Status of GADZOOKS!:

Neutron Tagging in Super-Kamiokande

Pablo Fernández, UAM
for the Super-Kamiokande collaboration
ICHEP2014, July 5th, Valencia

37th INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS
2-9-JULY-2014-VALENCIA

Outline

The Super Kamiokande Experiment

Outline

The Super Kamiokande Experiment

GADZOOKS!: The upgrade of SK for identifying anti-neutrinos
- main physics outcomes

Outline

The Super Kamiokande Experiment

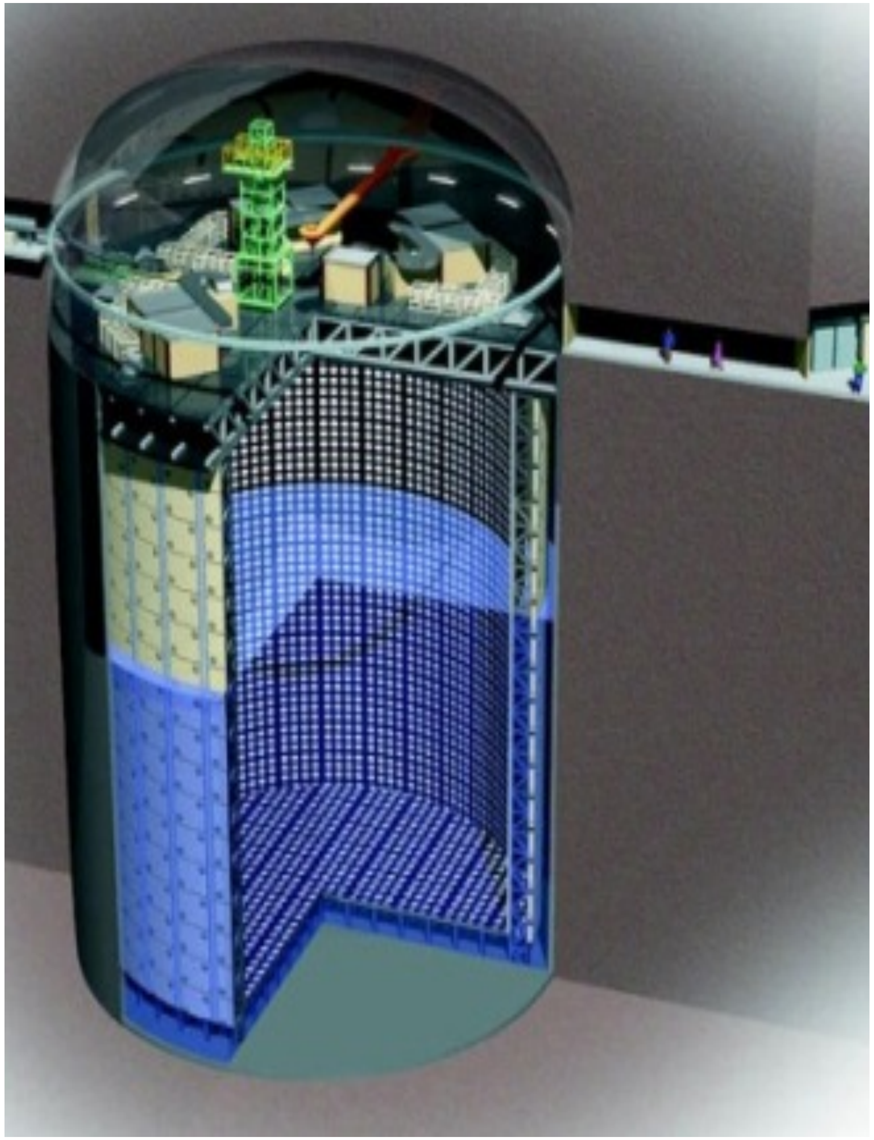
GADZOOKS!: The upgrade of SK for identifying anti-neutrinos

- main physics outcomes

EGADS: a full-system prototype of GADZOOKS!

- status and latest results
- other studies respecting the whole GADZOOKS!
- possible timeline

Super Kamiokande



50 kton water Cherenkov detector

~1000m overburden, in Kamioka mine

SK started the proton decay and neutrino physics searches in 1996

among world's best neutrino detectors

divided in inner and outer detector:
- inner: 11146 20"-PMTs
- outer: 1885 8"-PMTs

typical volume for physics 22.5kton

Super Kamiokande

Major achievements:

- Kamiokande, its predecessor: first detection of cosmic neutrinos (SN1987A)
- Oscillations from atmospheric neutrinos ➔ massive neutrinos
- Neutrinos coming from the Sun ➔ Solar neutrino problem, terrestrial effects
- As LBL far detector: confirmation of ATMν results (KEK), ν_e appearance (T2K)
- Best proton decay bounds
- Most stringent bounds on Diffuse SN neutrino background

Super Kamiokande

Major achievements:

- Kamiokande, its predecessor: first detection of cosmic neutrinos (SN1987A)
- Oscillations from atmospheric neutrinos ➔massive neutrinos
- Neutrinos coming from the Sun ➔ Solar neutrino problem, terrestrial effects
- As LBL far detector: confirmation of ATMν results (KEK), ν_e appearance (T2K)
- Best proton decay bounds
- Most stringent bounds on Diffuse SN neutrino background

The scientific capabilities of SK would improve dramatically if it is able to distinguish neutrino from anti-neutrino interactions

One of the main interactions in SK, specially at sub-GeV energies

$$\nu_\alpha + n \rightarrow l_\alpha + p \qquad \bar{\nu}_\alpha + p \rightarrow \bar{l}_\alpha + n$$

Super Kamiokande

Major achievements:

- Kamiokande, its predecessor: first detection of cosmic neutrinos (SN1987A)
- Oscillations from atmospheric neutrinos ➔ massive neutrinos
- Neutrinos coming from the Sun ➔ Solar neutrino problem, terrestrial effects
- As LBL far detector: confirmation of ATMν results (KEK), ν_e appearance (T2K)
- Best proton decay bounds
- Most stringent bounds on Diffuse SN neutrino background

The scientific capabilities of SK would improve dramatically if it is able to distinguish neutrino from anti-neutrino interactions

One of the main interactions in SK, specially at sub-GeV energies

$$\nu_\alpha + n \rightarrow l_\alpha + p \qquad \bar{\nu}_\alpha + p \rightarrow \bar{l}_\alpha + n$$

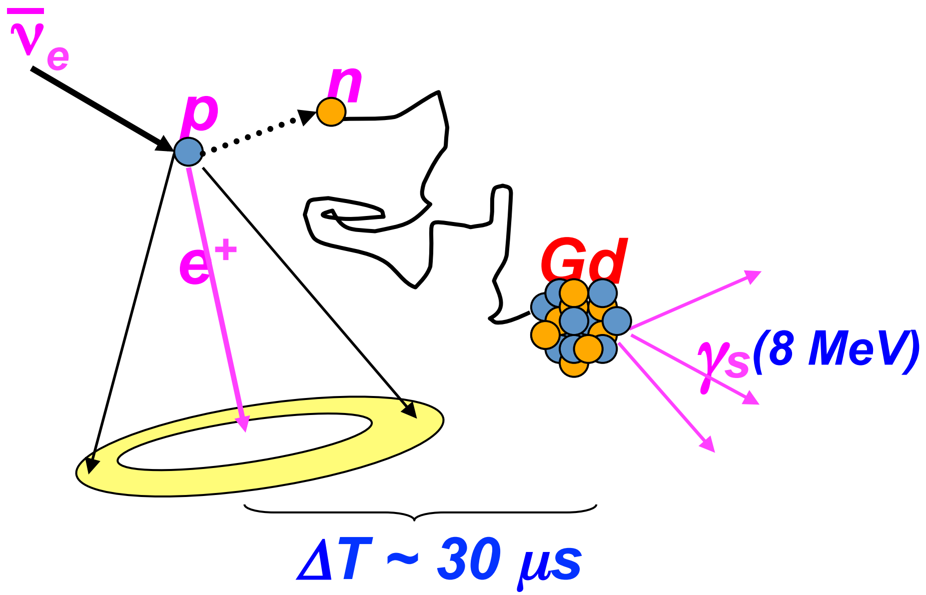
neutron tagging

GADZOOKS!

Gadolinium Antineutrino Detector Zealously Outperform Old Kamiokande Super!

[Beacom and Vagins, Phys. Rev. Lett. 93 171101, 2004]

- Gd has the largest thermal neutron capture cross section of all stable nuclei (~49000 barn)
- After the neutron has thermalized, it is captured by Gd which emits a **8 MeV γ cascade** at its de-excitation

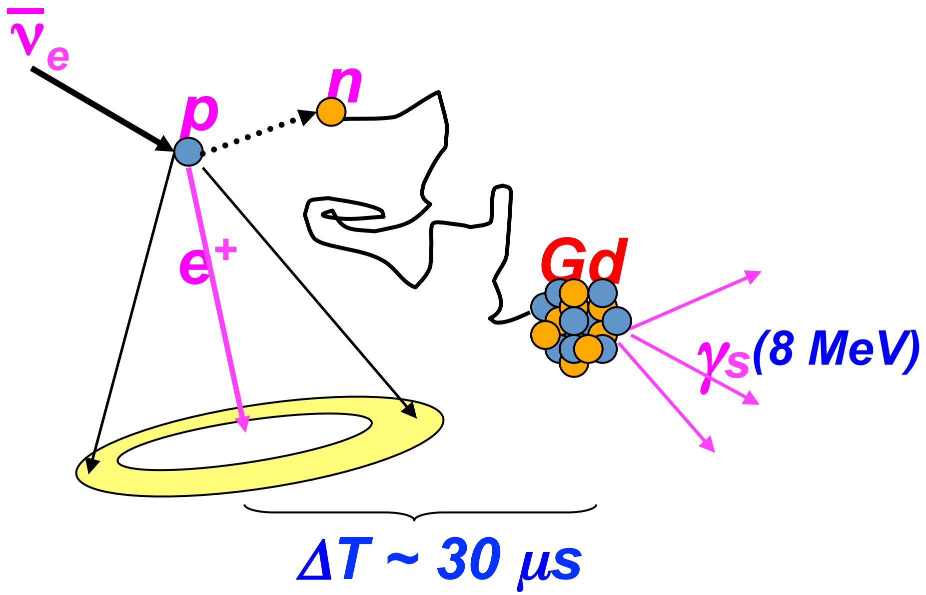


GADZOOKS!

Ga**d**olinium **A**ntineutrino **D**etector **Z**ealously **O**utperform **O**ld **K**amiokande **S**uper!

