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MAX-PLANCK-GESELLSCHAFT

Neutrino astronomy with supernova neutrinos

— the triangulation method

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Based on: 1802.02577 (JCAP), in collaboration with Vedran Brdar and Manfred Lindner

Introduction

Goal: locate SN by neutrinos

Why is it important?

SN neutrinos arrive before photons

Supernova Early Warning System

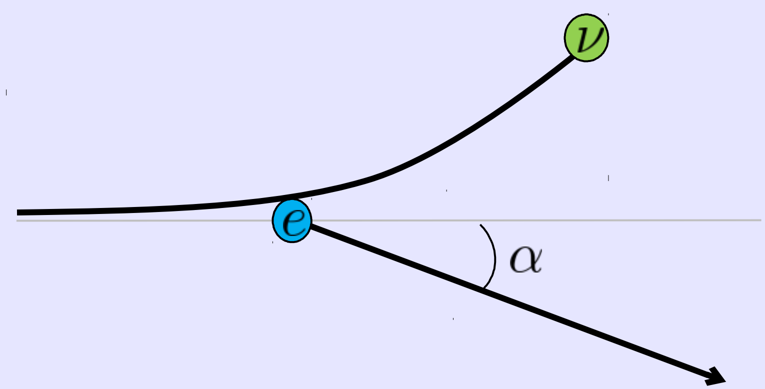
SN 1987A: neutrinos 3 hours before photons

Introduction

Two methods

Forward scattering

In $\nu + e$ scattering, α can be very small if E_ν is high.



$$\cos\alpha = \frac{E_\nu + m_e}{E_\nu}\left(\frac{T}{T+2m_e}\right)^{1/2}$$

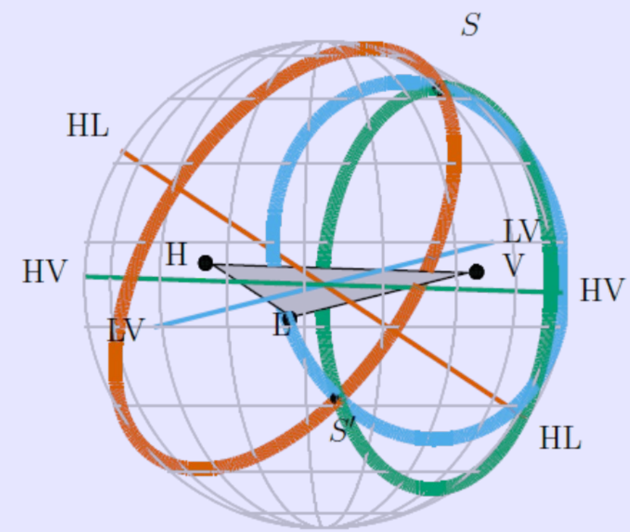
Triangulation

Need 3 or more detectors;

Measure $\Delta t \sim d/c \sim 40$ ms;

Only time information required;

Benefit from IBD (x-sec, bkg.).



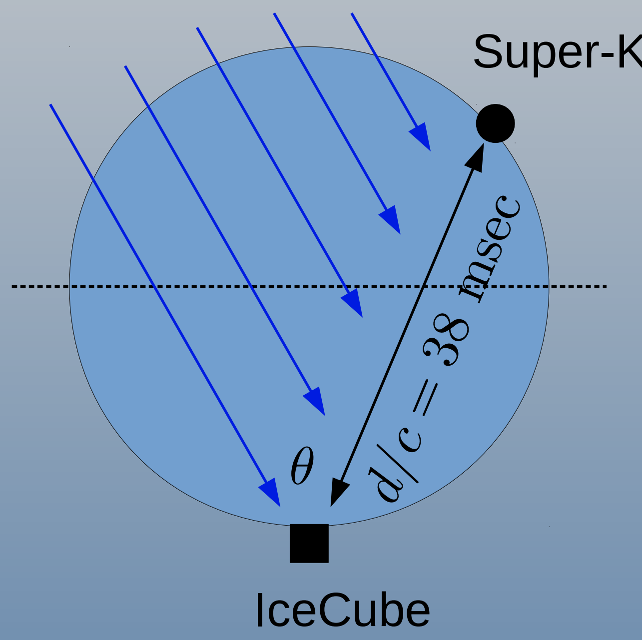
The triangulation method

Consider:

- an instantaneous neutrino pulse
- two dectors

Arrival time difference:

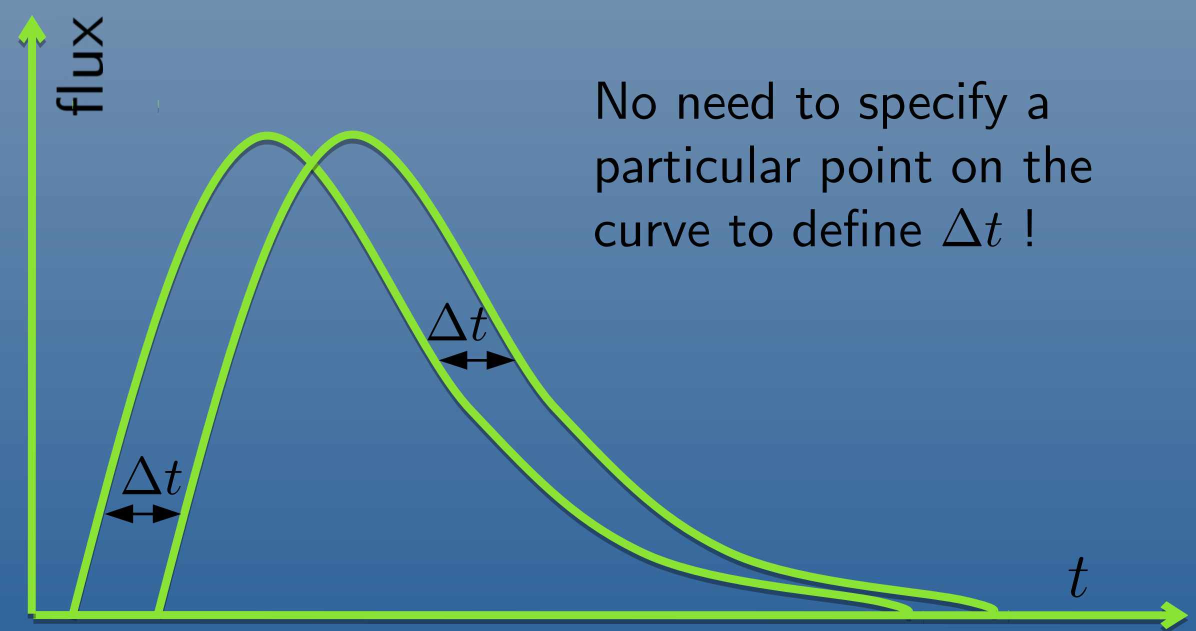
$$\Delta t = \frac{d}{c} \cos\theta$$



However, instantaneous ✗

How to define Δt properly?

— defined as time shift



No need to specify a particular point on the curve to define Δt !

Previous conclusion:

SNO: $\delta t = 15$ ms
Super-K: $\delta t = 3$ ms

$\Big\} \ \delta(\cos\theta) = 0.5$

HEP 1 records found Search

1. **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**
DOI: 10.1103/PhysRevD.60.033007
e-Print: **astro-ph/9811350** | **PDF**
References | BibTeX | LaTeX(US) | LaTeX(EU) | Harvmac | EndNote
ADS Abstract Service; OSTI.gov Server
Detailed record - Cited by 118 records 100+

Today we have:

- more detectors
- better knowledge of the flux

Our result

SN→ neutron star:
$1.5^\circ \sim 3.5^\circ$

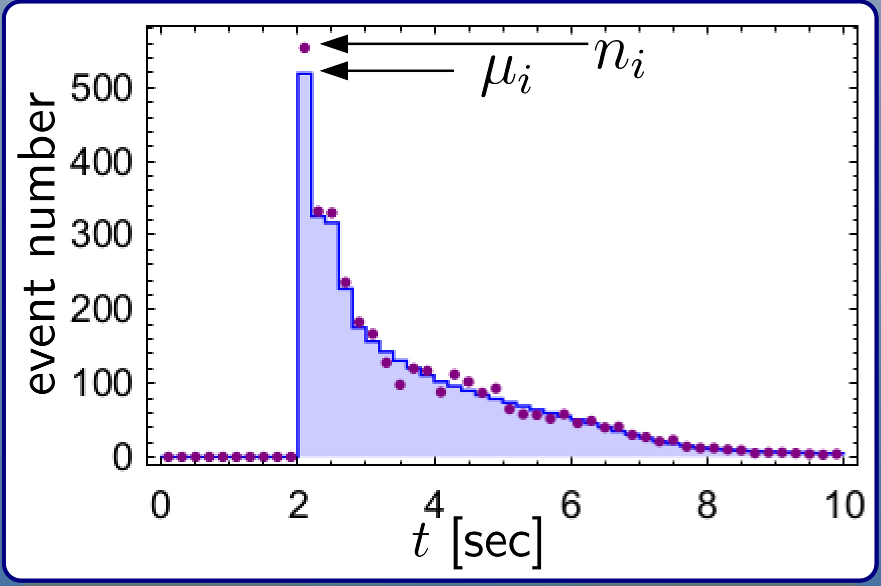
SN→ black hole:
$0.2^\circ \sim 0.5^\circ$

Our method

Likelihood analysis on binned data.

Assuming Poisson distribution in each bin,

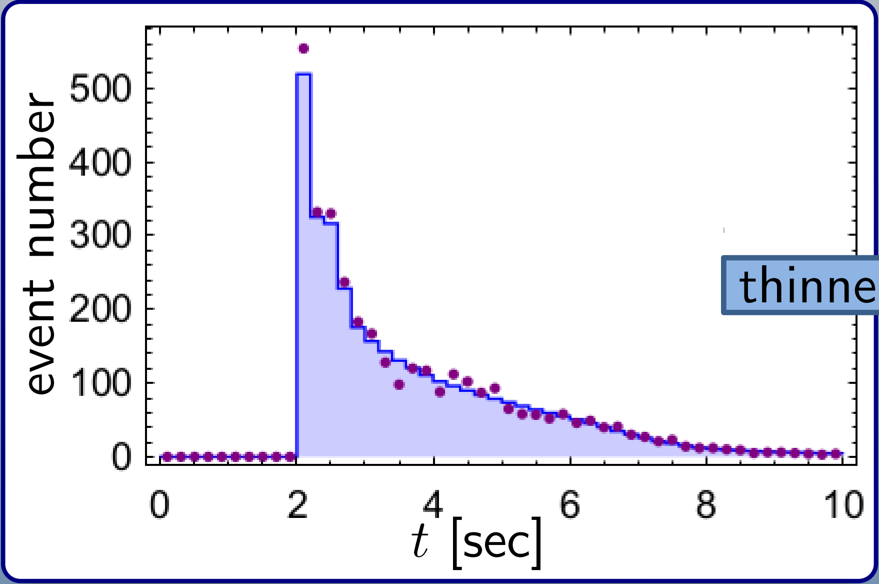
$$\chi^2(\Delta t) = 2\sum_i \left(\mu_i - n_i + n_i \ln \frac{n_i}{\mu_i}\right)$$

