Review on LAr Detectors

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@Tohoku Univ., Sendai

International symposium on revealing the history of the universe with underground particle and nuclear research 2019

Outline

- **Introduction (LArTPC)**
- **Recent Results on WIMP Search**
  - DarkSide-50 (incl. S2-only Analysis)
  - DEAP3600
- **R&D efforts by ANKOK in Japan**
  - Maximizing Light Yield
  - R&D on VUV(128nm)-sensitive SiPM
  - S1/S2 electric-field dependency (up to 3kV/cm)
- **Scaling up toward the *v* floor (DarkSide-20K & Beyond)**
- **Summary & Outlook**

A Brief History on "LAr-TPC"

- First proposed by Prof. Carlo Rubbia in 1977 (CERN EP INT-77-8)

Concept: "*Electronic Bubble Chamber*"

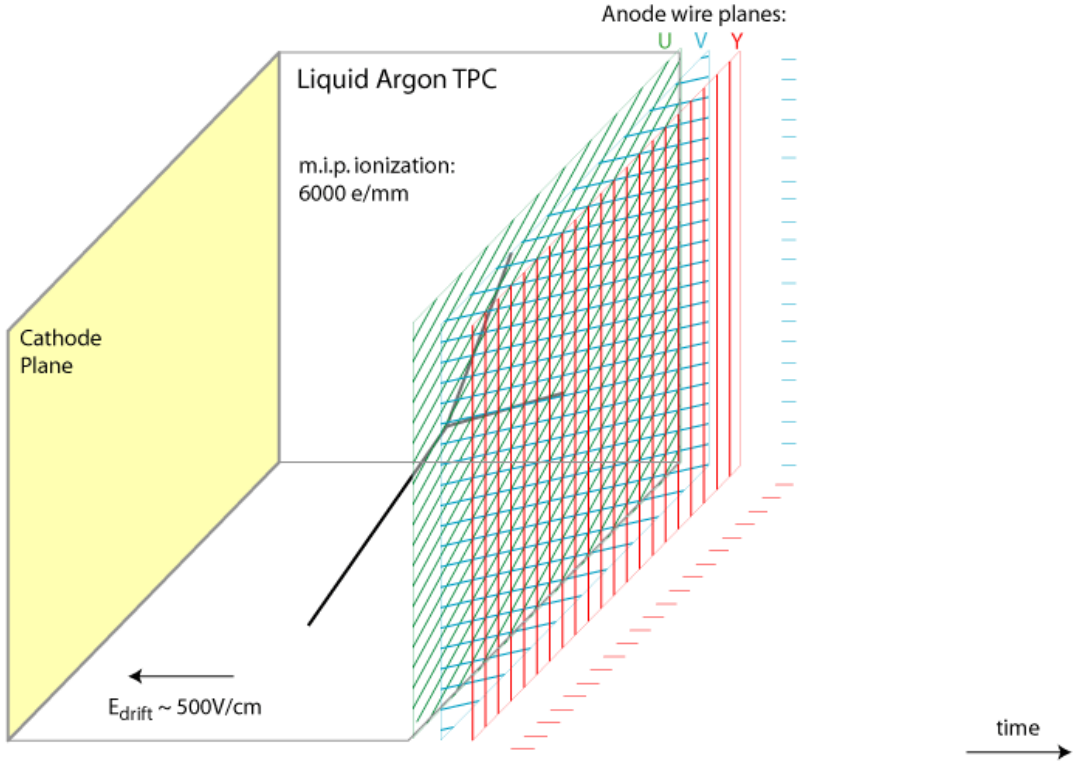
THE LIQUID-ARGON TIME PROJECTION CHAMBER:

A NEW CONCEPT FOR NEUTRINO DETECTORS

C. Rubbia

ABSTRACT

It appears possible to realize a Liquid-Argon Time Projection Chamber (LAPC) which gives an ultimate volume sensitivity of 1 mm^3 and a drift length as long as 30 cm. Purity of the argon is the main technological problem. Preliminary investigations seem to indicate that this would be feasible with simple techniques. In this case a multi-hundred-ton neutrino detector with good vertex detection capabilities could be realized.



https://www.phy.bnl.gov/wire-cell/

- Many technical developments done by ICARUS(LNGS) (now to DUNE(US) for the next generation *ν* experiment)

WArP in 2000's

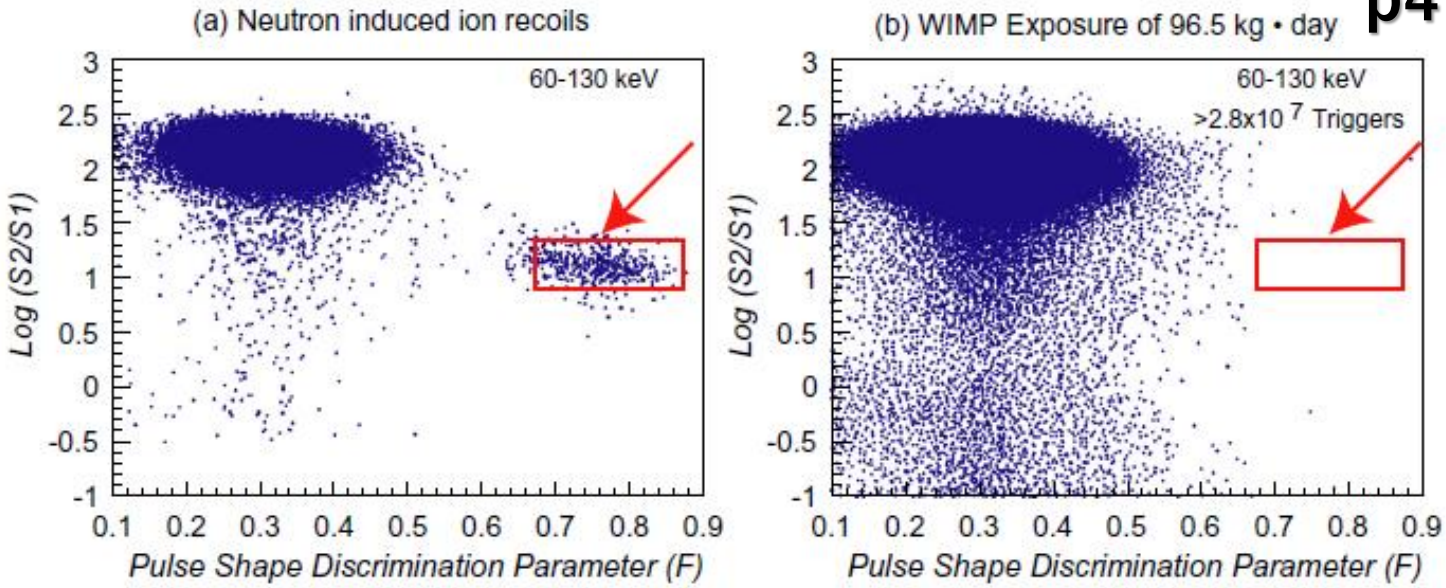
- **Exp. Parameters:**
  - 2.3L-TPC (1kV/cm E-drift) with one-side PMTs (on top in gas)
  - Exposure: 96.5kgd
    1.83kg(fid.) x 52.8days
  - LY = 1.26 PE/keVnr
  - E-thre. > 55 keVnr (0 event obs.)

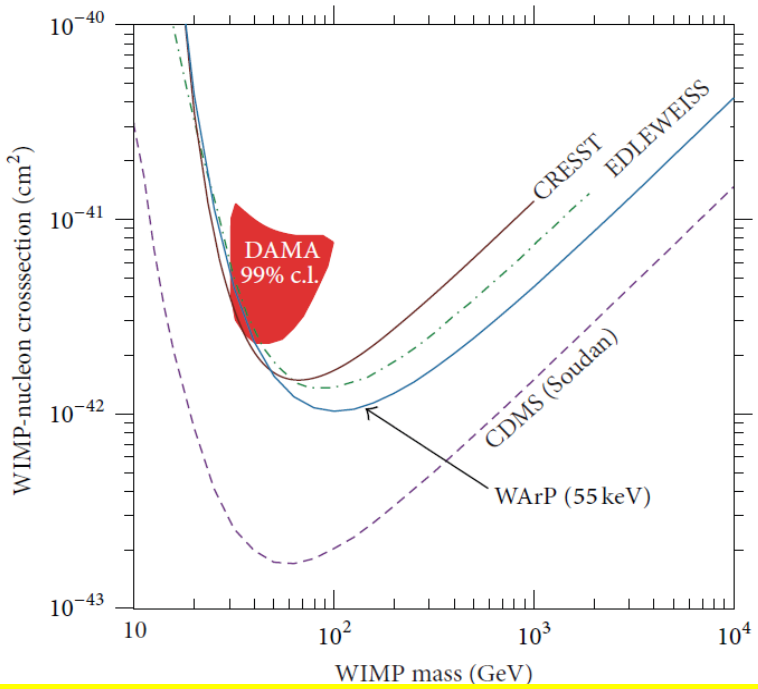
★ **First result for Ar-WIMP interaction**

■ **Not only the WIMP Search,**

- Effects of Oxygen contamination in LAr
- Effects of Nitrogen contamination in LAr
- Specific activity of ^{39}Ar in natural Ar
- Discovery of "Underground Argon"

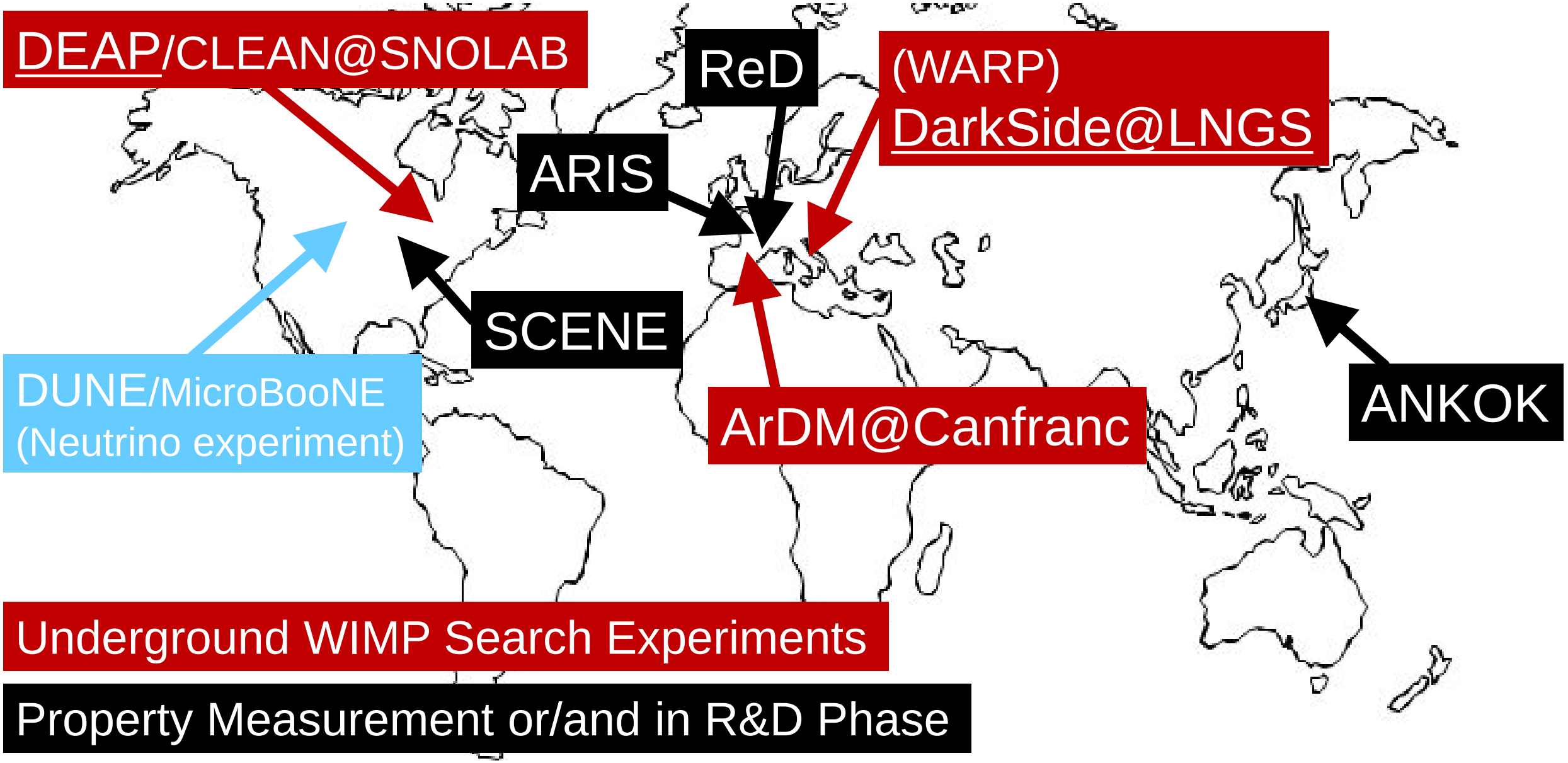
☞ "Pioneer of double phase Ar detector"





Astro.Phys.28(2008) 495-507

Now.... LAr Detectors in the World



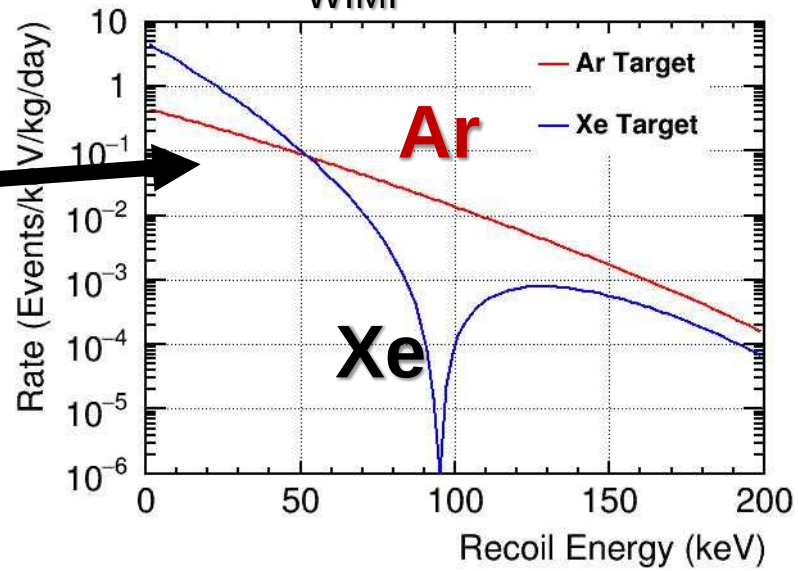
Argon Property

- A-dependent search strategy is essentially important for galactic WIMP, where Argon plays crucial role together with Xenon.

