EGADS approaching GADZOOKS!

Lluís Martí Magro, Kavli IPMU, Univ. Tokyo
for the **Super-Kamiokande Collaboration**
3rd International Conference on New Frontiers in Physics
Crete, Greece 2nd of August, 2014

Super-Kamiokande Detector

Outstanding successes and achievements:

- **Atmospheric neutrino oscillations:** neutrino mass

- **Solar neutrino oscillations:** contribution to the solar neutrino problem and firsts hints of terrestrial effects.

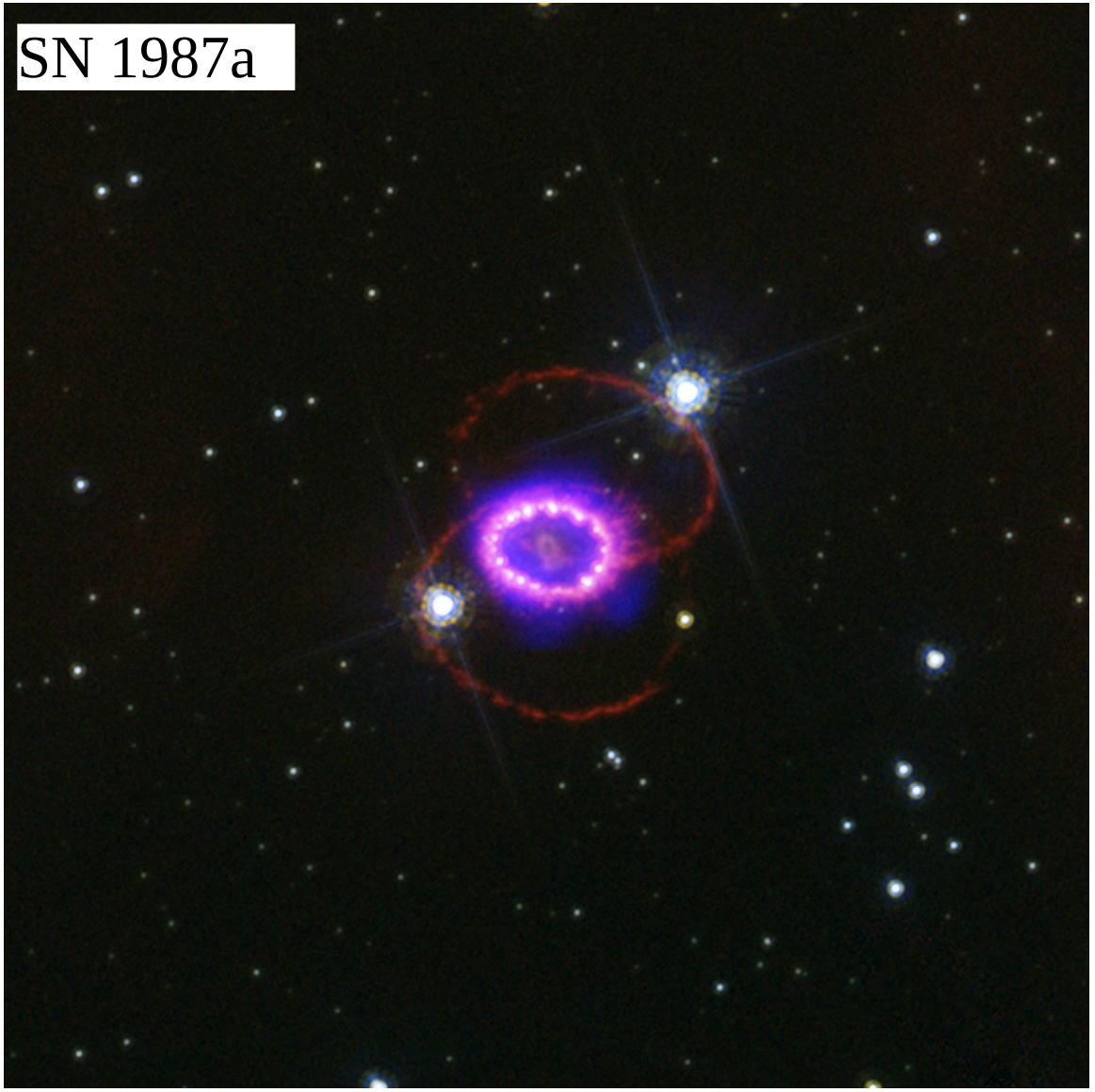
- With **T2K**: observation of ν_e appearance in ν_μ beam

- **Best proton decay limits:** most channels have no neutron

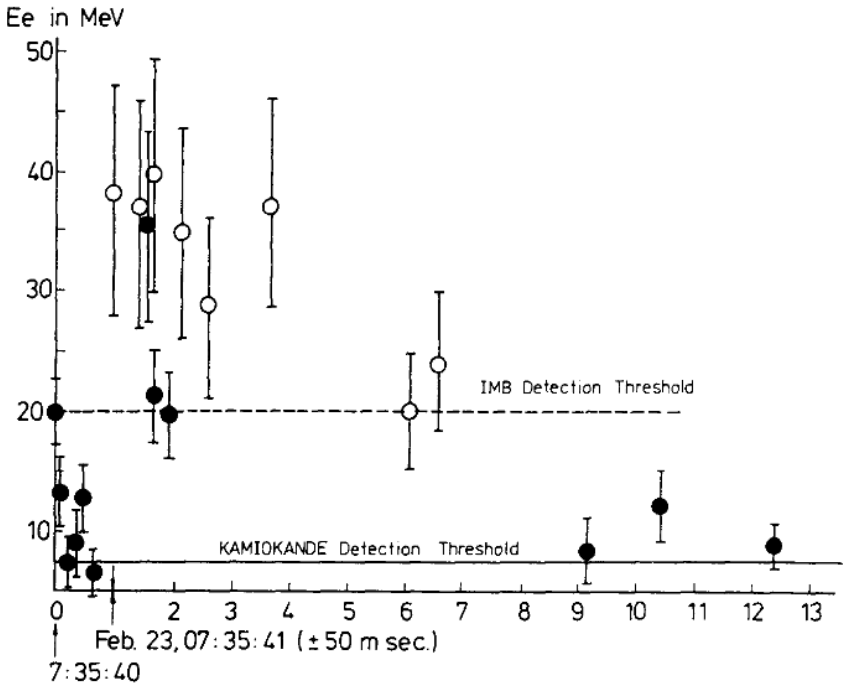
- Best **Diffuse Supernova Neutrino Background** limit [DSNB]

+ SK can detect galactic SNs and give an early alarm

The long wait for a Supernova



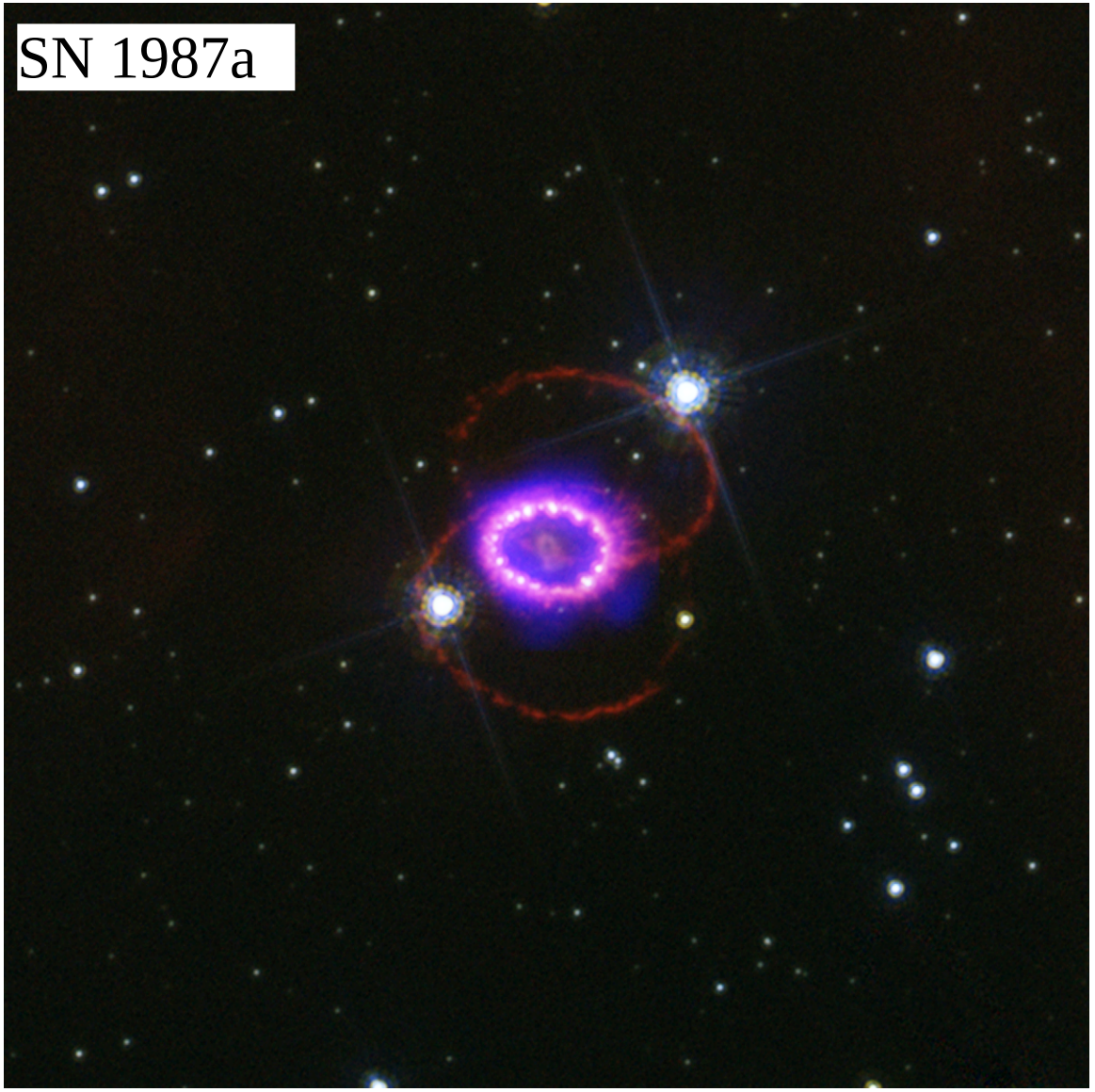
~10^{53} ergs released (99% in ν) within seconds



IMB and Kamiokande-II SN1987a events

These few events confirmed the basic picture about the explosion mechanism of core-collapse SNe

The long wait for a Supernova



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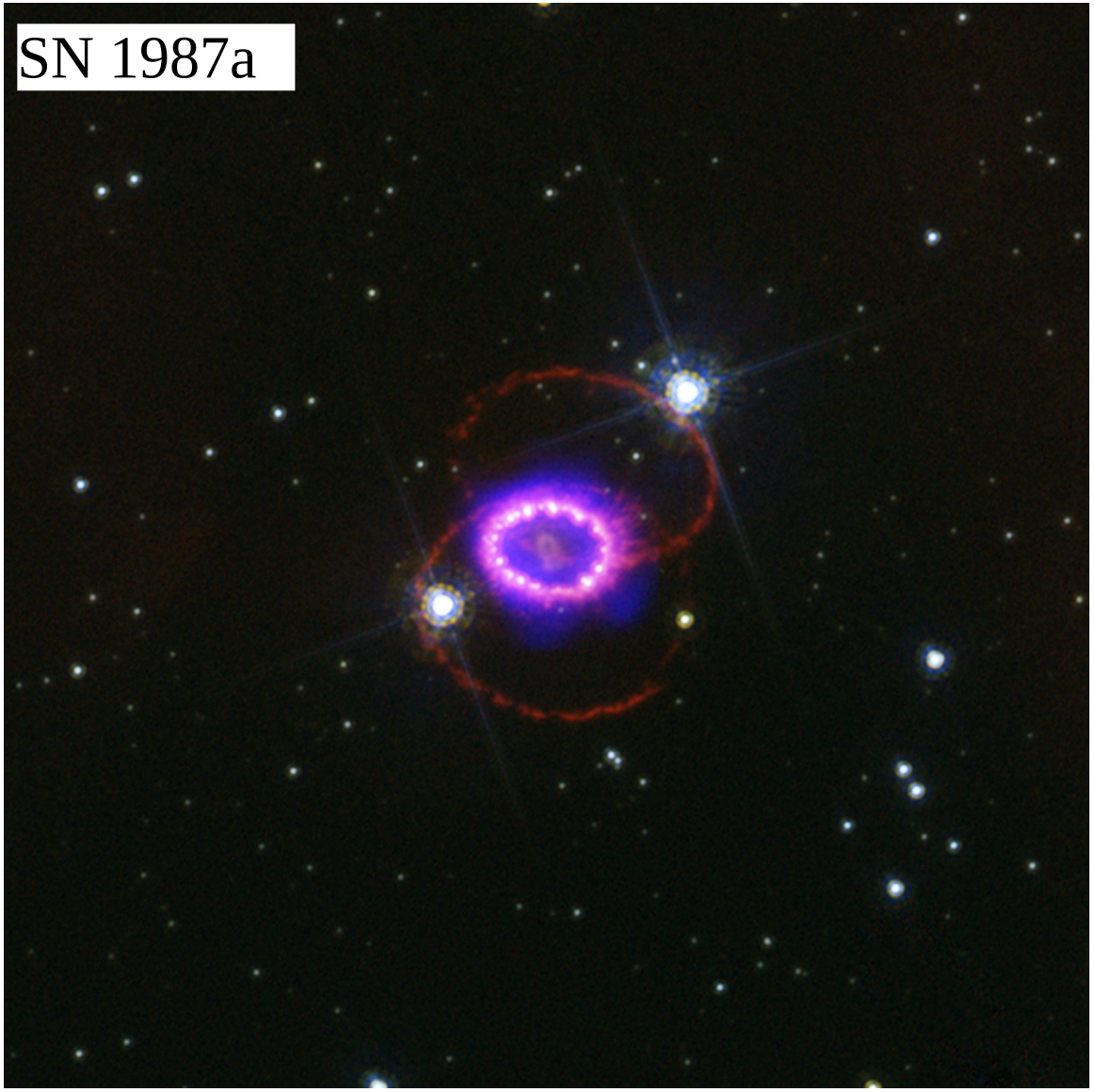
Detection: About 10^4 events expected at SK for a SN at the center of the galaxy (10 kpc)

Pointing: $\nu + e \rightarrow \nu + e$ elastic scattering provides information about the SN position

But there are about 2-3 SNe per century only. While we wait...

The long wait for a Supernova



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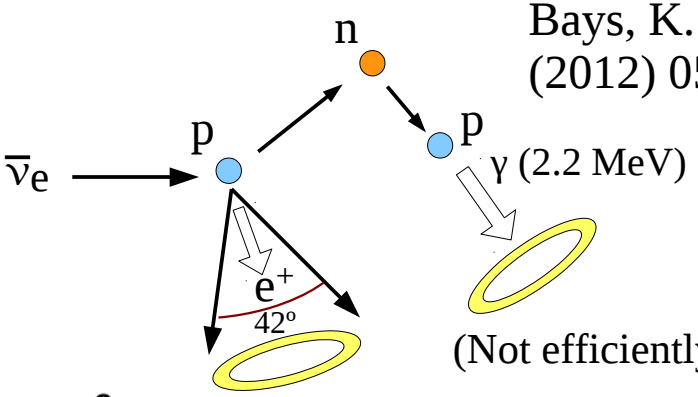
Pointing: $\nu + e \rightarrow \nu + e$ elastic scattering provides information about the SN position

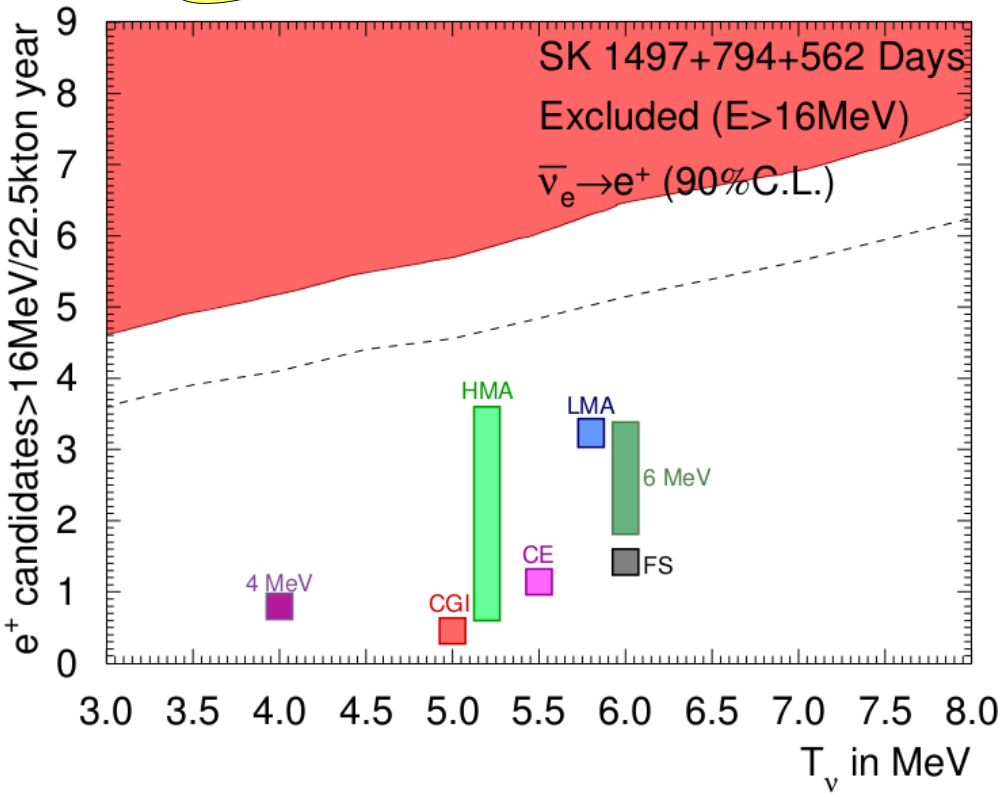
But there are about 2-3 SNe per century only. While we wait... can we detect the DSNB at last?

