Spectroscopy of rare isotopes with the Active Target Time Projection Chamber

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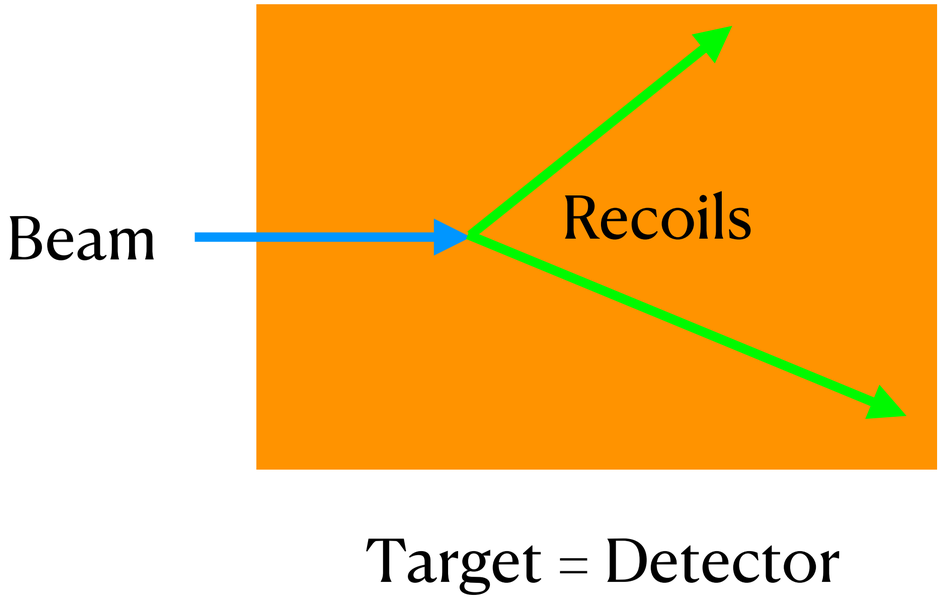
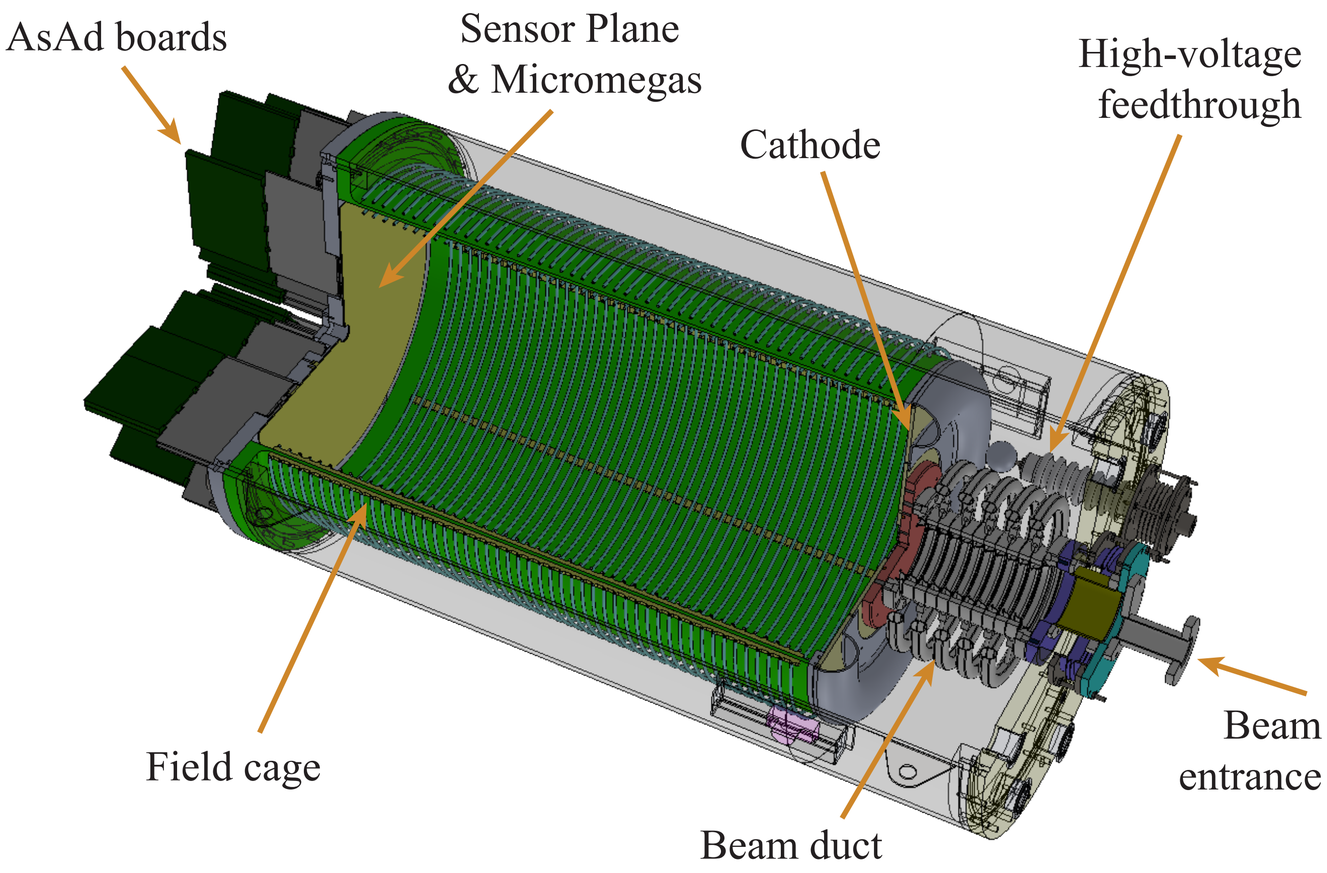
The promise of active targets

- Target thickness not constrained by energy resolution
  - *Gains by up to 2 orders of magnitude in thickness*
  - *Pure gas targets H_2, D_2 and $^{3,4}He$*
  - *Vertex and energy of each reaction measured*
- Solid angle coverage not limited by angular resolution and/or cost
  - *Detecting recoils inside target maximizes angular coverage*
  - *Geometrical efficiency close to 80%*
  - *Multiple reaction channels can be measured*
- Inverse kinematics requirements
  - *Need angular resolution < 1°*
  - *Need energy resolution < 200 keV*

