DMUK – University of Edinburgh – 28th July 2017

NEUTRINO ASTRONOMY AND DIRECT DETECTION

Based on **J.H.Davis, Phys.Rev.Lett. 117 (2016) 211101**
and **J.H.Davis and M.Fairbairn, arXiv:1704.05073 (to appear in JCAP)**

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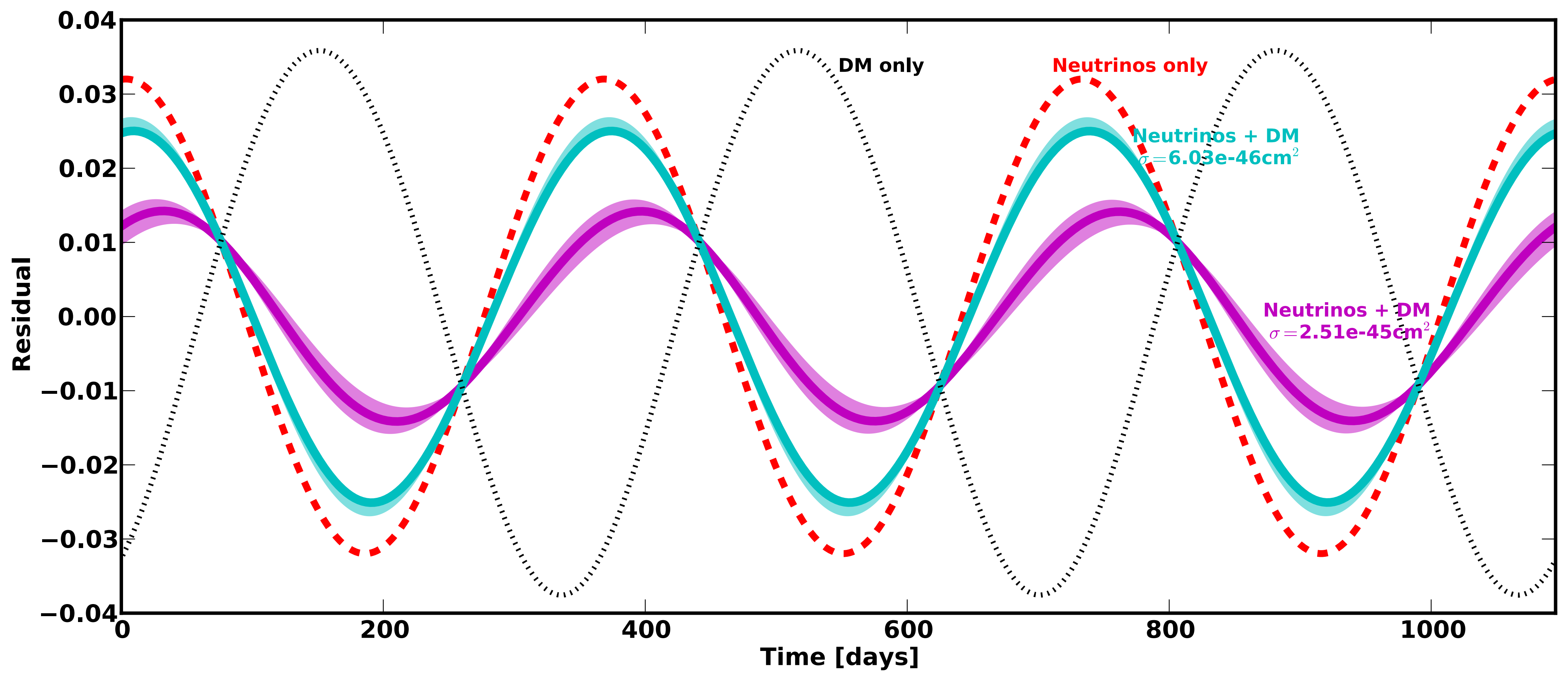
NEUTRINO ASTRONOMY

- In order to do astronomy with neutrinos we need to be able to work out where they are coming from in the sky.
- Interested in two cases: **supernova neutrinos** and **solar neutrinos**.
- If a supernova goes off in our galaxy and we detect its neutrinos, can we work out where in the galaxy it happened?
- Can we use neutrino directionality to probe the sun’s core?

TIME VARIATION OF DARK MATTER AND SOLAR NEUTRINOS

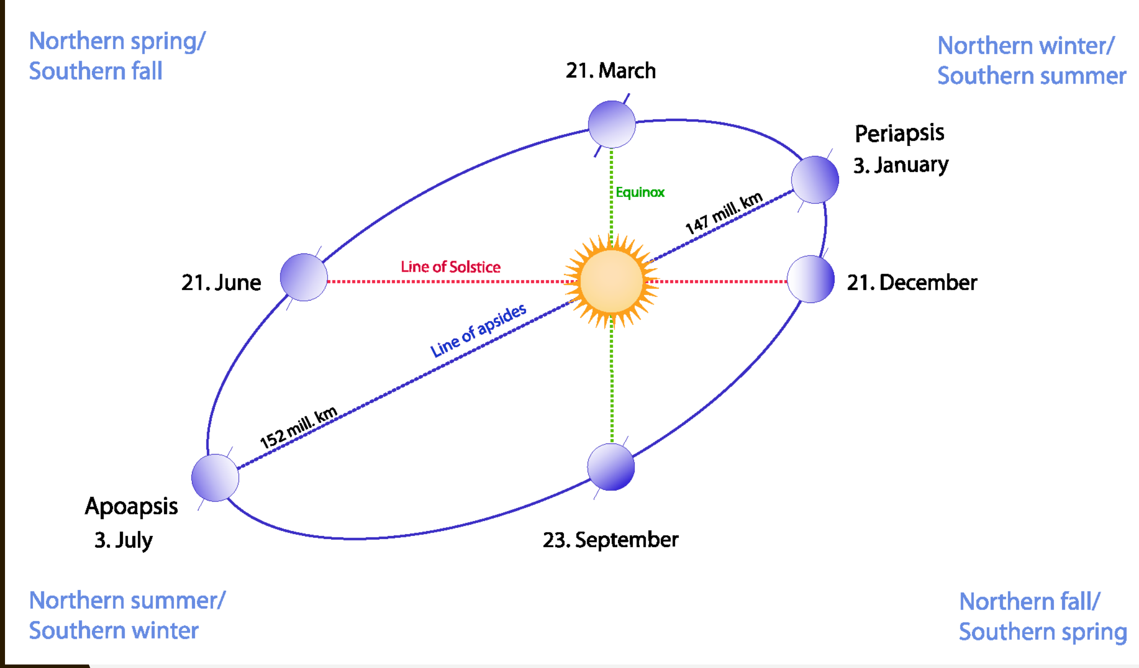
J.H.Davis, JCAP 1503 (2015) 012



Temporal dependence gives us an additional discrimination parameter.

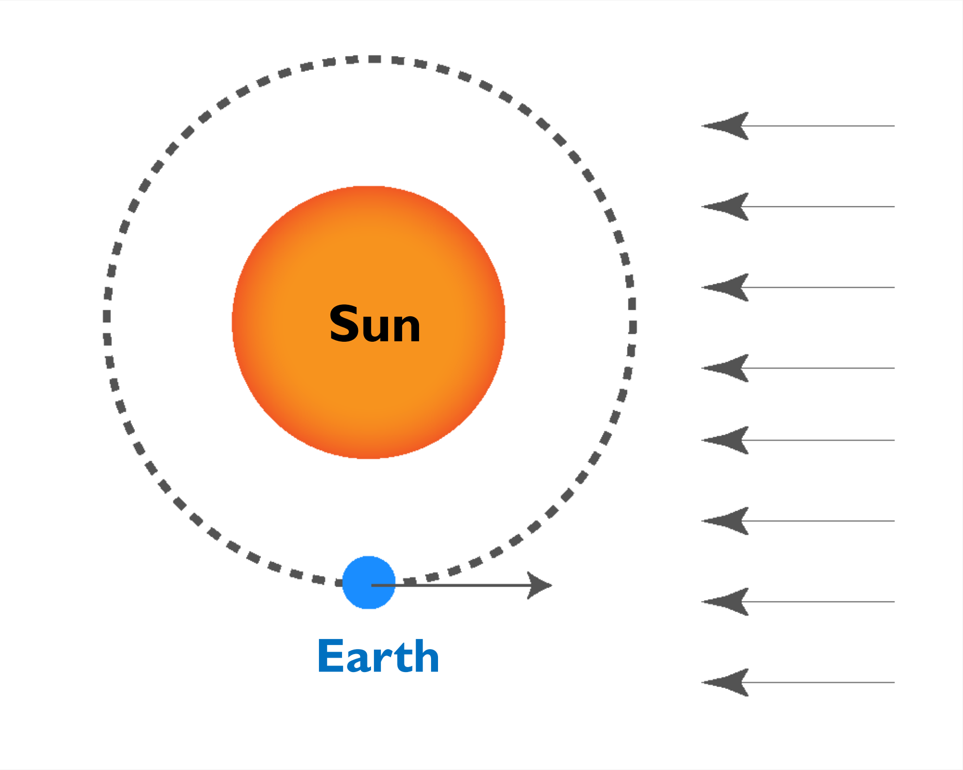
TIME VARIATION OF DARK MATTER AND SOLAR NEUTRINOS

Solar neutrinos



Varying Earth-Sun distance.

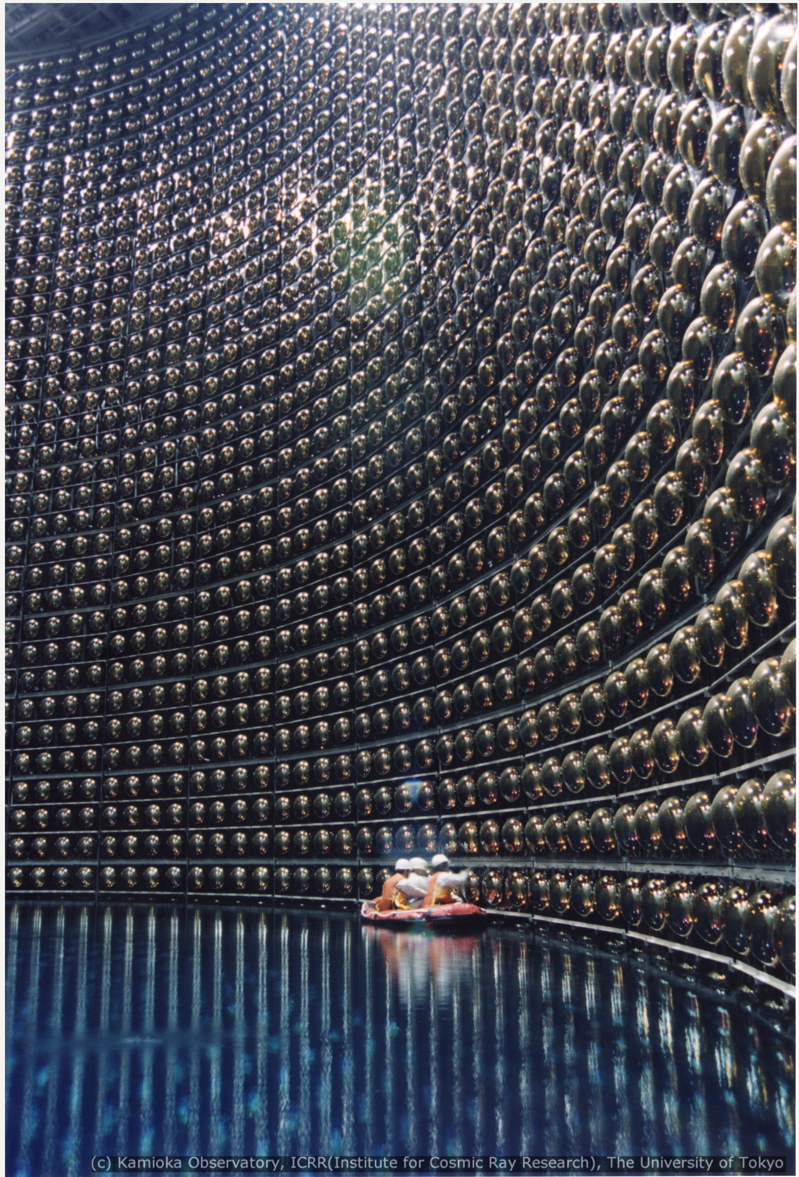
Dark matter



Varying Earth-DM relative velocity.

DETECTION OF NEUTRINOS

- I will focus on water Cherenkov detectors such as Super Kamiokande (SK).
- Very large detectors such as SK mean that it is possible to obtain large statistics even though neutrinos interact weakly.
- They are good for solar and supernova neutrinos and they **have directional sensitivity for incoming neutrinos**.



