# Pulse Shape Discrimination for fast Neutrons and atmospheric NC Interactions in JUNO

DSNB Topical Workshop @ MITP, 2024-09-20

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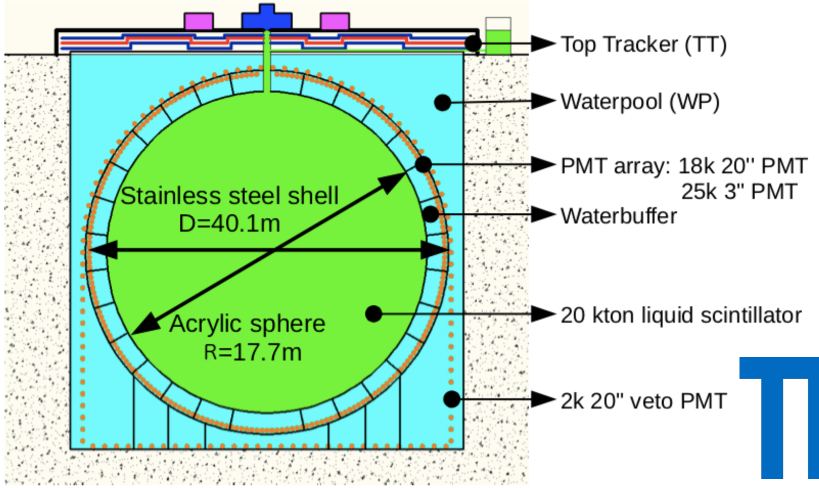
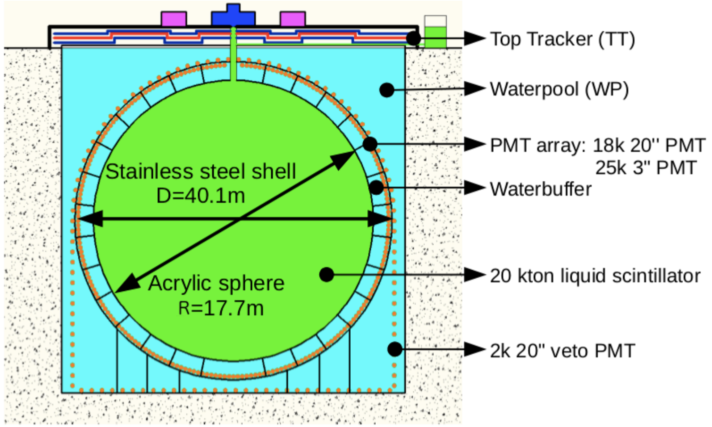
# Jiangmen Underground Neutrino Observatory (JUNO)

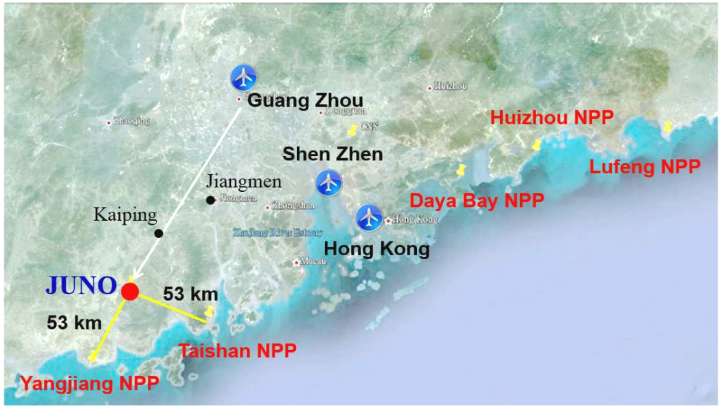
- Liquid scintillation detector using 20 kton of linear alkyl benzene (LAB)
- 17,612 20’’ PMTs and 25,600 3’’ PMTs observing the liquid scintillator volume
- 1600 PMTs are used for the water Cherenkov detector
- Shielded by ~1800m.w.e. of rock overburden
- Currently under construction, data taking starts Jan 2025



# Neutrino Physics with JUNO

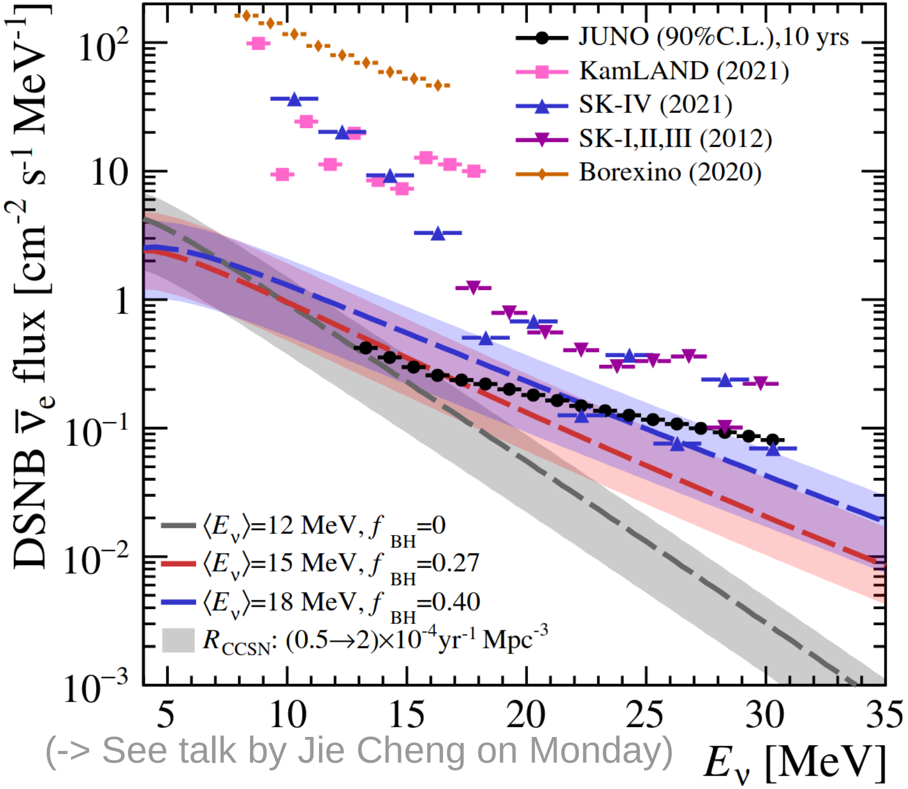
(examples)




- Reactor neutrinos
  -> Neutrino mass ordering
  -> Oscillation parameters
- Solar neutrinos
- Atmospheric neutrinos
- Geoneutrinos
- Supernova burst neutrinos
- **Diffuse Supernova Neutrino Background**

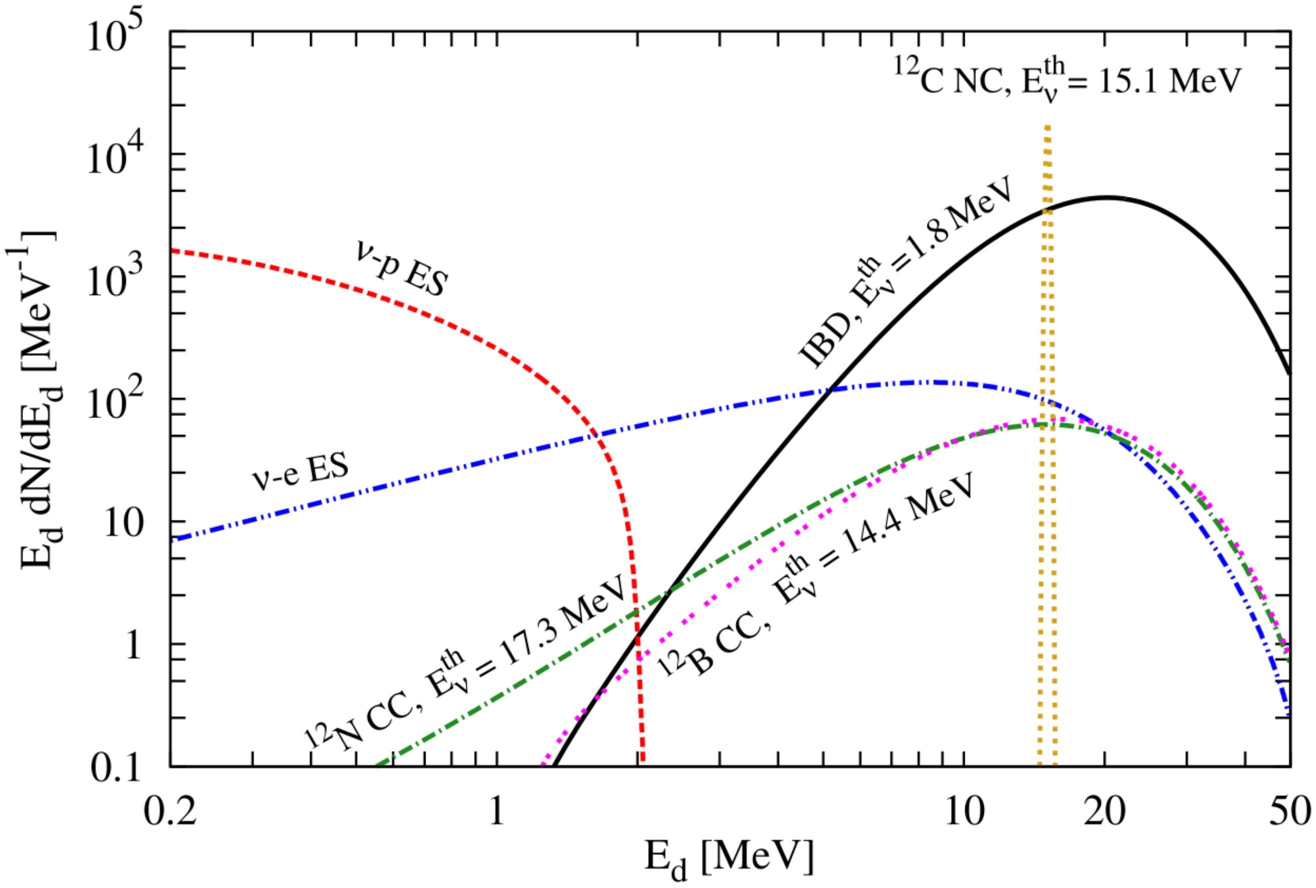
# DSNB Detection/Exclusion: Current Status




(-> See talk by Jie Cheng on Monday)

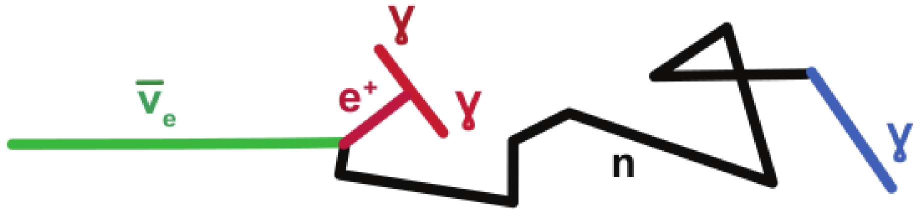
-> The detection of DSNB or the exclusion of various supernova models is possible within the lifetime of JUNO and HyperK!

# For scintillation experiments, the inverse beta decay is the most suitable detection channel in the DSNB energy ROI:



# For scintillation experiments, the inverse beta decay is the most suitable detection channel in the DSNB energy ROI:

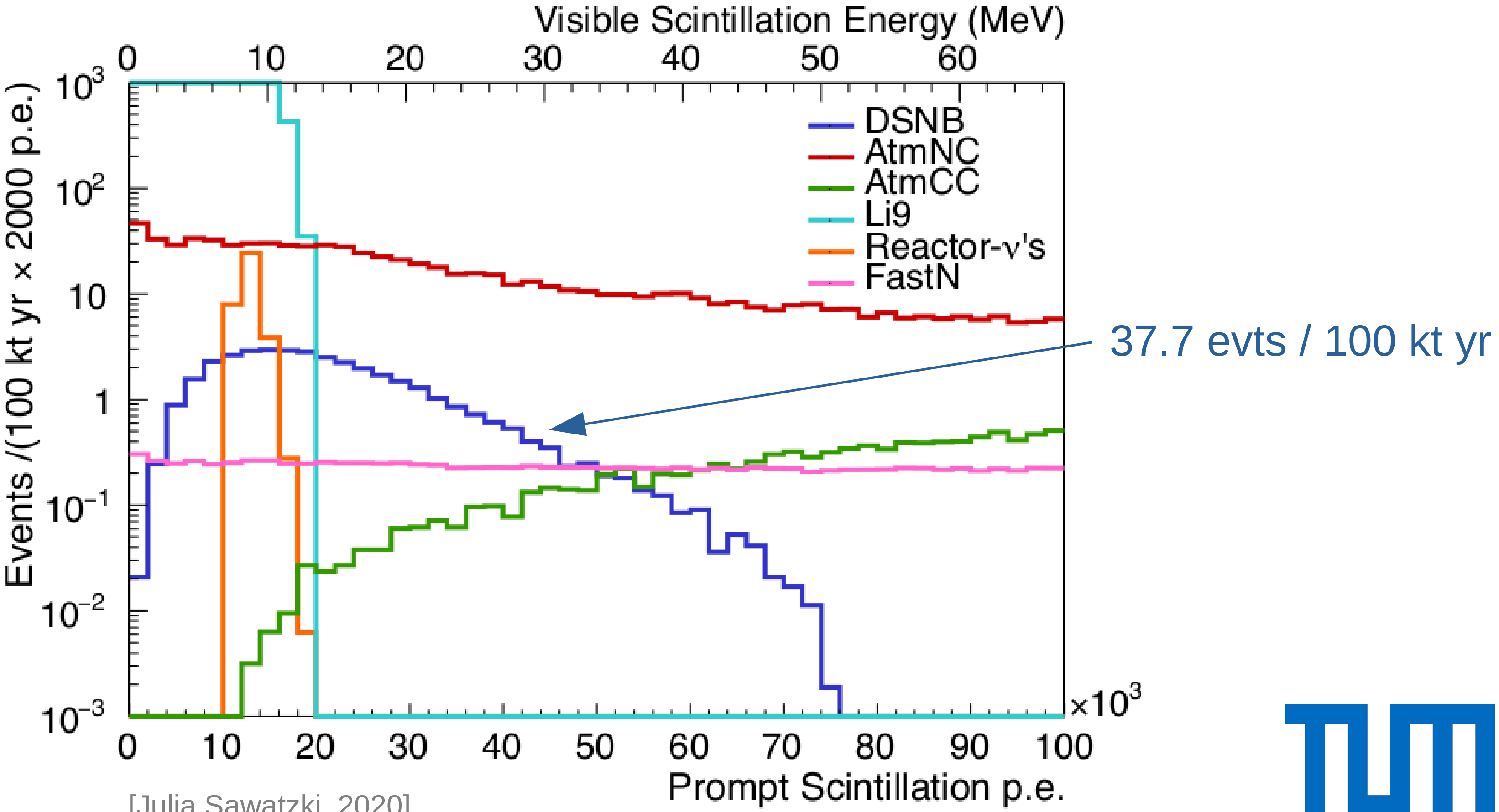
$$p^{+} + \bar{\nu}_e \rightarrow e^{+} + n^{0}$$




