Supernova Neutrino Simulations in Hyper-Kamiokande

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*they/them

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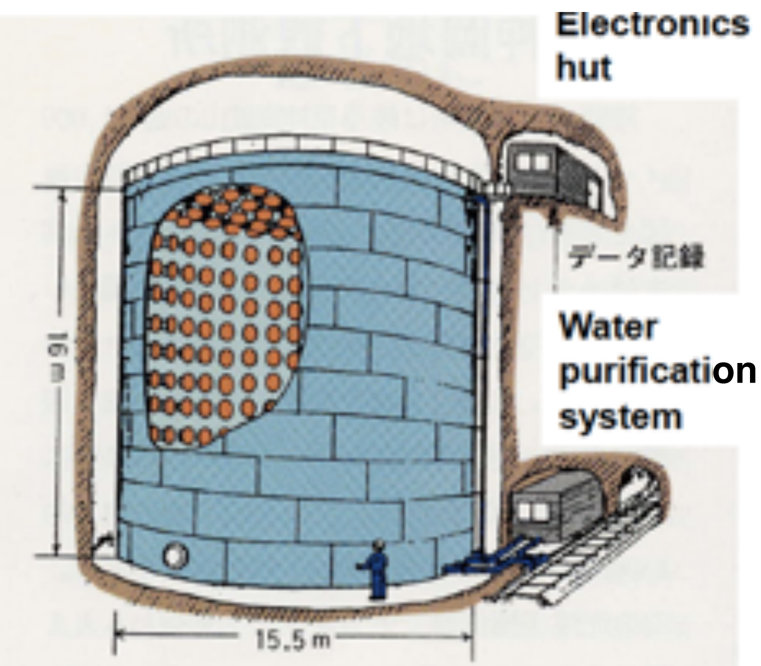
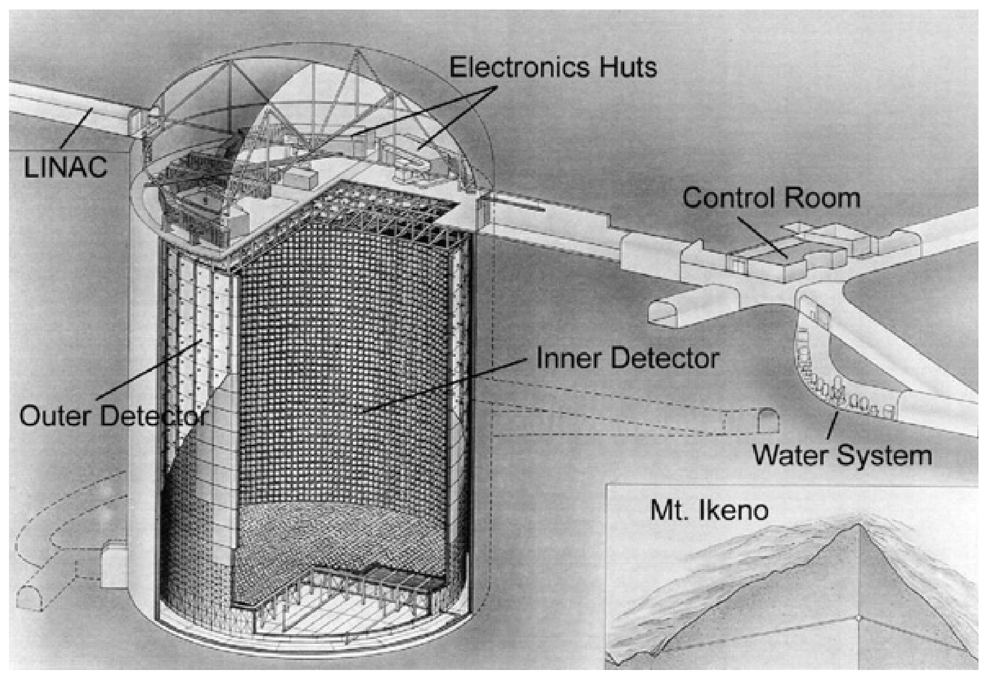
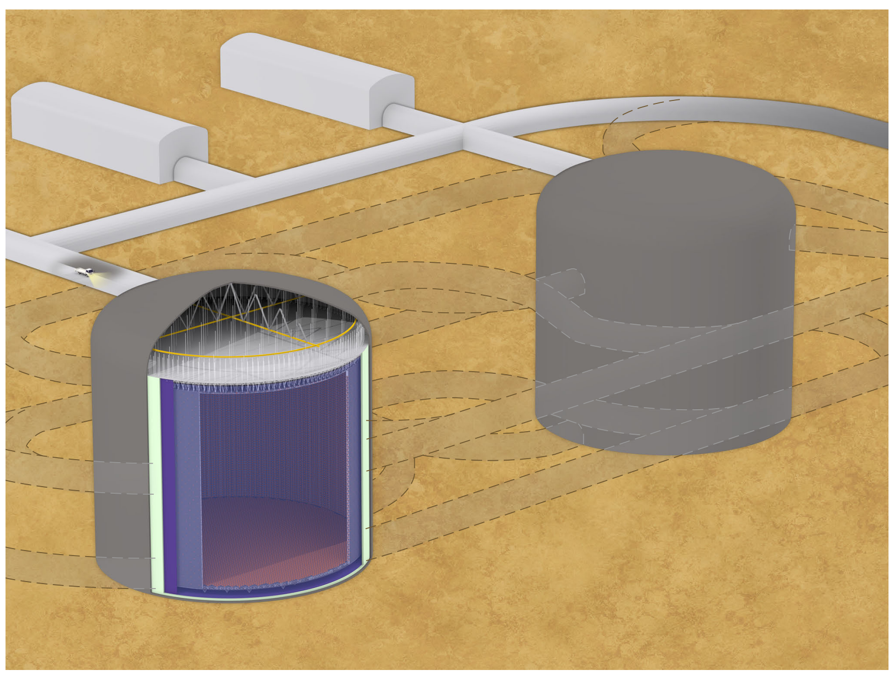
@JostMigenda

3rd Generation Water Cherenkov Detector

Kamiokande	Super-Kamiokande	Hyper-Kamiokande
1983–1996	1996–today (and beyond)	~2026–???







Koshiba, 2002

Kajita, 2015

???, 20??

