IceCube Supernova Detection and Contributions to SNEWS 2.0

Spencer Griswold

June 15, 2019

Department of Physics and Astronomy, University of Rochester, Rochester, NY, USA

The IceCube Neutrino Observatory

Supernova Detection at IceCube

SuperNova Data Acquisition - SNDAQ

Current & Future work

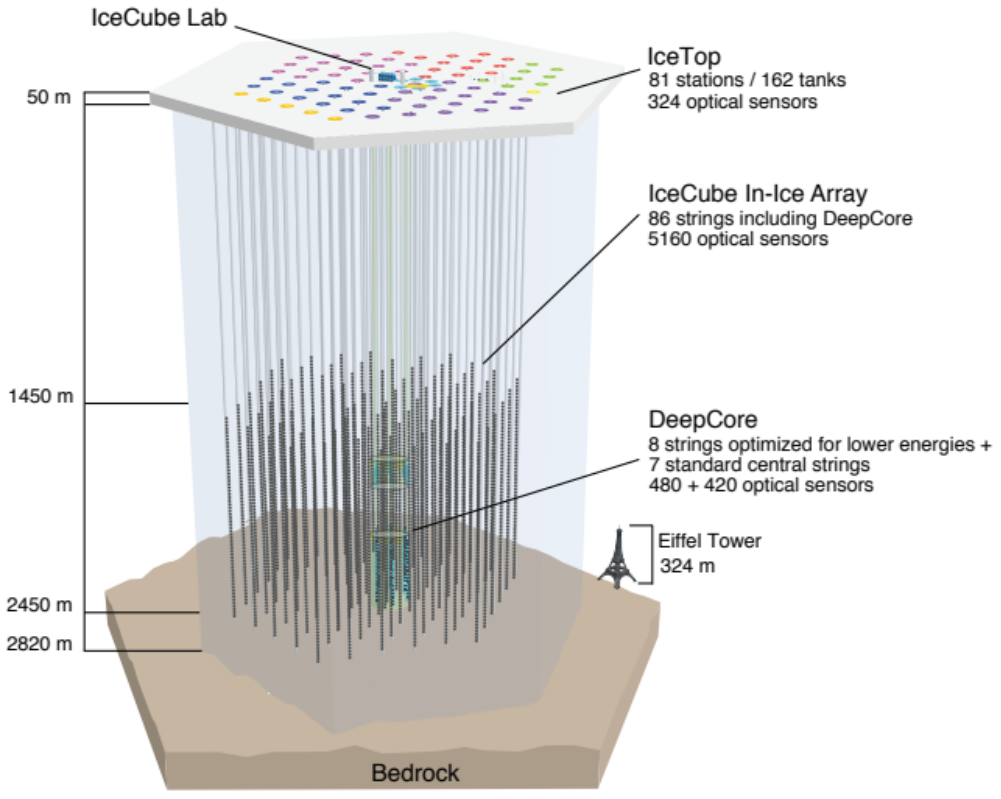
IceCube and SNEWS

Summary

The IceCube Neutrino Observatory

- IceCube instruments 1 km^3 (1 Gt) of the South Pole ice sheet
- Array of 5160 Digital Optical Modules (DOMs)
  - 86 strings, 125m apart
  - 60 DOMs/string, 17m vertical spacing
  - 1.5 $\sim$ 2.5 km below the surface
- Optimized for detection of $\mathcal{O}$(10 GeV) ν's
  - Significant background of down-going cosmic μ events

M.G. Aartsen et al 2017 JINST 12 P03012

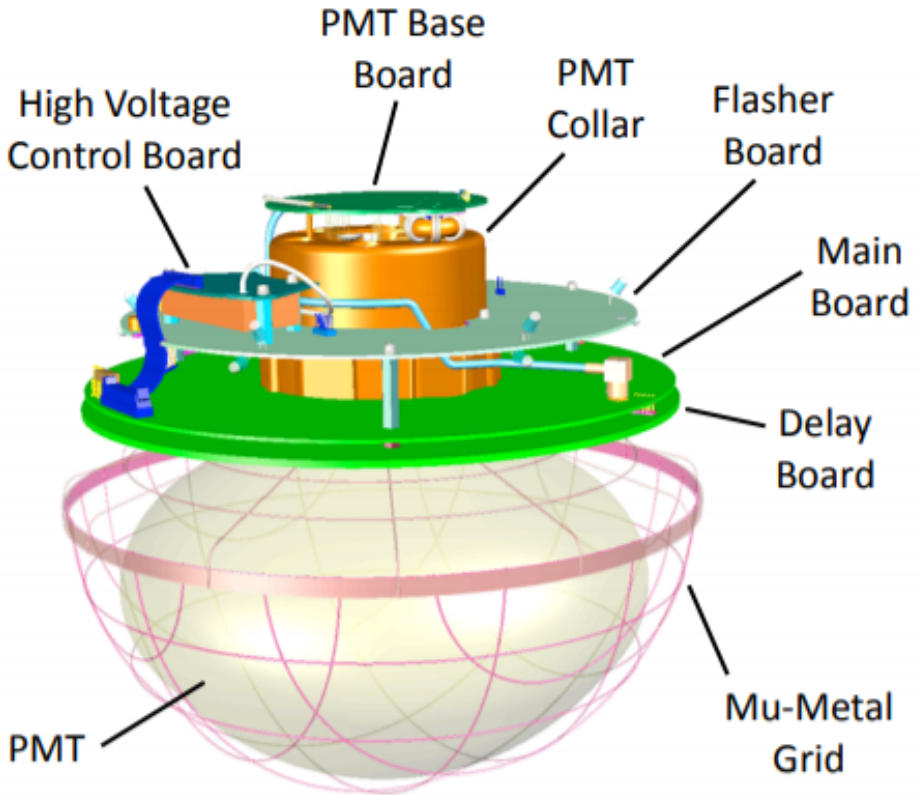


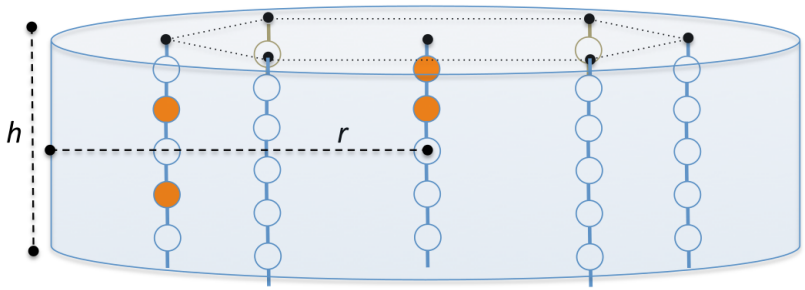
X

DOM Design

- Key features
  - **PMT**, facing downwards
  - **Flasher board LEDs** for calibrating the surrounding DOMS
  - **Glass sphere**, protecting against pressure and moisture
- 300 MHz and 25MHz digitization and FPGA rate scalers
- Simple multiplicity trigger based on coincident hits in groups of > 8 DOMs (SMT8)

