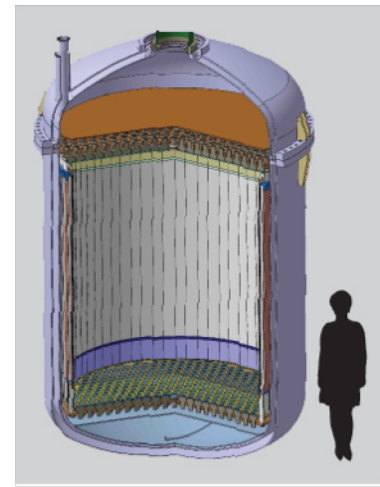




Towards a Generation-3 Xenon Dark Matter Experiment

Liang Yang

University of Illinois at Urbana-Champaign

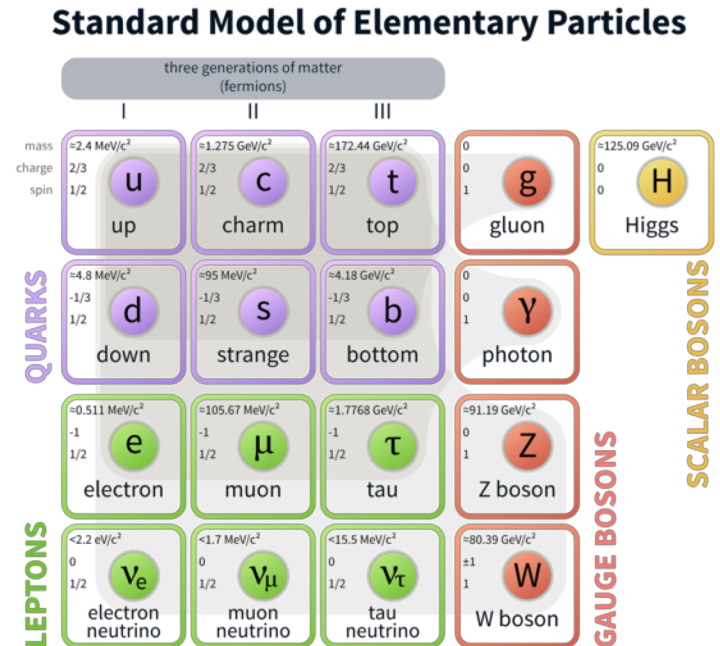
March 7, 2019

PNA Seminar, Yale University

Wright Lab: Exploring the Invisible Universe

Central Questions in Particle Physics

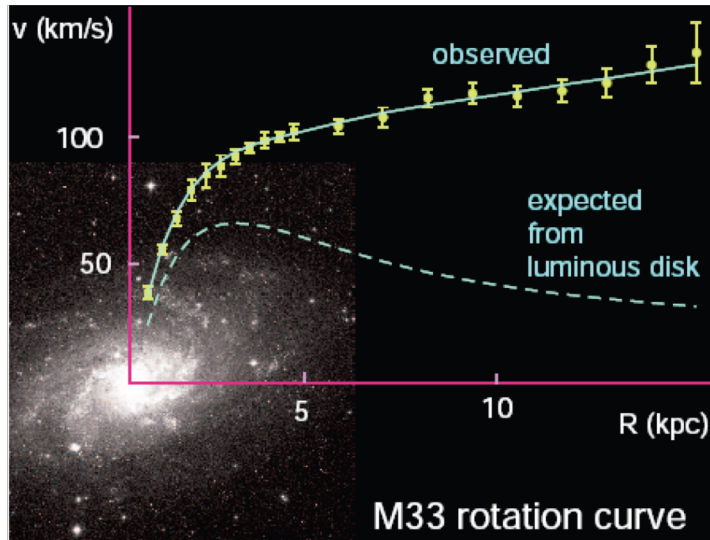
- Why Mass?
- Why Matter?
- Why Dark Matter?
- Why Standard Model?



Particle accelerators have been the most powerful instruments that directly answer these questions.

Low energy experiments and precision measurements provide important complementary searches

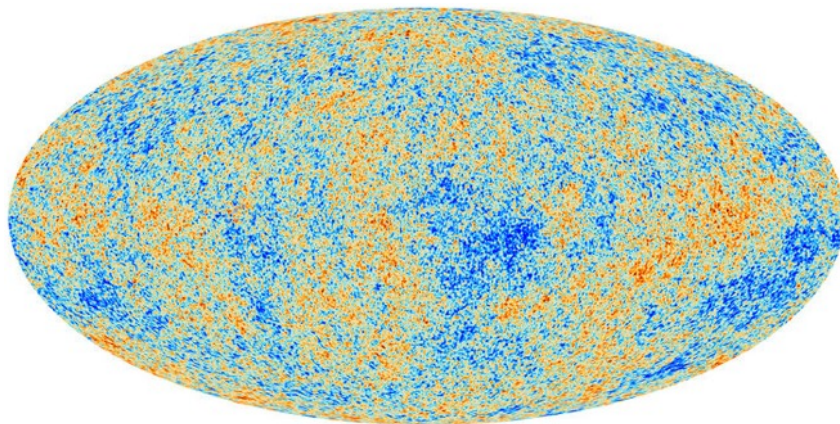
Experimental Evidence of Dark Matter



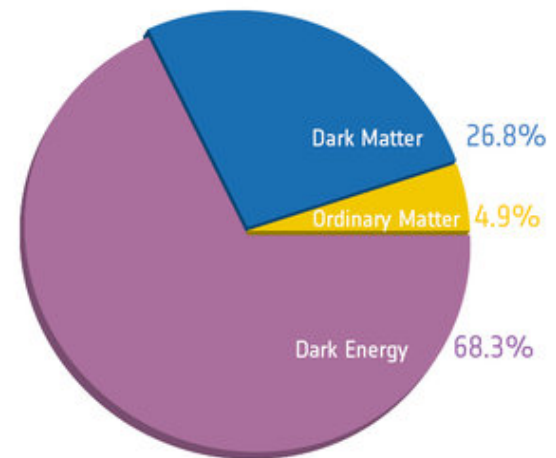
The rotational curves of spiral galaxies.



Bullet Cluster (2006)



Cosmic microwave background.



What is Dark Matter?

Observational evidence indicates:

- Non-baryonic
- Cold and massive (non-relativistic and exerts gravity)
- Interact little with ordinary matter
- Stable and long-lived
- Self interacting?

Dark Matter Candidates:

WIMPs: Weakly Interacting Massive Particles

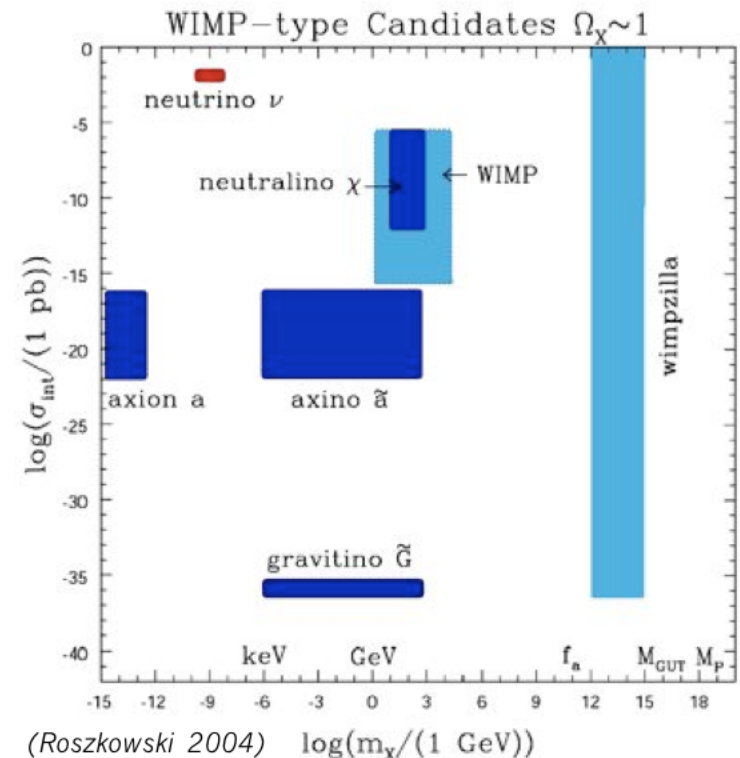
- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance

Axions

- mass $\sim 10^{-3} - 10^{-6}$ eV
- Arises in the Peccei-Quinn solution to the strong-CP problem

Non-thermal relics

- Wimpzilla

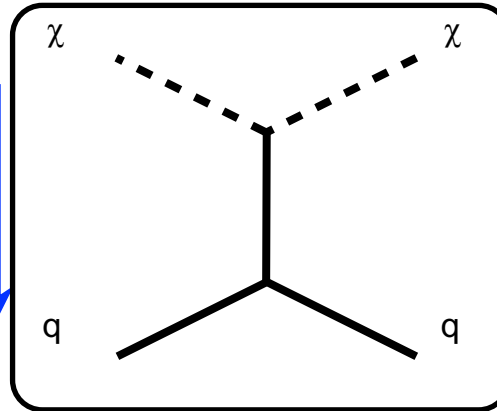
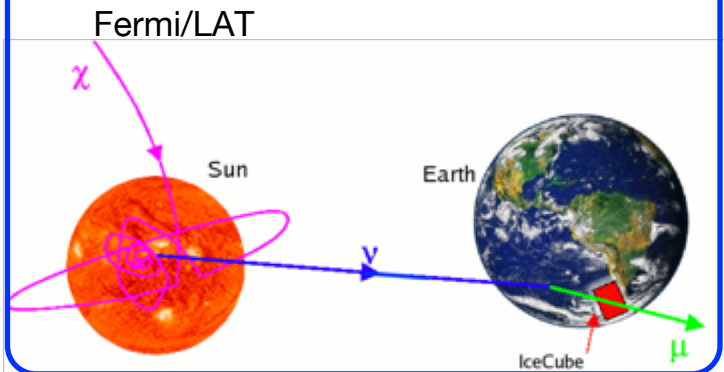


Detecting WIMPs

annihilation

“Indirect Detection”

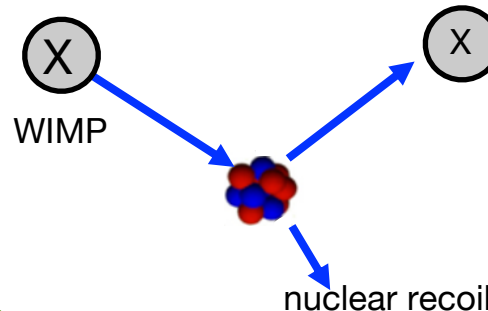
Dark matter annihilation signal from dark matter dense region
Signal: gamma rays, neutrinos, electron, positron, proton, antiproton



scattering

“Direct Detection”

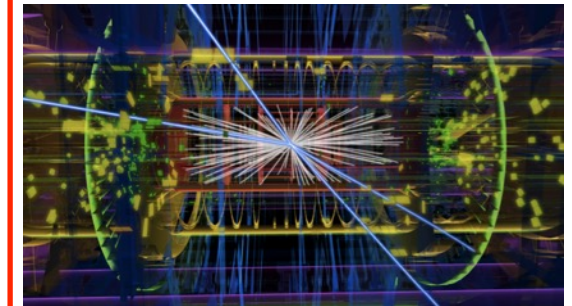
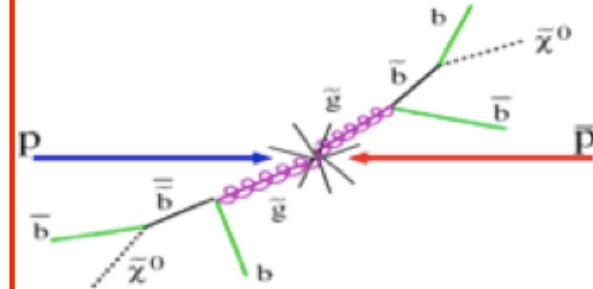
Scattering of dark matter from nuclei.
Signal: nuclear recoil



