Two-phase Cryogenic Avalanche Detectors in Ar with THGEM/GAPD-matrix optical readout

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Outline

1. CRAD concepts.

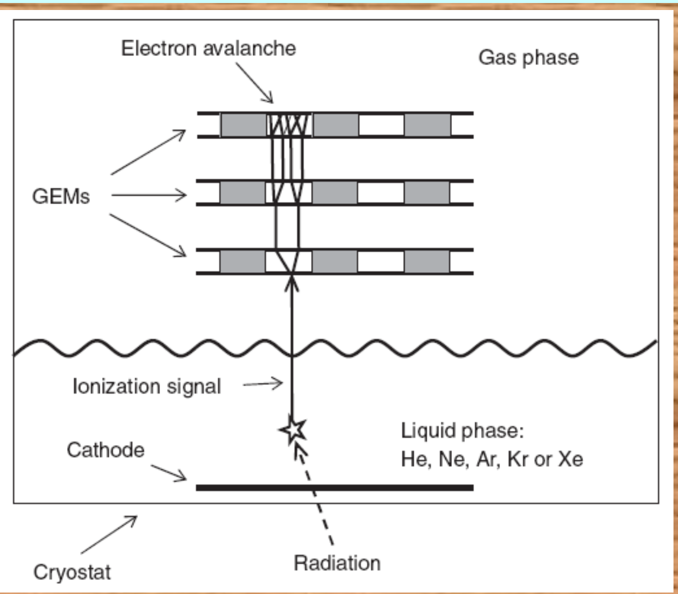
2. Our ongoing project on two-phase CRADs for dark matter search and low-energy neutrino detection.

3. Two-phase CRAD R&D results:
   - Two-phase CRADs with charge readout.
   - Two-phase CRADS with optical readout.

4. Recent results on two-phase Ar CRADs with THGEM/GAPD-matrix optical readout

5. Summary.

CRAD concepts



- Final goal: development of detectors of ultimate sensitivity (single-electron mode, with high spatial resolution, at extremely low noise) for rare-event experiments and other (i.e. medical) applications.

- Basic idea: combining hole-type MPGDs (GEMs and THGEMs) with cryogenic noble gas detectors, either in a gaseous, liquid or two-phase mode.

- We call such detectors "CRyogenic Avalanche Detectors": CRADs.

This concept was further developed, in particular suggesting to provide CRADs with:

- THGEM multiplier charge readout
- MPGD-based Gaseous Photomultiplier (GPM) separated by window from noble liquid
- CCD optical readout of GEM multiplier
- Combined THGEM/GAPD multiplier optical readout (GAPD = Geiger-mode APD or SiPM)

Our ongoing CRAD-related project

Accordingly, we need to develop

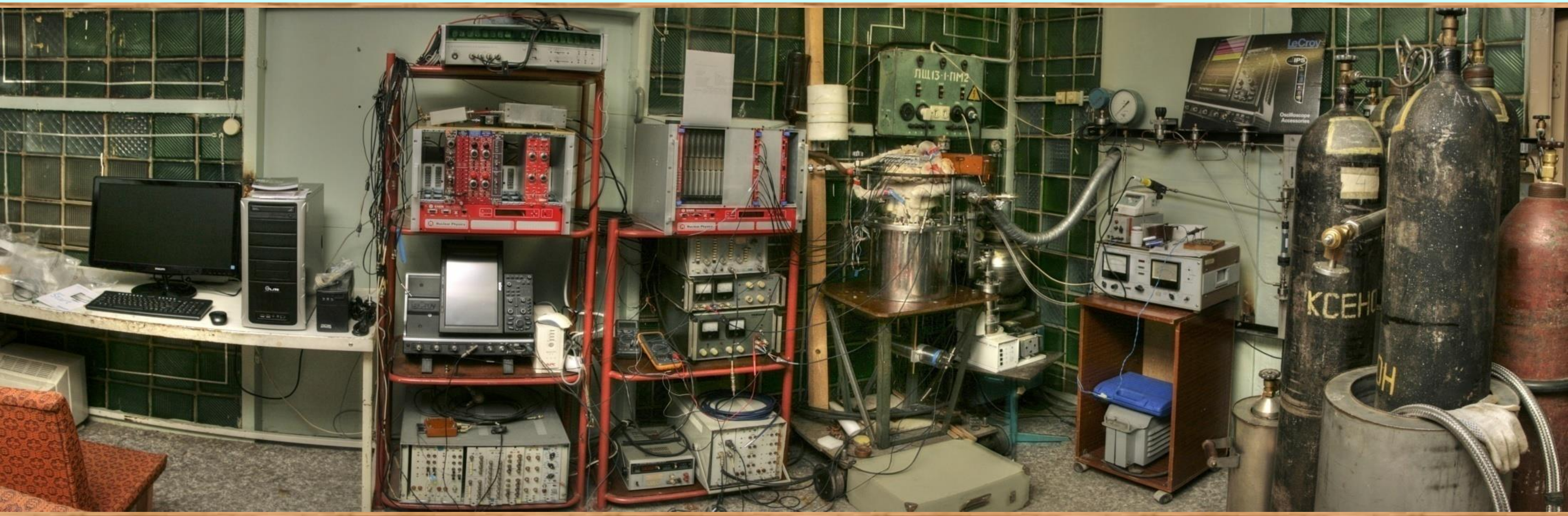
high-gain, extremely-low-noise and self-triggered two-phase CRADs having single-electron sensitivity, for 3 experiment types:

- Coherent Neutrino-Nucleus Scattering experiments;

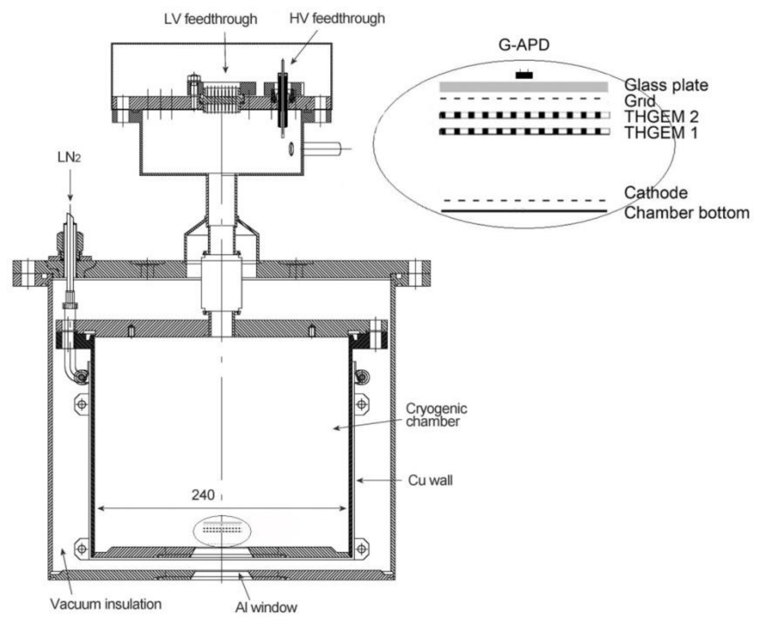
- Dark Matter search experiments;

- low-energy nuclear-recoil calibration experiments.

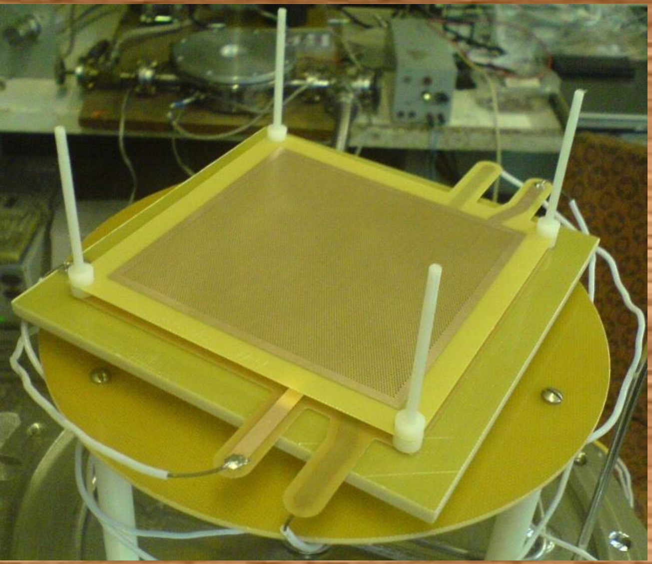
CRAD laboratory: experimental setup with 9 l cryogenic chamber in 2012

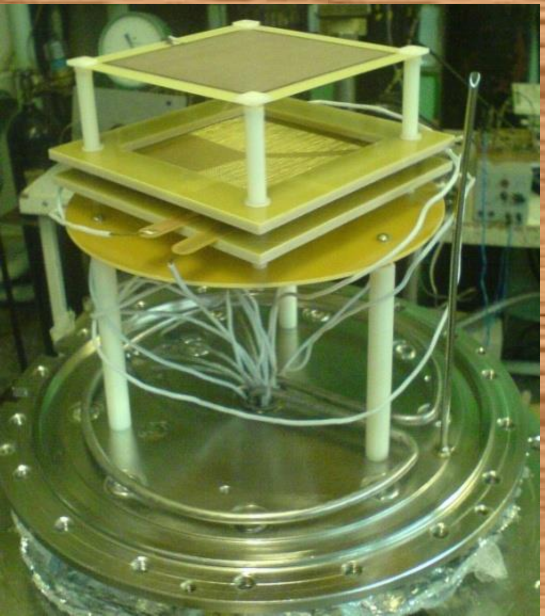


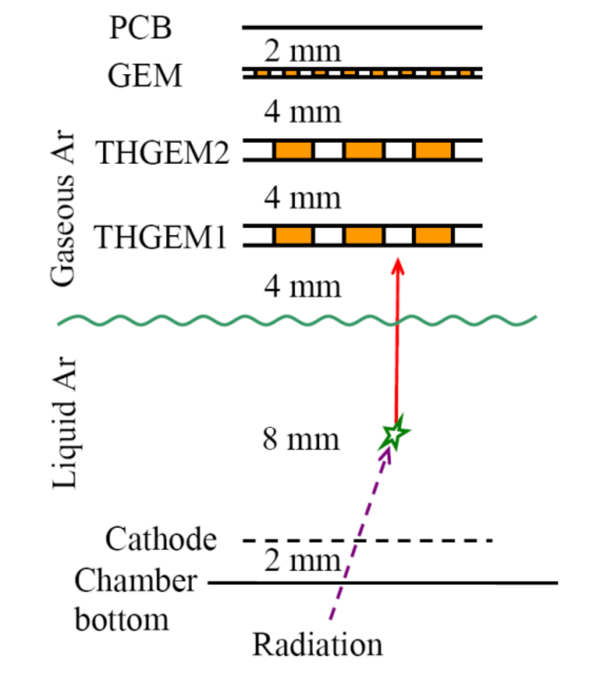
- 9 liters cryogenic chamber with 5cm-diameter Al X-ray windows
- ~0.5-2.5 liters of liquid Ar or Xe
- THGEM or THGEM/GAPD assembly inside
- Purification using Oxisorb: 20 μs e lifetime
- 1-day cooling cycle
- 1-3 hours liquid Ar collection time

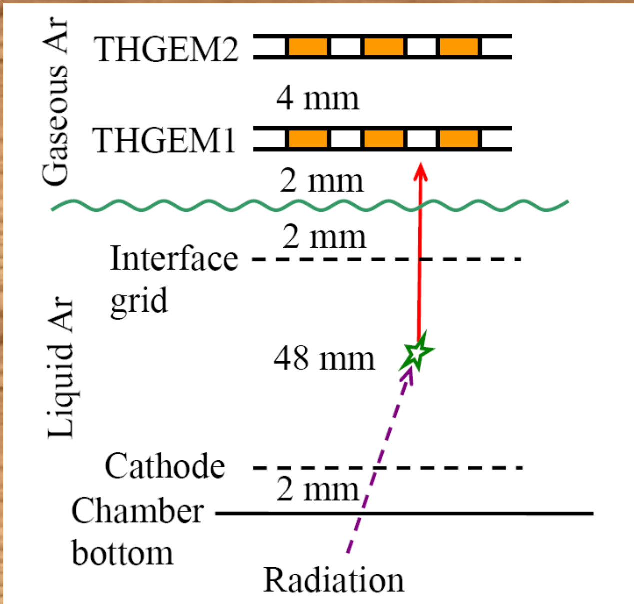


Two-phase CRADs in Ar with THGEM and hybrid THGEM/GEM multiplier (10×10 cm² active area)





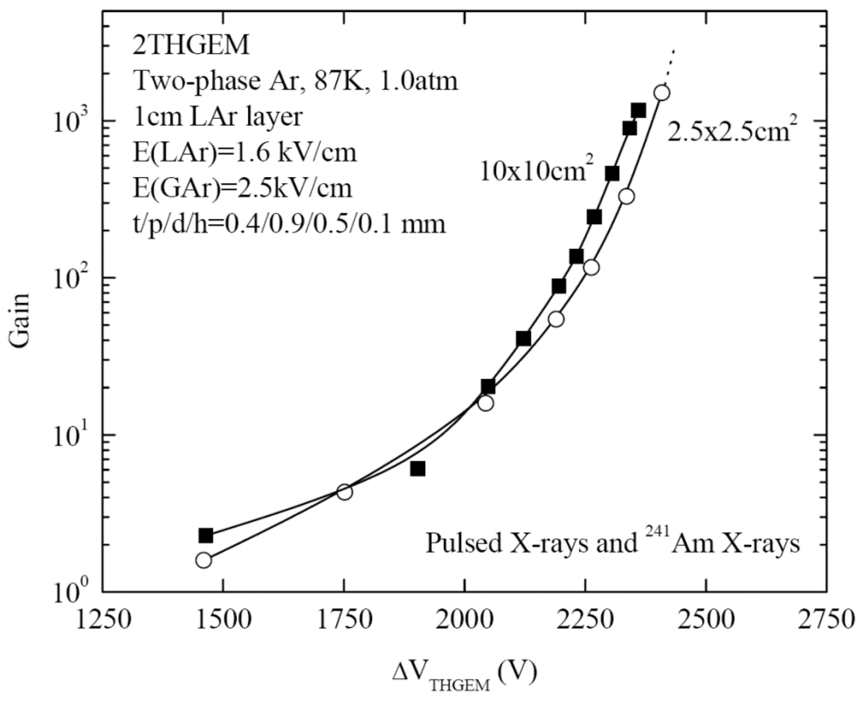


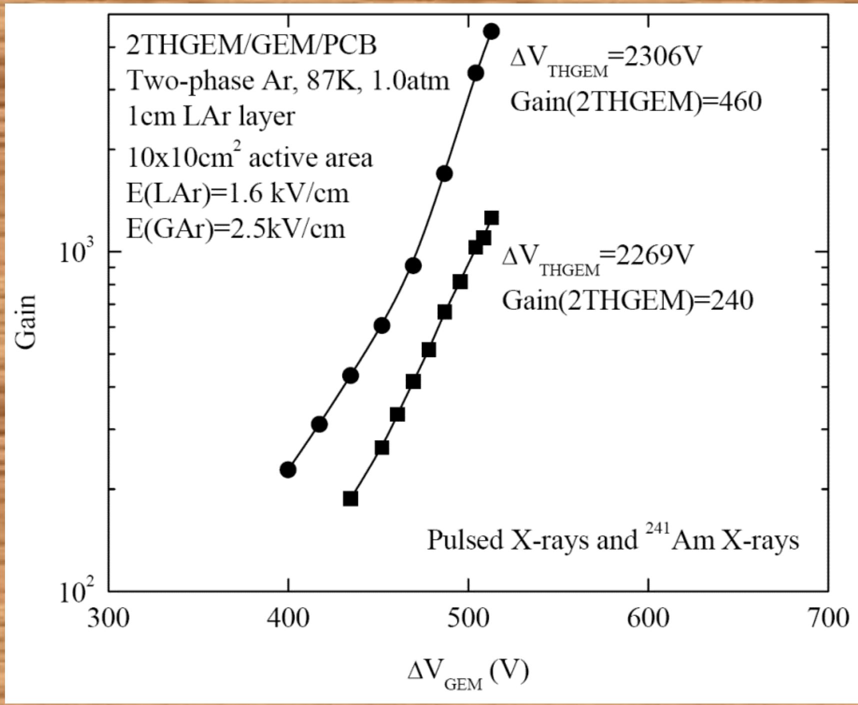


- 1 or 5 cm thick LAr layer
- Electron life time in LAr ~ 13 μs
- THGEM geometry: t/p/d/h=0.4/0.9/0.5/1 mm