➔ Hyper-K Design Report: hyperk.org/?p=215

3rd Generation Water Cherenkov Detector

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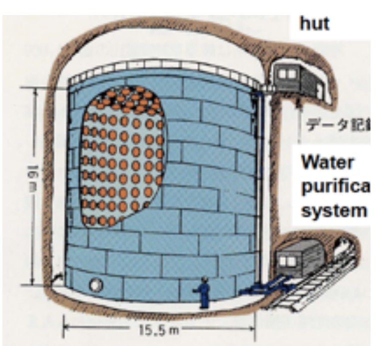
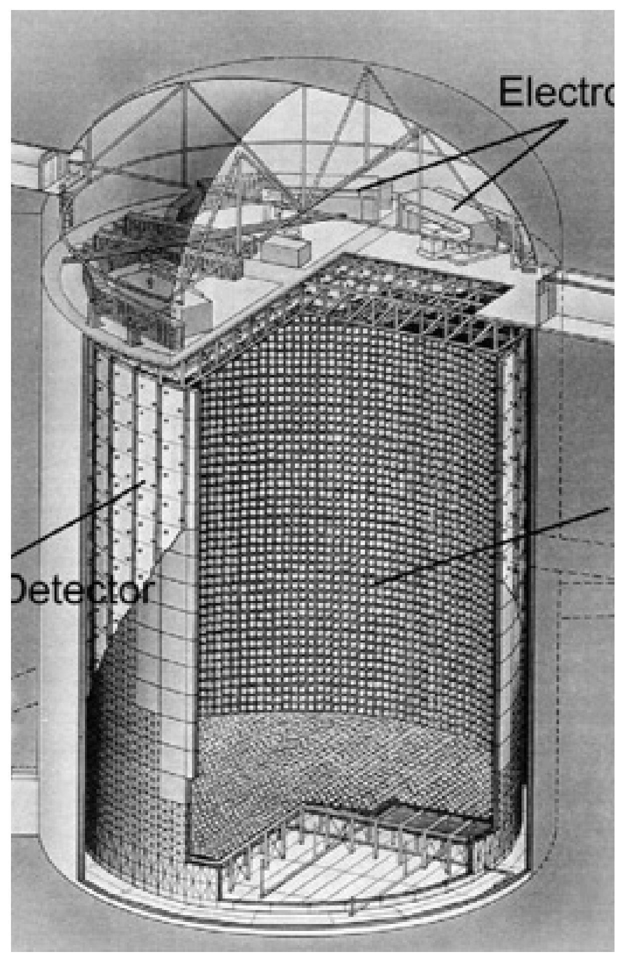
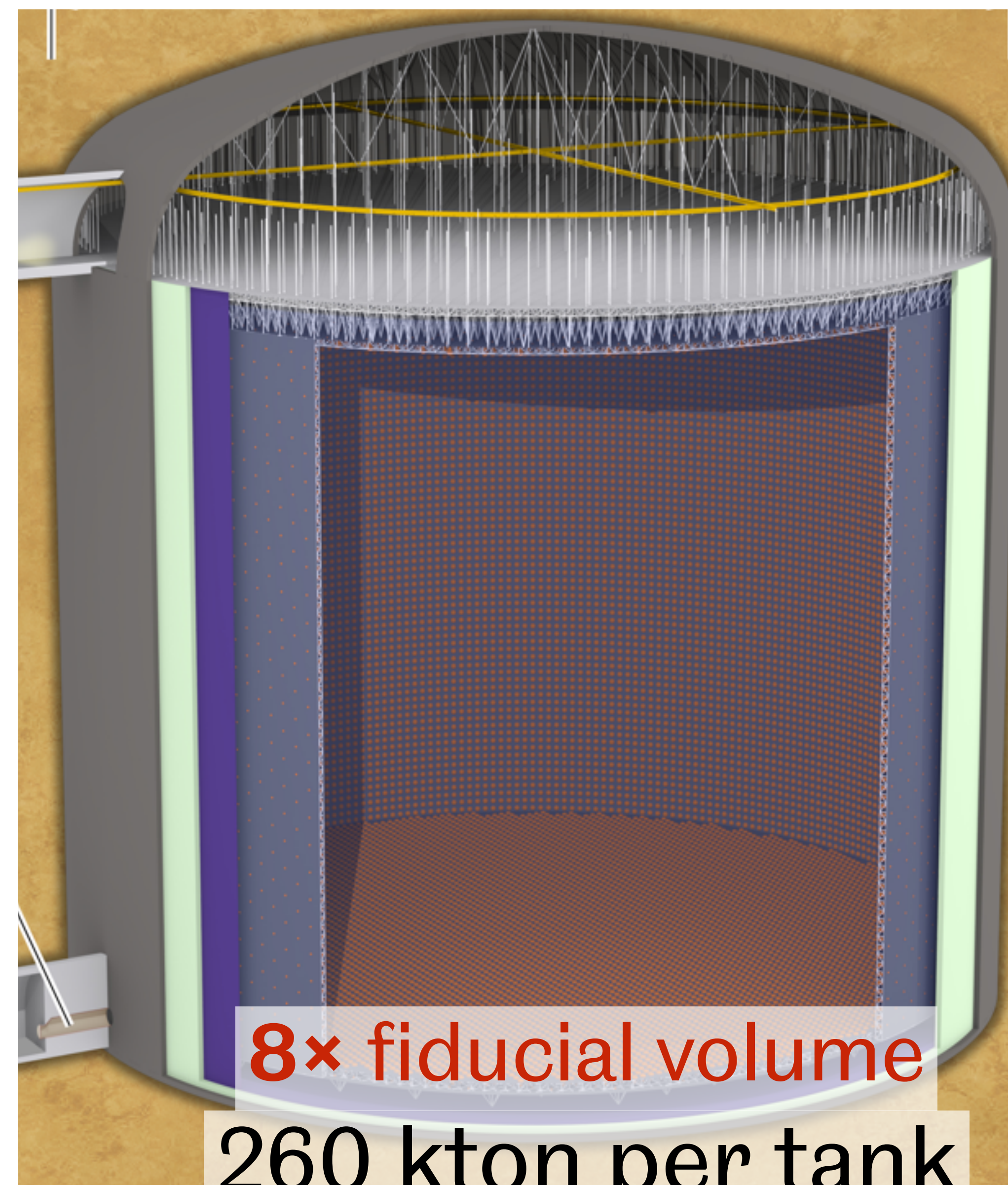


3 kton



50 kton

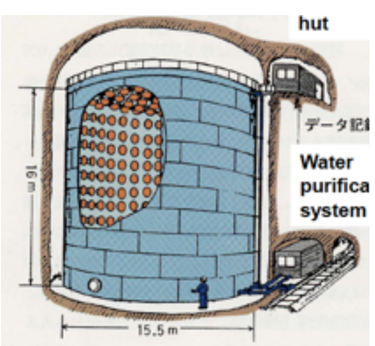


3rd Generation Water Cherenkov Detector

Kamiokande

1983–1996

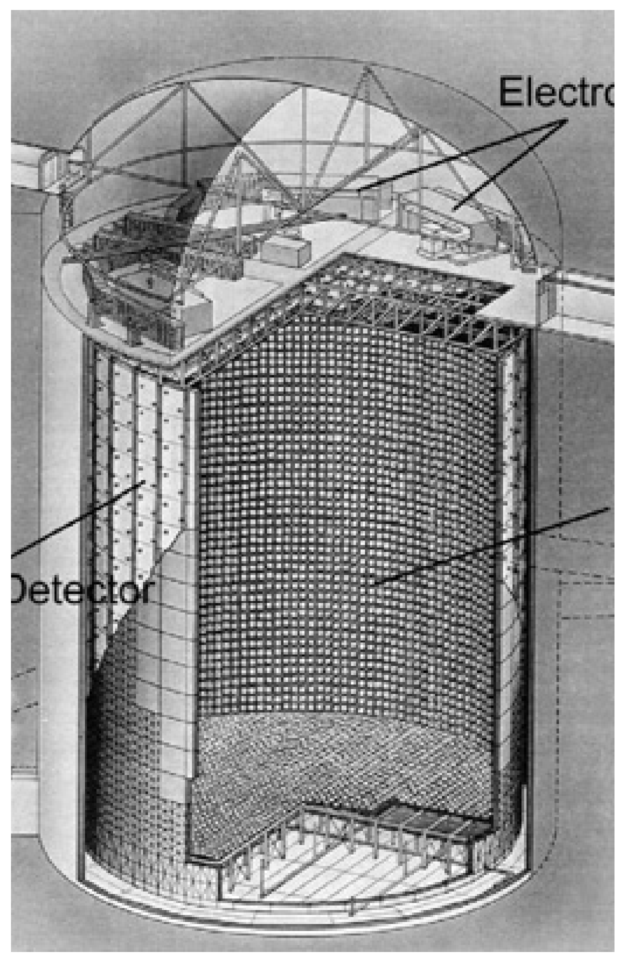
12 ν



3 kton

Super-Kamiokande

1996–today (and beyond)



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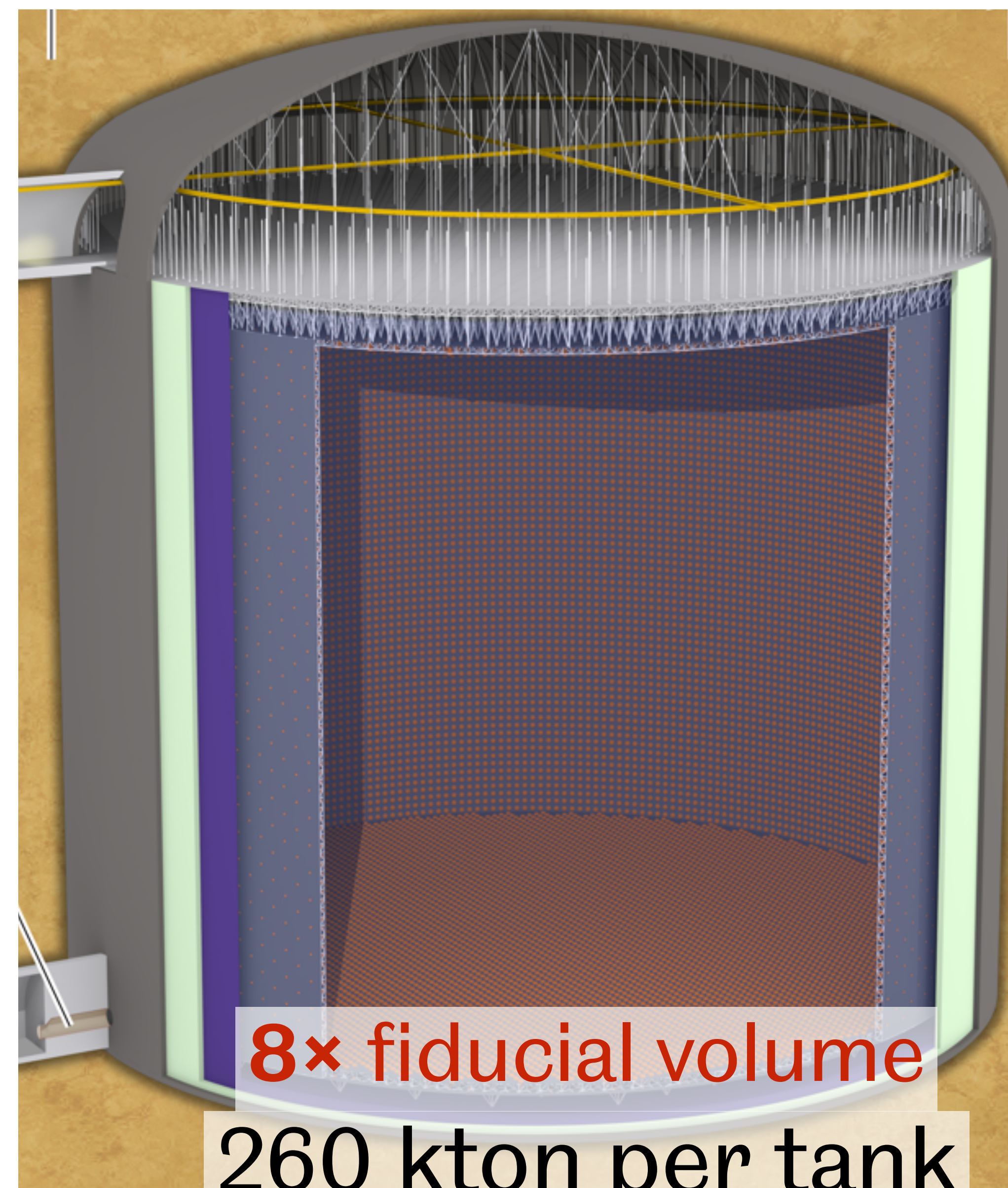
Hyper-Kamiokande

~2026–???

