Core-collapse Supernova Model Discrimination with Hyper-Kamiokande

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For the Hyper-Kamiokande Collaboration

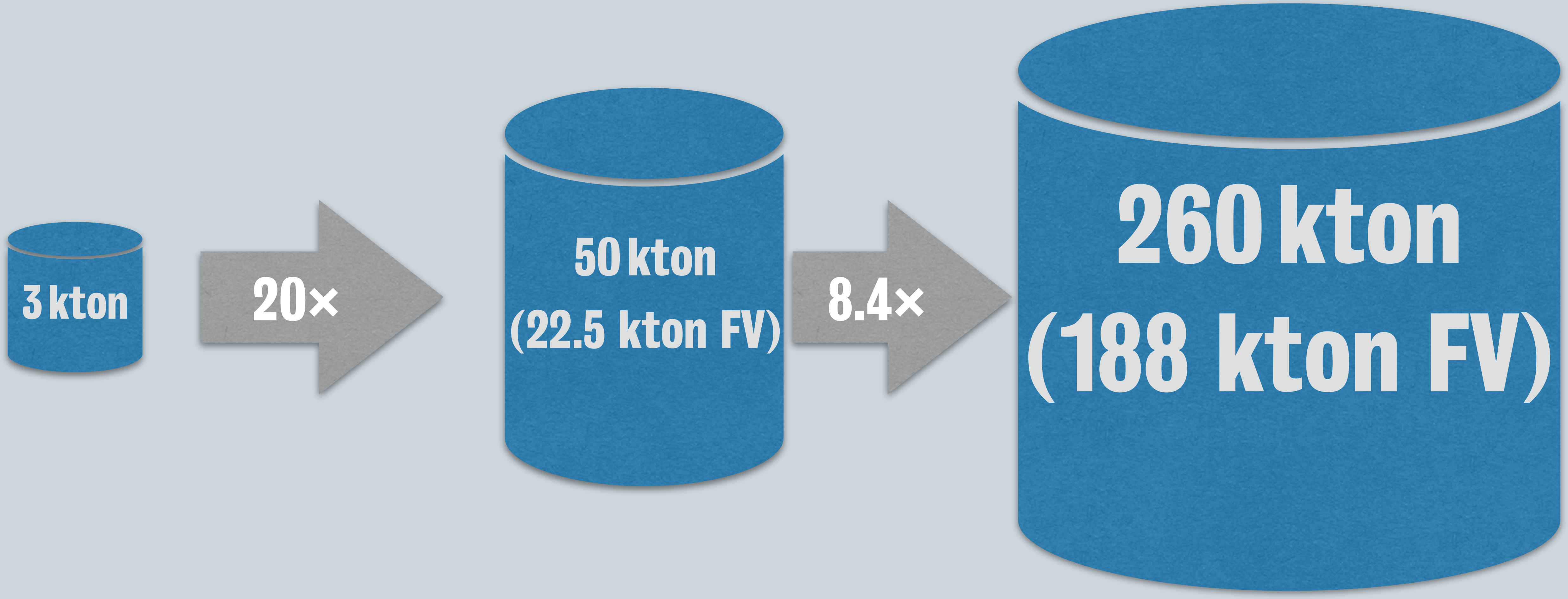
Based on arXiv:2002.01649 & 2101.05269

Hyper-Kamiokande

Kamiokande
1983–1996

Super-Kamiokande
1996–today *(and beyond)*

Hyper-Kamiokande
~2027–???



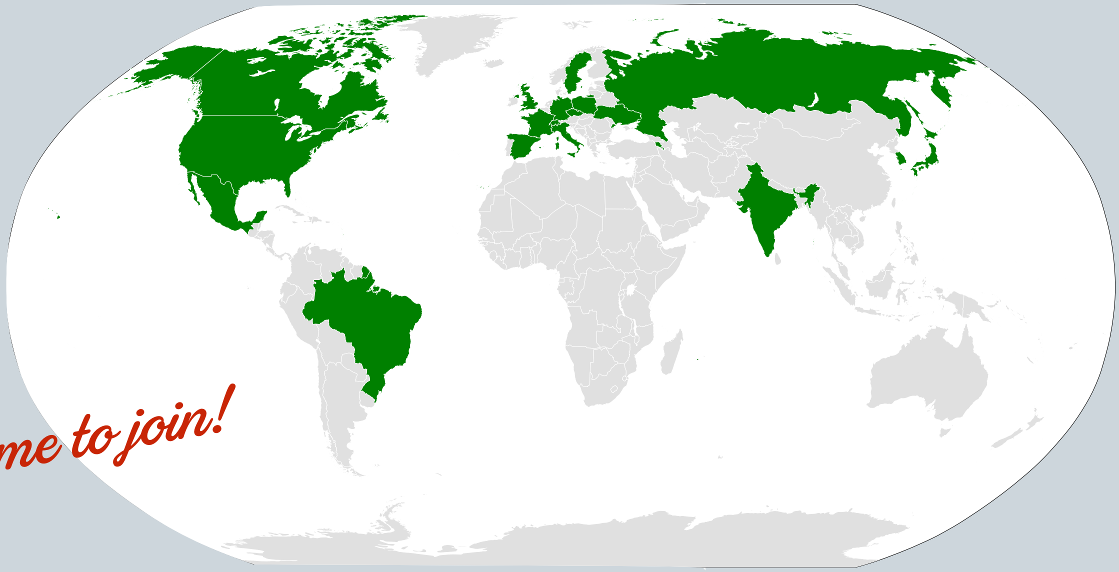

Koshiba, 2002


Kajita, 2015


To be determined …

Hyper-Kamiokande

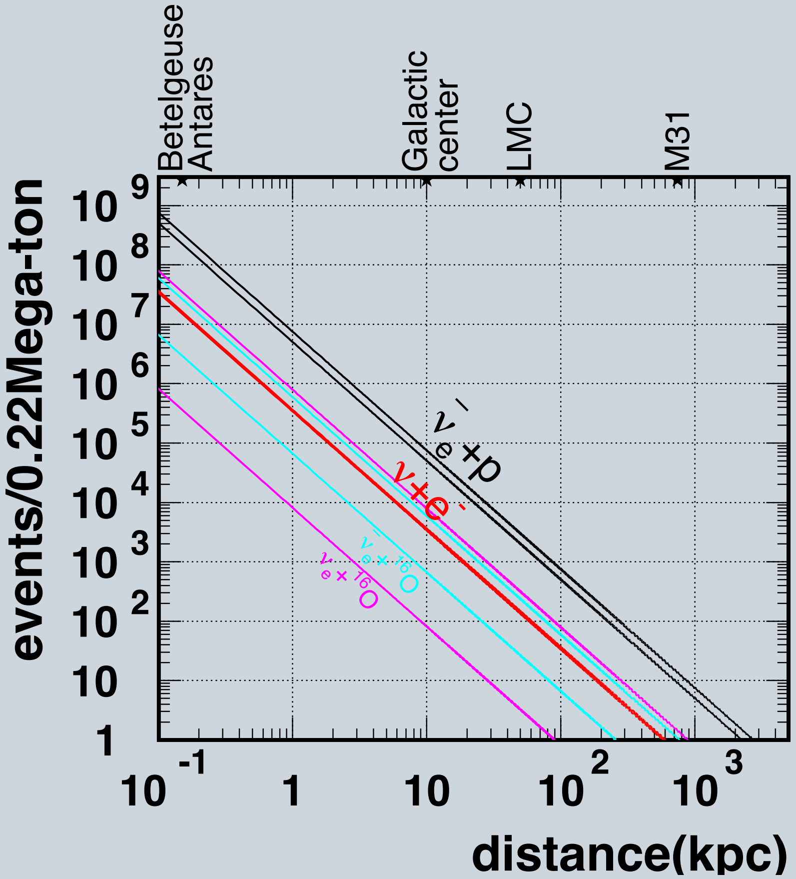
- Physics goals:
    - δ_{CP} & other ν oscillation parameters
    - Proton decay (reaching ~10^{35} years)
    - Solar & supernova neutrinos
    - … and much more!
- Updated design report published in 2018 arXiv:1805.04163
- Funding approved & excavation started in 2020
- 350+ members from 19 countries

