Track Reconstruction and Characterization in Liquid Scintillator Detectors at High Energies

Reconstruction and Machine Learning in Neutrino Experiments
Hamburg, September 16-18, 2019

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and

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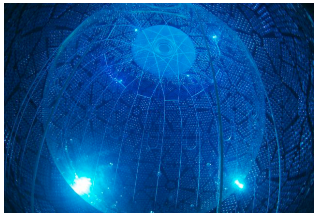
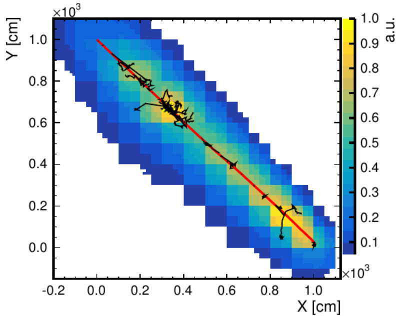
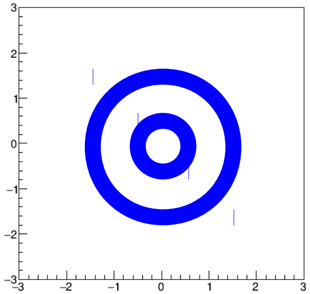
Outline





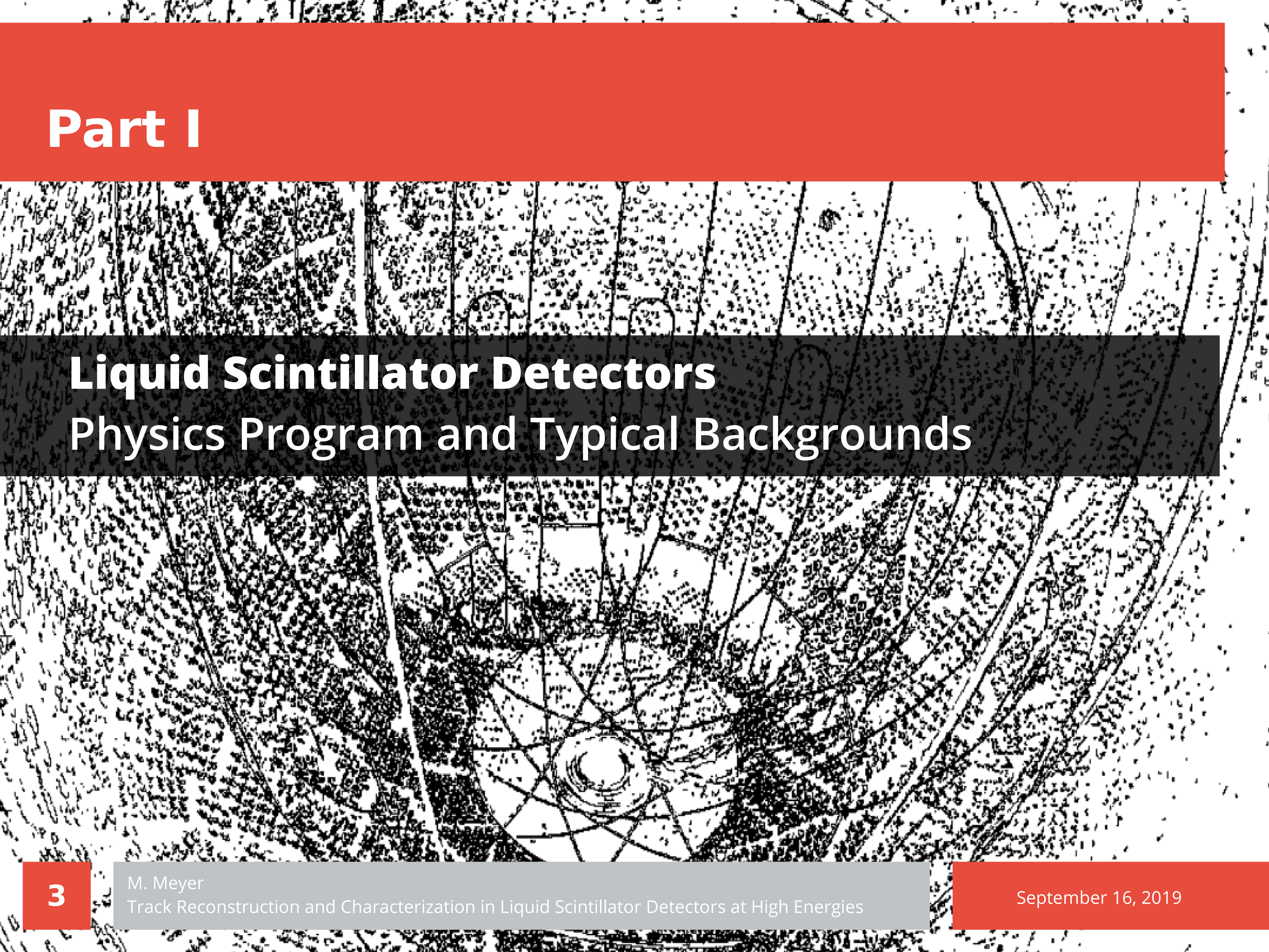


I Liquid Scintillator Detectors
Physics Program and Typical Backgrounds

II Tracking Algorithms
Overview
Topological Tracking
Backtracking

III Image Processing
Circle Identification
Edge Detection

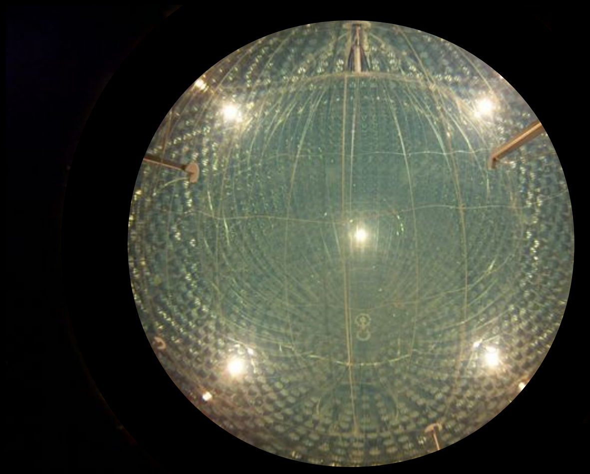
IV Summary

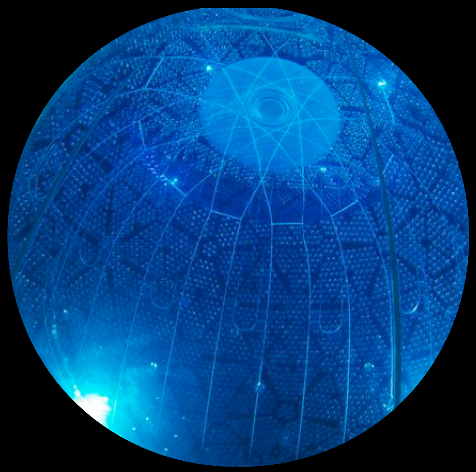


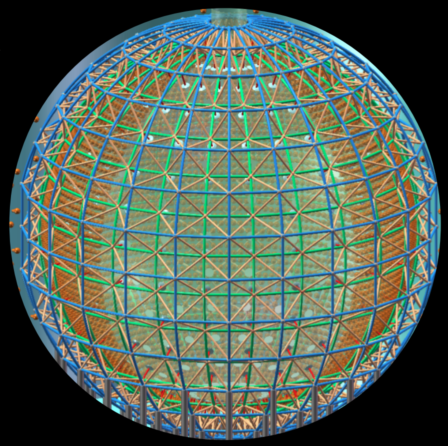
Part I

Liquid Scintillator Detectors
Physics Program and Typical Backgrounds

Liquid Scintillator Detectors

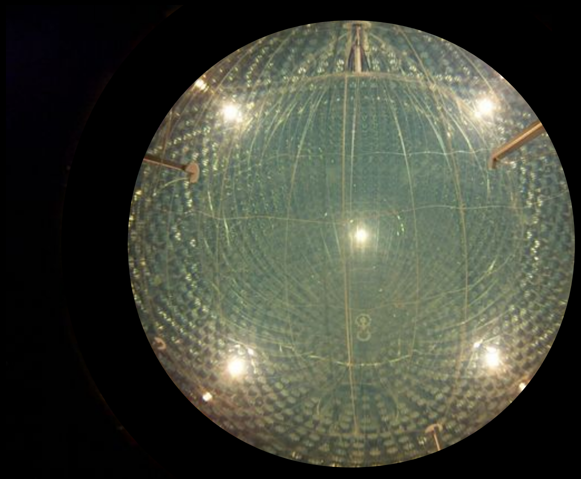




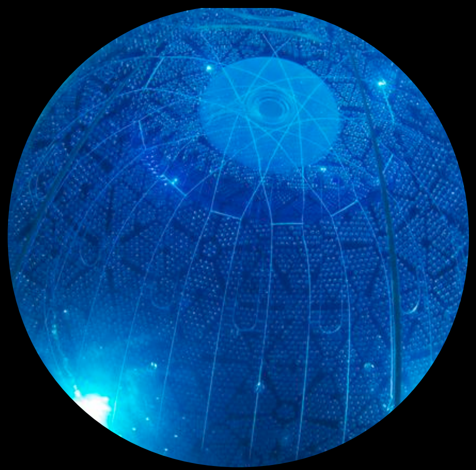


Liquid Scintillator Detectors

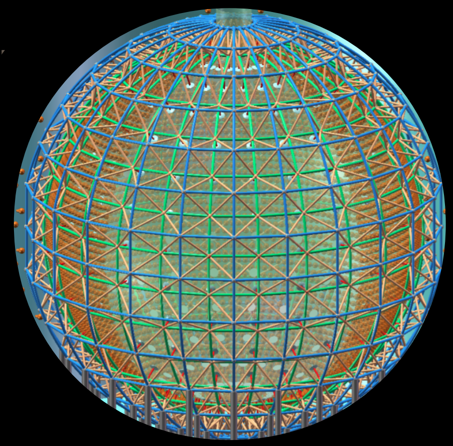
Borexino



SNO+

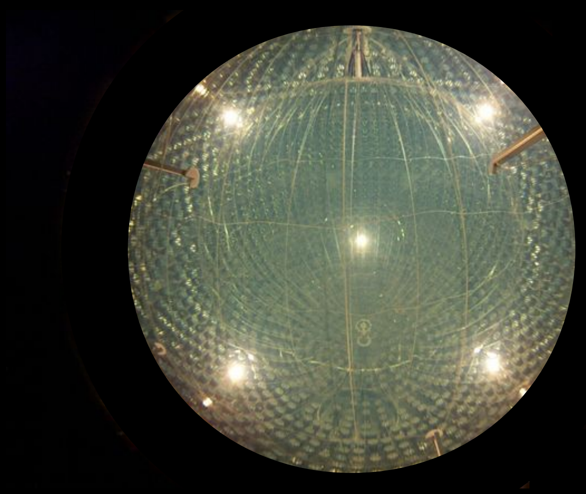


JUNO



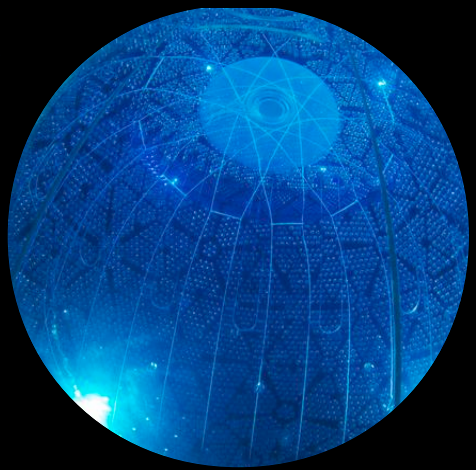
Liquid Scintillator Detectors

Borexino



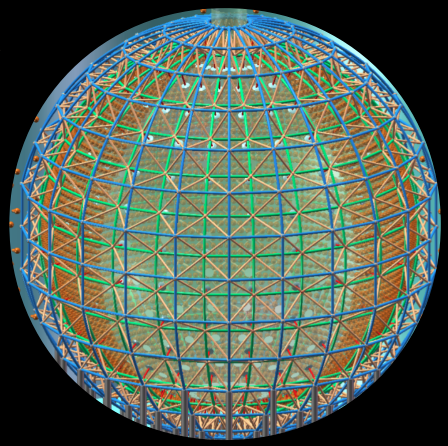
Solar Neutrinos
Geo-neutrinos

SNO+



$0\nu\beta\beta$ search
Solar Neutrinos

JUNO



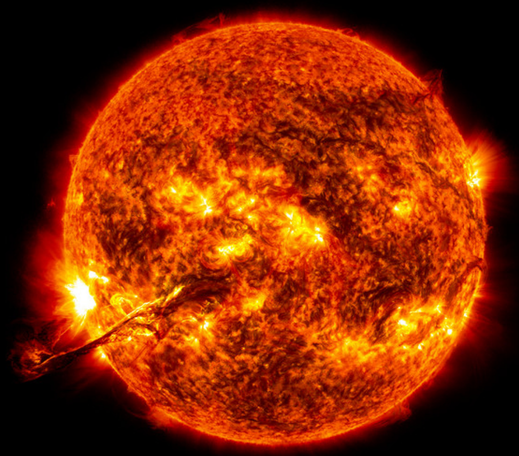
Reactor Neutrinos
(Solar Neutrinos)

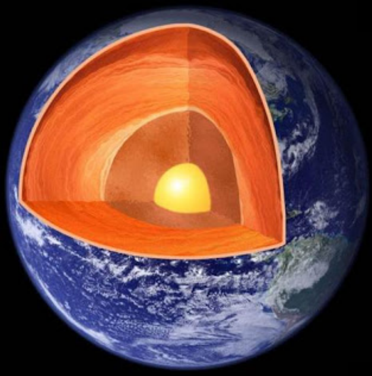
Physics and Typical Backgrounds

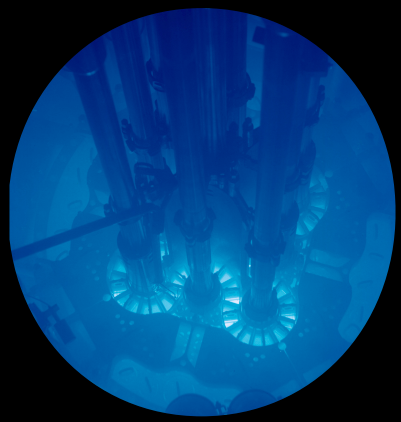
Solar Neutrinos

Reactor Neutrinos
Geo-neutrinos

$0\nu\beta\beta$ search







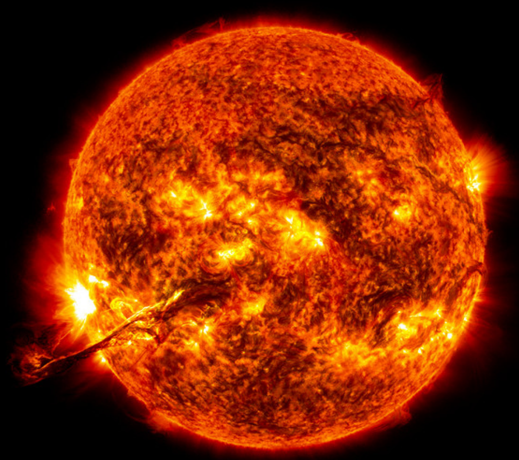
Carbon-11

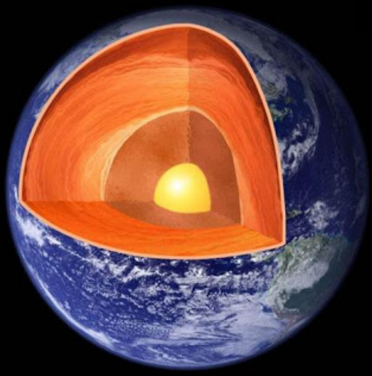
Lithium-9 / Helium-8

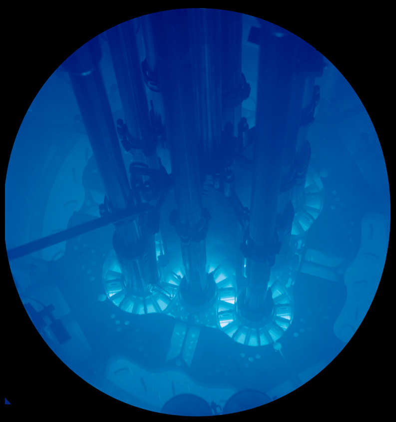
Boron-8 solar neutrinos, $2\nu\beta\beta$, ...