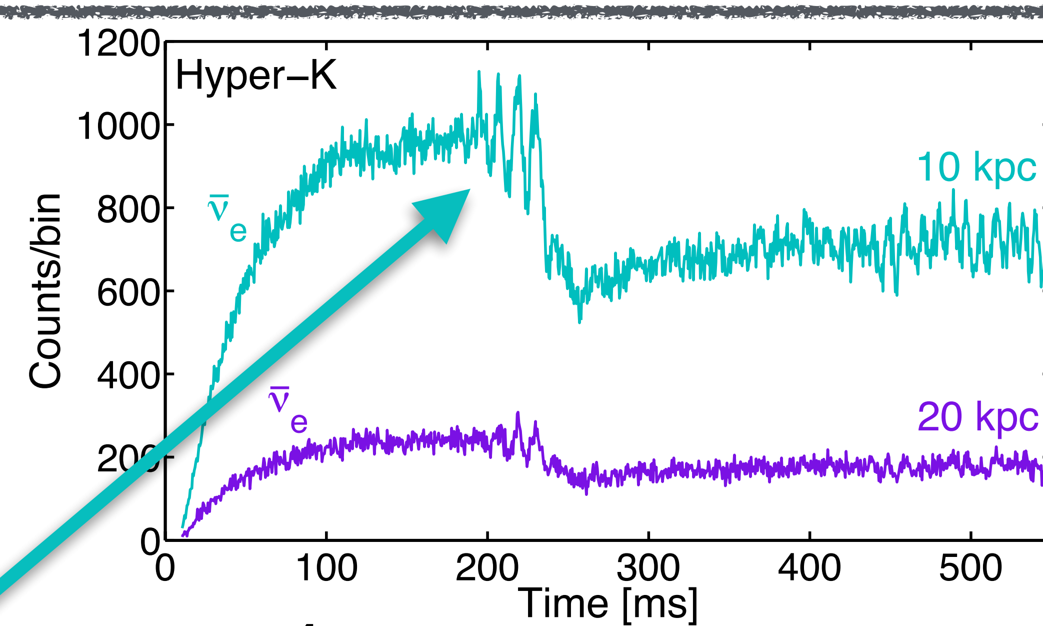


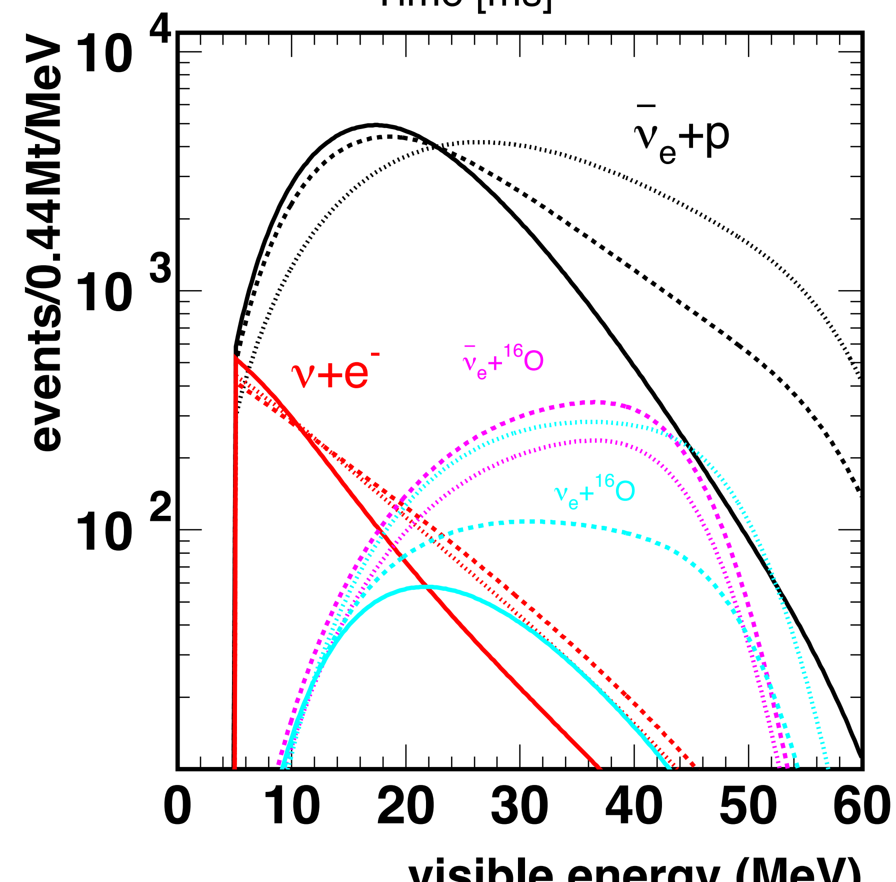
Supernova ν Burst

- at 10 kpc: **50 k – 80 k events** per tank (hierarchy-dependent) **in ~10 s**
- precise event-by-event **time & energy** information

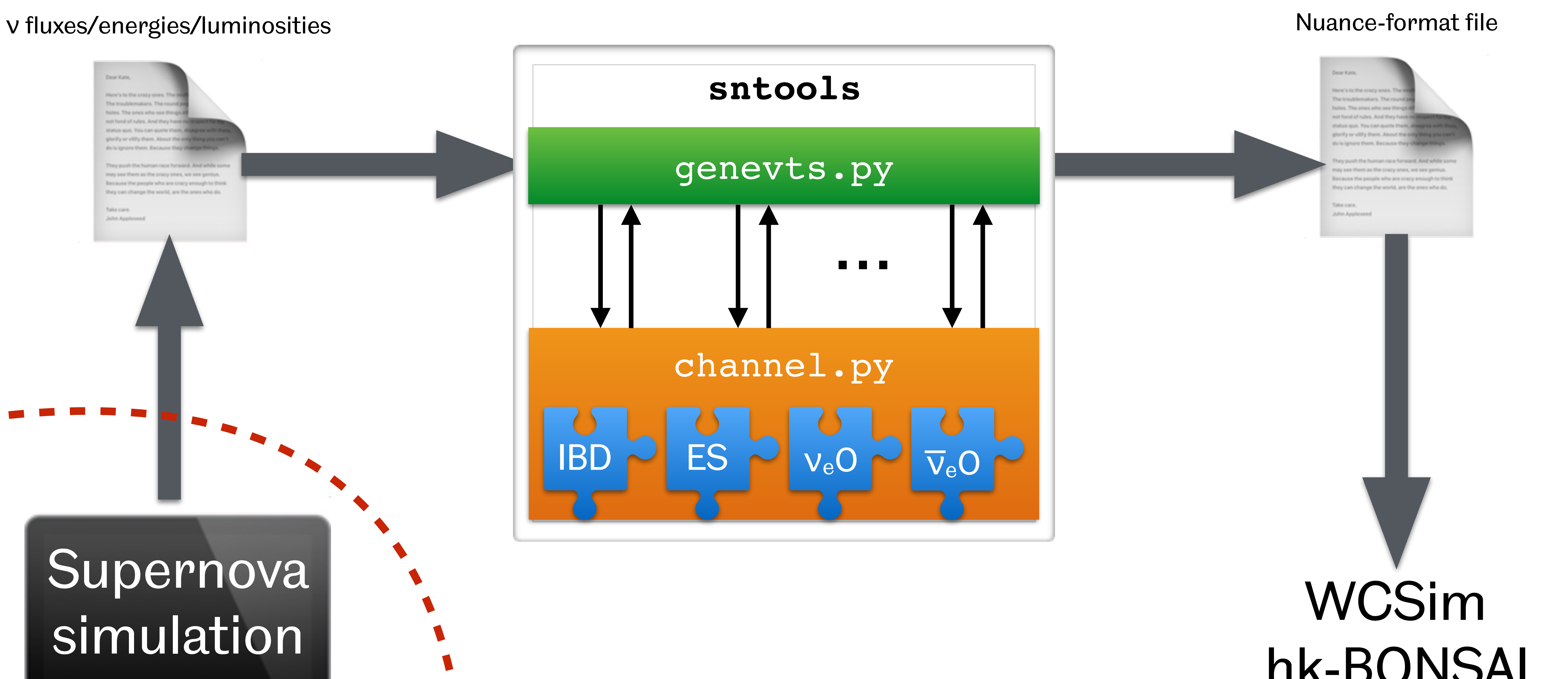
➔ detailed information on SN explosion mechanism (e.g. SASI)

