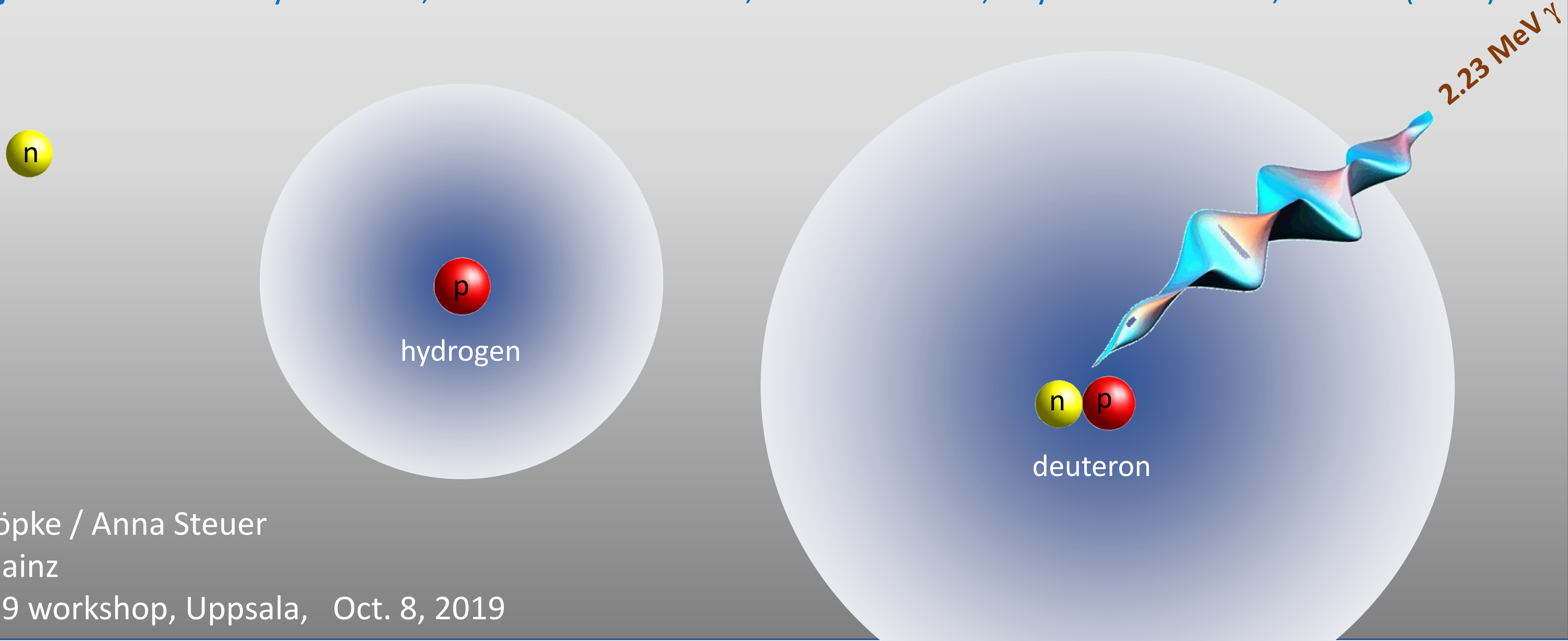
Neutron Echo in IceCube?

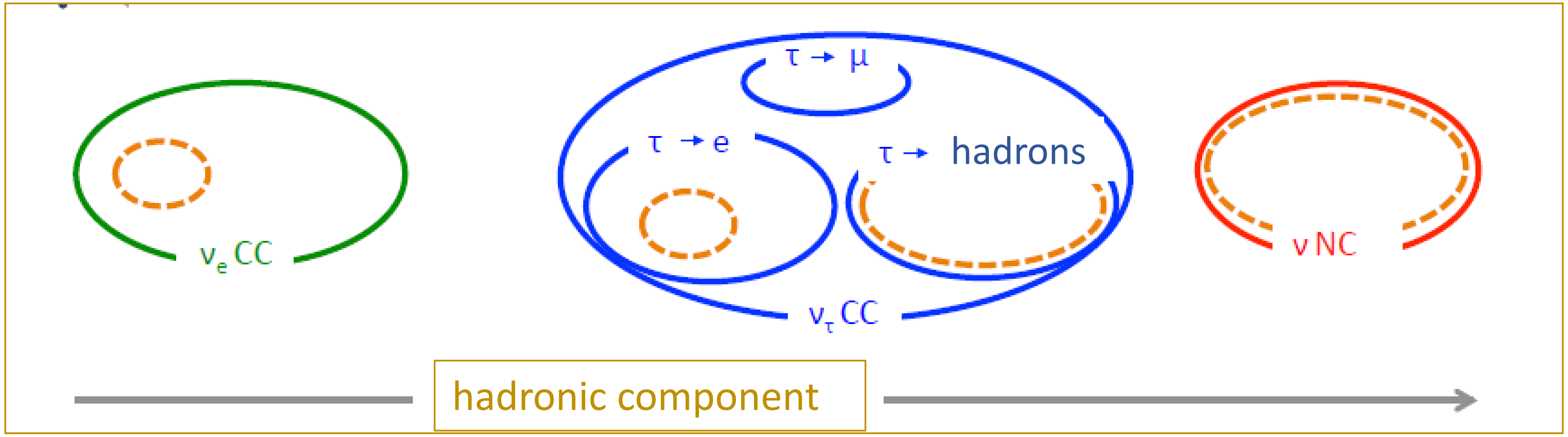
… a potential tool to tag hadronic showers and ν interaction at high energies

Major Stimulus: Shirley Weishi Li, Mauricio Bustamante, John F. Beacom, Phys. Rev. Lett. 122, 151101 (2019)



Lutz Köpke / Anna Steuer
JGU Mainz
PPNT19 workshop, Uppsala,   Oct. 8, 2019

Motivation: hadronic component is indicator of reaction



ν_e CC

$\tau \rightarrow \mu$

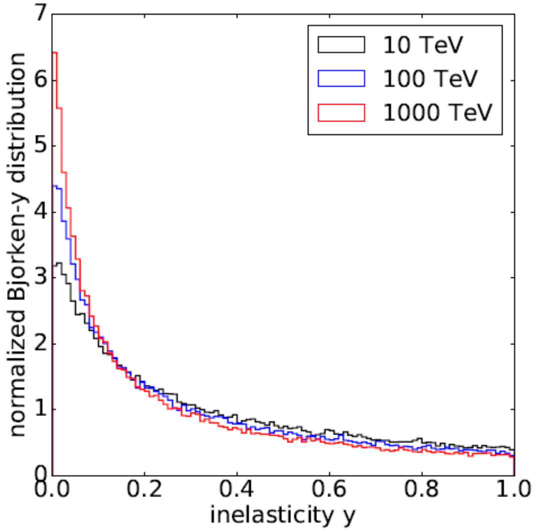
$\tau \rightarrow e$

$\tau \rightarrow$ hadrons

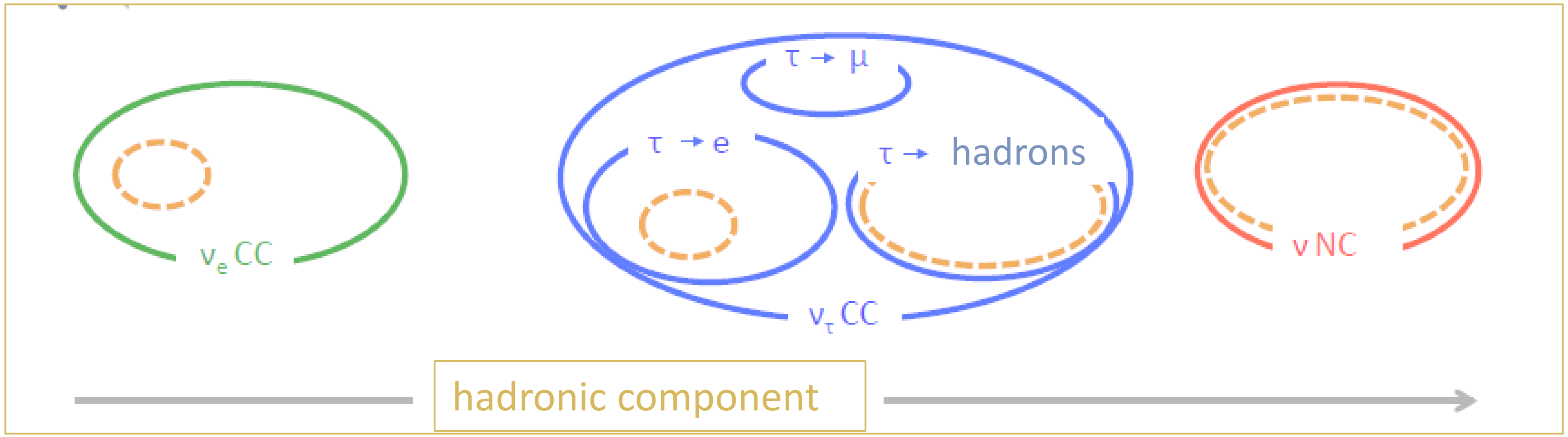
ν_τ CC

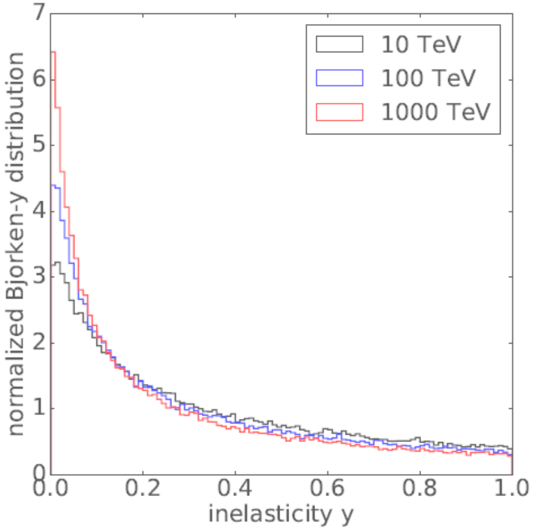
ν NC

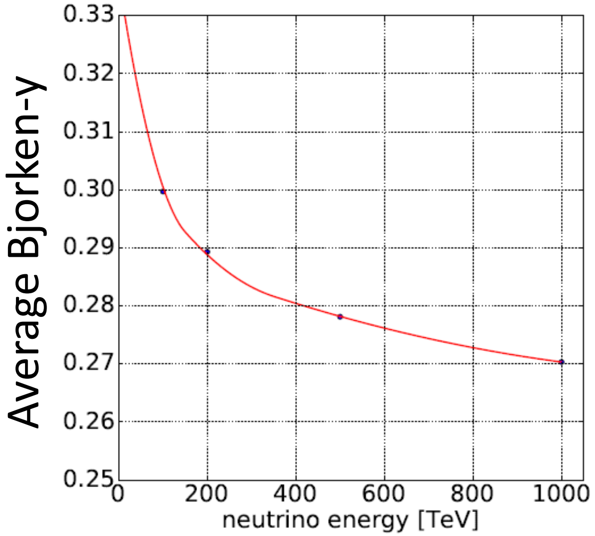
hadronic component



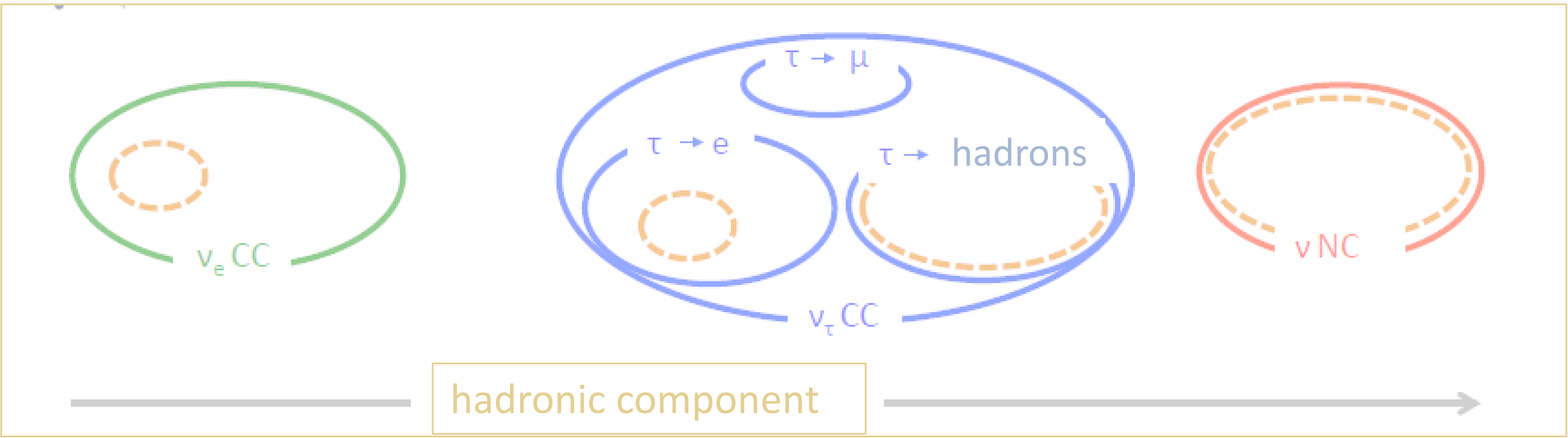
Motivation: hadronic component is indicator of reaction

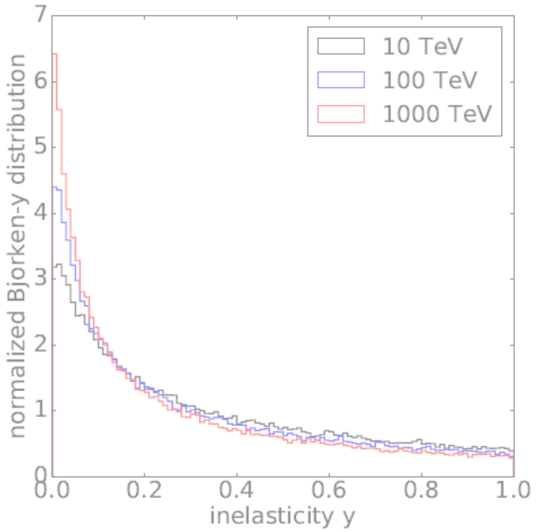






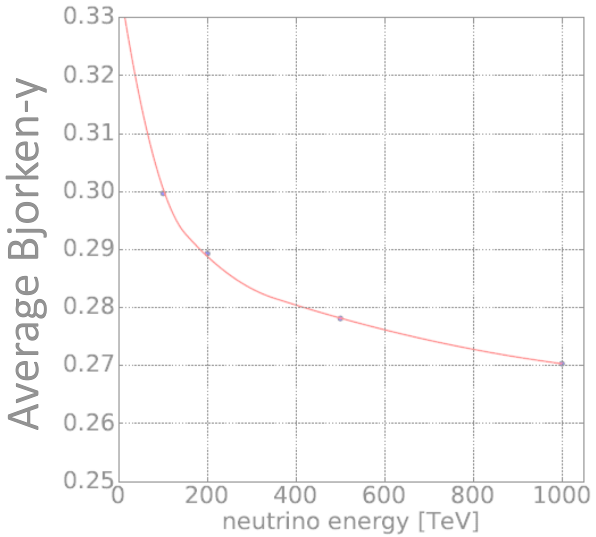
Motivation: hadronic component is indicator of reaction





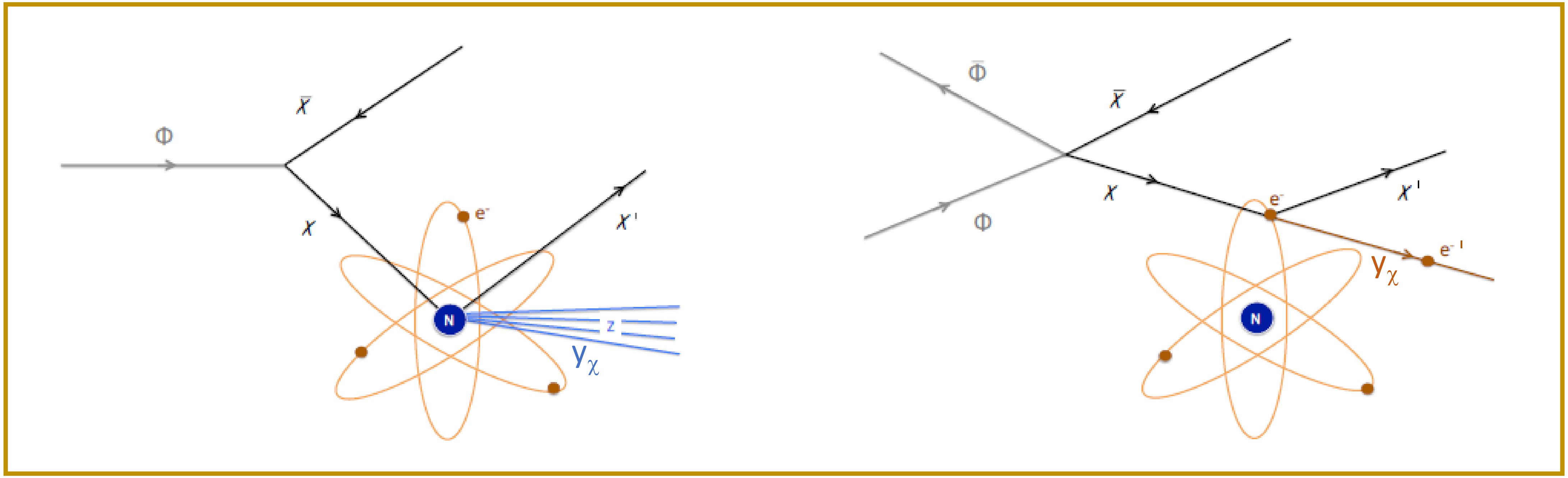
<y>=0.29 @ 200 TeV, showers only, corrected for hadronic shower detection (ν losses!)

