Silicon Burning Neutrinos at Super-K with Gadolinium

Charles Simpson

charles.simpson@physics.ox.ac.uk

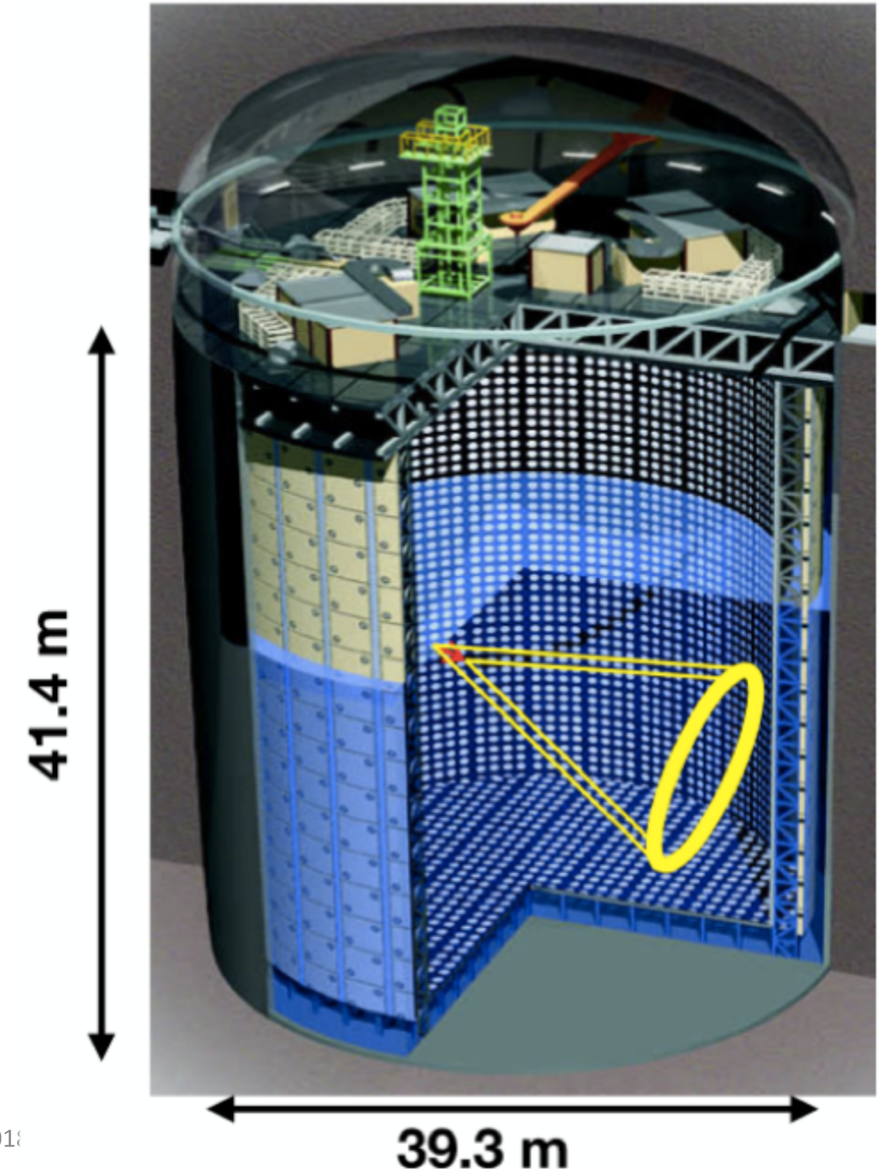
KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

UNIVERSITY OF OXFORD

Super-Kamiokande

- 50ktons water, 22.5 kton fiducial volume
- Under mountain to reduce cosmic muon rate
- Inner detector instrumented with >11000 20 inch PMTs
- Detects Cherenkov light from charged particles passing though water
- Running >20 years so far

- Studies atmospheric and solar neutrinos
- Far detector for T2K
- Waiting for supernova detection
- Proton decay search



Super-K *with Gadolinium*

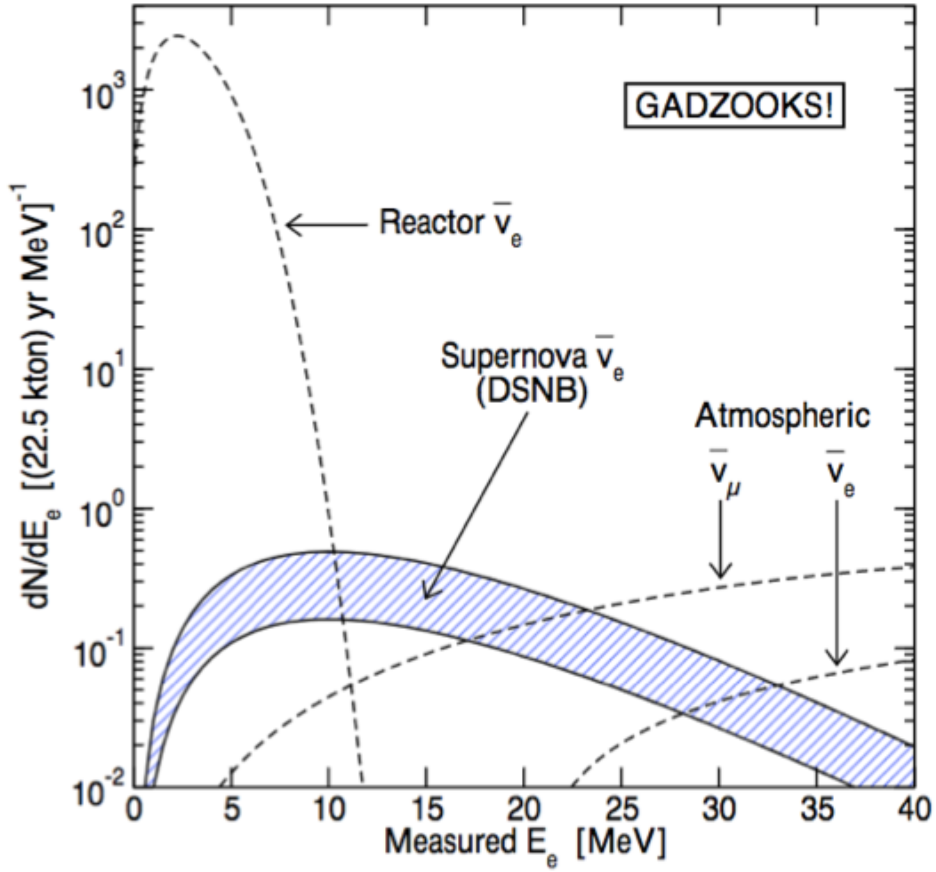
- Soon to be upgraded for next phase with gadolinium doping
- By adding 0.2% Gd salt by mass, will detect 80% of neutrons

- Detect the **diffuse supernova neutrino background**
- Enhance pointing ability for a supernova burst

