Core-collapse Supernova Model Discrimination

Jost Migenda

they/them

based on **arXiv:2002.01649**
and **arXiv:2101.05269**

… in Hyper-Kamiokande

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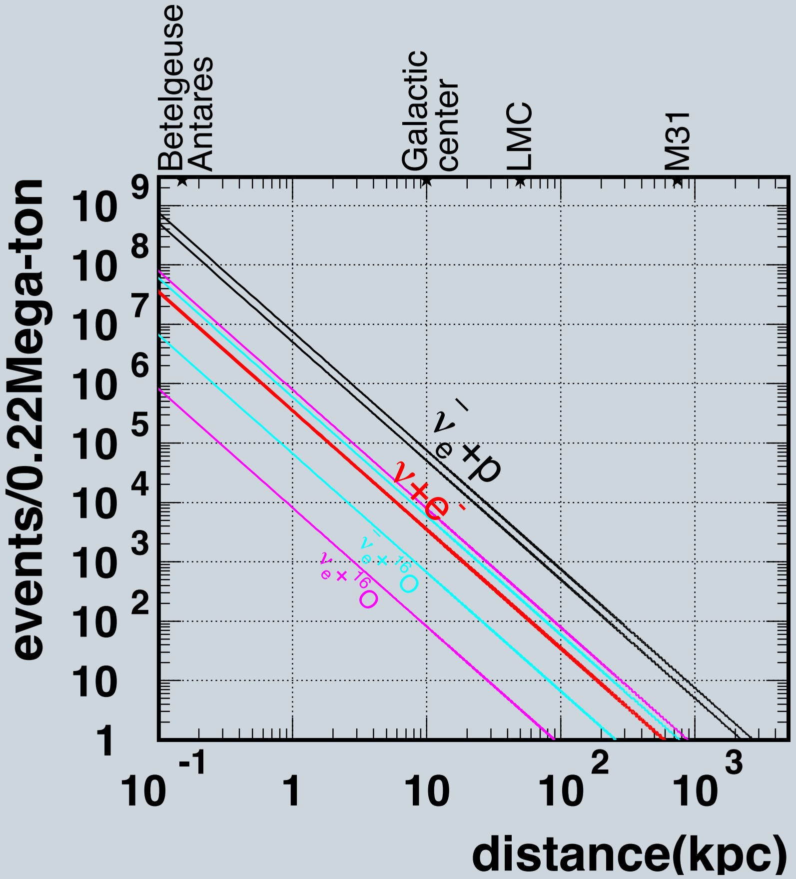
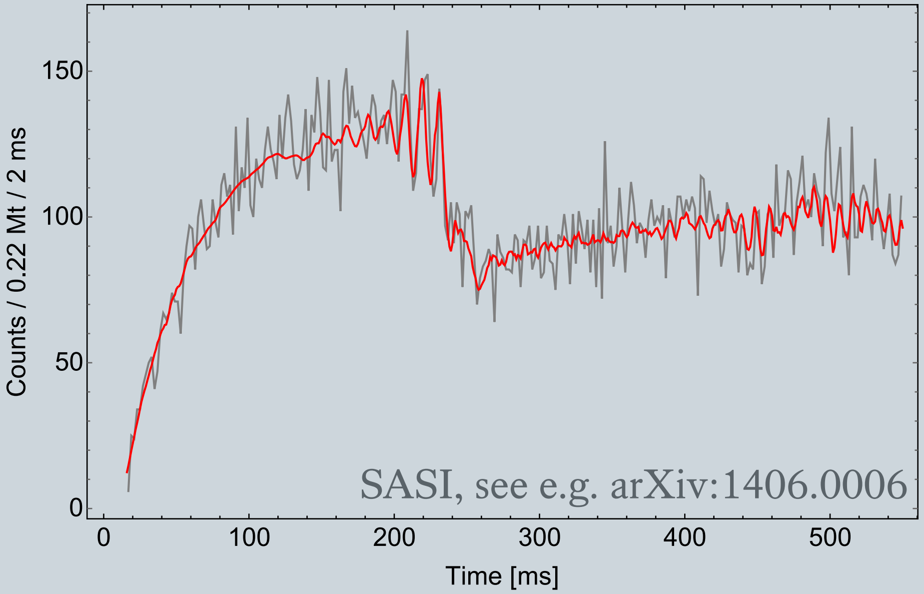
Core-collapse Supernova Observations with Hyper-Kamiokande

- HK offers both large statistics and event-by-event energy information
  - Order of magnitude larger than Super-K, DUNE, JUNO
  - IceCube: more events, but no energy information for individual events
- 54k–90k events for SN at 10 kpc
  - ~3k events for SN in LMC
- Directionality: ~1° (via νe-scattering)
- Most sensitive to $\bar{\nu}_e$