	LHe	LNe	LAr	LXe
A (Mass Number)	4	20	40	131
Boiling point (K)	4.2	27	87	165
Density (g/cm^3)	0.13	1.2	1.4	3.0
Radiation length (cm)	755	24	13	2.8
Scintillation (γ/keV)	20	15	40	42
Scintillation λ (nm)	80	77	128	175
Fast time constant	10ns	18ns	**6ns**	4ns
Slow time constant	13s	15μs	**1.5μs**	22ns
% in atmosphere	5x10^{-4}	2x10^{-3}	0.93	9x10^{-6}

Ref) A.Hitachi, PRB27, 9 (1983) etc

M_{WIMP}=100GeV



☹ **^{39}Ar Isotope:**

- β-emitter @1Bq/kg in AAr
- half-life of 269 years
- Q value of 565 keV

→ Strong PSD Rejection

→ Depletion/Distillation

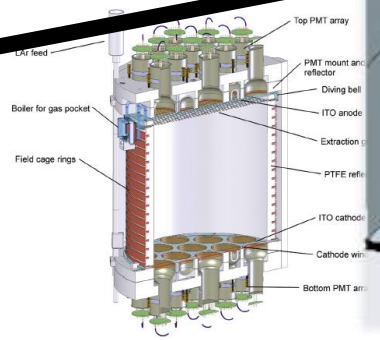
DarkSide-50@LNGS

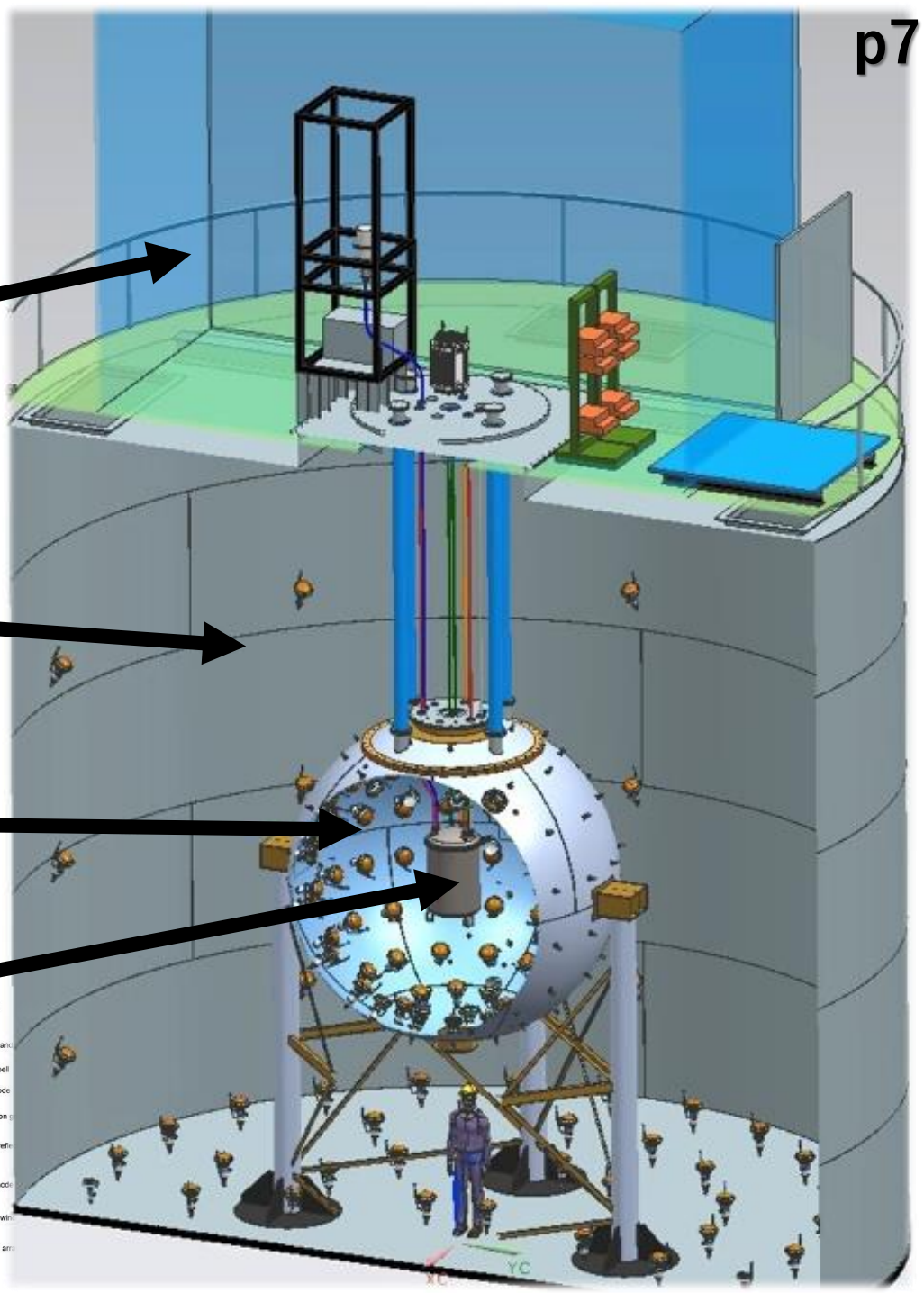
Radon-free (Rn levels < 5 mBq/m^3)
Assembly Clean Room

1,000-ton Water Cherenkov
Cosmic Ray Veto

30-ton Liquid Scintillator
Neutron and γ's Veto
Veto efficiency > 99.1%

Inner detector **TPC**
filled with 150 kg of liquid
Underground Ar



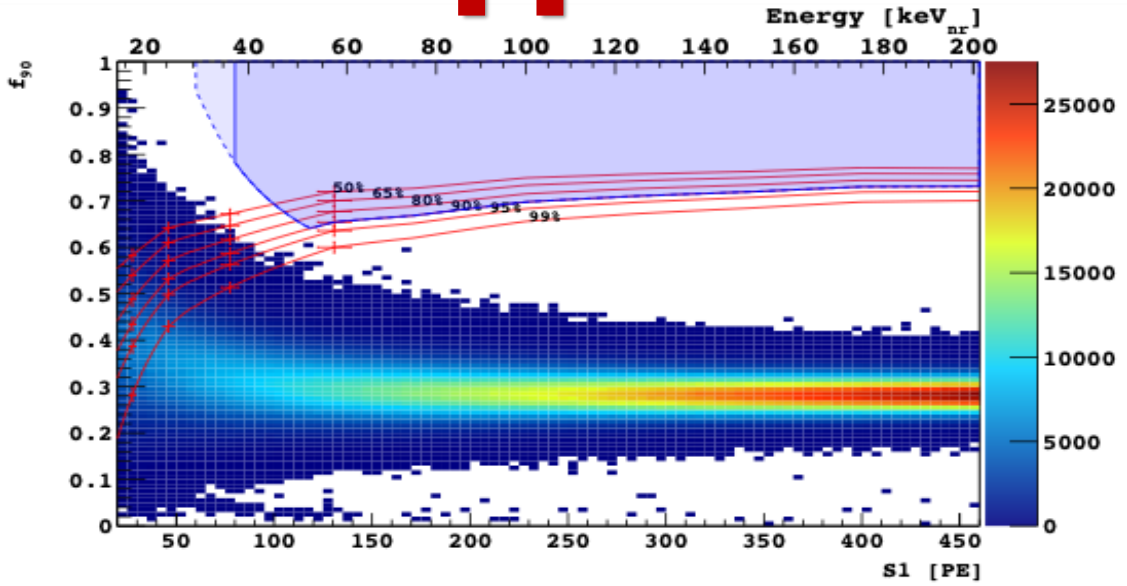


AAr Result ⇒ UAr for ^{39}Ar suppression

◆ DS50 with AAr (in 2013-2014)

- Exposure: **1422 kgd** (37kg x 47days)
- LY = **7.0 PE/keVee@200V** (7.9PE@null)
- 1.5x10^{7} ER events from ^{39}Ar activity
- Energy-thre. > **~40 keVnr** (0 event obs.)

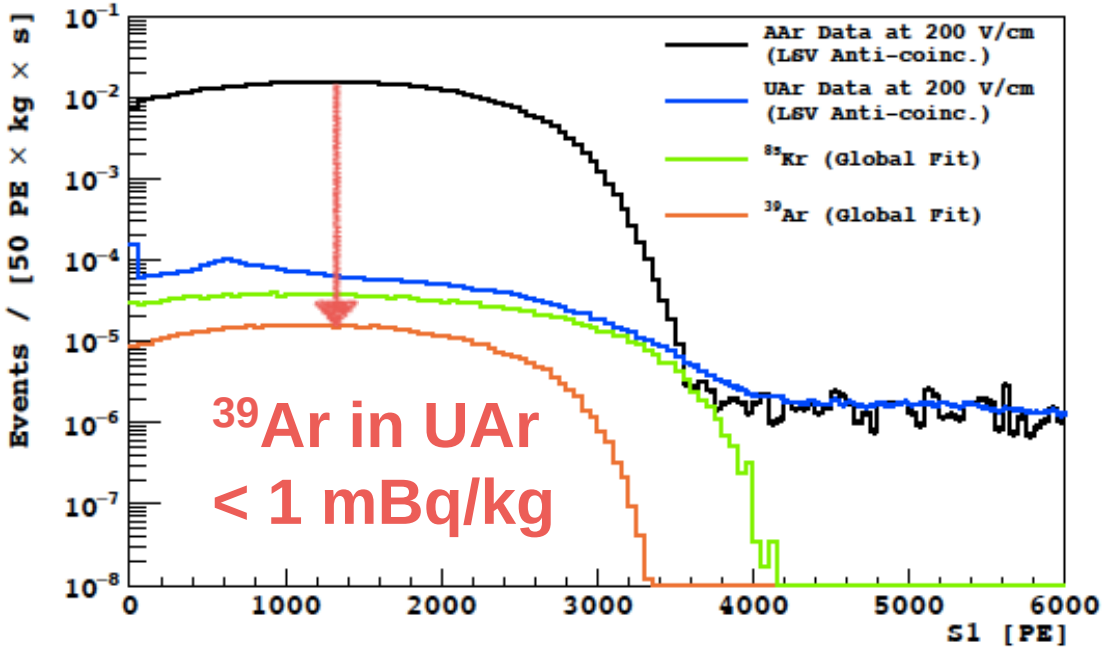
→ Set 90% C.L. limit **PLB743, 456 (2015)**



⇒ Underground Ar (UAr)

^{39}Ar is produced by cosmogenic activation via ^{40}Ar(n,2n)^{39}Ar

→ 150 kg successfully extracted from a CO_2 wells in Colorado (USA)

