Intermediate Distance Core-Collapse Supernova Neutrinos

(Heston et al., in prep)

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CNP Research Day
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VIRGINIA TECH

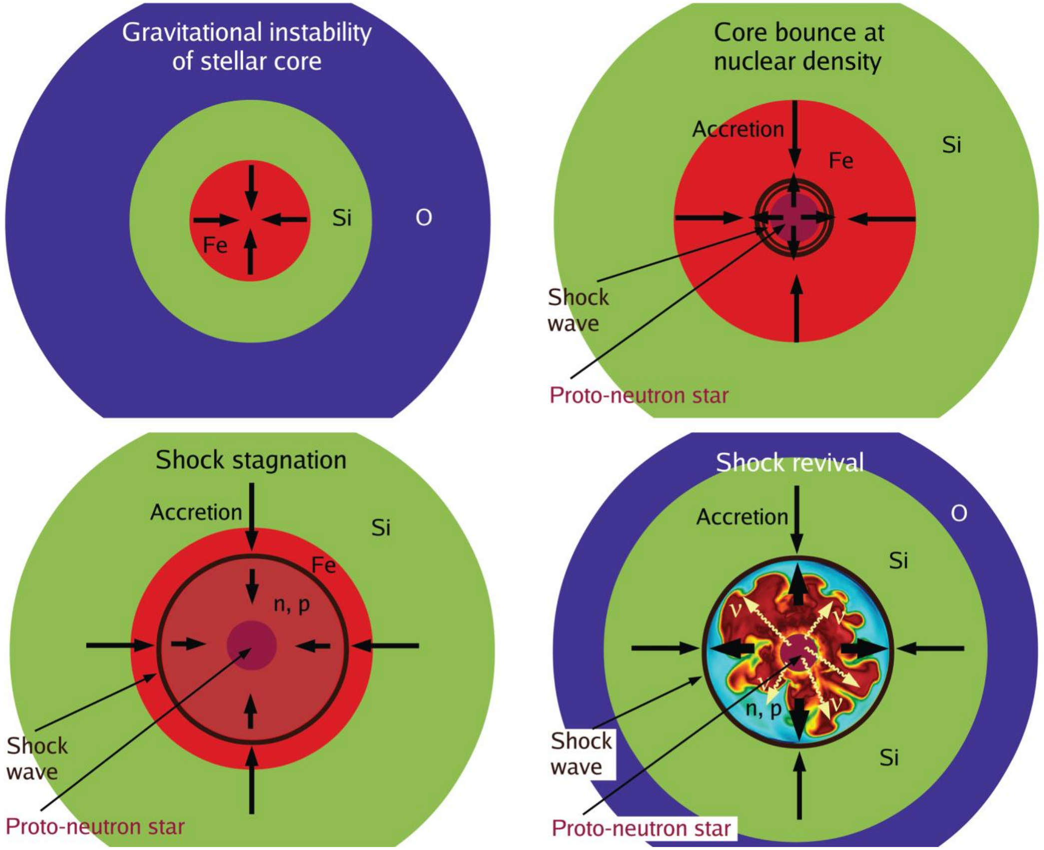
Intermediate Distance CCSNe

- Intermediate distance regime between galactic and diffuse supernova neutrino background (DSNB)
- Motivation: alternative way to get CCSNe neutrinos
  - cf. SN1987A: 24 events
  - Galactic CCSNe: 10^5 events every 40 years
  - DSNB: several per year
- Most CCSNe will produce $\ll 1$ event, so we need to study many SNe to get an appreciable number of neutrinos

Alexeyev E., et al., 1988, Physics Letters B, 205
Bionta R. M., et al., 1987, Phys. Rev. Lett., 58
Hirata K., et al., 1987, Phys. Rev. Lett., 58

CCSNe Explosion Theory

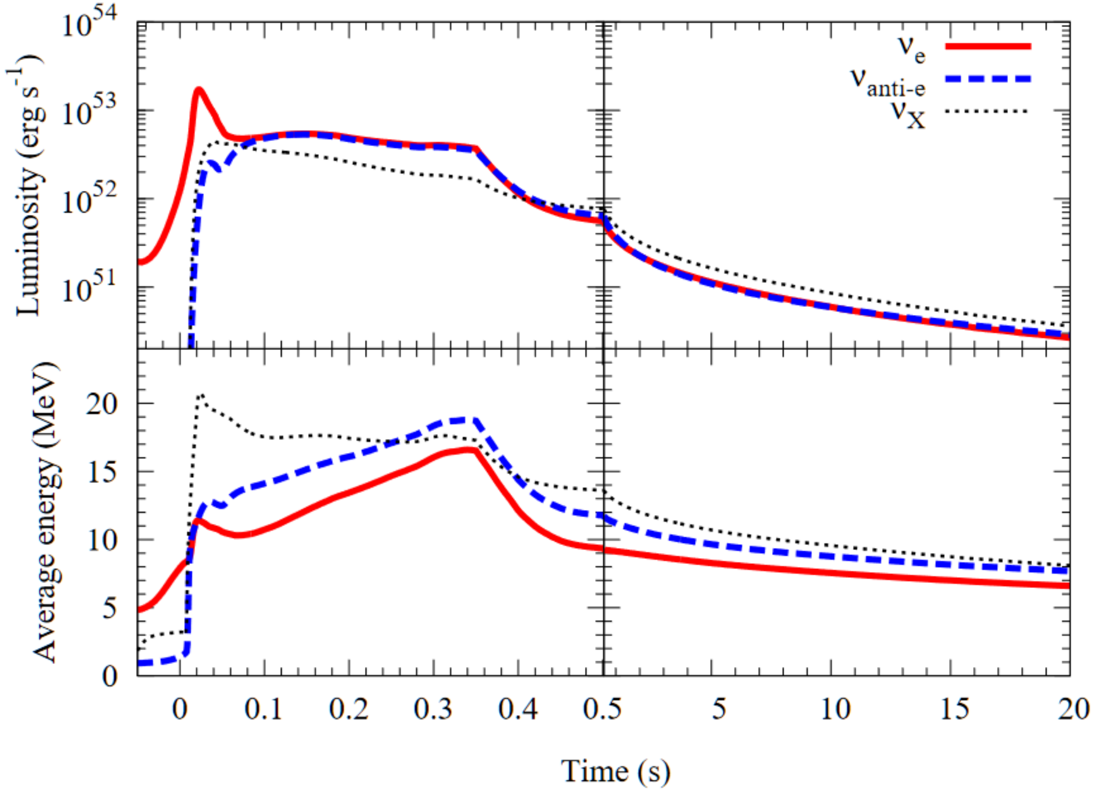
- Core-collapse supernovae (CCSNe) occur in stars of masses > 8 $M_\odot$
- Upon the Fe core reaching the Chandrasekhar mass, electron degeneracy pressure cannot support the core and collapse begins
- Once nuclear densities are achieved in the core, the core stiffens and an outgoing shock forms
- The shock eventually stalls due to losing energy to accreting matter and releasing neutrinos trapped within the star



