Search for Nucleon Decay in the future LENA detector

BLV 2011 Workshop
Gatlinburg, Sept 22

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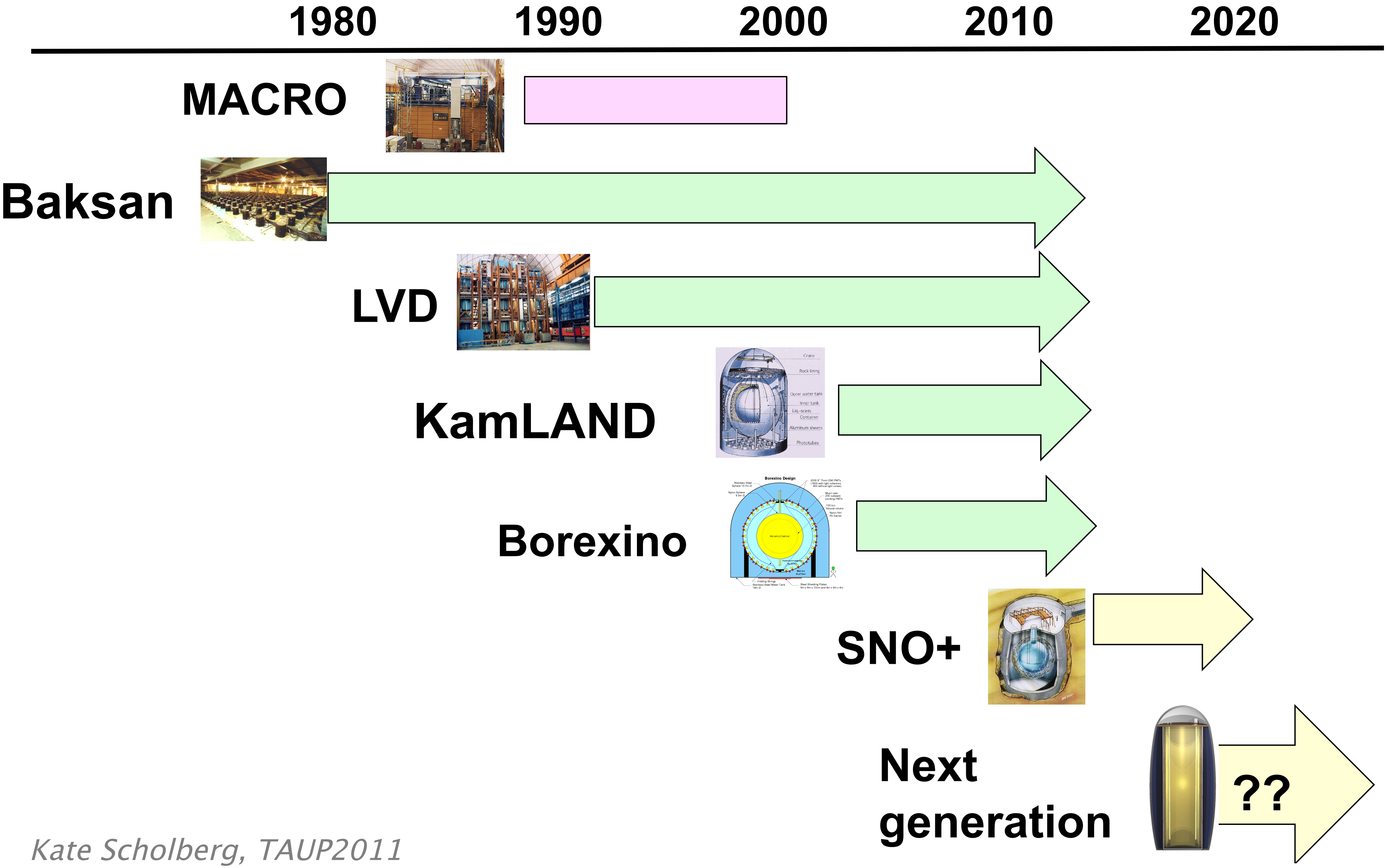
Universität Hamburg

Large volume liquid-scintillator detectors



1980 1990 2000 2010 2020

MACRO

Baksan

LVD

KamLAND

Borexino

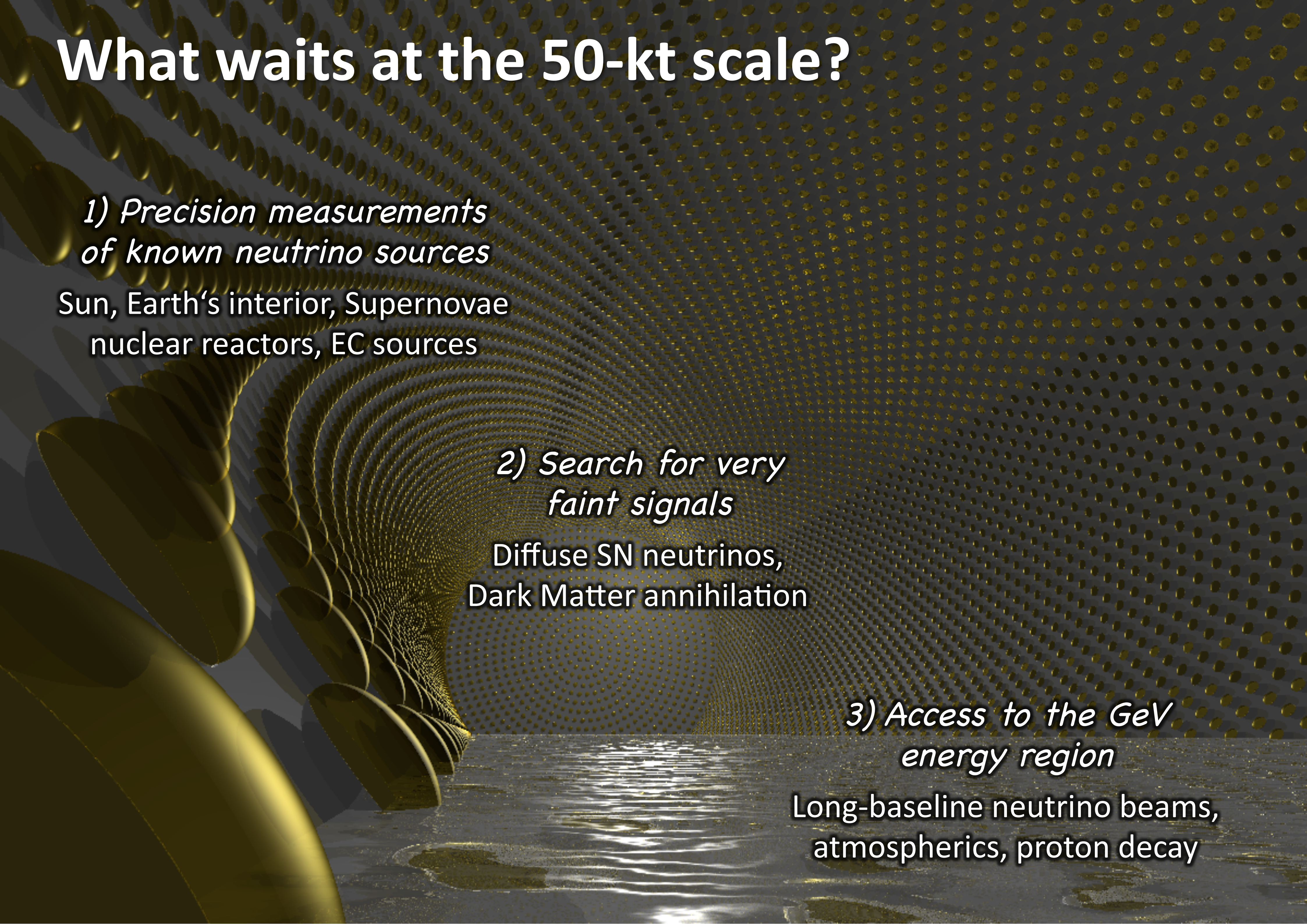
SNO+

Next generation

??

Kate Scholberg, TAUP2011

What waits at the 50-kt scale?



1) Precision measurements of known neutrino sources

Sun, Earth‘s interior, Supernovae
nuclear reactors, EC sources

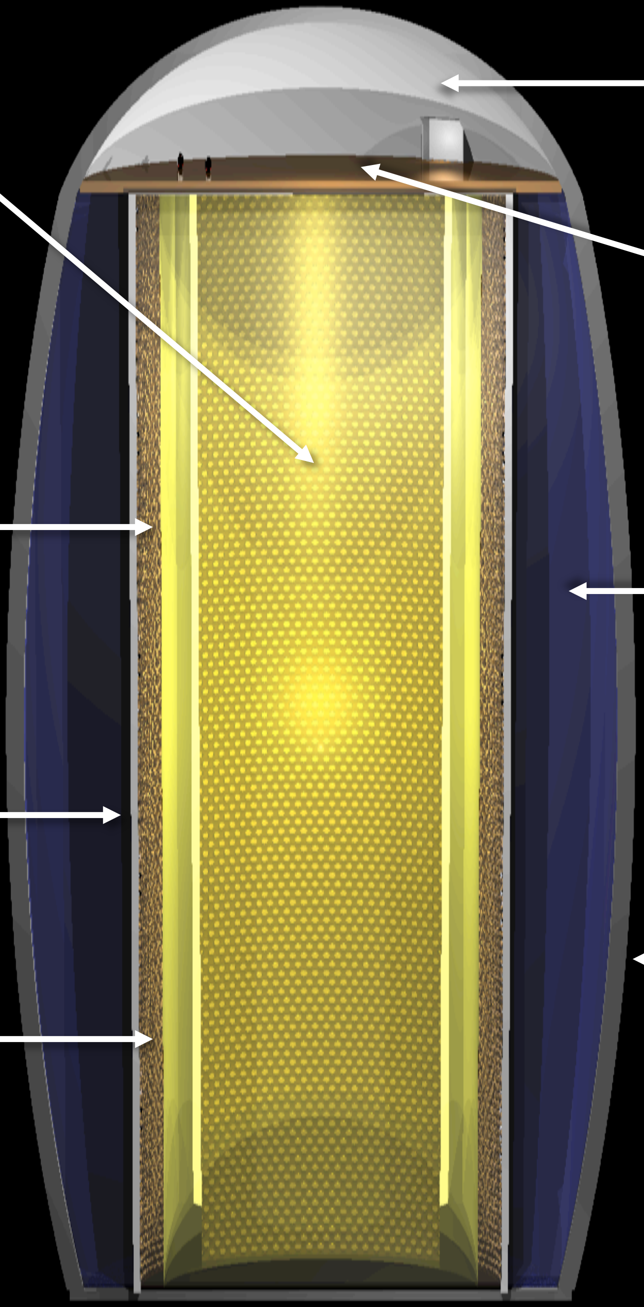
2) Search for very faint signals

Diffuse SN neutrinos,
Dark Matter annihilation

3) Access to the GeV energy region

Long-baseline neutrino beams,
atmospherics, proton decay

LENA detector layout



Liquid Scintillator
ca. 50kt LAB

Inner Nylon Vessel
radius: 13m

Buffer Region
inactive, $\Delta r = 2$m
ca. 20kt LAB

Steel Tank
r = 15m, h = 100m

50,000 8‘‘-PMTs
Winston cones
optical coverage: 30%

Electronics Hall
dome of 15m height

Top Muon Veto
limited streamer tubes
vertical muon tracking

Water Cherenkov Veto
3000 PMTs, $\Delta r > 2$m
fast neutron shield
inclined muons