Diffuse Supernova Neutrino Background

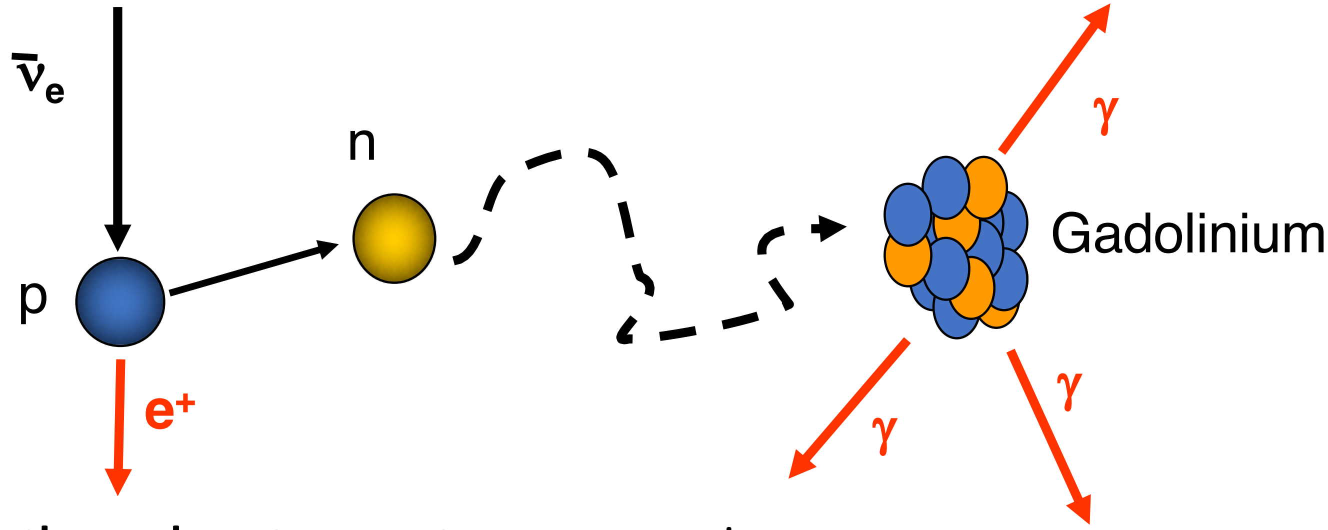
- Neutrinos from all past supernovae in the universe should still exist

- SK has set limits, but is background limited
- By eliminating backgrounds, SK-Gd will detect DSNB within two years of full Gd loading



J.F. Beacom and M.R. Vagins, PRL 93 (2004)

Inverse Beta Decay at SK-Gd



Gadolinium has a high **thermal neutron capture** cross section
High energy of gamma ray cascade gives highly efficient neutron tagging

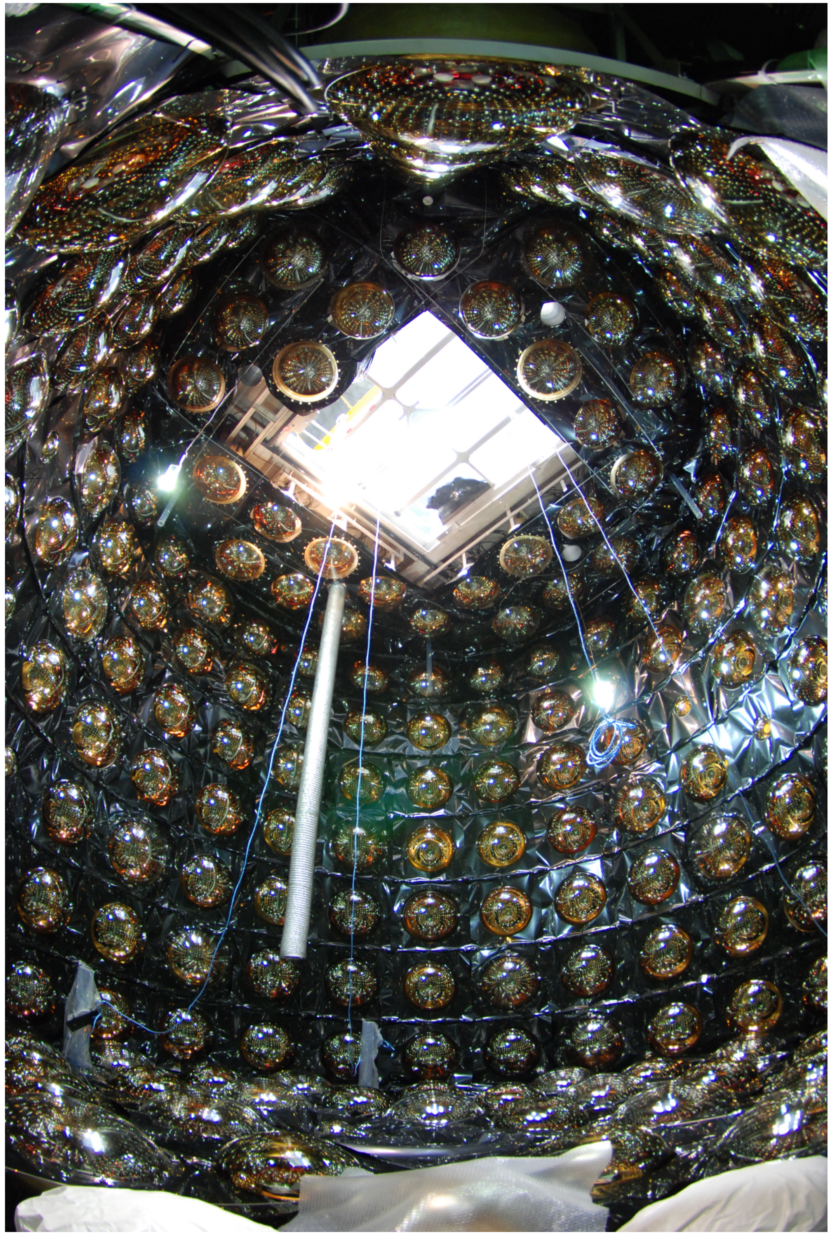
Allows IBD events to be separated from background, and from other neutrino events