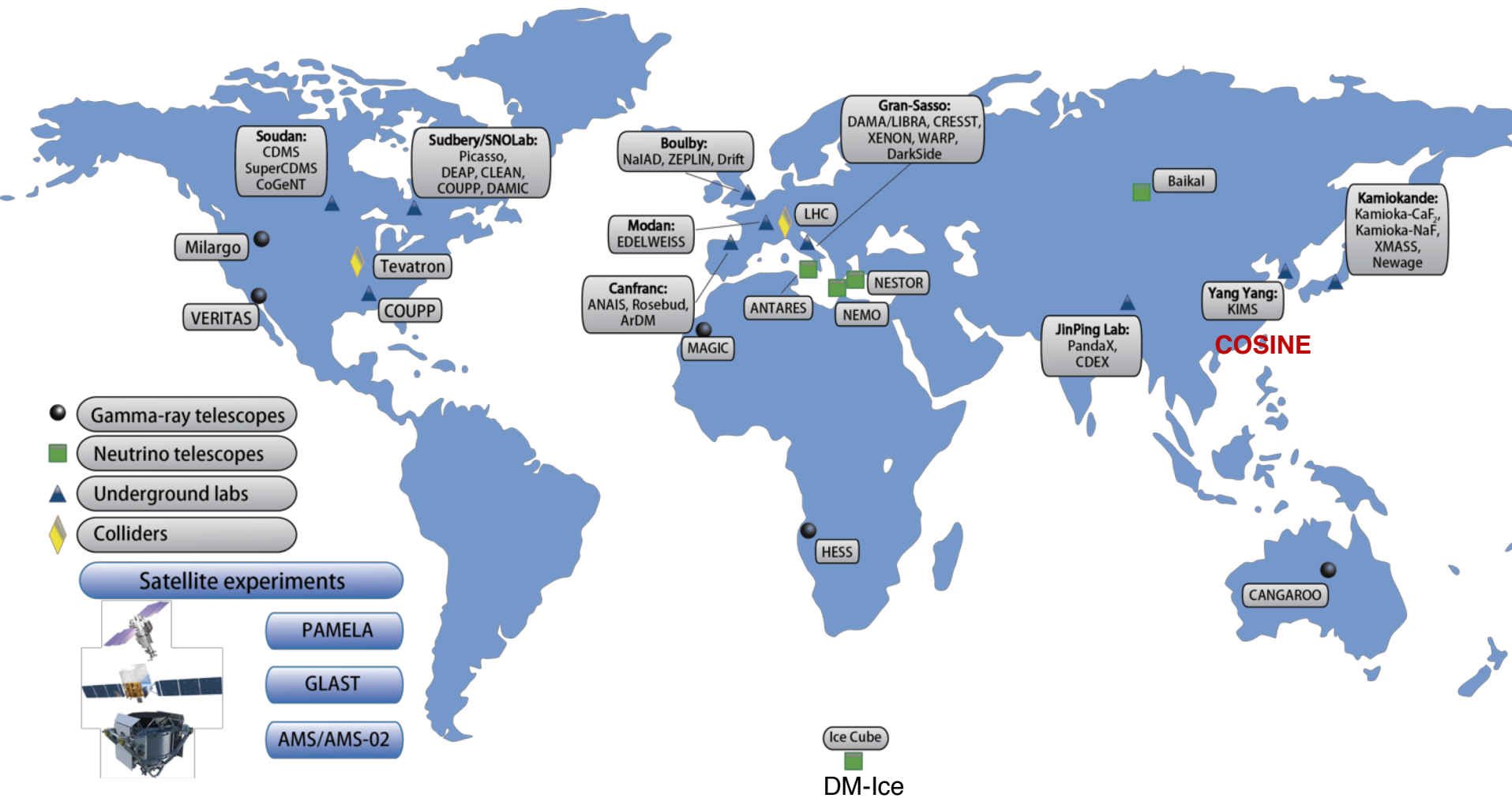
production

Colliders

Signal: missing energy

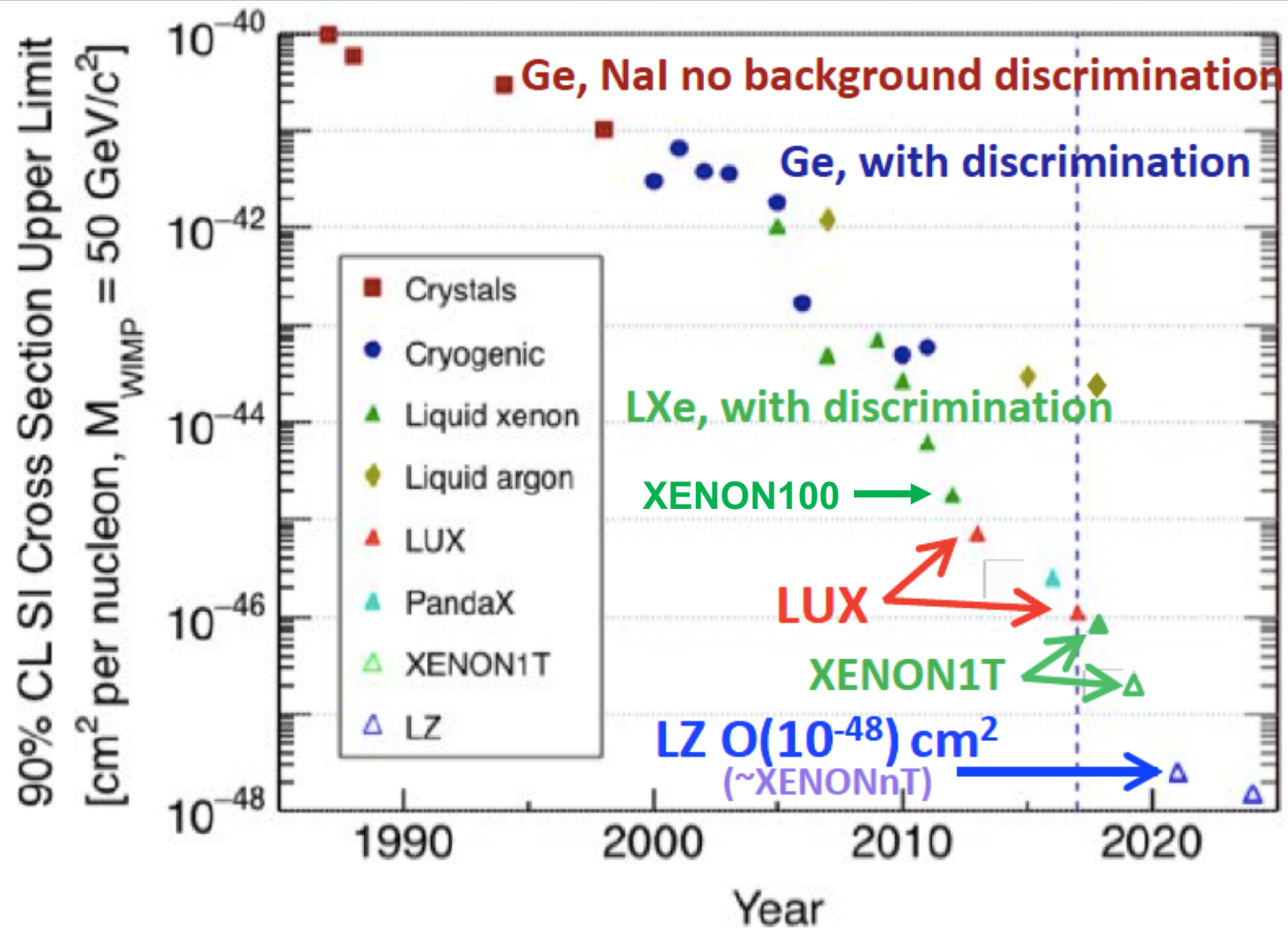


The World Wide Dark Matter Search is on....



Deliyergiyev, [arXiv:1510.06927](https://arxiv.org/abs/1510.06927)

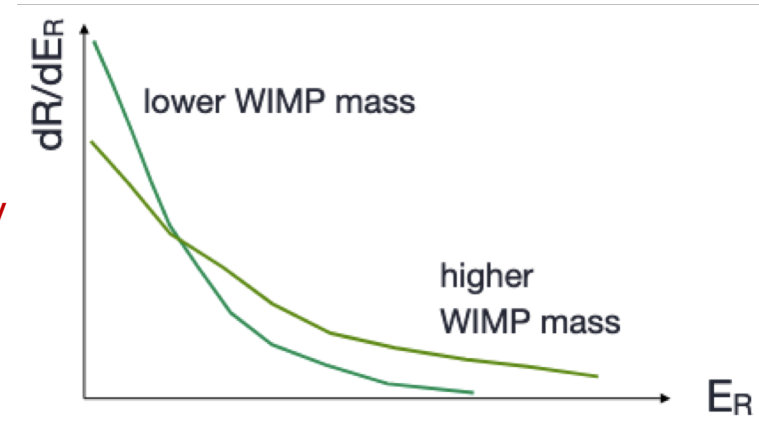
Historical Trend of Direct Dark Matter Searches



Characteristics of Good WIMP Detectors (Direct Detection)

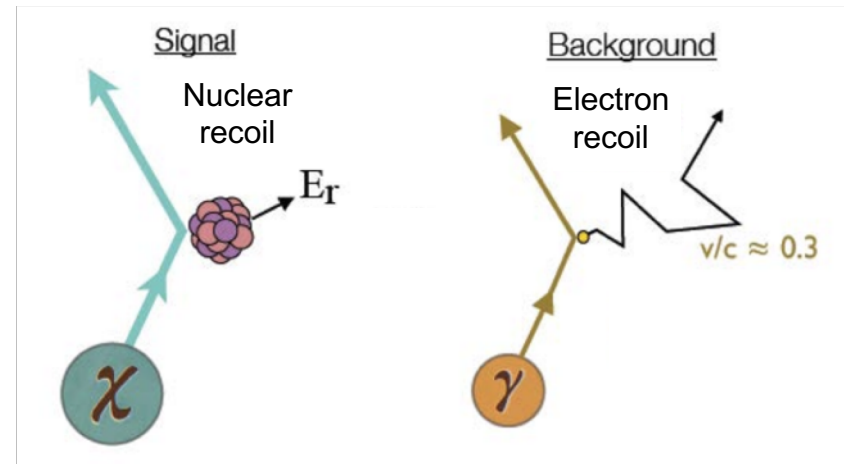
- **Low energy threshold**

- Recoil event rate increasing exponentially with lower threshold
- Lower mass WIMP has lower threshold

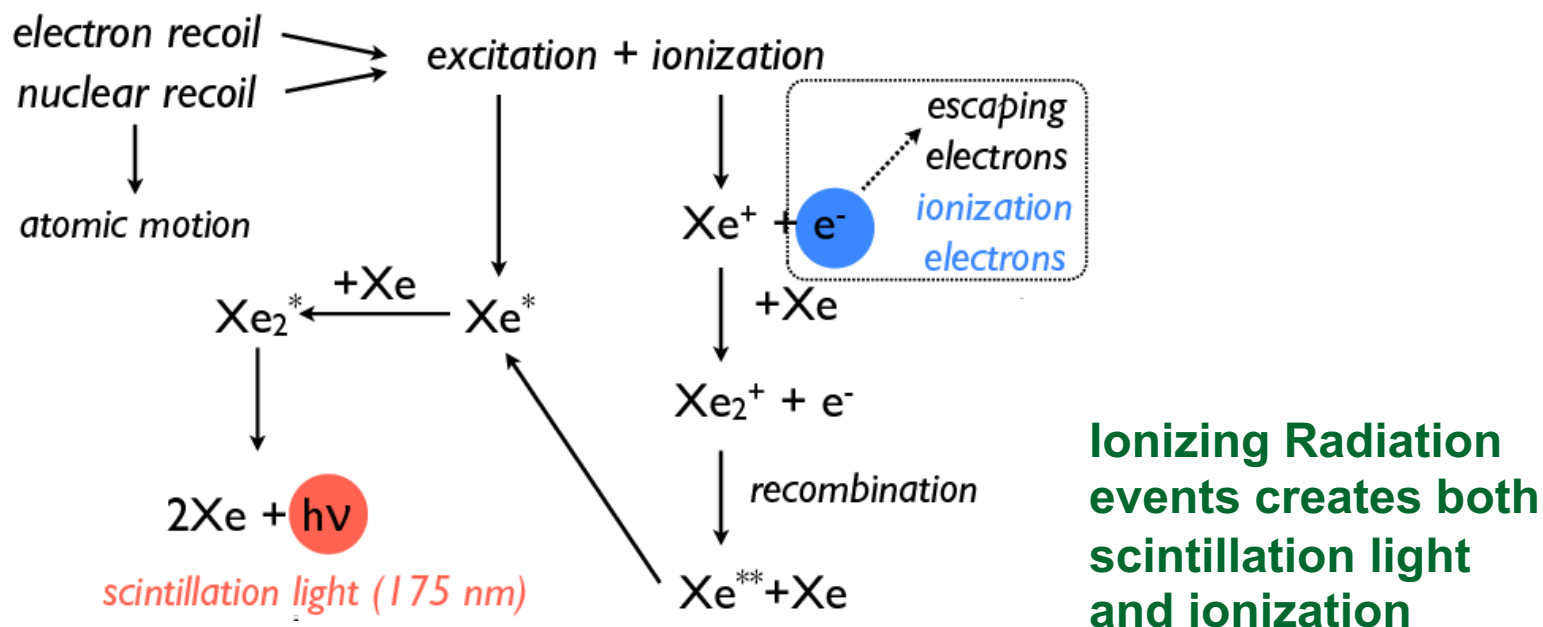


- **Background discrimination (NR vs ER)**

- Gamma and beta backgrounds are electron recoil events, while WIMP scattering are nuclear recoil events
- Need the discrimination to work even at low threshold.