[Beacom and Vagins, Phys. Rev. Lett. 93 171101, 2004]

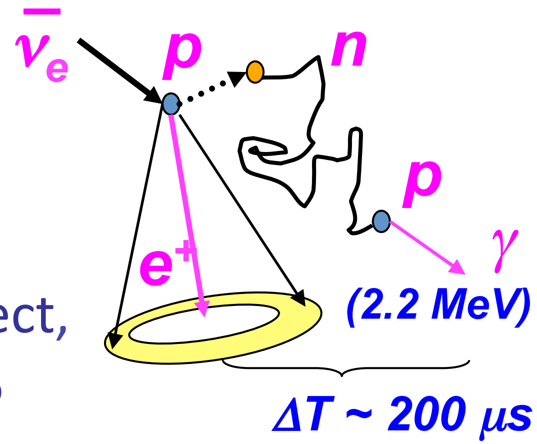
- Gd has the largest thermal neutron capture cross section of all stable nuclei (~49000 barn)
- After the neutron has thermalized, it is captured by Gd which emits a **8 MeV γ cascade** at its de-excitation



$\bar{\nu}$ can be detected through **space-time coincidence** of charged lepton and neutron capture, with **~80% efficiency**

currently in SK:

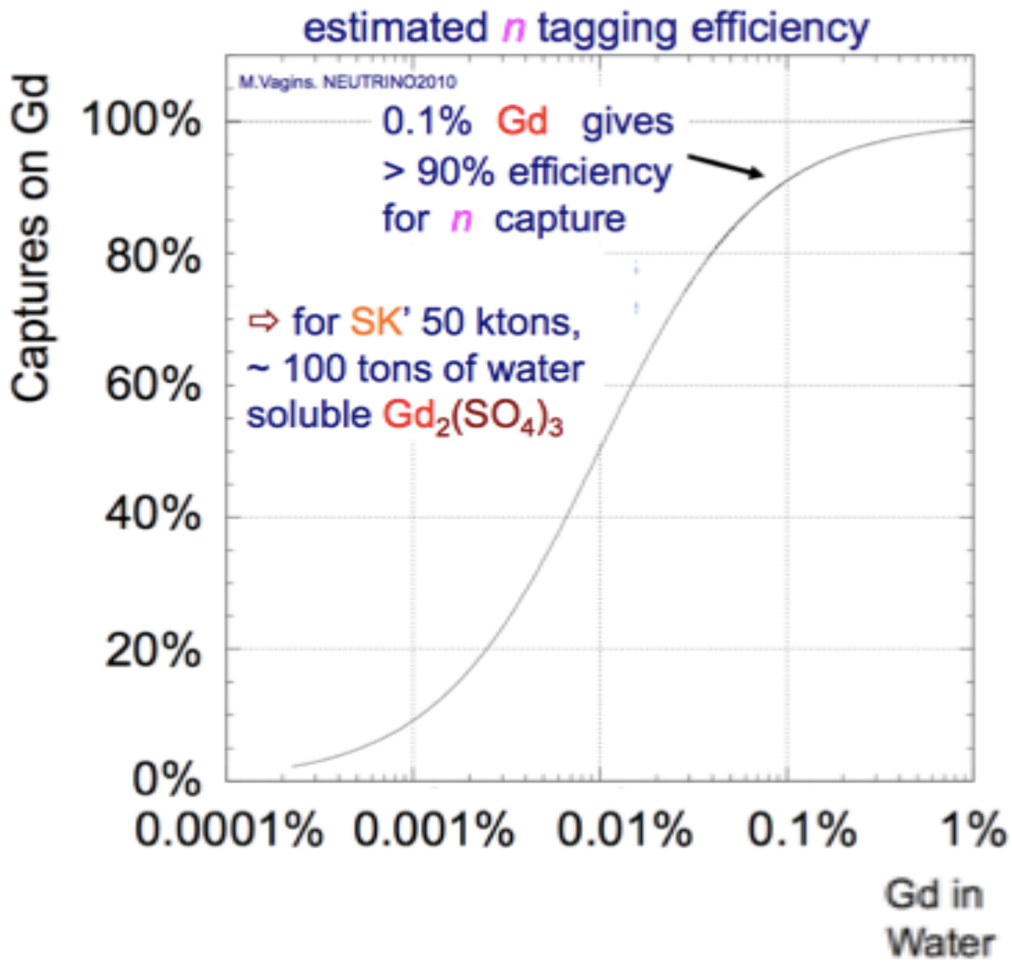
very difficult to detect,
IBD efficiency ~15%



GADZOOKS!

Upgrading SK by adding 0.2% of $Gd_2(SO_4)_3$, enables highly efficient neutron tagging method:

- **>5** times larger than neutron capture with hydrogen
- **>100** reduction factor in the rate of fake inverse-β decay events as compared with using hydrogen



The selection of $Gd_2(SO_4)_3$:

- very well soluble in water
- very low corrosion
- low effect on light transmission

Diffuse Supernova Neutrino Background (DSNB)

One of our main motivation for this upgrade is to first detect DSNB, neutrinos from all the supernovae in the history of the universe

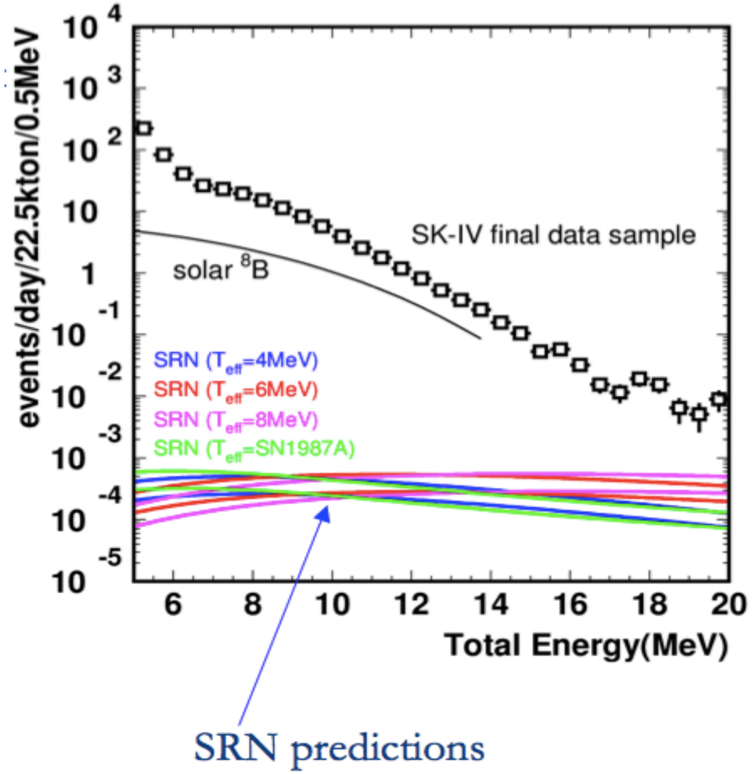
This would be detected through anti-neutrinos interacting inverse-β

Diffuse Supernova Neutrino Background (DSNB)

One of our main motivation for this upgrade is to first detect DSNB, neutrinos from all the supernovae in the history of the universe

This would be detected through anti-neutrinos interacting inverse-β

The measurement is affected by large backgrounds that can be excluded with neutron tagging



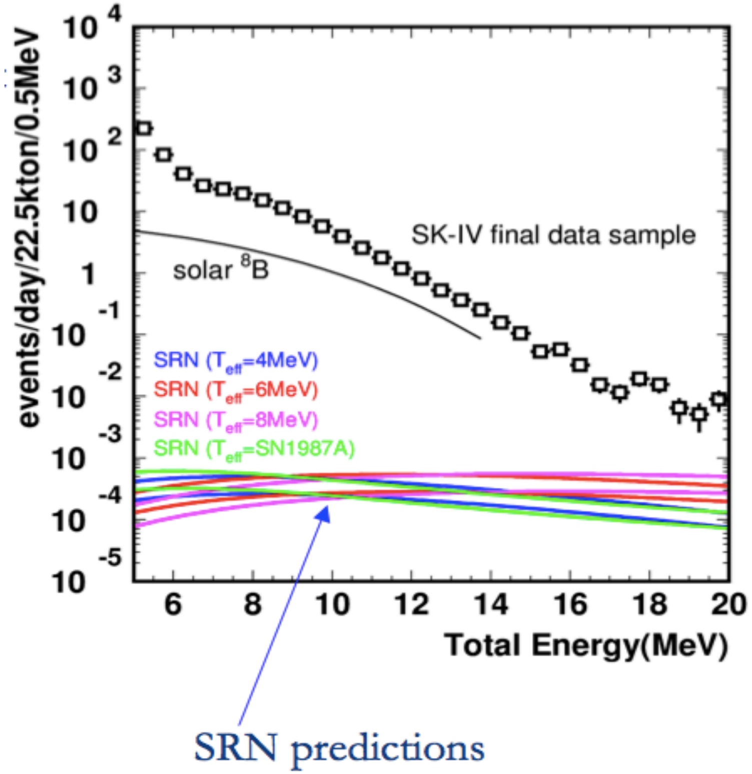
Diffuse Supernova Neutrino Background (DSNB)

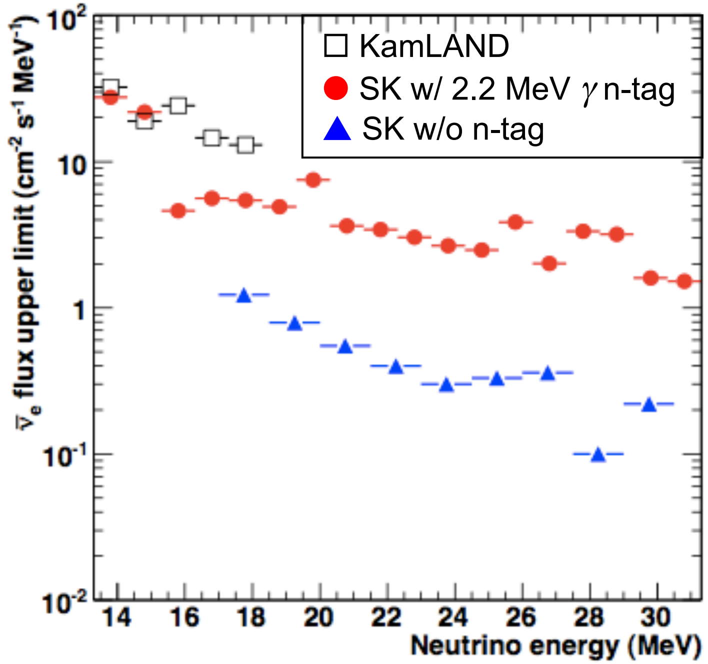
One of our main motivation for this upgrade is to first detect DSNB, neutrinos from all the supernovae in the history of the universe

This would be detected through anti-neutrinos interacting inverse-β

The measurement is affected by large backgrounds that can be excluded with neutron tagging

At the moment SK can only put upper limits and they are 2- 4 times larger than the theoretical predictions

