Supernova Observations with Hyper-Kamiokande

Jost Migenda

they/them

The University Of Sheffield.

Agenda

Things are easy when you're big in Japan
—Alphaville

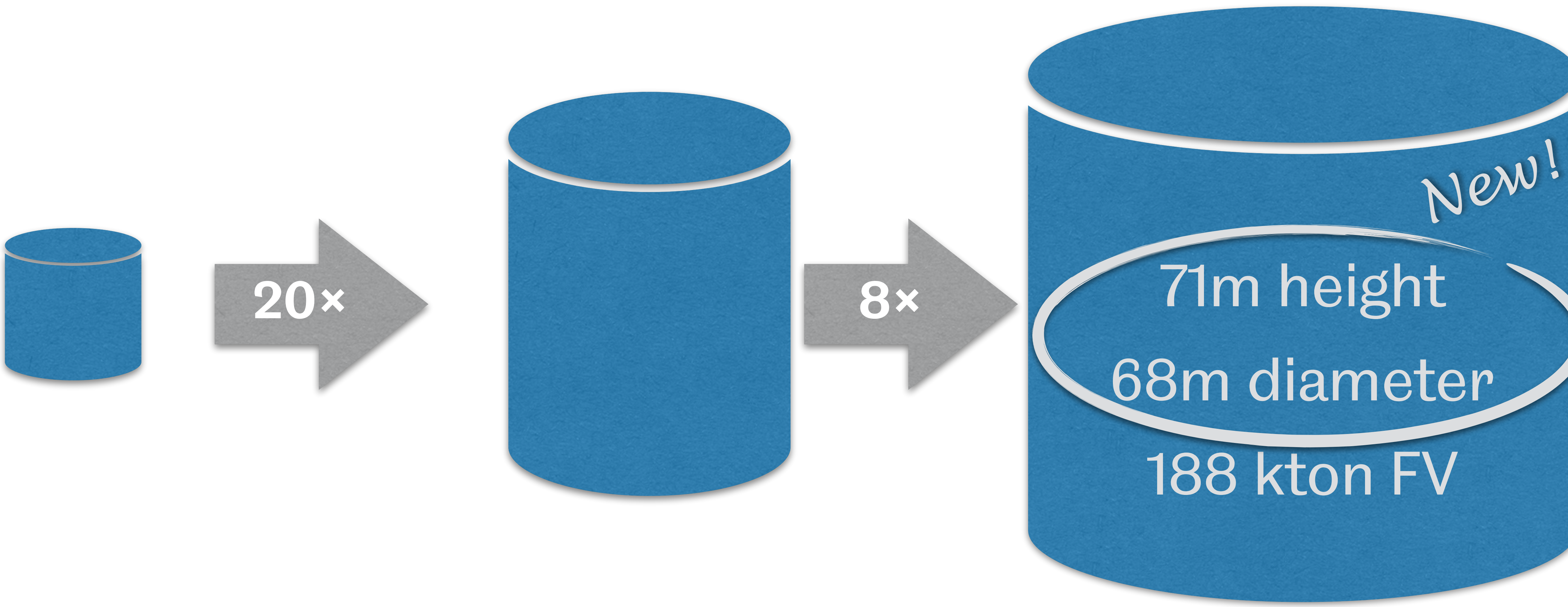
- **The Hyper-Kamiokande Experiment**
- Supernova Neutrino Observations with Hyper-K
- sntools: A Supernova Event Generator
- Supernova Model Discrimination

Hyper-Kamiokande

Kamiokande
1983–1996

Super-Kamiokande
1996–today (and beyond)

Hyper-Kamiokande
~2027–???



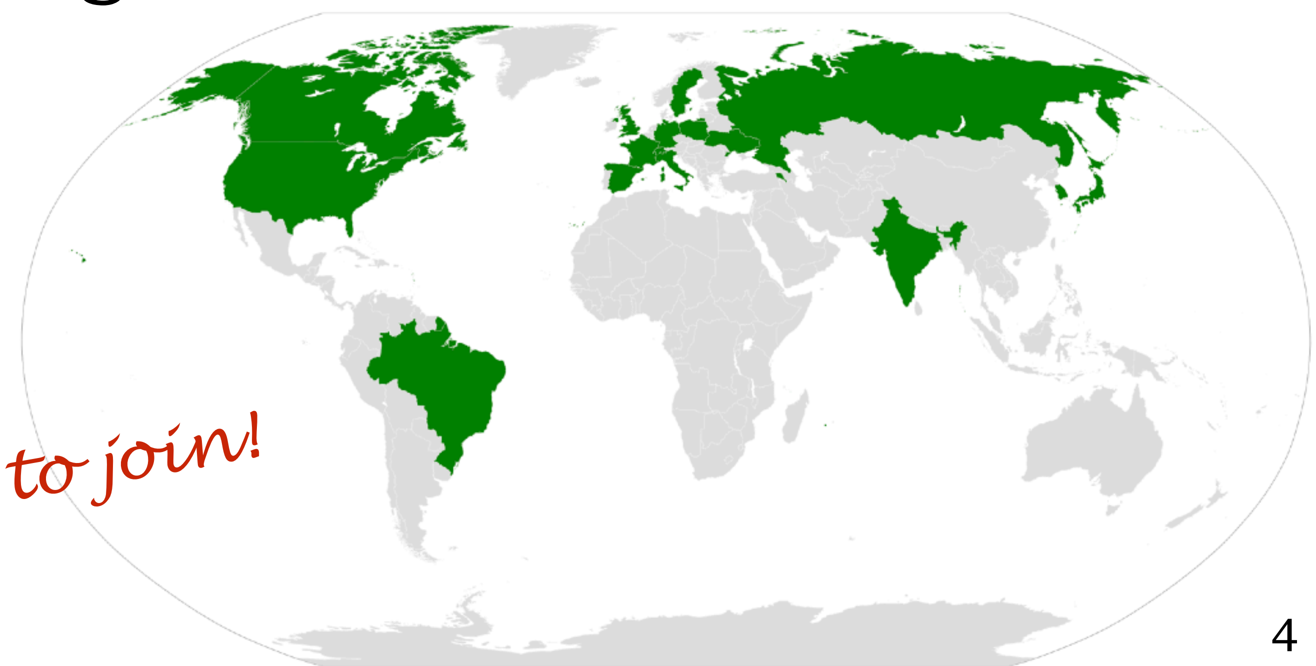
Koshiba, 2002

Kajita, 2015

???, 20??

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 by Japanese government
- Construction starts in 2020
- ~340 collaborators from 17 countries



Now is a great time to join!

Hyper-Kamiokande

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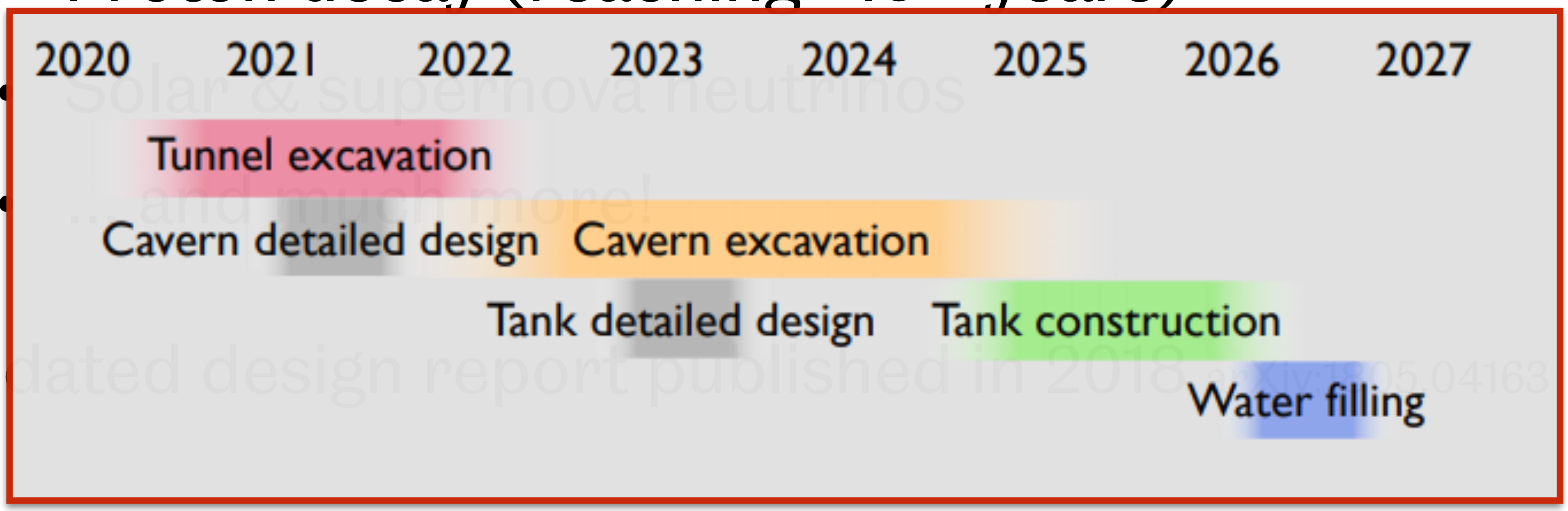

