A “nu” look at gravitational waves:

The black hole birth rate from neutrinos combined with the merger rate from LIGO

Based on **JCAP 07 (2017) 052** (arXiv:1704.05073) by J. H. Davis and M. Fairbairn

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INTRODUCTION:
ASTRONOMY WITH DIFFUSE SUPERNOVA NEUTRINOS

- We want to extract information on black holes from the **diffuse supernova neutrinos**, and combine this with LIGO data.

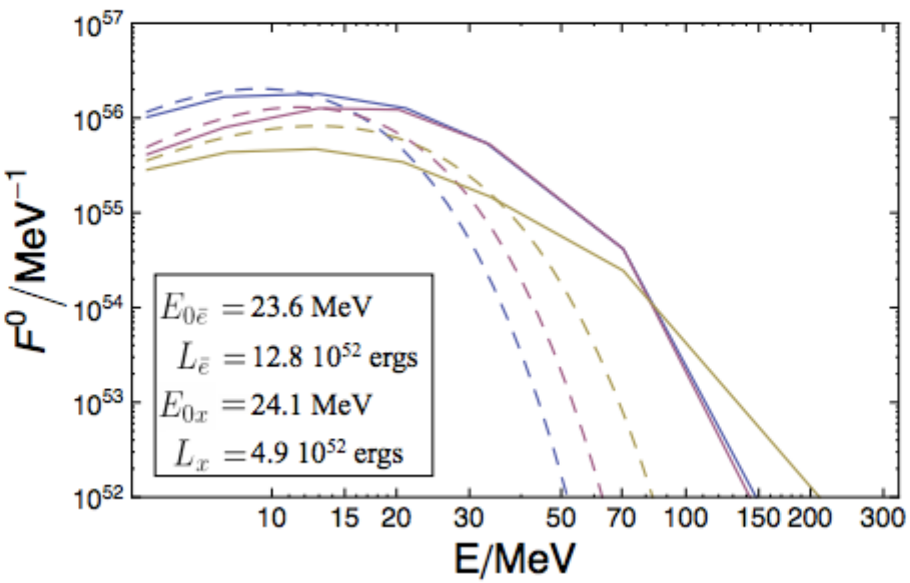
- The diffuse supernova neutrino background is made up of neutrinos emitted by all of the supernova the observable Universe.

- Can we measure the DSNB with enough precision to determine the **birth rate of black holes**?

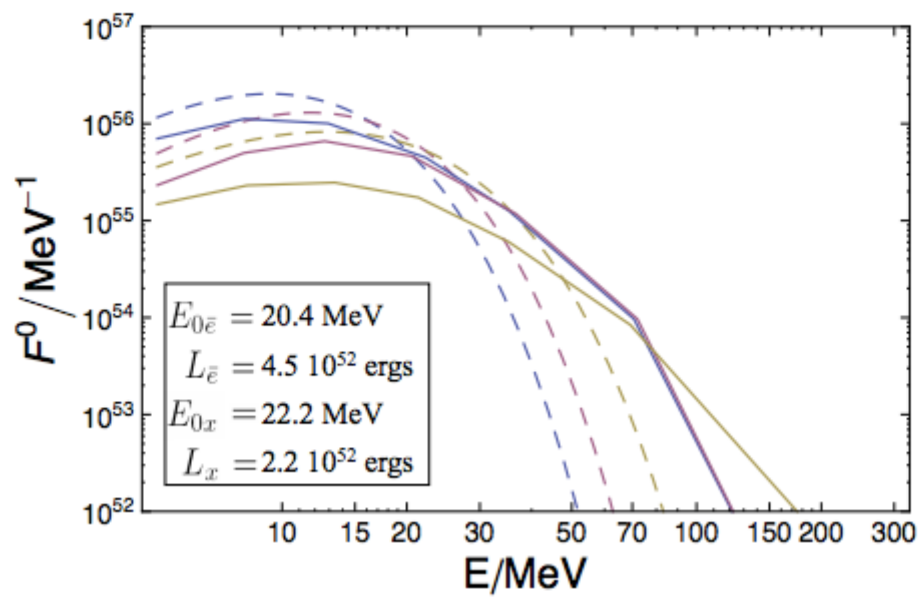
SUPERNOVAE AND UNNOVAE NEUTRINO SPECTRA

Key premise: Neutron-star-forming supernovae emit neutrinos with a different spectrum than for BH-forming supernova, which we call **unnovae.**

