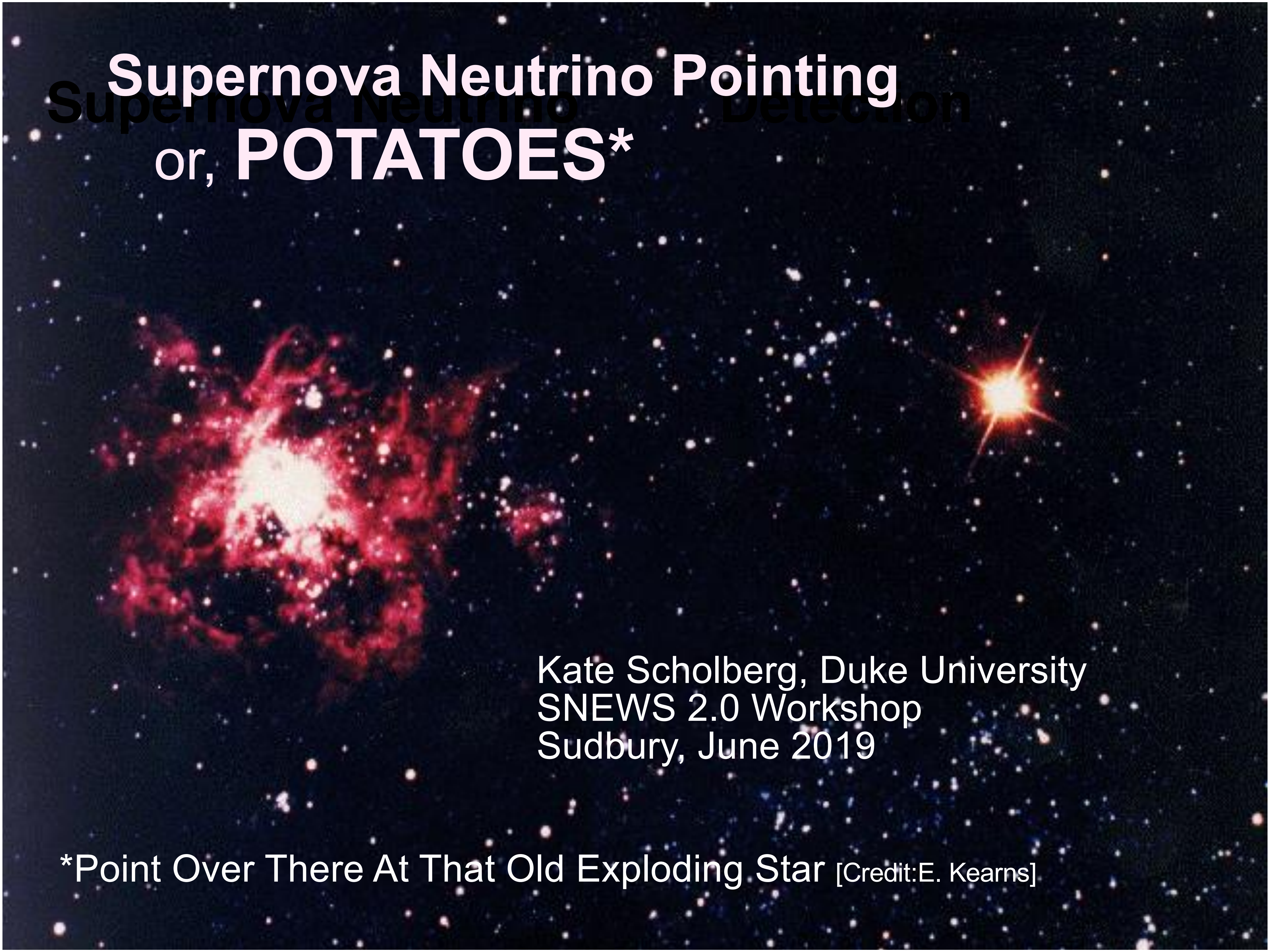
Supernova Neutrino Pointing

or, POTATOES*



Kate Scholberg, Duke University

SNEWS 2.0 Workshop
Sudbury, June 2019

*Point Over There At That Old Exploding Star [Credit:E. Kearns]

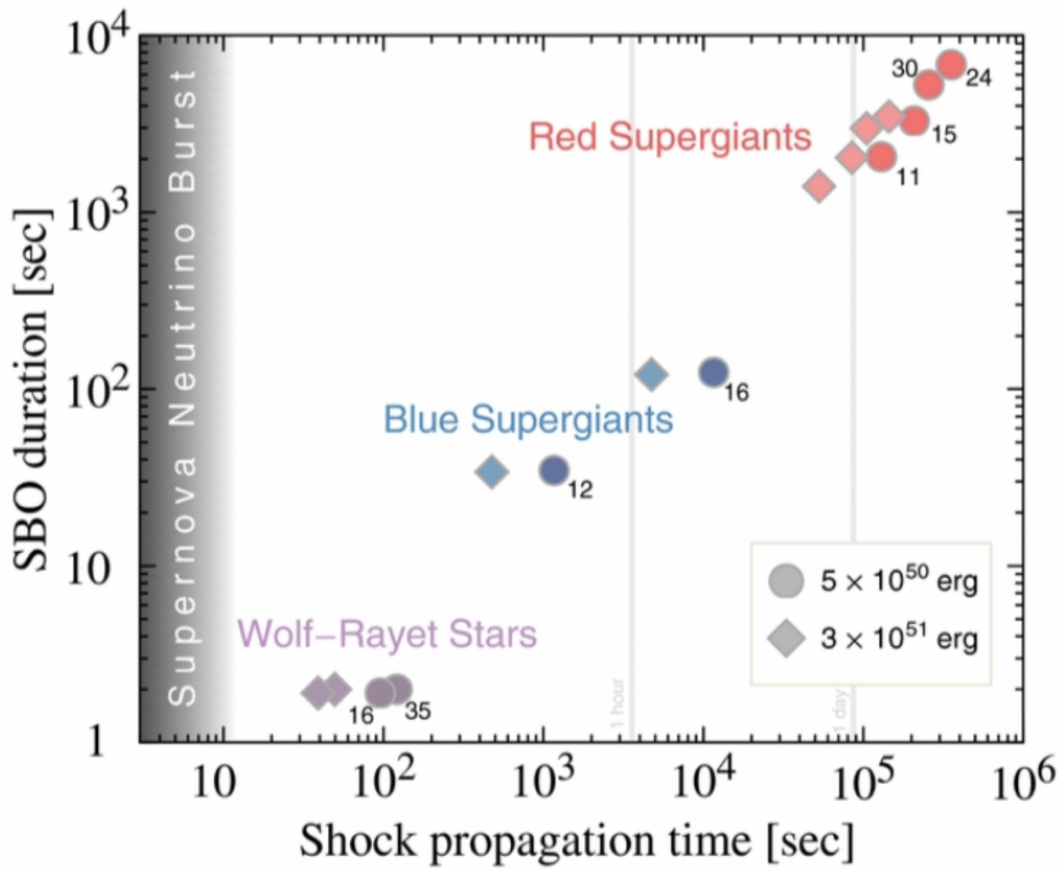
OUTLINE

- Motivation for pointing with neutrinos
- Methods
  - Anisotropic reactions
    - Water
    - Argon
    - Scintillator
  - Triangulation
  - Oscillation
  - High-energy neutrinos
- Realistic optimization for the future

Why point?

Find the supernova!

Early light observations are valuable….



Matthew D. Kistler, W. C. Haxton, and Hasan Yüksel. Tomography of Massive Stars from Core Collapse to Supernova Shock Breakout. ApJ, 778:81, 2013, arXiv:1211.6770.

We're racing the shock!

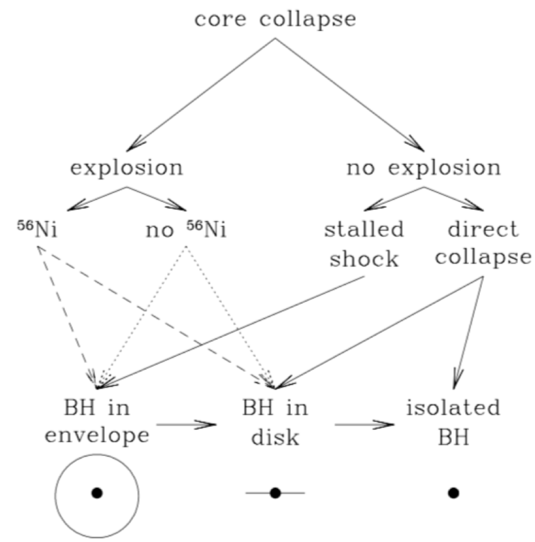
May have less than a half hour, or even just minutes

For this application, want to point with ***low latency***

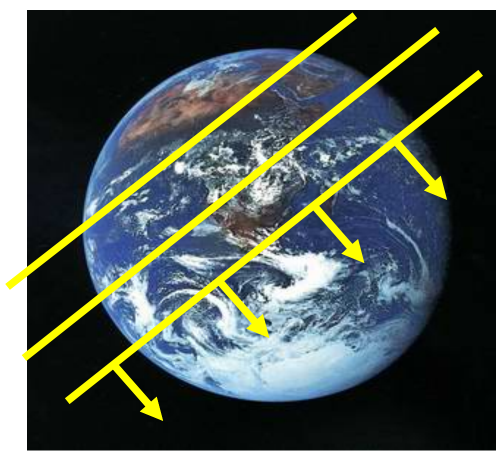
But even if it's not prompt, there are still motivations to use neutrinos to see the SN direction…

There may be no bright supernova!

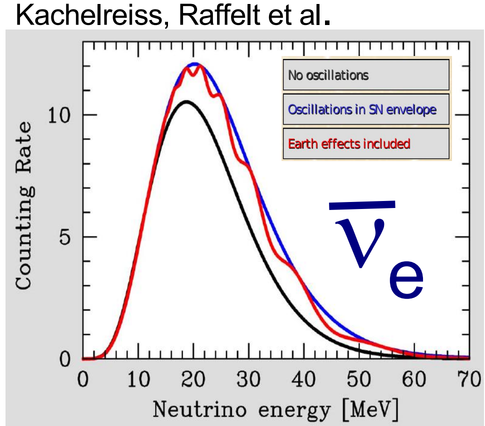
→ narrow down
the search for a progenitor,
or a "winked out" star



C. Kochanek et al., Ap.J.684:1336-1342,2008



Kachelreiss, Raffelt et al.

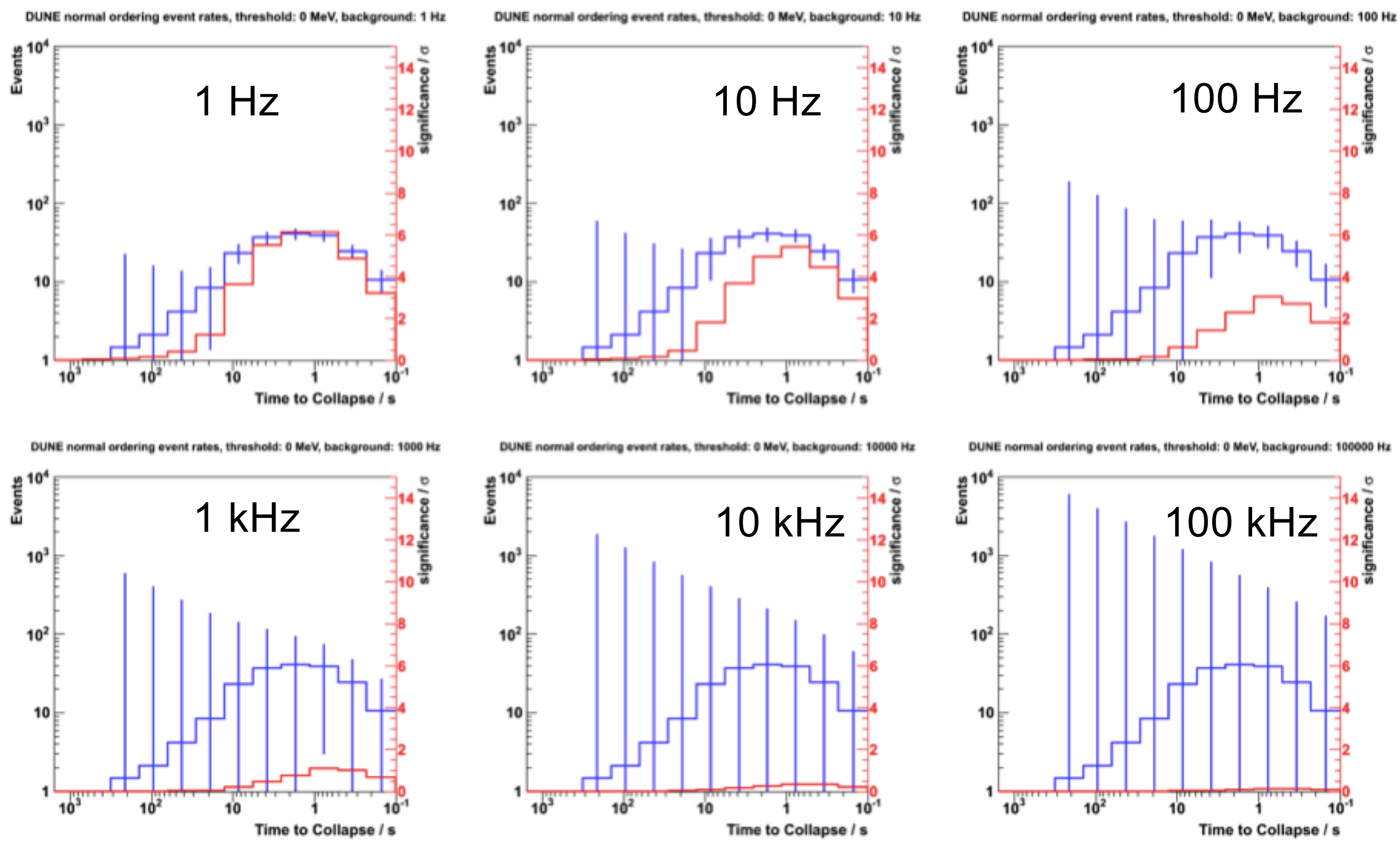


And even if we never find an optical counterpart or progenitor, we need to know the trajectory through the Earth for matter oscillation evaluation

