Light Detection In Noble Elements (LIDINE) 2022

Prediction of supernova neutrino signals by detectors and its future challenges

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Contents of my talk

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Introduction

- Weakly interacting particles produced when a star reaches the end of its life, carrying away 99% of gravitational energy .
- The order of 10^{59} neutrinos and antineutrinos of all flavors are emitted.
- The current generation of detectors, like, Super-Kamiokande (Super-K), LVD, Borexino, KamLAND, and IceCube, as well as HALO, Daya Bay and NOvA, have ability to detect only a few orders of magnitude of events and the next generation, like, Hyper-Kamiokande (Hyper-K), DUNE, and JUNO will have yet another order of magnitude in reach, as well as richer flavor sensitivity.
- Study using the SNOwGLoBES package is carried out for the calculation of core-collapse neutrino event rates in realistic detectors for different flux models, effects of different parameters on flux and its variation with time

Why study these particles ?

- Relatively reliable messenger of the supernova mechanism
- Give information about the physical conditions at the center of core collapse, which would be otherwise inaccessible
- Future observations of supernova neutrinos will constrain the different theoretical models of core collapse and explosion mechanism
- Can provide early alarm to astronomers to prepare the telescope to capture light from the supernova
- Offer an opportunity to examine neutrino flavor mixing under high-density conditions
- Being sensitive to neutrino mass ordering and mass hierarchy, they can provide information about various neutrino properties

Properties of supernova neutrinos

- Supernova neutrinos are weakly interacting particles produced during core-collapse supernovae explosion releasing 99% of energy of a dying star in the form of neutrinos
- These type of neutrinos have energies of few MeVs ,typically 10-20 MeV
- Luminosity of all species of these neutrinos and anti-neutrinos is approximately same (~ 10^{52} erg s^{-1})
- Average energy is of the order 10 MeV
- Neutrino heating is predicted to be responsible for the supernova explosion
- The core-collapse events are the strongest and most frequent source of cosmic neutrinos in the MeV energy range

How are these produced ?

- Star at the end of its life → Onion like structure → ^{56}Fe core (no more fusion/ heat production)
- Core contracts → Temperature ↑ → photodissociation of Fe(absorbs energy) and electron capture rxn
- Pressure and no. of electron ↓ → Onset of core collapse (chandrasekhar limit reached)

$$e^- + p \rightarrow \nu_e + n$$ → prompt neutrinos neutron star

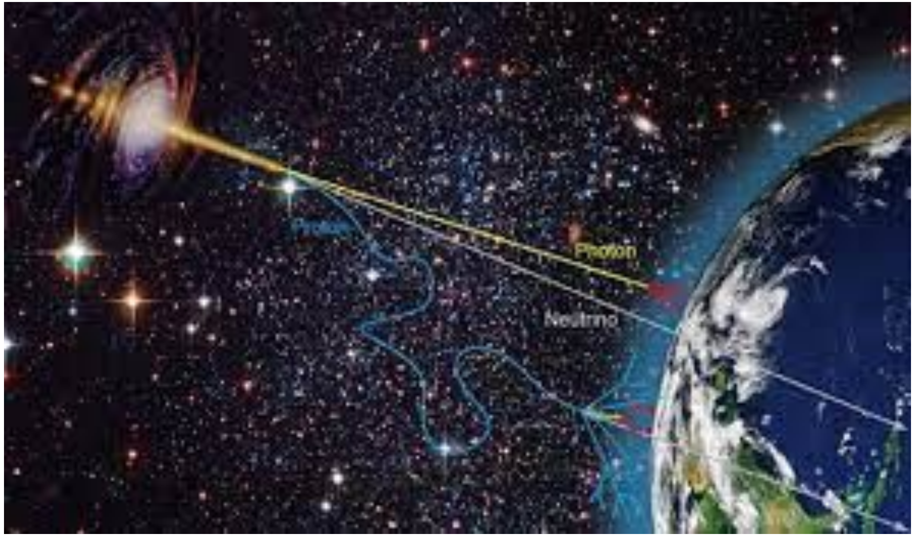
- Gravitational energy released in the form of neutrinos

How to detect ?

- Almost all methods involves the inverse beta decay reaction for the detection of neutrinos. The reaction is a charged current weak interaction,

$$\text{Anti -}\nu_e + p \longrightarrow n + e^+$$

- The positron retains most of the energy of the incoming neutrino producing a cone of Cherenkov light, which is detected by photomultiplier tubes (PMT's)
- With current detector sensitivities, it is expected that thousands of neutrino events from a galactic core-collapse supernova would be observed
- Large-scale detectors such as Hyper-Kamiokande or IceCube can detect up to 10^5 events
- SN1987A is the only supernova detected so far despite having rate of 1-3 per century
- So the next generation of underground experiments, like Hyper-Kamiokande, are designed to be sensitive to neutrinos from supernova explosions as far as Andromeda or beyond