Fraction detected energy in reaction	**electromagnetic**	**hadronic**
boosted dark matter on e^-	$100\% \cdot y_\chi$	-
boosted dark matter recoil	-	$100\% \cdot y_\chi$
neutral current	-	29%
ν_e charged current	71%	29%
ν_τ charged current	9.5%	69%
Glashow resonance	12%	82%



Example of exotic interaction: boosted dark matter

- Heavy dark matter particle ϕ decays into lighter dark matter particle X (with SM interactions)
- Since $m_\phi >> m_X$, X highly relativistic with up to PeV energy



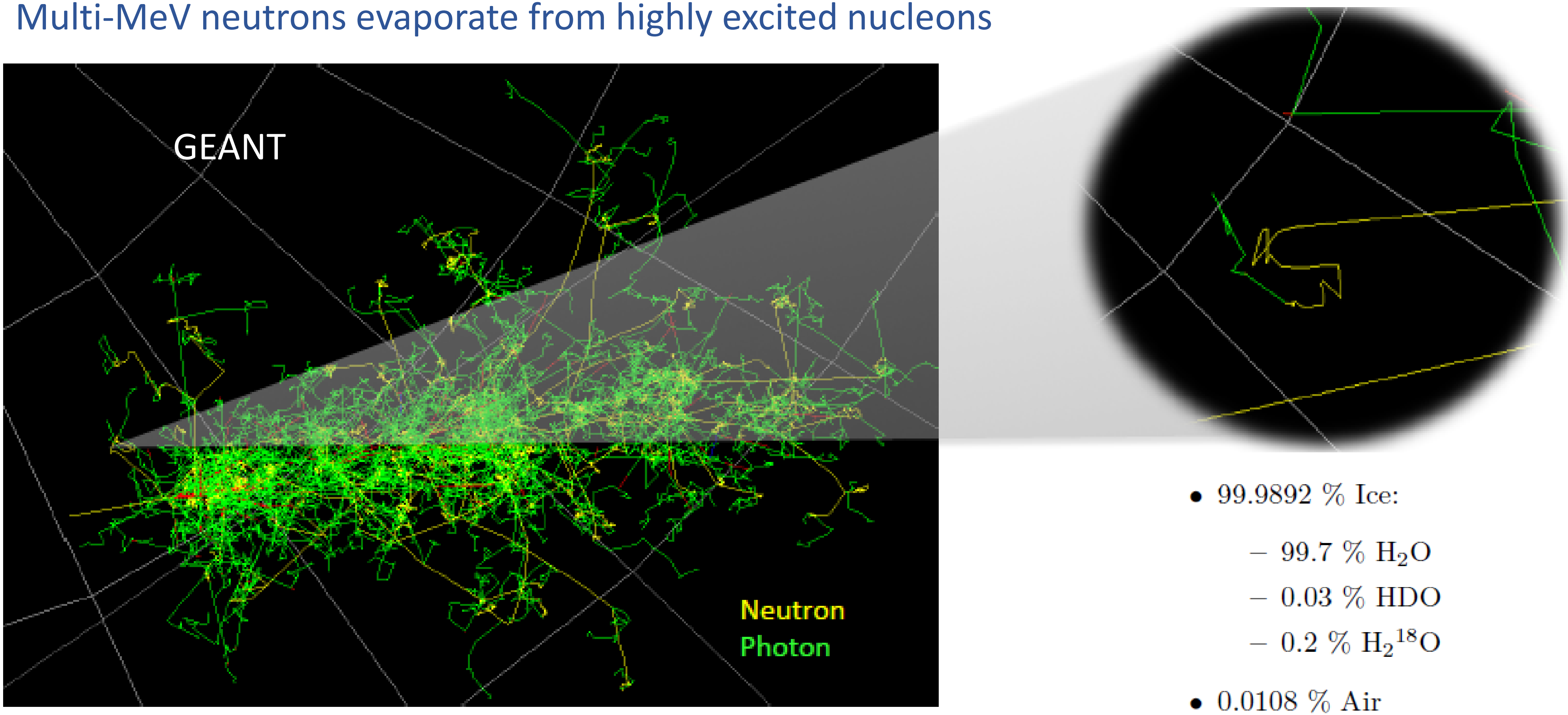
Deep inelastic scattering of X on nucleon:
hadronic cascade signature (like neutral current)

Scattering of X on atomic electrons:
purely electromagnetic signature (like ν_eCC)

IceCube acts as gargantuan recoil dark matter detector with monoenergetic hadronic or electromagnetic signature

Hadronic interactions: lots of neutrons !

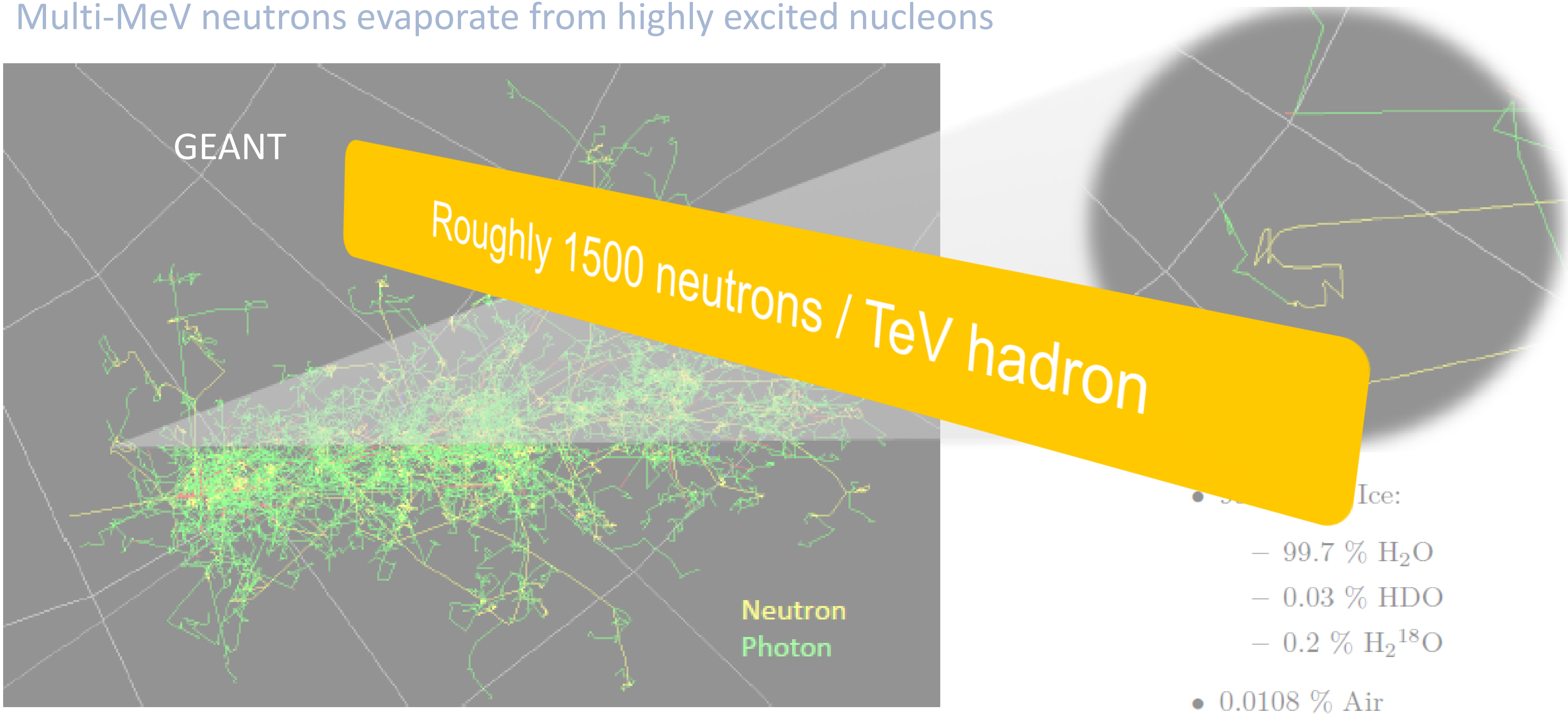
Multi-MeV neutrons evaporate from highly excited nucleons



- 99.9892 % Ice:
  - 99.7 % H_2O
  - 0.03 % HDO
  - 0.2 % $H_2{}^{18}O$
- 0.0108 % Air

Hadronic interactions: lots of neutrons !

Multi-MeV neutrons evaporate from highly excited nucleons

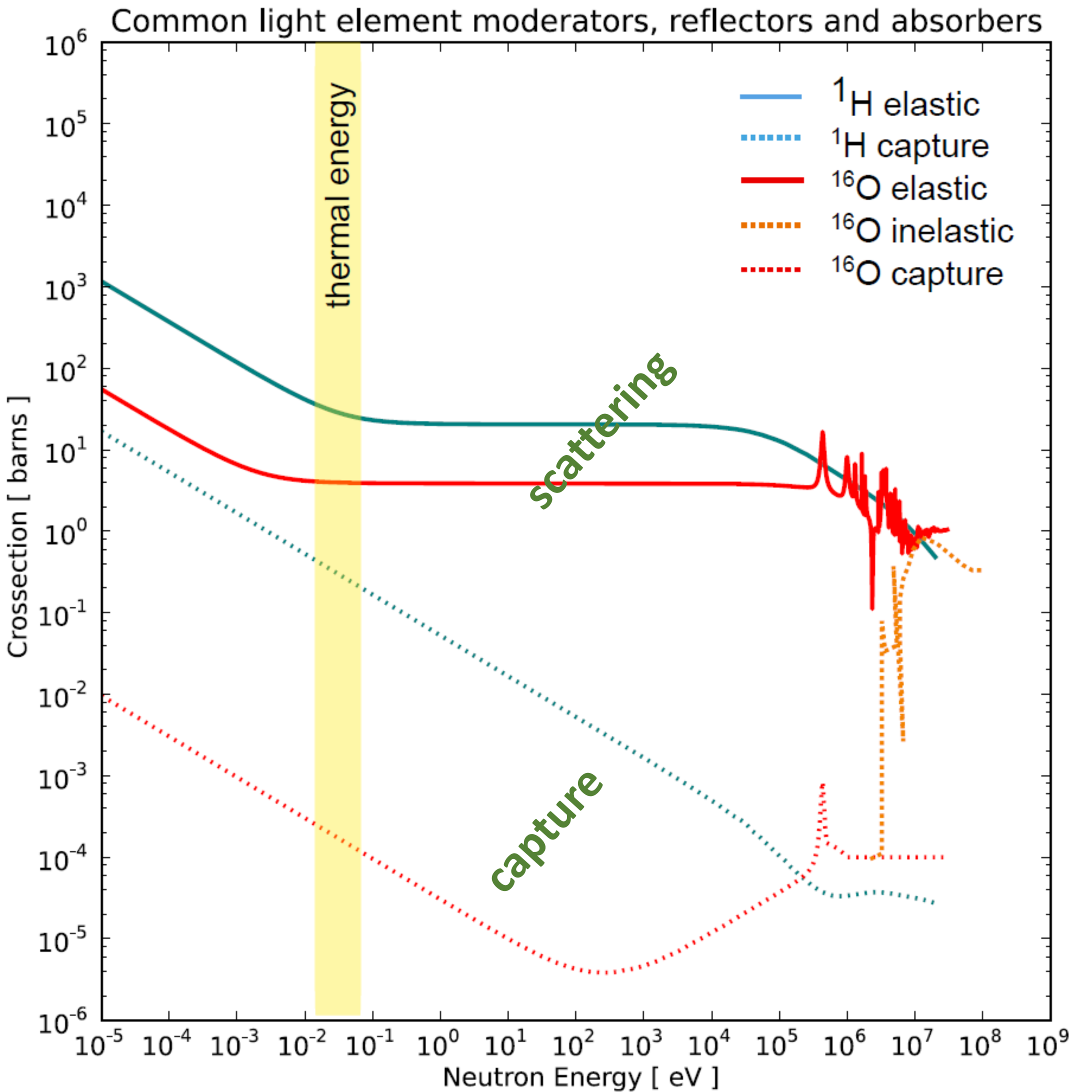


Roughly 1500 neutrons / TeV hadron

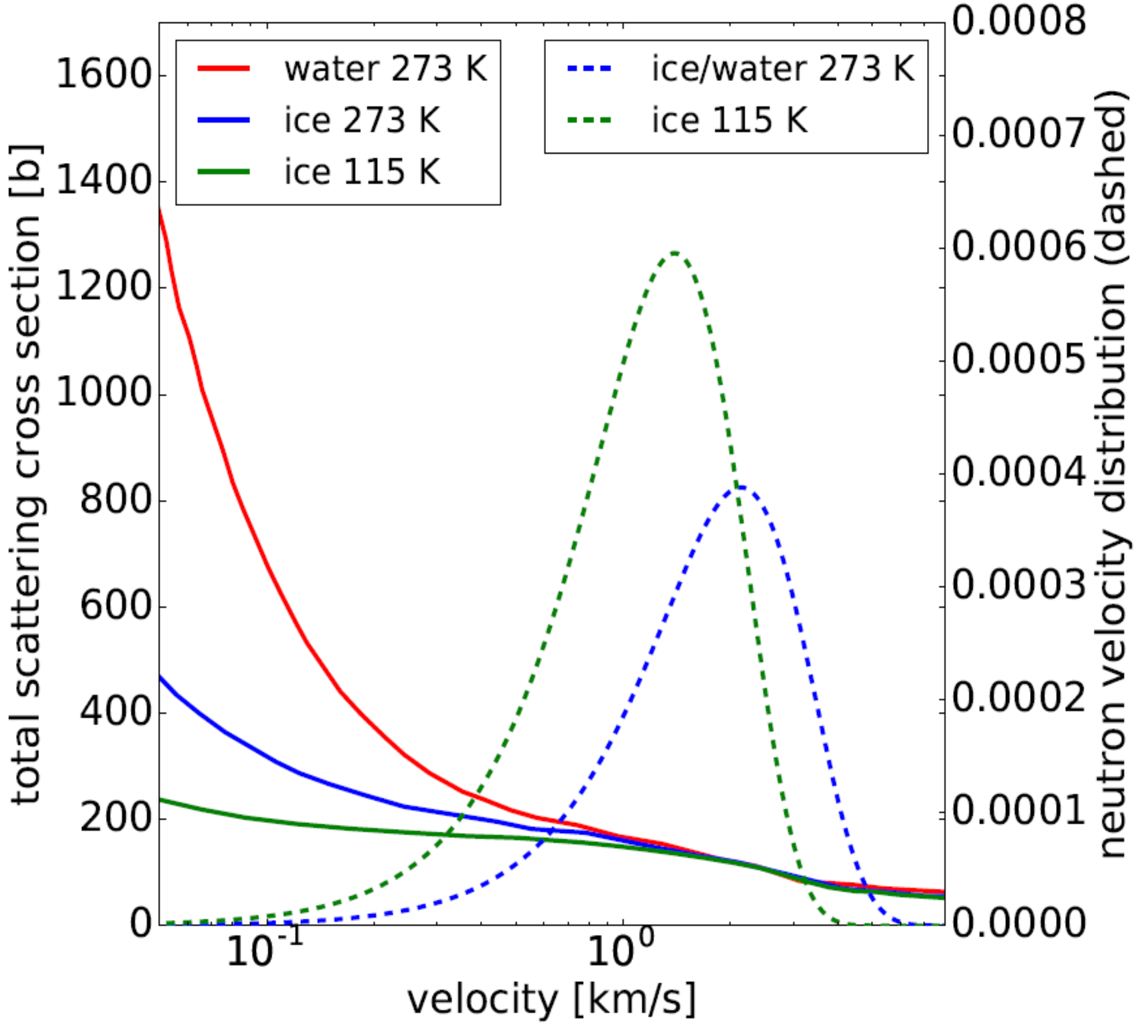
- Ice:
  - 99.7 % H_2O
  - 0.03 % HDO
  - 0.2 % $H_2{}^{18}O$
- 0.0108 % Air

Scattering and capture cross sections of neutrons

cross sections



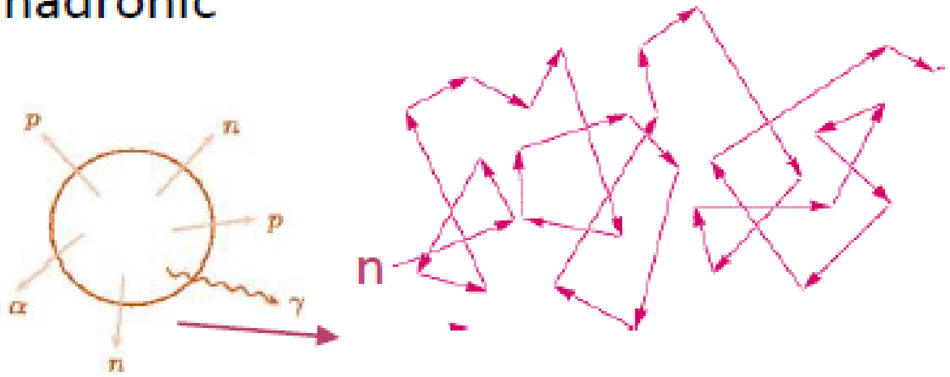
differences water / ice, thermal velocity



Summary neutrons: from evaporation to capture

n evaporation of highly excited nuclei in hadronic shower

~20 scatters until thermal (~ 1 μs)

