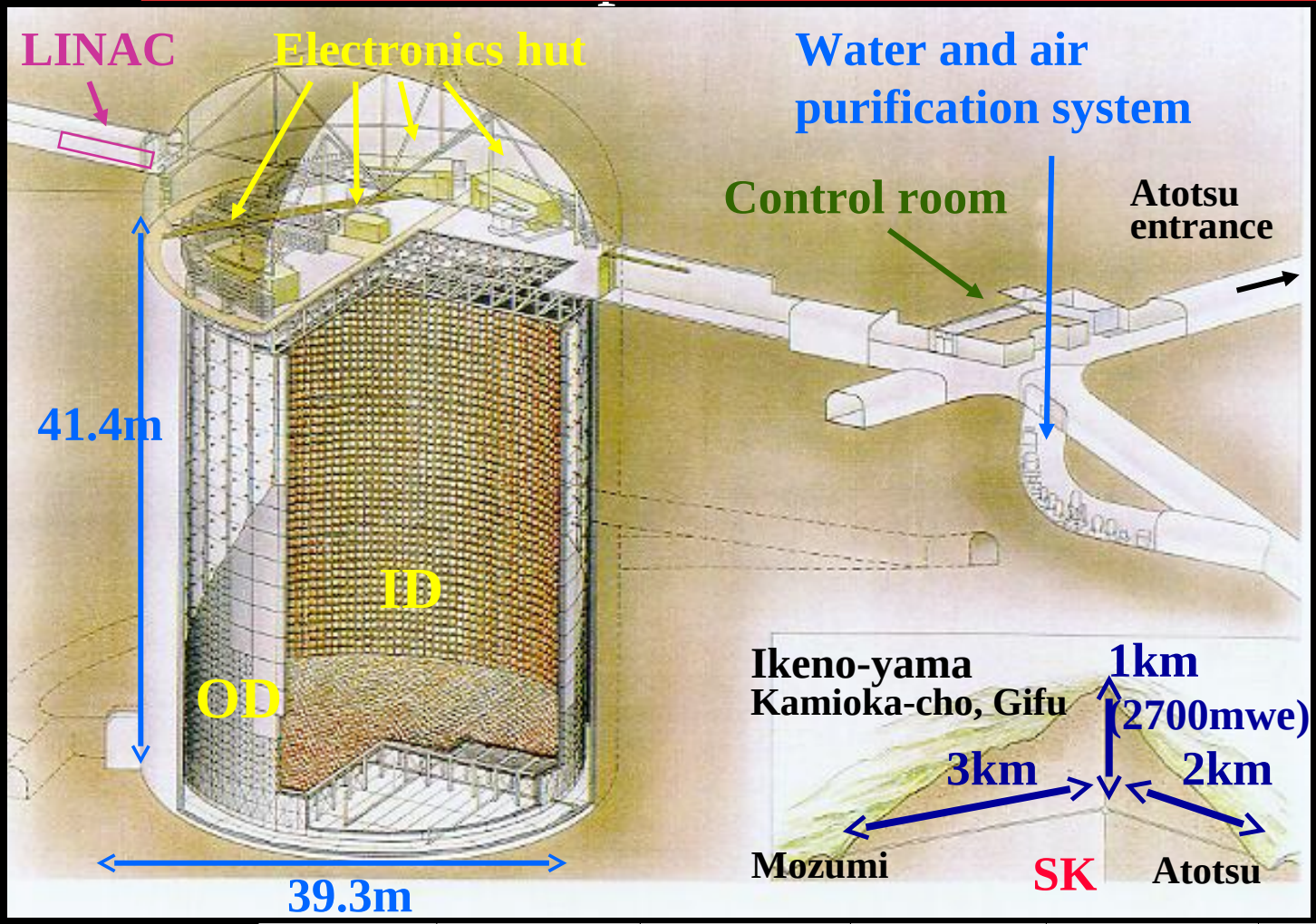
WIT: low energy and supernova **neutrinos** for **Super-Kamiokande** in the **Gd-phase**

Lluís Martí-Magro (Yokohama National University)

NuFact (WG 6), Seoul (Korea)

August 25th, 2023.

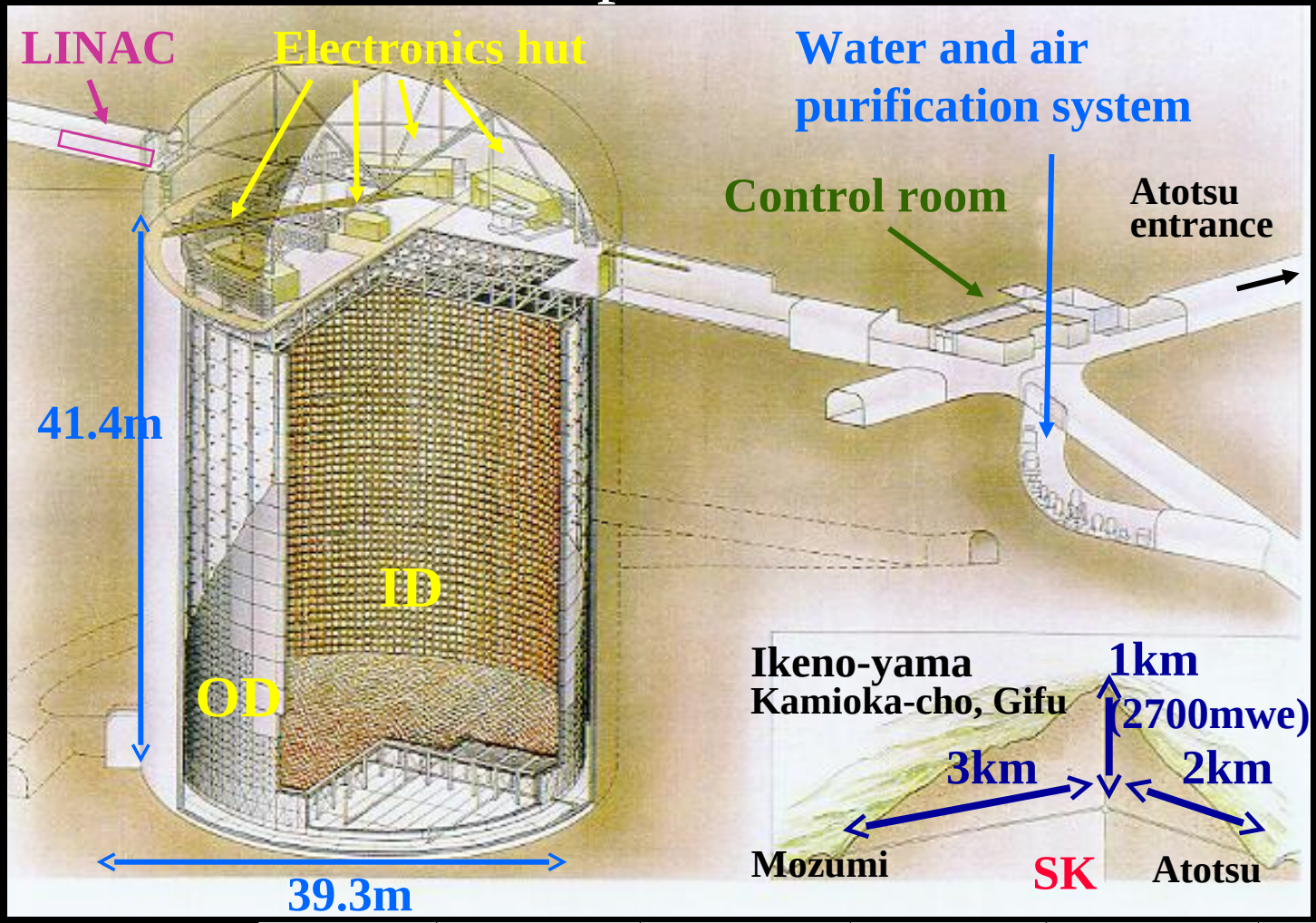
Super-Kamiokande Detector



- 50 kton water
- 13+26 tons of Gd sulfate octahydrate
- ~2 m OD viewed by 8-inch PMTs
- 32 kt ID viewed by 20-inch PMTs

		SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI	SK-VII
	Start - end	1996 Apr - 2001 Jul	2002 Oct - 2005 Oct	2006 Jul - 2008 Sep	2008 Sep - 2018 Mar	2019 Jan- 2020 Jul	2020 Jul- 2022 Jun	2022 July -
Captures on Gd							50%	75%
Number of PMTs	ID (coverage)	11146 **(40 %)**	5182 **(19 %)**	11129 **(40 %)**	11129 **(40 %)**	11129 **(40%)**	11129 **(40%)**	11129 **(40%)**
	OD	**1885**						

Super-Kamiokande Detector



Versatile detector:

Solar neutrinos,
Atmospheric neutrinos,
Proton decay,
(pre-)Supernovae,
Supernova Relic Neutrinos,
Indirect search for DM
and more

		SK-I	SK-II	SK-III	SK-IV	SK-V	SK-VI	SK-VII
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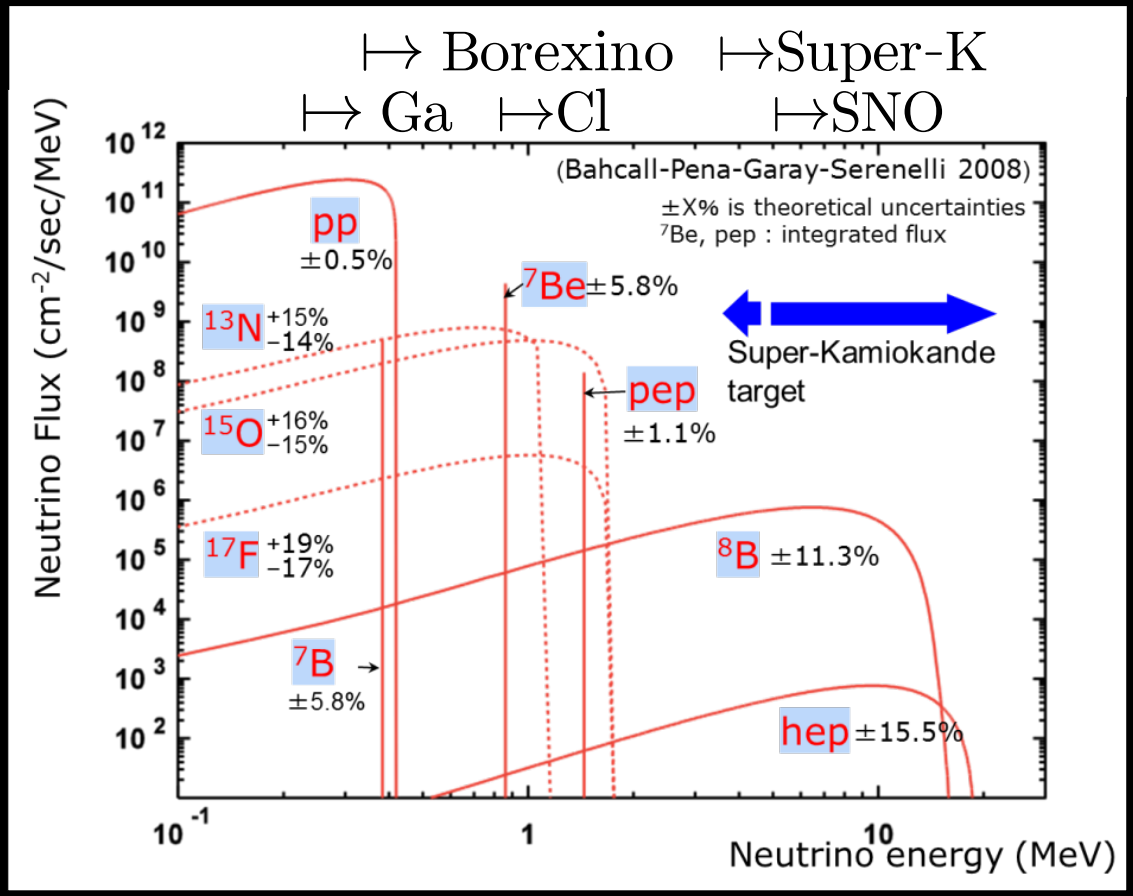
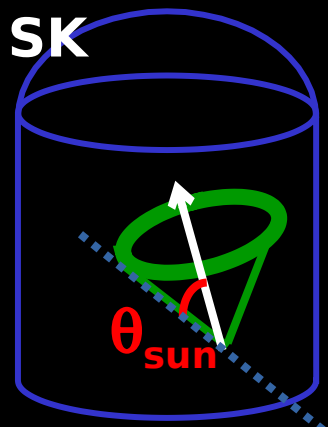
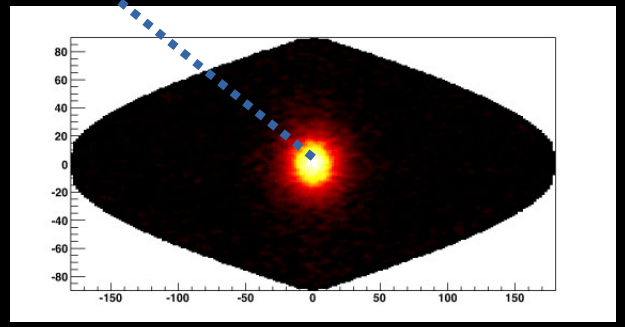
Solar neutrinos observation at SK



