DEEP UNDERGROUND NEUTRINO EXPERIMENT

ARTIE final results

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on the behalf of the ARTIE and DUNE Collaborations

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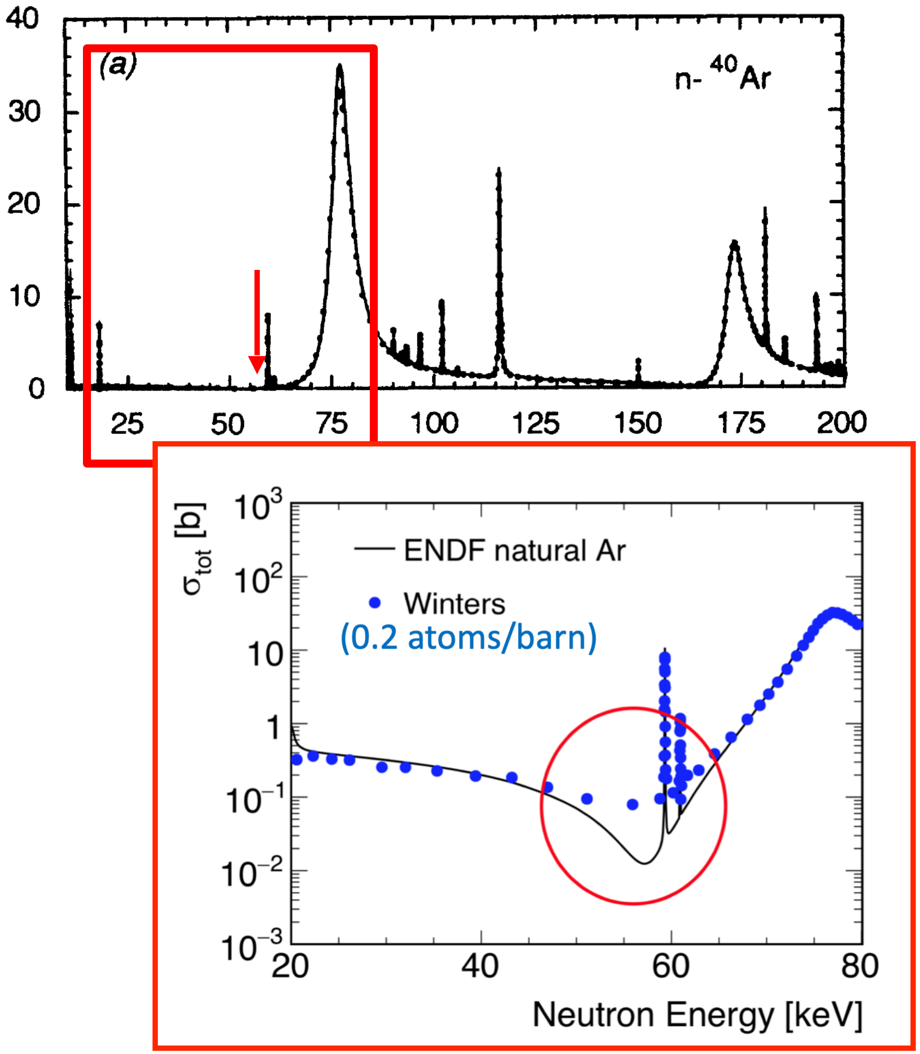
UCDAVIS DEPARTMENT OF PHYSICS

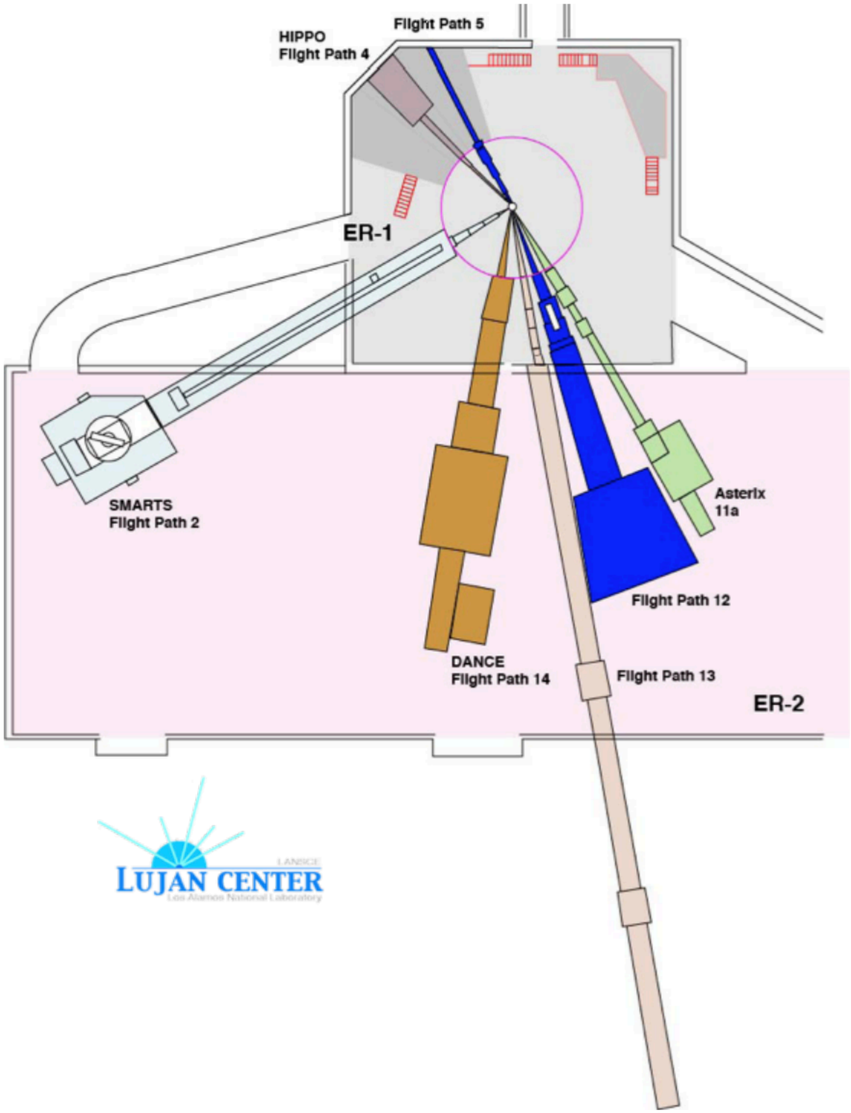
22nd edition PANIC Lisbon Portugal Particles and Nuclei International Conference

Why ARTIE?

