Topic formerly known as “triangulation”

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1 June 2023
SNνD @ LNGS

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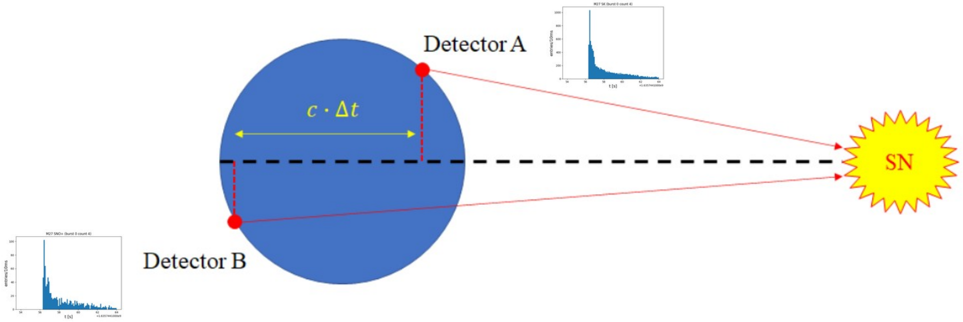
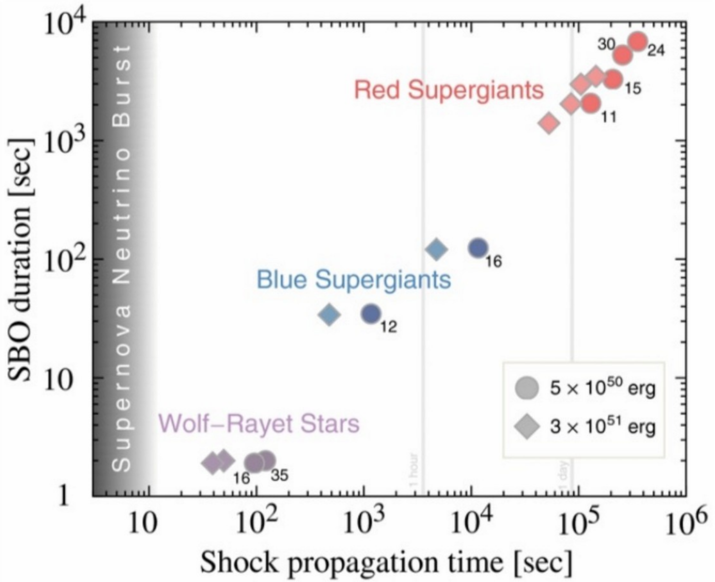
Triangulation

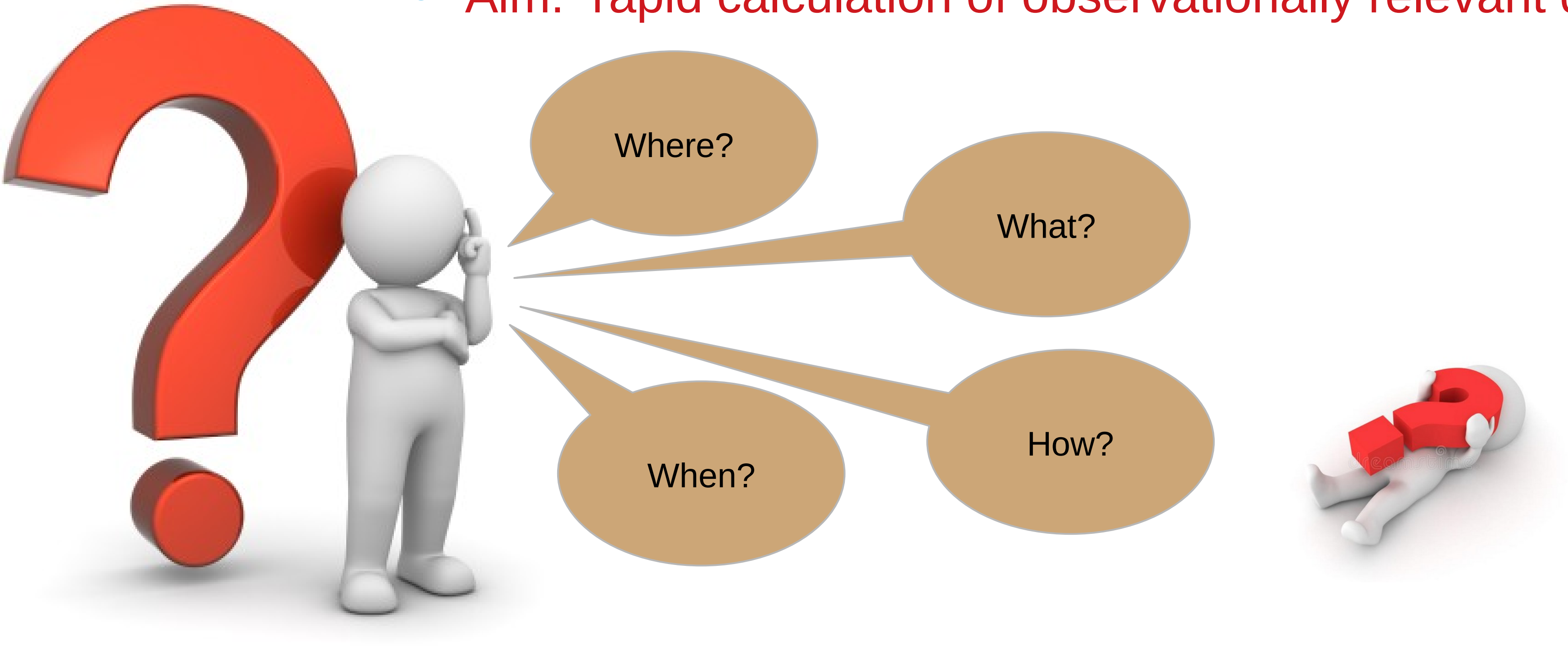




- Simple geometric problem: neutrino burst arrives at different times at different detectors
  - Maximum time difference ~40ms
- Very fast pointing back to supernova
  - Generally expect not as good as directional events, e.g., electron elastic scatters
  - Timescale: Super-Kamiokande pointing in ~3.5min [see Takeda, this conference]
  - Redundant over individual detector downtimes

Pointing+

- Pointing is not the only useful information we can glean
- Aim: rapid calculation of observationally relevant quantities

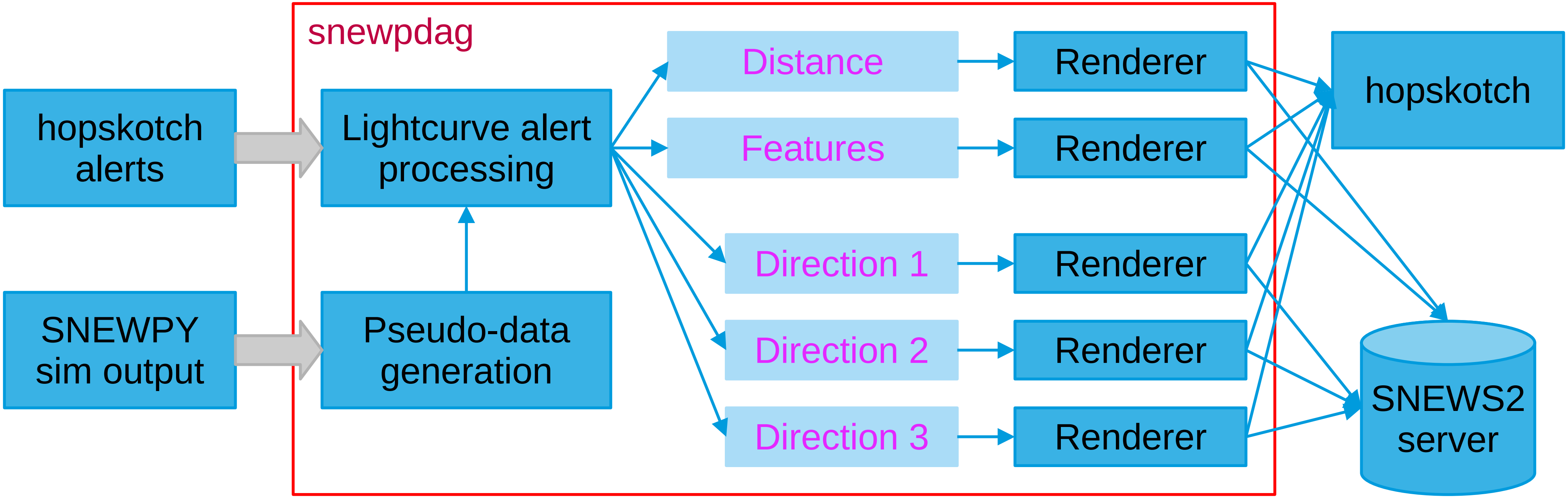


Outline

- Distance
- Burst features
- Triangulation
  - Methods
  - Time series matching
  - Skymap confidence intervals

SNEWS2 calculations: Pointing+

- Multiple pipelines with asynchronously fulfilled dependencies
- Supernova Neutrino Early Warning Pointing Directed Acyclic Graph...

