

Triangulation Method for Locating a Core-Collapse Supernova

based on: arXiv:1802.02577 (JCAP 1804 (2018) 025)
in collaboration with Manfred Lindner and Xun-Jie Xu

Vedran Brdar

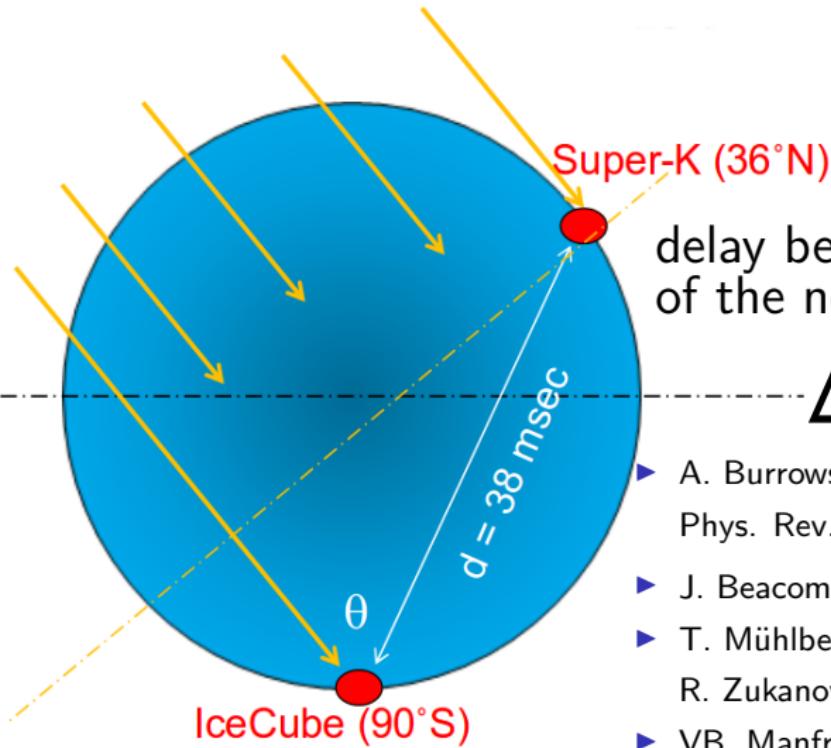


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SN Triangulation



delay between the arrival times
of the neutrino pulse

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

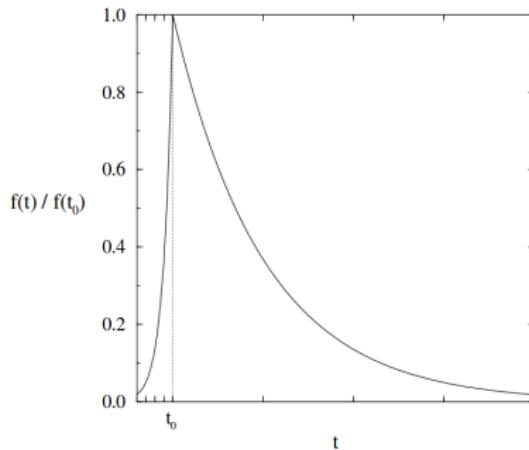
- ▶ A. Burrows, D. Klein, and R. Gandhi, Phys. Rev. D45, 3361 (1992)
- ▶ J. Beacom, P. Vogel, Phys. Rev. D60 (1999)
- ▶ T. Mühlbeier, H. Nunokawa, R. Zukanovich Funchal, Phys. Rev. D88 (2013)
- ▶ VB, Manfred Lindner, Xun-Jie Xu, JCAP 1804 (2018)

A. Burrows, D. Klein, and R. Gandhi, PRD45, 3361 (1992)

	SNO	KII	SK	LVD	MACRO
$\bar{\nu}_e p$	331	355	5310	342	219
$\nu_e e^-$	H ₂ O: 7.83	5.19	77.6	6.04	2.08
	D ₂ O: 4.35				
$\bar{\nu}_e e^-$	H ₂ O: 1.93	1.13	16.9	1.49	0.445
	D ₂ O: 1.07				
$\nu_\mu e^-$	H ₂ O: 4.25	3.34	49.9	3.28	1.50
	D ₂ O: 2.36				
$\nu_e O$ (CC)	H ₂ O: 2.11	2.41	36.0	—	—
	D ₂ O: 1.17				
$\bar{\nu}_e O$ (CC)	H ₂ O: 2.59	3.04	45.5	—	—
	D ₂ O: 1.44				
$\nu_e C$ (CC)	—	—	—	1.05	0.691
$\bar{\nu}_e C$ (CC)	—	—	—	1.02	0.750
$\nu_e C$ (NC)	—	—	—	2.22	1.88
$\bar{\nu}_e C$ (NC)	—	—	—	2.02	1.71
$\nu_\mu C$ (NC)	—	—	—	15.9	13.4
$\nu_e d$ (CC)	81.9	—	—	—	—
$\bar{\nu}_e d$ (CC)	66.7	—	—	—	—
$\nu_e d$ (NC)	35.2	—	—	—	—
$\bar{\nu}_e d$ (NC)	37.2	—	—	—	—
$\nu_\mu d$ (NC)	200	—	—	—	—
Total e^-	H ₂ O: 14.0 D ₂ O: 7.78	9.66	144	10.8	4.02
NC on D	272	—	—	—	—
NC on C	—	—	—	20.1	17.0
Total	H ₂ O: 350 D ₂ O: 431	370	5530	375	241