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

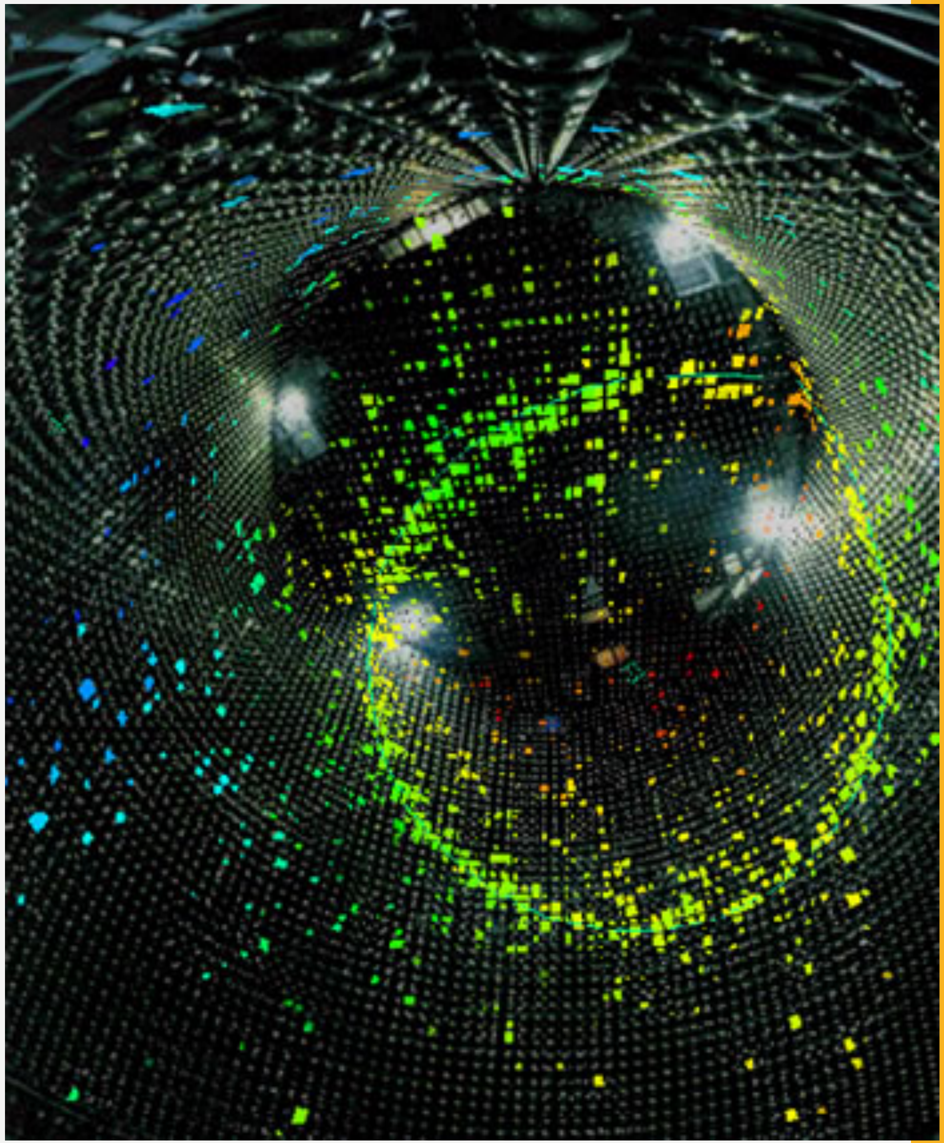
DETECTION OF SOLAR NEUTRINOS

- An MeV-energy neutrino scatters elastically off an electron.
- The electron emits Cherenkov light, which is observed by photomultiplier tubes.

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

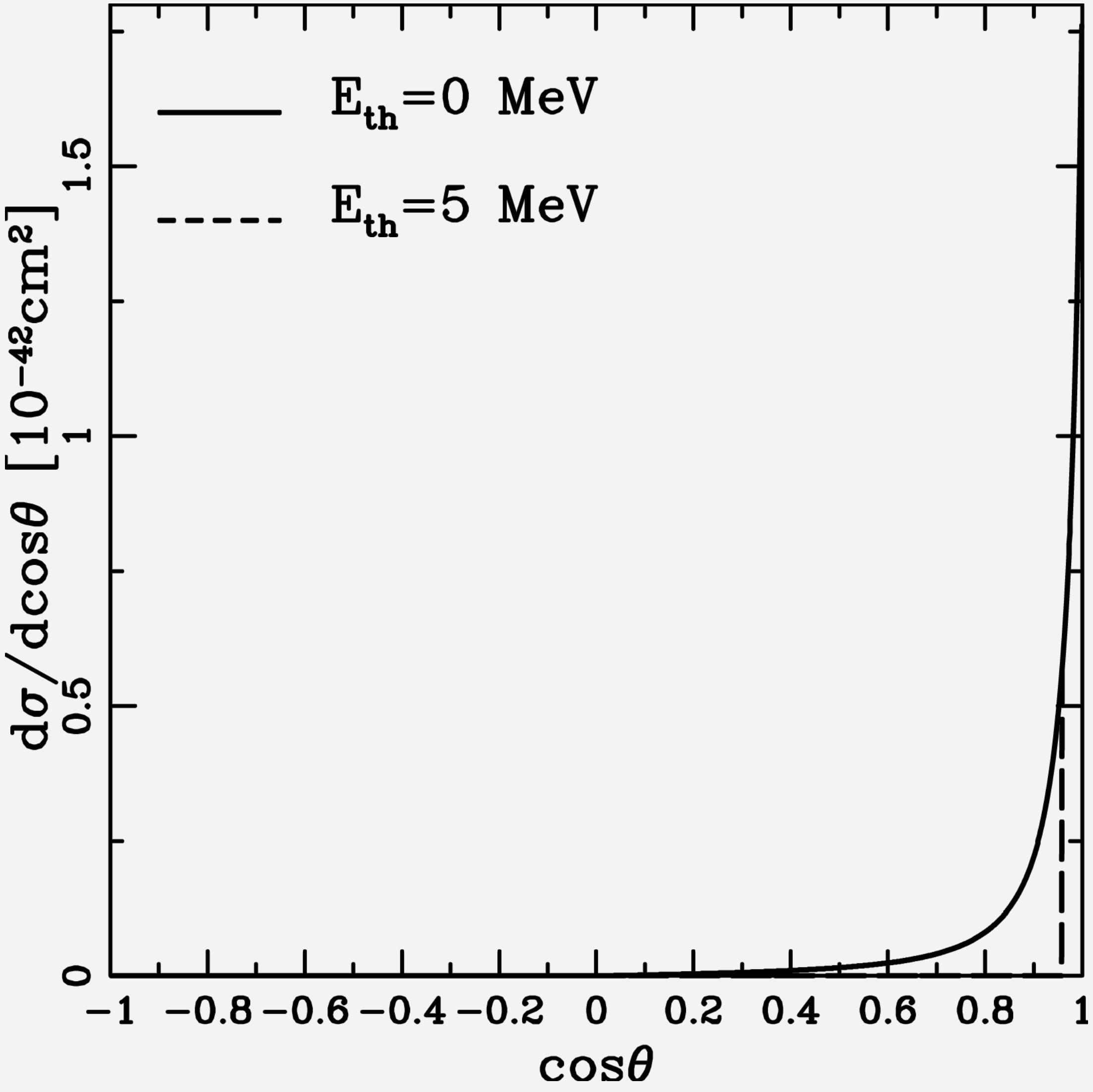
In H_2O

Emits Cherenkov Light



DETECTION OF NEUTRINOS

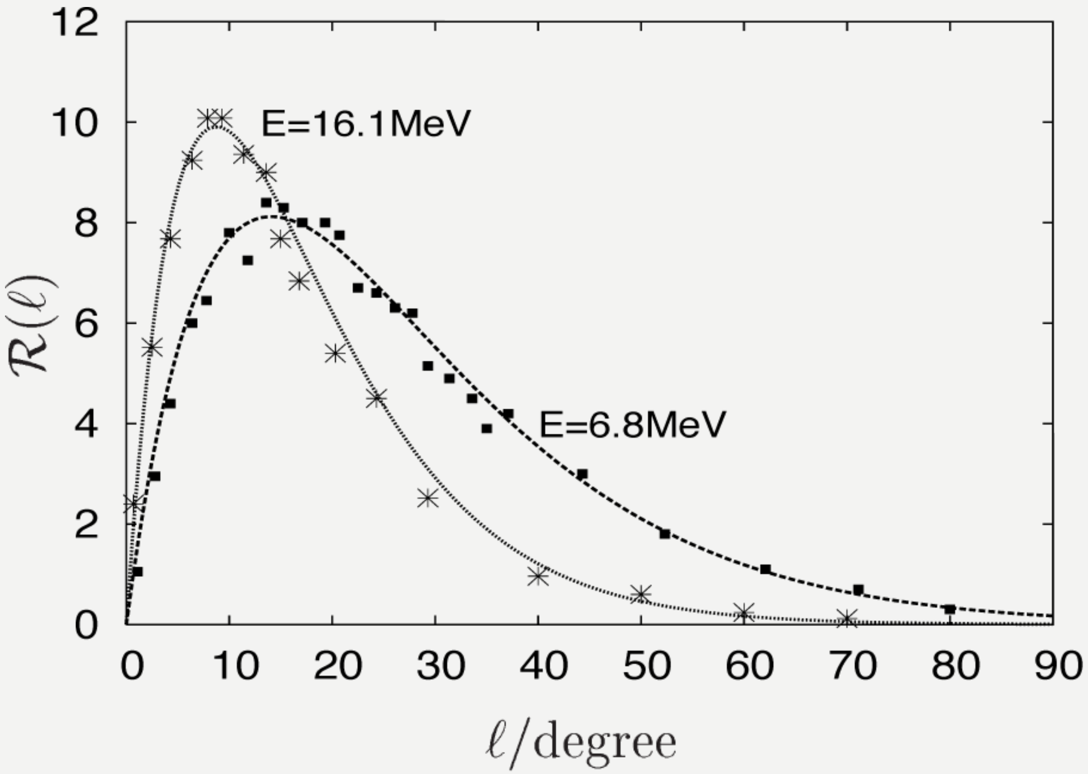
- The elastic scattering cross section is **strongly forward-peaked** for MeV-scale neutrinos, especially for higher recoil energies.
- Hence the electron after scattering will point back towards the original direction of the neutrino.



Ando and Sato, arXiv:hep-ph/0110187v4

THE ANGULAR RESOLUTION OF NEUTRINO DETECTORS

- Unfortunately the actual resolution is much worse, since **the electron scatters in the water multiple times**. Hence the observed electron direction is only weakly correlated with the incident neutrino direction.
- This multiple scattering contributes almost all of the angular resolution, and is **well-understood due to calibration data**.
- See e.g. Calibration of Super-Kamiokande using an electron LINAC, Nuclear Instruments and Methods in Physics Research A 421 (1999) 113-129.



R. Tomas et al. , Phys.Rev. D68 (2003) 093013

CASE STUDY: SUPERNOVA POINTING WITH NEUTRINOS

- Since the multiple-scattering of the electron is well-known, we can reconstruct the supernova direction.
- Obtain a simple approximate formula for the angular resolution for SN pointing:

$$\delta\theta \approx \frac{25^\circ}{\sqrt{N_s}}$$

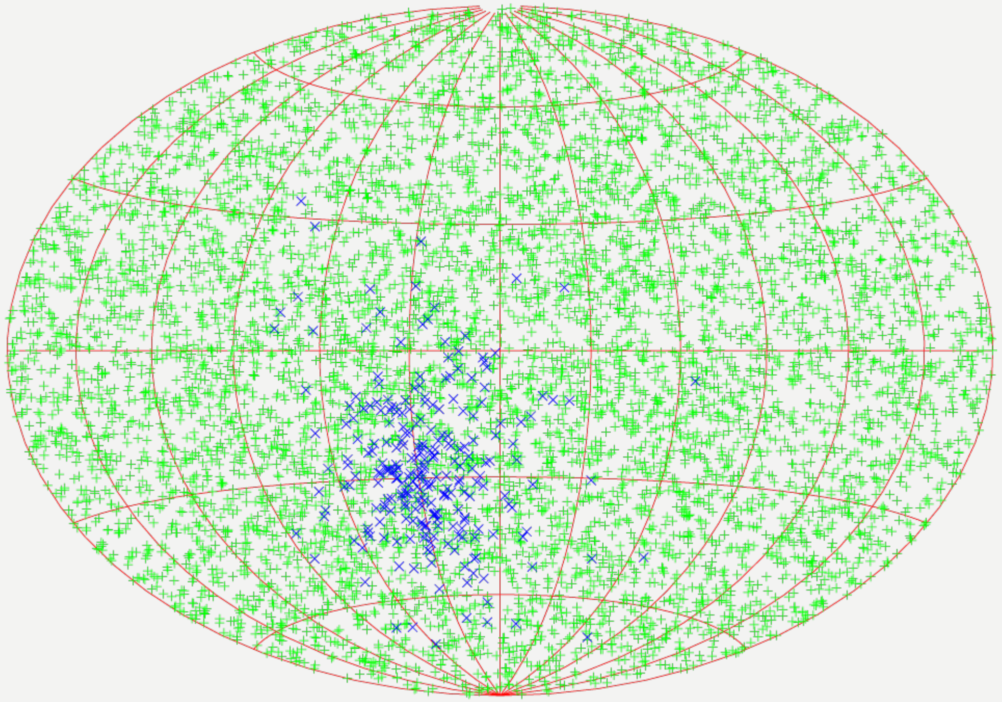
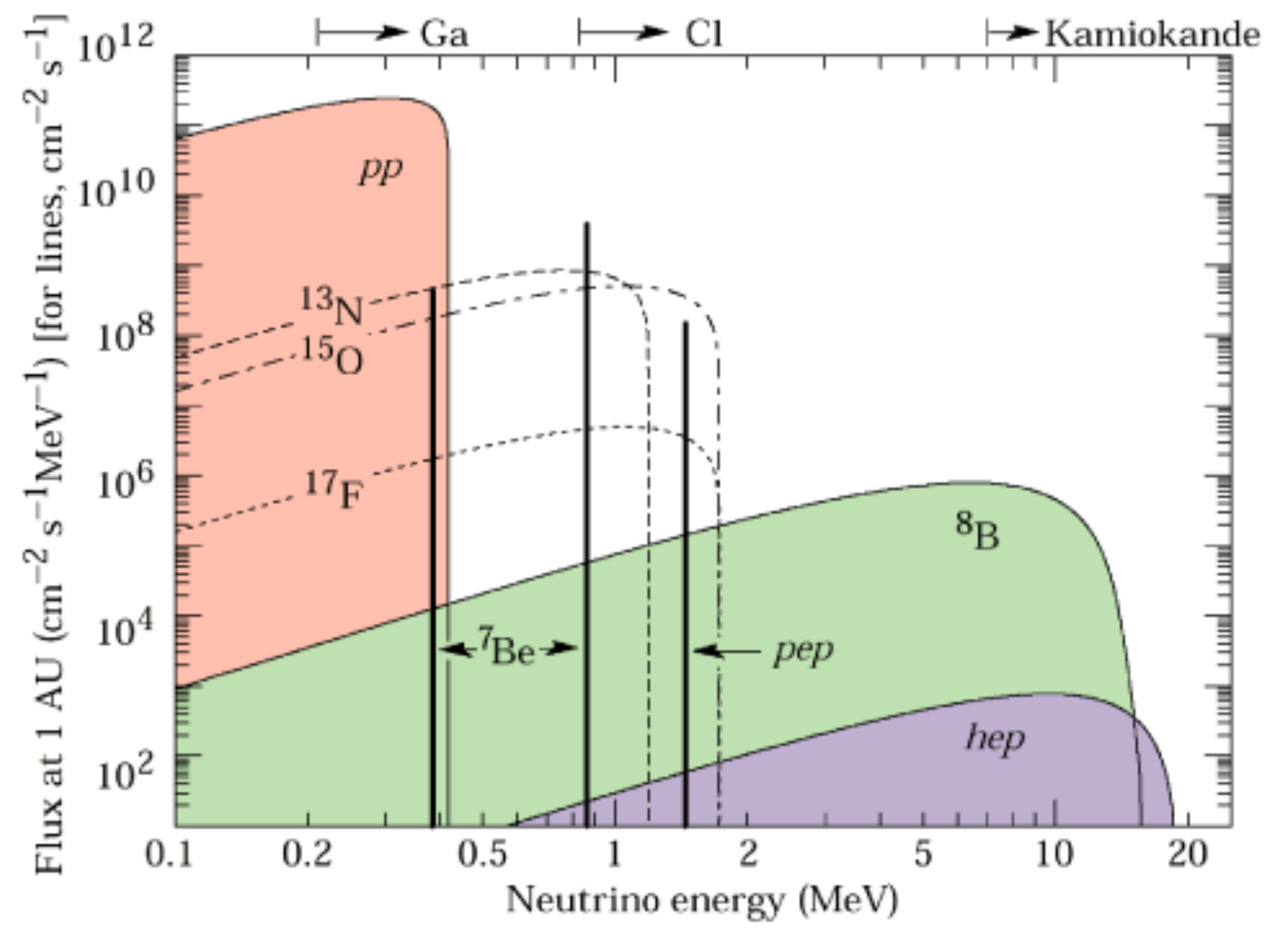


FIG. 4: Angular distribution of $\bar{\nu}_e p \rightarrow n e^+$ events (green) and elastic scattering events $\nu e^- \rightarrow \nu e^-$ (blue) of one simulated SN.

R. Tomas et al. , Phys.Rev. D68 (2003) 093013

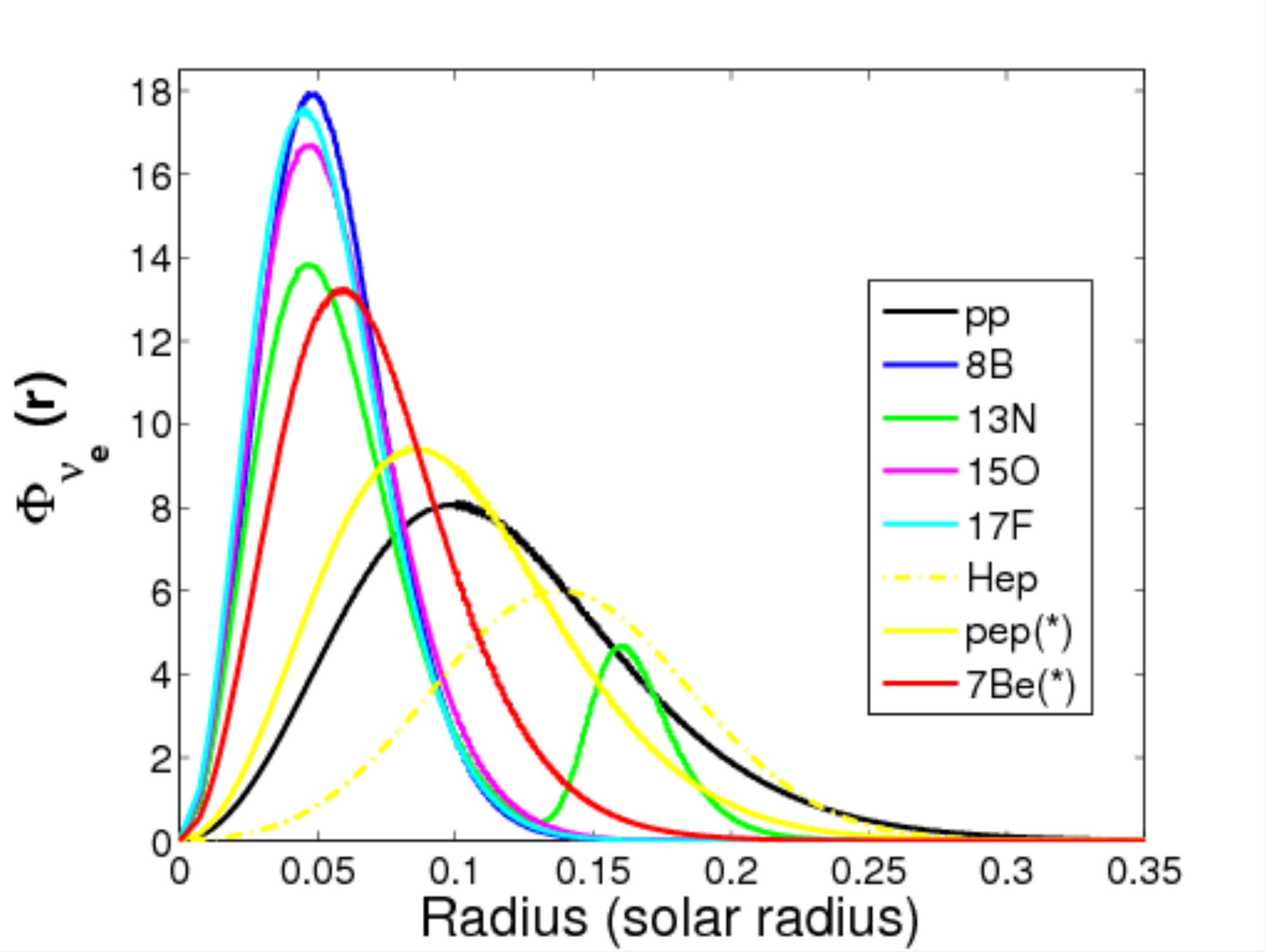
SOLAR NEUTRINOS

- Solar neutrinos are produced via fusion reactions occurring in the Sun’s core.
- The solar core has a radius of 20% to 25% of the solar radius.
- Their energies and fluxes depend on the fusion reactions in which they are created.



WHERE ARE 8B NEUTRINOS PRODUCED IN THE CORE?

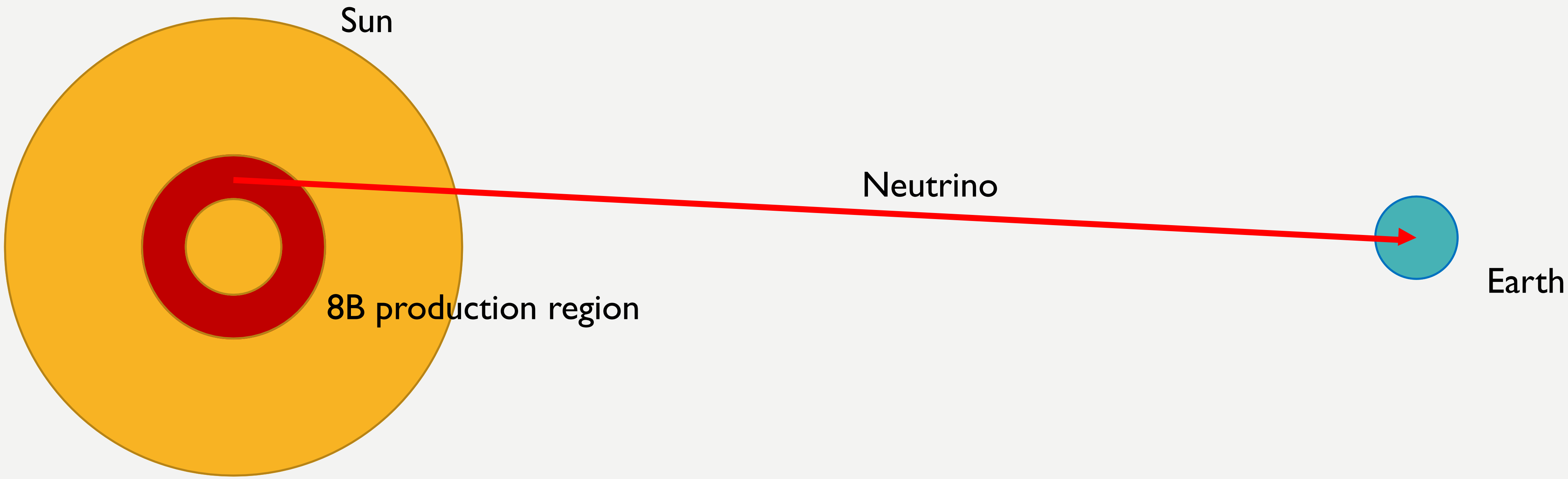
- Different fusion reactions should occur at different positions within the core.
- **We focus on 8B neutrinos**, which are predicted to be produced in a spherical ring located at 5% of solar radius from core centre.