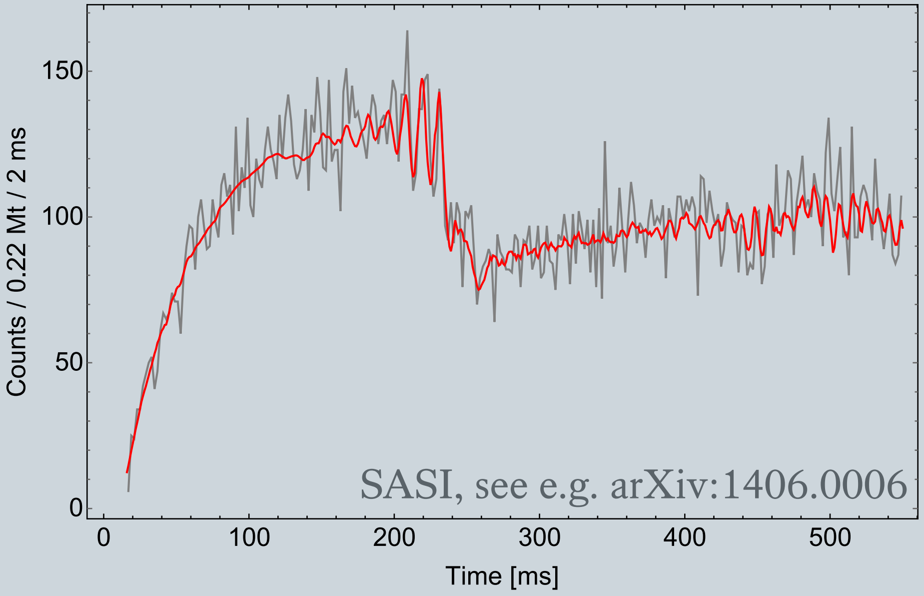


Now is a great time to join!

Core-collapse Supernova Observations with Hyper-Kamiokande

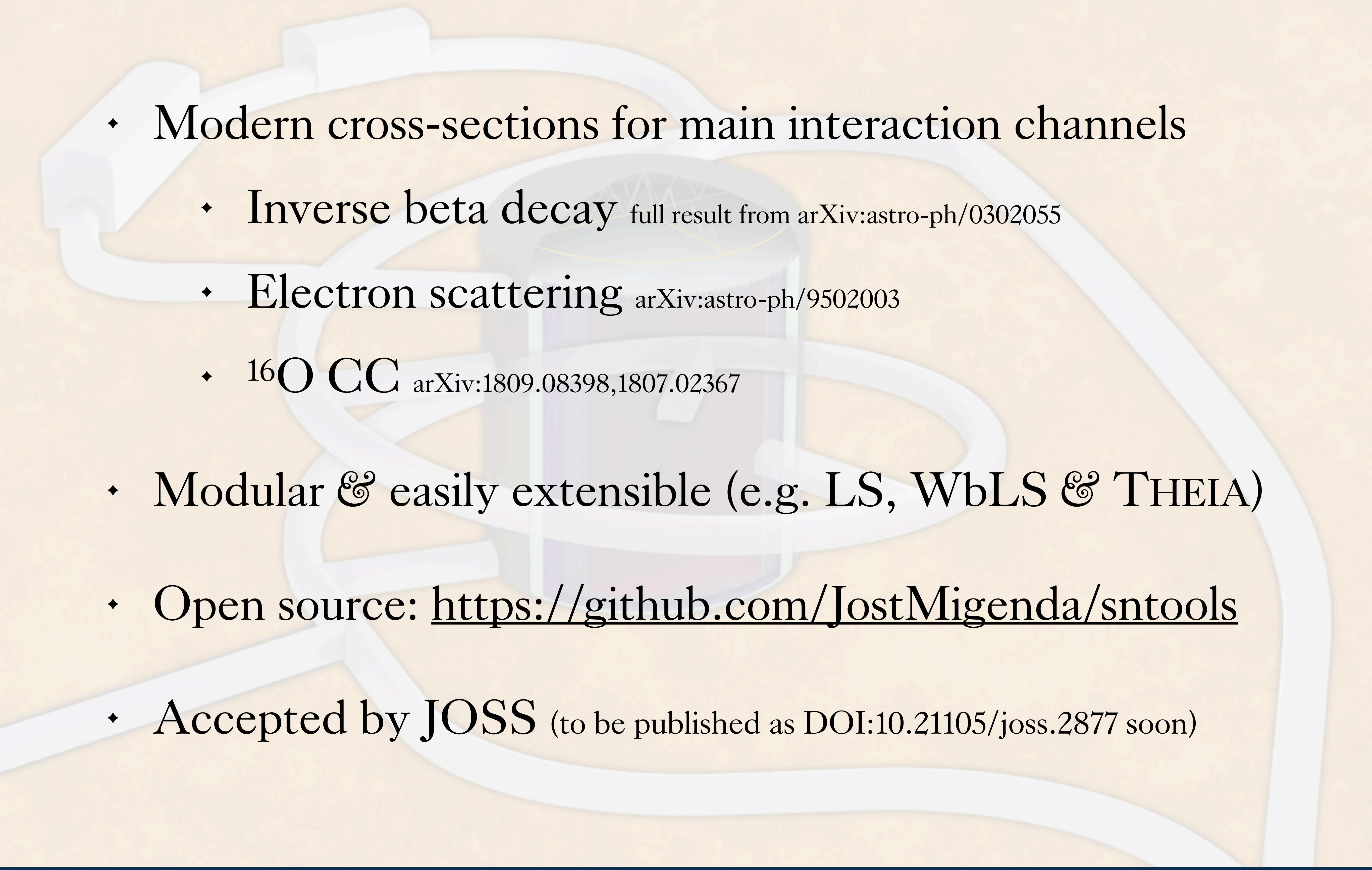
- HK offers both large statistics and event-by-event energy information
    - Order of magnitude larger than Super-K, DUNE, JUNO
    - IceCube: more events, but no energy information for individual events
- 54k–90k events for SN at 10 kpc
    - ~3k events for SN in LMC
- Directionality: ~1° (via νe-scattering)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