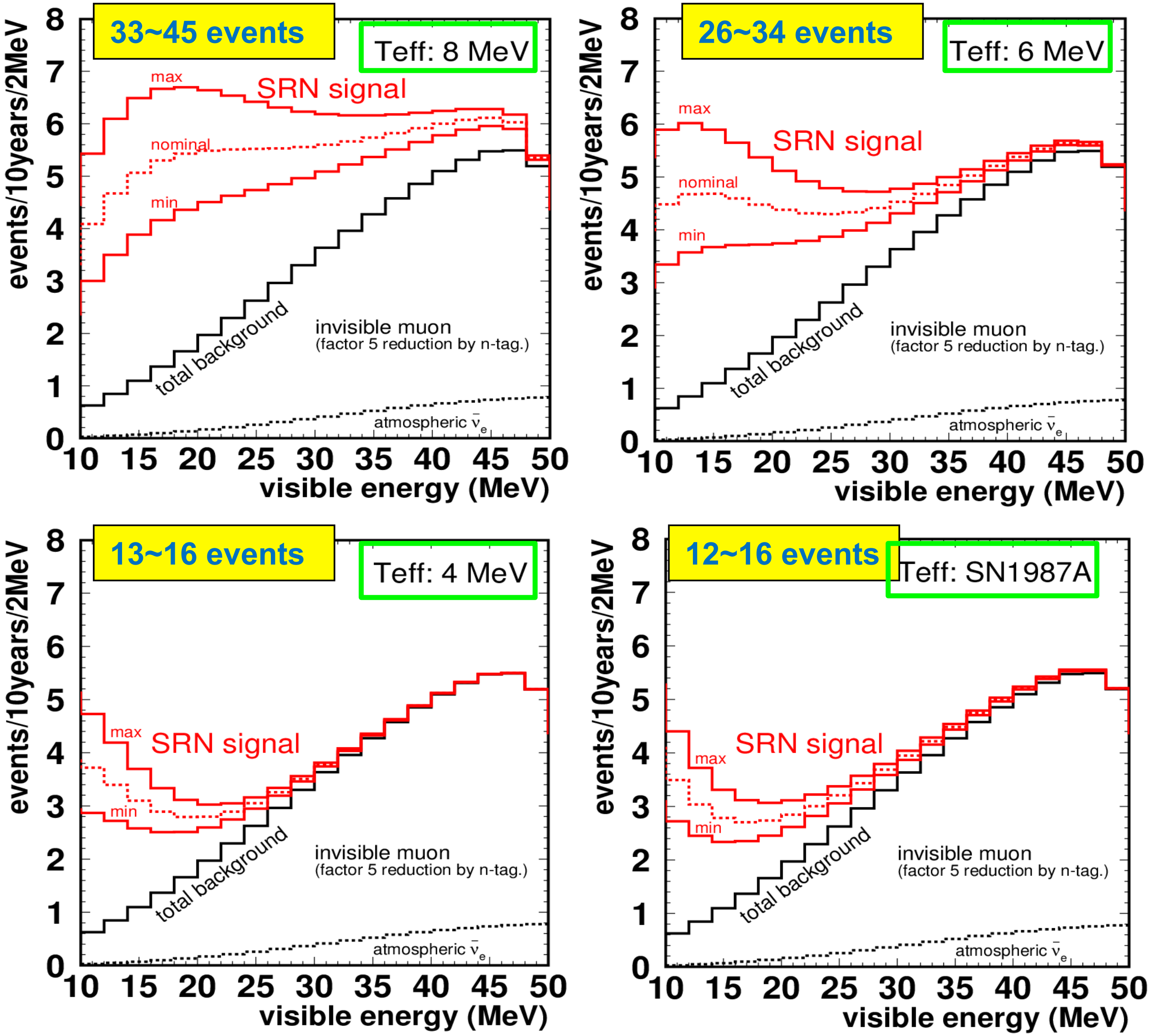




[SK Collab., Astro. Phys. 60, 41–46, 2014]

With efficient neutron tagging, we expect to be able to reduce most of backgrounds and be sensitive to DSNB

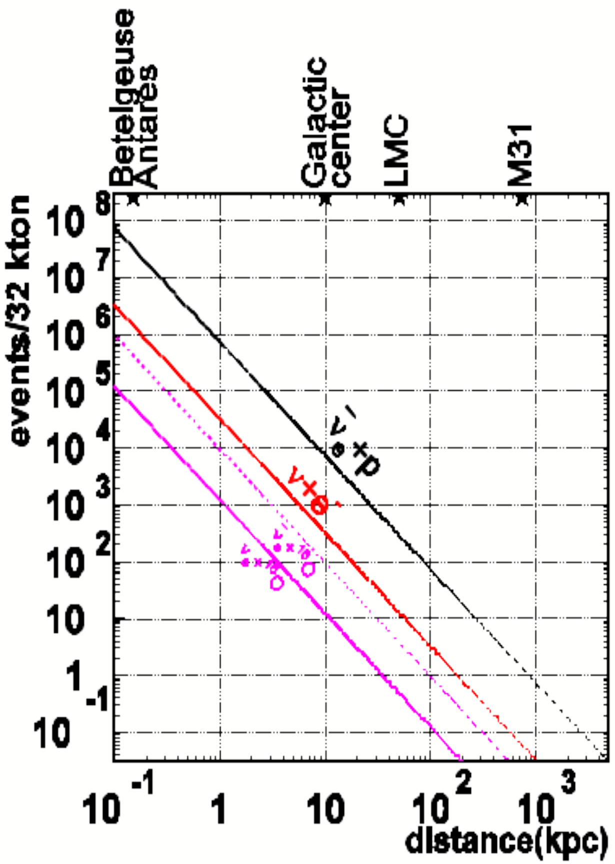
Expected number of events in 10 years in E_{vis} =10-30 MeV

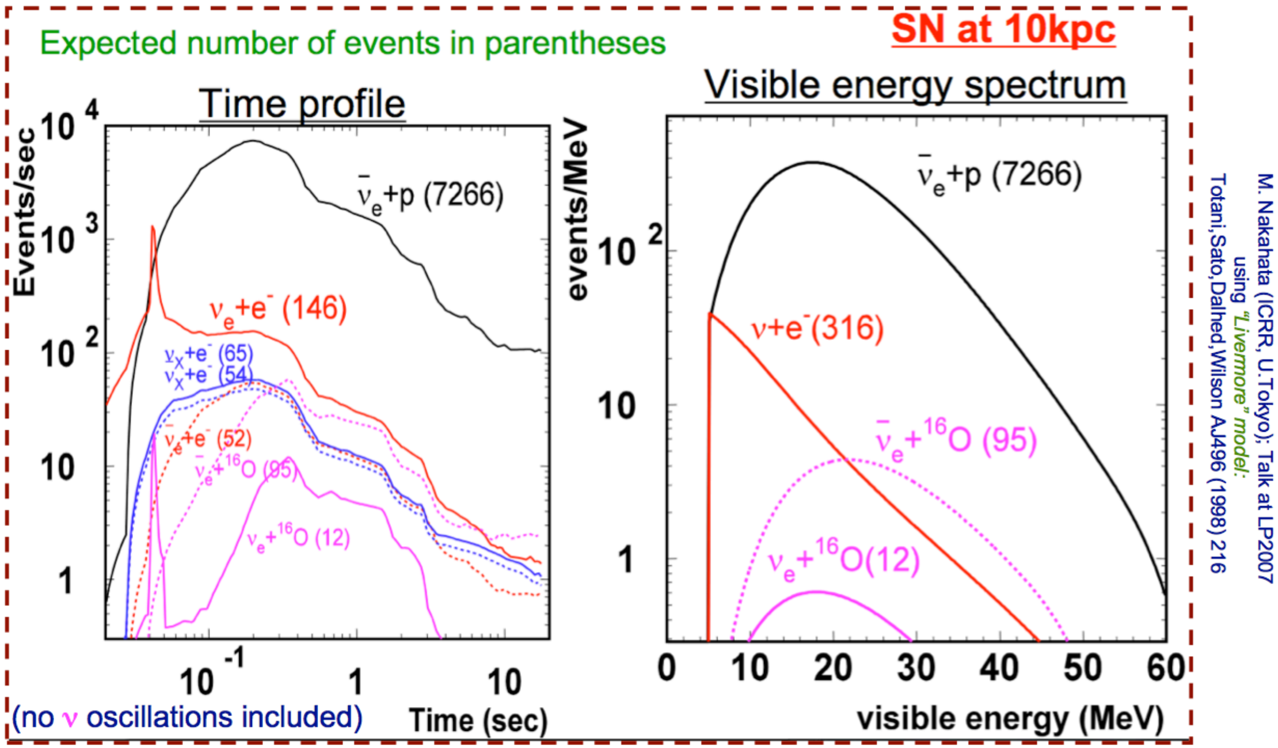


[Horiuchi et al. PRD, 79, 083013 (2009)]

Galactic Supernova Burst

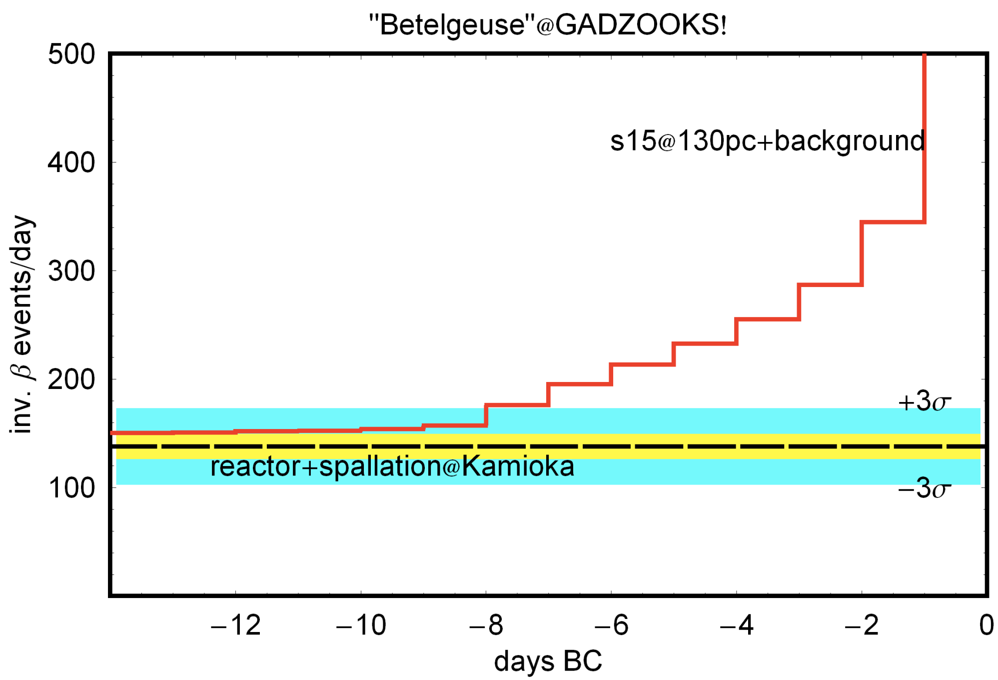
With neutron tagging, we can extract the $\bar{\nu}_e$ and ν_e spectra
Provides much more detailed information about the core-collapse process than that without neutron tagging





Pre-Supernova

Detection of $\bar{\nu}_e$ produced during late Si burning stage of nearby (≤ 2 kpc) stars, a few days before core-collapse



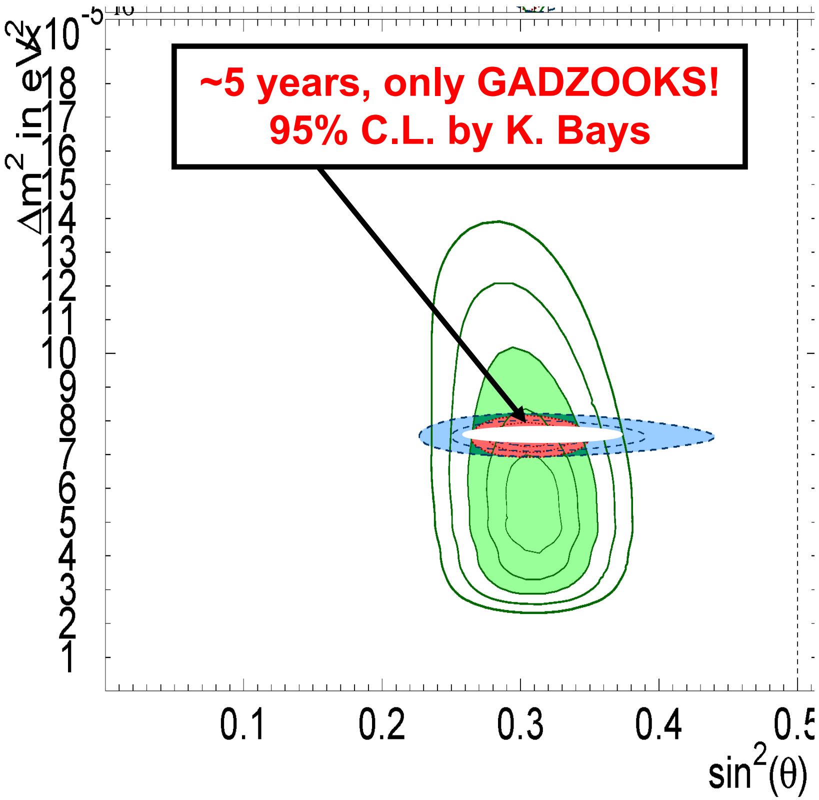
Detector	Target mass	Min. $\bar{\nu}_e$ energy	Events 48-24 hours before collapse	Events 24-0 hours before collapse	Events 3-0 hours before collapse
Super-K	32 kt	5 MeV	0.6	173	158
GADZOOKS!	22.5 kt	3.8(1.8) MeV	9 (204)	442 (1883)	345 (1130)