- Positron: Carries most of the kinetic energy,
  Capture within a few ns
  $E_{vis} \approx E_{\nu}$ - 0.8 MeV

- Neutron: low kinetic energy,
  Capture with a lifetime of ~220 μs
  - Capture on H: 2.2 MeV
  - Capture on C12: 4.9 MeV

# Irreducible background is caused by $\bar{\nu}_e$ from other sources reaching into the same energy range




[Julia Sawatzki, 2020]

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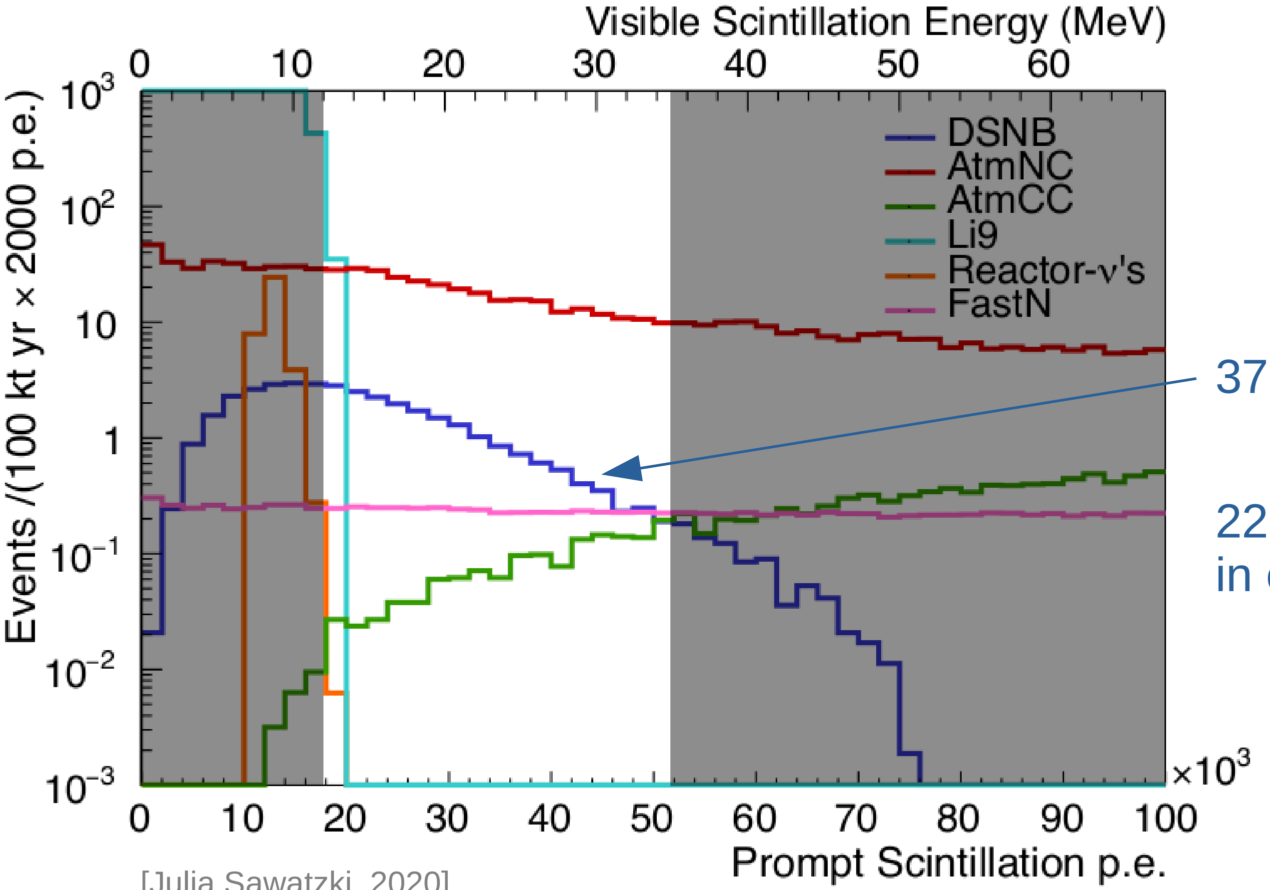


37.7 evts / 100 kt yr

22.6 evts / 100 kt yr in energy ROI

[Julia Sawatzki, 2020]

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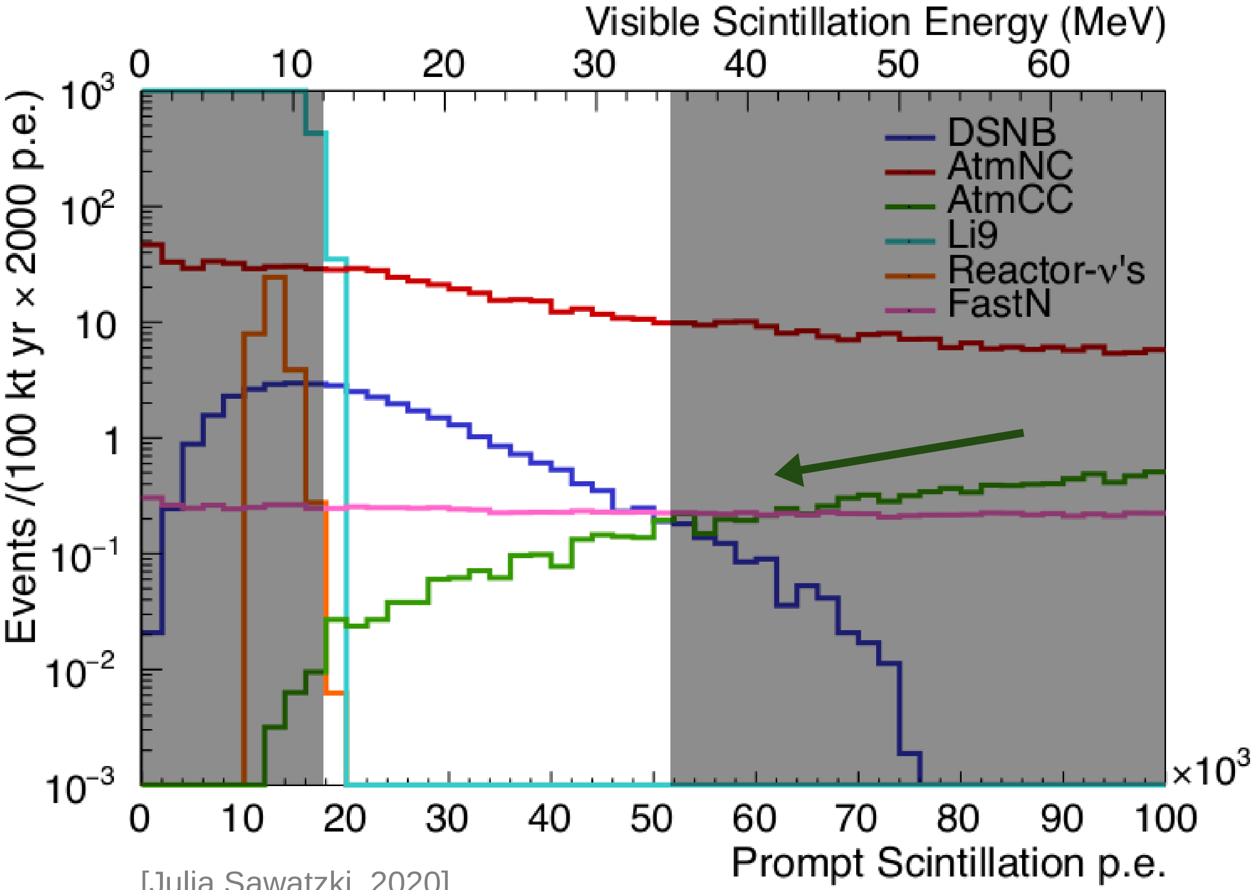
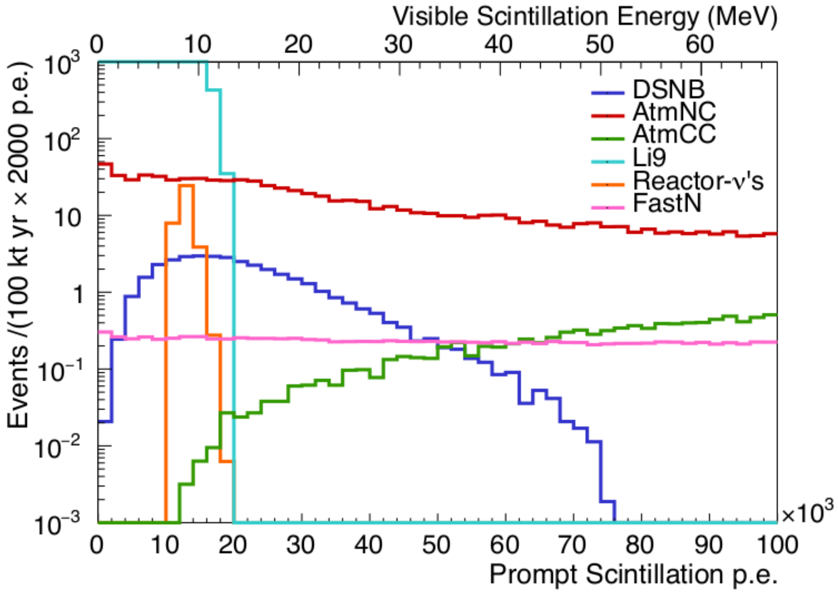



[Julia Sawatzki, 2020]

# NC interactions of all-flavour atmospheric neutrinos can create an event signature similar to an IBD event

| $\nu_x + {}^{12}\mathrm{C} \longrightarrow \nu_x +$ | | | |
|---|---|---|---|
| NC interactions in LS | [%] | after event selection | [%] |
| $\mathrm{p} + {}^{11}\mathrm{B}$ | 29.1 | $\mathrm{n} + {}^{11}\mathrm{C}$ | 33.1 |
| $\mathrm{n} + {}^{11}\mathrm{C}$ | 25.0 | $\mathrm{n} + \mathrm{p} + {}^{10}\mathrm{B}$ | 22.8 |
| $\mathrm{n} + \mathrm{p} + {}^{10}\mathrm{B}$ | 18.2 | $\mathrm{n} + 2\,\mathrm{p} + {}^{10}\mathrm{Be}$ | 9.3 |
| $2\,\mathrm{p} + {}^{10}\mathrm{Be}$ | 4.2 | $\mathrm{n} + \mathrm{p} + {}^{2}\mathrm{H} + {}^{8}\mathrm{Be}$ | 7.1 |
| $2\,\mathrm{n} + {}^{10}\mathrm{C}$ | 4.0 | $\mathrm{n} + \mathrm{p} + {}^{4}\mathrm{He} + {}^{6}\mathrm{Li}$ | 6.5 |
| $\mathrm{n} + 2\,\mathrm{p} + {}^{9}\mathrm{Be}$ | 1.1 | $2\,\mathrm{n} + {}^{10}\mathrm{C}$ | 5.1 |
| $2\,\mathrm{n} + \mathrm{p} + {}^{9}\mathrm{B}$ | 1.1 | $2\,\mathrm{n} + 2\,\mathrm{p} + {}^{8}\mathrm{Be}$ | 2.8 |
| $2\,\mathrm{n} + 2\,\mathrm{p} + {}^{8}\mathrm{Be}$ | 1.0 | $2\,\mathrm{n} + \mathrm{p} + {}^{9}\mathrm{B}$ | 2.7 |
| $3\,\mathrm{n} + 3\,\mathrm{p} + {}^{6}\mathrm{Li}$ | 0.9 | $\mathrm{n} + 3\,\mathrm{p} + {}^{8}\mathrm{Li}$ | 2.0 |
| other channels | 15.4 | other channels | 8.6 |
| 30.8 / (kt yr) | | 7.8 / (kt yr) | |

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| $2n + 2p + {}^{8}Be$ | 1.0 | $2n + p + {}^{9}B$ | 2.7 |
| $3n + 3p + {}^{6}Li$ | 0.9 | $n + 3p + {}^{8}Li$ | 2.0 |
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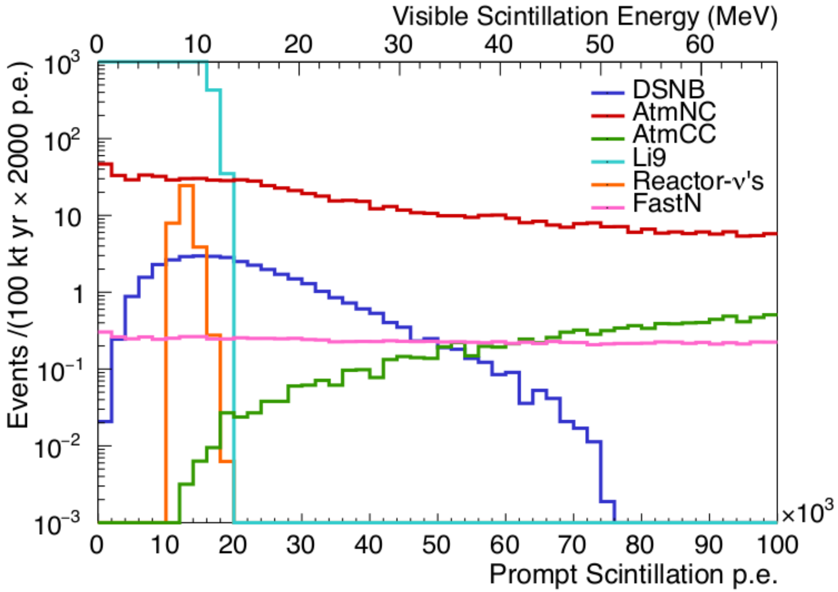
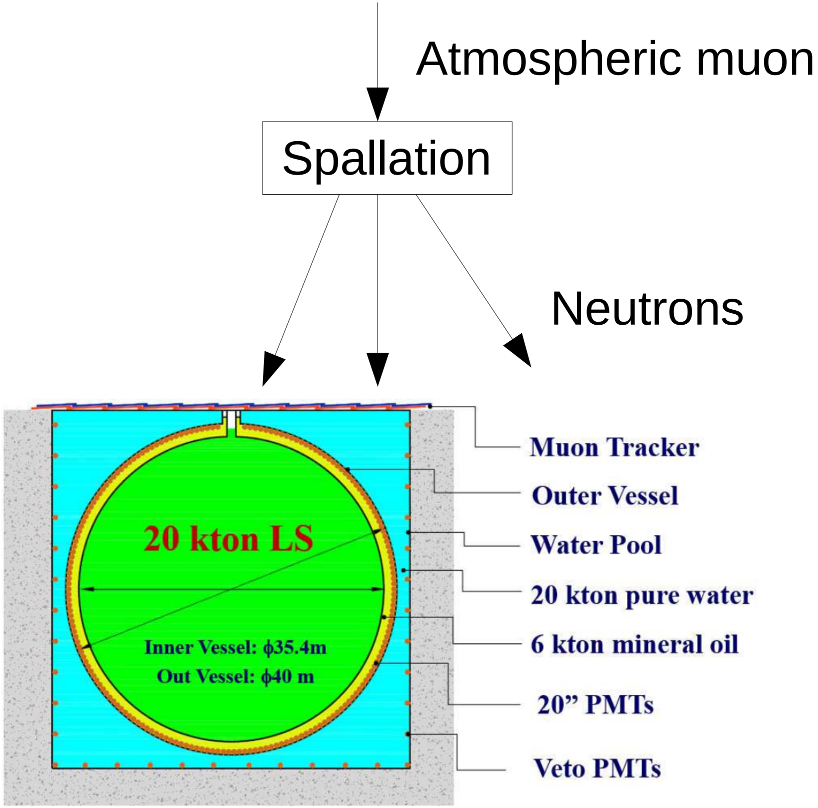
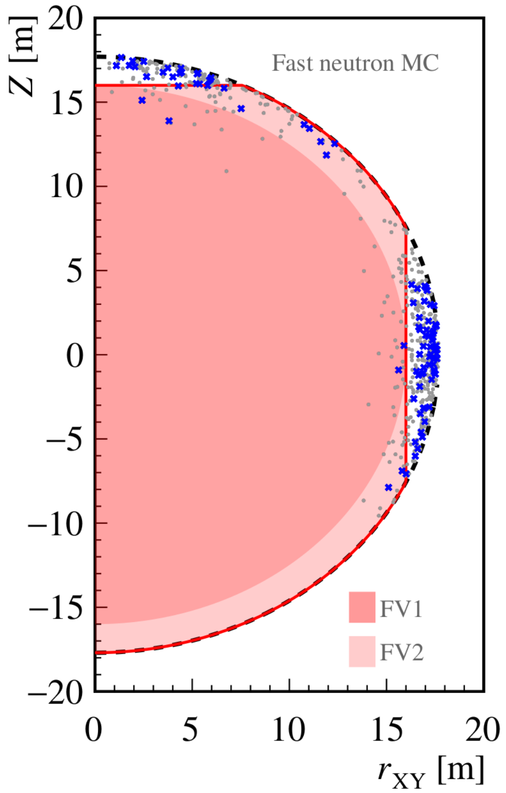



