Supernova Neutrino Pointing or, POTATOES*

Kate Scholberg, Duke University
SNνD 2023@LNGS
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*Point Over There At That Old Exploding Star [Credit:E. Kearns]

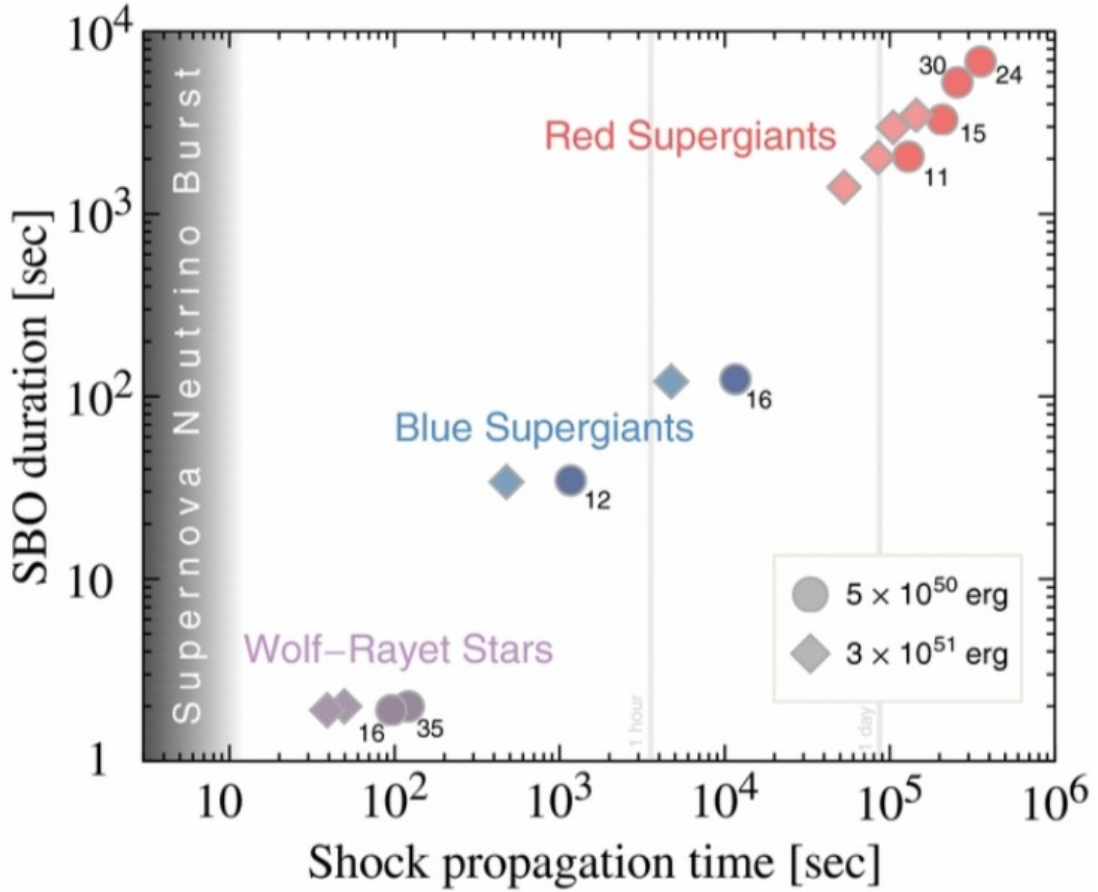
OUTLINE

- 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

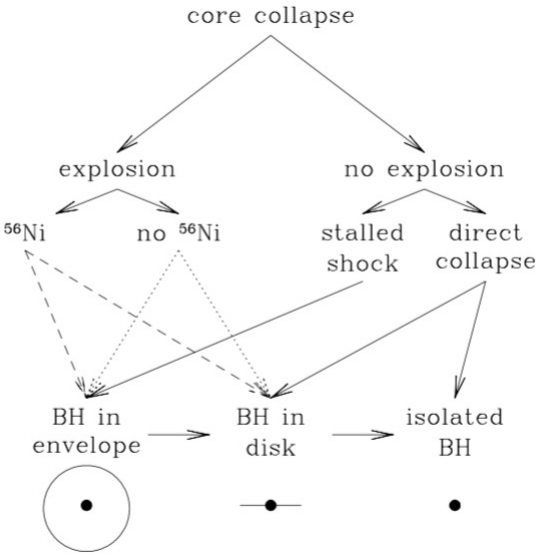
Want to point with ***low latency***

*Also physics reasons, e.g. neutrino energy resolution

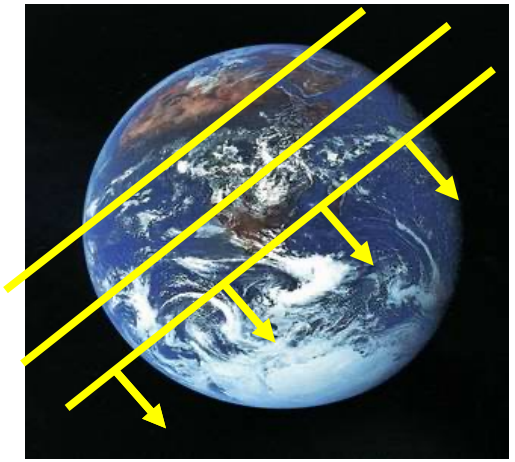
But even if it's not prompt, there are still motivations to use neutrinos to see the SN direction…

There may be no bright supernova!

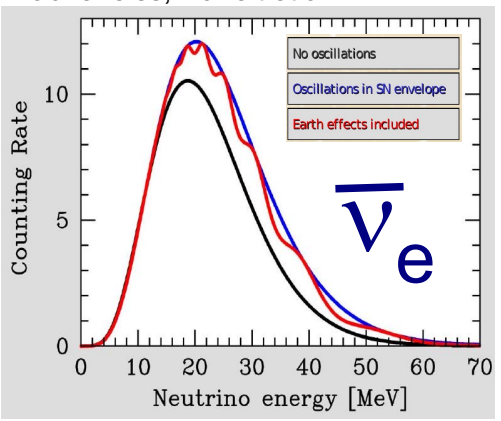
→ narrow down
the search for a progenitor,
or a "winked out" star



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

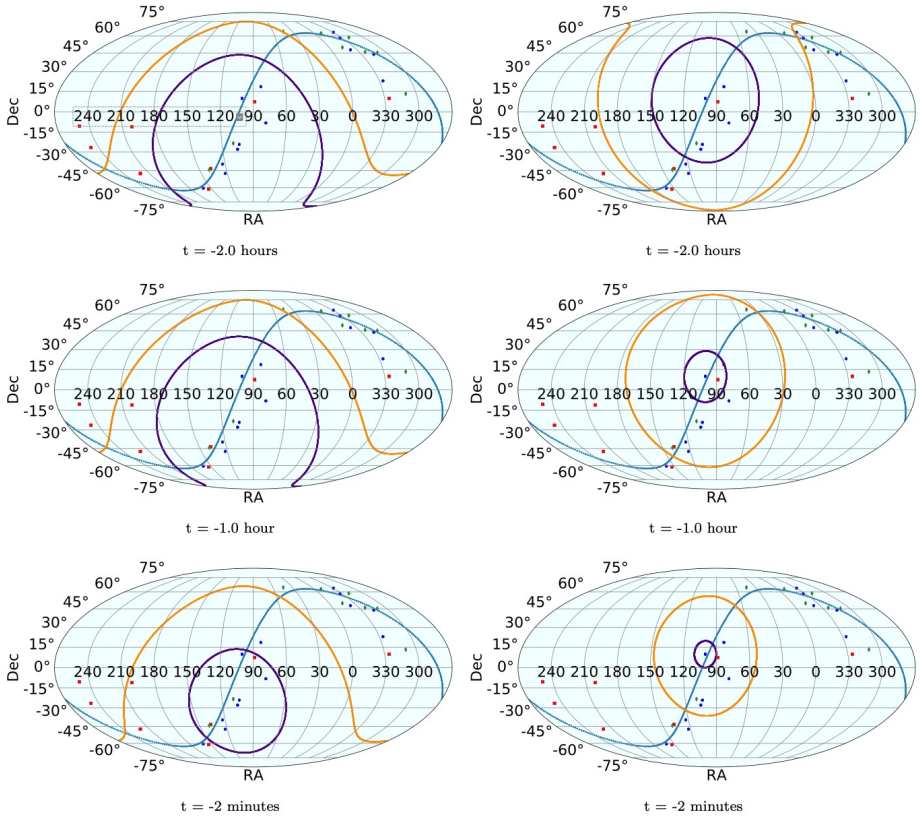
So refined direction information late is better than never…

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

Presupernova neutrinos: directional sensitivity and prospects for progenitor identification

Mainak Mukhopadhyay (Arizona State U., Tempe), Cecilia Lunardini (Arizona State U., Tempe), F.X. Timmes (Arizona State U., Tempe and Michigan State U., JINA), Kai Zuber (TU, Dresden (main)) (Apr 4, 2020)

Published in: *Astrophys.J.* 899 (2020) 2, 153 • e-Print: 2004.02045 [astro-ph.HE]



0.5 kpc

0.3 kpc

Orange: LS
Blue: LS-Li detector

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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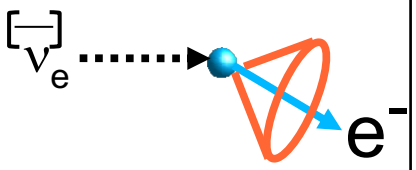
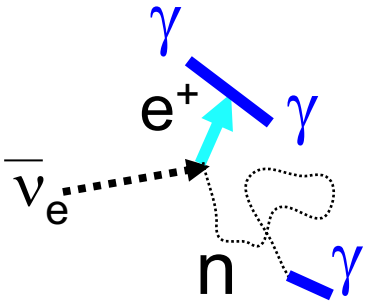
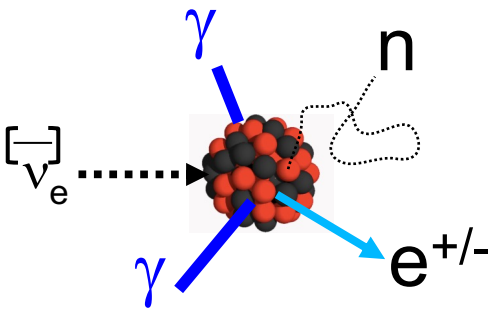
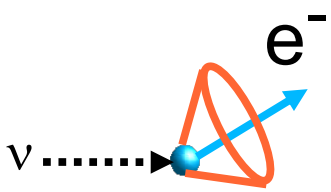
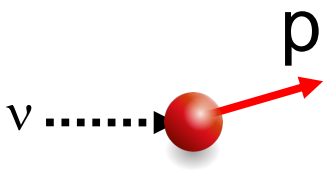
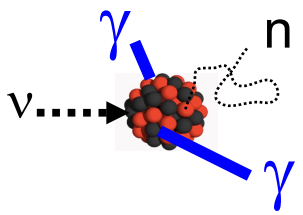
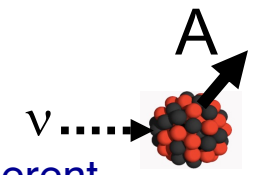
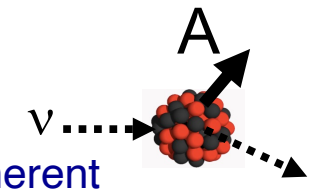
Supernova-relevant neutrino interactions

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

Various possible ejecta and deexcitation products

How do these interactions feel to the neutrino?

oops…



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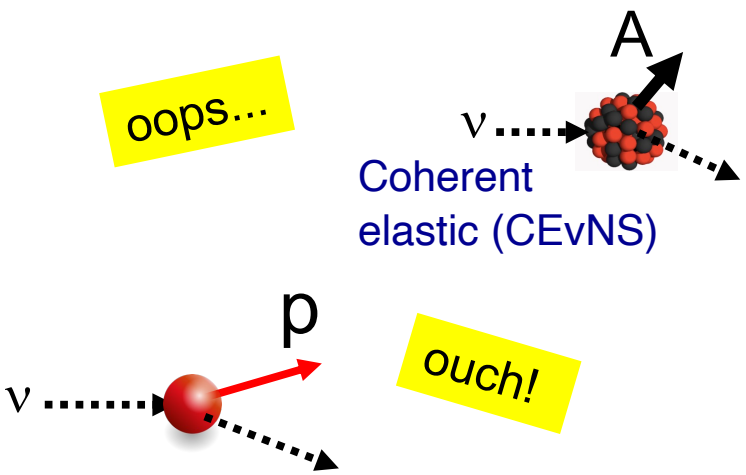

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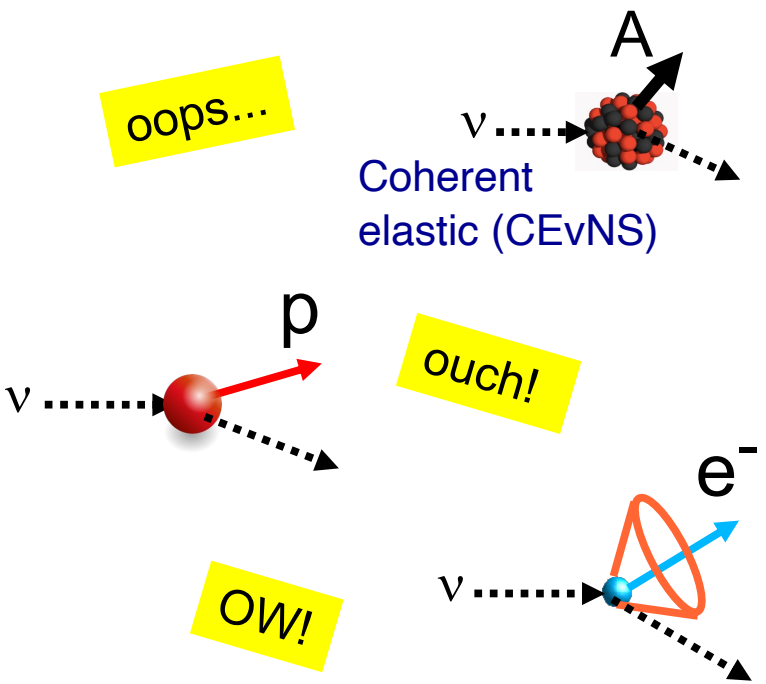