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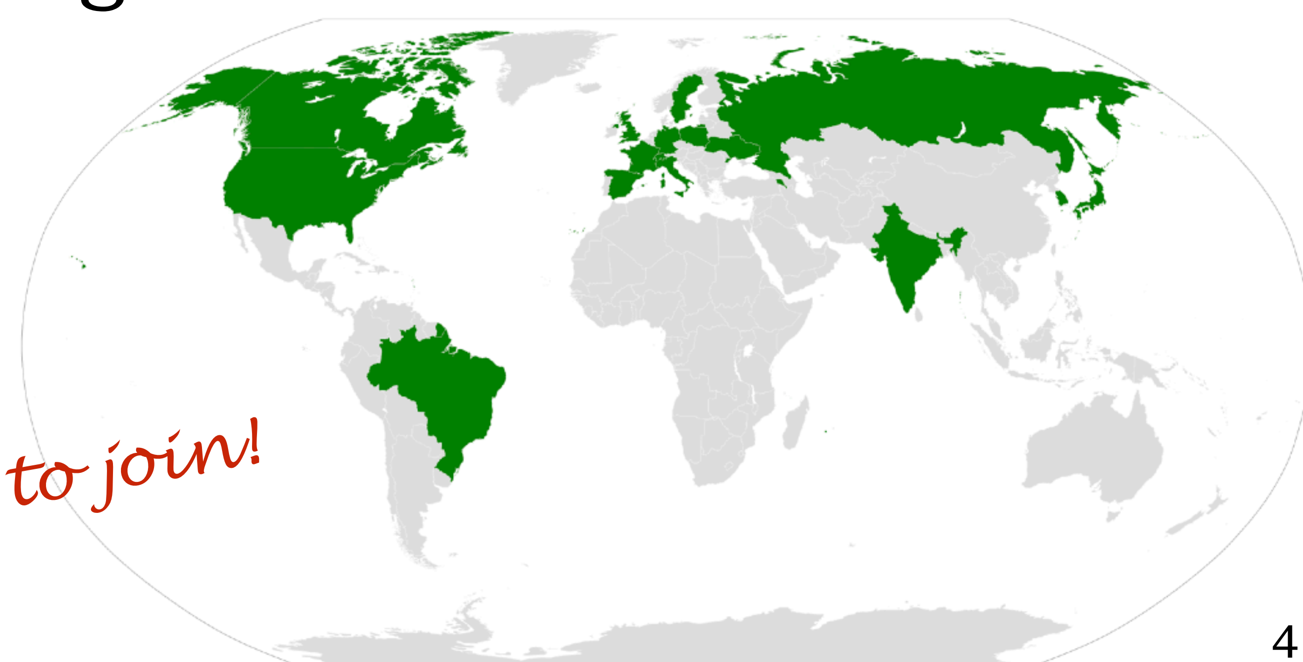
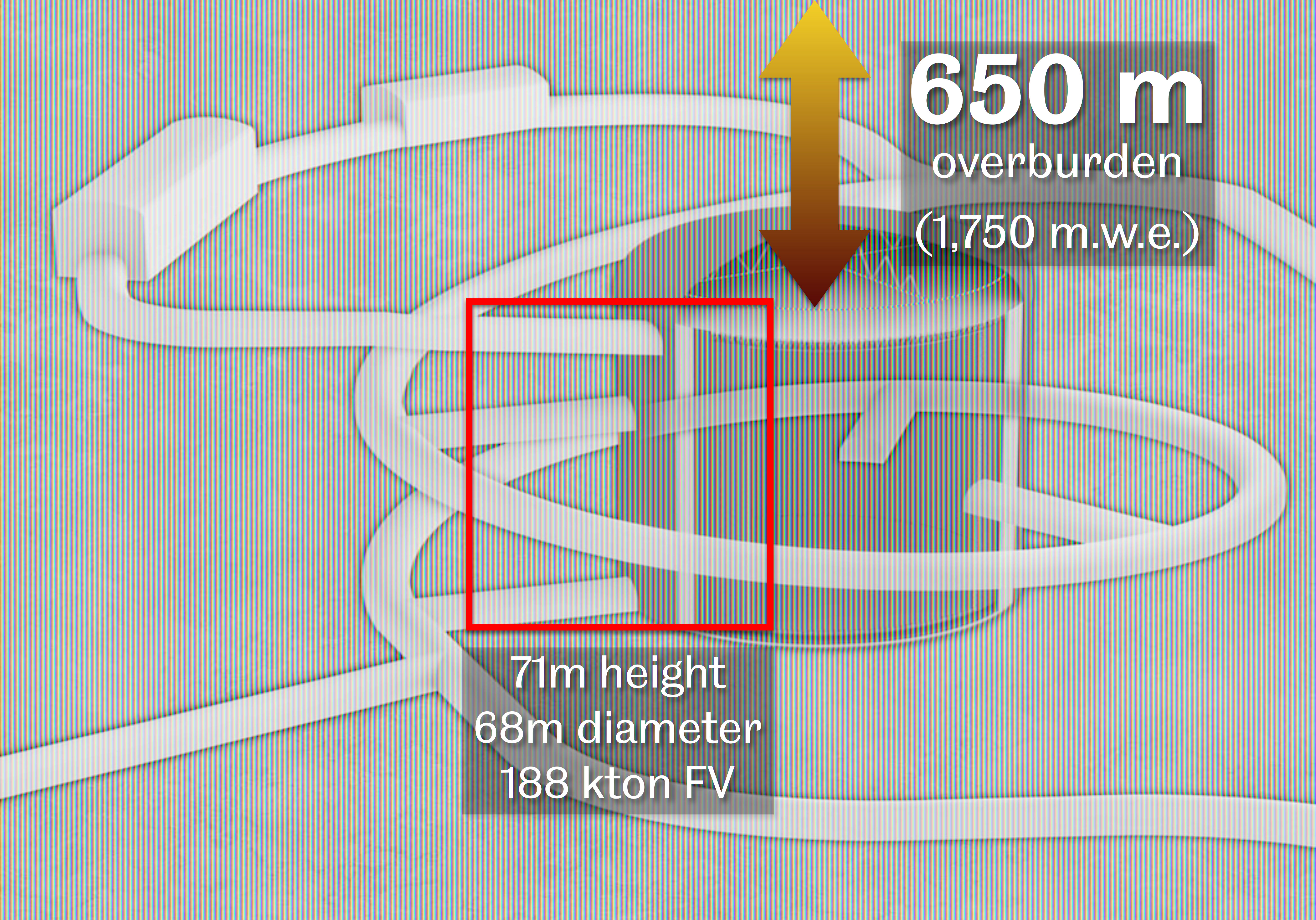
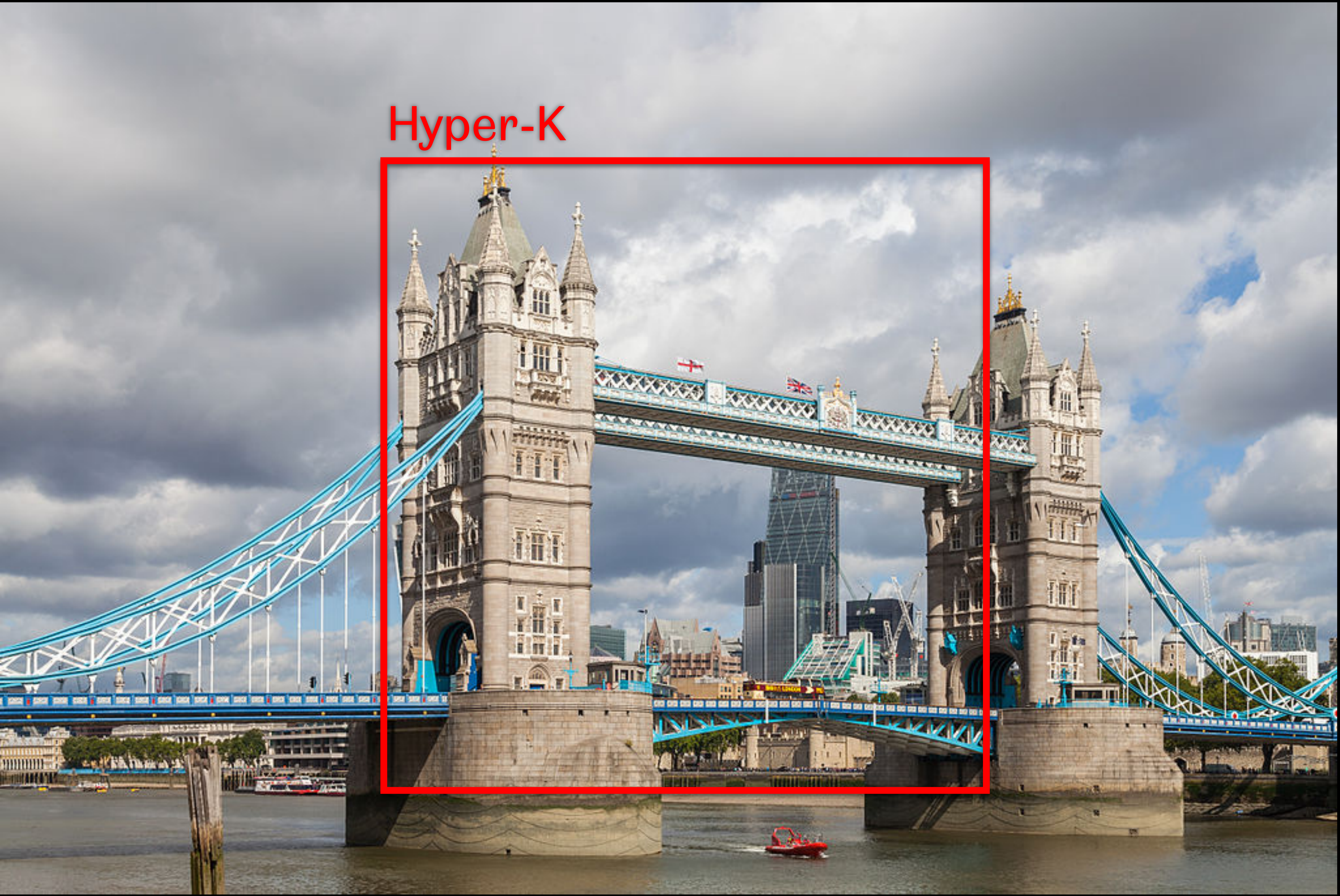
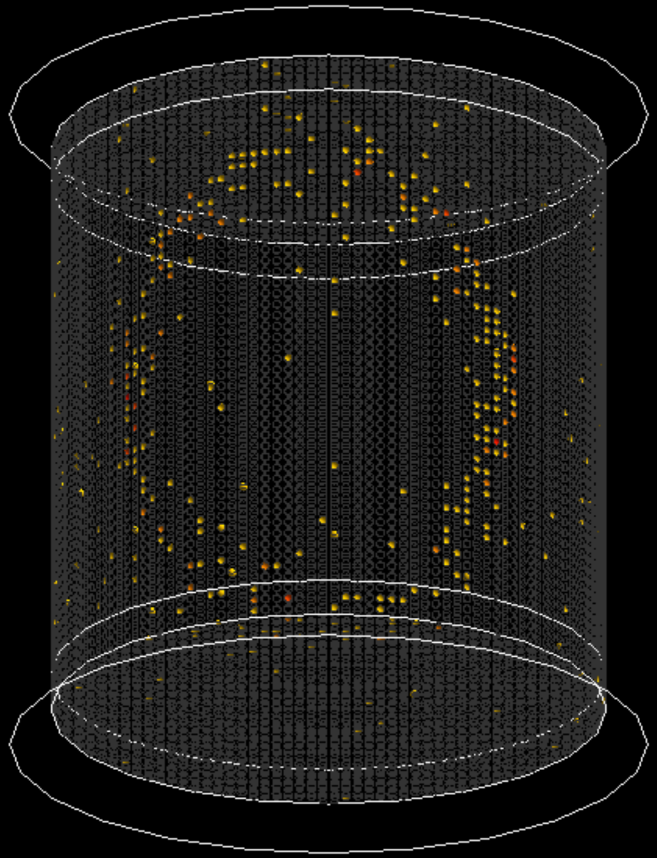
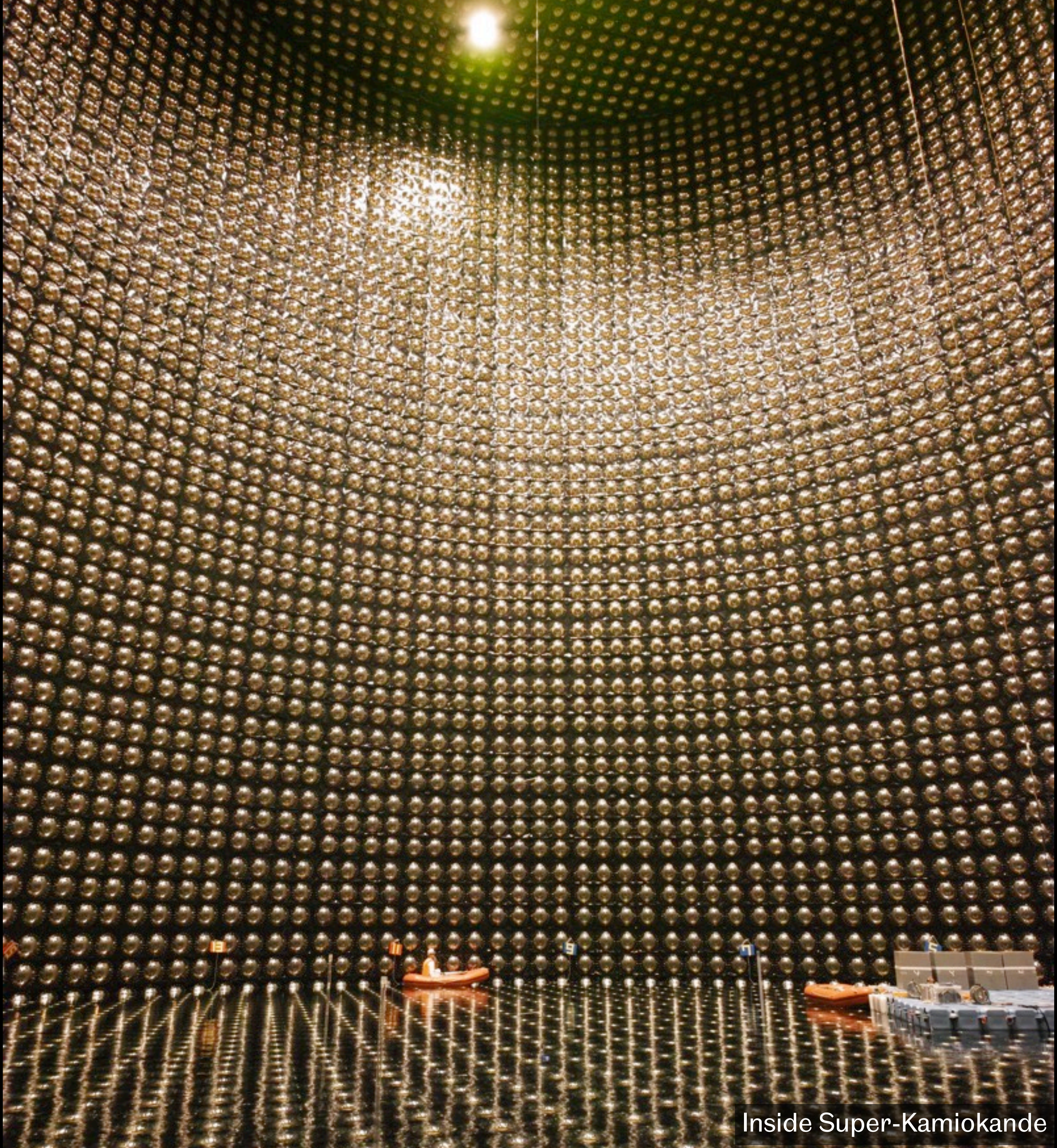



