SUPERNOVA DISCRIMINATION WITH A KILOTON-SCALE WATER CHERENKOV DETECTOR

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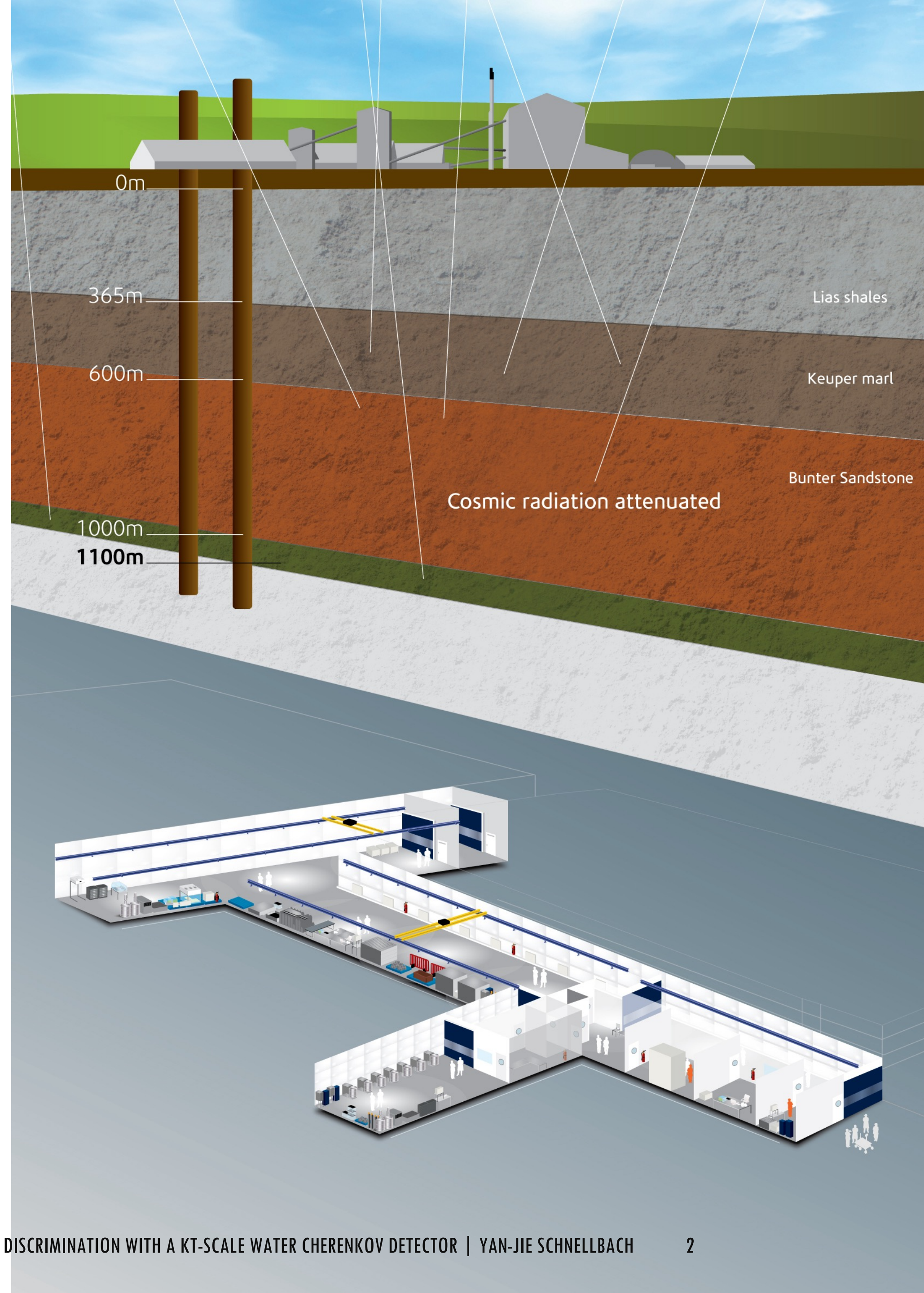
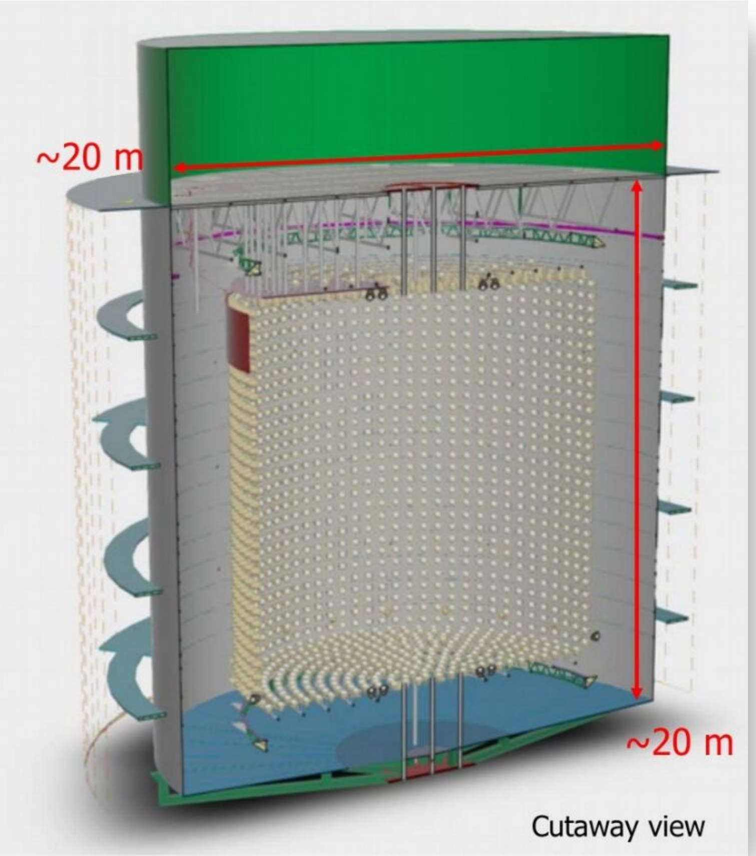
AIT FACILITY AT THE BOULBY UNDERGROUND LABORATORY

- AIT is the “Advanced Instrumentation Testbed”
  - Proposed expansion of existing STFC facility
  - Located in a working polyhalite mine
  - ~1100 m depth: background shielding (~2800 m.w.e / 10^{-6} attenuation of muons)
- Attractive location for several types of low-background experiments:
  - Neutrino, dark matter etc
  - Originally chosen as potential site for NEO (Neutrino Experiment One) due to proximity to nuclear power plants



NEO EXPERIMENT AT BOULBY UNDERGROUND LABORATORY

- Proposed non-proliferation experiment design for NEO
  - Designed by WATCHMAN Collaboration
  - Goal: to detect nuclear reactors at tens of km
  - See parallel talk by **Liz Kneale** on Monday for sensitivity to nuclear reactors
- Cylindrical tank with kiloton-scale fiducial volume: large water Cherenkov detector
  - Gd-H_2O fill option: 0.1% Gd to enhance neutron capture
- Steel frame surrounding supports PMTs and forms inner detector



FUTURE DEVELOPMENTS BASED ON NEO

- New from **January 2022**: Multiple reactors are planning to shutdown earlier than originally anticipated, meaning NEO will *not* go ahead as planned.