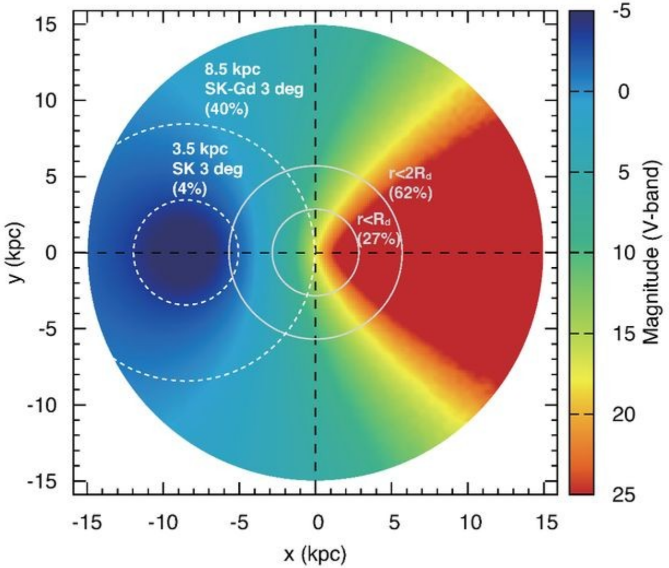


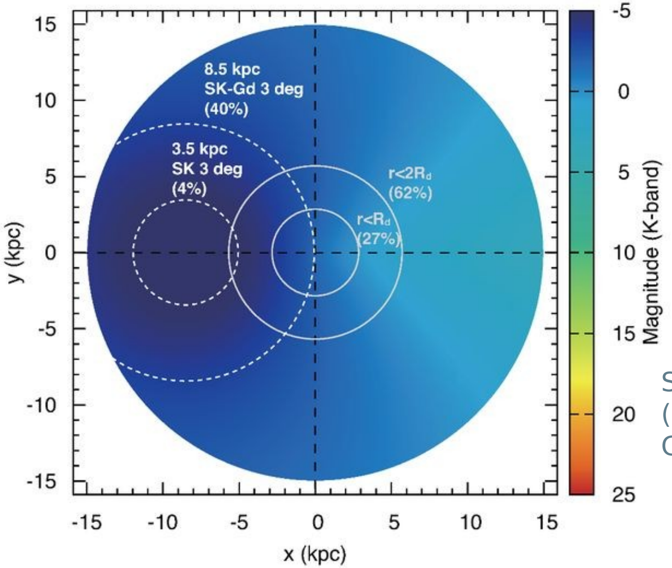
Distance

K Nakamura et al., MNRAS 461 (2016) 3296

- Why is distance relevant?

Optical magnitudes (plateau)





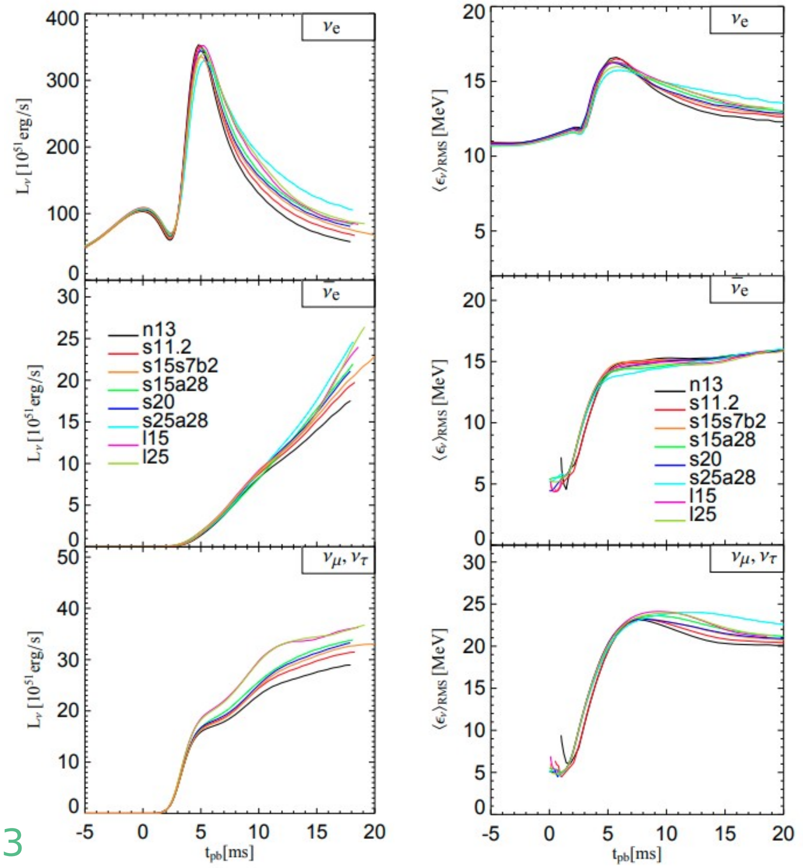
Near IR magnitudes (plateau)

SK pointing (% galactic CCSN rate)

- Sizable fraction of the galaxy obscured by dust
- May change optimal observation strategy

Distance

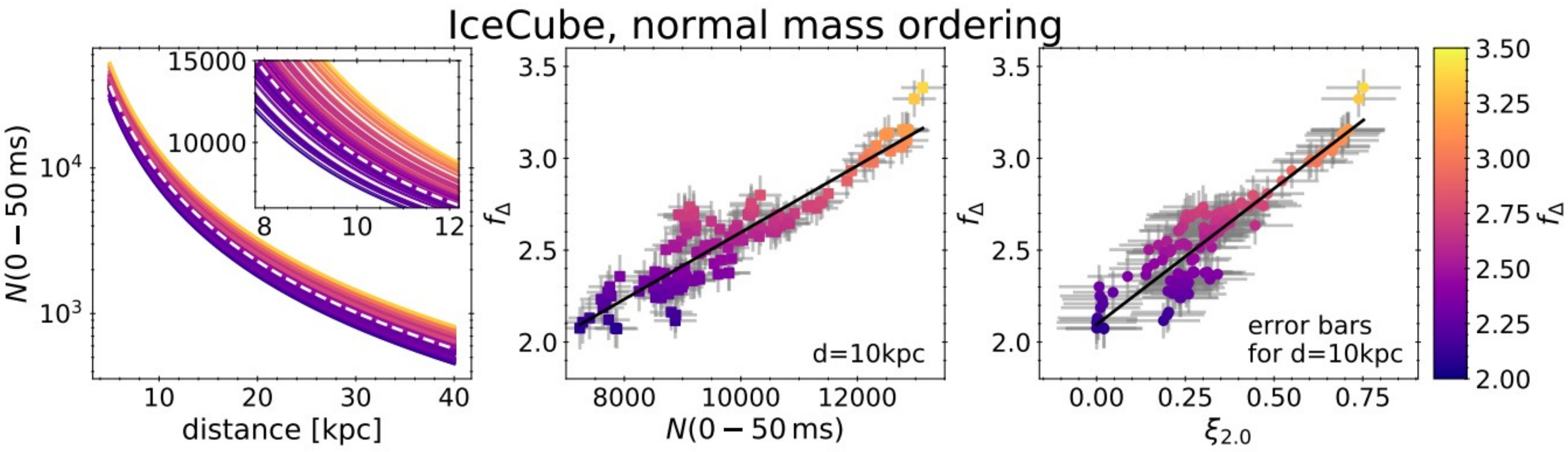
- Neutronization burst (ν_e) self-limited by electron captures
  - Potential standard candle, stable vs progenitor mass
  - Yield can be used to estimate distance to SN
- 1MT water Cherenkov detector
  - Average 112 electron elastic scattering events at 10kpc
  - 5% uncertainty on distance
- SNO+ and JUNO should also get a sizable number of proton elastic scattering events



