Latest results from Super-Kamiokande

Andrew Santos *(for the Super-K collaboration)*

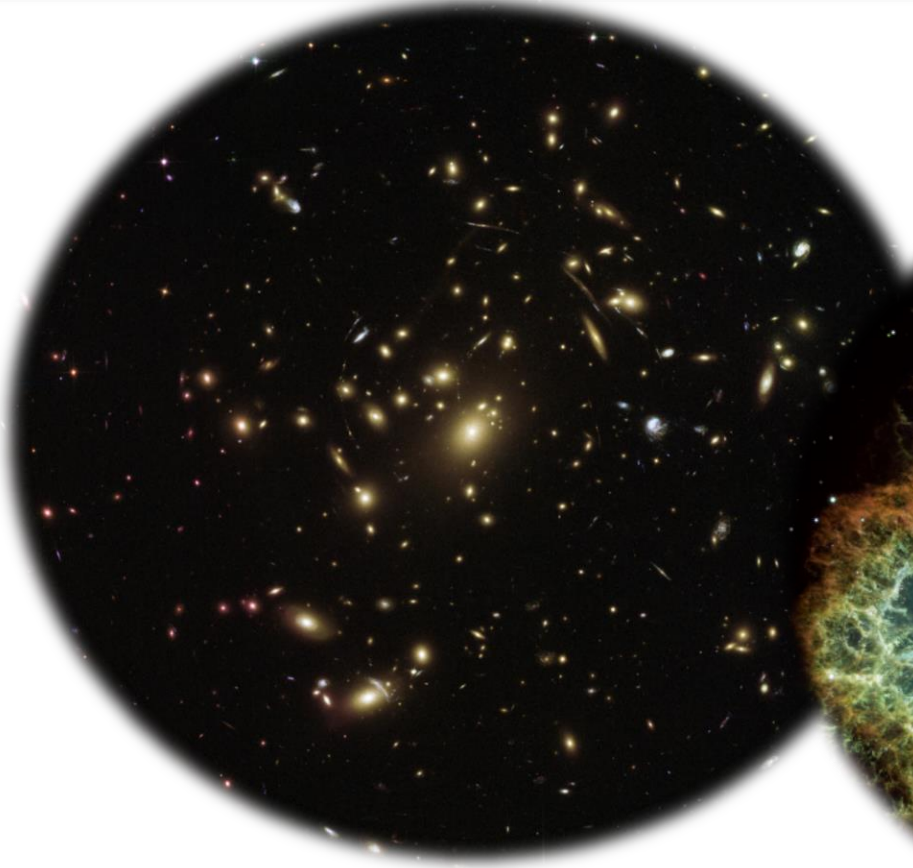
Laboratoire Leprince-Ringuet
École Polytechnique – IP Paris

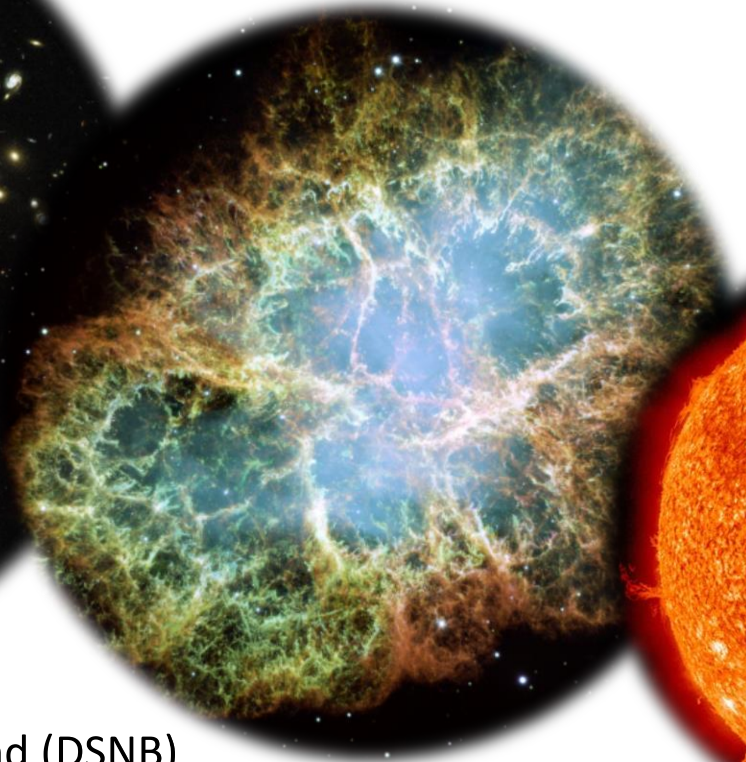
March 2024

Moriond EW

A journey through the universe with neutrinos

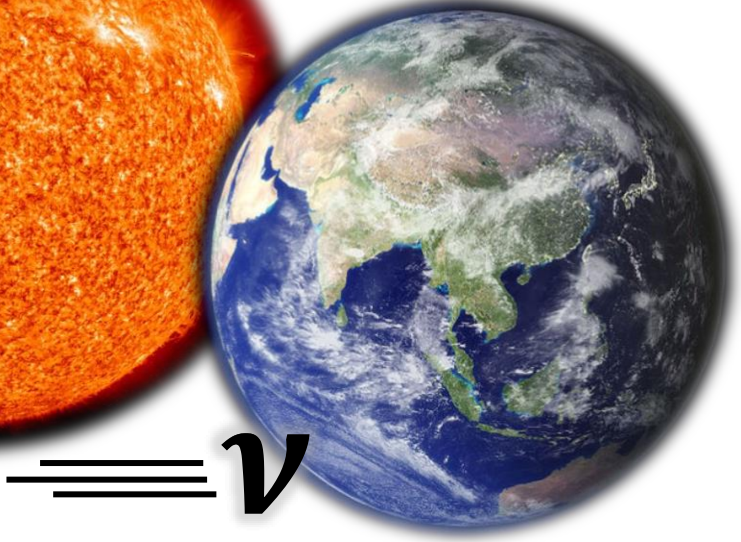
- Supernova burst ν
- Other transient ν





- Solar ν

- Atmospheric ν
- Accelerator ν
- Reactor ν
- Geophysical ν



- Diffuse Supernova Neutrino Background (DSNB)
- Cosmic neutrino background
- Dark matter search and more!

Why are we so excited about neutrinos?

- We have some **precision measurements** to do parameterizing flavor evolution and propagation!
- **Neutrinos can probe** objects that others cannot (or cannot do well)!
- They are a **gateway** to interesting, new physics (e.g., CP-violation for neutrinos??)

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{PMNS} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

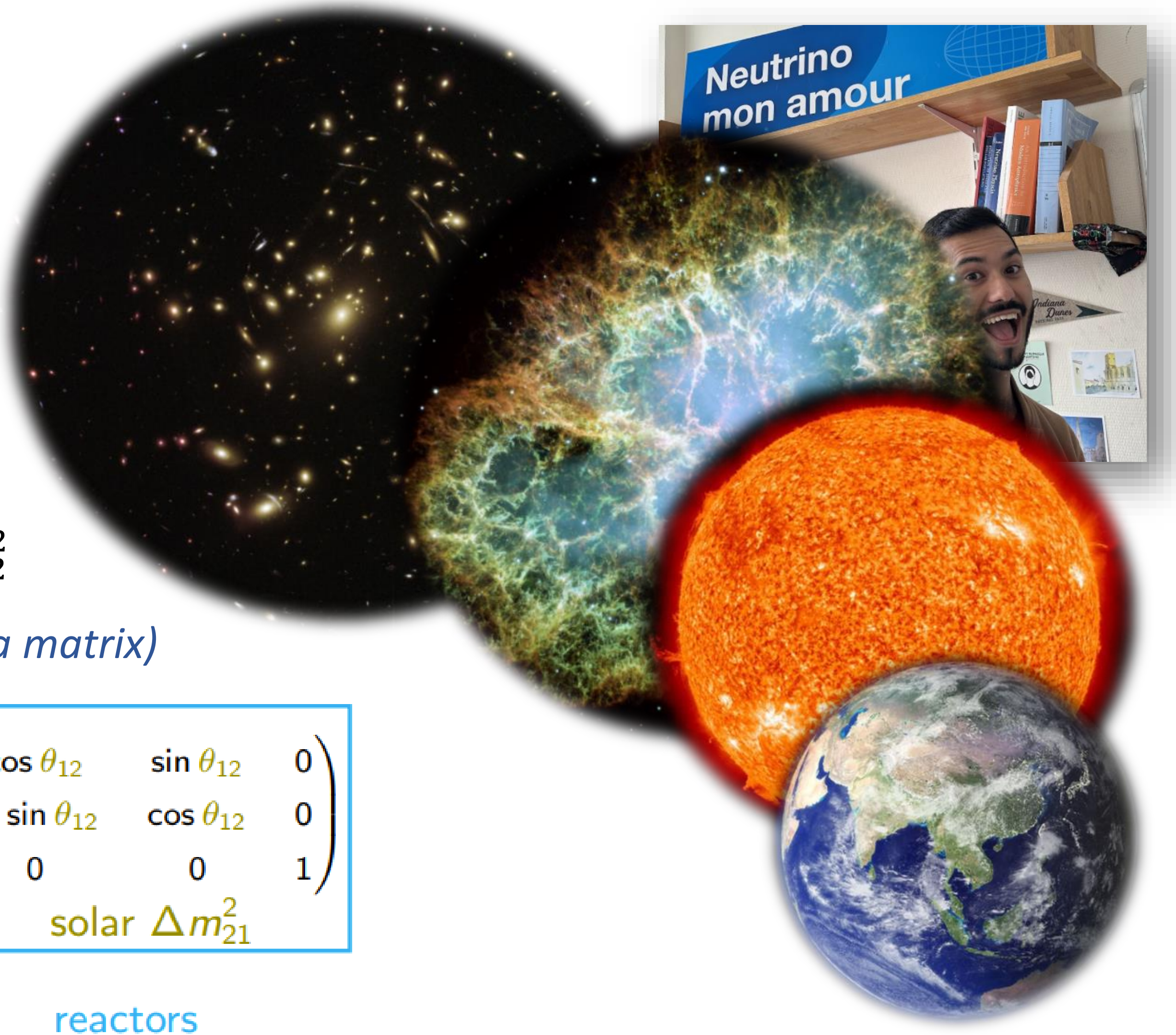
- "**Normal**" hierarchy: $m_1^2 < m_2^2 < \boldsymbol{m_3^2}$
- "**Inverted**" hierarchy: $\boldsymbol{m_3^2} < m_1^2 < m_2^2$

(Pontecorvo-Maki-Nakagawa-Sakata matrix)

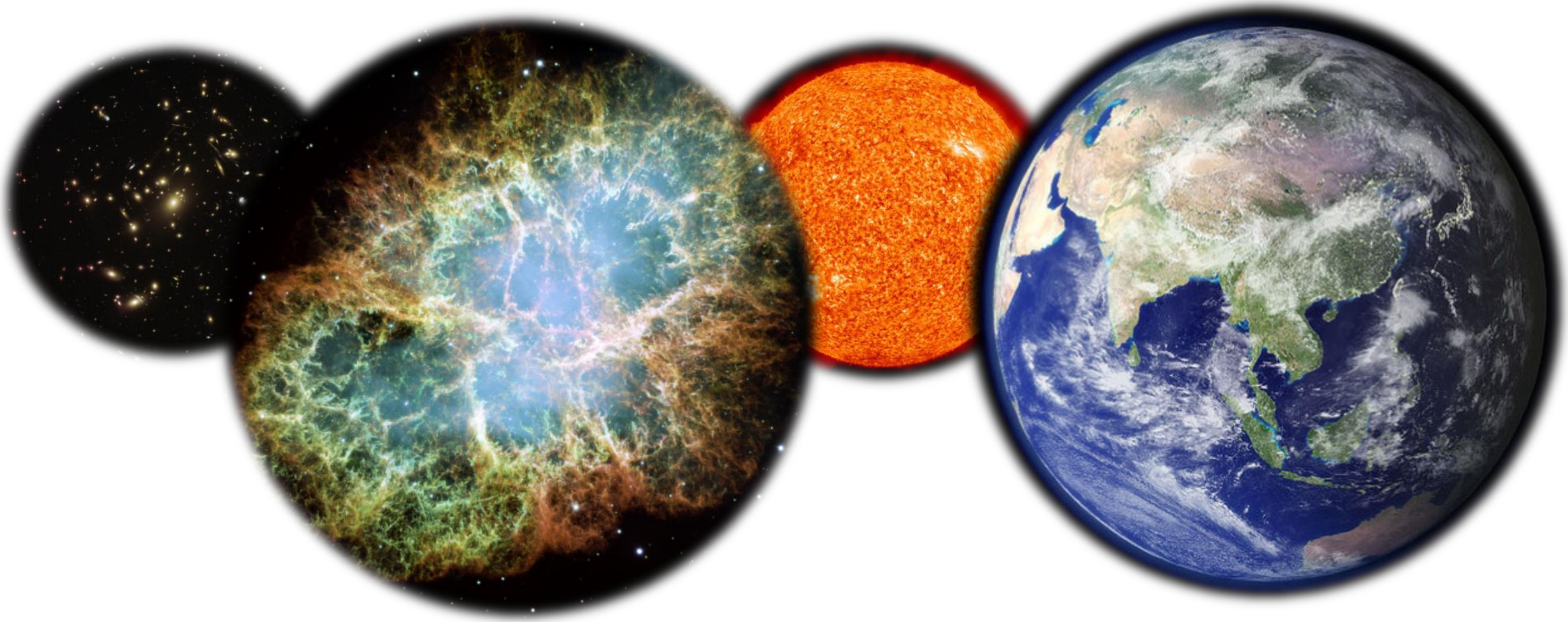
$$U_{\mathrm{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{+i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric Δm_{31}^2 solar Δm_{21}^2

accelerators reactors

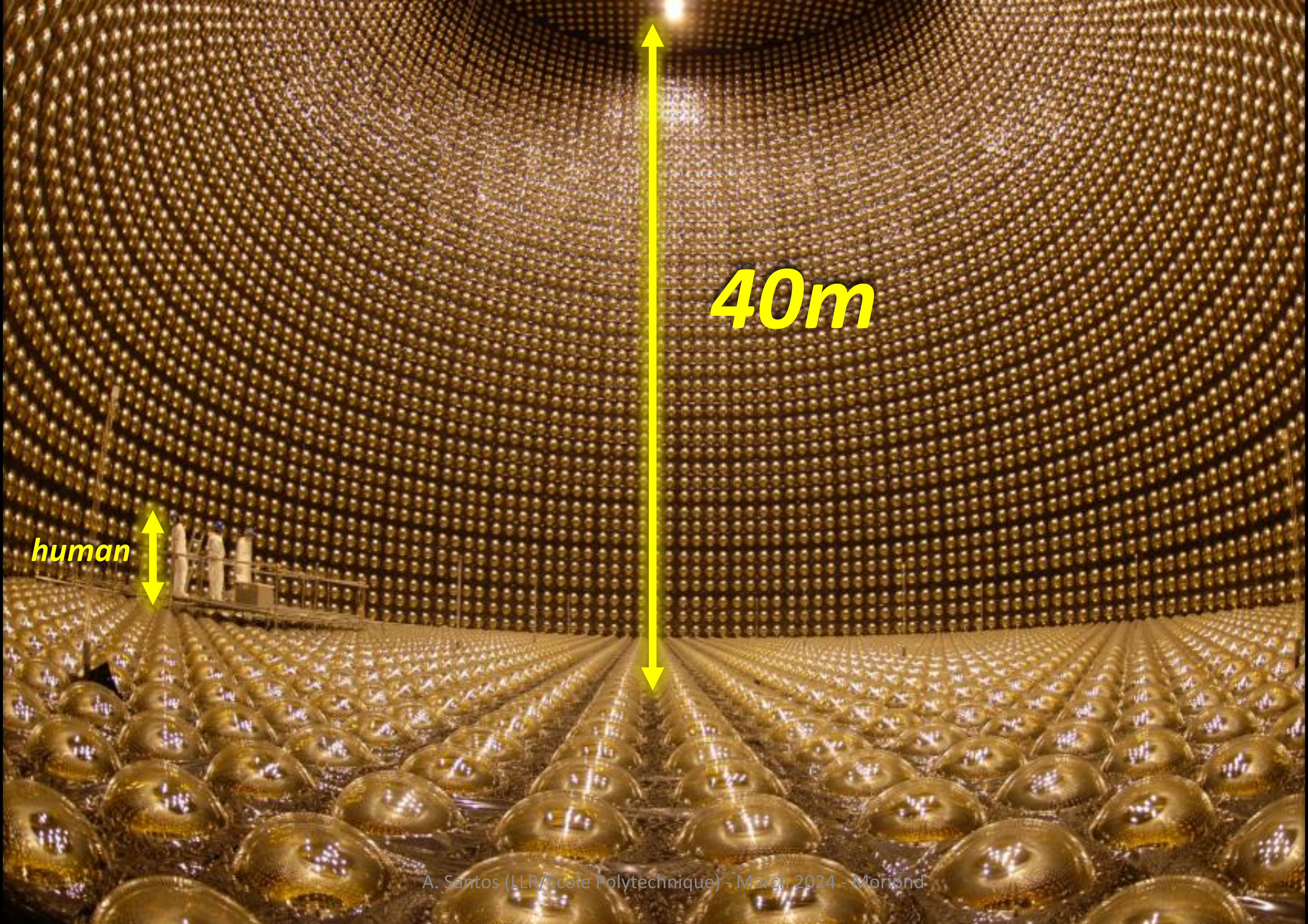


A storied history for the Kamiokande series



- 1987: Kamiokande experiment **observes supernova** with neutrinos for the first time!

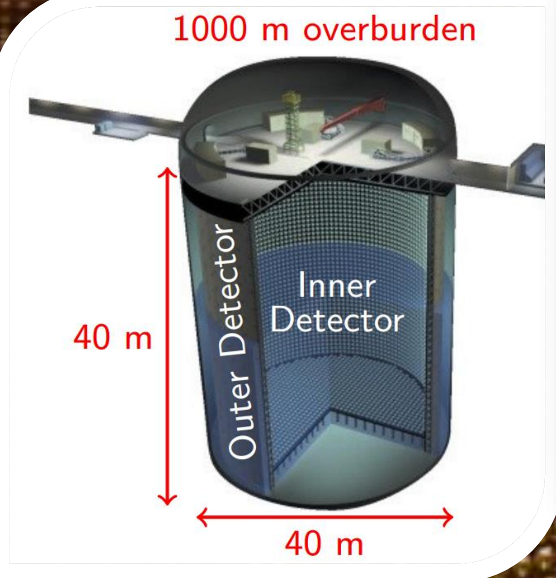
- 1998: Super-Kamiokande **observes neutrino oscillations** for the first time with atmospheric neutrinos!

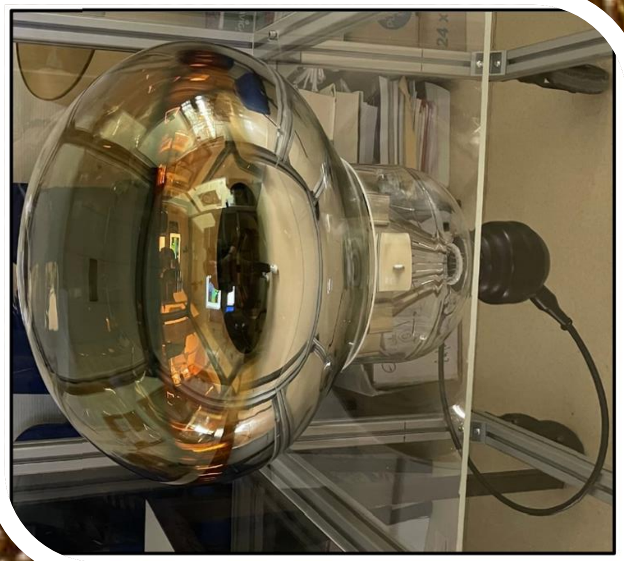

40m
human

Super-Kamiokande: A bedazzled water tank for neutrinos

Phase	SK-I	SK-II	SK-III	SK-IV
Begin	Apr. 1996	Dec. 2002	July 2006	Sep. 2008
End	June 2001	Nov. 2005	Sep. 2008	June 2018
ID PMTs	11,146	5,182	11,129	11,129
Electronics	ATM	ATM	ATM	QBEE
Trigger	Hardware	Hardware	Hardware	Software
DSNB trigger	SHE	SHE	SHE	SHE+AFT
Water	pure	pure	pure	pure

Phase	SK-V	SK-VI	SK-VII	Total
Begin	Feb. 2019	July 2020	June 2022	Apr. 1996
End	July 2020	June 2022	(running)	(running)
ID PMTs	11,129	11,129	11,129	-
Electronics	QBEE	QBEE	QBEE	-
Trigger	Software	Software	Software	-
DSNB trigger	SHE+AFT	SHE+AFT	SHE+AFT	-
Water	pure	0.01% Gd	0.03% Gd	-





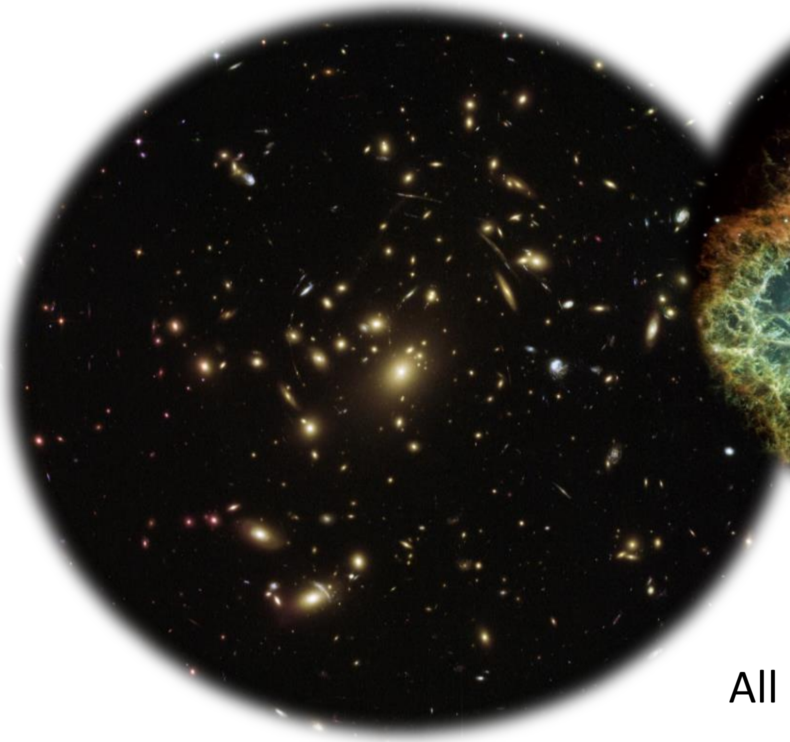
- Running **since 1996** (denoted by phases I-VII).
- Around **11 000 PMTs in inner detector** with an outer detector muon veto.
- **Gadolinium-doped** water since 2020 for easier neutron capture identification!

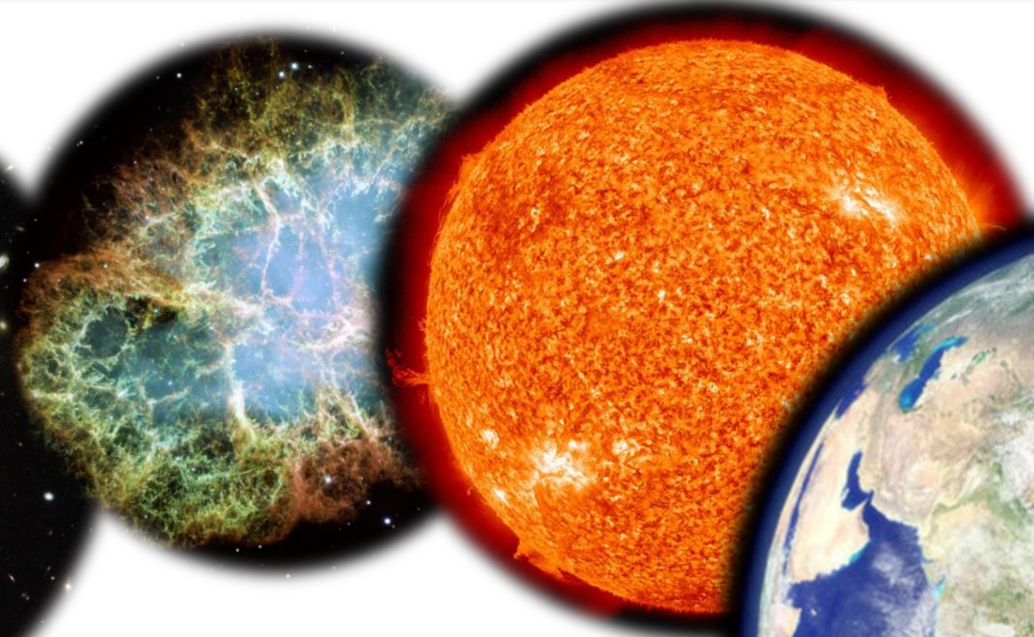
Super-Kamiokande: Hundreds of scientists across the world

(me with the Super-K collaboration in 2023!)

Photomultiplier tubes! → **Extracting physics!**

All our physics with Cherenkov radiation





(Let's see our latest results!)

All we know per PMT:

- Where is it?
- How much light did it see?
- When did it see the light?

Some of the latest Super-Kamiokande results (pg. 1/2)

- Atmospheric neutrinos
  - **Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I-V**
    T. Wester et al., arXiv:2311.05105 (**2023**)
- Solar neutrinos
  - **Solar neutrino measurements using the full data period of Super-Kamiokande-IV**
    K. Abe et al., arXiv:2312.12907 (**2023**)
  - **Search for Periodic Time Variations of the Solar ^{8}B Neutrino Flux Between 1996 and 2018 in Super-Kamiokande**
    K. Abe et al., arXiv:2311.01159 (**2023**)
- Supernova neutrinos
  - **Performance of SK-Gd's Upgraded Real-time Supernova Monitoring System**
    Y. Kashiwagi et al., arXiv:2403.06760 (**2024**)
  - **Searching for Supernova Bursts in Super-Kamiokande IV**
    M. Mori et al., ApJ. 938 (2022) 1, 23
- Diffuse Supernova Neutrino Background
  - **Search for Astrophysical Electron Antineutrinos in Super-Kamiokande with 0.01% Gadolinium-loaded Water**
    M. Harada et al., ApJL 951 (**2023**) 2, L27
  - **Diffuse Supernova Neutrino Background Search at Super-Kamiokande**
    K. Abe et al., PRD 104 (2021) 12, 122002

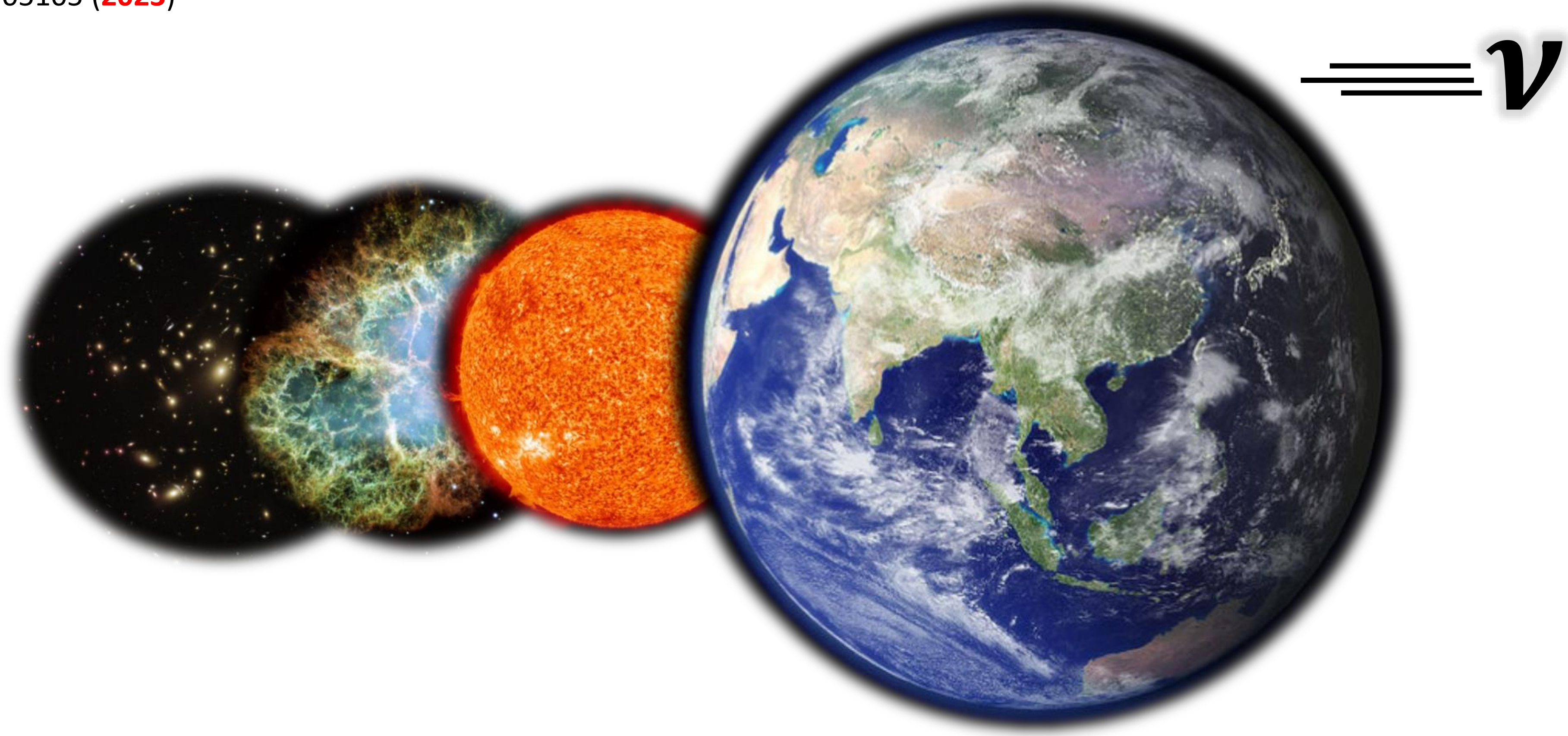
Some of the latest Super-Kamiokande results (pg. 2/2)

- Neutrino astrophysics
  - **Search for neutrinos in coincidence with gravitational wave events from the LIGO-Virgo O3a Observing Run with the Super-Kamiokande detector**
    K. Abe et al., ApJ 918 (2021) 2, 78
  - **Search for tens of MeV neutrinos associated with gamma-ray bursts in Super-Kamiokande**
    A. Orii et al., PTEP 2021 (2021) 10, 103F01
- Proton decay and other baryon number violating processes
  - **Search for proton decay via $p \to \mu K^0$ in 0.37 megaton-years exposure of Super-Kamiokande**
    R. Matsumoto et al., PRD 106 (2022) 7, 072003
  - **Neutron-antineutron oscillation search using a 0.37 megaton-years exposure of Super-Kamiokande**
    K. Abe et al., PRD 103 (2021) 1, 012008
- Dark matter search
  - **Search for Cosmic-Ray Boosted Sub-GeV Dark Matter Using Recoil Protons at Super-Kamiokande**
    K. Abe et al., PRL 130 (**2023**) 3, 031802
- Gadolinium loading of tank
  - **Second gadolinium loading to Super-Kamiokande**
    K. Abe et al., arXiv:2403.07796 (**2024**)

Atmospheric neutrinos!

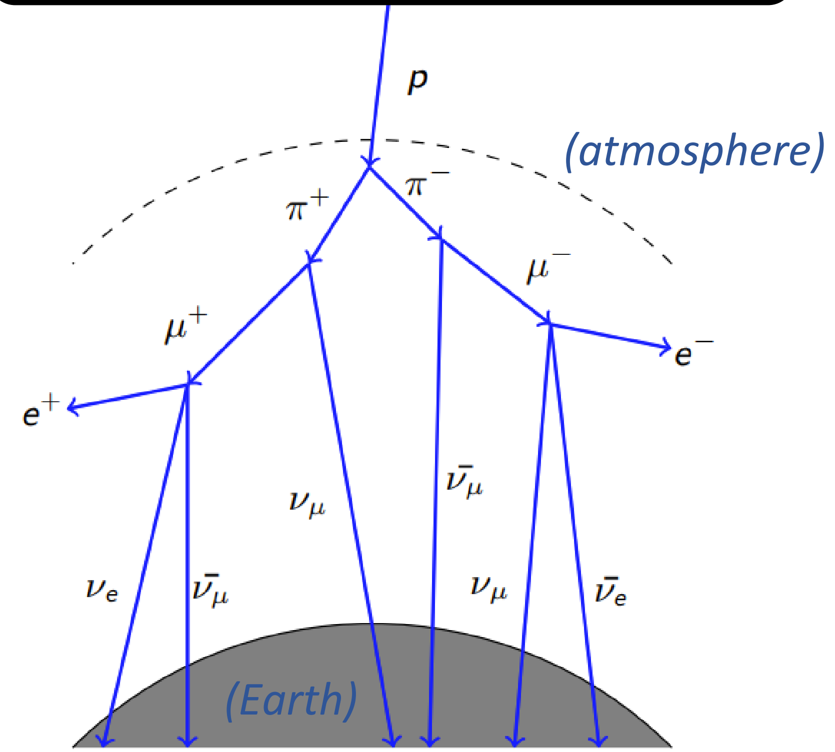
Atmospheric neutrino oscillation analysis with neutron tagging and an expanded fiducial volume in Super-Kamiokande I-V

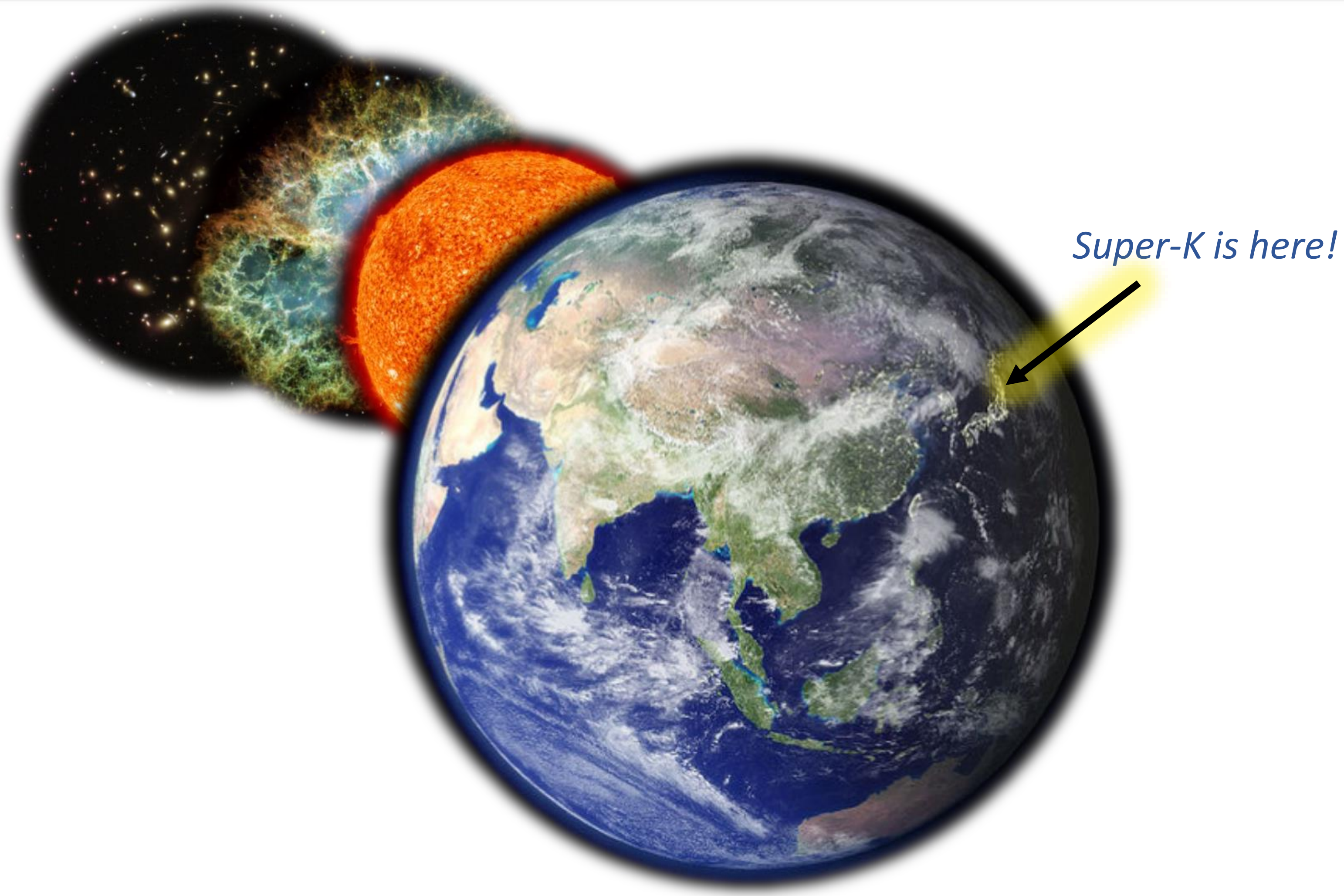
T. Wester et al., arXiv:2311.05105 (**2023**)



Extracting physics from atmospheric neutrino oscillations

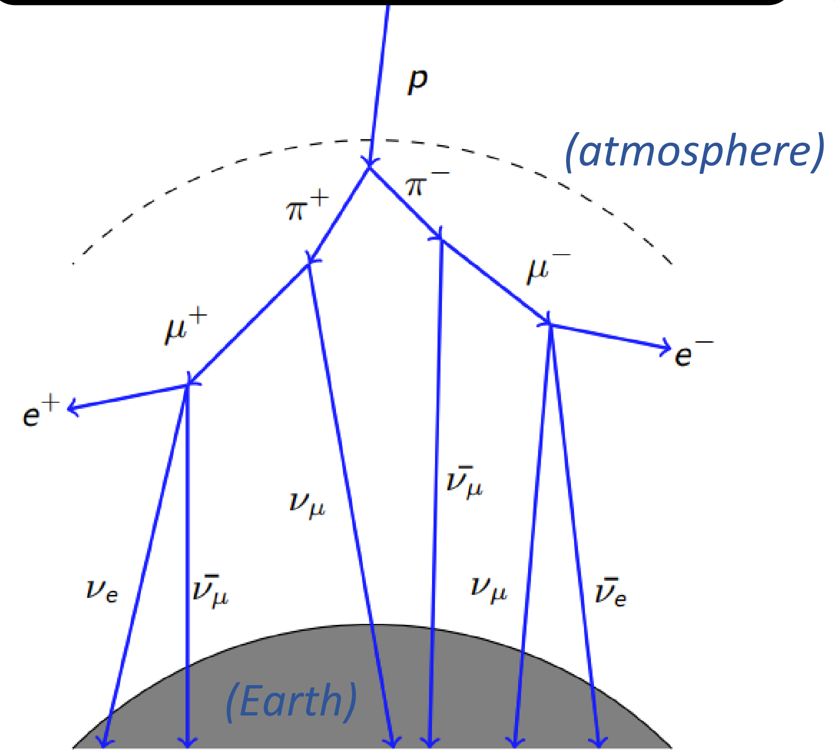
Neutrinos produced by cosmic rays!