Lopes and Turck-Chièze, Astrophys.J. 765 (2013) 14

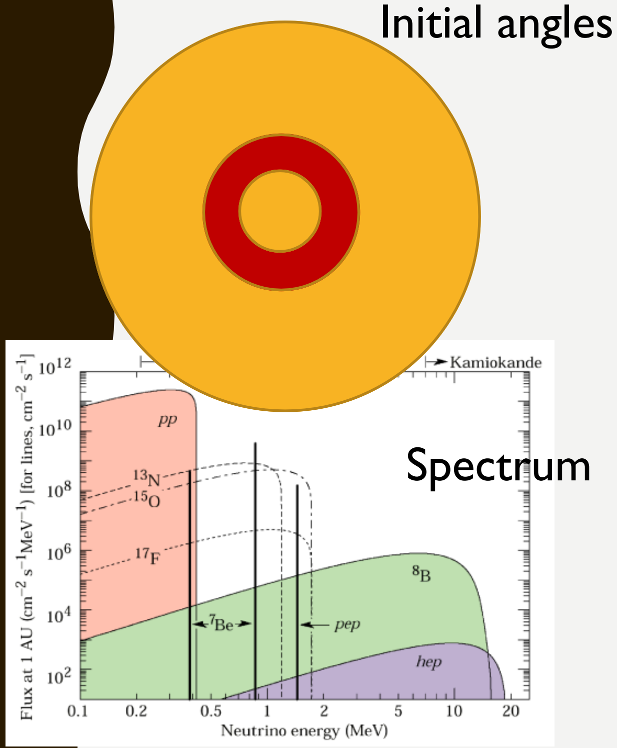
MAXIMUM LIKELIHOOD ANALYSIS – GENERATING SIGNAL DISTRIBUTIONS

- We need to generate the distribution of electrons in a water Cherenkov detector, given an assumption on the neutrino distribution in the solar core.
- Start by generating initial angles of the neutrinos as they arrive at Earth, given a distribution in the core:



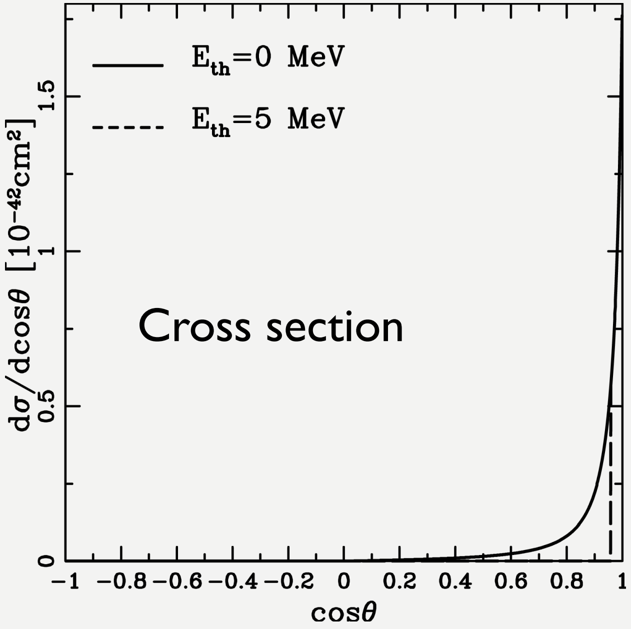
MAXIMUM LIKELIHOOD ANALYSIS – GENERATING SIGNAL DISTRIBUTIONS

- Combine the initial distribution of neutrinos, the differential cross section of electron-nu scattering and the distribution of electron multi-scattering in the detector.
- Repeat this process for different initial neutrino distributions within the solar core.

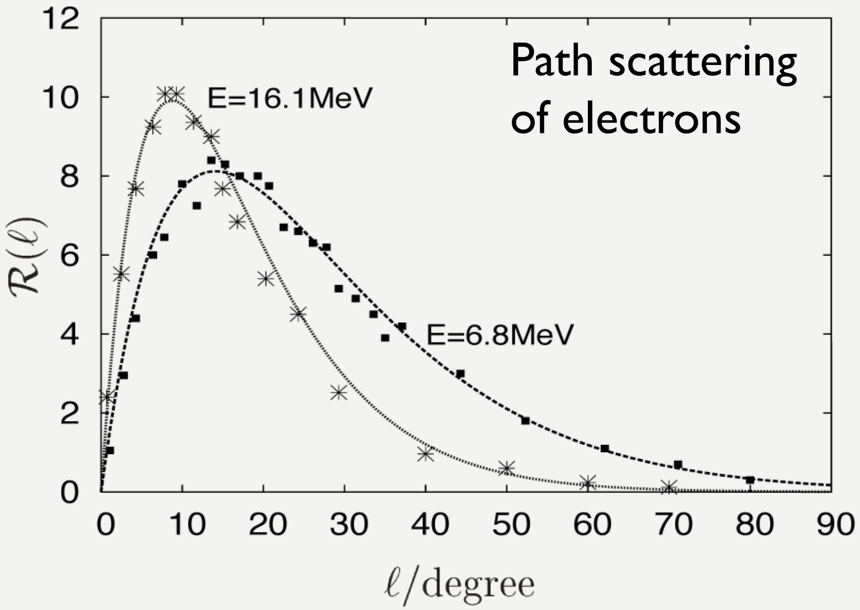

Initial angles

Spectrum

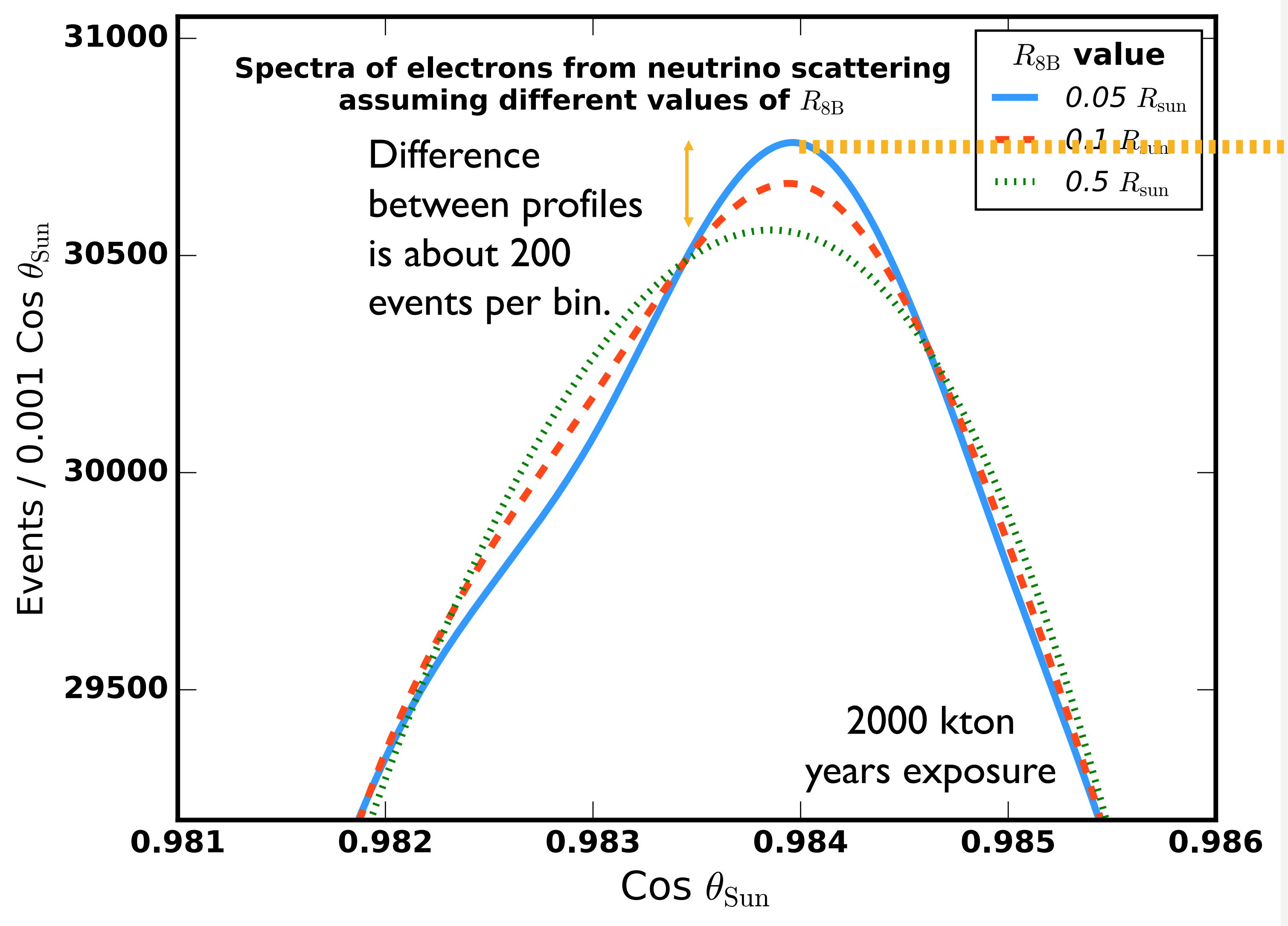
+


Cross section

+


Path scattering of electrons

MAXIMUM LIKELIHOOD ANALYSIS – GENERATING SIGNAL DISTRIBUTIONS



Spectra of electrons from neutrino scattering assuming different values of R_{8B}

Difference between profiles is about 200 events per bin.

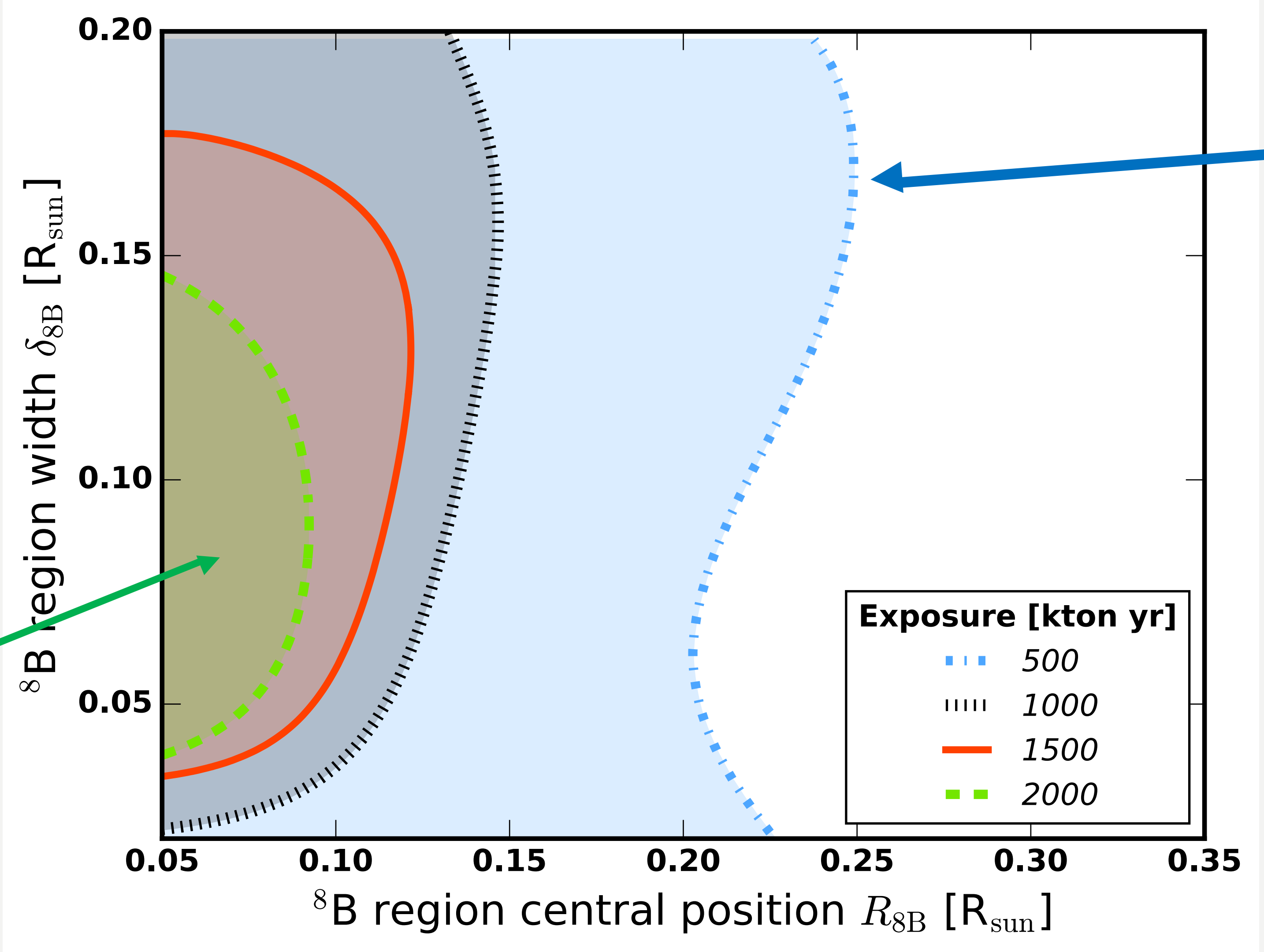
2000 kton years exposure

Poisson uncertainty is roughly Sqrt(31000) = 176.

The spectra are only just distinguishable above statistical noise.