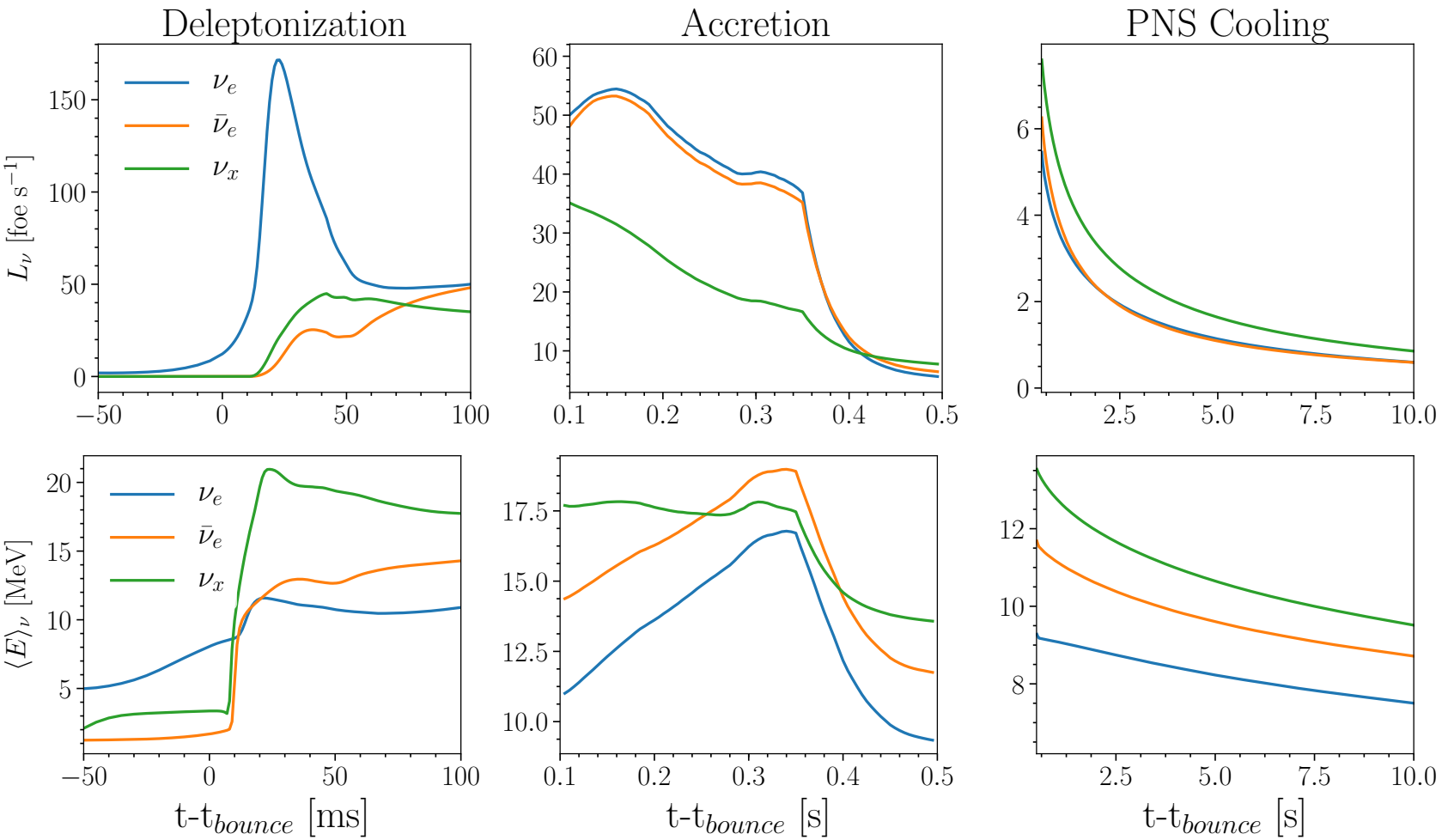
M.G. Aartsen et al 2017 JINST 12 P03012



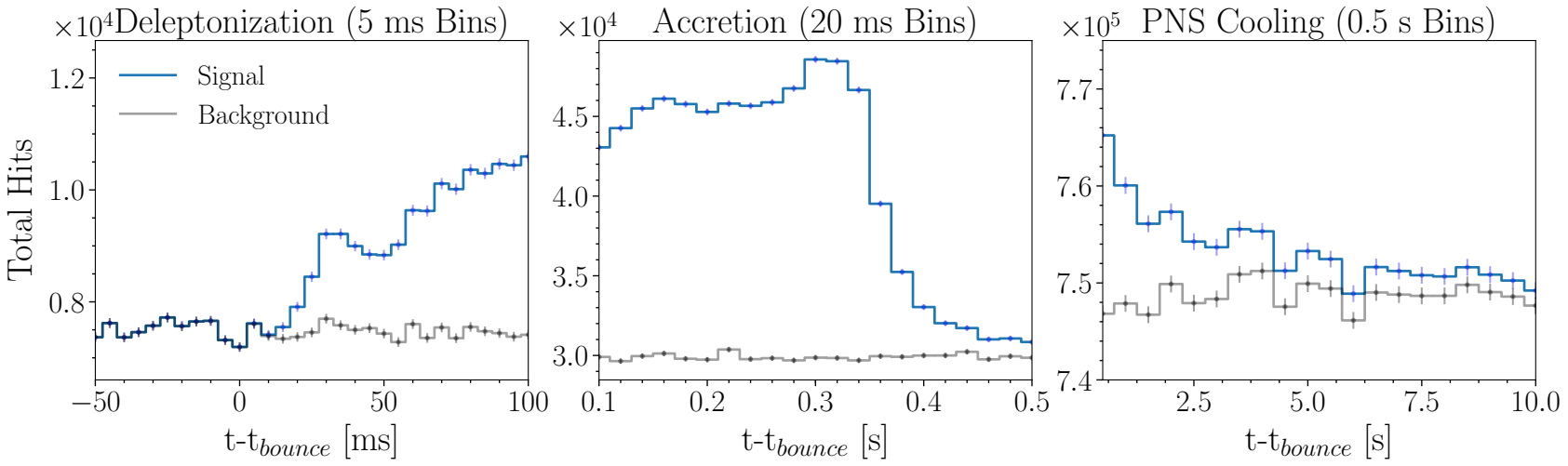


The Supernova Neutrino Signal in IceCube

- Using a model for a 13 $M_\odot$ progenitor at 10 kpc by Nakazato et. al



The Supernova Neutrino Signal in IceCube



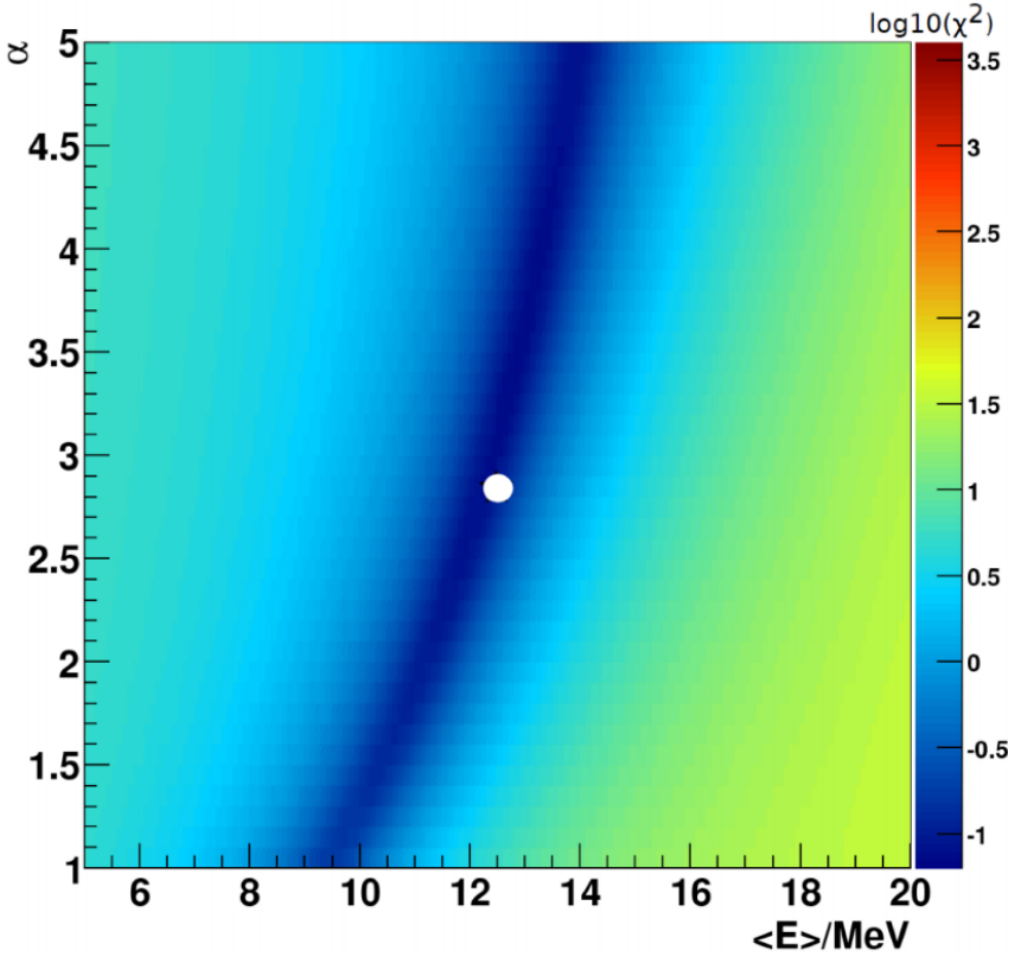
Performance:

1. High statistics measurements of the $\bar{\nu}_e$ light curve
2. Potential sensitivity to short time-scale phenomena
3. Using coincident hits, $\langle E_\nu \rangle$ can be estimated.

Current Sensitivity to $\langle E_\nu \rangle$

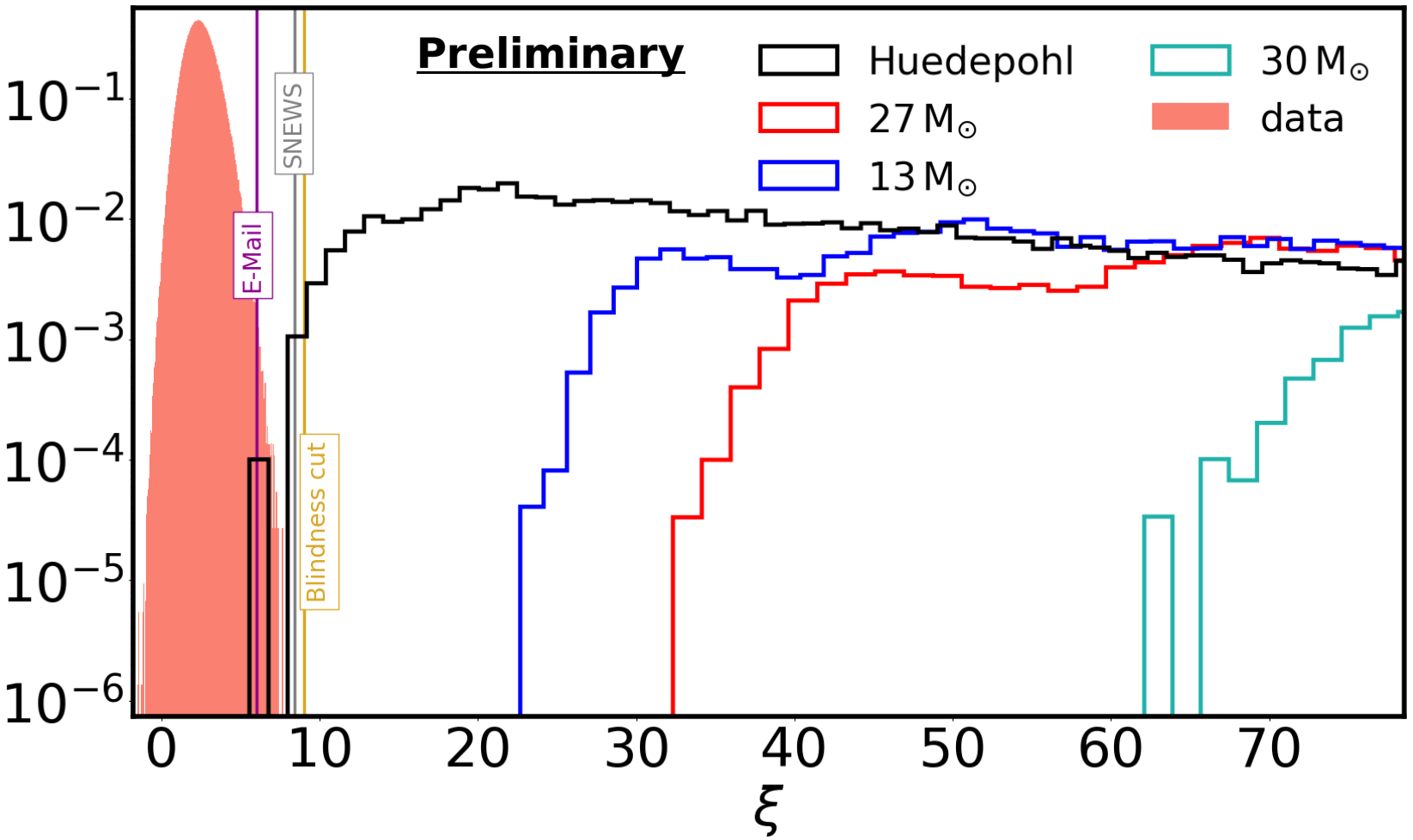
- Coincident hit distributions depend on the shape of the energy spectrum.
- χ^2 scan over $\langle E_\nu \rangle$ and α plane yields $\sigma(E_\nu)/\langle E_\nu \rangle \approx 30\%$
- Using a model for a $8.8 M_\odot$ progenitor at 10 kpc by Hüdepohl et. al
  - Initial Guess: $\langle E \rangle = 12.6$ MeV, $\alpha = 2.84$

L. Köpke, 8th Int. Symp. on Large TPCs (Dec. 2017)



IceCube SN Performance

From L. Köpke

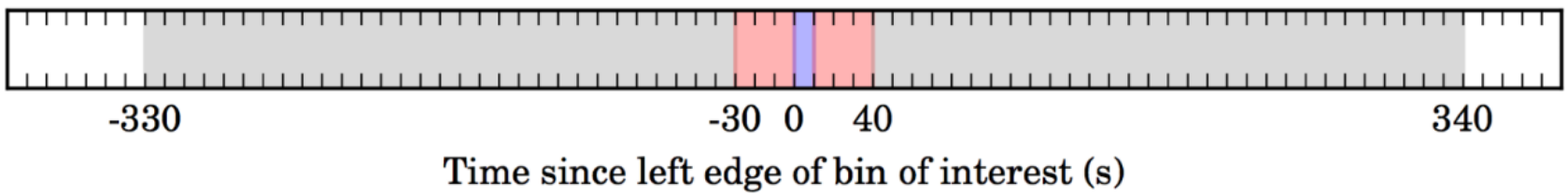


- For 4 progenitors, with randomly sampled distances, only the lightest has overlap with background.