Poster #5 by Jeong Yeol Yang

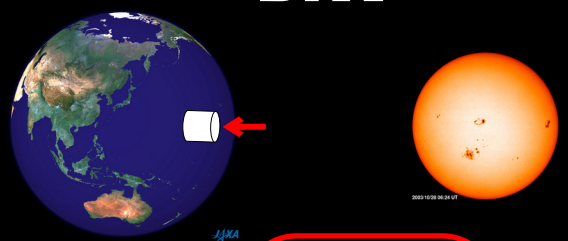




NIGHT

$\cos\theta_z = -1$,
$L \sim 13000$ km

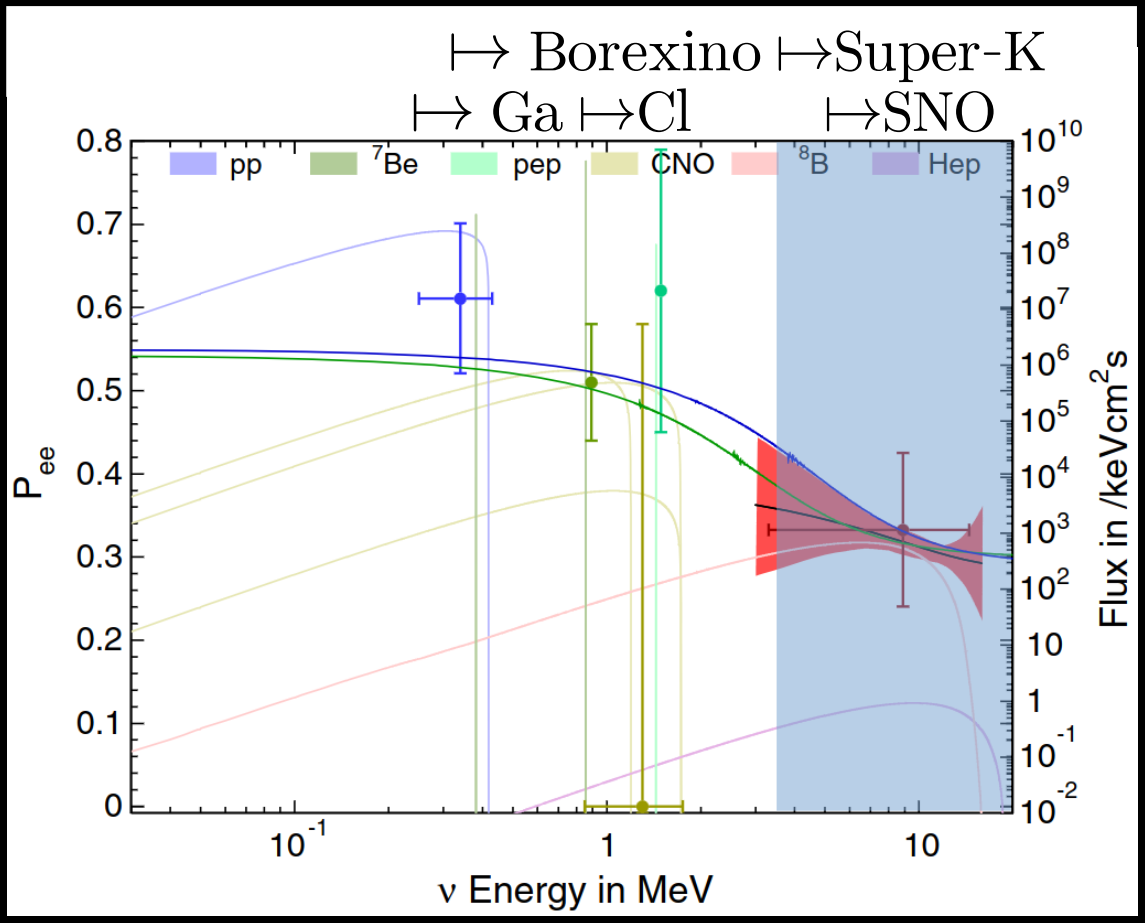
DAY



$\cos\theta_z = 1$
$L \sim 15$ km

Flux
Energy spectrum
Day/night asymmetry

Solar neutrinos observation at SK



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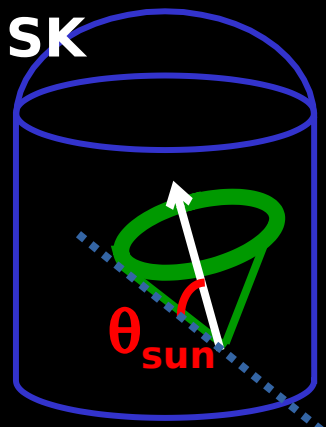
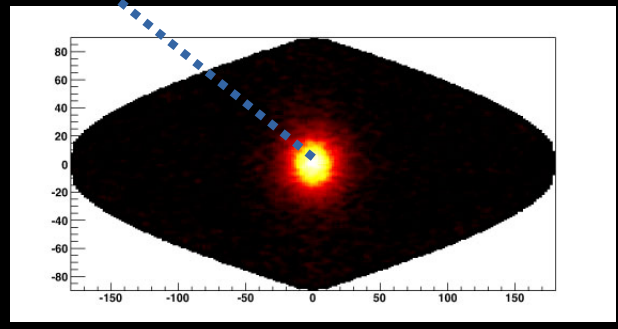
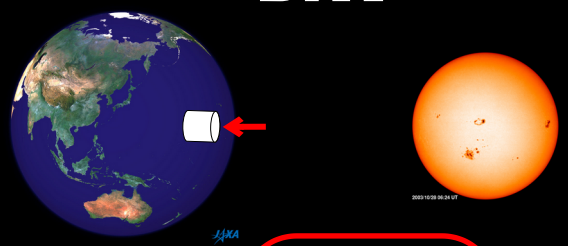




NIGHT

cosθ$_z$= -1,
L ~ 13000 km

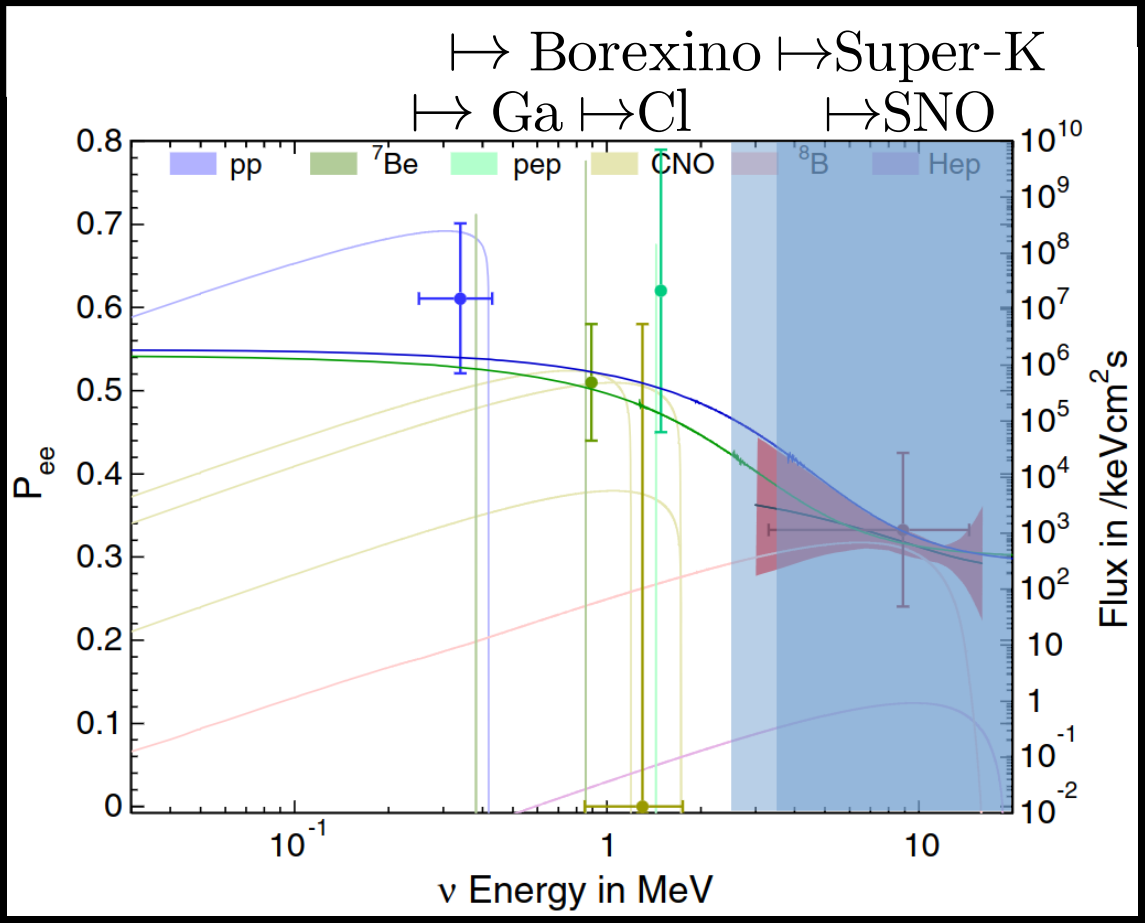
DAY



cosθ$_z$ = 1
L ~ 15 km

Flux
Energy spectrum
Day/night asymmetry

Solar neutrinos observation at SK



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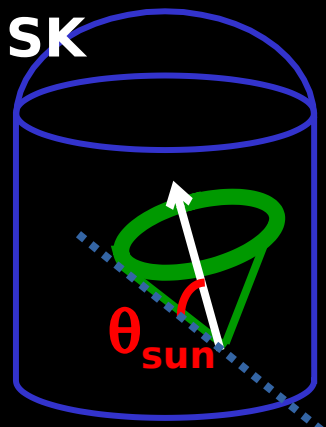

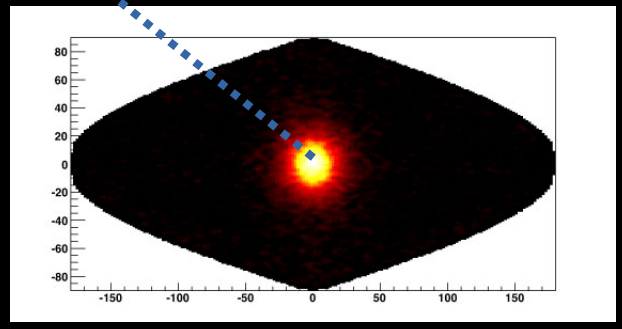

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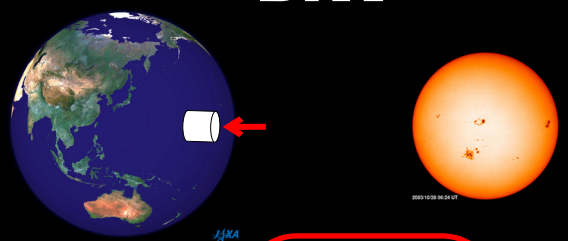
DAY

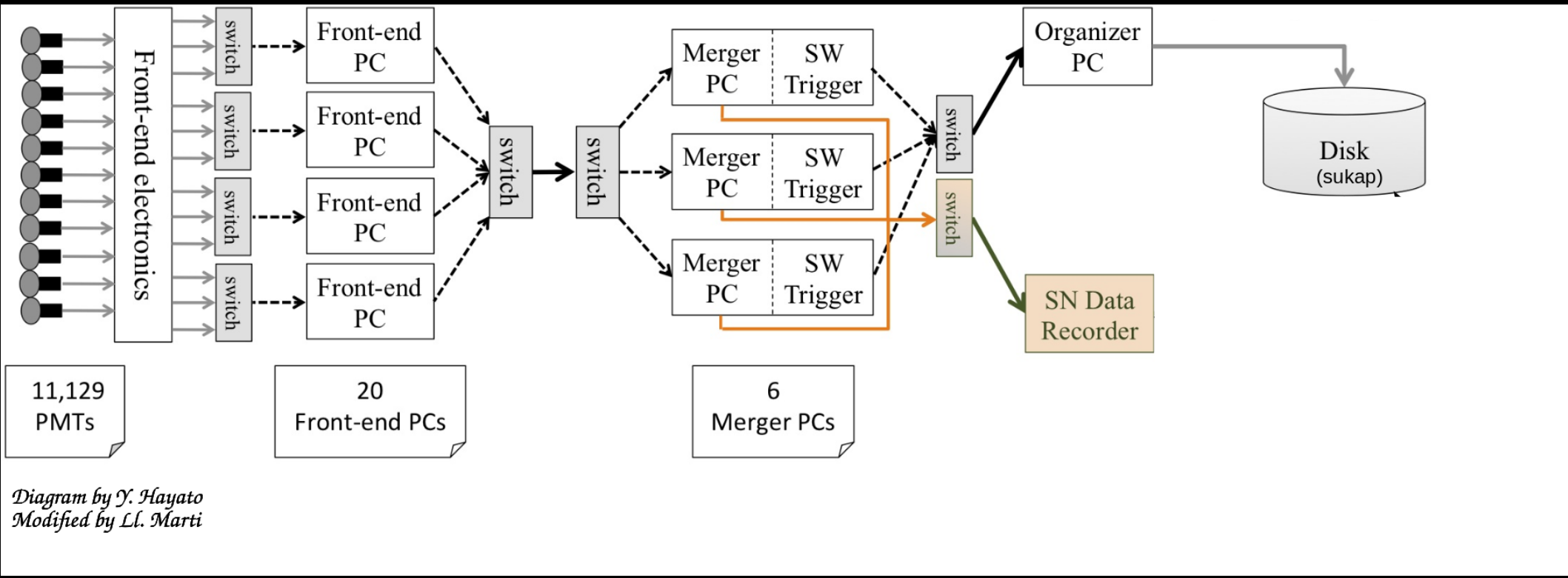


Flux
Energy spectrum
Day/night asymmetry

Push towards lower energies with WIT

WIT System

SK's standard DAQ system:

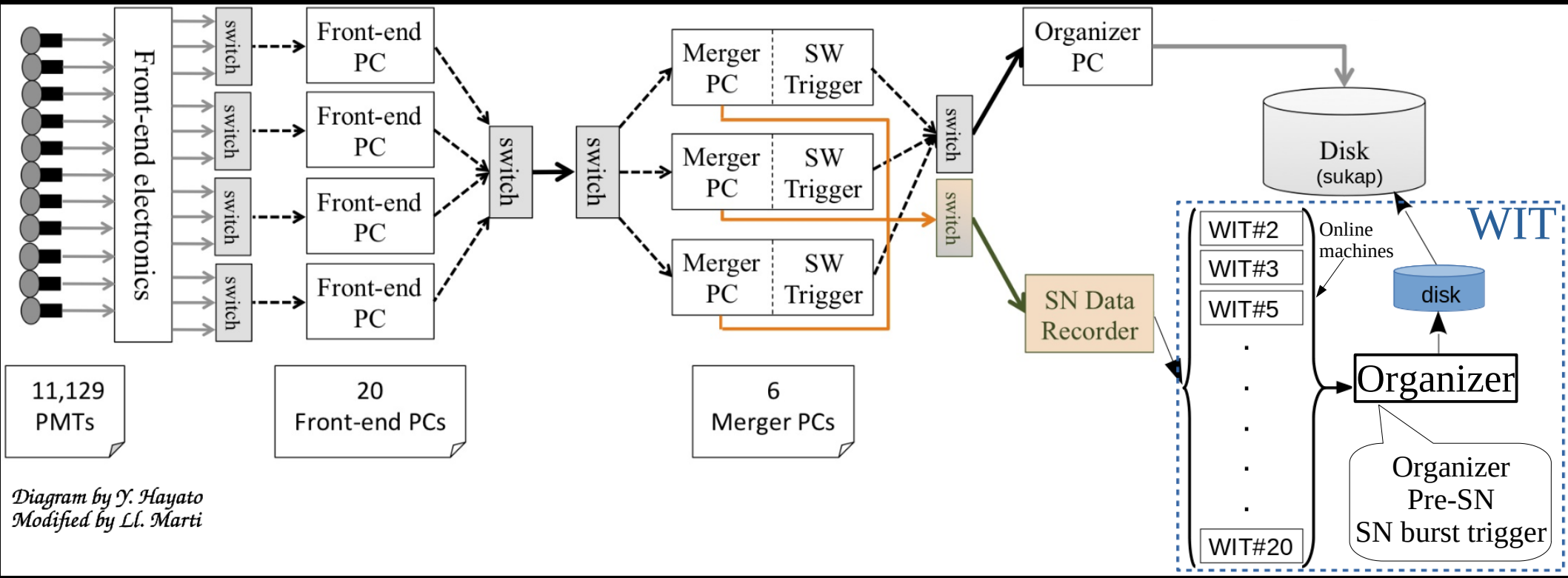


WIT System

Computer cluster running parallel software trigger:

Online machines: WIT#[2-20]
Receive 23 ms data blocks
+
Event reconstruction

→ Organizer
Sorts the data blocks



WIT hosts:
- Triggers low energy events (electrons of E_{kin} > 2.5 MeV).
- Online pre-supernova alarm.
- Online SN burst alarm and SN-triggered raw data saving system.