SASI, see e.g. arXiv:1406.0006

Supernova Models

Models by different groups, using various approximations

➔ telling models apart can help understand the explosion mechanism

Model	Mass		events at 10 kpc*	N=100	N=300
Totani arXiv:astro-ph/9710203	$20\ M_\odot$	1D	19716	140 kpc	81 kpc
Nakazato arXiv:1210.6841	$20\ M_\odot$	1D	17978	134 kpc	77 kpc
Couch arXiv:1902.01340	$20\ M_\odot$	1D	27539	166 kpc	96 kpc
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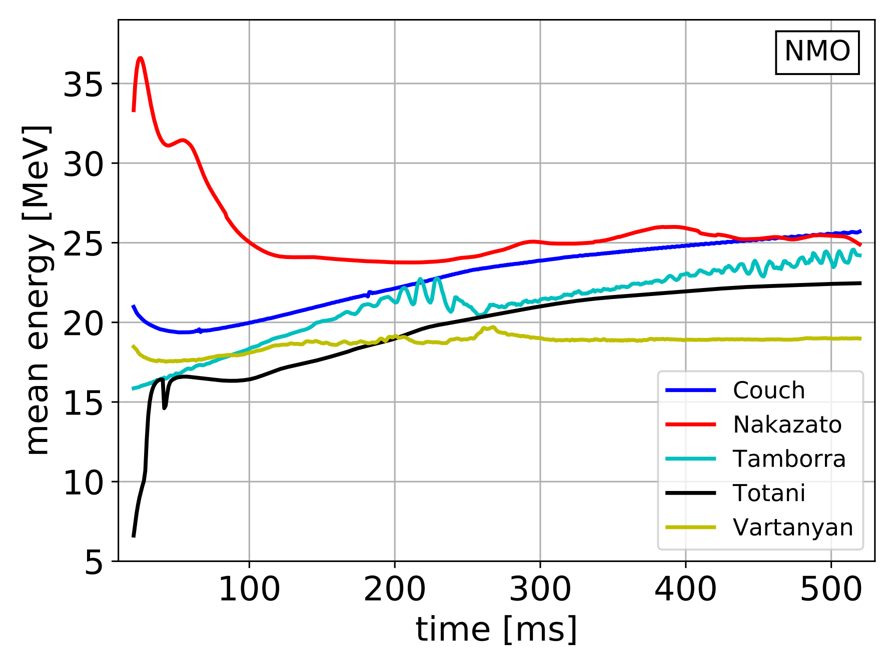
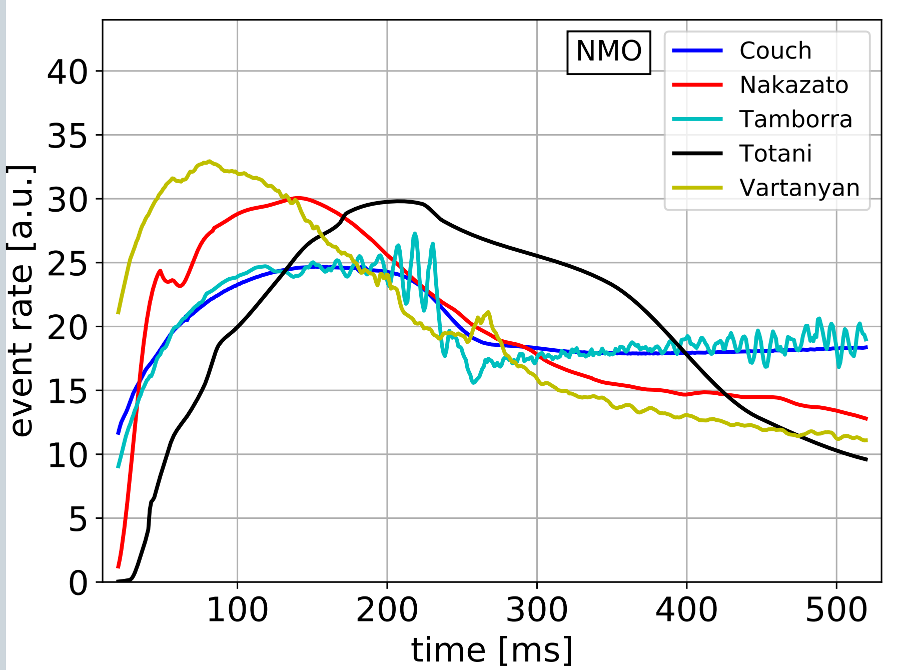
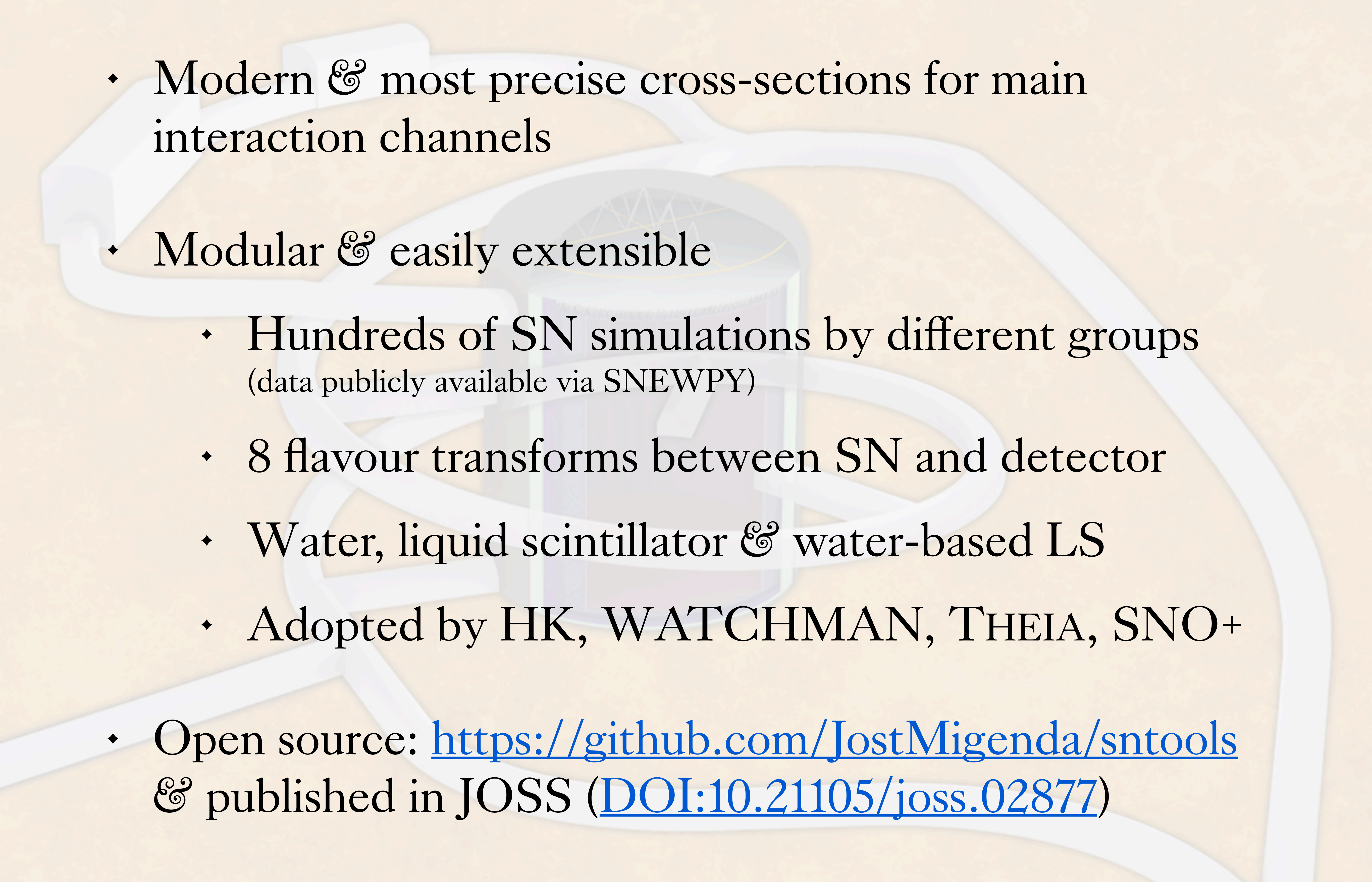




