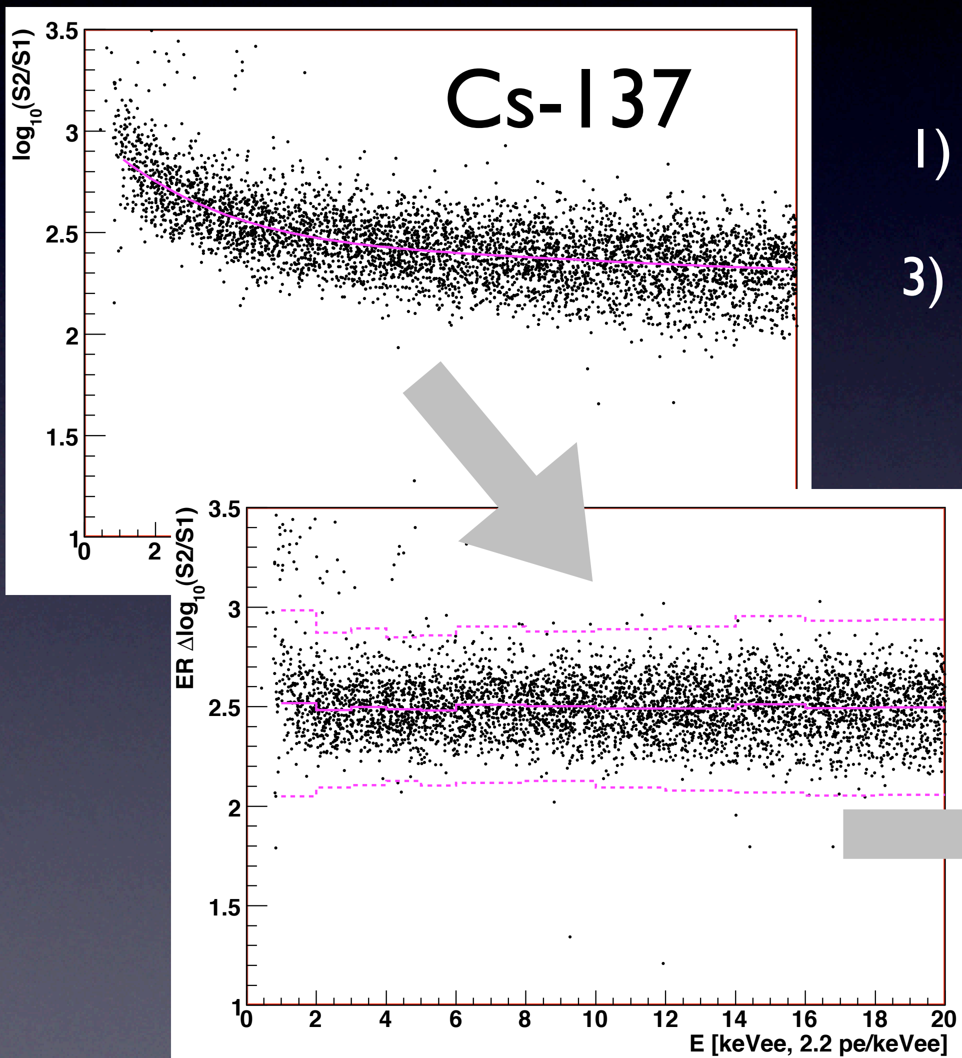
0.55phe/keV

99.5% rejection for 50% NR acc.