So refined direction information late is better than never…

Furthermore, direction info may enhance ***presupernova*** sensitivity, to select signal from bg

Example: Presupernova signal w/BG in DUNE (Kato et al. model, SNOwGLoBES, NH, 200 pc, no directional information)



$$\Delta S = \sqrt{2B + S}$$

M. Schoene

Significance should improve making use of directional information

Neutrino Pointing Methods

- **Anisotropic neutrino interactions**
  combined with detector technology that can exploit it,
  using the burst neutrino signal
- **Triangulation**
  using inter-detector timing
- **Oscillation pattern pointing**
  in high-energy resolution detectors
- **High-energy (~GeV) neutrino follow-on pointing**
  in directional detectors, using later neutrinos
- **All of the above!**

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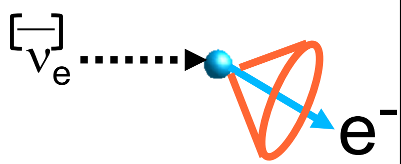
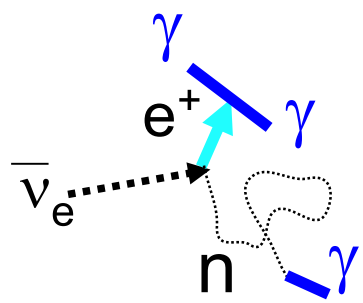
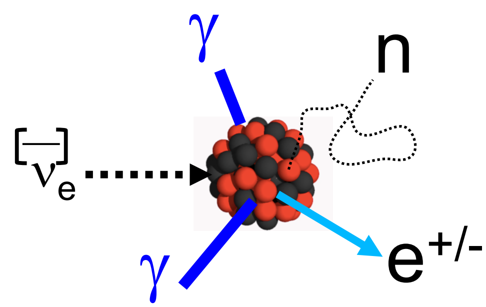
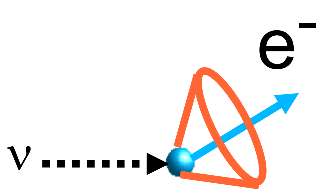
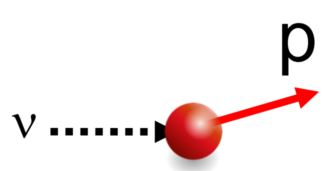
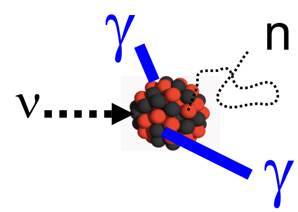
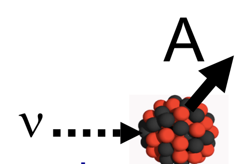
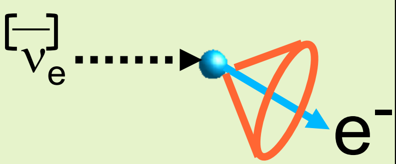
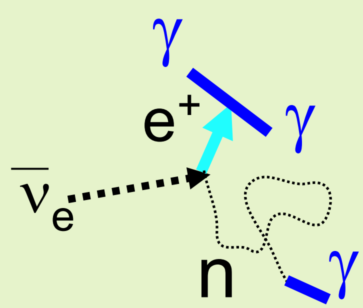
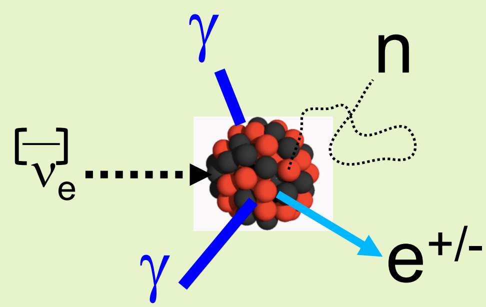
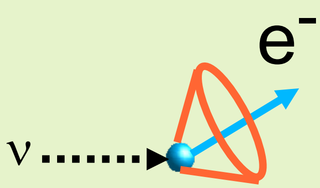
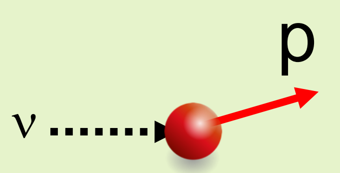
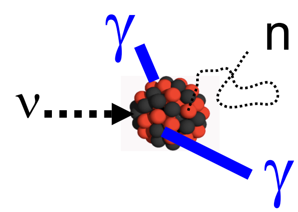
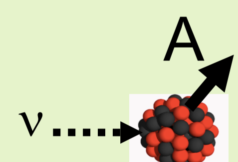
Supernova-relevant neutrino interactions

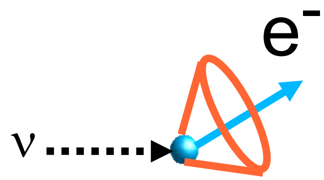
	Electrons	Protons	Nuclei
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N, Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N, Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$  $\nu + A \rightarrow \nu + A$  Coherent elastic (CEvNS)

Most of these have at least *some* intrinsic anisotropy

	Electrons	**Protons**	**Nuclei**
Charged current	Elastic scattering $\nu + e^- \rightarrow \nu + e^-$ 	Inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$ 	$\nu_e + (N,Z) \rightarrow e^- + (N-1, Z+1)$ $\bar{\nu}_e + (N,Z) \rightarrow e^+ + (N+1, Z-1)$  Various possible ejecta and deexcitation products
Neutral current	 Useful for pointing	Elastic scattering  very low energy recoils	$\nu + A \rightarrow \nu + A^*$   $\nu + A \rightarrow \nu + A$ Coherent elastic (CEvNS)

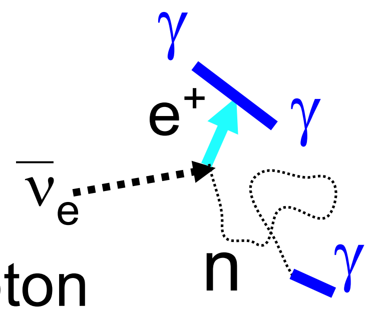
Anisotropic Neutrino Interactions

- **Neutrino-electron scattering (ES)**
  - Every detector has electrons
  - Good forward pointing
  - Low cross section, subdominant signal

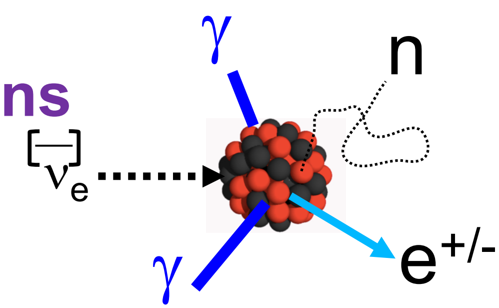


$$\sim \frac{25^\circ}{\sqrt{N}}$$

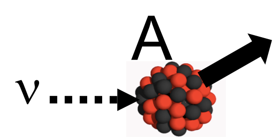
- **Inverse beta decay (IBD)**
  - Dominant in water and scintillator
  - Weak energy-dependent anisotropy for lepton
  - Neutron capture position can help



- **Neutrino-nucleus charged-current interactions**
  - Some anisotropy of lepton wrt neutrino
  - Nuclear structure uncertainties $\sim 1 + a\cos\theta$



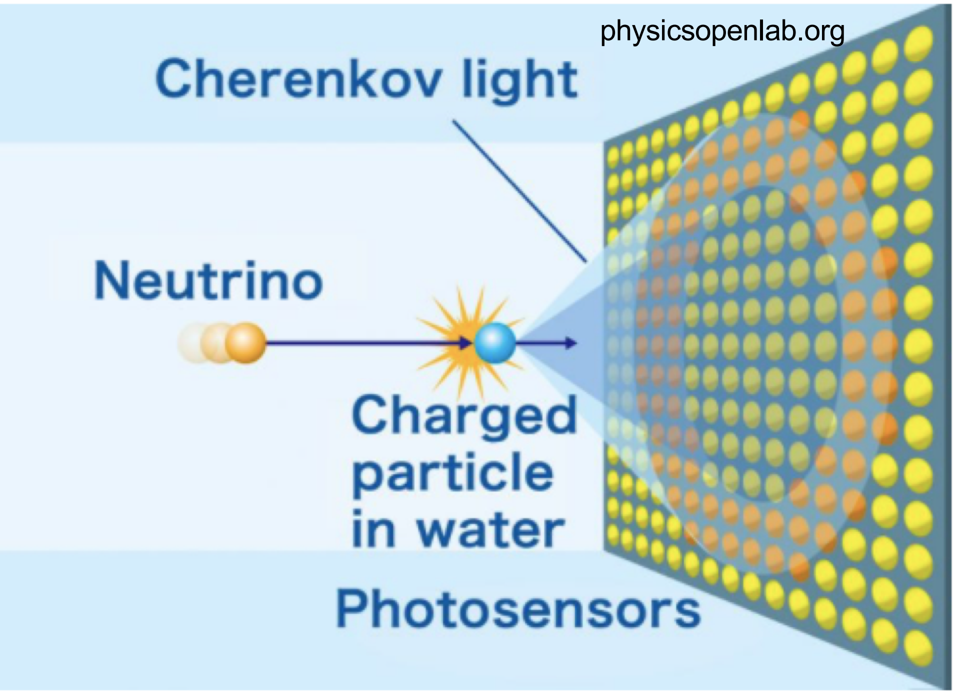
- **Elastic scattering on protons or nuclei**
  - Well-defined anisotropy [experimentally hard...]