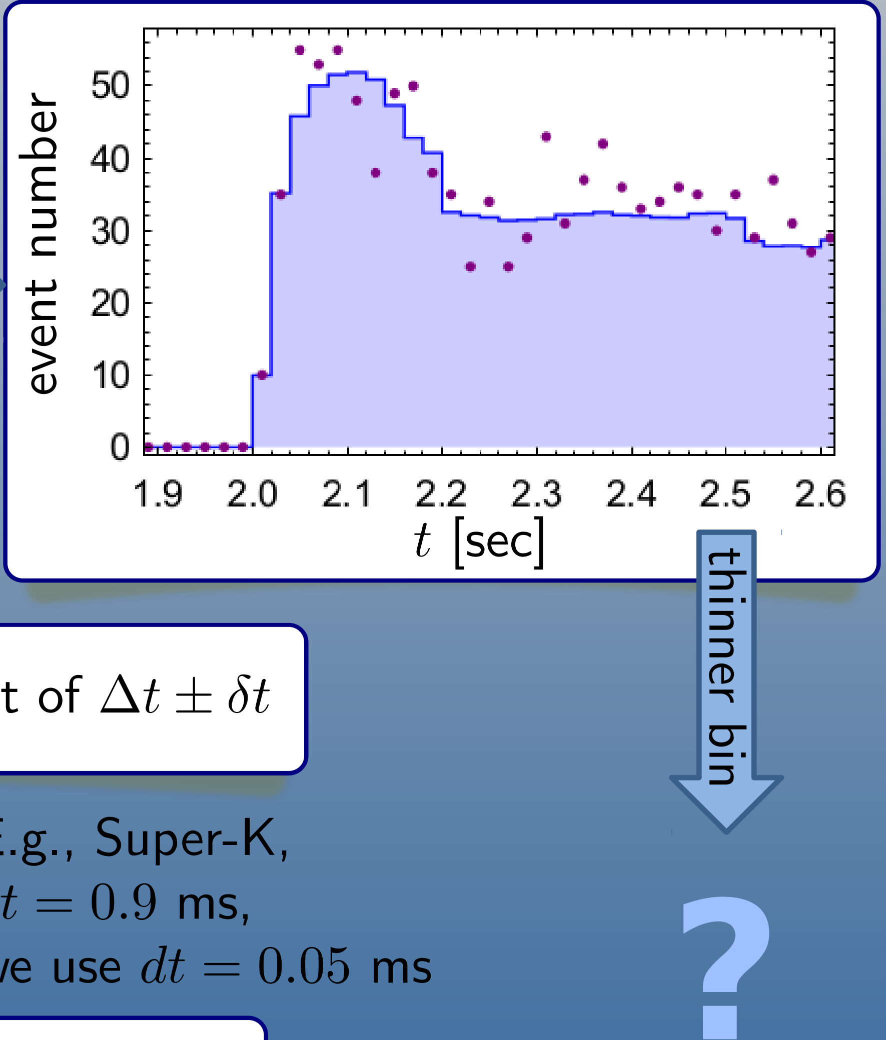


- n_i: event number observed
- μ_i: event number expected

Important:
when $\langle n_i \rangle$ & $\mu_i \ll 1$,
it is still valid.

... thinner and thinner





smaller dt (bin width) $\Rightarrow$ better measurement of $\Delta t \pm \delta t$

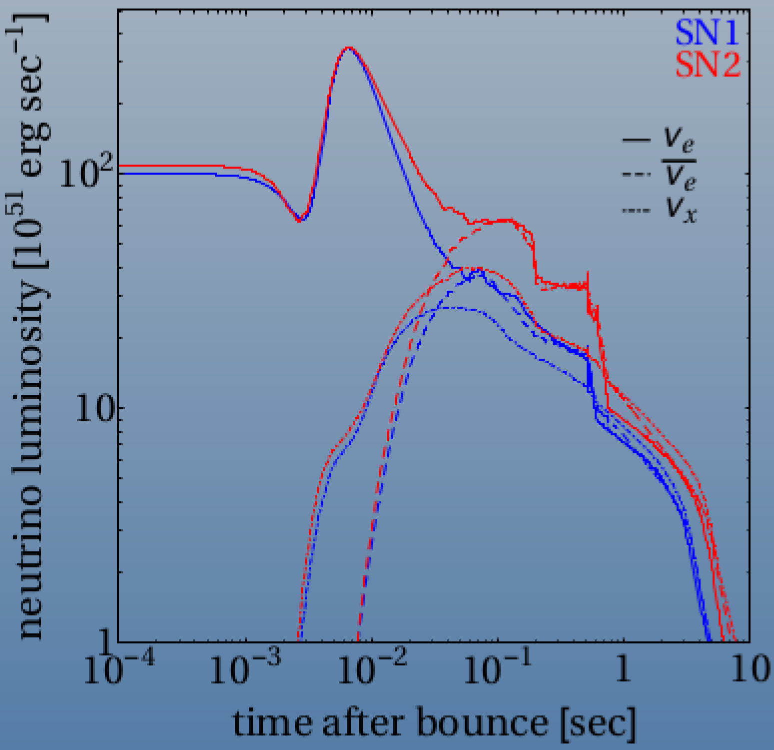
How small is enough? Answer: $dt \ll \delta t$