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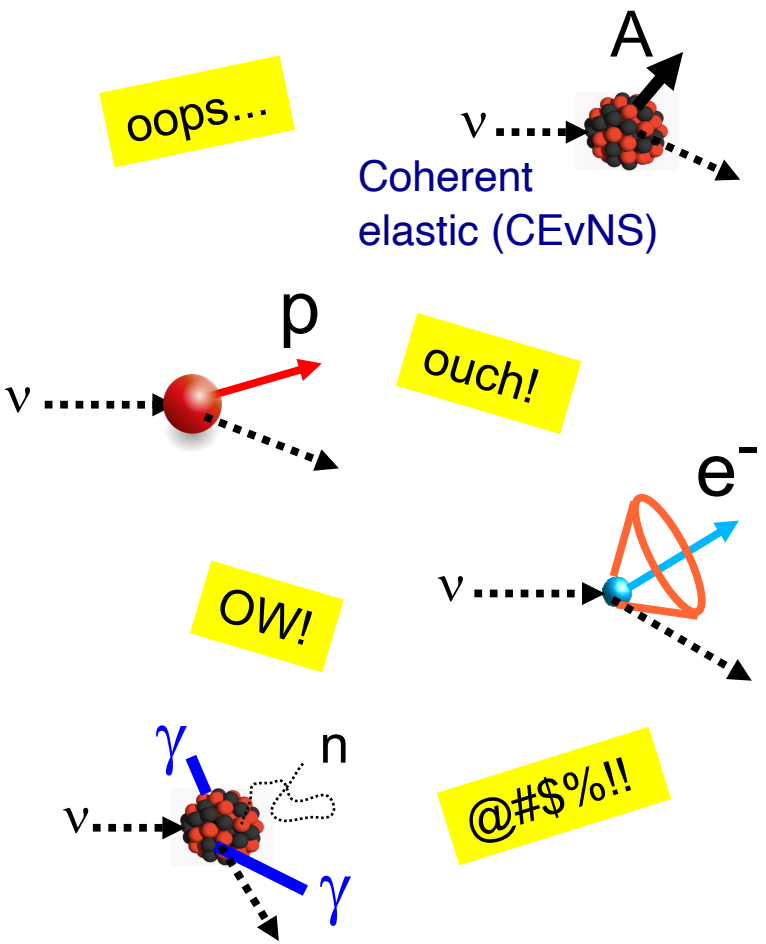

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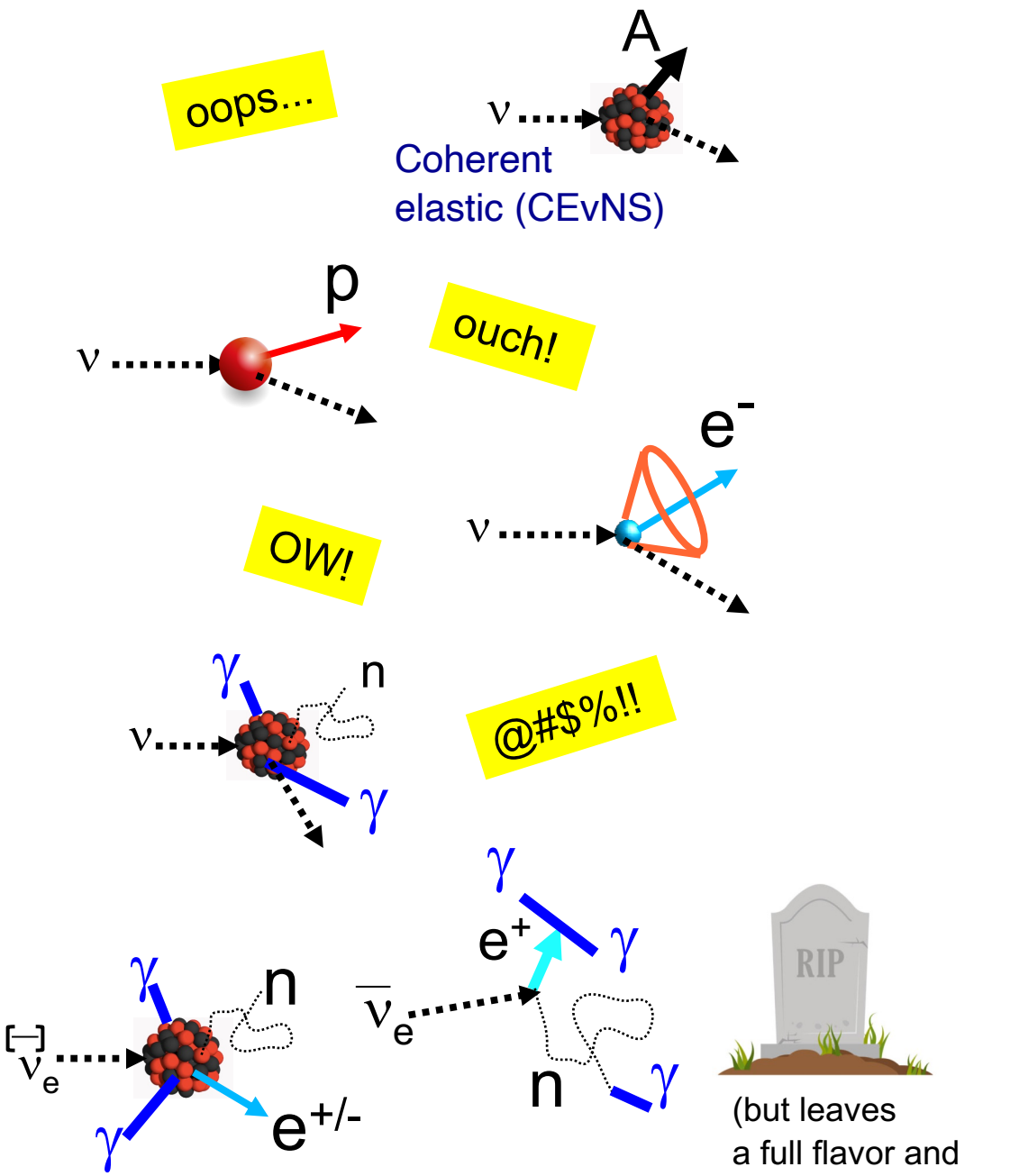

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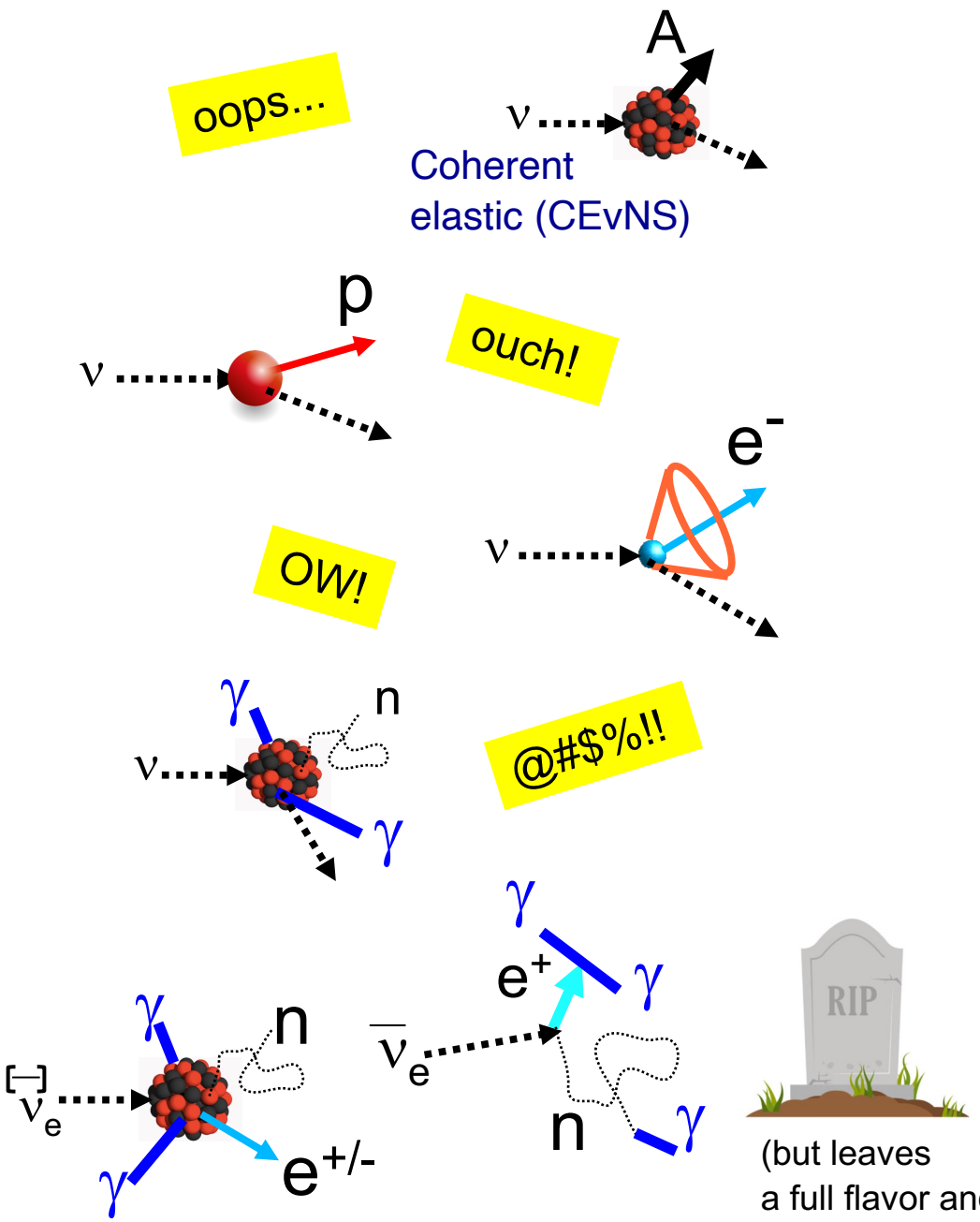

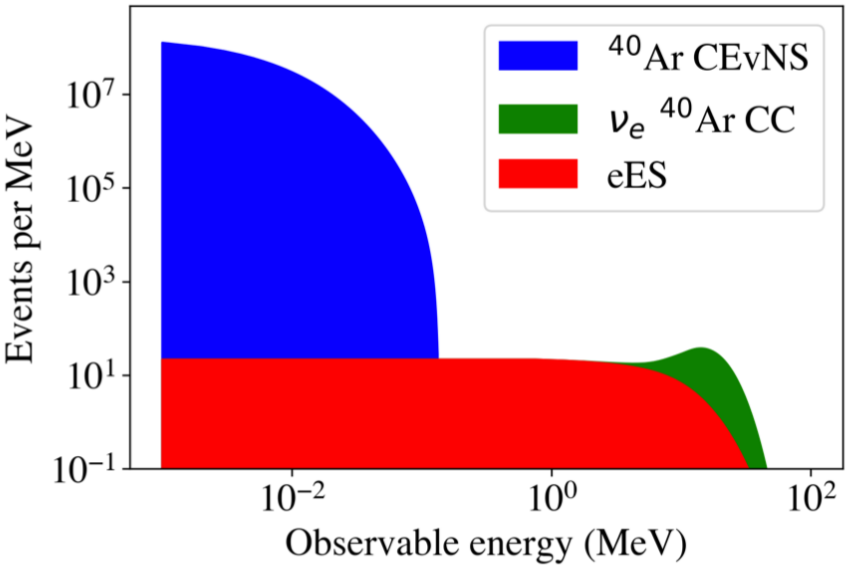

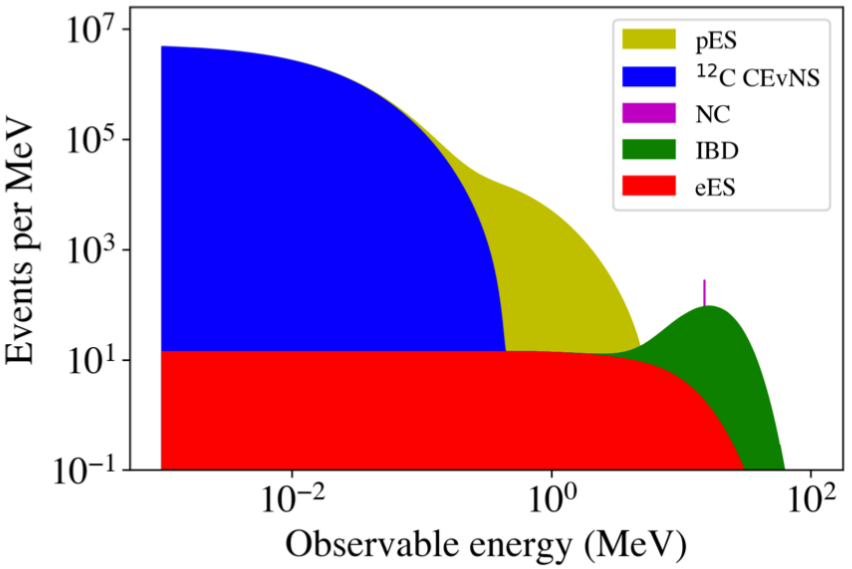

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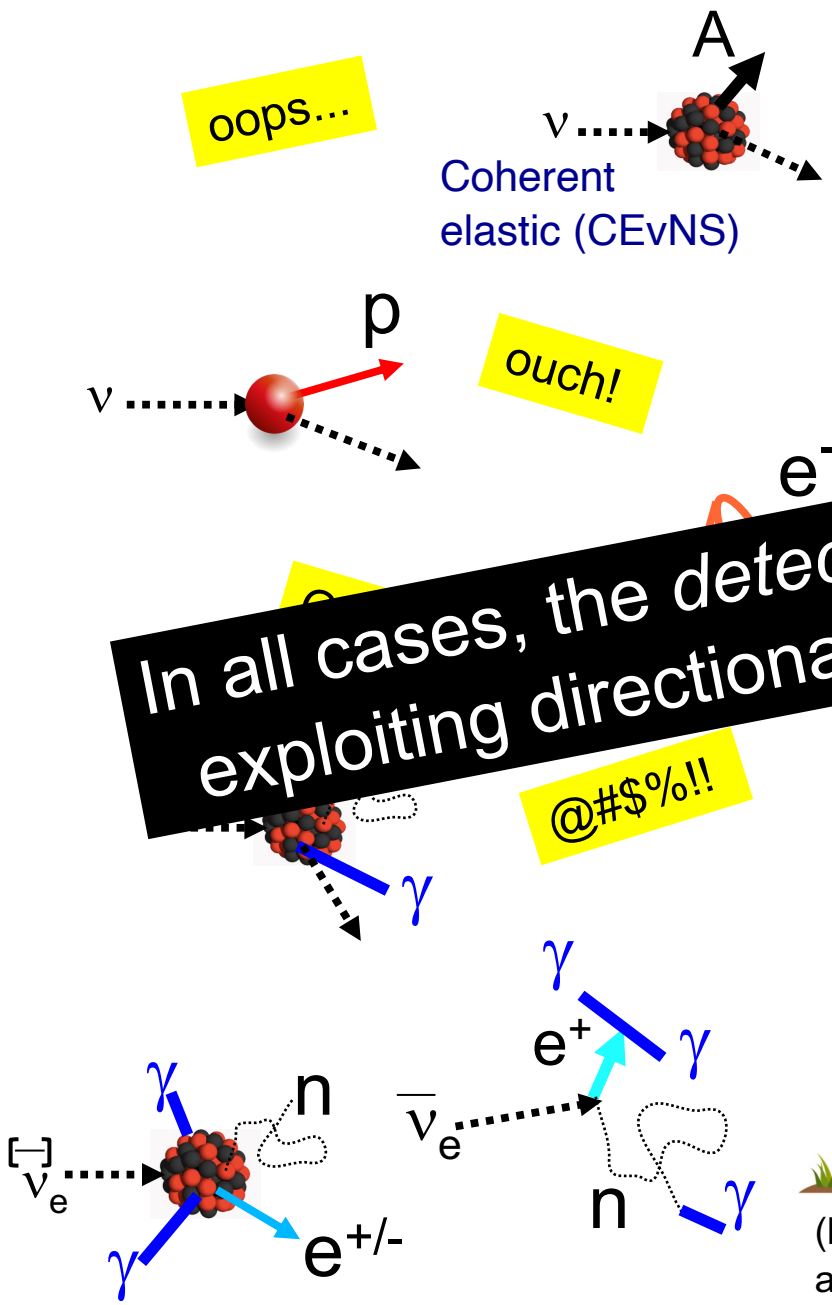
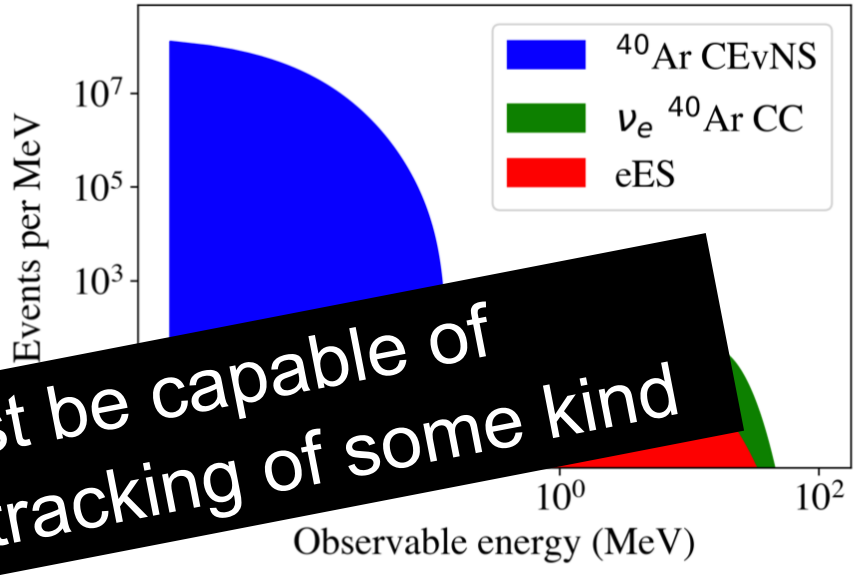
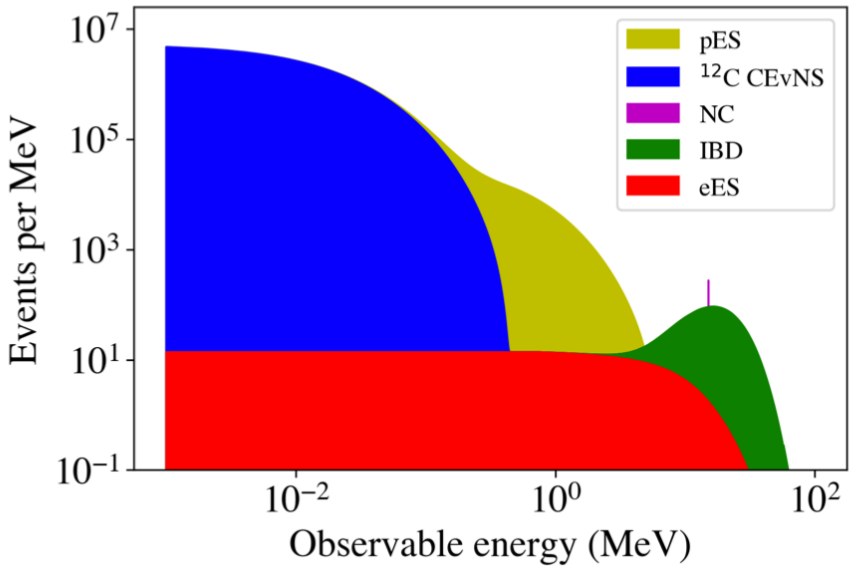