No or multiple neutrons produced

# Fast Neutron Events



# The Motivation behind PSD

Difference in fluorescence between neutrons, NC events, and IBD:

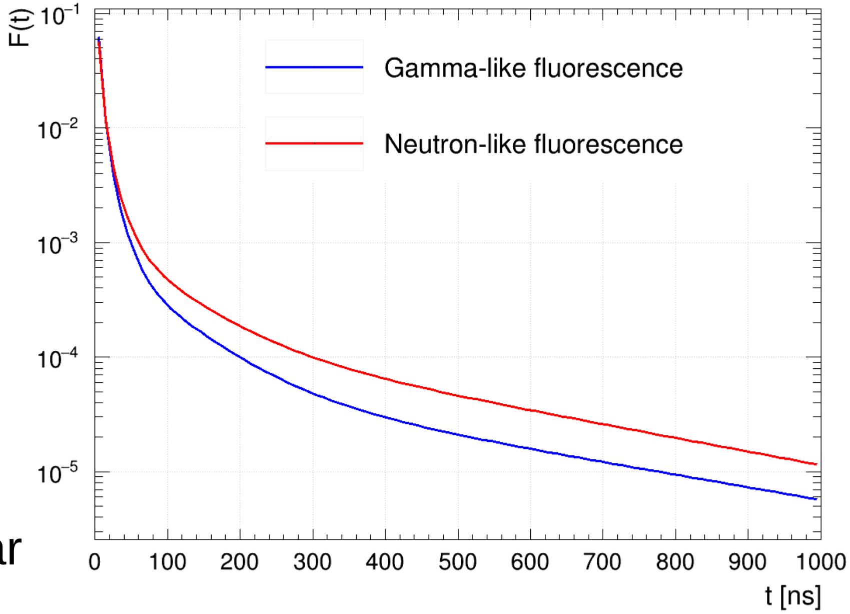
- IBD: Prompt scintillation caused by positron
- NC events and fast neutrons: no positron produced, most energy deposited by neutrons or protons

Difference in energy loss rate
=> Difference in fluorescence spectra

# We expect a difference between gamma-like and neutron-like fluorescence as already measured at MLL (Garching), Legnaro (ITA)

| | Weights (%) | | | | Decay-times (ns) | | | | (ns) |
|---|---|---|---|---|---|---|---|---|---|
| | $n_1$ | $n_2$ | $n_3$ | $n_4$ | $\tau_1$ | $\tau_2$ | $\tau_3$ | $\tau_4$ | $\sigma$ |
| | LAB + 2.5 g/l PPO + 3 mg/l bisMSB | | | | | | | | |
| Neutrons | 61.4 ±4.3 | 23.2 ±1.7 | 9.0 ±0.5 | 6.4 ±0.5 | 4.5 ±0.3 | 15.7 ±1.5 | 76.2 ±7.6 | 367 ±39 | 1.7 ±0.2 |
| Beam gammas | 70.7 ±6.0 | 20.5 ±2.5 | 6.0 ±0.4 | 2.8 ±0.4 | 4.6 ±0.4 | 15.1 ±1.9 | 76.1 ±10 | 397 ±91 | 1.9 ±0.1 |

[Raphael Stock, Hans Steiger, Neutrino 2020]




Neutron kinetic energies in measurements so far range from 1 to 11 MeV. -> Higher energies available in beamtimes in 2024/2025.

We expect a difference between gamma-like and neutron-like fluorescence as already measured at MLL (Garching), Legnaro (ITA)

Applies to IBD positrons

Applies to protons / recoil protons

| | Weights (%) | | | | Decay-times (ns) | | | | (ns) |
|---|---|---|---|---|---|---|---|---|---|
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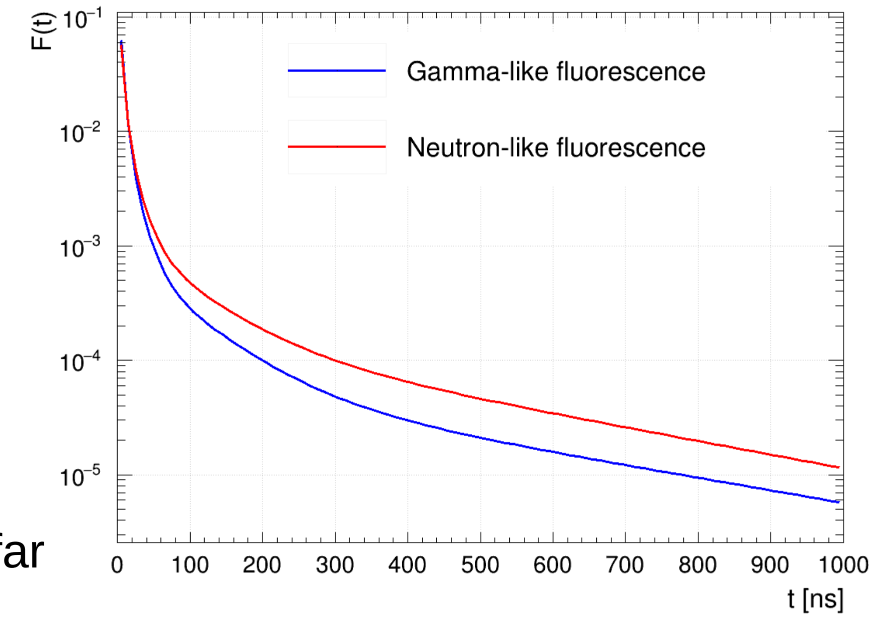
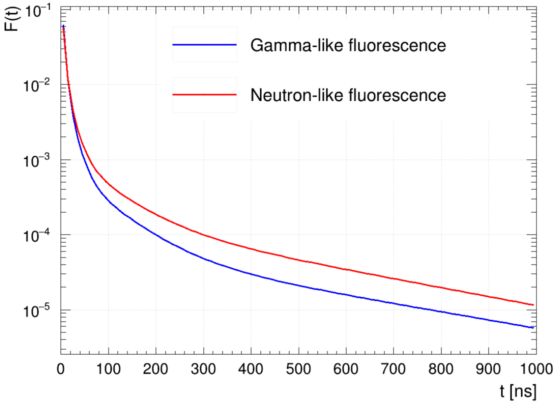
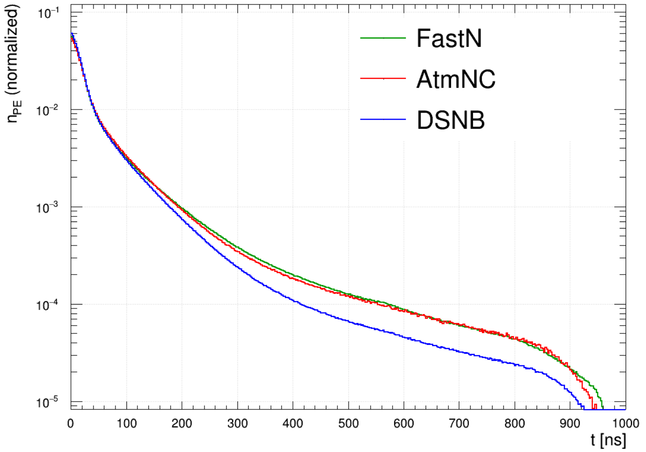



Neutron kinetic energies in measurements so far range from 1 to 11 MeV. -> Higher energies available in beamtimes in 2024/2025.

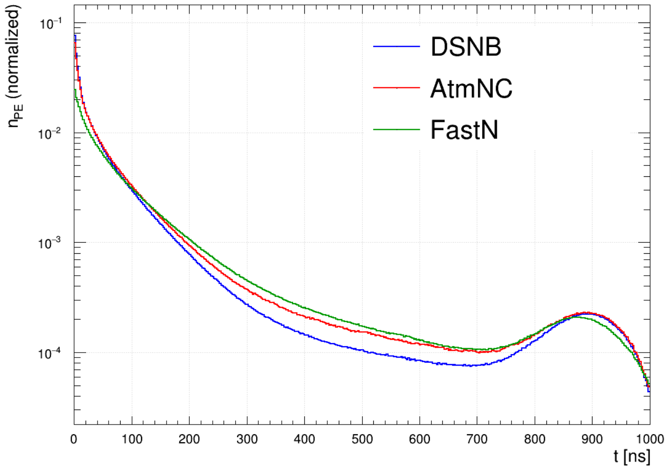
# The expected pulseshape difference survives the full detector simulation -> We will use it for PSD



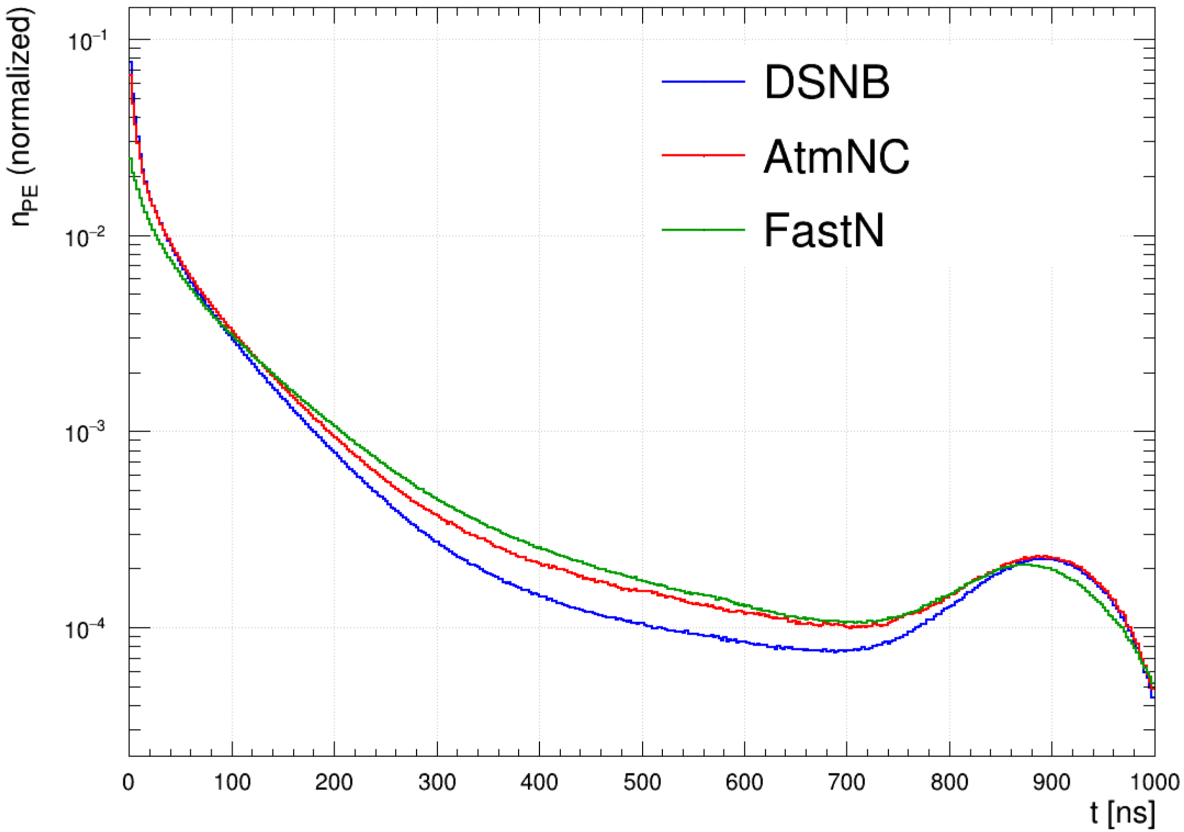

Detector Geometry




PMT Electronics



# Resulting pulseshapes from the full detector simulation



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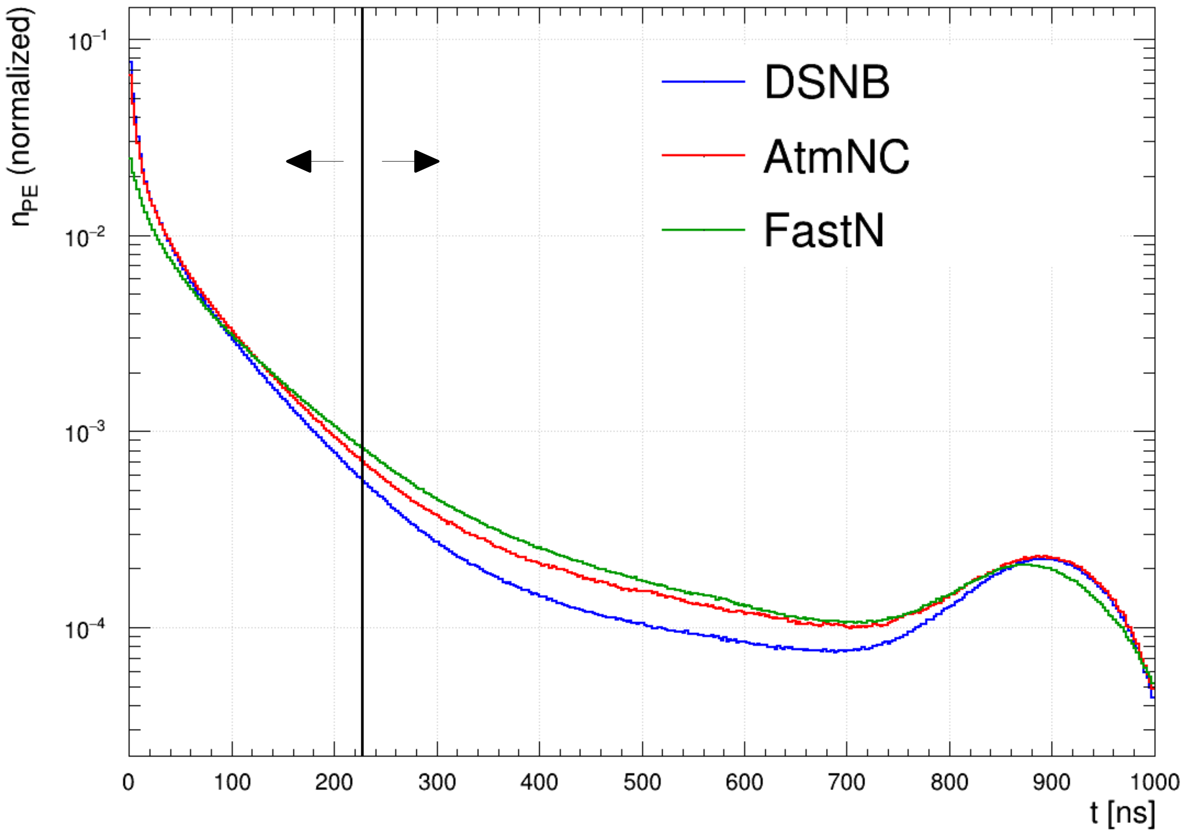



