The DEAP-3600 liquid argon optical model + NEST updates

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UC Riverside
LIDINE 2023, Madrid
20 September, 2023

Bing AI, show me a spherical acrylic LAr dark matter detector in a nest

DEAP-3600 and its optical model
Updates to the Noble Element Simulation Tool

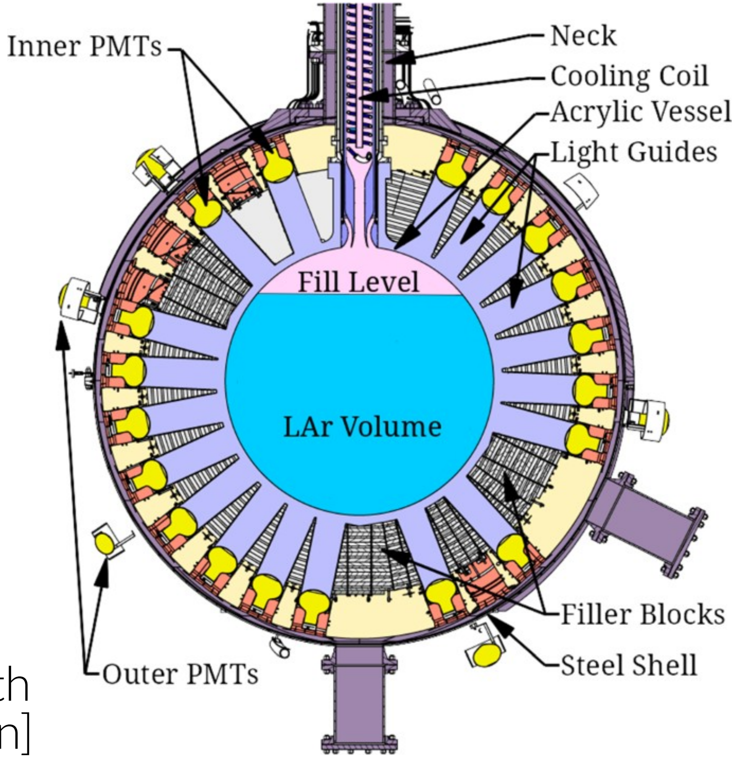
The DEAP-3600 dark matter detector

Overview

3.3 tonnes of LAr
1.7 m-ID, 5cm-thick Acrylic Vessel (AV)
45 cm-long PMMA light guides (LGs) between AV & PMTs
255 Hamamatsu R5912 HQE low radioactivity PMTs, 8" Ø
250 MS/s readout sampling rate with CAEN V1720 digitizer
6.1±0.4 PE/keV after removing afterpulses
O(1cm) position resolution for bulk LAr scintillation
<<1 ER bkgd w/ Pulse Shape Discrimination

See more

Status and prospects of the DEAP-3600 experiment
– Vicente Pesudo [Wed, 20 Sept, 10:20]
Study of the energy response and position reconstruction with ^{22}Na source in DEAP-3600 – Ludovico Luzzi, [Poster session]



Best hits

- "Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB". *PRD 100, 022004 (2019)*
- "First direct detection constraints on Planck-scale mass dark matter with multiple-scatter signatures using the DEAP-3600 detector". *PRL 128, 011801 (2022)*
- "Constraints on dark matter-nucleon effective couplings in the presence of kinematically distinct halo substructures using the DEAP-3600 detector". *PRD 102, 082001 (2020)*

Classic and novel dark matter searches, exploring new parameter space

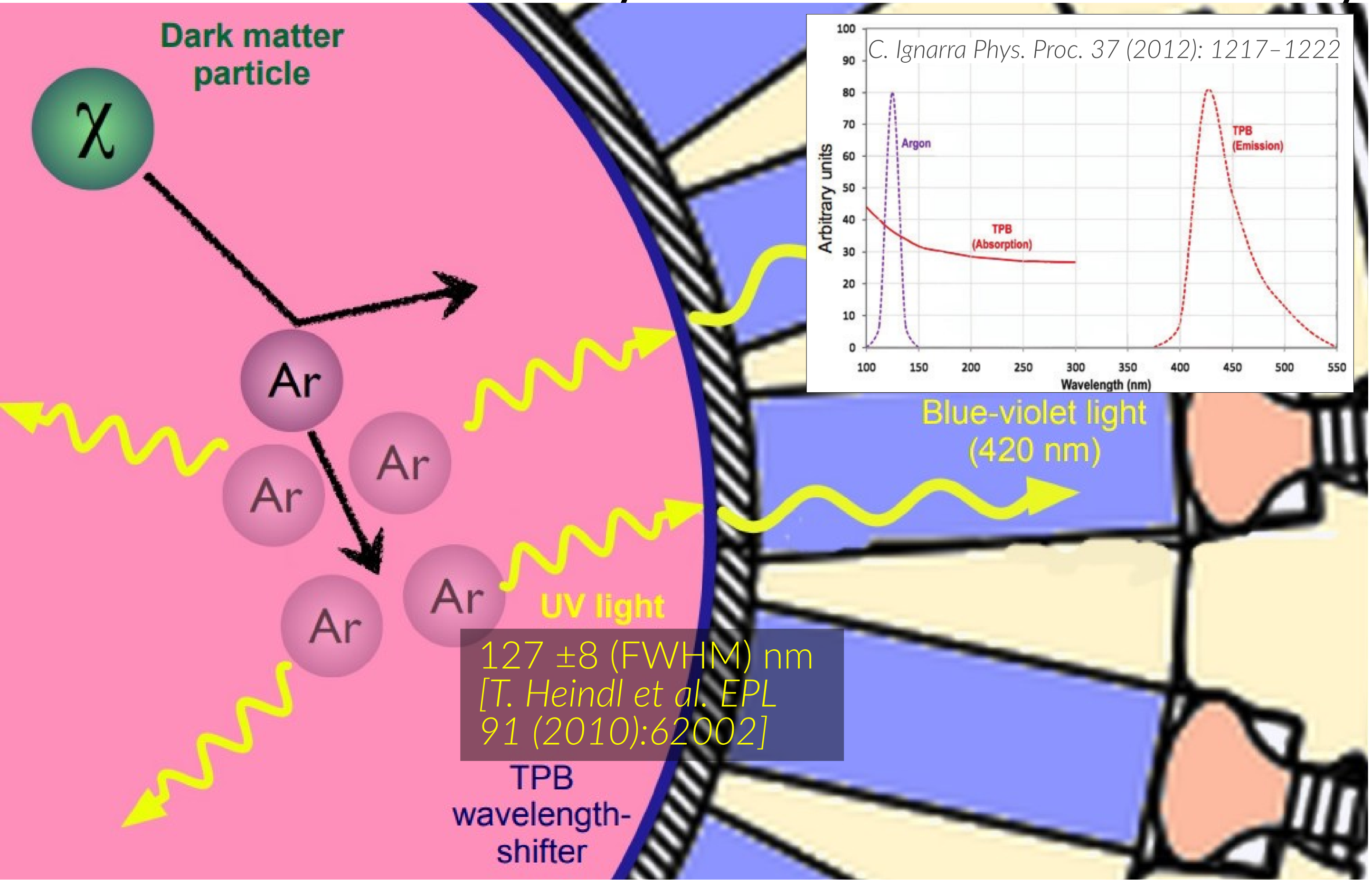
- "Precision measurement of the specific activity of ^{39}Ar in atmospheric argon with the DEAP-3600 detector". *EPJC 83, 642 (2023)*
- "Electromagnetic Backgrounds and Potassium-42 Activity in the DEAP-3600 Dark Matter Detector". *PRD 100, 072009 (2019)*