650 m
overburden
(1,750 m.w.e.)
71m height
68m diameter
188 kton FV


Hyper-K

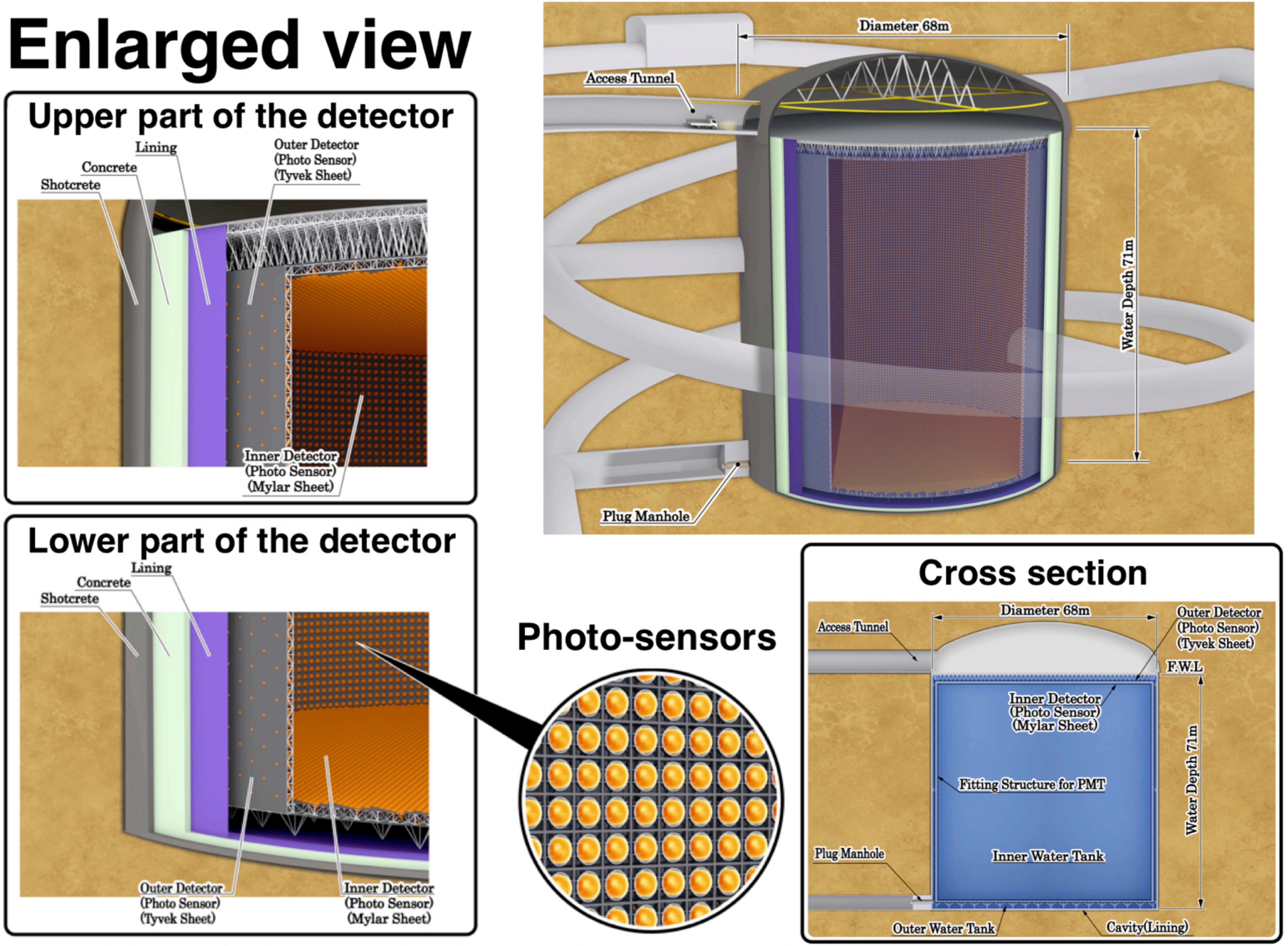


Cherenkov ring
of a 50 MeV e⁻



Inside Super-Kamiokande

Image credit: Kamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo



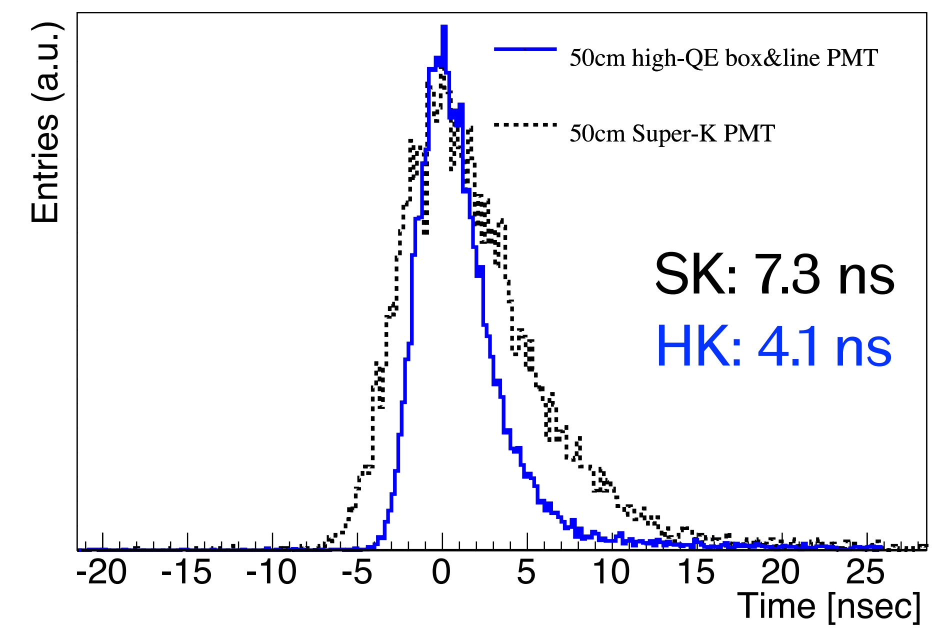
Enlarged view
Upper part of the detector
Lining
Concrete
Shotcrete
Outer Detector (Photo Sensor) (Tyvek Sheet)
Inner Detector (Photo Sensor) (Mylar Sheet)
Lower part of the detector
Lining
Concrete
Shotcrete
Outer Detector (Photo Sensor) (Tyvek Sheet)
Inner Detector (Photo Sensor) (Mylar Sheet)
Diameter 68m
Access Tunnel
Water Depth 71m
Plug Manhole
Photo-sensors
Cross section
Diameter 68m
Access Tunnel
Outer Detector (Photo Sensor) (Tyvek Sheet)
F.W.L
Inner Detector (Photo Sensor) (Mylar Sheet)
Fitting Structure for PMT
Water Depth 71m
Plug Manhole
Inner Water Tank
Outer Water Tank
Cavity(Lining)

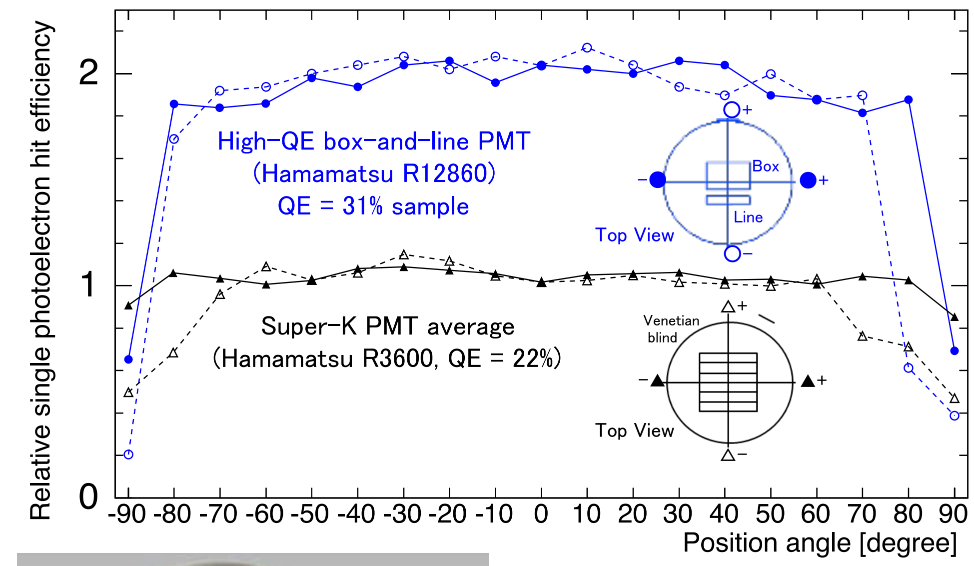
Changes for Low-E Physics

- Lower overburden ➔ higher μ flux (e.g. solar: 2.7× spallation background compared to SK)
    - 2nd tank in Korea could have SK-like overburden

- New PMTs with 2× timing resolution and 2× photon detection efficiency
    - **Better energy/vertex reconstruction**
      ➔ lower bkgd & enhanced physics capabilities
    - **Lower energy threshold**
    - R&D is still ongoing
      (e.g. lowering dark rate 8 ➔ 6 ➔ 4 kHz; combine 50 cm PMTs and multi-PMT modules – MoU with KM3NeT)

- Build on experiences of SK-Gd





50 cm PMT
Hamamatsu R12860

New and Enhanced Photosensor Technologies for Underground/underwater Neutrino Experiments (NEPTUNE 2020)

11-13 March 2020
Europe/Rome timezone

- Overview
- Timetable
- Scientific Programme
- Registration
- Participant List
- Venue and Travel Information
- List of accommodations
- Committees
- Conference poster

Over the last years some of the most important discoveries in particle (discovery of neutrino oscillations) and astro-particle physics (discovery of extra-galactic high-energy neutrinos) have been achieved by experiments detecting scintillation or Cherenkov light, produced by the charged particles produced in the neutrino interactions, by means of photosensors. Currently, several programs are ongoing for the upgrade of the existing facilities or the development of next generation ones. Also in this case the detection principle exploits the scintillation or Cherenkov light produced by charged-particles. Therefore, the development of new and enhanced photosensors is a key step towards the construction of new and more sensitive experiments both in particle and astro-particle physics.

The goal of this workshop is to review the state of the art and future developments in the field of photosensors, with particular attention to the high pixelation photosensor approach using small PMTs, and their applications. The properties of materials used to build instrumentation based on photosensors and the electronics will be some of the topics of the workshop. The calibration of the devices as well as the event reconstruction and Monte Carlo technique will be also addressed.

March 11–13, near Naples 🇮🇹

https://agenda.infn.it/event/20283/

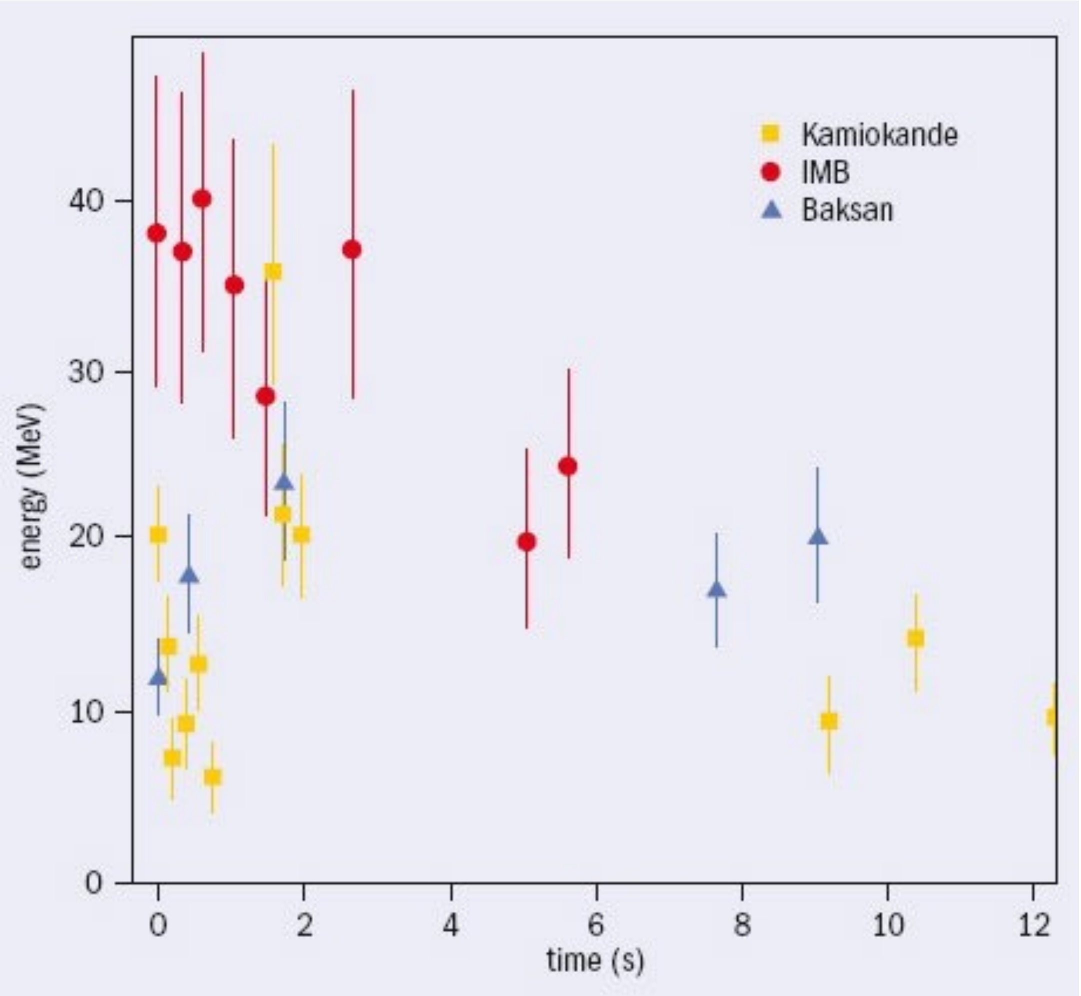
Agenda

A real Galactic supernova cannot, unfortunately,
be guaranteed on the timescale of a PhD studentship . . .
—Susan Cartwright

- The Hyper-Kamiokande Experiment
- **Supernova Neutrino Observations with Hyper-K**
- sntools: A Supernova Event Generator
- Supernova Model Discrimination

What We (Think We) Know …

- SN1987A: two dozen events, ~half of them in Kamiokande
- Confirmed basic picture:
  - ν burst ≈99% of energy
  - ~10^{53} erg, ~10^{58} ν
  - ν arrive ~hours before light



- Energy loss argument can constrain exotic particles

G. Raffelt, arXiv:hep-ph/9903472

- Simulations still limited by available computing power
  ➔ take any numbers with a grain of salt

What We (Think We) Know …

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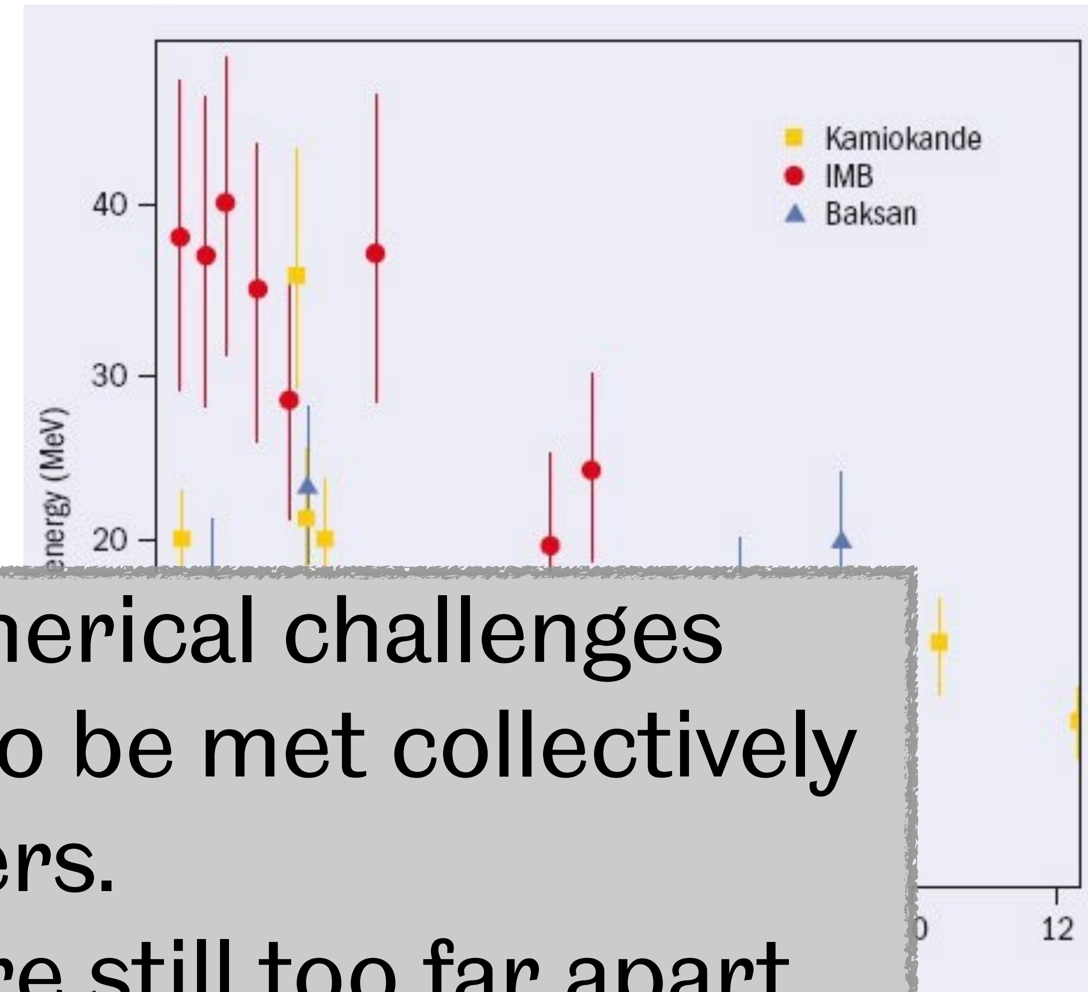
- Confirmed basic picture:



> "There is a rather long list of numerical challenges and code verification issues yet to be met collectively by the world's supernova modelers.
> The results of different groups are still too far apart to lend ultimate credibility to any one of them."
>
> — Skinner, Burrows, Dolence (arXiv:1512.00113)