EGADS

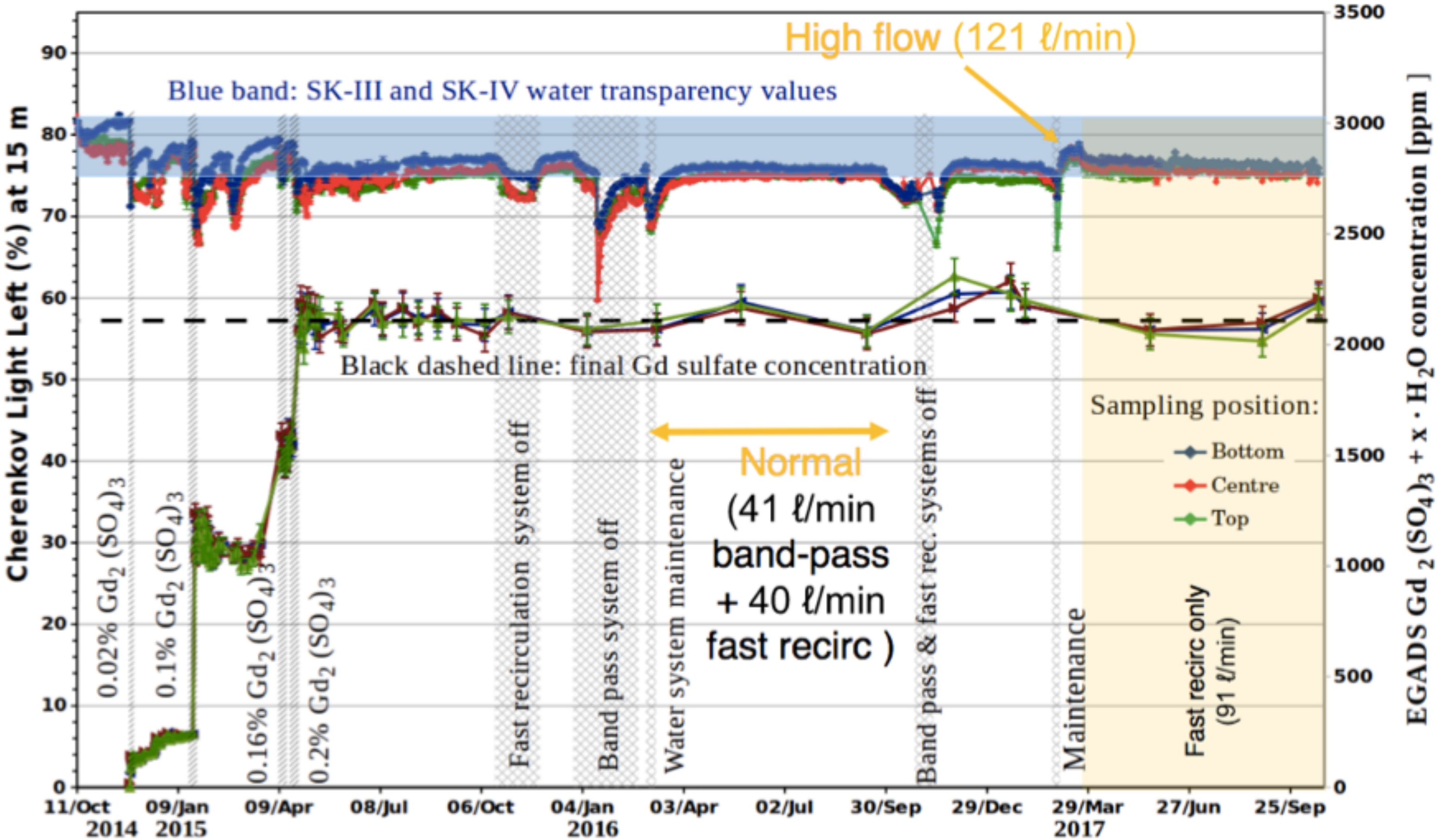
EGADS is a smaller 200 ton tank used to test detector systems

It will now run as an autonomous supernova detector while SK is down.

Recommend Nakajima-san's slides from NNN17 for more details



Light @ 15 meters and Gd conc. in the 200-ton EGADS tank



After two and a half years at full Gd loading, during stable operations EGADS water transparency remains within the SK ultrapure range.

Slide credit: Mark Vagins

→ No detectable loss of Gd after more than 650 complete turnovers. ←

Development of pure Gd powder

- U and Th/Ra contamination in Gd powder becomes backgrounds for solar neutrino measurements
- Intensively developing pure Gd powder with several companies
- Radio impurity measured w/ two methods:

Ge detector: Sensitive to ~1 mBq/kg (Canfranc, Boulby and Kamioka)
ICPMS: For isotopes w/ long life (Kamioka) [arXiv:1709.03417 (accepted by PTEP)]

* Goal for 0.2% Gd-sulfate loading

Series	Isotope	Typical	Goal*	Company A		Company B		Company C	
				Ge	ICPMS	Ge	ICPMS	Ge	ICPMS
^{238}U	^{238}U	50	**< 5**	< 13	**~ 0.7**	< 20	**~ 0.2**	< 9	**~ 0.1**
	^{226}Ra	5	**< 0.5**	0.7 ± 0.4	—	< 0.6	—	**< 0.3**	—
^{232}Th	^{232}Th	100	**< 0.05**	—	~ 0.3	—	~ 0.2	—	~ 0.2
	^{228}Ra	10	**< 0.05**	< 0.4	—	< 0.7	—	< 0.3	—
	^{228}Th	100	**< 0.05**	1.7 ± 0.4	—	0.5 ± 0.2	—	< 0.4	—
^{235}U	^{235}U	30	**< 3**	**< 1.3**	—	**< 0.7**	—	**< 0.6**	—
	$^{227}Ac/Th$	300	**< 3**	< 3.1	—	**< 2.3**	—	**< 1.9**	—

U, Ra: Achieved our goal, Th: Close to our goal

Unit: [mBq/kg $(Gd_2SO_4)_3$]

Each company is still making rapid progress on reducing radio impurity

EGADS is a success

- ✓ Operated fully loaded with Gd sulfate for over 650 turnovers
- ✓ No loss of gadolinium
- ✓ Low radioactivity Gd produced by working with manufacturers
- ✓ Water transparency maintained at SK-III/IV quality
- ✓ Gd removed successfully with resin at end of period

SK-Gd is ready to go!

SK-Gd Plan

- Open tank in summer 2018
  - Seal leaks
  - Install new Gd water system
  - Replace failed PMTs
- Gadolinium sulphate loaded in two stages 0 -> 0.02% -> 0.2% in near future

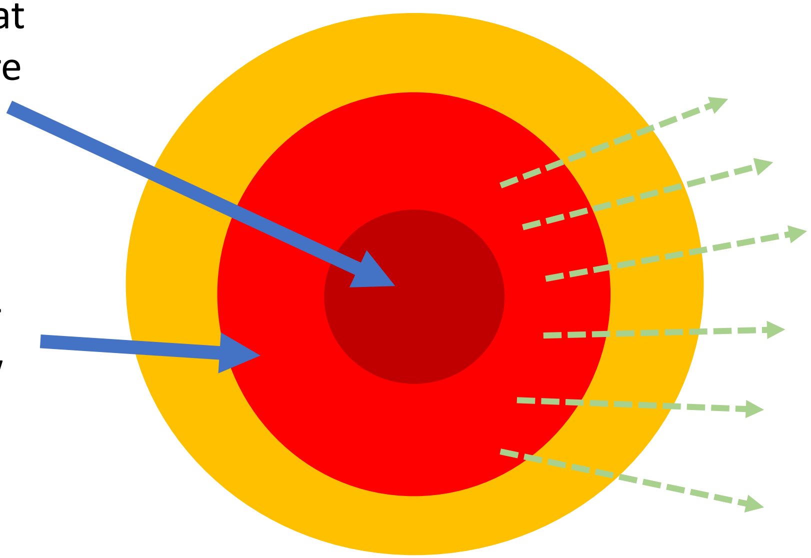
  Gd will capture 50%(90%) of neutrons at 0.02% (0.2%) loading)

Silicon Burning Basics

A massive star (initial mass >13 $M_{\odot}$), at the end of its life contracts and gets hotter…