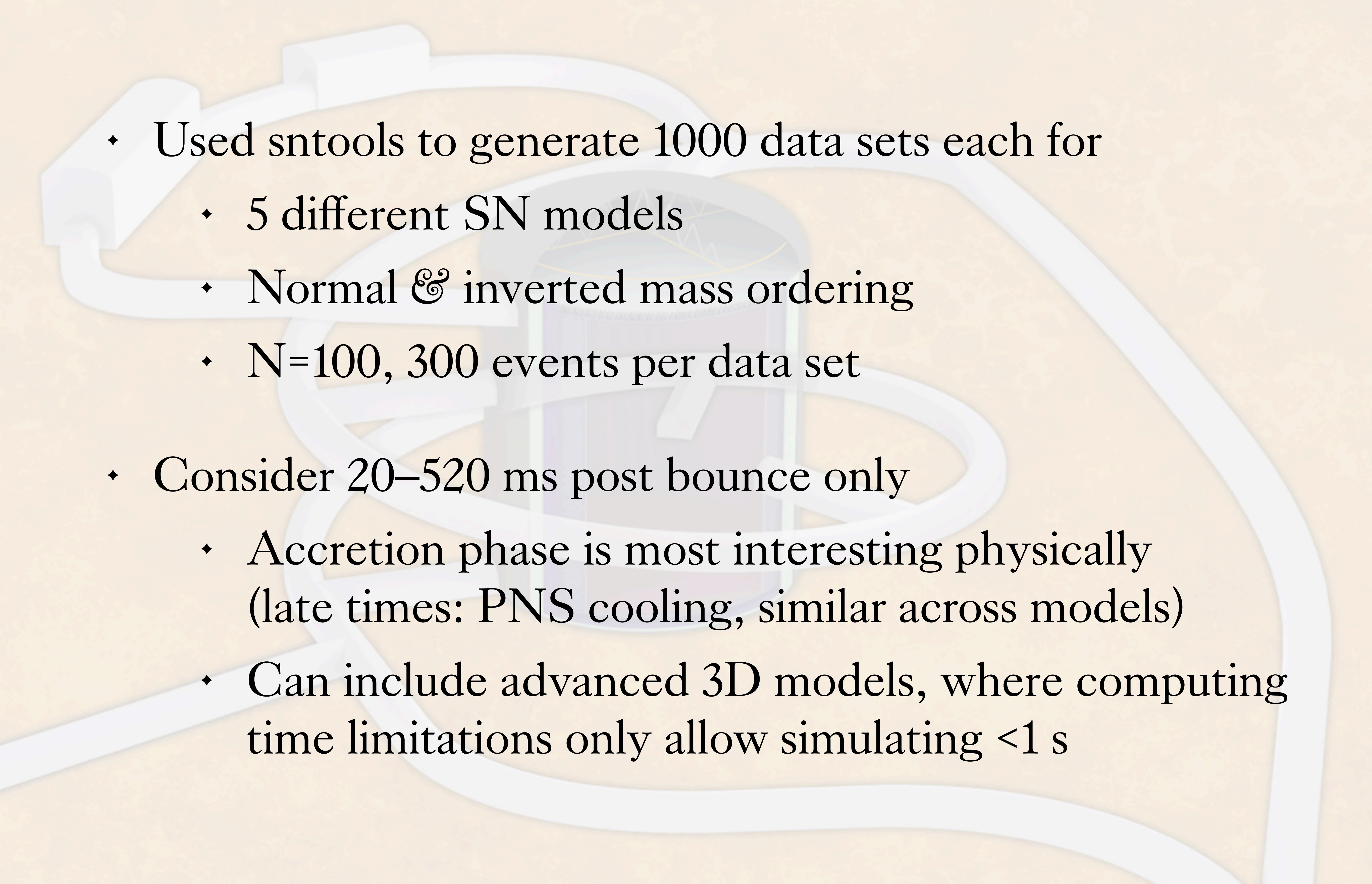
SASI, see e.g. arXiv:1406.0006

sntools: A Supernova Event Generator



- Modern cross-sections for main interaction channels
    - Inverse beta decay full result from arXiv:astro-ph/0302055
    - Electron scattering arXiv:astro-ph/9502003
    - ^{16}O CC arXiv:1809.08398,1807.02367
- Modular & easily extensible (e.g. LS, WbLS & Theia)
- Open source: https://github.com/JostMigenda/sntools
- Accepted by JOSS (to be published as DOI:10.21105/joss.2877 soon)

Data Sets



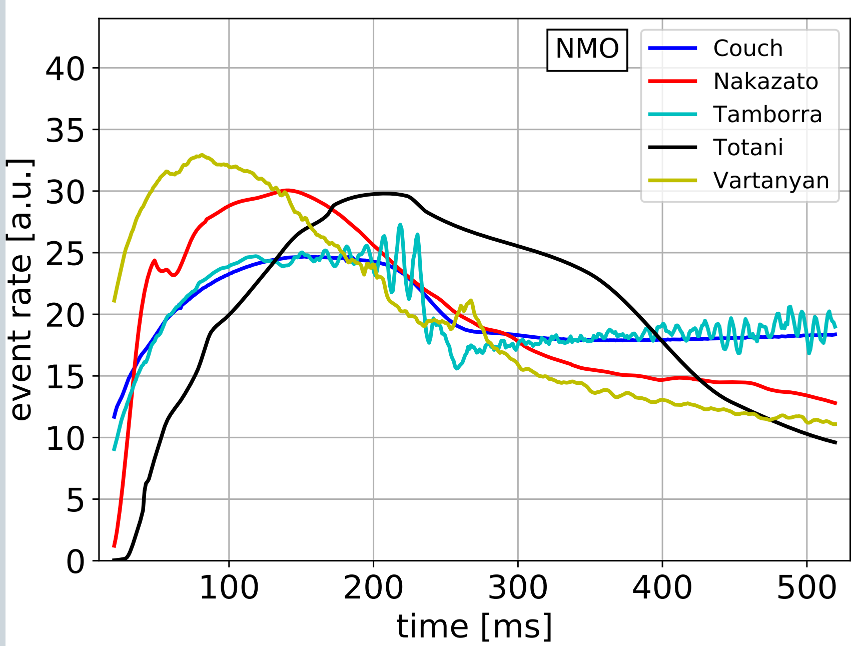
- Used sntools to generate 1000 data sets each for
  - 5 different SN models
  - Normal & inverted mass ordering
  - N=100, 300 events per data set
- Consider 20–520 ms post bounce only
  - Accretion phase is most interesting physically (late times: PNS cooling, similar across models)
  - Can include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

Supernova Models

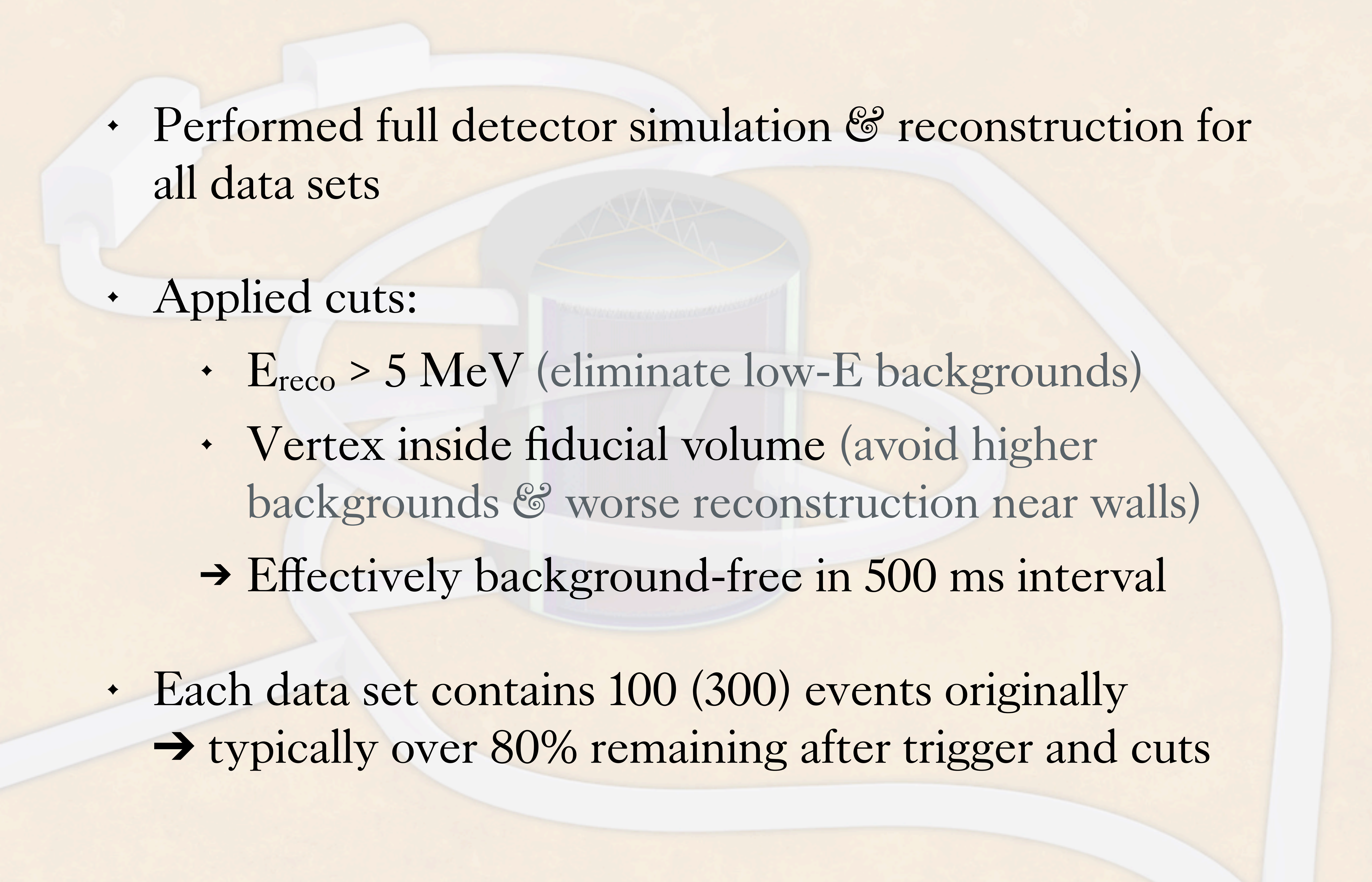
Model	Mass		events at 10 kpc*	N=100	N=300
Totani arXiv:astro-ph/9710203	20 $M_\odot$	1D	19716	140 kpc	81 kpc
Nakazato arXiv:1210.6841	20 $M_\odot$	1D	17978	134 kpc	77 kpc
Couch arXiv:1902.01340	20 $M_\odot$	1D	27539	166 kpc	96 kpc
Vartanyan similar to arXiv:1804.00689	9 $M_\odot$	2D	10372	102 kpc	59 kpc
Tamborra arXiv:1406.0006	27 $M_\odot$	3D	25021	158 kpc	91 kpc

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

Models by different groups, using various approximations
➔ telling models apart can help understand the explosion mechanism