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

Reactor Neutrinos

Improve sensitivity to solar sector oscillation parameters using reactor neutrinos

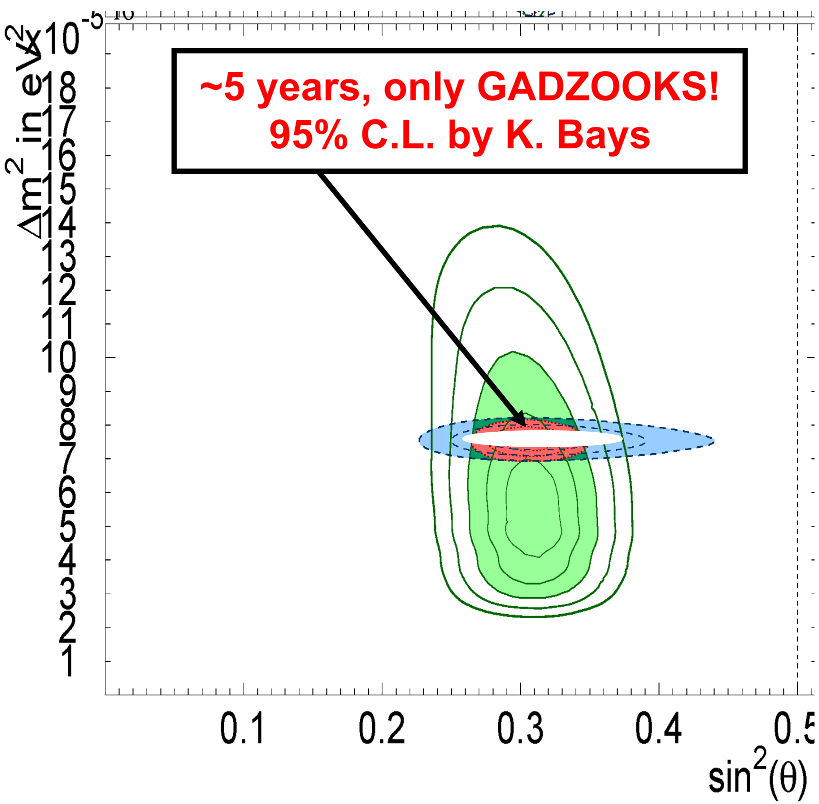
Although the future of japanese nuclear reactors is not clear, GADZOOKS! will detect a similar rate from korean reactors as KamLAND when all the japanese reactors were on



Reactor Neutrinos

Improve sensitivity to solar sector oscillation parameters using reactor neutrinos

Although the future of japanese nuclear reactors is not clear, GADZOOKS! will detect a similar rate from korean reactors as KamLAND when all the japanese reactors were on



Others

Improve our knowledge of atmospheric and accelerator neutrino interactions and final states

Neutron tagging can help discriminating between ν and $\bar{\nu}$ at GeV scale

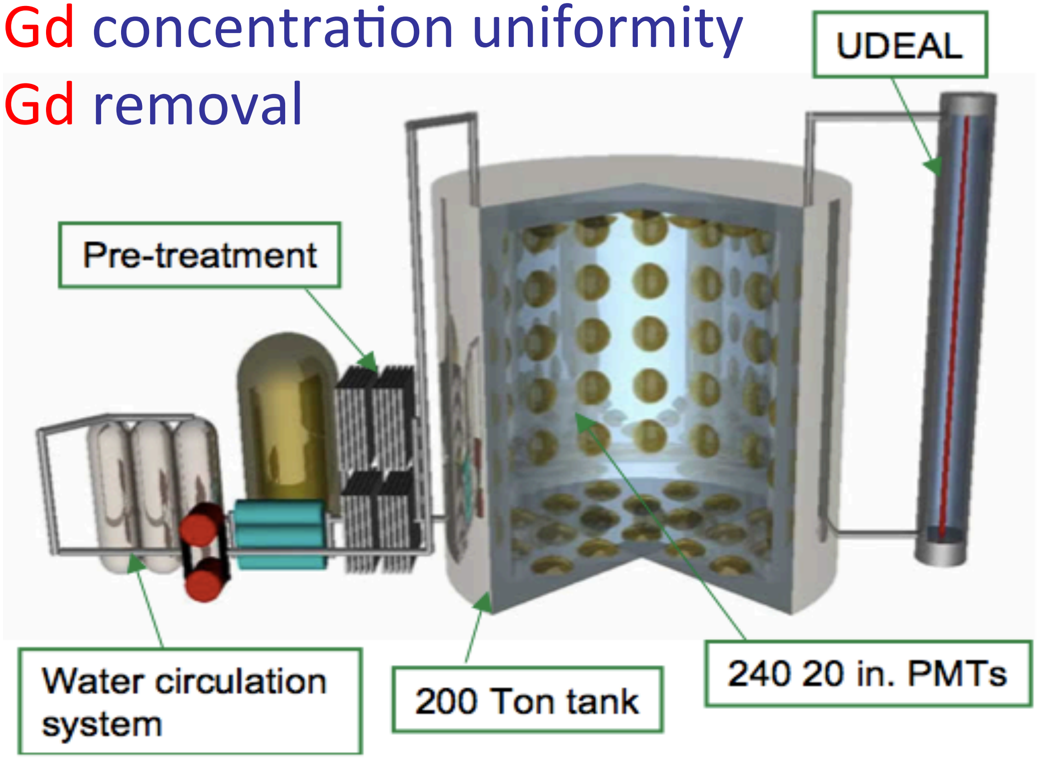
Neutron tagging also reduces background in proton decay searches by requiring final states with no neutrons

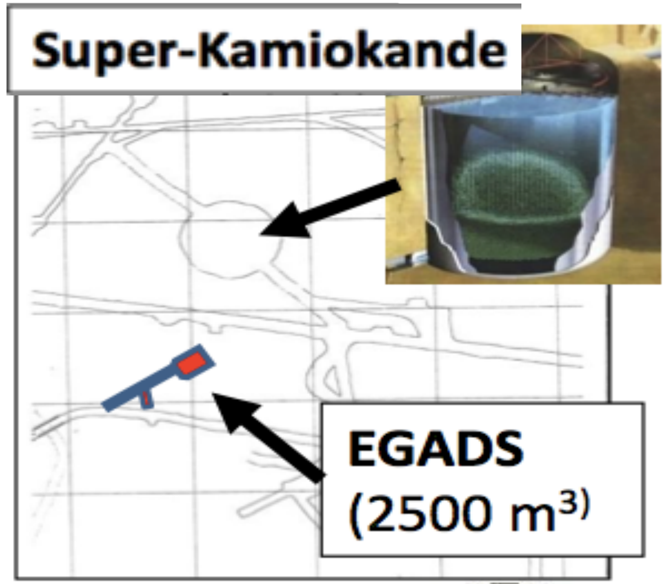
EGADS

Evaluating Gadolinium's Action on Detector Systems

Facility for testing the effect of Gd in water-Cherenkov detectors:

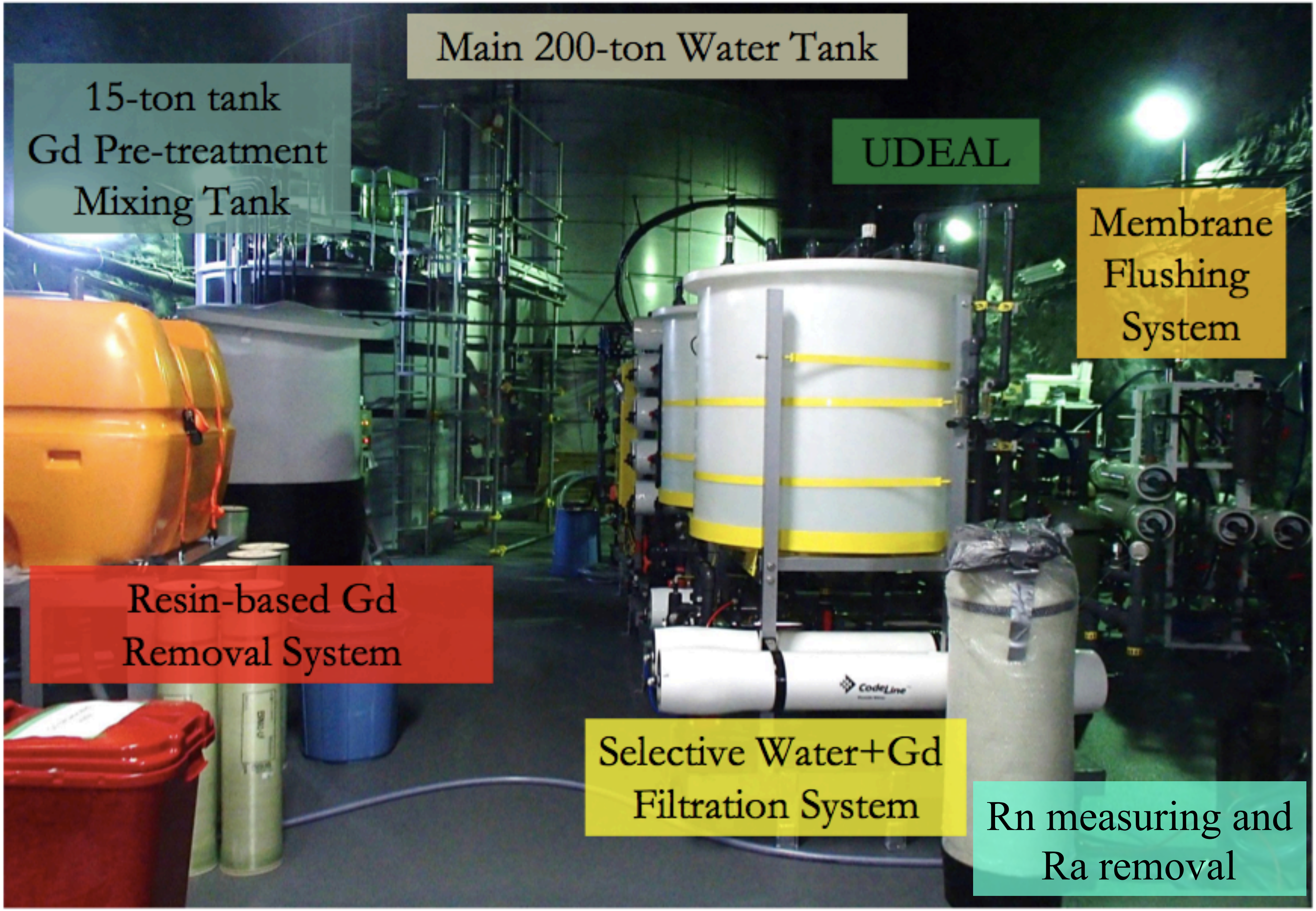
- Selective filtration for Gd water
- $Gd_2(SO_4)_3$ "cleaning" and dissolving
- water transparency monitoring
- Gd concentration uniformity
- Gd removal