Physics and Typical Backgrounds

Solar Neutrinos	Reactor Neutrinos Geo-neutrinos	$0\nu\beta\beta$ search







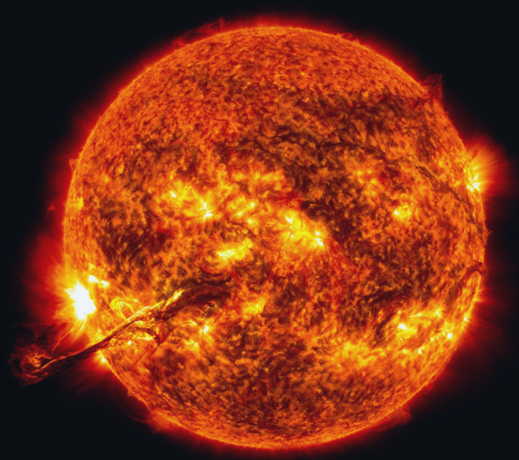
Carbon-11 Muon-induced	Lithium-9 / Helium-8 Muon-induced	Boron-8 solar neutrinos, $2\nu\beta\beta$, …

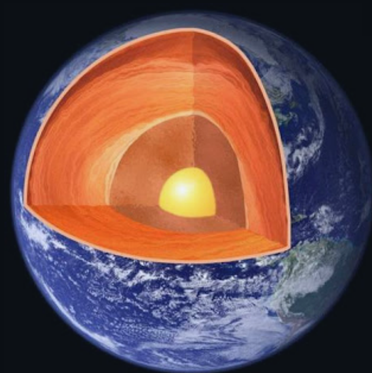
Physics and Typical Backgrounds

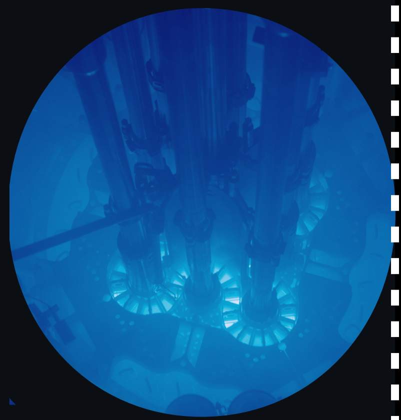
Solar Neutrinos

Reactor Neutrinos
Geo-neutrinos

$0\nu\beta\beta$ search







Carbon-11

Muon-induced

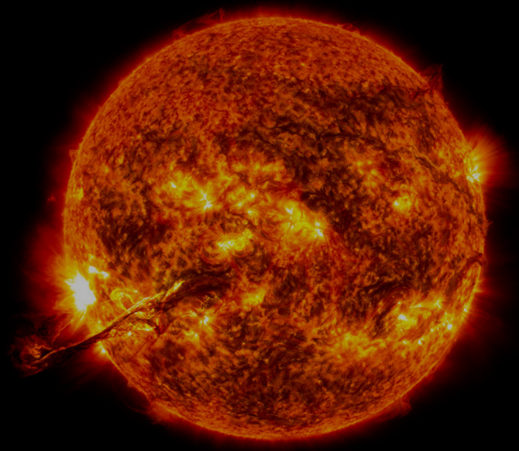
Lithium-9 / Helium-8

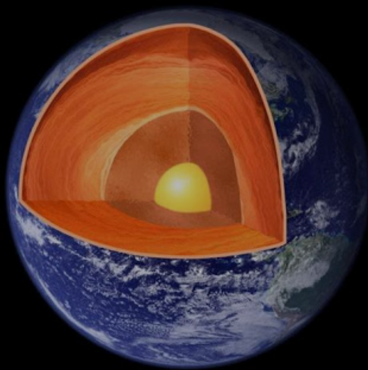
Muon-induced

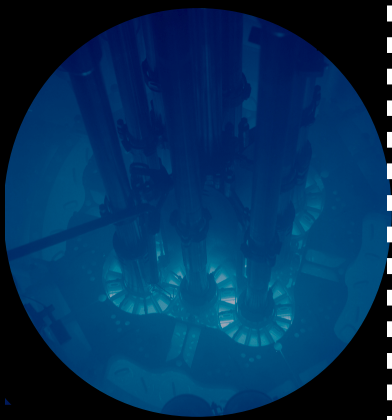
Boron-8 solar neutrinos, $2\nu\beta\beta$, ...

Physics and Typical Backgrounds

Background expected along muon track
→ Precise (topological) muon track reconstruction mandatory







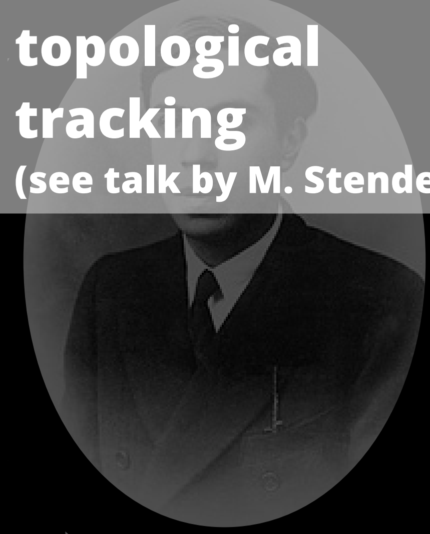
Carbon-11

Muon-induced

Lithium-9 / Helium-8

Muon-induced

Event classification based on topological tracking
(see talk by M. Stender)



Boron-8 solar neutrinos, 2νββ, …

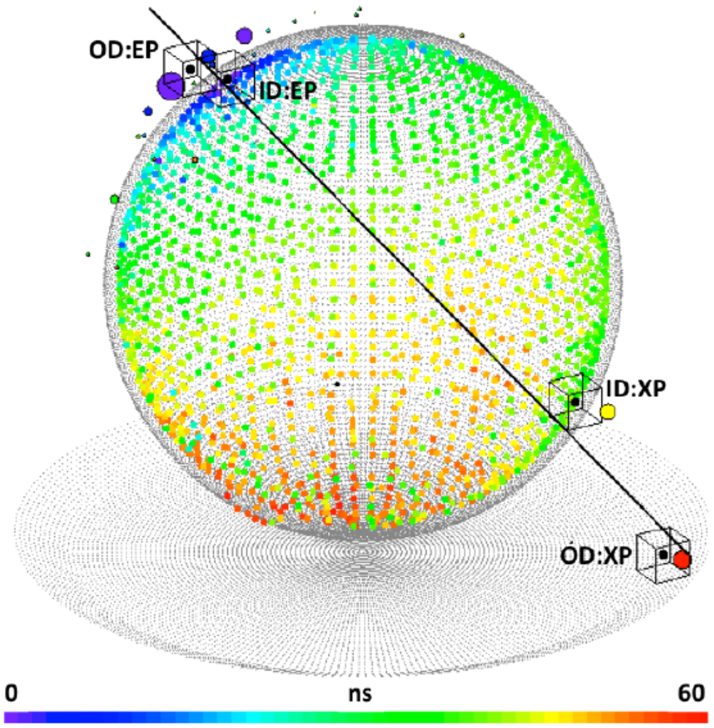
Part II

Tracking Algorithms

Overview – Topological Tracking - Backtracking

Track Reconstruction

- Many LS experiments use muon track reconstruction algorithm for background reduction
- Different approaches have been developed over the past years
  - Identification of entry and exit point
    G. Bellini et al., Muon and cosmogenic neutron detection in Borexino, JINST 6 (2011) P05005
  - Maximum likelihood fit
    R .B. Patterson et al., The extended-track event reconstruction for MiniBooNE, NIM-A 608 (2009) 206-224
  - Backtracking algorithm
    D. Hellgartner, Advanced Event Reconstruction in LENA and Precision Attenuation-Length Measurements in Liquid Scintillators, PhD thesis, TUM (2015)
  - Topological track reconstruction
    B. S. Wonsak et al., Topological track reconstruction in unsegmented, large-volume liquid scintillator detectors, JINST 13 (2018) no. 07, P07005

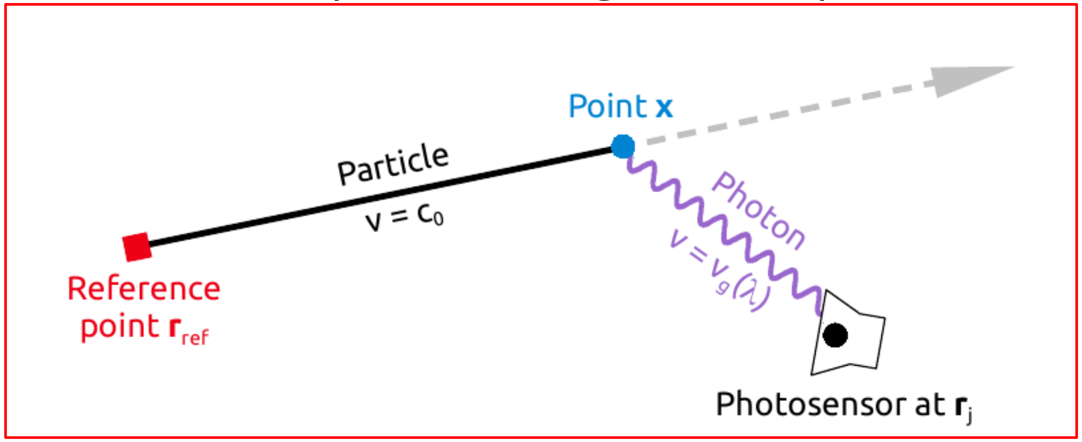


Global Muon tracking in Borexino. Figure taken from JINST 6 (2011) P05005.

Topological Track Reconstruction

- Topological track reconstruction: Reconstruction of spatial number density distribution of isotropic, optical photon emissions.
- Basic idea: Compute the origin of the photon emission via hit time

JINST 13 (2018) no. 07, P07005



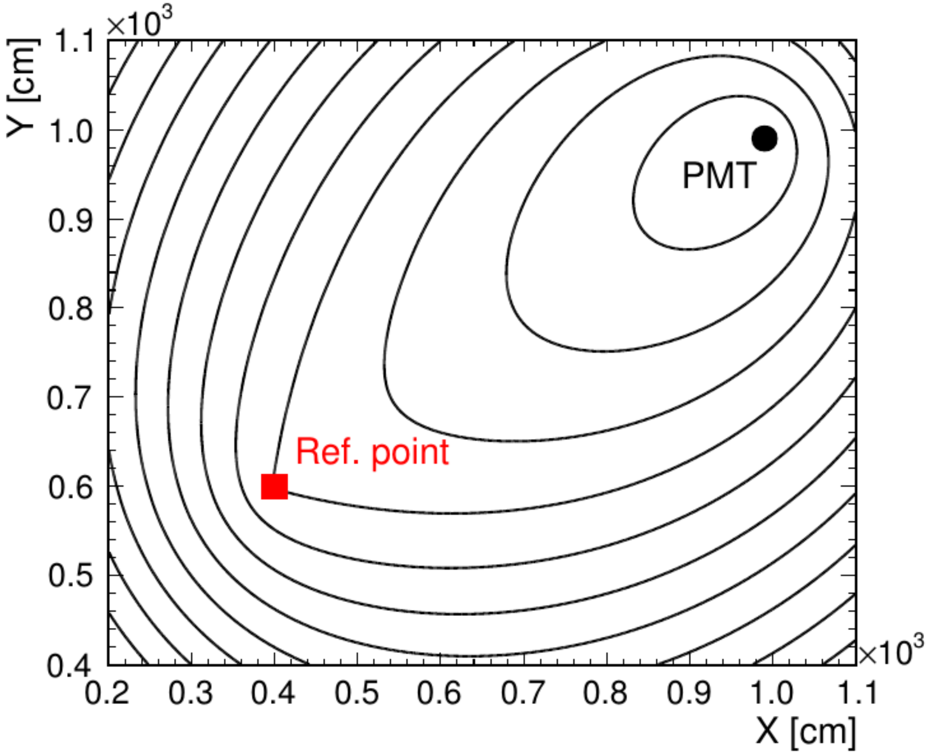
$$\hat{t}_j(\mathbf{x}) \equiv \hat{t}_j(\mathbf{x};\mathbf{r}_j,\mathbf{r}_{\mathrm{ref}},t_{\mathrm{ref}}) = t_{\mathrm{ref}} \pm \underbrace{\frac{|\mathbf{x}-\mathbf{r}_{\mathrm{ref}}|}{c_0}}_{\text{particle}} + \underbrace{t_{\mathrm{ph}}(\mathbf{x},\mathbf{r}_j)}_{\text{photon}} + t_s \ .$$

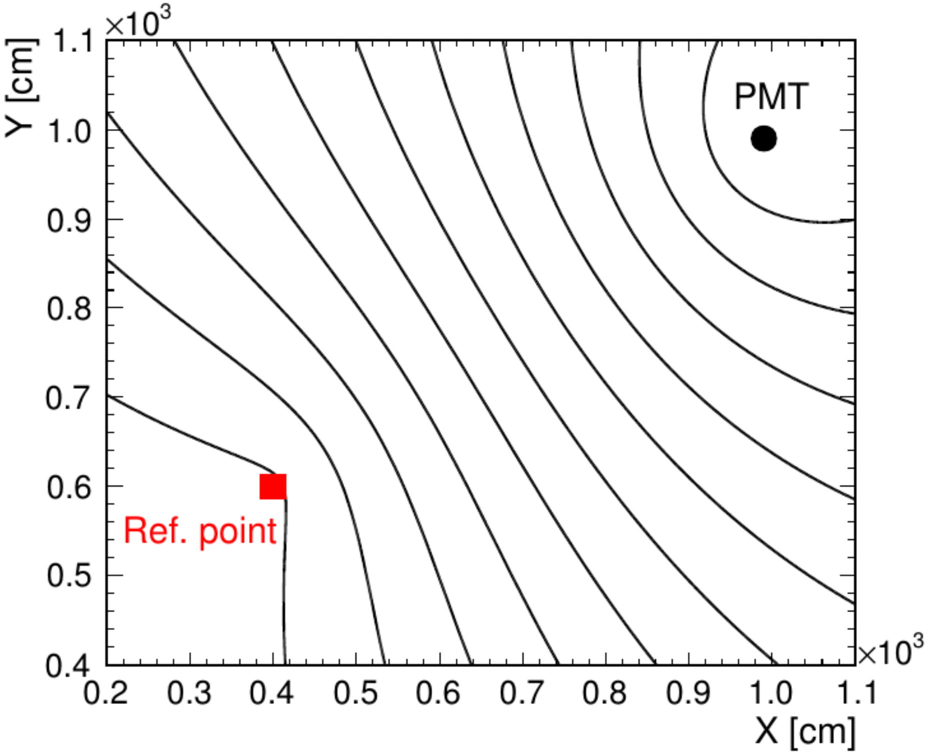
- Assumptions:
  - Known reference point with ($\mathbf{r}_{ref}$) and reference time ($\mathbf{t}_{ref}$)
  - Straight line through $\mathbf{r}_{ref}$ with velocity c

Topological Track Reconstruction

JINST 13 (2018) no. 07, P07005

- Possible origins of the scintillation photon describe an isochrone.