* during 20–520ms after core bounce, assuming Normal Ordering

sntools: A Supernova Event Generator

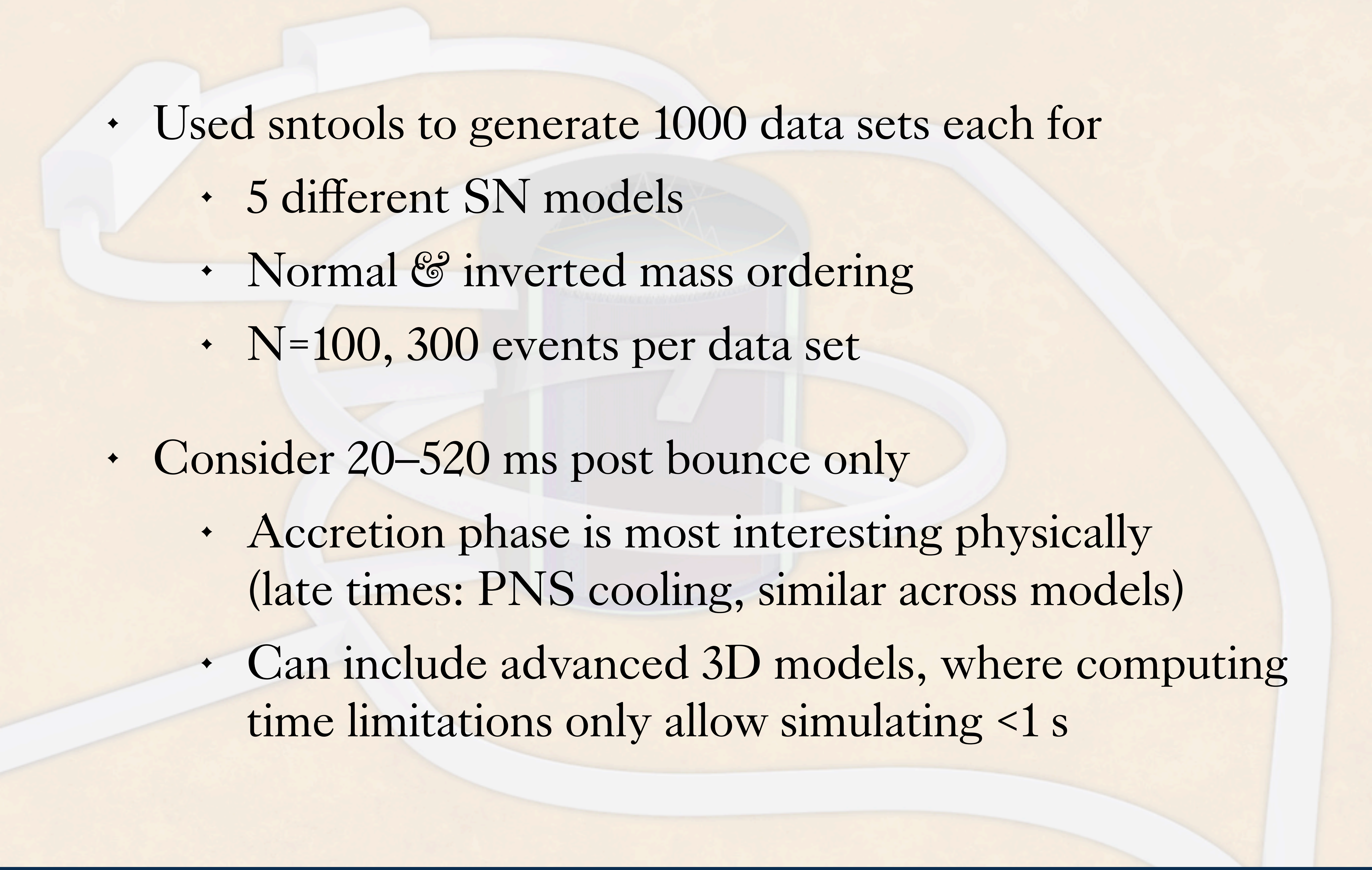


- Modern & most precise cross-sections for main interaction channels

- Modular & easily extensible
    - Hundreds of SN simulations by different groups
      (data publicly available via SNEWPY)