Supernova Detection

- CCSN produce $\mathcal{O}(10\text{ MeV})\nu$'s
  - Too dim to trigger the SMT8
  - Will produce a correlated rise in the individual hit rates of the DOMs

From R. Cross, ICRC 2017



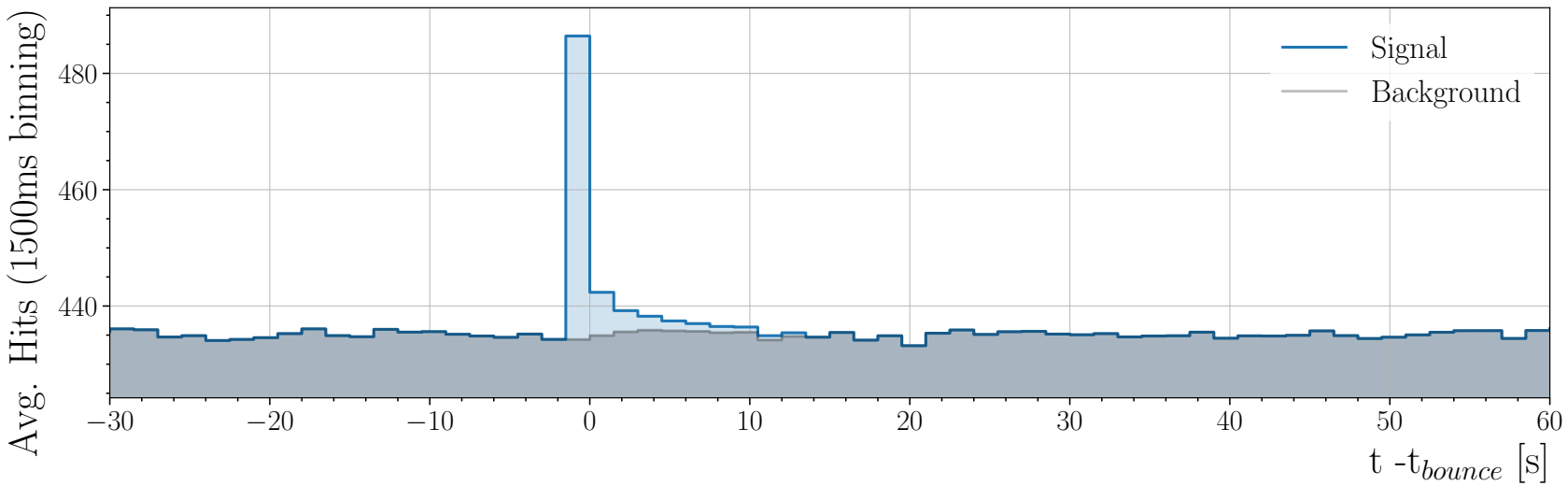
- SNDAQ: online software search correlated hit rates above background
  - Receives unprocessed data in 1.6384 ms bins, later rebinned to 2 ms
  - Searches binned to 0.5s, 1.5s, 4.0s, **10.0s** (Above)
  - Likelihood of excess correlated hits over background
  - Background estimated over $\sim$ 10-minute sliding interval

SNDAQ - Likelihood

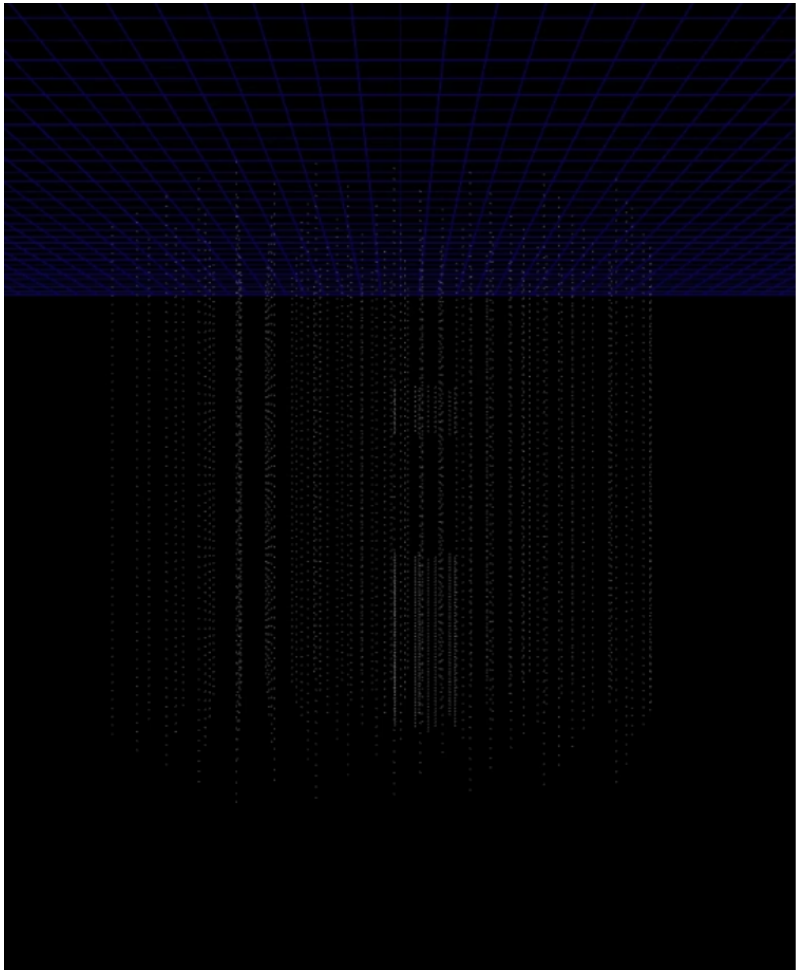
- SNDAQ sliding window maximum likelihood

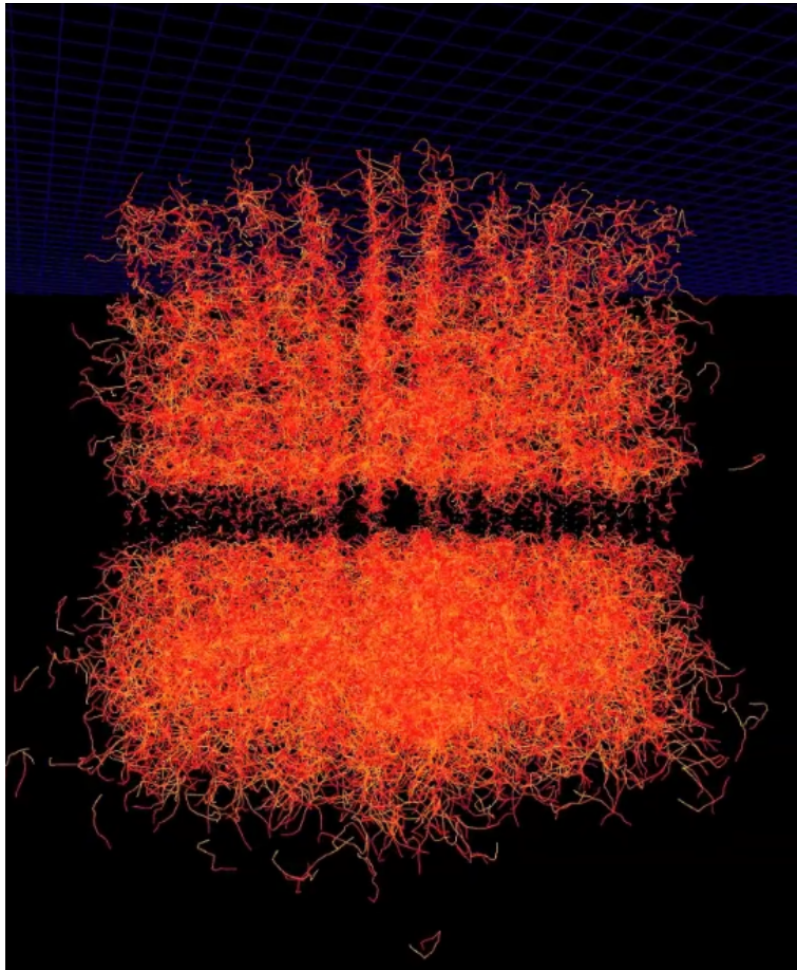
$$\ln \mathcal{L}(\Delta\mu) = \sum_{i=1}^{N_{DOM}} -\frac{\left[r_i - (\langle r_i \rangle + \varepsilon_i \Delta\mu)^2\right]}{2\langle\sigma_i\rangle^2} - \frac{1}{2}\ln 2\pi\langle\sigma_i\rangle^2$$

- r_i = count rate in DOM i
- σ_i = count rate uncertainty in DOM i
- ε_i = relative efficiency of DOM i
- $\Delta\mu$ = correlated increase in DOM rates across the full detector within sliding search window.