$$\delta\theta = 5.8^\circ \left(\frac{\delta t}{2 \text{ msec}} \right) \left(\frac{40 \text{ msec}}{d/c} \right) \left(\frac{D}{10 \text{ kpc}} \right)^2 \frac{1}{2 \sin \theta}$$

J. Beacom and P. Vogl, Phys.Rev.D60 (1999)



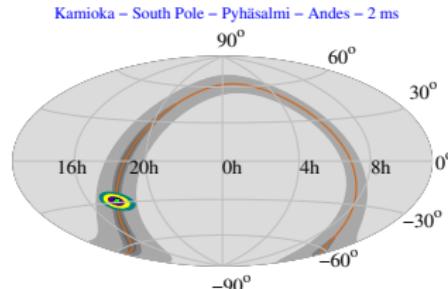
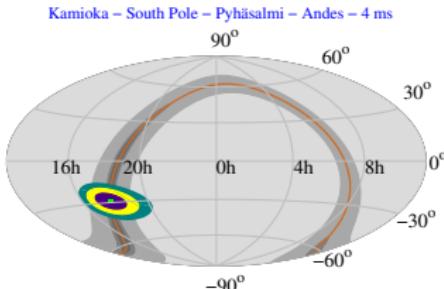
$$f(t) = \frac{\alpha_1}{\tau_1} \text{Exp} \left[\frac{t - t_0}{\tau_1} \right], t < t_0$$
$$f(t) = \frac{\alpha_2}{\tau_2} \text{Exp} \left[-\frac{t - t_0}{\tau_2} \right], t > t_0$$
$$\alpha_1 = \frac{\tau_1}{\tau_1 + \tau_2}, \quad \alpha_2 = \frac{\tau_2}{\tau_1 + \tau_2}.$$

- ▶ How well can t_0 be determined?

- ▶ Rao-Cramer theorem employed

$$\frac{1}{(\delta t_0)_{\min}^2} = N \int dt f(t, t_0) \left[\frac{\partial \ln f(t, t_0)}{\partial t_0} \right]^2 = N \left(\frac{\alpha_1}{\tau_1^2} + \frac{\alpha_2}{\tau_2^2} \right)$$

- ▶ $\delta t_0^{\text{SK}} = 3 \text{ ms}$, $\delta t_0^{\text{SNO}} \sim 10 \text{ ms} \rightarrow \delta(\cos \theta) = 0.5$



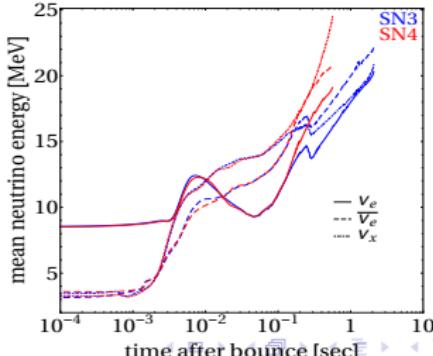
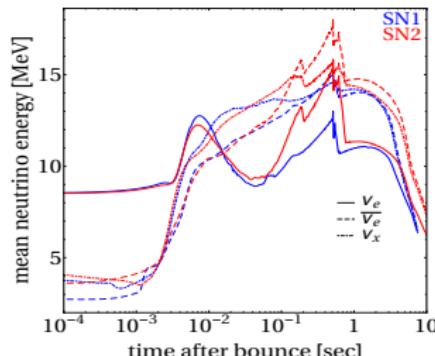
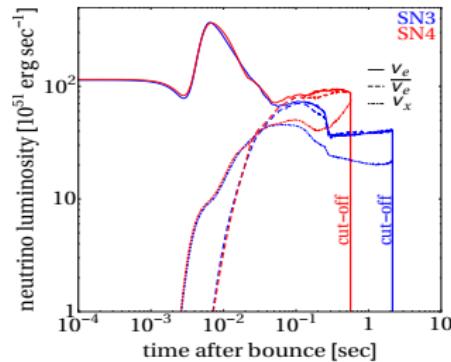
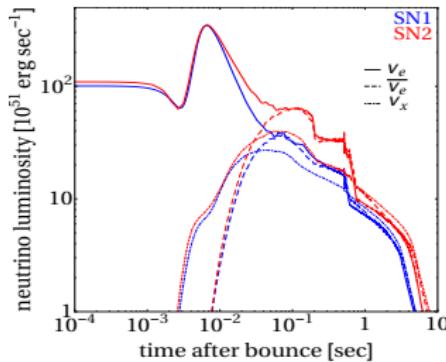
Detector	Fid. Mass (kt)	N	N_1	$\delta t_{\text{arrival}}$ (ms)
Super-K	32	8.0×10^3	80	3.4
Hyper-K	740	1.9×10^5	1.9×10^3	0.7
SNO+	0.8	400	4	15
LENA	44	1.8×10^4	1.8×10^2	2.7
ANDES	3	1.2×10^3	12	8.7
IceCube	$\sim 10^3$	$\sim 10^6$	$\sim 10^4$	0.3