Assaying trace radioisotopes in atmospheric argon

- "Pulseshape discrimination against low-energy Ar-39 beta decays in liquid argon with 4.5 tonne-years of DEAP-3600 data". *EPJC 81, 823 (2021)*
- "The liquid-argon scintillation pulseshape in DEAP-3600". *EPJC 80, 303 (2020)*

Improving LAr scintillation and PSD models

Optical simulations: Key to DEAP analyses



C. Ignarra Phys. Proc. 37 (2012): 1217–1222

127 ±8 (FWHM) nm
[T. Heindl et al. EPL 91 (2010):62002]

The goals

- Produce primary scintillation
- Track 120-500 nm photons over several meters of LAr
- WL-shift & scatter in TPB
- Propagate thru GAr & PMMA
- Detect with PMT, incl. noise

Used for

- Background modeling
- Signal modeling for
  - Superheavy DM
  - Neutrino signals
- Position reconstruction
- Multivariate analysis-based background discriminants

Optics is hard

Optics is hard

$$n^2 = a_0 + \frac{a_{UV}\lambda^2}{\lambda^2 - \lambda_{UV}^2} + \frac{a_{IR}\lambda^2}{\lambda^2 - \lambda_{IR}^2}$$

~107 nm

Refractive index at 128 nm sits right near a pole!
Limited data at UV → significant uncertainties

To propagate in LAr, need to know:

Refractive index
Rayleigh scattering length
Group velocity
Absorption length ← Depends mostly on purity of LAr

It’s all connected

Rayleigh scattering

Group velocity

Refractive index

Need coherent treatment of all parameters across full wavelength range with a fully correlated treatment of uncertainties

Going down the ~~rabbit~~ marmot hole…

Putting the pieces together

$$n^2 = a_0 + \frac{a_{UV}\lambda^2}{\lambda^2 - \lambda_{UV}^2} + \frac{a_{IR}\lambda^2}{\lambda^2 - \lambda_{IR}^2}$$

Sellmeier equation with UV and IR resonances covers the wavelength range of interest. Can be fit to data

Approach for this analysis is inspired by E. Grace's, with modifications

a_0 = 1.23
a_{UV} = 0.27
a_{IR} = 0.00085
λ_{UV} = 106.6 nm
λ_{IR} ~ 960 nm

Nominal values from *E. Grace et al. NIM A 867 (2017): 204–208*

UV resonance: Spectral line measured by *A. Lane and A. Kupperman. Rev Sci Instrum 39 1 (1968):126–127*

IR resonance: Absorption line measured by *S. Arai et al. J. Chem. Phys. 68, 4595–4603 (1978) – Some papers have used 908 nm; it doesn't seem to make a difference*

Putting the pieces together

$$n^2 = a_0 + \frac{a_{UV}\lambda^2}{\lambda^2 - \lambda_{UV}^2} + \frac{a_{IR}\lambda^2}{\lambda^2 - \lambda_{IR}^2}$$

$$\underline{v_g} = \frac{\partial \omega}{\partial k} = \frac{c}{n + \omega \frac{\partial n}{\partial \omega}} = \underline{v_p}\left(1 + \frac{\lambda}{n}\frac{\partial n}{\partial \lambda}\right)$$

Group velocity

Phase velocity
$v_p = c/n$

Landau and Lifshitz

$$\underline{L^{-1}_{\text{Rayleigh}}} = \frac{\omega^4}{6\pi c^4}\left[k_B T \rho^2(T)\underline{\kappa_T(T)}\left(\frac{\partial n^2}{\partial \rho}\right)_T^2 + \cancelto{\sim 0}{\frac{k_B T}{\underline{\rho}(T) c_v}\left(\frac{\partial n^2}{\underline{\partial T}}\right)_\rho^2}\right]$$

[G.M. Seidel et al. NIM A 489, 1 (2002): 189–194]

Rayleigh
scattering
length

Isothermal
compressability

Density Temperature

To understand $\kappa_T(T)$, $\rho(T)$, and $n(T)$, we need to dig into the weeds

The weeds

$$L^{-1}_{\text{Rayleigh}} = \frac{\omega^4}{6\pi c^4}\left[k_B T \rho^2(T)\kappa_T(T)\left(\frac{\partial n^2}{\partial \rho}\right)_T^2 + \frac{k_B T}{\rho(T) c_v}\left(\frac{\partial n^2}{\partial T}\right)_\rho^2\right]$$

Inverse Rayleigh scattering length
L. Landau, E. Lifshitz, "Electrodynamics of Continuous Media", 2nd Edition, Pergamon, Oxford, 1984.

$$\rho(T) = \rho_c \exp\left(A_\rho\left(1-\frac{T}{T_c}\right)^{1/3} + B_\rho\left(1-\frac{T}{T_c}\right)^{2/3} + C_\rho\left(1-\frac{T}{T_c}\right)^{7/3} + D_\rho\left(1-\frac{T}{T_c}\right)^{4}\right)$$

$$\rho_c = 0.5356\,\mathrm{g/cm^3}, T_c = 150.687\,\mathrm{K}, A_\rho = 1.5, B_\rho = -0.31, C_\rho = 0.086, D_\rho = -0.041$$

Empirical LAr density-temperature relation
E.W. Lemmon *et al.* "Thermophysical Properties of Fluid Systems". NIST 69
http://webbook.nist.gov/chemistry/fluid/

$$p(T) = A_p(T)\rho^2 + B_p(T)\rho^4 + C_p(T)\rho^6$$

$$A_p(T) = -241.8 + 3.8T - 330.3\times 10^4 T^{-2} + 54.5\times 10^3 T^4$$

$$B_p(T) = -192.3 + 2.8T + 0.01T^2, \quad C_p(T) = 174.7 + 0.9T$$

Global empirical fit of argon equation of state
Agrees with data to within 0.1% - See Eq 3.35 of V. Rabinovich *et al.* "Thermophysical properties of neon, argon, and xenon." Publisher Standards Moscow (1976)

$$\kappa_T(T) = \frac{1}{\rho}\left(\frac{\partial \rho}{\partial p}\right)_T = \left(2A_p(T)\rho^2 + 4B_p(T)\rho^4 + 6C_p(T)\rho^6\right)^{-1}$$

Definition of isothermal compressibility + empirical EoS → κ_T with C. Kittel "Intro. to Solid State Physics"

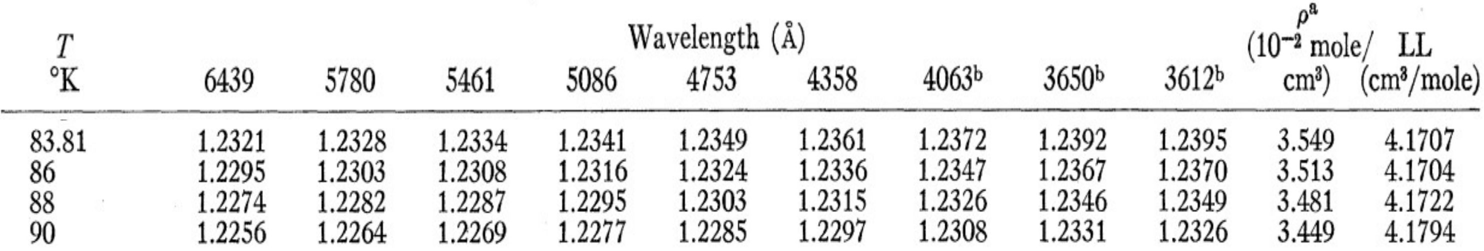
$$\frac{n^2-1}{n^2+2} = \frac{4\pi}{3}\frac{N_a\alpha_0}{M}\rho = A\rho$$