Kachelriess et al., PRD71 (2005) 063003

Distance

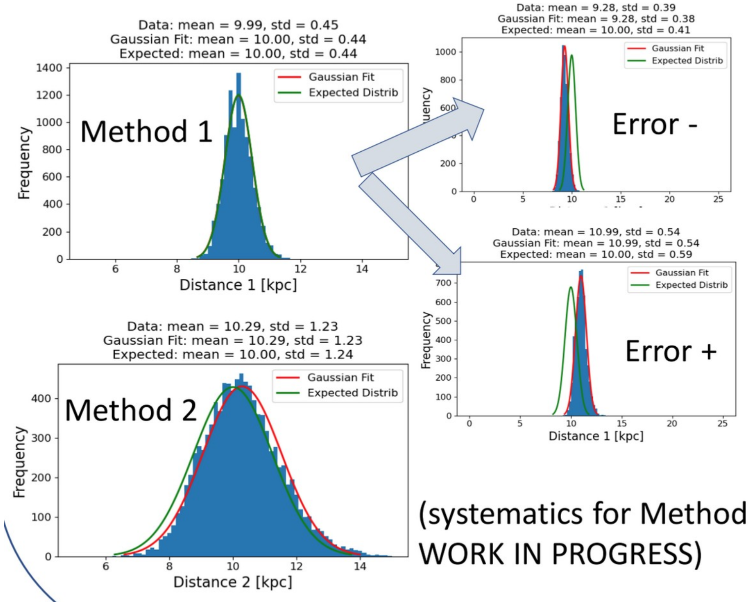
- Anti-ν_e yield ratio of (100,150)ms / (0,50)ms related to "compactness"
  - Can also be related to mass → similar sensitivity, smaller detectors using IBD



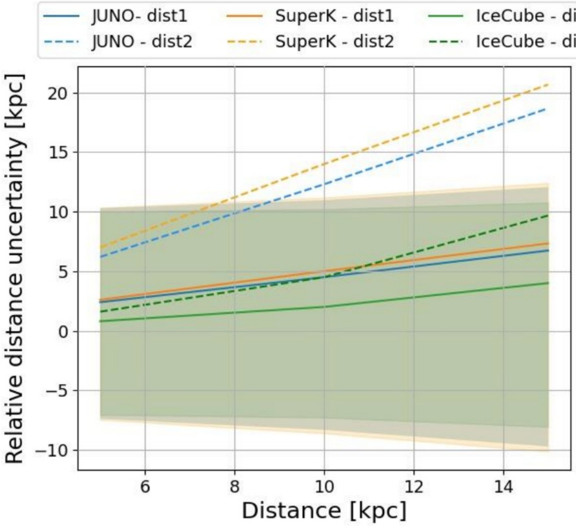
Segerlund et al., arxiv:2101.10624 (2021)

Distance

- 2 methods from Segerlund *et al.*, based on N_{50} = events observed in first 50ms
  - Expected signal weighted over initial mass function → lower stat unc, larger syst
  - Linear relation between N_{50} and $N_{50}/N_{100\text{-}150}$ → larger stat unc, lower syst
- Can report individually or (suggested) averaged



(systematics for Method 2:
WORK IN PROGRESS)



Statistical uncertainties for both methods (true distance 10kpc)

Bands include systematic uncertainties for method 1

Burst features

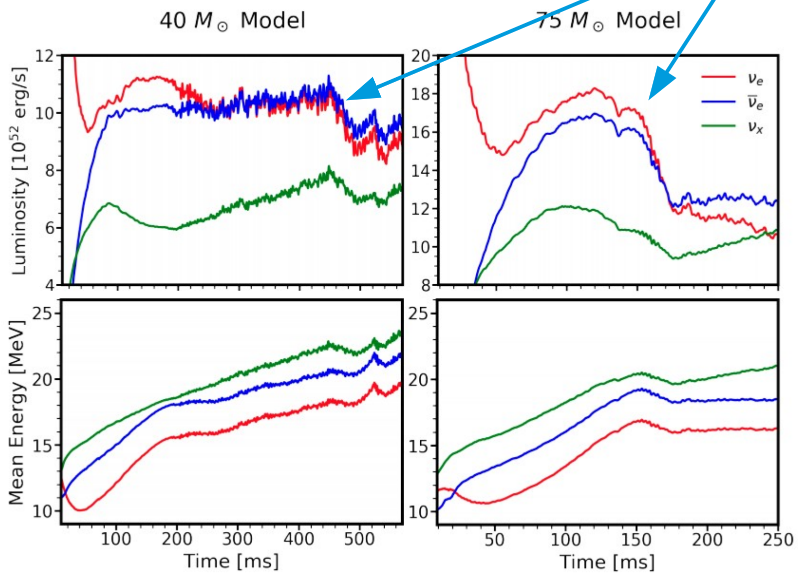
Software developed in SNEWS2 streamlines running diverse SN models and responses (e.g., SNEWPY)

Oscillations (formerly known as SASI?)

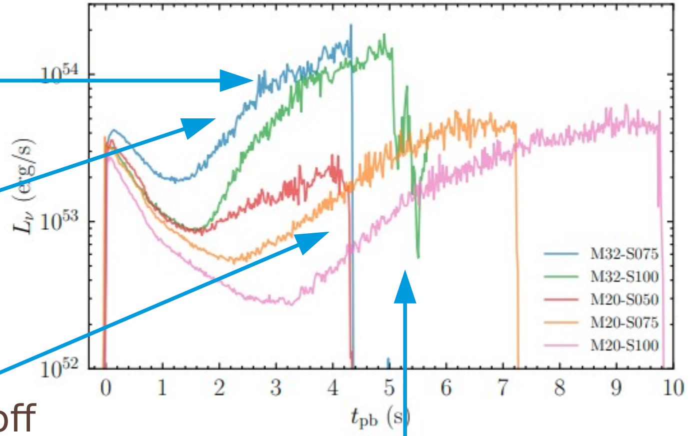
Long accretion (with angular momentum)

Abrupt cut-off

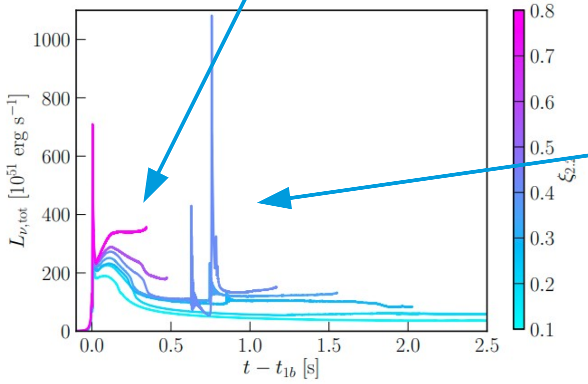
Secondary bursts (e.g., hadron-quark phase transition)



Walk et al., PRD 101, 123013 (2020)



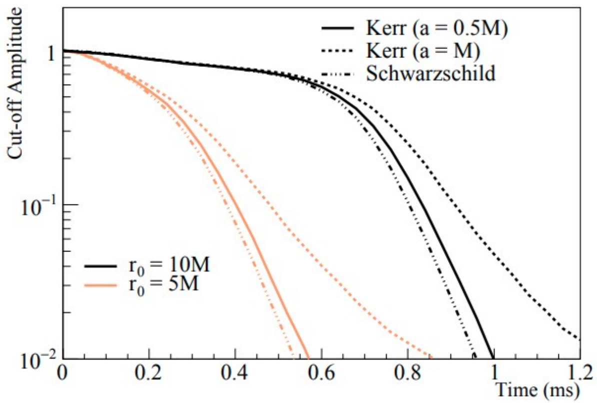
Fujibayashi et al., ApJ 919 (2021) 2, 80

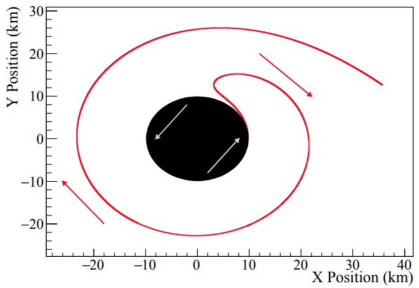


Zha et al., ApJ 911 (2021) 2, 74

Black hole cut-off

- How abrupt?
  - Simulations usually don't use full GR
  - Stop when approximations fail
  - Many simulations also consider only radial neutrino emissions
- Non-radial neutrino trajectories soften cut-off
  - Characteristic √27M time constant from leakage near photosphere of non-rotating BH
    [Podurets 1964; Ames, Thorne 1968]
    - O(0.1)ms for non-rotating BH
    - Systematic uncertainty with current experiments
  - Longer smearing for extreme rotation
  - Cut-off may encode information about PNS mass and rotation
- Neutrino echoes [Gullen, O'Connor, Wang, JT, ApJ 926 (2022) 2, 212]
  - Scattering of neutrinos off surrounnding material
  - Further softens cut-off, obscures √27M time constant



