Super-K: Gd Project

Tracking Supernova Relic Neutrinos with a Gd-loaded water Cerenkov detector

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OUTLINE

1 - Neutrino Physics

2 - Super-Kamiokande

3 - Supernova Neutrinos

4 - Supernova Relic Neutrinos

5 - Super-Kamiokande Gd

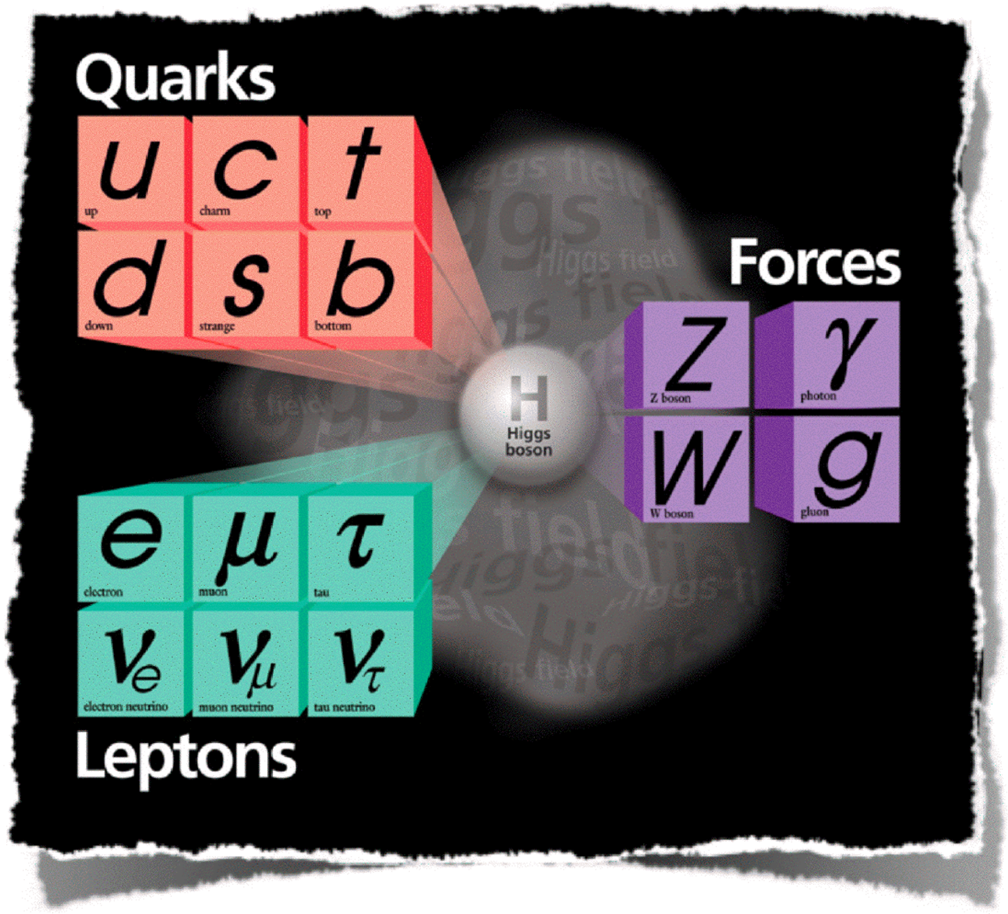
6 - EGADS

Neutrino physics

Standard Model

- **Standard Model** of particle physics:
- 3 classes of particles:
  - **Quarks** & **Leptons**, matter's component.
  - **Bosons**, force carriers that mediate the fundamental **Interactions**.

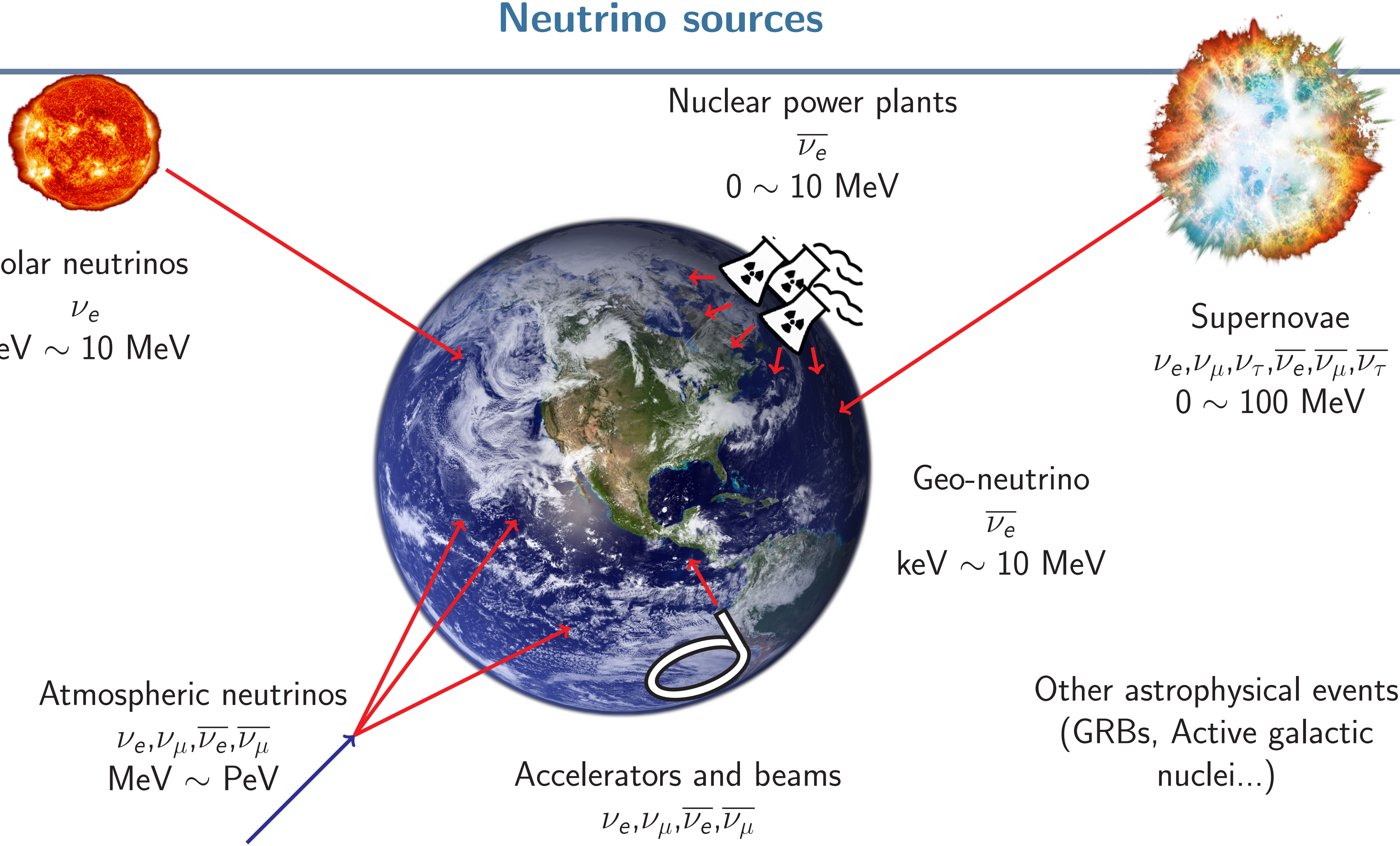
    (electromagnetic, weak, and strong nuclear interactions)
- In the Lepton class: The **Neutrinos**
  - **3 flavors** of Neutrino (ν_e, ν_μ, ν_τ).
  - **Neutral** particles.
  - Very low interaction in the matter.
  - Neutrino oscillations
    → demonstrated by Super-K and SNO (Nobel prize 2015)



Open questions in Neutrino physics

- Neutrino physics is an active research field with open questions:
  - What are the value of the ν oscillation parameters?
  - What is the CP violation in the leptonic sector?
  - What is the ν mass hierarchy?
  - Is ν its own anti-particle? i.e. is it a Majorana or a Dirac particle?
  - What are the ν masses?
  - Are there sterile ν's?

Neutrino sources



Solar neutrinos

ν_e

keV $\sim$ 10 MeV

Nuclear power plants

$\overline{\nu_e}$

0 $\sim$ 10 MeV

Supernovae

$\nu_e,\nu_\mu,\nu_\tau,\overline{\nu_e},\overline{\nu_\mu},\overline{\nu_\tau}$

0 $\sim$ 100 MeV

Geo-neutrino

$\overline{\nu_e}$

keV $\sim$ 10 MeV

Atmospheric neutrinos

$\nu_e,\nu_\mu,\overline{\nu_e},\overline{\nu_\mu}$

MeV $\sim$ PeV

Accelerators and beams

$\nu_e,\nu_\mu,\overline{\nu_e},\overline{\nu_\mu}$

MeV $\sim$ GeV

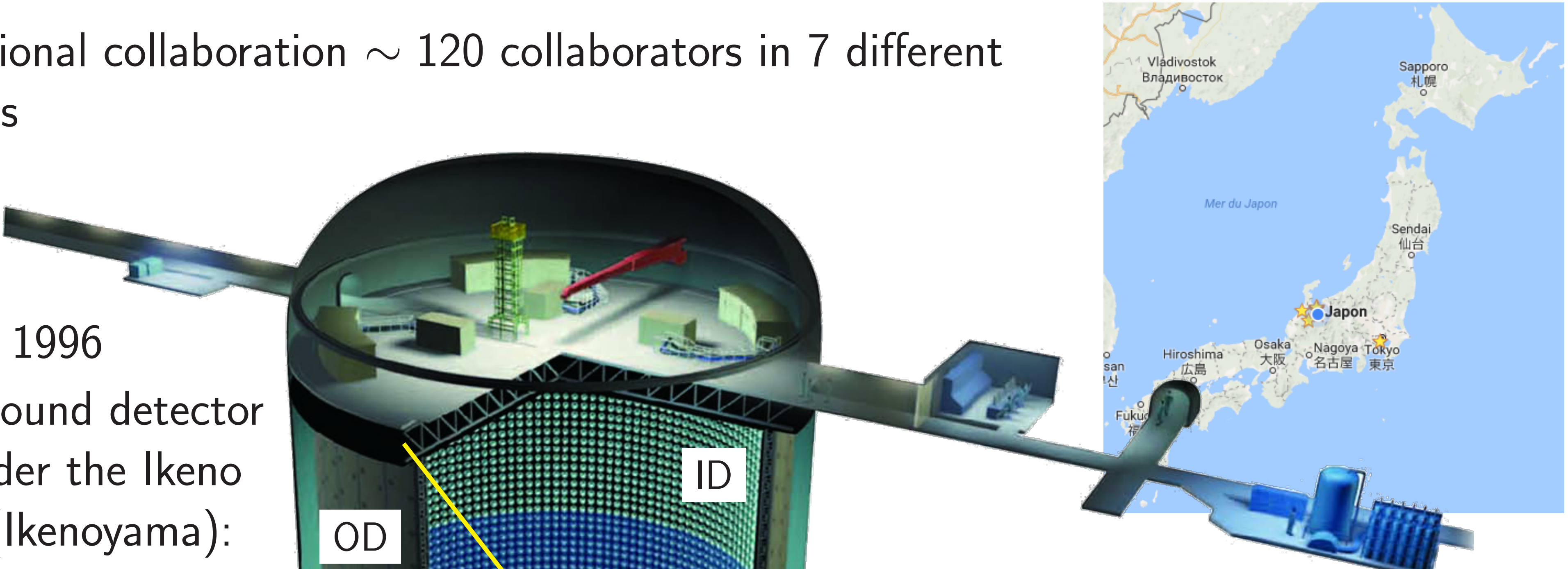
Other astrophysical events
(GRBs, Active galactic
nuclei...)

- ν can also be a probe to understand physical processes in the universe
- We need powerful and innovative experiments to detect them

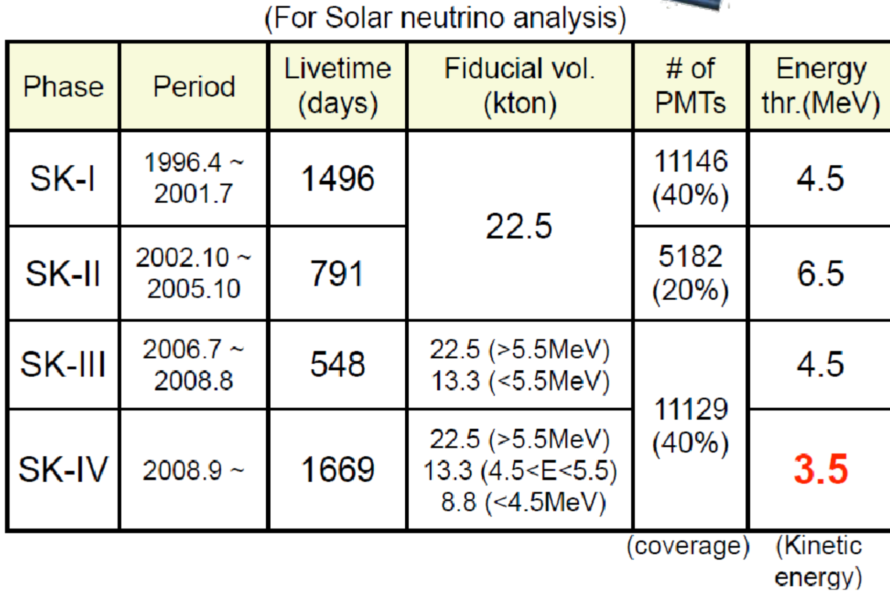
Super-Kamiokande

Super-K

- International collaboration ∼ 120 collaborators in 7 different countries



- Build in 1996
- Underground detector 1km under the Ikeno mount (Ikenoyama): → Overburden: ∼ 2780 m.w.e.
- 50 000 tons of pure water Cerenkov detector
- Analysis and hardware regularly improved since the construction