- most sensitive to $\bar{\nu}_e$ (~90% inverse beta decay on H)
- **directionality**: ~1° (via ν+e-scattering)





Supernova Simulation Toolchain Overview



IBD: $\bar{\nu}_e + p \rightarrow n + e^+$

ES: $\nu + e^- \rightarrow \nu + e^-$

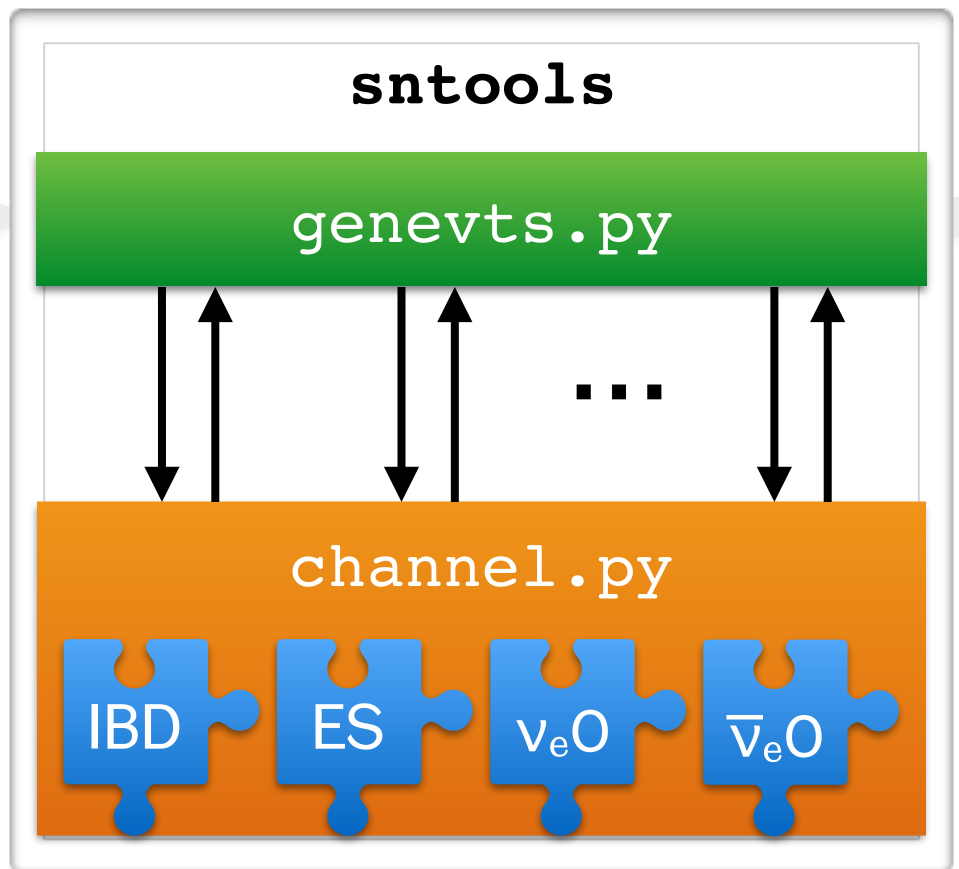
ν_eO: $\nu_e + O \rightarrow X + e^\pm$

→ https://github.com/JostMigenda/sntools

sntools Overview

genevts.py:

- handle options (detector, I/O file names, interaction channels, **mass hierarchy**)




```
$ python genevts.py --hierarchy=normal --channel=ibd --detector=HyperK --verbose
                                inverted          es               SuperK
                                noosc             o16e
                                                  o16eb
                                                  all
```

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`sntools` Overview

genevts.py:

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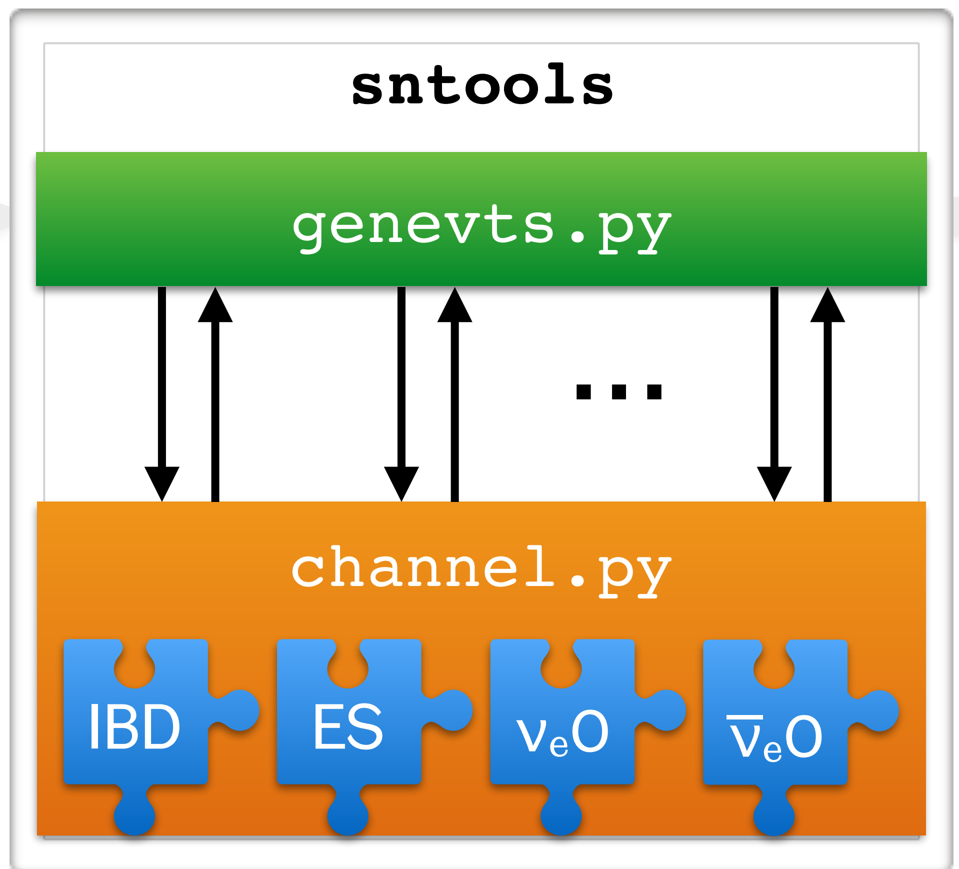

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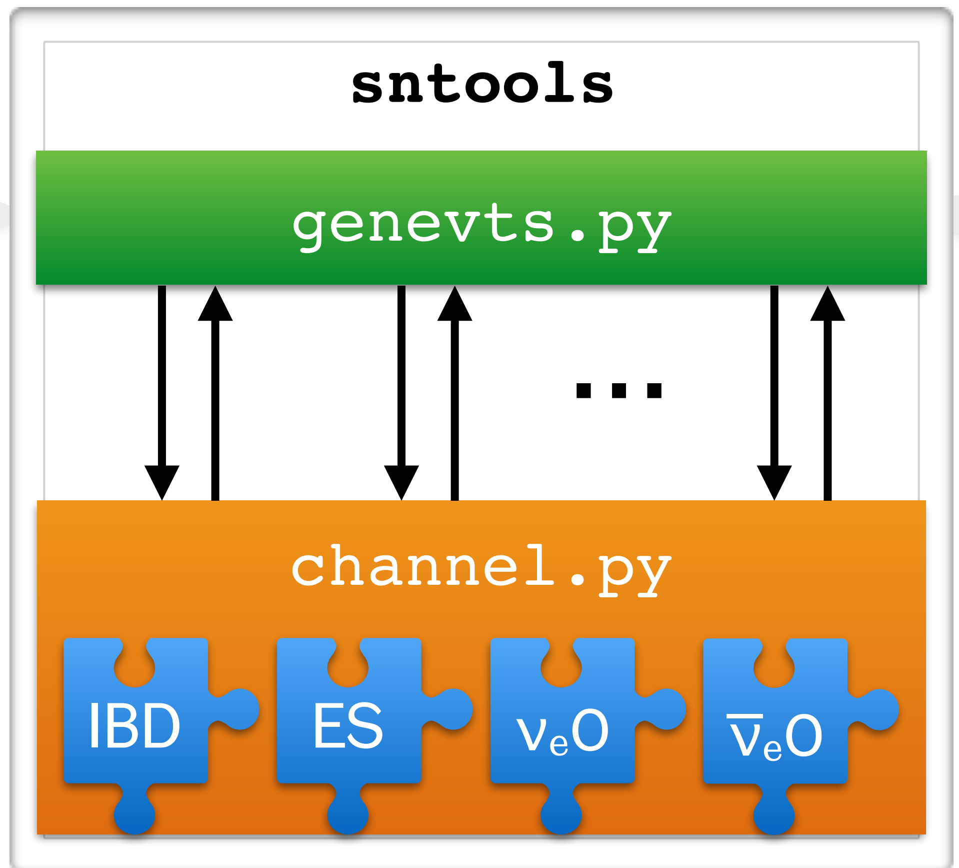