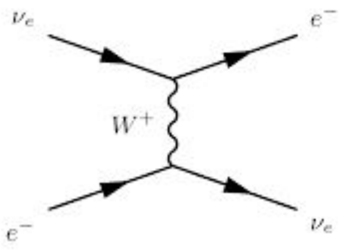


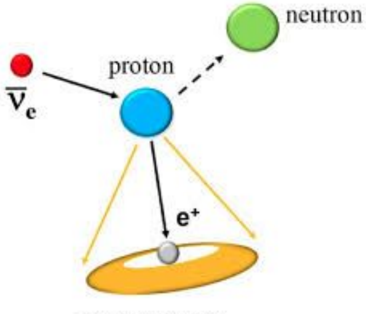
Neutrino interactions

Electrons

Nucleons

CC

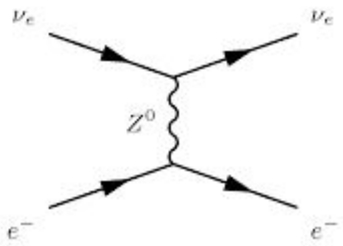


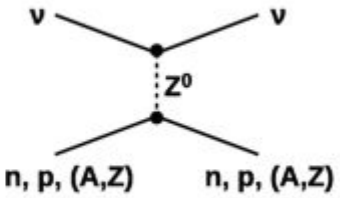


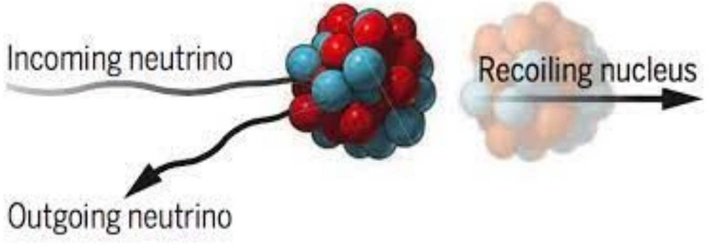
IBD

$$\nu_e +_Z X_N \rightarrow_{Z+1} X^*_{N-1} + e^-$$

NC





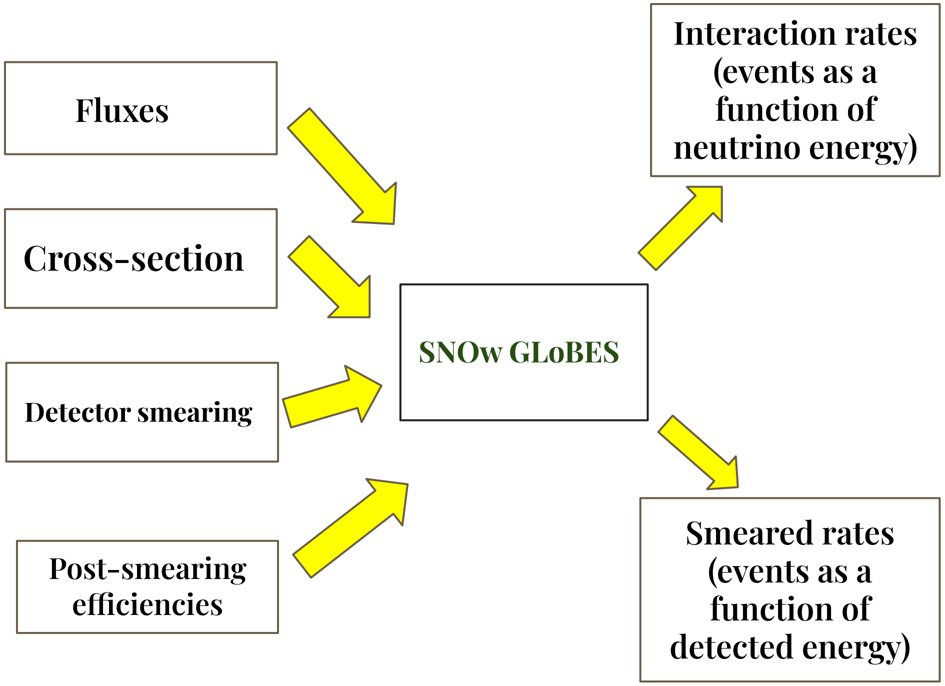


Elastic scattering

coherent elastic scattering

About SNOwGLoBES

- To enable fast, informative studies of the physics potential of the detection of supernova neutrinos, there has been developed a simple software and database package to compute expected event rates by folding input fluxes with cross-sections and detector parameters
- Evaluation of relative sensitivities of different detector configuration
- Input fluxes, cross sections, "smearing matrices" and post-smearing efficiencies
- The output is in the form of interaction rates for each channel as a function of neutrino energy, and "smeared" rates as a function of detected energy for each channel (i.e. the spectrum that actually be observed in a detector)



FLUX

- Livermore
  - 1-D numerical simulation
  - based on SN1987A
  - From onset of collapse till 18 seconds after core bounce
- Gvkm
  - 1st calculations with three flavors of collective and shock wave effects for neutrino propagation
  - Uses S matrix formalism, hydrodynamical density profiles
- Pinched

$$\phi(E_\nu) = \mathcal{N}\left(\frac{E_\nu}{\langle E_\nu\rangle}\right)^{\alpha} \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu\rangle}\right]$$

Eν= Neutrino energy

<Eν>= Mean neutrino energy (MeV)

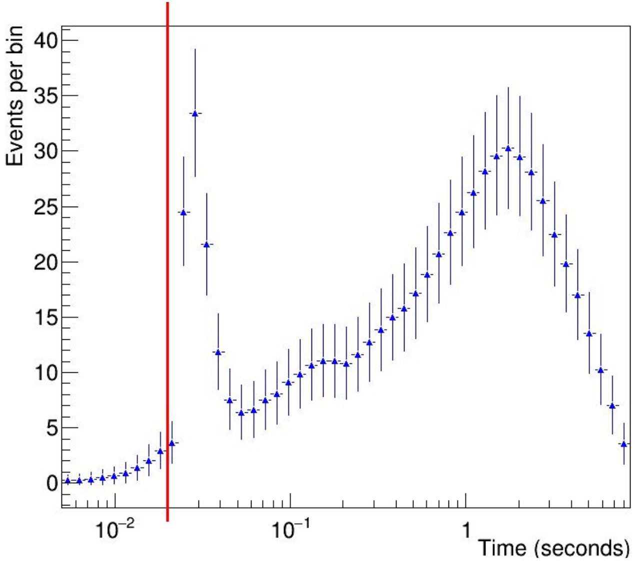
$\mathcal{N}$: Normalization constant (related to luminosity, ε, in ergs)