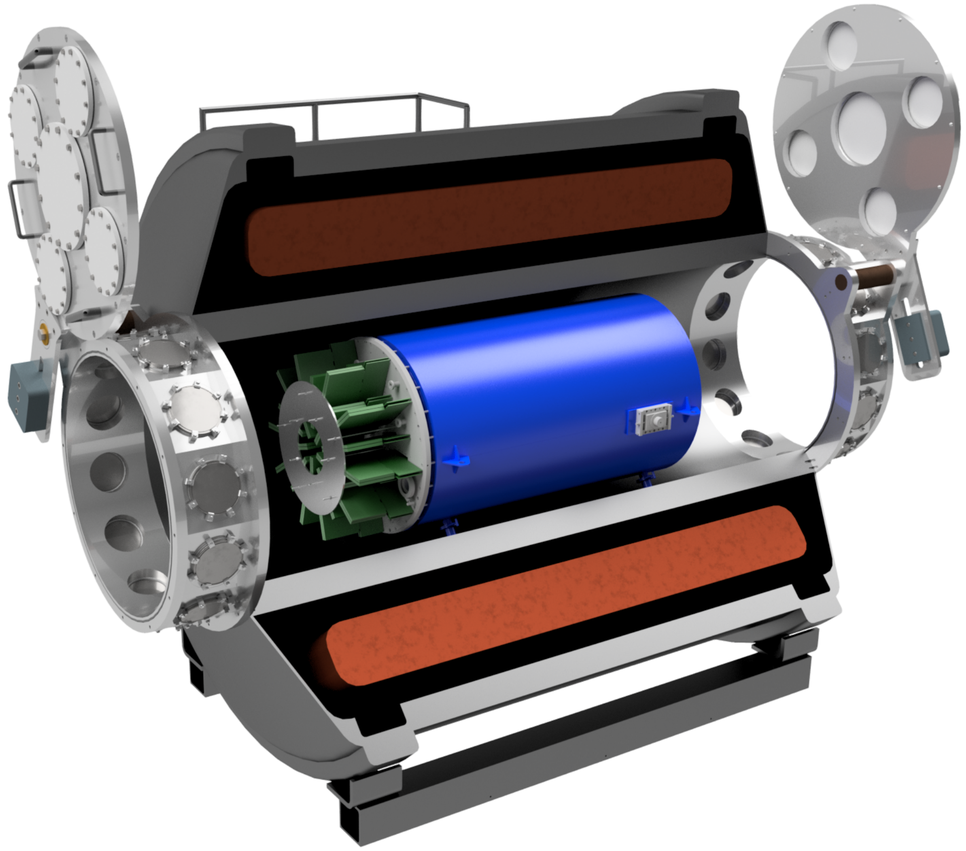


AT-TPC @ SOLARIS

Active Target Time Projection Chamber

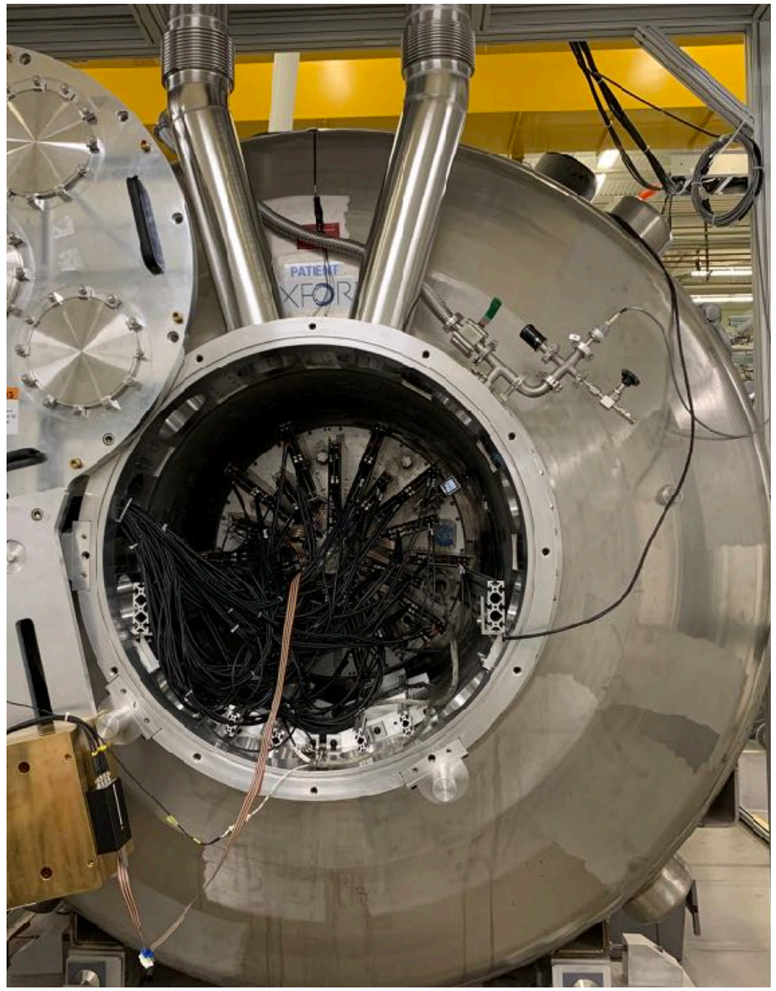


Solenoidal Spectrometer Apparatus for Reaction Studies



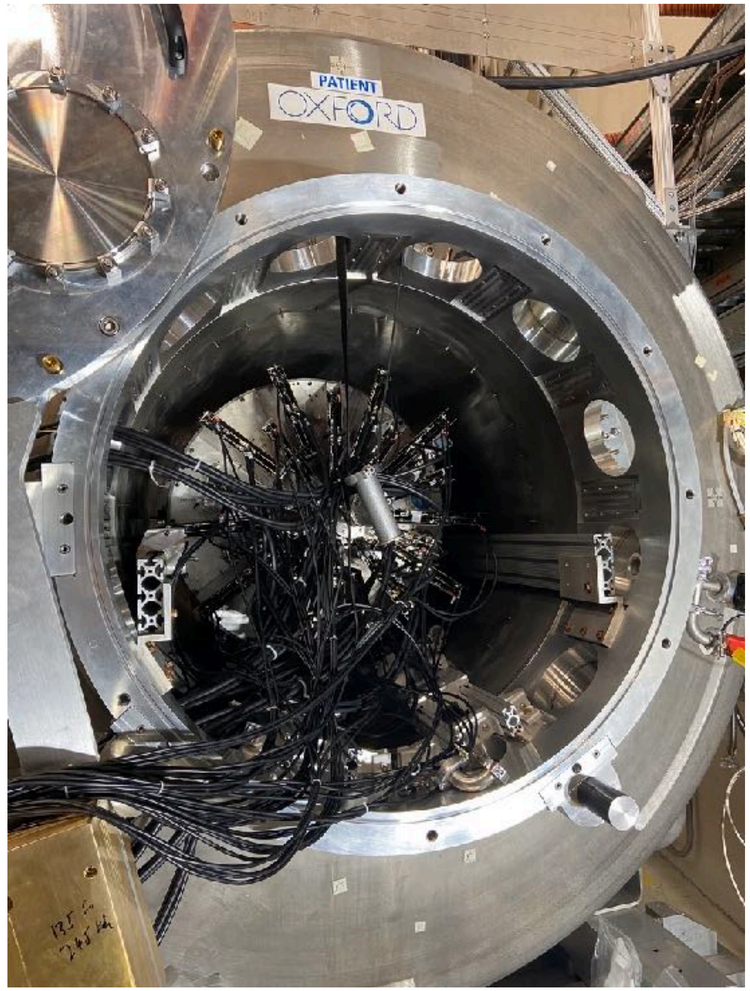
Two dual-mode solenoidal spectrometers

SOLARIS @ FRIB



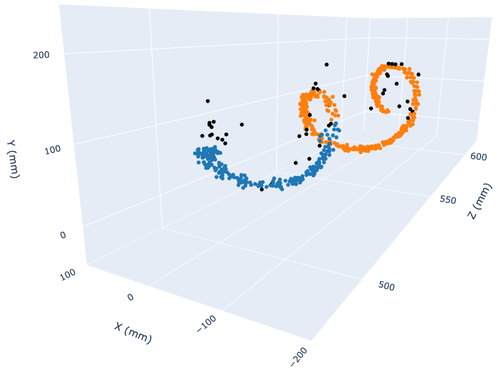
- Complementarity of detector setups
  - *Si-array for > 10^4 pps*
  - *AT-TPC for < 10^4 pps*
- Complementarity of facilities
  - *FRIB + ReA6 for isotopes far from stability*
  - *ATLAS + RAISOR for isotopes ±1n ±2n*