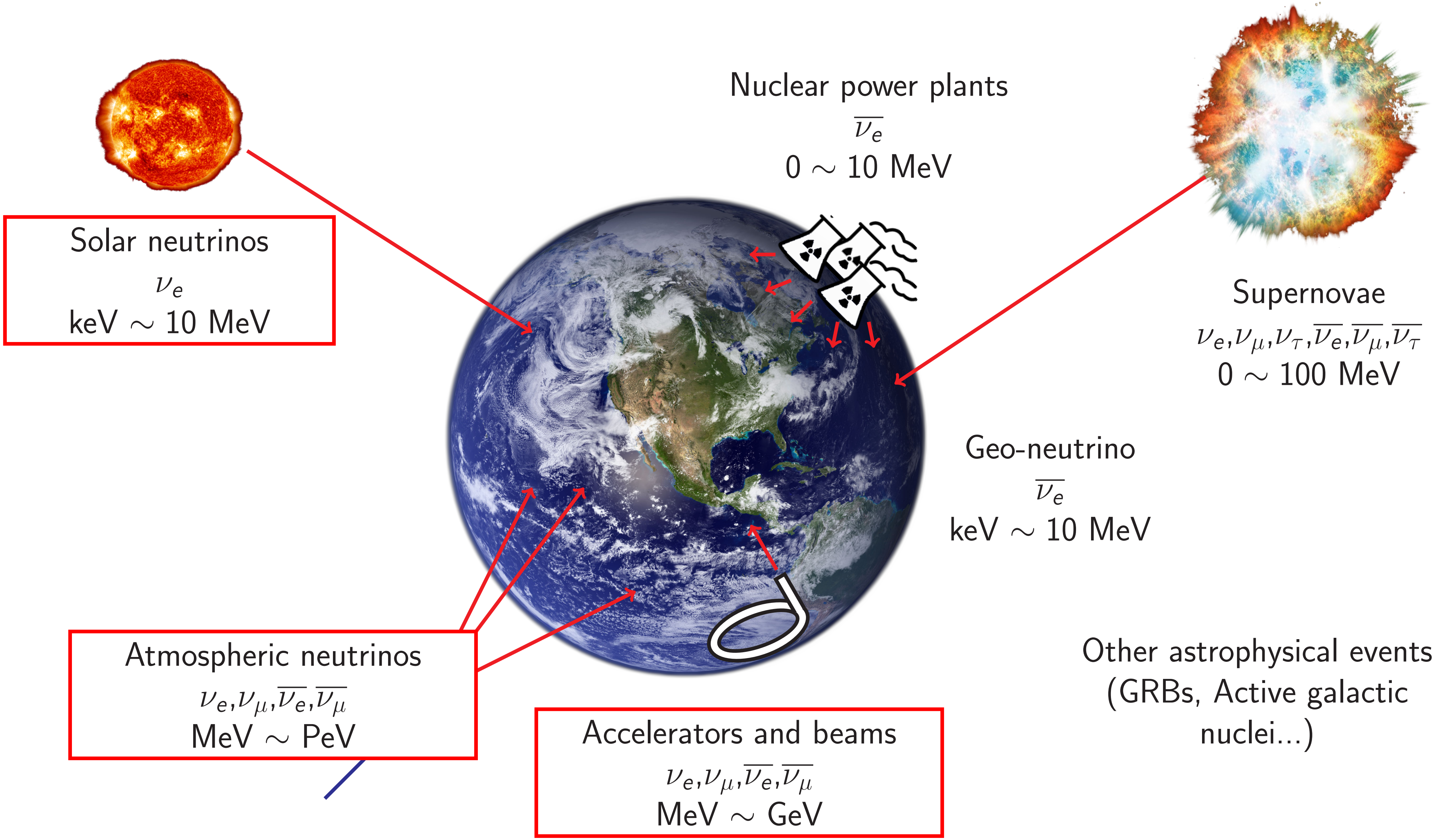


(For Solar neutrino analysis)

Phase	Period	Livetime (days)	Fiducial vol. (kton)	# of PMTs	Energy thr.(MeV)
SK-I	1996.4 ~ 2001.7	1496	22.5	11146 (40%)	4.5
SK-II	2002.10 ~ 2005.10	791		5182 (20%)	6.5
SK-III	2006.7 ~ 2008.8	548	22.5 (>5.5MeV) 13.3 (<5.5MeV)	11129 (40%)	4.5
SK-IV	2008.9 ~	1669	22.5 (>5.5MeV) 13.3 (4.5<E<5.5) 8.8 (<4.5MeV)		**3.5**

(coverage) (Kinetic energy)

Main neutrino sources used in Super-K



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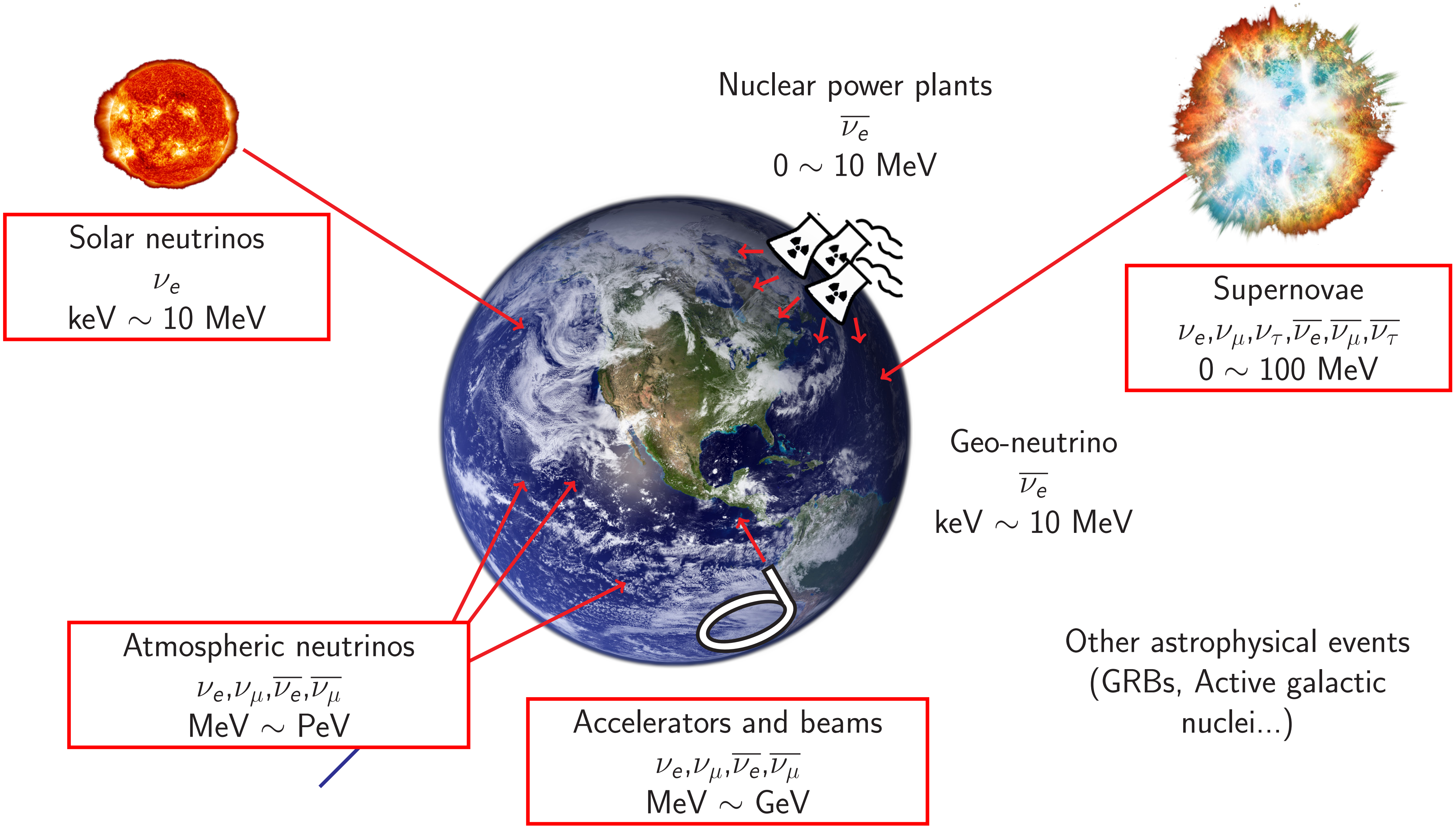

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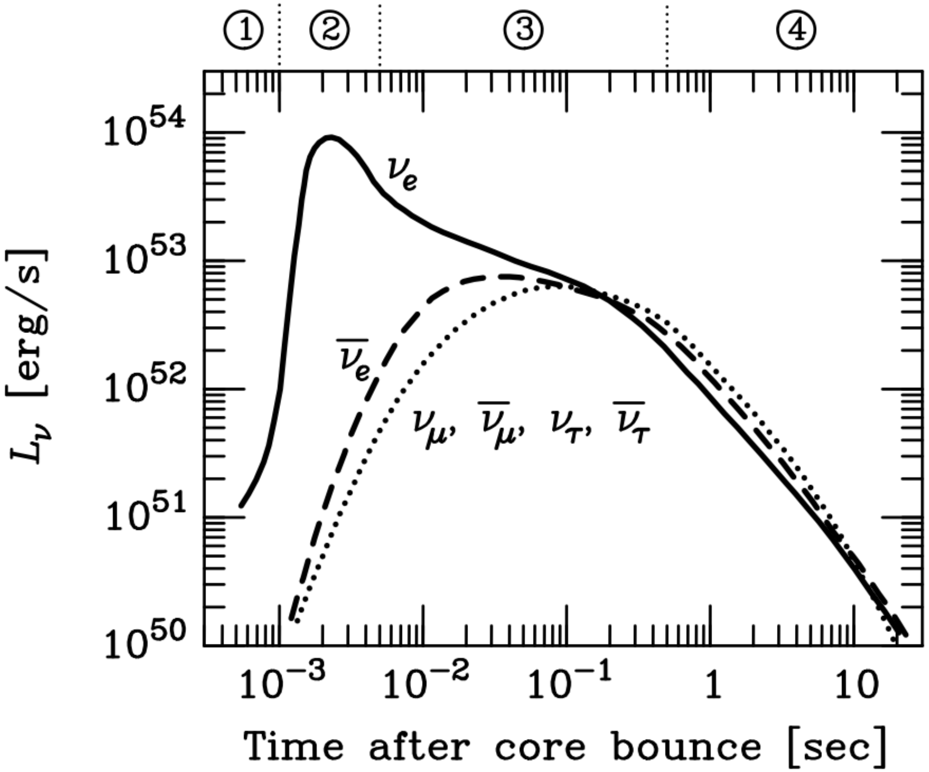
nuclei...)

Supernova Neutrinos

Supernovae neutrino

- Core-collapse supernovae occur when massive stars burned all their combustibles (Helium, Carbon, Neon, Oxygen and Silicon)
  - ν_e are produced through electron-capture on nuclei and release the energy of the incoming supernova (1)
  - High density of ν_e leads ν_e to have continuous interactions with e^- (2):
    - Build up of a degenerate ν sea, producing all the 6 types of ν and $\overline{\nu}$
- More than 99% of the supernova energy is released by ν

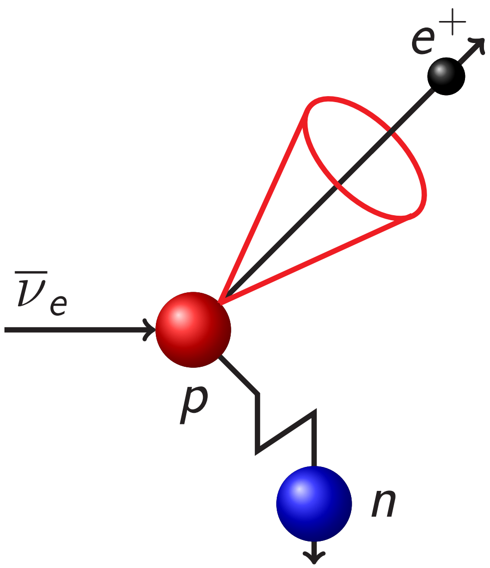


G. G. Raffelt, "Stars as laboratories for fundamental physics" (University of Chicago Press, 1996)

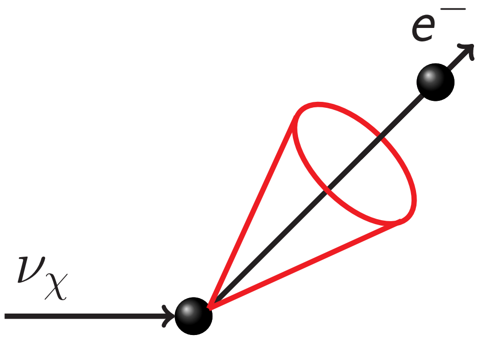
How Supernovae neutrino would be detected in Super-K?

- Due to interaction cross-sections and neutrino energies, a water Cerenkov detector will not detect ν in the same proportions than their production:

$\sim$ 88% will be $\overline{\nu}_e$ via Inverse β Decay (IBD)



$\sim$ 3% will be ν_χ through elastic scattering



When will we detect them?

Last galactic supernova was SN1987A whose neutrinos were detected by Kamiokande II, IMB and Baksan

With a rate of about 1 galactic supernova / 30 years (model dependent), the next one can be expected in the next decades

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However:

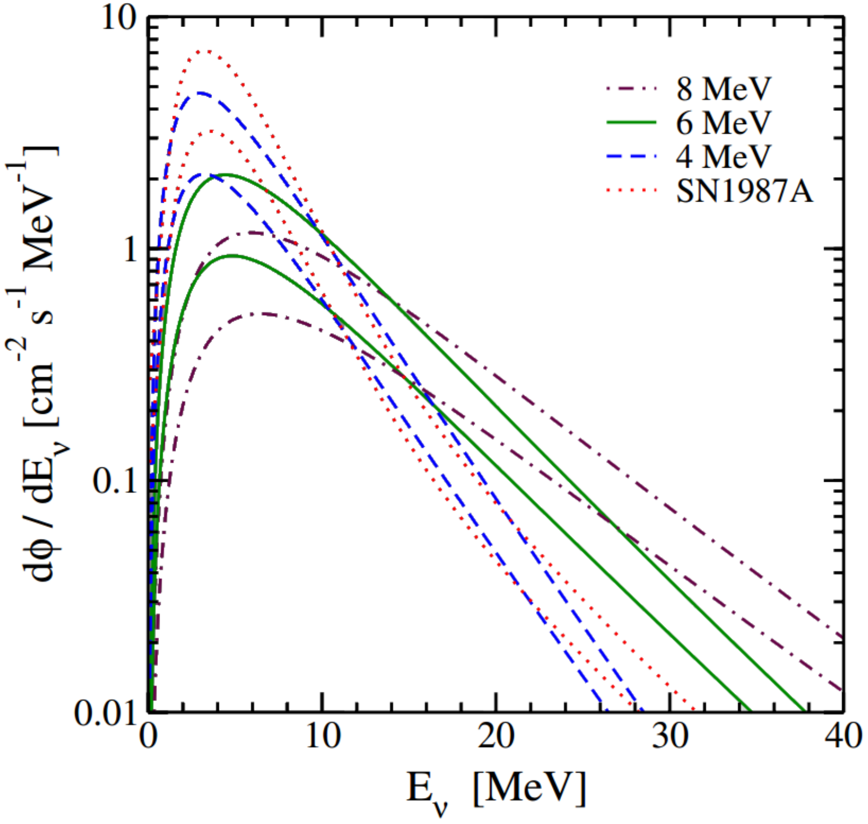
$\sim 10^{11}$ stars/galaxy $\times 10^{11}$ galaxies $\times 0.3\%$ (chance to become SNe)
$\rightarrow \sim \mathcal{O}(10^{19})$ SNe in the universe past

→ We could look at the neutrinos produced by these **past Supernovae**

Supernova Relic Neutrino

- Neutrinos from past SNe are called the "Diffuse Supernova Neutrino Background" or **"Supernova Relic Neutrino"** (SRN)
- Predicted in 1984 by L. M. Krauss, S. L. Glashow and D. N. Schramm