Clausius–Mossotti relation setting $\varepsilon = n^2$

$$\frac{\partial n}{\partial T} = \frac{3A}{2n}\frac{1}{(1-A\rho)^2}\frac{\partial \rho}{\partial T} = \frac{3}{2n}\frac{1}{\rho}\left(\frac{n^2-1}{n^2+2}\right)\left(1-\frac{n^2-1}{n^2+2}\right)^{-2}\frac{\partial \rho}{\partial T}$$

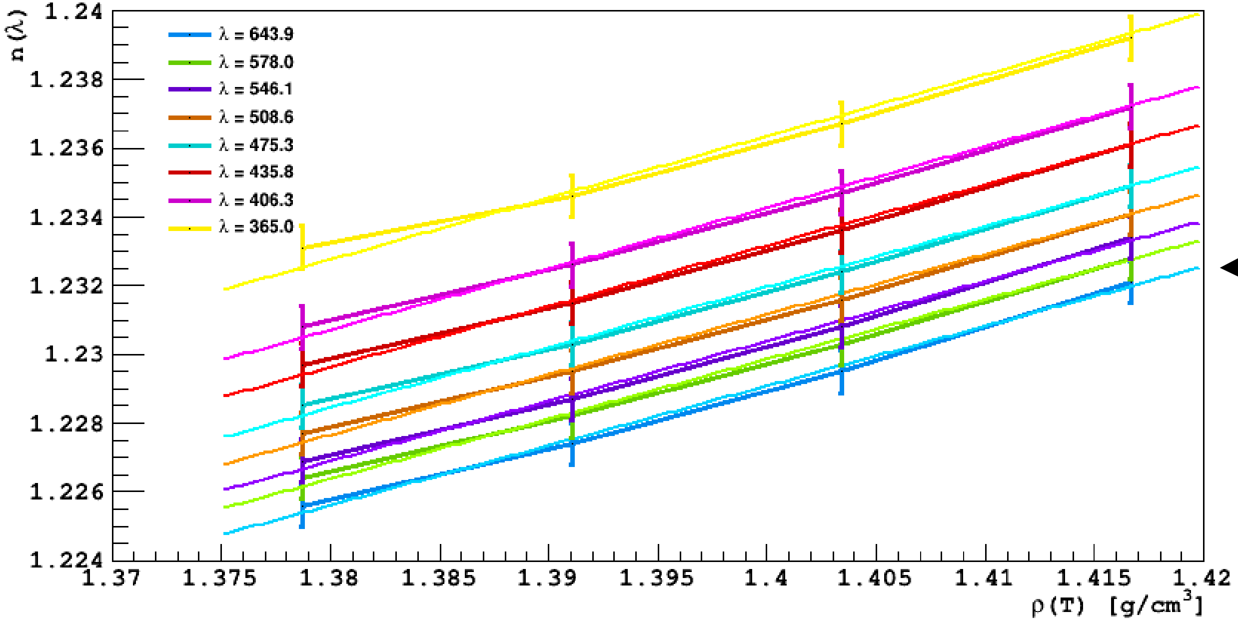
From differentiating Clausius-Mossotti

Refractive index T-dependence



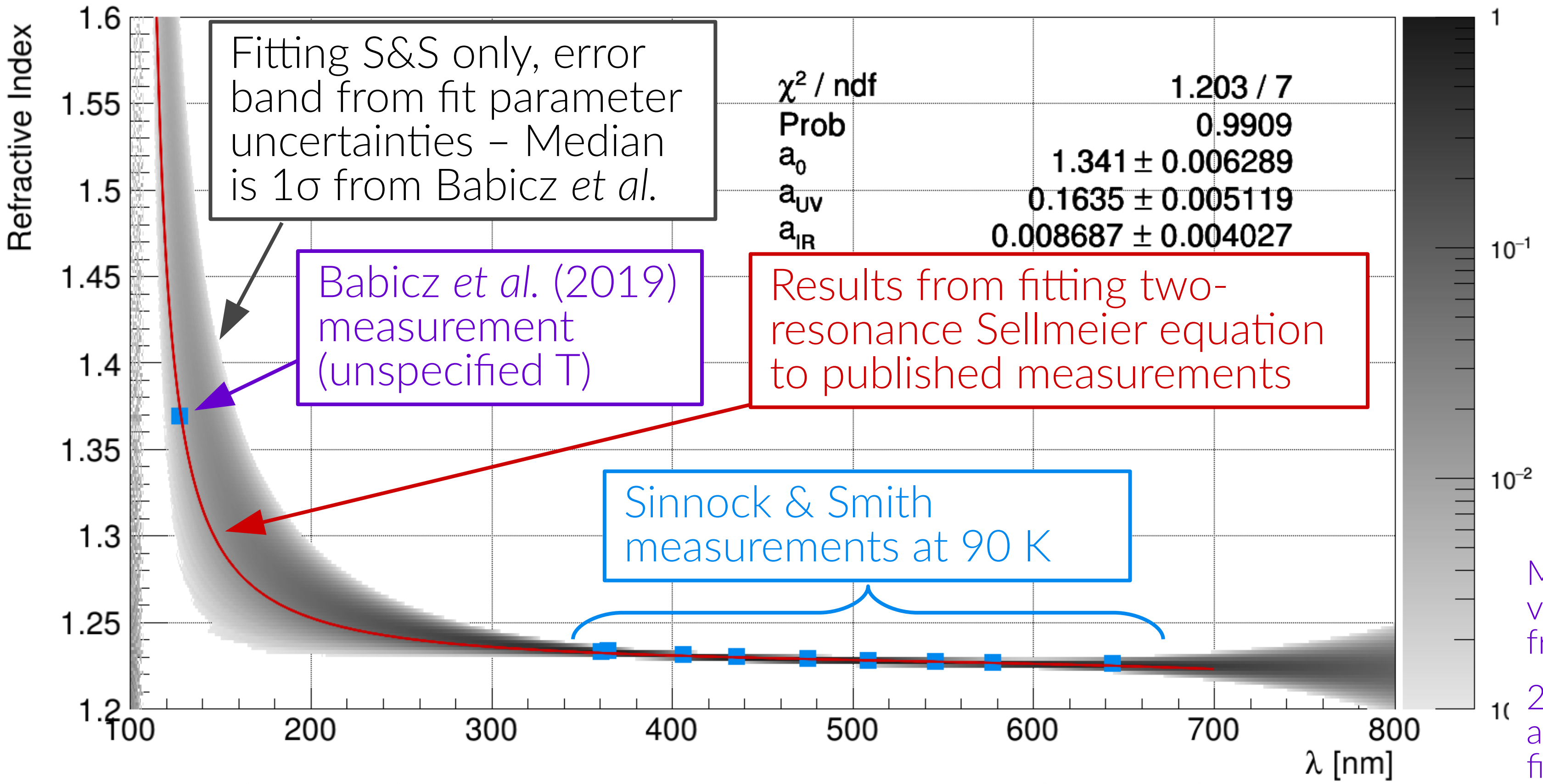
T °K	Wavelength (Å) 6439	5780	5461	5086	4753	4358	4063^b	3650^b	3612^b	ρ^a (10^{-2} mole/ cm³)	LL (cm³/mole)
83.81	1.2321	1.2328	1.2334	1.2341	1.2349	1.2361	1.2372	1.2392	1.2395	3.549	4.1707
86	1.2295	1.2303	1.2308	1.2316	1.2324	1.2336	1.2347	1.2367	1.2370	3.513	4.1704
88	1.2274	1.2282	1.2287	1.2295	1.2303	1.2315	1.2326	1.2346	1.2349	3.481	4.1722
90	1.2256	1.2264	1.2269	1.2277	1.2285	1.2297	1.2308	1.2331	1.2326	3.449	4.1794

[A. Sinnock and B. Smith. "Refractive Indices of the Condensed Inert Gases". Phys. Rev. 181, 3 (1969): 1297–1307]



Fitting Sellmeier coefficients, consistent with A being constant
Model agrees with temperature dependence in Sinnock & Smith

So what is n(λ)?