Traditonal cut variable for PSD: Fraction of PE after a certain time $t_{TTR}$

-> 'Tail-to-Total ratio' (TTR)

# First (old) PSD Method: Tail-to-Total Ratio

Cut variable for PSD: Fraction of PE after certain time $t_{TTR}$

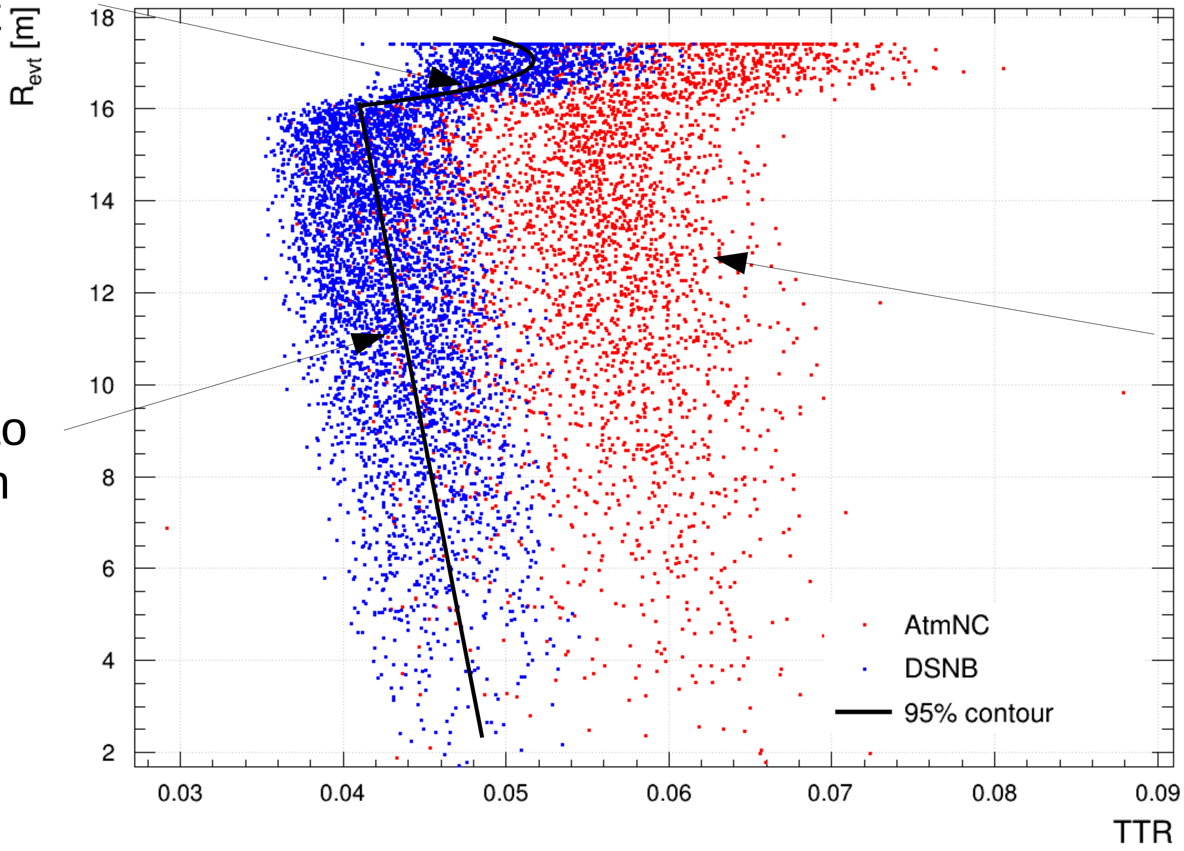
-> 'Tail-to-Total ratio' (TTR)

$$TTR = \frac{nPE\left(t_{TTR} < t < 1000\,ns\right)}{nPE\left(t < 1000\,ns\right)}$$

=> First variable for non-ML discrimination between IBD events (signal) and atmospheric NC events (background)

# TTR vs. $R_{evt}$

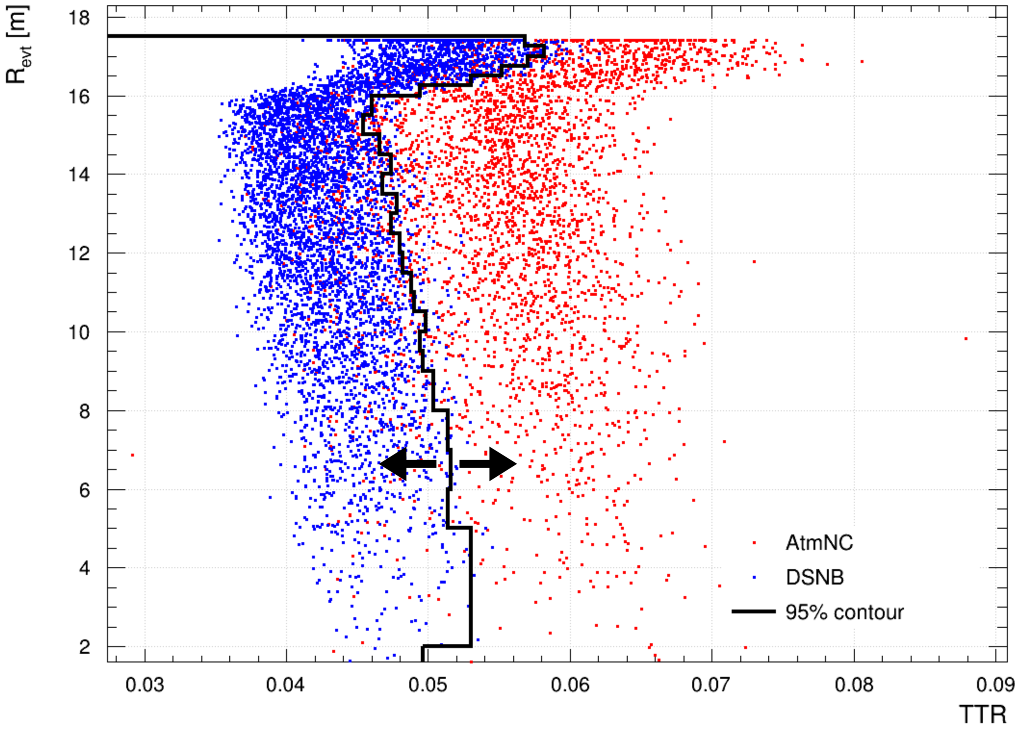
above 15.3m, light from the event position can undergo total reflection => more delayed light




linear up to $R_{evt}$ = 16m

AtmNC: analogous shape, but more diffuse

# Contour Cut in this 2D parameter space

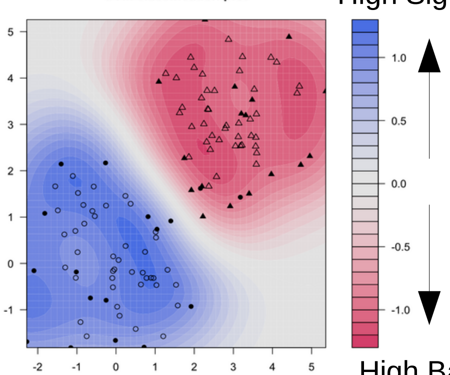



For each spherical shell, determine the TTR value, below which are 95% of signal events => contour function of variable resolution in $R_{evt}$

# Using Machine Learning Methods for DSNB PSD

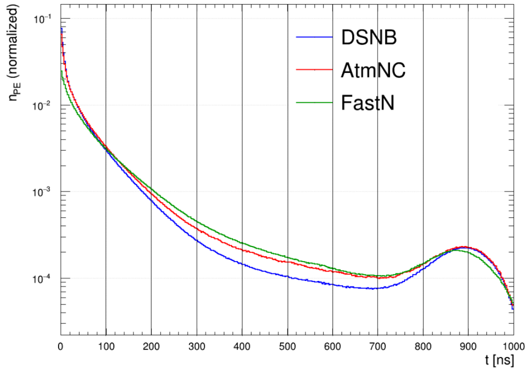
Generic Example of an SVM:

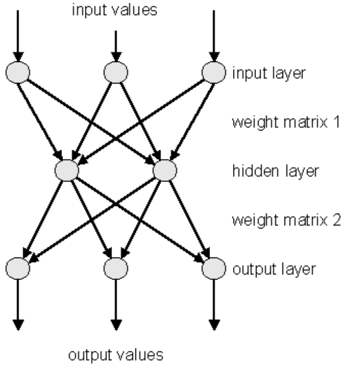
High Signal Likelihood




High Background Likelihood

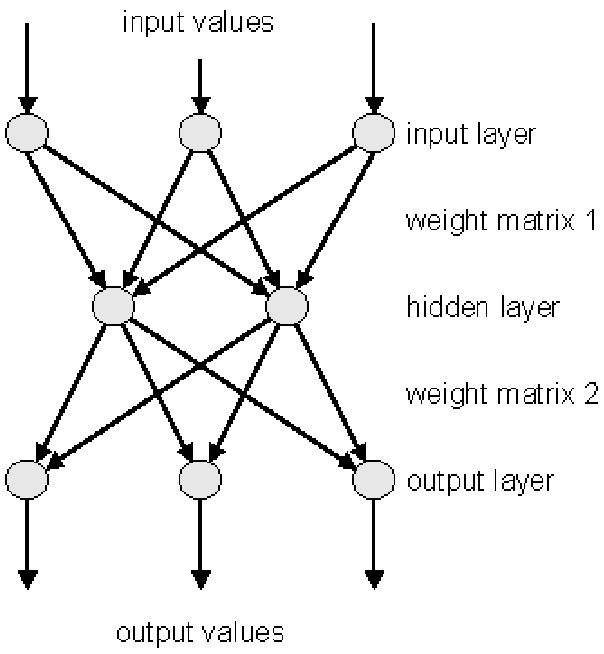
[stats.stackexchange.com]




- ML implementations used here:
  - Feed-Forward Neural Networks (NN)
  - Boosted Decision Trees (BDT)
  - Support Vector Machines (SVM)
- Input given to the classifier about each event:
  - Total and prompt event energy
  - Event vertex radius
  - Ten 100ns-timebins
- Each classifier then gives an ‘IBD likelihood’ as output.

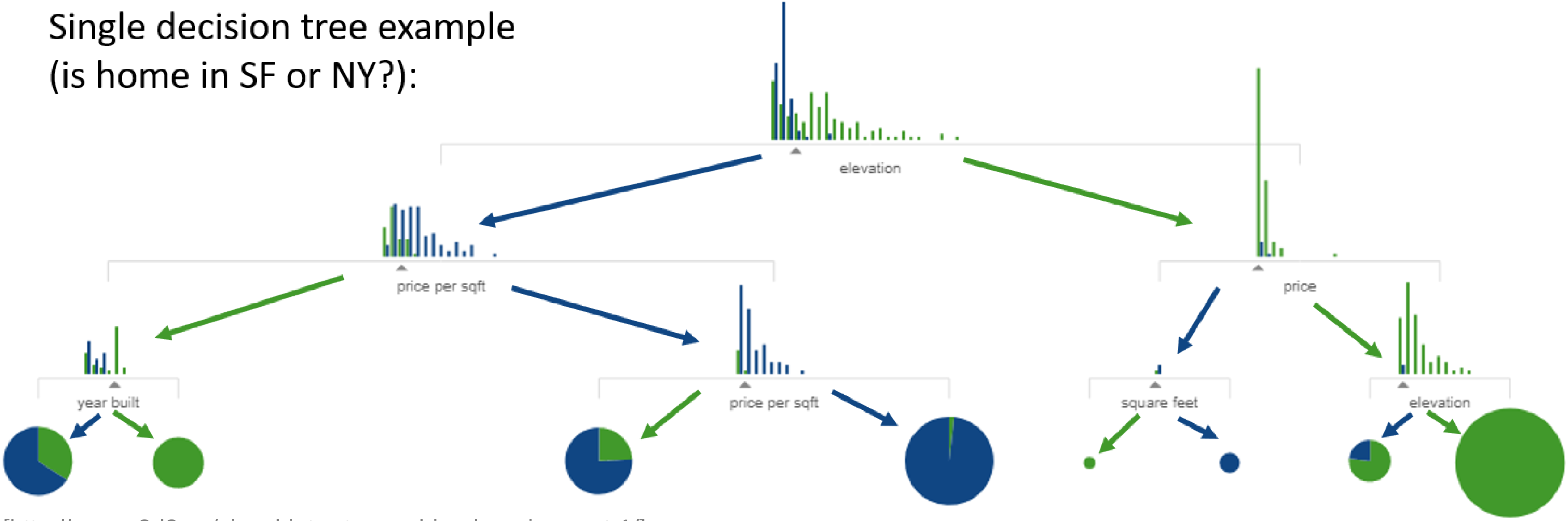
# Feed-forward Neural Networks




- Implementation used: Sequential model from Keras as provided by the TensorFlow package.
- Multiple input variables describing an event, ‘IBD likelihood’ as an output, variable number of hidden layers in between
- Neural Networks can provide great discrimination performance with the right parameters, but offer low transparency

# Boosted Decision Trees

Single decision tree example
(is home in SF or NY?):




[http://www.r2d3.us/visual-intro-to-machine-learning-part-1/]