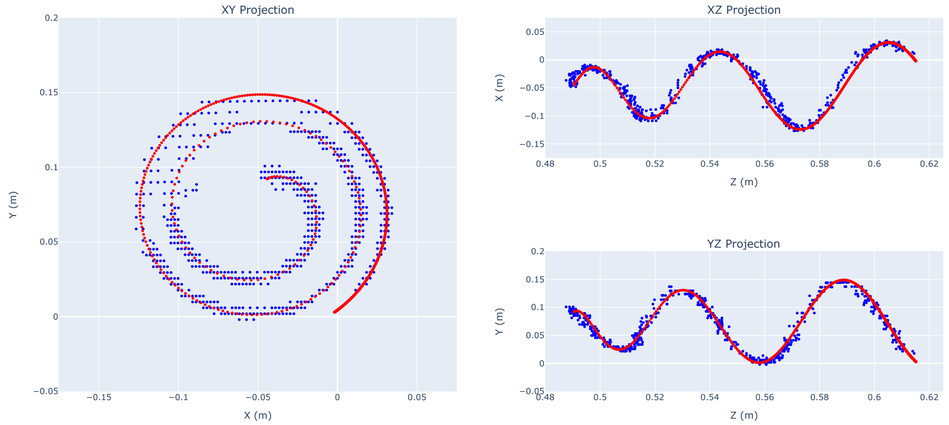
HELIOS @ ATLAS



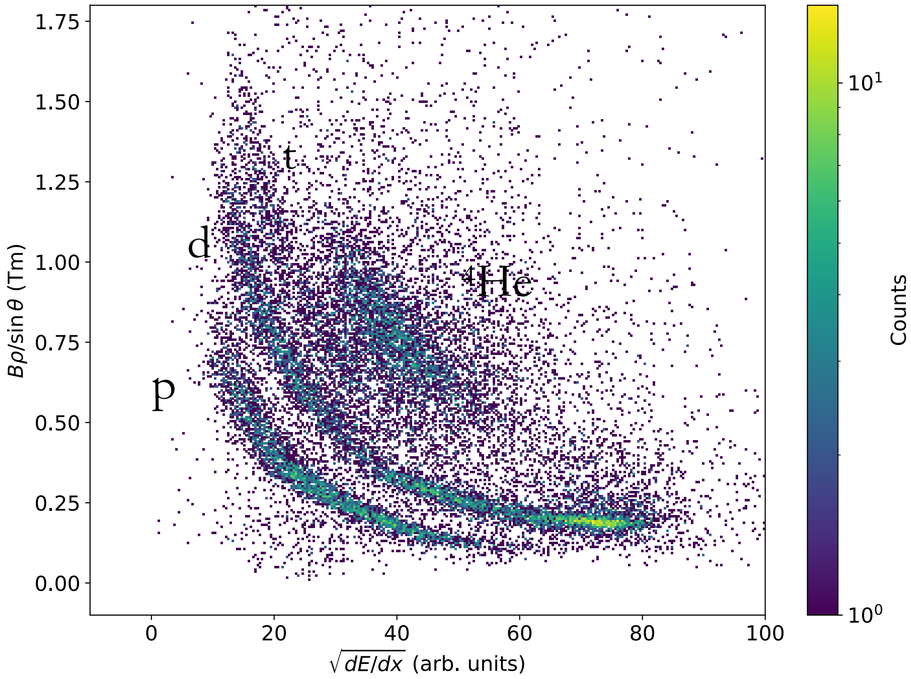
Spyral: data analysis of AT-TPC

- From 3D images of tracks to kinematical parameters
- Spyral is a python-based data analysis framework available on GiHub
- Complex analysis in particular for multi-track events