- ▶ angular position can be known within $\sim 5(10)^\circ$ in declination and $\sim 8(15)^\circ$ in right ascension for the time resolution of 2 (4) ms

Neutrino Luminosities and Mean Energies

- ▶ four different SN simulations performed by Garching group:

SN1,SN2 collapse into a neutron star; SN3, SN4 black hole collapse



Neutrino Luminosities and Mean Energies II

- The flux of (anti)neutrino flavor α at a distance D from the center of star

$$\phi_{\nu_\alpha}^0(t, E) = \frac{[1+\chi(t)]^{1+\chi(t)}}{\Gamma[1+\chi(t)]} \frac{L_{\nu_\alpha}(t)}{4\pi D^2 \langle E_{\nu_\alpha}(t) \rangle^2} \left(\frac{E}{\langle E_{\nu_\alpha}(t) \rangle} \right)^{\chi(t)} \text{Exp} \left[-\frac{(1+\chi(t))E}{\langle E_{\nu_\alpha}(t) \rangle} \right],$$

with $\frac{\langle E_{\nu_\alpha}^2(t) \rangle}{\langle E_{\nu_\alpha}(t) \rangle^2} = \frac{2+\chi(t)}{1+\chi(t)}$.

- upper fluxes hold in the region $\rho(D) \gtrsim 10^4 \text{ g cm}^{-3}$

- MSW resonances associated to $\Delta m_{\text{solar}}^2 \sim 7 \times 10^{-5} \text{ eV}^2$ and $|\Delta m_{\text{atm}}^2| \sim 2.3 \times 10^{-3} \text{ eV}^2$

Dighe, Smirnov Phys.Rev. D62 (2000)

$$\phi_{\nu_e} = \phi_{\nu_x}^0 \left(\frac{D}{d} \right)^2,$$

$$\phi_{\bar{\nu}_e} = (\phi_{\bar{\nu}_e}^0 \cos^2 \theta_{12} + \phi_{\nu_x}^0 \sin^2 \theta_{12}) \left(\frac{D}{d} \right)^2, \text{(normal mass ordering)}$$

$$\phi_{\nu_x} = \left(\frac{1}{4} (2 + \cos^2 \theta_{12}) \phi_{\nu_x}^0 + \frac{1}{4} \phi_{\nu_e}^0 + \frac{1}{4} \phi_{\bar{\nu}_e}^0 \sin^2 \theta_{12} \right) \left(\frac{D}{d} \right)^2$$

Event Rates in Neutrino Detectors

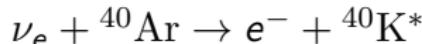
$$N_\alpha^i(A, t_0) = A \int dE \int_{t_i}^{t_i + \Delta t} dt \sigma(E) \phi_{\nu_\alpha}(t - t_0, E)$$

- ▶ IBD most important channel for Super-K and future Hyper-K and CJPL
- ▶ $\nu - p$ scattering not relevant for triangulation, but very important for the flavor studies in liquid scintillators (33% JUNO, 23% Borexino, 11% Kamland wrt IBD)
- ▶ DM detectors (Xenon1T, PandaX, Darwin) → coherent scattering