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Online machines: WIT#[2-20]
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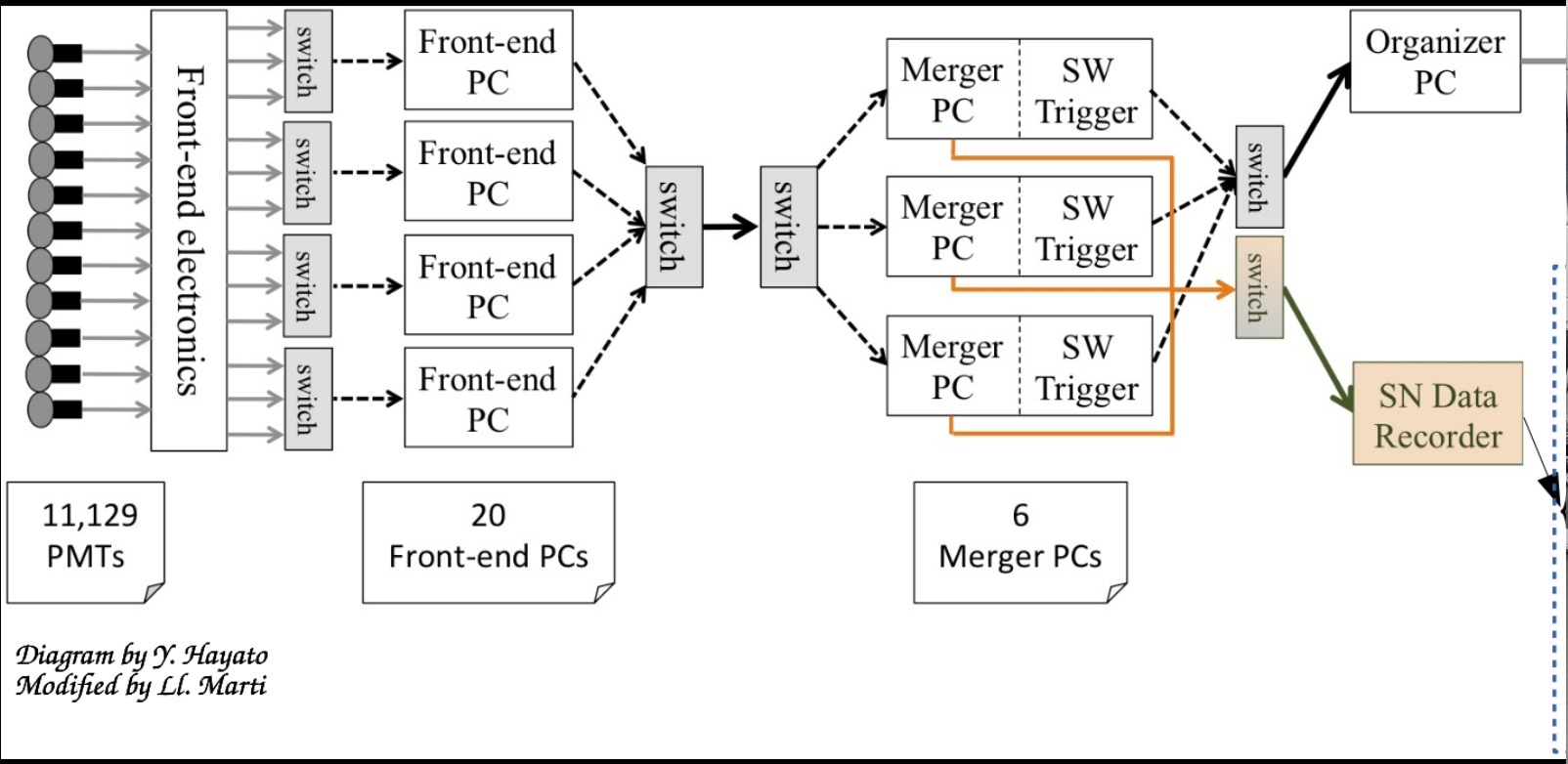
Sorts t



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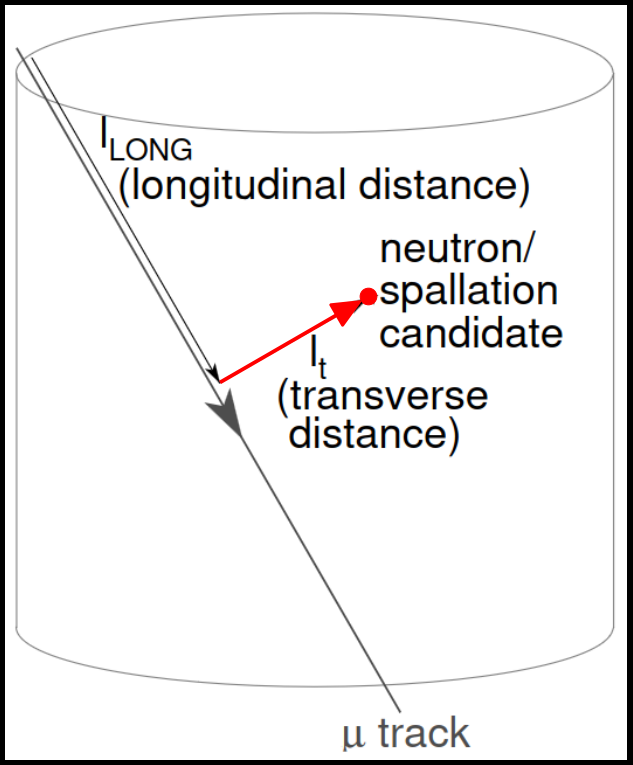
Removing Spallation Background



Variables: Δ_t, l_t and Q_{res} where:

Δ_t = time diff. between candidate and muon

Q_{res}= (Charge deposited) - (min. ionization)

→ Define PDFs

→ Define log likelihood

Resulted in:

90% spallation events removed

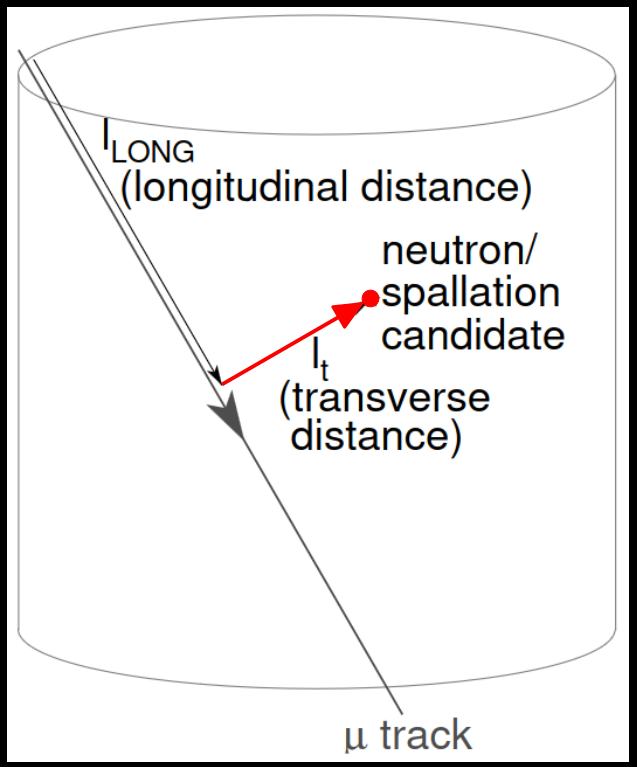
20% deadtime

More details in:

arXiv:1606.07538 [hep-ex]

arXiv:0508053 [hep-ex]

Removing Spallation Background with WIT



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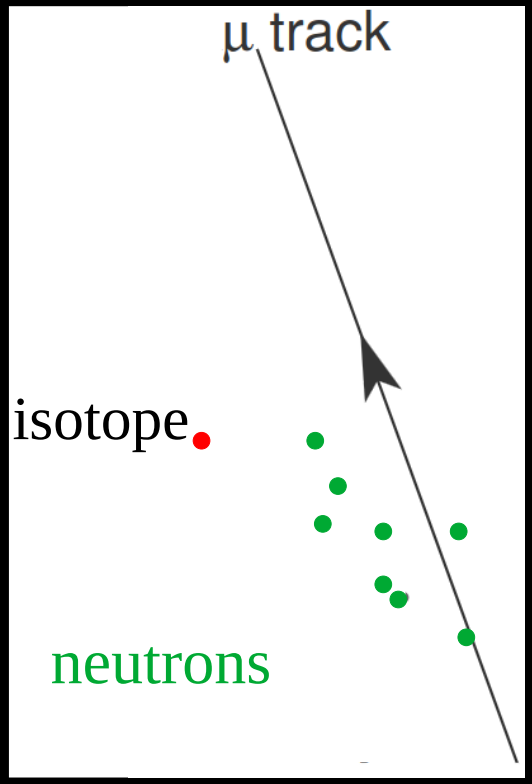


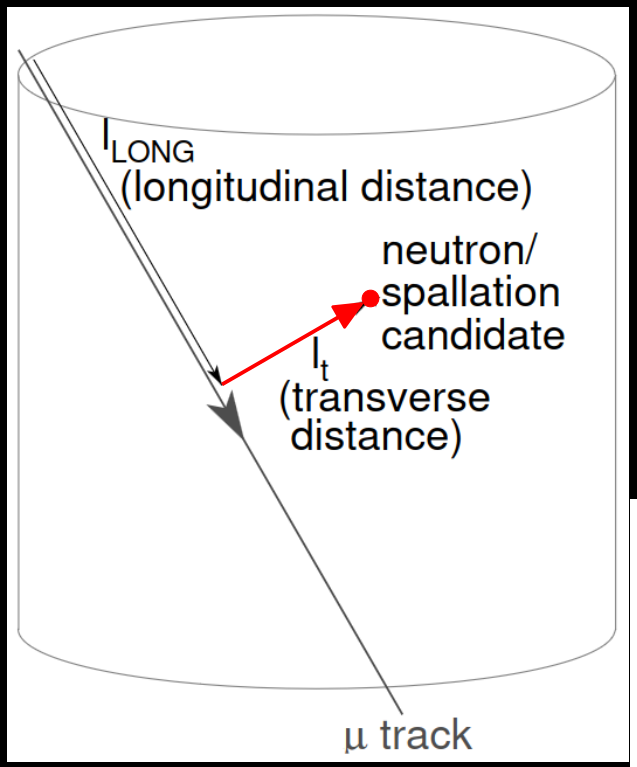
Tag neutrons with WIT:

→ neutron clouds

→ 388/2970 days in SK-IV

More details in (paper in preparation):
New Methods and Simulations for Cosmogenic Induced Spallation Removal in Super-Kamiokande-IV

Removing Spallation Background with WIT



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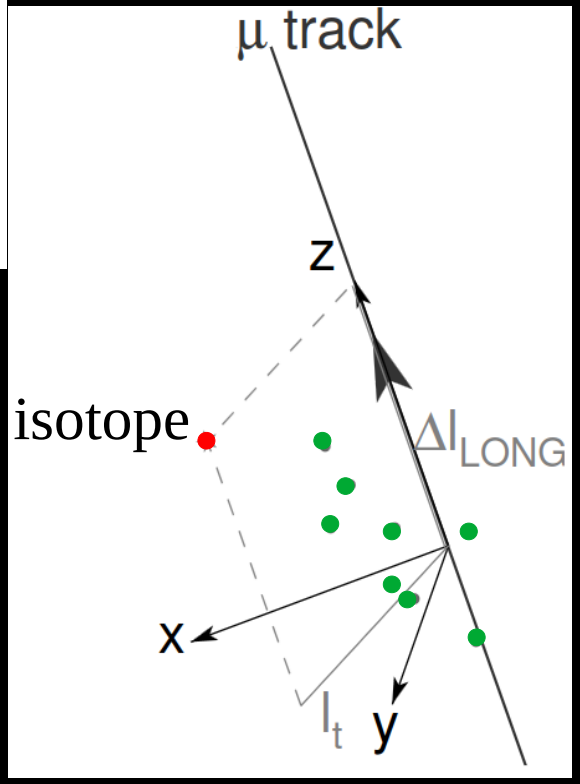

New variables:

Δl_{LONG}

Neutron multiplicity

More details in (paper in preparation):
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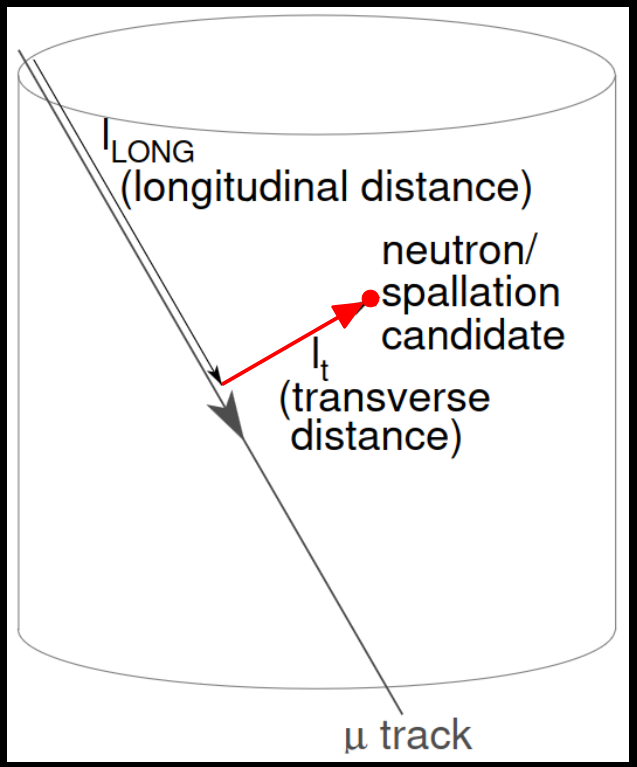
Removing Spallation Background with WIT