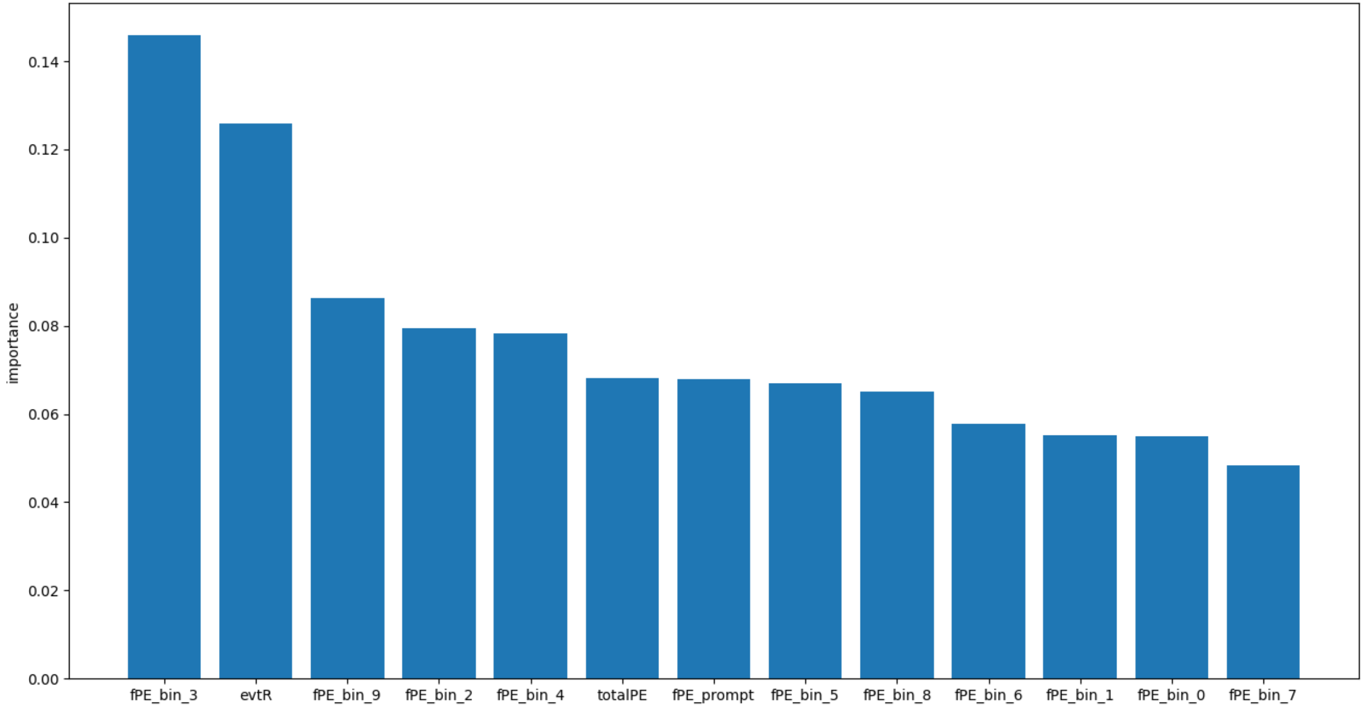
-> BDT: „Performance-weighted sum of trees“ -> Better training performance and continuous output from 0 to 1

# Boosted Decision Trees

-> BDT: „Performance-weighted sum of trees“ -> Better training performance
and continuous output from 0 to 1

- Implementation used: DecisionTreeClassifier from scikit-learn, boosted by AdaBoostClassifier
- Easy to set up, but not many options for parameter tuning
- Far more transparent than neural networks, leading to better insight into the discrimination power of individual variables
- Limited overall performance due to the nature of linear cuts

# BDT Parameter Comparison: Frequency of each Variable as a branch in a decision tree




(Only one example training run drawn)

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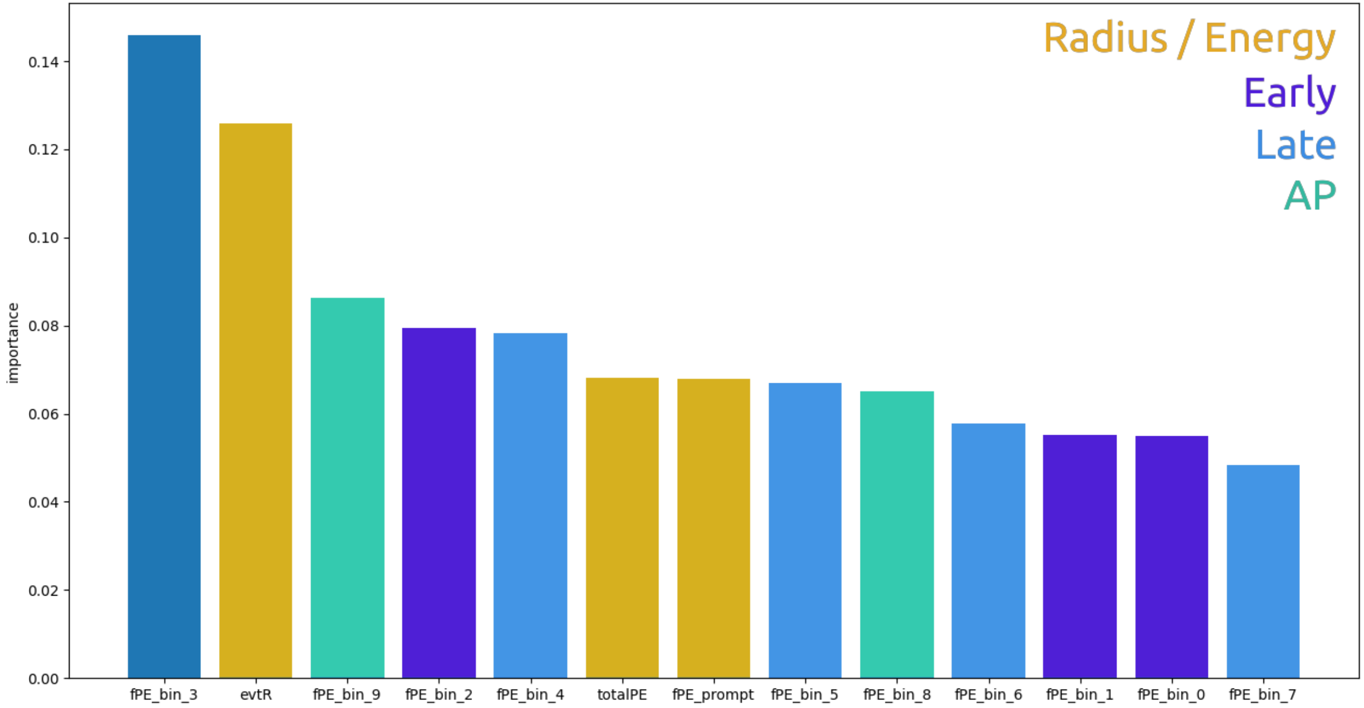


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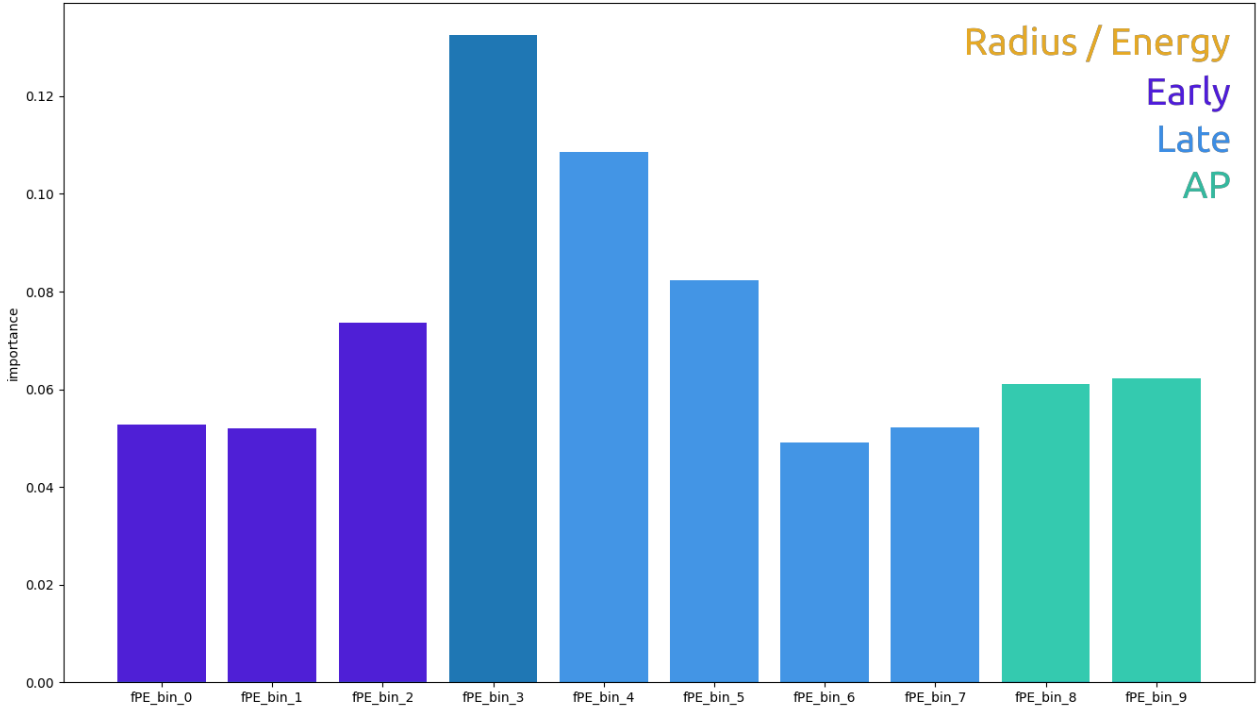
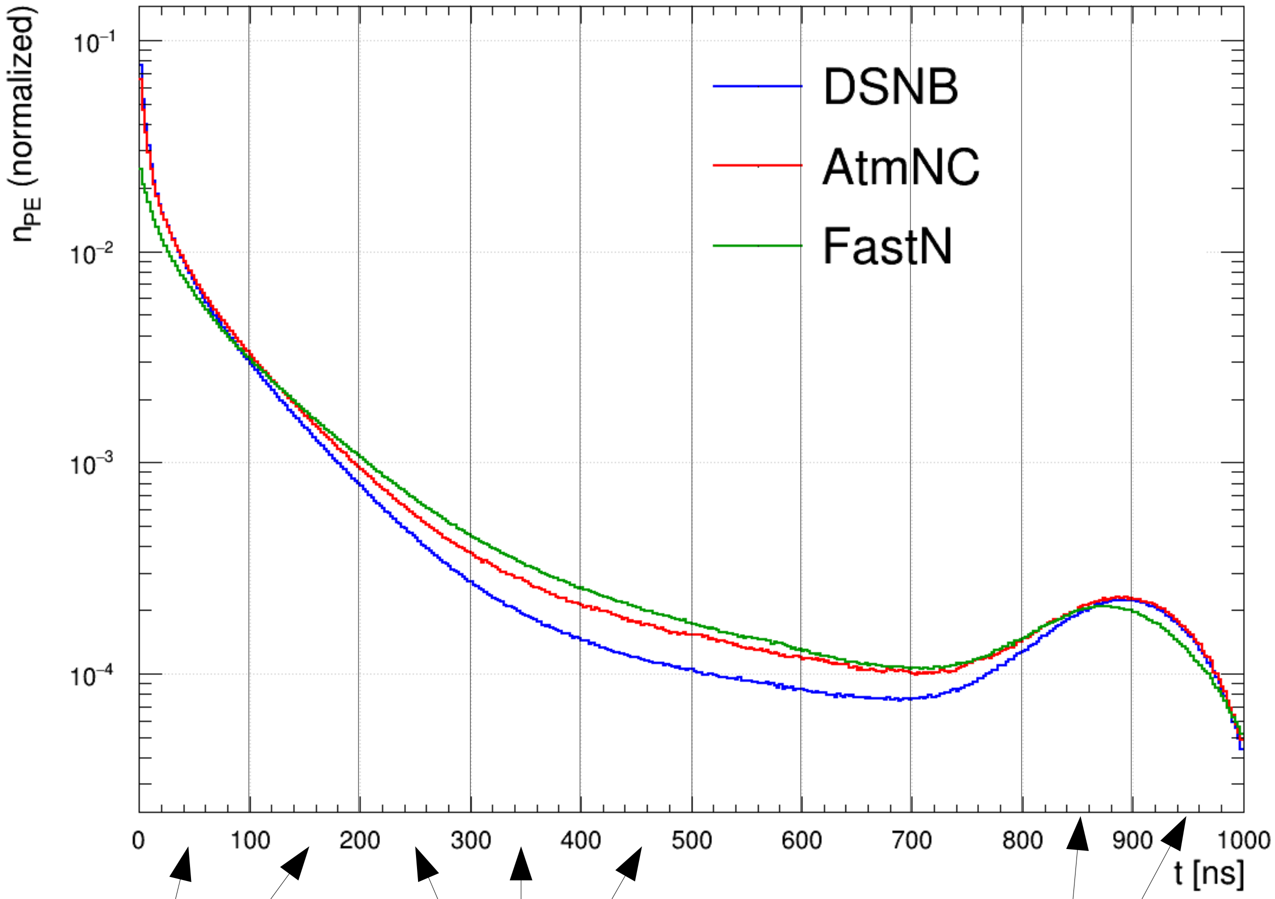



=> Importance of different time regimes of the detector event readout window!

(Only one example training run drawn)



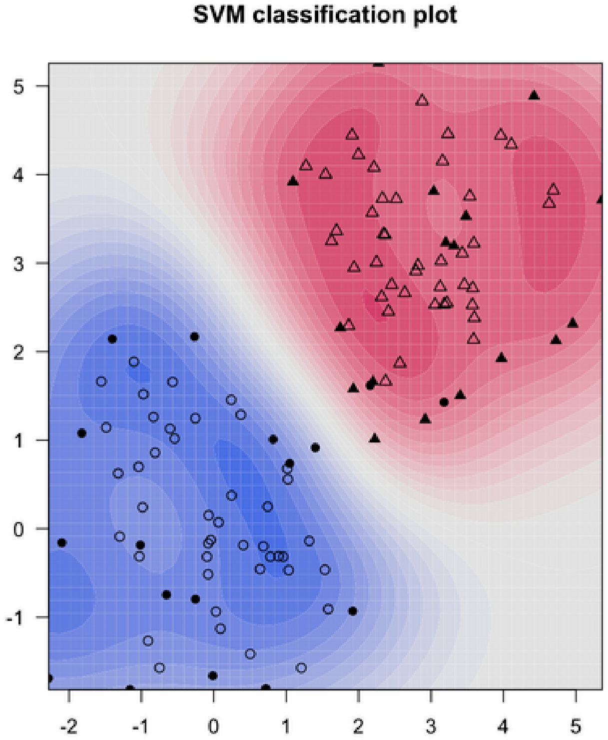

Not enough separation

sufficient separation and PE count

Afterpulsing

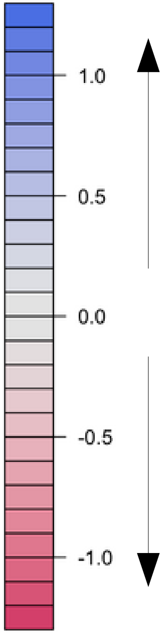
# Support Vector Machines

Generic Example:




[stats.stackexchange.com]

