Nucleon Decay Searches in Super-K

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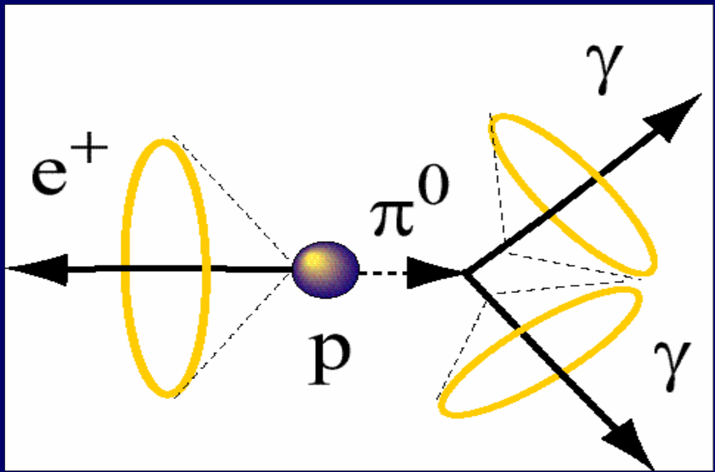
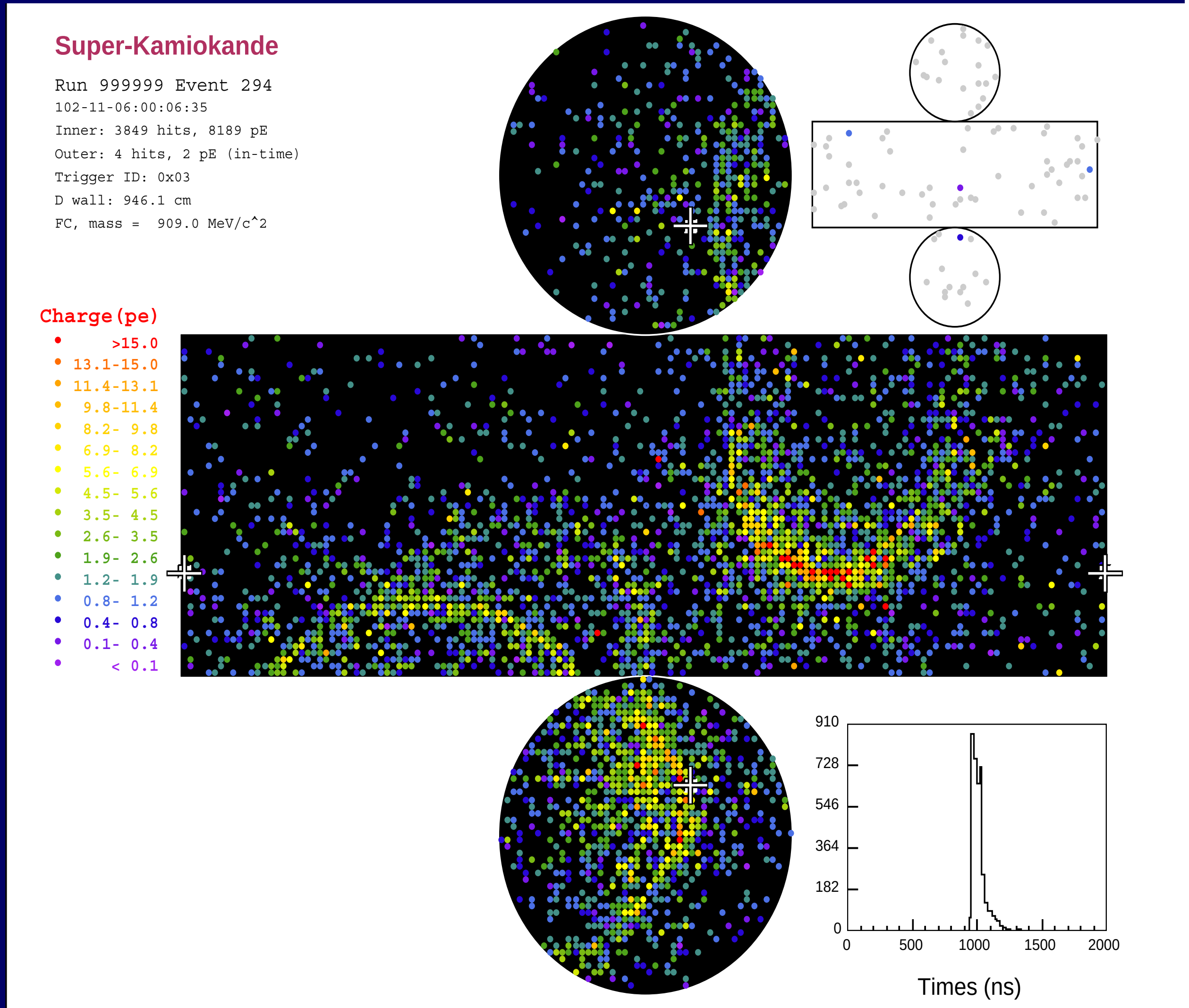
$p \rightarrow e^+\pi^0$ @Super-K