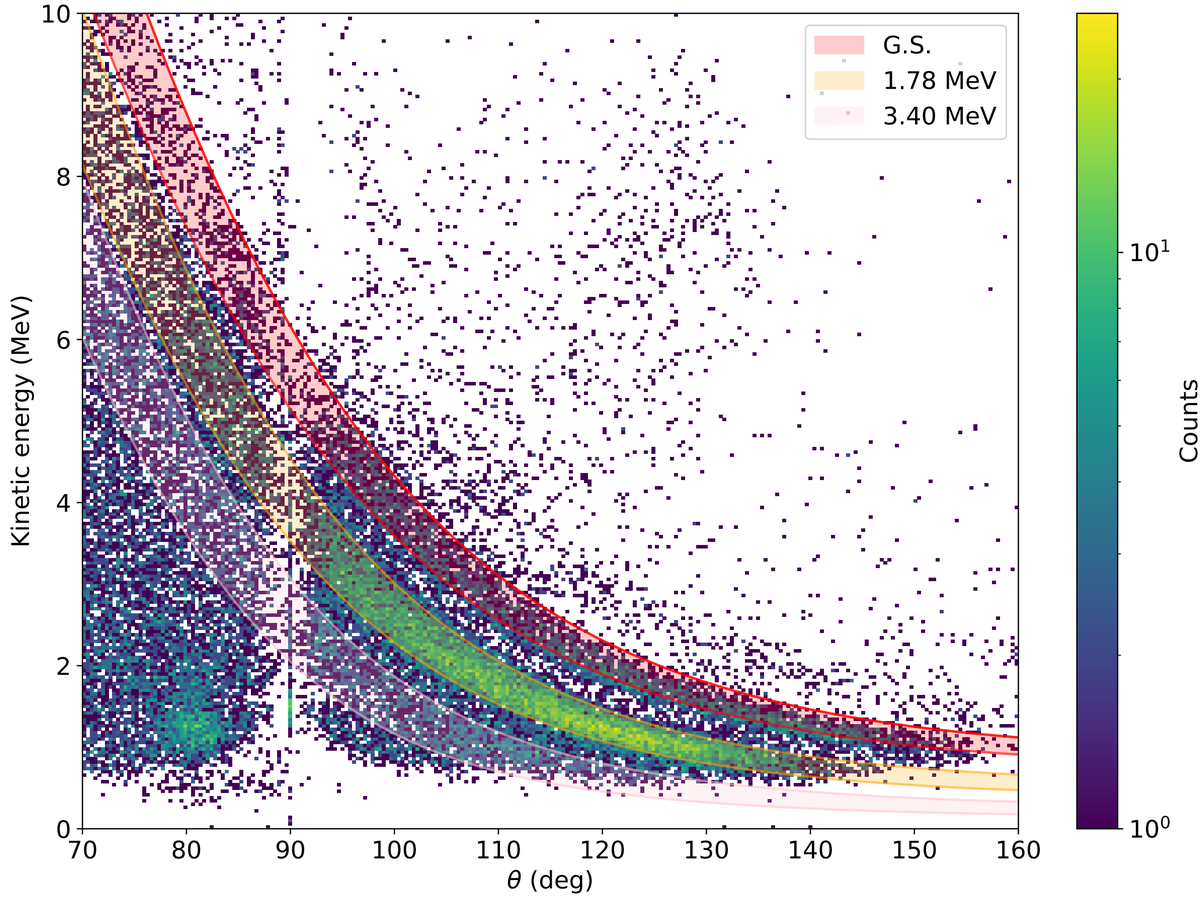
Particle Identification



Analysis by Z. Serikow

Kinematics plot of ^{10}Be(d,p)^{11}Be

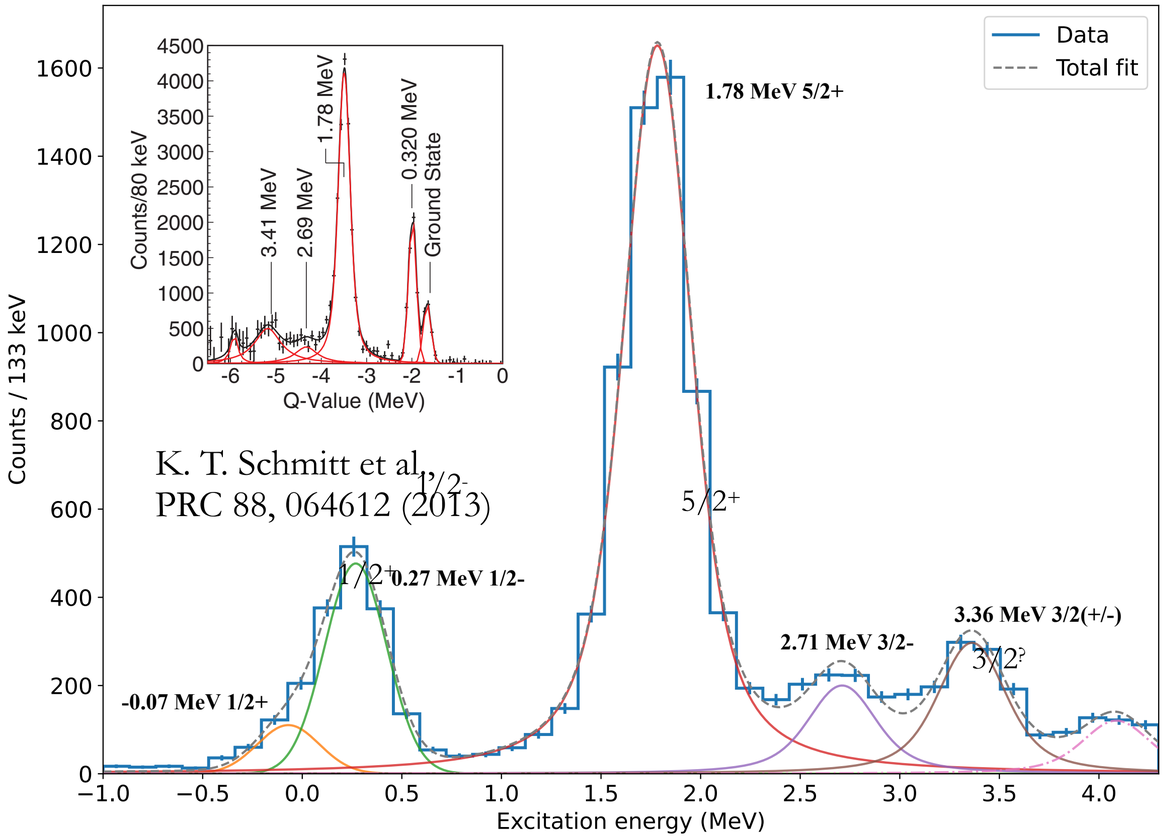
- Acceptance effects of AT-TPC
  - *Low energy cutoff at ~ 500 keV*
  - *Dependent on polar angle*
  - *Polar angle acceptance effects start at $\theta_{lab} < 20°$ and $\theta_{lab} > 160°$*
  - *Gap centered at $\theta_{lab} = 90°$ due to difficulty to analyze tracks perpendicular to beam axis*
- Resolution effects of AT-TPC
  - *Resolution degrading at higher energies*
    - *Due to limited track length at higher rigidities when target residues do not wrap around*



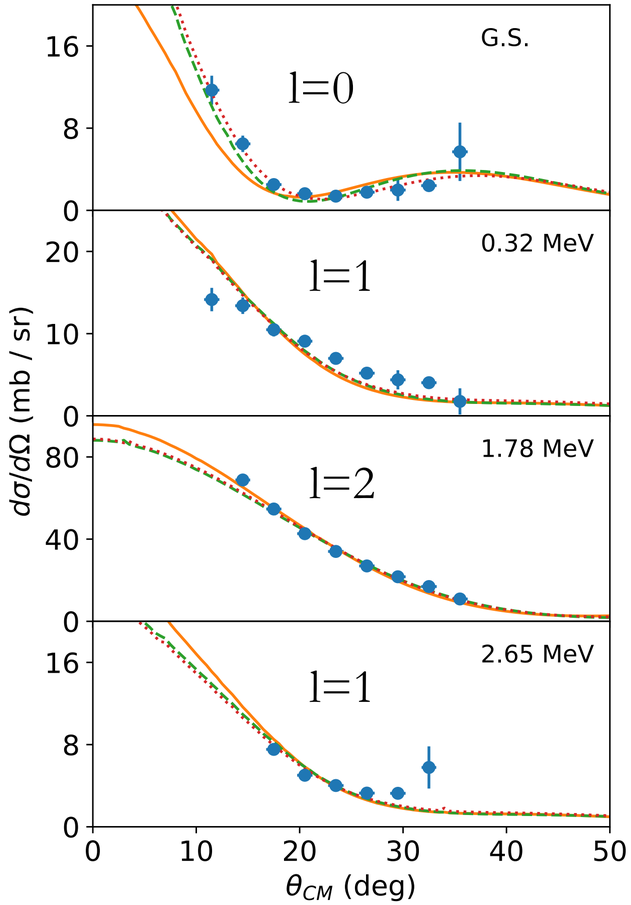
Analysis by Z. Serikow

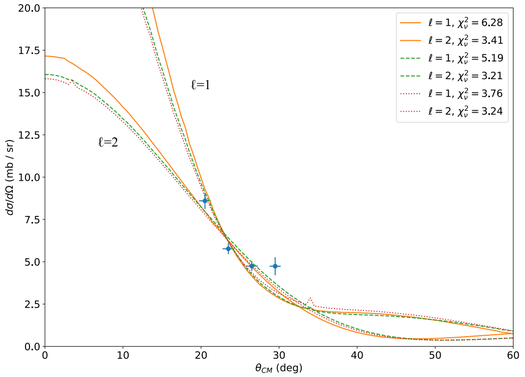
Excitation energy spectrum and angular distributions