Janka H.-T., 2012, Annual Review of Nuclear and Particle Science, 62, 407
Wilson J. R., 1985, Numerical Astrophysics, 422
Woosley S., Janka H.-T., 2005, Nature Physics, 1, 147–154

Neutrino Production on CCSNe

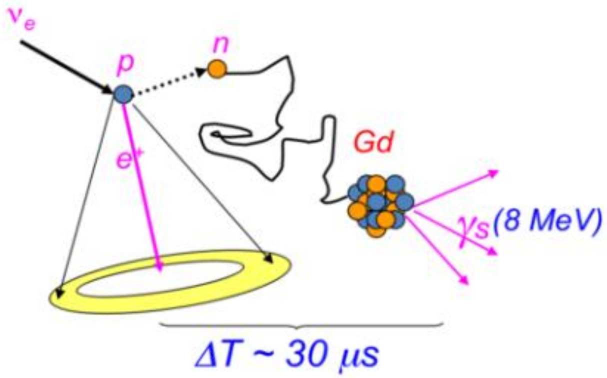
- Spike in ν production at beginning of core-collapse due to neutronization of infalling matter
- There is also pair annihilation, β decay, $e^{\pm}$ capture, and other processes
- The proto-neutron star (PNS) cools by releasing neutrinos
- Neutrinos interact with matter behind the shock causing shock revival which leads to an explosion



Bethe H. A., Wilson J. R., 1985, The Astrophysical Journal., 295, 14
Janka H.-T., 2001, Astronomy & Astrophysics, 368, 527–560
Langanke K., Martínez-Pinedo G., 2003, Rev. Mod. Phys., 75, 819
Suwa Y., et al., 2019, The Astrophysical Journal, 881, 139

Neutrino Detection

- Event detection is simulated for a two-tank Hyper-Kamiokande with a total fiducial volume of 375 kton
- Consider only detection channel to be inverse beta decay (IBD) : $\bar{\nu}_e + p \rightarrow e^+ + n$
  - Assumes Gd doping
- Neutron captured by the Gd, allows event tagging with $\sim$ 90% efficiency (8 MeV γ cascade)
  - Without Gd doping, neutron mostly captured by free protons, $\sim$ 20% tagging efficiency at Super-Kamiokande



Super-Kamiokande Collaboration, 2015, Astroparticle Physics, 60, 41–46
Hyper-Kamiokande Proto-Collaboration, Hyper-Kamiokande design report (2018), arXiv:1805.04163
Fernández P., 2016, Nuclear and Particle Physics Proceedings, 273-275, 353

Supernova Surveys

- Study prospect of time-correlated observable CCSNe and detected neutrino events
- ASAS-SN: ongoing survey, measures in *g*-band with a limiting magnitude of 17, full-sky coverage, 1 day cadence (cadence is the time to revisit a point on the sky)
- LSST: under construction, measures in *r*-band with a limiting magnitude of 24, coverage of almost half of the sky, 1 day cadence