Fitting S&S only, error band from fit parameter uncertainties – Median is 1σ from Babicz *et al.*

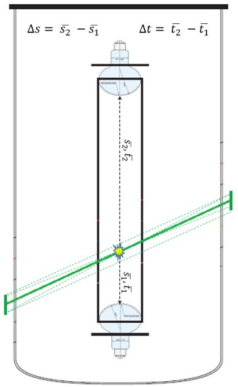
Babicz *et al.* (2019) measurement (unspecified T)

Results from fitting two-resonance Sellmeier equation to published measurements

Sinnock & Smith measurements at 90 K

Varying n(127 nm), fitting, and re-calculating v_g → n(127 nm)=1.363±0.003

Babicz et al.

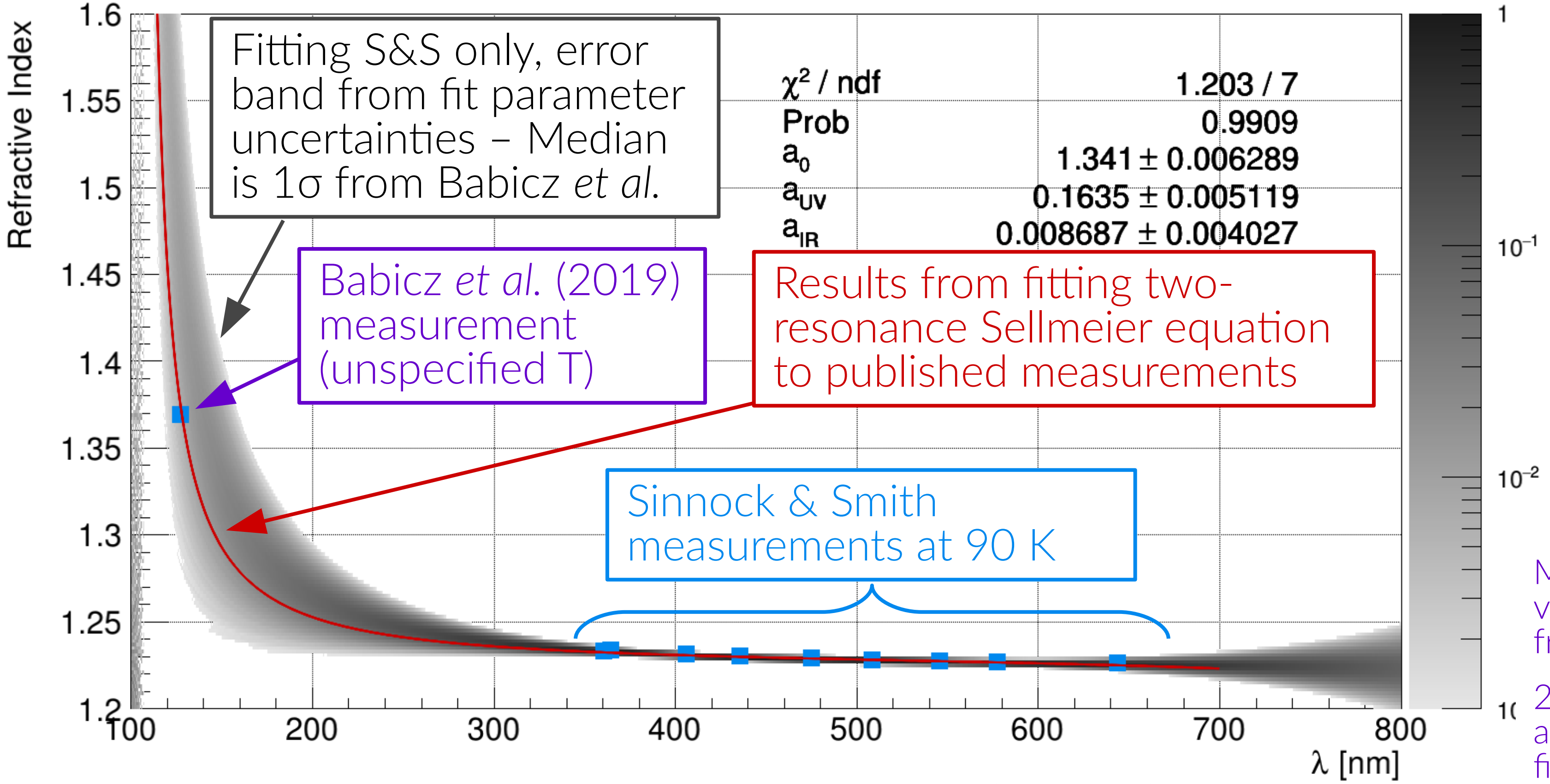


[M. Babicz et al NIMA 936 (2019): 178-179]
[M. Babicz et al JINST 15 (2020): P09009]

Measured v_g=13.40±0.15 cm/ns from passing muons

2020 paper added σ_{syst} analysis due to pulse finding and visible light contamination

So what is n(λ,T)?



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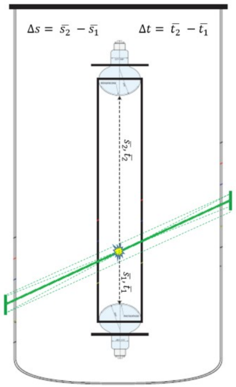
Sinnock & Smith measurements at 90 K

Actual T not precisely known: Vary 88–90 K → n(127 nm)=1.364±0.005

Babicz et al.