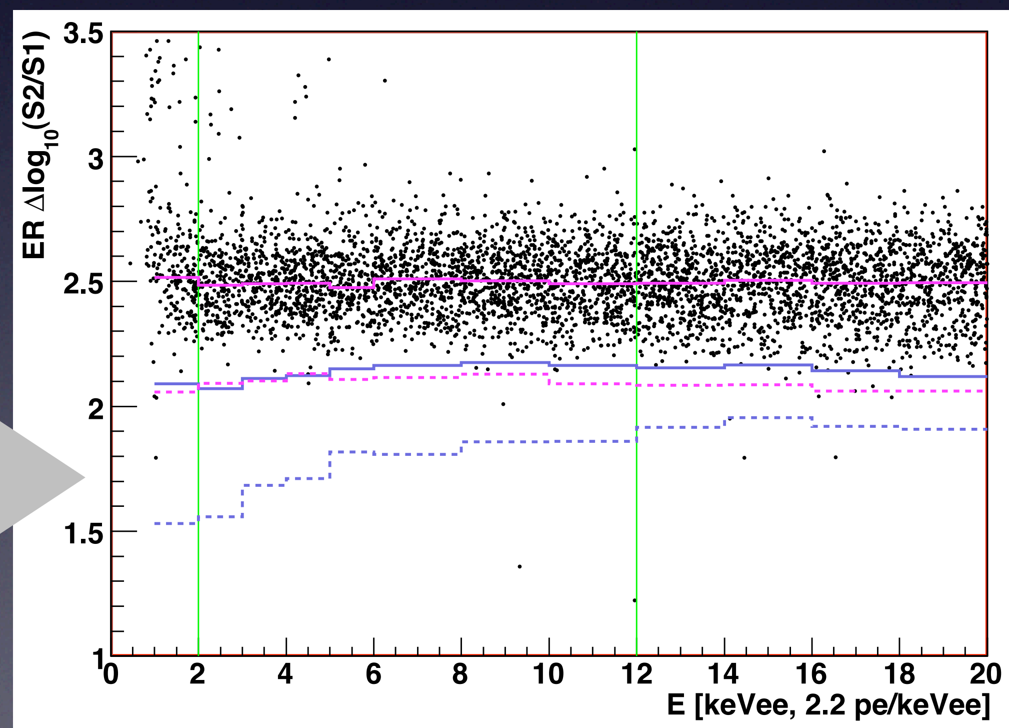
98.5% rejection for 50% NR acc.

# XENON-10: fit centroids

- In order to define NR acceptance and ER rejection, XENON analysis fits centroids and define band width around centroid based directly on calibration data ⇒ rely on actual data