Analysis



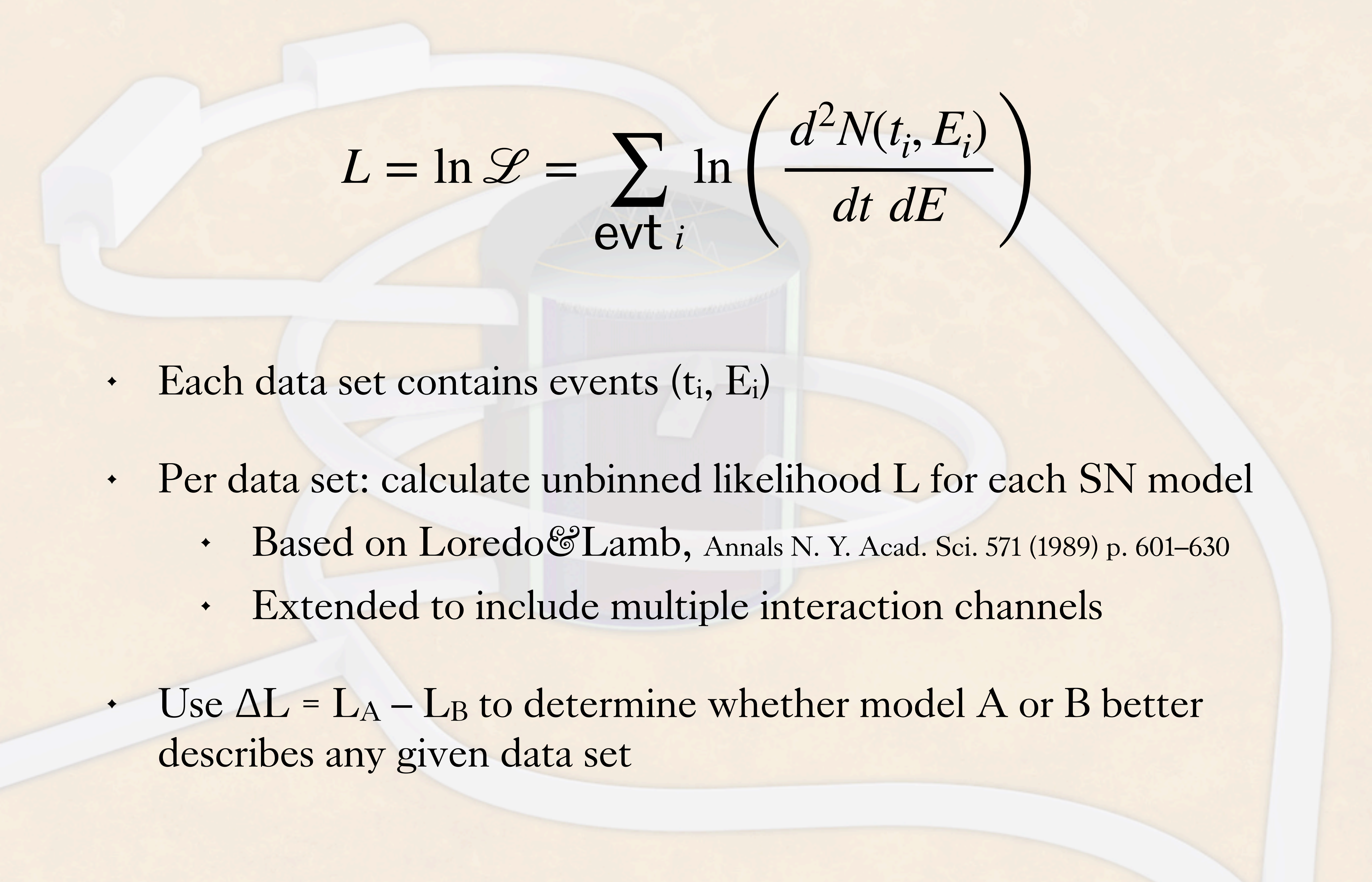
- Performed full detector simulation & reconstruction for all data sets

- Applied cuts:
  - $E_{reco} > 5$ MeV (eliminate low-E backgrounds)
  - Vertex inside fiducial volume (avoid higher backgrounds & worse reconstruction near walls)

  ➔ Effectively background-free in 500 ms interval

- Each data set contains 100 (300) events originally
  ➔ typically over 80% remaining after trigger and cuts

Analysis

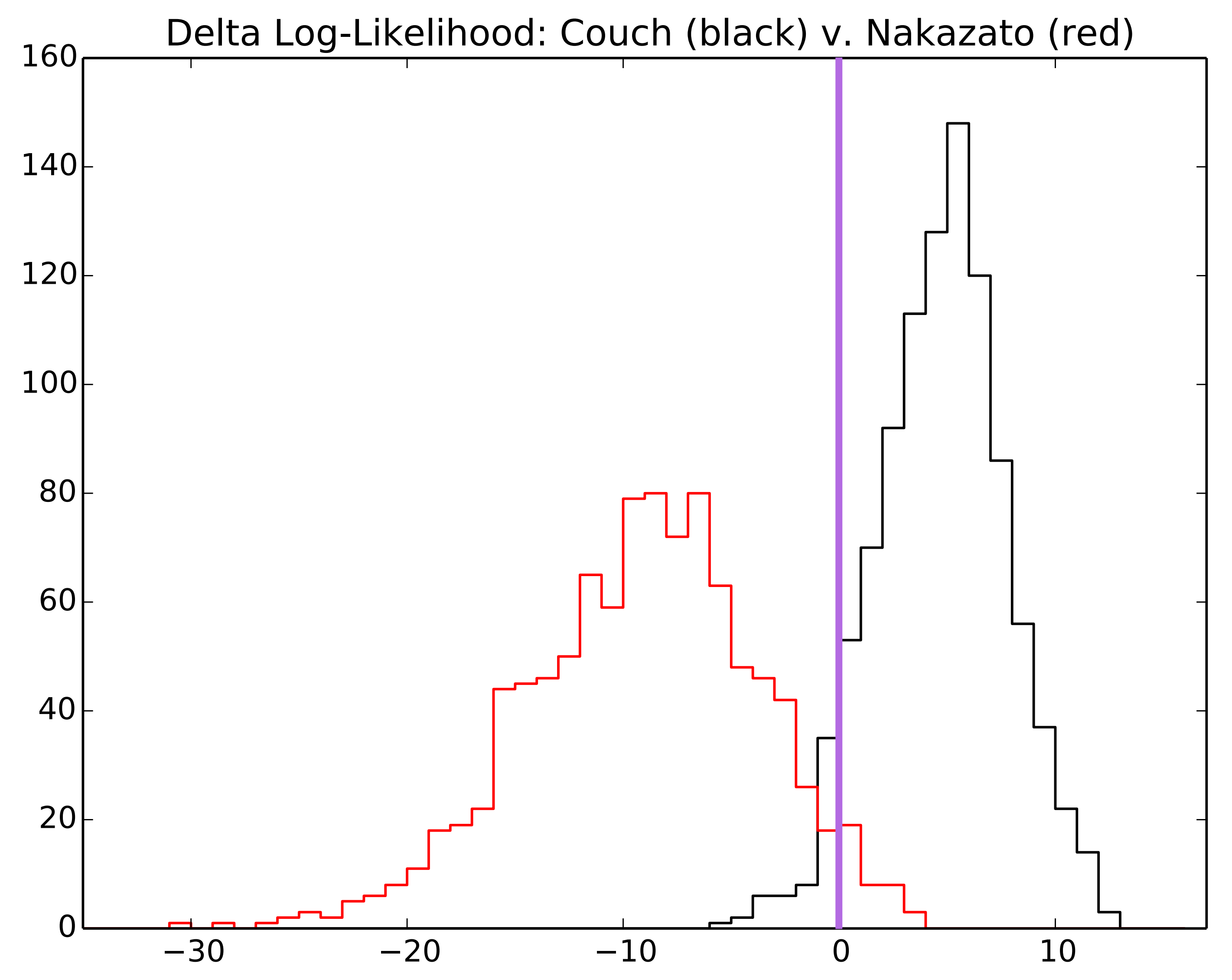


$$L = \ln \mathscr{L} = \sum_{\text{evt } i} \ln \left(\frac{d^2 N(t_i, E_i)}{dt \; dE} \right)$$

- Each data set contains events (t_i, E_i)
- Per data set: calculate unbinned likelihood L for each SN model
    - Based on Loredo&Lamb, Annals N. Y. Acad. Sci. 571 (1989) p. 601–630
    - Extended to include multiple interaction channels
- Use $\Delta L = L_A - L_B$ to determine whether model A or B better describes any given data set