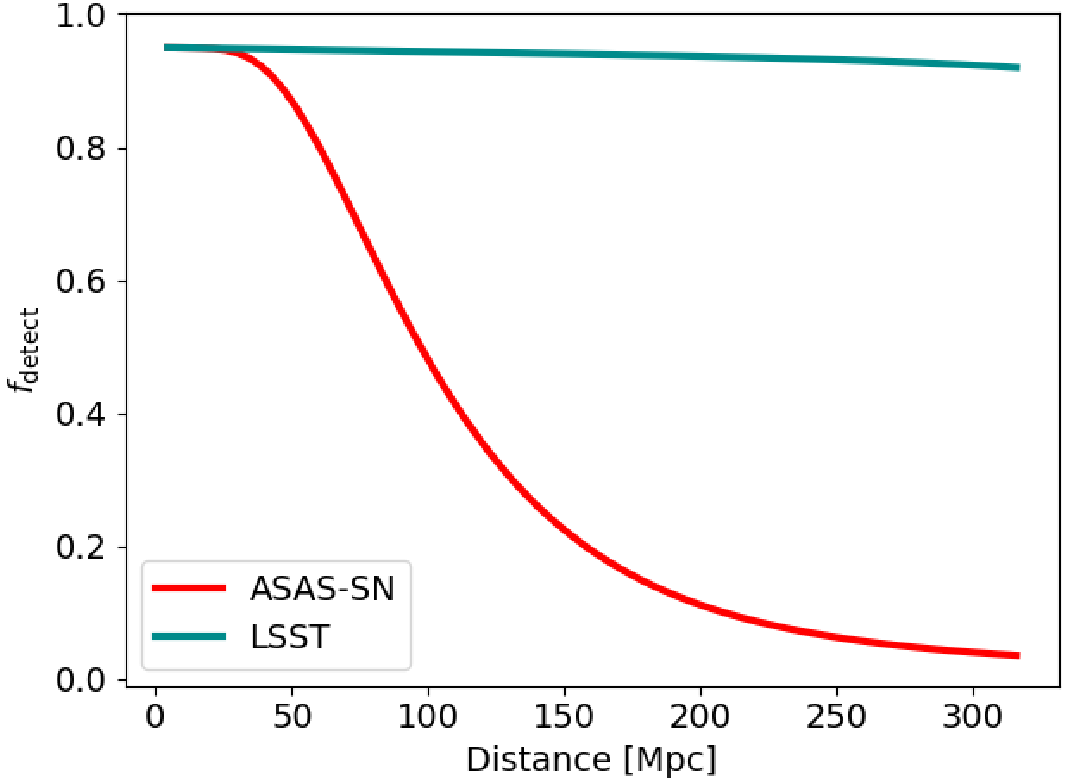

ASAS-SN


LSST

http://www.astronomy.ohio-state.edu/~shappee/assassin.html
https://gallery.lsst.org/bp/#/

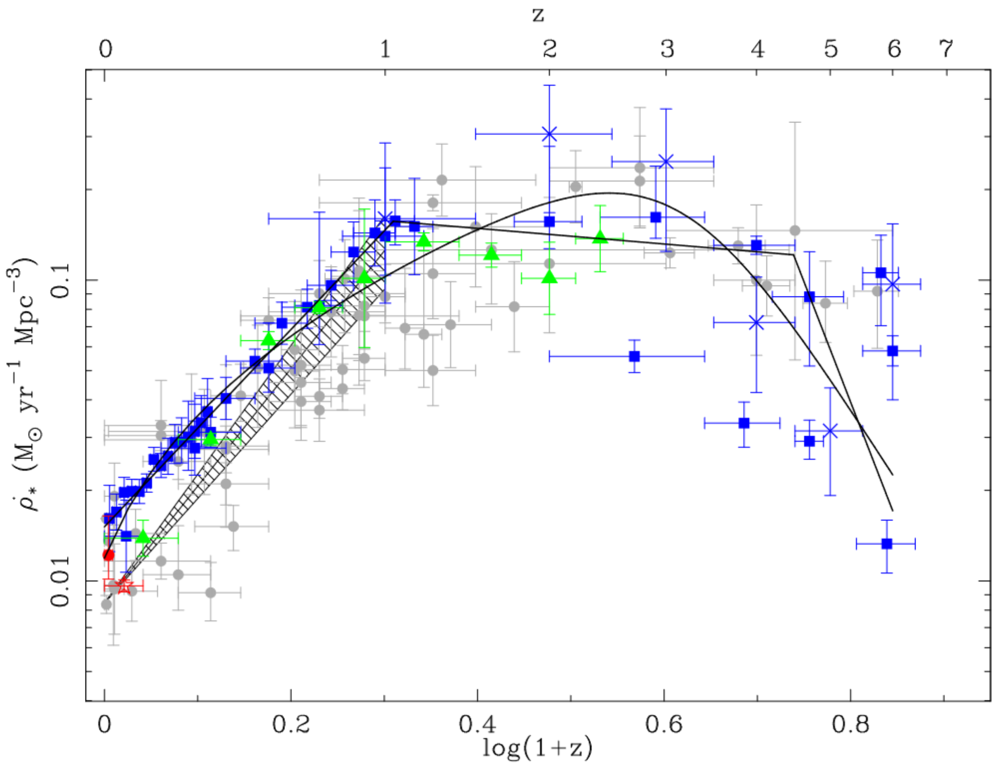
Completeness f_{detect}

- Define an ideal detection fraction f_{maglim}
- Multiply by, f_{dust}, the fraction eliminated via dust extinction



Cosmic CCSNe Rate

- Starting with the cosmic star formation rate (CSFR), pictured right, we want to get the cosmic (core-collapse) SN rate (CSNR)
- Assume that the CSFR and CSNR are proportional
- Constant of proportionality obtained from the initial mass function, assume Salpeter A IMF
  - Constant is the ratio of mass fraction of stars that will undergo core collapse and the mean CCSN progenitor mass
  - Assume core-collapse range is 8-50 $M_\odot$