^{10}Be beam @ 10 MeV/u - 1000 pps / 5 days



K. T. Schmitt et al., PRC 88, 064612 (2013)

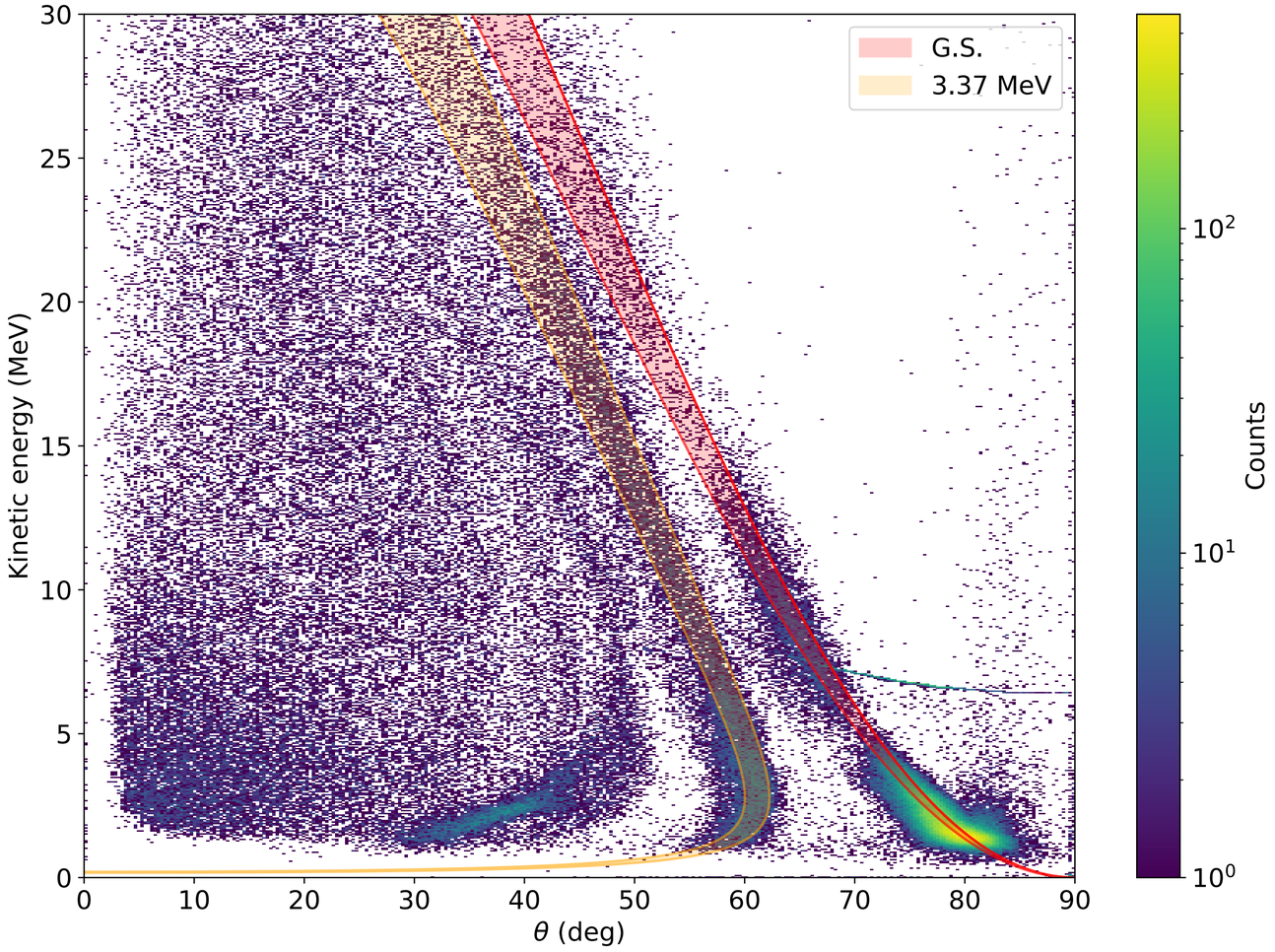




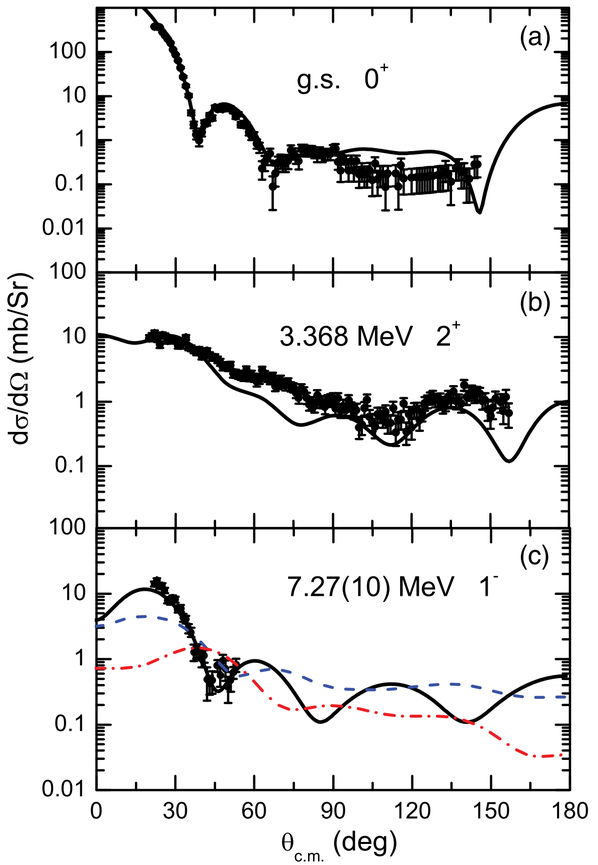
- Angular distribution for 3.4 MeV resonance
- Tentative l=2 assignment
- Also consistent with SF when compared with several SM calculations
- Better measurement could be done with higher beam energy