Silicon burns first at core, until iron core forms

Silicon continues to burn in a shell, over a timescale of a few days

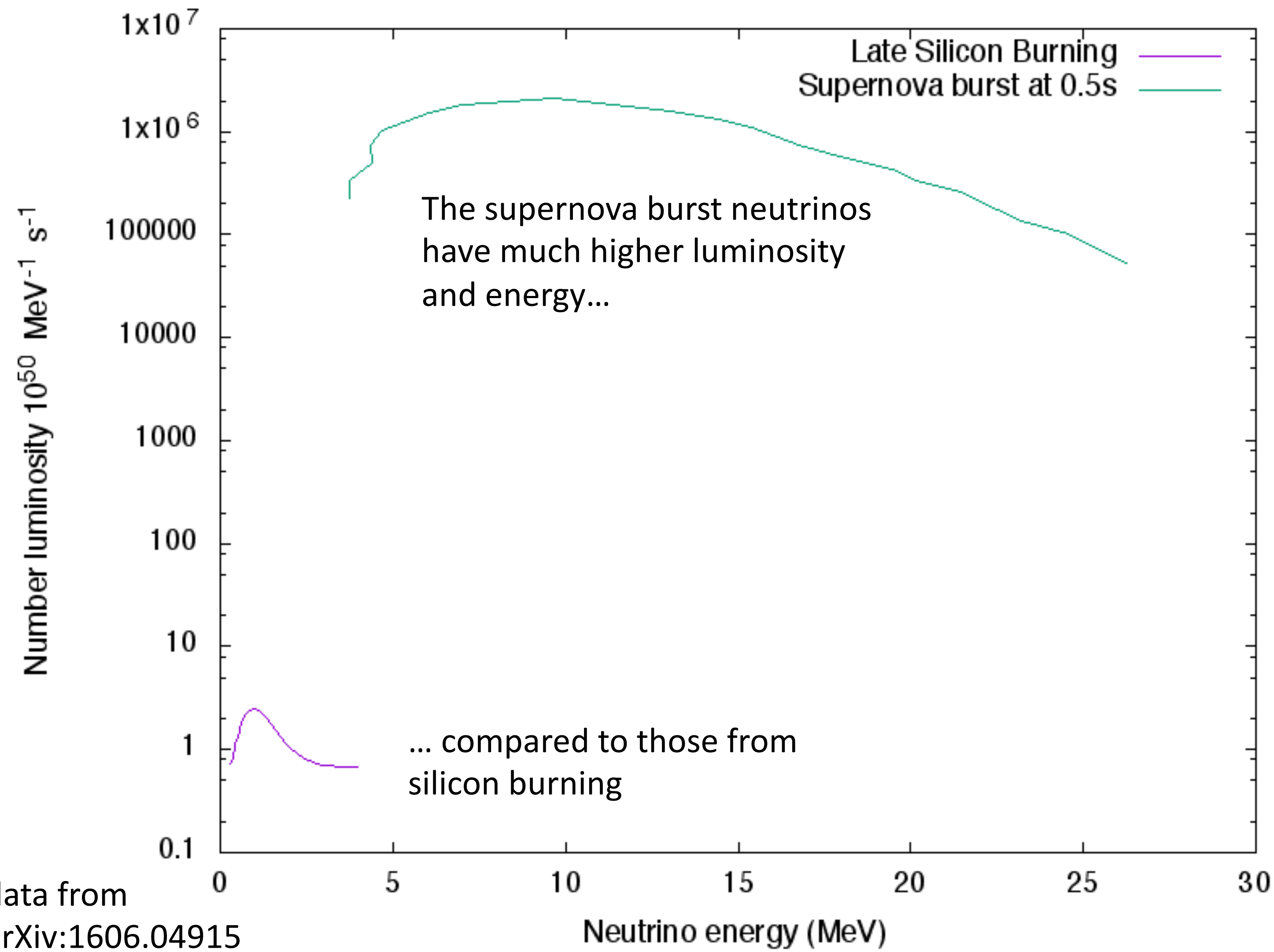


weak nuclear reactions and pair annihilations produce
more antineutrino emission at higher energies

… and this can be followed by a core collapse!

[Odrzywolek et al. arXiv:astro-ph/0311012v2]
[T. Yoshida et al. arXiv:1606.04915]

Supernova Neutrinos	Silicon Burning Neutrinos
Mean Energy ~20 MeV	Mean Energy ~2 MeV
Hours before light from SN	Days before light from SN
Detected in 1987	Never detected before
1000s of events in seconds at SK at >10kpc	100s of events in a day at SK-Gd for stars at <1kpc



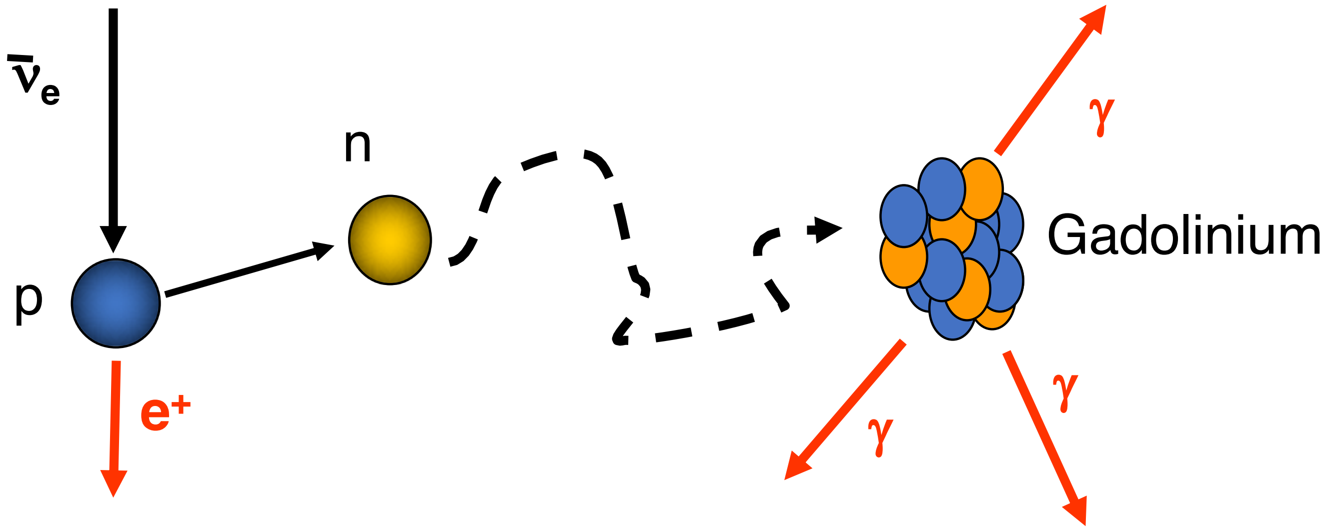
data from
arXiv:1606.04915
arXiv:astro-ph/9710203

Benefits of Detection

- "Supernova forecast" – we would be able to warn of a nearby supernova well before the main burst!
  - Don't miss the supernova
  - Warn the community