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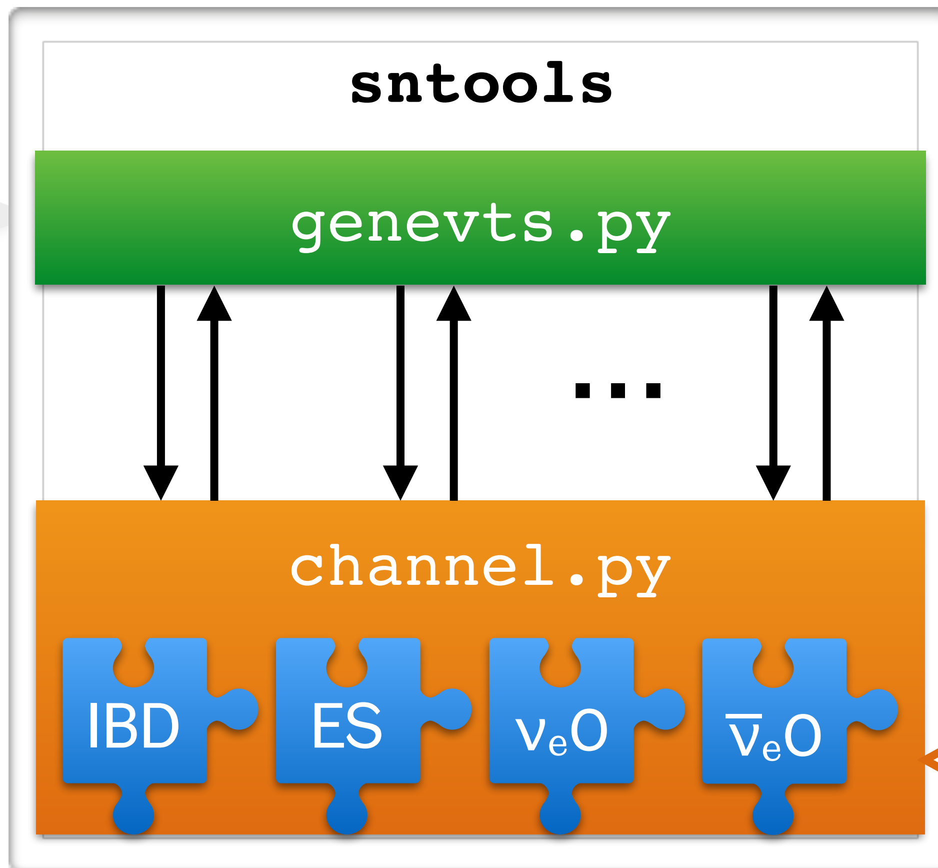

channel.py:

- read in ν flux
- calculate event count per bin
- generate event times, energies, directions
- write raw event info to tmp file
- *1 “plugin” per neutrino flux or interaction channel*

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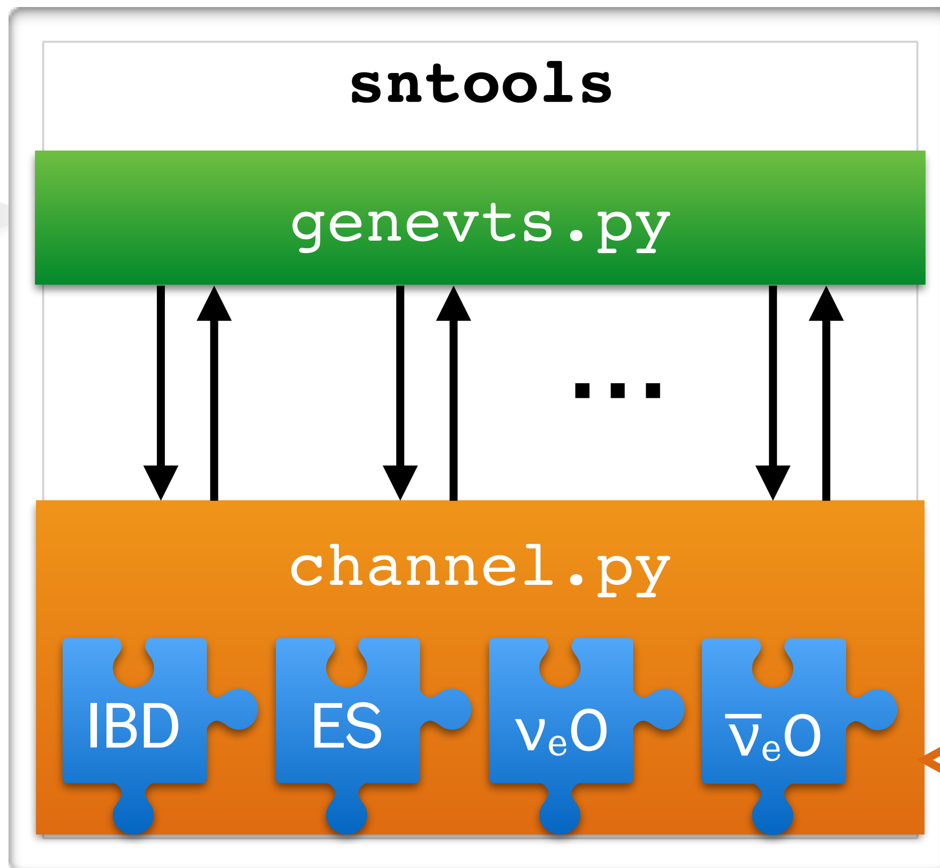

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"Plugins":

- neutrino flux: different input file formats, energy spectrum
- interaction channel: differential cross section, directionality, energy threshold, …

Inverse Beta Decay

- cross section: Strumia/Vissani, arXiv:astro-ph/0302055
- NLO in E_ν/m_p, radiative corrections

Table 2
Percentage difference between our full result and various approximations for $\bar{\nu}_e$ (above) and ν_e (below) total cross-sections. A negative (positive) sign means that a certain cross-section is an over(under)-estimate. It is easy to implement approximations made with ⋆⋆⋆, while implementing those marked with a ⋆ is not much simpler than performing a full computation

	E_ν, MeV		2.5	5	10	20	40	80	160
			Percentage difference in $\sigma(\bar{\nu}_e p \to n\bar{e})$						
(1)	Naïve	⋆⋆⋆	−3.9	−5.8	−9.9	−19	−38	−84	−210
(2)	Naïve+	⋆⋆⋆	0	0.3	−0.2	0.4	0.2	0.5	−0.9
(3)	Vogel and Beacom	⋆⋆	0	0	0.3	1.2	5.6	28	150
(4)	NLO in E_ν/m_p	⋆	0	0	0	0	0.1	1.5	13

Elastic Scattering

Thanks to Liz Kneale!

- Bahcall *et al.* 1995, arXiv:astro-ph/9502003 (appendices A, B)
    - incl. EW & QED corrections
    - for ν_e, $\bar{\nu}_e$, ν_x, $\bar{\nu}_x$ (x stands for μ or τ)

$$\frac{d\sigma}{dT} = \frac{2G_F^2 m}{\pi}\left\{ g_L^2(T)\left[1+\frac{\alpha}{\pi}f_-(z)\right] + g_R^2(T)(1-z)^2\left[1+\frac{\alpha}{\pi}f_+(z)\right] - g_R(T)g_L(T)\frac{m}{q}z\left[1+\frac{\alpha}{\pi}f_{+-}(z)\right]\right\}$$

$$g_L^{(\nu_e,e)}(T) = \rho_{NC}^{(\nu,l)}\left[\tfrac{1}{2} - \hat{\kappa}^{(\nu_e,e)}(T)\sin^2\hat{\theta}_W(m_Z)\right] - 1$$

$$g_R^{(\nu_e,e)}(T) = -\rho_{NC}^{(\nu,l)}\hat{\kappa}^{(\nu_e,e)}(T)\sin^2\hat{\theta}_W(m_Z)\ ,$$

ν_e + Oxygen CC

Thanks to Owen Stone!

