INSTITUTO PRINCIPIA

ICTP SAIFR
International Centre for Theoretical Physics
South American Institute for Fundamental Research

NUINT 2024 –
14th INTERNATIONAL WORKSHOP ON NEUTRINO-NUCLEUS INTERACTIONS

April 15-20, 2024
at Principia Institute - São Paulo, Brazil

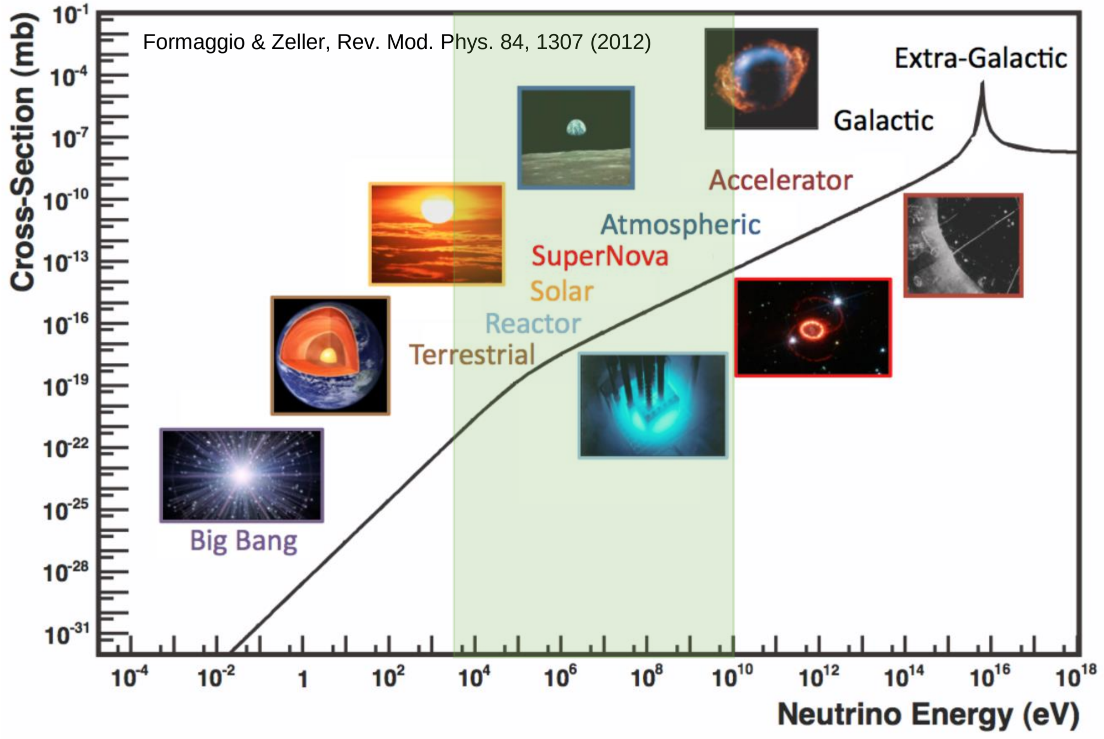
Characterization of neutral-current background induced by atmospheric neutrinos using neutrino generators and TALYS deexcitation package

Jie Cheng

North China Electric Power University

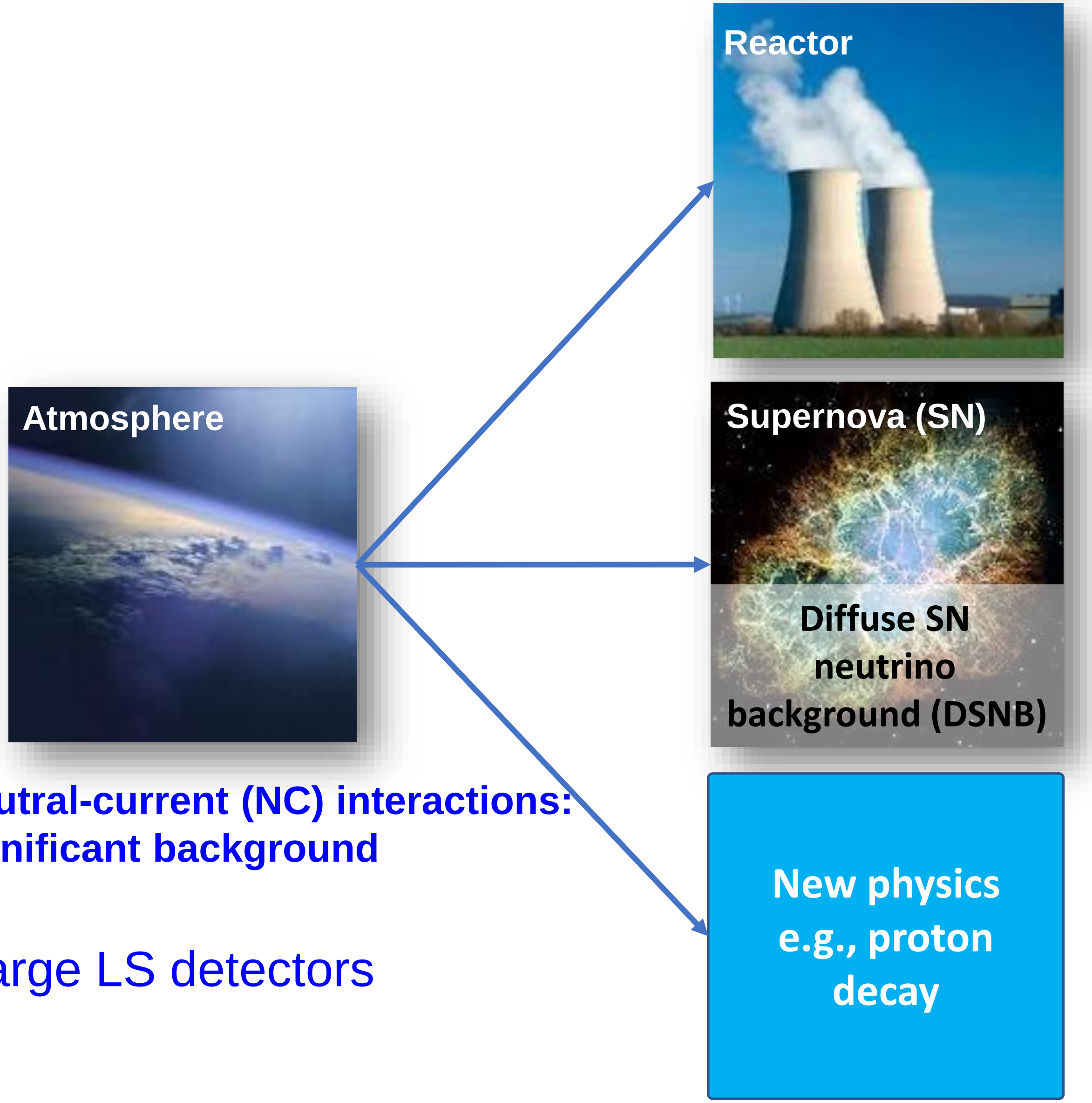
chengjie@ncepu.edu.cn

Atmospheric Neutrinos



Atmospheric neutrinos

- ☐ Signals for neutrino oscillation
- ☐ Background to rare event searches



Diffuse SN neutrino background (DSNB)

New physics e.g., proton decay

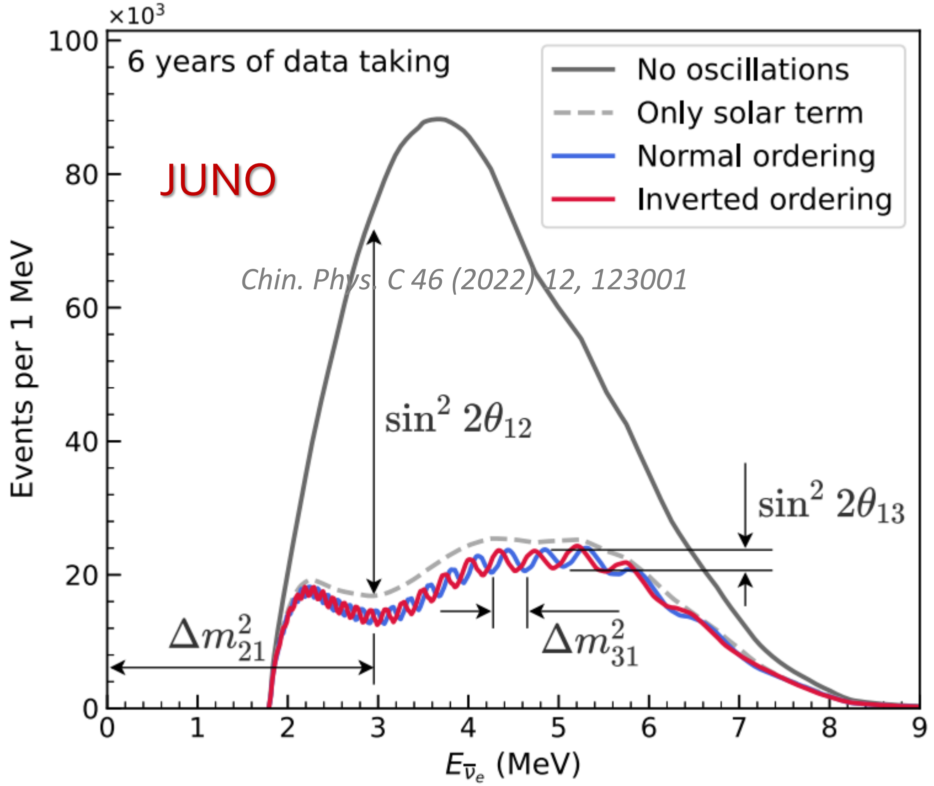
Neutral-current (NC) interactions: significant background

- ■ This talk focuses on the NC background in large LS detectors
- ■ Take the JUNO detector as the reference

Reactor $\bar{\nu}_e$

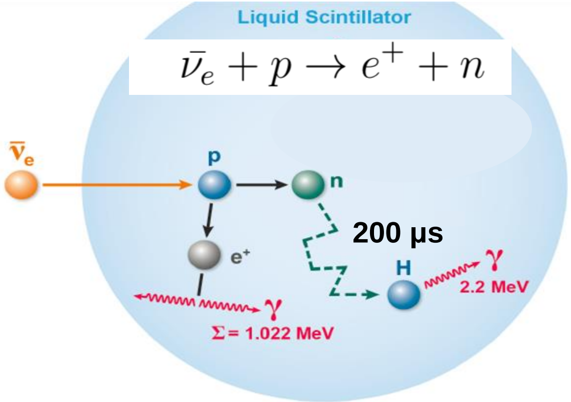
► Neutrino oscillation & properties

$$P_{\bar{\nu}_e\to\bar{\nu}_e} = 1 - \sin^2 2\theta_{13}(\cos^2\theta_{12}\sin^2\Delta_{31} + \sin^2\theta_{12}\sin^2\Delta_{32}) - \cos^4\theta_{13}\sin^2 2\theta_{12}\sin^2\Delta_{21}, \quad \boxed{\Delta_{ij} \equiv \Delta m^2_{ij} L/(4E)}$$



Chin. Phys. C 46 (2022) 12, 123001

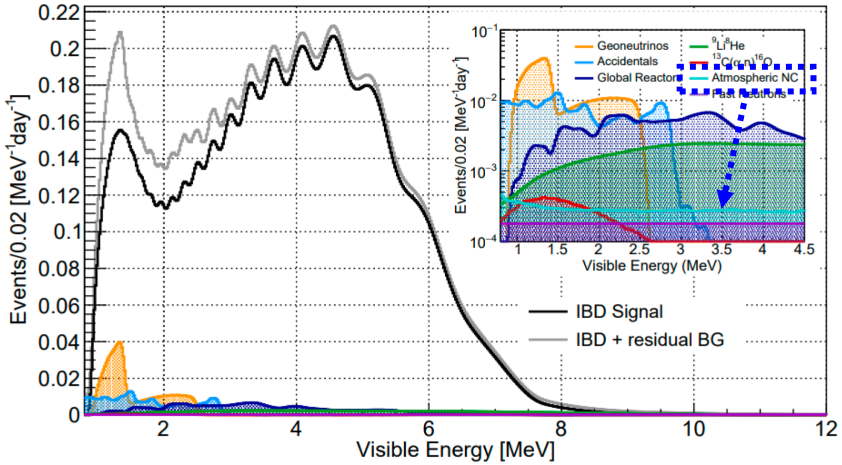
Detection via inverse beta decay (IBD):



- The double coincidence➔ suppression of background

JUNO, Chin. Phys. C 46 (2022) 12, 123001

Expected signal and background:



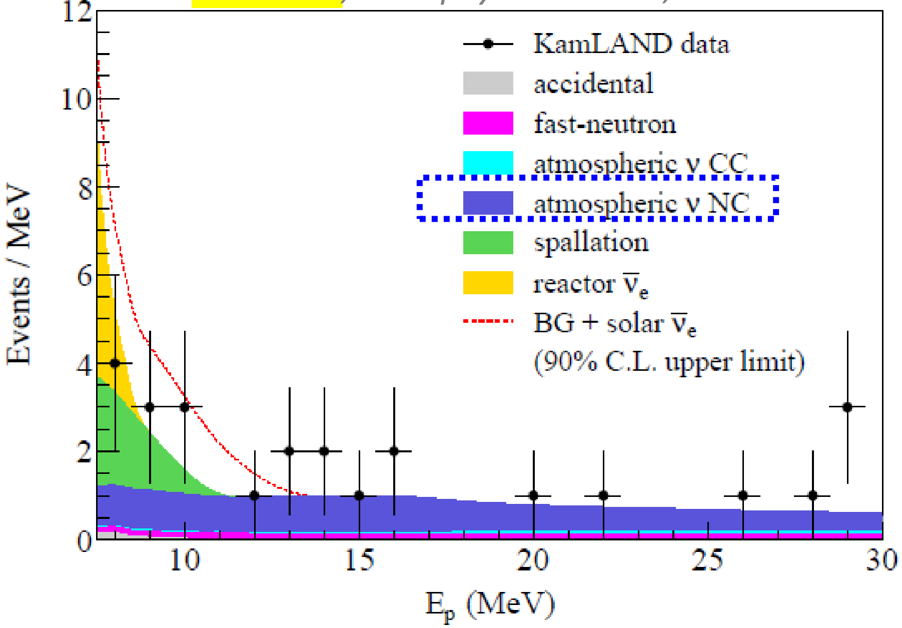
☐ Atmospheric NC➔ non-negligible background for precise measurement

DSNB Research: Signal v.s. Background

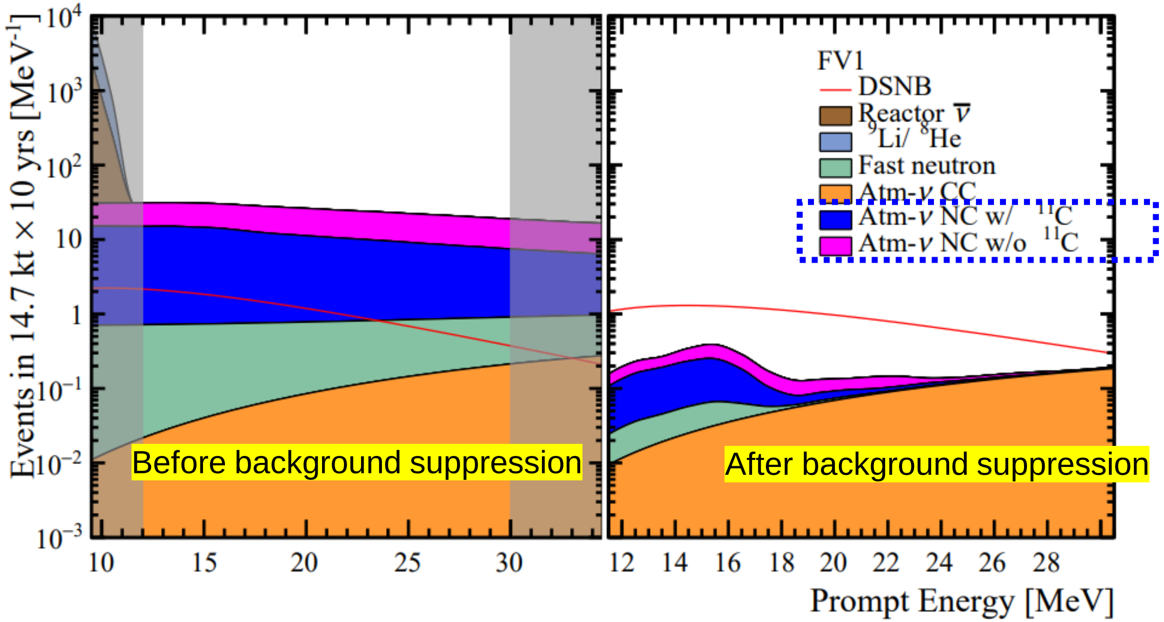
Integrated flux of all past SNe:

- ► cosmic star-information, average core-collapse neutrino spectrum, failed SNe rate, etc
- ► DSNB primary detection via IBD

KamLAND, Astrophys.J.745:193,2012



JUNO, JCAP 10 (2022) 033



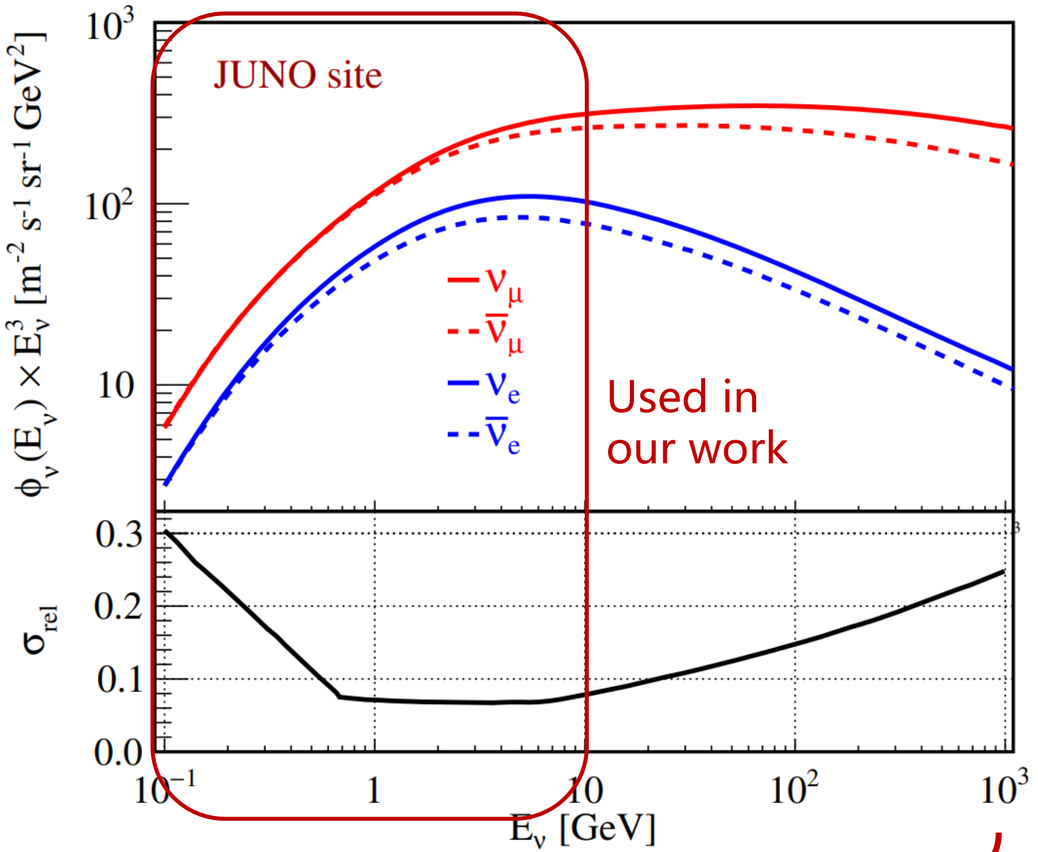
☐**KamLAND:** **NC interactions of atm. neutrino with ^{12}C in LS is the most significant source of the background in DSNB study.**

☐**JUNO:** **dominant background for DSNB is atm-ν NC interactions**

The key to detect DSNB in LS detector is the precise estimation of atm-ν NC background

Atmospheric Neutrino Flux

- ☐ **Atmospheric neutrino sources:** interactions of cosmic rays with nuclei in Earth's atmosphere, in the presence of geomagnetic field effect
- ☐ Initial fluxes of atmospheric neutrino calculated by Honda-san based on *Phys. Rev. D 92, 023004 (2015)*



Used in our work

$$\boxed{N_{det}} = \phi \otimes P \otimes \sigma \otimes \epsilon$$

Atm-ν measurement

Neutrino flux

Oscillation probability

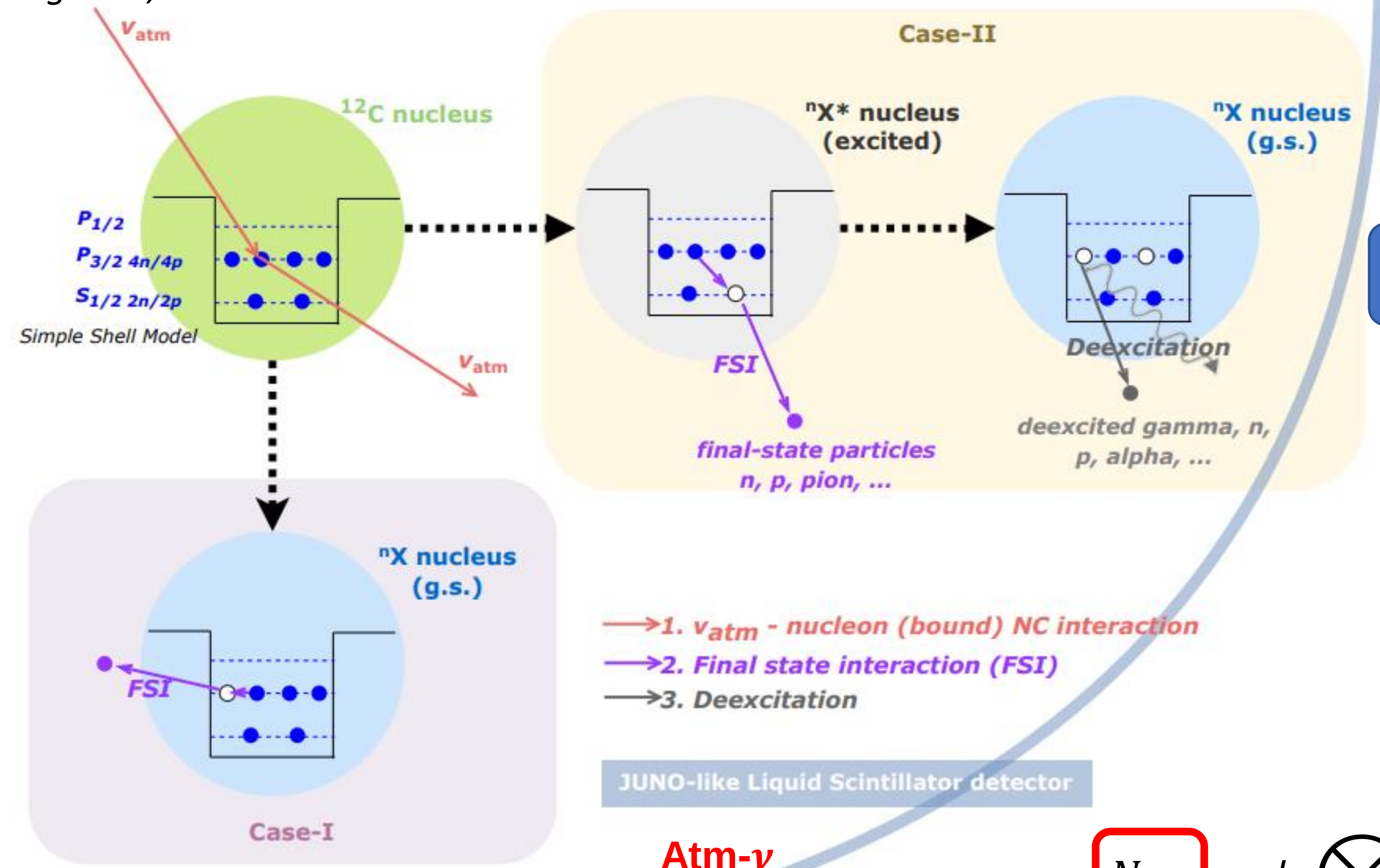
Cross section of $\nu_x + {}^{12}\mathrm{C}$

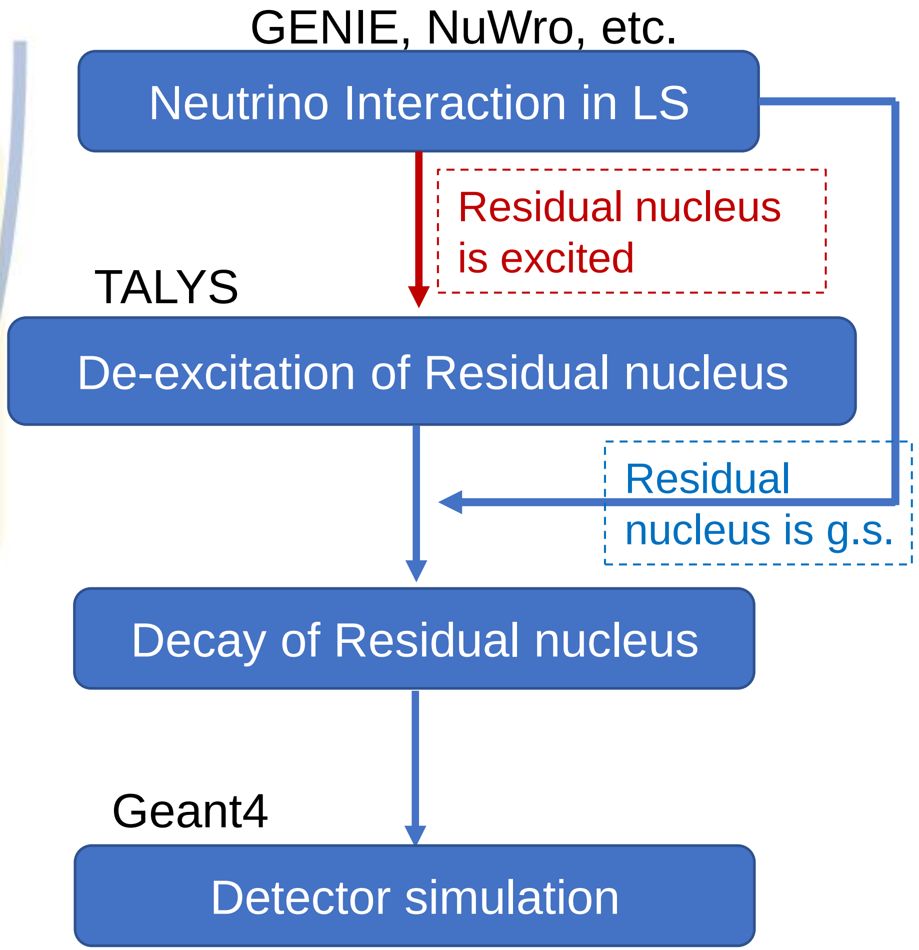
Detector efficiency

Methodology for Atm-ν and ^{12}C NC Interaction Prediction

Cheng et al, Phys. Rev. D 103. 05001 (2021)

Cheng et al, arXiv 2404.07429





GENIE, NuWro, etc.

Neutrino Interaction in LS

Residual nucleus is excited

TALYS

De-excitation of Residual nucleus

Residual nucleus is g.s.

Decay of Residual nucleus

Geant4

Detector simulation

Atm-ν measurement

$$\boxed{N_{det}} = \phi \otimes P \otimes \sigma \otimes \epsilon$$

Neutrino flux

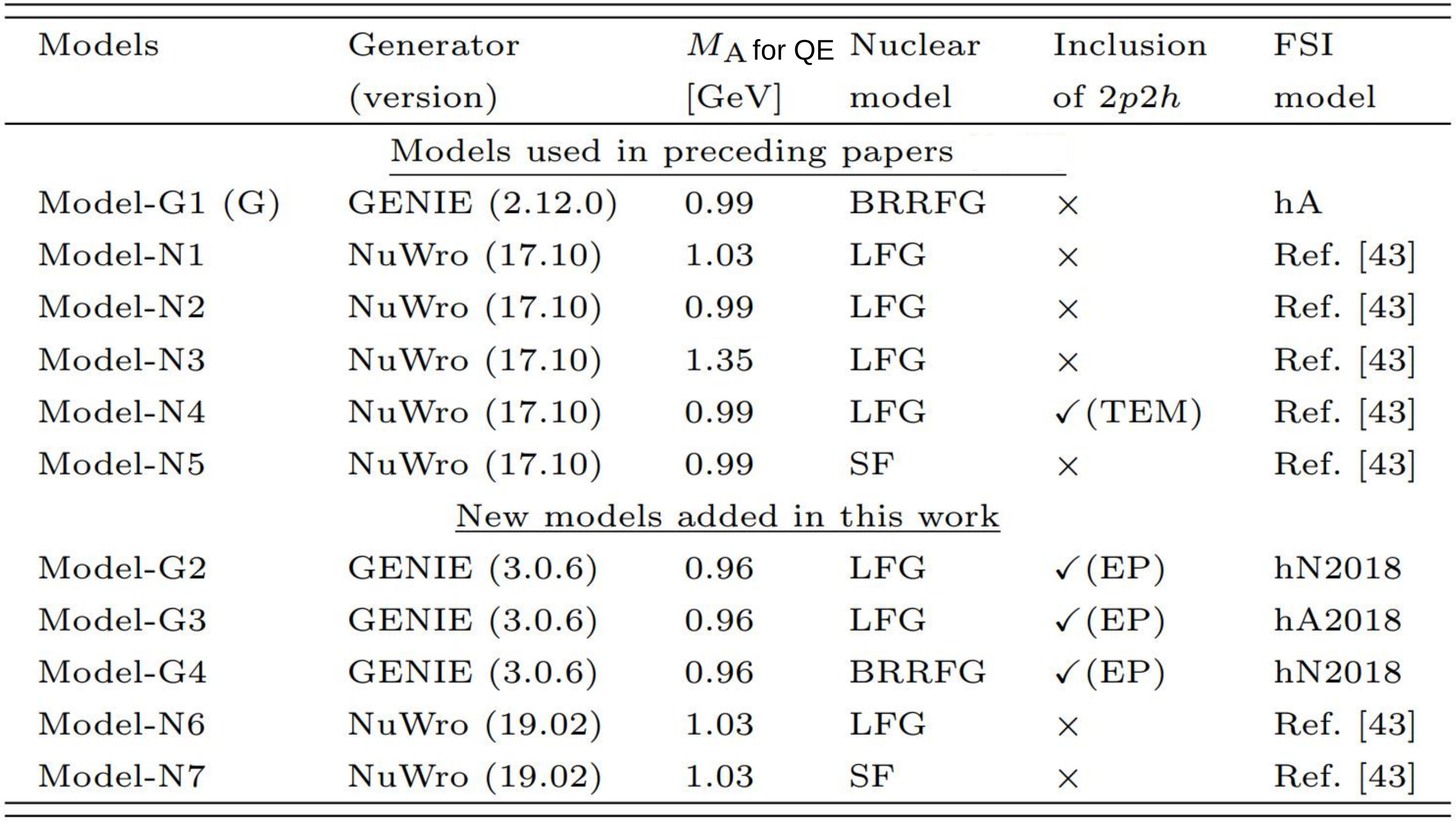
Oscillation probability

Cross section of $\nu_x + {}^{12}C$

Detector efficiency

Neutrino Generator Models

Summary of the main features of models used in early and recent stages



Models	Generator (version)	M_A for QE [GeV]	Nuclear model	Inclusion of $2p2h$	FSI model
Models used in preceding papers					
Model-G1 (G)	GENIE (2.12.0)	0.99	BRRFG	×	hA
Model-N1	NuWro (17.10)	1.03	LFG	×	Ref. [43]
Model-N2	NuWro (17.10)	0.99	LFG	×	Ref. [43]
Model-N3	NuWro (17.10)	1.35	LFG	×	Ref. [43]
Model-N4	NuWro (17.10)	0.99	LFG	✓(TEM)	Ref. [43]
Model-N5	NuWro (17.10)	0.99	SF	×	Ref. [43]
New models added in this work					
Model-G2	GENIE (3.0.6)	0.96	LFG	✓(EP)	hN2018
Model-G3	GENIE (3.0.6)	0.96	LFG	✓(EP)	hA2018
Model-G4	GENIE (3.0.6)	0.96	BRRFG	✓(EP)	hN2018
Model-N6	NuWro (19.02)	1.03	LFG	×	Ref. [43]
Model-N7	NuWro (19.02)	1.03	SF	×	Ref. [43]