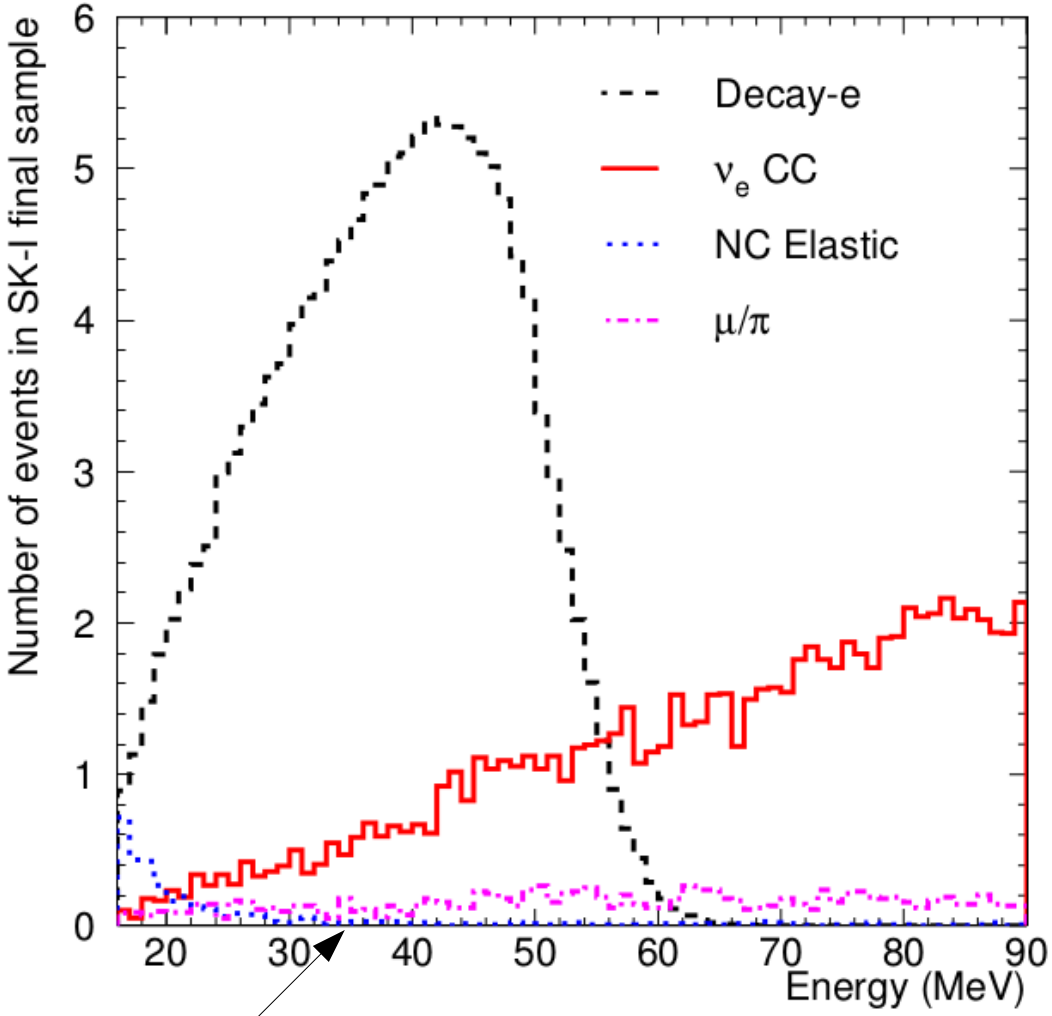
Diffuse Supernova Neutrino Background



Bays, K. et al., Phys.Rev. D85 (2012) 052007

(Not efficiently detected)





In this analysis, the backgrounds still dominate. Nevertheless, SK can set limits that are close to the predictions

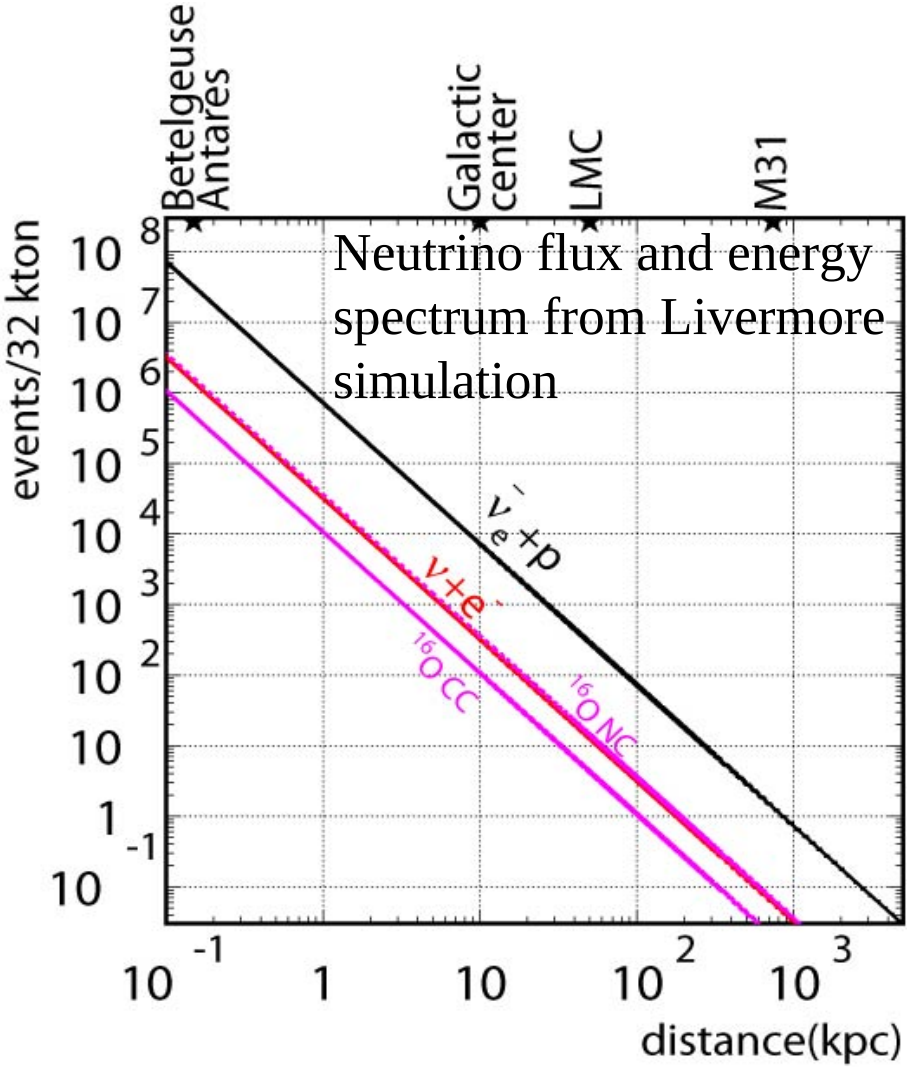
Diffuse Supernova Neutrino Background

These can be primarily seen from IBD the dominant cross section in case of SN:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$
$$+$$
$$p \rightarrow 2.2\ \text{MeV}\ \gamma$$

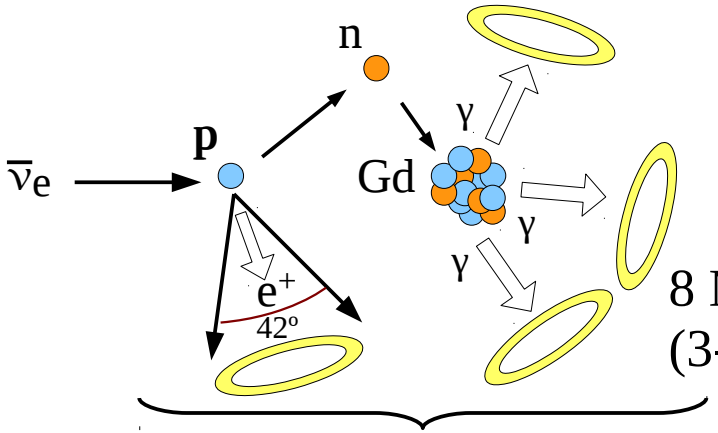
where at present only the **positron** can be efficiently detected.

If we could also detect the **neutron** we could reduce backgrounds and detect DSNB!



T.Totani, K.Sato, H.E.Dalhed and J.R.Wilson, ApJ.496,216 (1998)

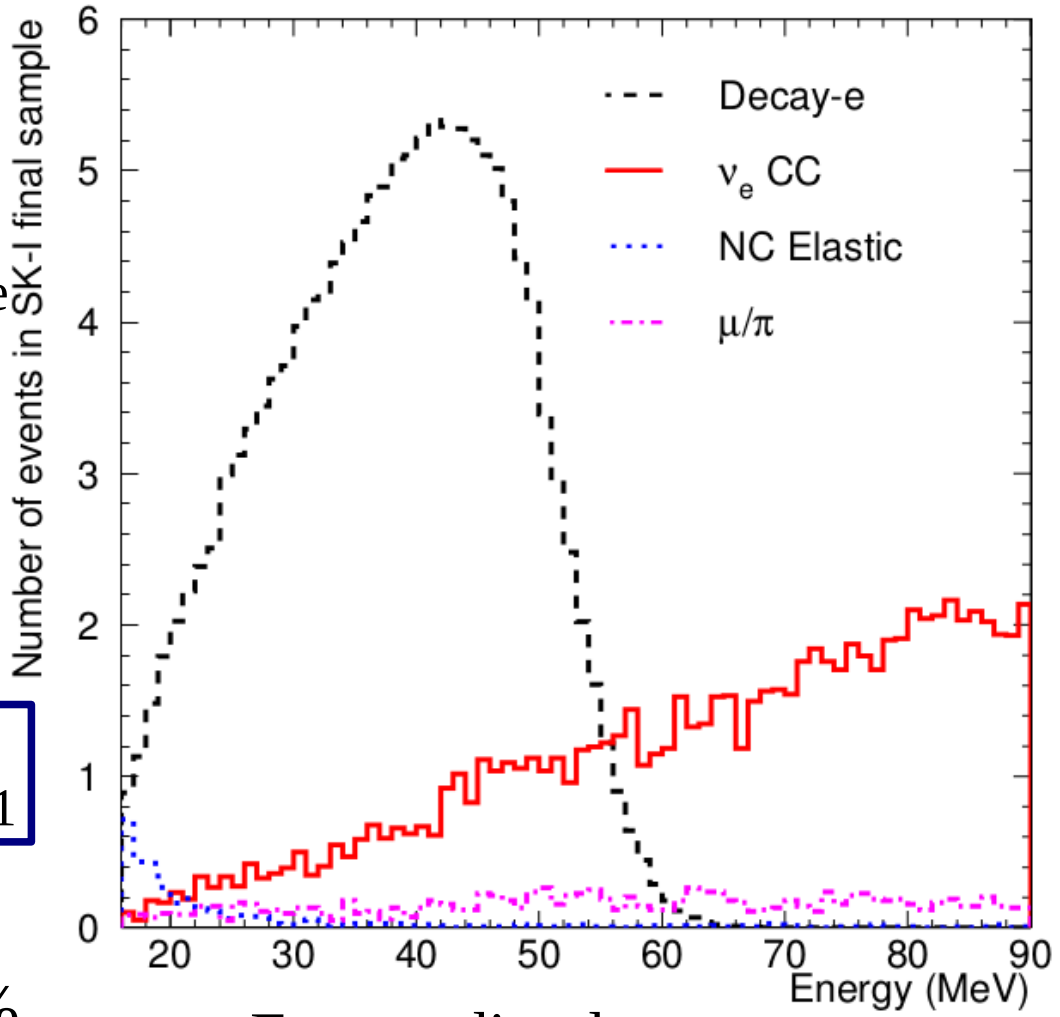
Diffuse Supernova Neutrino Background



8 MeV ɣ cascade
(3-4 gammas)

Tight time (delayed) and position coincidence between positron and neutron capture (80% efficiency)

Idea proposed as GADZOOKS!
by Beacom & Vagins PRL.93, (2004) 171101



Gadolinium has the largest neutron capture cross section: With just 0.2% concentration of $Gd_2(SO_4)_3$ we will be able to reduce backgrounds and detect DSNB for the first time!

- Easy to dissolve
- Good optical properties
- Compatible with detector components

Galactic Core-collapse SN & more

Core-collapse burst: gadolinium will allow us neutrino tagging, i.e. identify the dominant IBD events:

- Prompt recognition of a SN
- This would outline the ν_x elastic scattering: $\nu_x + e^+ \rightarrow \nu_x + e^+$ and hence greatly improve the pointing accuracy to the SN
- Measure $\bar{\nu}_e$ and ν_e spectra

Pre-burst signal: for $M > 8\ M_\odot$ during Si burning (last hours or days at most) pair annihilation νs are generated and if close enough (a few kp) could be detectable:

Detector	Target mass	Min $\bar{\nu}_e$ energy	48-24 hours before collapse	24-0 hours before collapse	3-0 hours before collapse
Super-K	32 kton	5 MeV	0.6	173	158
GADZOOKS!	22.5 kton	3.8 (1.8) MeV	9 (204)	442 (1883)	345 (1130)

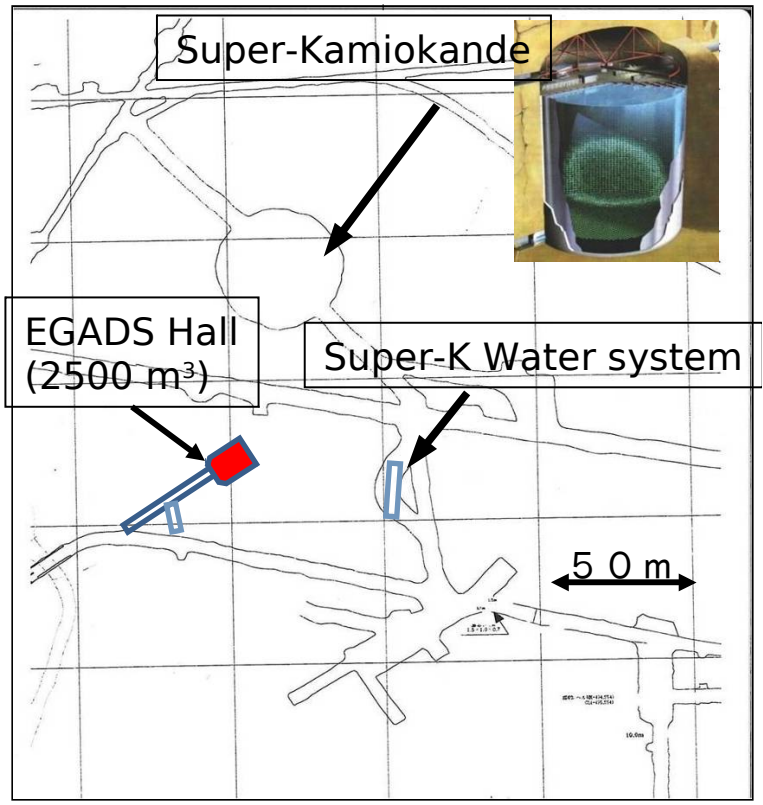
A.Odrzywolek et al. AIP Conf.Proc.944,109 (2007)