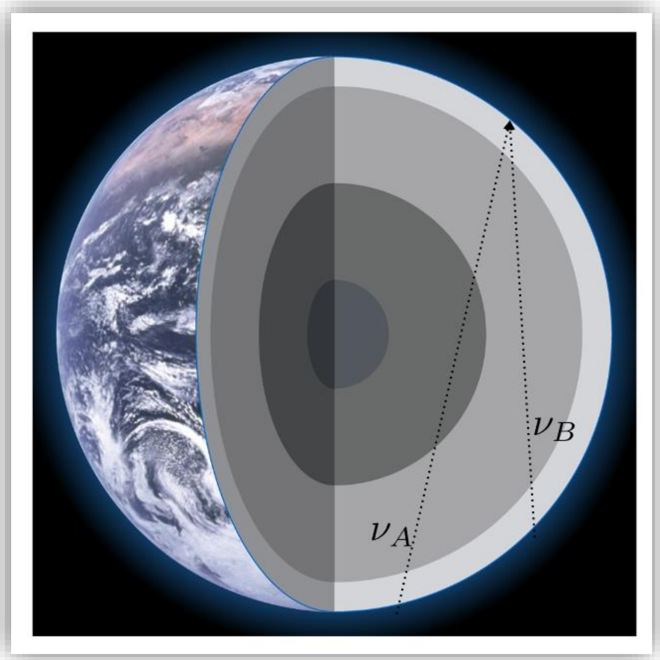


Extracting physics from atmospheric neutrino oscillations

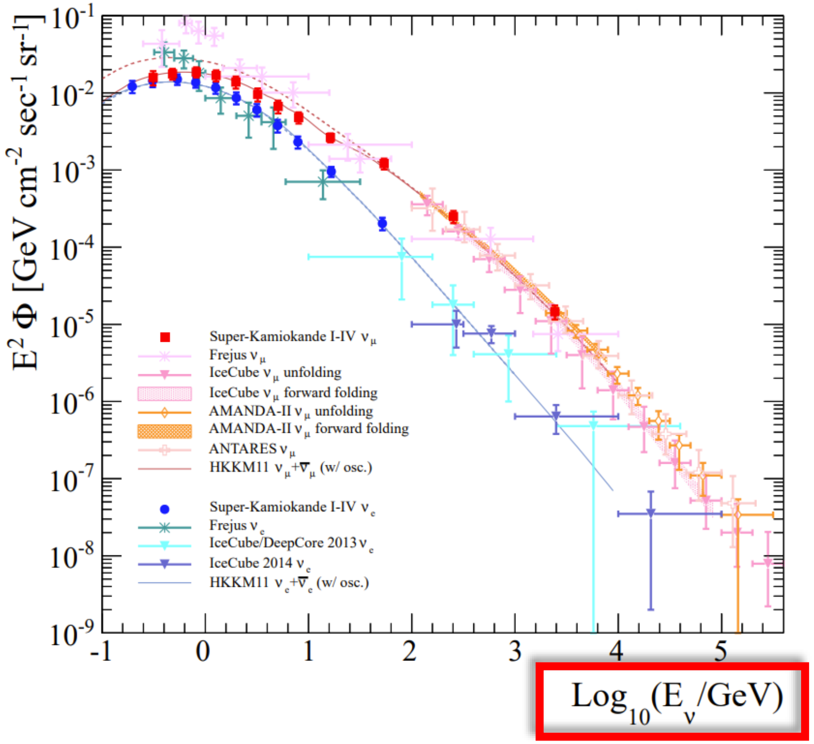
Neutrinos produced by cosmic rays!



Large range in energy and distances!

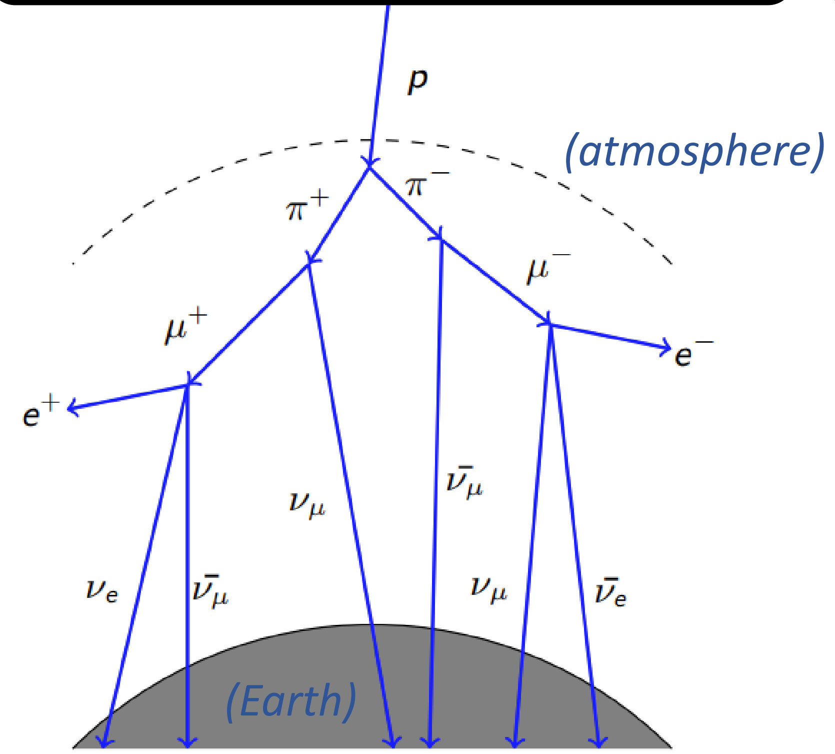


E. Richard et al., PRD ***94,*** *052001 (2016)*

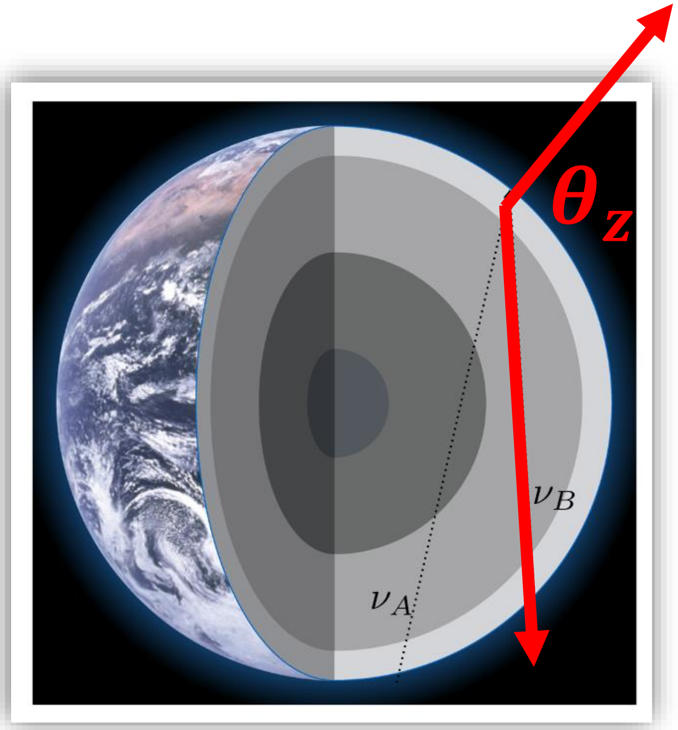


Extracting physics from atmospheric neutrino oscillations

Neutrinos produced by cosmic rays!

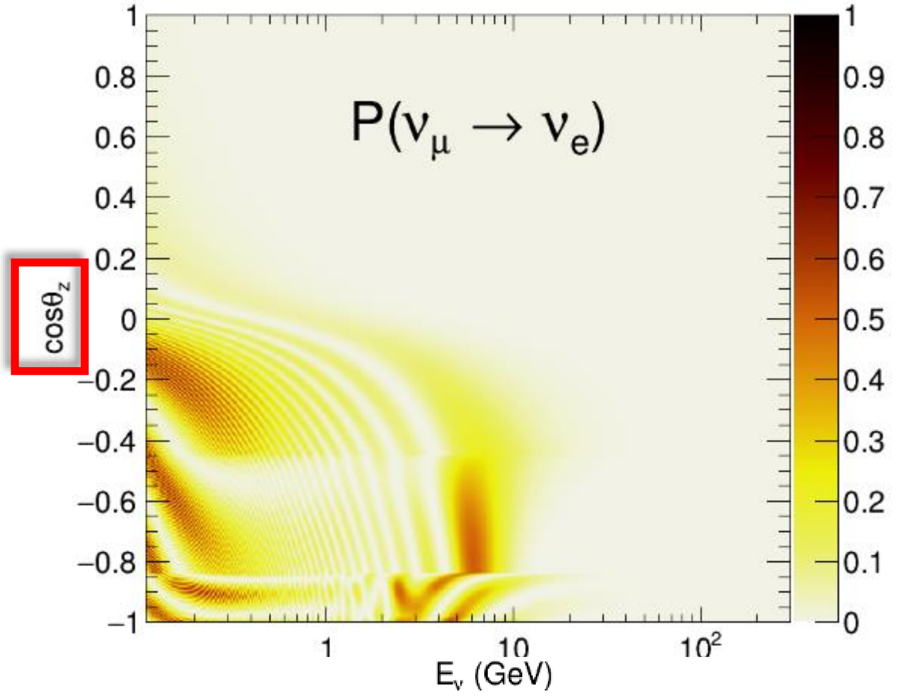


Large range in energy and distances!

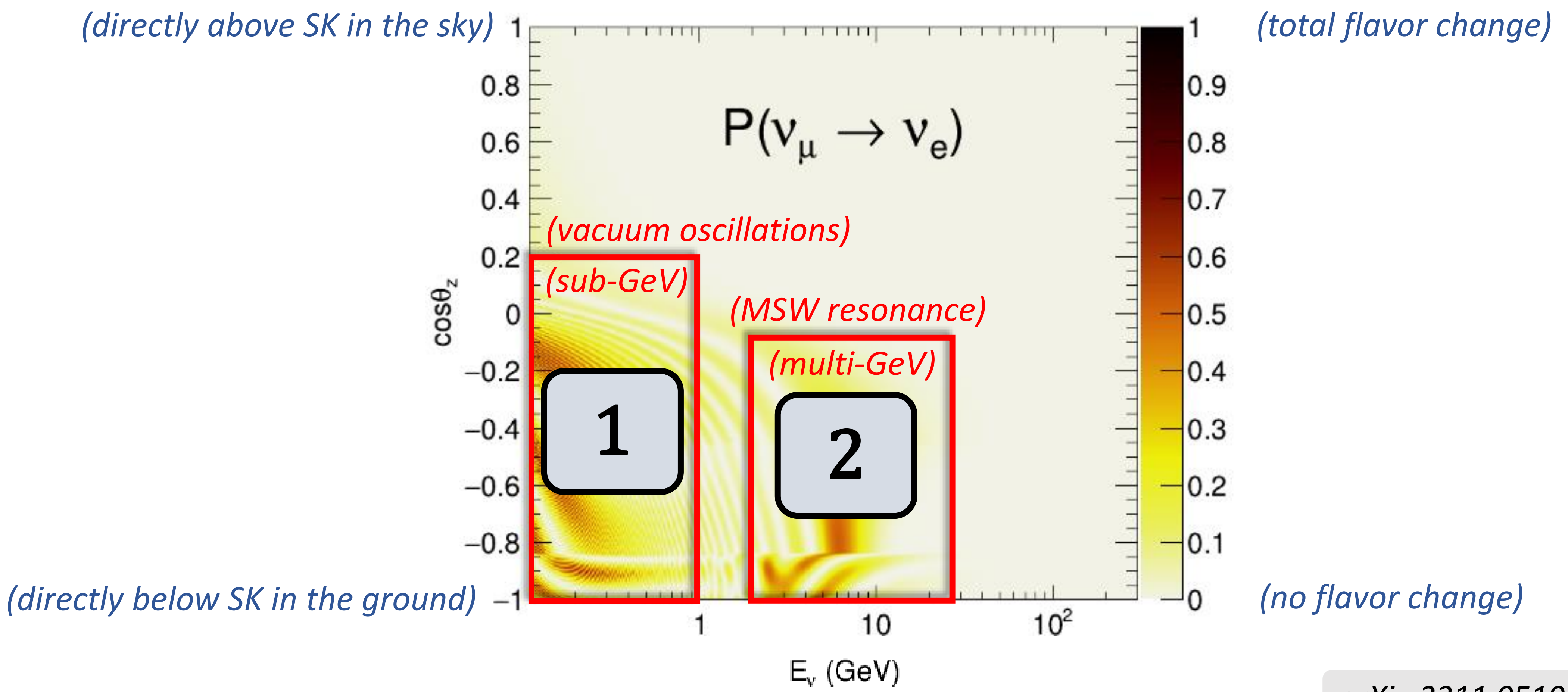


Rich landscape of flavor oscillations!

arXiv:2311.05105v1 (2023)



Extracting physics from atmospheric neutrino oscillations



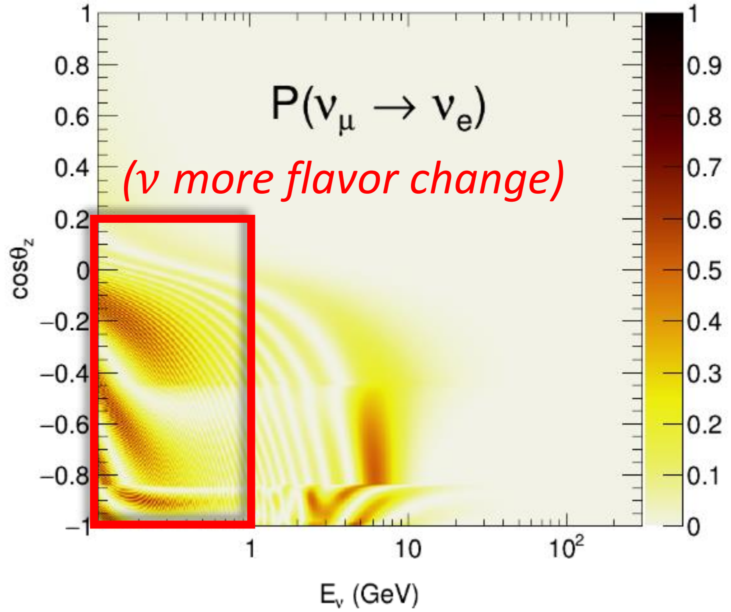
arXiv:2311.05105v1 (2023)

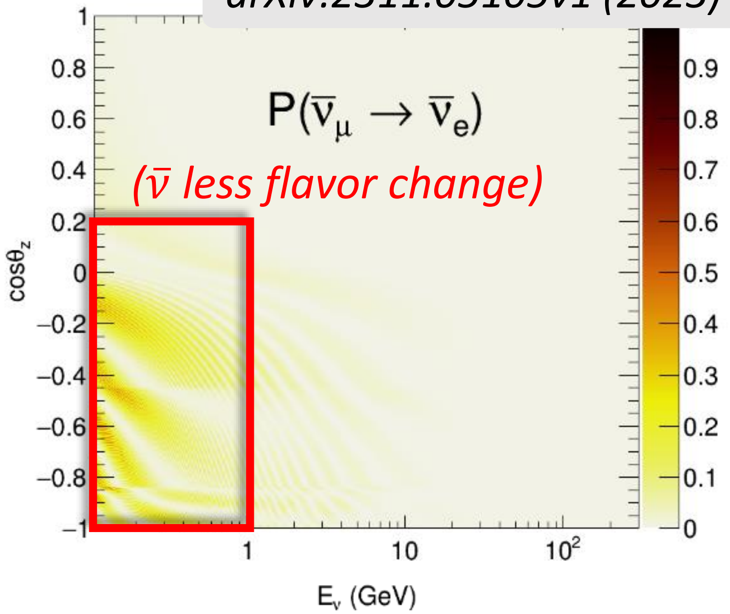
Extracting physics from atmospheric neutrino oscillations

arXiv:2311.05105v1 (2023)

CP-violation (ν-vs-$\bar{\nu}$)

- For $\delta_{CP} \neq 0, \pi$, neutrino and anti-neutrino $\boldsymbol{P_{\mu e}}$ **will differ**.
- These demonstrative plots set the **CP-violating phase** at $\delta_{CP} = -\pi/2$.





1

(vacuum oscillations)

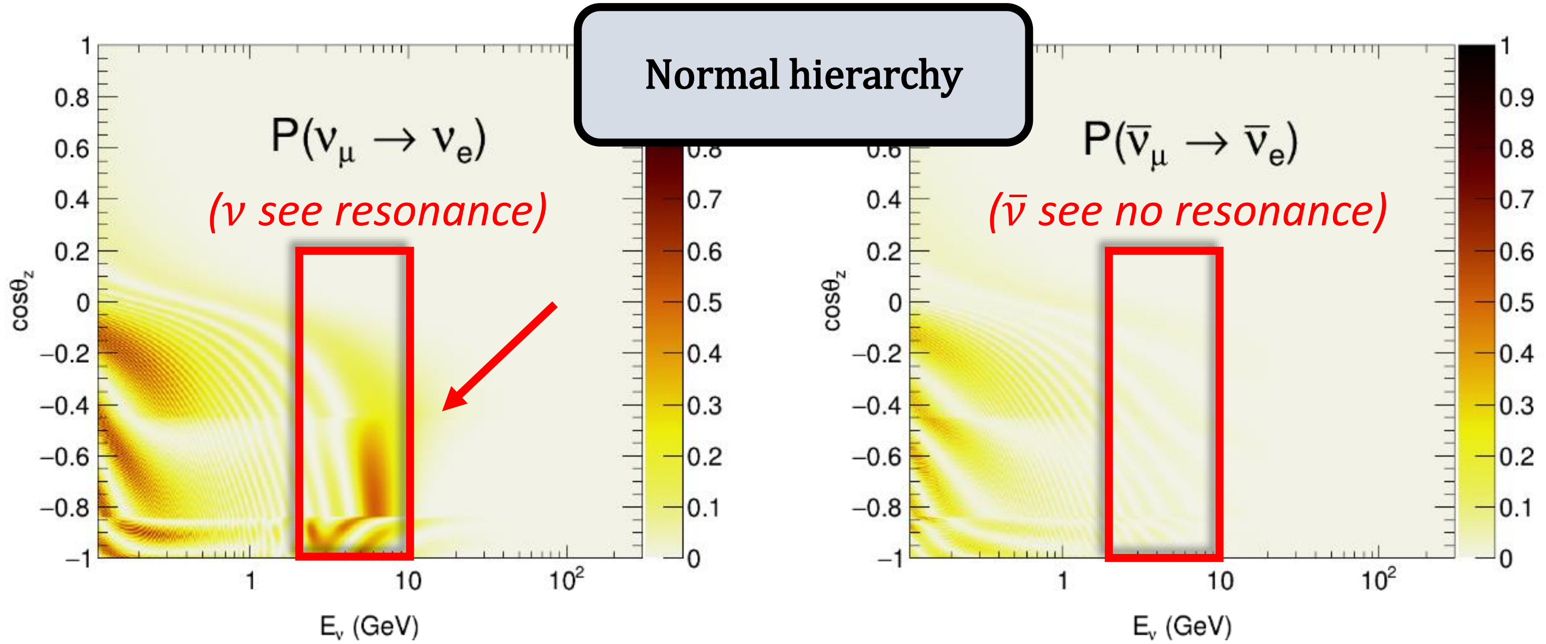
Extracting physics from atmospheric neutrino oscillations

2

(MSW resonance)

Mass hierarchy (high-energy resonance)

- The MSW **resonant electron density** n_e depends on neutrino **mixing**, **mass hierarchy**, and **energy**.



arXiv:2311.05105v1 (2023)

- "**Normal**" hierarchy: $m_1^2 < m_2^2 < \boldsymbol{m_3^2}$
- "**Inverted**" hierarchy: $\boldsymbol{m_3^2} < m_1^2 < m_2^2$

$$n_e = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2} G_F E_\nu}$$

(Mikheyev-Smirnov-Wolfenstein resonance)

Extracting physics from atmospheric neutrino oscillations

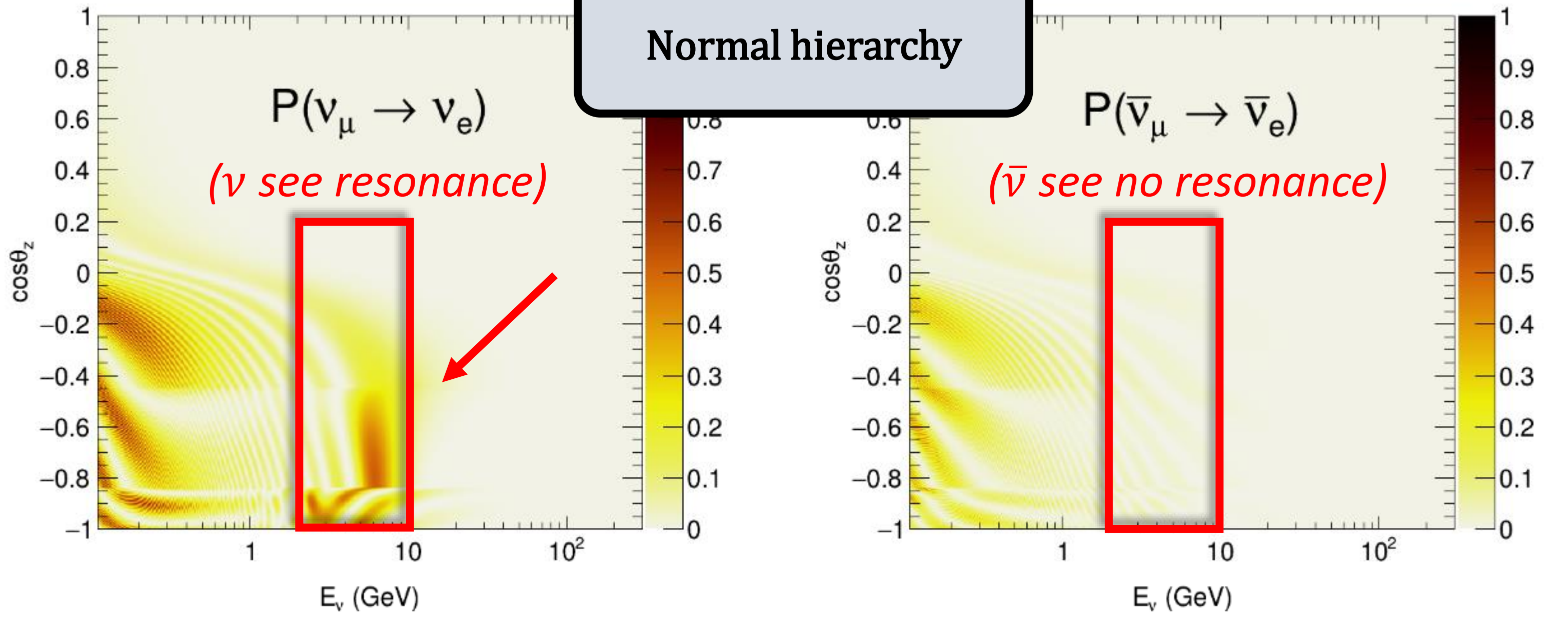
2

(MSW resonance)

Mass hierarchy (high-energy resonance)

- The MSW **resonant electron density** n_e depends on neutrino **mixing**, **mass hierarchy**, and **energy**.
- If neutrinos see a resonance, anti-neutrinos will not (and vice-versa).

Normal hierarchy



arXiv:2311.05105v1 (2023)

- "**Normal**" hierarchy: $m_1^2 < m_2^2 < \boldsymbol{m_3^2}$
- "**Inverted**" hierarchy: $\boldsymbol{m_3^2} < m_1^2 < m_2^2$

$$n_e = \frac{\Delta m_{31}^2 \cos 2\theta_{13}}{2\sqrt{2} G_F E_\nu}$$

(Mikheyev-Smirnov-Wolfenstein resonance)

Extracting physics from atmospheric neutrino oscillations

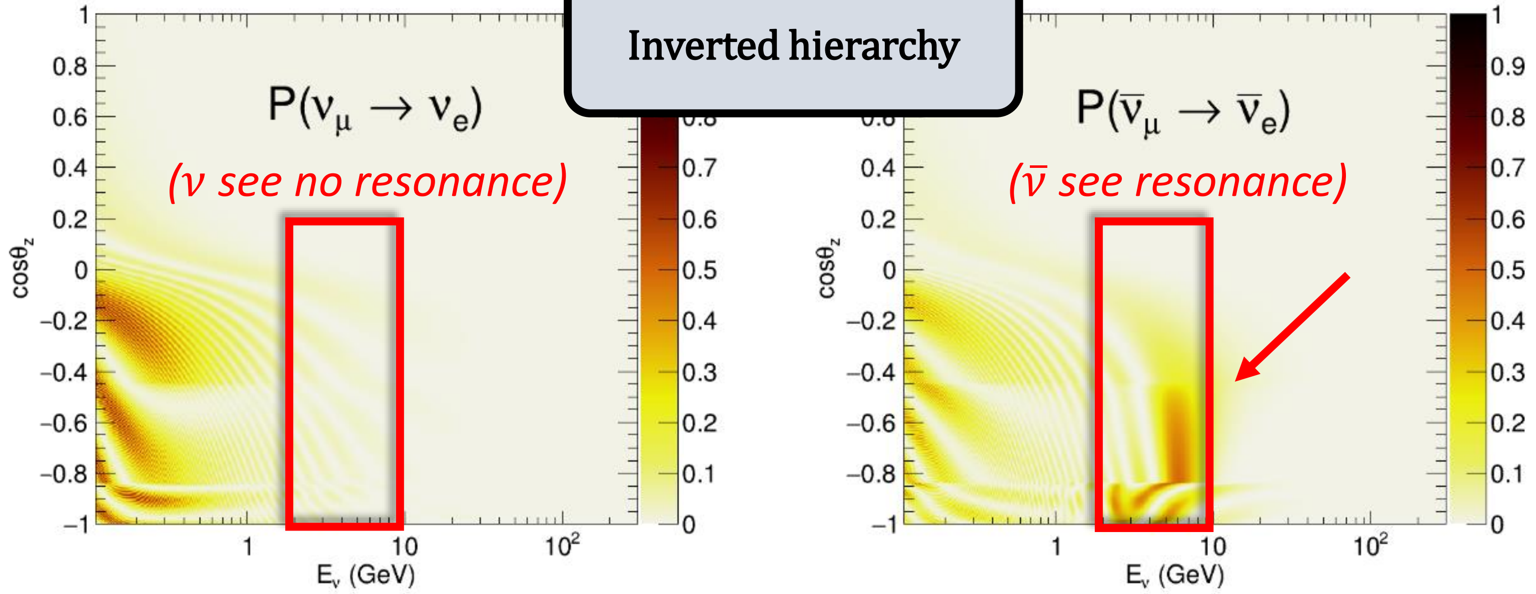
2

(MSW resonance)

Mass hierarchy (high-energy resonance)

- The MSW **resonant electron density** n_e depends on neutrino **mixing**, **mass hierarchy**, and **energy**.
- If neutrinos see a resonance, anti-neutrinos will not (and vice-versa).
- Normal-vs-inverted **mass hierarchy changes the sign** of Δm^2_{31}.

Inverted hierarchy



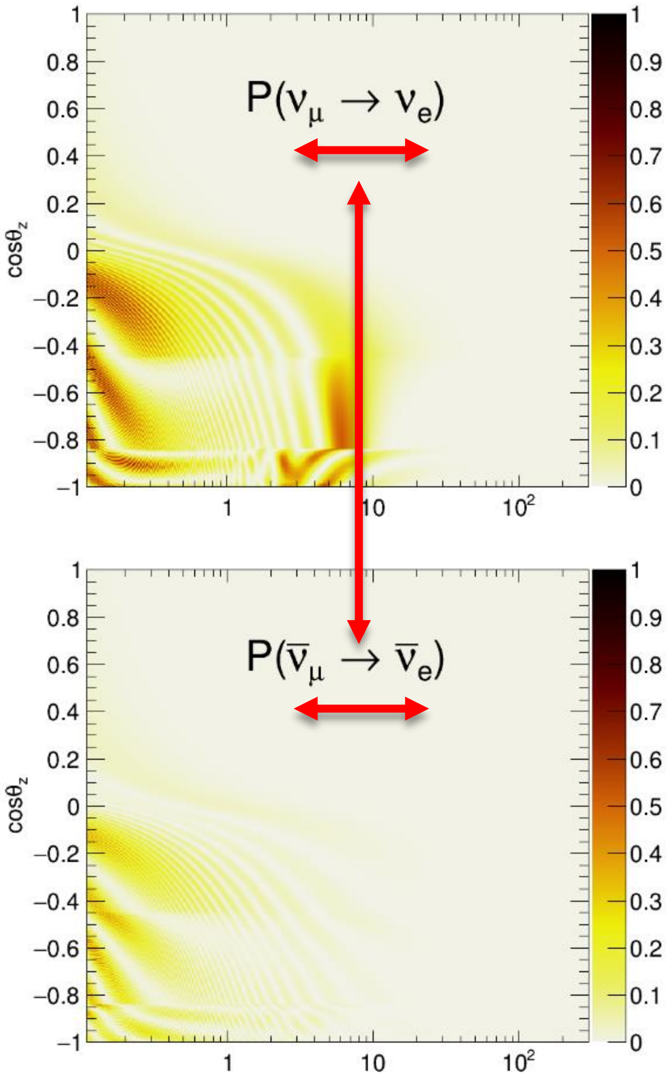
arXiv:2311.05105v1 (2023)

- "**Normal**" hierarchy: $m_1^2 < m_2^2 < \boldsymbol{m_3^2}$
- "**Inverted**" hierarchy: $\boldsymbol{m_3^2} < m_1^2 < m_2^2$

$$n_e = \frac{\Delta m^2_{31} \cos 2\theta_{13}}{2\sqrt{2} G_F E_\nu}$$

(Mikheyev-Smirnov-Wolfenstein resonance)

From atmospheric oscillations to physics results

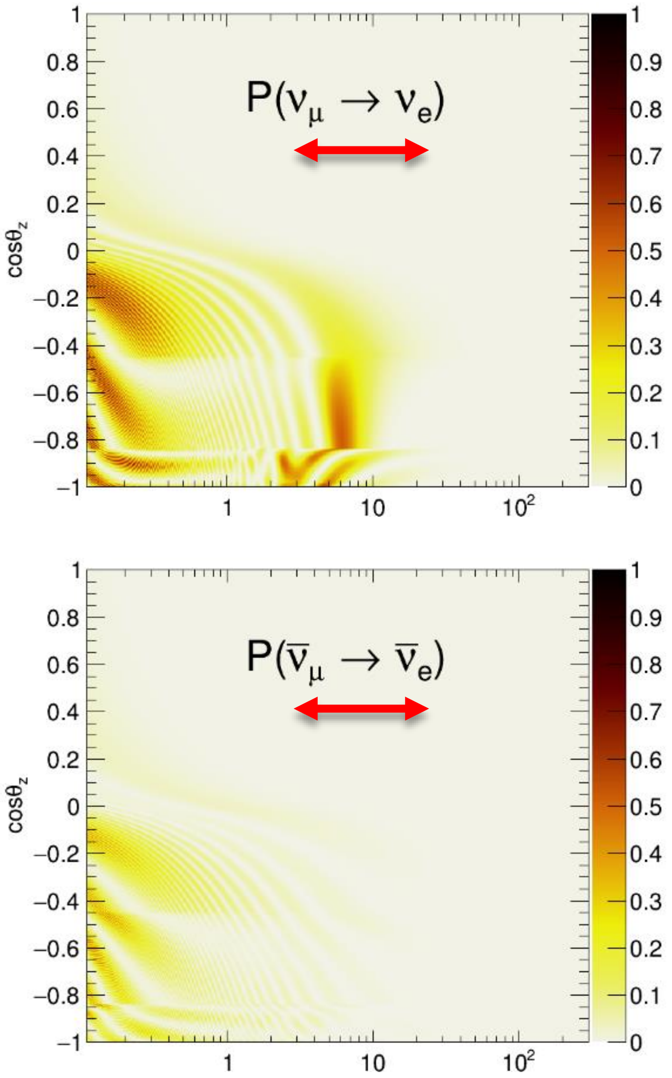


Need some μ/e and $\nu/\bar{\nu}$ separation!