    - 8 flavour transforms between SN and detector
    - Water, liquid scintillator & water-based LS
    - Adopted by HK, WATCHMAN, THEIA, SNO+

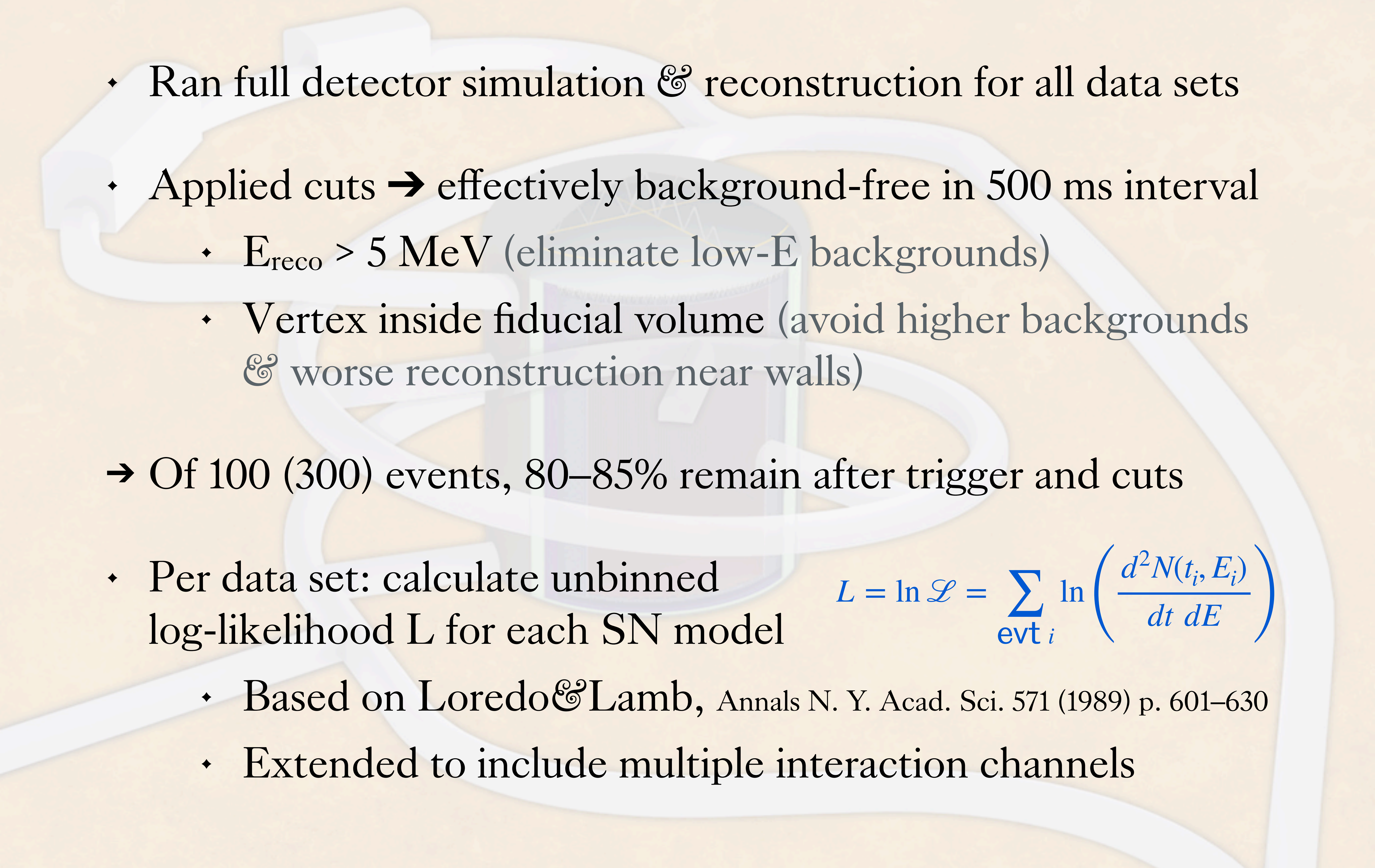
- Open source: https://github.com/JostMigenda/sntools & published in JOSS ([DOI:10.21105/joss.02877](https://doi.org/10.21105/joss.02877))