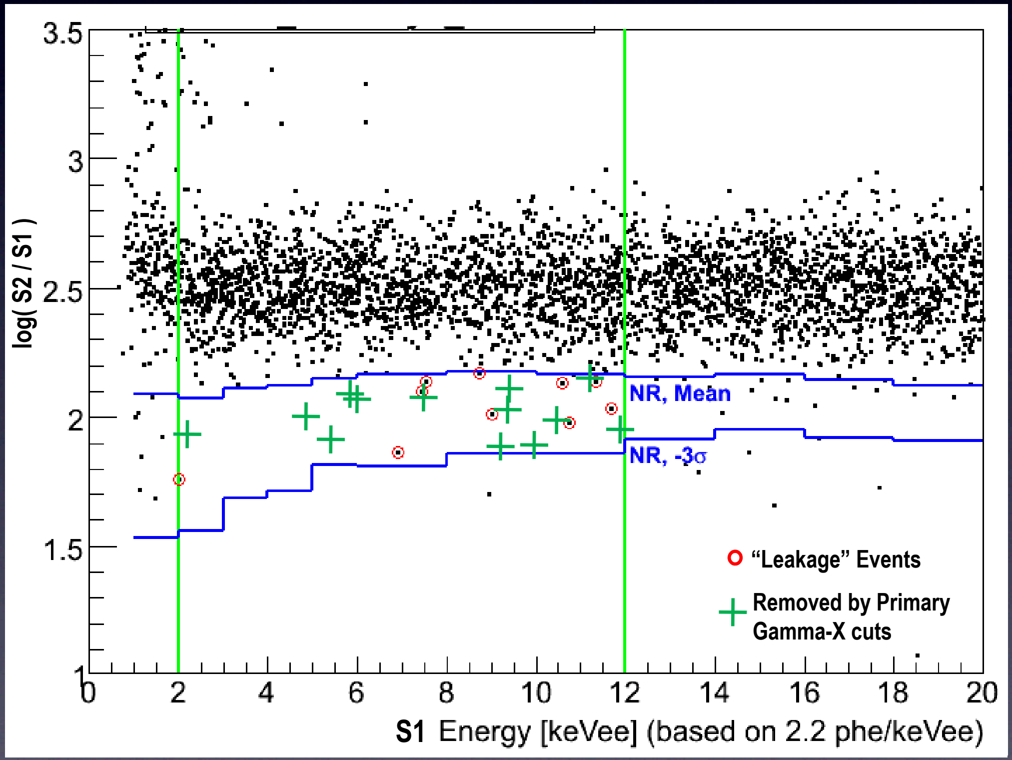



1) Straighten band + Gaussian-fit energy slice
2) similarly use AmBe NR data
3) define NR acceptance vs ER rejection band

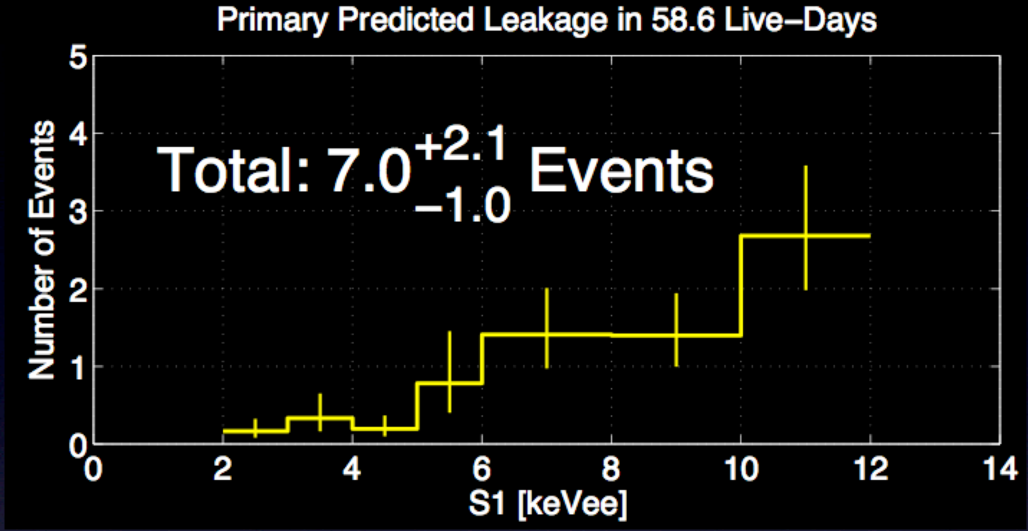


# XENON-10: WIMP data

- Blind analysis WIMP "box":
  - signal region 2-12 keVee (4.5-27 keVr @ QF=19%)
  - 50% acceptance for NR
- Additional "Gamma-X" cuts to remove 13 events (instrumental)




arXiv:0706.0039 [astro-ph]




After all cuts ➠ 10 observed events:

★5 consistent with "leakage" assuming Gaussian tails (expected 7.0+2.1-1.0)