Oscillations! → *Physics!*

arXiv:2311.05105v1 (2023)

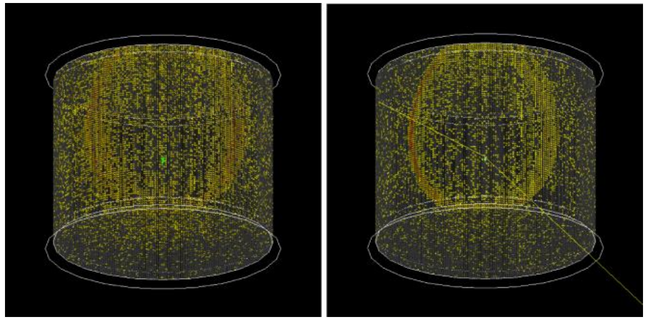
From atmospheric oscillations to physics results

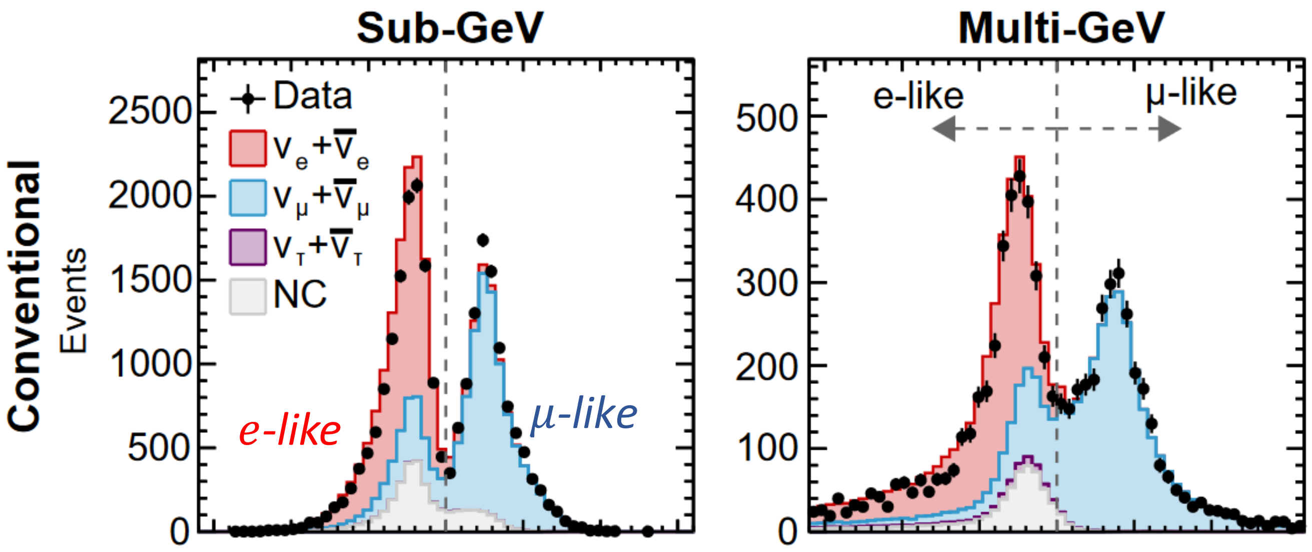


Main sample selection steps

- Fully-contained (expanded fiducial volume)
- e-like vs μ-like (event topology)

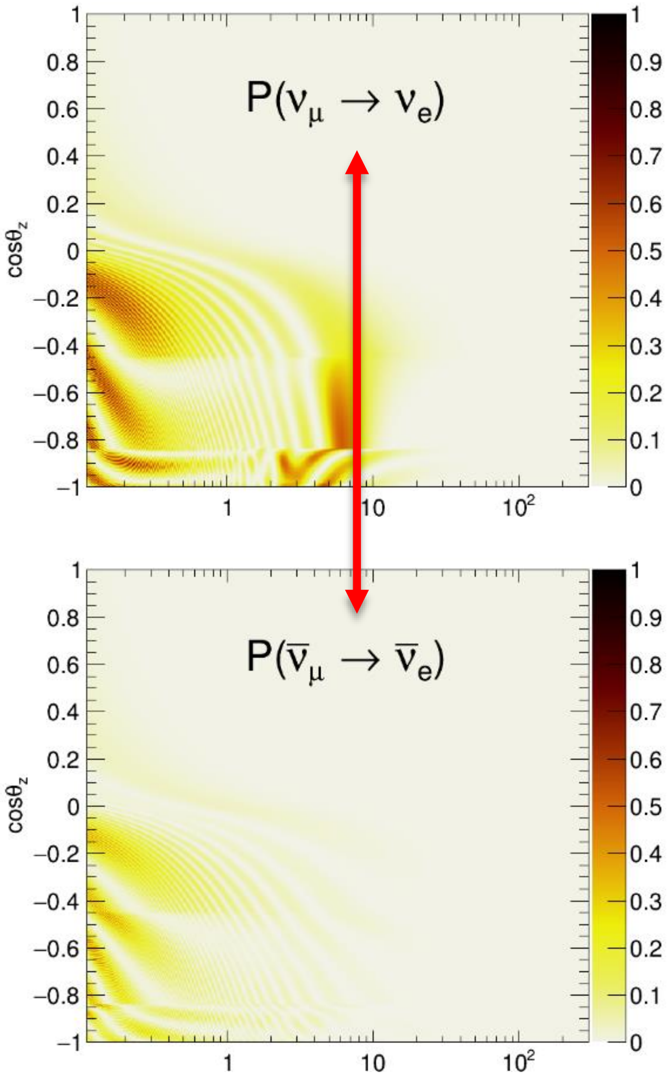
(e-like event) *(μ-like event)*





arXiv:2311.05105v1 (2023)

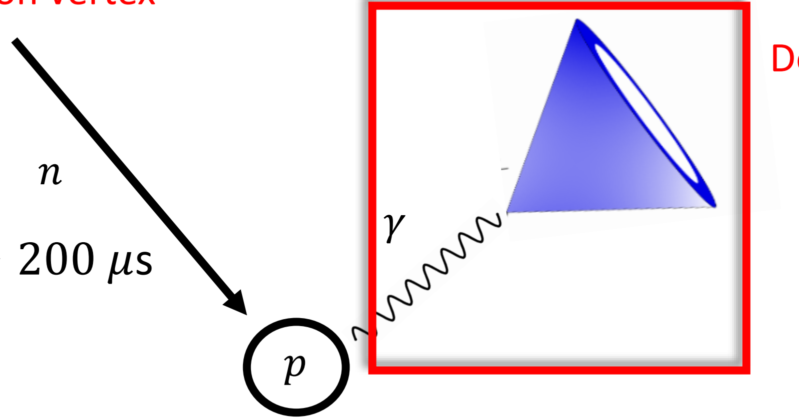
From atmospheric oscillations to physics results



Main sample selection steps

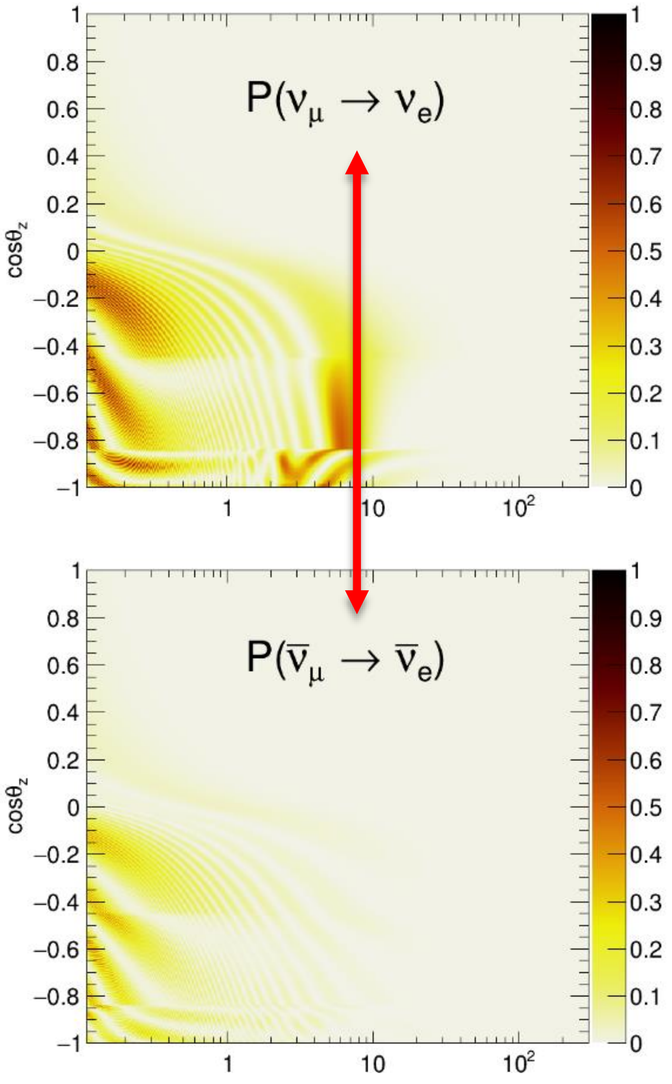
- Fully-contained (expanded fiducial volume)
- e-like vs μ-like (event topology)
- New neutron tagging (ν vs $\bar{\nu}$ interactions)

$$\bar{\nu}_l + p \to l^+ + n + X$$



arXiv:2311.05105v1 (2023)

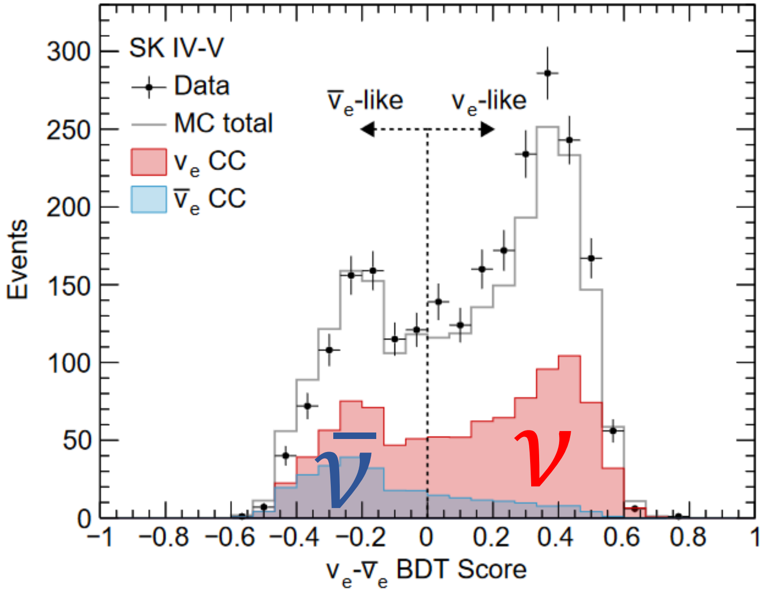
From atmospheric oscillations to physics results

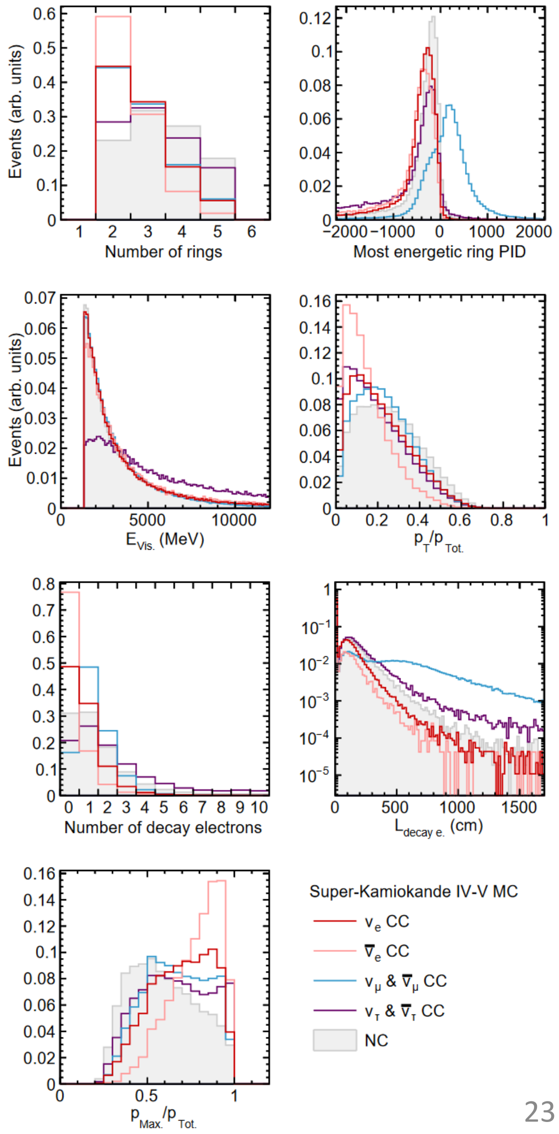


arXiv:2311.05105v1 (2023)

Main sample selection steps

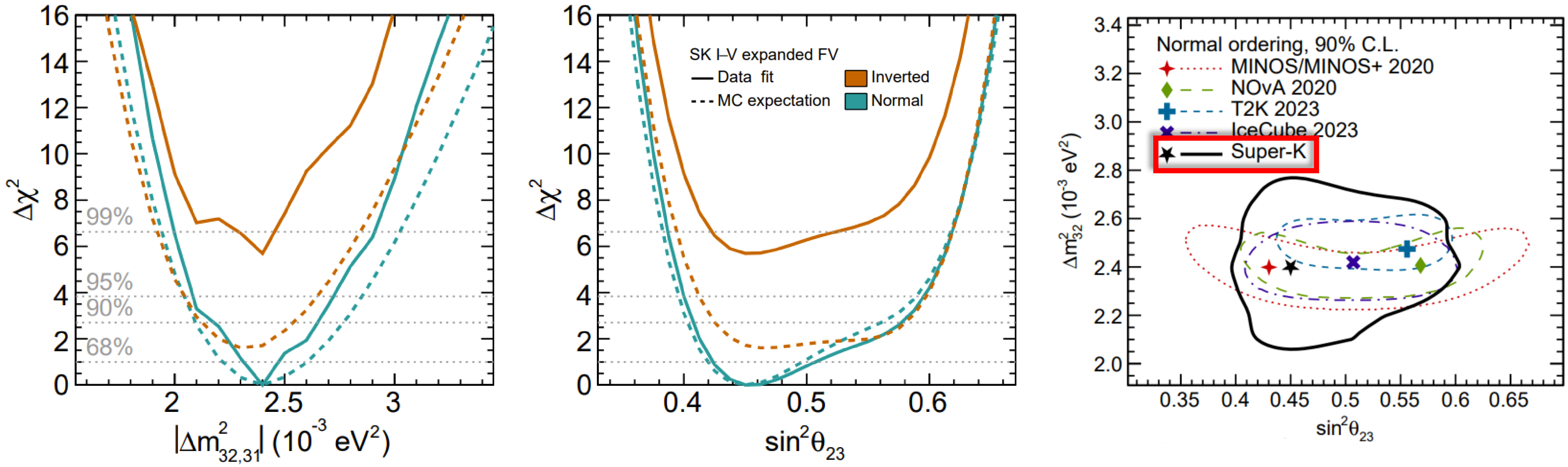
- Fully-contained (expanded fiducial volume)
- e-like vs μ-like (event topology)
- New neutron tagging (ν vs $\bar{\nu}$ interactions)
- New BDT for enhanced ν samples from $\bar{\nu}$





Latest Results: Atmospheric mixing parameters $\Delta m_{32,31}$, θ_{23}

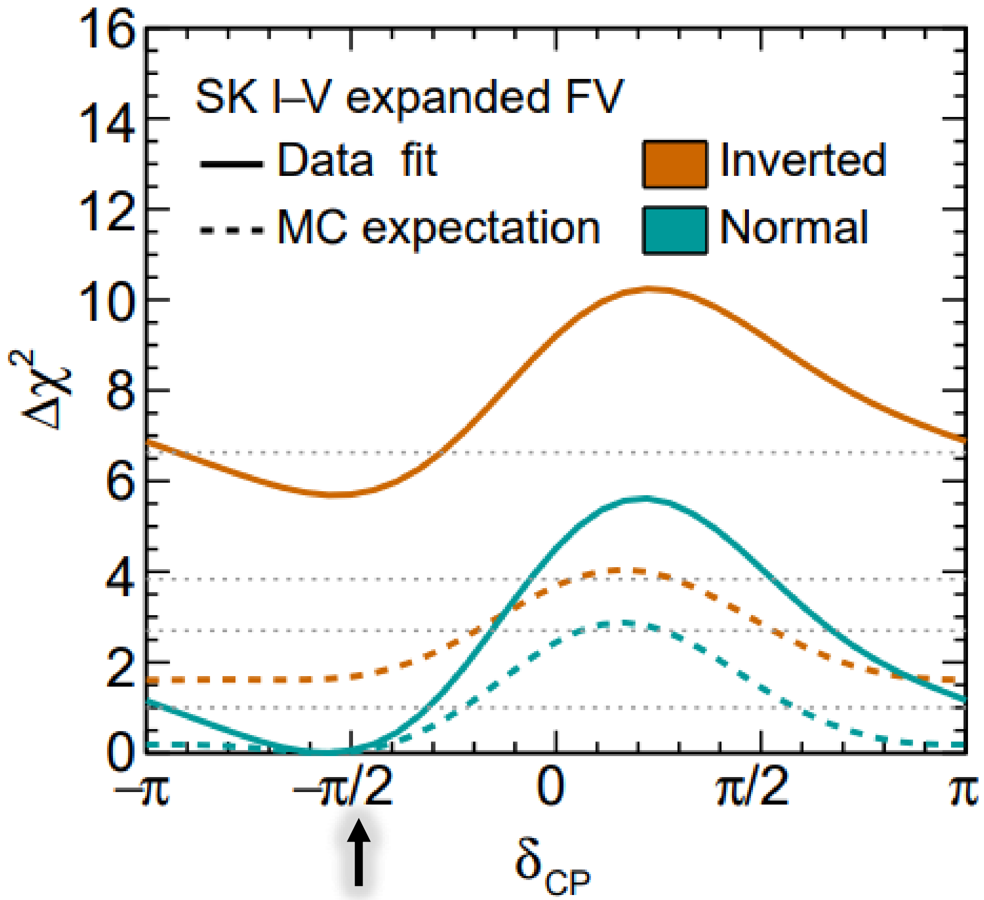
arXiv:2311.05105v1 (2023)

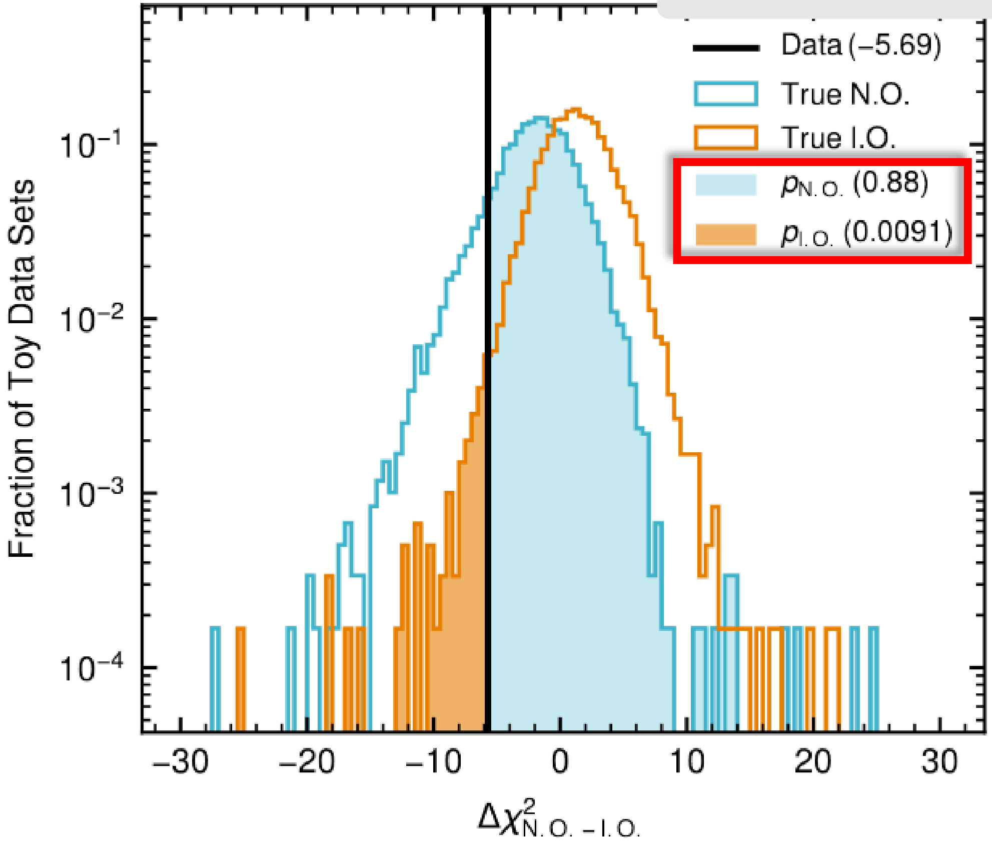


- Best-fit in the first octant (i.e., $\sin^2\theta_{23} < 0.5$) for θ_{23}.
- **Competitive** measurements (especially θ_{23}) with other experiments.

Latest Results: CP-violation δ_{CP}, mass hierarchy

arXiv:2311.05105v1 (2023)





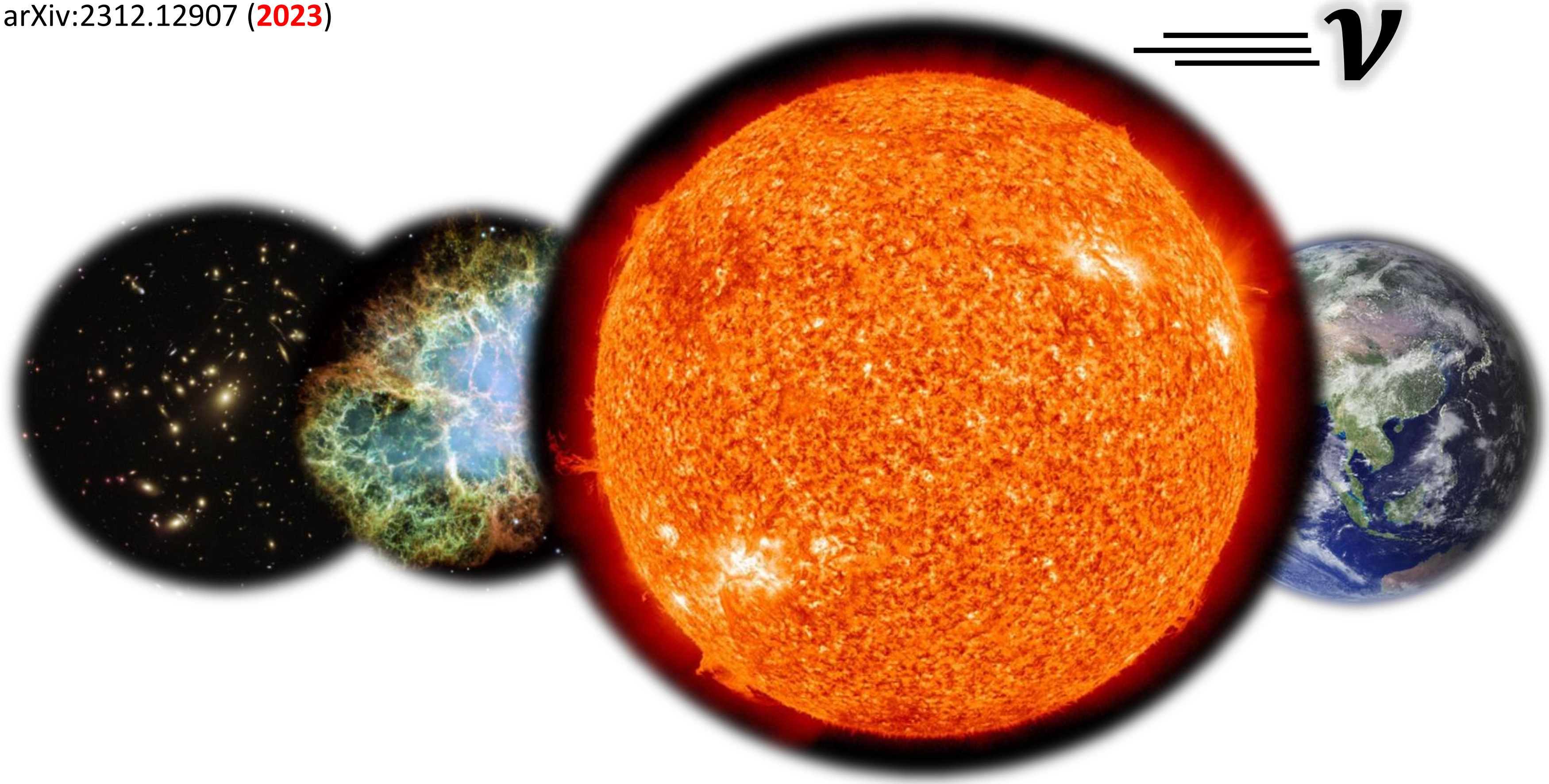
- $CL_S = \frac{p_{IO}}{1-p_{NO}}$

- Best-fit δ_{CP} **in agreement with T2K** results.
- Preferring $\delta_{CP} = -\pi/2$ is **maximal CP violation**!
- Favor **normal hierarchy** at around 2σ ($CL_S = 0.077$).
- See **T2K+SK joint fit results** presented by Phillip Litchfield!

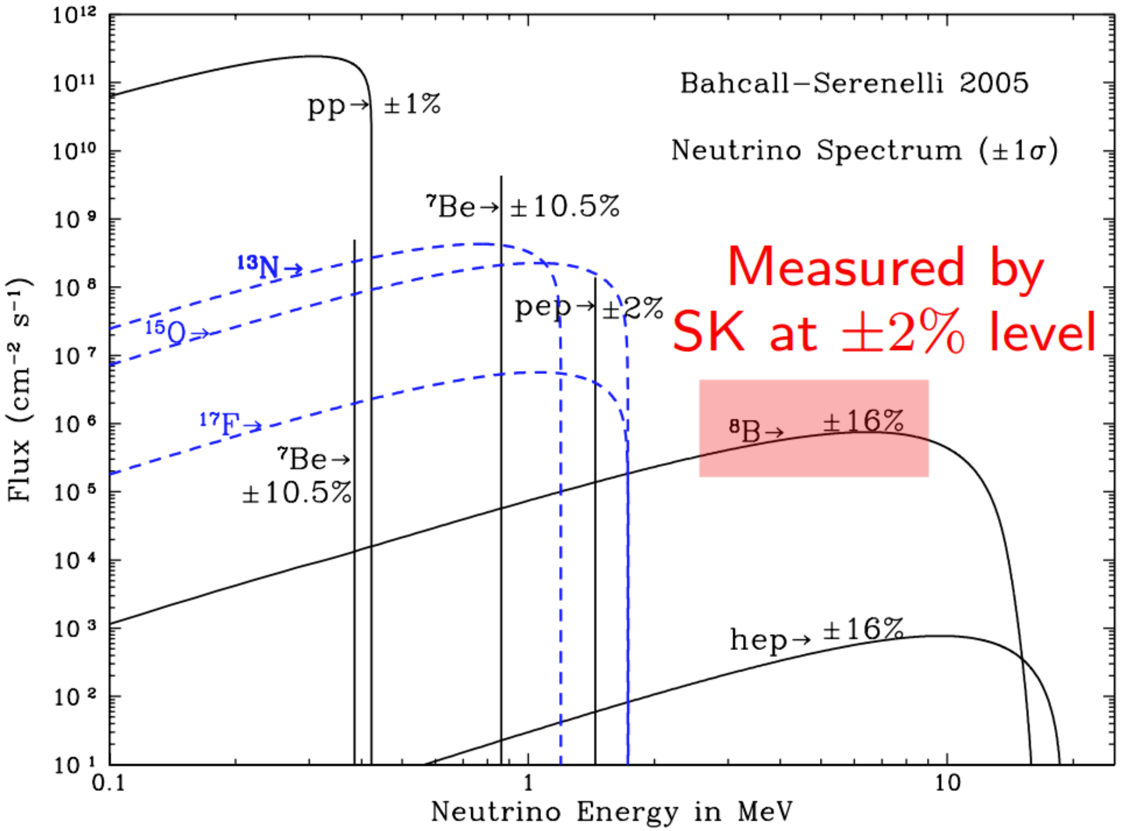
Solar neutrinos!

Solar neutrino measurements using the full data period of Super-Kamiokande-IV

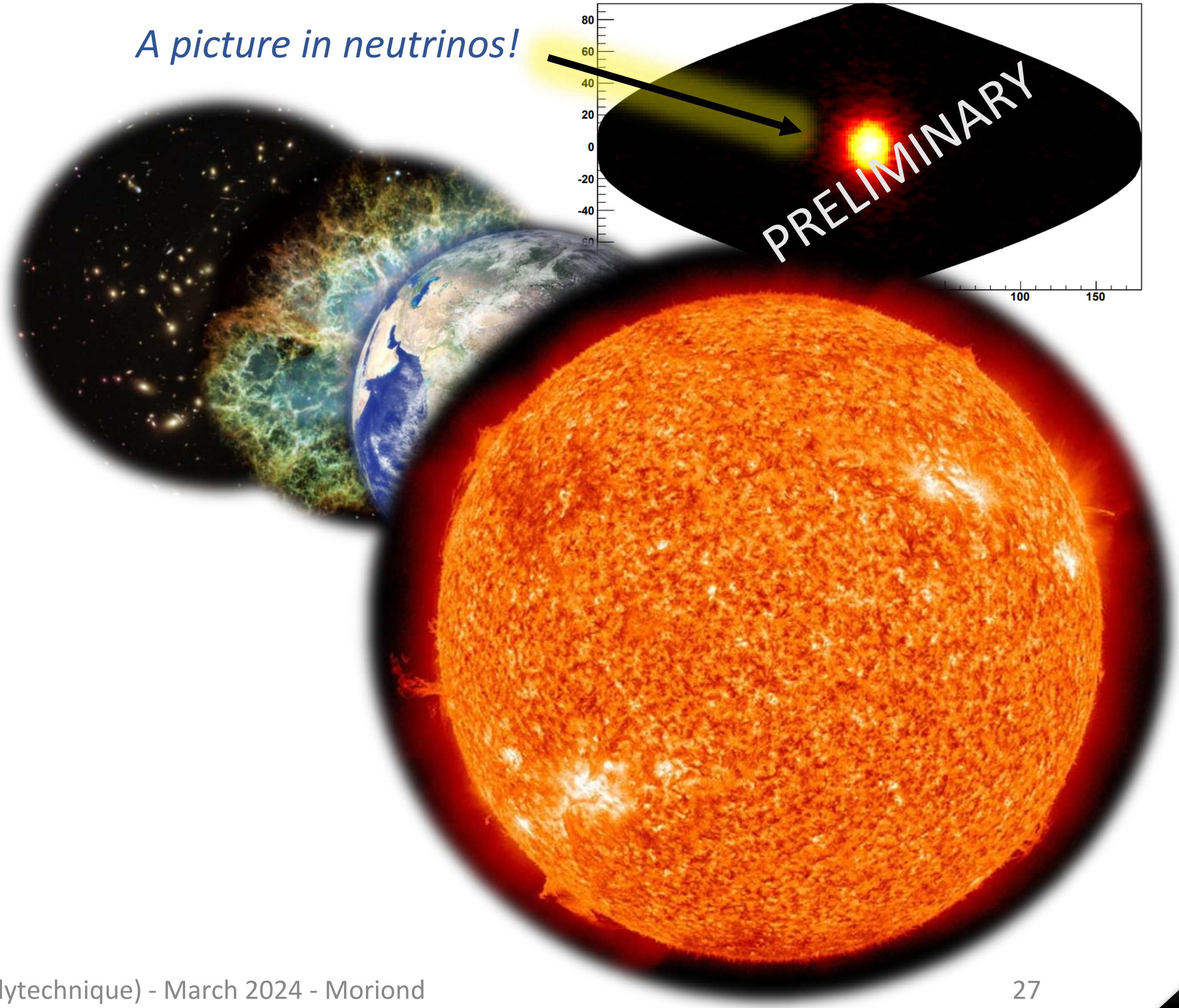
K. Abe et al., arXiv:2312.12907 (**2023**)



The Sun as seen by neutrinos

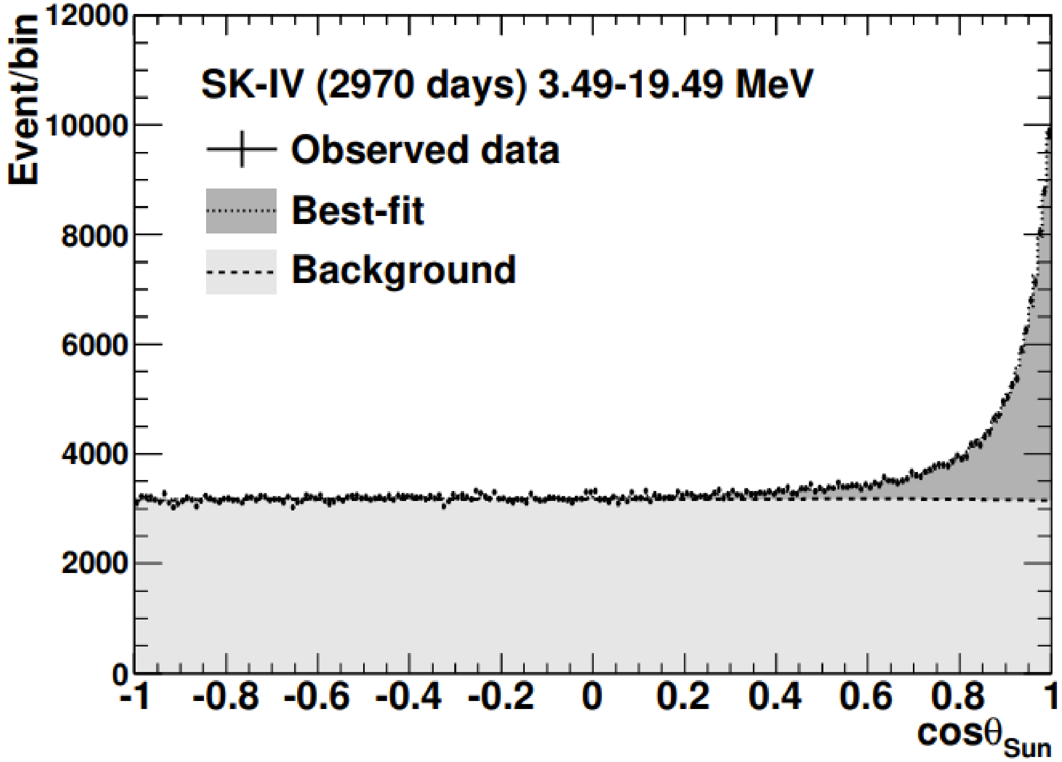


A picture in neutrinos!