S EoS



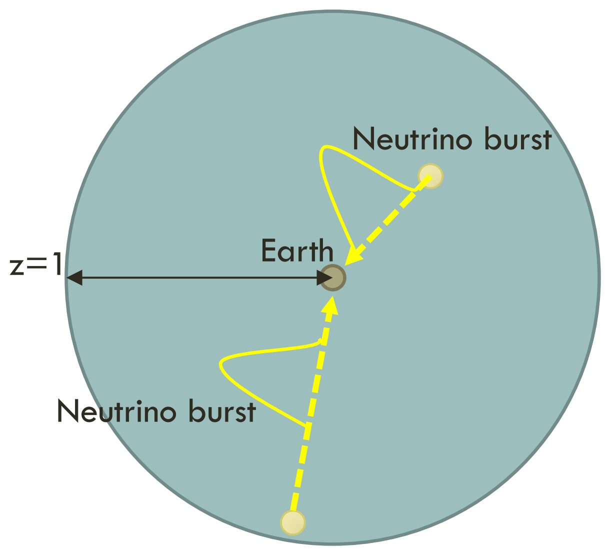
LS EoS

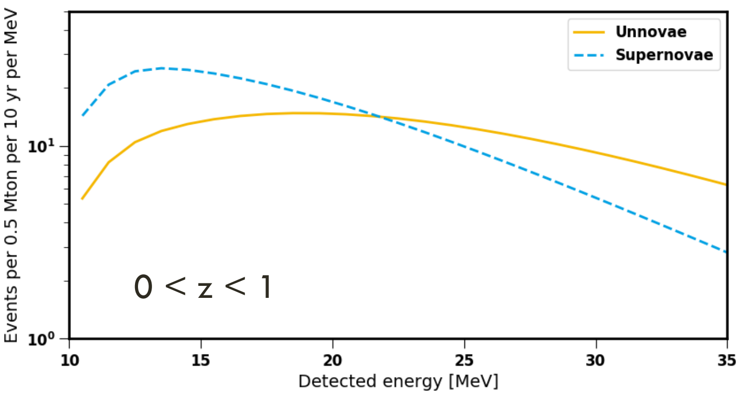


Solid = BH-forming Unnova, Dashed = NS-forming Supernova

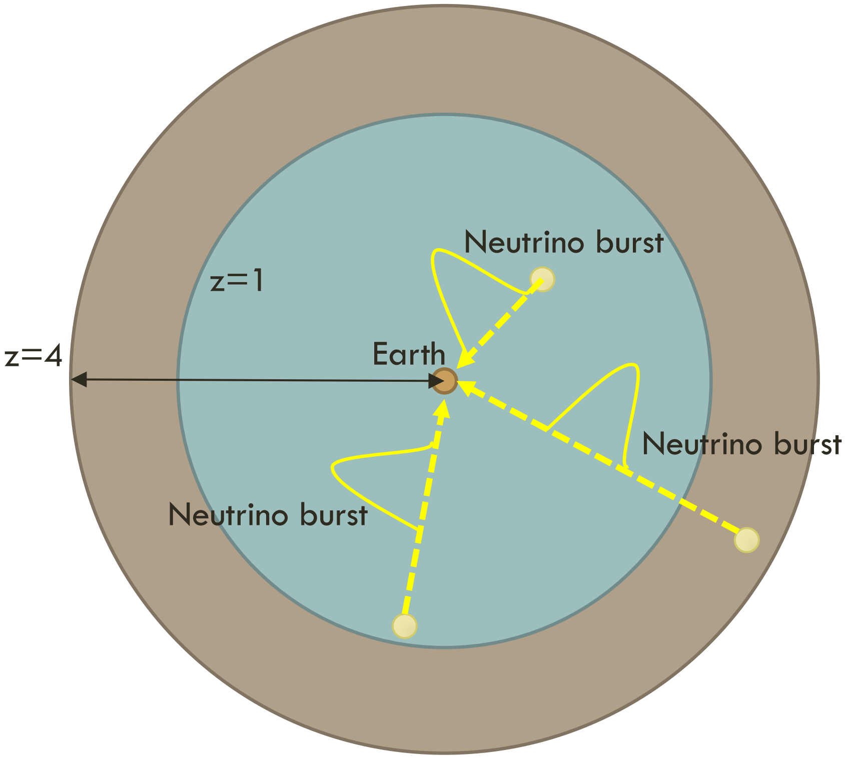
C. Lunardini, Diffuse neutrino flux from failed supernovae, Phys. Rev. Lett. 102 (2009) 231101, [0901.0568]

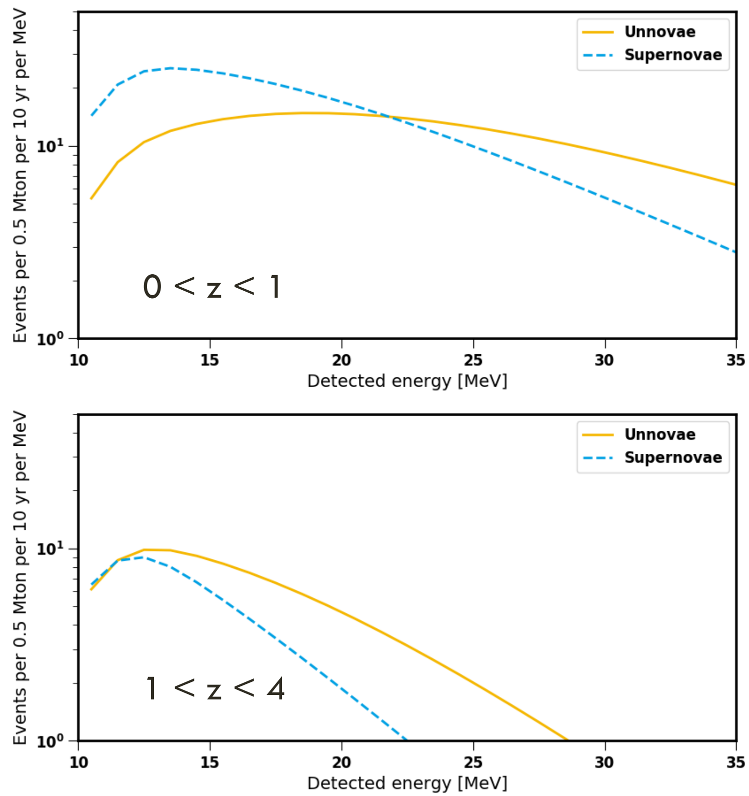
DIFFUSE SUPERNOVA NEUTRINO BACKGROUND





DIFFUSE SUPERNOVA NEUTRINO BACKGROUND





CALCULATING THE DIFFUSE SUPERNOVA NEUTRINO BACKGROUND

Integral over redshift z

Neutron star formation rate

Neutrino spectrum from supernovae

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{\max}} \frac{\mathrm{d}z}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \Big[R_{\mathrm{NS}}(z) F_{\mathrm{NS}}(E(1+z); \bar{E}_{e\mathrm{NS}}, \bar{E}_{x\mathrm{NS}}, L_{e\mathrm{NS}}, L_{x\mathrm{NS}})$$
$$+ R_{\mathrm{BH}}(z) F_{\mathrm{BH}}(E(1+z); \bar{E}_{e\mathrm{BH}}, \bar{E}_{x\mathrm{BH}}, L_{e\mathrm{BH}}, L_{x\mathrm{BH}}) \Big]$$