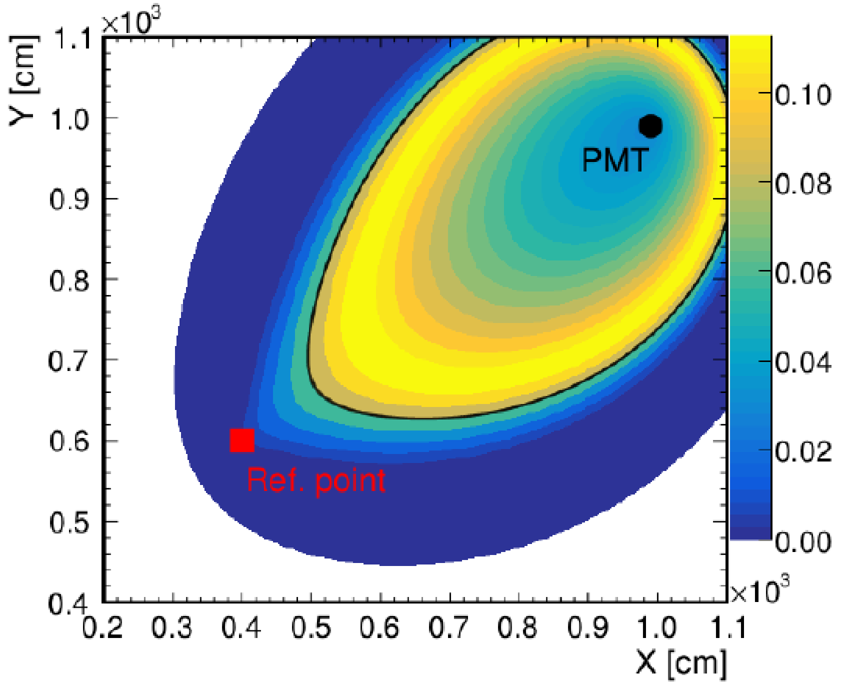


Topological Track Reconstruction

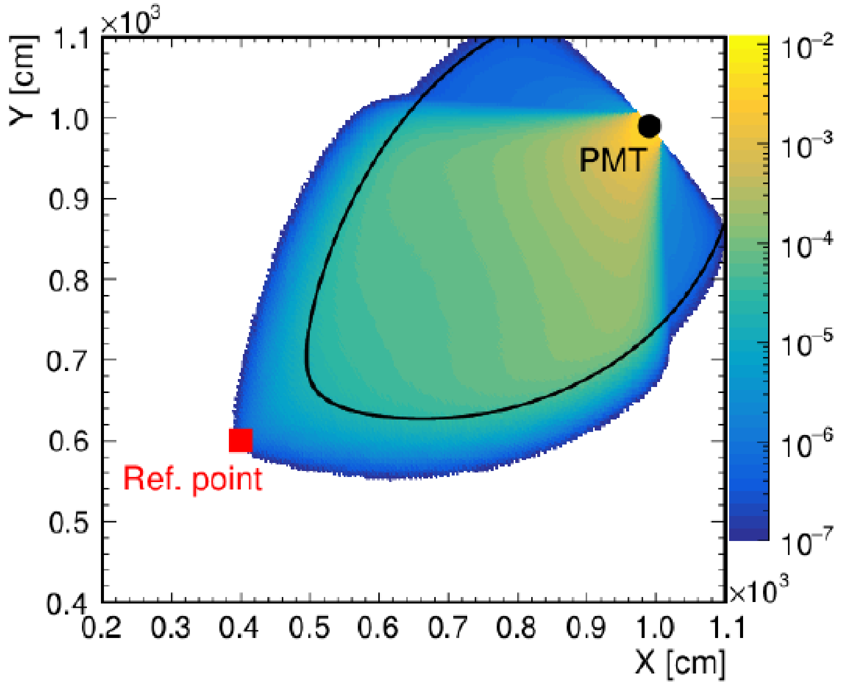
JINST 13 (2018) no. 07, P07005

- Computation of PDF for the k^{th} photon hit at PMT

$$\Phi_{j,k} = w_{j,k}\varepsilon_j(\vec{x}) \int_0^\infty \Phi_{t_s}(\Delta t)\Phi_{t_{ph}}(t_{ph};\vec{x},\vec{r}_j)\mathrm{d}t_{ph}$$

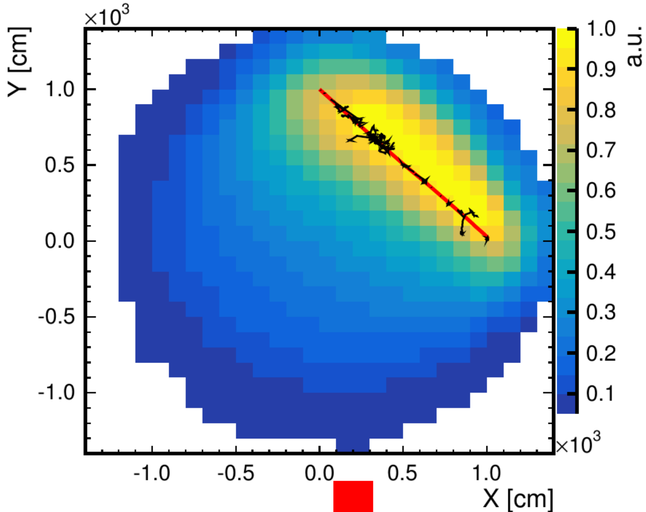


Without spatial detection efficiency



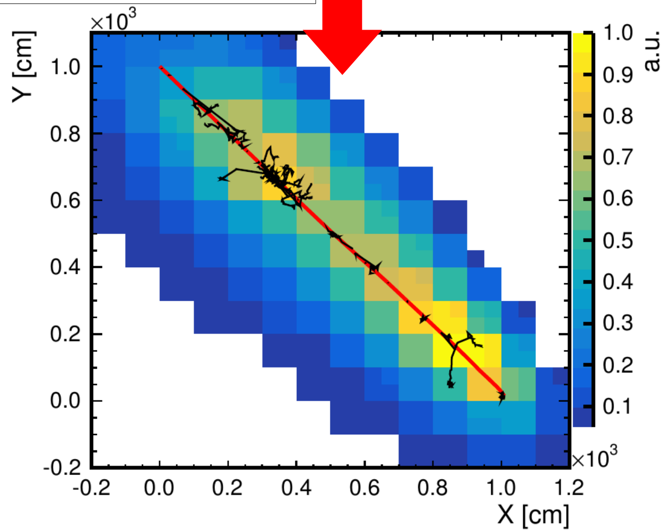
With spatial detection efficiency

Topological Track Reconstruction Results

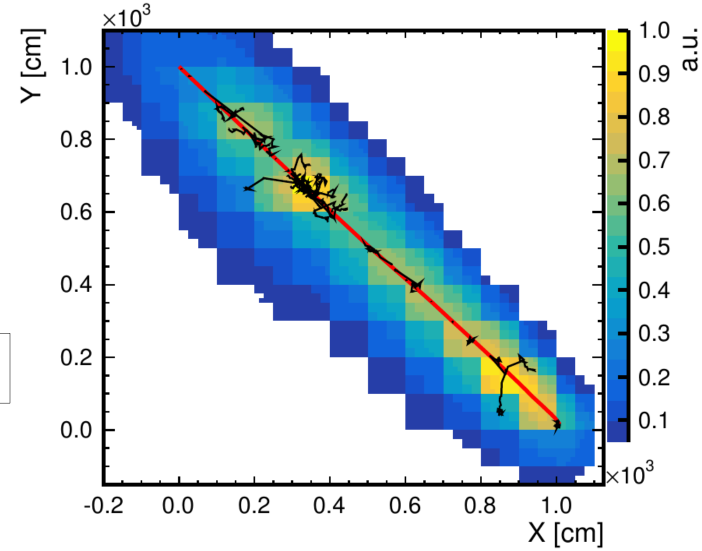


- Add up all signal (arrival time for every photon needed)
- Divide result by local detection efficiency
  → Number density of emitted photons
- Use knowledge that all signals belong to same topology to *connect* their information
  → Use prior result to re-evaluate p.d.f. of each signal

Decrease cell size



Decrease cell size



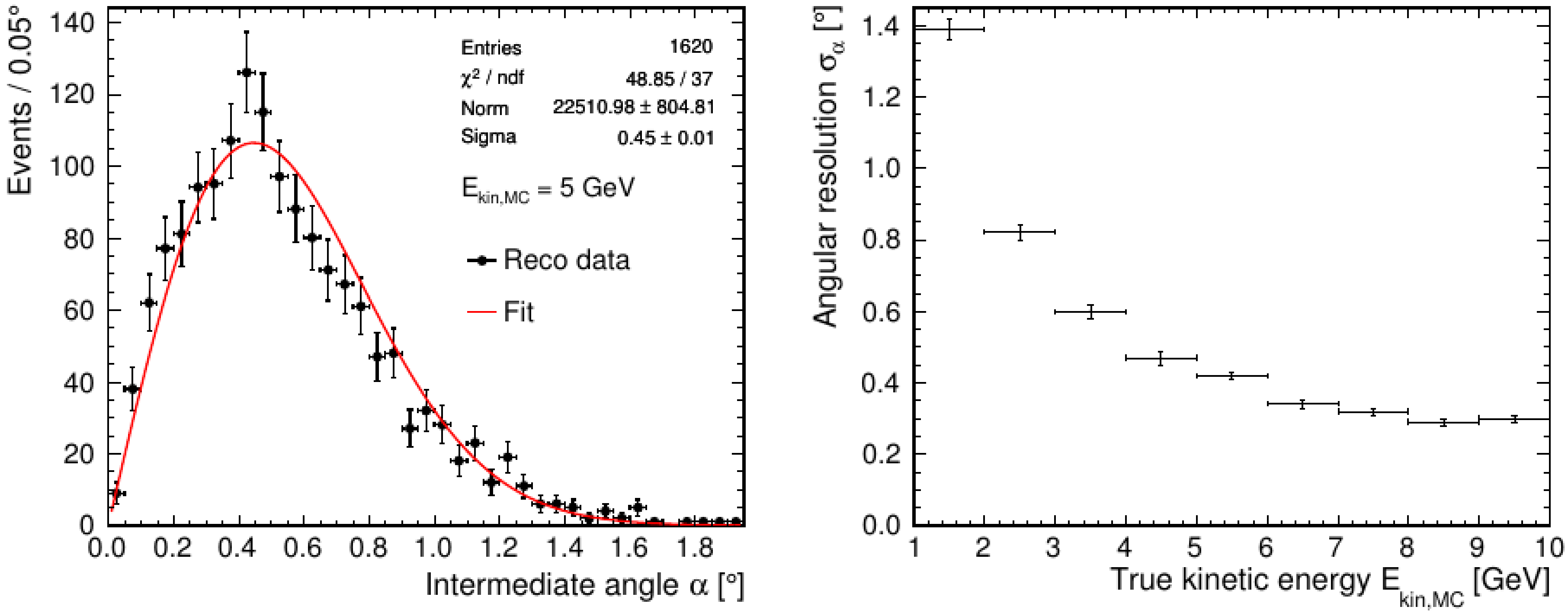
dE/dx accessible

Slide adopted from B. Wonsak

Topological Track Reconstruction Results (LENA)

JINST 13 (2018) no. 07, P07005

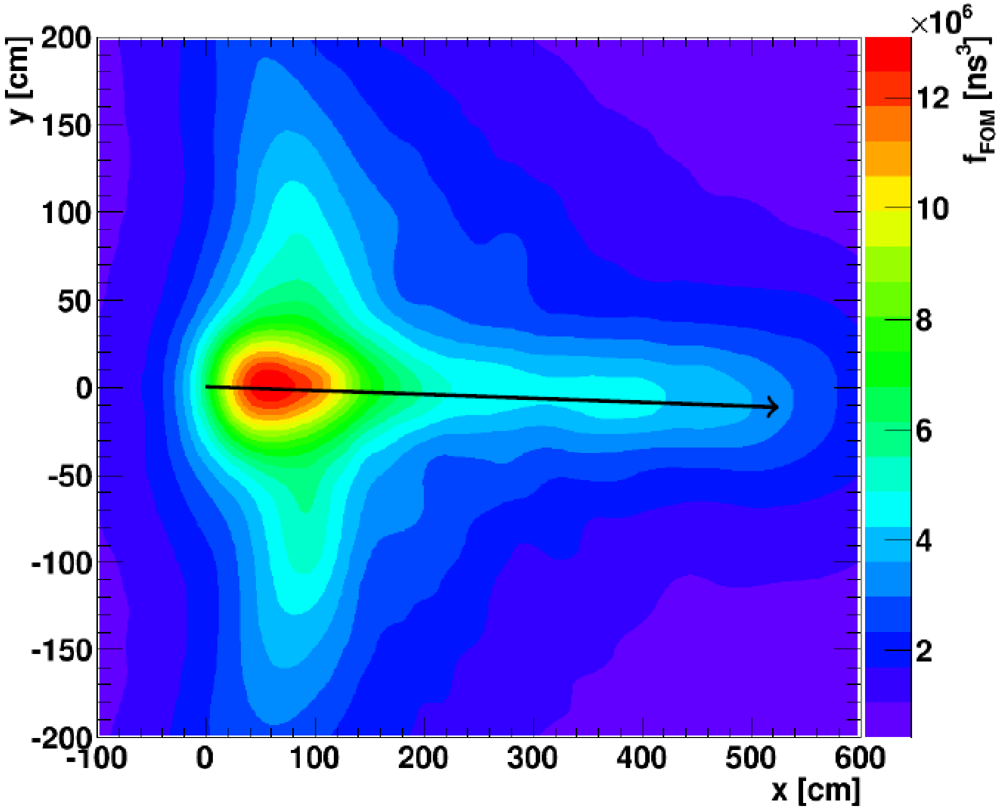
- Angle between reconstructed track line and MC mean direction



Backtracking

- **Backtracking**: Algorithm to create an image of an event without requiring any prior knowledge
- Output: Figure of merit to each point **r** in the detector, which is correlated to the number of photons emitted in the close vicinity of **r**
- Algorithm uses (corrected) first hit time spectrum (FHT) of PMTs

  → Expected peak for point on track
  → Expected flat spectrum for a point off the track
- Evaluate whether the corrected FHT features a peak