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/9903472

- Simulations still limited by available computing power
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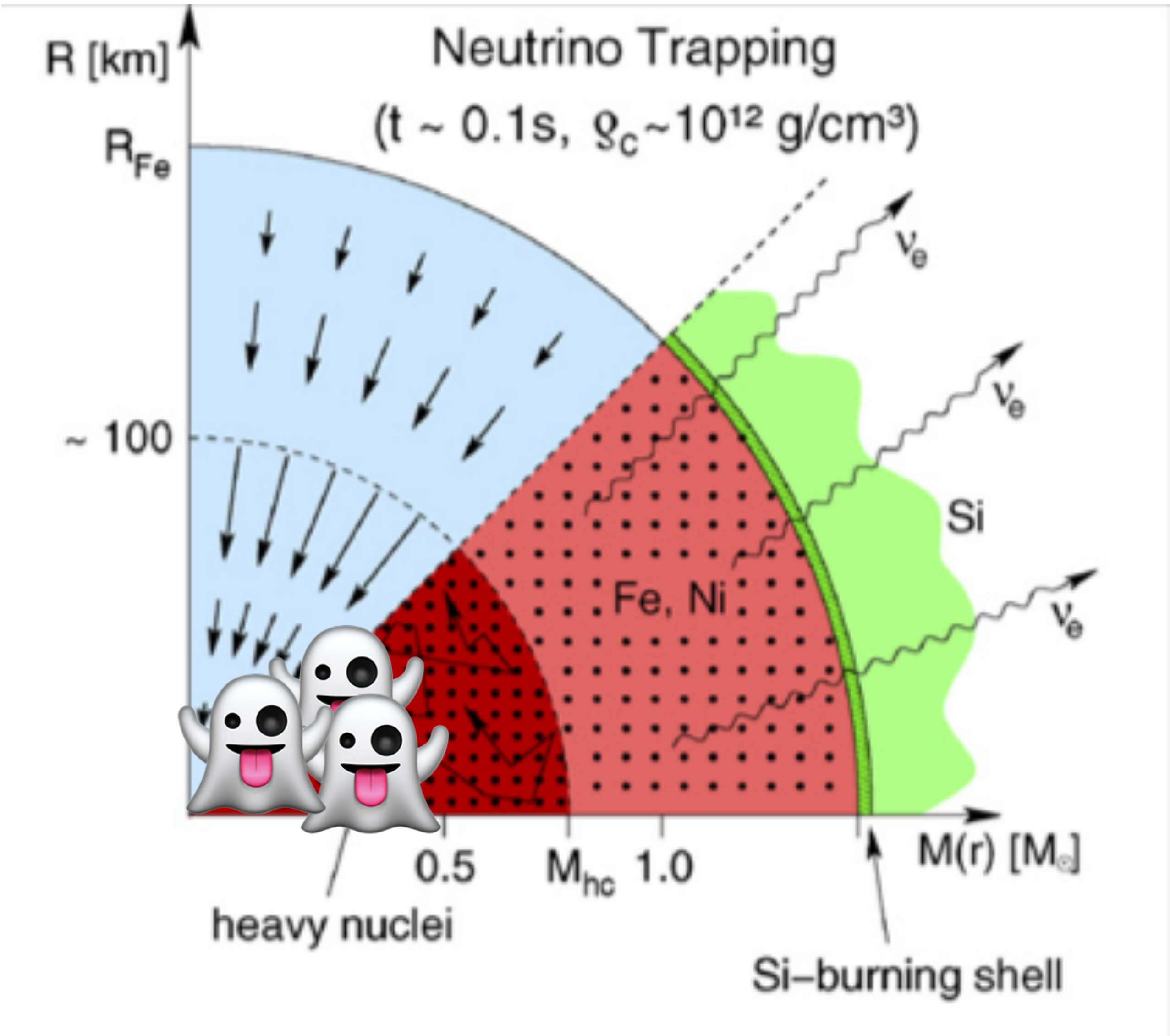
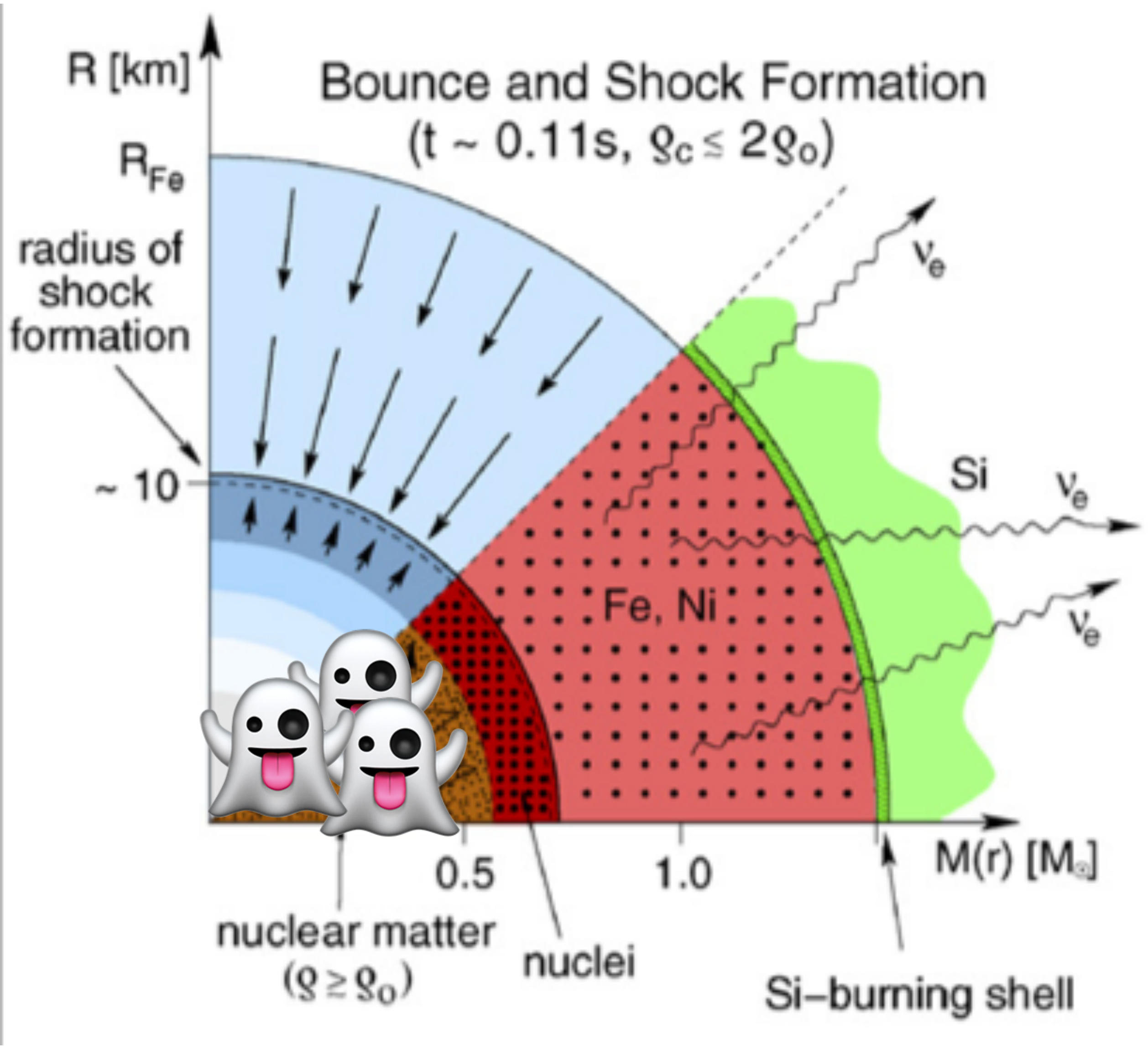
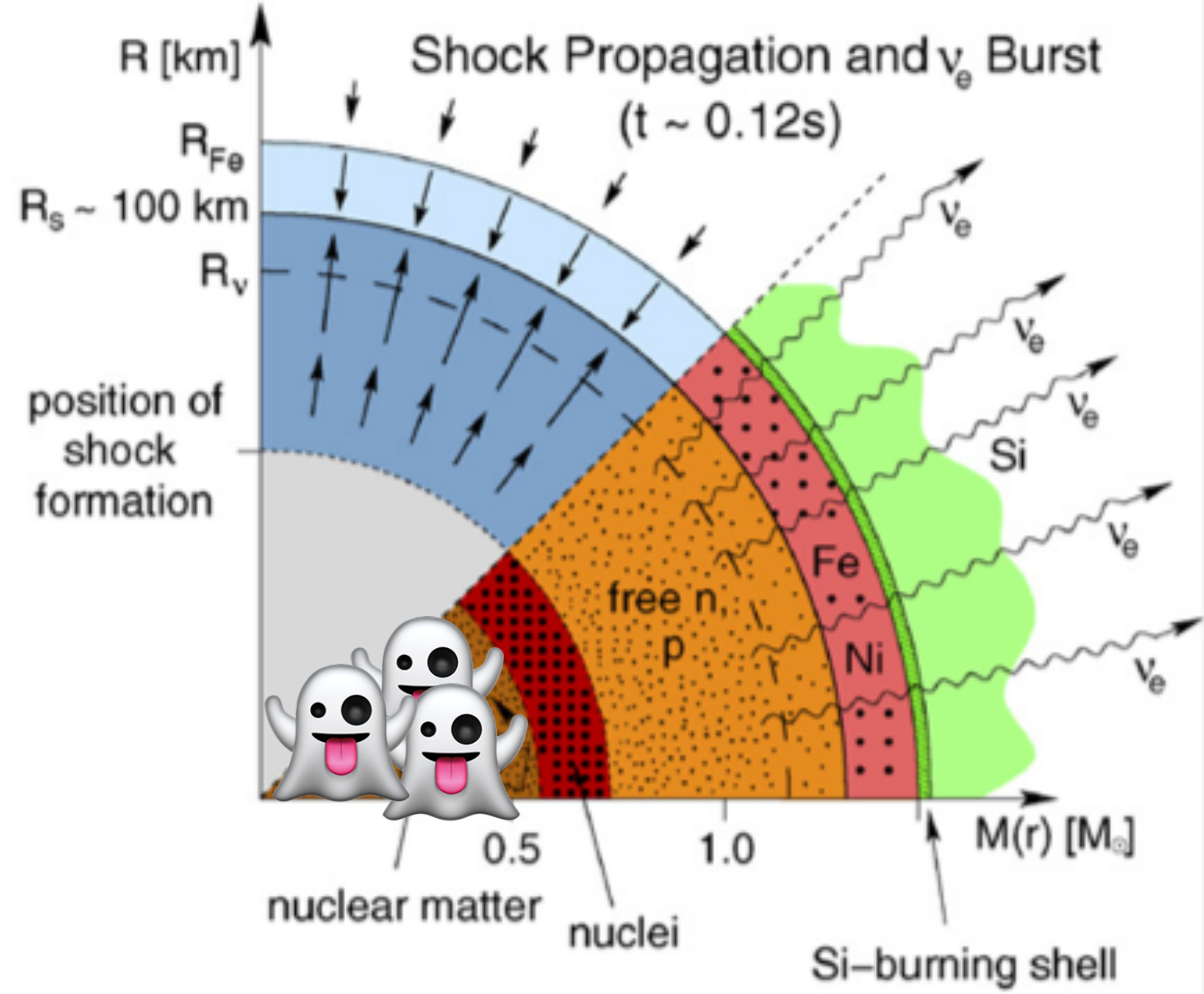
1) The Star Collapses



[Janka *et al.*, Phys.Rep. 442, pp. 38–74]

2) A Shock Wave Forms





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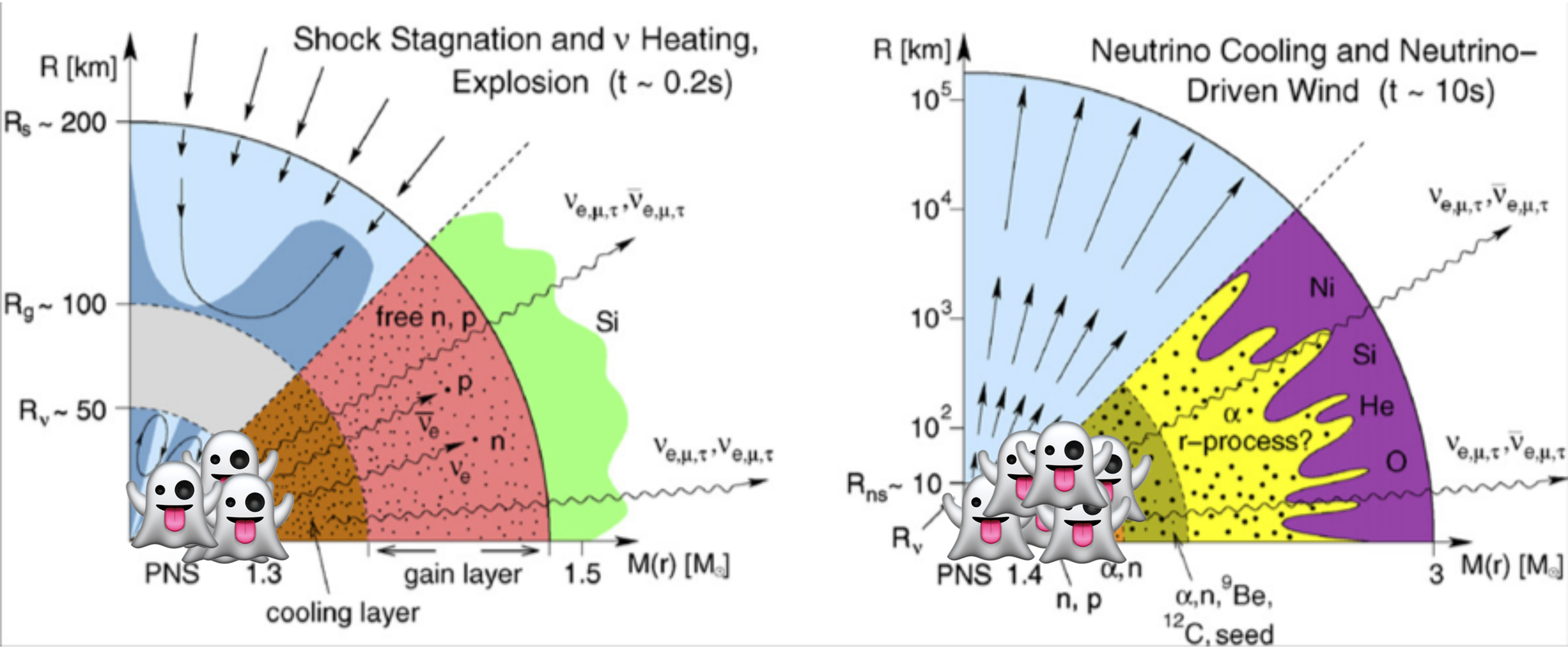
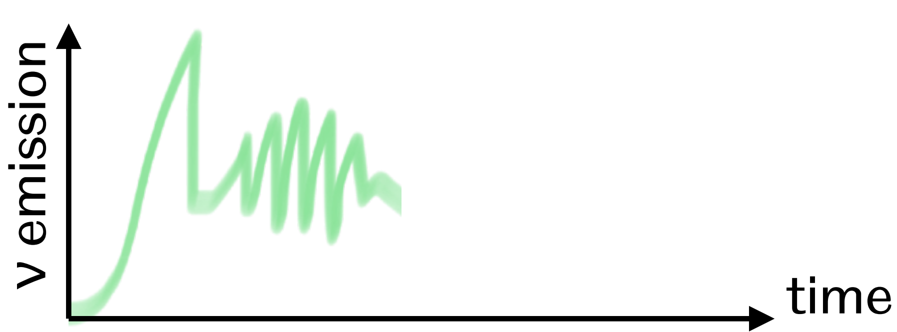
3) Shock Wave Is Restarted & Explodes