MAXIMUM LIKELIHOOD ANALYSIS - RESULTS

95% confidence contours



20 years for Super Kamiokande

4 years for a 500 kilo-tonne experiment

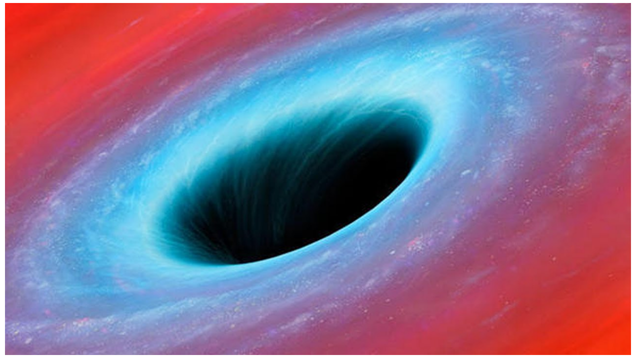
J. H. Davis, Phys.Rev.Lett. 117 (2016) 211101

ASTRONOMY WITH DIFFUSE SUPERNOVA NEUTRINOS

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

- It should have two components: a larger flux of lower energy neutrinos from neutron-star-forming supernovae, and a **smaller flux at higher energies from black-hole-forming “unnovae” collapse events.**

- Can we measure the unnovae flux in order to infer the **birth rate of black holes?**



SUPERNOVAE AND UNNOVAE NEUTRINO SPECTRA

We assume only two types of neutrino burst exist: NS-forming supernovae or BH-forming unnovae.

Solid = unnovae
Dashed = supernova

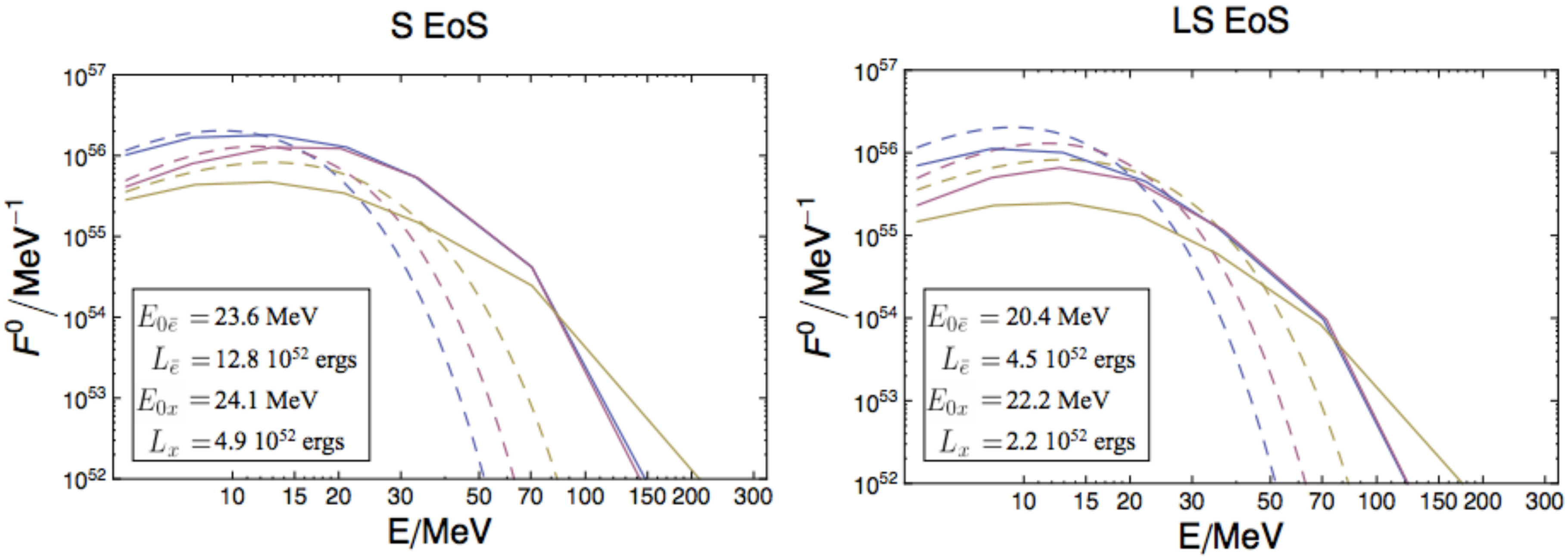
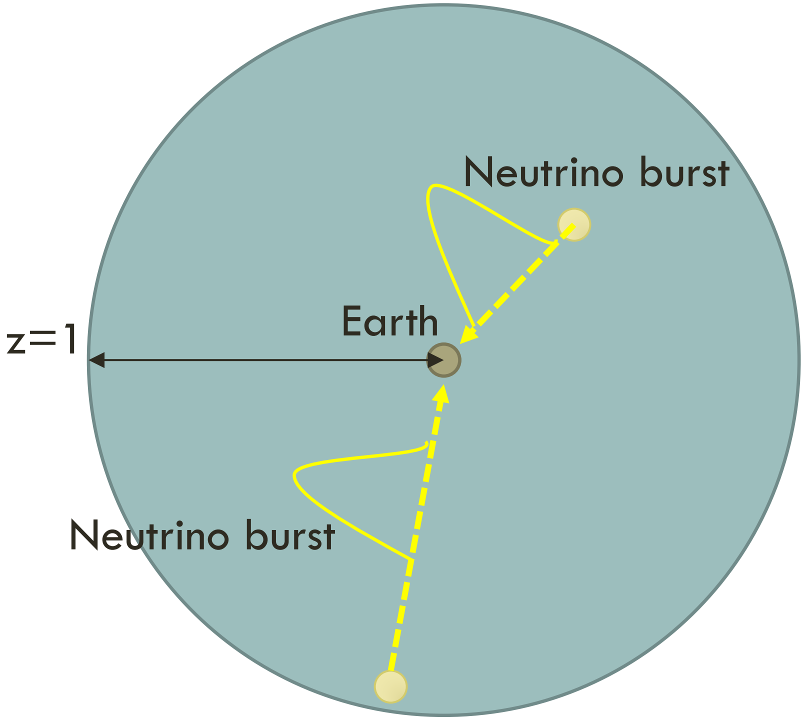
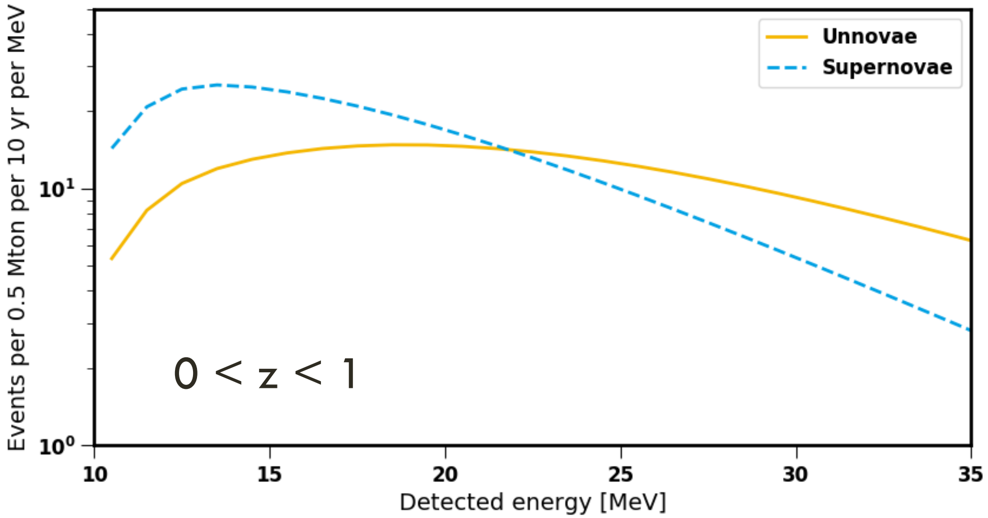


FIG. 1: Neutrino fluxes at production inside the star for direct black hole-forming collapse (solid, from [11]) , and neutron star-forming collapse (dashed, Eq. (2)). In both cases, the curves from upper to lower at 5 MeV correspond to ν_e, $\bar{\nu}_e$, ν_x. For direct black hole-forming collapse the neutrino spectra are shown for the Shen et al. (left panel) and Lattimer-Swesty (right) EoS. For each, the neutrino luminosities and average energies are given (inserts). See text for details.

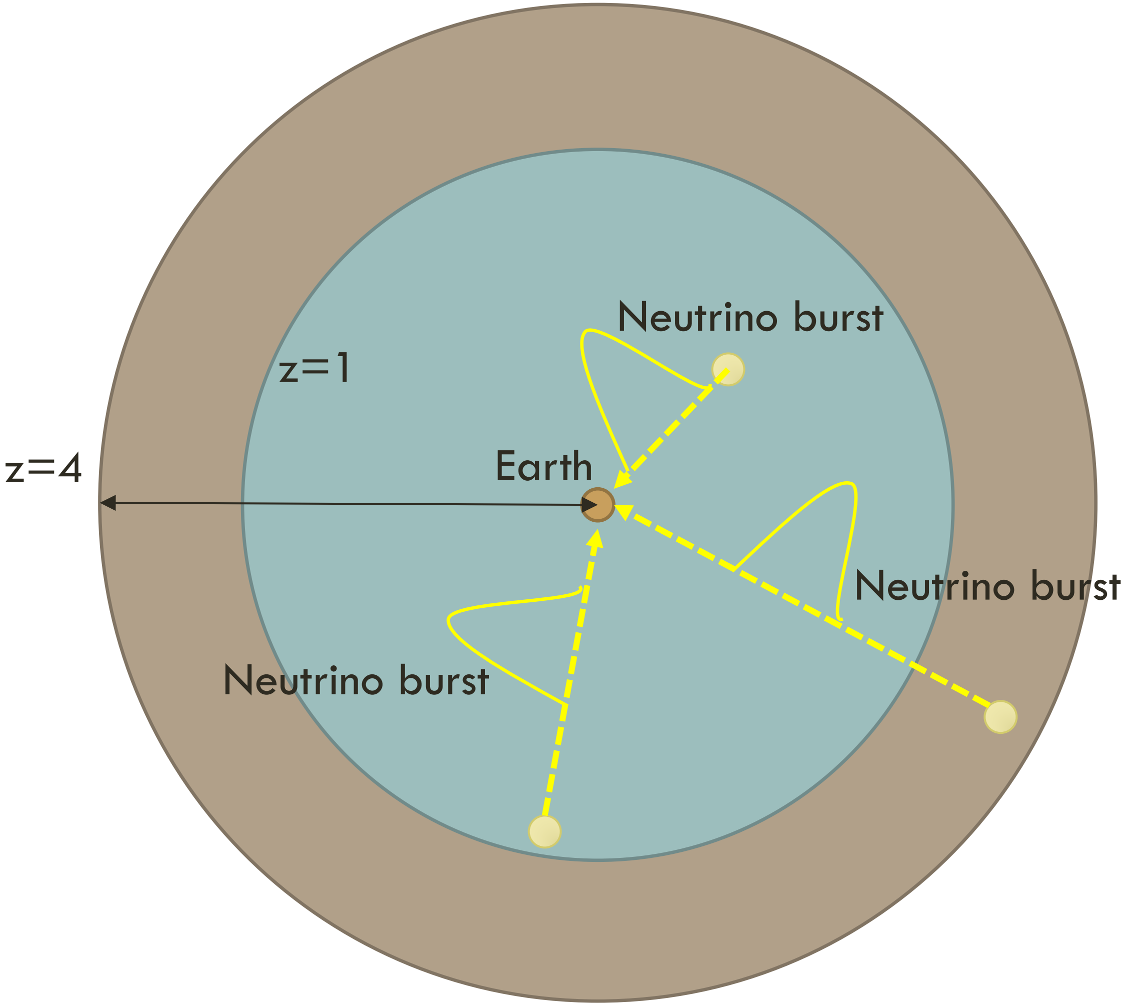
C. Lunardini, Diffuse neutrino flux from failed supernovae, Phys. Rev. Lett. 102 (2009) 231101, [0901.0568]