Black hole formation rate

Neutrino spectrum from unnovae

BH AND NS FORMATION RATES

- The supernova and unnova rate may differ due to changes in metallicity, for example.
- Lower metallicity stars tend to be more likely to form black holes (e.g. due to different density profiles), and are more common at higher redshifts.
- **Can we measure the unnova rate from the DSNB?**

$$R_{\rm NS}(z) = [1 - f_{\rm BH}(z)]R(z)$$
$$R_{\rm BH}(z) = f_{\rm BH}(z)R(z)$$

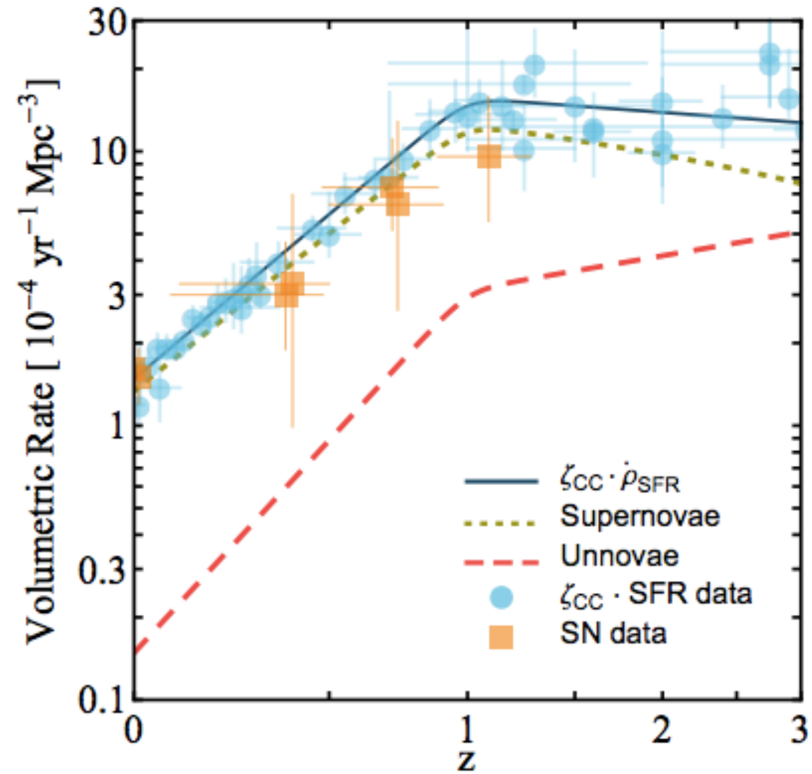


FIG. 1: The cosmic rate of core collapse. Shown are recent measurements of core-collapse supernovae [9–12] (*squares*; see [17] for older data), which fall just below the expectation from star formation rate data with all stars of mass $\gtrsim 8\,M_\odot$ yielding optical SNe (*circles*; [18]). These are compared to our model assuming a local 10% rate of unnovae that evolves with z (*dashed*), the predicted SN rate (*dotted*), and the total (*solid*).