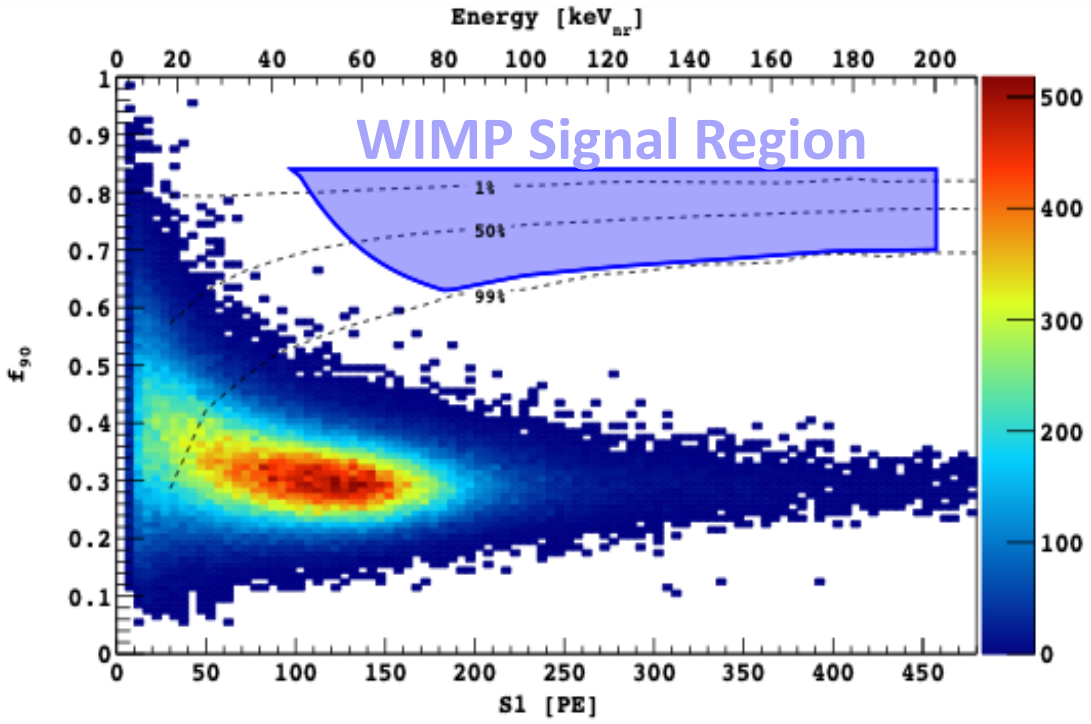


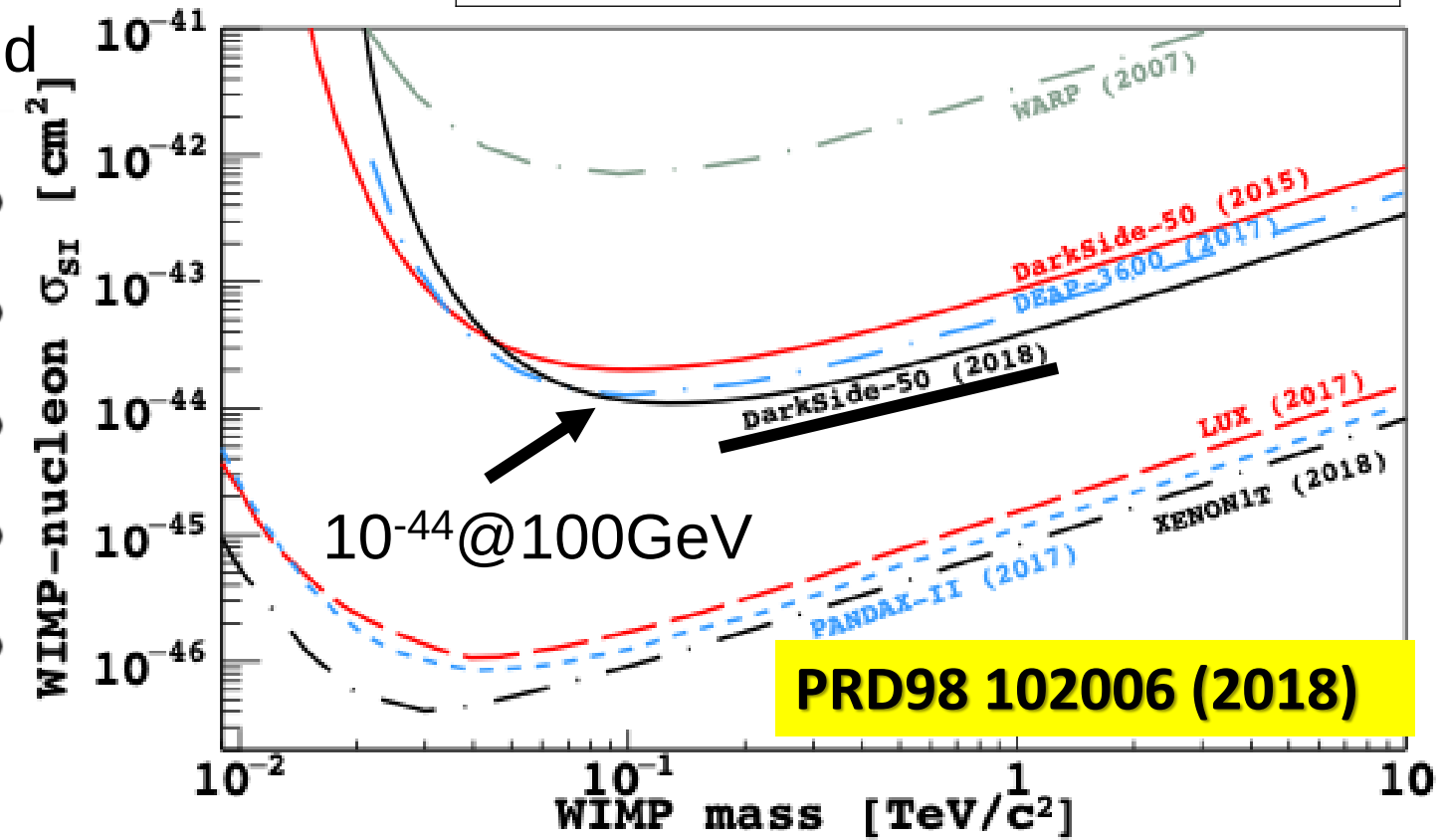
★ ^{39}Ar depletion factor > 1400

Latest Result from DS-50 w/ UAr-532d

- **DS50 with UAr (^{39}Ar ~ 0.73mBq/kg)**
  - Total Exposure: **16,660 kgd (~0.05 ton-year)**
  - Expected bkg : **0.09 ± 0.04 events**
  - **50(1)% acc.@ 60(40) keVnr**
  - **Zero event** observed after unblind

Background Type	# of Event
Surface alphas	0.001
Cosmogenic N	<0.0003
Radiogenic N	<0.005
Electron recoil	0.08





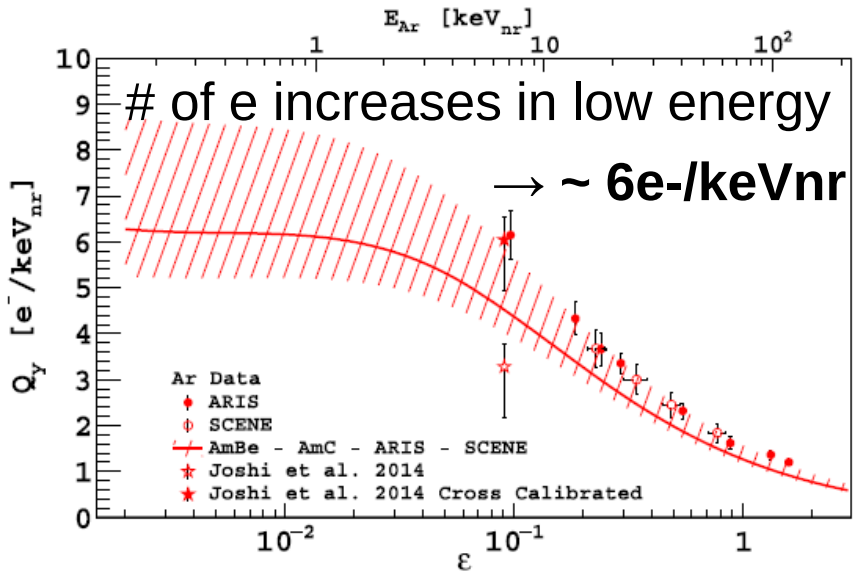
PRD98 102006 (2018)

S2-Only Analysis by DS-50

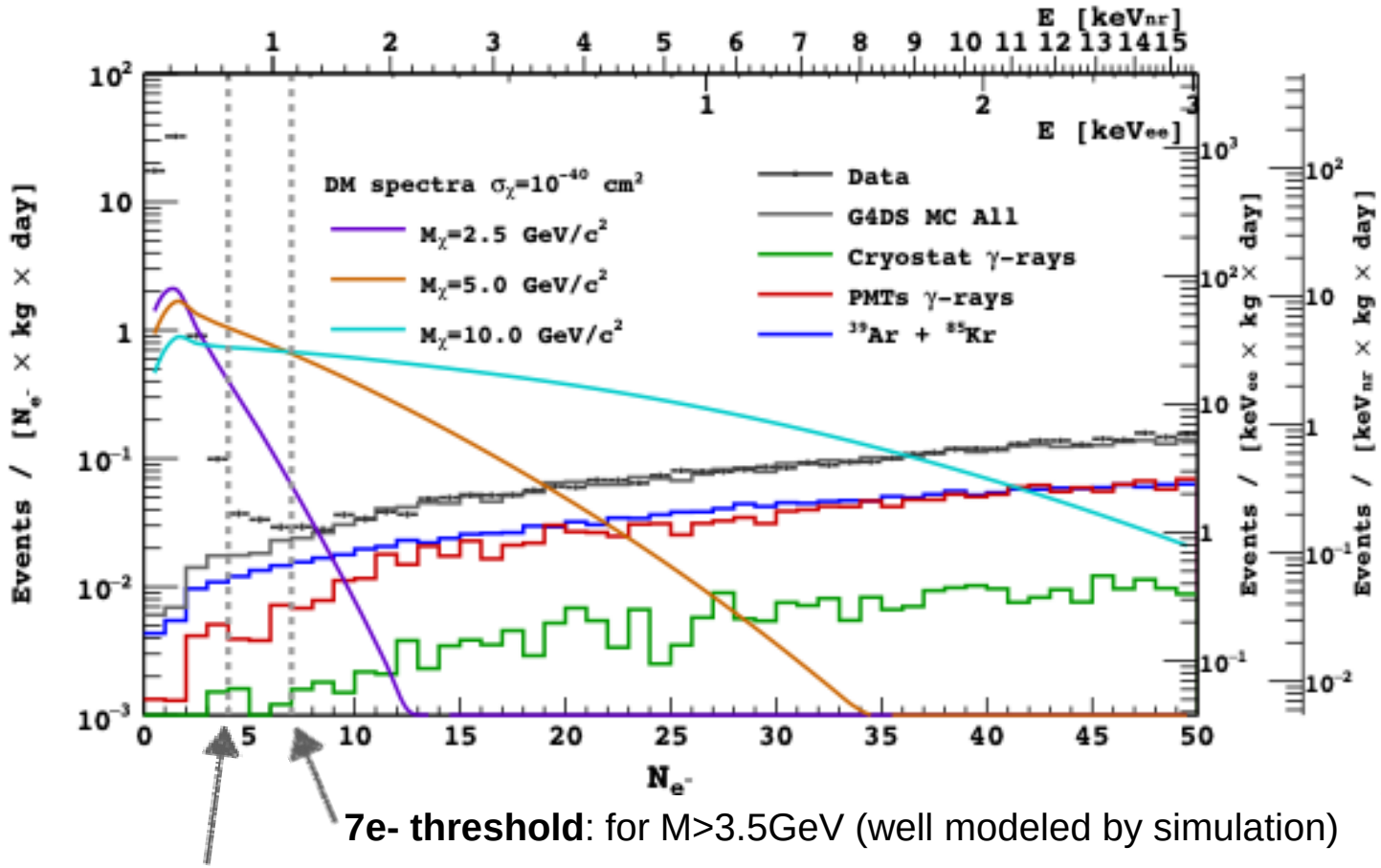
- To lower the effective energy threshold, drop S1 requirement (lose PID and z-info.)
  → Background-limited analysis (à la XEONO100's low mass search: **PRD94 092001(2016)**)

■ "Single-Electron Detector"

- Sensitive to a single extracted electron, amplified in the gas region by **23PE/e-**. (Trigger efficiency is 100% at >30PE)
- PMTs have almost zero dark rate@87K