High Signal Likelihood

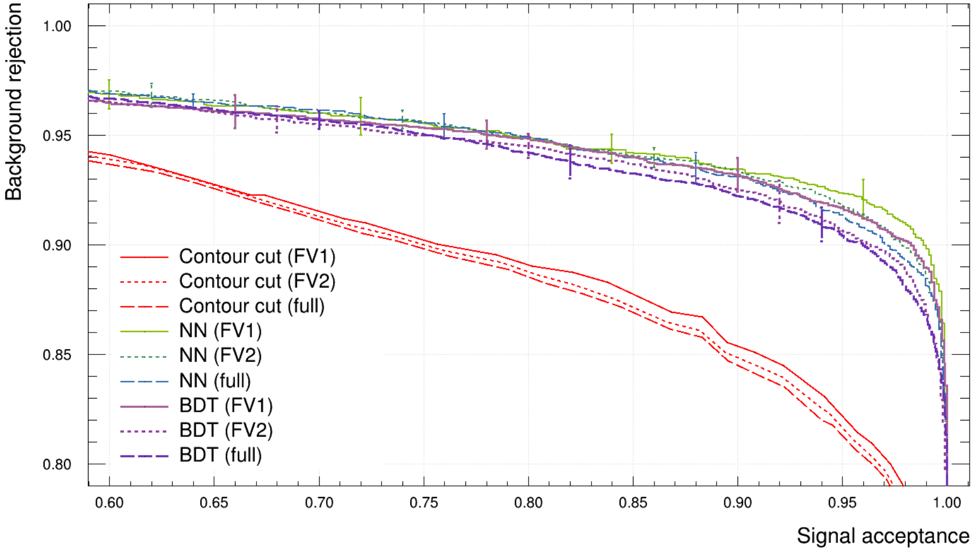



High Background Likelihood

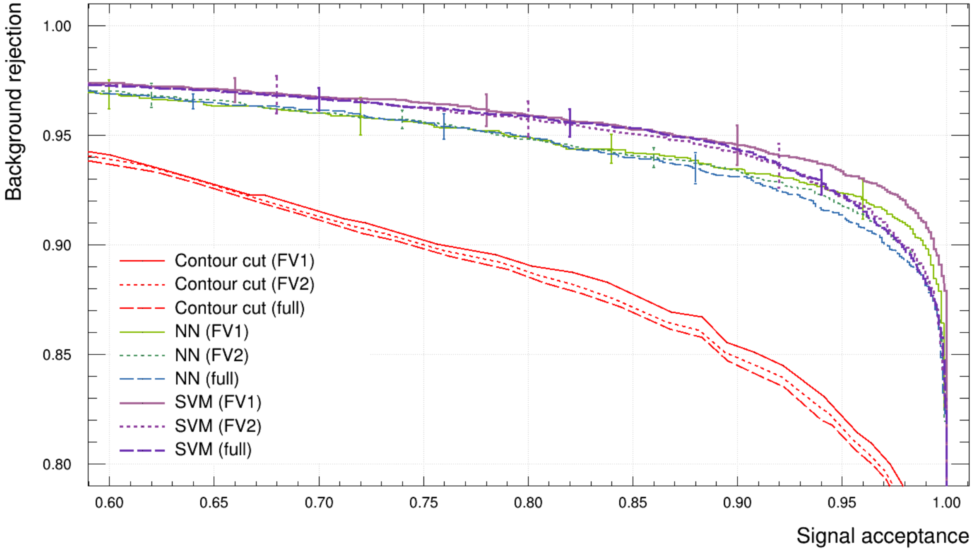
- Implementation used: SVC by scikit-learn
- SVMs try to find the ideal hypersurface cut between two event populations by transforming the input parameter space and classify input events by a resulting distance metric
- Best performance achievable with the ‘radial basis function’ kernel
- Usually better performance compared to boosted decision trees, but less transparency

# Machine learning methods can significantly outperform conventional TTR analysis

## Compared with BDT:

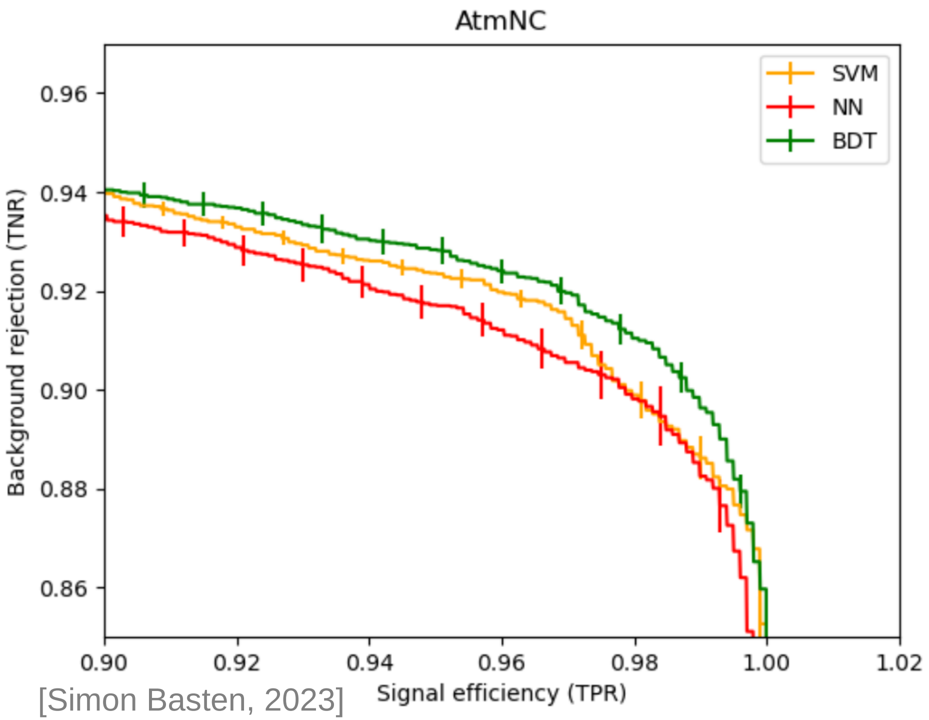



## Compared with SVM:




(Shown here: Discrimination against AtmNC background)

# => TUMKolleg student Simon Basten further improving BDT and SVM performance by careful hyper-parameter tuning

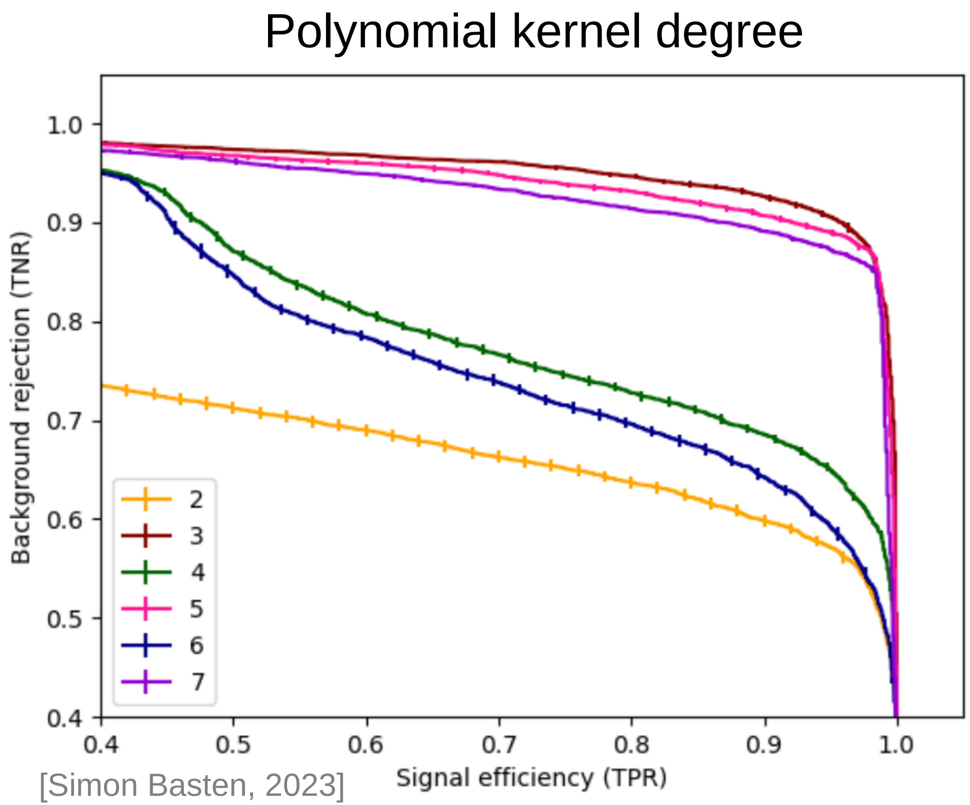



[Simon Basten, 2023]



(Shown here: Discrimination against AtmNC background)

# Interesting observations: SVM performance with a polynomial kernel function is highly dependent on its degree.

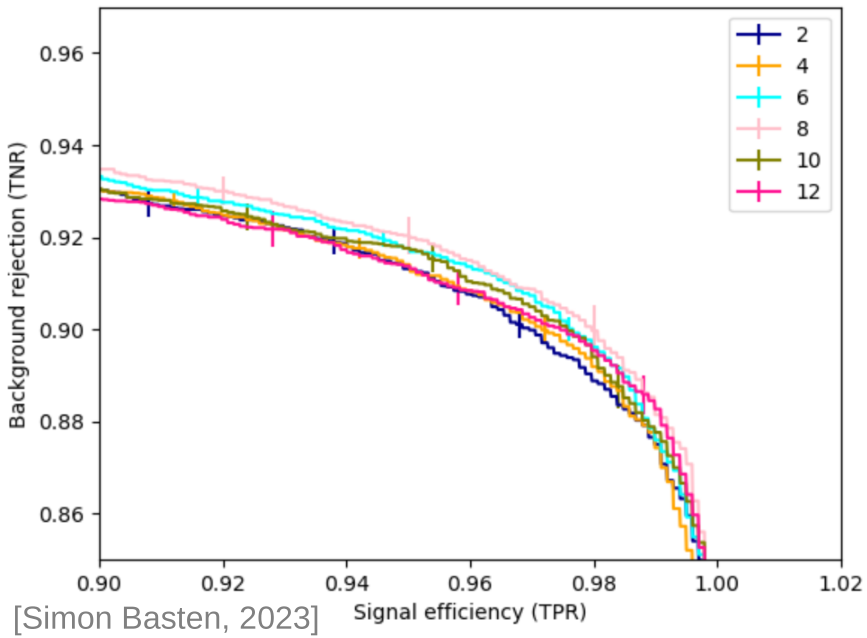



[Simon Basten, 2023]

=> Small insight into ‘shape’ of multi-dimensional event populations.

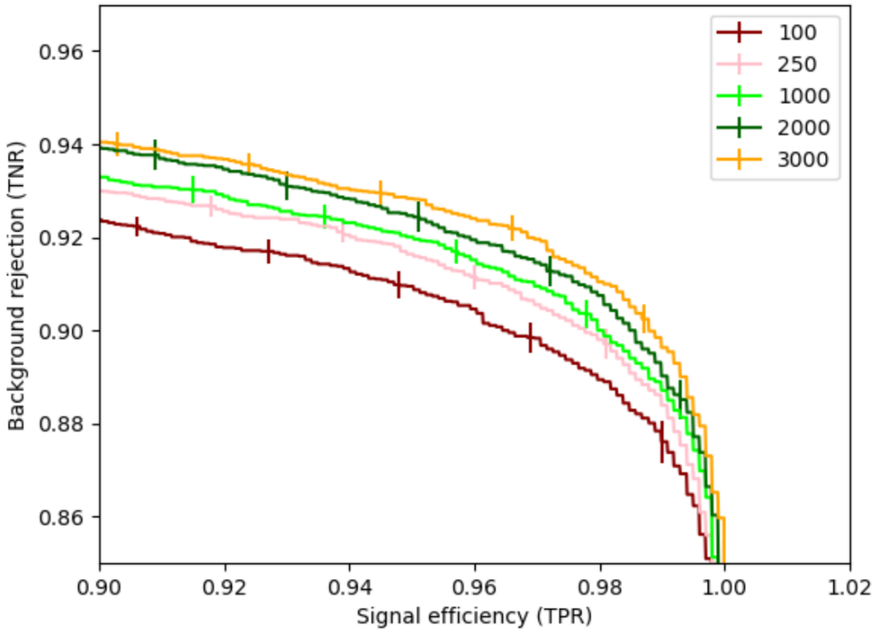
# Interesting observations: BDTs can reach greater performance as ‘weak learners’

SDT depth




[Simon Basten, 2023]

Number of SDTs per BDT




=> No notable performance gain from increased tree depth after a certain point, but greater performance increase from added SDTs.

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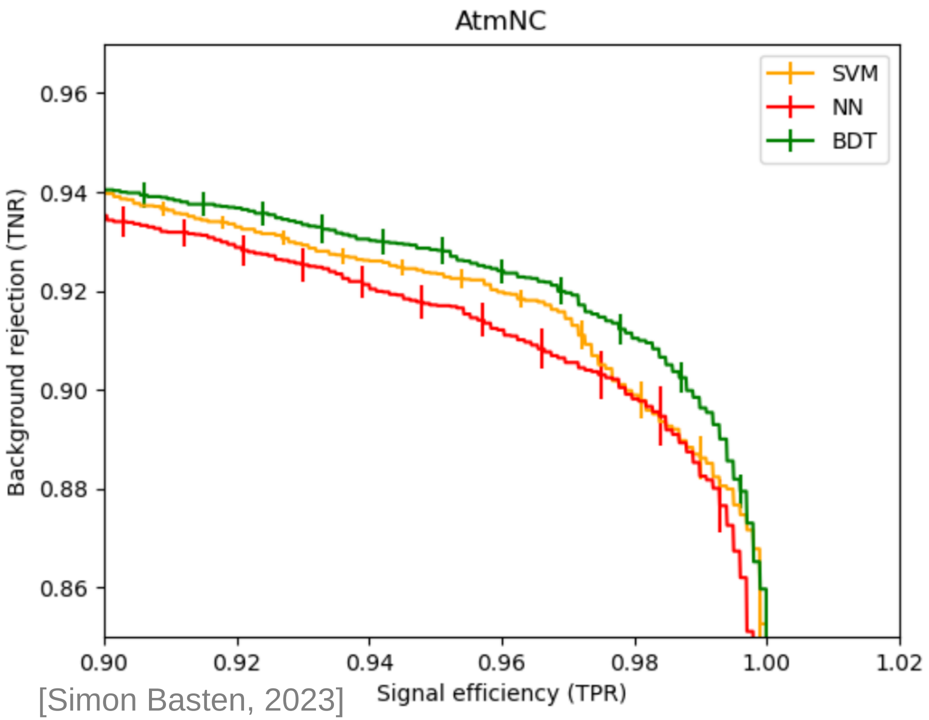



[Simon Basten, 2023]

=> BDT using ‘weak learner’ technique is now the best performing of the three studied ML tools.



(Shown here: Discrimination against AtmNC background)

# Conclusions / Outlook

- Our main background comes from atmospheric NC events, but machine learning can greatly help our pulse shape discrimination.
- Careful parameter optimization can notably improve the discrimination performance of our machine learning tools.
- Liquid scintillator particle identification PSD has not been done at such high energies in previous experiments.
- Depending on our recent/future beamtime results, we might have a more challenging PSD task at these high energies than estimated from low-MeV results.