The Sun as seen by neutrinos

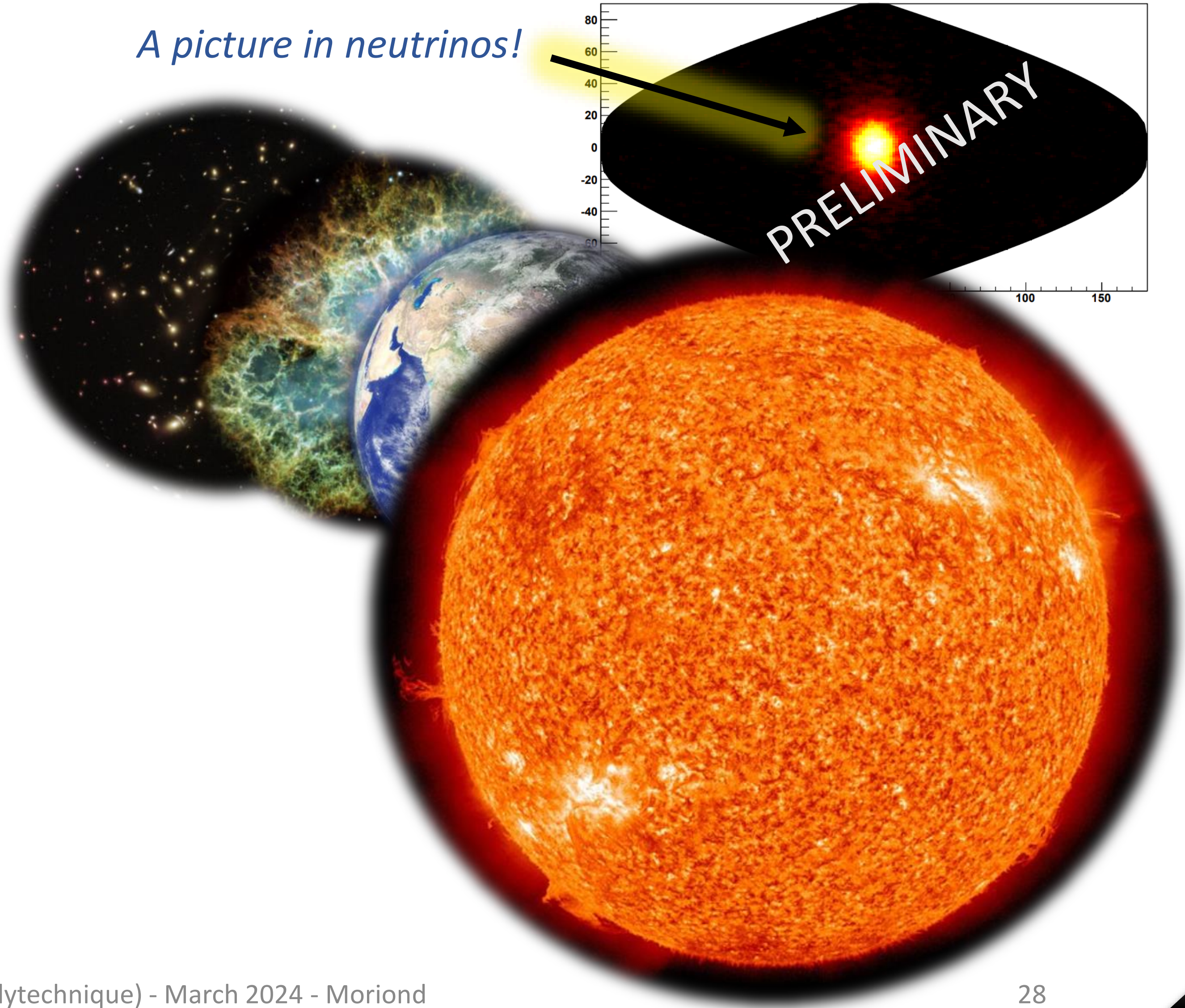
$$\nu + e^- \rightarrow \nu + e^-$$



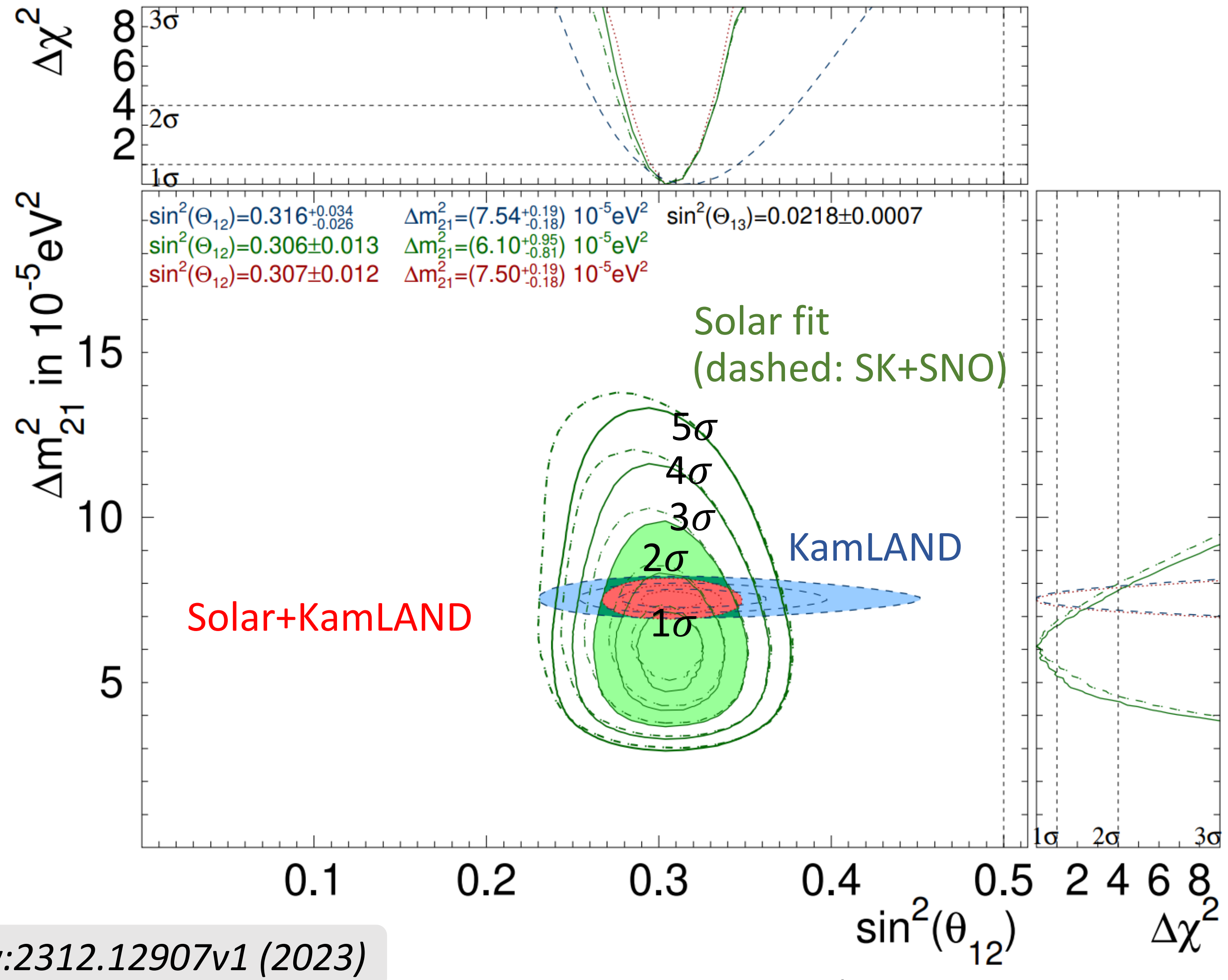
Solar ν: $65{,}443^{+390}_{-388}(\text{stat.}) \pm 925(\text{sys.})$

arXiv:2312.12907v1 (2023)

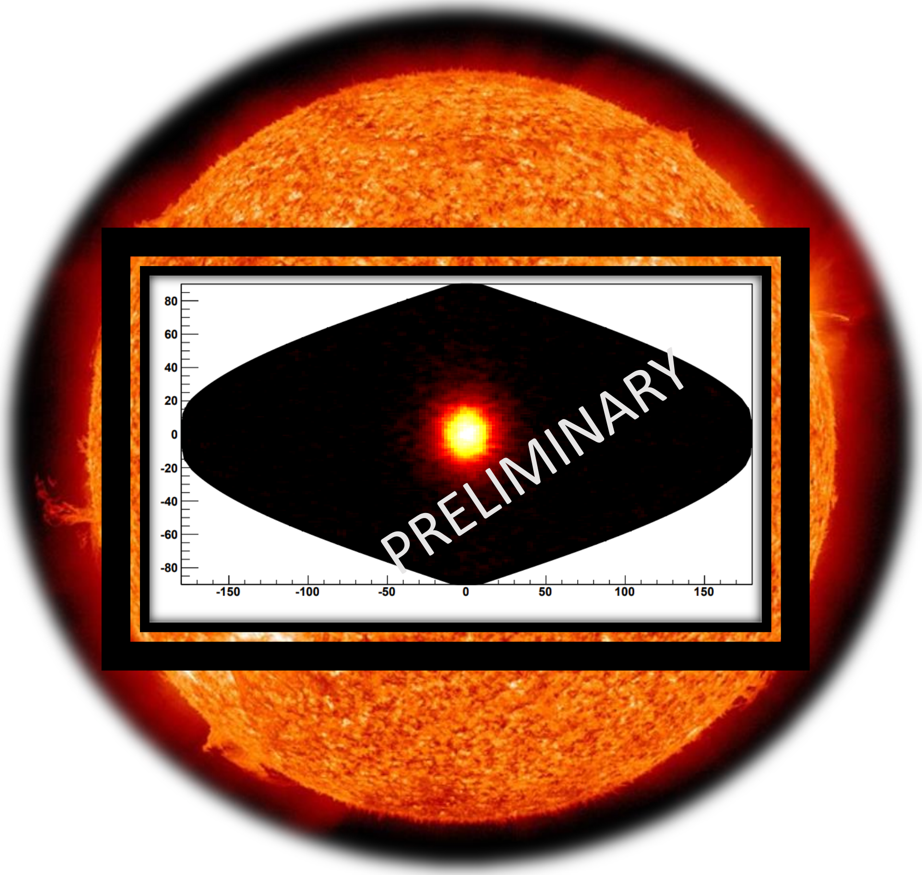
A picture in neutrinos!



Newest Results: Solar oscillation parameters

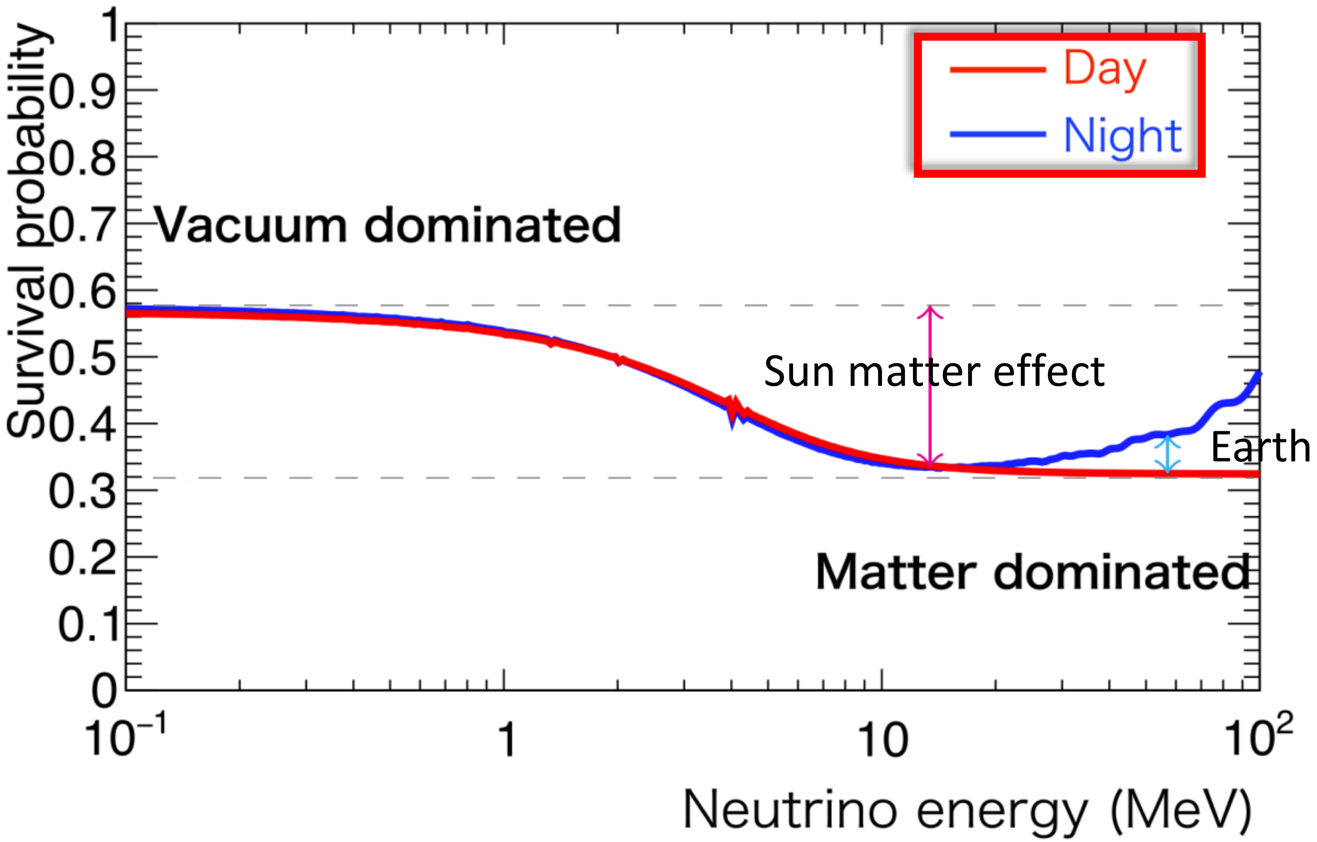


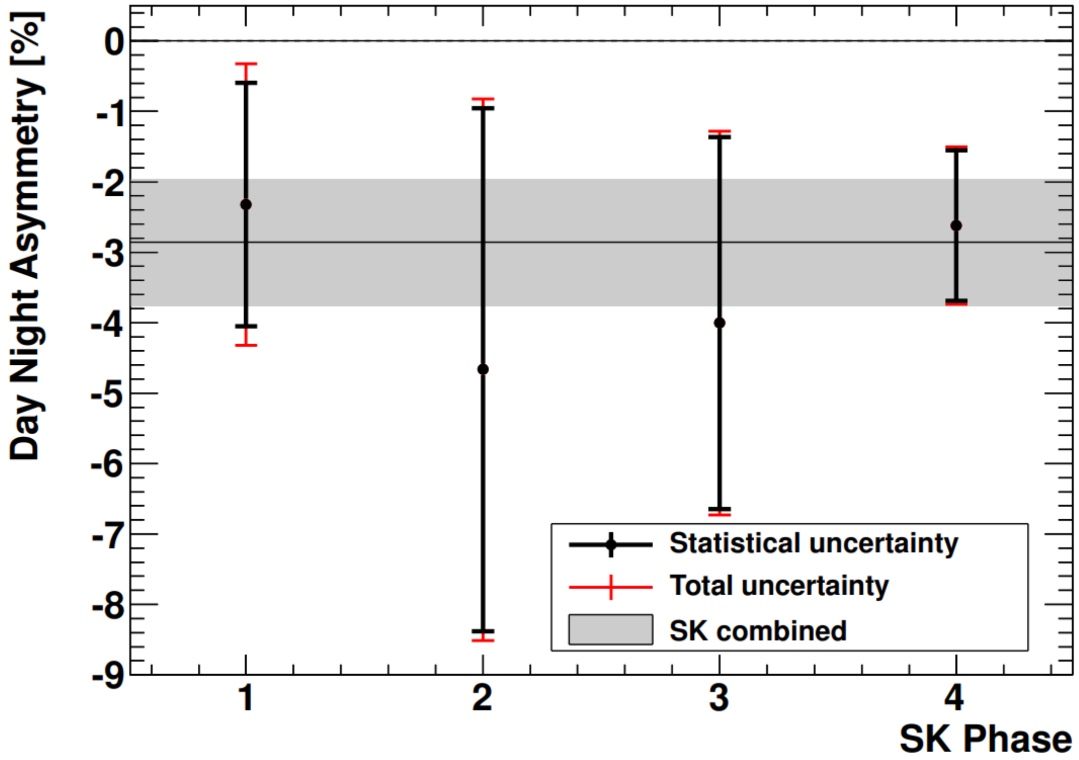
arXiv:2312.12907v1 (2023)



- Have **1.5σ tension** between solar fit and KamLAND fit for Δm^2_{21}.

Newest Results: Day/night asymmetry in solar neutrinos

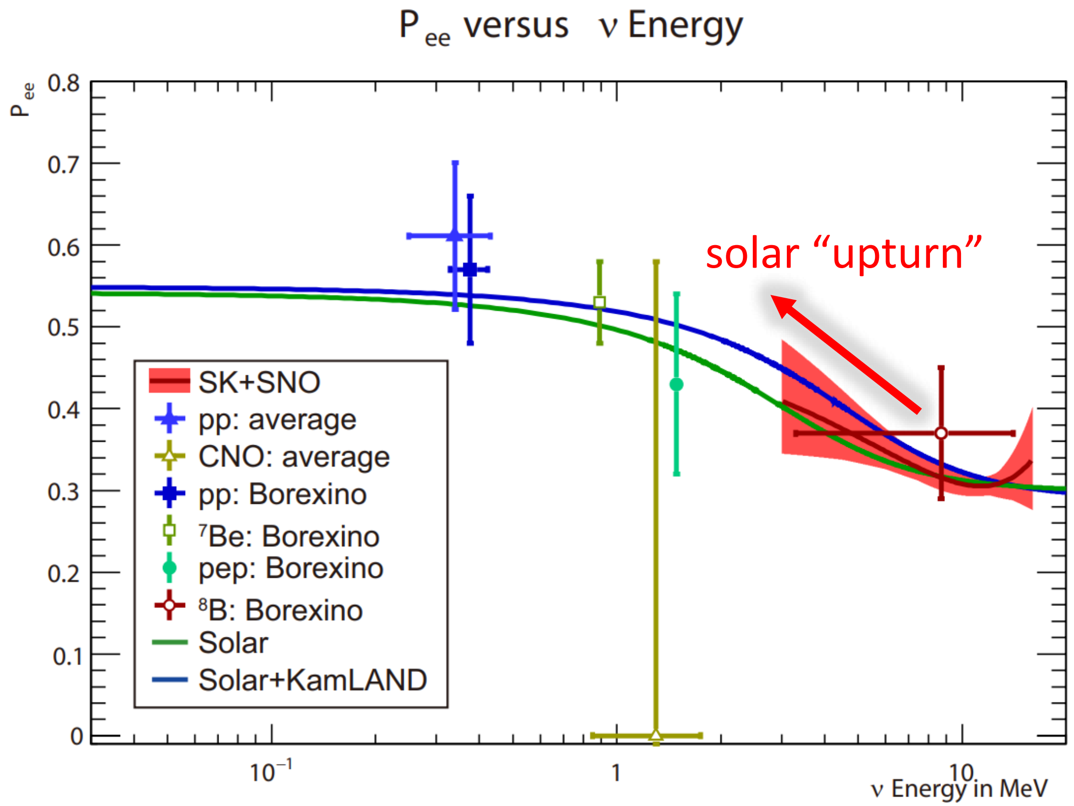


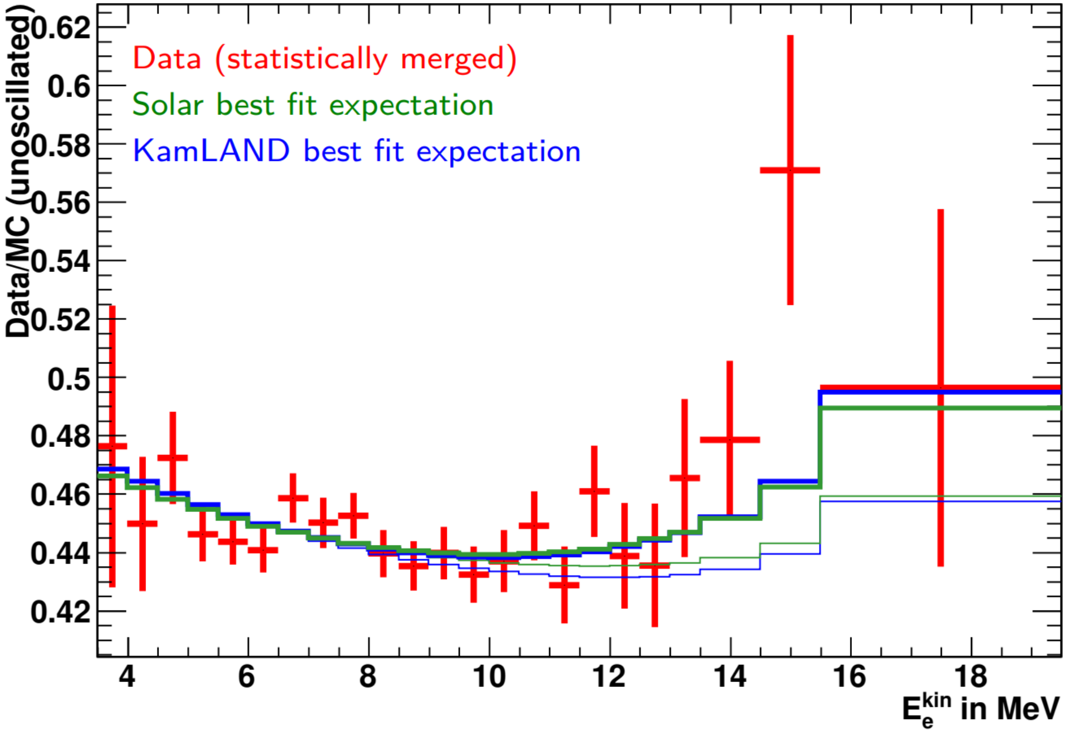


arXiv:2312.12907v1 (2023)

- As neutrinos pass through the Earth at night, **matter effects enhance ν_e**!
- We see this day/night asymmetry at **more than 3σ**!

Newest Results: Solar "upturn" in P_{ee} as function of ν energy

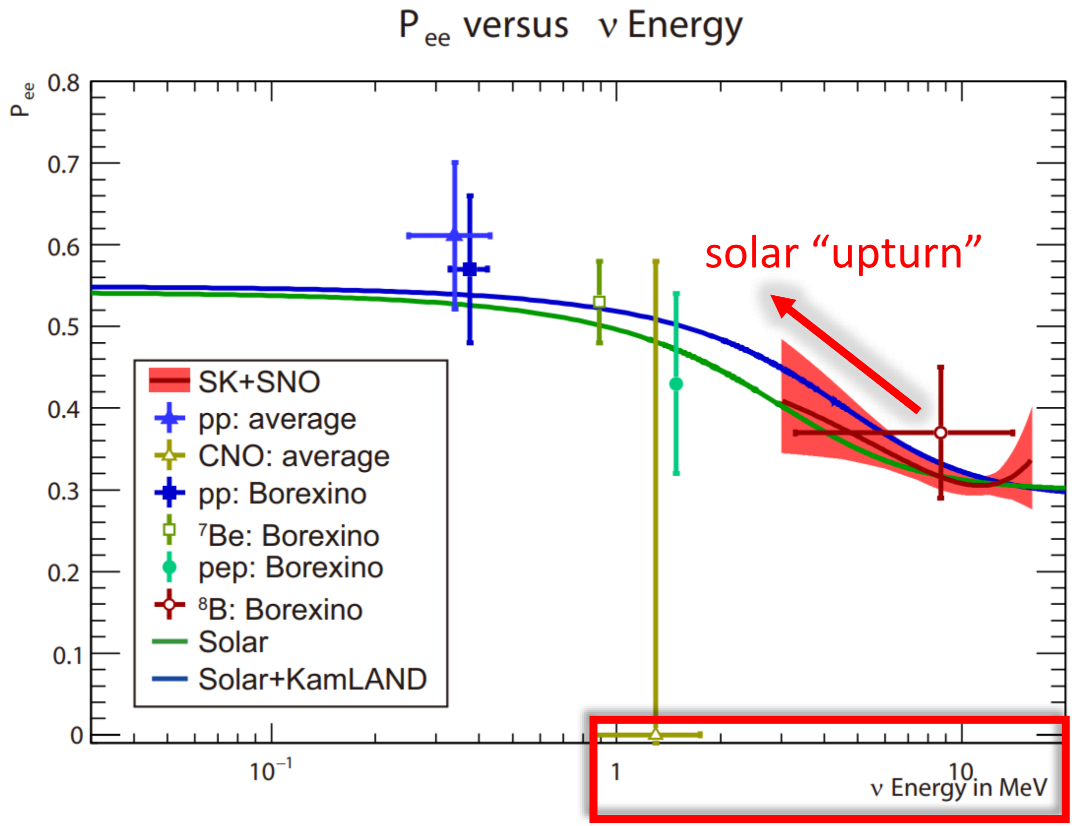




arXiv:2312.12907v1 (2023)

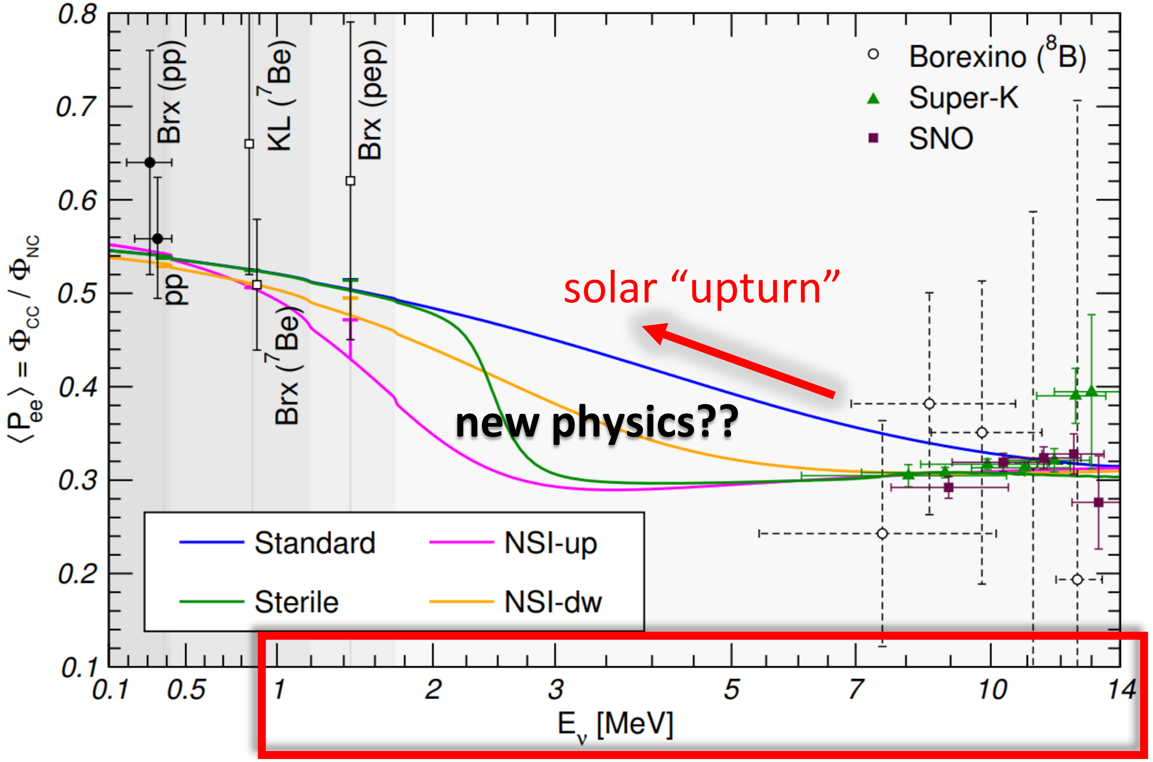
- Going **from high to low energies**, the solar ν_e have a higher survival probability, the so-called "**upturn**."
- Our **current fit disfavors flat distribution** at 1.2σ (2.1σ) with SK (SK+SNO).

Newest Results: Solar "upturn" in P_{ee} as function of ν energy



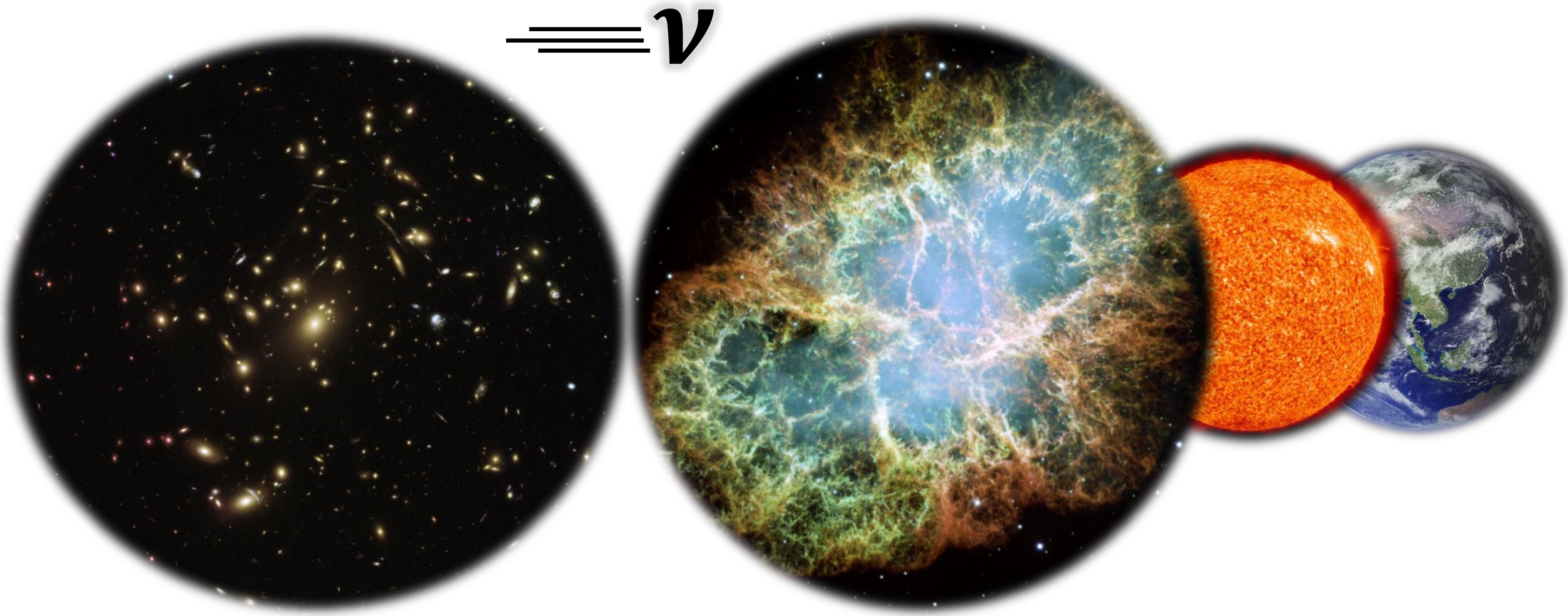
arXiv:2312.12907v1 (2023)

arXiv:1507.05287v4 (2017)



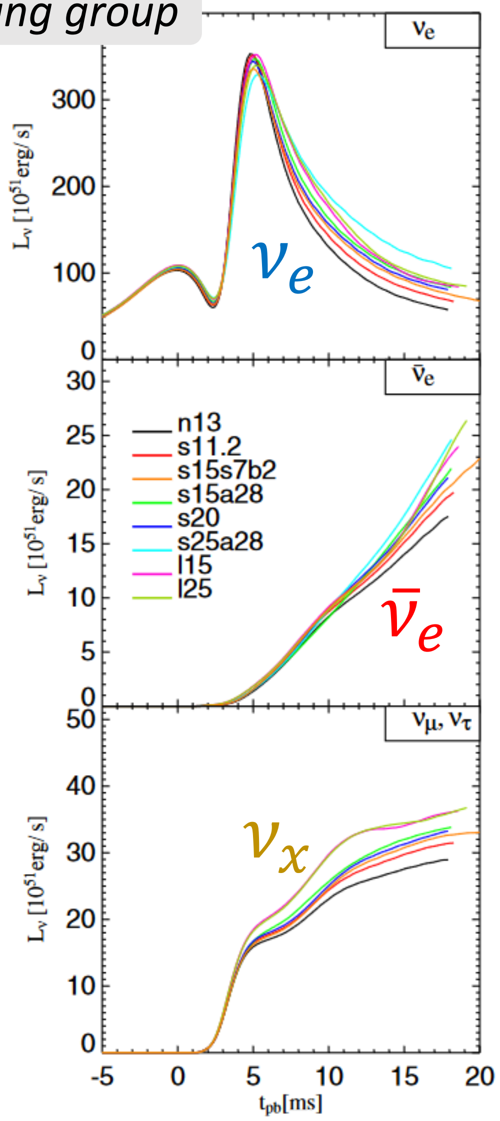
- Measuring the **upturn** can **probe non-standard interactions** or even **sterile neutrinos**!

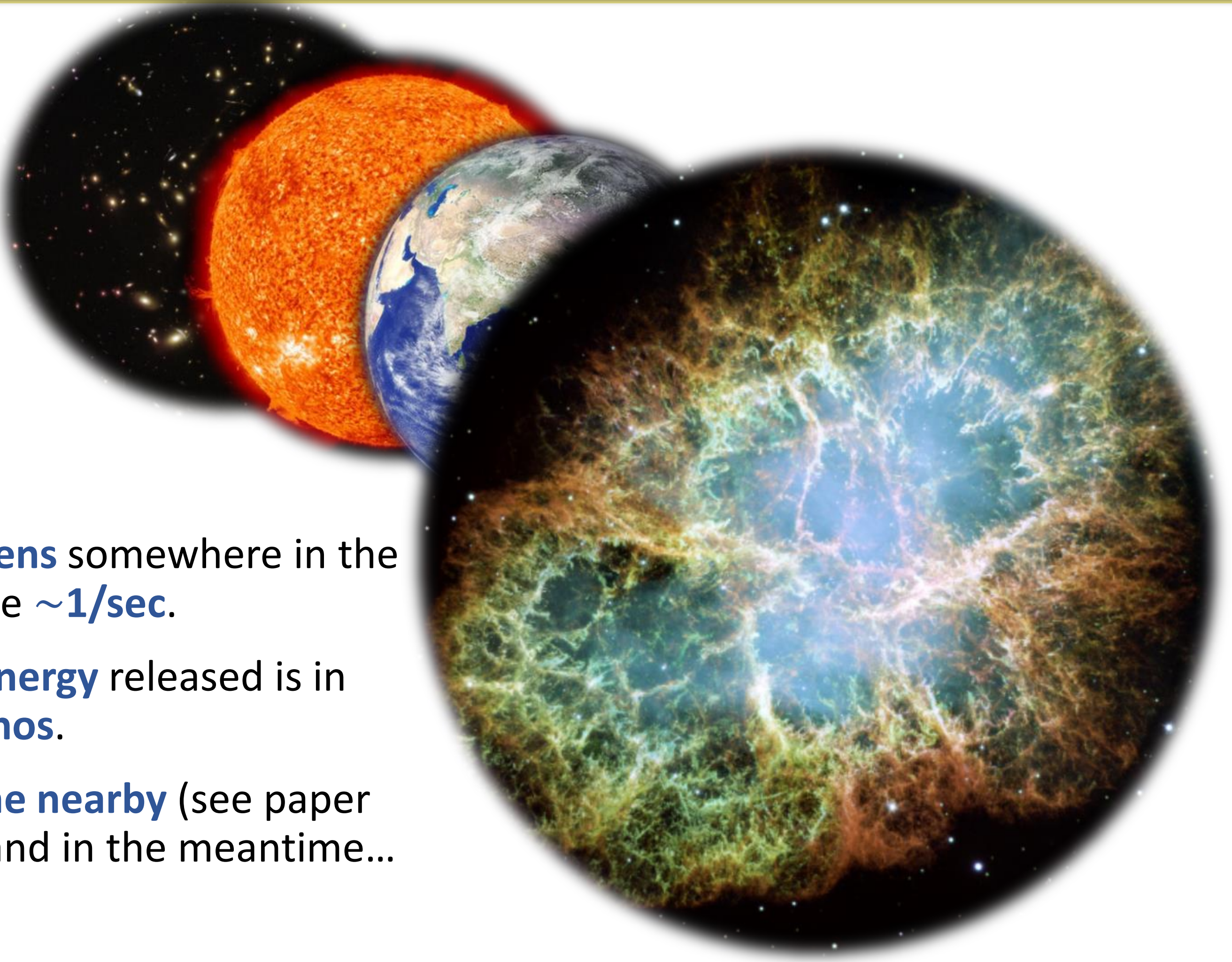
Supernova and DSNB neutrinos!