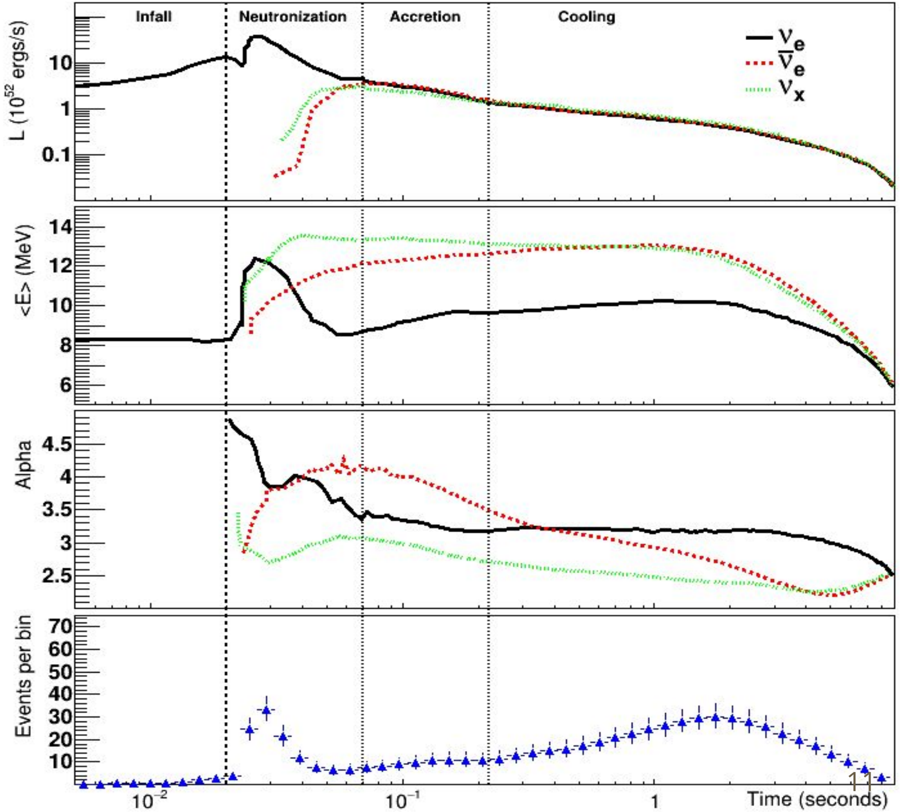
α: Pinching parameter; large α corresponds to more pinched spectrum

1. future Detection of Supernova Neutrino Burst and Explosion Mechanism by T. Totani, K. Sato, H. E. Dalhed, and J. R. Wilson
2. A dynamical collective calculation of supernova neutrino signals by J.Gava, J. Kneller, C. Volpe, G.C. McLaughlin
3. High-resolution supernova neutrino spectra represented by a simple t by Irene Tamborra, Bernhard Muller, Lorenz Hudepohl, Hans-Thomas Janka, and Georg Rafelt.

Garching parameterization

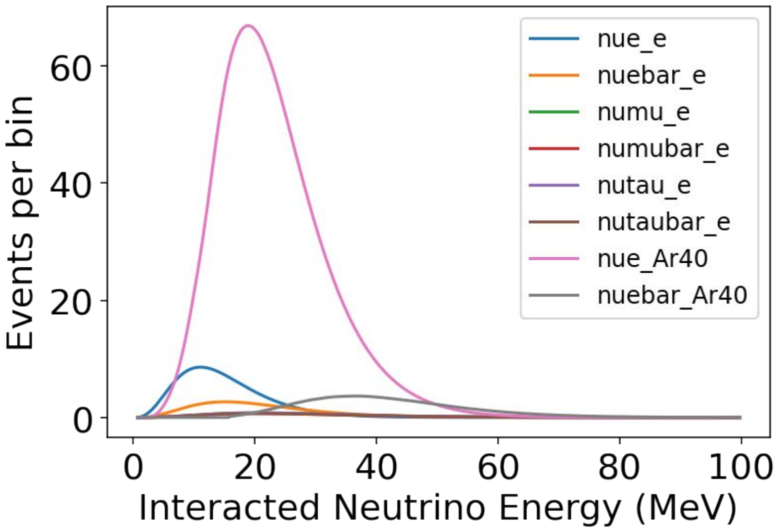
- Flux model that provides parameterization*
- Reproduce observable features

