LAr Doping for low-energy sensitivity of LArTPCs

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CPAD 2022

Fermilab

OVERVIEW

Photosensitive dopants (dopants that convert light into charge) might change what is achievable for small signals in LAr experiments.

Improvements to energy resolution at the MeV scale would also improve the physics sensitivity of **low-energy physics signals of interest** in current LArTPC experiments.

A low-energy LArTPC R&D program can **expand the physics reach of future LArTPCs** and by enabling new physics below the 10s of MeV.

LARTPC PHYSICS ENERGY RANGE

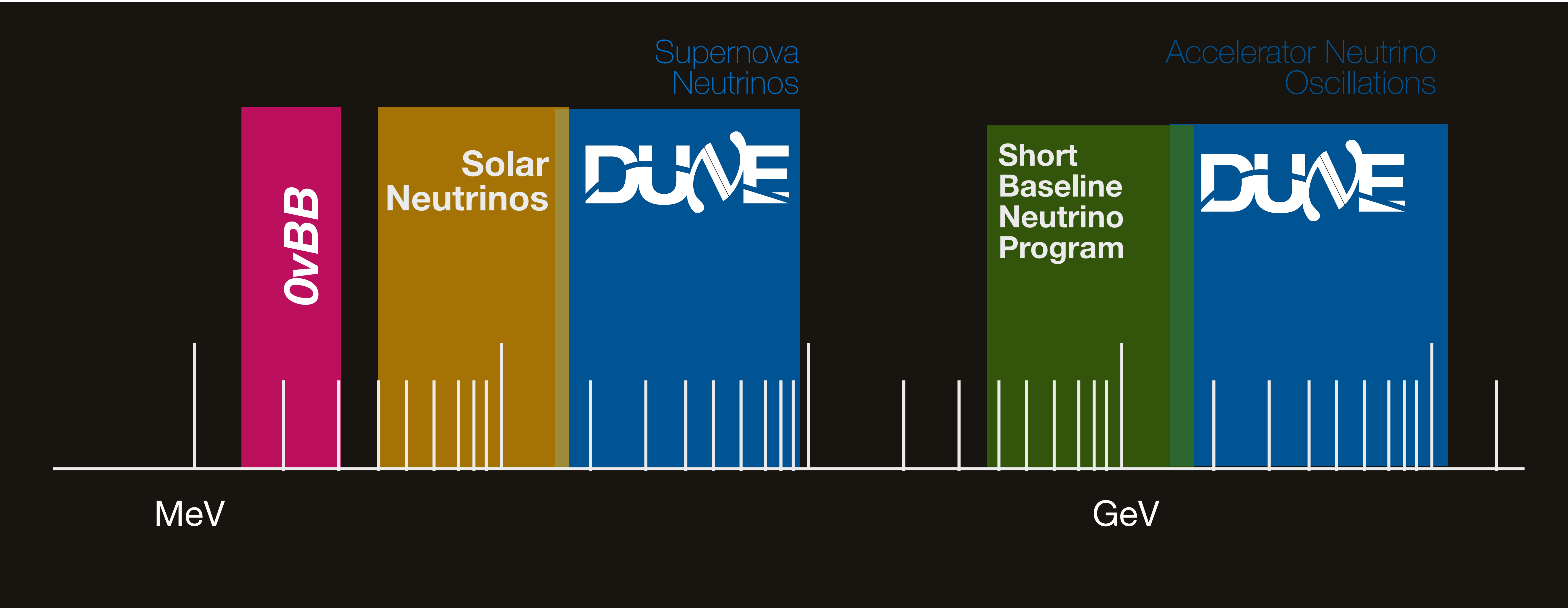
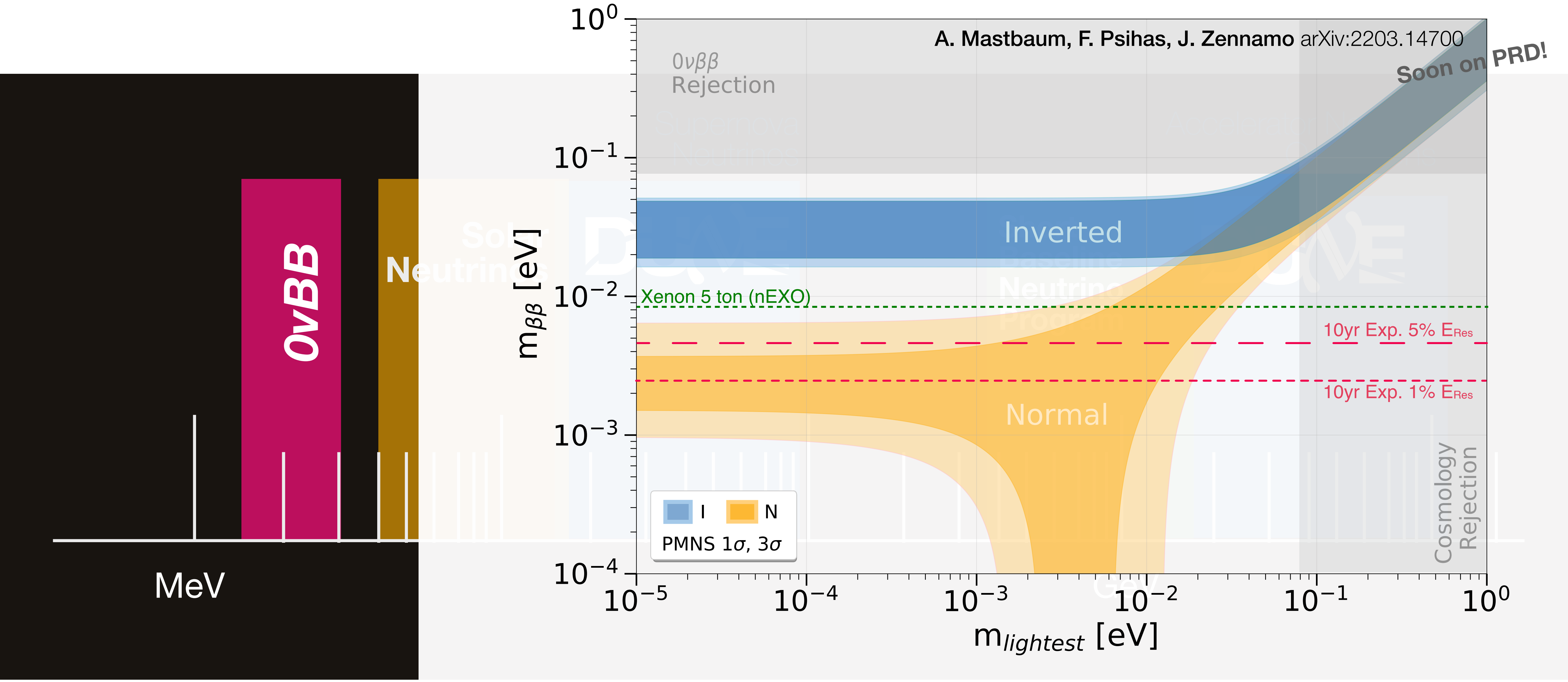


Photo-sensitive dopants can improve

Photo-sensitive dopants can enable

A 0νββ Sensitive kton LArTPC



A. Mastbaum, F. Psihas, J. Zennamo arXiv:2203.14700

Soon on PRD!

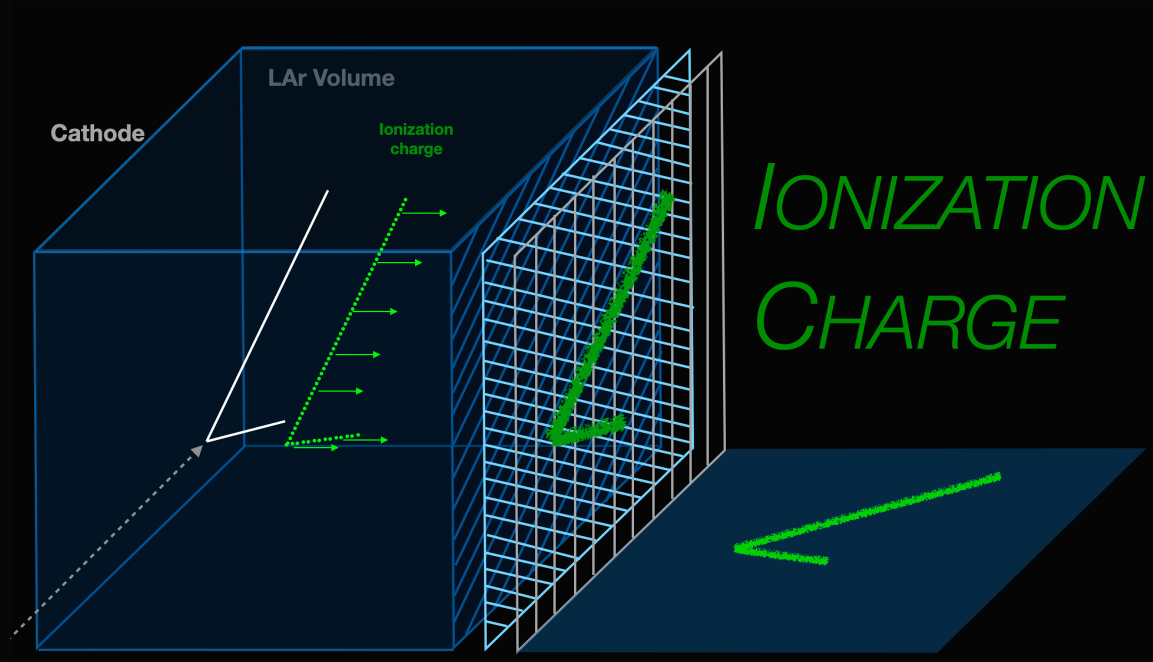
DUNE-β Concept

- ⚖️ Xenon doping at 2%
- 💡 Monolithic LAr TPC
- ❗ Depleted argon
- ⚖️ <3% energy resolution
- 💡 **Photosensitive dopants**

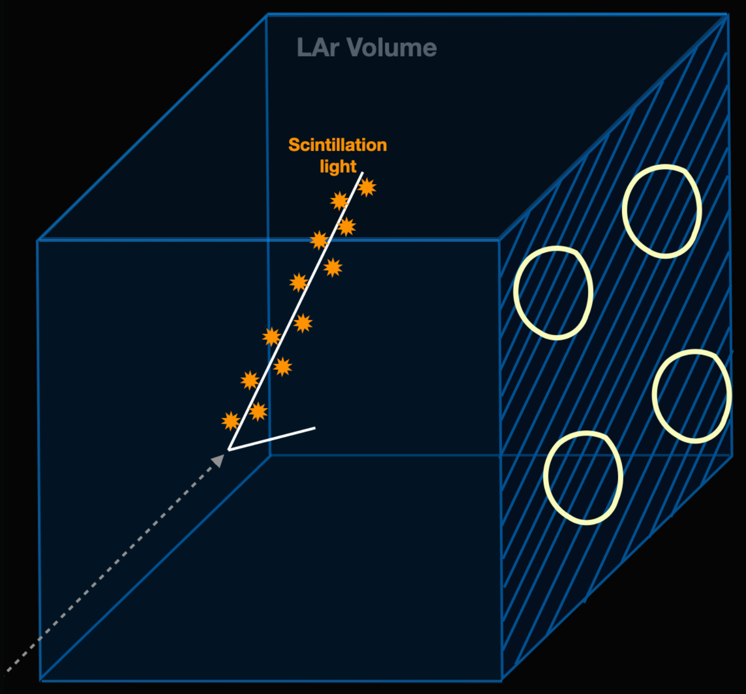
⚖️ **There is room for adjustment**
💡 **AN idea (others might work)**
❗ **Hard requirement**

THIS TALK

SIGNALS IN LARTPCS



IONIZATION CHARGE



SCINTILLATION LIGHT

- ➡️ Directional
- 🐢 Very slow
- 〽️ Information about trajectory and energy
- 🔆 Collected very efficiently

- ✳️ Isotropic
- ⚡ Very fast
- ⏱️ Information about timing and *possibly also energy
- 🔆 Collected with less efficiency