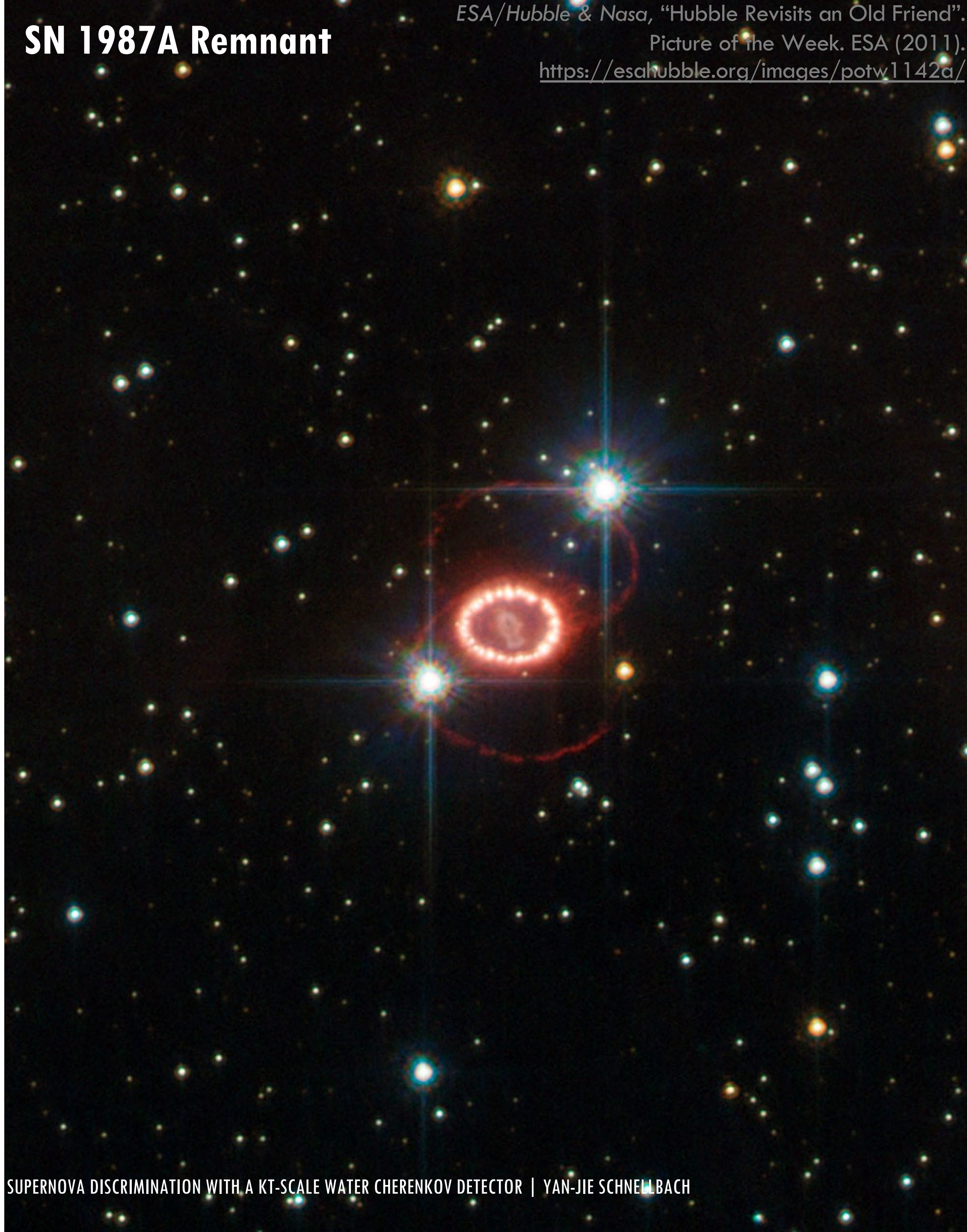
- However, the end of the NEO proposal has launched **three** new initiatives

- The AIT facility is still pursued with the potential for the UK to host large scale international underground science experiments
  - See plenary talk by **Sean Paling** on Wednesday
- The WATCHMAN collaboration is investigating alternative sites in the US that might be suitable reactor measurements
- The NEO technology advancements will be continued and tested in a low-background testbed, BOLEYN*, in the existing Boulby facility
  - See parallel talk by **Andrew Scarff** on Monday for more details

*name subject to change

PHYSICS EXPLORATION AT NEO: SUPERNOVA ANTI-NEUTRINOS

- As part of NEO design process, the physics potential for kiloton-scale anti-neutrino detectors was investigated
- Supernovae are one of the most spectacular sources of anti-neutrinos
  - Very rare events but interesting physics
- Explored NEO's suitability for supernova physics:
  - Reactor anti-neutrinos: up to ~8 MeV (1.8 MeV threshold)
  - Mean energy of supernova anti-neutrinos: ~15 MeV
  - High IBD efficiency (>75% for supernova neutrinos)
- Potential for astro-particle physics
  - Obvious: supernova early warning (SNEWS)
  - **But: How *well* can we study a supernova?**



SN 1987A Remnant

ESA/Hubble & Nasa, "Hubble Revisits an Old Friend". Picture of the Week. ESA (2011). https://esahubble.org/images/potw1142a/

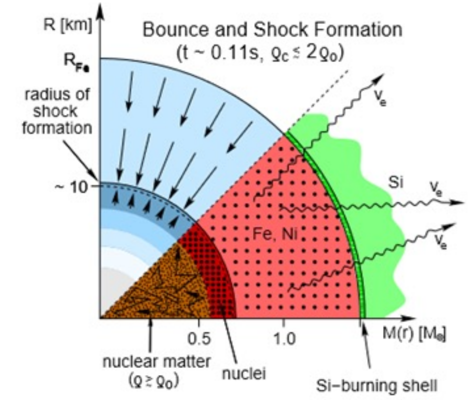
Janka, H.Th. et al., “Theory of core-collapse supernovae”. Phys. Rep. 442, issue 1-6, pg. 38-74 (2007).
https://doi.org/10.1016/j.physrep.2007.02.002

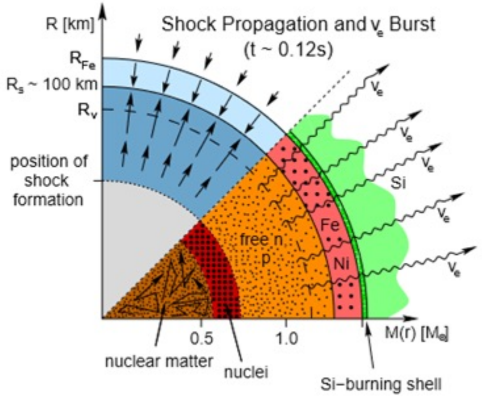
CORE COLLAPSE SUPERNOVA

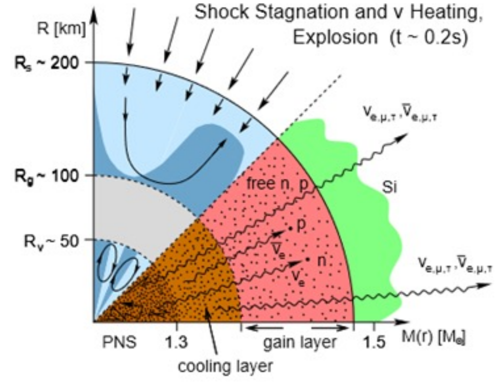
- (Anti-)neutrinos effectively carry information about the explosion mechanism

- Mechanism not well understood yet
  - Multiple models and approaches
  - Constrained by computational complexity
  - Very small anti-neutrino data set!

- Time window of interest: 20 – 520ms post-bounce
  - Largest difference between models