E.g., Super-K,
$\delta t = 0.9$ ms,
we use $dt = 0.05$ ms

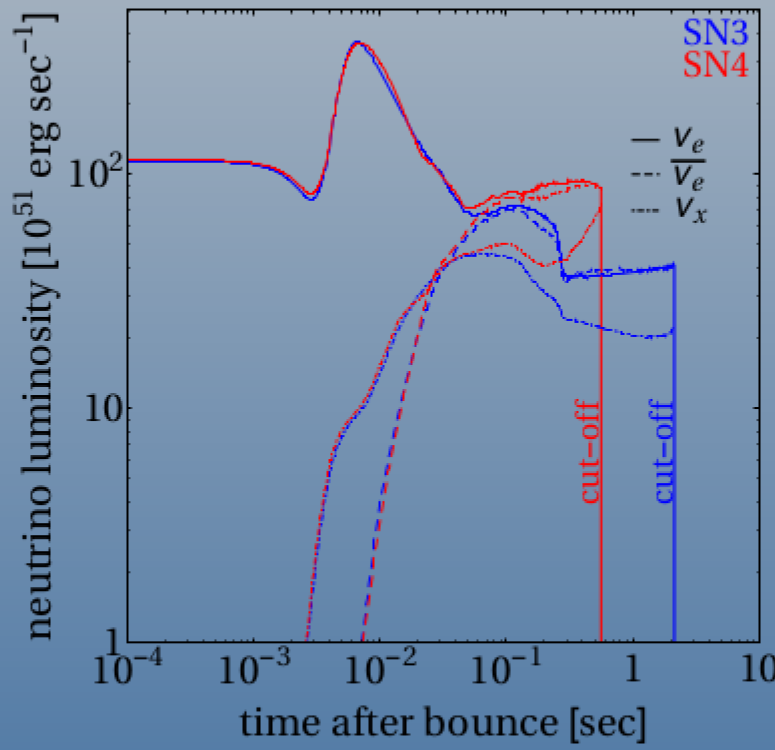
Note: $dt \ll \delta t \Rightarrow \mu_i \ll 1$. But the method is still valid.

SN → neutron star (NS) or black hole (BH)?

neutron star (NS)



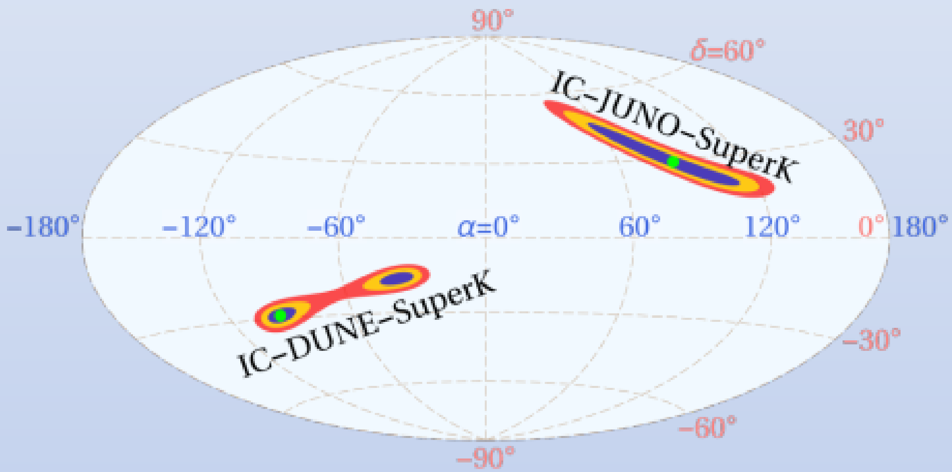
black hole (BH)