Data Sets



- Used sntools to generate 1000 data sets each for
  - 5 different SN models
  - Normal & inverted mass ordering
  - N=100, 300 events per data set
- Consider 20–520 ms post bounce only
  - Accretion phase is most interesting physically (late times: PNS cooling, similar across models)
  - Can include advanced 3D models, where computing time limitations only allow simulating <1 s

Analysis



- Ran full detector simulation & reconstruction for all data sets

- Applied cuts ➔ effectively background-free in 500 ms interval
  - $E_{\text{reco}} > 5$ MeV (eliminate low-E backgrounds)
  - Vertex inside fiducial volume (avoid higher backgrounds & worse reconstruction near walls)

➔ Of 100 (300) events, 80–85% remain after trigger and cuts

- Per data set: calculate unbinned log-likelihood L for each SN model

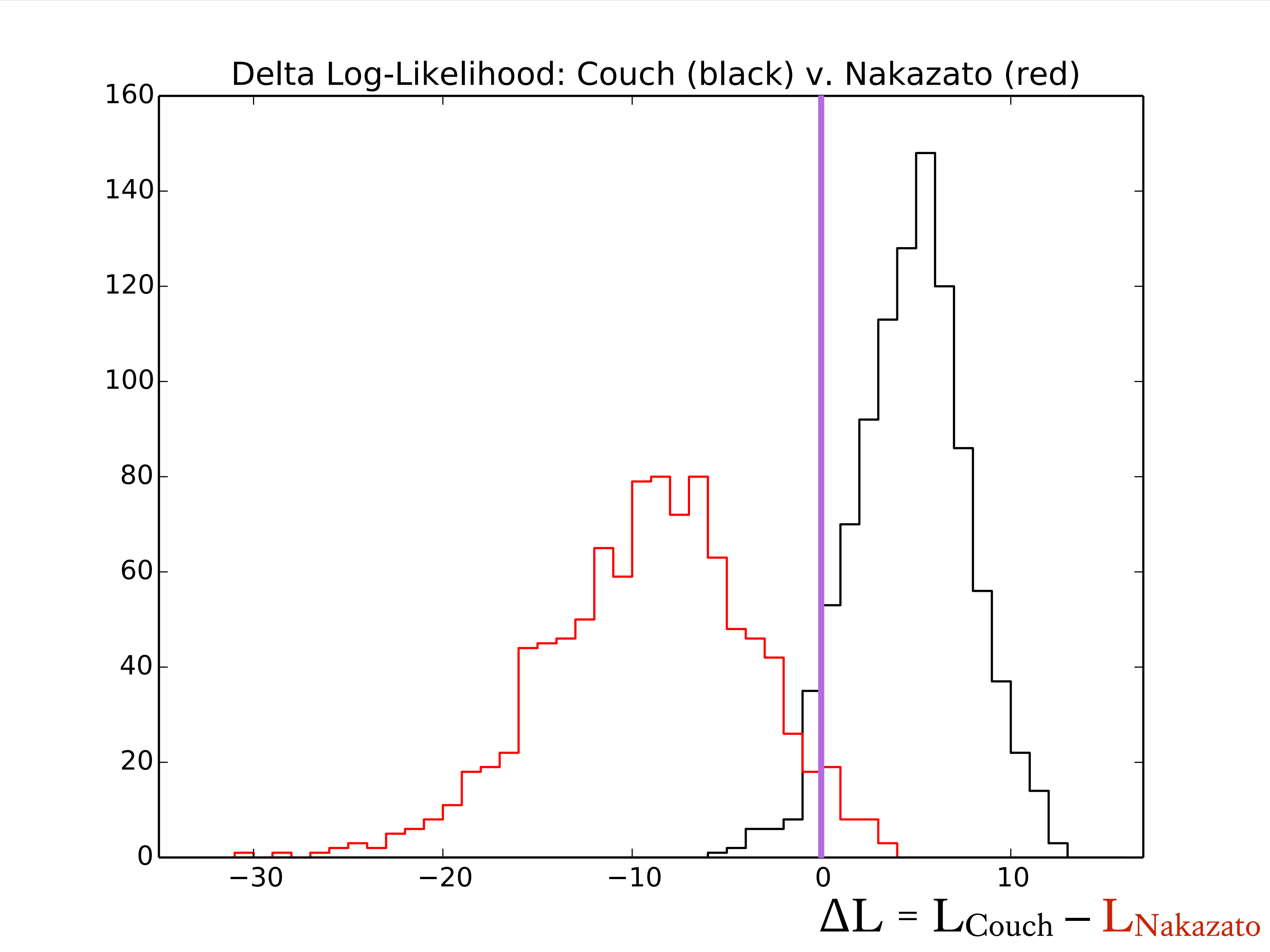
$$L = \ln \mathscr{L} = \sum_{\text{evt } i} \ln \left(\frac{d^2N(t_i, E_i)}{dt\, dE} \right)$$

  - Based on Loredo&Lamb, Annals N. Y. Acad. Sci. 571 (1989) p. 601–630
  - Extended to include multiple interaction channels

Model Comparison

Normal ordering
N=100 evt/dataset

➔ Use $\Delta L = L_A - L_B$ to determine whether model A or B better describes any given data set