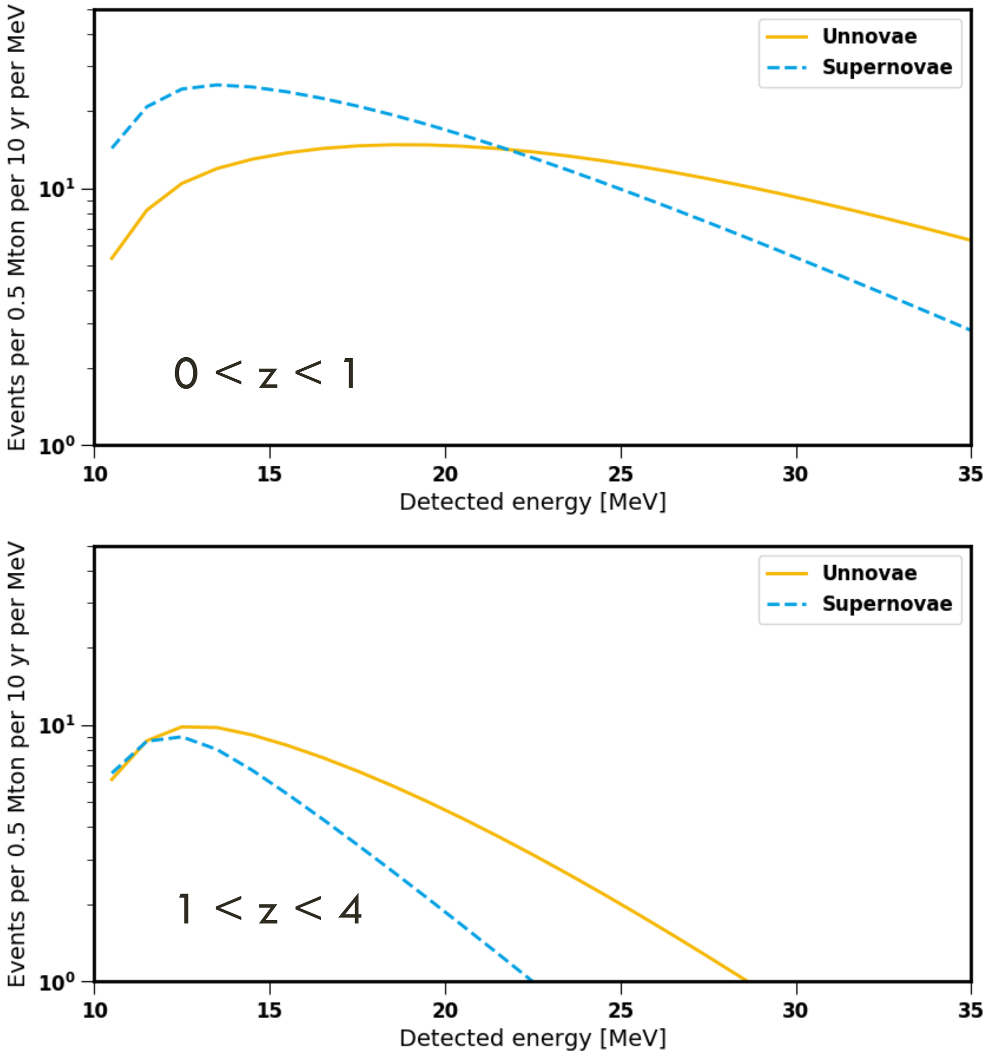
DIFFUSE SUPERNOVA NEUTRINO BACKGROUND



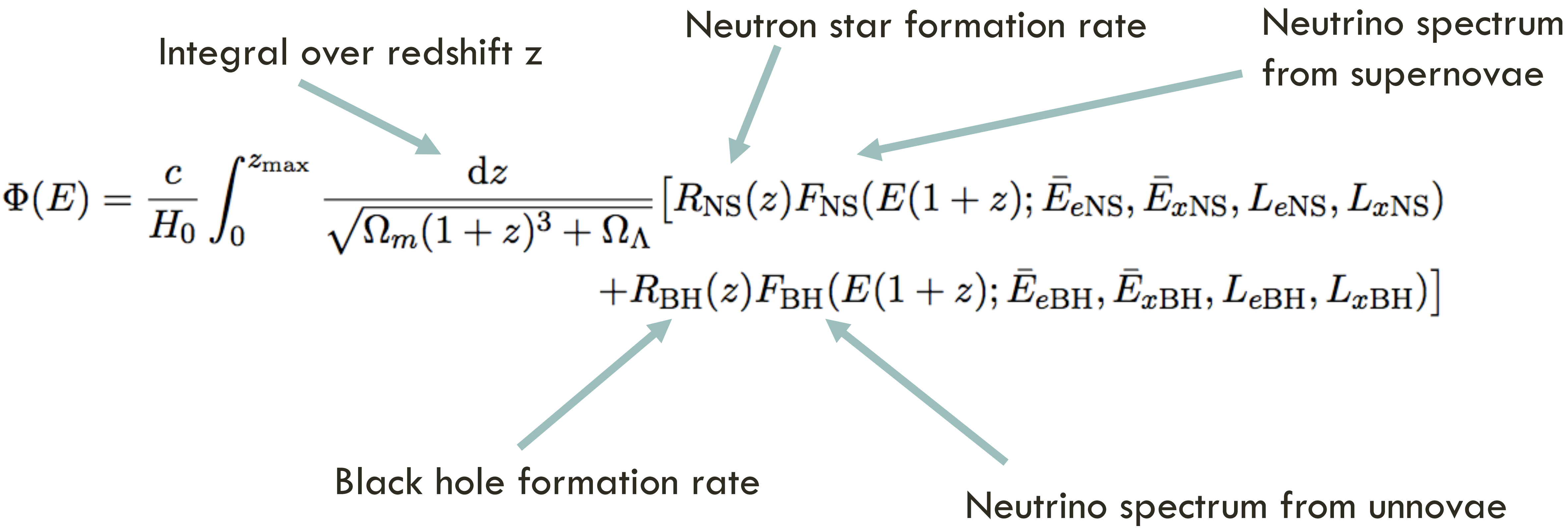


DIFFUSE SUPERNOVA NEUTRINO BACKGROUND





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 should be close to the star formation rate, but 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?**

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

$$R_{\rm BH}(z) = f_{\rm BH}(z)R(z)$$

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]

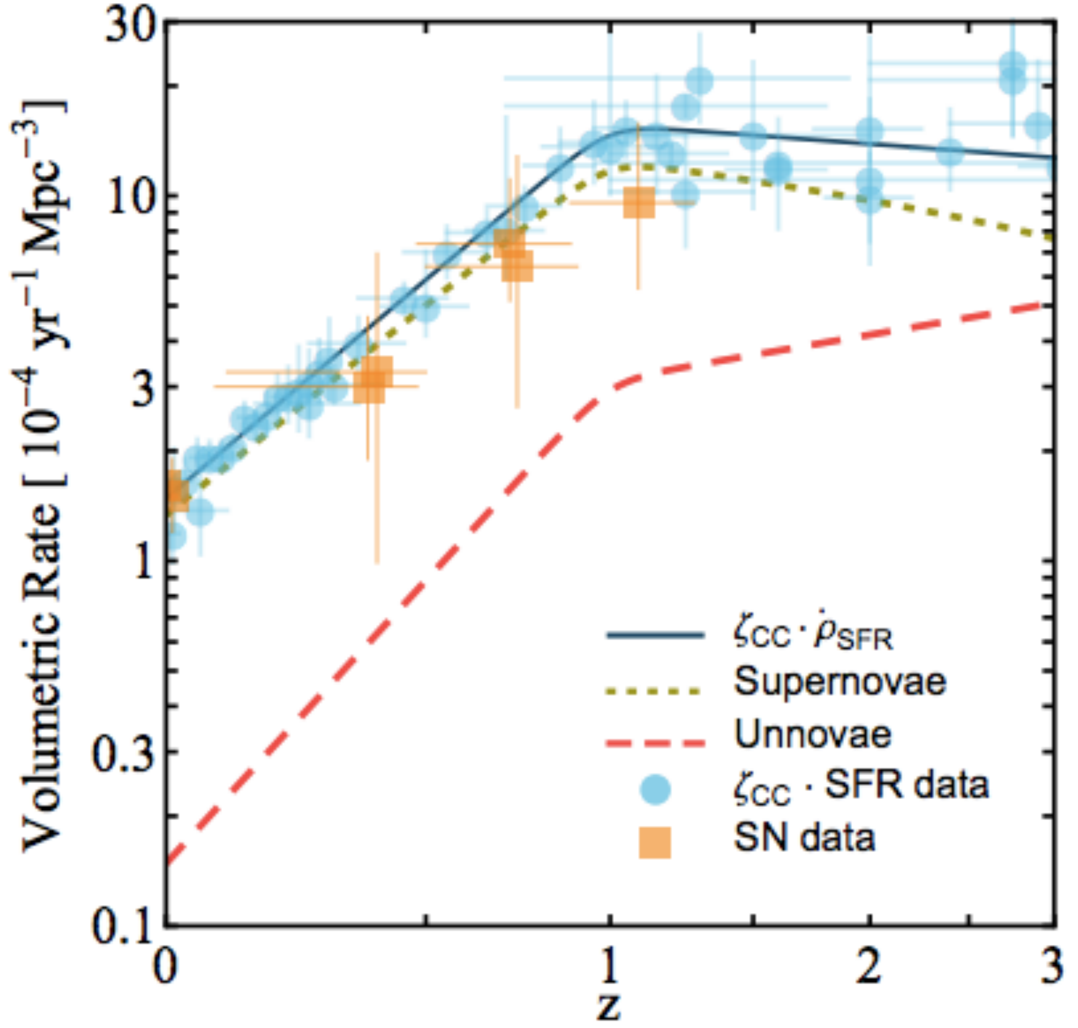
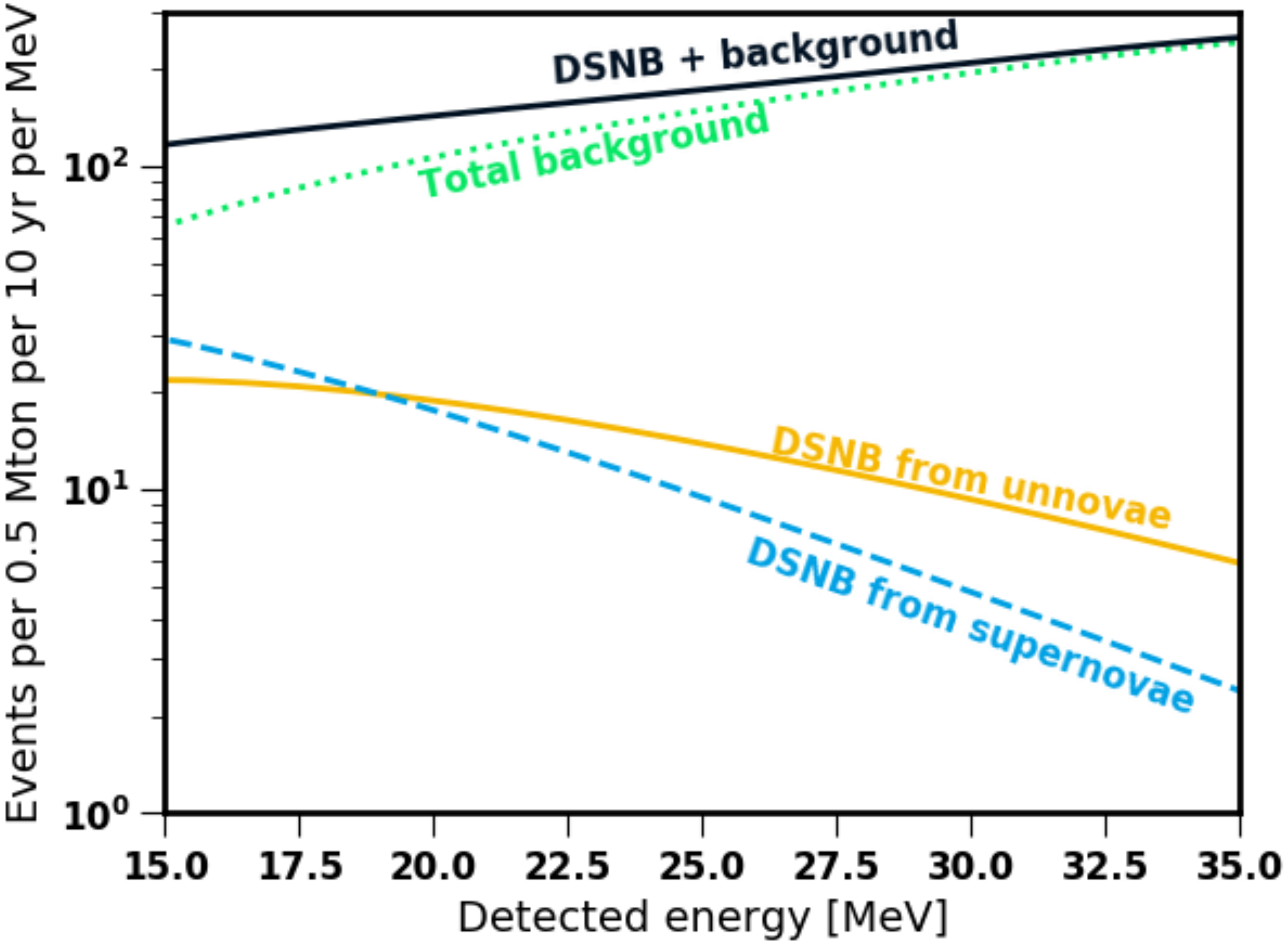


FIG. 1: The cosmic rate of core collapse. Shown are recent measurements of core-collapse supernovae [9–12] (*squares*; see [17] for older data), which fall just below the expectation from star formation rate data with all stars of mass $\gtrsim 8\,M_\odot$ yielding optical SNe (*circles*; [18]). These 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*).

DSNB IN HYPER KAMIOKANDE

- Detect the DSNB anti-electron neutrinos primarily through **inverse beta capture**: anti-nu + p -> n + e+
- 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).