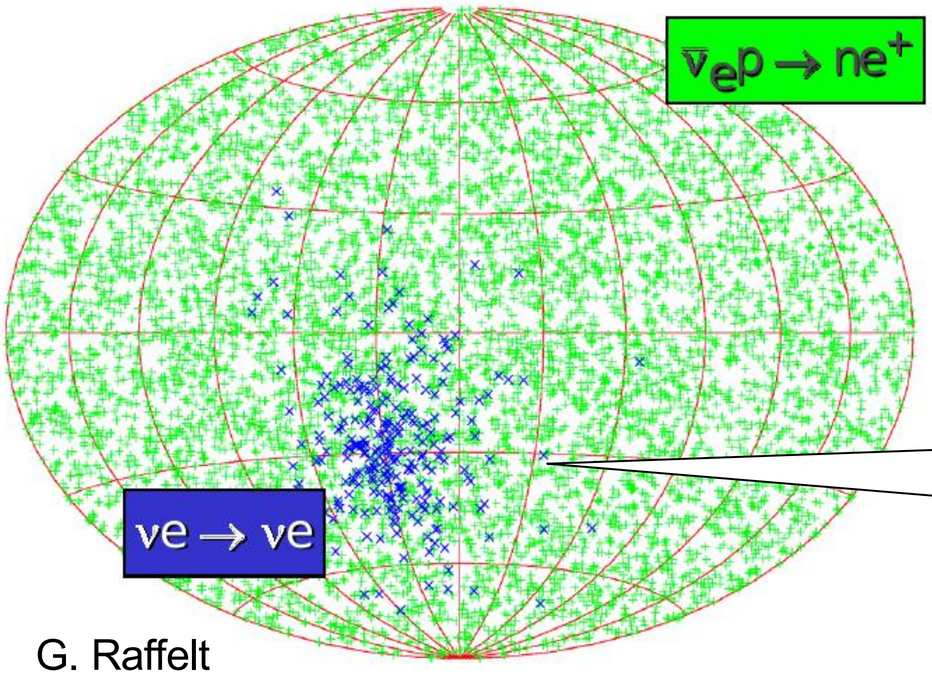


In all cases, the *detector* must be capable of exploiting directionality via tracking of some kind

Water Cherenkov Detectors

Excellent intrinsic directionality, including head-tail disambiguation

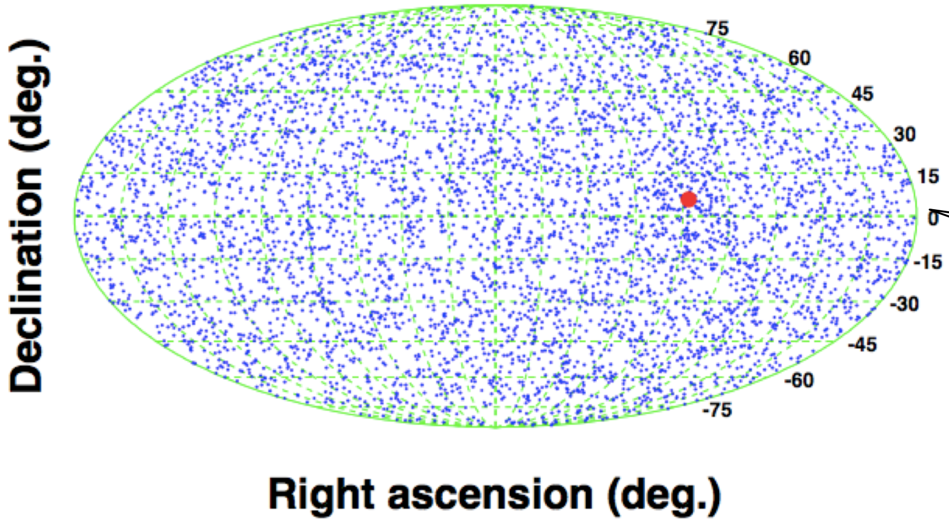




The go-to pointing method is ES in SK

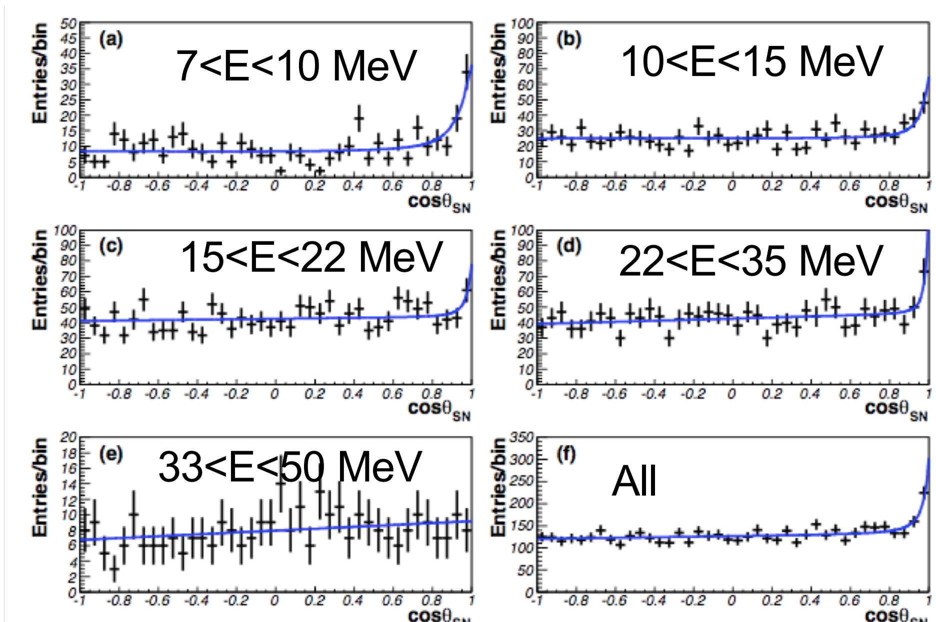
G. Raffelt

Pointing in Water Cherenkov: Super-K

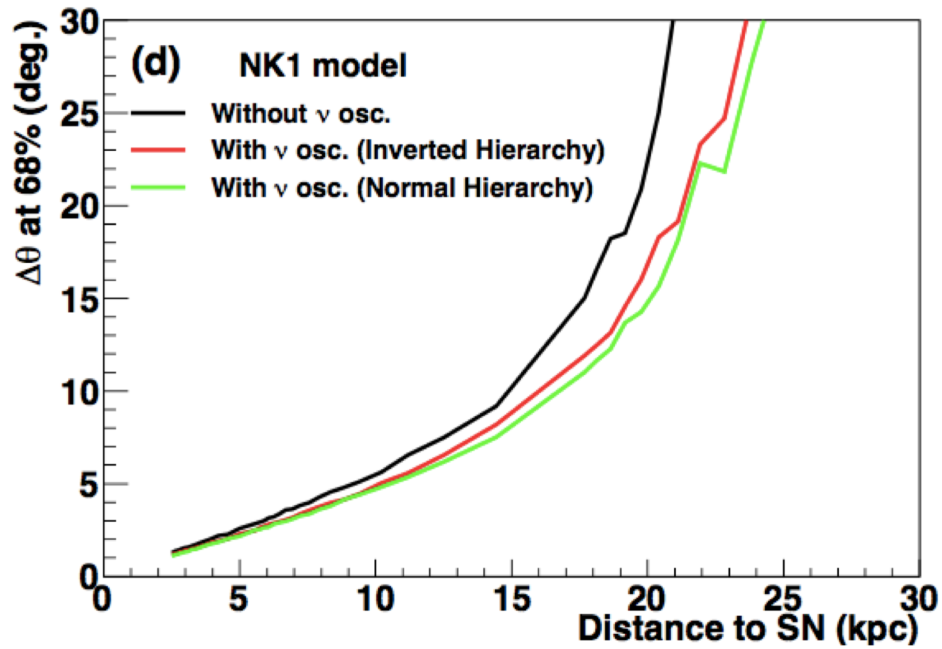


K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Harder when you don't have the interaction truth!



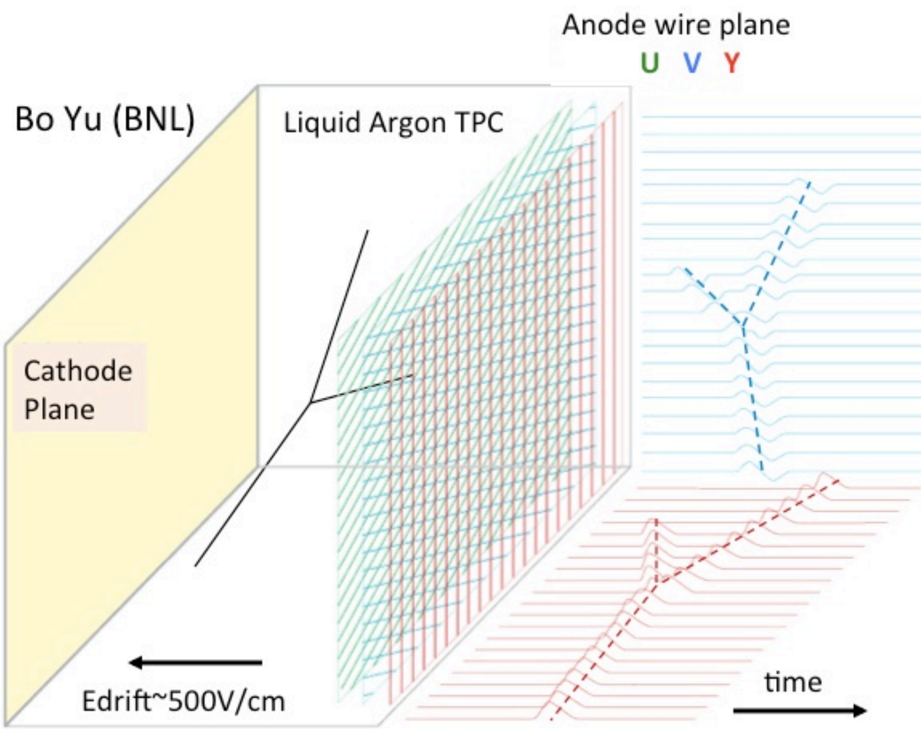
Fit to ES+ mildly anisotropic IBD (+^{16}O)



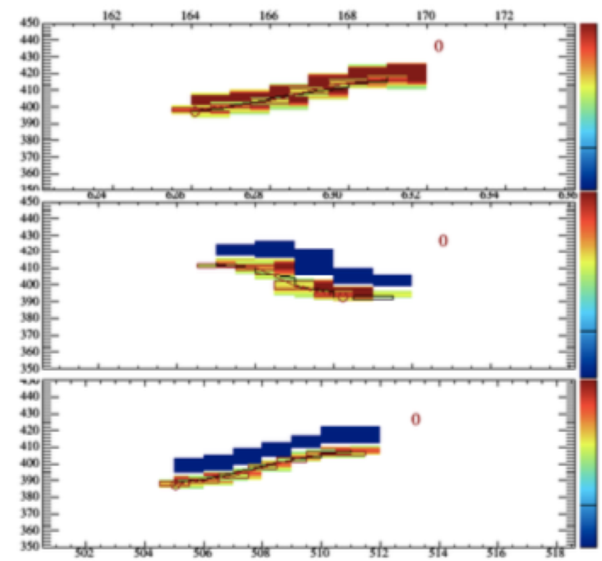
- Will improve w/SK-Gd
- HK will get to ~few deg

See talk by Masayuki Nakahata

Pointing to the supernova with LArTPCs



10.25 MeV electron



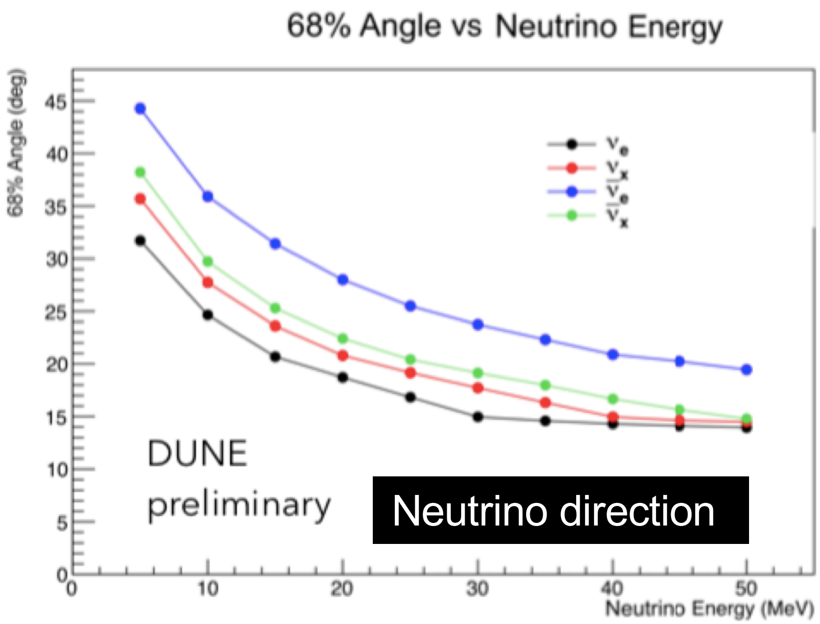
Fine-grained tracking...

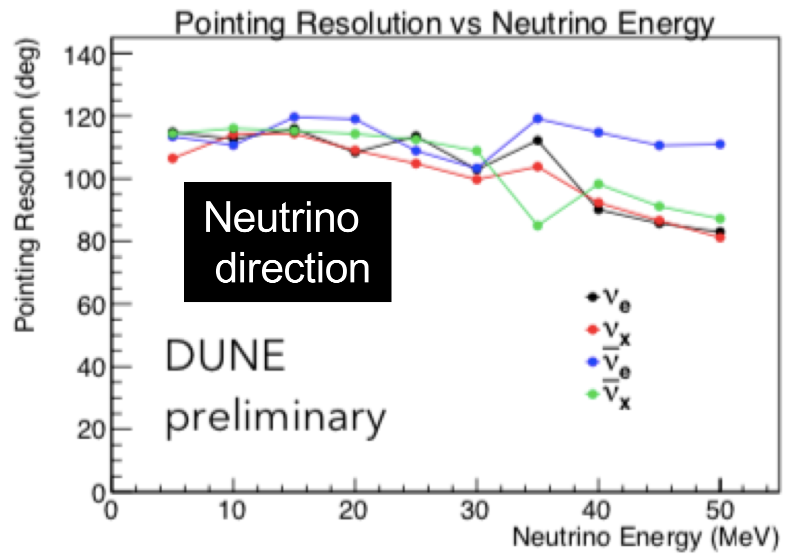
but note direction ambiguity, unlike Cherenkov!