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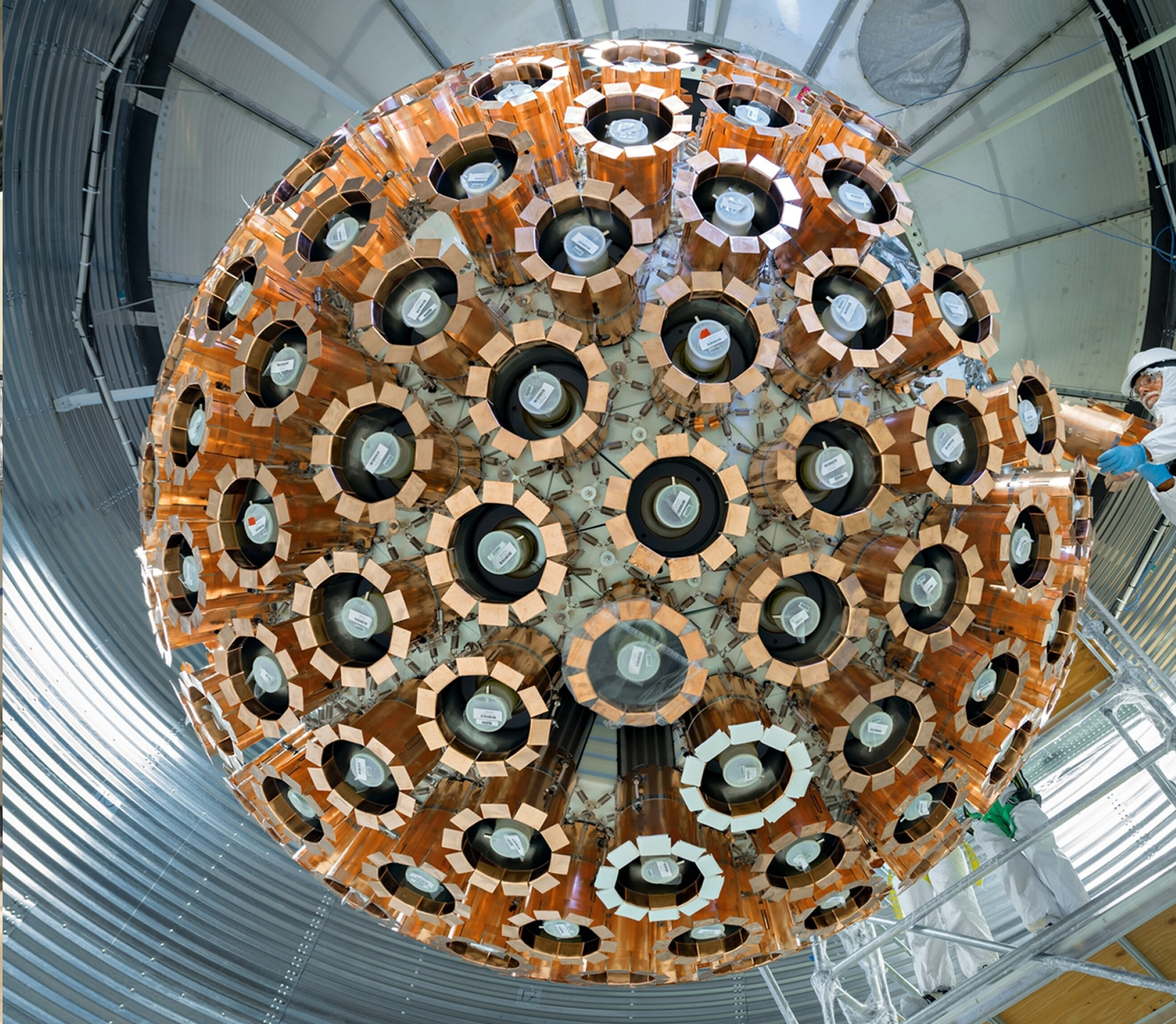
Going DEAP



LAr optical parameters in DEAP

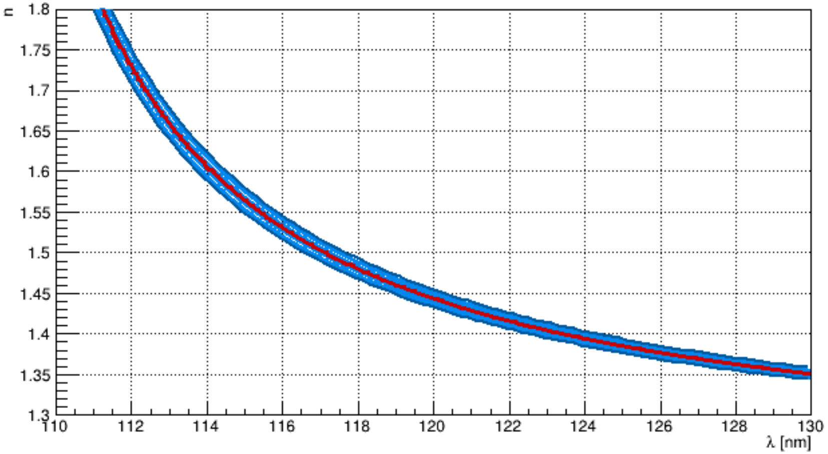
Fit uncertainties:
a_0, a_{IR}, a_{UV}

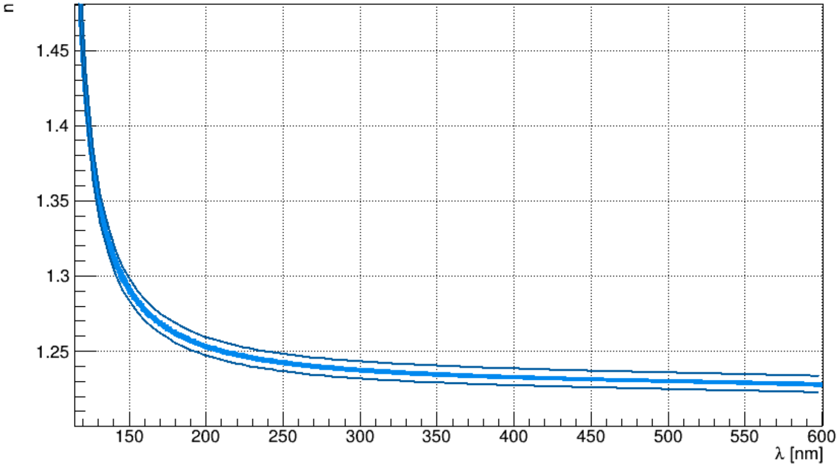
Treatment: Use fit covariance matrix to draw uncertainty bands for $n(\lambda)$, $v_g(\lambda)$, and $L_{Rayleigh}(\lambda) \rightarrow \sigma_{Fit}|_T$

LAr temperature:
84–90 K

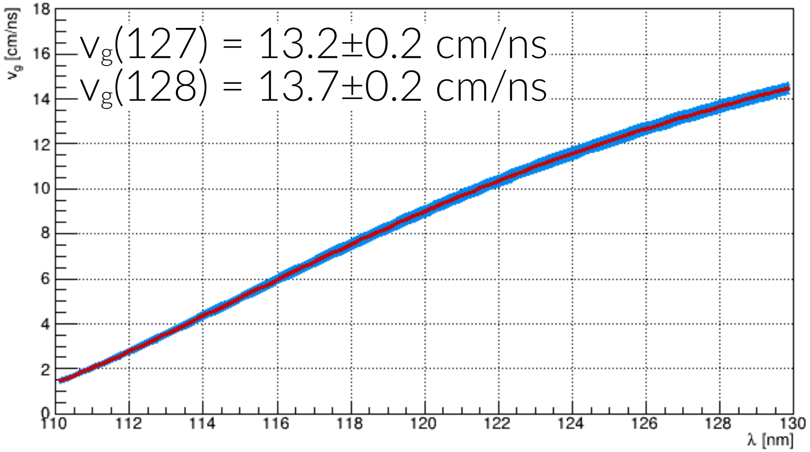
Treatment:
$\sigma_T = ({}^{dn}/_{dT})\delta T$
${}^{dn}/_{dT}$ from derivative of Clausius-Mossott eqn., using empirical $\rho(T)$. Use $\Delta n(\lambda)$ to get $\Delta v_g(\lambda)$ & $L_{Rayleigh}(\lambda)$