★5 not consistent as such ➠ 4 can be removed with additional cuts

★Finally 1 event survives all cuts

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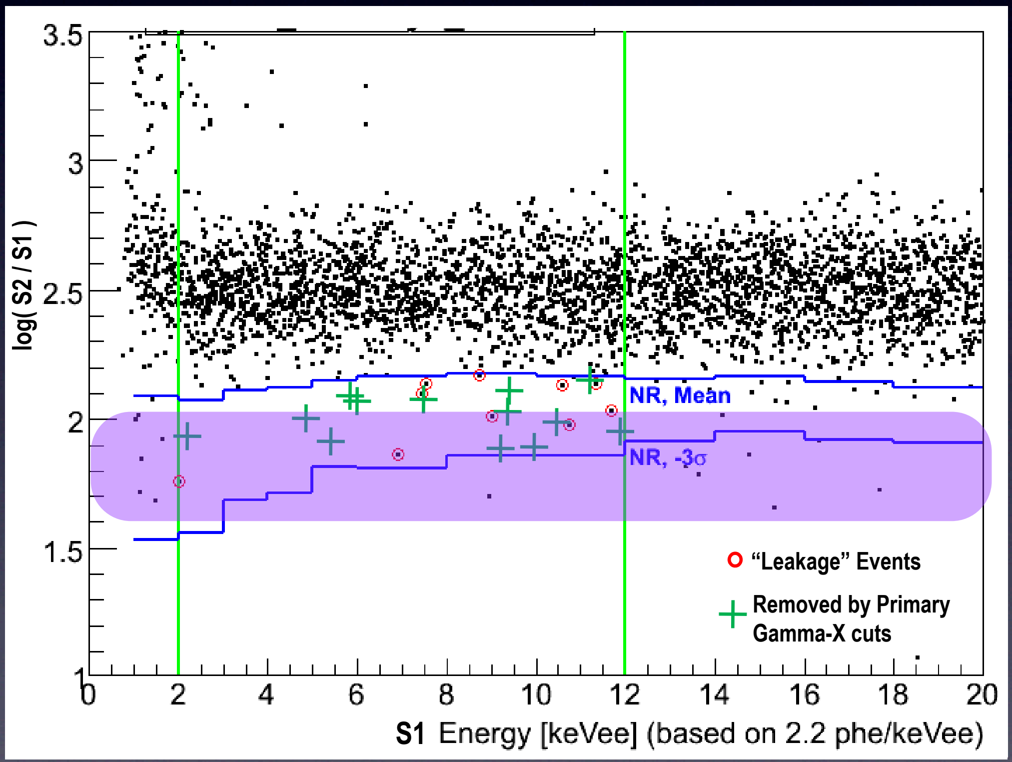
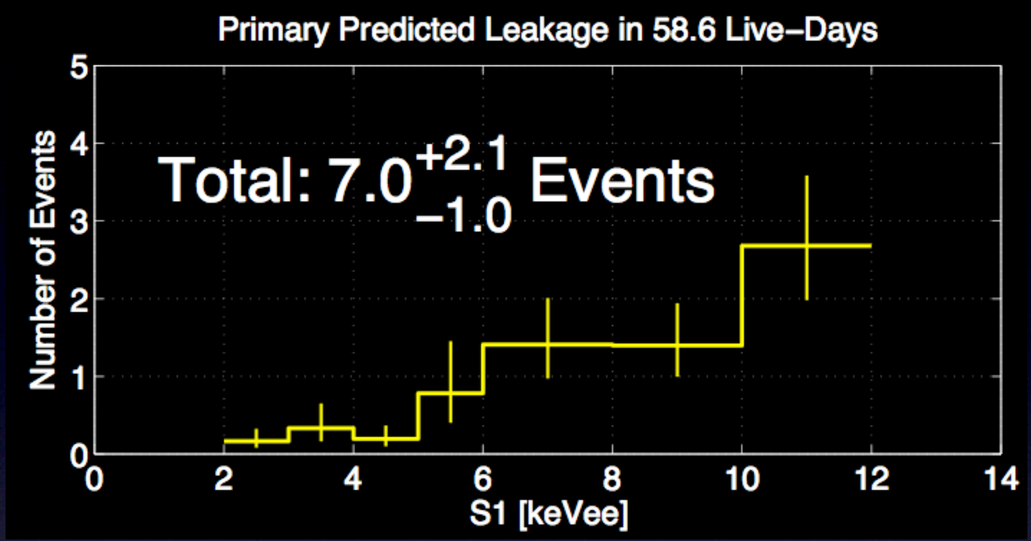



After all cuts ➠ 10 observed events:

★5 consistent with "leakage" assuming Gaussian tails (expected 7.0+2.1-1.0)