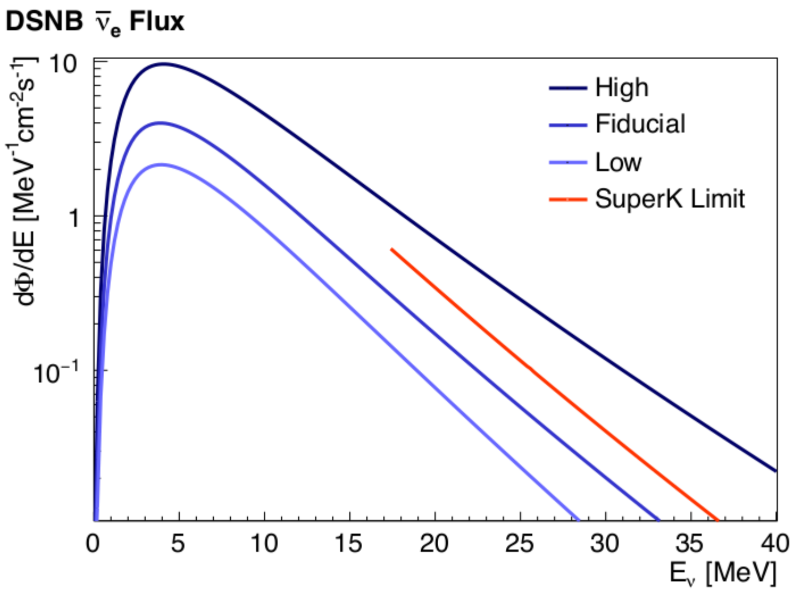
**Thank you for your attention!**

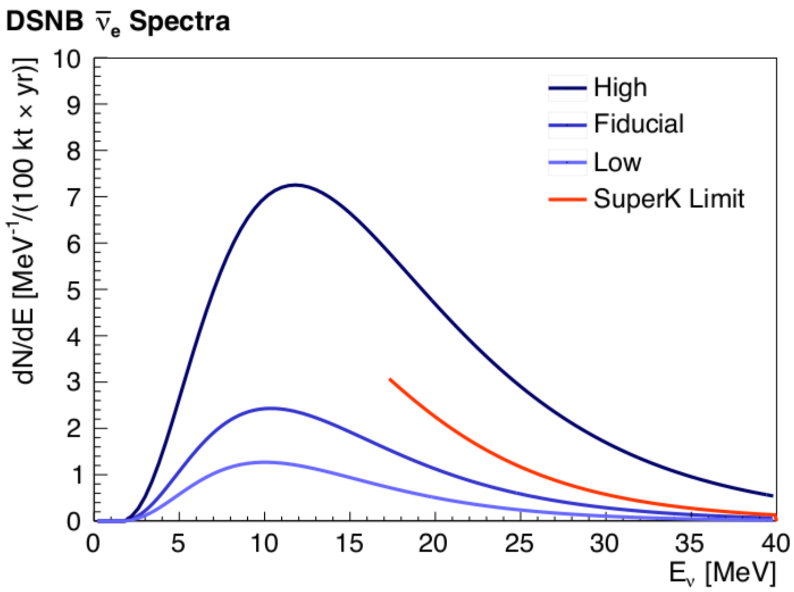
DFG Deutsche Forschungsgemeinschaft
SFB 1258 Neutrinos Dark Matter Messengers
ORIGINS Excellence Cluster
JUNO

# Backup Slides

# DSNB

# DSNB - Expected Signal



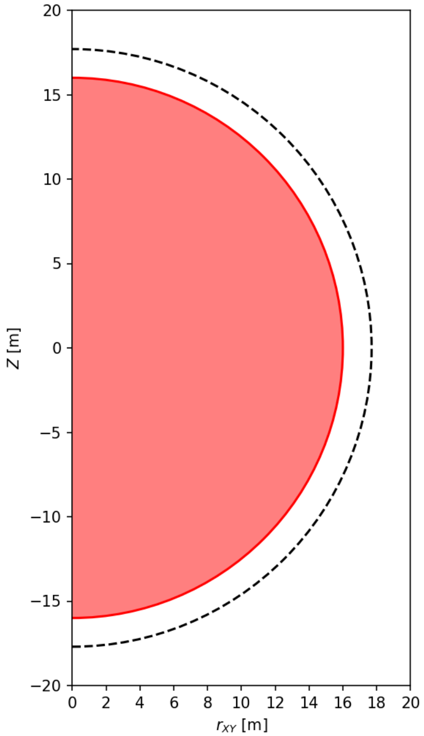

[Julia Sawatzki, 2020]

~6 orders of magnitude below solar $^{8}$B neutrino flux

# Data Preparation / Setup

# There are different fiducial volume options available for the DSNB event search in the JUNO LS

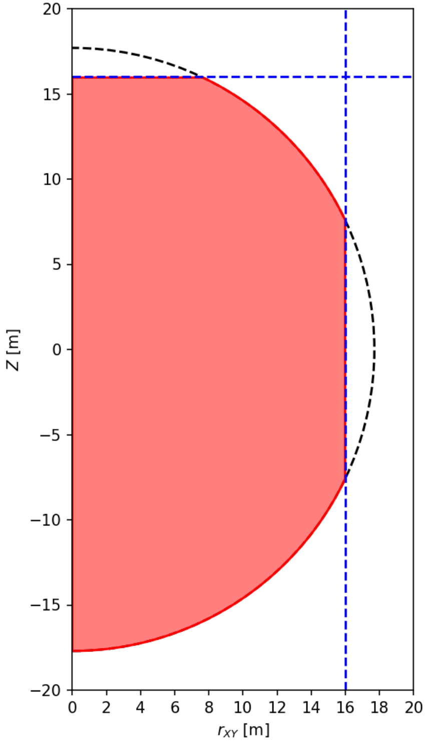
FV1:




73.9 % of the detector volume

$$R_{evt} < 16\,\mathrm{m}$$

FV2:




~ 92 % of the detector volume

$$\sqrt{x^2 + y^2} < 16\,\mathrm{m}$$

$$z < 16\,\mathrm{m}$$

# PSD and p-quenching study at the INFN-LNL

Technical University of Munich

Joint project:

- Technical University of Munich
- JGU Mainz with **PRISMA**+
- UC and LBNL Berkeley

Study:

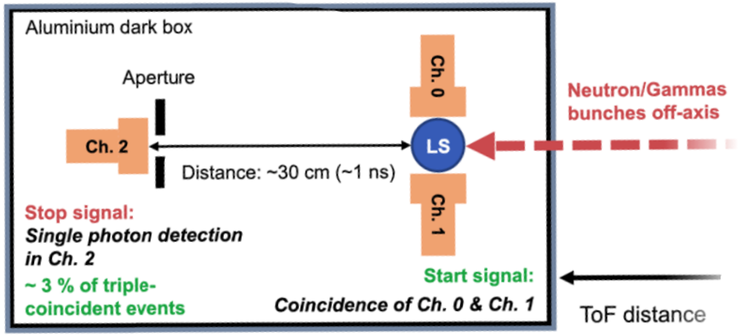
- **time profiles** for gamma and neutron excitation
- **QFs** for gamma and **neutron** interactions

Successfully measuring the scintillation time profiles and quenching factors for JUNO and JUNO-TAO LSs allows us to **improve our understanding of the energy transfer mechanisms!**

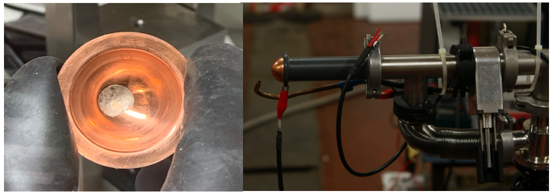
Measurements provide valuable input data for **JUNO and TAO**:

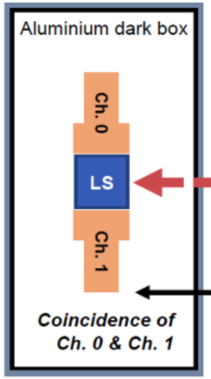
- Basis **for reliable Monte Carlo simulations**
- Development of **event reconstruction algorithms and PSD techniques**

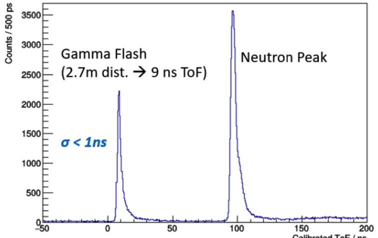
Beamtimes at the LNL in June 2021, December 2021, April/May 2022 ⇒ Data analysis ongoing!

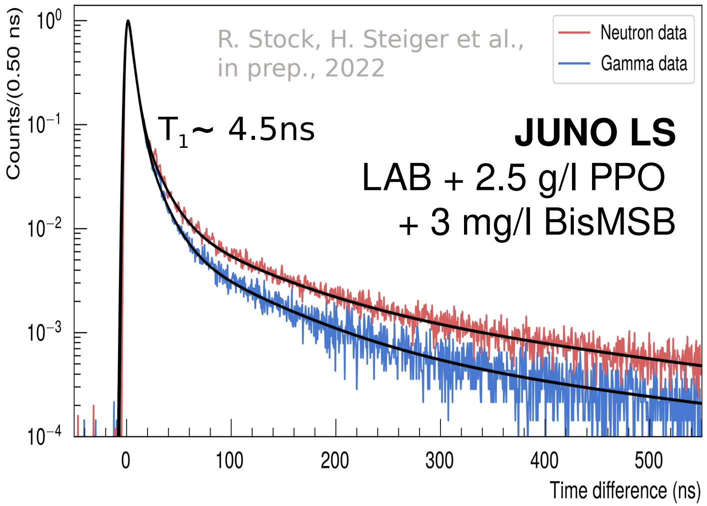


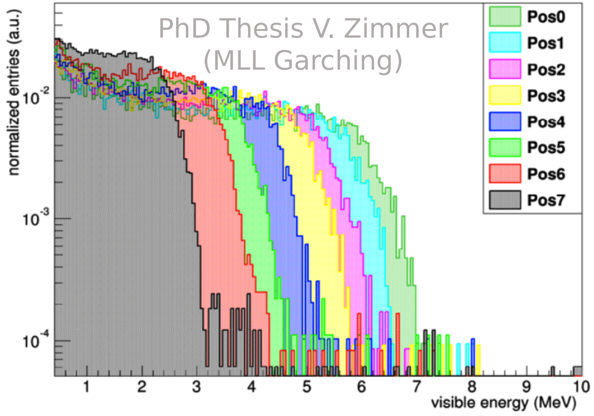

$$^7Li+p \rightarrow {}^7Be+n$$





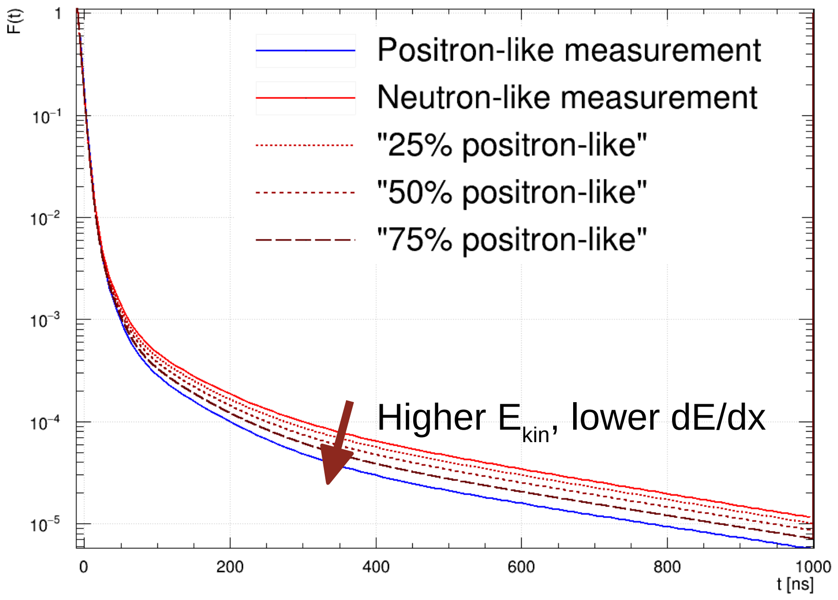



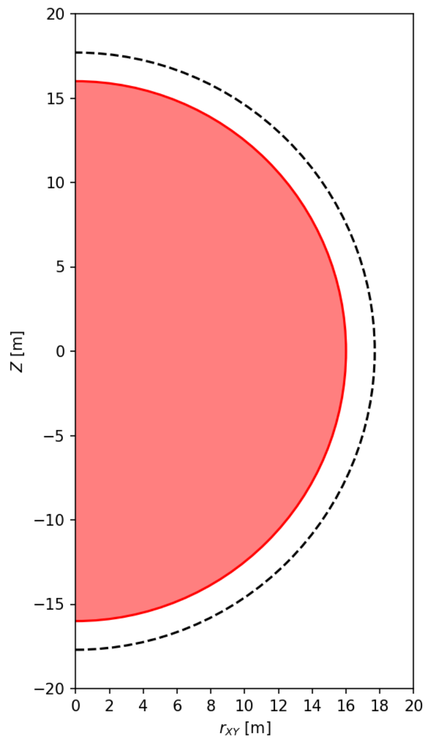

**Proton recoil spectra for different initial n energies**

# We expect the scintillation time profile of background neutrons/protons to become more signal-like at higher energies:

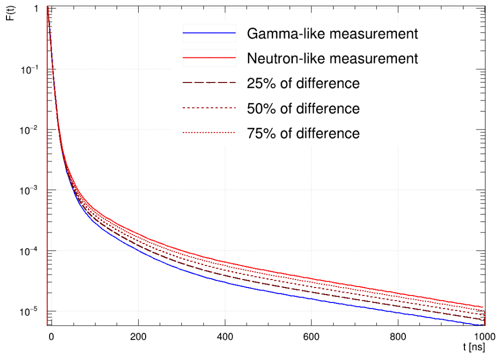


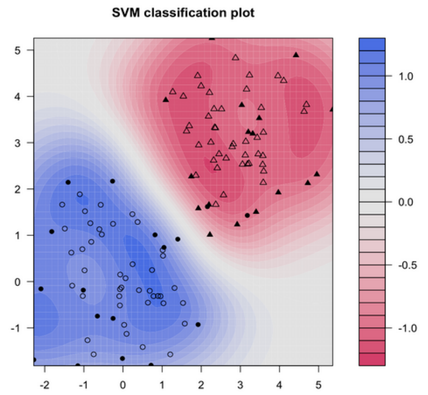

- The scintillation time profile caused by a particle in LAB mostly depends on its energy loss rate dE/dx.
- At lower energies (< 10 MeV): background neutrons/protons lose significantly more energy per distance than signal positrons.
- At higher energies: neutrons/protons lose **less** energy per distance than at lower energies.
  - Closer to the dE/dx of positrons
- We plan to measure this effect at beamtimes at LNL Legnaro.

# Setup




- IBD signal positrons and background neutrons in the DSNB energy ROI (12-35 MeV)
- Multiple sets of background neutrons for different linear combinations between n and e+ time profiles
- Then: SVM discrimination between each neutron time profile set and the IBD positron set.