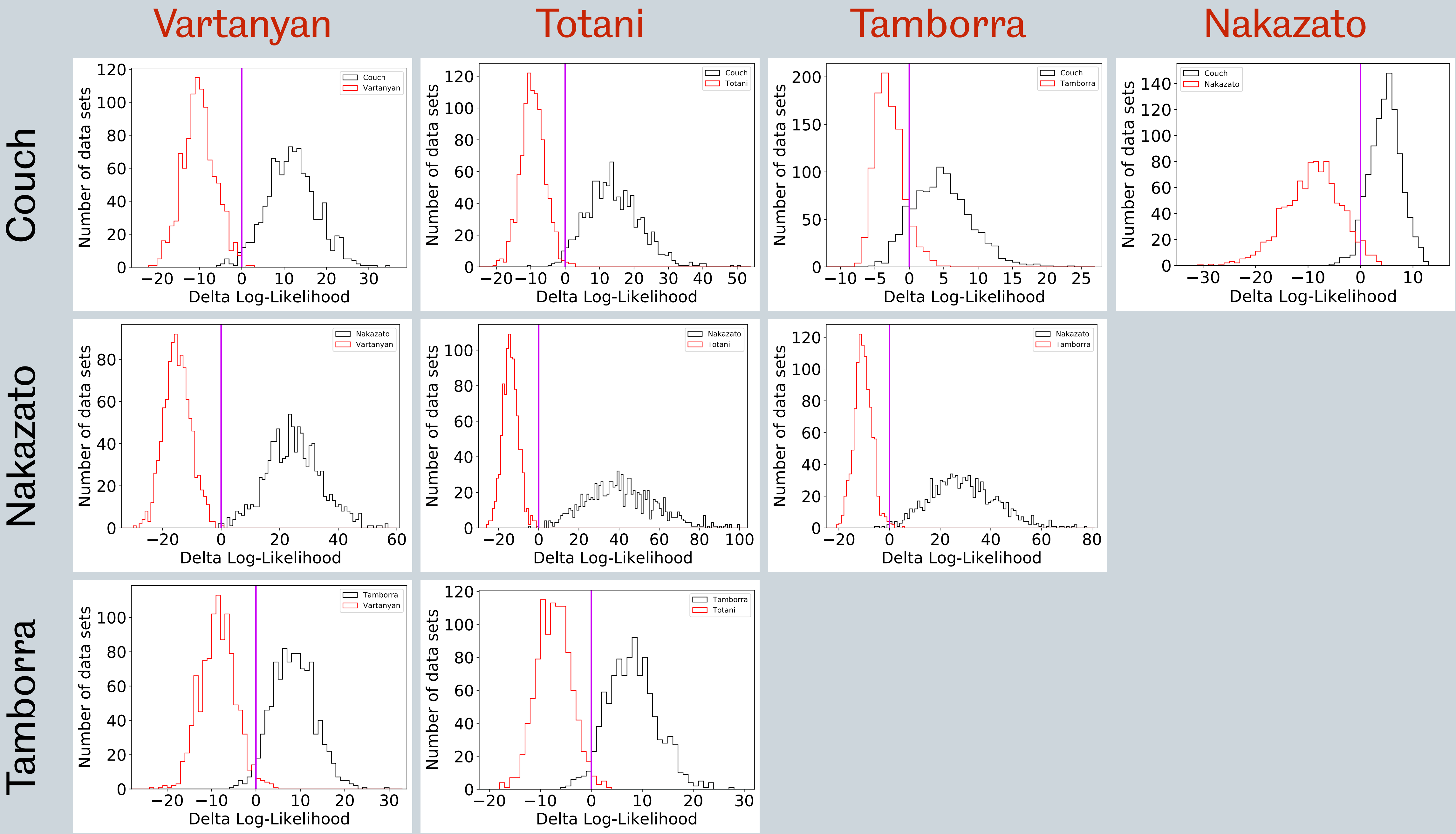


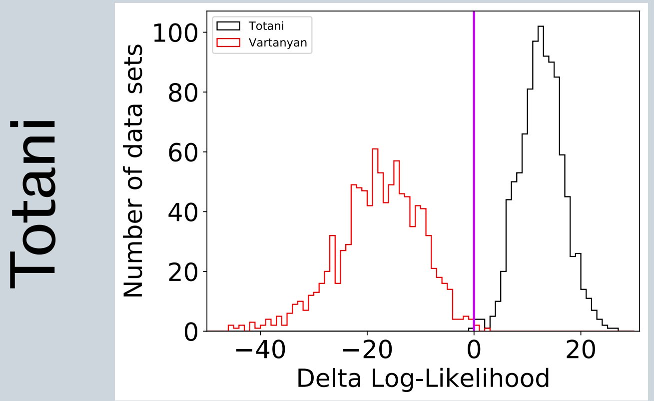
Data sets generated from Nakazato model

Data sets generated from Couch model

➔ Good model separation with just N=100 events

Pairwise Comparison of SN Models





vertical line indicates ΔL = 0

Normal ordering

N=100 events/data set

Model Identification, N=100

Identified as

True model

Normal	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	795	57	122	12	14
Nakazato	33	961	3	1	2
Tamborra	84	0	853	33	30
Totani	4	0	16	979	1
Vartanyan	0	1	17	3	979

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Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	**960**	35	4	1	0
Nakazato	8	**992**	0	0	0
Tamborra	0	1	858	21	120
Totani	3	0	20	**977**	0
Vartanyan	0	2	105	1	892

Tamborra model similar to Couch (Vartanyan) model in Normal (Inverted) Ordering.
Other models are separated well!