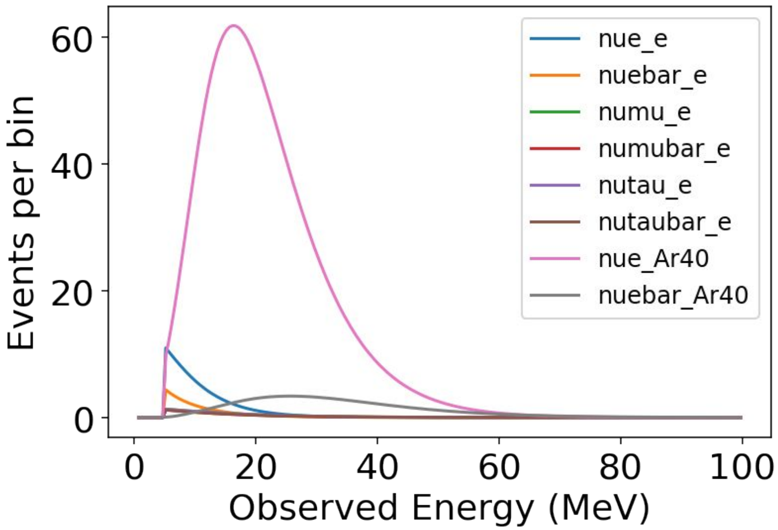




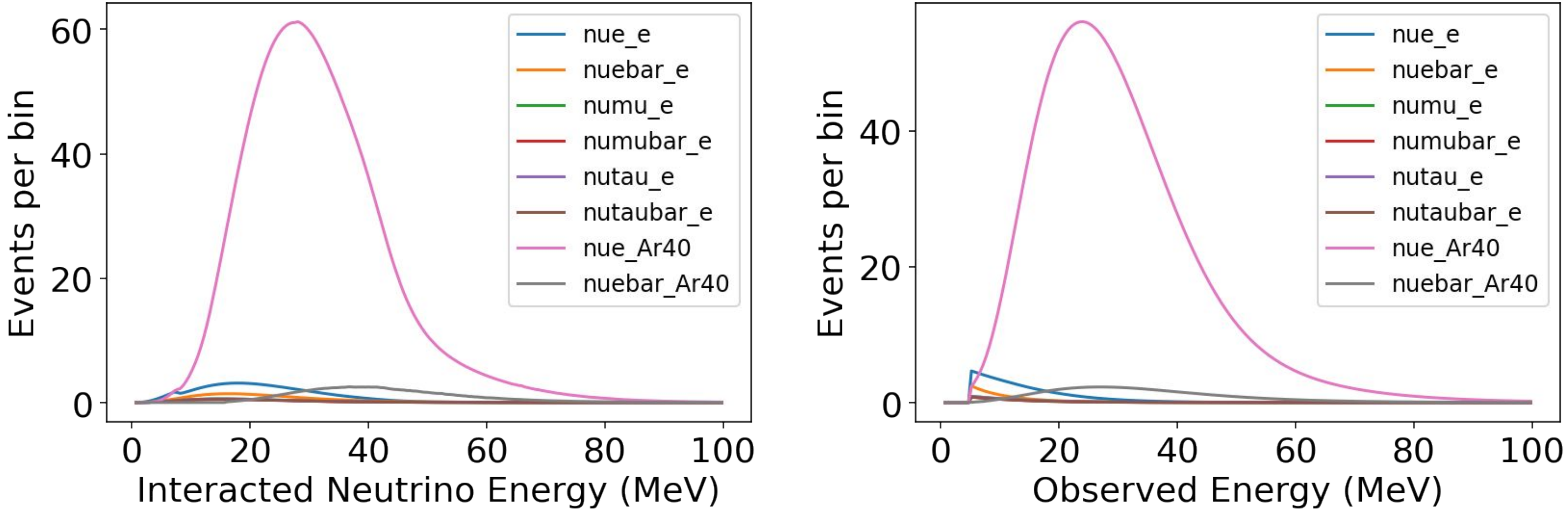
*High-resolution supernova neutrino spectra represented by a simple t by Irene Tamborra, Bernhard Muller, Lorenz Hudepohl, Hans-Thomas Janka, and Georg Rafelt.

Livermore flux (interacted and observed)





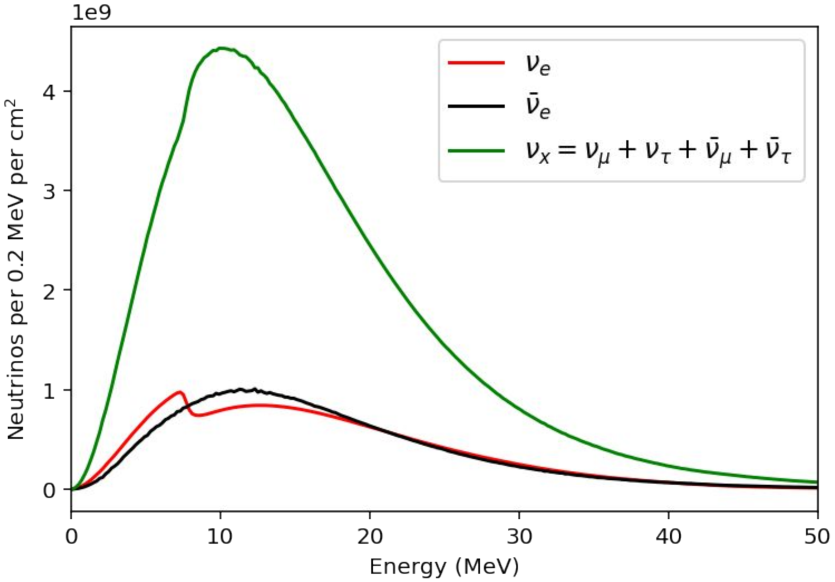
Gvkm flux (interacted and observed)