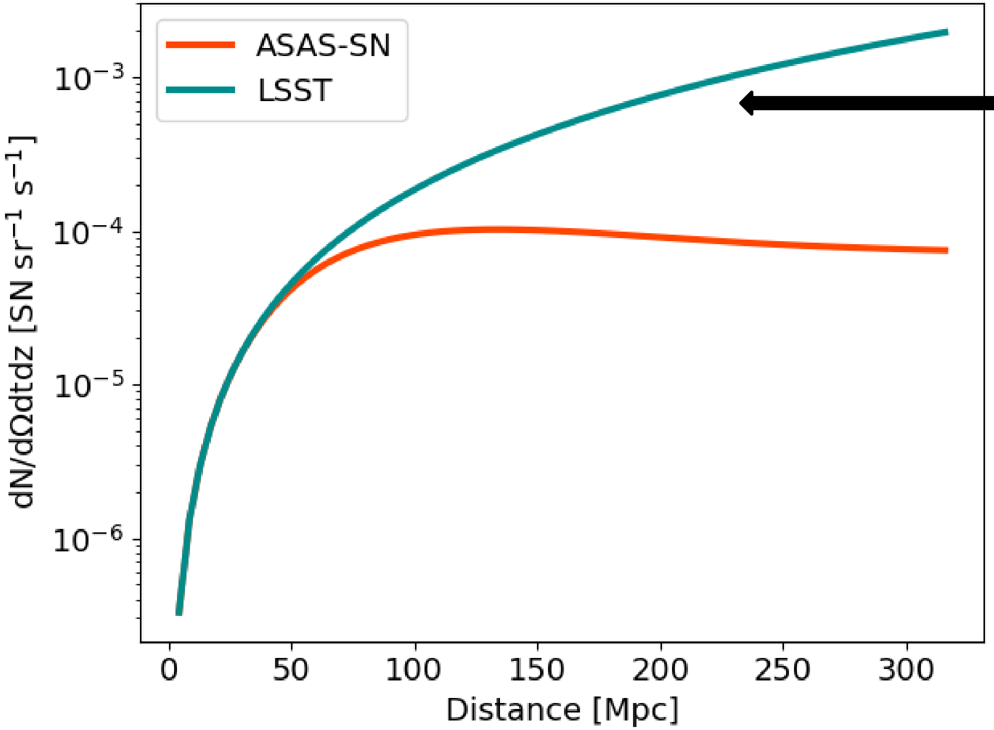


Cole S., et al., 2001, Monthly Notices of the Royal Astronomical Society, 326, 255–273
Hopkins A. M., Beacom J. F., 2006, The Astrophysical Journal, 651, 142–154
Lien A., Fields B. D., 2009, Journal of Cosmology and Astroparticle Physics, 047–047

Detection Rate

- Define a differential CCSNe detection rate per redshift per solid angle

$$\Gamma_{SN,obs,x}(z) \equiv \frac{dN_{SN,obs,x}}{d\Omega\, dt_{obs}\, dz} = \mathcal{R}_{SN}(z) f_{detect}(z; m_{lim}^{SN}) \frac{r_{com}(z)^2}{1+z} \frac{dr_{com}}{dz} \quad (1)$$



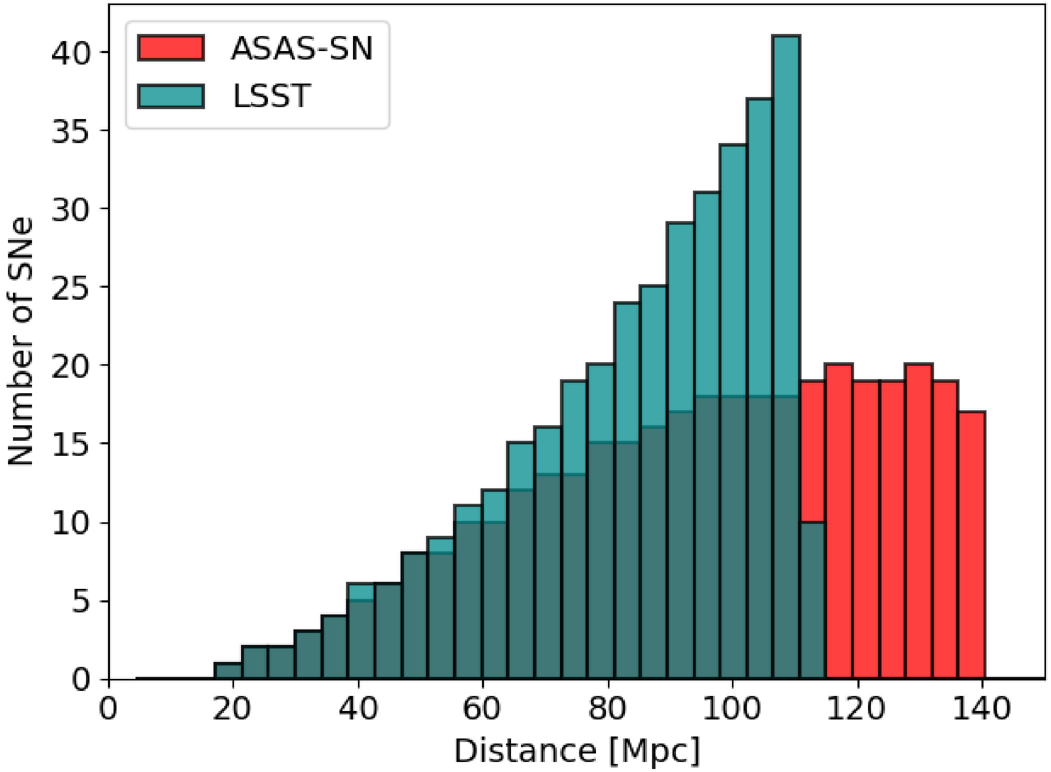
Volumetric increase

Lien A., Fields B. D., 2009, Journal of Cosmology and Astroparticle Physics, 047–047