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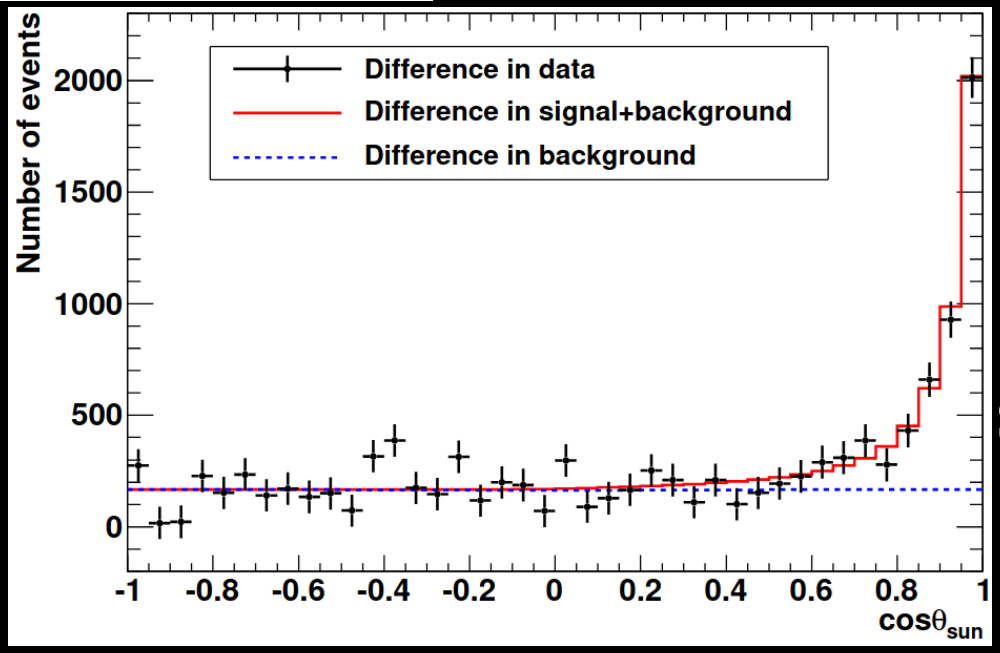
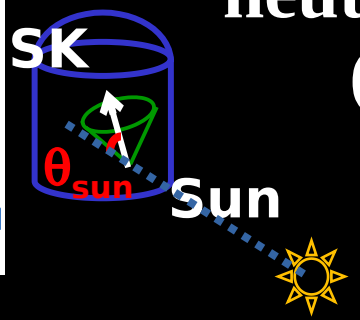


Define new cuts:

→ 47% spallation events removed

→ 1.3% effective deadtime

12% Increase in solar neutrino events (~7000)



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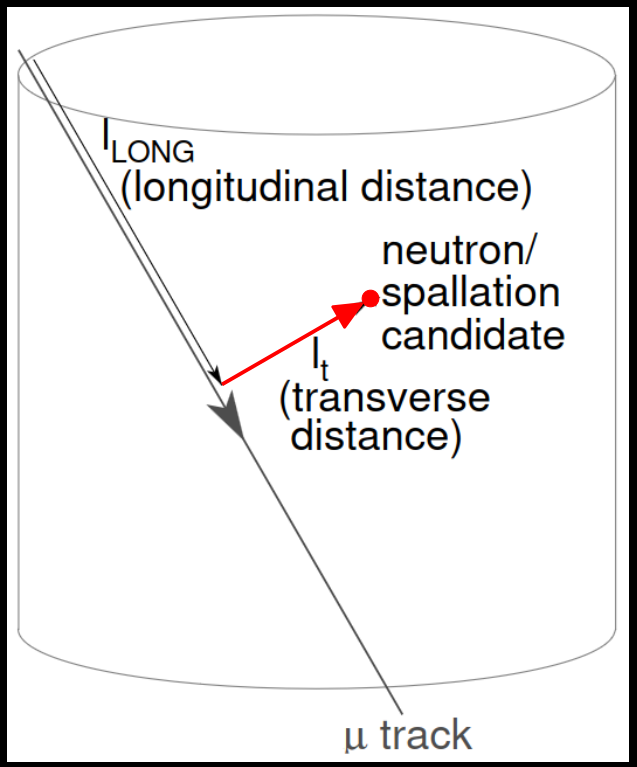

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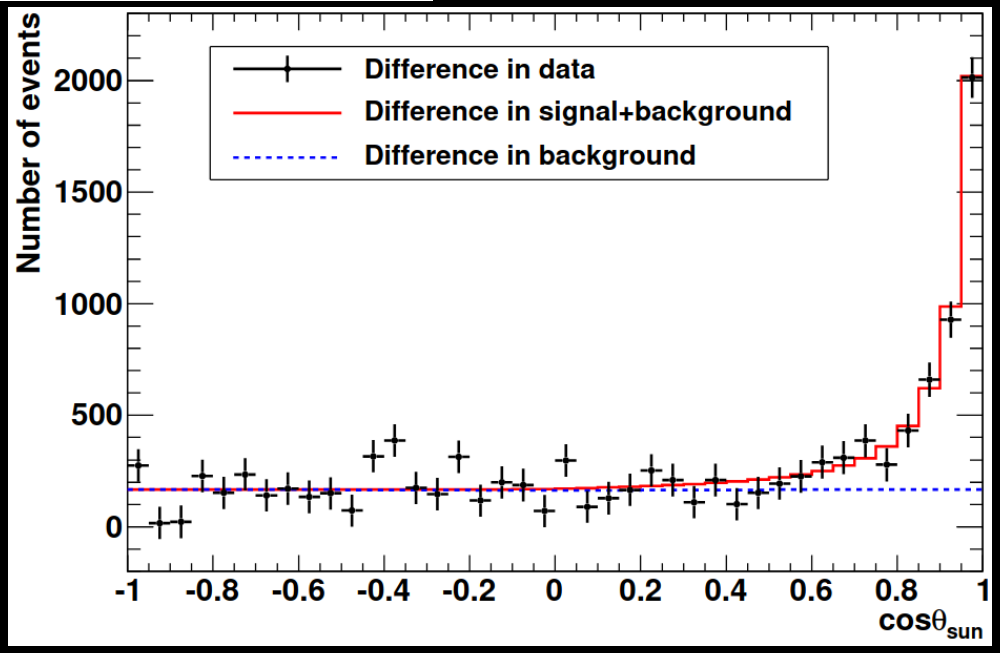

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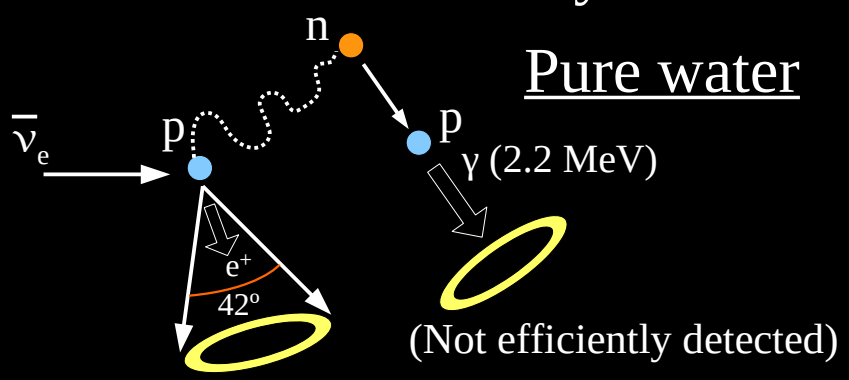
Improvement expected for Gd phases

Neutron tagging in water

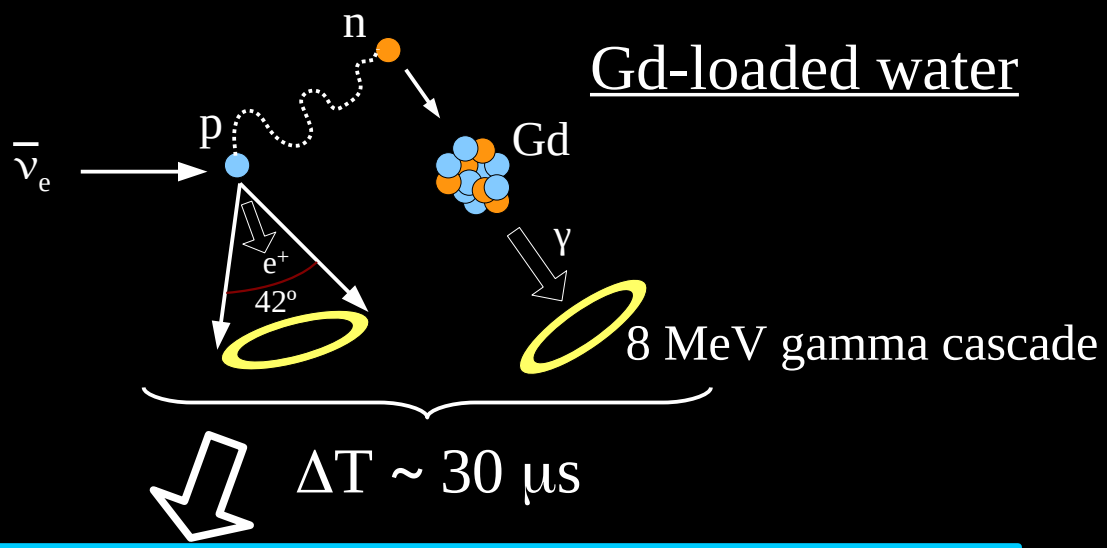
IBD: inverse beta decay.

Beacom, Vagins PRL.93, (2004) 171101



Pure water

ΔT ~ 200 μs



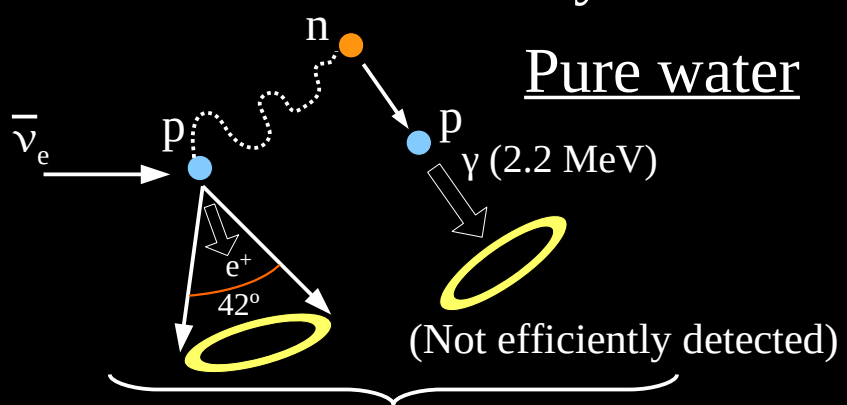
Gd-loaded water

ΔT ~ 30 μs

With tight time (delayed) and position coincidence between positron and neutron capture (90% neutron capture on Gd with 0.2% $Gd_2(SO_4)_3$ concentration) we will be able to tag neutrons with high efficiency.

Neutron tagging in water

IBD: inverse beta decay.



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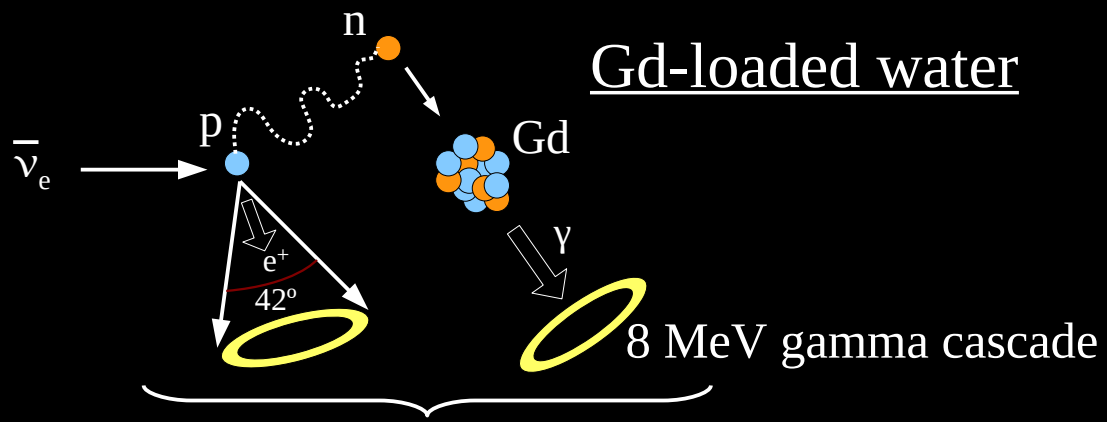

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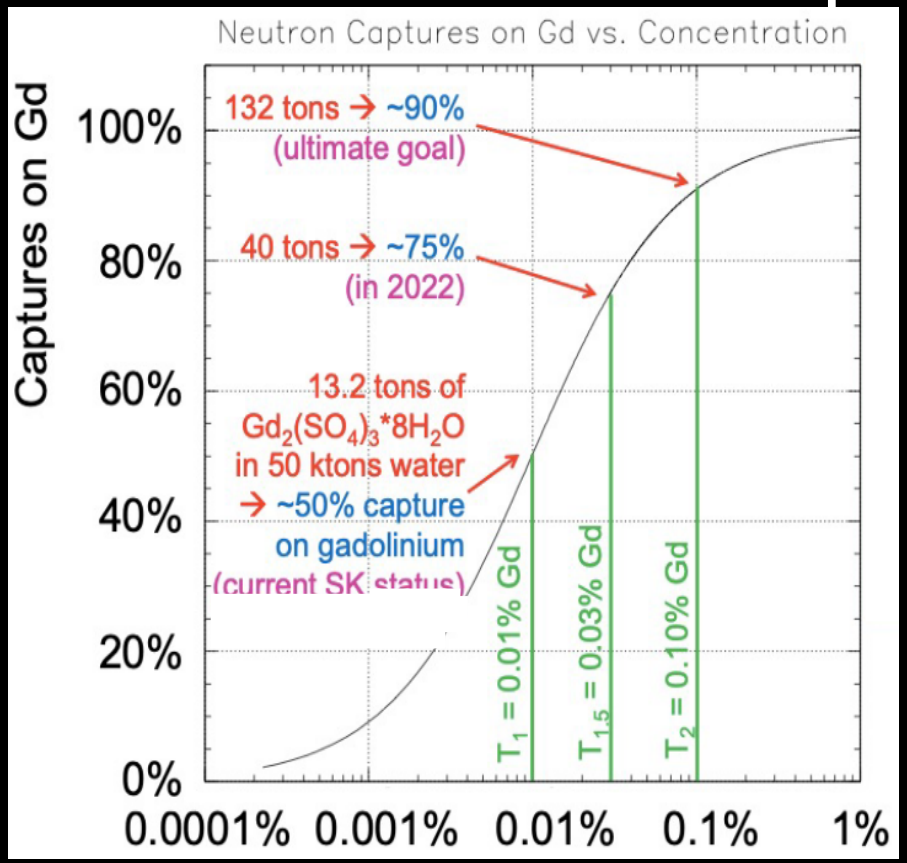


T1 (SK-VI) phase finished.

