

HEP Group Seminar

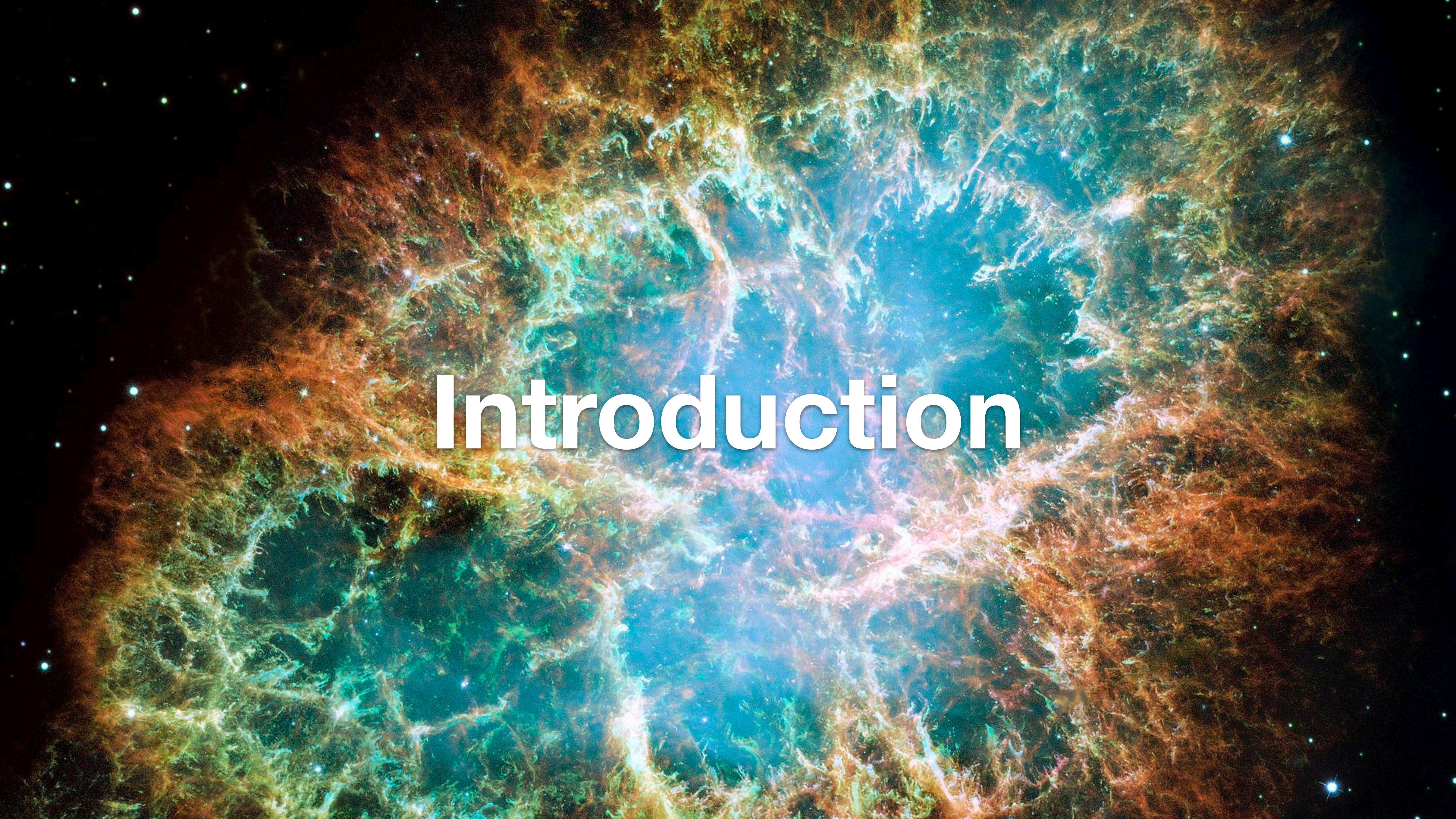
Kyoto University, July 15th, 2026

スーパーカミオカンデでついに捉えた 超新星背景ニュートリノの兆候?

Super-Kamiokande finally detects “Indication”
of diffuse supernova neutrino background?

Yosuke Ashida (Tohoku University)

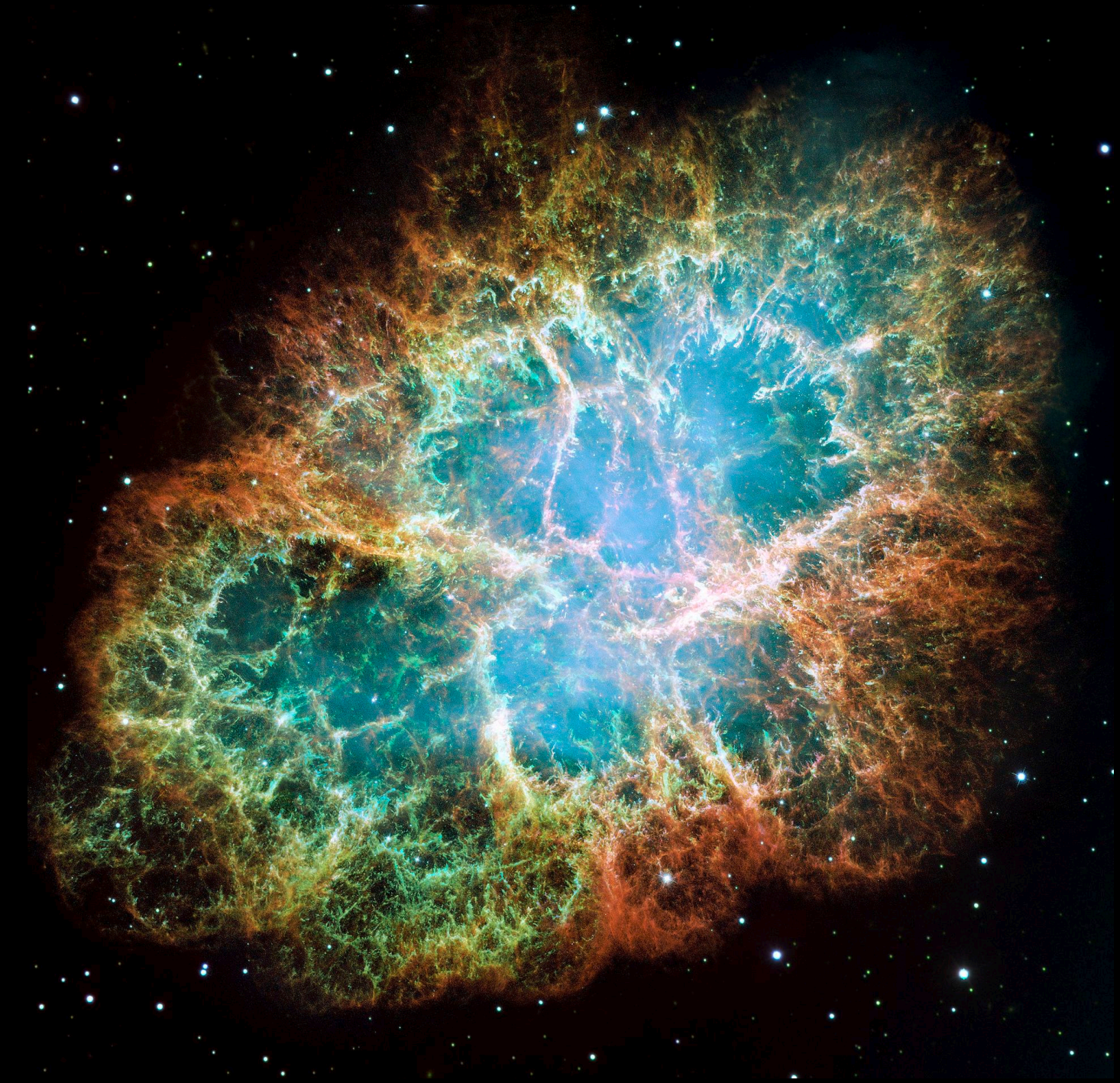
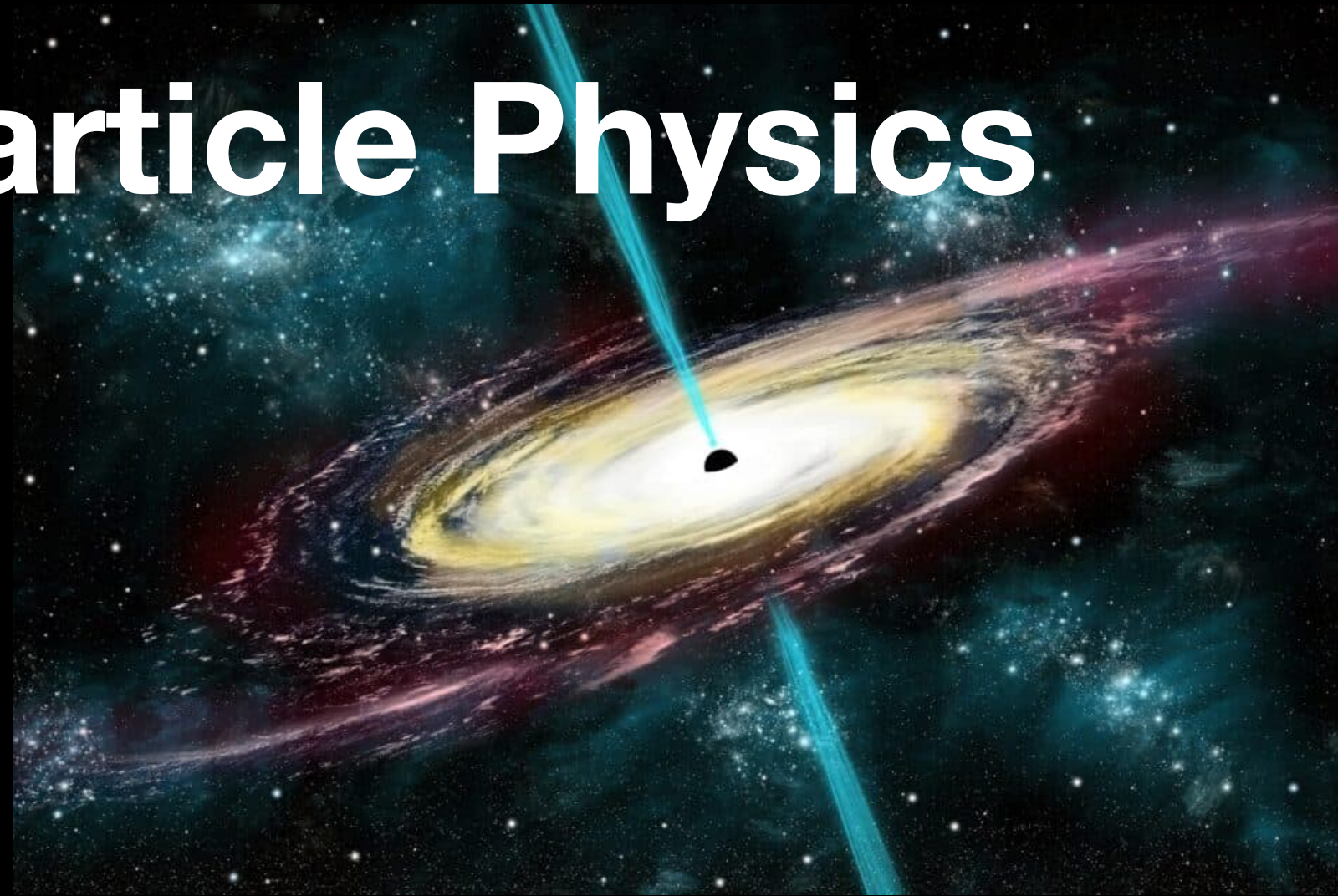
yosuke.ashida.a1@tohoku.ac.jp



