University of Sheffield

Supernova spotting in Super-Kamiokande Gd

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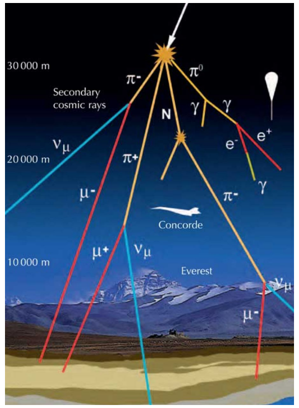
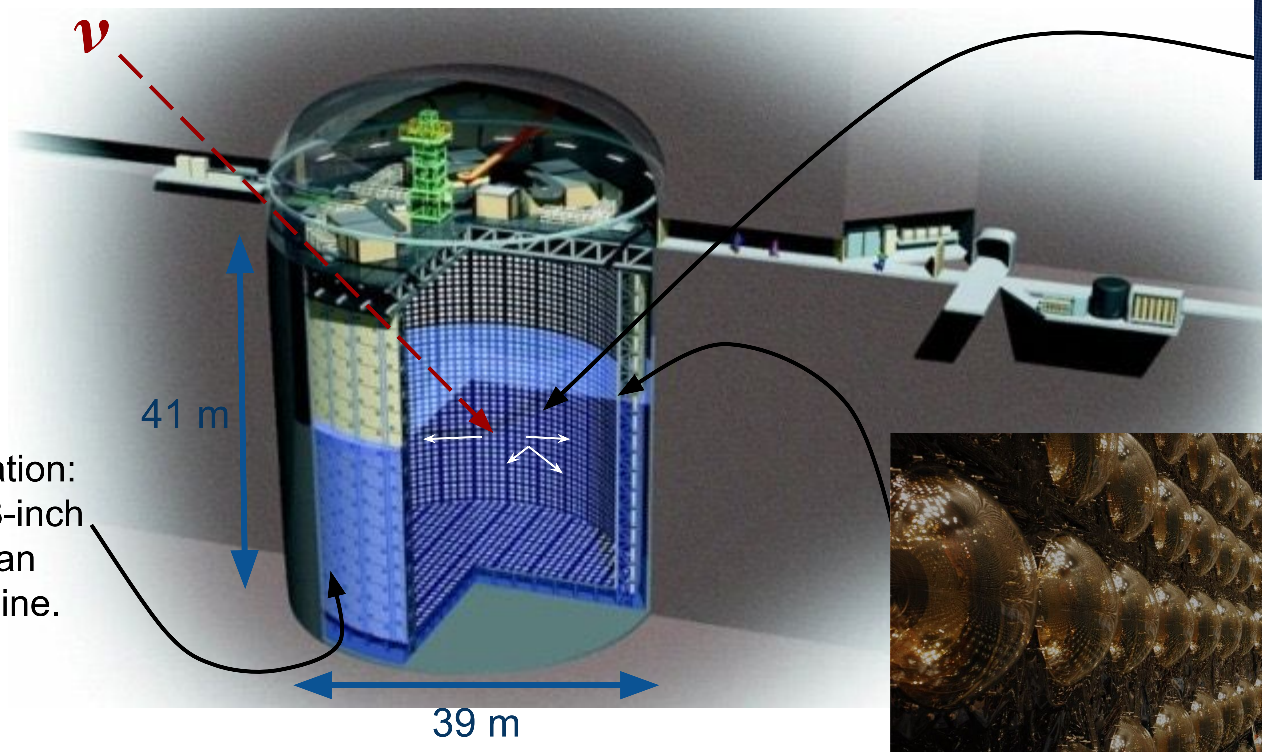
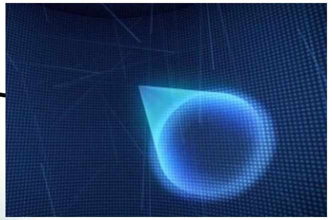
M. Weiss / Center for Astrophysics | Harvard & Smithsonian

Super-Kamiokande

50 ktonne water Cherenkov detector with 22.5 ktonne fiducial

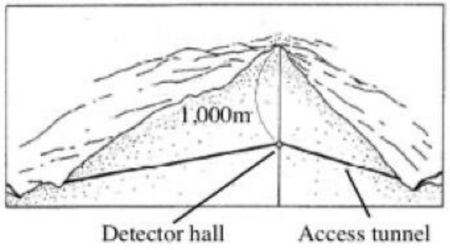


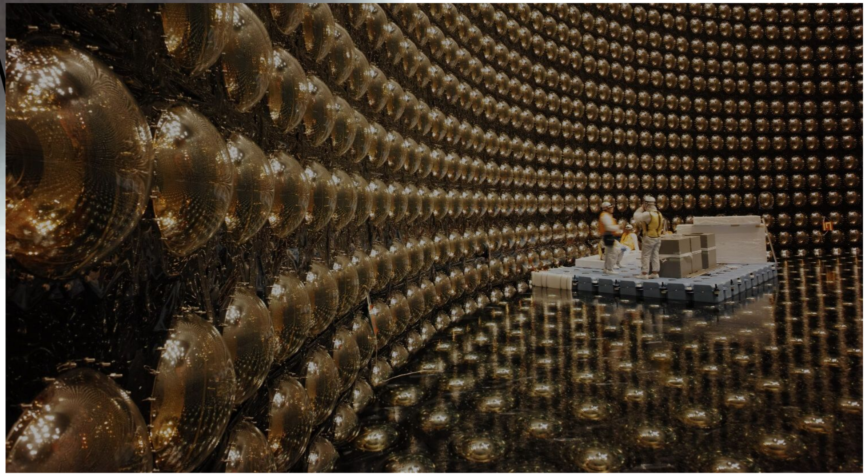




Neutrino interactions produce relativistic charged particles, which emit Cherenkov light

Cosmic-ray muon background mitigation: 2m thick outer detector with ~1,885 8-inch photomultiplier tubes (PMTs) and an underground location in Kamioka mine.





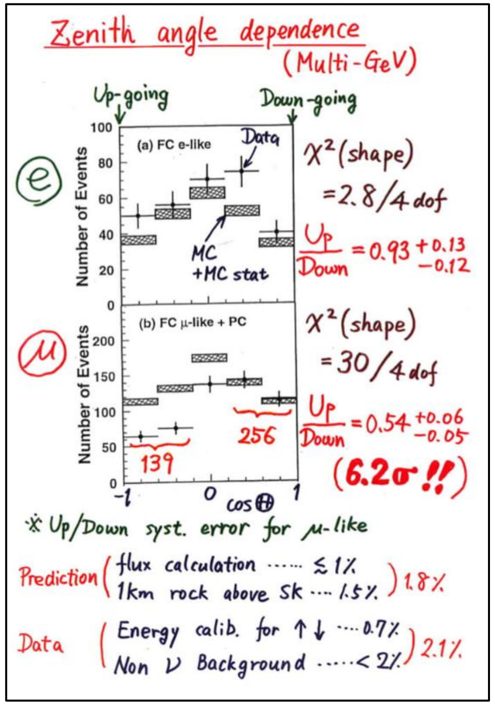
~11,000 20-inch PMTs facing inwards to detect the Cherenkov light signals

A distinguished history at Kamioka

1980s

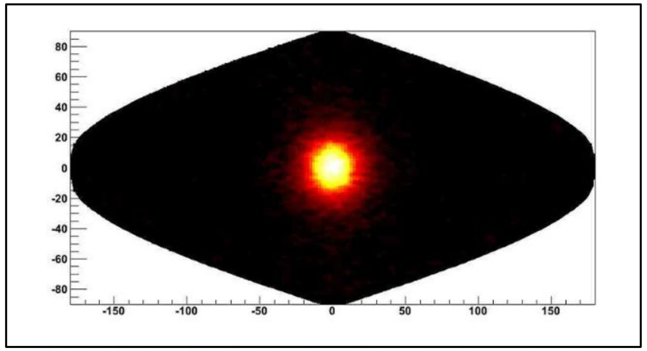
Kamiokande sees neutrinos from a supernova explosion.

1990s



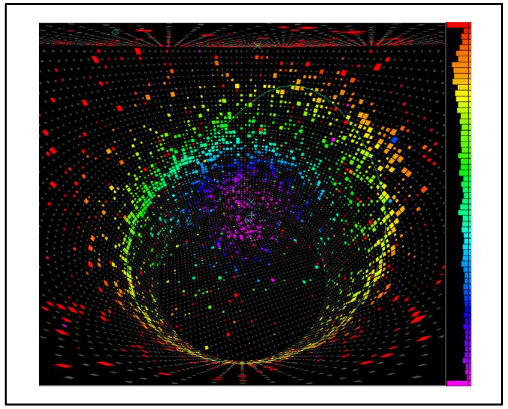
Super-K discovers atmospheric neutrino oscillation in 1998.

2000s



Super-K and SNO discover solar neutrino oscillation in 2001

2010s

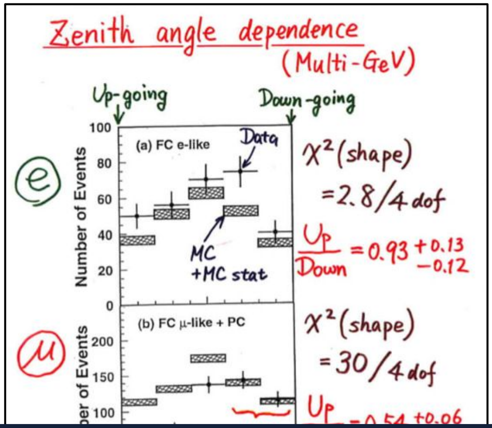


T2K discovers electron neutrino appearance in 2011

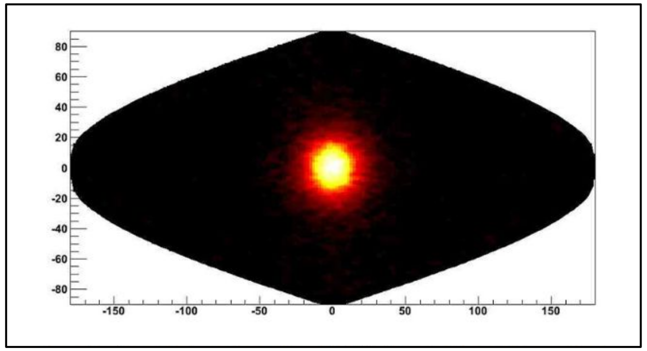
Still innovating

1980s

1990s

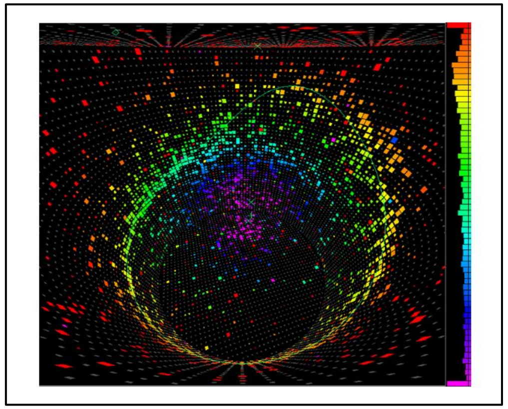


2000s



Super-K and SNO

2010s



Kamiok
neutrino
superno

011

Super-Kamiokande has been running with gadolinium (Gd) dissolved in the tank since 2020 and we're waiting for the next major discovery!