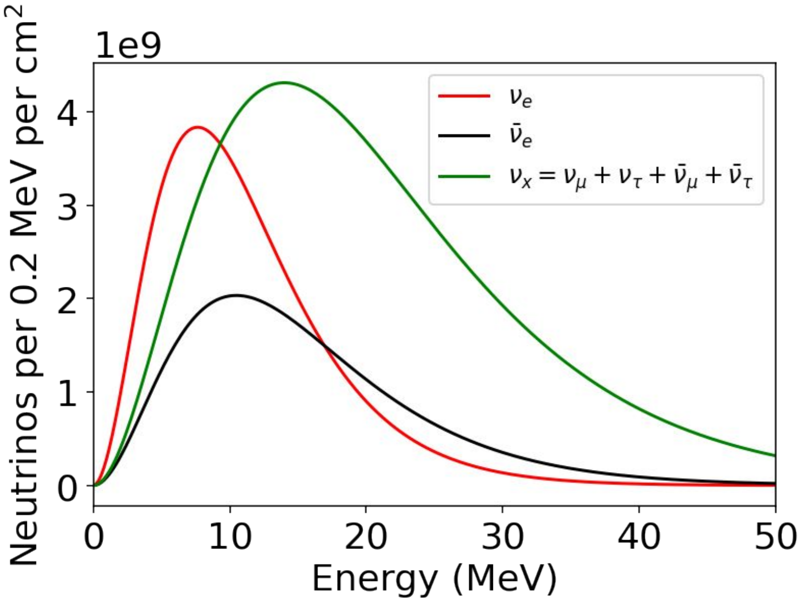
*10.1103/PhysRevLett.103.071101

Flux

GVKM

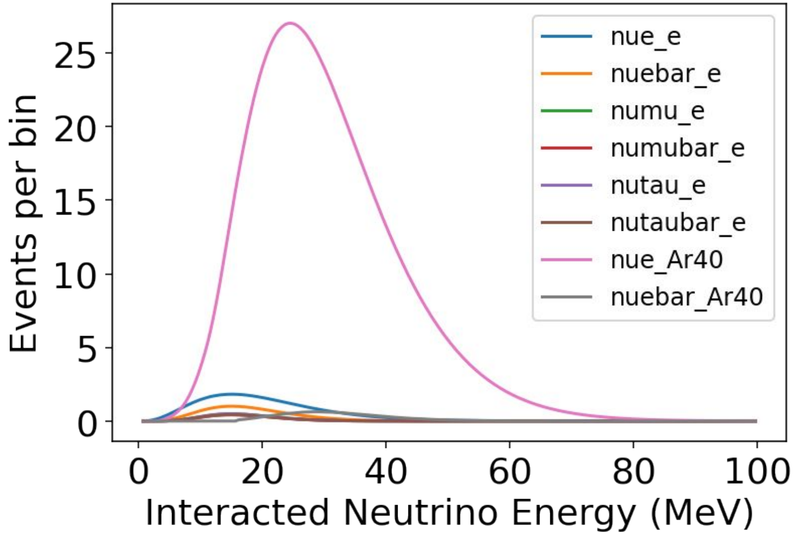


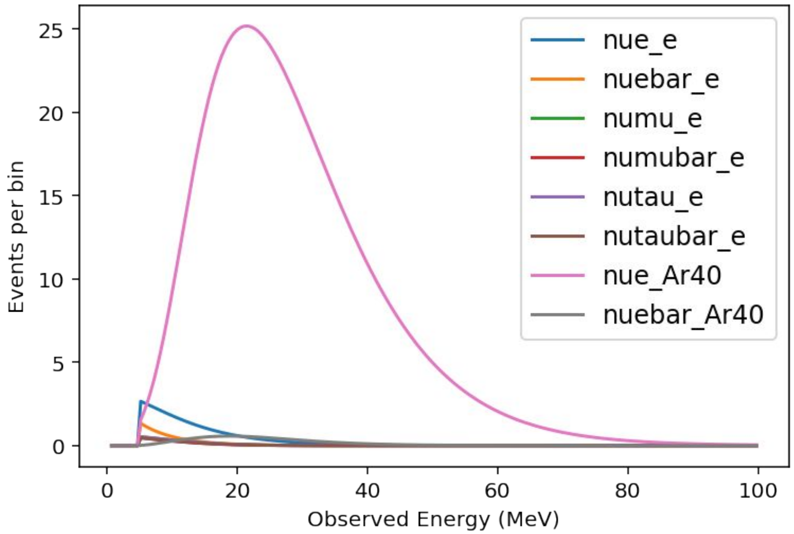
Livermore



Pinched flux (interacted and observed)

- Alpha , average energy , luminosity are three parameters being used for pinched flux and luminosity is assumed to be same for all flavors (5 x 10^{52} erg) while other two can be varied