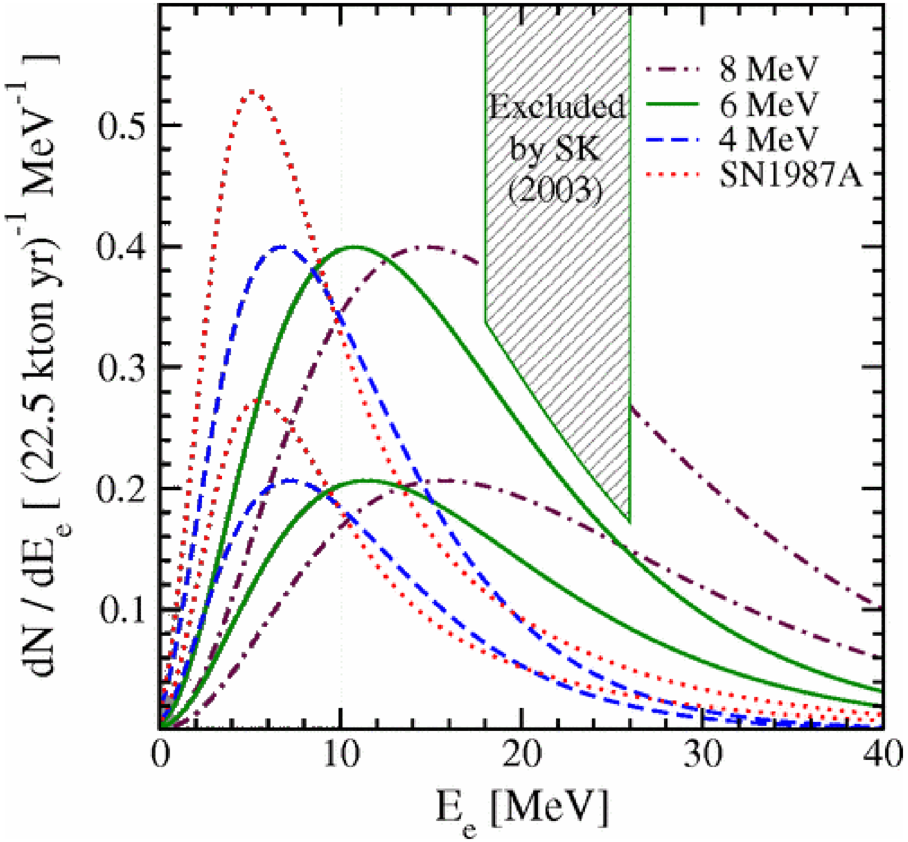
  Nature 310, 191 (1984)
- Theoretical flux prediction : $0.3 \sim 1.5$ /cm^2/s (17.3MeV threshold)



from Phys Rev D 79 083013 (2009)

T_{eff} effective temperature of the SN neutrino flux

SRN analysis in Super-K



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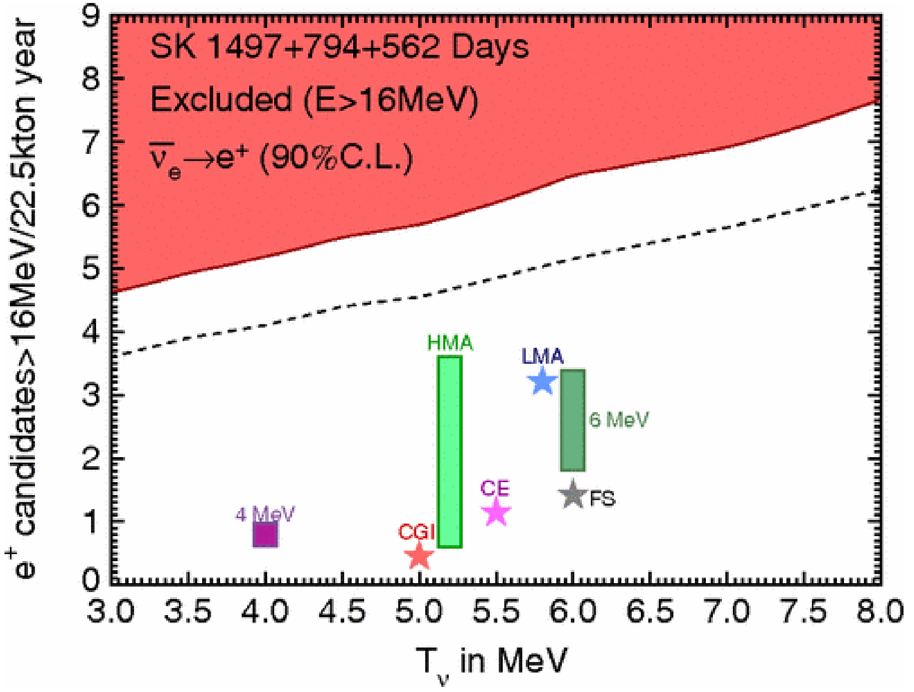
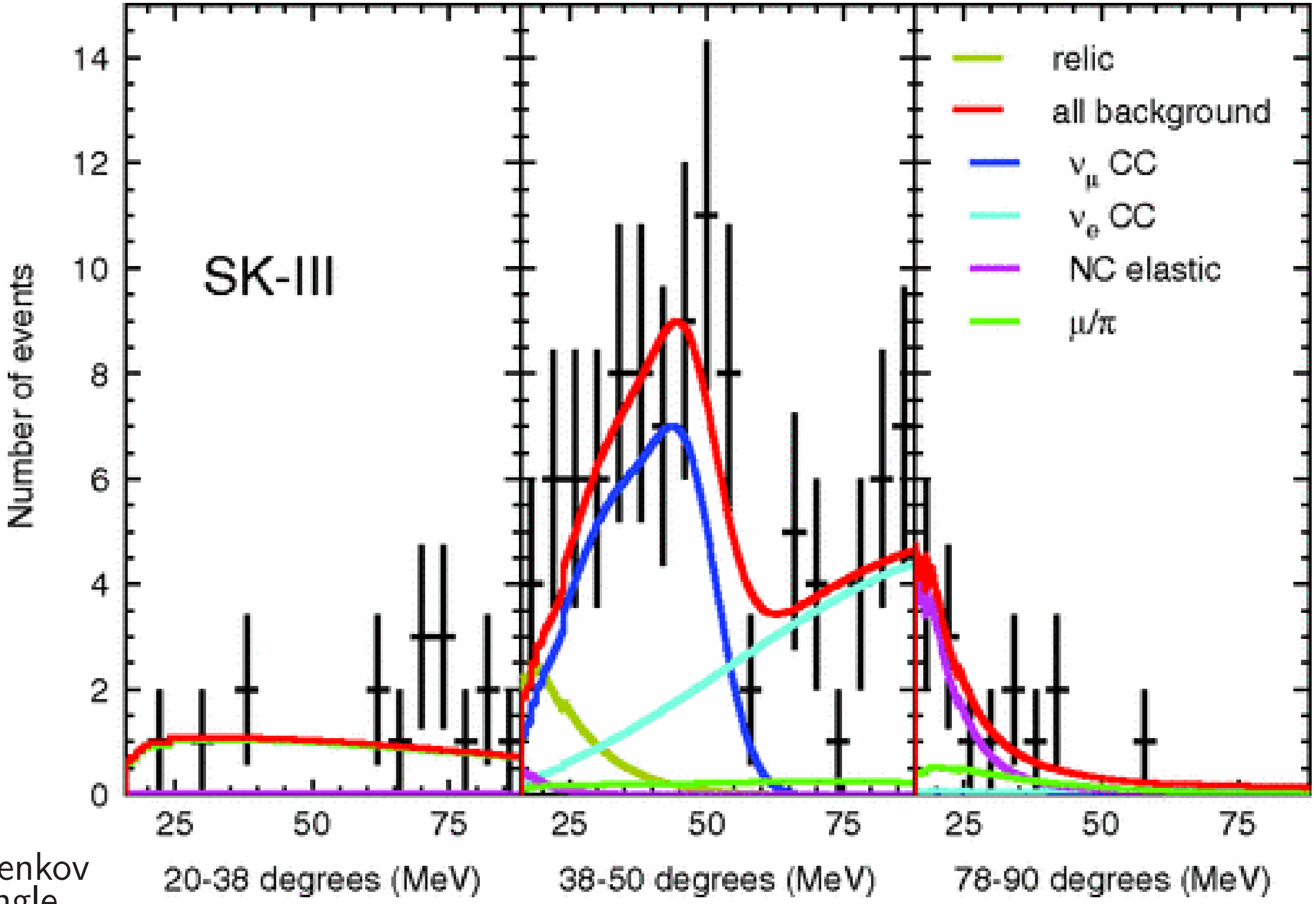


from Phys Rev D 85 052007 (2012)

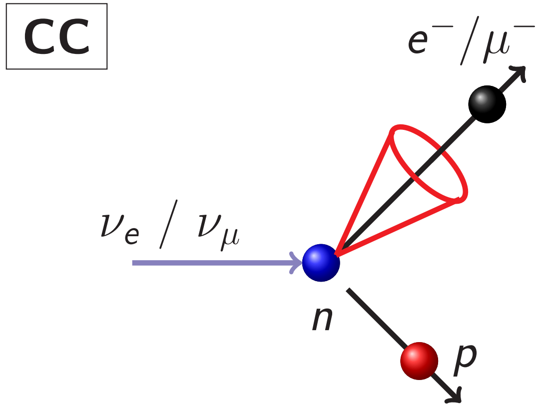
Super-K already performed several SRN analyses and set the **current best limits** on the SRN flux

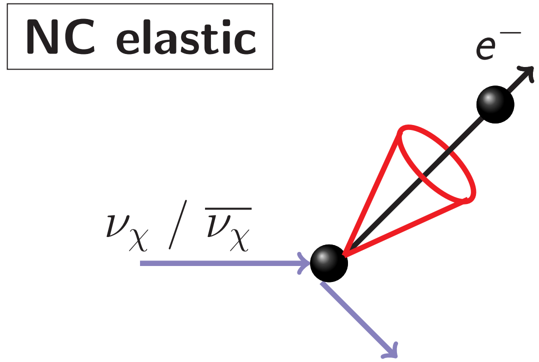
SRN analysis in Super-K: Backgrounds

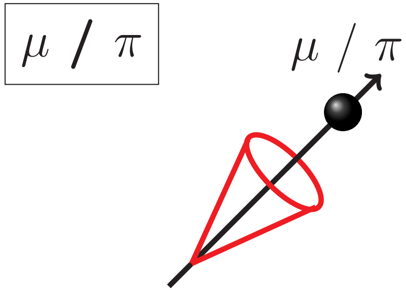


Cerenkov angle

from Phys Rev D 85 052007 (2012)





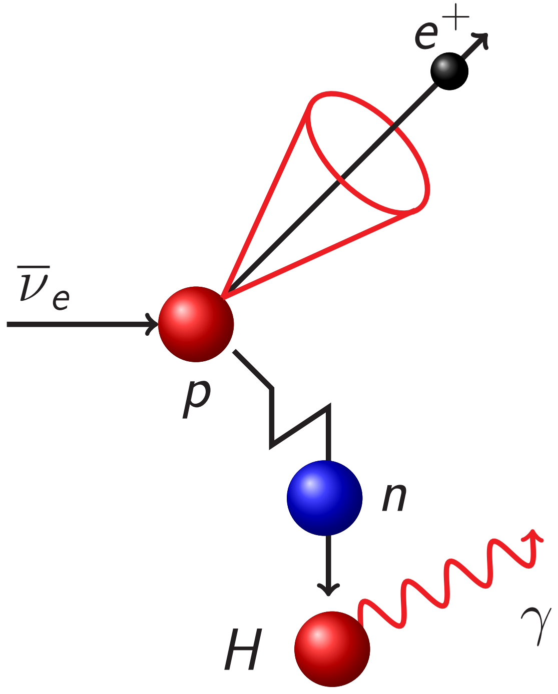


SRN analysis limited by BGs

Most BGs don't produce neutrons → neutron tagging for BG rejection

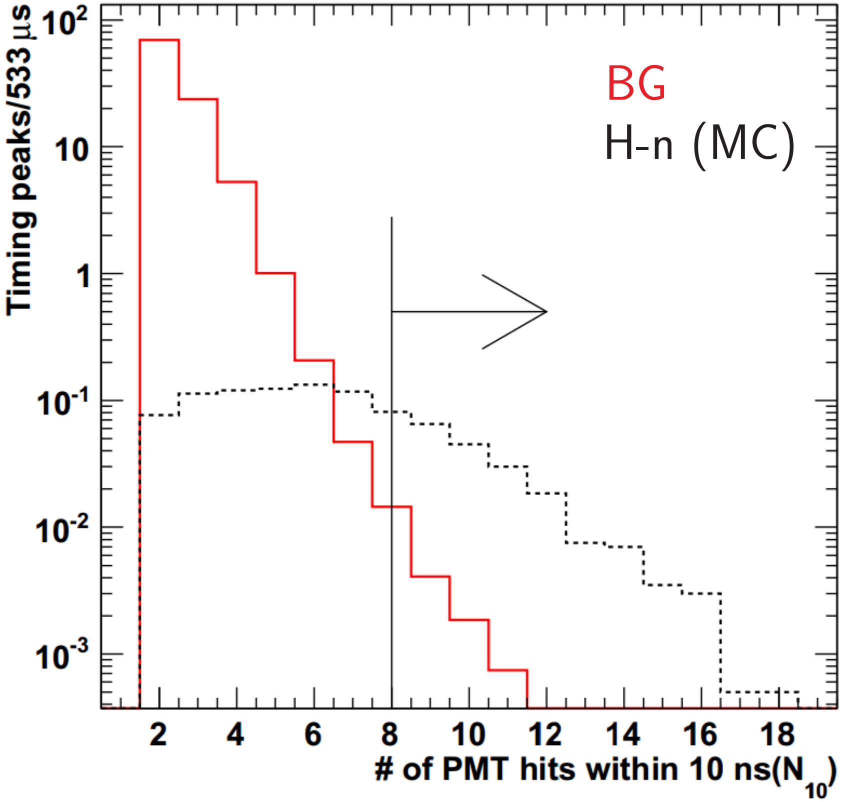
Neutron tag in Super-K: Hydrogen neutron capture

Neutron tagging analysis with Hydrogen neutron captures



H-n capture: only one γ of 2.2 MeV

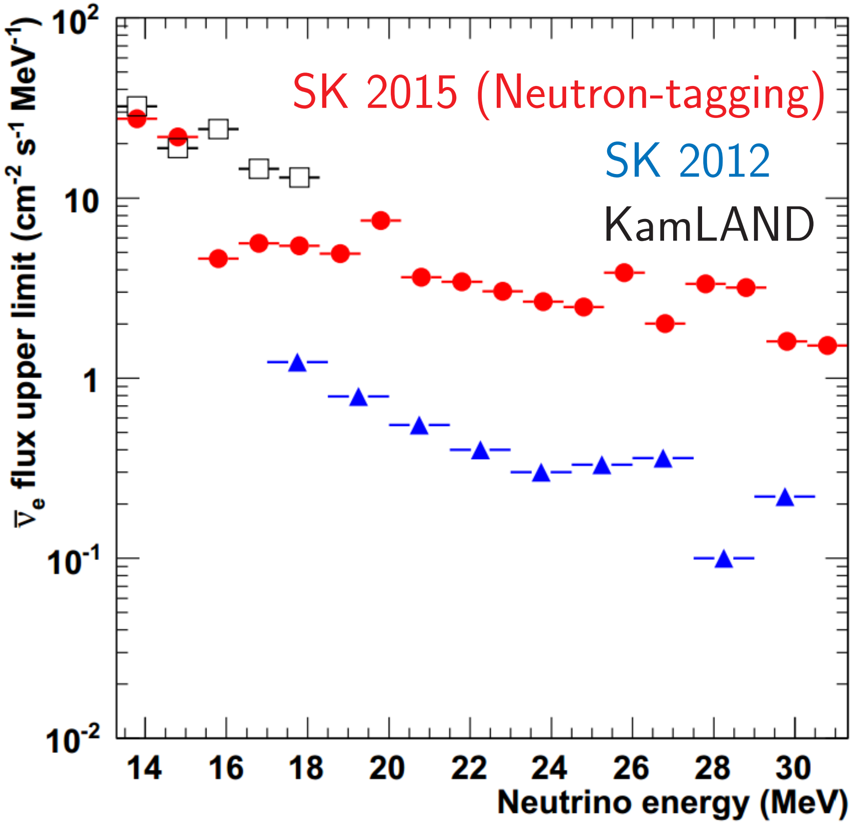
- Huge accidental background
- Spatial reconstruction difficult



from Astropart. Phys. 60, 41 (2015)