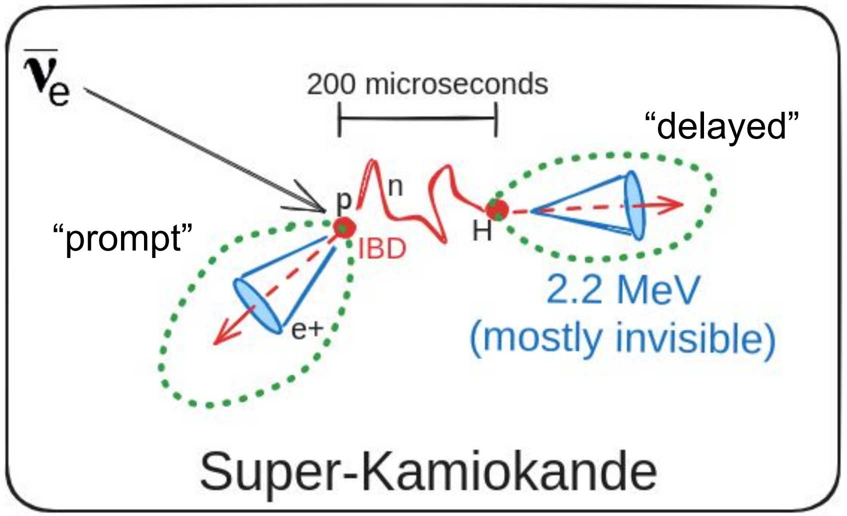
Gd for supernova spotting

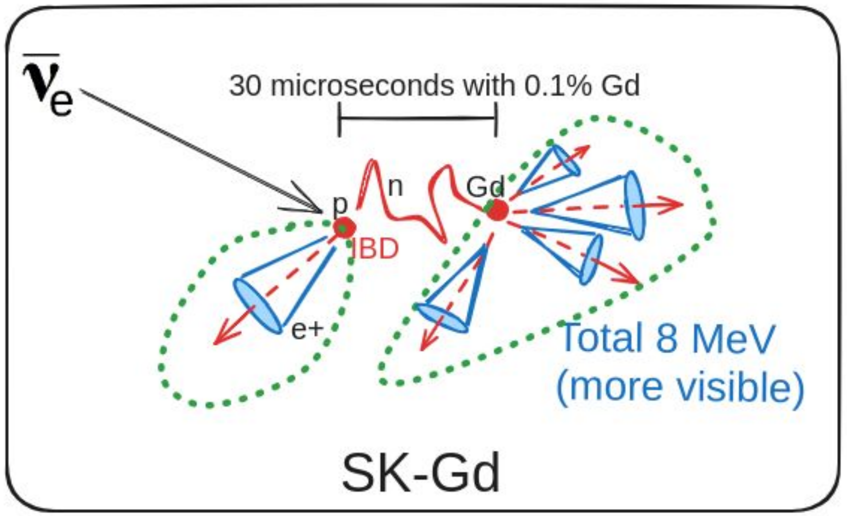
What can we do with Gd in the tank?

- See **pre-supernova neutrinos** from Si-burning
- Improve **pointing** accuracy for a galactic supernova
- See **Diffuse Supernova Neutrino Background** (DSNB) from all supernovae since the beginning of time
- See reactor neutrinos
- Enhance ν and $\bar{\nu}$ identification in atmospheric ν and T2K analyses
- Reduce background in nucleon decay search

For these goals, we need to detect the inverse beta decay (IBD) interaction (~90% of the expected supernova neutrino interactions).

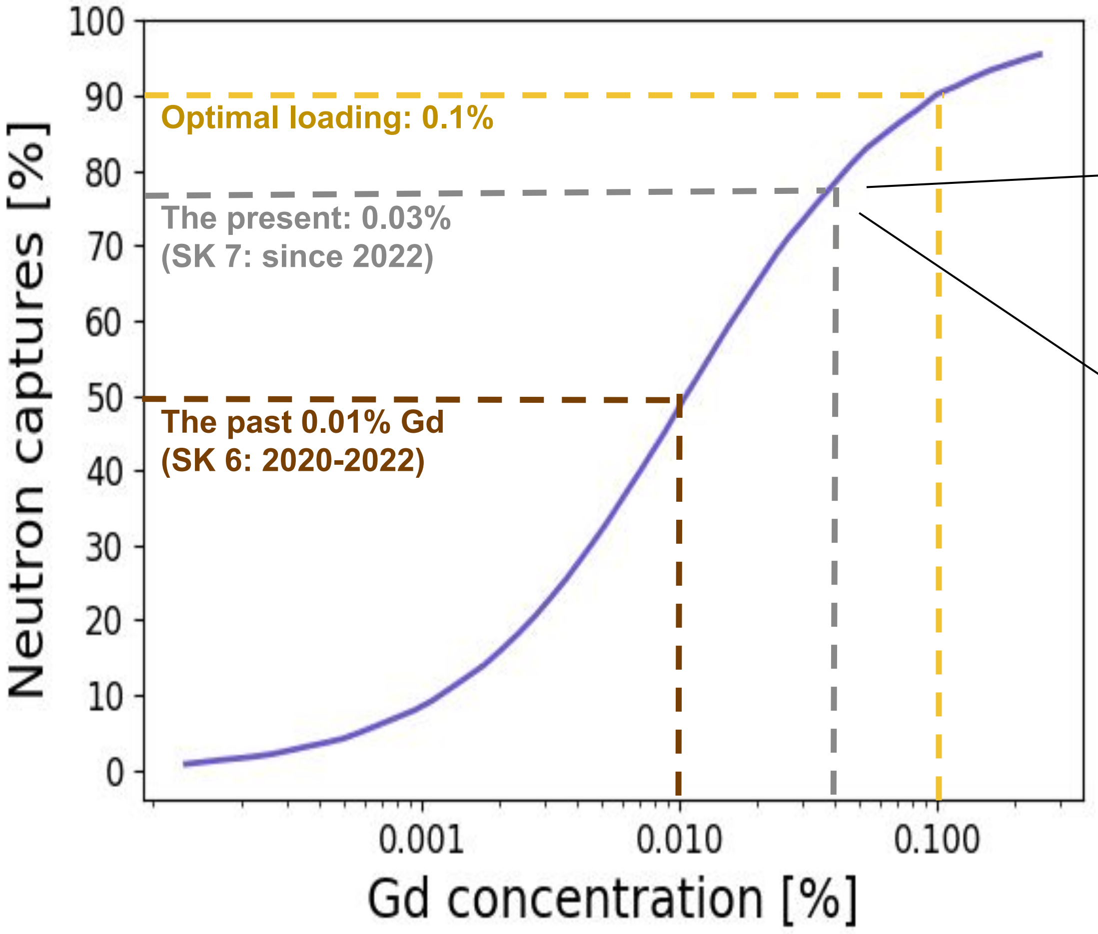
With Gd, we can tag the previously indistinct neutrons from IBD.