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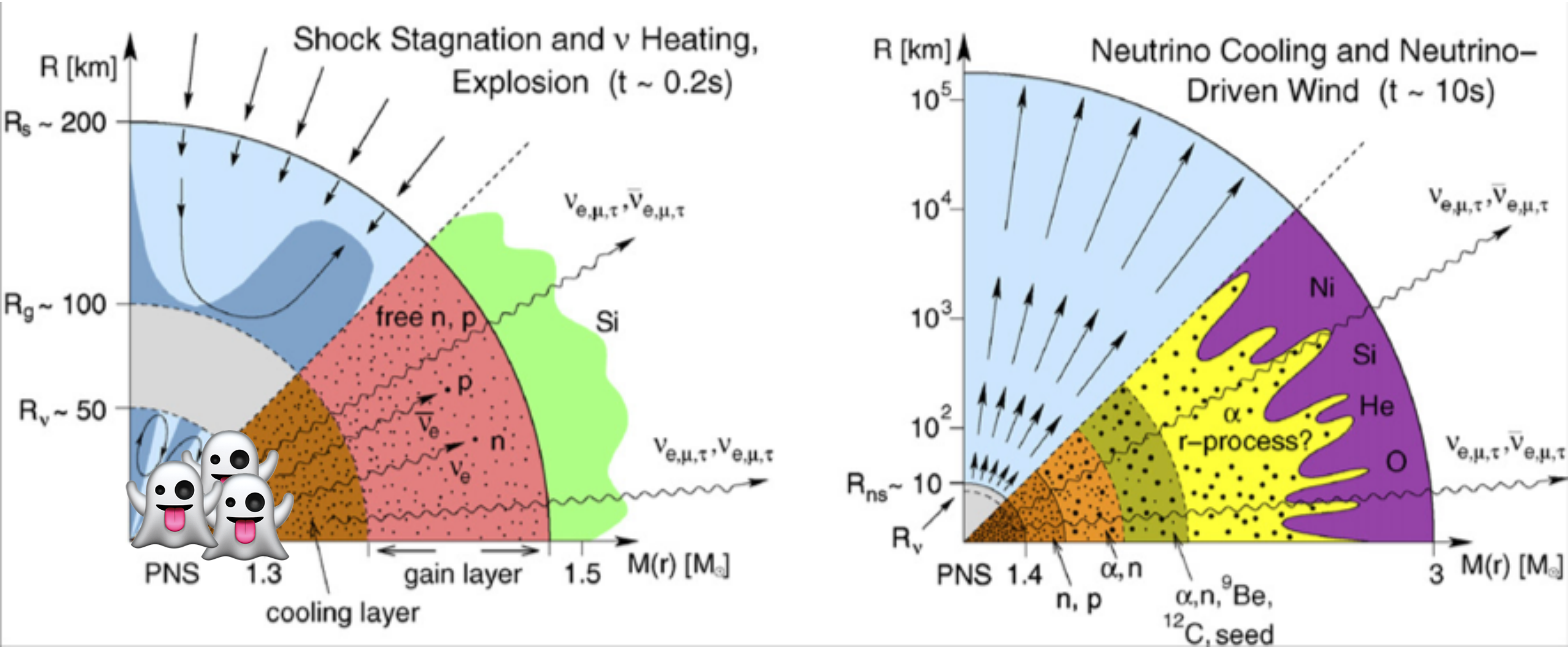
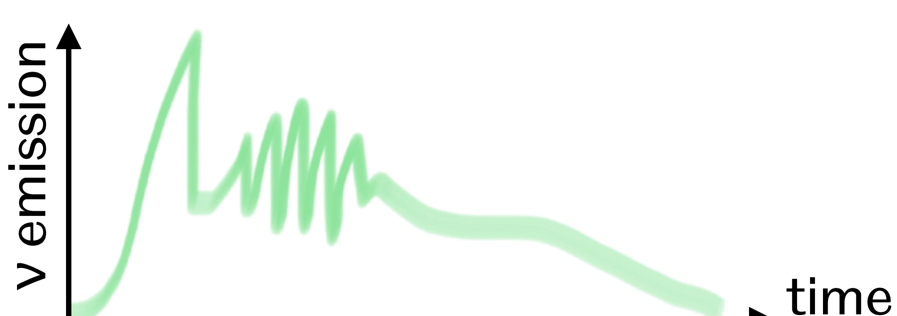




[Janka *et al.*, Phys.Rep. 442, pp. 38–74]

Operational Detectors for Supernova Neutrinos

HALO (30)
SNO+ (300)

LVD (400)
Borexino (100)

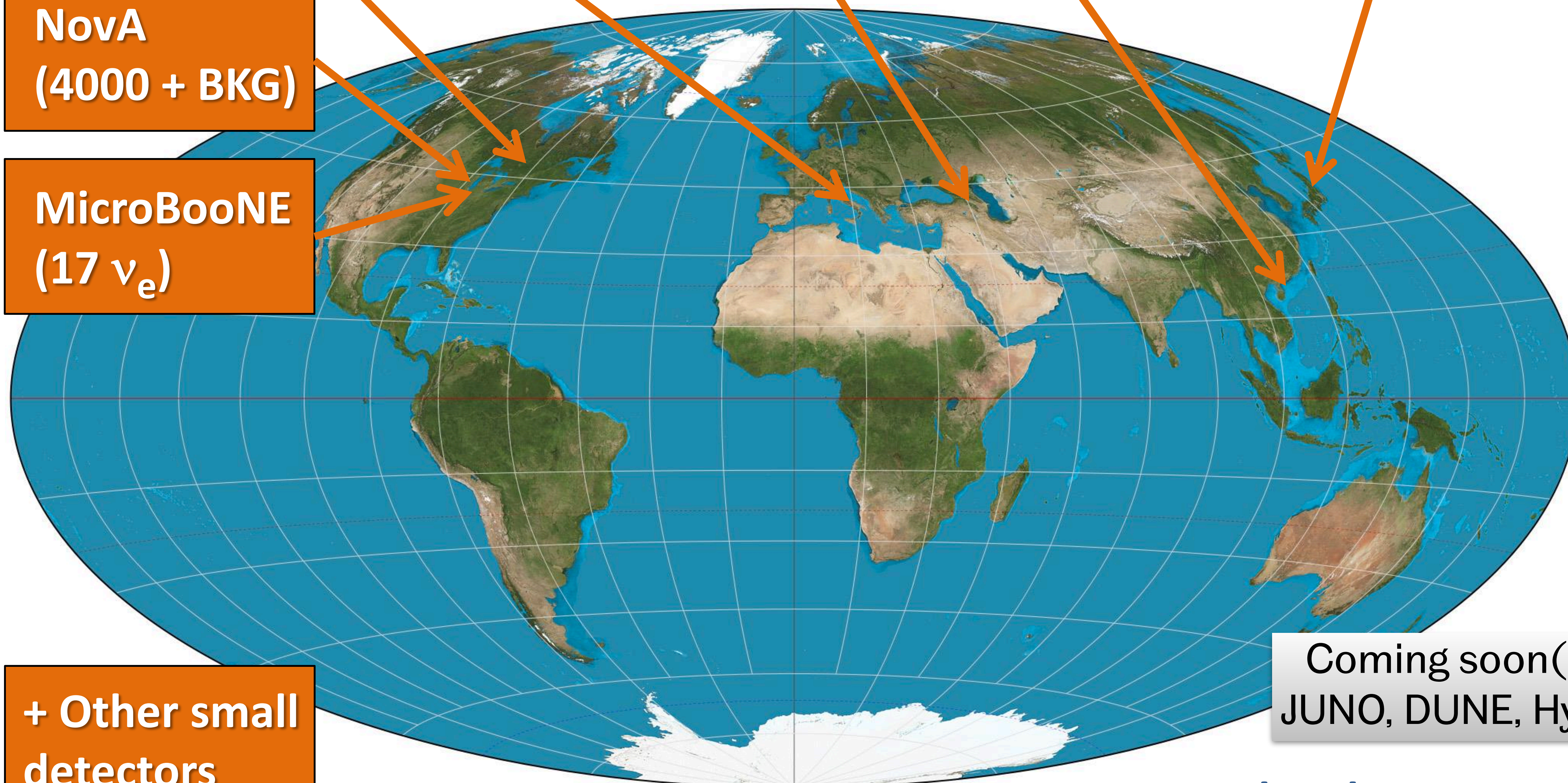
Baksan
(100)

Daya Bay
(100)

Super-K (4000)
KamLAND (400)

NovA
(4000 + BKG)

MicroBooNE
(17 ν_e)



+ Other small detectors with some SN sensitivity

IceCube (10^6)

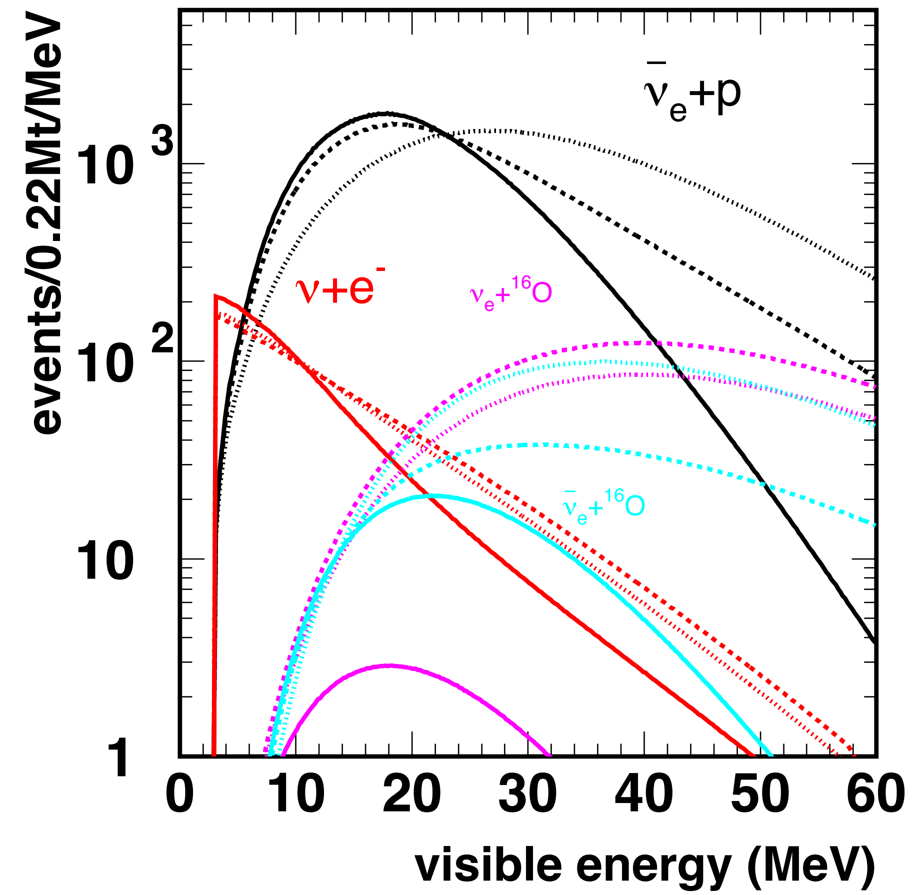
Coming soon(-ish):
JUNO, DUNE, Hyper-K

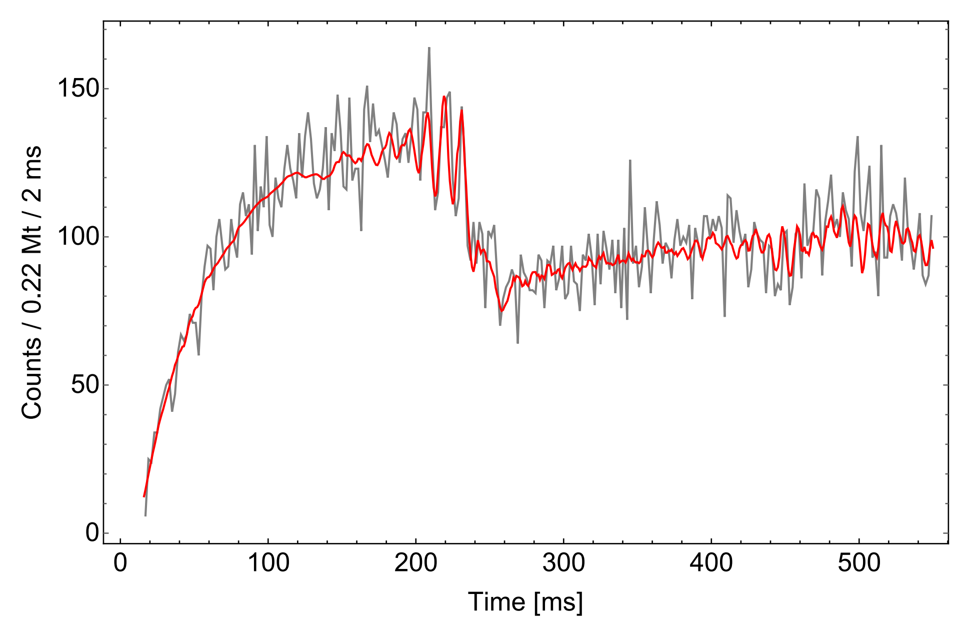
In brackets events for a "fiducial SN" at distance 10 kpc

Supernova ν Burst

- At 10 kpc: **54 k – 90 k events** per tank (hierarchy-dependent) **in ~10 s**
- Precise event-by-event **time & energy** information
- **Directionality**: ~1° (via ve-scattering)
- Most sensitive to $\bar{\nu}_e$ (~90% inverse beta decay on H)