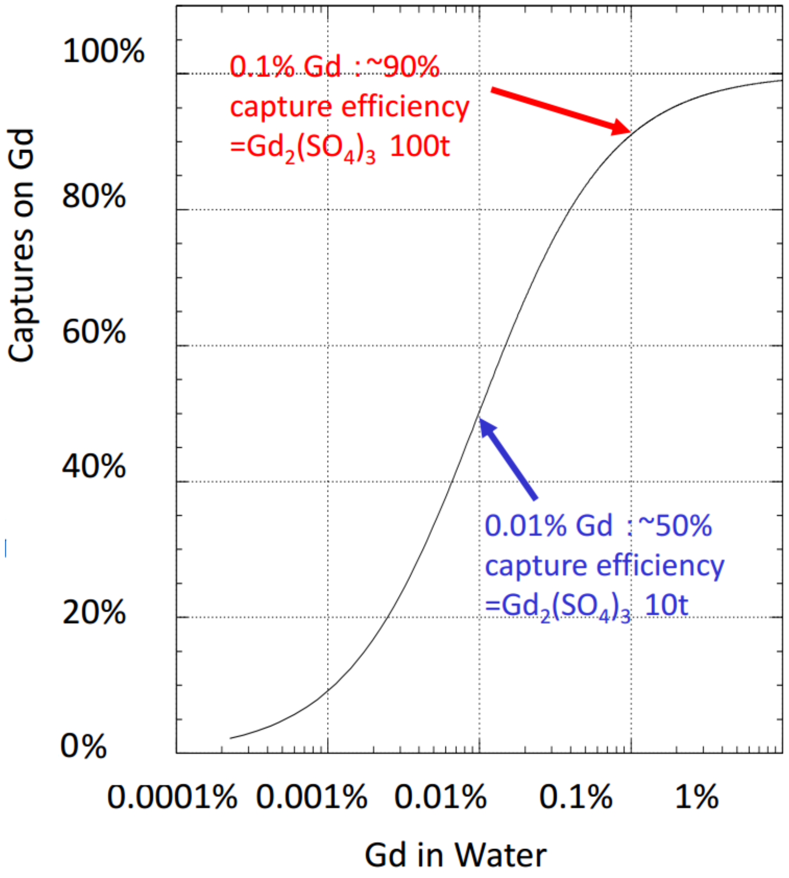
Neutron tag in Super-K: Hydrogen neutron capture

- H-n allowed to reduce the SRN analysis threshold from 17.3 MeV to 13.3 MeV
- H-n allows only a ∼ 20% neutron tagging efficiency
  - Poor statistics
    → No improvement of the SRN limits



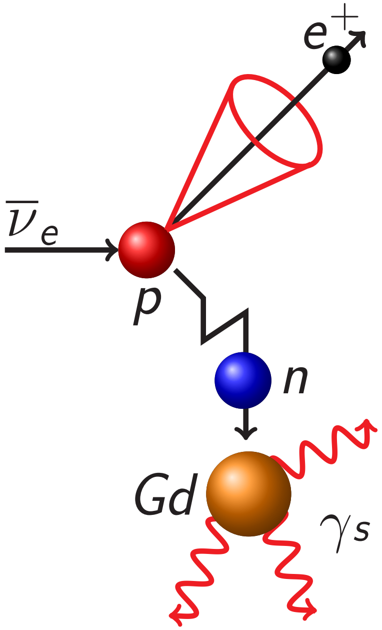
from Astropart. Phys. 60, 41 (2015)

Gd in Super-K water: improved neutron tagging

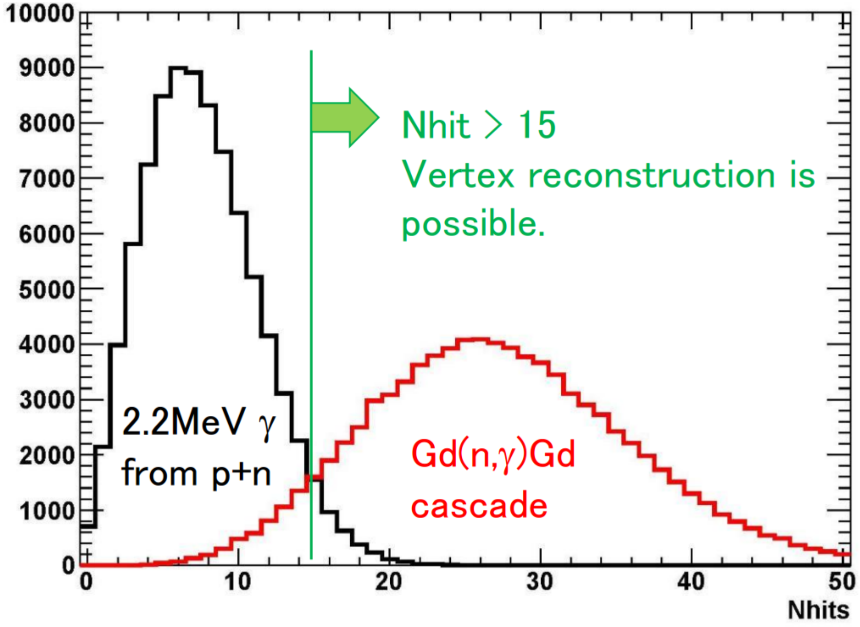


0.1% Gd :~90% capture efficiency =$Gd_2(SO_4)_3$ 100t

0.01% Gd :~50% capture efficiency =$Gd_2(SO_4)_3$ 10t



Number of hit PMT (Nhit) distributions

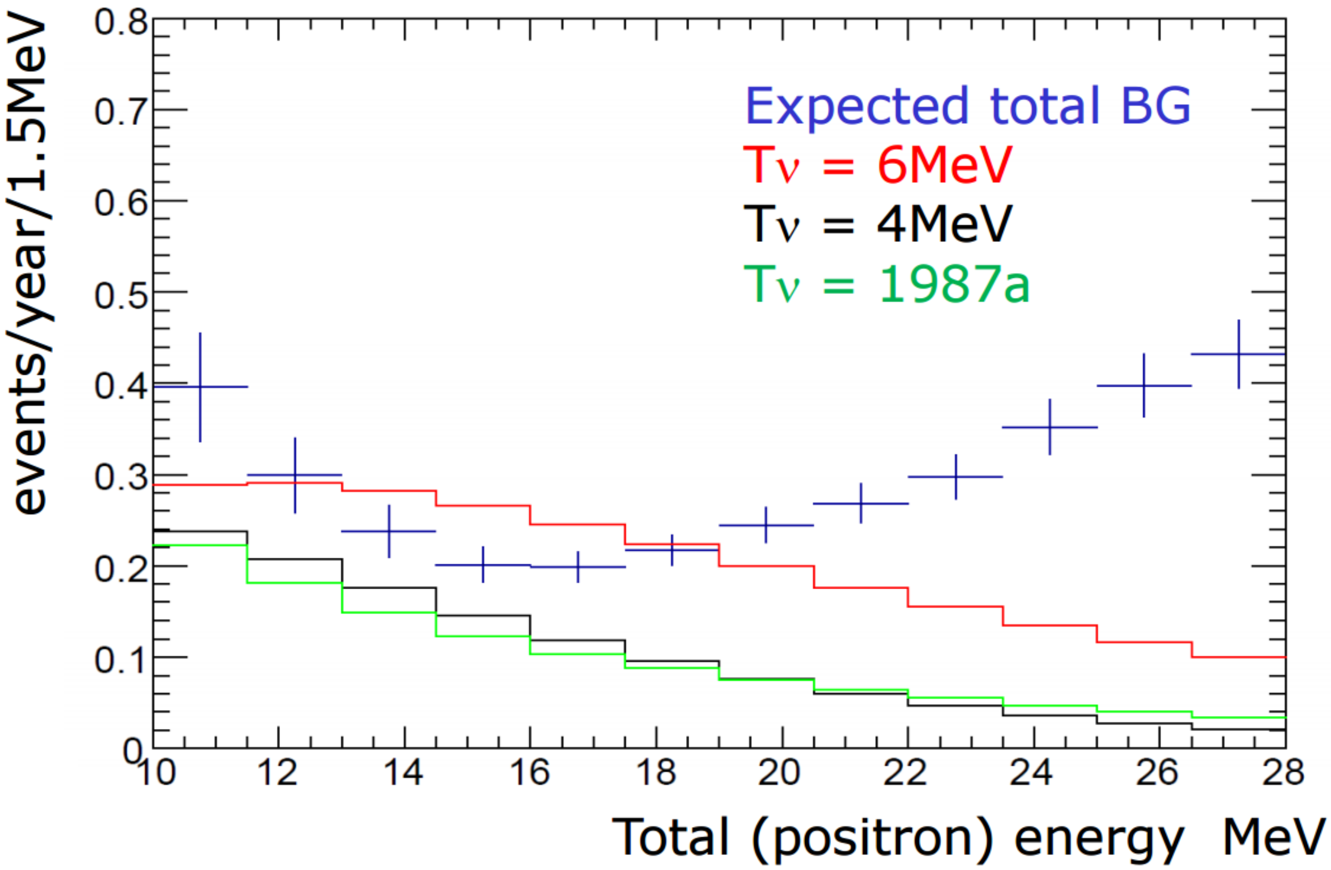


Nhit > 15
Vertex reconstruction is possible.

- Proposed in 2004 by Beacom and Vagins

  PRL93,171101 (2004)
- $\sim$ 90% capture efficiency with 0.1% Gd
- Gd-n: γ cascade (total E $\sim$ 8 MeV)
  - $\sim$ 80% of neutron tagging efficiency

SRN expectation with Gd in 10 years



Dependance on the typical SN emission spectrum

HDB*	10-16 MeV	16-28 MeV	Total	significance
T_{eff} 8 MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6 MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4 MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987A	5.1	6.8	11.9	2.1 σ
BG	10	24	34	–

In events/10years

Significance is determined with 2 energy bins

* Horiuchi, Beacom and Dwek, Phys Rev D 79 083013 (2009)

Physics targets of Gd-loading

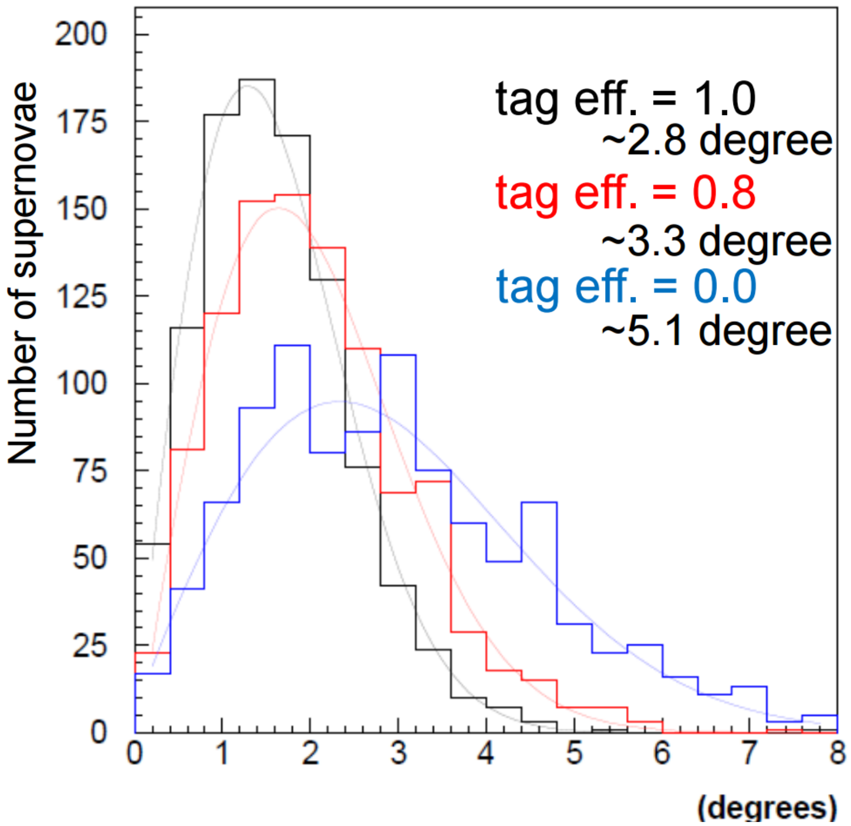
- Main target of Gd-loading: Detection of Supernova relic neutrino (SRN)

Gd-neutron tagging can lead to other analysis improvements / possibilities:

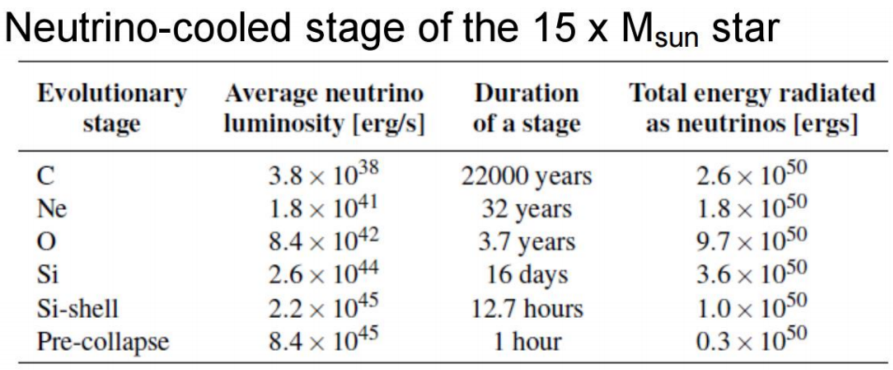
- Improvement of the pointing accuracy for galactic supernova
- Detection of pre-Supernova Si-burning neutrinos
- Reduction of the proton decay background
- Neutrino/anti-neutrino discrimination (Long-baseline and atmospheric ν)
- Other like detection of reactor neutrinos, black hole formation, etc.