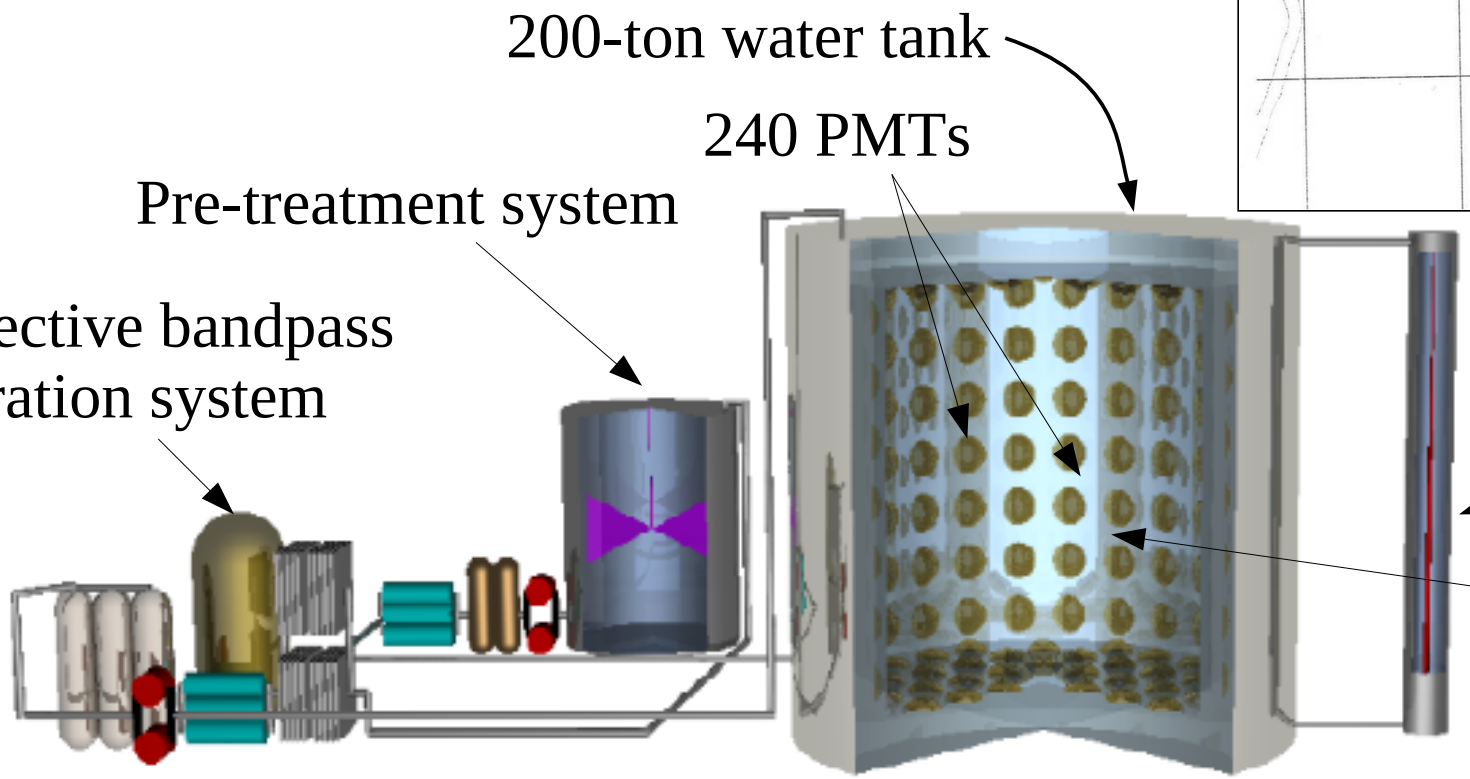
EGADS: goals, location and equipment

Evaluating Gadolinium's Action on Detector Systems

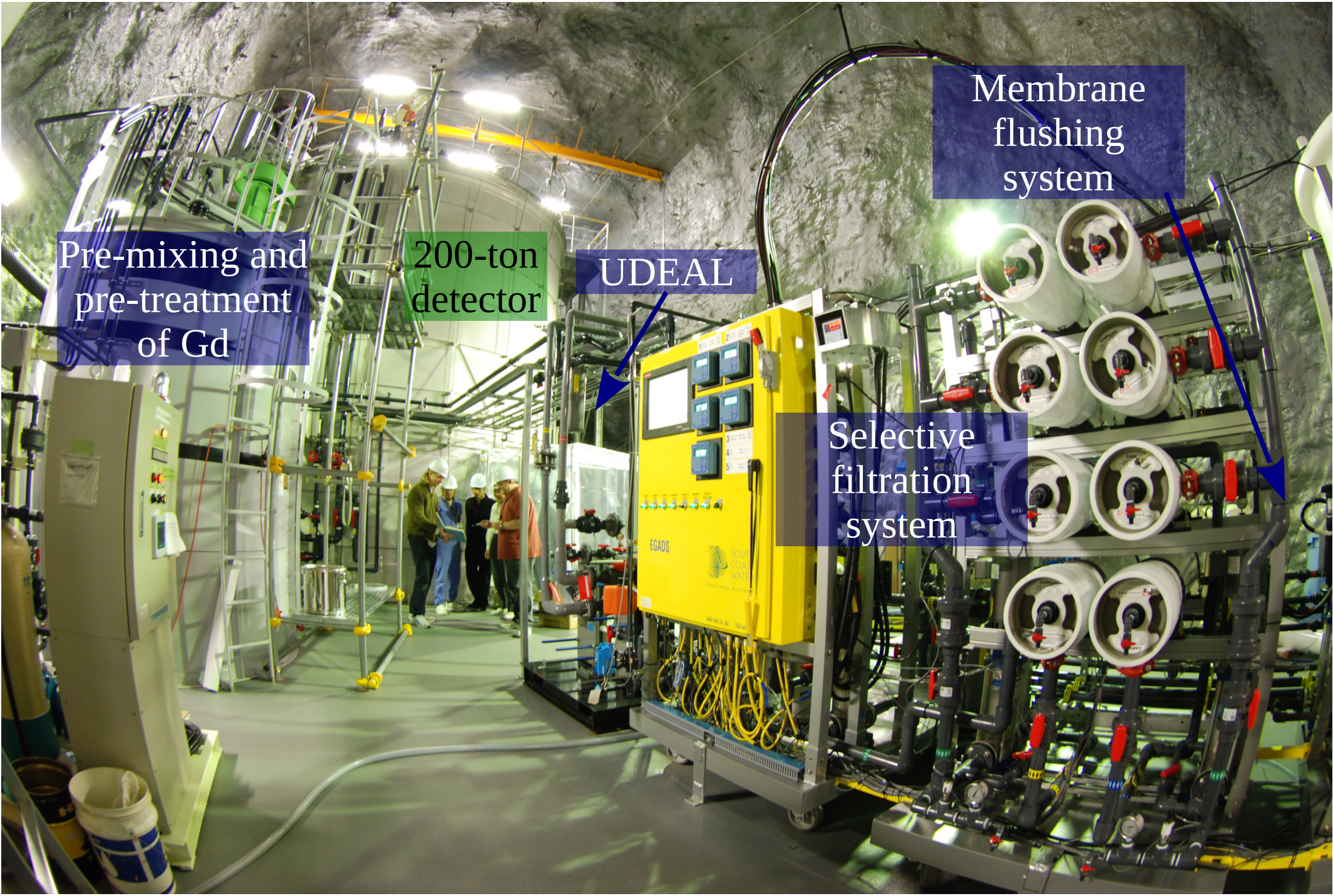
Our Goals:

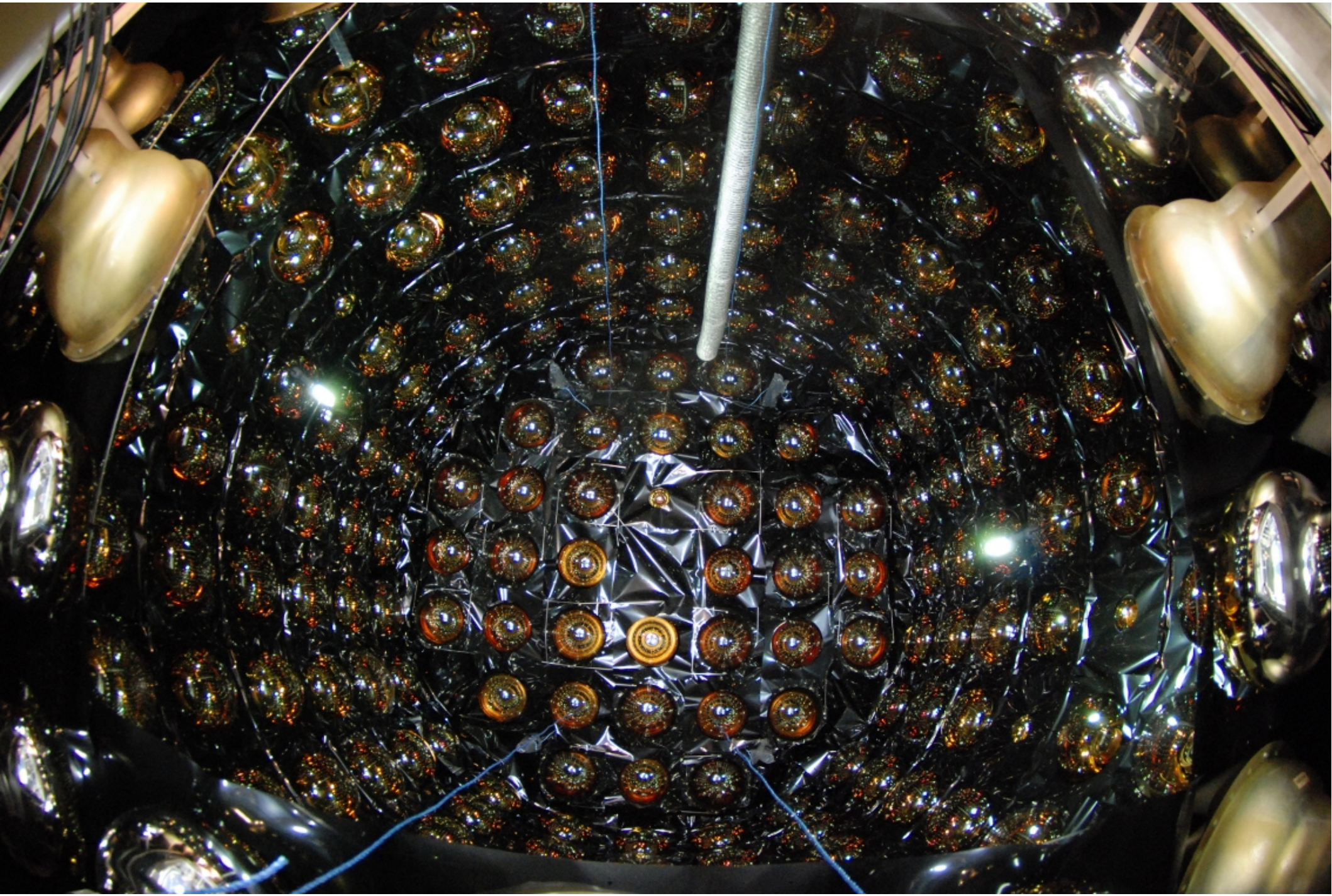
- ✔ Water purification system
- ✔ Monitor the water transparency
- ✔ Effects on detector components
- ✔ Adding/removing Gd
- ✔ Neutron background

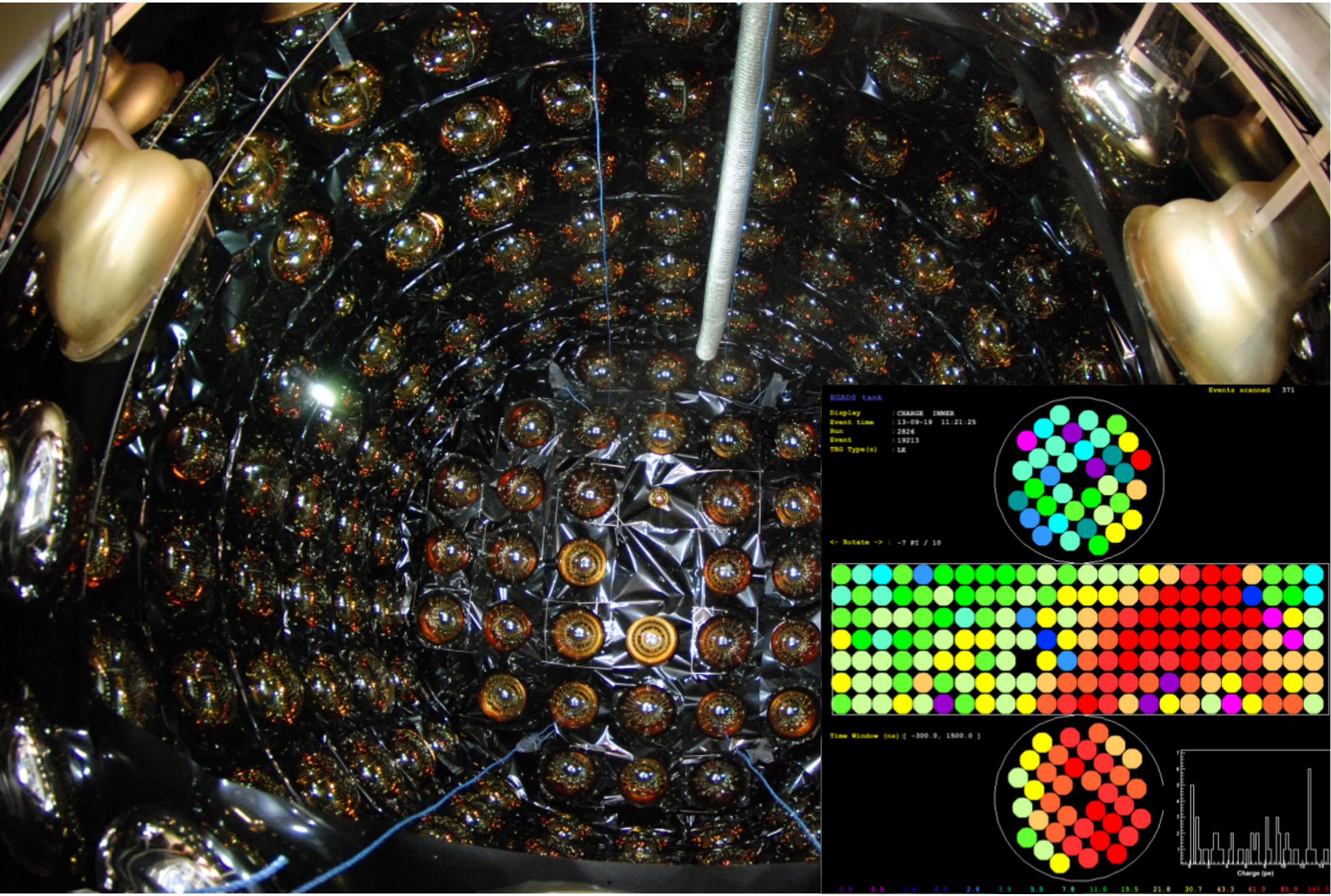




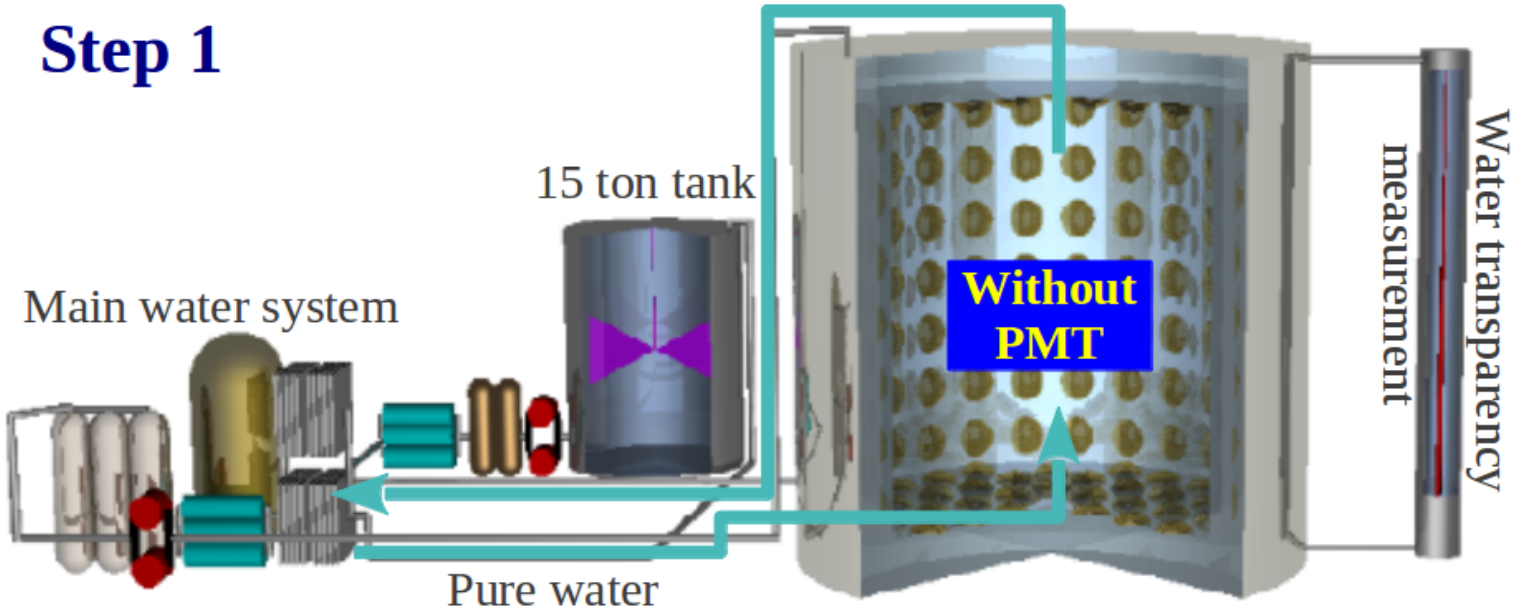
A.Kibayashi


Membrane flushing system
Pre-mixing and pre-treatment of Gd
200-ton detector
UDEAL
Selective filtration system



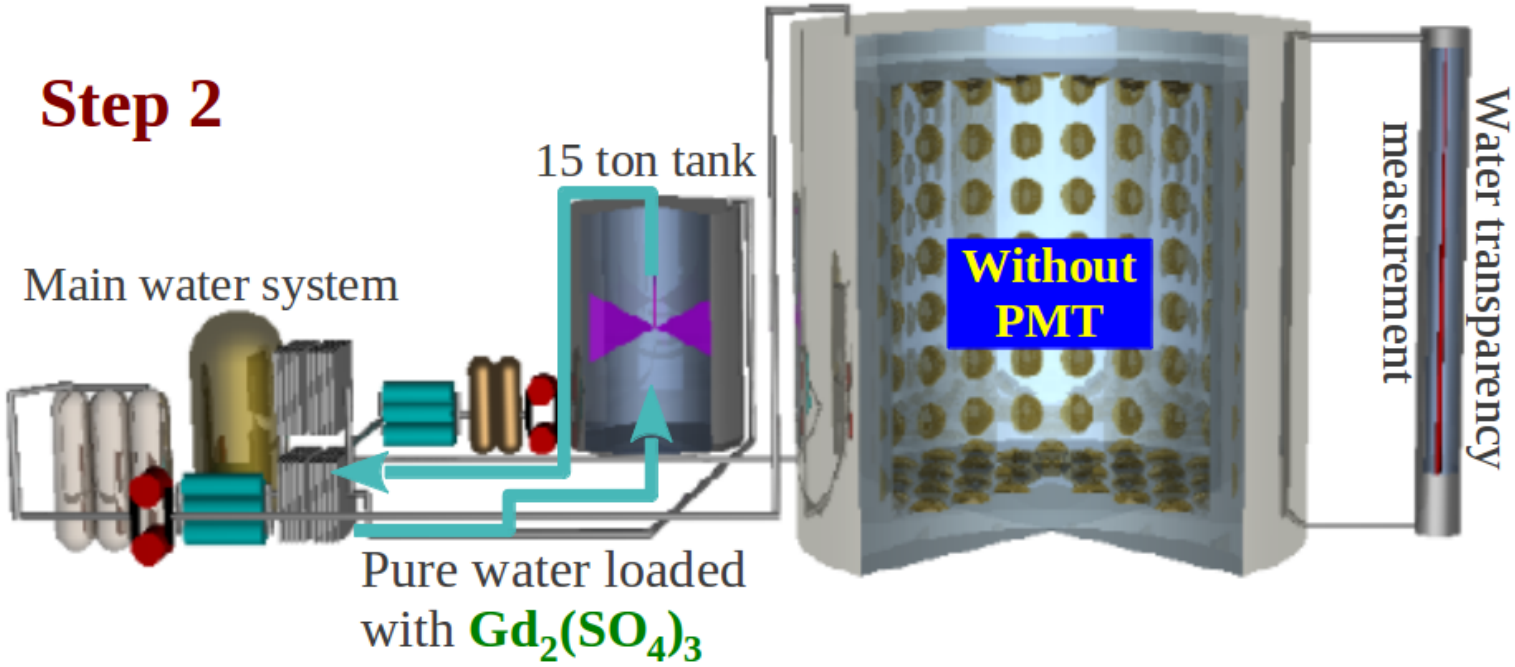

EGADS tank
Events scanned 371
Display : CHARGE INNER
Event time : 13-09-19 11:21:25
Run : 2826
Event : 19213
TRG Type(s) : LE
<- Rotate -> : -7 PI / 10
Time Window (ns) : [-300.0, 1500.0]
Charge (pe)
0.0 0.5 1.4 2.0 2.8 3.9 5.5 7.8 11.0 15.5 21.8 30.7 43.3 61.0 85.9 240.0