Ionizing Radiation Events in LXe

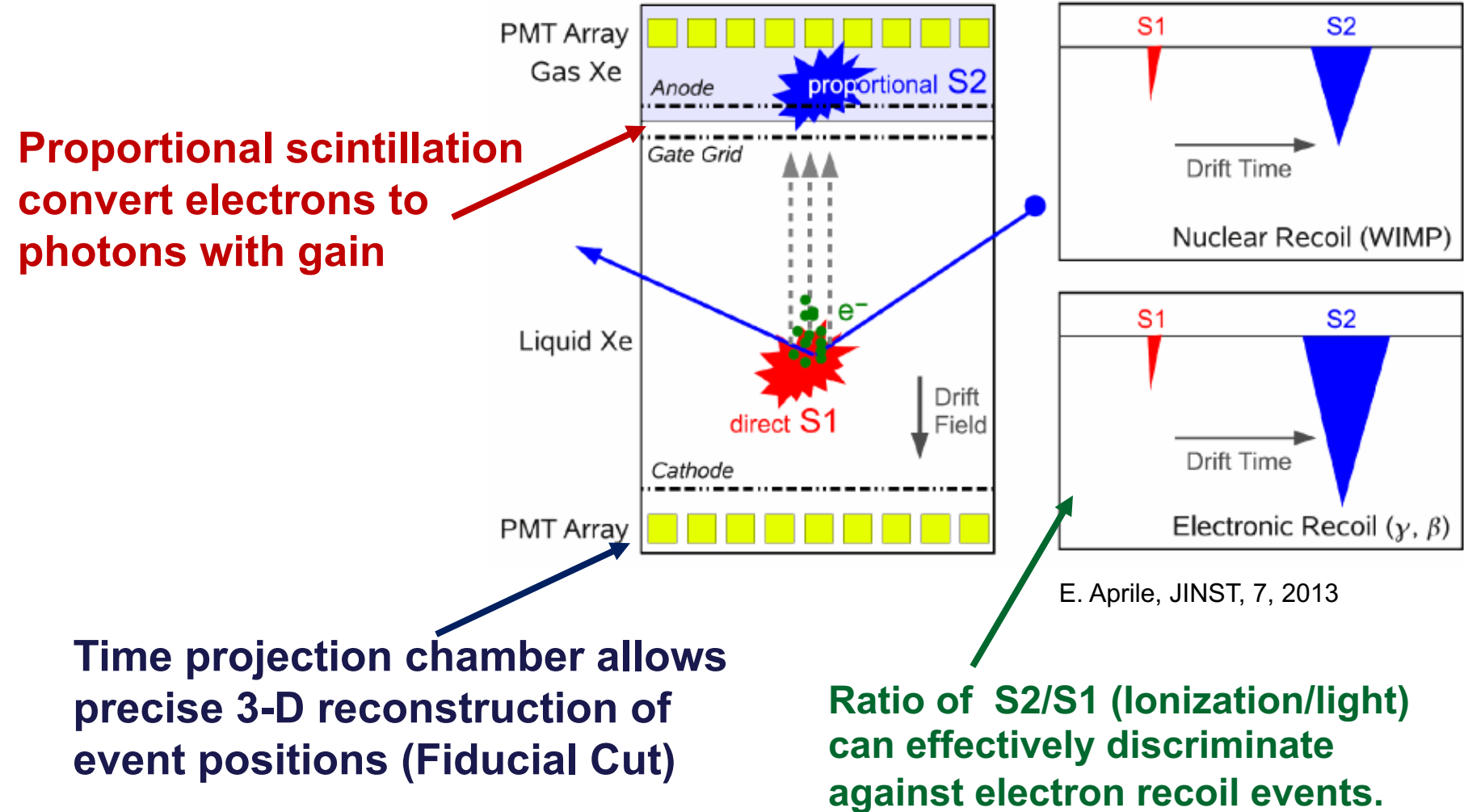


The properties of Xenon does not appear to be favorable at first

- The average energy required to create one electron-ion pair $\sim 10 \text{ eV}$, large than semiconductor $\sim 1 \text{ eV}$ and phonon detector $\sim 3 \times 10^{-2} \text{ eV}$
- The ratio of scintillation and ionization can be used for event discrimination, but the electron signal are too small to detect at low threshold.

Ge detectors and cryogenic bolometers appear to be superior in every way.

Two Phase Time Projection Chamber (TPC) — a Breakthrough Technology

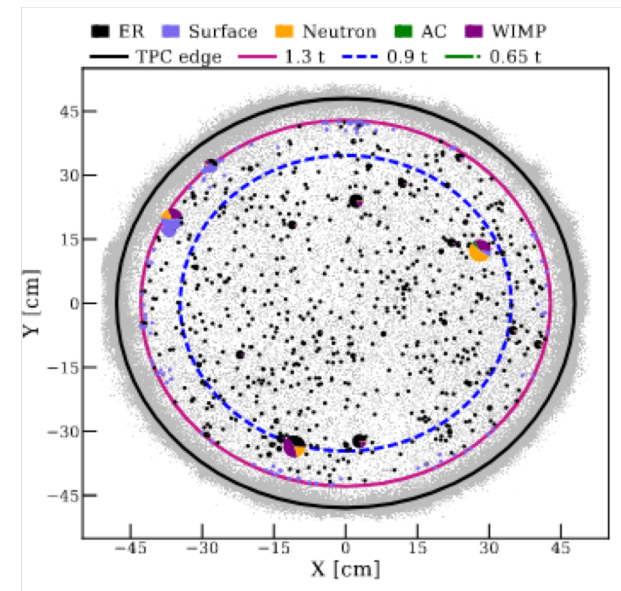


Other Enabling Technologies

- Low background photo-multiplier tubes (PMTs)
 - 100 times lower background than off-shelf units
- Xenon purification
 - Removal of Kr through gas distillation
 - Removal of electronegative impurities with gas purifiers
- Monolithic detector
 - Easy to scale up
 - Self-shielding very effective for low energy events
- Internal calibration sources for NR and ER events

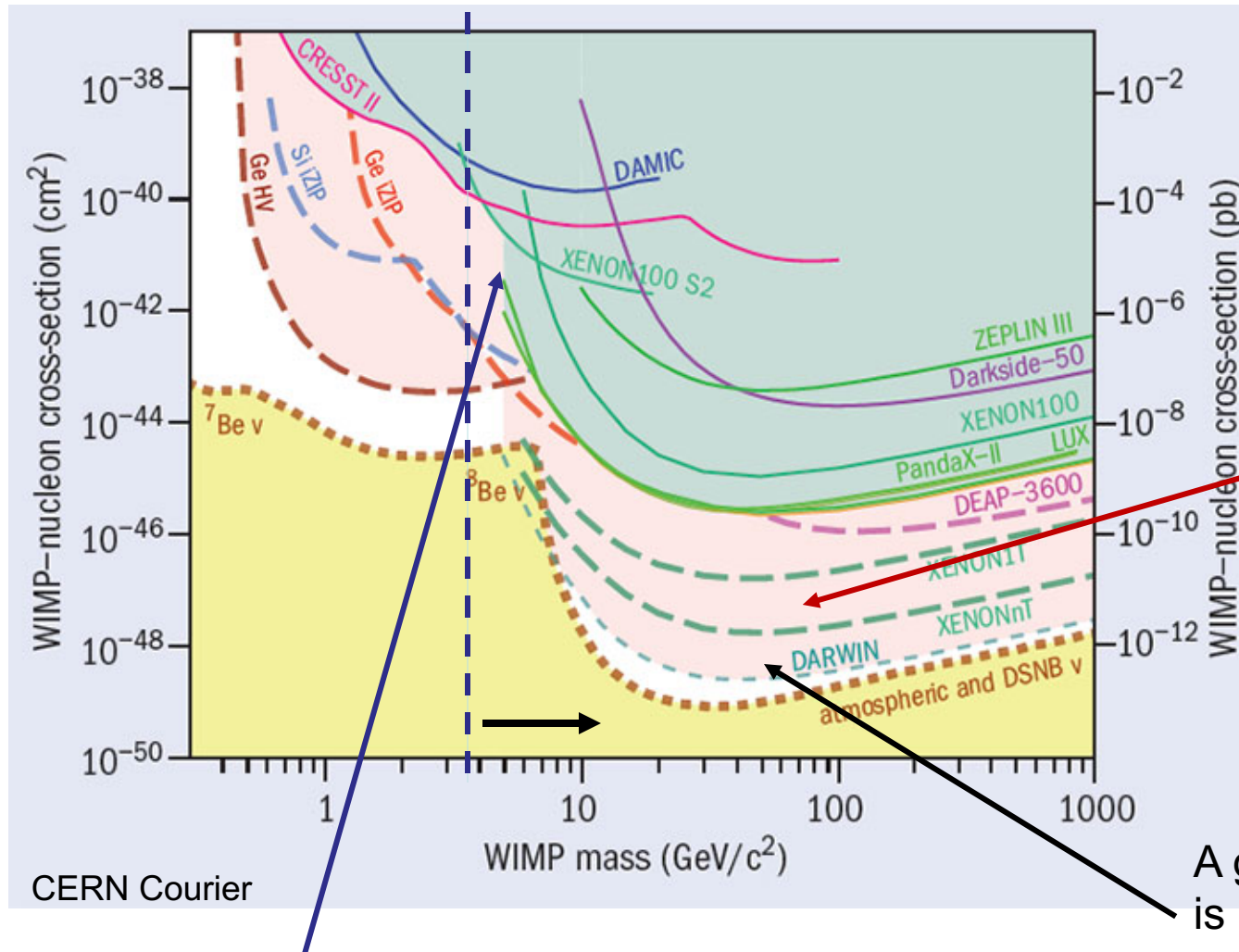


Low background PMTs



XENON1T event distribution

Comparing LXe Detector with Other Technologies

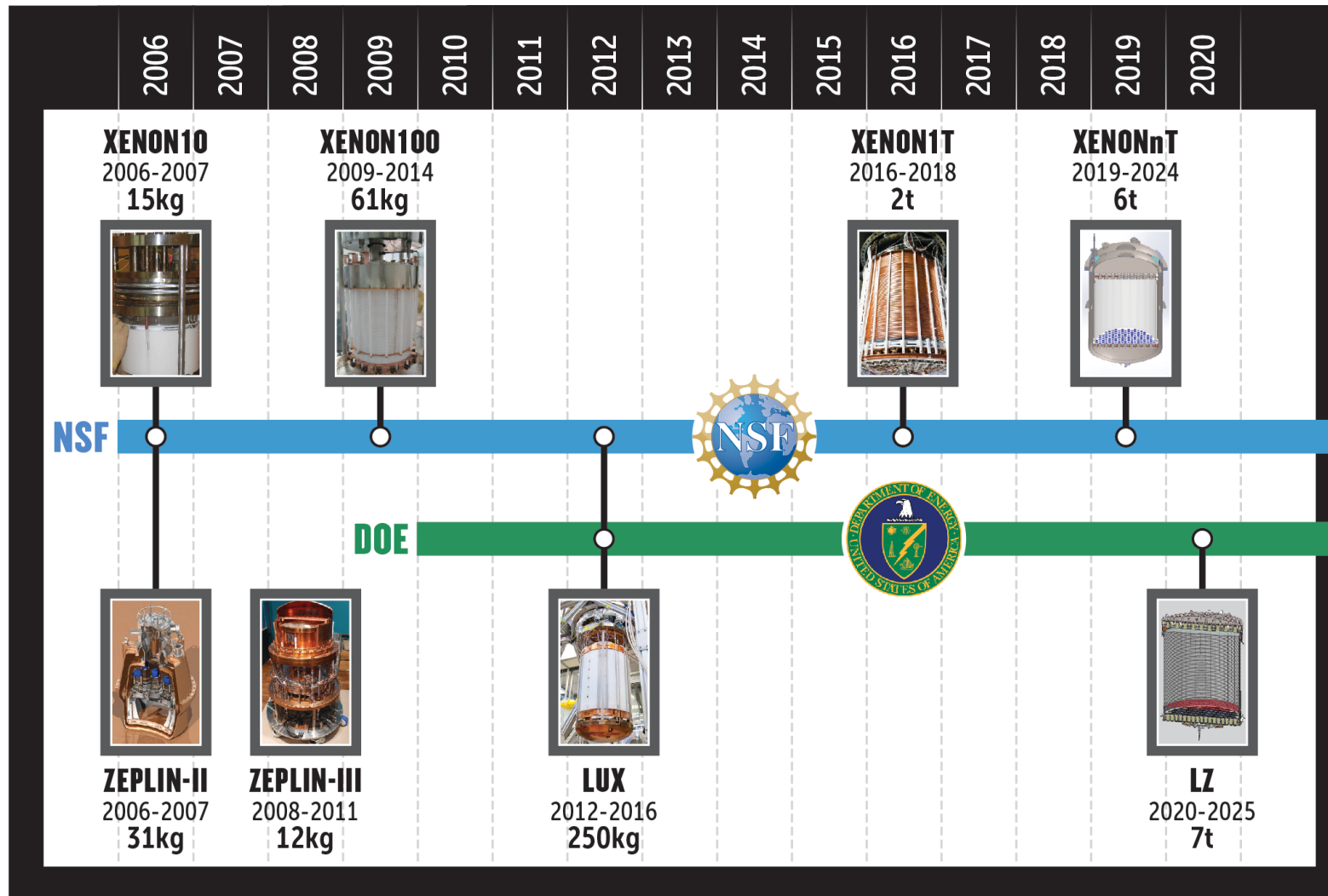


LXe detector is competitive down to 2-3 GeV WIMP mass region, as the state-of-art detectors can detect single electrons from the S2 signal