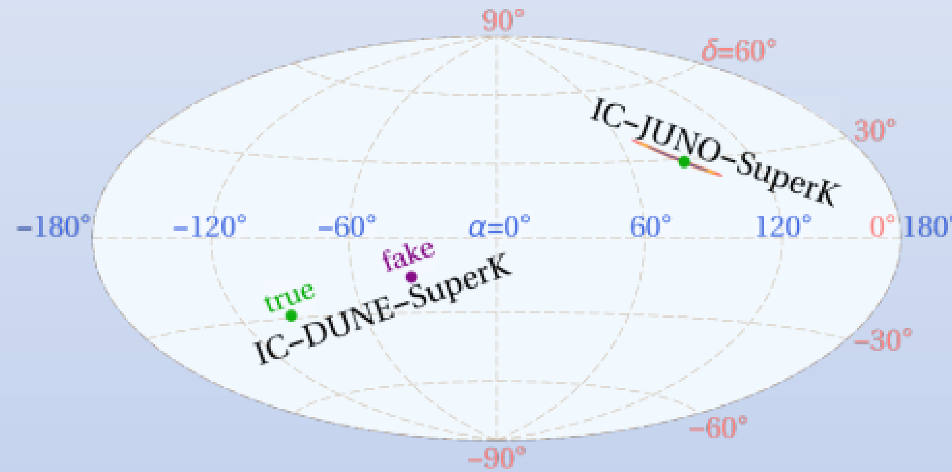
Difference: very sharp cut-off for BH.

Experiments	major process	target	N_{total}	δt	N_{total} (BH)	δt (BH)
Super-Kamiokande [27]	$\overline{\nu}_e + p \to e^+ + n$	32 kt H_2O	7625	0.9 ms	6666	0.14 ms
JUNO [43]	$\overline{\nu}_e + p \to e^+ + n$	20kt C_nH_m	4766	1.2 ms	4166	0.19 ms
DUNE [60]	$\nu_e + {}^{40}\text{Ar} \to e^- + {}^{40}\text{K}^*$	40 kt LAr	3297	1.5 ms	3084	0.18 ms
NOνA [61]	$\overline{\nu}_e + p \to e^+ + n$	15 kt C_nH_m	3574	1.4 ms	3125	0.24 ms
CJPL [62]	$\overline{\nu}_e + p \to e^+ + n$	3kt H_2O	715	3.8 ms	625	0.97 ms
IceCube [63]	noise excess	H_2O	$\mathcal{O}(10^6)$[64]	1ms	$\mathcal{O}(10^6)$[64]	0.16 ms
ANTARES [65]	noise excess	H_2O	$\mathcal{O}(10^3)$[66]	100ms	$\mathcal{O}(10^3)$[66]	32 ms
Borexino [67]	$\overline{\nu}_e + p \to e^+ + n$	0.3 kt C_nH_m	71.5	16 ms	62.5	5.5 ms
LVD [68]	$\overline{\nu}_e + p \to e^+ + n$	1 kt C_nH_m	238	7.5 ms	208	2.4 ms
XENON1T [69]	coherent scattering	2t X_e	31	27 ms	29	10 ms
DARWIN [57]	coherent scattering	40t X_e	622	1.3 ms	588	0.7 ms

Locating SN by neutrino triangulation: 3-detector combinations.

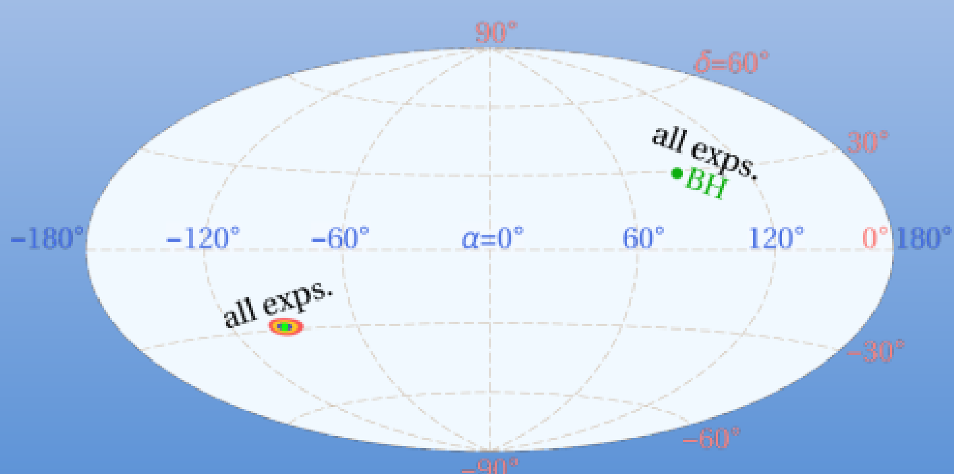


collapsed into neutron star (NS)



collapsed into black hole (BH)

Combine all detectors.