Model Comparison

Normal ordering
N=100 evt/dataset

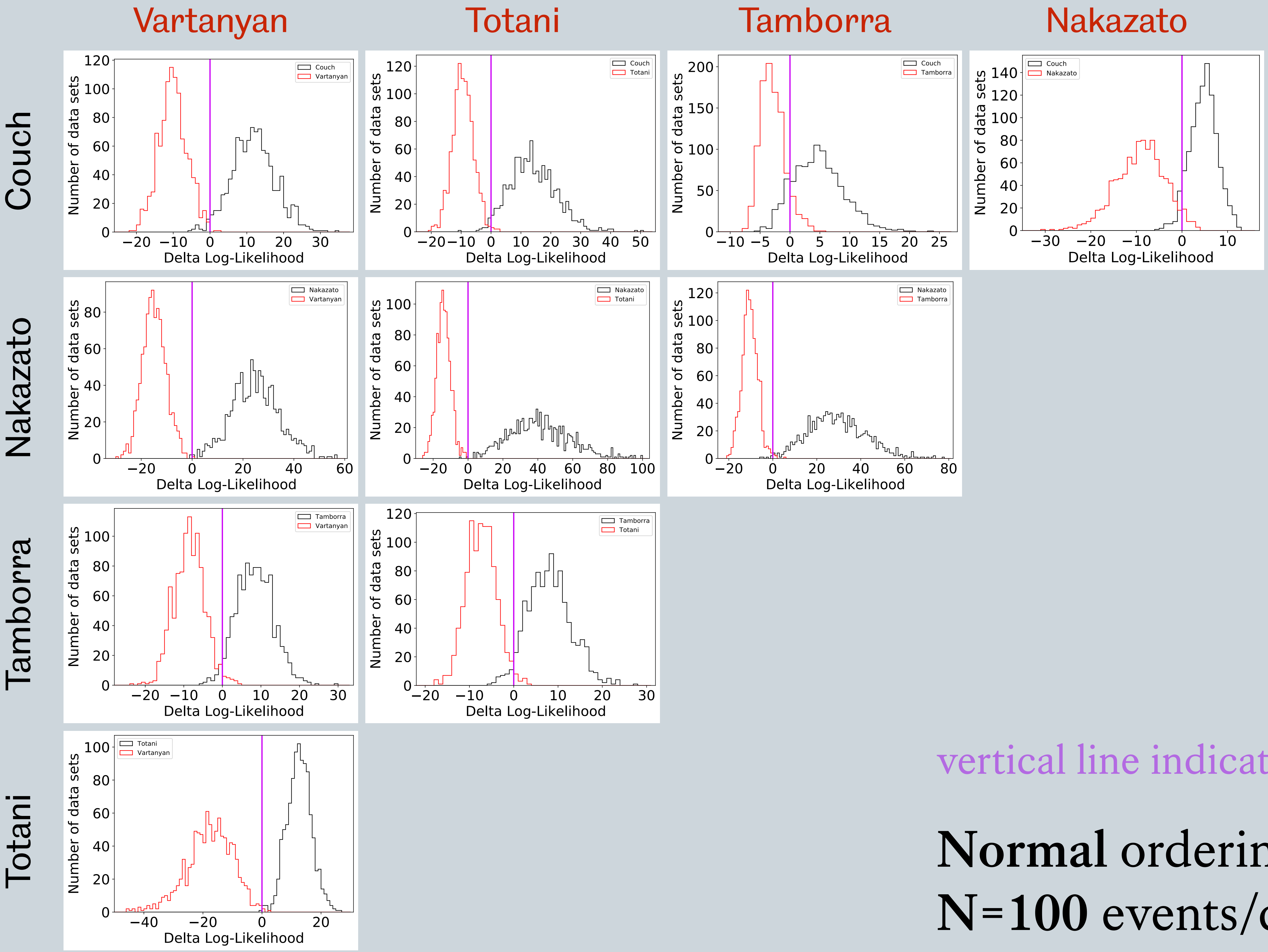


Data sets generated from Nakazato model

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

Identified as

True model

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.

One more thing…

- Hyper-K is still ~6 years away & SN simulations will make progress in the meantime

- Can we use this approach to determine progenitor properties?

- Use different Nakazato models

    - 13, 20, 30 M_{sol} with solar metallicity (z=0.02)

    - 20 M_{sol} with SMC metallicity (z=0.004)

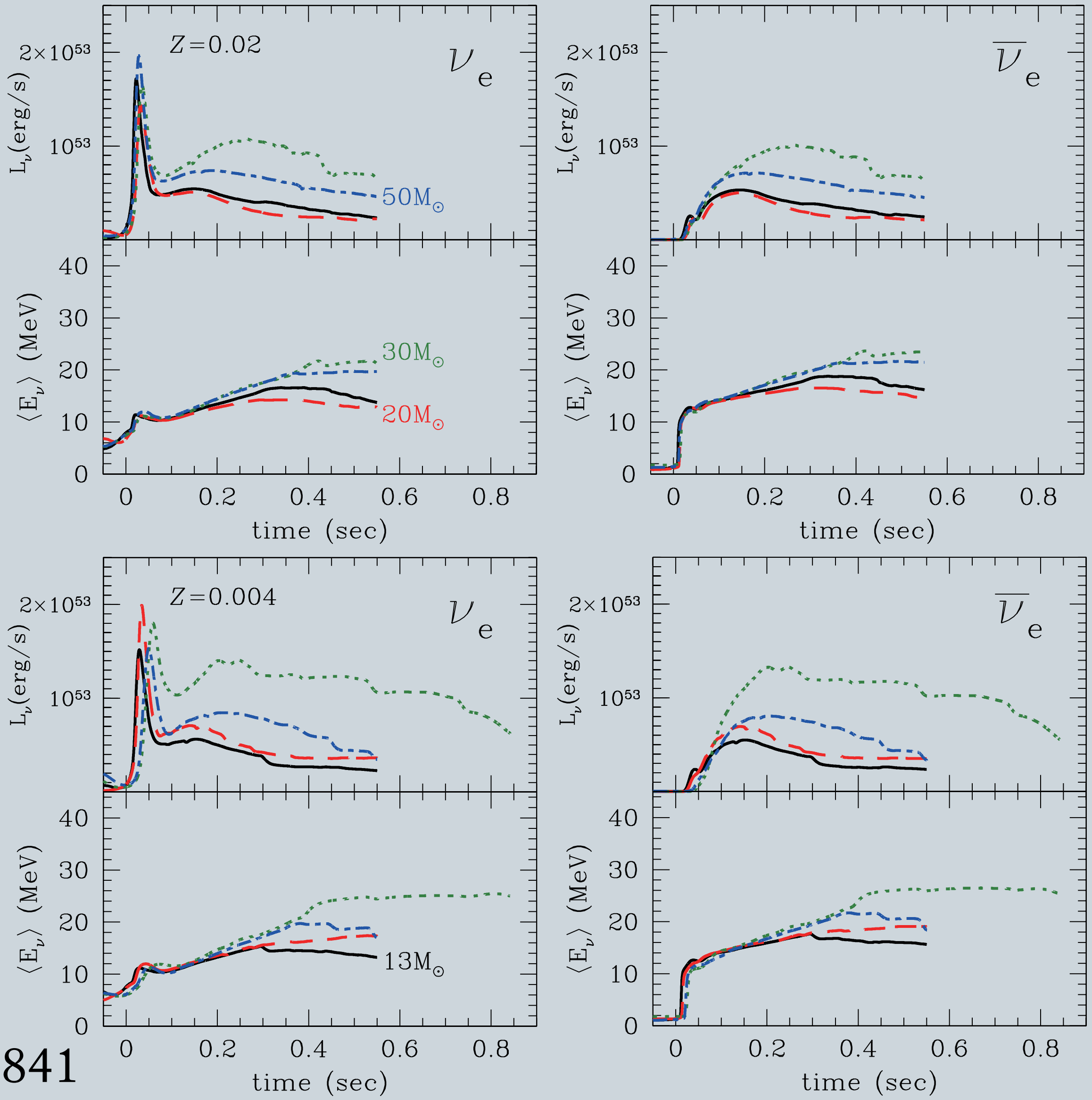


Figure from arXiv:1210.6841

Progenitor Properties, N=300

* lower metallicity (z=0.004)

Identified as

True model

Normal	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
30 M_{sol}	0	0	0	1000