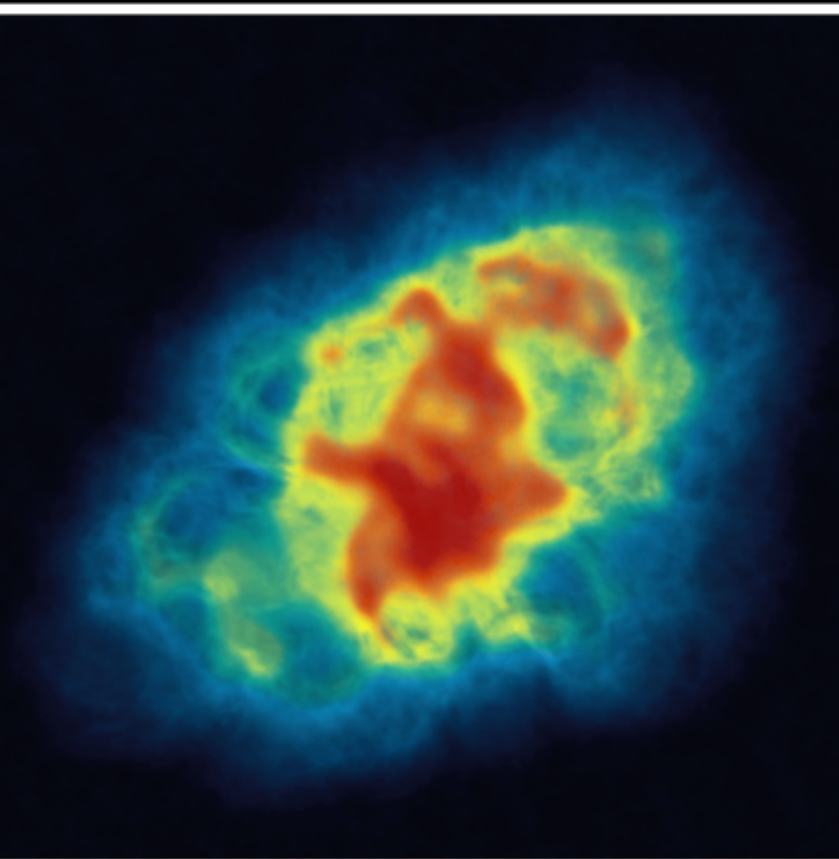
Introduction

Astrophysics

~ Astronomy + Particle Physics



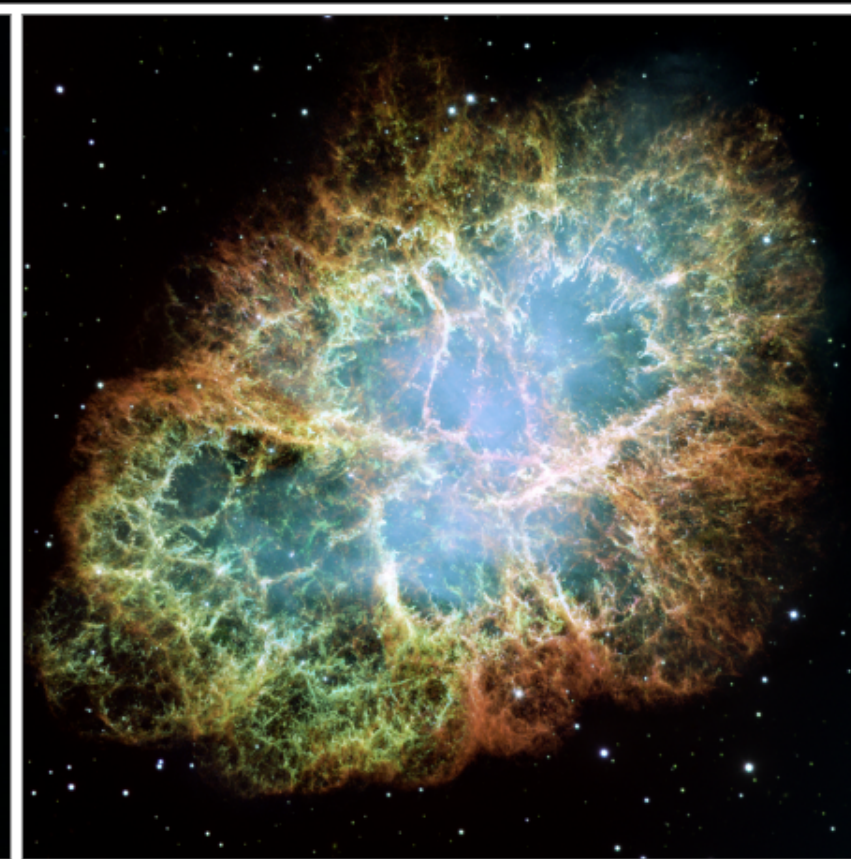
CRAB NEBULA



RADIO



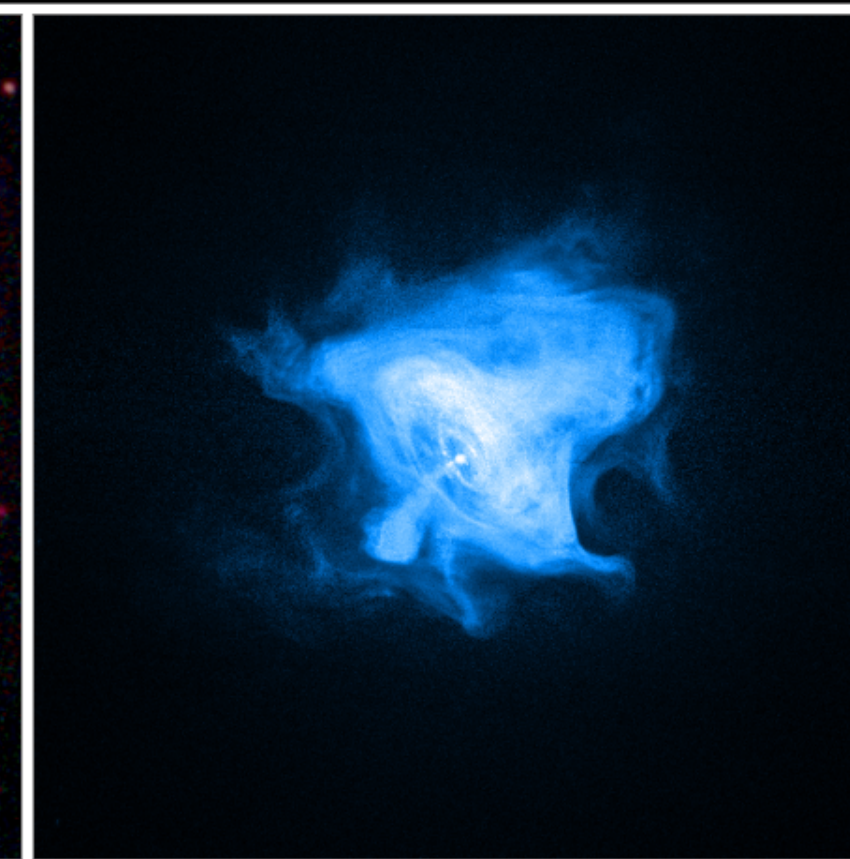
INFRARED



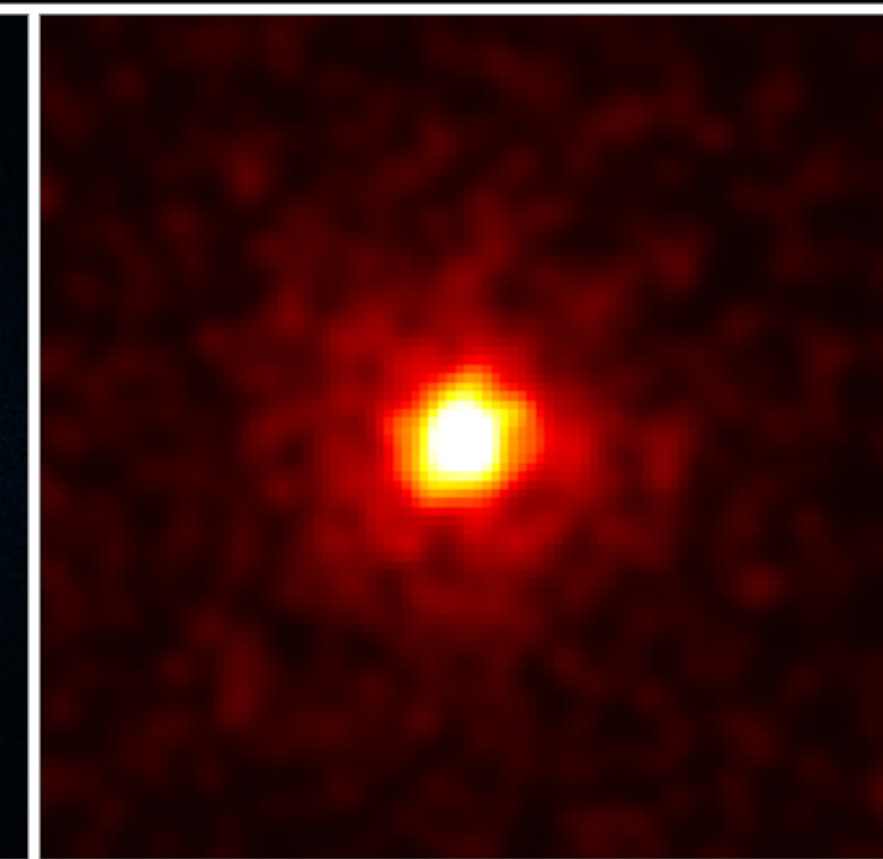
VISIBLE LIGHT



ULTRAVIOLET



X-RAYS



GAMMA RAYS

Photons

γ

Neutrinos

ν

TODAY



**MULTI-MESSENGER
ASTRONOMY**



p

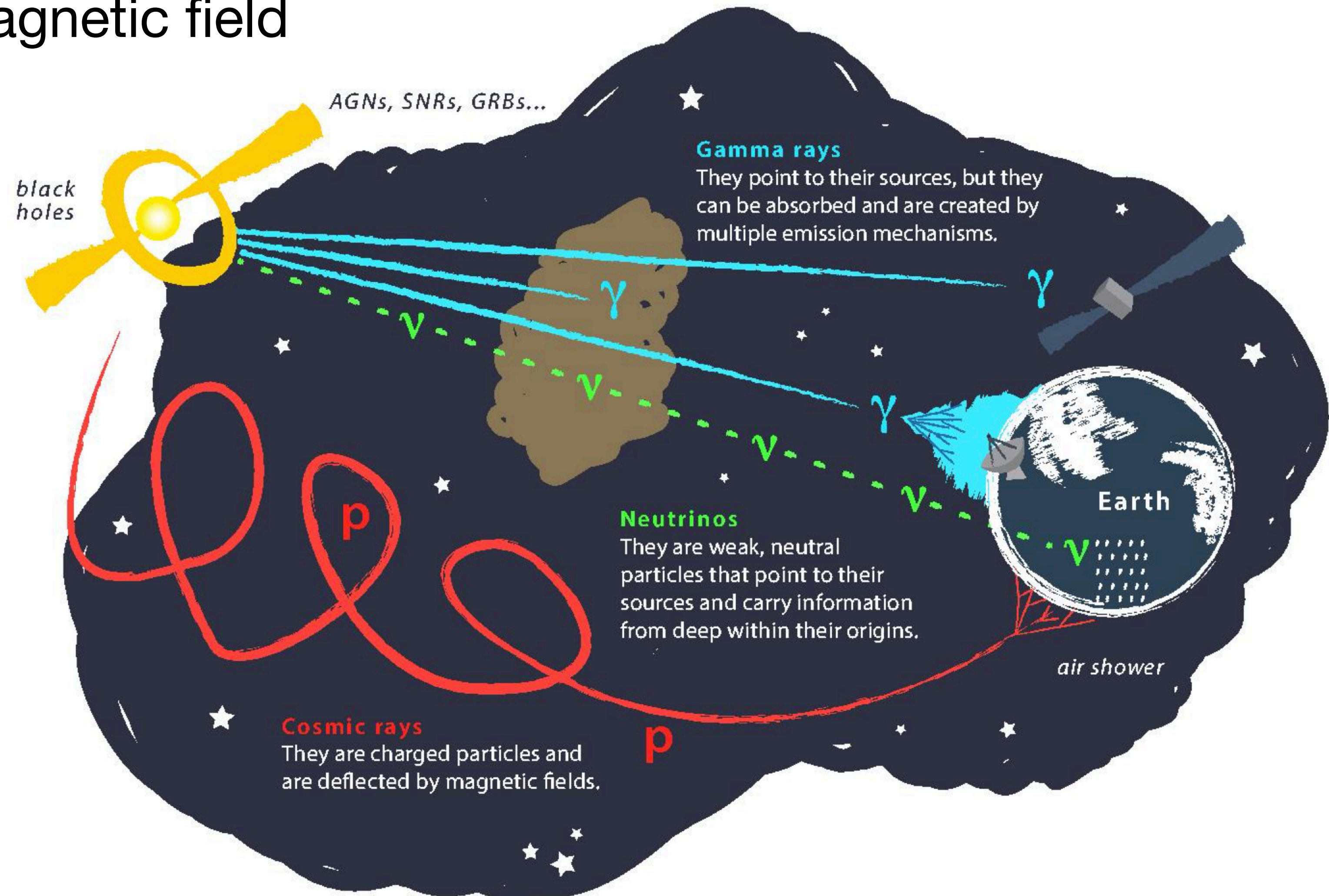
Cosmic rays

GW

Gravitational Wave

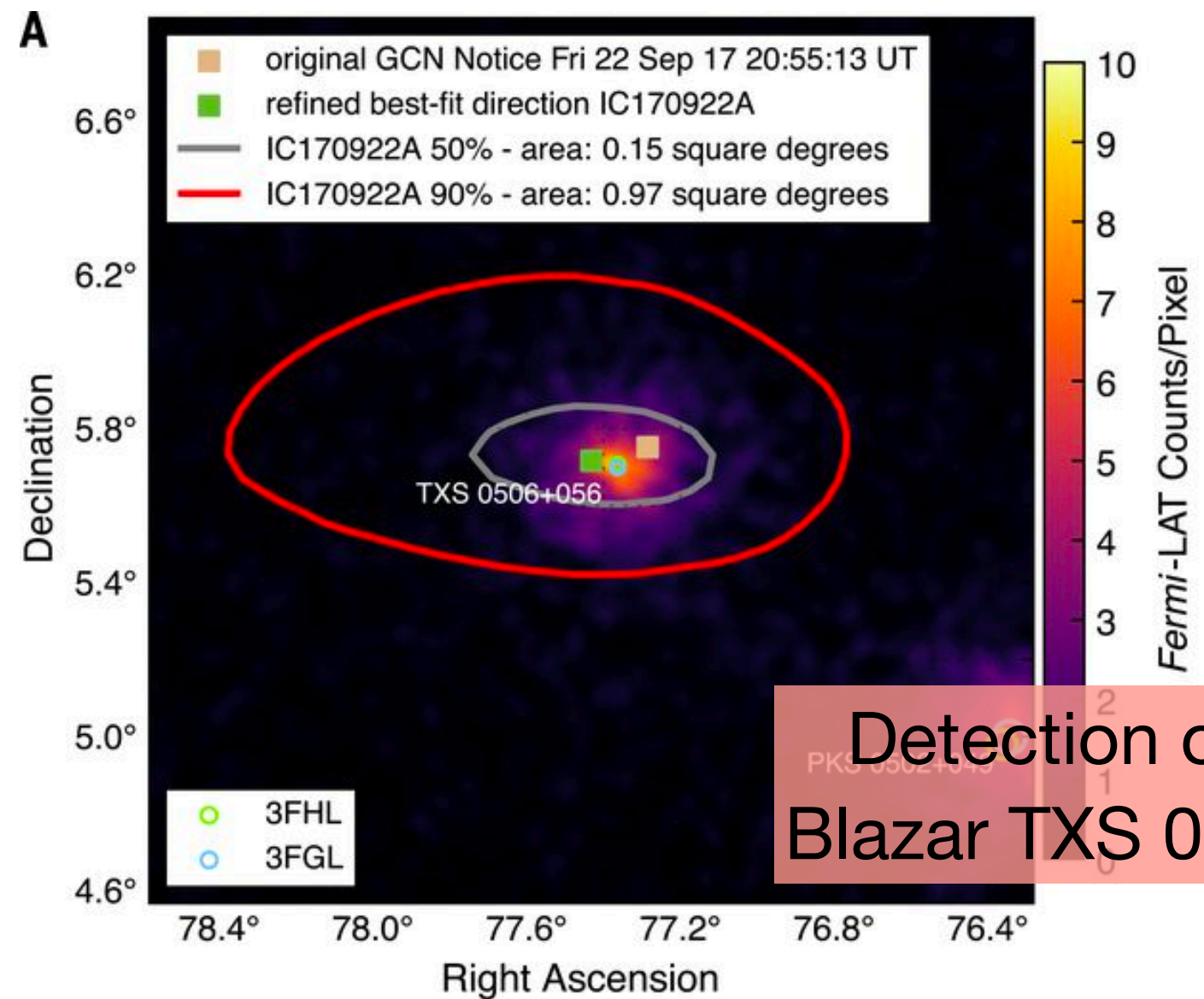
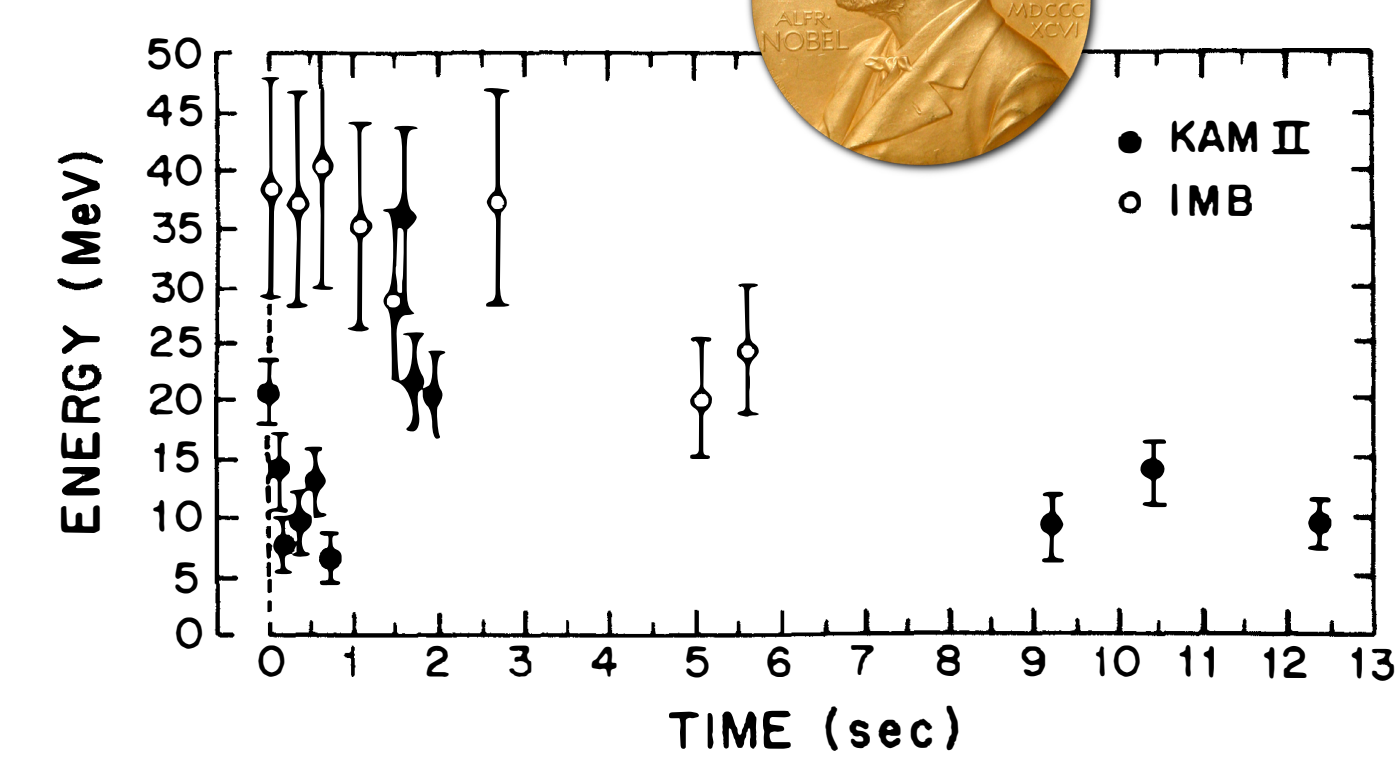
Neutrinos interact only **weakly**

- Escape from extremely **dense** area
- Travel over the **long** distance
- **Not deflected** by cosmic magnetic field

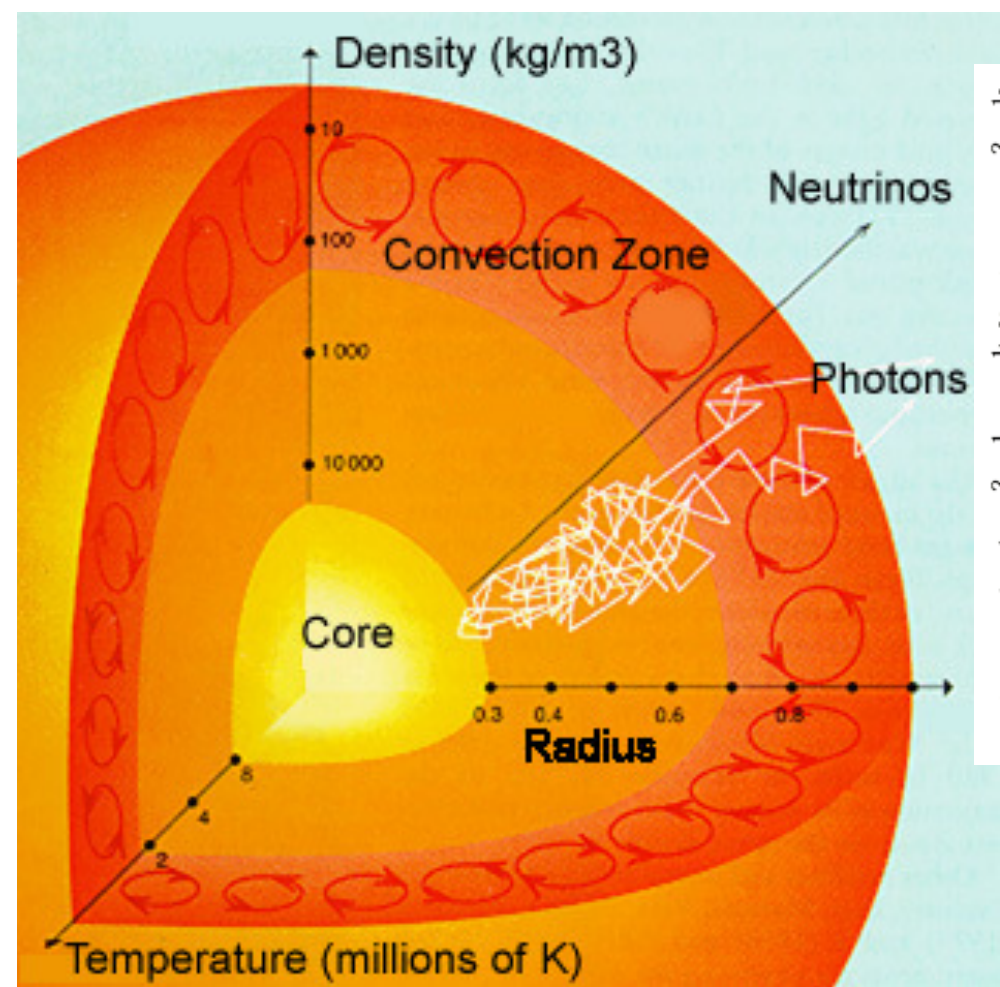
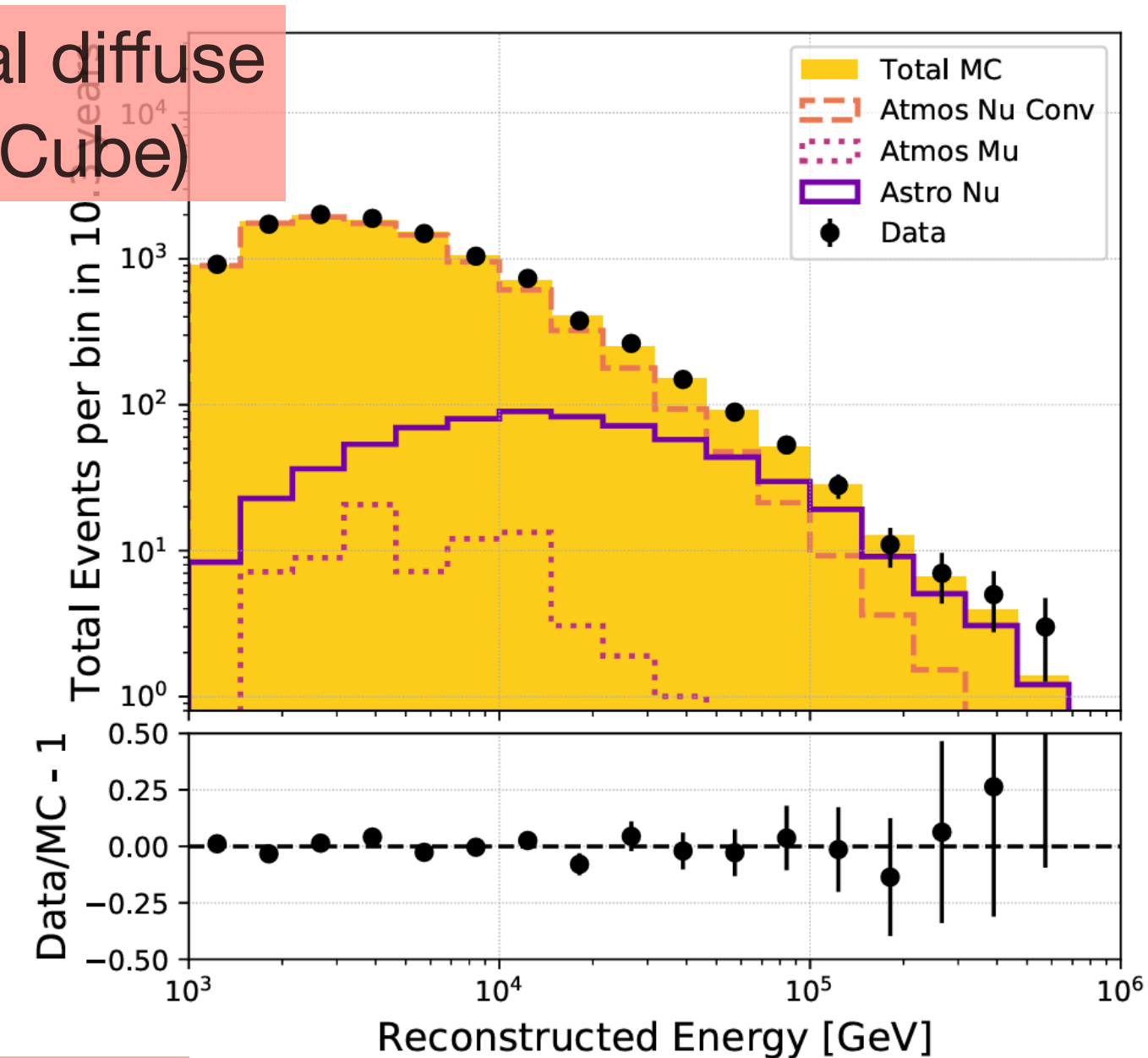




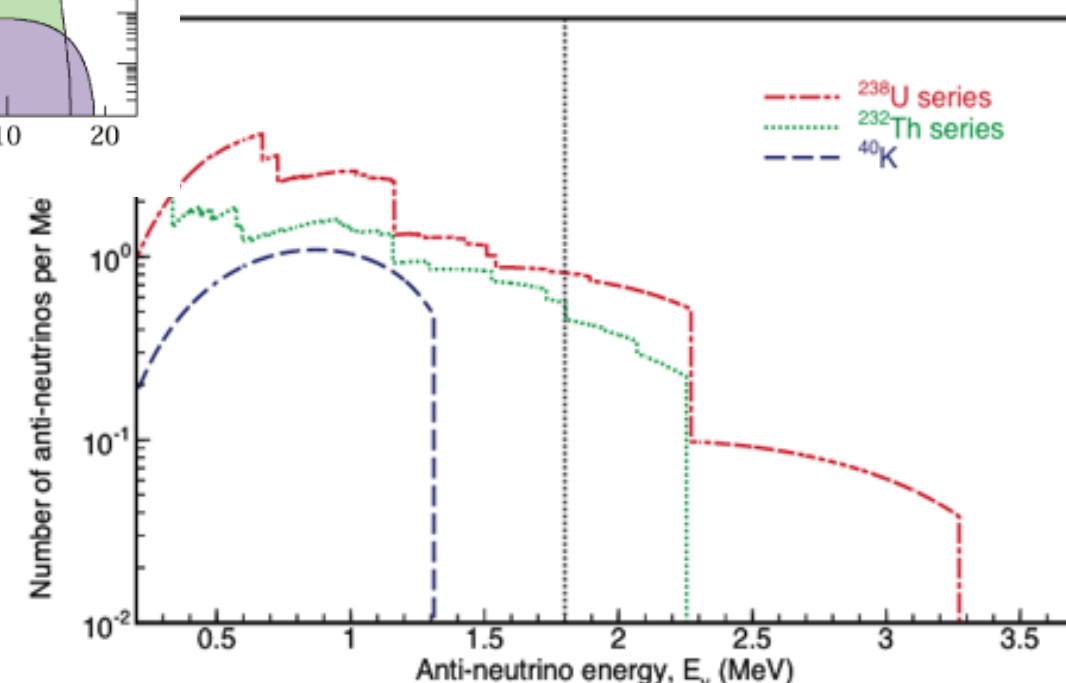
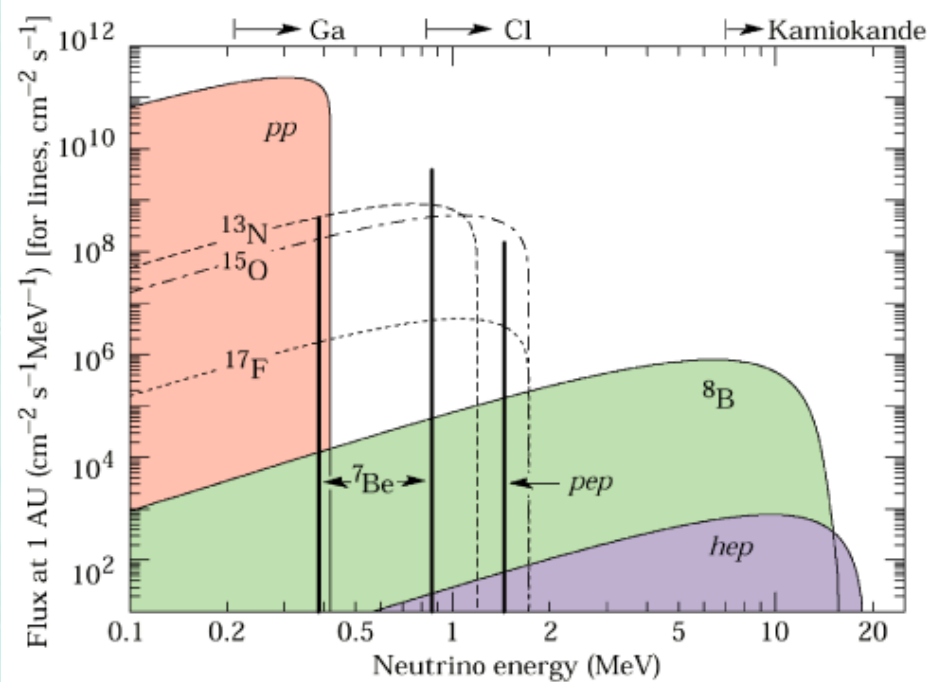
Detection of neutrinos from SN 1987A (Kamiokande else)



Detection of a neutrino from Blazar TXS 0506+056 (IceCube)

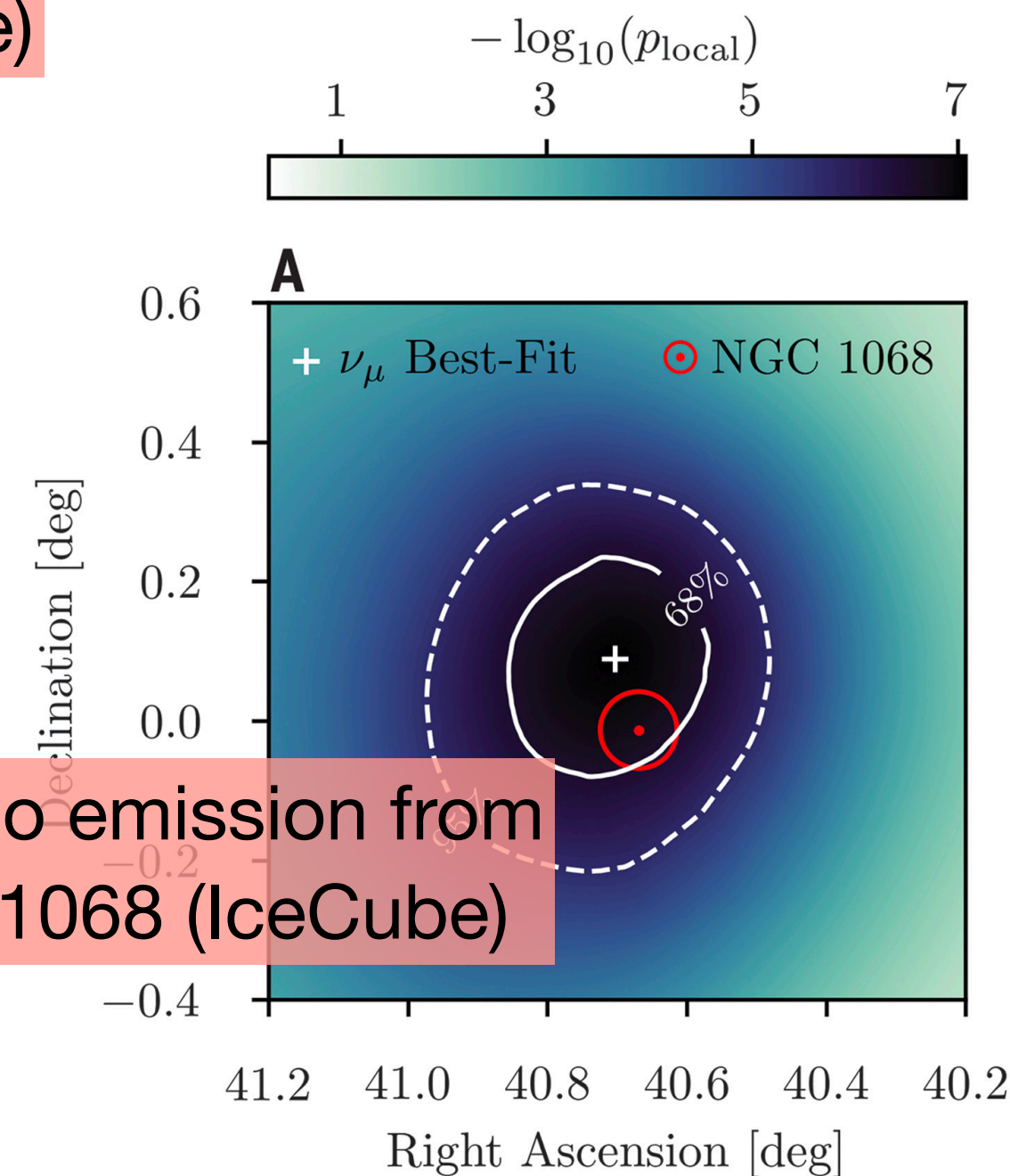


Detection of neutrinos from the Sun and Earth (Kamiokande, KamLAND else)



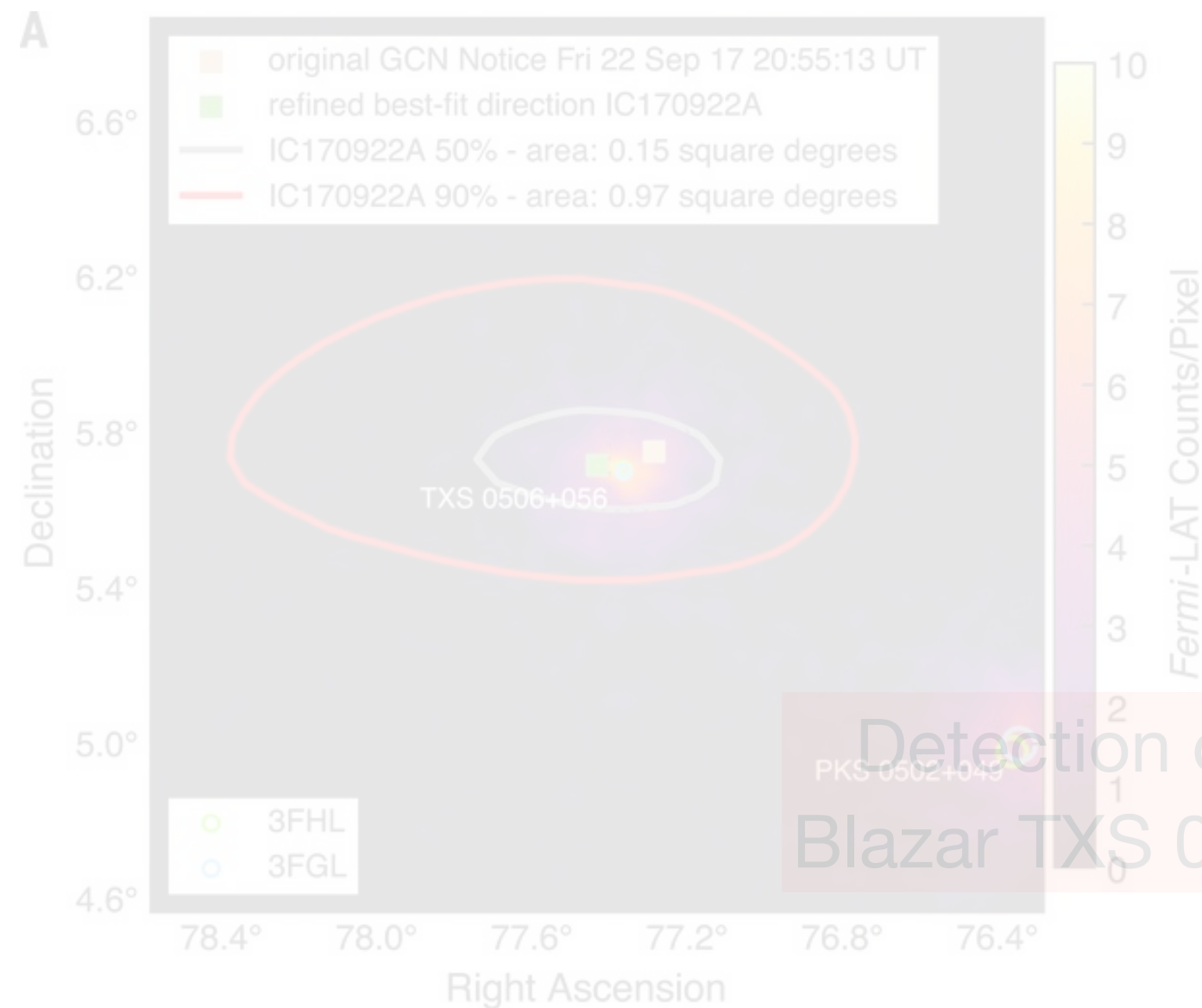
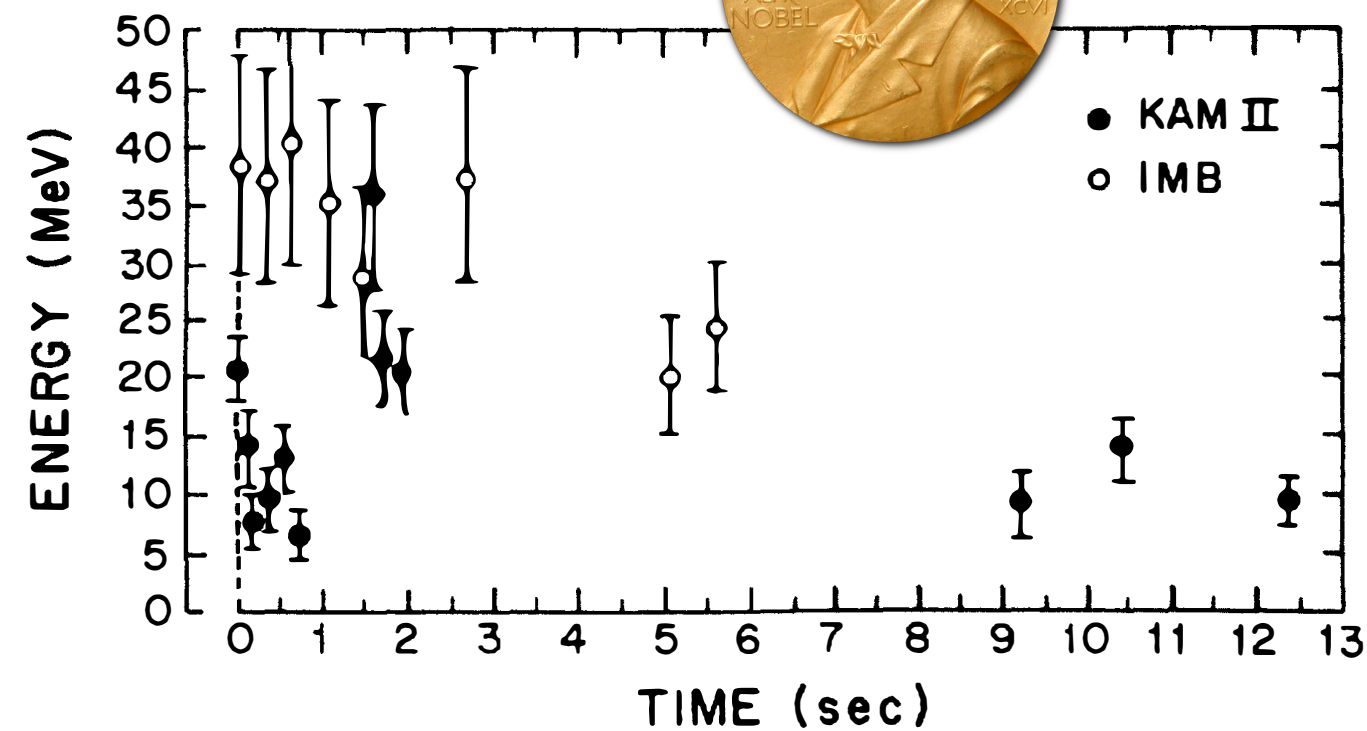
thermal
non-thermal