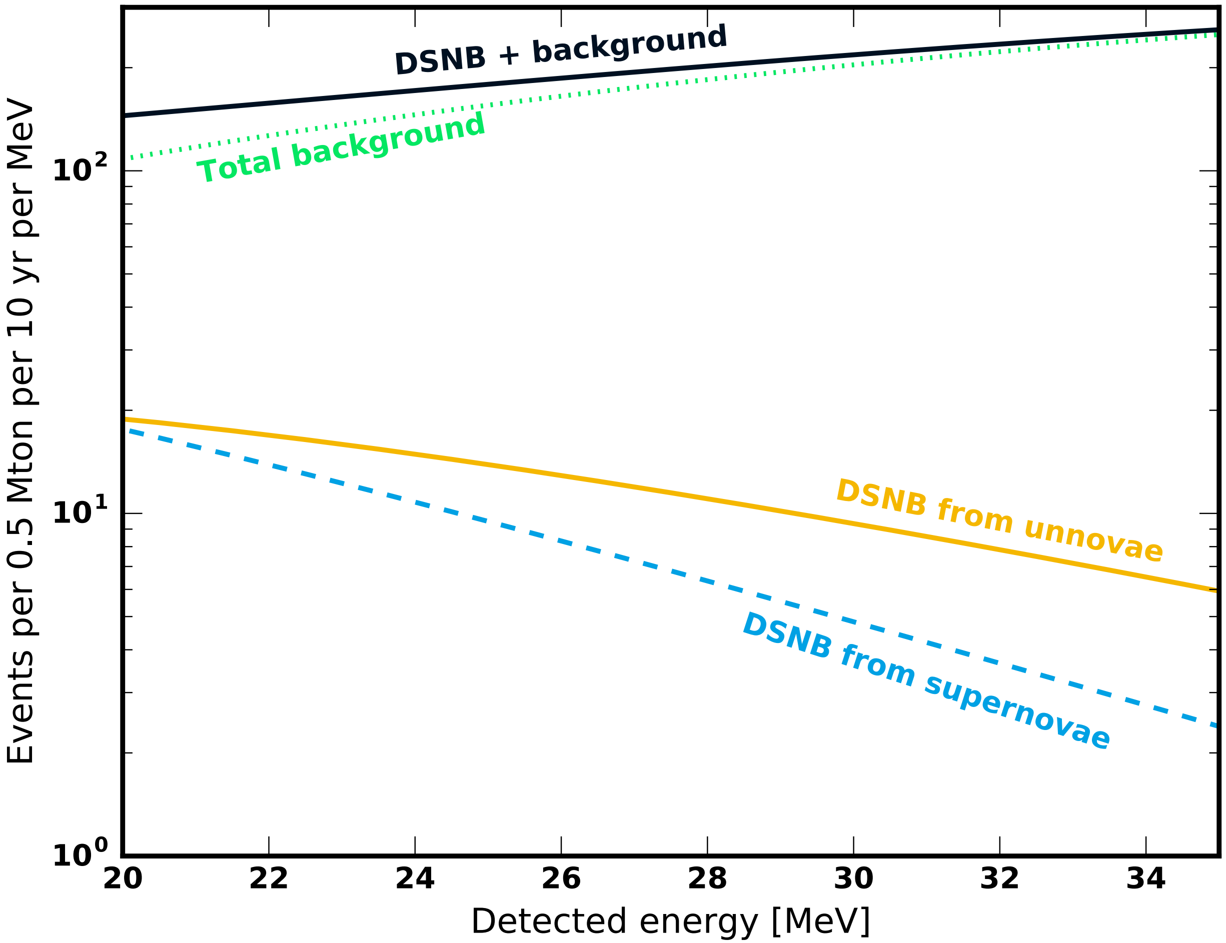
H. Yuksel and M. D. Kistler, The cosmic MeV neutrino background as a laboratory for black hole formation, Phys. Lett. B751 (2015) 413–417, [1212.4844]

THE DSNB IN HYPER KAMIOKANDE

- Detect the DSNB anti-electron neutrinos primarily through **inverse beta capture:**

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- Assume a **low-energy threshold of 20 MeV** for Hyper Kamiokande to avoid spallation backgrounds.
- Main background for our analysis is from **invisible muons** i.e. decay electrons from muons below the Cherenkov threshold, produced by atmospheric muon neutrinos (arXiv:1109.3262).



MARKOV CHAIN ANALYSIS

- If a future measurement of the DSNB was made, to what accuracy could one infer the black hole birth rate?
- We make **projected constraints** based on Hyper Kamiokande measuring the DSNB after running for 10 years, by generating simulated data.
- The **large number of parameters** means we need to perform an **MCMC analysis**, to extract the black hole birth rate.

$$\Phi(E) = \frac{c}{H_0}\int_0^{z_{\max}} \frac{\mathrm{d}z}{\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}\left[R_{\mathrm{NS}}(z)F_{\mathrm{NS}}(E(1+z);\bar{E}_{e\mathrm{NS}},\bar{E}_{x\mathrm{NS}},L_{e\mathrm{NS}},L_{x\mathrm{NS}}) \right.$$
$$\left. +R_{\mathrm{BH}}(z)F_{\mathrm{BH}}(E(1+z);\bar{E}_{e\mathrm{BH}},\bar{E}_{x\mathrm{BH}},L_{e\mathrm{BH}},L_{x\mathrm{BH}})\right]$$

MARKOV CHAIN ANALYSIS: PRIORS

Average neutrino energies

Average neutrino luminosities

Parameter	Optimistic priors	Pessimistic priors
$\bar{E}_{e\mathrm{NS}}$	$P \in [14, 16]$ MeV	$P \in [14, 16]$ MeV
$\bar{E}_{x\mathrm{NS}}$	$P \in [17, 19]$ MeV	$P \in [17, 19]$ MeV
$\bar{E}_{e\mathrm{BH}}$	$P \in [23, 25]$ MeV	$P \in [15, 25]$ MeV
$\bar{E}_{x\mathrm{BH}}$	$P \in [23, 28]$ MeV	$P \in [16, 33]$ MeV
$L_{e\mathrm{NS}}$	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs
$L_{x\mathrm{NS}}$	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs
$L_{e\mathrm{BH}}$	$P \in [12, 14] \cdot 10^{52}$ ergs	$P \in [0, 20] \cdot 10^{52}$ ergs
$L_{x\mathrm{BH}}$	$P \in [0.35, 0.45] L_{e\mathrm{BH}}$	$P \in [0.3, 1] L_{e\mathrm{BH}}$
R_0	$P \in [0.8, 1.2] \cdot 10^{-4}\mathrm{Mpc}^{-3}\mathrm{s}^{-1}$	$P \in [0.8, 1.2] \cdot 10^{-4}\mathrm{Mpc}^{-3}\mathrm{s}^{-1}$
β	$P \propto N(\beta, \mu = 3.28, \sigma = 0.05)$	$P \propto N(\beta, \mu = 3.28, \sigma = 0.05)$
γ	$P \propto N(\gamma, \mu = 0, \sigma = 0.1)$	$P \propto N(\gamma, \mu = 0, \sigma = 0.1)$
$\bar{p}$	$P \in [0.5, 0.68]$	$P \in [0, 0.68]$
f_0	$P \in [0, 1]$	$P \in [0, 1]$
f_1	$P \in [0, 1]$	$P \in [0, 1]$
f_4	$P \in [0, 1]$	$P \in [0, 1]$

Table 2. Priors for each of our parameters in either the optimistic or pessimistic case. Priors are flat within the range and zero outside unless otherwise stated, and $N(x, \mu, \sigma) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[\frac{-(x-\mu)^2}{2\sigma^2}\right]$ represents a normal distribution with mean μ and standard deviation σ.