Physics target: Improvement of the pointing accuracy for galactic supernova

- ν_e elastic scattering provide good directionality indication
- Currently, SN direction can be determined with an accuracy of $4 \sim 5$ degree.
- Neutron tagging allow to separate ν_e and $\overline{\nu}_e$ signals
  $\rightarrow$ Improvement of the directionality accuracy



Physics target: Detection of pre-Supernova Si-burning neutrinos

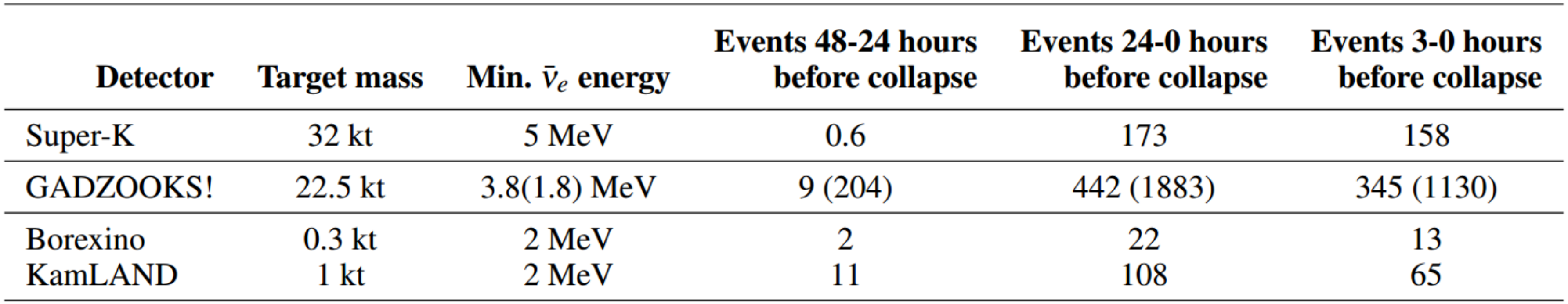


Neutrino-cooled stage of the 15 x M_{sun} star

Evolutionary stage	Average neutrino luminosity [erg/s]	Duration of a stage	Total energy radiated as neutrinos [ergs]
C	3.8×10^{38}	22000 years	2.6×10^{50}
Ne	1.8×10^{41}	32 years	1.8×10^{50}
O	8.4×10^{42}	3.7 years	9.7×10^{50}
Si	2.6×10^{44}	16 days	3.6×10^{50}
Si-shell	2.2×10^{45}	12.7 hours	1.0×10^{50}
Pre-collapse	8.4×10^{45}	1 hour	0.3×10^{50}

- During the Si-burning phase, massive star emits ν-$\overline{\nu}$ pair to balance the energy production
- Detection of these ν-$\overline{\nu}$ could allow to predict an incoming SN several hours before the neutrino burst

In case of Betelgeuse Supernova:

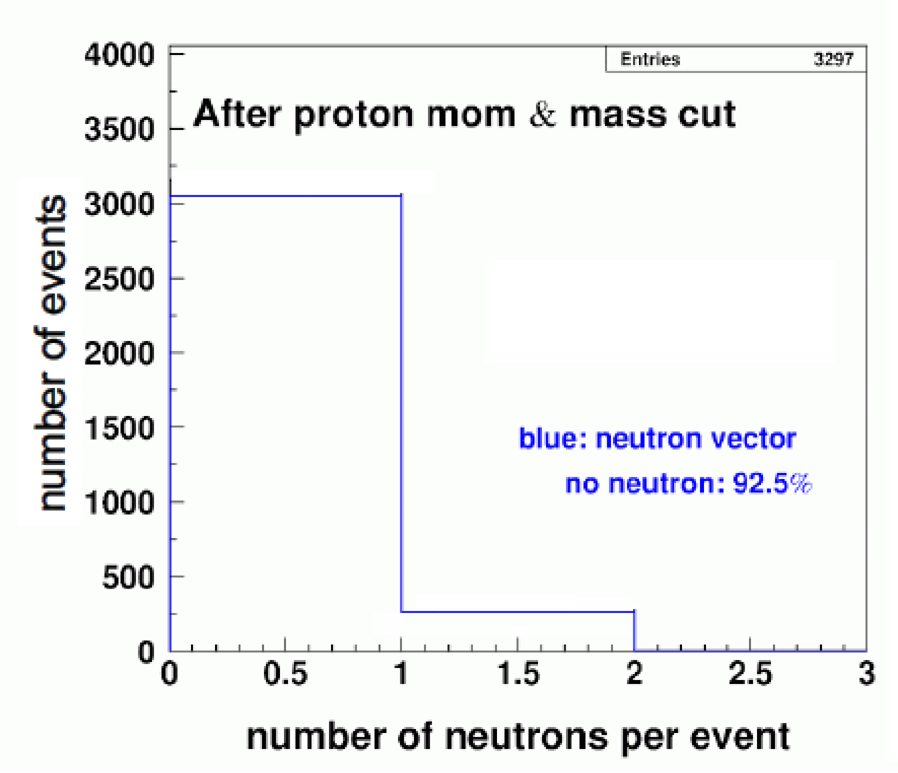


Detector	Target mass	Min. $\bar{\nu}_e$ energy	Events 48-24 hours before collapse	Events 24-0 hours before collapse	Events 3-0 hours before collapse
Super-K	32 kt	5 MeV	0.6	173	158
GADZOOKS!	22.5 kt	3.8(1.8) MeV	9 (204)	442 (1883)	345 (1130)
Borexino	0.3 kt	2 MeV	2	22	13
KamLAND	1 kt	2 MeV	11	108	65

from A. Odrzywolek, M. Misiaszek and M. Kutschera, AIP Conf. Proc. 944, 109 (2007)

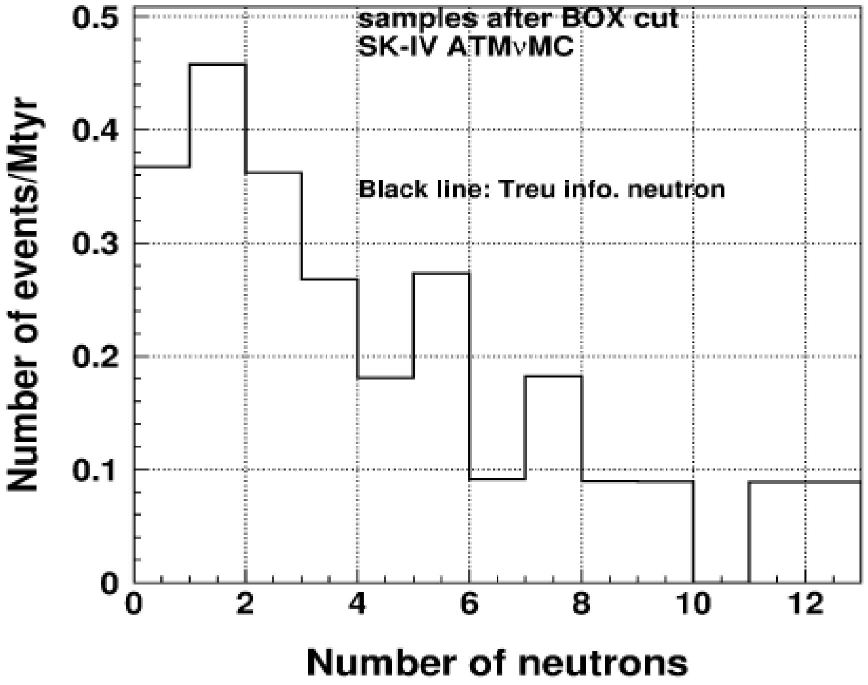
Physics target: Proton Decay

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



92.5% of events without neutron

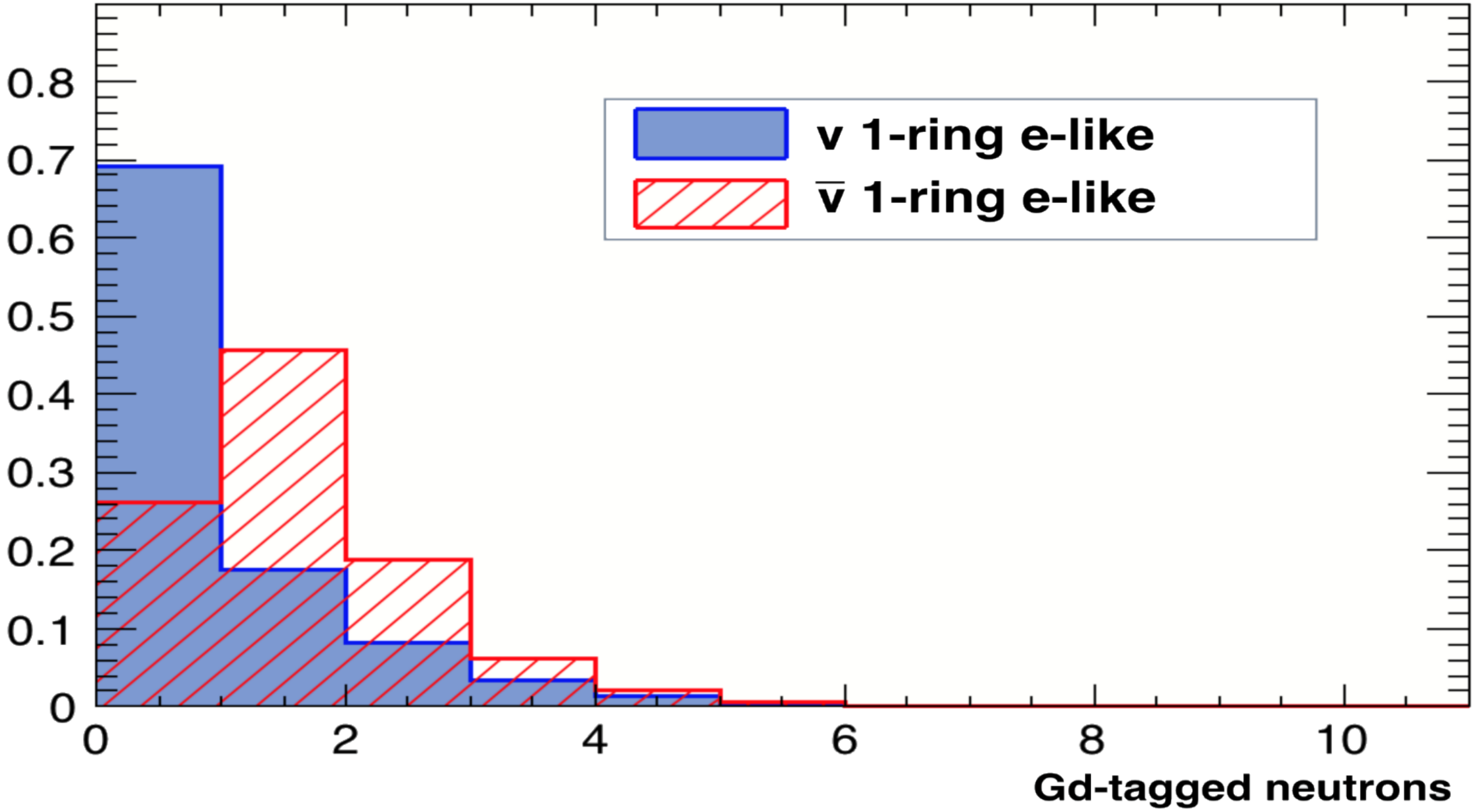
Atmospheric ν BG



Many neutrons accompagning

- Current background level: 0.58 events /10 years
- With neutron tagging: 0.098 events /10 years
- For one event in 10 years the BG probability will decrease from 44% to 9%

Physics target: ν / $\overline{\nu}$ discrimination



Atmospheric neutrino 1-ring e-like sample E $\in [0.5; 0.7]$ GeV

- Gd neutron tagging allow a $\overline{\nu}_e$ ID with $\sim$ 70% of efficiency (30% ν_e miss-ID)

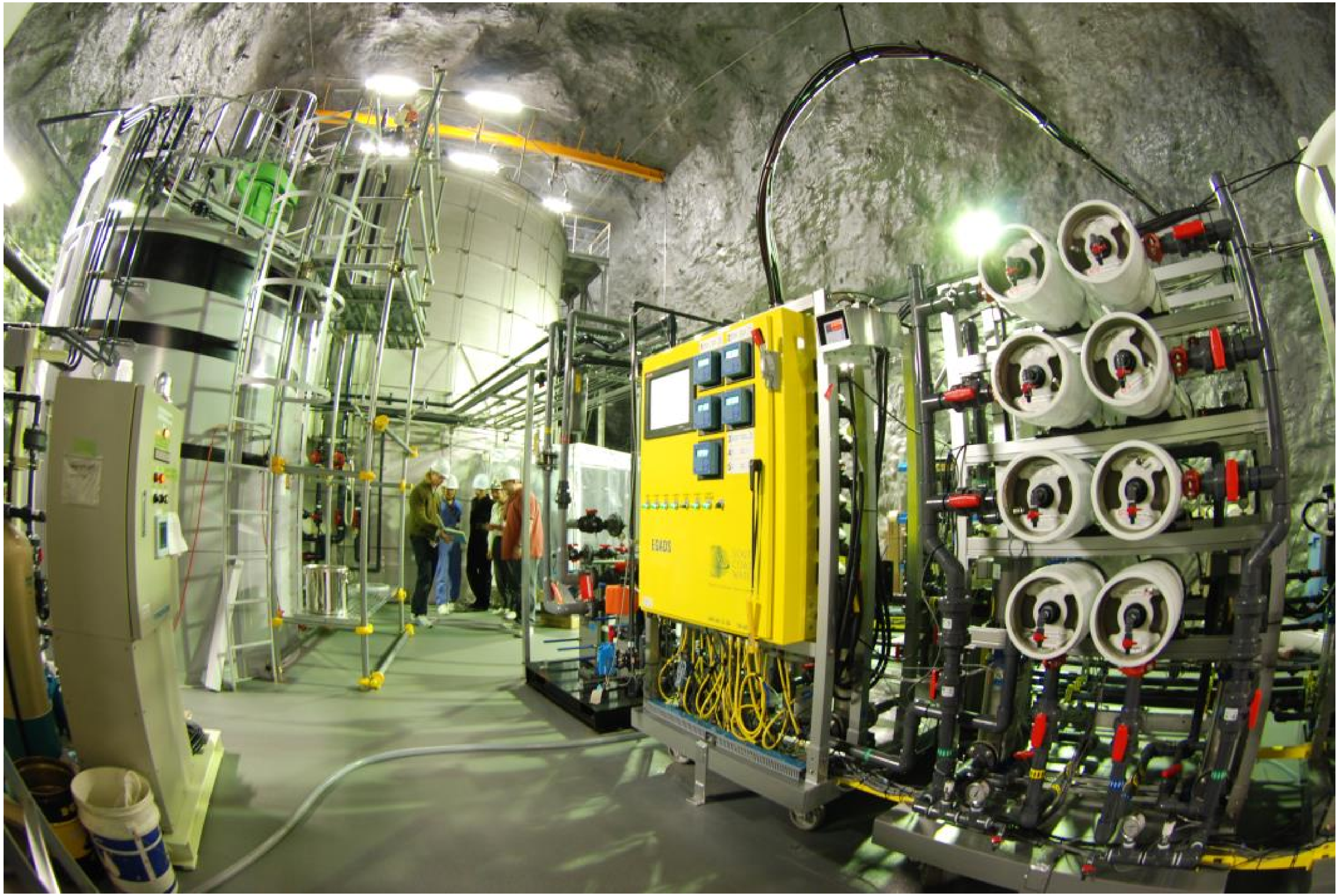
What do we need before putting Gd in Super-K?