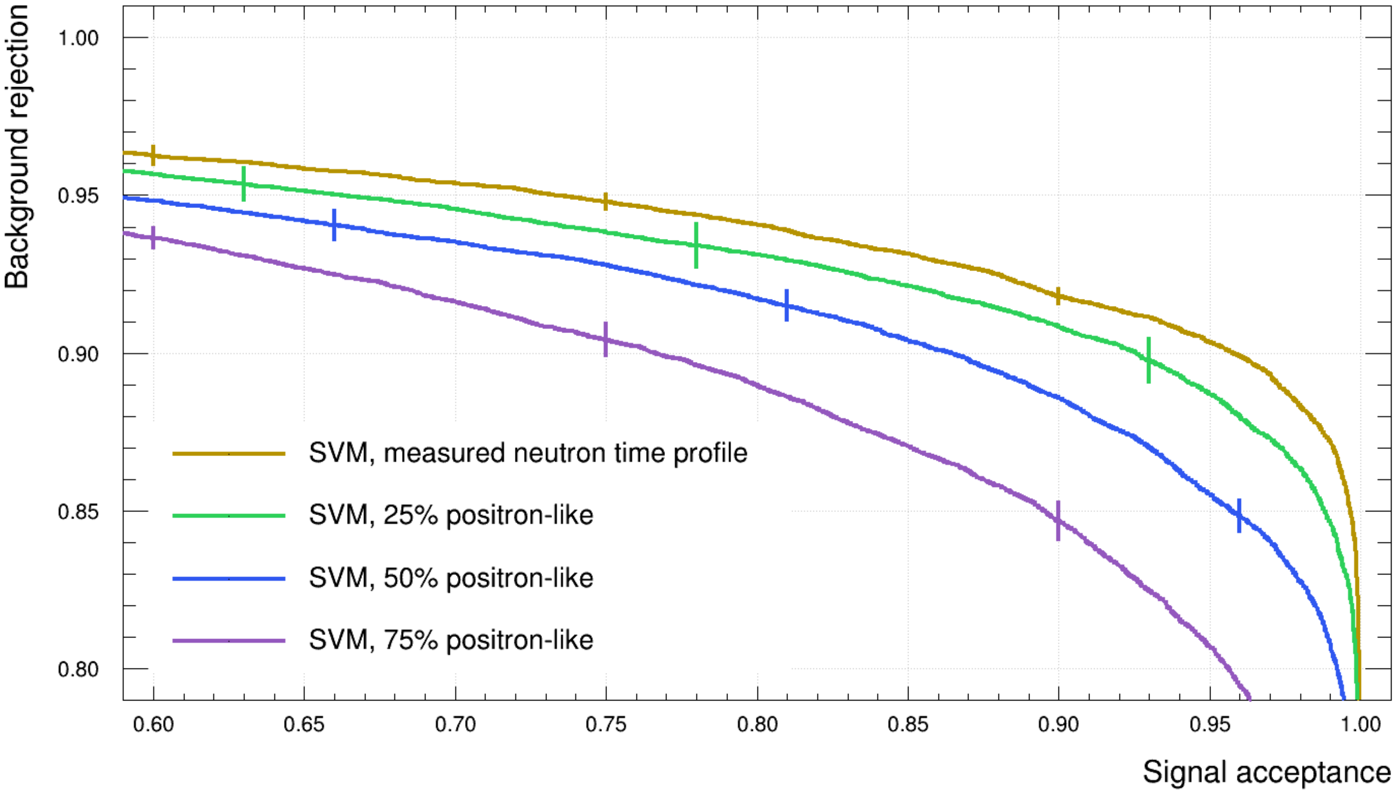


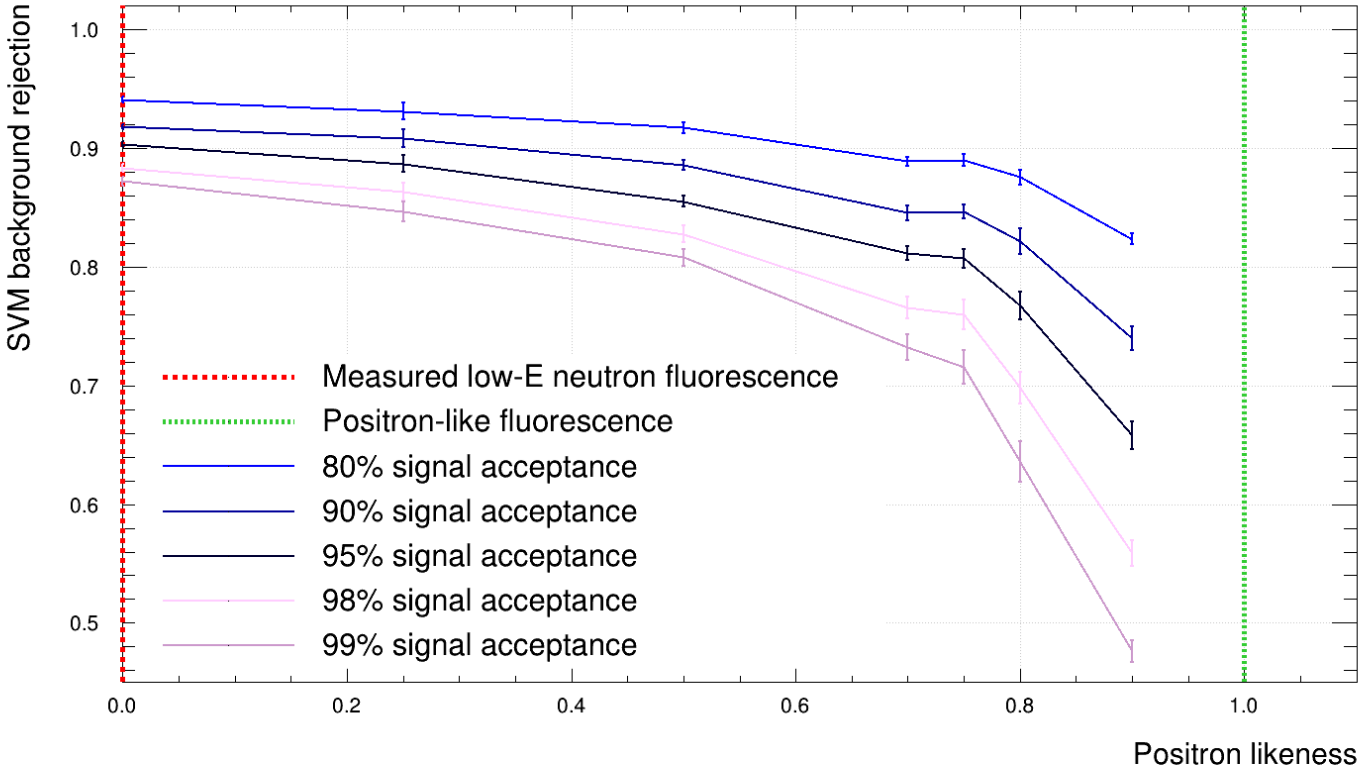

(generic SVM example)

# As the high-energy neutron time profile approaches the positron time profile, we steadily lose discrimination performance.

ROC curves:

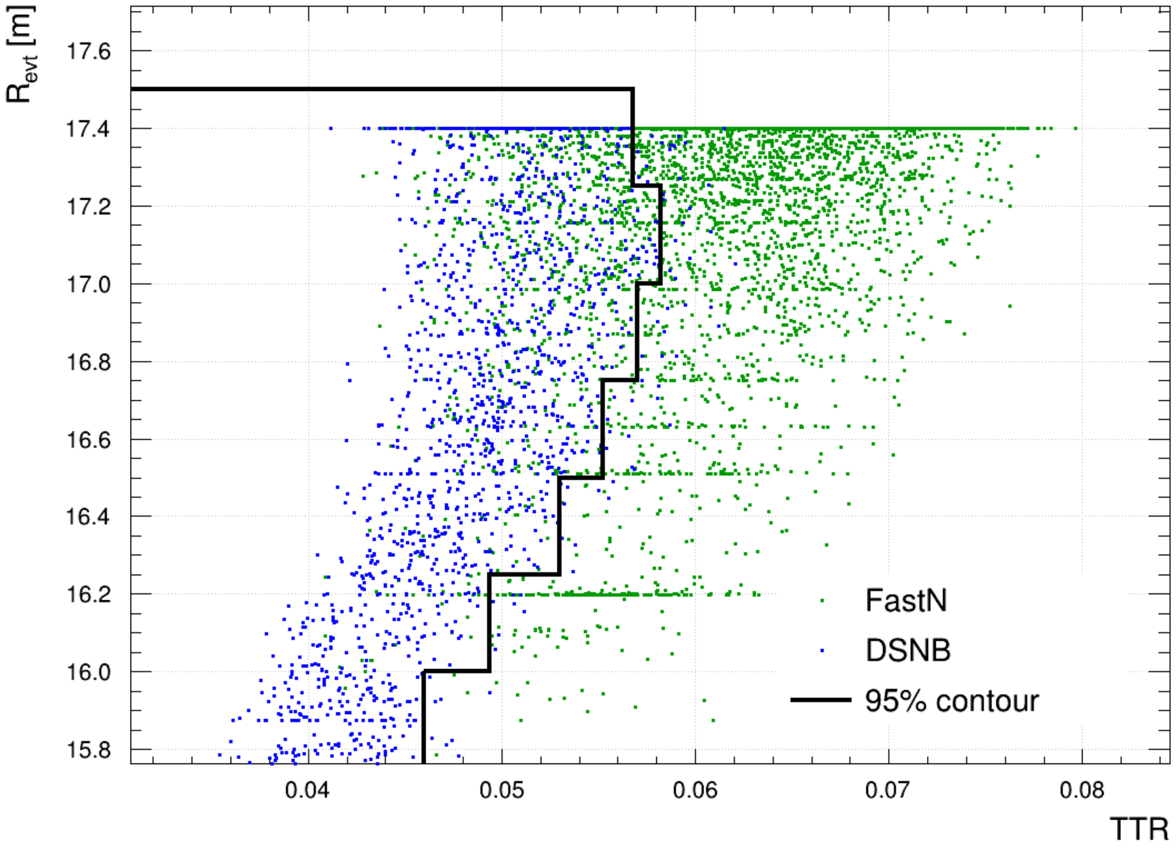


# After the half-way point between both time profiles we see an even stronger decrease in PSD performance.



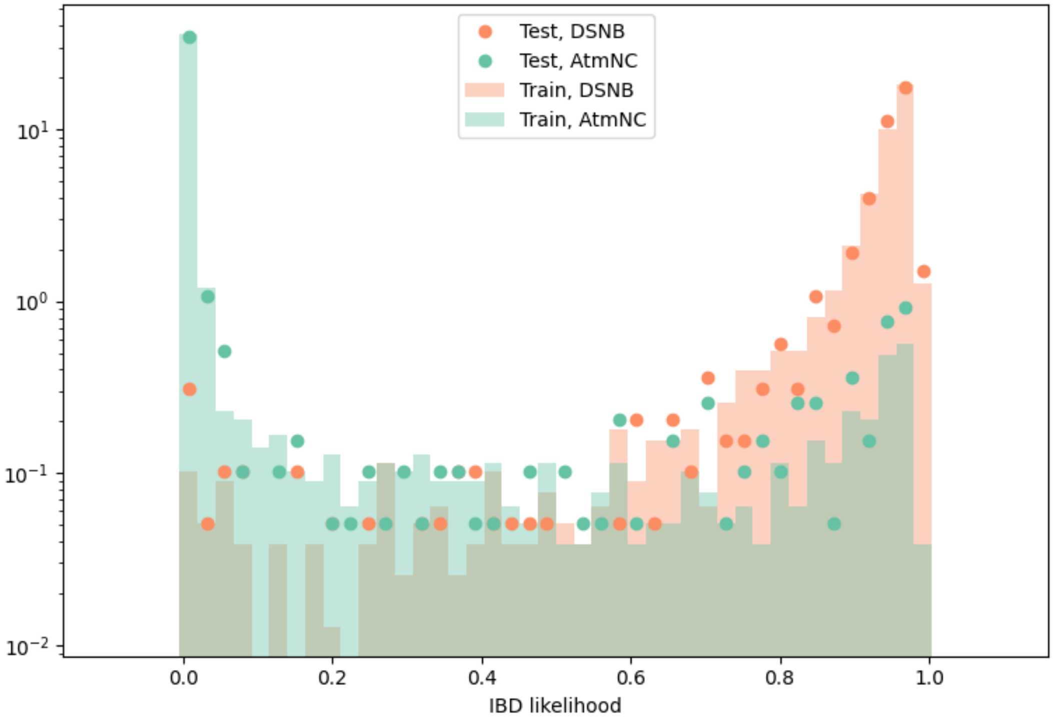
# TTR Analysis

# The same contour cut can also be applied in the rejection of FastN Events

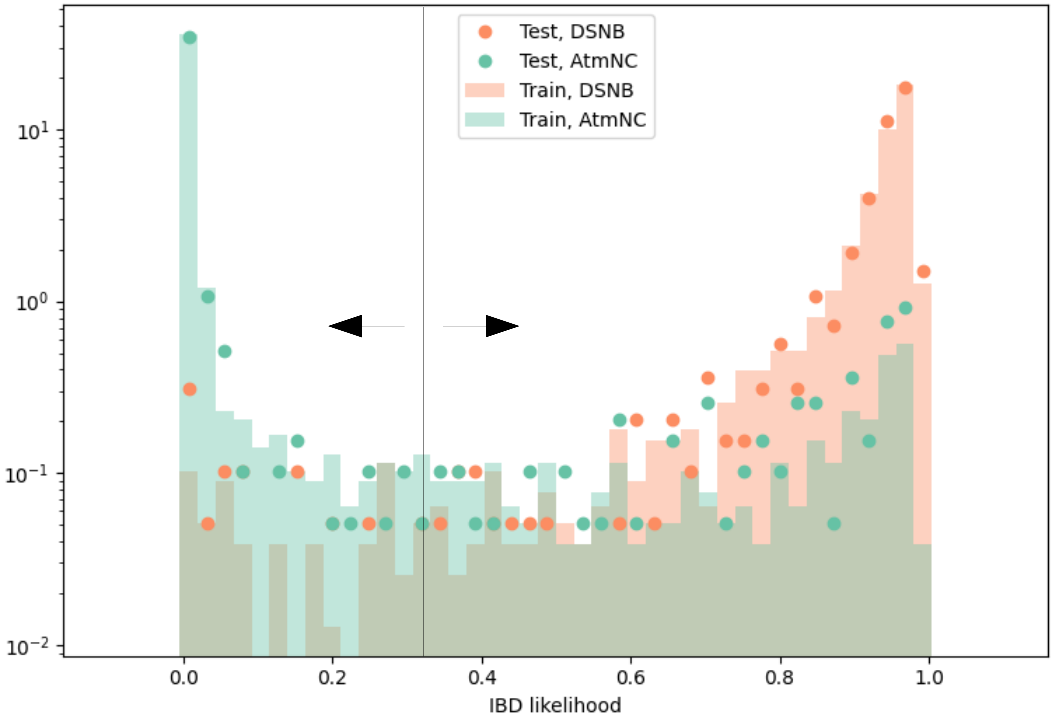


# Machine Learning

# Training results – Example Output



# Training results – Example Output




-> Alternating IBD likelihood cutoff to vary background rejection against signal acceptance (e.g. in an ROC curve)