- based on theoretical calculation
  Kolbe *et al.* (2002), PRD **66**, 013007
- schematic fit:
  Tomas *et al.* 2003, arXiv:hep-ph/0307050 (Appendix B.3)

experimental data is missing!

$$\sigma\left(\nu_e + {}^{16}\mathrm{O} \to \mathrm{X} + e^-\right) = 4.7 \times 10^{-40}\ \mathrm{cm}^2 \left[\left(\frac{E_\nu}{\mathrm{MeV}}\right)^{1/4} - 15^{1/4}\right]^6$$

we limit our investigation to a schematic implementation of this process where we assume that in every reaction the final-state energy is $E_e = E_\nu - 15$ MeV. For the angular distribution we assume

$$\frac{d\sigma}{d\cos\vartheta} = 1 - \frac{1 + (E_e/25\ \mathrm{MeV})^4}{3 + (E_e/25\ \mathrm{MeV})^4}\cos\vartheta\,, \qquad \text{(B7)}$$

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[redacted] $\times\, 10^{-40}\ \mathrm{cm}^2 \left[\left(\frac{E_\nu}{\mathrm{MeV}}\right)^{[redacted]} - \sout{15}\ 11.4\ [redacted]\right]^{[redacted]}$

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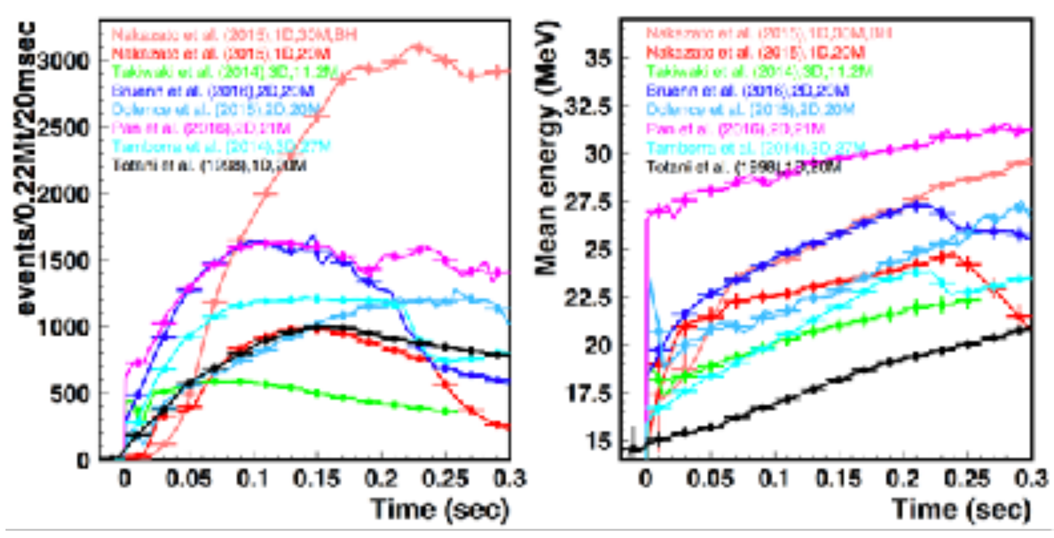
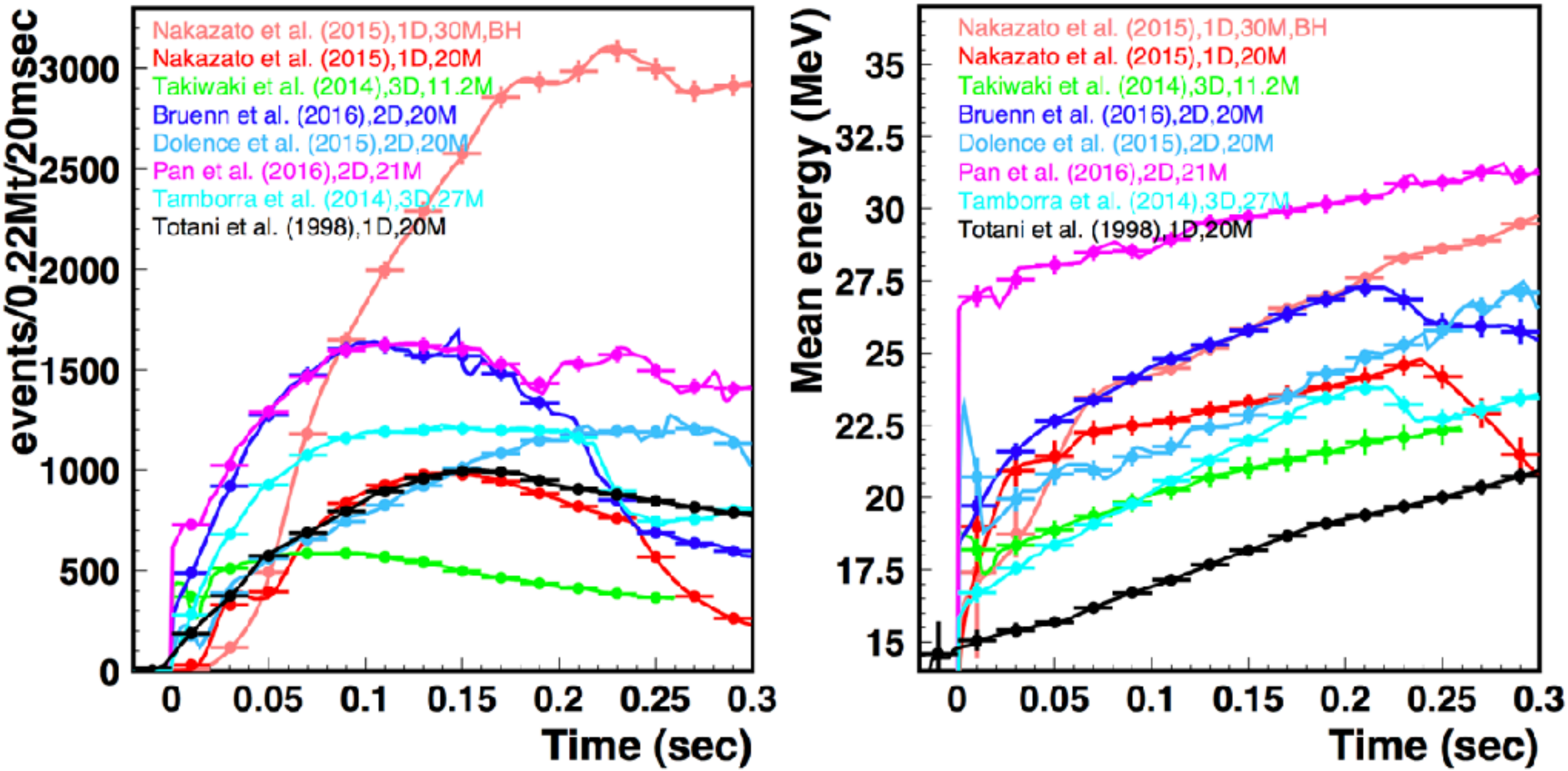
- **$\bar{\nu}_e$ + Oxygen CC:** same, but with custom fit parameters

Event generation

- **is fast:** In ~10 min, on my laptop …
  - 80k IBD events (1–1.5× SN@10kpc in 220kt)
  - 16k ES events (6–8×)
  - 200k ν_eO events (50–2500×)
  - 200k $\overline{\nu}_e$O events (50–300×)
- **is precise:**
  - IBD/ES cross-section: ~1% precision
  - ν+Oxygen CC: ~10% ???
  - still much smaller than the differences between SN models ➔ ➔ ➔