Step 1: pure water



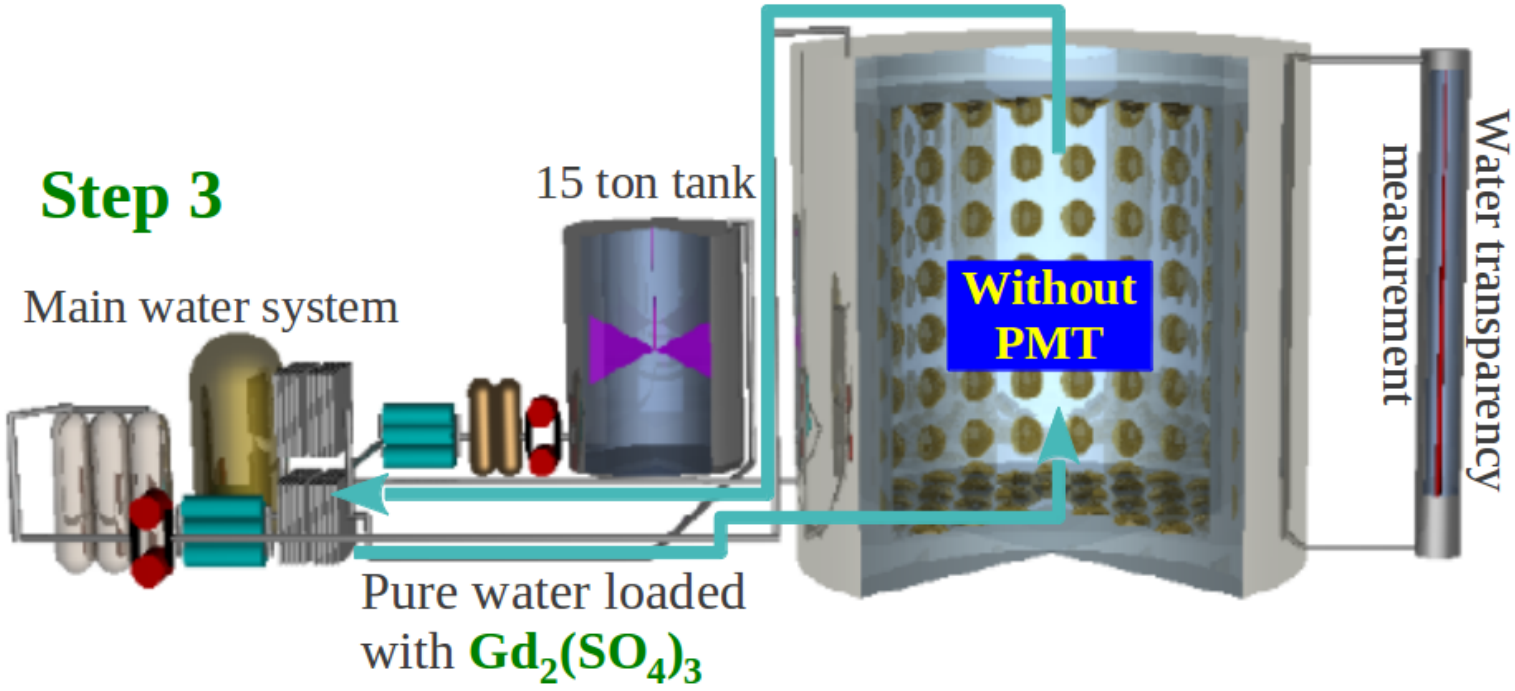
- **Step 1:** Circulation through the 200 ton tank with pure water (first half 2011 pure water circulation) **Done!**

Step 2: Gd water in 15 m^3 tank



- **Step 1:** Circulation through the 200 ton tank with pure water (first half 2011 pure water circulation) **Done!**
- **Step 2:** Circulation through the 15 ton tank with $Gd_2(SO_4)_3$ (from middle 2011 to end 2012) **Done!**

Step 3: Gd water in 200 m^3 tank



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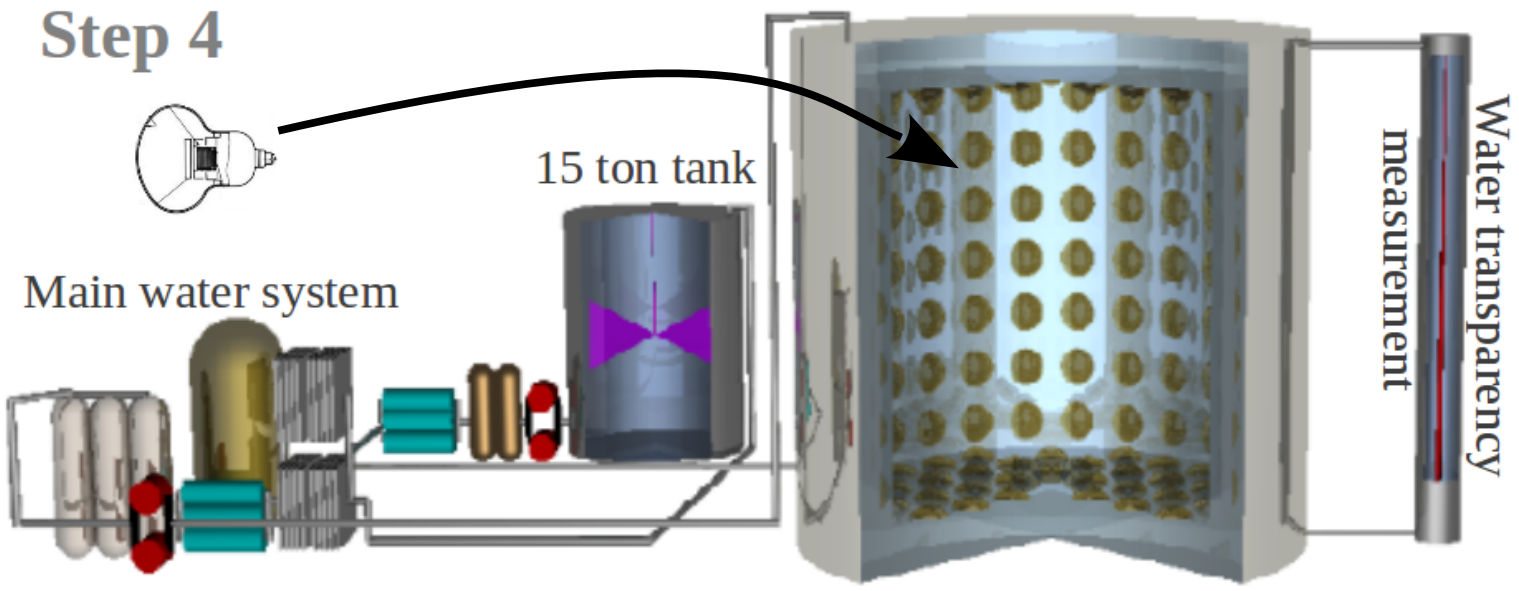
- **Step 3:** Circulation though the 200 ton tank with $Gd_2(SO_4)_3$ **Done!**

Step 4: EGADS Detector



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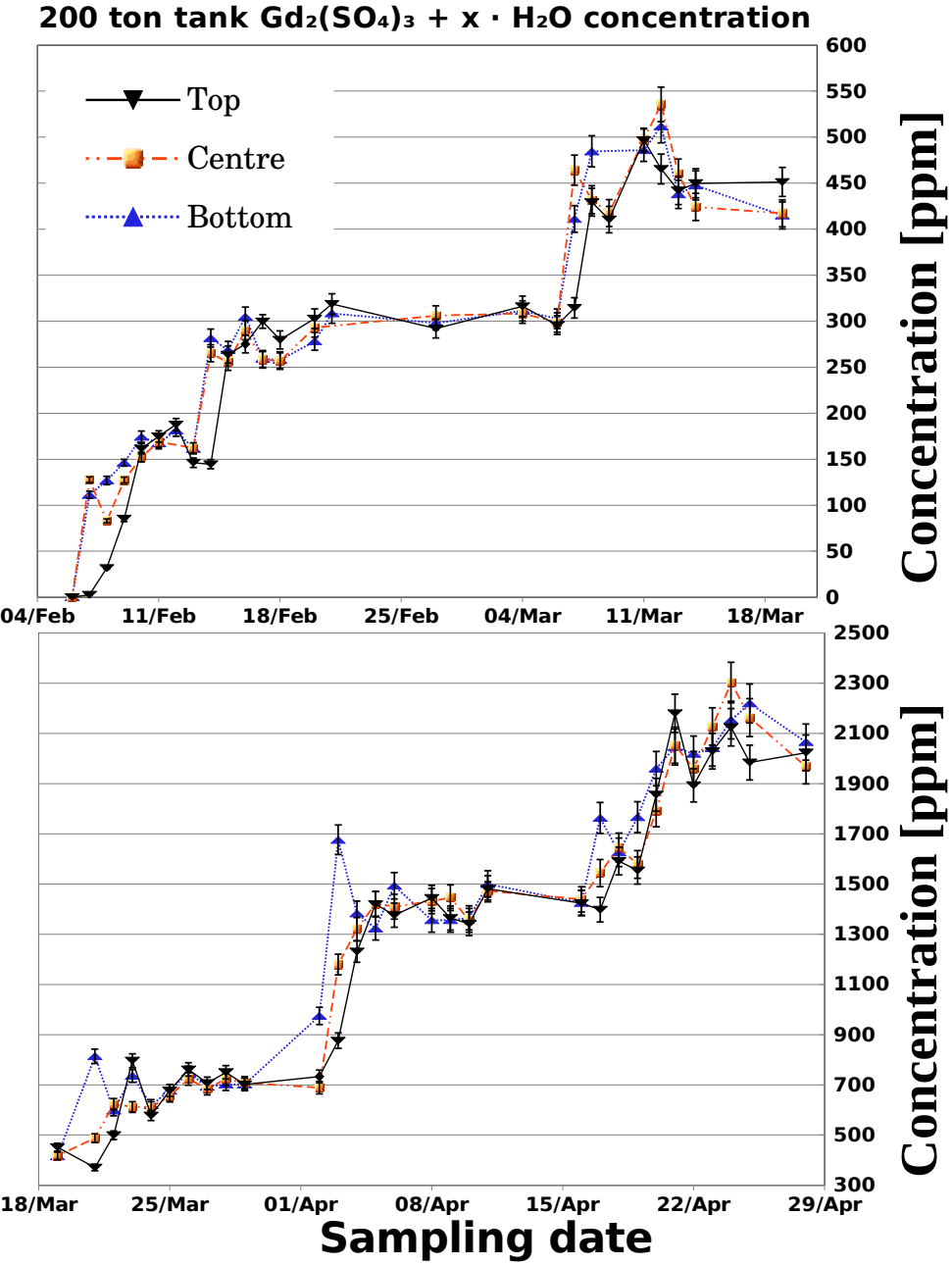
- **Step 3:** Circulation though the 200 ton tank with $Gd_2(SO_4)_3$ **Done!**
- **Step 4:** PMT mounting (240 in total). **Done!**
- **Step 5:** Full realization of the EGADS project

Gd concentration measurement



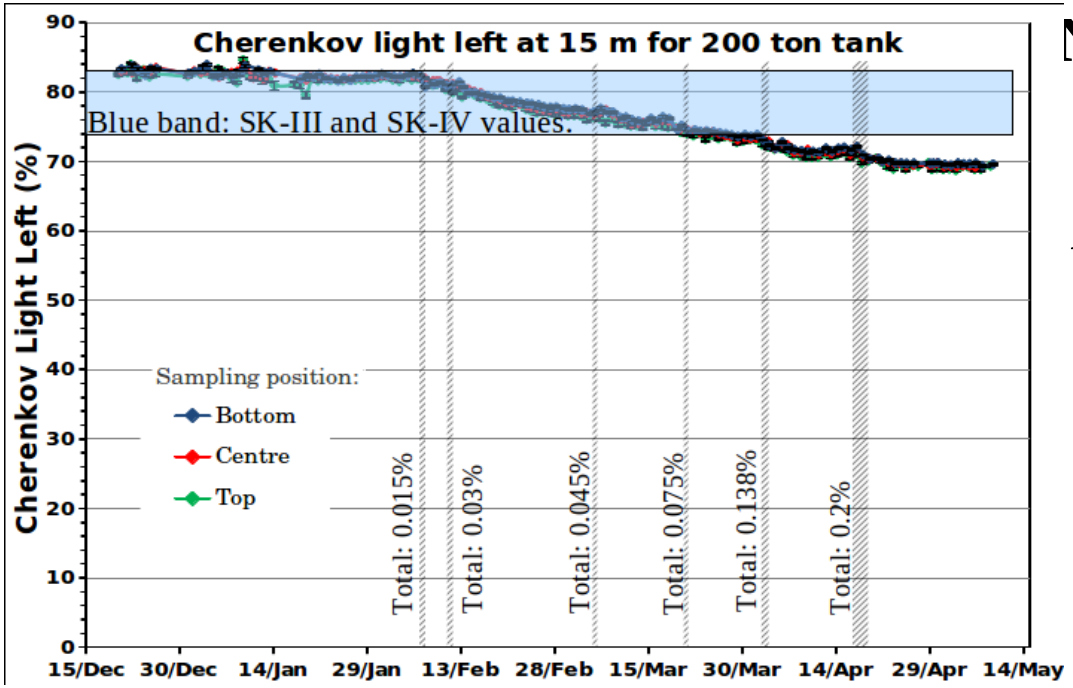
Tank loaded with Gd stepwise

Three different sampling points: **top**, **centre** and **bottom**

After each loading $Gd_2(SO_4)_3$ dissolves homogeneously after ~5 days and stays constant and homogeneous

Similar behaviour seen once the tank is instrumented (see backup slides)

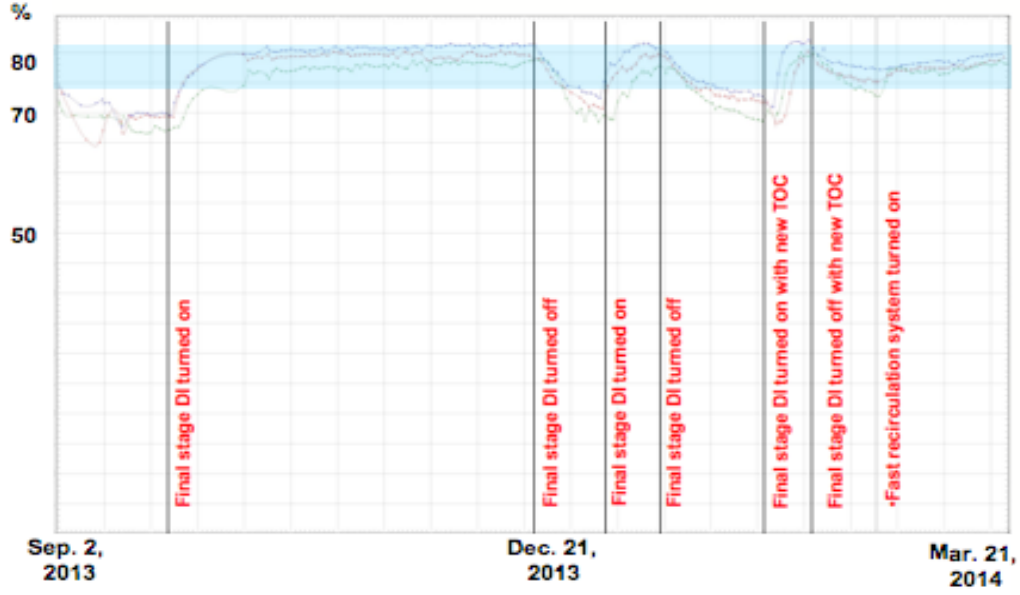
Gd loaded water attenuation



Non-instrumented EGADS tank:

The light left at 15 m in the 200-ton tank (stainless steel) was also ~69% in the 15-ton tank (plastic)

no reaction between $Gd_2(SO_4)_3$ and stainless steel



After PMT installation:

Unstable water transparency before Gd loading that got worse once we started loading

We found out a low quality stainless steel used by mistake

Summary and outlook

Following the idea proposed at **GADZOOKS!** adding Gd to Super-Kamiokande will allow **neutron tagging**:

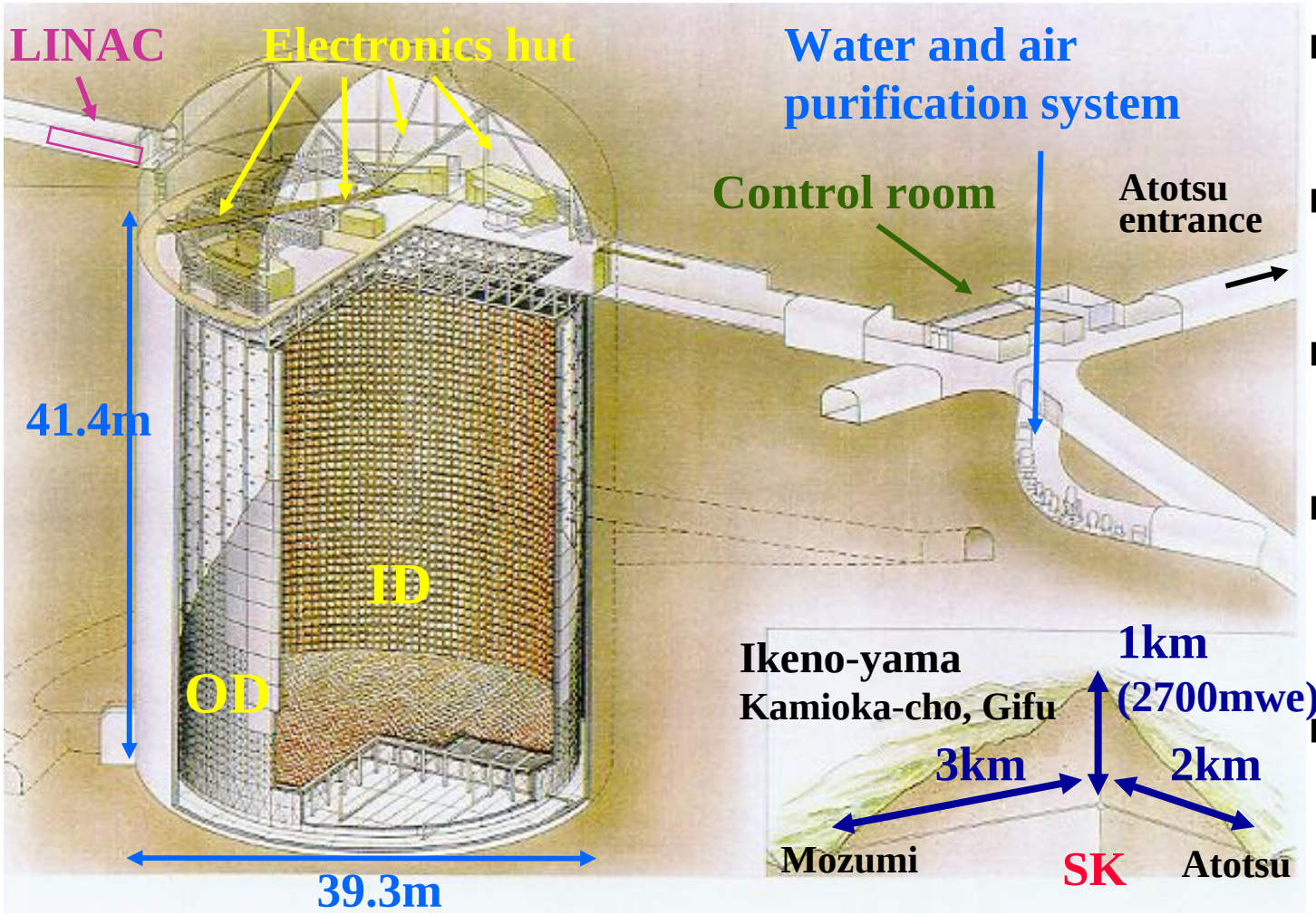
→ distinguish the copious IBD events from other channels, better **neutrino-antineutrino identification** and detect DSNB

→ **reduce backgrounds** in analyses with no neutron in the final state like in free proton decay studies

At **EGADS** we will soon show that this technique can be used at **Super-Kamiokande** in particular and in general in any water Cherenkov detector like the future **Hyper-Kamiokande**

Thank you for your attention!!