In the 50 GeV to 100 GeV WIMP mass region, LXe is clearly leading the field.

A generation-3 detector is under planning that can cover the entire phase space down to the neutrino floor.

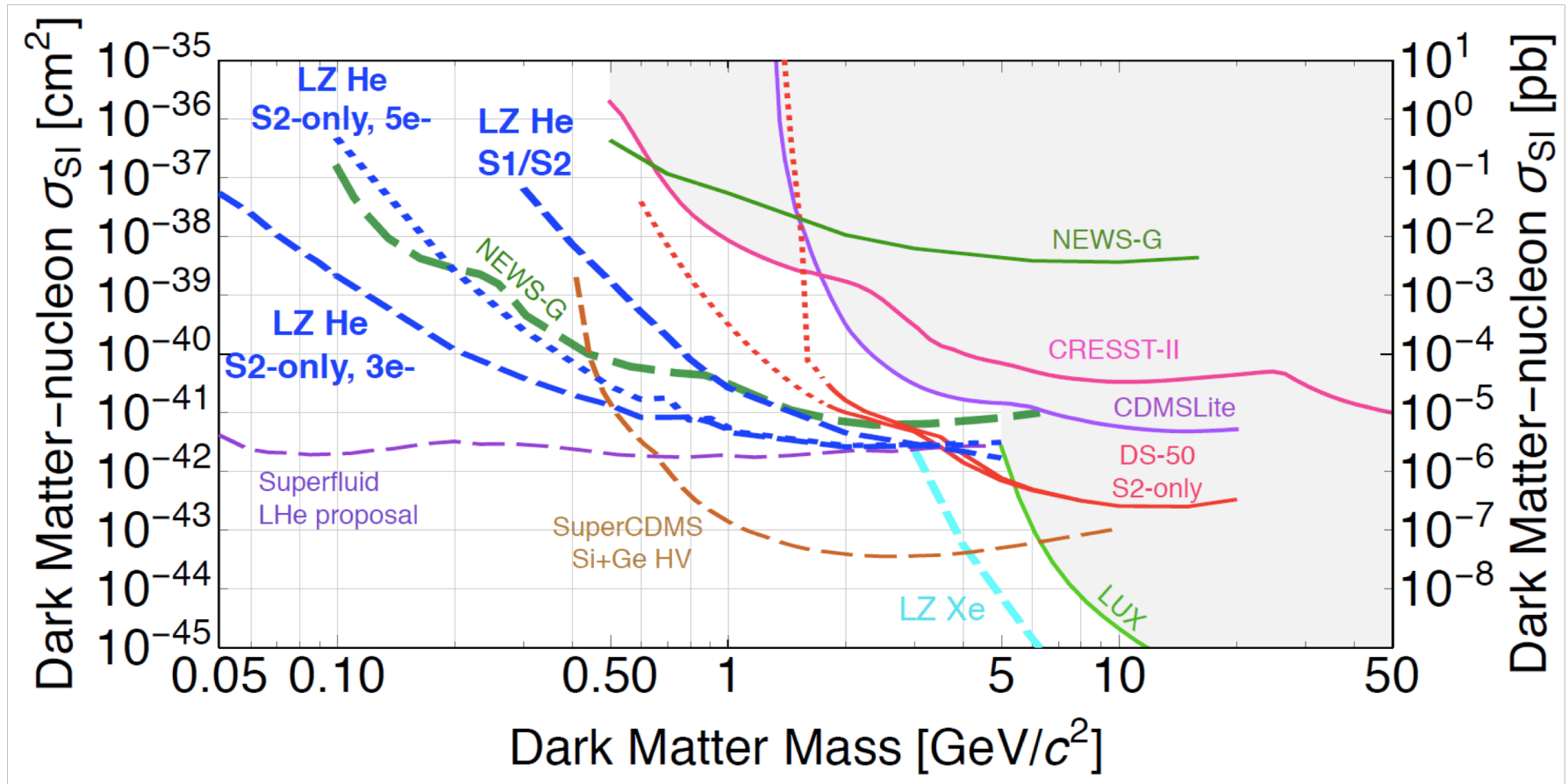
Evolution Liquid Xenon Dark Matter Detectors



?

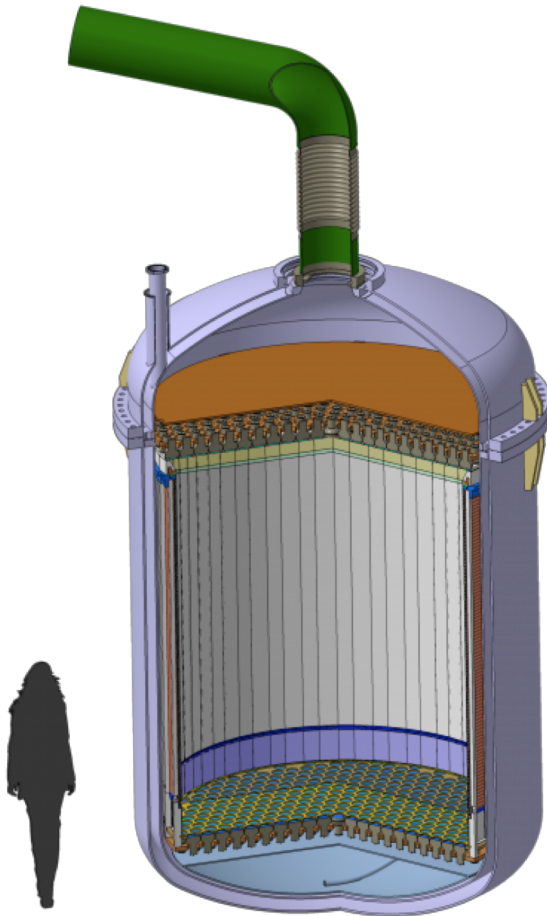
Low Mass WIMP Search

Dope LXe with He or H to search for low mass WIMP

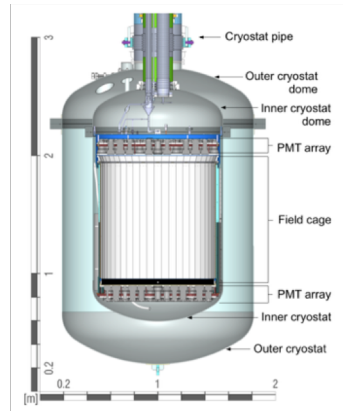


- Use the large low background facility and self-shielding of LXe
- Solubility unknown, needs R&D

Going bigger...



XENONnT



- 30 t fiducial mass (baseline)
- 40 t LXe TPC
- 50 t total LXe mass
- 130 kV HV for 500 V/cm
- ~ 14 m water tank
- 7 x current Xe storage facility

DARWIN (proposal in Europe)

Physics with Liquid Xenon TPCs

Dark Matter:

- spin-independent WIMPs
- spin-dependent WIMPs
- EFT couplings and inelastic WIMPs
- MeV WIMPs (“S2-only”)
- Planck mass dark matter
- Migdal & Bremsstrahlung searches
- Annual modulation searches
- Magnetic Inelastic WIMPs
- inelastic scattering
- axial-vector coupling
- Mirror & luminous DM
- Axion-like particles
- SuperWIMPs
- Dark photons

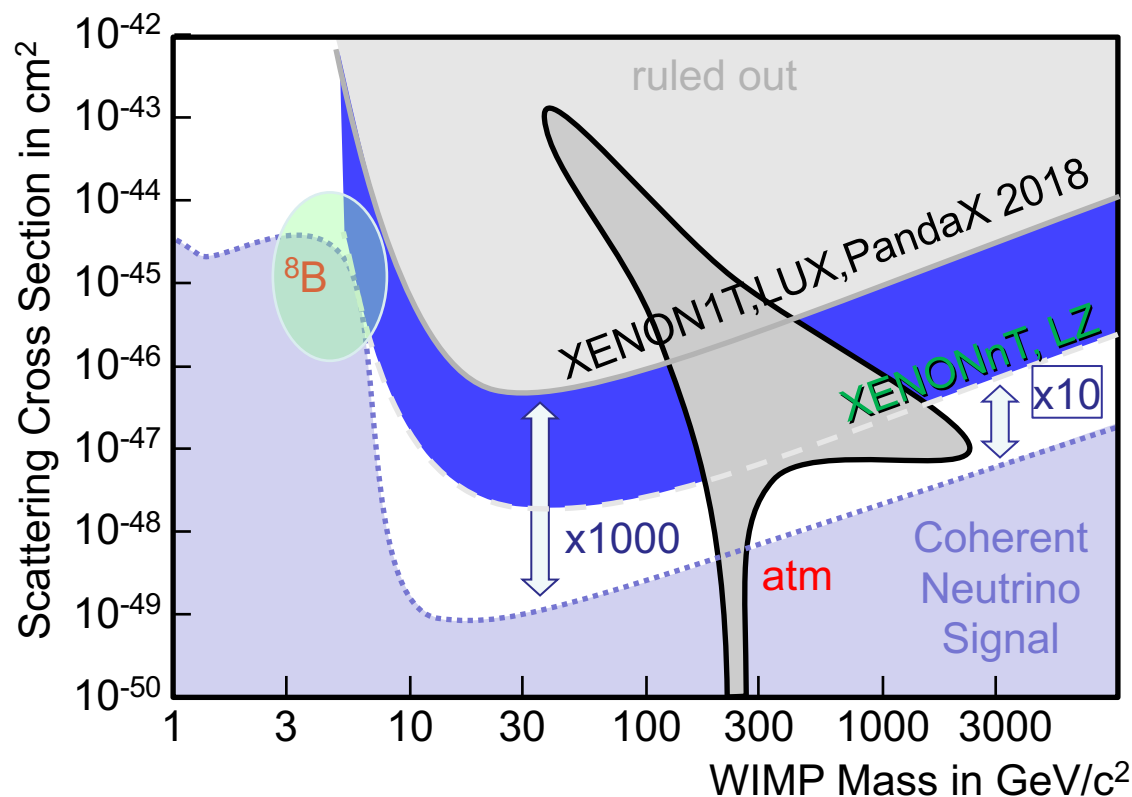
Neutrinos:

- solar pp neutrinos
- Galactic supernovae
- ^8B solar neutrinos
- atmospheric neutrinos
- neutrino oscillations
- sterile neutrinos
- neutrino magnetic moment
- $2\nu\beta\beta$ decay of ^{136}Xe
- $0\nu\beta\beta$ decay of ^{136}Xe
- double-EC on ^{124}Xe

Other:

- solar axions
- fractionally charged particles

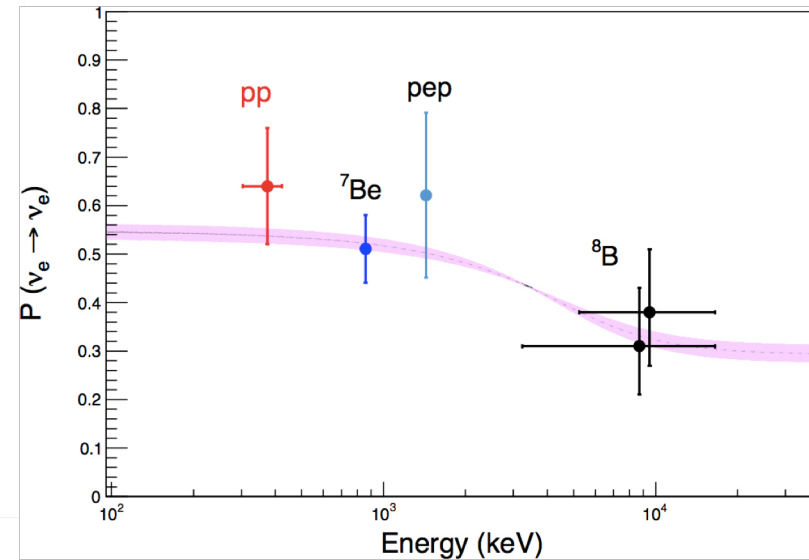
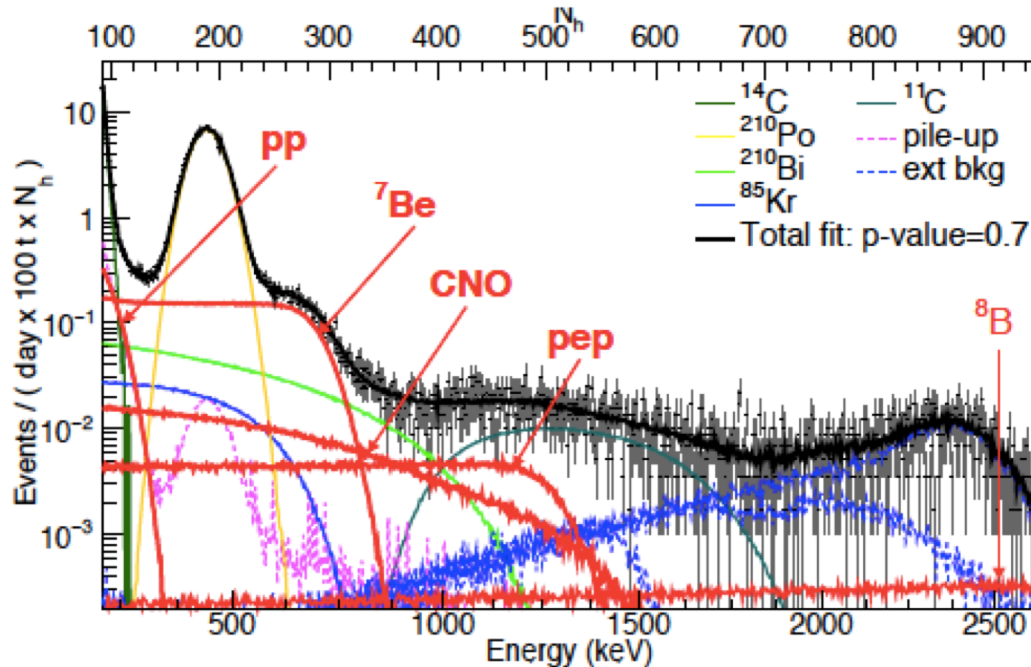
Probing WIMP down to the Neutrino Floor



- There is a large phase space between the G2 experiments and the neutrino floor
- LZ & XENONnT will detect ^8B CE ν NS.
- But CE ν NS from atmospheric vs requires generation-3 experiment

Solar Neutrino Spectroscopy

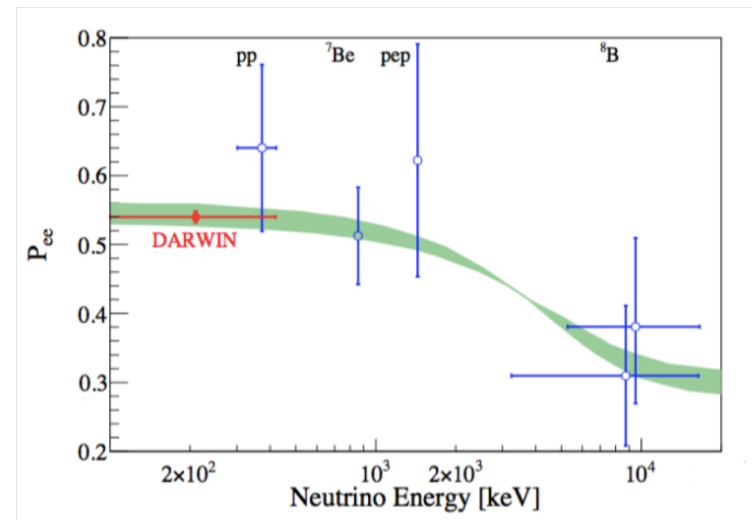
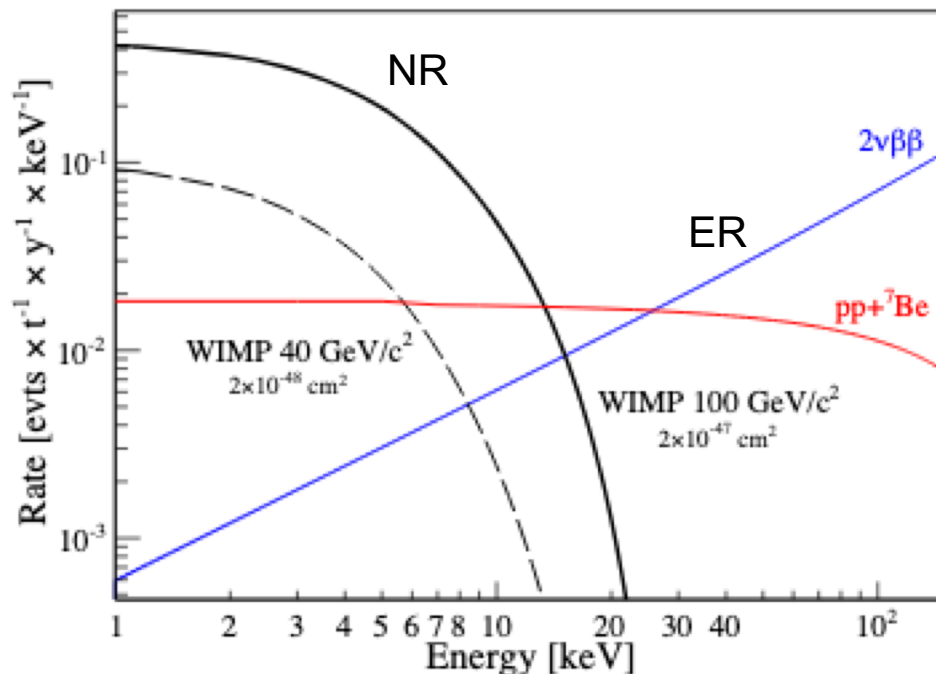
(Liquid scintillator)



- Multicomponent spectral analysis of low energy solar neutrinos
- 2.7% precision on ^7Be
- Strongest upper bound on CNO neutrinos
- Measurement limited cosmogenic and radioactive backgrounds

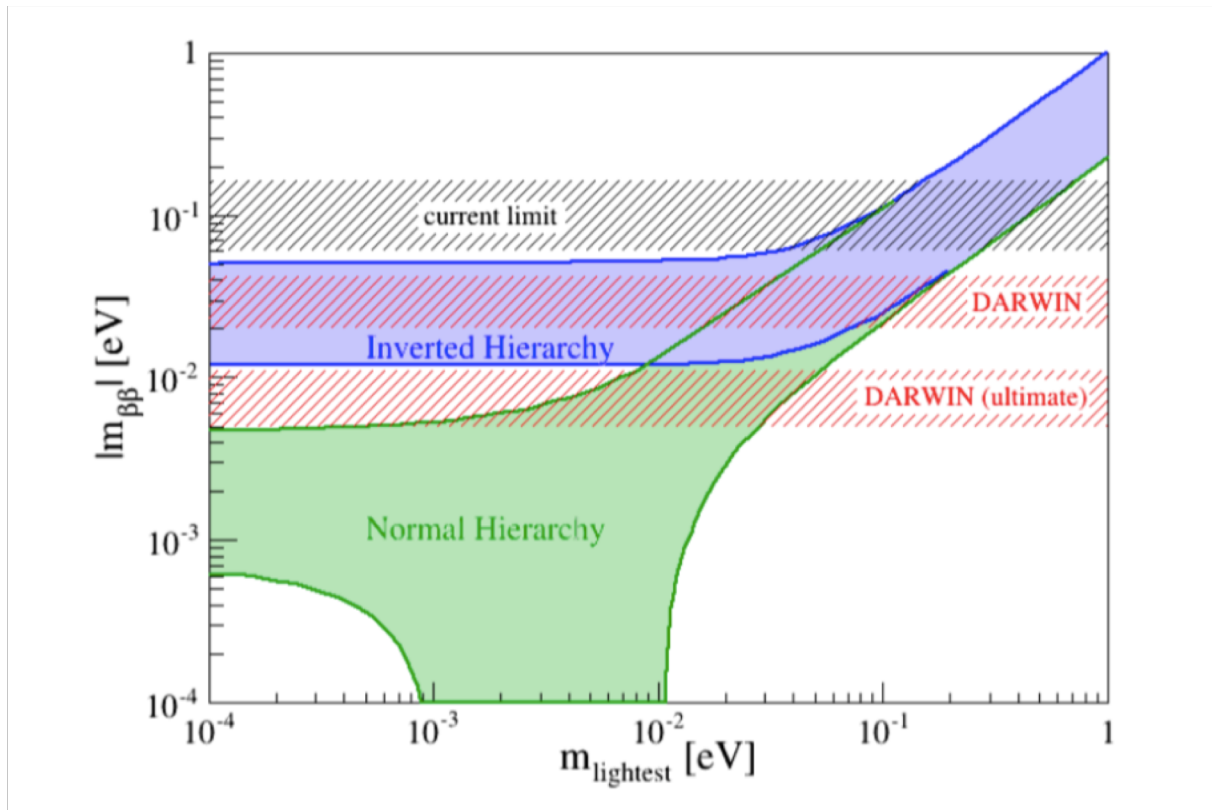
Solar Neutrino Spectroscopy (LXe)

- Improving the Standard Solar Model requires 1% precision measurement of the pp neutrino
- G3-detector will have enough statistics, but ^{136}Xe $2\nu\beta\beta$ presents an irreducible background
- Depleted xenon may directly measure the CNO neutrinos

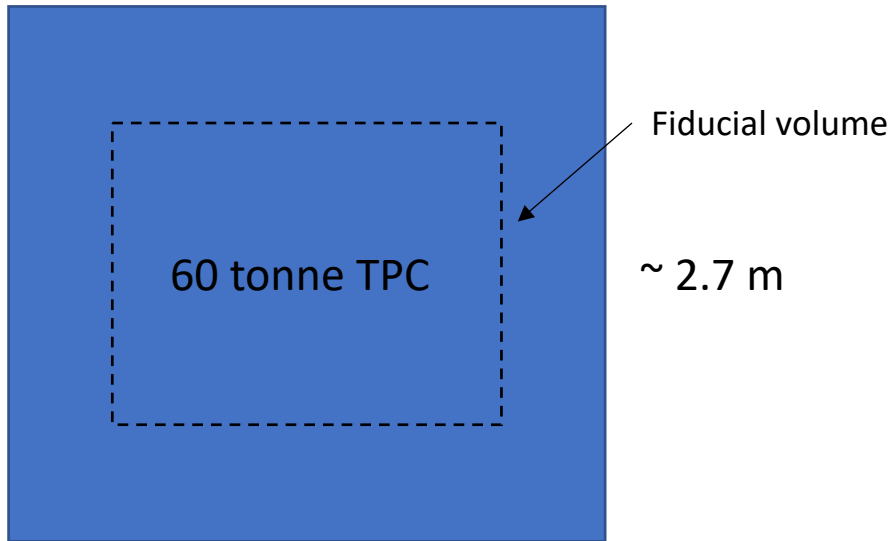


Neutrinoless Double Beta Decay

- ^{136}Xe , 8.9% natural abundance
- Different energy scale, keV vs MeV
- Although 1% energy resolution may be achievable, need to demonstrate β/γ discrimination



Radioactivity and self-shielding



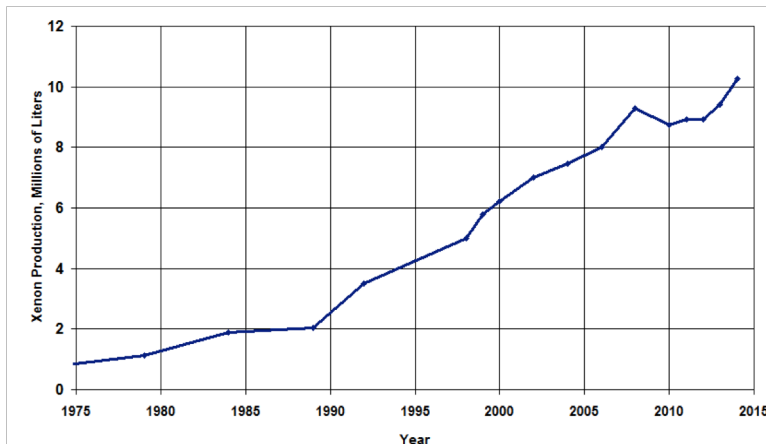
Schematics of a G3-DM detector

- LXe shelf-shield works really well for low energy events.
- However, for 2.5 MeV gamma, the attenuation length is about 8.5 cm.
- To reduce the background by 100, it needs about 60 cm shielding
- Fiducial volume will be $\sim 20\%$, translates to about a factor of 3-5 loss in $0\nu\beta\beta$ sensitivity
- No effective β/γ discrimination, contribute to another factor of 3-5
- There is also a conflict with the solar neutrino physics channel

Is It Feasible to Obtain so Much Xenon?