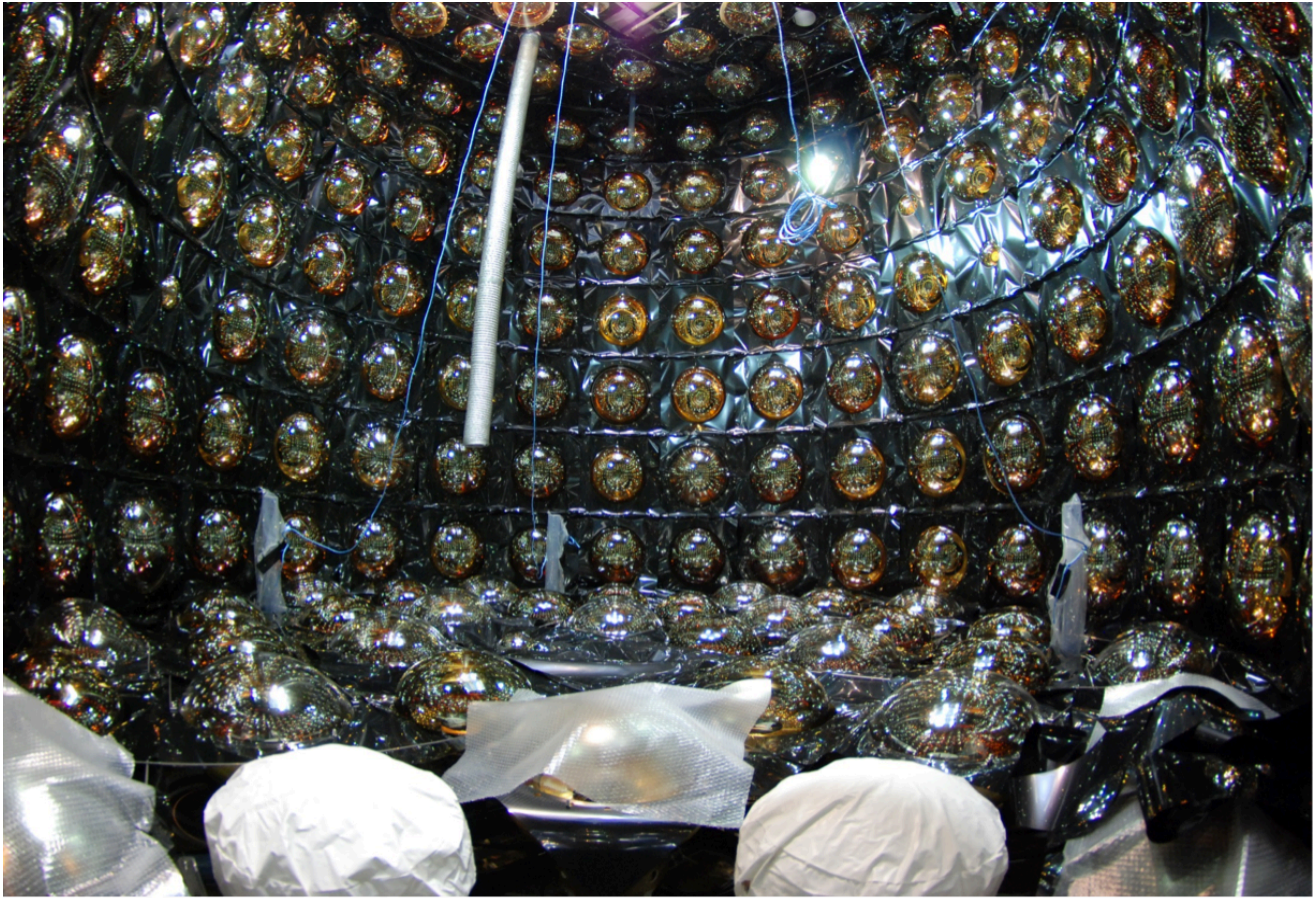
Last summer it became an actual detector, instrumented with 240 PMTs

EGADS hall

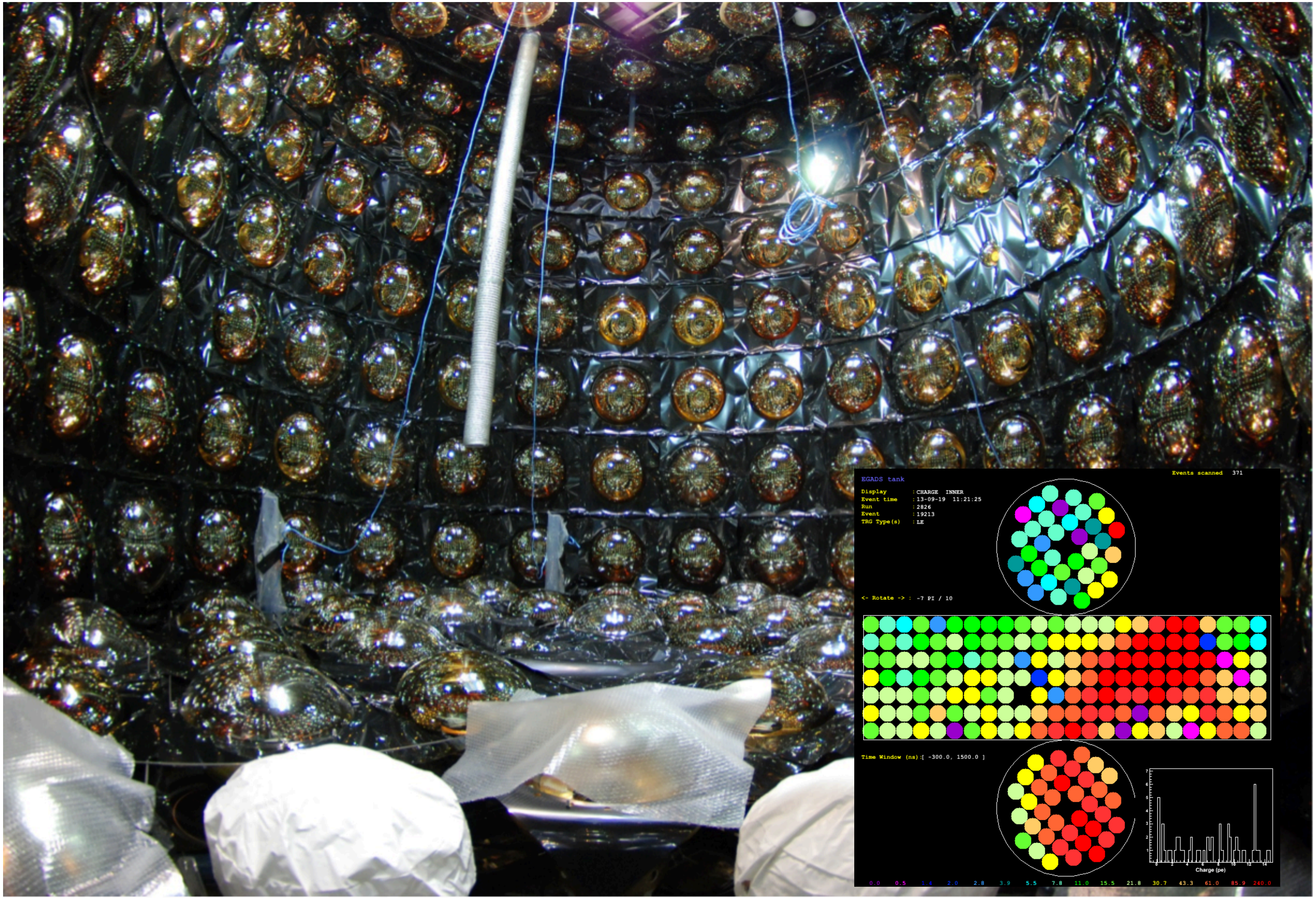


Main 200-ton Water Tank
15-ton tank
Gd Pre-treatment
Mixing Tank
UDEAL
Membrane
Flushing
System
Resin-based Gd
Removal System
Selective Water+Gd
Filtration System
Rn measuring and
Ra removal