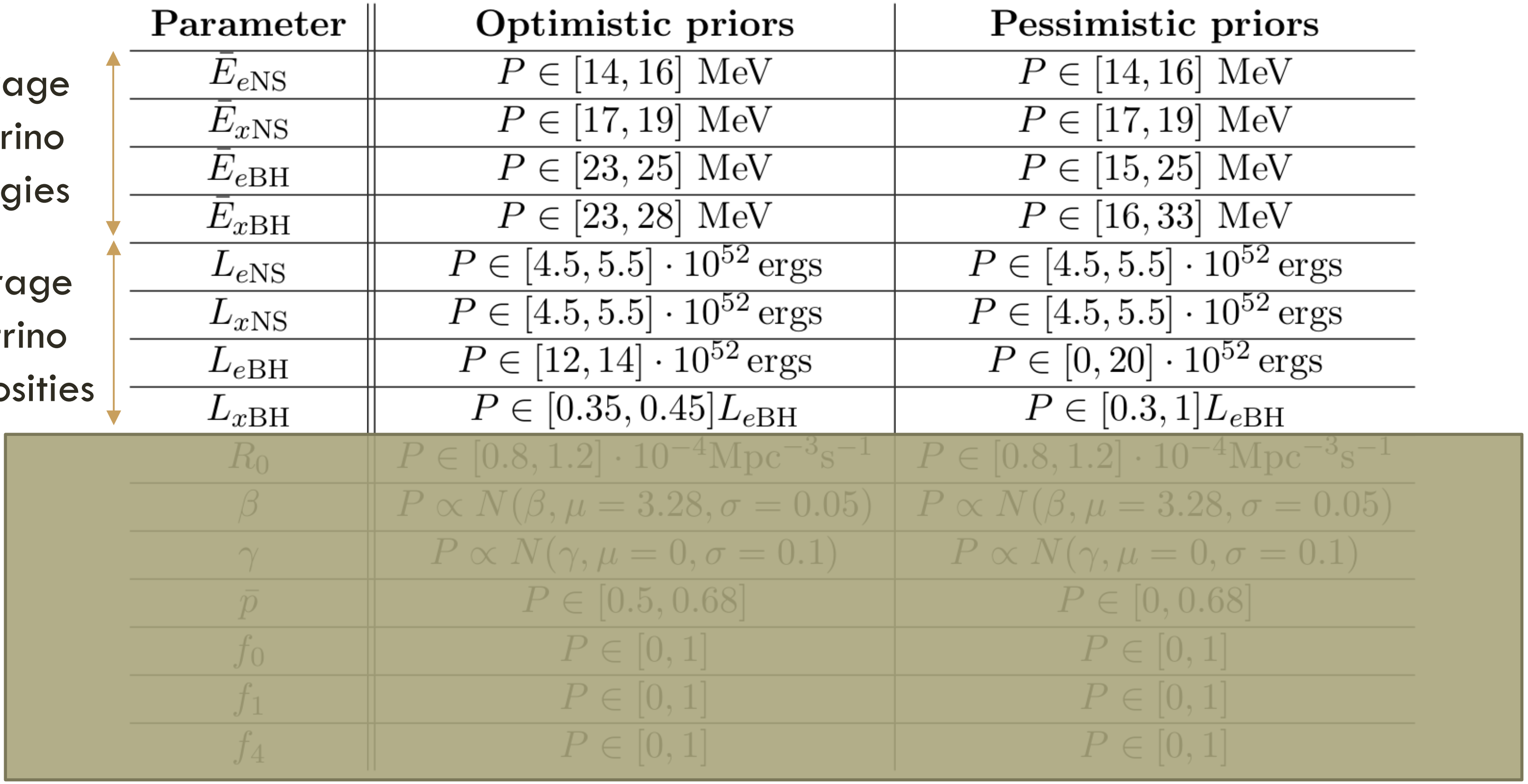


MARKOV CHAIN ANALYSIS

- **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.

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

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
	$\bar{E}_{x\mathrm{NS}}$	$P \in [17, 19]$ 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
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	$P \in [0, 1]$	$P \in [0, 1]$

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.

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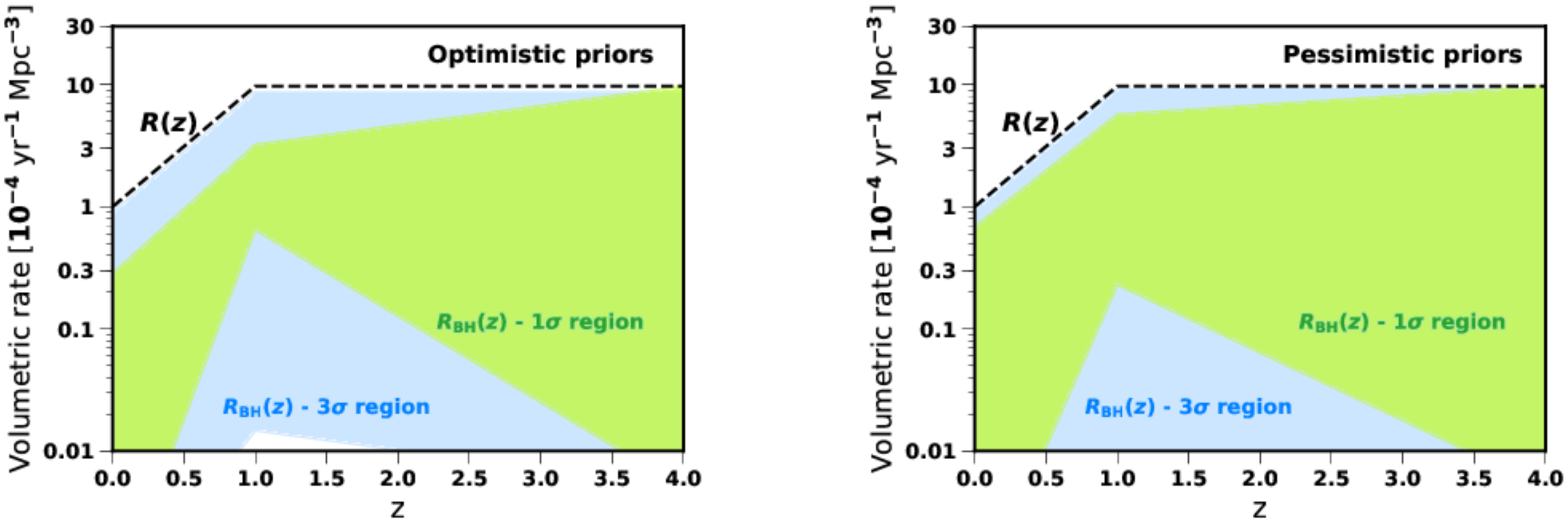
MEASURING THE BLACK HOLE BIRTH RATE



- 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.

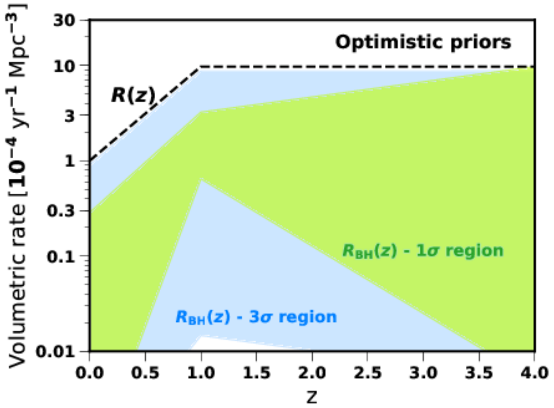
THE BLACK HOLE MERGER RATE FROM THE BIRTH RATE