Now @ T1.5 (SK-VII):

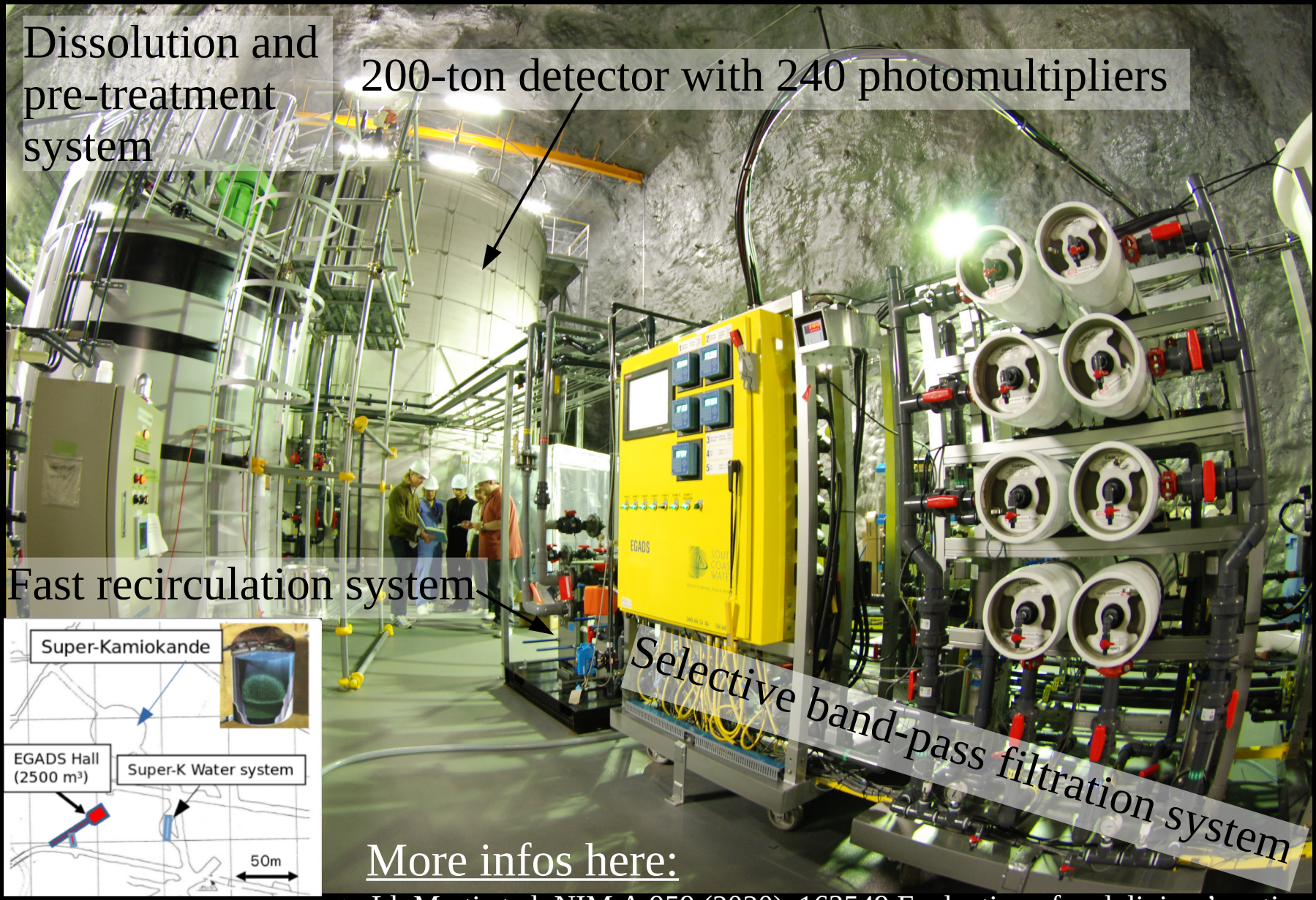
→ 75% of neutrons captured on Gd
→ High neutron detection efficiency!

More info: NIM, A 1027 (2022) 166248

EGADS: birth of a new detector

Evaluating Gadolinium's Action on Detector Systems

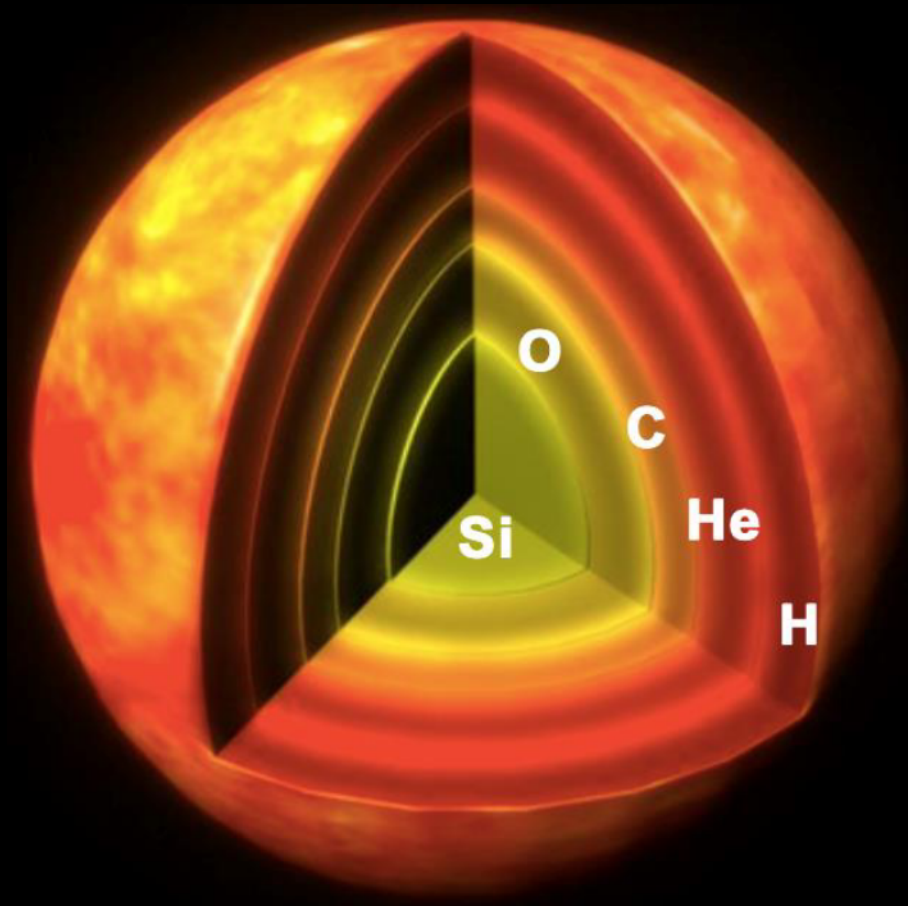
R&D test facility to prove Gd related techniques for SuperK (SK-Gd)



More infos here:

Ll. Marti et al, NIM A 959 (2020) 163549 Evaluation of gadolinium's action on water Cherenkov detector systems with EGADS

Pre-SuperNova Stars



After Carbon ignition of massive stars ($M > 8\ M_{\odot}$) neutrino emission becomes the main cooling mechanism.

Electron-positron annihilation generate thermal neutrinos:

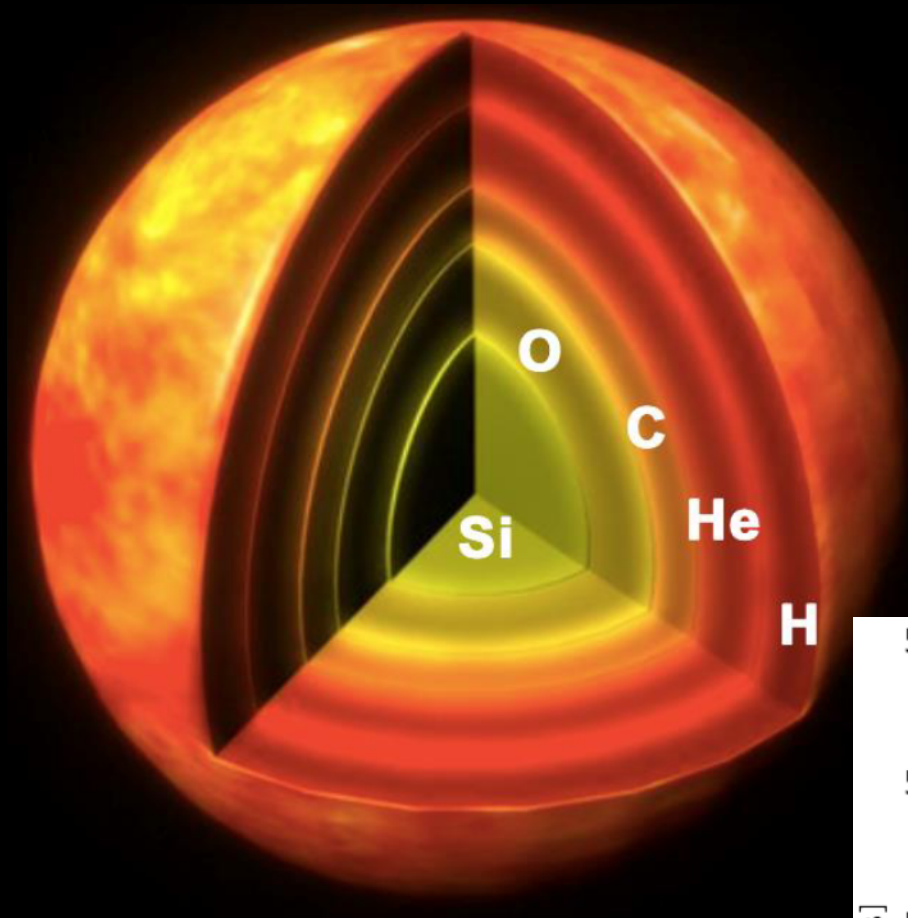
$$e^- + e^+ \longrightarrow \nu_X + \bar{\nu}_X$$

From there on up to the Silicon burning:

Burning phase	Duration	Neutrino <E>
Carbon	300 years	0.71 MeV
Neon	140 days	0.99 MeV
Oxygen	180 days	1.13 MeV
Silicon	~few days	1.85 MeV

Astropart.Phys. 21 (2004) 303-313

Pre-SuperNova Stars



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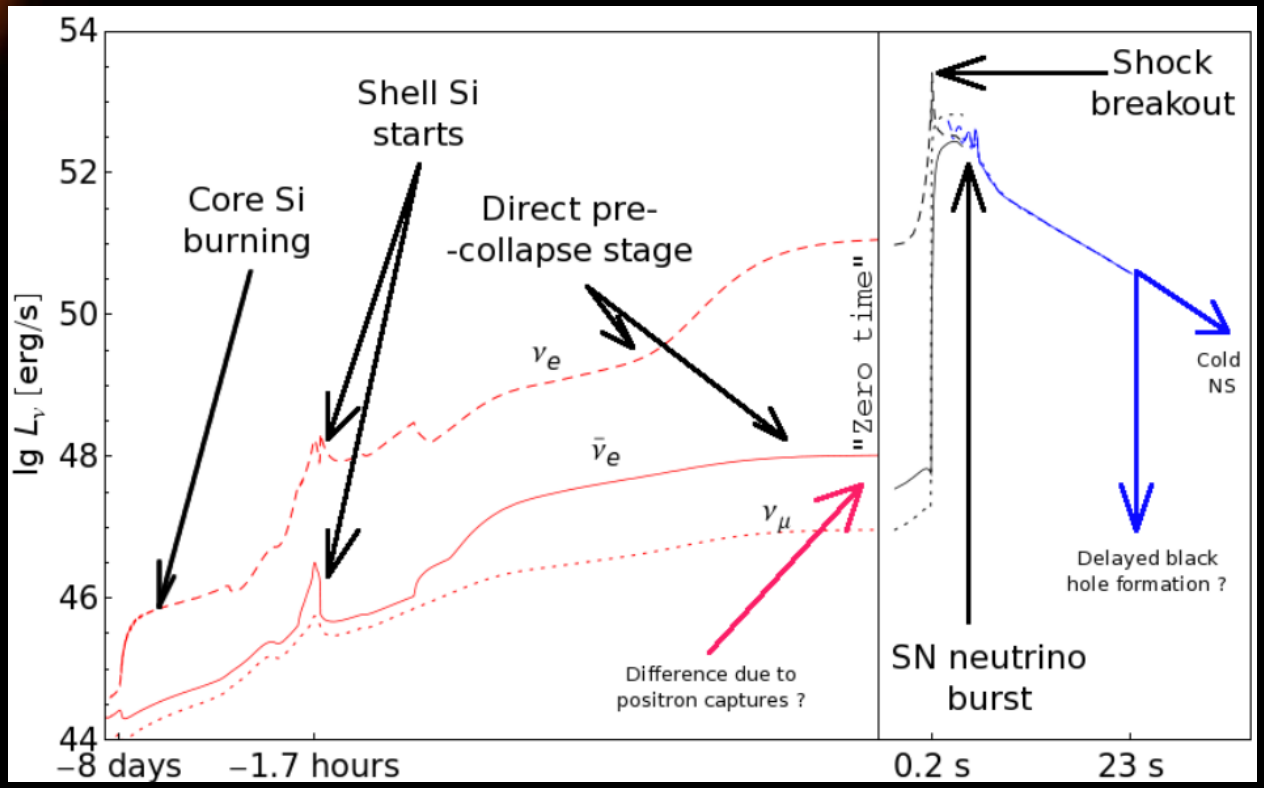
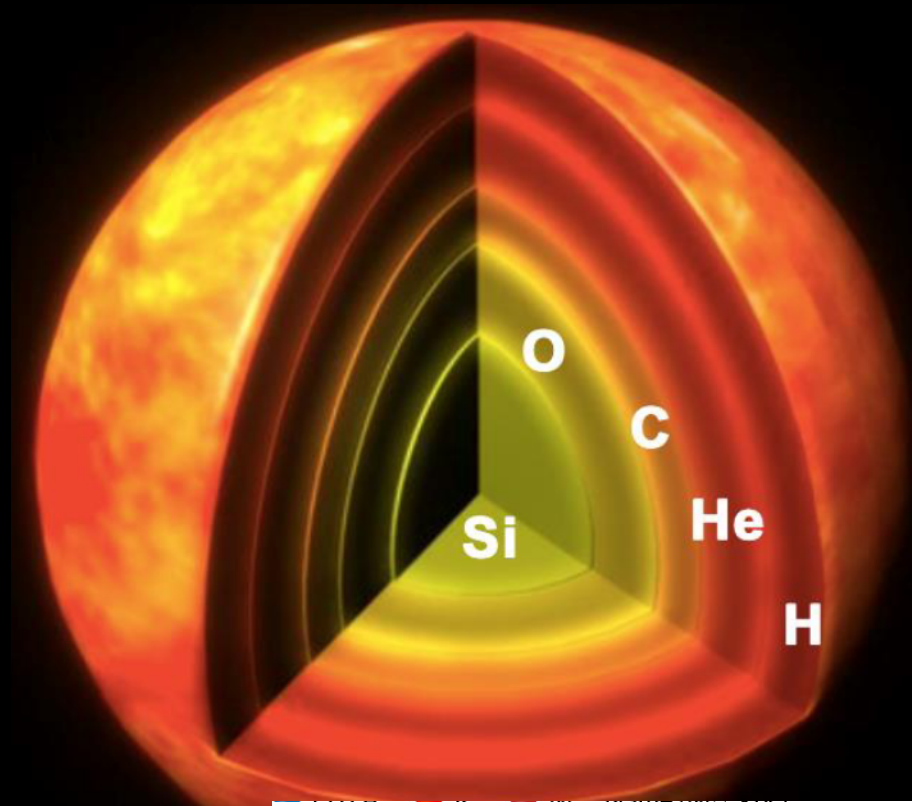


