# Distinctive nuclear probes of low-energy atmospheric neutrinos

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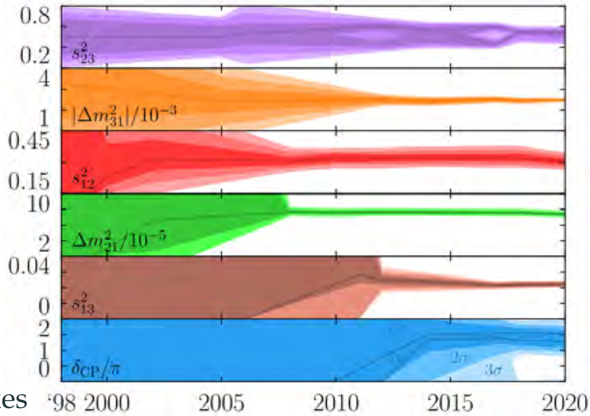
N3AS Network for Neutrinos, Nuclear Astrophysics, and Symmetries
PHYSICS FRONTIER CENTER

NSF

# Towards precise neutrino mixing measurements

**Past measurements**

- large mixing angles
- non-zero masses




Snowmass Neutrino Frontier Report

**Remaining questions**

- Majorana vs Dirac
- absolute masses
- degree of CP violation
- some low-energy $\nu$ fluxes

**How to achieve it? All hands on deck**

- Many new experiments comimg online soon, DUNE, JUNO, HK, DARWIN-LZ...
- variety of approaches $\rightarrow$ superb sensitivity

## Primary production channels

$\pi^+ \to \mu^+ + \nu_\mu;\ \mu^+ \to e^+ + \bar{\nu}_\mu + \nu_e$

$\pi^- \to \mu^- + \bar{\nu}_\mu;\ \mu^- \to e^- + \nu_\mu + \bar{\nu}_e$

## Non-oscilated flavor ratio

$\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$

## Sources of uncertainty

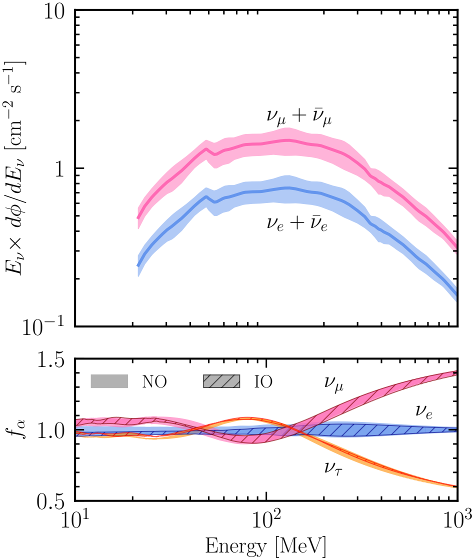
solar wind modulations

Earth's geomagnetic field

## Oscilated flavor ratio

$\nu_e : \nu_\mu : \nu_\tau \approx 1 : 1 : 1$

## Past measurements: energies > 100 MeV




Neutrino flux: Zhuang (2021)

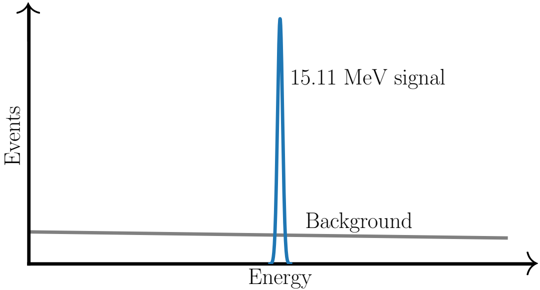
Mixing: NuCraft

# Distinctive nuclear channels

## Neutral current channels

$$\nu + {}^{12}\mathrm{C} \rightarrow \nu + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma,$$

$$\bar{\nu} + {}^{12}\mathrm{C} \rightarrow \bar{\nu} + {}^{12}\mathrm{C}^*$$
$${}^{12}\mathrm{C}^* \rightarrow {}^{12}\mathrm{C} + \gamma,$$



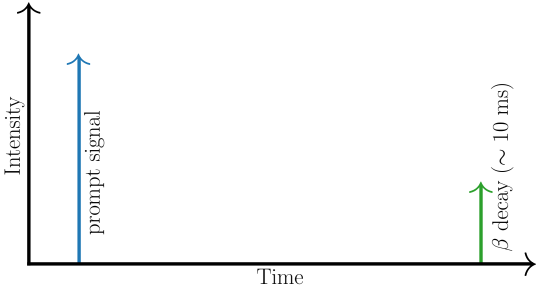

- instantaneous decay of ${}^{12}\mathrm{C}^*$
- emission of a monoenergetic $\gamma$

# Distinctive nuclear channels

## Charged current channels: $\nu_e$

$$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e,$$

$$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$${}^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e.$$