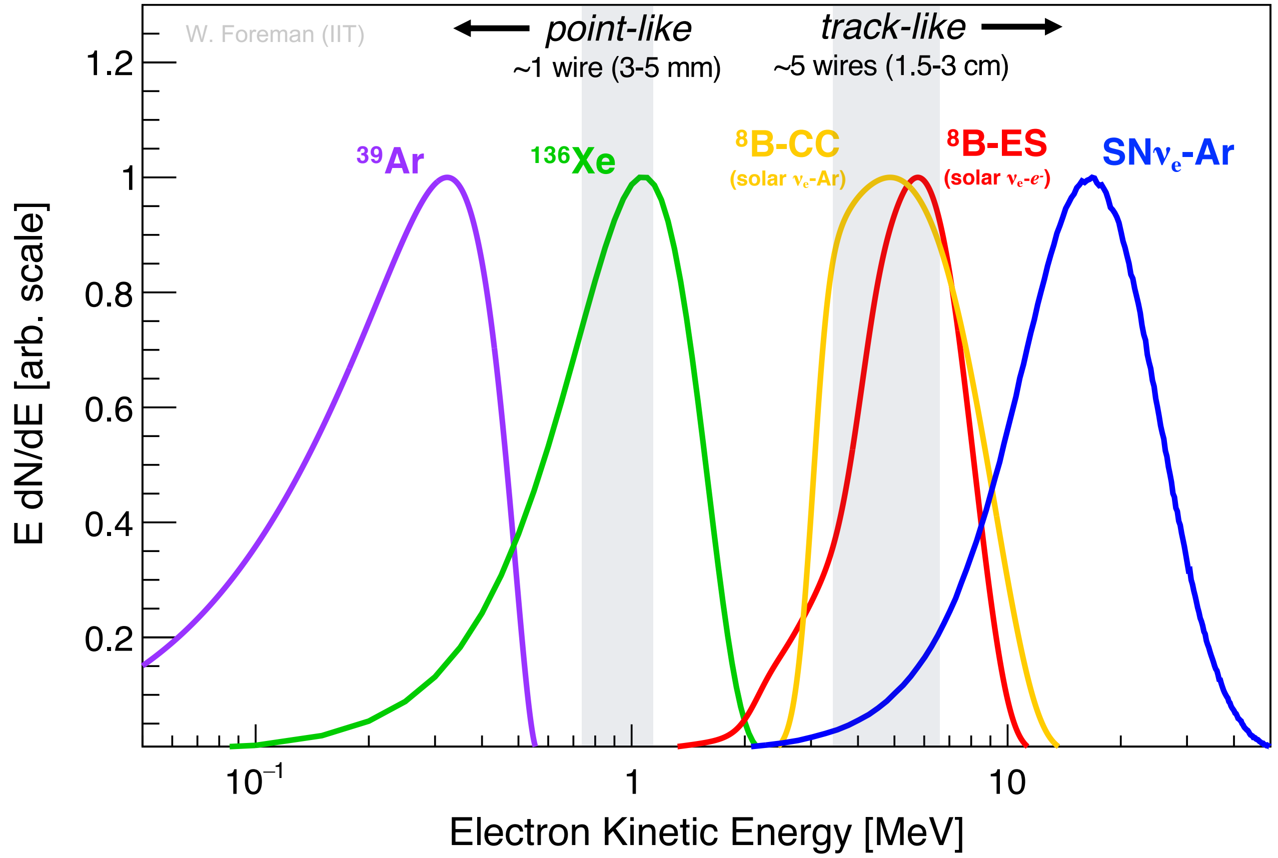
MATTERS A LOT AT LOW ENERGIES

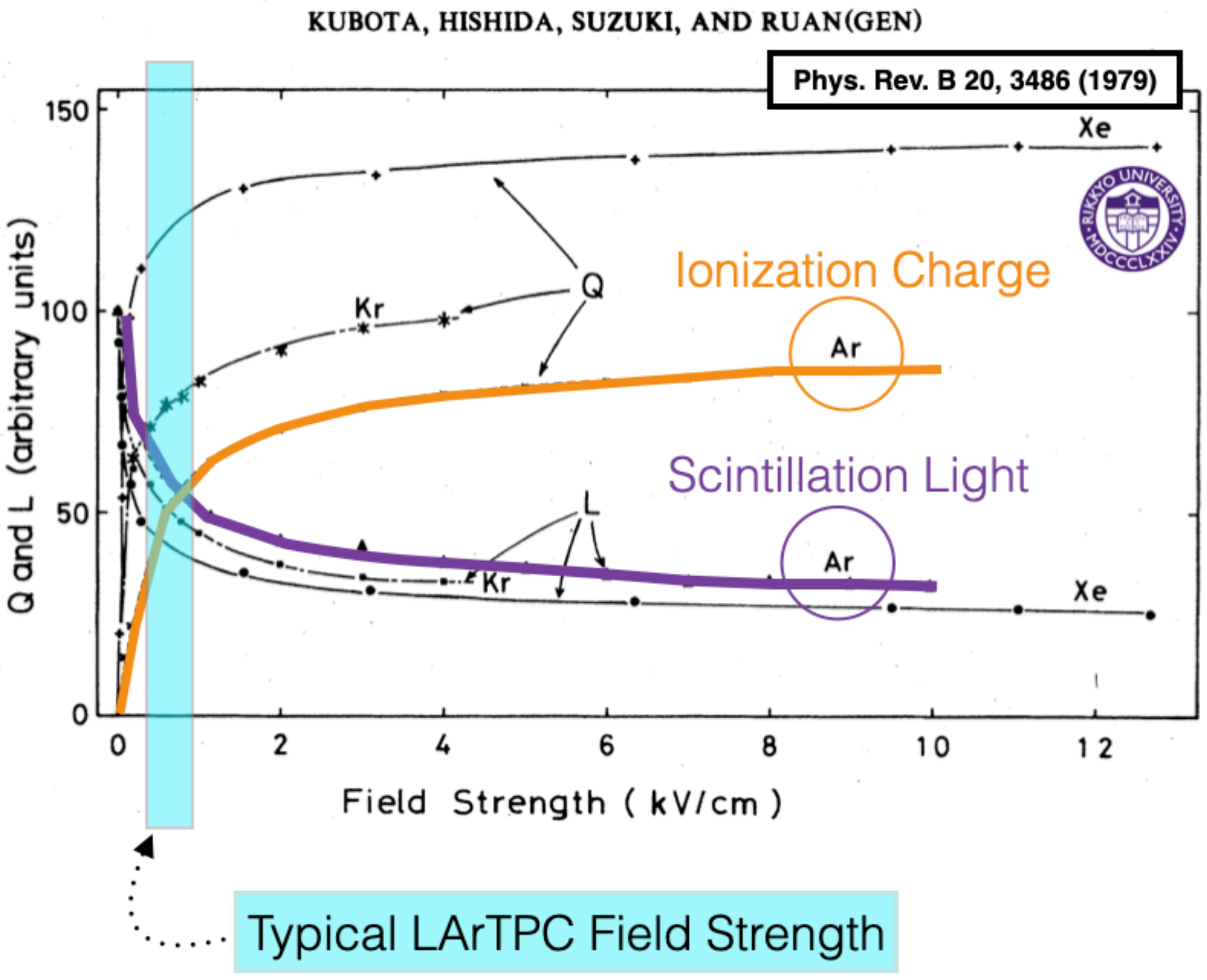
WHY LIGHT WILL MATTER FOR SMALL SIGNALS

Charge + Light = Constant

On DUNE, we'll expect ~50/50 **charge** to **light** breakdown.

D. Caratelli, *et. al*, arxiv:2203.00740

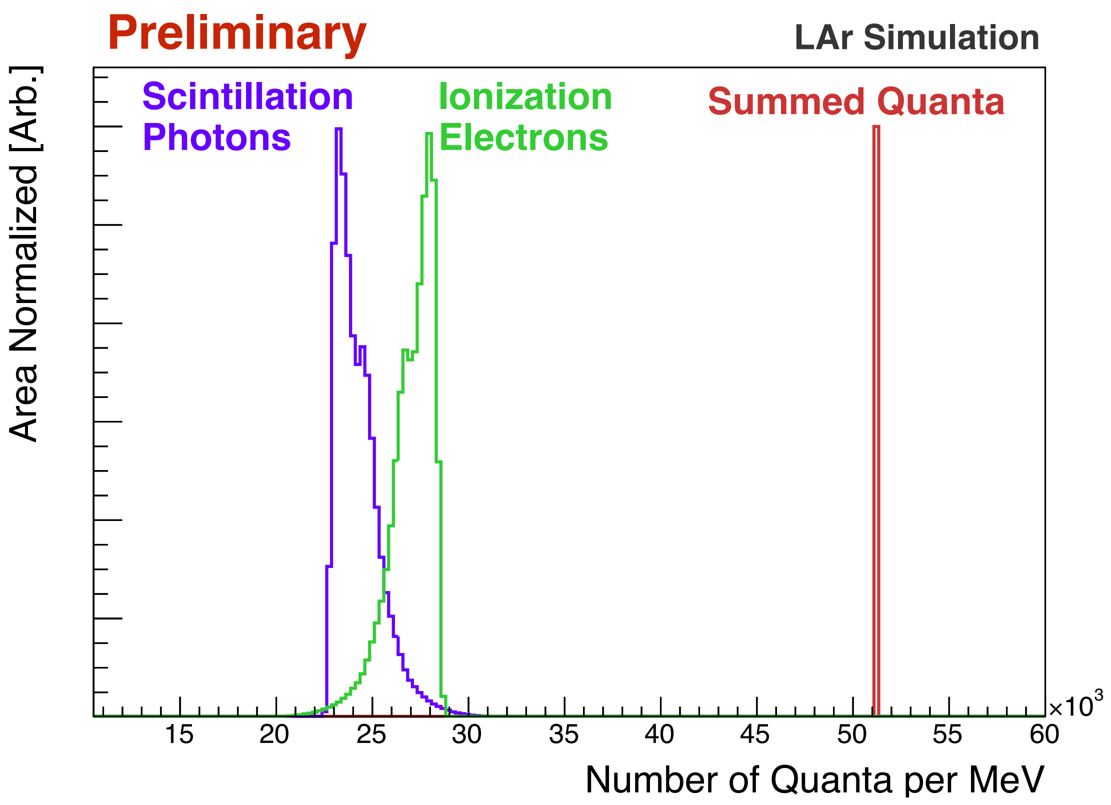




Typical LArTPC Field Strength

This ratio is sufficient for the needs of GeV physics but will impact our ability to do physics at the MeV scale

CHARGE + LIGHT = BETTER RESOLUTION AT LOW ENERGIES



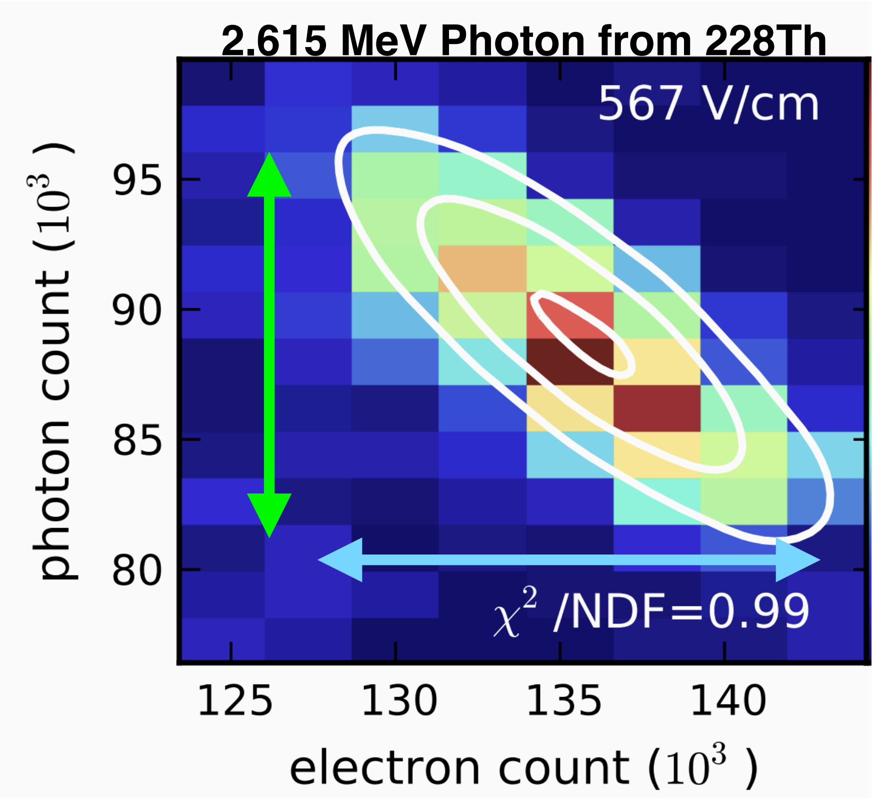
Anti-correlated light and charge signals

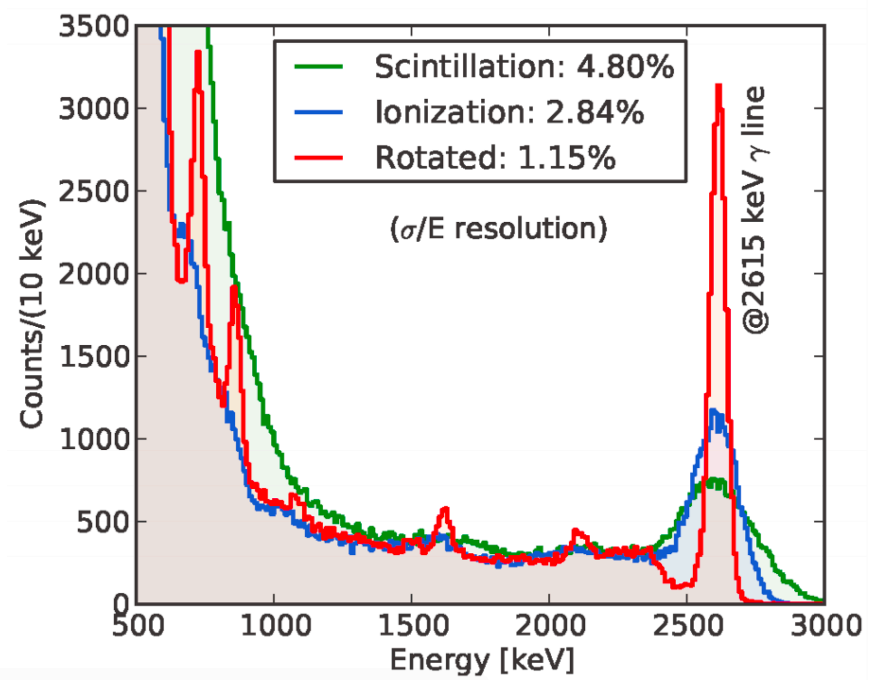
Using information from both signals can yield a more precise energy measurement.