... but can resolve statistically using bremsstrahlung directionality and multiple scattering

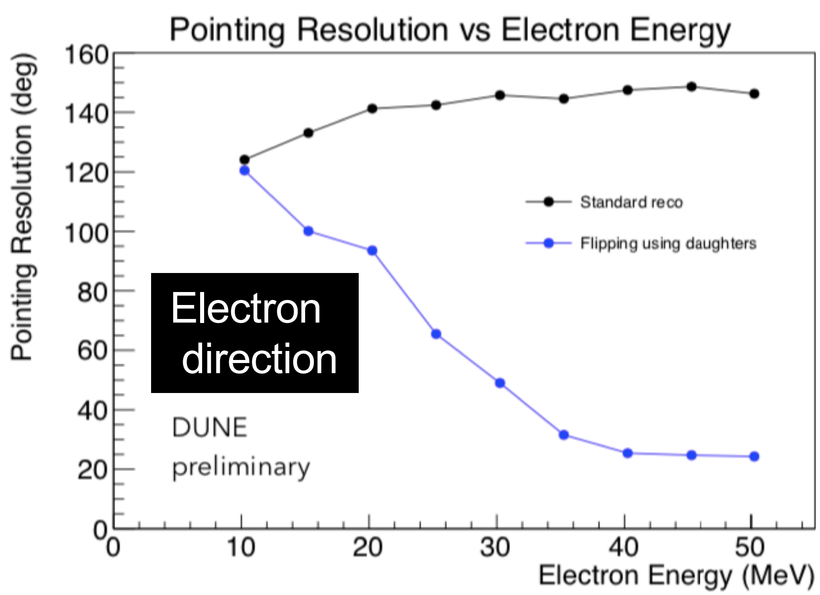
See talk by by AJ Roeth

Pointing to the supernova with ES in DUNE



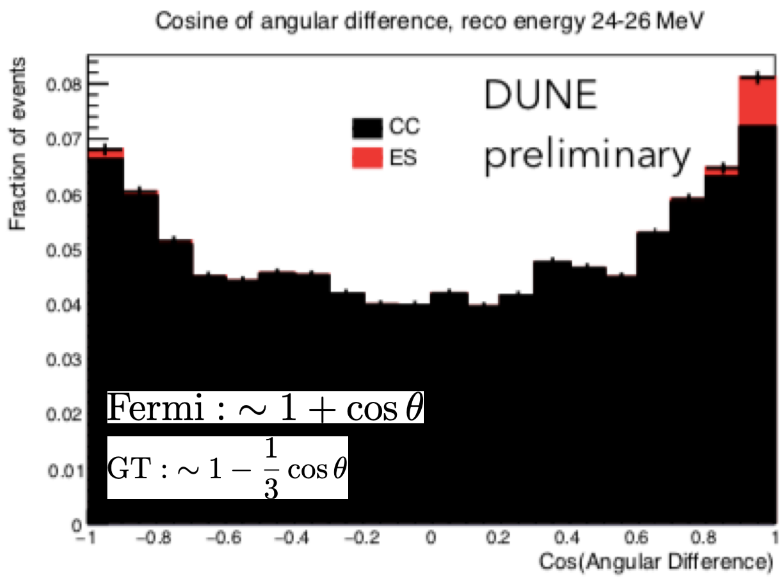


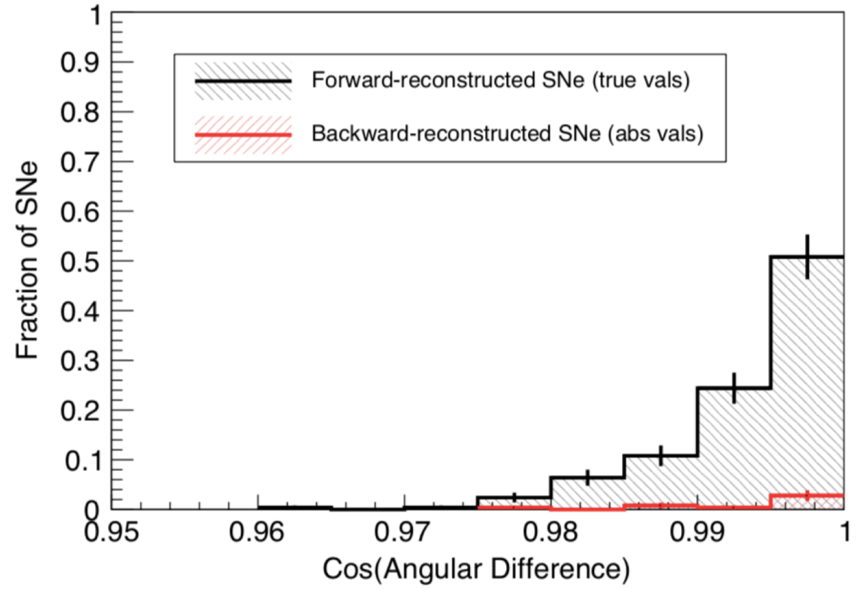
After daughter flipping



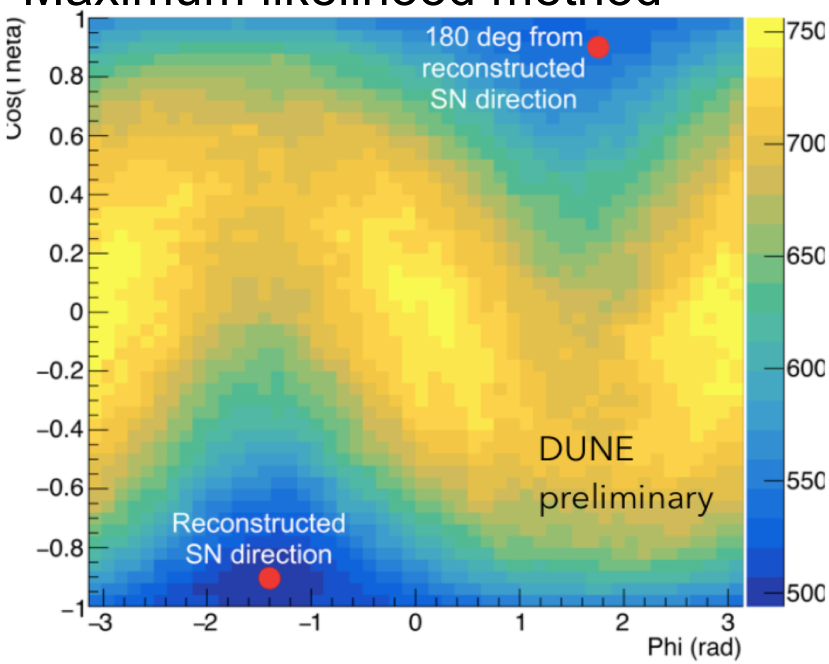
See talk by by AJ Roeth

Can make use of both ES and ν_eCC directionality





Maximum likelihood method



Overall pointing using an ensemble of events from a ~10 kpc supernova) → ~7.5°

...improvements still possible

See talk by by AJ Roeth

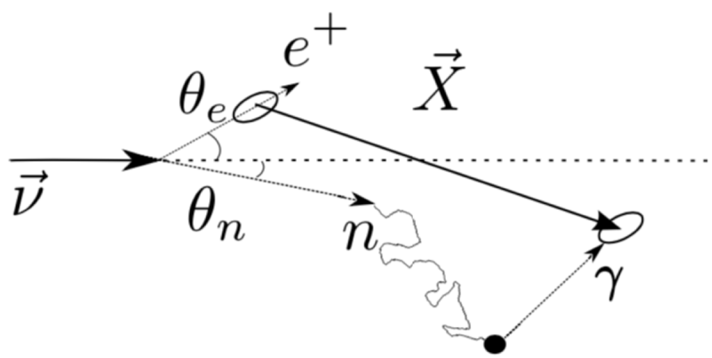
Pointing with Liquid Scintillator

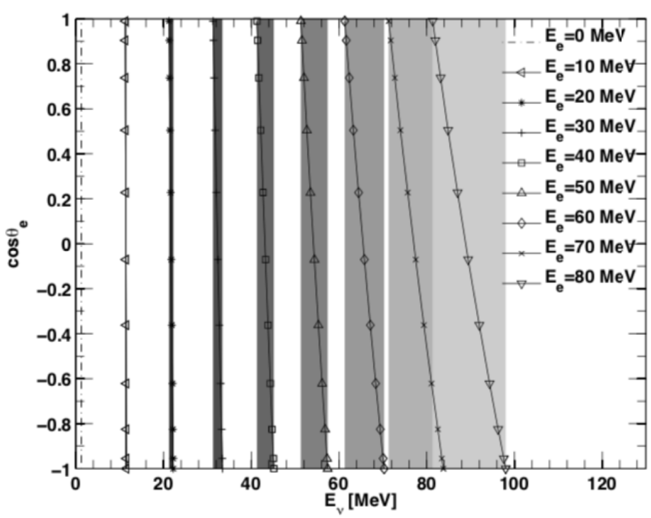
This is hard, as produced photons get quasi-isotropized...

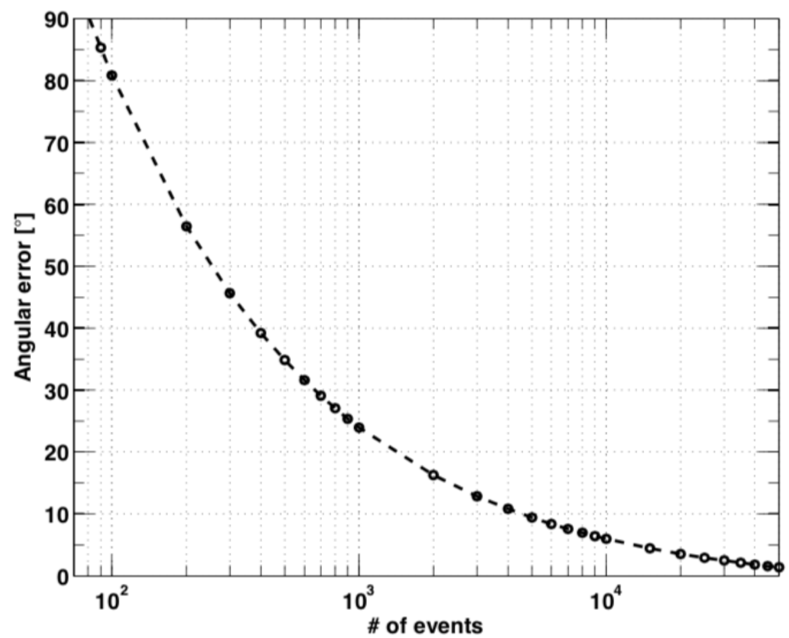
BUT, some statistical prospects using IBD kinematics

→ positron energy + reconstructed vertices of e^+ and n

Prompt directional detection of galactic supernova by combining large liquid scintillator neutrino detectors
V. Fischer (IRFU, Saclay) *et al.*. Apr 21, 2015. 25 pp.
Published in **JCAP 1508 (2015) 032**







Needs good statistics!

