The Diffuse Supernova Neutrino Background, an update: theory and detection prospects

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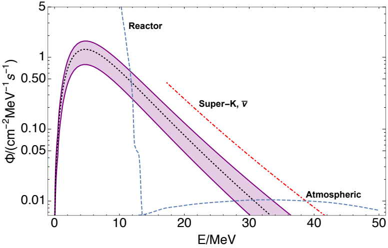
Alankrita Priya and CL, arXiv:1705.02122, funded by DOE/NSF

Introduction: **D**iffuse **S**upernova **N**eutrino **B**ackground



- *Cosmological* flux, image of *diverse* supernova population
- Constant in time. Searches are *background-limited*

SuperK limit: Bays et al., PRD 85, 2012 052007

Update: towards realistic predictions

- on the diverse SN population: stars collapsing into black holes (*failed supernovae*) CL, PRL 102, 2009
  - stronger observational case

    Horiuchi et al., MNRAS Letters 445 (2014) L99; Kochanek, ApJ 785 (2014) 28; Kochanek et al., ApJ 684 (2008) 1336
  - new, systematic simulations of BH formation

    K. Sumiyoshi et al., PRL 97 (2006) ; M. Liebendorfer, et al., AIP Conference Proceedings 586 (2001) 472477 ; Ugliano, et al., ApJ 757 (2012) 69; OConnor and Ott, ApJ 762 (2013) 126 ; Nakazato et al., ApJ 804 (2015) no.1, 75 ; Pejcha & Thompson, ApJ 801 (2015) 90. Ertl, et al., ApJ 818 (2016) 124; Mirizzi, et al., Riv. Nuovo Cim. 39 (2016)

- largest, *cleanest* detectors being built: JUNO, SuperK-Gd
    - *detection likely within* ~ 10 *years!*
    - new, realistic background studies

  Moellenberg et al., PRD 91 (2015); An et al., J. Phys. G, 43 (2016) 030401; H. Kunxian, PhD thesis, Kyoto University, 2015.

Formulation: integrating over the SN population

- integrate over redshift and progenitor star mass:

$$\Phi(E) = \frac{c}{H_0} \int_{8M_\odot}^{125M_\odot} \int_0^{z_{max}} \dot{\rho}(z, M) \frac{dF_{\bar{e}}(E(1+z), M)}{dM} \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} dM$$

- SN rate $\propto$ star formation rate; $z \lesssim 1$ and smaller M dominate

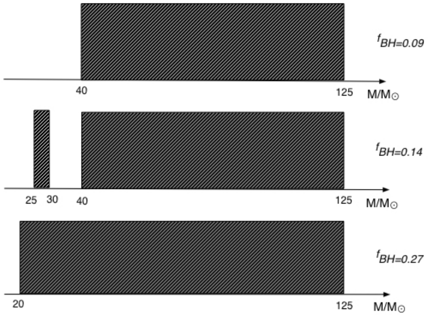
$$\dot{\rho}(z, M) = R_{SF}(z) \frac{\phi(M)}{\int_{0.5M_\odot}^{125M_\odot} M\phi(M) dM} \,, \qquad \phi(M) \propto M^{-2.35}$$

$$R_{SF}(z) = \mathcal{O}(10^{-2}) \ \mathrm{M_\odot Mpc^{-3} yr^{-1}} \begin{cases} (1+z)^{3.28} & 0 < z < 1 \\ 2^{3.54}(1+z)^{-0.26} & 1 < z < 4.5 \\ 2^{3.54} 5.5^{7.54} (1+z)^{-7.8} & 4.5 < z < 5 \end{cases} ,$$

- oscillations included: $F_{\bar{\nu}_e} = \bar{p} F^0_{\bar{\nu}_e} + (1-\bar{p}) F^0_{\bar{\nu}_x}$ $\qquad \bar{p} \simeq 0 - 0.68$

Simulations: mapping BH formation

- high- and *medium-M* stars can produce failed SN



Ugliano, et al., ApJ 757 (2012) 69; Pejcha & Thompson, ApJ 801 (2015) 90.

- detailed ν spectra available for $M/M_\odot = 11.2, 25, 25(BH), 27, 40(BH)$ L. Hudepohl, PhD thesis, 2013

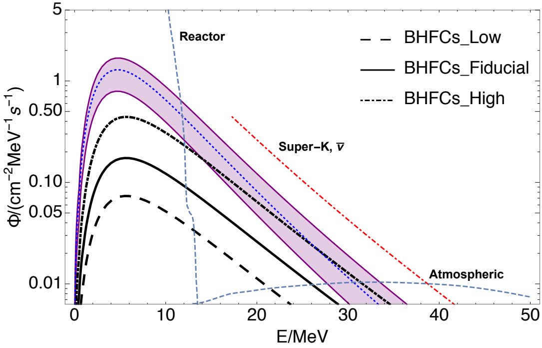
- Failed SN (BHFC): higher luminosity, hotter spectra!