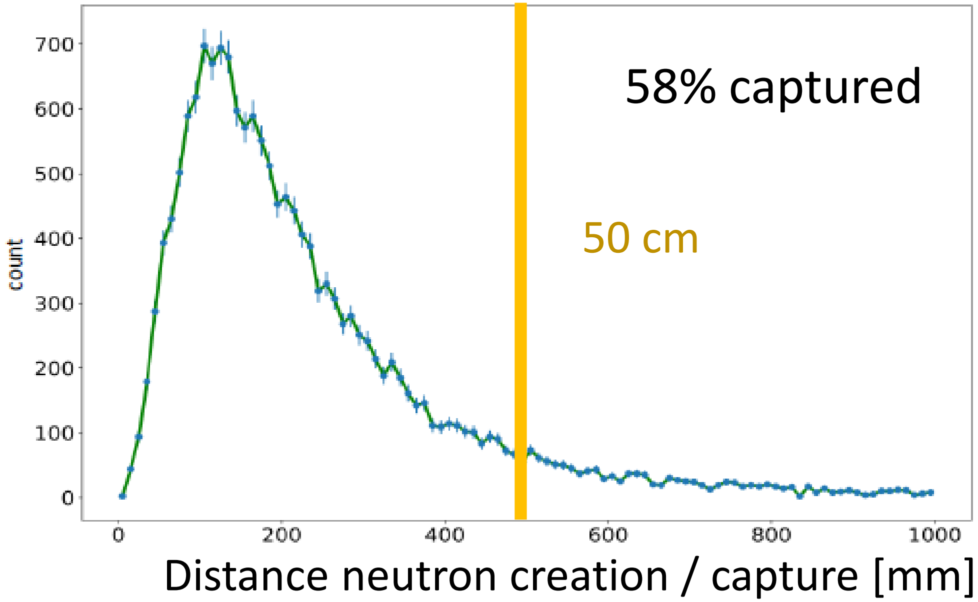


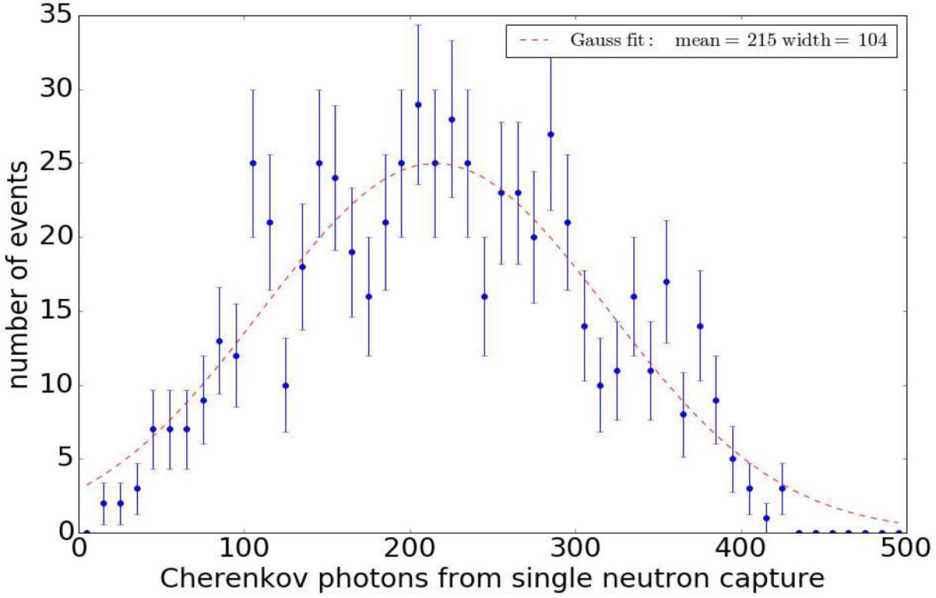
absorption ($\tau \approx 200\ \mu s$, 20 cm)

$d^* \rightarrow d + 2{,}223$ MeV γ

Compton $e^- \rightarrow \check{C}_\gamma$

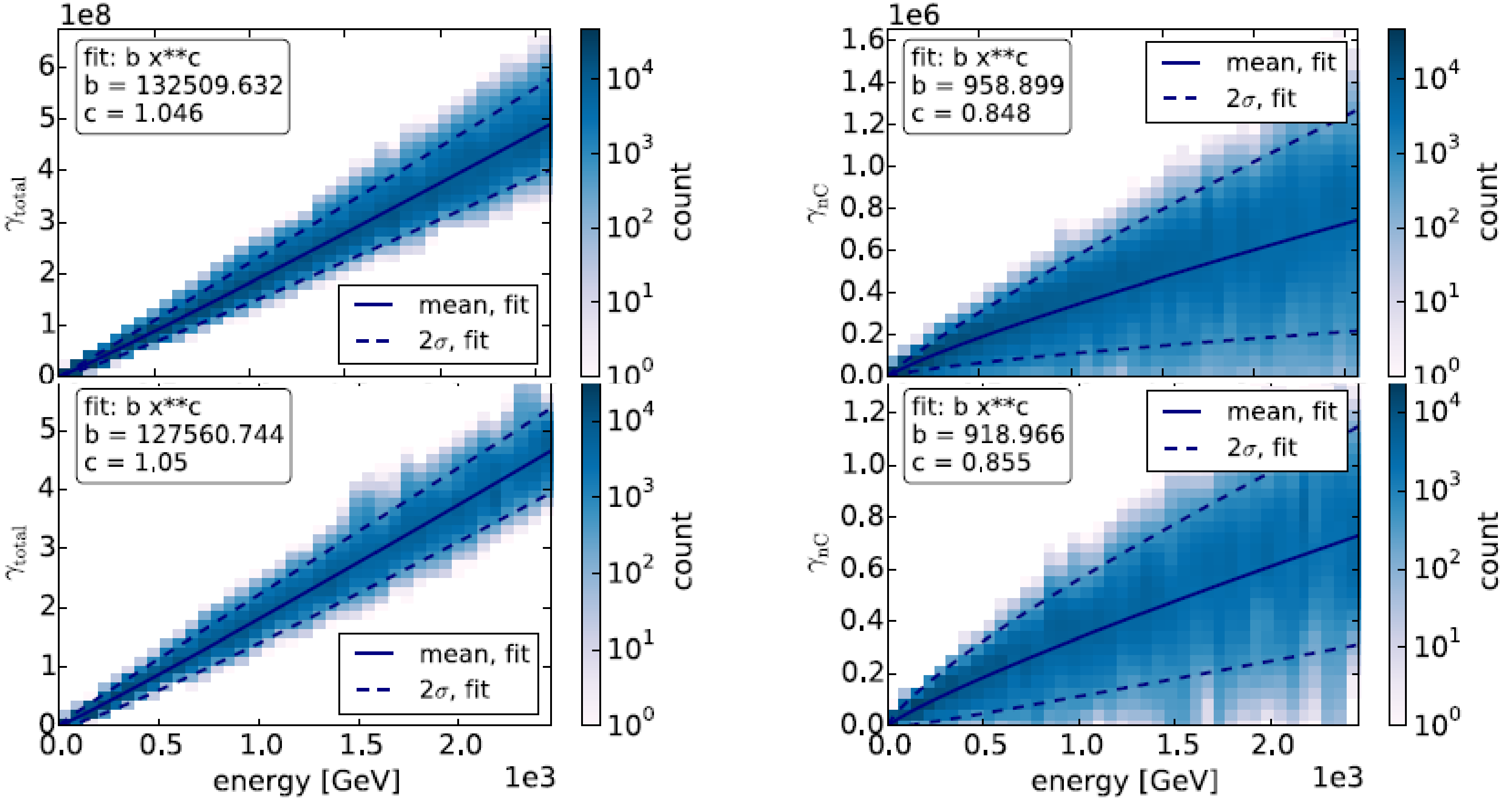
~200 delayed photons





GEANT slow: use photon count parametrization

GEANT calculation extremely time consuming → parametrize #prompt photons and #delayed photons



Photon count from π^-

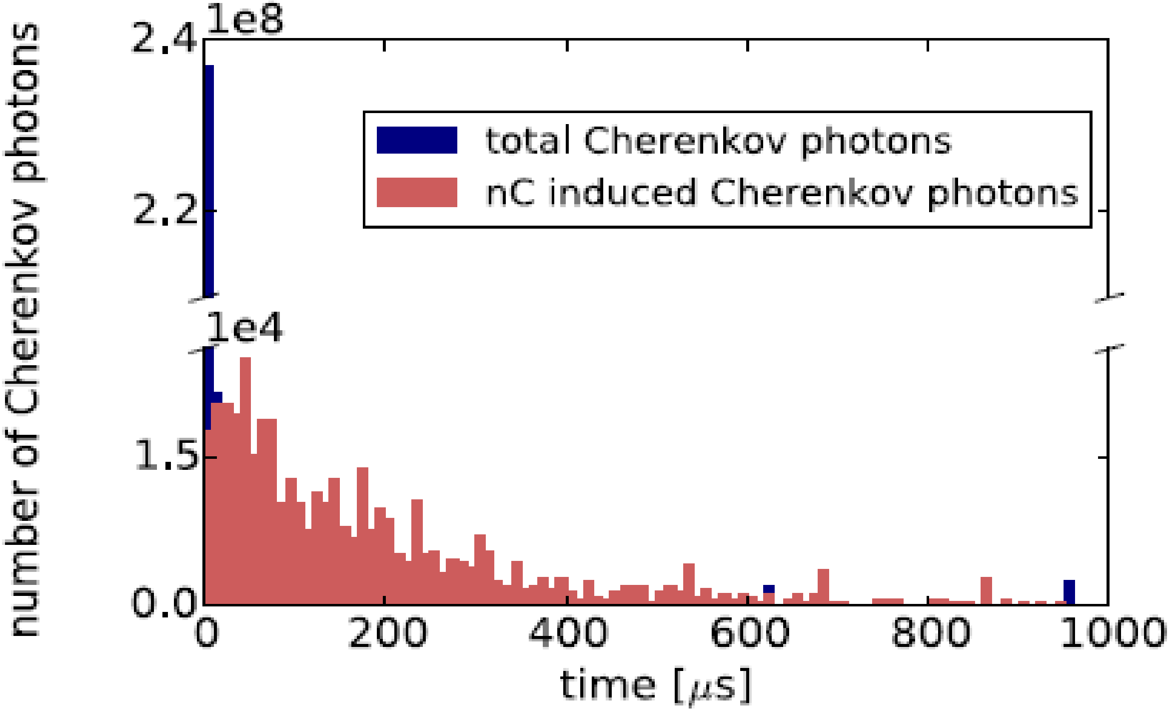
Photon count from K^-

Cherenkov photons from event

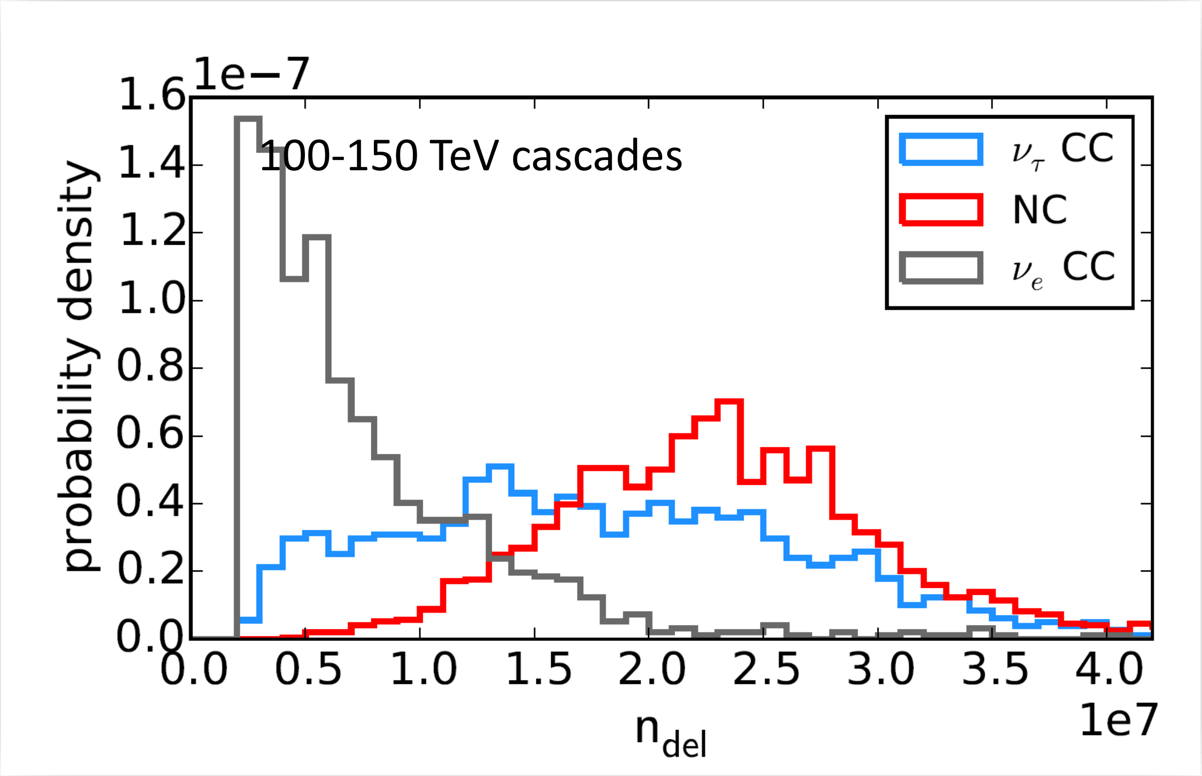
Cherenkov photons from neutron capture

Before detection: capture time and delayed photons

Exponential time distribution with τ≈217 μs in ice is signature for delayed light from neutron capture on hydrogen



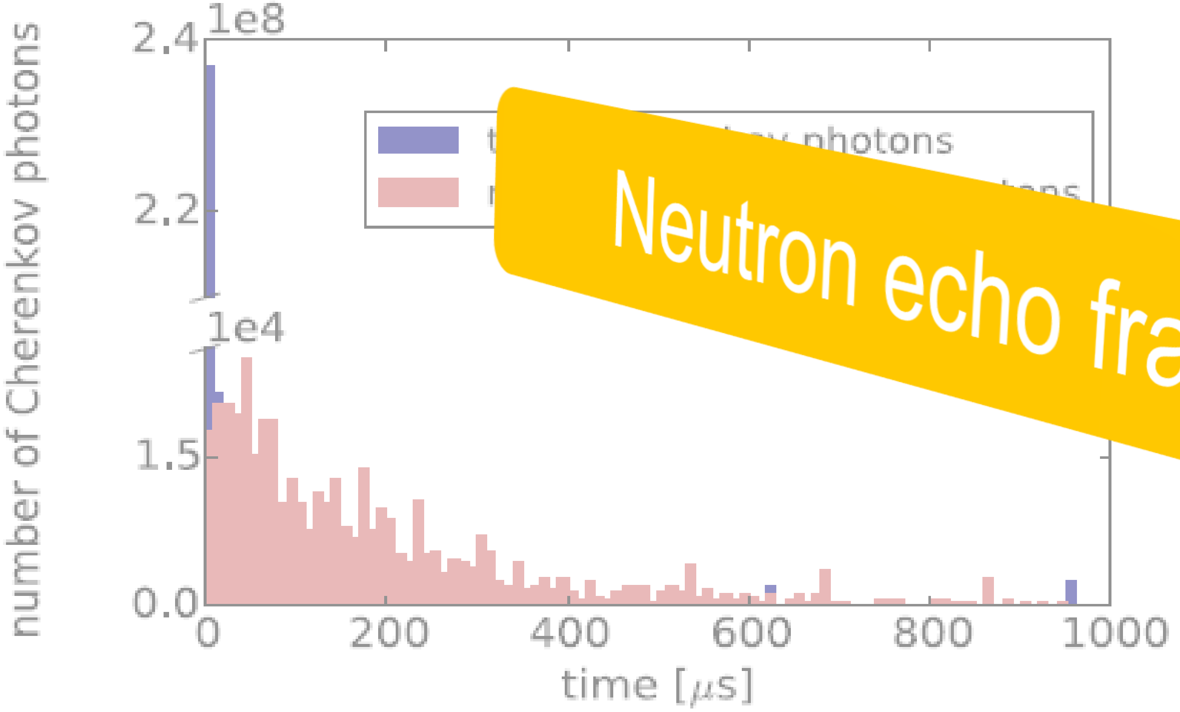
Expected time distribution (before detection)



delayed #photon probability for NC, ν_e and ν_τ

Before detection: capture time and delayed photons

Exponential time distribution with τ≈217 μs in ice is signature for delayed light from neutron capture on hydrogen