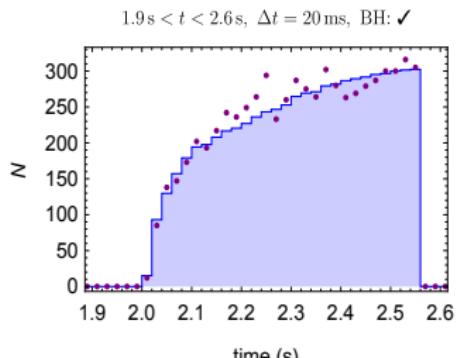
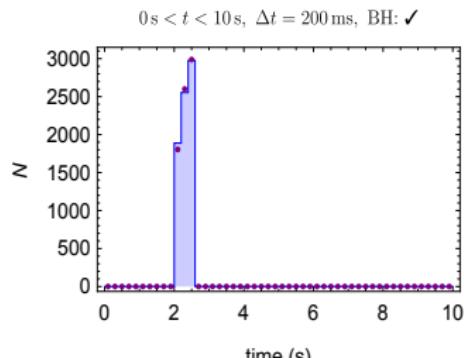
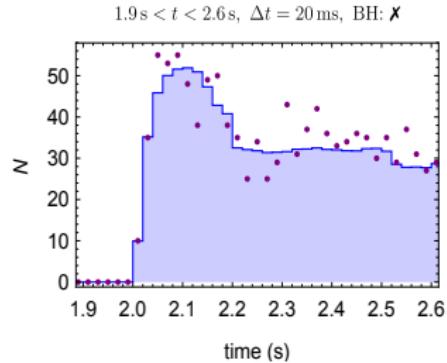
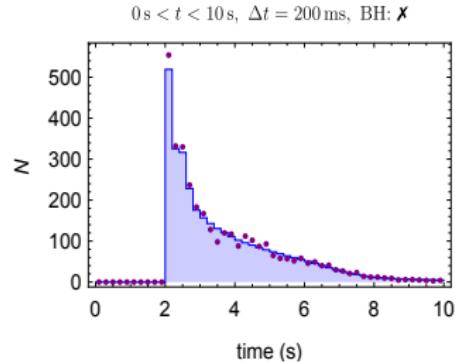
$$\sigma_{\text{coh}}(E) = \int_{E_{\text{th}}} dE_{\text{recoil}} \frac{d\sigma}{dE_{\text{recoil}}}$$

$$\frac{d\sigma}{dE_{\text{recoil}}} = \frac{G_F^2 m_{\chi_e}}{4\pi} \left[N_n - (1 - 4 \sin^2 \theta_W) N_p \right]^2 \left(1 - \frac{m_{\chi_e} E_{\text{recoil}}}{2E^2} \right) F^2(E_{\text{recoil}})$$

- ▶ DUNE: the relevant process is the charged-current process on ${}^{40}\text{Ar}$



Event Rates in Neutrino Detectors II



Uncertainties on SN Neutrino Arrival Times

- ▶ the minimal statistical uncertainties on the neutrino arrival time can be estimated by employing the **Rao-Cramer theorem**
- ▶ However, this does not work if one wants to include backgrounds or study cases with an instant growth or a drop of event rate (BH formation)
- ▶ to determine δt we adopt χ^2 fit: $\chi^2(t_0) = 2 \sum_{i=1}^{i_{\max}} \left(\mu_i - n_i + n_i \ln \frac{n_i}{\mu_i} \right)$
- ▶ the bin width has to be much smaller than the onset time uncertainty that we wish to estimate $\rightarrow \Delta t \ll \delta t$
- ▶ we include a background $\mu_{\text{bkg}} = 0.01$ events per second for Super-K (rescaled for others according to the fiducial volume)
- ▶ in neutron star formation scenario, the neutrino emission typically leaves a long tail. we checked that small changes in i_{\max} do not change χ^2
- ▶ the main impact on δt comes from the drastic variation of the number of events between the neighboring bins
- ▶ for the black hole case δt is almost exclusively determined by the last couple of percent of events (the cut-off yields a more significant statistical effect in comparison to the rise of flux at the signal onset)

Global picture for SN neutrino event rates and δt

Experiments	major process	target	N_{total}	δt	$N_{\text{total}}(\text{BH})$	$\delta t (\text{BH})$
Super-Kamiokande	$\bar{\nu}_e + p \rightarrow e^+ + n$	32 kt H ₂ O	7625	0.9 ms	6666	0.14 ms
JUNO	$\bar{\nu}_e + p \rightarrow e^+ + n$	20kt C _n H _m	4766	1.2 ms	4166	0.19 ms
RENO50	$\bar{\nu}_e + p \rightarrow e^+ + n$	18kt C _n H _m	4289	1.3 ms	3749	0.21 ms
DUNE	$\nu_e + {}^{40}\text{Ar} \rightarrow e^- + {}^{40}\text{K}^*$	40 kt LAr	3297	1.5 ms	3084	0.18 ms
NO ν A	$\bar{\nu}_e + p \rightarrow e^+ + n$	15 kt C _n H _m	3574	1.4 ms	3125	0.24 ms
CJPL	$\bar{\nu}_e + p \rightarrow e^+ + n$	3kt H ₂ O	715	3.8 ms	625	0.97 ms
IceCube	noise excess	H ₂ O	$\mathcal{O}(10^6)$	1ms	$\mathcal{O}(10^6)$	0.16 ms
ANTARES	noise excess	H ₂ O	$\mathcal{O}(10^3)$	100ms	$\mathcal{O}(10^3)$	32 ms
Borexino	$\bar{\nu}_e + p \rightarrow e^+ + n$	0.3 kt C _n H _m	71.5	16 ms	62.5	5.5 ms
LVD	$\bar{\nu}_e + p \rightarrow e^+ + n$	1 kt C _n H _m	238	7.5 ms	208	2.4 ms
XENON1T	coherent scattering	2t X _e	31	27 ms	29	10 ms
DARWIN	coherent scattering	40t X _e	622	1.3 ms	588	0.7 ms