Total uncertainty:
$\sigma^2_{tot} = \sigma^2_{Fit}|_T + \sigma^2_T$

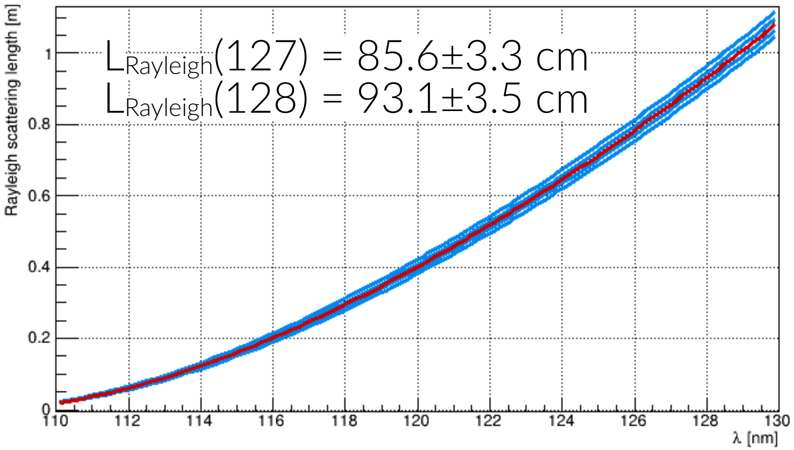




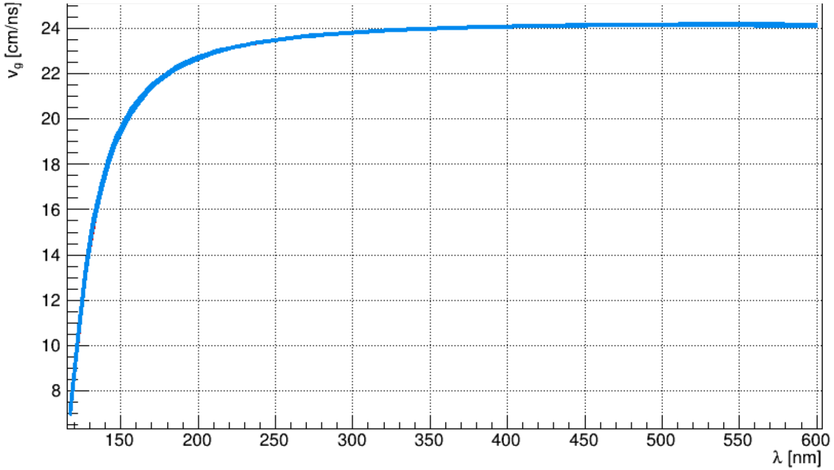
LAr optical parameters in DEAP

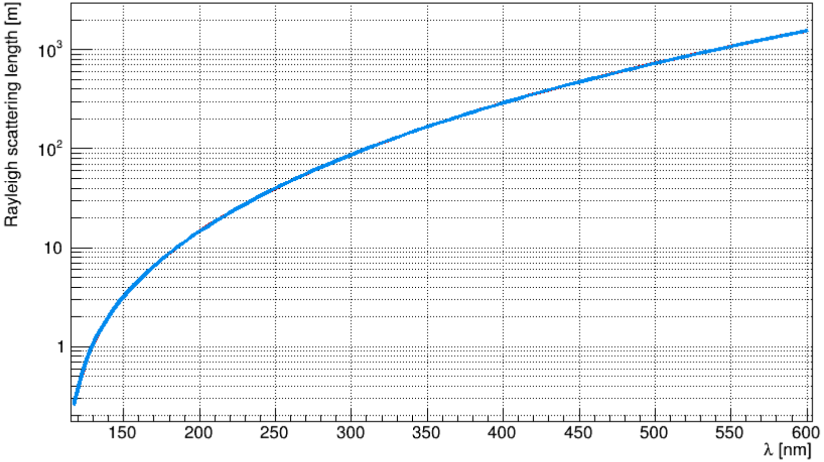


$v_g(127) = 13.2 \pm 0.2$ cm/ns
$v_g(128) = 13.7 \pm 0.2$ cm/ns



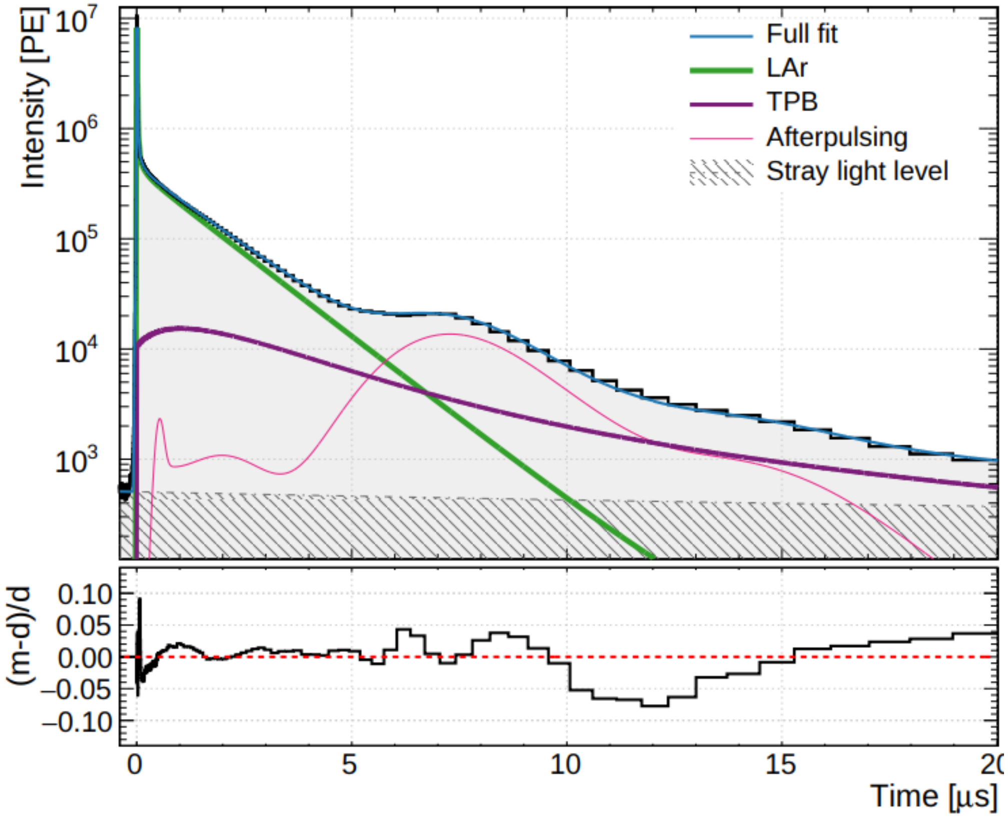
$L_{Rayleigh}(127) = 85.6 \pm 3.3$ cm
$L_{Rayleigh}(128) = 93.1 \pm 3.5$ cm