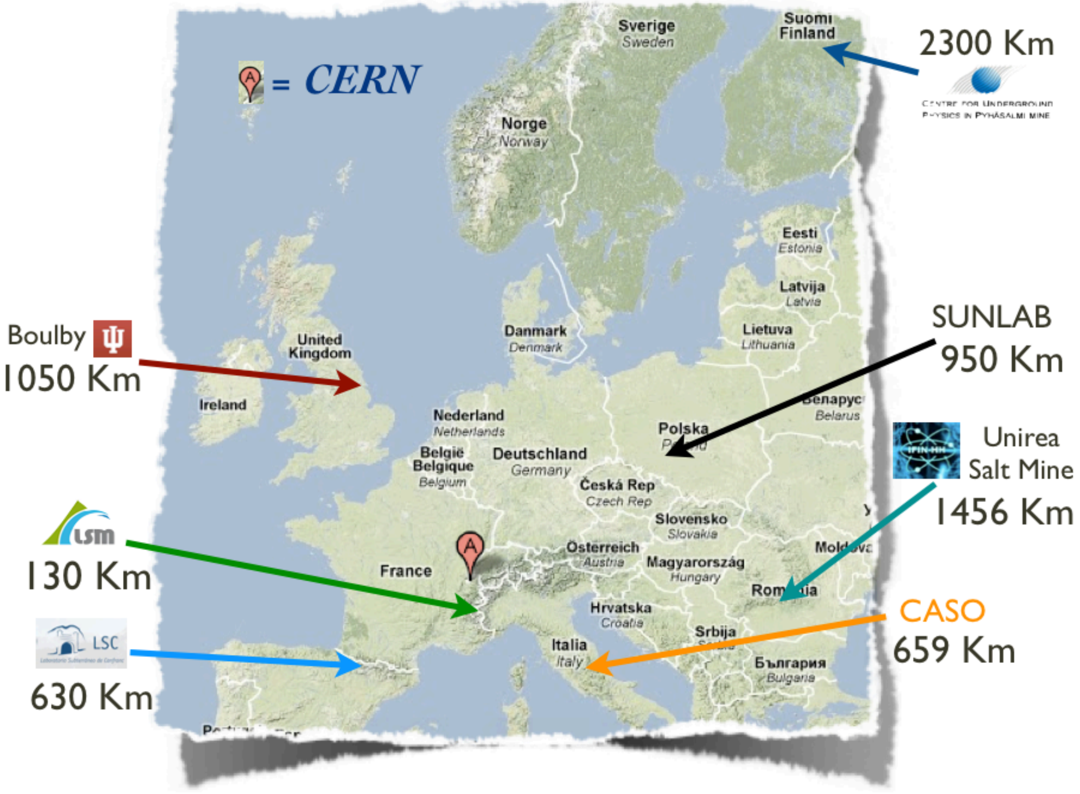
Egg-Shaped Cavern
about 10^5 m^3

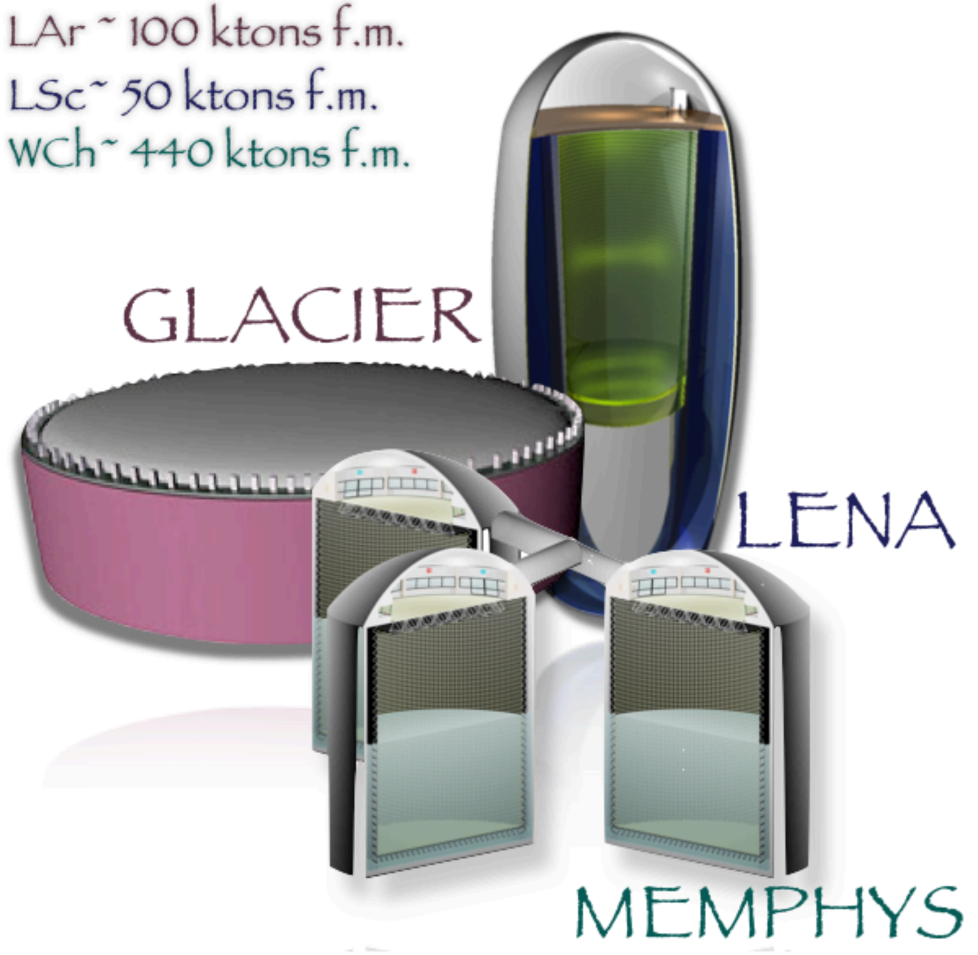
Rock Overburden
at least 3500 mwe

LAGUNA → LAGUNA-LBNO

- Consortium of European science institutions and industry partners
- Design studies funded by the European Community (FP7)
- **LAGUNA:** detector site, cavern, and oscillation baselines (2008-11)
- **LAGUNA-LBNO:** detector tank, instrumentation, and beam source (2011-14)

Seven sites, three detector technologies




LAr ~ 100 ktons f.m.
LSc ~ 50 ktons f.m.
WCh ~ 440 ktons f.m.

Considered proton decay modes

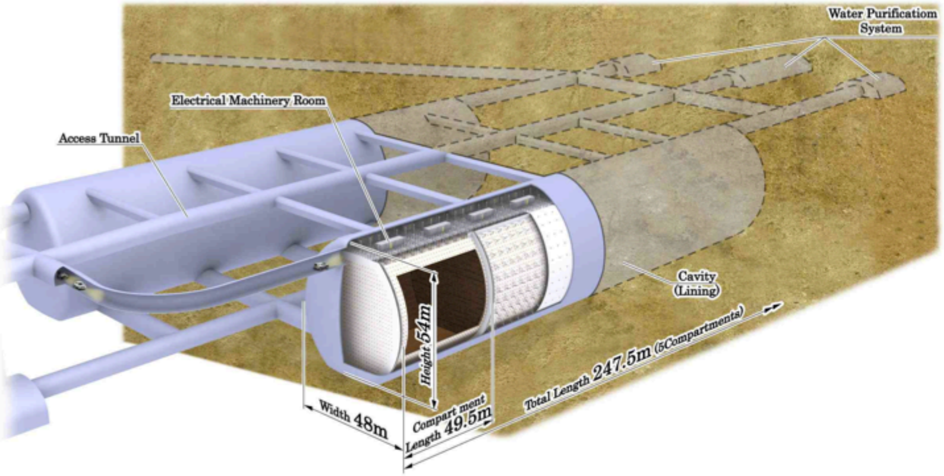
$p \rightarrow \pi^0 + e^+$

favored by standard GUTs

predicted proton lifetime:
$\tau \sim 10^{31-?}$ yrs

current best limit from SK:
$\tau \geq 5.4 \times 10^{33}$ yrs

Large detection efficiency in water, and in this case, size does matter ...



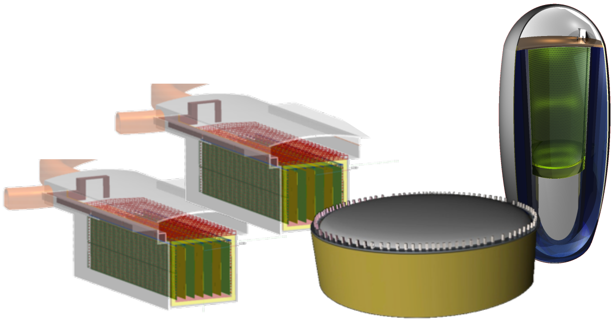
$p \rightarrow K^+ + \bar{\nu}$

favored by SUSY, large BR in SUGRA

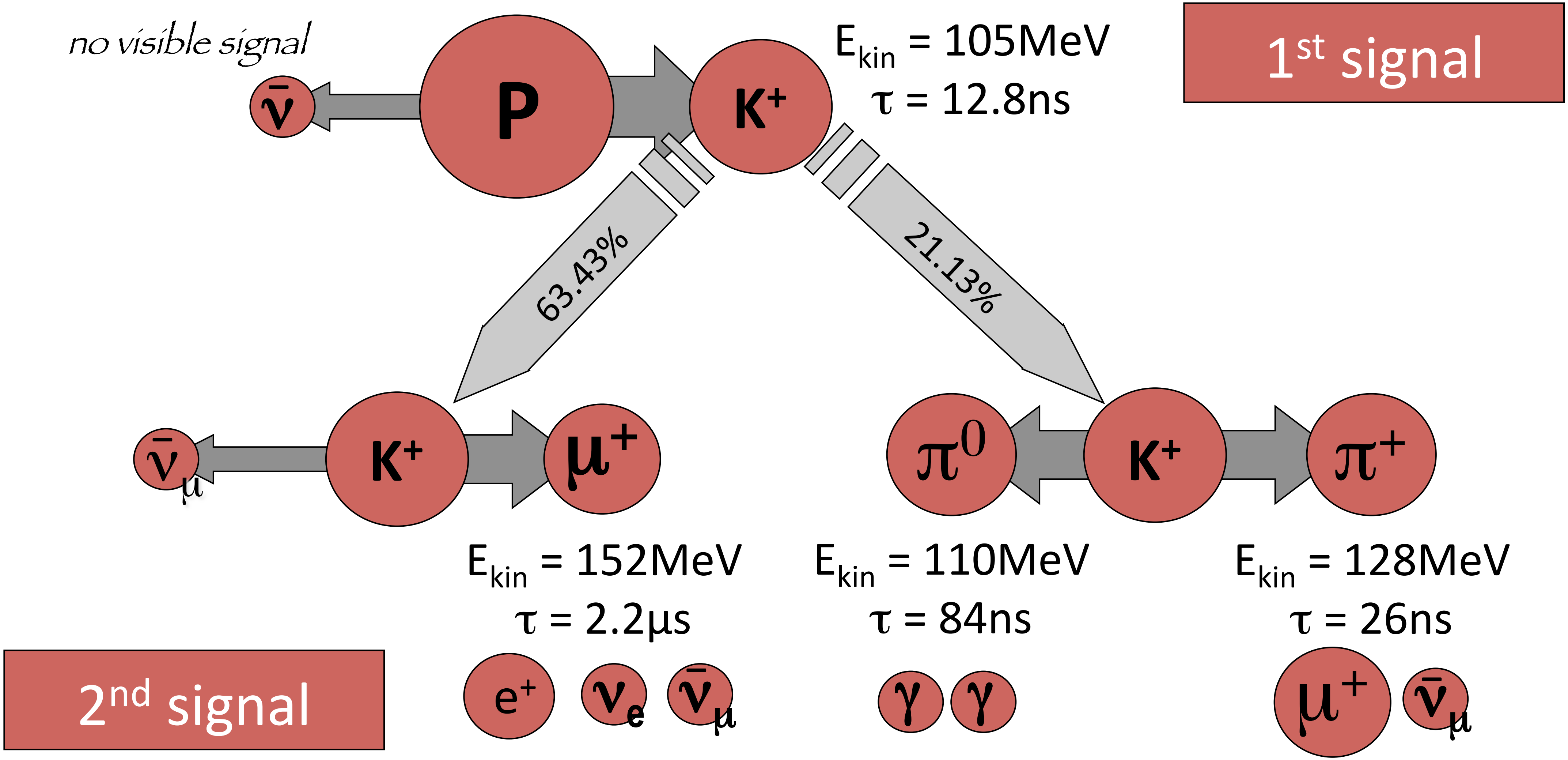
predicted proton lifetime:
$\tau \leq 10^{34-35}$ yrs

current best limit from SK:
$\tau \geq 2.3 \times 10^{33}$ yrs

Low efficiency in water as the kaon is below Cherenkov threshold.
→ Window for „small“ detectors