[NSU & Budker INP: A.Bondar et al, JINST 8 (2013) P02008]

Two-phase CRAD in Ar with THGEM and hybrid THGEM/GEM multiplier (10×10 cm² active area)





- Confirmed proper performance at high gains of two-phase Ar CRADs having practical size (10x10 cm2 active area and 1-5cm thick liquid layer)
- Gains reached 1000 with the 10x10cm2 double-THGEM multiplier

- Higher gains, of about 5000, have been attained in two-phase Ar CRADs with a hybrid triple-stage multiplier, comprising of a double-THGEM followed by a GEM (in 2THGEM/GEM/PCB readout mode, i.e. with patterned anode)

[NSU & Budker INP: A.Bondar et al, JINST 8 (2013) P02008]

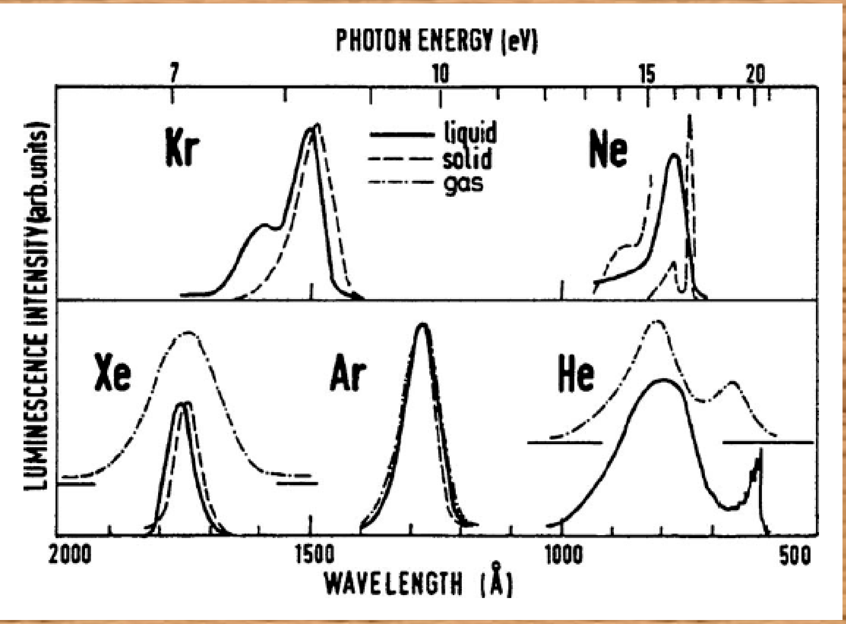
Concluding remarks to this section

Our general conclusion is that the maximum gains achieved in two-phase CRADs, of the order of 1000-5000 in Ar and 500 in Xe, might be sufficient for Giant LAr TPC and PET applications.

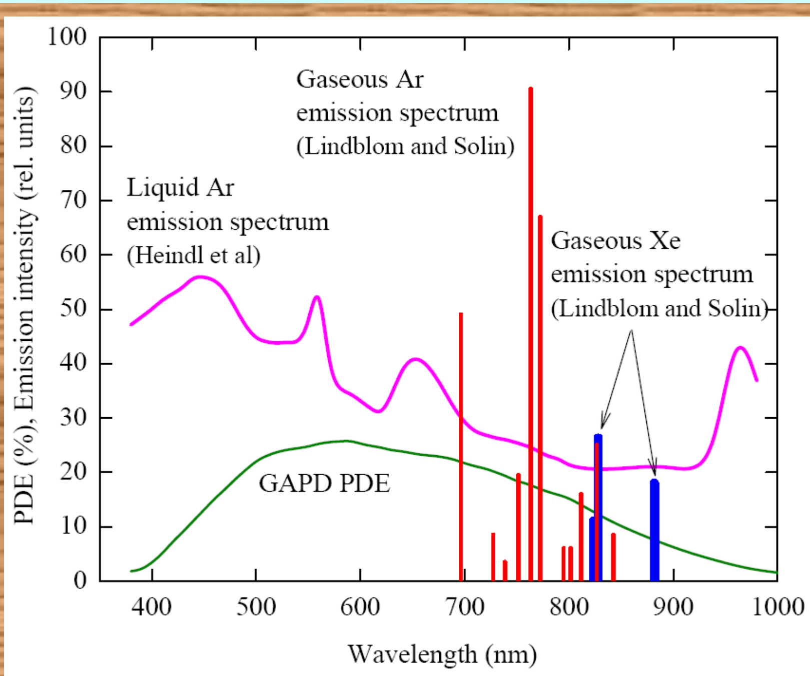
This however might not be sufficient for efficient single-electron counting, recording avalanche-charge in self-triggering mode (requiring gain values of 20,000-30,000). Accordingly, ways of increasing the overall gain should be looked for.

A possible solution is the optical readout of THGEM avalanches using Geiger Mode APDs (GAPDs); it is considered in the following.

Optical readout of CRADs with combined THGEM/GAPD multiplier: motivation



Primary scintillation emission spectra of noble gases [E.Aprile, T. Doke, Rev. Mod. Phys. 82 (2010) 2053]

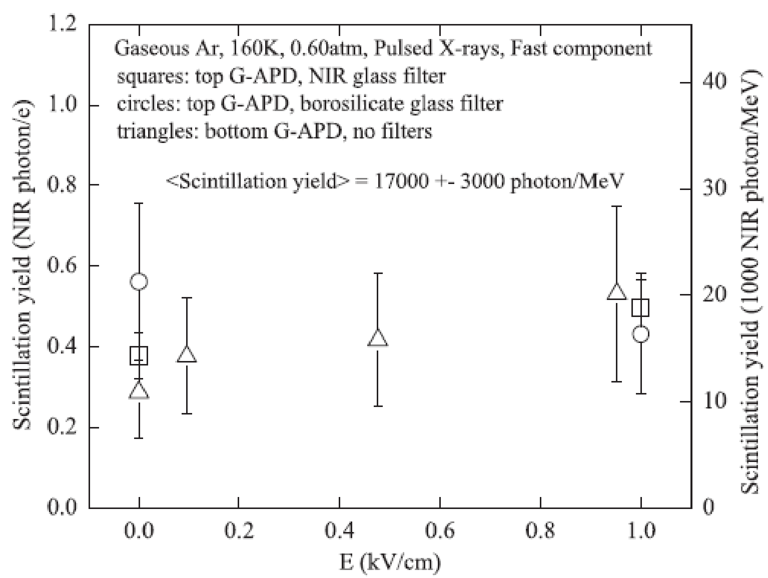


- Visible and NIR emission spectra of gaseous Ar and Xe and liquid Ar - GAPD PDE [A.Buzulutskov, JINST 7 (2012) C02025]

Noble gases have intense secondary scintillations both in VUV and NIR, while GAPDs have high quantum efficiency in the visible and NIR region. This results in two concepts of THGEM optical readout:

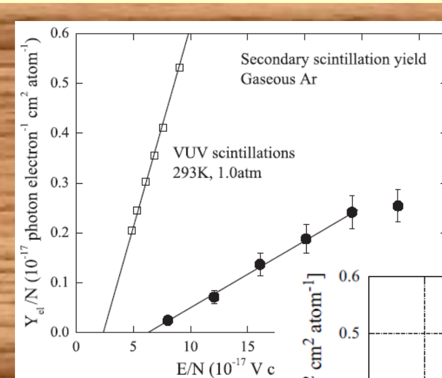
- using WLS-coated GAPD sensitive to the VUV;
- using uncoated GAPD sensitive to the NIR.

NIR scintillations in gaseous and liquid Ar: primary and secondary scintillation yield



Primary scintillation yield in the NIR has been measured:

- In gaseous Ar it amounted to <u>17000± 3000</u> photon/MeV in 690–1000 nm
- In liquid Ar it amounted to <u>510±90</u> photon/MeV in 400–1000 nm



- In GAr: secondary scintillations (electroluminescence) in the NIR were observed; fair agreement with simulation by *[C.A.B.Oliveira et al., NIMA A722 (2013) 1]*

- In LAr: no secondary scintillations in the NIR were observed up to 30 kV/cm

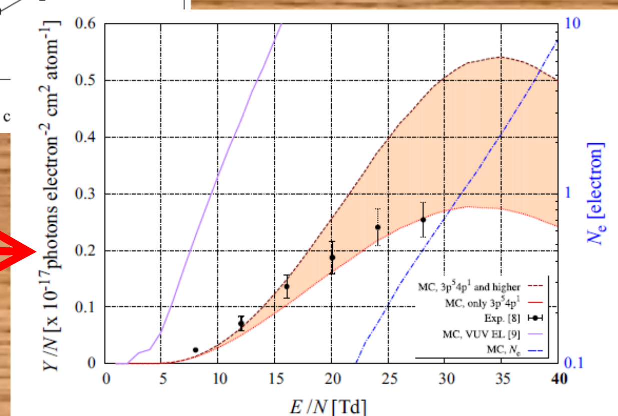
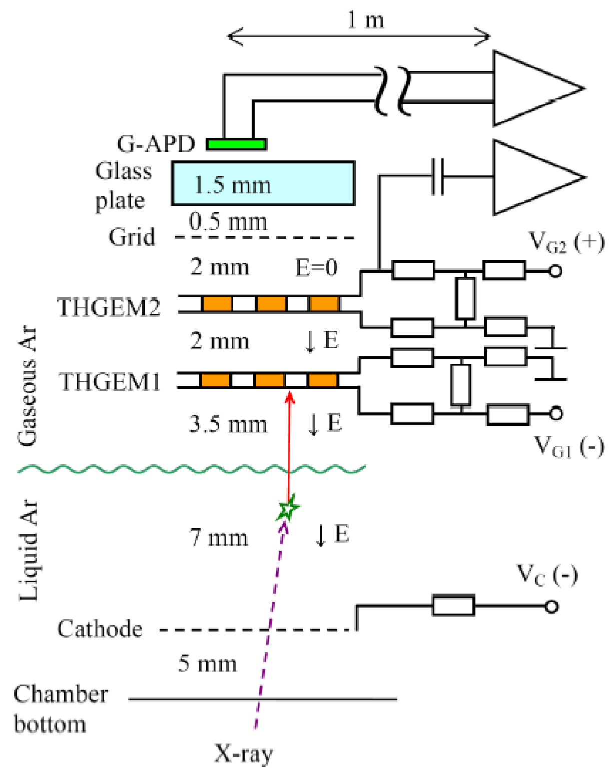


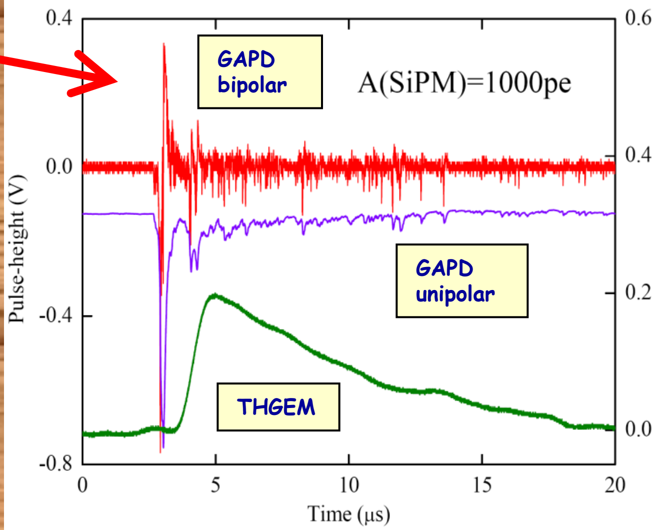
Fig. 3. Reduced NIR EL yield for argon, normalized to the total charge collected in the anode, N_e, as a function of the reduced electric field, for the two considered simulation approaches. The results were obtained considering a temperature of 163 K, a pressure of 0.60 atm and a EL gap of 2 mm width. The VUV EL yield is included. The number of produced secondary electrons is also plotted (notice the right axis for this quantity).

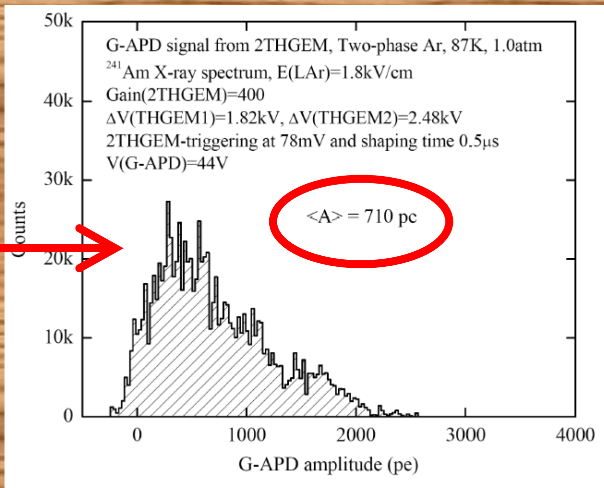
[Budker INP: A.Buzulutskov et al, EPL 94 (2011) 52001; A. Bondar et al. JINST 7 (2012) P06014]

Two-phase Ar CRADs with THGEM/GAPD optical readout in the NIR: combined multiplier yield



Avalanche scintillations from THGEMs holes have been observed in the NIR using uncoated GAPDs.