EXO-200, a LXeTPC searching for 0νββ, explored the anti-correlation between light and charge signals

By **combining light and charge** they were able **to improve their energy resolution** by 3x, to ~1%

To achieve this they collected 30,000 γ/MeV





PRC 101, 065501 (2020)

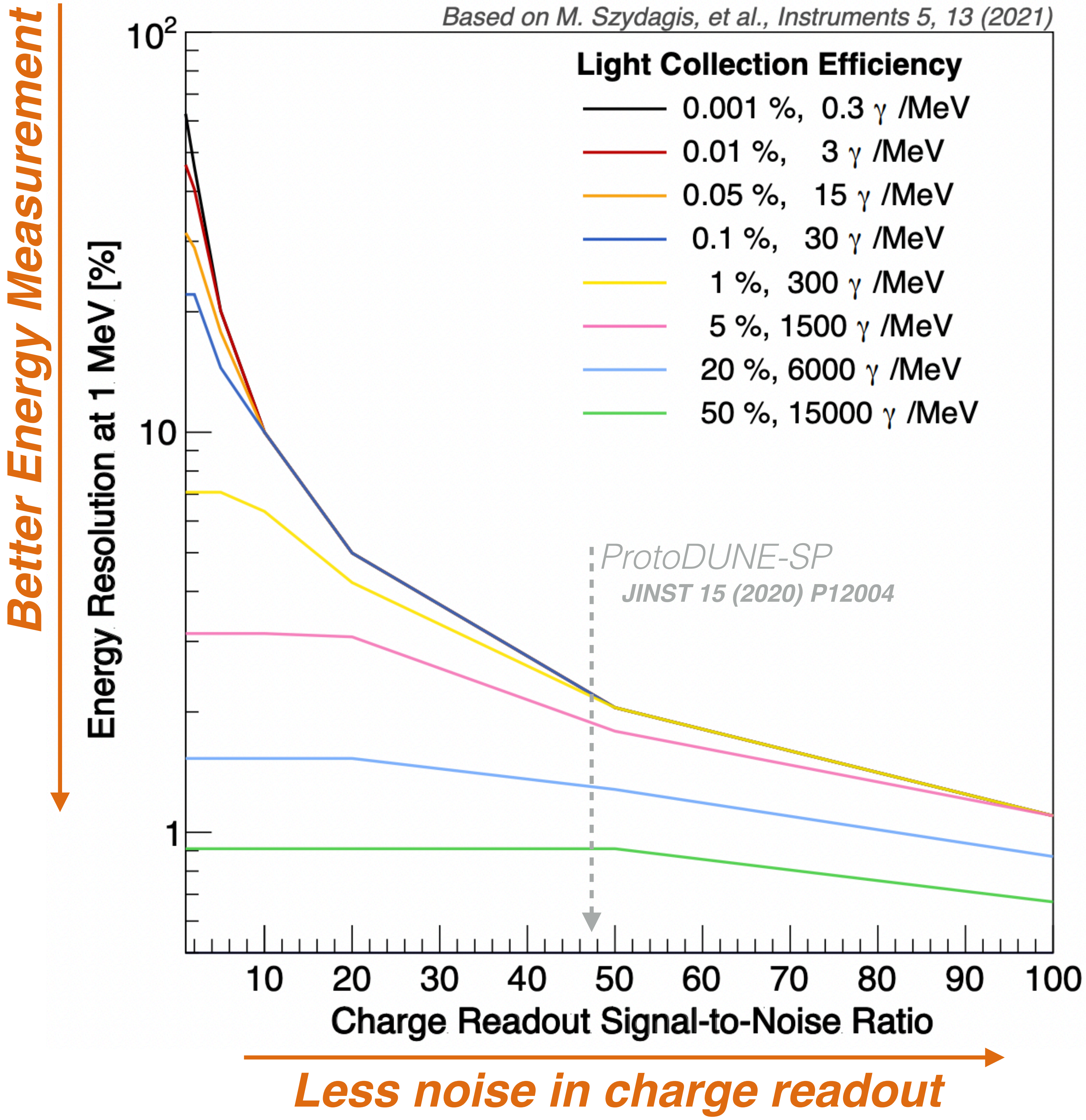
EXO-200 Collaboration

HOW MUCH LIGHT DO WE NEED?

NEST[*] models the microphysics of energy deposits in noble liquids and gases.

Explored the energy resolution for 1 MeV electrons in LAr for detectors with various efficiency and noise conditions

Achieving the best possible energy resolution need to collect at least 6000 photons per MeV


Based on M. Szydagis, et al., Instruments 5, 13 (2021)

[*] Noble Elements Simulation Technique, http://nest.physics.ucdavis.edu/

LIGHT COLLECTION ON DUNE

Traditionally light collected at anode plane

DUNE FD Module
5,600 cm by 1,200 cm

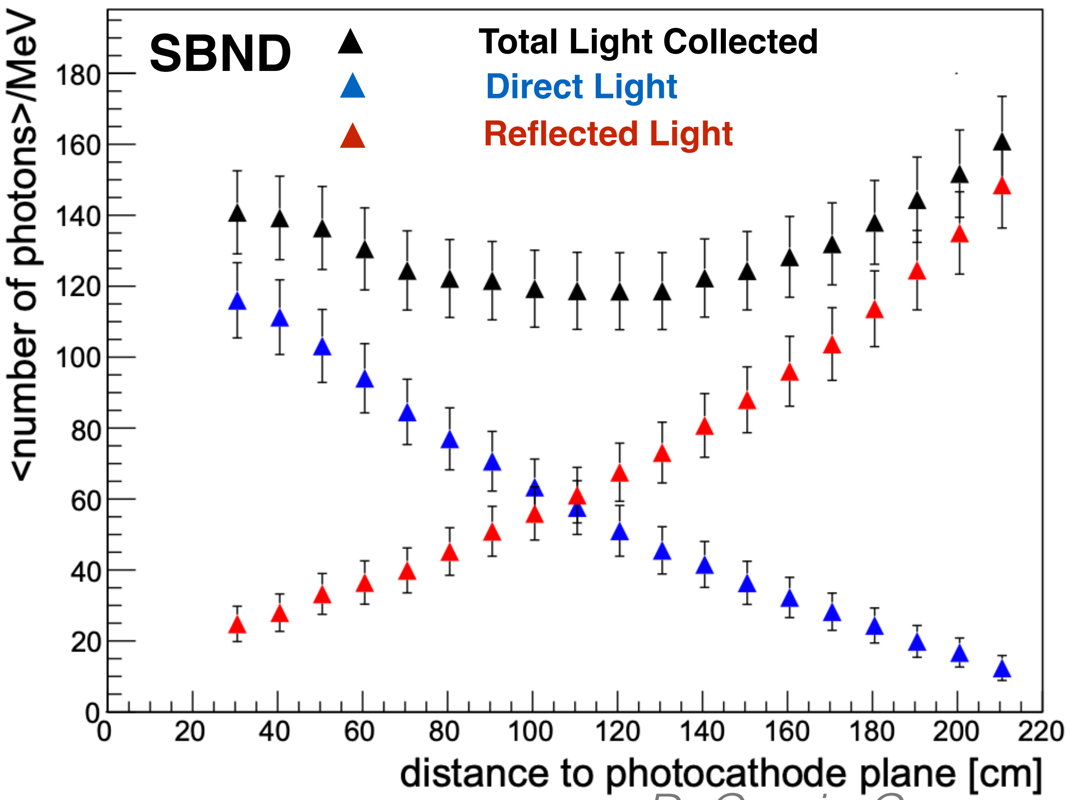
EXO-200 Detector
40 cm by 18 cm

Increasing light collection on large LArTPCs is a challenge:

- Scintillation photons have to travel large distances.
- Low photon detection coverage by design.

The best light collection efficiency has been accomplished on SBND

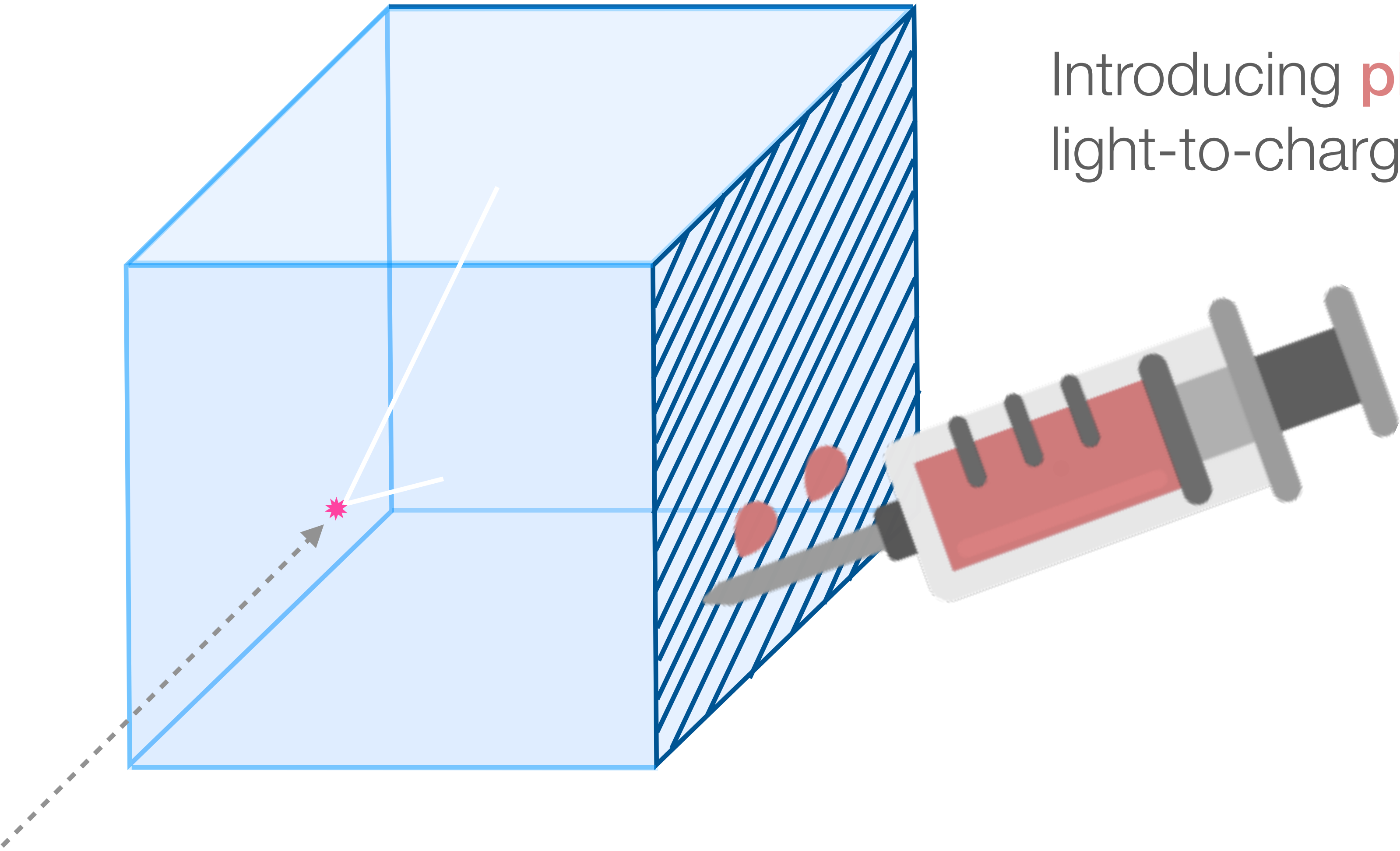
Best LArTPC
Light collection < 160 photons/MeV **<< 6000 photons/MeV**



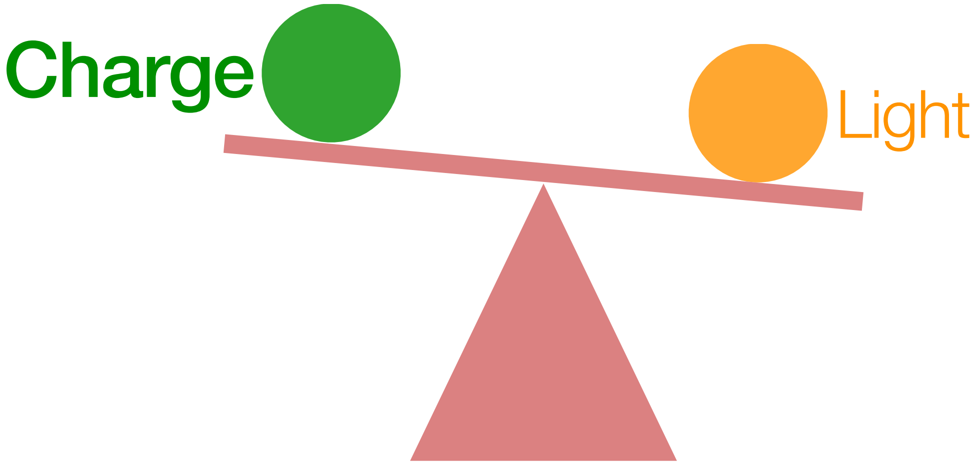
D. Garcia-Gamez

Journal of Physics: Conf. Series 888 (2017) 012094

PHOTOSENSITIVE DOPANT CONCEPT



Introducing **photosensitive dopants** will cause light-to-charge conversion



What we know:

✅ **Good indications that this is a promising avenue of R&D**

R&D Questions

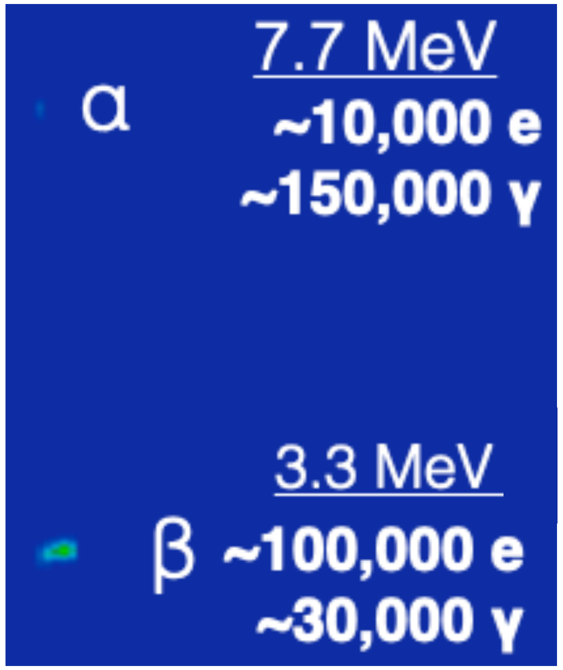
❓ **Lot’s of productive and impactful R&D for the coming years.**

R&D QUESTIONS FOR DOPANTS

Small test stands explored a variety of chemicals and found an increase in charge for highly scintillating particles.