- Keep Gd water transparency at a similar level than current SK water transparency
- Study the effect of Gd on the detector materials
- Study the effect of Gd on the physics analysis
- Fix the leaks in the detector

To perform these studies, we have build of a SK-Gd prototype: EGADS

EGADS

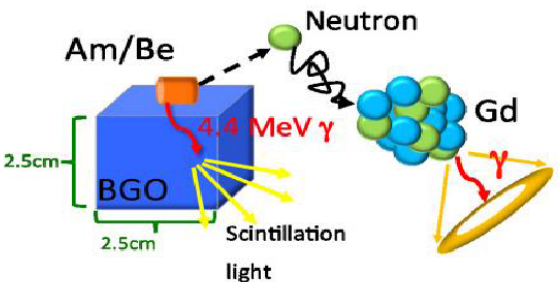
Evaluating **G**adolinium's **A**ction on **D**etector **S**ystems



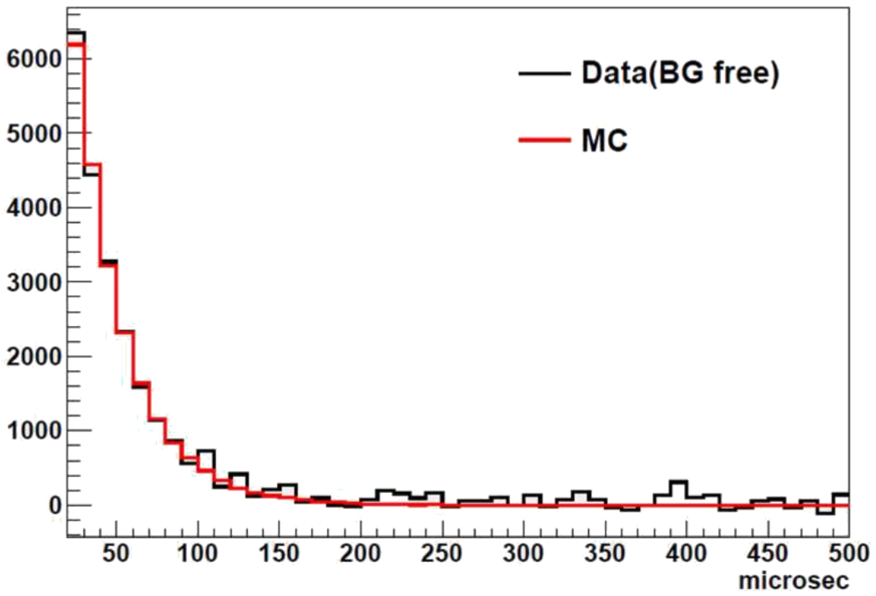
EGADS Detector

- 200 m^3 tank
- 240 PMTs
- Main goal is to test SK materials behavior in Gd water:
  - The detector fully mimics SK:
    Same stainless steel frame, PMTs and PMT cases, black sheets, etc.
- Detector completed in 2013
- Gd was progressively added in the water from November 2014 to May 2015

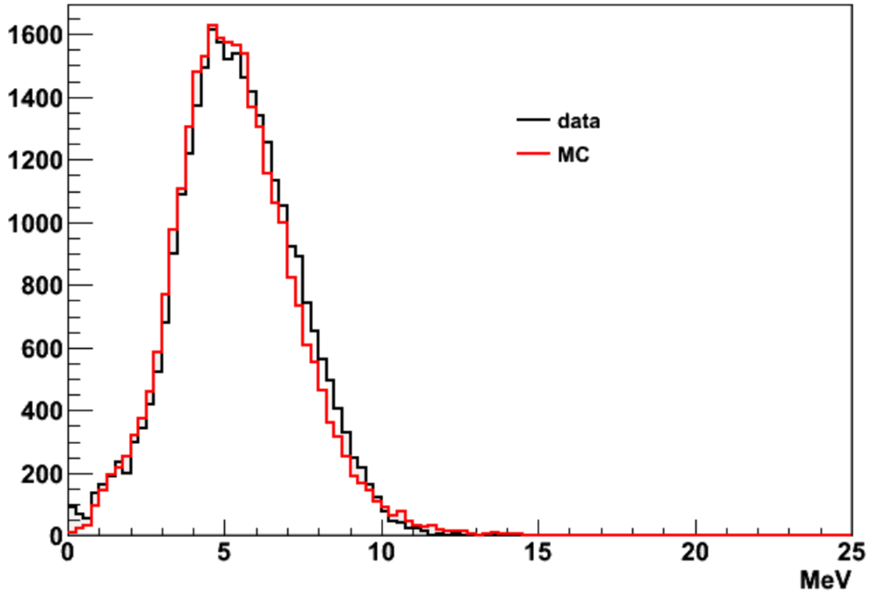
Gd-neutron tagging confirmation



Prompt-delayed Δt



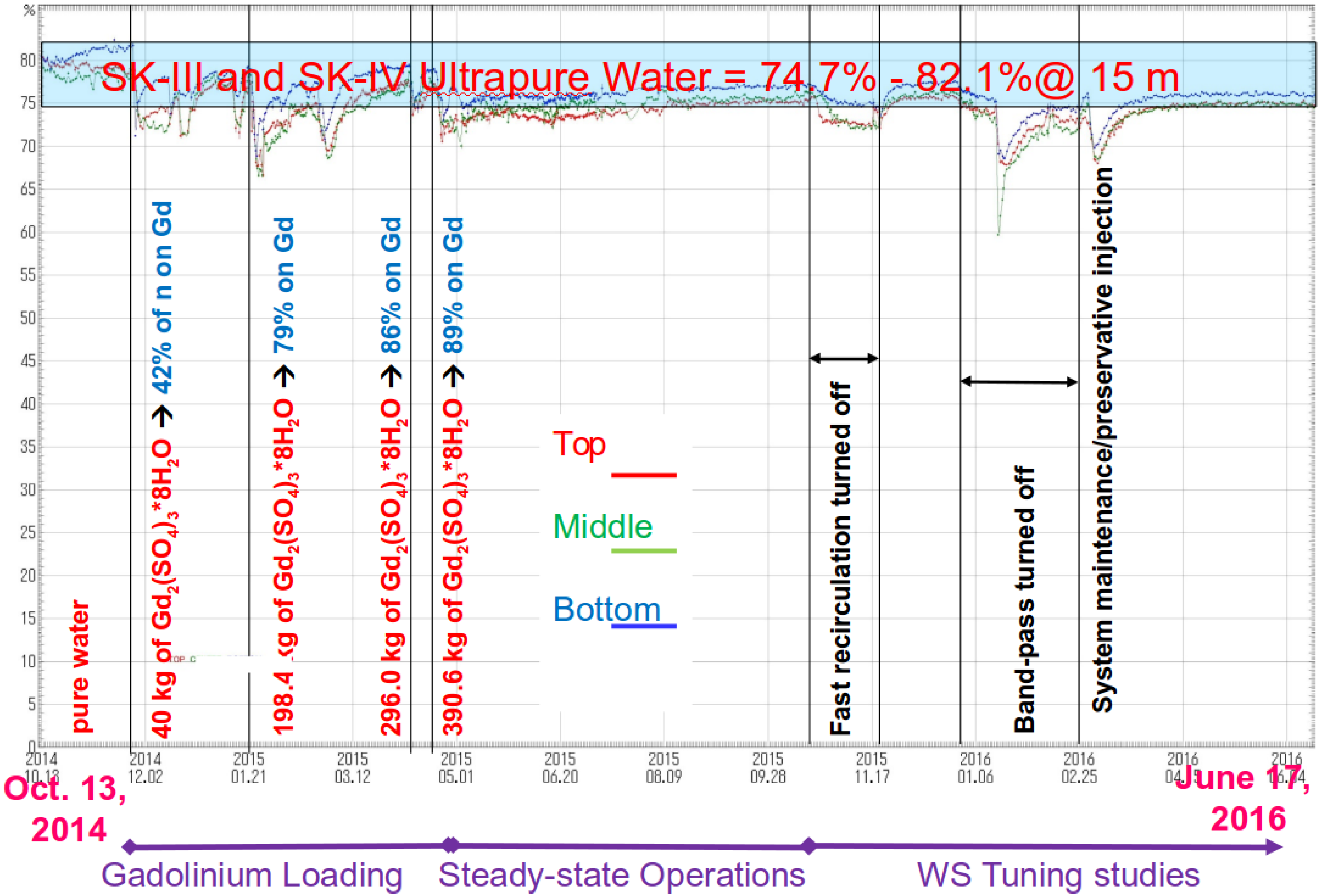
Delayed E



- Mean Prompt-delayed Δt:
  $\Delta t = 29.89 \pm 0.33\ \mu$s (Data)
  $\Delta t = 30.05 \pm 1.14\ \mu$s (MC)

- Confirmation that we are seeing Gd neutron capture

EGADS transparency



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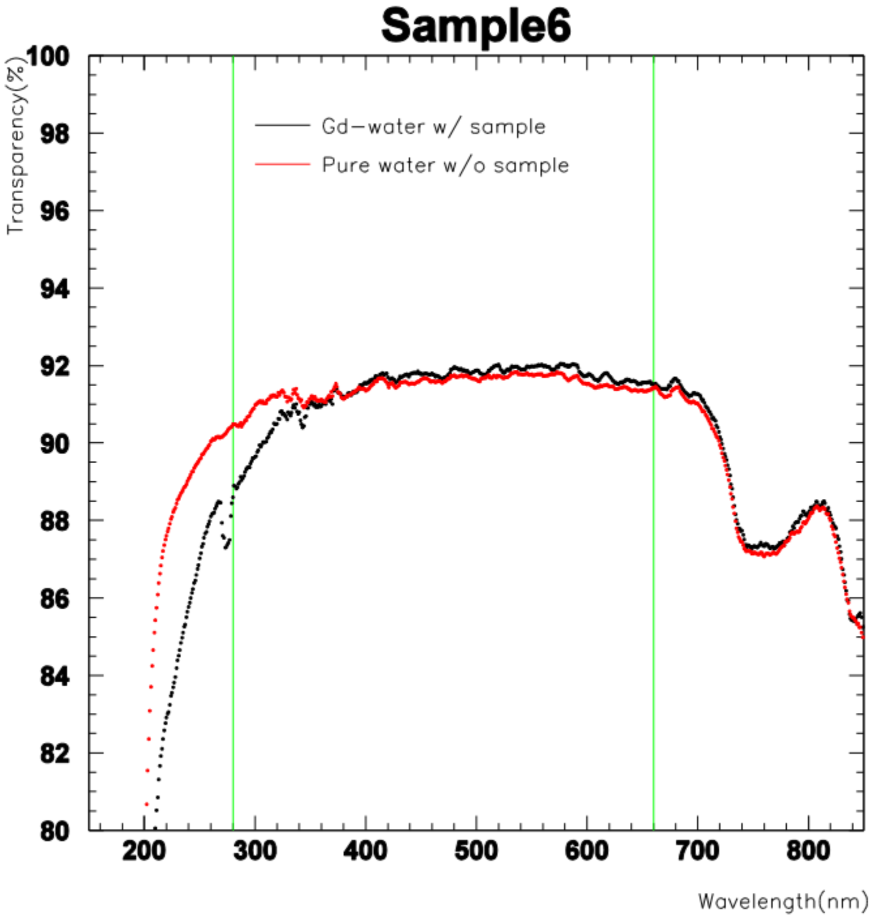
- Fix the leaks in the detector

Tests of materials behavior in Gd water

- Each materials used in Super-K have been soaked in Gd water
- Soaking time $\sim$ 3 months
- Transparency measurement with a spectrometer at different time interval
- Effect of material on the transparency found to be negligible
  - Transparency with material sample determined to be $> 90\%$ for almost all materials
  - Except for rubber... but it is used in EGADS without trouble and also demonstrated the same impact on transparency in pure water



ID PMT end-cap

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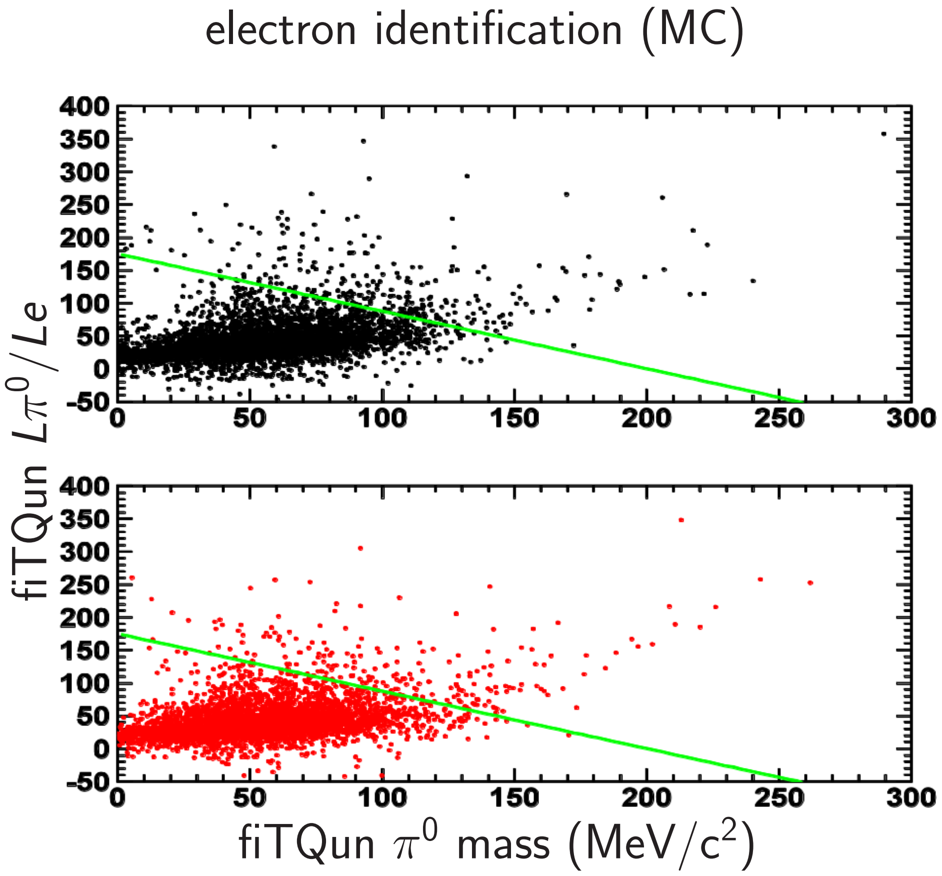
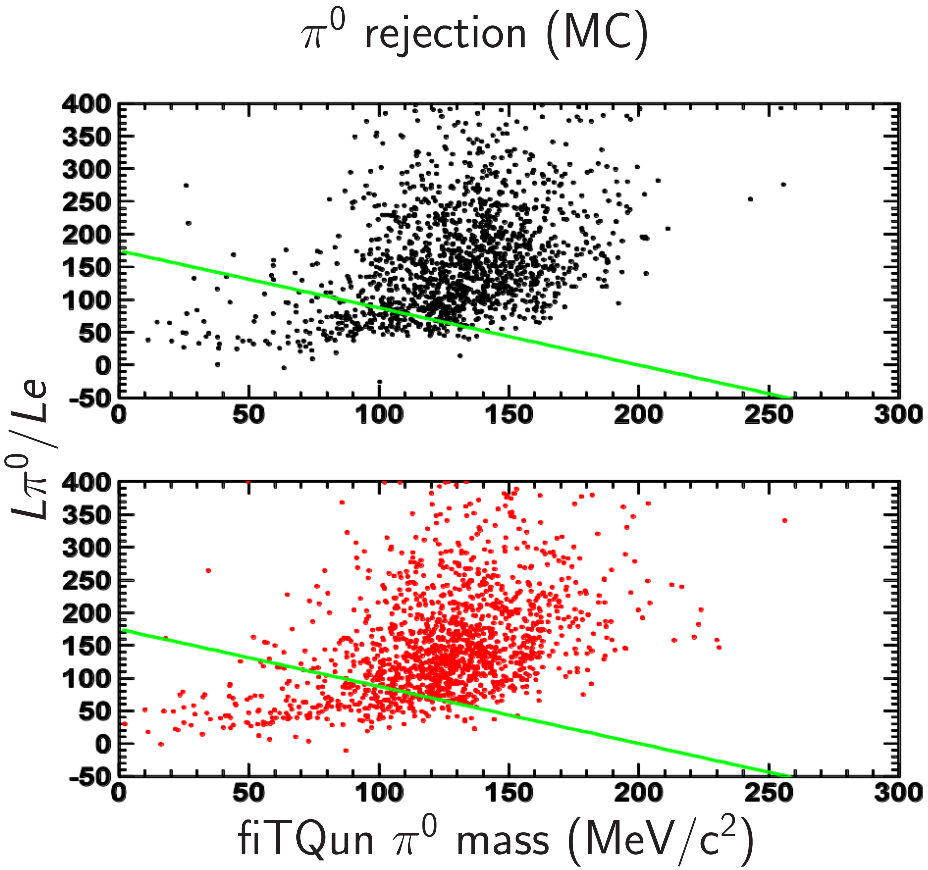
Effects on Physics Analysis: High Energy I


electron identification (MC)