A. Odrzywolek, A. Heger, Neutrino signatures of dying massive stars: From main sequence to the neutron star, Acta Phys.Polon.B 41 (2010)

Pre-SuperNova Stars



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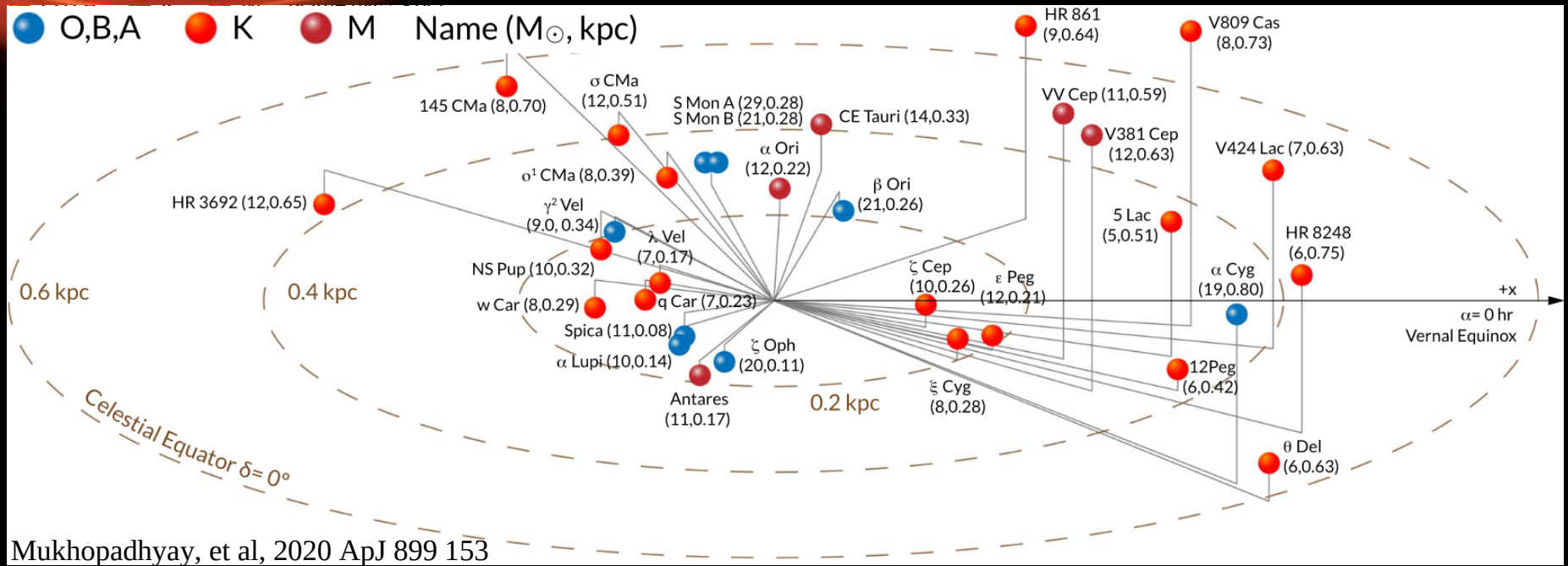
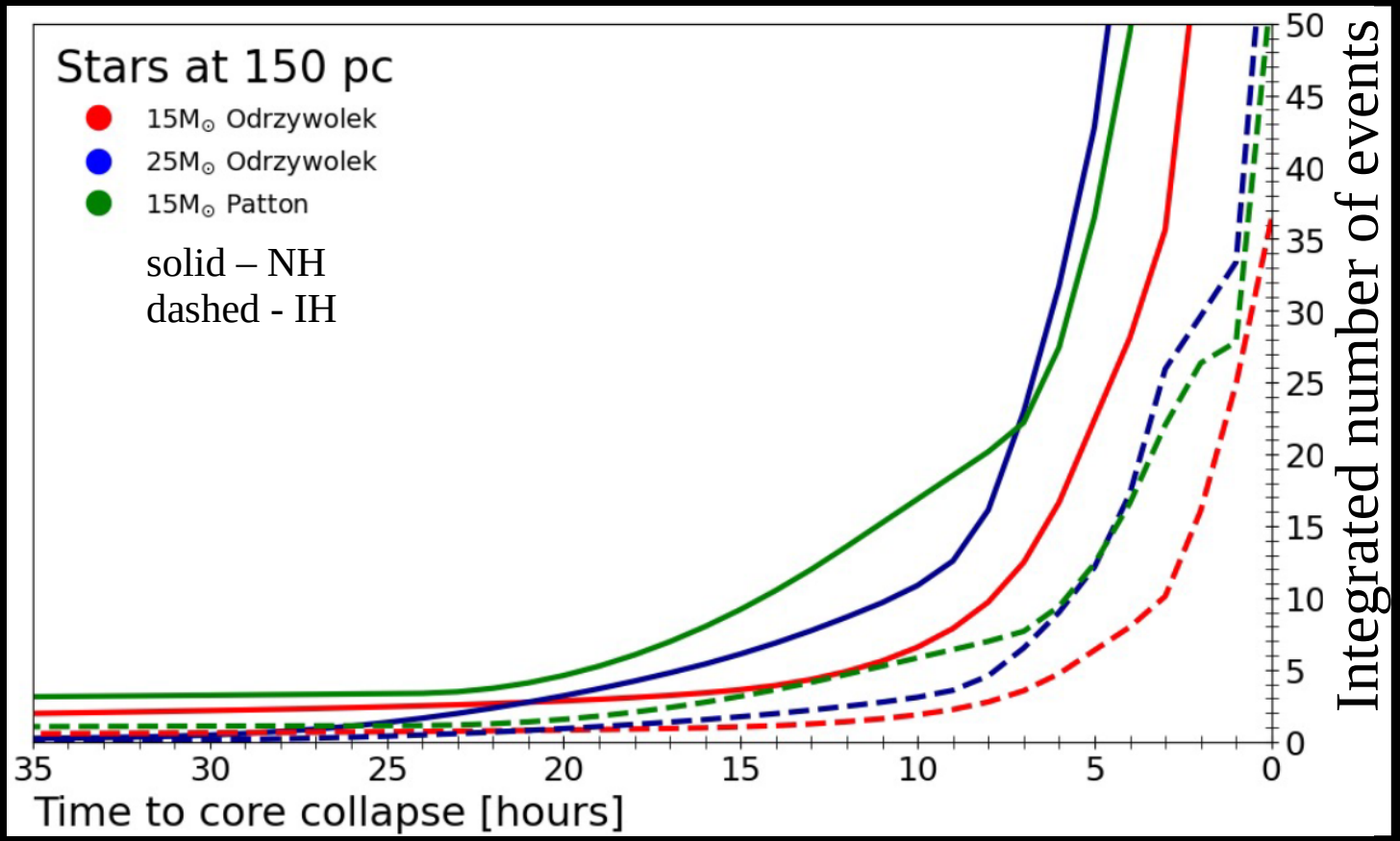


Mukhopadhyay, et al, 2020 ApJ 899 153

SK's Pre-SuperNova WIT Alarm



Mass hierarchy Sensitivity

Late stage stellar Evolution insight

Updated number of events and significance for SK-Gd with 0.03% Gd.

L. N. Machado, Pre-supernova Alert System for Super-Kamiokande, The Astrophysical Journal, 935, 40 (2022)
Patton, et al 2017 ApJ 851 6

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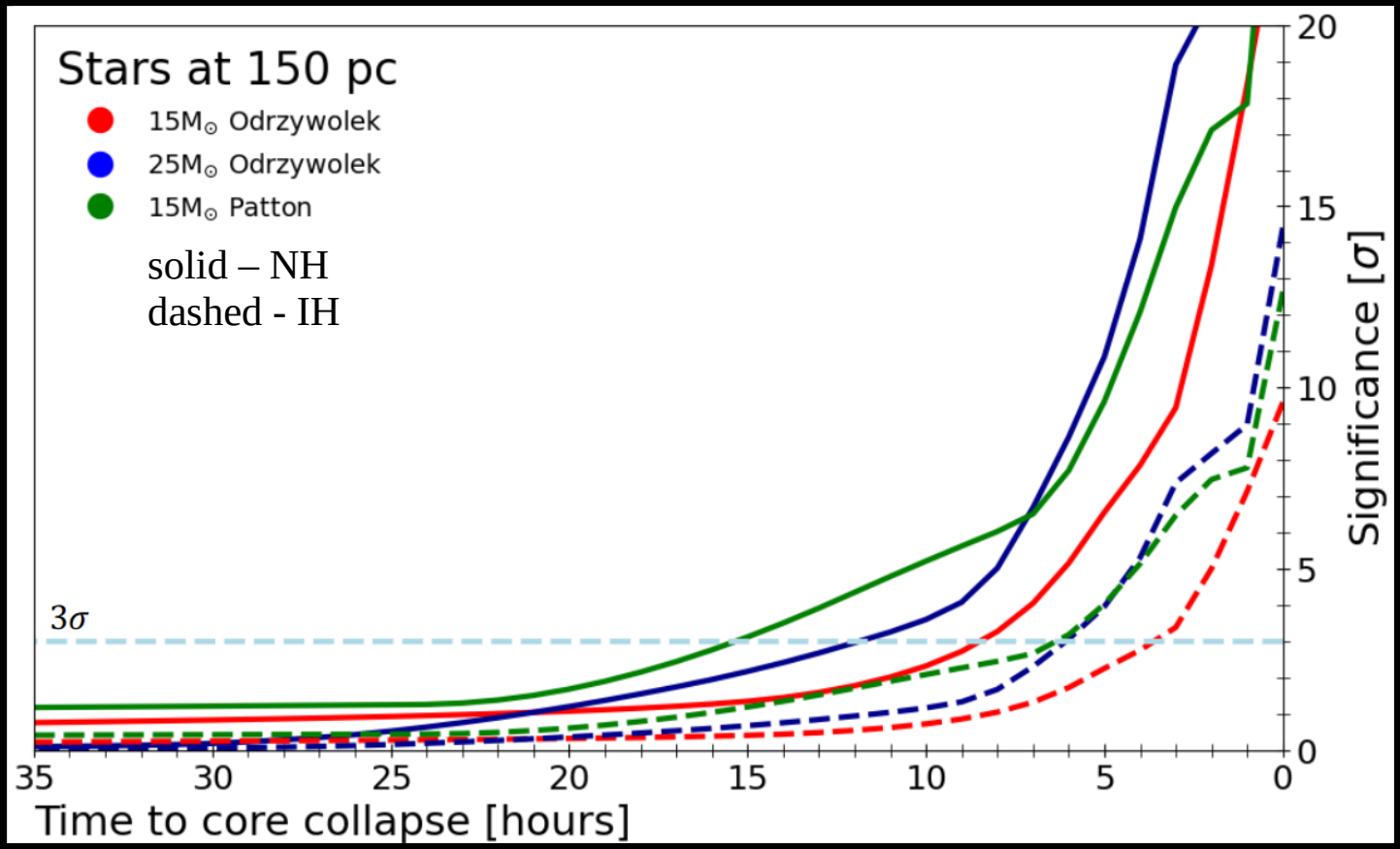

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→ Assuming 150 pc and M=15 $M_{\odot}$ a pre-SN warning could be issued ~15h before explosion

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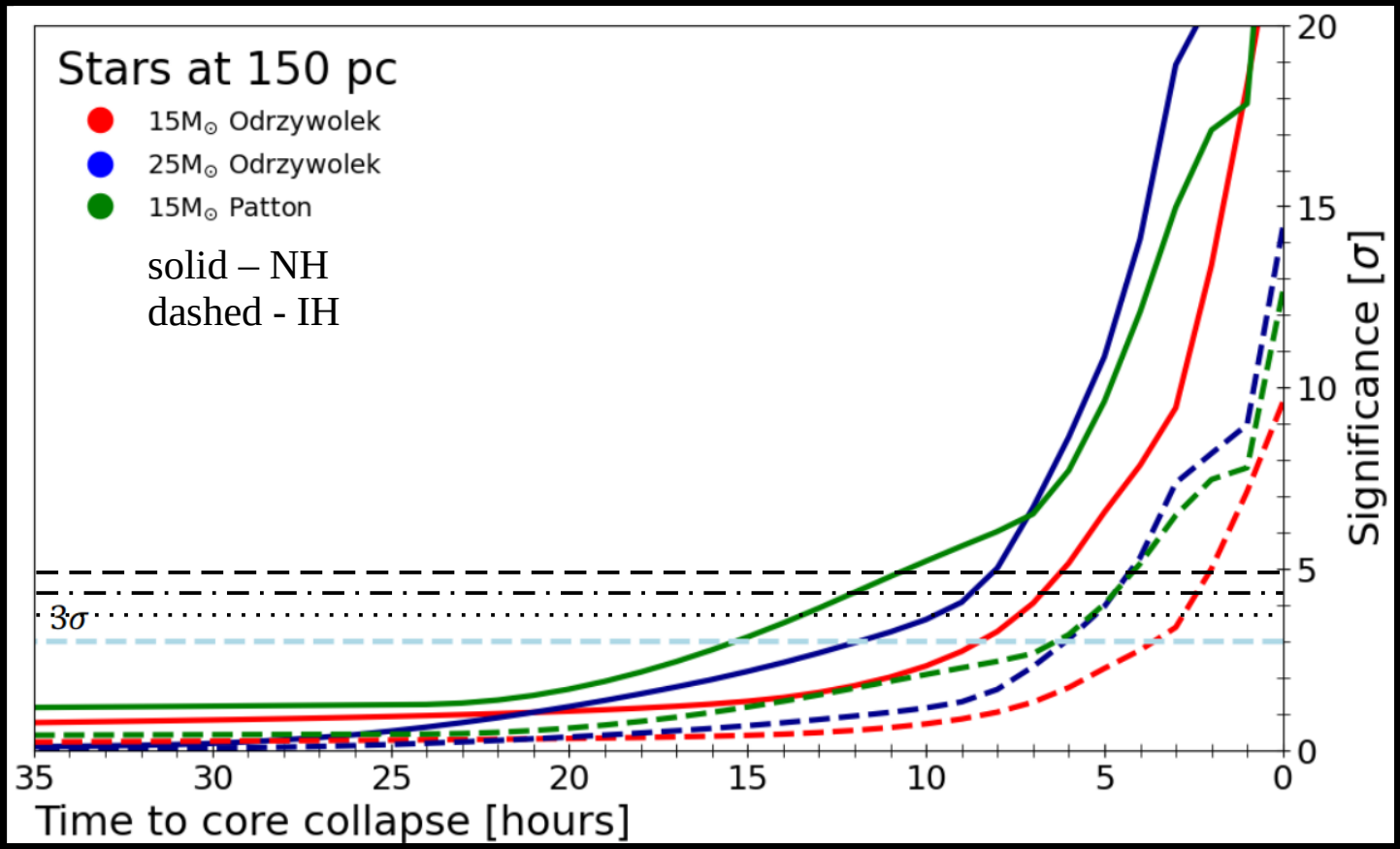