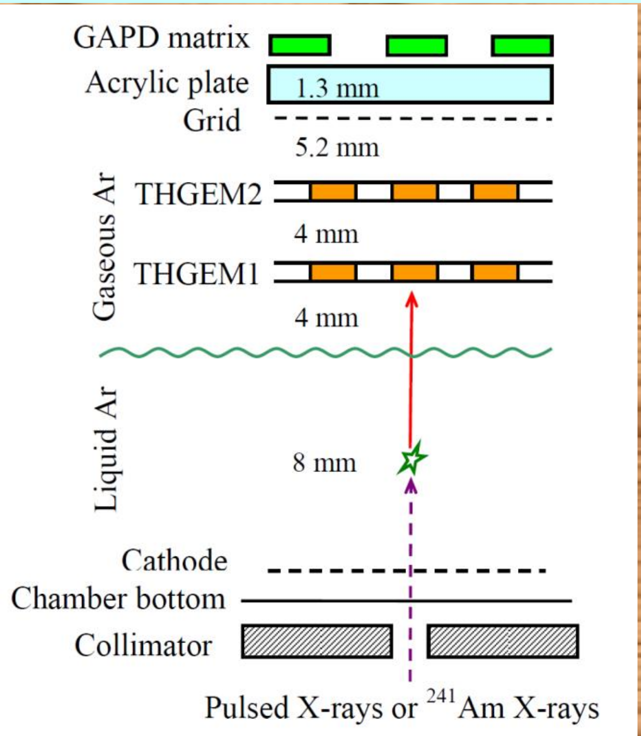


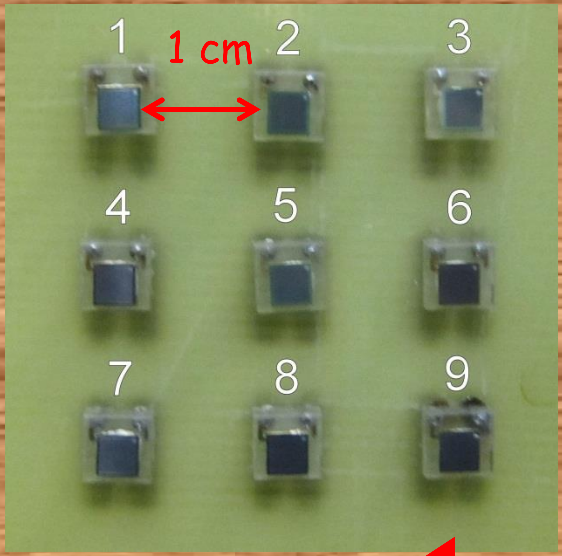


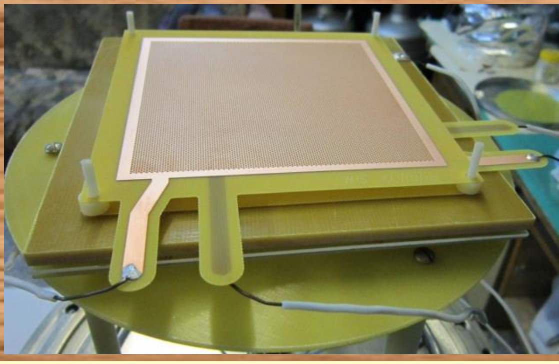
Combined multiplier yield =
= 700 pe per 60 keV X-ray at THGEM gain=400,
i.e 12 pe/keV at this particular solid angle
(±12mm field of view at a distance of 5 mm)

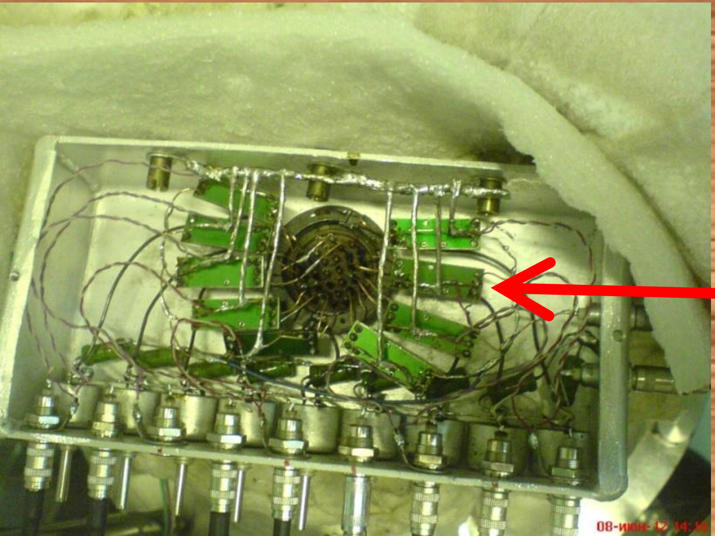
[Budker INP, ITEP, Weizmann Inst: A.Bondar et al, JINST 5 (2010) P08002; JINST 6 (2011) P07008]

Two-phase Ar CRAD with THGEM/GAPD-matrix optical readout in the NIR: experimental setup



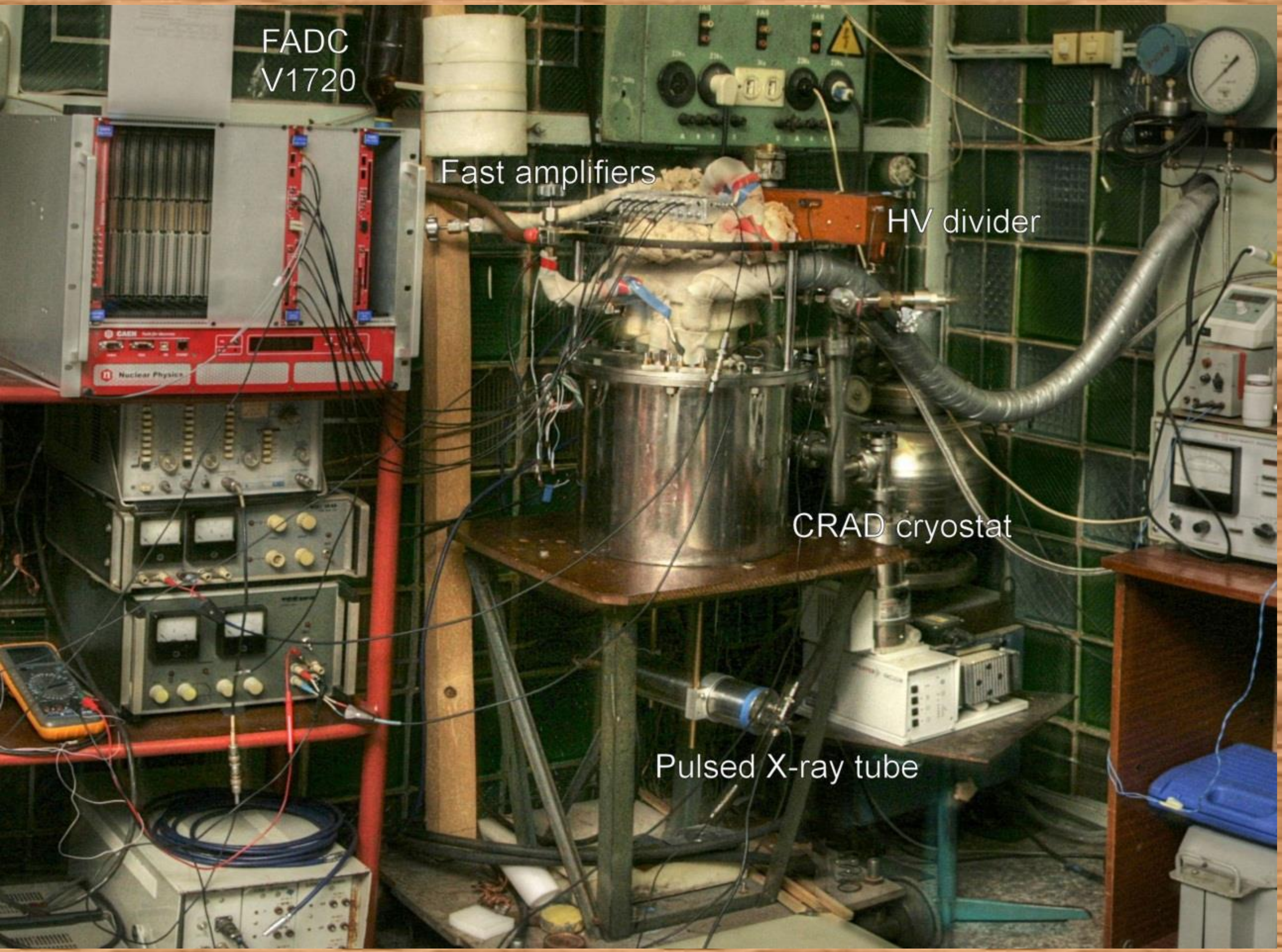


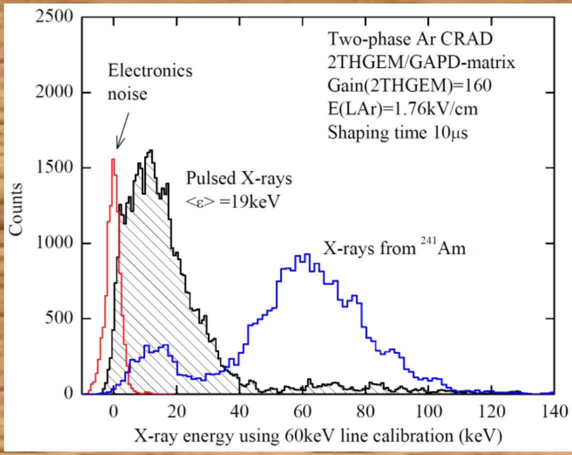




- Double-THGEM multiplier in the gas phase
- 3x3 GAPD matrix (1 cm spacing) optical readout in the NIR
- Each GAPD (CPTA 149-35) having 2x2 mm2 active area
- 9 fast amplifiers (CPTA) outside the chamber
- Irradiated with pulsed X-rays (~20 keV, 240Hz) through a 2mm diameter collimator, to estimate spatial resolution
- Operated in single X-ray photon counting mode

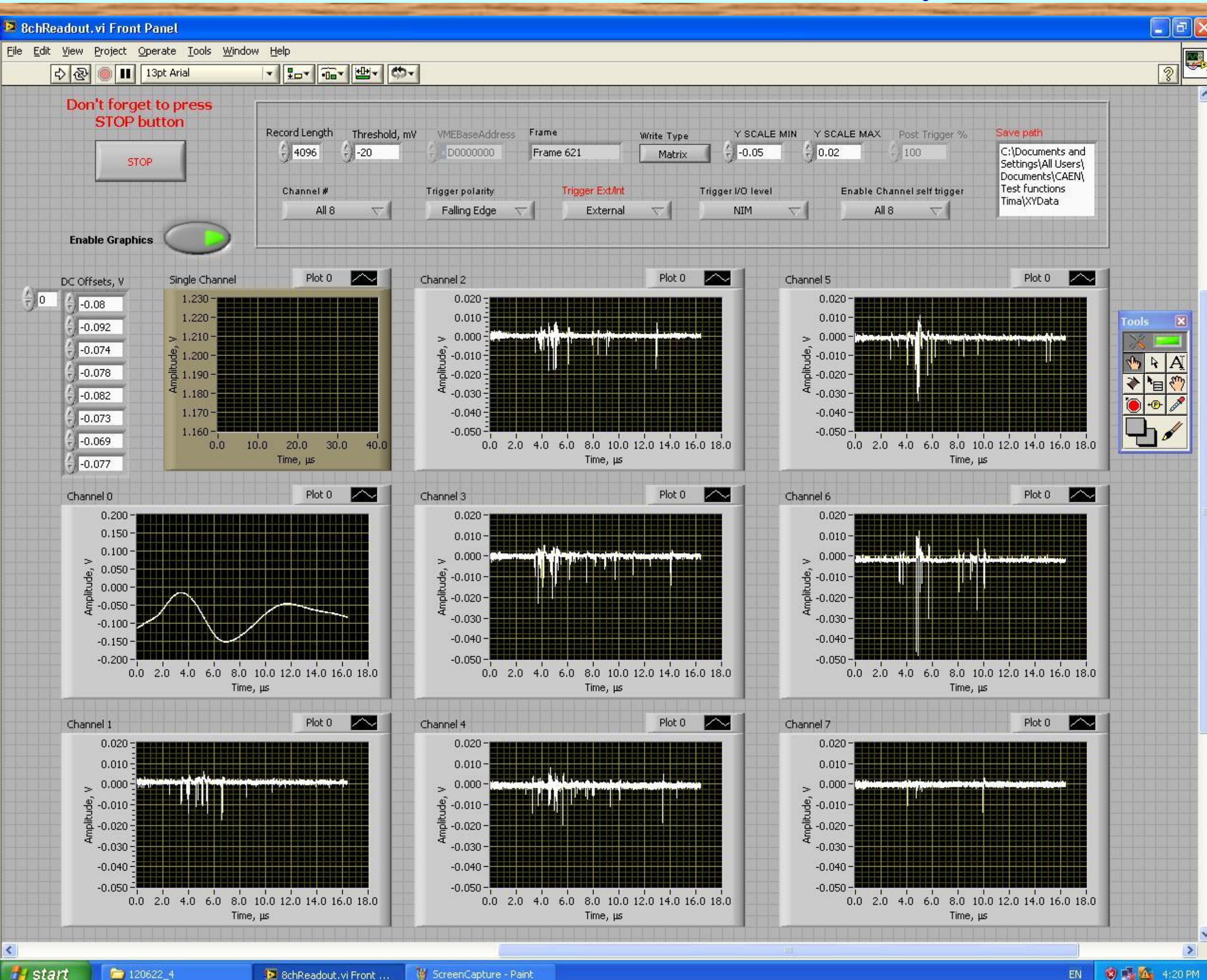
Two-phase Ar CRAD with THGEM/GAPD-matrix optical readout in the NIR: experimental setup





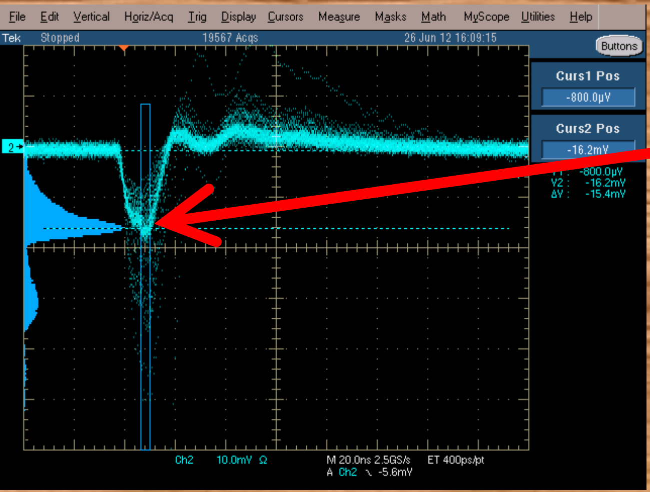
- Irradiated with pulsed X-rays (~20 keV, 240Hz) through a 2mm diameter collimator, to estimate spatial resolution
- Operated in single X-ray photon counting mode

Two-phase Ar CRAD with THGEM/GAPD-matrix multiplier: data acquisition

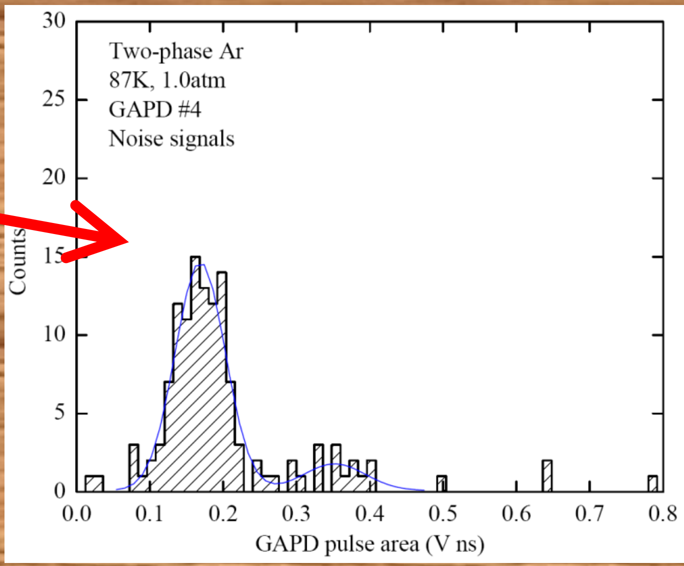


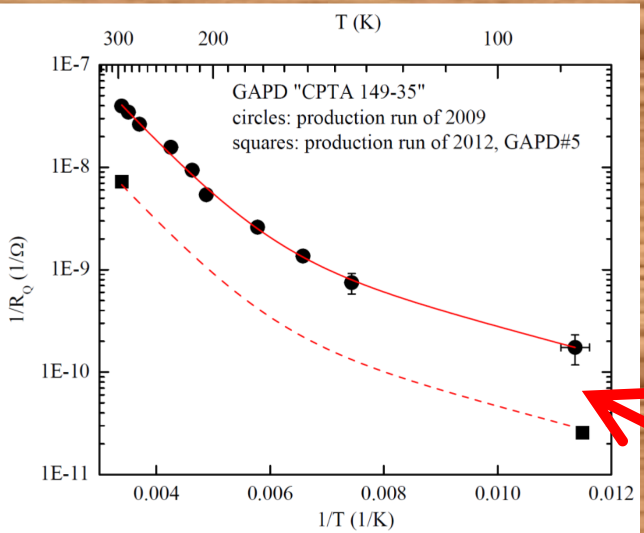
8 readout channels using fast flash ADC CAEN V1720 (250 MHz)