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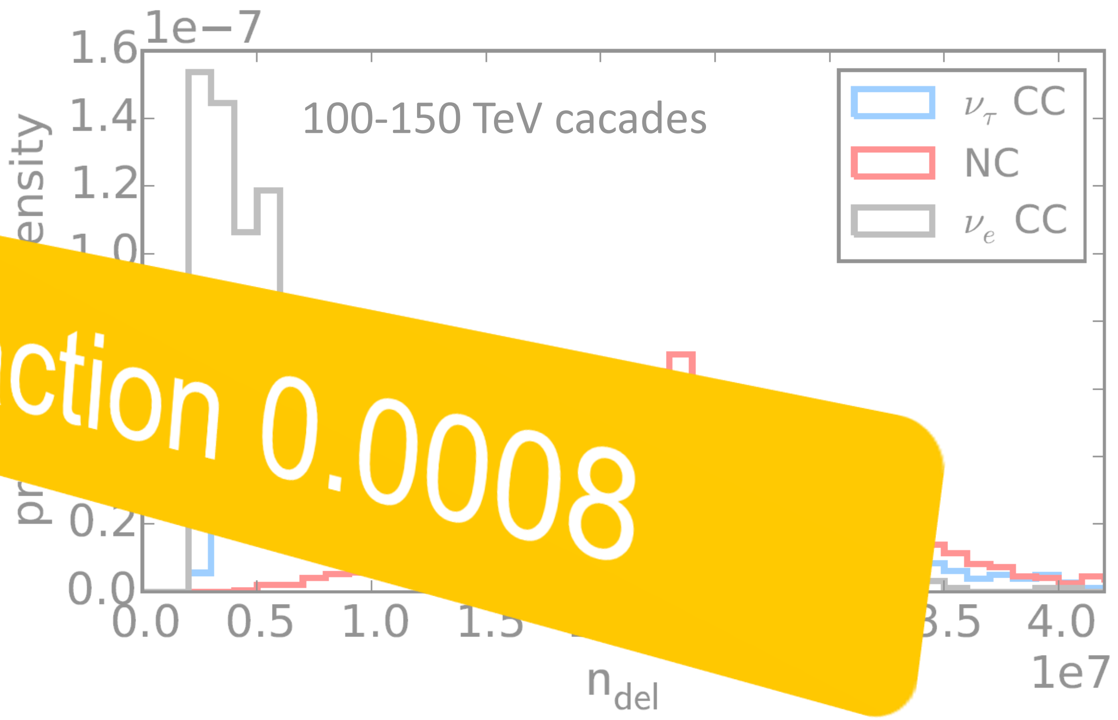
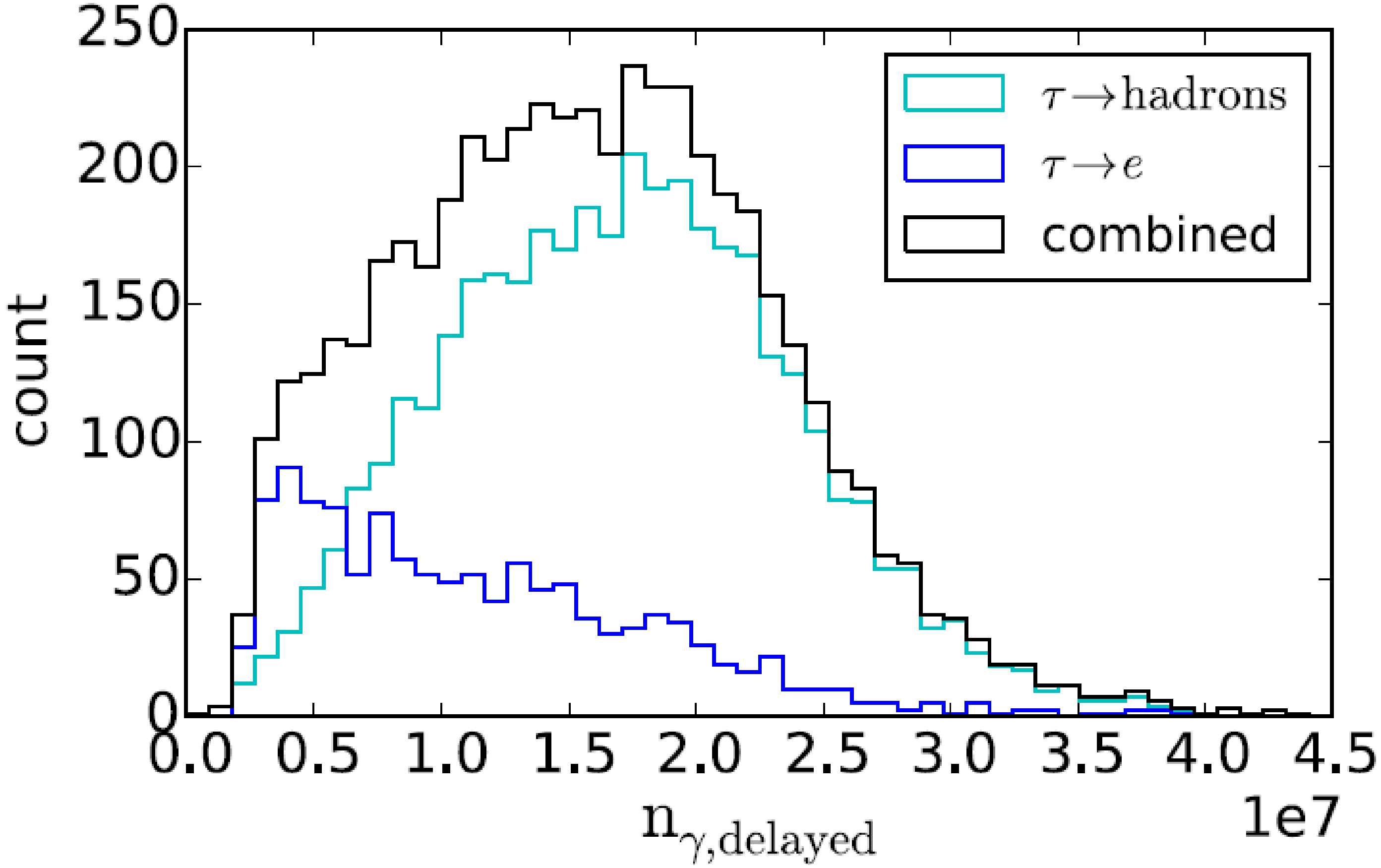


delayed #photon probability for NC, ν_e and ν_τ

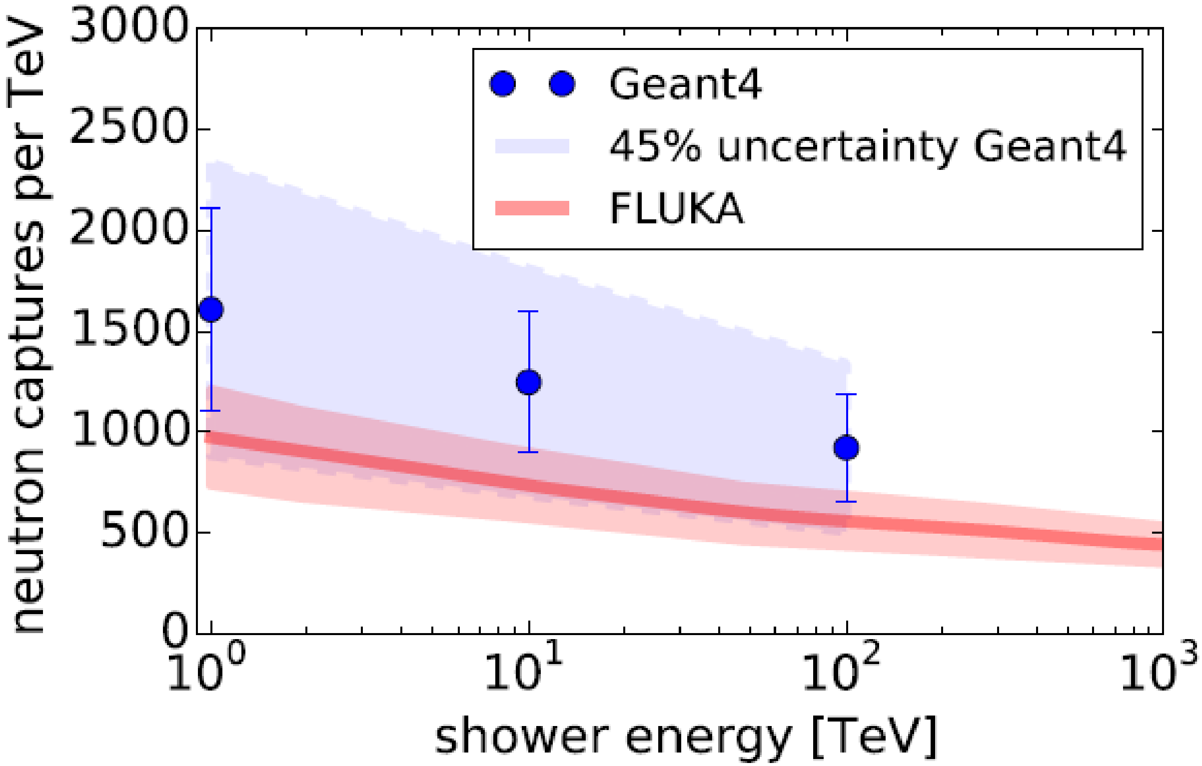
Neutron echo fraction 0.0008

Specific example: tau neutrino interactions

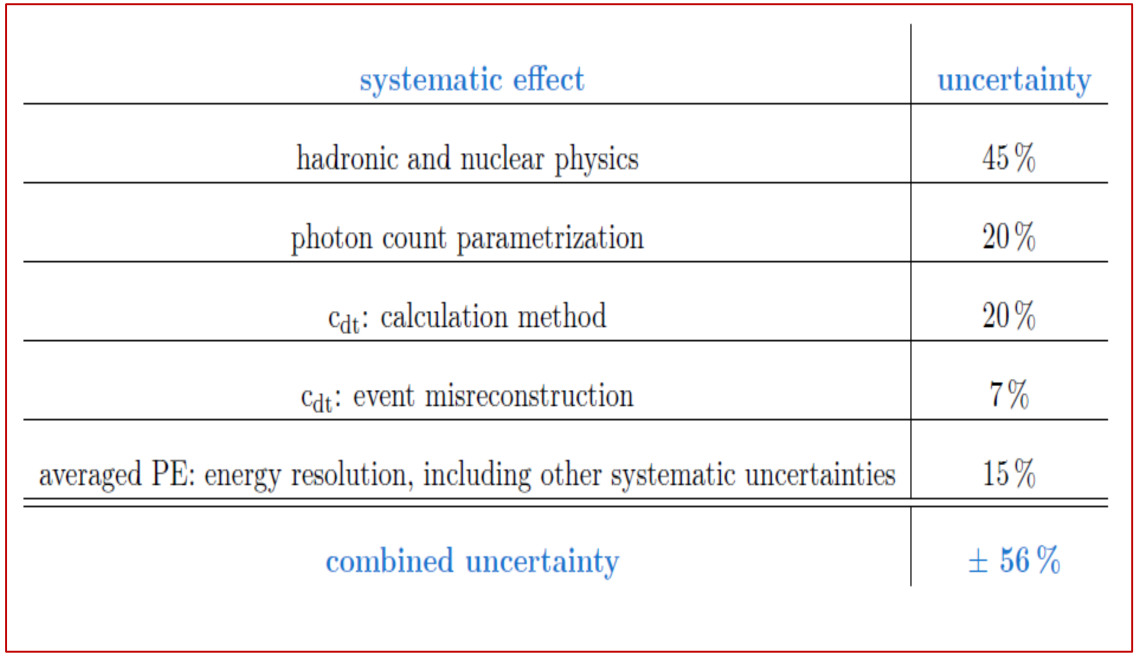


- energy loss from neutrinos (~ 25%)
- electromagnetic showers from τ→eνν (τ→μνν events rejected in sample)
- 1, 3 and 5 prong events responsible for hadronic fractions

A pity: Large uncertainties in neutron yield and capture



- Decreasing with energy because electromagnetic component is rising with energy
- Differences between FLUKA and Geant4 and between model assumptions made in Geant4

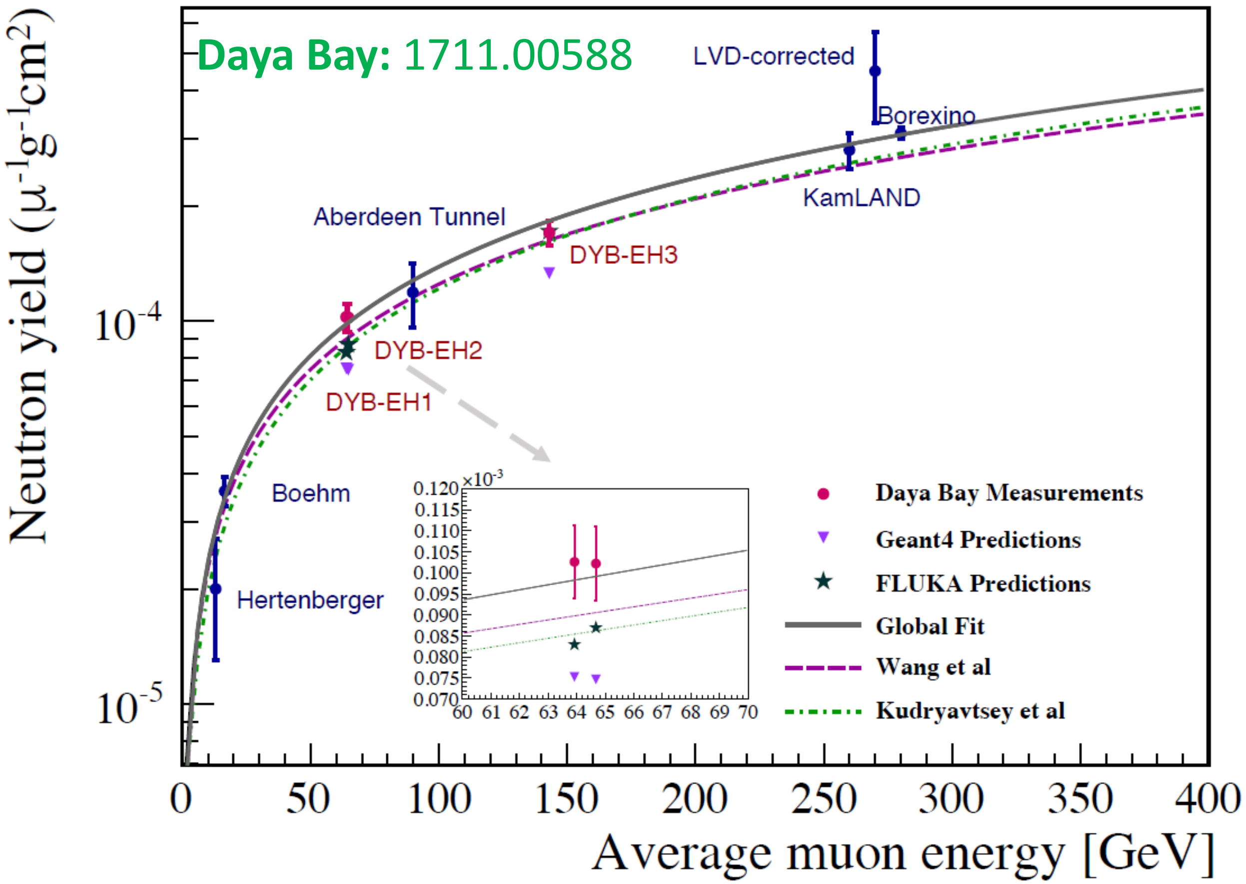


systematic effect	uncertainty
hadronic and nuclear physics	45 %
photon count parametrization	20 %
c_{dt}: calculation method	20 %
c_{dt}: event misreconstruction	7 %
averaged PE: energy resolution, including other systematic uncertainties	15 %
combined uncertainty	± 56 %

total uncertainty of 56% dominated by uncertainties in the neutron yield

Cross check: Studies by others (in scintillator/rock)

- Few measurements for **water** (Kamiokande)
- Neutrons produced by **cosmic ray muons in liquid scintillator** experiments

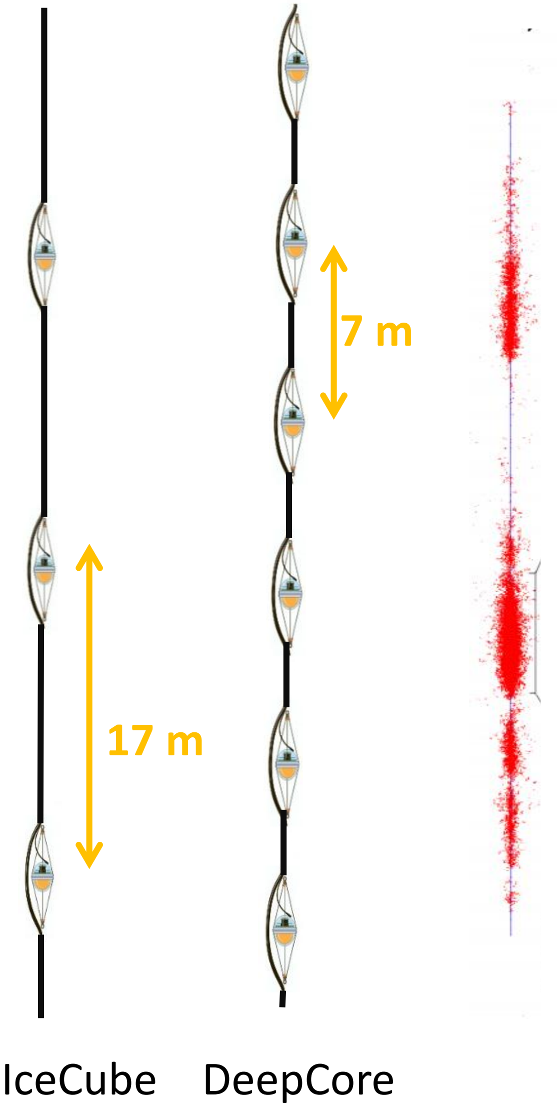

Daya Bay: 1711.00588

- Super-Kamiokande measured neutron capture time from muons and with a AmBe source
  Astropart. Phys. 31, 320 (2009) and 60, 41 (2015)
- $\tau_{capture}$=(203.7±2.8) μs consistent with expectation

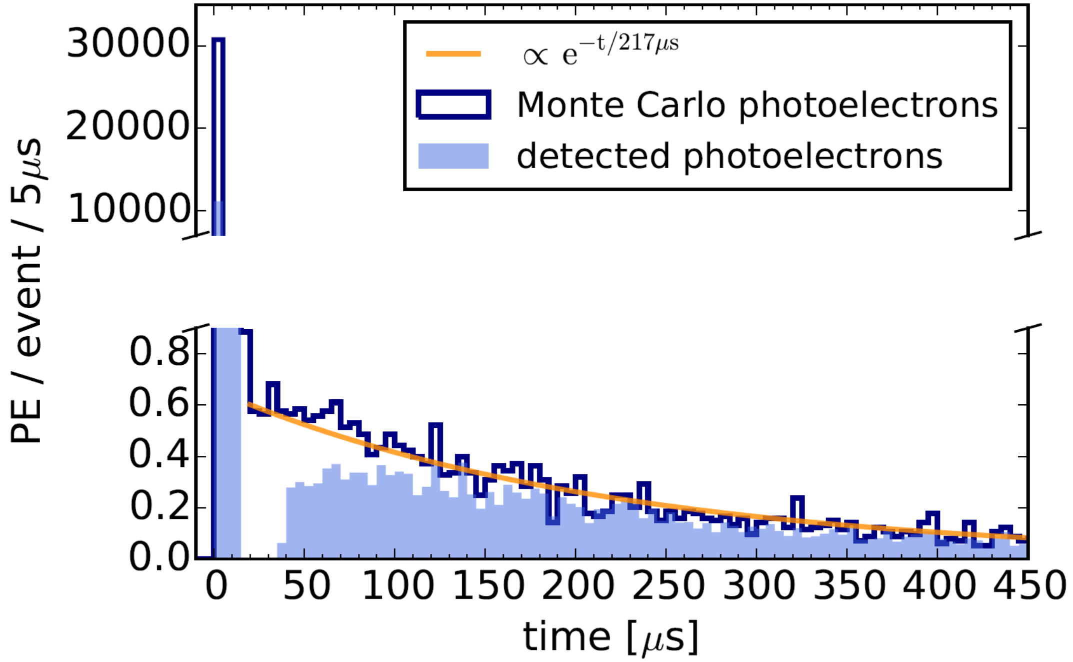
- **Data** typically **higher** than Fluka and GEANT predict
- Predictions depend on settings
- **Borexino**: measurement ~ GEANT > FLUKA
- **others:** measurement >~ Fluka > GEANT

Uncertainties 20% – 50%, depending on study

IceCube detector: what would one see/miss ?