Observation of neutrino emission from Seyfert galaxy NGC 1068 (IceCube)

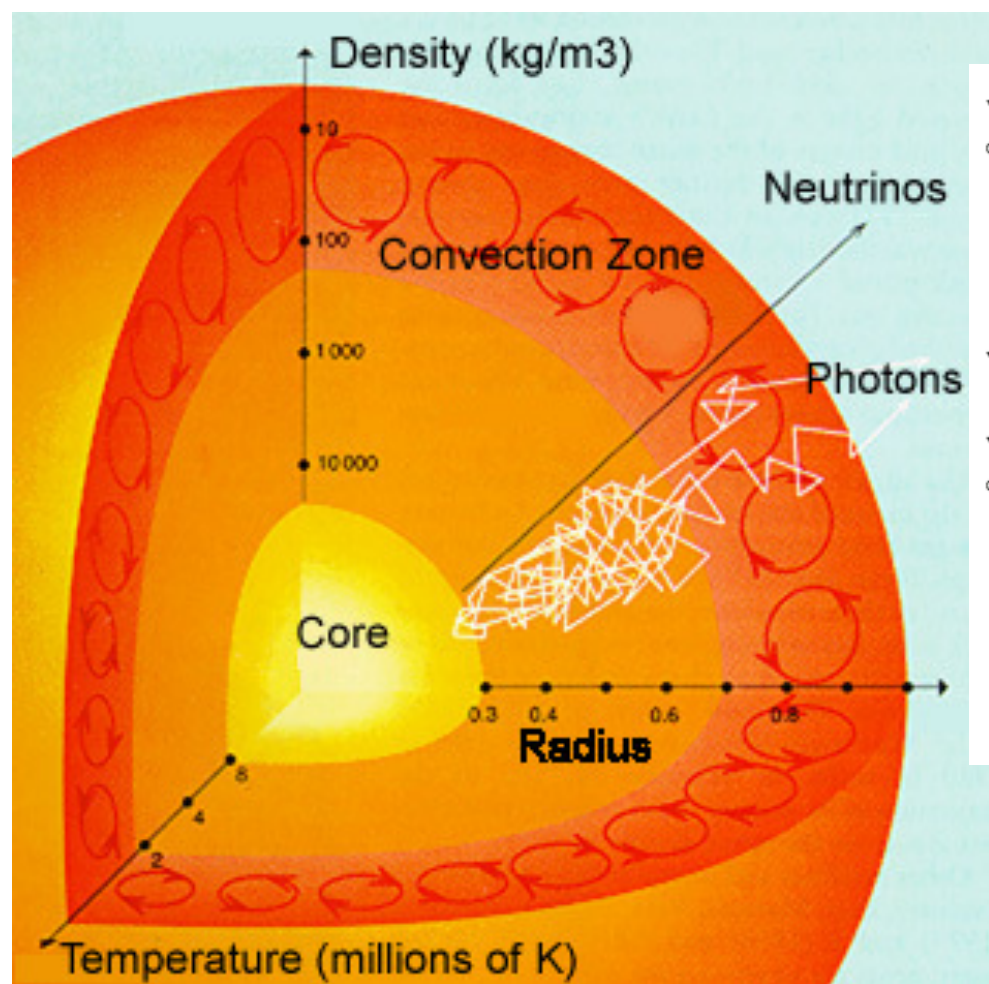
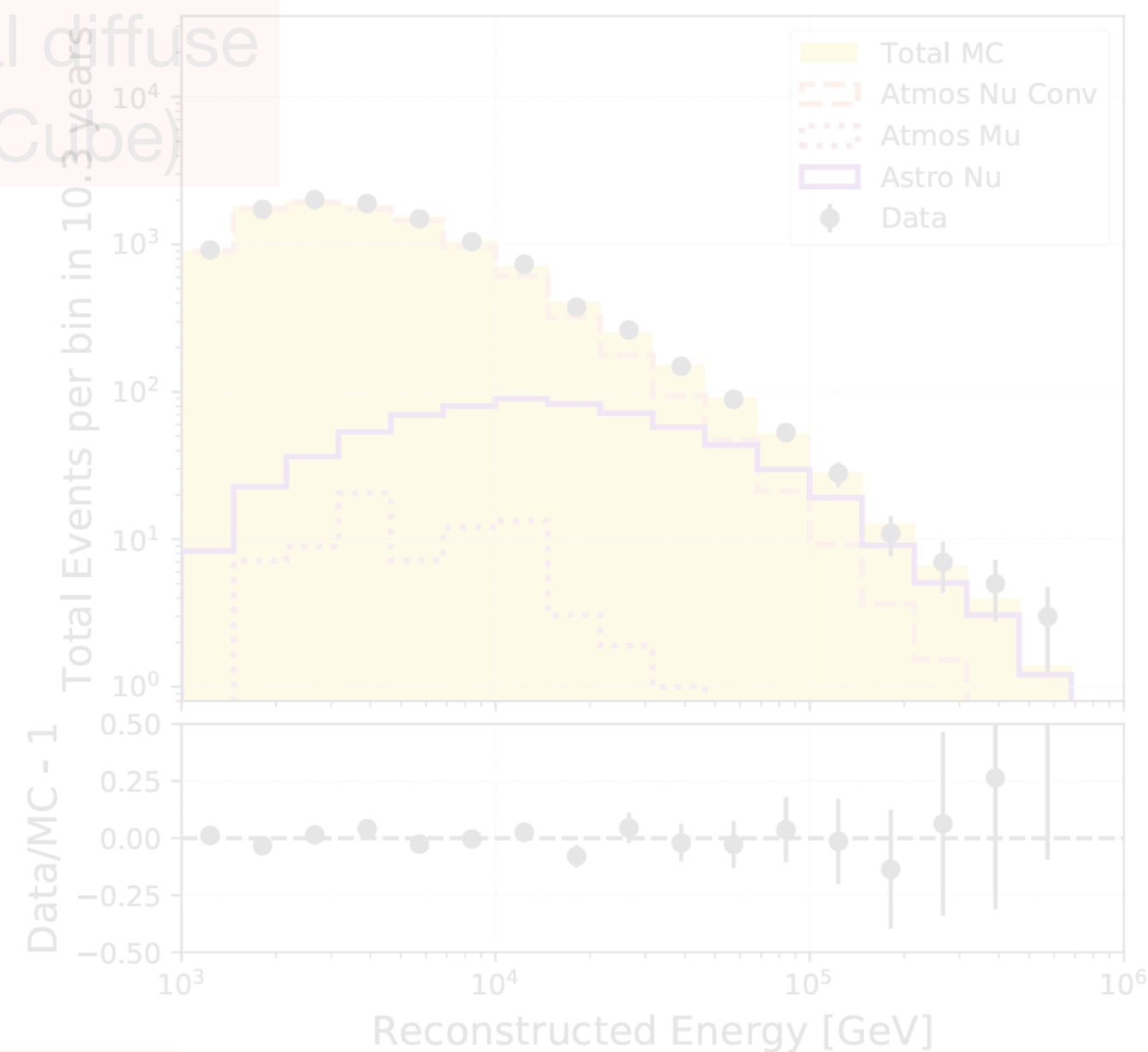




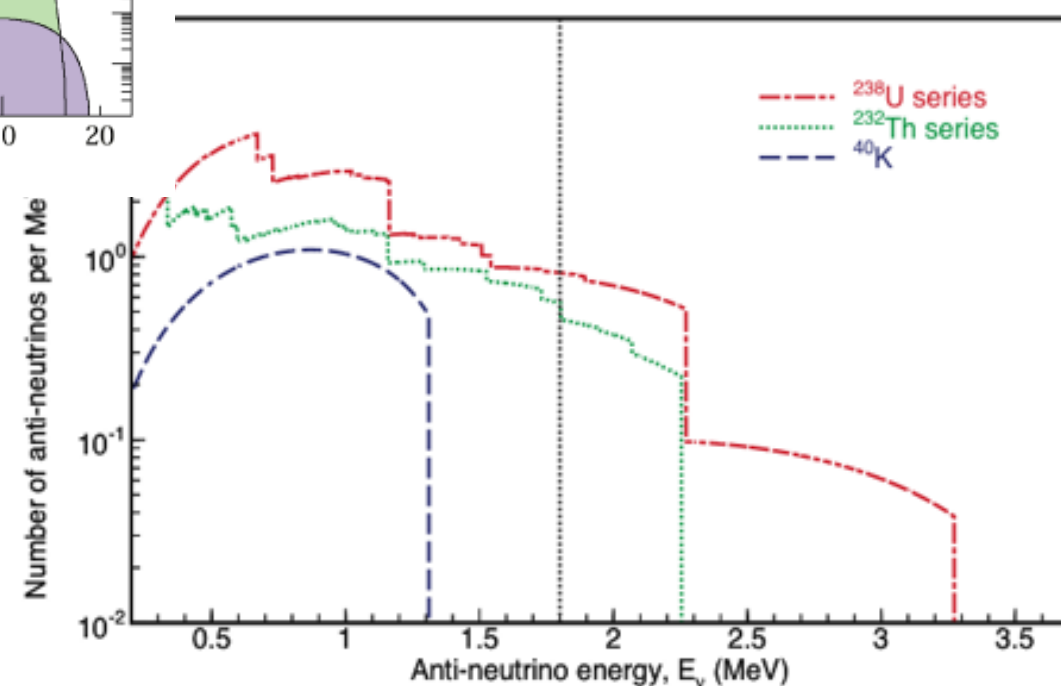
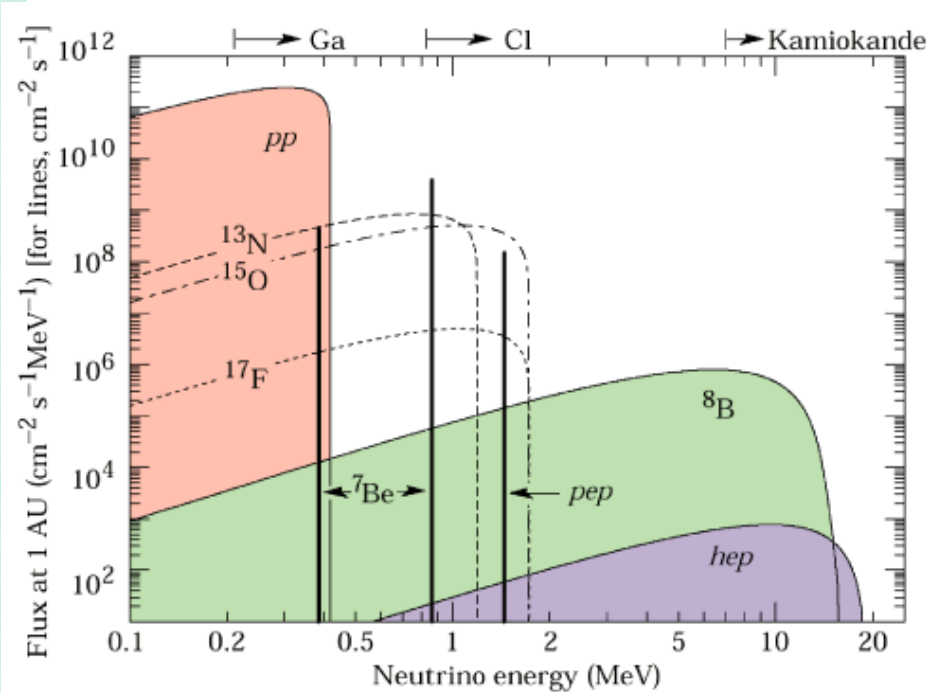
Detection of neutrinos from SN 1987A (Kamiokande else)



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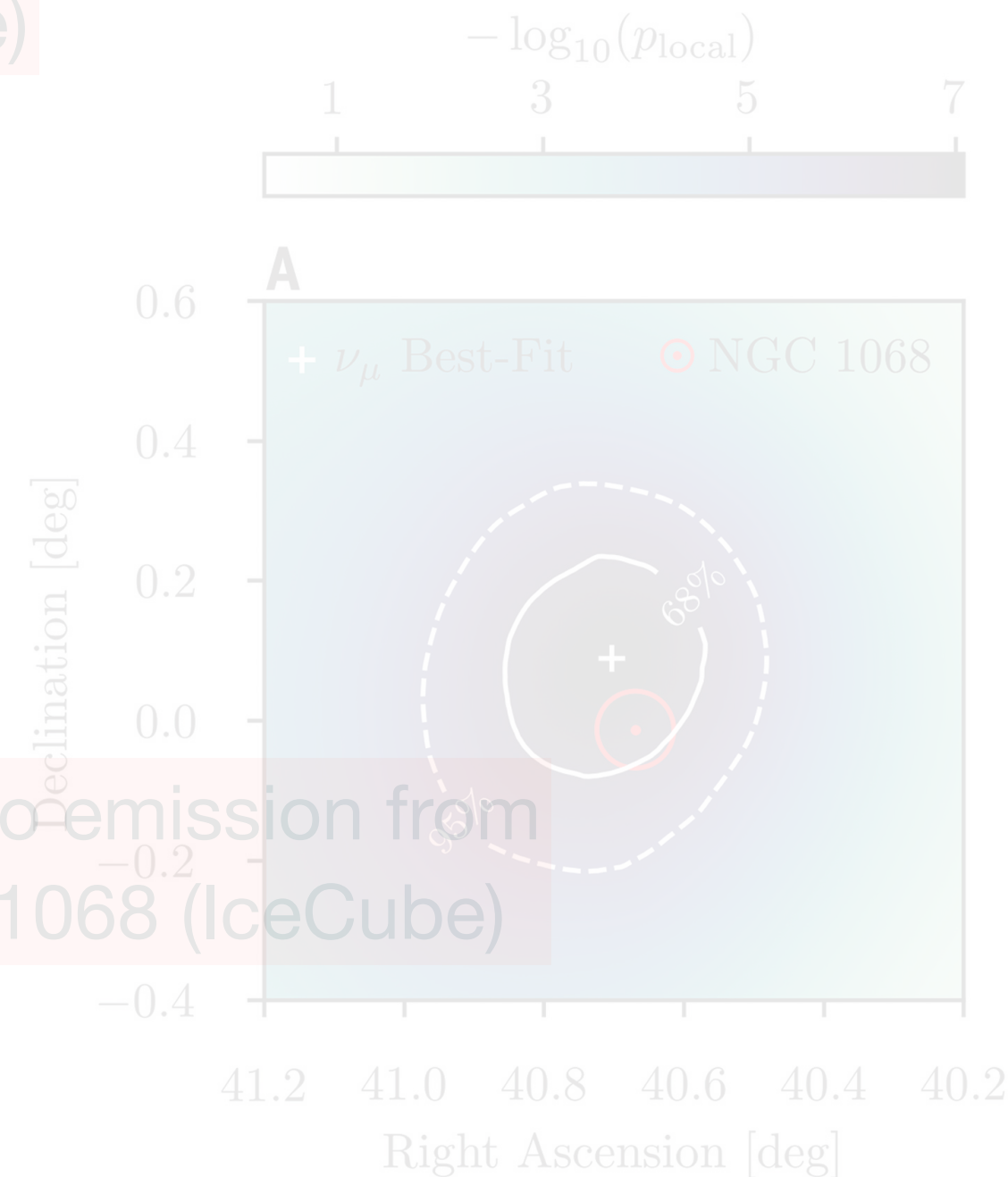


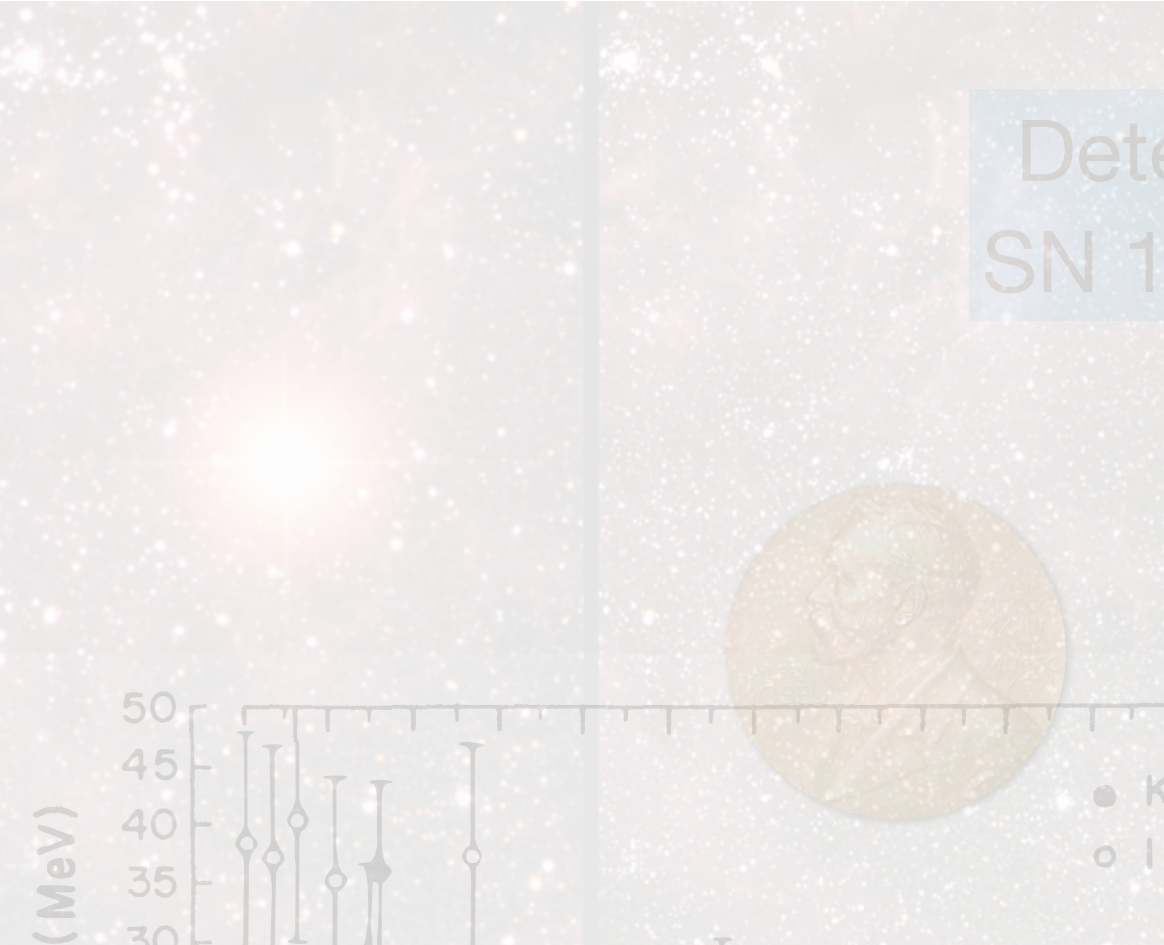
Detection of neutrinos from the Sun and Earth (Kamiokande, KamLAND else)



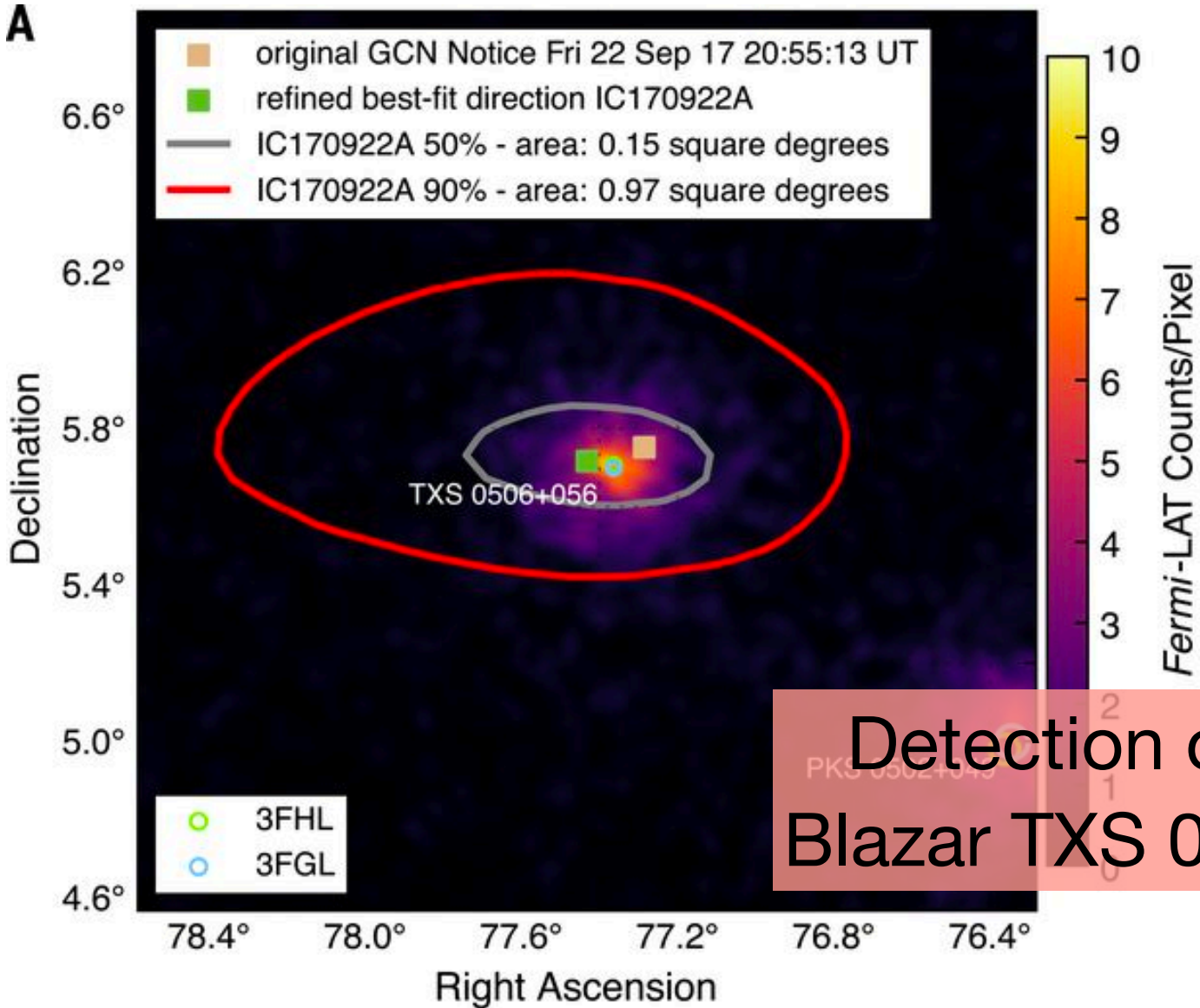
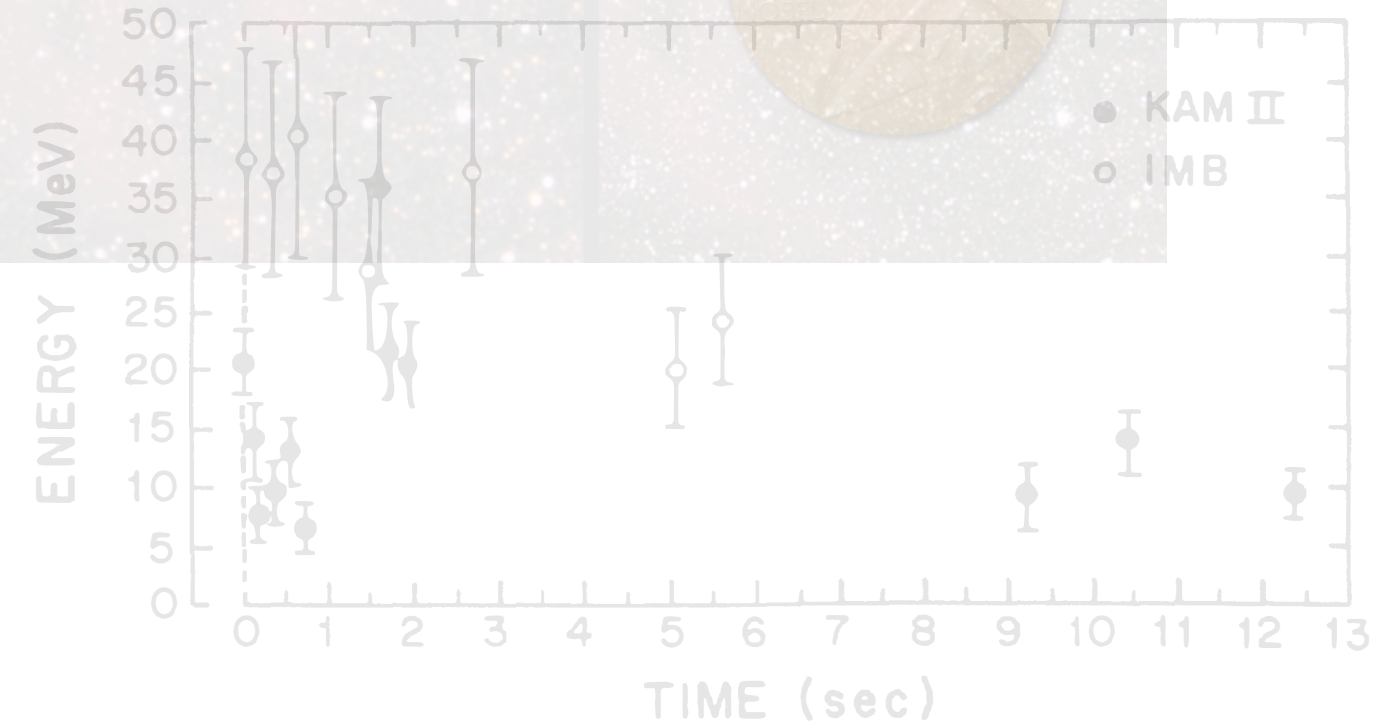
thermal
non-thermal

Observation of neutrino emission from Seyfert galaxy NGC 1068 (IceCube)