Supernova Event



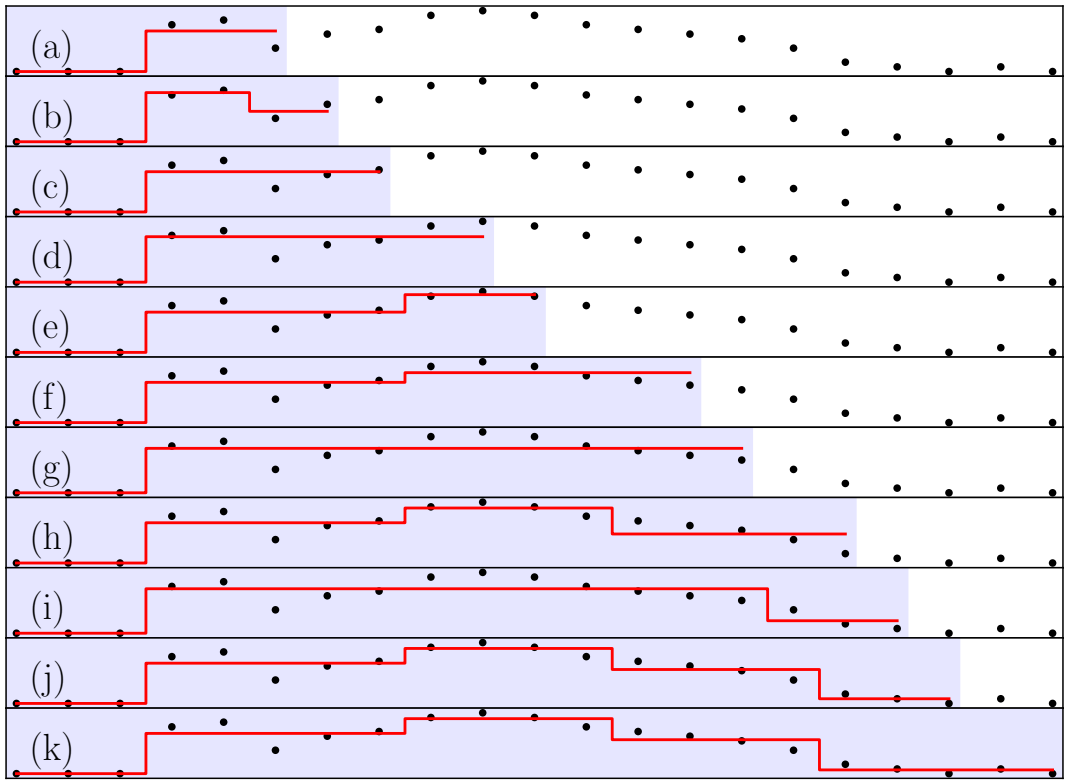


Bayesian Blocks

Let the data determine the optimal binning!

- SNDAQ Binning tuned to SN simulations and SN1987a.

From R. Cross, ICRC 2017



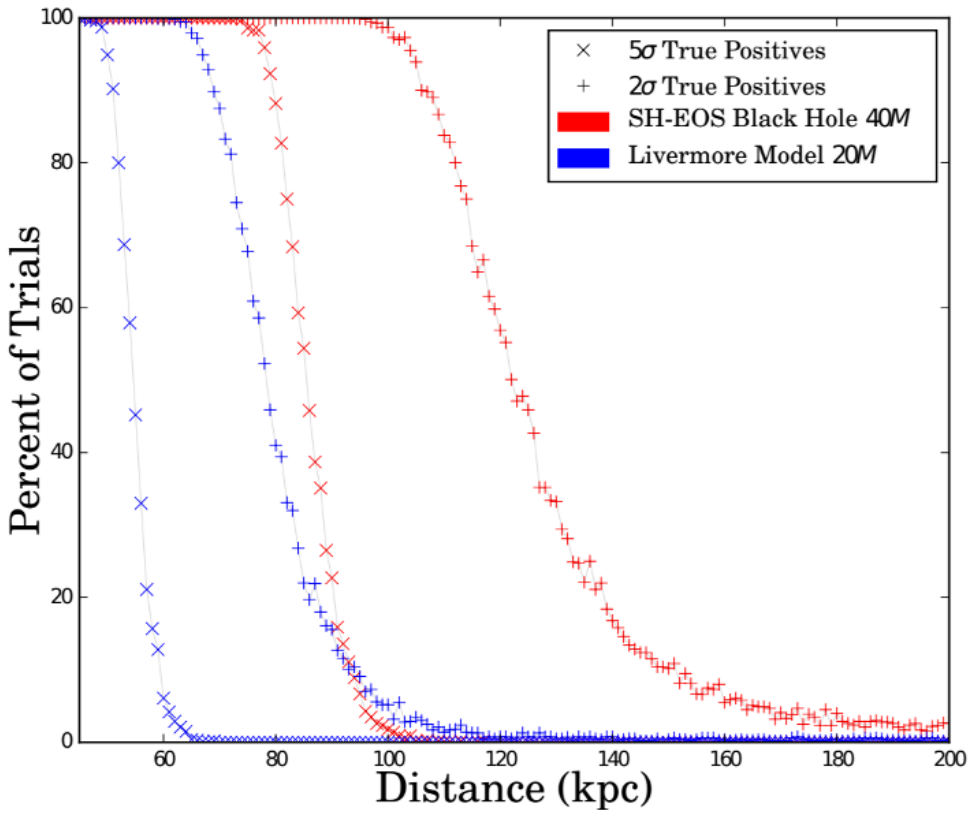
- Tune-able, sliding window for SNDAQ. Easy-to-optimize trade-off between sensitivity and false-positive rate

Bayesian Blocks

Let the data determine the optimal binning!

- SNDAQ Binning tuned to SN simulations and SN1987a.

From R. Cross, ICRC 2017

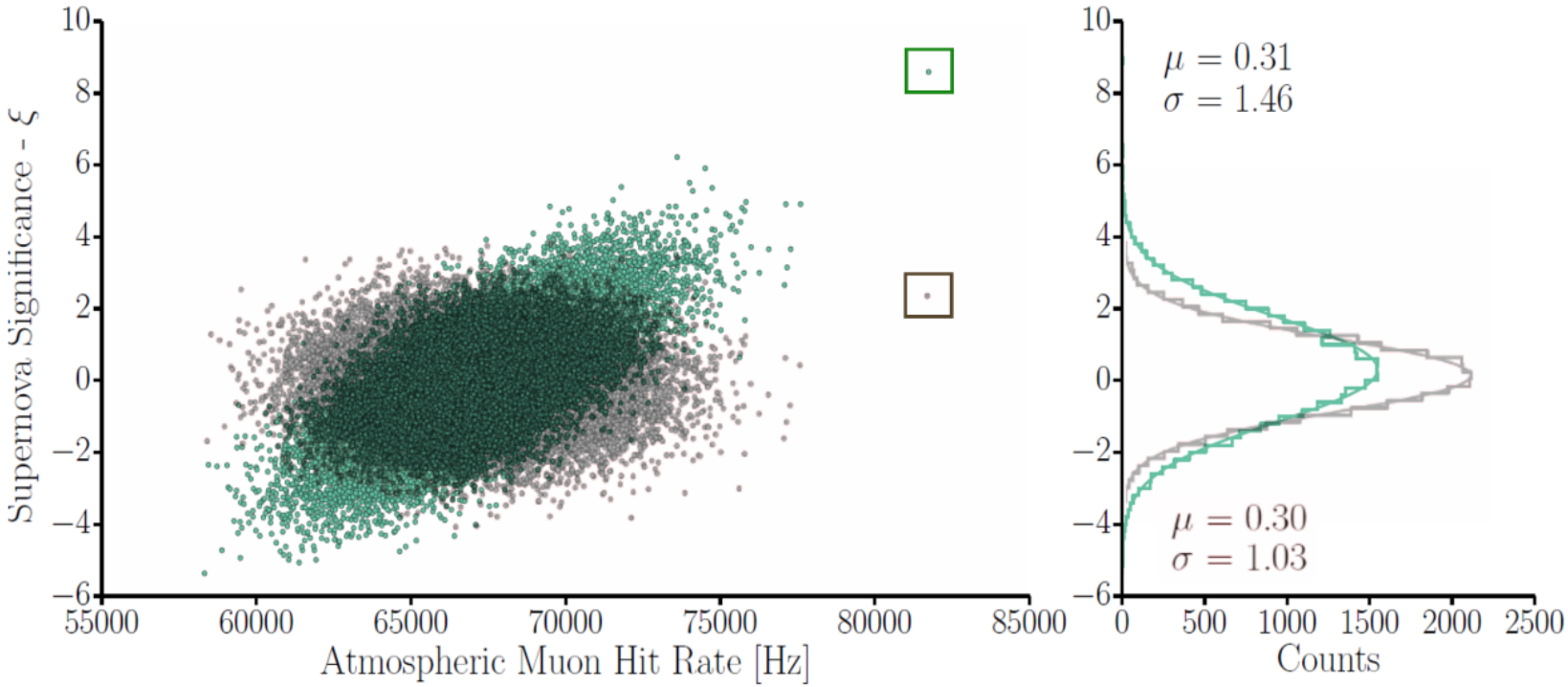


- Tune-able, sliding window for SNDAQ. Easy-to-optimize trade-off between sensitivity and false-positive rate

Atmospheric Muon Correction

- Depth dependent atmospheric muon rate (3-30Hz)
- Causes seasonal dependence in SNDAQ test statistic $\xi = \Delta\mu/\sigma_{\Delta\mu}$
- Main DAQ provides SMT8 rate; correlation with ξ is zeroed out.