- The **A**rgon **R**esonant **T**ransmission **I**nteraction **E**xperiment (**ARTIE**) is a measurement of the depth of the anti-resonance at 57keV in the total cross section of neutrons on argon
- Theoretical calculation (ENDF) predicts an anti-resonance but the only experiment before ARTIE did not observe it
- Knowledge of this parameter is of utmost importance when argon is used as a target or a shield (*e.g.* rate at which neutrons from environment enters the fiducial volume, or how far neutrons can travel from an interaction vertex and thus contribute to lost energy in calorimetry)

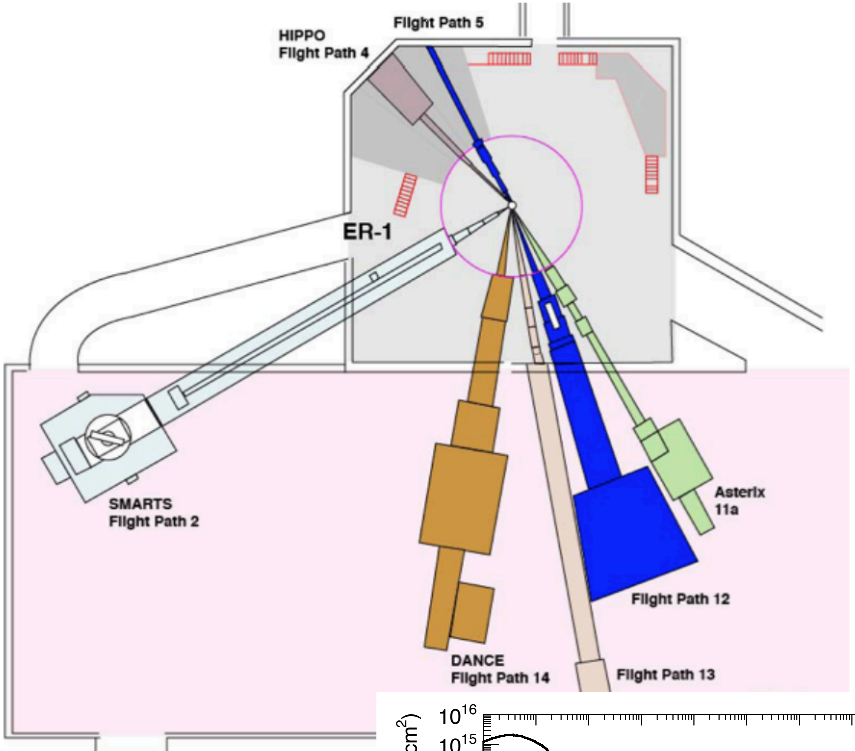


What is ARTIE?

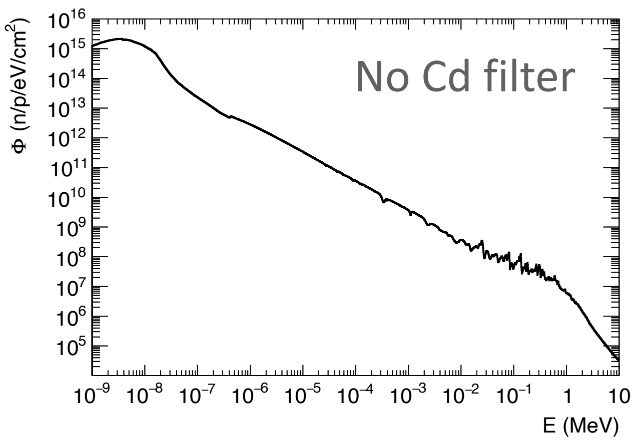


- ARTIE is located on Flight Path 13 (FP13) at the Lujan Neutron Scattering Center (LANSCE) at LANL and data was collected in October 2019
- ARTIE uses Time Of Flight (TOF) technique to measure neutron energy
- ARTIE designed to contain liquid argon (LAr) at atmospheric pressure
- ARTIE uses a **1.68 m** long (longest to fit at FP13) x **1”** diameter (≫ beam size) liquid argon (99.99% pure) target with a column density of **3.5 atoms/b**
  - Because of its thickness, the target is nearly opaque to neutrons away from anti-resonance:
    ⇒ **ROI is 30-70keV**

Neutron energy flux



- Neutrons are produced via spallation reactions caused by a 800 MeV proton beam impinging on a tungsten target (typical beam current of 80μA) at a repetition of 20Hz
- A 1/16'' Cadmium filter is used to suppress slow neutron flux below 0.5eV
  - It removes most "overlap" between pulses and thermal neutron background (could lead to dead time)