Signature in liquid scintillator



no visible signal

E_{kin} = 105MeV
τ = 12.8ns

1st signal

E_{kin} = 152MeV
τ = 2.2μs

E_{kin} = 110MeV
τ = 84ns

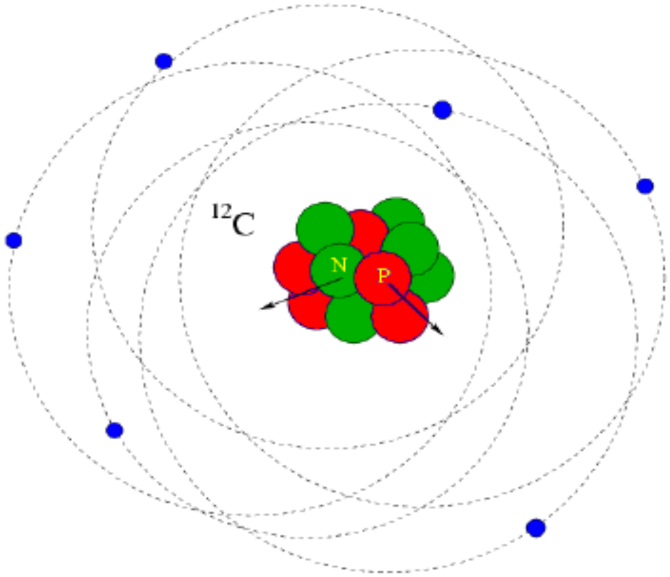
E_{kin} = 128MeV
τ = 26ns

2nd signal

→ **Fast coincidence of K$^+$ and decay products,** subsequent decays of muons

→ Two-body decays (p, K): decay particles feature fixed energies

Nuclear effects for proton decays in Carbon



Binding energy per nucleon

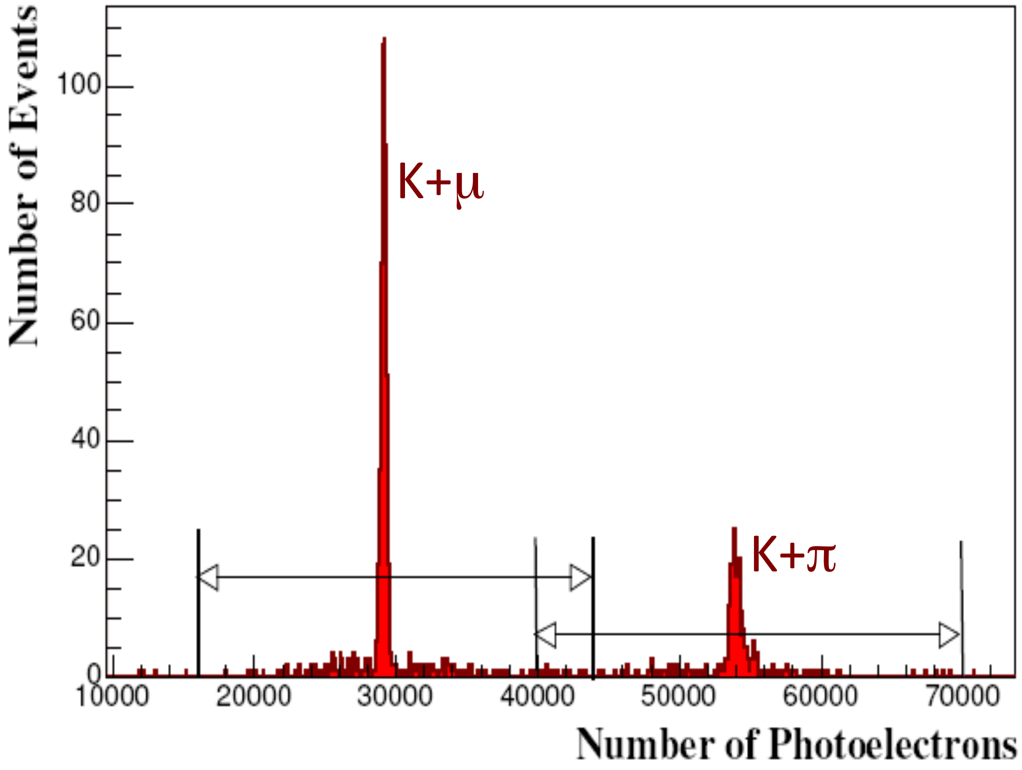
S-state: ~ 37 MeV

P-state: ~ 16 MeV

Smearing by Fermi motion

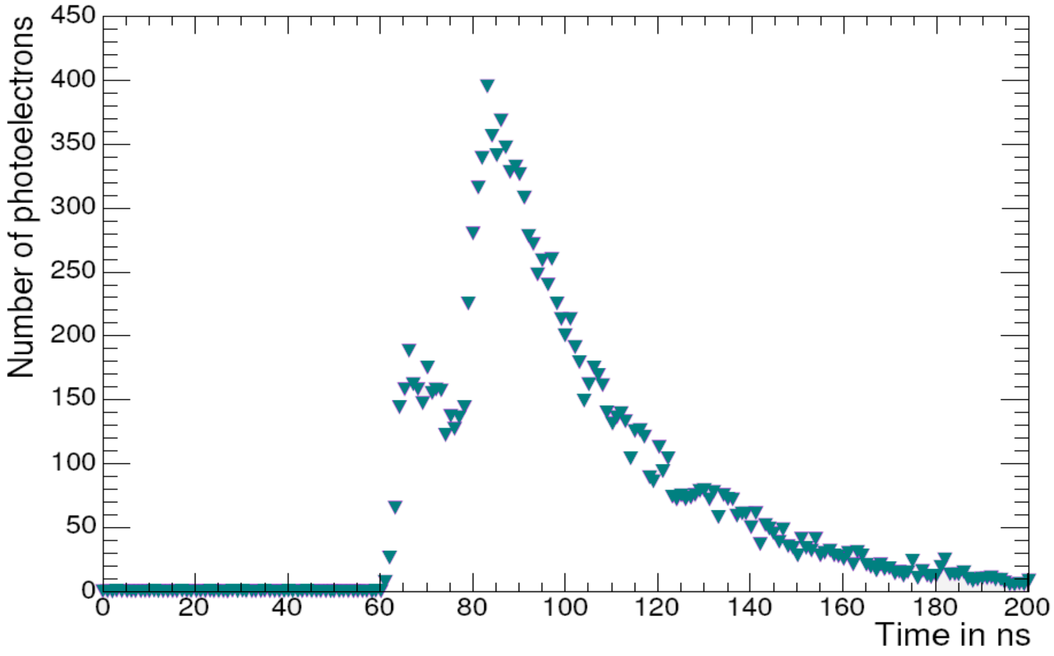
momenta < 250 MeV/c

→ ***shift and broadening of lines***



For wide energy window,
efficiency is still 99.5%

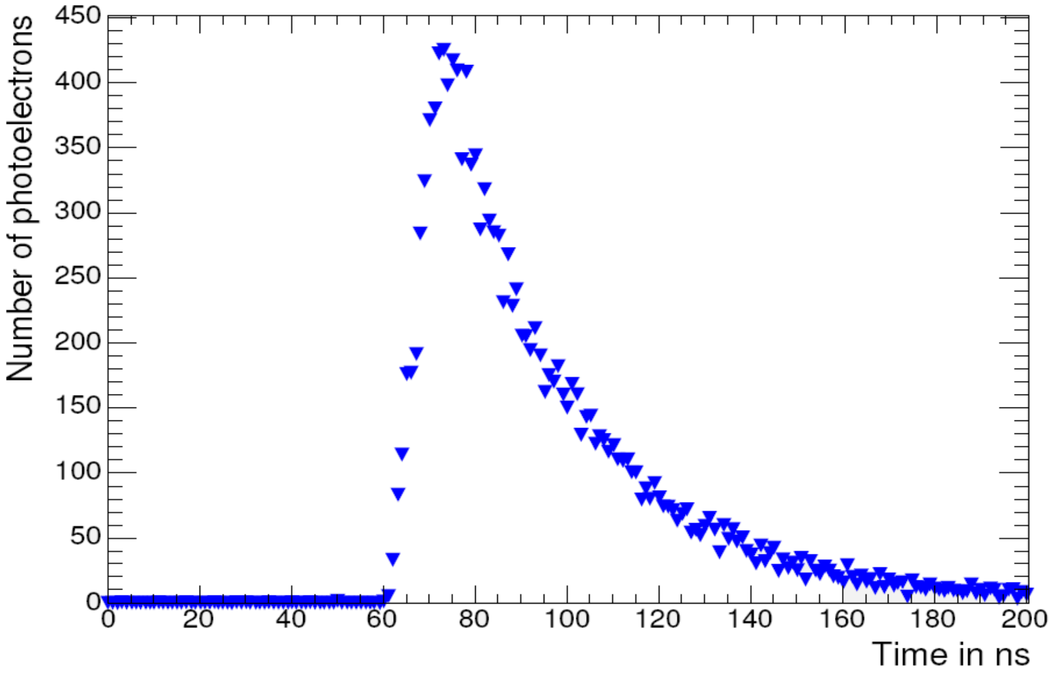
Simulated proton decay events



Analysis based on sum signal of all 10^4 PMT channels.

→ *Kaon decays after 18ns*

Experimental challenge:
recognize fast Kaon decays
(τ = 12.8ns)