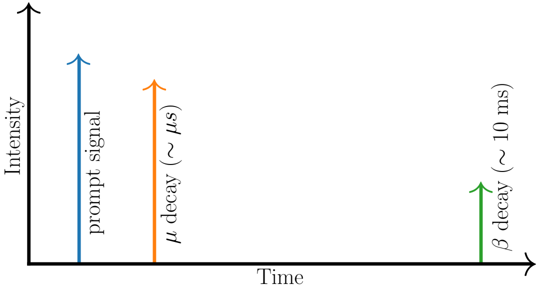

- coincidence detection of $e^+$ and $e^-$
- difference in ${}^{12}\mathrm{B}_{\mathrm{g.s.}}$ and ${}^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes → $\nu_e$ vs. $\bar{\nu}_e$ distinction

# Distinctive nuclear channels

## Charged current channels: $\nu_e$

$$\nu_\mu + {}^{12}\mathrm{C} \to \mu^- + {}^{12}\mathrm{N}_{\mathrm{g.s.}}$$
$$^{12}\mathrm{N}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^+ + \nu_e$$
$$\mu^- \to e^- + \bar{\nu}_e + \nu_\mu,$$

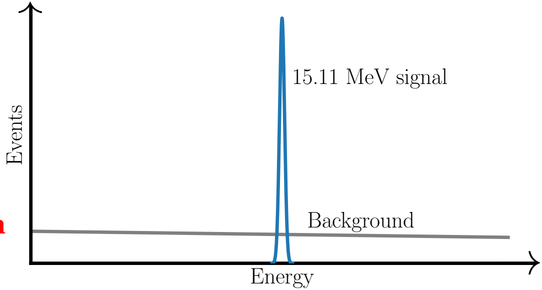
$$\bar{\nu}_\mu + {}^{12}\mathrm{C} \to \mu^+ + {}^{12}\mathrm{B}_{\mathrm{g.s.}}$$
$$^{12}\mathrm{B}_{\mathrm{g.s.}} \to {}^{12}\mathrm{C} + e^- + \bar{\nu}_e$$
$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu.$$

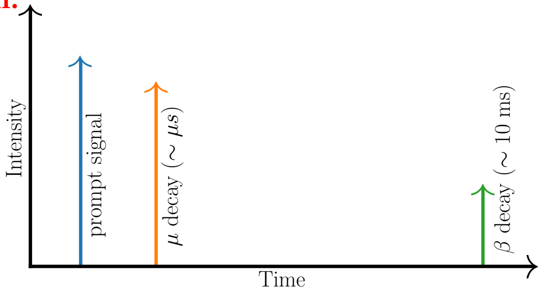



- coincidence detection of $\mu$, its decay $e$ and $\beta$-decay $e$
- difference in $^{12}\mathrm{B}_{\mathrm{g.s.}}$ and $^{12}\mathrm{N}_{\mathrm{g.s.}}$ lifetimes $\to$ $\nu_\mu$ vs. $\bar{\nu}_\mu$ distinction
- triple vs. double coincidence detection $\to$ $\nu_e$ vs. $\nu_\mu$ distinction

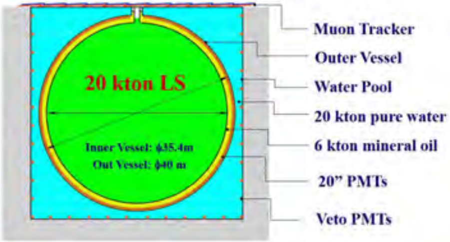
# Distinctive nuclear channels

**Also suggested for supernova neutrino detection, see, e.g., Fukugita et al. 1988, Laha et al. 2014, Lu et al. 2016**



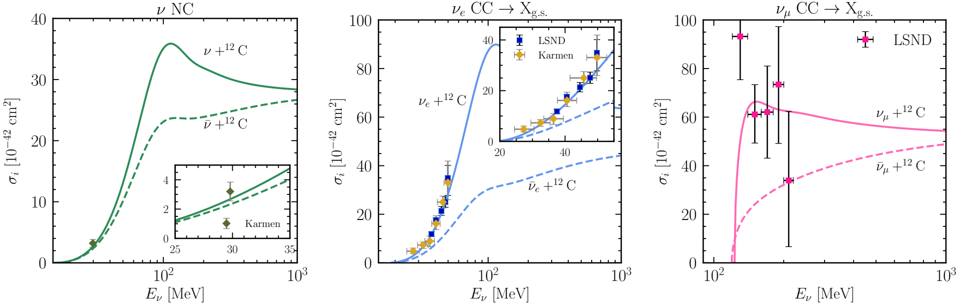
# The Jiangmen Underground Neutrino Observatory (JUNO)




- large-scale carbon-based liquid scintilator detector
- soon operational ($\sim$ 2024)
- excelent energy resolution $\leq 3\%$
- excelent spatial resolution $\mathcal{O}(5)$ cm
- low backgrounds in the considerd channels