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

Comparison with previous results

- ▶ 2 improvements :

1)

- ▶ neutrino fluxes are taken from state-of-the-art simulations
- ▶ event rates depart from assumed two-sided exponential taken in previous works
- ▶ analytical evidence for discrepancy: Rao-Cramer for two-sided exponential

$$\delta t = \sqrt{\frac{\tau_1 \tau_2}{N}}$$

- ▶ for general power law, $f \propto \left(\frac{t-t_0+\tau_1}{\tau_1}\right)^p$

$$\delta t = \sqrt{\frac{\tau_1 \tau_2 (p-1)}{N p^2}}$$

- 2) We provide a global picture by combining all the relevant current and future neutrino detectors

Triangulation Results

The time difference of SN neutrino arrival at two detectors located at \vec{r}_i and \vec{r}_j is

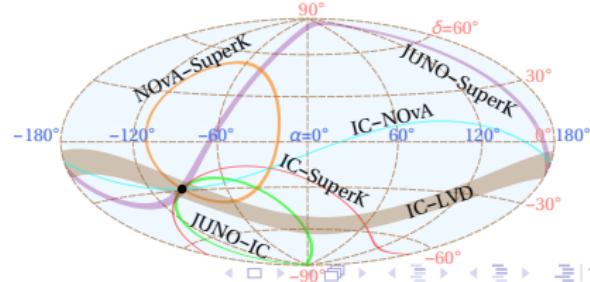
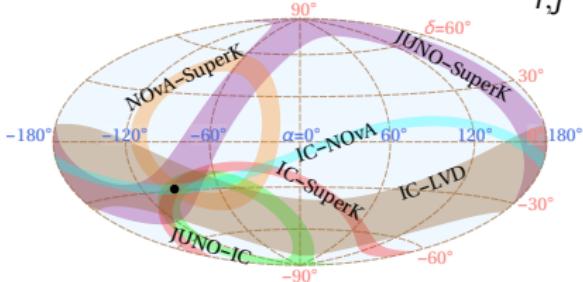
$$t_{ij} = \frac{(\vec{r}_i - \vec{r}_j) \cdot \vec{n}}{c}.$$

χ^2 for a pair of detectors is defined as

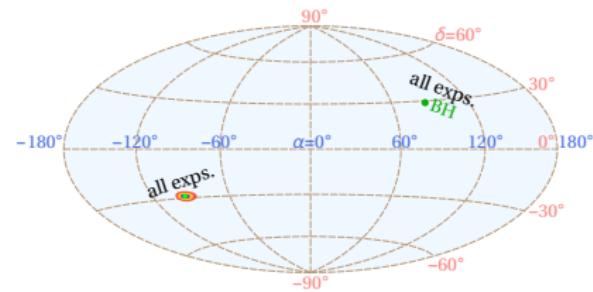
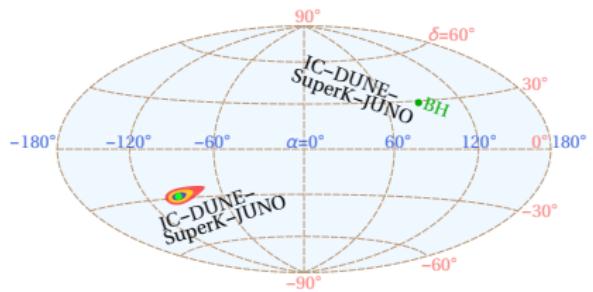
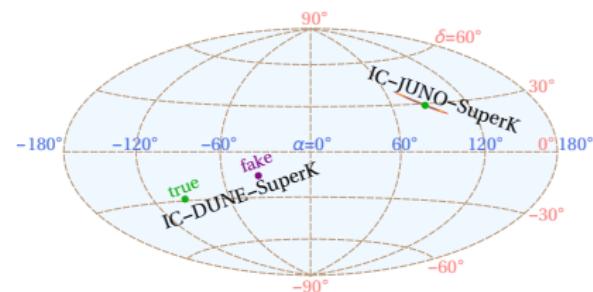
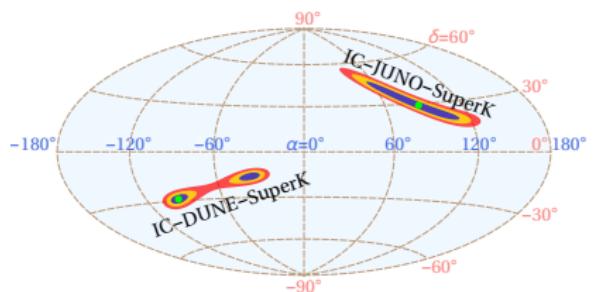
$$\chi_{ij}^2(\alpha, \delta) = \left(\frac{t_{ij}(\alpha', \delta') - t_{ij}(\alpha, \delta)}{\text{Max}(\delta t_i, \delta t_j)} \right)^2,$$