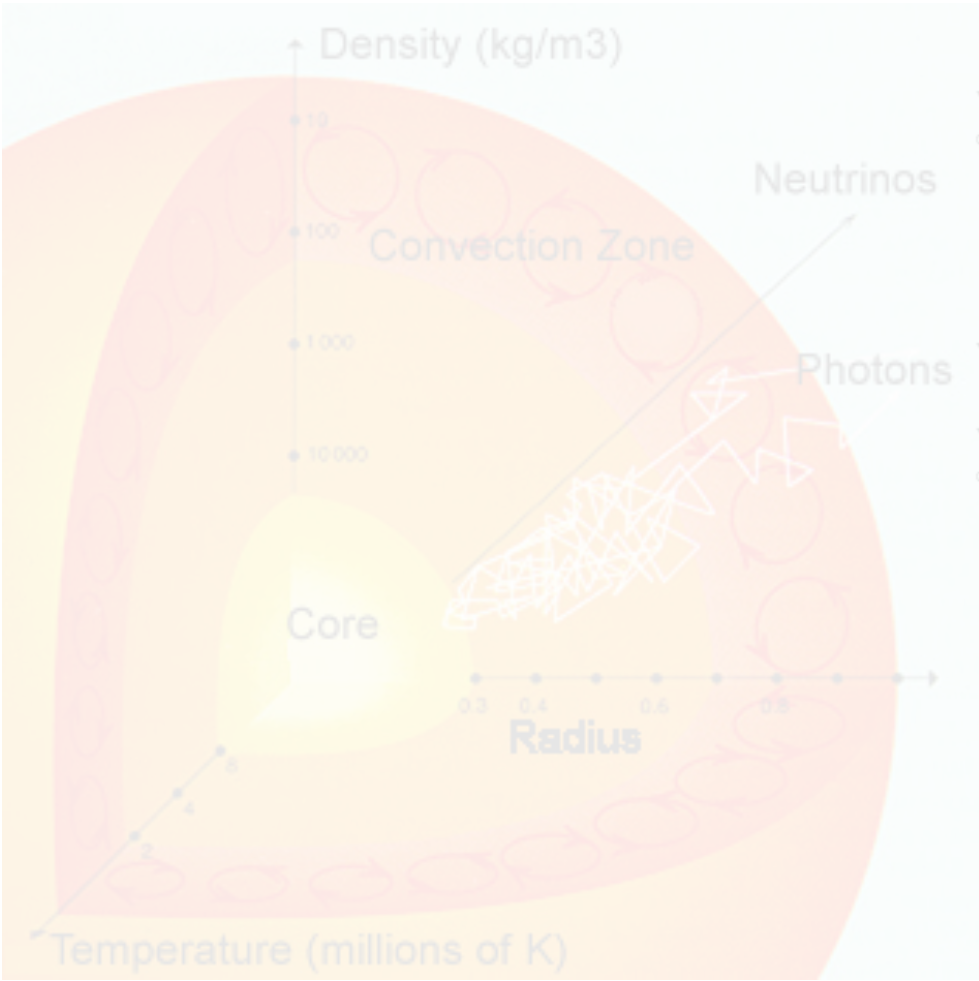
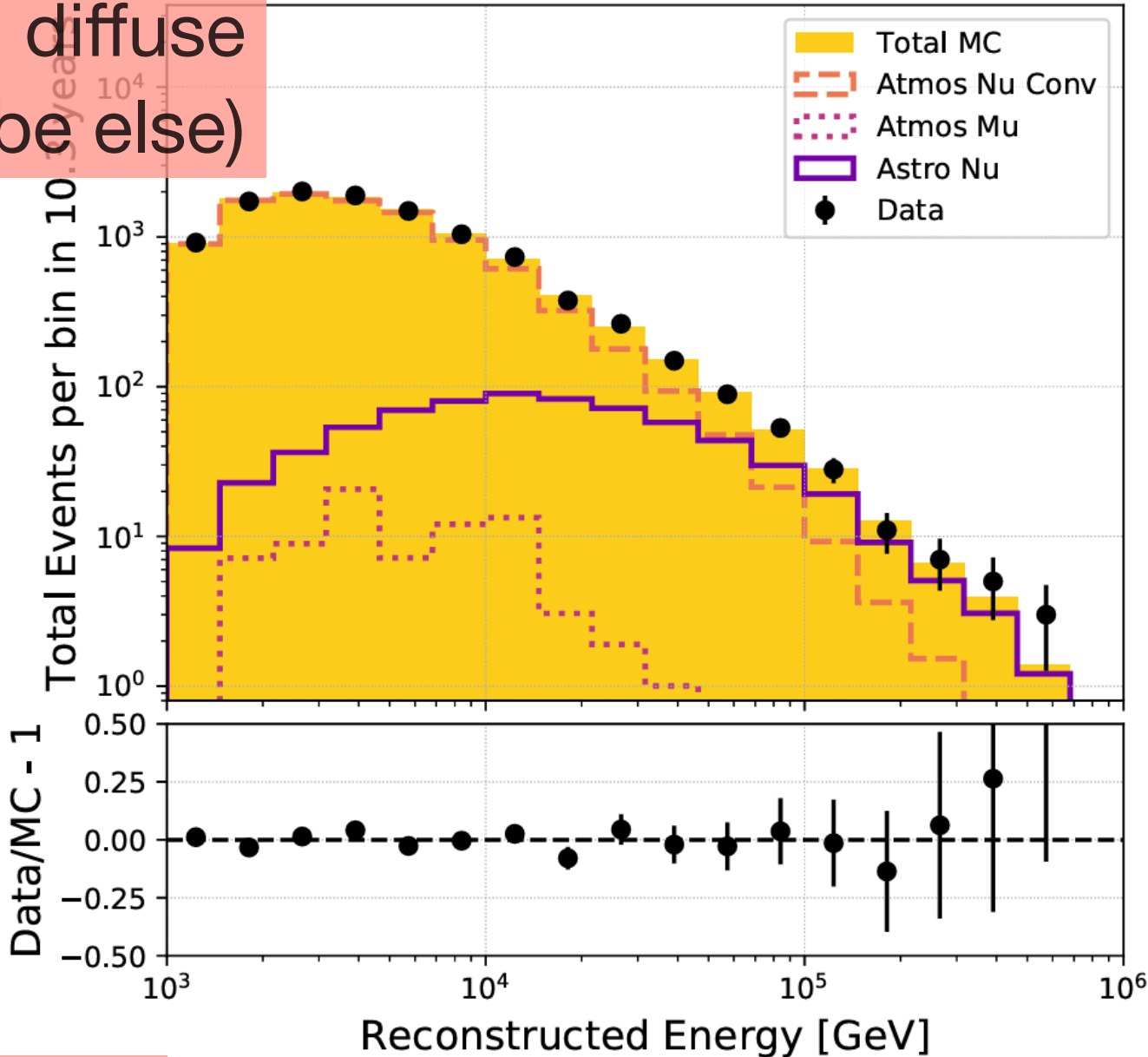




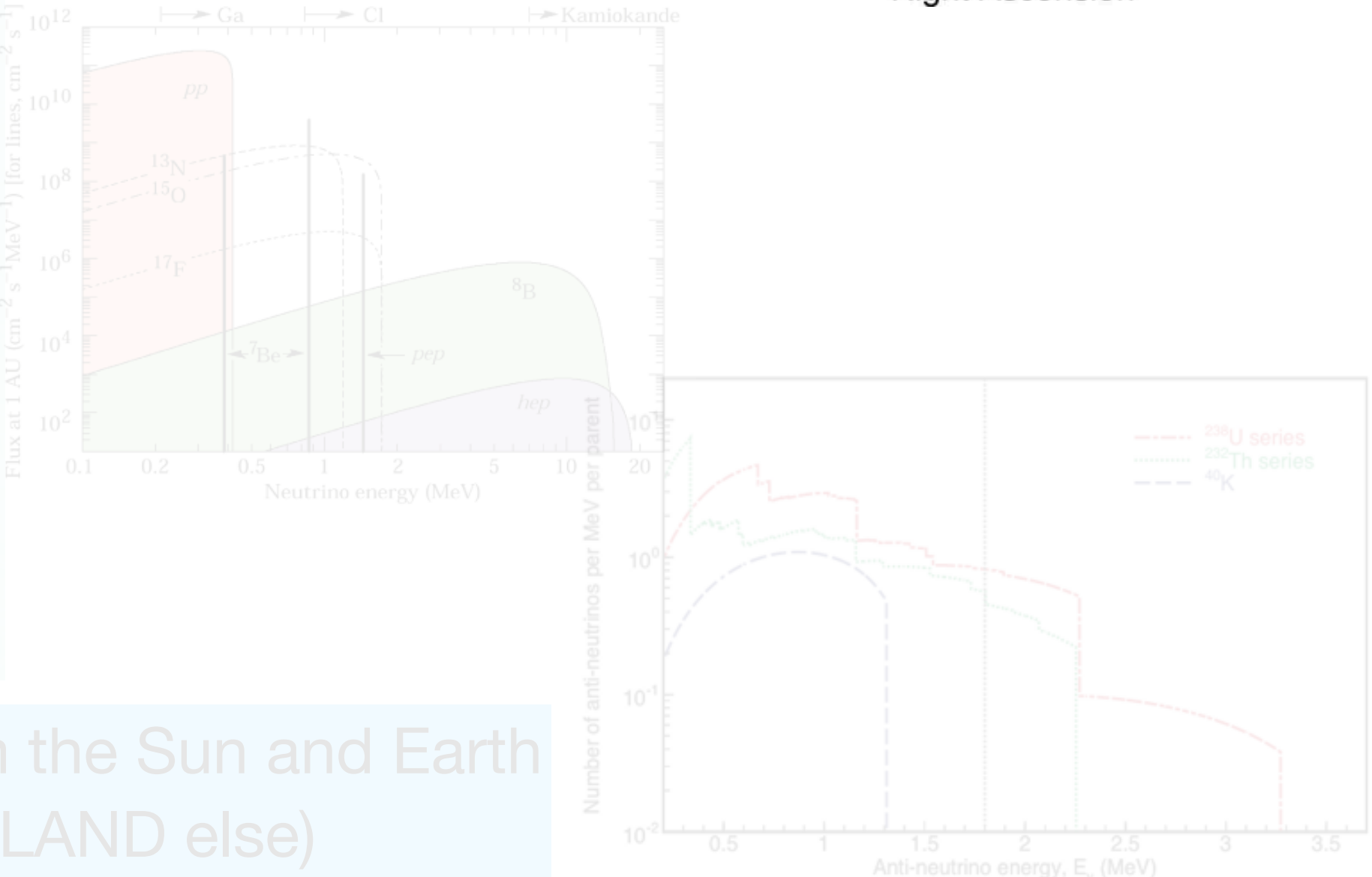
Detection of neutrinos from SN 1987A (Kamiokande else)



Detection of a neutrino from Blazar TXS 0506+056 (IceCube)

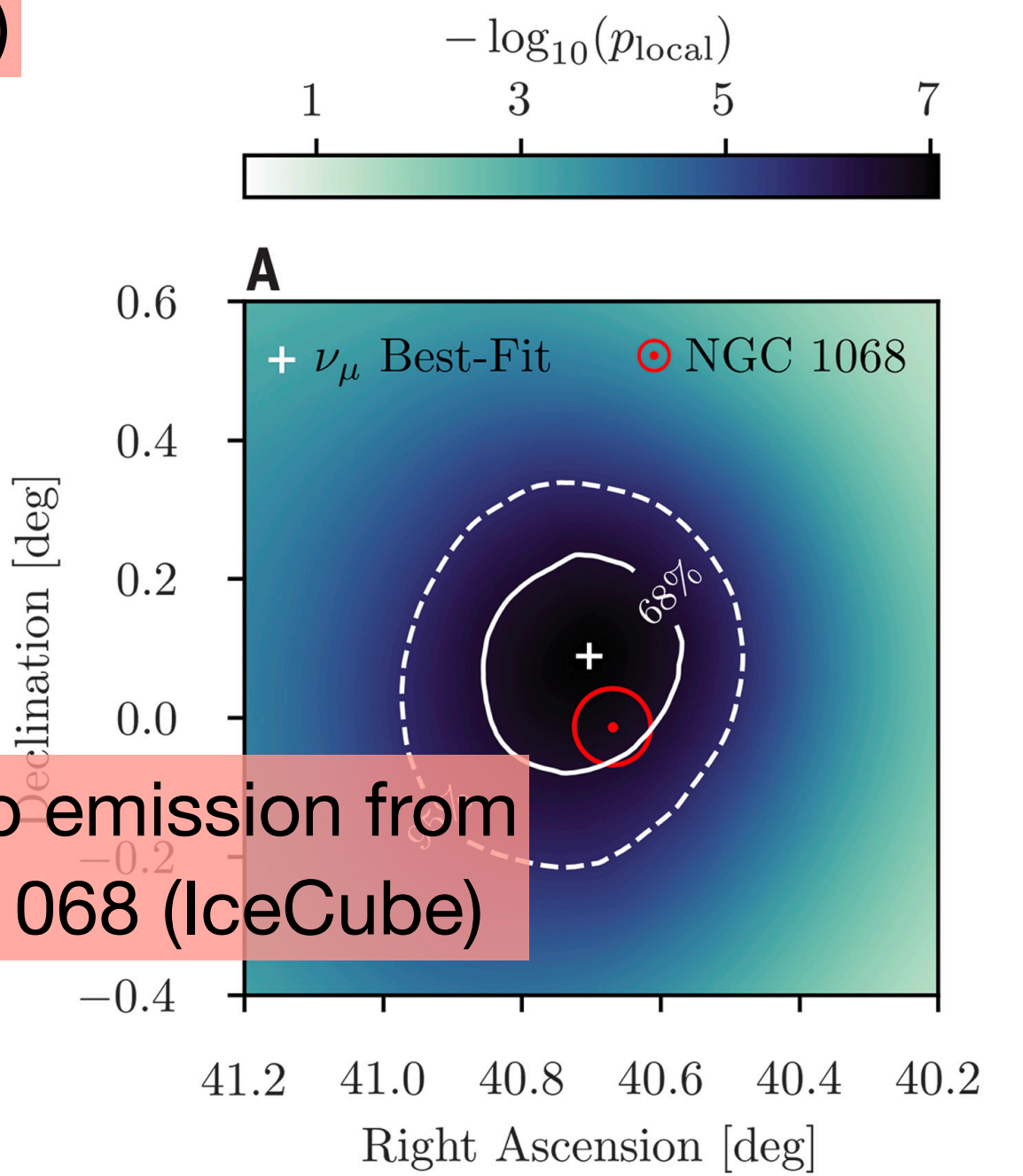


Detection of neutrinos from the Sun and Earth (Kamiokande, KamLAND else)

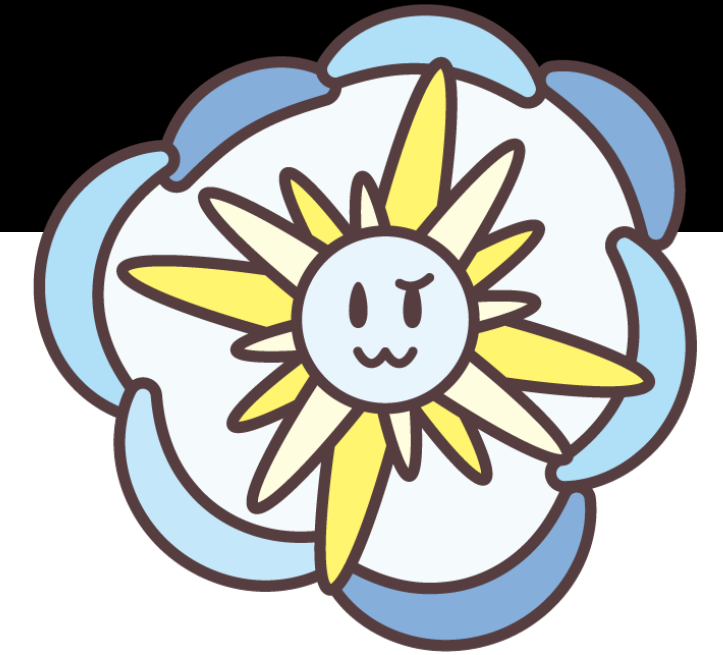


thermal
non-thermal

Observation of neutrino emission from Seyfert galaxy NGC 1068 (IceCube)

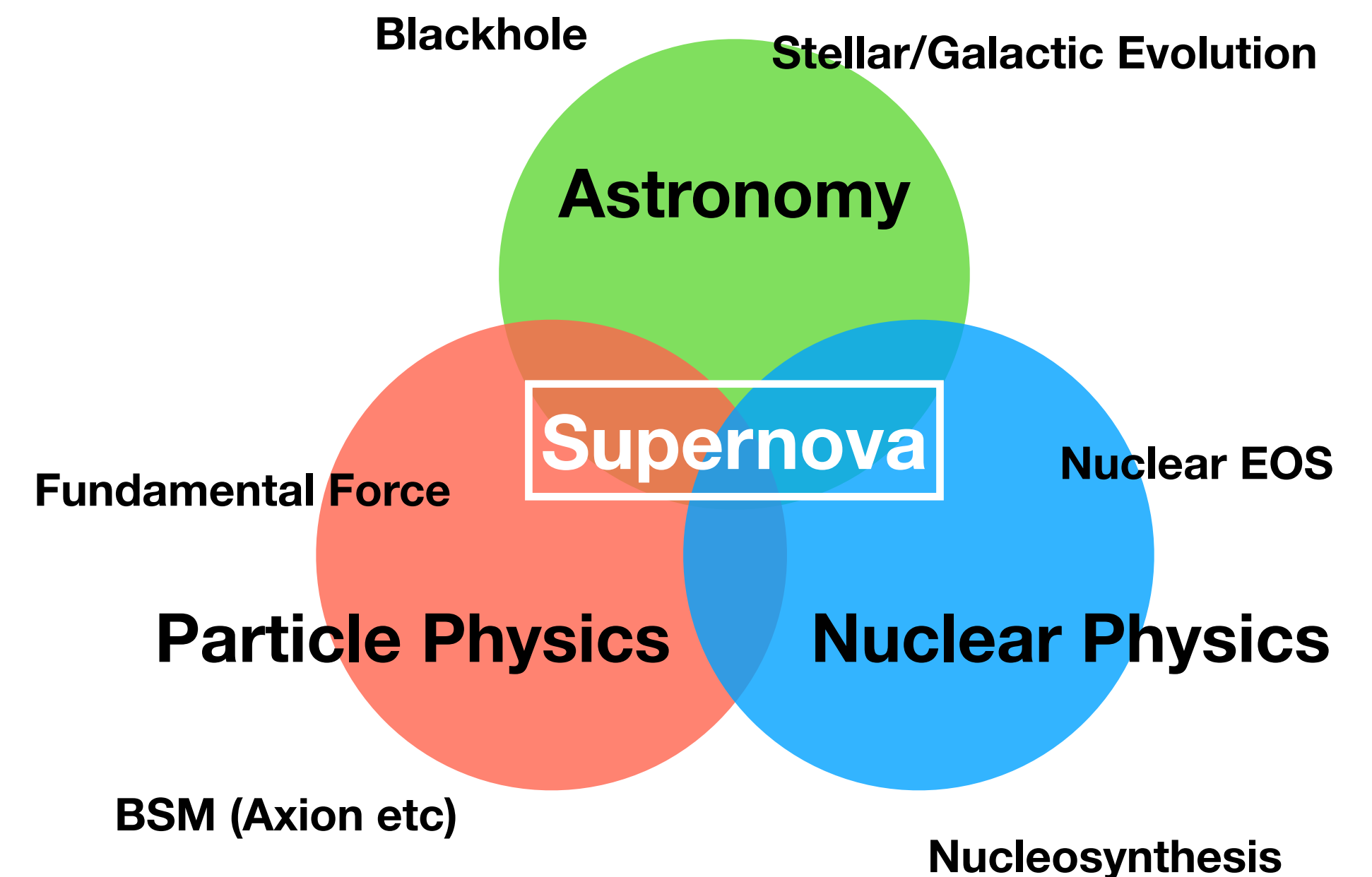


Supernova Explosion



Higgstan

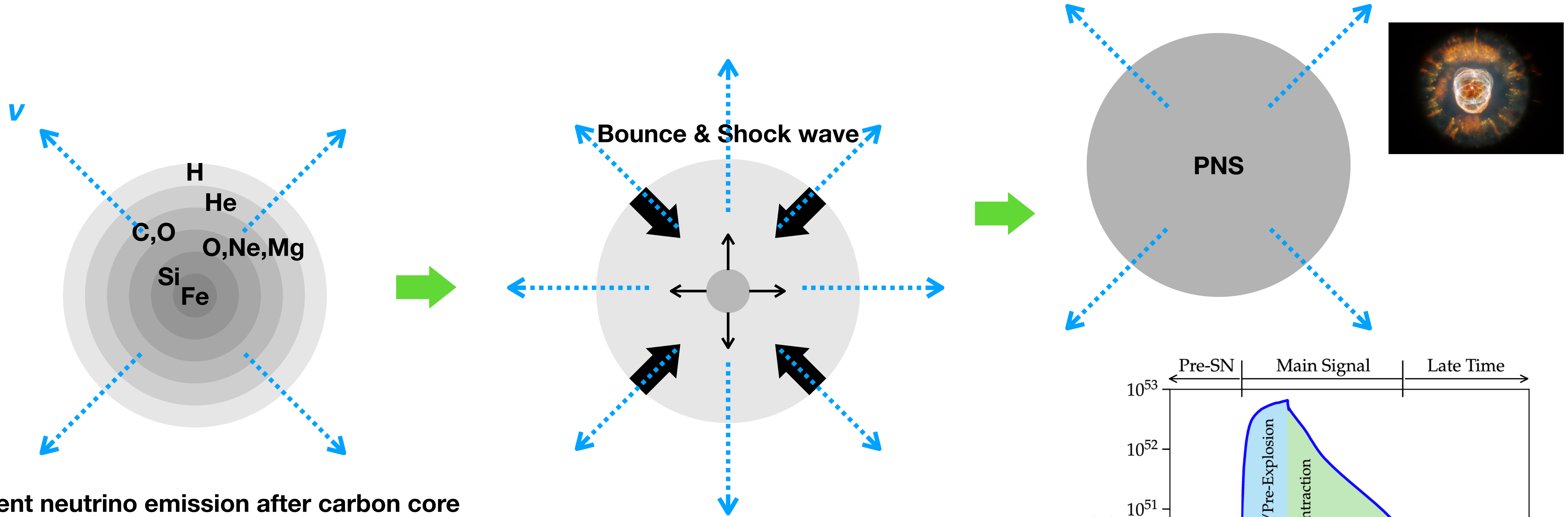
- A star with $>\sim 8M_{\text{sun}}$ cannot stand its self-gravity and hence collapses at the end of its life, leading to an explosion ($\sim$ supernova) or a blackhole formation.
 - Kinetic energy: $\sim 10^{51}$ erg (1 erg $\sim 10^{-7}$ J $\sim 6 \times 10^{11}$ eV)
 - Luminosity: $\sim$ galaxy
 - Rate: **a few times per century per galaxy**
- SN has been the center of many scientific interests *across* the fields.
 - Heavy nucleosynthesis, galactic chemical evolution
 - Blackhole formation from single star evolution
 - Nuclear equation-of-state (EOS)
 - Beyond Standard Model (BSM) physics
 - etc



Neutrinos from Collapsing Stars

10

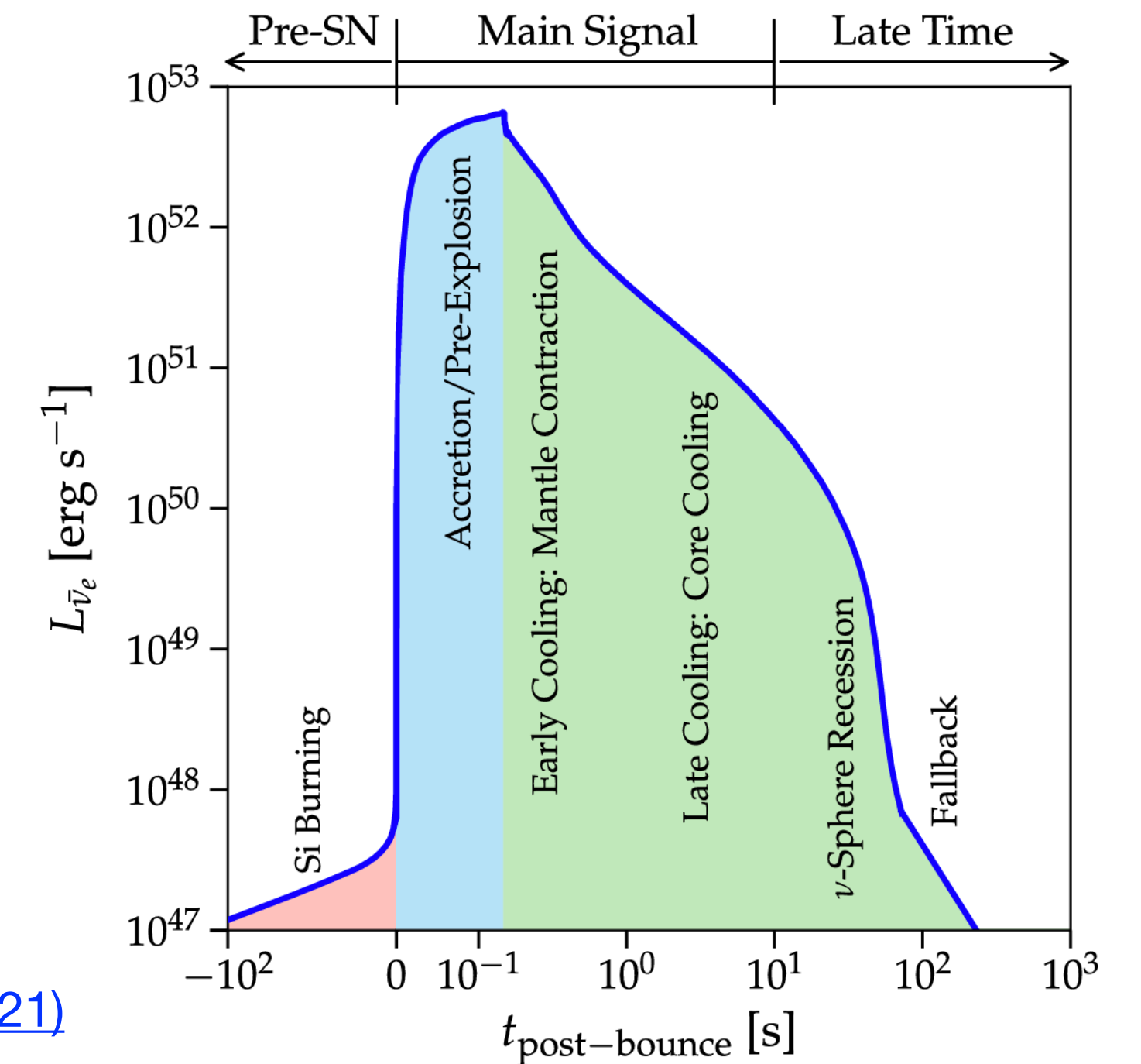
Neutrino emission from proto-neutron star cooling



Efficient neutrino emission after carbon core
(= **pre-supernova neutrinos**)

Neutrino emission along shock transition

~99% of energy released as “neutrinos”