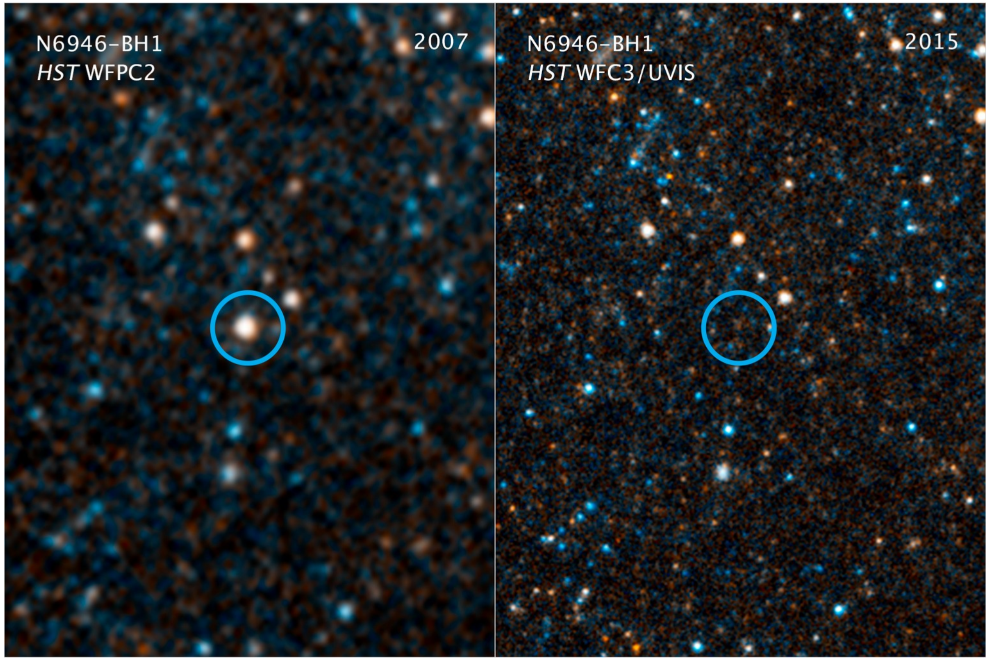


Sample neutrino trajectory around rotating BH

Wang, JT, O'Connor, Gullen, PRD 104 (2021) 10, 104030

Failed supernovae

- Black hole formation is interesting and better for pointing
  - But can fail to revive shock / explosion → may not see in visible spectrum!
- Search for disappearing massive stars → failed SN $0.16^{+0.23}_{-0.12}$ at 90% CL [Neustadt et al 2021, MNRAS, 508, 516]
- Consistent with search in PTF/ZTF surveys over 10 yr, 231 galaxies, 17M [Byrne & Fraser 2022, 2201.12187]
- Aim to calculate confidence level of detecting a feature such as a cut-off



NASA, ESA, and C Kochanek (OSU)

Pointing

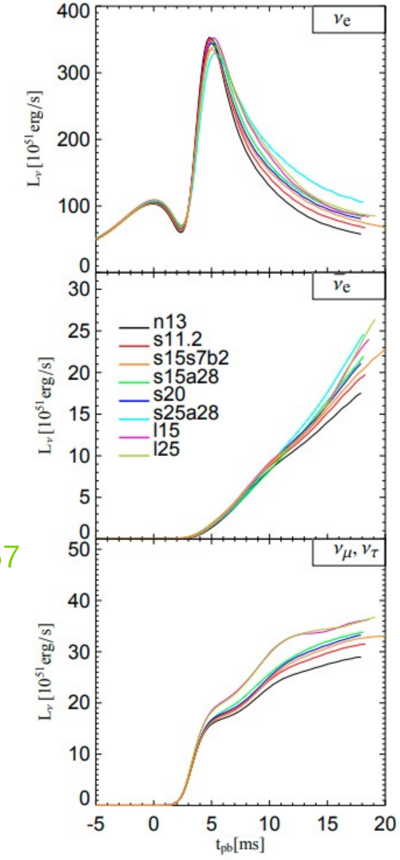
- Calculate Δt for burst arrival times
  - Need to make sure experiments synchronize, e.g., with GPS
- Can use burst times at each detector
  - Need to agree a common definition of the burst time, e.g.,
    - First event in a burst (for experiments with low backgrounds)
    - Extrapolation to zero flux
    - Model extrapolation to (e.g.) core bounce time
  - Potential to compare different ν detection channels
    - Neutrino oscillations and mass hierarchy may change behaviors
- Time series matching with comparable channels, e.g., IBD
- May want to publish multiple pointings
with different assumptions

Linzer, Scholberg,
PRD 100 (2019)
10, 103005

Hill, Virtue,
Laurentian Univ,
12 Aug 2021

e.g., Brdar, Xu,
JCAP 08 (2022) 067

Coleiro et al.,
EPJ C80 (2020) 856;
Brdar, Lindner, Xu,
JCAP 04 (2018) 025



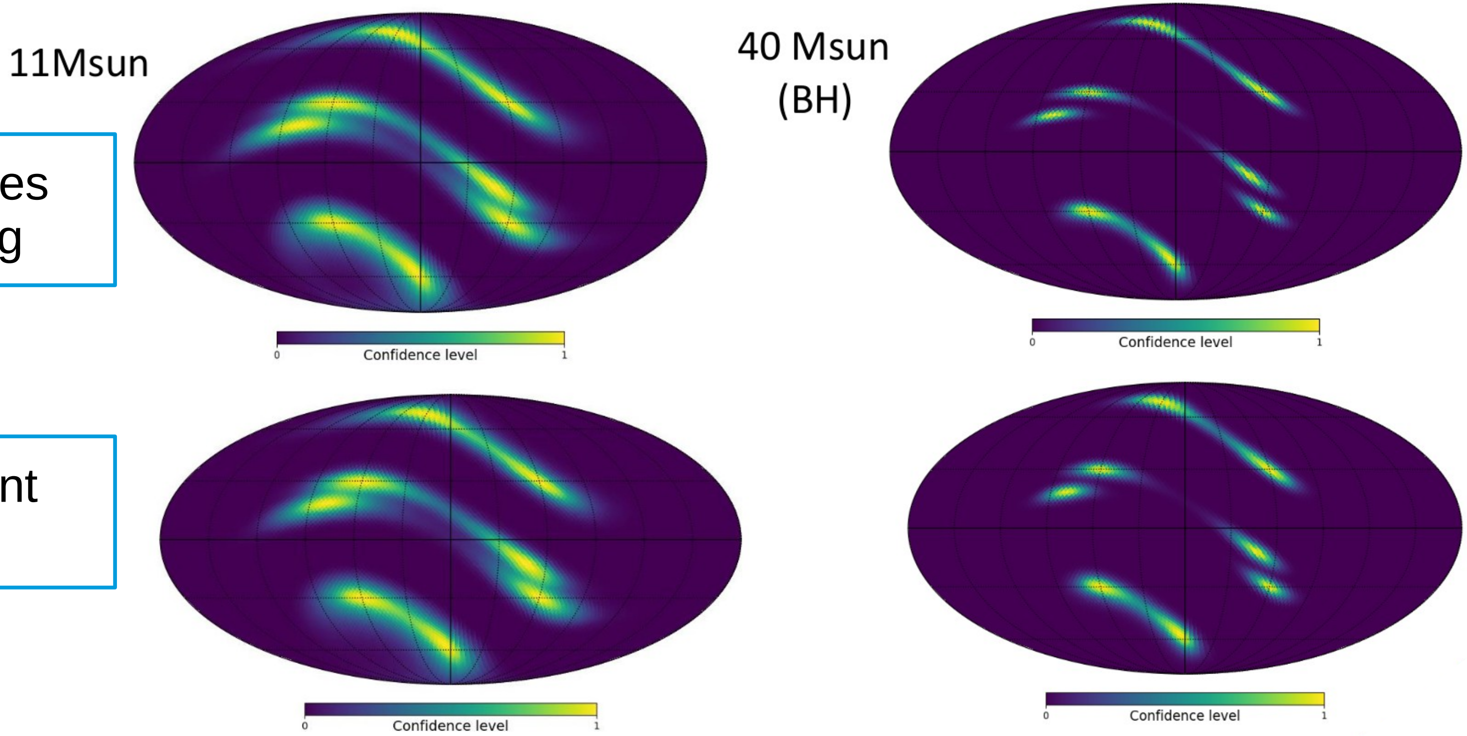
Pointing

- Results combining IceCube + Super-Kamiokande + JUNO
- Uncertainties and bias for 10kpc from 4 different true directions

[Colomer, JT, Neutrino 2022]