➔ Detailed information on SN explosion mechanism (e.g. Standing Accretion Shock Instability – SASI)

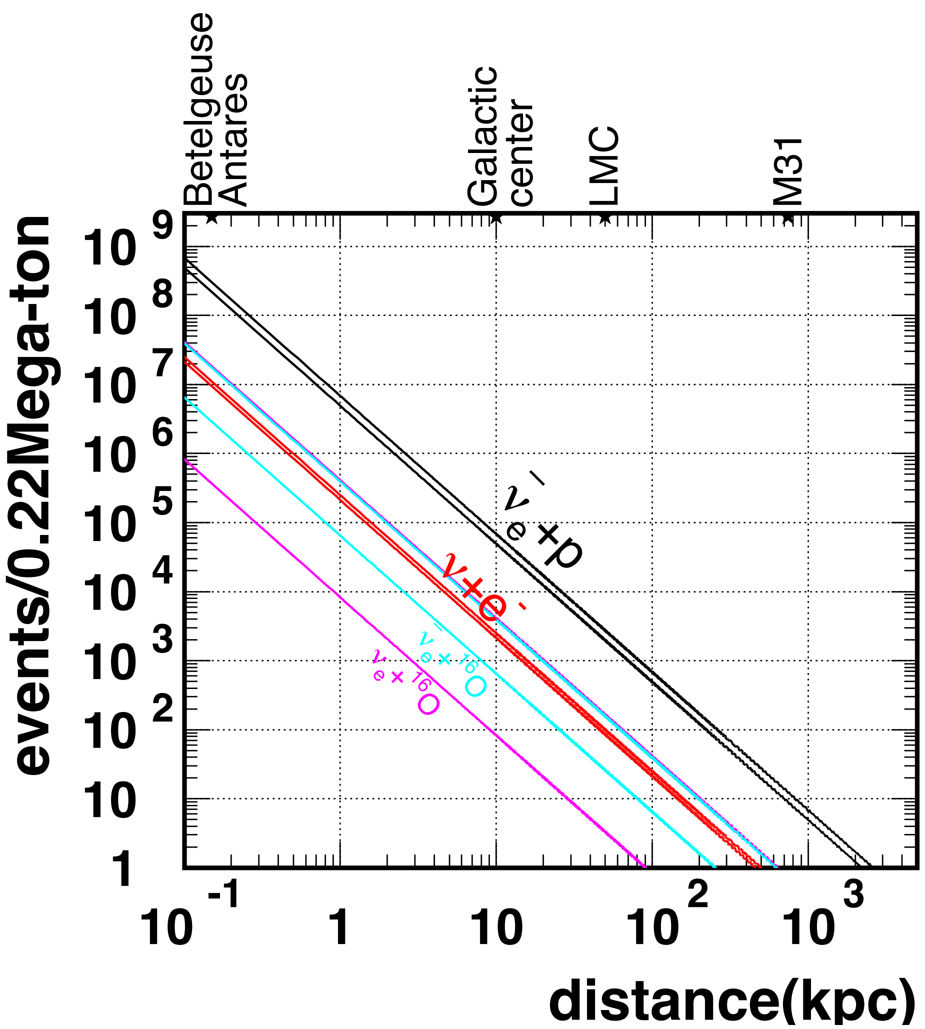


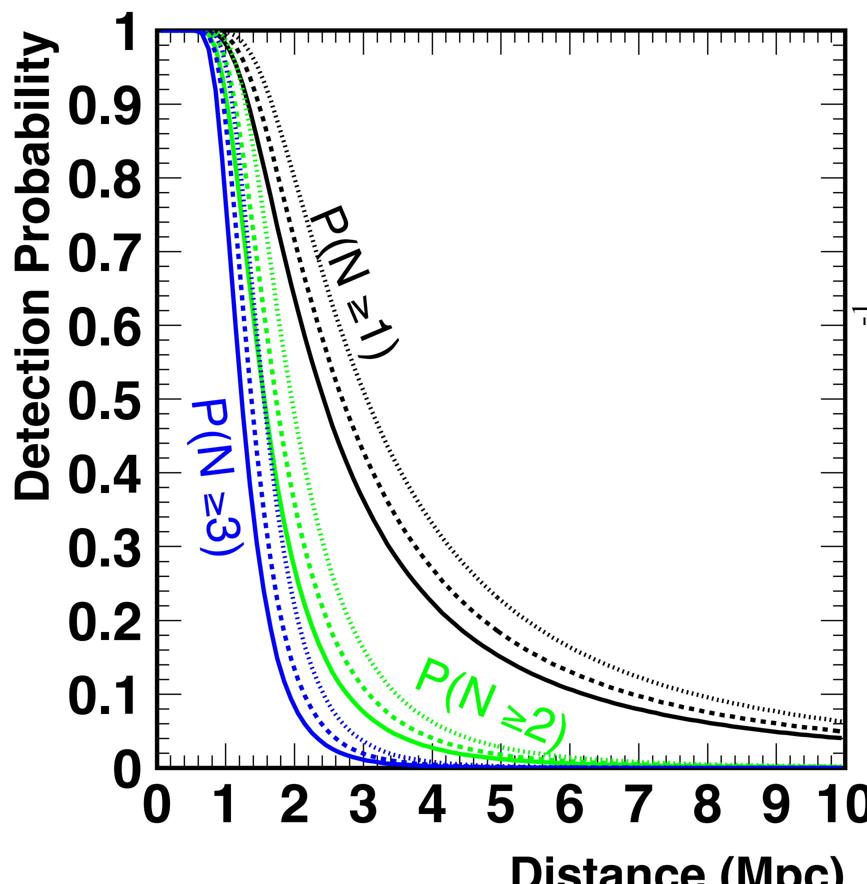


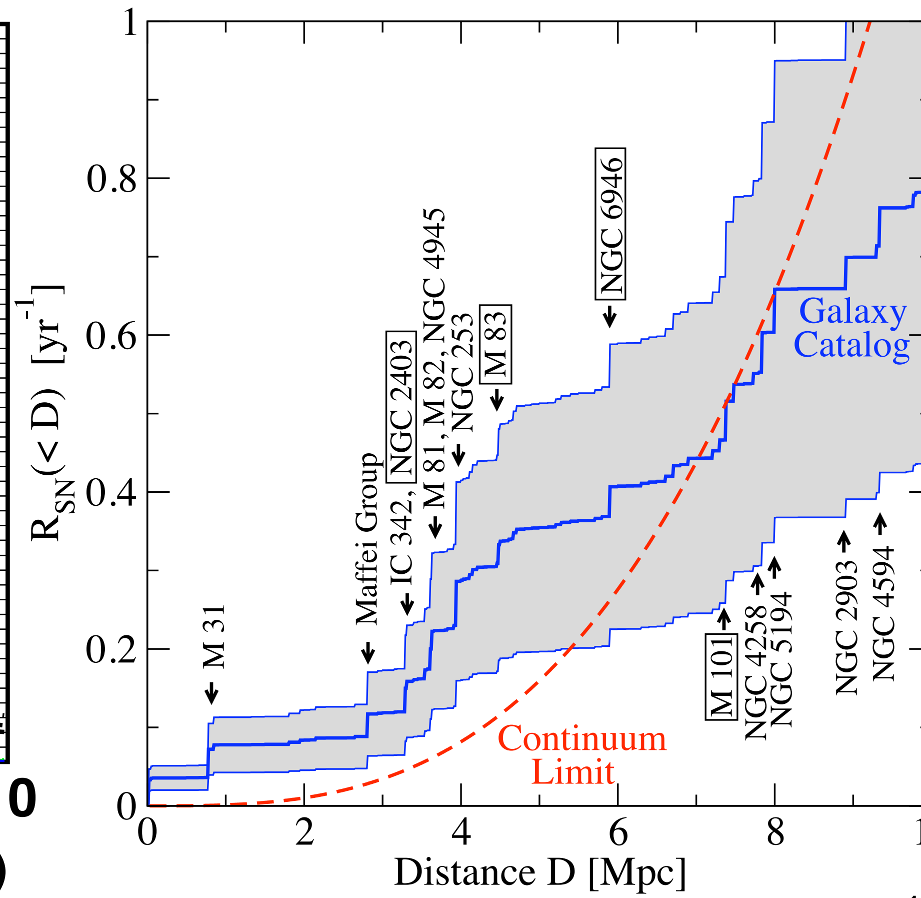
SN in Nearby Galaxy

- 2100–3150 events in LMC (SN1987A-like)
- 9–13 events in Andromeda
- ≥1 event out to few Mpc

➔ still an important test for SN simulations

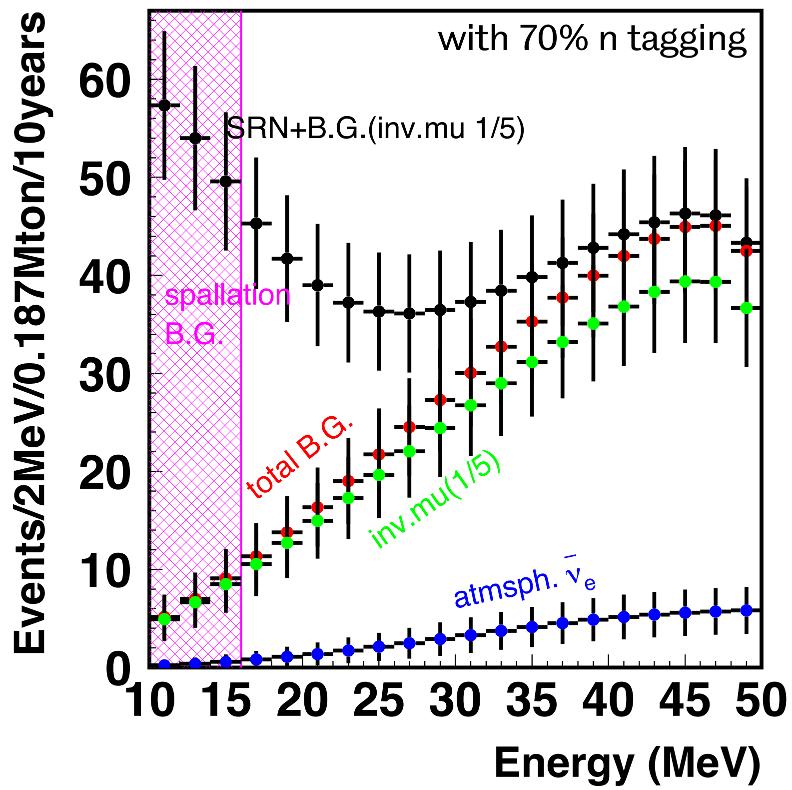


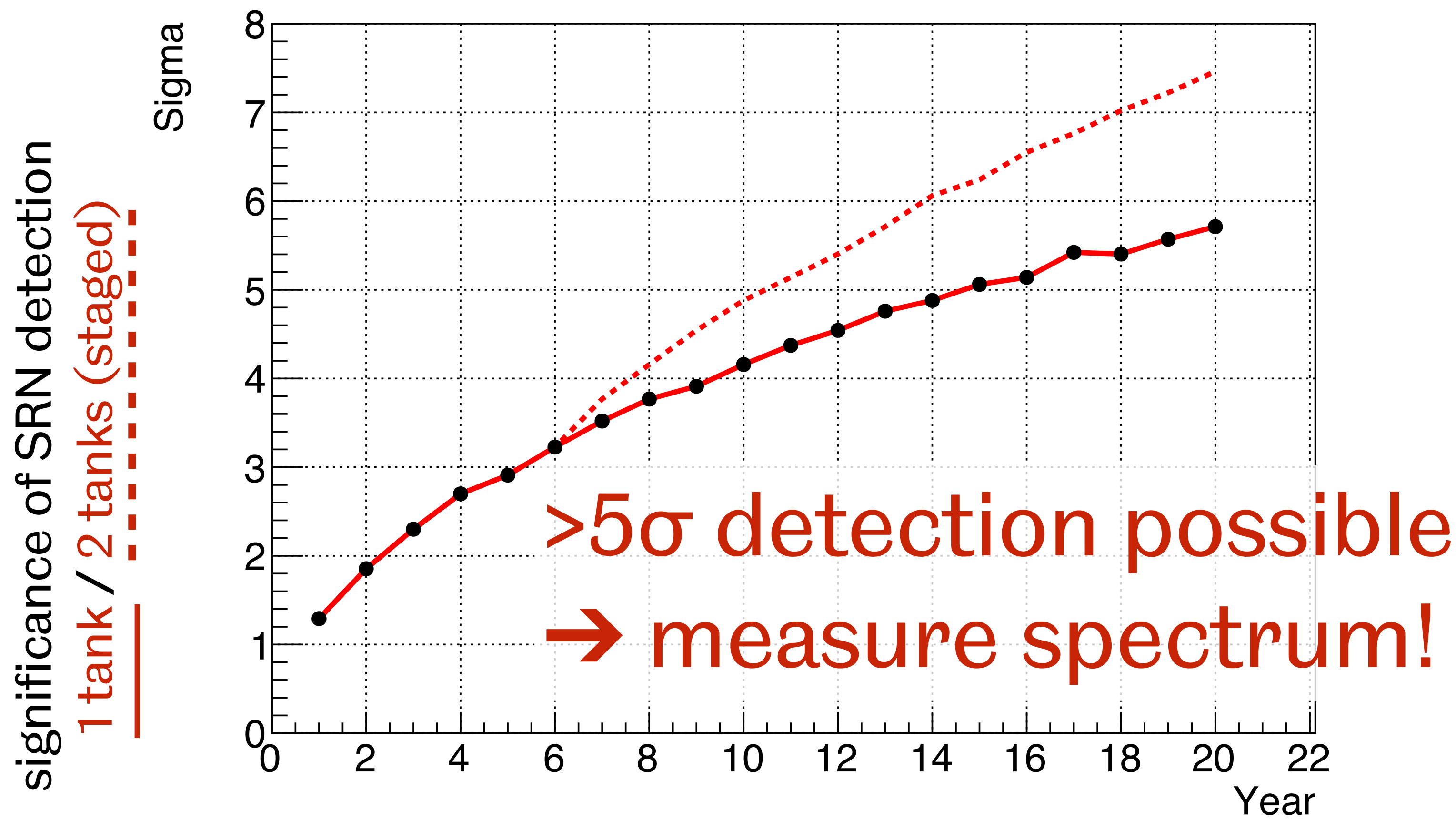


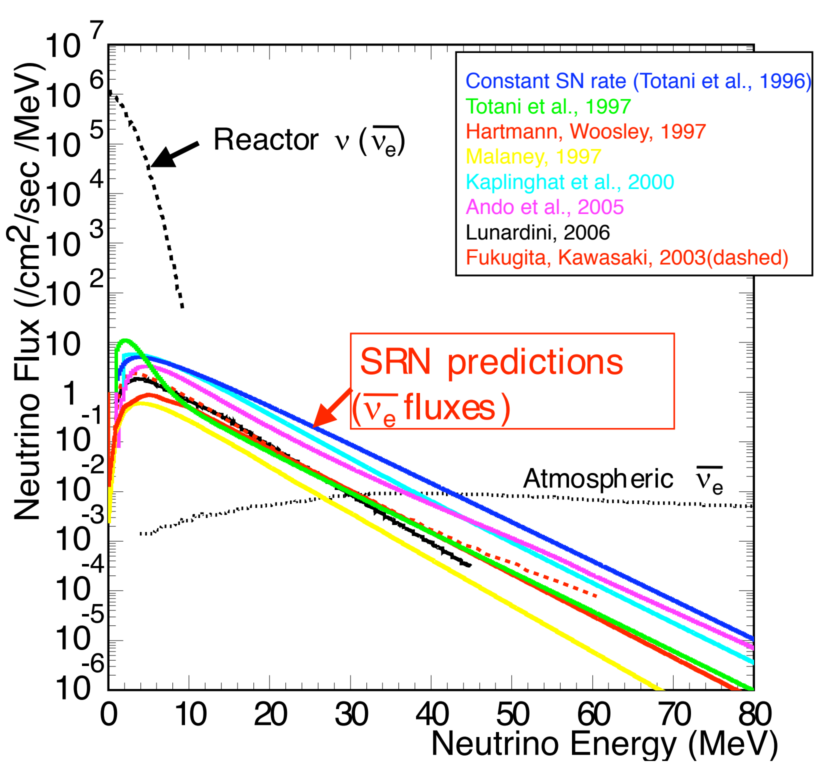


Supernova Relic Neutrinos

- ν from all SN integrated over the history of the universe
  - Encode history of star formation
  - Information on dim SNe & black hole formation