The most commonly used have ionization energies of 7-9 eV:
Tetramethylgermane (**TMG**), $(CH_3)_4Ge$, Trimethylamine (**TMA**), $N(CH_3)_3$, Triethylamine (**TEA**), $N(CH_2CH_3)_3$

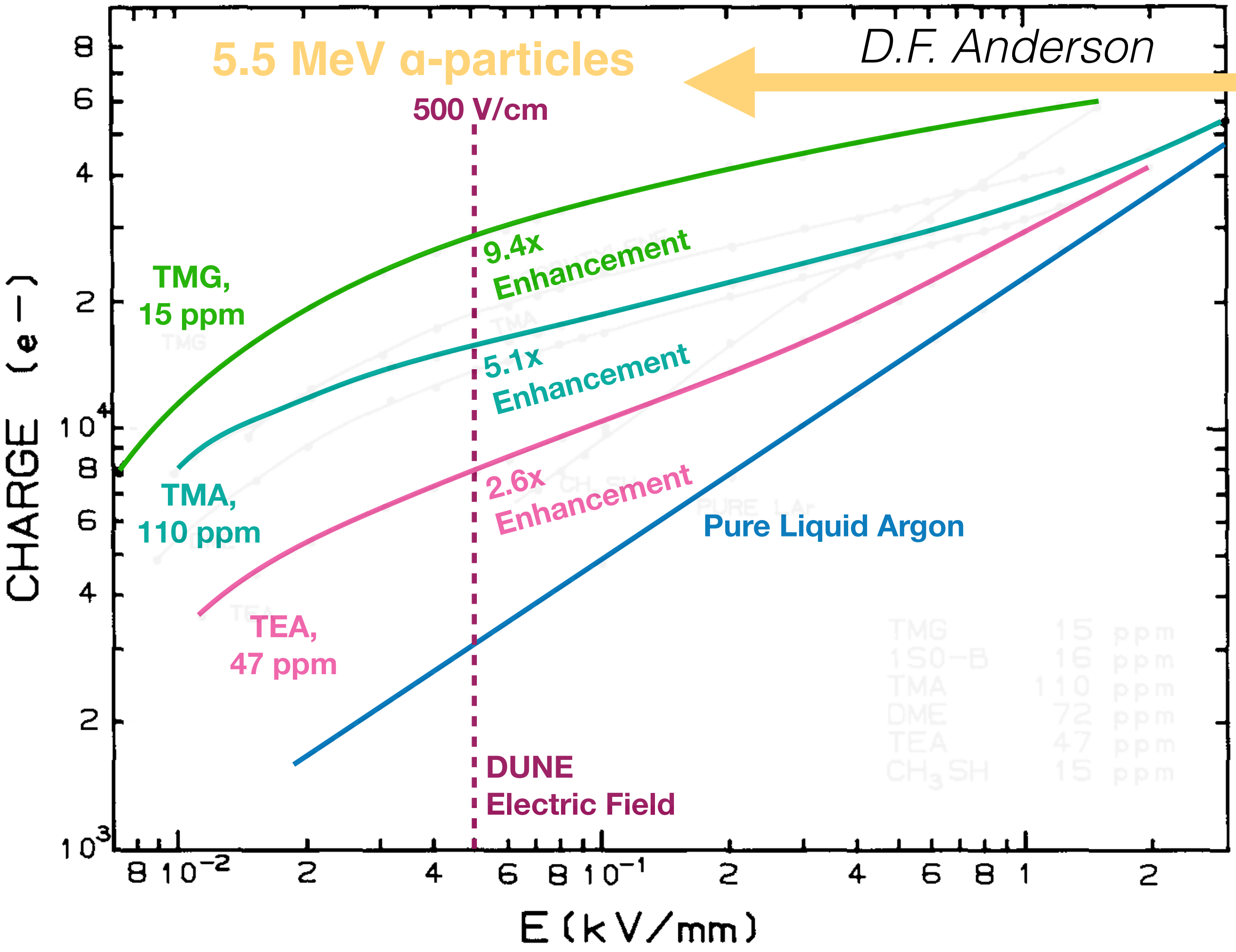
Simulated Event in Pure LAr



Courtesy of Ivan Lepetic

RUTGERS

Nucl. Instr. and Meth. A 242 (1986) 256



Does this extend to β's below 5 MeV?

What does the improvement look like and what fraction (if any) of the light survives after doping?

What energy resolutions are achievable below 5MeV with the addition of dopants?

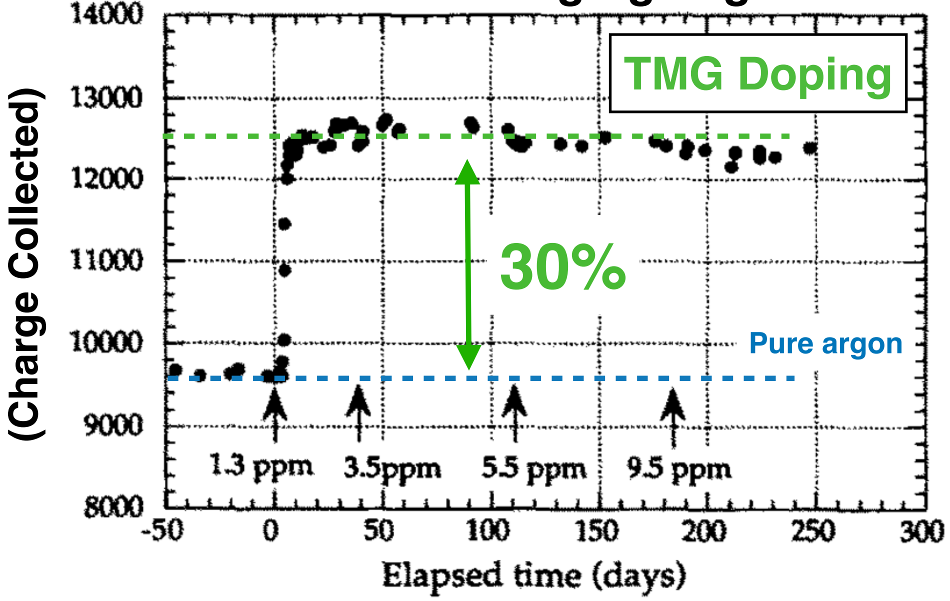
EXPECTED IMPROVEMENTS

Nucl. Instrum. Methods. Phys. Res. B 355, 660 (1995).

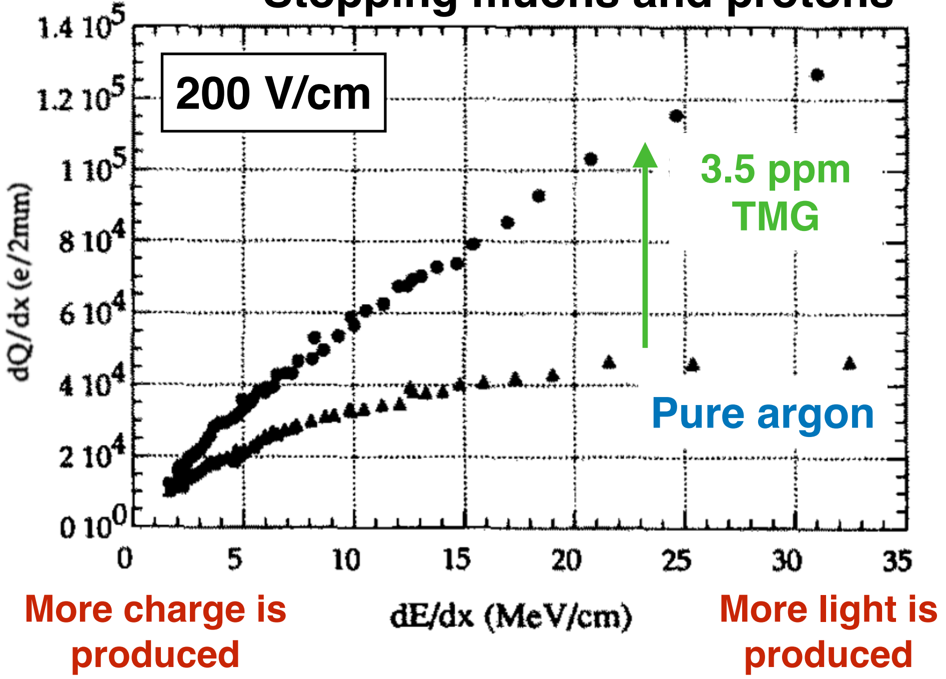
ICARUS Collaboration

- ICARUS doped a 3-ton prototype LArTPC with TMG to the few ppm level
  - TMG was selected because it didn't react with their filter material and was easily purified

- After introducing TMG observed:
  - 30% increase in muon charge signals
  - Stable operation for 250 days
  - Found a more linear detector response for highly ionizing particles