→ E-threshold can be below 1keVnr

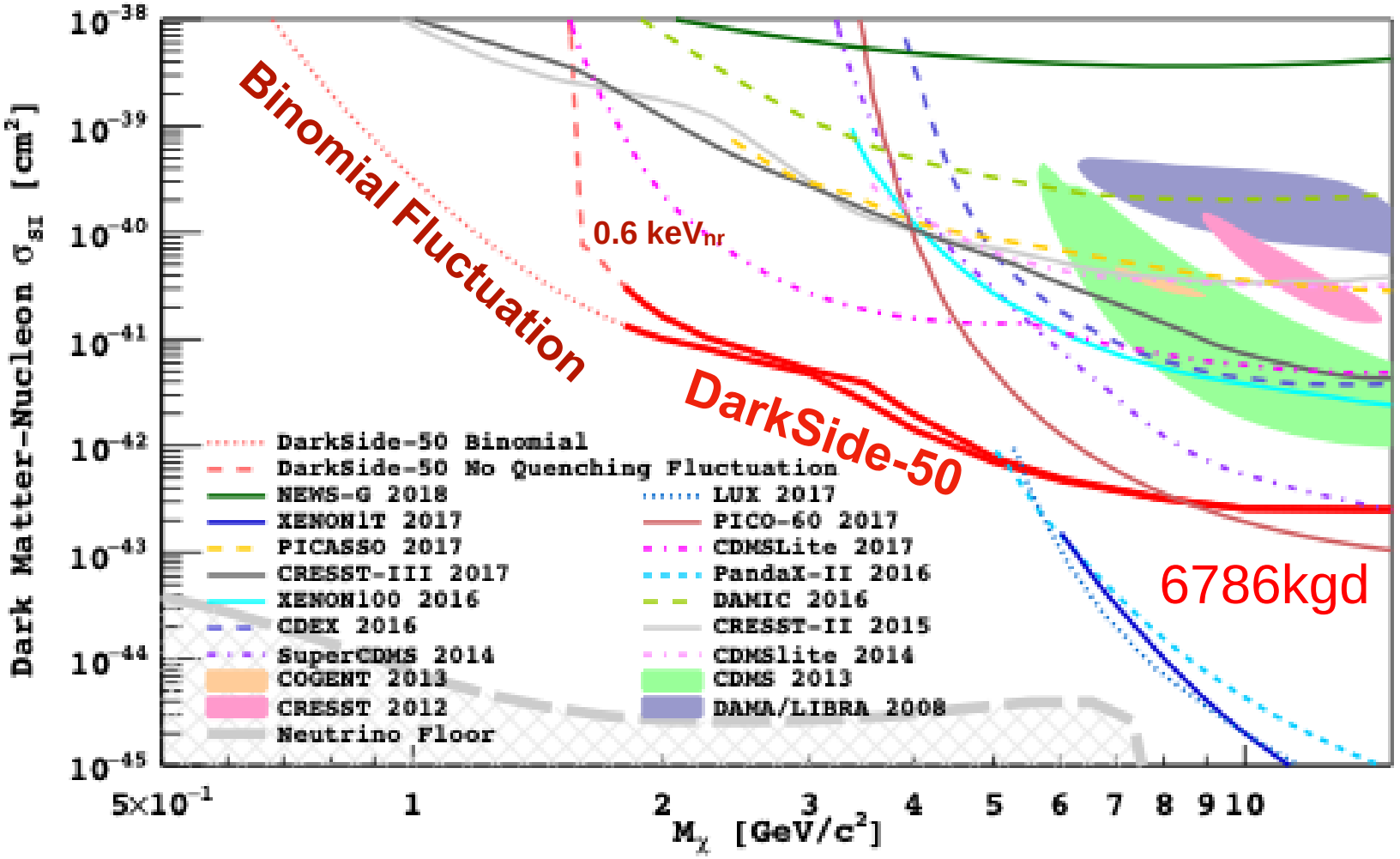


7e- threshold: for M>3.5GeV (well modeled by simulation)

4e- threshold: sensitive to all mass range (especially for lower mass) but contaminated by events not included by bkg model→Weaker limits

Result for low mass WIMP search

PRL 121 081307 (2018) ← Editor's Suggestion!



The world's best limit for low mass below ~5 GeV

■ **Signal uncertainties:**
- NR ionization yield
- Single electron yields

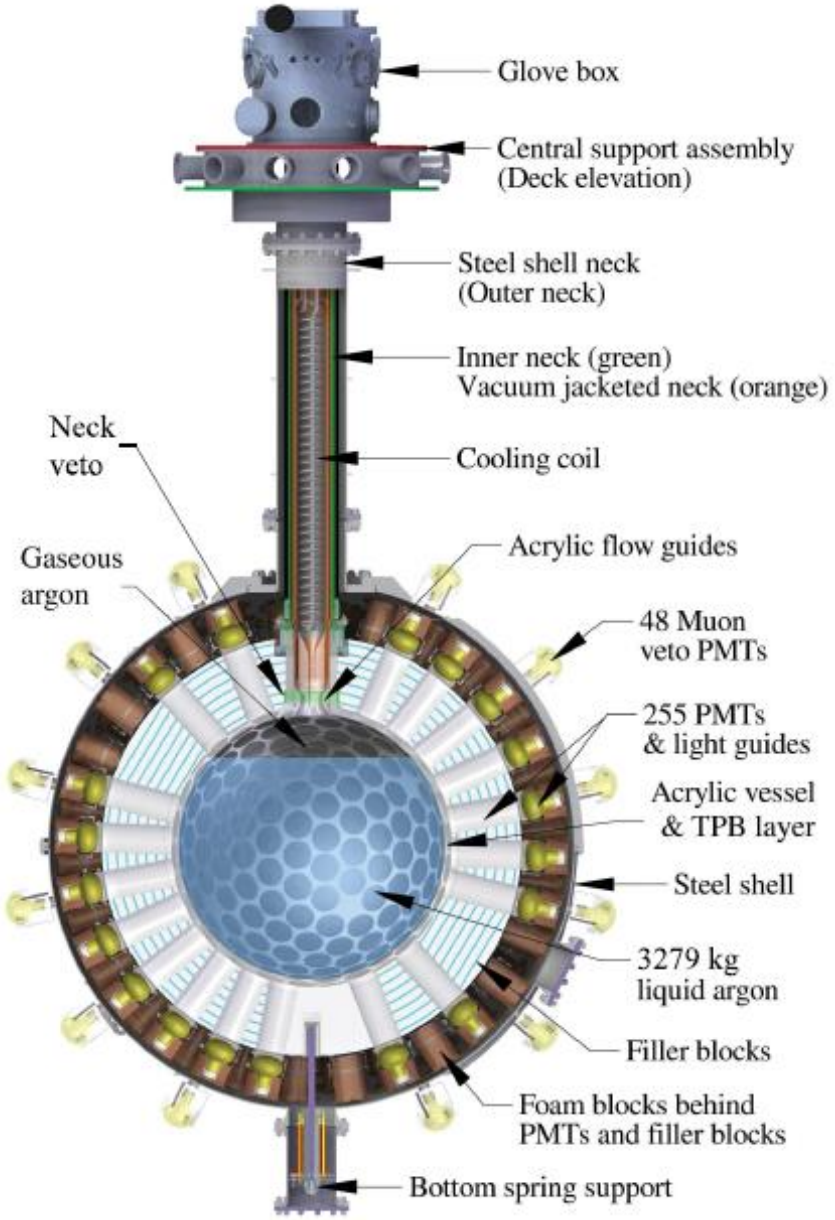
■ **Bkg uncertainties:**
- Rates, ER ionization yield

are included in binned profile LH.

★ For $M\chi$ > 1.8 GeV, insensitive to choice of energy quenching fluctuations. But below 1.8 GeV, it is impossible to claim exclusion without realistic fluctuation model or additional constraints.

→ **Left for Future work**

DEAP3600

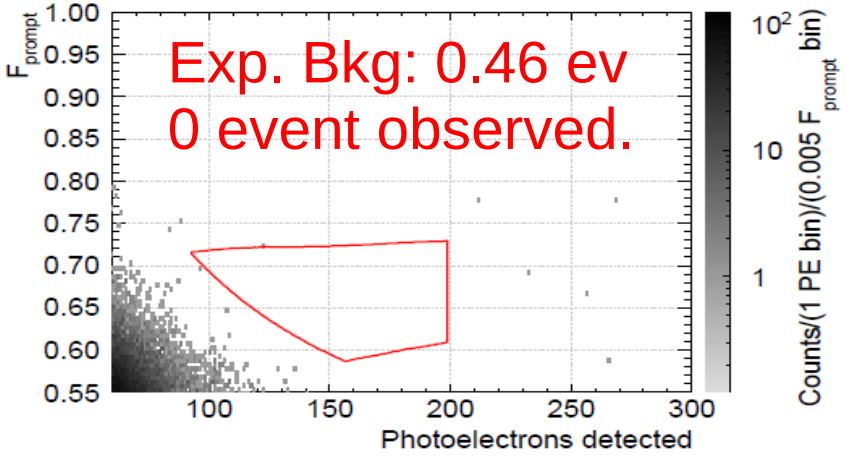


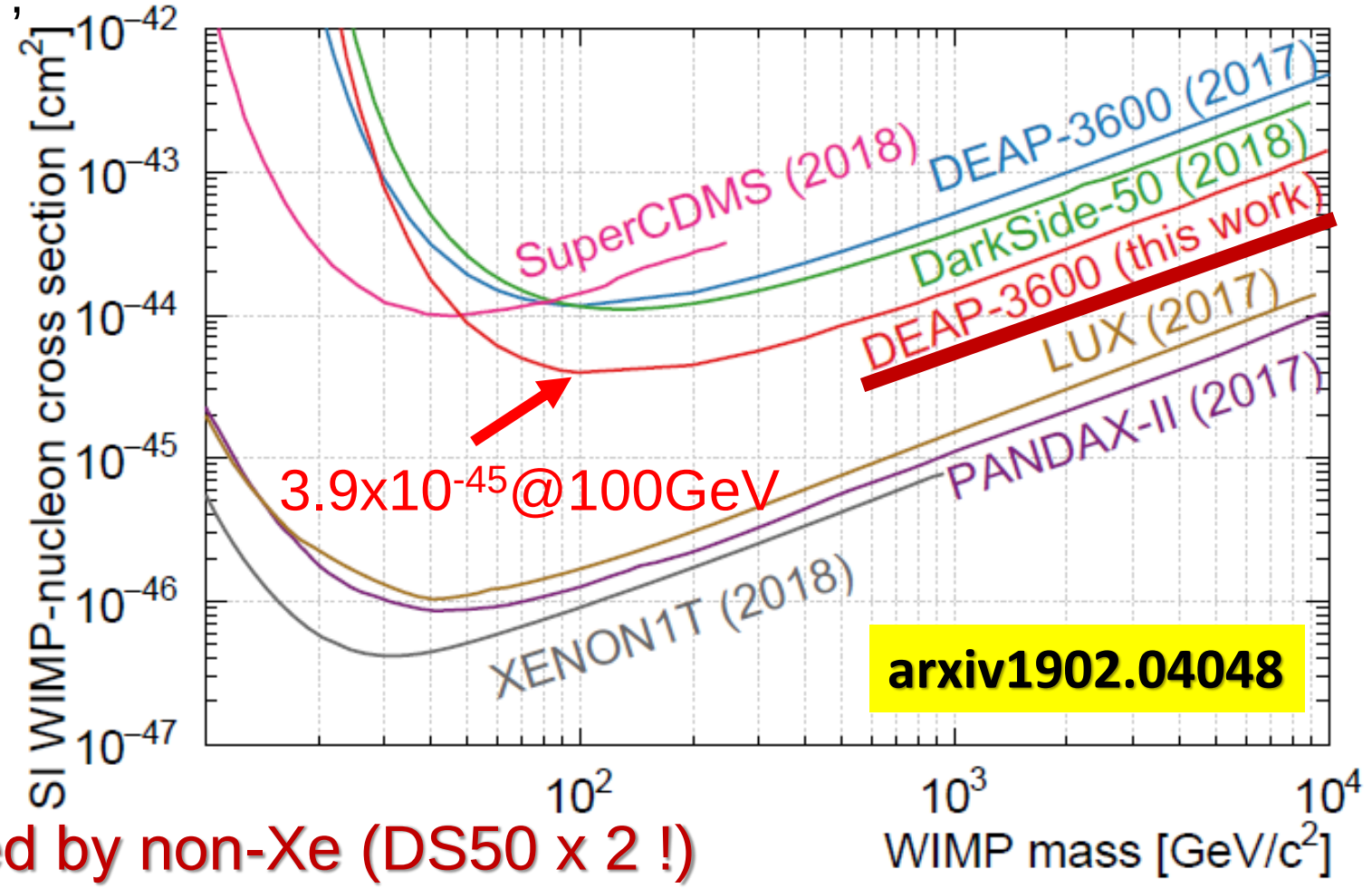
- Single Phase 4π LAr Detector with 3.3 ton target (AAr) inside the ultraclean acrylic vessel at SNOLAB (2km underground).
- ~1000kg LAr after fiducial cuts, PSD only.
- Vacuum evaporated TPB on $10m^2$ surface
- 255 Hamamatsu 8-inch PMTs (R5912)
  - QE: 32%, 75% coverage
- LAr Detector immersed in 8m water shield, instrumented with PMTs for muon veto.