Run (Type)	Mass/$M_\odot$	$\mathcal{L}_{\nu_e}$	$\mathcal{L}_{\bar{\nu}_e}$	$\mathcal{L}_{\nu_x}$	$\langle\epsilon\rangle_{\nu_e}$	$\langle\epsilon\rangle_{\bar{\nu}_e}$	$\langle\epsilon\rangle_{\nu_x}$
			[10^{52} ergs]			[MeV]	
s11.2c (NSFC)	11.2	3.56	3.09	3.02	10.43	12.89	12.93
s25.0c (NSFC)	25	7.18	6.78	6.02	12.67	15.5	15.41
s25.0c (BHFC)	25	7.08	6.51	3.7	15.32	18.2	17.62
s27 (NSFC)	27	5.87	5.43	5.1	11.3	13.89	13.85
s40.0c (BHFC)	40	9.38	8.6	4.8	15.72	18.72	17.63

Results from Garching group:

L. Hudepohl, PhD thesis, 2013 (advisor, H. T. Janka); Mirizzi, et al., Riv. Nuovo Cim. 39 (2016).

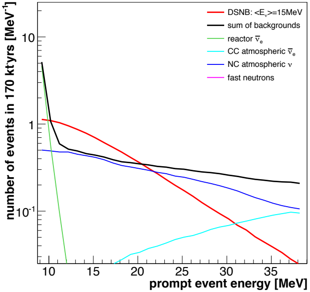
Results



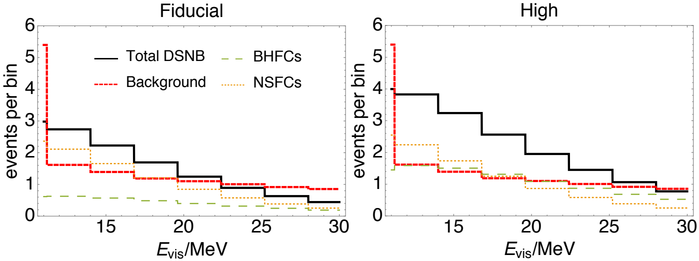
- failed SN dominate at $E \gtrsim 20 - 30$ MeV
- uncertainty band: $\sim 25\%$ on the SN rate normalization, varying BH-formation pattern

Detectability: JUNO

- 17 kt liquid scintillator, $\bar{\nu}_e + p \rightarrow n + e^+$
- $\gtrsim \mathcal{O}(10^2)$ reduction of fast neutrons and atmospheric NC backgr.
- efficiency $\epsilon \sim 50\%$ after background cuts



An et al., J. Phys. G, 43 (2016) 030401, see also Moellenberg et al., PRD 91 (2015).



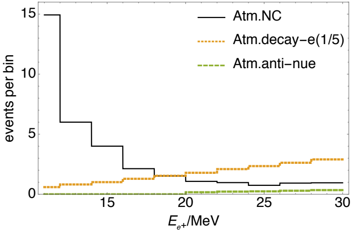
Detectors	energy range (MeV)	NSFCs	BHFCs	Total DSNB	Background ($N_{3\sigma}$)	P_{ev}(%)
Liquid Scintillator						
JUNO (10 yrs)	11-30	7.14 [7.43]	3.04 [7.53]	10.18 [14.96]	8.02 (17)	64 [91.5]

P_{ev}= probability that, *if our model is true*, an excess larger than 3σ ($n_{obs} > N_{3\sigma}$) is realized with respect to background only.

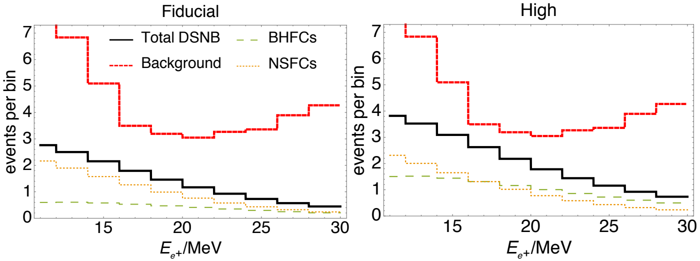
Detectability: SuperK-Gd

Beacom and Vagins, PRL 93 (2004) 171101

- 22.5 kt water, $\bar{\nu}_e + p \rightarrow n + e^+$, n capture on Gd
- reduction of spallation, sub-Cherenkov muons
- *NC atmospheric previously not included*
- signal efficiency $\epsilon \sim 67\%$