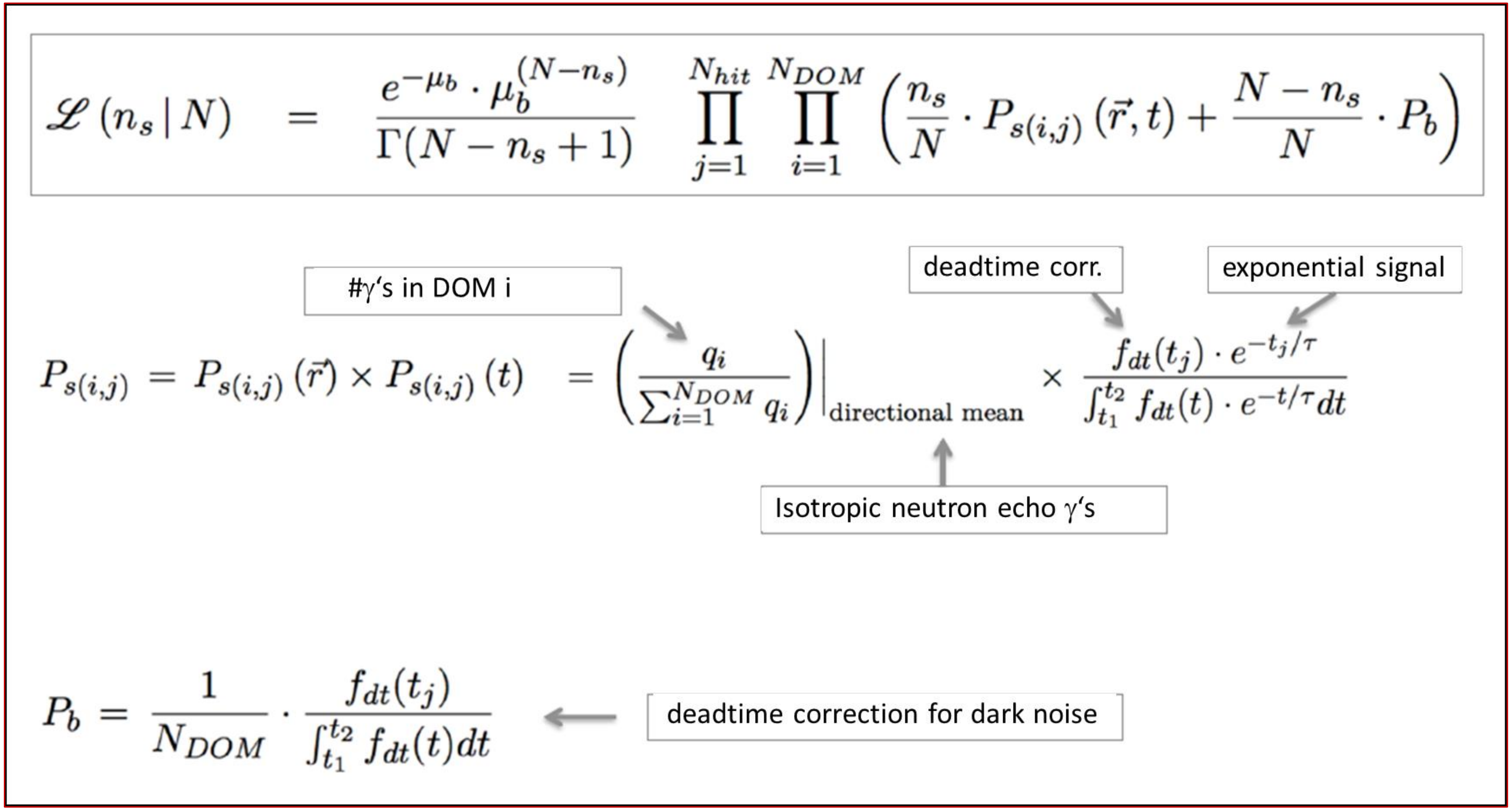


- Sparse IceCube/DeepCore detectors: ~ 10^{-6} probability to see single photon
  → need 100 TeV contained showers to see clear delayed signal
- Save all hits in the detector within ±0.5 s of HESE event with > 1500 PE
  → automatic satellite transfer/processing from Feb 2016
- readout is deadtime free for prompt event but not for delayed signals
  → affects delayed signal up to 150 μs (~40% loss, energy dependent)



Neutron echo: Likelihood extraction of delayed signal

Take position and time information into account in likelihood:



$$\mathscr{L}\left(n_s\,|\,N\right) = \frac{e^{-\mu_b}\cdot\mu_b^{(N-n_s)}}{\Gamma(N-n_s+1)}\prod_{j=1}^{N_{hit}}\prod_{i=1}^{N_{DOM}}\left(\frac{n_s}{N}\cdot P_{s(i,j)}\left(\vec{r},t\right)+\frac{N-n_s}{N}\cdot P_b\right)$$

#γ's in DOM i

deadtime corr.

exponential signal

$$P_{s(i,j)} = P_{s(i,j)}\left(\vec{r}\right)\times P_{s(i,j)}\left(t\right) = \left(\frac{q_i}{\sum_{i=1}^{N_{DOM}} q_i}\right)\Bigg|_{\text{directional mean}}\times\frac{f_{dt}(t_j)\cdot e^{-t_j/\tau}}{\int_{t_1}^{t_2} f_{dt}(t)\cdot e^{-t/\tau}dt}$$

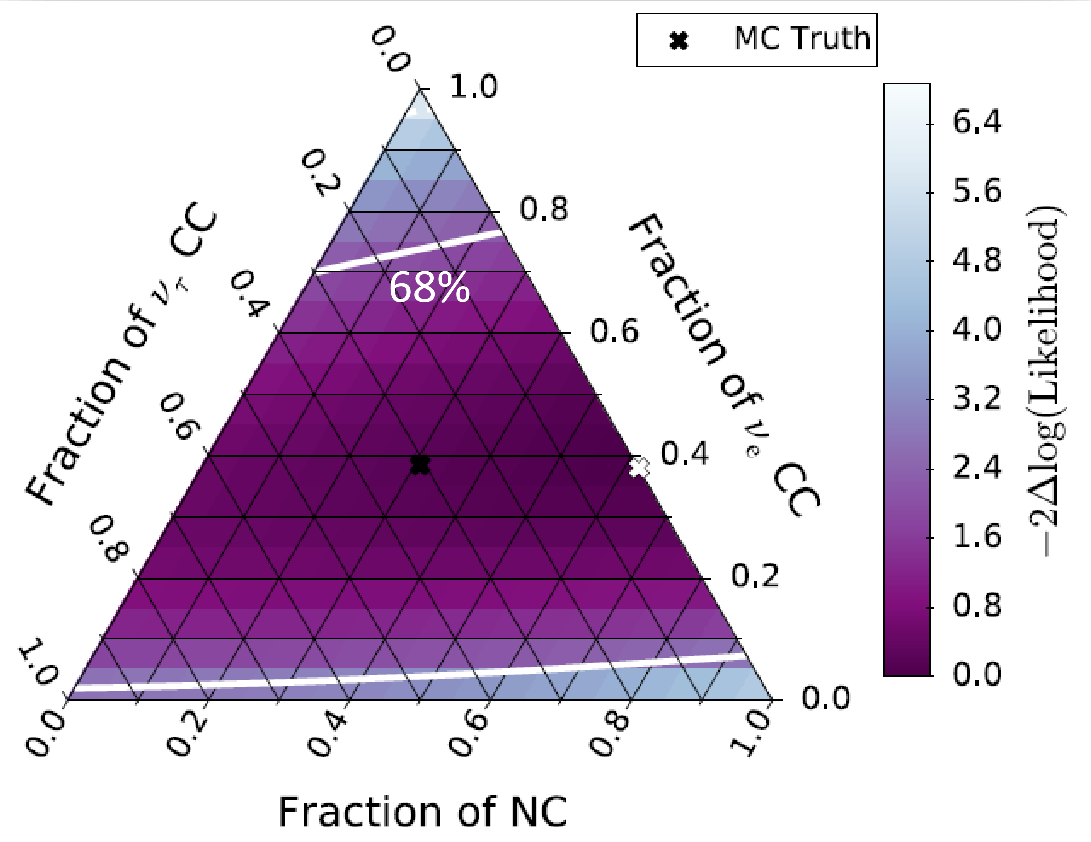
Isotropic neutron echo γ's

$$P_b = \frac{1}{N_{DOM}}\cdot\frac{f_{dt}(t_j)}{\int_{t_1}^{t_2} f_{dt}(t)dt}$$

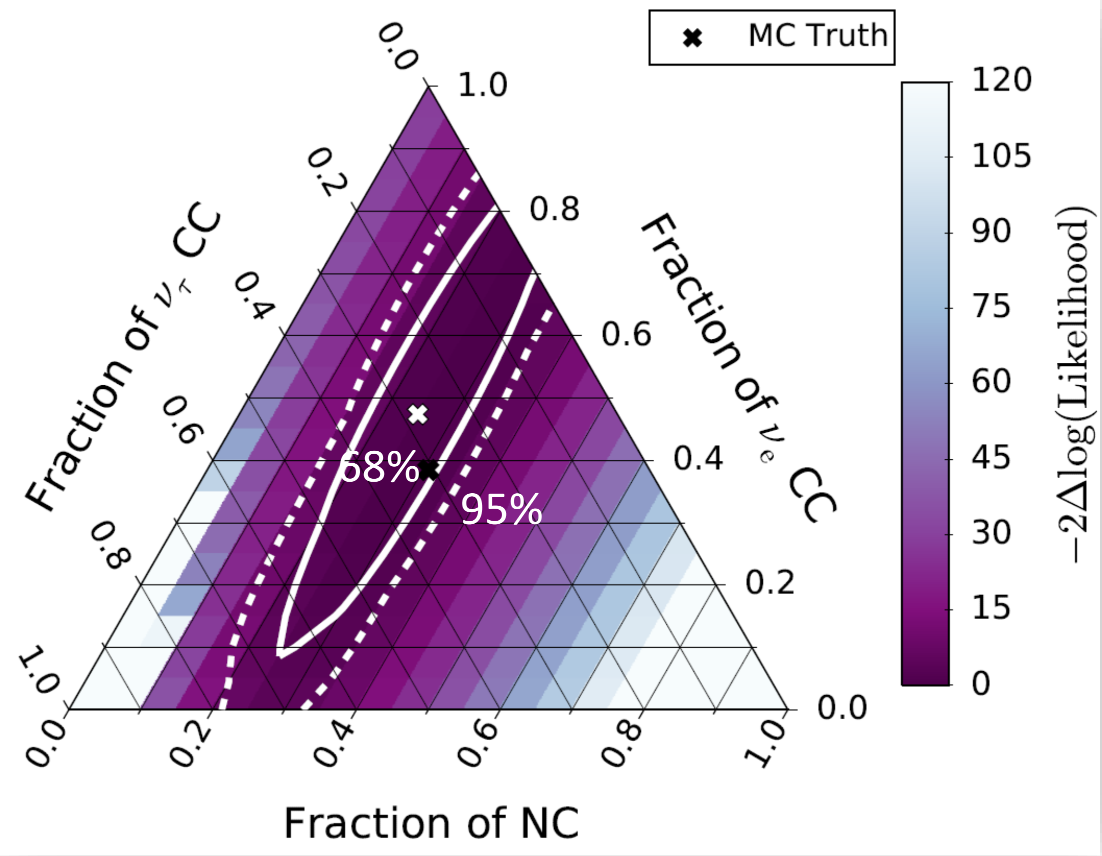
deadtime correction for dark noise

Simulation Results: based on 13 random HESE events

Cascade type space

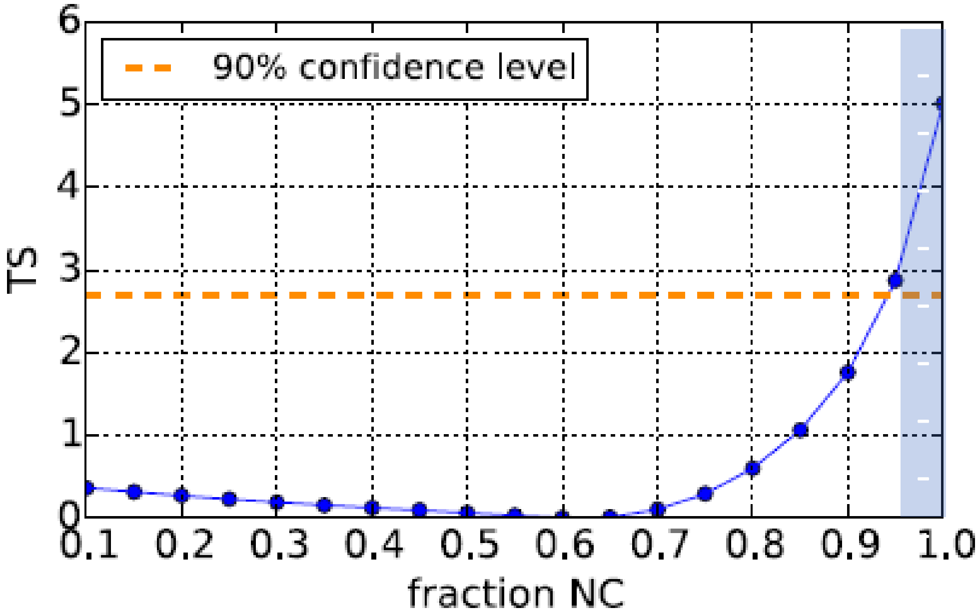


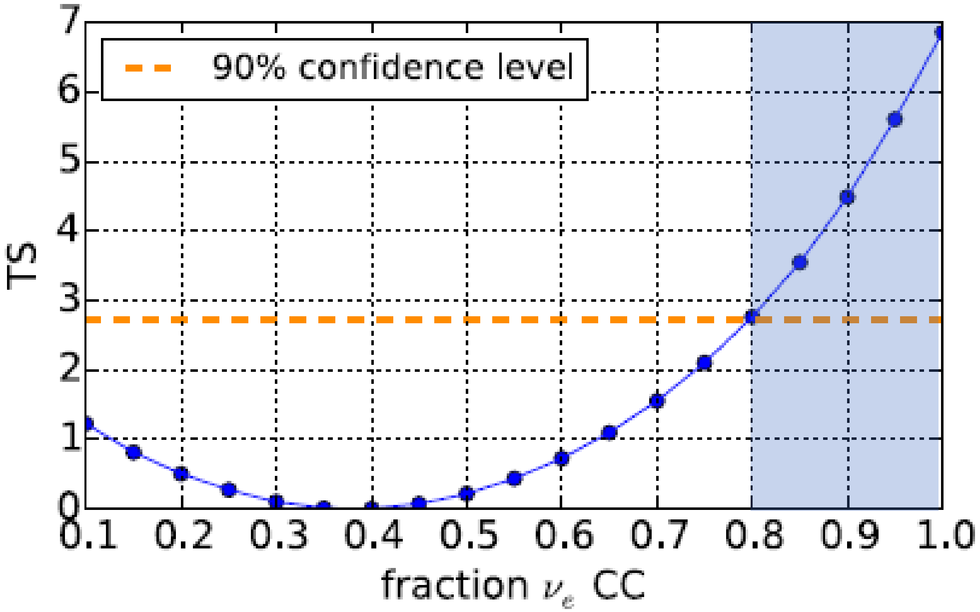
Cascade type space (with ν_μ information)



Assumptions: 13 randomly chosen MC showers, corresponding to the number of events seen in data by Dec 18 (56 % systematic uncertainty), SM cross section ratios are assumed in right plot

Simulation results: Projected distributions



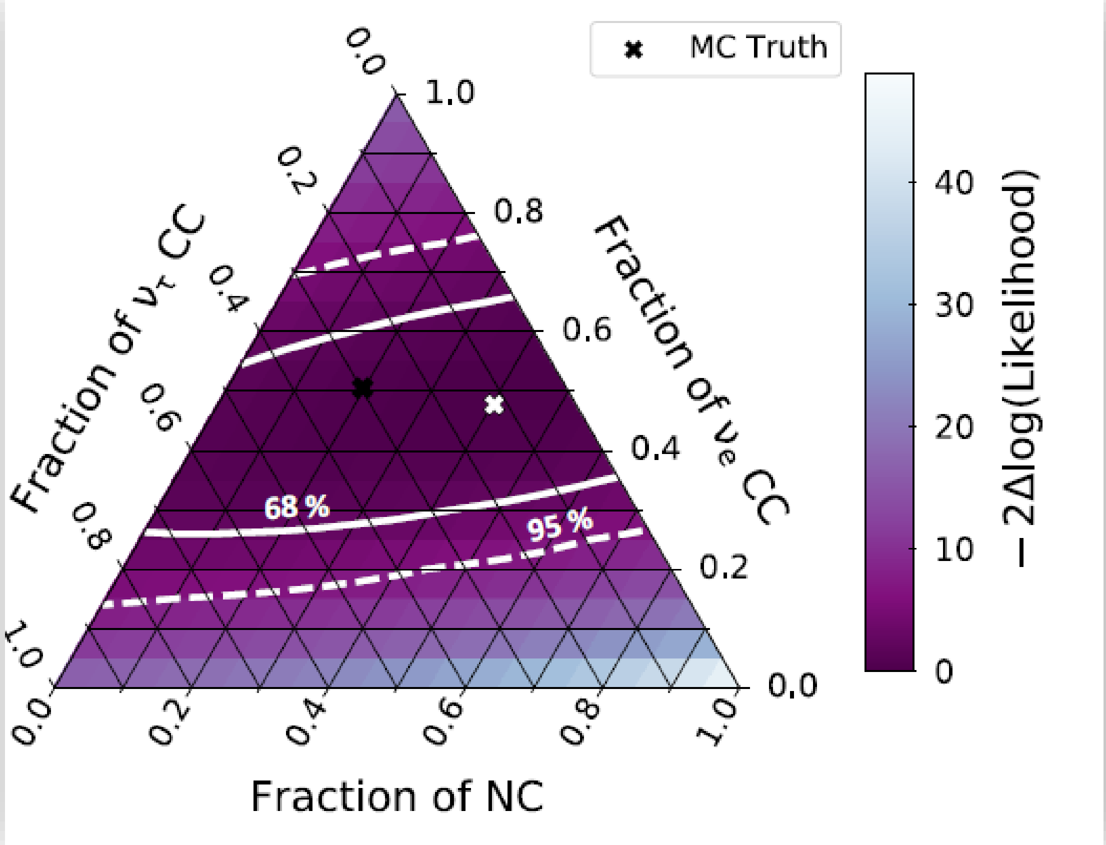


Wilks theorem assumed, i.e. a χ^2 with one degree of freedom determines the 90% confidence level