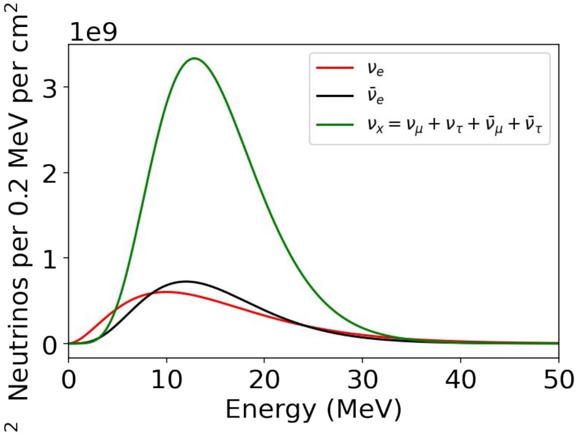


*Resso et al. , https://arxiv.org/abs/1712.05584

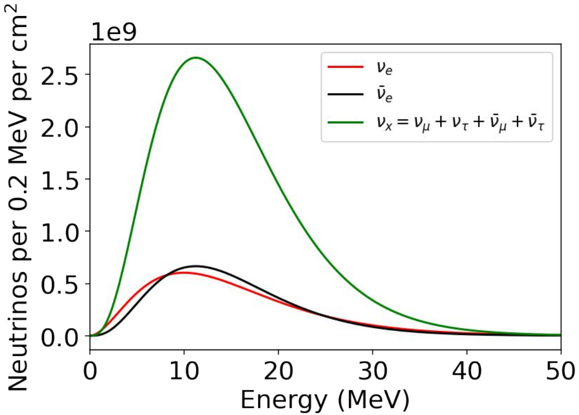
Effect of Pinching Parameter on Flux

<E> = 15 MeV

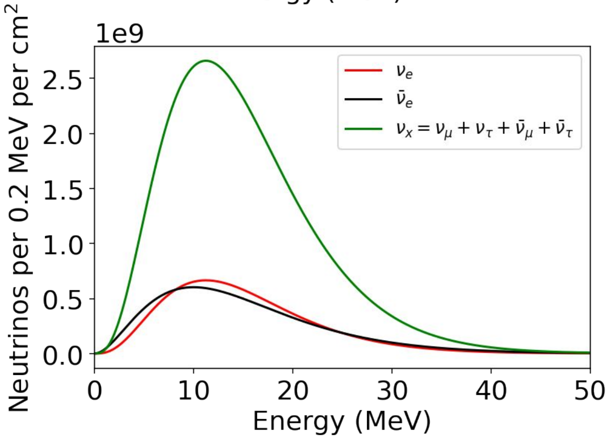
(α = 2 ,4 ,6)



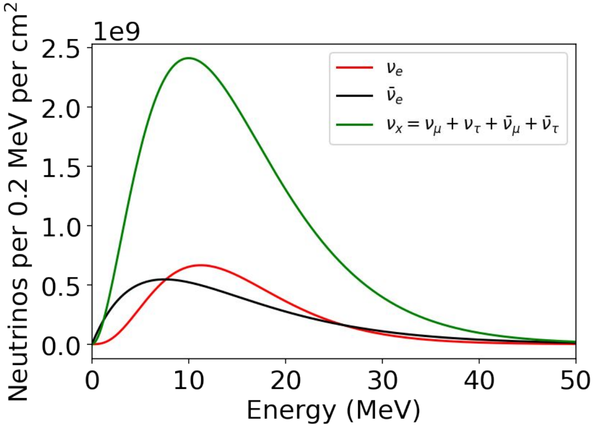
(α = 2,3,3)



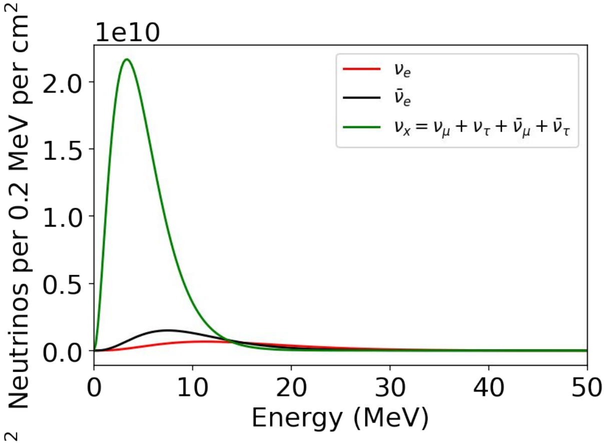
(α = 3,2,3)



(α =3,1,2)



Effect of Average Energy on Flux

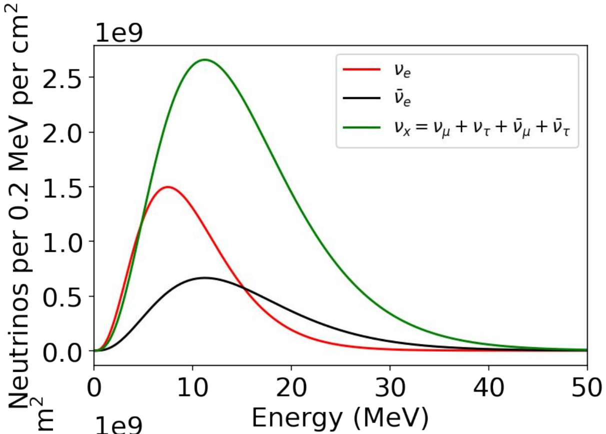


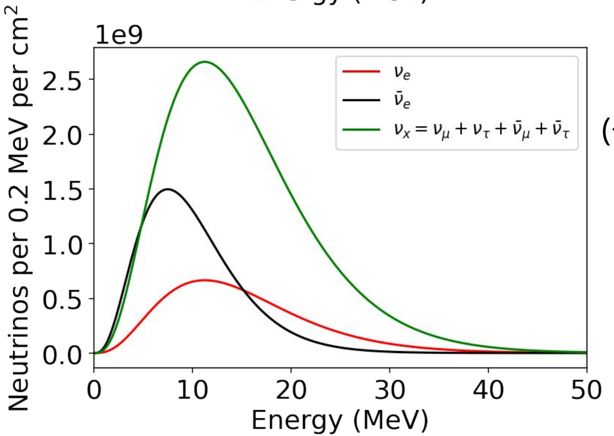
(<E> =15 ,10 , 5)

(α= 3,3,2)

(<E>=10 ,15 ,15)

(α=3,3,3)



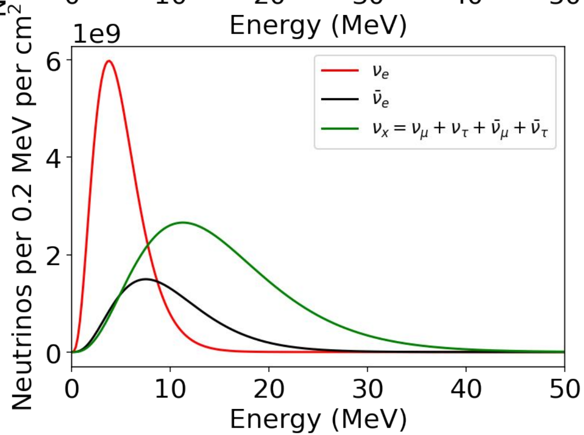


(<E>=15 , 10 ,15)