EGADS tank fully instrumented…

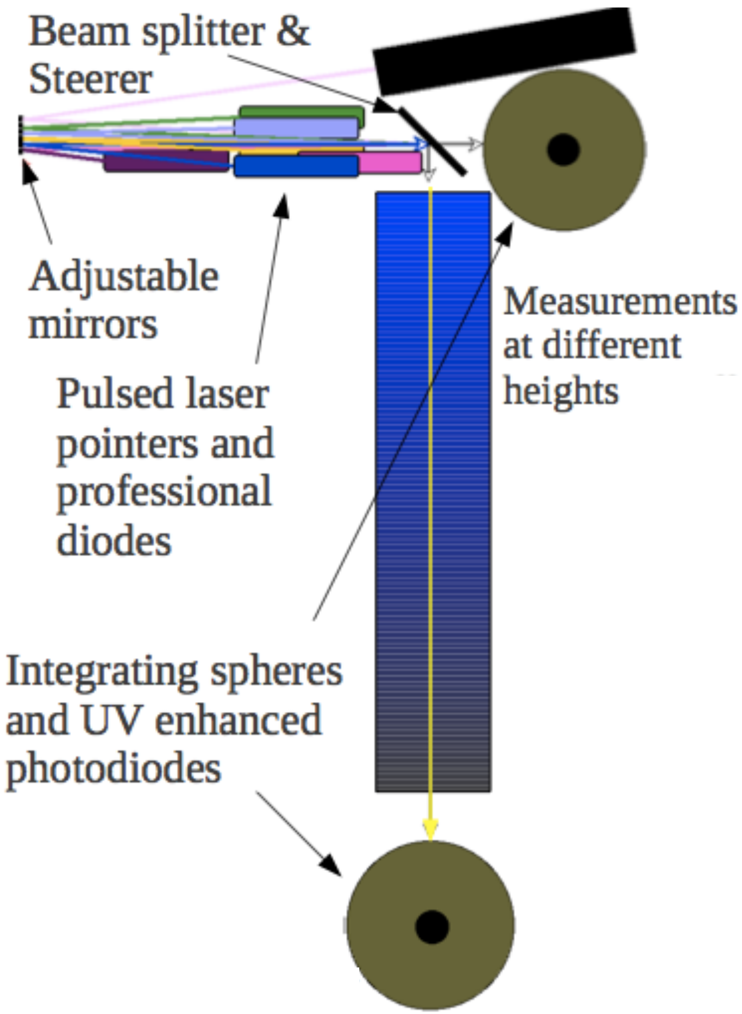


EGADS tank fully instrumented... and already taking data

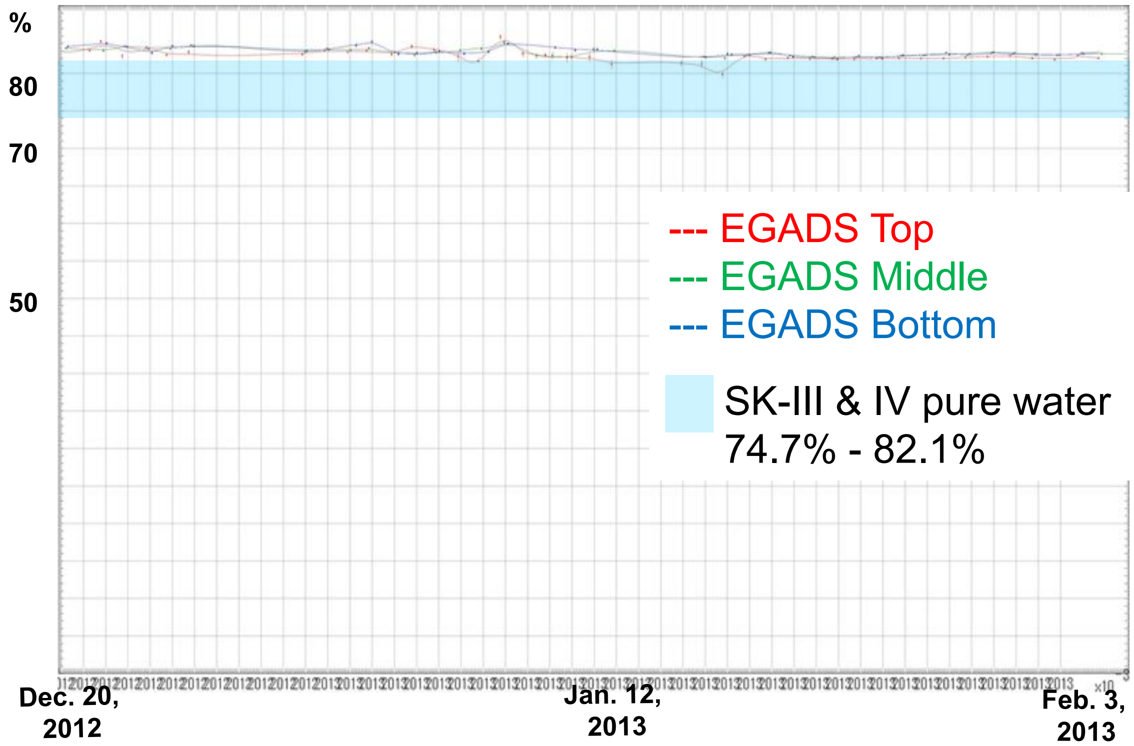


Water transparency measurement with UDEAL

UDEAL: Underground Device Evaluating Attenuation Length



Cherenkov light left at 15 m

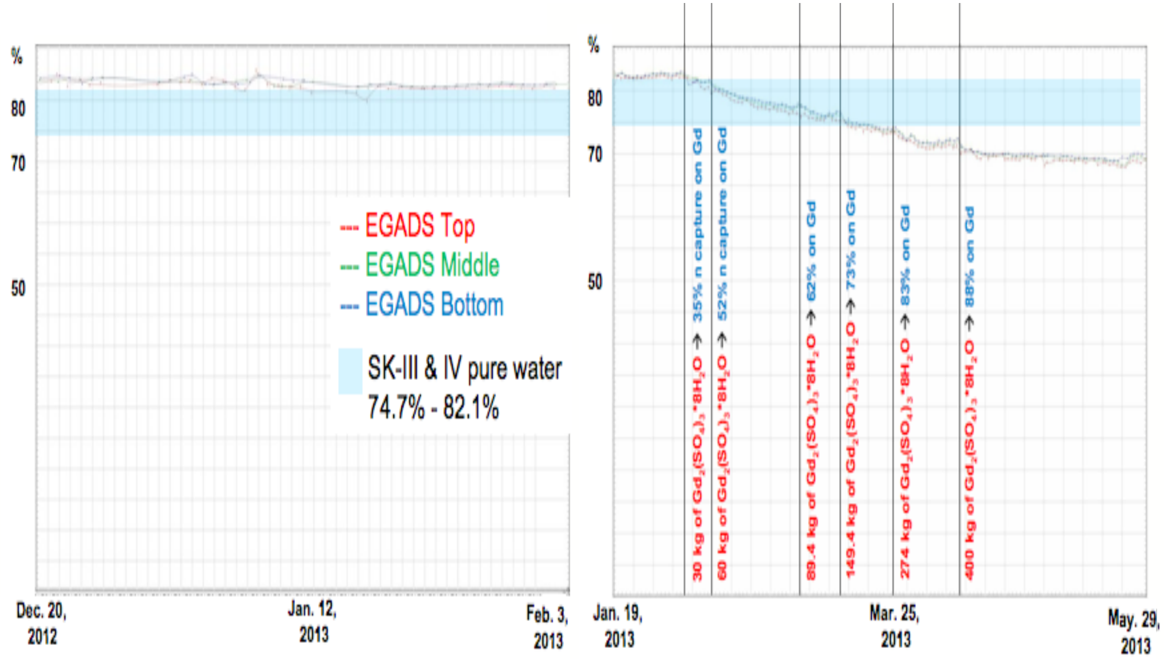


Water transparency measurement with UDEAL

Non-instrumented EAGDS

For pure water, transparency was very stable and very good quality

Good behavior when introducing Gd, < 15% drop

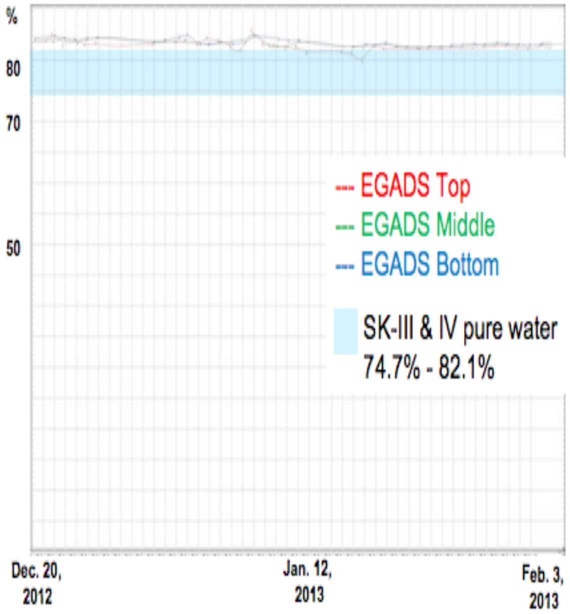


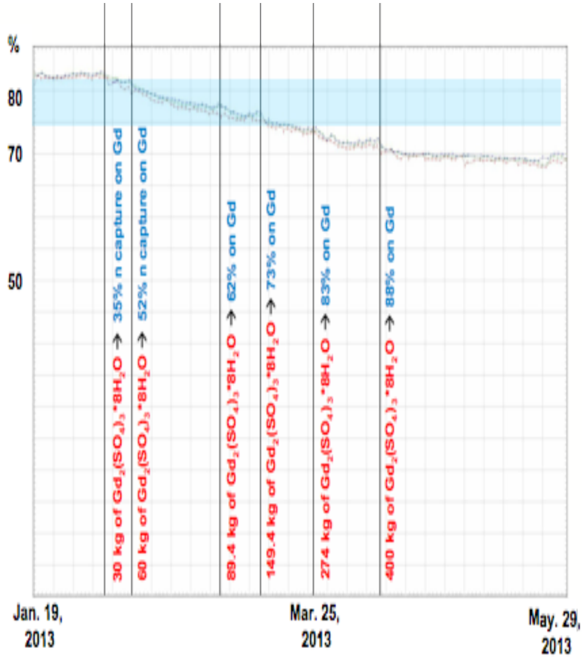
Water transparency measurement with UDEAL

Non-instrumented EAGDS

For pure water, transparency was very stable and very good quality

Good behavior when introducing Gd, < 15% drop



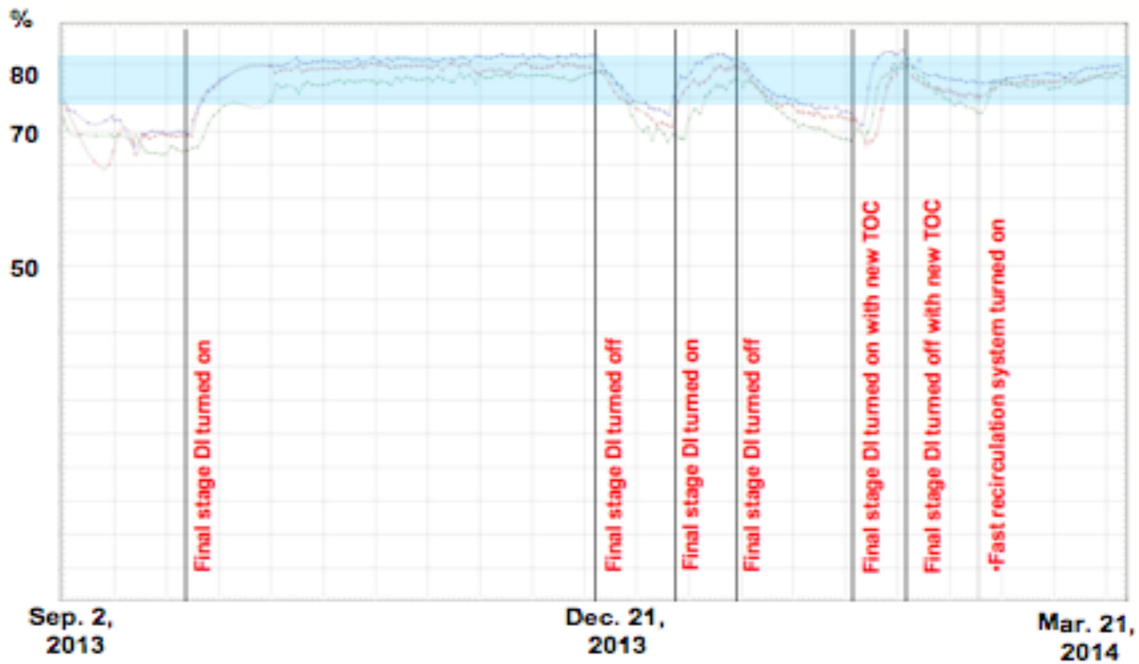


Instrumented EAGDS

For pure water, transparency was not so good quality

Became worse during the procedure of adding Gd, when changing the water level

After investigation, we found that there was a bad material

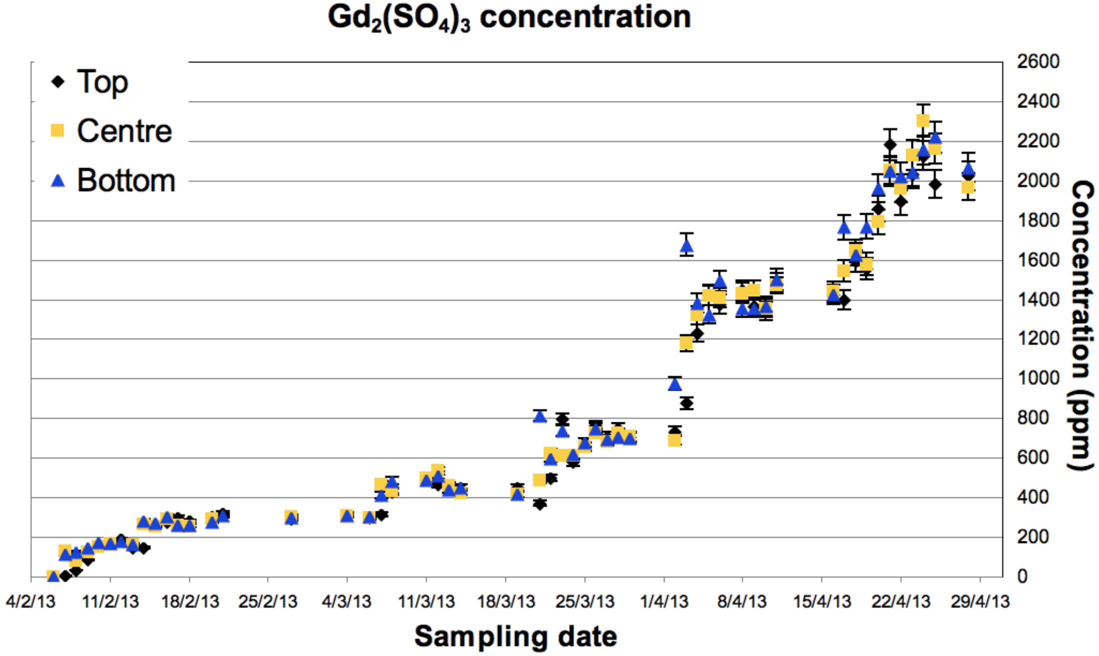


Gd concentration measurement with AAS

Non-instrumented EAGDS

Concentration becomes rapidly uniform along the whole volume of the detector after each Gd insertion