Global Production of 53 metric tonne/year

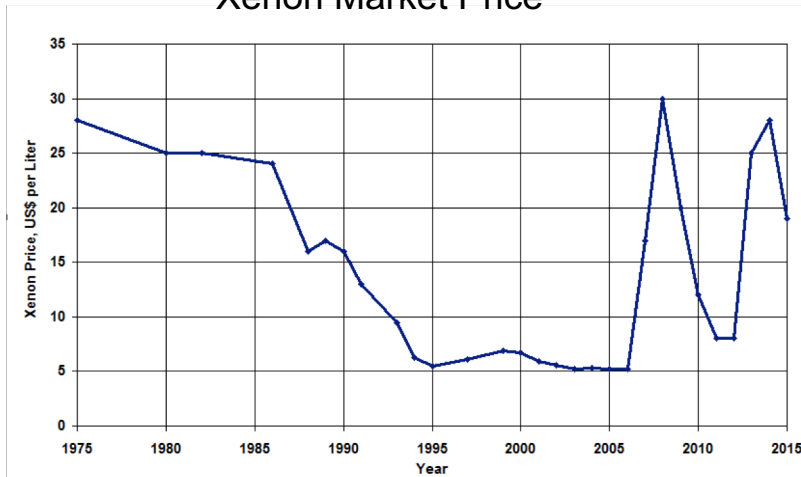
Worldwide Xenon Production



Applications

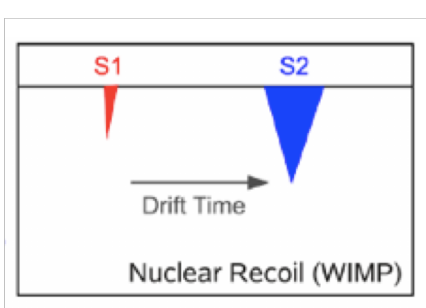
- Light bulb
- Plasma display
- Detectors
- Dark Matter
- Anesthesia
- Semiconductor etching
- Solar electric propulsion (NASA)

Xenon Market Price



NASA is looking into missions that will need 100 metric ton, perhaps a national stockpile of xenon

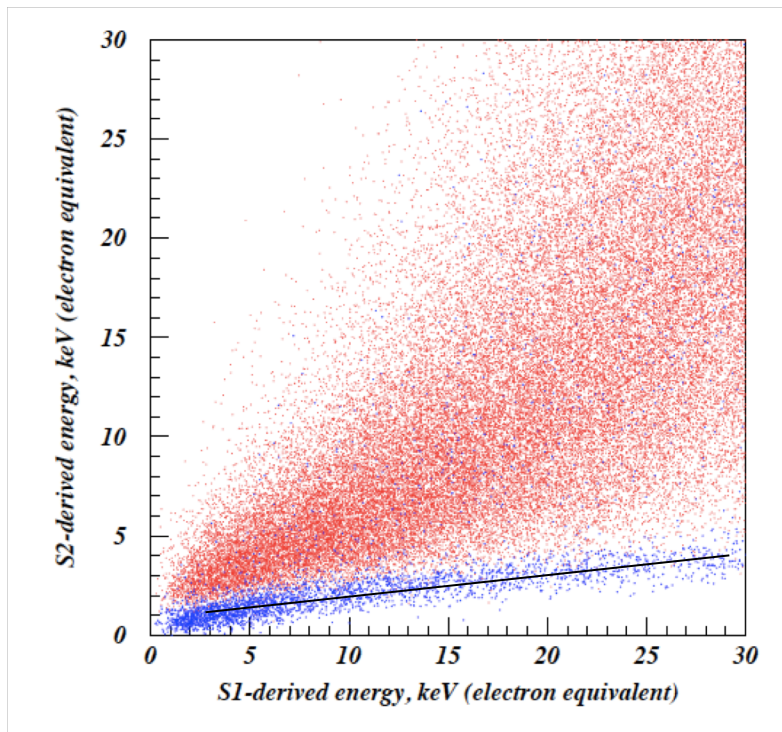
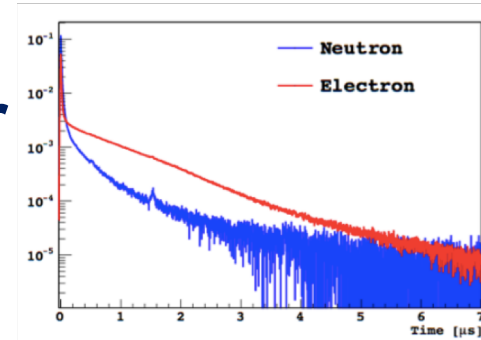
Synergy between G3-DM and nEXO



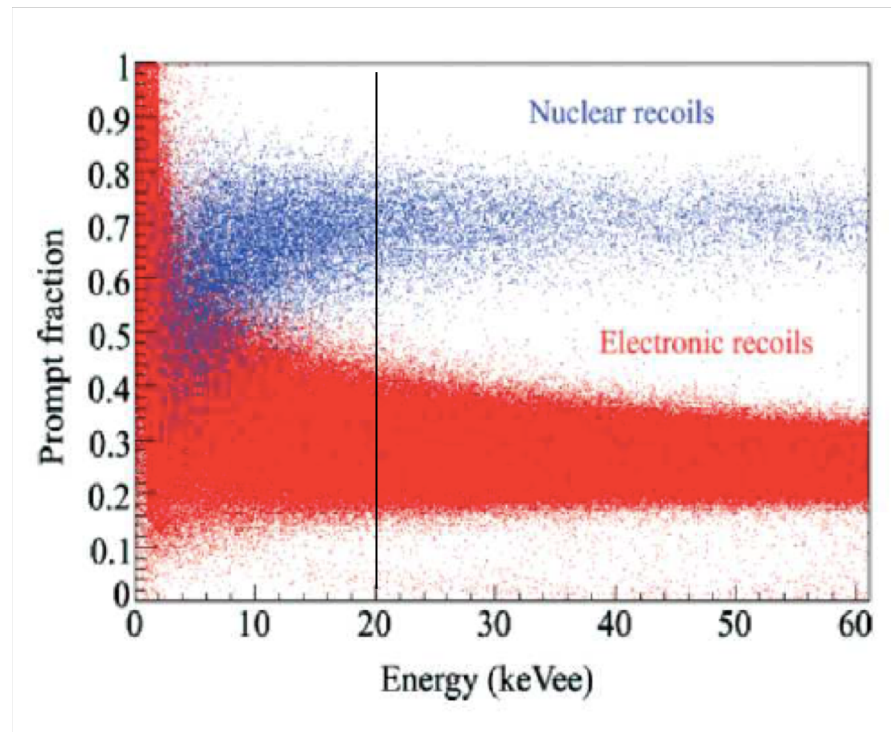
LXe

vs

LAr



LXe is actually not very good at ER rejection, to achieve 99.5% rejection, NR acceptance is only 50%



LAr has PSD (shape of S1) up to 10^{-9} , but only at high threshold, i.e. high mass WIMP, > 100 GeV

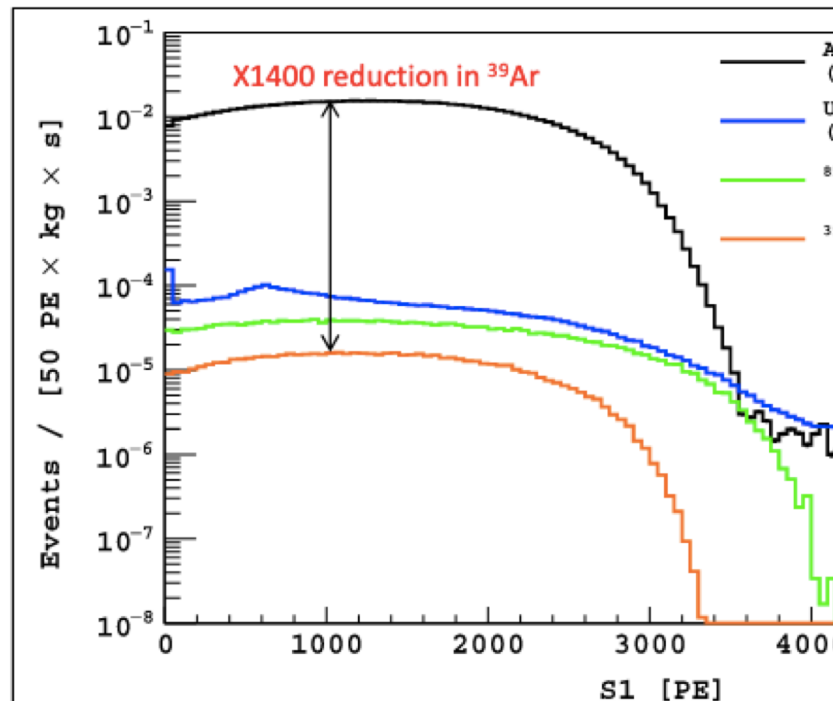
Underground Ar is necessary for ton-scale detector

Atmosphere Ar price ~ \$.50 per 100 g, Xe price \$120 per 100 g

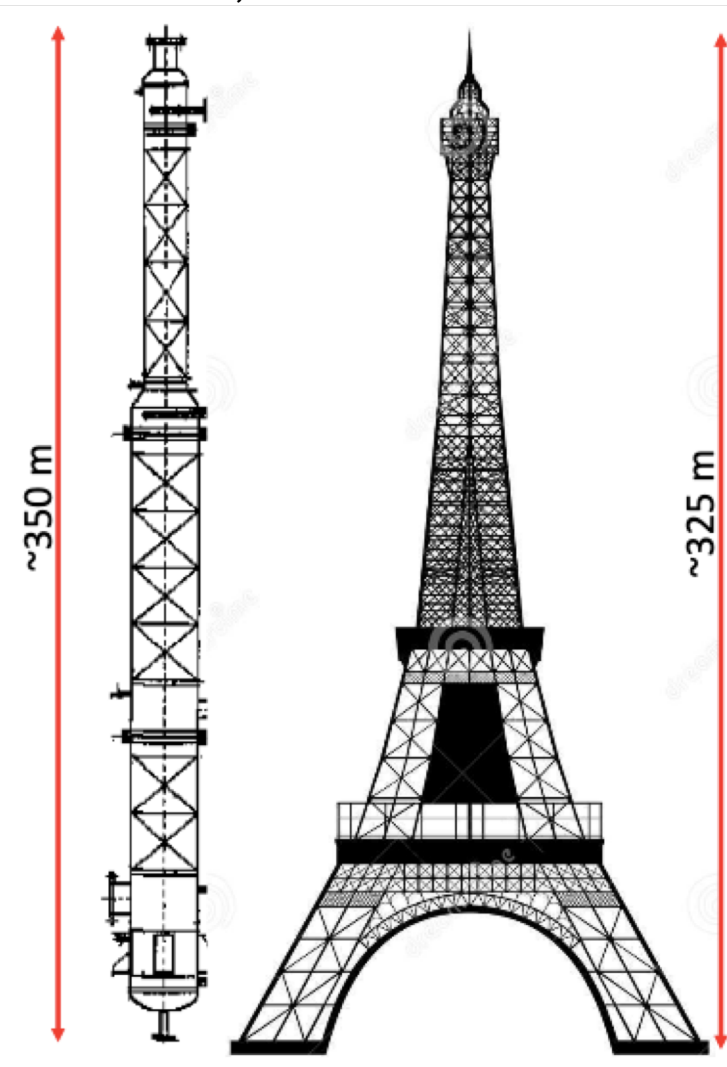
Underground Ar, reduced the ^{39}Ar , by a factor of 1,000