BRRFG: relativistic Fermi gas model with "Bodek-Ritchie" modifications

LFG: local Fermi gas model

SF: spectral function

0.99 GeV: deuterium measurements

1.35 GeV: MiniBooNE neutrino QE data

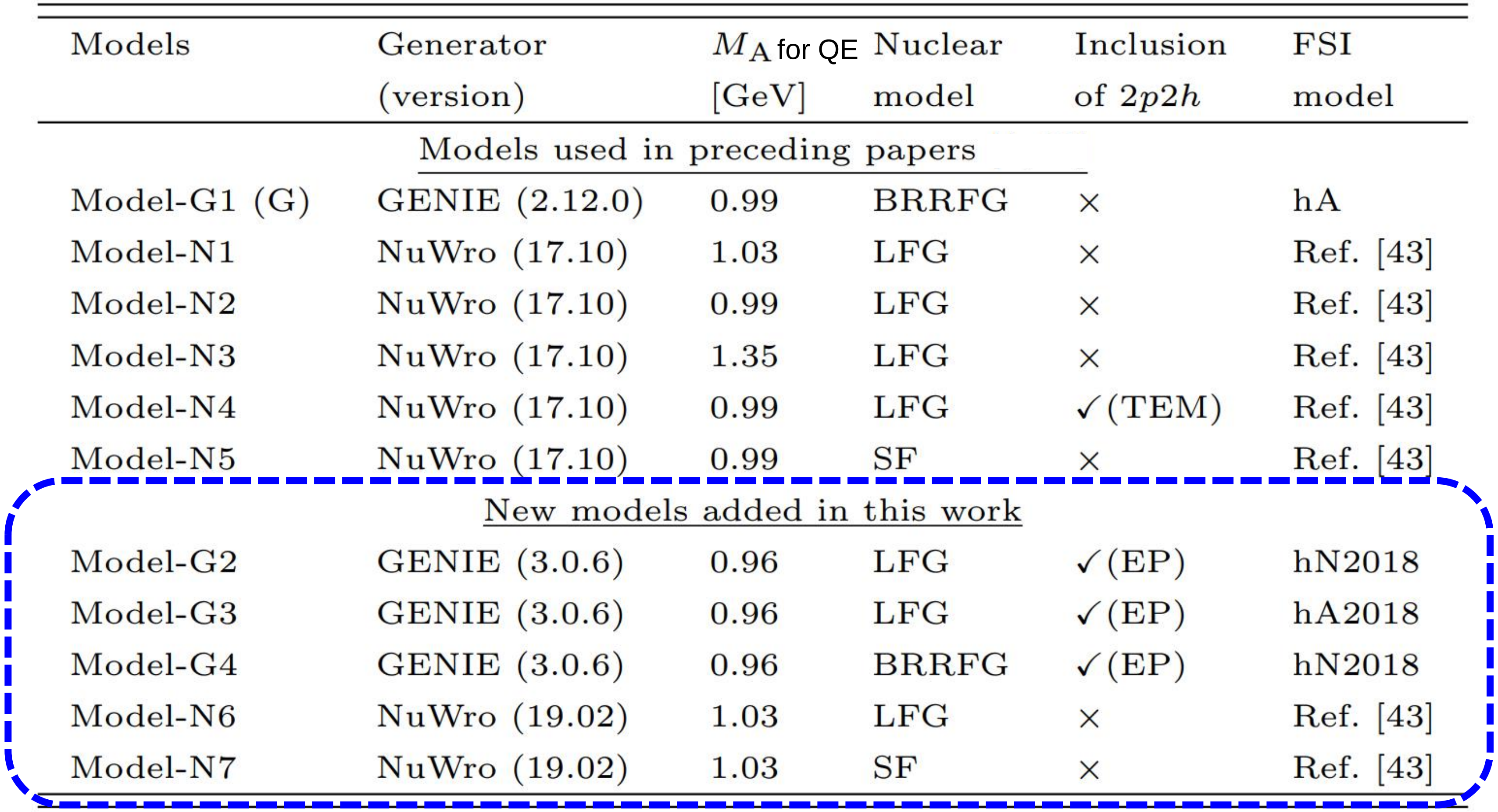
TEM: Transverse Enhancement model for *2p2h*

EP: Empirical model for *2p2h*

Ref.[43]: Phys. Rev. D 79, 053003 (2009)

Neutrino Generator Models

Summary of the main features of models used in early and recent stages



Models	Generator (version)	M_A for QE [GeV]	Nuclear model	Inclusion of $2p2h$	FSI model
	Models used in preceding papers				
Model-G1 (G)	GENIE (2.12.0)	0.99	BRRFG	×	hA
Model-N1	NuWro (17.10)	1.03	LFG	×	Ref. [43]
Model-N2	NuWro (17.10)	0.99	LFG	×	Ref. [43]
Model-N3	NuWro (17.10)	1.35	LFG	×	Ref. [43]
Model-N4	NuWro (17.10)	0.99	LFG	✓(TEM)	Ref. [43]
Model-N5	NuWro (17.10)	0.99	SF	×	Ref. [43]
	New models added in this work				
Model-G2	GENIE (3.0.6)	0.96	LFG	✓(EP)	hN2018
Model-G3	GENIE (3.0.6)	0.96	LFG	✓(EP)	hA2018
Model-G4	GENIE (3.0.6)	0.96	BRRFG	✓(EP)	hN2018
Model-N6	NuWro (19.02)	1.03	LFG	×	Ref. [43]
Model-N7	NuWro (19.02)	1.03	SF	×	Ref. [43]

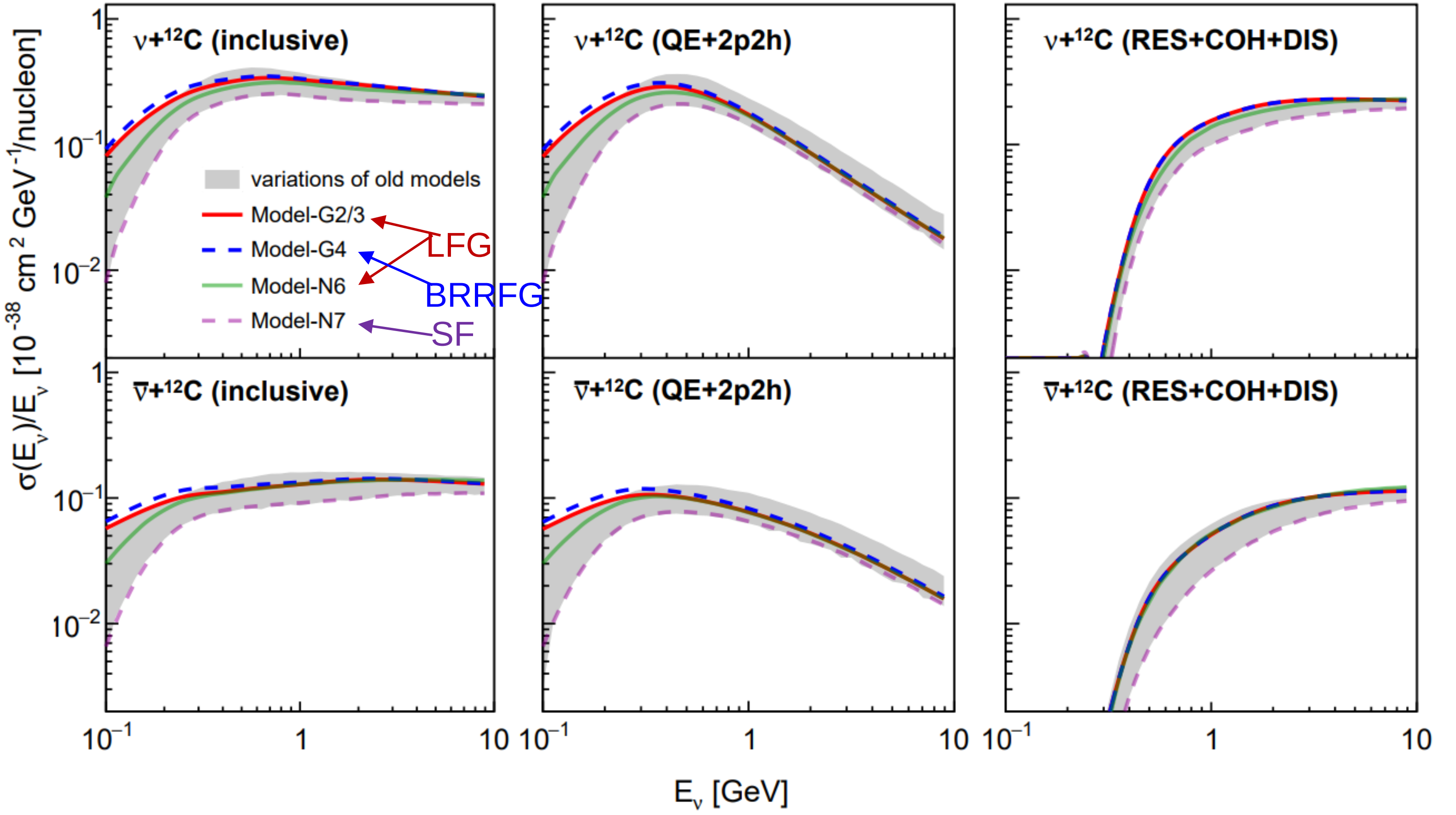
Validated with MINERvA data

https://zenodo.org/records/6774990

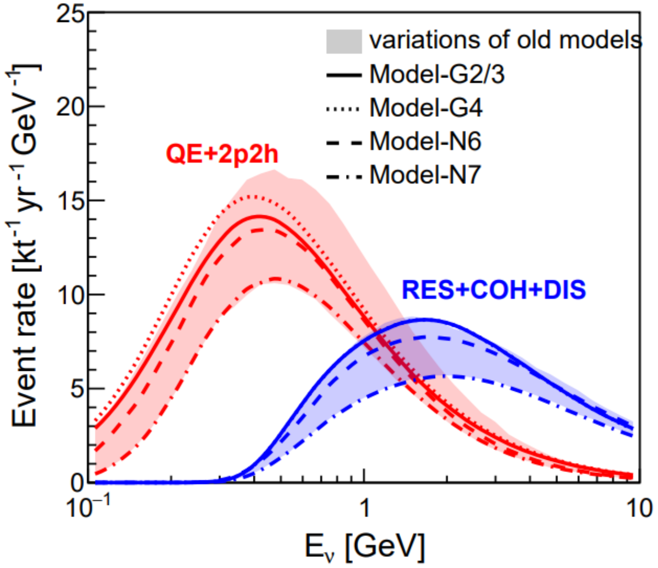
- Investigate the impact of different generators, nuclear model, FSI models on the NC bkg prediction

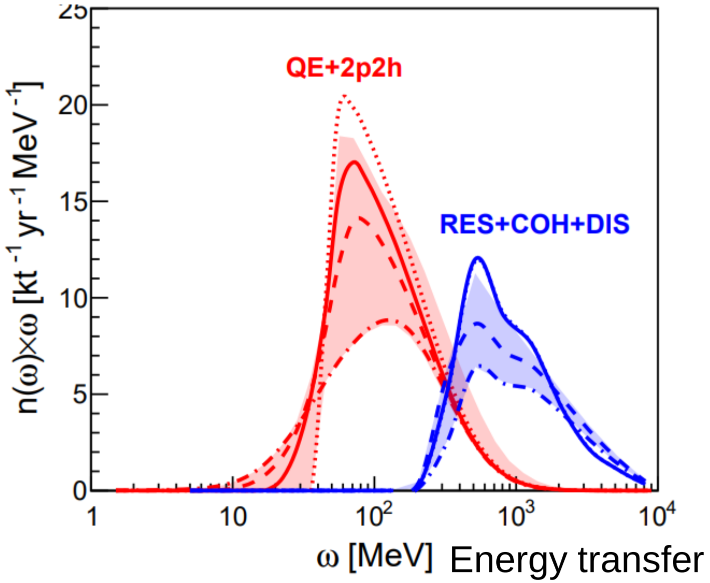
- All processes are included, new models primarily focus on variations related to QE and do not fully explore variations related to RES, COH, and DIS
- Plan to include GiBUU and NEUT in our calculation

Cross-section and Event Rate



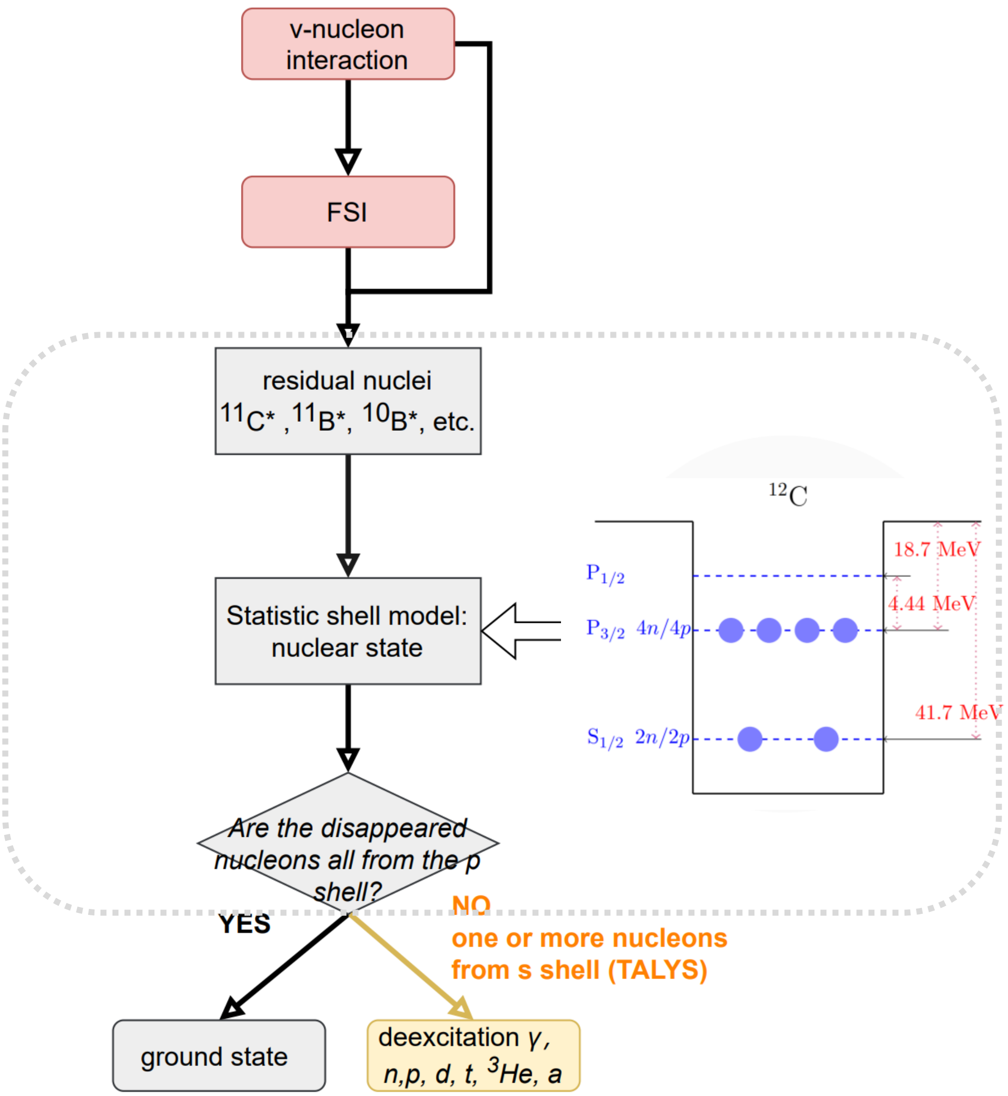
Cheng et al, arXiv 2404.07429





- Model variations regarding the initial interactions: a systematic uncertainty
- QE and *2p2h* events: ~99% of the NC background in the searches for IBD signals below 100 MeV visible energy
- The following final-state investigations of the NC interactions focus on QE and *2p2h*

TALYS-based Deexcitation Model of Residual Nucleus



v-nucleon interaction

FSI

residual nuclei $^{11}C^*$, $^{11}B^*$, $^{10}B^*$, etc.