and for more than two detectors involved in the analysis χ^2 reads

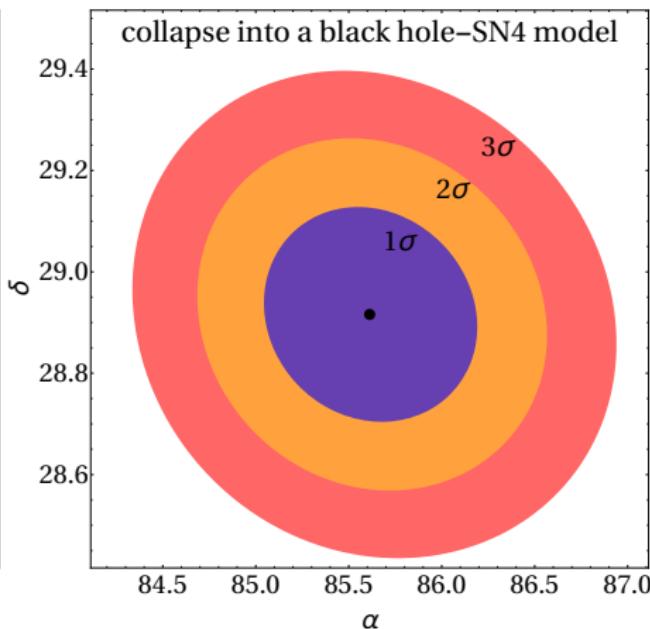
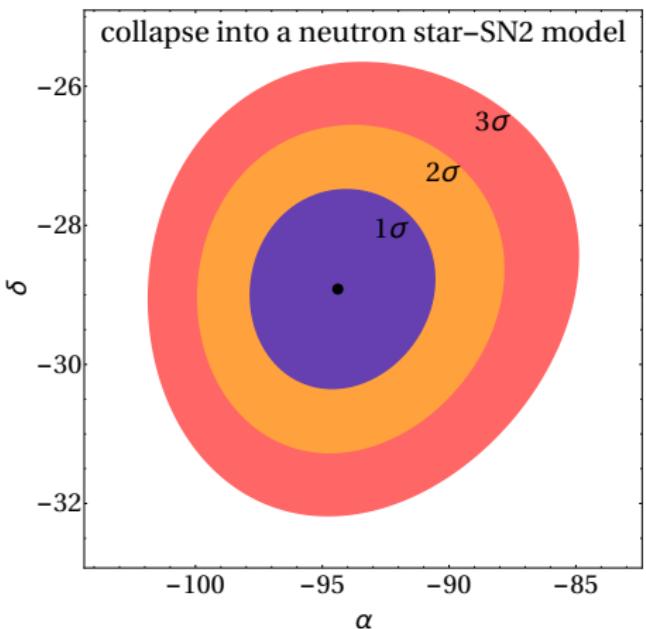
$$\chi_{\text{tot}}^2(\alpha, \delta) = \sum_{i < j} \chi_{ij}^2(\alpha, \delta).$$



Triangulation Results II



Triangulation Results III

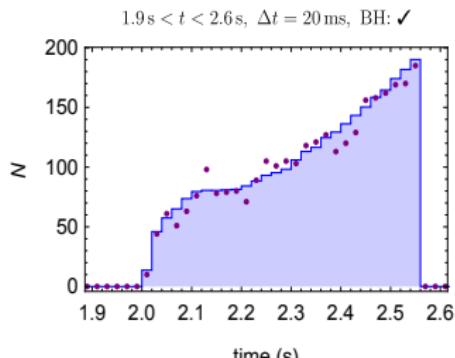
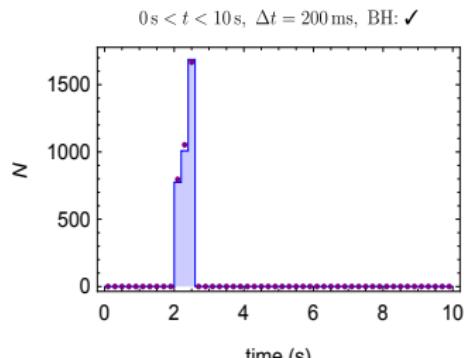
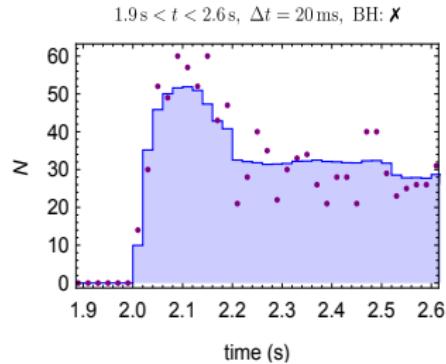
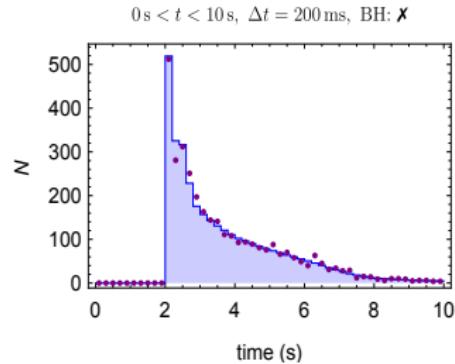