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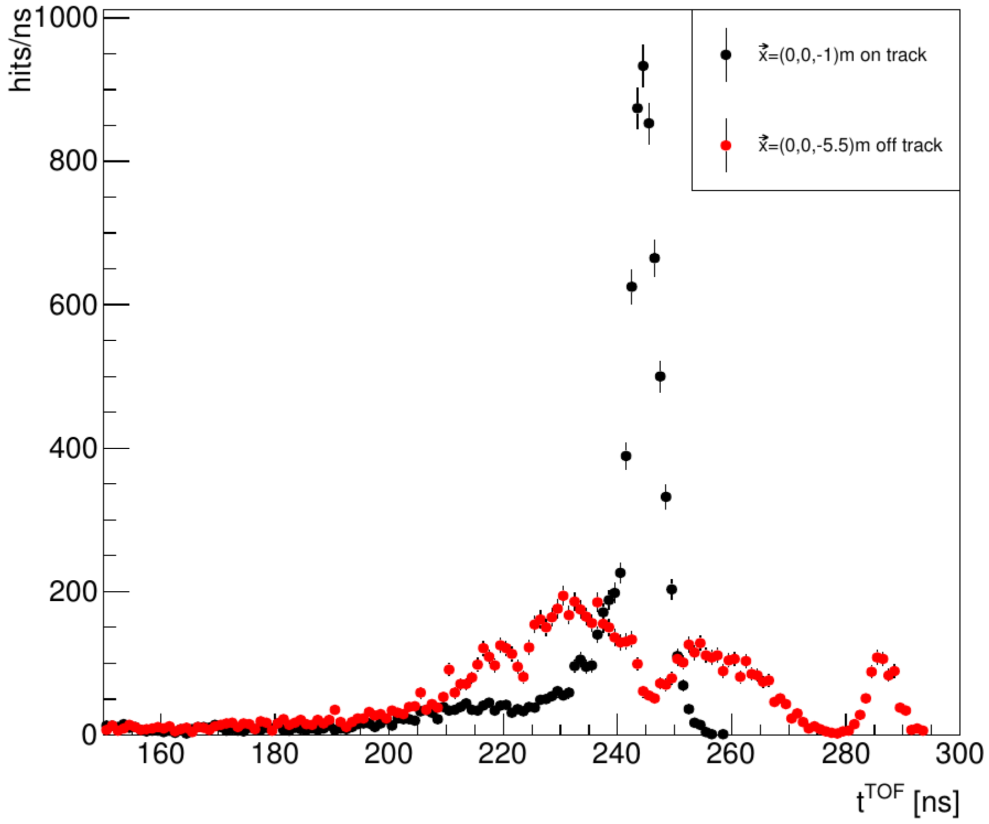
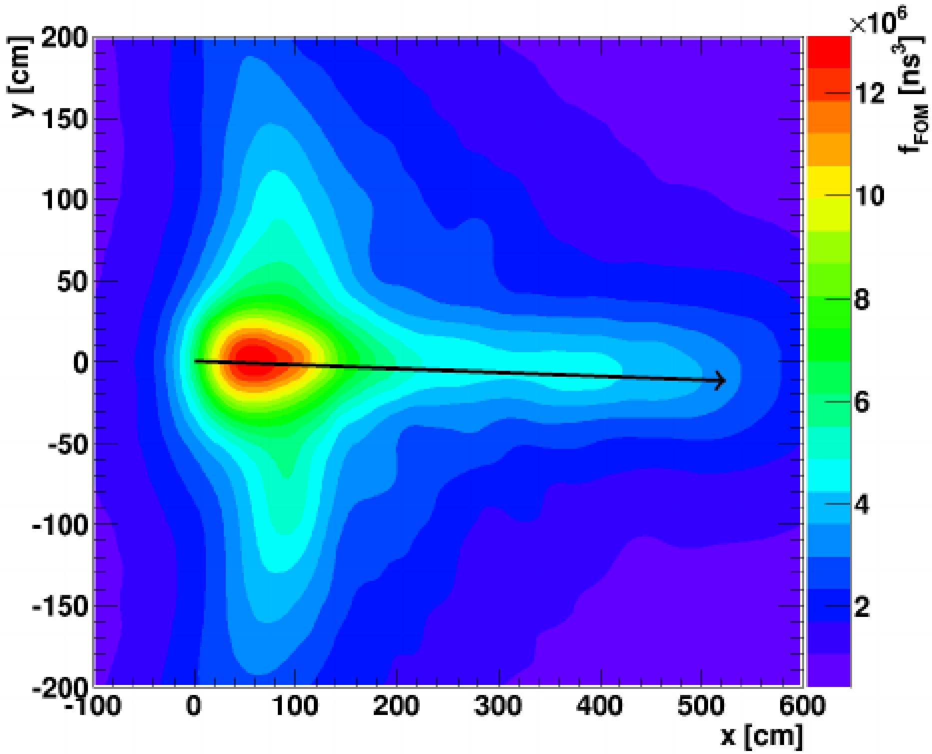


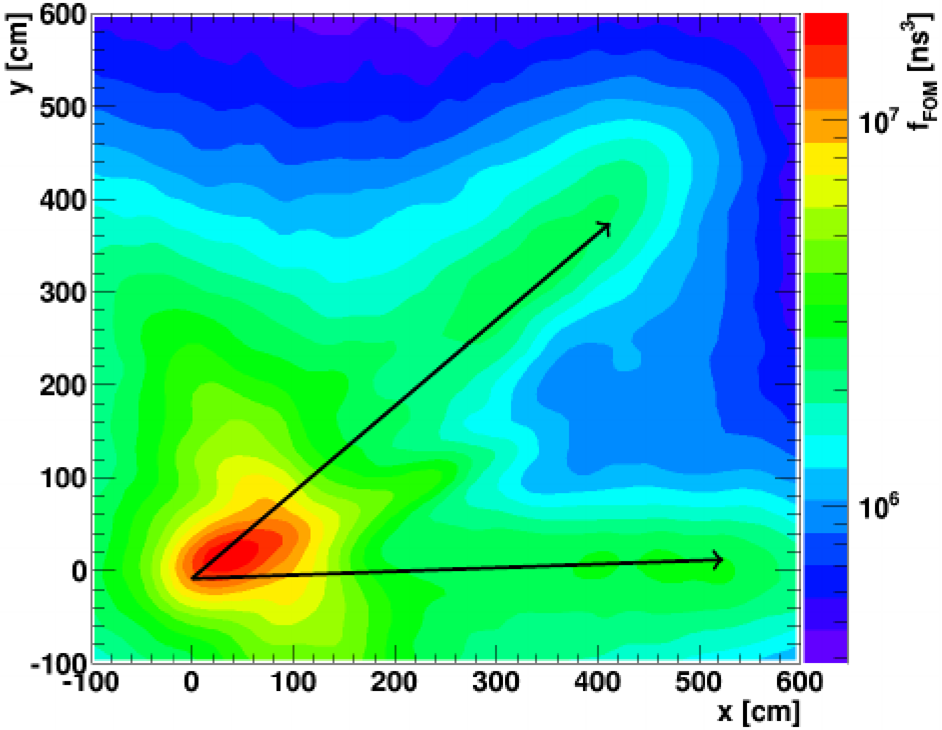
Backtracking (LENA)

Backtracking estimator $f_{FOM}(\mathbf{r})$ as a function of x and y (z=0)

1 GeV muon



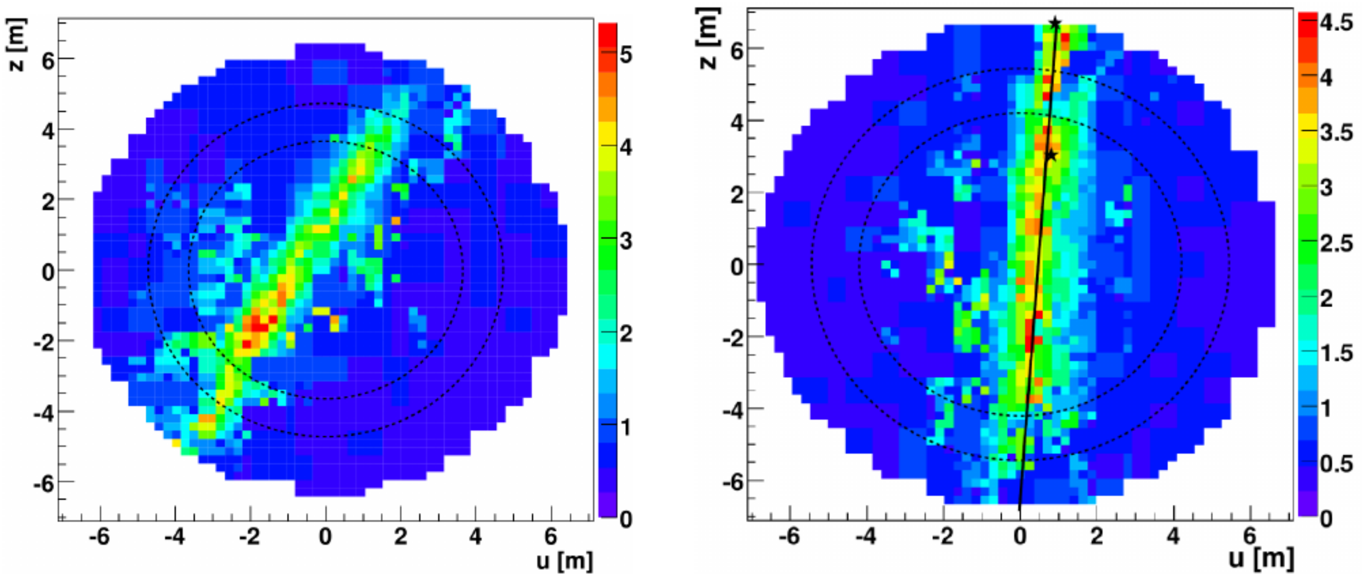
Two 1 GeV muons



D. Hellgartner, PhD thesis, TUM (2015)

Backtracking (Borexino Results)

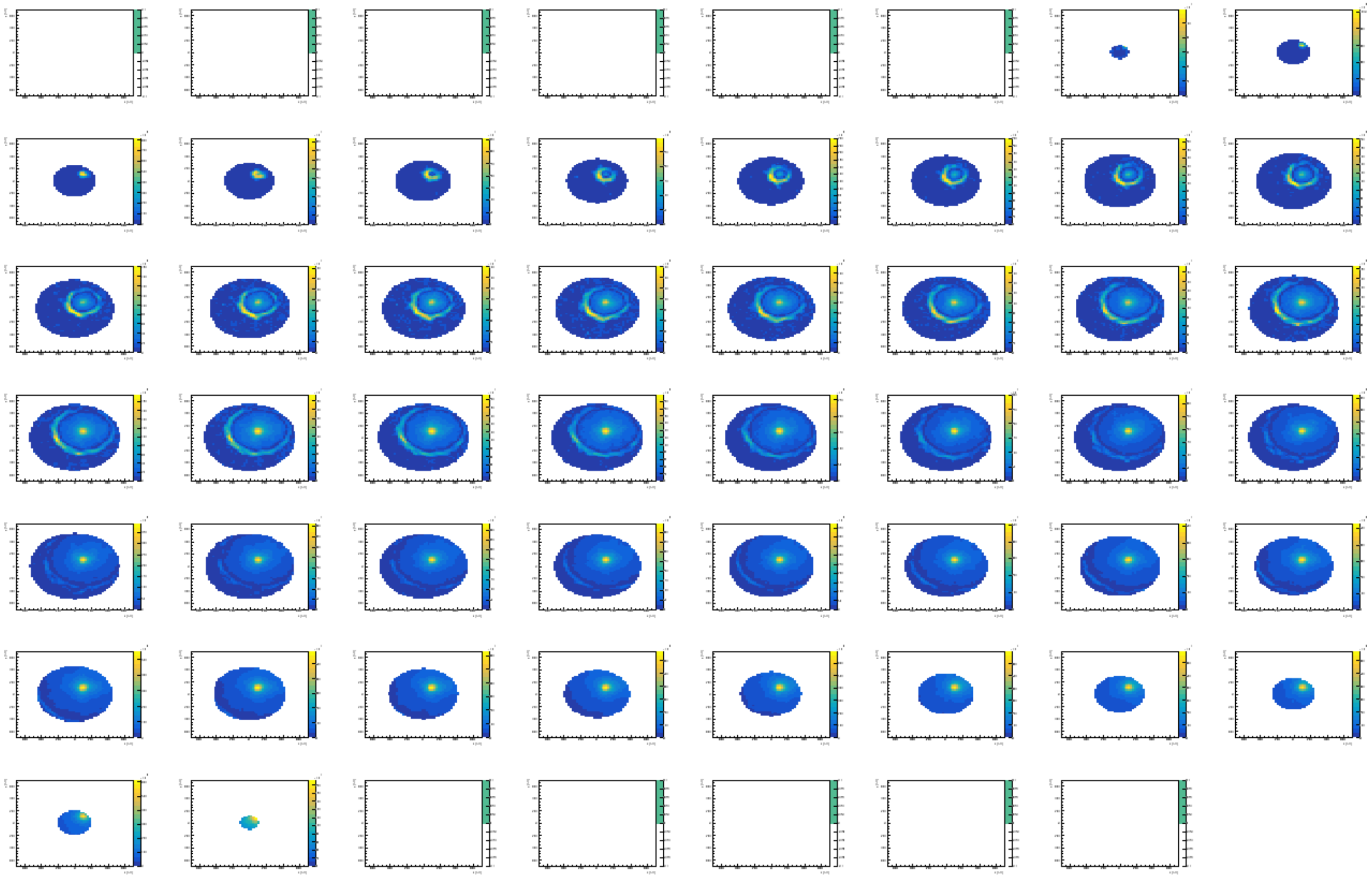
- Backtracking for cosmic events at Borexino



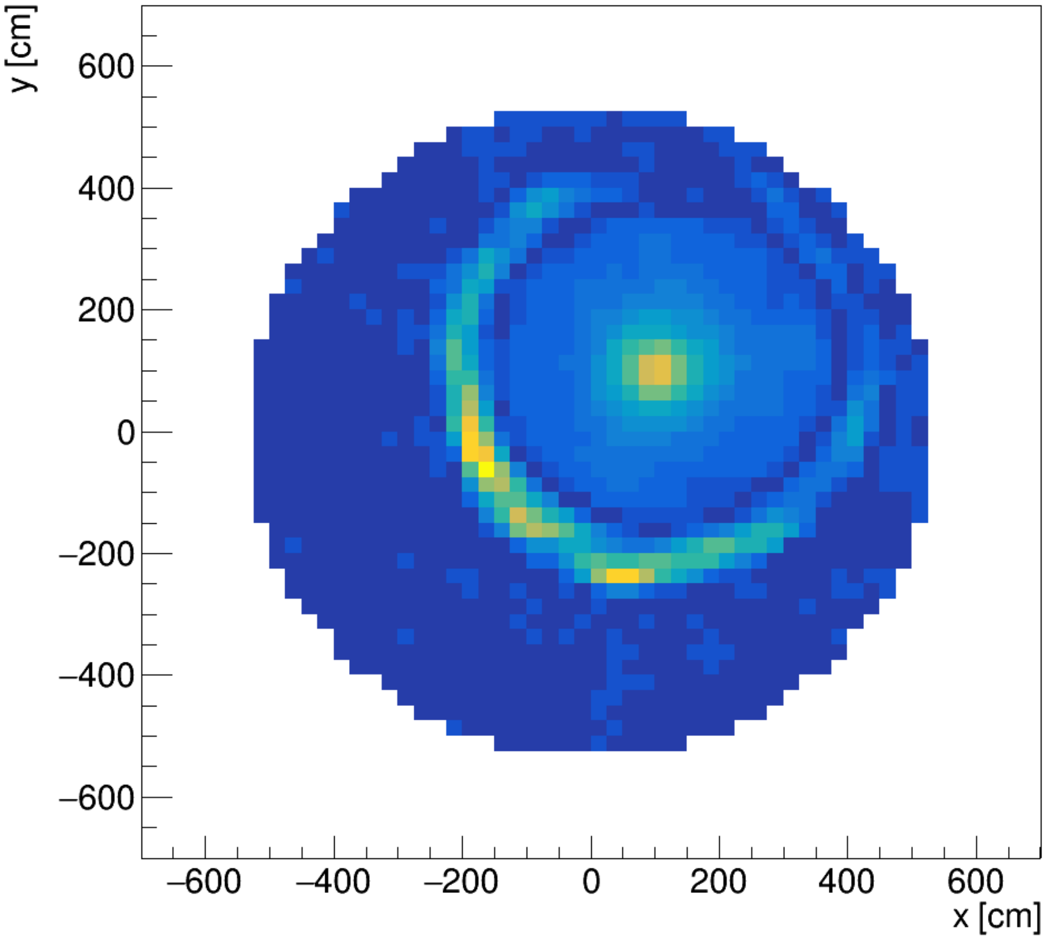
	Backtracking	ID Tracking	OD Tracking
σ_α [deg]	1.63 ± 0.10	2.44 ± 0.19	3.01 ± 0.15
σ_y [cm]	35 ± 4	36 ± 5	28 ± 7
σ_z [cm]	38 ± 4	31 ± 6	45 ± 7