Observed CCSNe

- ASAS-SN and LSST: maximum uncertainty in time of core-collapse, Δt, of 1 day (cadence) ⇒ stack 365 CCSNe
- If we stack more with the same Δt, we enter the DSNB regime
- Pinpointing time of core-collapse to smaller uncertainties will allow us to stack more CCSNe while remaining outside the DSNB regime

Closest 365 CCSNe

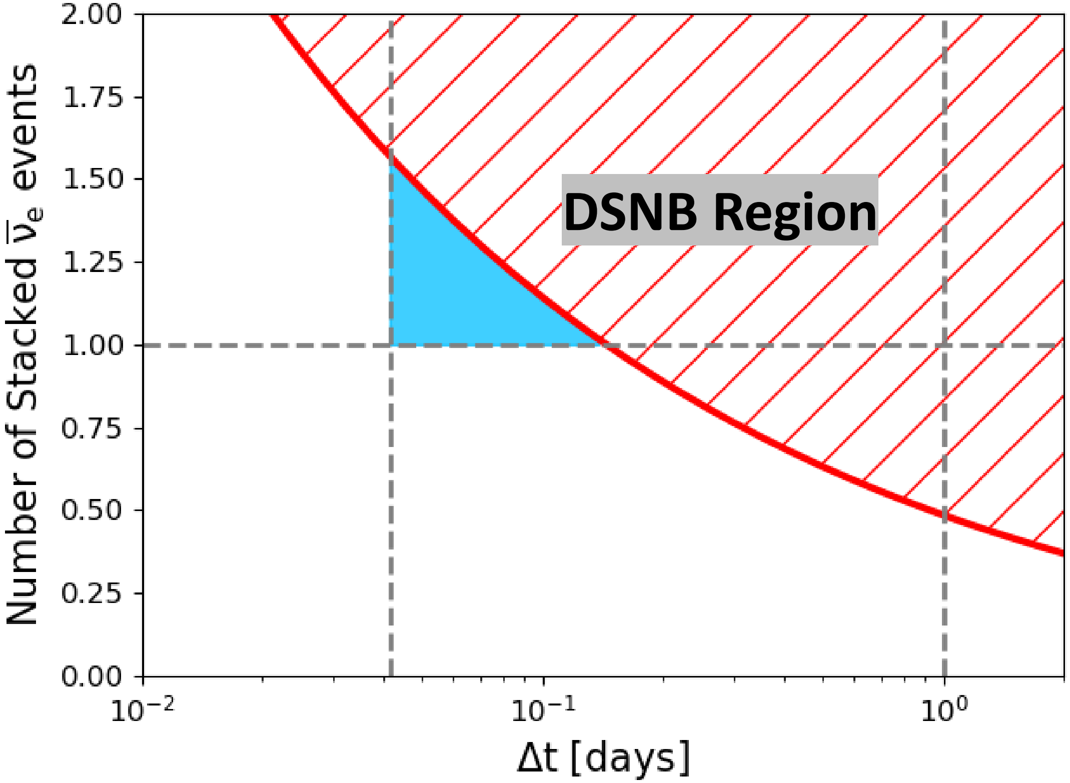


Calculating CCSNe Neutrino Events

- Again, we only assume detection via IBD with no flavor oscillation.
- Event number given by $N_\nu = \frac{N_t}{4\pi D^2} \int_{E_{low}}^{E_{high}} \sigma(E_\nu)\, F(E_\nu)\, dE_\nu$ (2)
    - N_t: number of target protons, D: distance, $\sigma(E_\nu)$: cross section, $F(E_\nu)$: ν energy spectrum
- The energy range we look at is from 11 MeV to 30 MeV for Gd doped Hyper-K
- Assume time-integrated flux with $L_{\overline{\nu}_e} = 5 \times 10^{52}$ erg, $\langle E_{\overline{\nu}_e} \rangle = 15$ MeV
    - Motivated by CCSNe simulations
- Closest 365 CCSNe give average of 0.61 events for ASAS-SN and 0.48 events for LSST

LSST Stacking Region of Interest

- Theoretical predictions retrieve for Δt = 1 day, we do not obtain $\sim$ 1 event
- What if we decrease Δt, thus allowing us to stack more CCSNe?
  - Comes from modelling CCSN early light curves
- Vertical lines correspond to Δt of one day and one hour
- Light blue area is the region in which LSST can detect $\sim$ 1 event outside of the DSNB region



Hyper-K Estimated Background Rate

- Use Super-K backgrounds from their SK-I, SK-II, and SK-III runs
  - Crude estimate: average background rate of 0.000150 events per day per kton
  - SK-III background larger than the other runs due to an accident
- Need to stack background events as we stack neutrino events
- As both $\Delta t's$ are close in value, background estimate is similar
- Outcome: 20.58 background events compared to signal of ~ 1 SN neutrino event