- Probes late stellar burning – very interesting to many astrophysicists

Inverse Beta Decay at SK-Gd

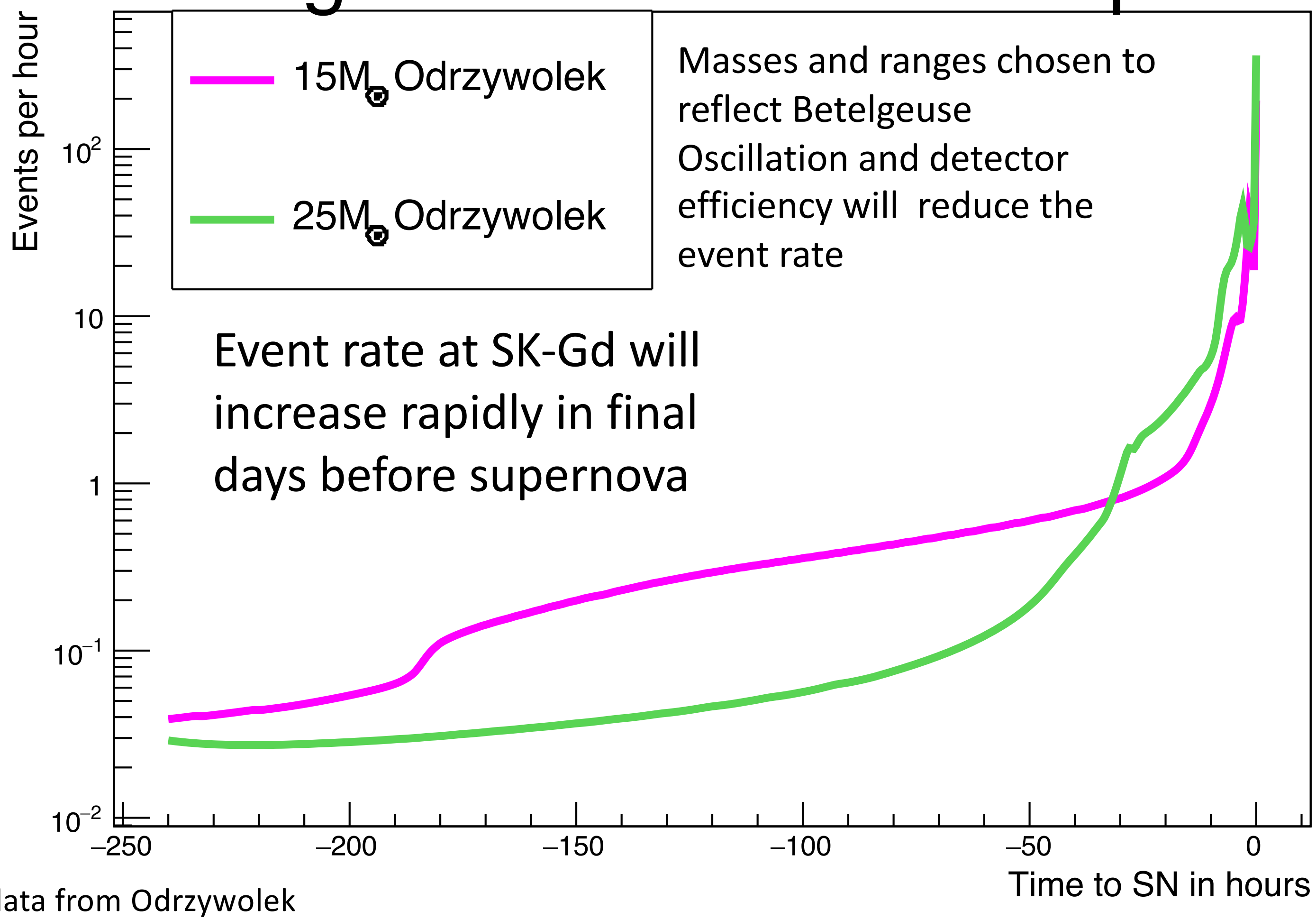


Two event categories

- *Coincidence*: both the positron and neutron capture are detected in coincidence
- *Neutron single*: only the neutron capture is detected

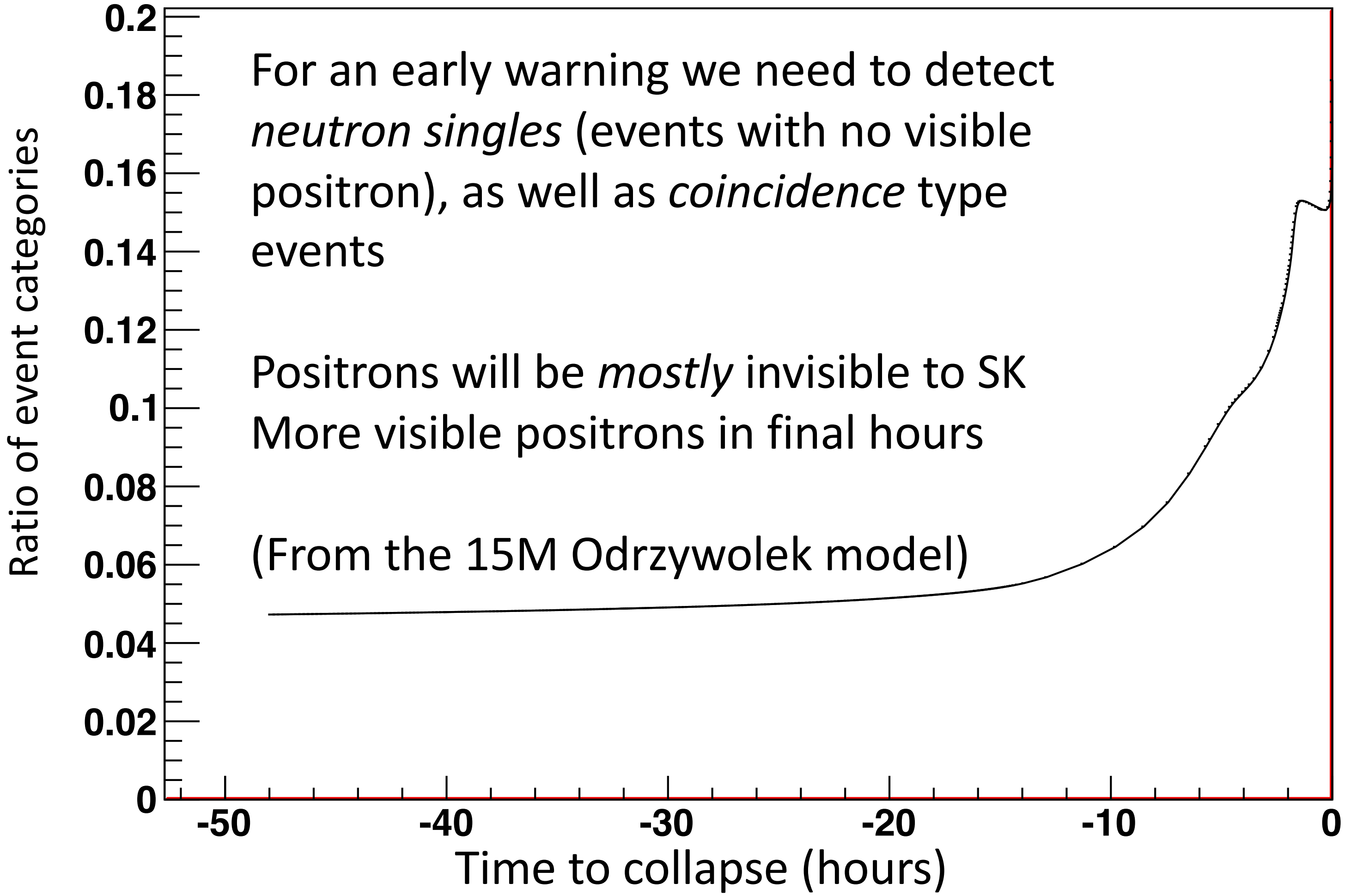
See *GADZOOKS! Anti-neutrino spectroscopy with large water Cherenkov detectors,* Beacom and Vagins, PRL 53, 2004