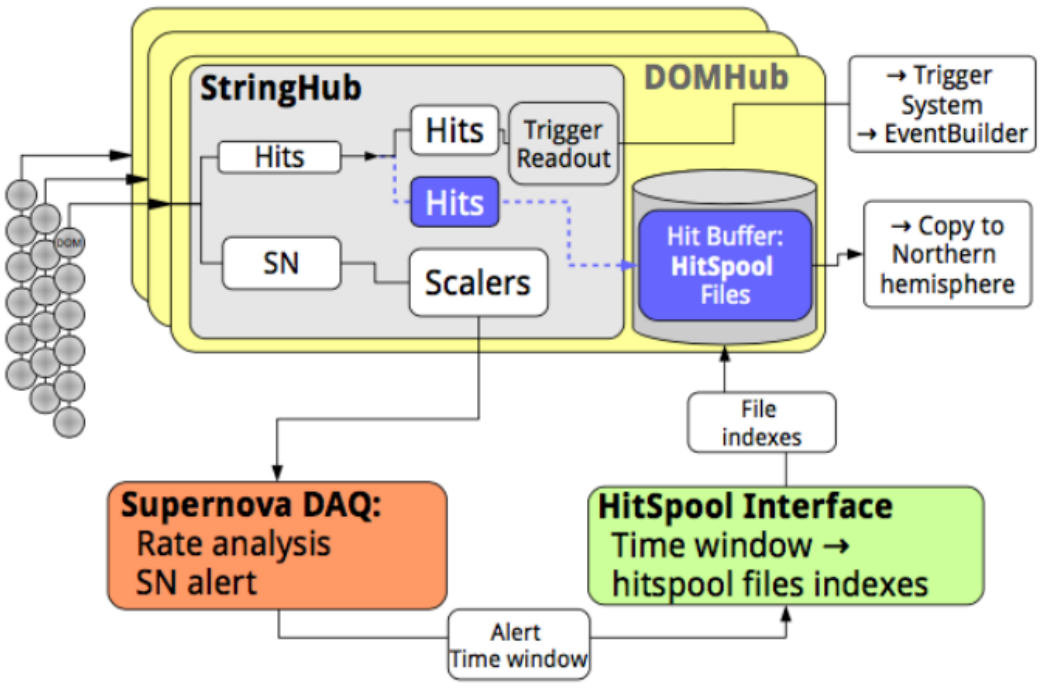
From B. Volker, ICRC 2015



HitSpool

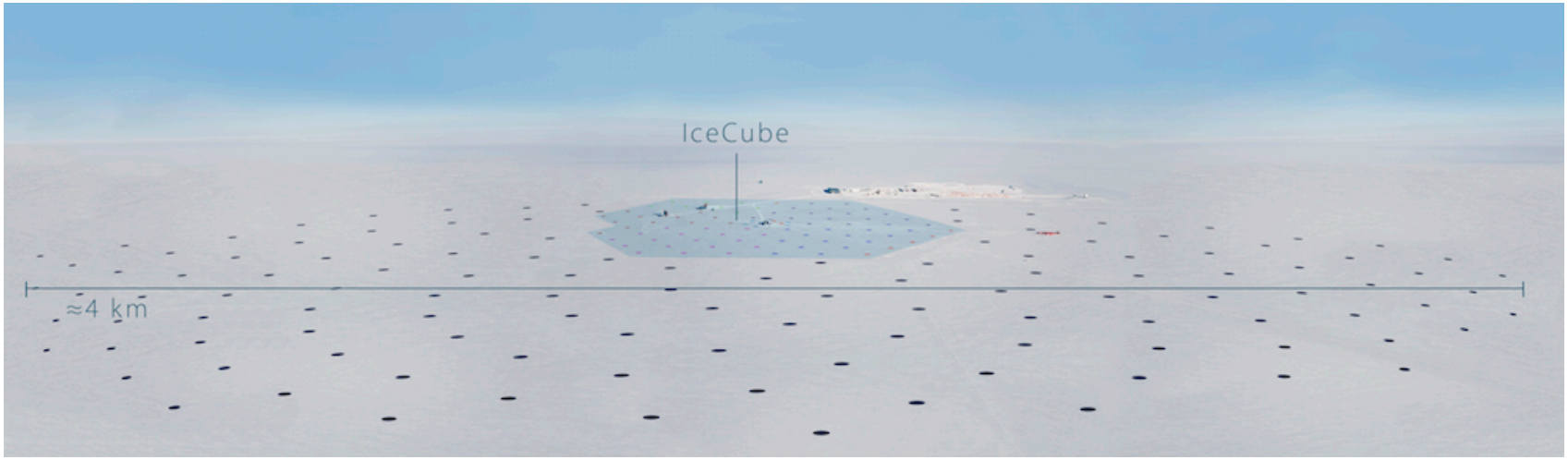
HitSpool: Online system for storing and accessing raw DOM waveforms.

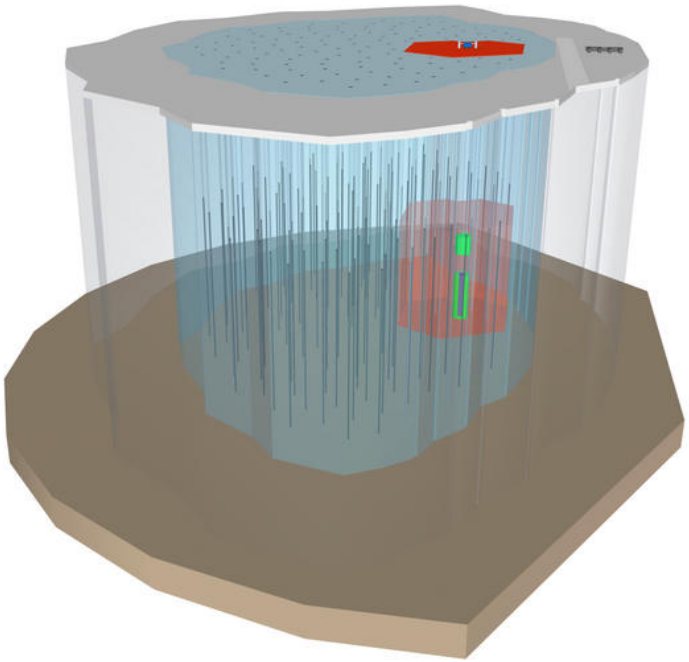
From D. Heereman (Ph.D. thesis, 2015)



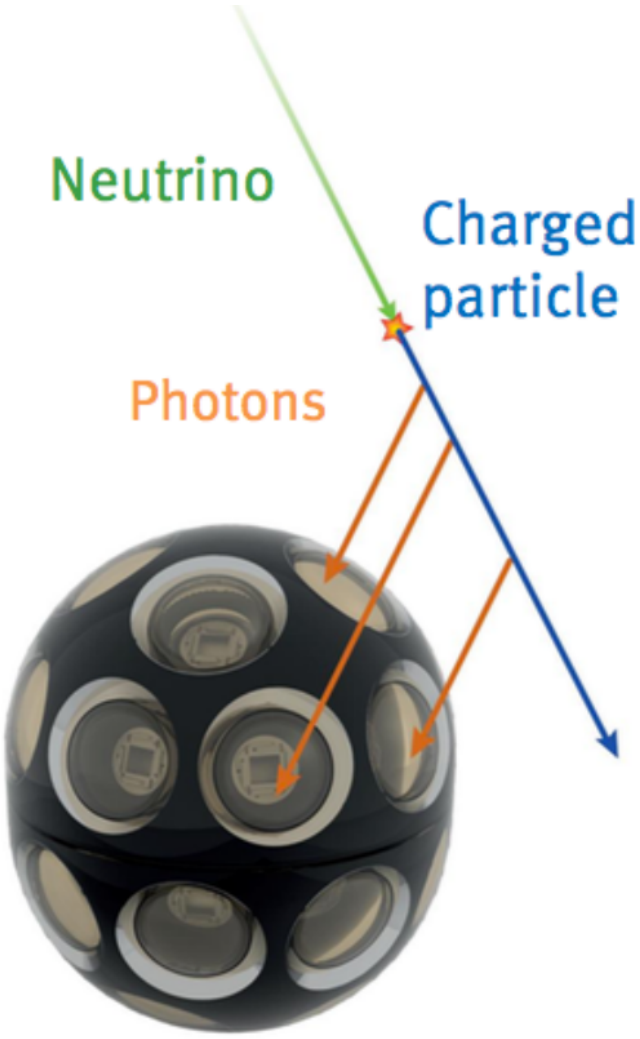
- SNDAQ retrieves SN Candidate data from HitSpool Buffer.
  - Not limited to the 2 ms resolution of SNDAQ!
- Useful general tool for handling raw data – LVC HitSpool requests

IceCube Gen2 Upgrade





IceCube Gen2 Hardware



Multi-PMT optical Module (mDOM)

- 24× 3” PMTs (Larger area)
- 4π acceptance
- Single-mDOM local coincidence
- Sensitivity to low energy ν

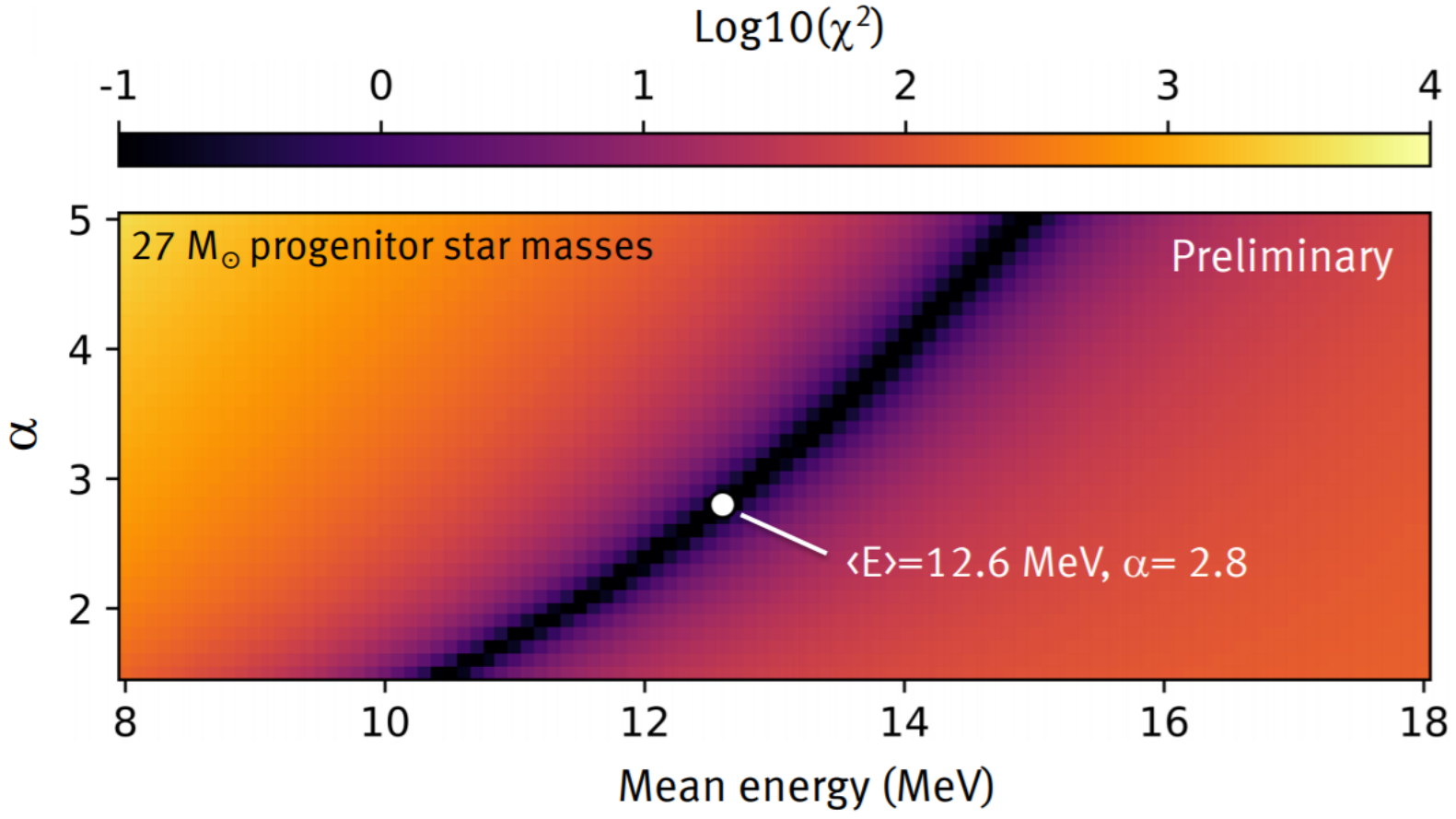
Multiple other OM designs (e.g. WOM)