Statistic shell model: nuclear state

Are the disappeared nucleons all from the p shell?

YES

NO one or more nucleons from s shell (TALYS)

ground state

deexcitation γ, *n,p, d, t, ^{3}He, a*

1. Simple shell model → Status of the residual nuclei

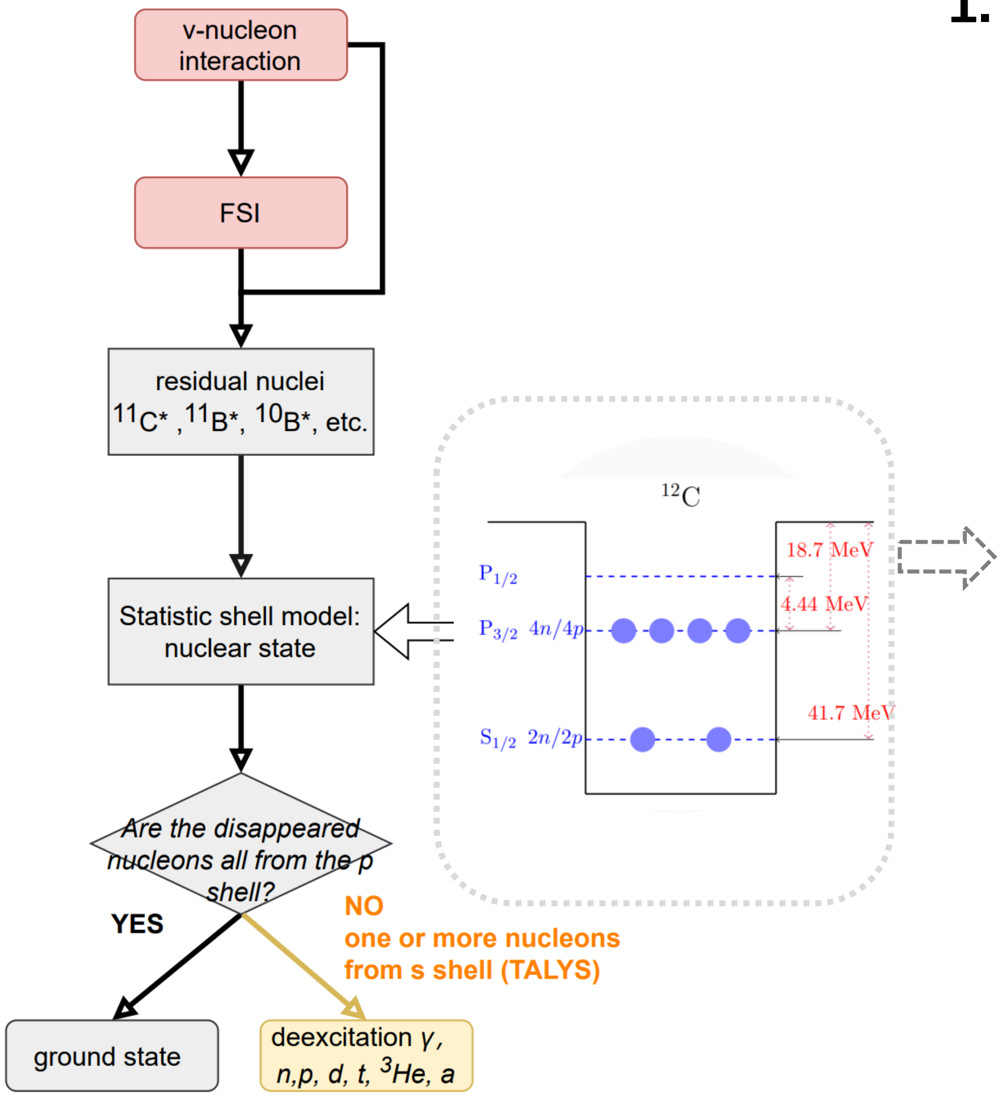
Phys. Rev. D 67 (2003) 076007

- All residual nuclei with A>5 have been considered
- Taking ^{11}C*, ^{11}B*, ^{10}C*, ^{10}Be* and ^{10}B* for example

Daughter Nuclei	Shell Hole	Configuration Probability	Excitation Energy
$^{11}C^*$ or $^{11}B^*$	$s_{1/2}$	$1/3$	$E^* = 23$ MeV
	$p_{3/2}$	$2/3$	$E^* = 0$ MeV
$^{10}C^*$ or $^{10}Be^*$	$s_{1/2}$	$1/15$	$E^* = 46$ MeV
	$p_{3/2}$	$6/15$	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	$8/15$	$E^* = 23$ MeV
$^{10}B^*$	$s_{1/2}$	$1/9$	$E^* = 46$ MeV
	$p_{3/2}$	$4/9$	$E^* = 0$ MeV
	$s_{1/2}$ & $p_{3/2}$	$4/9$	$E^* = 23$ MeV

Assume each neutron or proton has same possibility(1/6) to leave the shell.

TALYS-based Deexcitation Model of Residual Nucleus


v-nucleon interaction

FSI

residual nuclei $^{11}C^*$, $^{11}B^*$, $^{10}B^*$, etc.

Statistic shell model: nuclear state

Are the disappeared nucleons all from the p shell?

YES

ground state

NO one or more nucleons from s shell (TALYS)

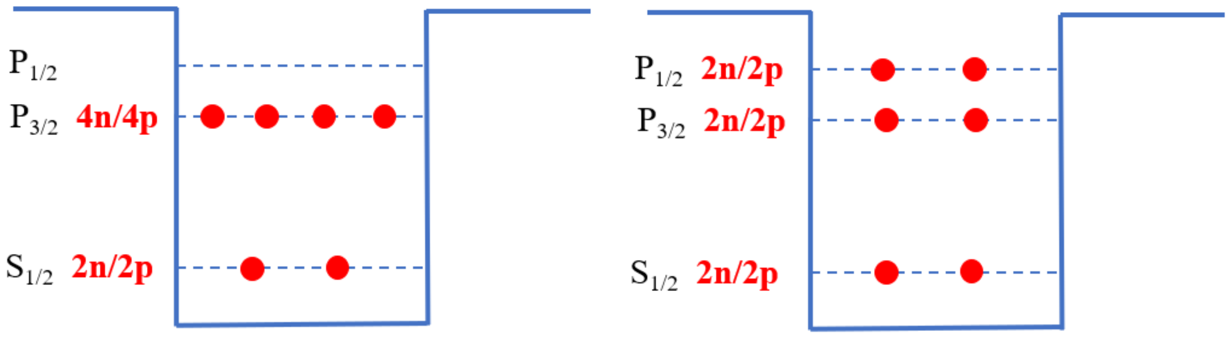
deexcitation γ, n,p, d, t, ^{3}He, a

1. Simple shell model → Status of the residual nuclei

Phys. Rev. D 67 (2003) 076007

- Go beyond simple shell model
  - ✓ considering the correlation between P shell ($P_{1/2}$ and $P_{3/2}$)
  - ✓ will be implemented

Assume each neutron or proton has same possibility(1/6) to leave the shell.



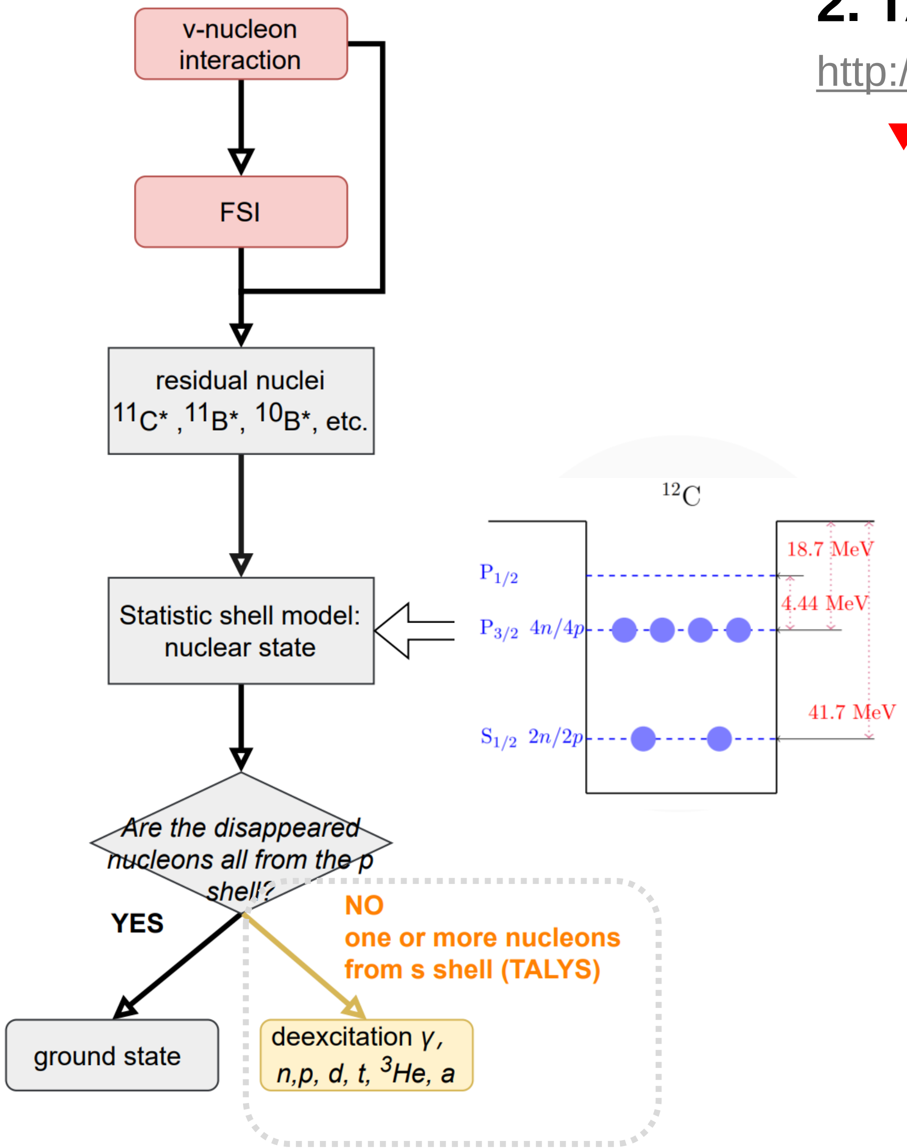
(case1: 60%)

(case2: 40%)

e.g, a neutron as well as a proton disappearance (nucleus: ^{11}C, ^{11}B):

Shell	**State**	
$S_{1/2}$	$E^* = 23$ MeV	**33.3%**
$P_{3/2}$	**ground state**	**53.4%**
$P_{1/2}$	$E^* = 2$ MeV	**13.3%**

TALYS-based Deexcitation Model of Residual Nucleus



ν-nucleon interaction

FSI

residual nuclei $^{11}C^*$, $^{11}B^*$, $^{10}B^*$, etc.

Statistic shell model: nuclear state

Are the disappeared nucleons all from the p shell?

YES

ground state

NO

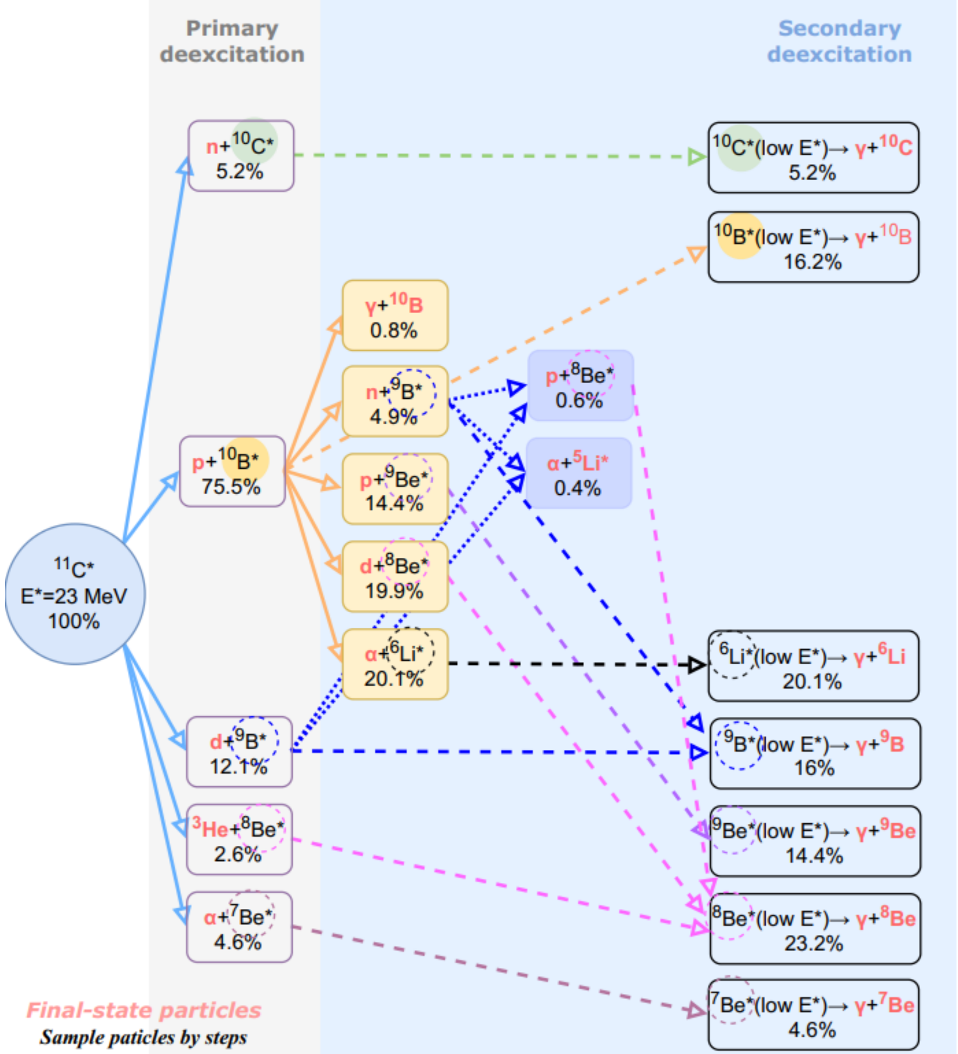
one or more nucleons from s shell (TALYS)