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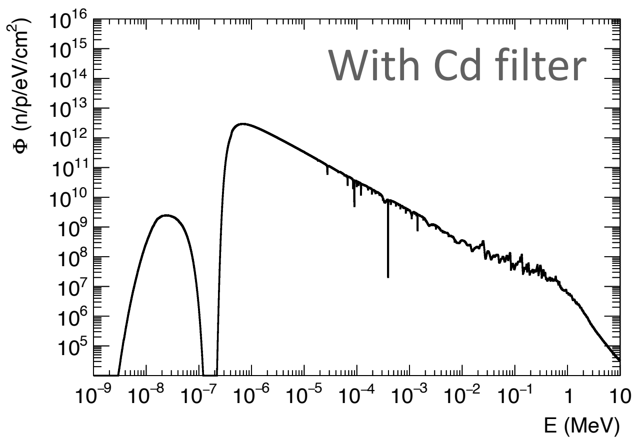
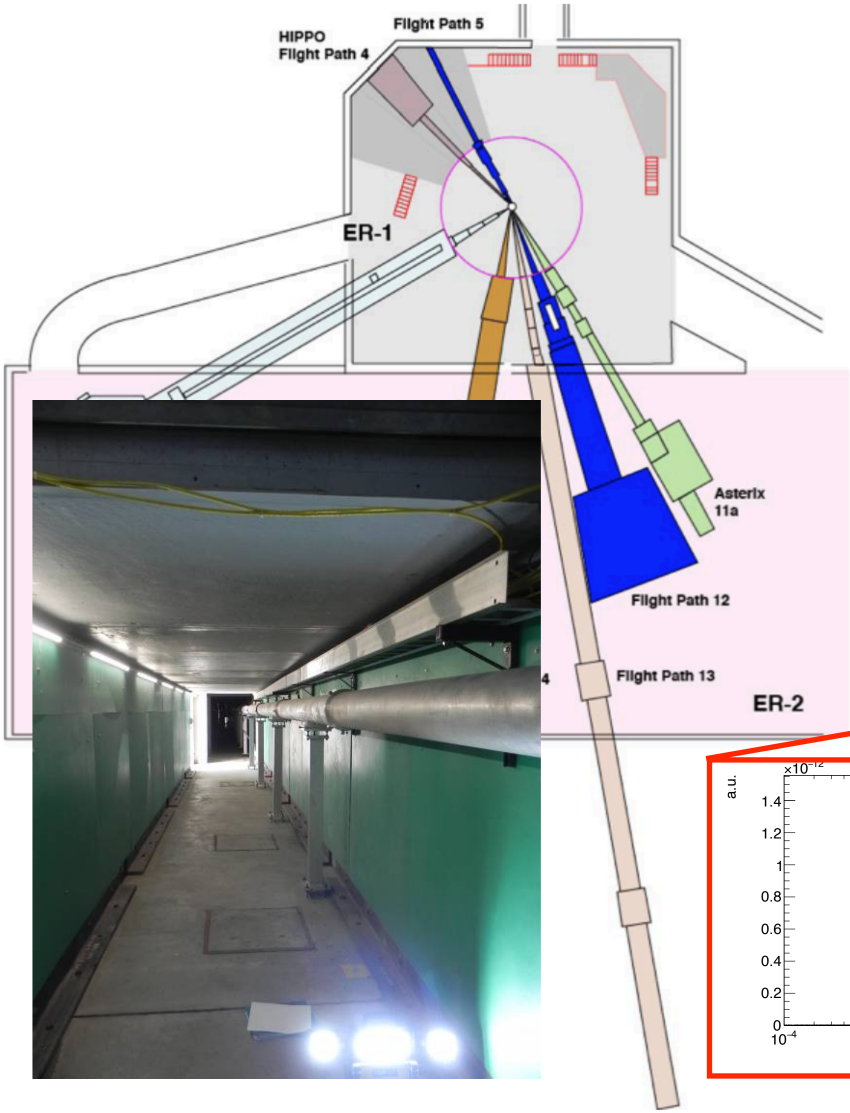
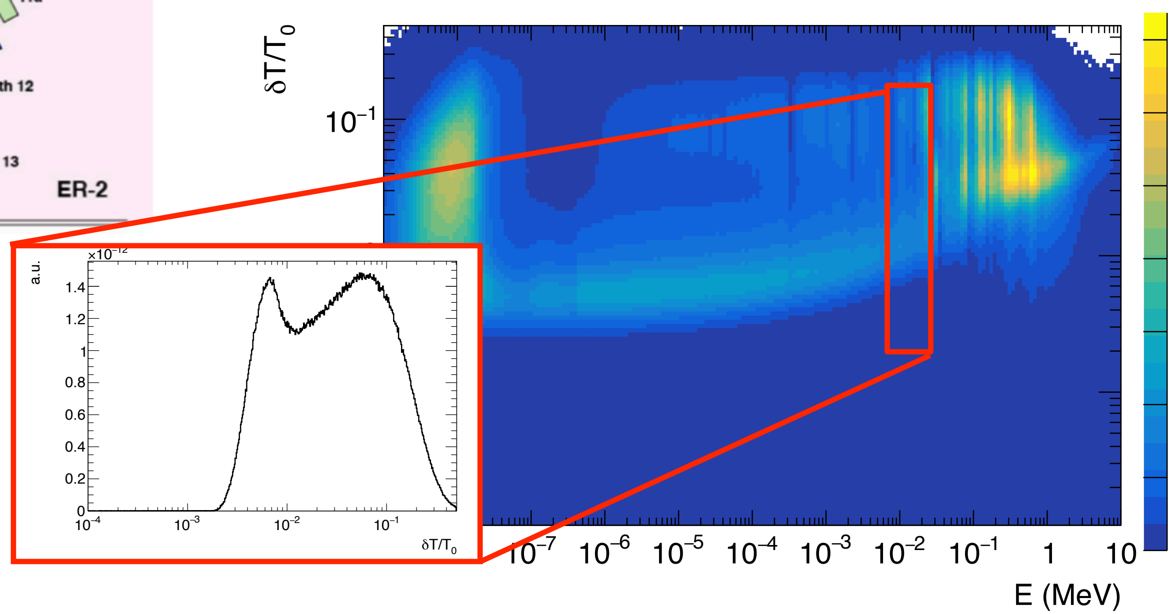


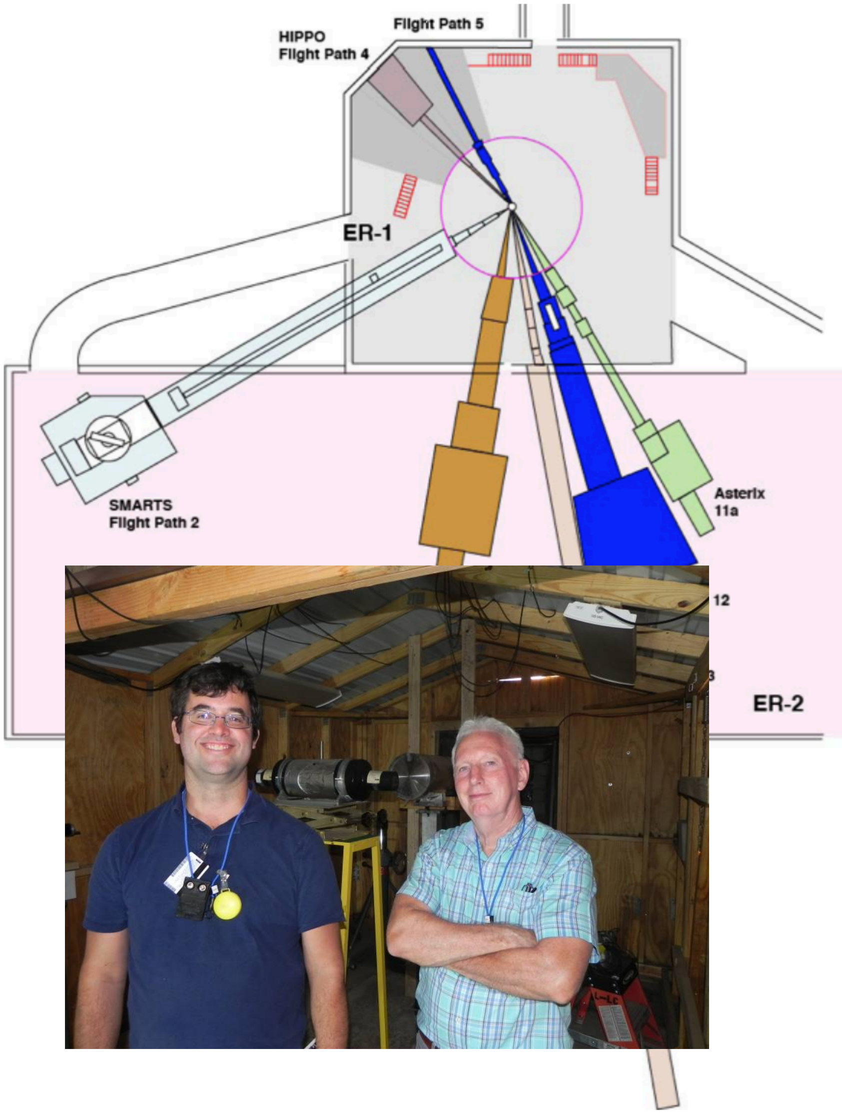
Liquid hydrogen moderator & vacuum lines