Two-phase Ar CRAD with THGEM/GAPD-matrix multiplier: GAPD performance at 87K → The problem of gain saturation at higher rates for CPTA GAPDs

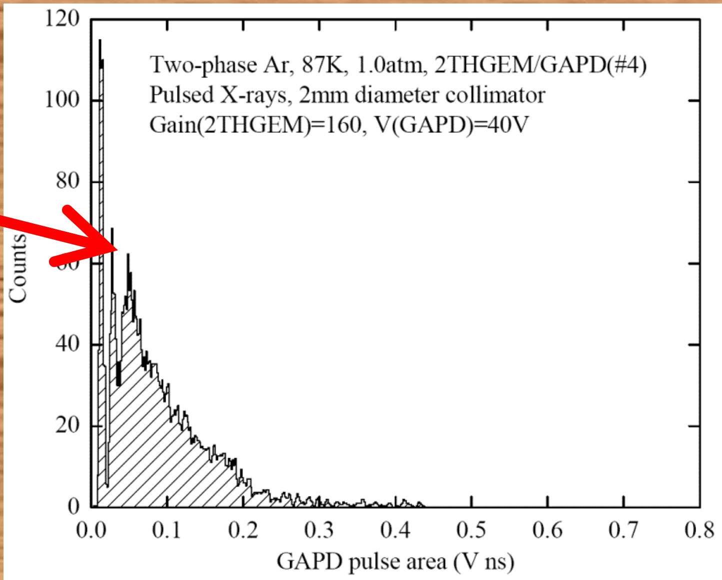


The infrequent nose signals had a nominal GAPD pulse-area distribution: single-pixel peak is accompanied with secondary (cross-talk) peaks

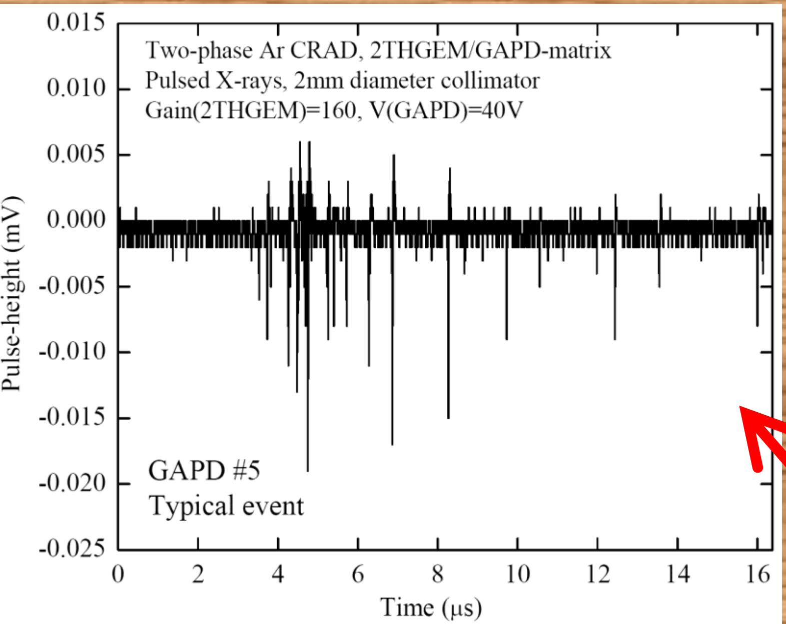


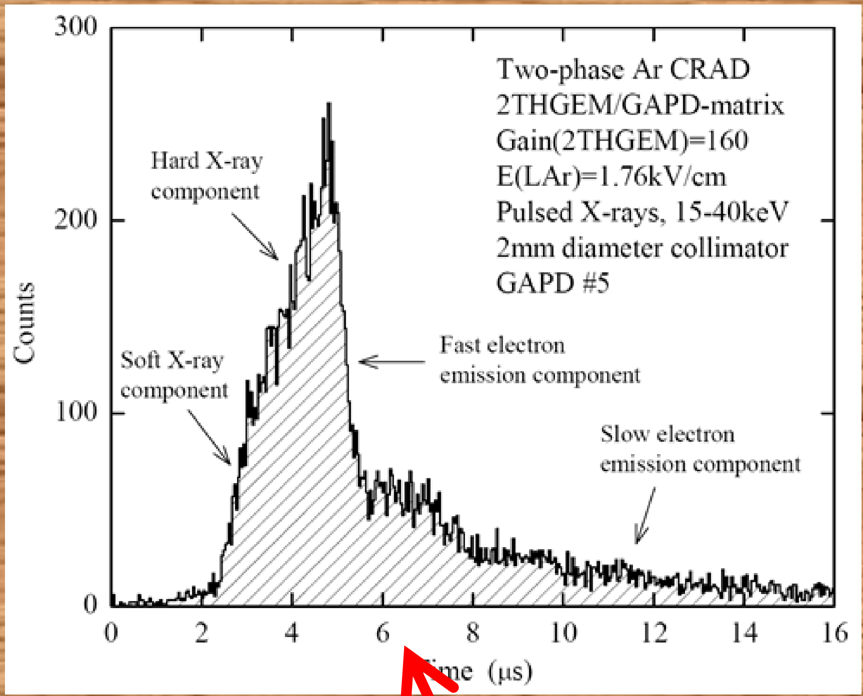


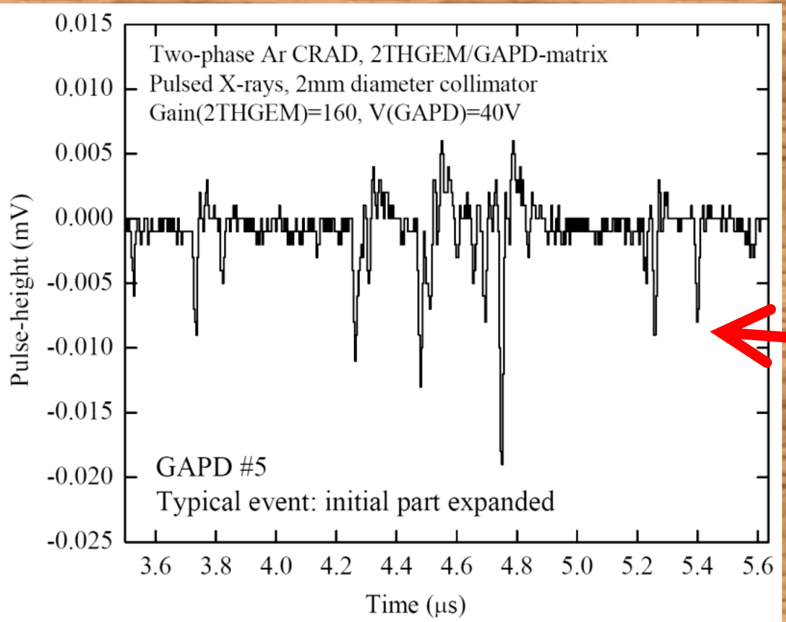
- However, at higher rates (240Hz) and intense photon flux the single pixel pulse-area spectrum was degraded → Saturation and even reduction of the GAPD gain
- This is induced by considerable increase of the pixel quenching resistor at low T



Two-phase Ar CRAD with THGEM/GAPD-matrix multiplier: GAPD signal example and time properties

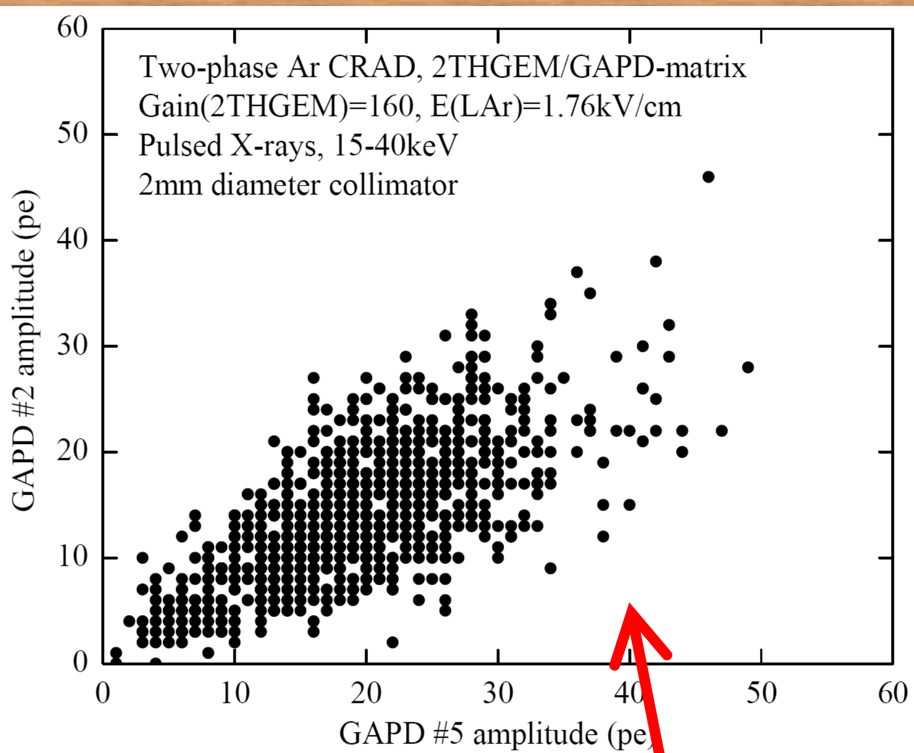


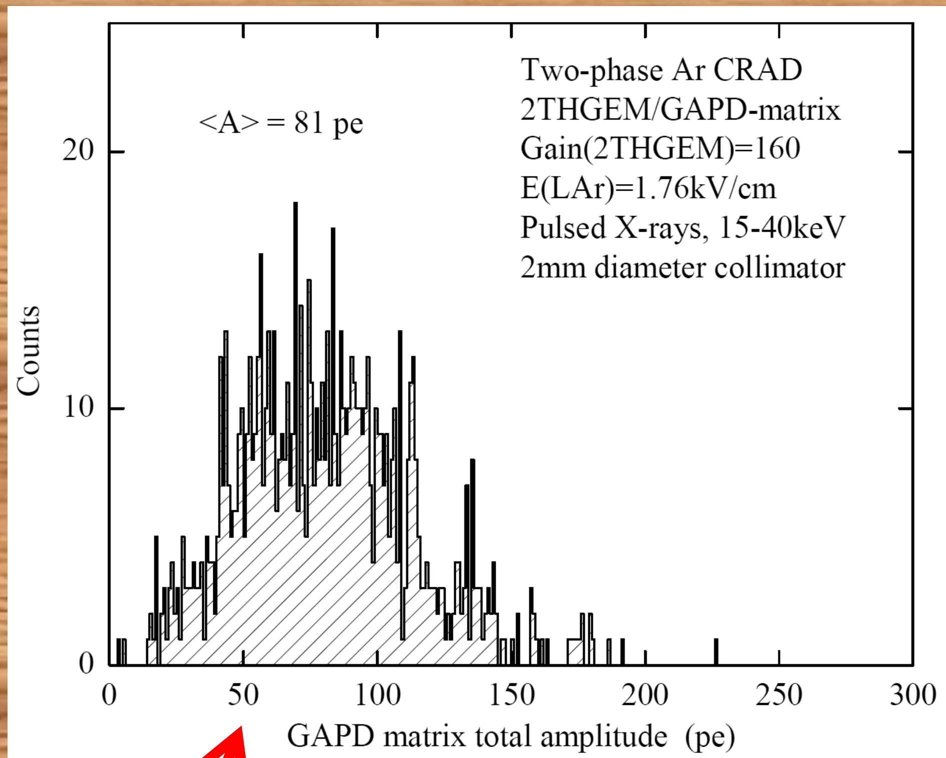




- Typical GAPD signal: ~20 pe per 20 keV X-ray
- Long (>16 μs) signal due to slow electron emission component presented in two-phase Ar systems → see signal time spectrum
- Measuring GAPD amplitude: counting the number of peaks using dedicated peak-finder algorithm
- Part of signal is lost under threshold due to GAPD rate-dependence problem → reduces the GAPD pe yield

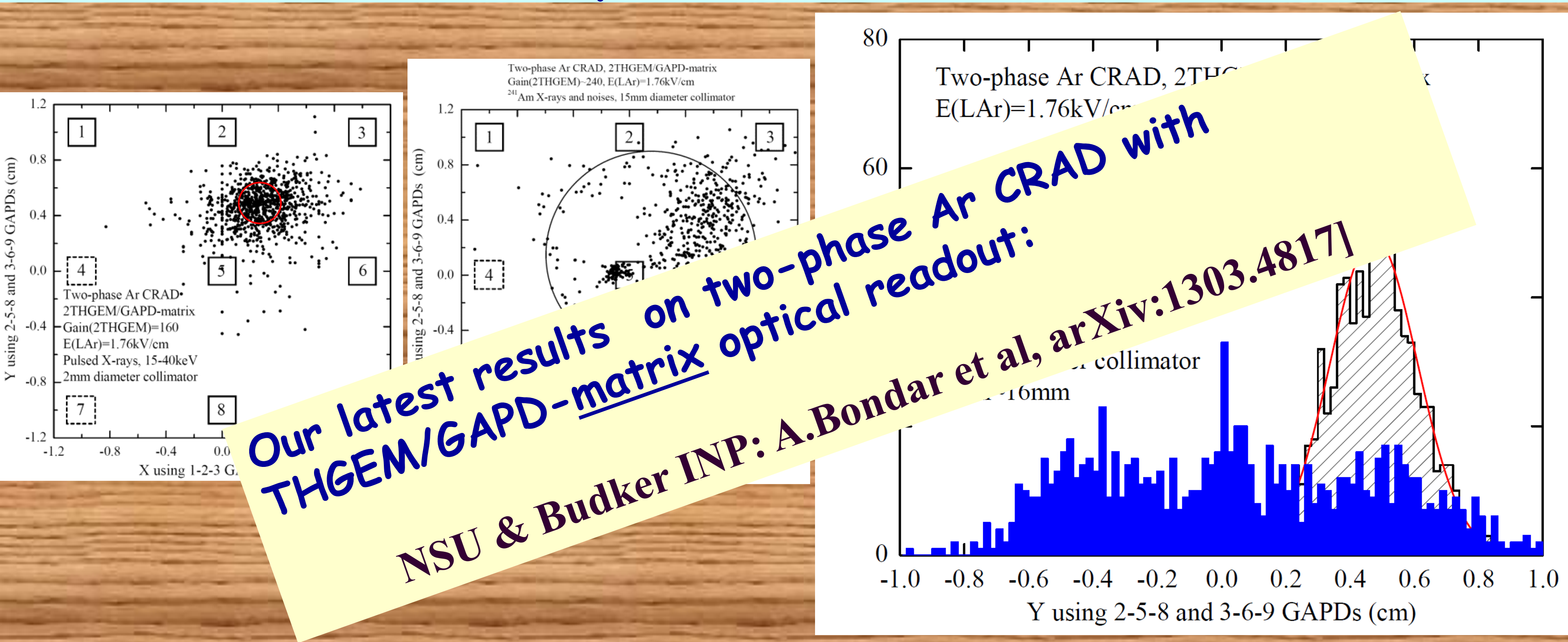
Two-phase Ar CRAD with THGEM/GAPD-matrix multiplier: GAPD-matrix yield





- Correlation between GAPD channel amplitudes
- Total GAPD-matrix (7 active channels) amplitude: 80 pe per 20 keV X-ray, at charge gain of 160
- That means that we may still have reasonable GAPD matrix yield for low energy deposition: >10 pe per 1 keV at charge gain of 600
- Higher yield is expected when the GAPD rate problem will be solved

Two-phase Ar CRAD with THGEM/GAPD-matrix multiplier: spatial resolution



Our latest results on two-phase Ar CRAD with THGEM/GAPD-matrix optical readout:

NSU & Budker INP: A.Bondar et al, arXiv:1303.4817]

- Reconstructed image of X-ray conversion region (defined by 2 and 15 mm collimators) from GAPD-matrix amplitudes
- Using center-of-gravity algorithm corrected for simulation of light rays gives FWHM=3 mm → spatial resolution of THGEM/GAPD-matrix is 1 mm (σ).
- Spatial resolution of THGEM/GAPD-matrix readout is far superior compared to that of PMT-matrix: of the order of 1 mm, for deposited energy of 20 keV at charge gain of 160.