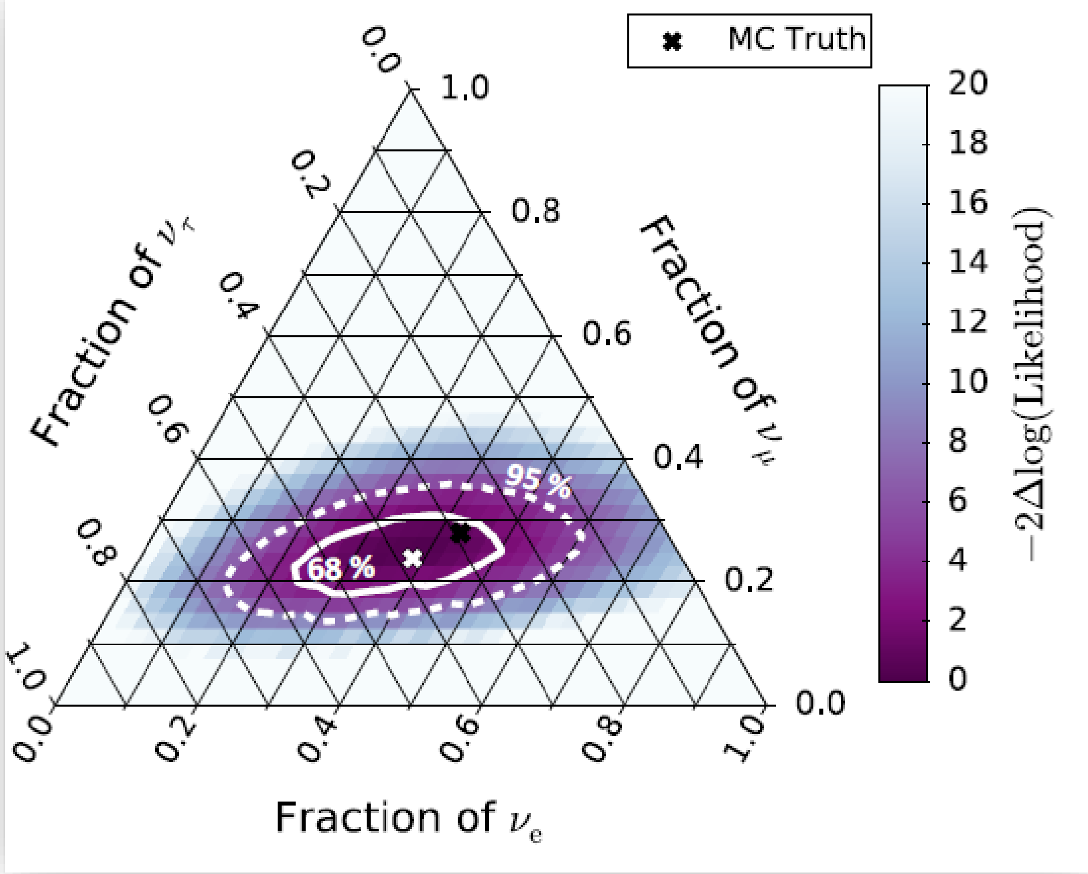
Just 13 events would allow one to rule out 100% neutral current or 100% purely electromagnetic interactions

Future: Expectations for three years of GEN-2 data

Cascade type space

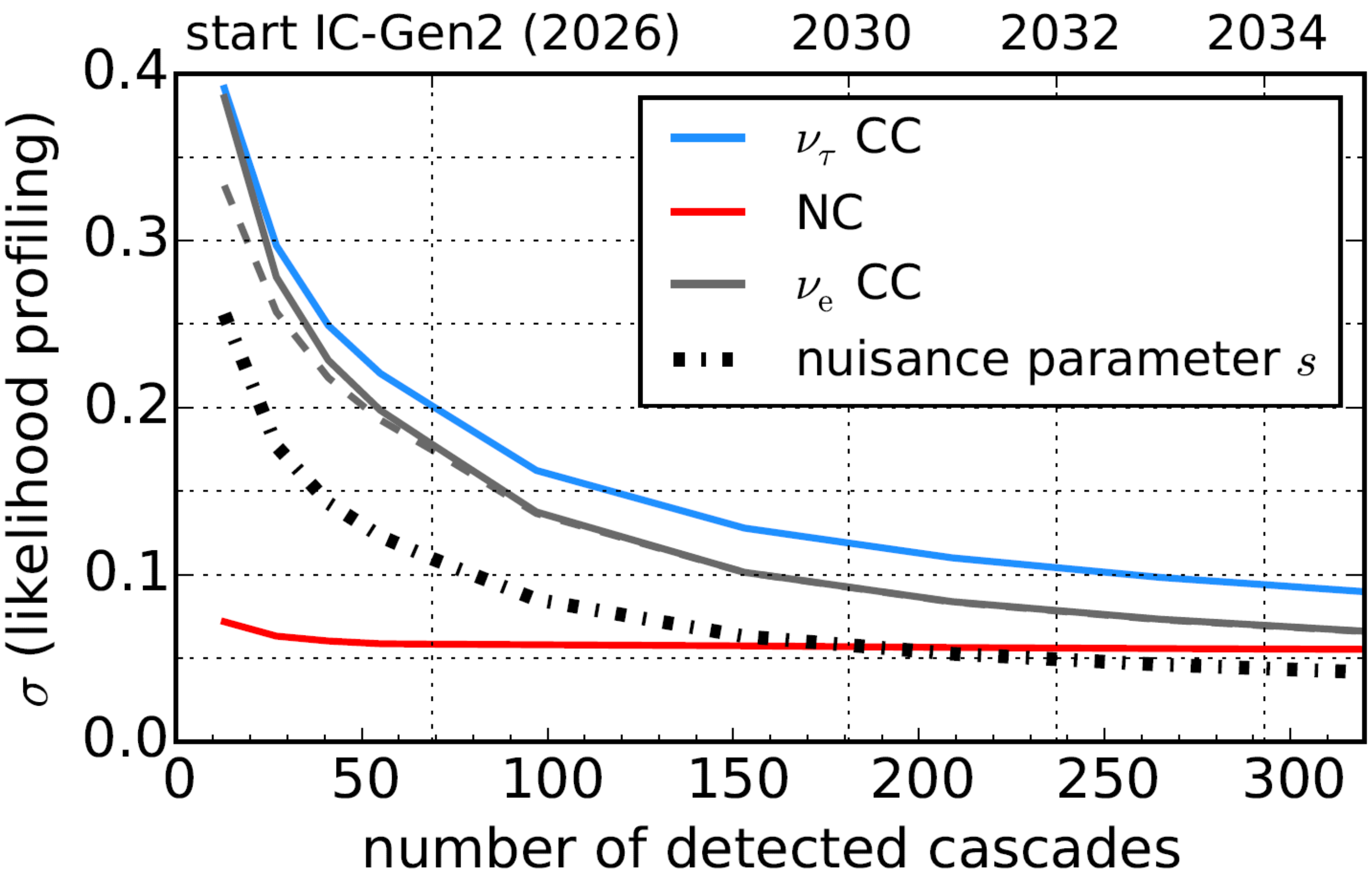


Flavor space (with ν_μ information)



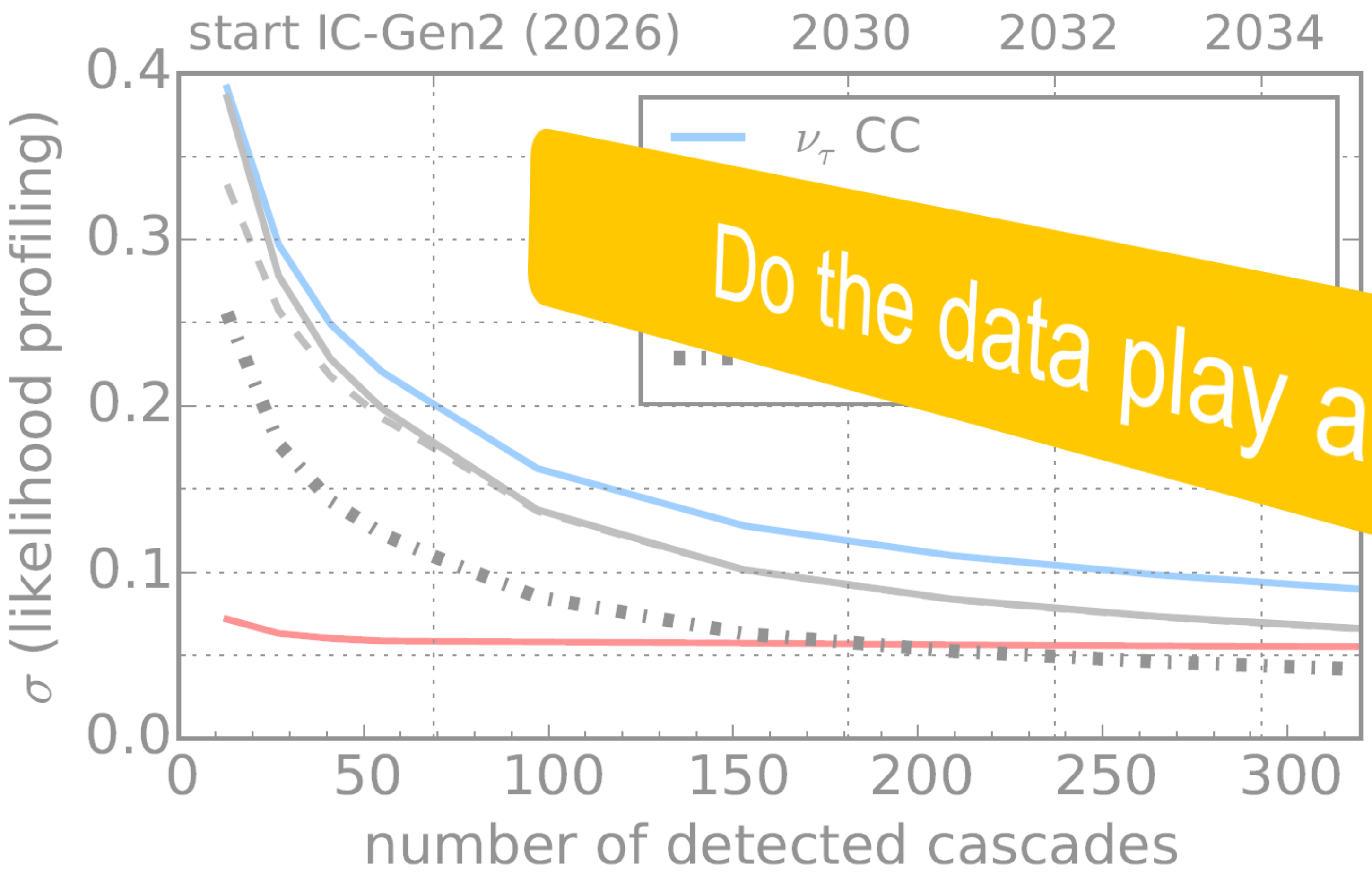
Assumptions: 84 showers in 3 years with 4 x higher event rate and 2 x higher Cherenkov detection efficiency no DAQ deadtime (56 % systematic uncertainty is minor effect for large datasets)

Future: Expectations for GEN-2 (+ IceCube) data



- Resolutions of better than 20% for ν_τ and ν_e fractions achievable rather quickly
- Systematic uncertainty soon unimportant → fitted as nuisance parameter
- In principle, powerful addition to flavor id

Future: Expectations for GEN-2 (+ IceCube) data

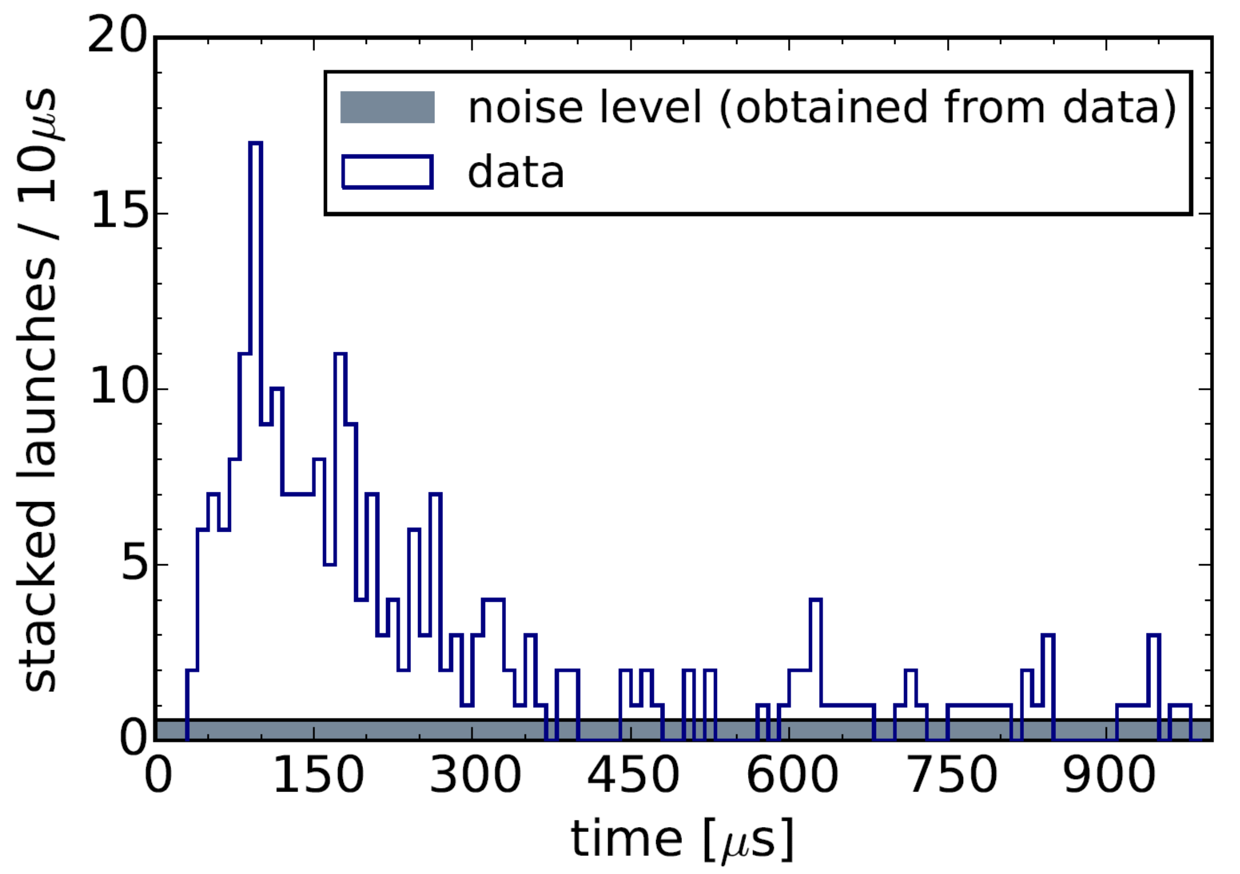


Do the data play along?

- Resolutions of better than 20% ν_τ and ν_e achievable rather quickly
- Systematic uncertainty soon unimportant d as nuisance parameter
- ve to flavor id

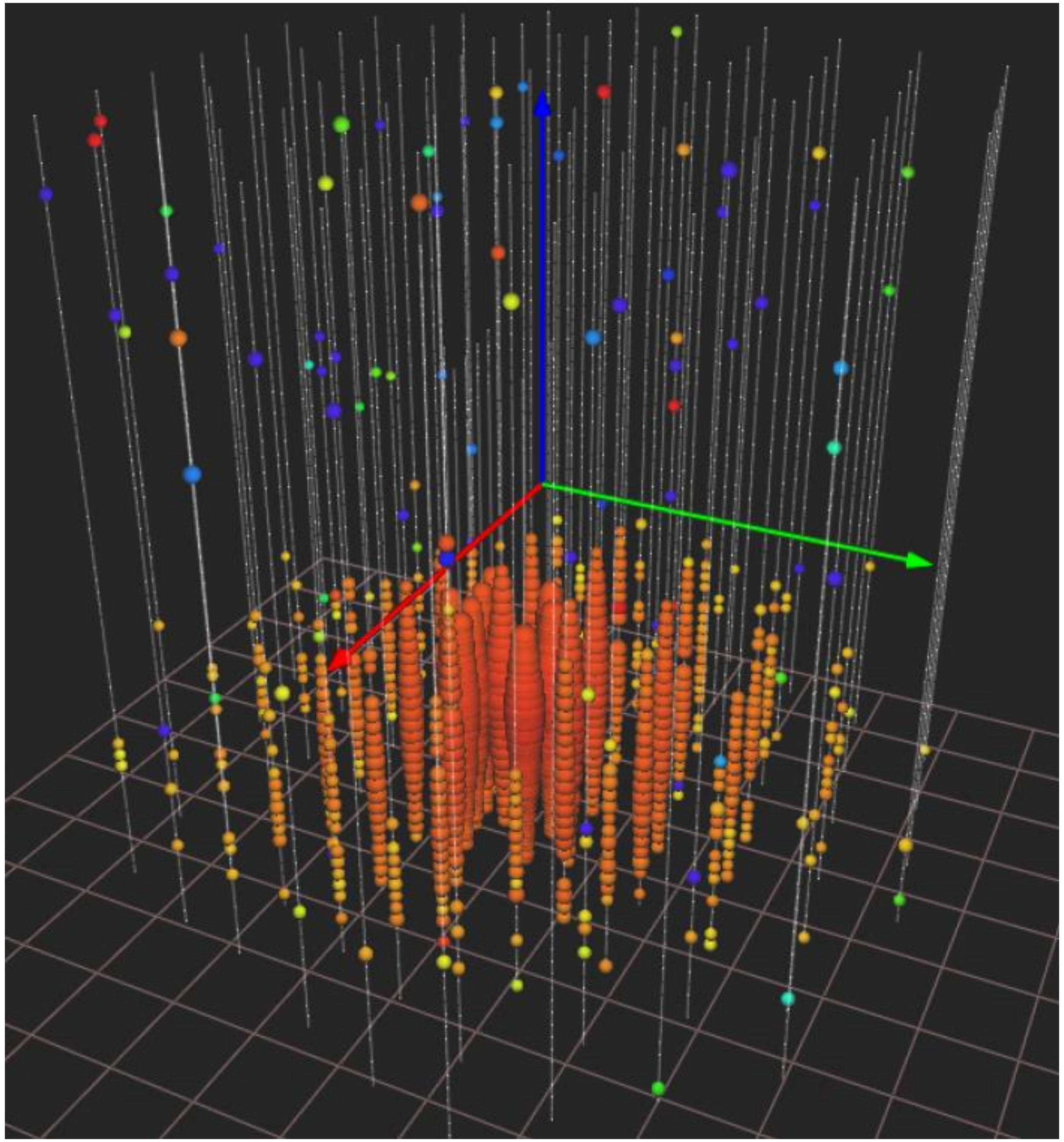
Data: Looking at 13 HESE events taken after 2016