Summary

- ▶ we studied how precisely the next Galactic supernova may be located via its neutrinos by means of the triangulation method
- ▶ we update previous results by considering all relevant current and near-future experiments as well as constructing event rates by employing data from state-of-the-art simulations
- ▶ for the core-collapse into a neutron star, precision of 1.5° in declination and 3.5° in right ascension is obtained
- ▶ for the case of the core collapsing into a black hole we demonstrated for the first time that sub-degree precision could be reached
- ▶ we envision that this procedure may be straightforwardly implemented and shared through the Supernova Early Warning System

BACKUP SLIDES

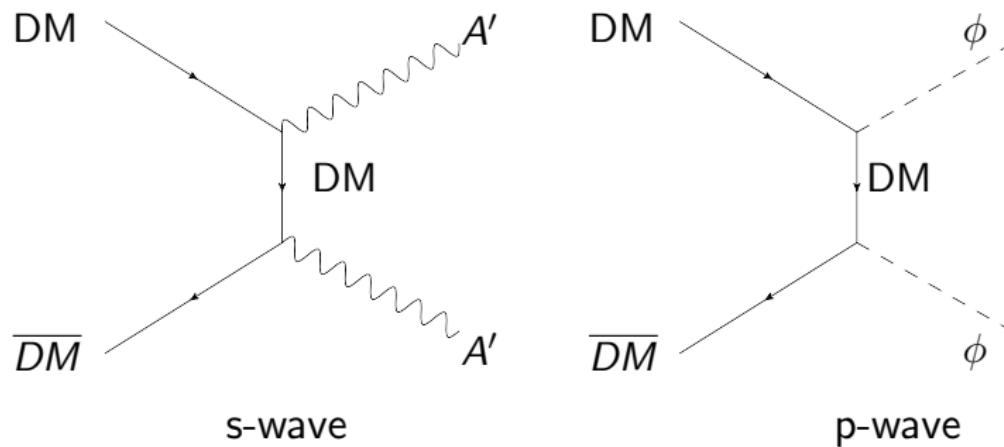
Event Rates in Neutrino Detectors - DUNE



Relevance for DM searches – “Dark Gamma Ray Bursts”

VB, Kopp, Liu, Phys. Rev. D 95 (2017)

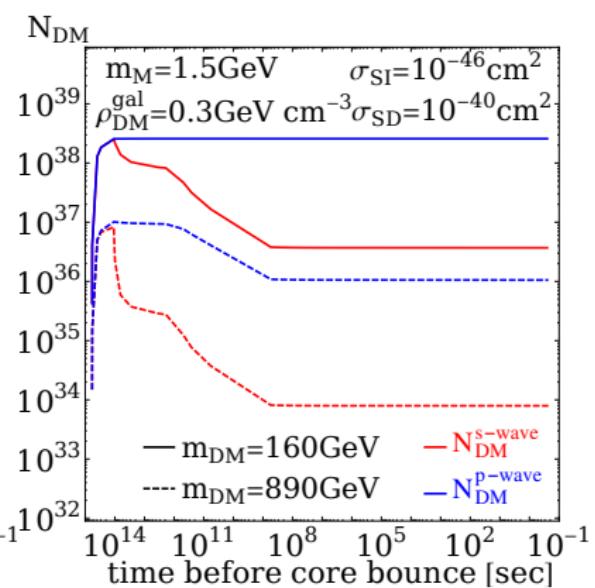
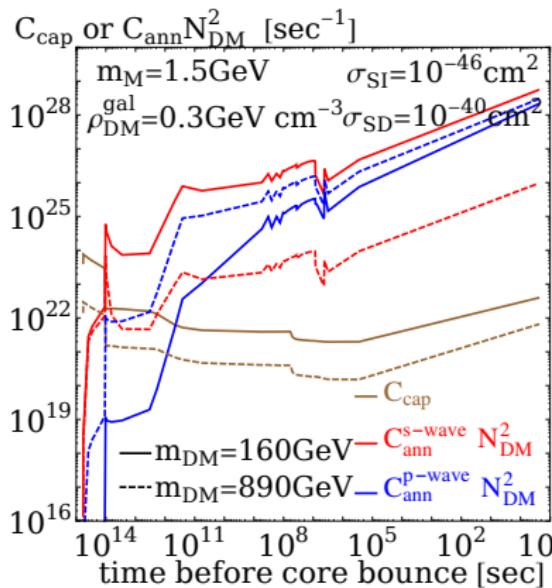
- ▶ fermionic (Dirac) DM $\sim (1,1,0)$
- ▶ $\sim \mathcal{O}(1)$ GeV dark photon or scalar coupling to
 - ▶ DM
 - ▶ SM via kinetic mixing (vector) or higgs portal (scalar)