π^0 rejection (MC)

e **MC, detected**			**π^0 MC, remaining**		
true (MeV/c)	**Pure water**	**Gd water**	**true (MeV/c)**	**Pure water**	**Gd water**
250	$92.9 \pm 2.1\%$	$91.9 \pm 2.1\%$	250	$1.7 \pm 0.2\%$	$1.9 \pm 0.2\%$
500	$89.3 \pm 2.0\%$	$88.4 \pm 2.0\%$	500	$4.7 \pm 0.3\%$	$6.1 \pm 0.4\%$
1000	$75.7 \pm 1.8\%$	$77.7 \pm 1.8\%$	1000	$15.8 \pm 0.7\%$	$16.7 \pm 0.7\%$

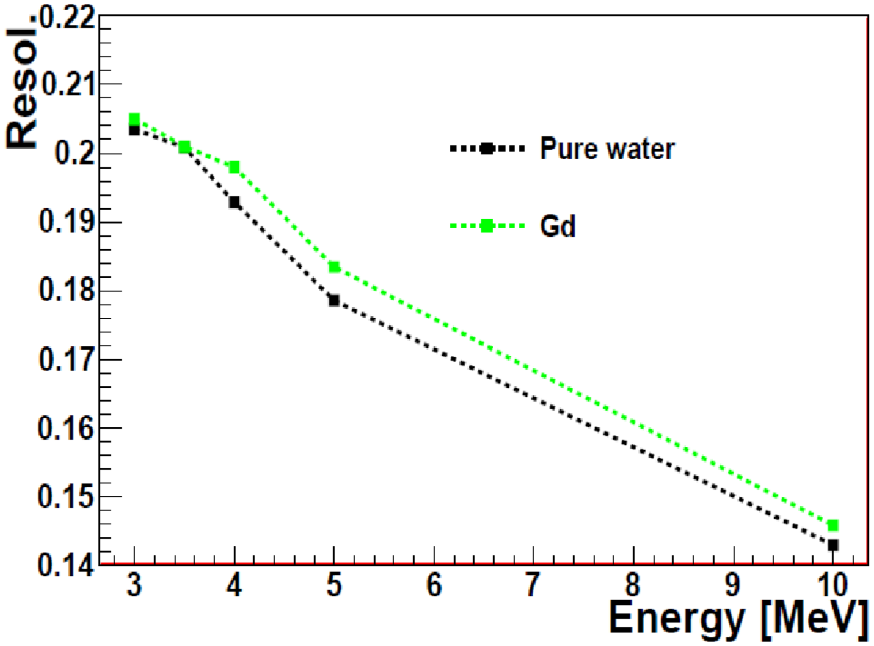
Effects on Physics Analysis: High Energy II

	Pure water	**Gd water**
Momentum resolution		
electron (500 MeV)	4.9%	4.9%
muon (500 MeV)	2.5%	2.5%
Miss-PID		
muon (500 MeV) → e-like	$0.59 \pm 0.12\%$	$1.00 \pm 0.15\%$
π^0 (500 MeV) → 1-ring e	$4.7 \pm 0.3\%$	$6.1 \pm 0.4\%$
Number of T2K events (ν-mode 3.9×10^{21} POT)		
Appearance signal	98.5	97.7
Appearance BG	24.6	25.2
Disappearance signal	622.2	623.8
Disappearance BG	45.6	48.6

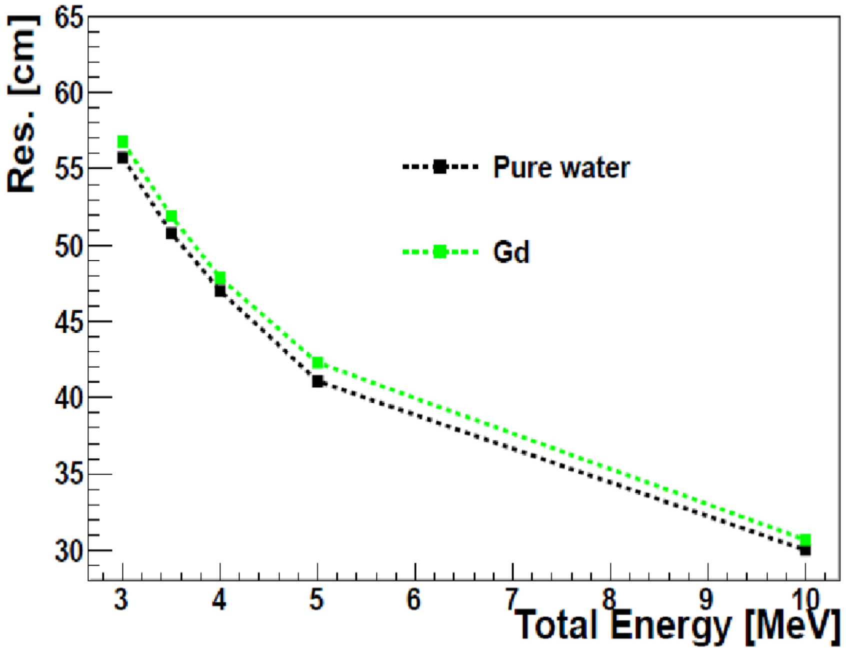
→ Numbers relatively close, except for Miss-PID, impact acceptable

Effects on Physics Analysis: Low Energy

Energy resolution

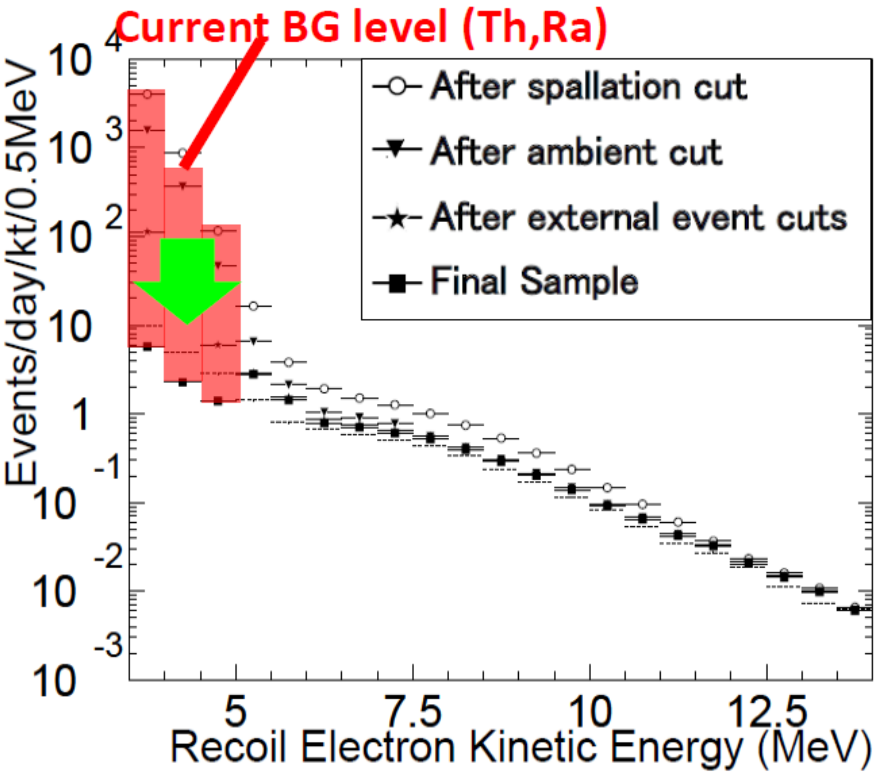


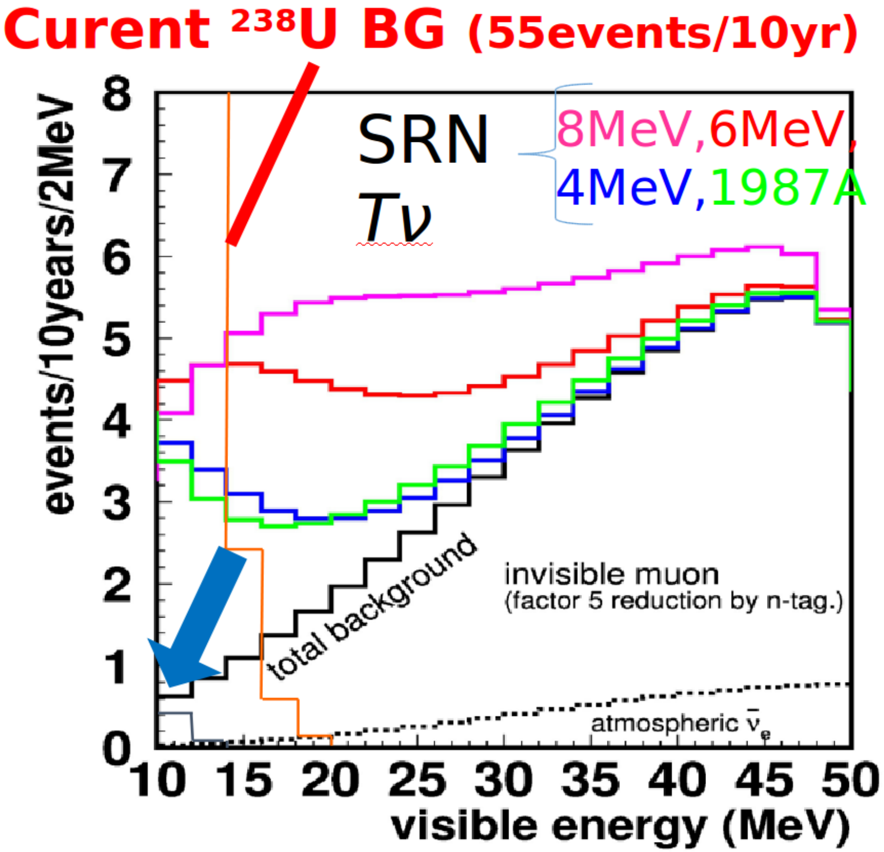
Reconstructed Vertex resolution



- A little worse resolution, but acceptable for the current Low Energy analysis

Impact of the radioactivity on the analysis





Solar neutrino spectrum

Th and Ra are a BG for the solar analysis, dominant below 5 MeV

Spontenous fission will be a BG for the SRN analysis

Removing radioactivity in the Gd powder

Typical $Gd_2(SO_4)_3$ on the market

Chain	Main sub-chain isotope	Radioactive Concentration
^{238}U	^{238}U ^{226}Ra	50 mBq/kg 5 mBq/kg
^{232}Th	^{228}Ra ^{228}Th	10 mBq/kg 100 mBq/kg
^{235}U	^{235}U ^{227}Ac/^{227}Th	32 mBq/kg 300 mBq/kg

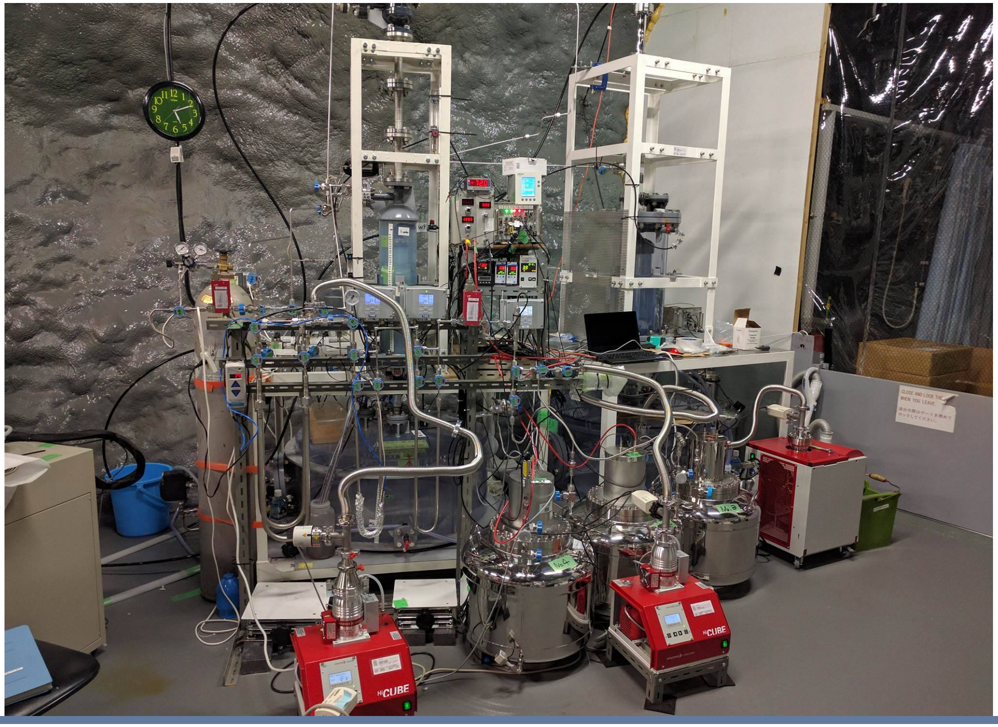
Aim to reduce Th/Ra by 3 orders

Aim to reduce U by 1 order

- Two complementary solutions are investigated:
  - Use ion exchange resine in order to remove the ions like Ra (cation), or U (anion)
  - Work with the companies in order to reduce the contamination in their production method

Removing radioactivity in the Gd powder: Ion exchange resine

- Ion exchange resine:
  - Uranium can be removed using Anion exchange resin AJ4400
  - Ra can be removed by Cation exchange resign, but a special resine need to be developped to remove since Gd is also a cation in the solution (tests ongoing)
- We developped a special setup to measure Ra removal:
  - Using the same technique as Super-K, we can measure Ra by detecting Rn
  - Extract Rn from water in air-gas mixer



Removing radioactivity in the Gd powder: Work with companies

Chain	Main sub-chain isotope	Typical $Gd_2(SO_4)_3$	$Gd_2(O_3)$ L236	$Gd_2(O_3)$ 201512	$Gd_2(SO_4)_3$ 201512	$Gd_2(SO_4)_3$ 201508
^{238}U	^{238}U	50	< 317	< 280	< 139	< 37
	^{226}Ra	5	< 8.9	< 4	< 2.1	< 0.8
^{232}Th	^{228}Ra	10	< 4.39	< 10	2.8 ± 1.9	< 1.1
	^{228}Th	100		< 9	1.8 ± 0.9	2.0 ± 0.5
^{235}U	^{235}U	32	< 52.2	< 7	< 2.4	< 0.6
	$^{227}Ac/^{227}Th$	300		< 11	< 10	11 ± 4
Other	^{40}K		< 44.6	< 11	< 14	< 3
	^{137}Cs		< 1.85	< 0.8	< 0.9	2.6 ± 0.3

Work on-going, radioactivity level seems close to reach our requirement

What do we need before putting Gd in Super-K?