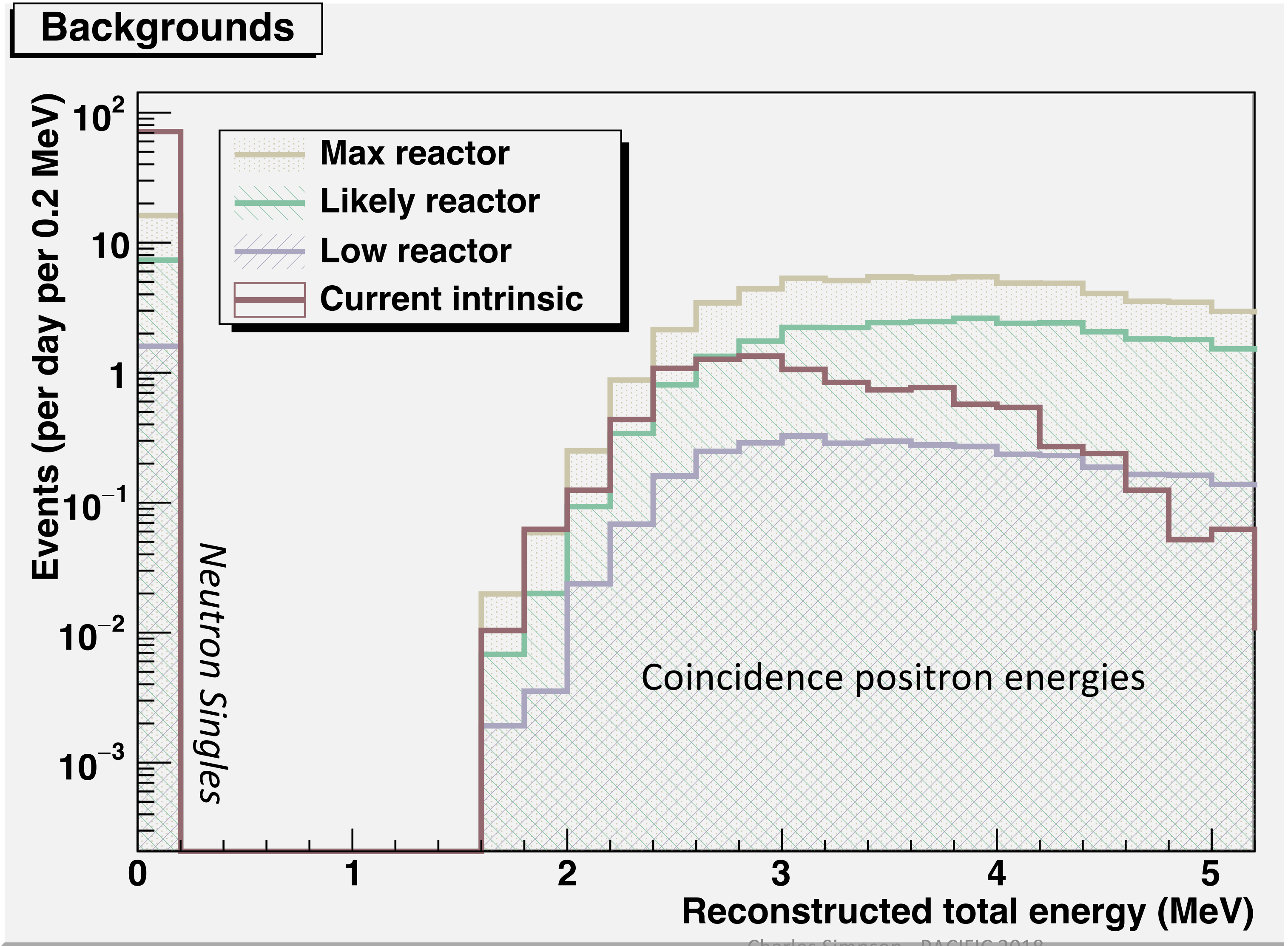
Signal event rate at 0.2kpc



data from Odrzywolek
http://th.if.uj.edu.pl/~odrzywolek/

Delayed coincidence events : single neutrons ratio

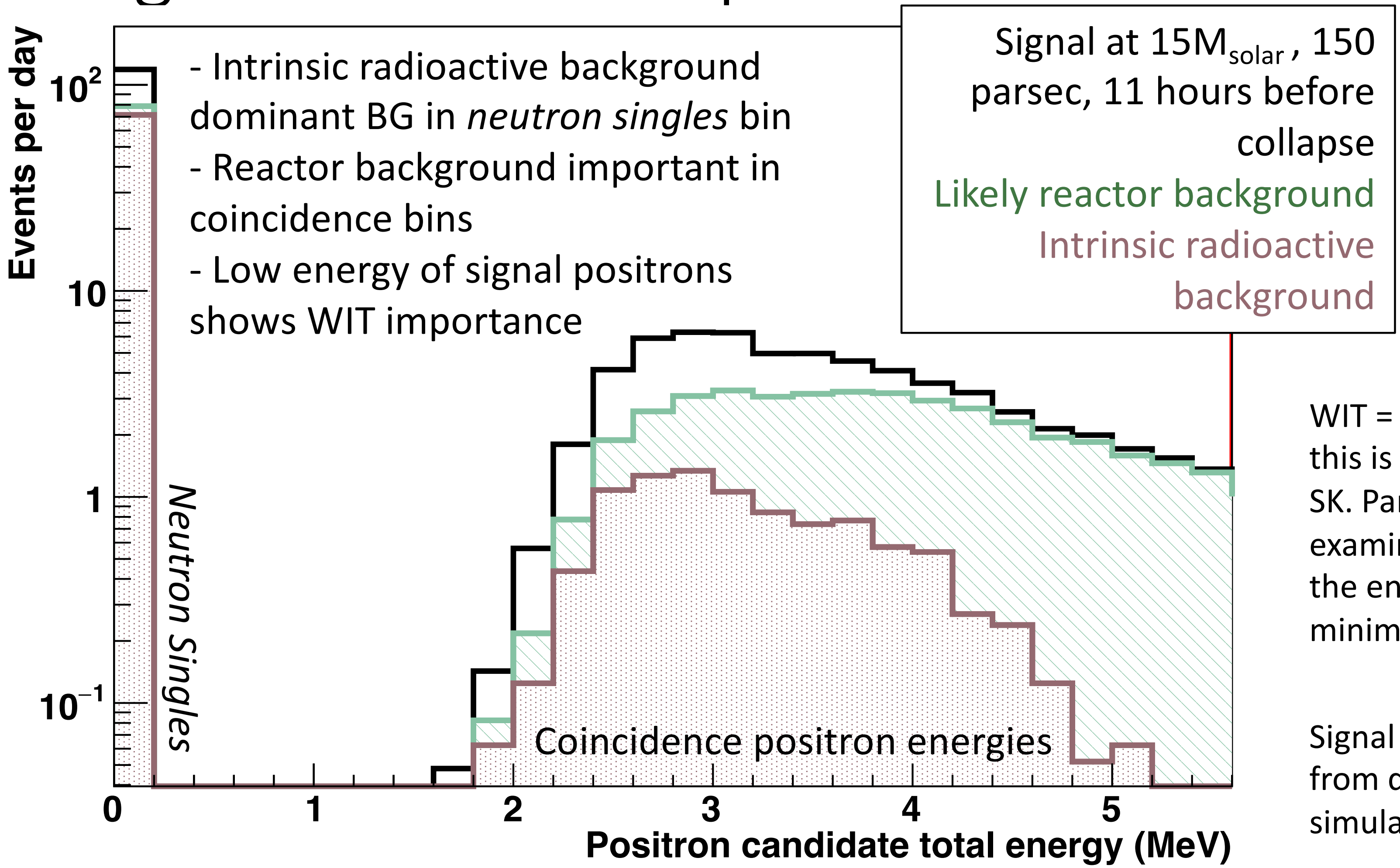




- Reactor and geo neutrino flux from geoneutrinos.org
- Intrinsic background estimated from existing trigger data