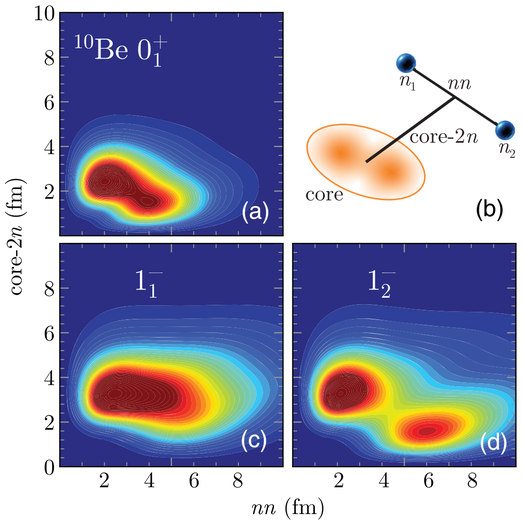
Analysis by Z. Serikow

Near-Threshold Dipole Strength in ^{10}Be with Isoscalar Character



J. Chen et al., PRL 134, 012502 (2025)

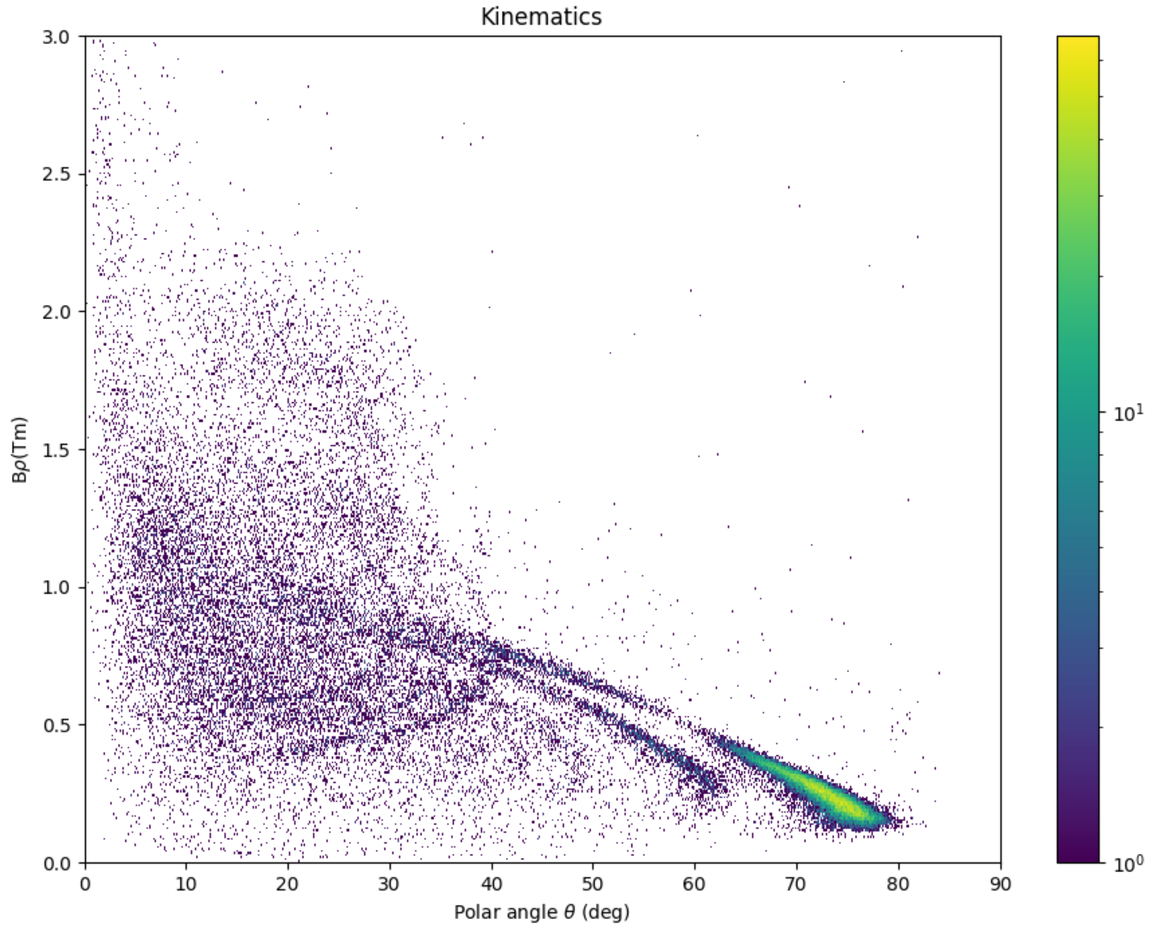




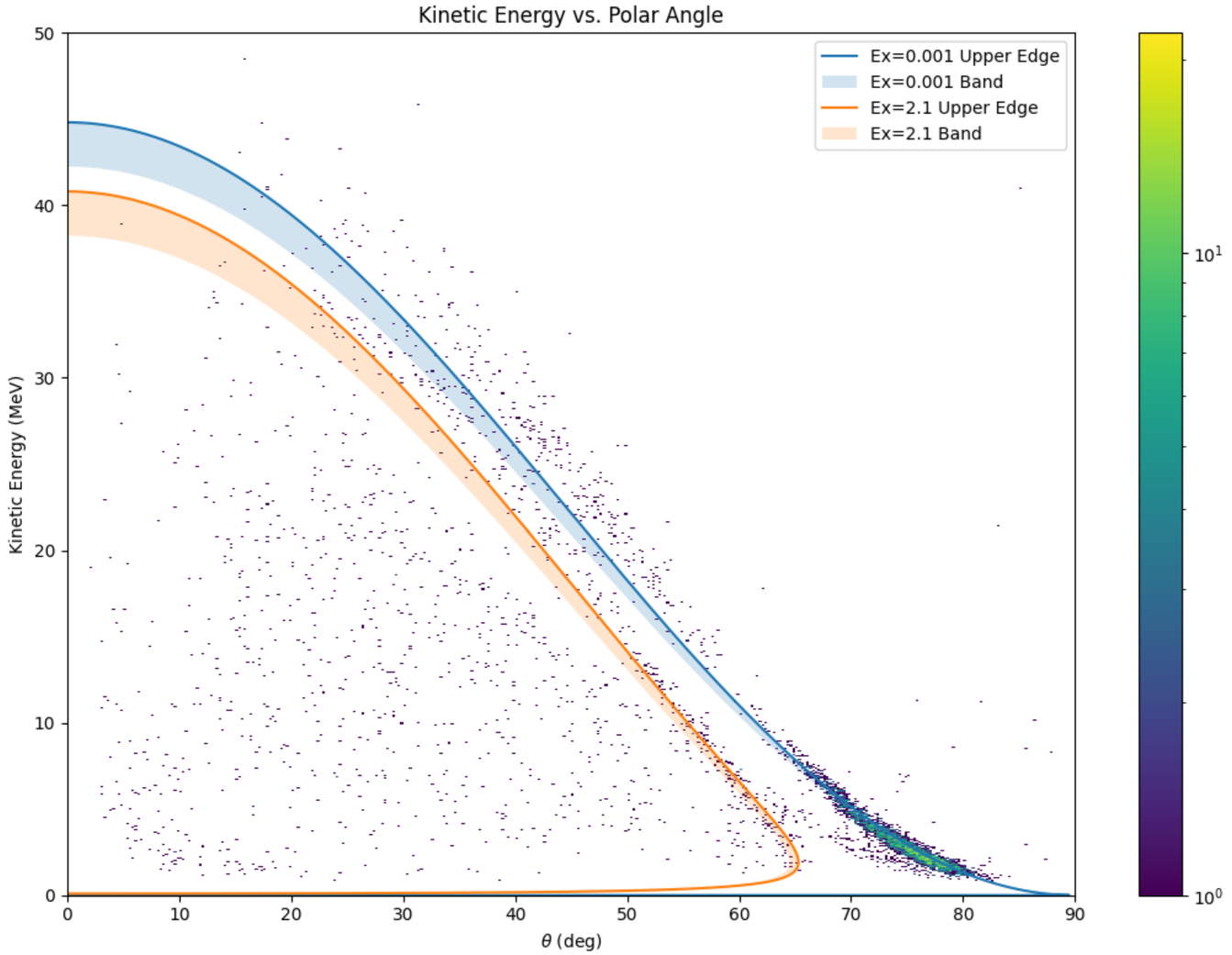
GCC calculations assuming deformed ^{8}Be core + 2 neutrons

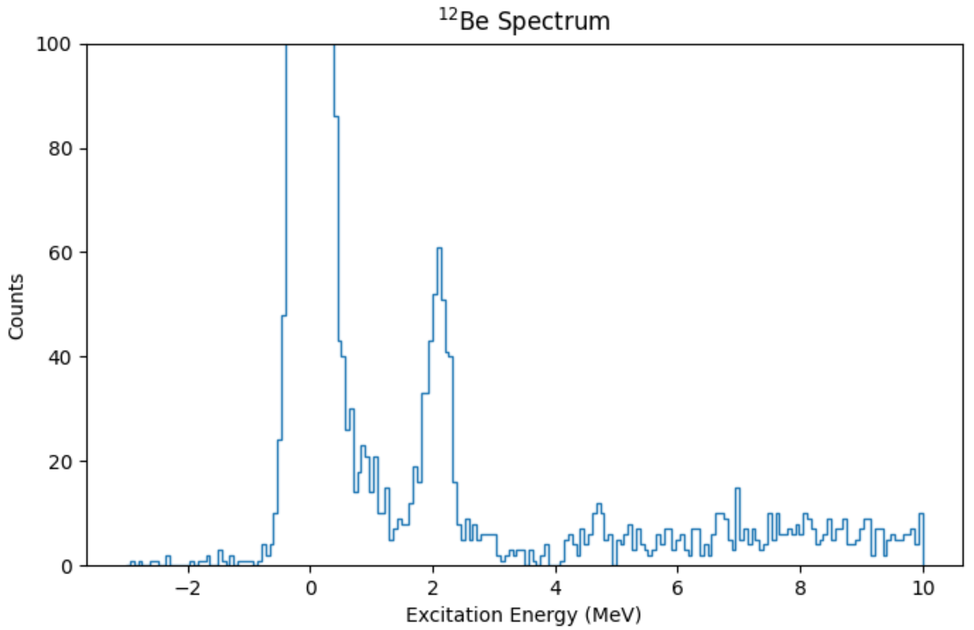
^{12}Be reactions on proton target

- ^{12}Be at ~12 MeV/u provided by the RAISOR separator from ATLAS ^{14}C primary beam
- **Beam intensity 100 pps**
- Pure $^{1}H_2$ target at 600 Torr
- Equivalent CH_2 target thickness (number of protons): 110 mg/cm^2
- **3 days of beam exposure**
- Pre-kinematics plot from estimation phase showing Bρ versus energy loss
- Kinematics lines from elastic, inelastic, (p,d) and a hint of (p,t) reactions