Mass hierarchy Sensitivity

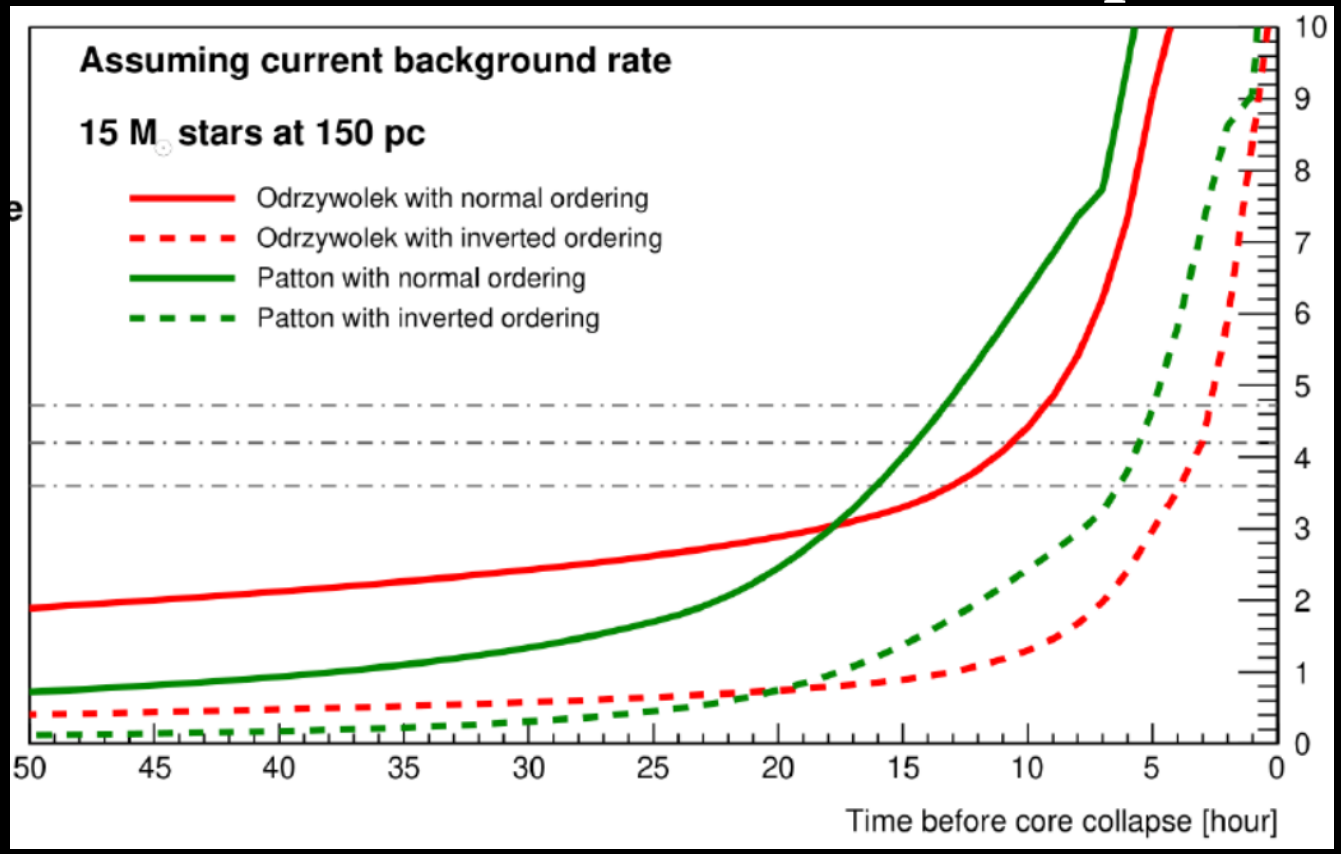
Late stage stellar Evolution insight

Updated number of events and significance for SK-Gd with 0.03% Gd.

→ Assuming 150 pc and M=15 $M_\odot$ a pre-SN warning could be issued ~11h before explosion (~1 false alarm/century)

L. N. Machado, Pre-supernova Alert System for Super-Kamiokande, The Astrophysical Journal, 935, 40 (2022)
Patton, et al 2017 ApJ 851 6

SK and KamLAND Pre-SuperNova Alarm



MoU between SK & KamLAND

Paper in preparation

Time to core collapse with false alarm rate at 1/100 years.

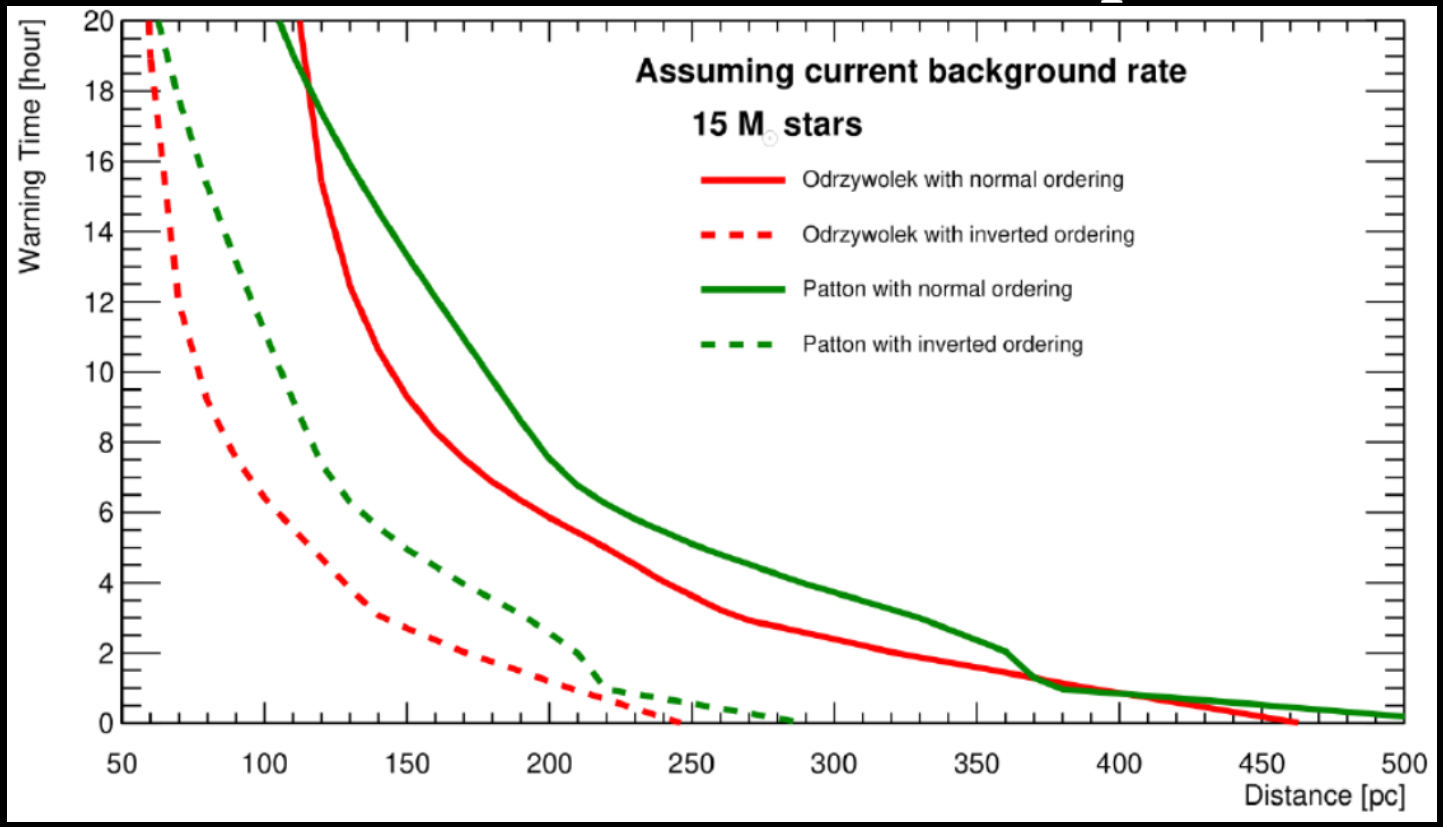
KamLAND and SK have their own pre-SN alarms since 2015 and 2021.

Reduce false alarms and increase sensitivity to close pre-SNe.

→ Assuming 150 pc and M=15 $M_{\odot}$ a pre-SN warning could be issued ~13h before explosion (~1 false alarm/century)

L. N. Machado, Pre-supernova Alert System for Super-Kamiokande, The Astrophysical Journal, 935, 40 (2022)
K. Asakura et al., 'KamLAND Sensitivity to Neutrinos from Pre-Supernova Stars', 2016 ApJ 818 91

SK and KamLAND Pre-SuperNova Alarm



Time to core collapse with false alarm rate at 1/100 years.

KamLAND and SK have their own pre-SN alarms since 2015 and 2021.

Reduce false alarms and increase sensitivity to close pre-SNe.

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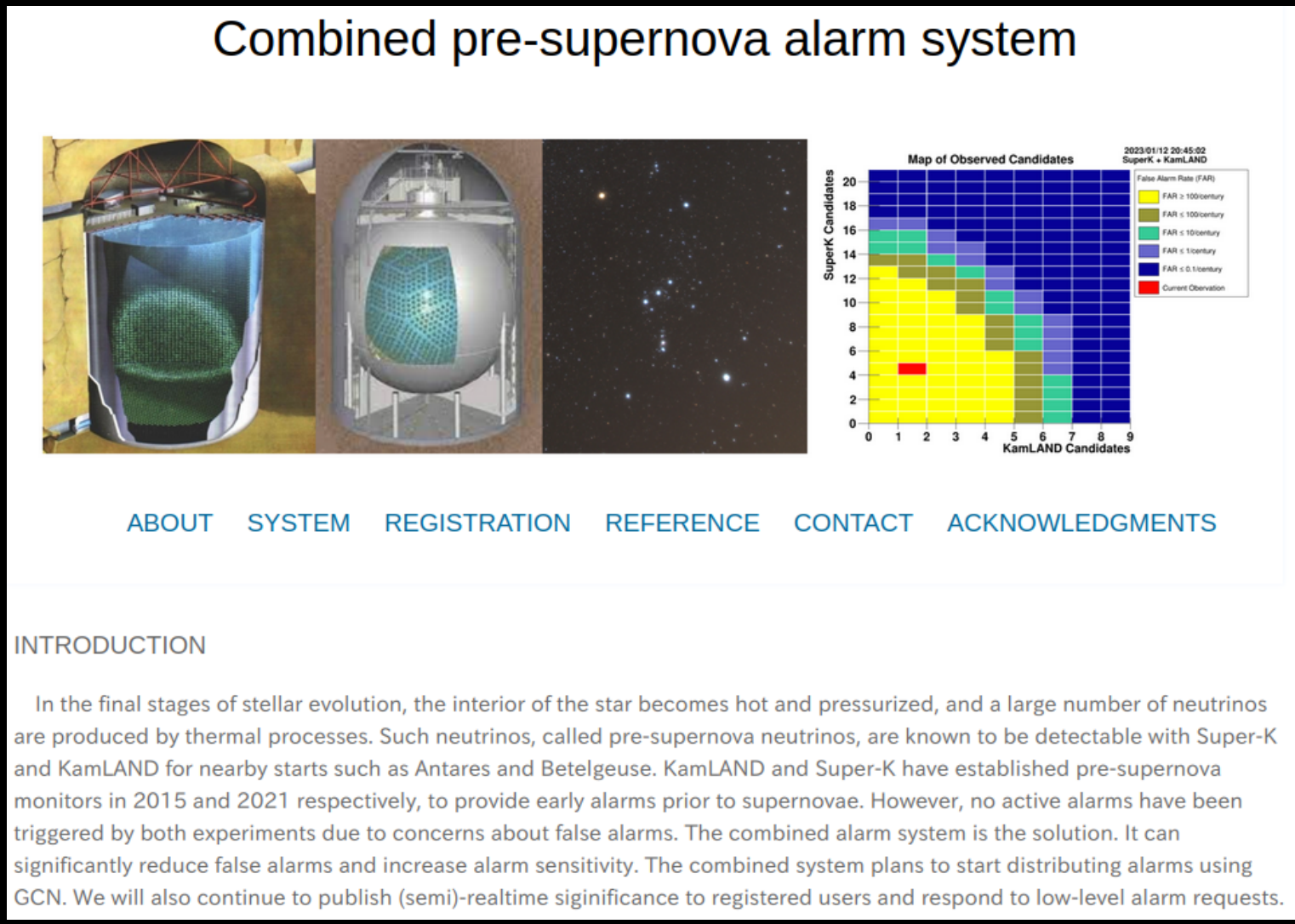
SK and KamLAND Pre-SuperNova Alarm

Do you want to have access to the real-time alarm status?