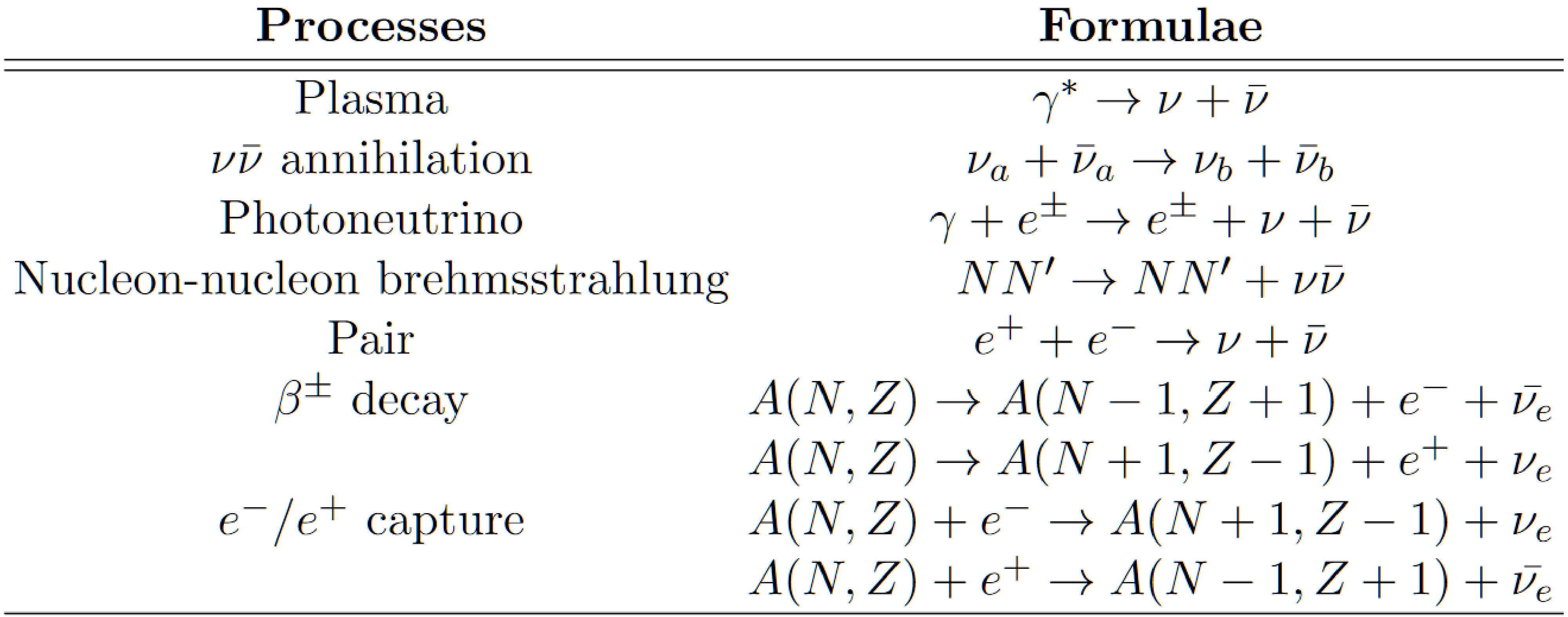
Super-Kamiokande Collaboration, 2012, Physical Review D, 85

Conclusions

- Δt of 1 day (survey cadence) is too slow, in the DSNB region for LSST's theoretical observed CCSNe rate for $\sim 1\ \bar{\nu}_e$ event
- If LSST can reach a Δt of 1 hour, then we can detect $\sim 1\ \bar{\nu}_e$ event
- However, we have a background signal of ~ 20 events
- Must collect data over long periods of time (5-10 years) and only select the closest CCSNe for best prospects

Backup Slides

Processes for Neutrino Production

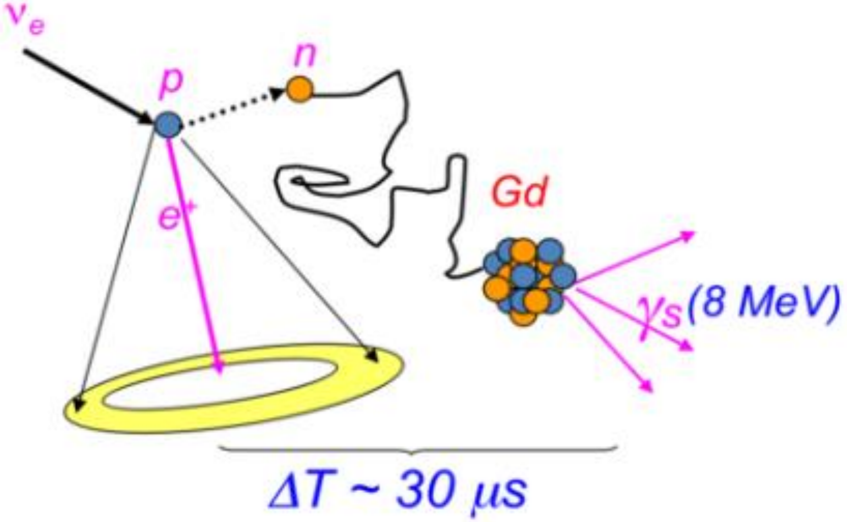


Processes	**Formulae**
Plasma	$\gamma^* \to \nu + \bar{\nu}$
$\nu\bar{\nu}$ annihilation	$\nu_a + \bar{\nu}_a \to \nu_b + \bar{\nu}_b$
Photoneutrino	$\gamma + e^{\pm} \to e^{\pm} + \nu + \bar{\nu}$
Nucleon-nucleon brehmsstrahlung	$NN' \to NN' + \nu\bar{\nu}$
Pair	$e^+ + e^- \to \nu + \bar{\nu}$
$\beta^{\pm}$ decay	$A(N, Z) \to A(N-1, Z+1) + e^- + \bar{\nu}_e$
	$A(N, Z) \to A(N+1, Z-1) + e^+ + \nu_e$
e^-/e^+ capture	$A(N, Z) + e^- \to A(N+1, Z-1) + \nu_e$
	$A(N, Z) + e^+ \to A(N-1, Z+1) + \bar{\nu}_e$