From C. Lozano, Neutrino 2018

n_{coinc}	N_ν	False SN rate (yr^{-1})	d [kpc] for 50% SN detection $27M_\odot$ ($9.6M_\odot$)
≥5	51	1.7	177 (109)
≥5	55	0.04	170 (105)
≥6	7	3.3	323 (193)
≥6	**9**	**<0.001**	**286 (171)**

mDOM Sensitivity to SN $\langle E_\nu \rangle$

From C. Lozano, Neutrino 2018

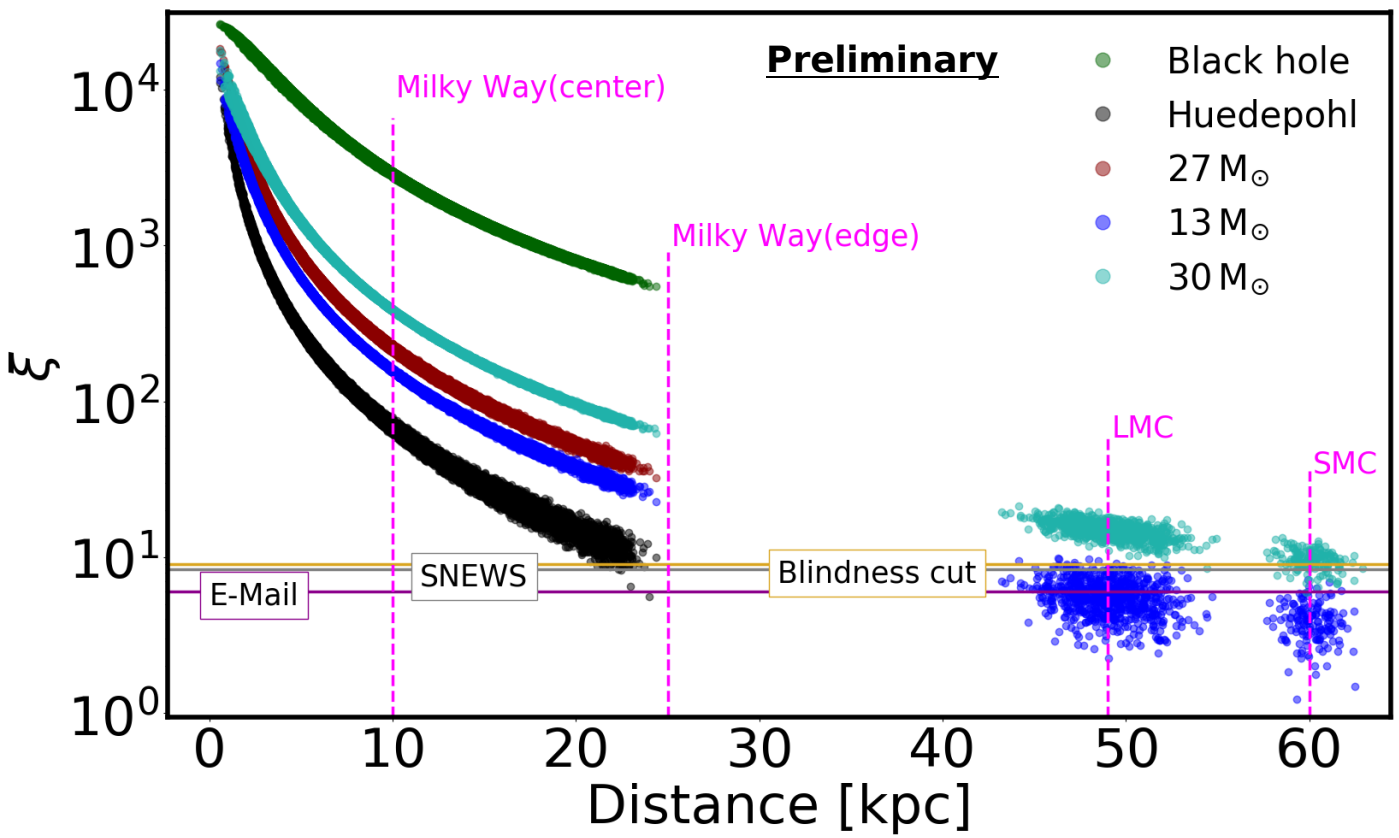


- Simulation of SN at 10 kpc with 27 $M_\odot$ Background
- χ^2 scan over $\langle E_\nu \rangle$ and α plane yields $\sigma(E_\nu)/\langle E_\nu \rangle \leq 5\%$
  - Recall, current hardware yields $\sigma(E_\nu)/\langle E_\nu \rangle \approx 30\%$

IceCube and SNEWS

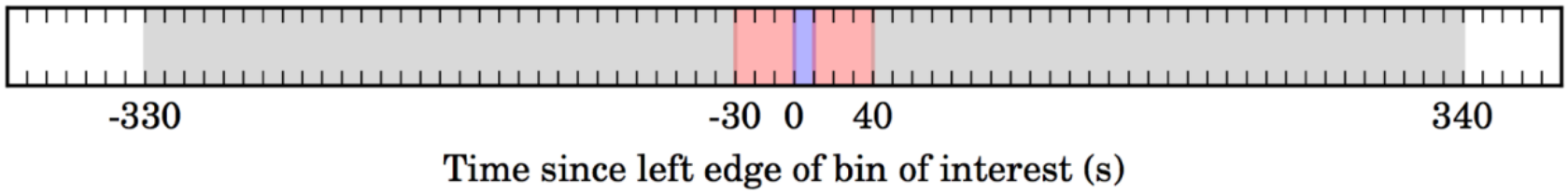
- Currently, we send significance ξ and time of alerts.
- Lowering the alert threshold could provide a trigger for a new low threshold SNEWS network.
  - Also for data pipeline tests.