You can get more info and register at: https://www.lowbg.org/presnalarm/



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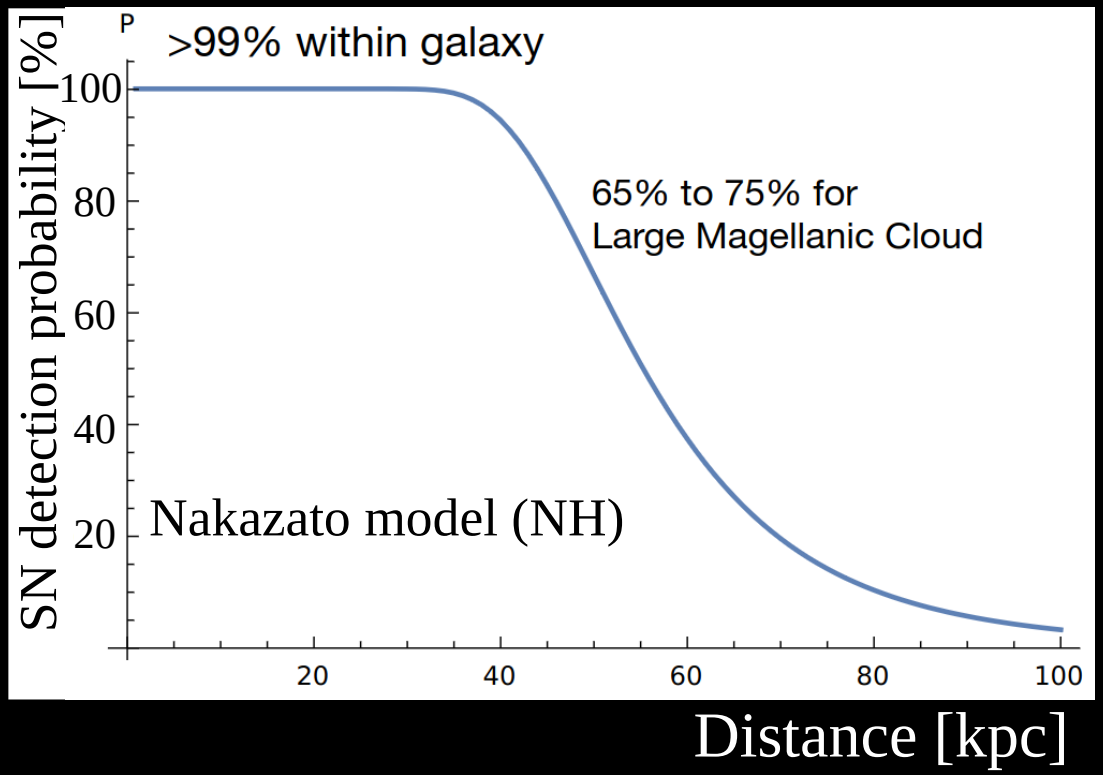
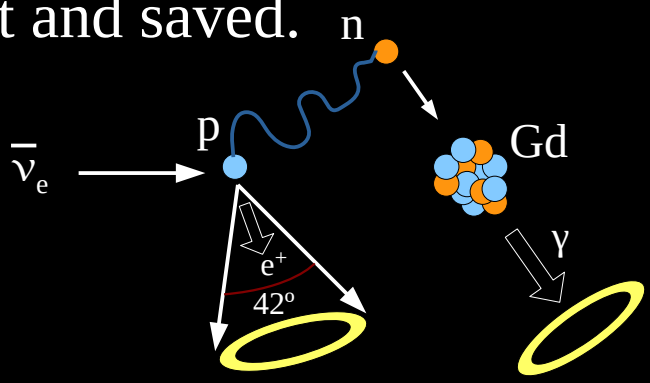
WIT online SN alarm



Searches IBD candidate events in a 10 sec window.

When more than 10 candidates are found a SN alarm is issued.

Raw data for the last ~5 minutes is being kept and saved.



It can process all the SN related data in 20 seconds even for a close SNe.

Now implementing SN direction capabilities and improving the SN detection efficiency.

It is expected to be able to deliver information such as event energy spectrum, number of events and SN direction within 40 seconds.

Summary

Super-Kamiokande has been running since 1st of April 1996 with impressive results.

Continuous efforts to improve the detector through each phase.

The **W**ide-band **I**ntelligent **T**rigger (WIT) started taking data during SK-IV and it has improved low energy physics → more in the future!

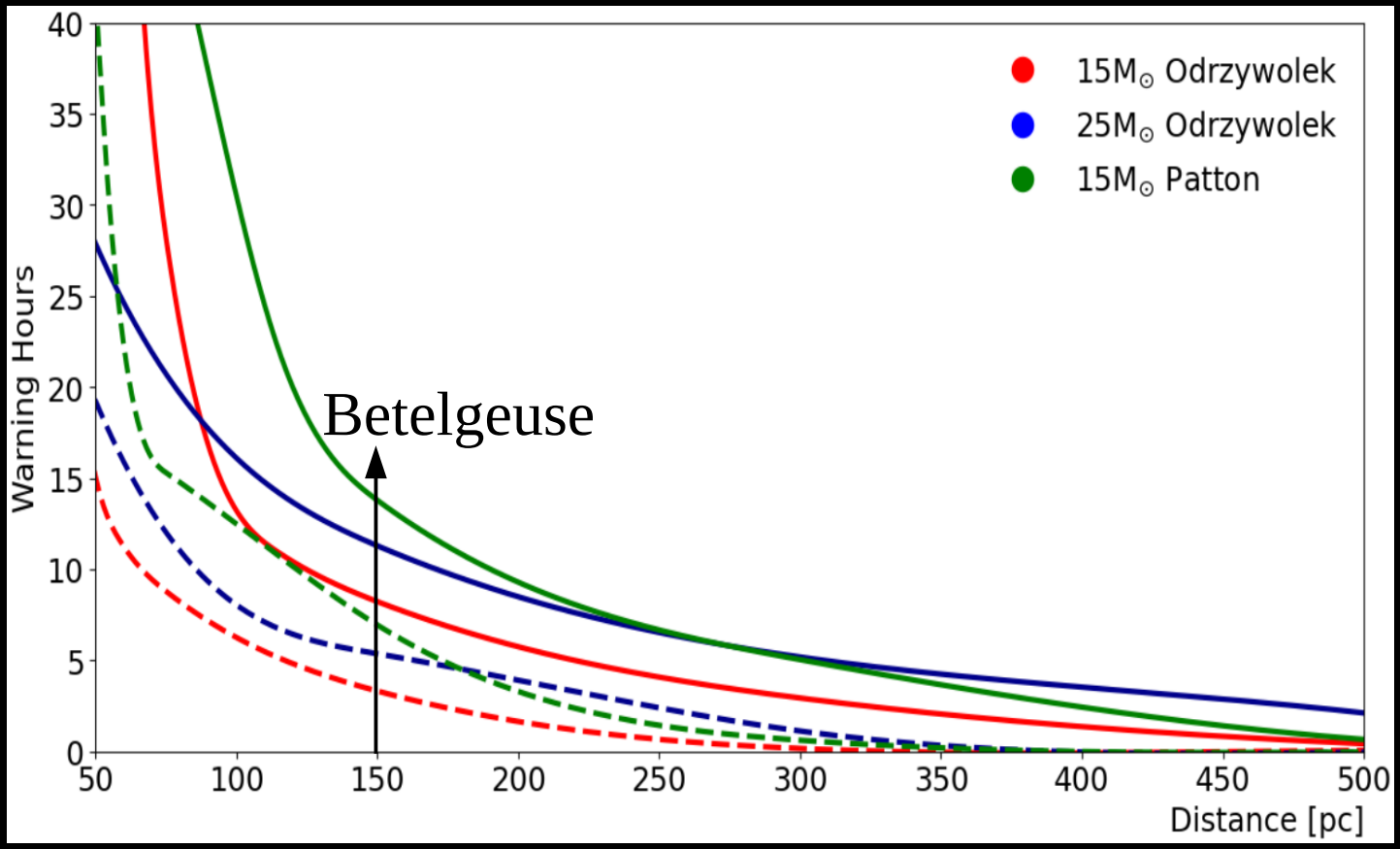
→ SK solar paper in preparation including full SK-IV phase data.

Since July 2022 it is loaded with 0.03% Gd which has vastly improved SK's neutron efficiency detection → SK-Gd !!

WIT can now search for close pre-SN and galactic SN neutrinos:

→ Early pre-warning: avoid missing such a golden opportunity.
→ Save SN raw data for later improved analysis.
→ Under development: a new SN direction fitter based on WIT.

SK's Pre-SuperNova WIT Alarm



Updated number of events and significance for SK-Gd with 0.03% Gd

→ Assuming 150 pc and M=15 $M_\odot$ a pre-SN warning could be issued ~15h before explosion.

Warning hours for a 3 σ detection (12 hour sliding window)

L. N. Machado, Pre-supernova Alert System for Super-Kamiokande, The Astrophysical Journal, 935, 40 (2022)

EGADS/HEIMDALL

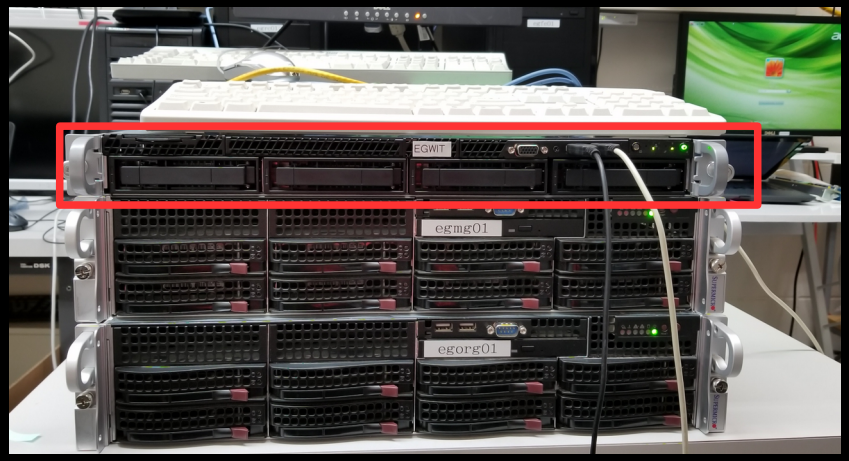
High **E**fficiency **I**BD **M**onitoring **D**etector and **A**utomated ca**LL**

HEIMDALL is an online machine that searches for IBD (prompt + delayed neutron capture) events in real time:

If ≥ 3 events (within 10 sec) are detected, a SN automated alarm is issued.

→ Latency time ≃ 5 seconds

→ False alarm rate: 1/decade (at threshold).



- EGADS/HEIMDALL is watching for SNe:

→ HEIMDALL watches for galactic SNe and would give an instant, automatic and independent alert to us and the community.

EGADS/HEIMDALL

High **E**fficiency **I**BD **M**onitoring **D**etector and **A**utomated ca**LL**

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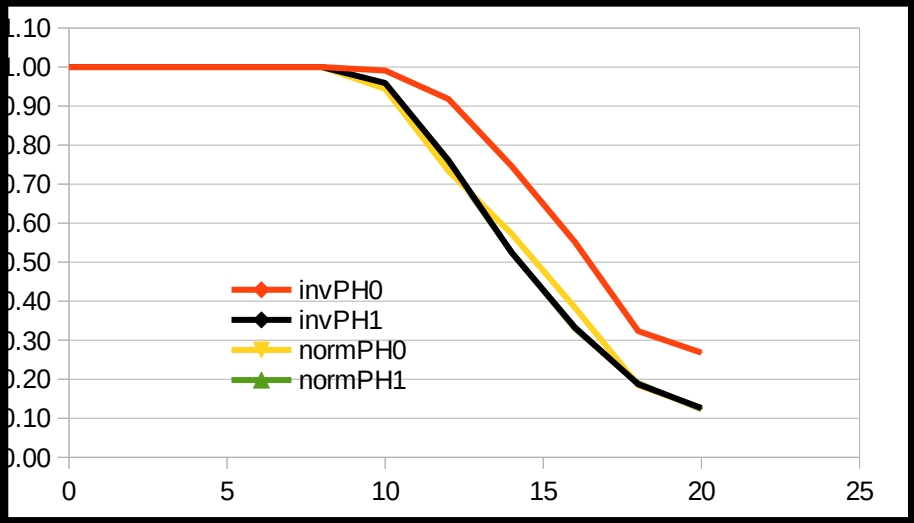
Good galactic coverage already with the current concentration:

→ to be increased in the future to 0.1% (90% of captures on Gd)



- EGADS/HEIMDALL is watching for SNe:

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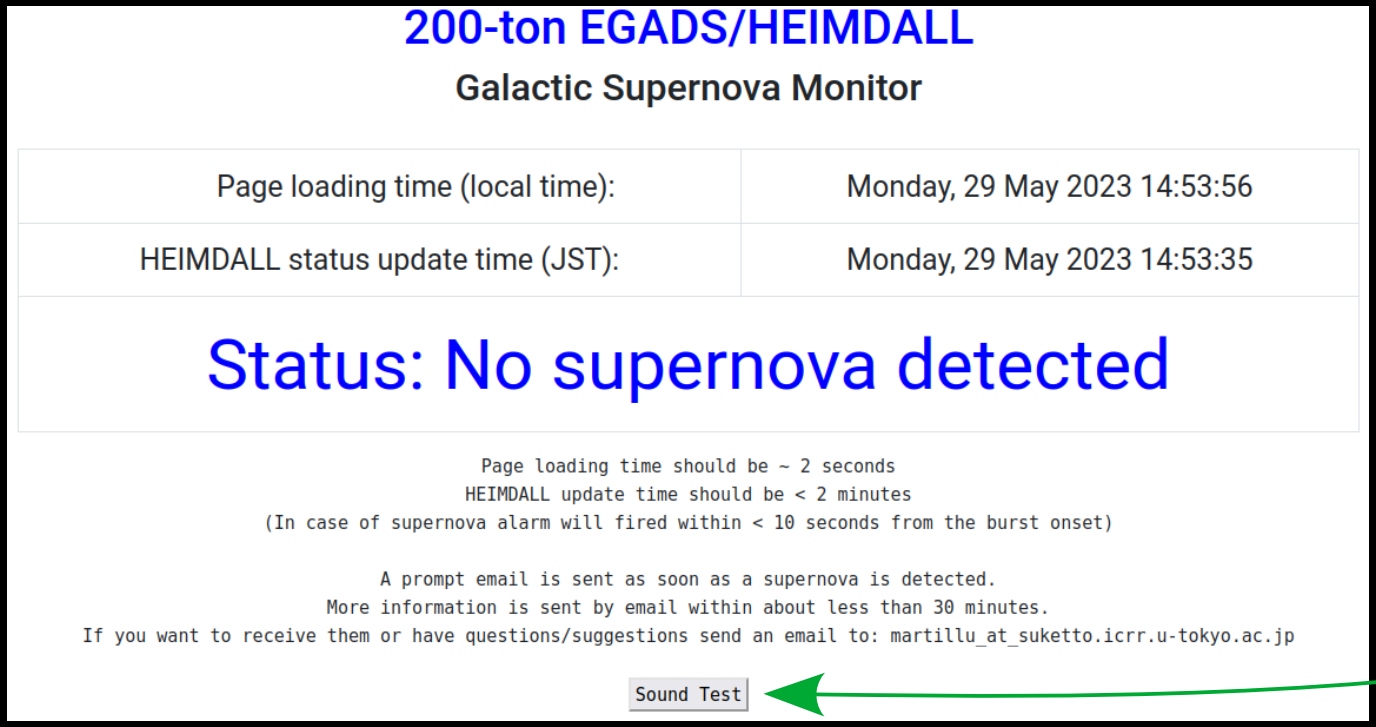
"inv" for inverse and "norm" for normal neutrino hierarchy
PH: 0 adiabatic transitions, 1 w/o
Nakazato model for: M=13, Z=0.02 trev=100 ms

HEIMDALL public SN webpage

- Public SN webpage:

Available for everyone at: https://www-sk.icrr.u-tokyo.ac.jp/egadsSNalarm/

The page includes a **sound alarm.** **You can open it and check it**



For Automated SN Warning Mails contact: martillu_at_suketto.icrr.u-tokyo.ac.jp

Evaluating
Gadolinium's
Action on
Detector
Systems

Employing
Gadolinium to
Autonomously
Detect
Supernovas