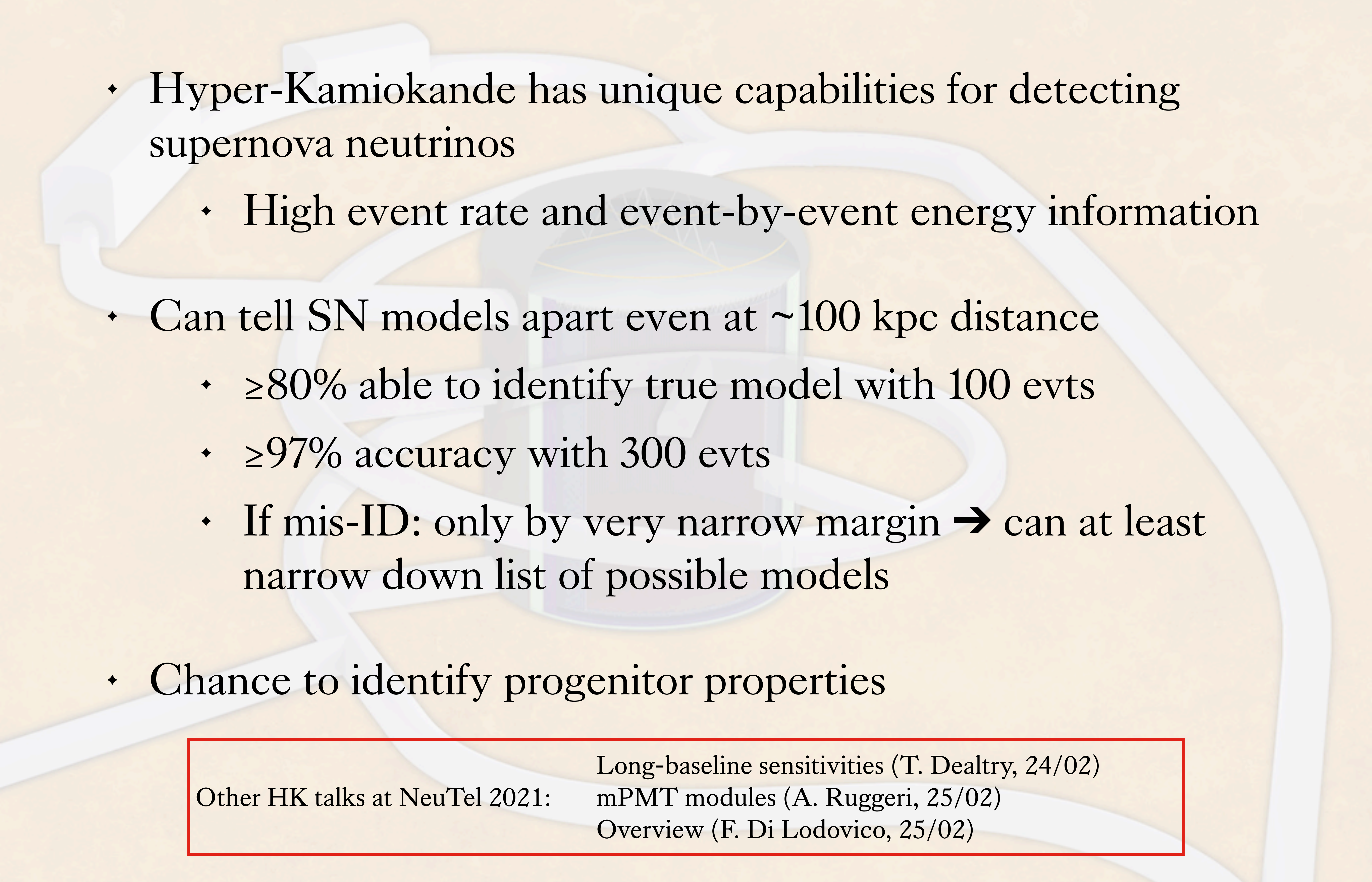
Identified as

True model

Inverted	13 M_{sol}	20 M_{sol}	20 M_{sol}*	30 M_{sol}
13 M_{sol}	866	78	56	0
20 M_{sol}	64	848	88	0
20 M_{sol}*	53	88	859	0
30 M_{sol}	0	0	0	1000

Different progenitors simulated with the same code.
If SN simulations converge, HK can be used to study the progenitor!

Conclusions

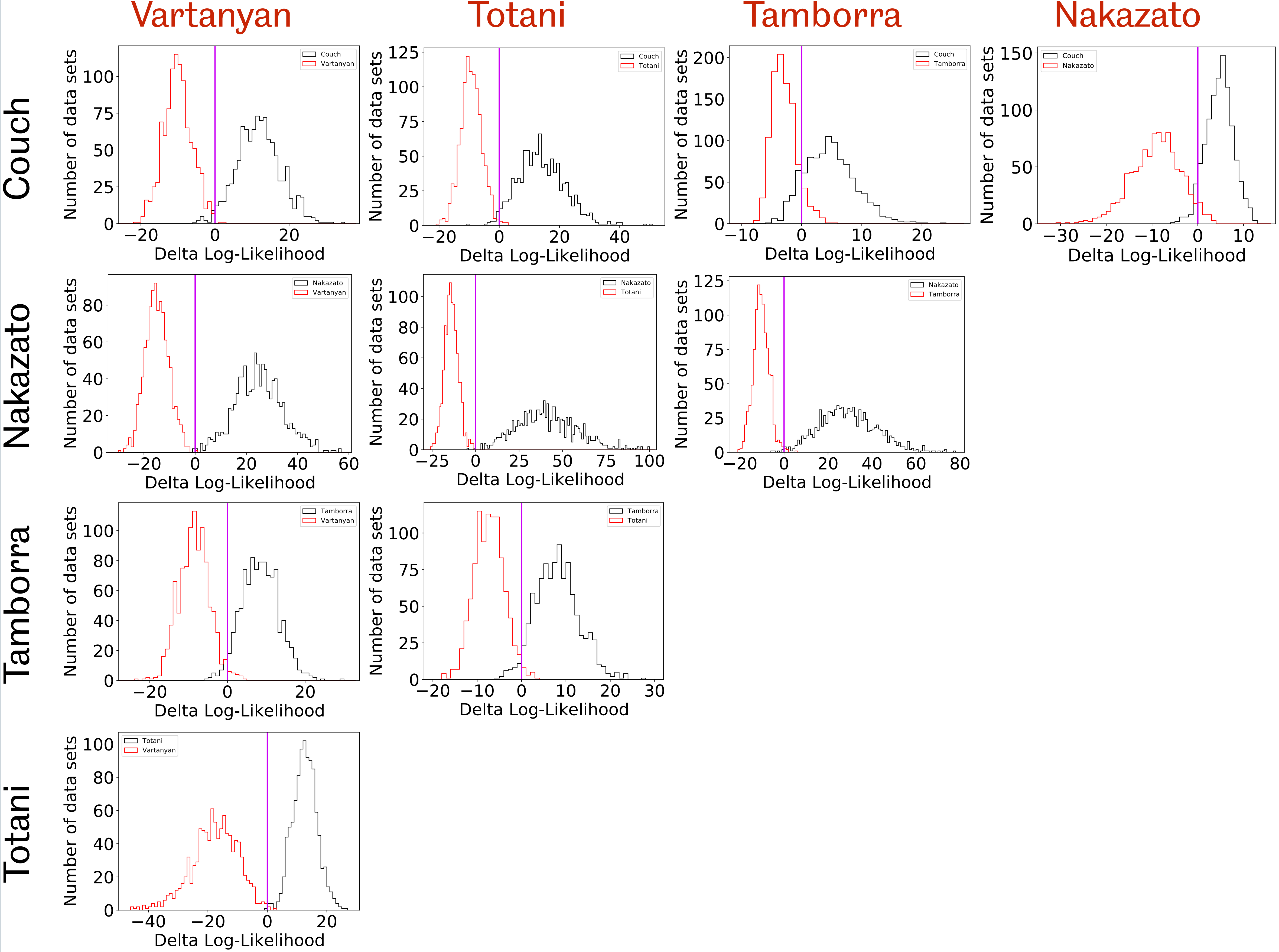


- Hyper-Kamiokande has unique capabilities for detecting supernova neutrinos
  - High event rate and event-by-event energy information
- Can tell SN models apart even at ~100 kpc distance
  - ≥80% able to identify true model with 100 evts
  - ≥97% accuracy with 300 evts
  - If mis-ID: only by very narrow margin ➔ can at least narrow down list of possible models
- Chance to identify progenitor properties