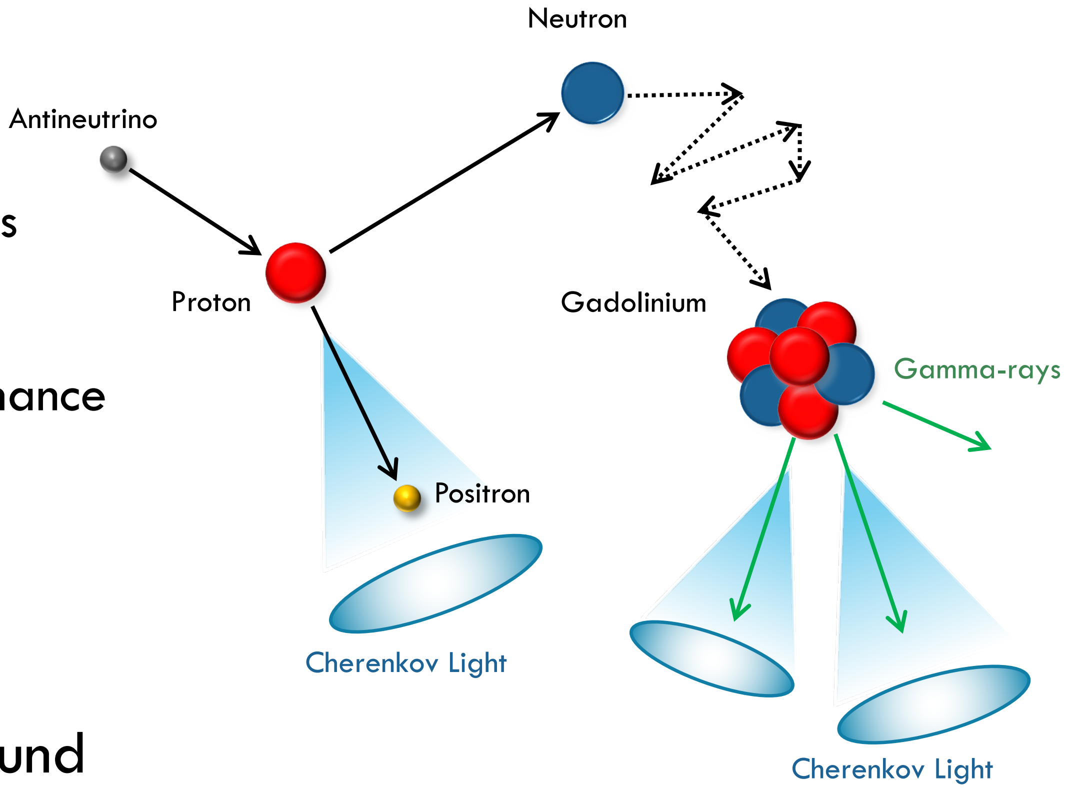






ANTI-NEUTRINO DETECTION IN WATER CHERENKOV DETECTORS

- Main channel: inverse beta decay (IBD)
  - $\overline{\upsilon}_e + p \rightarrow e^+ + n$
  - Positron: prompt signal
  - Neutron: thermalises (tens of μs) and captures on nucleus
- In the NEO concept:
  - Gd-H2O fill option uses 0.1% gadolinium doping to enhance neutron capture cross-section
  - Yields ~8 MeV γ-ray cascade
  - ~50% detection efficiency for reactor IBD events
  - This talk only covers the $\overline{\upsilon}_e$ channel via IBD
- For 500ms time window, effectively no background
  - Expected IBD background after selection: <10 events/week



HOW WELL CAN NEO DISTINGUISH MODELS?

- Explore how model discrimination power varies with detector parameters
- This study is effectively a detector benchmark to understand impact of:
  - PMT Coverage
  - Inner detector size/fiducial volume
  - Expanded fiducial volume for SN physics thanks to low background/high energy
- Variables of interest:
  - Anti-neutrino energy
  - Arrival time
- Using normal neutrino mass hierarchy

INPUT PARAMETERS

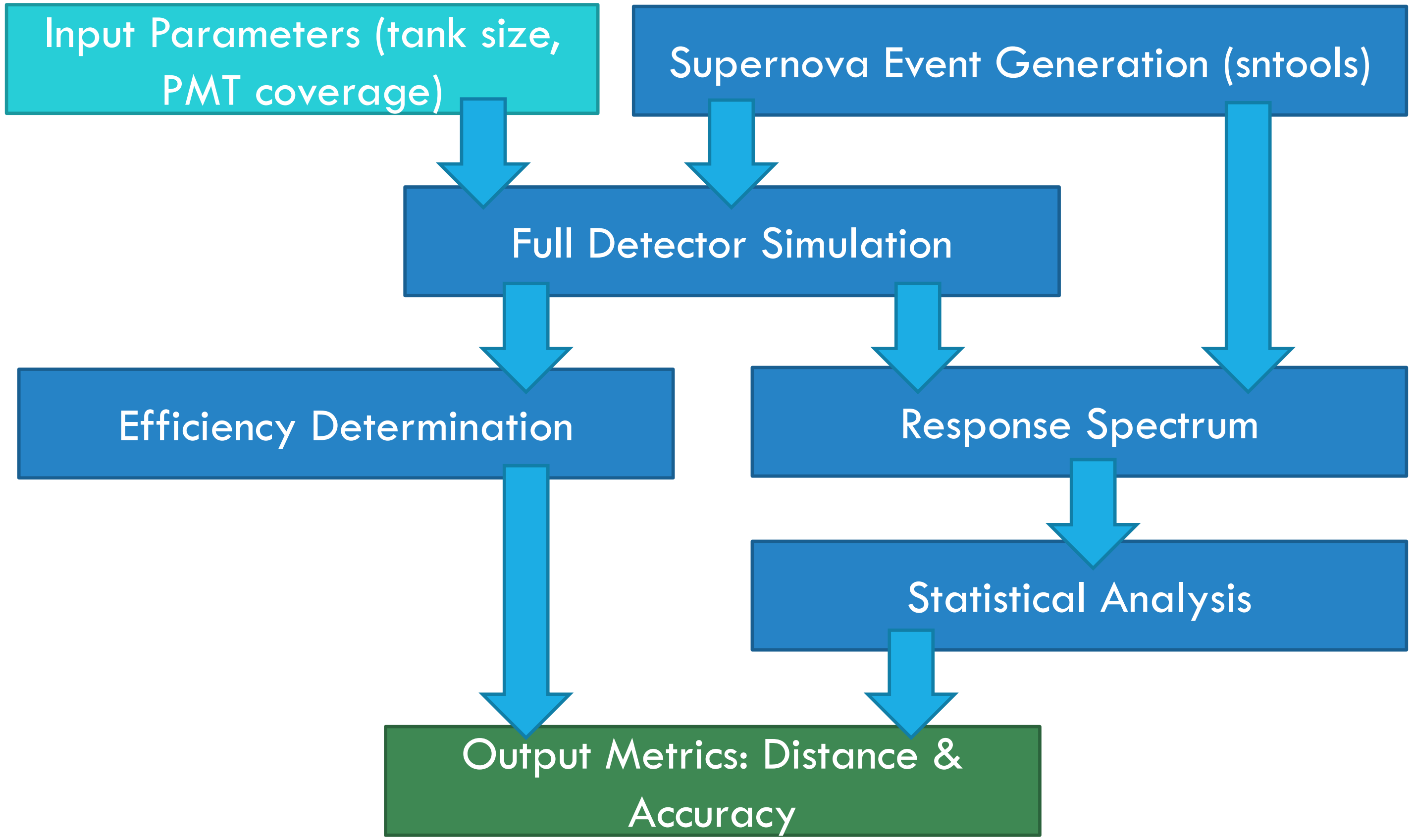
- PMT Coverage:
  - 10%, 15% and 20%
- Tank Sizes:

Tank Size (diameter/height) [m]	Inner Detector (ID) Radius [m]	Fiducial Radius [m]
22	9.0	8.0
18	7.7	6.7
16 (a)	6.7	5.7
16 (b)	5.7	4.7

Migenda, J. et al., "sntools: An event generator for supernova burst neutrinos". JOSS, 6(60), 2877 (2021). https://doi.org/10.21105/joss.02877

ANALYSIS METHODOLOGY (1)

- Event generator: `sntools`
  - By Jost Migenda: https://github.com/JostMigenda/sntools
  - Uses fluxes from SN models
  - Generates events for detector volume
  - Multiple channels
    (only IBD used here)
- Full detector simulation:
  - RAT-PAC: based on Geant4 + ROOT


Input Parameters (tank size, PMT coverage)

Supernova Event Generation (sntools)