deexcitation γ, *n,p, d, t, ^{3}He, a*

2. TALYS → Simulate residual nucleus at certain excited energy

http://www.talys.eu/home/

- Taking the deexcitation chain of $^{11}C^*$ with E^*=23 MeV for example



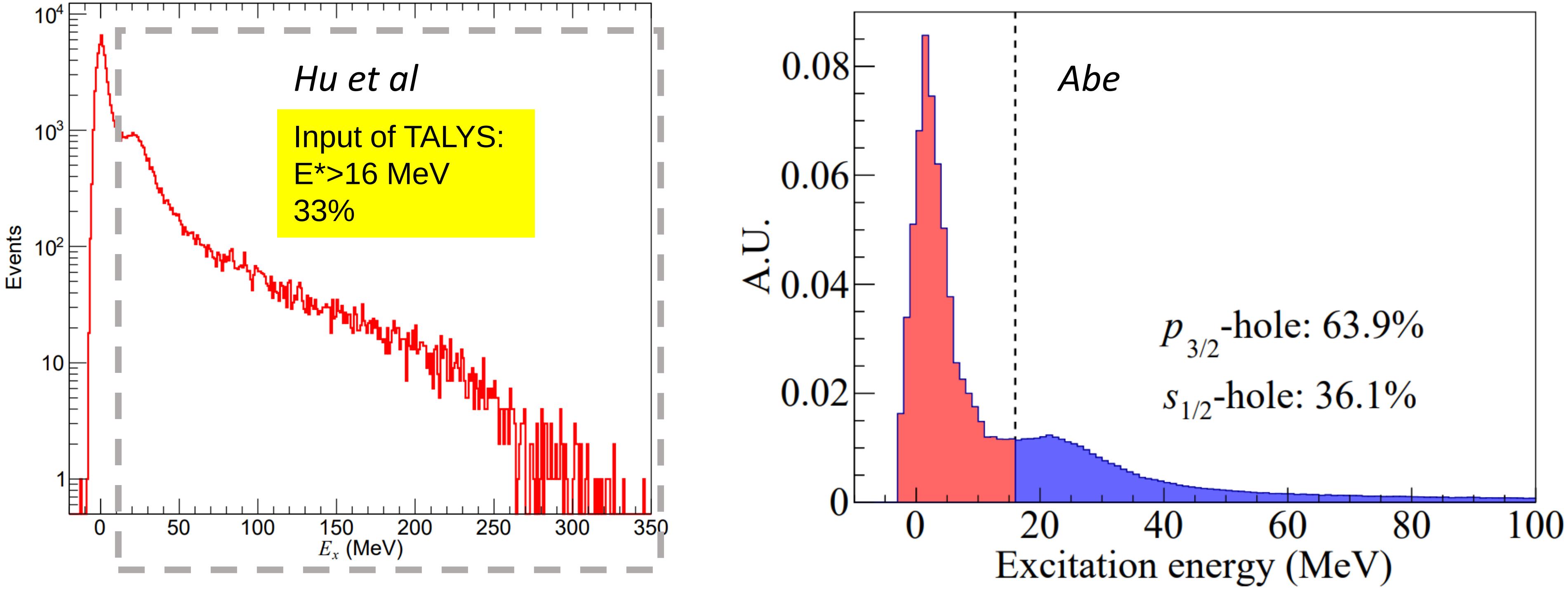
Reaction channels $^{11}C^* \to \gamma +$ $(E^*= 23$ MeV : 1/3)	**Fraction [%]**
$p + d + {}^8$Be	20
$p + \alpha + {}^6$Li	20
$p + {}^{10}$B	17
$2p + {}^9$Be	14
$d + {}^9$B	11
$n + {}^{10}$C	5
$n + p + {}^9$B	5
$\alpha + {}^7$Be	4
^{3}He $+^8$ Be	3
others	1

✓ TALYS also provides the energy spectra of the associated final-state particles

Other Publications for TALYS-based Deexcitation Model

Hu et al, Phys. Lett. B 831 (2022) 137183
Abe, Phys. Rev. D 109 (2024) 3, 036009

- The differences from our method:
  1. E* is estimated by (removal energy and separation energy) or (the invariant mass and ground-state mass of the residual nuclei) v.s. the statistic models (our work)
  2. Input of TALYS is the continuous excitation energy spectrum v.s. e.g., 23 MeV for ^{11}B* (our work)



Input of TALYS:
E*>16 MeV
33%

$p_{3/2}$-hole: 63.9%
$s_{1/2}$-hole: 36.1%

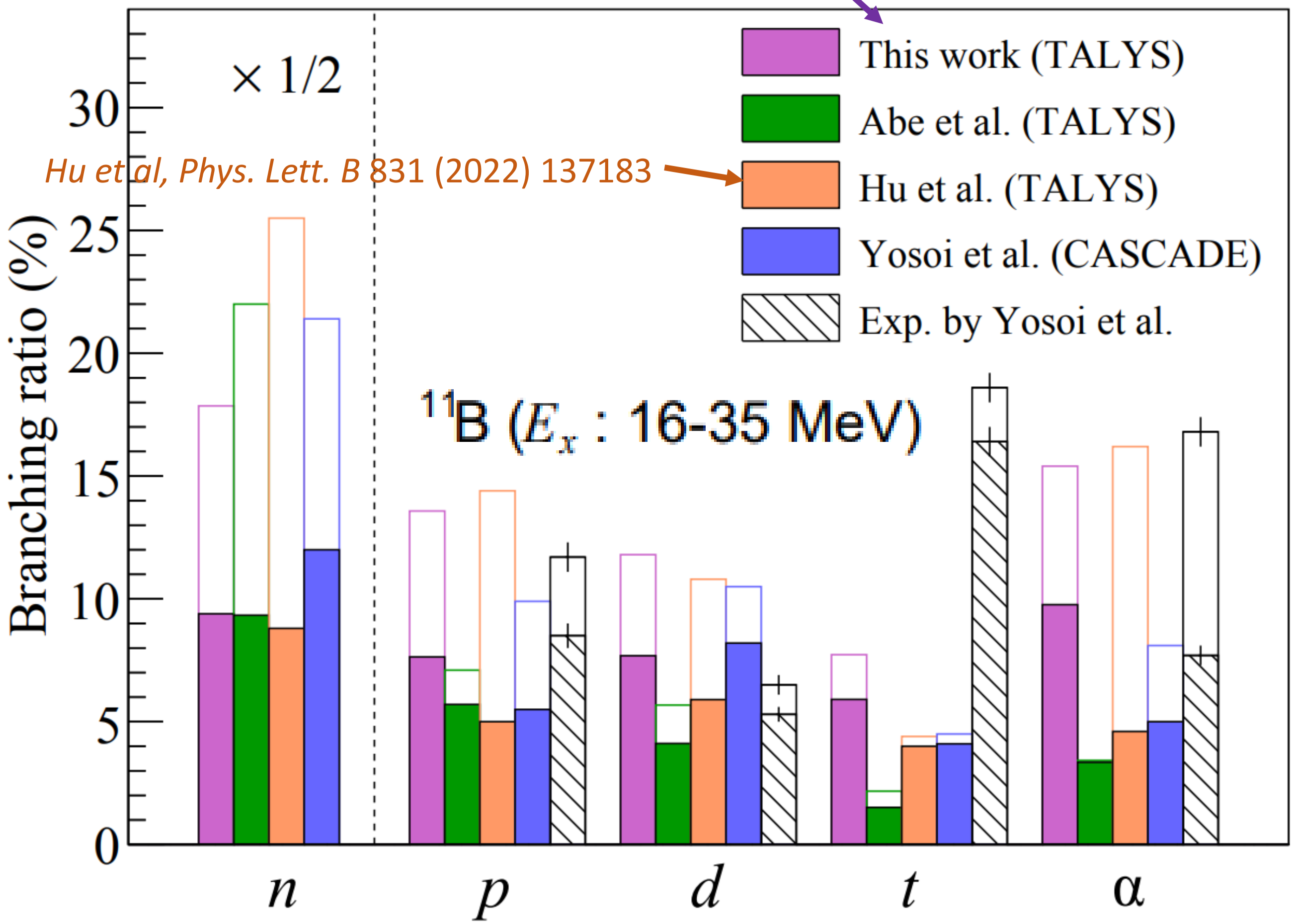
Excitation energy E* distribution of ^{11}B* based on SF model

Challenge for this method:

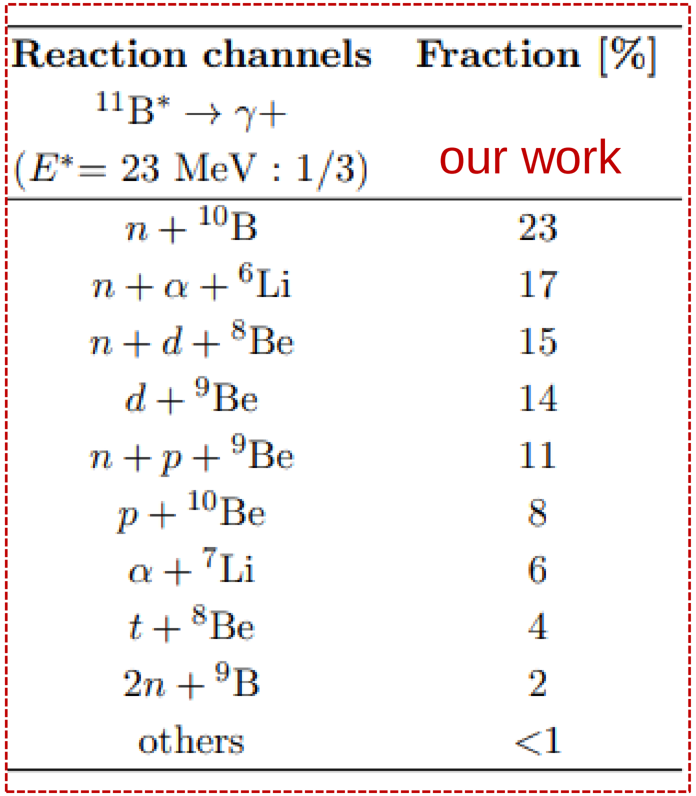
- difficult to get E* of the residual nuclei with using other nuclear models, such as RFG, LFG in neutrino generators

Comparison of Deexcitation Channels of $^{11}B^*$

Abe, Phys. Rev. D 109 (2024) 3, 036009



Hu et al, Phys. Lett. B 831 (2022) 137183

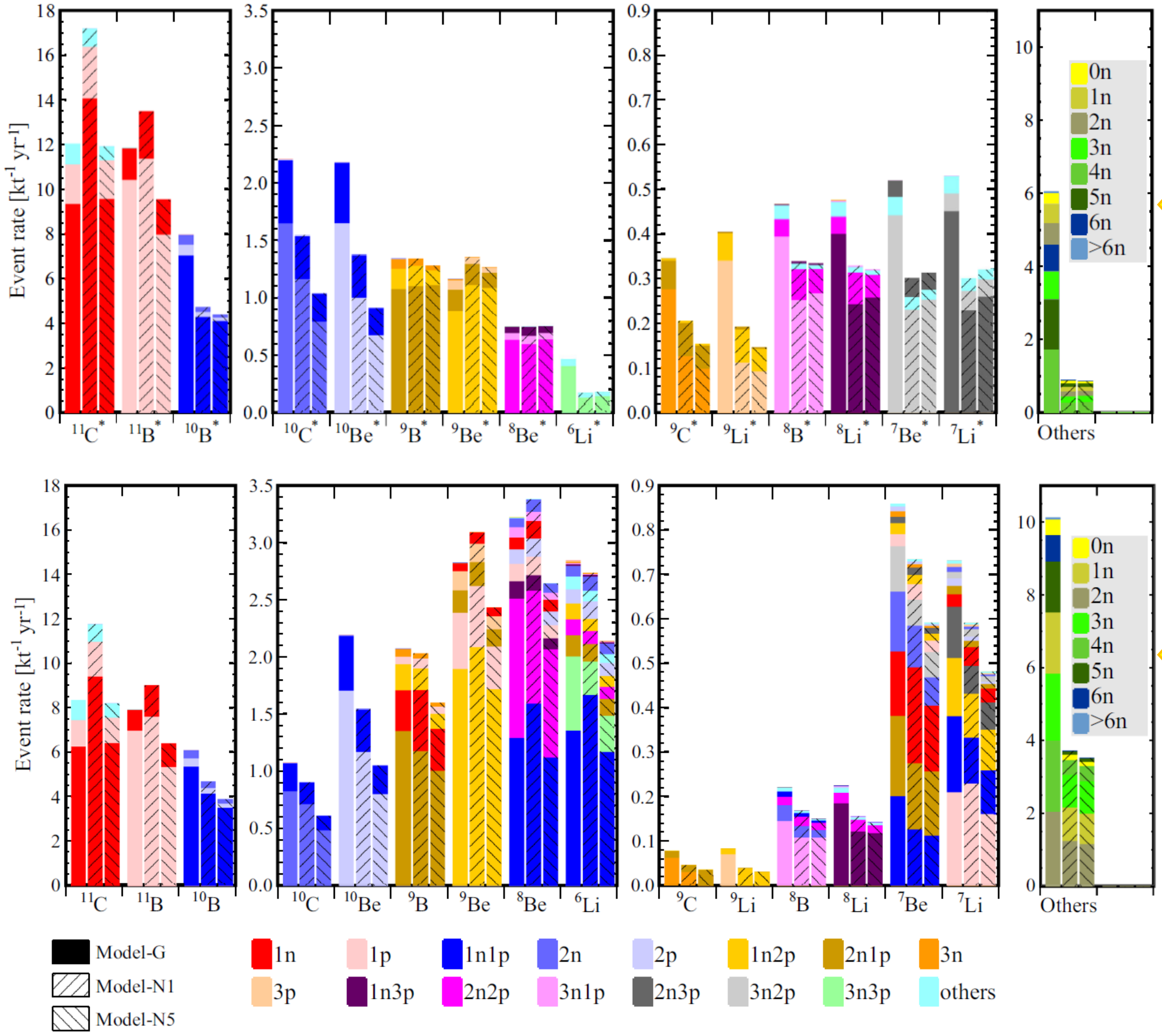


Reaction channels	Fraction [%]
$^{11}B^* \to \gamma +$ (E^*= 23 MeV : 1/3)	our work
$n + ^{10}B$	23
$n + \alpha + ^{6}Li$	17
$n + d + ^{8}Be$	15
$d + ^{9}Be$	14
$n + p + ^{9}Be$	11
$p + ^{10}Be$	8
$\alpha + ^{7}Li$	6
$t + ^{8}Be$	4
$2n + ^{9}B$	2
others	<1

Reaction ratio with neutron production: ~68% (our work)

Impact of Deexcitation on Final-state Production of NC Events

Cheng et al, Phys. Rev. D 103. 05001 (2021)



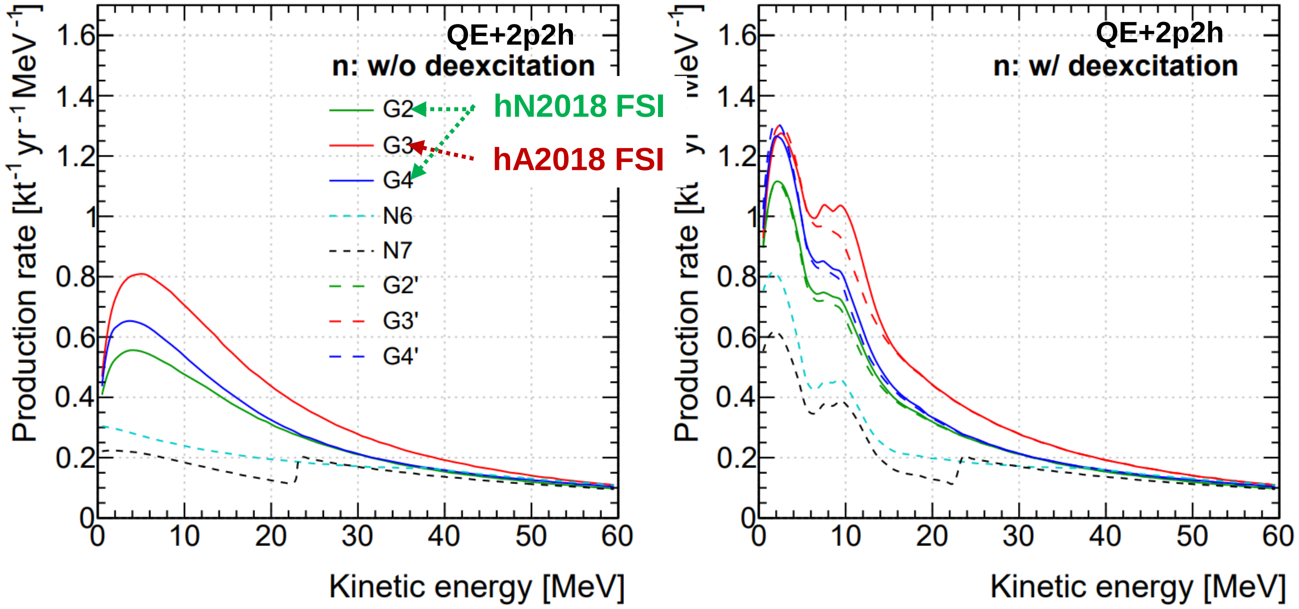
Before deexcitation, ^{11}C, ^{11}B, ^{10}B dominated