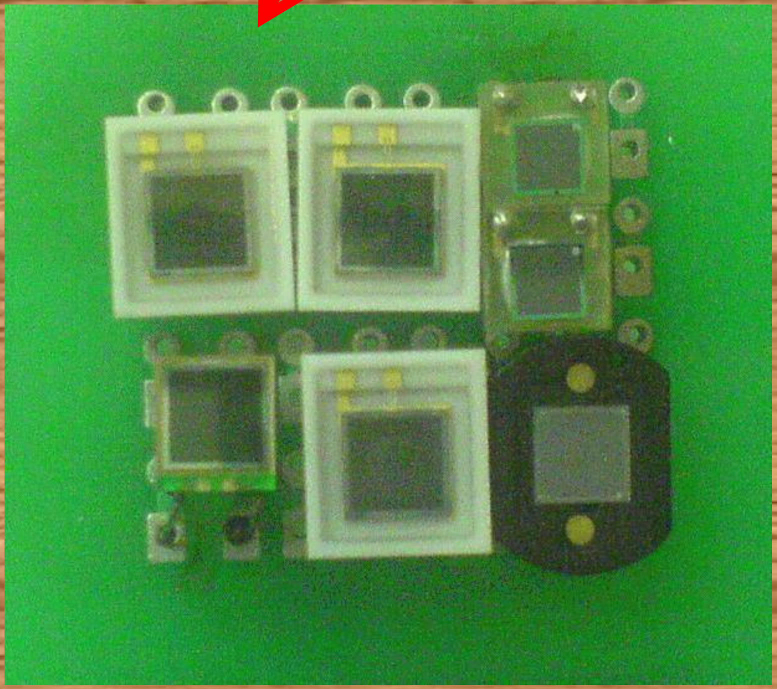
Two-phase Ar CRAD with THGEM/GAPD-matrix optical readout: preparing new setup → Selecting GAPD type

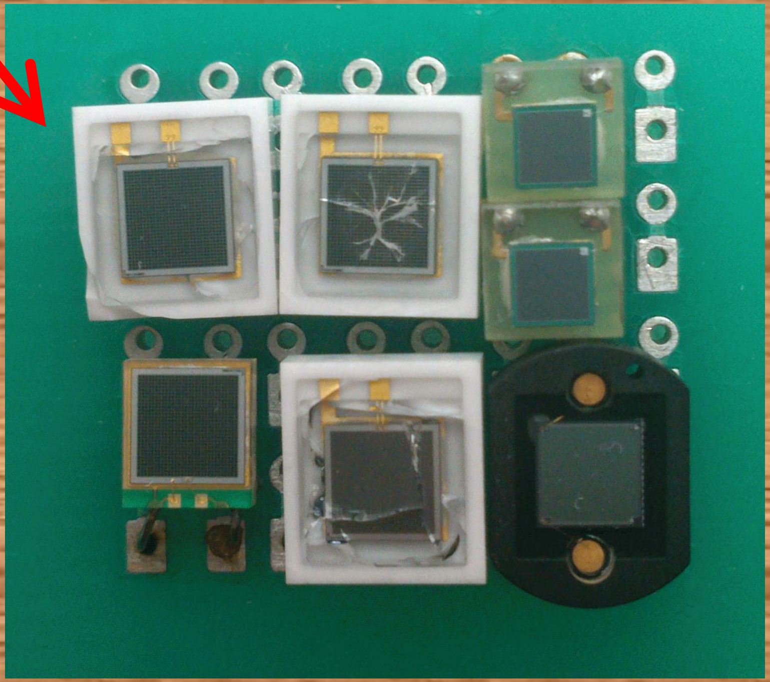
Hamamatsu MPPCs (3x3mm), CPTA MRS APDs (2.1x2.1 mm) and Sensl SiPM (3x3mm): before and after cryogenic runs

→ All those with ceramic package were cracked: should be avoided

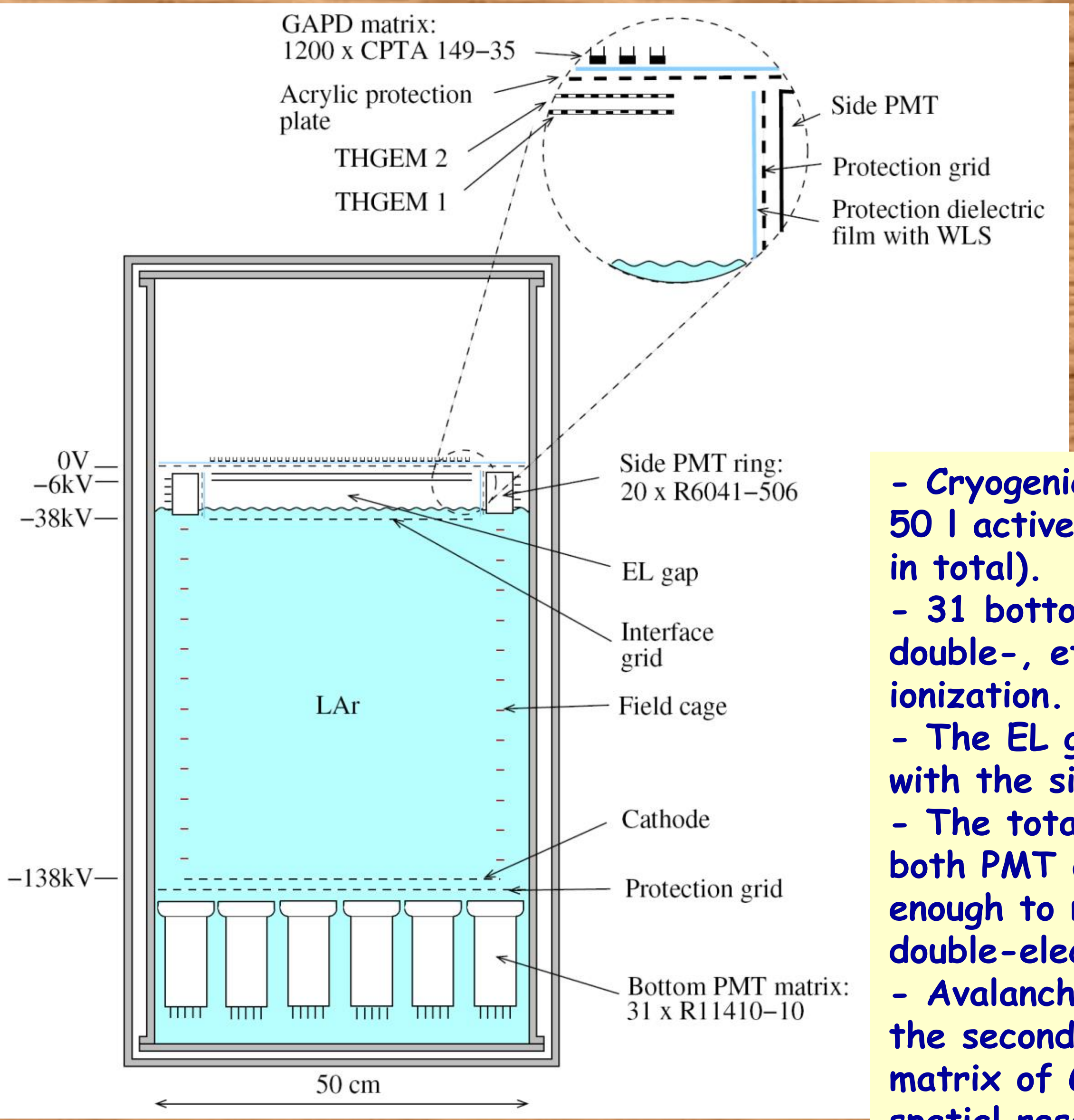
→ GAPDs with plastic package should be used in cryogenic environment

→ Our choice for the future is Hamamatsu S10931-100P (3x3 mm)





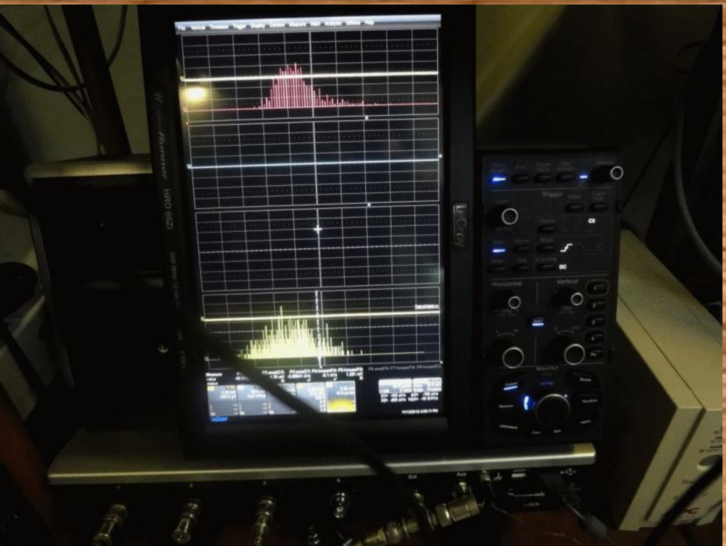
Two-phase CRAD in Ar with THGEM/GAPD-matrix optical readout: elaborated project with 160 l cryogenic chamber

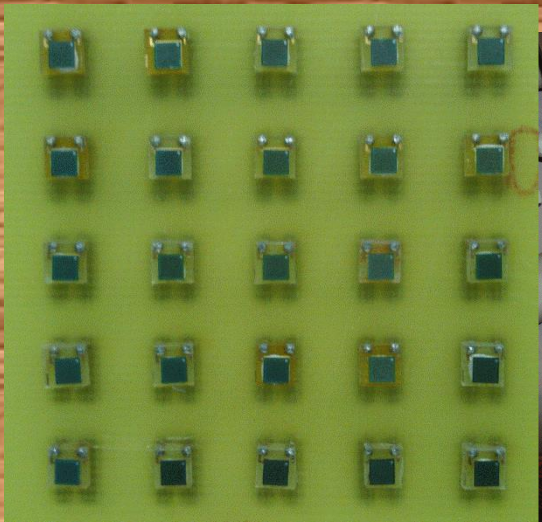


- Cryogenic chamber with 50 cm electron drift and 50 l active volume (70 kg of active LAr and 200 kg in total).
- 31 bottom and 20 side PMTs provide single-, double-, etc.- electron trigger for primary ionization.
- The EL gap, having a thickness of 4 cm, matches with the size of the side PMT.
- The total number of photoelectrons recorded by both PMT arrangements will be 23 pe. This is enough to make a selection between single- and double-electron events.
- Avalanche scintillations produced in the holes of the second THGEM are recorded in the NIR using a matrix of GAPDs: this will provide a high (sub-cm) spatial resolution.

[NSU & Budker INP: A. Bondar et al. JINST 7 (2012) P06014]

Two-phase CRAD in Ar with 160 l cryogenic chamber: some elements of PMT, cryogenic, vacuum, DAQ, GAPD and electronics systems



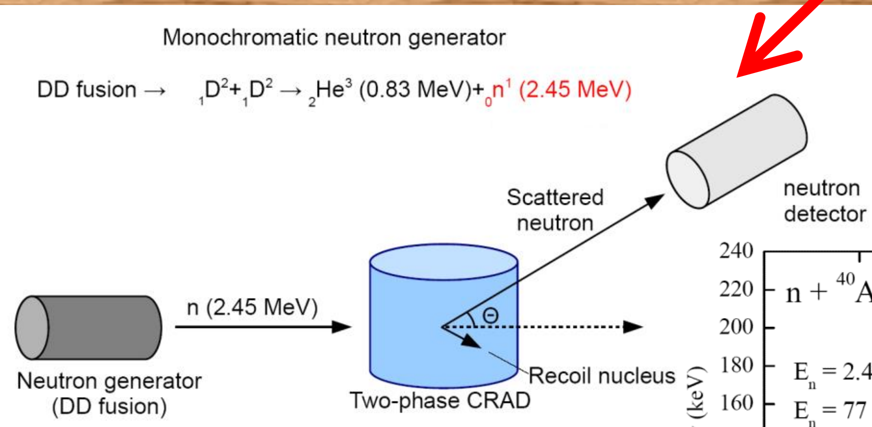


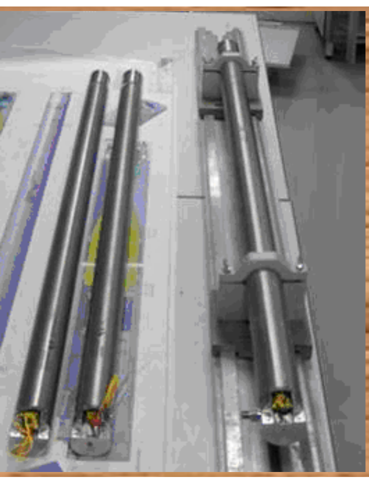
Neutron scattering systems

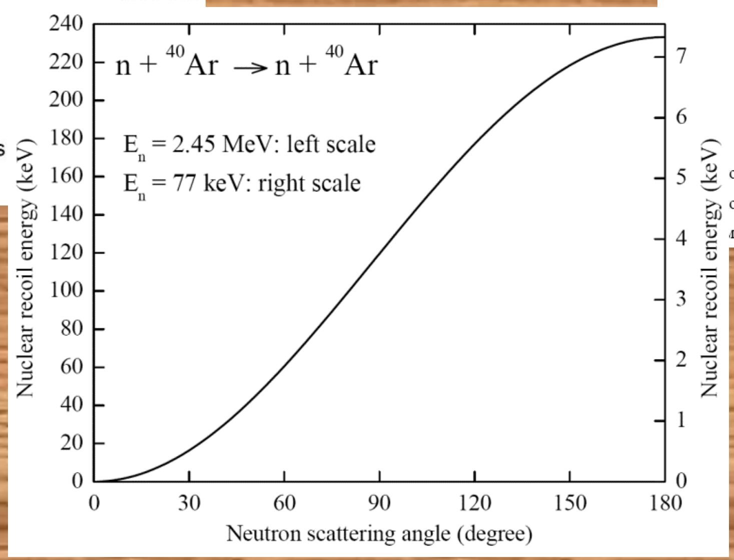
Two neutron scattering systems are being developed by Plasma Physics Division teams:

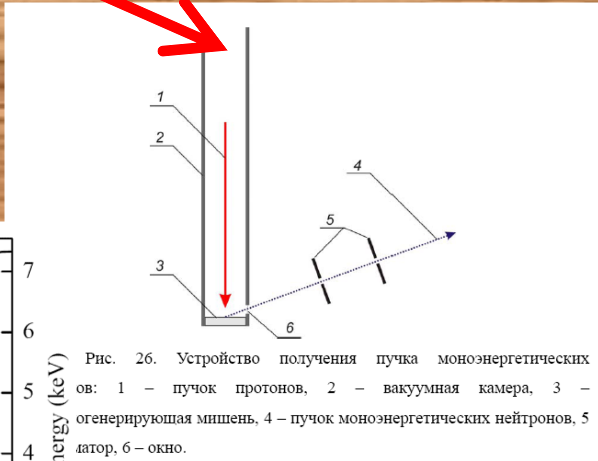
- DD generator (tube) of monochromatic 2.45 MeV neutrons + neutron counters *[A. Burdakov, S. Polosatkin, E. Grishnyaev]*

- $^{7}Li(p,n)^{7}Be$ monochromatic neutron beam (of 77 keV energy) using 2MeV proton accelerator and ^{7}Li target *[S. Taskaev et al.]*.