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



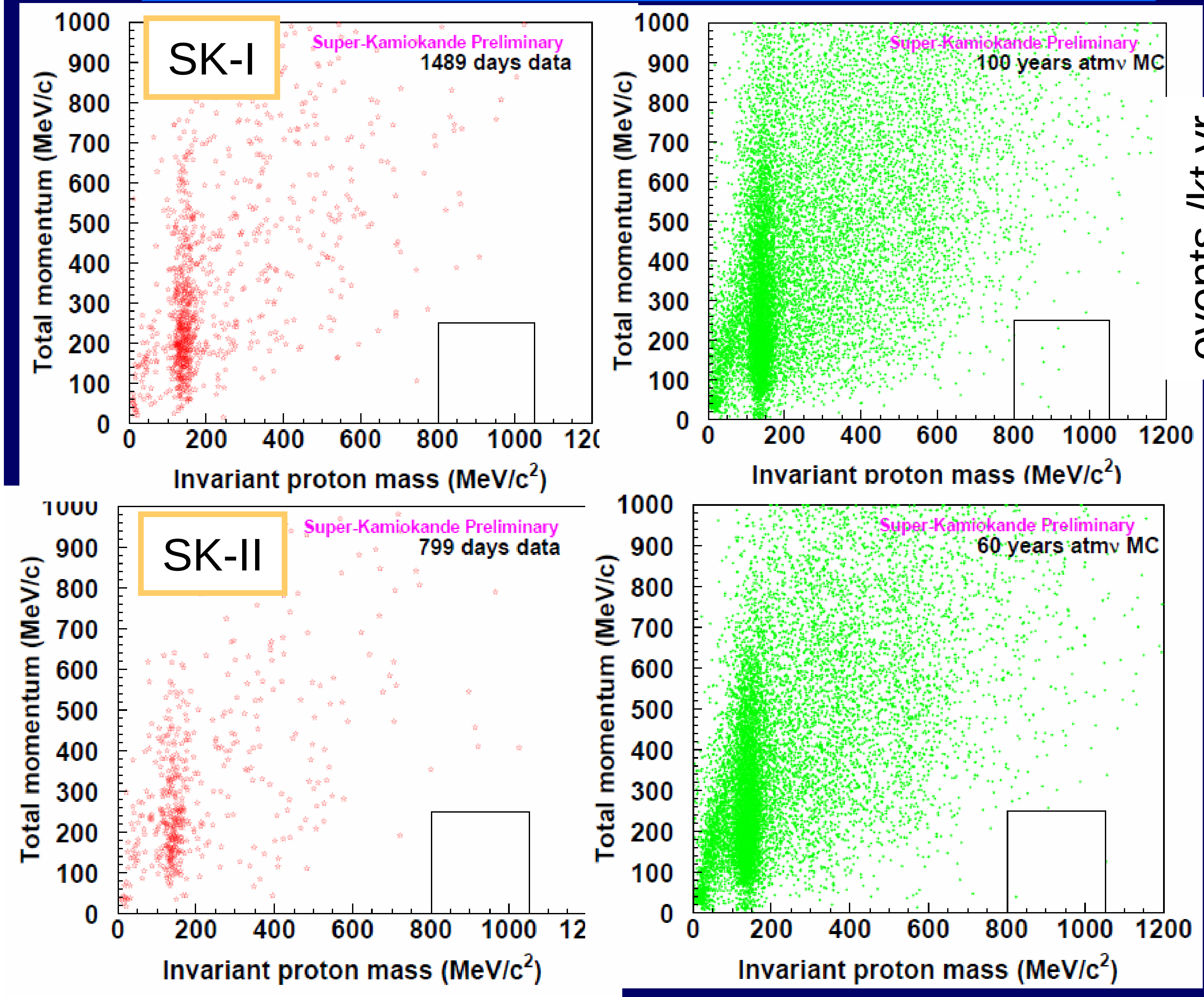


Criteria for $p \rightarrow e^+ \pi^0$

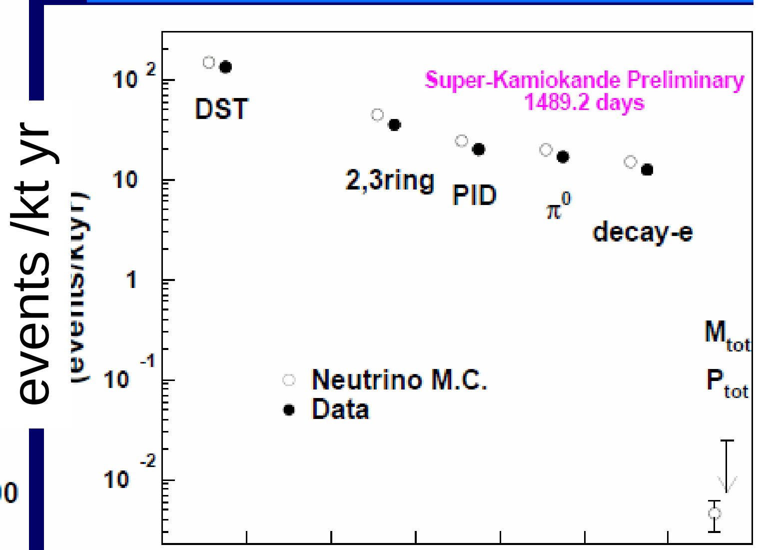
- 2 or 3 Cherenkov rings
- All rings are showering
- $85 < M_{\pi 0} < 185 \mathrm{MeV/c^2}$ (3-ring)
- No muon decay electron
- $800 < M_{proton} < 1050 \mathrm{MeV/c^2}$ $P_{total} < 250 \mathrm{MeV/c}$

Observed data and background MC

Invariant proton mass and total momentum for data & atmν



Events after each selection criteria



No signal candidates were observed in SK-I (1489days) and SK-II (799days)

while expected BG are 0.44 events in total.

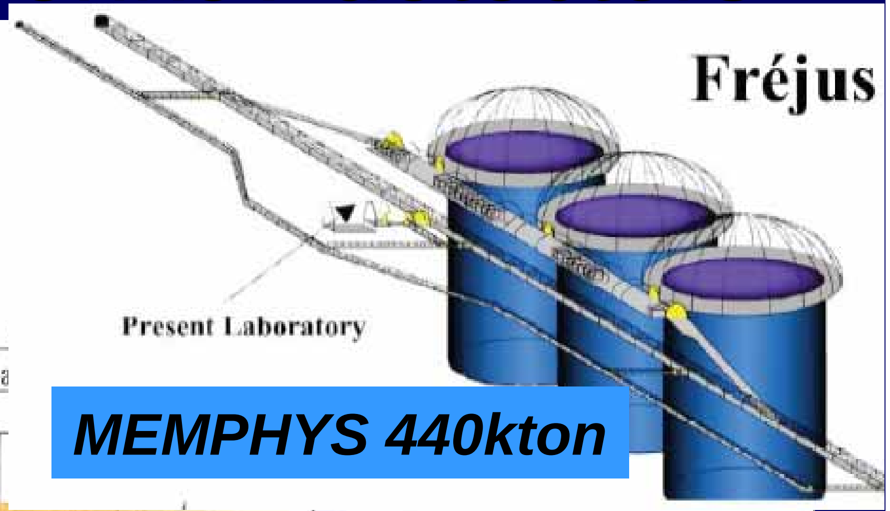
Lifetime limit of protons

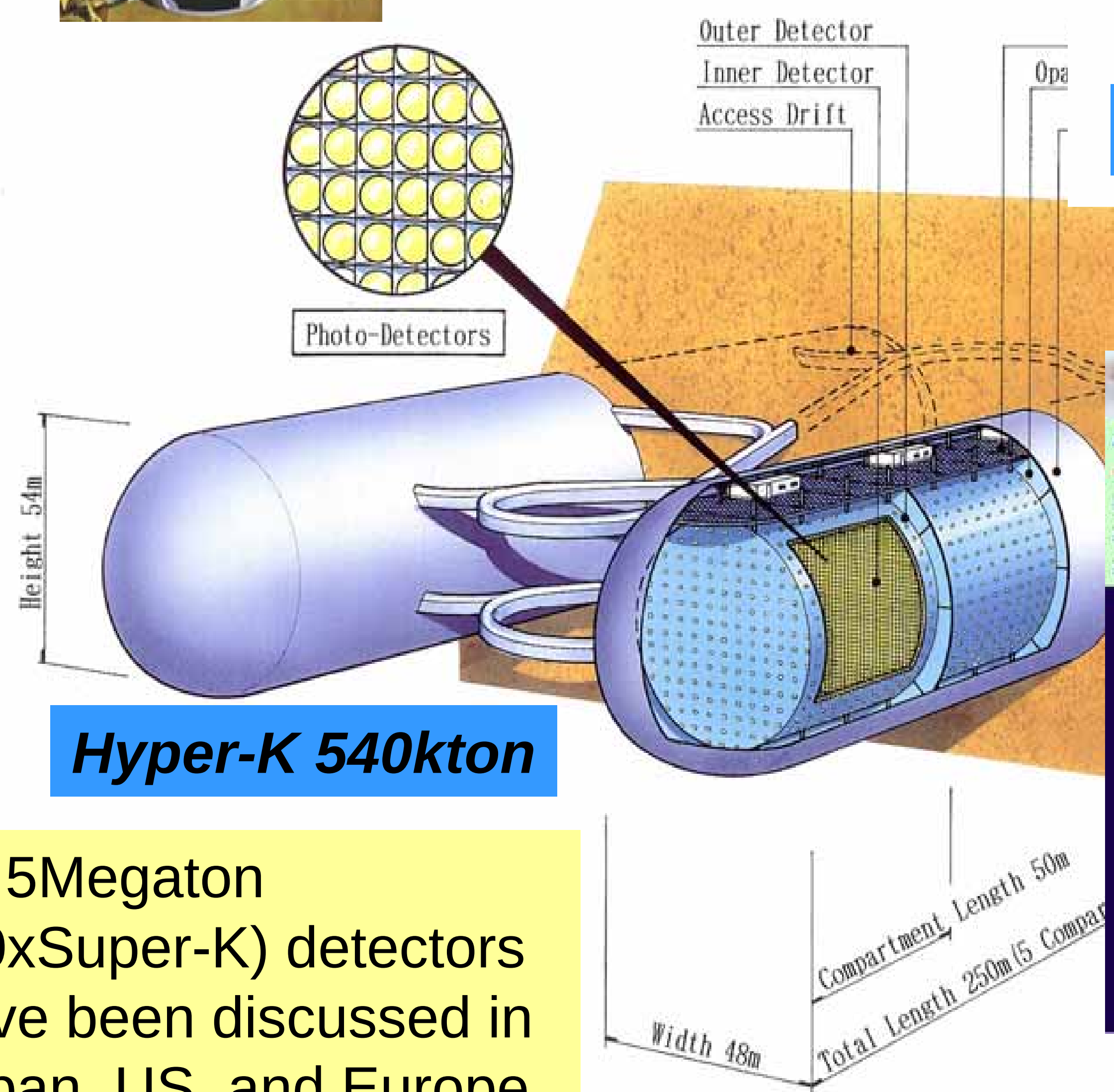
- $p \rightarrow e^+\pi^0$
  - Detection Efficiency: 45.0 %(SK-I), 43.6% (SK-II)
  - Expected BG: 0.44 events (SK-I + SK-II)
  - Exposure: 140.9kton yr (SK-I: 1489.2, II: 798.6days)
  - SK-I+II: $\tau_p/B_{e\pi 0}$ > 8.4 x 10^{33} years (90 % C.L.)
- $p \rightarrow \mu^+\pi^0$
  - Detection Efficiency: 35.6 % (SK-I), 35.5 % (SK-II)
  - Expected BG: 0.6 events (SK-I + SK-II)
  - Exposure: 140.9kton yr (SK-I: 1489.2, II: 798.6days)
  - SK-I+II: $\tau_p/B_{\mu\pi 0}$ > 6.7 x 10^{33} years (90 % C.L.)