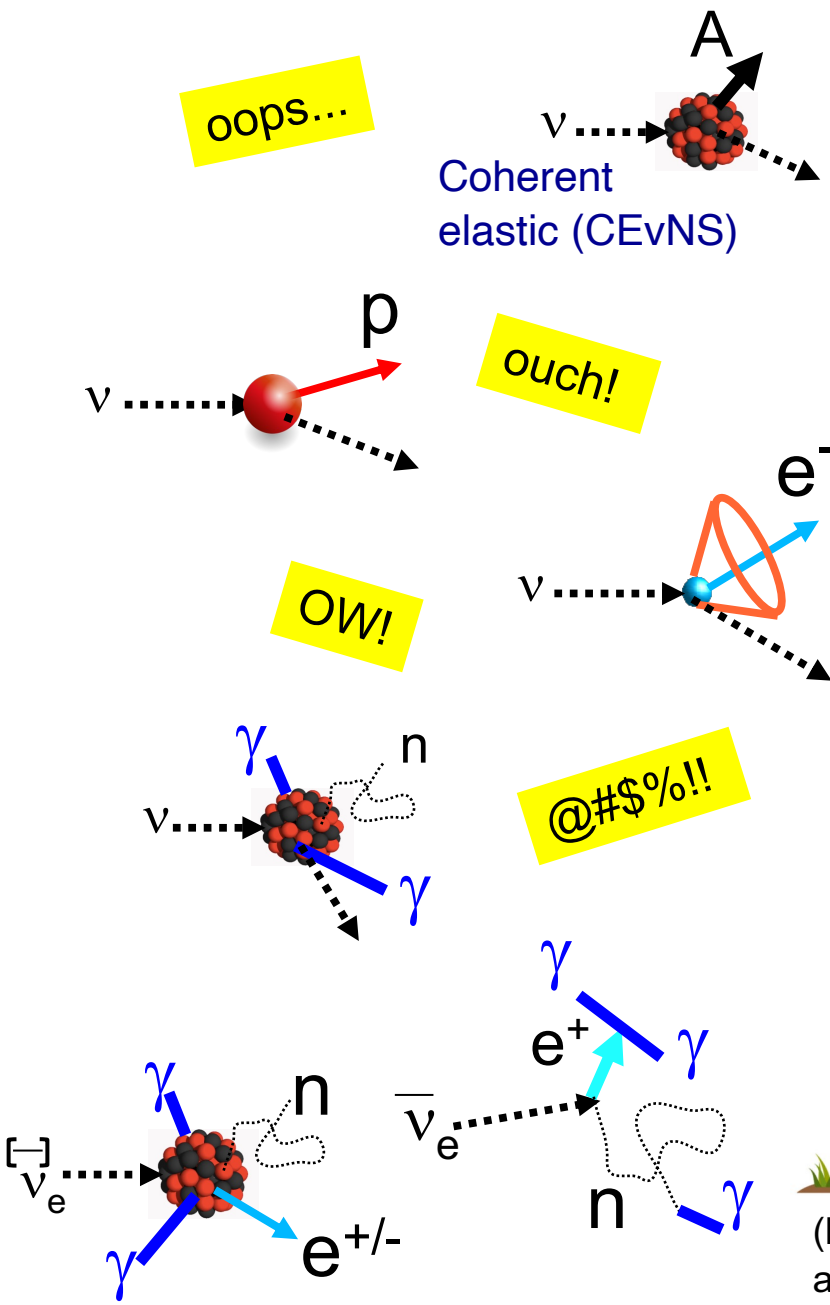




In all cases, the detector must be capable of exploiting directionality via tracking of some kind

(but leaves
a full flavor and
four-mom legacy)

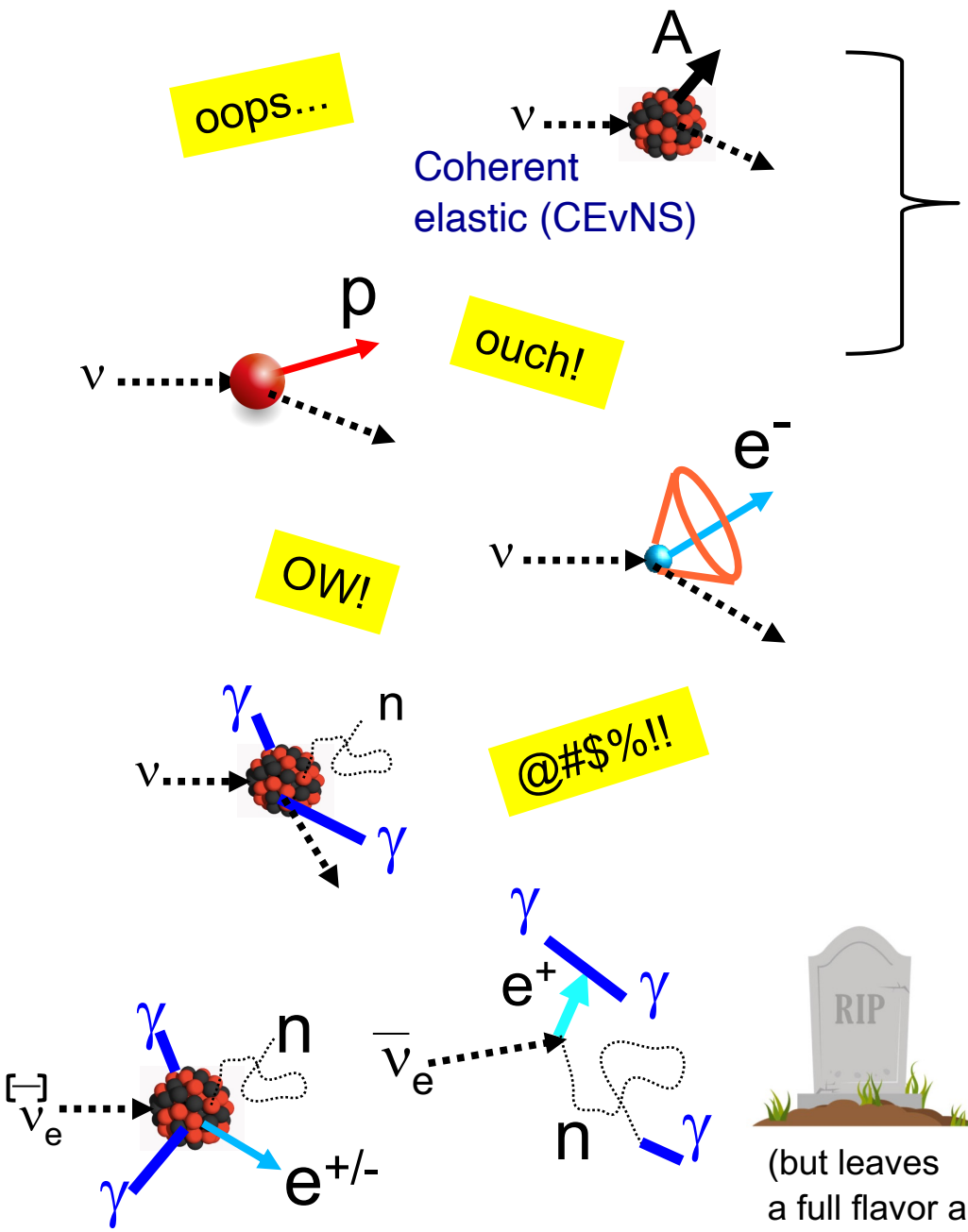
Prospects for use in pointing



NC ν-nucleus

- Poorly understood
- Low cross section
- ~Isotropic observables

Prospects for use in pointing

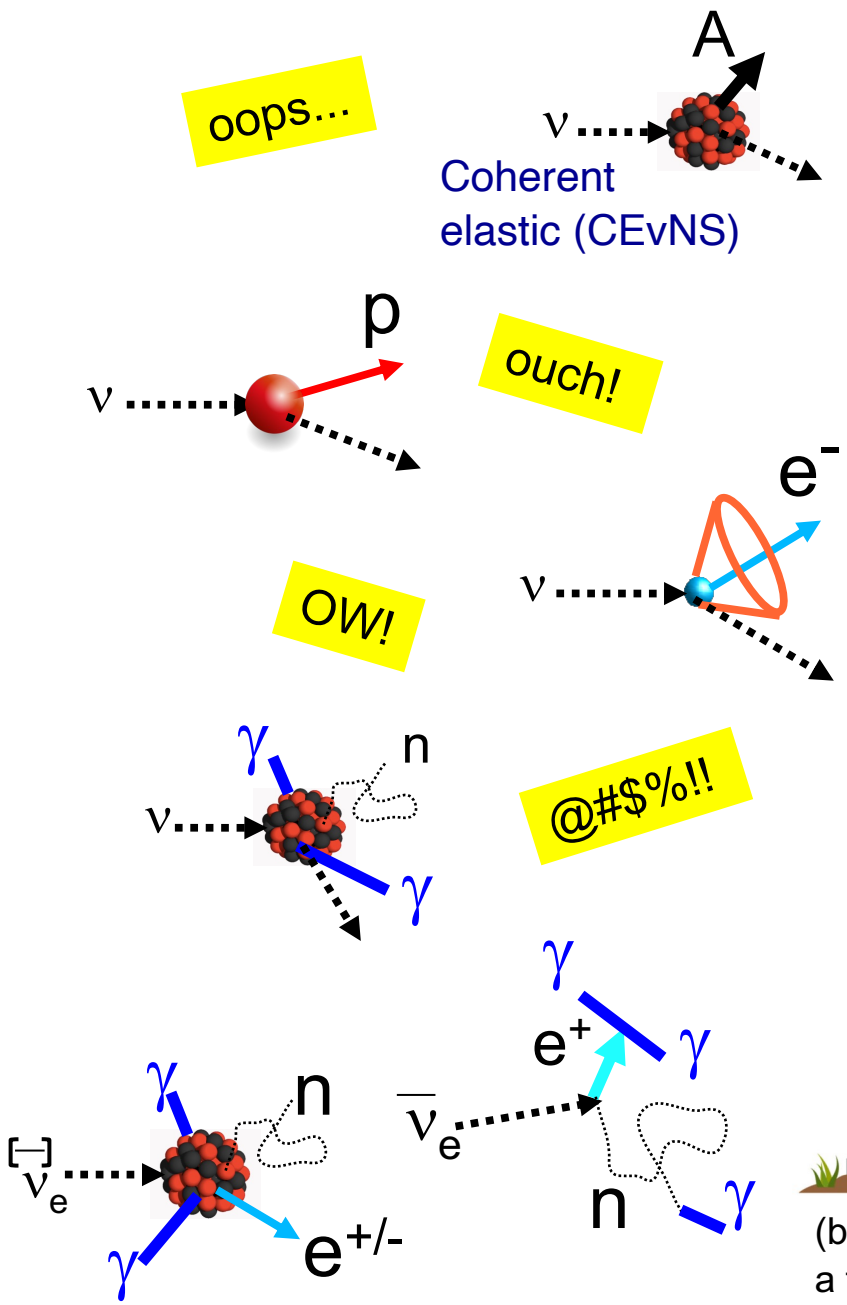


CEvNS and pES

- Well-defined anisotropy
- Large statistics
- Experimentally hard...(tiny recoils, tracking hard w/ high stats)

(but leaves
a full flavor and
four-mom legacy)