Large investment in infrastru

Another factor of 10 reduction will be
cryogenic distillation, for the 300 t



P. Agnes et al. (DarkSide Collaboration), Phys. Rev. D



Technical Challenges for G3 Detector

- **Radon** emanation from detector material
 - Dominant internal ER background
- Outgassing from **PTFE** and all detector materials
 - Difficult to achieve ~ms electron lifetime (~meter long drift length)
- **PTFE** charge-up and field distortion
 - Surface background from PTFE panels
 - Limitation to obtain a larger fiducial volume
- Light and electron emission from electrodes (HV issues)
 - Limitation to achieve a higher drift field
 - Contribute to accidental coincidence background
- Large detector background, limiting sensitivity to solar neutrinos and $0\nu\beta\beta$

Radon background in Xe Detectors

Experiments	Active LXe mass (ton)	^{222}Rn (^{214}Pb) Concn. ($\mu\text{Bq/kg}$)	Total Radon in the Active Target (mBq)	^{214}Pb ER events /ton/year	Solar neutrino ER events /ton/year	References
XENON100	0.06	38~77	2.3~4.6			1708.03617
EXO-200	0.12	360/98.5 ~ 3.6	0.44			1205.5608
LUX	0.25	~32	8.0			A LUX talk
PandaX-II	0.6	7.7	4.6			1708.06917
XENON1T	2.0	5.1~12.6	10~25			1805.12562
PandaX-4T	4.0	1*	4*	36/9 keVee	30/9 keVee	1806.02229
XENONnT	6.0	1*	6*	62/10 keVee	36/10 keVee	1512.07501
LZ	7.0	1.8*	13*	44/5 keVee	17/5 keVee	1802.06039
nEXO	4.0		1.8			

* goals

Electron lifetimes in the past/current Xe detectors

Experiments	Active LXe mass (ton)	Max. drift length (cm)	e- lifetime (μ s)	References
XENON100	0.06	30	294~720	1609.06154
EXO-200	0.12	20 x 2	200 us -> 3 ms	1707.08707
LUX	0.25	48	640~950 (R3) >1 ms (WS14-16)	1712.05696 1608.07648
PandaX-II	0.6	60	348->623->850->940	1708.06917
XENON1T	2.0	97	380->650->1 ms	1805.12562
PandaX-4T	4.0	120		1806.02229
XENONnT	6.0	144	~1 ms*	
LZ	7.0	146	850*	1802.06039
nEXO	4.0	130	> 10 ms	

* design parameters

Limiting HVs in LXe Detectors

Experiments	Active LXe mass (ton)	Max. drift length (cm)	cathode voltage (-kV)	Drift field (V/cm)	References
XENON100	0.06	30	16 -> 15	533 -> 500	1609.06154
EXO-200	0.12	20 x 2	8 -> 12	400 -> 600	1707.08707
LUX	0.25	48	~10	~200	1712.05696 1608.07648
PandaX-II	0.6	60	29 -> 24	480 -> 400	1708.06917
XENON1T	2.0	97	12 -> 8	120 -> 80	1805.12562
PandaX-4T	4.0	120	48*	400*	1806.02229
XENONnT	6.0	144	30~50*	200~350*	
LZ	7.0	146	50~100*	300~700*	1802.06039
nEXO	4.0	130	50	400*	

* design parameters

XENON1T – Emanation results

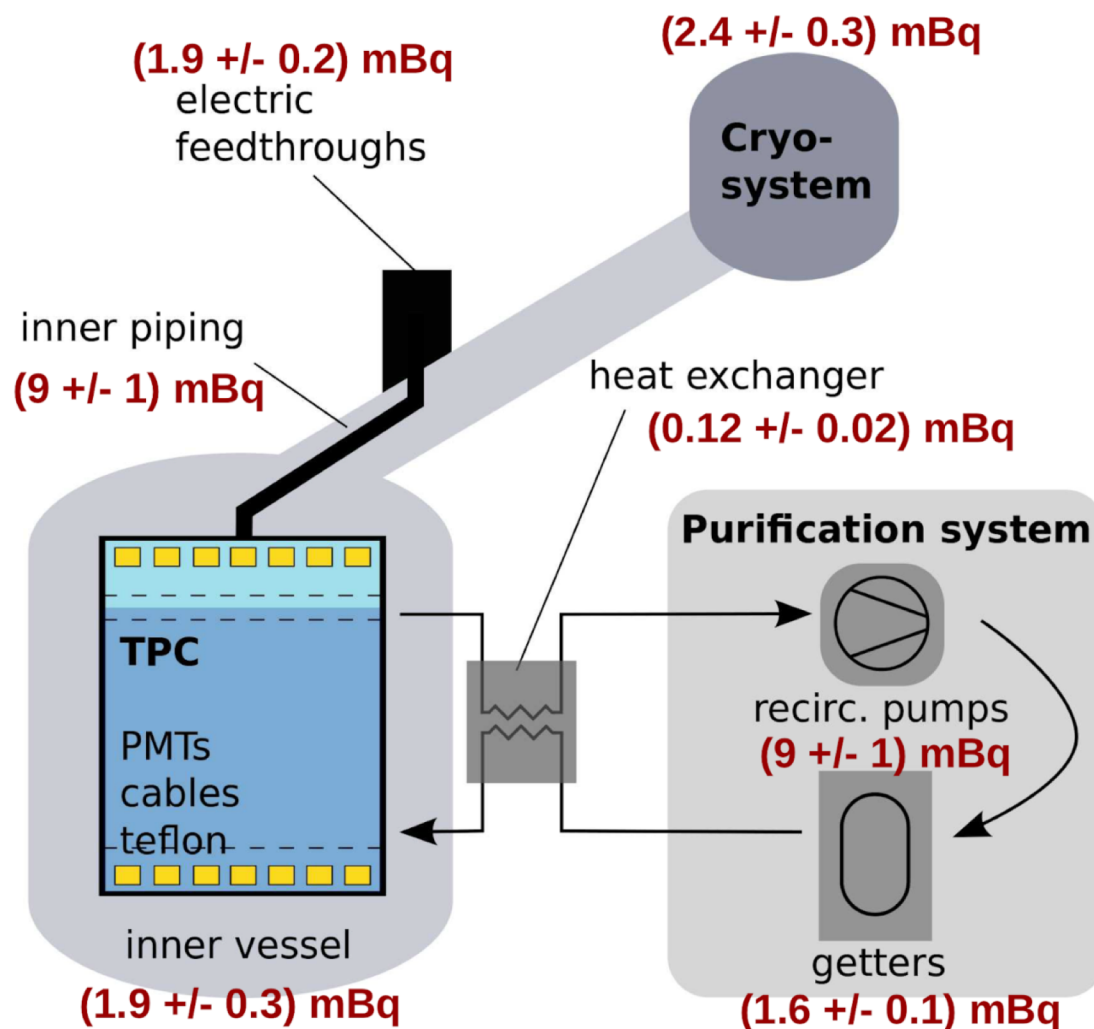
Stefan Br nner (MPIK),
July 08, 2016



Integral measurement of the cryostat including TPC

preliminary result:

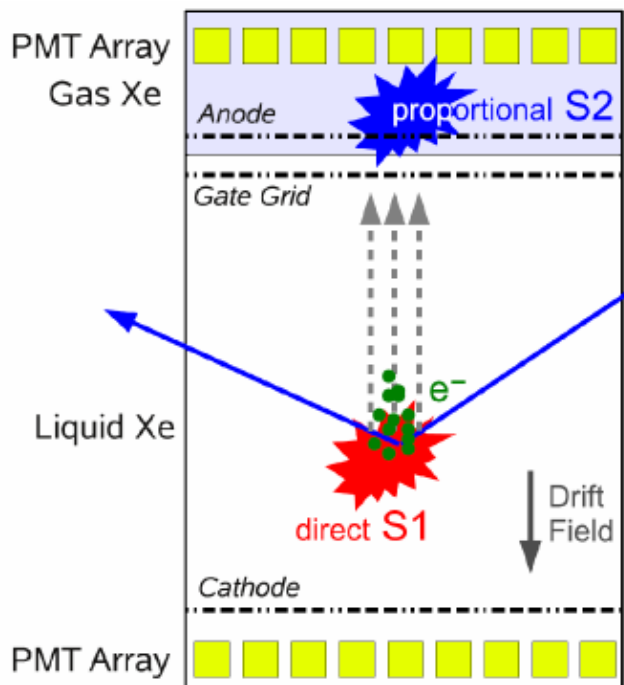
(19 +/- 4) mBq



High Voltage R&D

- High voltages in noble liquids for high energy physics, (Fermilab HV workshop summary), arXiv:1403.3613
- **Problems** of stainless steel (wire or mesh) electrodes in liquid xenon
 - Local strong field on wire/mesh edges
 - Malter effect (enhanced electron emission with positive ions)
 - UV light induced emission (on metal surface and negative ions in the liquid)
 - Bubbles
- **Acid treatment** to reduce the electron emission (single wire), Tomas et al. arXiv:1801.07231 (the enhanced emission related to wire surface quality, corrosion, and oxide layer)

Photodetectors in G2 Dual Phase TPC (LXe, LAr)



Schematics of a dual Phase TPC
Schematics of a dual Phase TPC



XENON1T top and bottom PMT arrays



LZ TPC active volume and skin PMTs

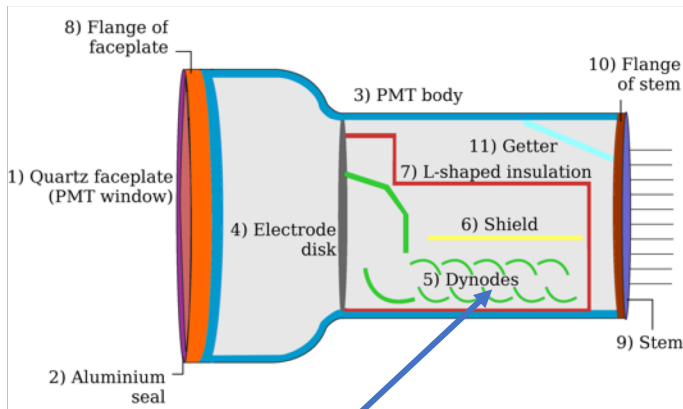
- Hamamatsu R11410 PMT is the detector for choice of the G2 experiments
- 30% Quantum efficiency at 175 nm
- 1000 times less radioactivity than Off-the-shelf PMTs

Why look for alternatives for the G3-Detector

- Cost
- Radioactivity
- Spatial resolution

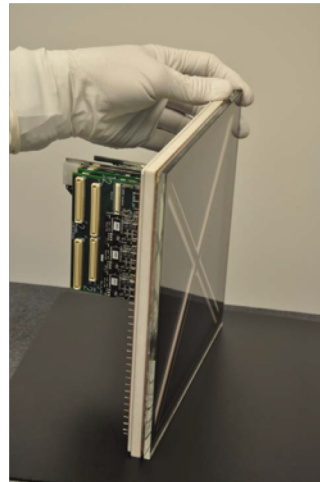
Option 1: Vacuum based photodetectors

Internal structure the R11410 PMT
Eur.Phys.J. C75 (2015)



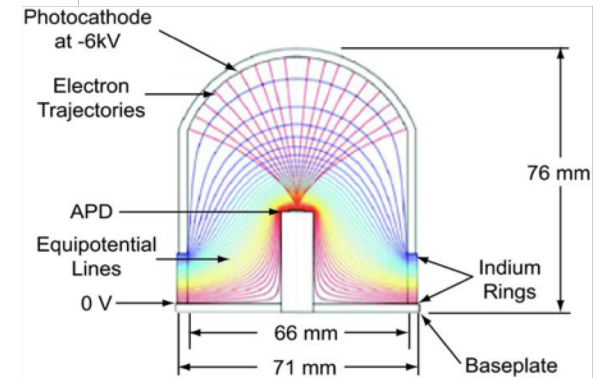
Replace the dynode structure with MCP, or silicon detectors