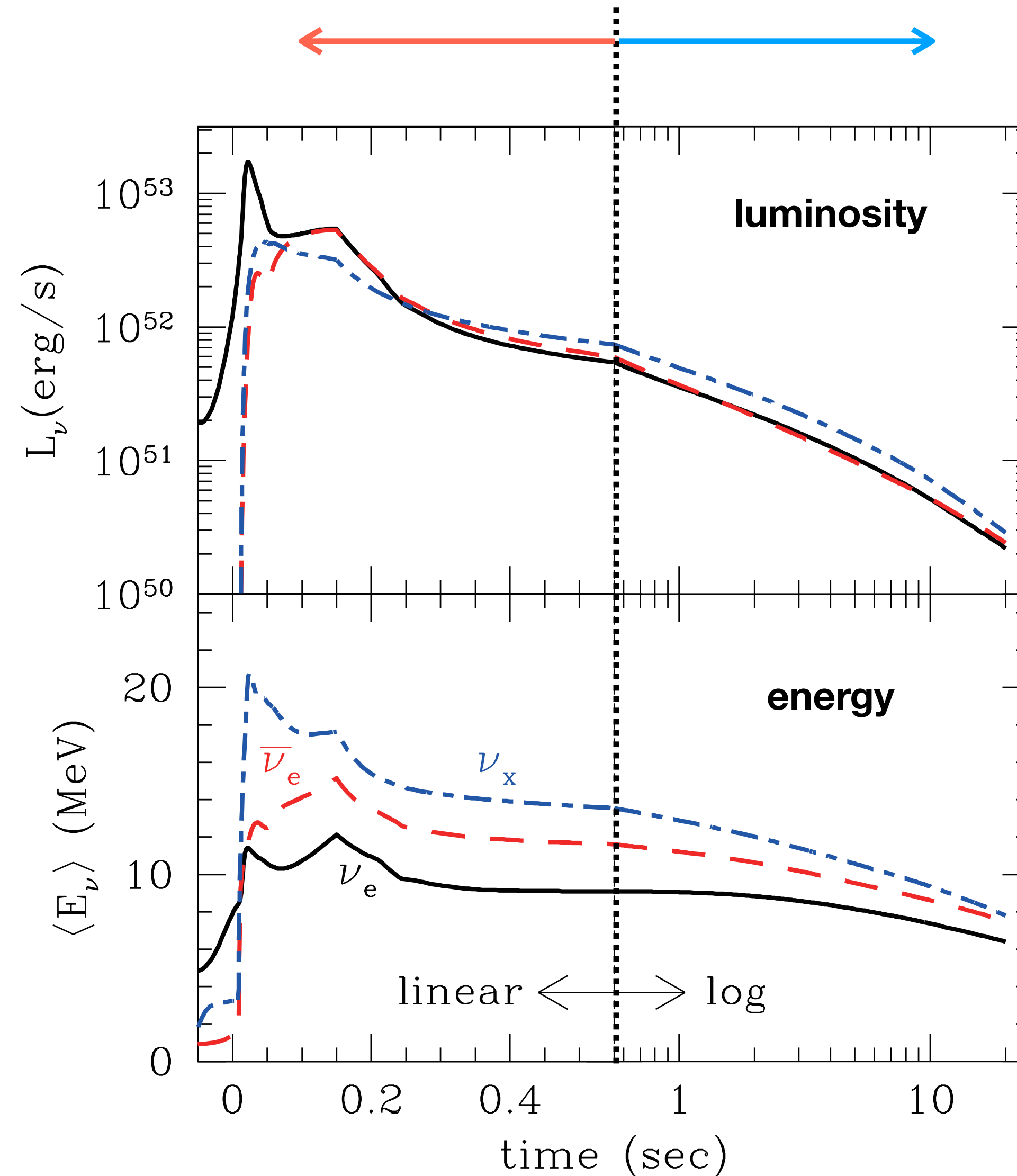
[S. W. Li, L. F. Roberts, and J. F. Beacom, PRD 103, 023016 \(2021\)](#)

accretion phase

- Both **NS** and **BH** cases
- Longer accretion for BH case
- Mainly ν_e and anti- ν_e
- Higher energy

cooling phase

- Only **NS** case
- Large integrated flux
- All flavors
- Lower energy

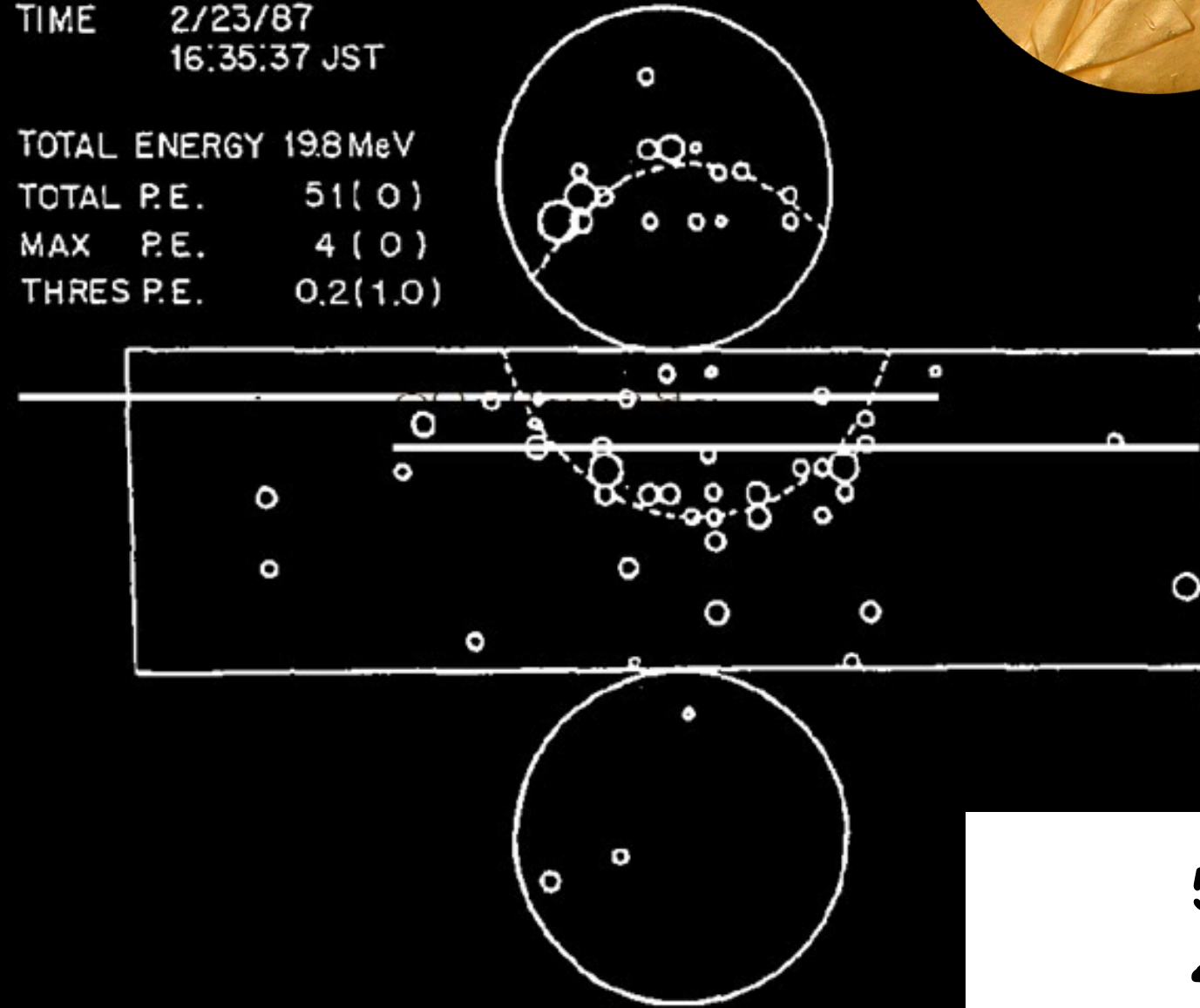
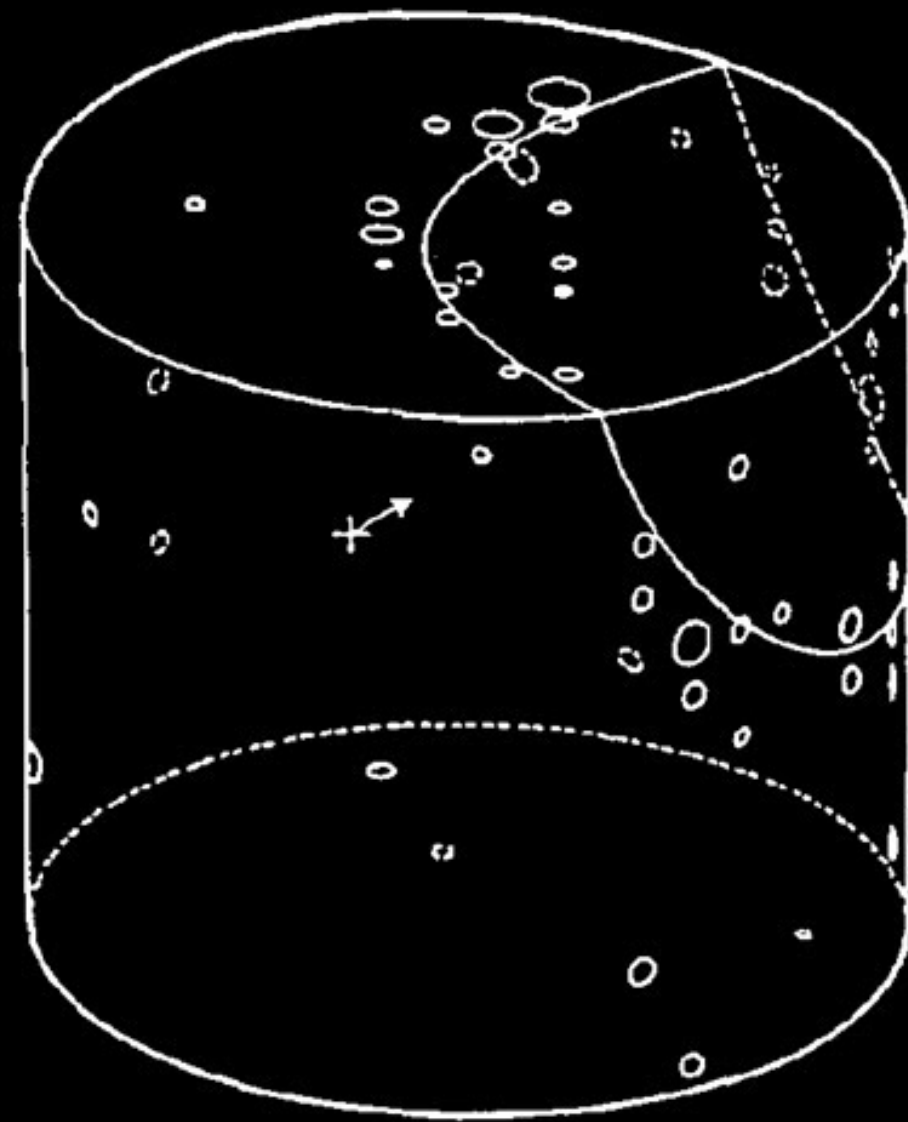


SN1987A

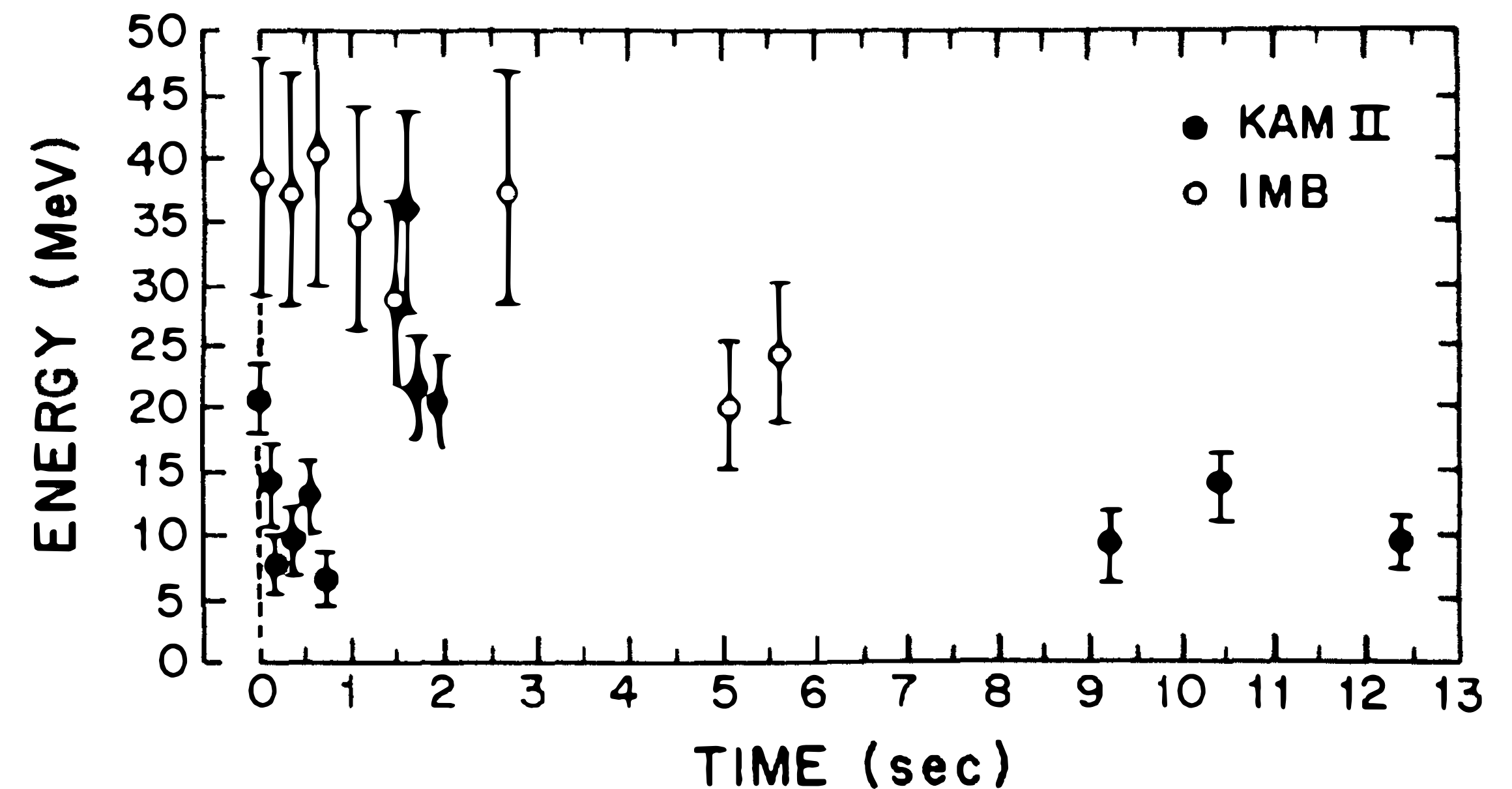
KAMIOKANDÉ 2

NUM 9
RUN 1892
EVENT 139372
TIME 2/23/87
16:35:37 JST

TOTAL ENERGY 19.8 MeV
TOTAL P.E. 51(0)
MAX P.E. 4(0)
THRES P.E. 0.2(1.0)



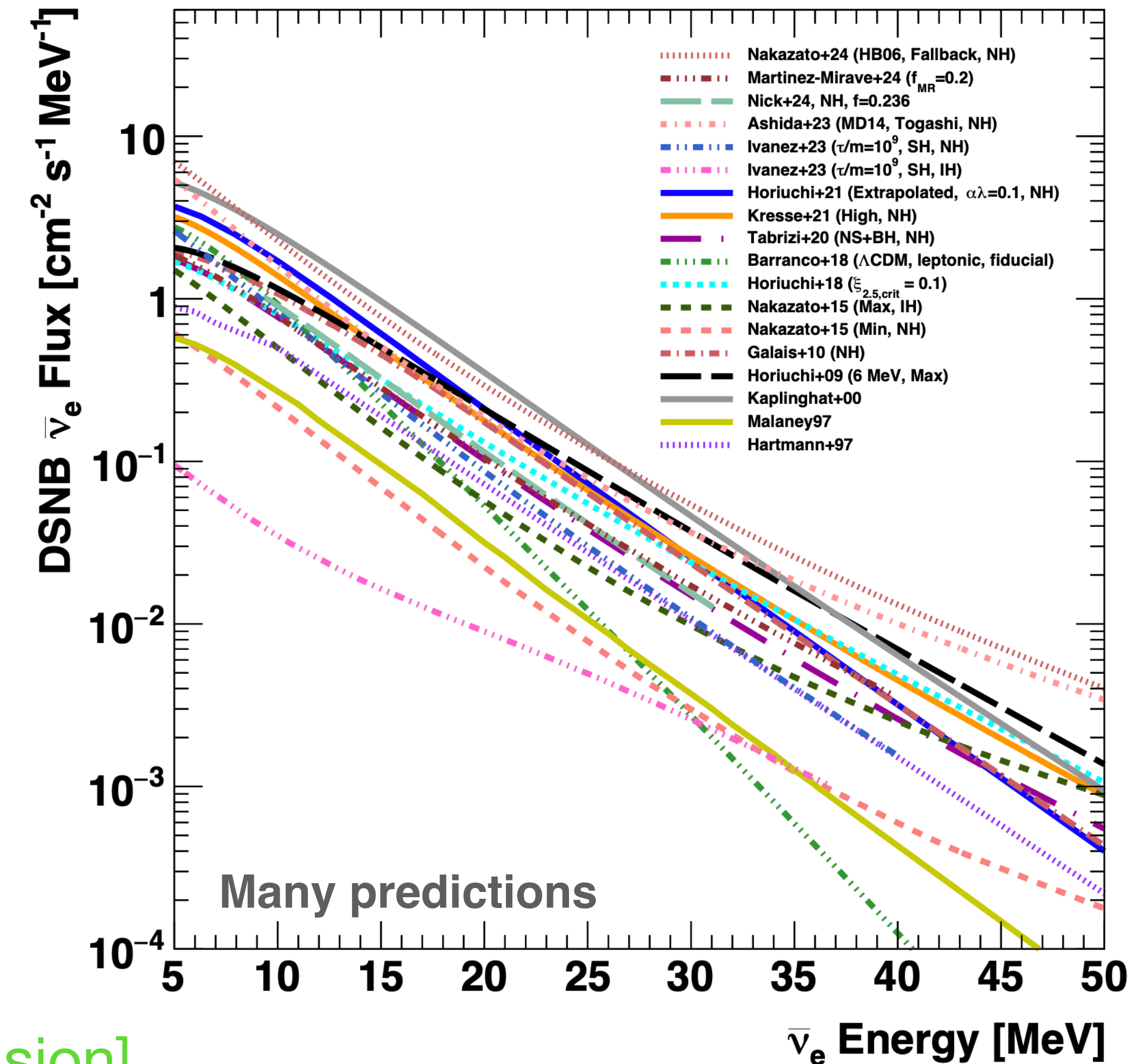
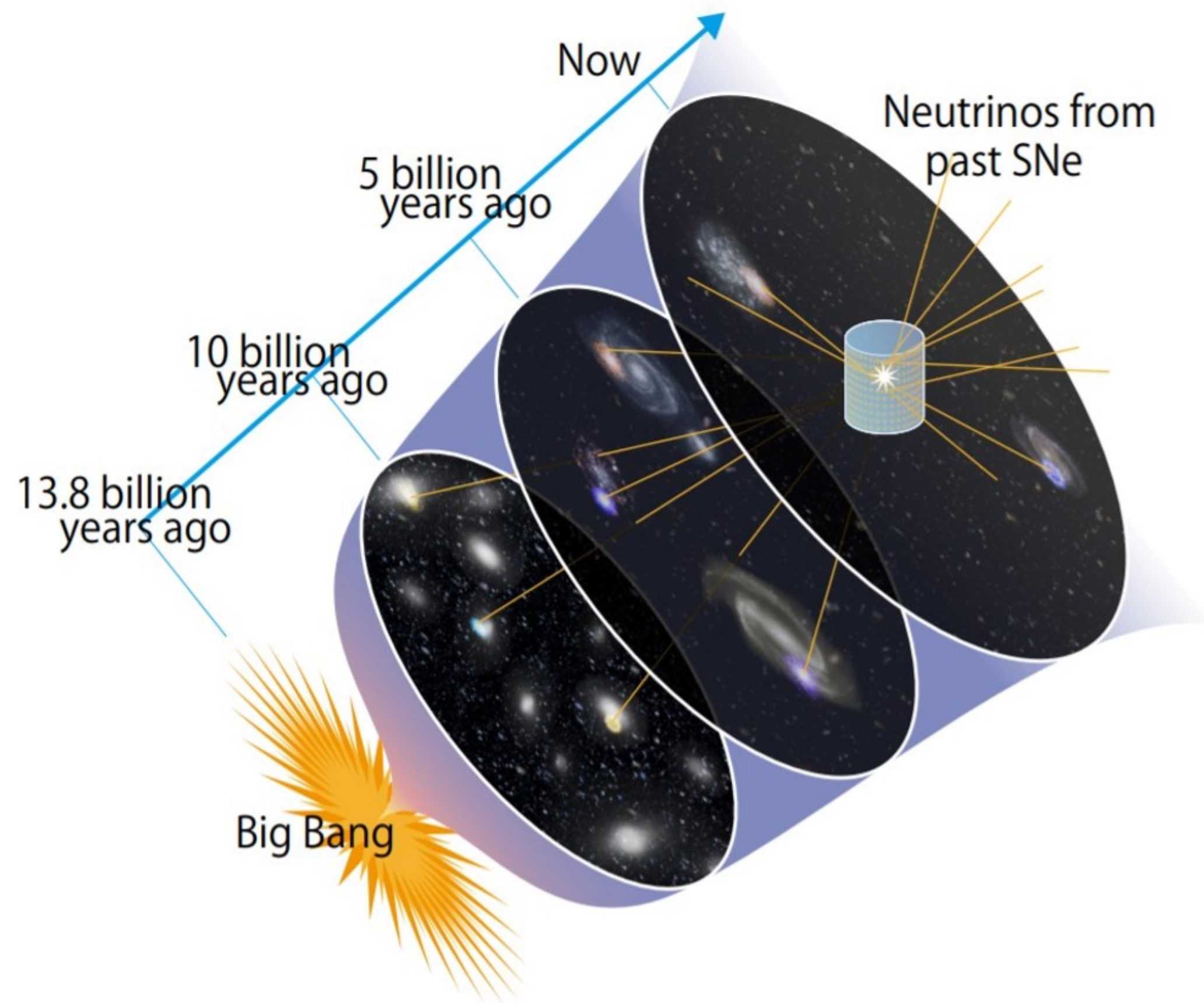
Only one case so far, the *historic* SN 1987A
We are waiting for the next one!



Message from Stars in the Past

The accumulated flux of neutrinos released from stellar core collapse over the cosmic history

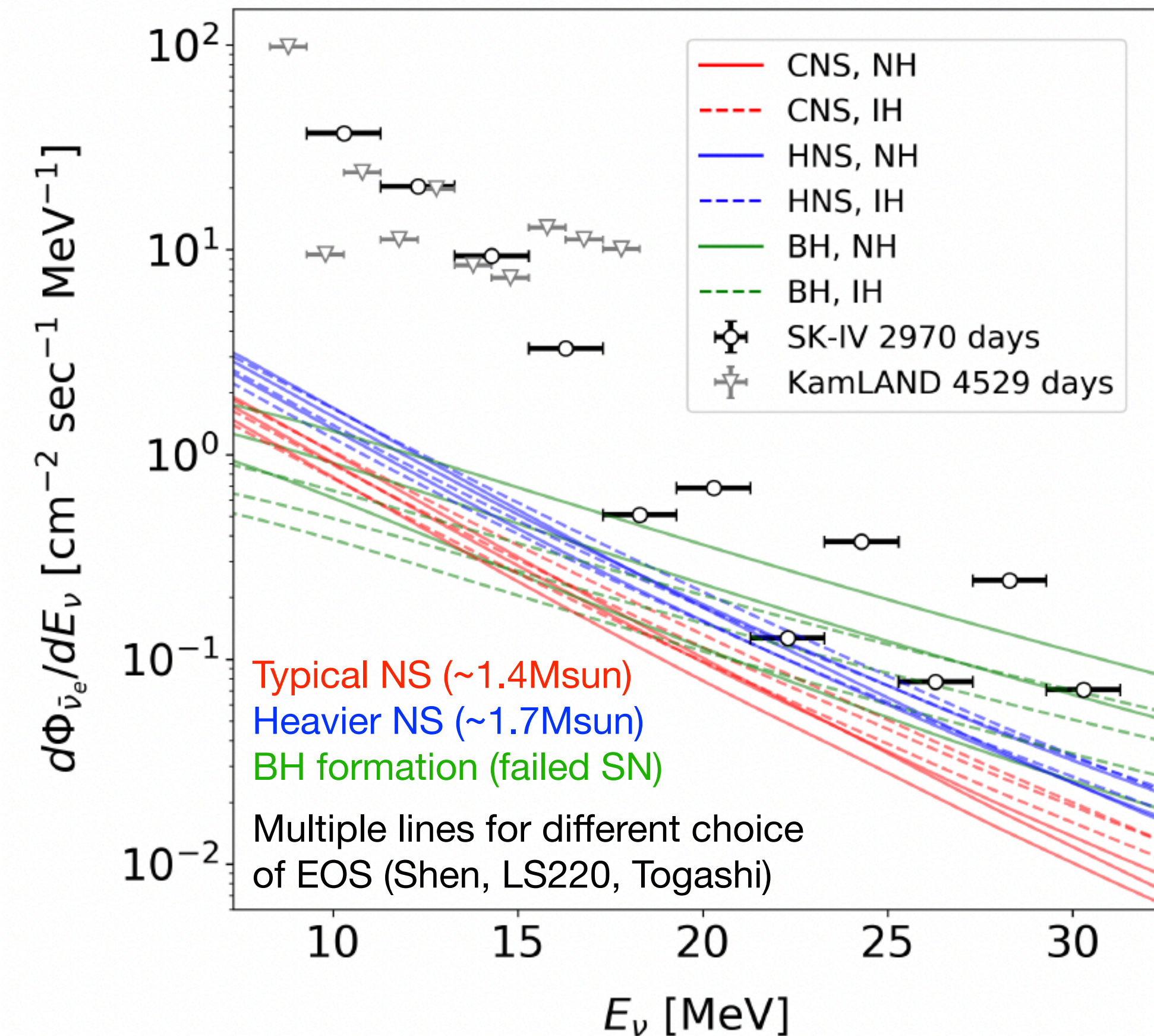
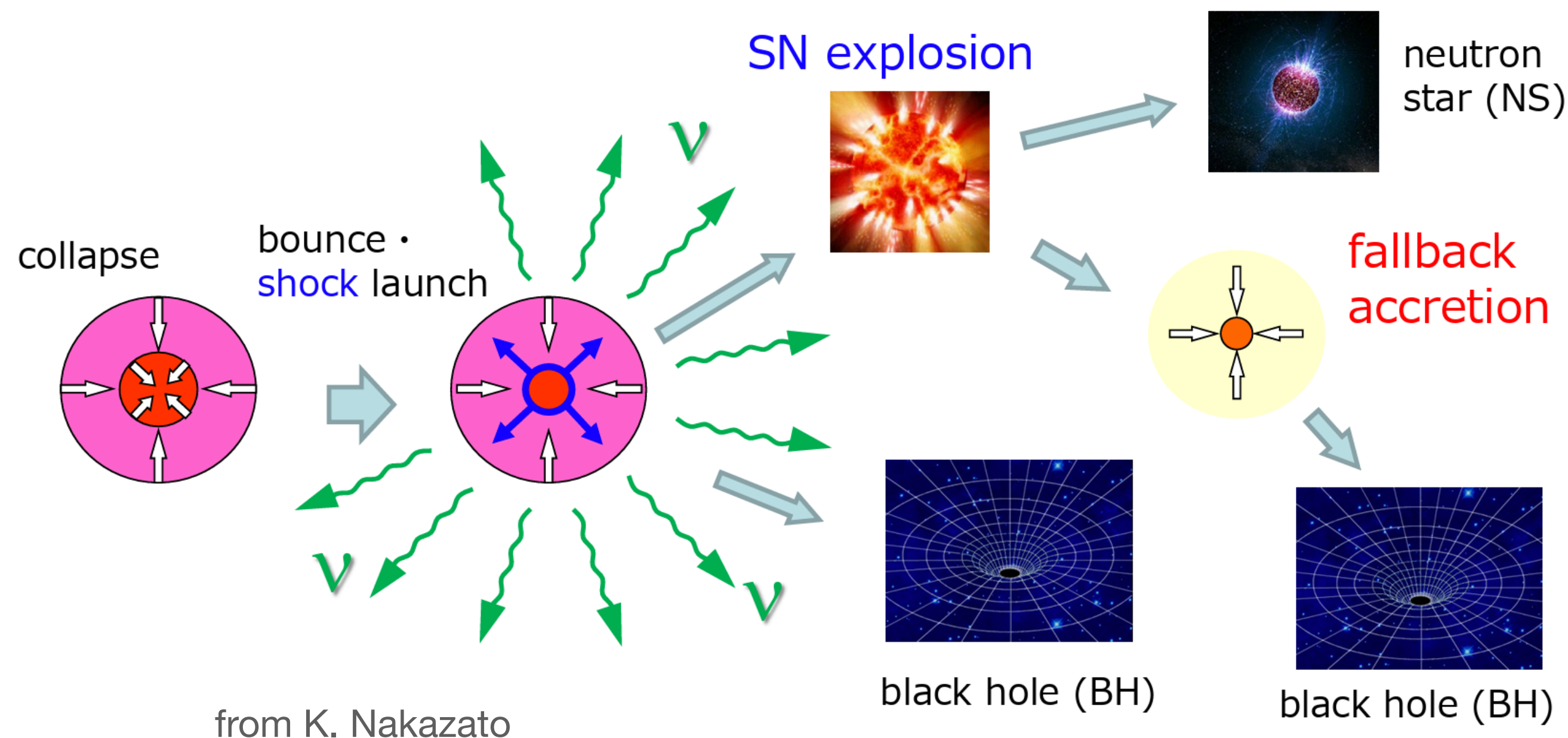
= **Diffuse Supernova Neutrino Background; DSNB**



$$\Phi = \int [\text{v emission}] \otimes [\text{Star formation}] \otimes [\text{Universe expansion}]$$