Neutrino Pointing Methods

- **Anisotropic neutrino interactions**
  combined with detector technology that can exploit it, using the burst neutrino signal
- **Triangulation**
  using inter-detector timing
- **Oscillation pattern pointing**
  in high-energy resolution detectors
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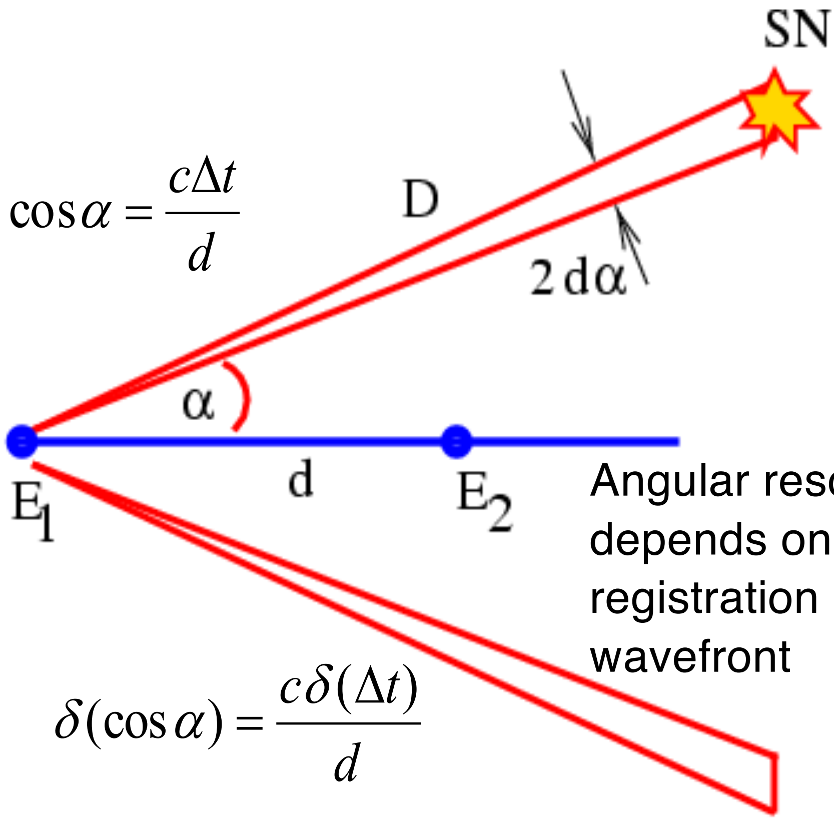
Triangulation

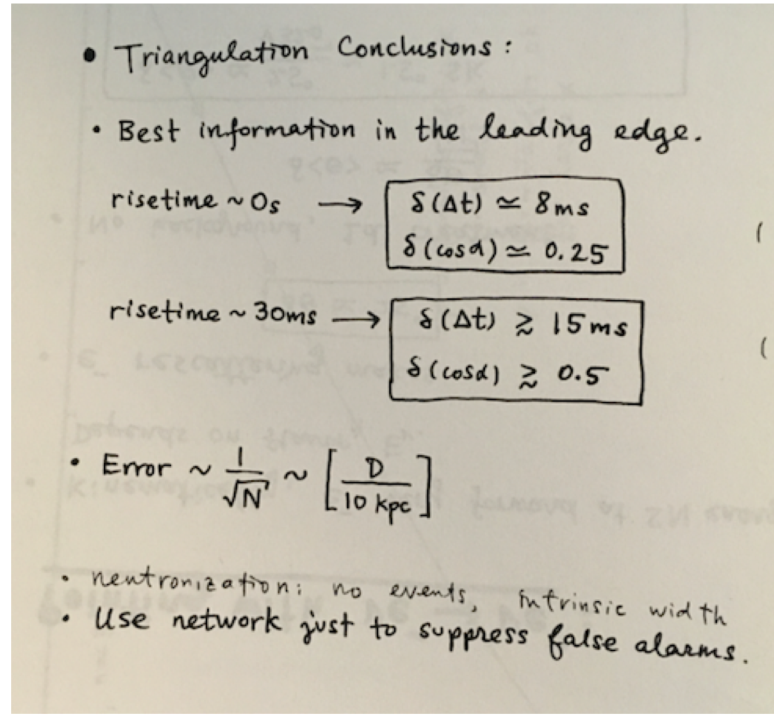


$$\cos\alpha = \frac{c\Delta t}{d}$$

$$\delta(\cos\alpha) = \frac{c\delta(\Delta t)}{d}$$

Angular resolution depends on timing registration of wavefront

In 1998, John Beacom was pretty down on this....



- Triangulation Conclusions :
  - Best information in the leading edge.

risetime ~ 0s → $\delta(\Delta t) \simeq 8ms$, $\delta(\cos\alpha) \simeq 0.25$

risetime ~ 30ms → $\delta(\Delta t) \gtrsim 15ms$, $\delta(\cos\alpha) \gtrsim 0.5$

- Error $\sim \frac{1}{\sqrt{N}} \sim \left[\frac{D}{10\ kpc}\right]$
- neutronization: no events, intrinsic width
- Use network just to suppress false alarms.

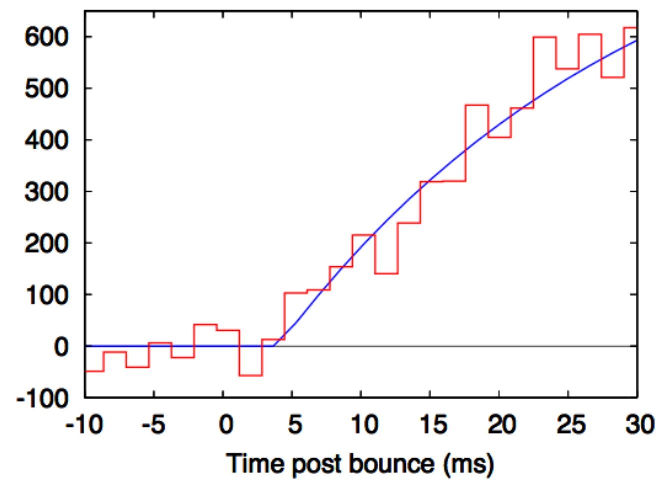
Can a supernova be located by its neutrinos?
John F. Beacom, P. Vogel (Caltech). Nov 1998. 10 pp.
Published in **Phys.Rev. D60 (1999) 033007**

Conclude that triangulation is not a good prospect
... too low stats, also hard in practice;
requires extensive data exchange to account for detector response...

But... things have evolved...

- new, very high stats detectors on the horizon (HK, DUNE, JUNO,)
- good timing (~ms) from IceCube likely possible (and KM3Net?)
- ways to exploit BH formation

Reconstructing the supernova bounce time with neutrinos in IceCube
Francis Halzen (Wisconsin U., Madison), Georg G. Raffelt (Munich, Max Planck Inst.). Aug 2009. 3 pp.
Published in **Phys.Rev. D80 (2009) 087301**

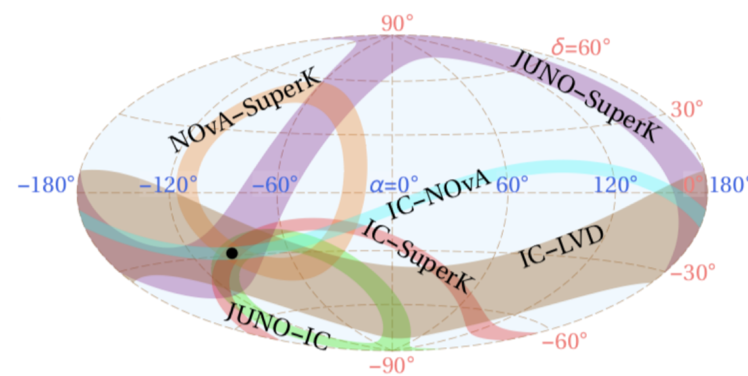


Some new(ish) papers:

Revisiting the Triangulation Method for Pointing to Supernova and Failed Supernova with Neutrinos
T. Mühlbeier, H. Nunokawa (Rio de Janeiro, Pont. U. Catol.), R. Zukanovich Funchal (Sao Paulo U.). Apr 17, 2013. 7 pp.
Published in **Phys.Rev. D88 (2013) 085010**

Neutrino astronomy with supernova neutrinos
Vedran Brdar, Manfred Lindner, Xun-Jie Xu (Heidelberg, Max Planck Inst.). Feb 7, 2018
Published in **JCAP 1804 (2018) no.04, 025**

Timing the Neutrino Signal of a Galactic Supernova
Rasmus S.L. Hansen (Heidelberg, Max Planck Inst. & Aarhus U.), Manfred Lindner, Oliver Scholer (Heidelberg, Max Planck Inst.).
e-Print: **arXiv:1904.11461 [hep-ph]**



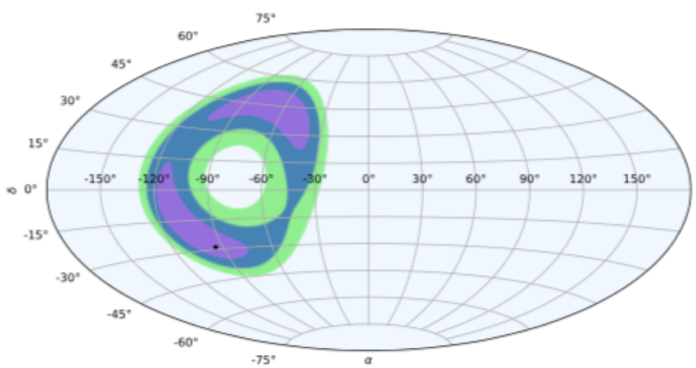
....and there may be strategies for *fast* response!

Coming soon: work by N. Linzer

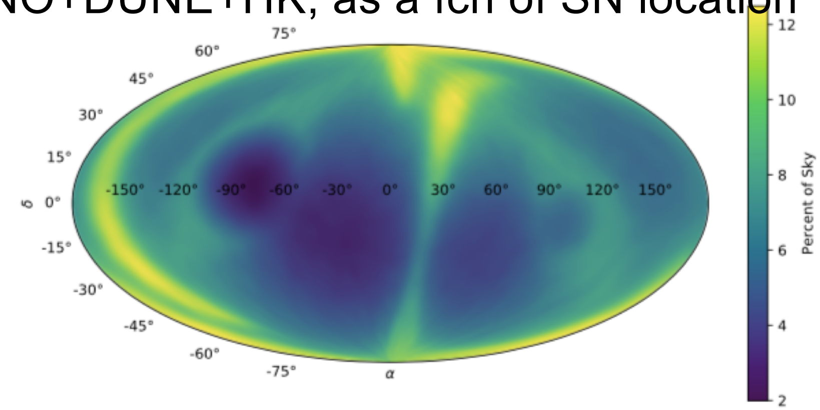
Simple, robust method based on Δt of first events, taking into account (and partially correcting for)

- bias due to realistic detector response
- background (pick first event with another within 20 ms)

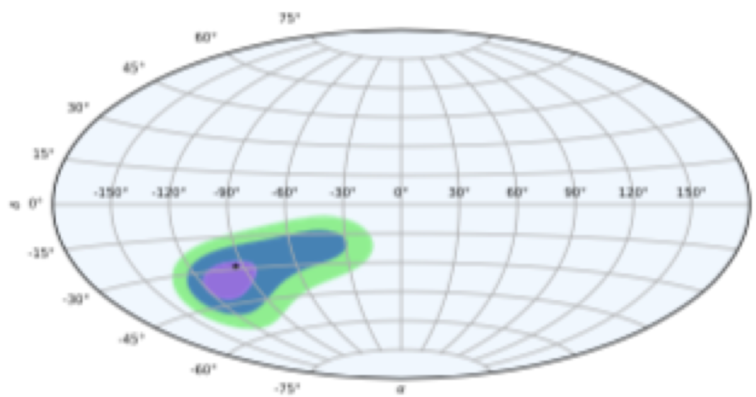
JUNO+DUNE+HK



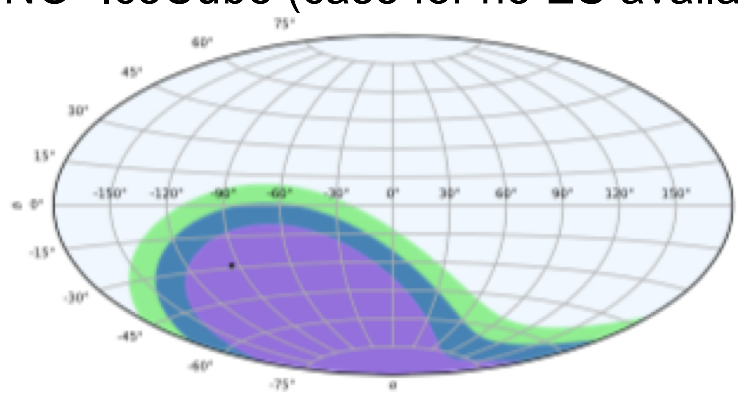
JUNO+DUNE+HK, as a fcn of SN location



JUNO+DUNE+HK+IceCube



JUNO+IceCube (case for no ES available)



Preliminary results, 10 kpc, “Garching” model (conservative); true point is black dot