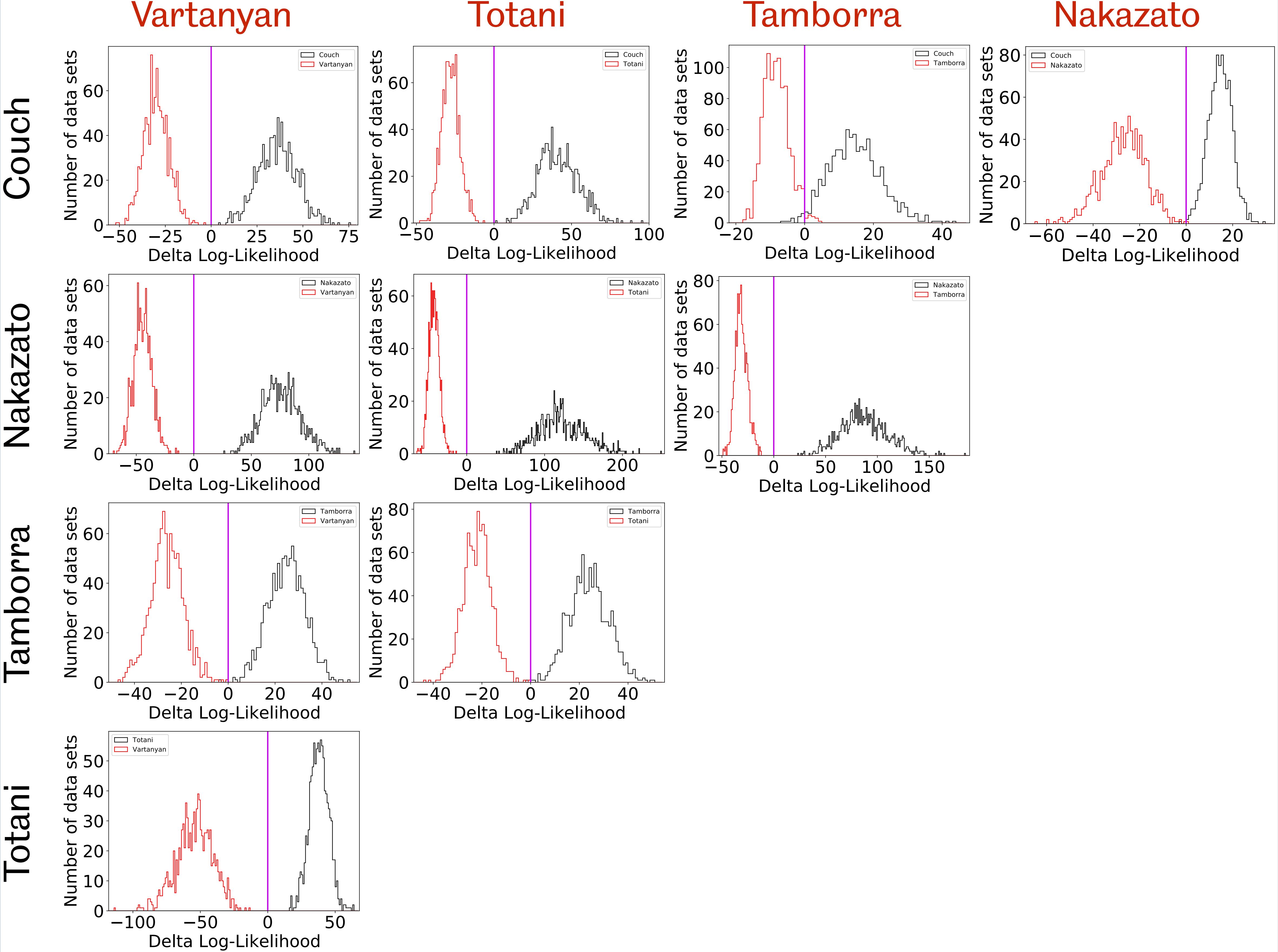
Other HK talks at NeuTel 2021:
Long-baseline sensitivities (T. Dealtry, 24/02)
mPMT modules (A. Ruggeri, 25/02)
Overview (F. Di Lodovico, 25/02)