D. Hellgartner, PhD thesis, TUM (2015)

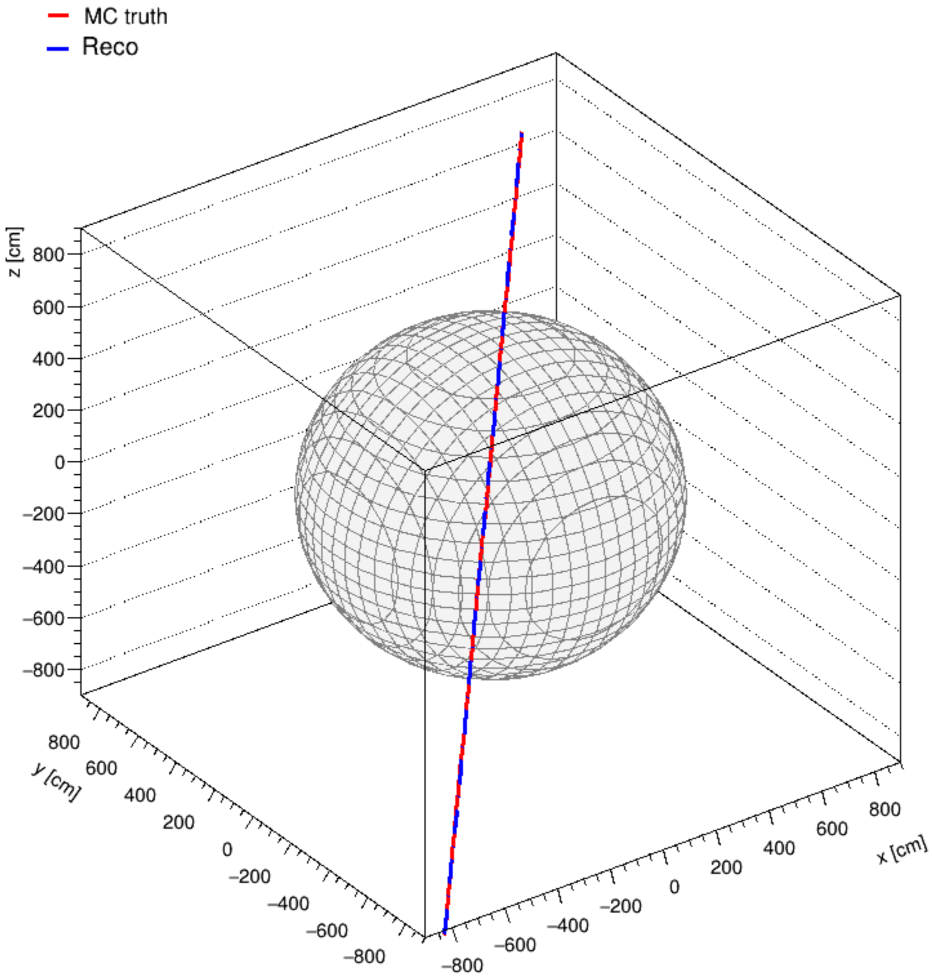
Backtracking (SNO+)

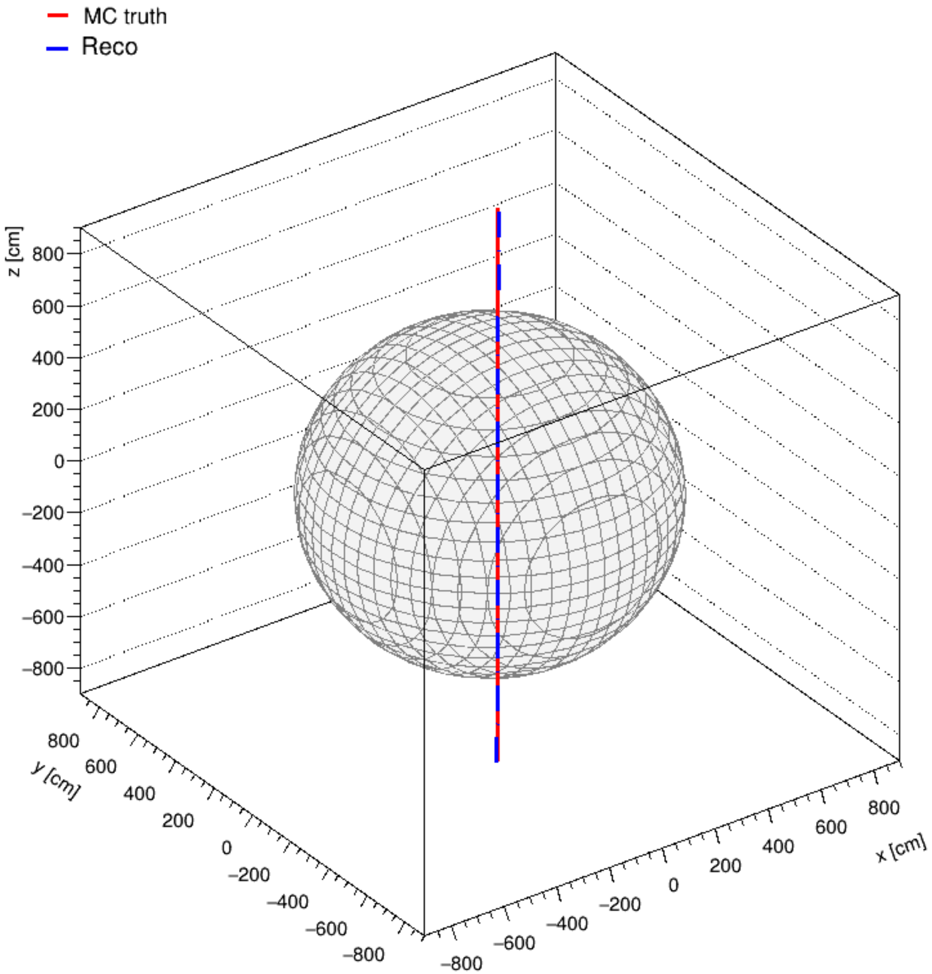


Backtracking (SNO+)



Backtracking (SNO+)





Part III

Image Processing
Circle Identification – Edge Detection

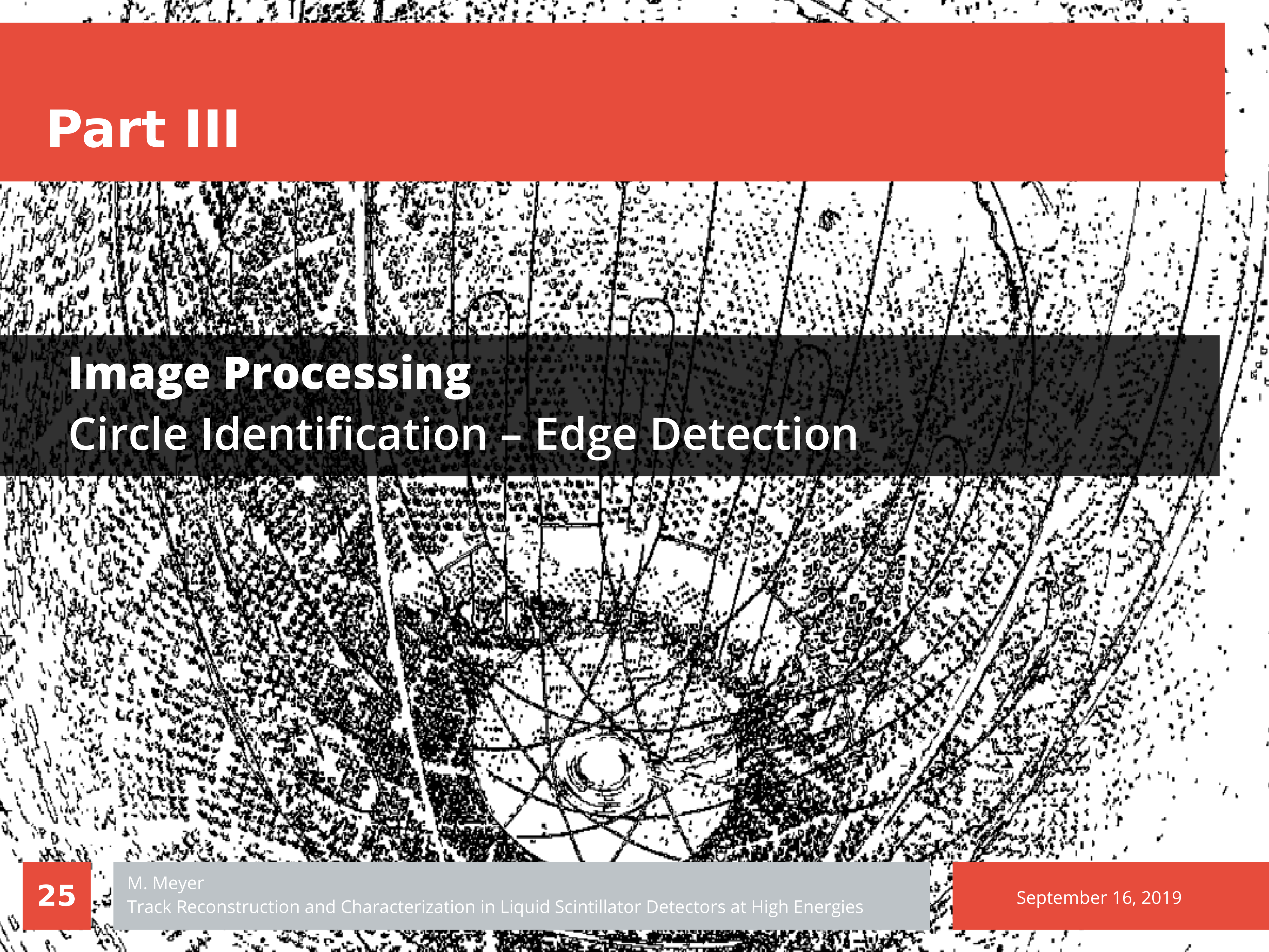
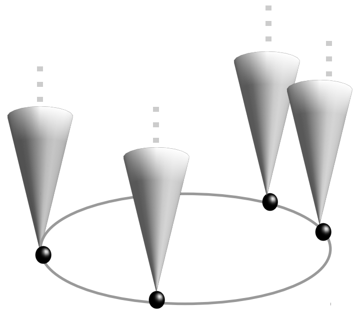


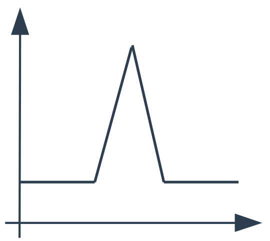
Image Processing: Circle Fit

- Circle Identification via simple geometric considerations

  1st step: For each point, circles are drawn with different radii. (see B)

  2nd step: Evaluate intersection points depending on R





3rd step: Retrieve result (see C and D)

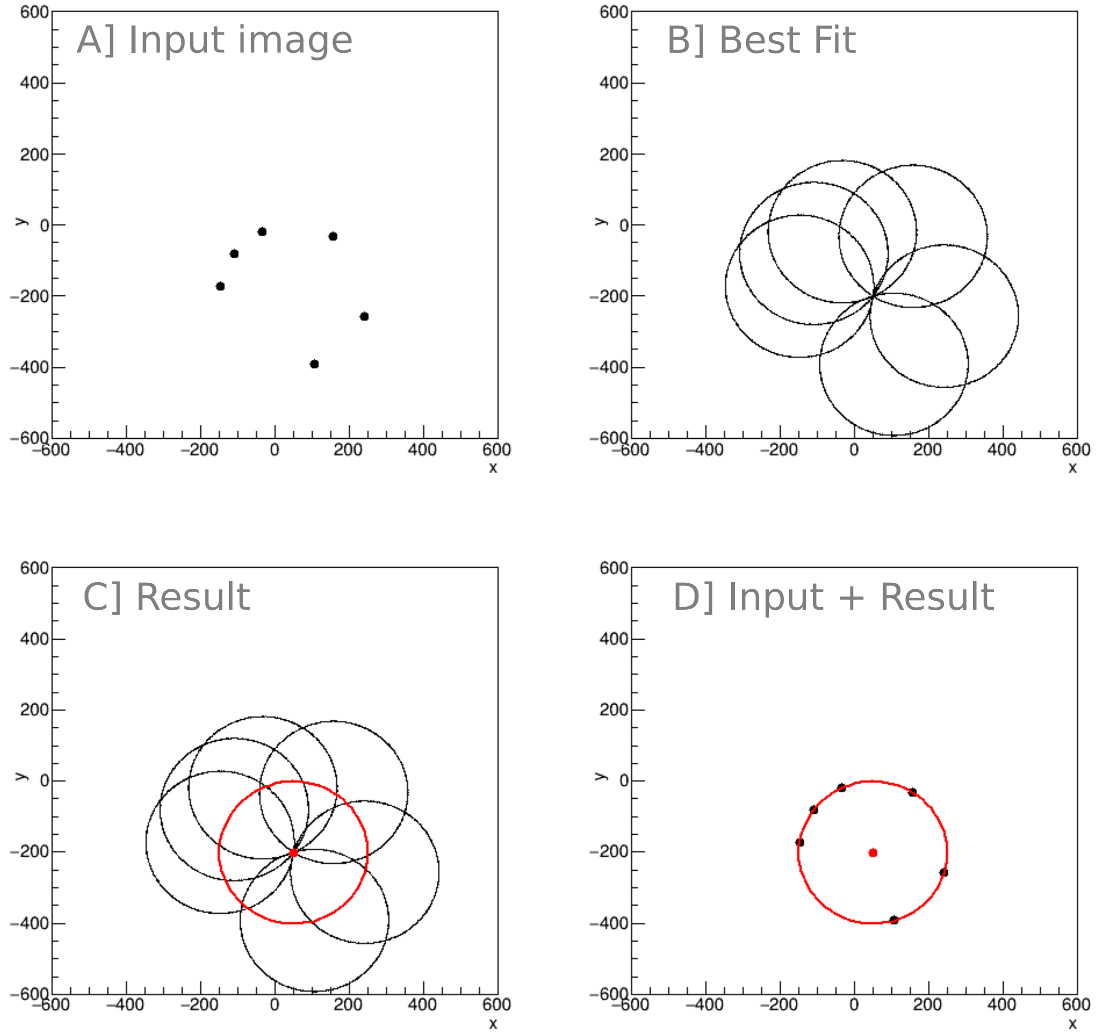


Image Processing: Circle Fit

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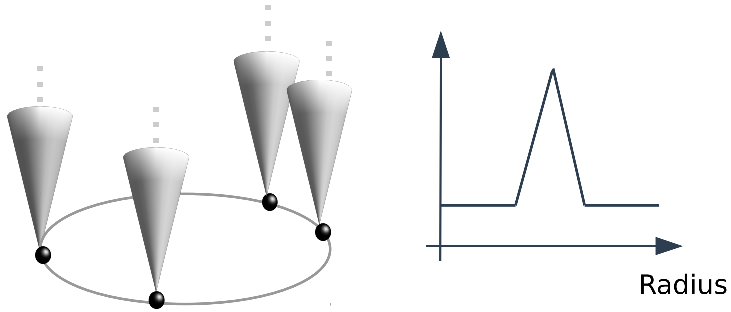