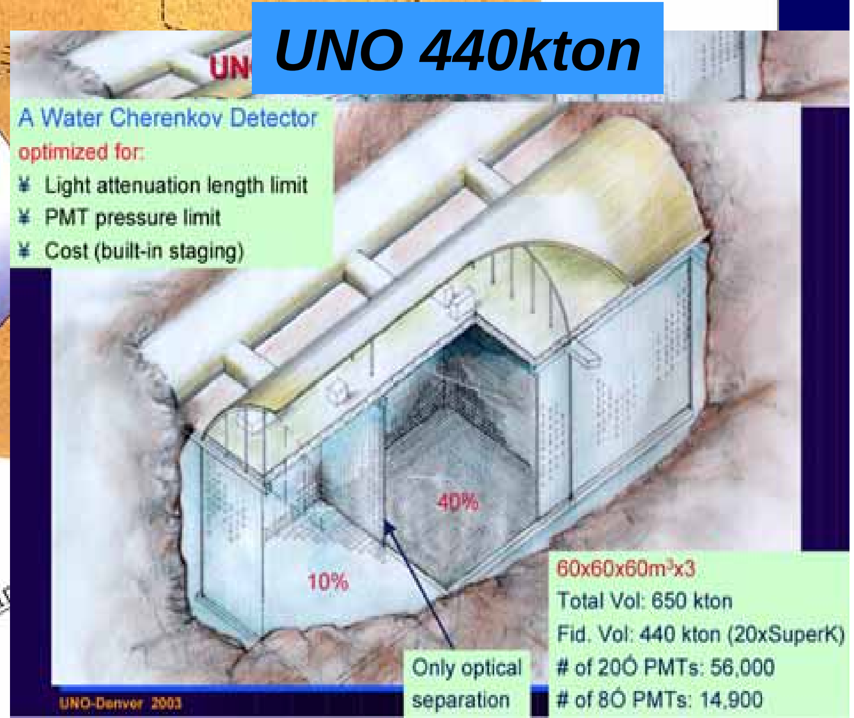
Summary of Nucleon Decay Searches

mode	exposure (kt· yr)	εB_m (%)	observed event	B.G.	τ/B limit (10^{32} yrs)
$p \rightarrow e^+ + \pi^0$	141	44-45	0	0.4	84
$p \rightarrow \mu^+ + \pi^0$	141	36	0	0.6	67
$p \rightarrow e^+ + \eta$	92	17	0	0.2	23
$p \rightarrow \mu^+ + \eta$	92	9	0	0.2	13
$n \rightarrow \nu + \eta$	45	21	5	9	5.6
$p \rightarrow e^+ + \rho$	92	4.2	0	0.4	5.6
$p \rightarrow e^+ + \omega$	92	2.9	0	0.5	3.8
$p \rightarrow e^+ + \gamma$	92	73	0	0.1	98
$p \rightarrow \mu^+ + \gamma$	92	61	0	0.2	82
$p \rightarrow \overline{\nu} + K^+$	92				23
$K^+ \rightarrow \nu\mu^+$ (spectrum)		36	–	--	6.4
prompt $\gamma + \mu^+$		8.6	0	0.7	10
$K^+ \rightarrow \pi^+\pi^0$		6.0	0	0.6	7.8
$n \rightarrow \overline{\nu} + K^0$	92				1.3
$K^0 \rightarrow \pi^0\pi^0$		6.9	14	19.2	1.3
$K^0 \rightarrow \pi^+\pi^-$		5.5	20	11.2	0.69
$p \rightarrow e^+ + K^0$	92				10
$K^0 \rightarrow \pi^0\pi^0$		9.2	1	1.1	8.4
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		7.9	5	3.6	3.5
3-ring		1.3	0	0.04	1.6
$p \rightarrow \mu^+ + K^0$	92				13
$K^0 \rightarrow \pi^0\pi^0$		5.4	0	0.4	7.0
$K^0 \rightarrow \pi^+\pi^-$					
2-ring		7.0	3	3.2	4.4
3-ring		2.8	0	0.3	3.6

Future large water Cherenkov detectors

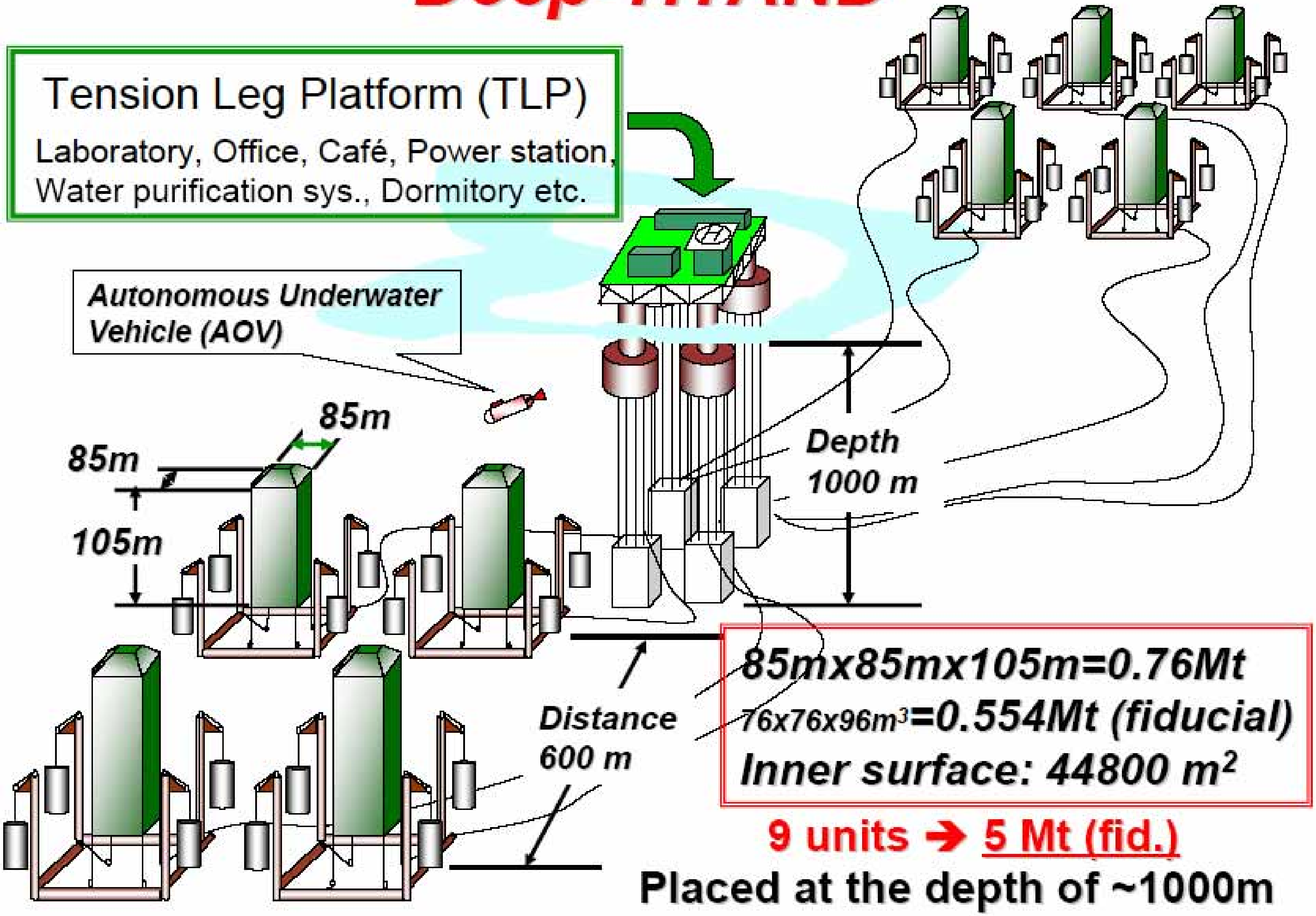






~0.5Megaton (20xSuper-K) detectors have been discussed in Japan, US, and Europe.

Deep-TITAND


Tension Leg Platform (TLP)
Laboratory, Office, Café, Power station, Water purification sys., Dormitory etc.
Autonomous Underwater Vehicle (AOV)
85m
85m
105m
Depth 1000 m
Distance 600 m
85mx85mx105m=0.76Mt
76x76x96m3=0.554Mt (fiducial)
Inner surface: 44800 m2
9 units ➔ 5 Mt (fid.)
Placed at the depth of ~1000m