Super-Kamiokande Detector



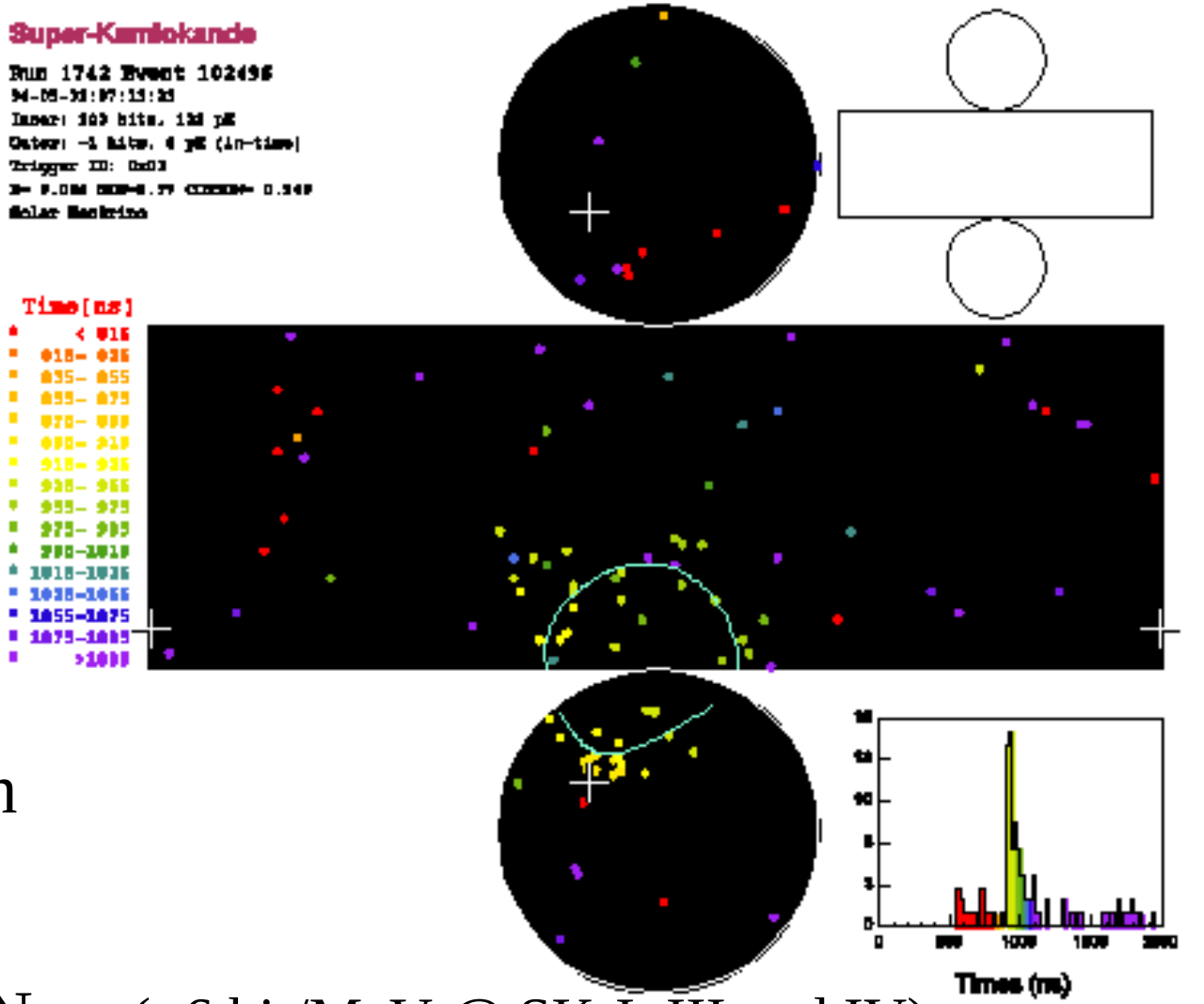
- 50 kton of ultrapure water
- ~2 m OD viewed by 8-inch PMTs
- 32 kt ID viewed by 20-inch PMTs
- 22.5 kt fiducial volume (2 m from wall)
- April 1996~

Inner Detector (ID) PMT: ~11100 (SK-I, III, IV), ~5200 (SK-II)
Outer Detector (OD) PMT: 1885

Event reconstruction in a Nutshell

Solar neutrino

$\nu\ e^- \rightarrow \nu\ e^-$

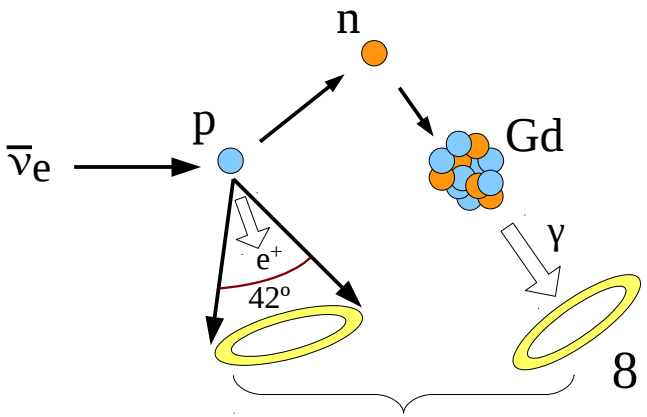


✔ Reconstruction method:

- Interaction vertex:
  - ⇨ Timing information
- Electron direction:
  - ⇨ Cherenkov Ring pattern
- Electron energy:
  - ⇨ Number of hit PMTs, N_{eff} , (~6 hit/MeV @ SK-I, III and IV)

Resolution (10 MeV electron@SK-I)
Vertex: 87cm Direction: 26° Energy: 14%

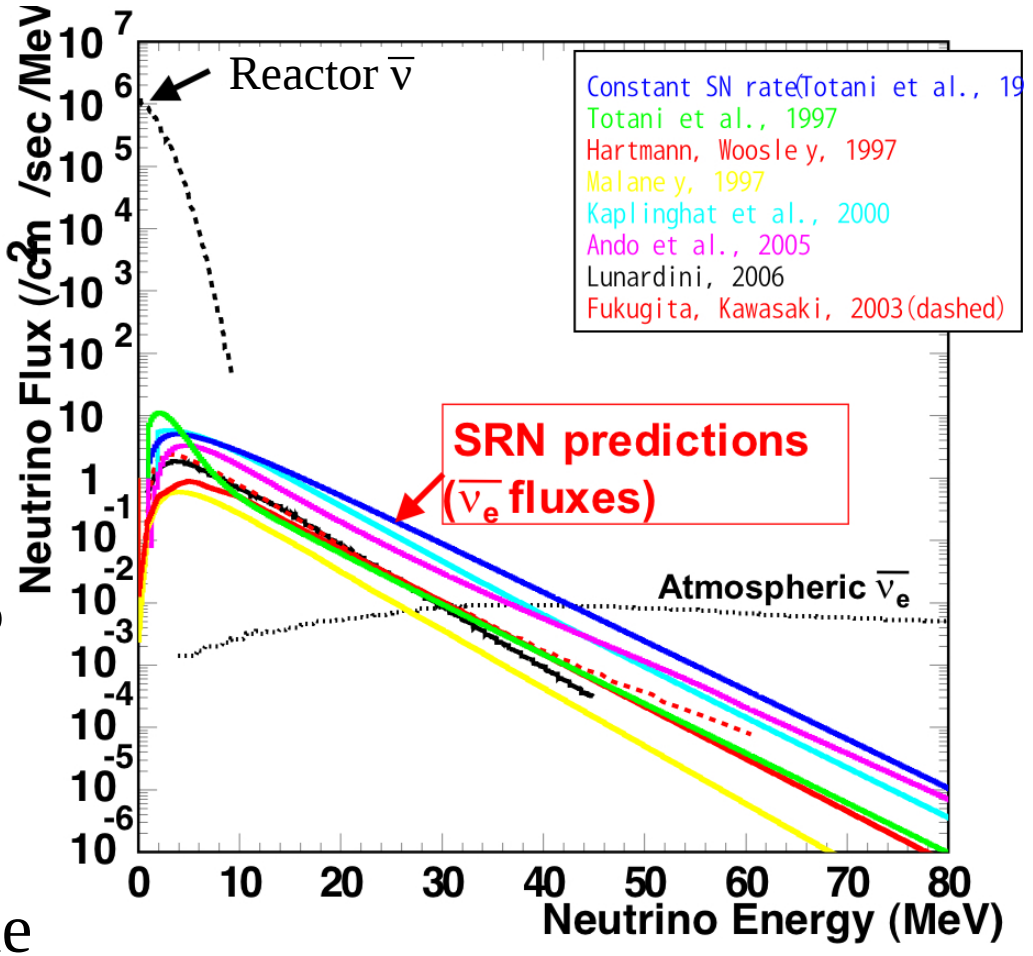
Doping Water with Gadolinium



8 MeV cascade

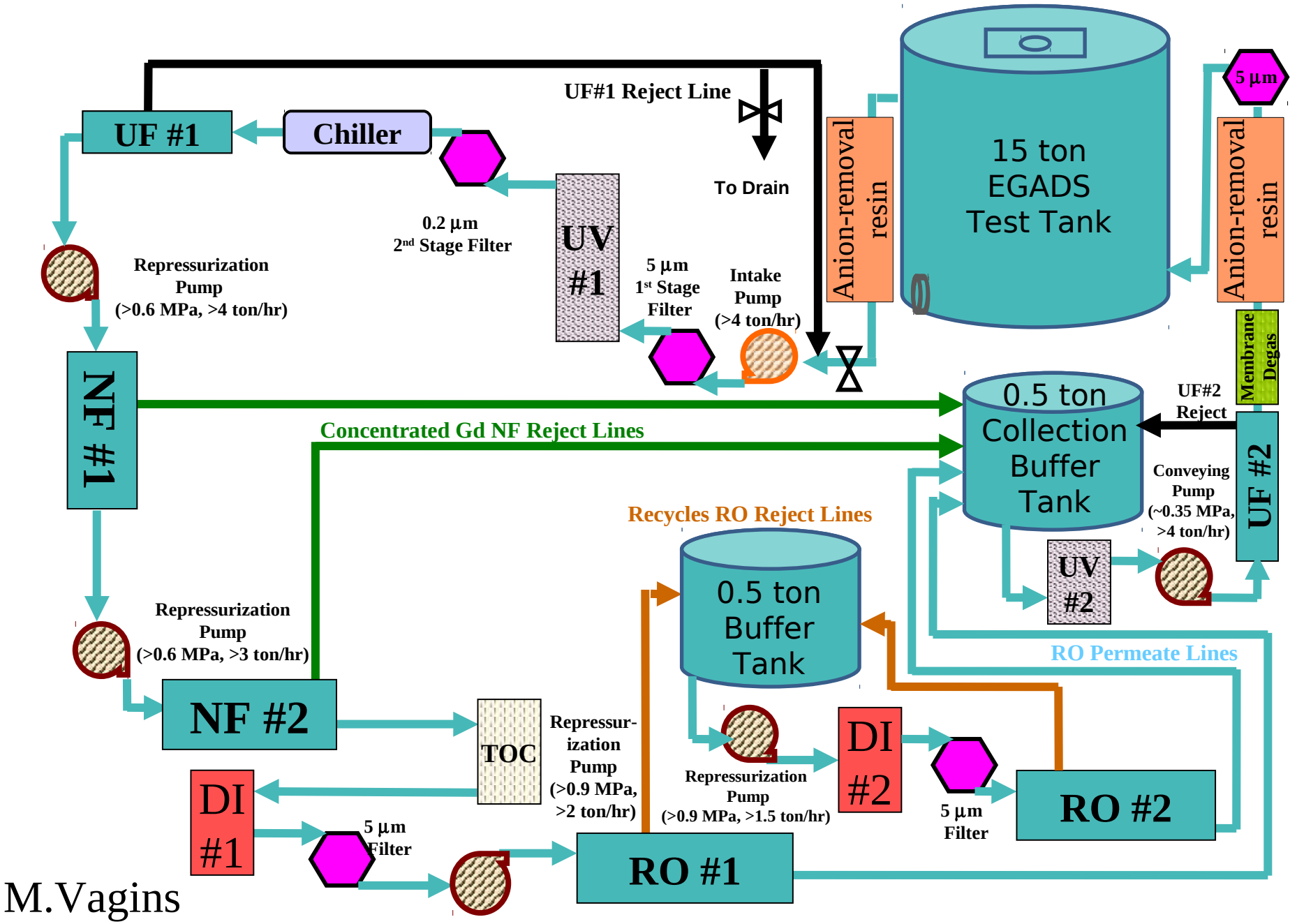
ΔT~30 μs
Vertices within 50 cm

Idea proposed as GADZOOKS!
by Beacom & Vagins PRL.93, (2004) 171101



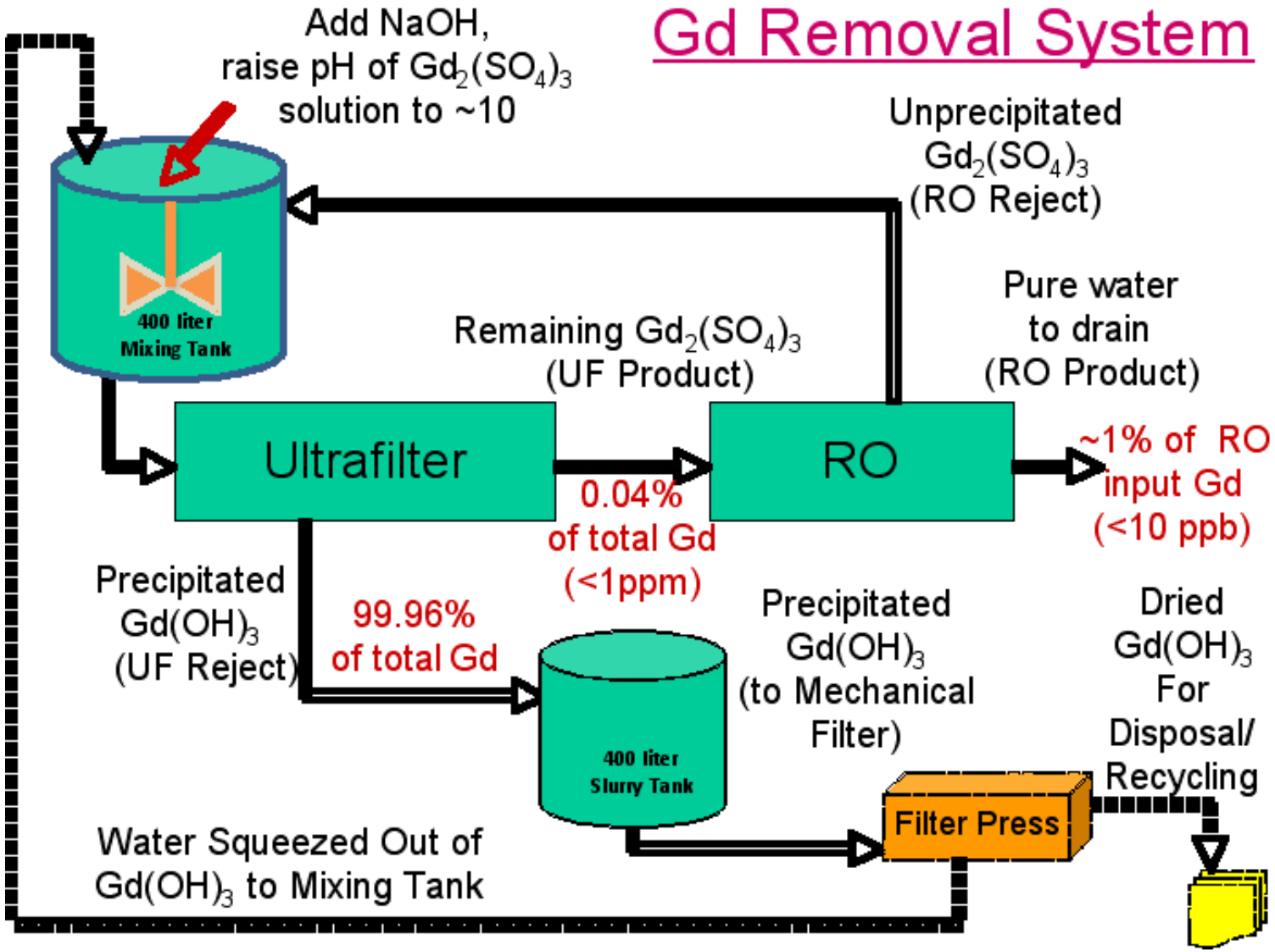
Gadolinium has the largest neutron capture cross section. With just 0.2% concentration of $Gd_2(SO_4)_3$ and by requiring a delayed coincidence detection we will be able to reduce backgrounds and detect DSNB for the first time!