Probing supernovae using neutrinos in Super-K

Garching group



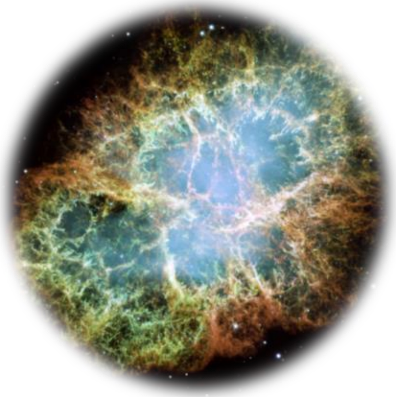


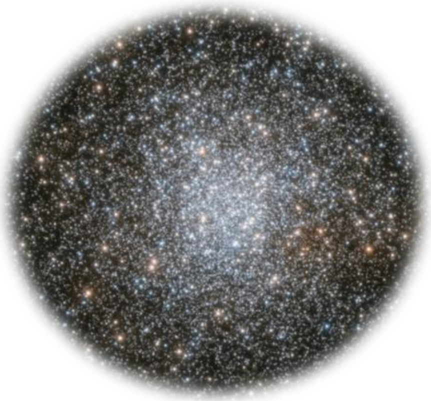
- A **supernova happens** somewhere in the observable universe ~**1/sec**.
- About **99% of all energy** released is in the form of **neutrinos**.
- Ready to **detect one nearby** (see paper list for SN alarm), and in the meantime…

What is the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi}{dE} = \iint R_{SN}(z,M) \left[\frac{dF(E(1+z),M)}{dM}\right] \left| c\,\frac{\mathrm{dt}}{dz} \right| dz\,dM$$

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × Universe **expansion**



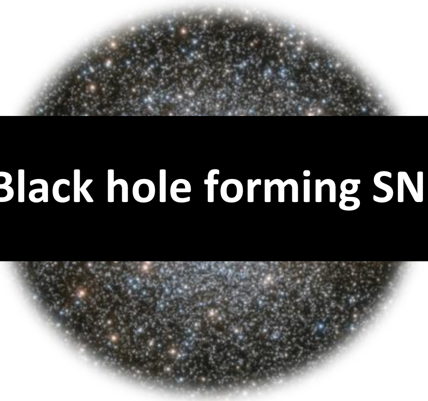


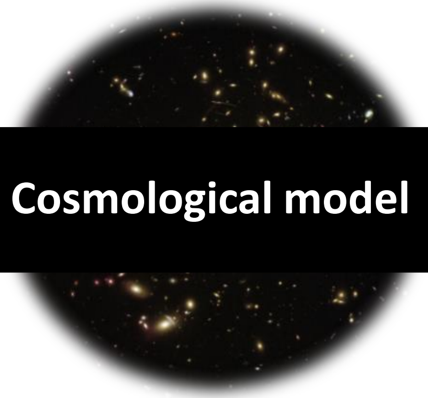
Why study the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi}{dE} = \iint R_{SN}(z, M) \left[\frac{dF(E(1+z), M)}{dM}\right] \left| c\,\frac{\mathrm{dt}}{dz} \right| dz dM$$

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × Universe **expansion**

Probe these!



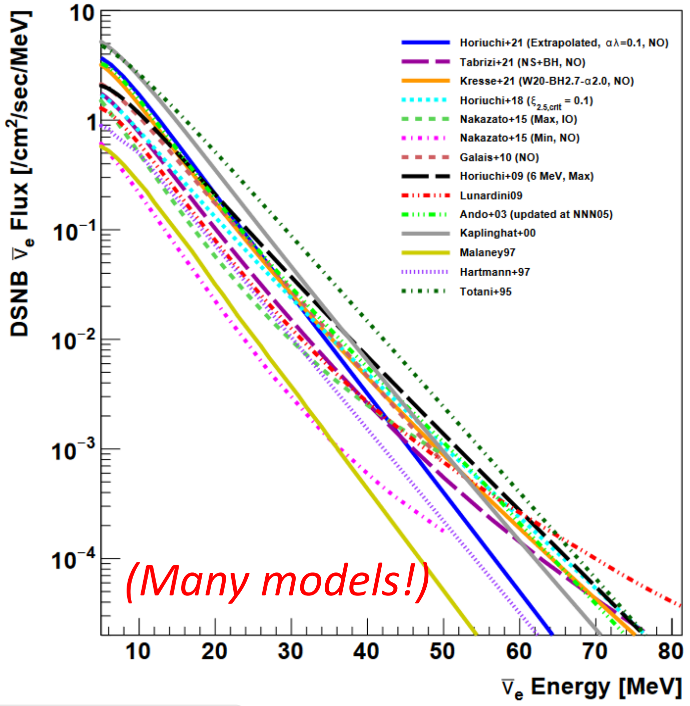


- Ingredients include **astrophysics**, **particle physics**, and **cosmology**.
- Can **constrain parameters** (e.g., the **star formation rate** in the universe or the fraction of supernovae that form **black holes**).

Why study the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi}{dE} = \iint R_{SN}(z, M) \left[\frac{dF(E(1+z), M)}{dM}\right] \left| c\,\frac{\mathrm{dt}}{dz} \right| dz dM$$

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × Universe **expansion**

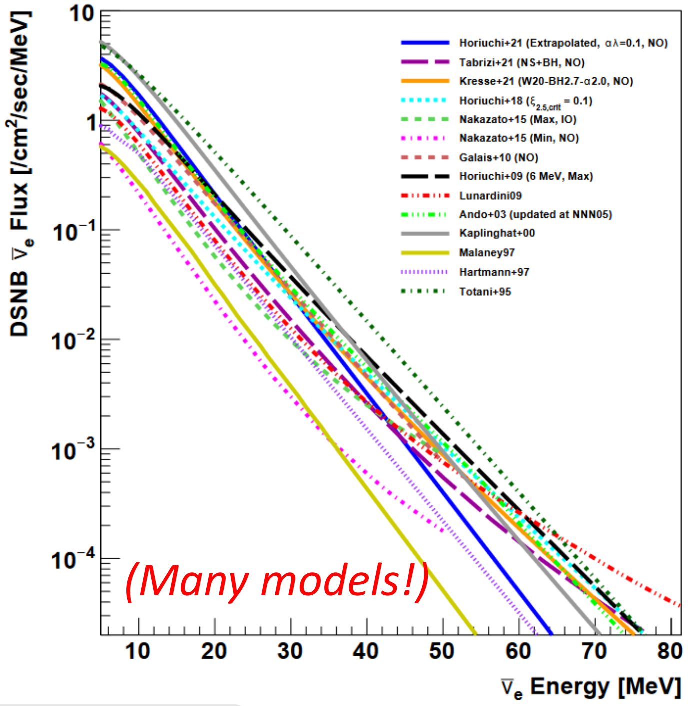


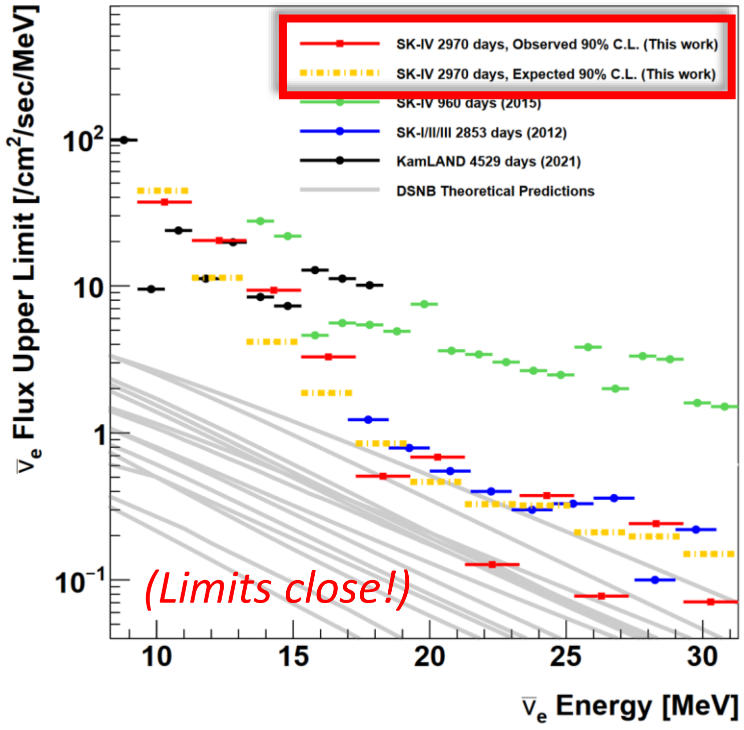
Phys. Rev. D ***104****, 122002 (2021)*

Why study the Diffuse Supernova Neutrino Background?

$$\frac{d\Phi}{dE} = \iint R_{SN}(z, M) \left[\frac{dF(E(1+z), M)}{dM}\right] \left| c \frac{\mathrm{dt}}{dz} \right| dz dM$$

DSNB = **Supernova** rate × **Neutrinos** emitted per supernova × Universe **expansion**





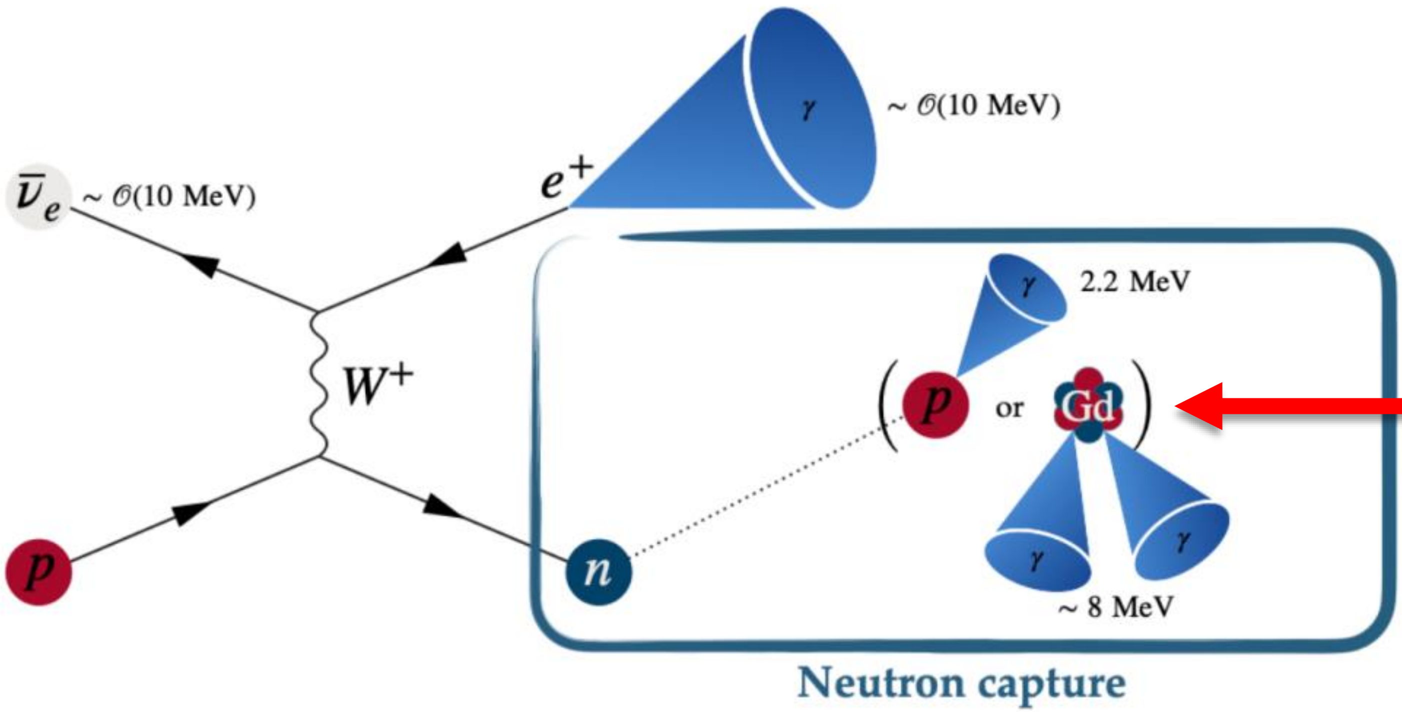
Phys. Rev. D ***104****, 122002 (2021)*

How to wrangle a DSNB neutrino: With inverse β decay!

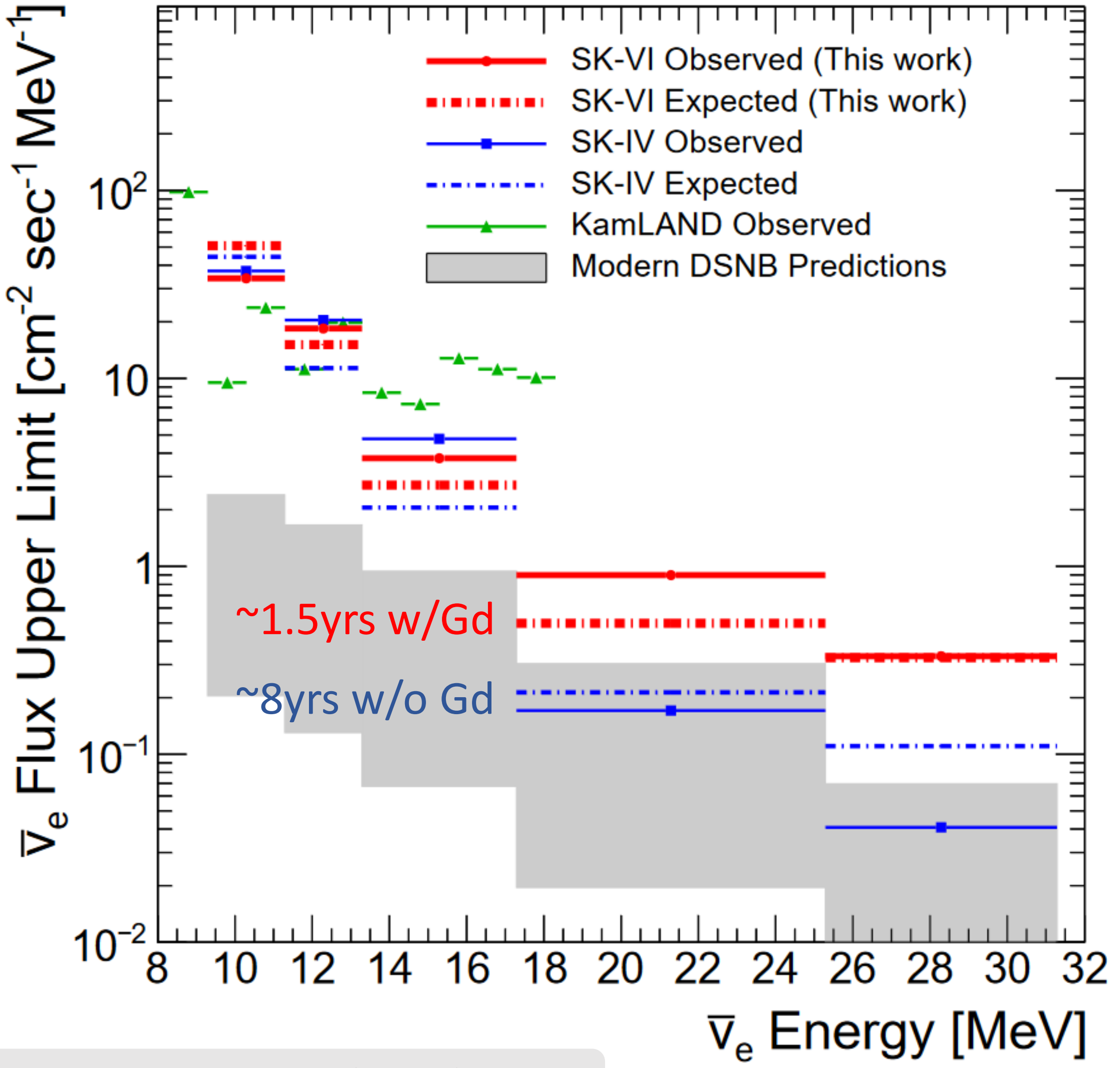
A two-flash signal!

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

Gadolinium loading 2020s!



Last published results: The SK-Gd era is moving us along quickly!

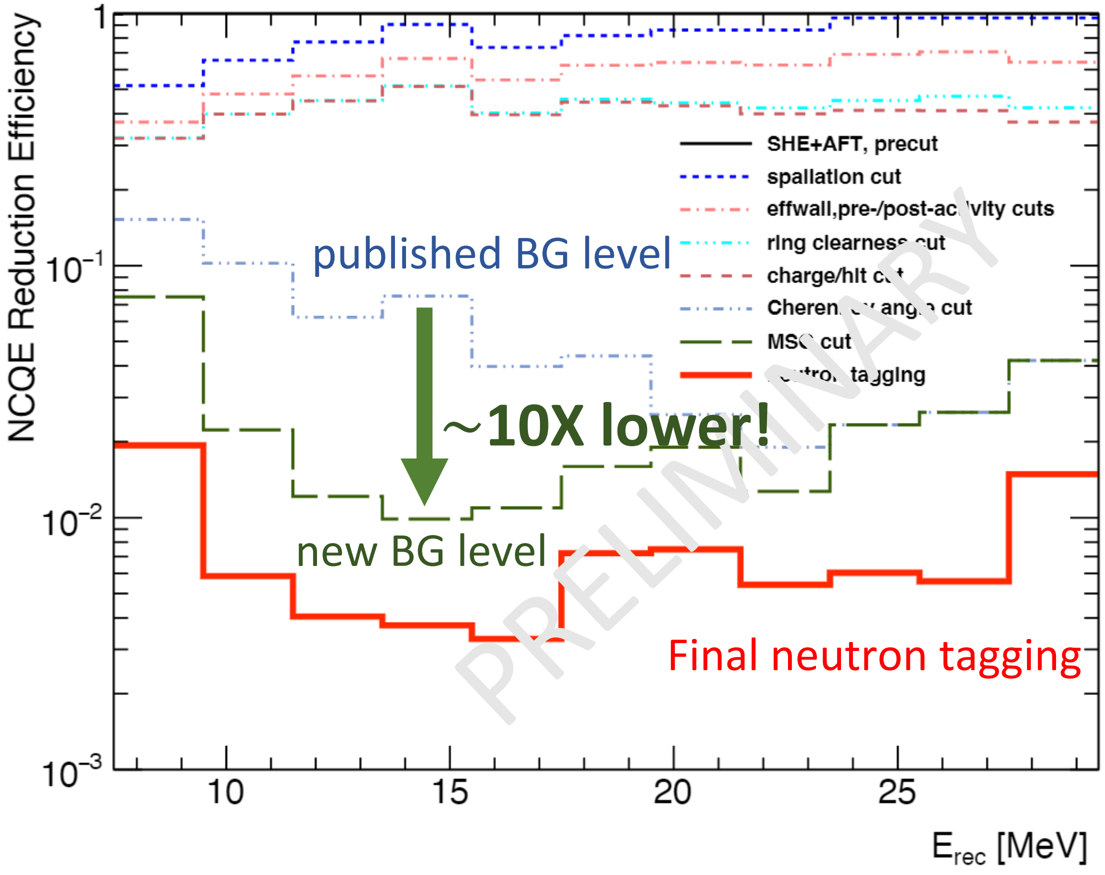


- **Without gadolinium** to improve neutron tagging, we started dipping into interesting territory.
- **With gadolinium**, we approach the theoretical predictions much more quickly!

M. Harada et al., ApJL ***951*** *(2023) 2, L27*

Soon-to-be released results: New and improved SK-Gd analysis!

Reducing one of main DSNB backgrounds!



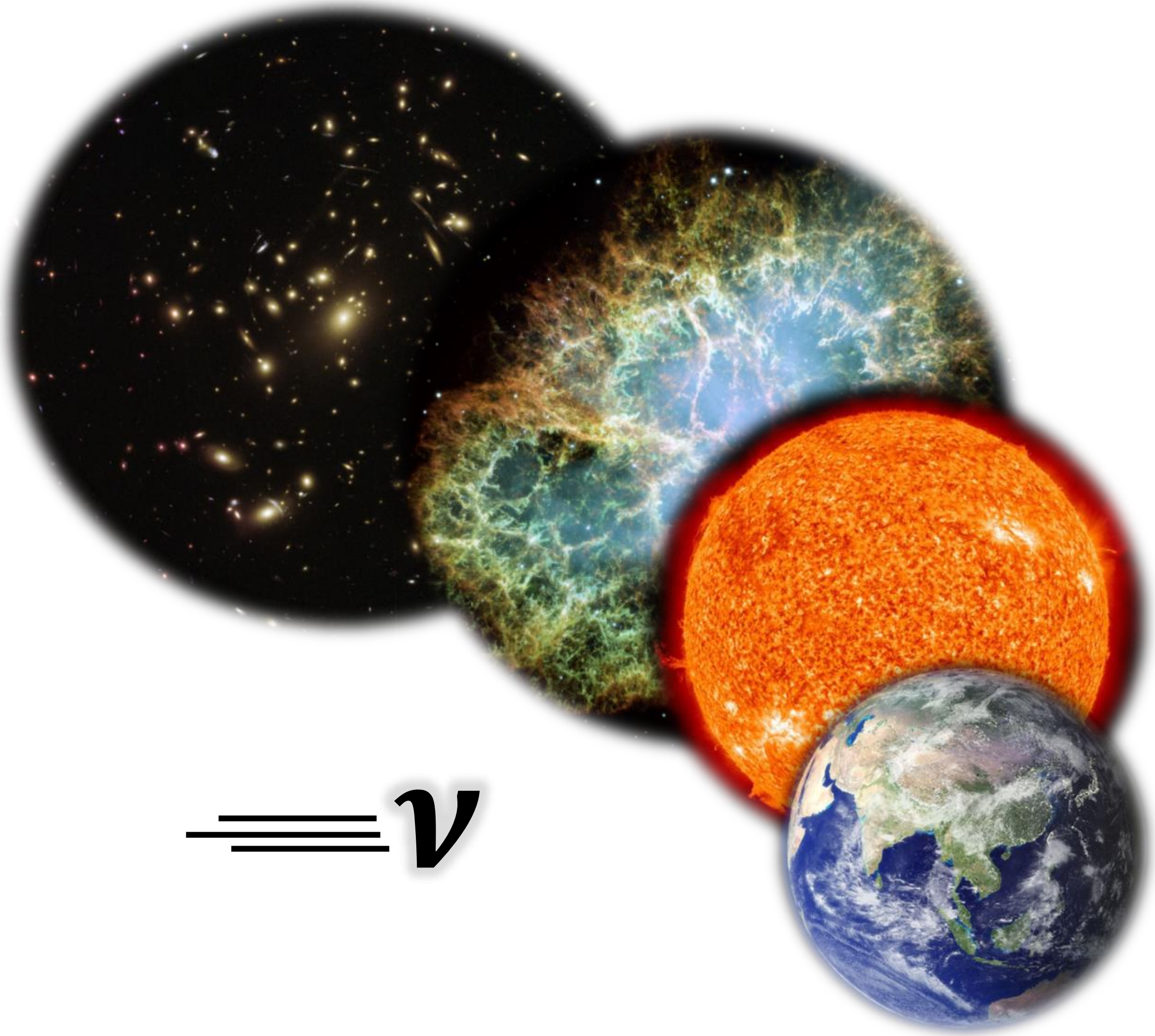
officialized, paper preparation (2024)

- **Without gadolinium** to improve neutron tagging, we started dipping into interesting territory.
- **With gadolinium**, we approach the theoretical predictions much more quickly!
- A **full analysis** (2024) is **finishing up** as we speak!
- Going from cut-based neutron tagging to **Boosted Decision Tree/neural network**.
- **Adding a spectral fit** of signal+backgrounds beyond model-independent, binned analysis.
- **New background reduction** for atmospheric neutrinos is included, too (**targets multi-cone background events**)!

Where we are today with the Super-Kamiokande experiment

Some highlights of latest Super-K results

- Competitive measurements of $|\Delta m^2_{31,32}|, \theta_{23}$ preferring lower octant. (nov. 2023)
- Normal hierarchy favored at 2σ and best-fit $\delta_{CP} = -\pi/2$ maximal CP-violation. (nov. 2023)
- Day/night solar ν asymmetry observed at >3σ. (dec. 2023)
- Data suggestive of observing solar "upturn." (dec. 2023)
- Most stringent limits on the Diffuse Supernova Neutrino Background already with SK-IV period.
- Ongoing DSNB analysis in SK-Gd era continues to show promising results. (2024)
- And so much more in atmospheric, solar, supernova, astrophysical ν and even dark matter and proton decay!



Backup

Atmospheric

Solar

SN/DSNB

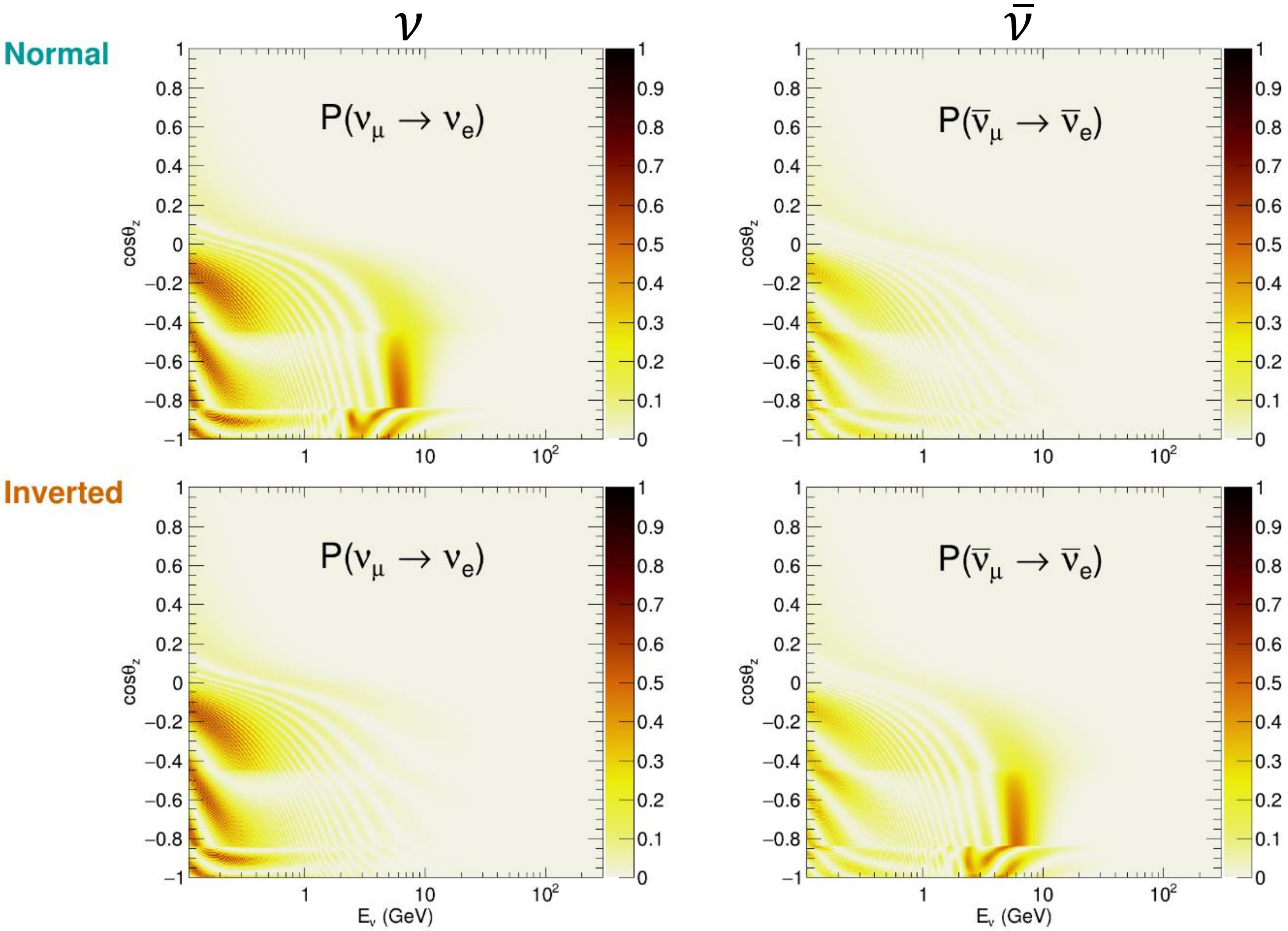
CP-violation

Other

Atmospheric ν

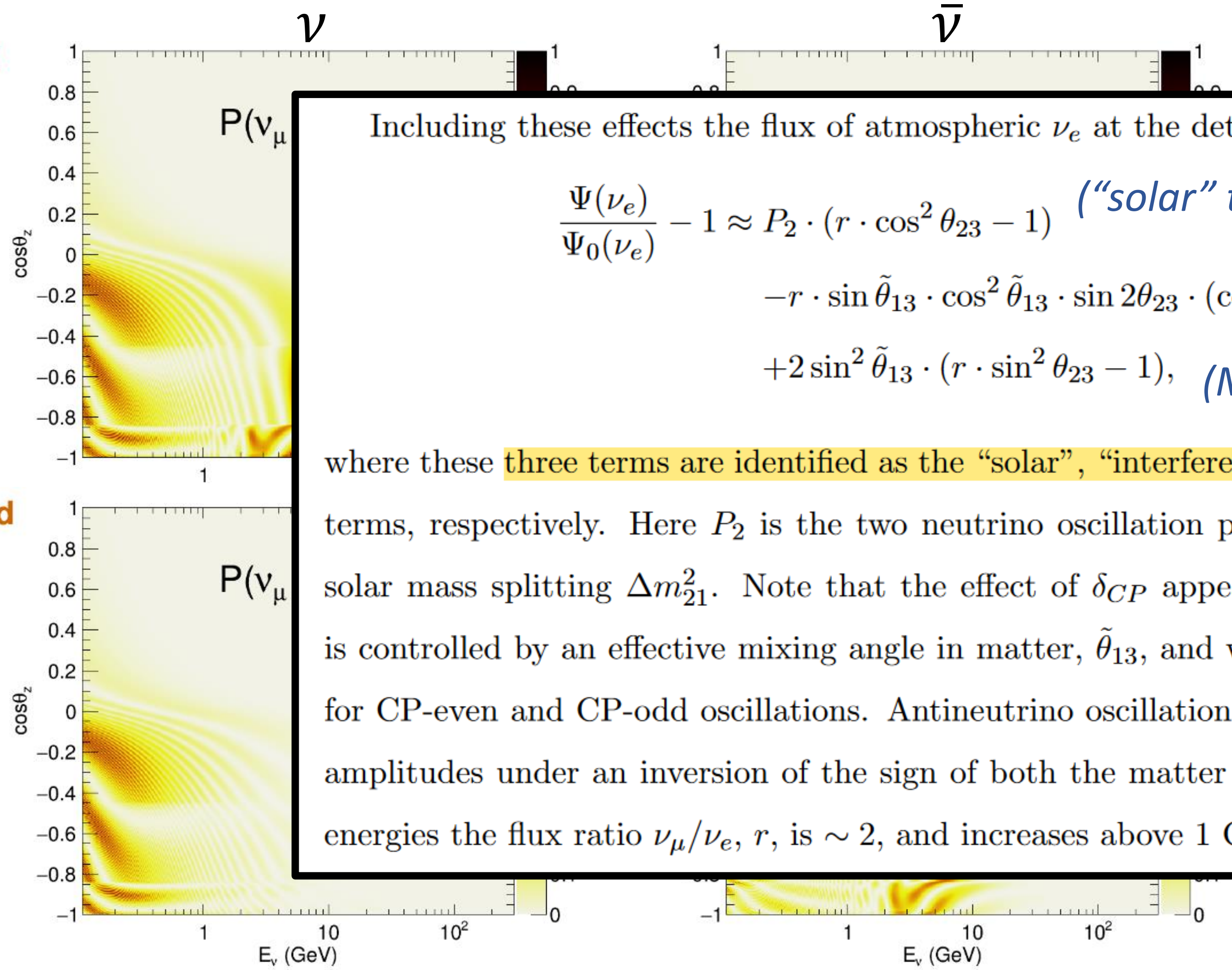
(backup page)

Extracting physics from atmospheric neutrino oscillations



arXiv:2311.05105v1 (2023)

Extracting physics from atmospheric neutrino oscillations



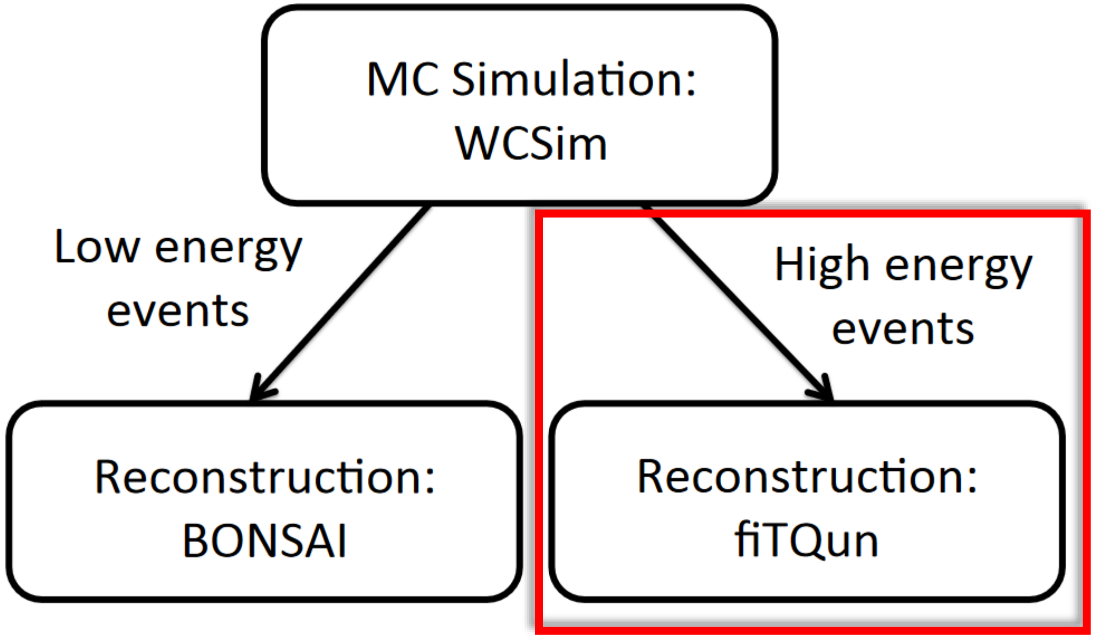
Including these effects the flux of atmospheric ν_e at the detector may be written roughly as,

$$\frac{\Psi(\nu_e)}{\Psi_0(\nu_e)} - 1 \approx P_2 \cdot (r \cdot \cos^2\theta_{23} - 1) \quad \text{(“solar” term)}$$
$$-r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2) \quad (\delta_{CP} \text{ effect})$$
$$+2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1), \quad \text{(MSW resonance)} \qquad (19)$$

where these three terms are identified as the “solar”, “interference,” and “parametric (resonance)” terms, respectively. Here P_2 is the two neutrino oscillation probability $\nu_e \to \nu_{\mu,\tau}$ driven by the solar mass splitting Δm^2_{21}. Note that the effect of δ_{CP} appears in the interference term, which is controlled by an effective mixing angle in matter, $\tilde{\theta}_{13}$, and where R_2 and I_2 denote amplitudes for CP-even and CP-odd oscillations. Antineutrino oscillations are described by changes to these amplitudes under an inversion of the sign of both the matter potential and of δ_{CP}. At sub-GeV energies the flux ratio ν_μ/ν_e, r, is ~ 2, and increases above 1 GeV until reaching ~ 3 at 10 GeV.