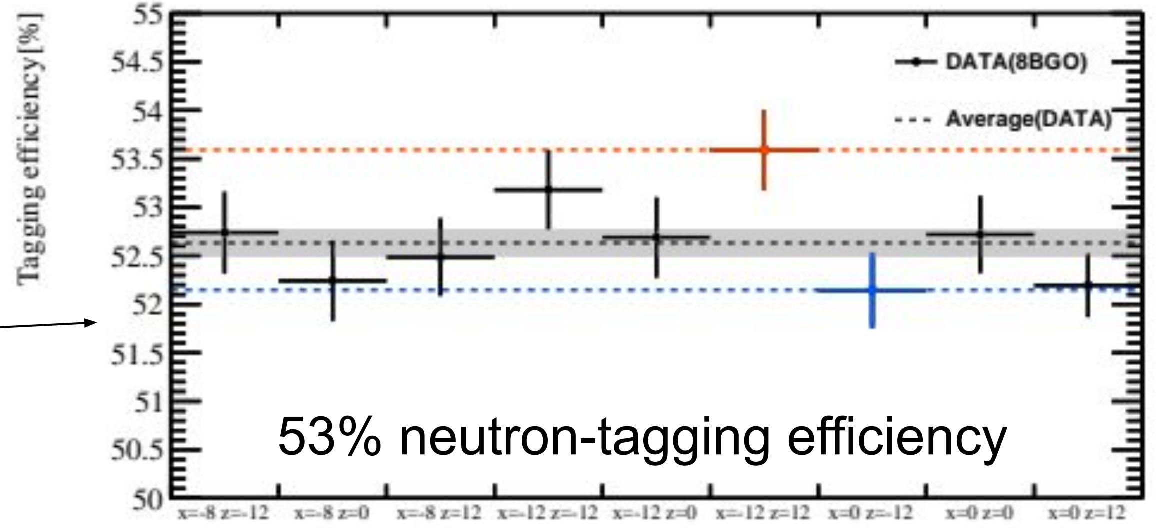


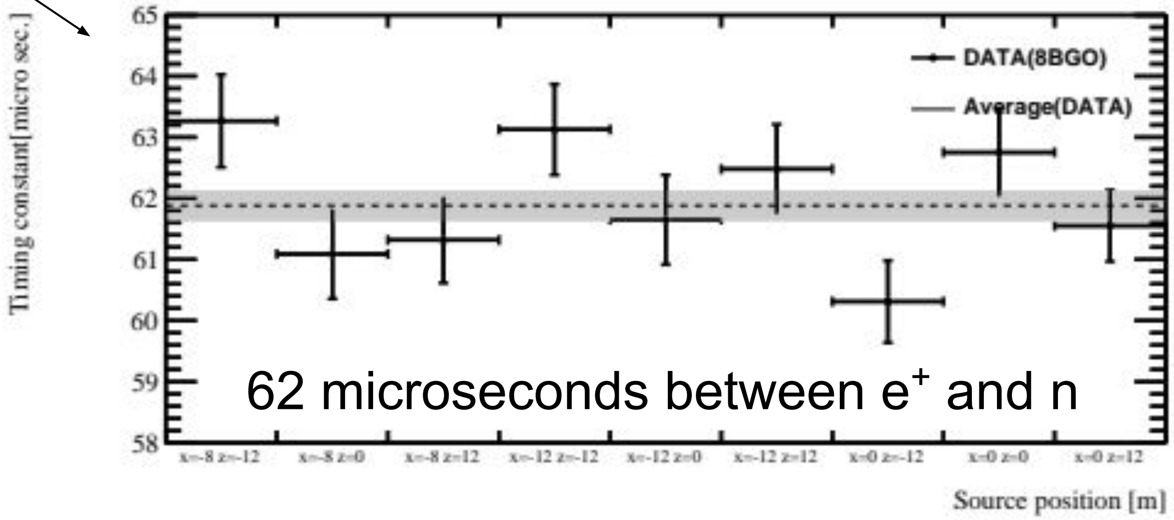


Now running with 0.03% Gd

F. Nakanishi







Supernova neutrinos

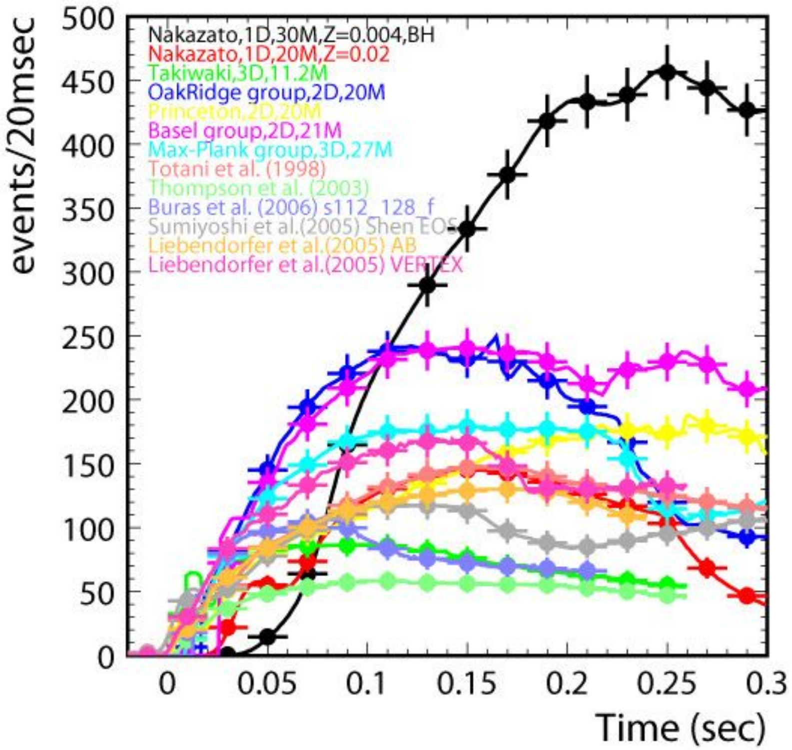
Visible light signal came later

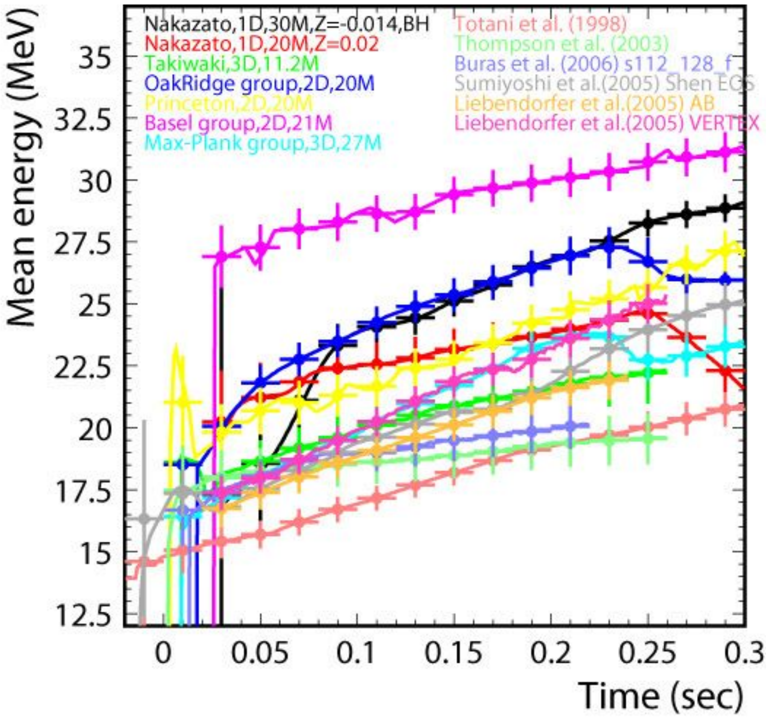
Neutrinos from supernova 1987A in the Large Magellanic Cloud (50kpc):

- Kamiokande-II (11 evts.)
- IMB-3 (8 evts.)
- Baksan (5 evts.)

- Core-collapse supernovae (“supernovae” in this talk) produce a neutrino burst which we can detect on Earth
- **Neutrinos are produced at multiple stages**:
  - initial matter infall
  - subsequent shock revival
  - remnant proto-neutron star cooling
- Neutrinos carry away >99% of the energy from supernova explosions
- Neutrino signal produced a few minutes to several hours **before the stellar explosion** so we can give advance warning to the wider supernova community

Many supernova models to disentangle





A large disparity between supernova models!

Shown here for number of neutrinos (left) and neutrino energy (right) as a function of time in Super-K for a supernova at 10 kpc.

Progress:

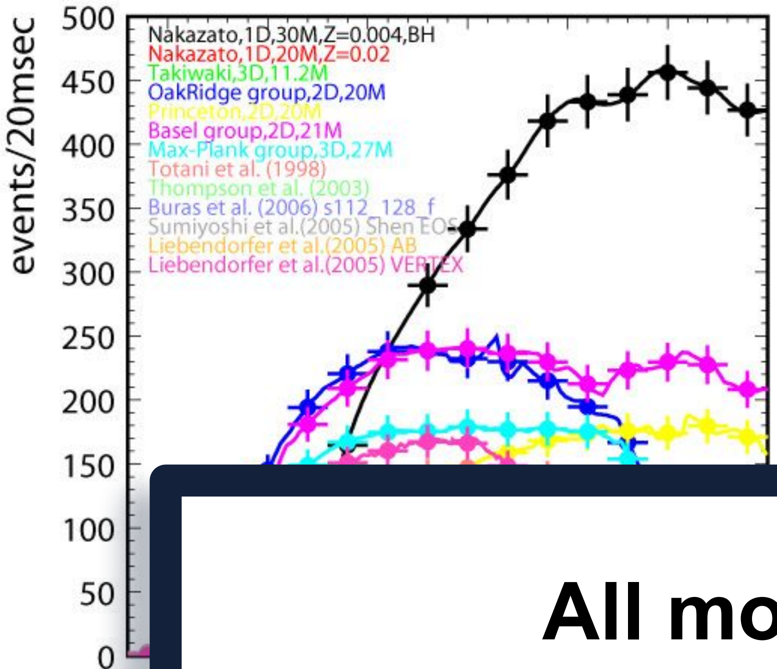
- Recent multi-dimensional supernova simulations successfully reproduce SN explosion.
- Several contributions to explosion mechanism (SASI[1], LESA[2], rotation, convection, equation of state).

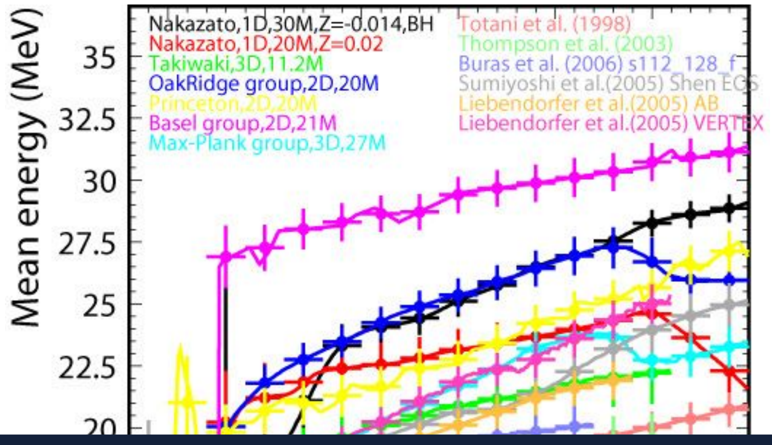
Challenges:

- Neutrino oscillation in high density
- MSW effect in much, much higher density than in the SUN!
- And many more…

[1]Standing Accretion-Shock Instability, [2] Lepton-number Emission Self-sustained Asymmetry

Many supernova models to disentangle





Progress:

- Recent multi-dimensional supernova simulations successfully reproduce SN explosion.
- Several contributions to explosion mechanism (SASI[1], LESA[2], rotation, convection…

All models agree that neutrinos are key.
Three fields of investigation: pre-supernova, supernova-burst and supernova relic neutrinos (DSNB).

A lot

Show… N!

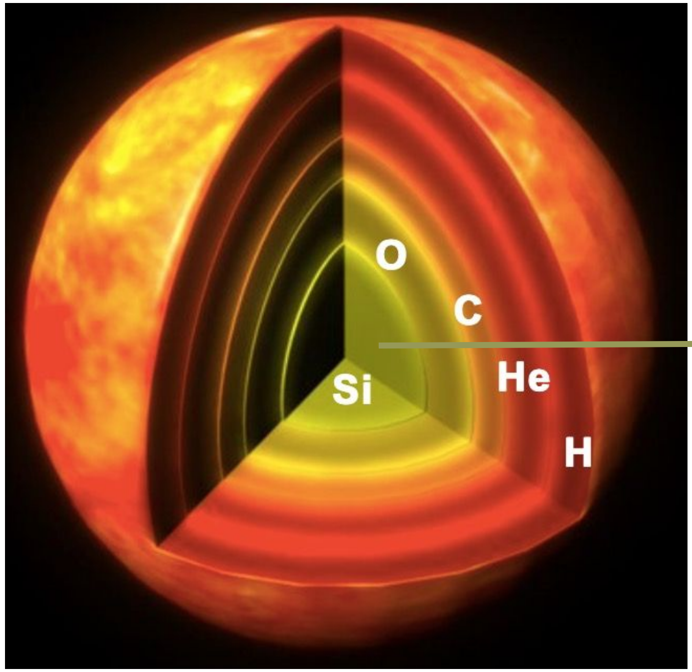
function of time in Super-K for a supernova at 10 kpc.

- And many more…

[1]Standing Accretion-Shock Instability, [2] Lepton-number Emission Self-sustained Asymmetry

Pre-SN neutrinos: the calm before the storm

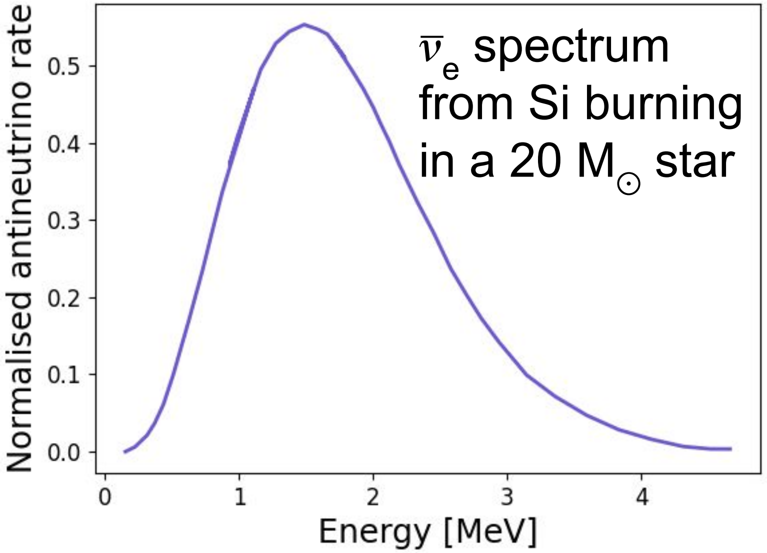
Neutrino emission increases as a massive star approaches the core-collapse supernova



Thermal neutrino emission from e^-e^+ annihilation is the dominant cooling in a pre-supernova (pre-SN) star.

~1 day of Si burning

(Adapted from Odrzywolek et al., 2004)



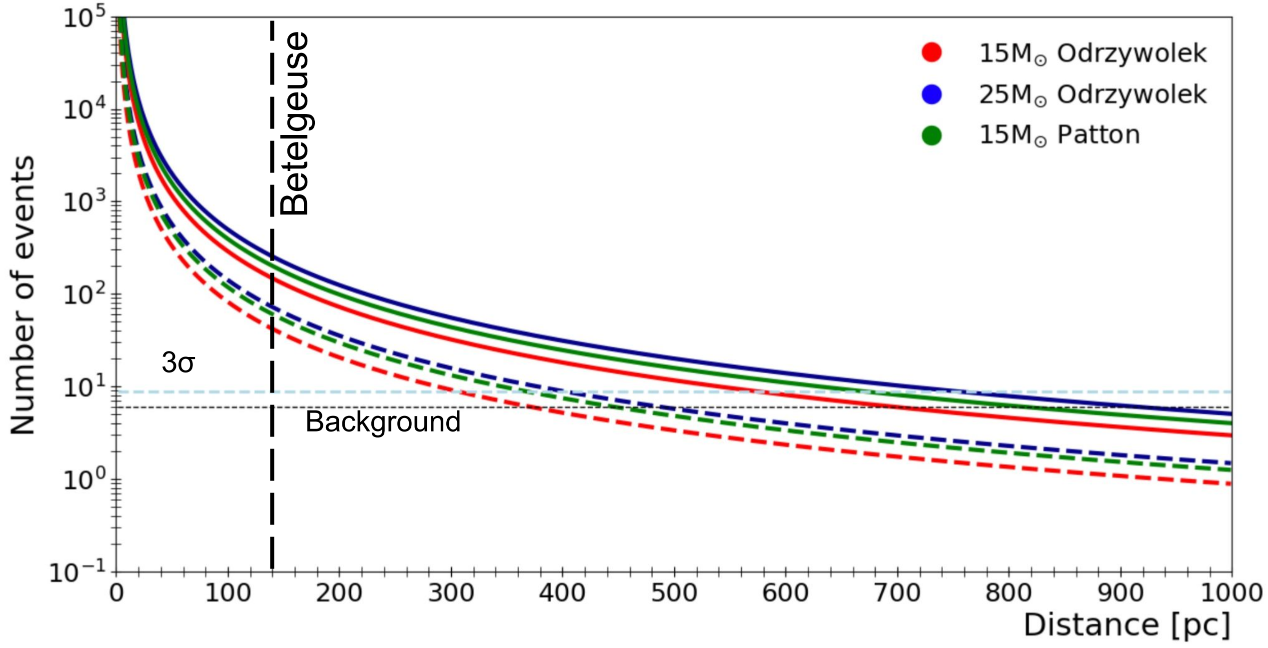
Silicon-burning in a pre-SN star produces **very low-energy neutrinos which are very difficult to see without Gd!**