Langanke K., Martínez-Pinedo G., 2003, Rev. Mod. Phys.,75, 819

Gadolinium Doping

- Neutron tagging allows us to reject backgrounds that only produce relativistic leptons, like atmospheric muon neutrinos.
- Gd has the largest thermal neutron cross-section of all stable nuclei
- Gd captures a neutron and enters an excited state, then releasing a γ ray cascade with a total energy of 8 MeV



Fernández P., 2016, Nuclear and Particle Physics Proceedings, 273-275, 353

More on the CCSNe Rate, $\mathcal{R}_{SN}(z)$

$$\mathcal{R}_{SN}(z) = \frac{X_{SN}}{\langle m_{SN} \rangle} \dot{\rho}_*(z)$$

$$\frac{dN_{SN}}{d\Omega \, dt_{obs} \, dz} = \mathcal{R}_{SN}(z) \frac{r_{com}^2}{1+z} \frac{dr_{com}}{dz}$$

$$\frac{dN_{SN}}{dV_{com} \, dt \, dM_p} \equiv \mathcal{R}_{SN}(z) \phi_{snlf,x}(M_p)$$

- X_{SN} is the mass fraction of stars which will undergo core-collapse
- $\langle m_{SN} \rangle$ is the average CCSN progenitor mass
- $\dot{\rho}_*(z)$ is the cosmic star formation rate density

Lien A., Fields B. D., 2009, Journal of Cosmology and Astroparticle Physics, 047–047

More on Event Number Calculations

$$F(E_\nu) = \frac{L_\nu}{\langle E_\nu \rangle^2} \frac{(\alpha+1)^{(\alpha+1)}}{\Gamma(\alpha+1)} \mathrm{Exp}\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

$$\frac{\left\langle E_\nu^k \right\rangle}{\left\langle E_\nu^{k-1} \right\rangle} = \frac{k+\alpha}{1+\alpha} \langle E_\nu \rangle$$

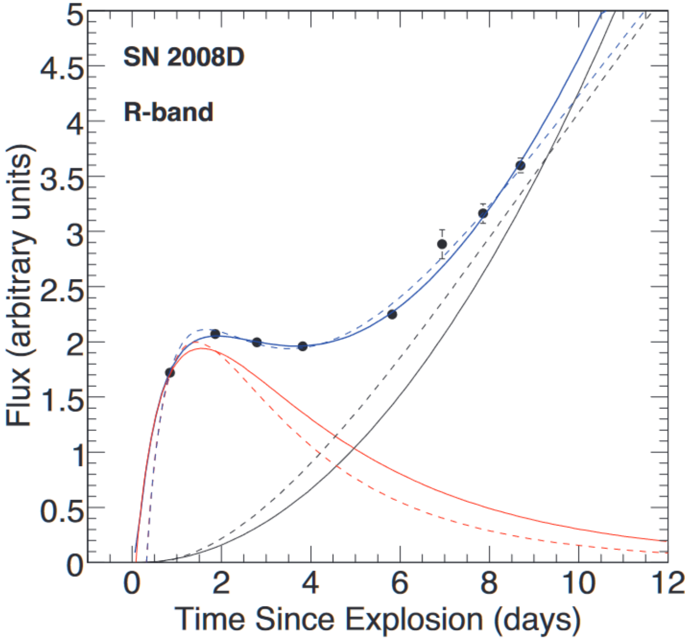
$$\sigma(E_\nu) = 9.5 \times 10^{-44} \mathrm{cm}^2 \left(1 - 6\frac{E_\nu}{M}\right)\left[\frac{E_\nu - \Delta}{\mathrm{MeV}}\right]$$

- M is the nucleon mass (∼939 MeV)
- Δ is the nucleon mass difference (∼1.29 MeV)

Horiuchi S., Kneller J. P., 2018, Journal of Physics G: Nuclear and Particle Physics, 45