[A. Makarov, S. Taskaev, Pisma v JETF 97 (2013) 769]

[A. Bondar et al. , Proposal for neutron scattering systems for calibration of dark matter search and low-energy neutrino detectors, in preparation]

Summary

The idea of Cryogenic Avalanche Detectors (CRADs) had triggered intense and difficult R&D work in the course of last 10 years. This resulted in a variety of amazing CRAD concepts; for the time being the most intensively studied concepts are:

- **two-phase CRADs with THGEM multiplier readout;**
- **optical readout of CRADs with combined THGEM/GAPD-matrix multipliers.**

Thanks the Organizing Committee for inviting me to give this talk!

sensitivity (>100 pe per 20 keV at charge gain of ~100) and superior spatial resolution (~1 mm).

Such kinds of CRADs may come to be in great demand in rare-event experiments, such as those of Coherent Neutrino-Nucleus Scattering, Dark Matter Search and Giant LAr TPCs for (astrophysical) neutrino physics, as well as in medical imaging fields (e.g. PET).

Budker INP and NSU teams of CRAD laboratory

CRAD lab location: Budker INP. CRAD lab is operated in the frame of Budker INP and NSU research programs.

<u>Laboratory of Cosmology and Elementary Particles (NSU) and Cryogenic Avalanche Detectors "Laboratory" (Budker INP):</u>
A. Dolgov (head of the lab). Experimental group:
A. Bondar, R. Belousov, A. Buzulutskov (coordinator), A. Chegodaev, A. Grebenuk, S. Peleganchuk, L. Shekhtman, E. Shemyakina, R. Snopkov, A. Sokolov

We collaborate with two teams from Plasma Division of Budker INP on neutron scattering systems development: A. Burdakov, S. Polosatkin and E. Grishnyaev and S. Taskaev et al.

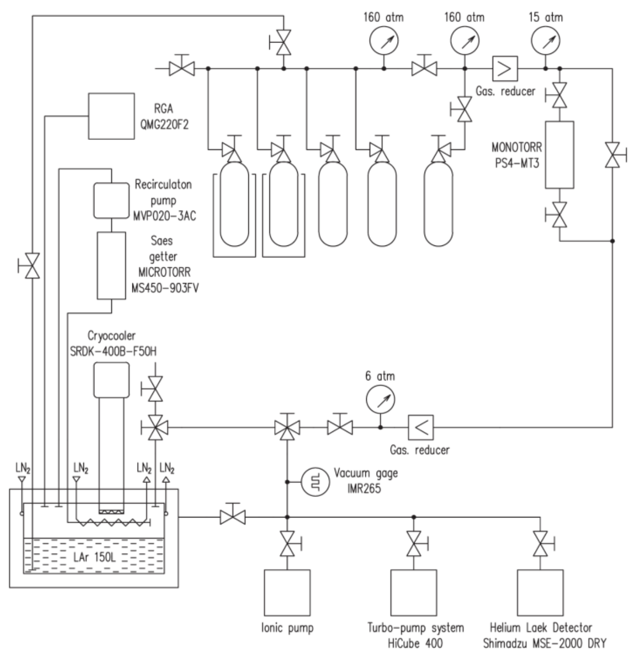
We also collaborate on CRAD R&D with A. Breskin (Weizmann Inst.) and D. Thers (Nantes Univ.), in the frame of RD51 collaboration.

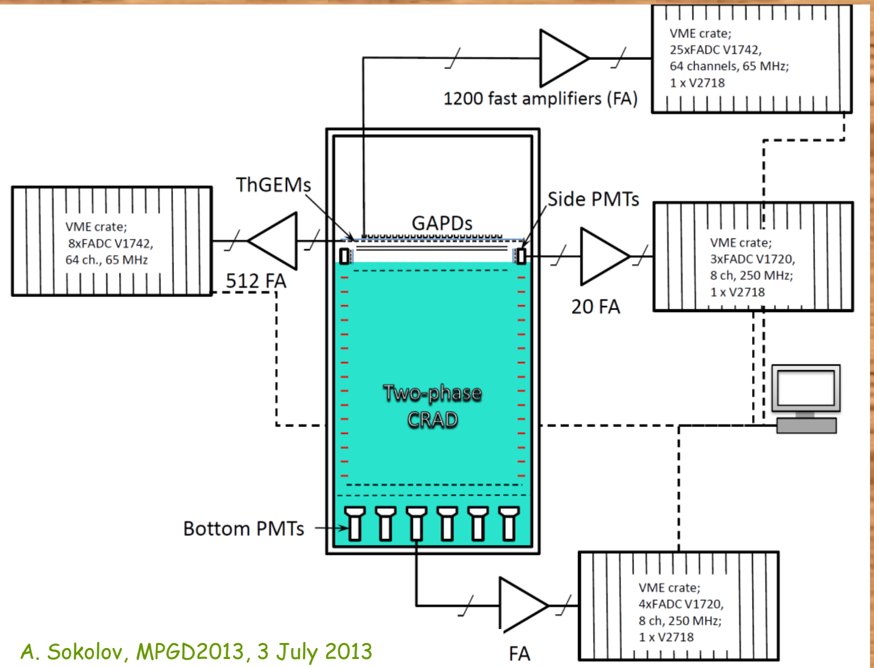
This work supported in parts by Ministery of Science an Education of RF (grant 11.G34.31.0047) and Russian Foundation for Basic Research (12-02-91509-CERN_a and 12-02-12133-ofi_m)

Backup slides

Two-phase CRAD in Ar with 160 l cryogenic chamber: systems

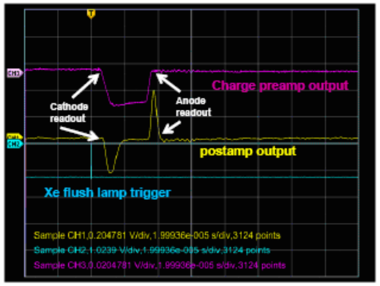
- Cryogenic and vacuum systems (including LAr high purity providing and monitoring)
- PMT arrays systems: bottom matrix and side ring
- THGEM and GAPD-matrix systems
- High and low voltage supply systems
- WLS (TPB) coating system (including evaporation facility to coat films and light guides)
- DAQ, trigger and slow control systems
- Neutron scattering system

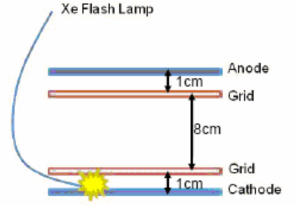




Hardware component (3); Purity Monitor

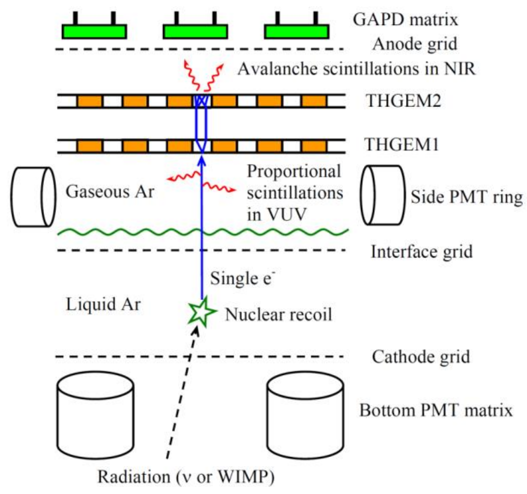
- We made ICARUS type purity monitor. (bottom)
  - Use Xe flush lamp, optical fibers and photo-cathode, and measure the attenuation of the electrons.
  - Useful for the cross check of the purity meas. from cosmic rays. (but rather difficult to meas. abs)
  - We didn't use it during test-beam.





CRAD laboratory: main entrance, future clean room and 160 l cryogenic chamber prototype

Afterwards: the benefits of research in the field of radiation detection physics



The technique of two-phase CRADs with optical readout is based on new physical effects in the field of radiation detection physics, observed and studied in detail by Novosibirsk group:

1. High gain operation of GEMs in pure noble gases ("avalanche confinement in GEM holes")
2. Successful operation of GEM and THGEM multipliers at cryogenic temperatures, including in saturated vapour in the two-phase mode ("electron avalanching at low temperatures").
3. Effective (100%) electron emission from the liquid to gas phase in two-phase Ar at low (~1 kV/cm) fields.
4. High light yield of primary and secondary scintillations in Ar in the NIR ("NIR scintillations in noble gases")
5. Superior GAPD performance at cryogenic temperatures, in particular in LAr.

DM search results: possible light WIMP signal

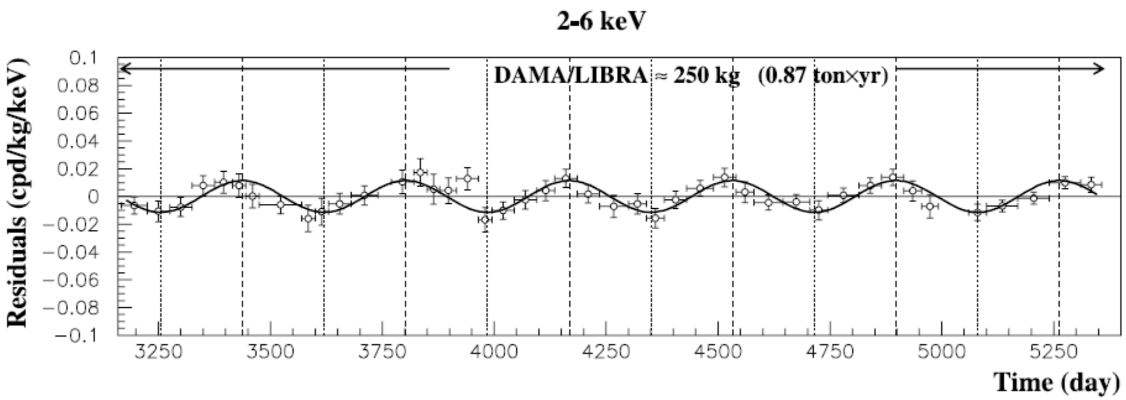


Fig. 1 Experimental model-independent residual rate of the *single-hit* scintillation events, measured by DAMA/LIBRA,1,2,3,4,5,6 in the (2–4), (2–5) and (2–6) keV energy intervals as a function of the time. The zero of the time scale is January 1st of the first year of data taking of the former DAMA/NaI experiment [31]. The experimental points present the errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functions behaviors $A\cos\omega(t-t_0)$ with a period $T = \frac{2\pi}{\omega} = 1$ yr, with a phase $t_0 =$ … to th… ing … expe… and … max… verti…

- **DAMA/LIBRA** *[R. Bernabei et al. Eur. Phys. J. C 67 (2010) 39]*
- $E_{threshold}$=2 keVee

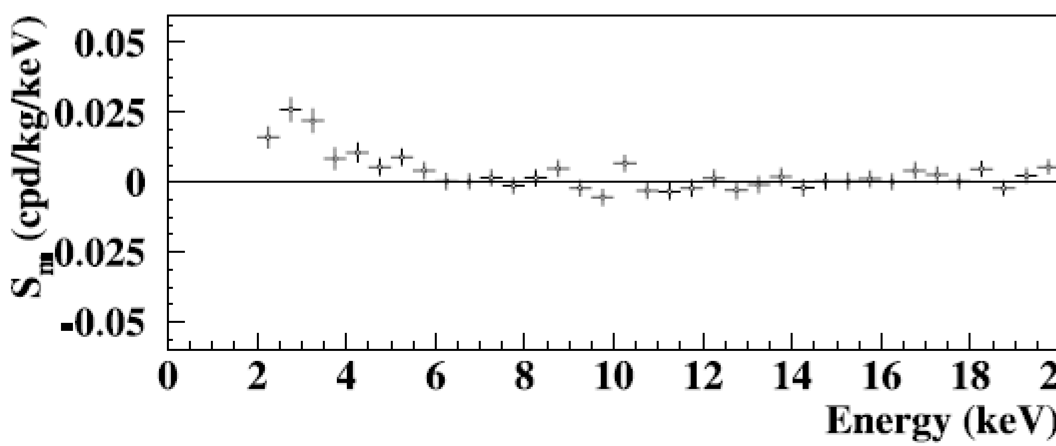


Fig. 6 Energy distribution of the S_m variable for the total cumulative exposure 1.17 ton×yr. The energy bin is 0.5 keV. A clear modulation is present in the lowest energy region, while S_m values compatible with zero are present just above. In fact, the S_m values in the (6–20) keV energy interval have random fluctuations around zero with χ^2 equal to 27.5 for 28 degrees of freedom

DM search results: possible light WIMP signal

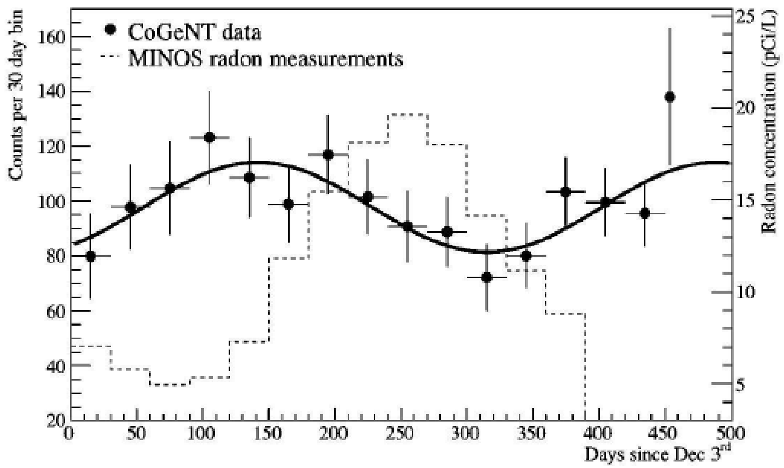


FIG. 29. Counts per 30 day bins from the 0.5-3.0 keVee CoGeNT energy window (black dots) compared to the MINOS radon data at SUL (dashed), averaged over the period 2007-2011, exhibiting a peak on August 28th [44, 45]. The solid curve represents a sinusoidal fit to CoGeNT data. An analysis by the MINOS collaboration finds a three-sigma inconsistency between the phase of their measured seasonal modulation in radon concentration at SUL and CoGeNT data [26].