Water system



M.Vagins

Gd Removal System

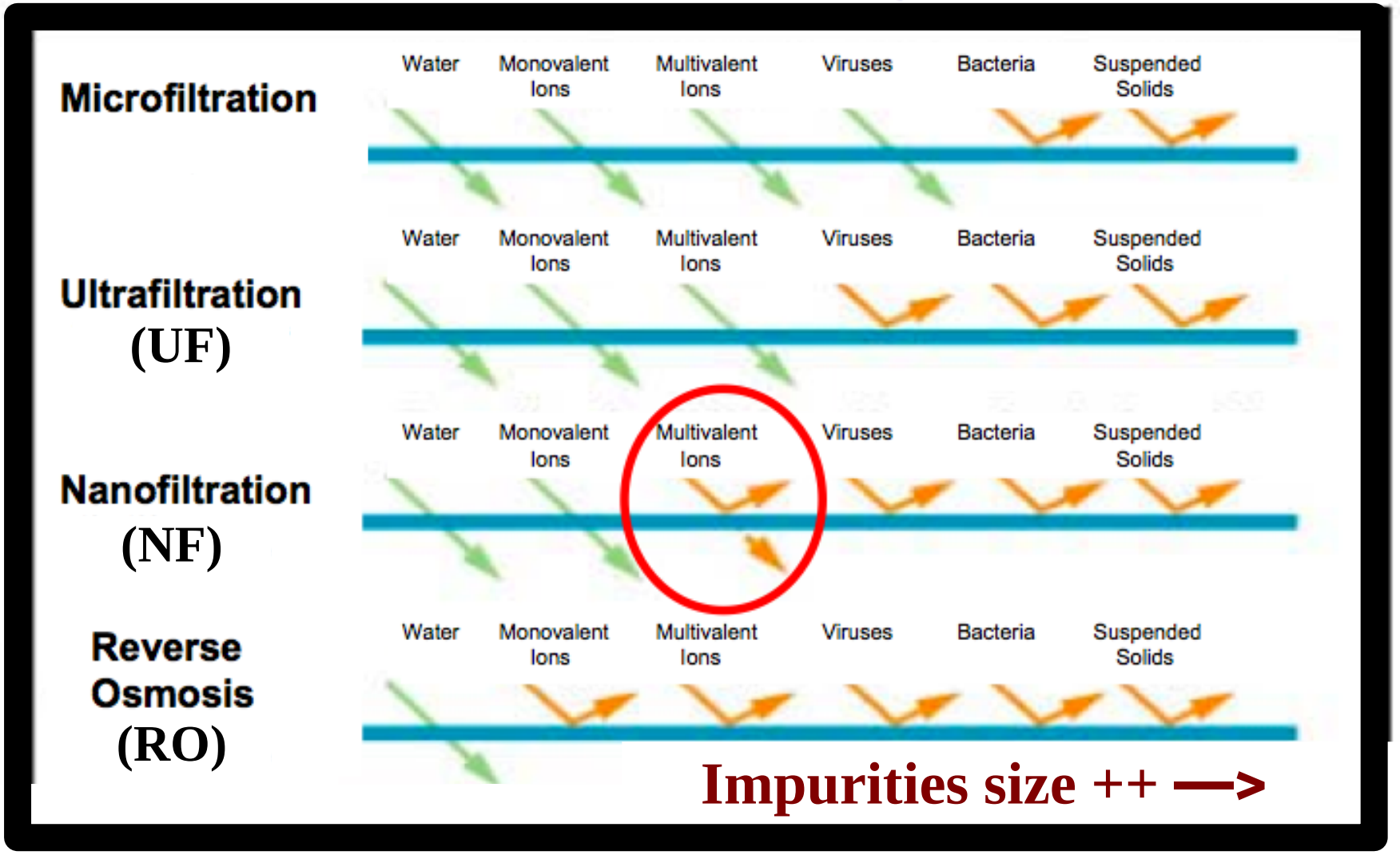


Filtration of Gd loaded water

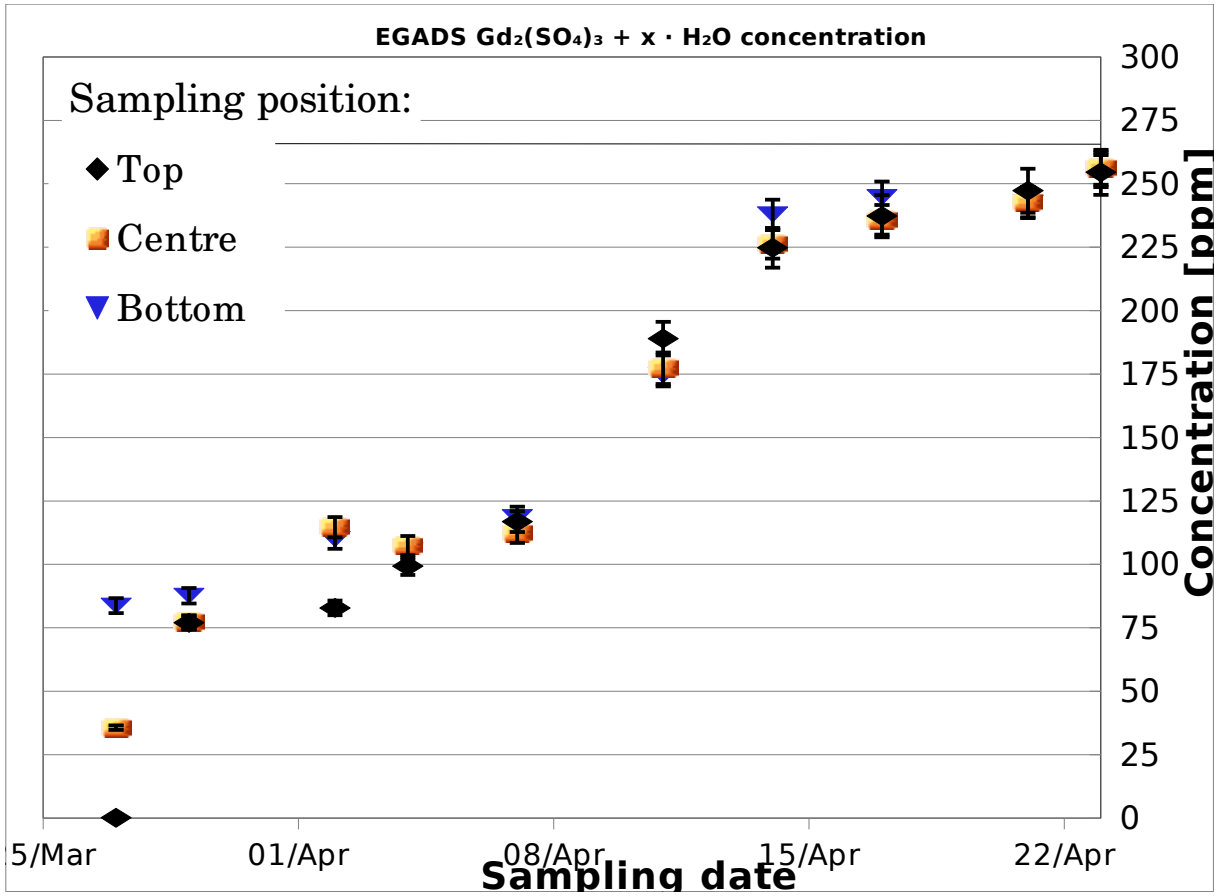
Membrane-based Filtering Technologies

Idea by M. Vagins

$Gd_2(SO_4)_3 \rightarrow 2\ Gd^{3+} + 3\ (SO_4)^{2-}$



Gd concentration measurement



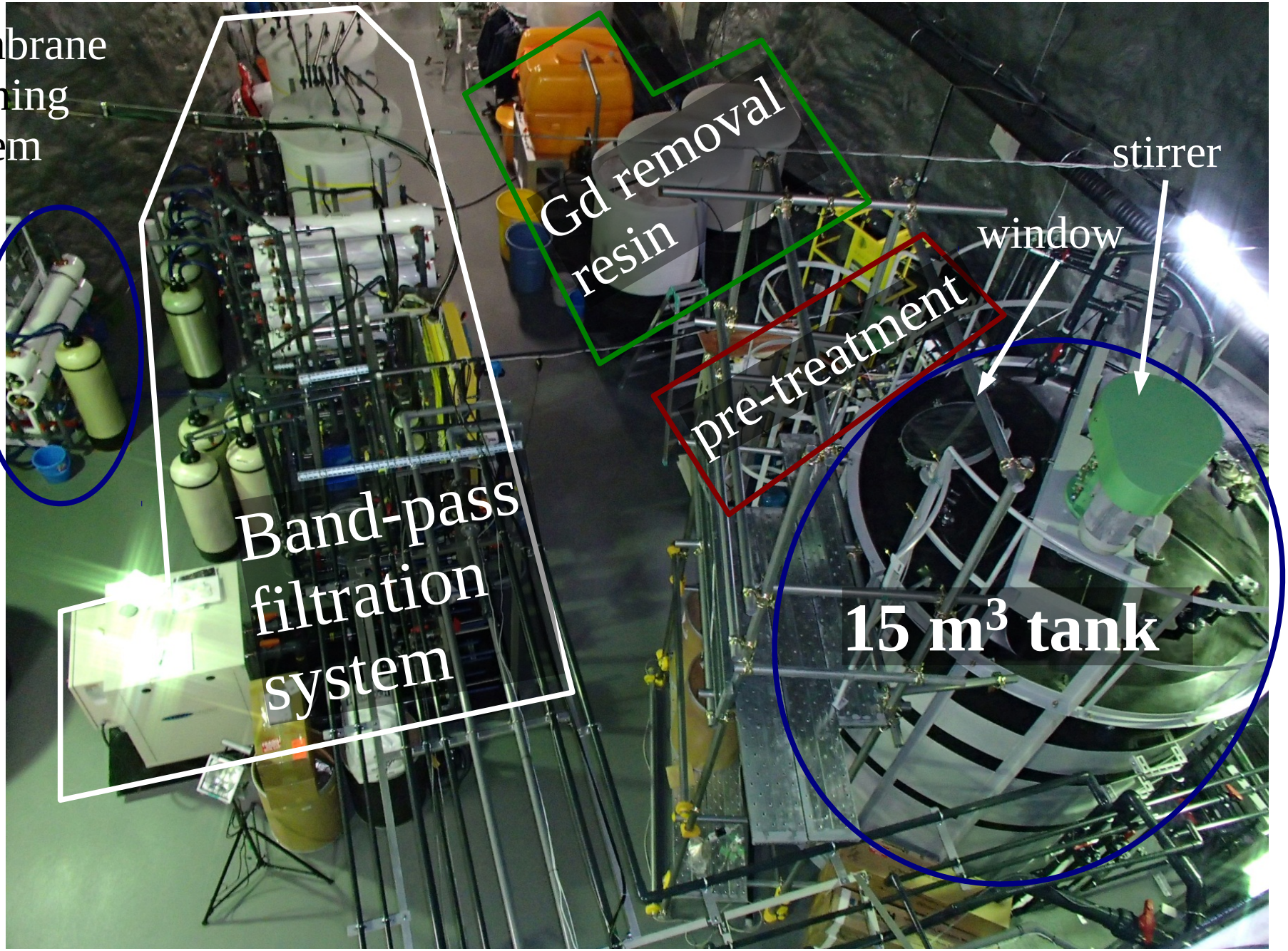
EGADS detector

Tank loaded with Gd stepwise

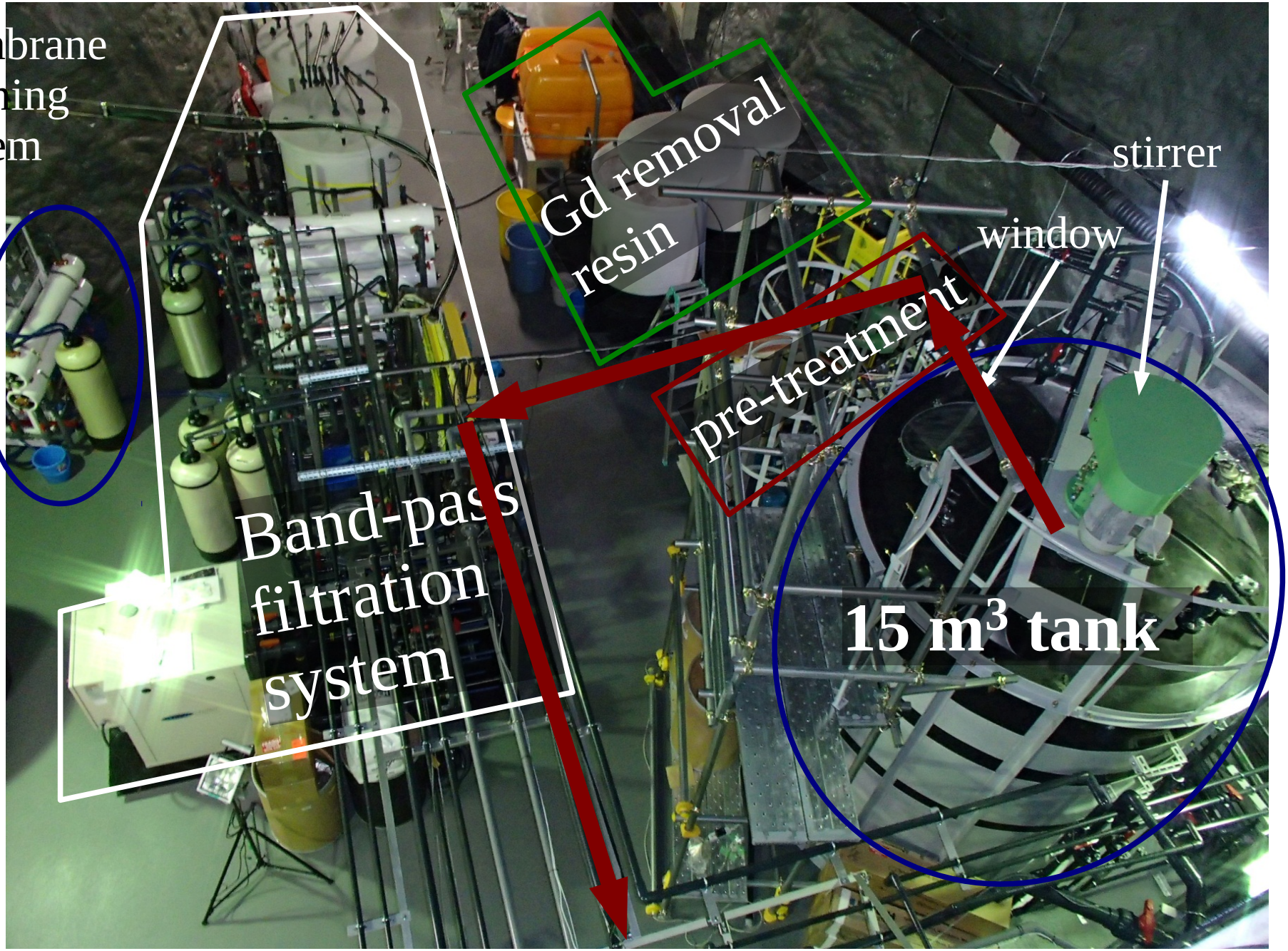
Three different sampling points: **top**, **centre** and **bottom**

After each loading $Gd_2(SO_4)_3$ dissolves homogeneously after ~5 days and stays constant and homogeneous