Detecting pre-SN neutrinos would give **early warning of a supernova explosion** and **relate pre-SN conditions to explosion dynamics**

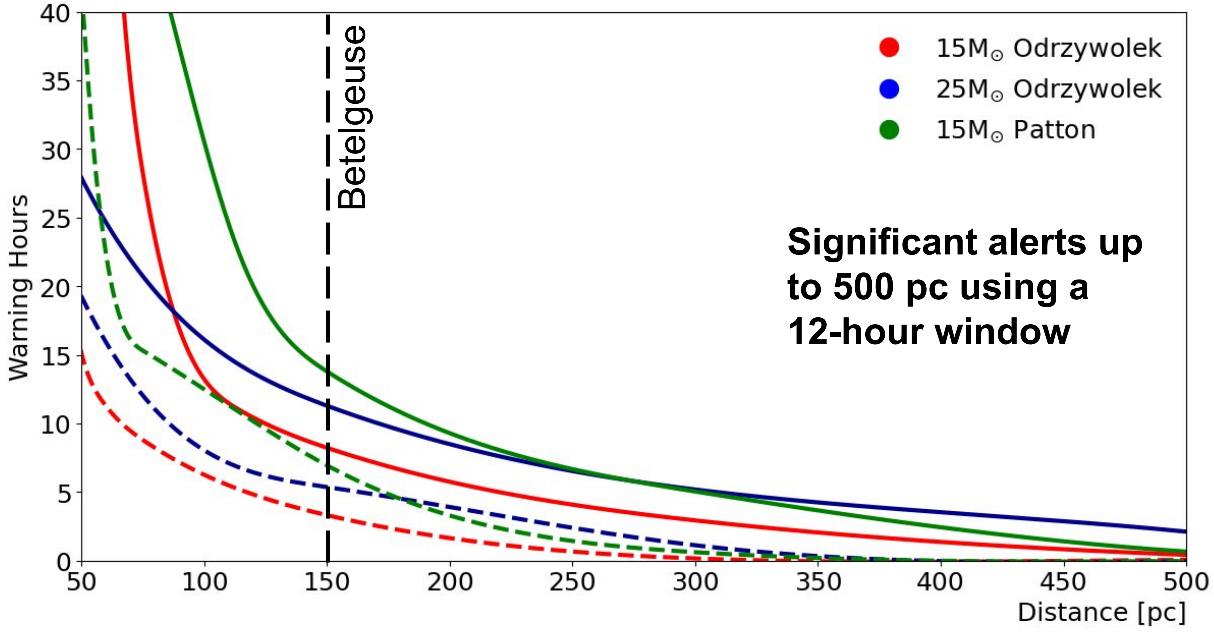
Pre-SN neutrinos from up to 800 pc away at 3σ

Up to 15 hours warning if Betelgeuse goes supernova!

L. Machado



Expected total number of IBD events in SK7 with 0.03% Gd as a function of distance to SN.



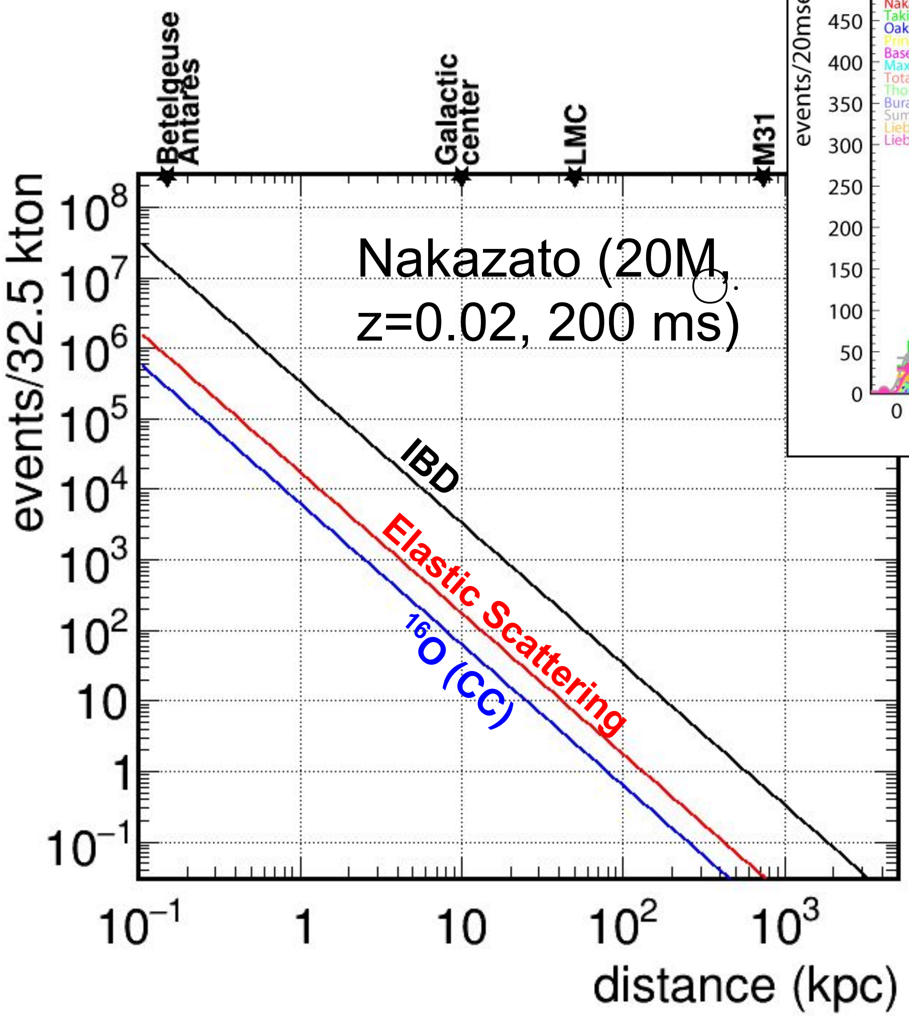
Expected warning hours as function of distance to SN for a 3σ detection.

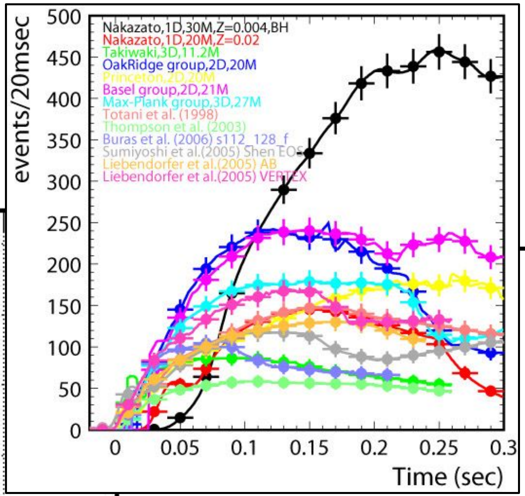
Online pre-supernova alert system went live in October 2021 (Machado et al, 2022).

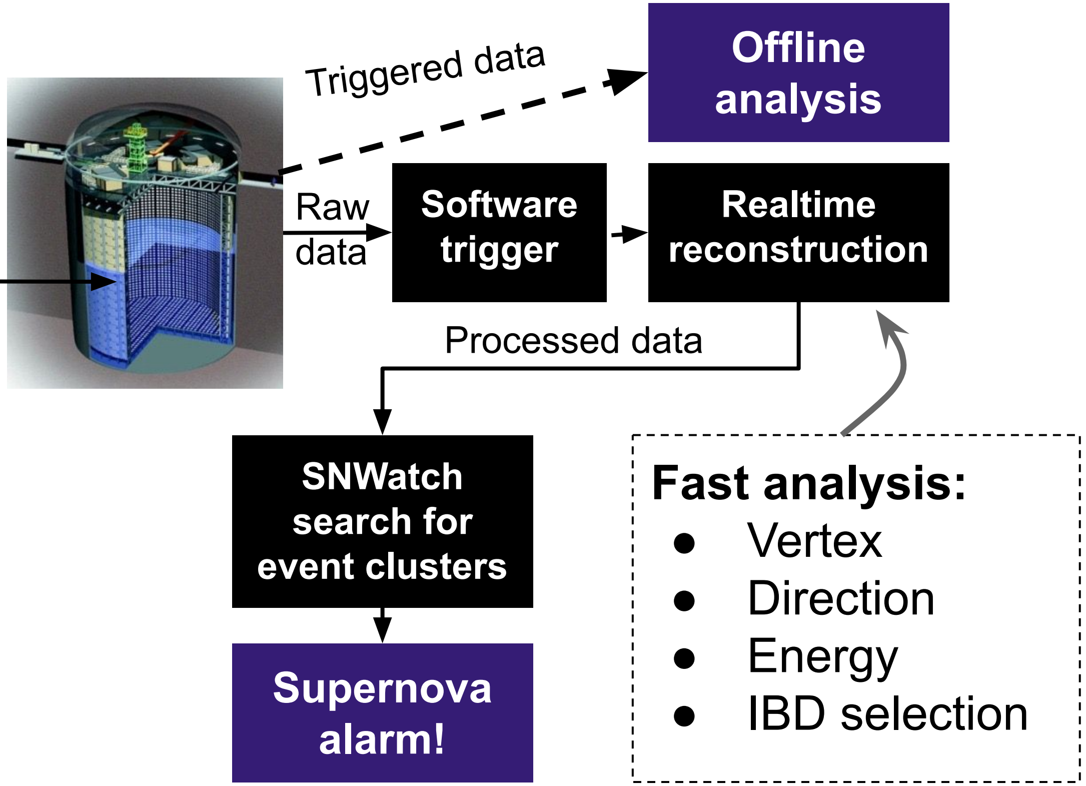
Combined pre-SN public alert system with KamLAND here.

Supernova burst neutrinos in SK-Gd

SK could detect a burst of neutrinos from a supernova >100kpc away (model-dependent).