H. Kunxian, PhD thesis, Kyoto University, 2015.

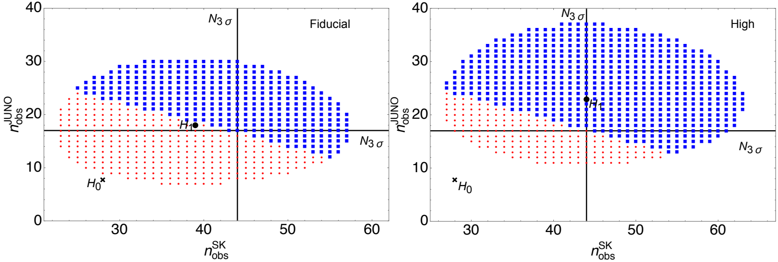


Detectors	energy range (MeV)	NSFCs	BHFCs	Total DSNB	Background ($N_{3\sigma}$)	P_{ev}(%)
SuperK-Gd (10 yrs)	12-26	7.5 [7.78]	3.24 [8.01]	10.74 [15.8]	28.3 (44)	23 [52.3]

high significance excess is moderately likely

Analyzing two detectors together

- the statistical variable is the pair $p = \left(n_{obs}^{SK}, n_{obs}^{JUNO}\right)$.

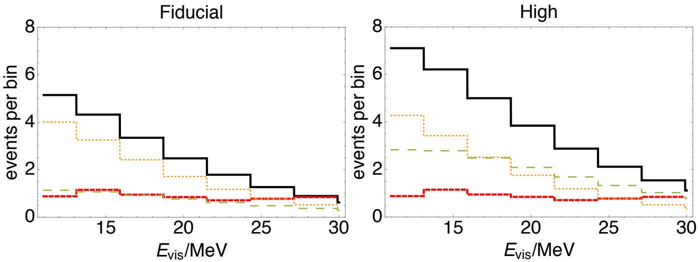


H_0 =Background only; H_1 =Signal+Background. Blue (squares): likelihood$(p|H_1)$ /likelihood$(p|H_0)\geq 10^3$

Beyond JUNO: Slow Liquid Scintillator

- separation of Cherenkov and scintillation light; reduction of NC atm. background
- signal efficiency $\epsilon \simeq 90\%$
- $P_{ev} \gtrsim 98.5\%$

Wei, Wang and Chen, PLB 769 (2017) 255 261.

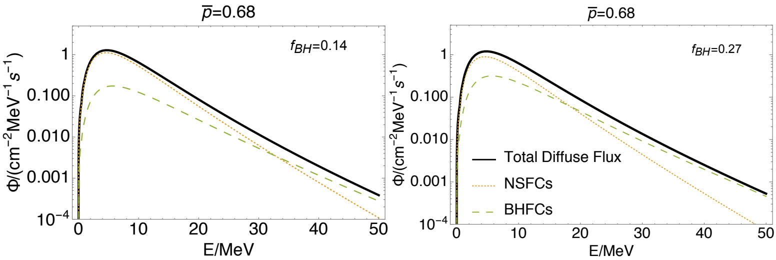


Conclusions

- up to $\sim 50\%$ of a DSNB signal might be due to *(rare)* failed supernovae
    - probing black hole birth! Interdisciplinary implications...
- NC atmospheric background limits sensitivity at JUNO and SuperK-Gd
    - chances of detection in 10 years are moderate-to-high
    - progress is needed on reducing NC background and/or improving signal efficiency

BACKUP

- Results: failed SN dominance at $E \gtrsim 20-40$ MeV.



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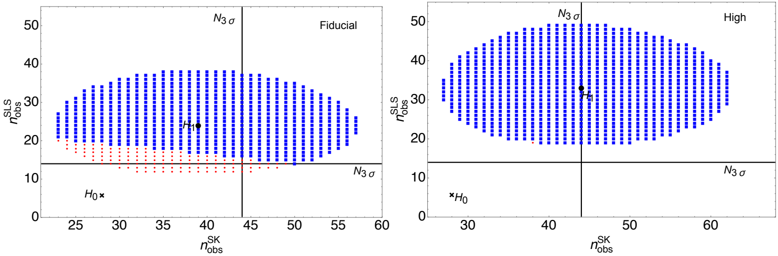
Liquid Scintillator						
JUNO	11-30	7.14 [7.43]	3.04 [7.53]	10.18 [14.96]	8.02 (17)	64 [91.5]
SLS	11-30	12.85 [13.37]	5.47 [13.55]	18.32 [26.92]	5.95 (14)	98.7 [99.7]
Water Cherenkov						
SuperK-Gd	12-26	7.5 [7.78]	3.24 [8.01]	10.74 [15.8]	28.3 (44)	23 [52.3]


Fiducial
High
$N_{3\sigma}$
$N_{3\sigma}$
H_1
H_0
$n_{\rm obs}^{\rm SLS}$
$n_{\rm obs}^{\rm SK}$
0
10
20
30
40
50
25
30
35
40
45
50
55
60

Chance of high significance excess?

the observed number of events n_{obs} fluctuates with respect to the true value, n.

- H_0: background only hypothesis
  H_1: background + signal (this model) hypothesis
- P_{ev}= probability that, *if* H_1 *is true*, an excess larger than 3σ ($n_{obs} > N_{3\sigma}$) with respect to H_0 is realized in the detector