Comparison of Supernova Simulations



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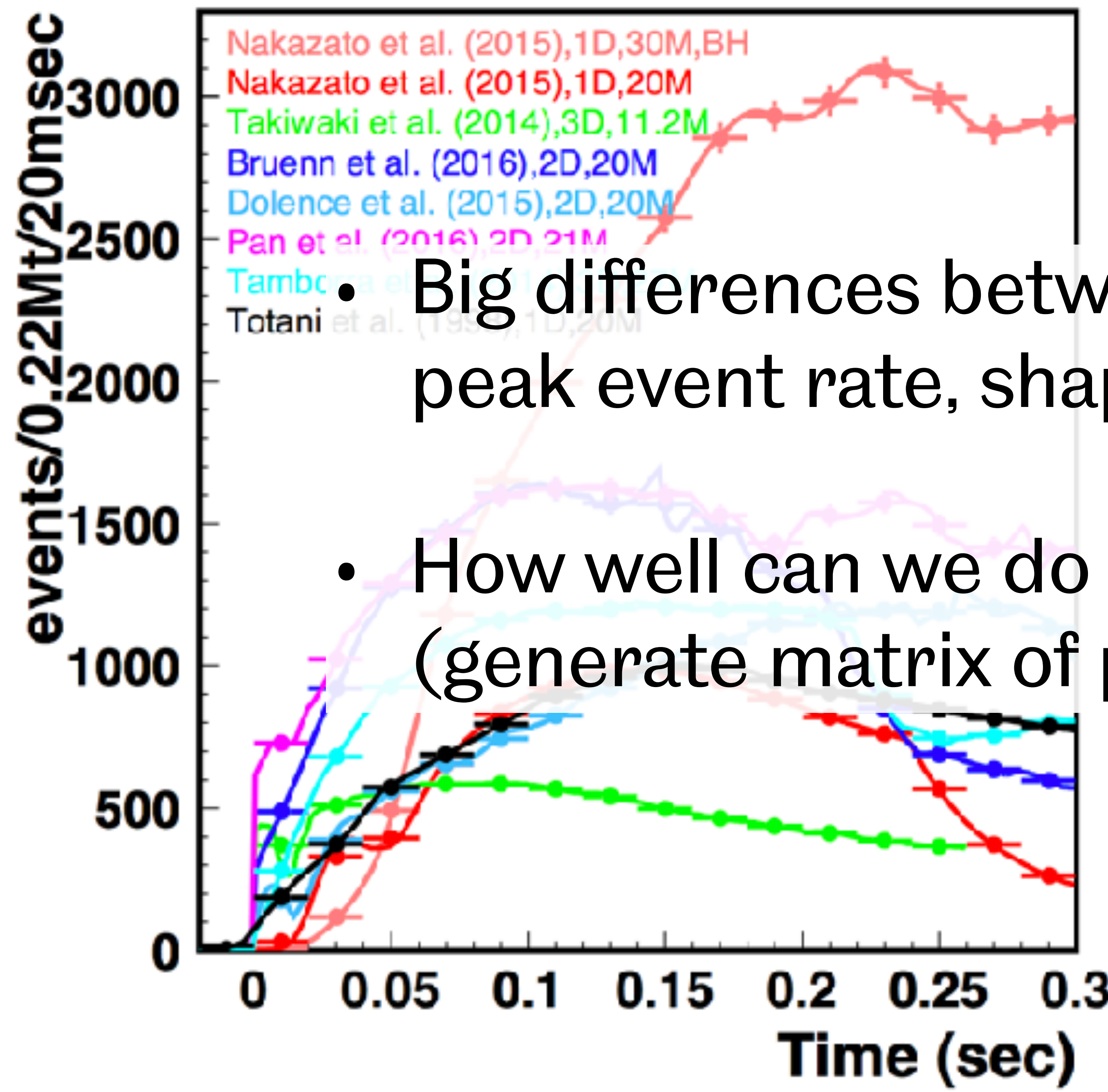
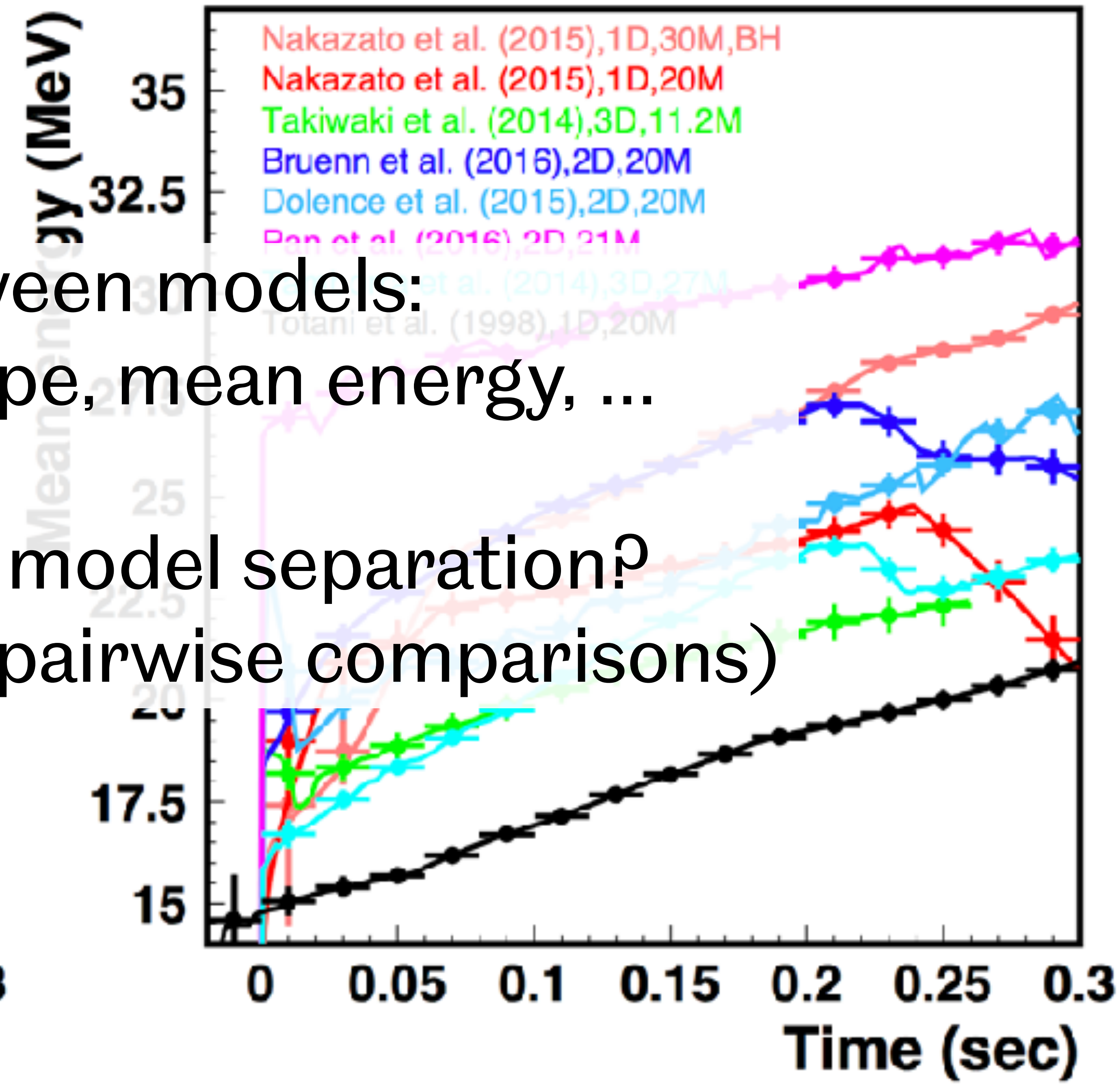




- Big differences between models: peak event rate, shape, mean energy, ...
- How well can we do model separation? (generate matrix of pairwise comparisons)

Summary

- Hyper-K is the next step in the very successful Japan-based neutrino research programme & will observe ~10^5 events from next galactic supernova.

- Developed a new supernova event generator that's
  - fast (<15 min to generate signal from a fiducial SN in 1 HK tank)
  - precise (~1% level for two main interaction channels)
  - modular & extensible (currently supports 4 interaction channels and 3 input formats, need just ~100 lines of code to add more)
  - open source (see `https://github.com/JostMigenda/sntools`)

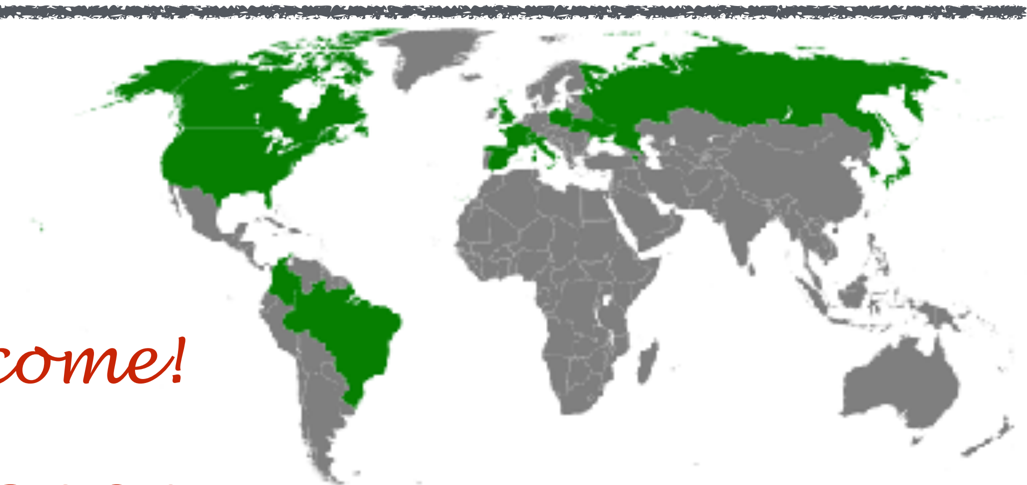
- Investigate model separation ability of Hyper-Kamiokande