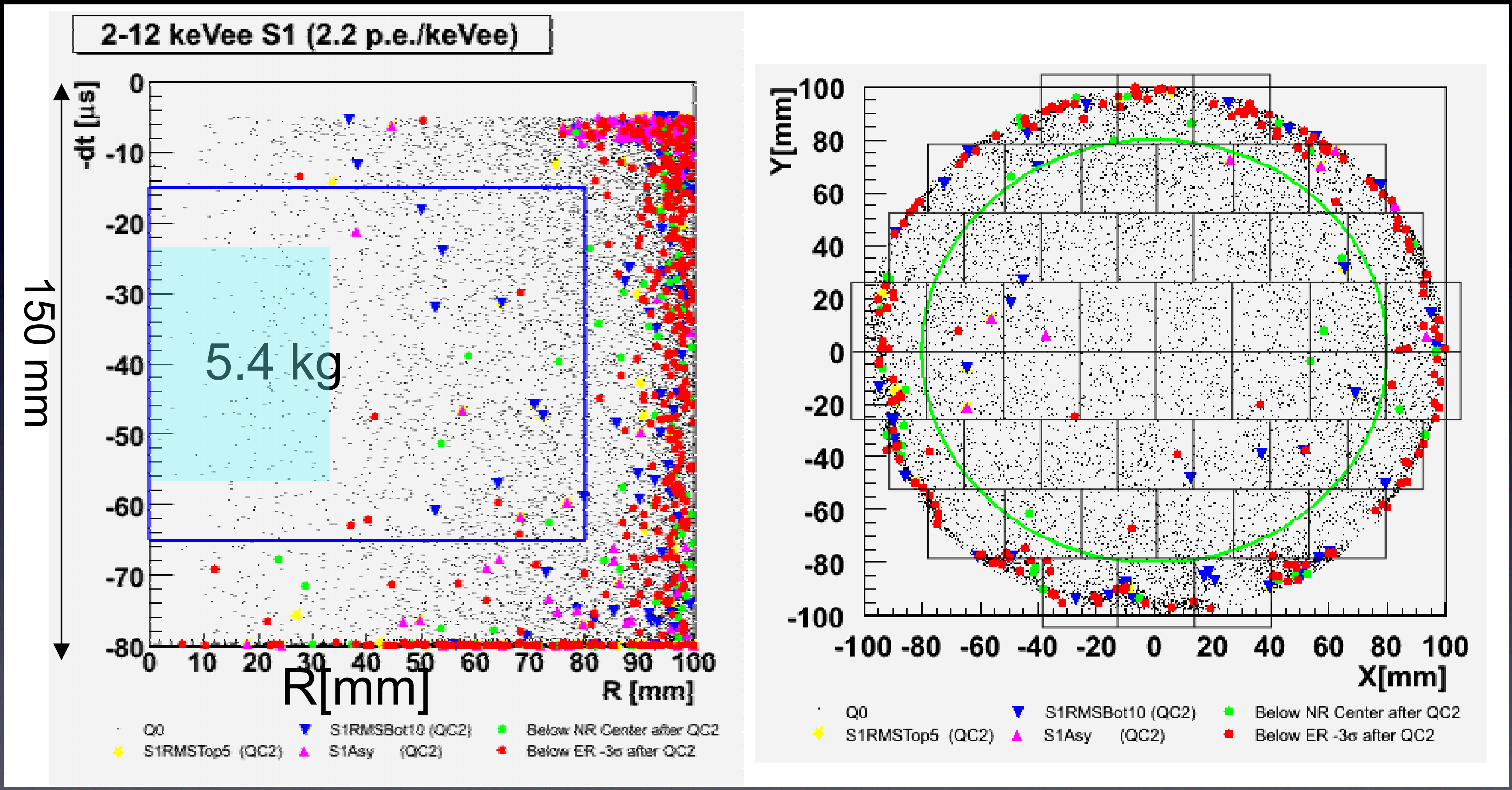
★5 not consistent as such ➠ 4 can be removed with additional cuts