Latest Result from DEAP-3600

- First results with 4.4 live days (fid. exposure 9.87ton-day) **PRL121, 071801 (2018)**
  → Updated with 231 days (total exposure 758ton-day)

- Data collected in Nov.2016-Oct.2017, 824kg after applying all fiducial cuts
  → Fid. exposure: **190 ton-day**
- LY = **6.1 PE/keVee**
- ROI: **~50 to ~100 keVnr**

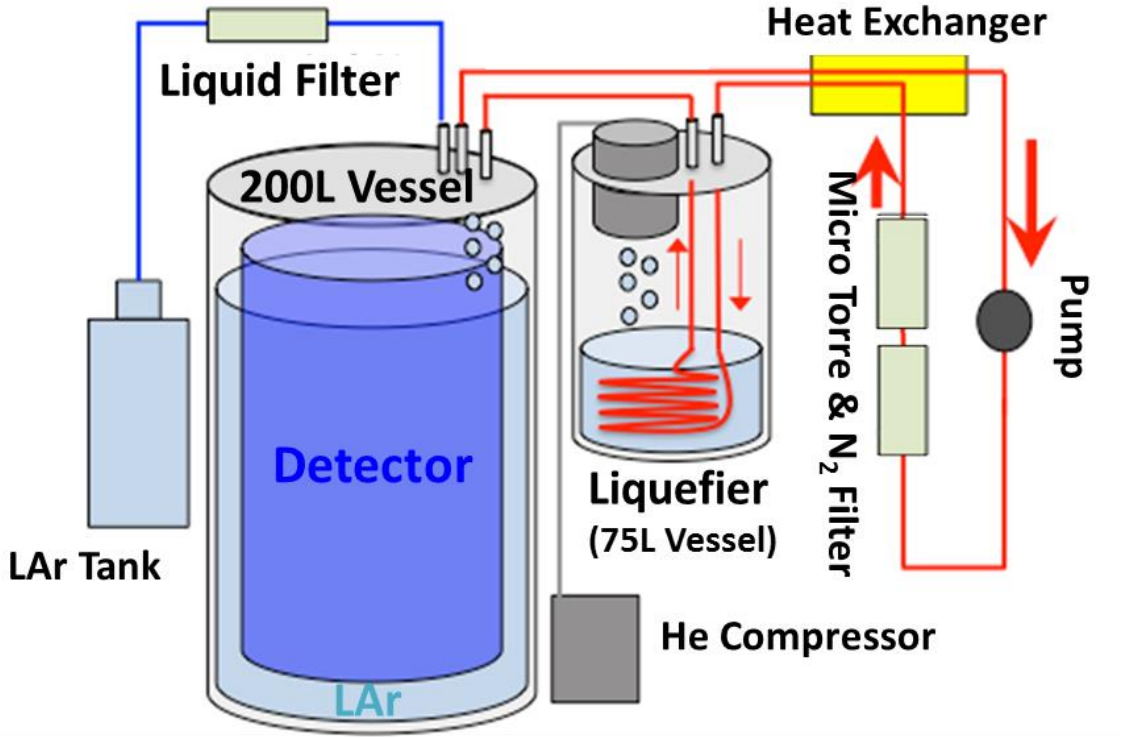


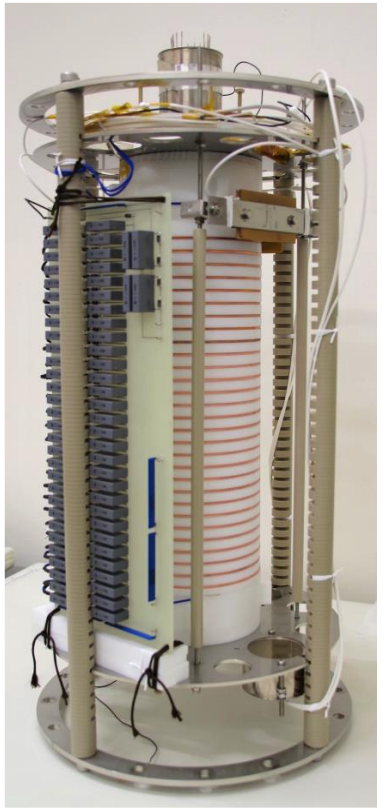


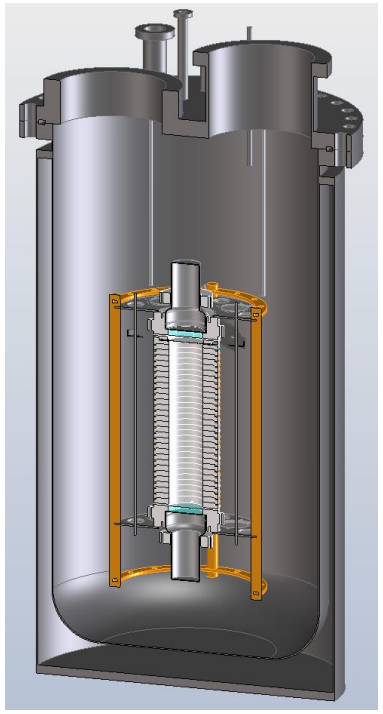
☞ World's best limit ever achieved by non-Xe (DS50 x 2 !)

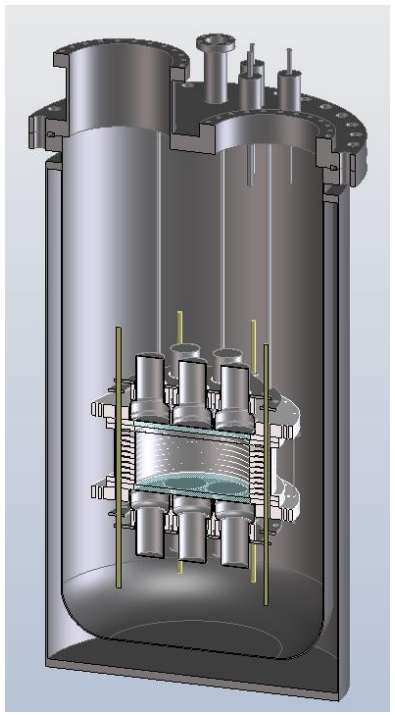
R&D Activity in Japan (ANKOK)

◆ At Waseda Univ., we built LArTPC test-stand and achieved high purity (<ppb) and high E-field by CW circuit inside LAr.










C. Rubbia visited my lab at Waseda

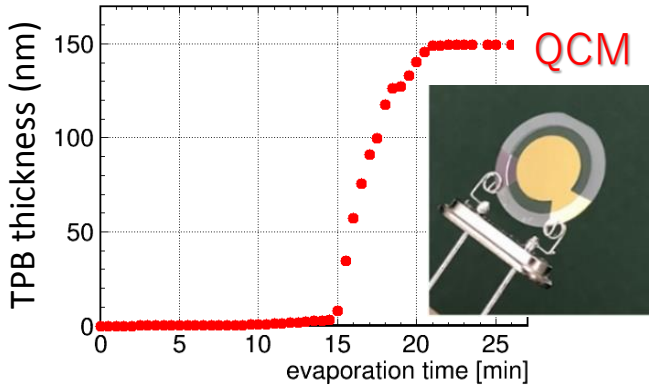
- Maximizing Light Yield including R&D on VUV-MPPC
- Understanding scintillation(S1) and Ionization(S2) process for low recoil energy and also high E-field up to 3kV

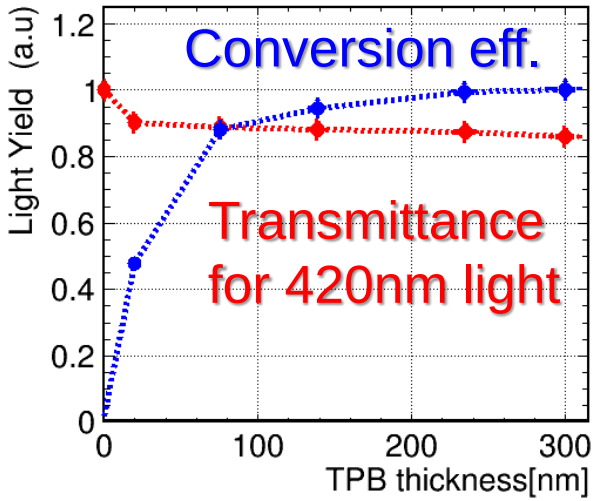
Efforts for Maximizing Light Yield

■ Scintillation light: 40γ / keVee (physics)
→ Reduced by WLS, detector-geo. and PMT QE etc.

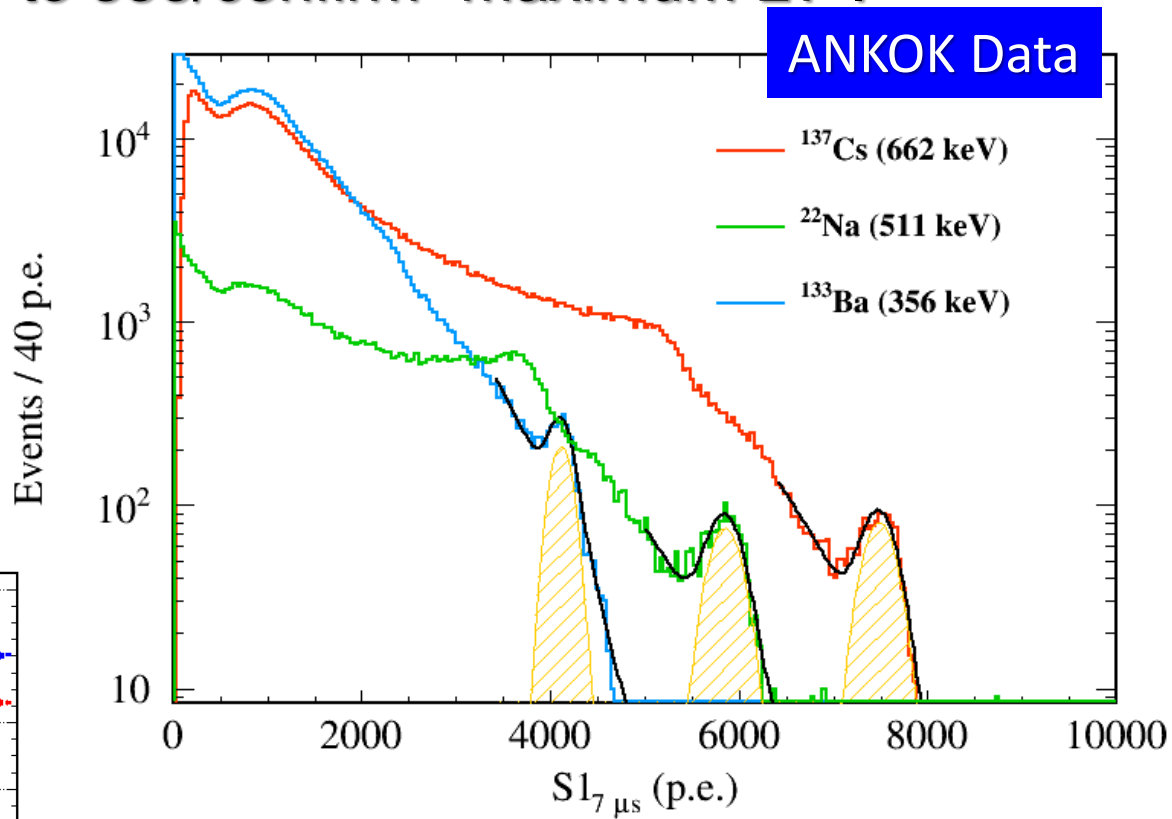
Experiment	L.Y./ keVee
WARP	~ a few PE (1.3PE/keVnr)
Darkside50	7.9 PE @null
DEAP3600	6.1-7.8 PE
ArDM	1.1 PE
SCENE	6.3 PE
ARIS	6.4 PE

■ ANKOK made well-controlled TPB evaporation system





◆ Tested by our small single-phase detector to see/confirm “maximum LY”.



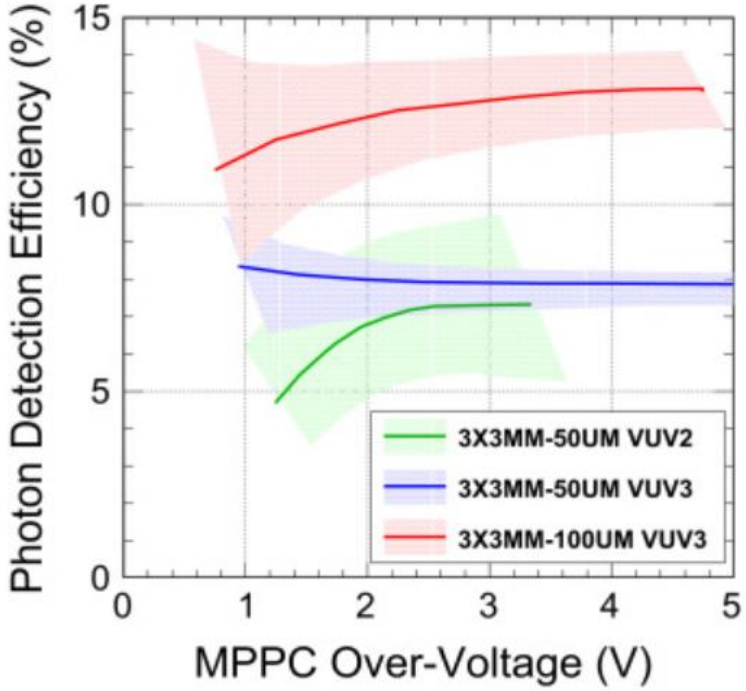
★ **11.5 PE/KeVee established !**
→ limited by PMT QE(30%) only !

→ Paper preparation underway

R&D on "VUV-direct-sensitive" MPPC

- The most optimal photo-sensor should have High PDE and direct sensitivity to 128nm VUV LAr scintillation light.
- Since 2014, collaborating with HAMAMATSU photonics, we have performed R&D on VUV-MPPC.