Through-going muons



Stopping muons and protons

More charge is produced

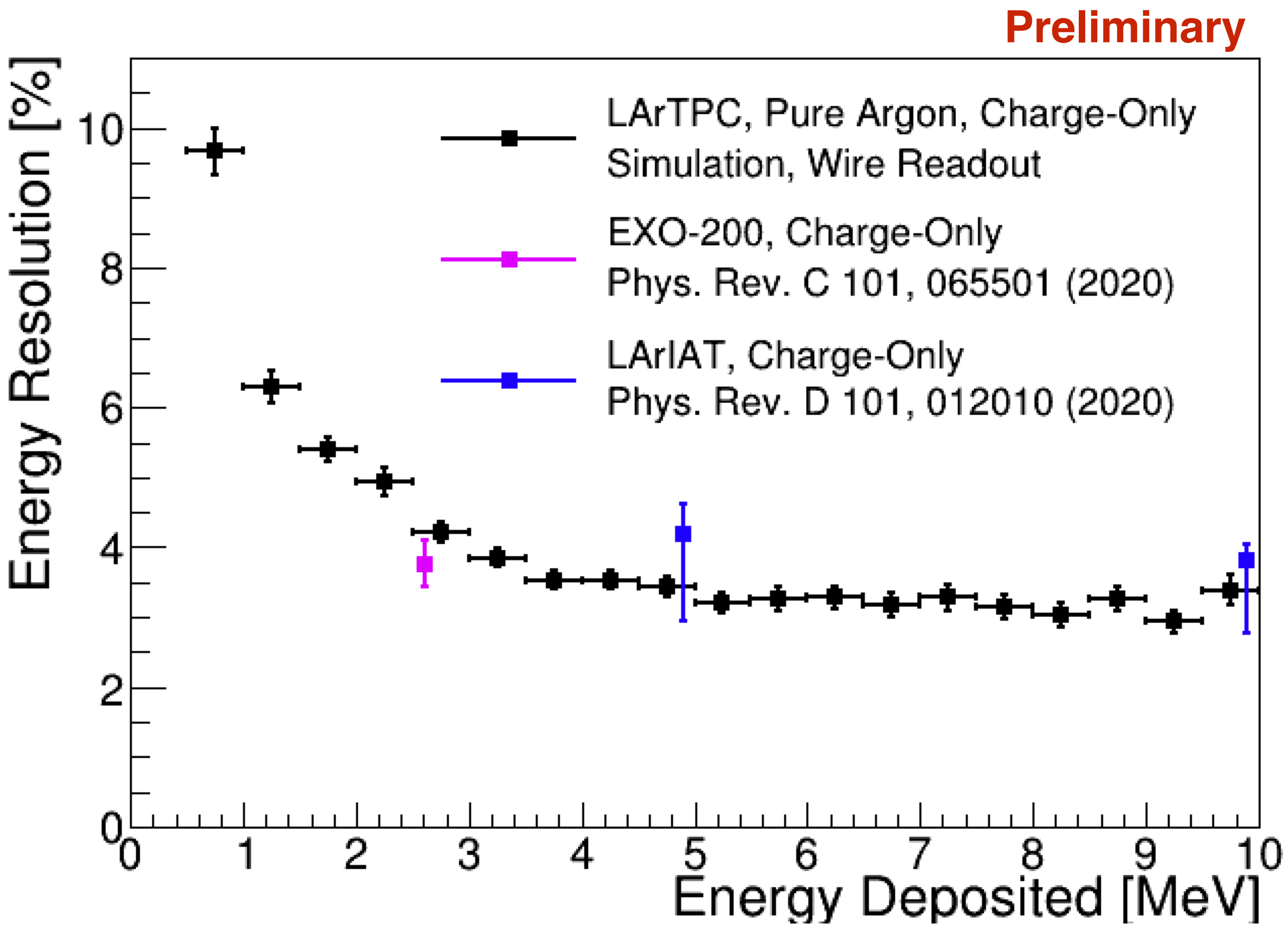
More light is produced

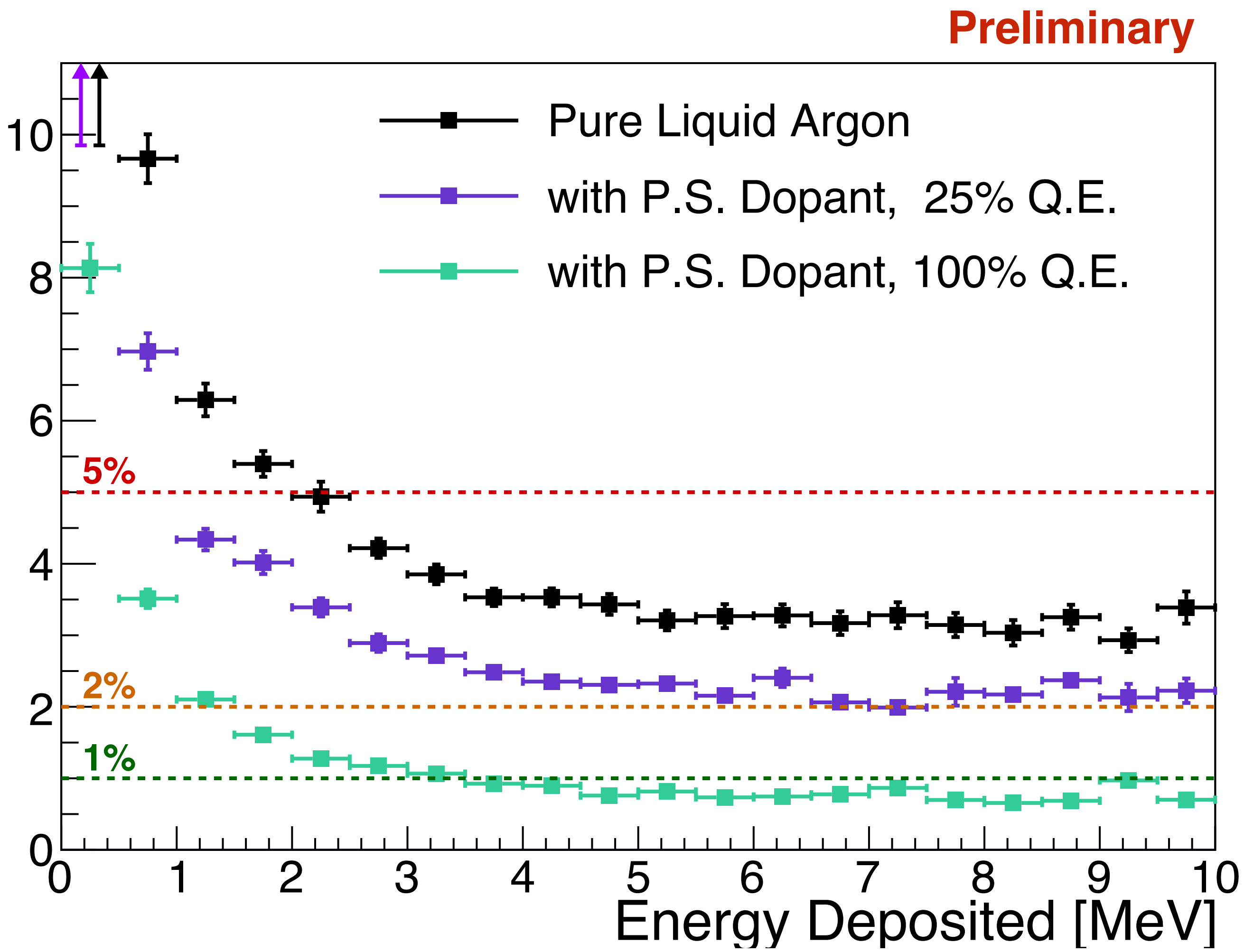
SIMULATION-EXPECTED IMPROVEMENTS

WORK DONE BY GEM FELLOW AT
LeRayah Neely-Brown
FERMILAB-POSTER-22-126-ND-STUDENT

- **Studied improved electron response with simulation of dopants**
  - Converts scintillation light to ionization charge, fully integrated into LArSoft
- Performed a full large LArTPC detector simulation
  - Included wire noise (~350 ENC, ~40 SNR for MIPs), microphysical effects, detector response, noise filtering, signal processing, and energy reconstruction

Done in LArSoft!

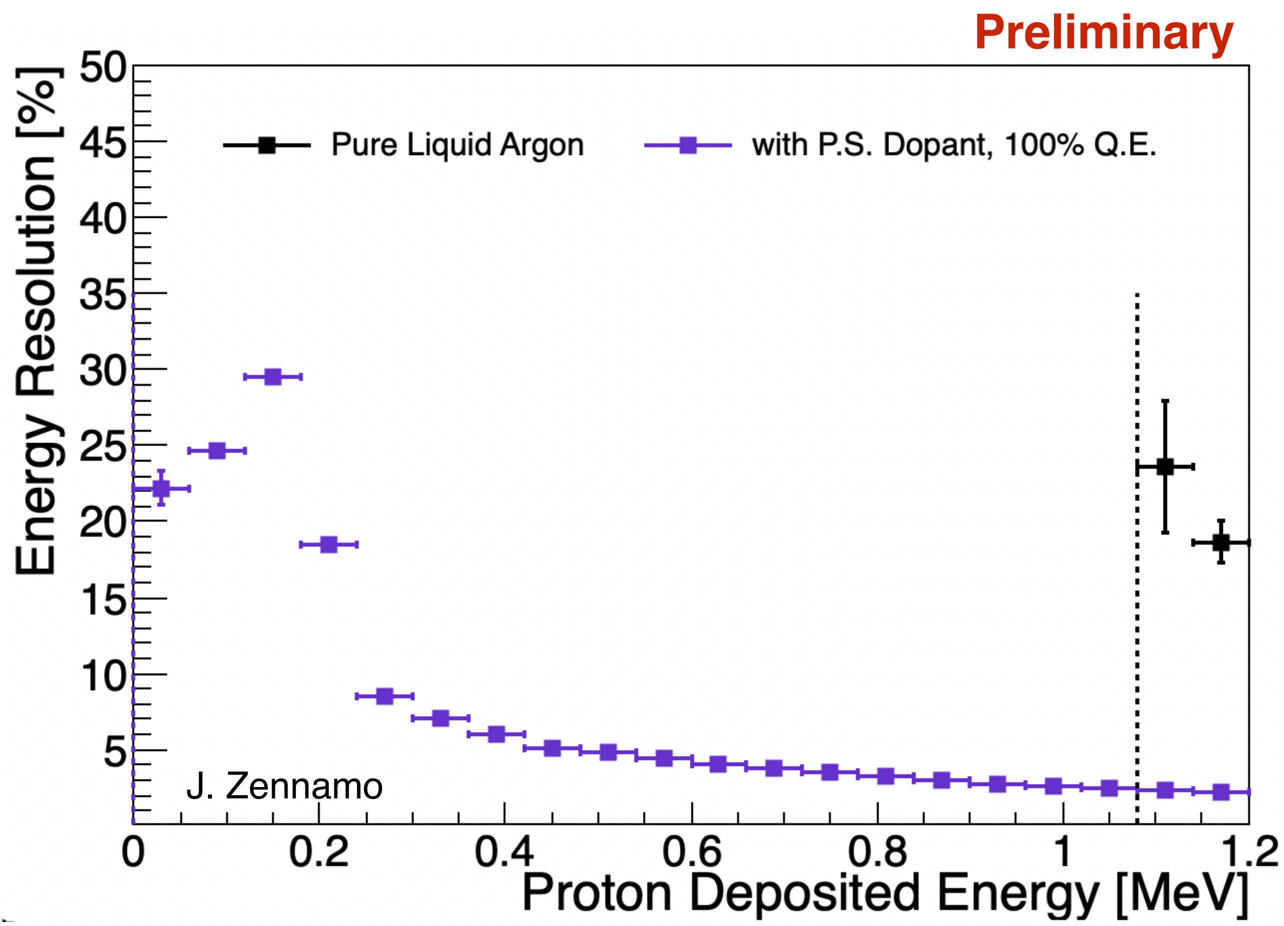


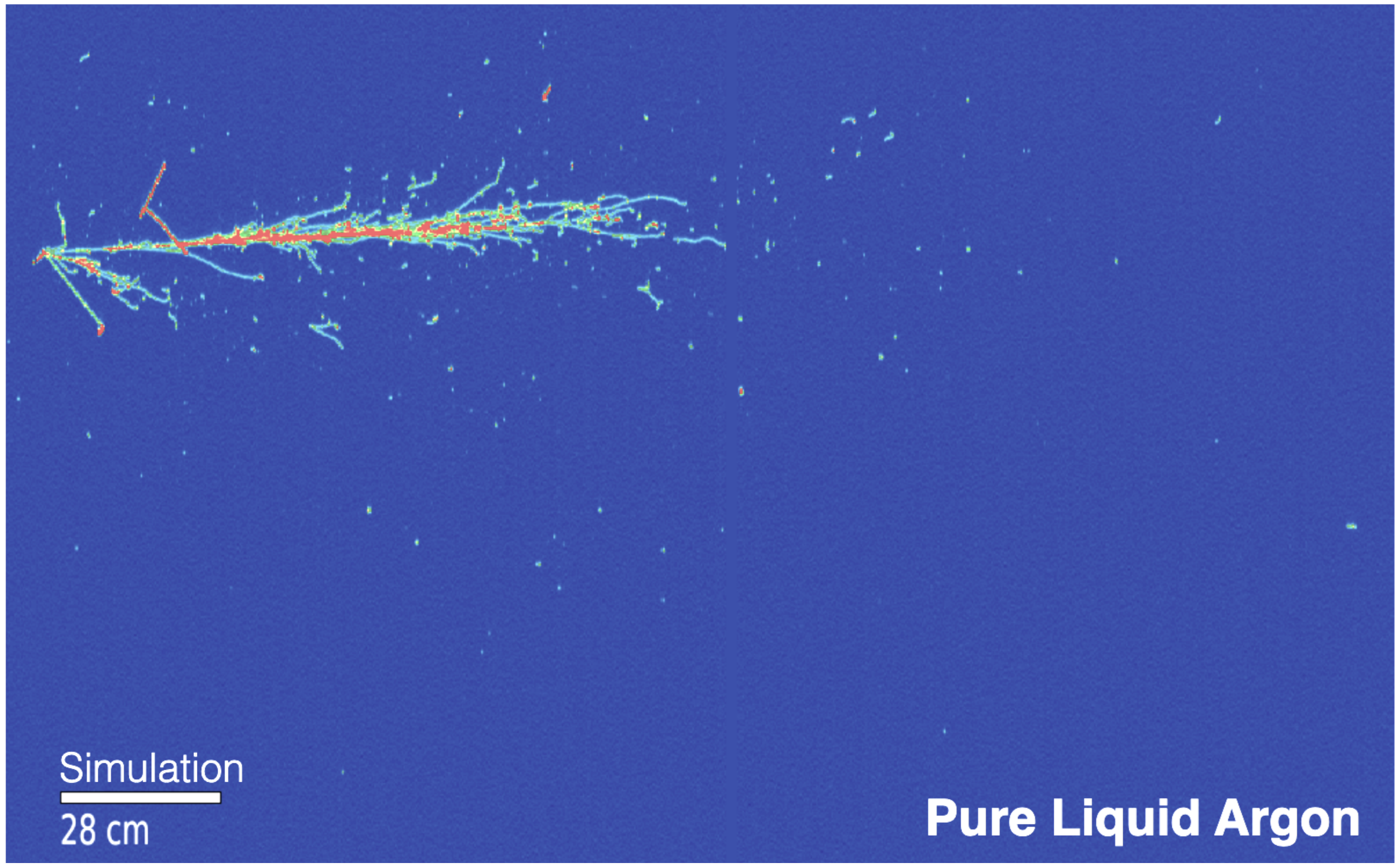


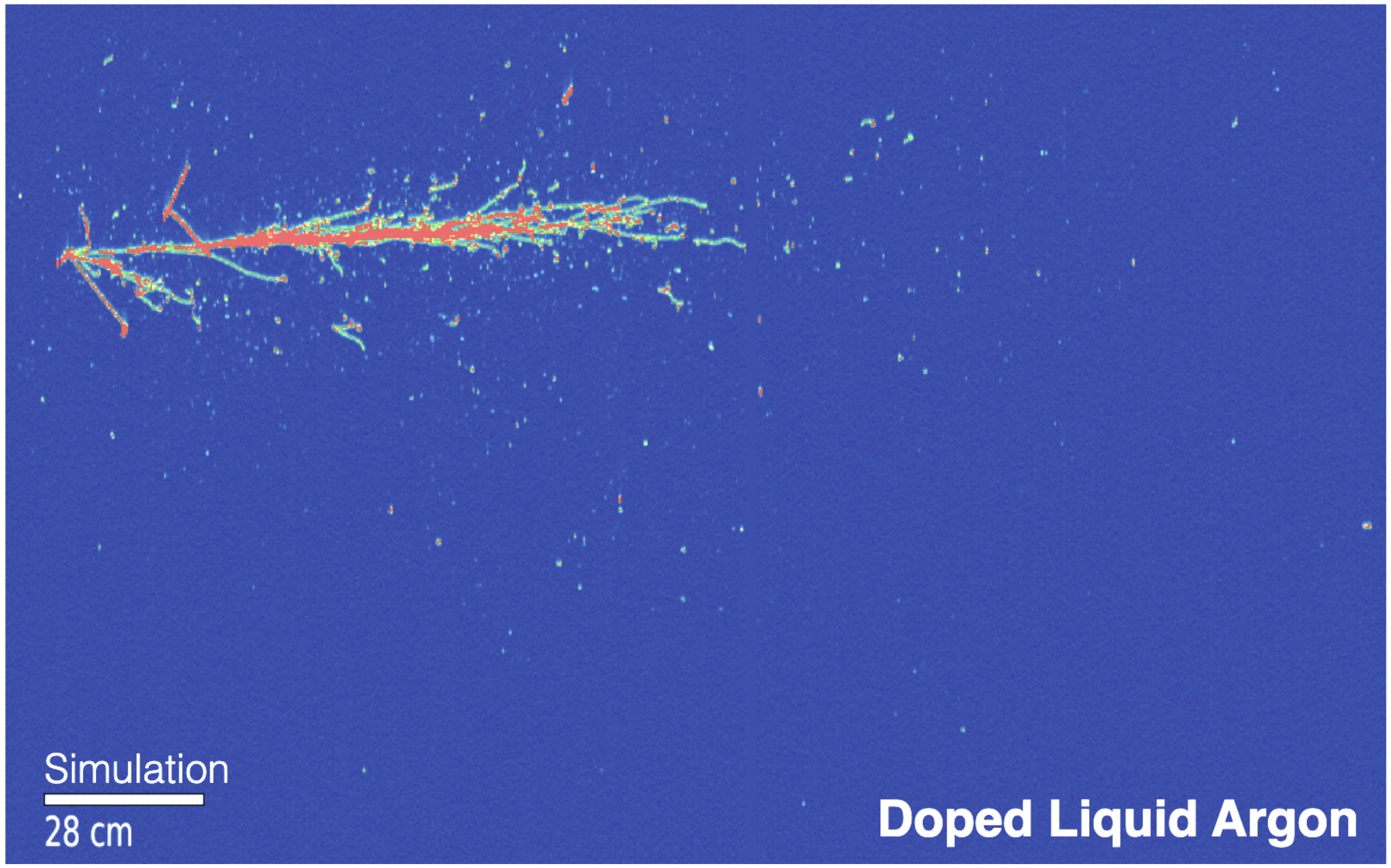
SIMULATION-EXPECTED IMPROVEMENTS

Converting the light to charge:

- Lowers threshold 1.1 MeV to 10 keV
- Improves charge only energy resolution







TinyTPC @ Fermilab

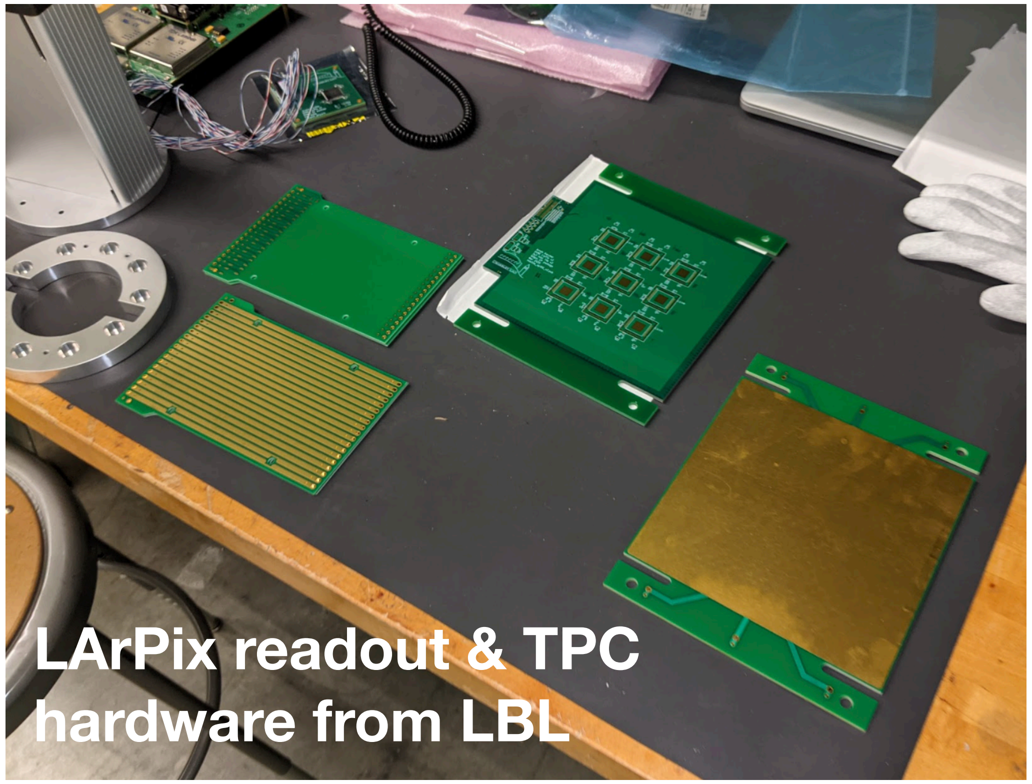
Low-energy LArTPC test-stand for photo-sensitive dopants:

Stage 1:
Operate TinyTPC with LArPix v2 pixel readout in a cryostat at Fermilab. (Min bias data run)

Stage 2:
Introduce radioactive sources and benchmark LArPix v2 performance at low energies

Stage 3:
Introduce dopants and demonstrate charge enhancement

Stage 4:
Explore performance enhancements for low energy signals and optimal doping strategies



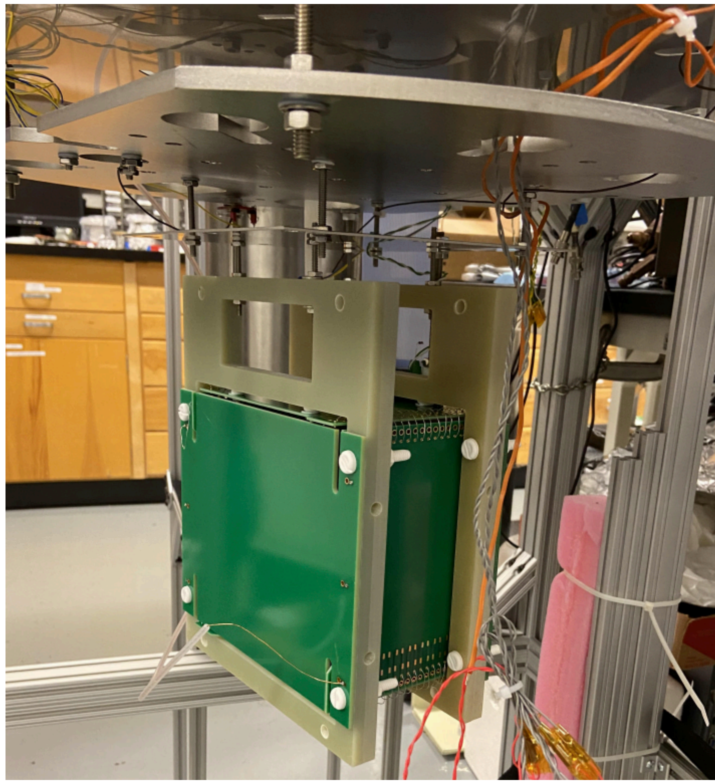
LArPix readout & TPC hardware from LBL

GOALS

**Demonstrate that dopants produce charge enhancement for low energy signals.*

**Characterize performance of pixel readouts for low energy signals with and without doping.*

Plan for deployment (post assembly & bench tests)



TINYTPC @ FERMILAB

Raofa Raisa SIST INTERN

Panos Englezos RUTGERS

Stage 1 deployment expected in early 2023.

Operate TinyTPC with LArPix v2 in **cryostat** for min bias data

Stay tuned!

Thank you for the support from Fermilab cryo facilities and staff.

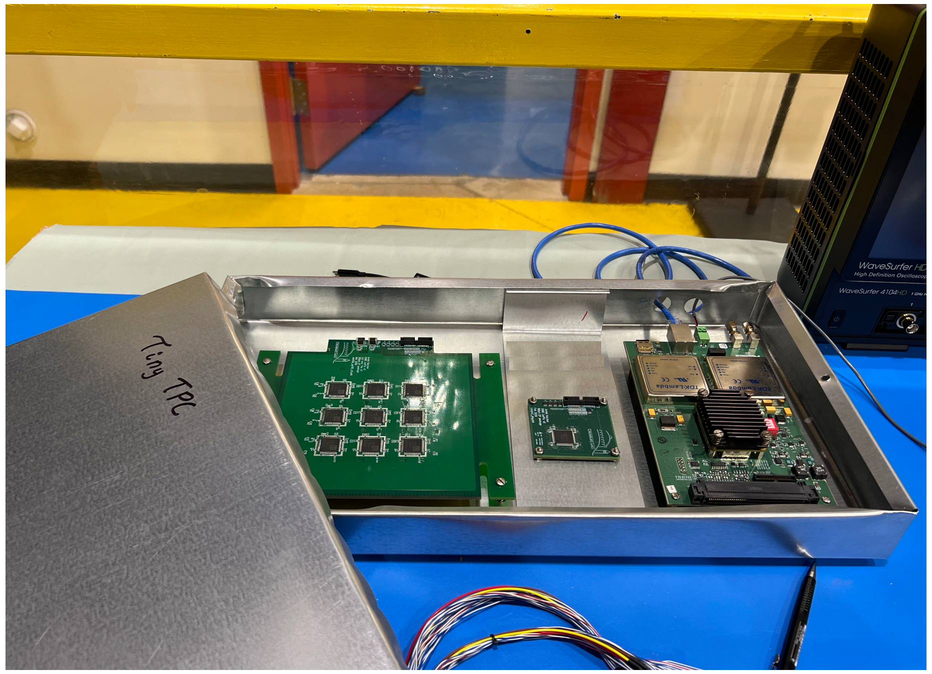
Funding from DOE, FNAL New Initiatives Grant and the FNAL Neutrino Division

SIST Internship & GEM internship program at Fermilab

Thank you yo LBNL for parts and electronics !

Assembly at Fermilab

Bench testing



Andy Mastbaum
Bench testing at Rutgers

Mechanical support design & prototyping

Joseph Zennamo
Blanche Cryostat at Fermilab

WIDER R&D PROGRAM

Extend demonstrations of dopant effects at energies below 5 MeV

Demonstrations of **feasibility at kton-scale**

Searches for & design of **optimal doping scenarios** for desired light-to-charge ratios

Studies of the **interaction** of dopants with:

- other dopants (i.e. Xe)
- filtration systems
- fluid dynamics in the cryostat

What is the impact on the **LArTPC physics capabilities**?

- Timing in a light-less DUNE
- Enhancement of low energy components of GeV events
- Improvements to other low energy signal sensitivities

THOUGHT-PROVOKING IDEAS FOR PHOTOSENSITIVE DOPANTS

Photo-sensitive dopant R&D could change how we think of low energy physics with LArTPCs

LArTPC runs with reduced light, enhanced charge and ~1% energy resolution at 1 MeV.

Large LArTPC data runs with interchangeable doping strategies.

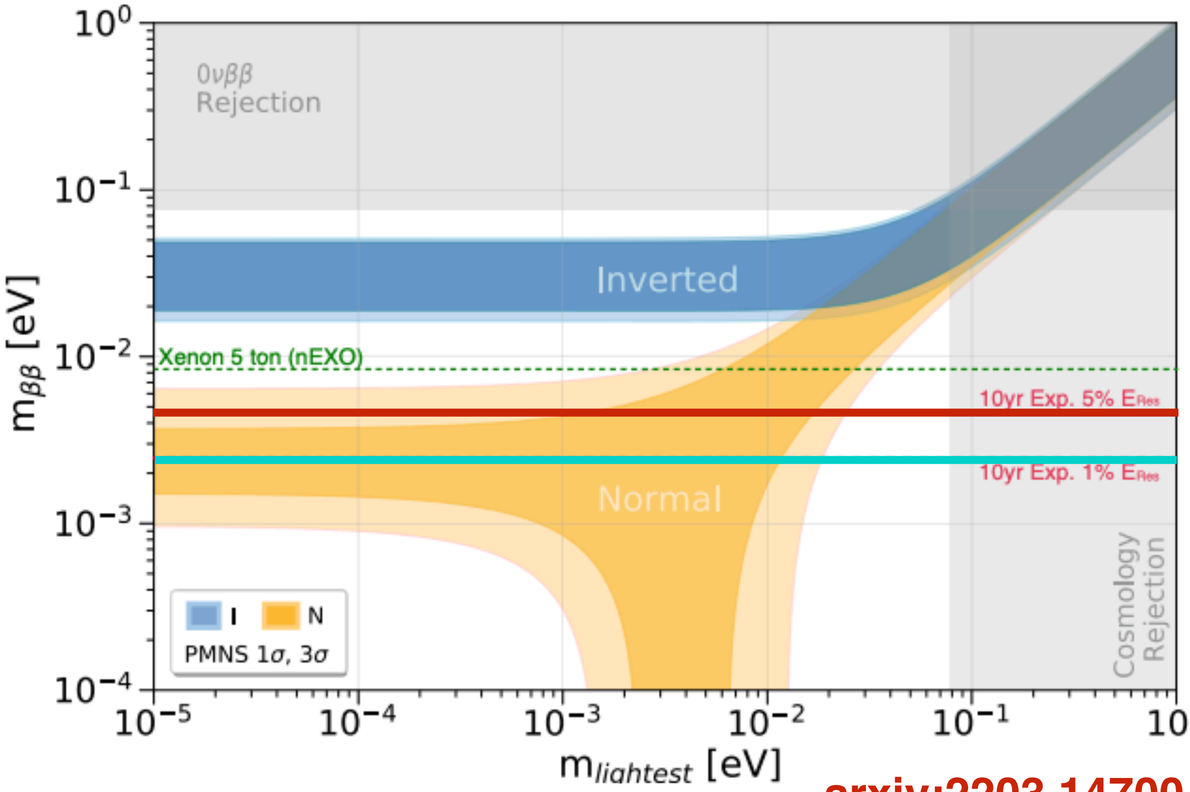
Your low-energy analysis idea enabled by the ability to alter LArTPC light-to-charge ratio