★Finally 1 event survives all cuts

Non-gaussian tails? 1 event below 3σ band in ROI; more above 12 KeVee

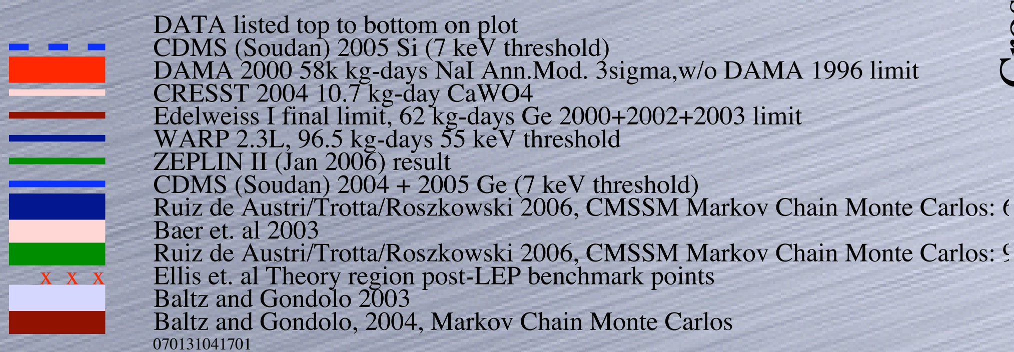
# XENON-10: WIMP data

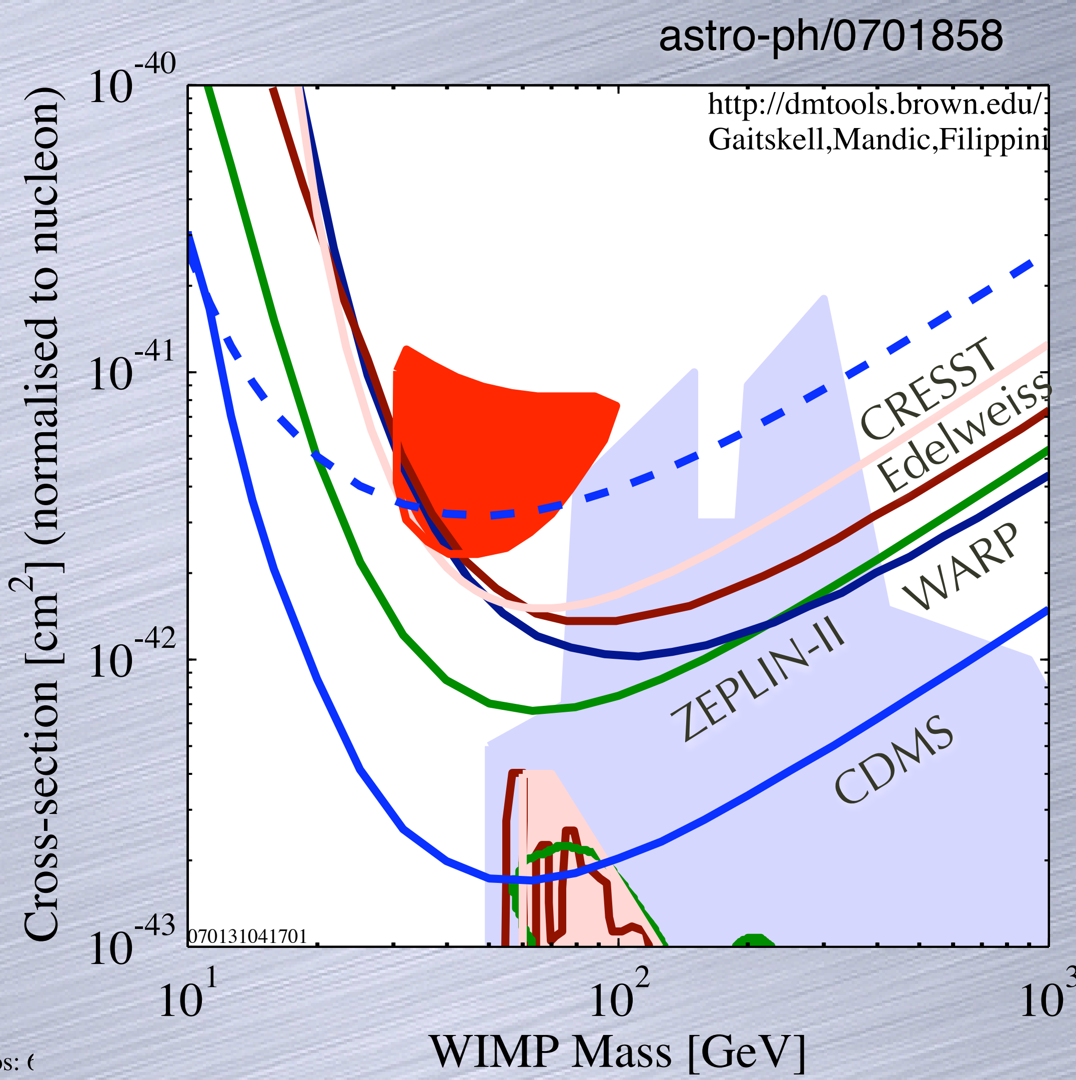
- Self-shielding in action: Spatial distribution of candidate events suggest “lower background” region?