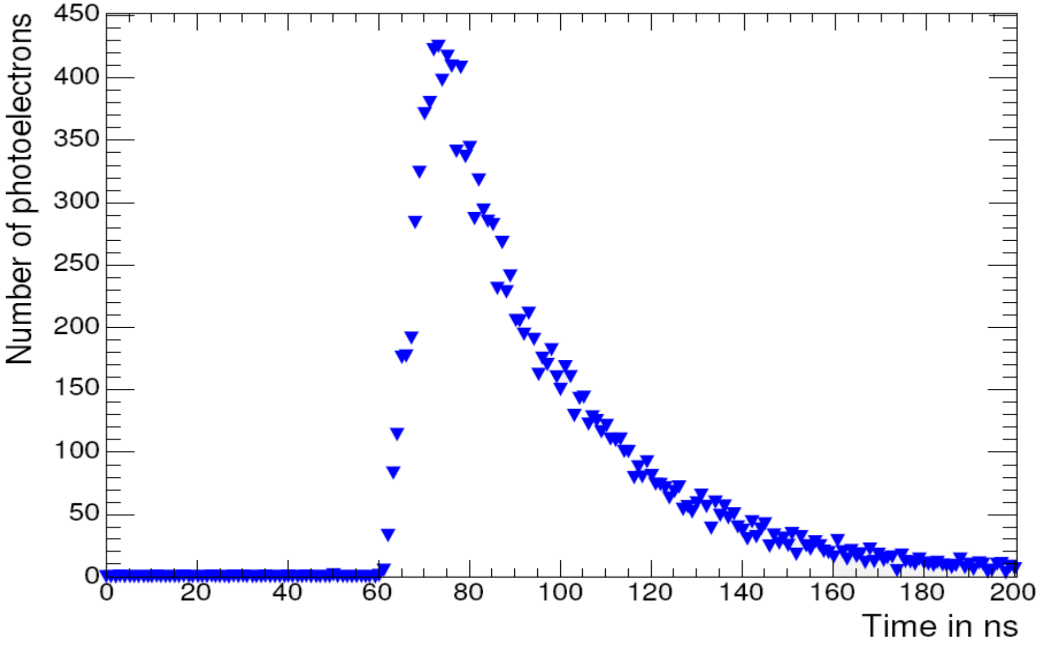
→ *Kaon decays after 5ns*

by Teresa Marrodán Undagoitia,
PRD 72 (2005) 075014

Atmospheric neutrino background

Signal: Proton decay

Kaon decaying after 5ns

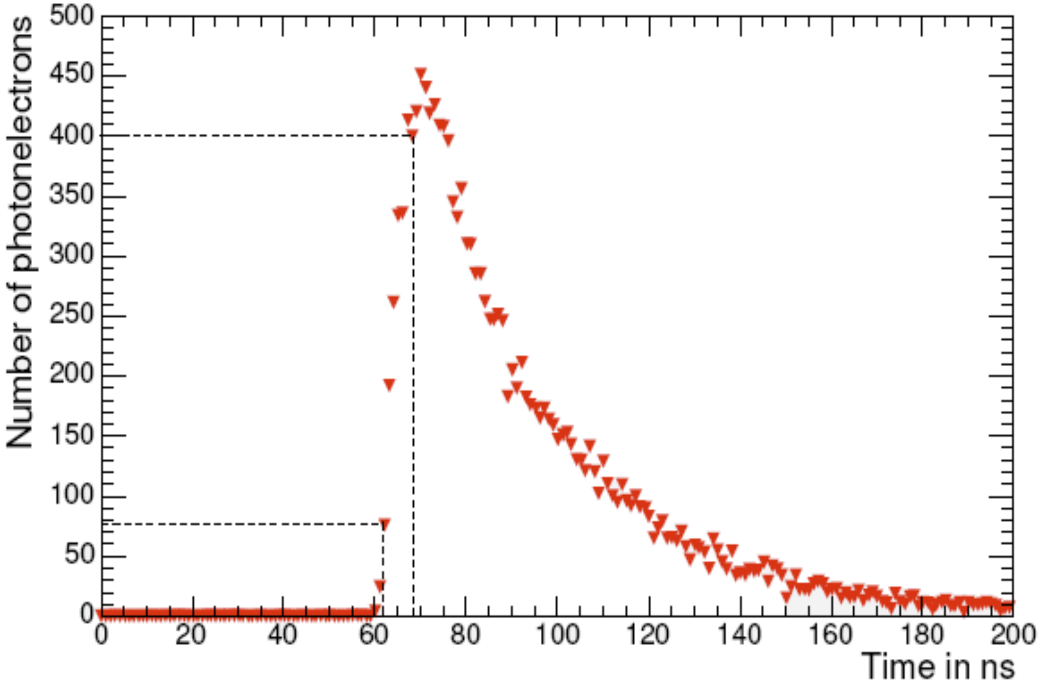


Background: Atmospheric ν's

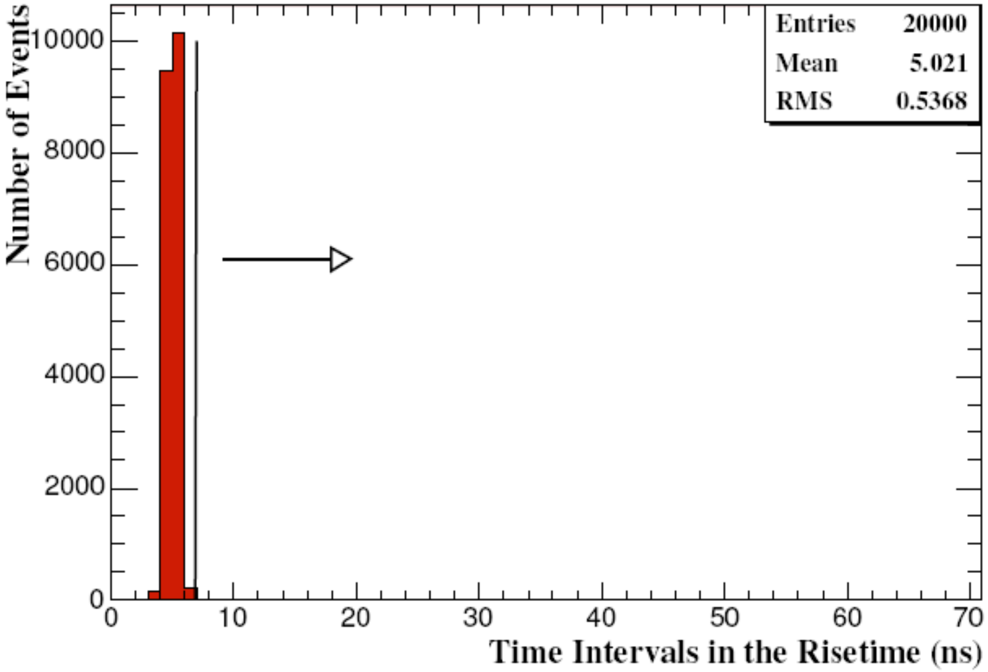
CC reaction of ν_μ on target nuclei:

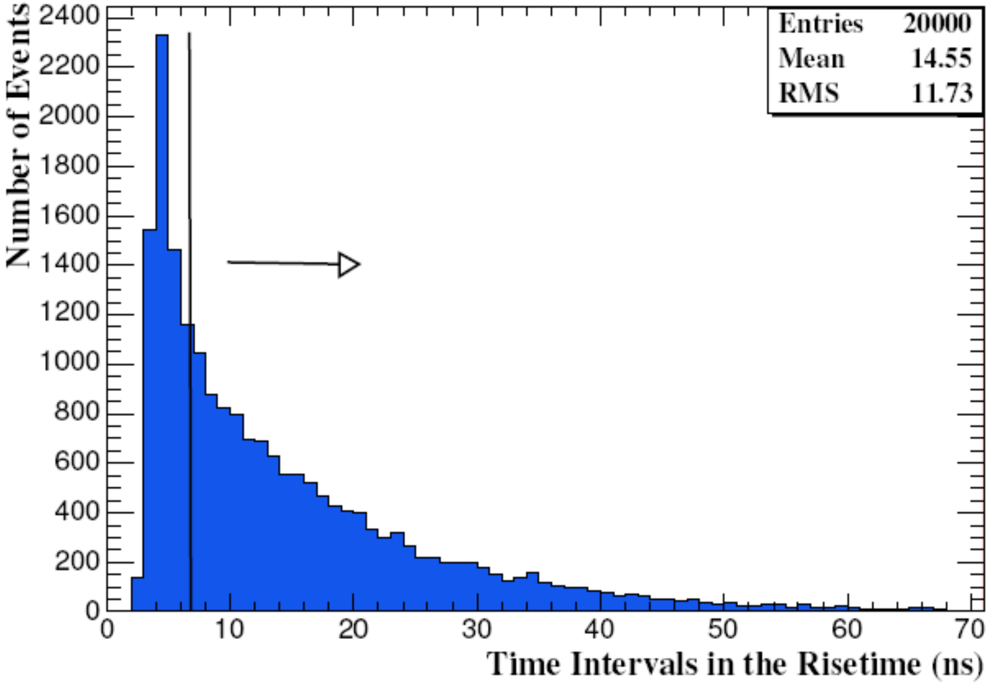
$$\nu_\mu + {}^{A}Z \rightarrow {}^{A}(Z+1) + \mu^-$$

pulse-shape analysis
of signal rise-time



Rise time analysis





→ ***Background from atmospherics:***
maximum μ rise time is limited

- 2×10^4 signal/bg events simulated
- for $t_{rise} > 7$ns, no bg event is selected
  → bg suppression of at least 5×10^{-5}!
- remaining efficiency: 67%

→ ***Coincidence signal:***
rise-time is spread to larger values

Resonant production of hadrons

- **Single pion production**

$$\nu_\mu + p \to \mu^- + \pi^+ + p'$$

- $\pi^+ \to \mu^+ + \nu_\mu \quad \tau_{\pi^+} = 26\text{ ns}$
- $\mu^+ \to e^+ + \nu_e + \overline{\nu}_\mu$

→ 2^{nd} signal from π decay very small
→ rejection possible

- **Production of kaon + hyperon (ΔS=0)**

$$\nu_\mu + n \to \mu^- + K^+ + \Lambda^0$$

- $\Lambda^0 \to p + \pi^- \quad \tau_{\Lambda^0} = 0.26\text{ ns}$
- $\Lambda^0 \to n + \pi^0$

$$\nu_\mu + n \to \mu^- + K^+ + \Lambda^0 + \pi^0$$

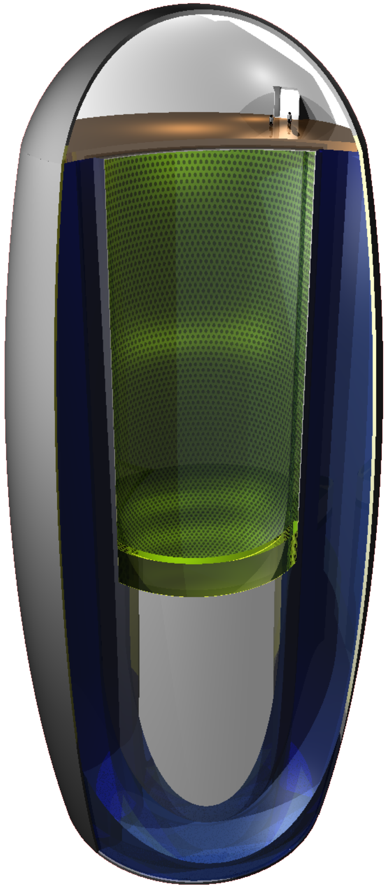
→ prompt signal too large ($K^+ + \Lambda^0$)
→ rejection possible

- **Single kaon production (ΔS=1)**

$$\nu_\mu + p \to \mu^- + K^+ + p$$

→ no discrimination if one decay e^- coincides with $1^{st}/2^{nd}$ signals (4%)
→ **background rate: 0.064 per year**

Efficiency and detector performance



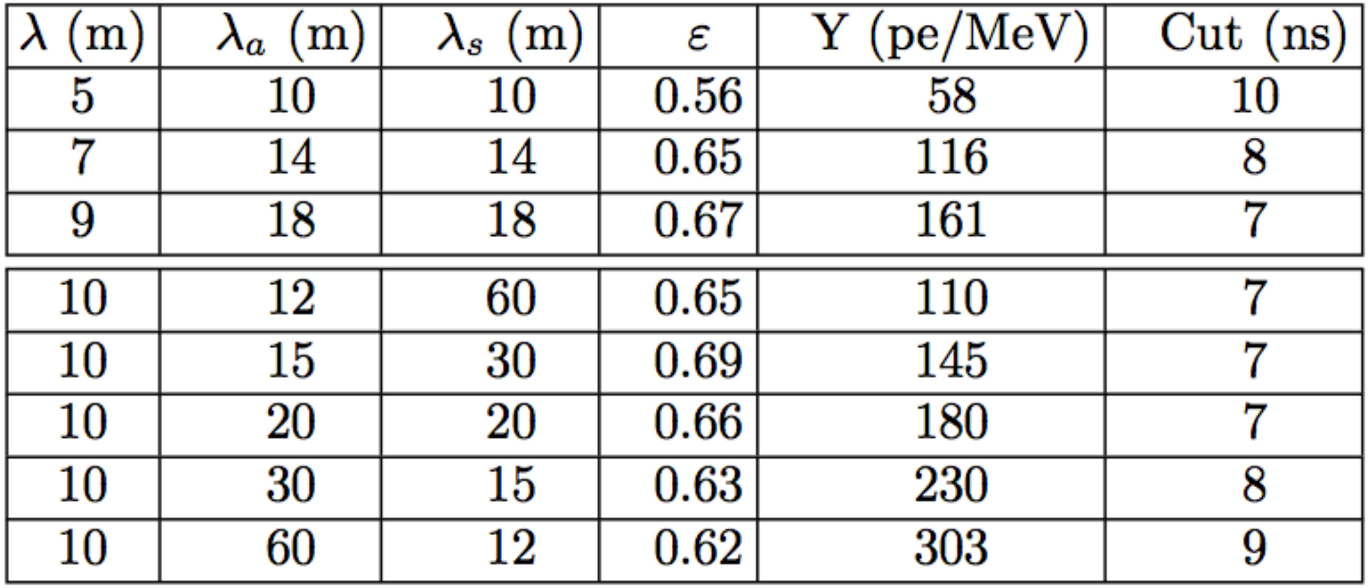
Most important parameter

- Time resolution for pulse shape analysis

depends mostly on scintillator properties:

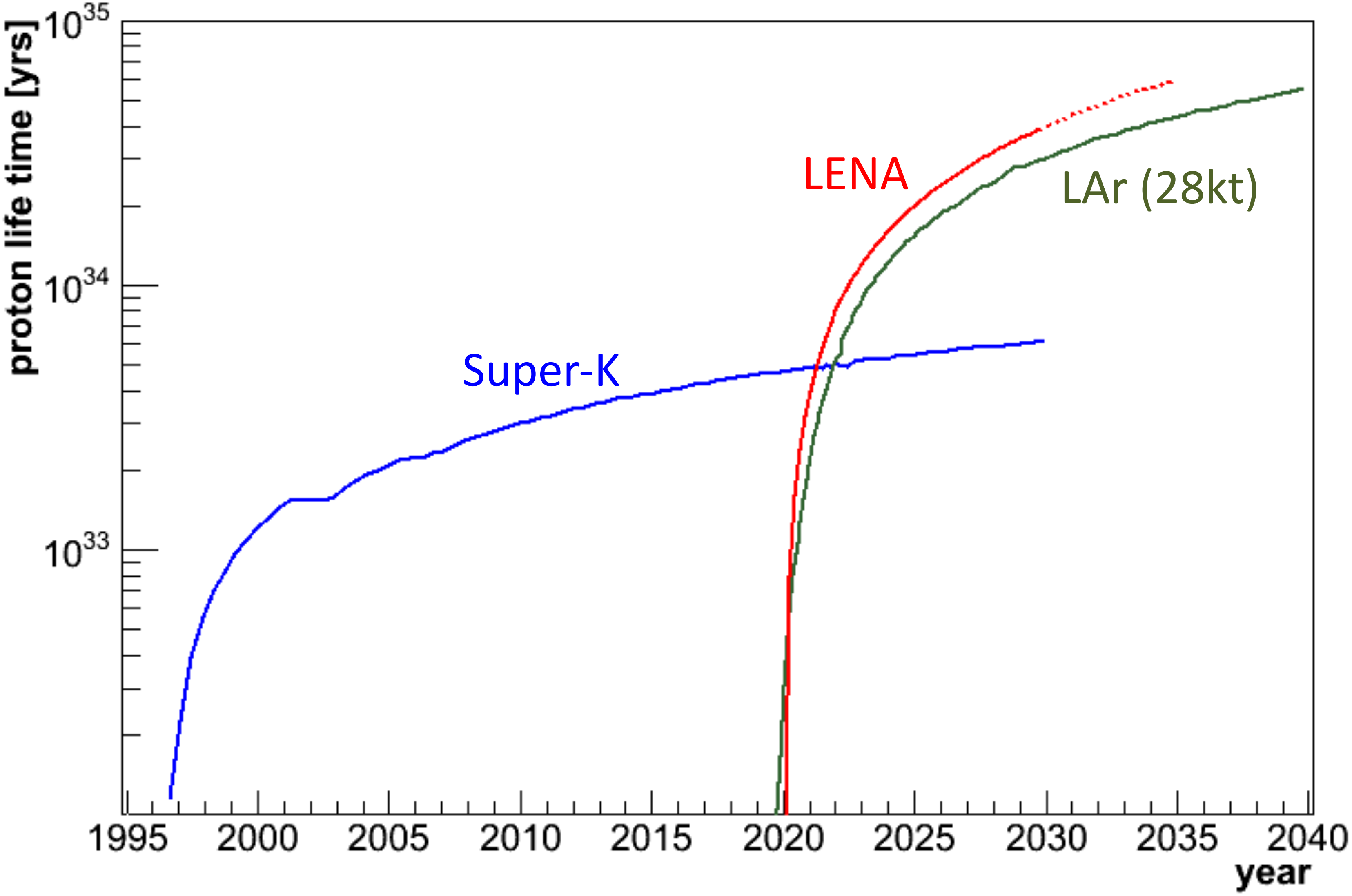
- fast fluorescence component (3.4ns)
- light yield (10^4 γ/MeV)
- scintillator transparency:
  λ attenuation length
  λ_a absorption length
  λ_s scattering length

→ **no large spread expected**



λ (m)	λ_a (m)	λ_s (m)	ε	Y (pe/MeV)	Cut (ns)
5	10	10	0.56	58	10
7	14	14	0.65	116	8
9	18	18	0.67	161	7
10	12	60	0.65	110	7
10	15	30	0.69	145	7
10	20	20	0.66	180	7
10	30	15	0.63	230	8
10	60	12	0.62	303	9

Projected sensitivity for p→$K^+\bar{\nu}$



Expected BG events:

0.64 in 10 yrs

No event observed: $\tau_{p\rightarrow K\nu} > 4\times10^{34}$ **(90% C.L.)**

One event observed: $\tau_{p\rightarrow K\nu} > 3\times10^{34}$

Expected impact of tracking

on p→$K^+\nu$

- will further increase efficiency to suppress μ from atmospheric ν_μ's
- for kaon production from atmospherics:

$$\nu_\mu\, p \rightarrow p\, K^+\, \mu^- \rightarrow p\, (\nu_\mu\, \mu^+)\, \mu^-$$

→ rejection of double-muon events will increase background-free exposure

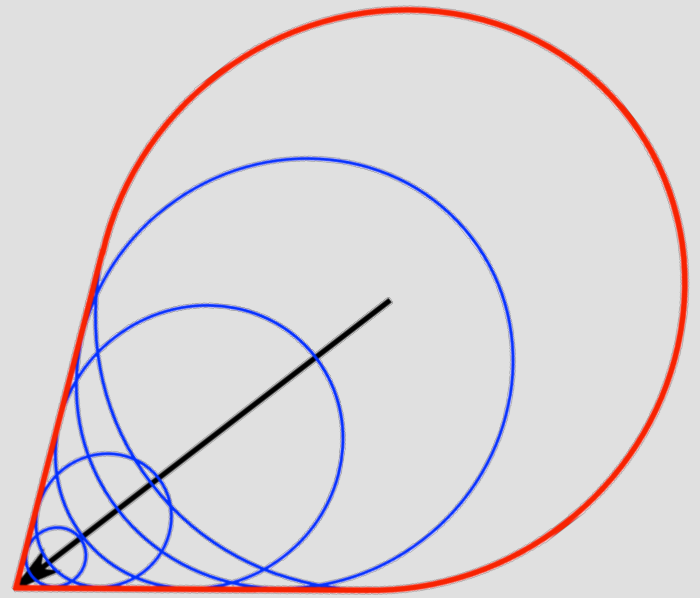
on p→π^0e+

- allows to discriminate decay signature

$$p \rightarrow \pi^0\, e^+ \rightarrow (\gamma\gamma)\, e^+$$

from CC atmospherics background

- still, both detector mass and detection efficiency will be of the order of Super-K



Tracking principle:

- In liquid scintillator, HE particles create Cherenkov-like light cone from superposition of spherical light fronts
- Reconstruction of single lepton tracks for E>0.2GeV,

e.g. ΔE=0.5%, Δθ=4°
for single muons @ 0.3GeV

Conclusions

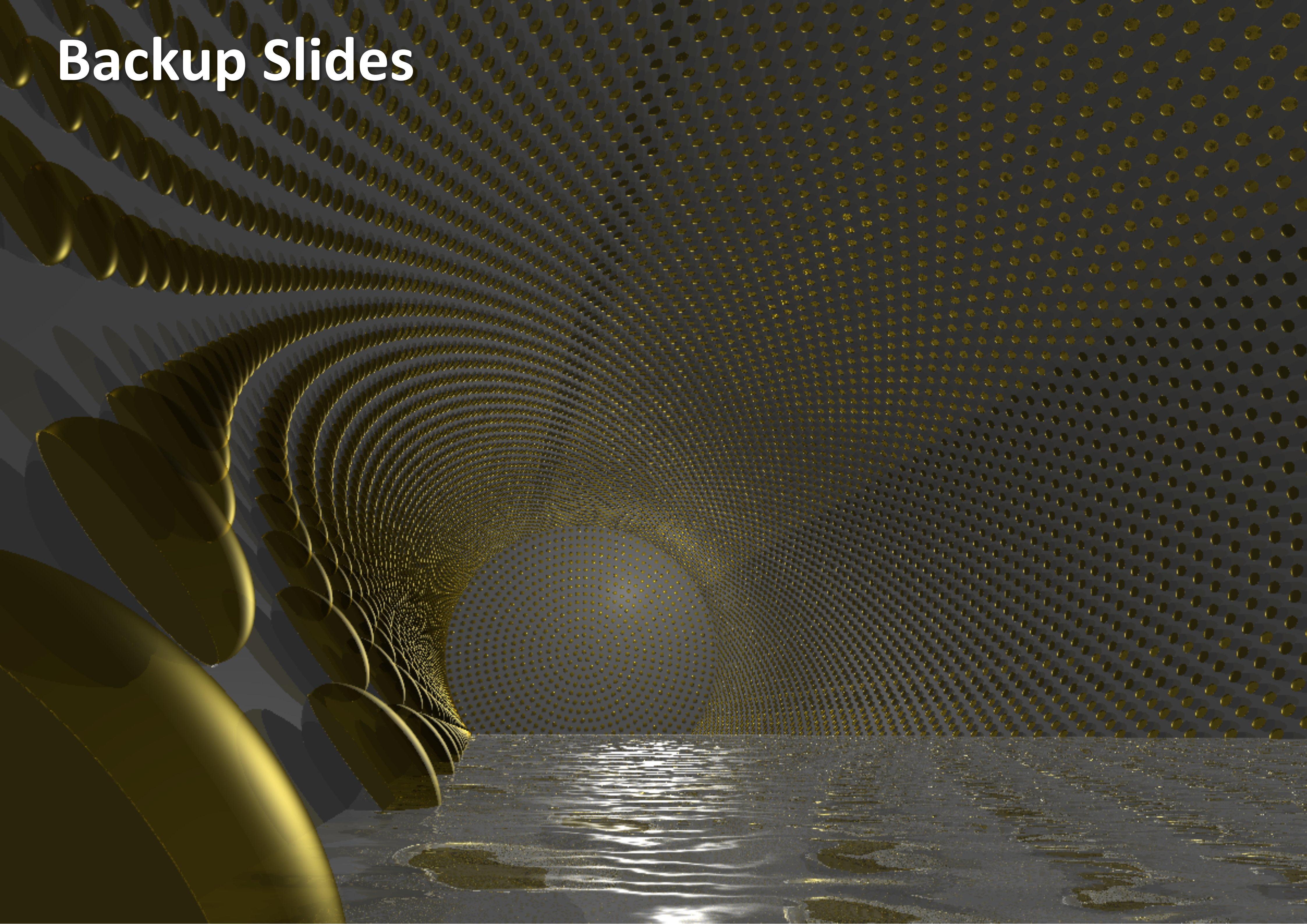
- Very-large volume liquid-scintillator detectors like LENA offer a lot of particle, geo- and astrophysics.

- The visibility of the kaon allows for a high detection efficiency for $p \rightarrow K^+\nu$.