Hyper-K Design Report (2018)

Overview of Super-K reconstruction



Reconstruction	fiTQun	APFit
True CCQE ν_e sample		
Vertex Resolution	20.6 cm	24.9 cm
Direction Resolution	1.48°	1.68°
Momentum Bias	0.43%	0.63%
Momentum Resolution	2.90%	3.56%
Mis-PID rate	0.02%	0.50%
True CCQE ν_μ sample		
Vertex Resolution	15.8 cm	17.3 cm
Direction Resolution	1.00°	1.28°
Momentum Bias	-0.18%	0.54%
Momentum Resolution	2.26%	2.60%
Mis-PID rate	0.05%	0.91%

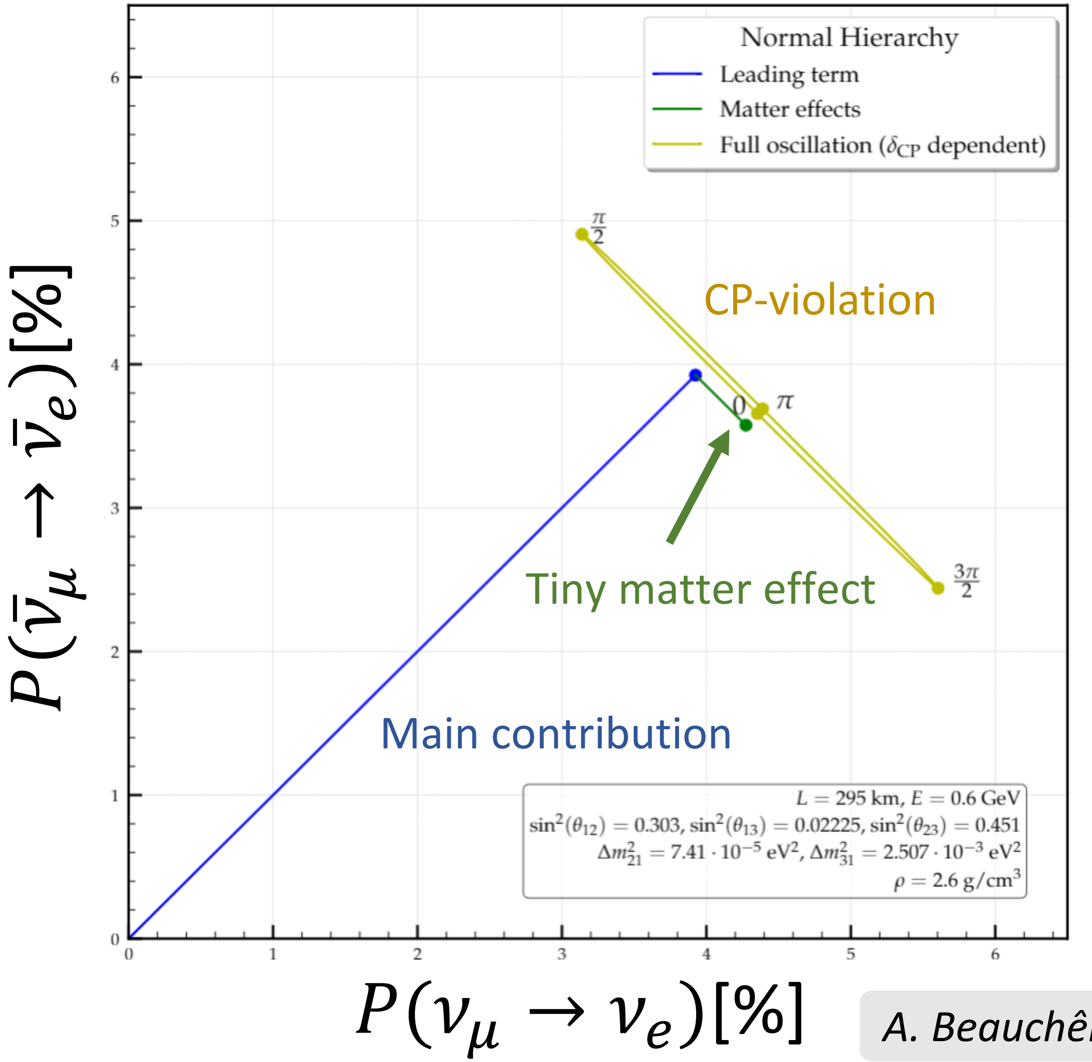
(performance at 1 GeV, fully-contained events)

M. Jiang (2019), PhD Thesis, Kyoto University

Extracting physics from atmospheric neutrino oscillations

CP-violation (ν-vs-$\bar{\nu}$)

- For $\delta_{CP} \neq 0, \pi$, neutrino and anti-neutrino $P_{\mu e}$ **will differ**.
- Here is one **specific example** for δ_{CP} effect on probabilities.

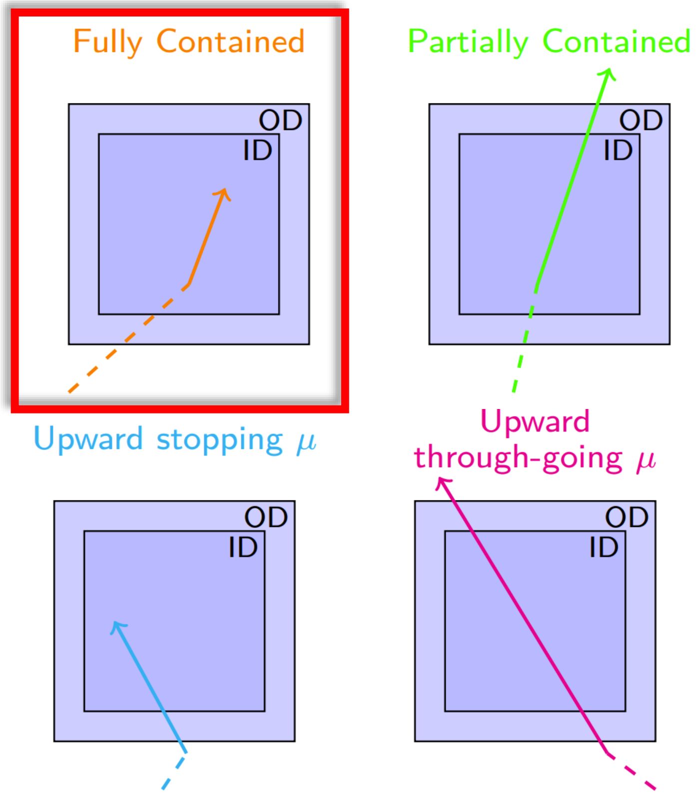


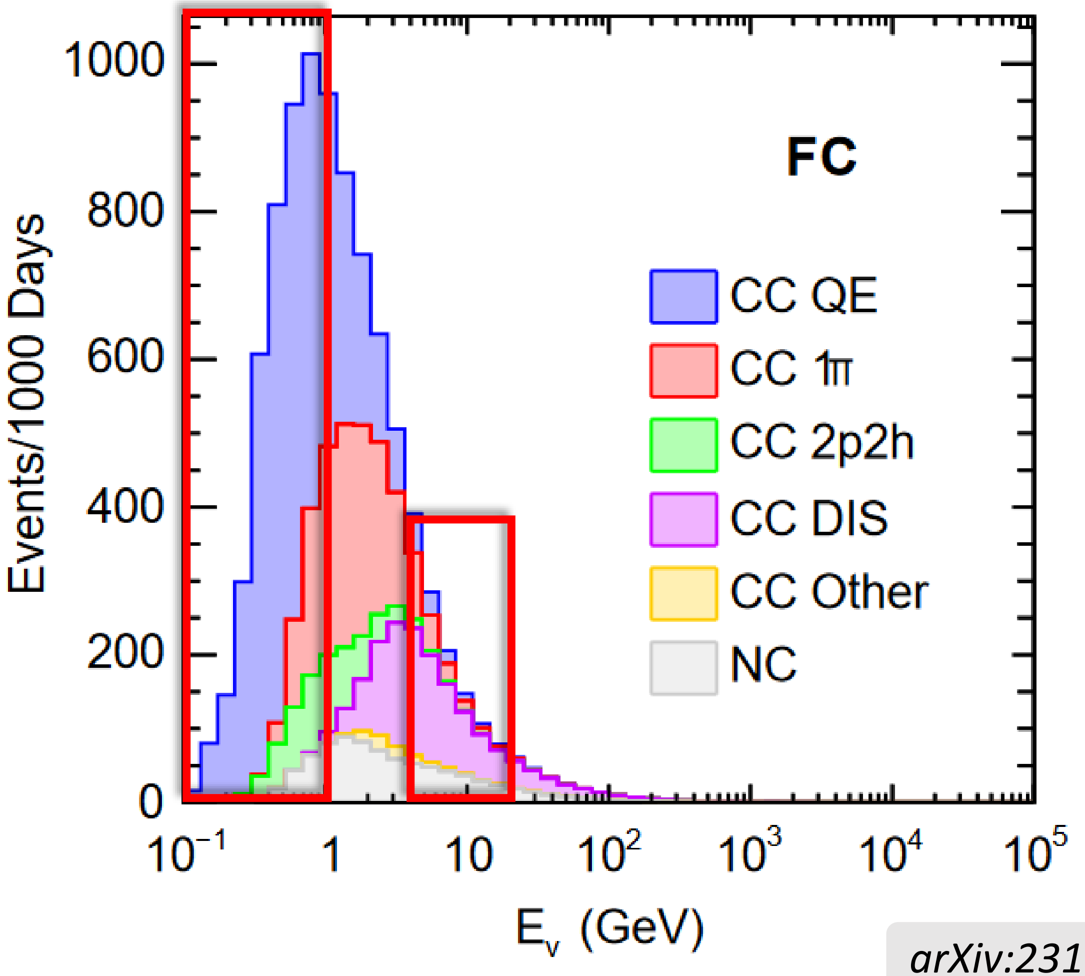
A. Beauchêne

Atmospheric ν event selection

Main sample selection steps

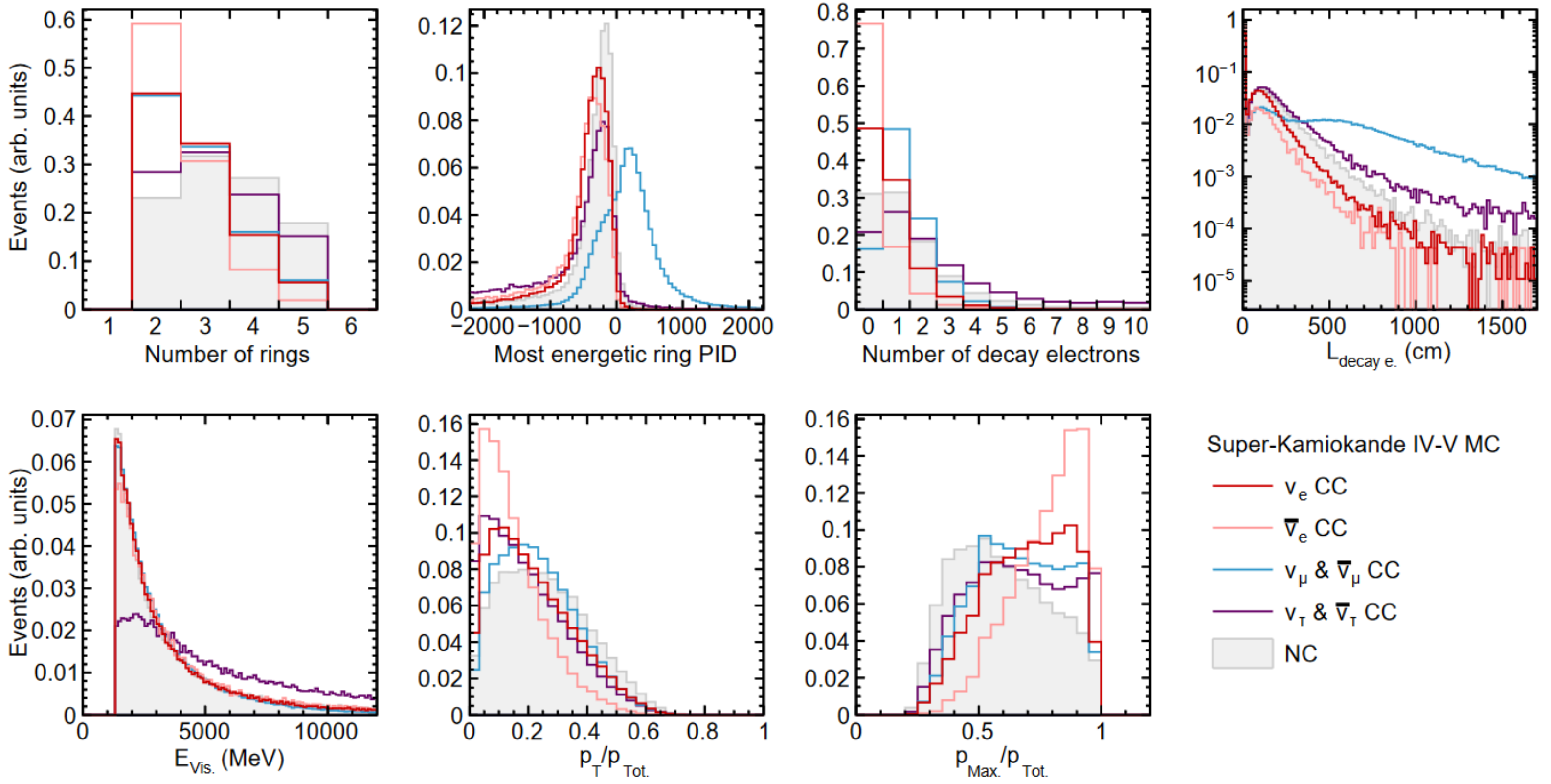
- Prefer events whose final states are **within inner detector** (now even more volume!).

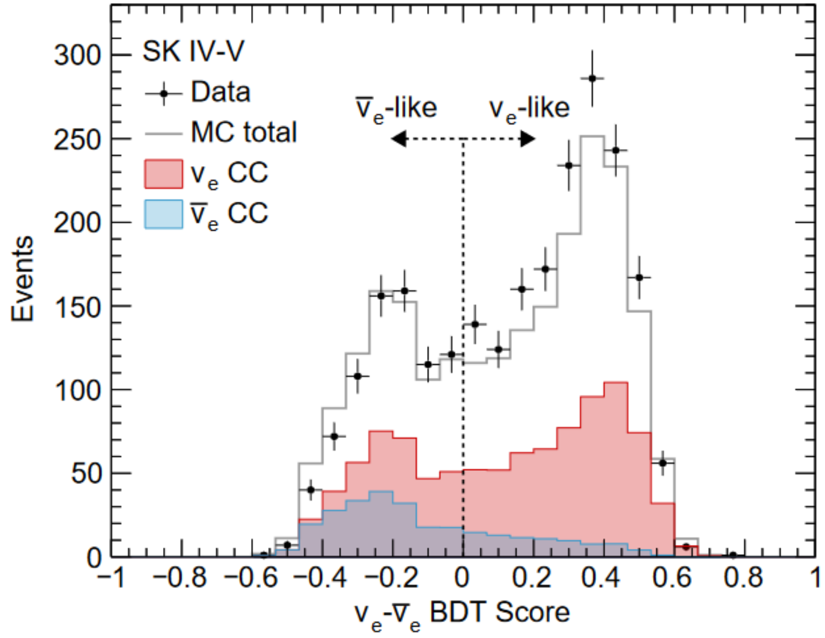




arXiv:2311.05105v1 (2023)

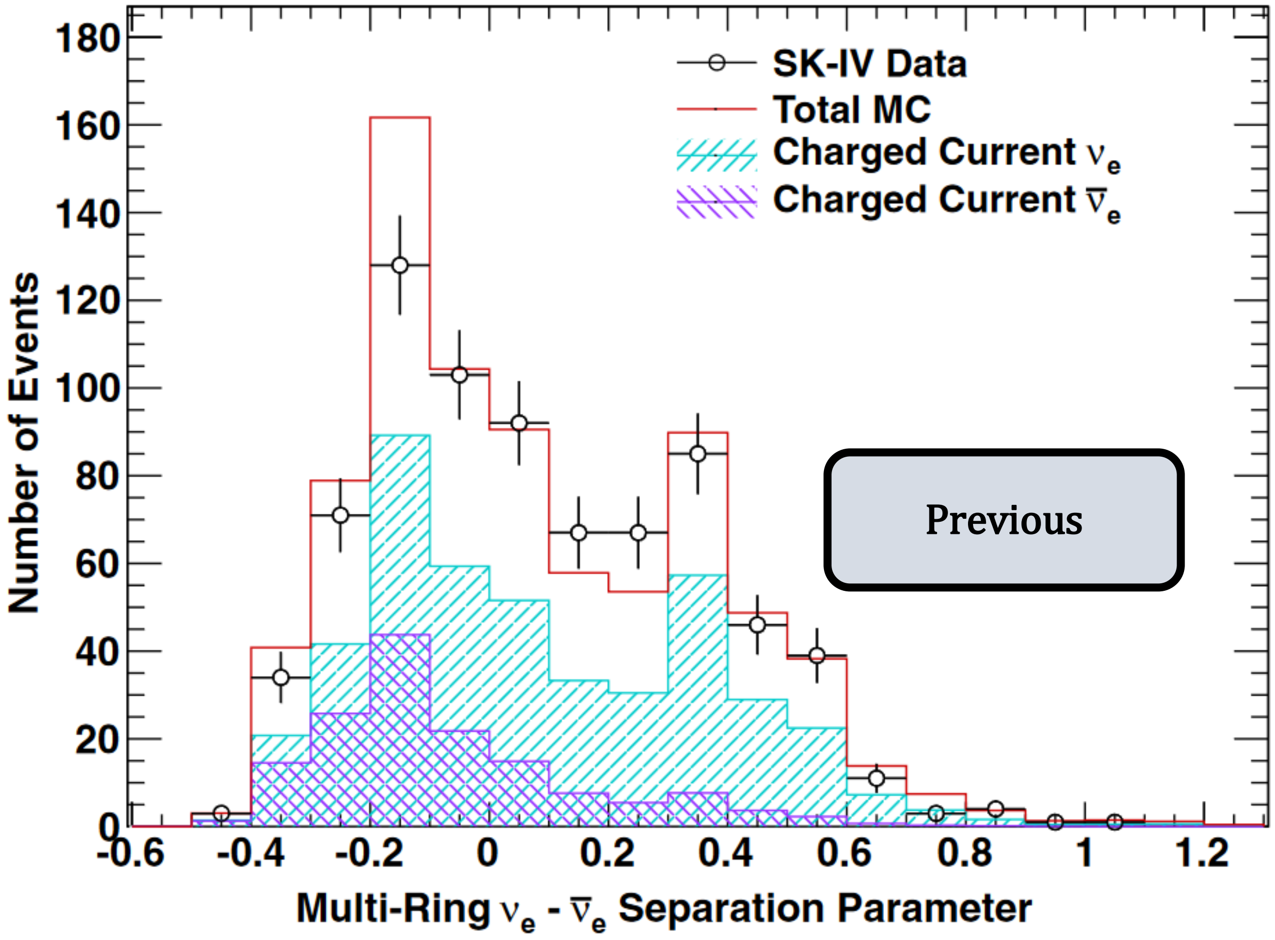
Atmospheric ν event selection: BDT inputs in more detail



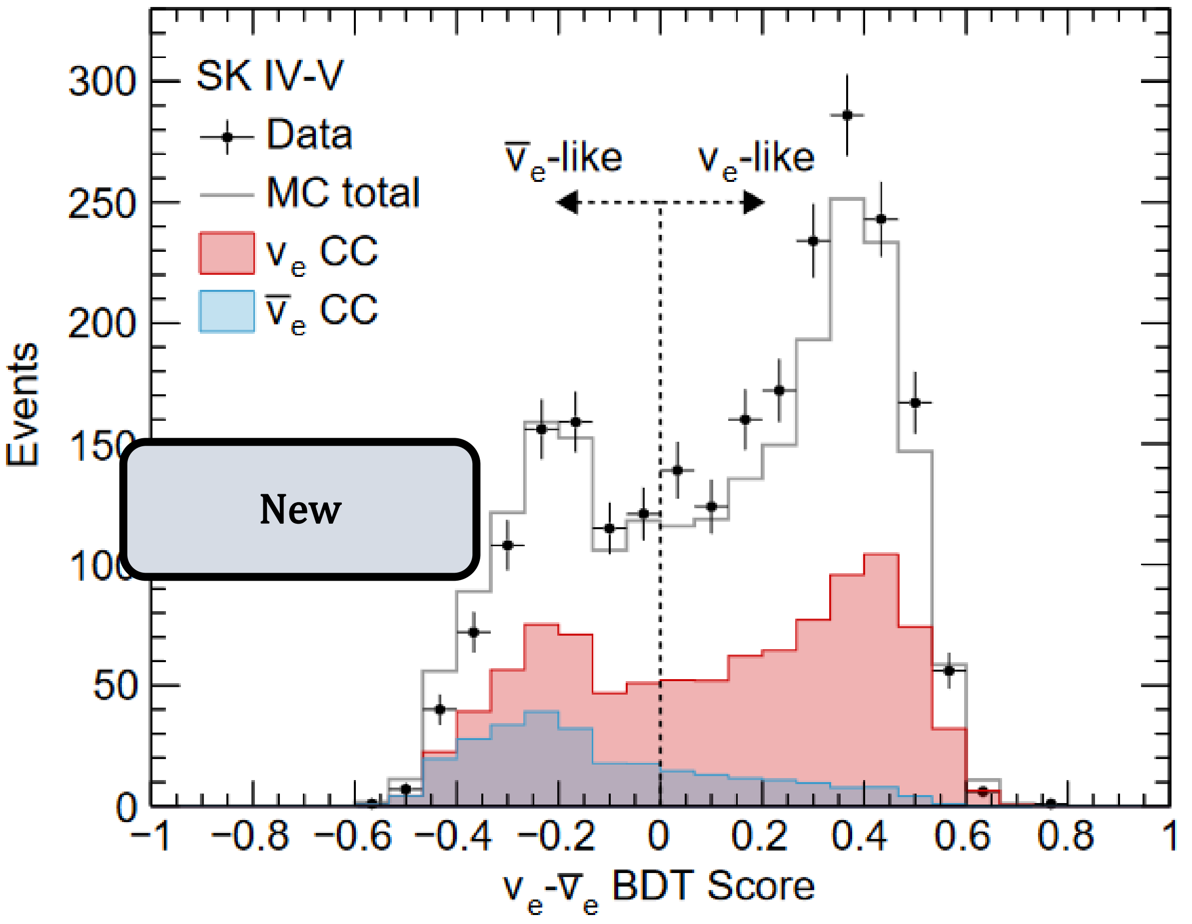


arXiv:2311.05105v1 (2023)

Improvement of multi-ring classification with BDT



*Abe et al., PRD **97**, 072001 (2018)*



arXiv:2311.05105v1 (2023)

Some factors determining $\nu/\bar{\nu}$ separation

(CC ν_e interactions)

$$\nu_e + N \to e^- + N' + \pi^+$$

$$\hookrightarrow \mu^+ + \nu_\mu$$

$$\hookrightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

(more particles in the end!)

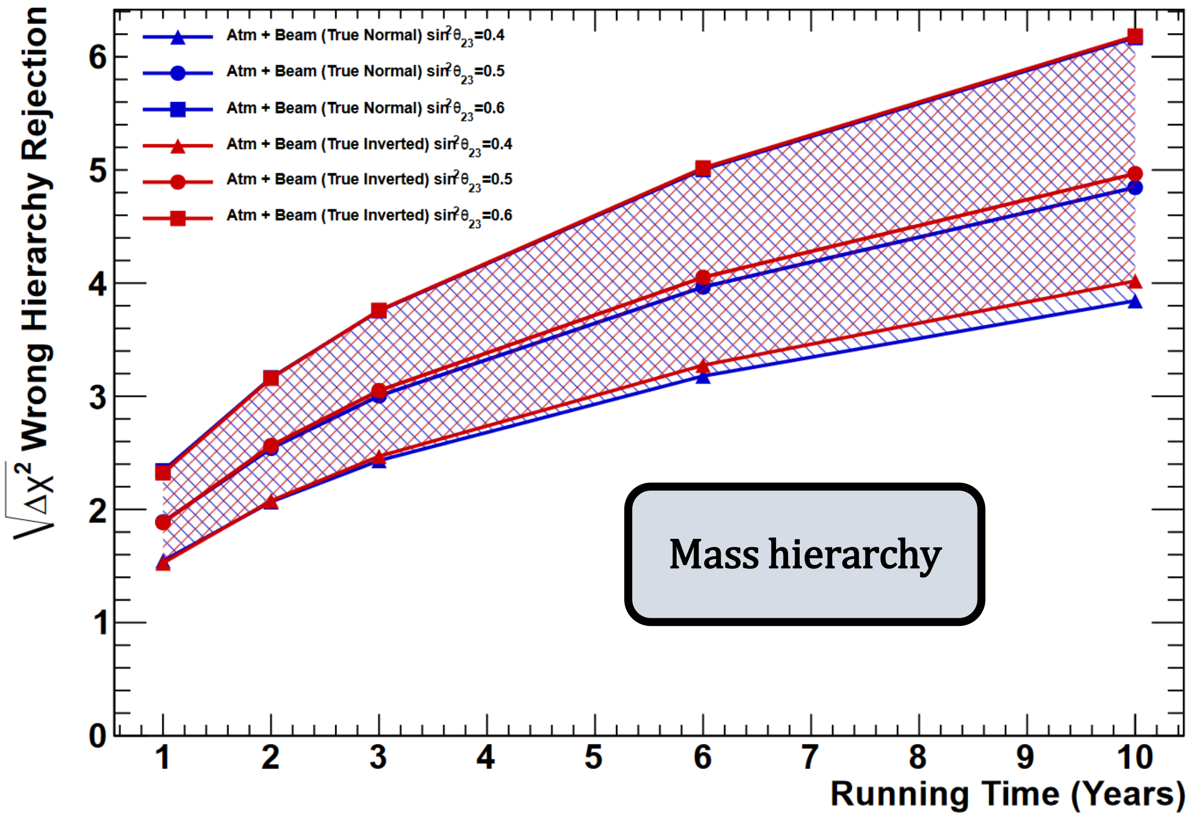
(CC $\bar{\nu}_e$ interactions)

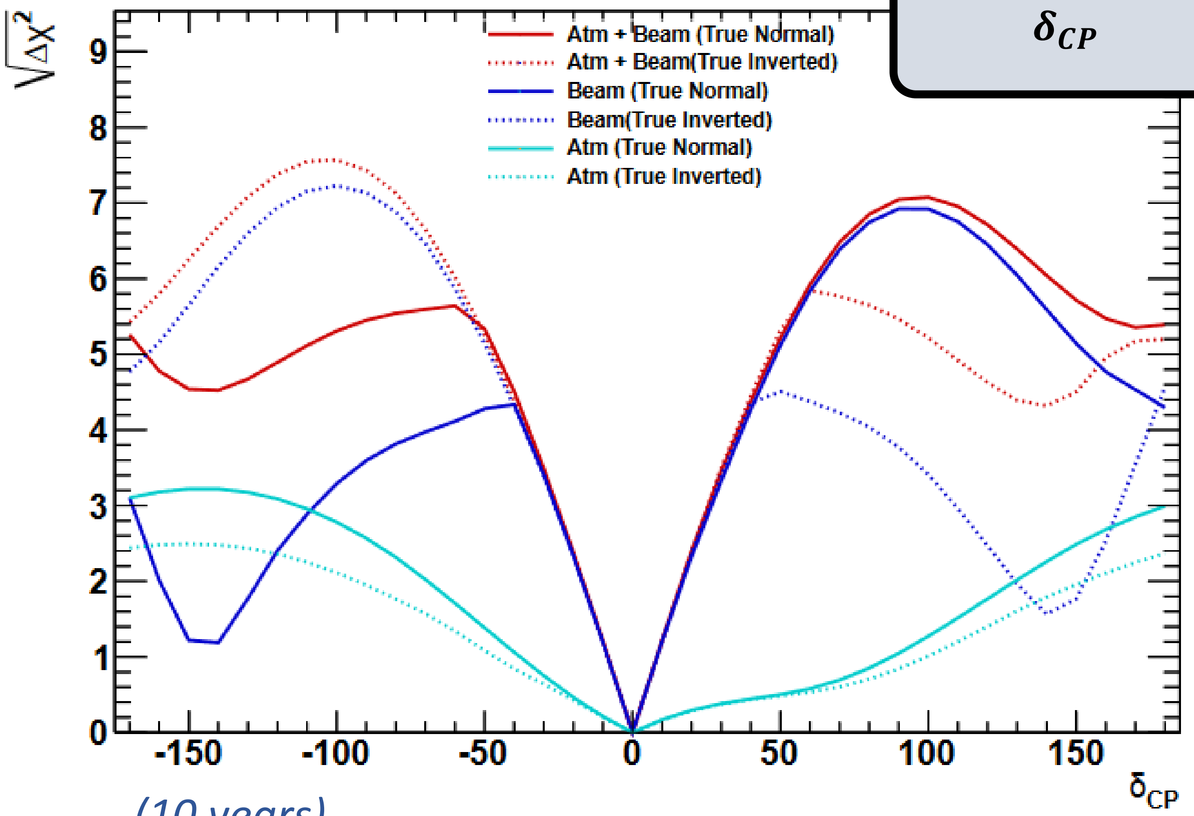
$$\bar{\nu}_e + N \to e^+ + N' + \pi^-$$

(captured in water!)

(more forward!)

Expectations for atmospheric ν studies with Hyper-K





δ_{CP}

(10 years)

Hyper-K Design Report (2018)

Solar ν

(backup page)

Solar ν analysis systematic uncertainties in SK-IV

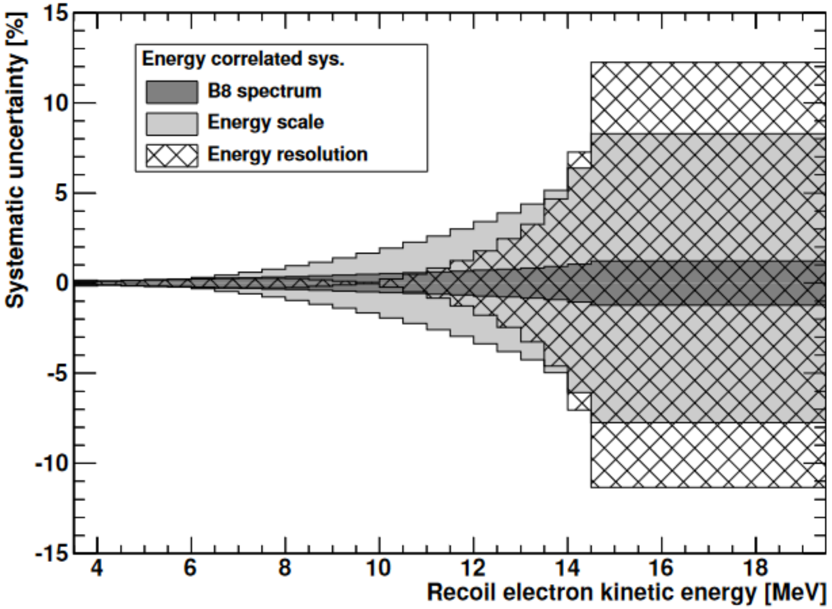
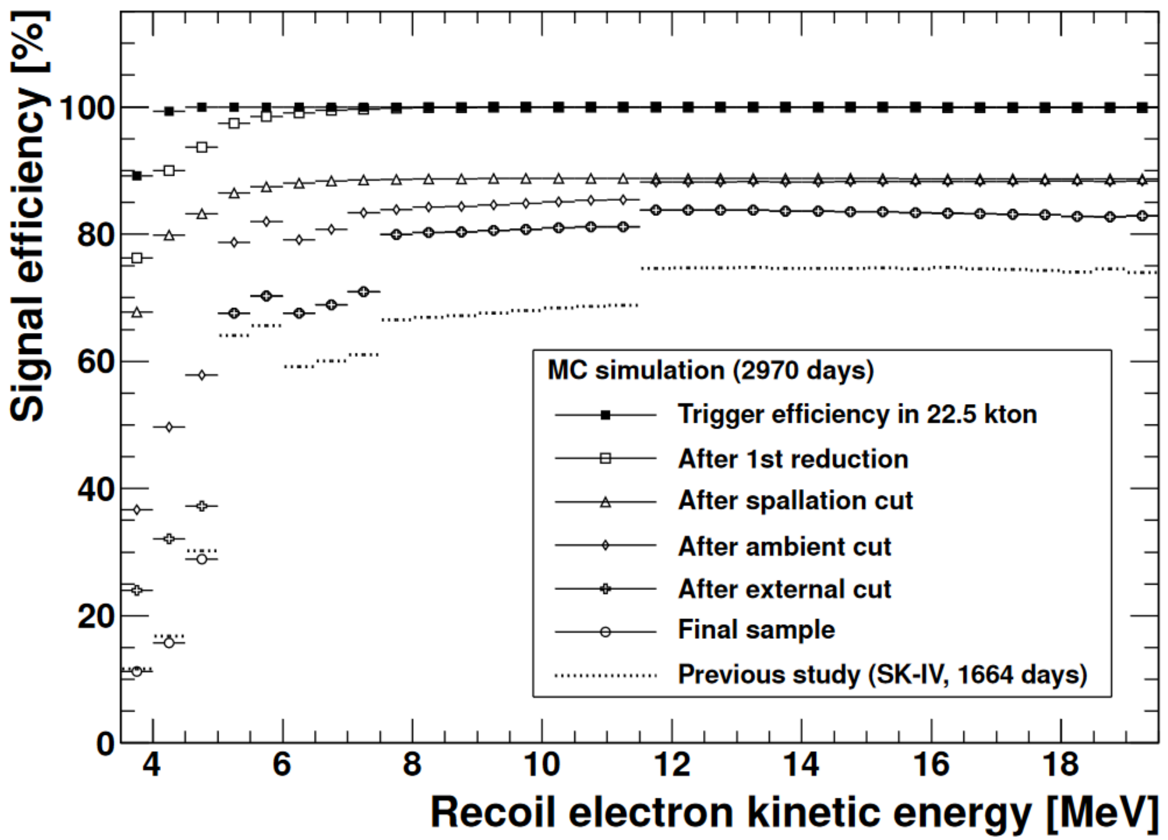


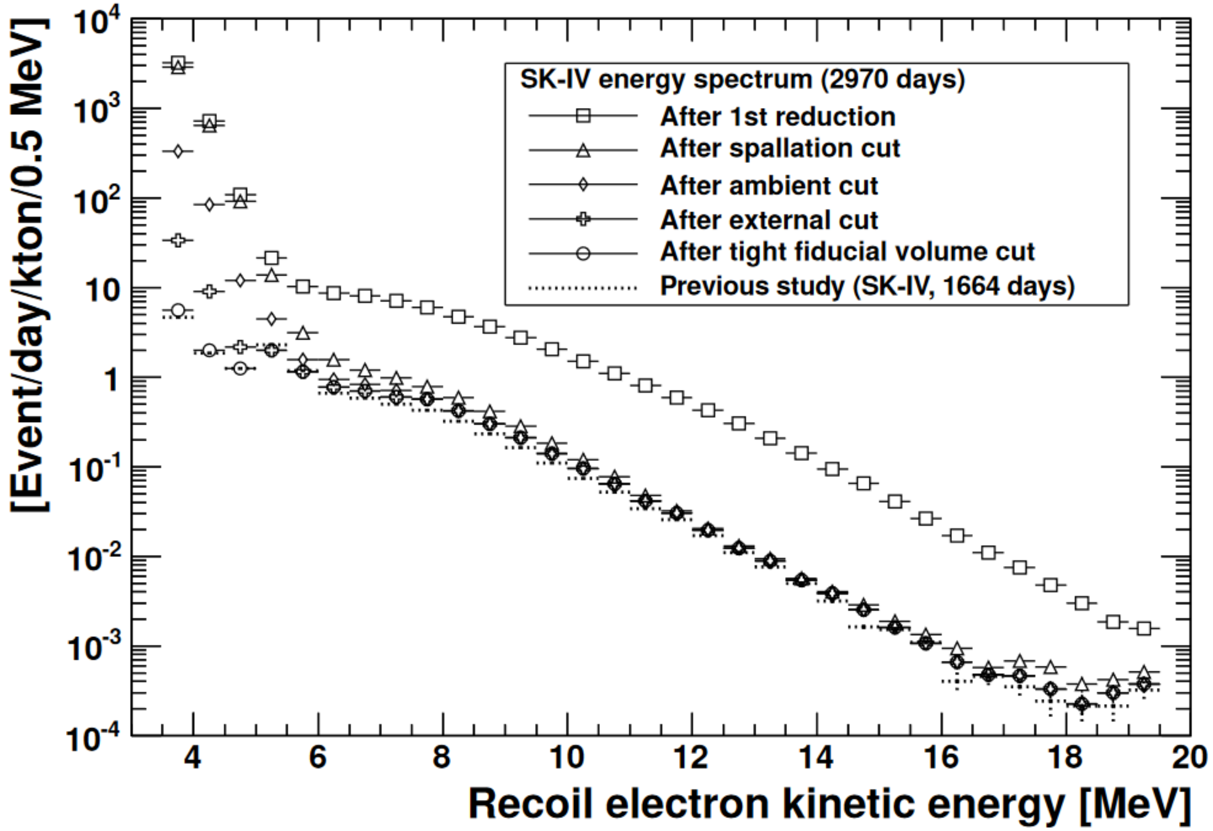
TABLE V. Energy-uncorrelated systematic uncertainty in each energy region in SK-IV.