# ZEPLIN-II: WIMP data

- 29 events seen in box
- 28.6±4.3 expected (total)
- 10.4 upper limit to n.r
- Translates to limit shown
  - ‘canonical’ halo model



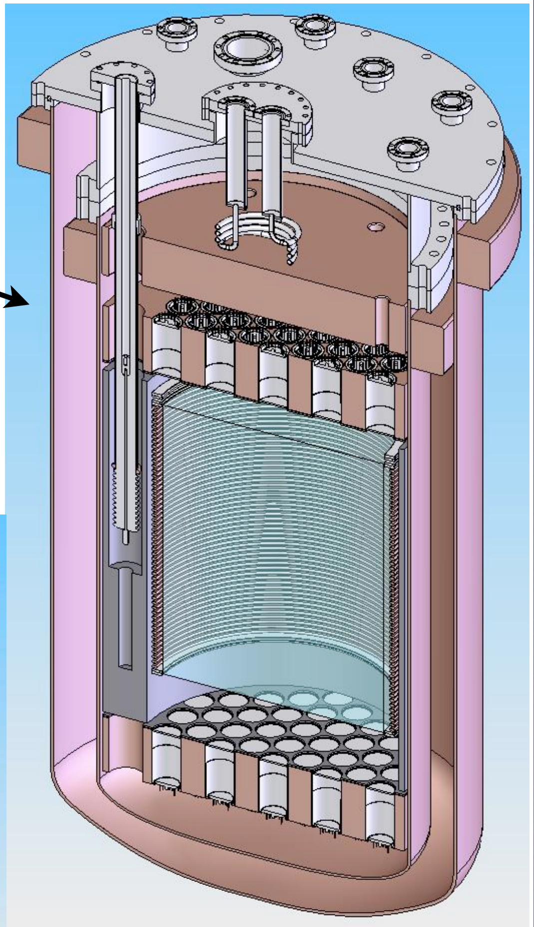



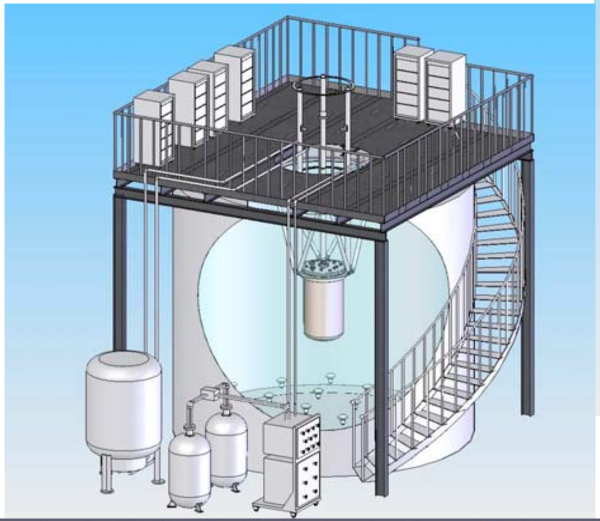

Courtesy of N.J.T. Smith

# Future Xenon in US

- DMSAG:
  - ➡ *The show must go on...*
  - ➡ Xenon is priority among noble liquids