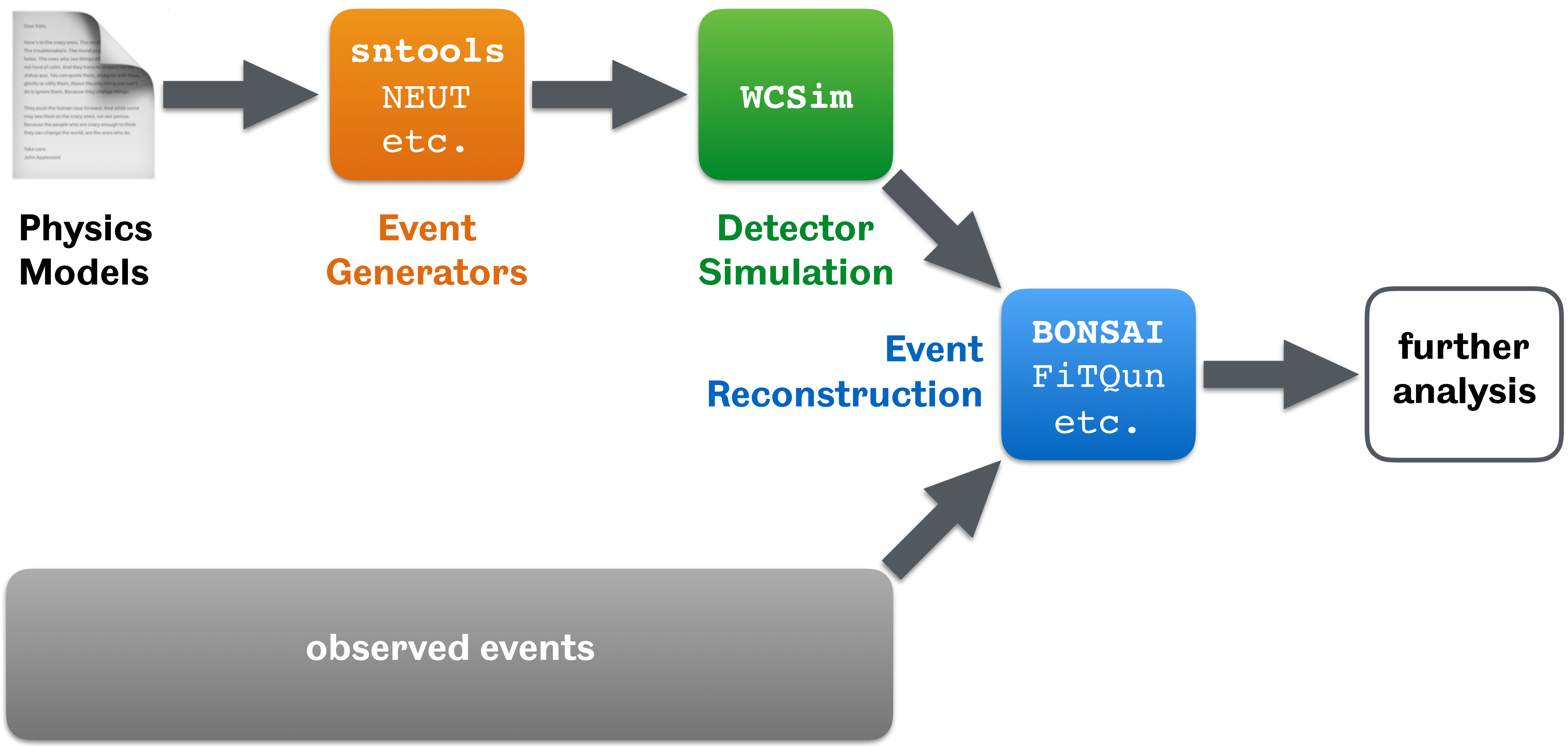


Agenda

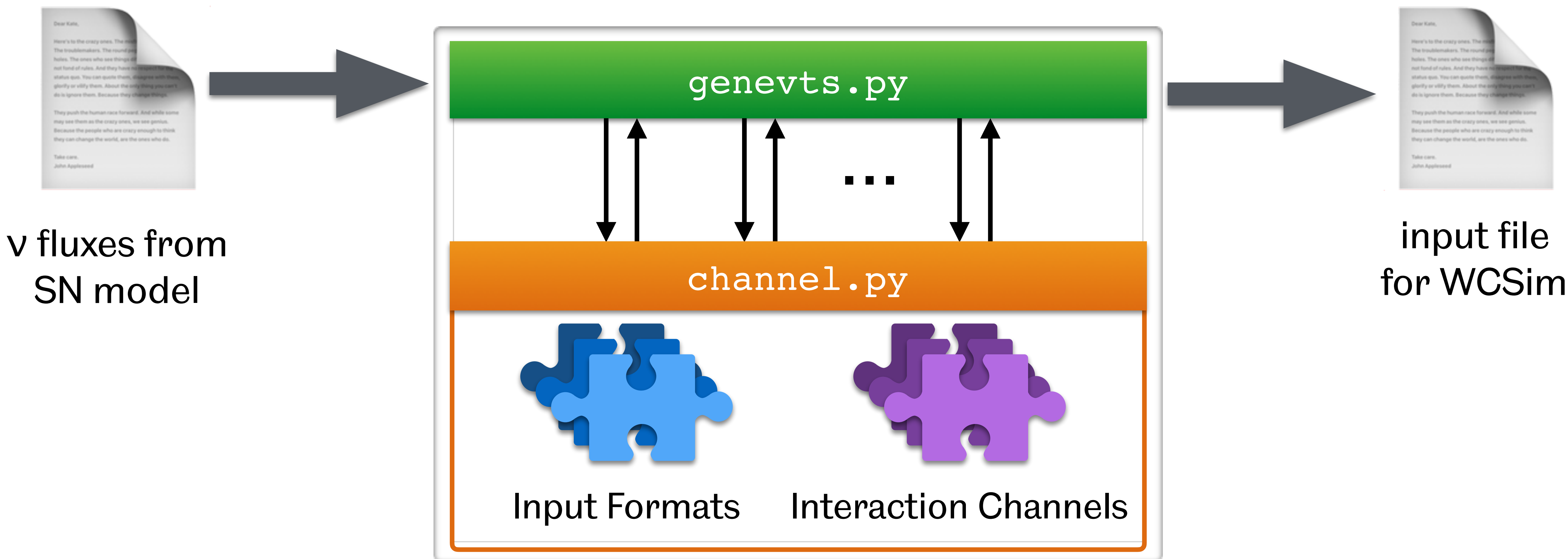
I broke the code; the code broke me!
—Atari Teenage Riot

- The Hyper-Kamiokande Experiment
- Supernova Neutrino Observations with Hyper-K
- **sntools: A Supernova Event Generator**
- Supernova Model Discrimination

HK Software Toolchain



sntools: A SN Event Generator



- Modern, precise cross-sections for main interaction channels
    - Inverse beta decay ($\bar{\nu}_e + p \rightarrow n + e^+$) full result from arXiv:astro-ph/0302055
    - Electron scattering ($\nu + e^- \rightarrow \nu + e^-$) arXiv:astro-ph/9502003
    - ^{16}O CC ($\nu_e + {}^{16}O \rightarrow X + e^\pm$) arXiv:1809.08398,1807.02367
- Extensible, fast & open source: https://github.com/JostMigenda/sntools

Thanks to Elisabeth Kneale and Owen Stone for their contributions!

Agenda

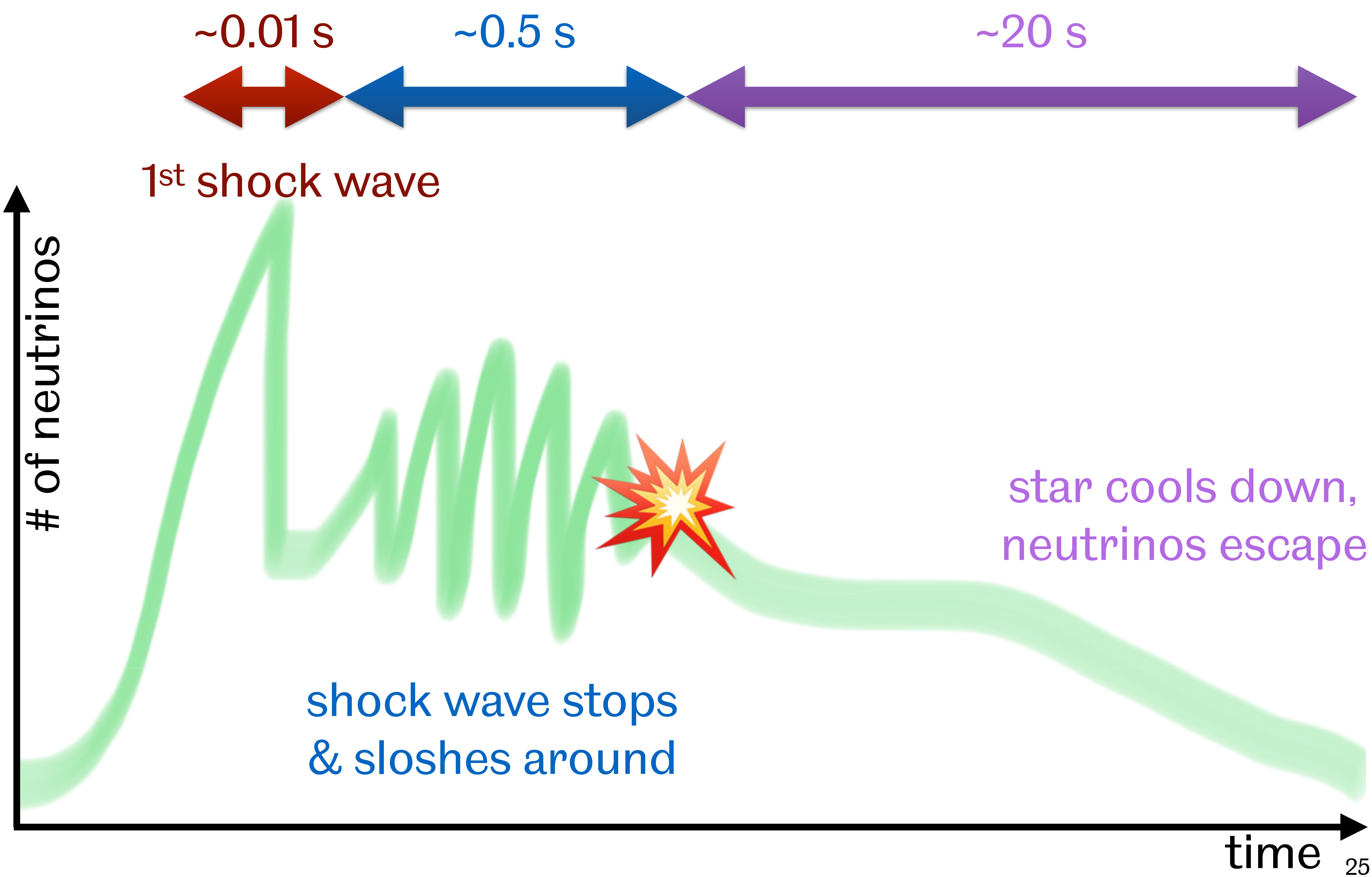
All supernova models are different,
but some are more different than others.
—George Orwell

- The Hyper-Kamiokande Experiment
- Supernova Neutrino Observations with Hyper-K
- sntools: A Supernova Event Generator
- **Supernova Model Discrimination**