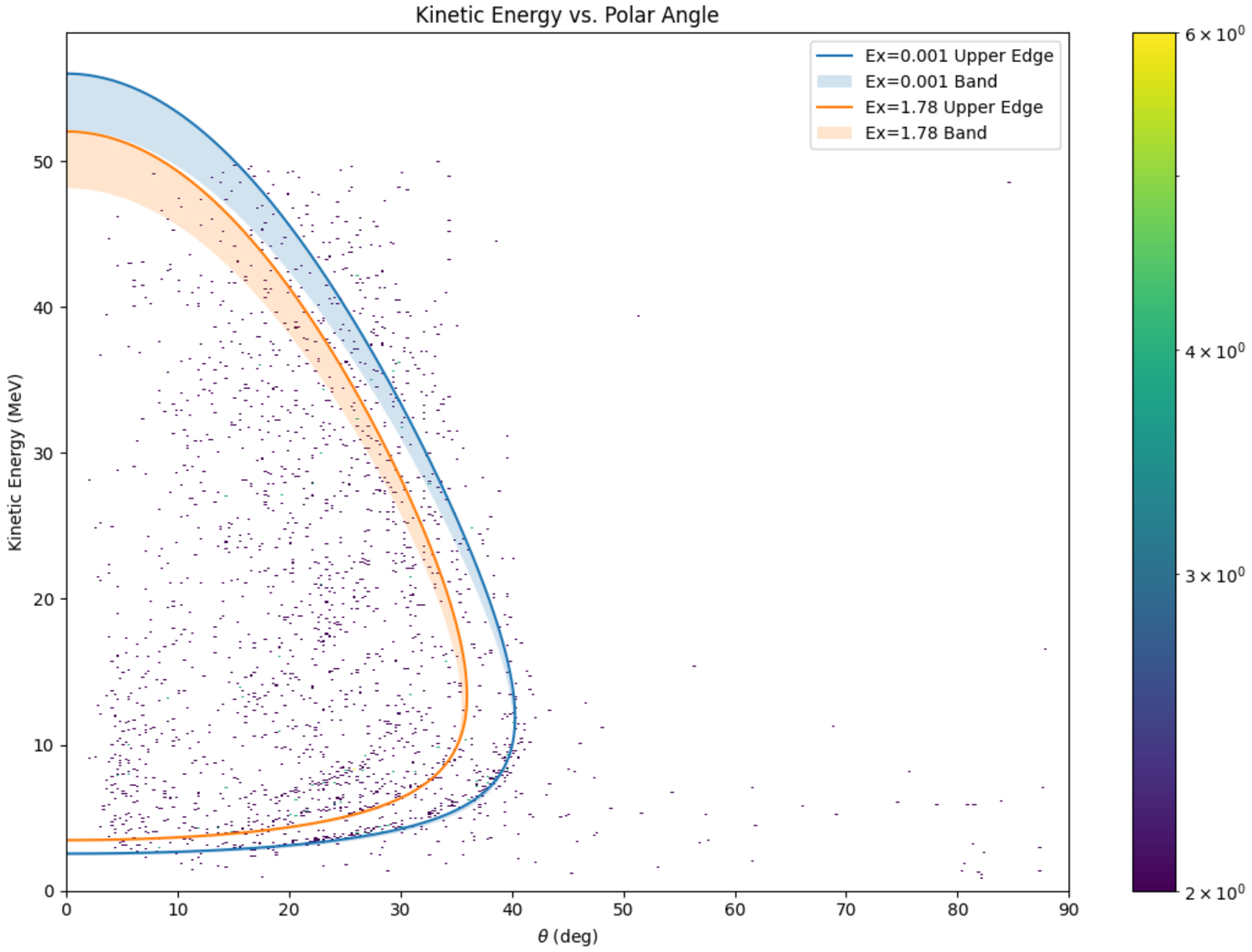
^{12}Be elastic and inelastic on proton

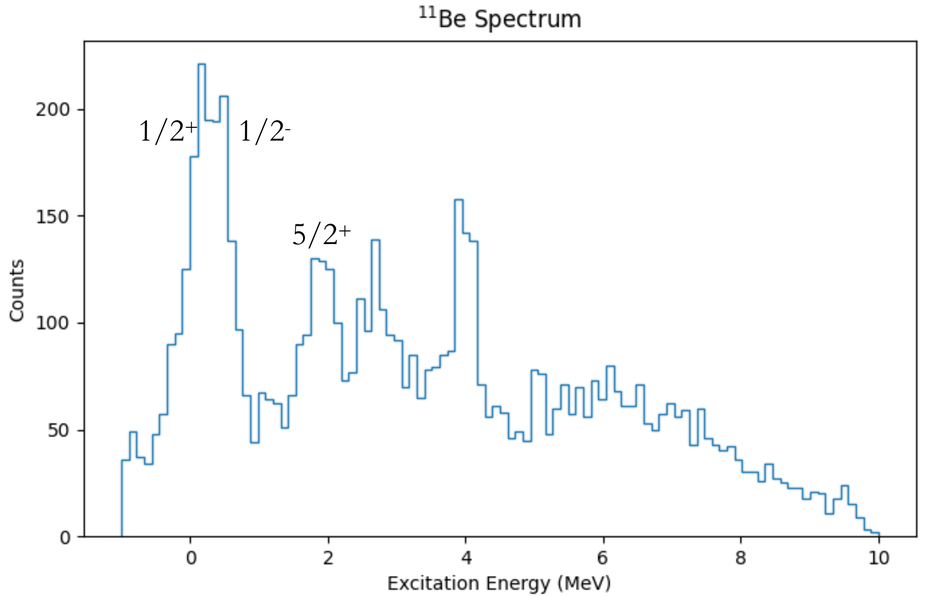




- Higher energy resonances in ^{12}Be
- Reactions on isomeric 0^+ (0.23μs)?