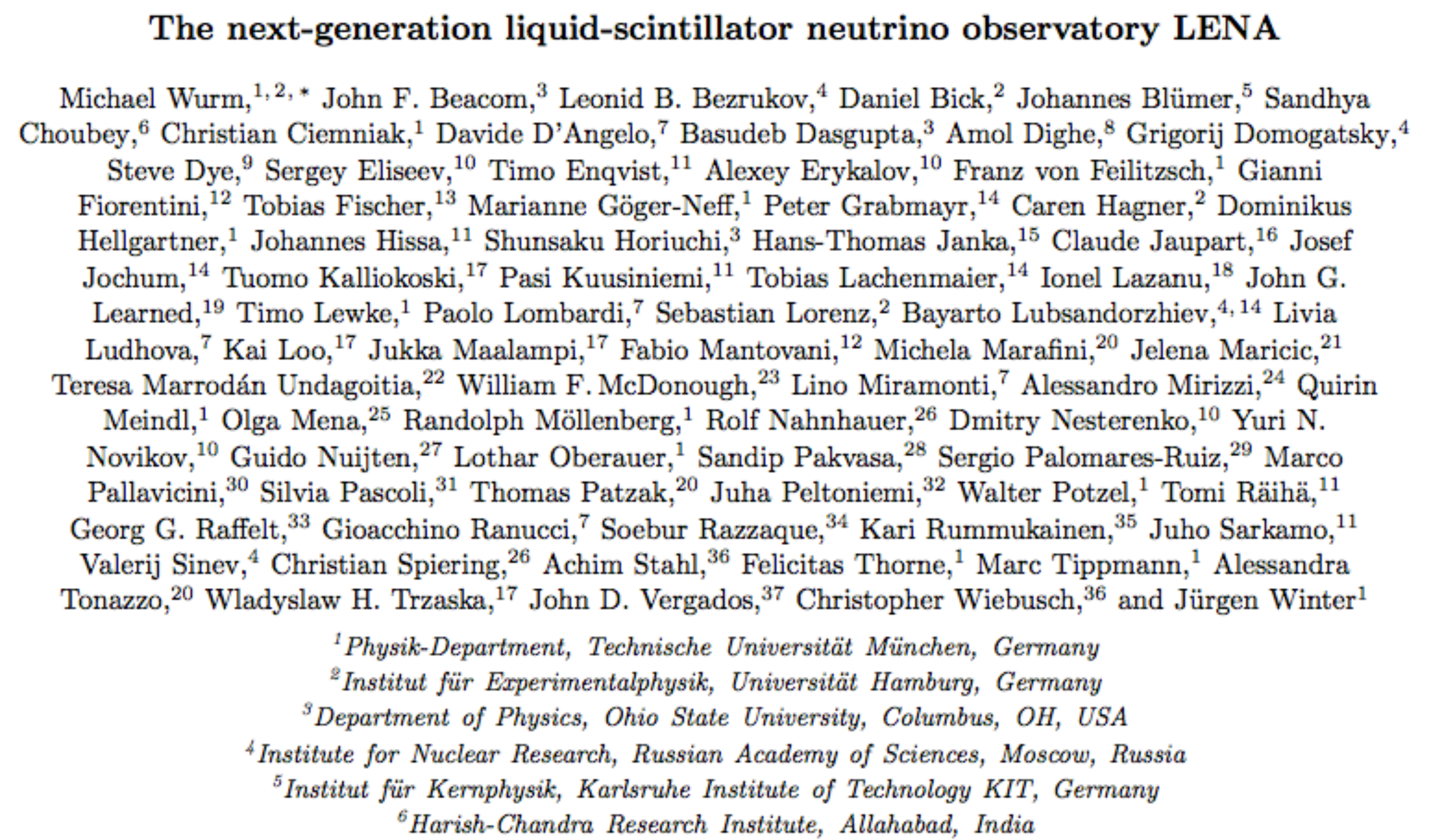
- After 10 years of background-free measurement, a limit of $p > 4x10^{34}$ yrs can be established.

- A white paper has been prepared this spring and can be found at arXiv:1104.5620

Backup Slides



Summary



The next-generation liquid-scintillator neutrino observatory LENA

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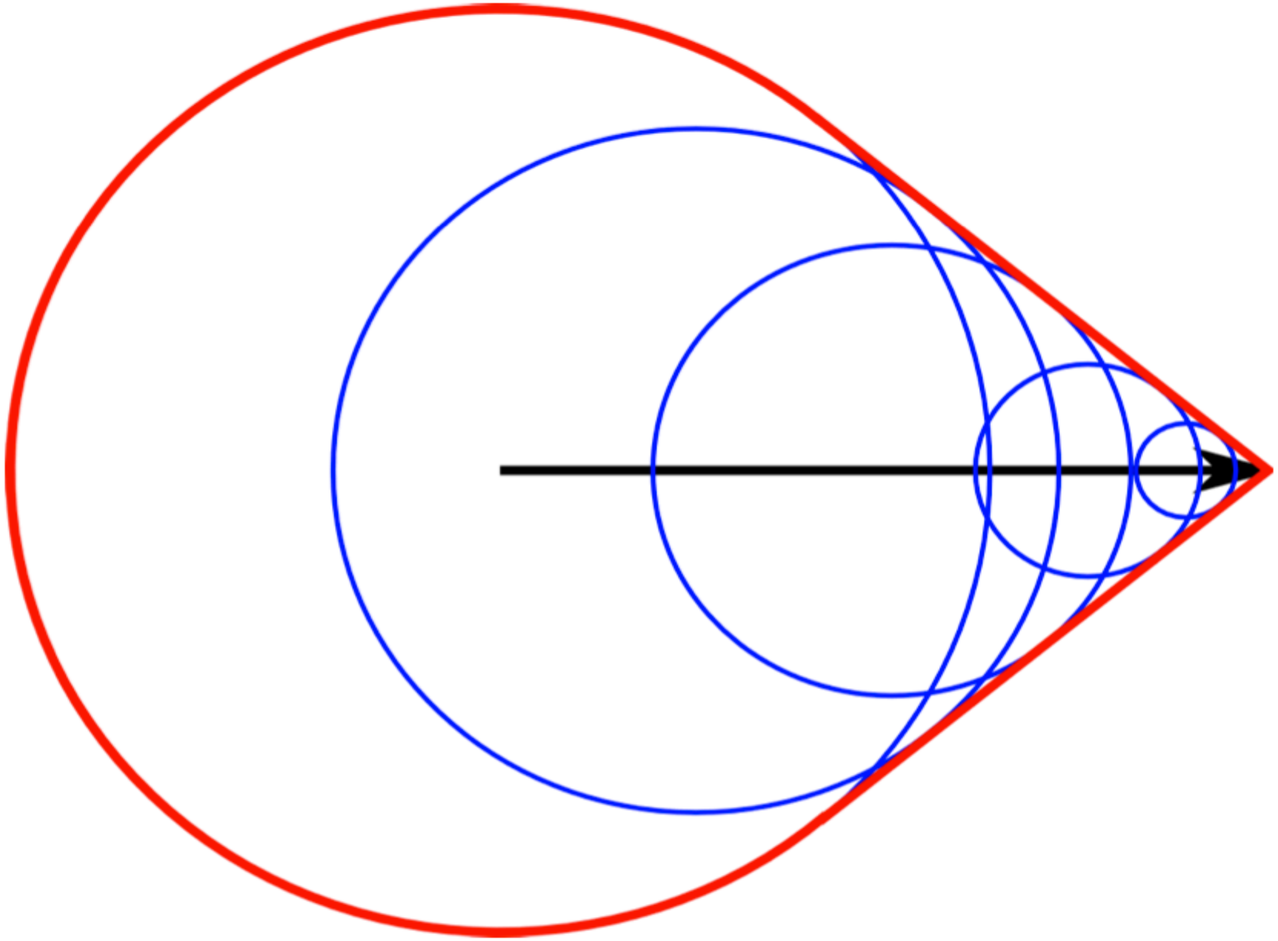
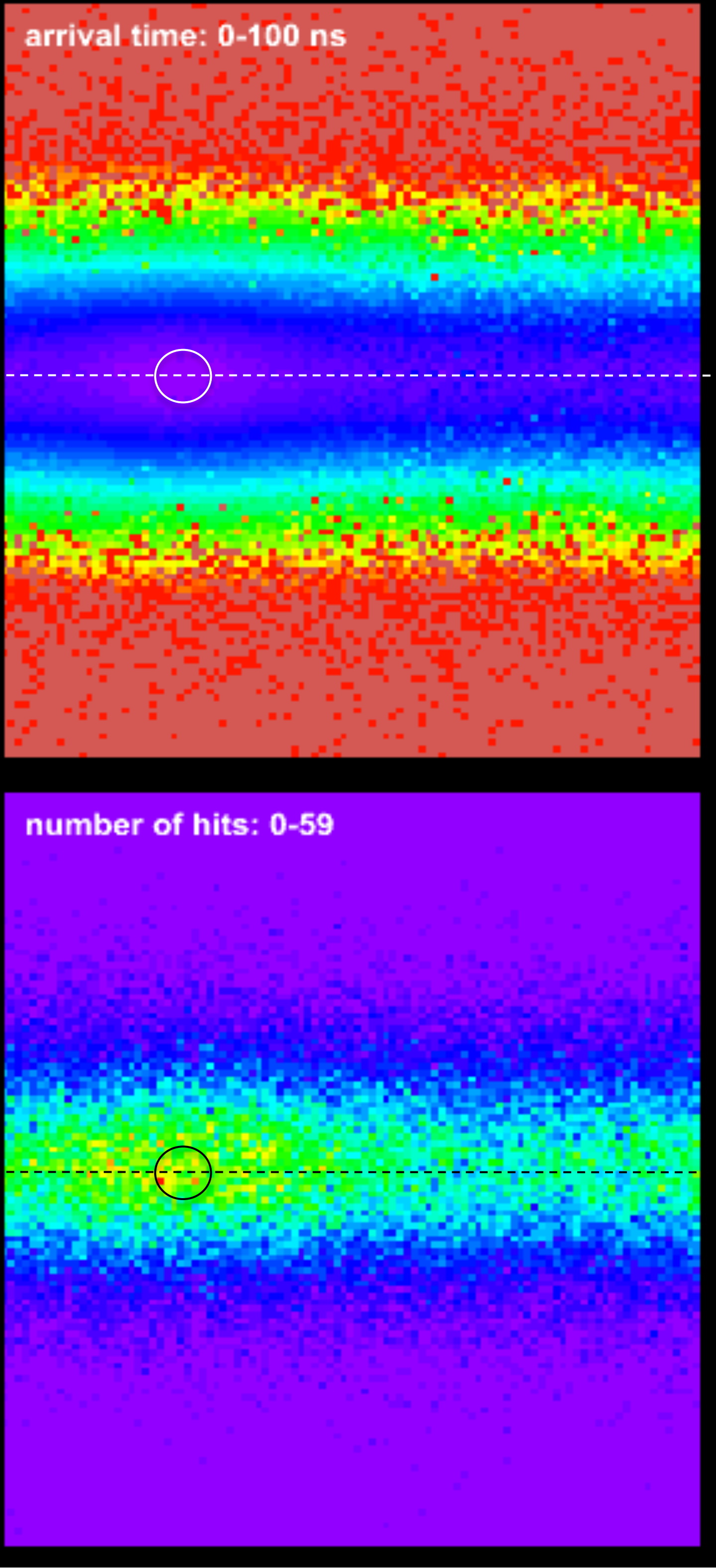
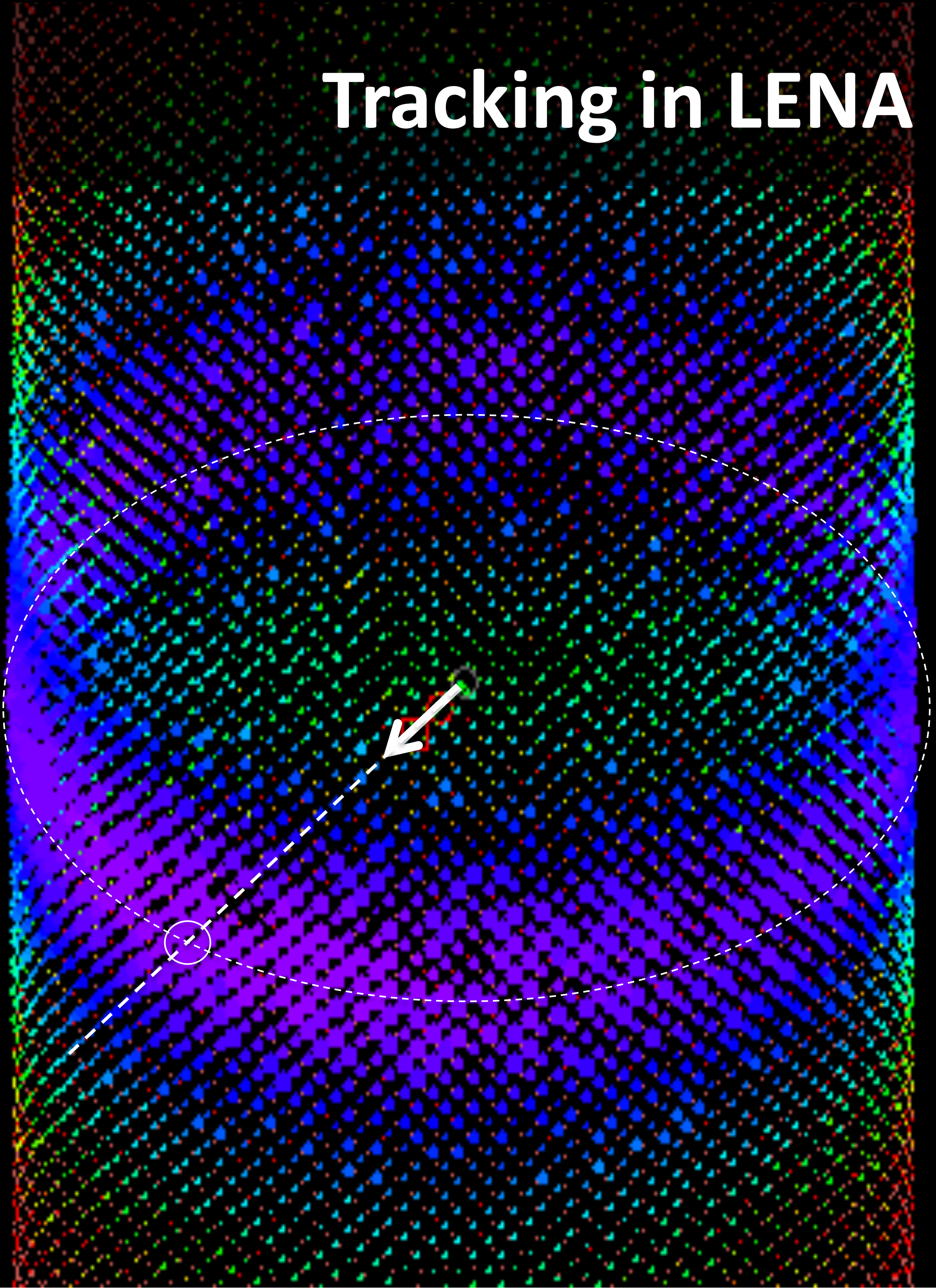
Tracking in LENA – scintillation light front