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

Focus on First 0.5 s

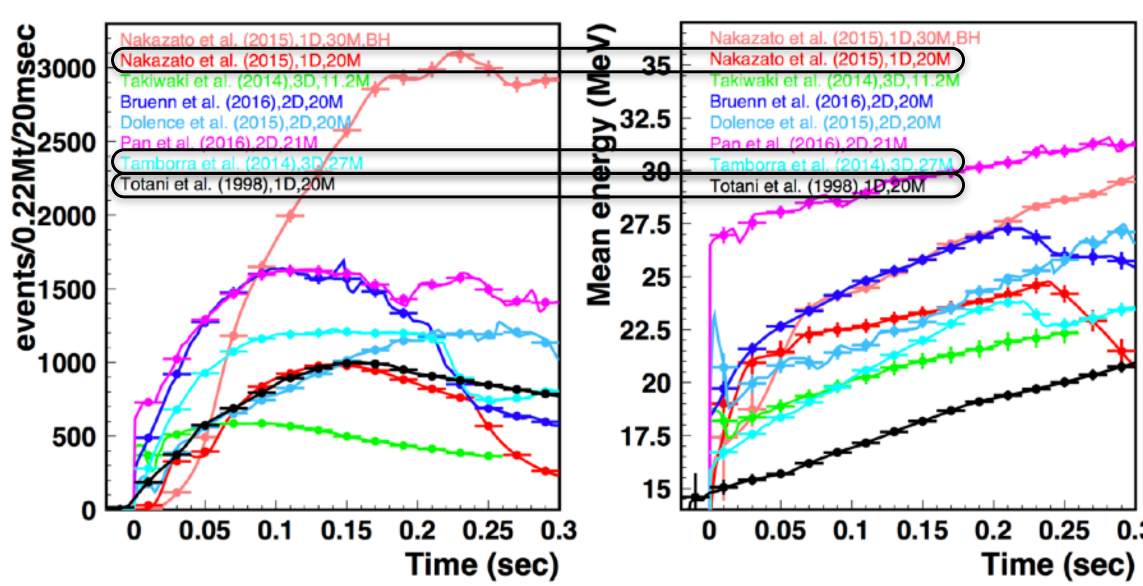


Supernova Models

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)

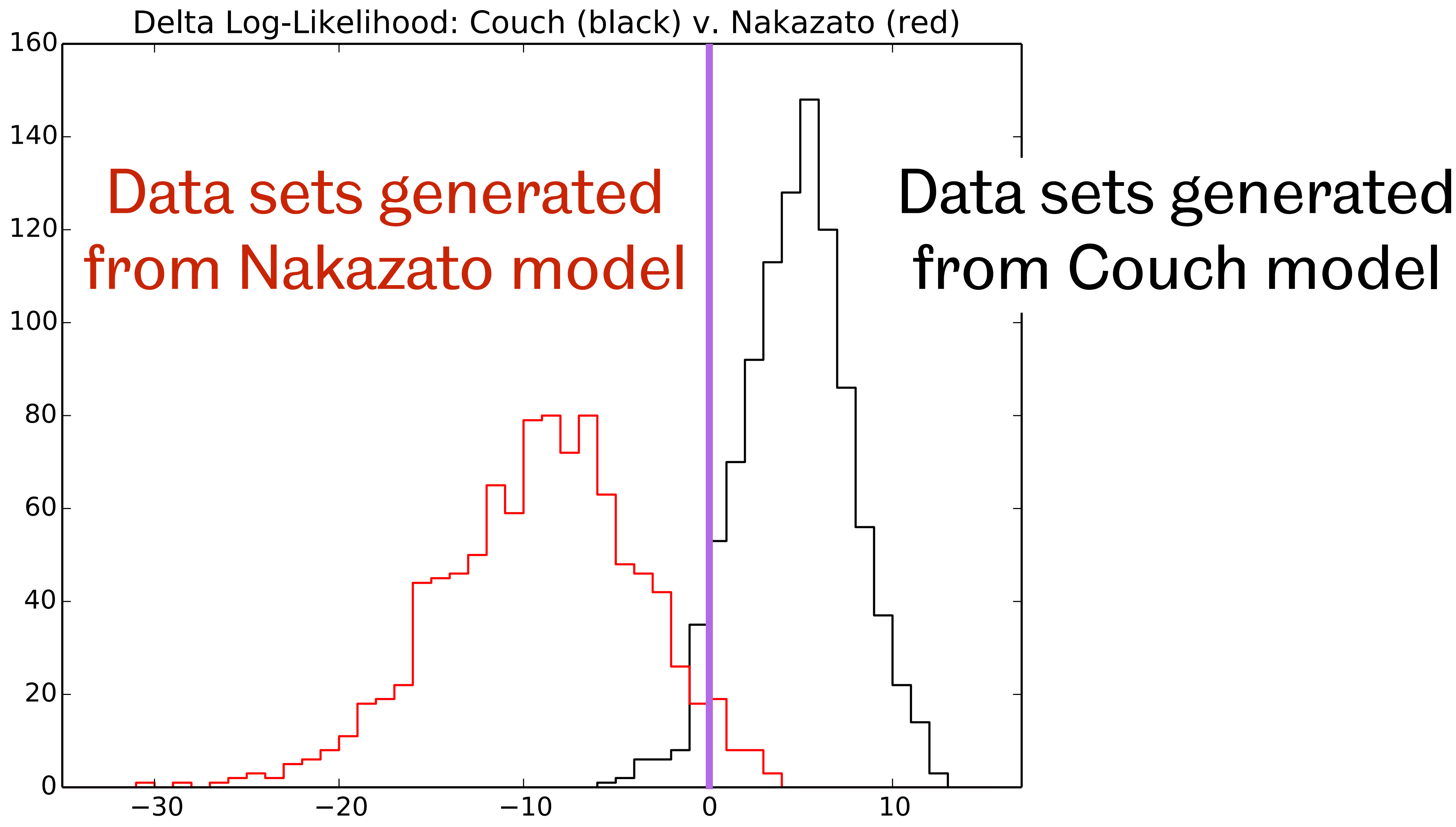
  ➔ Effectively background-free in 500 ms interval
- Each data set contains 100 (300) events originally
  ➔ over 80% remain after trigger and cuts

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 likelihood function L for each SN model
  - Based on Loredo&Lamb [Annals N. Y. Acad. Sci. **571** (1989) p. 601–630]
  - I have extended it 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

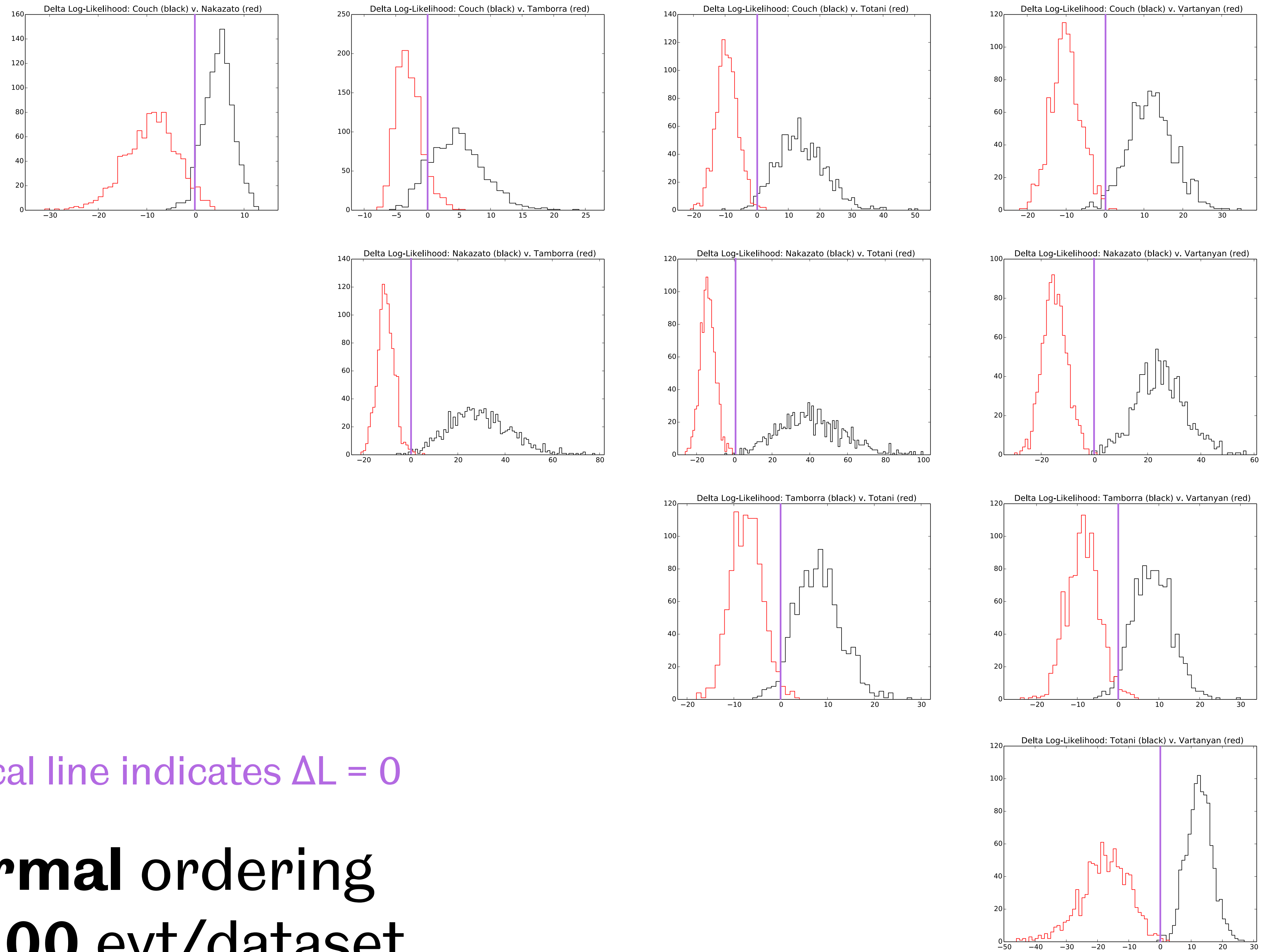


➔ Good model separation with just N=100 events

Normal ordering
N=100 evt/dataset

Pairwise Comparison of SN Models

Nakazato Tamborra Totani Vartanyan



Couch

Nakazato

Tamborra

Totani

vertical line indicates ΔL = 0

Normal ordering

N=100 evt/dataset

Model Identification, N=100

Identified as (rows: 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 (rows: 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

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**

True model

Identified as

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**

True model

Higher statistics reduce random fluctuations & improve accuracy.

Model ID – Conclusions

- Accurate model discrimination at up to ~100 kpc 🤯
- Quantitative technique for figuring out the explosion mechanism

Supernova ν Burst

Step 1:

- At 10 kpc: **54 k – 90 k events** per tank (hierarchy-dependent) **in ~10 s**

- Precise event-by-event **time & energy** information

Step 2: ...????

- **Directionality**: ~1° (via νe-scattering)

- Most sensitive to $\bar{\nu}_e$ (~90% inverse beta decay on H)

Step 3:

➔ Detailed information on SN explosion mechanism (e.g. Standing Accretion Shock Instability – SASI)

Model ID – Conclusions

- Accurate model discrimination at up to ~100 kpc 🤯
- Quantitative technique for figuring out the explosion mechanism
- Very versatile approach, can (in principle) be used to determine anything that affects the neutrino fluxes

Sneak Peek: Progenitor Properties

- Hyper-K is still ~7 years away & SN simulations will make progress in the meantime
- Using same simulation code, can we identify progenitor?
- Use different Nakazato models
  - 13, **20,** 30 M_{sol} with solar metallicity (z=0.02)
  - 20* M_{sol} with SMC metallicity (z=0.004)

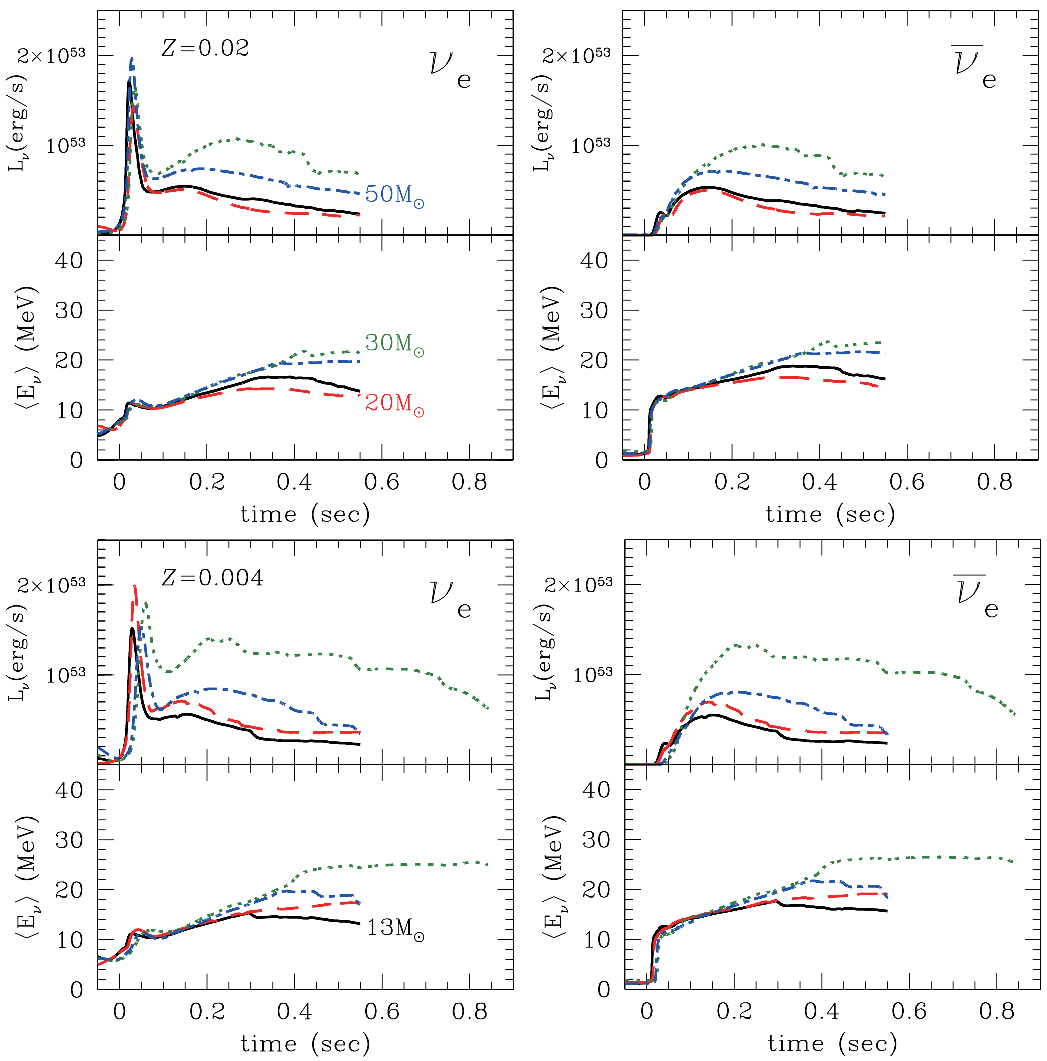


Figure from arXiv:1210.6841

Progenitor Properties, N=300

Identified as

Normal (True model)	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

Inverted (True model)	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
- Developed versatile method of using full time & energy information available in HK
  - Distinguish supernova models at ~100 kpc distance
  - If mis-ID: only by very narrow margin
    ➔ can still narrow down list of possible models
- Chance to identify progenitor properties