- 'low background' = low reactor + current intrinsic background
- 'high background' scenario = max reactor + double intrinsic background

Signal Alarm Example

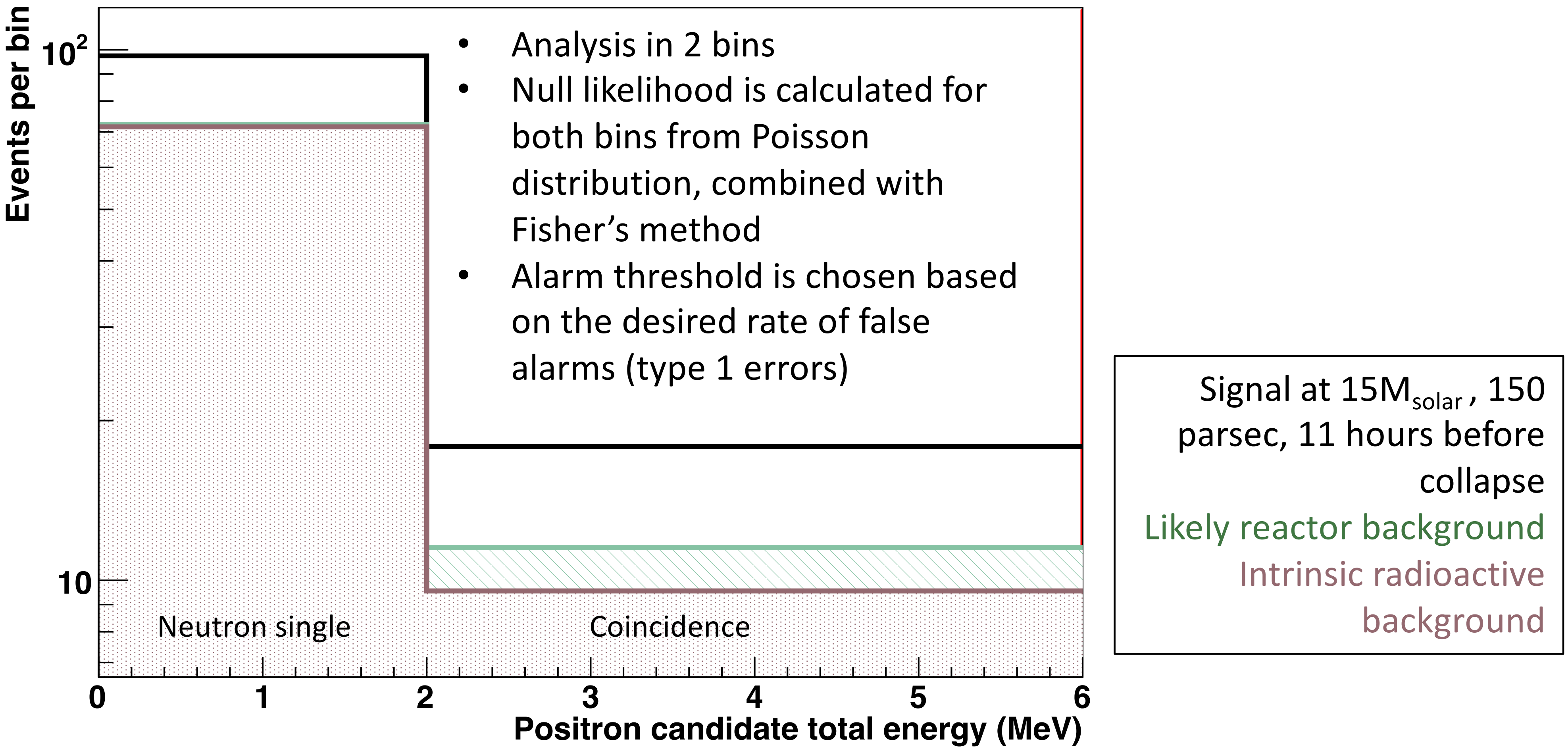


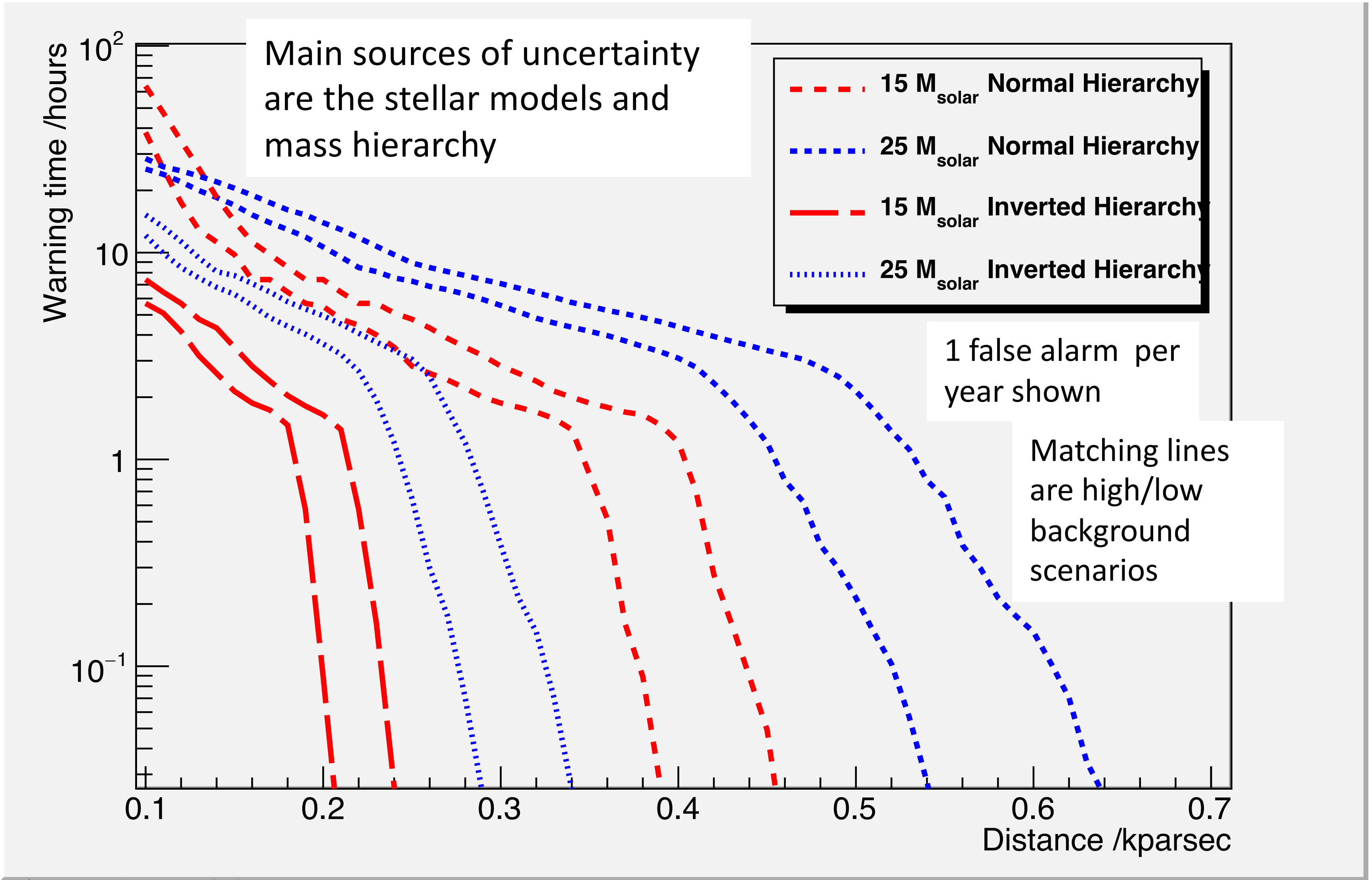
WIT = "Wide Intelligent Trigger" this is a software trigger system at SK. Parallel computers are used to examine every single hit, reducing the energy threshold to the minimum possible.