Full Detector Simulation

Efficiency Determination

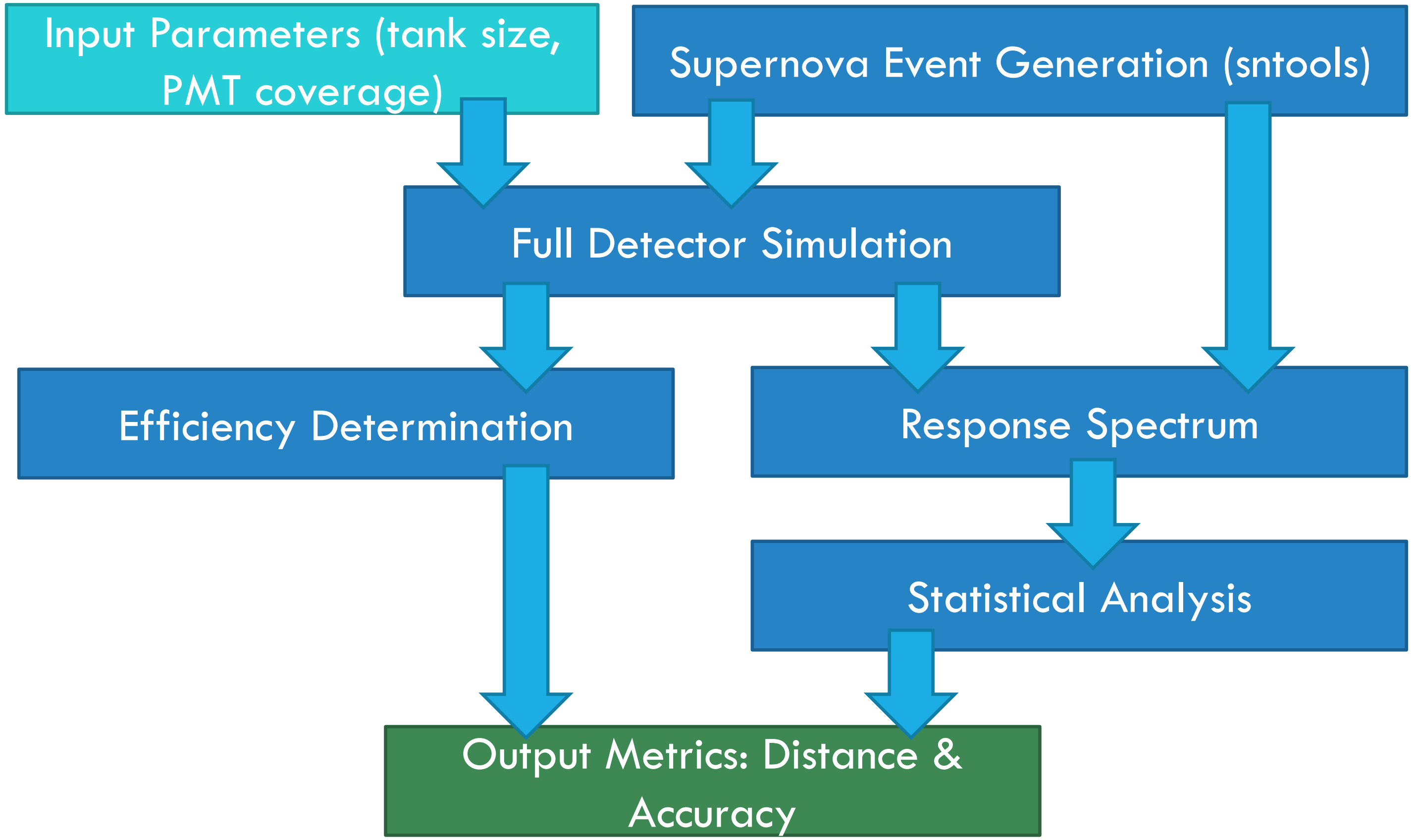
Response Spectrum

Statistical Analysis

Output Metrics: Distance & Accuracy

ANALYSIS METHODOLOGY (2)

- For sufficient statistics:
  - Full simulation not feasible for all model/detector parameter iterations
  - 10,000 pseudo-experiments (PE)
  - 10s – 100s detected $\overline{\nu}_e$ at benchmark distance of 10 kpc
- Instead, use single high statistics spectra to study:
  - Efficiency: provides normalisation
  - Response spectrum: provides parametrised energy response function



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Output Metrics: Distance & Accuracy

Loredo, T.J. and Lamb, D., "Neutrinos from SN1987A".
Annals N.Y. Acad. Sci 571 (1989), pg 601-630.
https://doi.org/10.1111/j.1749-6632.1989.tb50547.x

STATISTICAL APPROACH

- Use energy and time of each simulated event
- $L = \ln \mathcal{L} = \sum_{i=1}^{N_{obs}} \ln N_i,$
  - Where:
    - *i* runs over all "observed" events
    - N_i is the number of events predicted by the model in an infinitesimal bin around event *i*
- Based on Loredo & Lamb's methodology
- Effectively, this compares the simulated supernova vs. the expectation spectrum and returns a log-likelihood
- Choose determined model A or B using highest likelihood by using $\Delta L = L_A - L_B$

SUPERNOVA MODELS CONSIDERED

- Three models were chosen to understand for this study:
  - **Nakazato Model** (20 $M_\odot$): Modern descendant of the Totani model (which was used by SuperK collaboration and for HyperK design report) and publicly available at http://asphwww.ph.noda.tus.ac.jp/snn/index.html
    Nakazato et al., "Supernova Neutrino Light Curves and Spectra from Various Progenitor Stars: From Core Collapse to Proto-Neutron Star Cooling", Astrophys. J. Supp. 205 (2013) 2, arXiv:1210.6841 [astro-ph.HE]
  - **Vartanyan Model** (9 $M_\odot$): 2D simulations using FORNAX code, files provided by authors
    Seadrow et al., "Neutrino Signals of Core-Collapse Supernovae in Underground Detectors", MNRAS, 480, 4710, 2018, arXiv:1804.00689 [astr-ph.HE]
  - **Warren Model** (20 $M_\odot$): 1D simulation with simulated turbulence (STIR approach), updated version of the Couch model, large variety of public files available: https://zenodo.org/record/3952926#.X4I5qS8RqJ8
    Warren et al., "Constraining properties of the next nearby core-collapse supernova with multi-messenger signals", Astrophys. J. 898 (2020) 2, 139, arxiv:1912.03328 [astro-ph.HE]