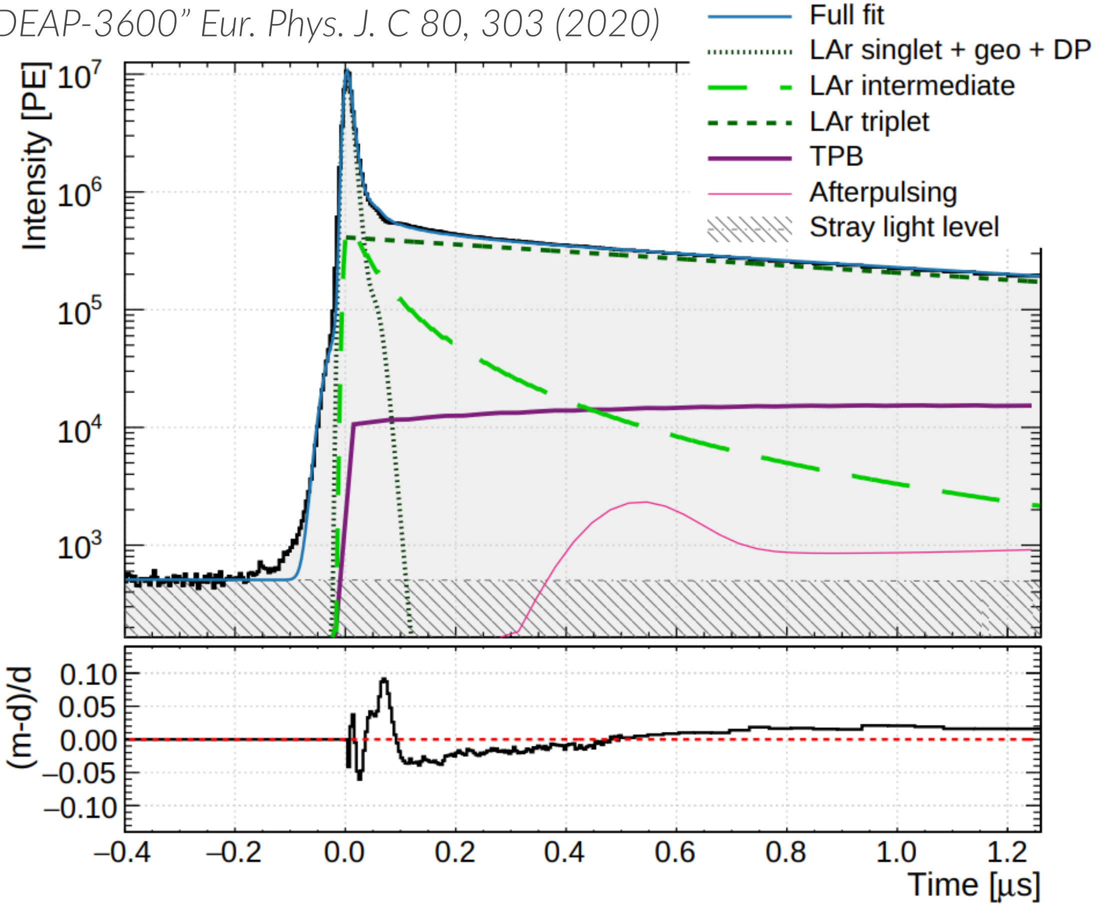




Scintillation pulse shape

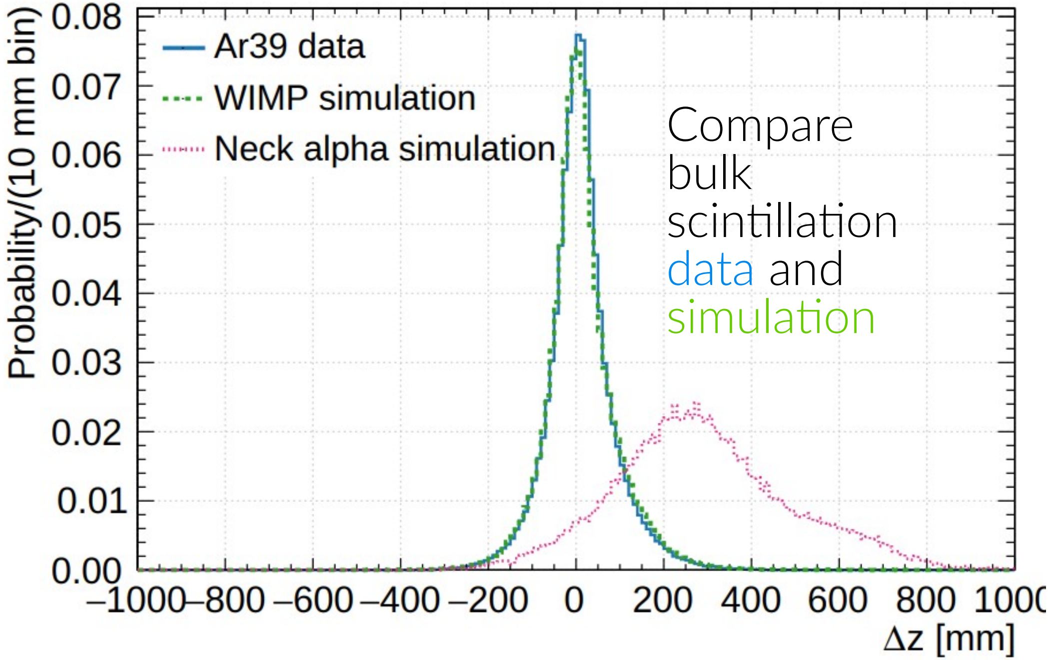
DEAP Collaboration. "The liquid-argon scintillation pulseshape in DEAP-3600" Eur. Phys. J. C 80, 303 (2020)





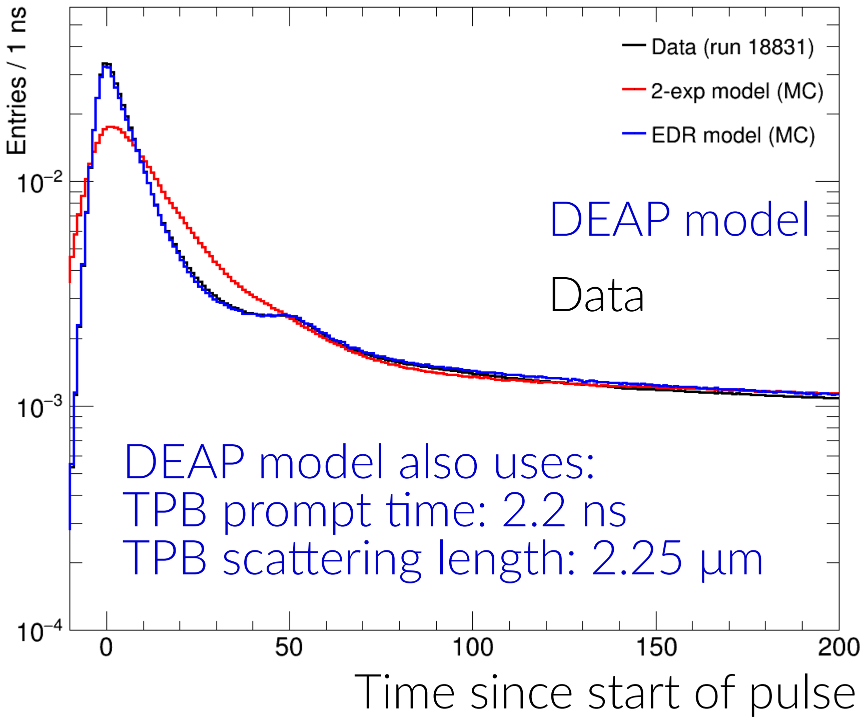
Excellent data/simulation agreement

Diff. in reconstructed z for 2 algorithms



Compare bulk scintillation data and simulation

^{39}Ar Average waveform



DEAP model

Data

DEAP model also uses:
TPB prompt time: 2.2 ns
TPB scattering length: 2.25 μm

DEAP Collaboration. Search for dark matter with a 231-day exposure of liquid argon using DEAP-3600 at SNOLAB.” PRD 100, 022004 (2019)

Sina Safarabadi. PhD thesis, University of Alberta (2023)