- ***CoGeNT [C.E. Aalseth et al. arXiv:1208.5737]***
- $E_{threshold}$=0.5 keVee

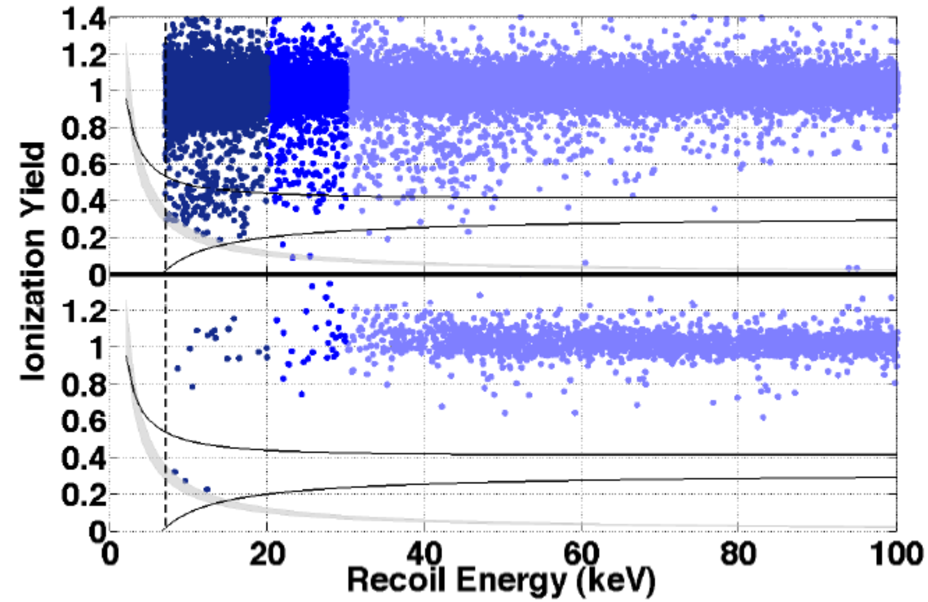


FIG. 2. Ionization yield versus recoil energy in all detectors included in this analysis for events passing all signal criteria except (*top*) and including (*bottom*) the phonon timing criterion. The curved black lines indicate the signal region (-1.8σ and +1.2σ from the mean nuclear recoil yield) between 7 and 100 keV recoil energies, while the gray band shows the range of charge thresholds. Electron recoils in the detector bulk have yield near unity. The data are colored to indicate recoil energy ranges (dark to light) of 7–20, 20–30, and 30–100 keV to aid the interpretation of Fig. 3.

- ***CDMS [R. Agnese et al. arXiv:1304.4279]***
- $E_{threshold}$=7 keVnr

DM search results: light WIMP observation problem

On the other hand, Xenon10, Xenon100, Zeplin3 and Edelweiss experiments don't observe light WIMP signal, having similar nuclear-recoil energy threshold, of about 7 keVnr.

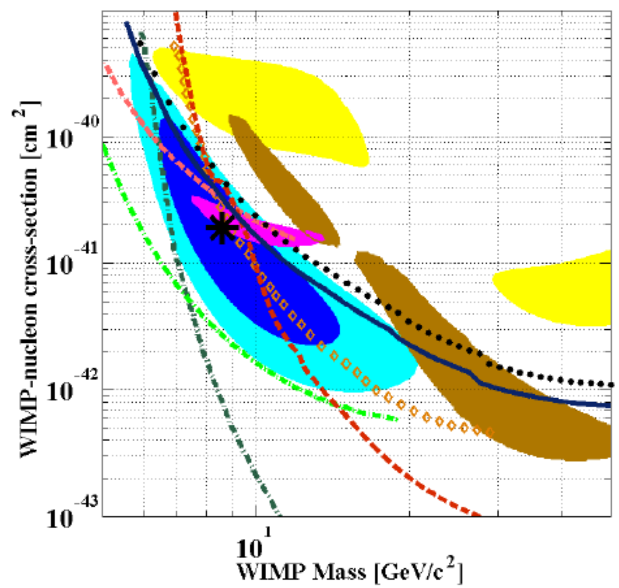


FIG. 4. Experimental upper limits (90% confidence level) for the WIMP-nucleon spin-independent cross section as a function of WIMP mass. We show the limit obtained from the exposure analyzed in this work alone (*black dots*), and combined with the CDMS II Si data set reported in [22] (*blue solid line*). Also shown are limits from the CDMS II Ge standard [11] and low-threshold [27] analysis (*dark and light dashed red*), EDELWEISS low-threshold [28] (*orange diamonds*), XENON10 S2-only [29] (*light dash-dotted green*), and XENON100 [30] (*dark dash-dotted green*). The filled regions identify possible signal regions associated with data from CoGeNT [31] (*magenta*, 90% C.L., as interpreted by Kelso *et al.* including the effect of a residual surface event contamination described in [32]), DAMA/LIBRA [16, 33] (*yellow*, 99.7% C.L.), and CRESST [18] (*brown*, 95.45% C.L.) experiments. 68% and 90% C.L. contours for a possible signal from these data are shown in blue and cyan, respectively. The asterisk shows the maximum likelihood point at (8.6 GeV/c^2, 1.9×10^{-41} cm^2).

Figure taken from CDMS paper *[R. Agnese et al. arXiv:1304.4279]*

Low-energy nuclear-recoil calibration problem

- Both ionization and scintillation yields for low-energy nuclear-recoils (<10 keVnr) should be measured to solve DM search puzzle.
- In addition, very low energy nuclear recoils (< 1keVnr) should be studied for Coherent Neutrino-Nuclei Scattering experiments.

Terminology for nuclear recoils:
- Ionization (scintillation) yield = number of ionization electrons (scintillation photons) per keV
- Quenching factor L_{eff} = nuclear recoil yield (scintillation, ionization or total) relative to that of electron recoil

E_e [keVee] = $L_{eff} \times E_r$ [keVnr]

Nuclear recoil data in LAr

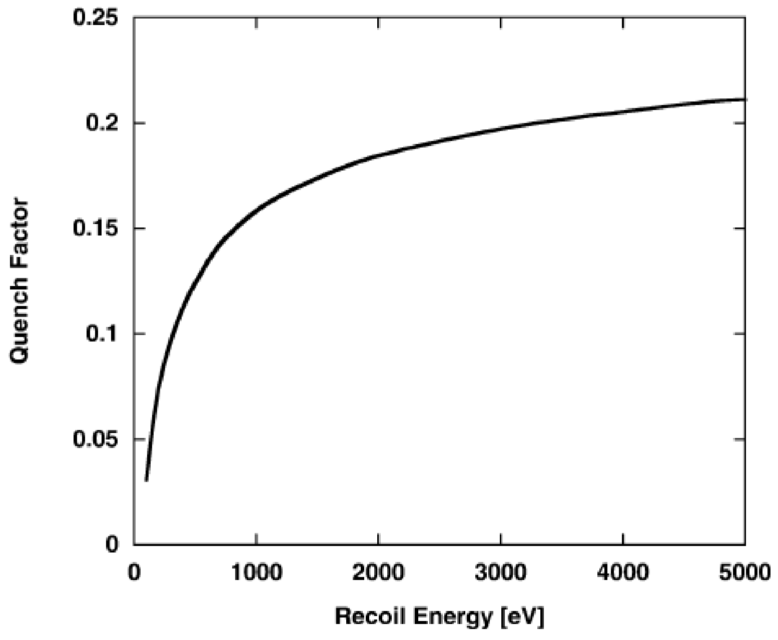
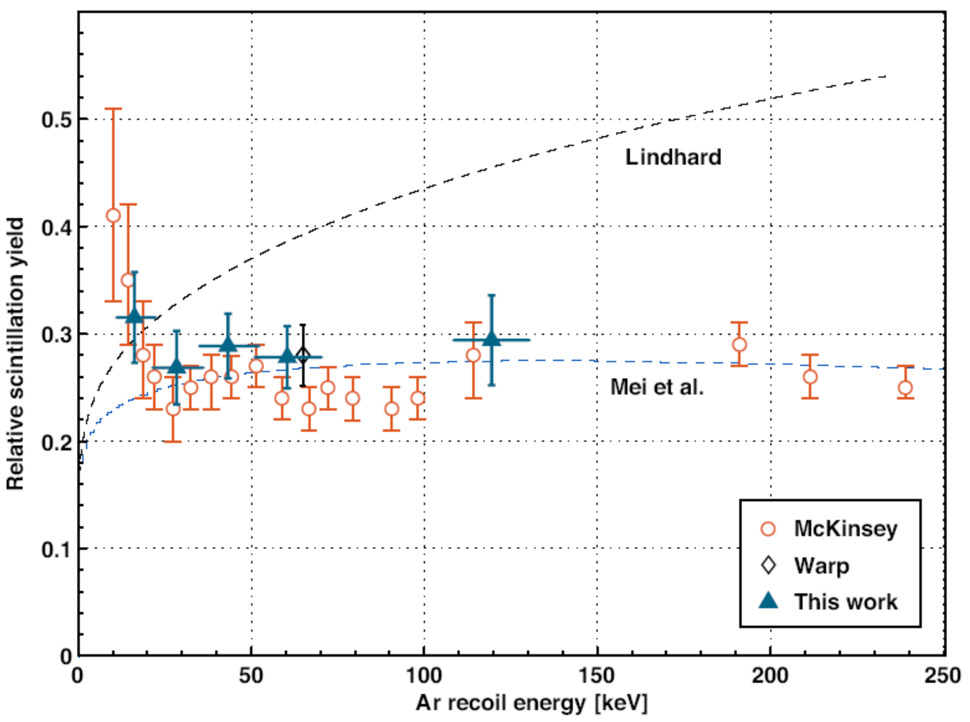


Fig. 3. Calculated quench factor of liquid argon, defined as the ratio of the nuclear to electron recoil induced inelastic (ionization or excitation) yield.



Total quenching factor for both ionization and excitation: LAr, theory *[C. Hagmann, A. Bernstein IEEE Trans. Nucl. Sci. 51 (2004) 2151]*

Scintillation quenching factor: LAr, experiment *[Gastler et al. Phys. Rev. C 85, 065811 (2012); C. Regenfus et al. J. Phys. Conf. Series 375 (2012) 012019]*

Nuclear recoil data in LNe and LHe

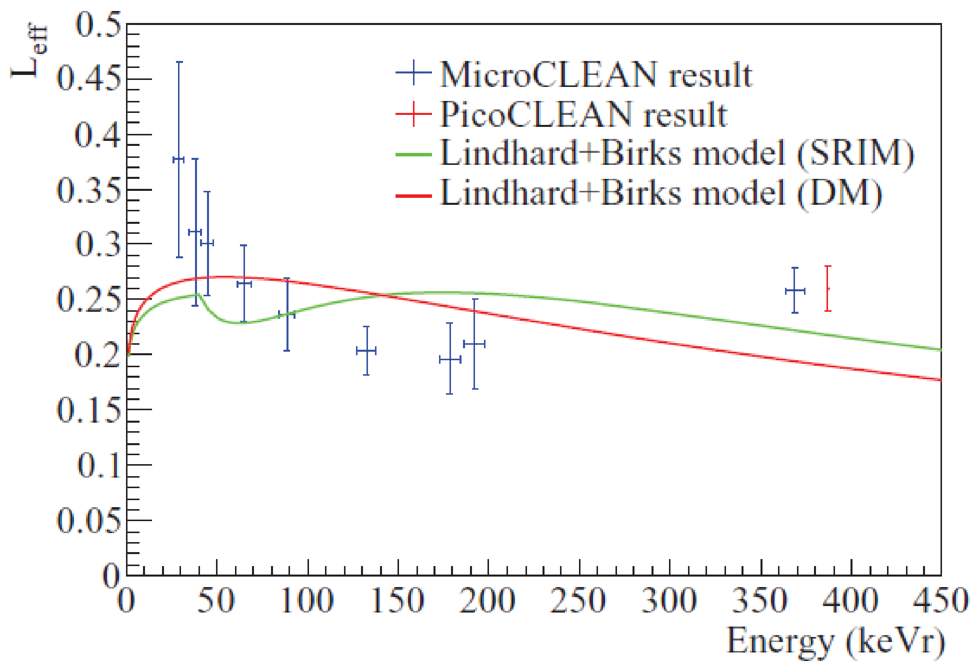


FIG. 13. (Color online) The observed nuclear recoil scintillation efficiency vs nuclear recoil energy in neon, along with the Lindhard + Birks model described in the text.

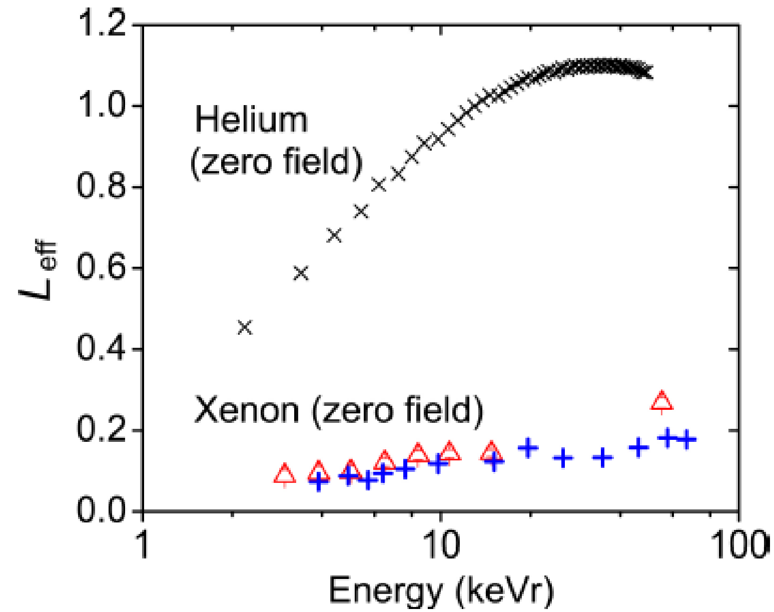


FIG. 11: (color online) The effective quenching factor L_{eff} as a function of the recoil event energy. The × represents the calculated L_{eff} for helium under zero applied electric field. The measured data for liquid Xenon by G. Plante *et al.* [88] (△) and by A. Manzur *et al.* [89] (+) are also shown.