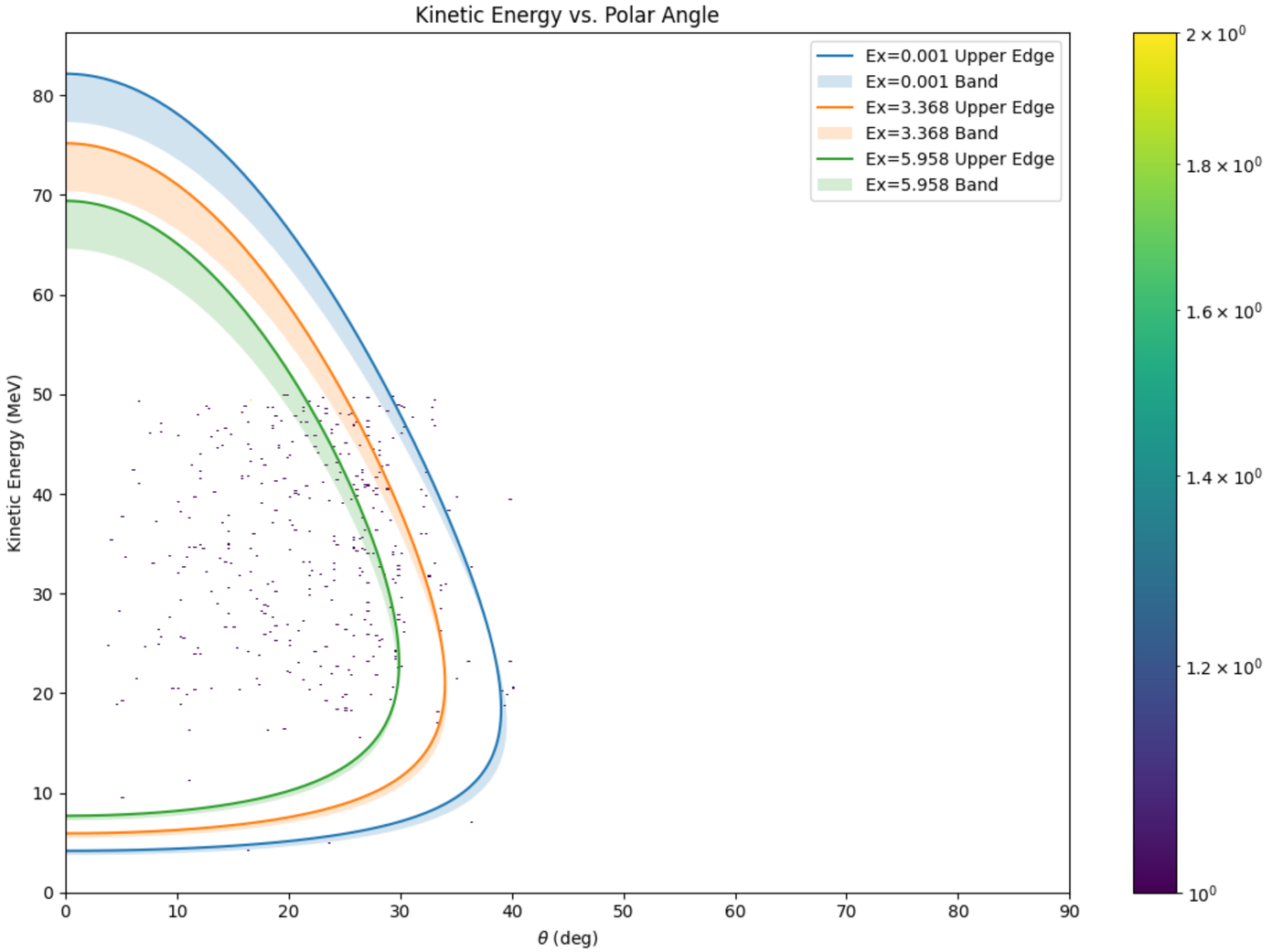
^{12}Be(p,d)^{11}Be

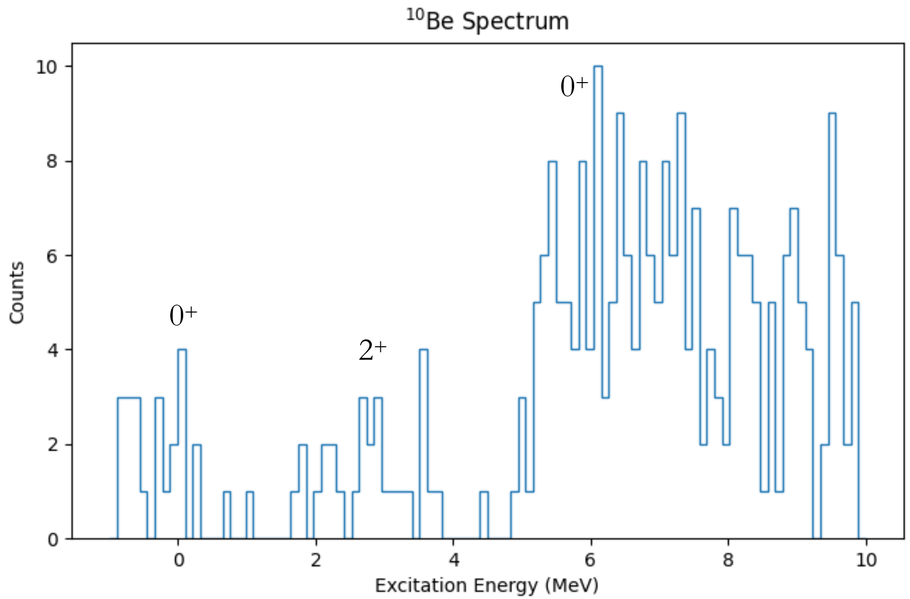




- Large cross sections to $1/2^+$ and $1/2^-$ bound states
- Similar reaction to ^{12}Be-1n knockout
  - *Breakdown of N=8, A. Navin et al., PRL 85, 266 (2000)*
  - *d-wave component, S. D. Pain et al., PRL 96, 032502 (2006)*
  - *Neutron-unbound resonances, W. A. Peters et al., PRC 83, 057304 (2011)*
- More details on ^{12}Be wave function from population to other unbound resonances

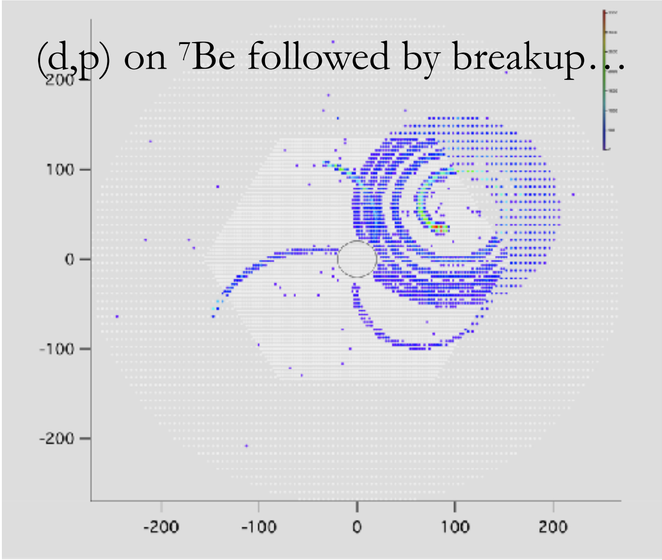
^{12}Be(p,t)^{10}Be

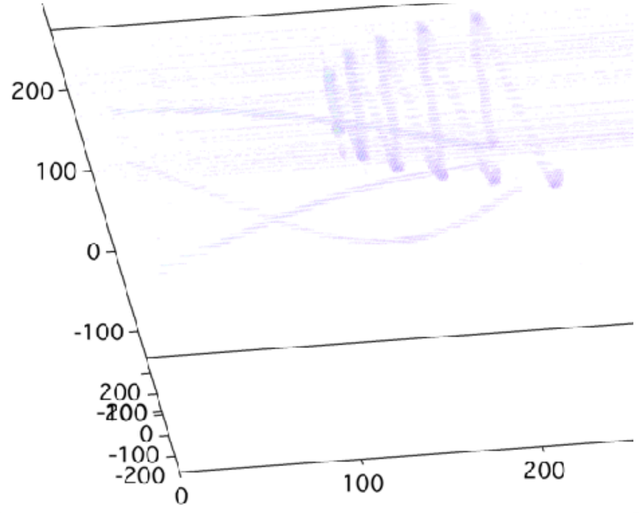

Kinetic Energy vs. Polar Angle
Ex=0.001 Upper Edge
Ex=0.001 Band
Ex=3.368 Upper Edge
Ex=3.368 Band
Ex=5.958 Upper Edge
Ex=5.958 Band
Kinetic Energy (MeV)
θ (deg)
0
10
20
30
40
50
60
70
80
90
2 × 10^0
1.8 × 10^0
1.6 × 10^0
1.4 × 10^0
1.2 × 10^0
10^0


^{10}Be Spectrum
Counts
Excitation Energy (MeV)
0⁺
2⁺
0⁺
0
2
4
6
8
10

Outlook

- Active targets such as the AT-TPC offer a breakthrough in measurements of Direct Reactions with Exotic Beams
  - *Luminosity gain of **two to three orders of magnitude** compared to passive targets, while retaining comparable resolutions*
  - *Transfer reaction cross sections (~ 10 mb/sr) now accessible at **100 pps***
  - *Solid angle coverage allows measurements of **full kinematics** of reactions (target-like and beam-like residues)*
- New avenues of exploration
  - *Missing mass spectroscopy of exotic nuclei **further from stability***
  - *Exploration of unbound resonances and **deformation** via rotational bands*
  - ***Effects of continuum** via study of unbound resonances near particle decay thresholds*





Upcoming experiments

- S800 campaign (2024)
  - *GT strength in 32Na via ^{32}Mg(d,^{2}He)*
  - *PGR and GR in ^{11}Li via ^{11}Li(p,p')*
- SOLARIS experiment (Fall 2024)
  - *NP pairing in ^{56}Ni via ^{56}Ni(^{3}He,p)*
- RCNP campaign (Jun-Nov 2025)
  - *6 proposals approved*
- Argonne campaign (early 2026)
  - *3 proposals approved*
- FRIB campaign (2026…)
  - *4 proposals approved*

AT-TPC collaboration