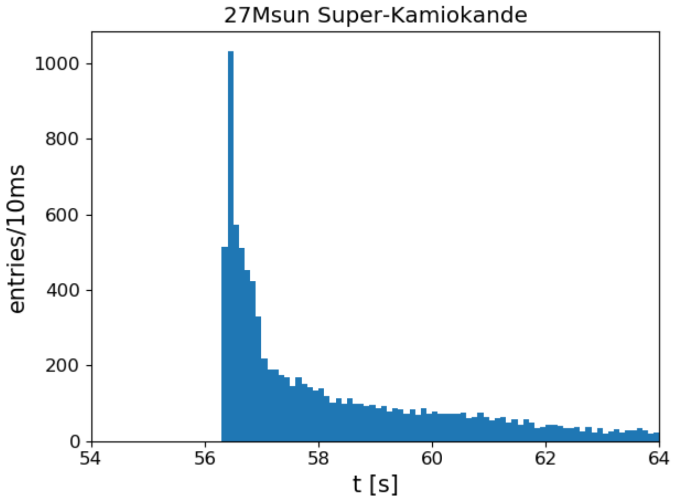
Time series matching

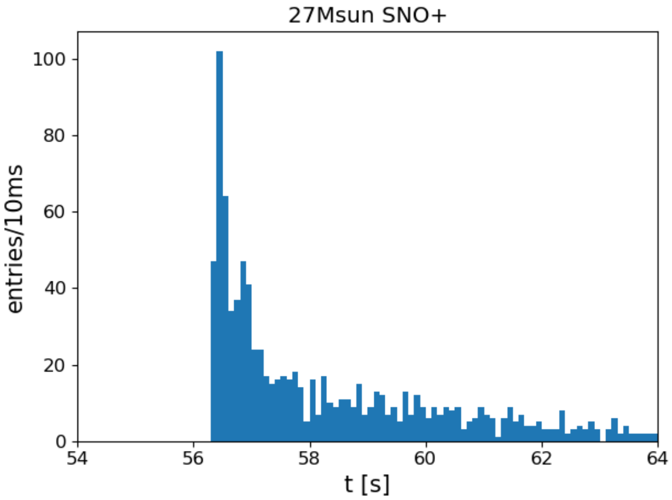
First event times



Further investigation into time series matching

- Improve Δt for pairs of comparable time series, e.g., of IBD events
  - Cross covariance, χ^2, other metrics
  - Aim to calculate at least a first estimate of uncertainties → CL skymap





Cross covariance

$$R_c(\tau) = \frac{1}{N}\sum_{j=1}^{N} n_j m_j(\tau)$$

One lightcurve, unshifted

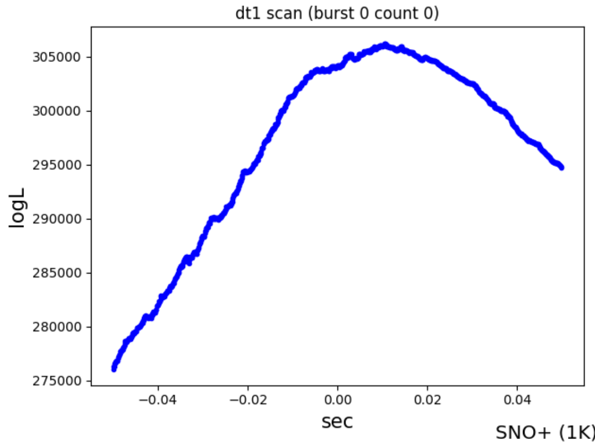
Second lightcurve, shifted by lag τ

Sum over time bins

- Often used to match lightcurves and spectra with offsets
- Equivalent to χ^2 with uniform uncertainties
  - Zucker (MNRAS 342, 1291 (2003)) wrote analytical expressions for associated uncertainties under these assumptions

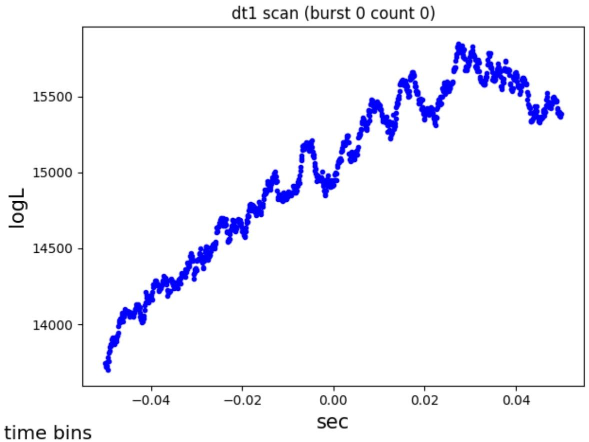
$$\mathcal{L} = \prod_{j=1}^{N} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2}\left(\frac{n_j - m_j(\tau)}{\sigma}\right)^2\right]$$

Cross covariance tests

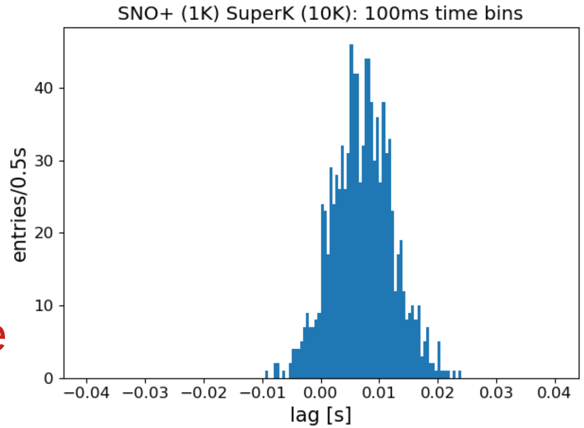


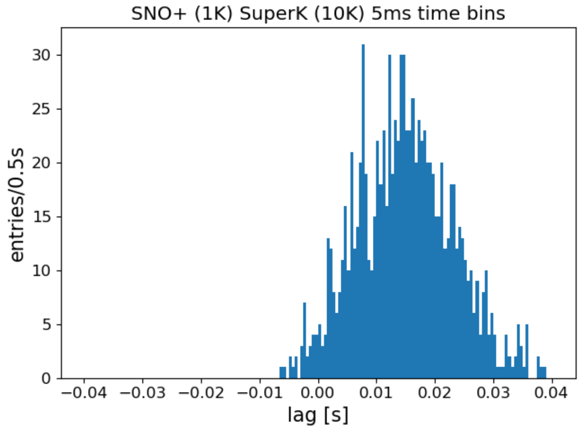
Evaluate cross covariance as a function of lag hypothesis

1000 SN trials



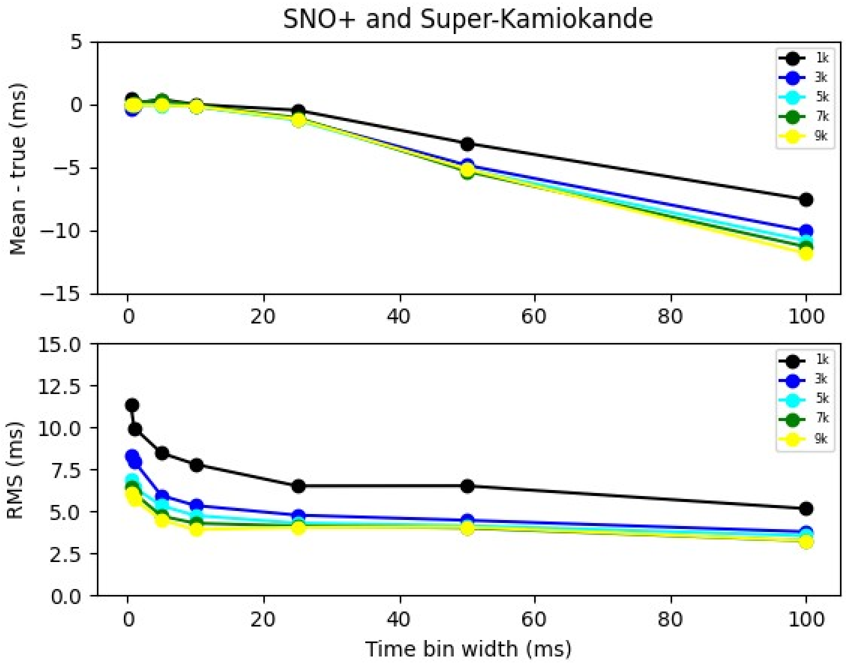
Uses detector locations – yields not to scale



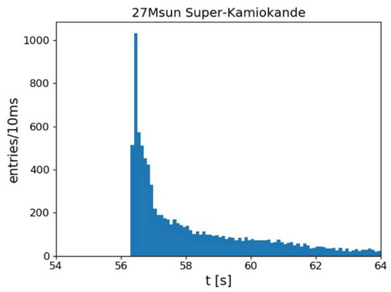


True lag: 14.7ms

Cross covariance tests



- 10K events at SK location
- 1/3/5/7/9k events at SNO+ location
  - Corresponding SNO+ yield actually ~250 events
- Smaller time bins for cross covariance comparison → smaller bias
- Smaller time bins → also larger statistical uncertainty
- Happy medium here: 10ms time bins
  - Roughly time scale of most peak-like feature