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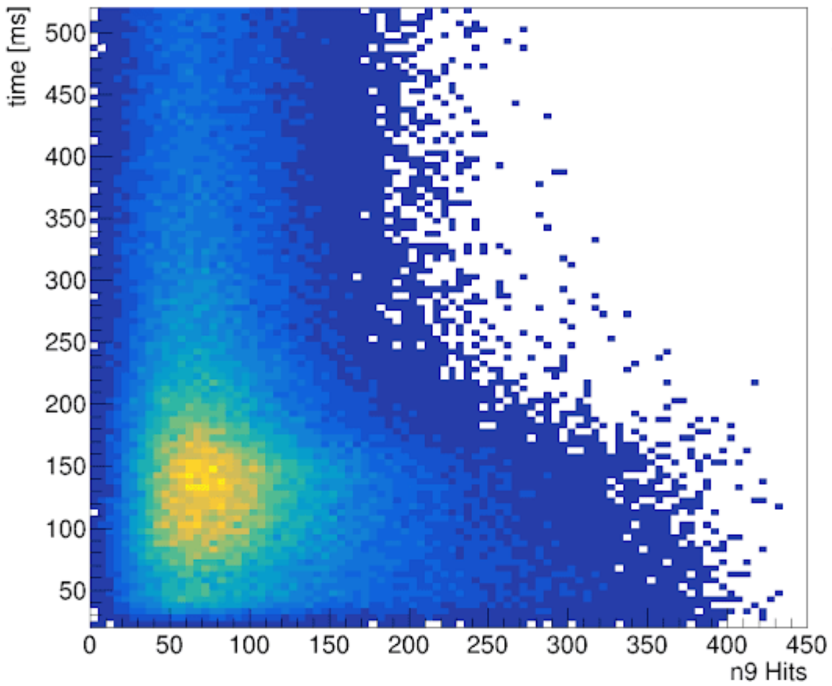
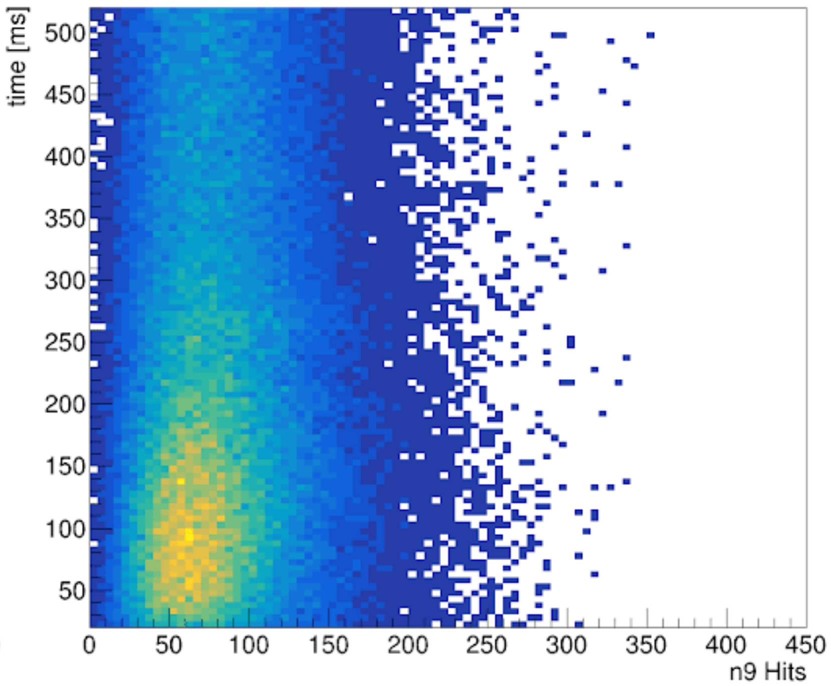
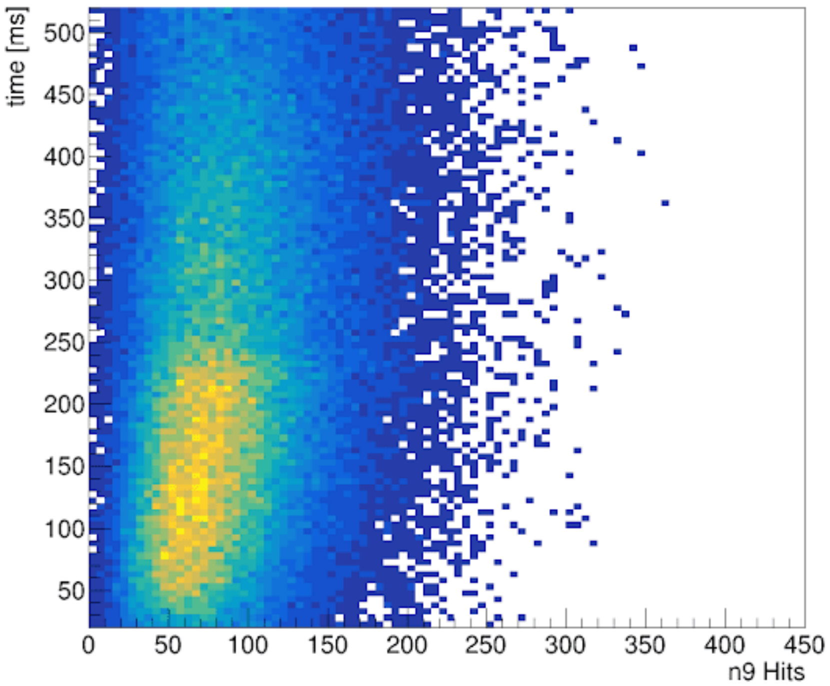
EXAMPLE SPECTRA OF MODELS



Nakazato



Vartanyan



Warren

n9 Hits: energy estimator

All histograms for 20% PMT Coverage

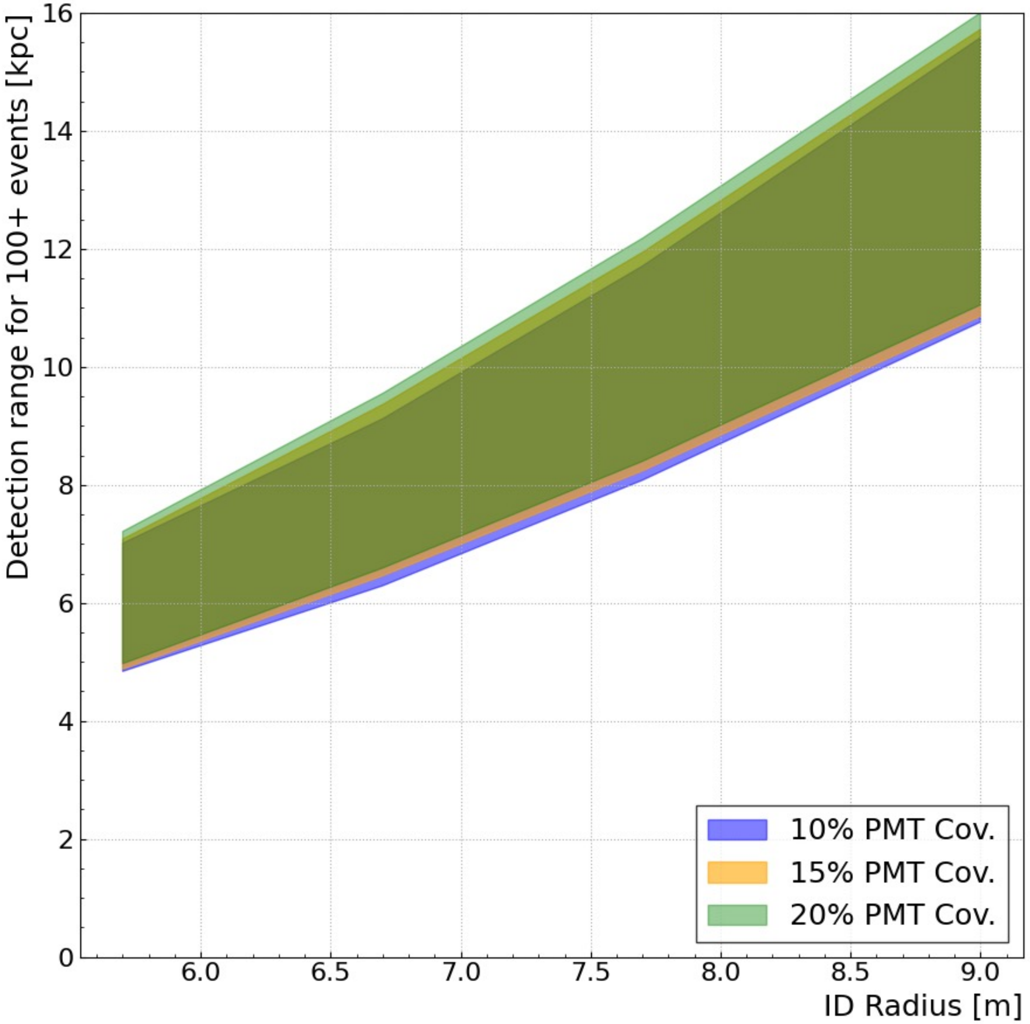
RANGE PER MODEL & DETECTOR CONFIGURATION

Detection Efficiency

	5.7m	6.7m	7.7m	9.0m
10% PMT	78.5%	79.2%	80.4%	83.6%
15% PMT	82.2%	83.4%	83.6%	85.1%
20% PMT	85.3%	86.8%	87.0%	88.2%

Detection Distance (20% PC)

Model	Interactions at 10 kpc	Visible events at 10 kpc	Distance for 100 events [kpc]
Nakazato	138.56	122.21	11.05
Vartanyan	138.23	121.92	11.04
Warren	290.34	256.98	16.03