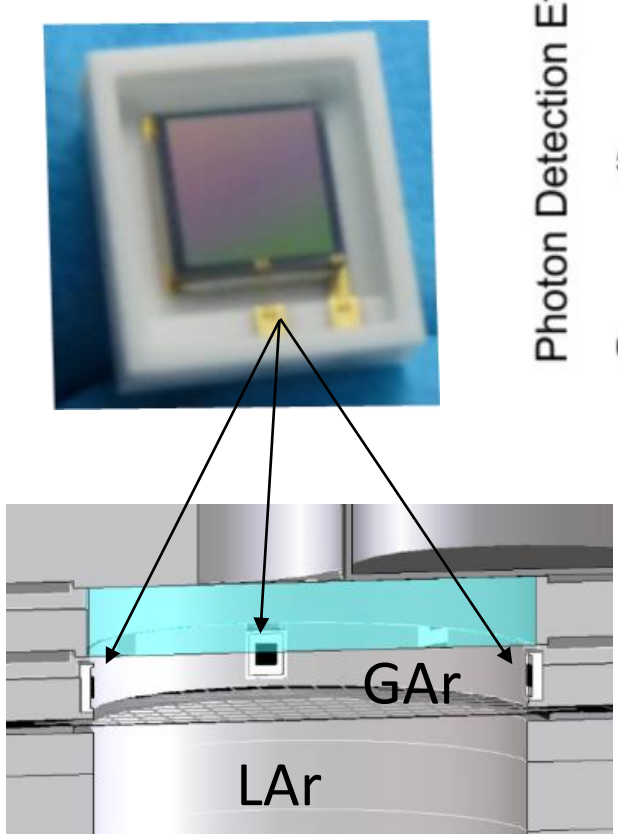
T. Washimi, KY et.al, NIM A833 (2016) 239-244



◆ We successfully detect 128nm without TPB and measured the PDE for LAr scintillation light.

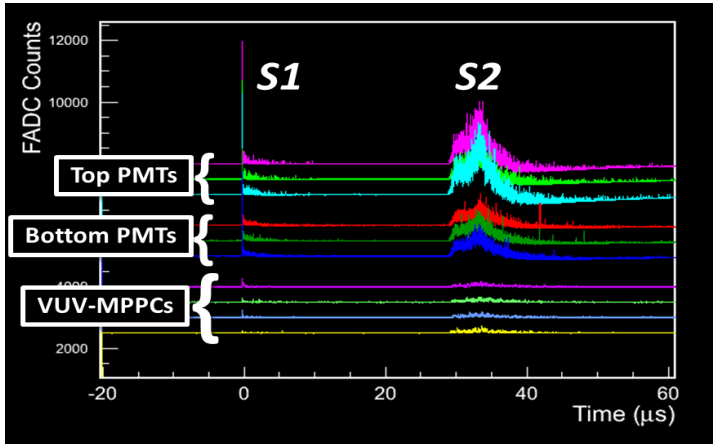
→ Current max PDE is ~12%, still too low for the purpose of WIMP search.

→ R&D to be continued.



◆ As a test, 4 VUV-MPPCs are mounted near the liquid surface of the 2-phase detector at our test-stand.

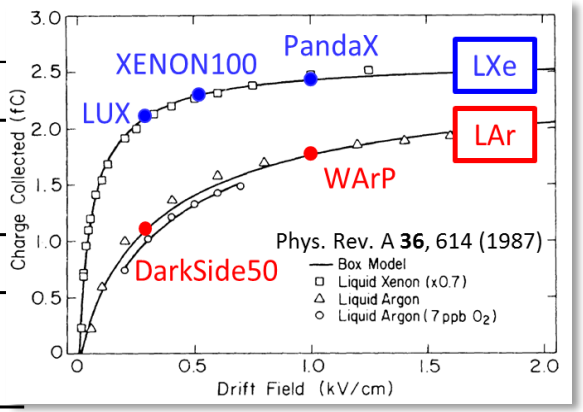
- Coincidence signal with top-bottom PMTs was observed for S1 & S2.



Argon Property Measurements

- Compared to Xe(NEST), Argon property is not so systematically understood.
  → Recently many efforts have been done by various groups in the world.

	Signal	Recoil Energy ER [keV_{ee}]	Recoil Energy NR [keV_{nr}]	Drift-Field [V/cm]
ANKOK	S1, S2	2–60	10–150	0, 200–3000
SCENE [101, 105]	S1, S2	41.5	10.3–57.3	0, 100–1000 (S1) 100–500 (S2)
ARIS [102]	S1	42–511	7.1–117.8	0, 50-500
Joshi et al. [126]	S2	2.82	6.7	240–2130 (NR) 240–3000 (ER)
Sangiorgi et al. [127]	S2	0.27, 2.82, 5.89	–	2400
Bondar et al. [128, 129, 130]	S2	25, 59.5	80, 233	560, 620, 2300 (NR) 600, 1750, 2300 (ER)

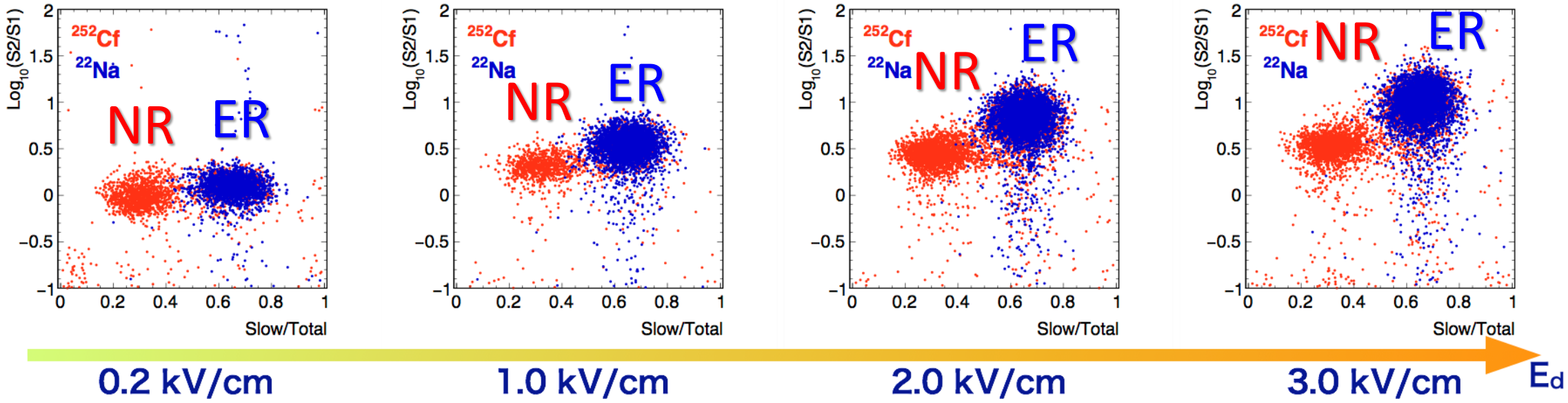


★ Table from T. Wasimi's Ph.D thesis (ref # in there)

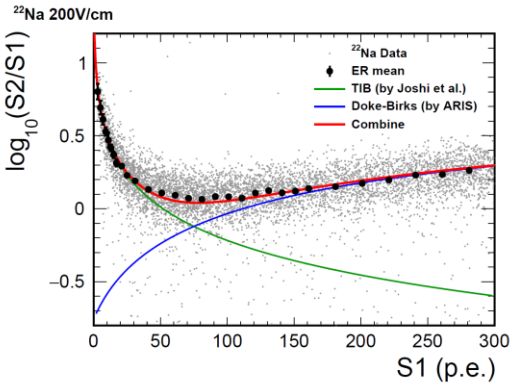
- ANKOK has performed S1&S2 simultaneous fit for low energy ER/NR region, up to 3kV/cm by NEST inspired functions (Doke-Birks & TIB models).

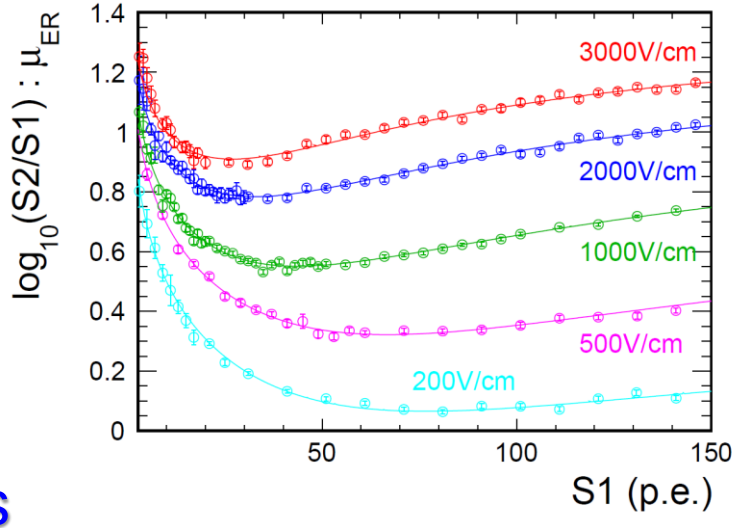
E-dependence of S2/S1 ratio

ANKOK Data



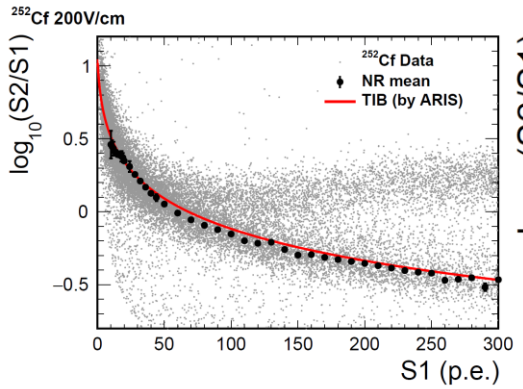
✓ ER event

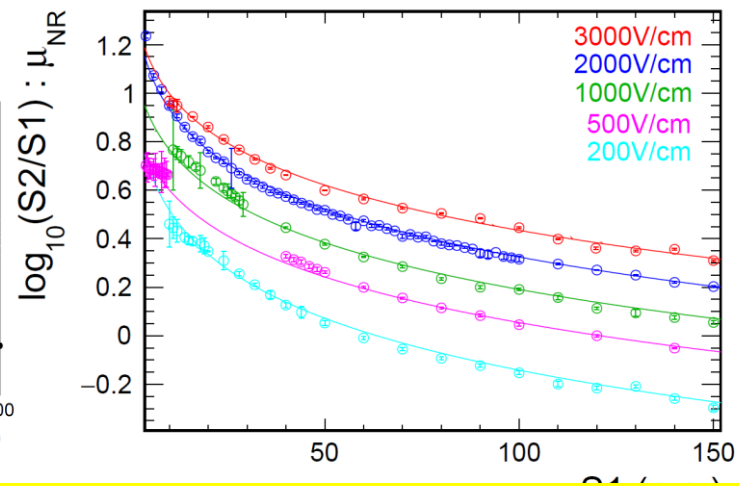




TIB + Dork-Birks

✓ NR event

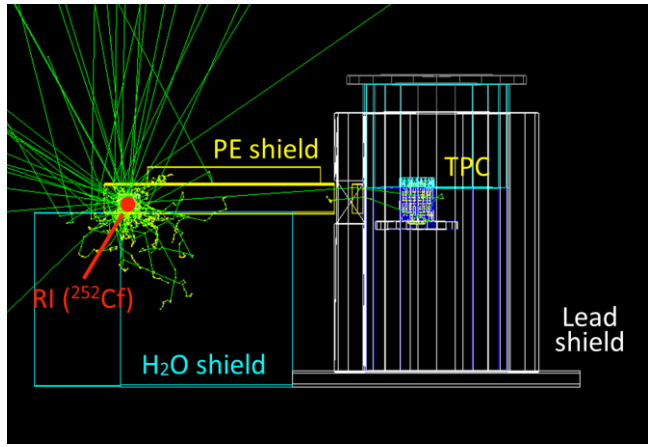




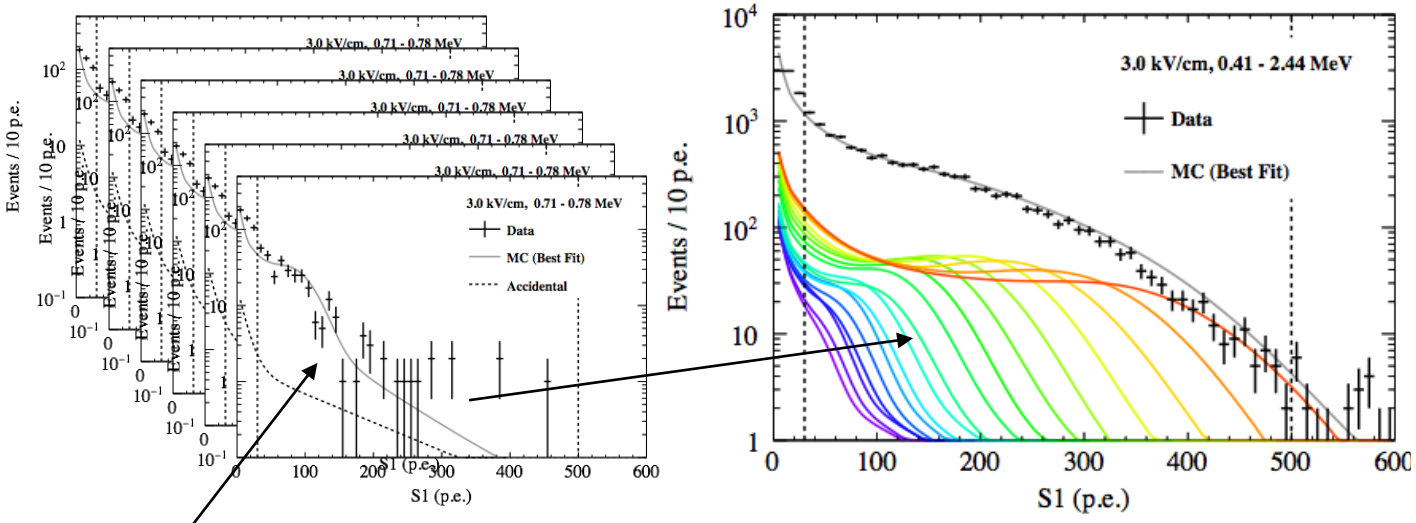
T. Washimi, KY et.al. NIM A v910, 22-25 (2018)