After deexcitation , ^{11}C, ^{11}B, ^{10}B reduced, with more lighter nuclei

Exclusive final-state information, such as the neutron multiplicity, the charge pion multiplicity, the unstable nuclei, is important for tagging and reducing the background

Production of Final-state Neutrons

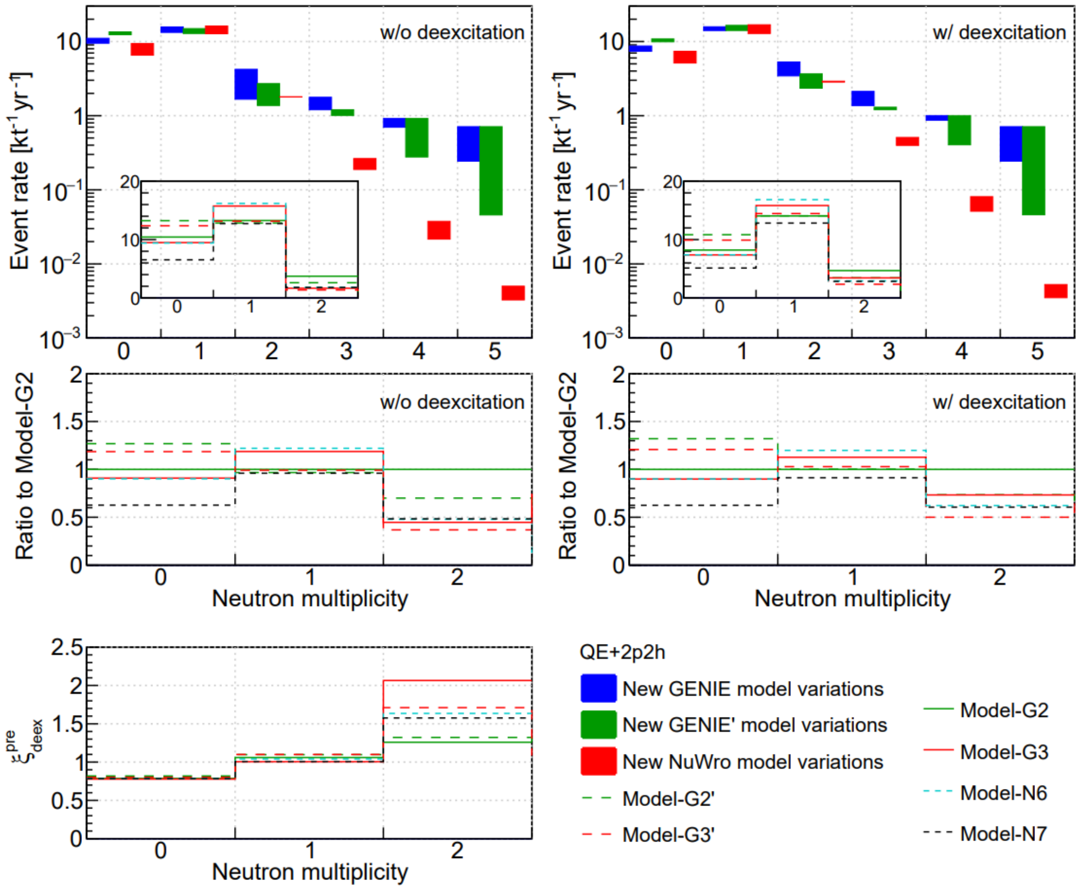
Cheng et al, arXiv 2404.07429



- **Have found final-state nucleons with zero kinetic energy in GENIE models**

  https://github.com/GENIE-MC/Generator/issues/369

  - **GENIE authors suggest to mark a nucleon as intermediate if its kinetic energy = 0**
  - **modify G(2-4) to G'(2-4) that no zero kinetic energy in the final-state and the corresponding residual nuclei are modified.**

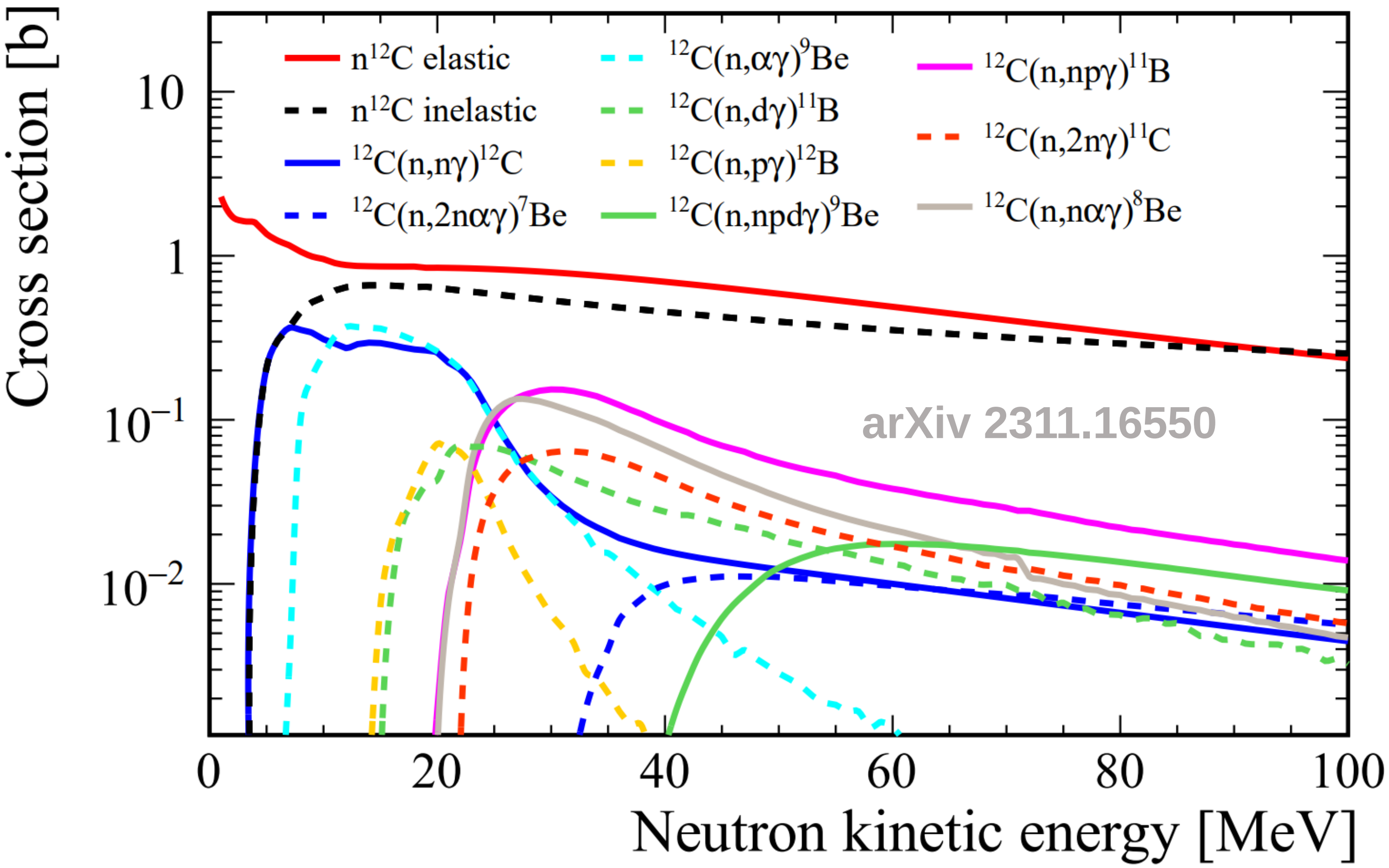


- **New GENIE model:** Model-G2, G3, G4
- **New GENIE' model:** Model-G2', G3', G4'
- **New NuWro model:** Model-N6, N7
- ξ_{deex} **: the ratio of the event rate with deexcitation to that without deexcitation**

GEANT4-based Detector Simulation

- ☐ **GEANT4 (4.10.p02)➔ simulate the propagation of final-state particles in LS**
- ☐ **Hadronic models: QGSP_BERT_HP**
- ☐ **JUNO detector as our reference**
- ☐ **Considering decay processes of unstable isotopes after deexciation stage in detector simulation**
- ☐ **Secondary interactions (SI): final-state particles produced by a primary interaction, subsequently interact within the LS**
- ☐ **Neutron tagging takes place after the SI**