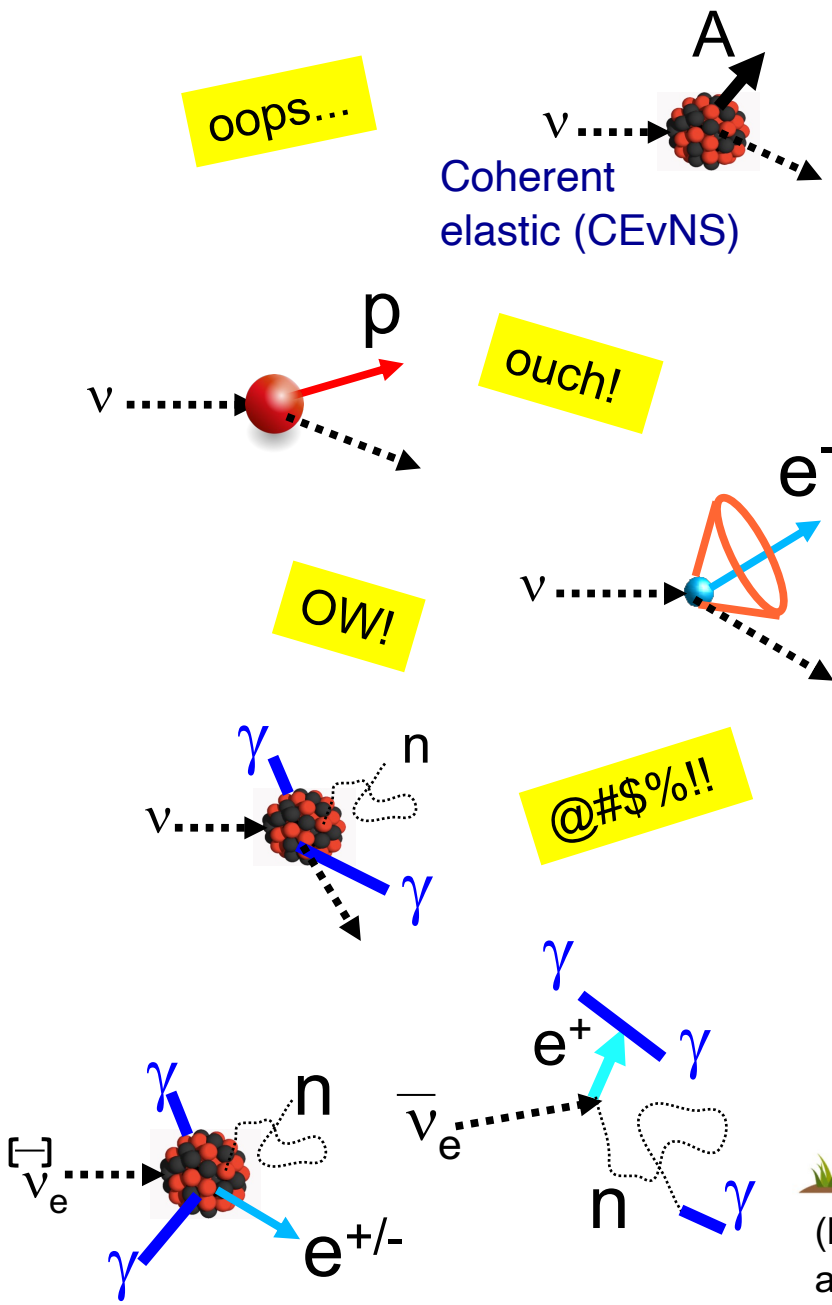
Prospects for use in pointing



IBD & ν_eCC

- Can be high event rate (e.g. pIBD)
- Poorly understood xscns on nuclei
- In principle, full final-state kinem available, but lepton anisotropy weak (in practice full reco is hard)

Prospects for use in pointing



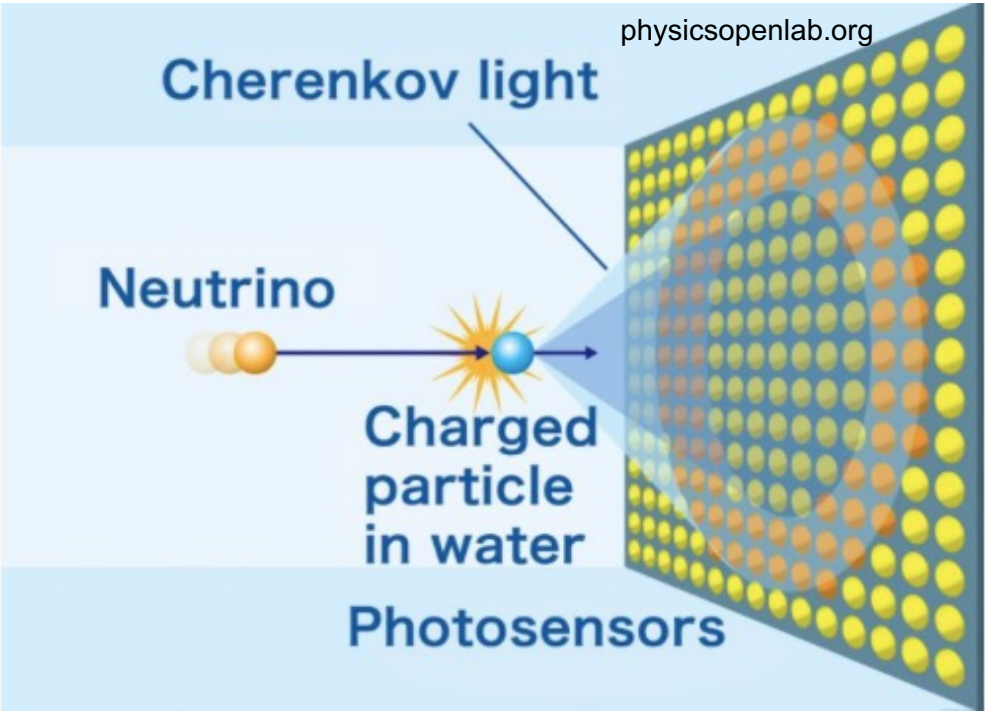
eES

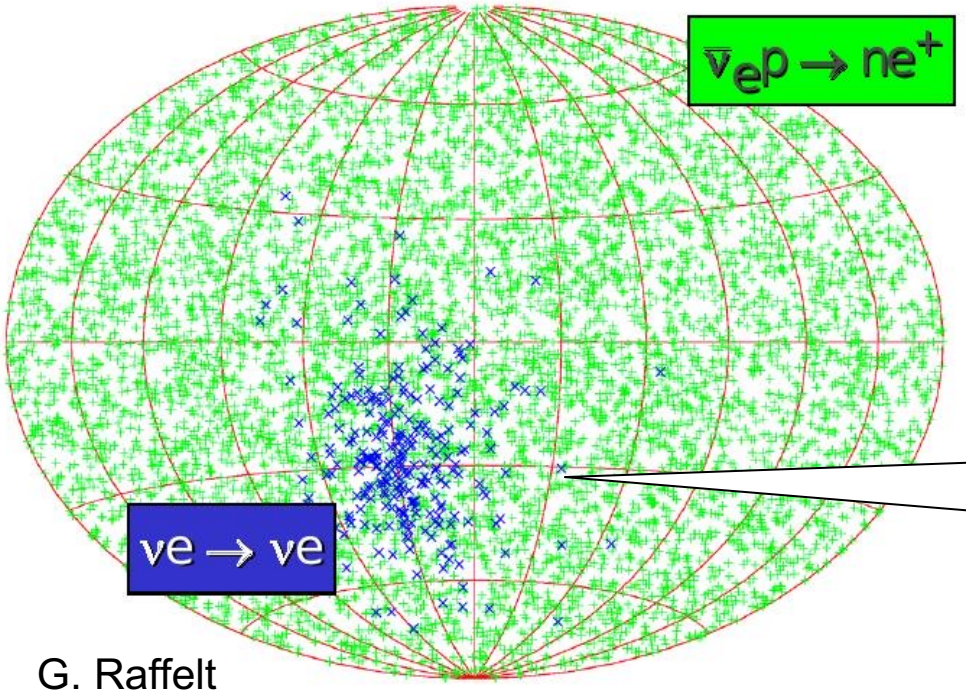
- Every detector has electrons
- Well-defined anisotropy
- Low cross section
- Forward pointing

(but leaves
a full flavor and
four-mom legacy)

Water Cherenkov Detectors

Excellent intrinsic directionality, including head-tail disambiguation

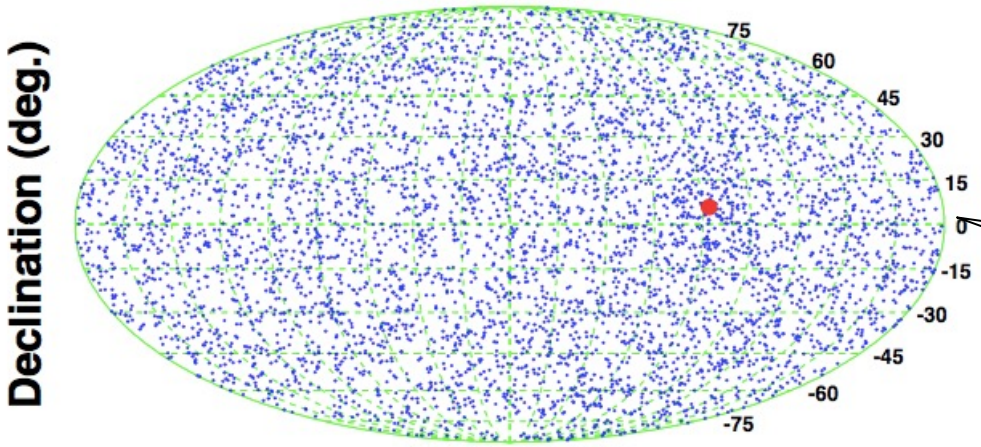




G. Raffelt

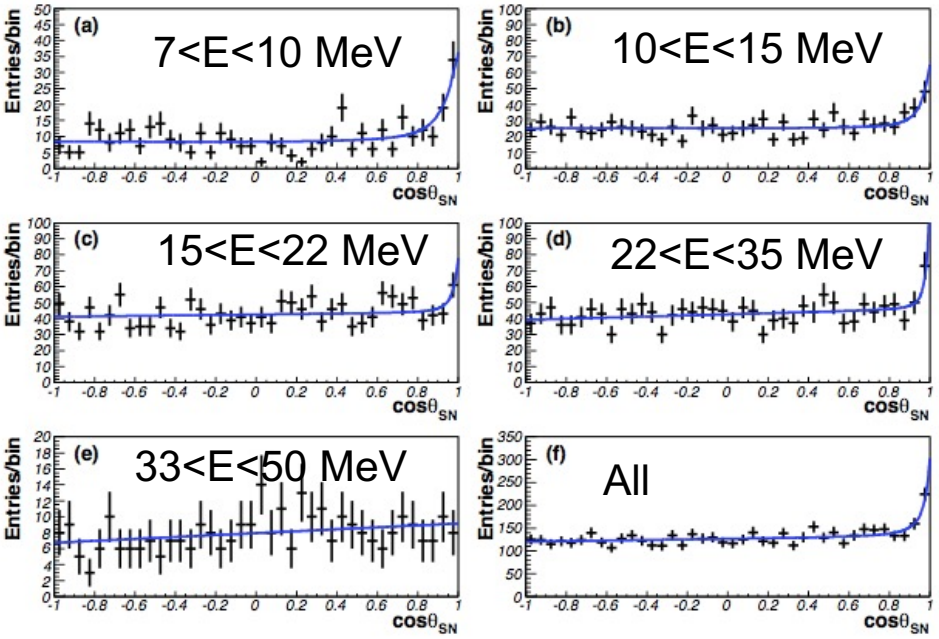
The go-to pointing method is ES in SK

Pointing in Water Cherenkov: Super-K

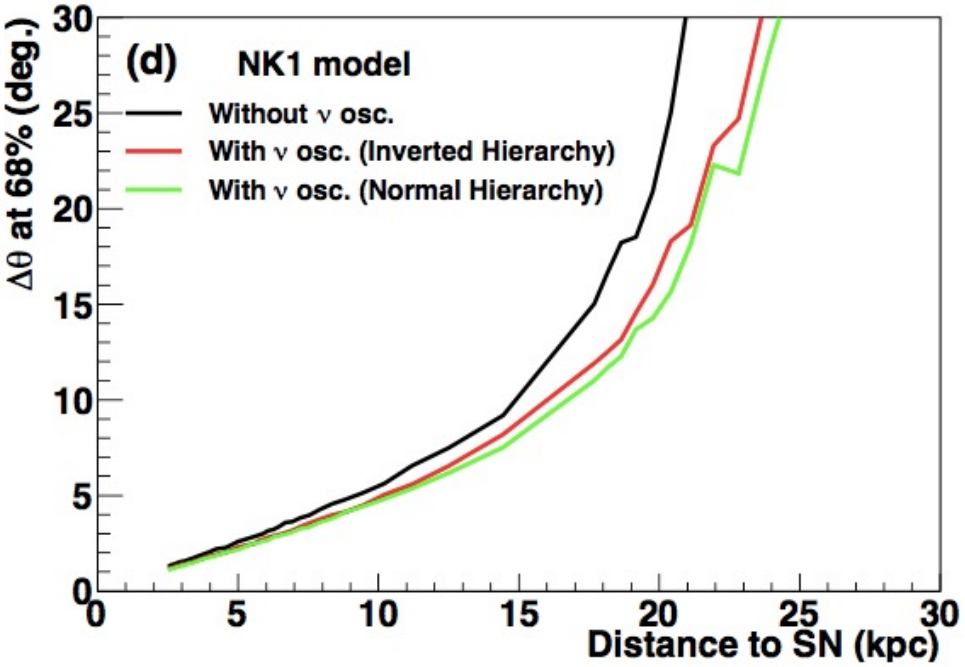


K. Abe et al., Astropart. Phys. 81 (2016) 39-48

Harder when you don't have the interaction truth!

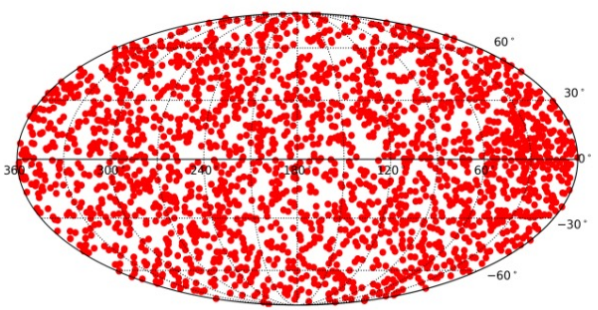


Fit to ES+ mildly anisotropic IBD (+^{16}O)

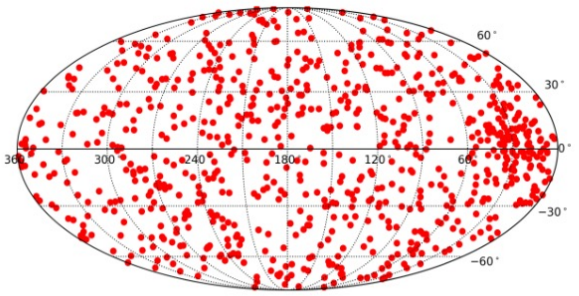


- Improve w/SK-Gd
- HK will get to ~few deg

From Takeda-san's talk at this workshop:



SN burst events w/o IBD tagging
(10kpc simulation)

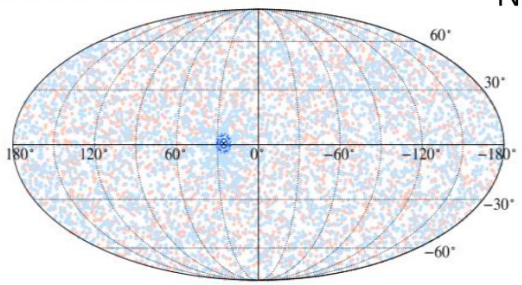


Tagged IBD events are removed

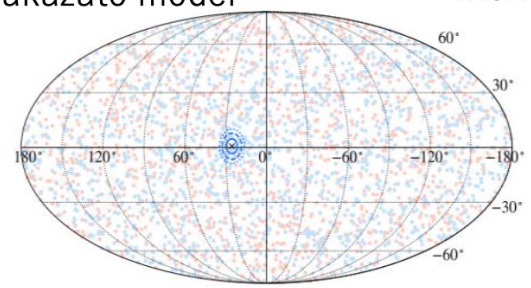
SN burst events w/ 72% IBD events tagged/removed
(10kpc simulation) (Expected with 0.1% Gd)

Detailed MC study showed that the direction pointing accuracy is 3-7 degrees at 10 kpc with IBD tagging (Gd 0.03 wt%) among several models and neutrino oscillation assumption.