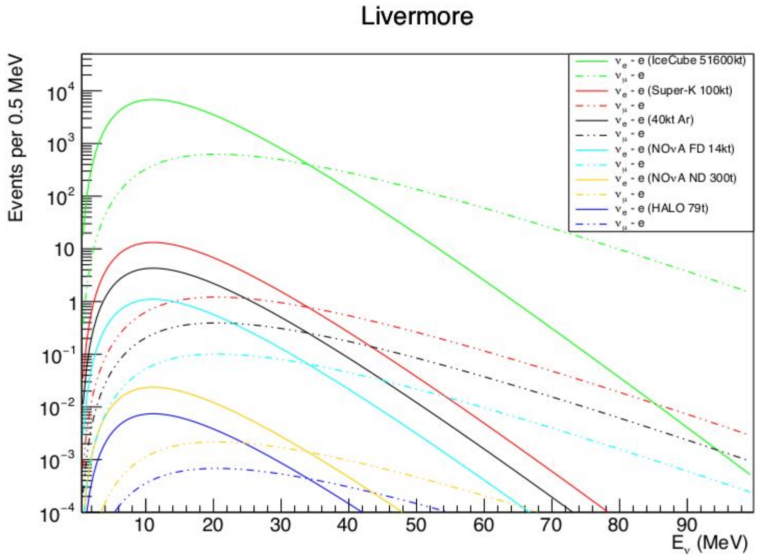
(α= 3,3,3)

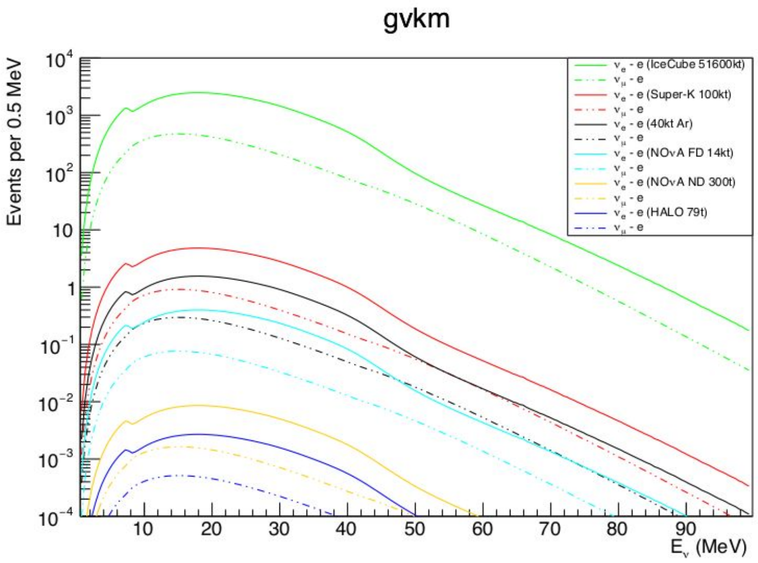
(<E>= 5 ,10 ,15)

(α=3,3,3)



Comparing event rates for two detectors





- We compare the event rates for a few detectors for Livermore and GVKM flux models
- When we see the $\nu_{\mu,e} - e$ events only, the event rates increase with size of detector.

Future aspects

- Detector parameters
  - Overall energy resolution
  - Energy loss due to background
  - Cross-section
    - modelling,
    - uncertainty,
    - shape systematics
  - Uncertainties in post-smearing efficiency in the model
  - Interaction channel identification

Conclusion

- **Different detectors being flavor sensitive give different neutrino signal , but electron flavor neutrinos are produced more than other flavors in a supernova explosion, so a detector which is sensitive to electron flavor is highly needed (e.g DUNE)**
- **Average energy has more effect on flux than pinching parameter**
- **SNOwGLoBES is a powerful tool that can help to better understand the physics of core collapse supernova and various neutrino properties using different flux parameterization , cross-section models and detector parameters !**

Thank you for listening

References

- http://www.phy.duke.edu/~schol/snowglobes.
- https://www.mpi-hd.mpg.de/personalhomes/globes/
- "Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment" https://arxiv.org/pdf/2008.06647.pdf
- Neutrino Signal of Electron-Capture Supernovae from Core Collapse to Cooling by L.Hüdepohl, B. Müller, H.-T. Janka, A. Marek, and G. G. Ra elt
- future Detection of Supernova Neutrino Burst and Explosion Mechanism by T. Totani, K. Sato, H. E. Dalhed, and J. R. Wilson
- A dynamical collective calculation of supernova neutrino signals by J.Gava, J. Kneller, C. Volpe, G.C. McLaughlin
- High-resolution supernova neutrino spectra represented by a simple t by Irene Tamborra, Bernhard Muller, Lorenz Hudepohl, Hans-Thomas Janka, and Georg Rafelt.
- Flux true parameters , Resso et al. , https://arxiv.org/abs/1712.05584

Backup slides

Flux parameters

- Alpha , average energy , luminosity for electron neutrino ,antineutrino and all other flavors respectively
- Alpha is dimensionless , energies are in MeV , and luminosity is in erg.