HE particles create spherical light fronts along their track that lead in superposition to a Cherenkov-like light cone.
But: about 50x more light!

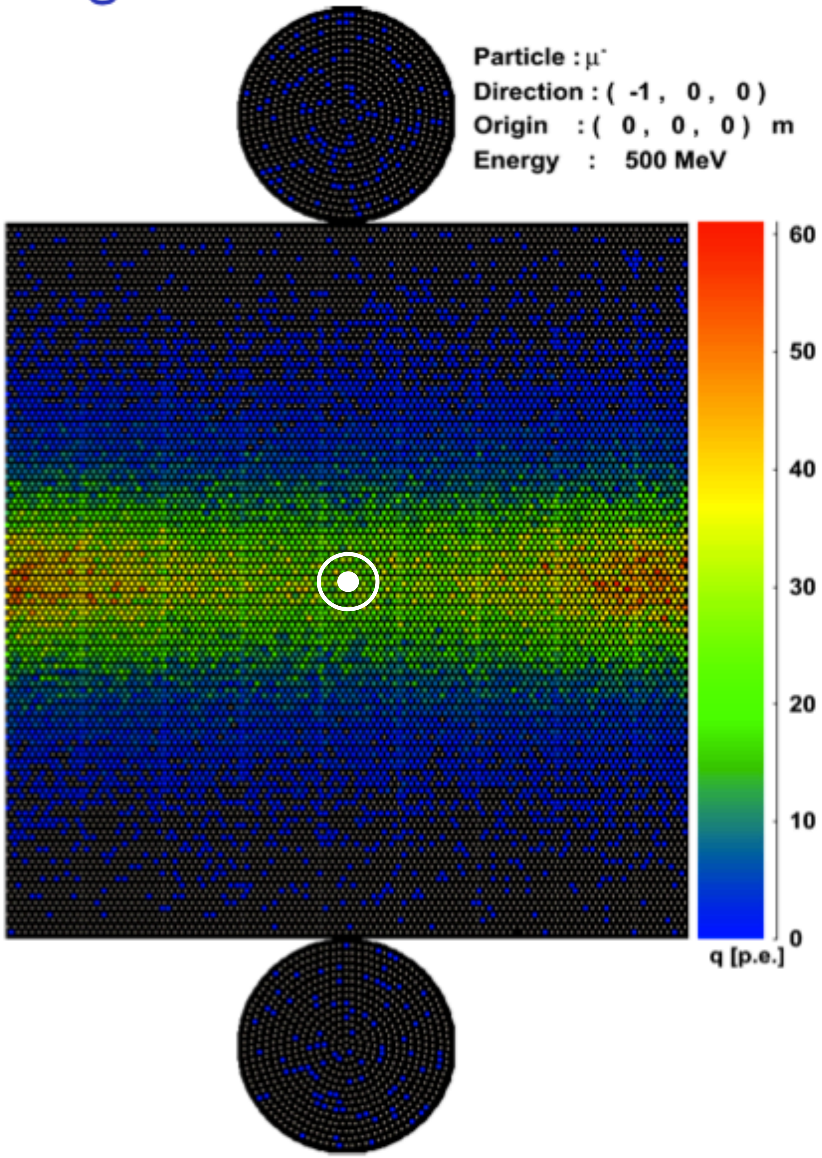
Tracking in LENA



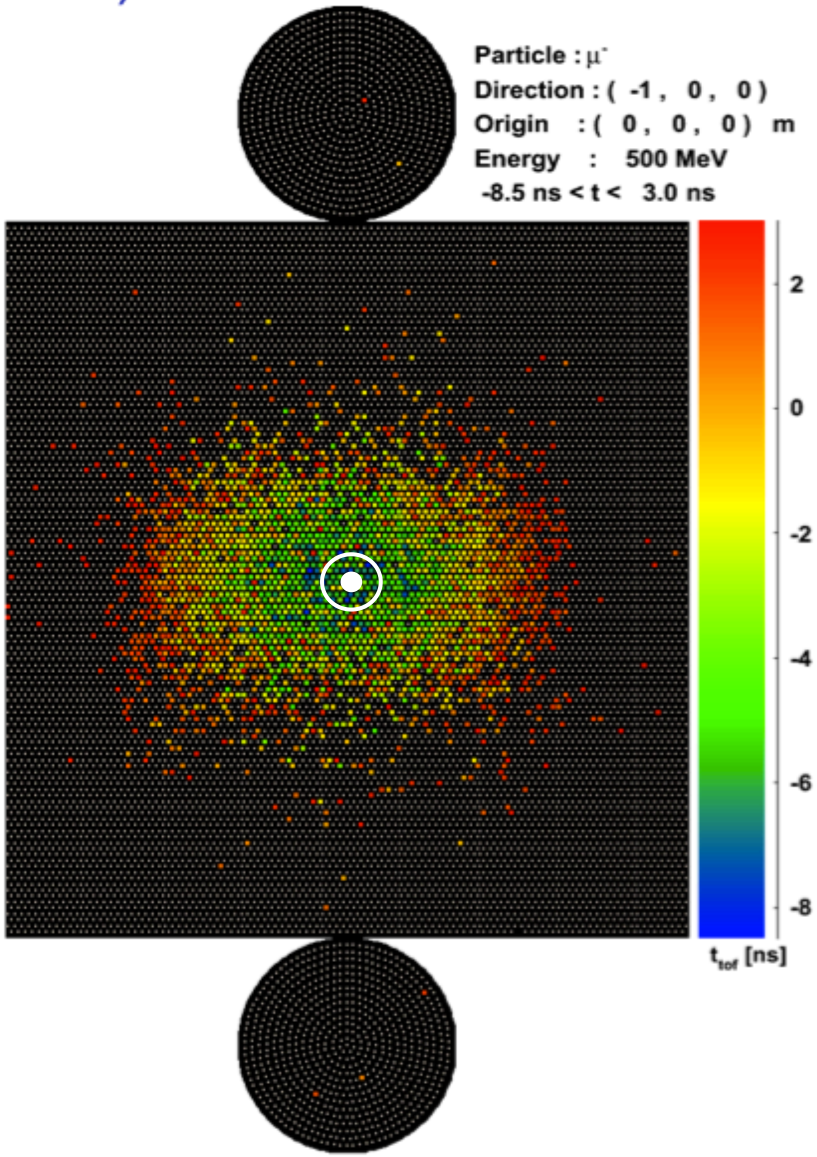


Photoelectron distribution for 0.5 GeV muon

Charge

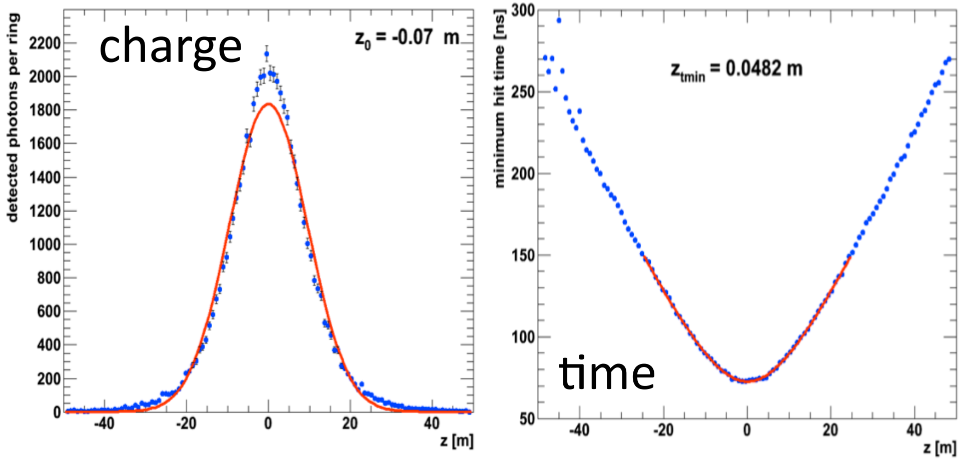


(First-)hit-time



Sub-GeV tracking: Strategy

i) Initial guess from fits to PMT rings



ii) Compute charge PDFs for all PMTs

mean charge of PMT (i)

light emitted by track element

light lost by attenuation

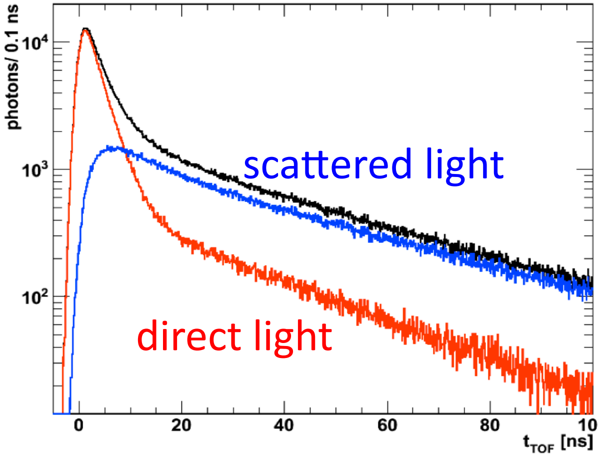
$$\mu_i(\boldsymbol{X},\boldsymbol{r}_i,\hat{n}_i) = \int_{\boldsymbol{x}_s(\boldsymbol{X})}^{\boldsymbol{x}_e(\boldsymbol{X})} ds \left\langle \frac{dL}{dx} \right\rangle (s) \cdot \frac{\Omega(\boldsymbol{s},\boldsymbol{r}_i,\hat{n}_i)}{4\pi} \cdot \exp\left(-\frac{|\boldsymbol{s}-\boldsymbol{r}_i|}{\lambda_{att}}\right) \frac{1}{R(\boldsymbol{s},\boldsymbol{r}_i)}$$