Detector requirements

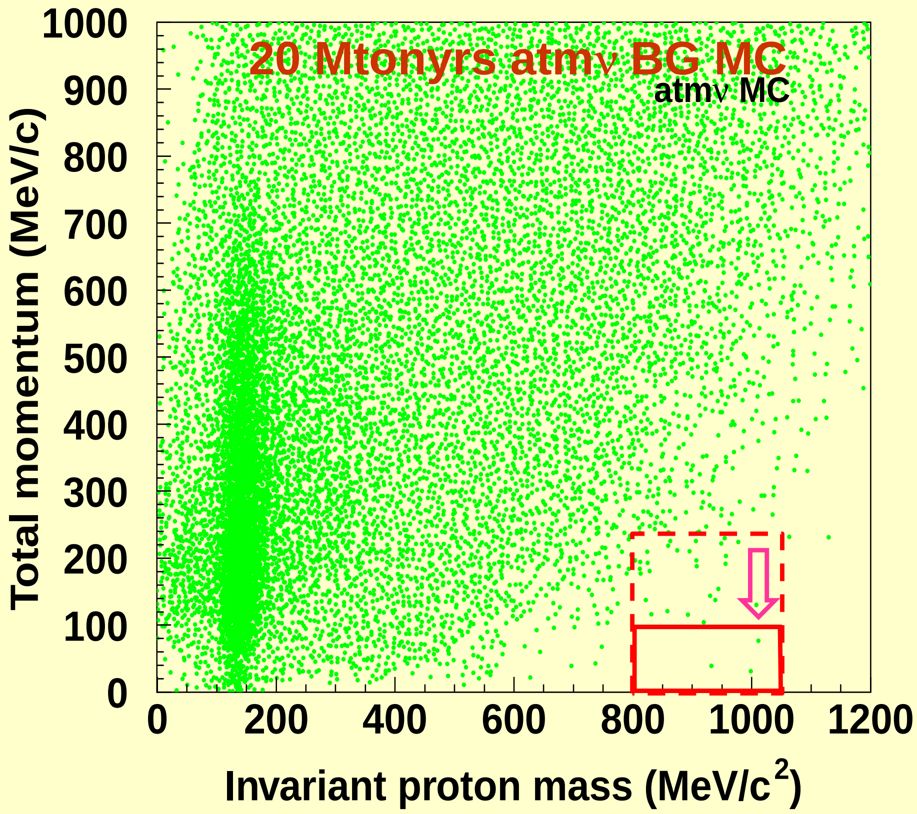
- Need more protons (detector volume)
  - Larger is better because theorists never guarantee the proton lifetime
- We will surely suffer non-negligible backgrounds in the high statistic data
  - ~2.2 BG events/Megatonyear for $p \rightarrow e^+\pi^0$
  - BG reduction is indispensable to maximize the lifetime sensitivity

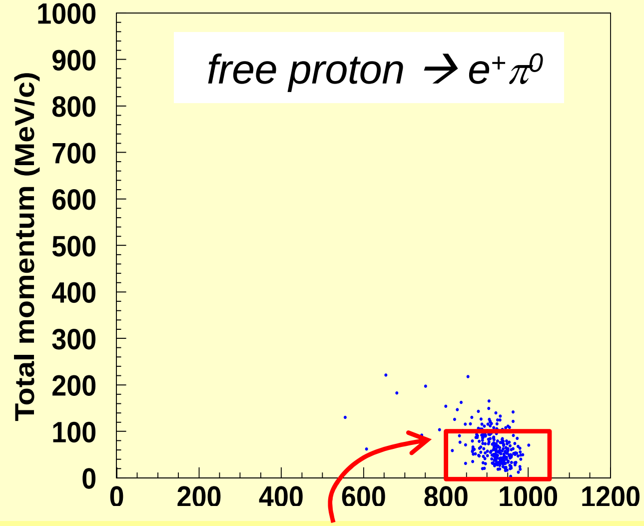
Background reduction for p→$e^+\pi^0$ (tighter momentum cut)

- Ptot < 250 MeV/c (SK cut)
  BG=***2.2*** ev/Mtonyrs, eff.=***44%***

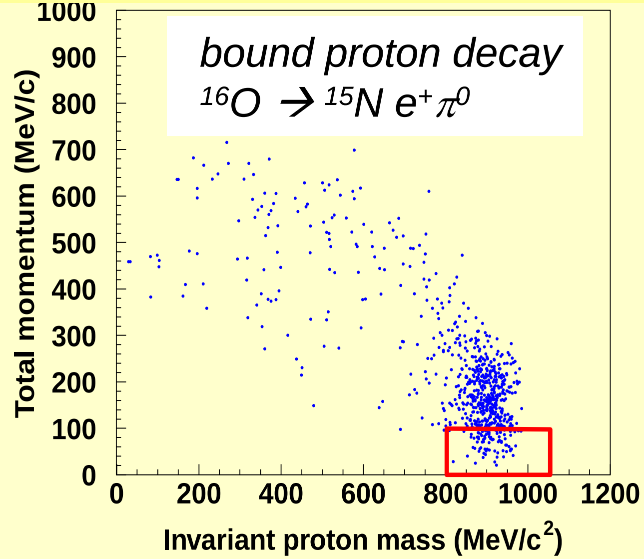
BG reduction by ~15

- Ptot < 100 MeV/c (tighter cut)
  BG=***0.15***ev/Mtonyrs, eff.=***17.4%***





main target is *free proton decays*



Further BG reduction?

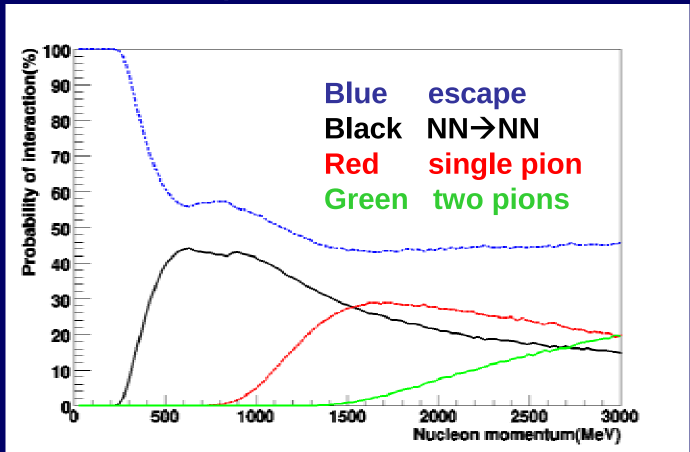
Many BG are accompanied by neutrons

Background events for $p \rightarrow e^+\pi^0$ (4.5Megaton years)

	ν interactions	secondary interactions in water
1	$\nu n \rightarrow e^- p \pi^0$	Neutron production by the proton
2	$\nu p \rightarrow e^- p \pi^+$	Neutron by π^+
3	$\nu p \rightarrow e^- p (\pi^+) \pi^0$	
4	$\nu n \rightarrow \nu p \pi^- \pi^0$	
5	$\nu n \rightarrow e^- p$	Neutron by the proton
6	$\nu n \rightarrow e^- n \pi^+ \pi^-$	
7	$\nu p \rightarrow e^- p (\pi^+) \pi^0$	
8	$\nu p \rightarrow \nu p \rho$	
9	$\nu O \rightarrow e^- O \pi^+$	Neutron by π^+
10	$\nu n \rightarrow n \rho$	neutron and π^- by the neutron

More n should be there because

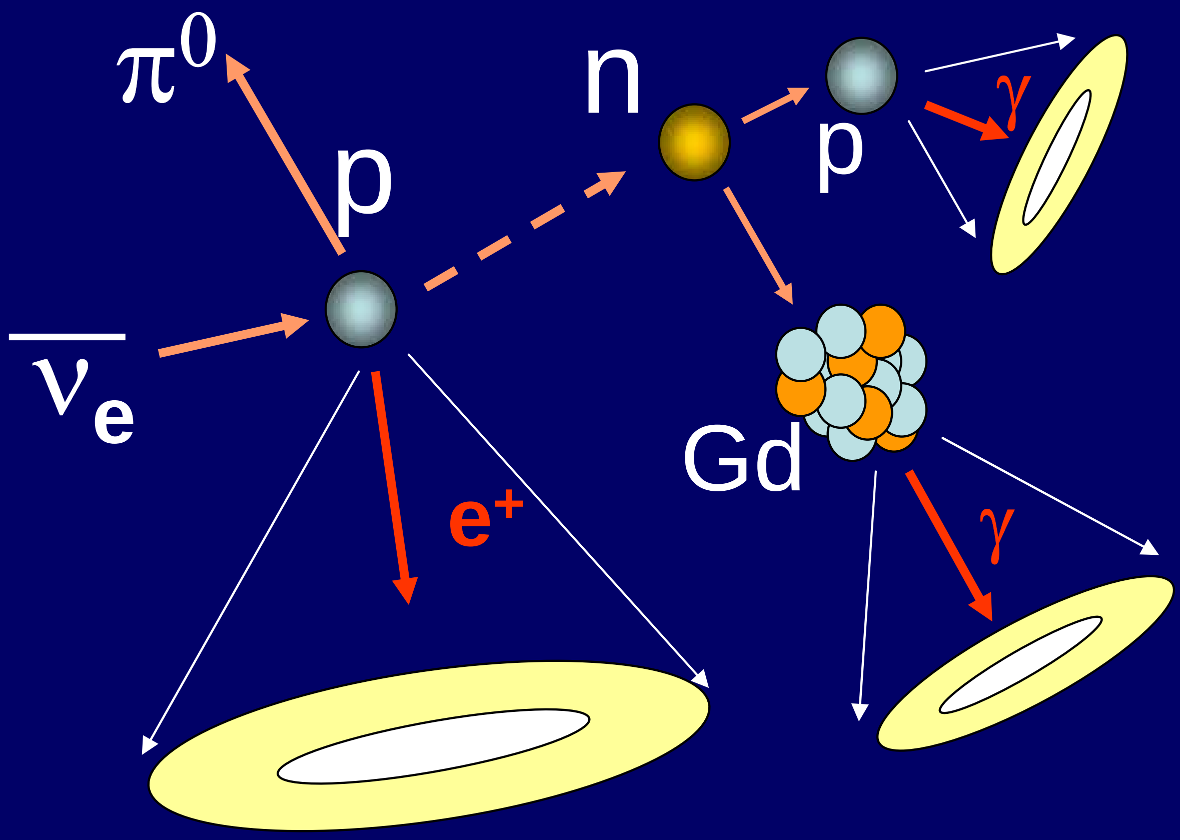
- Secondary interactions of protons in ^{16}O;
  $pp \rightarrow pp$, $pn \rightarrow pn$, $pn \rightarrow np$
  sometimes produce neutrons (not simulated now)