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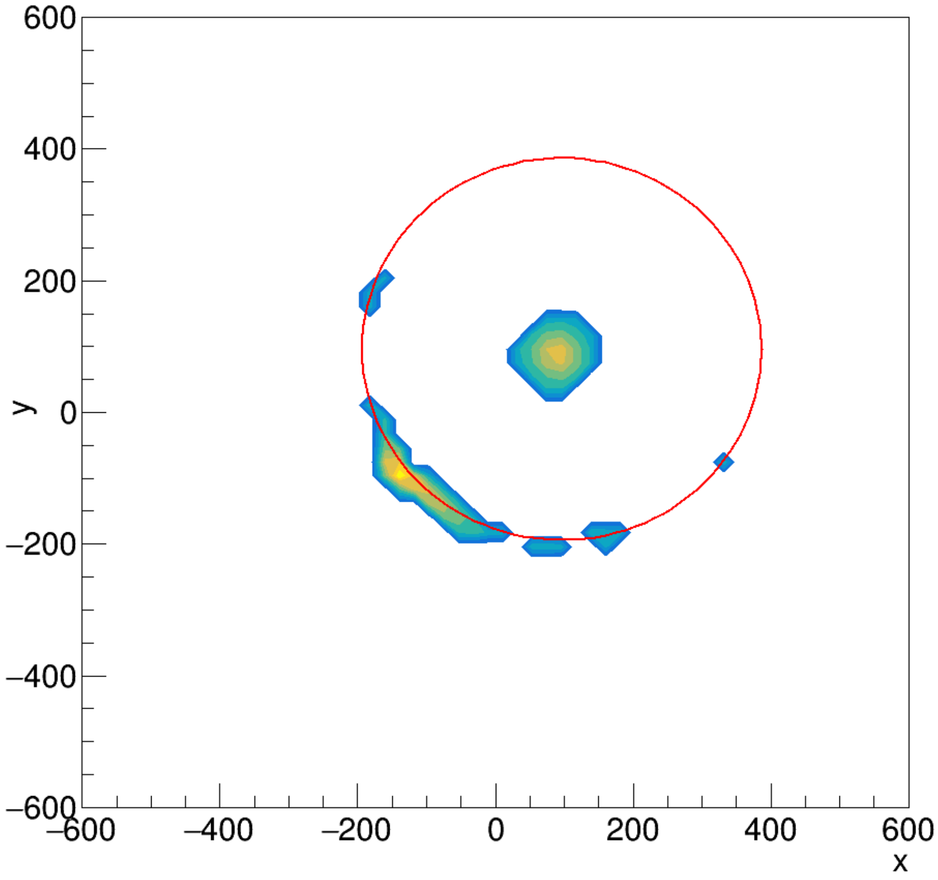
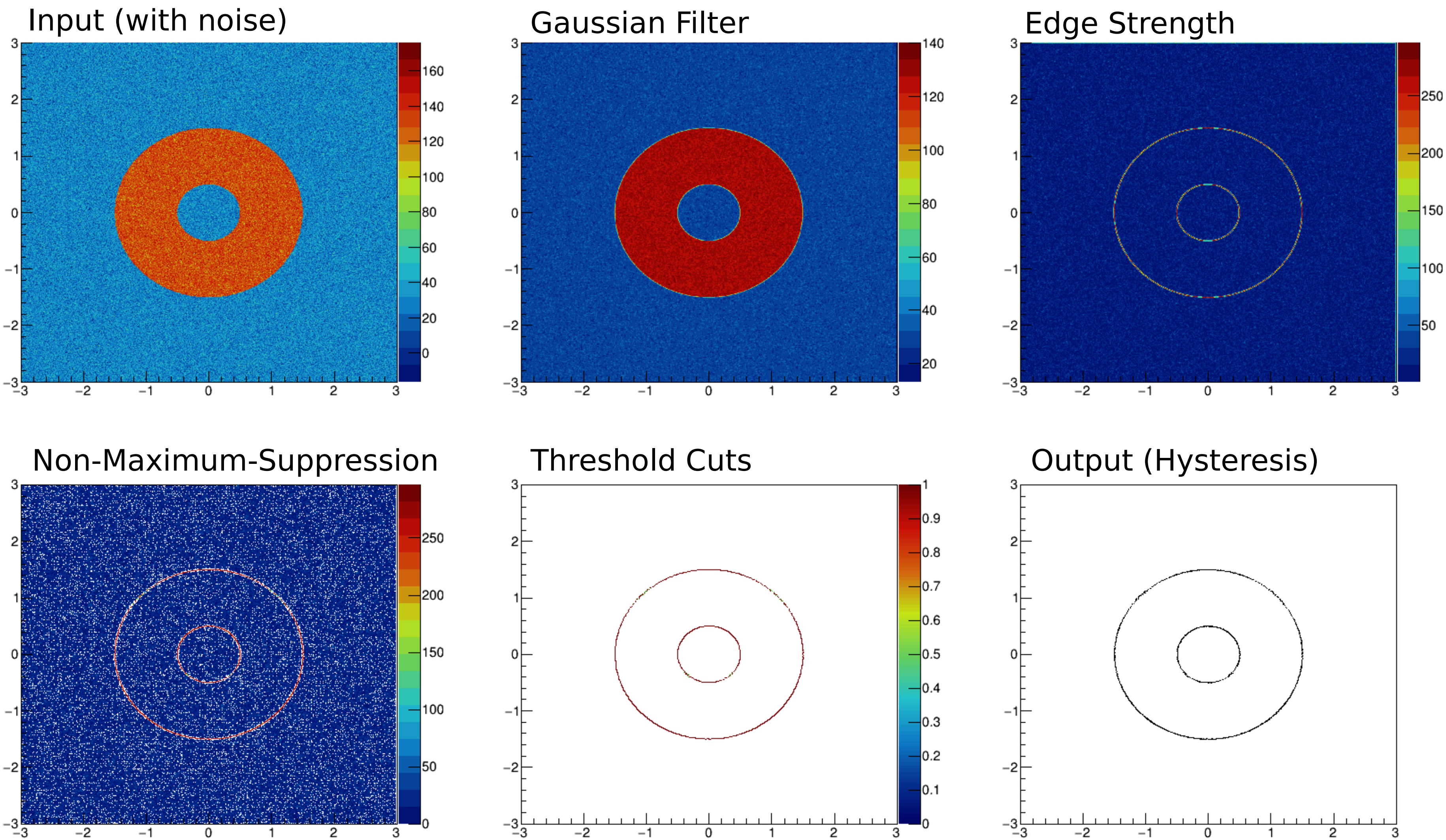


Image Processing

Start gif animation

Image Processing: Edge Detection

Canny Edge Detection (Toy MC)



Work in progress

Image Processing: Edge Detection

Canny Edge Detection (Complex Object)

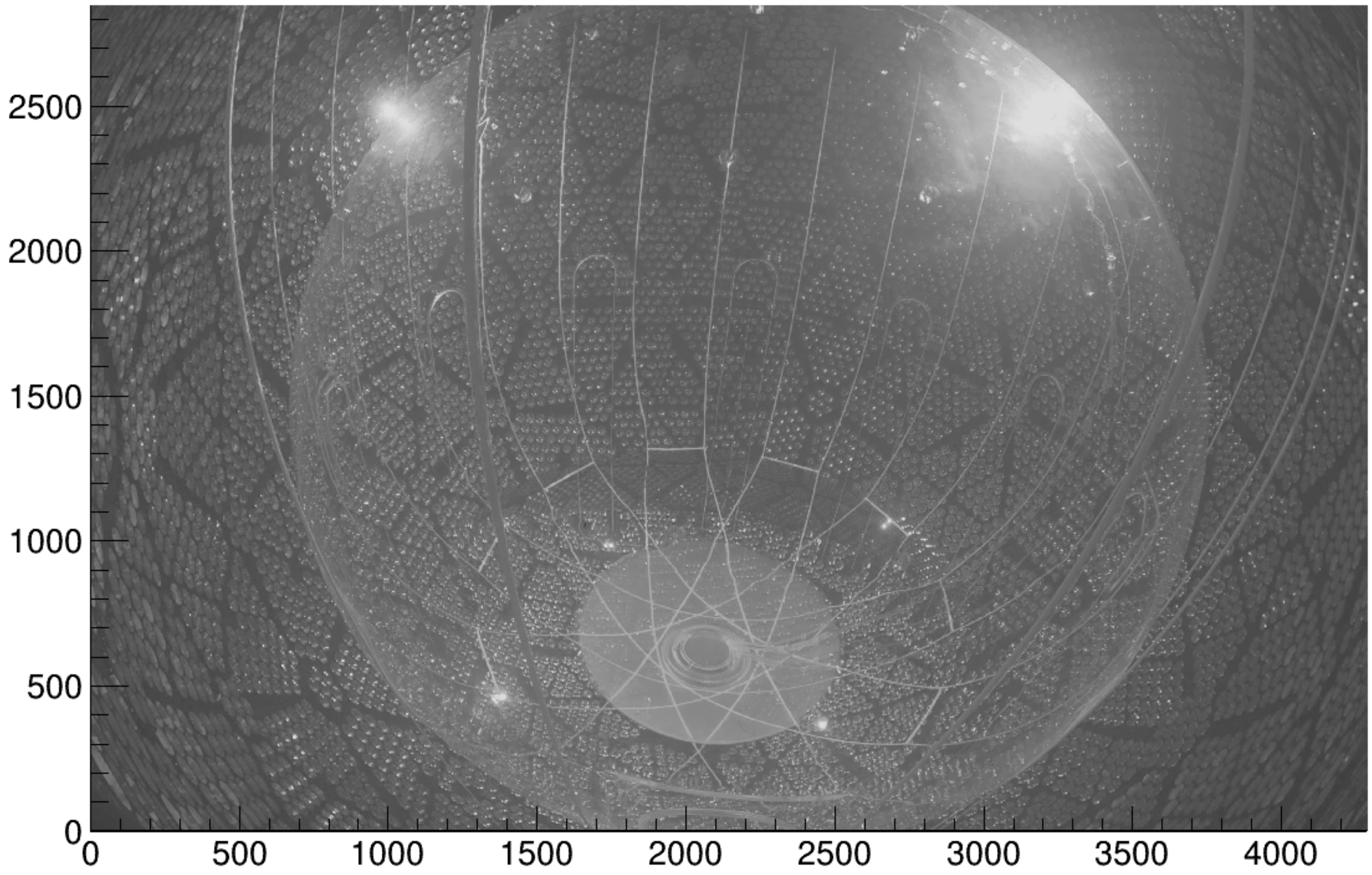


Image Processing: Edge Detection

Canny Edge Detection (Complex Object)

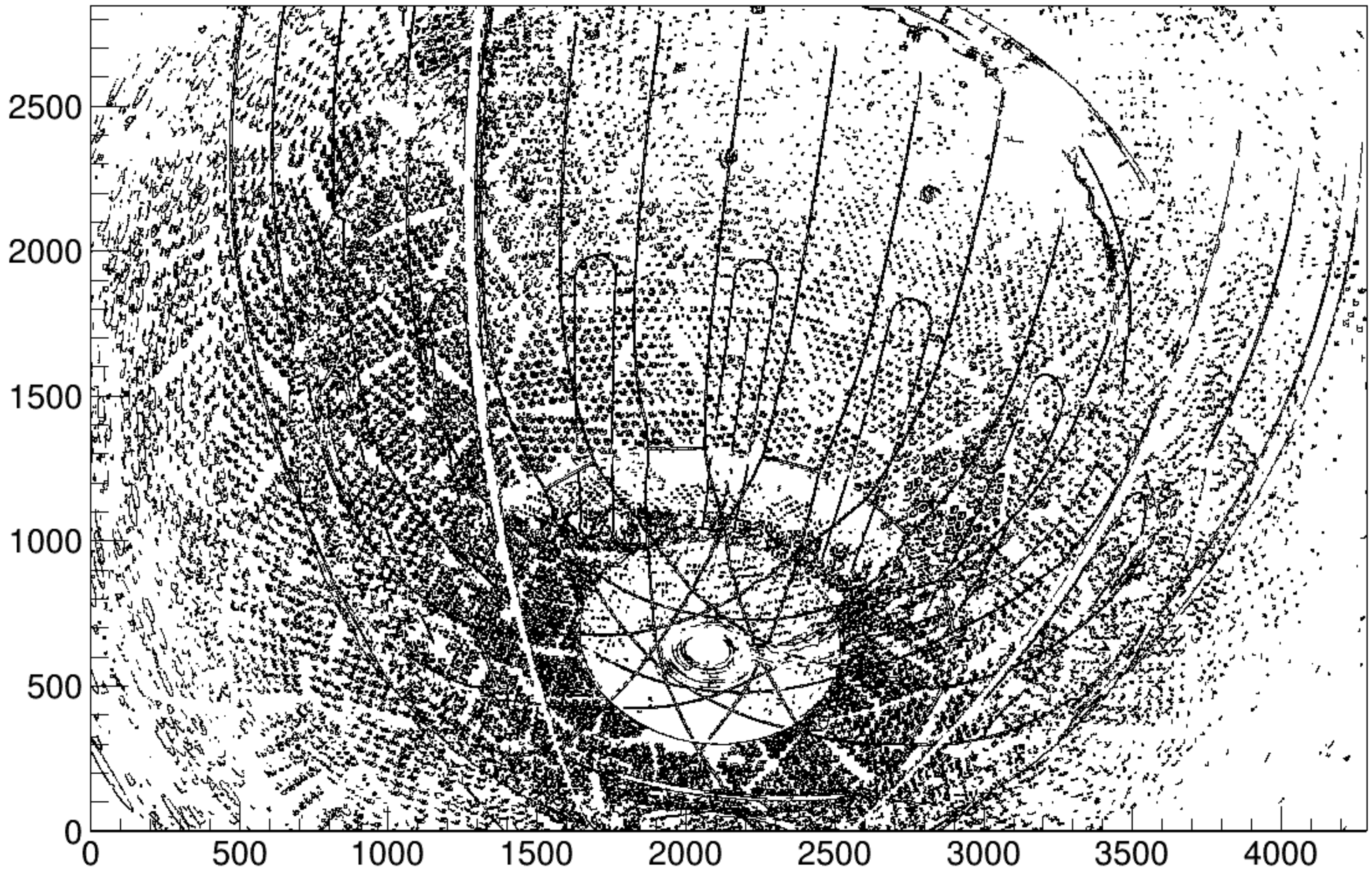


Image Processing: Edge Detection

Canny Edge Detection (Complex Object)