0	2	4	6	15	15	15	1.6e52	1.6e52	1.6e52
1	2	3	3	15	15	15	1.6e52	1.6e52	1.6e52
2	3	2	3	15	15	15	1.6e52	1.6e52	1.6e52
3	3	1	2	15	15	15	1.6e52	1.6e52	1.6e52
4	3	3	2	15	10	5	1.6e52	1.6e52	1.6e52
5	3	3	3	10	15	15	1.6e52	1.6e52	1.6e52
6	3	3	3	15	10	15	1.6e52	1.6e52	1.6e52
7	3	3	3	5	10	15	1.6e52	1.6e52	1.6e52

SNOwGLoBES flux

Flux in SNOwGLoBES is calculated using ,

$$F(E_\nu) = \frac{1}{4\pi d^2}\frac{\varepsilon}{\langle E_\nu \rangle}\phi(E_\nu, \langle E_\nu \rangle, \alpha)\times(\text{binning factor})$$

Where $\phi(E_\nu, <E_\nu>, \alpha)$ is defined by,

$$\phi(E_\nu, \langle E_\nu \rangle, \alpha) = N\left(\frac{E_\nu}{\langle E_\nu \rangle}\right)^\alpha \exp\left[-(\alpha+1)\frac{E_\nu}{\langle E_\nu \rangle}\right]$$

Where N is given by

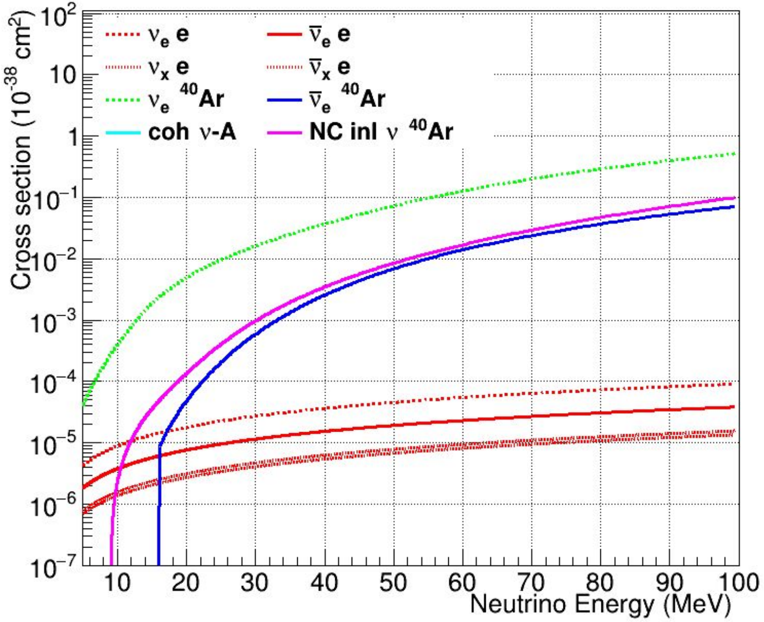
$$N = \frac{(\alpha+1)^{\alpha+1}}{\langle E_\nu \rangle\, \alpha!}$$

Parameter fit algorithm

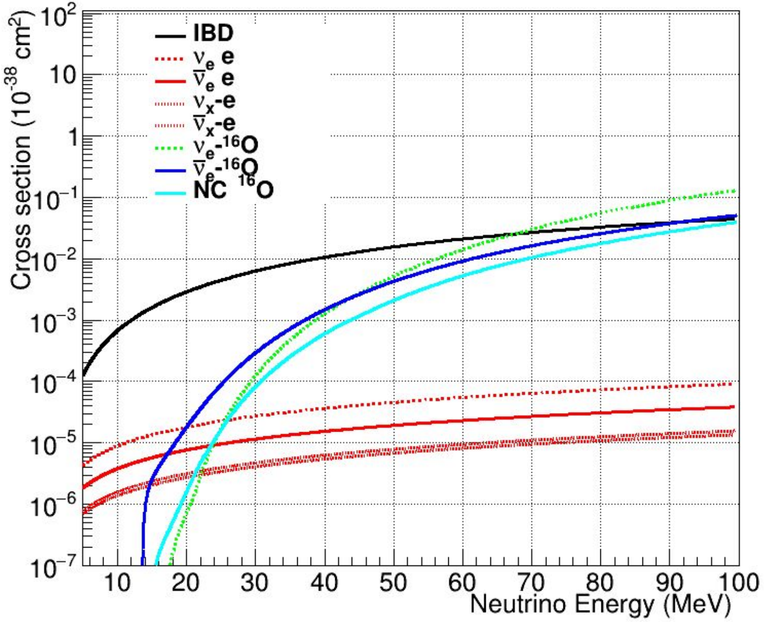
- These parameter define the time dependent fluxes for the analysis
- Using true values spectrum and grid spectrum by simulating different models , one can put constraints on the parameters for better reconstruction of signal by detector

	ν_e	$\bar{\nu}_e$	ν_x
$\mathcal{E}_i^*$ [10^{53} erg]	$0.5 \in [0.2,\ 1]$	$0.5 \in [0.2,\ 1]$	$0.5 \in [0.2,\ 1]$
$\langle E_i^* \rangle$ [MeV]	$9.5 \in [5,\ 30]$	$12 \in [5,\ 30]$	$15.6 \in [5,\ 30]$
α_i^*	$2.5 \in [1.5,\ 3.5]$	$2.5 \in [1.5,\ 3.5]$	$2.5 \in [1.5,\ 3.5]$
κ^*		$1 \in [0.8,\ 1.2]$	

Cross-section graphs



"argon "



"water"

Cross-section models used in SNOwGLoBES

- Neutrino-nucleon scattering model for IBD
- neutrino -electron scattering for elastic scattering
- CRPA model for interaction of neutrino with oxygen
- RPA model for CC interaction with carbon
- χ^2 method for interaction with argon