Backup

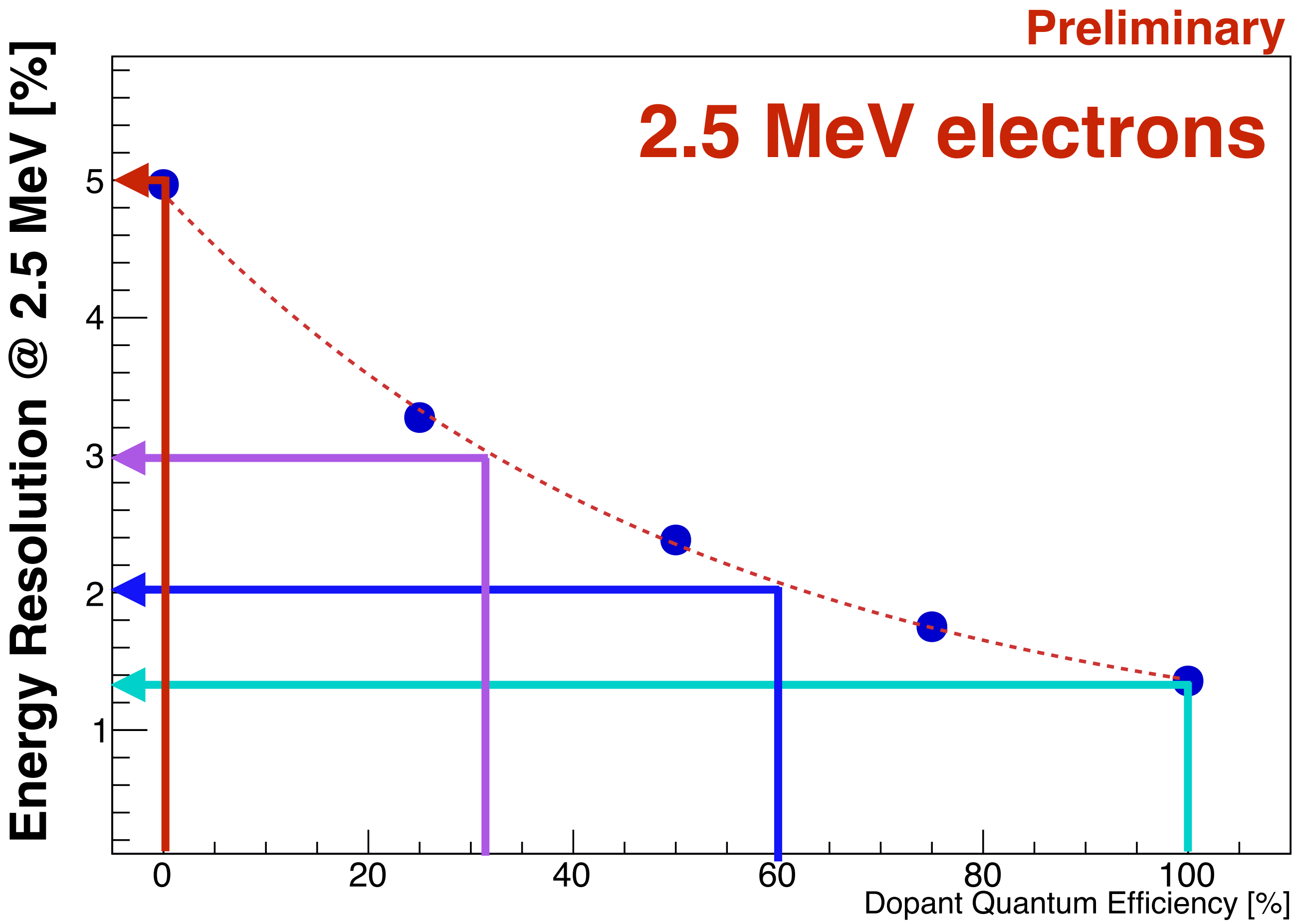
These are not the slides you're looking for

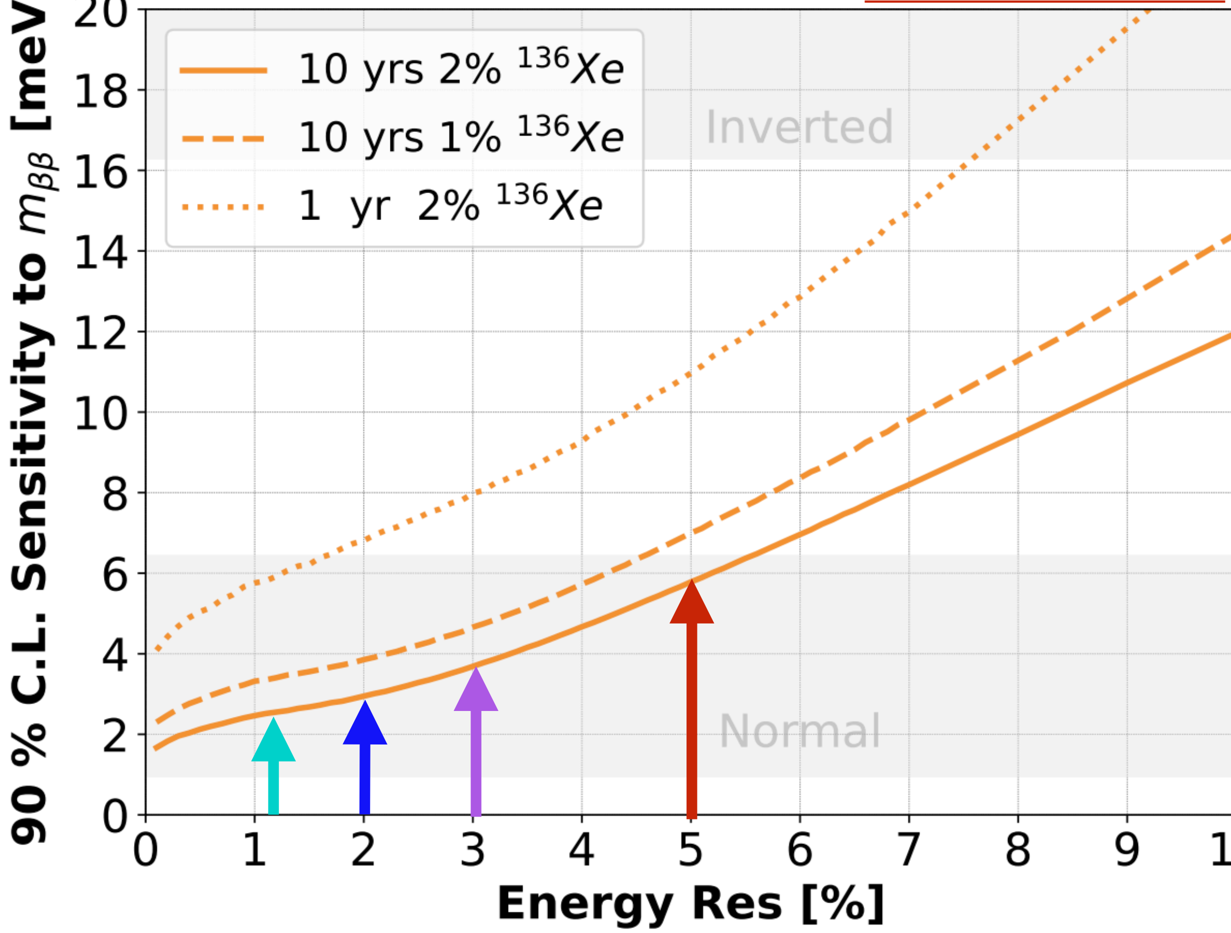
The achievable energy resolution will have a direct impact on how strong of a 0νββ search we can perform

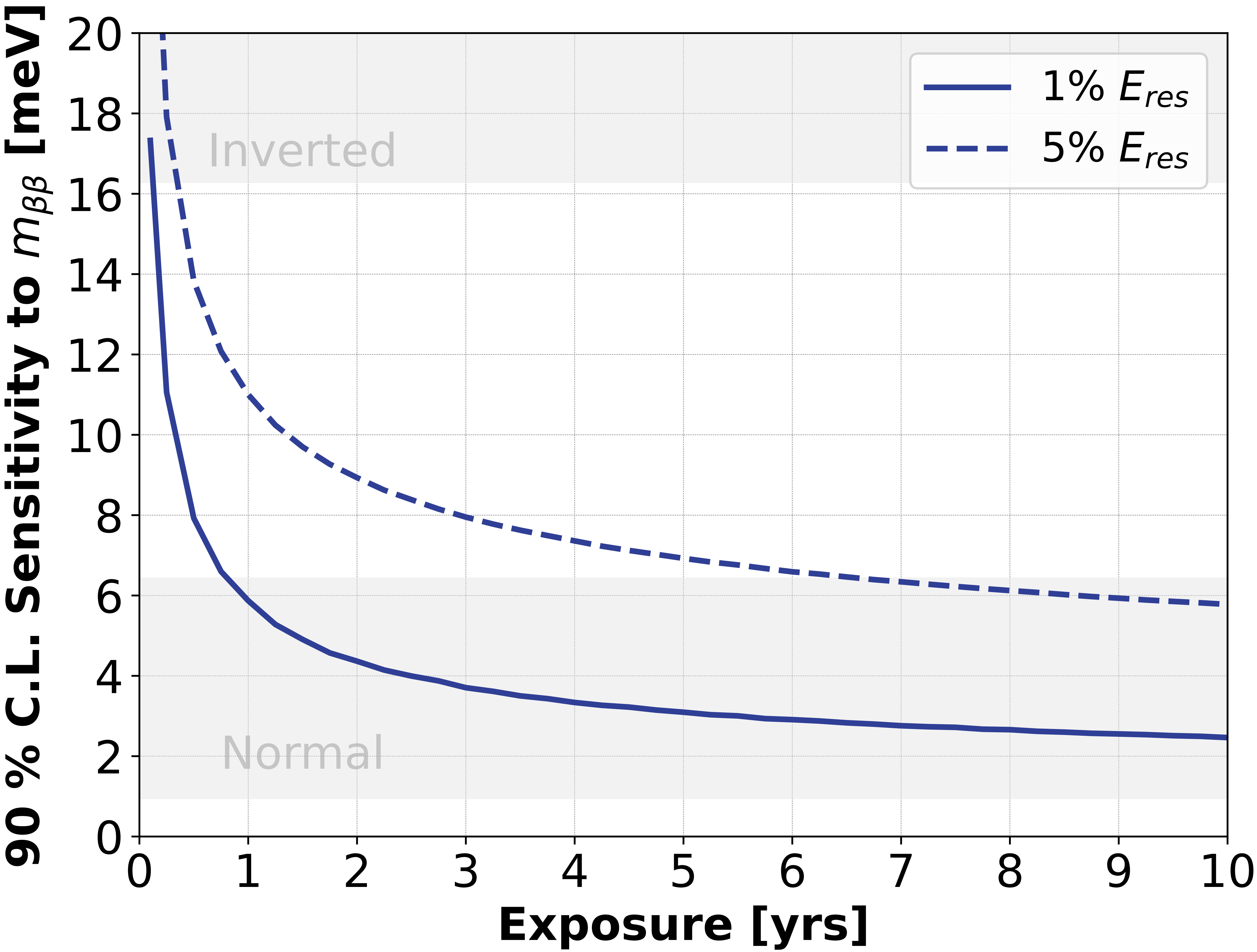
Even without doping, DUNE could reach into the normal heirarchy



arxiv:2203.14700






90 % C.L. Sensitivity to $m_{\beta\beta}$ [meV]
Exposure [yrs]
Inverted
Normal
1% E_{res}
5% E_{res}
0
2
4
6
8
10
12
14
16
18
20
0
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2
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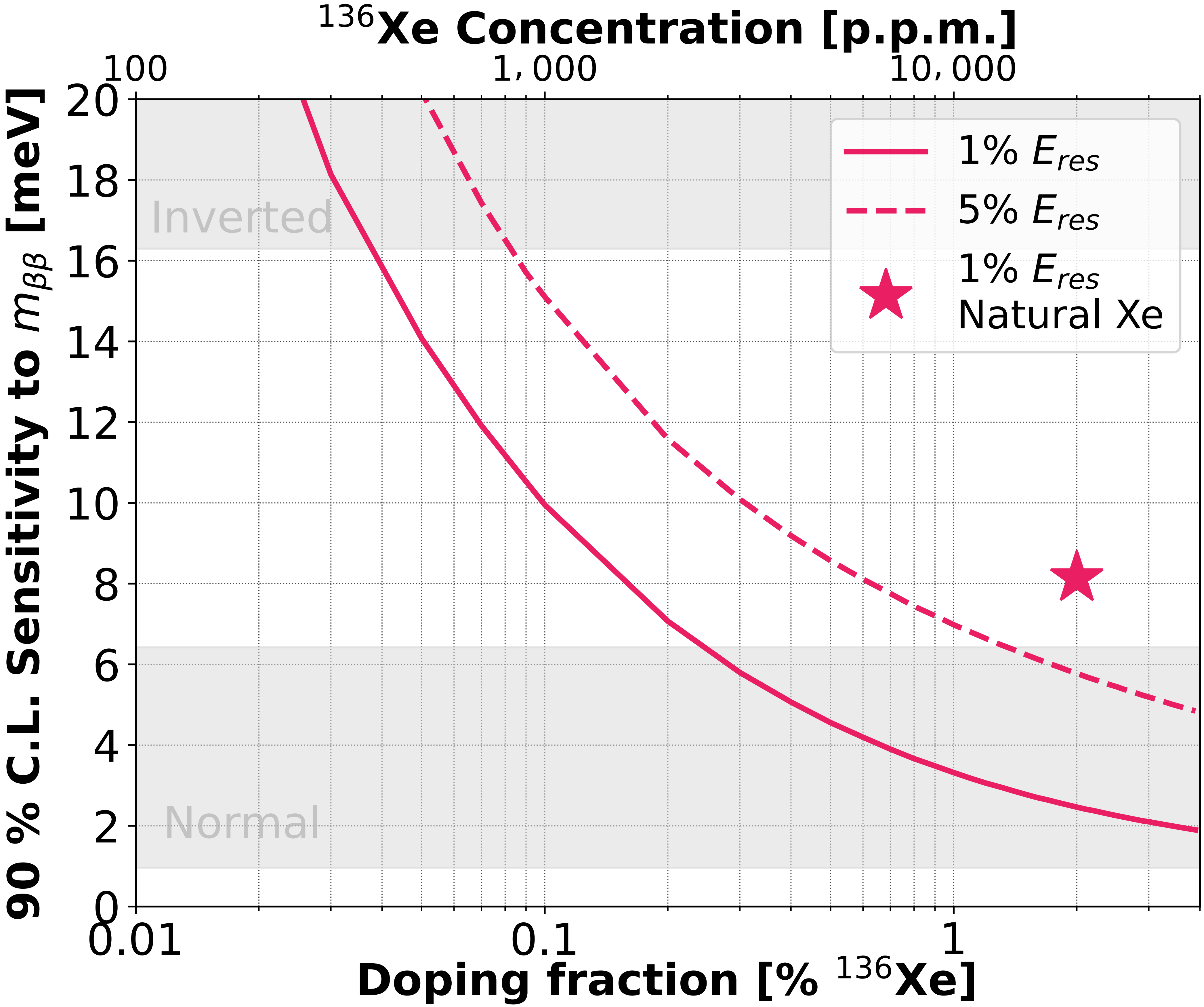
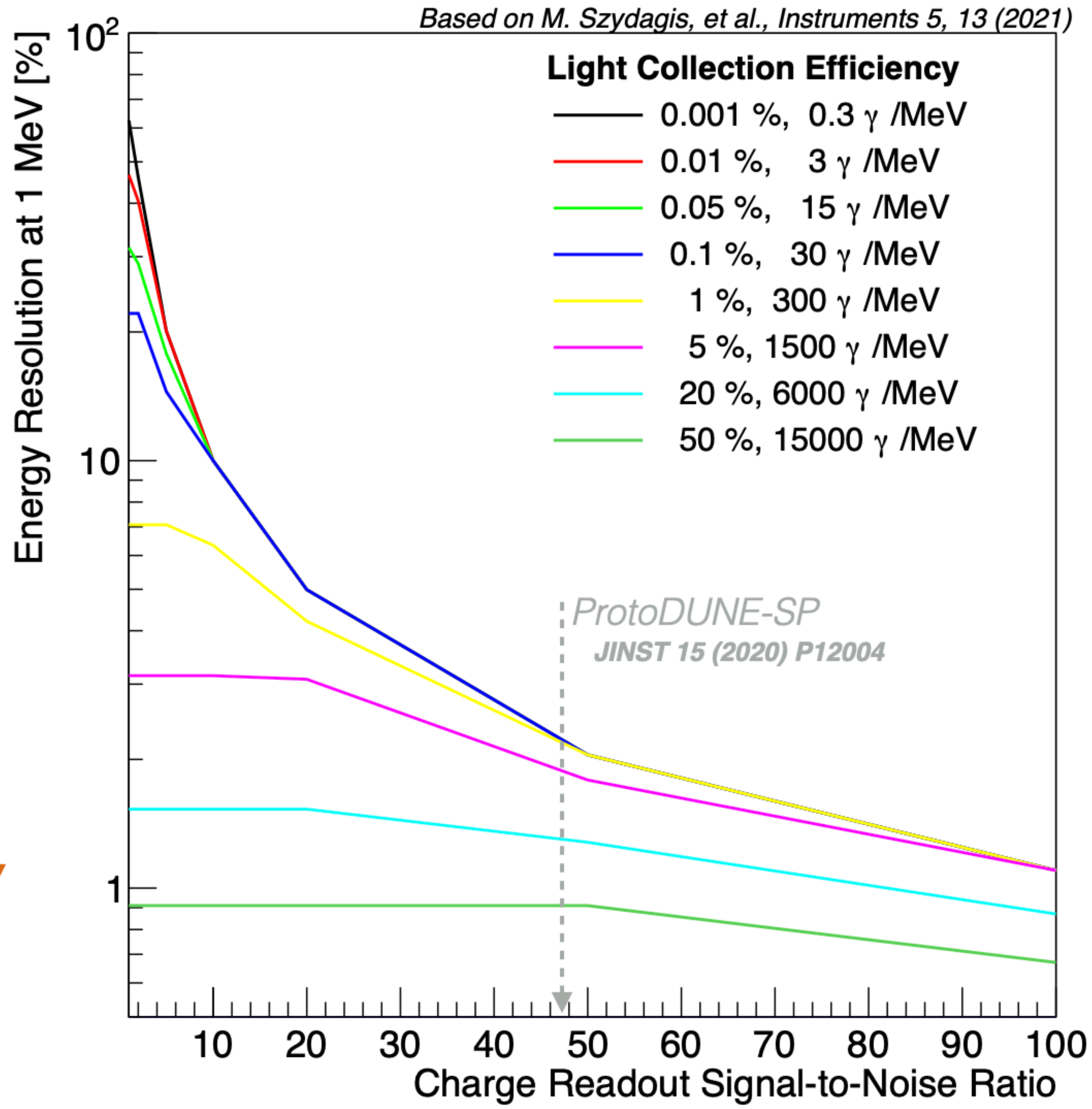
4
5
6
7
8
9
10