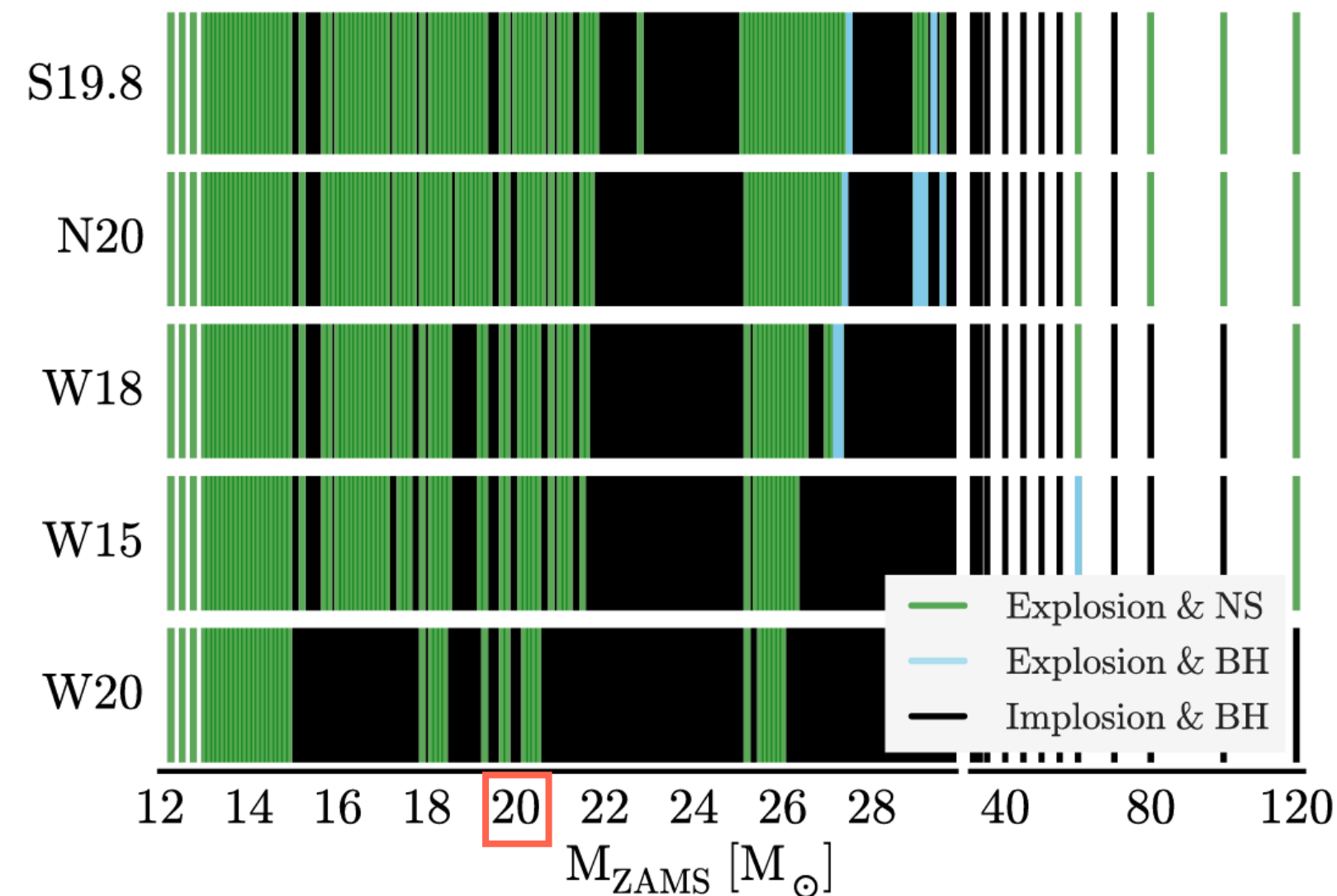
Core Collapse Fate and DSNB

- Emitted ν spectrum is expected to depend on the remnant after core collapse (“*fate*”).
 - Information about the fate are accessible by other observations (pulsar, failed SN monitoring, GW etc).
- Consider three major cases as a fate and calculate DSNB flux for each.
 - Canonical mass neutron stars ($\sim 1.4M_{\text{sun}}$)
 - High mass neutron stars ($\sim 1.7M_{\text{sun}}$)
 - Black holes (failed SNe)

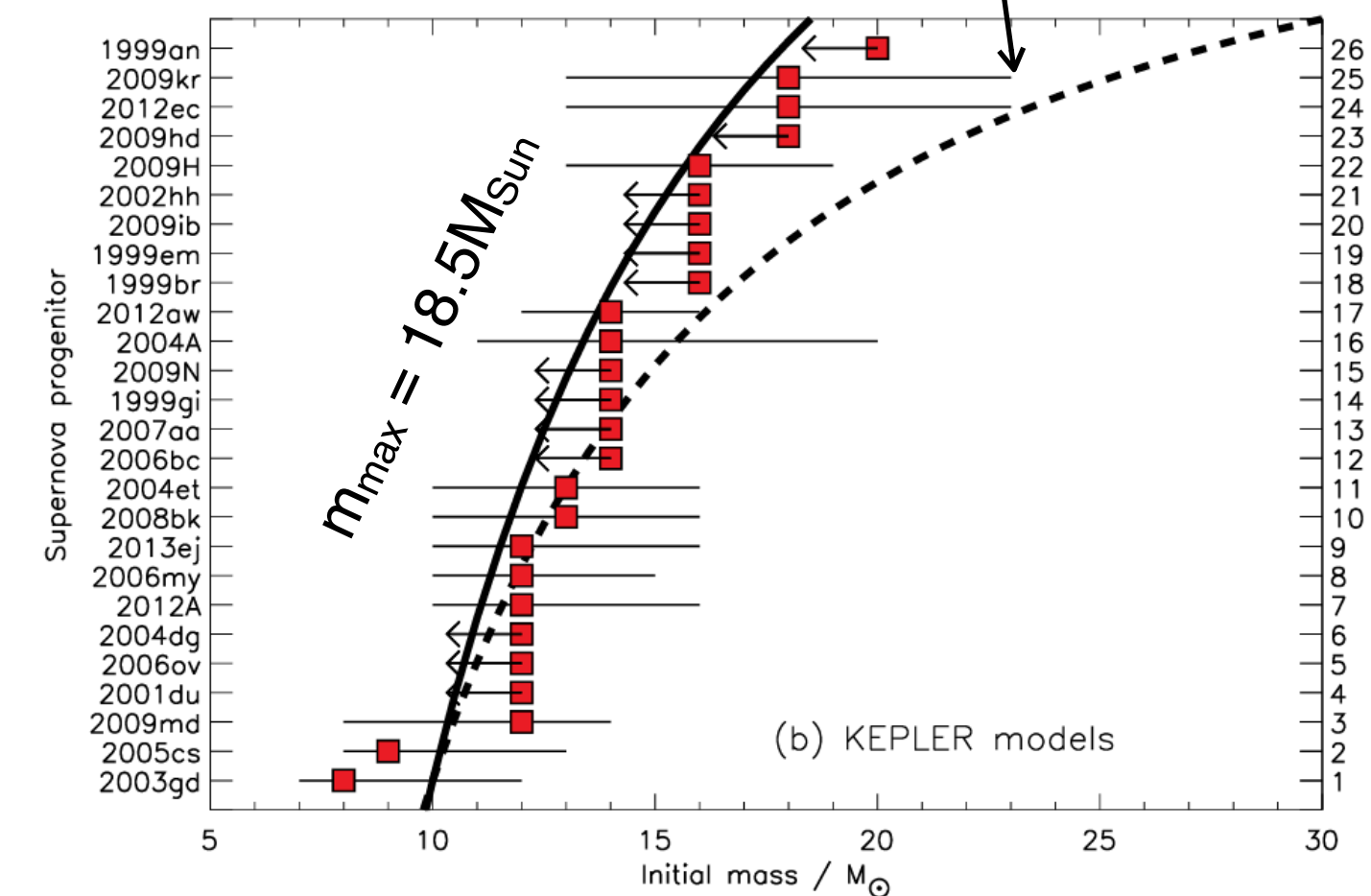
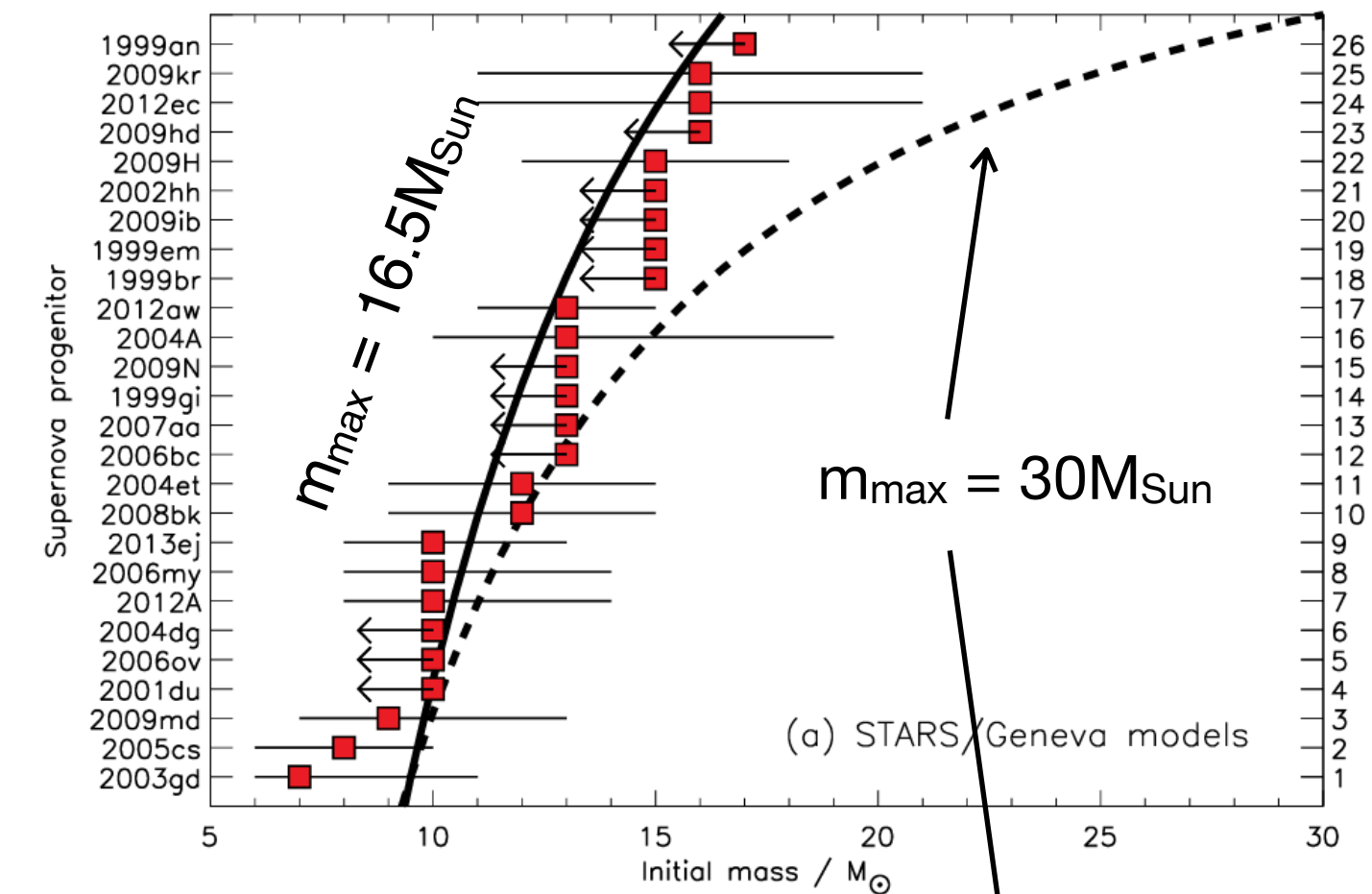


- We set the maximum mass of progenitors for successful explosions to $18M_{\text{Sun}}$.
 - Observationally, $m_{\text{min}} \sim 8M_{\text{Sun}}$ and $m_{\text{max}} \sim 18M_{\text{Sun}}$ are supported.
 - There is a theoretical work that implies failed SNe above $\sim 20M_{\text{Sun}}$.
- Many galactic chemical evolution schemes adopt a high m_{max} ($50\sim 100M_{\text{Sun}}$)
 - Our $m_{\text{max}} = 18M_{\text{Sun}}$ assumption reduces the number of CCSNe to $\sim 70\%$.
 - Accordingly, the total amount of heavy elements is reduced to $\sim 50\%$.

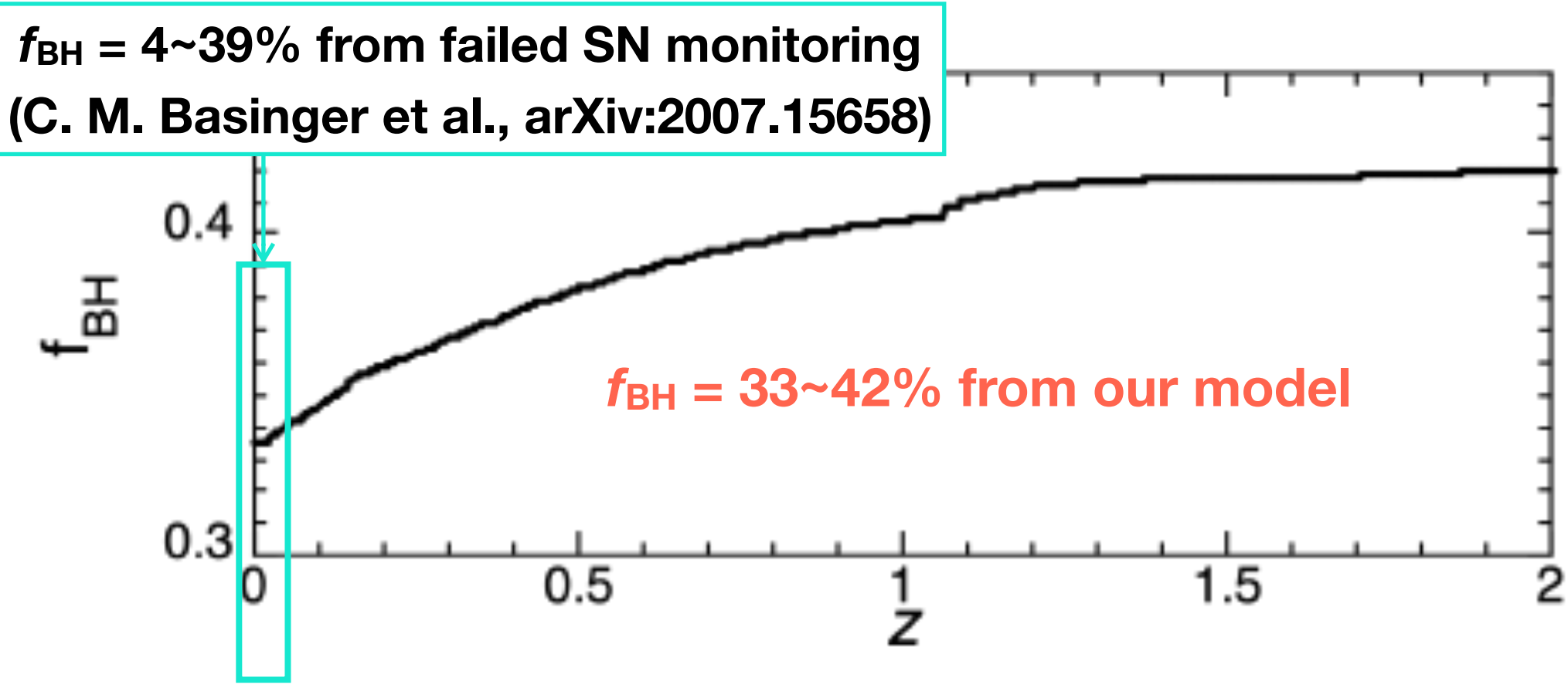
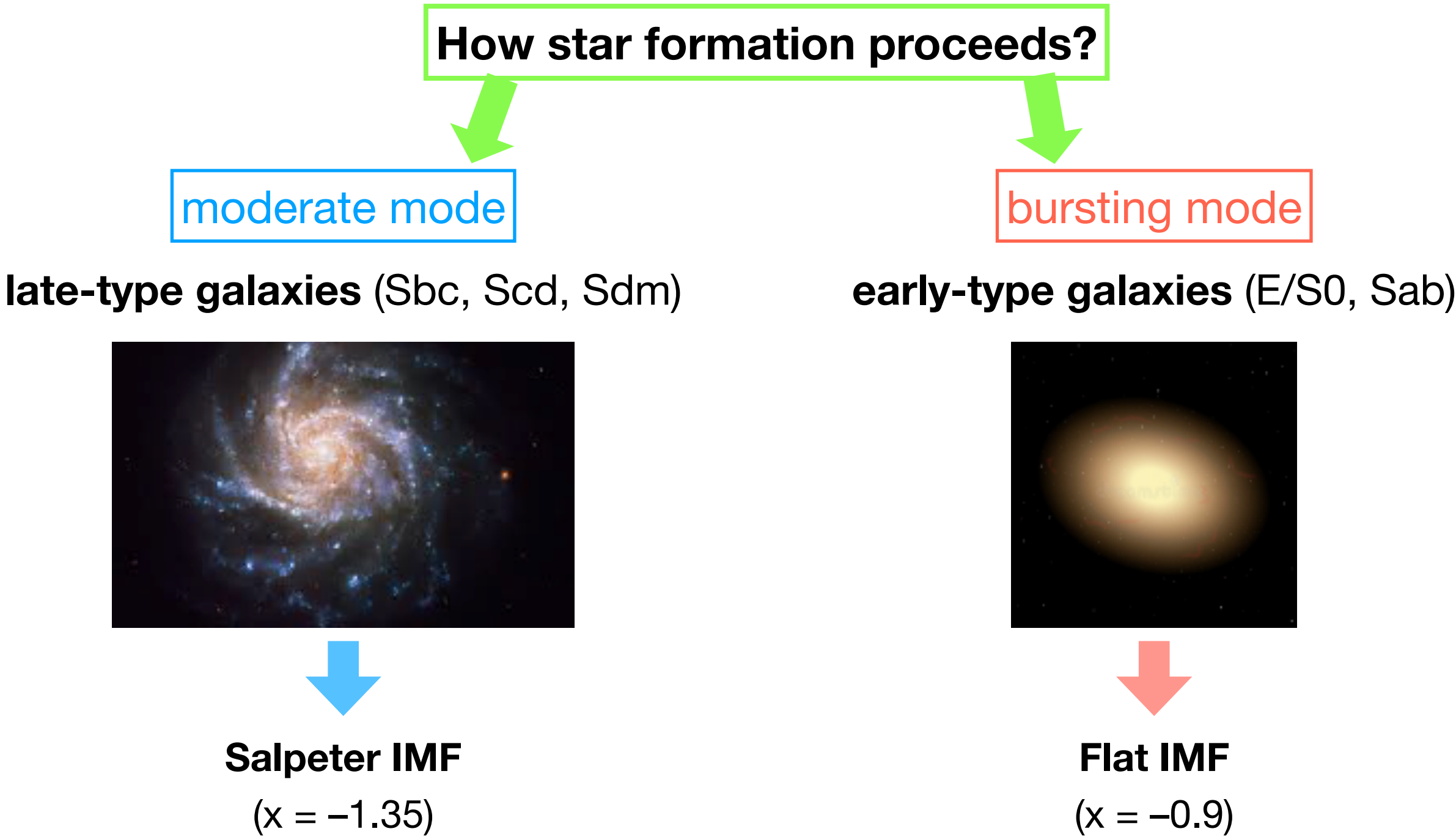
T. Sukhbold et al., ApJ 821, 38 (2016)



S. J. Smartt, PASA 32 (2015)



- In order to achieve consistency with observed chemical abundance, we propose a new evolution model.
- We categorize galaxies into five and assume different initial mass functions (IMF) depending types.
- The fraction for BH formation from this model is 33~42% (higher rate than many other DSNB models).



Our model nomenclature

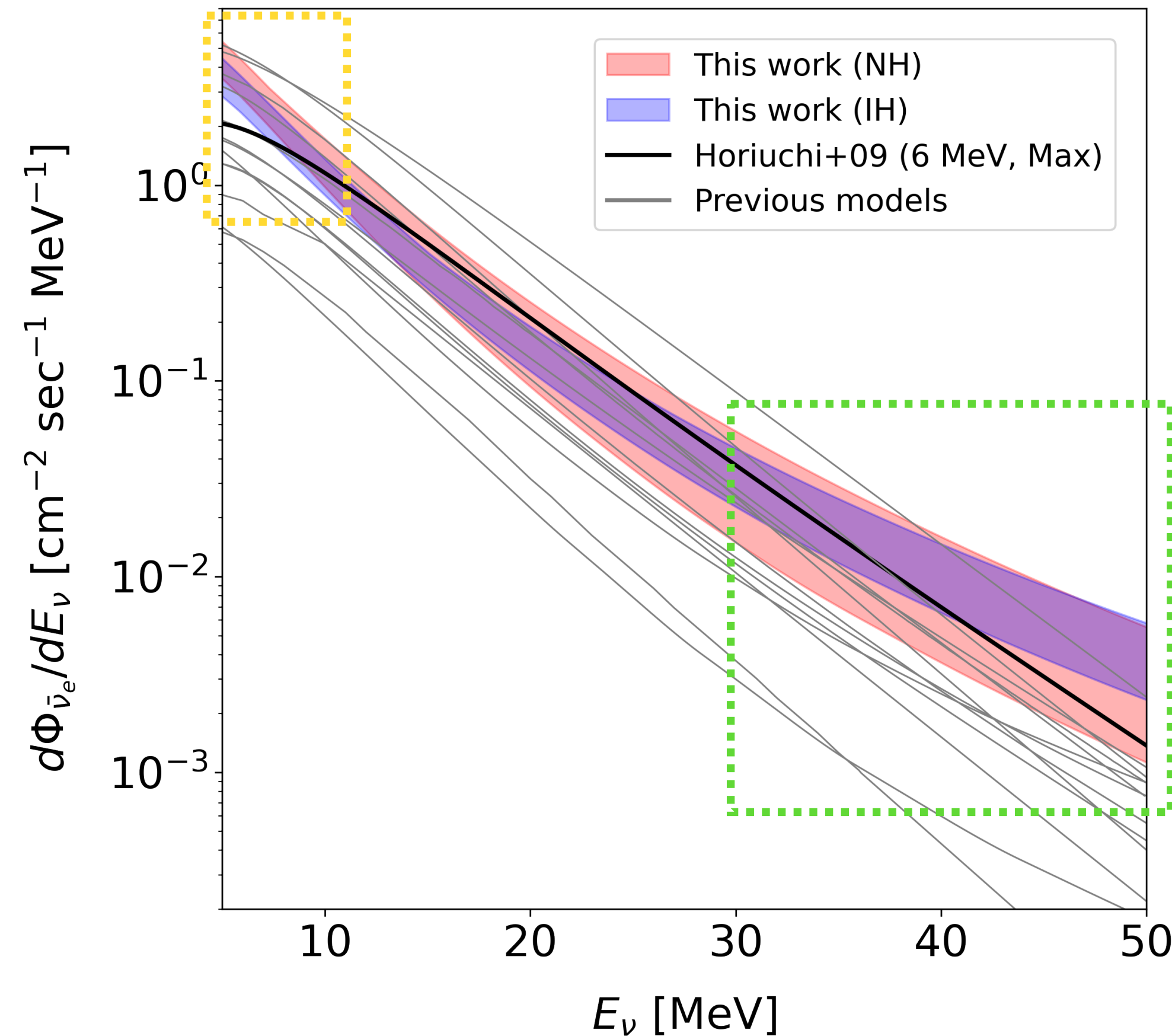
Name	IMF form	BH treatment
GDIMF-wBH (ref.)	Variable	BHs for $18\text{--}100M_{\odot}$
GDIMF-noBH	Variable	No BH
SalIMF-wBH	Salpeter	BHs for $18\text{--}100M_{\odot}$
SalIMF-noBH	Salpeter	No BH

DSNB Flux with a Novel Galactic Chemical Evolution

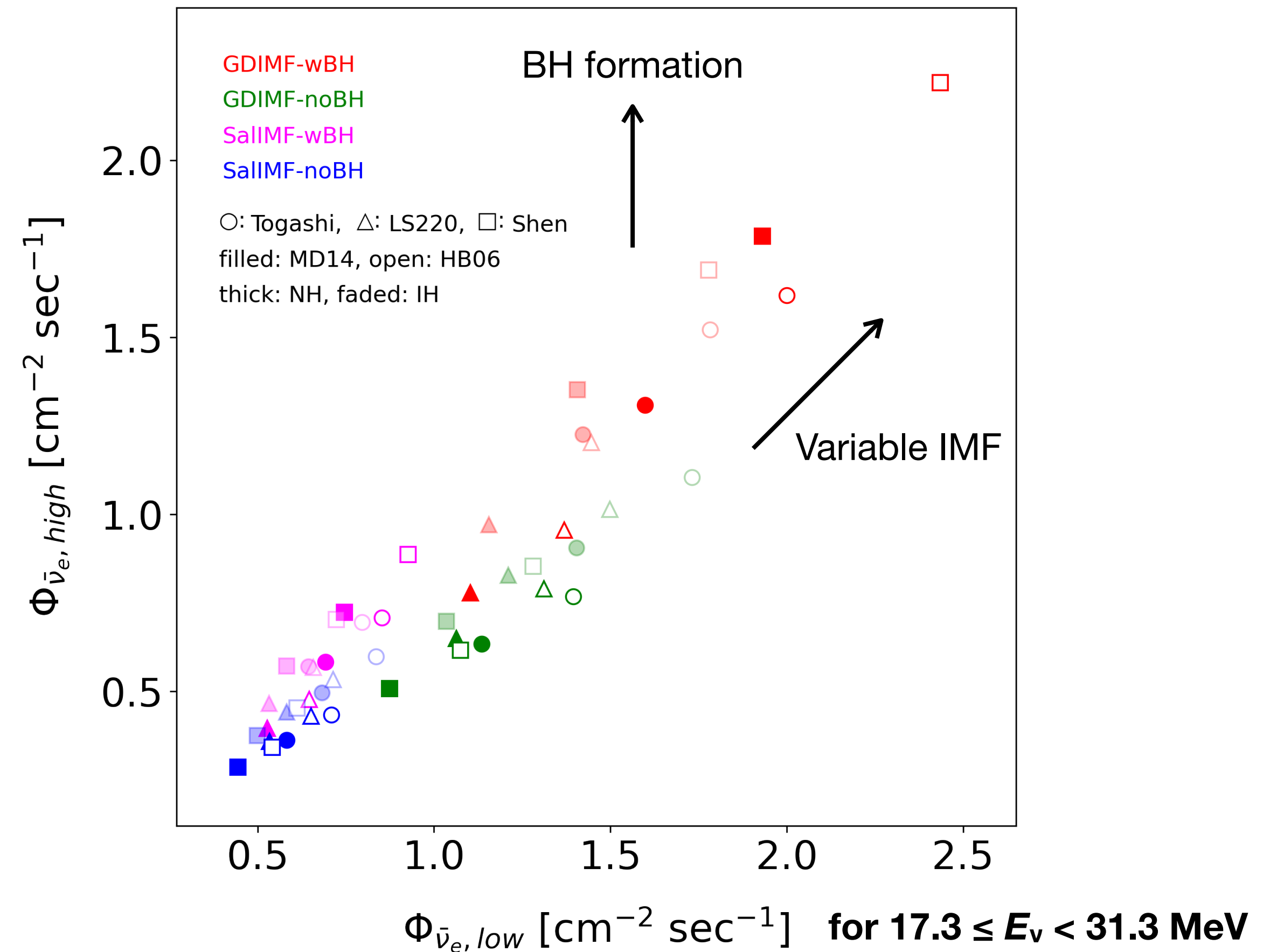
17

- Our model shows DSNB flux enhancements at high and low energies.
- High energy (>30 MeV): Large contribution from BH formation.
- Low energy (<10 MeV): Redshifted neutrinos from early-type galaxies with large CCSN rates.