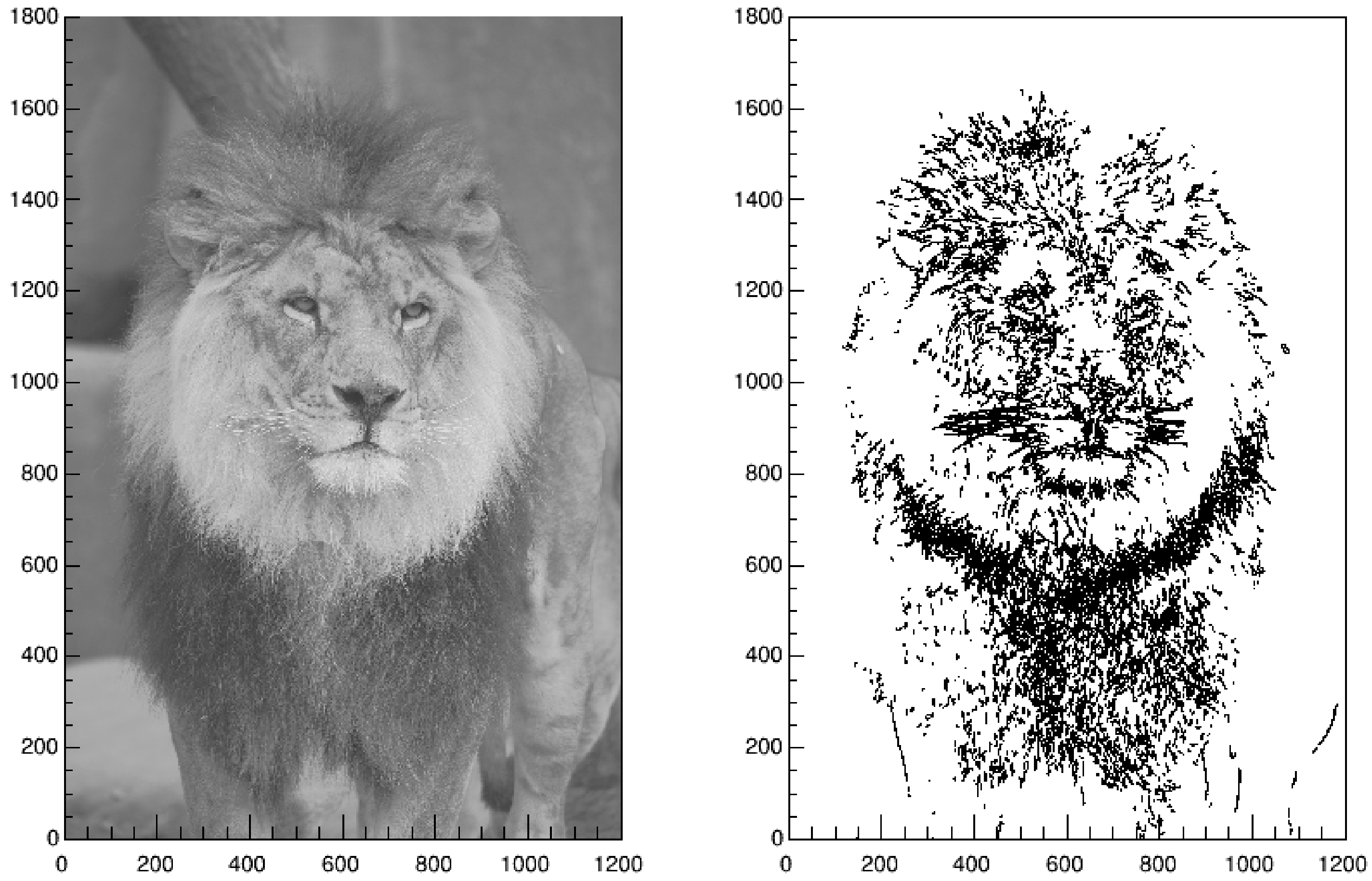
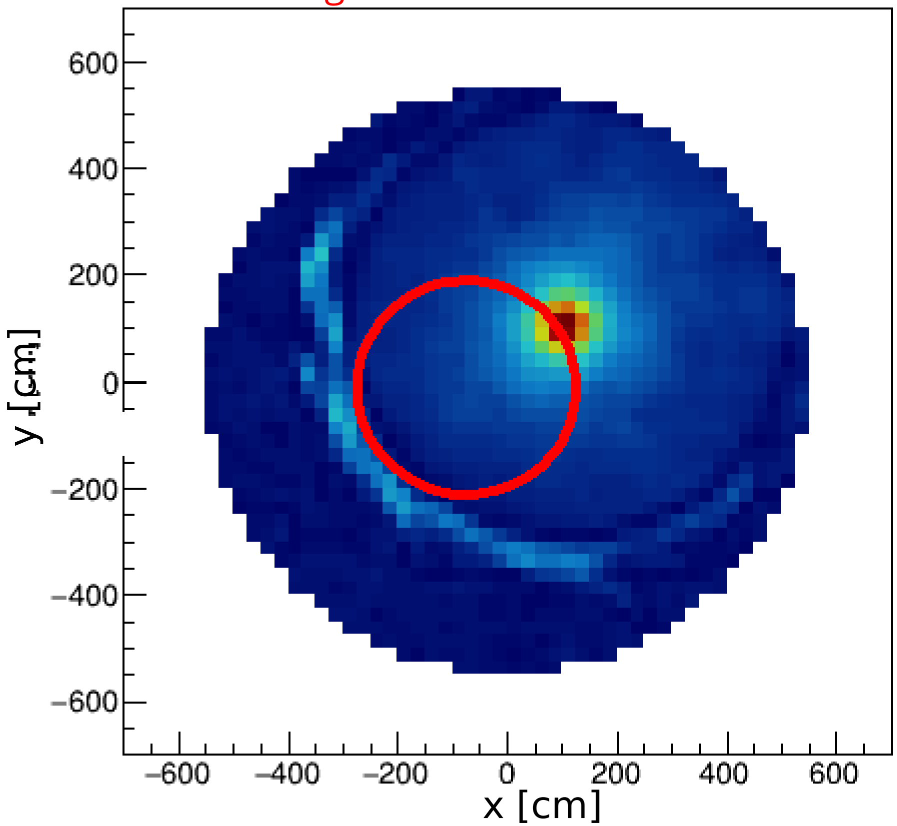


Image Processing: Edge Detection

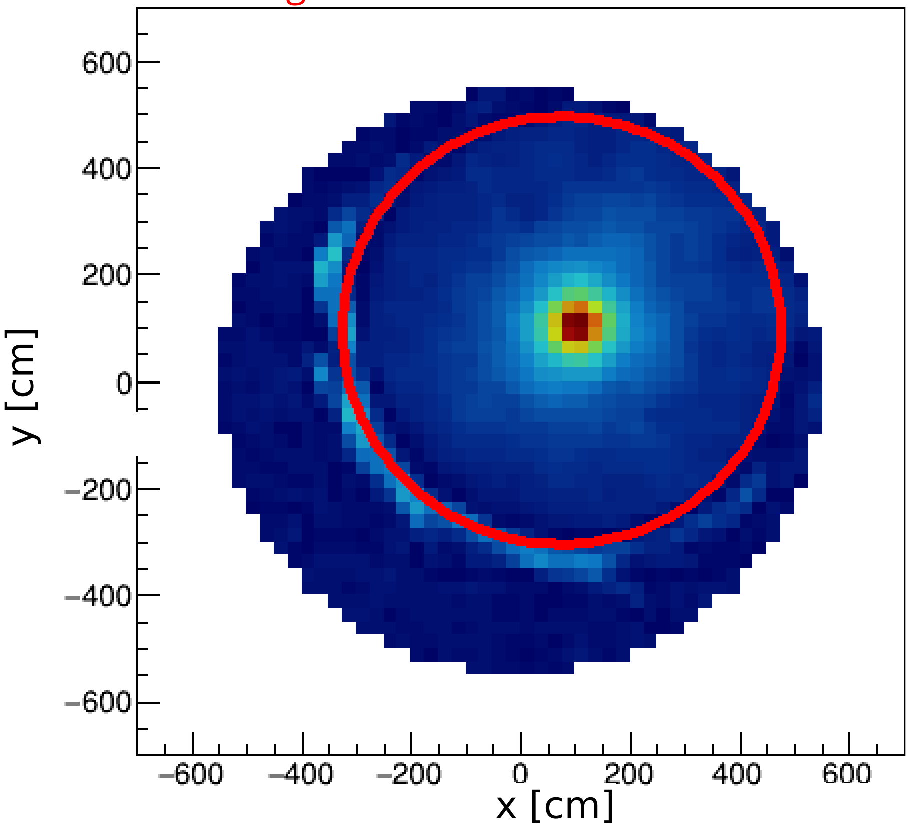
Canny Edge Detection (Ring Structure)

Raw image and circle fit

Without edge detection



With edge detection



Part IV

Summary and Conclusion

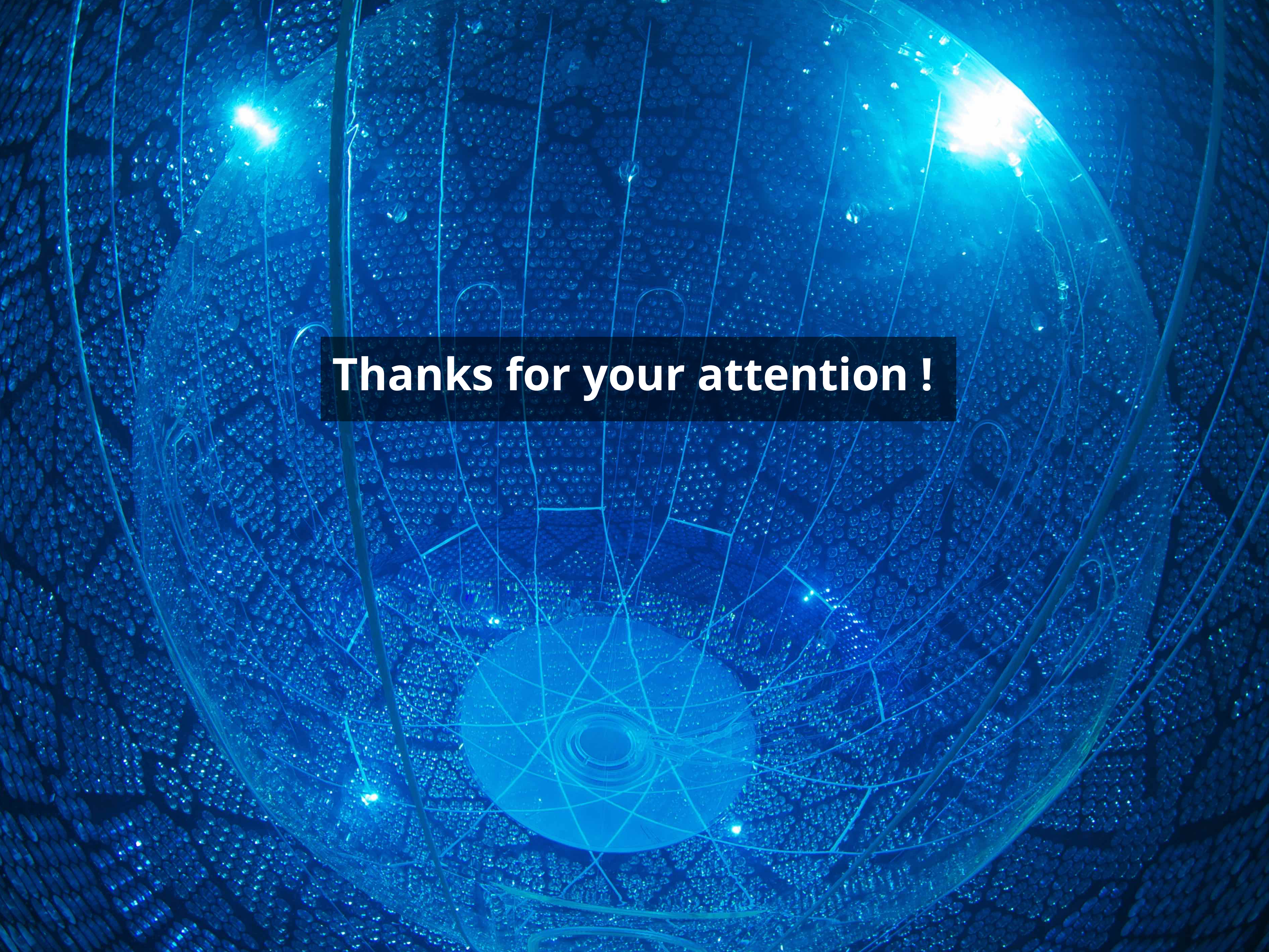
Summary

- Liquid scintillator detectors well established in the field of neutrino physics
- Advanced tracking algorithm in development
  - Backtracking
  - Topological Tracking
- Topological tracking gives access to energy loss

  → Foundation to reduce dead-time in large LS detectors

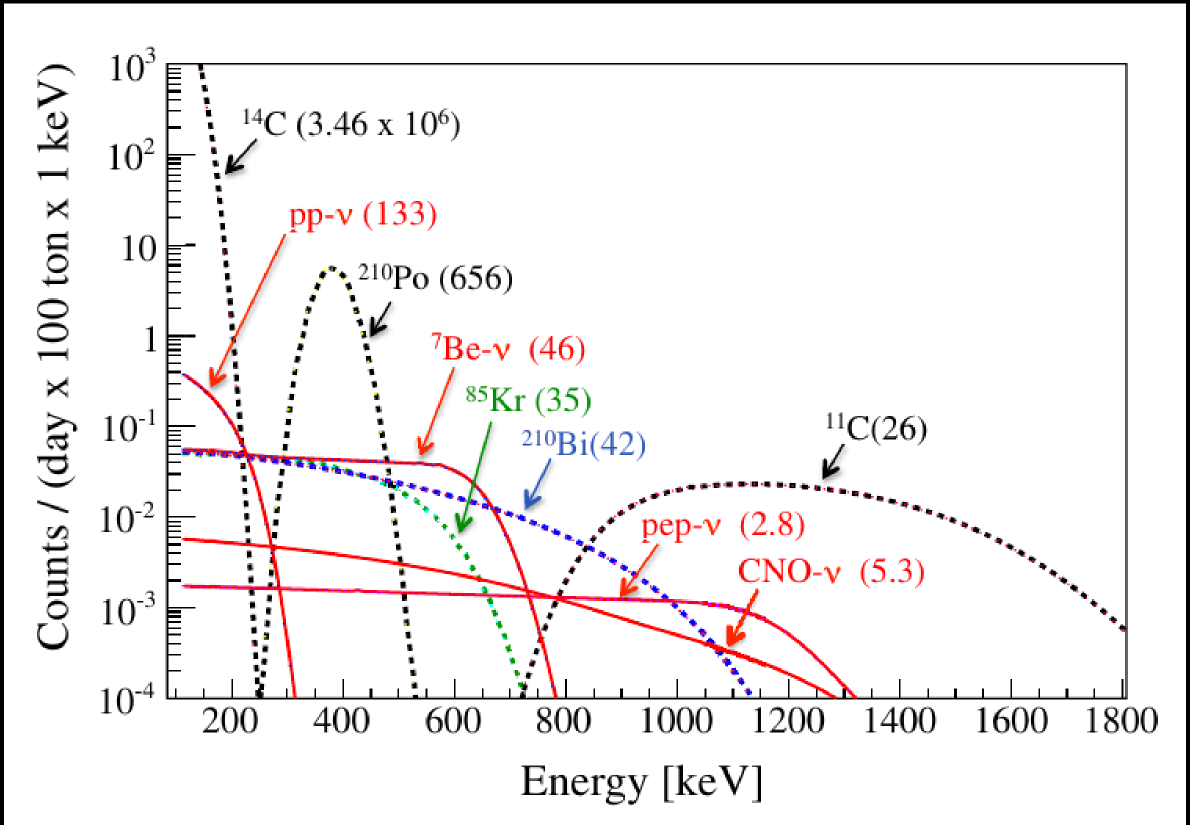
  → Foundation for sophisticated event classifications