^{136}Xe Concentration [p.p.m.]
100
1,000
10,000
90 % C.L. Sensitivity to $m_{\beta\beta}$ [meV]
0
2
4
6
8
10
12
14
16
18
20
Inverted
Normal
1% E_{res}
5% E_{res}
1% E_{res} Natural Xe
0.01
0.1
1
Doping fraction [% ^{136}Xe]

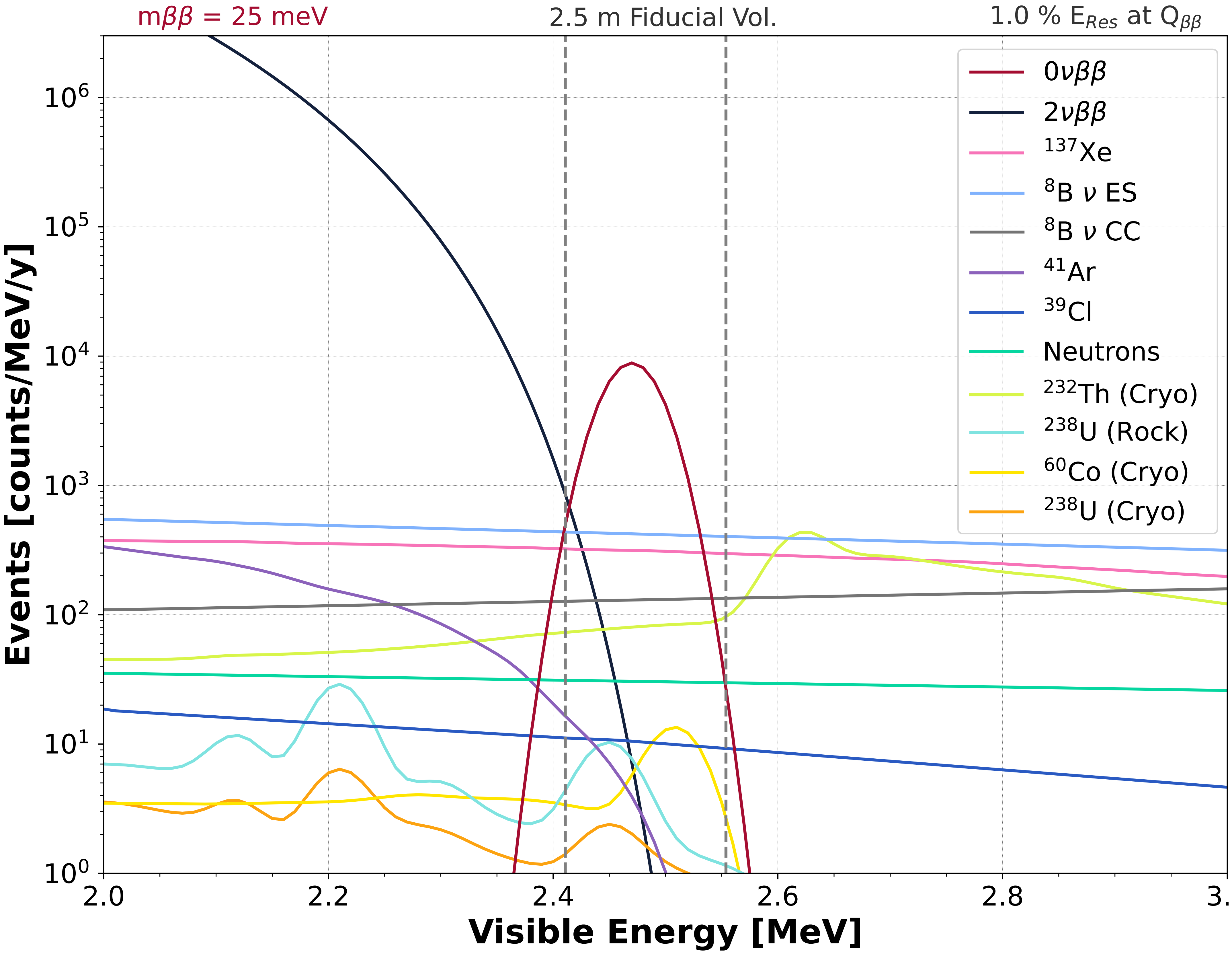
Better Energy Measurement

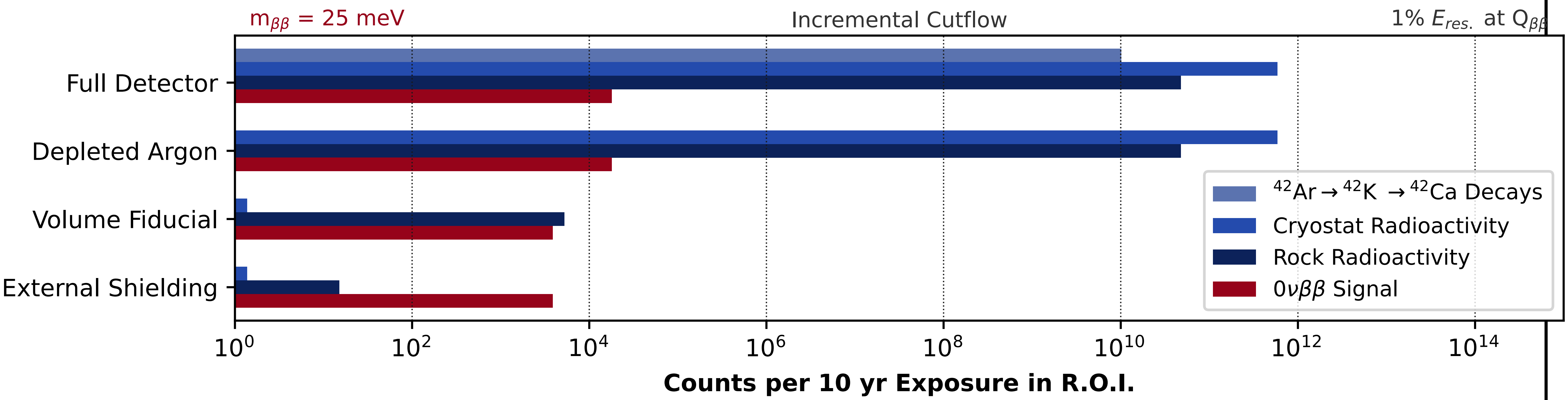

Based on M. Szydagis, et al., Instruments 5, 13 (2021)

ProtoDUNE-SP

JINST 15 (2020) P12004

Less noise in charge readout


$m\beta\beta$ = 25 meV
2.5 m Fiducial Vol.
1.0 % E_{Res} at $Q_{\beta\beta}$
$0\nu\beta\beta$
$2\nu\beta\beta$
^{137}Xe
^{8}B ν ES
^{8}B ν CC
^{41}Ar
^{39}Cl
Neutrons
^{232}Th (Cryo)
^{238}U (Rock)
^{60}Co (Cryo)
^{238}U (Cryo)
Events [counts/MeV/y]
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Visible Energy [MeV]
2.0
2.2
2.4
2.6
2.8
3.0



$m_{\beta\beta}$ = 25 meV
Incremental Cutflow
1% $E_{res.}$ at $Q_{\beta\beta}$
Full Detector
Depleted Argon
Volume Fiducial
External Shielding
^{42}Ar → ^{42}K → ^{42}Ca Decays
Cryostat Radioactivity
Rock Radioactivity
$0\nu\beta\beta$ Signal
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Counts per 10 yr Exposure in R.O.I.

BACKGROUND MITIGATION

Background	Activity	Events in ROI	Mitigation strategy
Isotope Intrinsic			
^{136}Xe, $2\nu\beta\beta$	2%, $T_{1/2} = 2.165 \times 10^{21}$ years [61]	130.28	None
Environmental Radiological Backgrounds			
^{232}Th, Rock	3.34 ppm [8, 52]	46.71	Passive Shielding
^{238}U, Rock	7.11 ppm [8, 52]		Passive Shielding
^{232}Th, Steel	0.1 ppb [50]	117.80	Fiducialization
^{238}U, Steel	1 ppb [50]	2.24	Fiducialization
^{60}Co, Steel	0.013 mBq/g [50]	10.09	Fiducialization
^{39}Ar, LAr	1 Bq/kg [62]	Negligible	Energy threshold
^{222}Rn, LAr	10 mBq/m^3 [8]	Negligible	Coincident ^{214}Po Tag
^{42}Ar, LAr	Negligible [63]	Negligible	Use of ^{42}Ar depleted LAr
Solar Neutrinos			
^{8}B ν Elastic Scatters	Standard Solar Model Flux [64]	662.04	
^{8}B ν_e Charged Current	Standard Solar Model Flux [64]	196.00	Photon Coincidence Tag
Spallation Products			
^{32}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag
^{39}Cl	150 day^{-1}(10 kton)$^{-1}$ [59]	14.59	Coincident Muon Timing
^{41}Ar	1600 day^{-1}(10 kton)$^{-1}$ [59]	6.54	Photon Coincidence Tag
^{137}Xe	3.8 day^{-1}(10 kton)$^{-1}$ [65]	449.43	Photon Coincidence Tag
^{16}N	0.033 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{30}Al	1.4 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{40}Cl	27 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{20}F	2 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{34}P	12 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing
^{38}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None
^{36}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None
^{37}Ar	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag
^{33}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag
^{11}Be	0.34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing

See Andy Mastbaum's
talk from this meeting

And paper on arxiv
arxiv 2203.10147

Demonstrated the feasibility of reconstructing the MeV-scale signal 214Bi-214Po topology in a large-scale wire-readout LArTPC

Veto photon coincidence within 32 cm of signal candidates

Veto window within 2m and 60sec of all muon tracks.

BACKGROUND MITIGATION

Background	Activity	Events in ROI	Mitigation strategy	
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^{34}P	12 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	
^{38}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None	
^{36}Cl	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	None	
^{37}Ar	110 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag	
^{33}P	34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Photon Coincidence Tag	
^{11}Be	0.34 day^{-1}(10 kton)$^{-1}$ [59]	Negligible	Coincident Muon Timing	