Tagged neutrons ≠ final-state neutrons



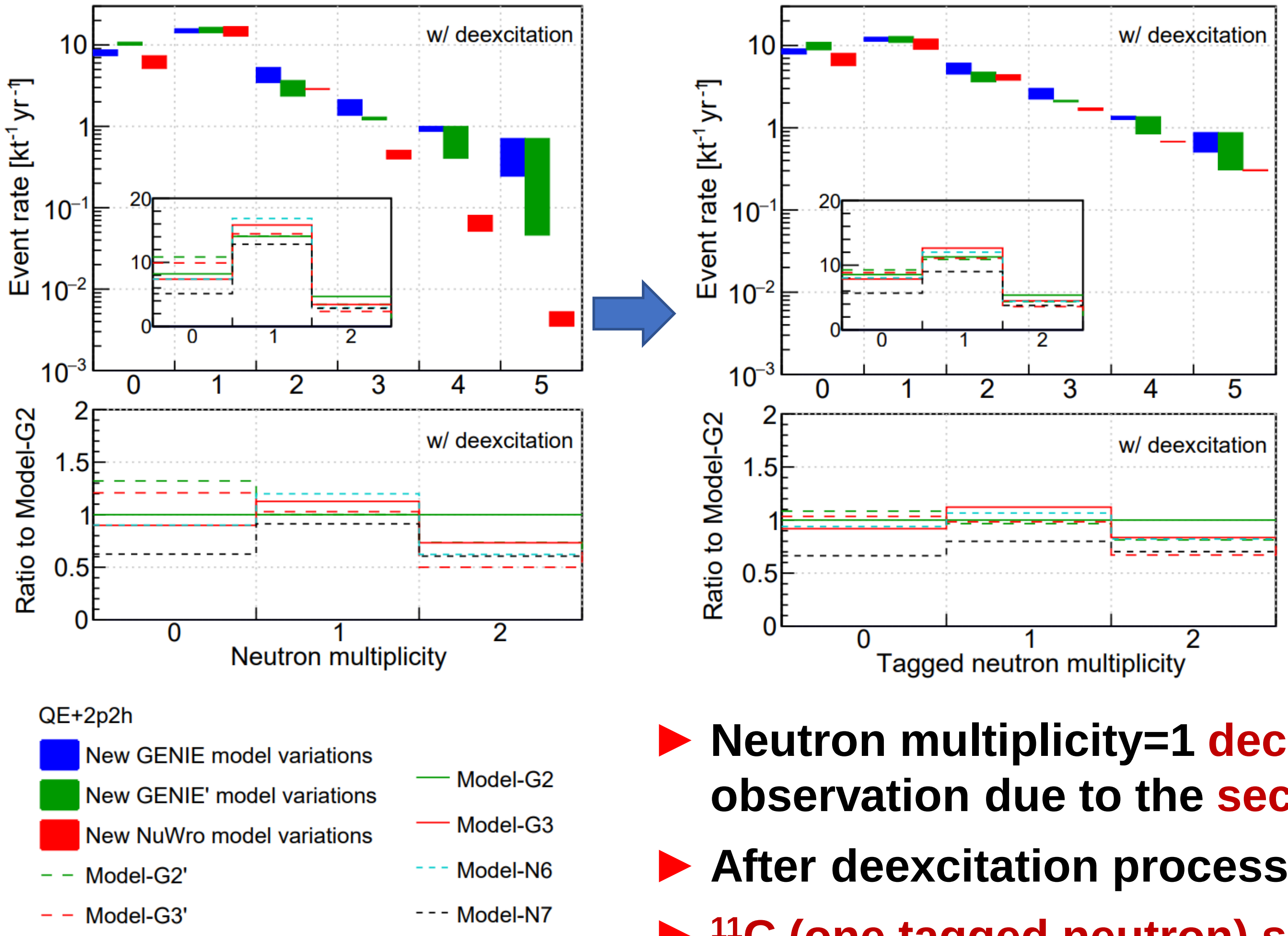
Extracted from the results of TALYS

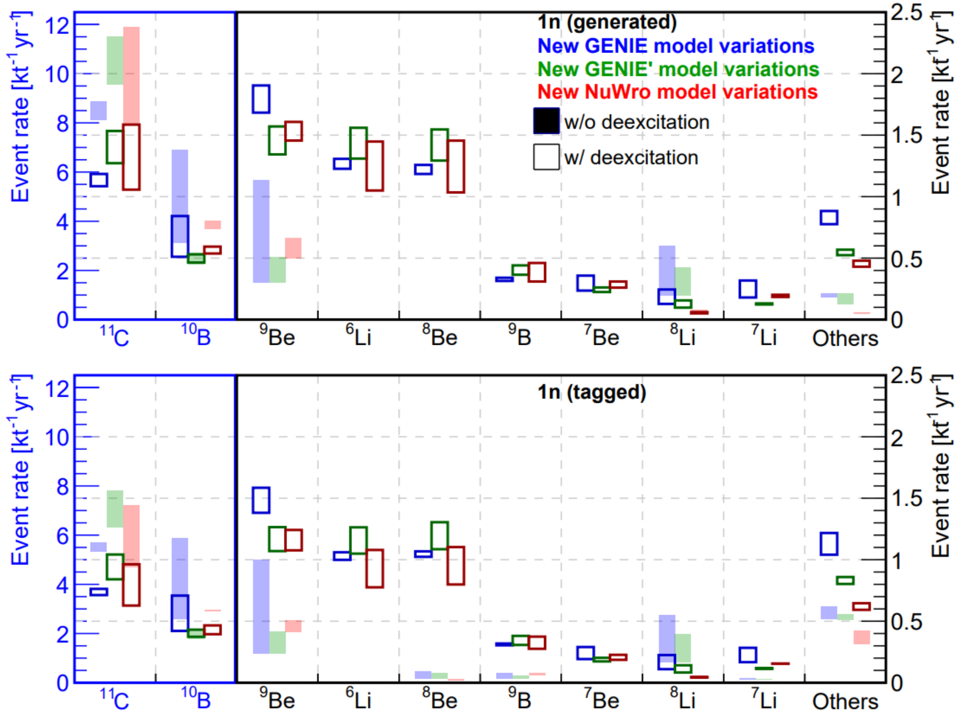
Comparisons

Cheng et al, arXiv 2404.07429

Final-state

Observed

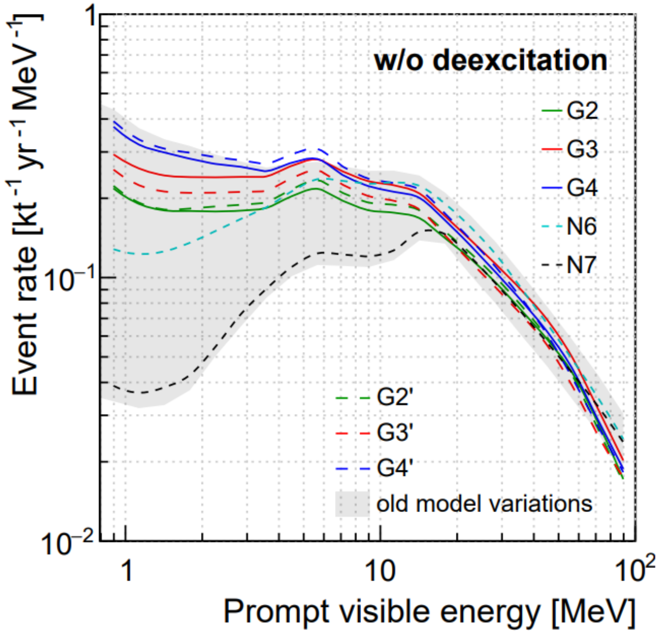


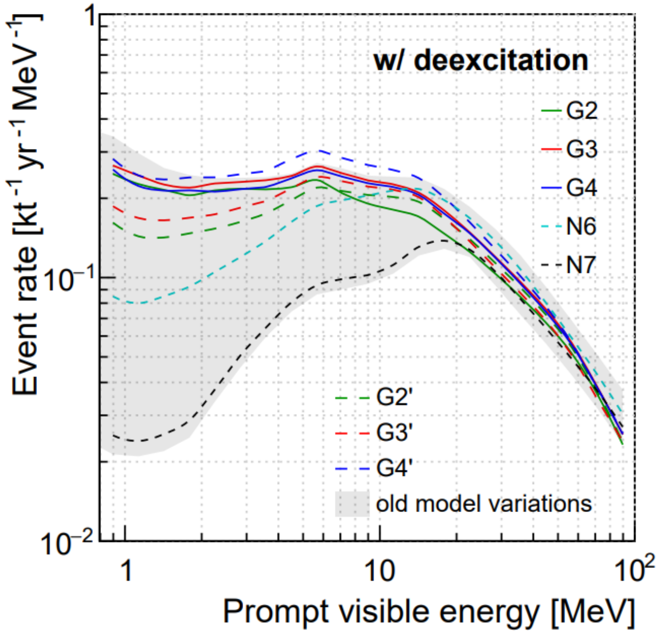


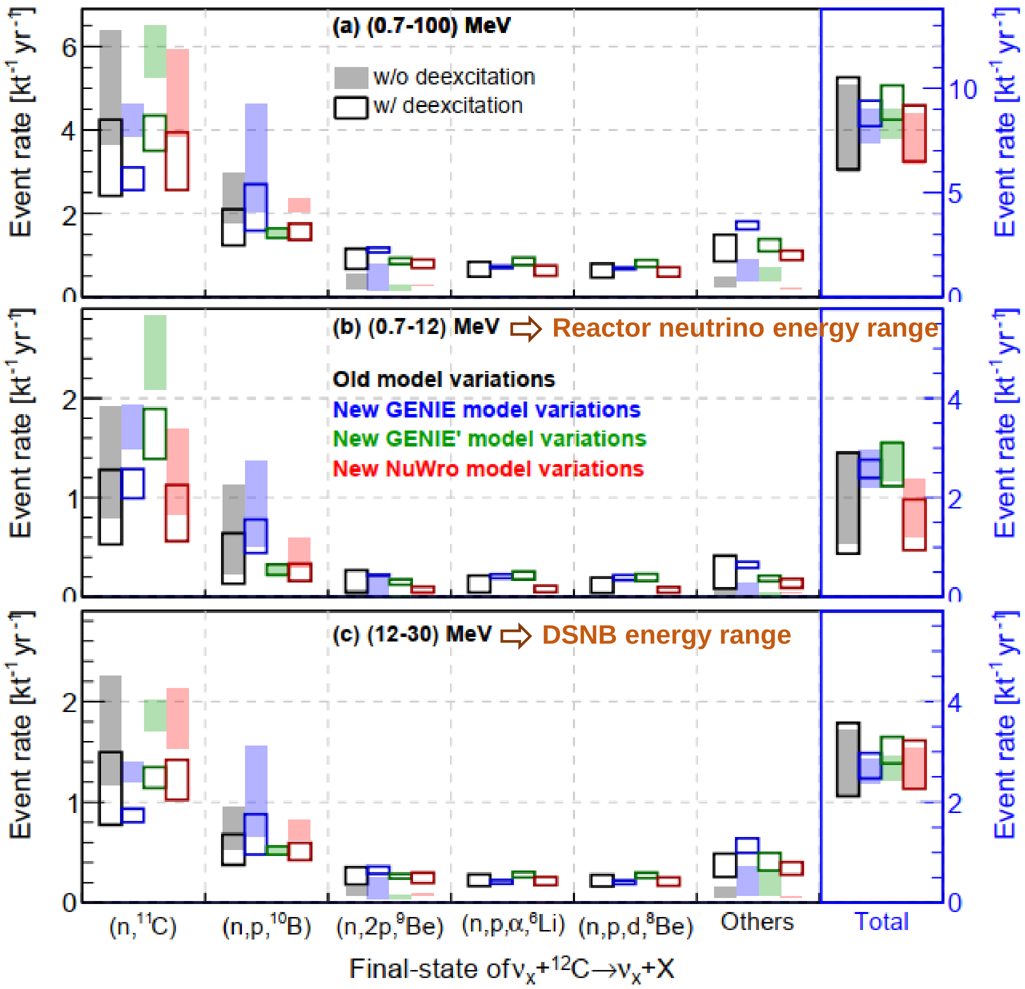
- **Neutron multiplicity=1 decrease significantly from the final-state to observation due to the secondary interactions**
- **After deexcitation process, ^{11}C, ^{10}B reduced, with more lighter nuclei**
- **^{11}C (one tagged neutron) significantly decreased due to the higher kinetic energies of fast neutron from NC with ^{11}C, making them more prone to inelastic scattering in LS**

IBD-like NC Background

Cheng et al, arXiv 2404.07429







- **Focus on the prompt visible energy below 100 MeV**
- **Large model variation in energy < 20 MeV, the model prediction lack sufficient experimental constraints.**
- **With deexcitation,**
  - **energy spectra shift to higher energies and enlarge the model variations**
  - **dominant channels with ^{11}C and ^{10}B reduce, and channels with lighter nuclei increase**

- The NC background rate with deexcitation as the nominal result

Summary

a) **Atmospheric neutrinos are one of most crucial backgrounds for many rare searches, such as DSNB, proton decay, dark matter, as well as reactor neutrinos**

b) **Neutrino interactions including deexcitation (combination of neutrino generators and TALYS) as well as detector response are developed.**

c) **Our work will help estimate single, double-coincident and triple-coincident backgrounds**

d) **The method of the NC background prediction has been adopted in JUNO related studies, e.g.,**

   1. **DSNB (**JCAP 10 (2022) 033**)**
   2. **Reactor neutrino (**Chin. Phys. C 46 (2022) 12, 123001**)**
   3. **Indirectly dark matter research (**JCAP 09 (2023) 001**)**

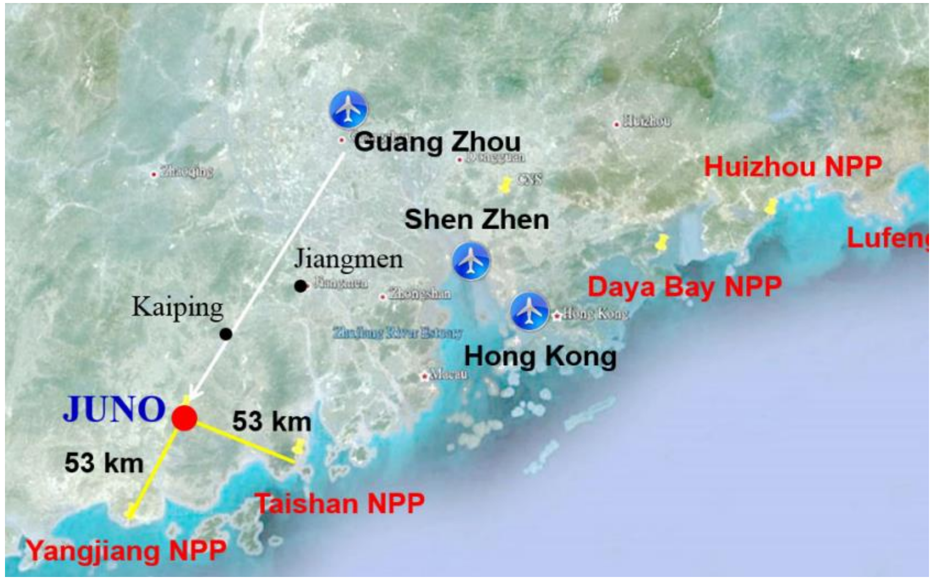
e) **Also suitable for various experimental settings, such as HyperK, THEIA, DUNE**

Thank you for your attention!

backup

Jiangmen Underground Neutrino Observatory (JUNO)

PPNP 123 (2022) 103927




JUNO site
Civil construction finished in 2021/12

Overburden
~650 m (1800 m.w.e.)

- Multi-purpose neutrino experiment


Reactor

~60 $\overline{\nu}_e$ / day


Atmosphere

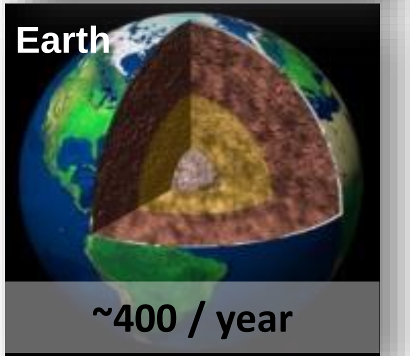
Hundreds / year


Solar

Hundreds / year for ^{8}B


Supernova

Supernova burst: ~7300 at 10 kpc
DSNB: 2-4 $\overline{\nu}_e$ /year

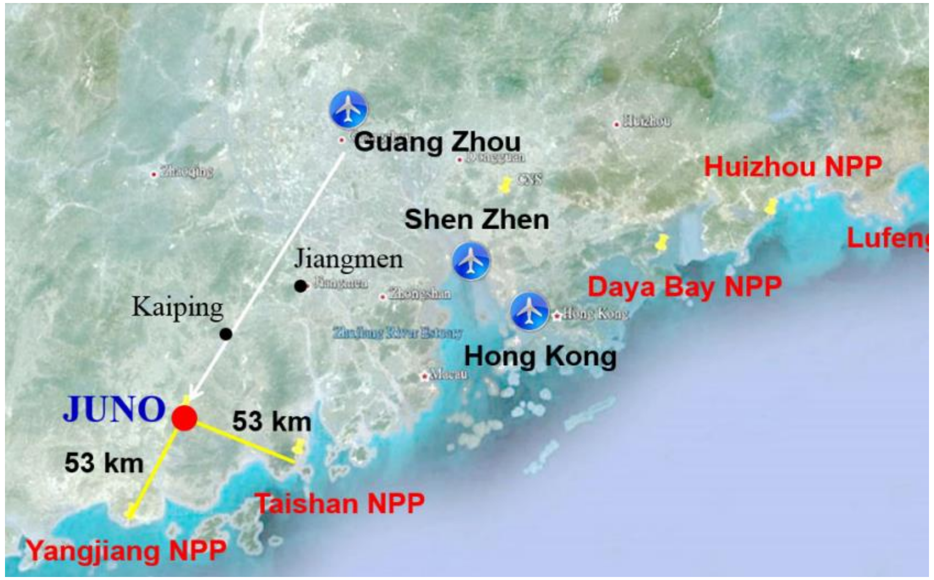

Earth

~400 / year

New physics e.g., proton decay

Jiangmen Underground Neutrino Observatory (JUNO)

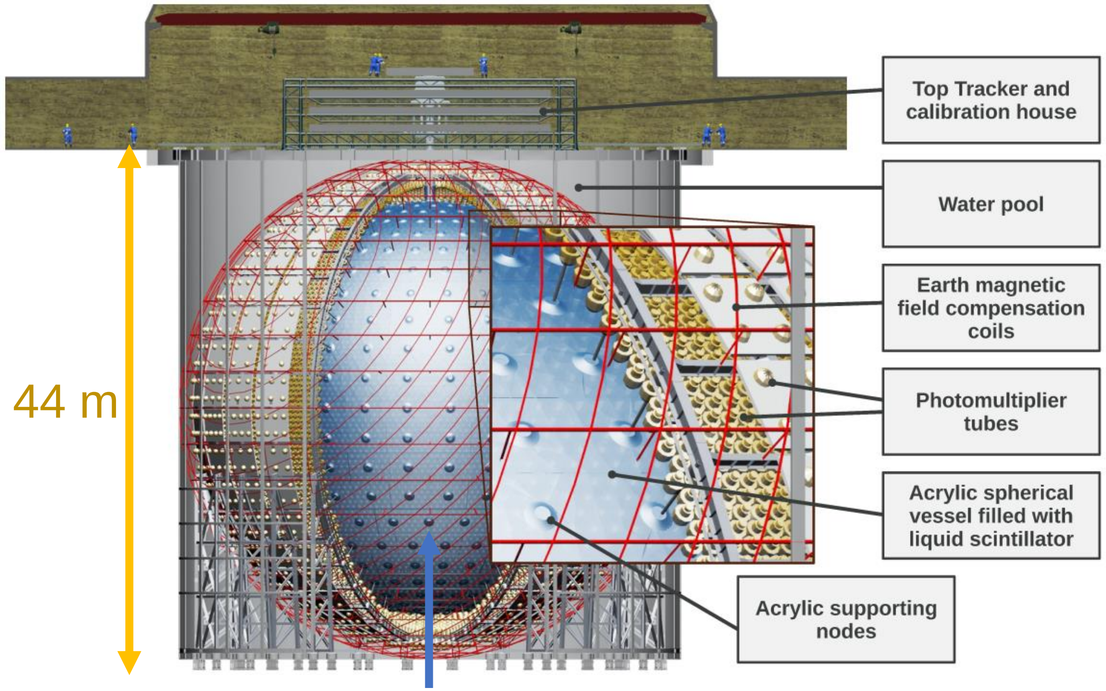
PPNP 123 (2022) 103927



JUNO site
Civil construction finished in 2021/12

Overburden
~650 m (1800 m.w.e.)

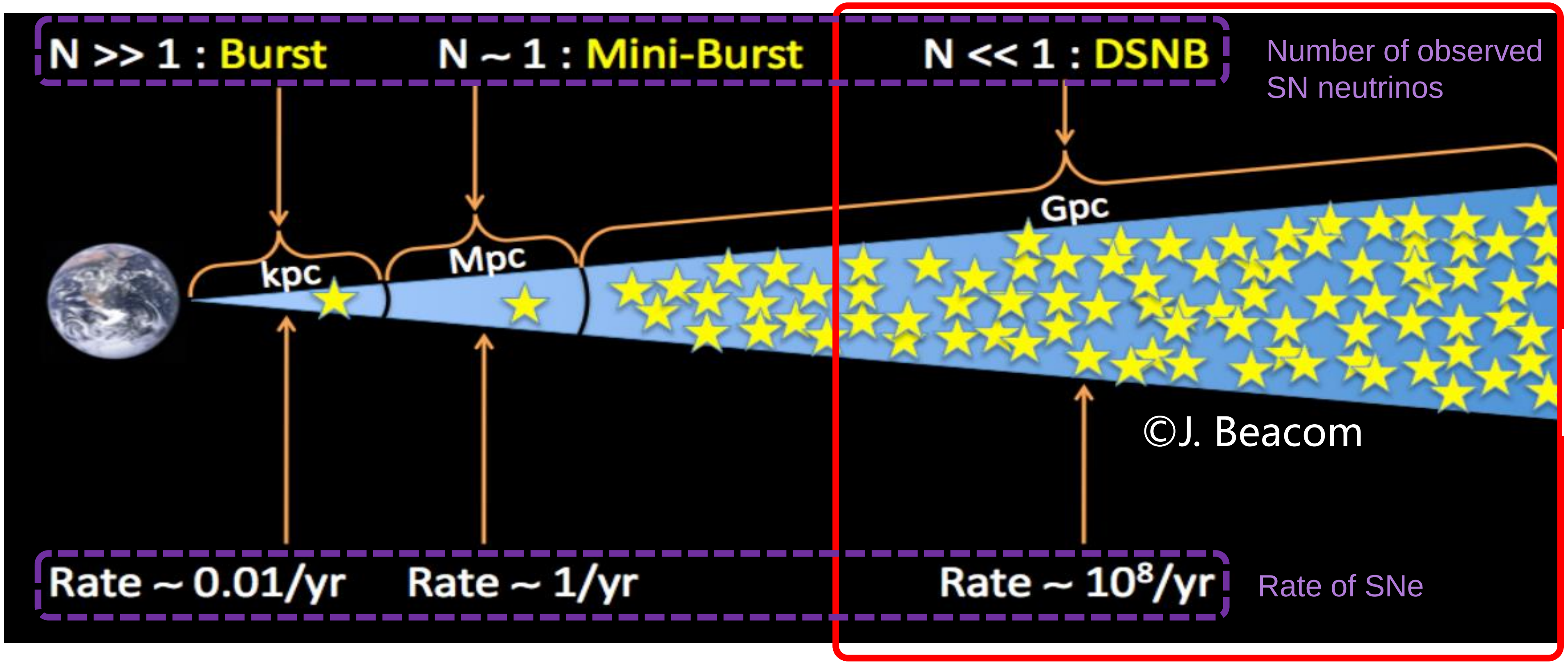
- JUNO detector



Central Detector: 20 kton Liquid Scintillator (LS)