- We want to know how sensitive our results are to knowledge of the unnova neutrino burst.
- Hence we pick two sets of priors: optimistic and pessimistic.
- The former assumes that we understand unnovae well from simulations.
- The latter assumes that unnovae are poorly understood.

MARKOV CHAIN ANALYSIS: PRIORS

	Parameter	Optimistic priors	Pessimistic priors
Average neutrino energies	$\bar{E}_{e\mathrm{NS}}$	$P \in [14, 16]$ MeV	$P \in [14, 16]$ MeV
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	$\bar{E}_{e\mathrm{BH}}$	$P \in [23, 25]$ MeV	$P \in [15, 25]$ MeV
	$\bar{E}_{x\mathrm{BH}}$	$P \in [23, 28]$ MeV	$P \in [16, 33]$ MeV
Average neutrino luminosities	$L_{e\mathrm{NS}}$	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs
	$L_{x\mathrm{NS}}$	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs	$P \in [4.5, 5.5] \cdot 10^{52}$ ergs
	$L_{e\mathrm{BH}}$	$P \in [12, 14] \cdot 10^{52}$ ergs	$P \in [0, 20] \cdot 10^{52}$ ergs
	$L_{x\mathrm{BH}}$	$P \in [0.35, 0.45] L_{e\mathrm{BH}}$	$P \in [0.3, 1] L_{e\mathrm{BH}}$
Astrophysical parameters	R_0	$P \in [0.8, 1.2] \cdot 10^{-4}\mathrm{Mpc}^{-3}\mathrm{s}^{-1}$	$P \in [0.8, 1.2] \cdot 10^{-4}\mathrm{Mpc}^{-3}\mathrm{s}^{-1}$
	β	$P \propto N(\beta, \mu = 3.28, \sigma = 0.05)$	$P \propto N(\beta, \mu = 3.28, \sigma = 0.05)$
	γ	$P \propto N(\gamma, \mu = 0, \sigma = 0.1)$	$P \propto N(\gamma, \mu = 0, \sigma = 0.1)$
Flavour ratio	$\bar{p}$	$P \in [0.5, 0.68]$	$P \in [0, 0.68]$
Parameters we want to measure	f_0	$P \in [0, 1]$	$P \in [0, 1]$
	f_1	$P \in [0, 1]$	$P \in [0, 1]$
	f_4	$P \in [0, 1]$	$P \in [0, 1]$

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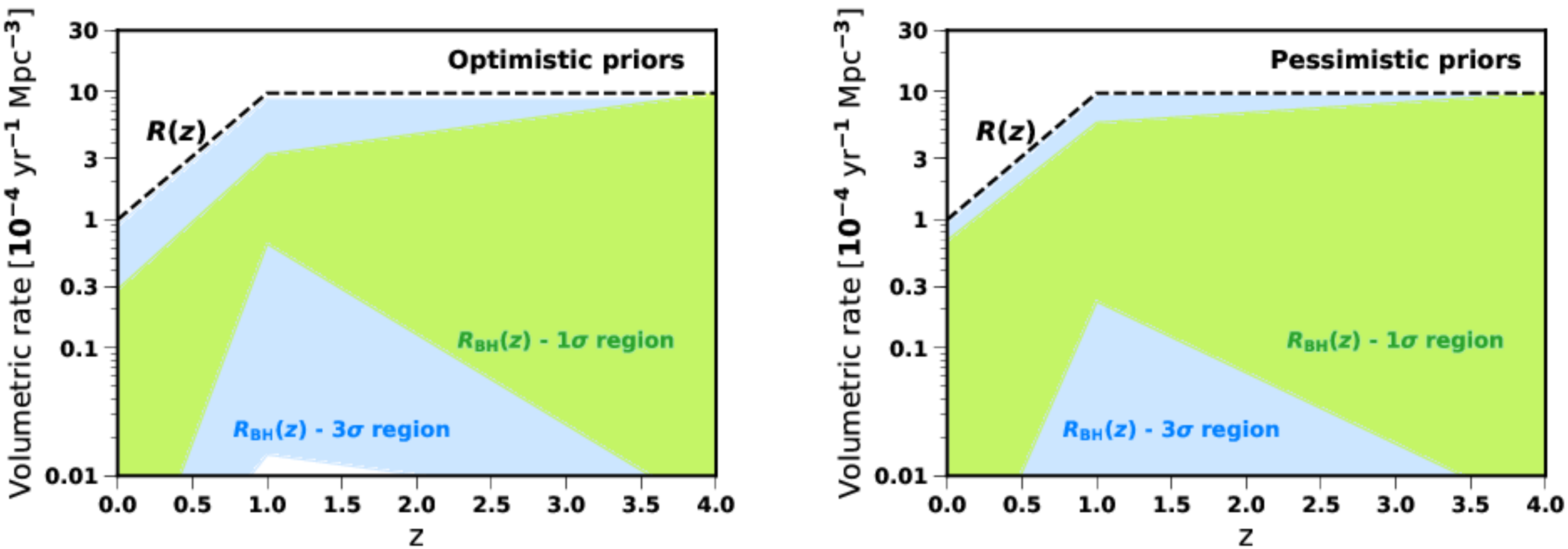
MEASURING THE BLACK HOLE BIRTH RATE



- Our MCMC analysis allows us to infer the black hole birth rate from projected measurements of the DSNB in Hyper Kamiokande.
- The strength of the constraint on the birth rate depends strongly on how well we know the spectrum of neutrinos from unnovae.