An et al. (2015), Sitsi (2022)

# Cross section: elementary particle treatment (EPT)




- superallowed transitions from $0^+$ to $1^+$ states
- the exclusive $\nu$ - $^{12}$C cross sections measured only at low energies
- experimental data agrees well with the EPT treatment
- 5-40% difference with respect to, e.g., RPA calculations

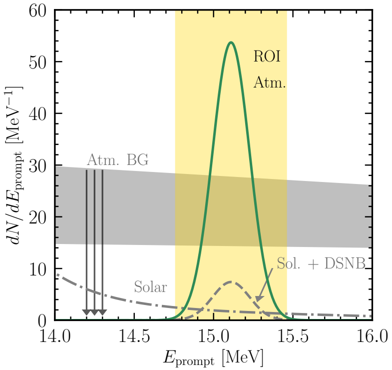
Fukugita et al. (1988), Pourkaviani & Mintz (1990), Kubodera & Nozawa (1993), Engel et al. (1996), Kolbe (1996), Samana et al. (2010)

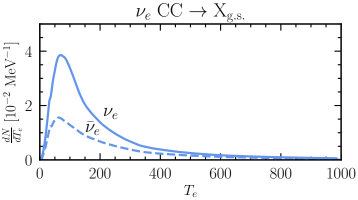
**NC channel detection: single events**

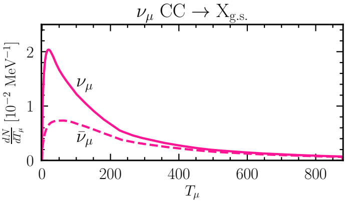
Irredicuble BG: solar and DSNB $\nu$

Reducible BG: atm. $\nu$ - p scattering

**85 kton yr exposure → 25(40)% uncertainty of the atmospheric $\nu$ rate**




**CC channel detection: coincidence events**

Irredicuble BG: accidental coincidences

Rate per 20 kton yr: 0.05; spatial cuts ↓

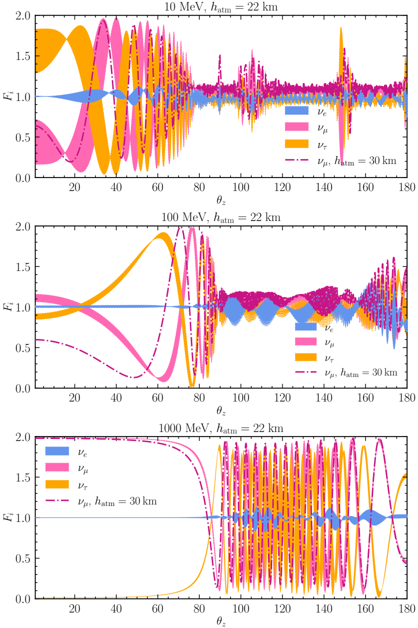
**esentially background free channels**

# Conclusions

- high statistic era of neutrino physics
- goal is exploring all the available channels
- high-precision measurements of the mixing parameters and neutrino fluxes
- exclusive nuclear channels $\rightarrow$ clean observables
- similar channels exist for different nuclei?

**Thank you for the attention!**

# Atmospheric neutrino oscillations



# EPT cross sections

$$\sigma(E_\nu) = \frac{3G_F^2}{2\pi} F_A^2 (E_\nu')^2 I \;, \quad \sigma(E_\nu) = \frac{3G_F^2}{\pi} \cos\theta_C^2 F_A^2 E_e p_e I \mathcal{F}^{\pm}(Z, E_e) \;, \tag{1}$$

$$I = \frac{1}{2}\int_{-1}^{1} dz f(\mathbf{q}^2)\,(A + B + C)\;, \tag{2}$$

$$f(\mathbf{q}^2) = \left(\frac{F_A(q)}{F_A}\right)^2 = \left(1 - \frac{1-\rho}{6(b|\mathbf{q}|)^2}\right)^2 \exp\left(-\frac{(b|\mathbf{q}|)^2}{2}\right)\;, \tag{3}$$

$$A = 1 - \frac{z}{3} \;\pm\; \frac{4}{3}(E_\nu + E_\nu')(1 - 2\sin^2\theta_W)(1-z)\,\frac{F_M}{F_A}\;, \tag{4}$$

$$B = \frac{2}{3}\left(E_\nu' E_\nu (1 - z^2) + (1-z)\mathbf{q}^2\right)(1 - 2\sin^2\theta_W)^2 \left(\frac{F_M}{F_A}\right)^2\;, \tag{5}$$

$$C = -\frac{2}{3}\Delta M(1+z)\frac{F_T}{F_A} \;+\; \frac{1}{3}(1+z)\mathbf{q}^2\left(\frac{F_M}{F_A}\right)^2\;. \tag{6}$$

# CQRPA cross sections