$Gd_2(SO_4)_3$ remains homogenously dissolved

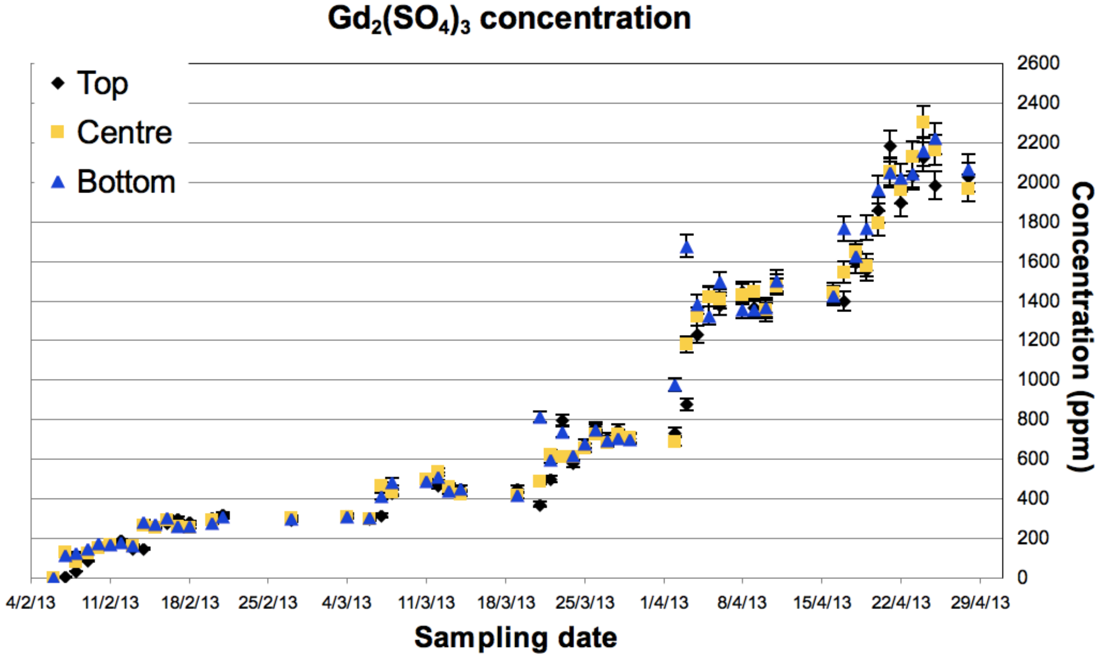


Gd concentration measurement with AAS

Non-instrumented EAGDS

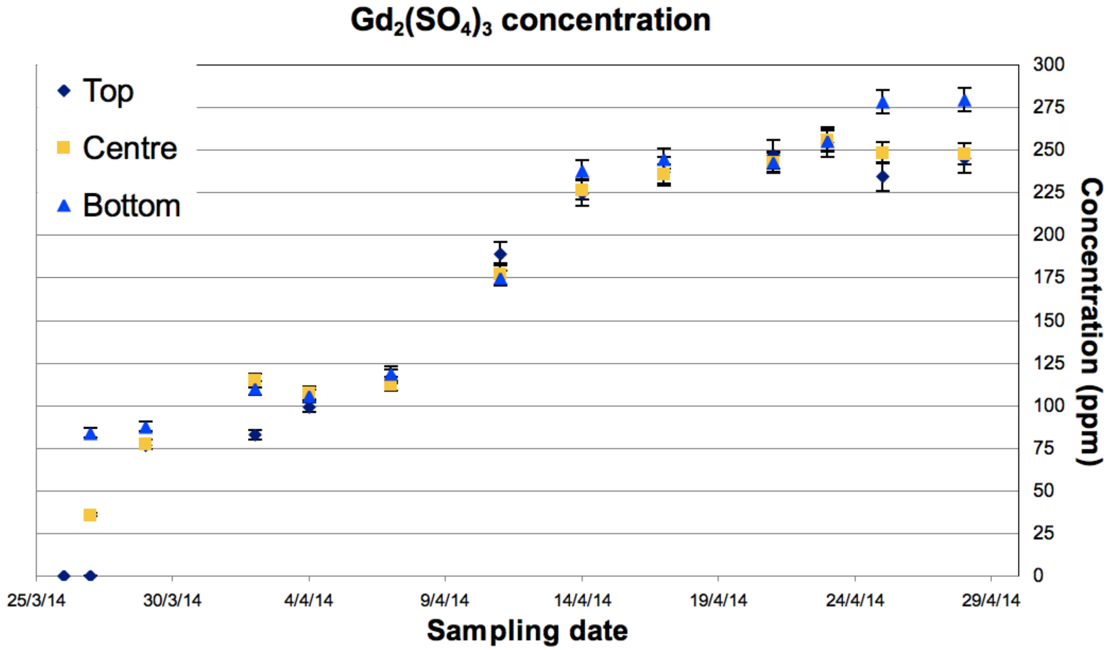
Concentration becomes rapidly uniform along the whole volume of the detector after each Gd insertion

$Gd_2(SO_4)_3$ remains homogenously dissolved



Instrumented EAGDS

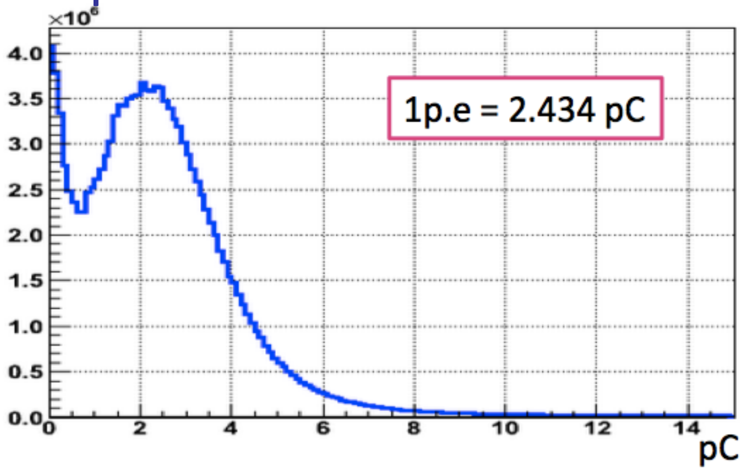
No major effect in uniformity and stability of Gd concentration once the PMTs were installed



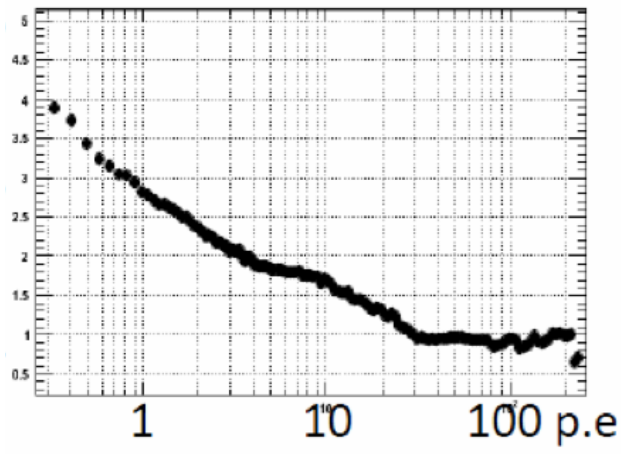
EGADS calibrations

All calibrations show stable and reliable performance of the detector

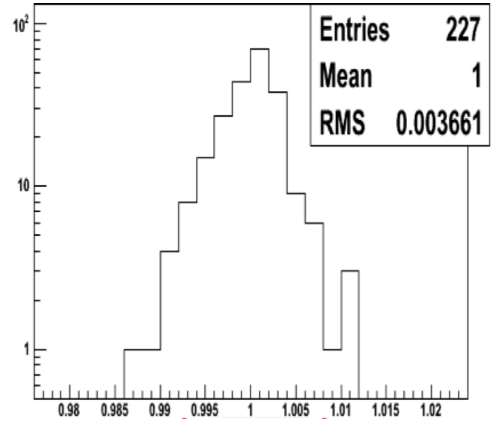
- 1photo-electron



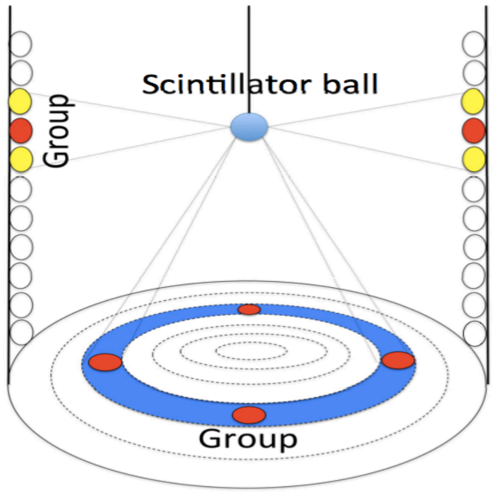
- Timing resolution

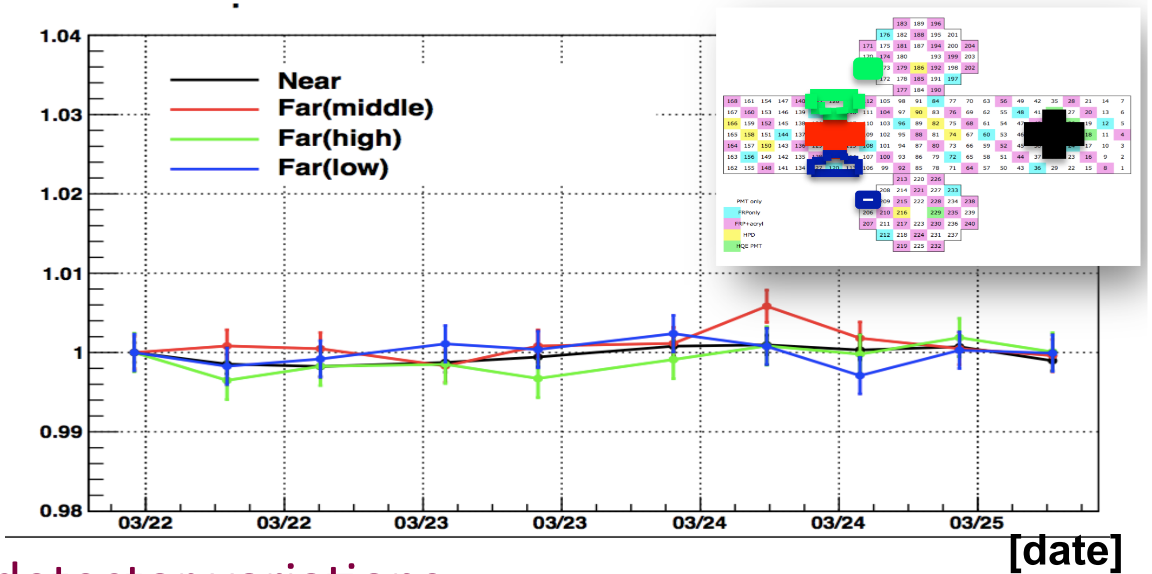


- PMT Q uniformity



- auto-Xe lamp





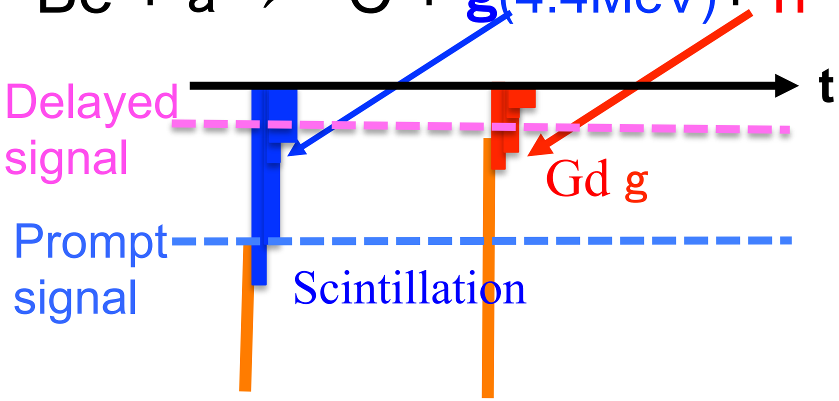
Precise monitoring of the detector variations