Poisson likelihood method

- Use maximum likelihood to find lag and estimate uncertainty
- Start with signal only
  - Analysis including background in progress

Relative yield

$$\mathcal{L} = \prod_{j=1}^{N} L_j$$

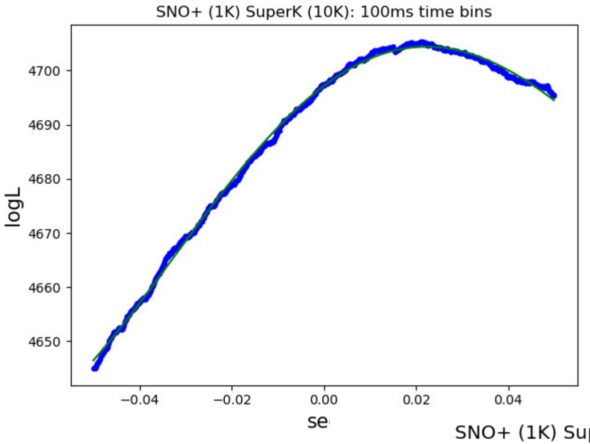
Over time bins

$$L_j = \int_0^\infty \frac{\mu^{n_j}}{n_j!} e^{-\mu} \frac{(a\mu)^{m_j}}{m_j!} e^{-a\mu} d\mu$$

$$= \frac{(n_j + m_j)!}{n_j! m_j!} \frac{a^{m_j}}{(1+a)^{n_j+m_j+1}}$$

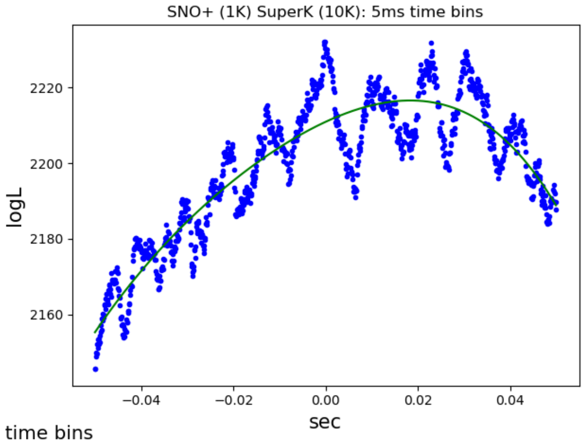
$$R_p(\tau) = \sum_{j=1}^{N} [\log(n_j + m_j(\tau))! - \log m_j(\tau)!]$$

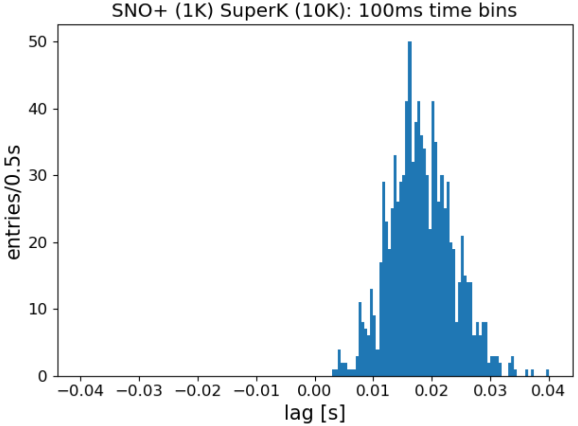
Poisson likelihood tests (signal only)

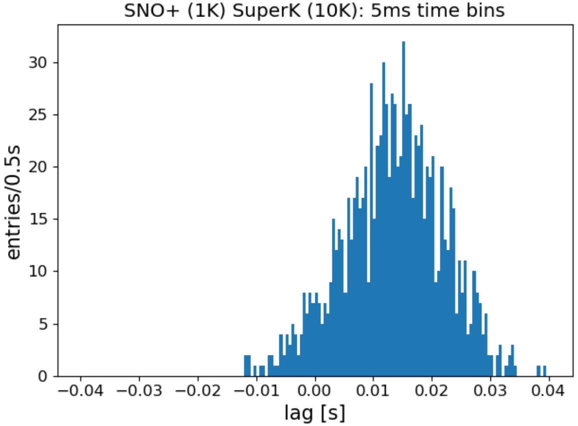


Evaluate logL as a function of lag hypothesis

1000 SN trials



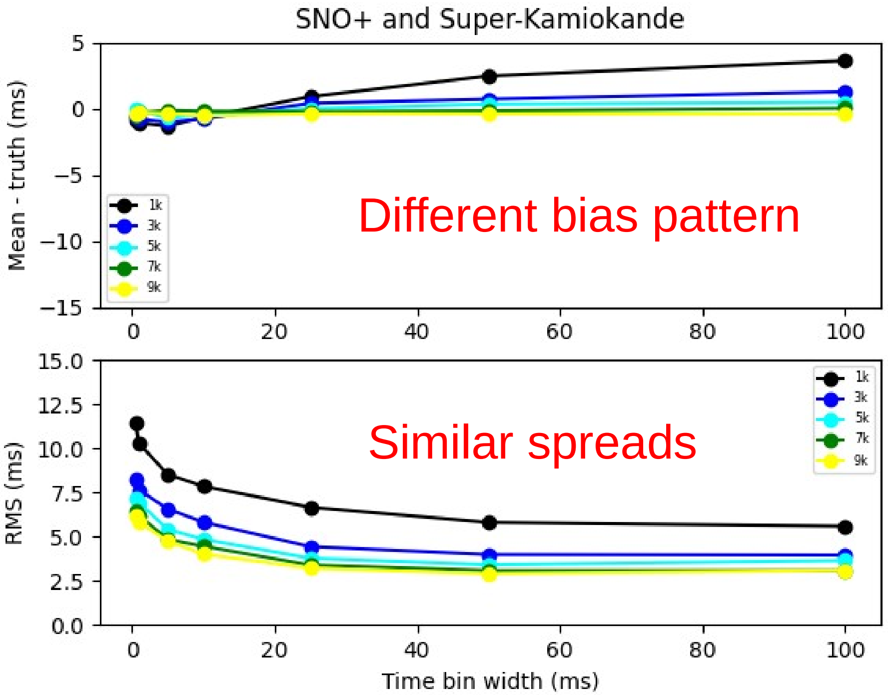




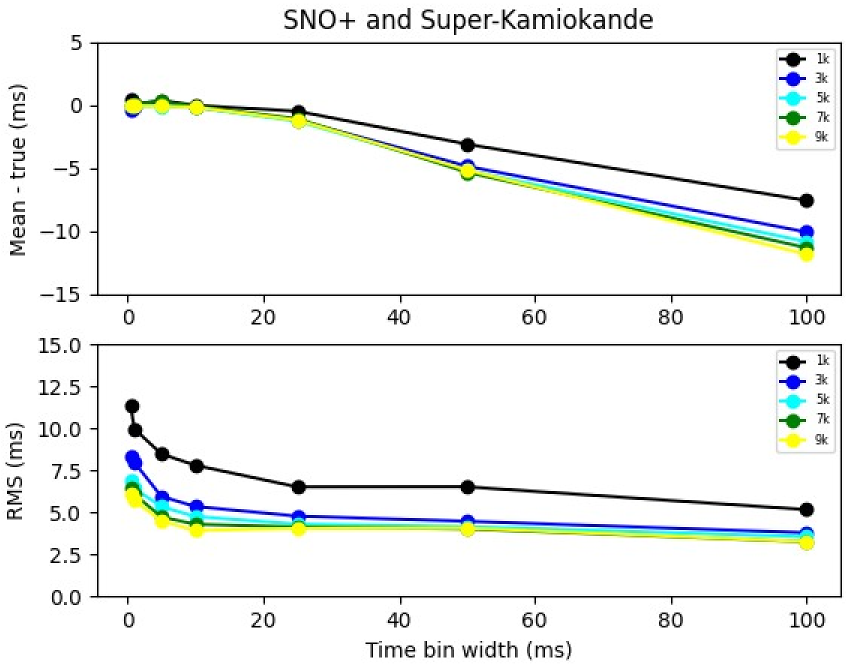
True lag: 14.7ms

Poisson likelihood tests (signal only)

Poisson likelihood (signal only)