- Keep Gd water transparency at a similar level than current SK water transparency ✓
- Study the effect of Gd on the detector materials ✓
- Study the effect of Gd on the physics analysis ✓
- Reduction of the radioactive background in the Gd powder → On-going (Affect only the low energy analysis)
- Fix the leaks in the detector

Leaks fix I

- We need to minimize the rejection of Gd in the environment
- Since there is no legislation for Gd rejection, we took the worst case: Mercury
- Reducing the current leak flow by a factor 10 should allow to reach the worst effluent rejection standards

	In front of SK (4.59t/min)	**Jinzu River (163.6t/sec)**
Hg standard	Effluent 5 ppb	Environmental 500 ppt
Current leak	30 ppb	10 ppt
1/10 leak	3 ppb	1 ppt

Leaks fix II

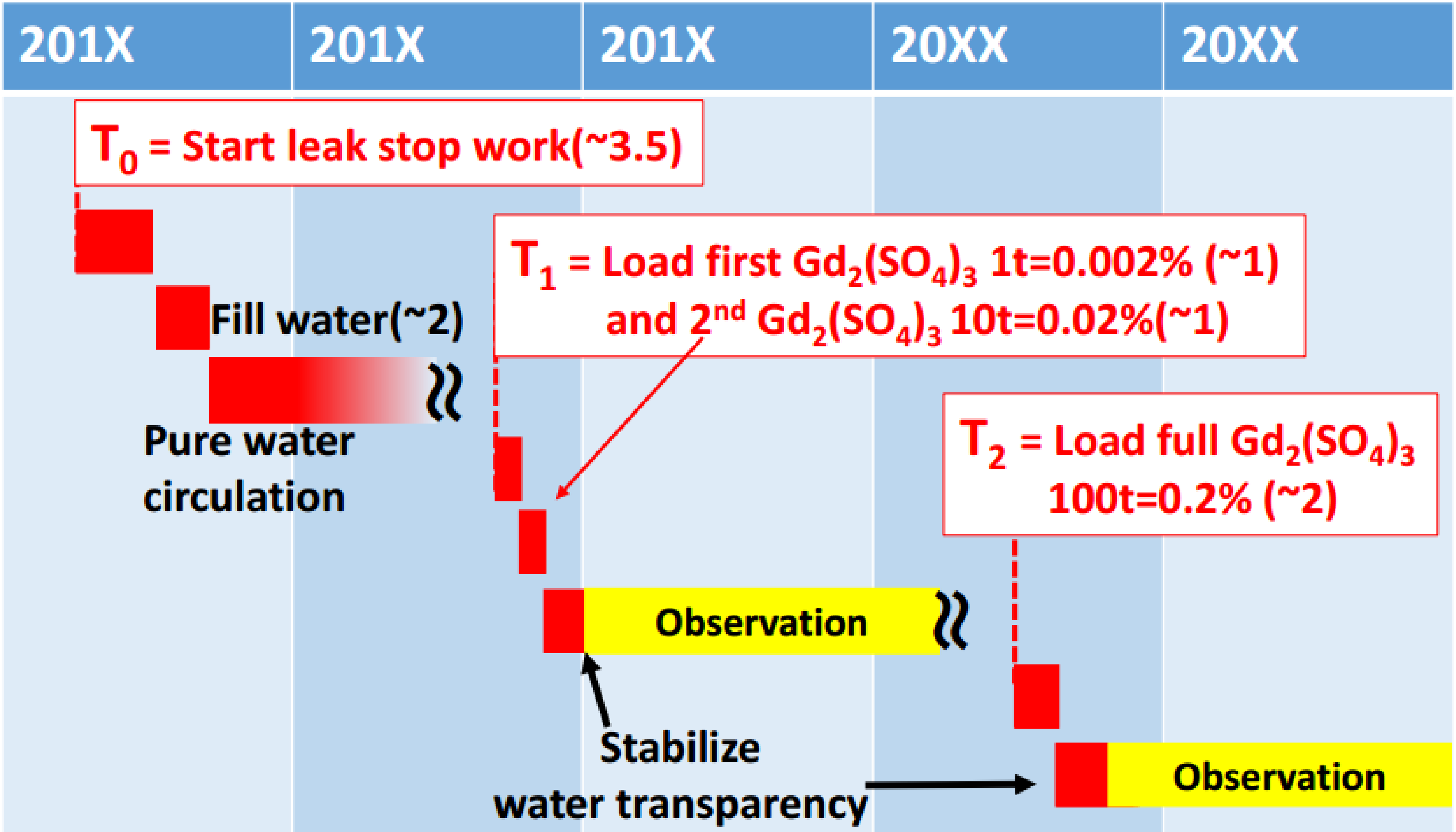
- Current scenario is that leak coverage will be done with two layers:
  - Lower layer, BIOS-SEAL 197, which can sneak into small gap
  - Upper layer, a material which allow more displacement (current candidate MineGuard C)
- Candidate selected for low Radon emanation and good mecanical behavior
- Tests ongoing to study the behavior of the material in Gd water

What do we need before putting Gd in Super-K?

- Keep Gd water transparency at a similar level than current SK water transparency ✓
- Study the effect of Gd on the detector materials ✓
- Study the effect of Gd on the physics analysis ✓
- Reduction of the radioactive background in the Gd powder → On-going (Affect only the low energy analysis)
- Fix the leaks in the detector → On-going

SK Gd timetable

- SK collaboration approved the Gadolinium project on June 27, 2015. The schedule of the project, including refurbishment of the tank and Gd-loading will be determined taking into account the T2K schedule.



201X 201X 201X 20XX 20XX

T_0 = Start leak stop work(~3.5)

Fill water(~2)

Pure water circulation

T_1 = Load first $Gd_2(SO_4)_3$ 1t=0.002% (~1) and 2nd $Gd_2(SO_4)_3$ 10t=0.02%(~1)

T_2 = Load full $Gd_2(SO_4)_3$ 100t=0.2% (~2)

Observation

Stabilize water transparency

Observation

Summary

- The Gd project started in 2002 (known as GADZOOKS! at this time)
  - The EGADS prototype construction started in 2009
  - In 2015, we reached the 0.1% concentration of Gd aimed
  - Gd project validated by SK collaboration in June 2015
  - Work to fix leaks and to reduce the radioactivity in Gd powder ongoing and promissing
- Gd neutron tagging would allow Super-K to detect SRN within 10 years
- Other physical analysis can also be improved / accessible with Gd neutron tagging
- Let's enjoy Gd neutron tagging physics with Super-K in few years!

Work in the mine

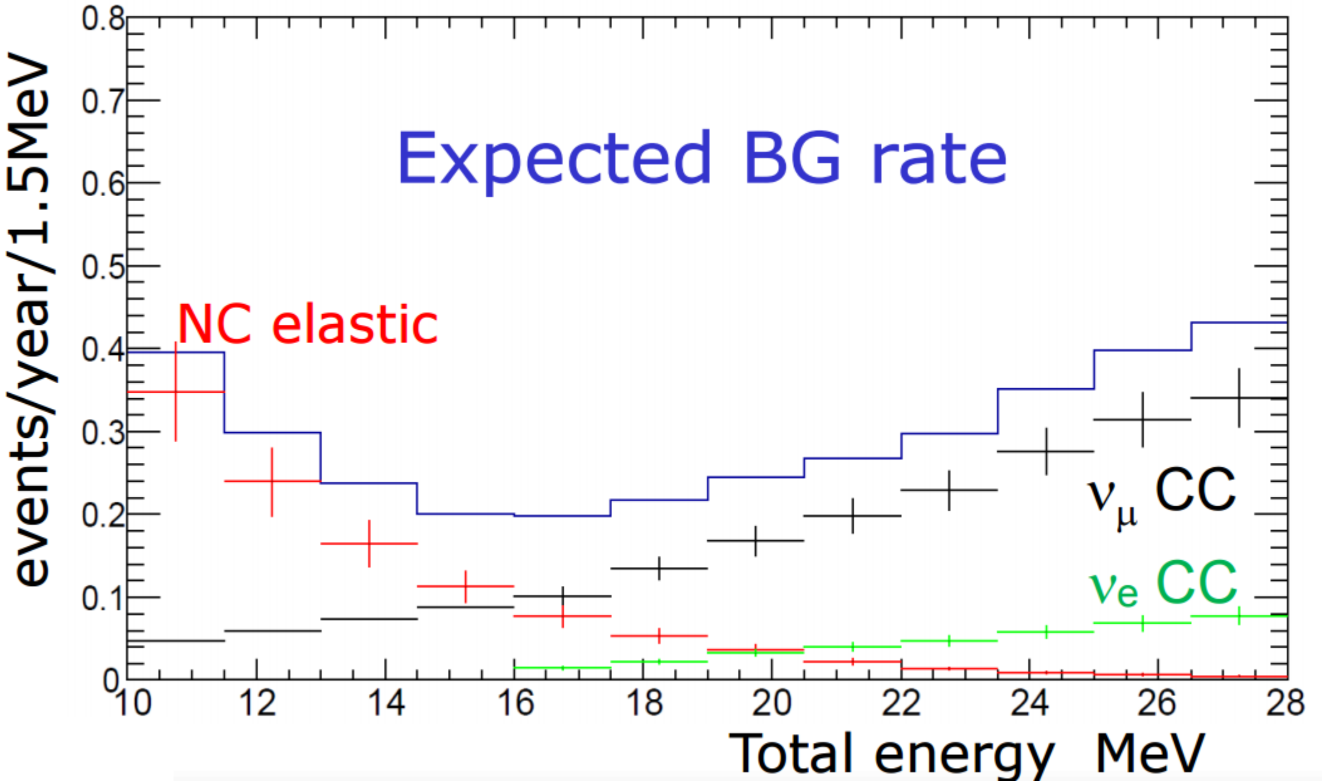
- New hall build for the Gd water system, called “Hall G”.

Backup

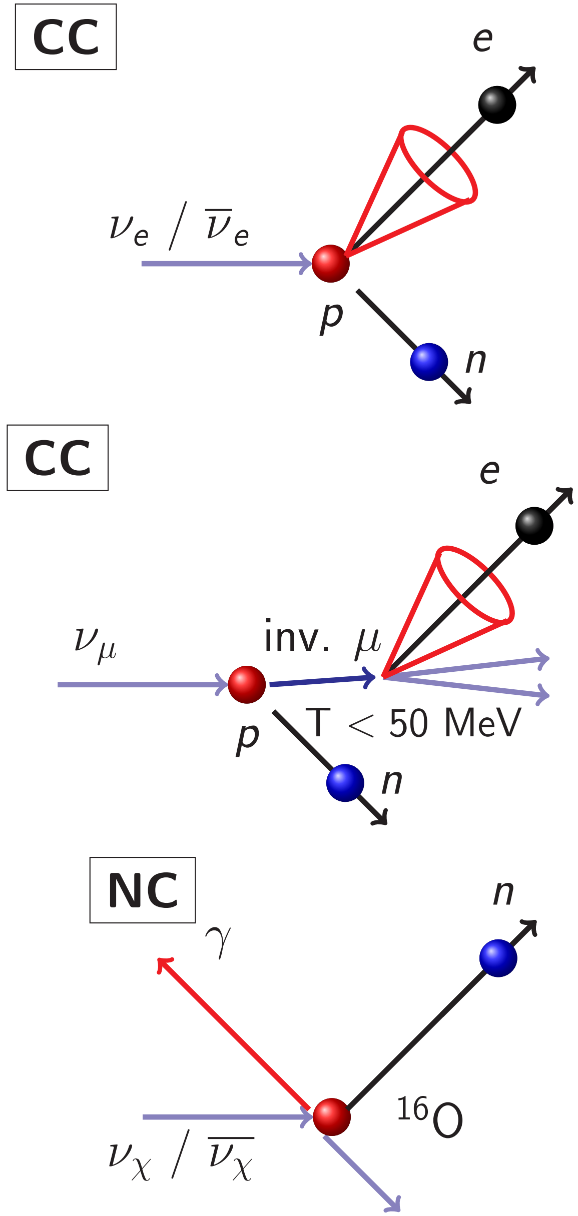
‘

Backup

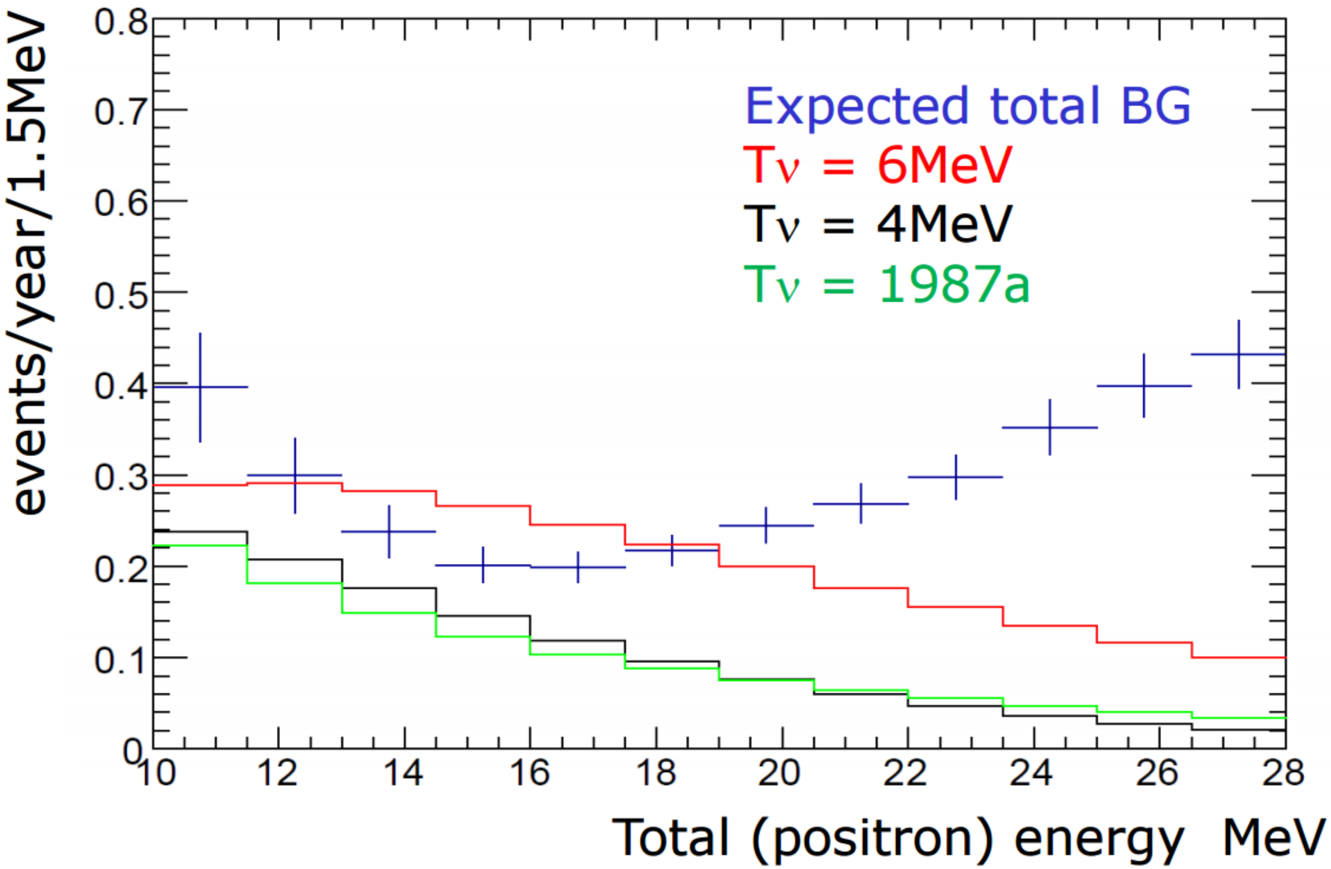
SRN analysis in Super-K: Gd-n tag backgrounds



Vertex information can allow further BG reduction



SRN expectation with Gd in 10 years



Dependance on the typical SN emission spectrum

HDB[*]	10-16 MeV	16-28 MeV	Total	significance
T_{eff} 8 MeV	11.3	19.9	31.2	5.3 σ
T_{eff} 6 MeV	11.3	13.5	24.8	4.3 σ
T_{eff} 4 MeV	7.7	4.8	12.5	2.5 σ
T_{eff} SN1987A	5.1	6.8	11.9	2.1 σ
BG	10	24	34	–

In events/10years

Significance is determined with 2 energy bins

[*] Horiuchi, Beacom and Dwek, Phys Rev D 79 083013 (2009)