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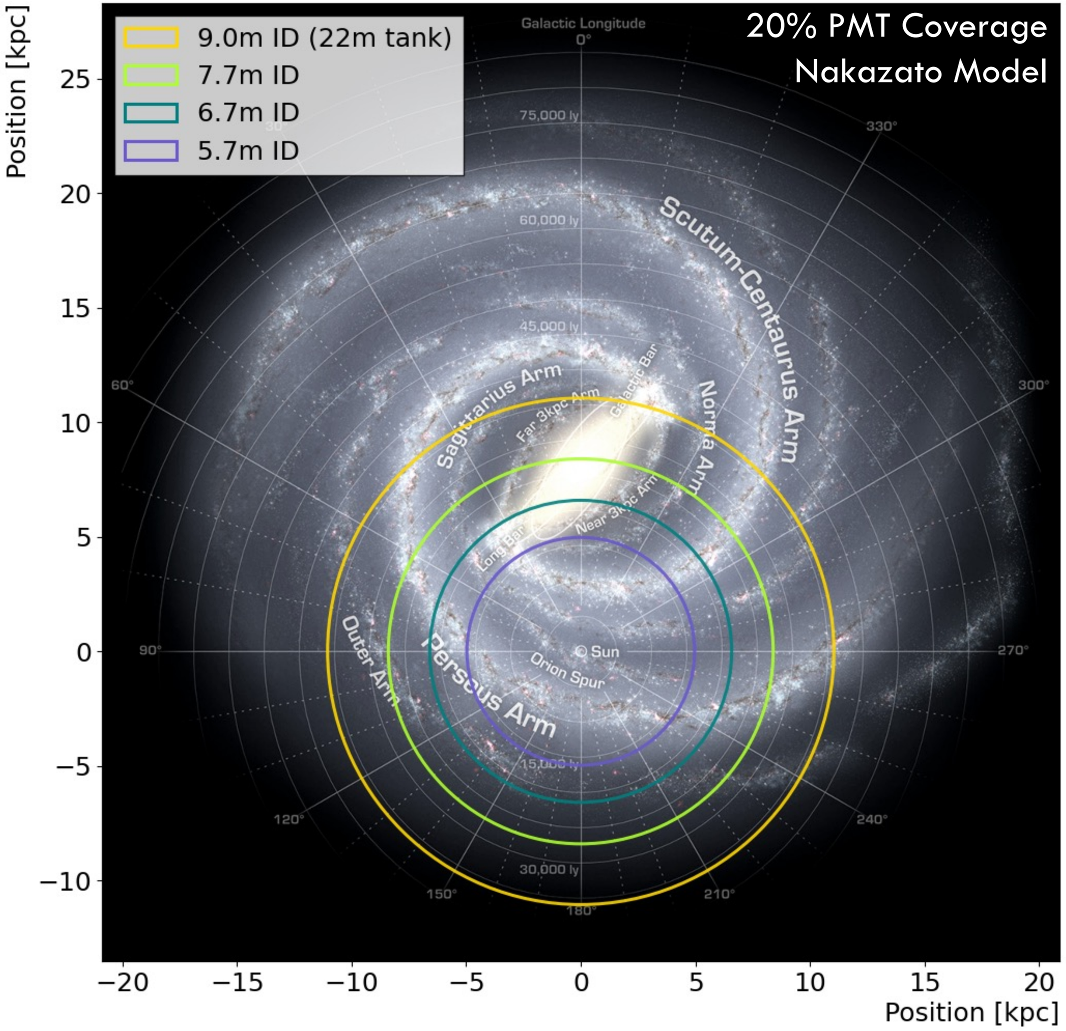

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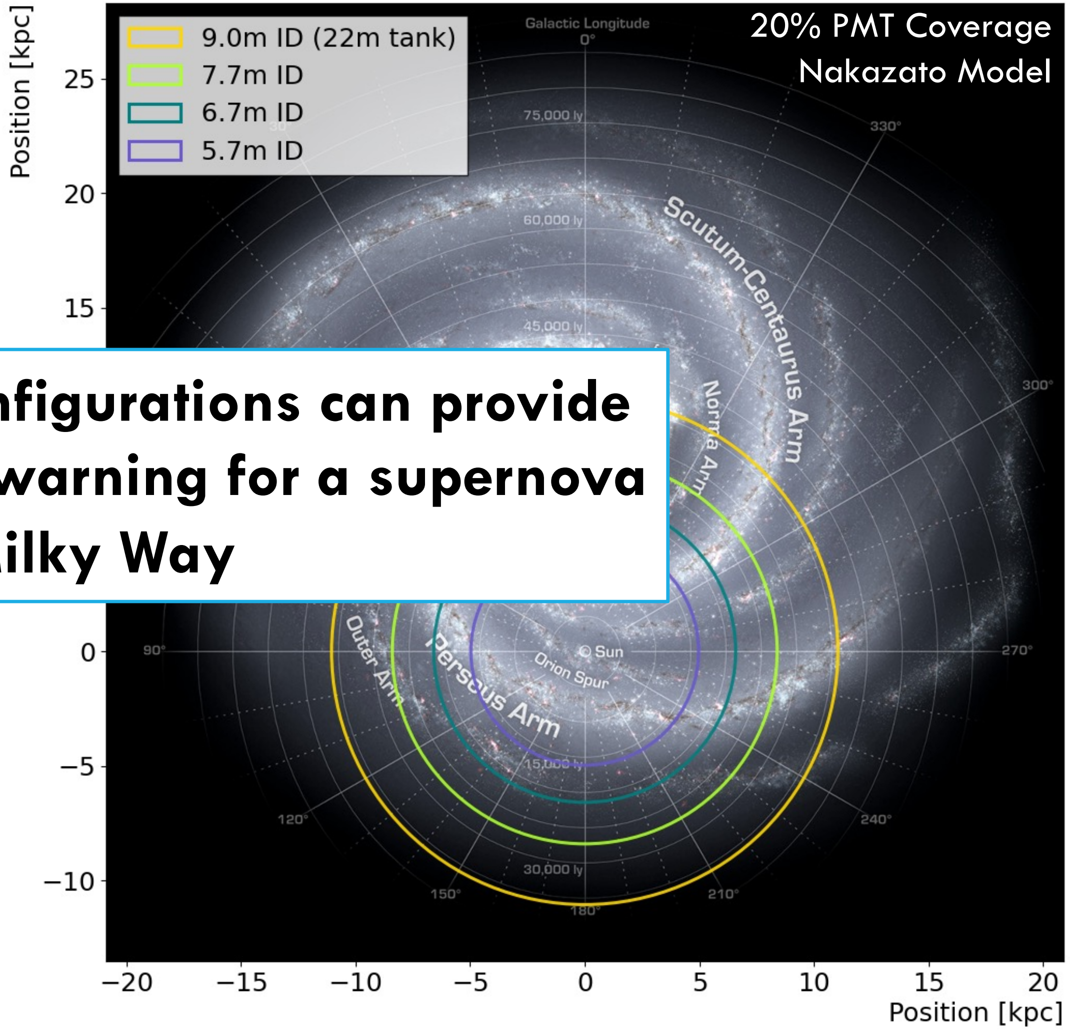
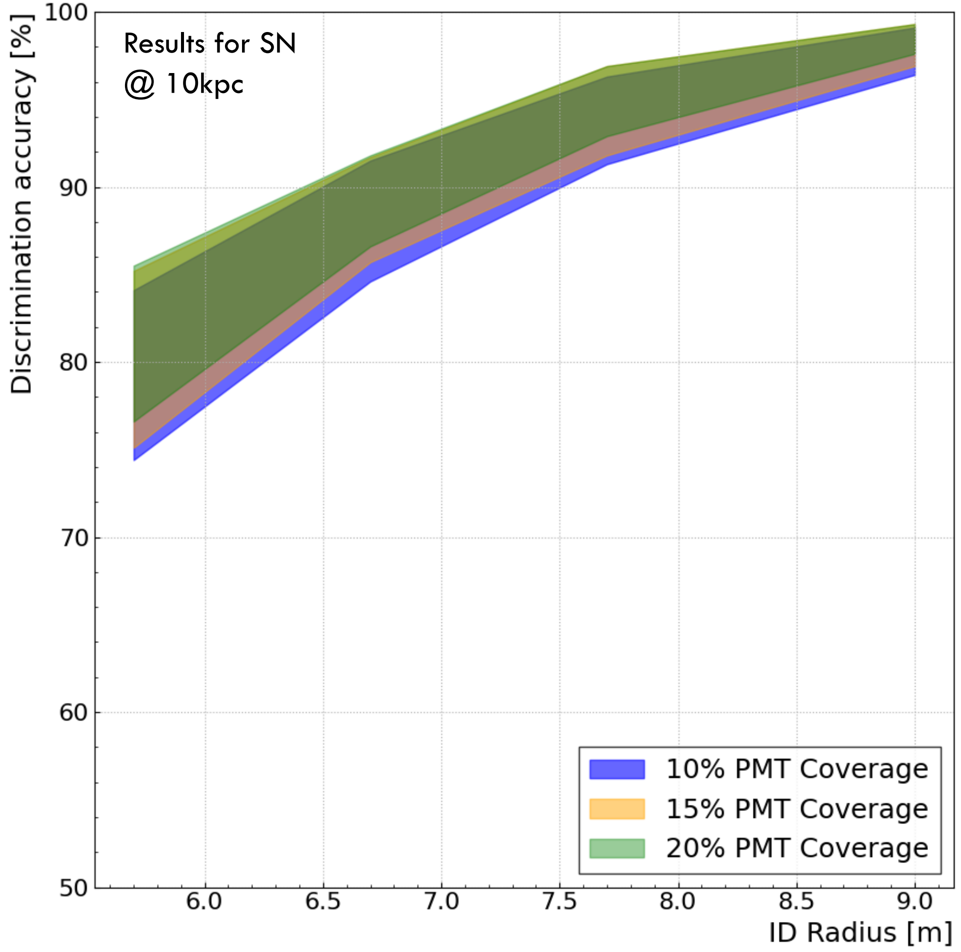
This also shows that all configurations can provide supernova triggering/early warning for a supernova within the Milky Way