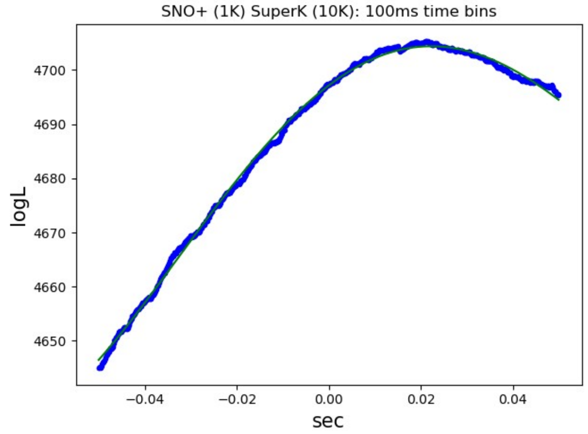
Cross covariance (signal only)

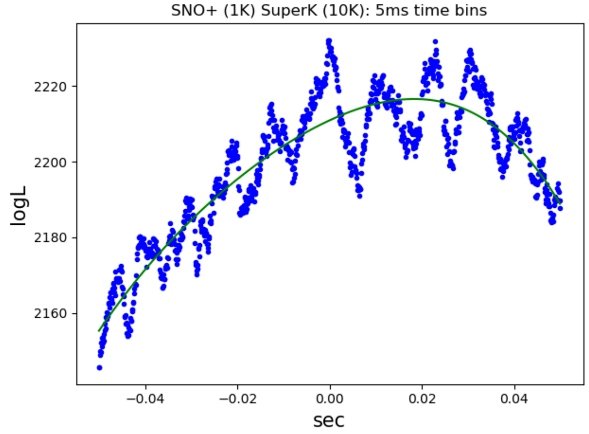


Bias patterns appear consistent with different detector pairs

Uncertainty calculation

- Aim to calculate first estimate of uncertainty
  - Fit logL profile with a 4th order polynomial
  - Estimate uncertainty with second derivative at maximum of polynomial
    - Still need to scale up with a factor of $\sqrt{(1+r\delta)}$
    - δ = RMS of deviations of logL profile from polynomial fit
    - r = 0.5 lines up calculated uncertainties with observed RMS
- Can follow up with uncertainty based on MC trials

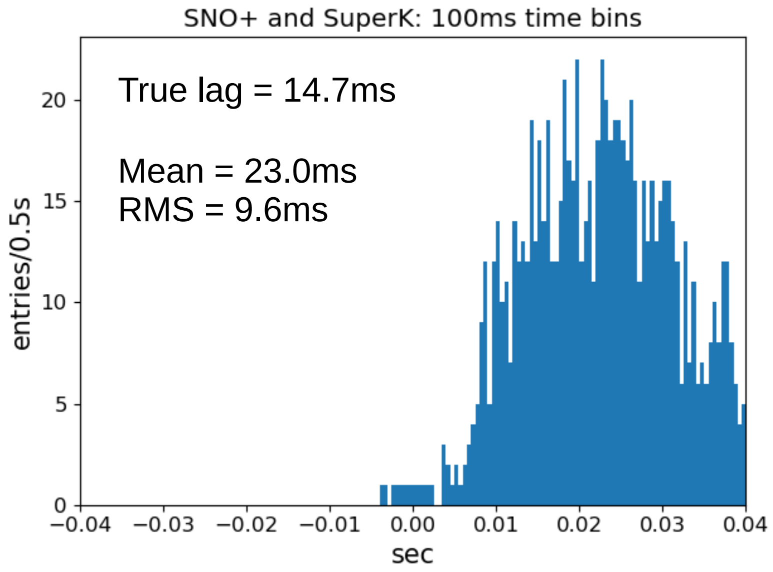


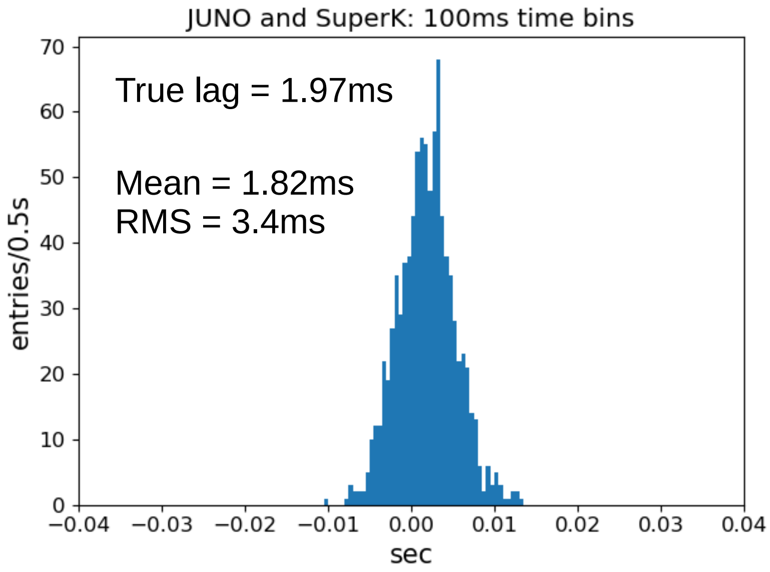


Confidence intervals (signal only)

- More realistic signals: $27M_{\odot}$ (LS220) at 10kpc, normal ordering

Super-Kamiokande: 7800
JUNO: 7200
SNO+: 195
IceCube: 1000 (fake!)



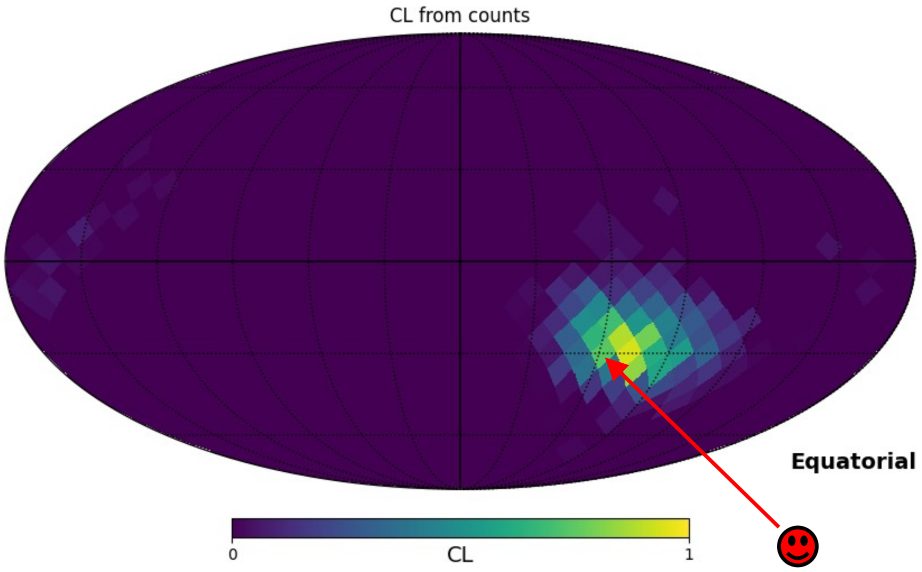


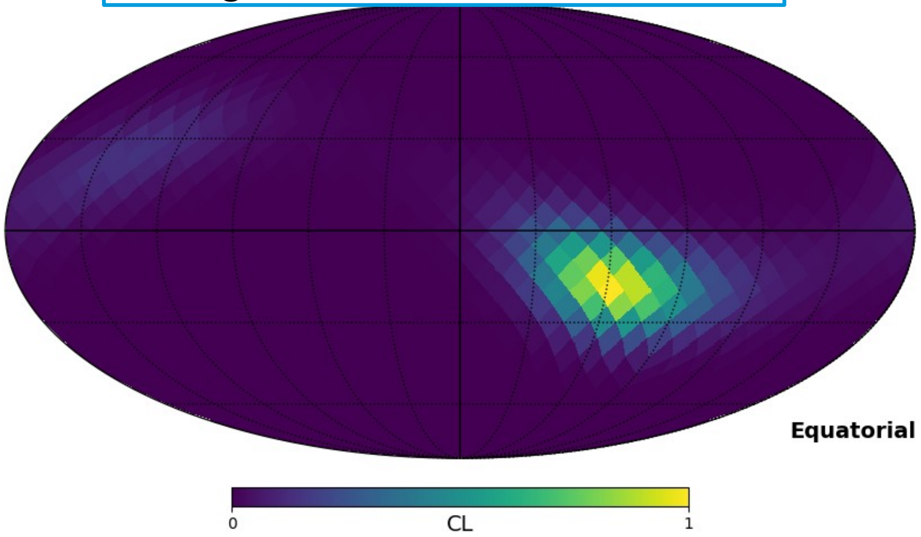
Confidence intervals (signal only)

- Count pixels with maximum logL over 1000 MC trials

Super-Kamiokande: 7800
JUNO: 7200
SNO+: 195
IceCube: 1000 (fake!)