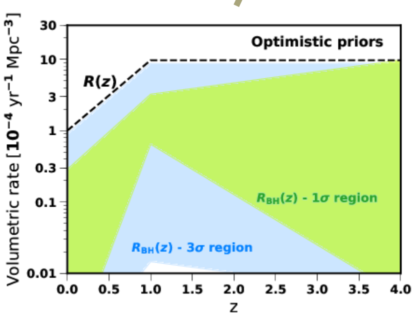
THE BLACK HOLE MERGER RATE FROM THE BIRTH RATE

Merger fraction

$$\mathcal{R}_{\mathrm{BH-BH}} = \frac{\epsilon}{2}\int_0^{t_0} \mathrm{d}t\, R_{\mathrm{BH}}(t_0 - t) P(t)$$

Black hole merger rate

Birth rate from DSNB



Merger time distribution

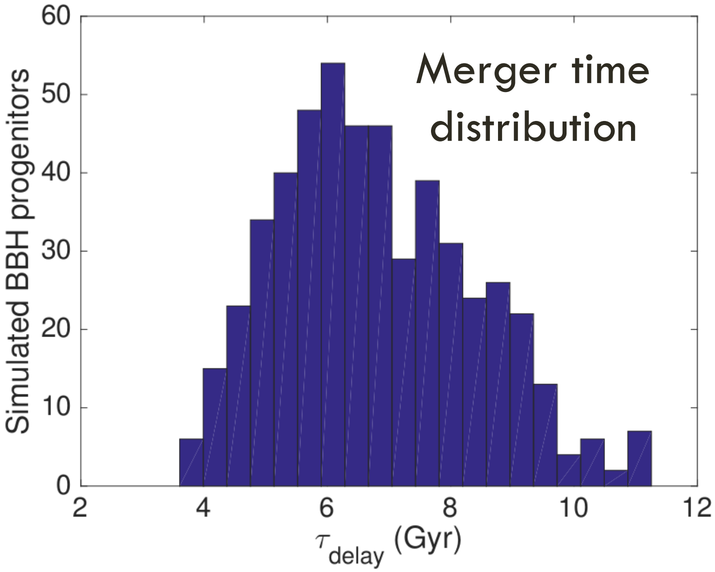
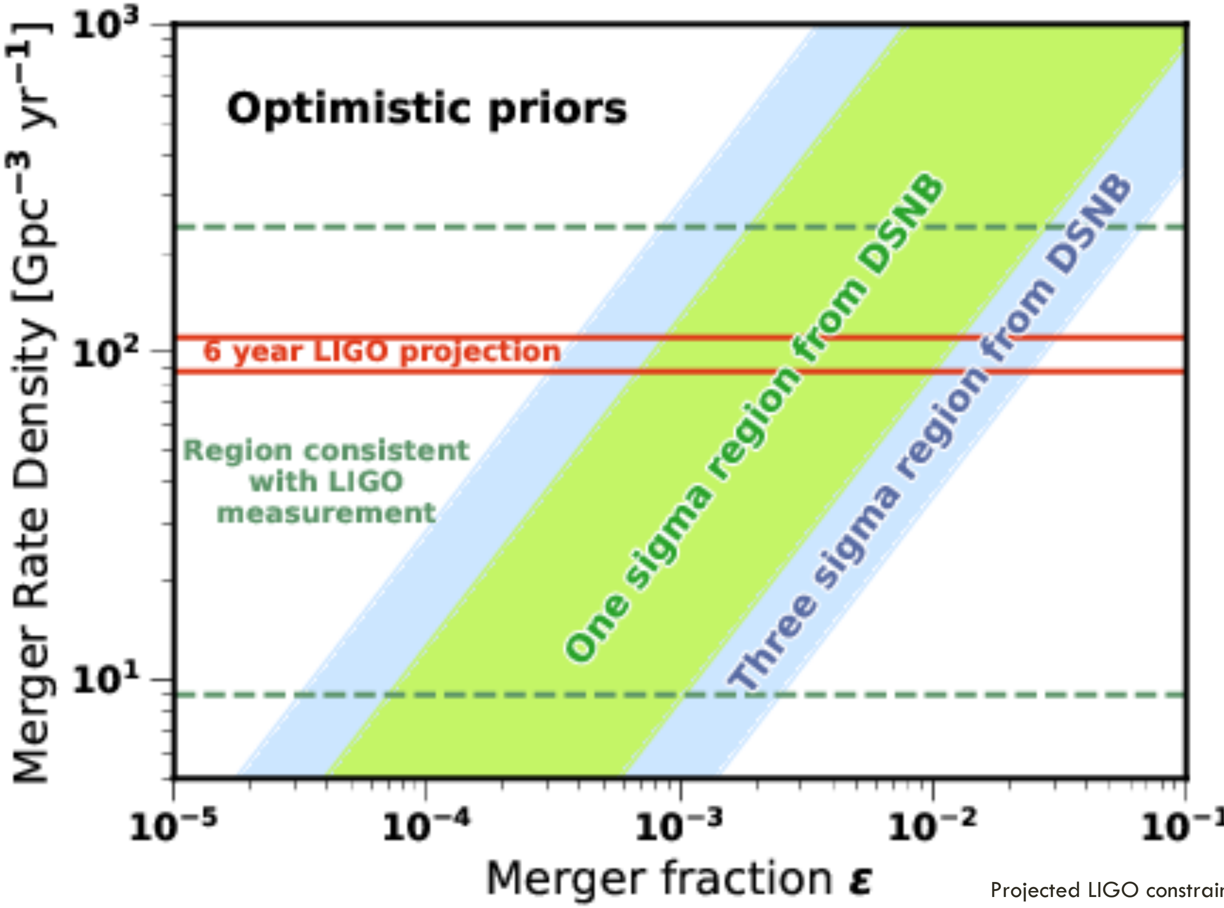


FIG. 6.— The distribution of delay times between formation and merger for binary black holes formed in the Case M scenario.