Quenching factors up to 3kV/cm

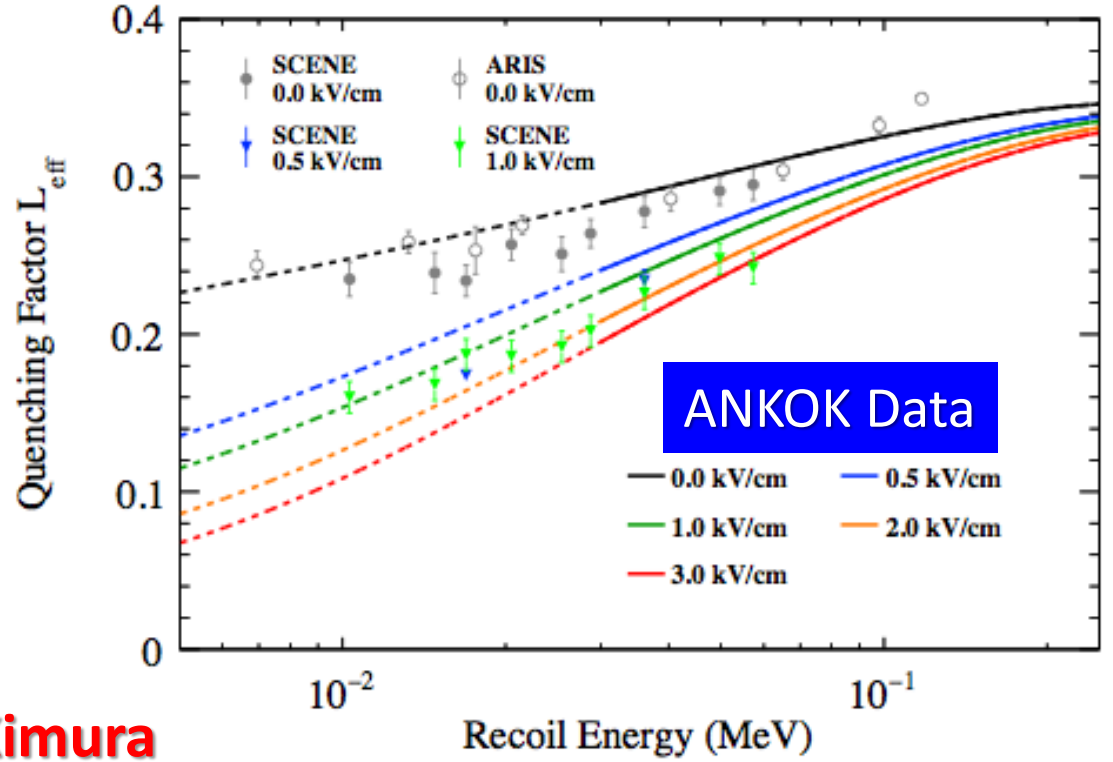
- Using ^{252}Cf neutron with TOF method, we tag and specify incident neutron momentum and generate MC sample with GEANT4 accordingly.
- At each E-field(0 to 3kV/cm) and TOF bin(14bins in total), **S1 and S2 spectra are simultaneously fitted** with Mei Model/TIB model functions.



M. Kimura, KY et.al. arxiv 1902.01501



back-scattering edge



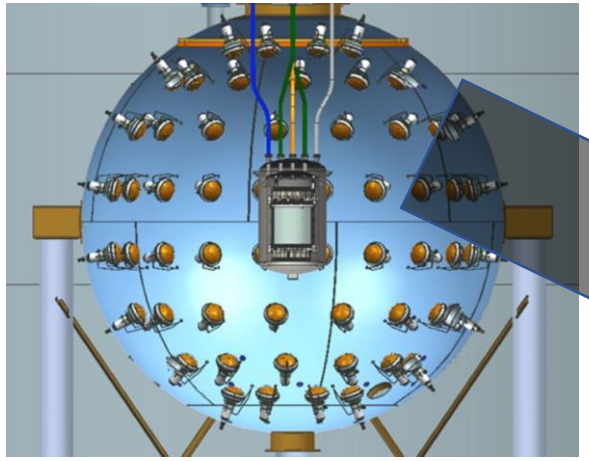
☞ **Poster by M. Kimura**

Future of Ar Detector
“Scaling up toward the *ν* floor”

★ Special Thanks to C. Galbiati (Princeton)
for the latest materials & information !

Global Argon DM Collaboration (GADMC)

DarkSide



DEAP3600

GADMC

miniCLEAN

ArDM

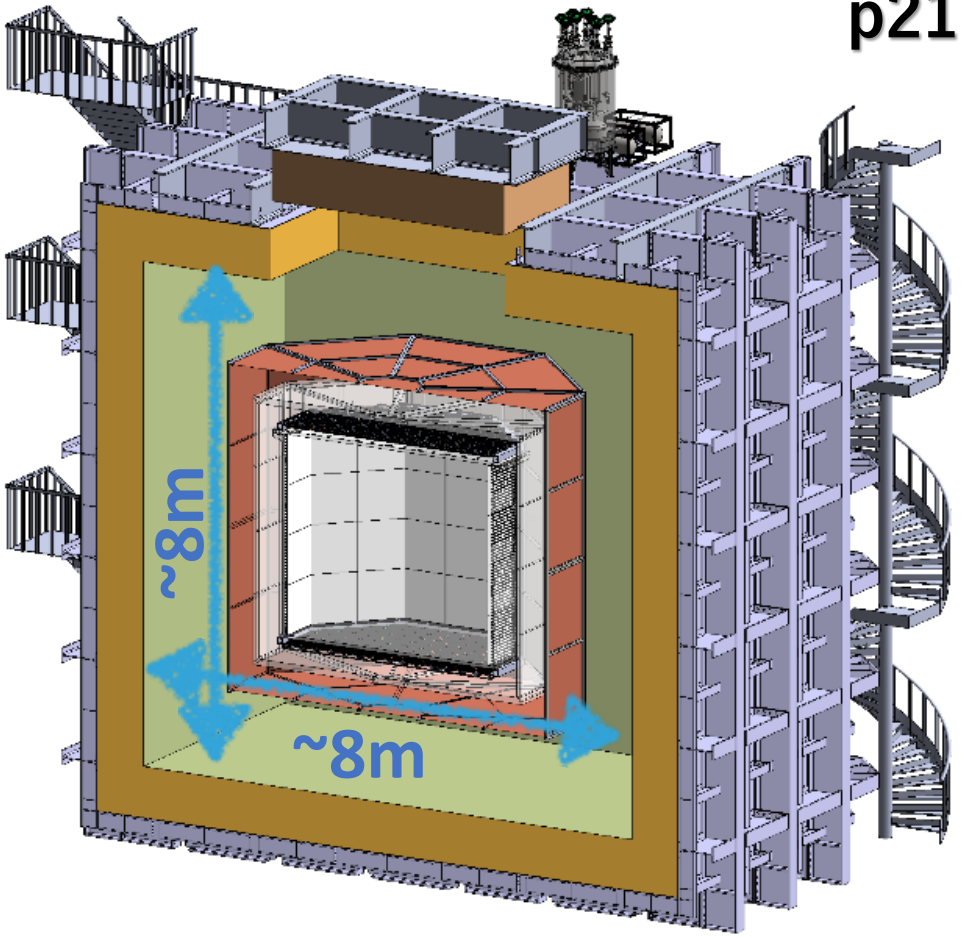
→ **DarkSide-20K@LNGS**

More than 350 collaborators

from ~80 institutes

DARKSIDE-20K

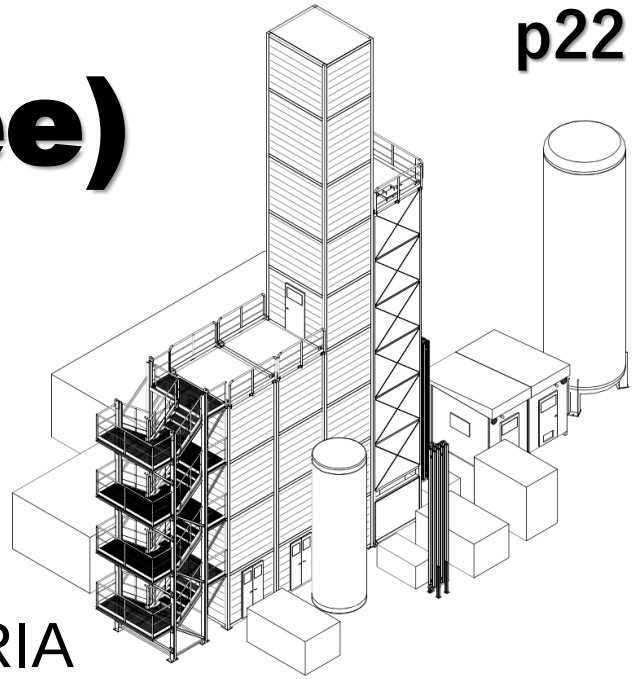
- A 20 tons fiducial argon detector fully filled with Underground Argon (Total 50 tons).
- Cryogenic low-bkg SiPMs(14m^2) instead of PMTs.
- 100 ton-year background-free search for DM.
- Approved by INFN & NSF with €80M capital cost.
  - Construction started, completion by 2022.
  - Veto based on CERN tech for ProtoDUNE cryostat,
    → TPC acrylic vessel surrounded by AAr as n-veto.




ProtoDUNE@CERN

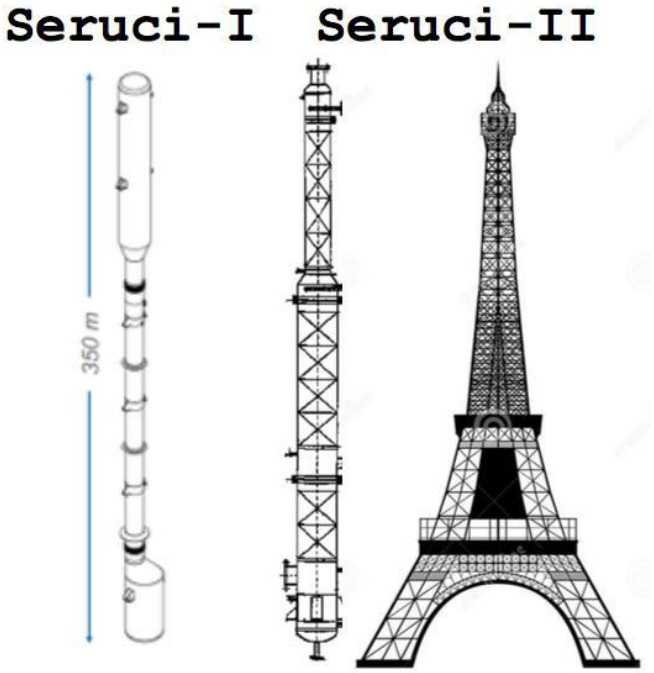
- ProtoDUNE: Two identical cryostats built at CERN
  - LNG technique from industry
  - 8m x 8m x 8m for each one (750 ton)
  - Construction: 55 weeks(NP04), 37 weeks(NP02)
  → Installable in underground

Underground Argon (^{39}Ar free)



URANIA funded by INFN, start operation in 2020

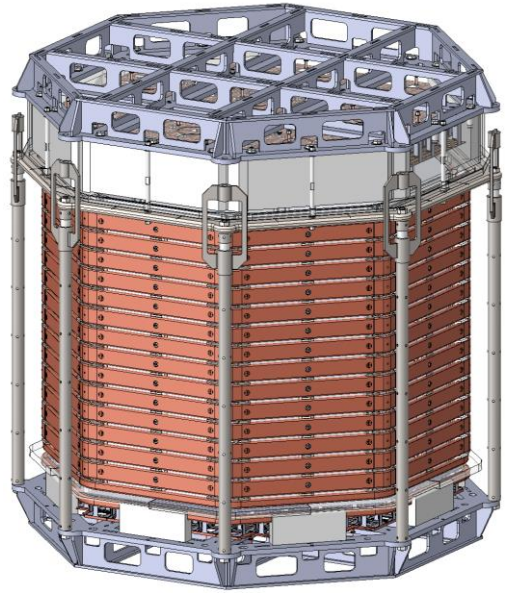
- Procurement of 50 tons of UAr from Colorado source, the same as for DS50.
- Extraction of 250kg/day with 99.9% purity
- UAr transported to Sardinia for final chemical purification at ARIA



ARIA ready by the end of 2020

- Big cryogenic distillation column in Seruci.
- Final chemical purification of the UAr.
- Can process O(1 ton/day) with 10^3 reduction of all chemical impurities.
- Ultimate goal is to isotopically separate ^{39}Ar from ^{40}Ar at the rate of 10kg/day in Seruci-I.