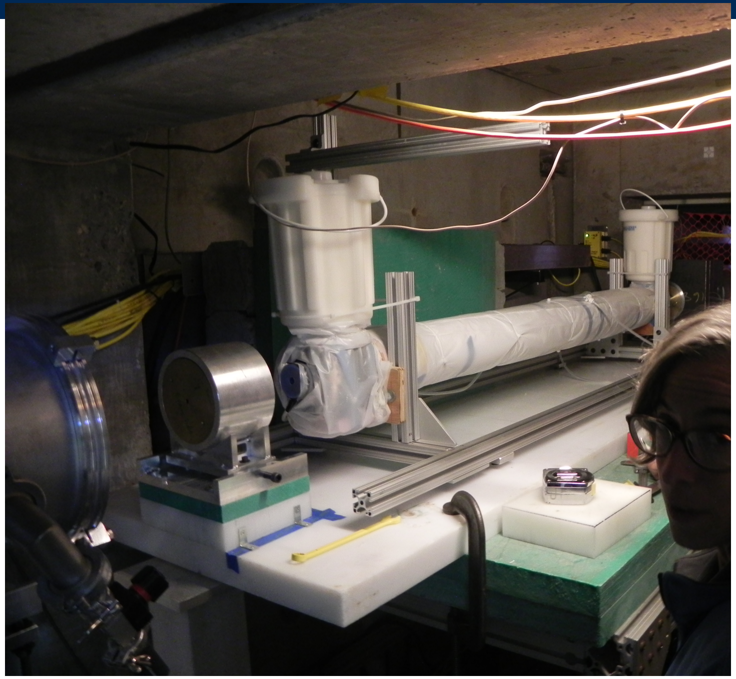


- A liquid hydrogen moderator is present ~31m upstream from the target
- Moderator induces a time delay to neutrons modeled via Monte Carlo simulation (Moderator Response Function - MRF)
- Neutrons travel in vacuum lines



ARTIE target and neutron detector





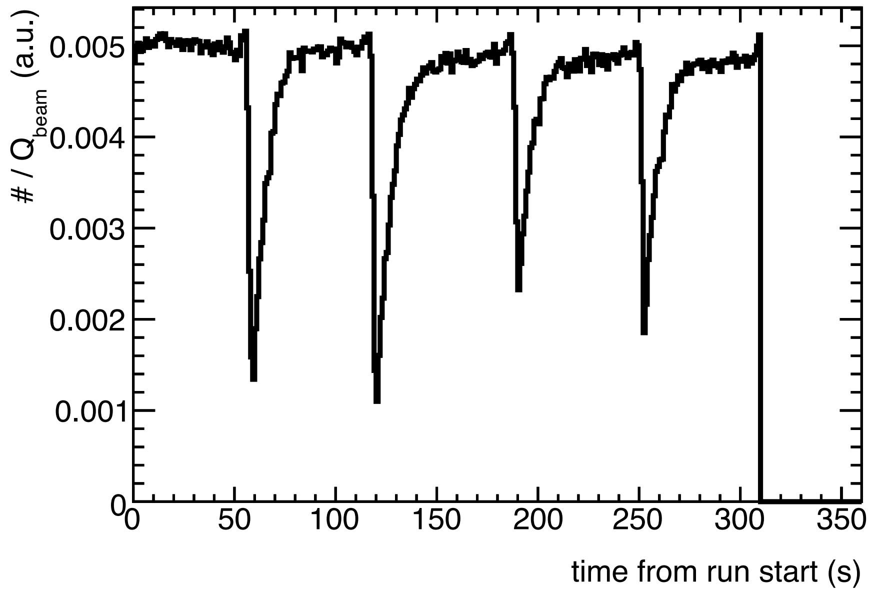
- The ARTIE features an open dewar design where the target is vented to the atmosphere and insulated by foam
- At ~64m from the moderator, neutrons are detected by a ^{6}Li-glass scintillator detector coupled to 2 5" PMTs s
  - Neutrons detected by: $n+{}^{6}Li \rightarrow {}^{4}He+{}^{3}H$, Q=4.78MeV

How to measure the cross section

- For any given filling the # of neutron reaching the TOF detector is:
- **$N(E) = f(E)\,Q\,T(E)$** where:
  - f is a scaling factor,
  - Q is the # of produced neutrons,
  - **$T(E) = \exp[\,-n\,\sigma(E)\,]$** is the transmission coefficient being
  - n the column density (atoms/b) (which depends on the dimensions d and density ρ of the target material):
    - $n = d[\mathrm{cm}] * N_A[\mathrm{atoms/mol}] * \rho[\mathrm{g/cm^3}] / m_A[\mathrm{g/mol}]*10^{-24}\ \mathrm{cm^2/b}$ the
  - And, σ the cross section (b)
- Consider data taken with target in — with liquid argon (LAr) — and target out — with gaseous argon (GAr) — then
  - **$\sigma(E) = -1/(n_{in} - n_{out})\ \ln(\,N_{in}\,Q_{out} / N_{out}\,Q_{in}\,)$**
- What follows is a summary of the analysis procedure and related uncertainties and systematic