Location uncertainties (10 kpc SN)

SN→NS: $1.5^\circ \sim 3.5^\circ$

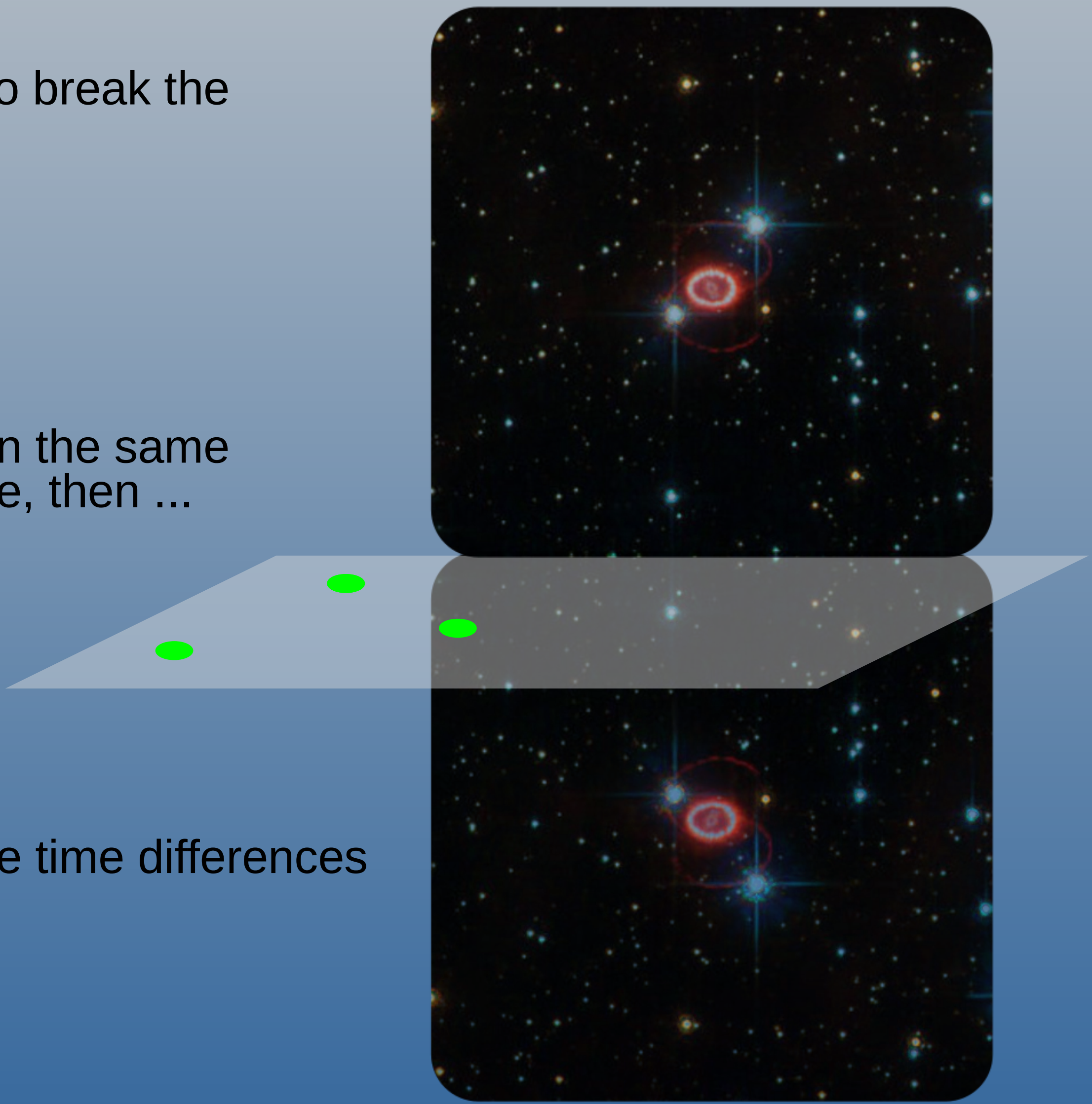
SN→BH: $0.2^\circ \sim 0.5^\circ$

Backup

Three detectors are not enough to break the mirror degeneracy

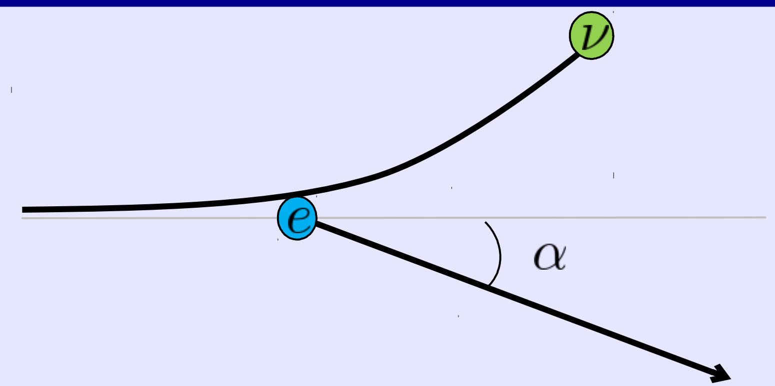
Reason: any 3 detectors can be in the same plane. If the SN is not in this plane, then ...

The mirror image has all the same time differences



Backup

$\nu + e$ scattering



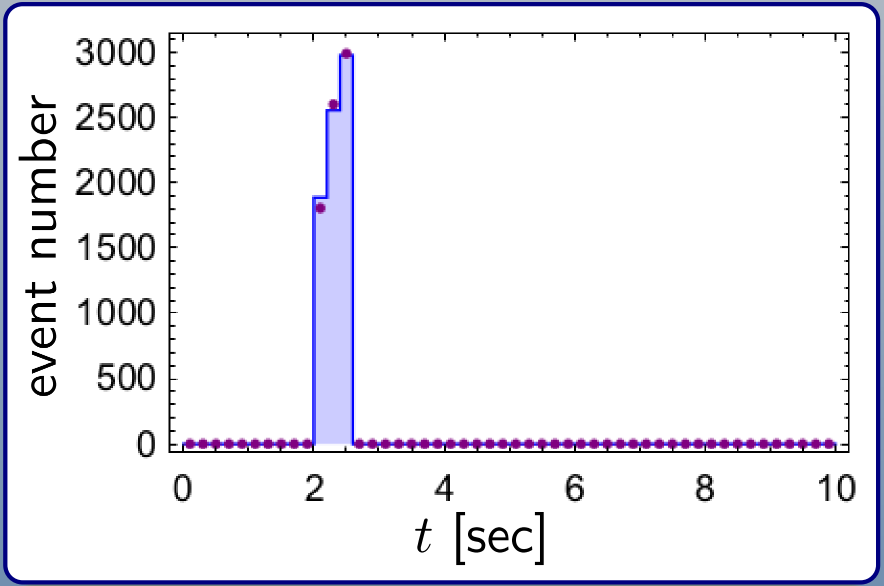
Super-K [1601.04778]

We have developed an algorithm to identify the SN direction and its error using a maximum likelihood method. The pointing accuracy estimated by the ensemble study is found to be $3.1 \sim 3.8°(4.3 \sim 5.9°)$ at 68.2% coverage for the Wilson (NK1) model at 10 kpc, where the range covers various neutrino oscillation scenarios.

Hyper-K [1805.04163]

events, the angular distributions for lower energy events show more enhanced peaks. The direction of a supernova at 10 kpc can be reconstructed with an accuracy of about 1 to 1.3 degrees with Hyper-K, assuming the performance of event direction reconstruction similar to Super-K [252].

If collapses to black hole



total events	SN1 (11 $M_\odot$)	SN2 (27 $M_\odot$)	SN3 (BH)	SN4 (BH)
10^5	0.2 ms	0.2 ms	0.06 ms	0.02 ms
10^4	0.8 ms	0.8 ms	0.3 ms	0.1 ms
10^3	2.9 ms	3.1 ms	1.9 ms	0.6 ms
10^2	11 ms	13 ms	7.3 ms	4 ms