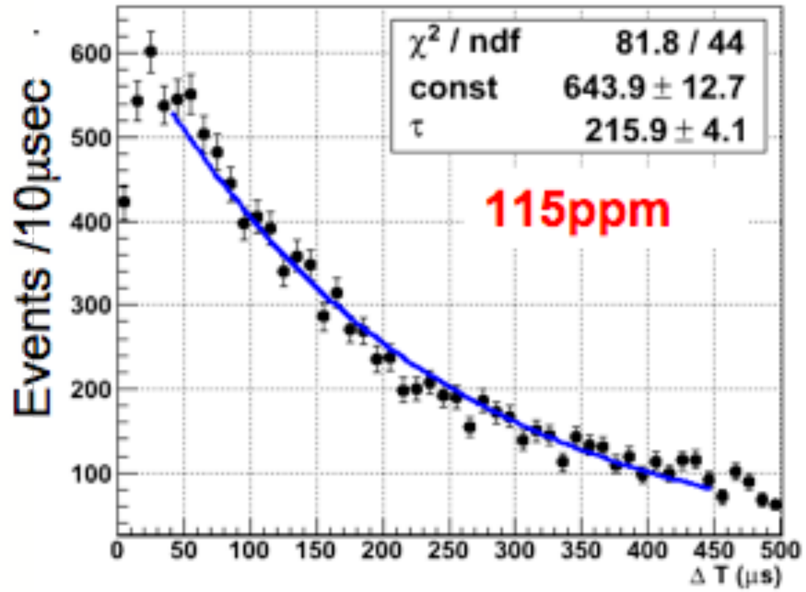
• Am - Be source

Used to test detector performance and check Gd neutron capture efficiency

$^{241}Am \rightarrow {}^{237}Np + a$

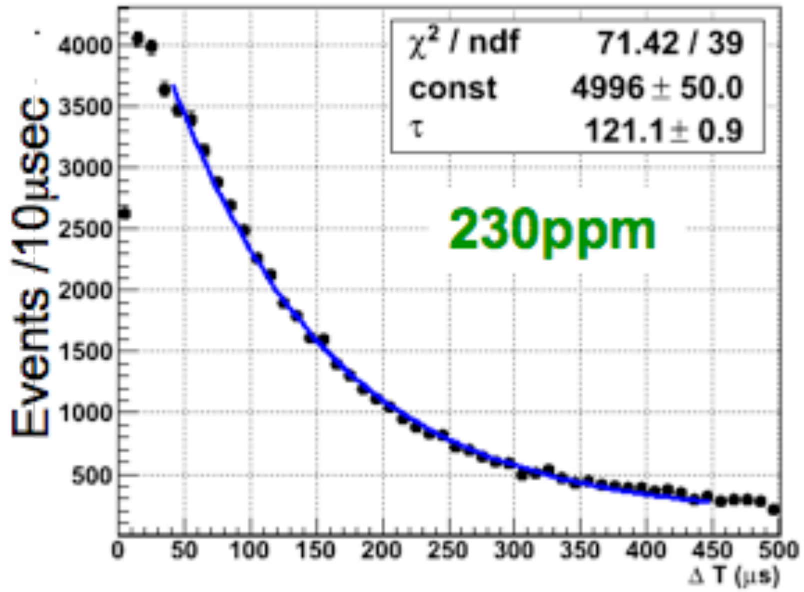
$^{9}Be + a \rightarrow {}^{12}C + g(4.4MeV) + n$





neutron capture delay after prompt signal depends on Gd concentration as expected from Monte Carlo simulations

$Gd_2(SO_4)_3$	Data [ms]	MC [ms]
115ppm	215.6 ± 4.1	221.8 ± 2.3
230ppm	121.1 ± 0.9	124.8 ± 2.1



Others respecting the whole GADZOOKS!: Inverse-β reconstruction

We are thoroughly investigating with realistic Monte Carlo simulations procedures for reconstructing the inverse-β reaction in GADZOOKS!

This is affected by the effect of the $Gd_2(SO_4)_3$ on light transmission (~15%). Two extreme cases considered: either **Abs**orption or **Ray**leigh scattering

Others respecting the whole GADZOOKS!: Inverse-β reconstruction

We are thoroughly investigating with realistic Monte Carlo simulations procedures for reconstructing the inverse-β reaction in GADZOOKS!

This is affected by the effect of the $Gd_2(SO_4)_3$ on light transmission (~15%). Two extreme cases considered: either **Abs**orption or **Ray**leigh scattering

Current results for neutron capture efficiency and purity using a multivariate likelihood method:

	$e^+ + \gamma$s			e^- only		
	SKwater	**Ray**	**Abs**	**SKwater**	**Ray**	**Abs**
e reconstruction	99.6%	99.6%	99.7%	99.6%	99.5%	99.7%
γs Volume cut	89.4%	87.5%	80.3%	25.8%	25.7%	25.8%
Likelihood	96.5%	94.8%	91.7%	<0.001%	<0.001%	<0.001%
Total eff.	**85.95%**	**82.64%**	**73.46%**	**< $4 \cdot 10^{-4}$ %**	**< $4 \cdot 10^{-4}$ %**	**< $4 \cdot 10^{-4}$ %**
	efficiencies			***un-purities***		

Others respecting the whole GADZOOKS!: Inverse-β reconstruction

We are thoroughly investigating with realistic Monte Carlo simulations procedures for reconstructing the inverse-β reaction in GADZOOKS!

This is affected by the effect of the $Gd_2(SO_4)_3$ on light transmission (~15%). Two extreme cases considered: either **Abs**orption or **Ray**leigh scattering

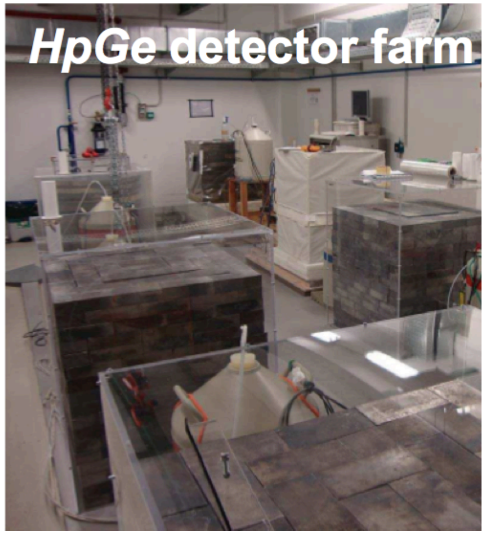
Current results for neutron capture efficiency and purity using a multivariate likelihood method:

	$e^+ + \gamma$s			e^- only		
	SKwater	**Ray**	**Abs**	**SKwater**	**Ray**	**Abs**
e reconstruction	99.6%	99.6%	99.7%	99.6%	99.5%	99.7%
γs Volume cut	89.4%	87.5%	80.3%	25.8%	25.7%	25.8%
Likelihood	96.5%	94.8%	91.7%	<0.001%	<0.001%	<0.001%
Total eff.	**85.95%**	**82.64%**	**73.46%**	**< $4 \cdot 10^{-4}$ %**	**< $4 \cdot 10^{-4}$ %**	**< $4 \cdot 10^{-4}$ %**

efficiencies ***un-purities***

Studies at U. C. Irvine point that the effect of Gd is mainly scattering of light

Others respecting the whole GADZOOKS!: radioactivity contamination of $Gd_2(SO_4)_3$



The Gd compound will be dissolved uniformly along the whole active material of the experiment

➔ its radiopurity is an important issue

Most of the radioactivity measurements for GADZOOKS! are performed in the **Canfranc Underground Laboratory**

The contaminations are non-negligible:

Chain	sub-chain	Gd-0904	Gd-1008	Gd-1208	Gd-1302	Gd-1303	Gd-1308	Gd-1307a	Gd-1307b
^{238}U	^{238}U	51± 21	< 33	292±67	74±28	242±60	71±20	47±26	73±27
	^{226}Ra	8±1	2.8±0.6	74±2	13±1	13±2	8±1	5±1	6±1
^{232}Th	^{228}Ra	11±2	270±16*	1099±12	205±6	21±3	6±1	14±2	3±1
	^{228}Th	28±3	86±5	504±6	127±3	374±6	159±3	13±1	411±5
^{235}U	^{235}U	< 32	< 32	< 112	< 25	< 25	< 32	<12	<30
	^{227}Ac	214±10	1700±20	2956±30	1423±21	175±42	295±10	<6	<18
Other	^{40}K	29±5	12±3*	101±10	60±7	18±8	3±2	3±2	8±4
	^{138}La	8±1	<	683±15	3±1	42±3	5±1	<1	<2
	^{176}Lu	80±8	21±2	566±6	12±1	8±2	30±1	1.6±0.3	<2

Results in mBq/kg

Others respecting the whole GADZOOKS!:

Effects of radioactivity contamination in $Gd_2(SO_4)_3$

Basically two measurements are affected

Estimate by using typical values measured in the different batches:

Chain	sub-chain	assumed radioactivity (*mBq/kg*)
^{238}U	^{238}U *(upper)*	50
	^{226}Ra *(bottom)*	5
^{232}Th	^{228}Ra *(upper)*	10
	^{228}Th *(bottom)*	100
^{235}U	^{235}U *(upper)*	< 32
	^{227}Ac *(bottom)*	300

Others respecting the whole GADZOOKS!:
Effects of radioactivity contamination in $Gd_2(SO_4)_3$

Basically two measurements are affected

Estimate by using typical values measured in the different batches:

Chain	sub-chain	assumed radioactivity (*mBq/kg*)
^{238}U	^{238}U *(upper)*	50
	^{226}Ra *(bottom)*	5
^{232}Th	^{228}Ra *(upper)*	10
	^{228}Th *(bottom)*	100
^{235}U	^{235}U *(upper)*	< 32
	^{227}Ac *(bottom)*	300

Diffuse SN neutrino Background

expected signal: **5 events/year/22.5kton**

background: comes mainly from **^{238}U SF** ➔ **5.5 events/year/22.5kton**

tested purification (AJ4400) ➔ **< $3 \cdot 10^{-2}$ events/year/22.5kton**

Others respecting the whole GADZOOKS!:
Effects of radioactivity contamination in $Gd_2(SO_4)_3$

Basically two measurements are affected

Estimate by using typical values measured in the different batches:

Chain	sub-chain	assumed radioactivity (*mBq/kg*)
^{238}U	^{238}U *(upper)*	50
	^{226}Ra *(bottom)*	5
^{232}Th	^{228}Ra *(upper)*	10
	^{228}Th *(bottom)*	100
^{235}U	^{235}U *(upper)*	< 32
	^{227}Ac *(bottom)*	300

Diffuse SN neutrino Background

expected signal: **5 events/year/22.5kton**

background: comes mainly from **^{238}U SF** ➔ **5.5 events/year/22.5kton**

tested purification (AJ4400) ➔ **< $3 \cdot 10^{-2}$ events/year/22.5kton**

Solar analysis

expected signal from 3.5 MeV: **200 events/day/22.5kton**

background: mainly from **^{208}Tl** β-decay ➔ ~ **10^5 events/day/22.5kton**

Ra and **Th** removal and analysis methods under study

a *possible* timeline for EGADS & GADZOOKS!

06/2014 - 08/2014: EGADS 200-ton tank works
08/2014 - 11/2014: new EGADS test
05/2015: Make a decision among the SK collaboration

the 200m^3 tank and ancillary instruments after EGADS

EGADS will continue as instant supernova detector with all the advantages of neutron tagging, capable to measure

~ 100 events from core-collapse in the center of our galaxy
~ 100000 events from Betelgeuse

EGADS is part of the new Multimessenger SN Astronomy in Japan

Summary

Very efficient neutron tagging can be achieved by adding 0.2% $Gd_2(SO_4)_3$ into SK, which will greatly improve antineutrino identification

Summary

Very efficient neutron tagging can be achieved by adding 0.2% $Gd_2(SO_4)_3$ into SK, which will greatly improve antineutrino identification

This will allow the first observation of DSNB and improve various current SK measurements

Summary

Very efficient neutron tagging can be achieved by adding 0.2% $Gd_2(SO_4)_3$ into SK, which will greatly improve antineutrino identification

This will allow the first observation of DSNB and improve various current SK measurements

EGADS will soon provide the complete de proof-of-principle tests of a Gd-loaded Water Cherenkov detector