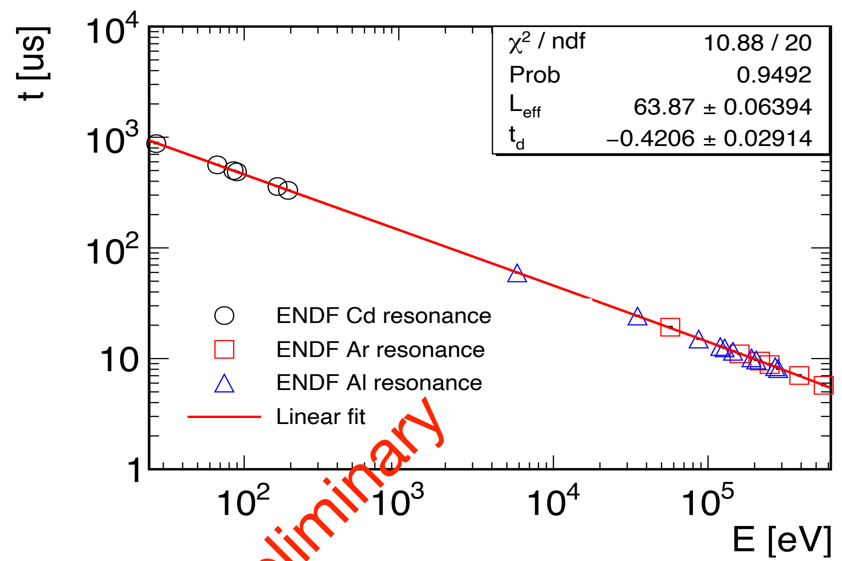
Run quality cut and beam-target alignment

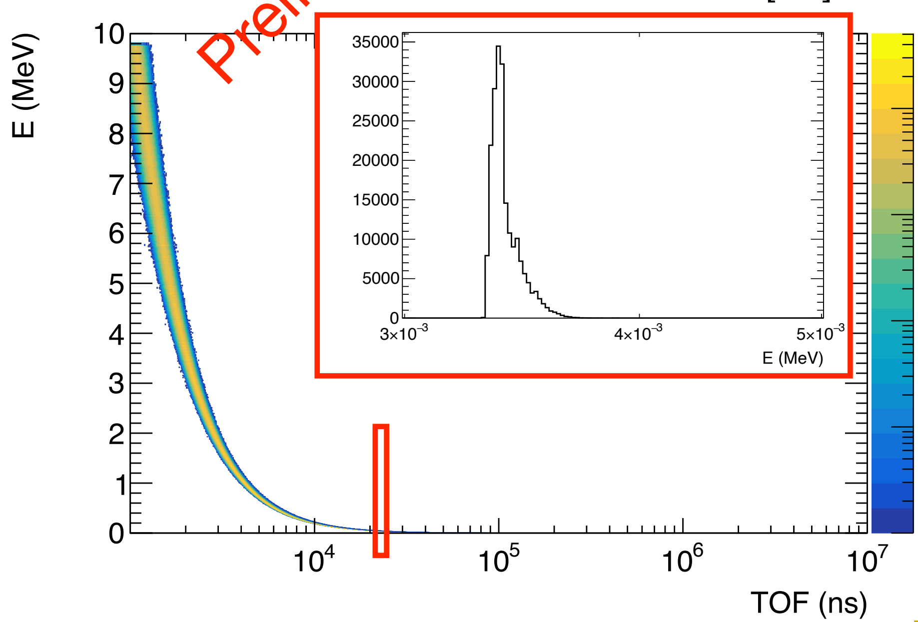
- Good data were selected excluding periods where DAQ had problems or the neutron beam was unstable
- For liquid argon runs, dara in correspondence of target refill were excluded
  - Big change in event rate (factor ~2, independent from energy) due to misalignment: some liquid or vapor spilled onto brass collimator causing it to shrink (~0.5 mm for ΔT ~ 200 K)
  - This cut accounts for a 12% data loss for liquid argon runs and introduces a ~5% uncertainties (conservative) in the neutron flux



Energy calibration & energy resolution

- TOF technique: energy is determined by measuring the time (t) a neutron travels through the flight path distance (L):
  - $E = mc^2 (1/\sqrt{1-L^2/c^2t^2} - 1)$
- Observed TOF ($t_{meas}=t-\delta t_{MRF}$) relates to t by subtracting the delay due to the MRF and other causes so that:
  - $E = mc^2 (1/\sqrt{1-L^2_{eff}/c^2t^2_{eff}} - 1)$
- Using several known resonances (from Al, Cd, and Ar), obtain effective length and delay:
  - L_{eff}=63.87±0.06m, and
  - t_{eff}=0.42±0.03μs
- Various factors affect energy resolution ΔE/E (initial proton pulse width, MRF, L_{eff}, ^{6}Li-glass detector and PMTs response). In ROI, ΔE/E=+3.1,-1.3%