[Y. Ashida, K. Nakazato, T. Tsujimoto, ApJ 953, 2 \(2023\)](#)

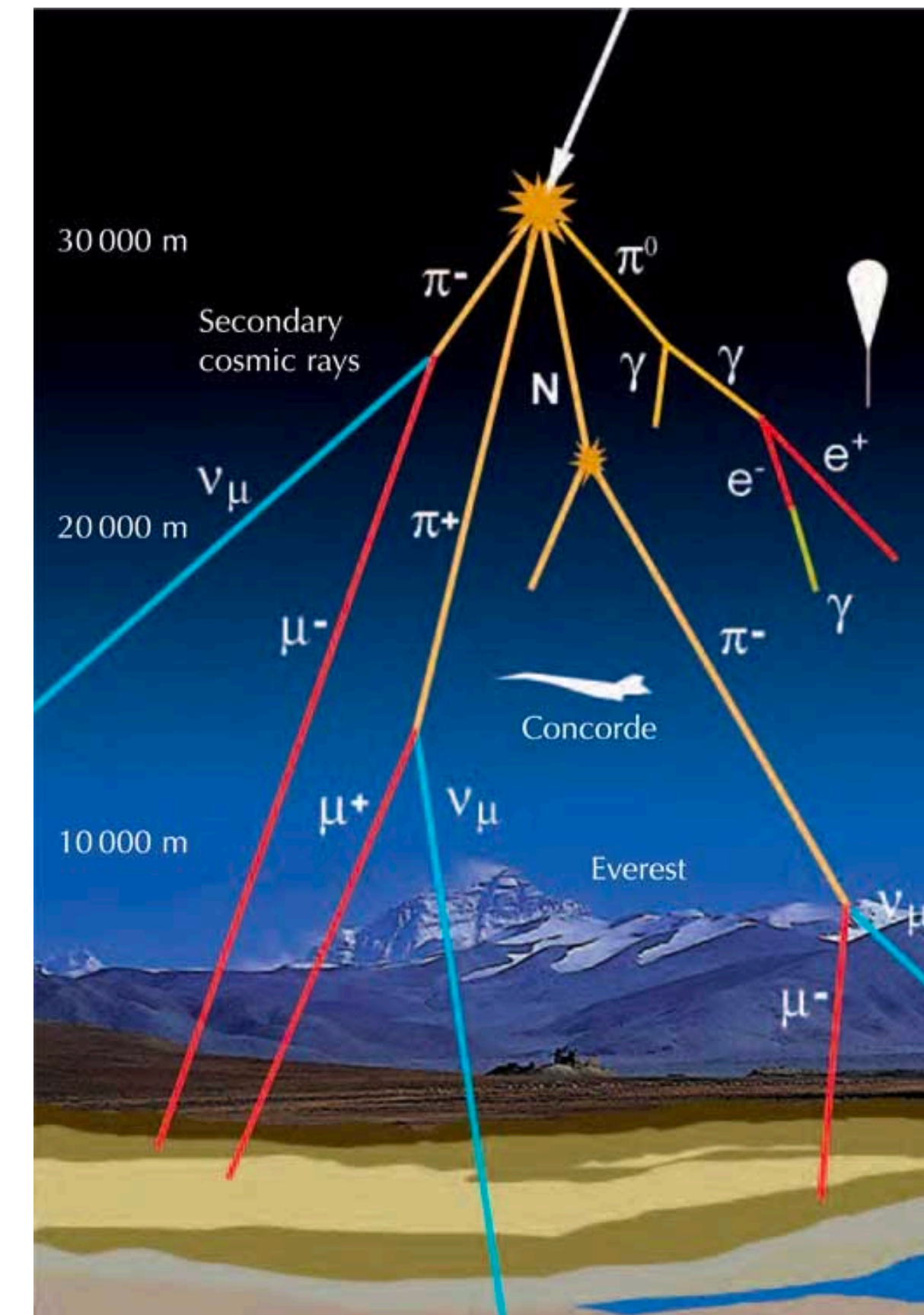
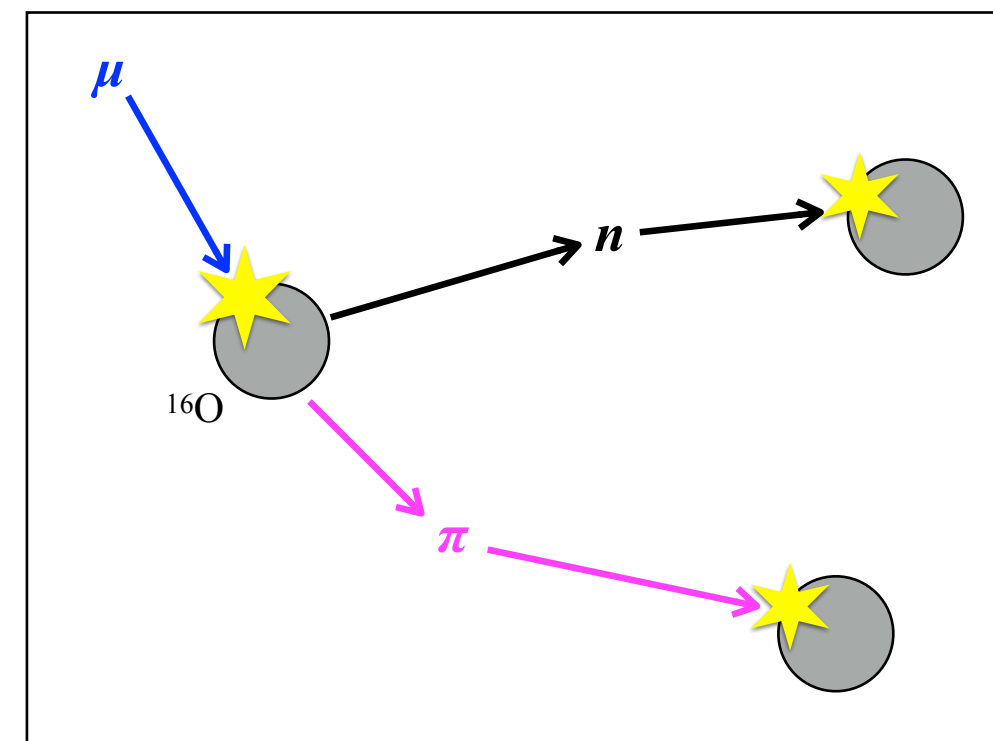
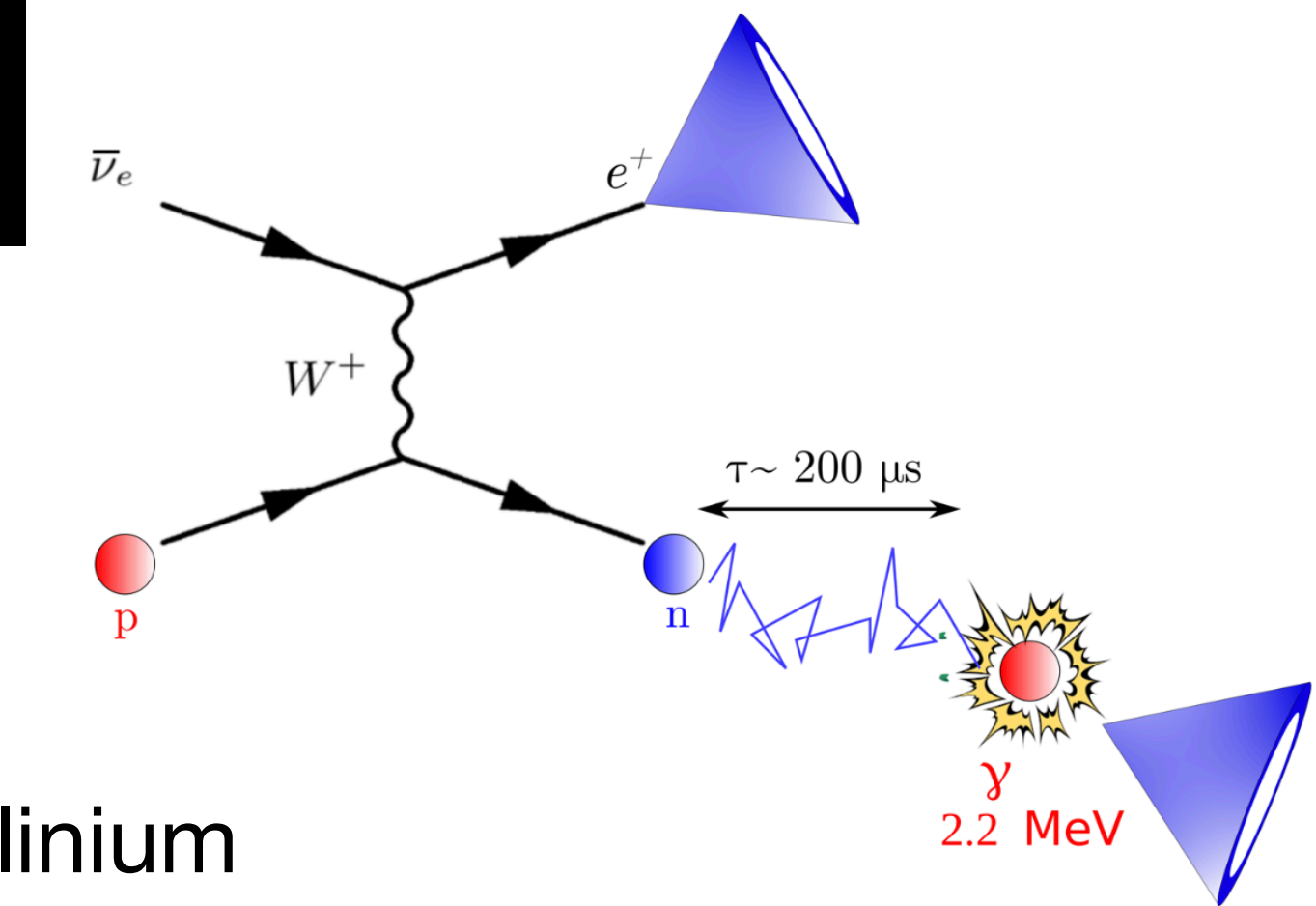


for $13.3 \leq E_\nu < 17.3$ MeV

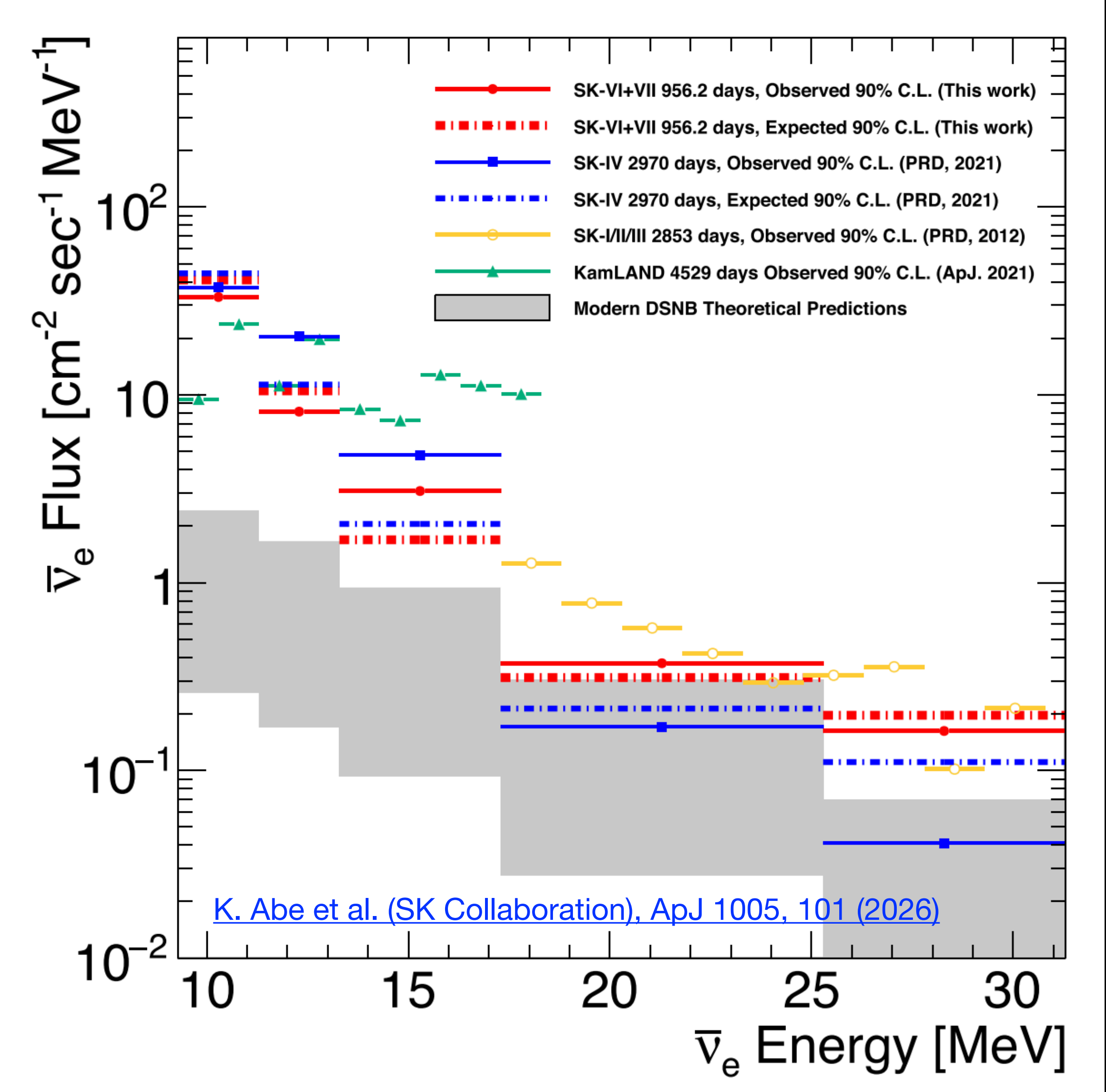
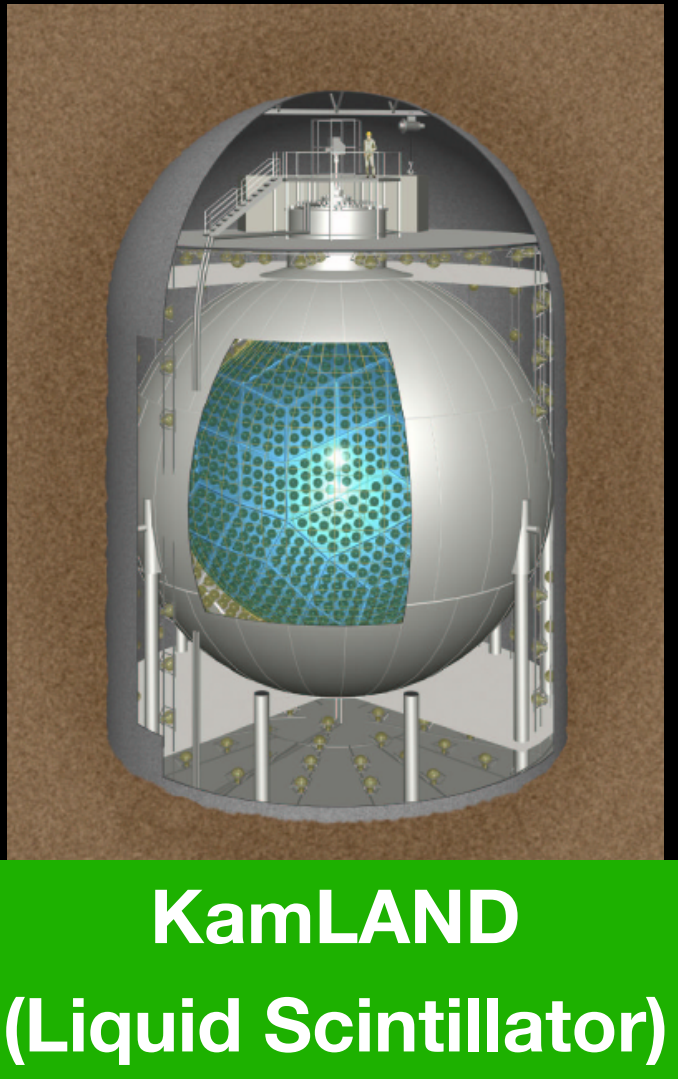
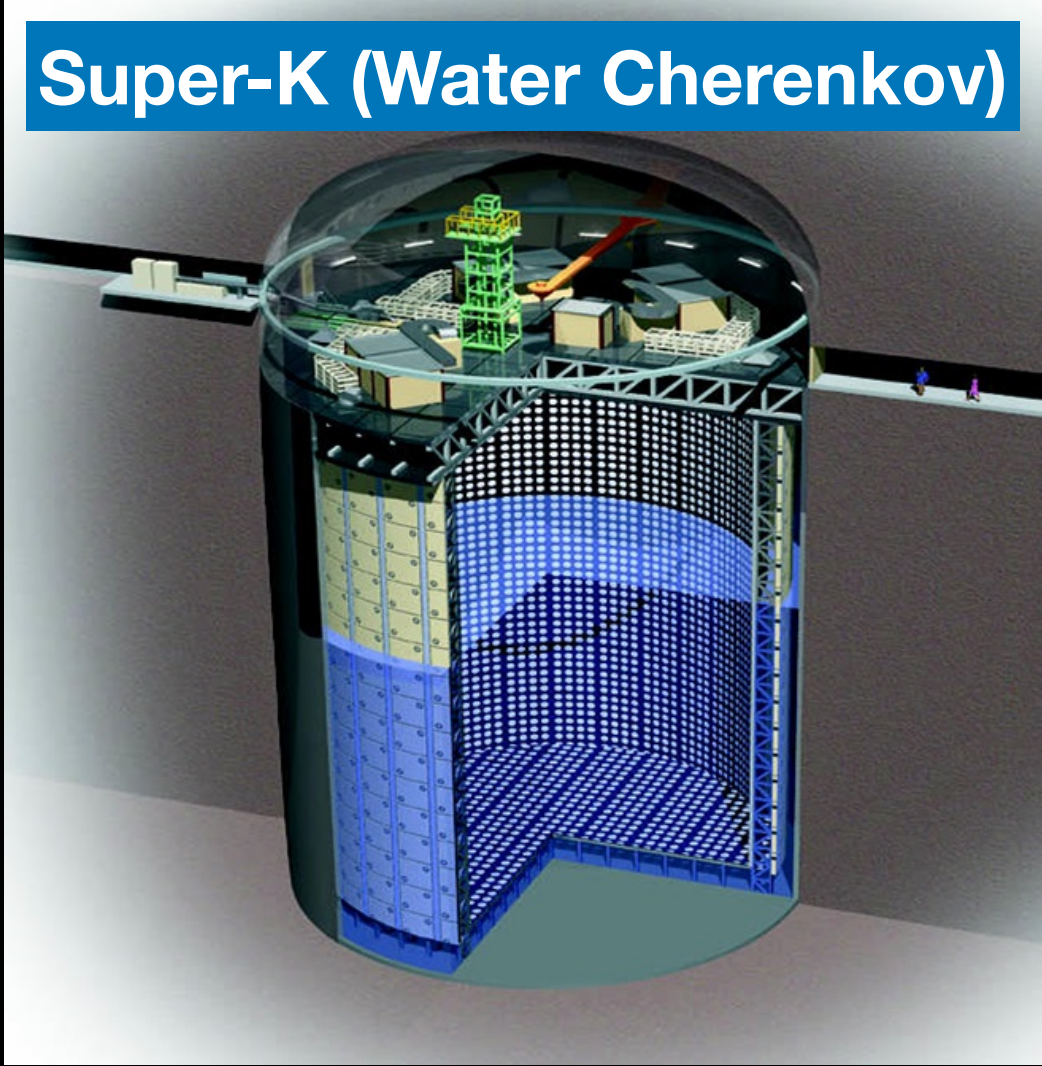


Experimental Search

- Signal = **inverse beta decay (IBD)**, $\bar{\nu}_e + p \rightarrow e^+ + n$ (dominant channel)
 - e^+ = “*prompt*” signal (main energy range: **O(1–10) MeV**)
 - n = “*delayed*” signal via **γ -ray(s)** from thermal capture on hydrogen or gadolinium
- Many types of backgrounds mimicking this signature.
 - Atmospheric neutrinos (charged / neutral current)
 - Radioactive isotopes and neutrons by atmospheric muons
 - Solar neutrinos
 - Reactor neutrinos



Before *This* Summer...



超新星背景ニュートリノ！

カミオカンデさんの
見つけた超新星爆発、
なかなか次のが
見つからないねえ

どこかで爆発が
起きないと、
見つからないからね...

スーパーカミオカンデさん

J-PARCさん

でもさ、
起きないものは
しょうがないよねえ

...ううん、
実はそうでもないんだ

無いものは
見えない！

宇宙が生まれて今までに、
10の17乗個の
超新星爆発が起きてる
はずだから、
その時のニュートリノの
名残が見えるはずなの

WOW!