Model Identification, N=300

Identified as

True model

Normal	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	982	2	16	0	0
Nakazato	1	999	0	0	0
Tamborra	16	0	980	2	2
Totani	0	0	0	1000	0
Vartanyan	0	0	0	0	1000

Identified as

True model

Inverted	Couch	Nakazato	Tamborra	Totani	Vartanyan
Couch	999	1	0	0	0
Nakazato	0	1000	0	0	0
Tamborra	0	0	974	1	25
Totani	0	0	0	1000	0
Vartanyan	0	0	8	0	992

Higher statistics reduce random fluctuations & improve accuracy.

… and beyond Hyper-Kamiokande

SN Model Discrimination by Super-K

- Works for any ν detector that can measure t, E of individual events
- For Super-K, scale with detector volume to get a rough estimate
- SK is 8× smaller than HK, so expect similar capability for a SN that is $\sqrt{8} \approx 2.8\times$ closer

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21–34 kpc
for Super-K

SN Model Discrimination by WATCHMAN

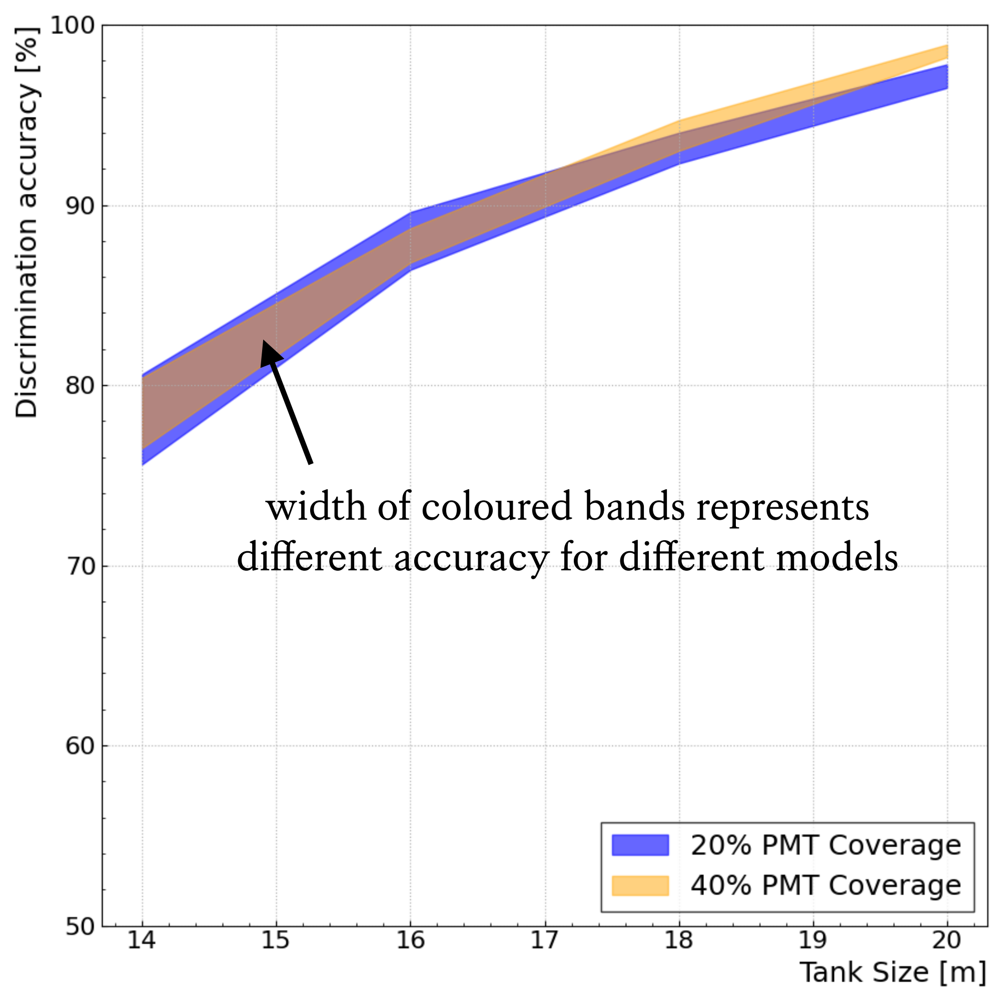
- Works for any ν detector that can measure t, E of individual events
- Detailed analysis by WATCHMAN/NEO finds comparable results
  (IBD only; using 3 models: Nakazato, Vartanyan, Warren)
- Also used this to benchmark different potential detector configurations: detector volume & photocoverage

Number of expected events ➡️

PMT Coverage	Tank Size			
	14m	16m	18m	20m
20%	21	39	64	**100**
40%	21	40	67	104

Model discrim. accuracy ⬇️

	Tank Size			
PMT Coverage	14m	16m	18m	20m
20%	75.6 – 80.6%	86.4 – 89.6%	92.3 – 94.0%	96.5 – 97.8%
40%	76.5 – 80.4%	86.8 – 88.7%	92.9 – 94.8%	98.2 – 99.0%



width of coloured bands represents different accuracy for different models

Work by Yan-Jie Schnellbach (Liverpool), presented at IOP APP/HEPP/NP Conference 2021

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    - 300 events (60–100 kpc)
    - Nakazato model
    - 13, 20, 30 M_{sol}
    - 20 M_{sol} with 2 metallicities