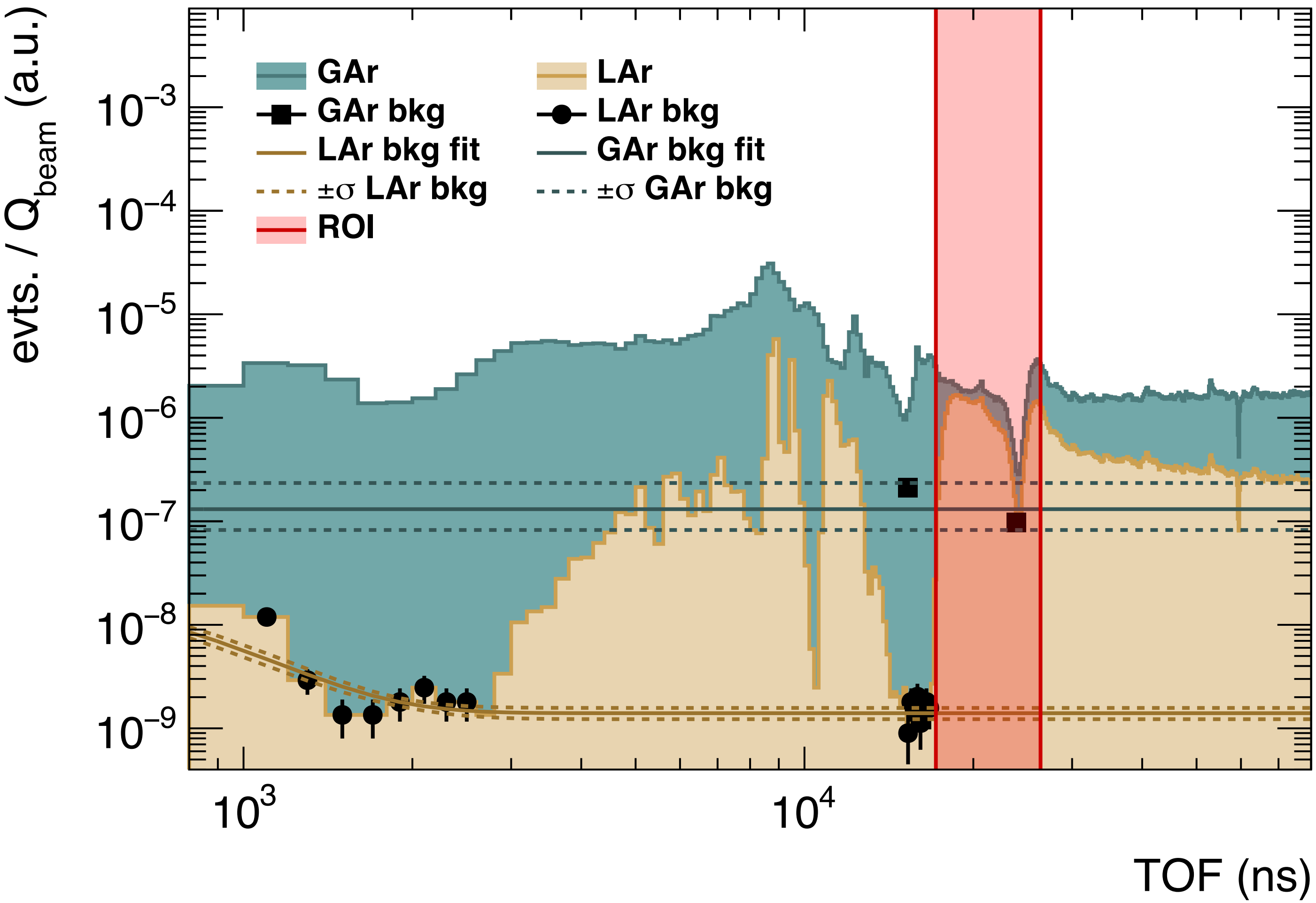




Background subtraction

- **$T(E) = (N_{in}-B_{in})\, Q_{out} \,/\, (N_{out}-B_{out})\, Q_{in}$**
  where N represents counts with target in/out and Bs are backgrounds
- Bs accounts for events from non-beam (e.g. radiogenic neutrons) and beam-relates sources with TOF inconsistent with neutron kinetic energy
  - Beam off data: beam independent backgrounds are negligible
  - Beam on but with shutter close data: background from accelerator complex (e.g. sky shine or scattering neutrons from other experiments) are negligible
  - Beam on data: late-arriving high-energy multiple scatters neutrons are most dangerous background. TOF and energy correlation is lost so they appear as flat background in TOF. Bs are determined using the standard “black notch” method: look at region where material in beam line has large positive resonances. Events in the notch must be background
    - **Aluminum** (1’’ thick): two deep resonances at 35 and 88 keV. Background determined from recorded counts corrected by Al transmission. Flat background in ROI
    - **Argon**: well-measured absorption resonance at ~100 keV. Background modeled as exp+flat

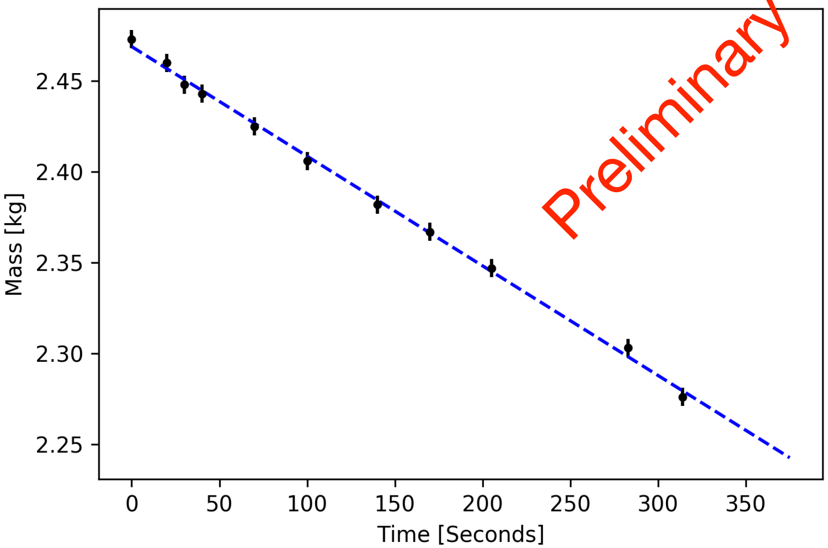
Background subtraction



- Backgrounds contribution in ROI is **small**: **0.14%** for LAr and **7.1%** for GAr

Effective density

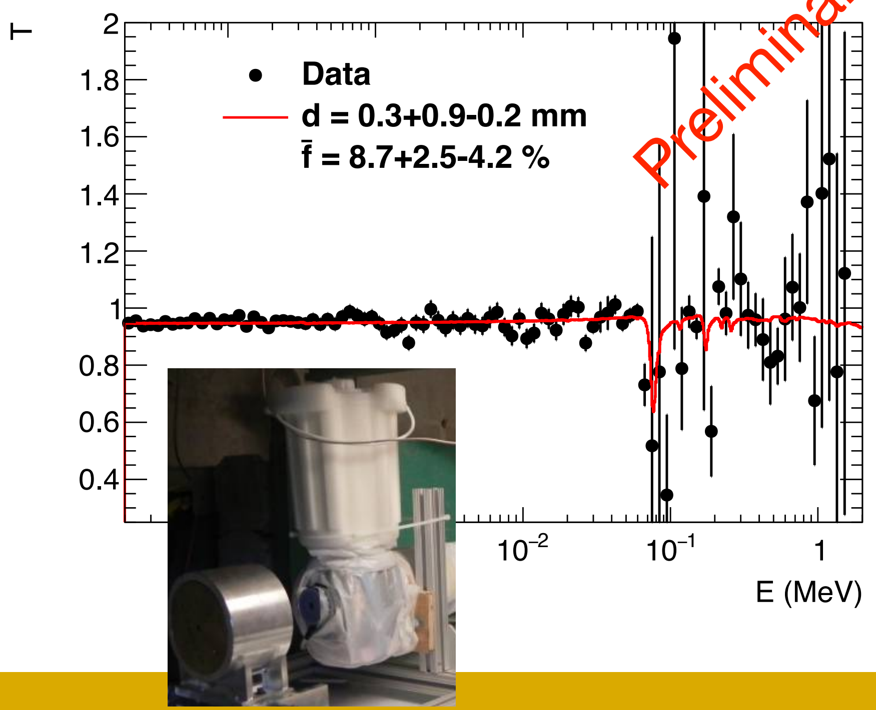
- Unpressurized vessel makes target a mixture of gaseous and liquid argon (argon constantly slow boiling inside) characterized by effective density ρ_{eff}
- A separate experiment done at UC Davis mimicking the fill/boil cycle as done at LANSCE. The target filled with argon was allowed to boil off naturally while measuring its mass and liquid level as a function of time
- Measuring boil of rate of 1.56L/h allows to determine ρ_{eff}=1.32±0.02kg/L (~6% fraction of gas mixed in the target)