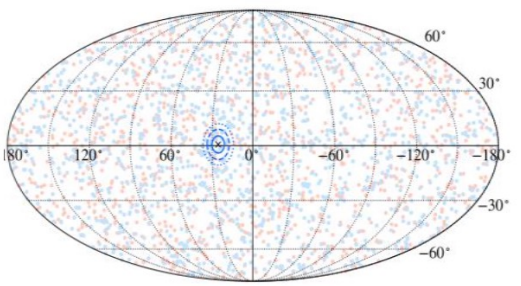
Wilson model



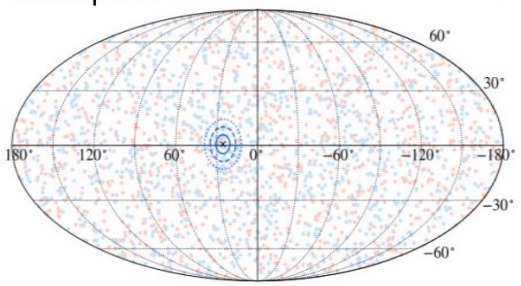
Nakazato model



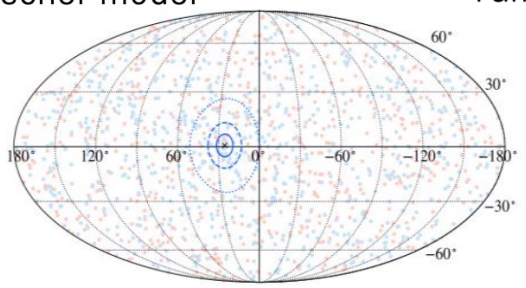
Mori model



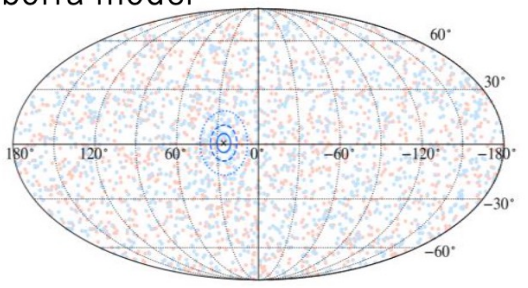
Hudelpohl model



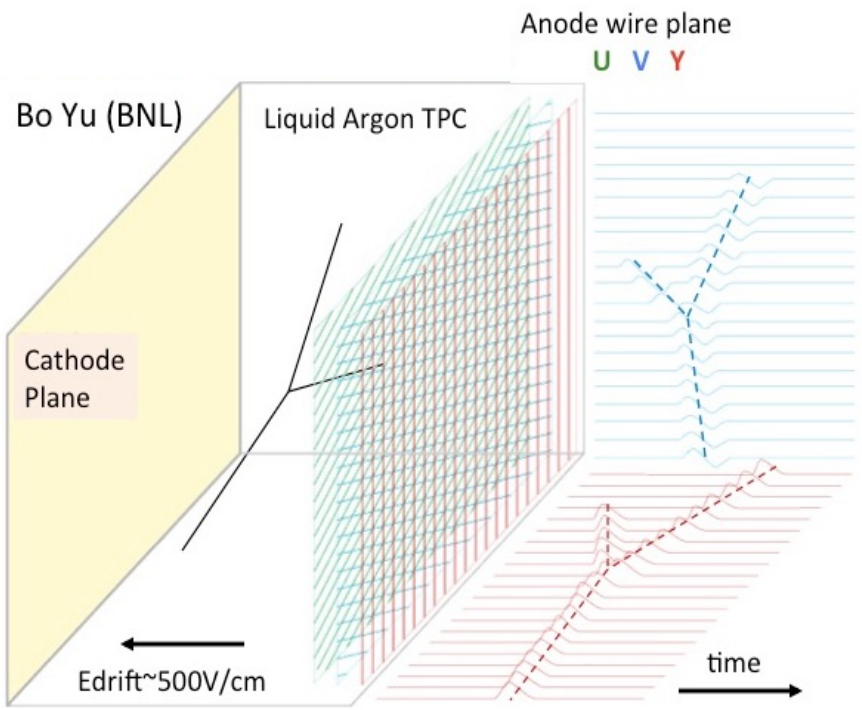
Fischer model



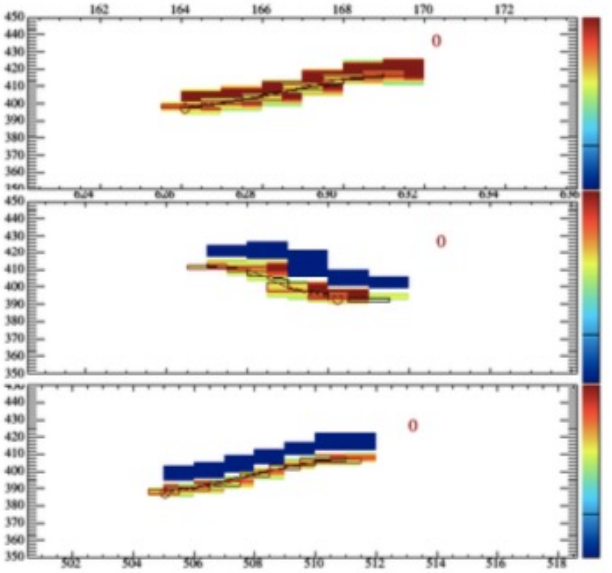
Tamborra model

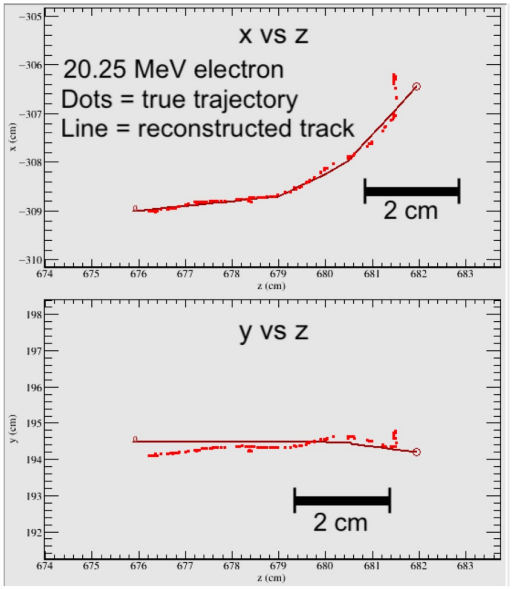


Pointing to the supernova with LArTPCs



10.25 MeV electron





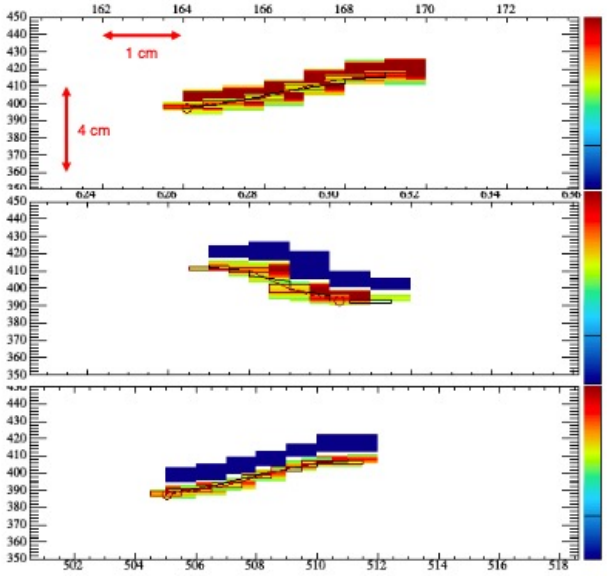
Tracks can be reconstructed,
but note direction ambiguity,
unlike Cherenkov!

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

Pointing to the supernova with DUNE

eES $\nu + e^- \rightarrow \nu + e^-$

ν_eCC $\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$



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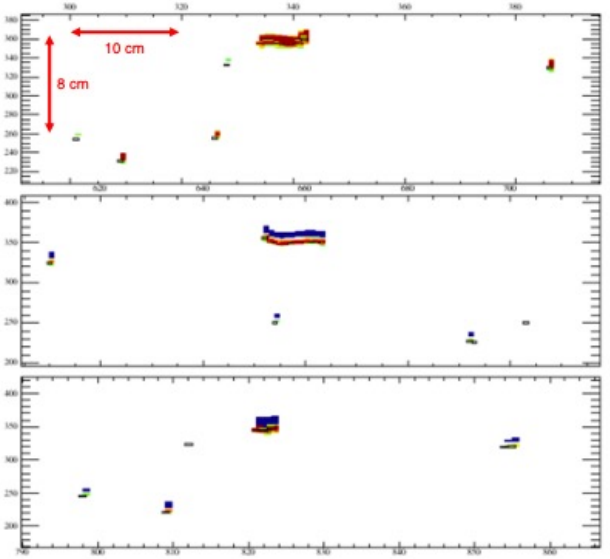
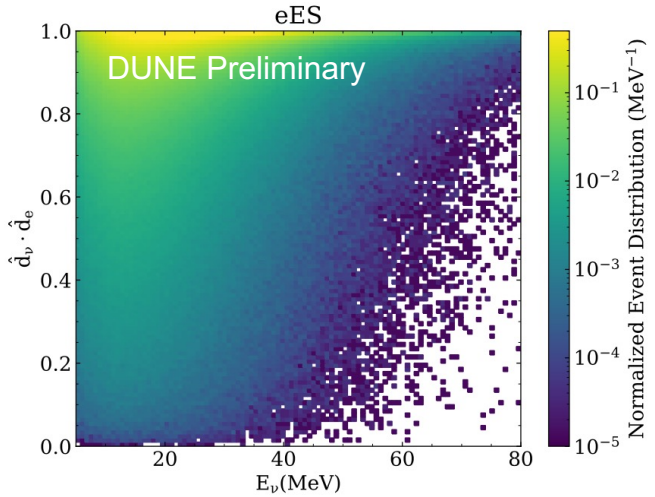
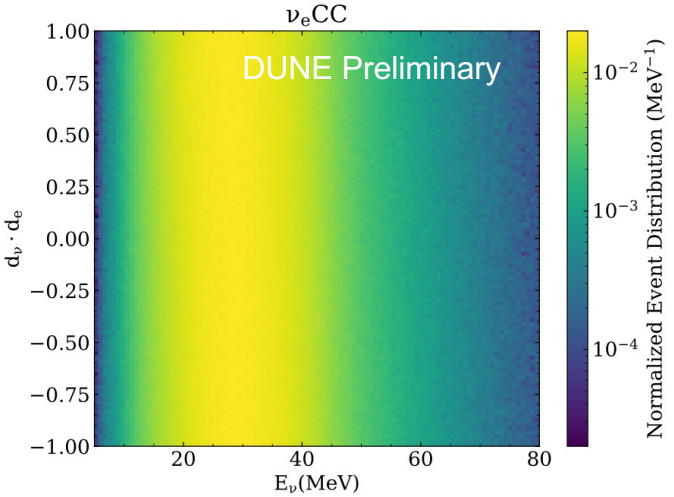


20.25 MeV neutrino



Forward-pointed

~300 events/40 kt @10 kpc



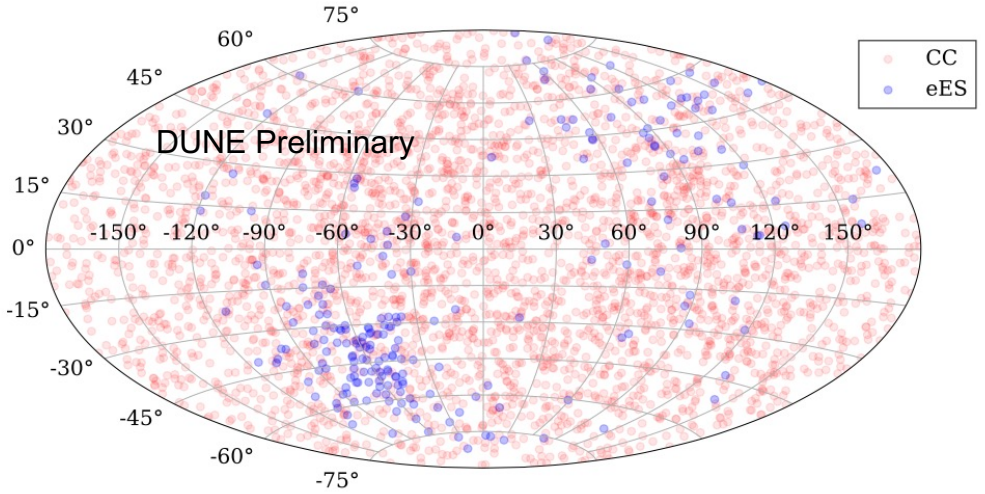
Quasi-isotropic*

~3000 events/40 kt @10 kpc

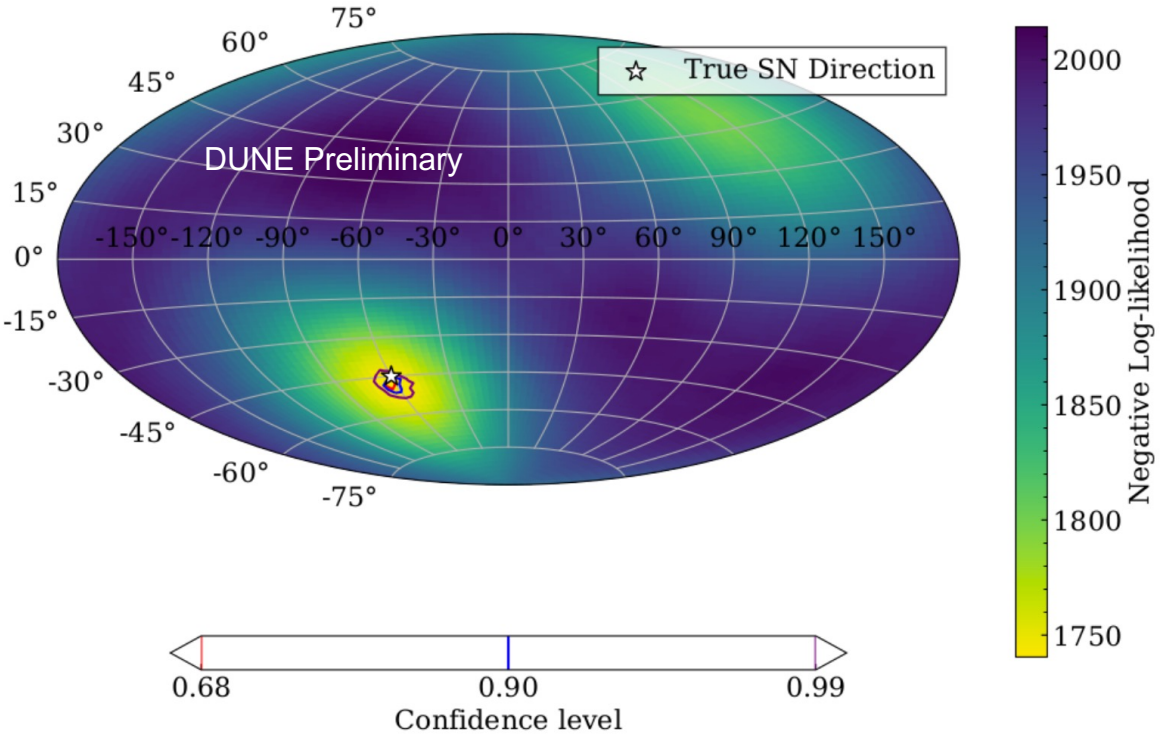
Work by:
James Shen
Janina Hekenmüller
Josh Queen