MODEL DISCRIMINATION ACCURACY AT 10 KPC DISTANCE

- Statistical evaluation performed:
  - Benchmark supernova distance at 10 kpc
  - Number of expected detected $\overline{\upsilon}_e$ based on Nakazato model (fixed event count to do shape-only comparison)
  - Repeated for 10,000 PE

- For each model, find percentage of correctly identified models – "accuracy"
  - Yields three (one per model) accuracies per detector configuration
  - Summarised as range of model identification accuracies



Expected event count (10 kpc):

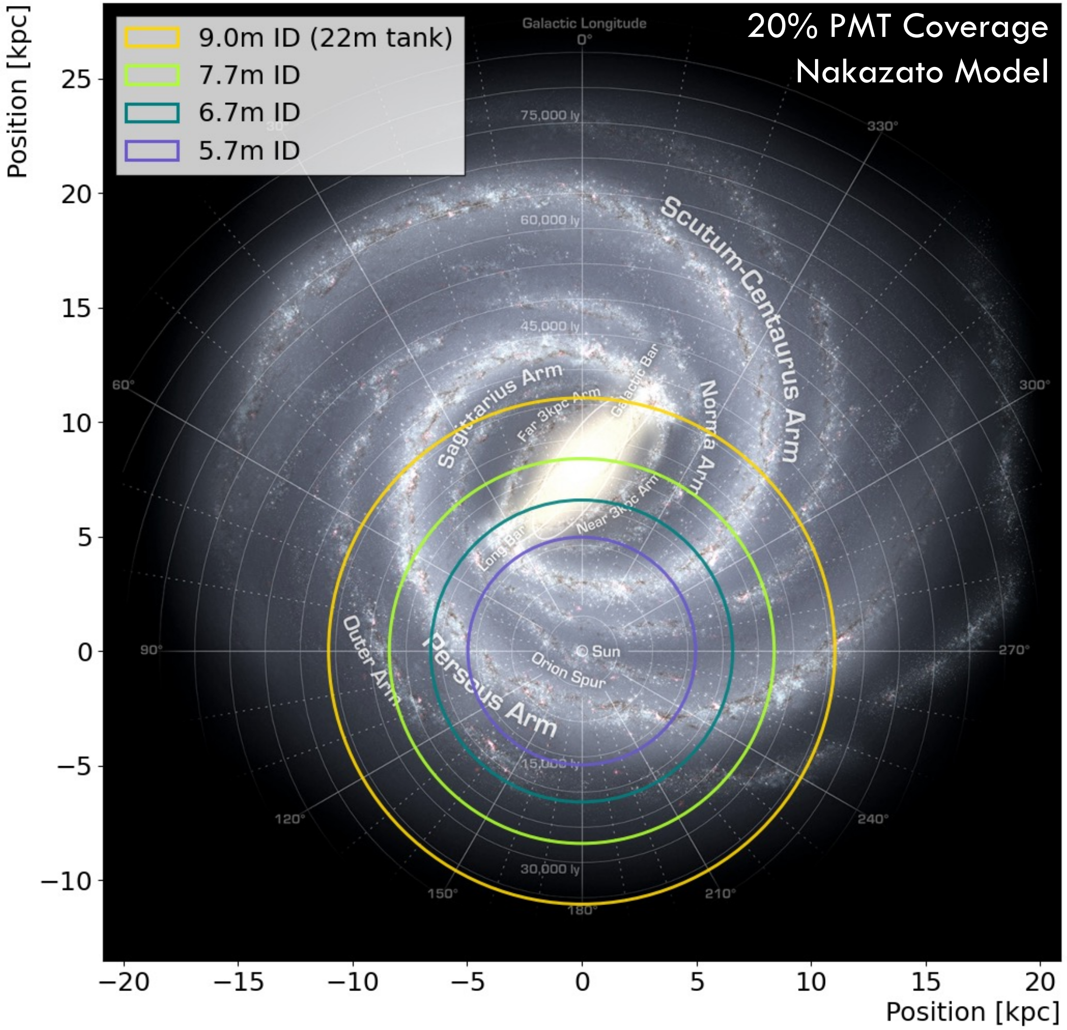
PMT Coverage	PMT Radius [mm]			
	5700	6700	7700	9000
10%	23	40	65	116
15%	24	42	68	118
20%	25	44	71	122

Model discrimination accuracies (range for all three models)

	PMT Radius [mm]			
PMT Coverage	5700	6700	7700	9000
10%	74.4-84.1%	84.6-91.5%	91.3-96.3%	96.4-99.1%
15%	75.1-85.2%	85.7-91.7%	91.8-96.9%	97.1-99.3%
20%	76.6-85.5%	86.6-91.8%	92.9-96.9%	97.6-99.3%

SUMMARY & CONCLUSIONS

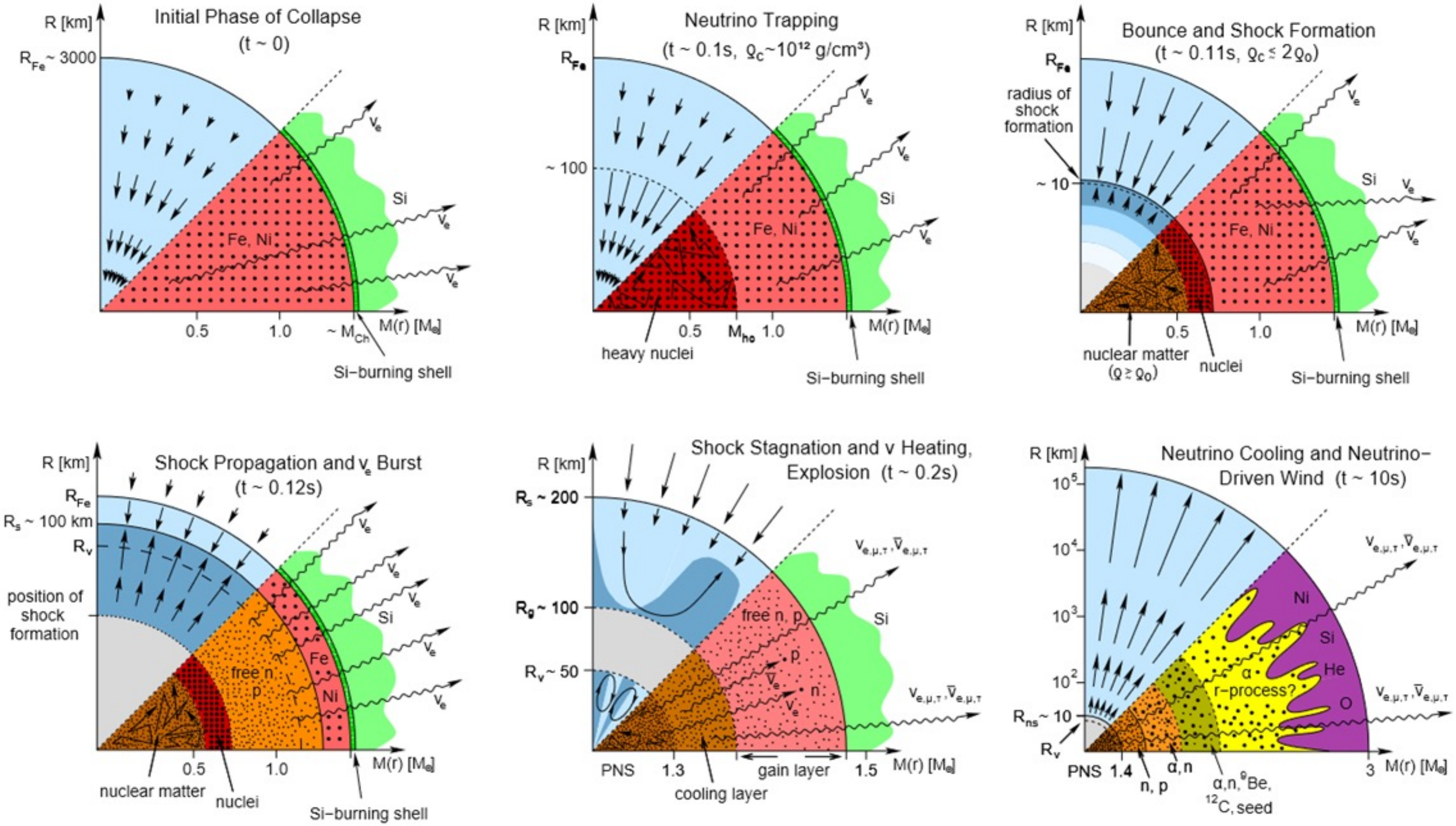
- Study of gadolinium-water Cherenkov detector configurations with:
  - Tank sizes between 16m – 22m diameter
  - Photo-coverages between 10% - 20%
- Kiloton-scale gadolinium-water Cherenkov detectors are capable of extracting physics information from energy spectrum of a supernova burst event
  - >90% discrimination accuracy for ID radius of 7.7+m
- Even smaller configurations are capable of detecting bursts from within the Milky Way, but size drives the viability of measurements