	Target mass	PMT Coverage	Energy resolution @ 1 MeV	Light yield [PE/MeV]
Daya Bay	20 ton (x8)	12%	8%	160
Borexino	300 ton	34%	5%	500
KamLAND	1 kton	34%	6%	250
JUNO	20 kton	78%	3%	>1300

Diffuse Supernova Neutrino Background



Galactic:
High statistics,
All flavors

Extra-galactic:
Small statistics

Integrated flux of all past SNe:
cosmic star-information, average core-collapse neutrino spectrum, failed SNe rate, etc

DSNB primary detection via IBD:

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

Prompt **Delayed**

- **Very rare event rate :**
  2-4 events in JUNO per year
  - ✓ Not detected yet

Atmospheric Neutrino Challenges in Large LS Detectors

Challenges in LS detectors:

- ✓ **Neutrino interactions in LS rely on nuclear models**
  - **➔Precise model prediction (this talk)**

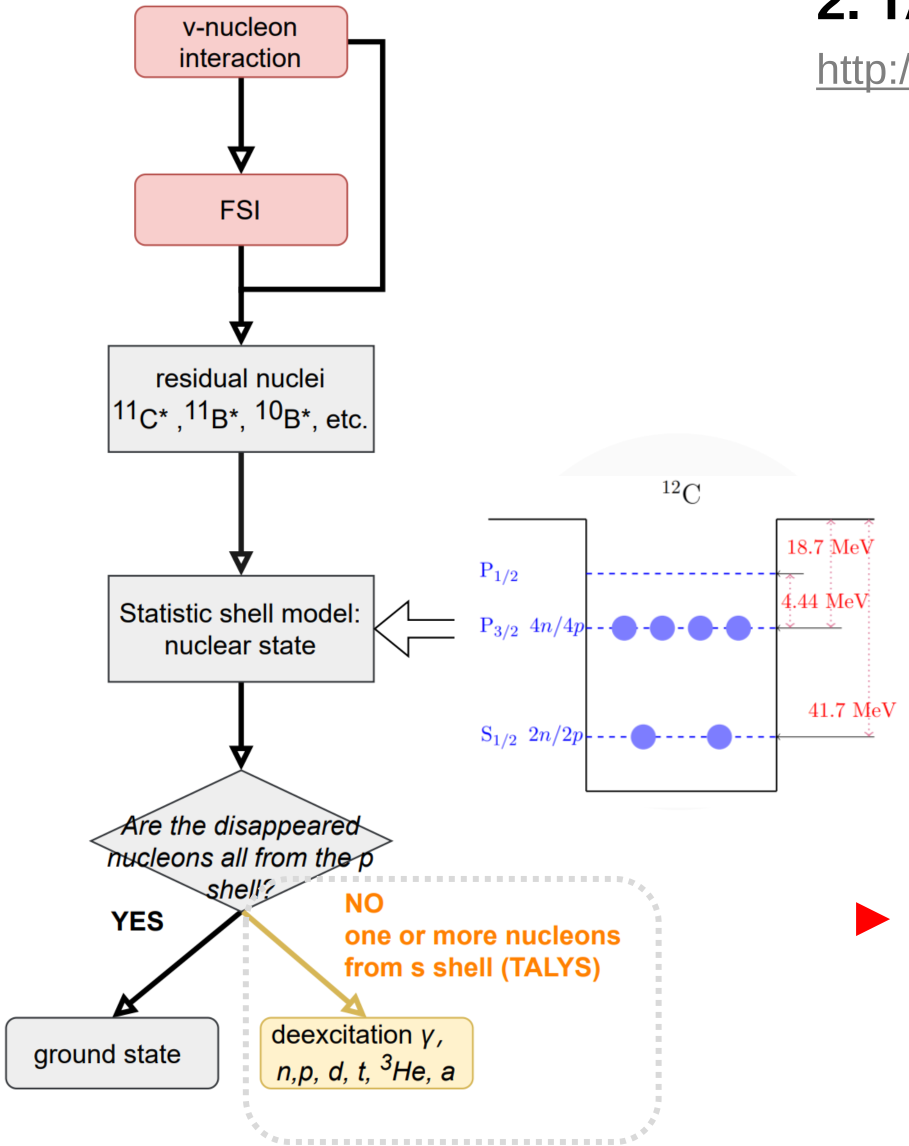
    CHENG, LI, WEN, ZHOU, Phys. Rev. D 103. 05001 (2021)

    CHENG, LI, LI, LI, LU, WEN, paper in preparation
- ✓ **Few data measurement of atm-v NC interactions**
  - **➔*In-situ* measurement**

    CHENG, LI, LU, WEN, Phys. Rev. D 103. 05002 (2021)
- ✓ **The requirement of background suppression is quite high**
  - **➔Developed pulse shape discrimination (PSD) tools**

    CHENG, LUO, LI, LI, LI, et al., arXiv2311.16550

TALYS-based Deexcitation Model of Residual Nucleus



2. TALYS → Simulate residual nucleus at certain excited energy

http://www.talys.eu/home/

Taken from TALYS's calculation

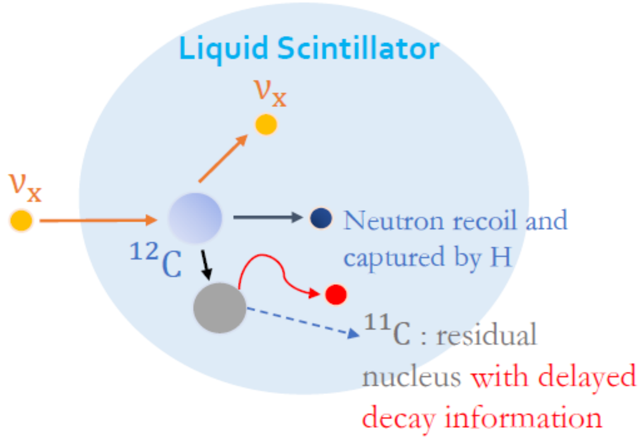
Reaction channels	Fraction [%]	Reaction channels	Fraction [%]
$^{11}C^* \to \gamma +$ $(E^* = 23$ MeV : $1/3)$		$^{11}B^* \to \gamma +$ $(E^* = 23$ MeV : $1/3)$	
$p + d + {}^{8}Be$	20	$n + {}^{10}B$	23
$p + \alpha + {}^{6}Li$	20	$n + \alpha + {}^{6}Li$	17
$p + {}^{10}B$	17	$n + d + {}^{8}Be$	15
$2p + {}^{9}Be$	14	$d + {}^{9}Be$	14
$d + {}^{9}B$	11	$n + p + {}^{9}Be$	11
$n + {}^{10}C$	5	$p + {}^{10}Be$	8
$n + p + {}^{9}B$	5	$\alpha + {}^{7}Li$	6
$\alpha + {}^{7}Be$	4	$t + {}^{8}Be$	4
$^{3}He + {}^{8}Be$	3	$2n + {}^{9}B$	2
others	1	others	<1

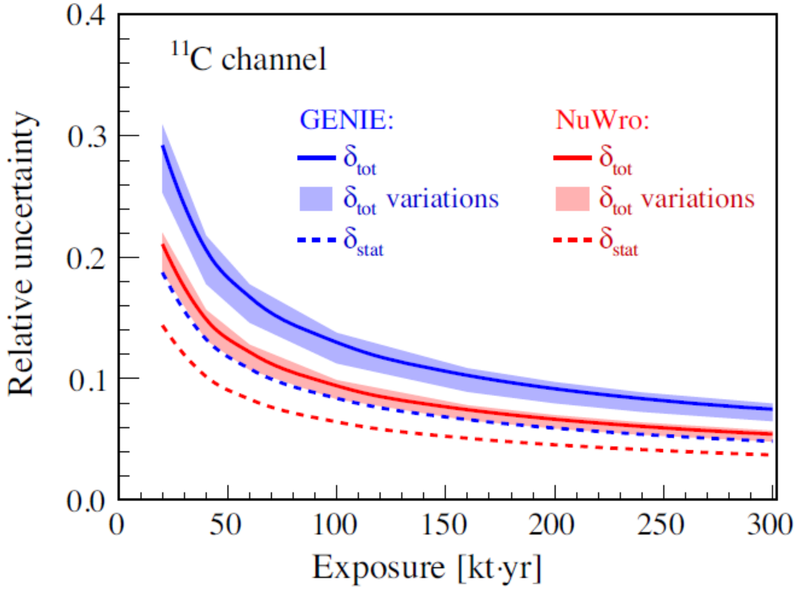
► Final production of neutrons and unstable residual nuclei is crucial for tagging and reducing NC background in LS detectors

Atm-ν NC interaction: *in-situ* measurement

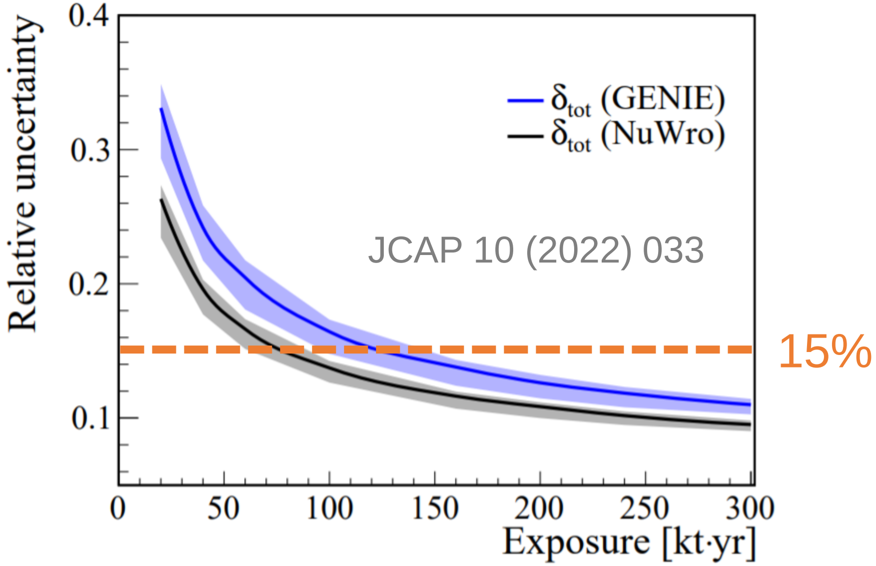
Phys. Rev. D 103 (2021) 5, 053002

- We perform a systematic study on the measurement of the NC background and evaluate the associated uncertainties
- According to the possible association with unstable residual nuclei, a maximum-likelihood method is proposed to measure the triple-coincident signature of the NC background
- The uncertainty of the NC background for DSNB is evaluated
- Future JUNO will be able to make a unique contribution to the worldwide dataset to improve the prediction of NC interaction on ^{12}C





Reproduce NC background uncertainty from the summary in **Phys.Rev.D 103 (2021) 5, 053002**

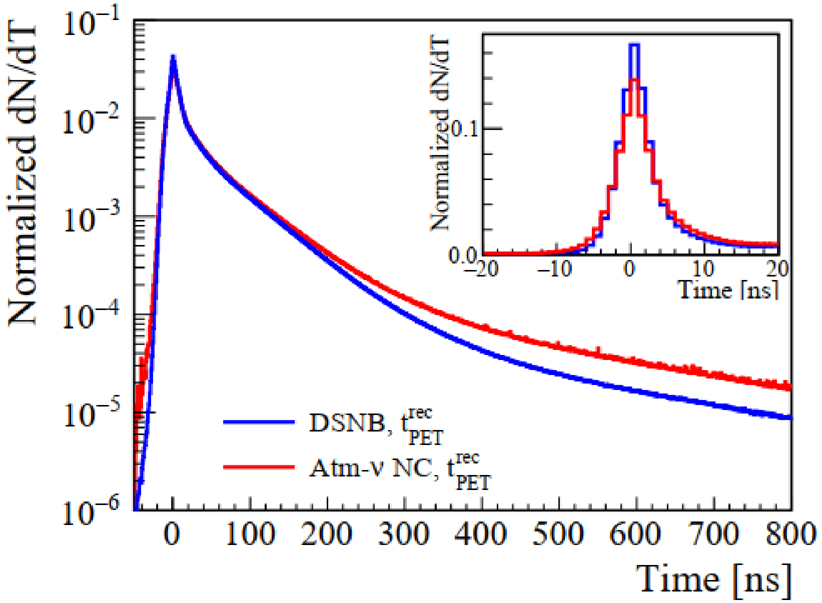


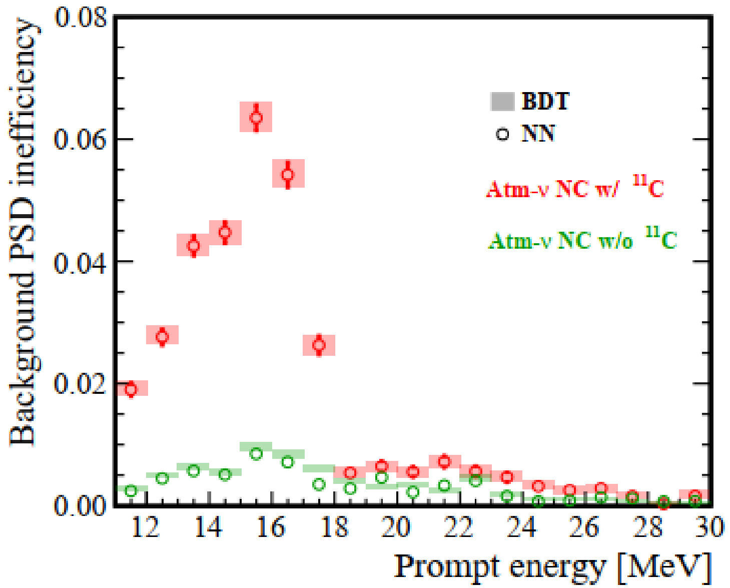
- Within 10 years JUNO data, NC background rate can be constrained on 15% level

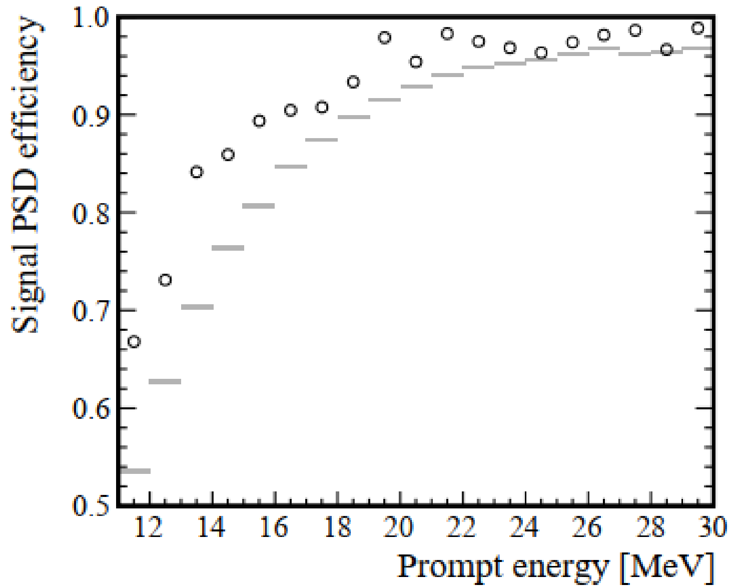
Developed PSD discriminator

arXiv 2311.16550

- The S/B ratio in DSNB study before the PSD cut is about 0.05
- Pulse shape discrimination (PSD): a powerful tool to significantly suppress atmospheric NC and fast neutron backgrounds
- Methods based on Boosted Decision Trees and Neural Networks are developed, instead of simple tail-to-total method







- ✓ The PSD efficiency for DSNB is about 80%, compared to 50% DSNB PSD efficiency in JUNO physics book (2016)
- ✓ The energy dependent PSD efficiency is applied in the DSNB study for the first time