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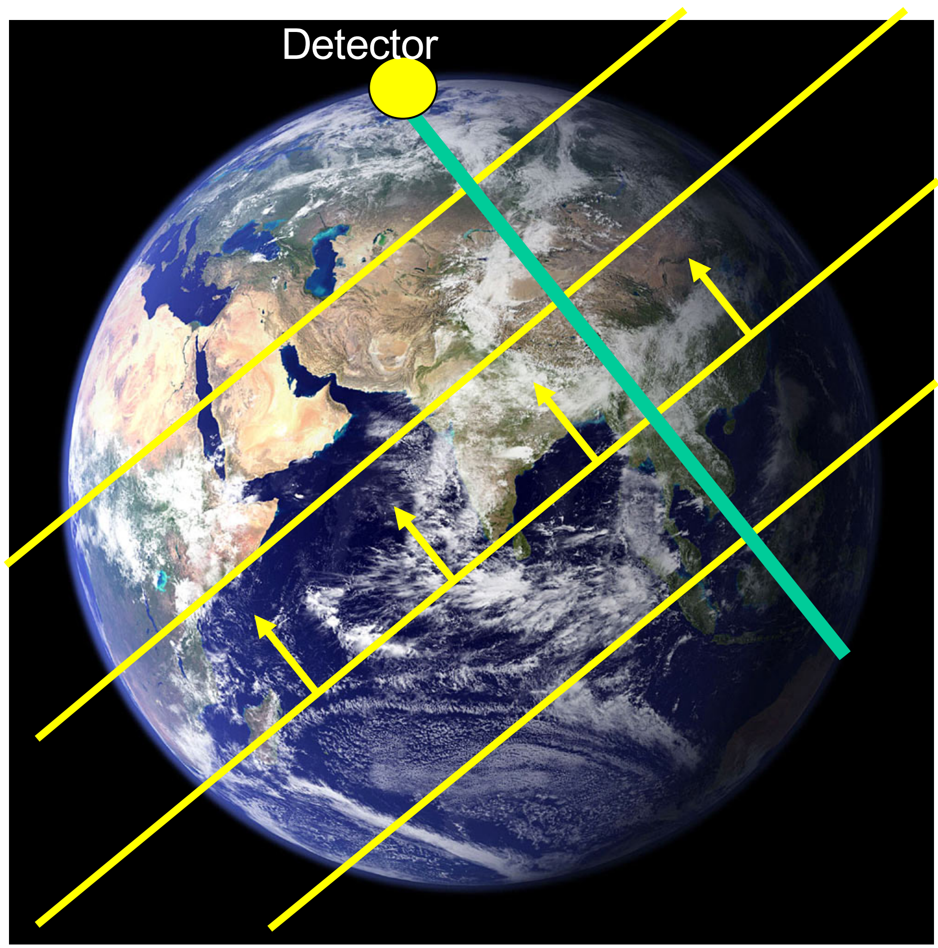
- **All of the above!**

A different approach: use the **matter oscillation energy spectrum** to find the pathlength L traveled in the Earth
(assume oscillation parameters well known)

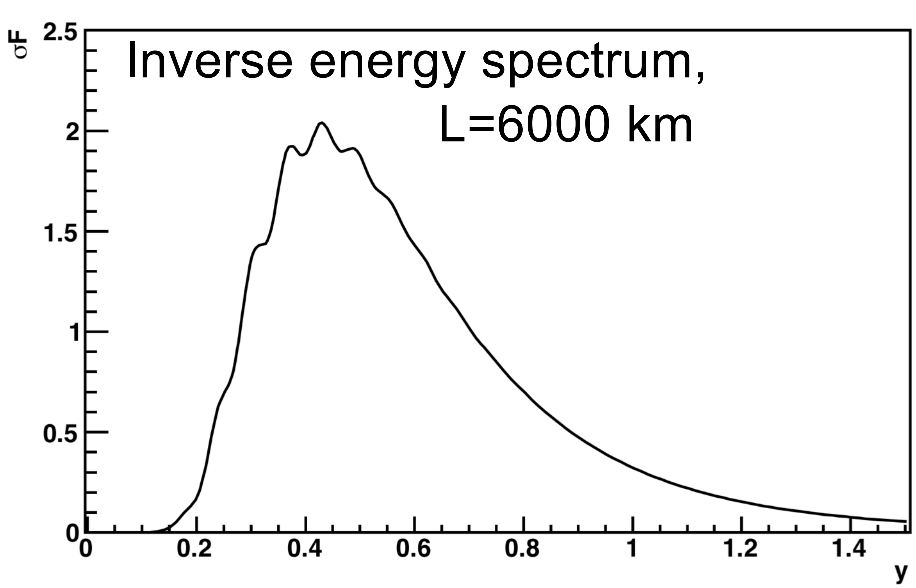
Obtaining supernova directional information using the neutrino matter oscillation pattern
Kate Scholberg (Duke U.), Armin Burgmeier (Karlsruhe U.), Roger Wendell (Duke U.). Oct 2009. 11 pp.
Published in **Phys.Rev. D81 (2010) 043007**



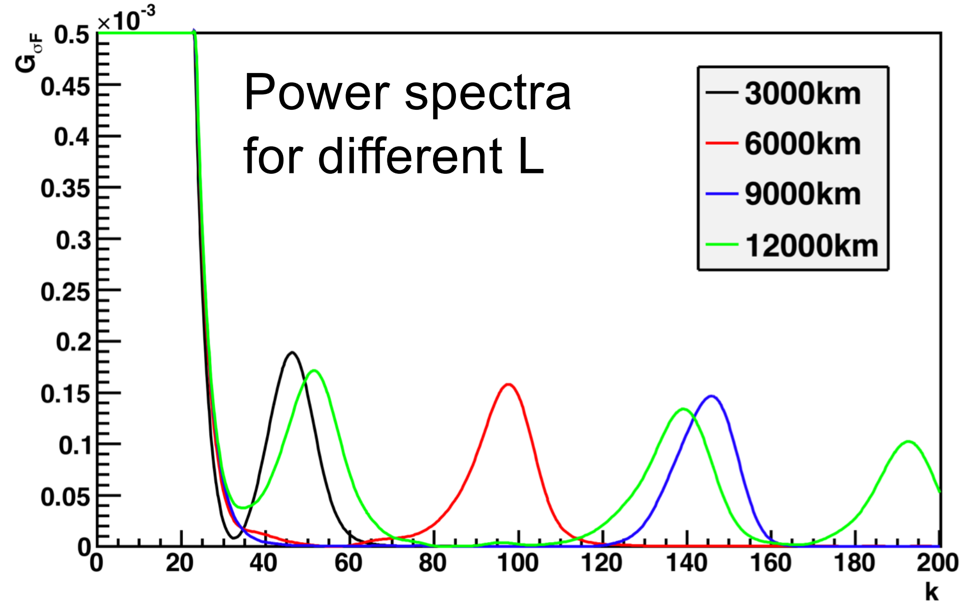
If you can determine the pathlength traveled in the Earth, you know the supernova will be found on a ***ring on the sky***

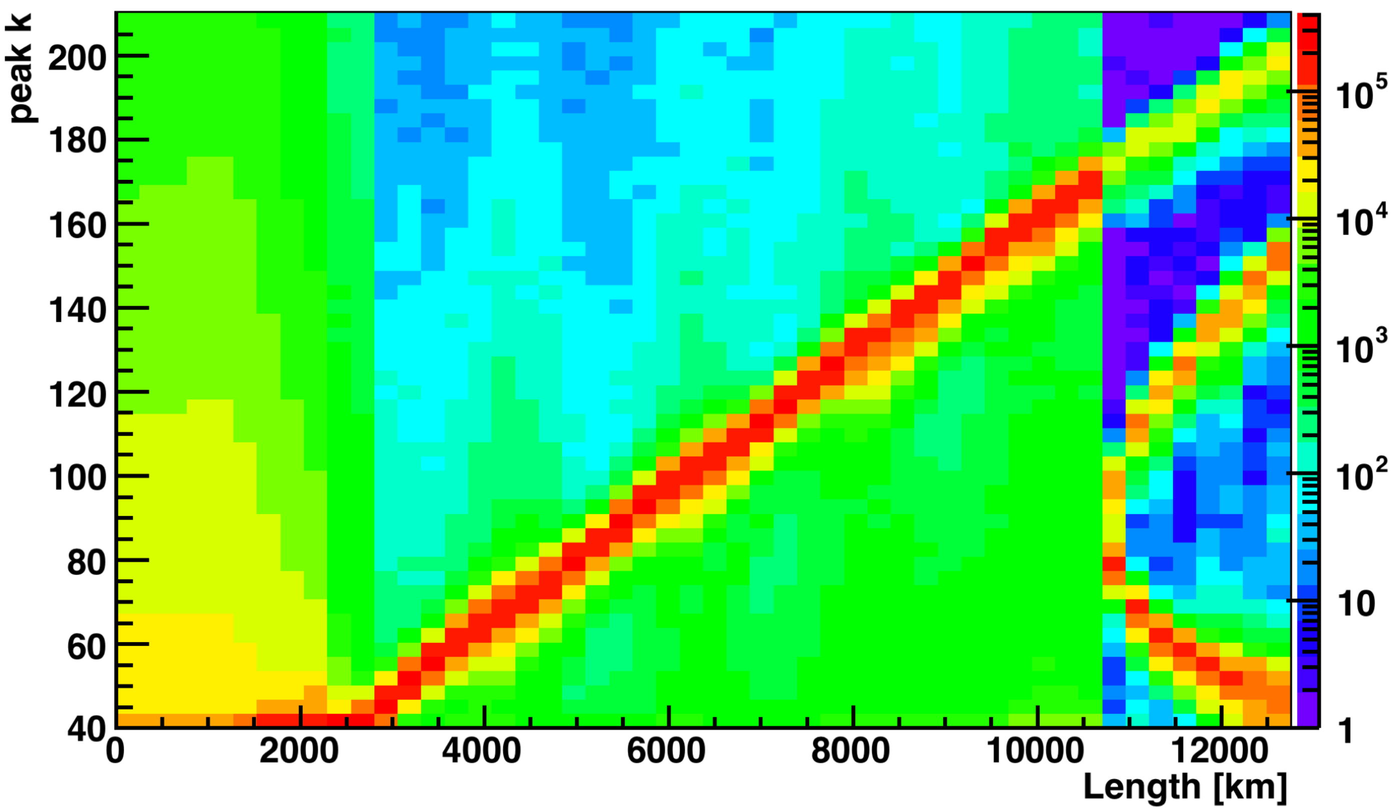
Method requires
very good energy resolution
(scintillator)
and **large statistics**

[Caveat: collective oscillations could interfere]



A. S. Dighe, et al. hep-ph/ 0311172

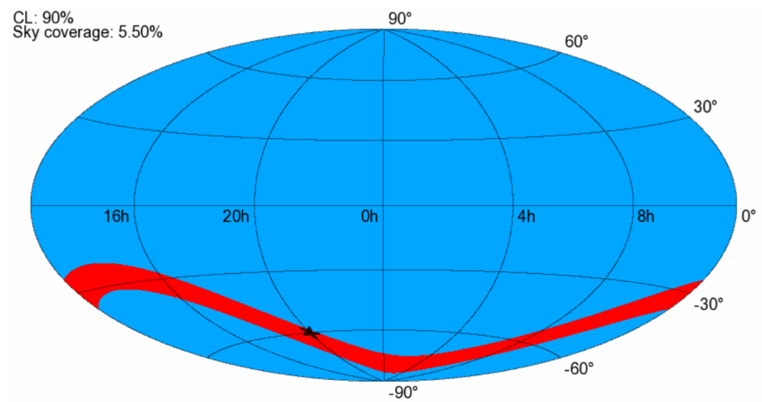




Peak in power spectrum vs L for 500,000 simulated SNae, 60,000 events each (perfect energy resolution)

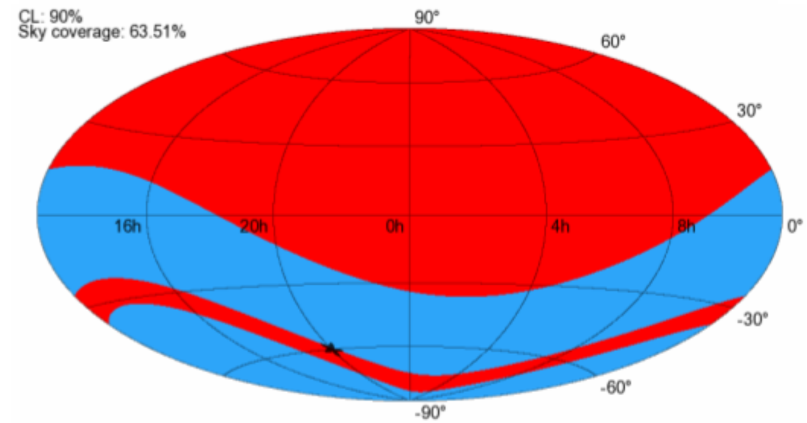
➔measure k_{peak} to find allowed L values;
peak height info also usable

Example skymaps from oscillation pointing



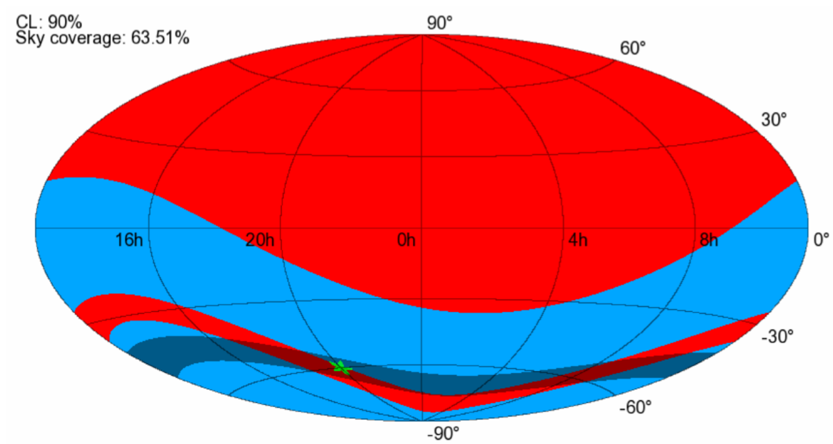
One detector

Perfect energy resolution
60,000 neutrino events
SN at dec=-60^{o}, RA=20^{h}, 0:00
Finland



One detector

Scint energy resolution
60,000 neutrino events
SN at dec=-60^{o}, RA=20^{h}, 0:00
Finland



One scintillator detector + IceCube

(assume ~ 1 ms timing)

oscillation: red

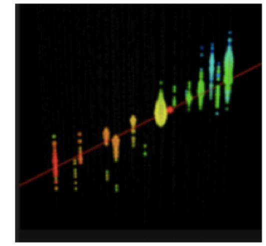
timing: dark

It would be interesting to redo this study w/JUNO, latest assumptions...