- For $E\nu$ 1~10GeV, residual nuclei may become fragment producing additional neutron (not simulated now)
- Stopping π^- absorbed by medium could also cause neutron emission (no simulation now)

Further BG reduction is possible if WC detector can tag neutrons.
(need studies by experimental tests and full MC simulation)
Fraction of BG accompanied by neutron is roughly ~90%.

Possibilities of neutron tagging



Possibility 1

n+p→d + γ

2.2MeV γ-ray

ΔT = ~ 200 μsec

Number of hit PMT is about 6 in SK-III

Possibility 2

n+Gd →~8MeV γ

(Visible E: 1~8MeV)

ΔT = ~20 μsec

Add 0.2% $GdCl_3$ or $GdNO_3$

(ref. Vagins and Beacom)

R&D is going on

- Issues for Gd:
  - water transparency, how to operate water purification system, corrosion of materials so on
- need high speed DAQ electronics to achieve very low threshold

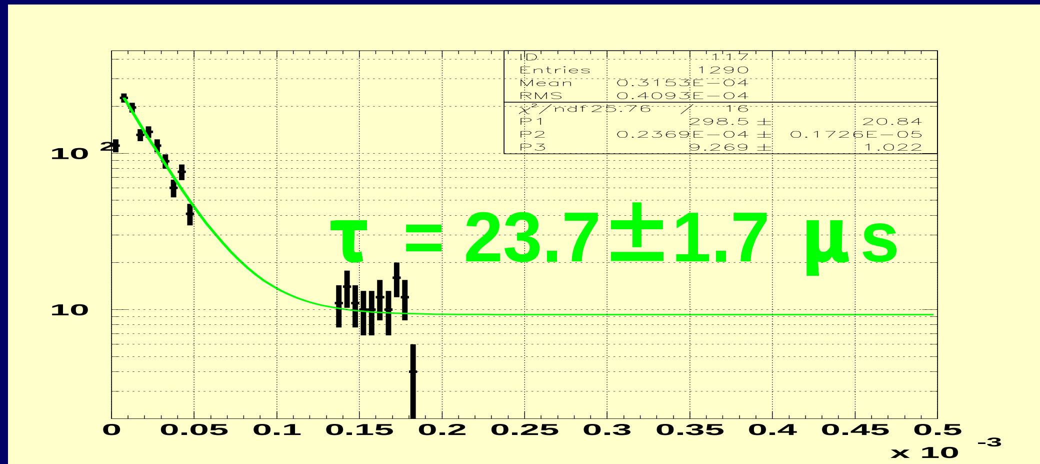
Feasibility check of neutron tagging @ Super-K

$GdCl_3$ Vessel

⇒ Acrylic Cylinder. @Center

Placed Am/Be Embedded BGO.

Number of γ hit



Timing difference of γ

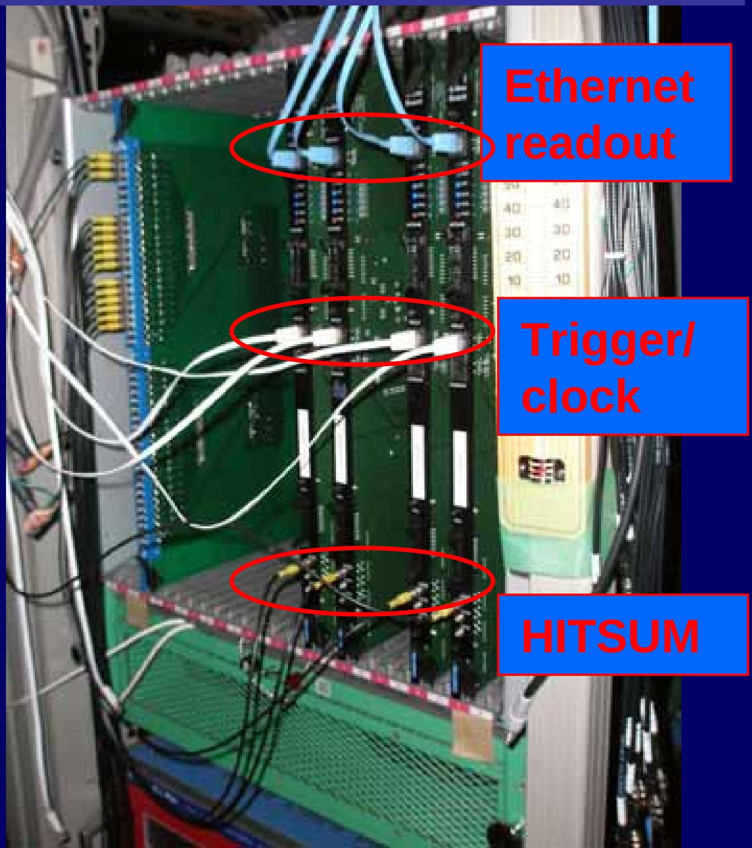
This Apparatus Deployed @Detector Center in SK.

➔ 0.2 % $GdCl_3$ Sol. in This Apparatus ←→ 28 % *n* Det. Efficiency,

0.2 % $GdCl_3$ Sol. **in SK Volume ←→ 90 %** *n* Det. Efficiency.

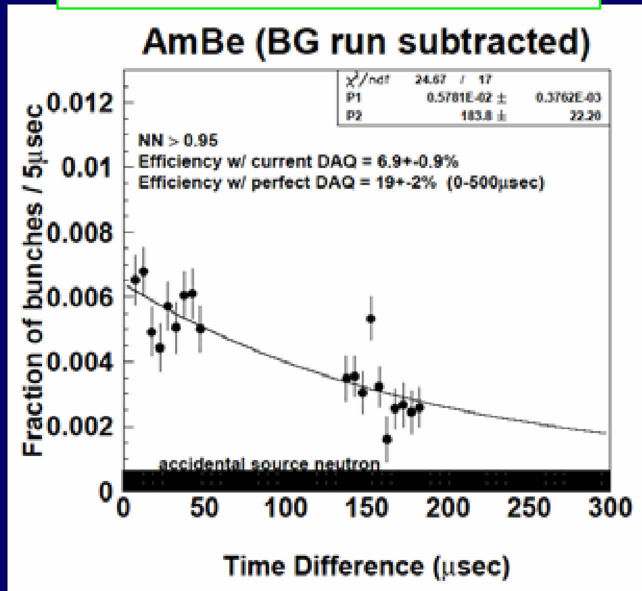
New DAQ erelectronics

QBEE prototype at Super-K



We will replace SK electronics with new *high speed pipelined electronics system* in 2008.
→
start recording faint neutron signature; n+p→d+γ**(2.2MeV)**