I. Mandel and S. E. de Mink, Merging binary black holes formed through chemically homogeneous evolution in short-period stellar binaries, Mon. Not. Roy. Astron. Soc. 458 (2016) 2634–2647, [1601.00007]

COMPARING OUR INFERRED MERGER RATE TO DATA FROM LIGO

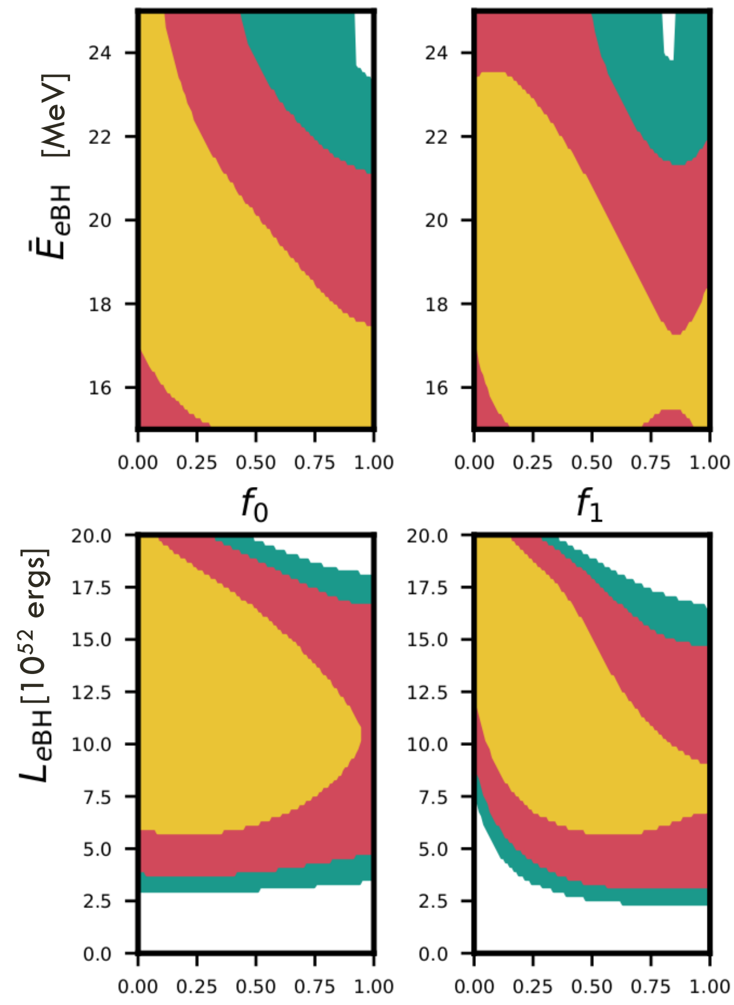


- The coloured regions show our calculated merger rate from the birth rate inferred from the DSNB.
- Where this region intersects the LIGO bounds gives the allowed values of the merger fraction.

Projected LIGO constraints from:
E. D. Kovetz, I. Cholis, P. C. Breysse and M. Kamionkowski, The Black Hole Mass Function from Gravitational Wave Measurements, Phys. Rev. D 95, 103010 (2017), 1611.01157

IMPROVING ON OUR RESULTS

- **The most crucial input is the neutrino spectrum from unnovae.**
- Measuring the average energy E_{eBH} and neutrino luminosity L_{eBH} will greatly improve the bounds on f_0 and f_1.
- Is there a more realistic assumption than having only two types of neutrino burst?