Backup Slides

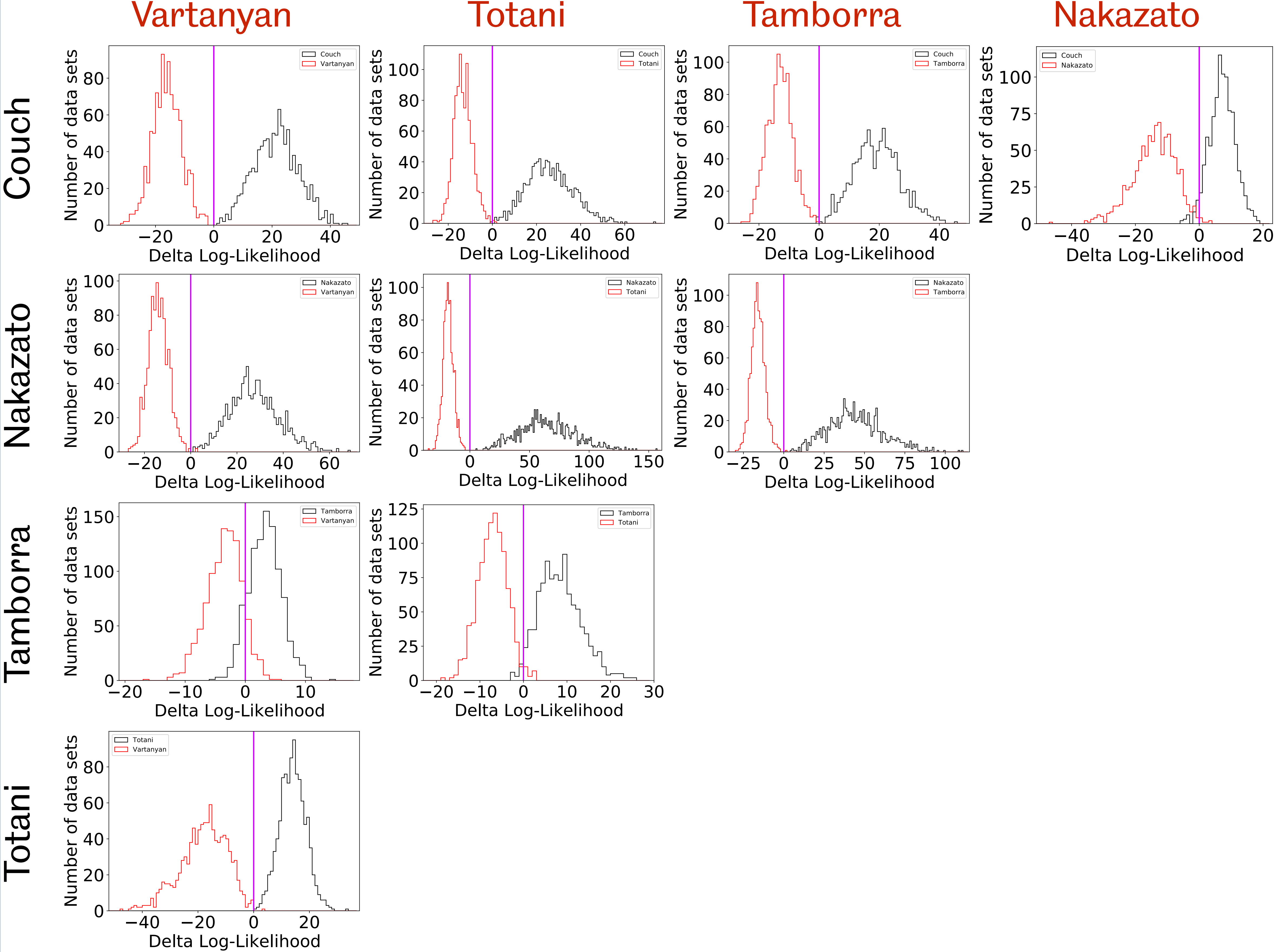
N=100, Normal Ordering



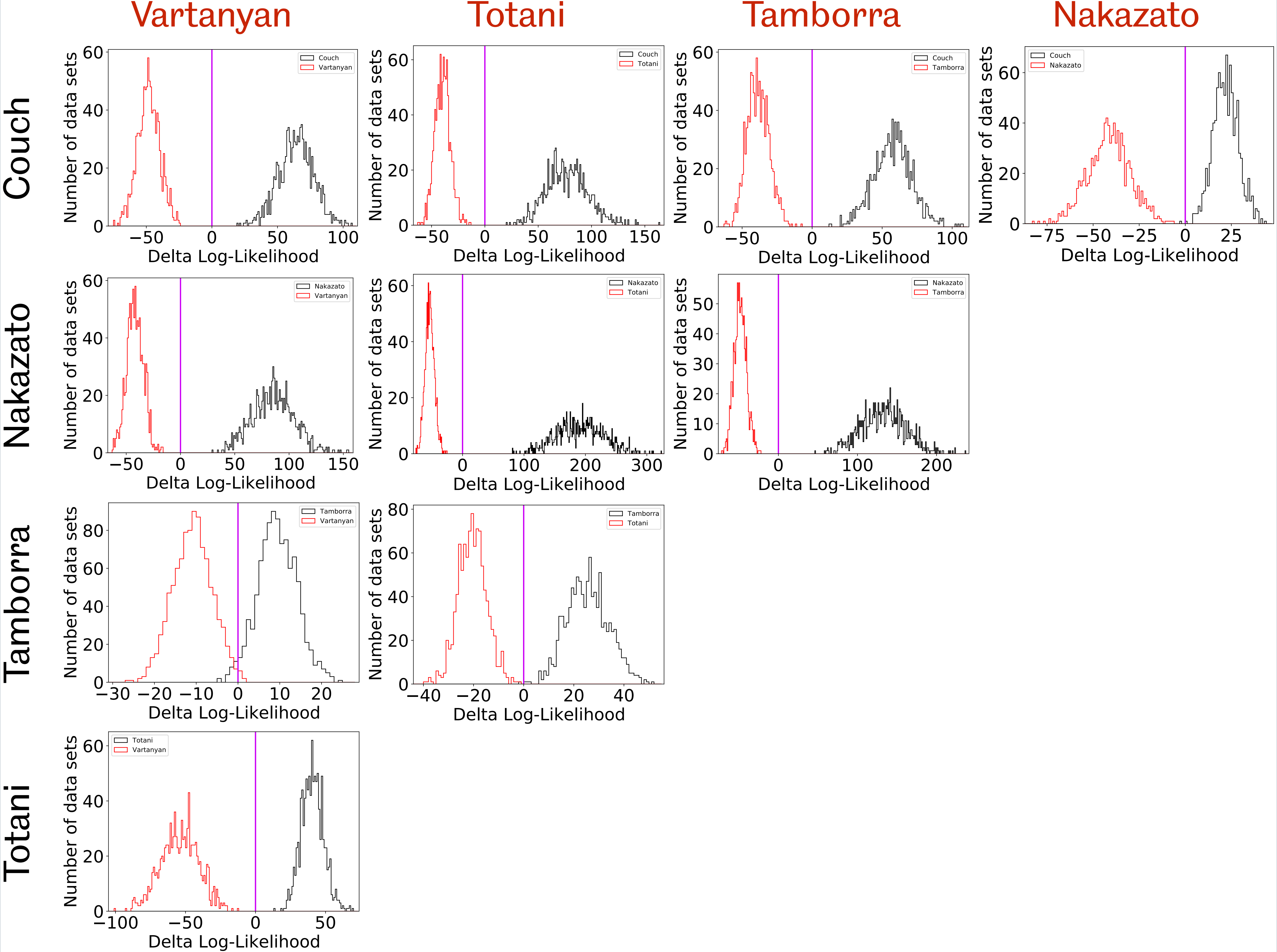
N=300, Normal Ordering



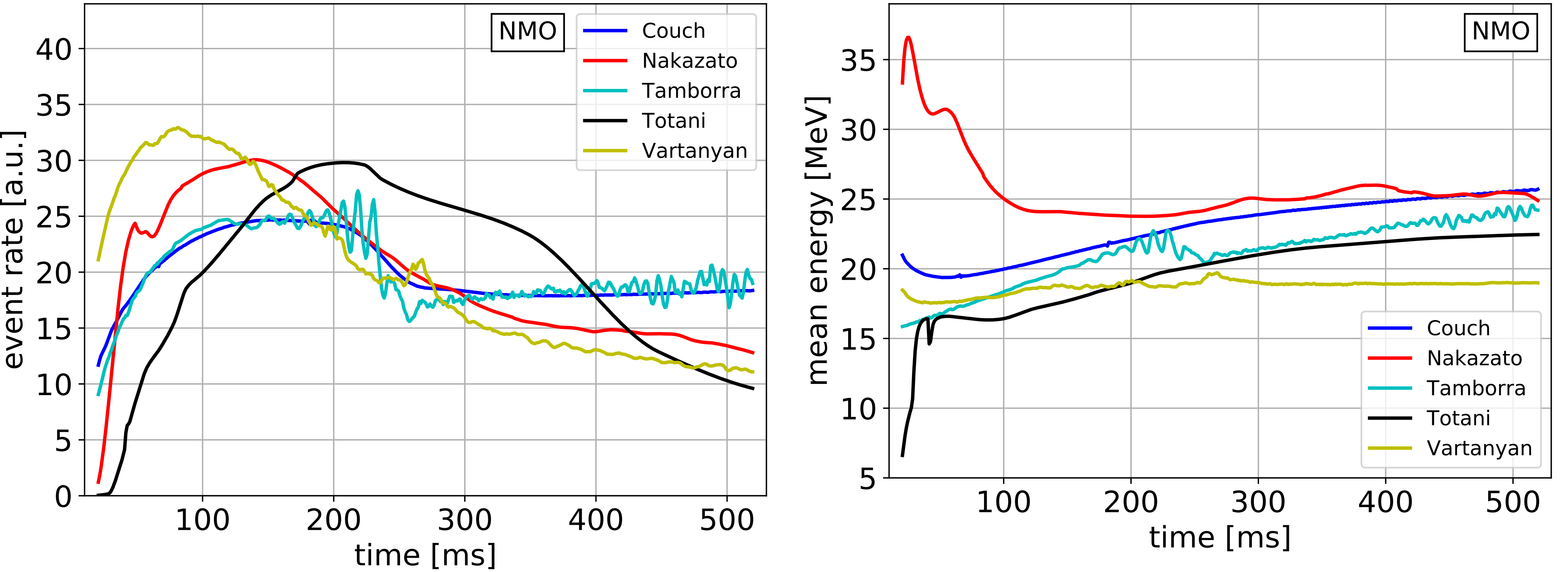
N=100, Inverted Ordering



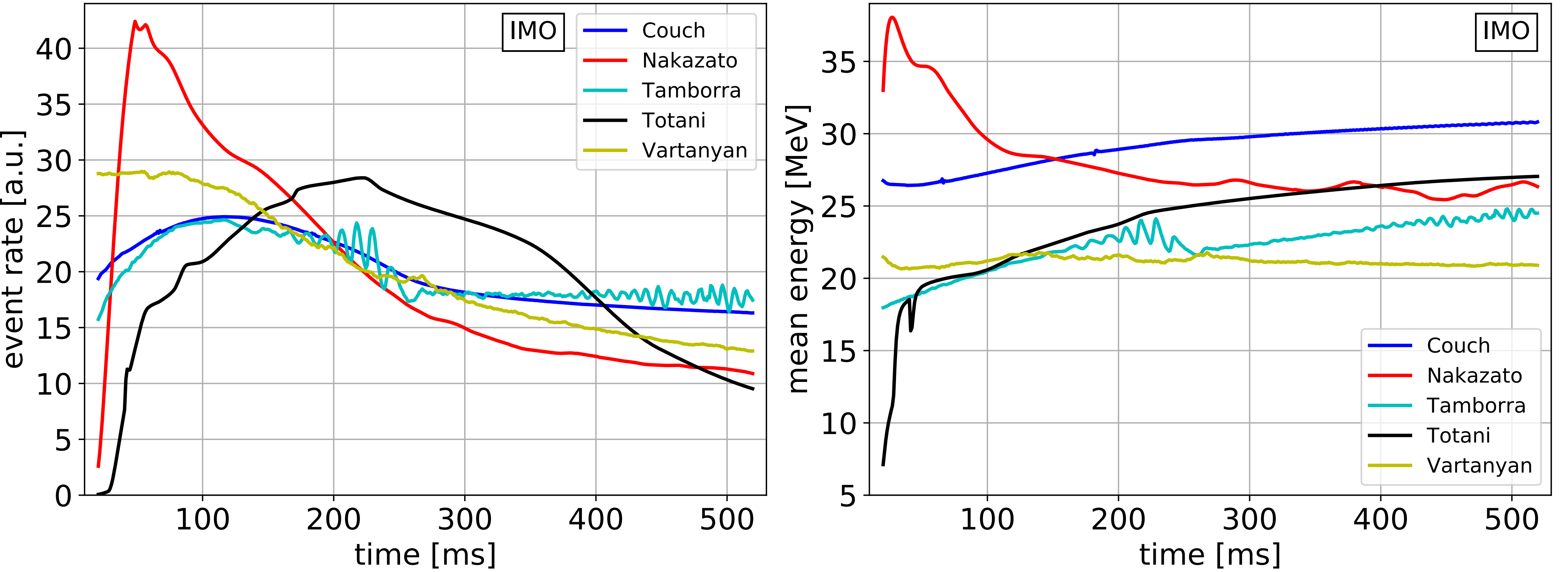
N=300, Inverted Ordering



Event Rate & Mean Energy of 5 Models



NMO: Tamborra & Couch most similar



IMO: Tamborra & Vartanyan most similar