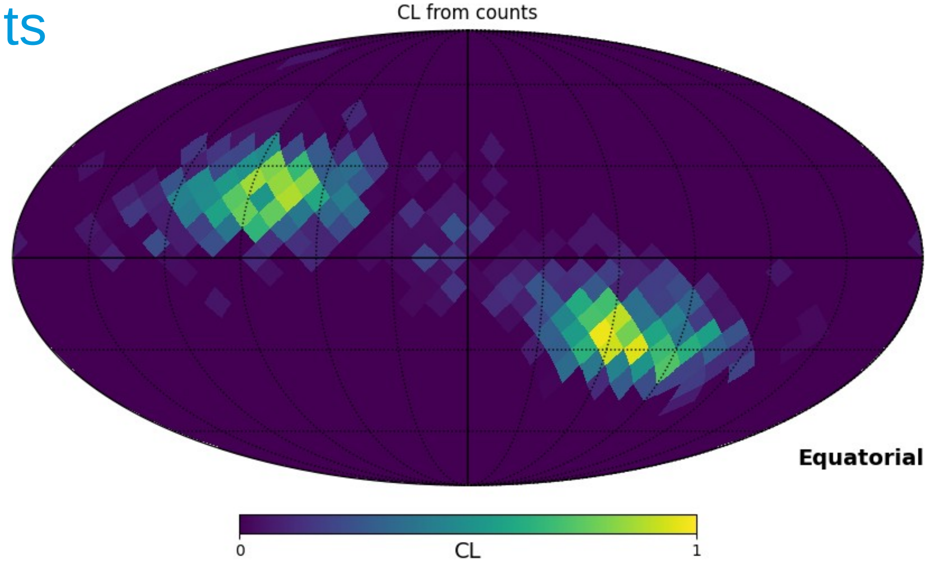
Single trial,
using calculated uncertainties

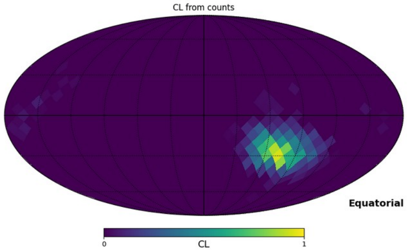




Confidence intervals (signal only)

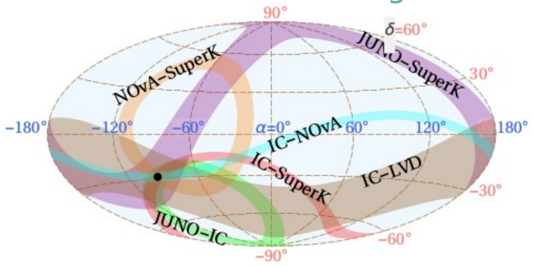
- Using Super-Kamiokande, JUNO, IceCube
  - Exclude SNO+ and its 195 events





(with SNO+)

From Brdar, Lindner, Xu, JCAP 04 (2018) 025, based on Garching models

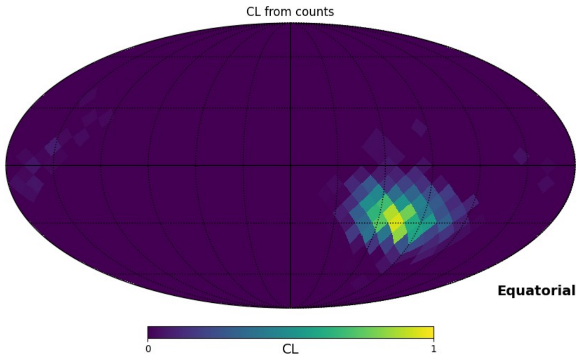


- Geographical dispersion is an important factor

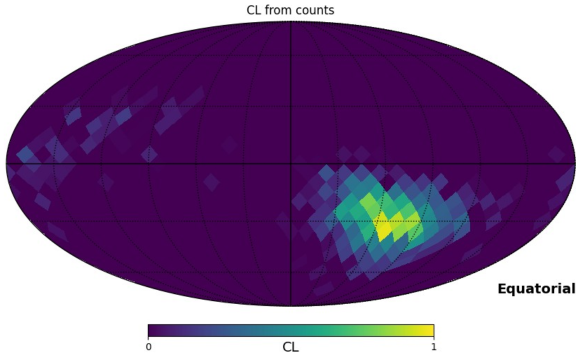
Confidence intervals (signal only)

- Effect of different time bin widths
  - Here Poisson likelihood; cross covariance similar

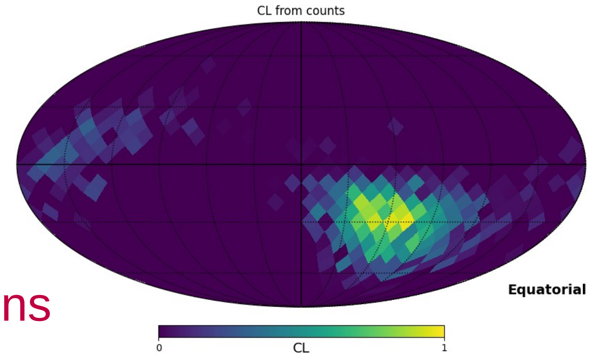
1000 MC trials,
counting max-logL pixels



100ms bins



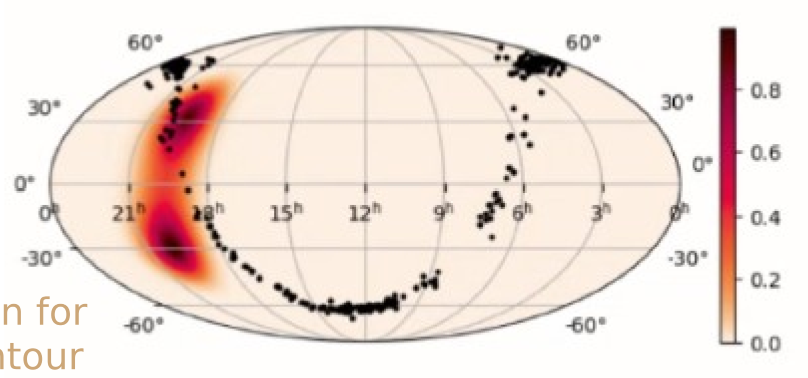
25ms bins



10ms bins

Pointing: result

- Successive improvement as experiment data comes in
  1) Burst times → rough triangulation
  2) Time distributions → improved triangulation
  3) Experiment pointing using EES → likely to dominate in the end
- Aim to report pointing as a skymap of confidence levels
  - Superimpose on candidate stars



Sample result - deliberately chosen for big, non-trivial contour

Conclusion

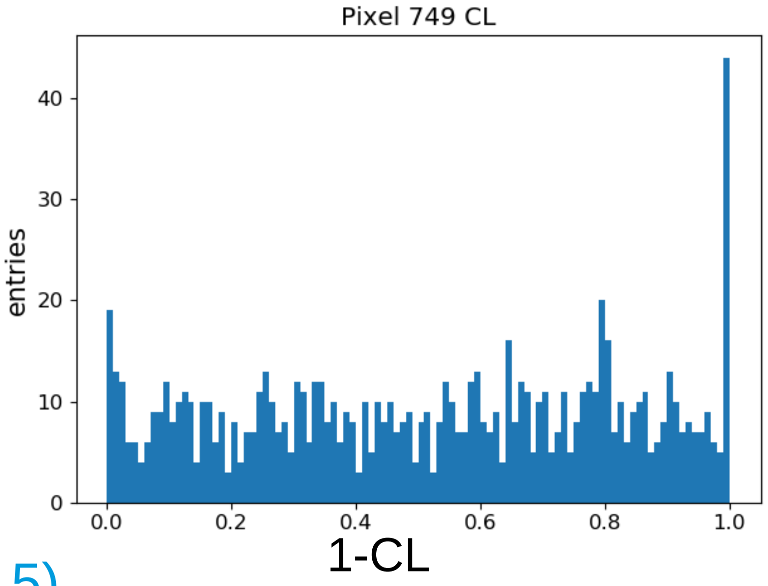
- SNEWS2 aims to provide rapid calculation of observationally relevant quantities: direction, distance, and feature detection
- SNEWS2 can accommodate multiple pipelines for complicated dependencies among asynchronous inputs/updates
- Current work includes improving direct calculation of confidence intervals to inform follow-up quickly

SNEWS
SUPERNOVA EARLY WARNING SYSTEM

Backup

Confidence intervals (signal only)

- Confidence interval test at target pixel
  - Δt's with calculated $\sigma_{\Delta t}$ fed into triangulation module, which returns χ^2 at each pixel
- Plot CL of pixel containing true direction
  - (For some reason I plotted 1-CL)
  - Should be uniform over (0,1)
    if calculated uncertainties are reasonable



- Uncertainty calculation not too far off (with r=0.5)