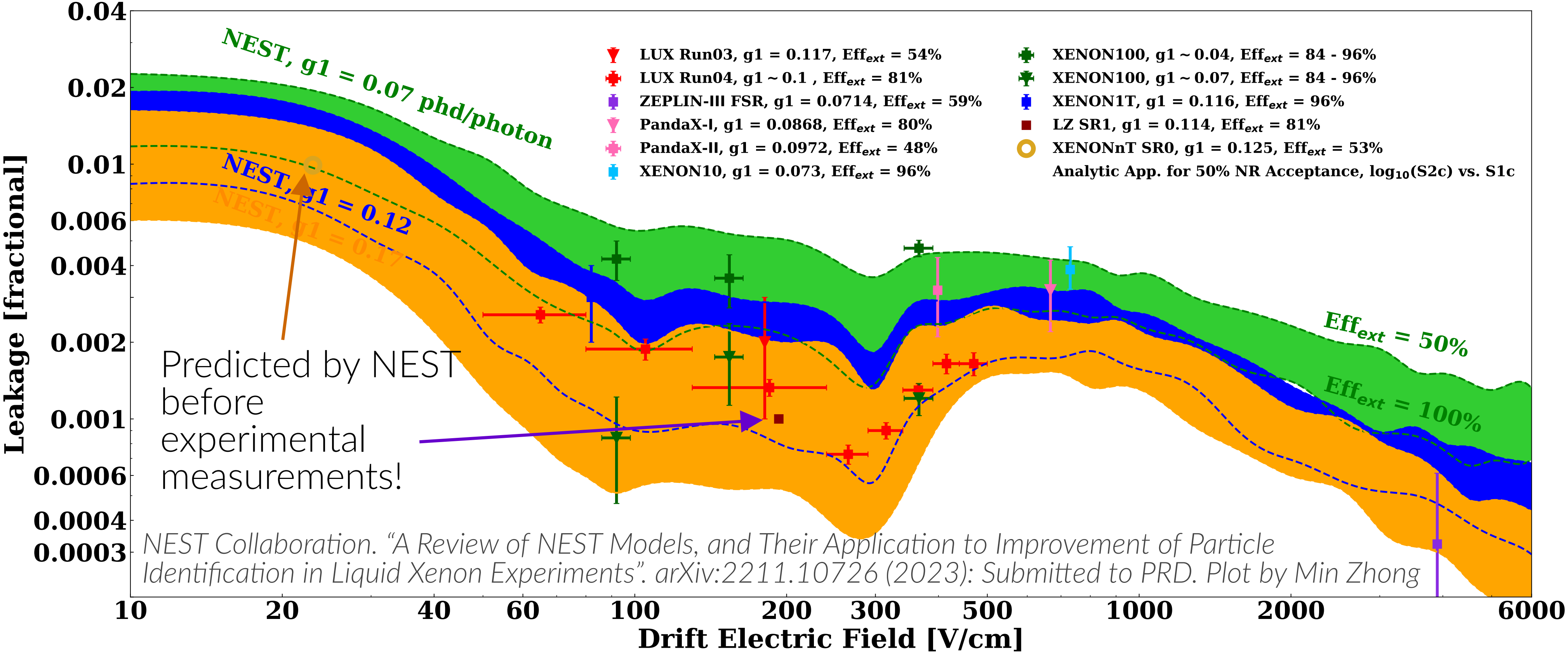
Brief NEST update

Bing AI, draw a picture of a nest made of liquid argon and liquid xenon

NEST: Noble Element Simulation Technique:
A cross-collaboration team developing tools to model signals in Xe and Ar detectors

Reproducing & foretelling detector response

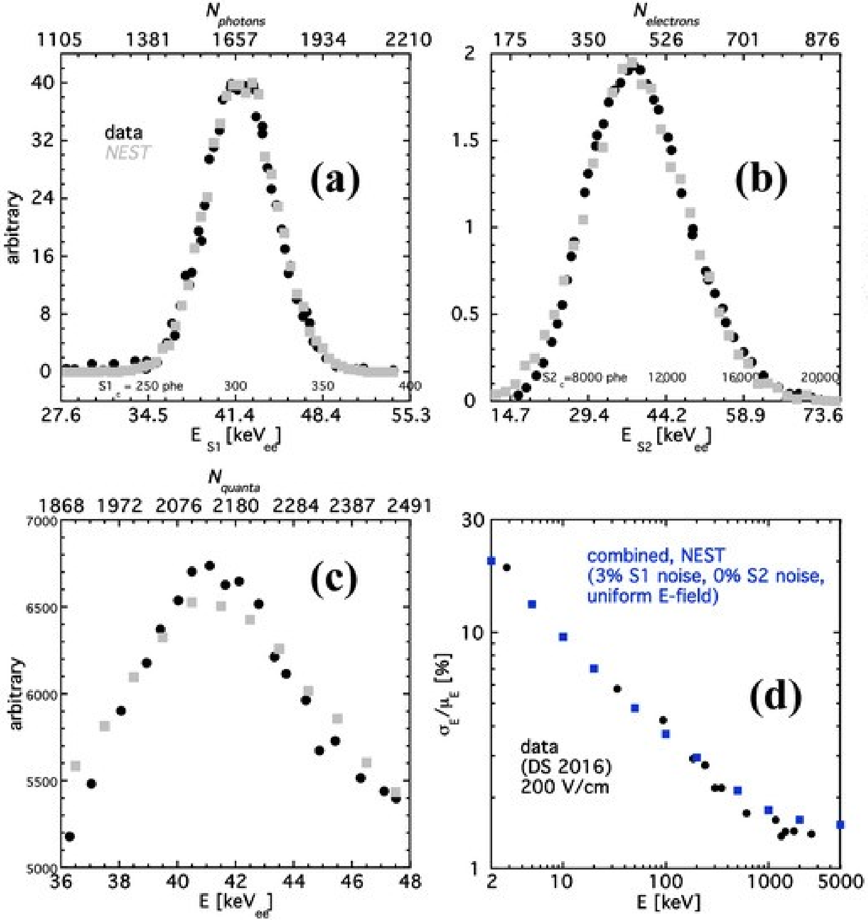
Electronic recoil leakage (ER/NR discrimination) using S2/S1 in LXe TPCs

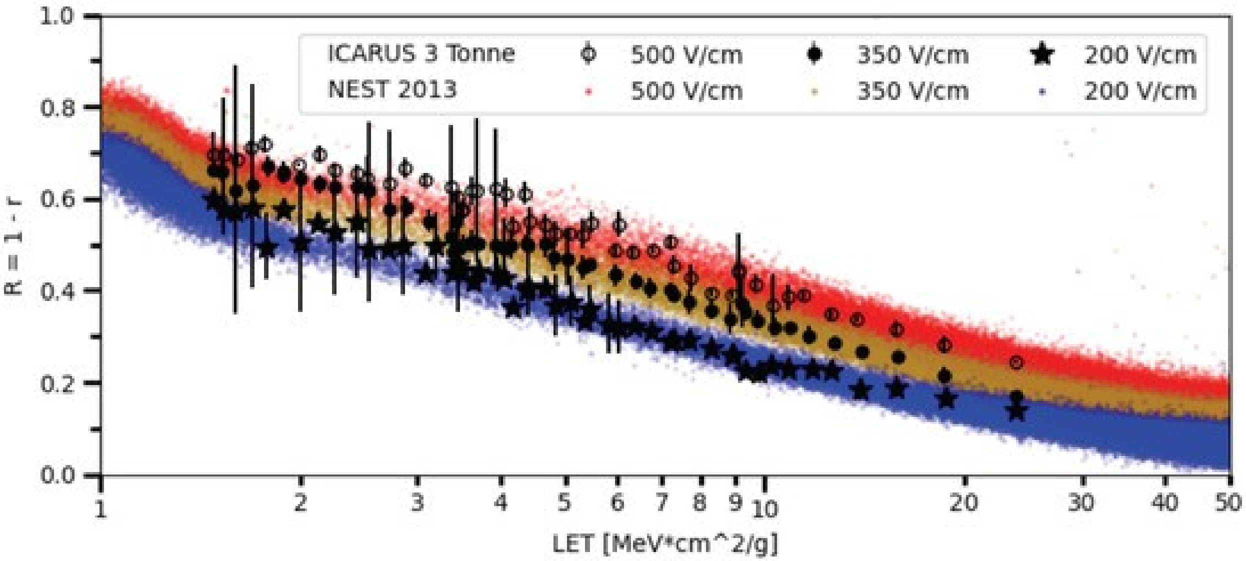


Predicted by NEST before experimental measurements!

NEST Collaboration. "A Review of NEST Models, and Their Application to Improvement of Particle Identification in Liquid Xenon Experiments". arXiv:2211.10726 (2023): Submitted to PRD. Plot by Min Zhong

Reproduces LAr data across wide E range





NEST Collaboration. "A Review of Basic Energy Reconstruction Techniques in Liquid Xenon and Argon Detectors for Dark Matter and Neutrino Physics Using NEST". Instruments 5(1), 13 (2021)

END