Integral over track elements *ds*

solid angle rel. to ds

percentage of scattered light

iii) Compute first hit time PDFs for PMTs



PDF depends on:

- scintillation time constants
- light scattering
- distance of track to PMT

iv) Log-likelihood minimization of PDF

overall PDF

charge PDF for PMTs with hits

$$P(\boldsymbol{q},\boldsymbol{t}|\boldsymbol{X}) = \prod_{i}^{\text{unhit}} P(q_i=0|\boldsymbol{X},\boldsymbol{r}_i,\hat{n}_i) + \prod_{i=1}^{\text{hit}} P(q_i|\boldsymbol{X},\boldsymbol{r}_i,\hat{n}_i) \cdot P(t_i|\boldsymbol{X},\boldsymbol{r}_i,\hat{n}_i,q_i)$$

charge PDF for PMTs w/o hits

first hit time PDF of PMT

Lepton flavor identification

For beta beams:

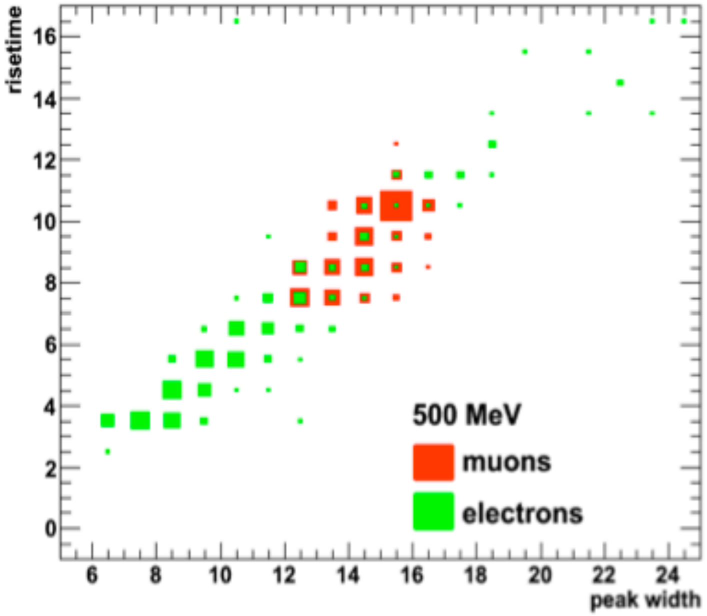
ν_μ appearance → ν_e rejection.

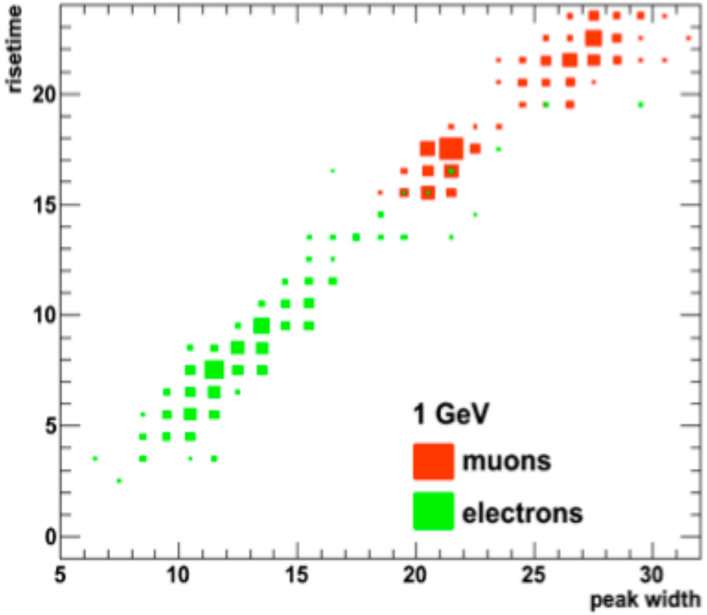
i) Muon-decay electron:

- muon has to decay sufficiently late
- energy threshold to reject spallation neutrons
- ν_e rejection efficiency: >99.95% (95%C.L.)
- ν_μ acceptance: 85%

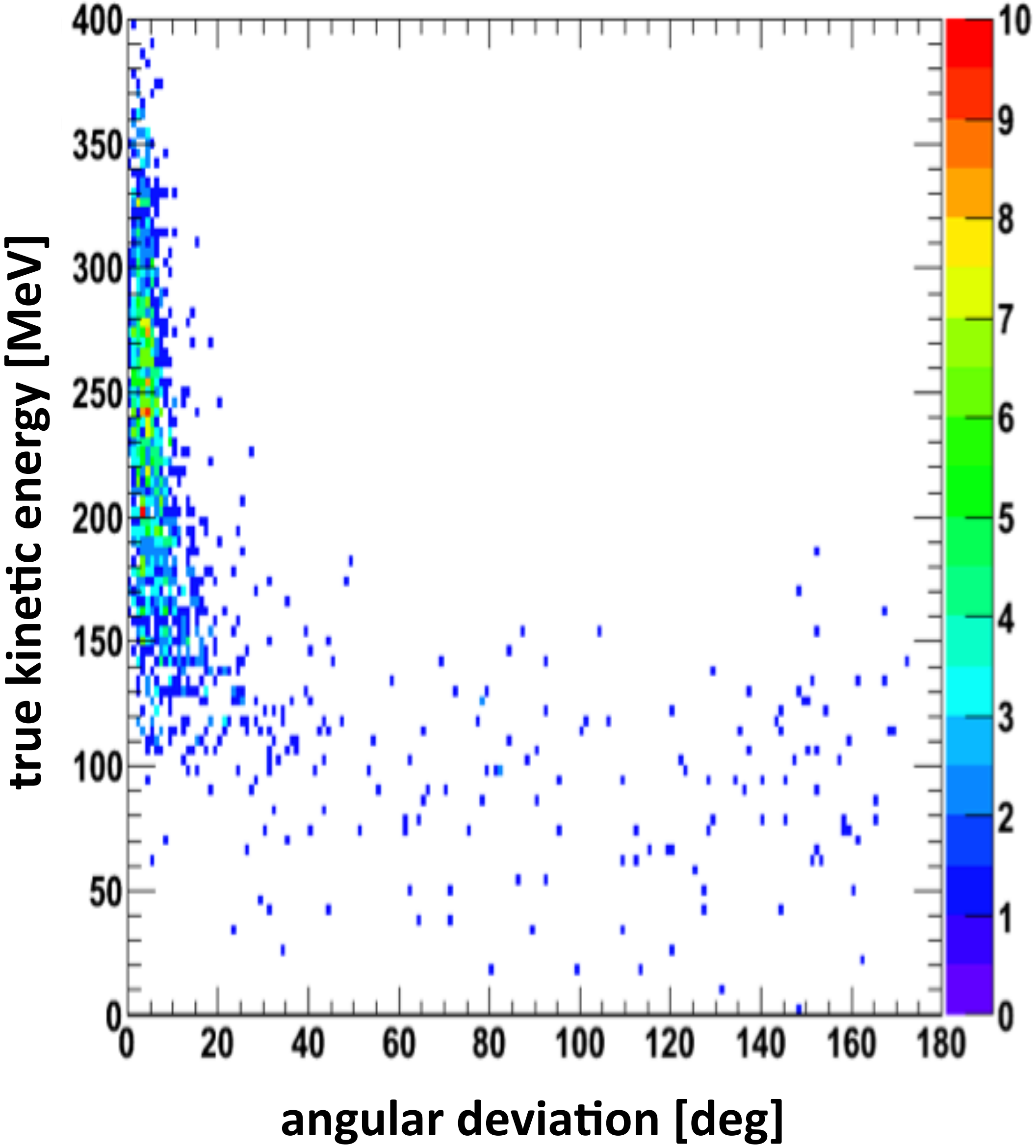
ii) Pulse-shape discrimination:

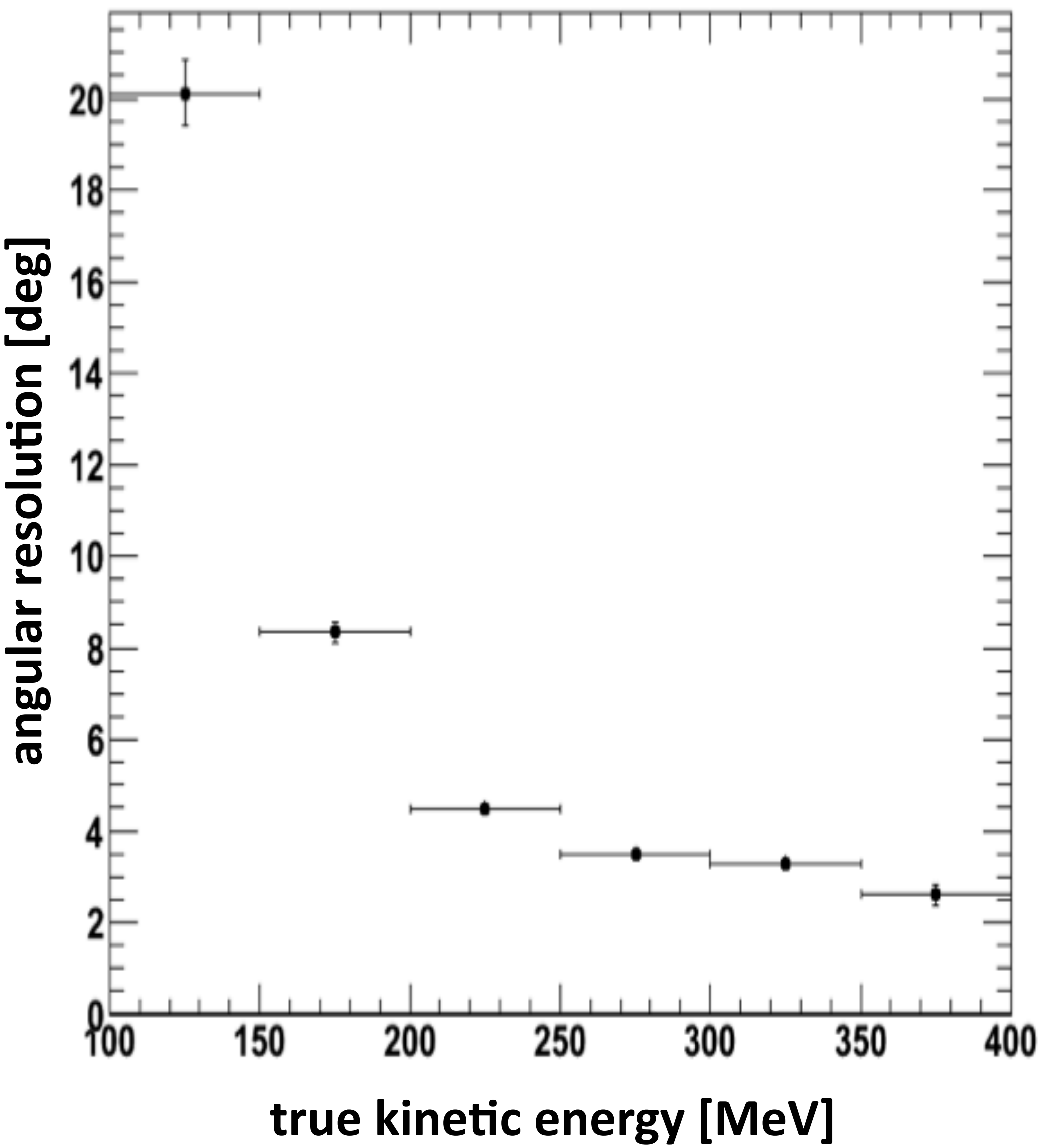
- rise time and peak width
- about 80% efficiency for ν_e rejection, but very powerful for ν_e selection
- discrimination of CC ($\nu_e+\pi^\pm$) interactions?





Angular resolution, ν_μ QE events





Energy resolution, ν_μ QE events