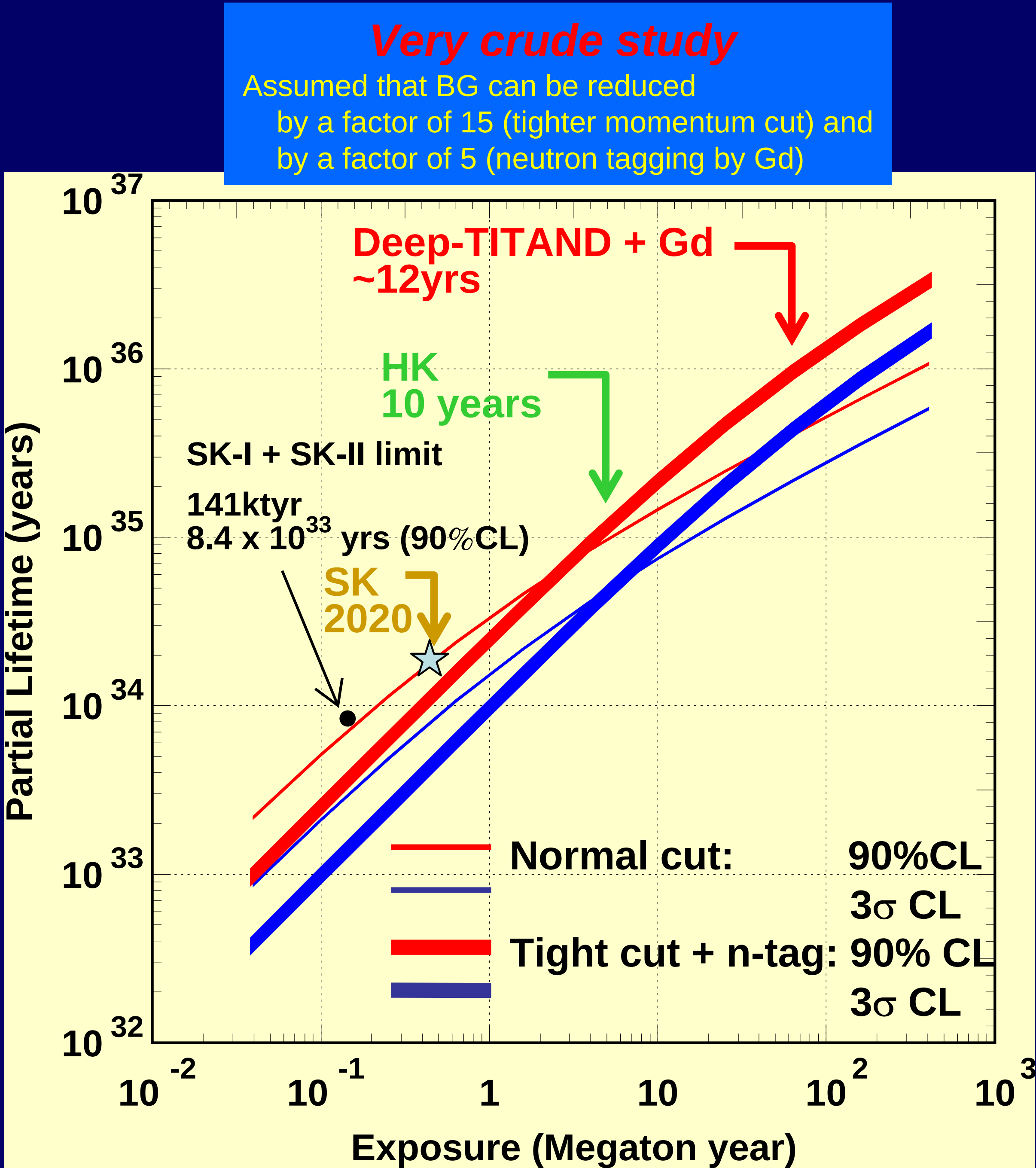
Test data @ Super-K



Detection eff.(np→dγ) is small ~20% (measured at SK).

But we can study neutron production probability in atmospheric ν interactions.

p→$e^+\pi^0$ sensitivity



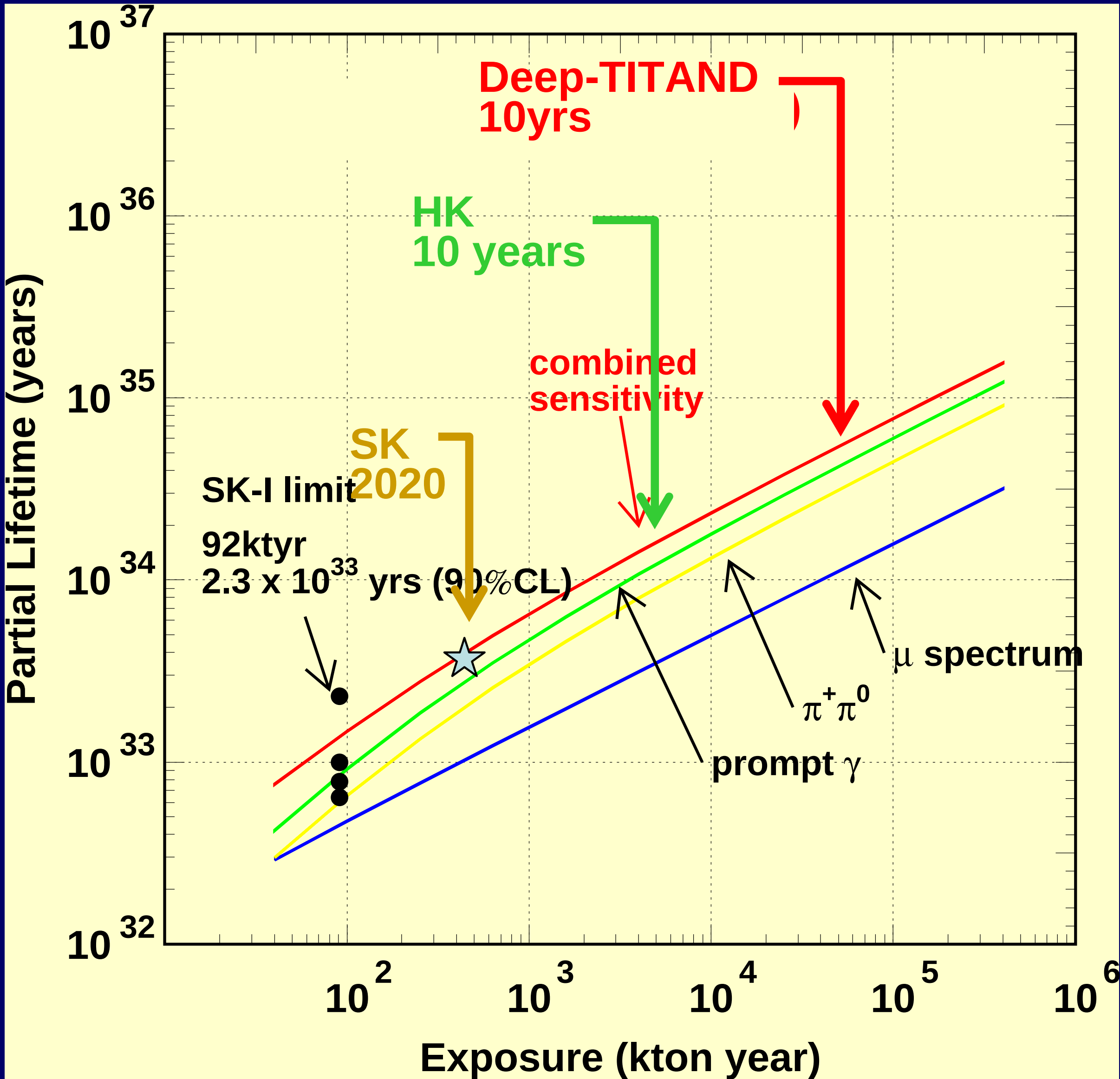
SK(0.022 Mt):2020
→
2x10^{34} yrs @ 90% CL

HK(0.5 Mt):10years
→
~10^{35} yrs @ 90% CL

10^{36} yrs @ 90% CL
→
Deep-TITAND(5 Mt) + Gd :~12years

$p \rightarrow \nu K^+$ sensitivity

Assume 40% PMT coverage (SK efficiency and BG rate)