* potential for Fermi/GT separation

Channel-tagging (interaction classification) matters



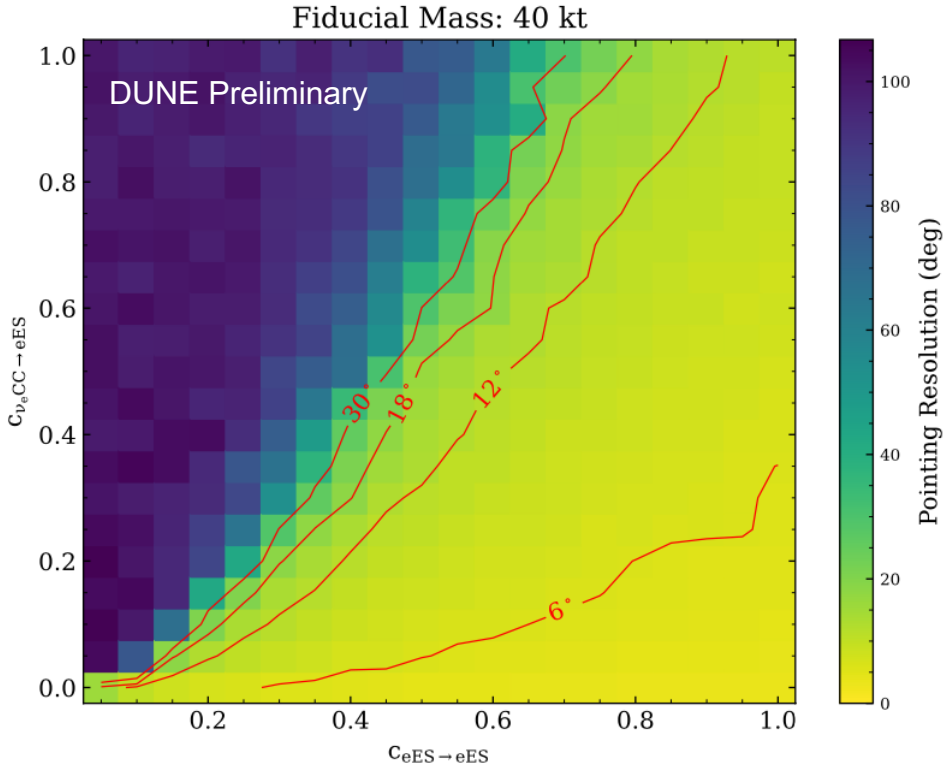
directional signal on an ~isotropic background



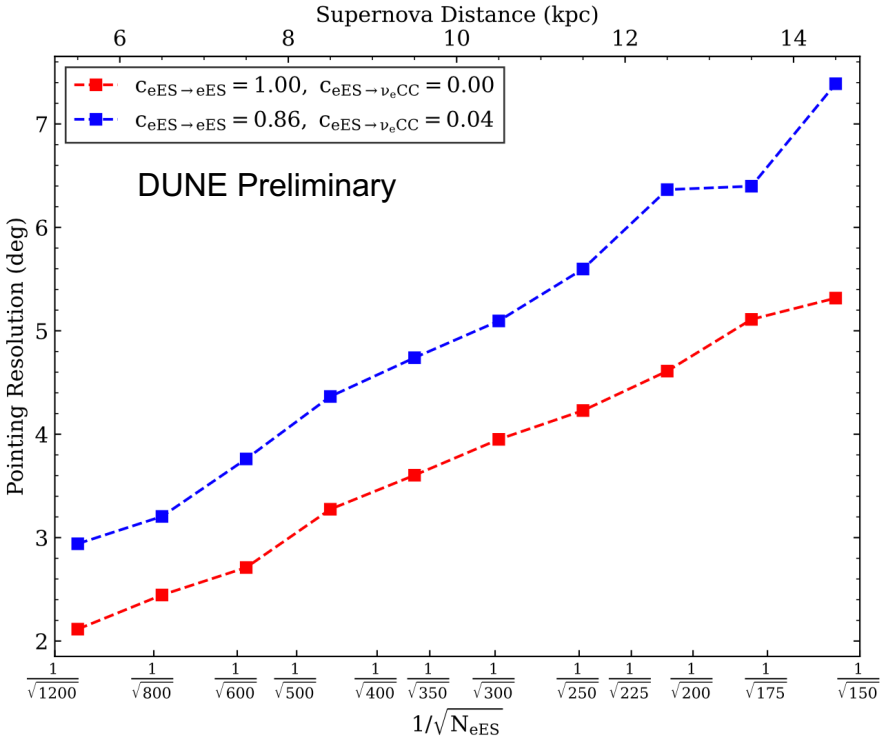
10 kpc, 40 kton
GKVM model

$$c_{eES \to eES} = 0.86 \text{ and } c_{\nu_e CC \to eES} = 0.04$$

Pointing resolution
as a function
of channel-tagging
assumption



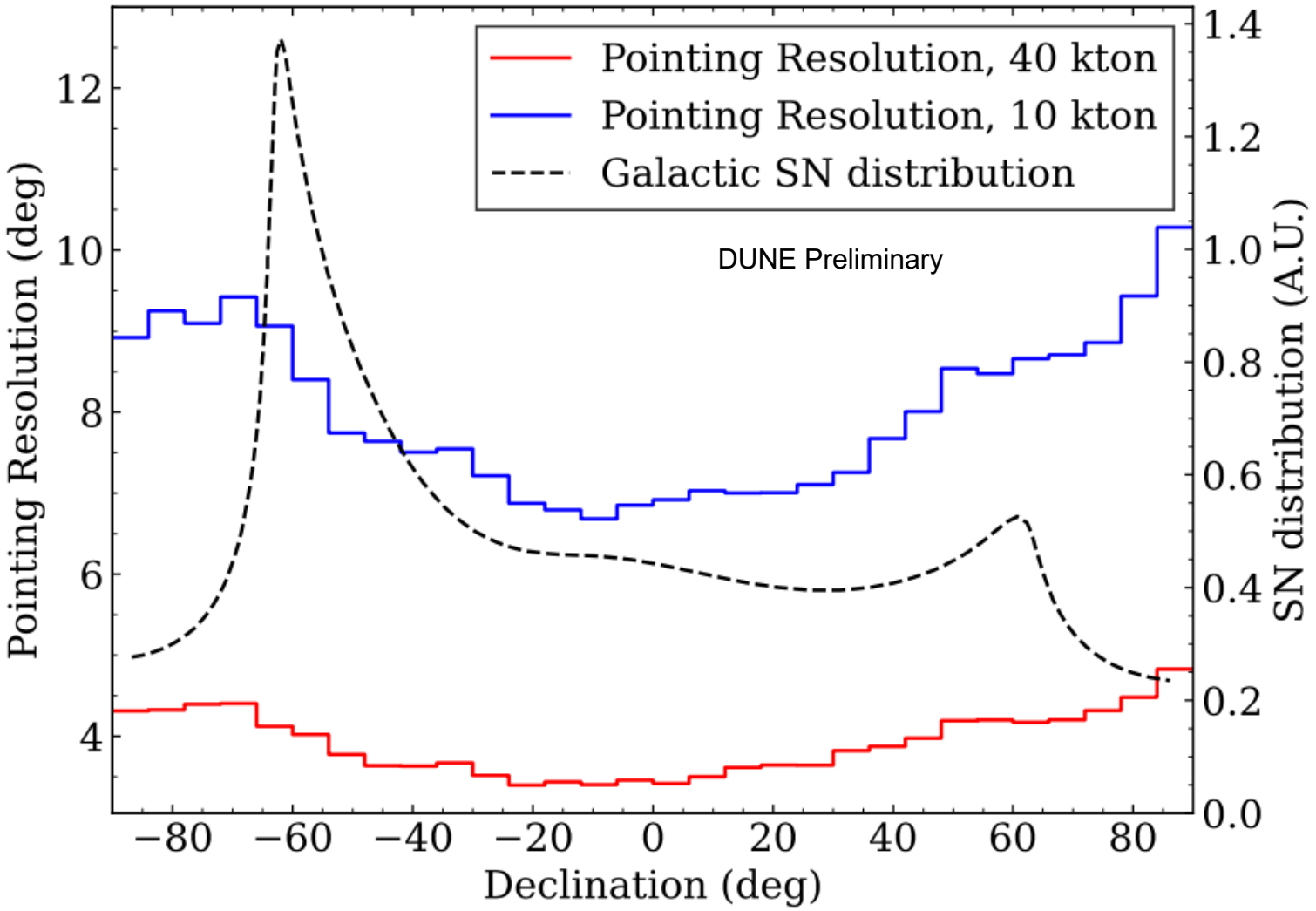
Pointing resolution
as a function of statistics



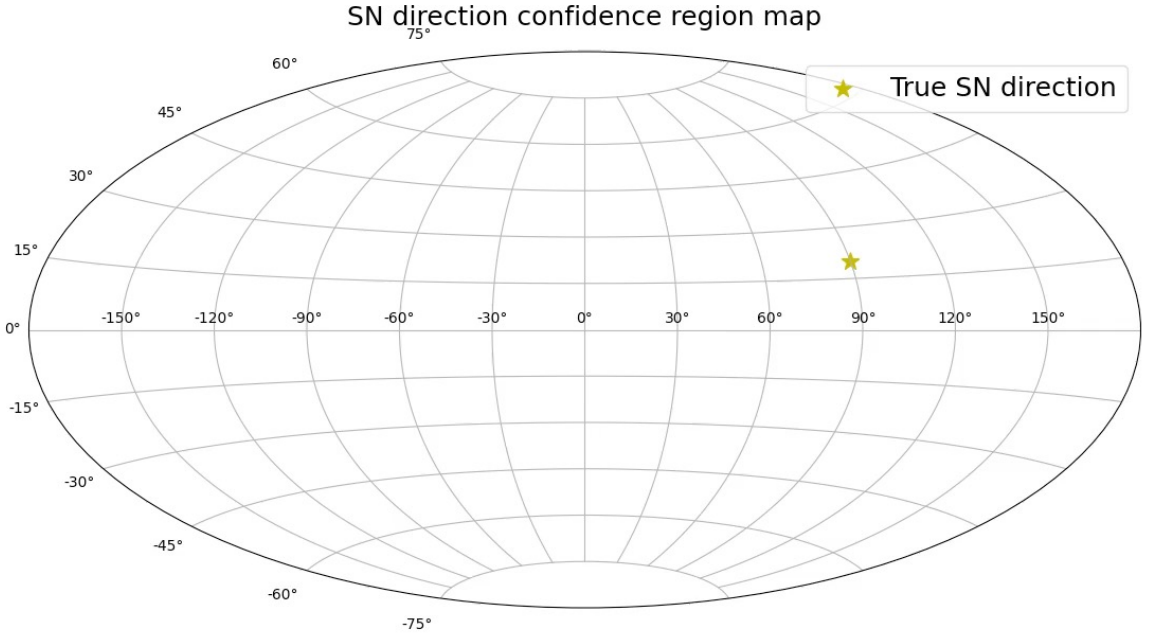
Reasonable pointing
does not require
extremely clean separation

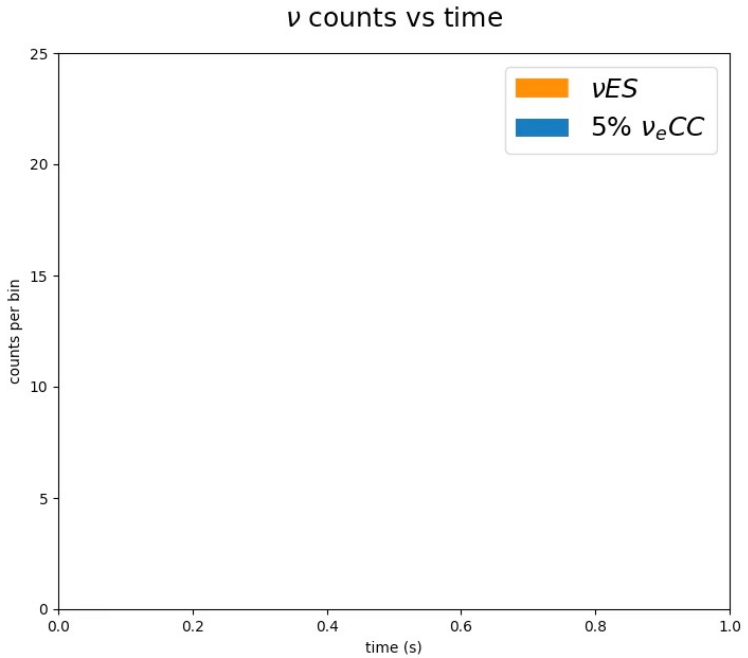
Scales (as expected)
as inverse square of stats

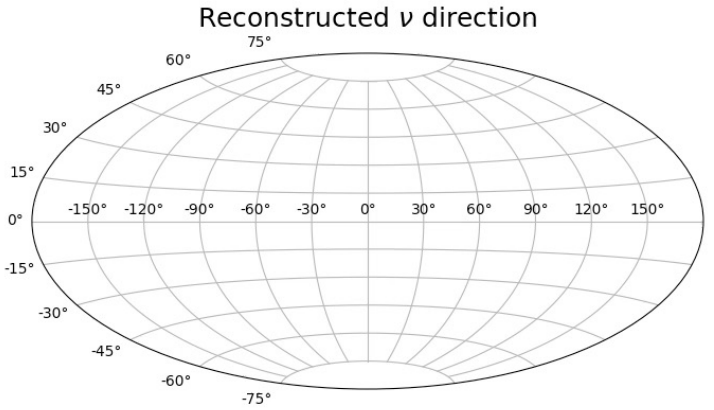
Mild DUNE detector anisotropy



By Joshua Queen







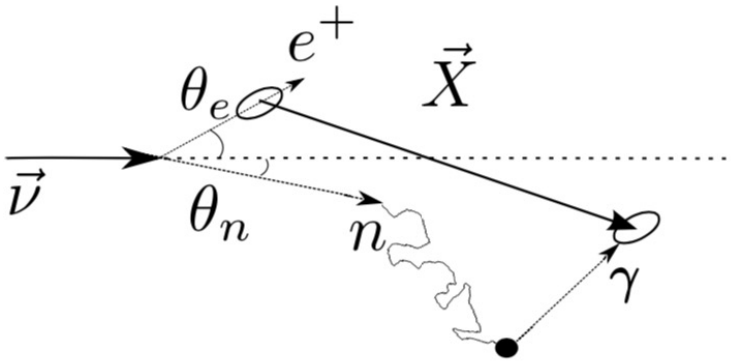
Pointing with Liquid Scintillator

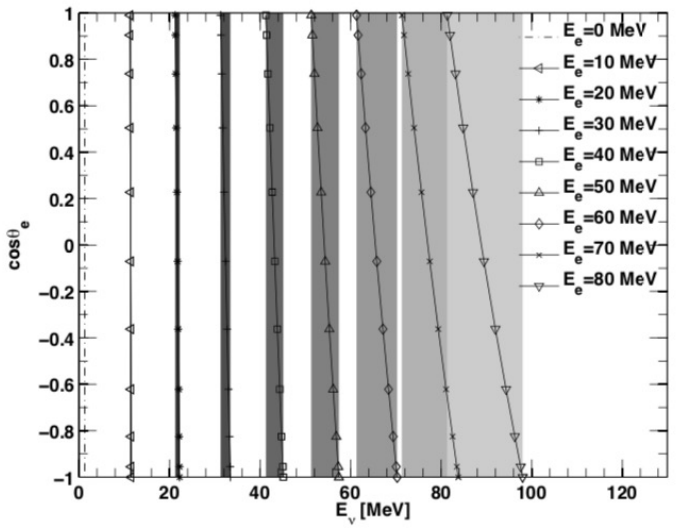
This is hard, as produced photons get quasi-isotropized...