Loading Gd in the 200-ton tank

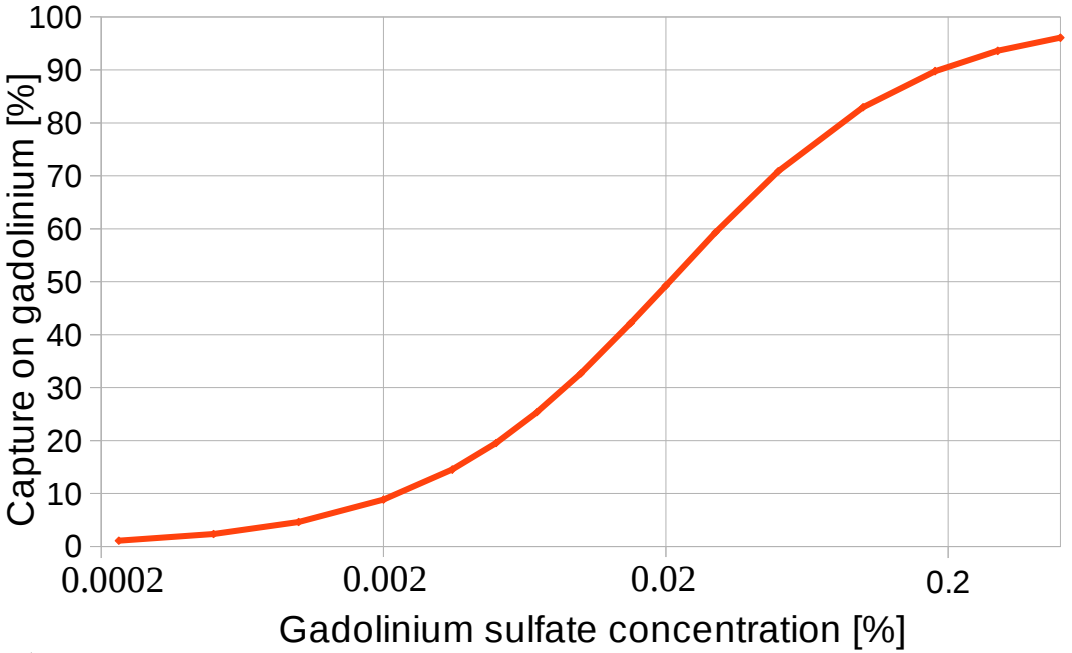


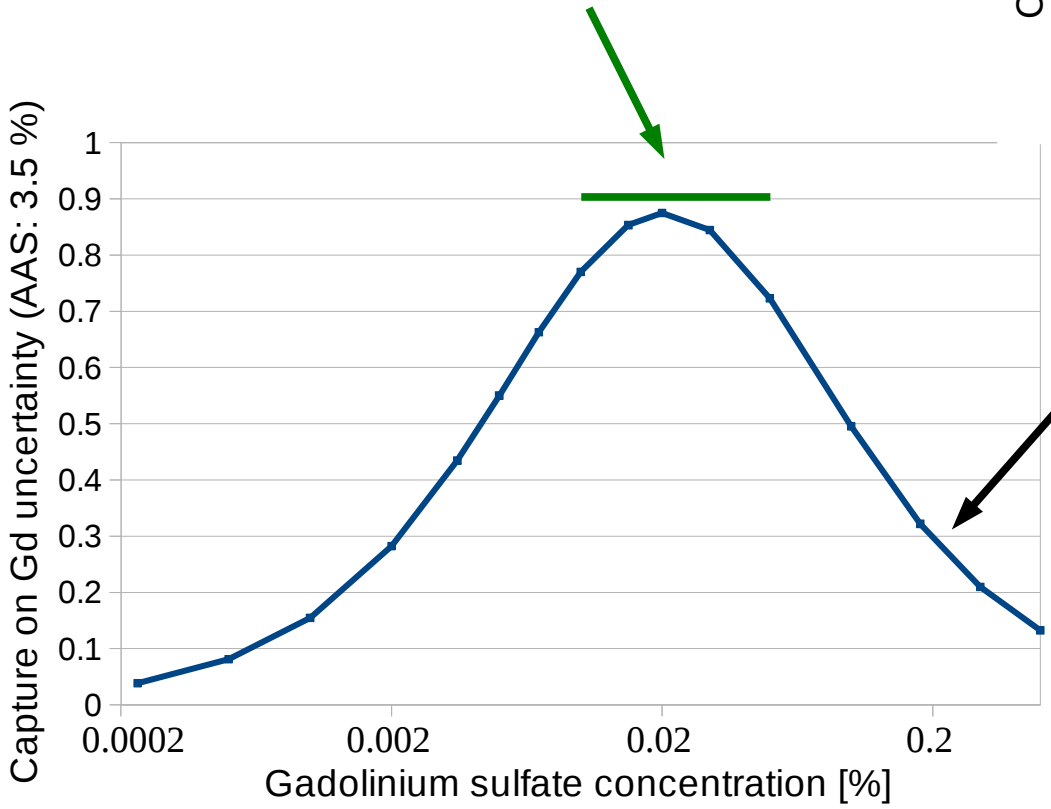
Loading Gd in the 200-ton tank



Concentration uncertainties

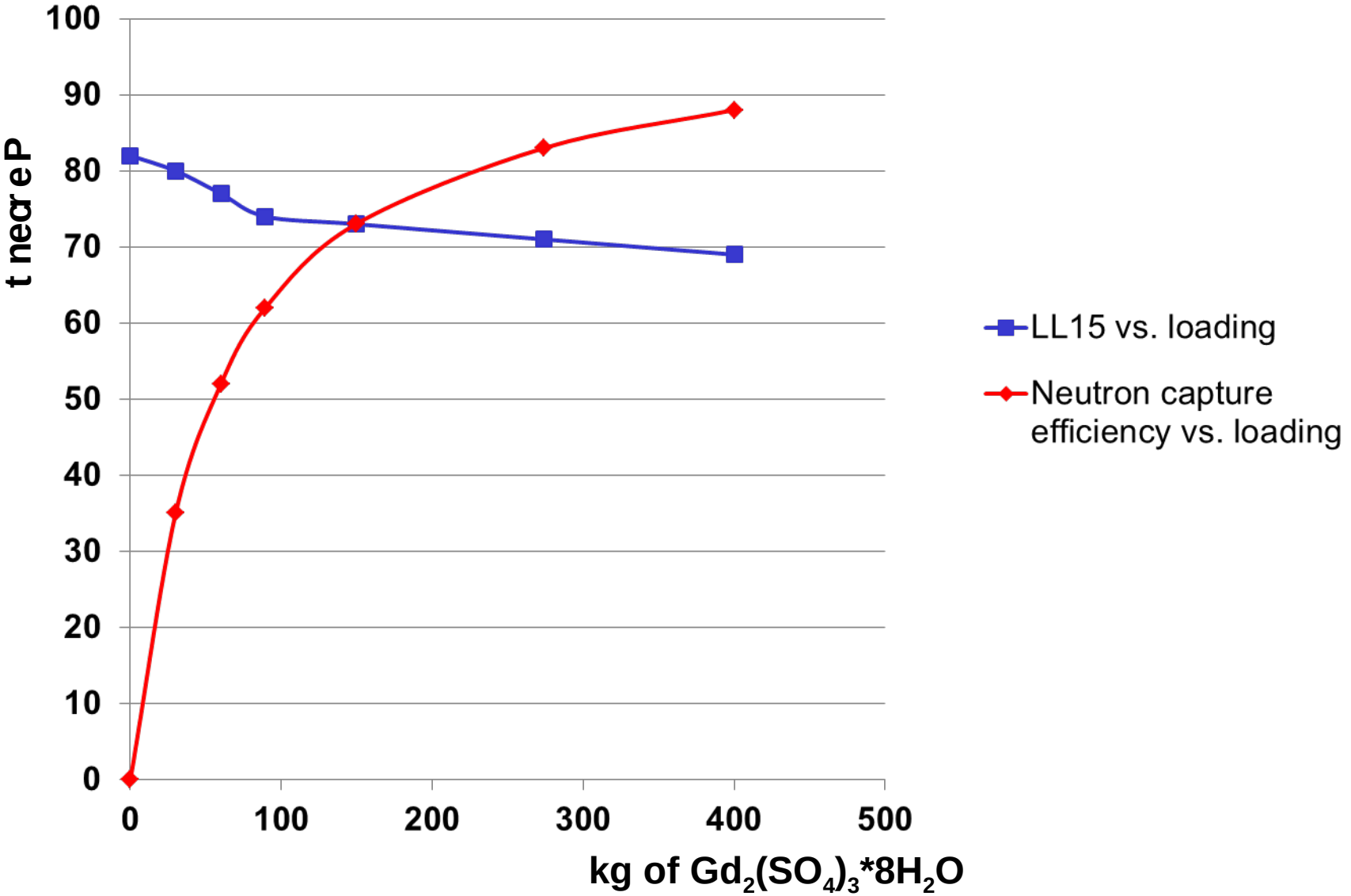
The uncertainty on the % of Gd capture is less than 0.9% (max. at 0.02% of gadolinium sulfate considering 3.5% uncertainty from the AAS)



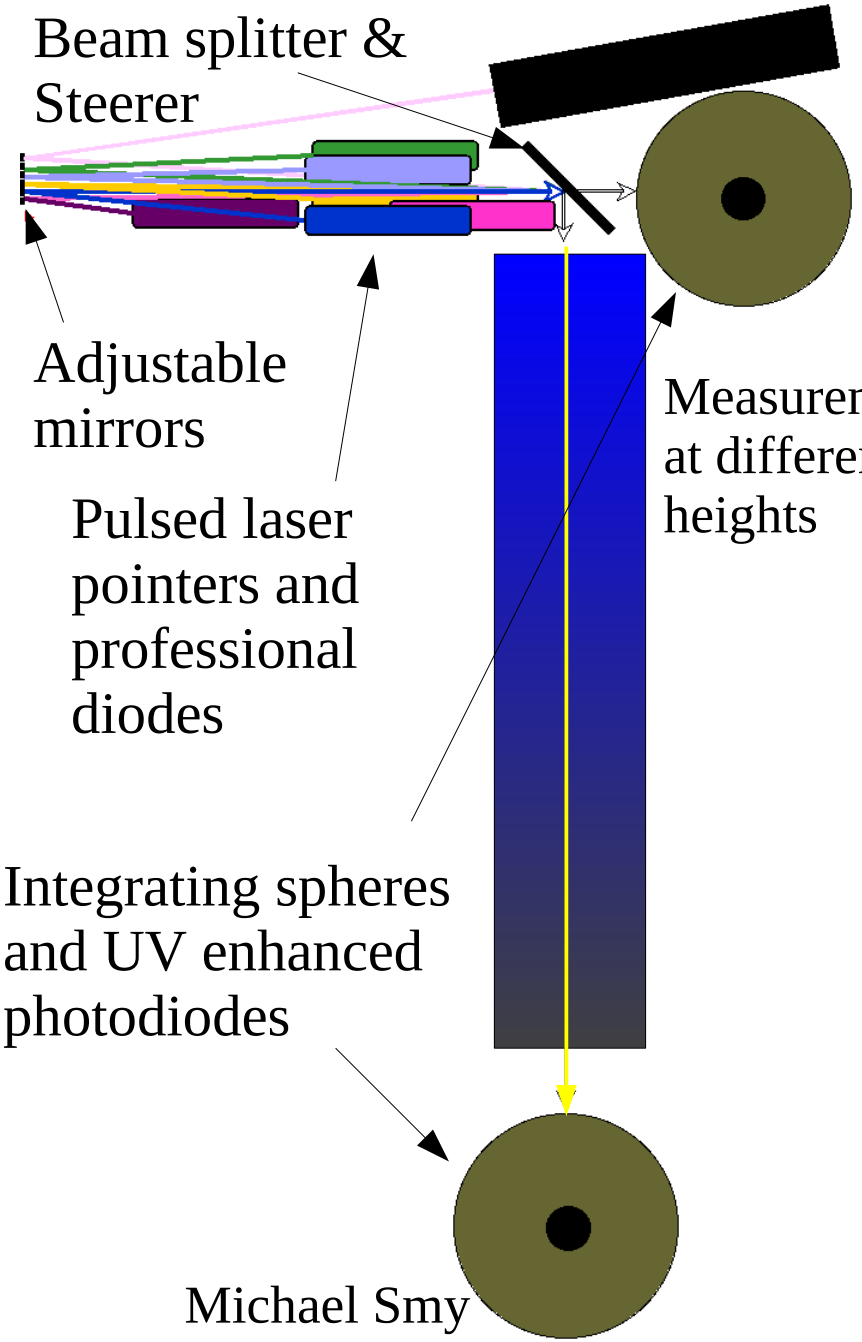


~0.3% uncertainty at 0.2% $Gd_2(SO_4)_3$

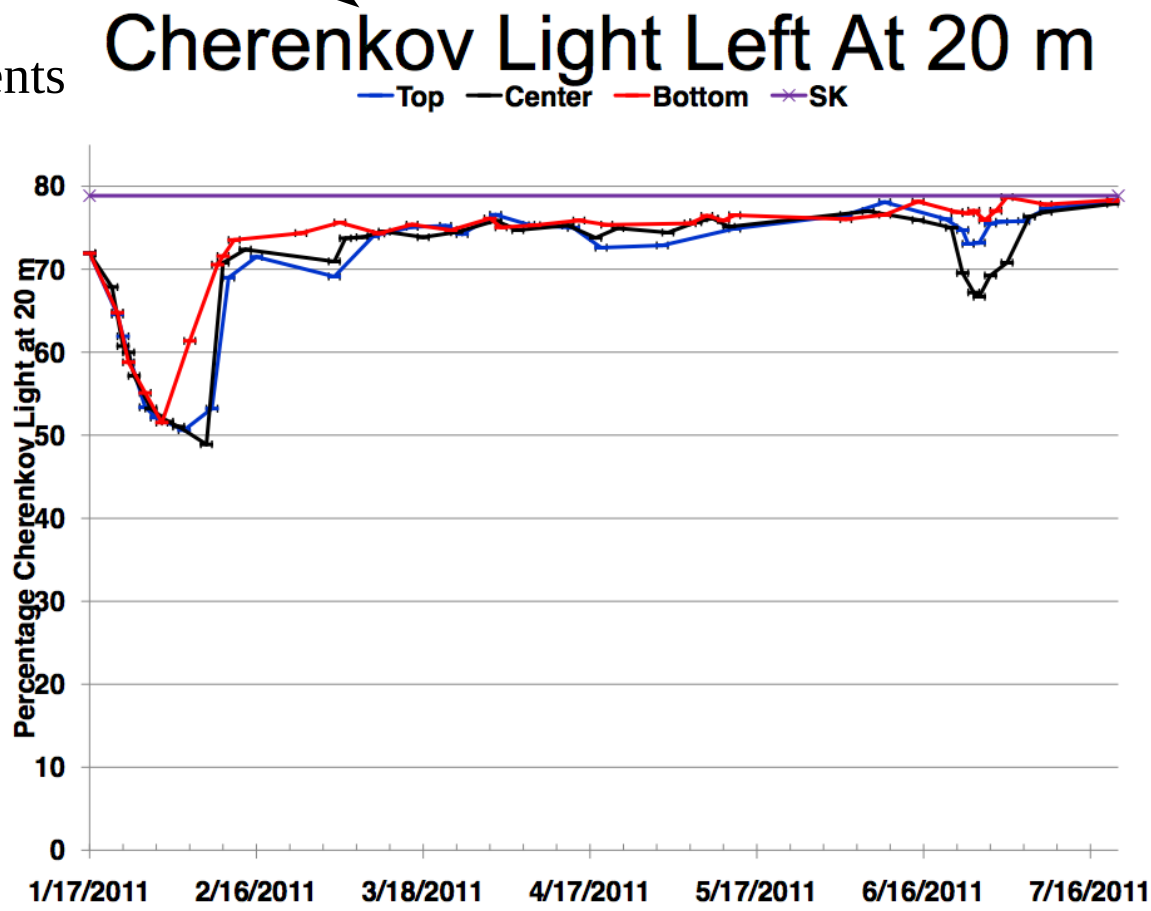
water attenuation vs Gd load



Water Attenuation: UDEAL

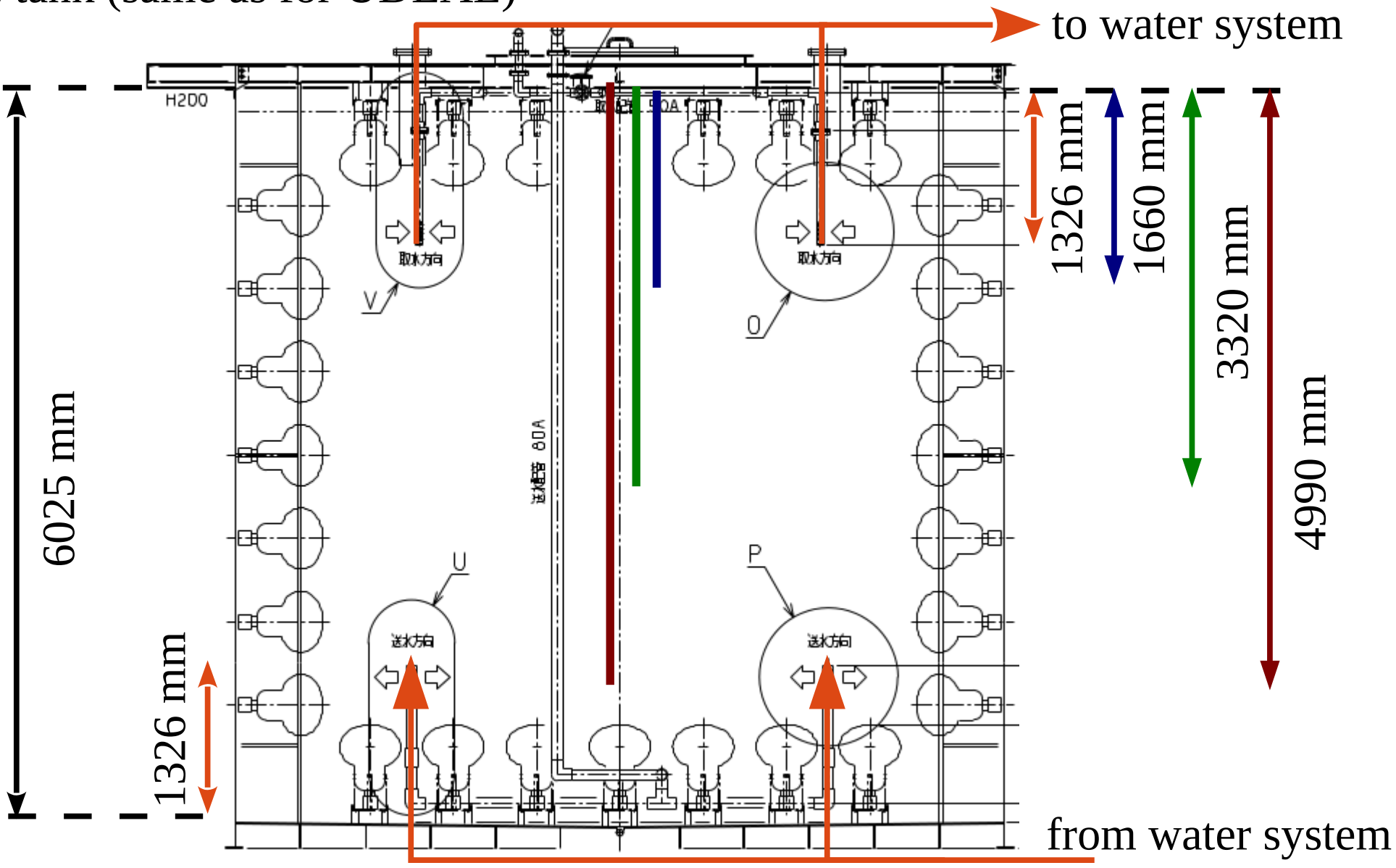


Data taken at: 337nm, 375nm, 405nm, 445nm, 473nm, 532 nm and 595nm wavelengths and weighted to the Cherenkov light