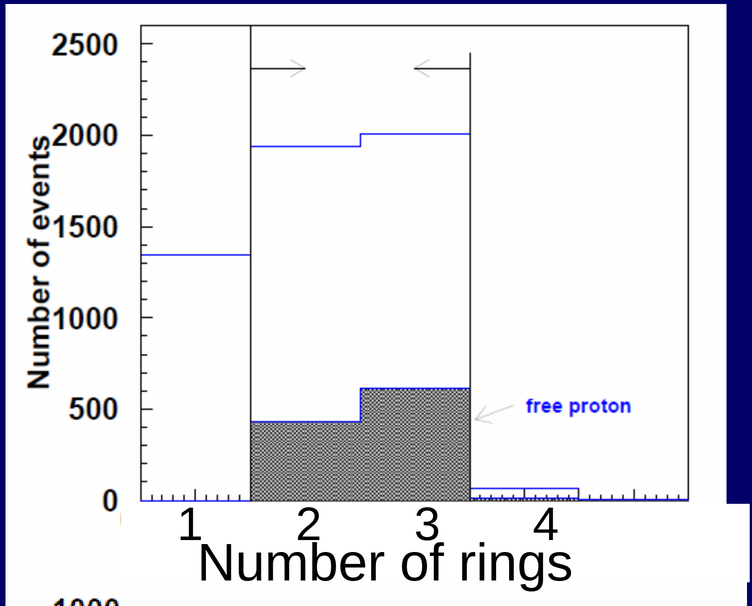


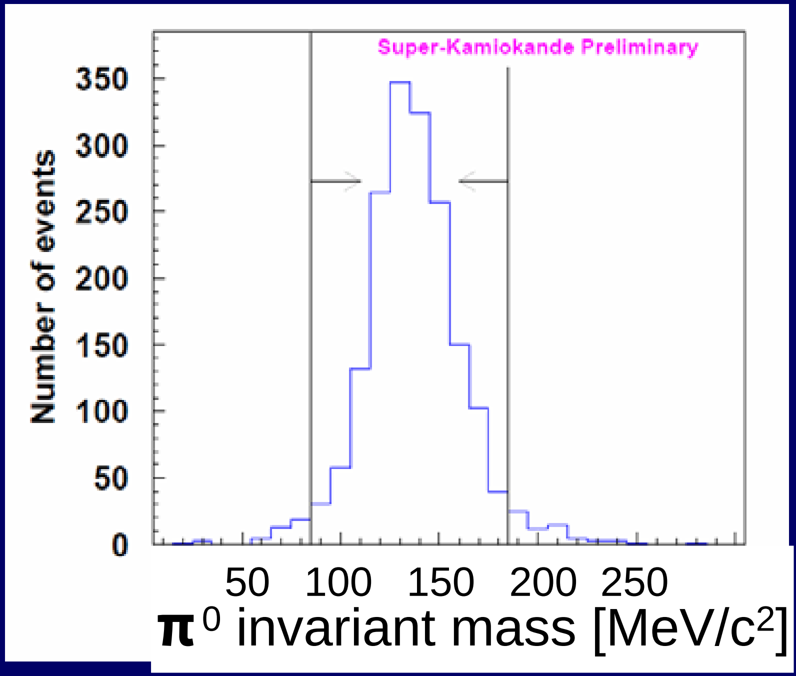
SK(0.022 Mt):2020
→
~3 x10^{33} yrs @ 90% CL

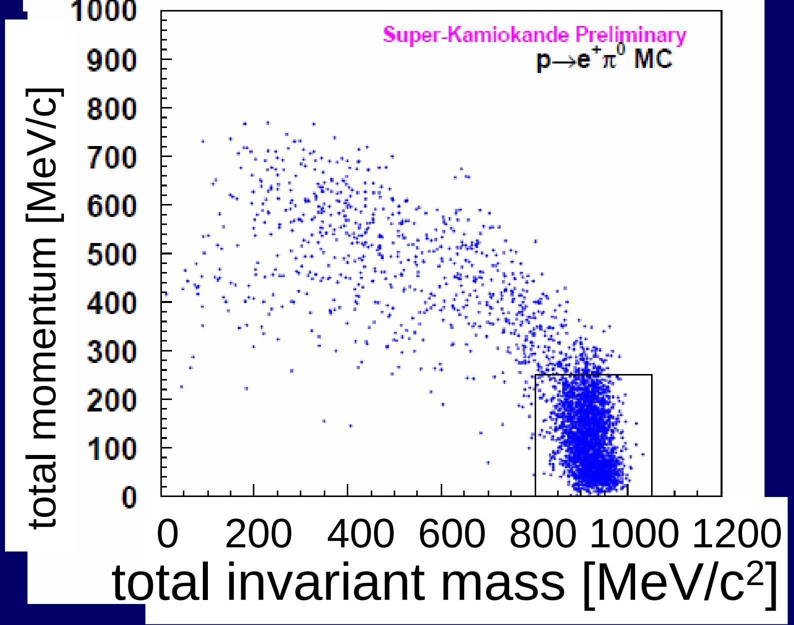
HK(0.5 Mt):10years
→
~2 x10^{34} yrs @ 90% CL

Deep-TITAND(5 Mt):
10yrs
→
7 x 10^{34} yrs @ 90CL

Detection efficiency







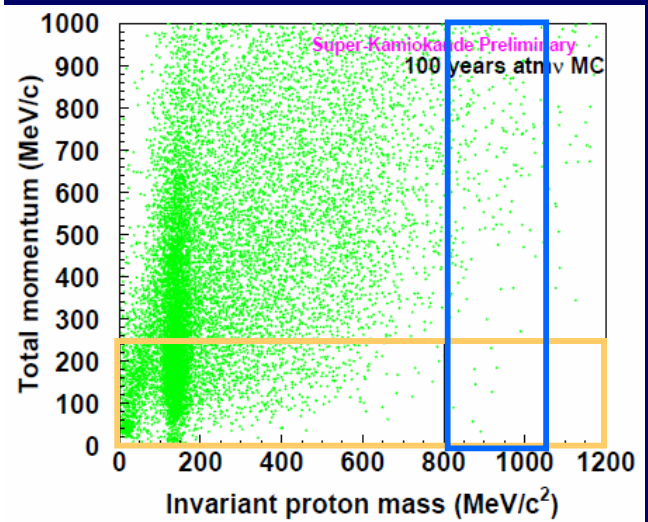
efficiency

- SK-I : 45.0 % (42.6 %)
- SK-II: 43.6 % (42.9 %)

(previous numbers)

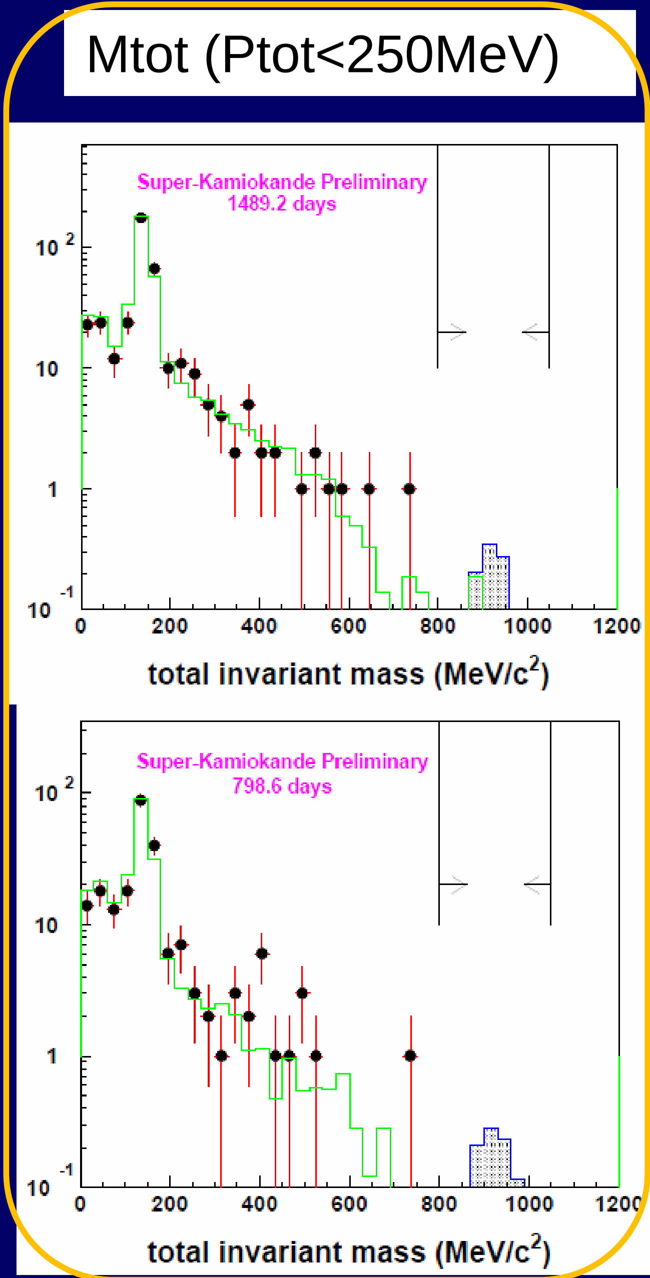
Detailed comparisons btw data and atmospheric n MC