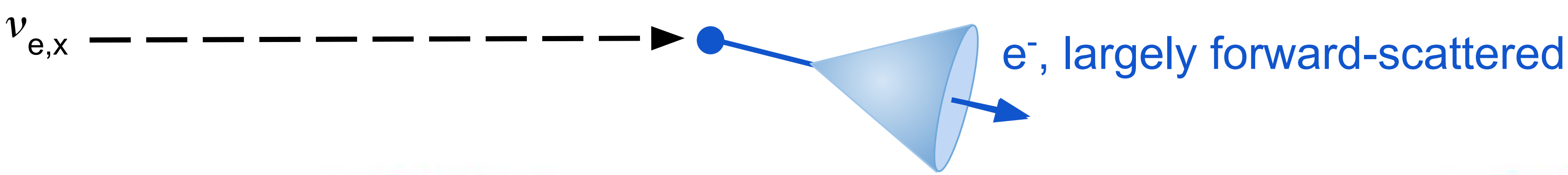


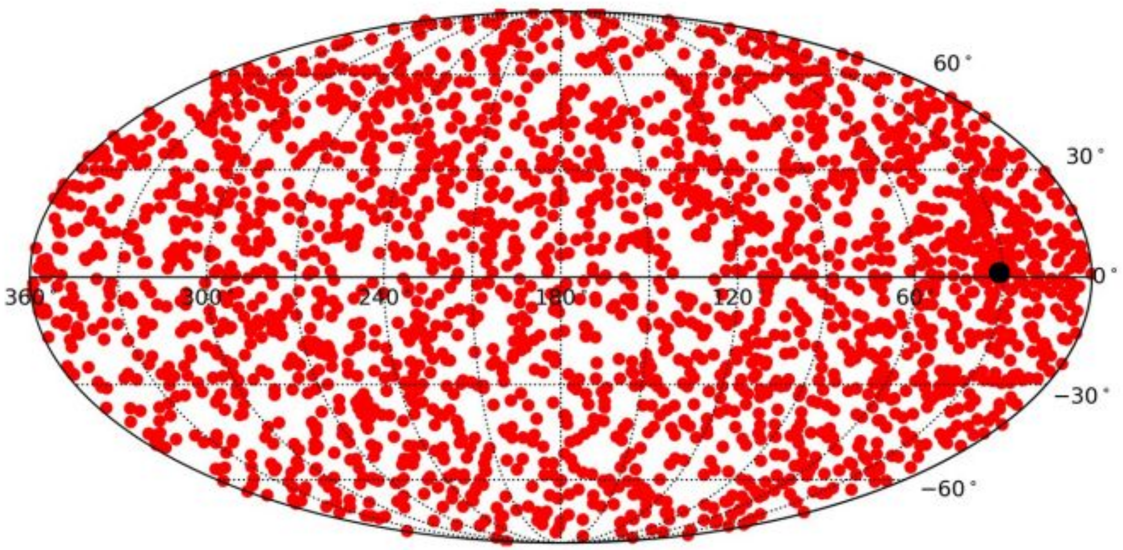


Alarm could be released in about 1 minute following a SN burst at 10 kpc (preliminary)

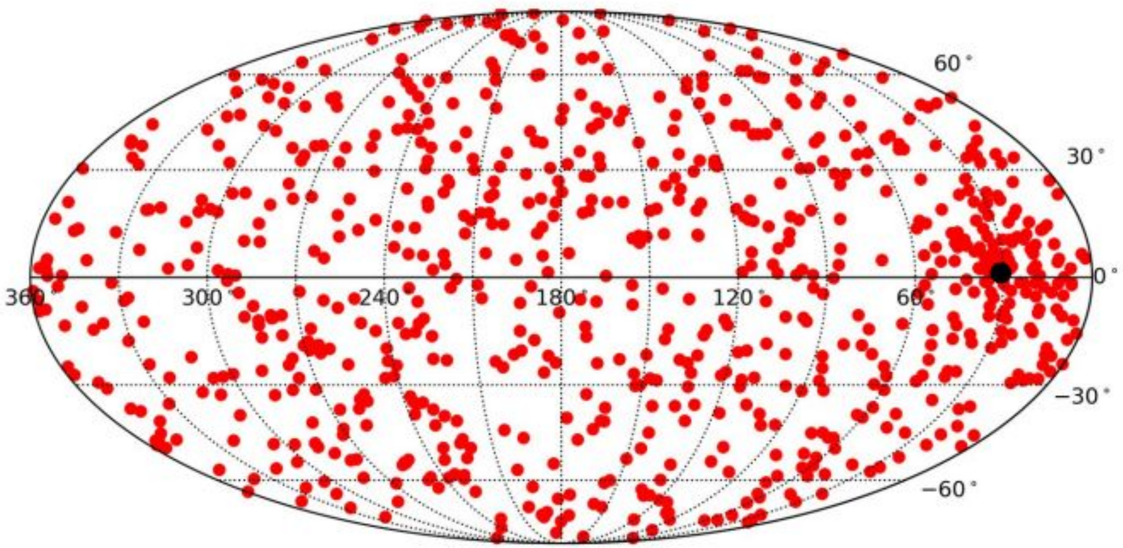
Isolate elastic scatters to point to supernova

Need to remove the IBD events to see the signal from elastic scatters on electrons





SN burst events with no IBD tagging
(10 kpc simulation)

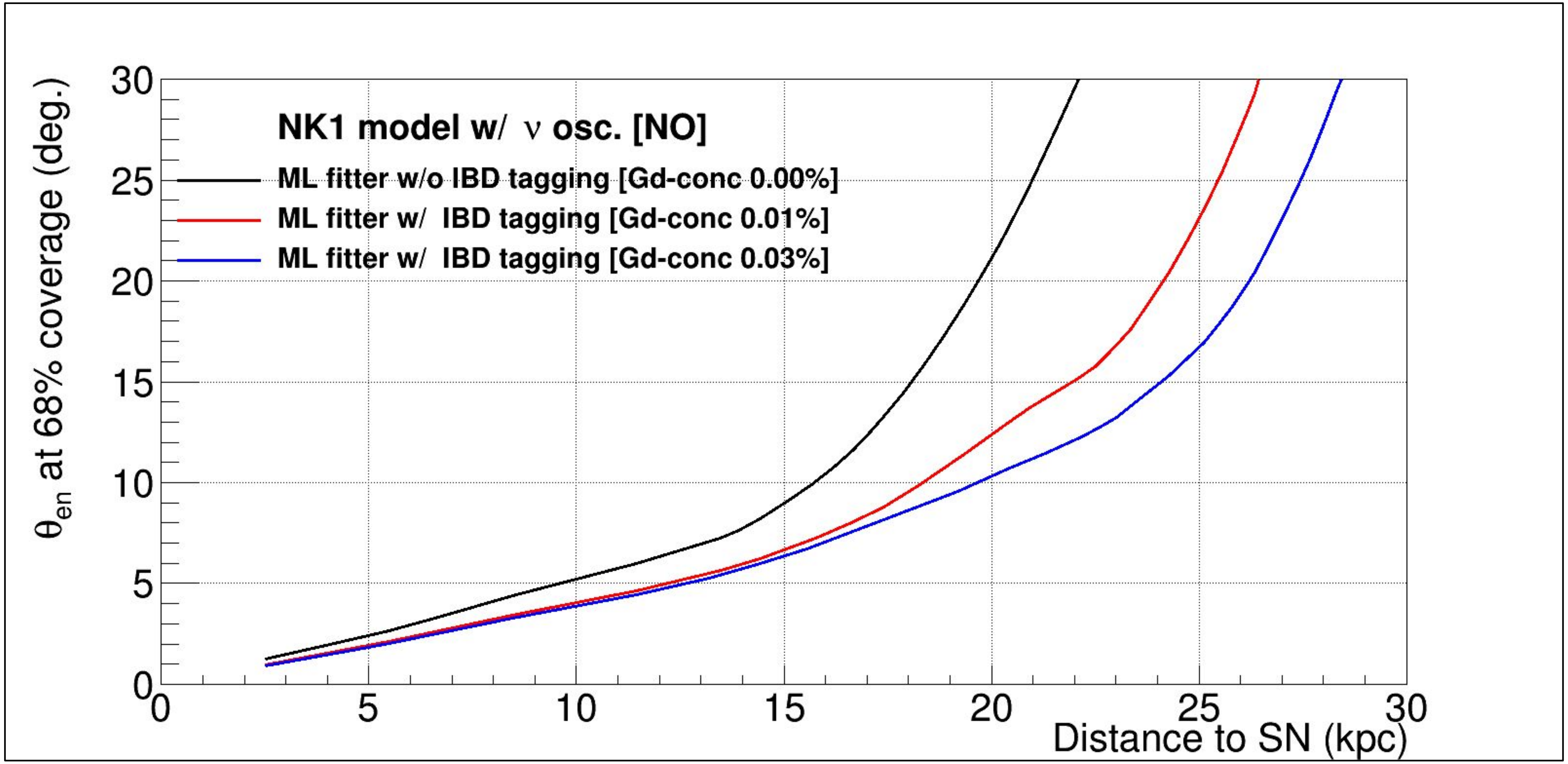


SN burst events with 72% of IBD events removed
(10 kpc simulation, 0.1% Gd)

Gd is vital to achieve good pointing accuracy!

Pointing within a few degrees for SN at 10 kpc

G. Pronost

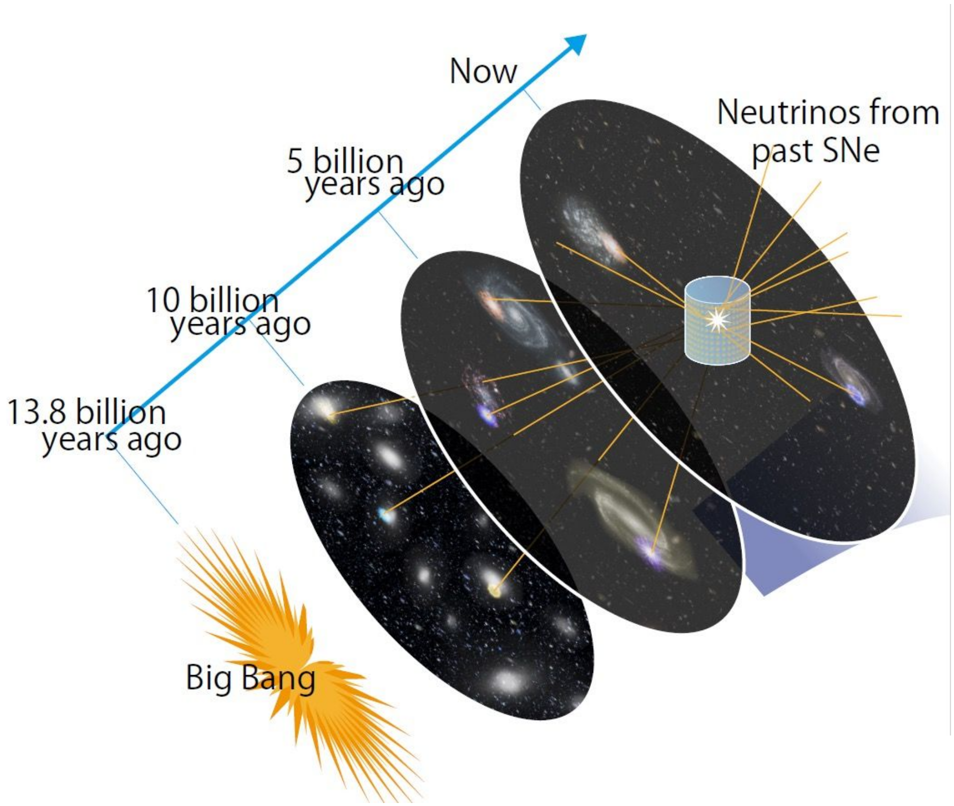


Pointing accuracy increasing with Gd concentration

DSNB - messengers from the beginning of time

Diffuse Supernova Neutrino Background (Supernova Relic Neutrinos):