- **XENON-50 and 100-kg to continue at Gran Sasso (Columbia et al)**
- **LUX 100-kg proposed for Homestake (Case/Brown/LLNL et al)**
  - early implementation in old "Davis" cavern
  - site of possible future Deep Underground Science and Engineering Lab (Dusel)

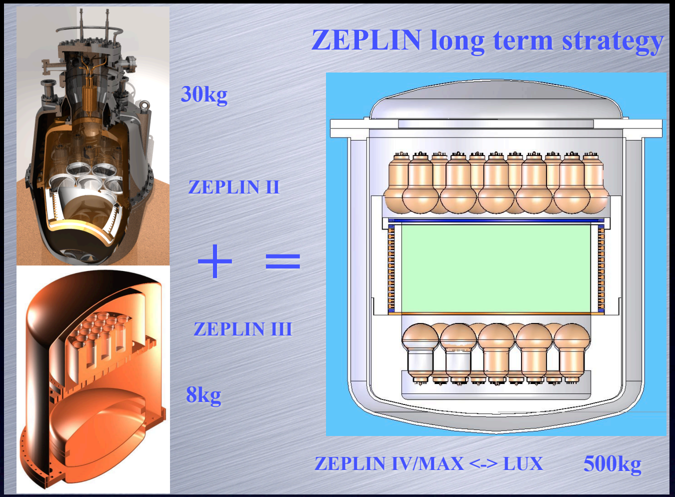




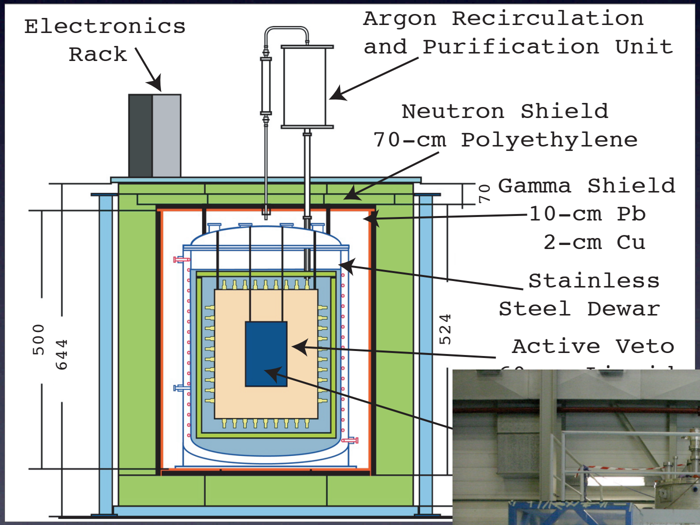
# Future DDMS in Europe

- ASPERA/ApPEC roadmap
- Xenon:
  - ZEPLIN-III (8kg) being deployed
  - ZEPLIN ➡ELIXIR “ton-scale”
  - Synergy with US proposal(s)
- Argon:
  - WARP-140kg: under construction @ LNGS
  - ArDM 1 ton: proof of concept on surface (CERN)
  - Challenge: cost of Ar39-depleted Argon ?
  - Synergy with CLEAN/DEAP ?
- Synergies between Xe & Ar ?

ELIXIR




WARP




ArDM

# Conclusion

- Liquid noble gases experiments have shown dramatic progress during the last year.
- Pioneering WIMP results from WARP /ZEPLIN-II / XENON-10 show great potentials for these technologies.
- Ready to reach the $10^{-44}$ $cm^2$ sensitivity.
- Extended detectors under consideration with realistic chances to reach a few $10^{-45}$ $cm^2$ in the next years... Window of opportunity?