Energy [MeV]	3.49–3.99	3.99–4.49	4.49–4.99	4.99–5.49	5.49–5.99	5.99–6.49	6.49–6.99	6.99–7.49	7.49–19.49
Trigger efficiency	$^{+3.5}_{-3.2}\%$	±0.7%	–	–	–	–	–	–	–
Angular resolution	±0.2%	±0.2%	±0.2%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%
Reconstruction goodness	±0.1%	±0.2%	±0.1%	±0.1%	±0.1%	±0.3%	±0.5%	±0.7%	±0.4%
Hit pattern	–	–	–	–	–	±0.5%	±0.5%	±0.4%	±0.4%
Small hit cluster	±0.1%	±0.1%	±0.1%	–	–	–	–	–	–
External event cut	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.1%	±0.2%
Vertex shift	±0.4%	±0.4%	±0.4%	±0.7%	±0.4%	±0.4%	±0.4%	±0.4%	±0.1%
Background shape	±2.7%	±0.6%	±0.6%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.1%
Signal extraction	±2.1%	±2.1%	±2.1%	±0.7%	±0.7%	±0.7%	±0.7%	±0.7%	±0.7%
Cross section	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%	±0.2%
Multiple scattering goodness	±0.4%	±0.2%	±0.3%	±0.3%	±0.3%	±0.6%	±1.3%	±1.3%	–
Total	$^{+4.9}_{-4.8}\%$	±2.4%	±2.3%	±1.1%	±0.9%	±1.2%	±1.7%	$^{+1.8}_{-1.7}\%$	±0.9%

arXiv:2312.12907v1 (2023)

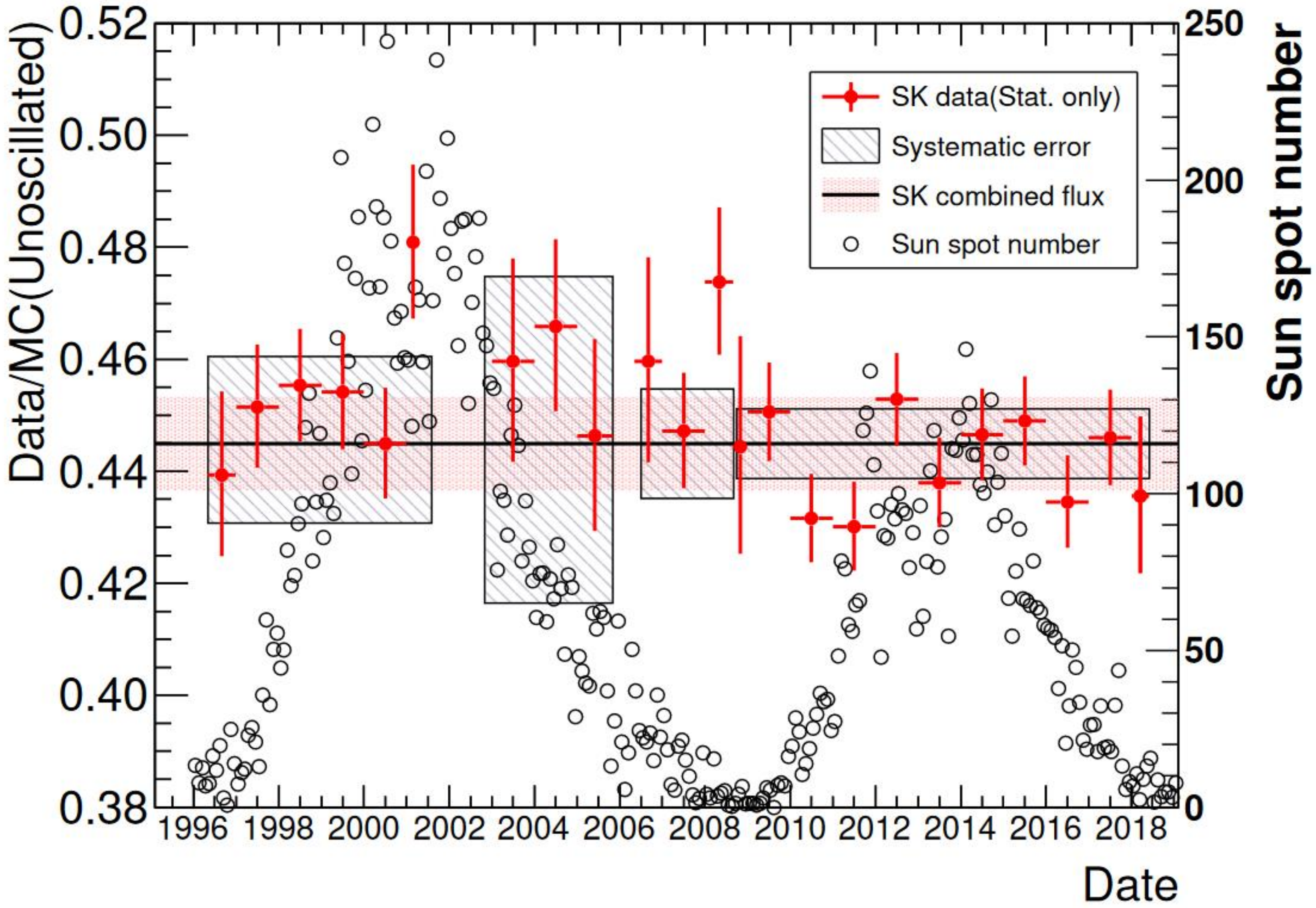
Solar ν analysis reduction steps





arXiv:2312.12907v1 (2023)

Solar ν flux stability across solar cycles



- χ^2/N_{dof} = 19.94/22
- Consistent with constant flux

arXiv:2312.12907v1 (2023)

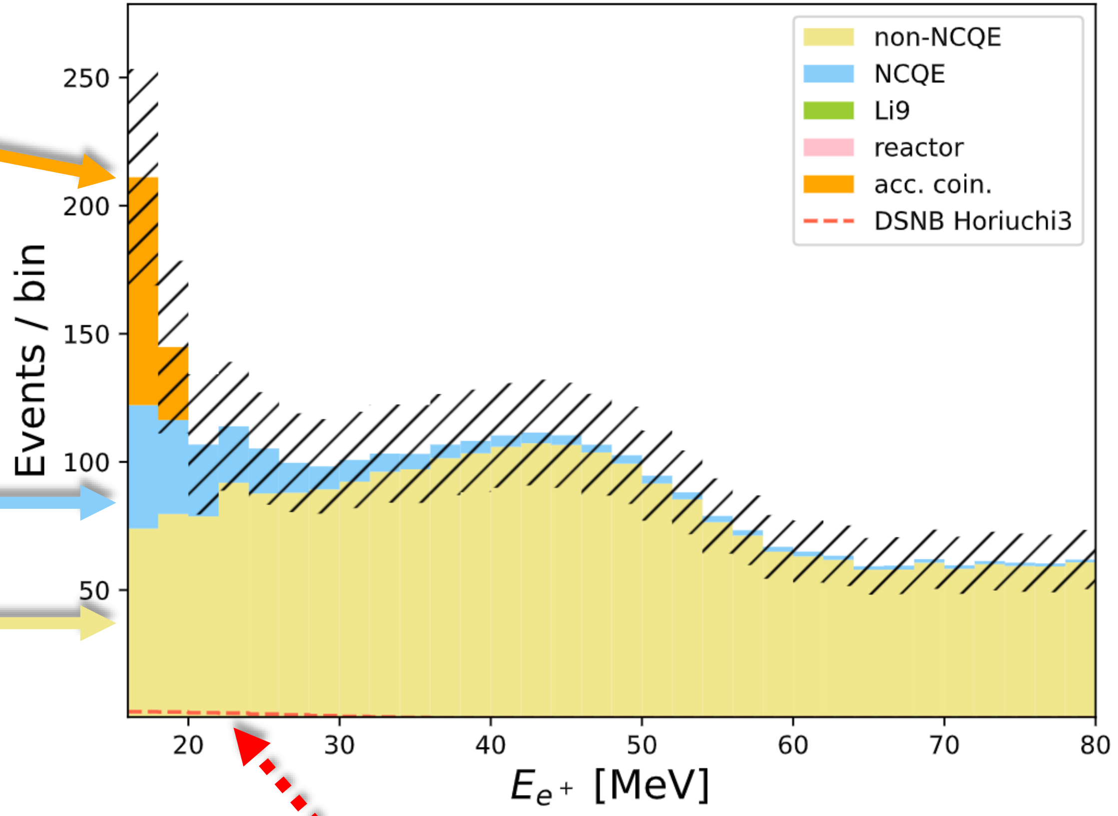
SN/DSNB

(backup page)

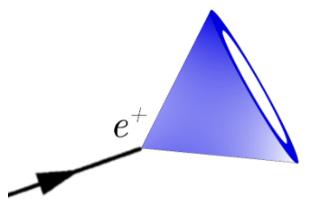
Isolating the IBD events using positron and neutron coincidence

Tagging positron only :

- The product of cosmic ray interactions form **"spallation" background** at low energy.
- **Solar neutrinos** are a background at energies up to around 20 MeV (not shown in plot).
- **Reactor neutrinos** form an irreducible background at low energy because they produce an IBD signal.
- **Atmospheric neutral-current (NC)** interactions produce photons **mimicking** the positron.
- **Atmospheric neutrinos** after around produce **charged-current (CC)** interaction backgrounds.

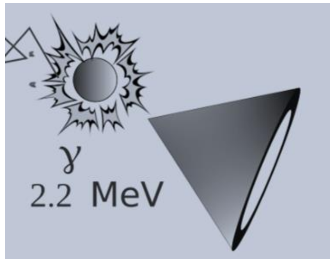


One DSNB model!



prompt positron

+

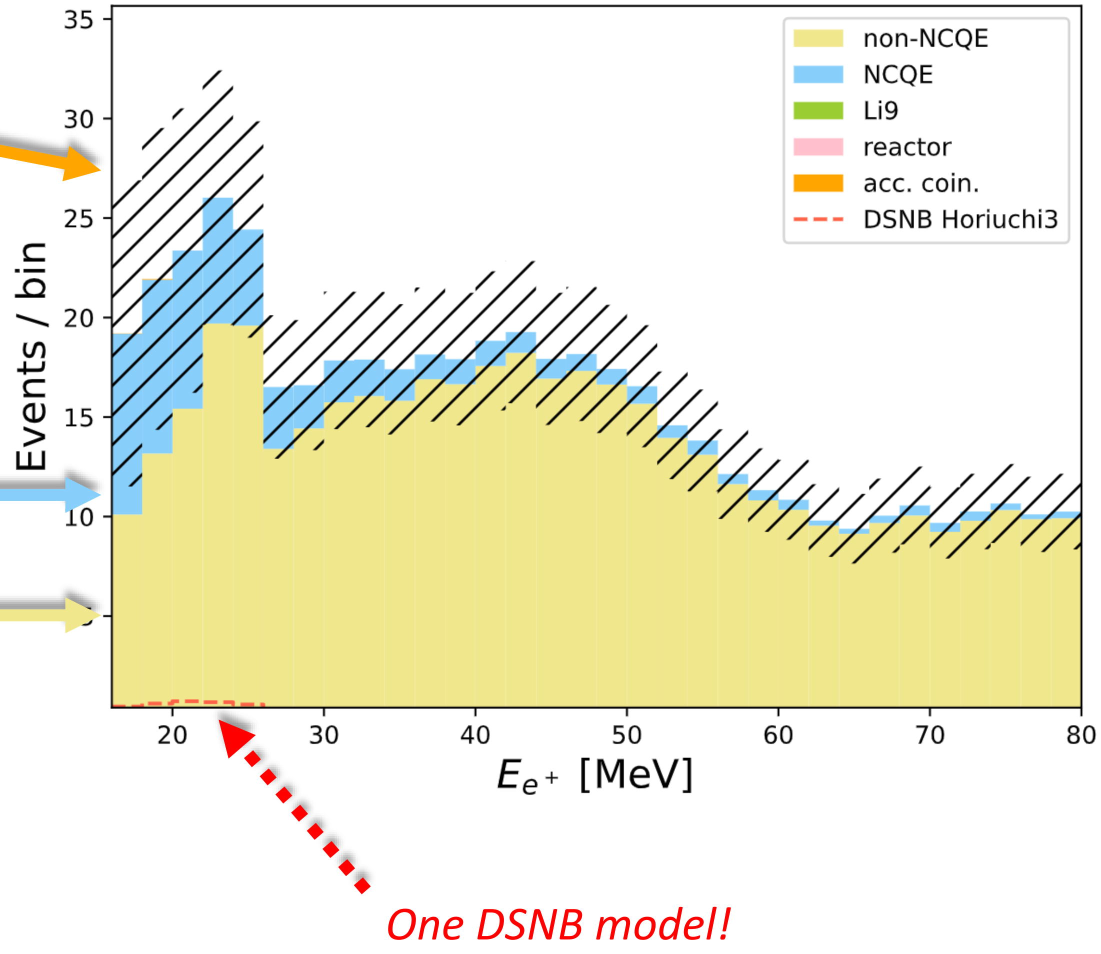


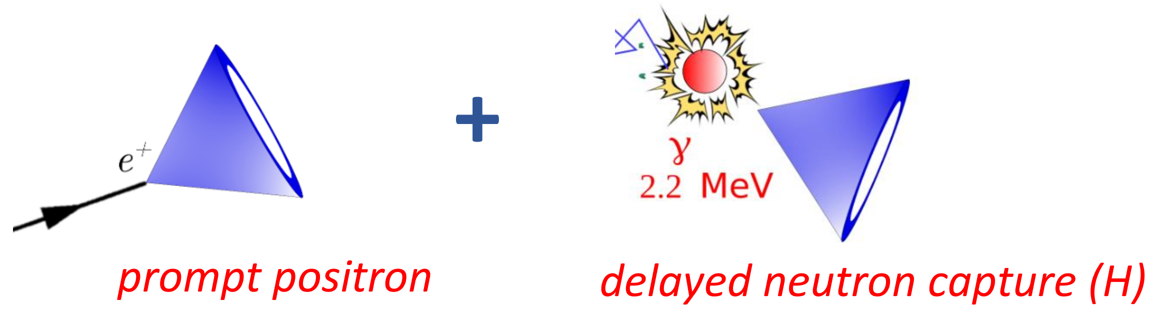
delayed neutron capture (H)

Isolating the IBD events using positron and neutron coincidence

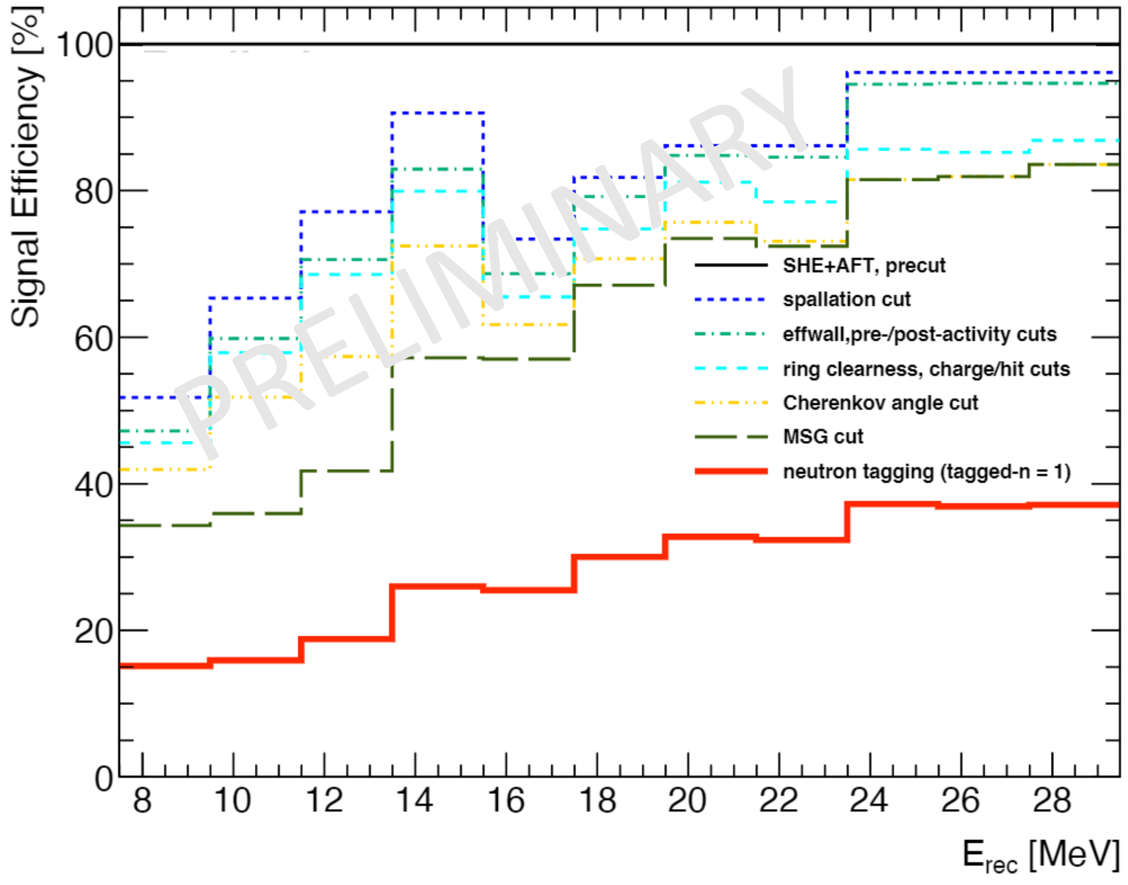
Tagging positron + neutron:

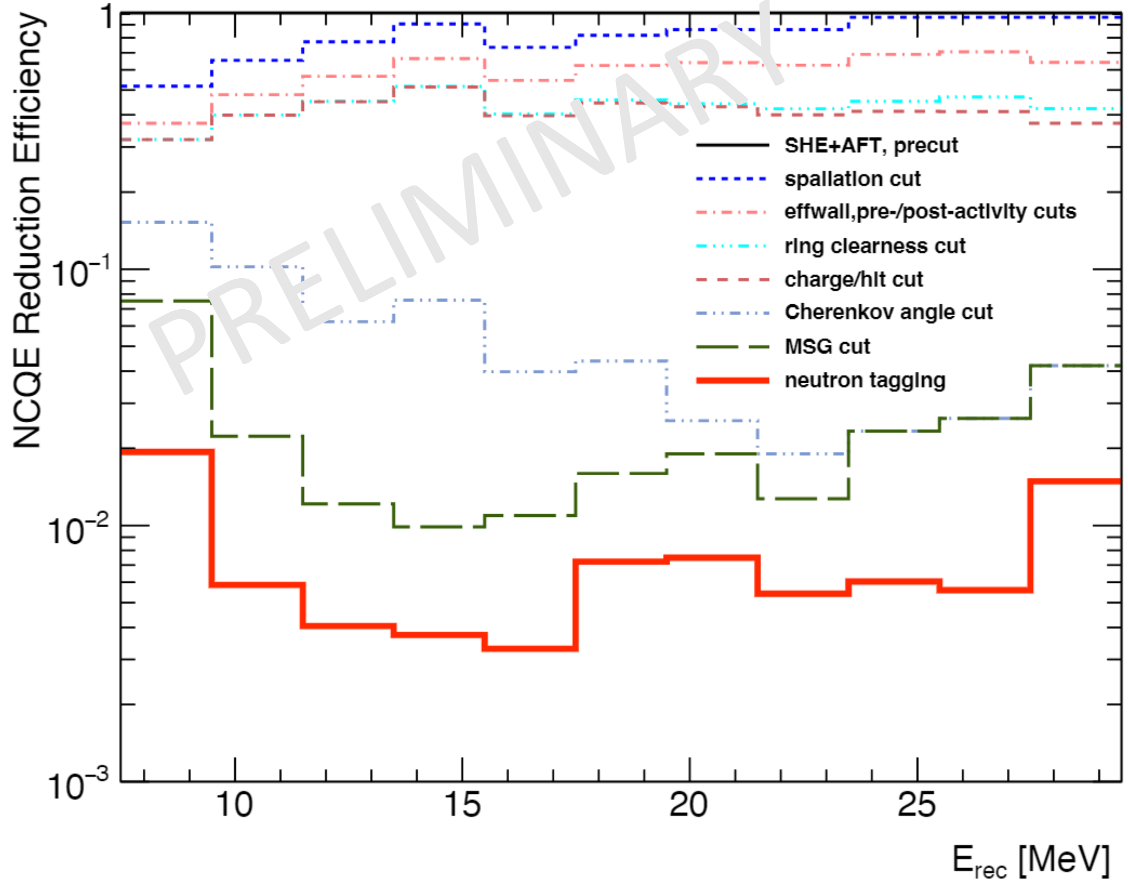
- The product of cosmic ray interactions form **"spallation" background** at low energy.
- **Solar neutrinos** are a background at energies up to around 20 MeV (not shown in plot).
- **Reactor neutrinos** form an irreducible background at low energy because they produce an IBD signal.
- **Atmospheric neutral-current (NC)** interactions produce photons **mimicking** the positron.
- **Atmospheric neutrinos** after around produce **charged-current (CC)** interaction backgrounds.





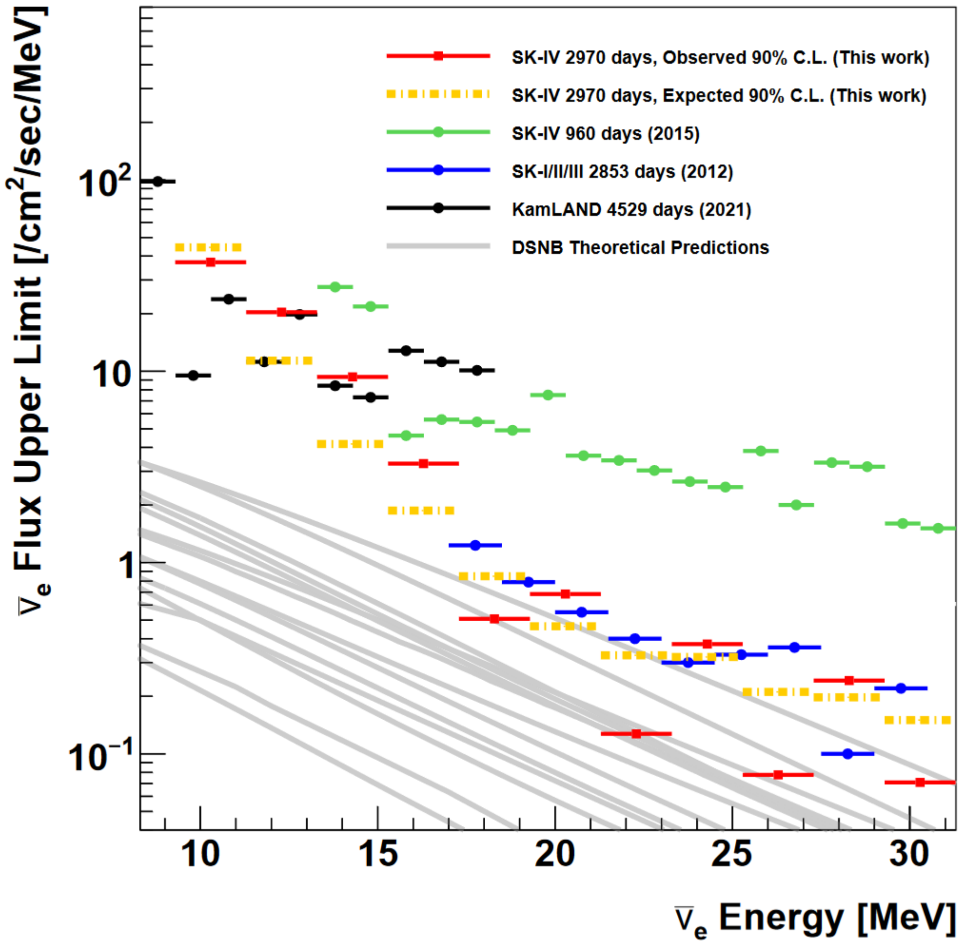
Signal and NCQE background efficiencies after cuts





officialized, paper preparation (2024)

Estimating DSNB sensitivity using upper limits (throw toys)



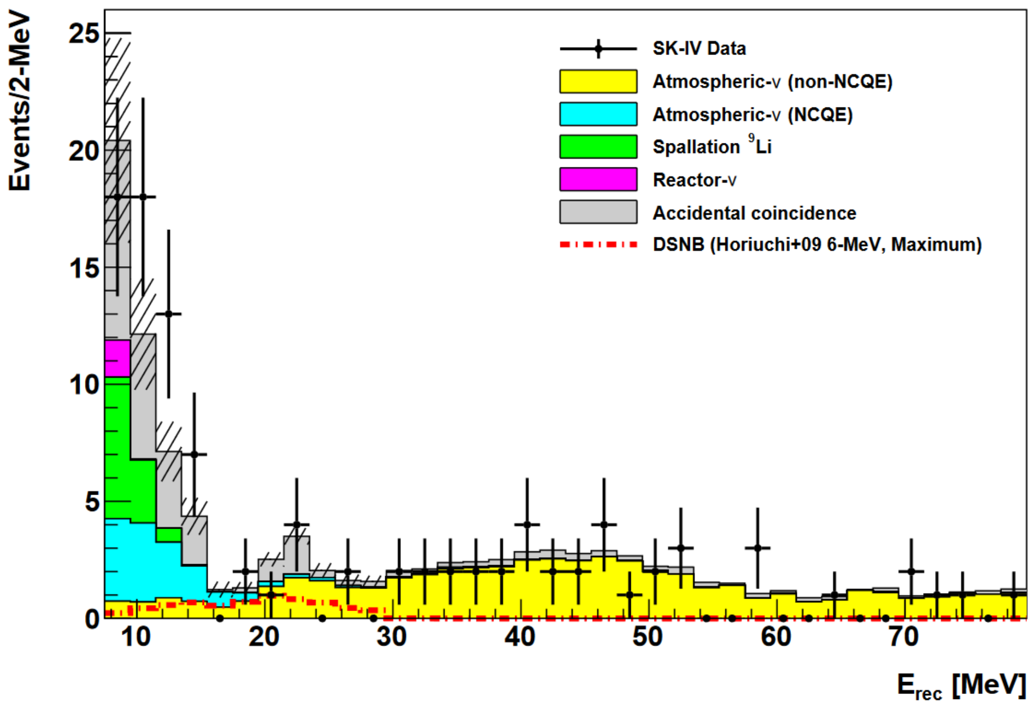
Phys. Rev. D **104**, 122002 (2021)

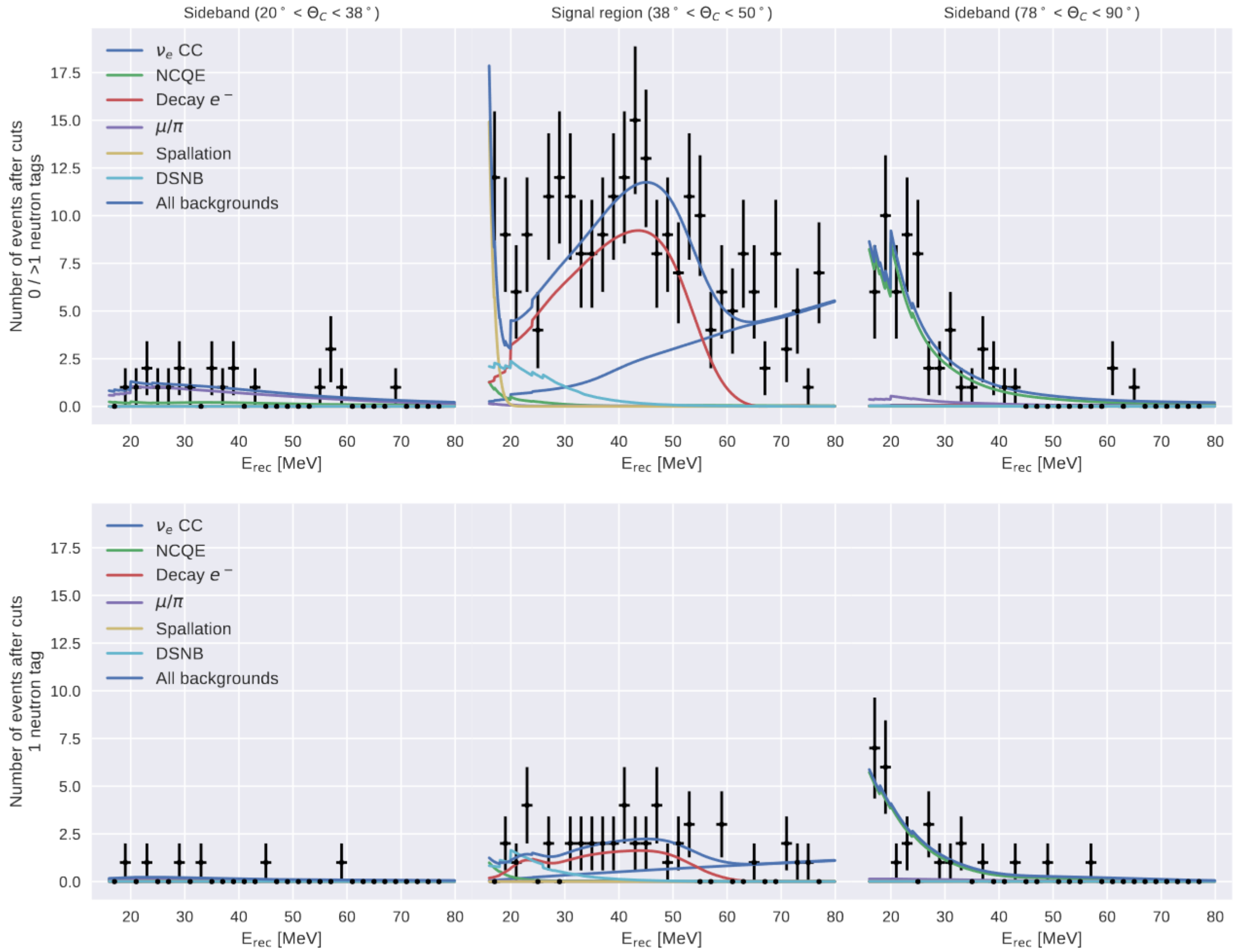
Upper limit steps

1. Sample $N_{obs}(E_{rec})$ from $\mathbf{P}\left(\boldsymbol{N}(\boldsymbol{\mu} = \boldsymbol{N}_{pred}, \boldsymbol{\sigma} = \boldsymbol{\delta N}_{sys})\right)$
2. Sample $N_{pred}(E_{rec})$ from $\mathbf{P}(\boldsymbol{N}_{pred})$
3. Perform $\boldsymbol{N}_{obs}(\boldsymbol{E}_{rec}) - \boldsymbol{N}_{pred}(\boldsymbol{E}_{rec})$ to generate PDF of excess BG events after **many toys thrown**
4. **Integrate excess BG PDF** until reach 90% of curve to define number of events N_{90}^{limit} for 90% CL
5. Convert N_{90}^{limit} into **flux limit $\boldsymbol{\phi}_{90}^{\text{limit}}$**

$$\phi_{90}^{\text{limit}} = \frac{N_{90}^{\text{limit}}}{t \cdot N_p \cdot \bar{\sigma}_{\text{IBD}} \cdot \epsilon_{\text{sig}}}$$

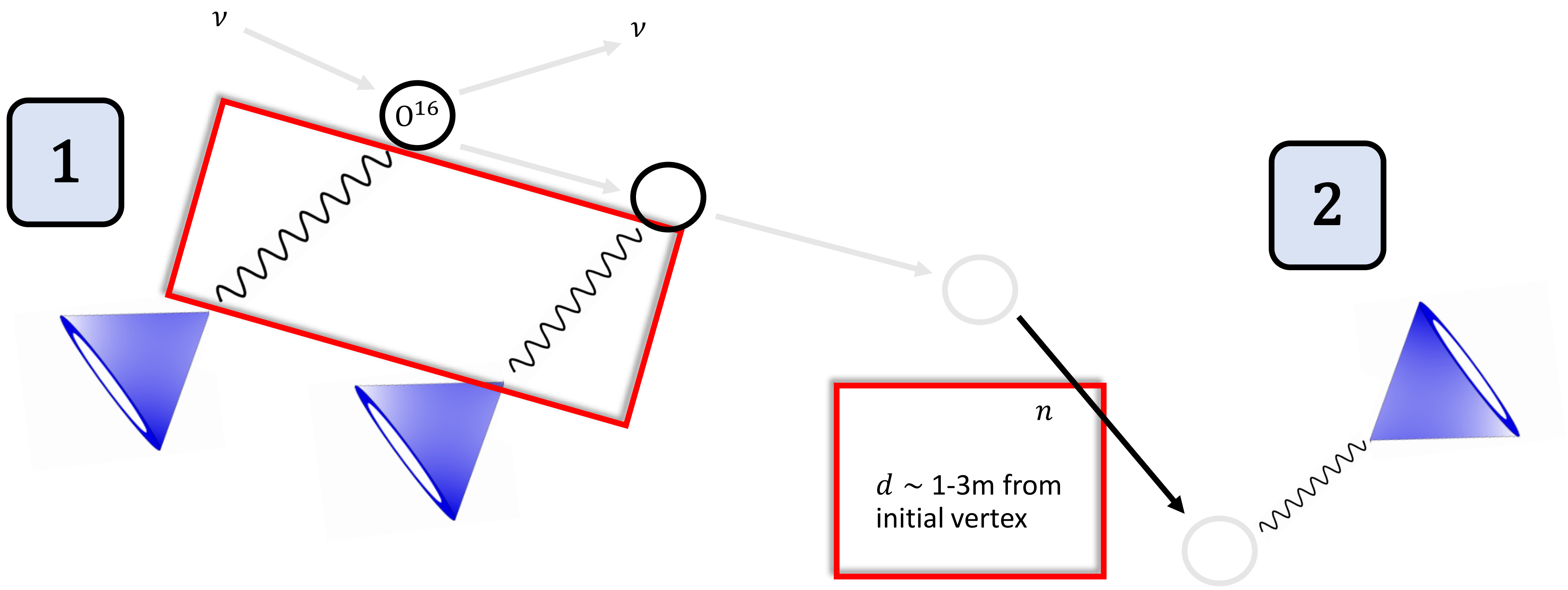
SK-IV DSNB analysis results in more detail





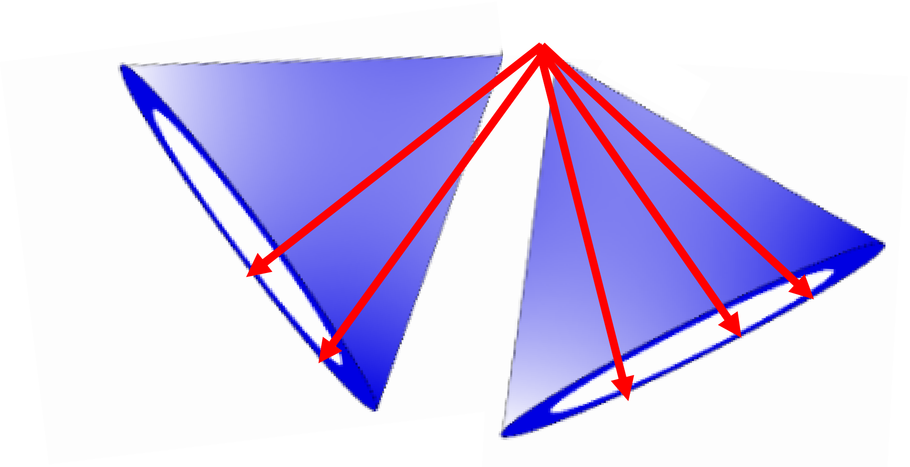
Phys. Rev. D **104**, 122002 (2021)

Differences of overall NCQE from DSNB IBD signal



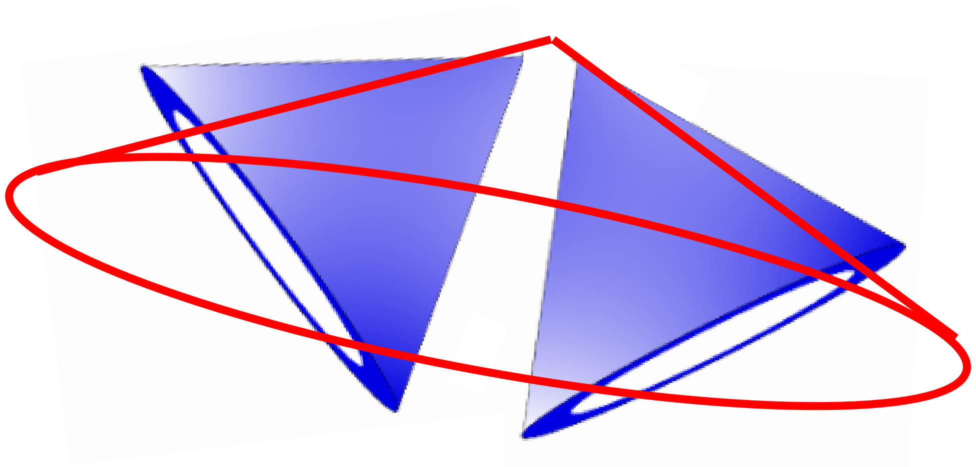
Comparison of θ_c and MSG variables

MSG



- Sensitive to **possible directions** for assuming only one cone made the observed event.