Scintillation quenching factor: LNe, experiment *[Lippincott et al. Phys. Rev. C 86, 015807 (2012)]*

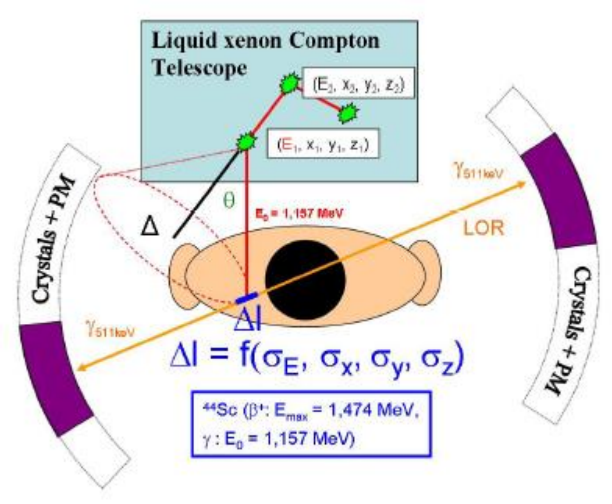
Scintillation quenching factor: LHe, theory *[W. Guo, D.N. McKinsey arXiv:1302.0534]*

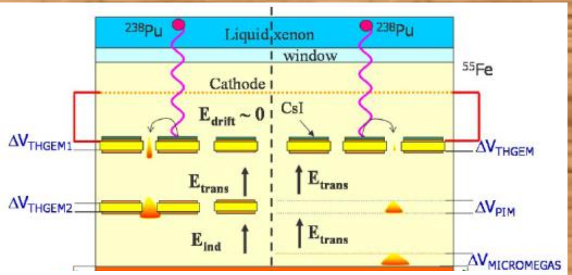
CRAD-related projects

Medical applications

Concept: 3γ-PET with LXe TPC

Principle (not proven):
- PET + LXe Compton telescope
[Nantes Univ: C.Grignon et al, NIMA 571 (2007) 142; S.Duval et al, JINST 4 (2009) P12008]

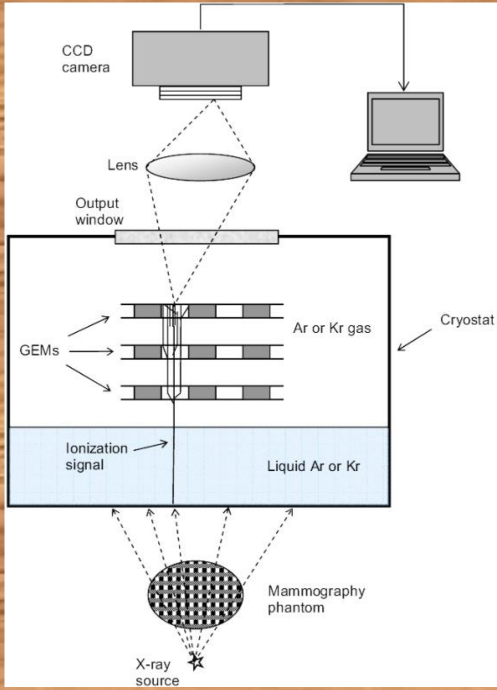




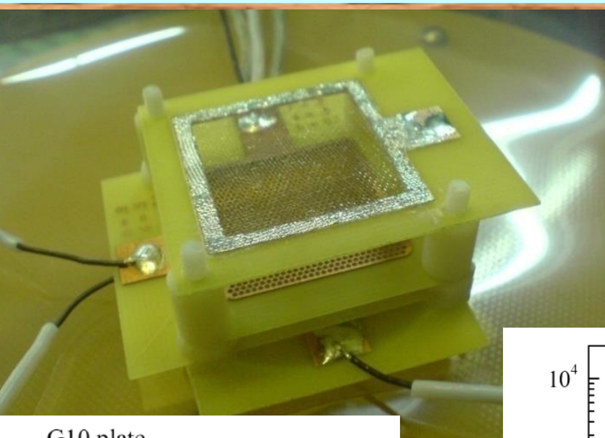
S. Duval et al, JINST 6 (2011) P04007

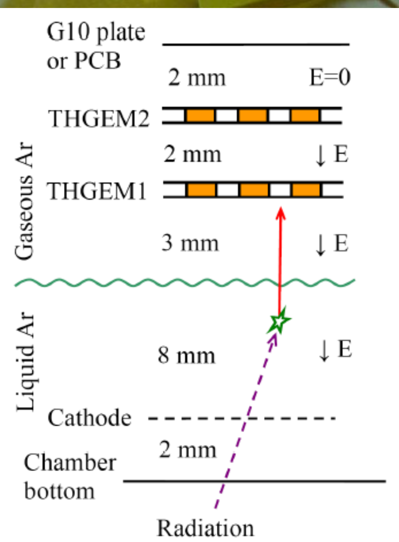
Concept: Two-phase Ar or Kr CRAD with combined GEM/CCD readout for digital radiography

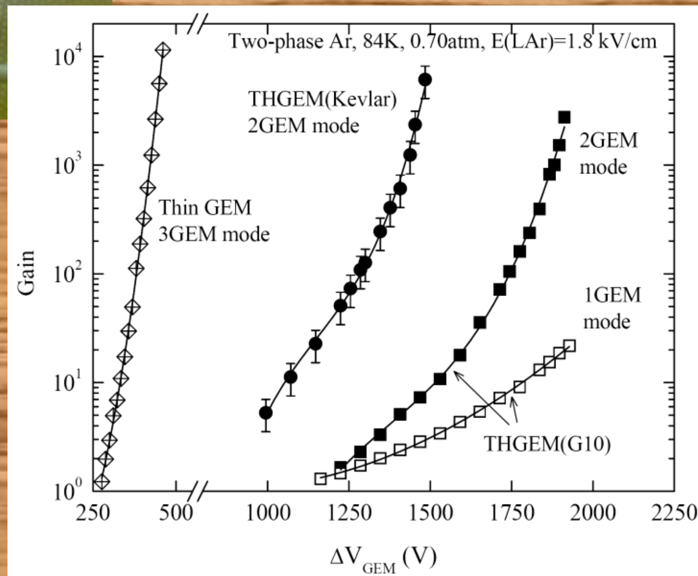
Not proven
[Budker INP: A.Buzulutskov, JINST 7 (2012) C02025]

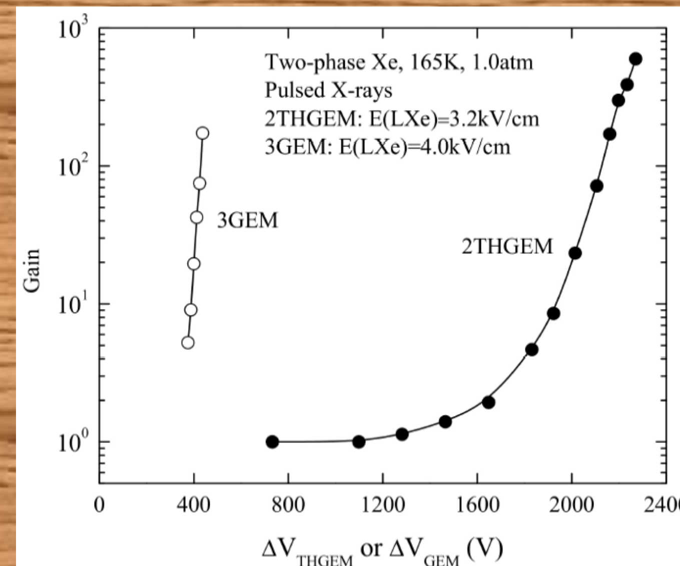


Two-phase CRADs in Ar and Xe with <u>THGEM</u> multiplier (2.5×2.5 cm² active area)









Stable operation of double-THGEM in two-phase Ar and Xe at gains reaching 3000 and 600 respectively, for small 2.5x2.5cm2 active area.

[Budker INP, Weizmann Inst: A.Bondar et al JINST 3 (2008) P07001 and 6 (2011) P07008]

Two-phase CRADs with GEM and THGEM multiplier charge readout: summary of maximum gains in Ar, Kr and Xe

Table 1. Summary of maximum charge gains reached with MPGD multipliers operated in two-phase Ar, Kr and Xe CRADs, obtained by different groups. The charge gain is defined as that of the Budker INP and Weizmann Institute groups.

Group	Two-phase medium	Multiplier type and operation mode	Active area, cm	Typical maximum gain	Reference
Budker INP	Ar	3GEM	2.8×2.8	$(5-10)\times10^3$	A. Bondar et al., *Nucl. Instrum. Meth.* **A 556** (2006) 273, *ibid* **A 598** (2009) 121
Budker INP, Weizmann Inst.	Ar	2THGEM	2.5×2.5	3000	Bondar et al., 2008 *JINST* **3** P07001
Budker INP, Weizmann Inst.	Ar	1THGEM	2.5×2.5	> 200	Bondar et al., 2008 *JINST* **3** P07001
Sheffield Univ.	Ar	1THGEM	4×4	300	Lightfoot et al., 2009 *JINST* **4** P04002
ETH Zurich	Ar	1THGEM +PCB	10×10	80	A. Badertscher et al., *Nucl. Instrum. Meth.* **A 641** (2011) 48
Budker INP	Ar	2THGEM	10×10	1000	A. Bondar et al., in preparation
IRFU CEA-Saclay, ETH Zurich	Ar	1MM	10×10	5	M. Zito et al., presented at GLA2011 (2011)
Budker INP	Kr	3GEM	2.8×2.8	600	A. Bondar et al., *Nucl. Instrum. Meth.* **A 556** (2006) 273
Budker INP	Xe	3GEM	2.8×2.8	200	A. Bondar et al., *Nucl. Instrum. Meth.* **A 556** (2006) 273
LIP-Coimbra	Xe	1GEM	2.8×2.8	150	Balau et al., *Nucl. Instrum. Meth.* **A 598** (2009) 126
Budker INP, ITEP, Weizmann Inst.	Xe	2THGEM	2.5×2.5	600	Bondar et al., 2011 *JINST* **6** P07008

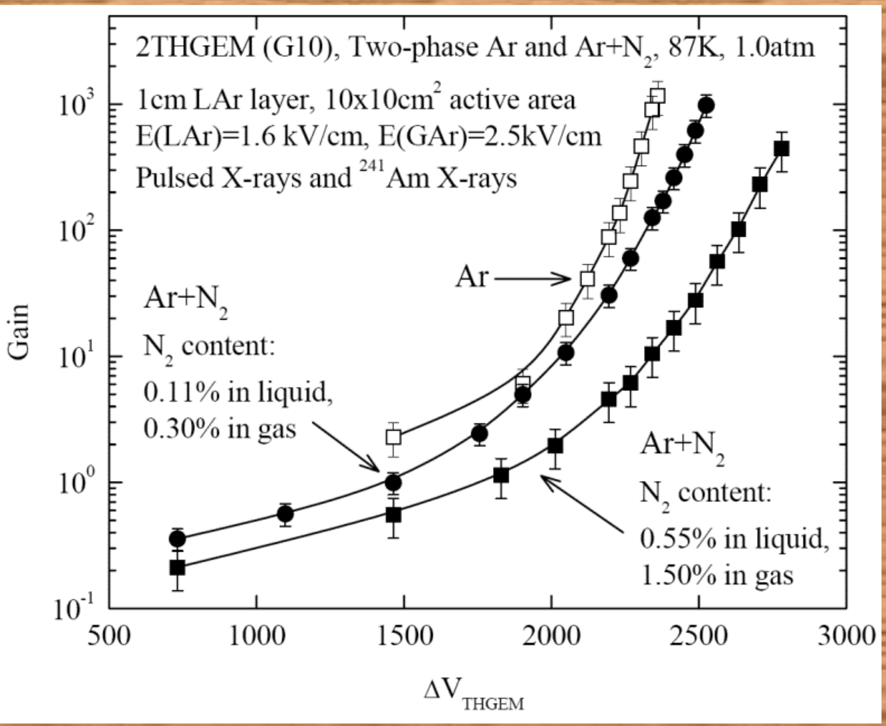
Two-phase medium	Multiplier type	Active area	Typical maximum gain	Reference
Ar	3GEM	2.8×2.8 cm^2	$(5\text{-}10)\times10^3$	[5],[6]
Ar	2THGEM	2.5×2.5 cm^2	3000	[7]
Ar	1THGEM	2.5×2.5 cm^2	>200	[7]
Ar	1THGEM	4.5 cm in diameter	300	[15]
Ar	1THGEM/PCB	10×10 cm^2	80	[8]
Ar	2THGEM	10×10 cm^2	1200	This work
Ar	1THGEM	10×10 cm^2	300	This work
Ar	2THGEM/GEM/PCB	10×10 cm^2	4500	This work
Ar+N_2(0.1%)	2THGEM	10×10 cm^2	1000	This work
Ar+N_2(0.1%)	2THGEM/GEM/PCB	10×10 cm^2	900	This work
Ar	2GEM(polyimide)	5 cm in diameter	30	This work

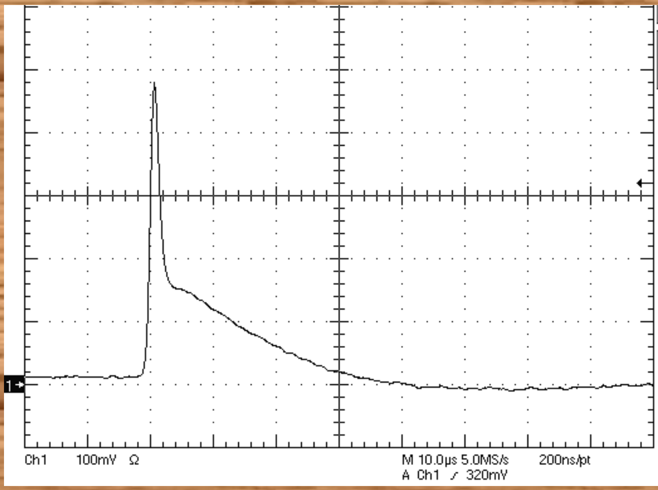
Table 2. Summary of maximum charge gains reached in two-phase Ar and Ar+N_2 CRADs. All THGEMs presented in the table were made of G10, except of that of the last row which was made of polyimide.

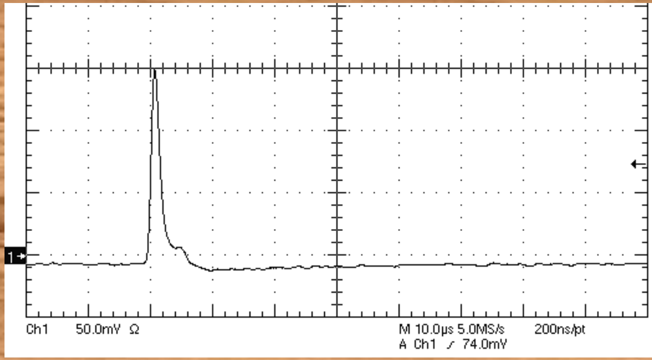
Summary of maximum charge gains attained with GEM and THGEM multipliers operated in two-phase Ar, Kr and Xe, obtained by different groups. The gain is defined as that of Budker INP.

tskov, JINST 7 (2012) C02025 ; A.Bondar et al, JINST 8 (2013) P02008]

Two-phase CRAD in Ar+N_2 with THGEM multiplier (10×10 cm^2 active area)







Two-phase CRADs operated in Ar doped with N2 (0.1-0.6%) yielded faster signals. However, such conditions resulted in a reduced ionization yield from higher ionization-density tracks and did not offer higher maximum gains compared to that of pure Ar. These would make difficult the application of two-phase Ar+N2 CRADs in rare-event experiments.