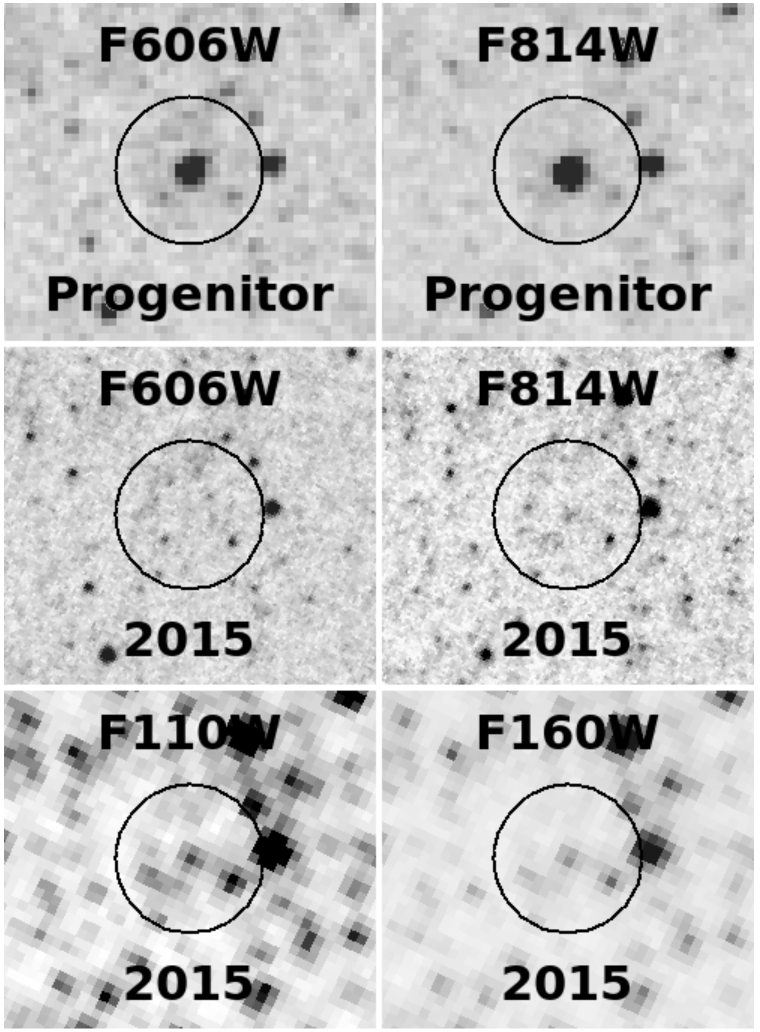


Contours bound a given percentage of the total integrated posterior volume

99.7% = Green
95% = Red
68% = Yellow

IMPROVING ON OUR RESULTS

- **Astrophysical input** such as the star formation rate or the rate of supernova events will also **improve our measurement** of the black hole birth rate.
- **Also measurements of disappearing stars.** In this case we need to know if all BH-forming collapse events lead to optical disappearance events, or if some have optical counterparts.



S. M. Adams, C. S. Kochanek, J. R. Gerke, K. Z. Stanek and X. Dai, The search for failed supernovae with the Large Binocular Telescope: confirmation of a disappearing star, Mon.Not.Roy.Astron.Soc. 468 (2017) 4968, 1609.01283

S. M. Adams, C. S. Kochanek, J. R. Gerke and K. Z. Stanek, The Search for Failed Supernovae with the Large Binocular Telescope: Constraints from 7 Years of Data, MNRAS (2017) 469 (2), 1610.02402

IMPROVING ON OUR RESULTS

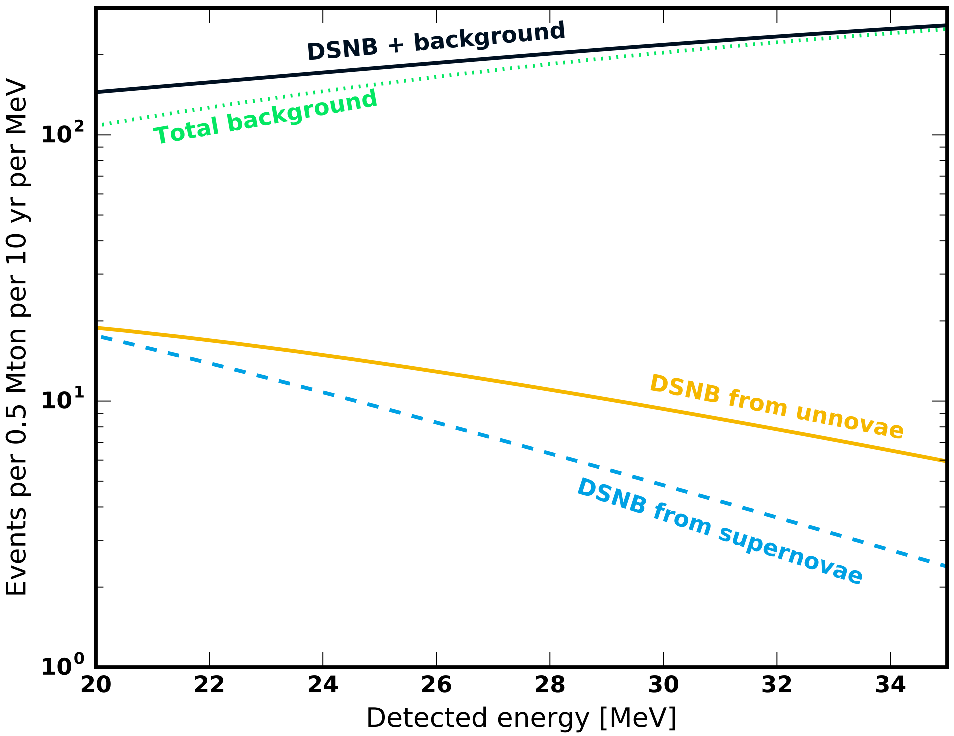
- Lowering the energy threshold or reducing the background in Hyper Kamiokande would make precision measurements of the DSNB much easier.

- Perhaps possible with a **second Hyper Kamiokande site in Korea,** where the rock over-burden could be larger (meaning a smaller spallation background below 20 MeV).

- See: "*Physics Potentials with the Second Hyper-Kamiokande Detector in Korea*", *arXiv:1611.06118*

- Also interesting to **consider other experiments e.g. DUNE or JUNO**, which have different backgrounds.

- For example: *"Diffuse neutrinos from luminous and dark supernovae: prospects for upcoming detectors at the O(10) kt scale" by Alankrita Priya and Cecilia Lunardini, arXiv:1705.02122*



CONCLUSION

- **The DSNB is a plentiful source of untapped information about the Universe.**
- A precision measurement of the diffuse supernova neutrino background with Hyper Kamiokande opens up the possibility to **measure the black hole birth rate.**
- When combined with the BH-BH merger rate from LIGO this gives information on the fraction of black holes which form binaries and merge.
- Our results depend crucially on how well neutrino bursts associated with BH-forming collapse events are understood, particularly the luminosity and spectra of their associated neutrino bursts.

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