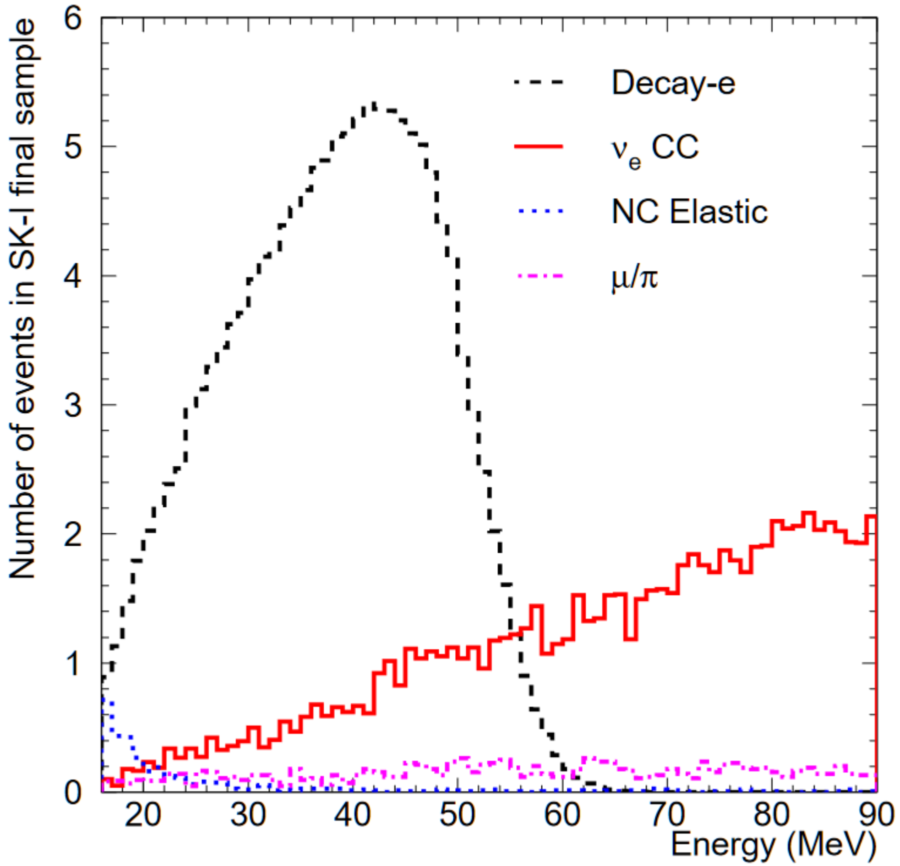
Pinpointing Time of Core-Collapse

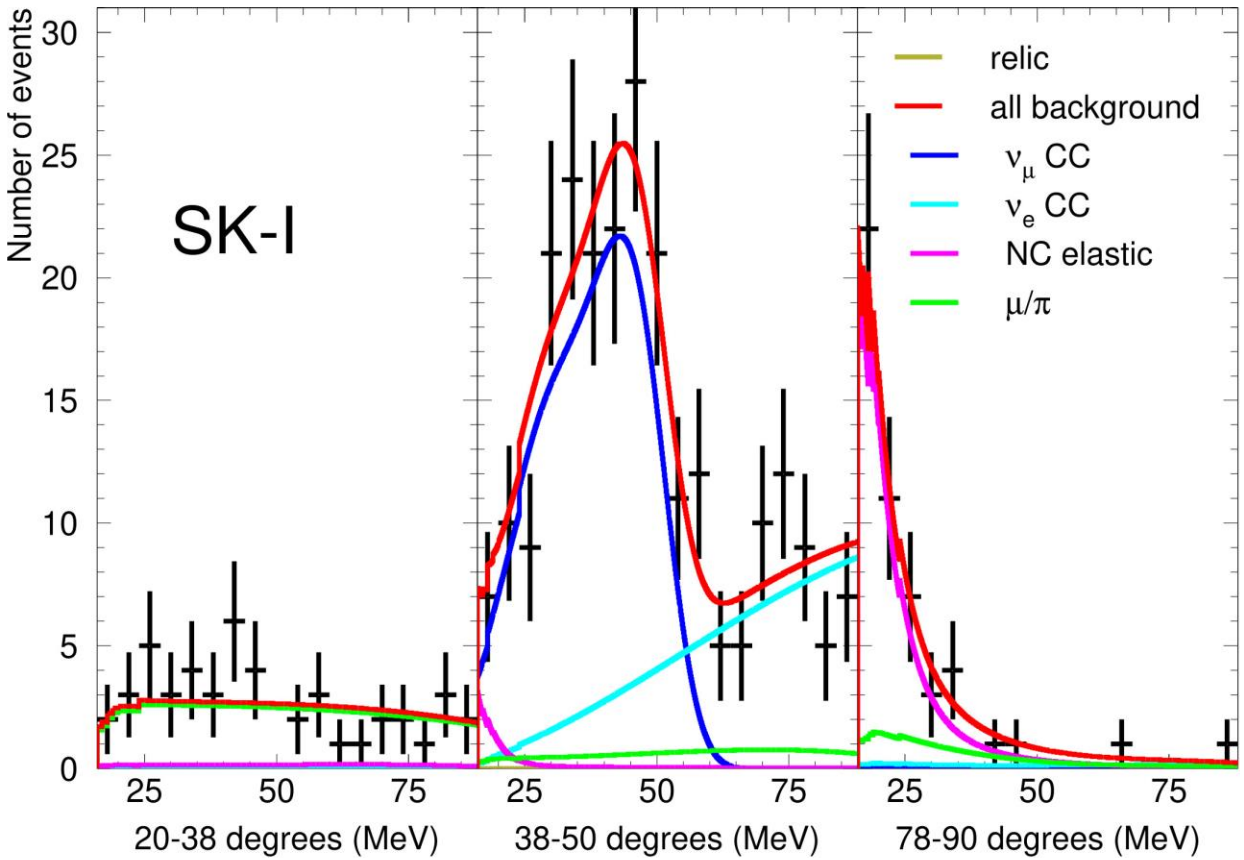
- Explosion time is estimated by fitting the SN light curves
- Assume an initial blackbody emission from shock breakout (red)
- This is followed by a phase dominated by the expansion of a luminous shell (black)



Cowen D., Franckowiak A., Kowalski M., 2010, Astroparticle Physics, 33, 19–23

More on Super-K Backgrounds





Super-Kamiokande Collaboration, 2012, Physical Review D, 85