Sampling points

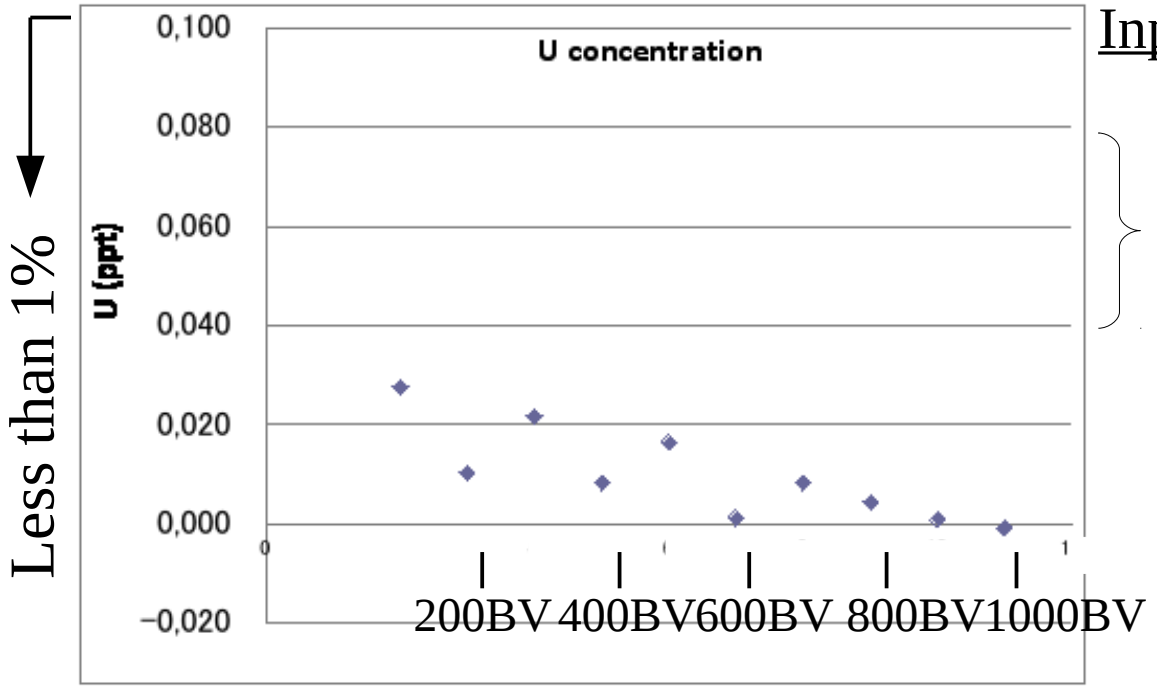
Sampling points are situated at 1660 mm, 3320 mm and 4990 mm from the top of the tank (same as for UDEAL)



Neutron Background

At Super-Kamiokande the neutron background is very low. However, we have seen that U and Th are present in our $Gd_2(SO_4)_3$ (15ppb and 1ppb, respectively). They would yield about 1800 neutrons/day in the SK ID (U chains are the most important source of neutrons)

These can be reduced by removing U with the resin AJ4400 to less 1% of the original amount:

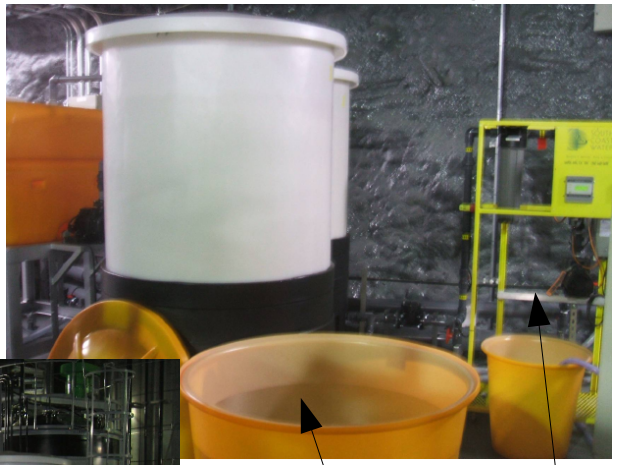


We conservatively we estimate that we can reduce the original amount to 600 neutrons/day in the SK ID (solar ~400 events/day, 4.5MeV threshold)

Gadolinium removal

$Gd_2(SO_4)_3$ drums

Resin Gd removal system



400 L water

Pump unit

Buffer tank

815g $Gd_2(SO_4)_3$ + 10g H_2SO_4

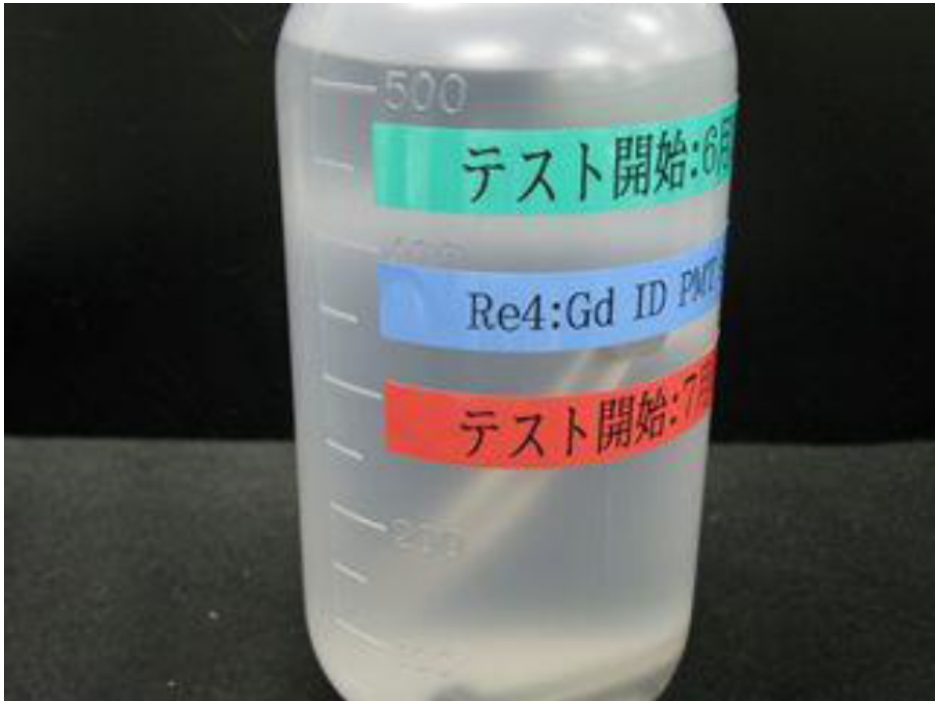
Analysis with an AAS and ICP/MS shows that the resulting concentration is < 0.5 ppb

Material Soak tests

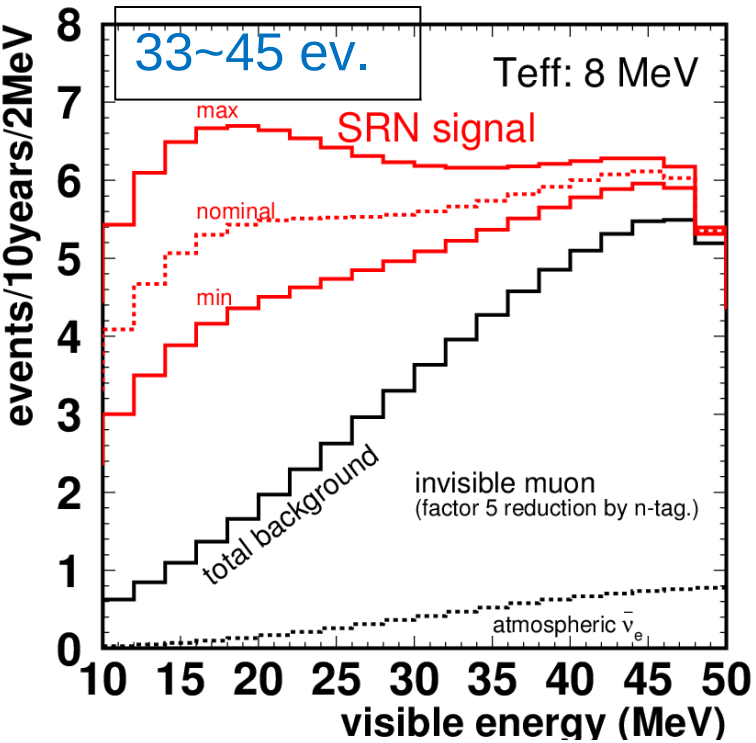
Different materials (31 in total) used at Super-Kamiokande have been soaked in pure water or 0.2% $Gd_2(SO_4)_3$ solutions and its effects on them have been studied.

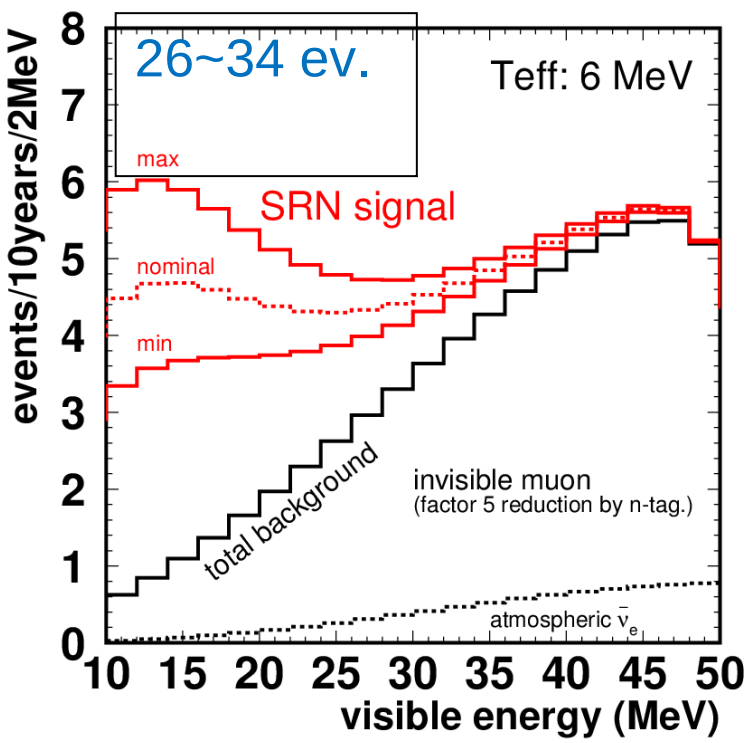
These studies show that if the water temperature is kept below 15ºC the effect is expected to be small.

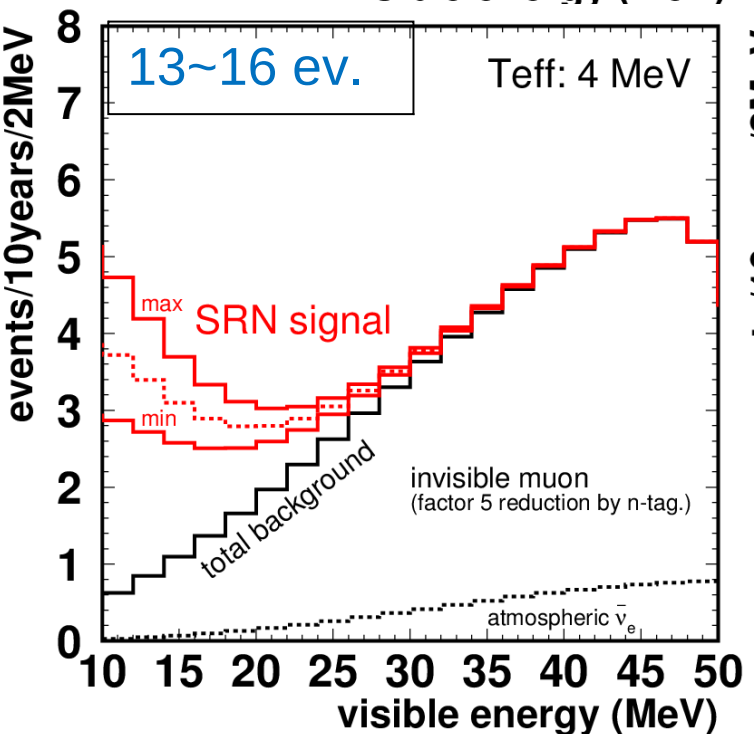
At EGADS will use similar materials to those at SK and this will allow us to further test them

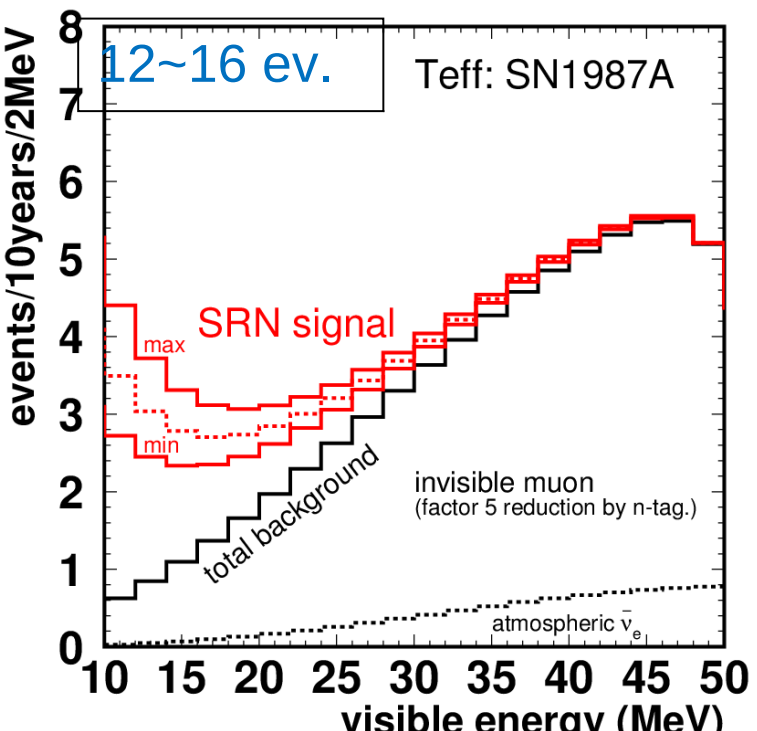


Expected signal and background









Expect number of events in 10 years in E_{total} =10-30 MeV

Assuming

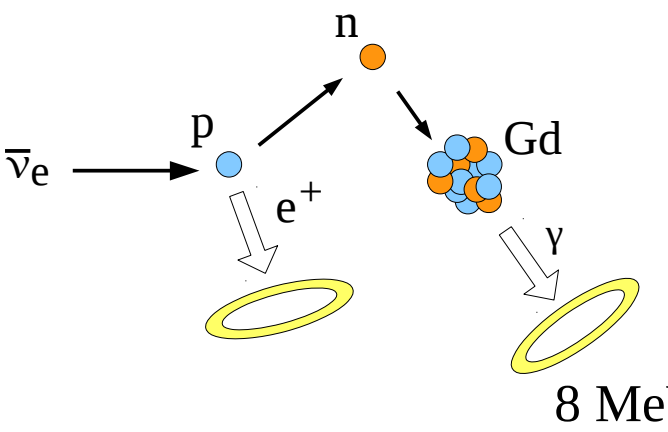
Capture efficiency of 90% and Gd gamma detection efficiency of 74%.

Invisible muon B.G. is 35% of the SK-IV invisible muon BG.

Min/nominal/Max are due to uncertainties in astronomy.

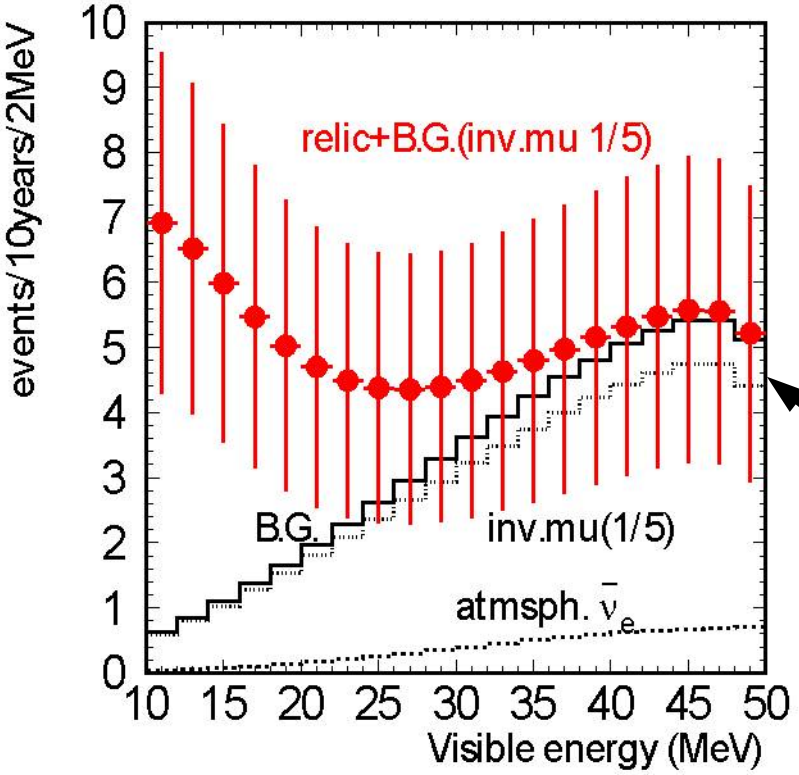
Background: ~18 ev.

Gadzooks!



Idea: add 0.2% of Gd in the SK water
Phys. Rev. Lett. 93, 171101 (2004)
J.Beacom and M.Vagins

$\bar{\nu}_e$ signal could be separated from BG by neutron tagging, i.e. coincidence detection of positron and neutron
Vertex correlation ~50cm



Relic model: Astropart.Phys.18, 307(2003) with flux revise in NNN05.

After 10 years of SK data taking:
Signal: 33 events; Background: 27 events
E_{vis} = 10-30 MeV

Assumption:
- 67% detection efficiency
- Invisible μ background can be reduced by a factor of 5

Anything else?

Anything else to offer? Apart from the two mentioned new signals, this technique opens up for new possibilities:

Nearby SN burst early warning

Full deconvolution of a galactic SN νs

(free) proton decay background reduction

New solar antineutrino flux limit

New long-baseline flux normalization for T2K

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