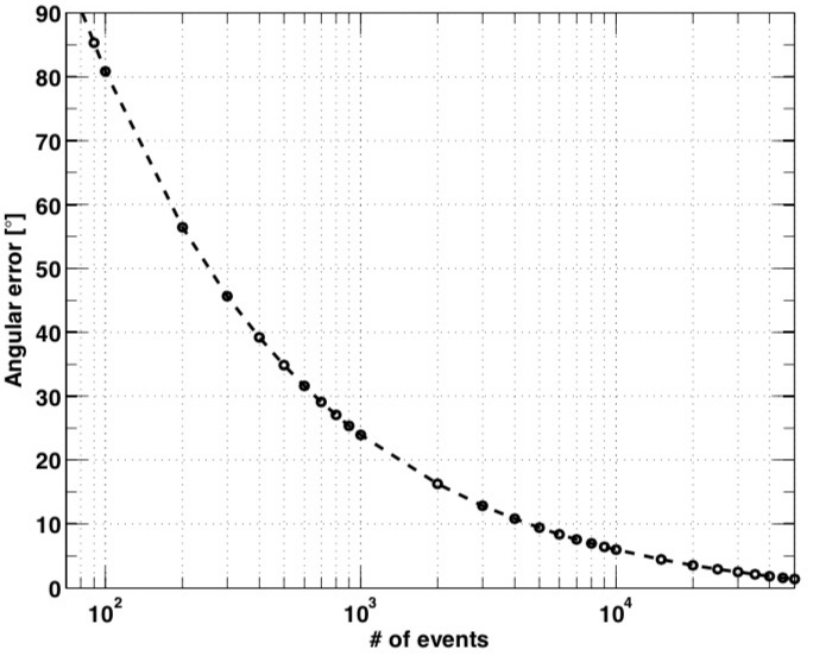
BUT, some statistical prospects using IBD kinematics

→ 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!

[maybe can use Cherenkov for eES? See J. Tseng talk]

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- **Triangulation**
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- **Oscillation pattern pointing**
  in high-energy resolution detectors
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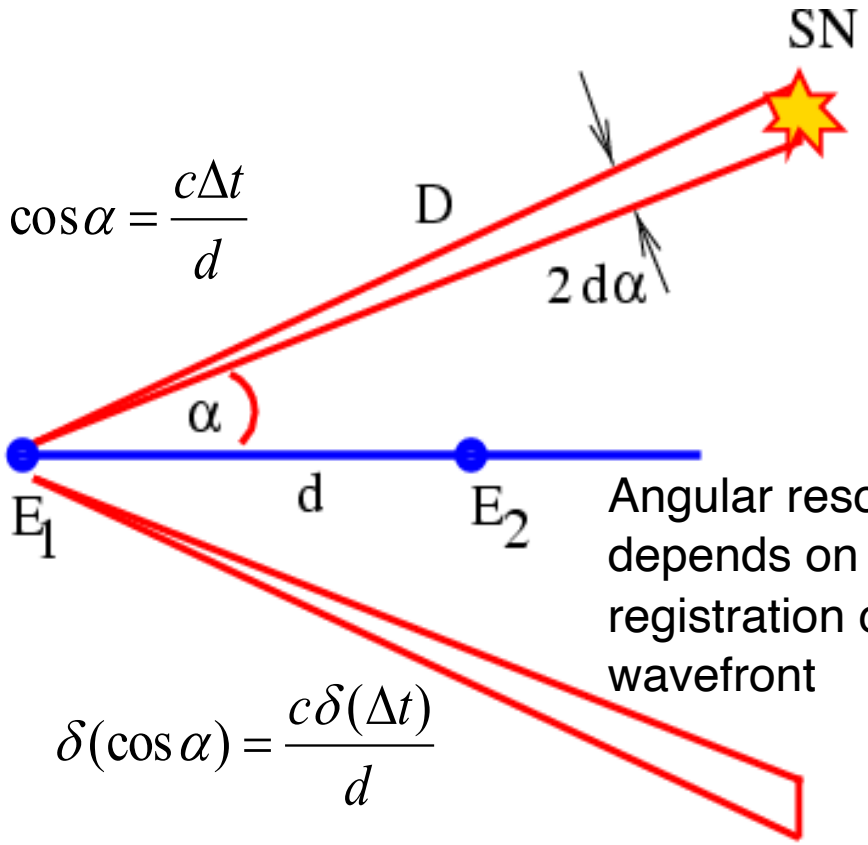
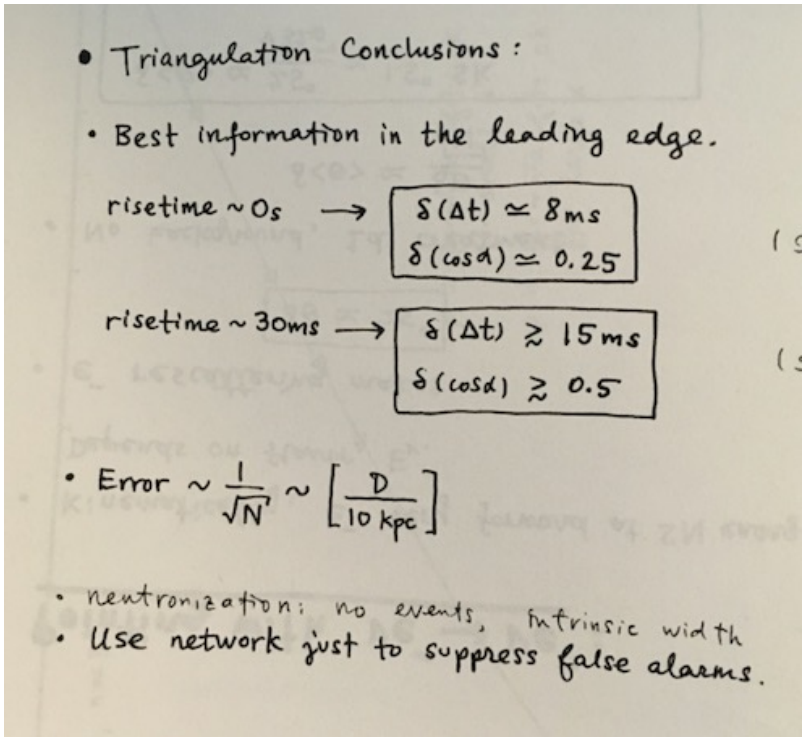
  in directional detectors, using later neutrinos
- **All of the above!**

Triangulation



Angular resolution depends on timing registration of wavefront

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



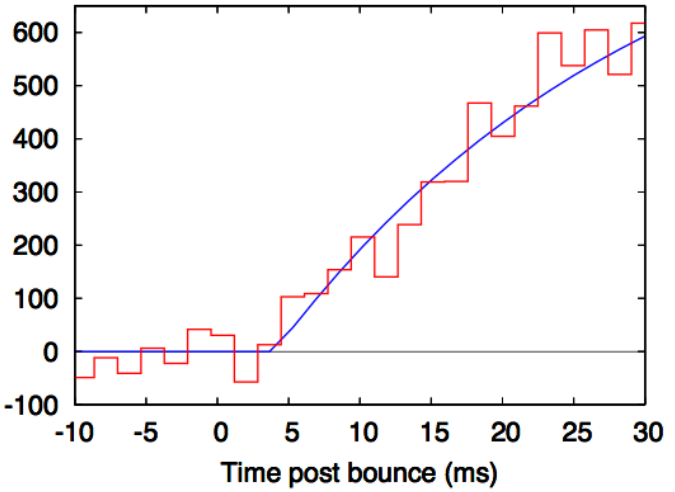
Can a supernova be located by its neutrinos?
John F. Beacom, P. Vogel (Caltech). Nov 1998. 10 pp.
Published in **Phys.Rev. D60 (1999) 033007**

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

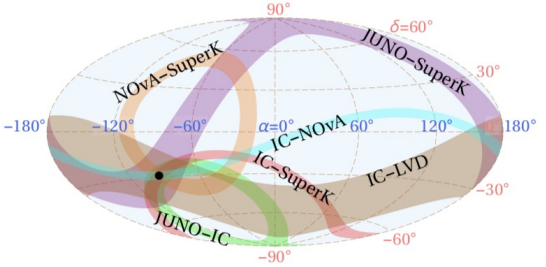
Reconstructing the supernova bounce time with neutrinos in IceCube
Francis Halzen (Wisconsin U., Madison), Georg G. Raffelt (Munich, Max Planck Inst.). Aug 2009. 3 pp.
Published in **Phys.Rev. D80 (2009) 087301**



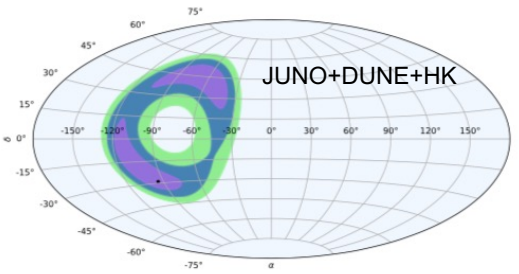
Some new(ish) papers:

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. 17 pp.
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]



Triangulation Pointing to Core-Collapse Supernovae with Next-Generation Neutrino Detectors
N.B. Linzer (Duke U. (main)), K. Scholberg (Duke U. (main)) (Sep 7, 2019)
Published in: *Phys.Rev.D* 100 (2019) 10, 103005 • e-Print: 1909.03151 [astro-ph.IM]

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

See Jeff Tseng's talk

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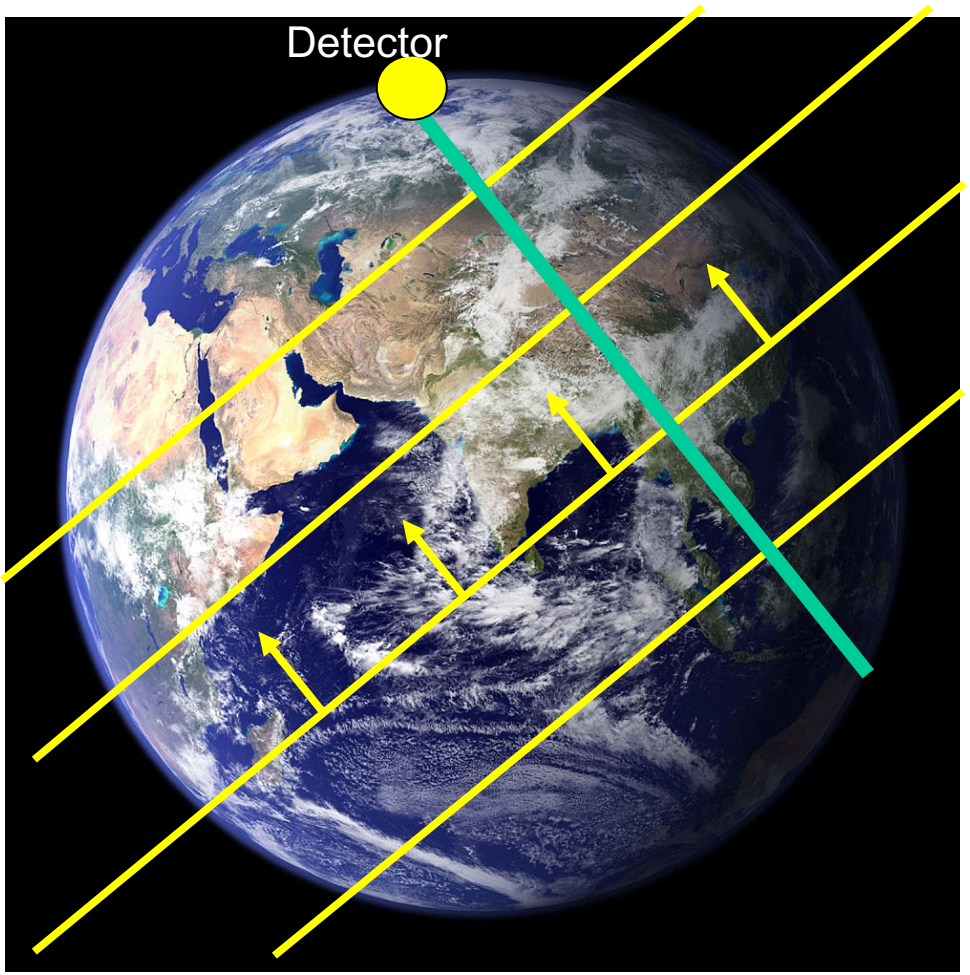
- **High-energy (~GeV) neutrino follow-on pointing**
  in directional detectors, using later neutrinos
- **All of the above!**

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

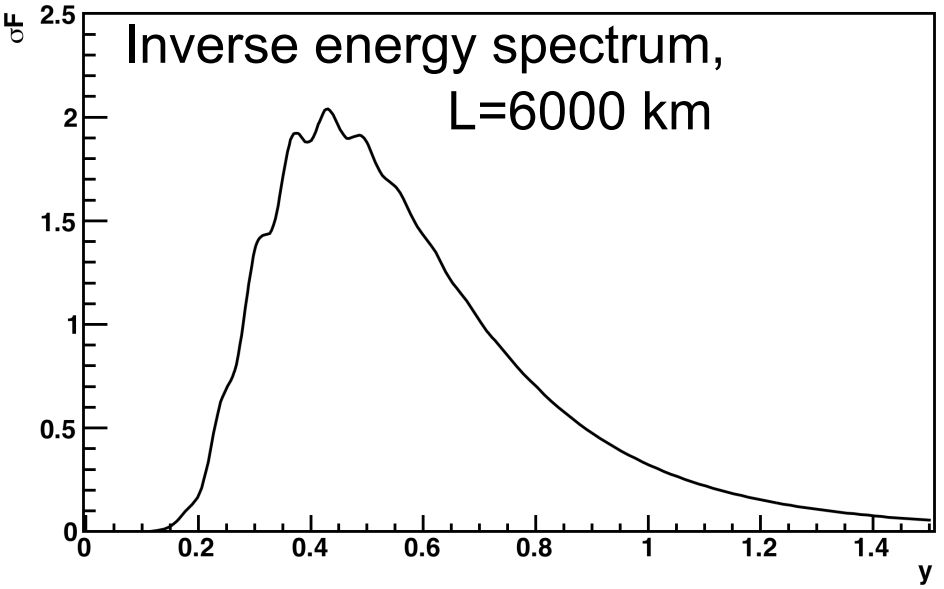
Obtaining supernova directional information using the neutrino matter oscillation pattern
Kate Scholberg (Duke U.), Armin Burgmeier (Karlsruhe U.), Roger Wendell (Duke U.). Oct 2009. 11 pp.
Published in **Phys.Rev. D81 (2010) 043007**