Signal efficiency estimated from detector and trigger simulation

Signal Alarm Example

- Analysis in 2 bins
- Null likelihood is calculated for both bins from Poisson distribution, combined with Fisher's method
- Alarm threshold is chosen based on the desired rate of false alarms (type 1 errors)





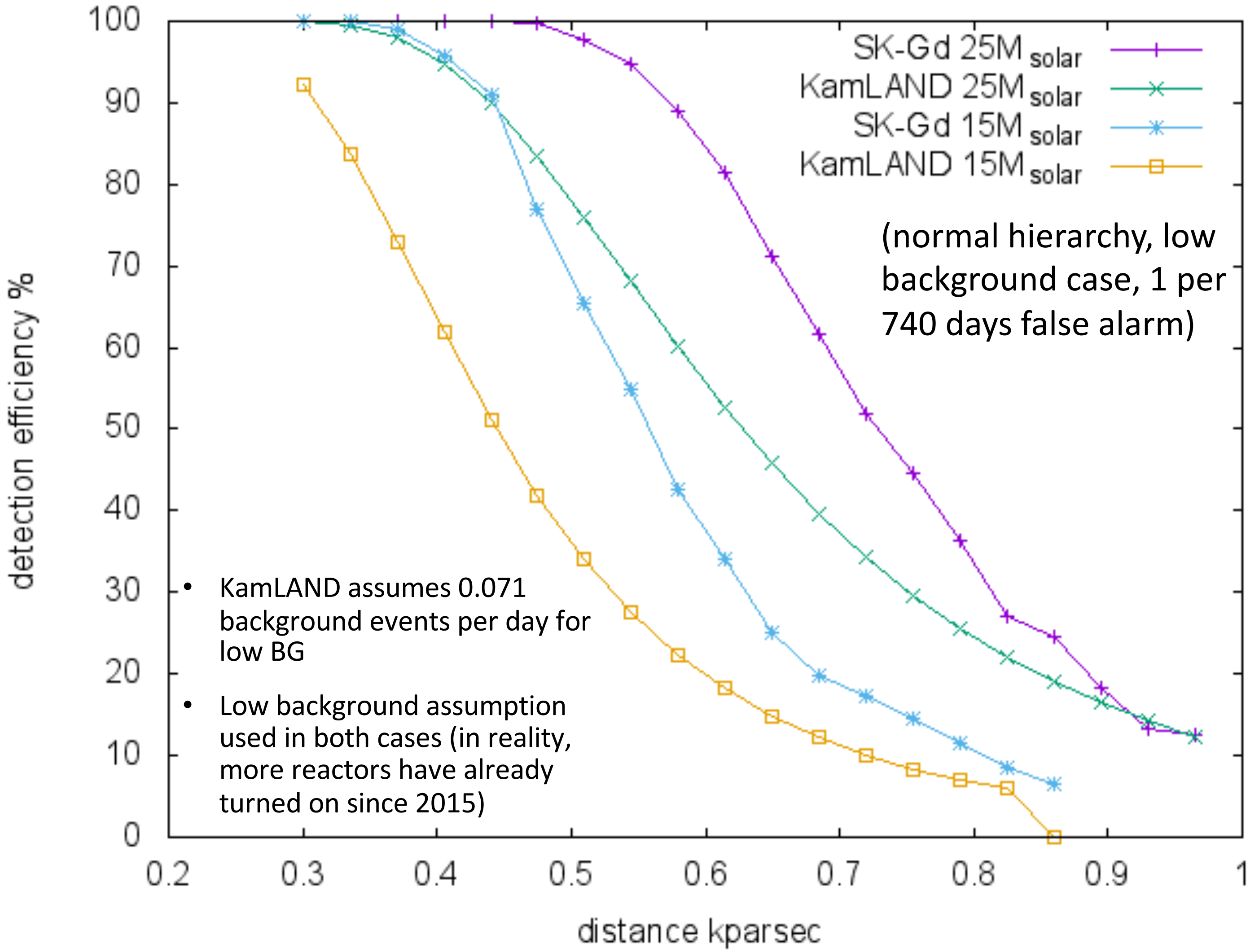
Signal models from Odrzywolek
http://th.if.uj.edu.pl/~odrzywolek/

Short range warning time compared to KamLAND

Case	Distance (parsec)	SK-Gd warning (hours)	KamLAND warning (hours)
25 M_{solar}	250	8 - 10	11 - 17
15 M_{solar}	150	10 - 15	46 - 87

- KamLAND assumes 0.071 – 0.355 background events per day
- The stellar mass assumptions are chosen to reflect Betelgeuse
- Normal mass hierarchy is assumed
- Threshold is 1 per 740 days
- Have not considered Poisson fluctuations of signal

KamLAND from arXiv:1506.01175



SK-Gd 25M solar
KamLAND 25M solar
SK-Gd 15M solar
KamLAND 15M solar
(normal hierarchy, low background case, 1 per 740 days false alarm)
• KamLAND assumes 0.071 background events per day for low BG
• Low background assumption used in both cases (in reality, more reactors have already turned on since 2015)
detection efficiency %
distance kparsec
0
10
20
30
40
50
60
70
80
90
100
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1

Summary

- Super-Kamiokande will be gadolinium doped
  - Detect the DSNB in 2 years
  - Improve pointing for supernova burst
- Necessary refurbishment will happen this summer (2018)

- Pre supernova stars burn silicon and are powerful antineutrino sources
- SK-Gd will be able to detect this in advance of a supernova, provided the star is close enough
- Max range is about 700 parsecs, max warning is about 19 hours, but this is dependent on stellar models and mass hierarchy