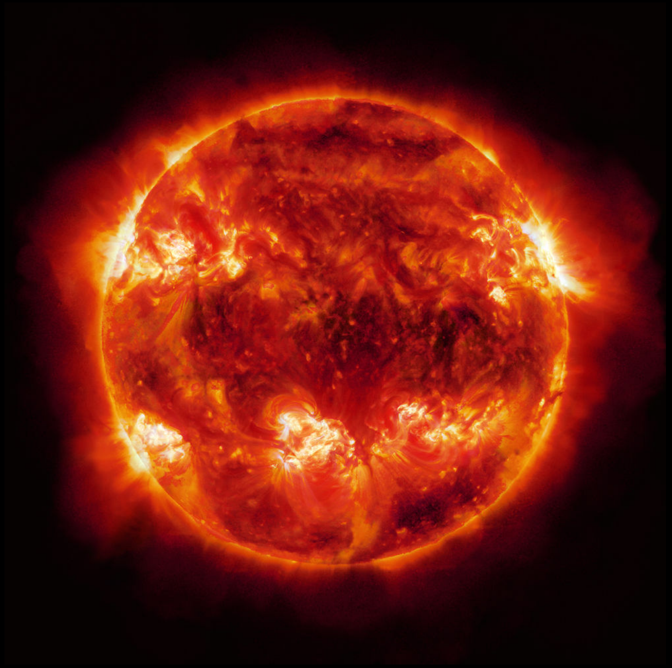
    - Combination of machine learning techniques / object recognition algorithms is the next logical step
- Reconstruction methods has also potential for low energy events
  - See talk by M. Stender on Tuesday: Applications of the Topological Track Reconstruction to low energy events


Thanks for your attention !


Additional Slides...

Solar Neutrino Background





Solar Neutrino Background

Figure: External view of the Borexino detector

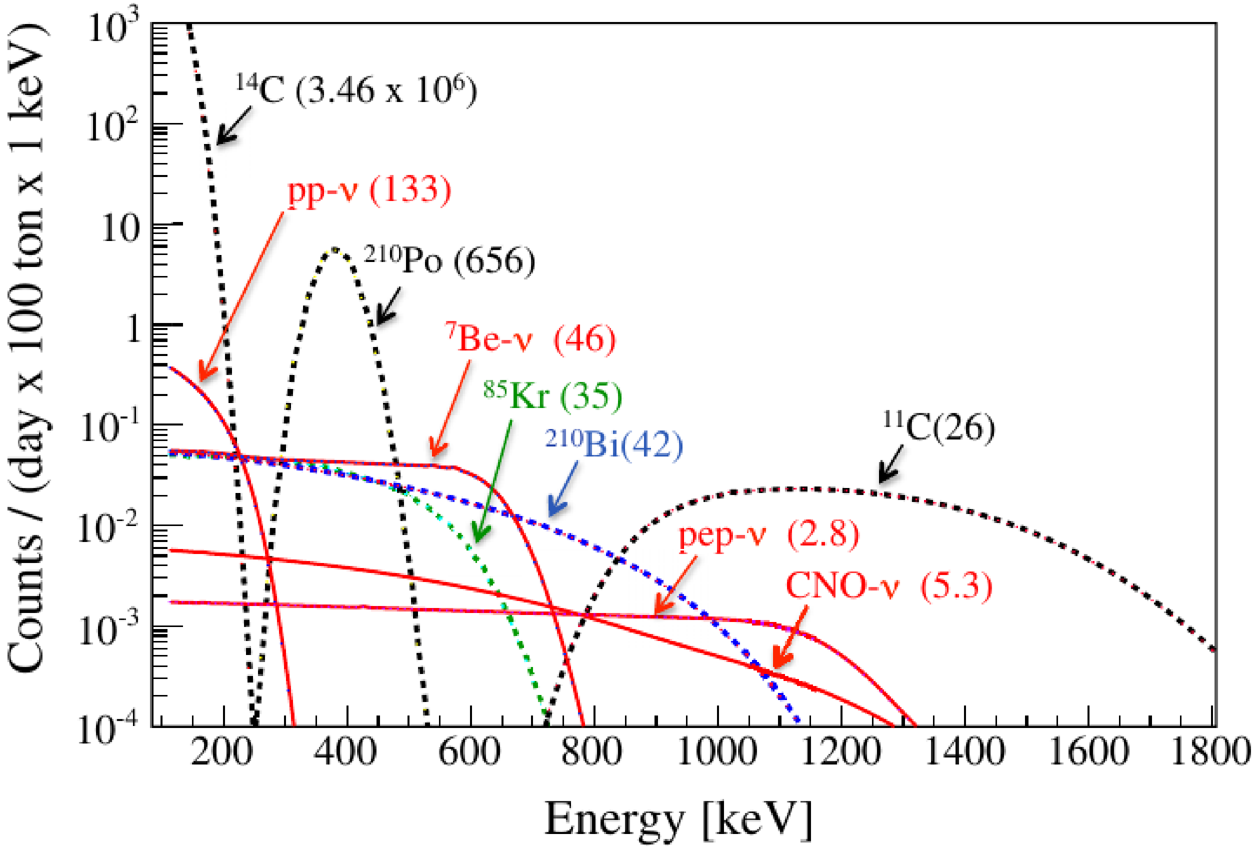
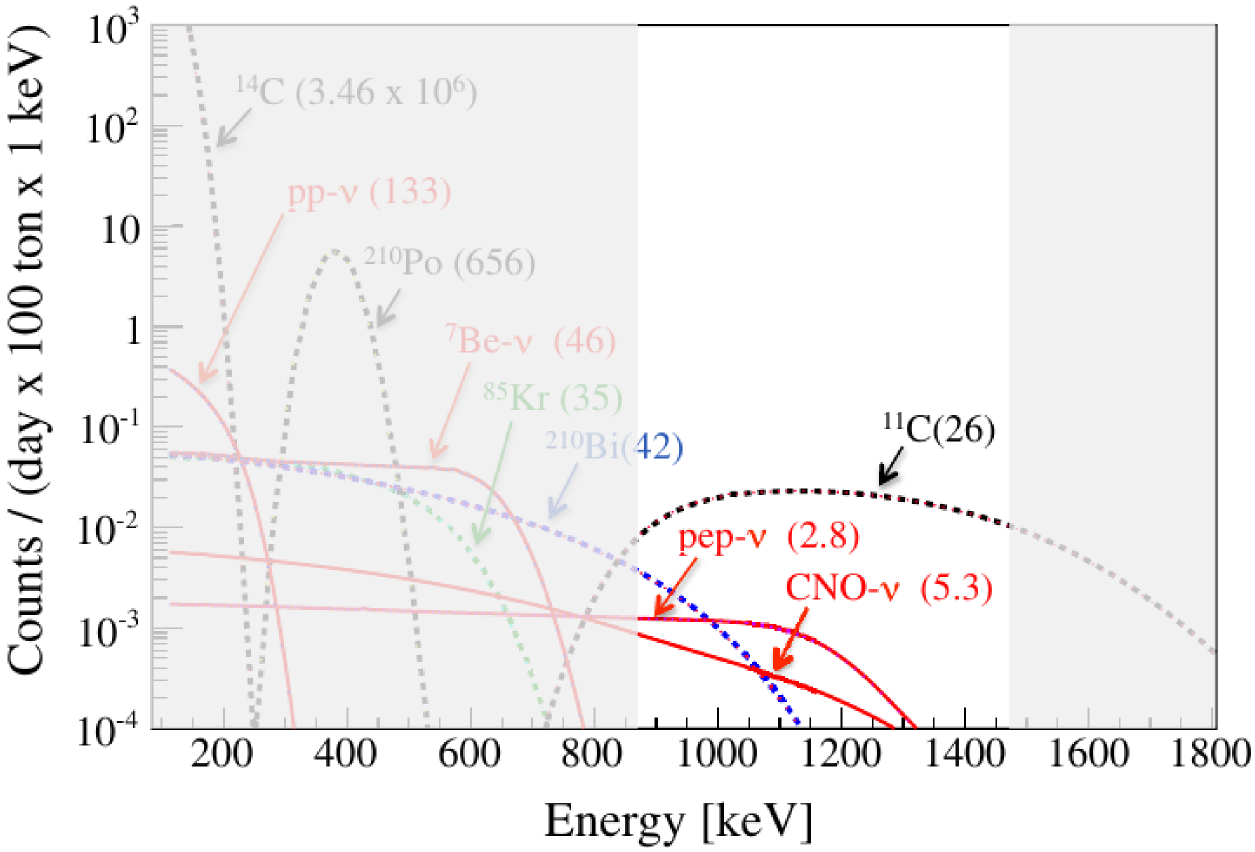


Figure: Calculated recoil spectrum (neutrino-electron scattering)

Solar Neutrino Background

Figure: External view of the Borexino detector



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Solar Neutrino Background

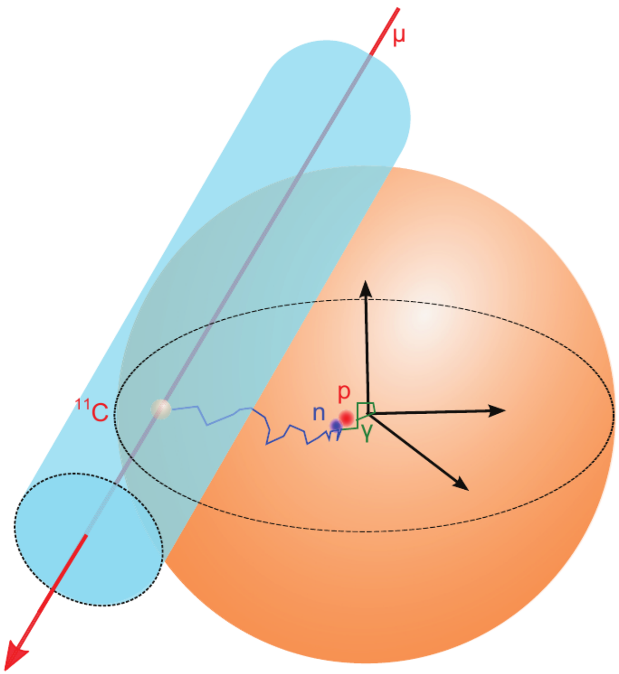

Figure: Basic principle of the 'threefold coincidence method' (TFC) to tag C-11

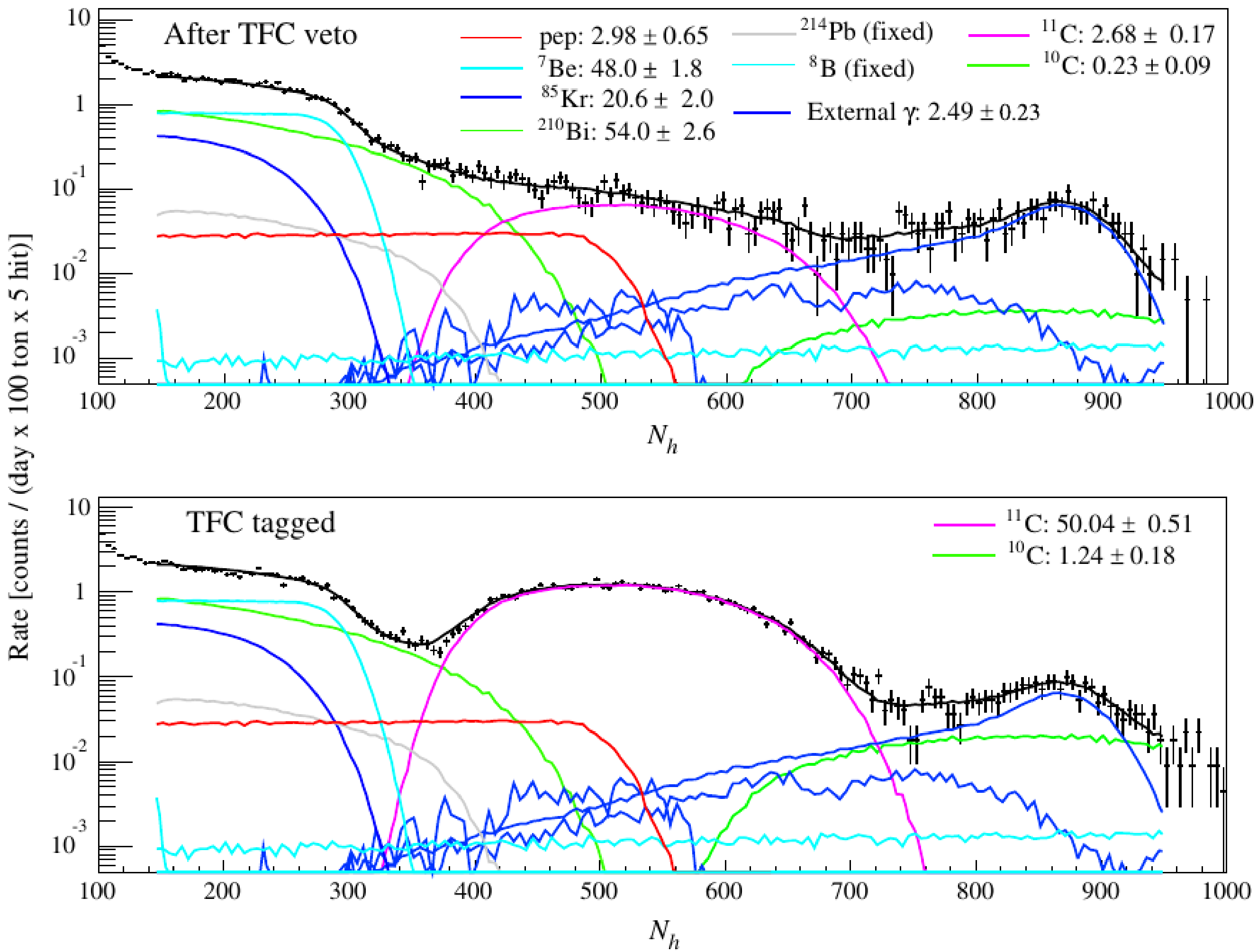

Figure: Application of the TFC method to Borexino data

Image Processing: Edge Detection

Canny Edge Detection (Complex Object)