Backup Slides

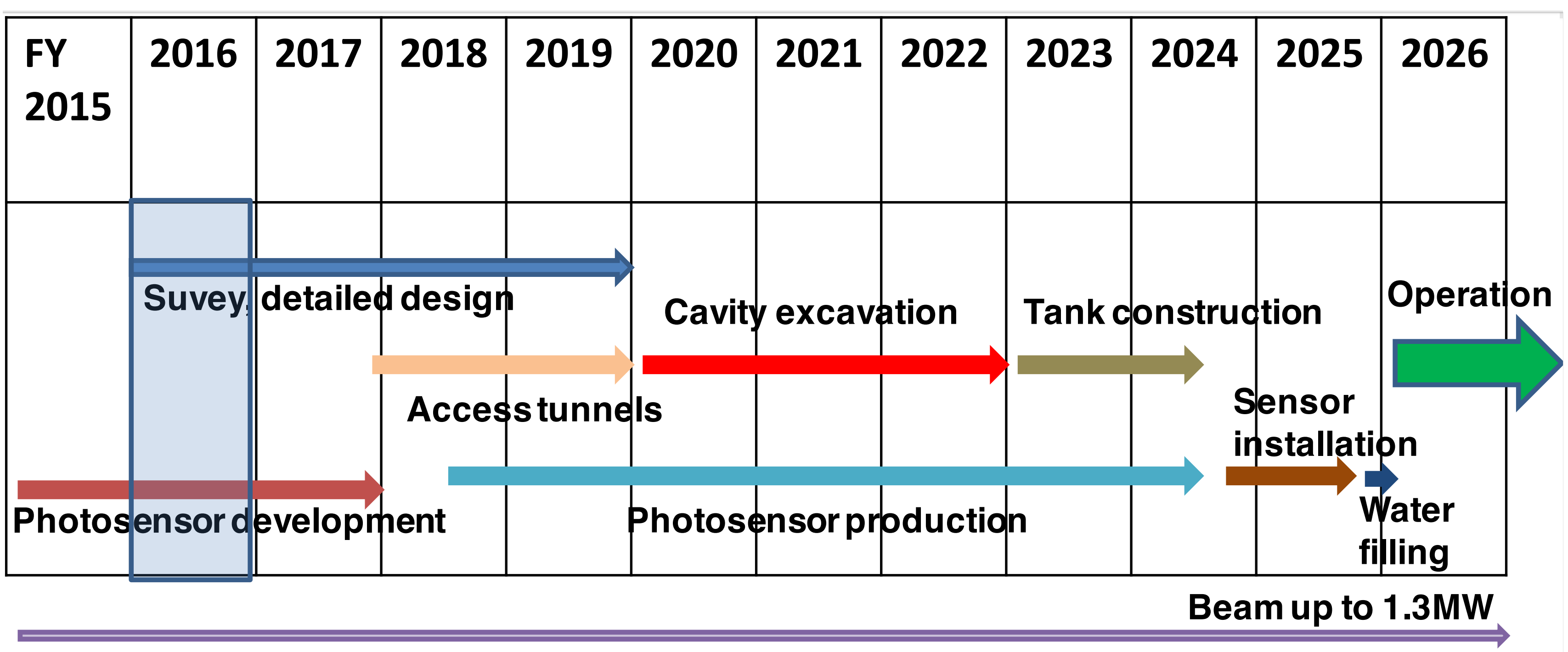
Status of Hyper-K

- Proto-Collaboration formed in 2015
  - now: 300 people in 15 countries

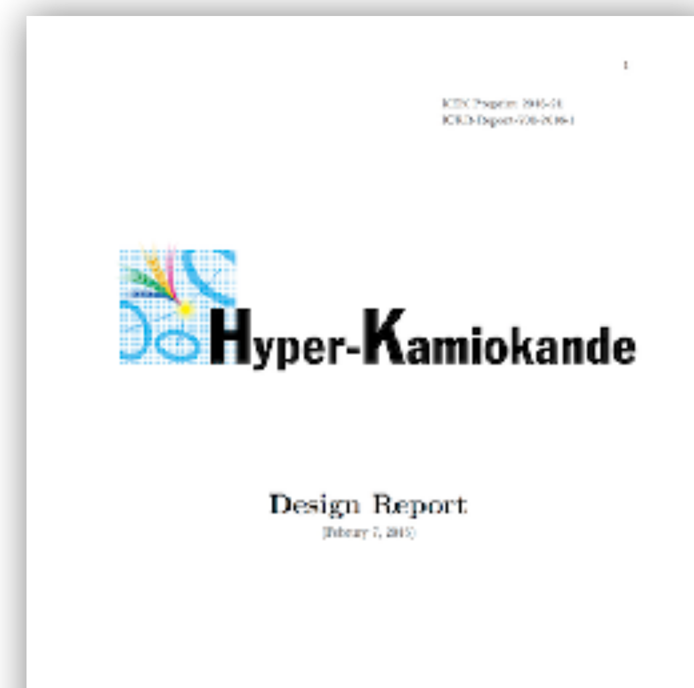
New members welcome!



- published Design Report and White Paper for 2nd tank in Korea in 2016



Timeline for 1st tank (2nd tank up to 6 years later)

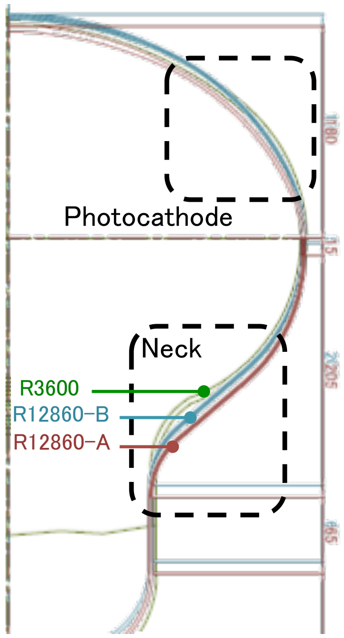


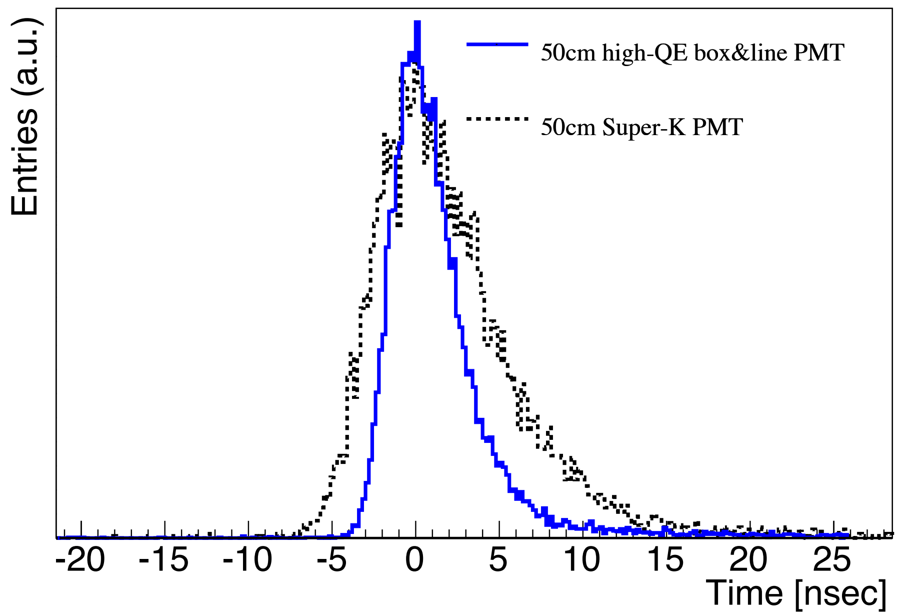
KEK Preprint 2016-21
ICRR-Report-701-2016-1

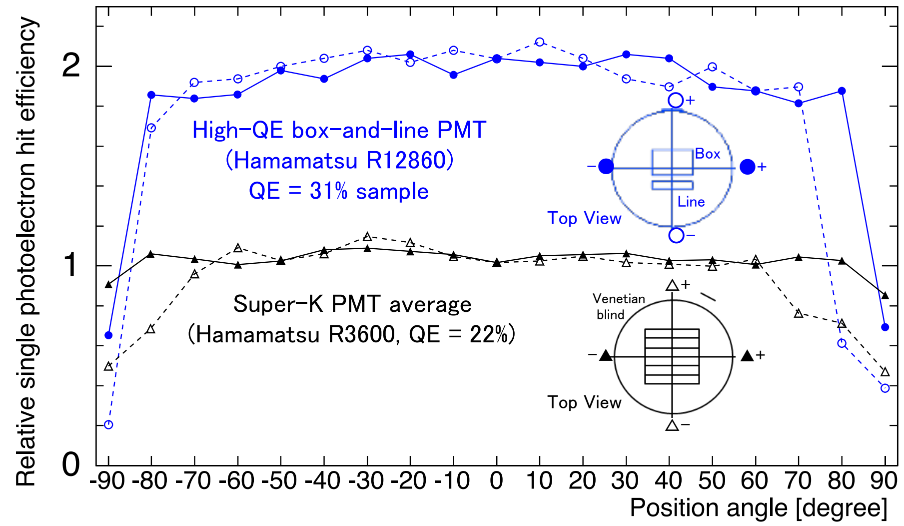
http://hyperk.org/?p=215

Changes for Low-E Physics

- lower overburden ➔ 2.7× higher spallation background
    - 2nd tank in Korea would 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. mPMTs – MoU with KM3NeT)
- build on experiences of SK-Gd







50cm PMT
Hamamatsu R12860