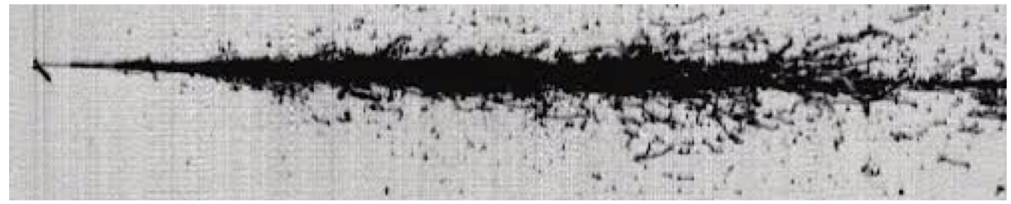
Neutrino Pointing Methods

- **Anisotropic neutrino interactions**
  combined with detector technology that can exploit it, using the burst neutrino signal
- **Triangulation**
  using inter-detector timing
- **Oscillation pattern pointing**
  in high-energy resolution detectors
- **High-energy (~GeV) neutrino follow-on pointing**
  in directional detectors, using later neutrinos NEW
- **All of the above!**

One more: *high energy neutrino events,*



GeV-TeV+ neutrinos,
produced in the
supernova explosion



First pointed out in:

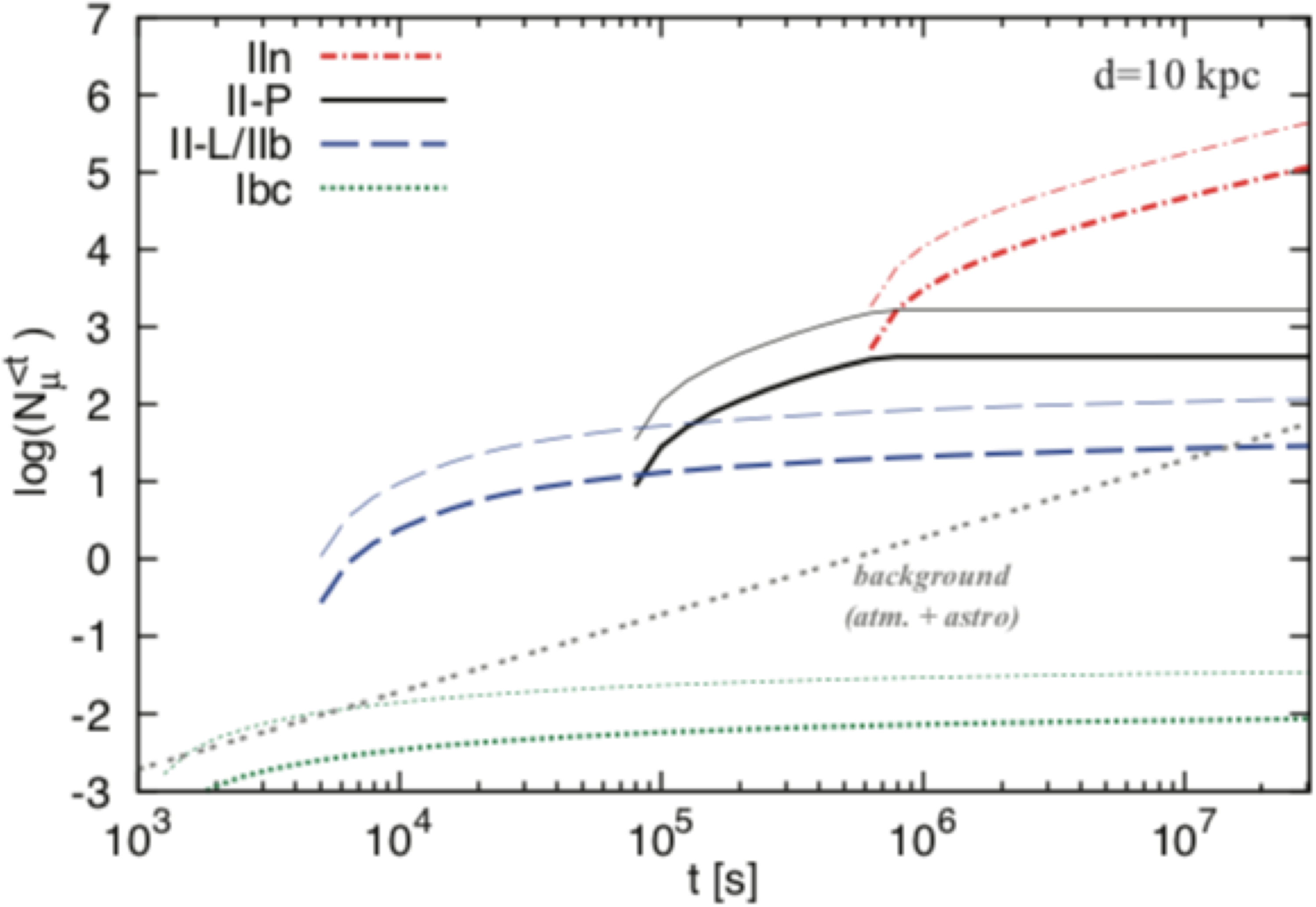
Supernova pointing with low-energy and high-energy neutrino detectors
R. Tomas, D. Semikoz, G.G. Raffelt, M. Kachelriess, A.S. Dighe (Munich, Max Planck Inst.). Jul 2003. 12 pp.
Published in **Phys.Rev. D68 (2003) 093013**

but this reference was pessimistic on the timescale...
>12 hours, up to years

But some recent work predicts earlier fluxes..
might lose the shock race, but still reasonably early
Advantage: **precision pointing** (<~ deg) at high energy,
both from physics (ν-charged particle correlation)
and detectors (IceCube, maybe DUNE?)

New Prospects for Detecting High-Energy Neutrinos from Nearby Supernovae
Kohta Murase (Penn State U. & Penn State U., Astron. Astrophys. & Kyoto U., Yukawa Inst., Kyoto). May 12, 2017. 1 pp.
Published in **Phys.Rev. D97 (2018) no.8, 081301**

Events in IceCube



Possibly good things come to those who wait (a bit)...
very important to keep detectors running after the burst

Summary comments on the methods

Method	Comments
Anisotropic interactions	• ES very good in in SK... several ° at 10 kpc • Will be even better in SK-Gd, HK • DUNE also excellent • Some info from scintillator via IBD
Triangulation	• Some good, fast info from next generation, especially with IceCube
Oscillation pattern	• Hard: needs good energy resolution & stats • But scintillator detectors could add useful information
High-energy events	• May not be too late for the party... <hour scale in some scenarios • Excellent (possibly sub-deg) intrinsic pointing

Neutrino Pointing Methods

- ❑ **Anisotropic neutrino interactions**
  combined with detector technology that can exploit it, using the burst neutrino signal
- ❑ **Triangulation**
  using inter-detector timing
- ❑ **Oscillation pattern pointing**
  in high-energy resolution detectors
- ❑ **High-energy (~GeV) neutrino follow-on pointing**
  in directional detectors, using later neutrinos
- ❑ **All of the above!**

We should consider **staged methods**...

what can be done fast? Refined later?

→ develop SNEWS strategy for

continual updates as information flows in

Summary

Directional information is valuable

- Need it fast!
- But late may be better than never

Multiple strategies

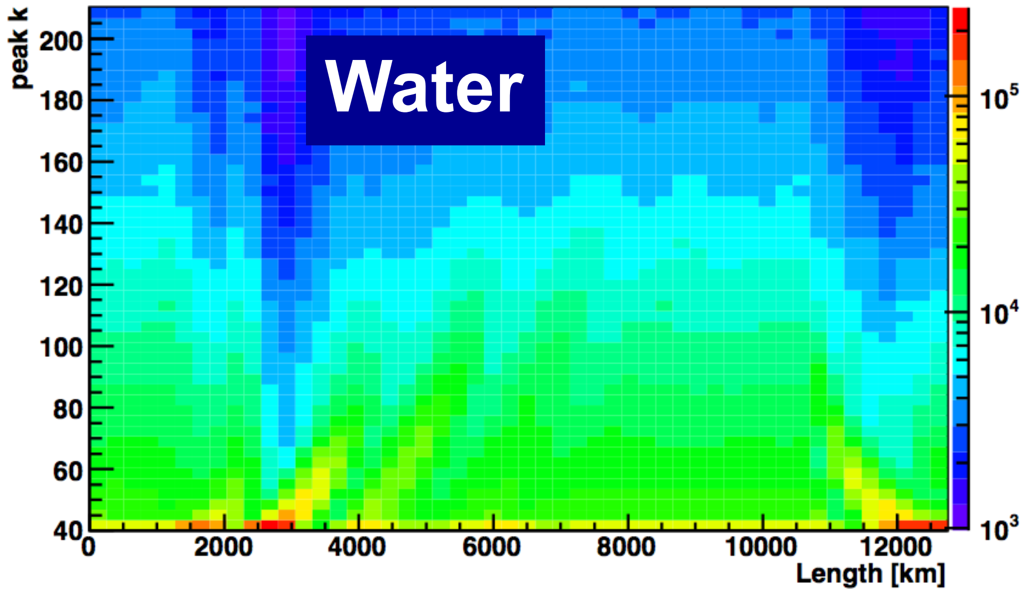
- Anisotropic information in single detectors probably best
- But other methods may improve the response,
  may be faster

Need to develop strategy:

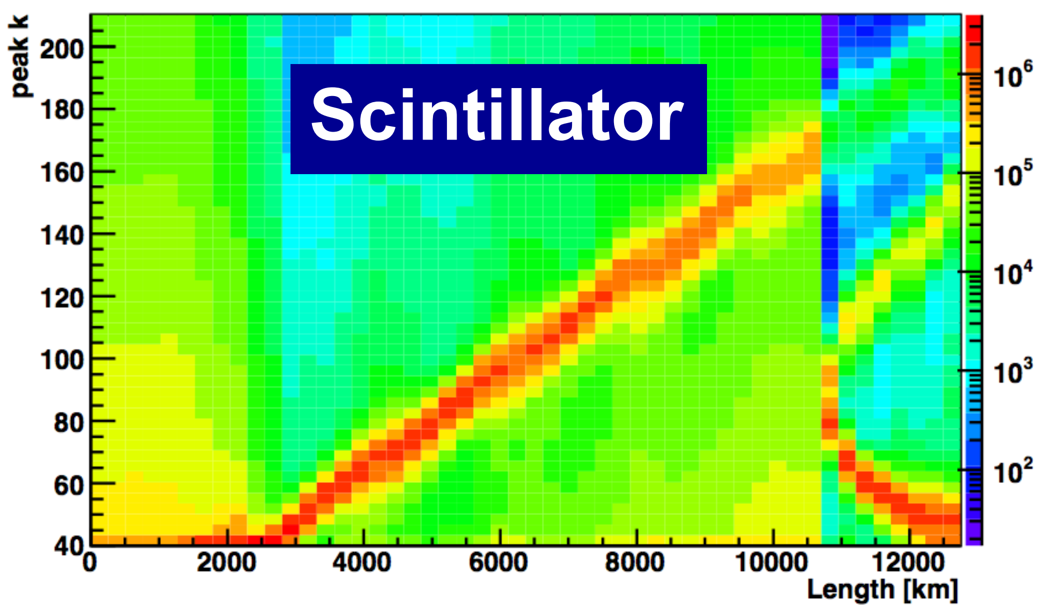
- Staged approach may be best...
  how to share, incorporate
  refined information
  on different timescales?