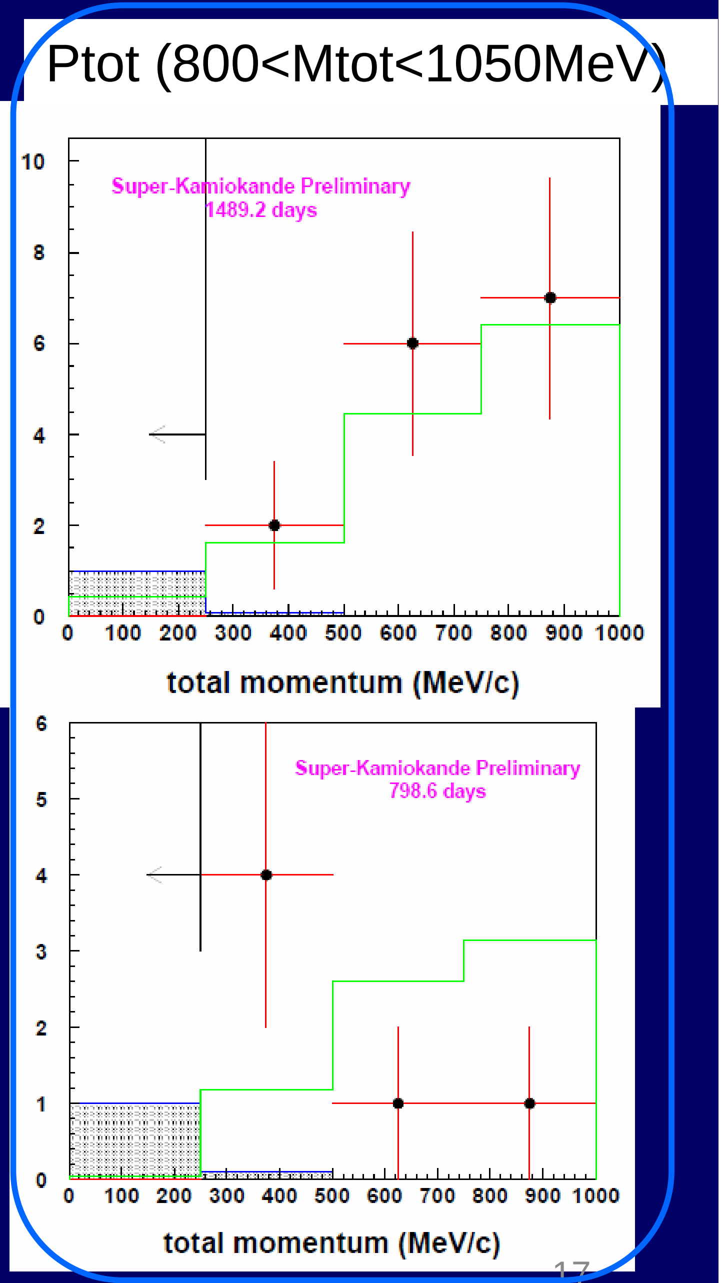
— Atm. nu MC
— Data



SK-I

SK-II



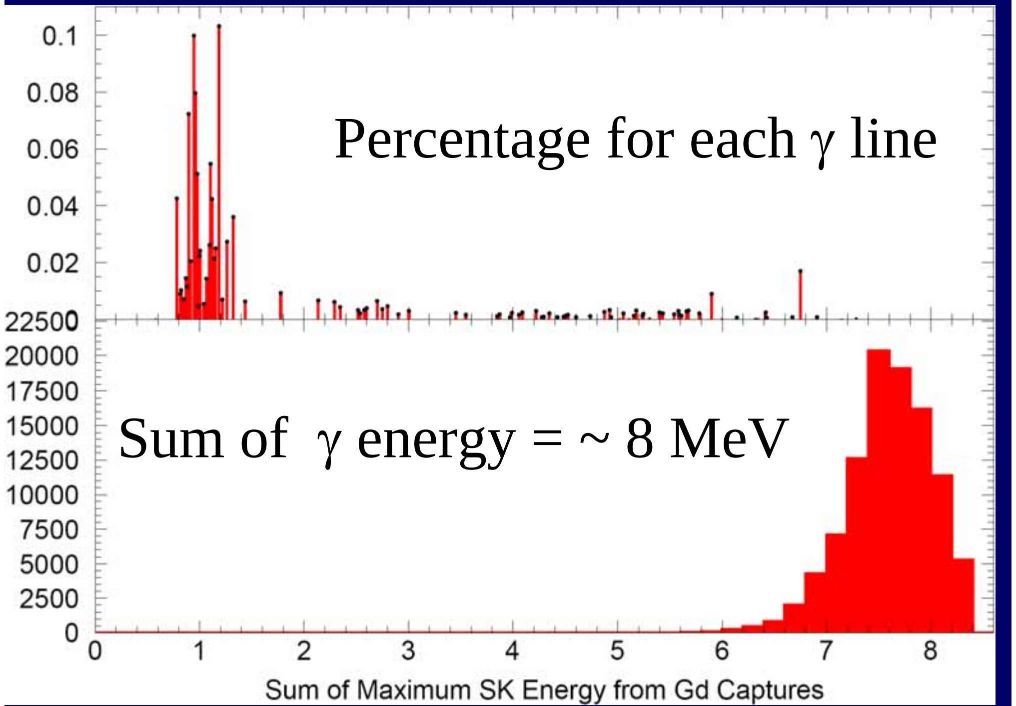


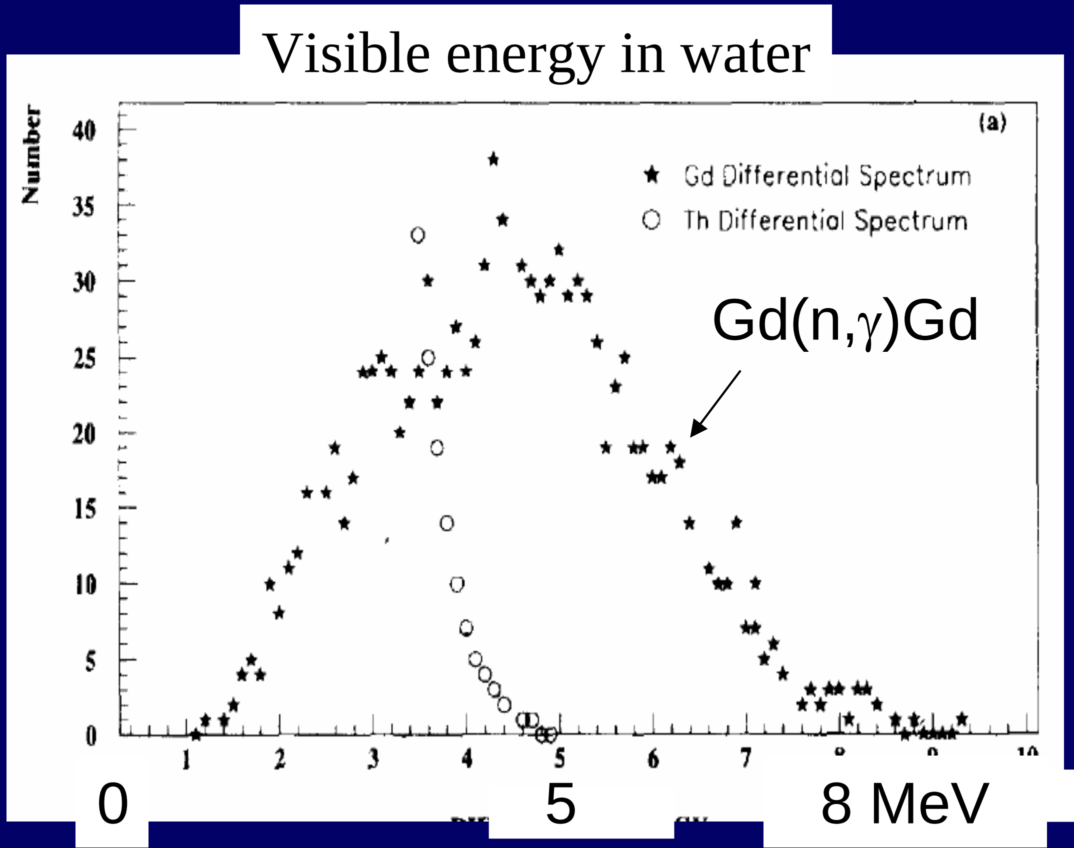
Observed data are well explained by atm ν interactions.

$\bar{\nu}_e$ identification: possibility 2

J.Beacom and M.Vagins, Phys.Rev.Lett.93:171101,2004

~0.2% $GdCl_3$ solution. Detect neutrons by Gd(n,γ)Gd reaction.





Simulation in C.K.Hargrove et al., N.I.M. A357, 157-169(1995)

Higher light yield.

Questions: water transparency, how to operate water purification system, corrosion of materials

- Summary of Det. Eff

  (Single Case Basis)

  (1) N10 > 15 Cut 58.3+-0.2 %

  (2) Ratio of (N300/N10) < 4 Cut 93.4+-0.6 %

  (3) DirKS < 0.4 Cut 98.8+-0.3 %

  (4) Goodness > 0.4 Cut 99.4+-0.2 %

  (5) Ther. *n*-capt. on Gd negligible 99.99 %

.

Isotope	Nat. Abun. (%)	X-sec. (barns)
^{152}Gd	0.20(1)	700.(200)
^{153}Gd	---	20000.(10000)
^{154}Gd	2.18(3)	(0.06 + 60.)
^{155}Gd	**14.80(12)**	**61.(1) x 10^3**
^{156}Gd	20.47(9)	~ 2.0
^{157}Gd	**15.65(2)**	**2.54(3) x 10^5**
^{158}Gd	24.84(7)	2.3(3)
^{160}Gd	21.86(19)	1.5(7)
^{161}Gd	---	2.0(6) x 10^4