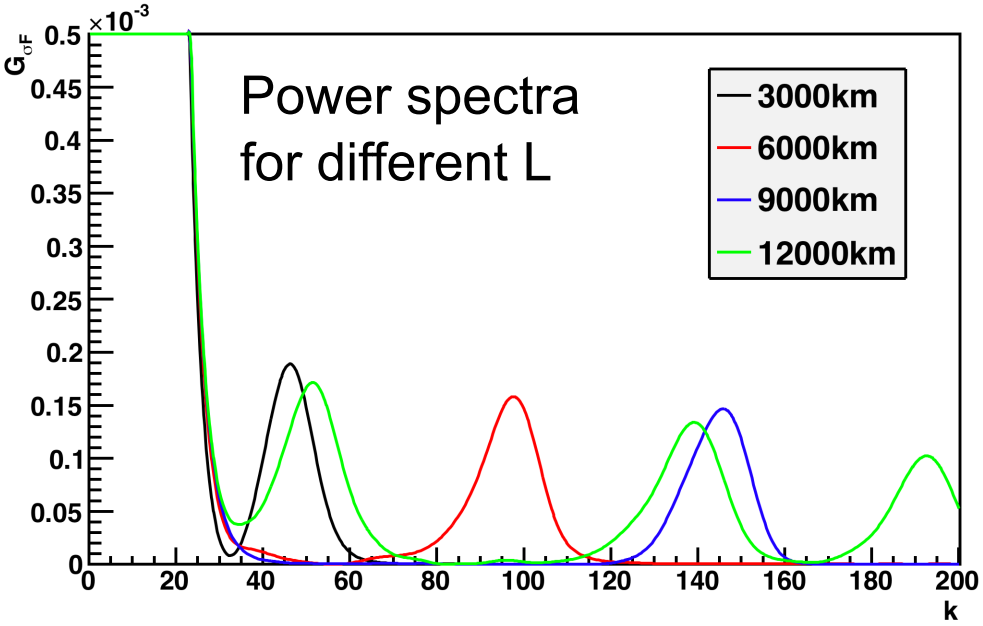
If you can determine the pathlength traveled in the Earth, you know the supernova will be found on a ***ring on the sky***

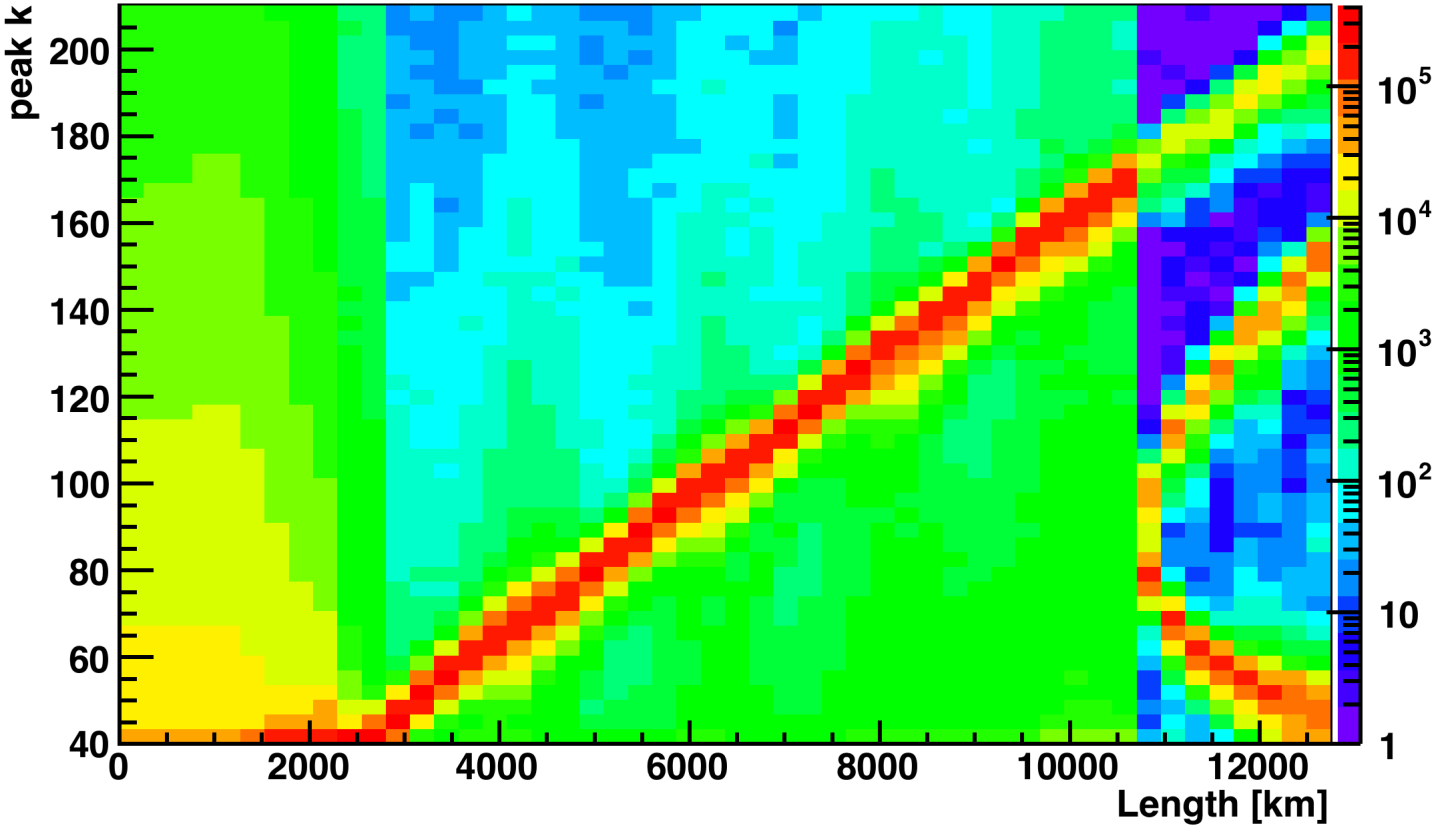
Method requires **very good energy resolution** (scintillator) and **large statistics**

[Caveat: collective oscillations could interfere]



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



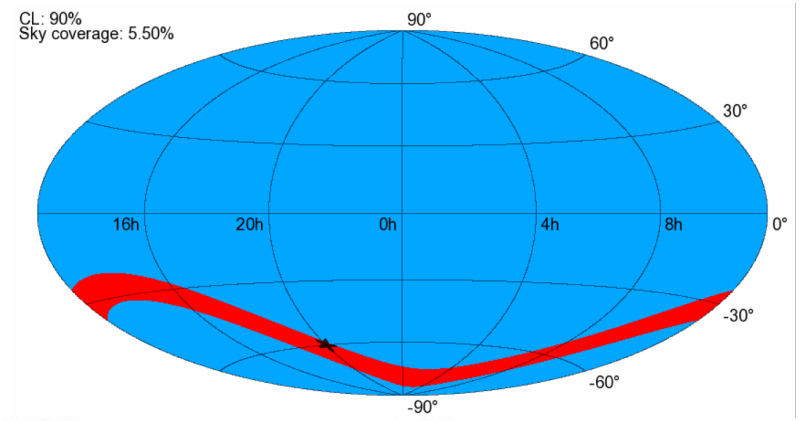


Peak in power spectrum vs L for 500,000 simulated SNae, 60,000 events each (perfect energy resolution)

➔measure k_{peak} to find allowed L values;

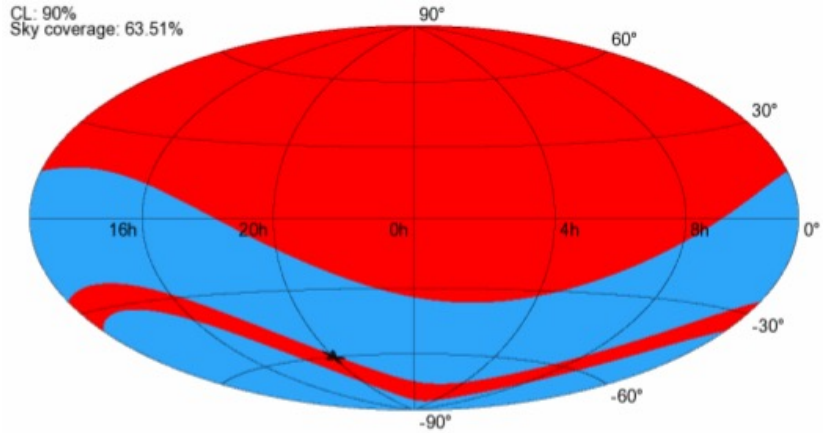
peak height info also usable

Example skymaps from oscillation pointing



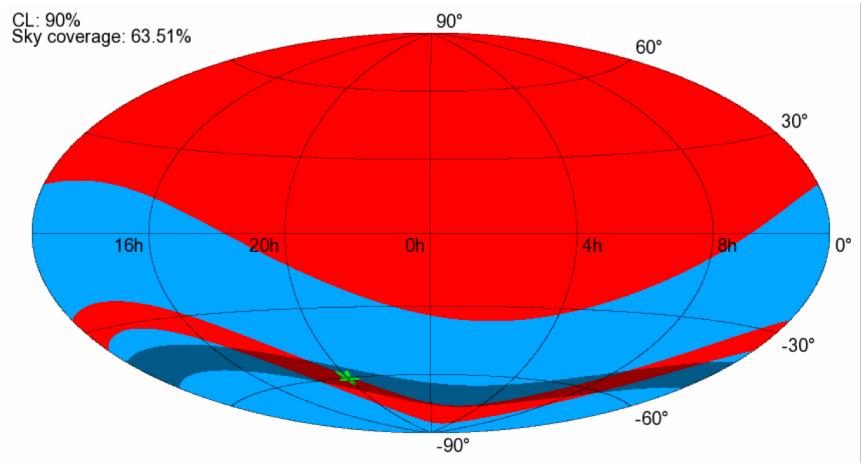
One detector

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...

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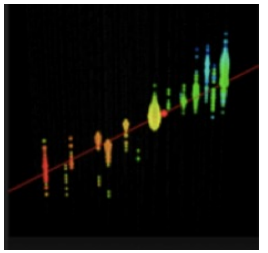
One more: *high energy neutrino events,*



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

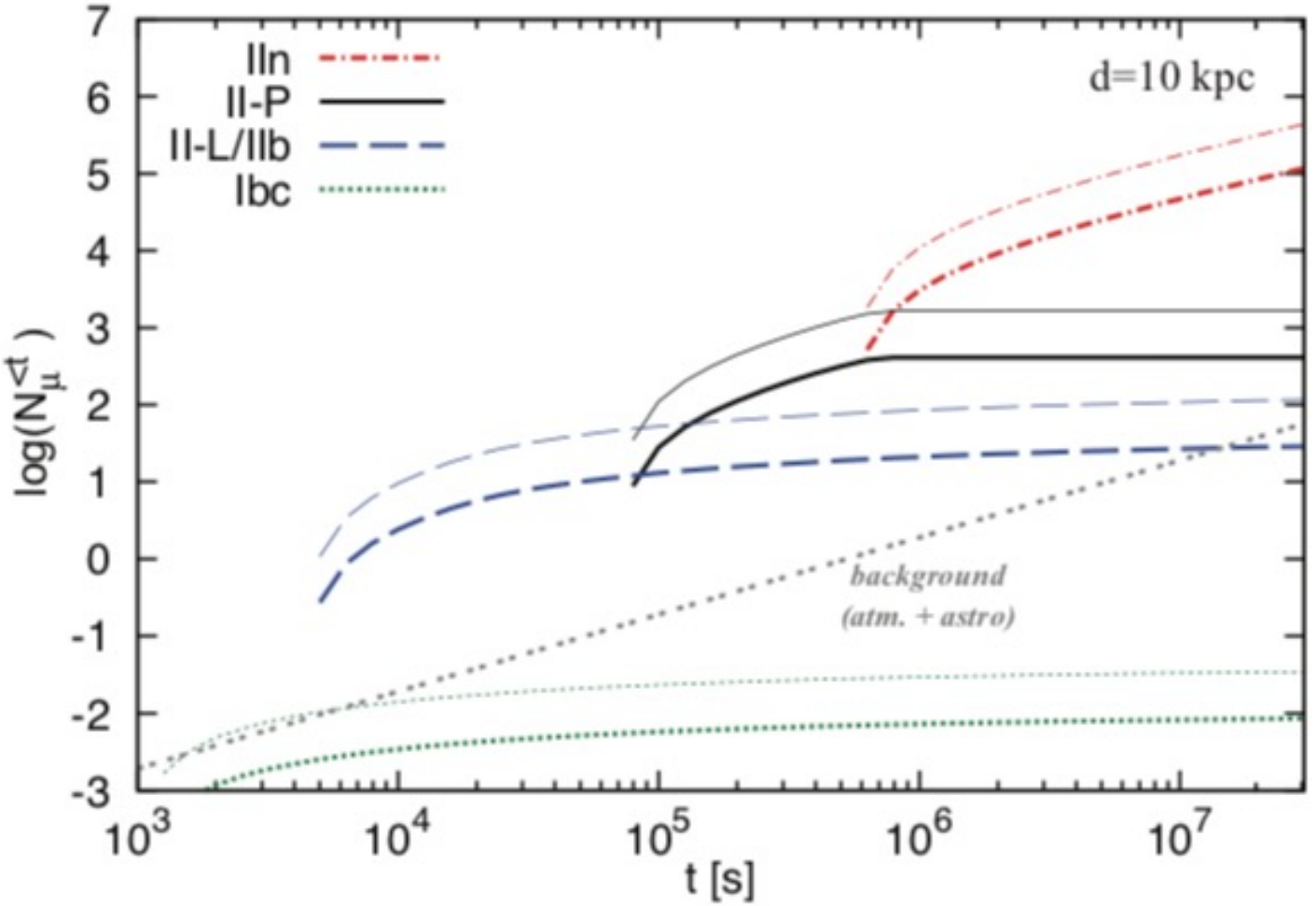
Kohta Murase (Penn State U. & Penn State U., Astron. Astrophys. & Kyoto U., Yukawa Inst., Kyoto). May 12, 2017. 1 pp.
Published in **Phys.Rev. D97 (2018) no.8, 081301**

Prospects for Extending the Core-collapse Supernova Detection Horizon Using High-energy Neutrinos

Nora Valtonen-Mattila (Uppsala U.), Erin O'Sullivan (Uppsala U.) (Jun 1, 2022)

Published in: *Astrophys.J.* 945 (2023) 2, 98 • e-Print: 2206.00450 [astro-ph.HE]

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 ^{o} at 10 kpc • Will be even better in SK-Gd, HK • DUNE also excellent • Some info from scintillator via IBD (eES?)
Triangulation	• Some good, *fast* info from next generation, especially with IceCube
Oscillation pattern	• Hard: needs good energy resolution & stats • But scintillator detectors could perhaps 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

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- **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?