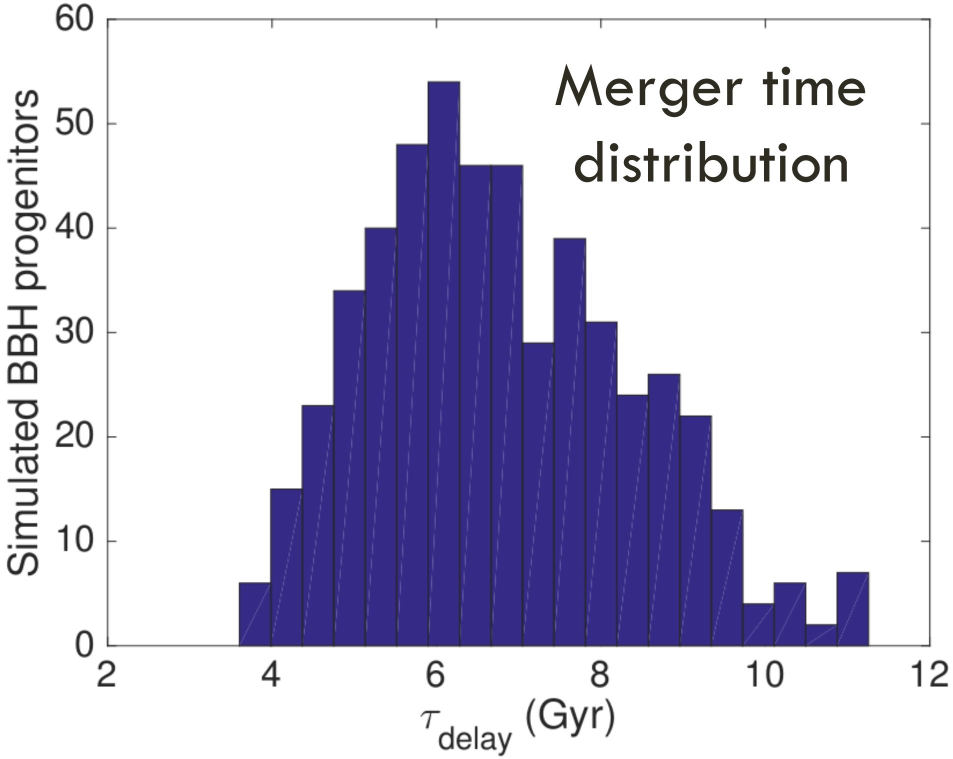
Merger fraction

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

Black hole merger rate

Birth rate from DSNB



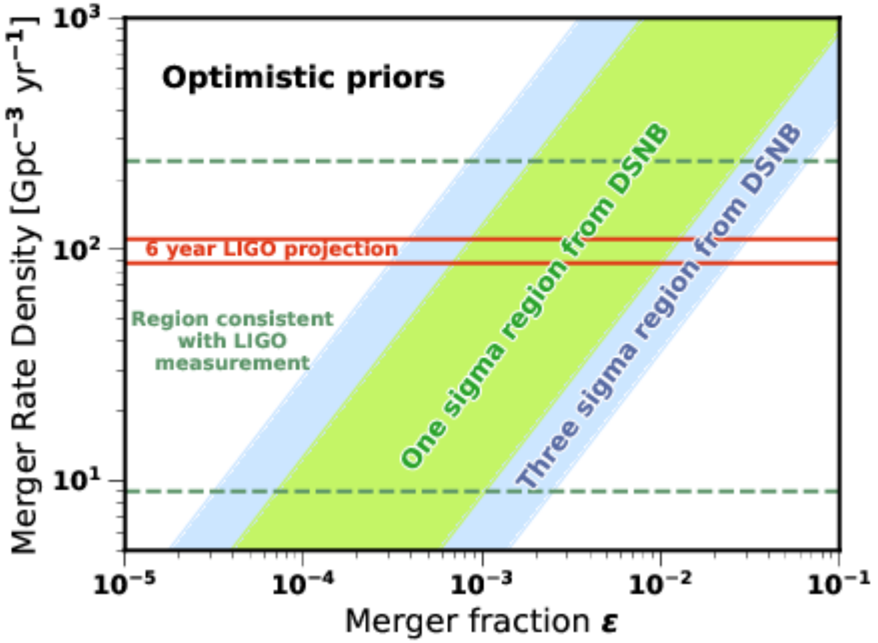


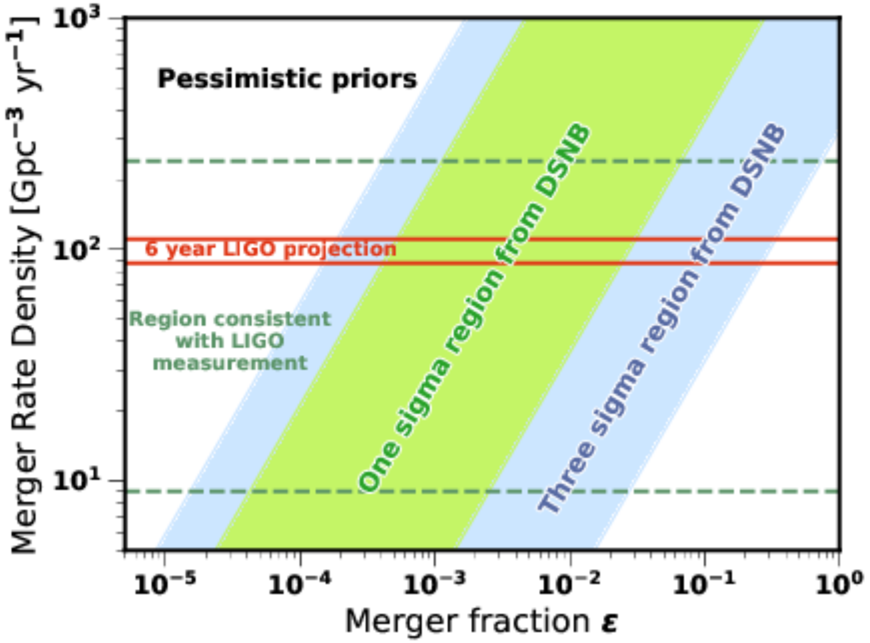
Merger time distribution

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



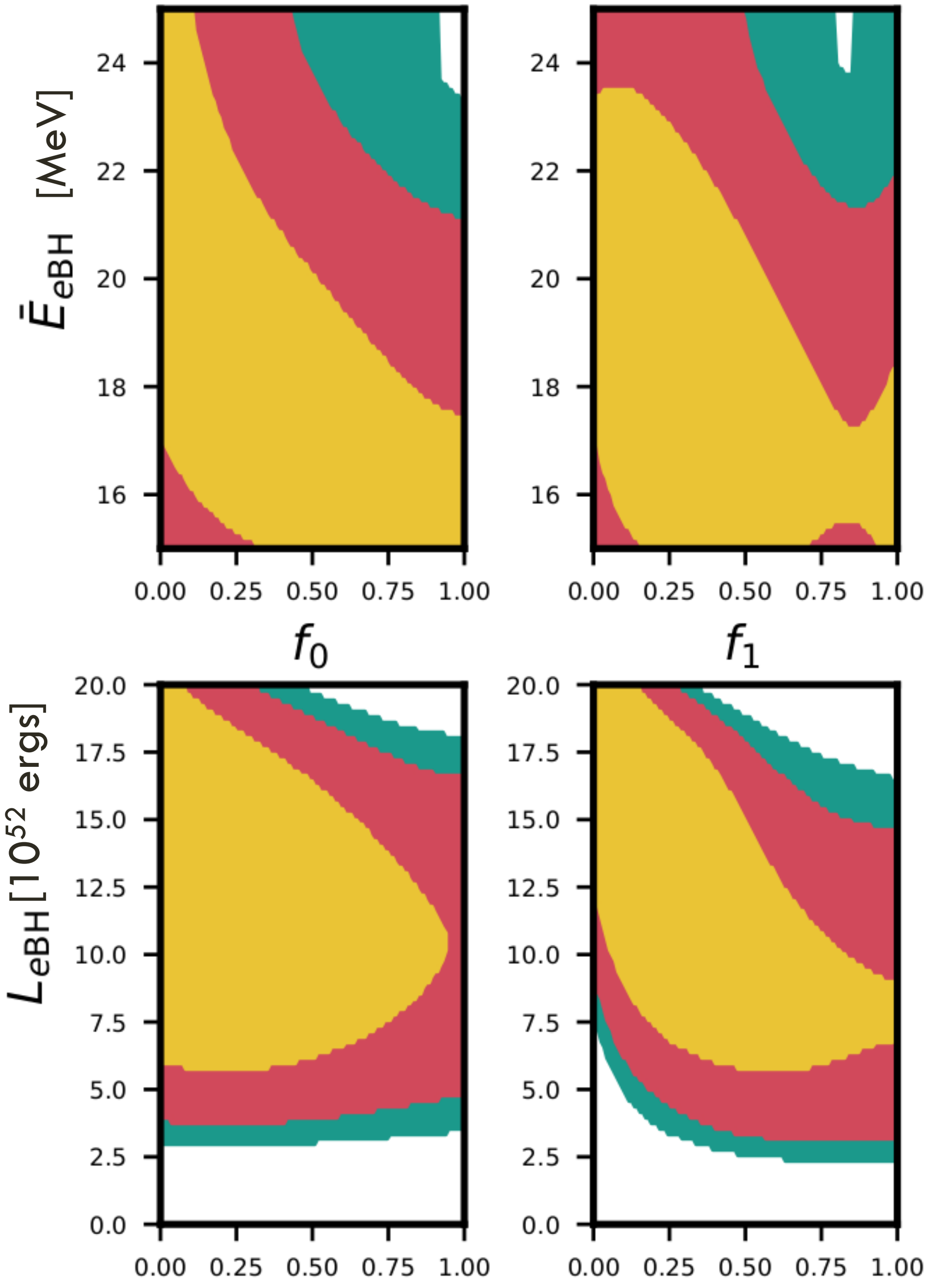


- The coloured regions show our calculated merger rate from the birth rate inferred from the DSNB.
- Where this region intersects the LIGO bounds gives the allowed values of the merger fraction.

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?

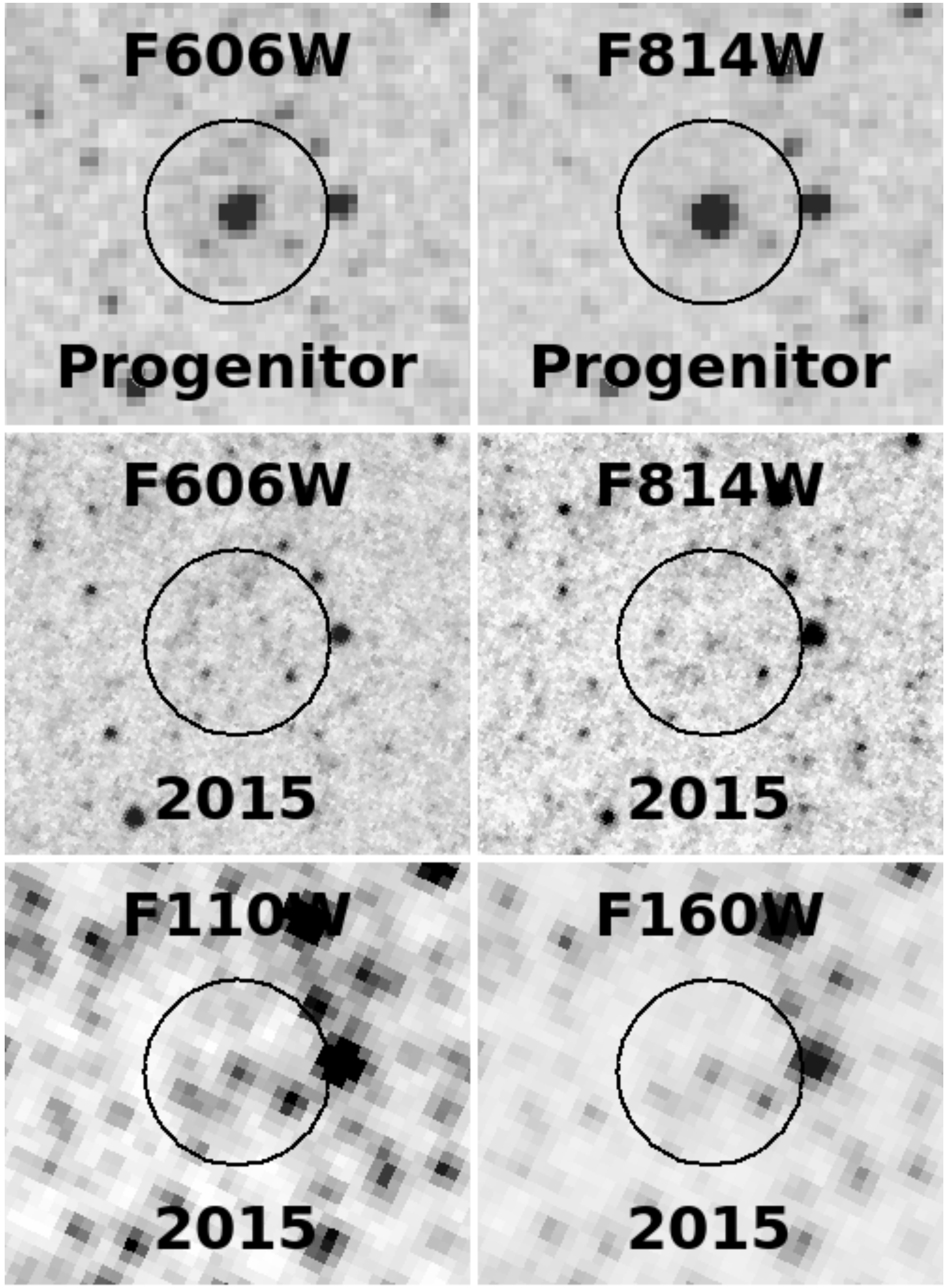


Contours bound a given percentage of the total integrated posterior volume

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

IMPROVING ON OUR RESULTS

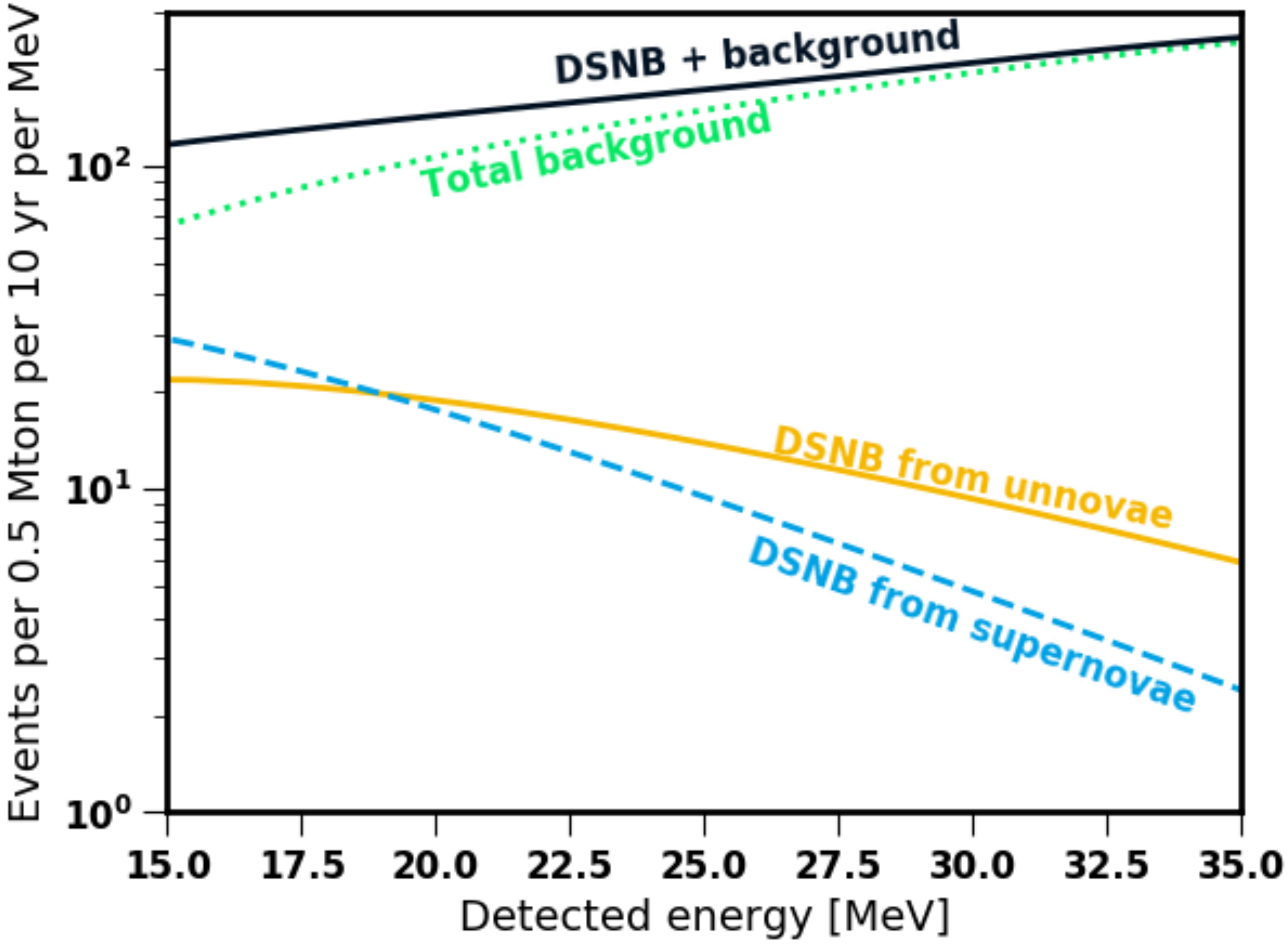
- **Astrophysical input** such as the star formation rate or the rate of supernova events will also **improve our measurement** of the black hole birth rate.
- **Also measurements of disappearing stars**. In this case we need to know if all BH-forming collapse events lead to optical disappearance events, 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 directionality of solar neutrinos is important for future direct dark matter searches.
- Conversely, we can use solar neutrino experiments as **telescopes of the solar interior.**
- 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.

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