Ice buildup on the target

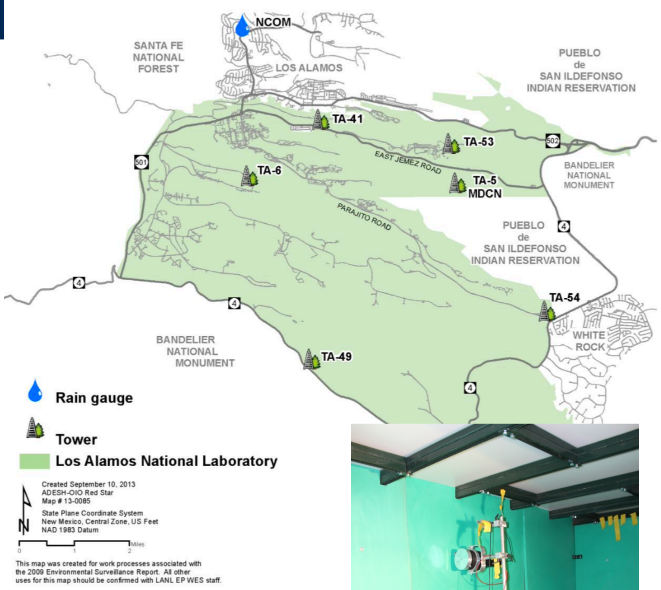
- Despite flushing target's end-cap windows with dry gases, a thin layer of ice formed on the Kapton windows over the course of many hours
- To reduce ice effect, target was warmed up to allow the ice to melt
- To assess the ice layer thickness, data immediately before (thickest ice layer) and after (windows are free of ice) warming up are compared

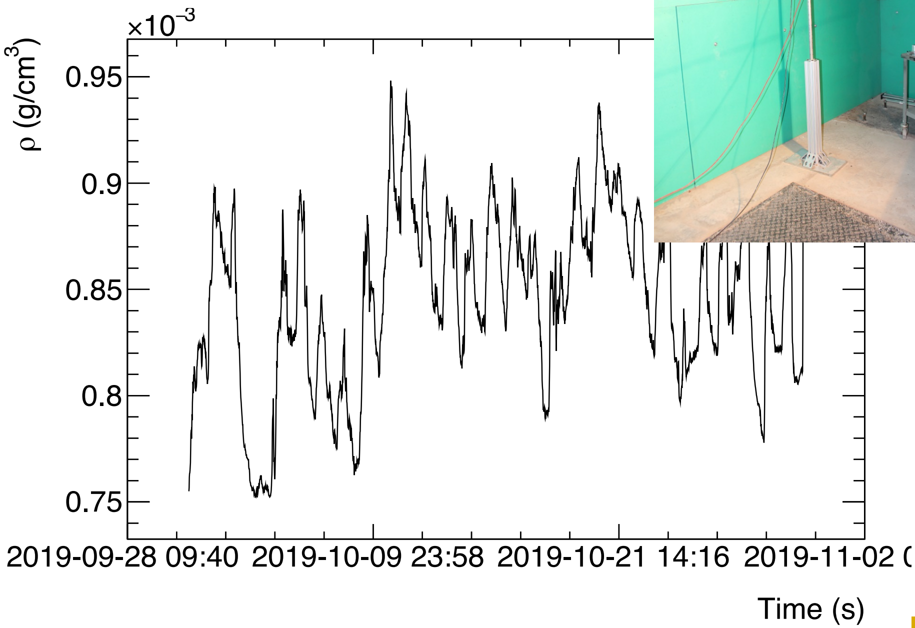
- Fitting function accounts for different conditions of the target setup and is informed via a toy Monte Carlo
- Ice thickness d=0.3 mm induces a maximum reduction in number of neutrons when the target is filled with liquid of ~3.8% (independent of energy in the ROI)
- Maximum ice effect is taken as a systematic uncertainty for LAr runs



Environment air density

- Part of the flight path (~2 m) is not under vacuum but is exposed to ambient conditions
- Day-to-day and day-night temperature/pressure variation can affect the neutron flux at the detector
- Air density variation is determined thanks to data provided by LANL meteorological stations
- During data tacking period: <ρ>=0.00085 g/cm^3 with +12% and -11% maximum variation
  - Via simulation of the air column, a neutron counts reduces by 3.4±0.4%