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True model

Normal Mass Ordering	13 M_{sol}	20 M_{sol}	20 M_{sol}*	30 M_{sol}
13 M_{sol}	878	61	61	0
20 M_{sol}	17	944	39	0
20 M_{sol}*	74	75	850	1
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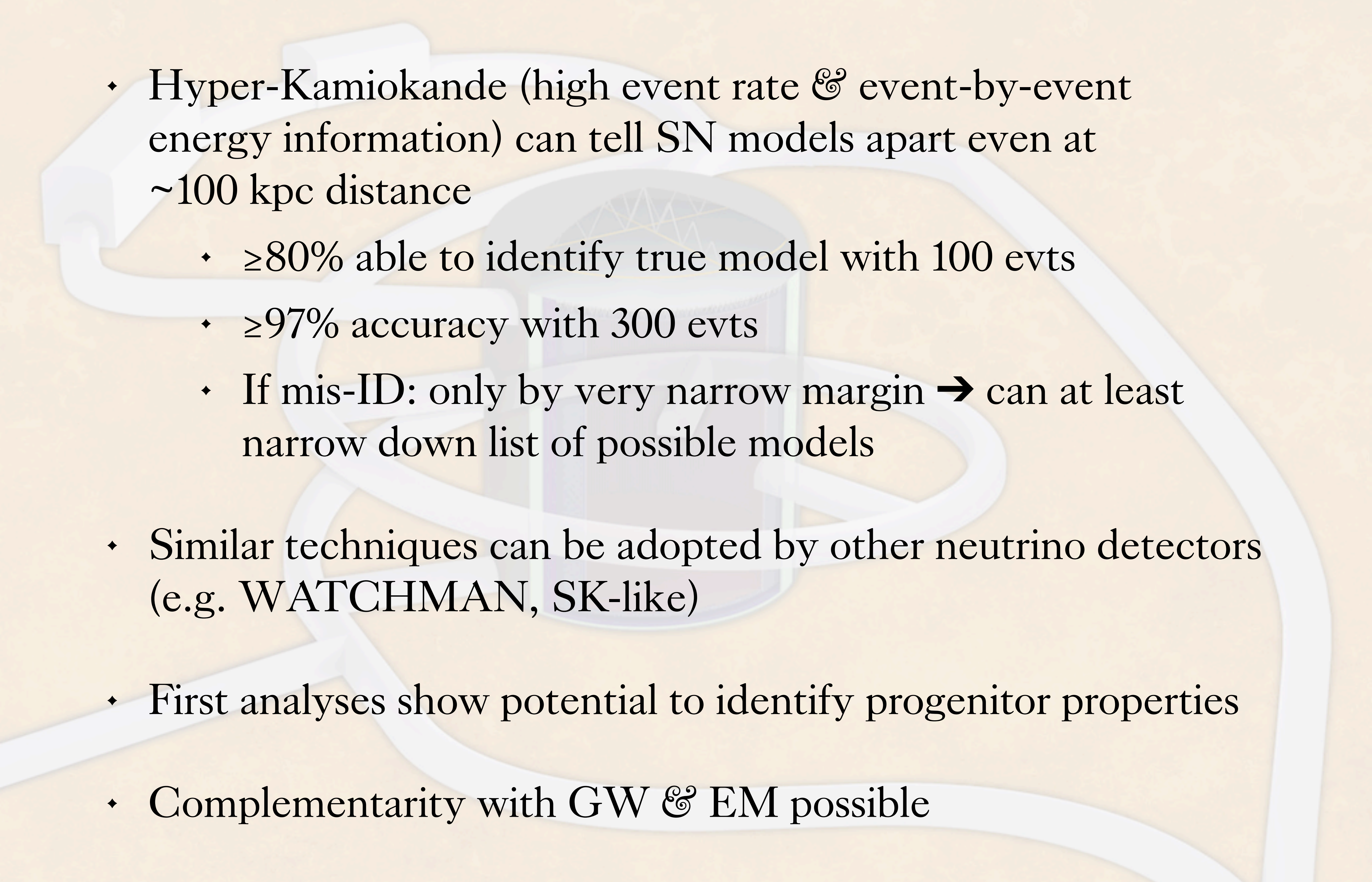
- New pre-print by Olsen & Qian (arXiv:2202.09975)
  - Compare simulations with different progenitor masses (9.6, 18.6, 20, 27 M_{sol}) and equations of state (SFHo, LS220)
  - Simpler detector model (Super-K-like), more sophisticated statistical approach
  - Maximum distance to distinguish models is 10–25 kpc

Beyond Neutrinos

- Gravitational waves
  - Complementary ways of studying the SN core!
  - A few simulations provide both ν and GW signals (Warren et al., DOI:10.3847/1538-4357/ab97b7) ➔ enables cross checks and/or joint likelihood function for improved accuracy
- Electromagnetic
  - Complementary ways of extracting information on the progenitor!
    - … and its core? (Barker et al., arXiv:2102.01118)
  - Relies on stellar evolution code?
- Plenty of room for discussion today!

Conclusions



- Hyper-Kamiokande (high event rate & event-by-event energy information) can tell SN models apart even at ~100 kpc distance
    - ≥80% able to identify true model with 100 evts
    - ≥97% accuracy with 300 evts
    - If mis-ID: only by very narrow margin ➔ can at least narrow down list of possible models
- Similar techniques can be adopted by other neutrino detectors (e.g. WATCHMAN, SK-like)
- First analyses show potential to identify progenitor properties
- Complementarity with GW & EM possible