From L. Köpke



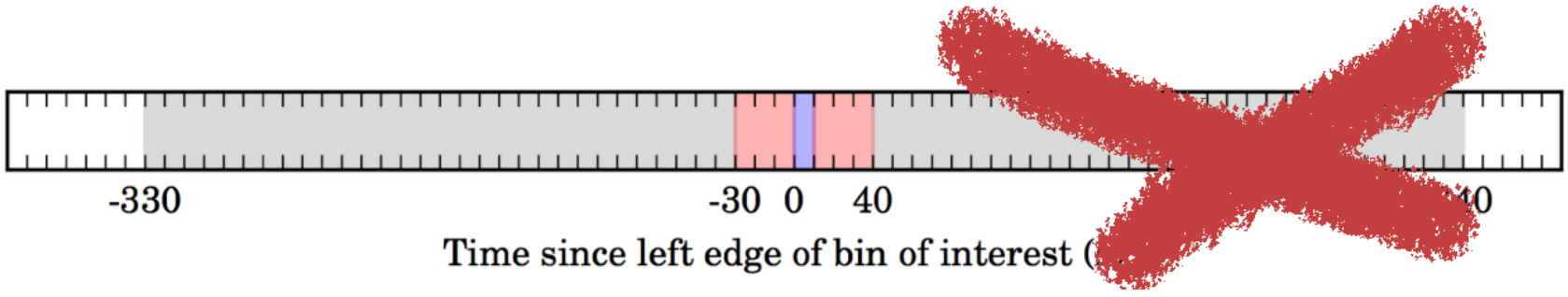
IceCube and SNEWS

- Alert latency of ∼7 min is due mainly to symmetric search window

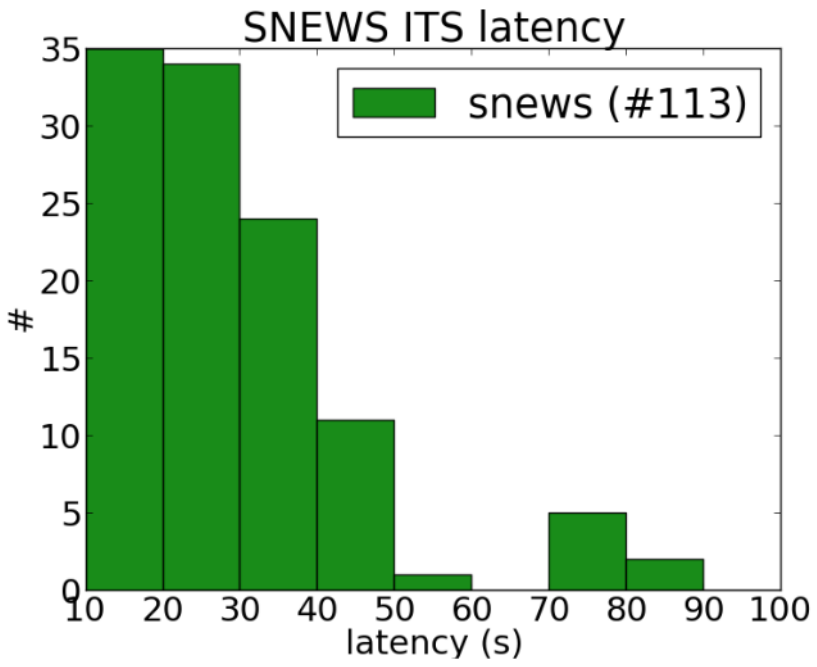


IceCube and SNEWS

- Alert latency of ∼7 min is due mainly to symmetric search window



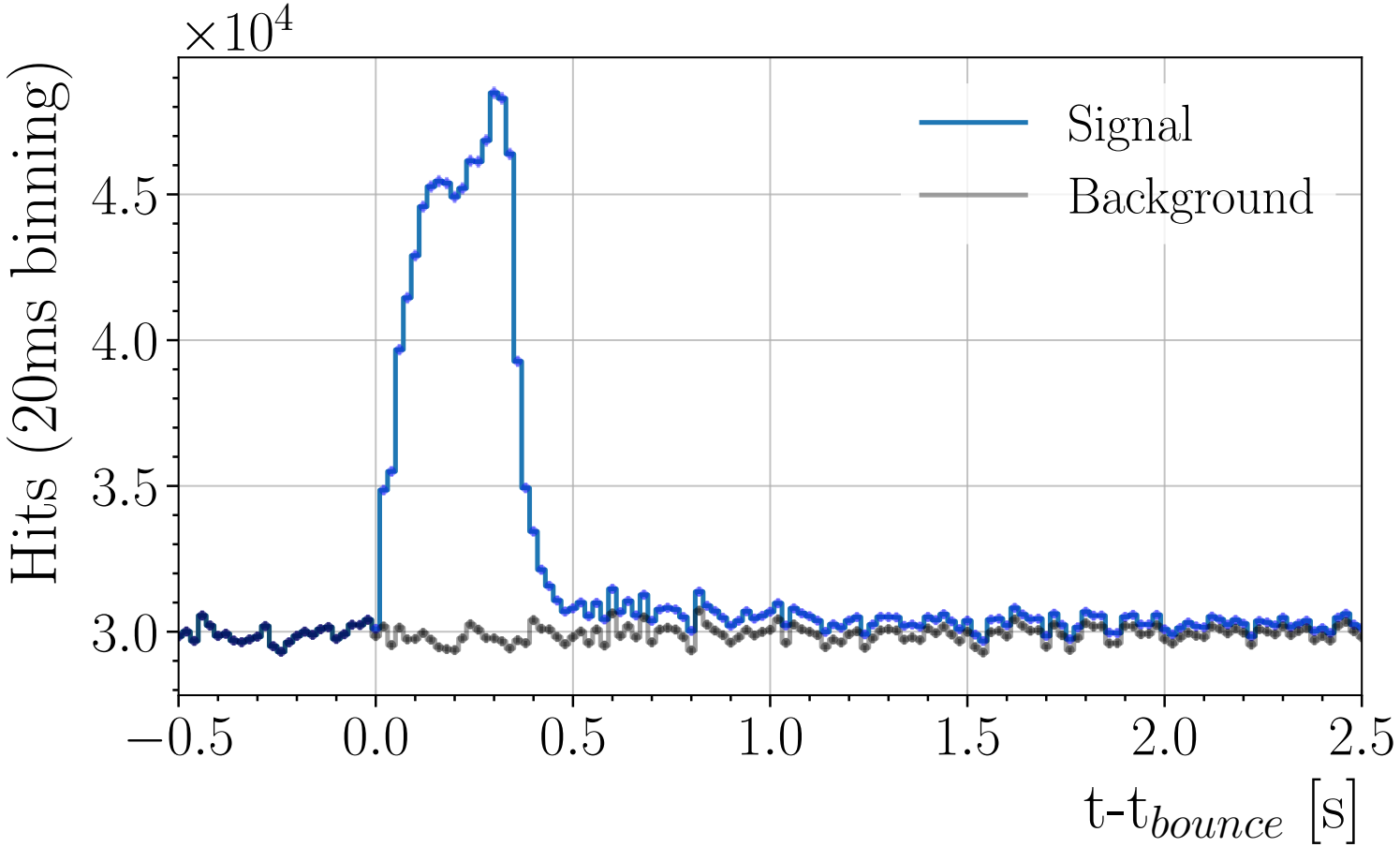
- *Why not use an asymmetric window?*
- Latency with SNEWS is reducible to ∼ 2 min



From B. Eberhardt, (Ph.D. thesis, 2017)

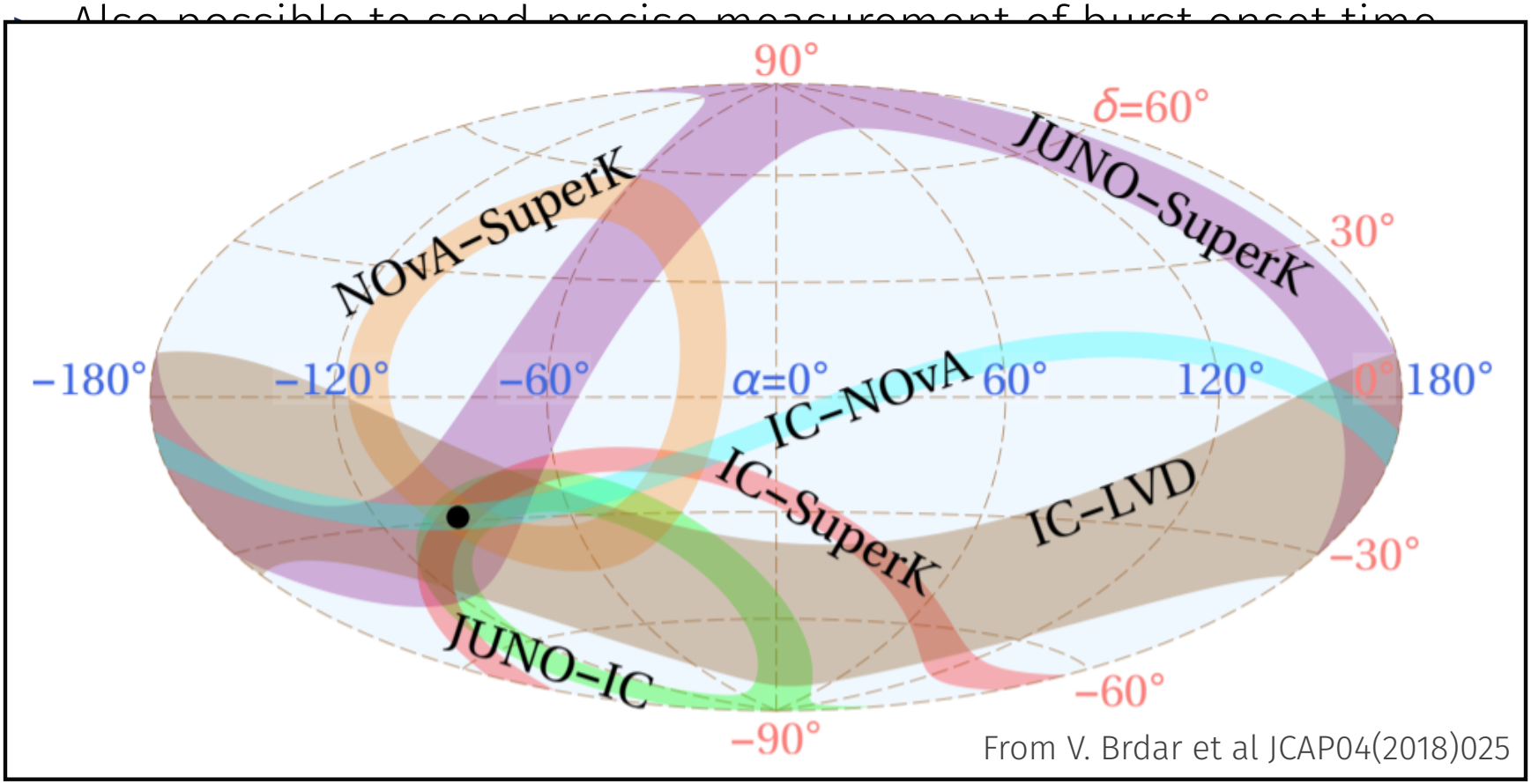
IceCube and SNEWS

- Technically easy to share light curves, but a M.o.U. is required.
  - Light curves (2ms binning) for triangulation
  - Raw waveforms available after $\sim 3 - 4$ days
  - Directional information from mDOMs (Eventually)
- Also possible to send precise measurement of burst onset time.



IceCube and SNEWS

- Technically easy to share light curves, but a M.o.U. is required.
  - Light curves (2ms binning) for triangulation
  - Raw waveforms available after $\sim 3 - 4$ days
  - Directional information from mDOMs (Eventually)
- Also possible to send precise measurement of burst onset time



From V. Brdar et al JCAP04(2018)025

Summary

1. IceCube has the largest effective volume for SN neutrino detection
   - For a CCSN, will provide high statistics measurement of $\bar{\nu}_e$ light curve
   - High chance of detection (80%) in the LMC, SMC
   - Some sensitivity to $\langle E_\nu \rangle$ (30% resolution)

2. Software improvements
   - HitSpool – Reduce limitations from time binning
   - Muon Correction – Reduce the effect of cosmic rays
   - Bayesian Blocks – reduce model dependence of online trigger

3. Improvements to Hardware, specifically the mDOM, will substantially improve background reduction and sensitivity to $\langle E_\nu \rangle$

4. A variety of data could be sent to SNEWS with little technical effort, but a detailed M.o.U. is required

Summary

1. IceCube has the largest effective volume for SN neutrino detection
   - For a CCSN, will provide high statistics measurement of $\bar{\nu}_e$ light curve
   - High chance of detection (80%) in the LMC, SMC
   - Some sensitivity to $\langle E_\nu \rangle$ (30% resolution)

2. Software improvements
   - HitSpool – Reduce limitations from time binning
   - Muon Correction – Reduce the effect of cosmic rays
   - Bayesian Blocks – reduce model dependence of online trigger

3. Improvements to Hardware, specifically the mDOM, will substantially improve background reduction and sensitivity to $\langle E_\nu \rangle$