Large Area Picosecond Photo Detector (LAAPD)



- Use multichannel plate for electron multiplication
- Better timing and spatial resolution, likely low cost, but worse radiopurity

Quartz Photon Intensifying Detector (QUPID)

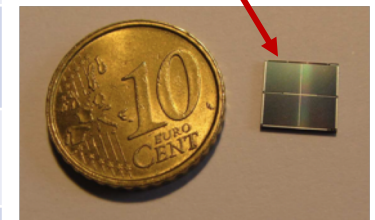
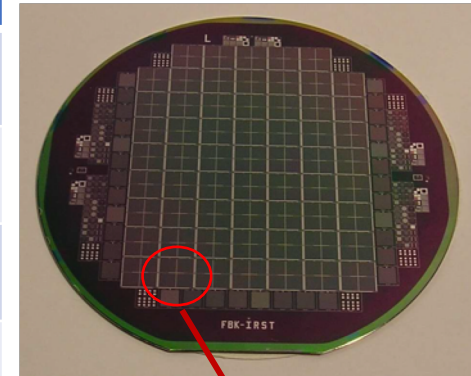


E. Panticet al. NIM-A695(2012)121

- Use avalanche photodiode for signal amplification
- Timing improvement, moderate gain in cost and radiopurity

Option 2: Silicon photomultipliers (SiPMs)

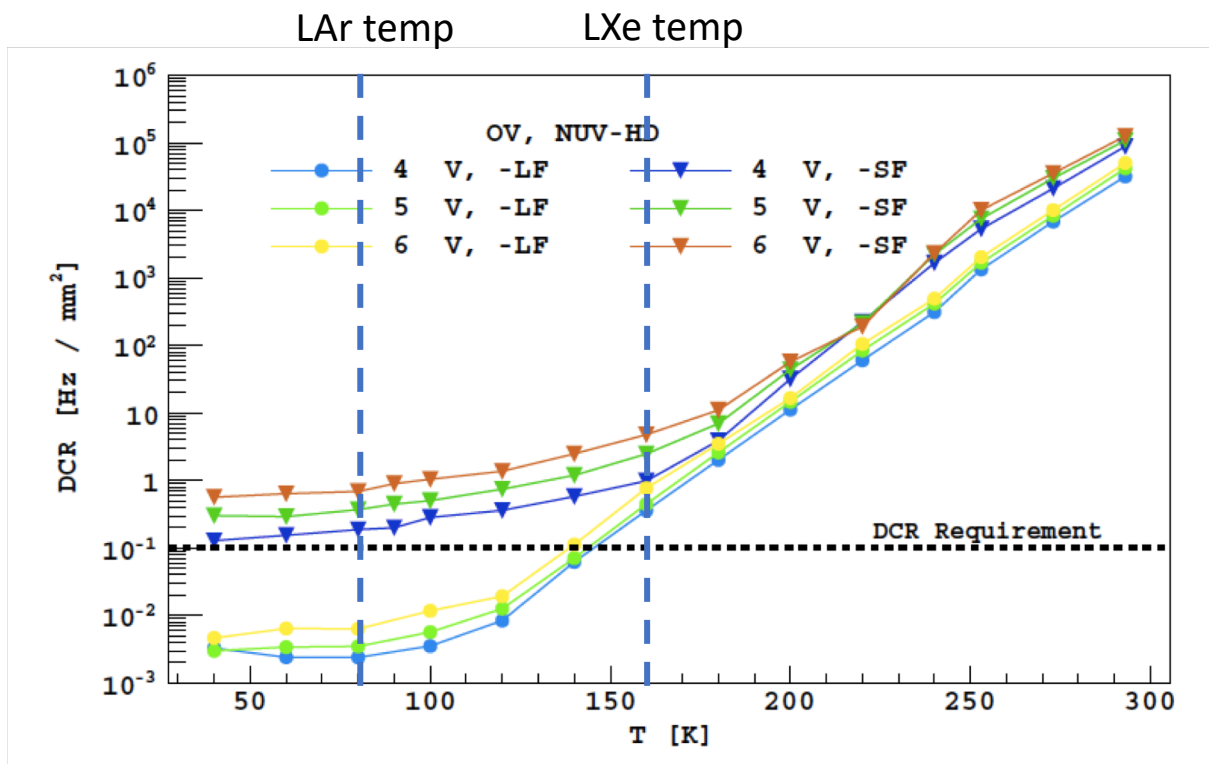
	PMT (Hamamatsu)	SiPM (FBK)
QE (PDE)	> 30%	> 15%
Dark counts (Hz/mm ²)	~ 0.01	~ 0.5
Correlated noise	~ 10%	~ 20%
Capacitance	< 10 pf/in²	~ 10nF/in ²
Radioactivity (U/Th)	~ 0.1 mBq /in ²	~ 0.1 μBq/in²
Cost (sensor only)	~ 1.5 M\$/m ²	~ 0.5 M\$/m²
Sensor unit size	~ 40 cm ²	1 cm²



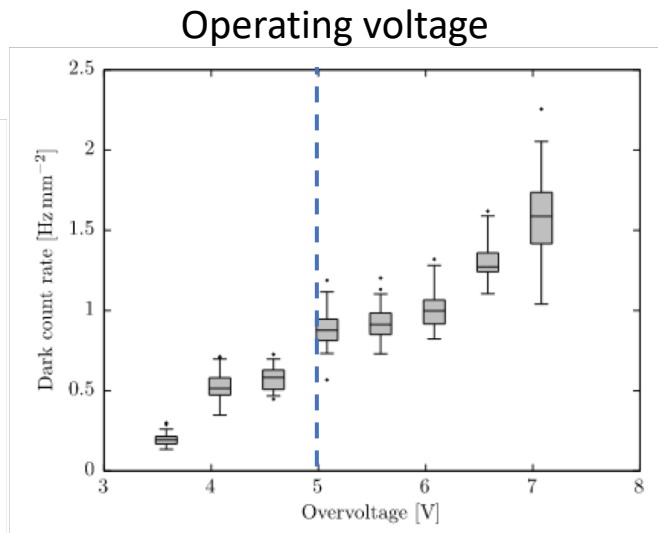
FBK SiPM 2x2 array

SiPM technology is fast developing. It already wins in terms of cost, radioactivity and spatial resolution. Can it overcome drawbacks in other areas?

Dark noise



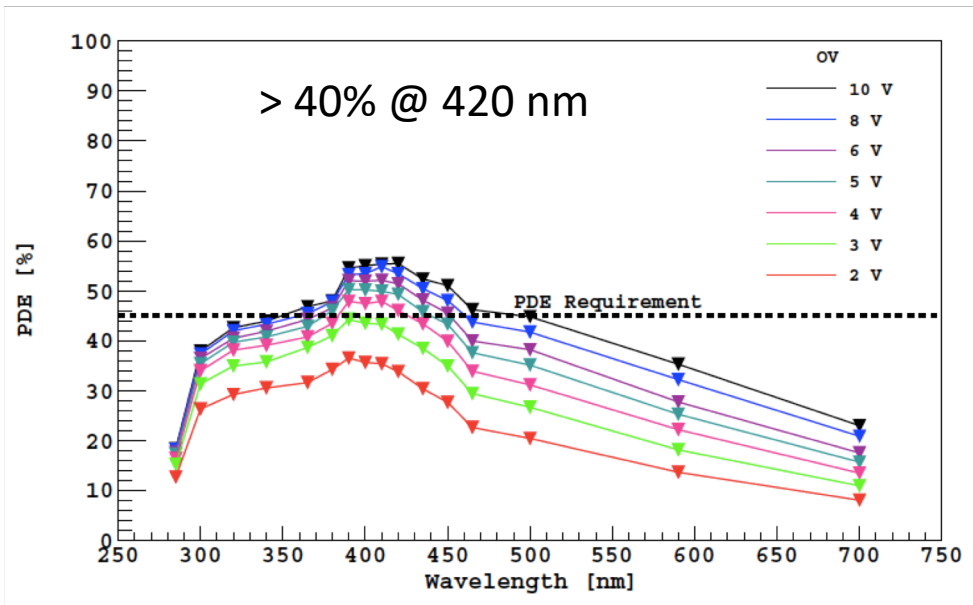
Dark noise of FBK device developed for DarkSide
FERMILAB-PUB-17-298-PPD



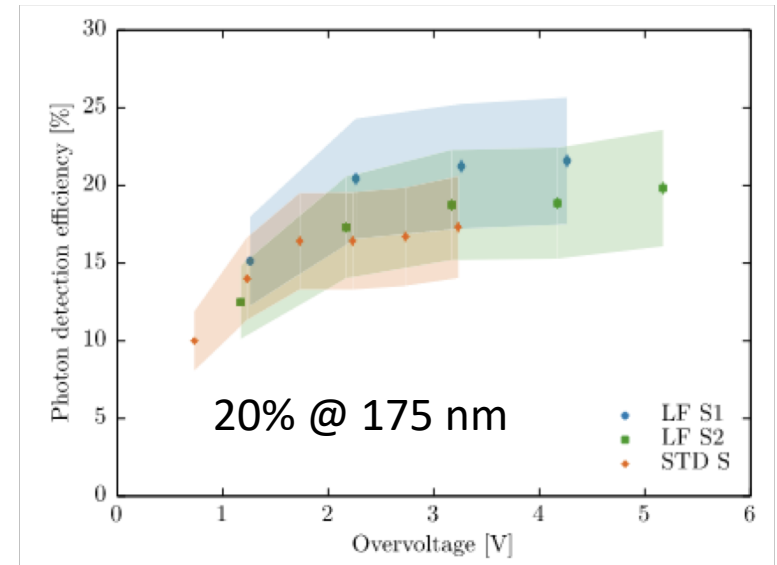
FBK UV sensitive SiPM dark noise

- Current generation SiPM dark noise at LXe temp is about 1 order of magnitude too high
- Further reduction in DCS is possible with new manufacturing techniques

Photodetection efficiency



PDE versus wavelength for a NUV-HD-SF SiPM at 300 K.
(darkside collaboration)

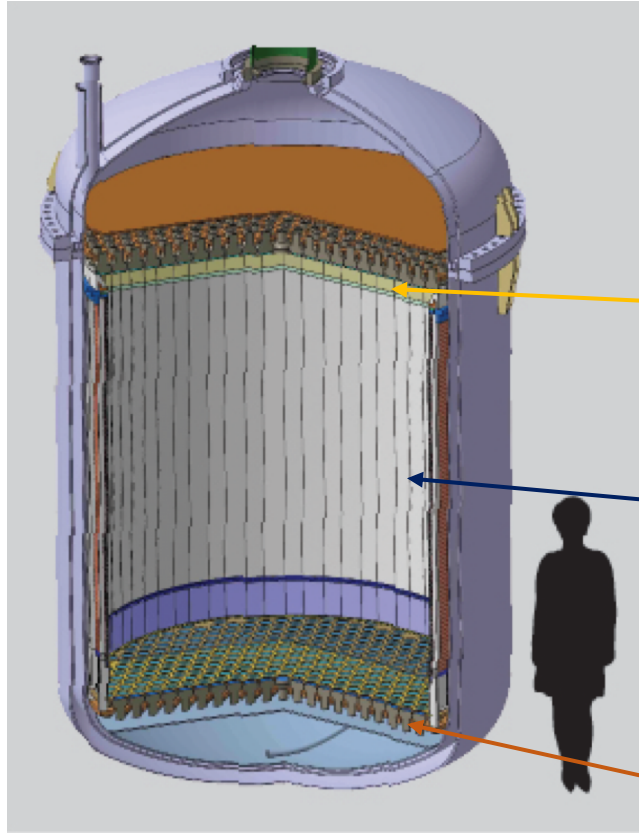


VUV SiPM from FBK for nEXO

- Wavelength shifter poses purity issue for LXe detectors
- Direct detection of 175 nm light has ~ 20% PED, up to 50% possible with AR coating

Conceptual Design for a G3 Detector

Current conceptual design based on a scaled up version of XENONnT and LZ



Conceptual design for
DARWIN, G3-DM

Replacing the top (bottom) PMT arrays with SiPM arrays, low background, better spatial resolution

Remove the Teflon reflectors and go to 4π photodetector coverage

Use buffer liquid for cooling and pressure balancing so the TPC vessel can be built with thin wall copper

These design changes and other ideas need both R&D and engineering studies

Path Forward

- DARWIN has secured R&D funding in Europe
- G3-DM effort in the US is seeking R&D funding

White paper describing science goals in 2019

Next four years, community building, R&D and technical design report.

New groups and people are welcome to join the effort.