Extras/Backups

Method degraded for more realistic cases:

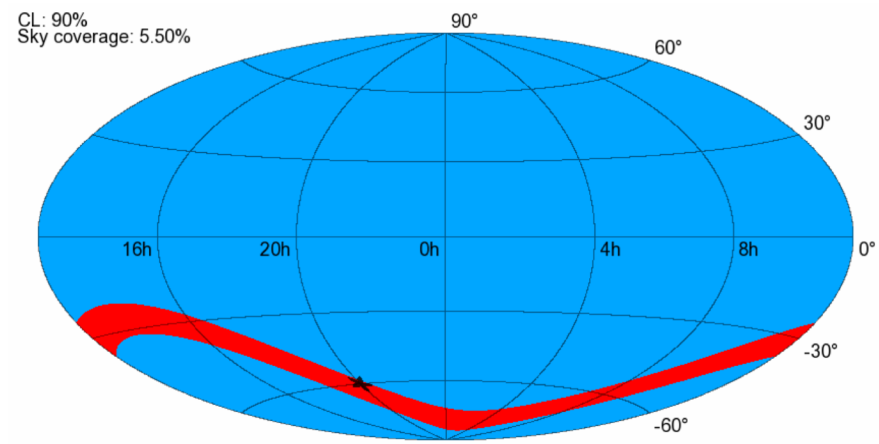


Peaks too smeared to be usable



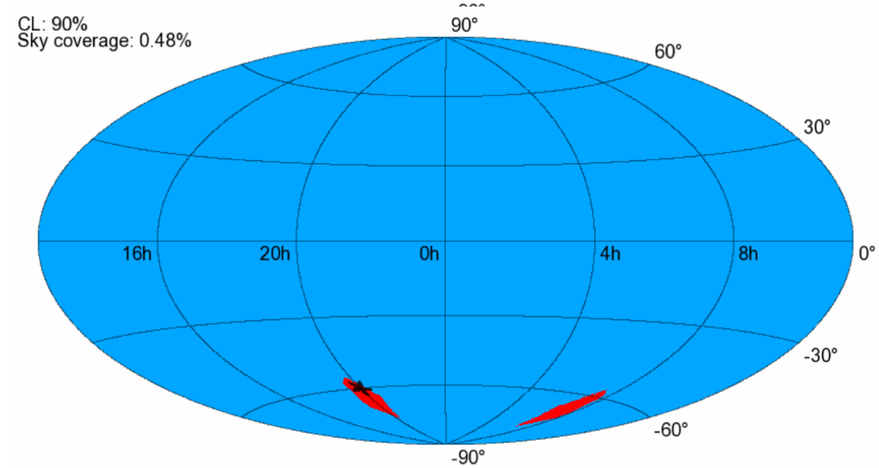
Potentially doable

Example skymaps: perfect energy resolution



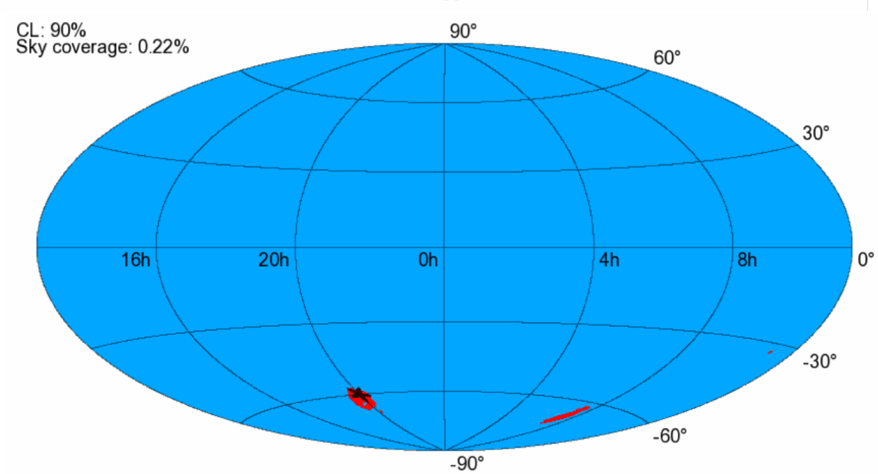
One detector

Perfect energy resolution
60,000 neutrino events
SN at dec=-60^{o}, RA=20^{h}, 0:00
Finland



Two detectors

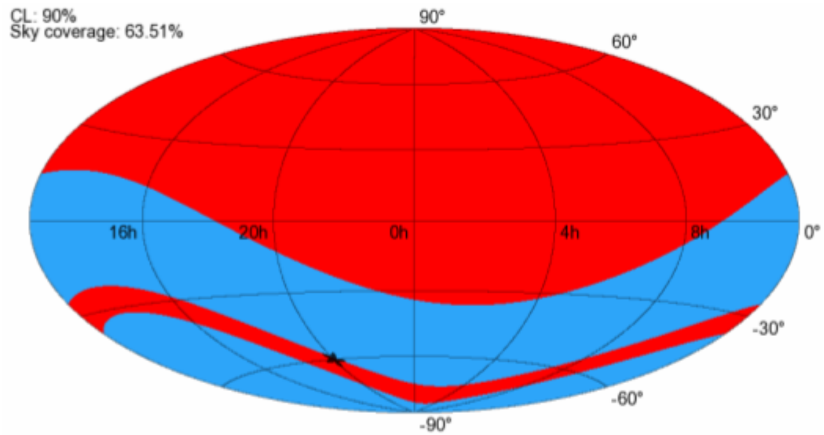
Finland+Hawaii



Three detectors

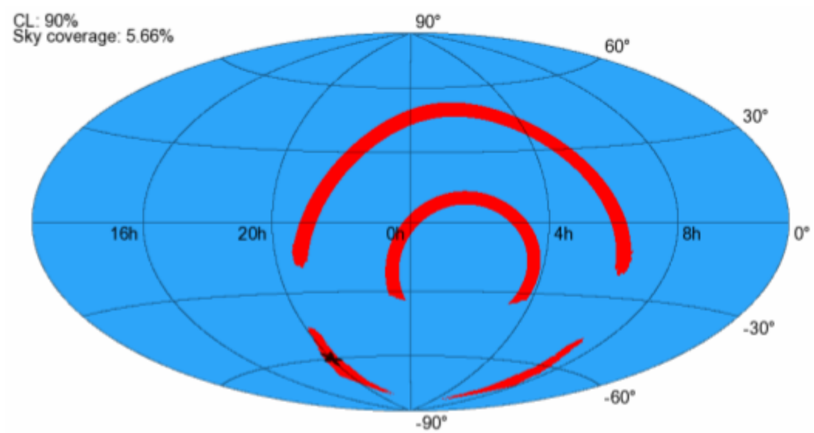
Finland+Hawaii+SD

Example skymaps: scintillator energy resolution



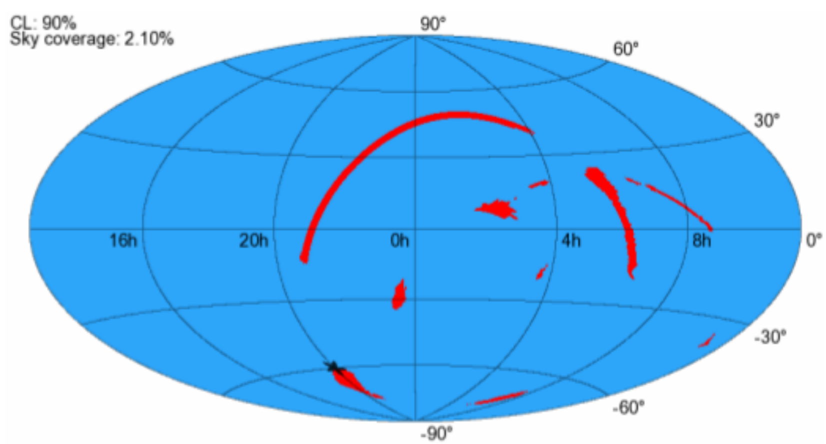
One detector

Scint energy resolution
60,000 neutrino events
SN at dec=-60^{o}, RA=20^{h}, 0:00
Finland



Two detectors

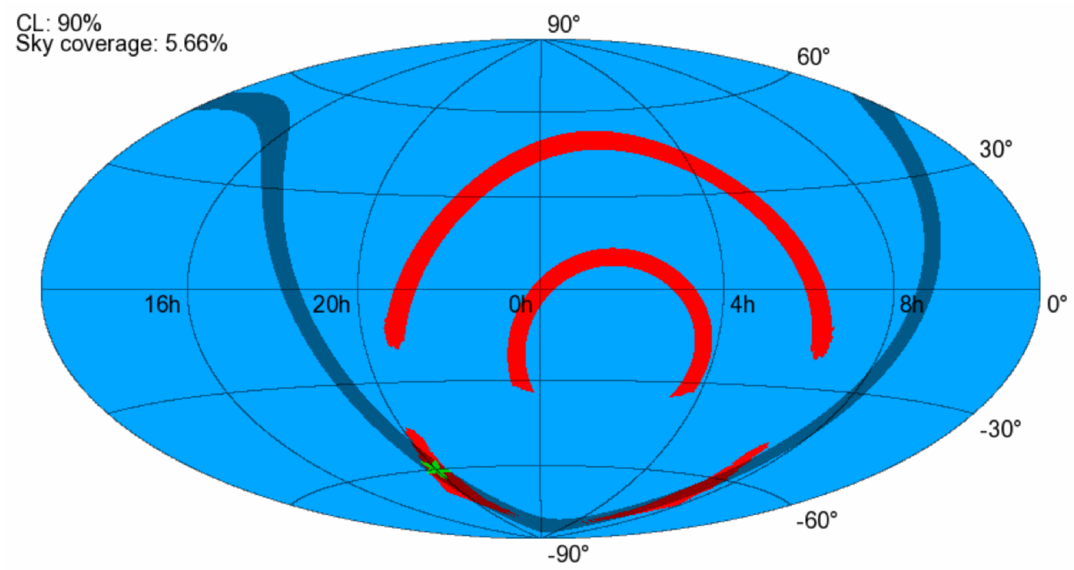
Finland+Hawaii



Three detectors

Finland+Hawaii+SD

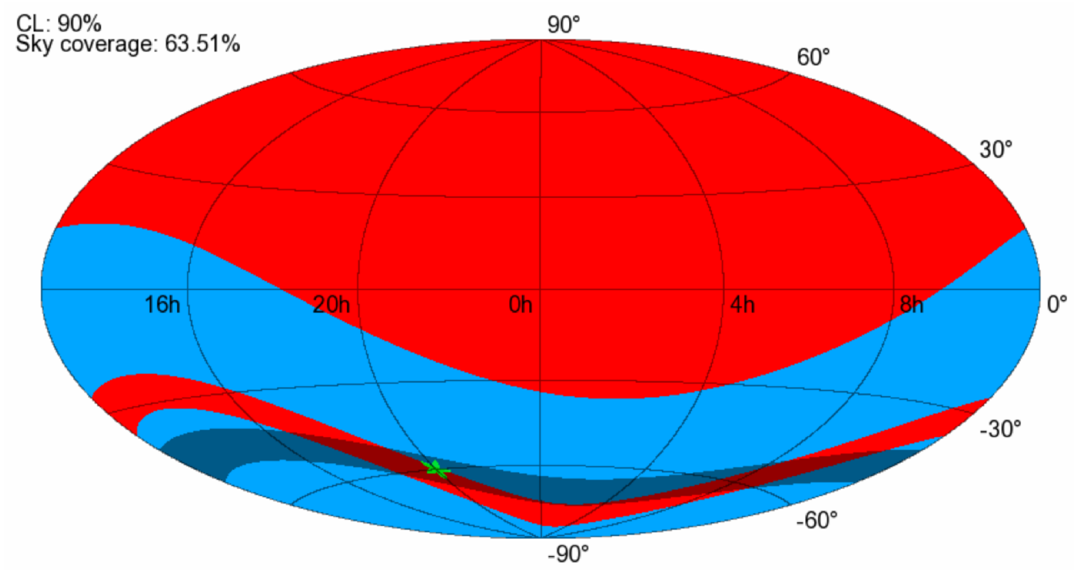
Can improve using relative timing information



Two scintillator detectors

oscillation: red

timing: dark



One scintillator detector + IceCube

(assume ~ 1 ms timing)

oscillation: red

timing: dark

Large statistics as well as good resolution required!

Scintillator-like energy resolution, one detector in Finland