4. A variety of data could be sent to SNEWS with little technical effort, but a detailed M.o.U. is required

Summary

1. IceCube has the largest effective volume for SN neutrino detection
   - For a CCSN, will provide high statistics measurement of $\bar{\nu}_e$ light curve
   - High chance of detection (80%) in the LMC, SMC
   - Some sensitivity to $\langle E_\nu \rangle$ (30% resolution)

2. Software improvements
   - HitSpool – Reduce limitations from time binning
   - Muon Correction – Reduce the effect of cosmic rays
   - Bayesian Blocks – reduce model dependence of online trigger

3. Improvements to Hardware, specifically the mDOM, will substantially improve background reduction and sensitivity to $\langle E_\nu \rangle$

4. A variety of data could be sent to SNEWS with little technical effort, but a detailed M.o.U. is required

Summary

1. IceCube has the largest effective volume for SN neutrino detection
   - For a CCSN, will provide high statistics measurement of $\bar{\nu}_e$ light curve
   - High chance of detection (80%) in the LMC, SMC
   - Some sensitivity to $\langle E_\nu \rangle$ (30% resolution)

2. Software improvements
   - HitSpool – Reduce limitations from time binning
   - Muon Correction – Reduce the effect of cosmic rays
   - Bayesian Blocks – reduce model dependence of online trigger

3. Improvements to Hardware, specifically the mDOM, will substantially improve background reduction and sensitivity to $\langle E_\nu \rangle$

4. A variety of data could be sent to SNEWS with little technical effort, but a detailed M.o.U. is required

Summary

1. IceCube has the largest effective volume for SN neutrino detection
   - For a CCSN, will provide high statistics measurement of $\bar{\nu}_e$ light curve
   - High chance of detection (80%) in the LMC, SMC
   - Some sensitivity to $\langle E_\nu \rangle$ (30% resolution)

2. Software improvements
   - HitSpool – Reduce limitations from time binning
   - Muon Correction – Reduce the effect of cosmic rays
   - Bayesian Blocks – reduce model dependence of online trigger

3. Improvements to Hardware, specifically the mDOM, will substantially improve background reduction and sensitivity to $\langle E_\nu \rangle$

4. A variety of data could be sent to SNEWS with little technical effort, but a detailed M.o.U. is required

Thank You

—

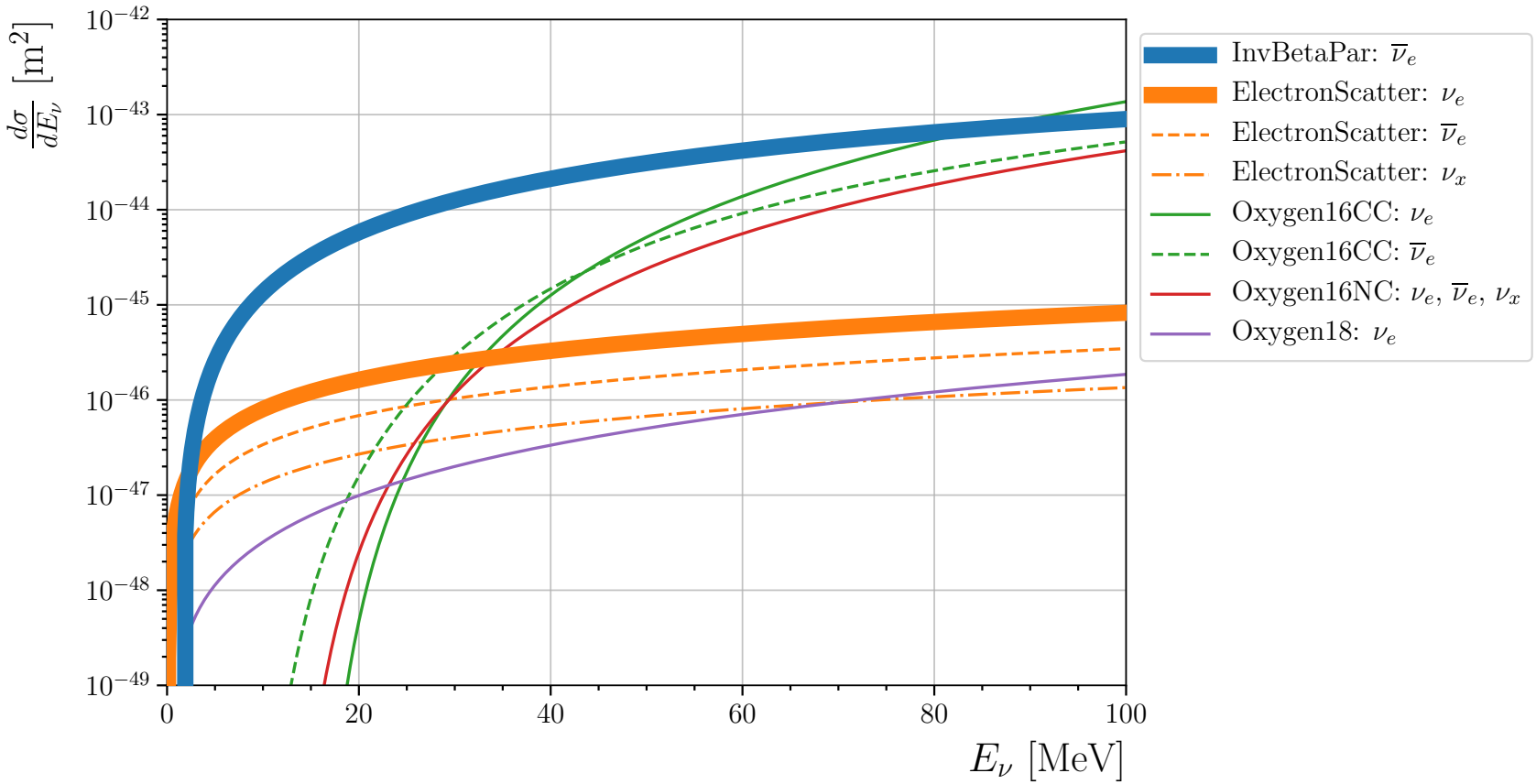
Questions?

Neutrino Interactions

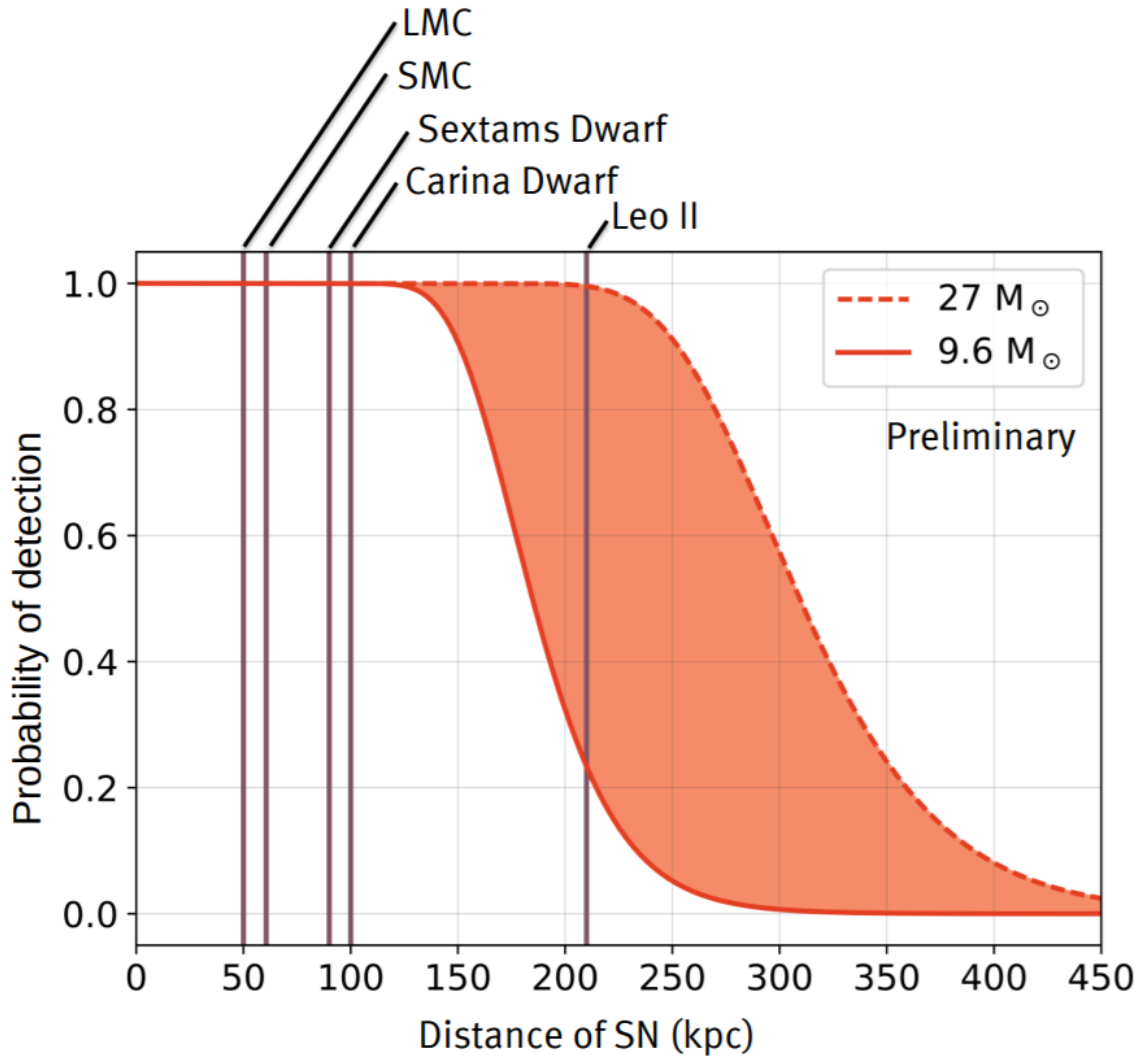
- The primary supernova neutrino signals in IceCube are

$$\bar{\nu}_e + p \rightarrow n + e^+ (\sim \mathbf{94\%})$$

$$\nu_e + e^- \rightarrow \nu_e + e^- (\sim \mathbf{2\%})$$



IceCube Gen2 Extra-galactic SNe Detection



From C. Lozano, Neutrino 2018

- Simulated detector with 10,000 mDOMs, using $n_{coinc} \geq 6$, $N_\nu = 9$
- 50% chance of SN detection for $27M_\odot (9.6M_\odot)$ at 309 (185) kpc