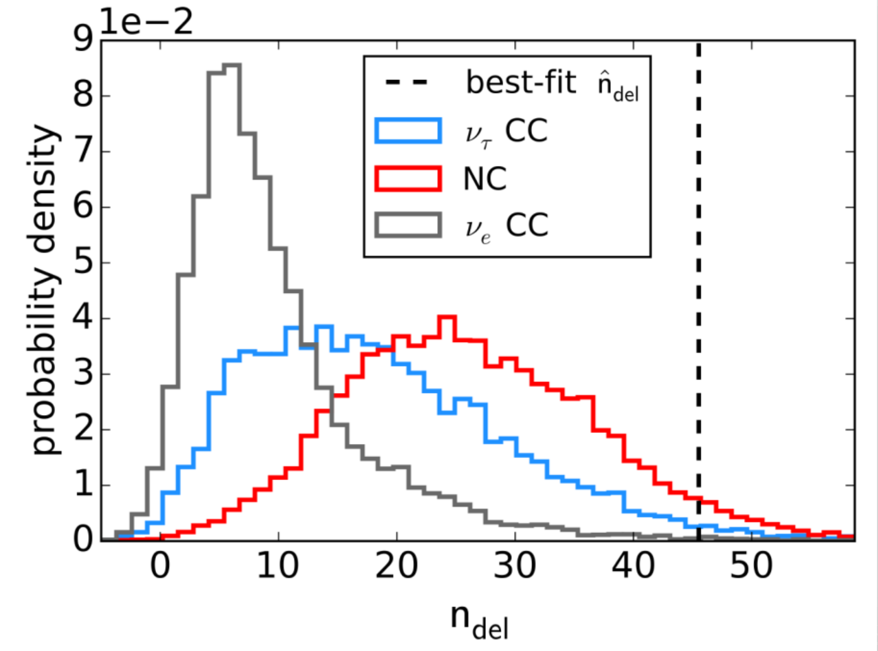
Clear delayed signal seen above noise level !

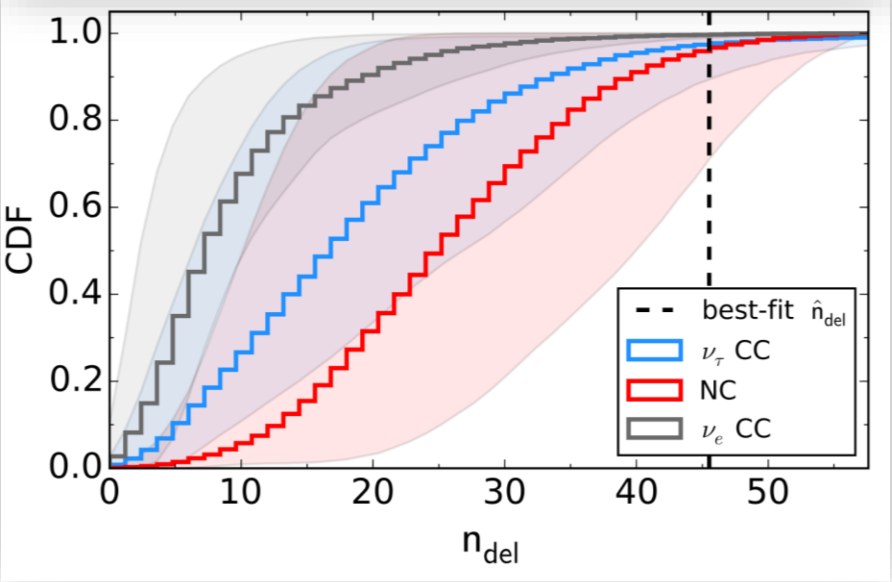


- Rate within 56% uncertainty of neutron expectation
- Expected effects of deadtime seen
- Noise level reasonably low (8 DOMs/event selected)
- Strong contribution by one event in DeepCore

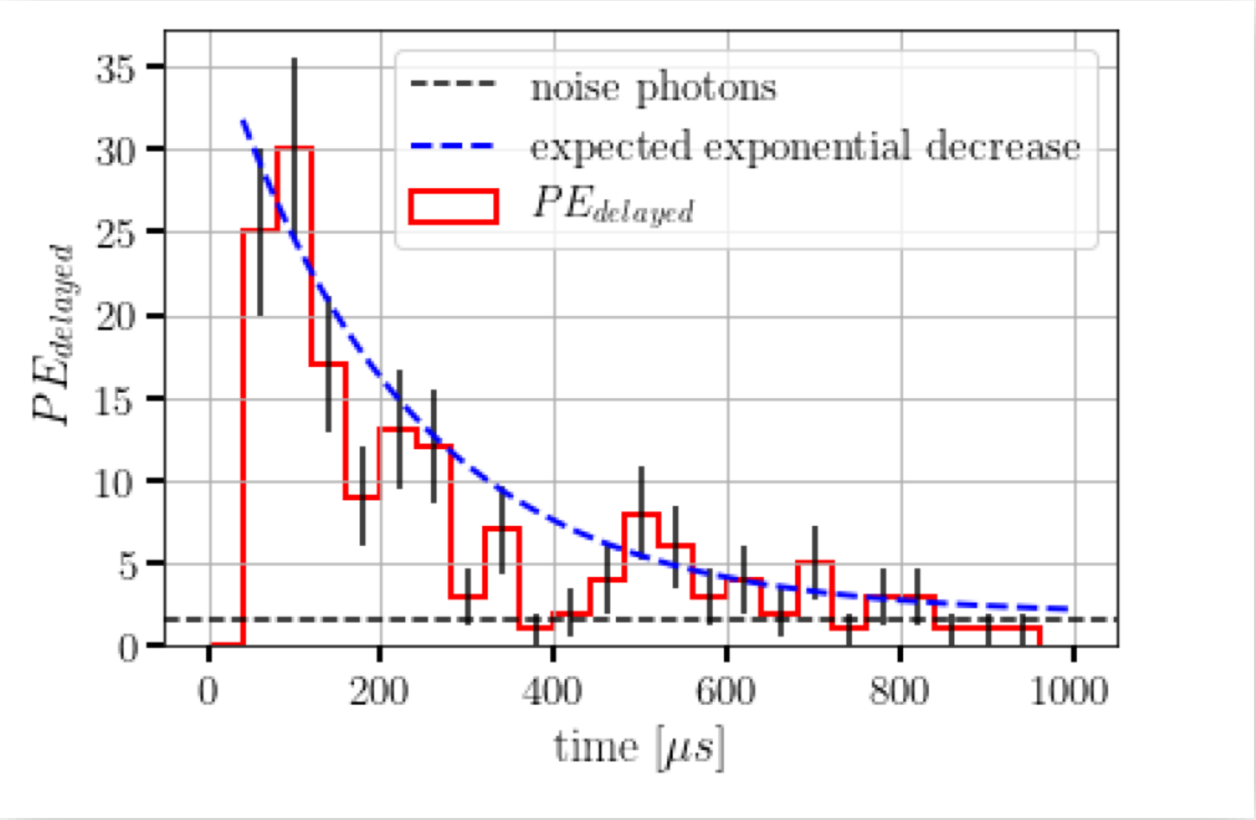
26.6.2017: Event with largest observed afterglow

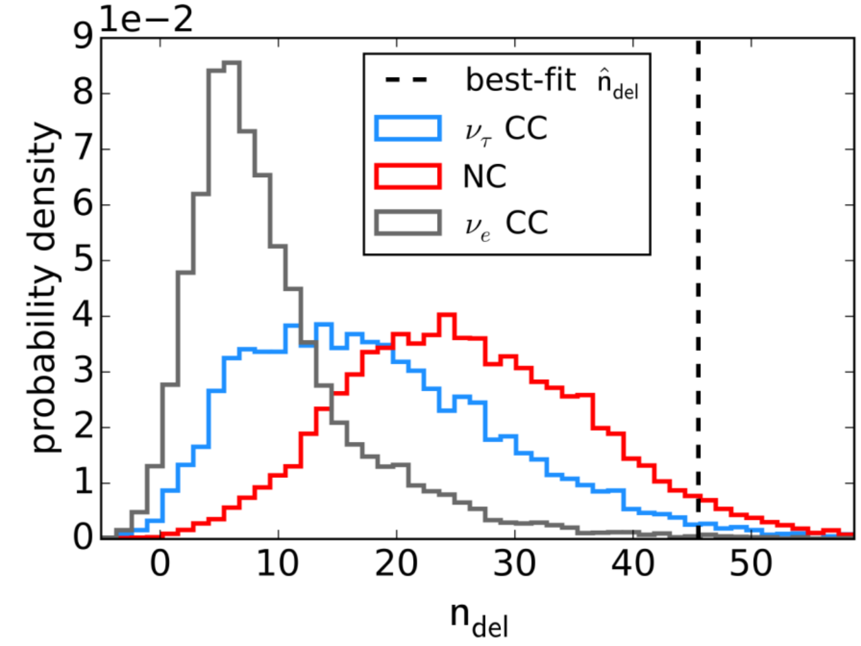


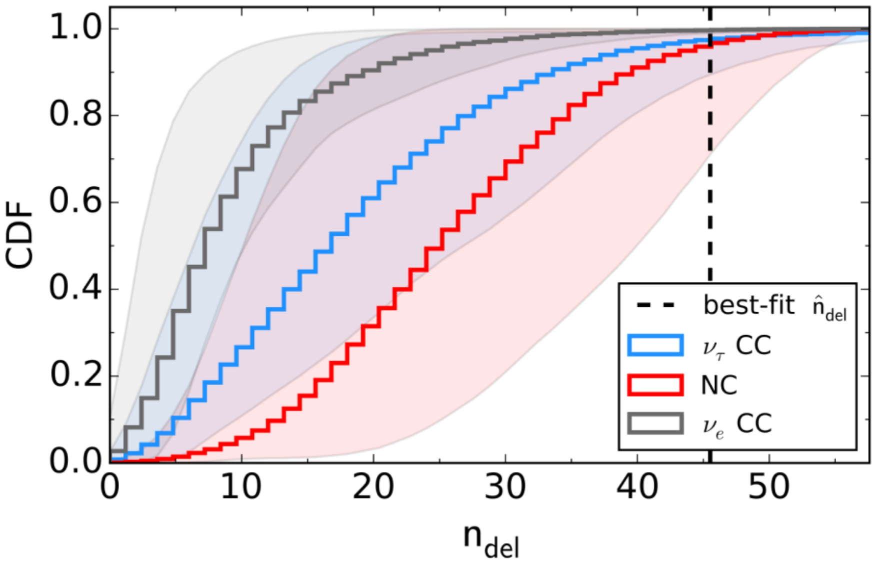




26.6.2017: Event with largest observed afterglow



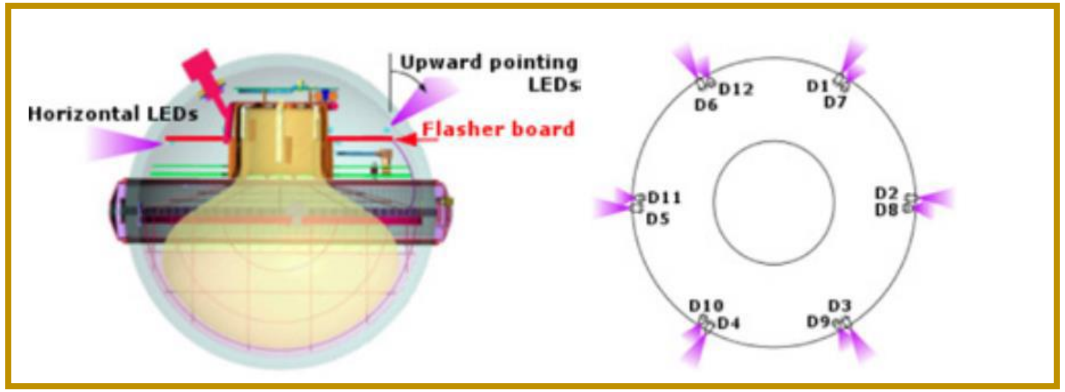


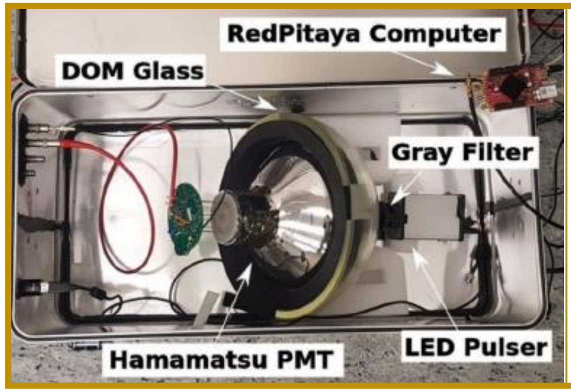


BUT

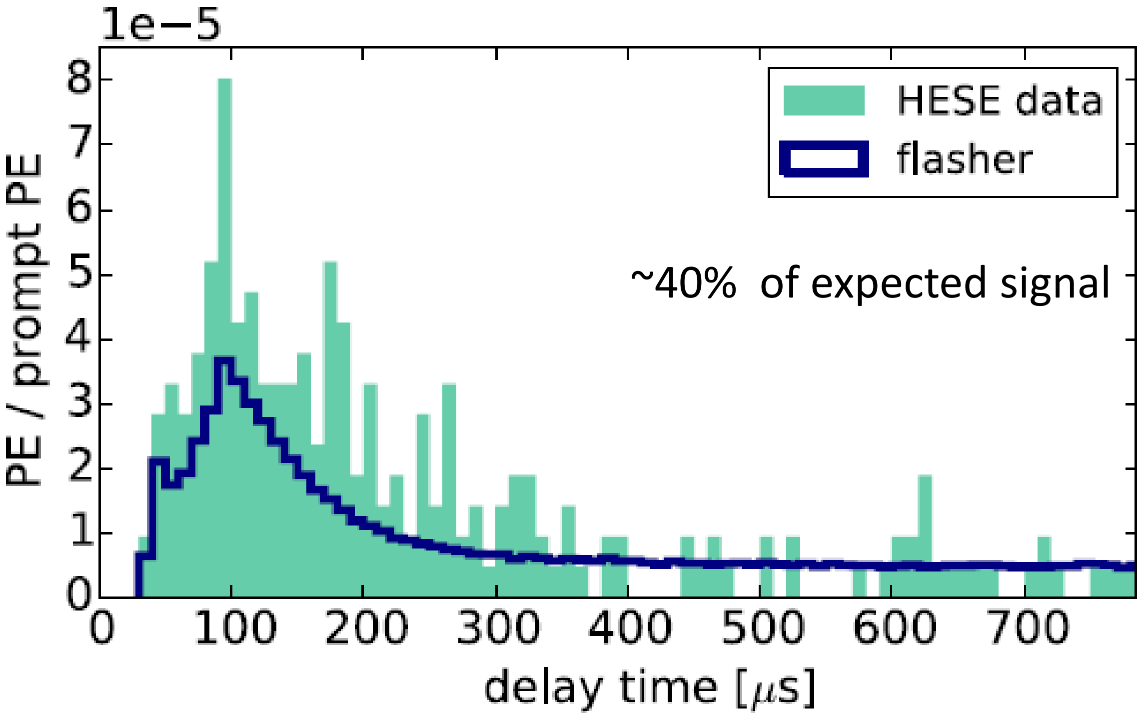
Artifact: Lab and in-situ measurements with LEDs

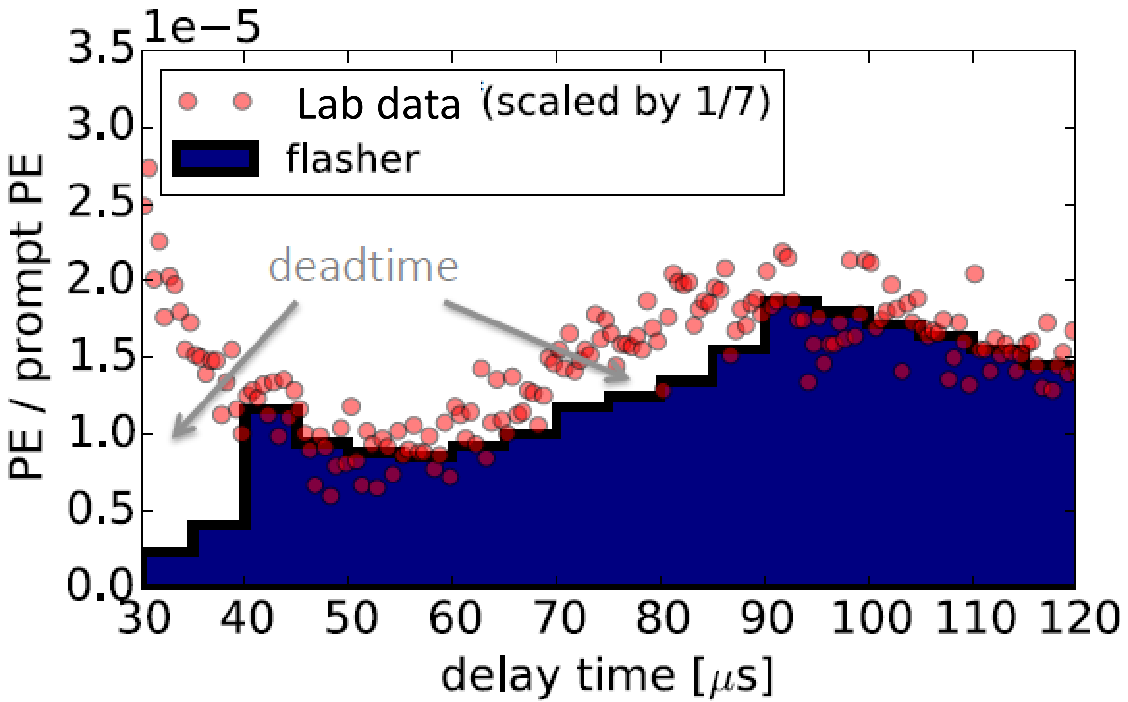
Unexpected delayed signal from PMT seen at 40% of expected signal:





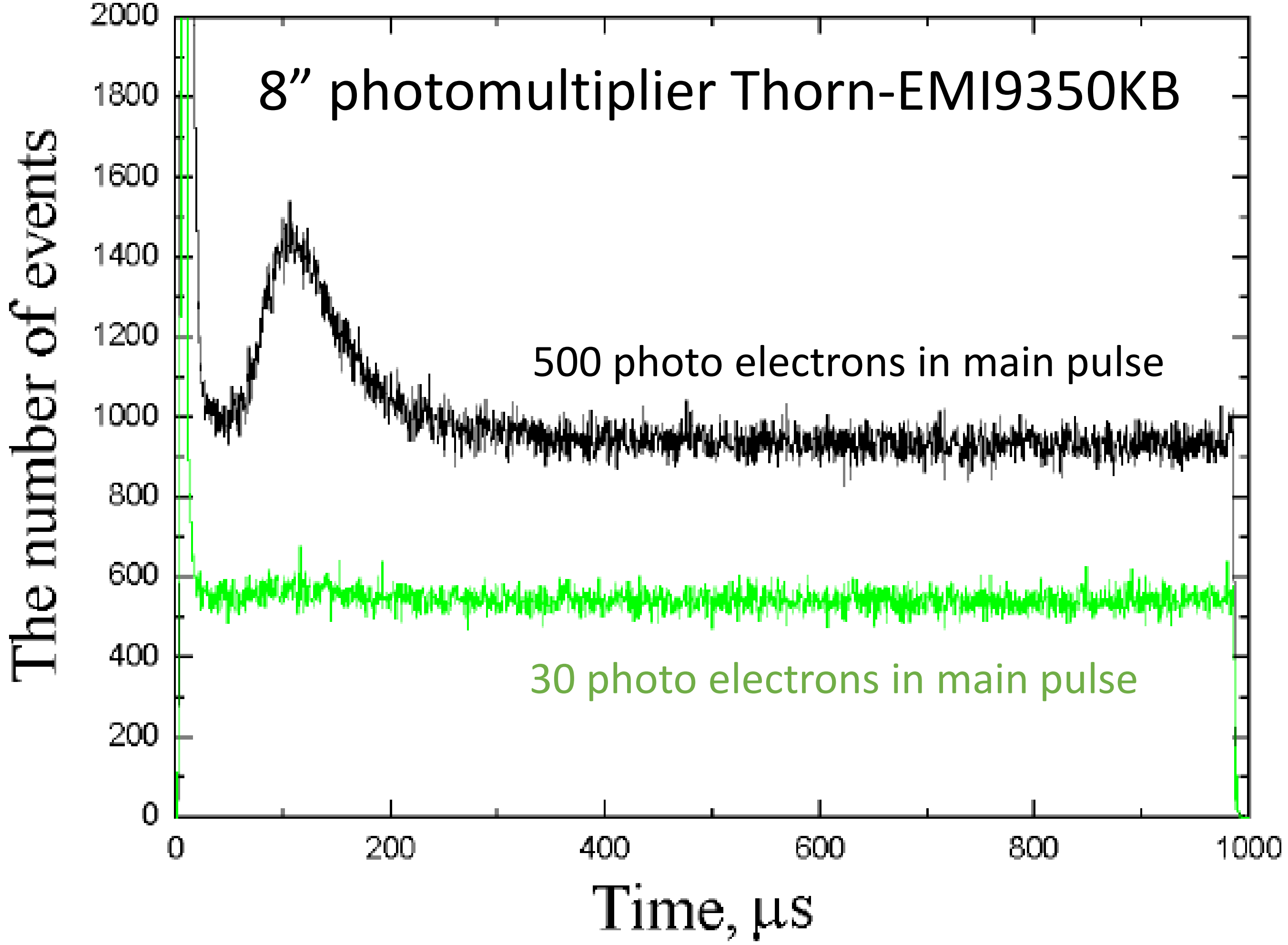
375 nm LED





Seen before: similar effect with different PMT!

R.V. Poleshchuk, B.K. Lubsandorzhiev, R.V. Vasiliev: NIMA: NIMA 695 (2012)

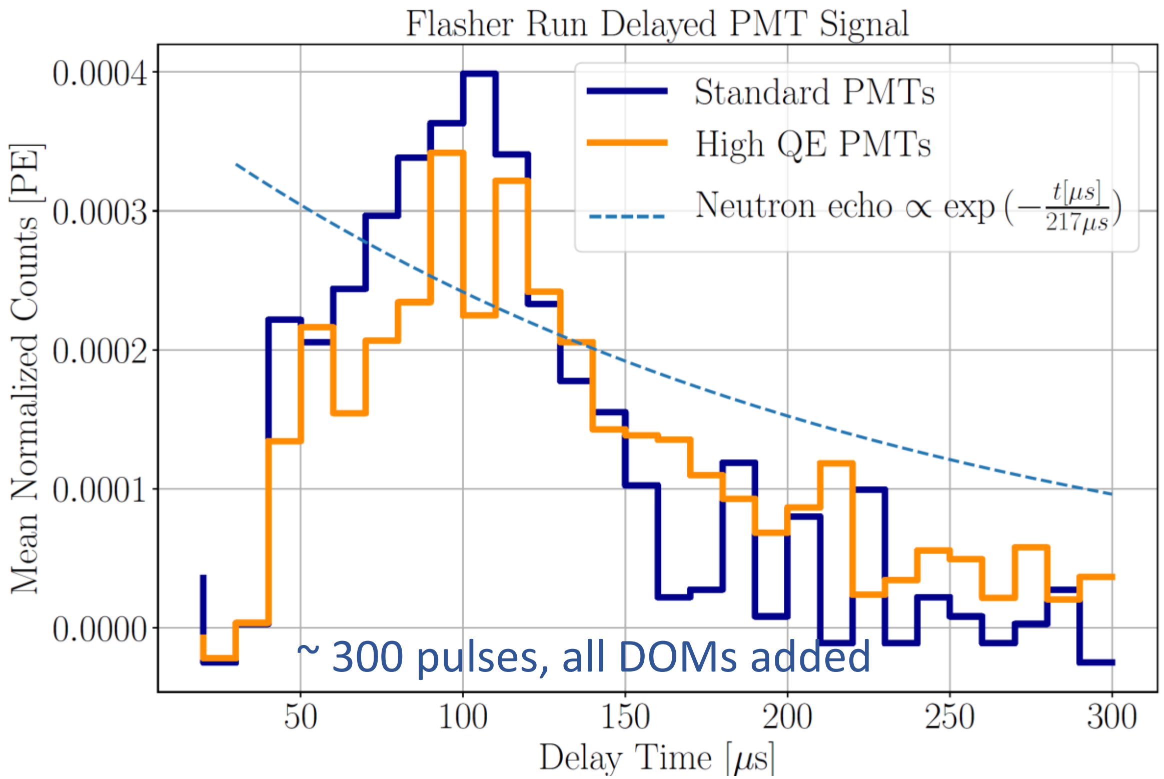


Specific problem with large diameter PMTs?
Cathode effect?

New: also confirmed by Hamamatsu

Characteristics: properties of delayed pulses

- Rate ~ 40% of neutron capture expectation, time distribution similar but not the same
- Rate and time depend on PMT, cathode and temperature but not voltage, glass luminescence or activation
- Approximately linear dependence on prompt signal



~ 300 pulses, all DOMs added

Is there any chance to distinguish delayed pulses from neutron echo?

Yes: time distribution slightly different
different geometric pattern (Cherenkov / 4π)

Summary

- **Neutron tagging has great potential for > 100 TeV contained cascades**
  - Discover exotic interactions resulting in electron or hadron recoil
  - Tag τ neutrinos, Glashow resonance events or neutral current events …
- Muon tagging much more difficult (delayed light, afterpulses)
- Large systematic uncertainty on neutrons can be treated as nuisance parameter
- **Need low noise PMTs without PMT related delayed signal around 100 μs!**

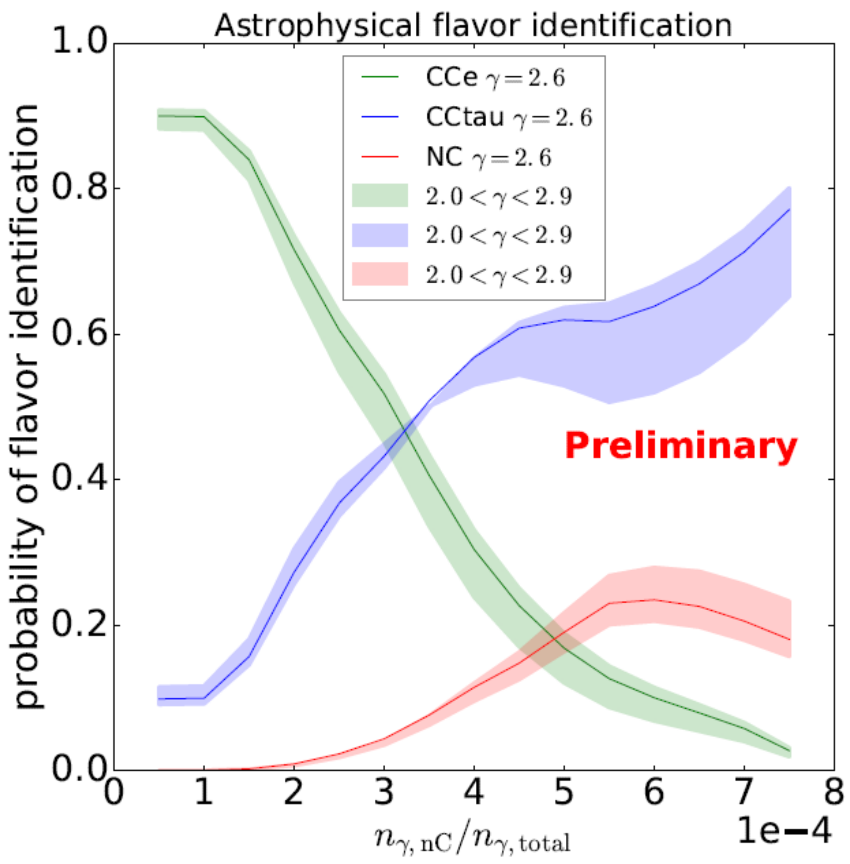
Background: Anna Steuer, PhD thesis, JGU Mainz (2018); A. Steuer, L. Köpke, PoS ICRC2017, 1008 (2017)

Theory: *Echo Technique to Distinguish Flavors of Astrophysical Neutrinos*
Shirley Weishi Li, Mauricio Bustamante, John F. Beacom, Phys. Rev. Lett. 122, 151101 (2019); arXiv:1606.06290

Additional material

Bayesian interpretation

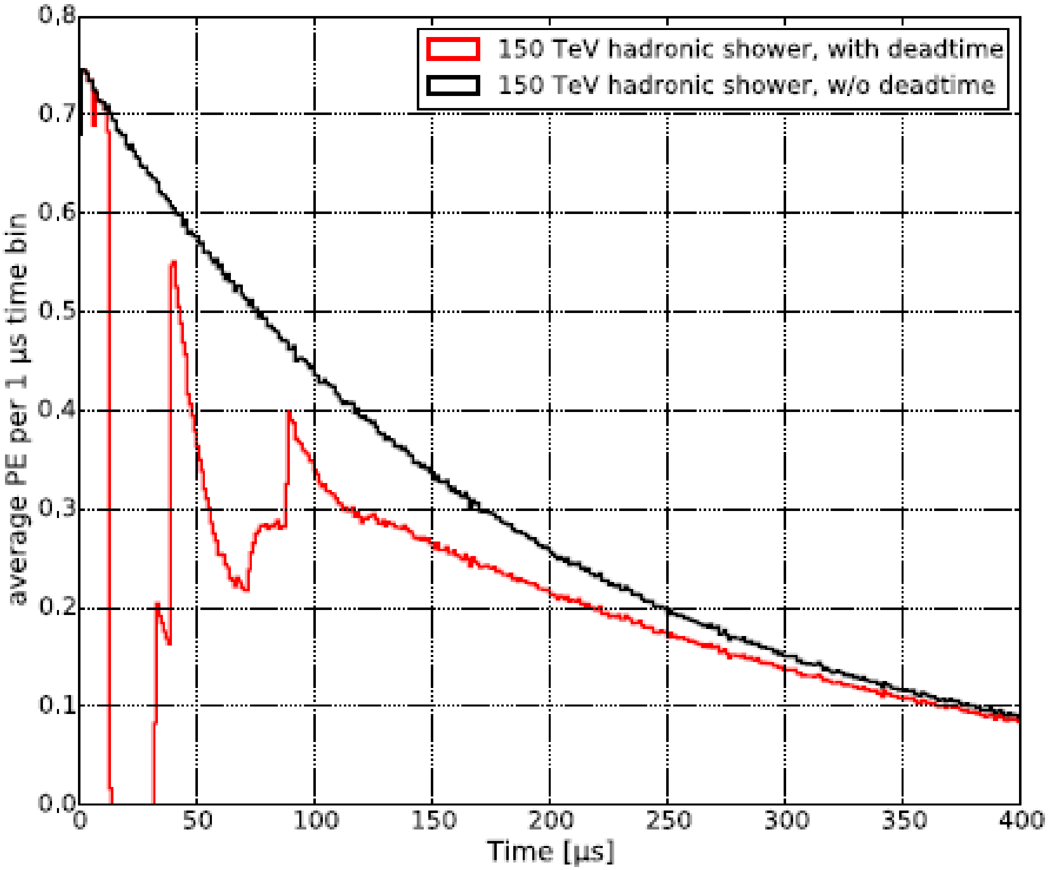
Following method decribed in Appendix of S. Li, M. Bustamente and J.F. Beacom, arXiv:1606.06290



Example showing dependence on assumed energy dependence on flux

Example for deadtime effect (Monte Carlo)

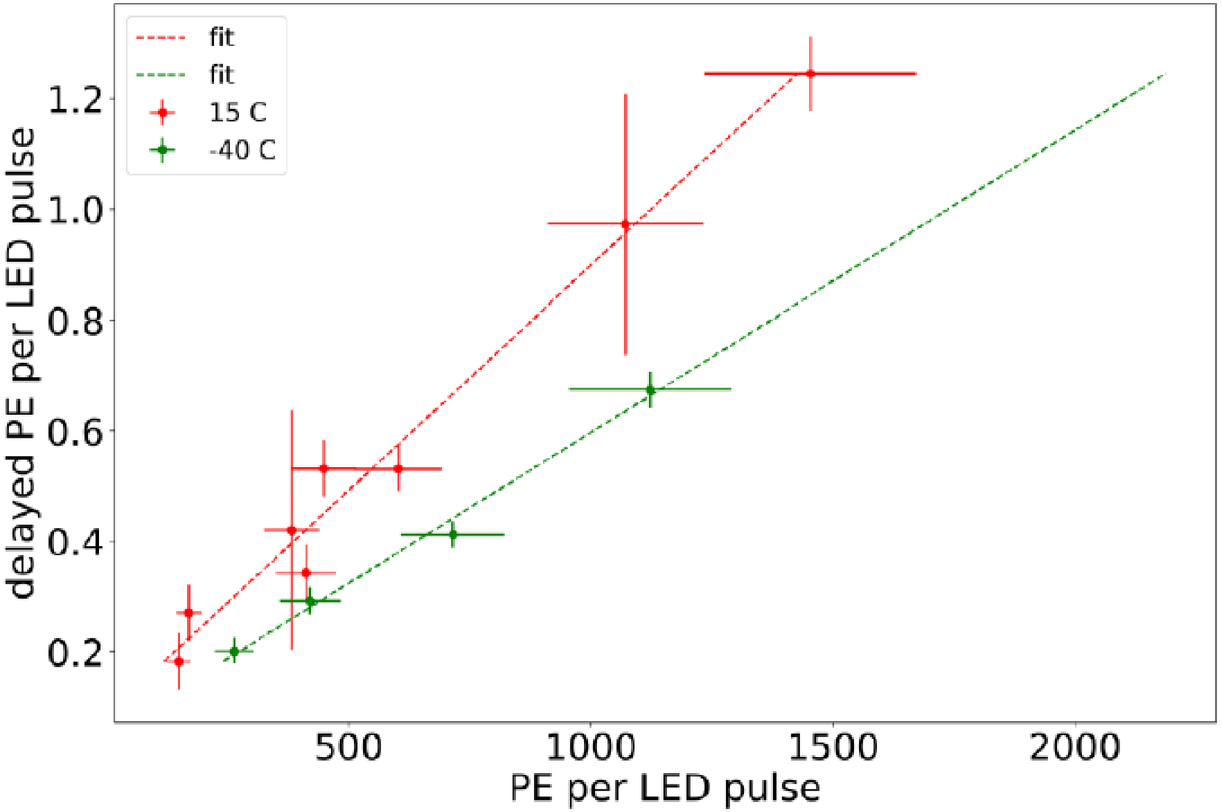
IceCube electronics introduce complex deadtime effect for times > a few microseconds
(the effects do not influence the analysis of standard IceCube events!)



Example for a 700 TeV shower close to string

Linearity & temperature dependence of delayed pulses

Laboratory results at room temperature and in freezer



- Linear dependence on light level
- temperature / photo cathode / individual PMT dependent
- no dependence on pressure sphere observed

PMT effects are not easy to understand …