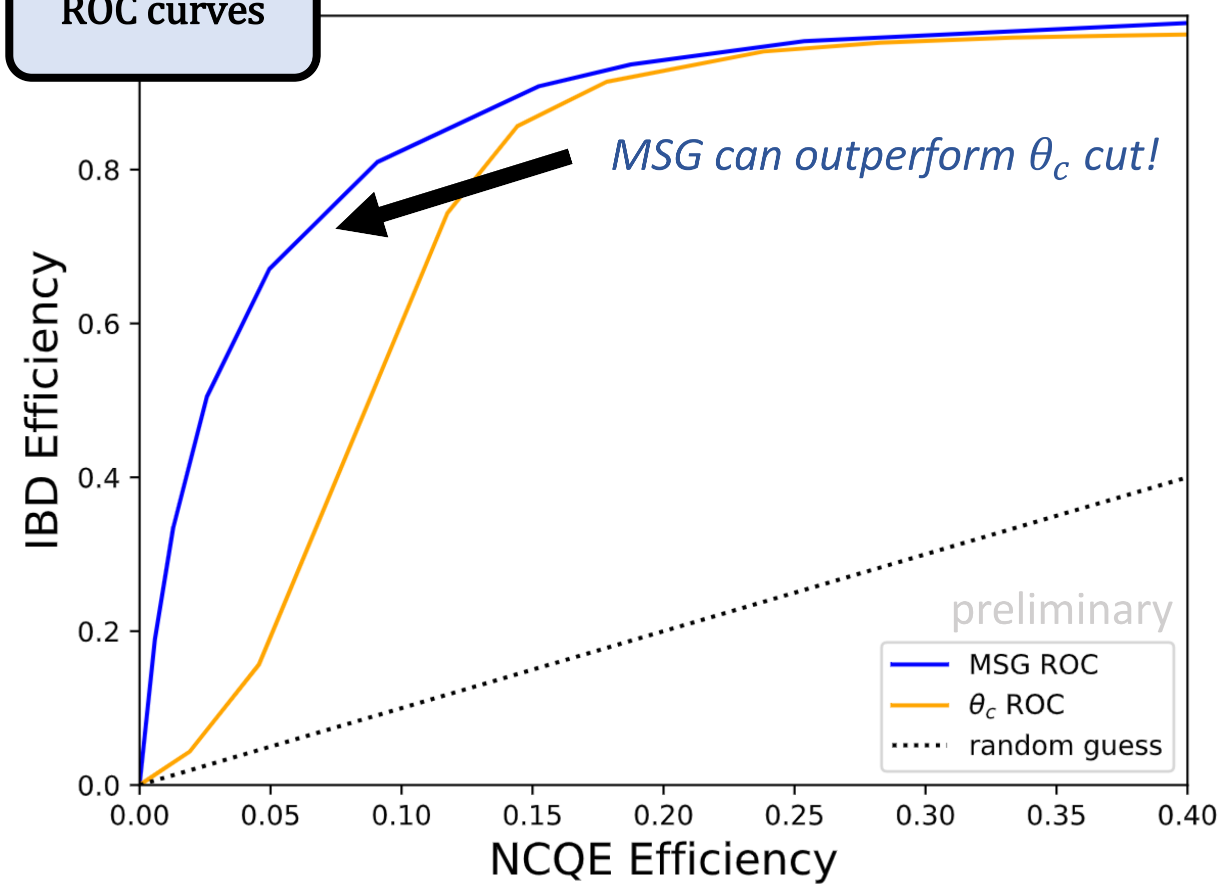
θ_c



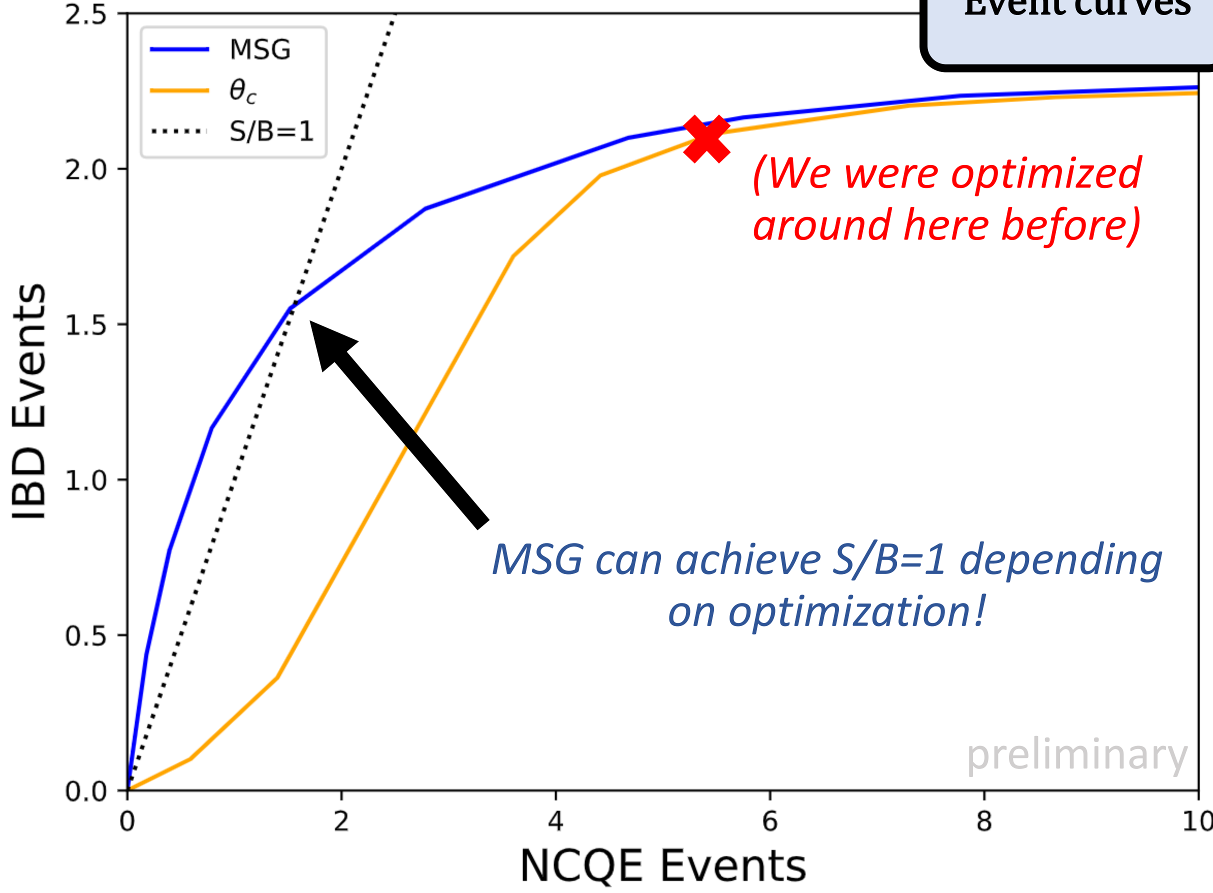
- Sensitive to **overall size** for assuming only one cone made the observed event.

SK6 MSG and θ_c cut comparisons ($E_{e^+} \in [8, 24]$ MeV)

ROC curves



Event curves



CP-violation

(backup page)

Baryogenesis through leptogenesis from CP-violation in $\boldsymbol{\nu}$

Through CPV in seesaw mechanism

- For $\delta_{CP} \neq 0, \pi$, neutrino and anti-neutrino $\boldsymbol{P_{\mu e}}$ **will differ**.
- This also induces CP violation more broadly in lepton sector.
- Neutrino mass generation happens through seesaw with one heavy Majorana neutrino N.
- Heavy Majorana neutrinos into lH and $\bar{l}\bar{H}$ lead to $\Delta L \neq 0$ for out-of-equilibrium decays.
- SM sphaleron processes can convert $\Delta L \neq 0 \rightarrow \Delta B \neq 0$.

$$\mathcal{L} \supset \frac{1}{2}(\bar{\nu}_L \;\; \bar{\nu}_L^c)\begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_R^c \\ \nu_R \end{pmatrix} + h.c.$$

$$m_\nu \sim \frac{m_D^2}{M_R} \qquad m_N \sim M_R$$

$$N \rightarrow lH, \qquad N \rightarrow \bar{l}\bar{H}$$

Other

(backup page)

Neutrino oscillations from mismatched mass, flavor states

$$|\nu_\alpha\rangle = \sum_i U^*_{\alpha i}|\nu_i\rangle$$

(flavor basis) (mass basis)

$$\begin{pmatrix}|\nu_e\rangle\\|\nu_x\rangle\end{pmatrix} = \begin{pmatrix}\cos\theta & \sin\theta\\-\sin\theta & \cos\theta\end{pmatrix}\begin{pmatrix}|\nu_1\rangle\\|\nu_2\rangle\end{pmatrix}$$

(2-flavor framework)

$$|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$$

(approximations)

$$|\nu_e(L)\rangle = e^{-\frac{im_1^2L}{2E}}\cos\theta\,|\nu_1\rangle + e^{-\frac{im_2^2L}{2E}}\sin\theta\,|\nu_2\rangle$$

(different phases in t-evolution)

$(\Delta m^2_{ij} \equiv m_i^2 - m_j^2)$ (frequency of oscillation)

$$P_{ee} = |\langle\nu_e(L)|\nu_e\rangle|^2 = 1 - \sin^2 2\theta\,\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

(amplitude of oscillation)

Parameterizing full mixing matrix between mass, flavor bases

(flavor basis) *CP-violating Dirac phase* *Majorana phases* *(mass basis)*

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \\ |\nu_\tau\rangle \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta_{CP}} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta_{CP}} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha_1} & 0 \\ 0 & 0 & e^{i\alpha_2} \end{pmatrix} \begin{pmatrix} |\nu_1\rangle \\ |\nu_2\rangle \\ |\nu_3\rangle \end{pmatrix}$$

$s_{ij} \equiv \sin\theta_{ij}\,, c_{ij} \equiv \cos\theta_{ij}$

$\theta_{12} = 33.41^{\circ}{}^{+0.75^{\circ}}_{-0.72^{\circ}}$, $\theta_{23} = 49.1^{\circ}{}^{+1.0^{\circ}}_{-1.3^{\circ}}$, $\theta_{13} = 8.54^{\circ}{}^{+0.11^{\circ}}_{-0.12^{\circ}}$, $\delta_{CP} = 196^{\circ}{}^{+42^{\circ}}_{-25^{\circ}}$ *Source: NuFIT 2022*

(maximal mixing?) *(hints of CP-violation)*

NuFIT 2022 results in detail

NuFIT 5.2 (2022)

without SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.3$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.572^{+0.018}_{-0.023}$	$0.406 \to 0.620$	$0.578^{+0.016}_{-0.021}$	$0.412 \to 0.623$
$\theta_{23}/^\circ$	$49.1^{+1.0}_{-1.3}$	$39.6 \to 51.9$	$49.5^{+0.9}_{-1.2}$	$39.9 \to 52.1$
$\sin^2\theta_{13}$	$0.02203^{+0.00056}_{-0.00059}$	$0.02029 \to 0.02391$	$0.02219^{+0.00060}_{-0.00057}$	$0.02047 \to 0.02396$
$\theta_{13}/^\circ$	$8.54^{+0.11}_{-0.12}$	$8.19 \to 8.89$	$8.57^{+0.12}_{-0.11}$	$8.23 \to 8.90$
$\delta_{CP}/^\circ$	197^{+42}_{-25}	$108 \to 404$	286^{+27}_{-32}	$192 \to 360$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.511^{+0.028}_{-0.027}$	$+2.428 \to +2.597$	$-2.498^{+0.032}_{-0.025}$	$-2.581 \to -2.408$

with SK atmospheric data

	Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 6.4$)	
	bfp $\pm1\sigma$	3σ range	bfp $\pm1\sigma$	3σ range
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$	$0.270 \to 0.341$	$0.303^{+0.012}_{-0.011}$	$0.270 \to 0.341$
$\theta_{12}/^\circ$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$	$33.41^{+0.75}_{-0.72}$	$31.31 \to 35.74$
$\sin^2\theta_{23}$	$0.451^{+0.019}_{-0.016}$	$0.408 \to 0.603$	$0.569^{+0.016}_{-0.021}$	$0.412 \to 0.613$
$\theta_{23}/^\circ$	$42.2^{+1.1}_{-0.9}$	$39.7 \to 51.0$	$49.0^{+1.0}_{-1.2}$	$39.9 \to 51.5$
$\sin^2\theta_{13}$	$0.02225^{+0.00056}_{-0.00059}$	$0.02052 \to 0.02398$	$0.02223^{+0.00058}_{-0.00058}$	$0.02048 \to 0.02416$
$\theta_{13}/^\circ$	$8.58^{+0.11}_{-0.11}$	$8.23 \to 8.91$	$8.57^{+0.11}_{-0.11}$	$8.23 \to 8.94$
$\delta_{CP}/^\circ$	232^{+36}_{-26}	$144 \to 350$	276^{+22}_{-29}	$194 \to 344$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$	$7.41^{+0.21}_{-0.20}$	$6.82 \to 8.03$
$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \text{eV}^2}$	$+2.507^{+0.026}_{-0.027}$	$+2.427 \to +2.590$	$-2.486^{+0.025}_{-0.028}$	$-2.570 \to -2.406$

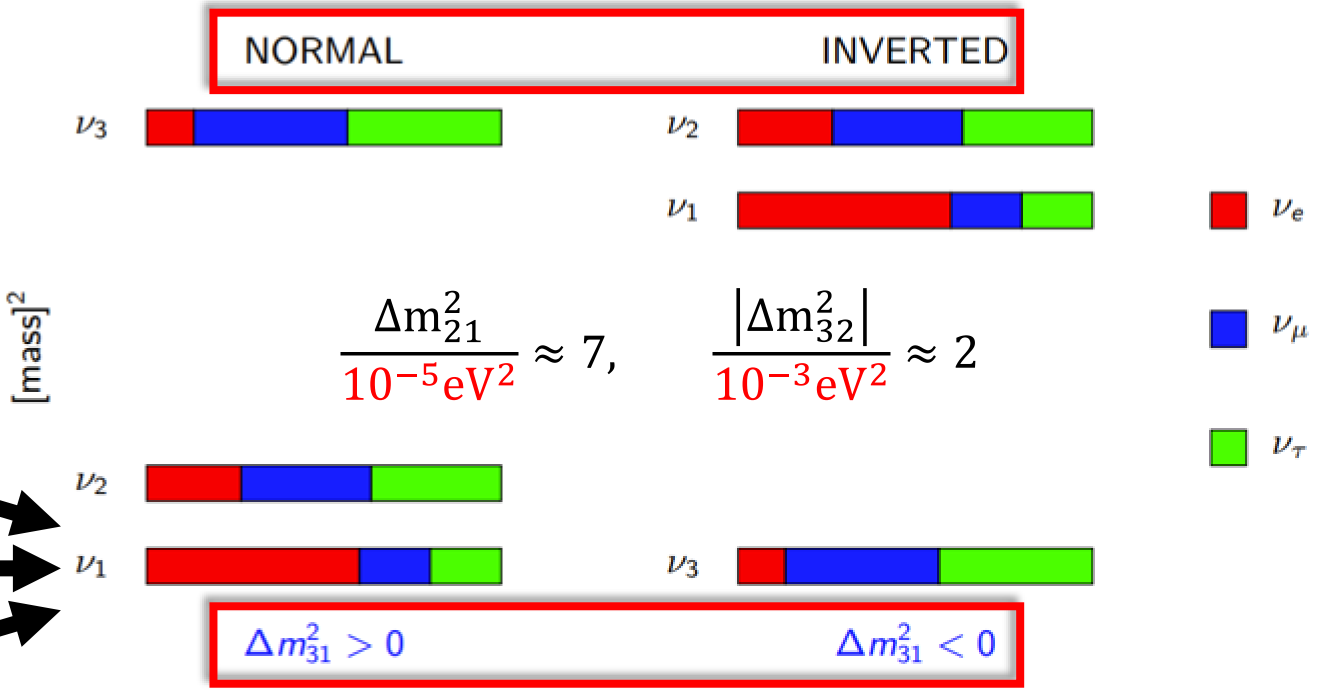
The mass hierarchy problem (normal vs inverted)

$$|U_{PMNS}| \approx \begin{pmatrix} 0.8 & 0.5-0.6 & 0.1-0.2 \\ 0.2-0.5 & 0.5-0.7 & 0.6-0.8 \\ 0.3-0.5 & 0.5-0.7 & 0.6-0.8 \end{pmatrix}$$

$$|\langle \nu_e|\nu_1\rangle|^2 = |U_{e1}|^2 \approx 0.8^2 = 0.64$$

$$|\langle \nu_\mu|\nu_1\rangle|^2 = |U_{\mu 1}|^2 \approx 0.4^2 = 0.16$$

$$|\langle \nu_\tau|\nu_1\rangle|^2 = |U_{\tau 1}|^2 \approx 0.4^2 = 0.16$$



Punchline for the effect of matter on neutrino propagation

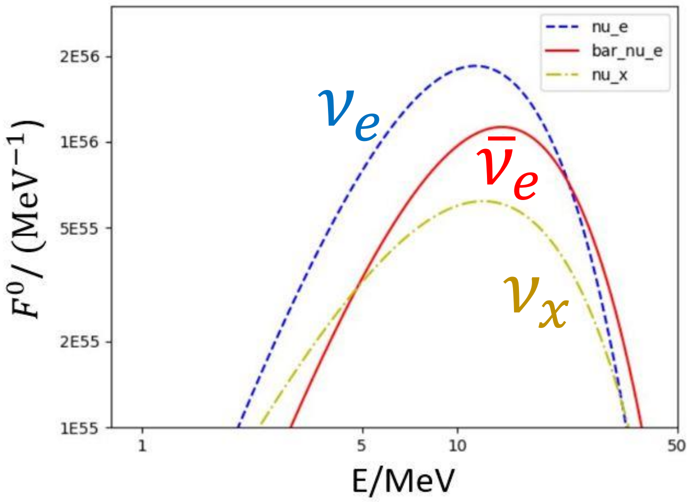
The Sun

$$F_{\nu_e}^{2>1} = |\langle \nu_e | \nu_2 \rangle|^2 F_{\nu_e}^0 \approx 0.3 F_{\nu_e}^0 \qquad m_2 > m_1!$$

$$F_{\nu_e}^{1>2} = |\langle \nu_e | \nu_1 \rangle|^2 F_{\nu_e}^0 \approx 0.7 F_{\nu_e}^0$$

Supernovae

(time-integrated SN neutrino spectra)



Different mass orderings give different final spectra!

$$m_3 > m_2 > m_1\ ? \quad F_{\nu_e}^{3>2} = \left(0 \times F_{\nu_e}^0\right) + \left(1 \times F_{\nu_x}^0\right)$$

$$m_2 > m_1 > m_3\ ? \quad F_{\nu_e}^{2>3} = \left(0.3 \times F_{\nu_e}^0\right) + \left(0.7 \times F_{\nu_x}^0\right)$$

Modified flavor oscillations in the presence of matter (2 flavors)

(usual Hamiltonian) *(additional CC potential for ν_e)*

$$H = \frac{\Delta m^2}{4E}\begin{pmatrix} -\cos 2\theta & \sin 2\theta \\ \sin 2\theta & \cos 2\theta \end{pmatrix} + \sqrt{2}G_F n_e \begin{pmatrix} 1 & 0 \\ 0 & 0 \end{pmatrix}$$

$$\tan 2\theta_M = \frac{\left(\frac{\Delta m^2}{2E}\right)\sin 2\theta}{\left(\frac{\Delta m^2}{2E}\right)\cos 2\theta - \sqrt{2}G_F n_e}$$

(new effective mixing angle)

Mikheyev-Smirnov-Wolfenstein (MSW) effect

$$\begin{pmatrix} |\nu_e\rangle \\ |\nu_\mu\rangle \end{pmatrix} = \begin{pmatrix} \cos\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos\theta_M \end{pmatrix}\begin{pmatrix} |\nu_{1M}\rangle \\ |\nu_{2M}\rangle \end{pmatrix}$$

(new propagation basis)

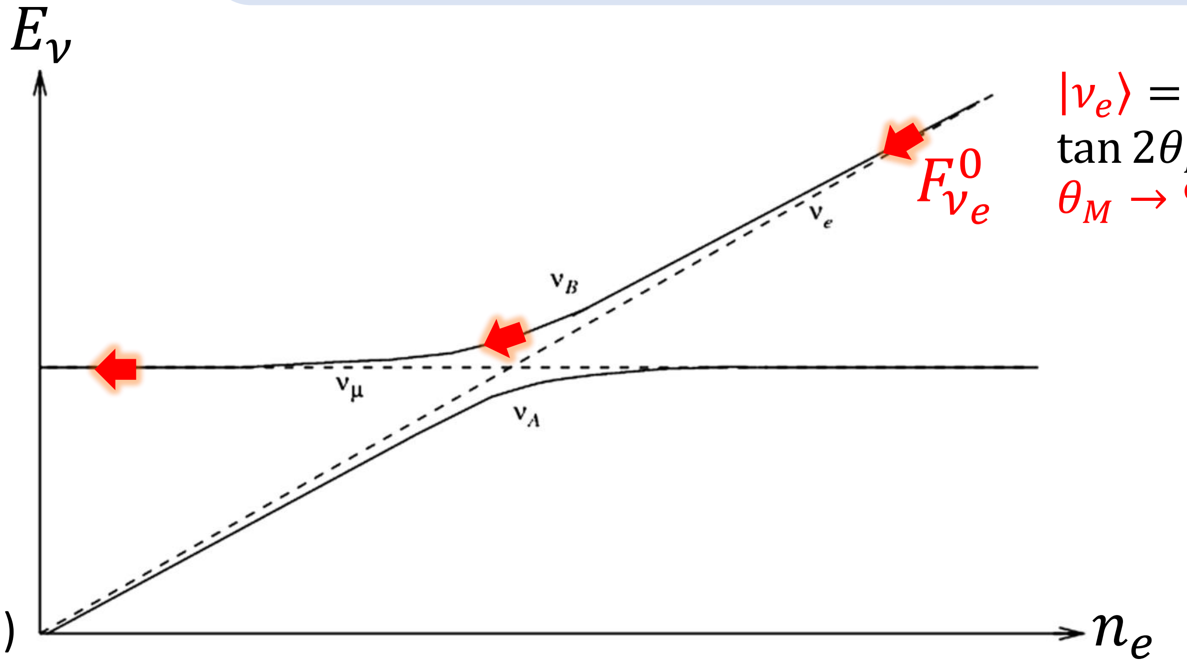
Two flavors!

Modified flavor oscillations in the presence of matter (2 flavors)

Mikheyev-Smirnov-Wolfenstein (MSW) effect

$$\tan 2\theta_M = \frac{\left(\frac{\Delta m^2}{2E}\right)\sin 2\theta}{\left(\frac{\Delta m^2}{2E}\right)\cos 2\theta - \sqrt{2}G_F n_e}$$

$$\begin{pmatrix}|\nu_e\rangle \\ |\nu_\mu\rangle\end{pmatrix} = \begin{pmatrix}\cos\theta_M & \sin\theta_M \\ -\sin\theta_M & \cos\theta_M\end{pmatrix}\begin{pmatrix}|\nu_{1M}\rangle \\ |\nu_{2M}\rangle\end{pmatrix}$$



$|\nu_e\rangle = \cos\theta_M|\nu_{1M}\rangle + \sin\theta_M|\nu_{2M}\rangle \sim |\nu_{2M}\rangle$
$\tan 2\theta_M \to 0^-$
$\theta_M \to 90°$

$|\nu_{2M}(n_e = 0)\rangle = |\nu_2\rangle$
$\tan 2\theta_M \to \tan 2\theta$
$\theta_M \to \theta$

Vacuum ($n_e = 0$)

MSW resonance
$\tan 2\theta_M \to \infty$
$\theta_M \to 45°$

Observed from Sun ($\Rightarrow \Delta m^2_{21} > 0$)!

$$F^{2>1}_{\nu_e} = |\langle\nu_e|\nu_2\rangle|^2 F^0_{\nu_e} \approx 0.3 F^0_{\nu_e}$$

$$F^{1>2}_{\nu_e} = |\langle\nu_e|\nu_1\rangle|^2 F^0_{\nu_e} \approx 0.7 F^0_{\nu_e}$$

Two flavors!

Example calculation of flavor oscillations in supernovae

(normal hierarchy: $m_1 < m_2 < m_3$)

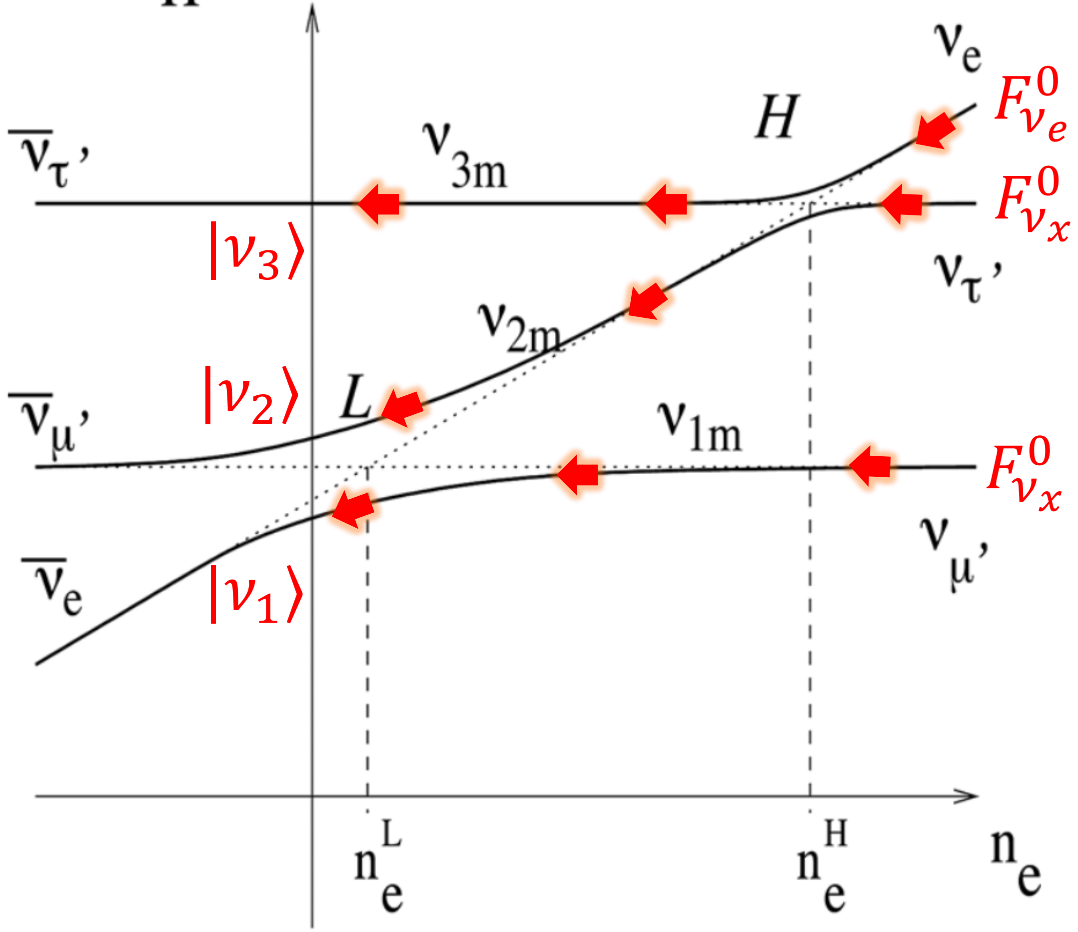
$$F_{\nu_e}^{NH} = |U_{e3}|^2 F_{\nu_e}^0 + \cdots , \qquad |U_{e3}|^2 = |\langle \nu_e | \nu_3 \rangle|^2$$

$$= \left| s_{13} e^{-i\delta_{CP}} \right|^2 F_{\nu_e}^0 + \cdots ,$$

$$= s_{13}^2 \, F_{\nu_e}^0 + |U_{e2}|^2 F_{\nu_x}^0 + \cdots , F_{\nu_x}{}^0 \equiv F_{\nu_\mu}^0 = F_{\nu_\tau}^0$$

$$= s_{13}^2 \, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + |U_{e1}|^2 F_{\nu_x}^0$$

$$= s_{13}^2 \, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + c_{12}^2 c_{13}^2 F_{\nu_x}^0$$



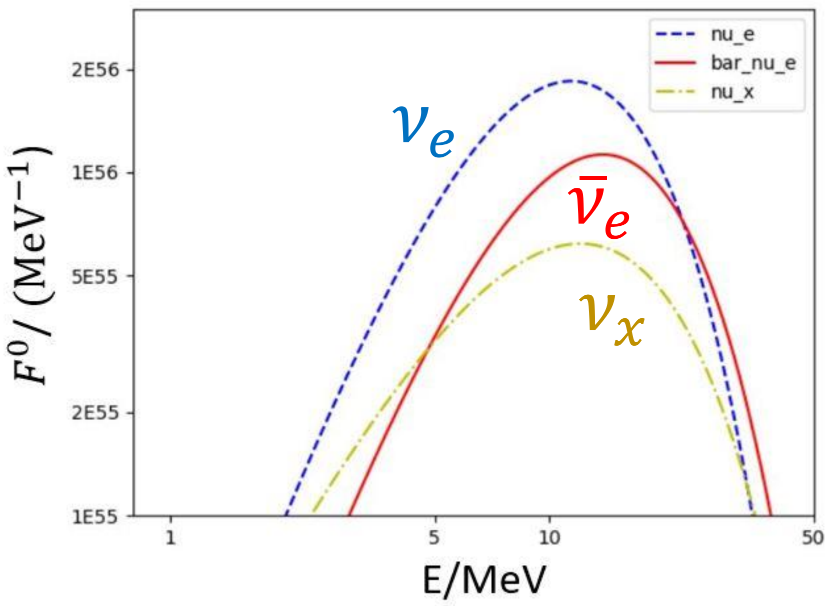
Three flavors!

Example calculation of flavor oscillations in supernovae

$$F_{\nu_e}^{NH} = |U_{e3}|^2 F_{\nu_e}^0 + \cdots\,, \qquad |U_{e3}|^2 = |\langle \nu_e | \nu_3 \rangle|^2$$
$$= \left| s_{13} e^{-i\delta_{CP}} \right|^2 F_{\nu_e}^0 + \cdots\,,$$
$$= s_{13}^2\, F_{\nu_e}^0 + |U_{e2}|^2 F_{\nu_x}^0 + \cdots, F_{\nu_x}{}^0 \equiv F_{\nu_\mu}^0 = F_{\nu_\tau}^0$$
$$= s_{13}^2\, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + |U_{e1}|^2 F_{\nu_x}^0$$
$$= s_{13}^2\, F_{\nu_e}^0 + s_{12}^2 c_{13}^2 F_{\nu_x}^0 + c_{12}^2 c_{13}^2 F_{\nu_x}^0$$

$$F_{\nu_e}^{NH} = \left(0 \times F_{\nu_e}^0\right) + \left(1 \times F_{\nu_x}^0\right)$$
$$F_{\nu_e}^{IH} = \left(0.3 \times F_{\nu_e}^0\right) + \left(0.7 \times F_{\nu_x}^0\right)$$

(time-integrated SN neutrino spectra)



MSW: Different mass hierarchies give different final spectra!

Three flavors!