Capture and Annihilation Rates

$$\dot{N}_{\text{DM}}(t) = C_{\text{cap}}(t) - C_{\text{ann}}(t) N_{\text{DM}}(t)^2 + C_{\text{self}}(t) N_{\text{DM}}(t)$$

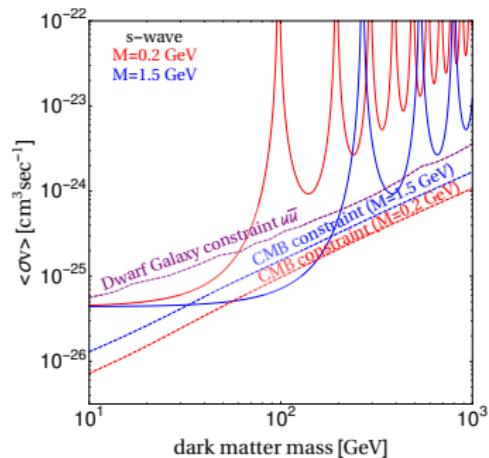
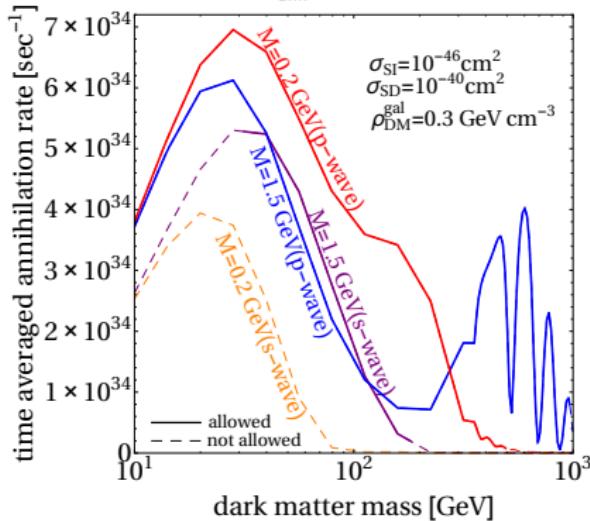
$$C_{\text{cap}} = \sum_i \int_0^{R_{\text{star}}} dr 4\pi r^2 \frac{dC_i(r)}{dV} \quad C_{\text{ann}} N_{\text{DM}}^2 \equiv \int d^3r \langle \sigma v_{\text{rel}} \rangle n_{\text{DM}}^2(r)$$



DM Annihilation Burst during Supernova cooling phase

- ▶ density and temperature fixed to $10^{14} \text{ g cm}^{-3}$ and 3 MeV
- ▶ DM particles within $R_{\text{core}} \sim 30 \text{ km}$ (size of proto-neutron star)
- ▶ DM gets thermalized within $\sim 10^{-6}$ seconds

$$\blacktriangleright N_{\text{DM}}(t) = \frac{N_0}{1+t \mathcal{C}_{\text{ann}}^{SN} N_0} \quad \Delta t_{\text{dur}} \sim (\mathcal{C}_{\text{ann}}^{SN} N_0)^{-1} \quad \mathcal{C}_{\text{ann}}^{SN} = \langle \sigma v_{\text{rel}} \rangle \left(\frac{G_N m_{\text{DM}} \rho_{\text{PSN}}}{3 T_{\text{SN}}} \right)^{3/2}$$



Dark Gamma Ray Burst

Properties

- ▶ An observable gamma ray signal after ν arrival
- ▶ $\Delta t_{burst} = (C_{ann}^{SN} N_0)^{-1}$ related to sensitivity
- ▶ $\Delta t_{burst} \in [\mathcal{O}(10), \mathcal{O}(10^3)]$ sec for p-wave, $\mathcal{O}(10^2)$ sec for s-wave
- ▶ Benchmark locations: 0.1 kpc and 8 kpc from GC