BACK-UP SLIDES

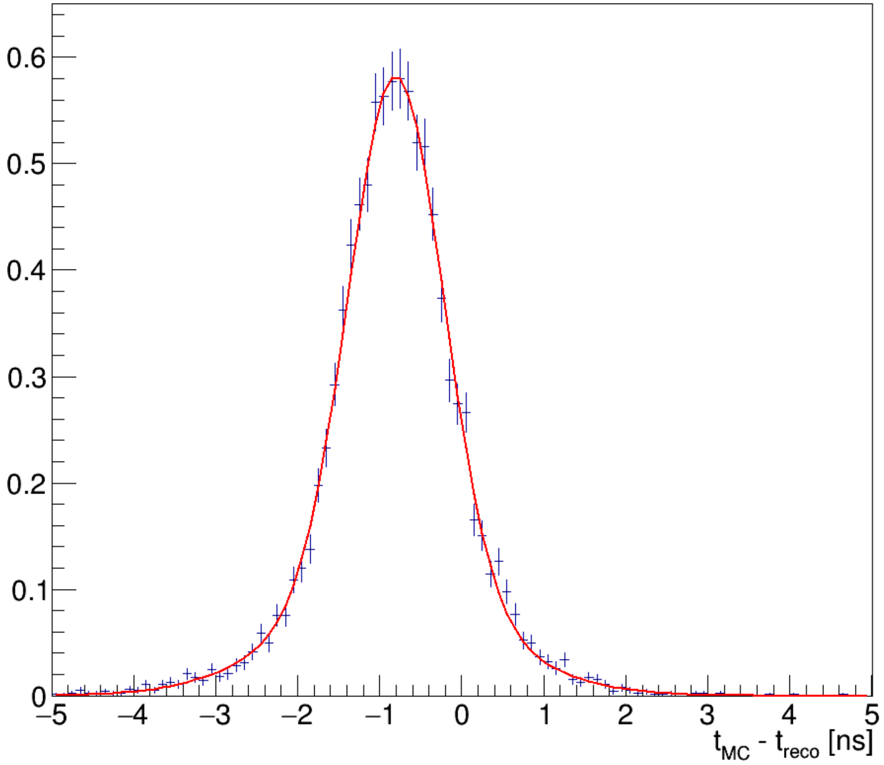
Janka, H.Th. et al., “Theory of core-collapse supernovae”.
Phys. Rep. 442, issue 1-6, pg. 38-74 (2007).
https://doi.org/10.1016/j.physrep.2007.02.002

PHASES OF CORE COLLAPSE



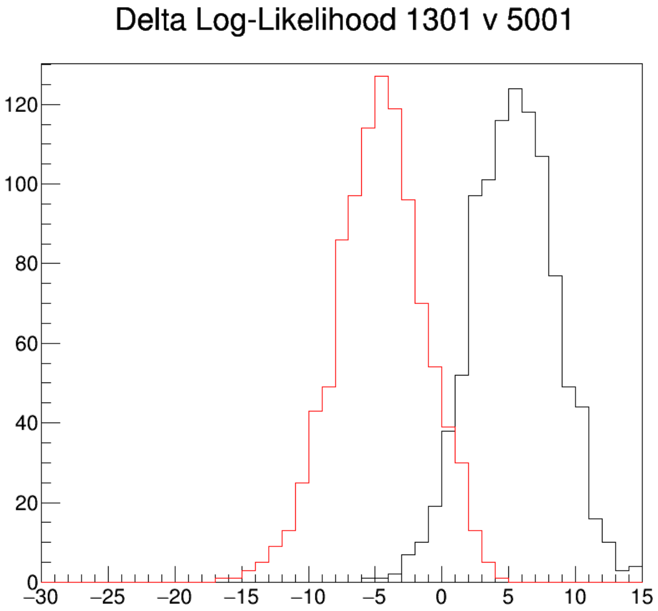
TIME SMEARING

- Similarly, as event time is a key input parameter, time shifts due to reconstruction/detector effects have to be considered
- This is done by fitting $\Delta T = t_{MC} - t_{Reco}$ for the energy response sample using the same cuts
- Most appropriate fit: double Gaussian
- Shift is minimal: relevant event information on millisecond scale



MODEL DISCRIMINATION EXAMPLE:
DISCRIMINATION BETWEEN TWO PROGENITORS MASSES

- Example discrimination using two progenitors, both using Nakazato model:
  - 1301: 13 $M_\odot$
  - 5001: 50 $M_\odot$
- Using 1,000 PEs and likelihood output
- Comparing correct identification (ID) and misidentification (Mis-ID)



Model	ID	Mis-ID
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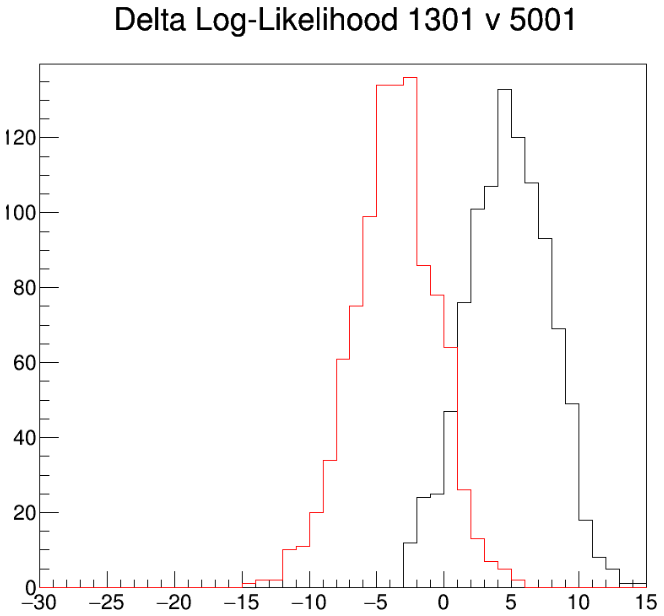
5001	95.6%	4.4%



Model	ID	Mis-ID
1301	88.3%	11.7%
5001	93.6%	6.4%