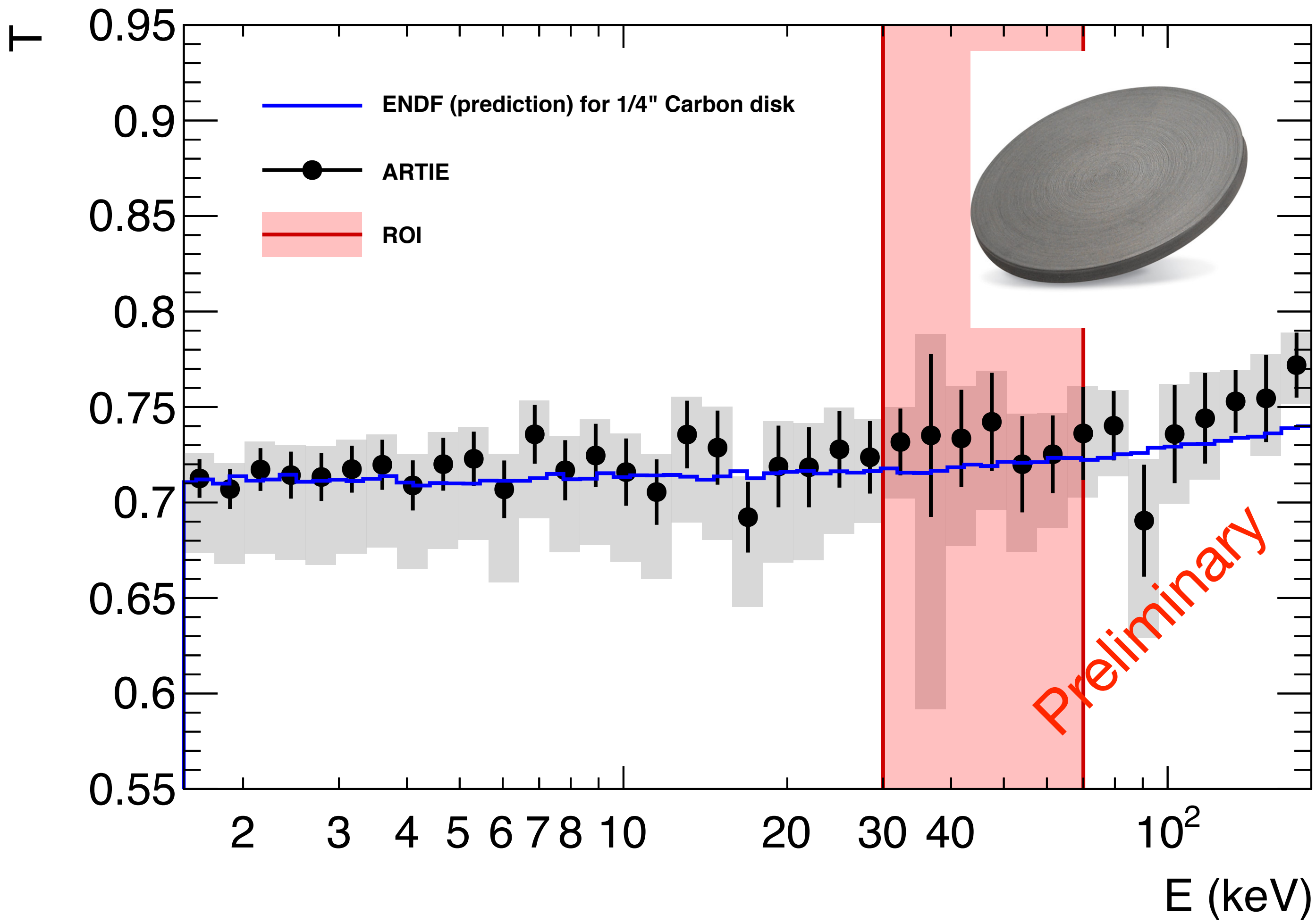


Uncertainties' summary

- Table summarizes the various uncertainties and how they affect the cross section
- Others:
  - Nitrogen contamination of the LAr measured by RGA (0.4 ppm): negligible
  - Dead time: each neutron recorded triggers a latency of 200 ns in the electronic. A second neutron arriving in this time window is lost. Analytical correction and toy Monte Carlo simulation suggests a ~1% and 0.2% correction for gaseous and liquid target respectively
  - Background due to other experiment: found that activities nearby ARTIE produces variation on background but it is negligible

ERROR	PAR UNCERTANTY (%)	σ UNCERTANTY (%)
Overall beam stability	±1.1	±1
Filling period stability	-5	-3.1
Effective density	±1.5	±1.5
Ice build up	-3.8	-2.4

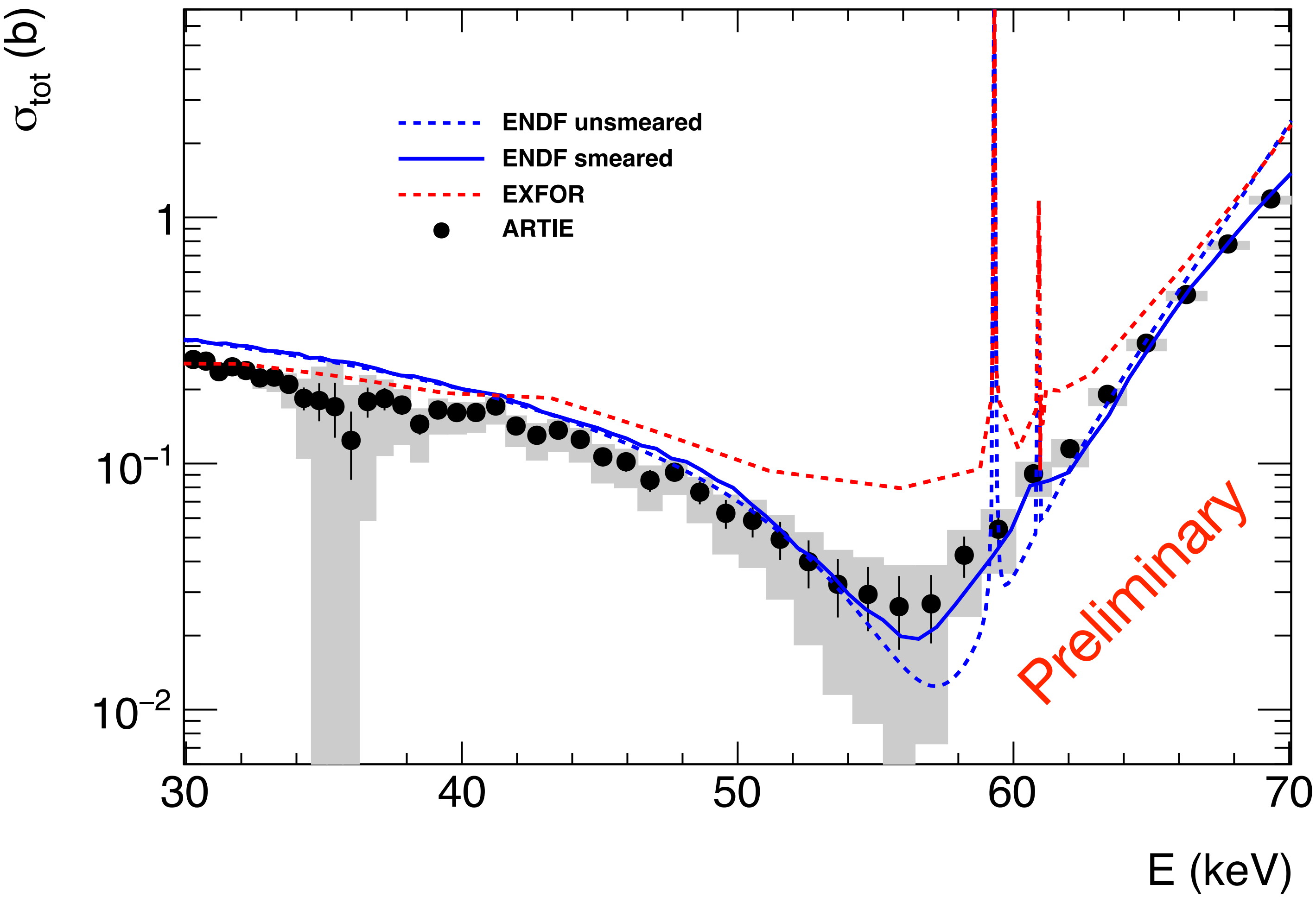
Analysis cross check: carbon data



Carbon (Graphite) (C) Sputtering Target by Kurt J. Lesker

- Analysis strategy repeated on a carbon sample of known composition (99.999% purity) and dimension (x2 0.125±0.010''): good agreement (χ^2/NDF=2.7/6) when compared with evaluation

Final results & conclusions



- Confirmed presence of anti-resonance at 57keV! Paper almost ready to be submitted. Stay tuned!