DARKSIDE Low Mass(DS-LM)

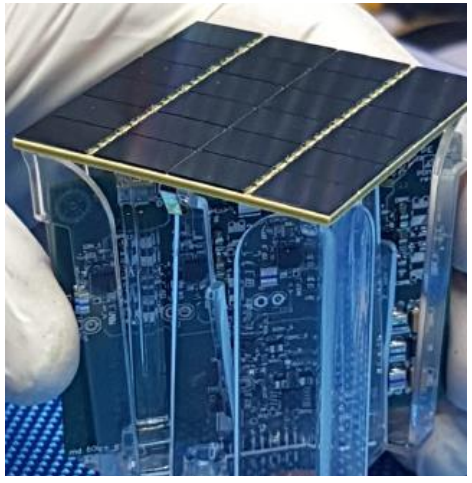


- **1 ton fiducial Ar detector specific to WIMP mass < 10 GeV.**
- Depleted UAr (^{39}Ar<1μBq/kg) by multi-path cryogenic distillation.
- S2-only analysis:
  - Lower threshold than DS-50 by reducing the single electron bkg.
  - Need low energy calibrations for NR below 1keVnr

★ This is actually "1-ton prototype" of DS-20K and will allow
- validation of the design of TPC mechanics and cryogenics
- integration tests of the custom SiPMs and full readout electronics & DAQ.

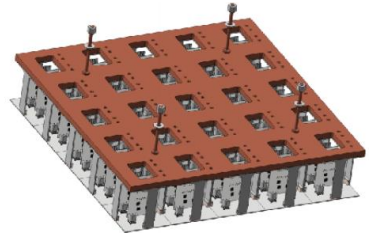
★ **SiPM (Silicon photomultiplier) :**
- 50% PDE@420nm(after TPB-WLS)→ High LY
- Much lower radioactivity than PMTs
- Cost effective and great stability (low-voltage)
- Suitable device at LAr temperature (low dark rate)

Status: R&D completed. Facility for large scale production of PhotoDetector Module(PDM) will be ready in Fall 2019 with produce rate of the order of 15 m^2 per year.

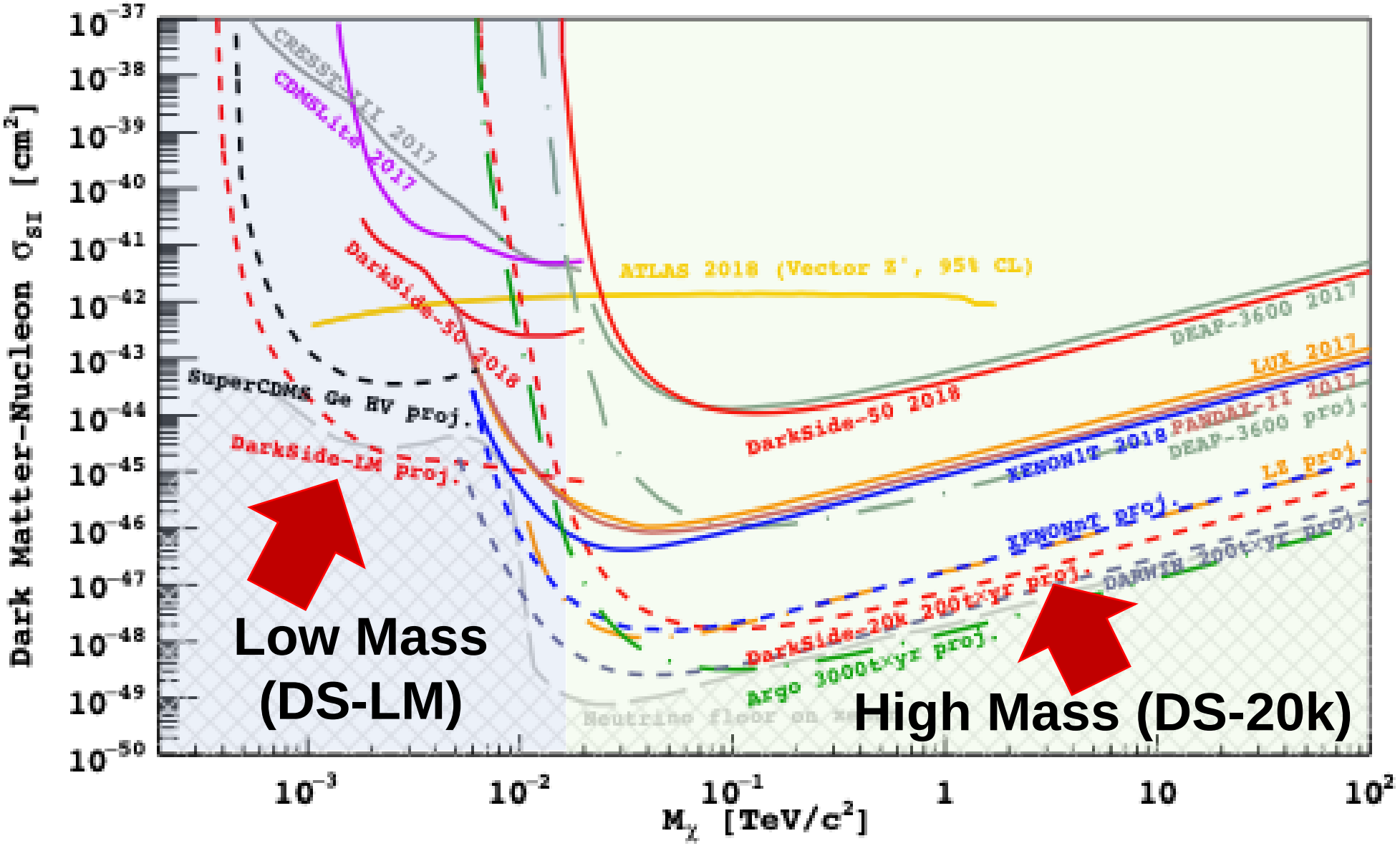


5cmx5cm PDM

6 SiPMs/ch
4 ch/tile (PDM)
15or25 PDM/MB
→370PDMs
for DS-LS

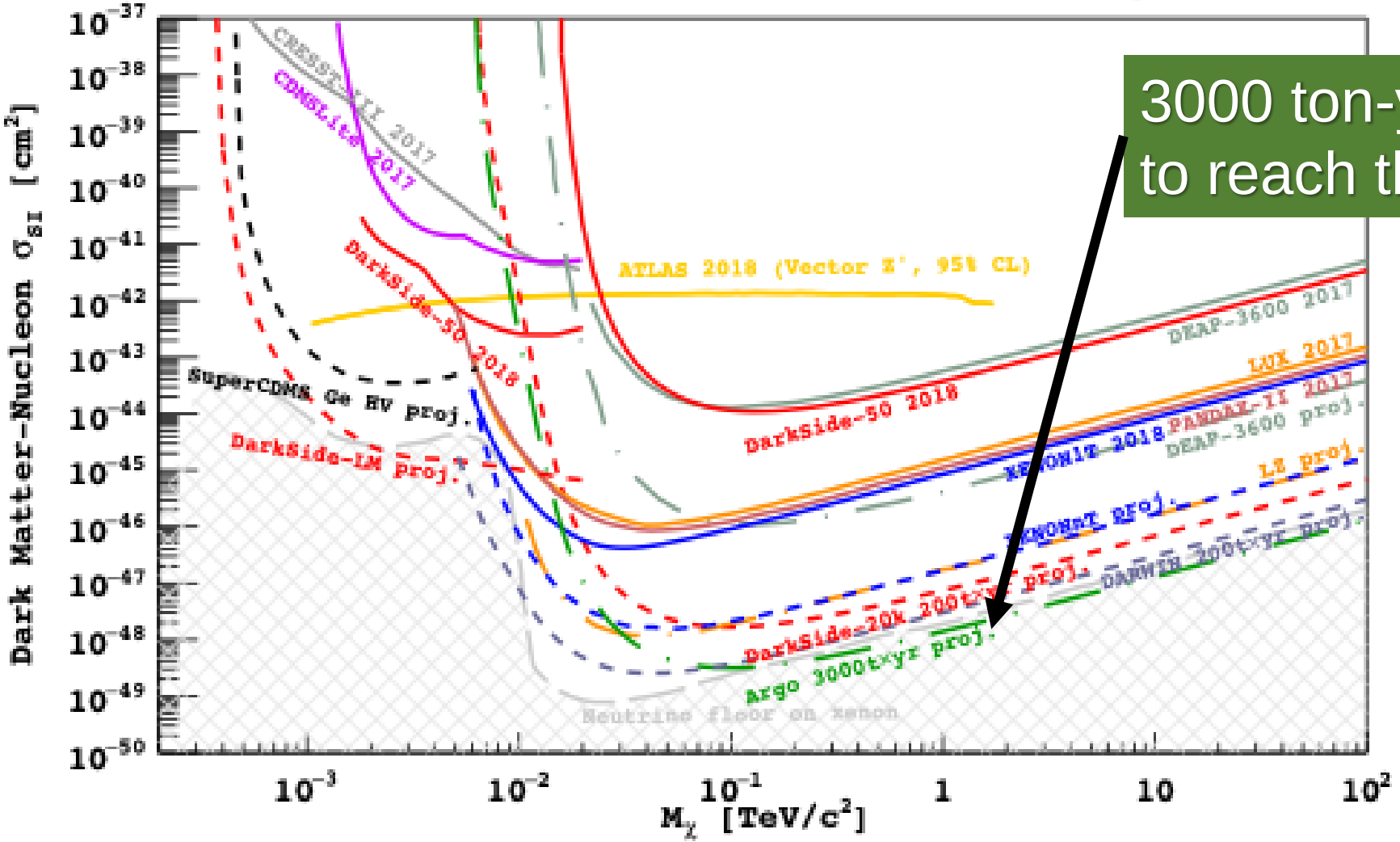


DARKSIDE-LM & -20K Sensitivity



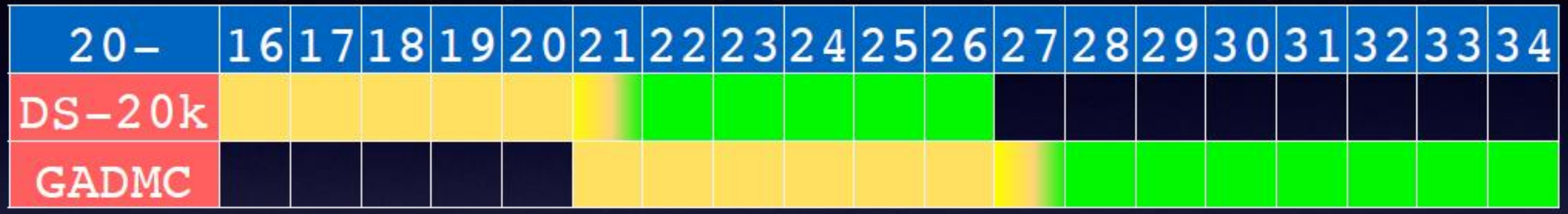
Going Further: "ARGO"

- The Ultimate (Last!?) Double Phase Ar Detector for WIMP :
  A 300-ton fiducial Ar detector filled with underground Argon



3000 ton-year exposure
to reach the neutrino floor

Timeline for “Bright Future” by Argon



DarkSide-20k

a 20-tonnes fiducial argon detector

100 tonne×year background-free search for dark matter

“ARGO”

GADMC detector

a 300-tonnes depleted argon detector

1,000 tonne×year background-free search for dark matter

→ Expect to start in 2022

Slide from G. Fiorillo

Summary & Outlook

- In the last years, significant progress of LAr detectors has been made:
  - Physics outcomes (DarkSide50/DEAP3600 etc)
  - Deep understanding of Ar response (SCENE/ARIS/ANKOK)
  - Basic Technologies (UAr, Cryostat, Cryo-SiPM etc)

  → now Ar is pretty mature media/detector, we know how to deal with!

- Next-10-year program is well planned based on world-wide collaboration (GADMC) to cover both low & high mass dark matter.

  ★ Also for further possibility, aiming for directionality, ReD (Recoil Directionality in LAr) experiment that also utilizes SiPMs is actively ongoing (partially proto-DSLM).

- Putting all together, i.e. High LY & Low Bkg by SiPM, UAr, Radiopurity, PID makes Ar Detector a good candidate as a leading experiment toward *ν* floor.

  → Together with Xe, ready to reveal the mystery of the Dark Matter !

  ★ The race has to be always competitive ☺