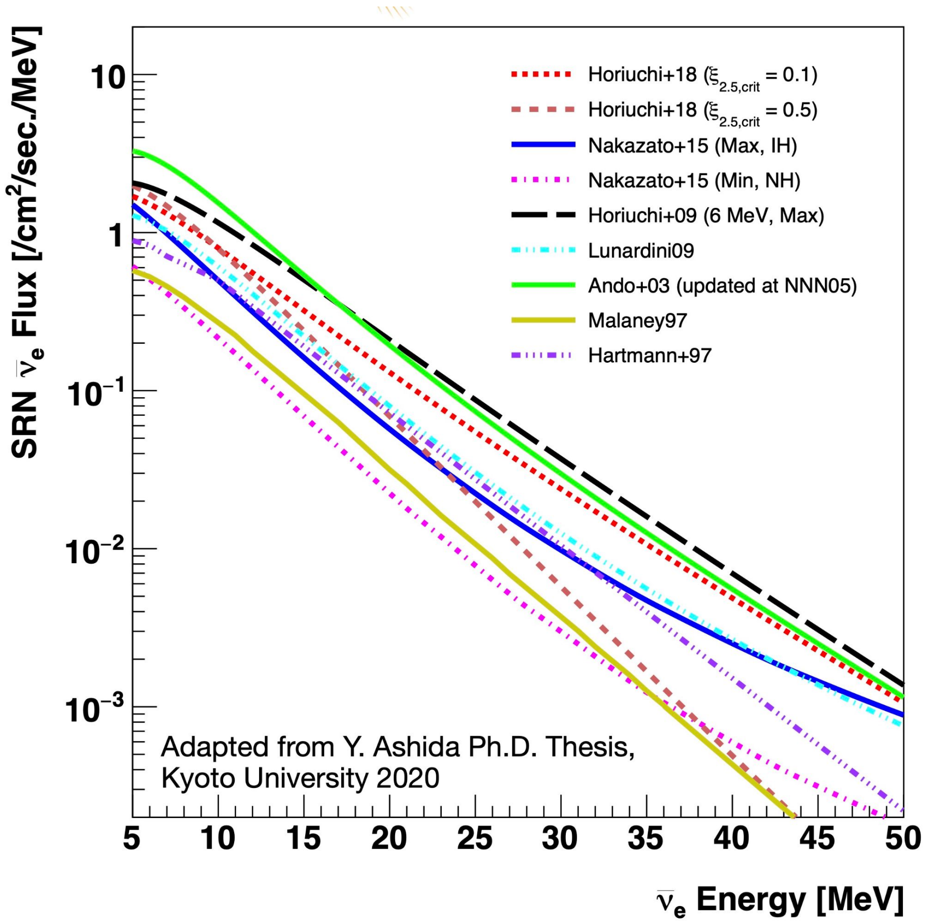
Background neutrino ‘fuzz’ from all core-collapse supernovae since the beginning of time!



What can DSNB tell us?

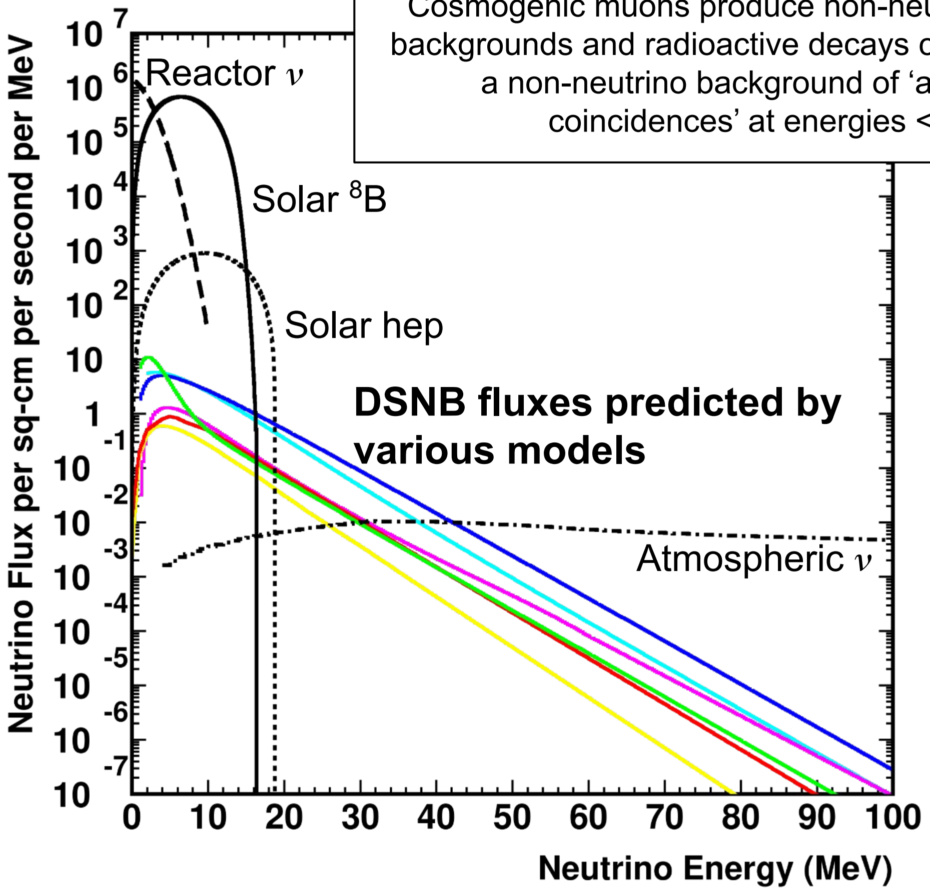
- Test of star formation rate
- SN rate as function of z
- Average energy spectrum of SN burst neutrinos
- Average temperature inside the SN
- Black-hole formation, dim supernovae rate

Challenges in DSNB detection



Many models to discriminate between

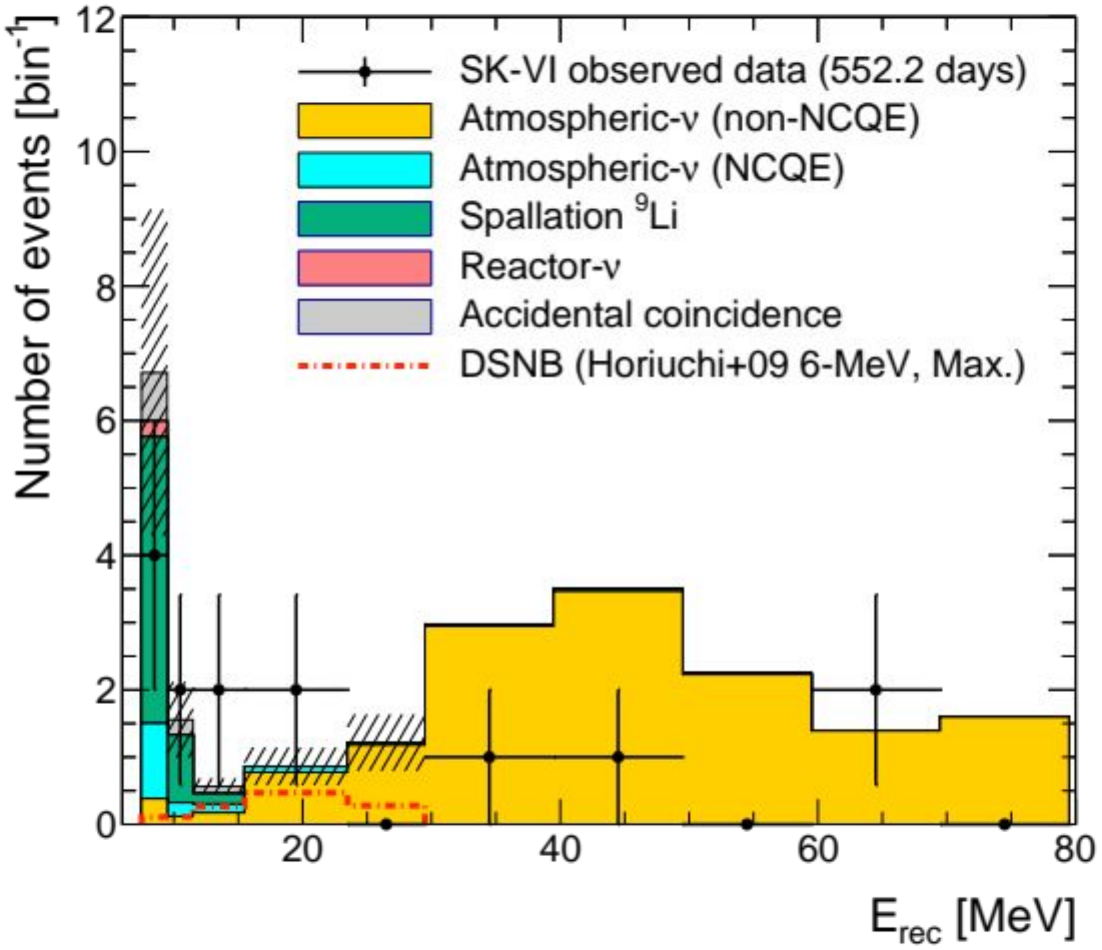
Cosmogenic muons produce non-neutrino β-n backgrounds and radioactive decays contribute a non-neutrino background of ‘accidental coincidences’ at energies < 20 MeV.



Small window to see DSNB - need to aggressively drive down backgrounds

Honing in on the DSNB

Spectrum-independent analysis (M. Harada)



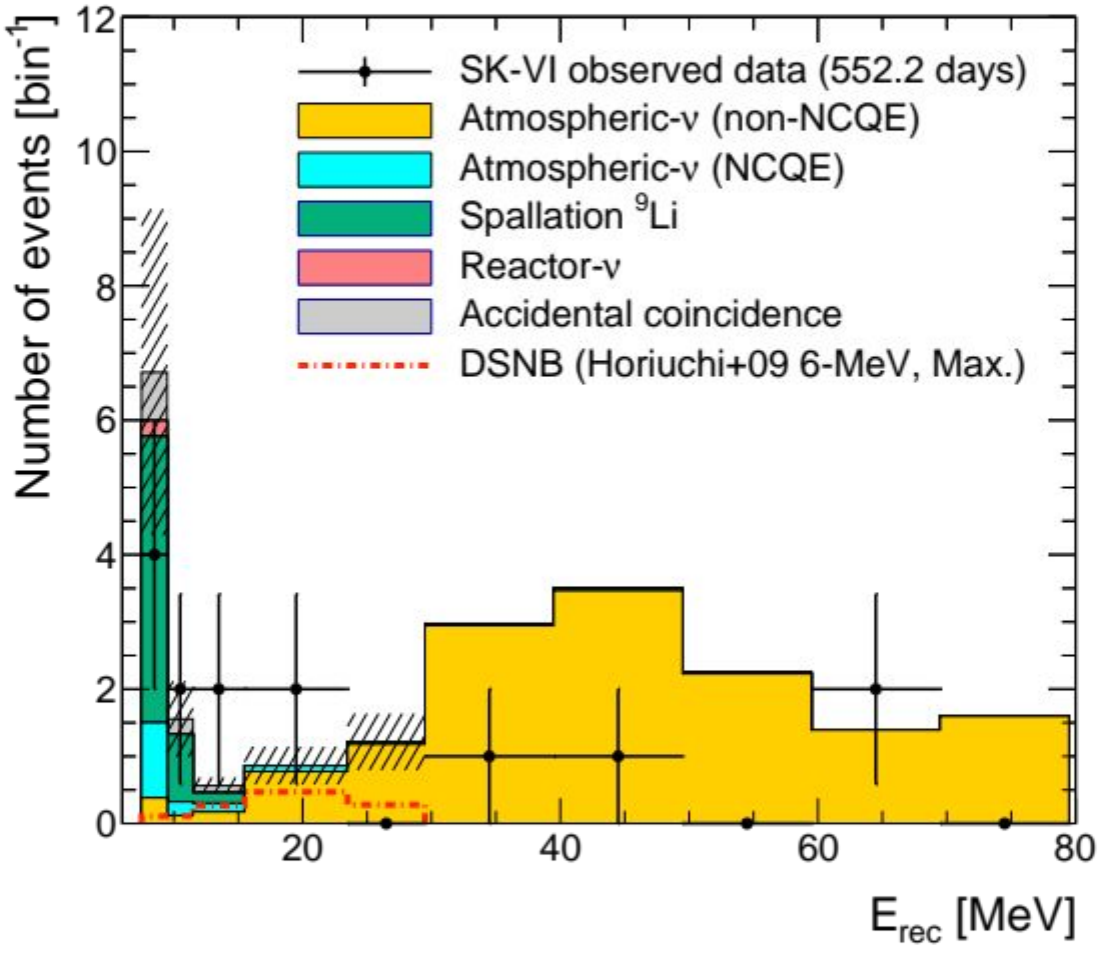
Latest results for SK-6 (0.01% Gd) with improved background rejection compared to [Harada et al, 2023]:

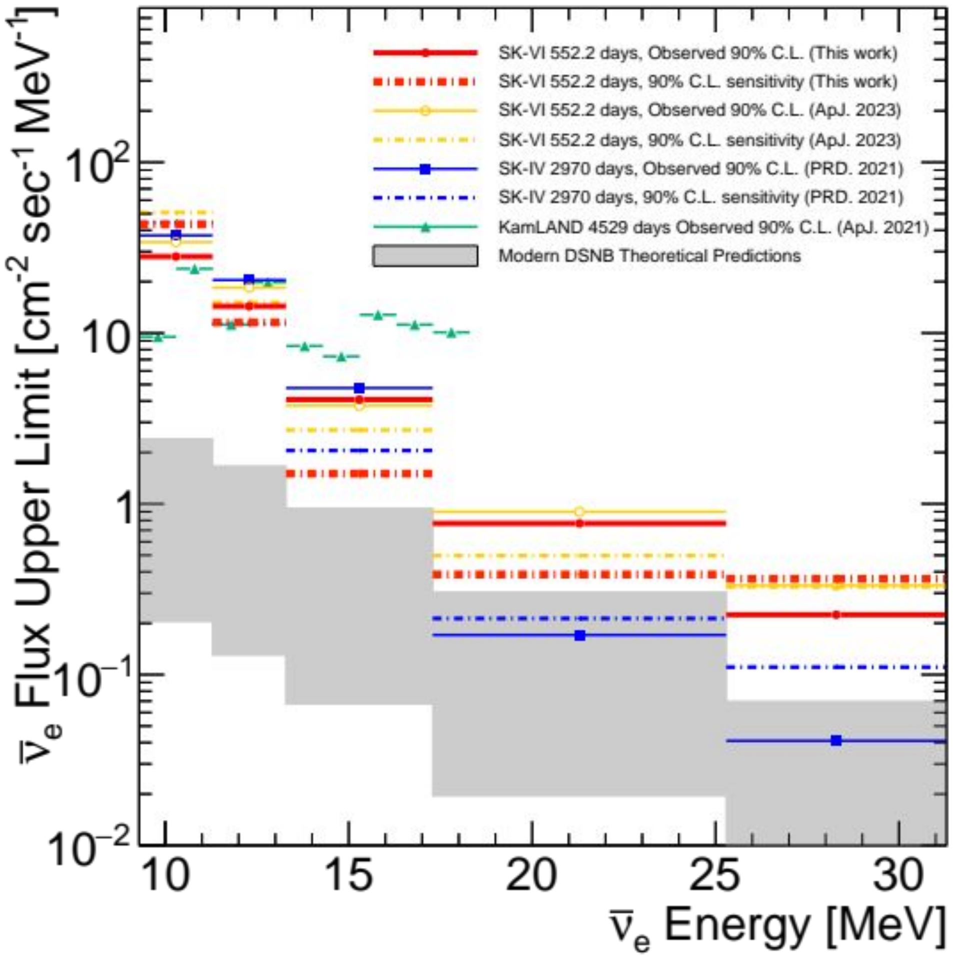
- Neural-network based neutron tagging
- “Multiple scattering goodness” cut (A. Santos) to remove atmospheric backgrounds where multiple Cherenkov cones have been reconstructed as a single cone (in the prompt event)
- Updated atmospheric neutrino simulation

14 events found

New limit at < 17 MeV with ⅕ observation time

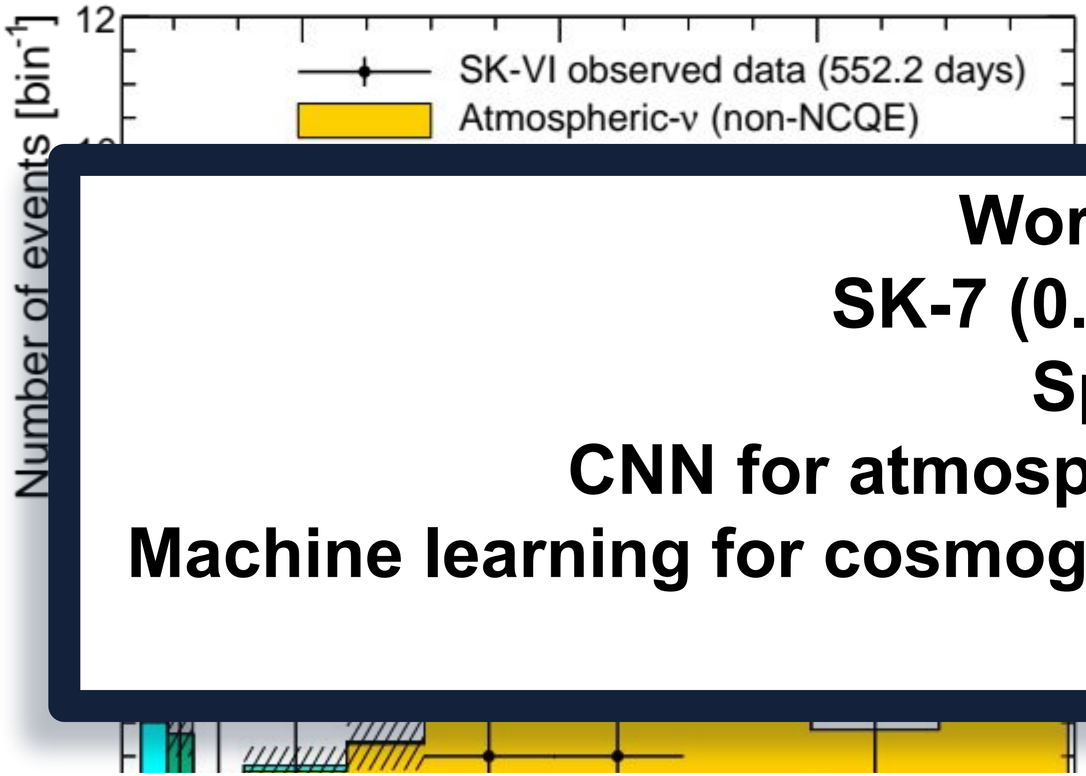
Spectrum-independent analysis (M. Harada)

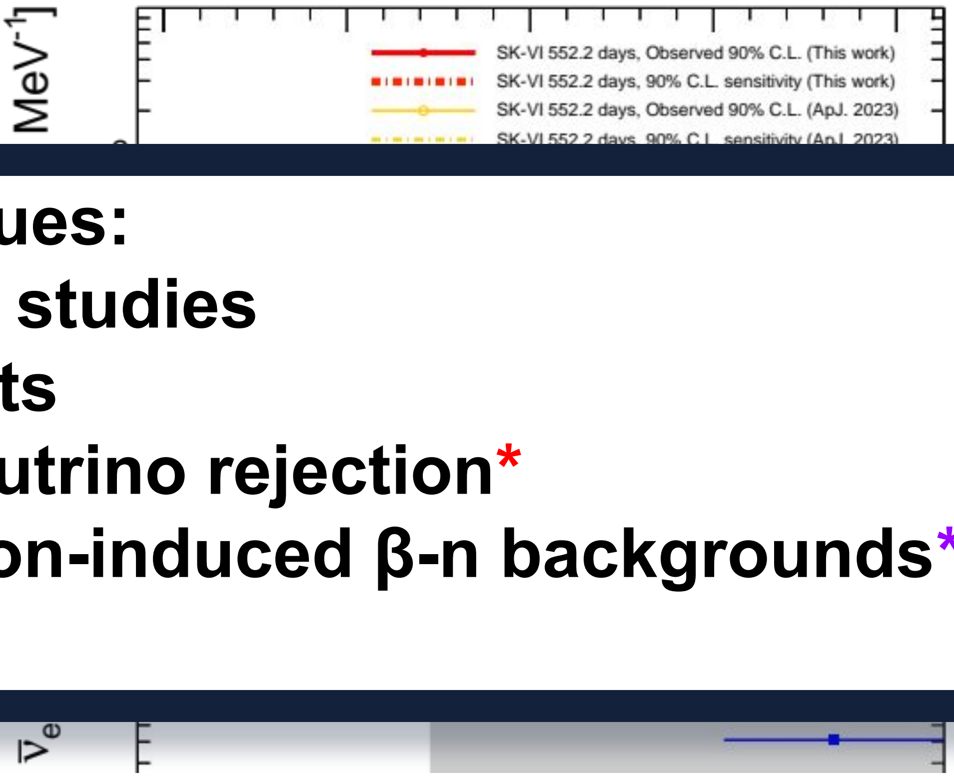




What can we do with 0.03% Gd?!

Spectrum-independent analysis (M. Harada)





Work continues:
SK-7 (0.03% Gd) studies
Spectral fits
CNN for atmospheric neutrino rejection*
Machine learning for cosmogenic muon-induced β-n backgrounds*

*See poster #57 and poster talk today at 17:30 (S. Samani):
Atmospheric Background Reduction using CNNs in DSNB Searches at Super-Kamiokande Gd
*See poster #EX-14 and poster talk today at 17:33 (J. Fannon):
Modelling Cosmic Ray Muon Spallation for Super & Hyper-Kamiokande DSNB

Supernova spotting in SK-Gd

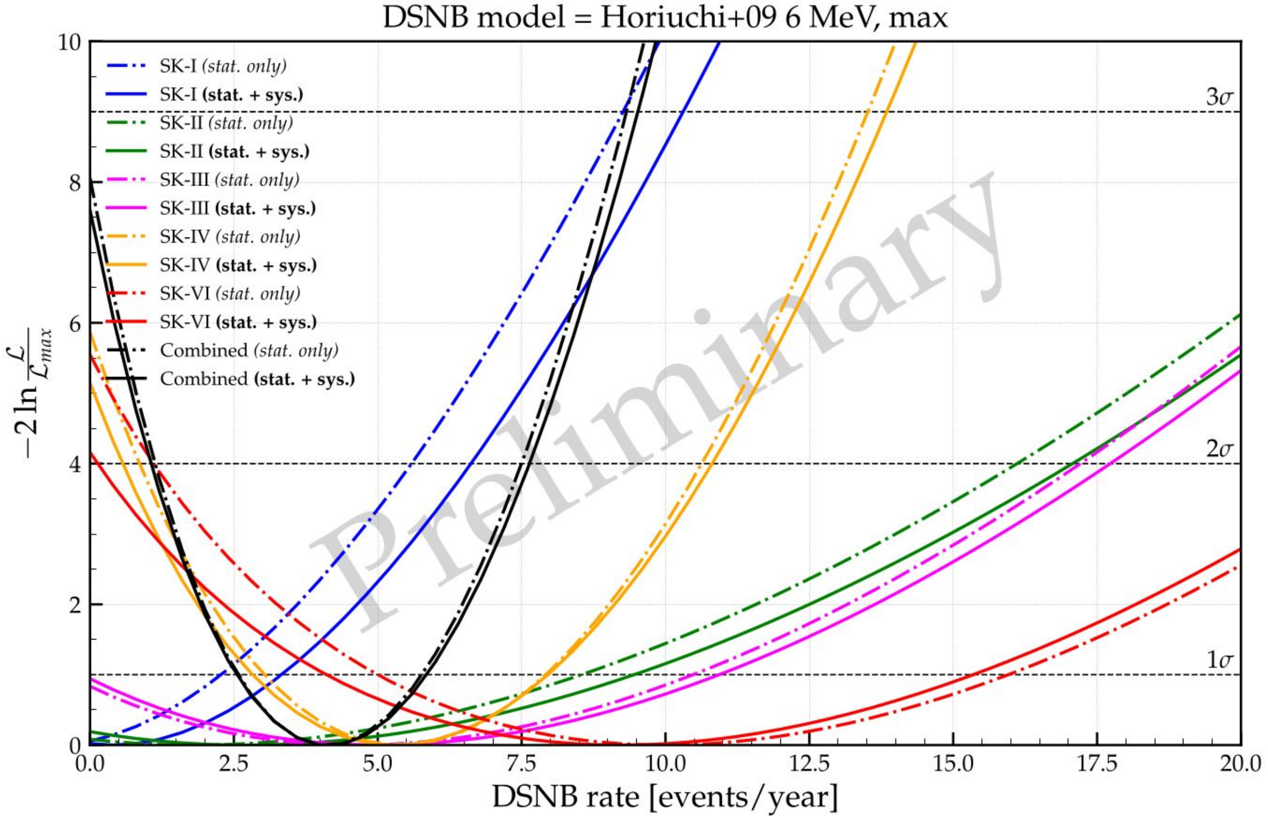
Super-Kamiokande Gd is a new era in SN detection:

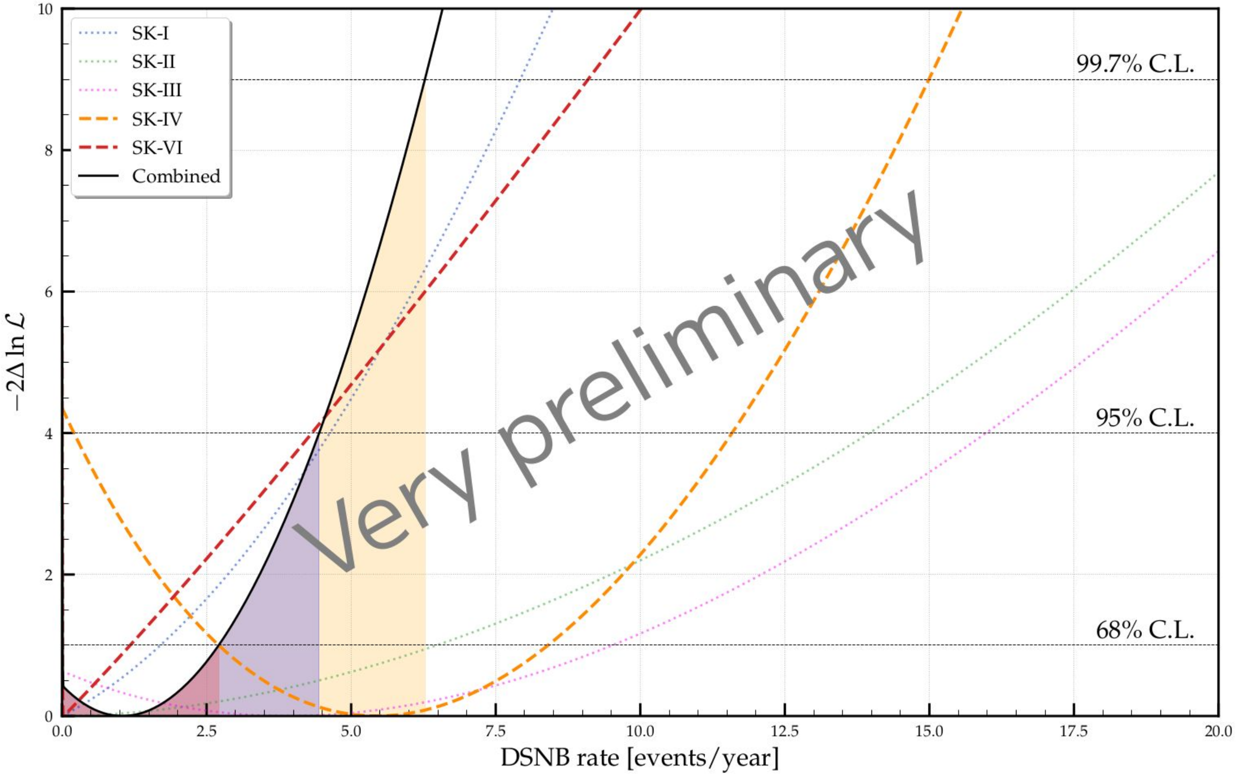
- Detection of neutrinos from pre-supernova stars up to 800 pc away at 3σ, and from Betelgeuse up to 15 hours before the explosion.
- Supernova pointing accuracy has been improved to a few degrees for a 10-kpc supernova.
- Supernova alert could be issued in less than a minute for a supernova burst at 10 kpc.
- New limits on DSNB at < 17 MeV in SK-6 (0.01% Gd) with ⅕ of the observation time compared to pre-Gd phase.

Work is now focused on using the increased Gd concentration in SK-7 (0.03%), all the time innovating and improving the existing analyses. **Watch this space!**

Backups

Spectral fits

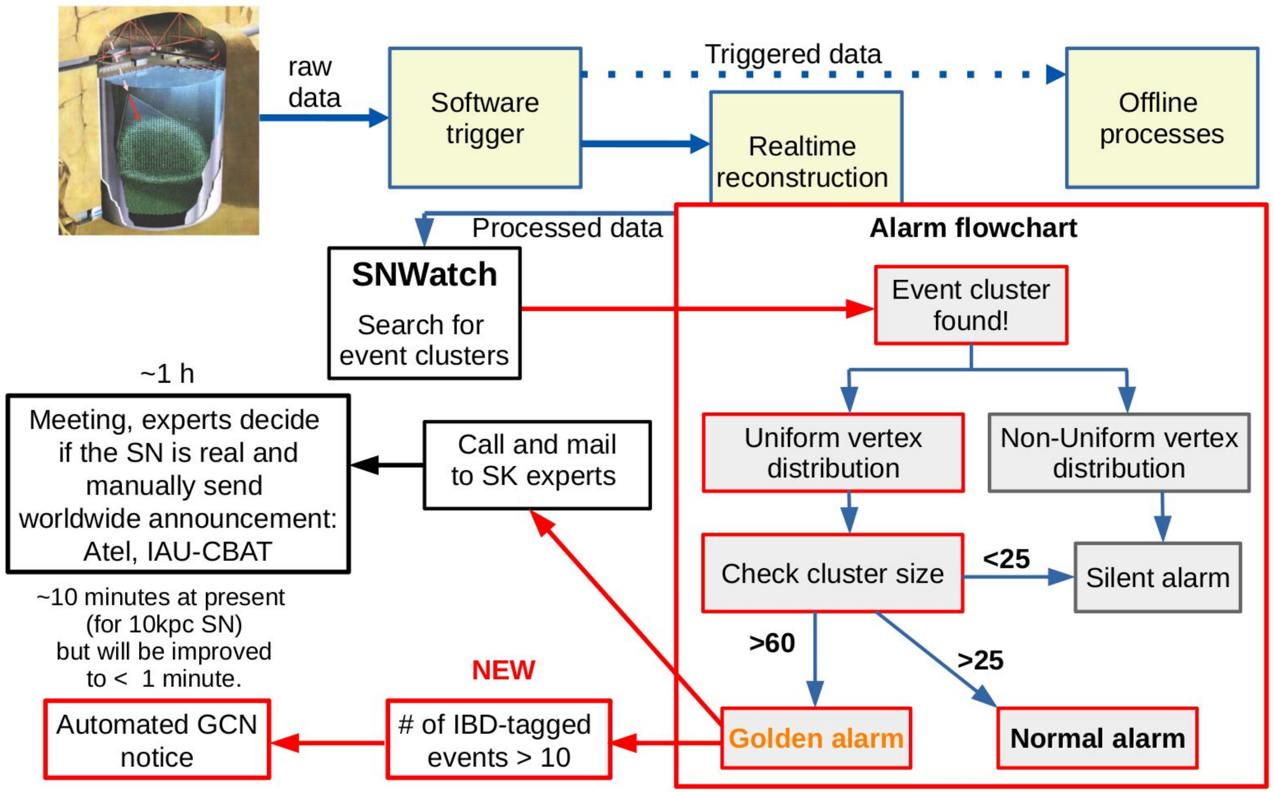




A. Beauchêne & R. Rogly
Model: Horiuchi+09
Prediction: ~4.25 per year combined best fit result

S. Izumiyama
Model: Horiuchi+09
Prediction: 3.54 events per year upper limit at 90% CL (stat.)

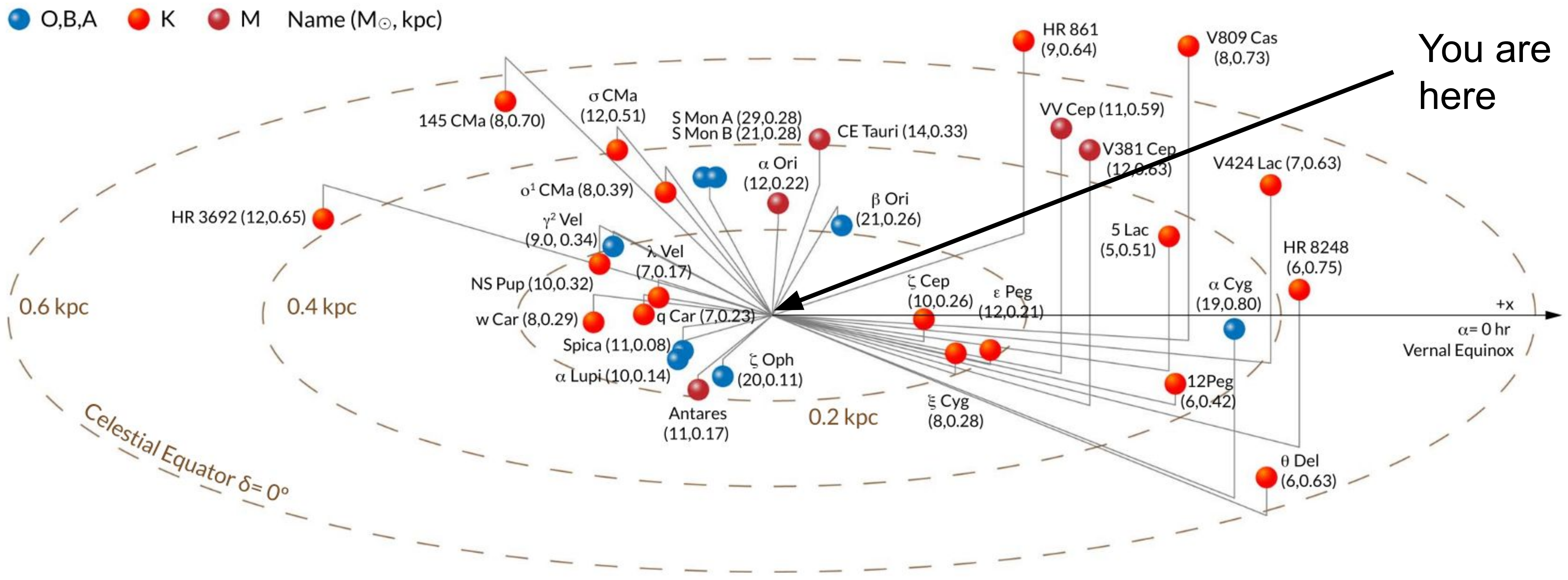
Relay early warning FAST



Thanks to software and algorithm upgrades SNWatch processing time is going to be largely improved:

- Event reconstruction: Improved by using multi-threading
  → <1 min for 10 kpc SN (~5 min for 3 kpc SN)
- Supernova direction reconstruction: Under investigation, promising results
  → Preliminary results indicate ~2 sec for 10 kpc SN (<5 sec for any SN)
- Alarm release: automated alarm shortly after the SN direction reconstruction
  → Alarm could be released in about 1 minute following the SN burst (Preliminary)

Seeing the future (predicting a supernova)



Many pre-supernova candidates within 1 kpc of Earth!

Mukhopadhyay, et al, 2020

Online pre-supernova alert system went live in October 2021 (Machado et al, 2022).

Combined pre-SN public alert system with KamLAND here.