反電子ニュートリノが
多いっぽい

たくさんの
超新星爆発

...でもね、
それもまだ
見つかってないの

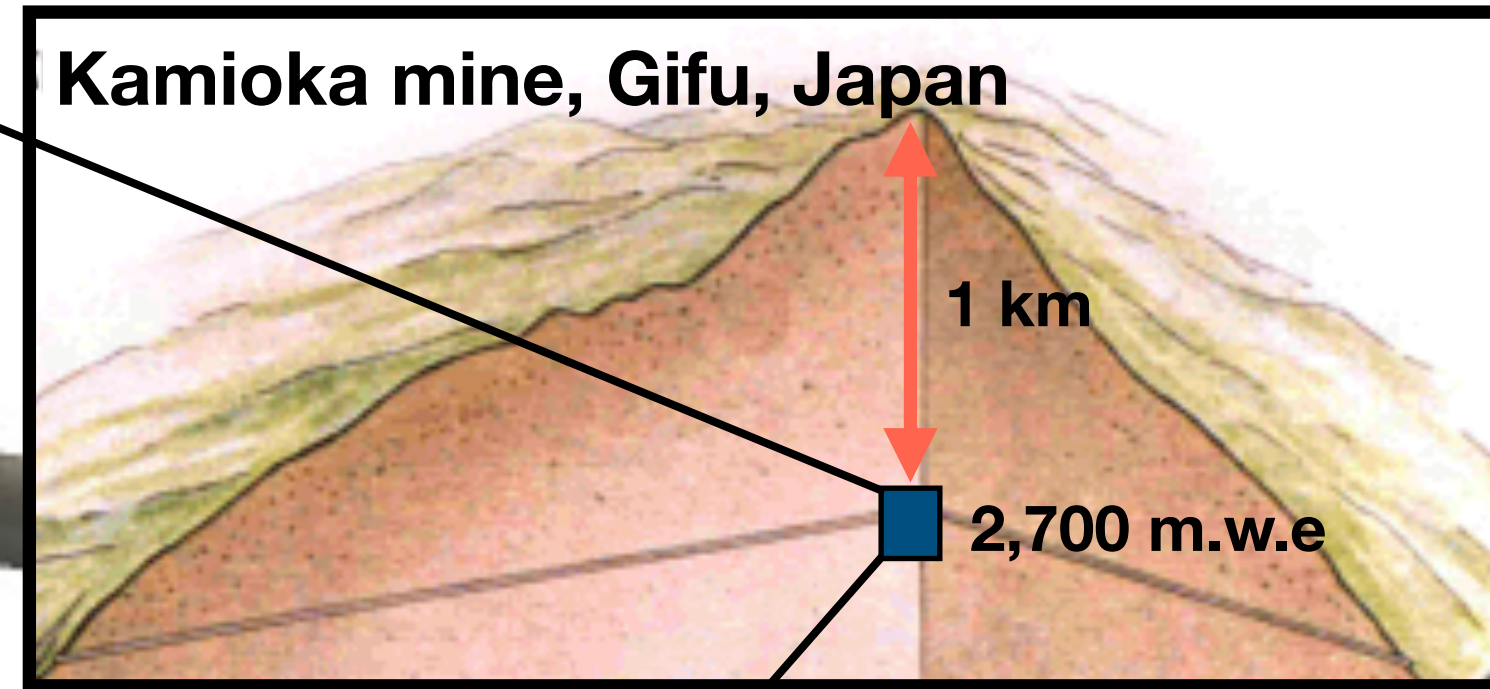
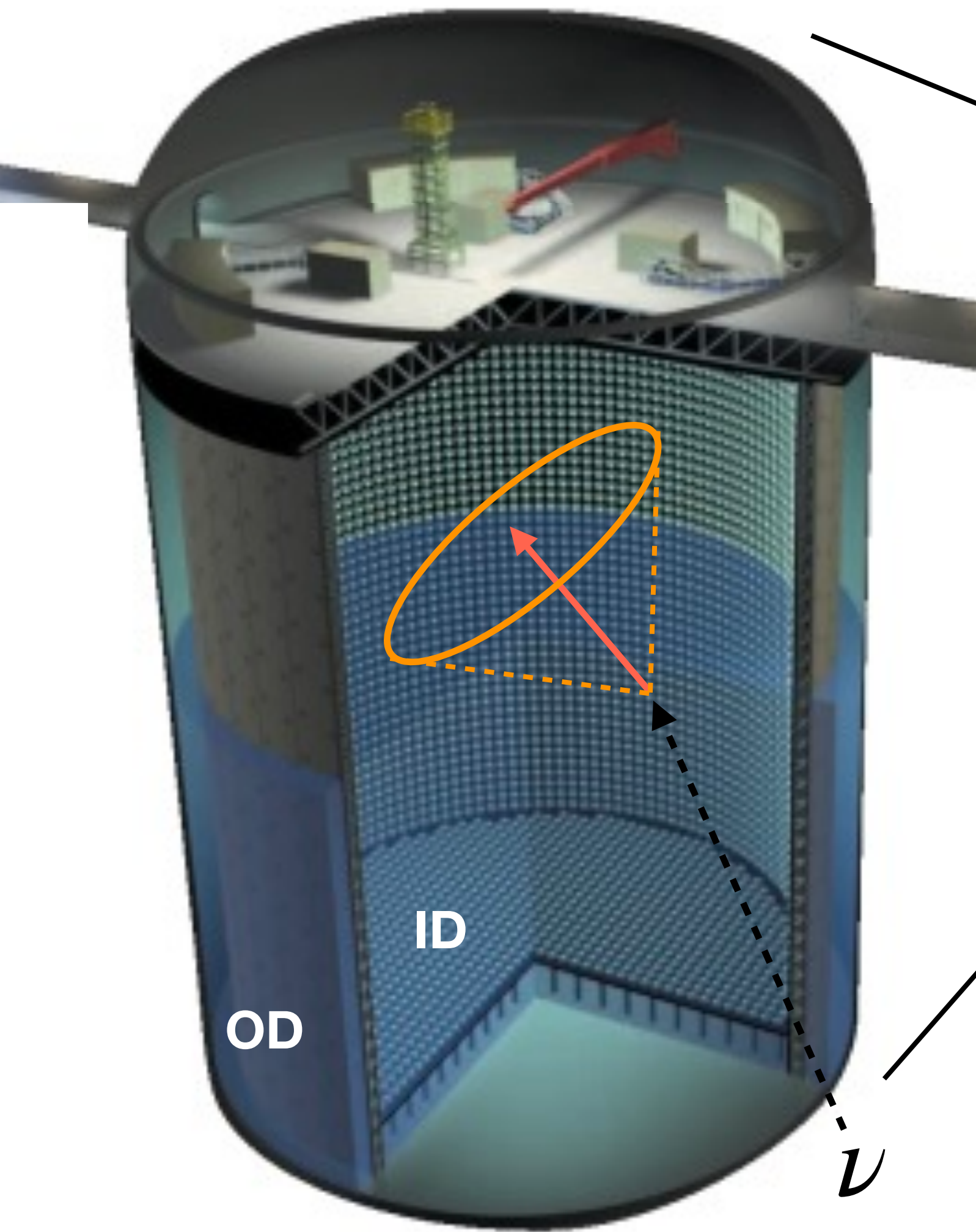
頑張っ
て探して
るんだ
なあ

超新星爆発って
難しいんだなあ

©Yuki A., higgstan.com

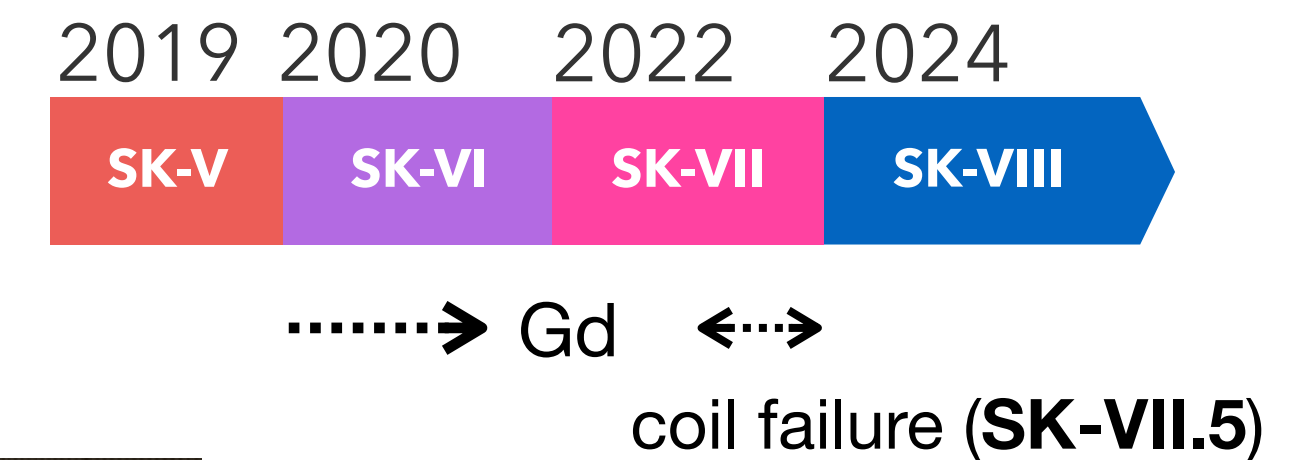
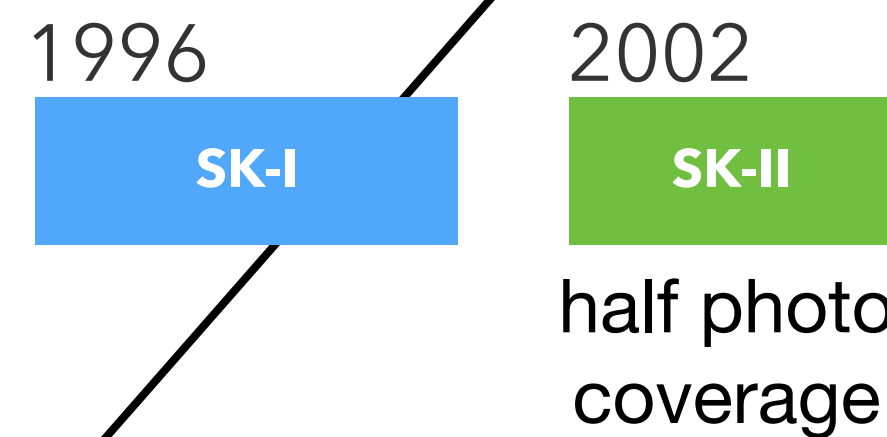
Latest Search at Super-K



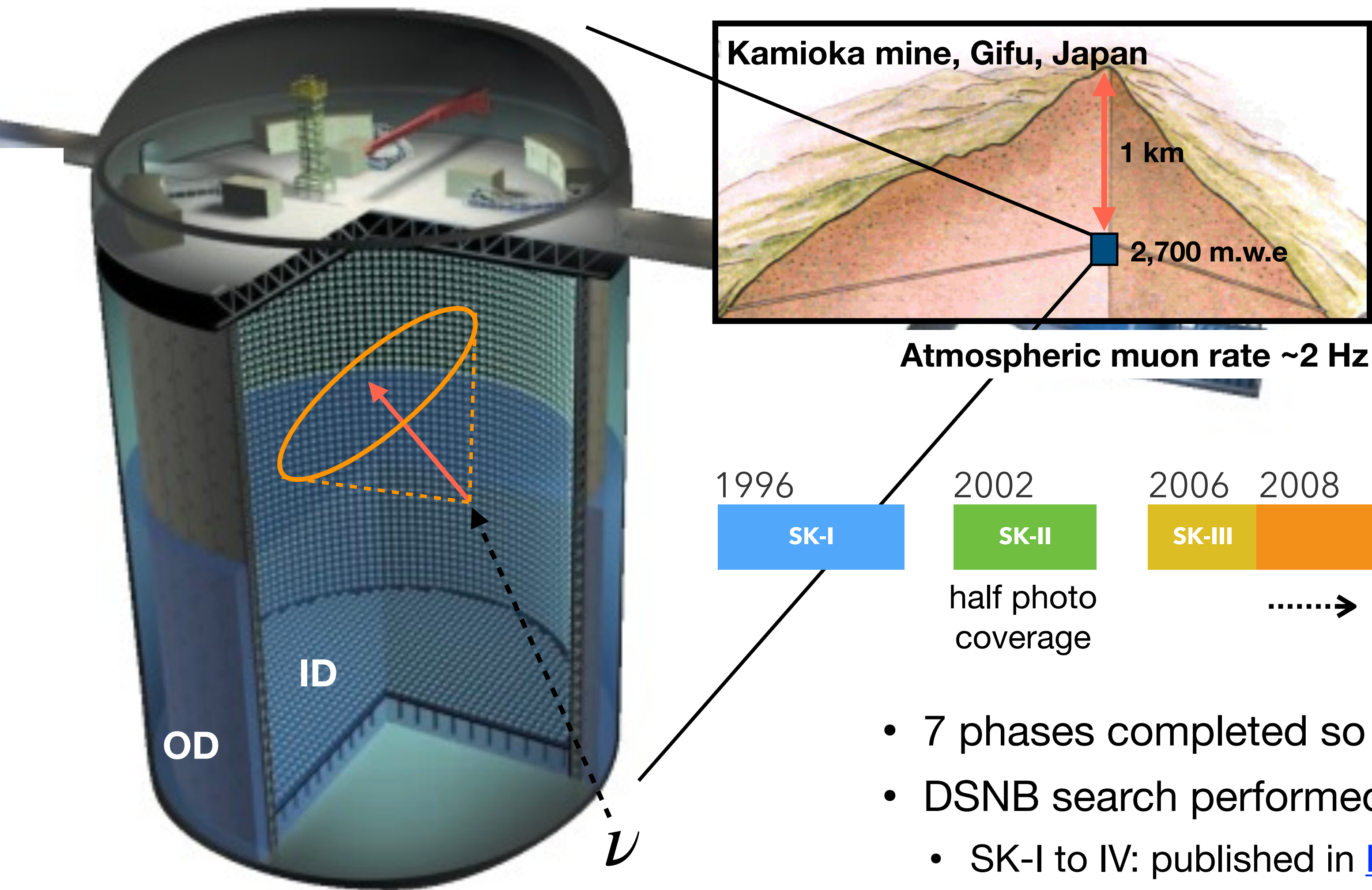


Atmospheric muon rate ~ 2 Hz

- 50 kton water (**22.5 kton** for analysis)
- **11,129** 20-inch PMTs (Inner Detector)
→ Physics event of interest
- **1,885** 8-inch PMTs (Outer Detector)
→ Background veto (muon etc)



30 year anniversary!



- 50 kton water (**22.5 kton** for analysis)
- **11,129** 20-inch PMTs (Inner Detector)
→ Physics event of interest
- **1,885** 8-inch PMTs (Outer Detector)
→ Background veto (muon etc)



- 7 phases completed so far, and SK-VIII is on-going now.
- DSNB search performed multiple times.

(Based on my Ph.D thesis)

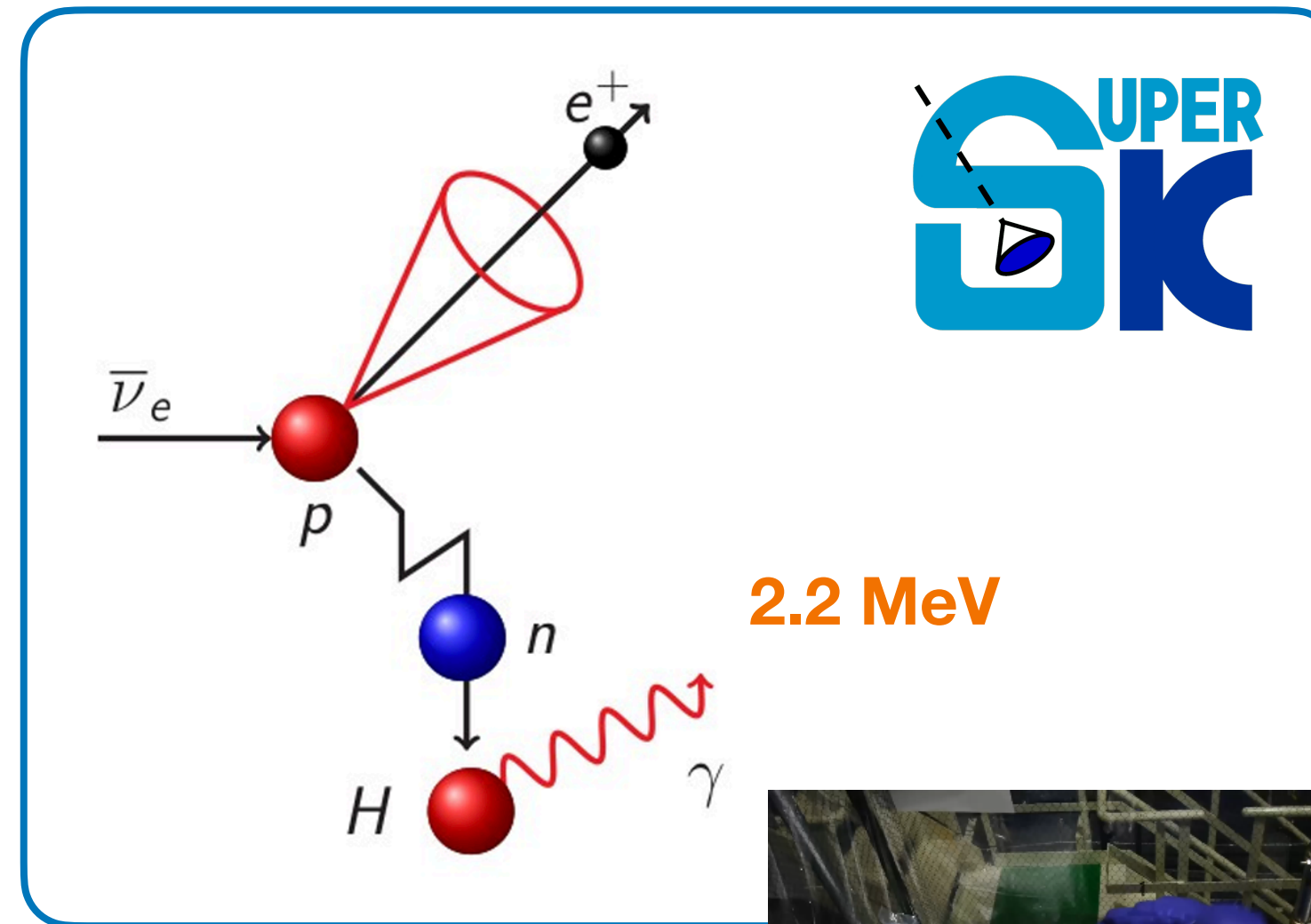
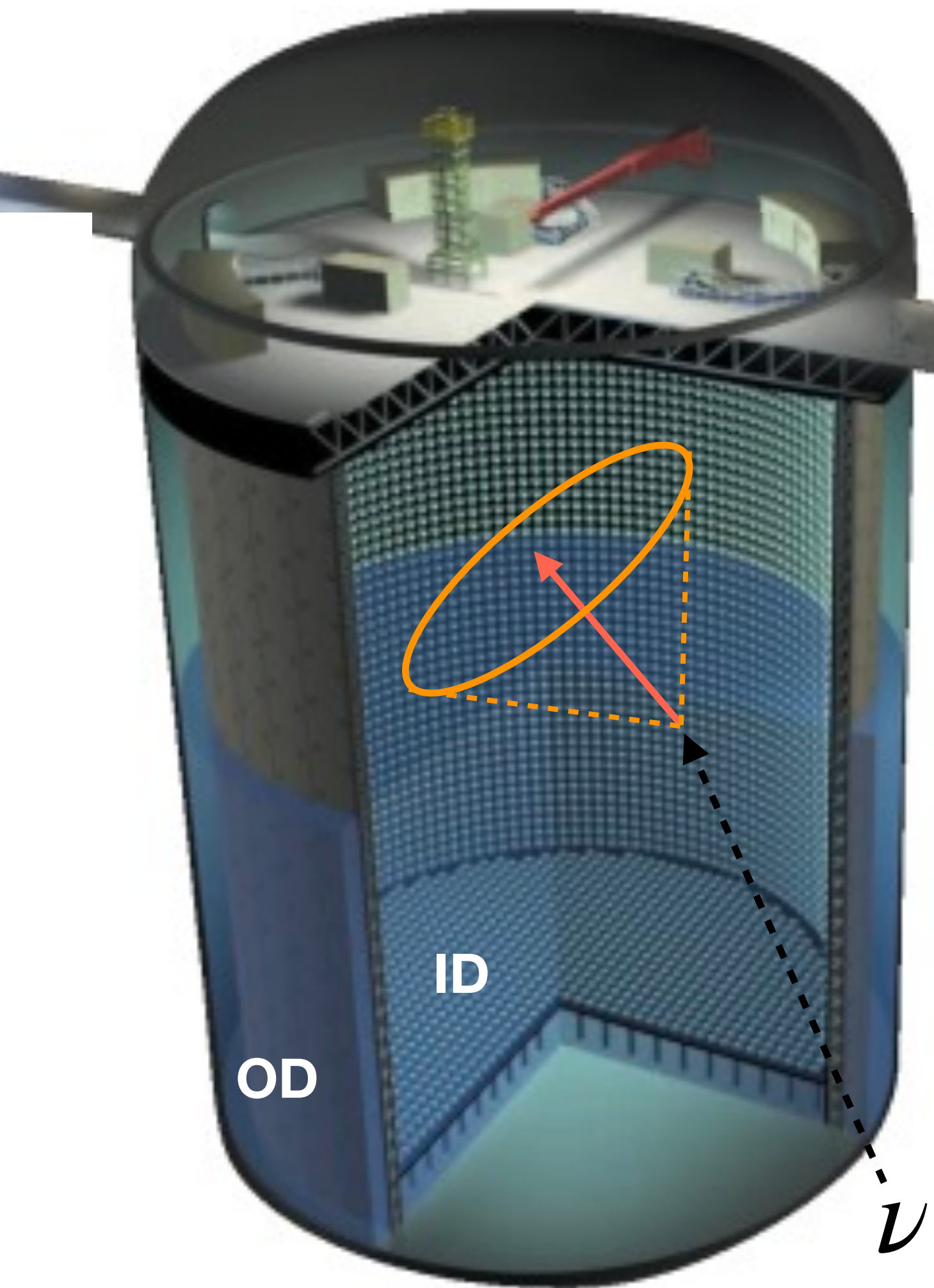
- SK-I to IV: published in [Physical Review D 104, 122002 \(2021\)](#)
- SK-VI & VII: published in [The Astrophysical Journal 1005, 101 \(2026\)](#)
- SK-IV to VIII: paper in prep **TODAY**

Super-Kamiokande with Gadolinium

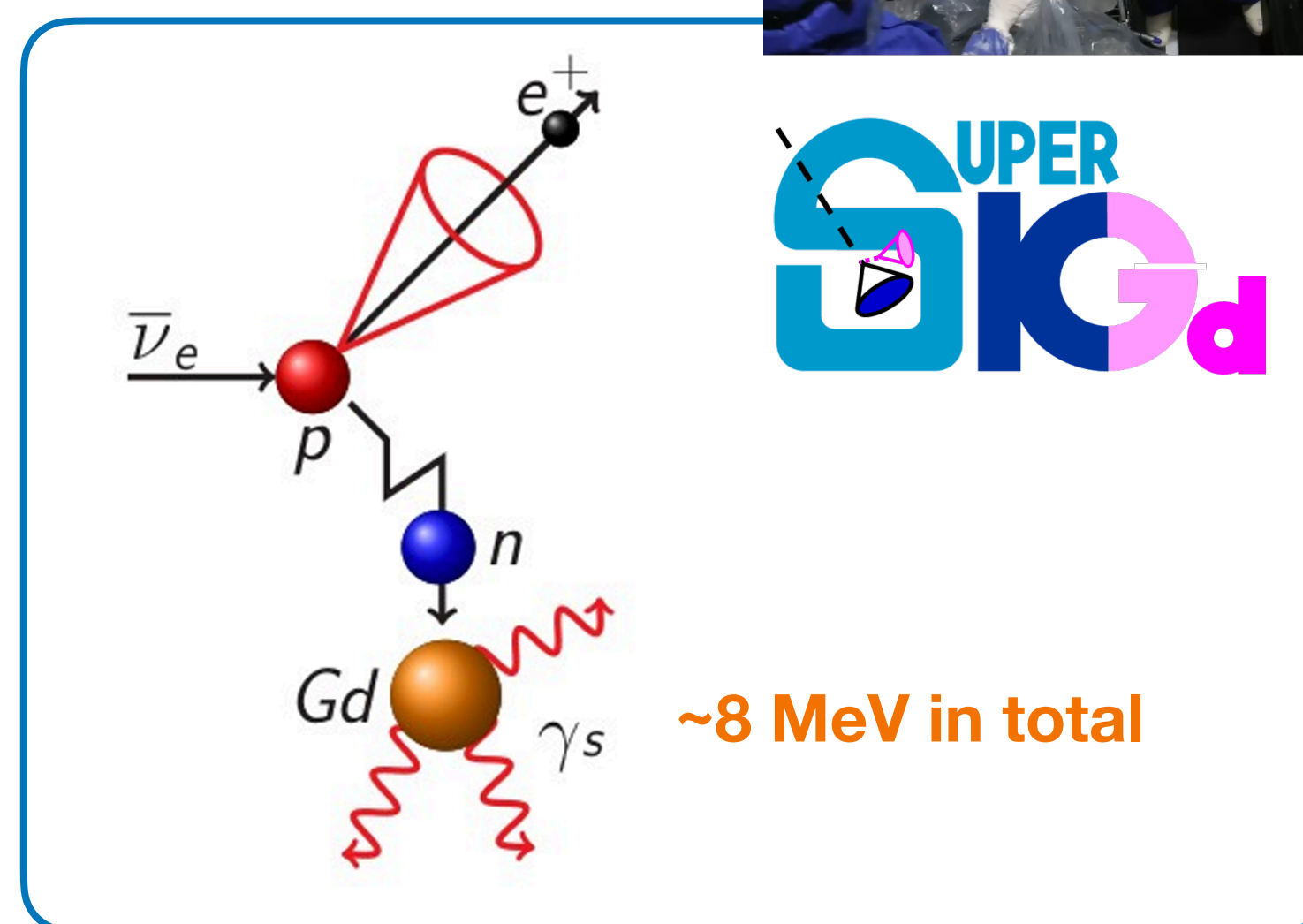
J. Beacom & M. Vagins, PRL 93, 171101 (2004) **23**

K. Abe et al. (SK Collaboration), NIMA 1027, 166248 (2022)

K. Abe et al. (SK Collaboration), NIMA 1065, 169480 (2024)

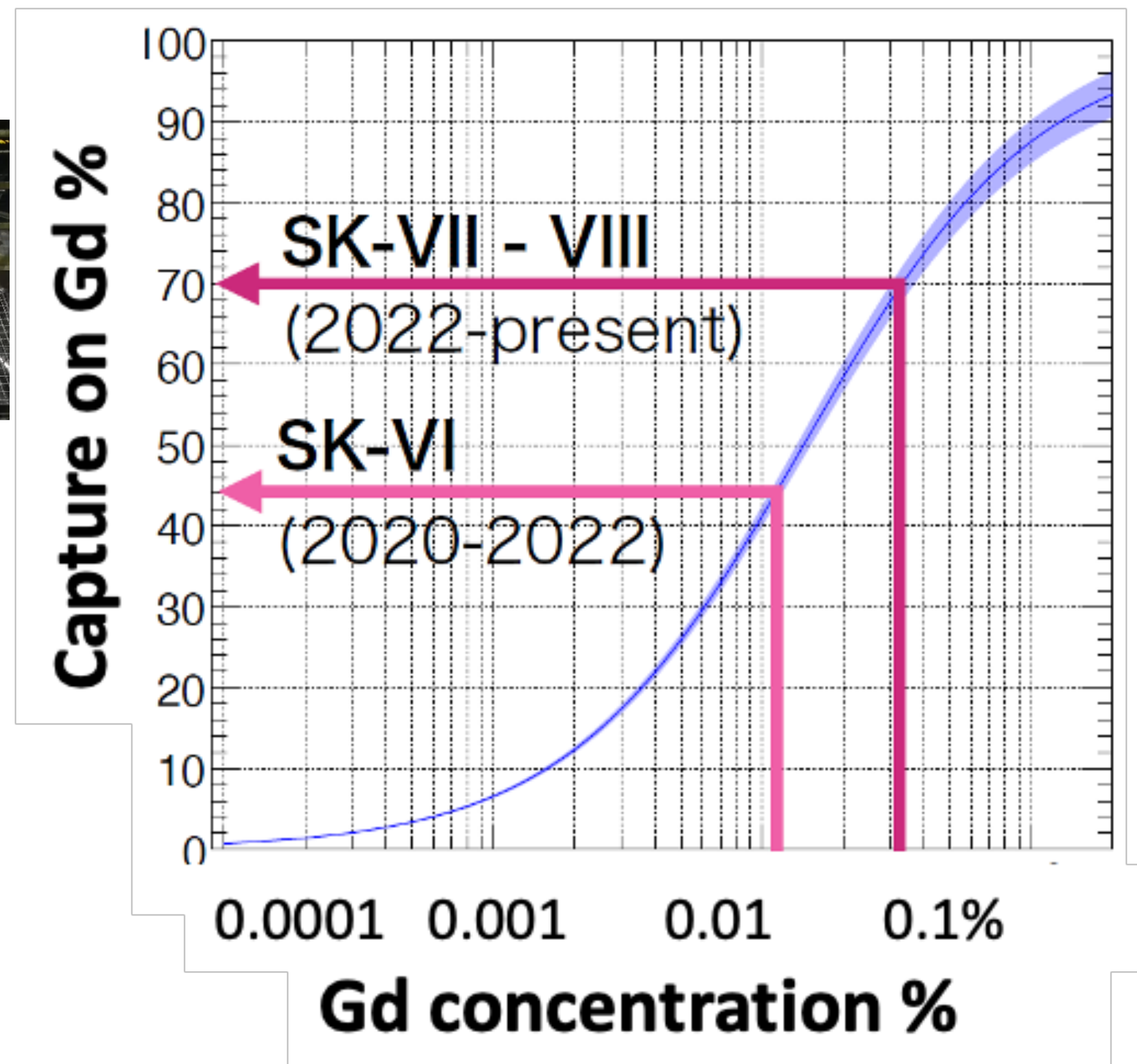


Upgrade



Gd loaded to improve neutron detection.

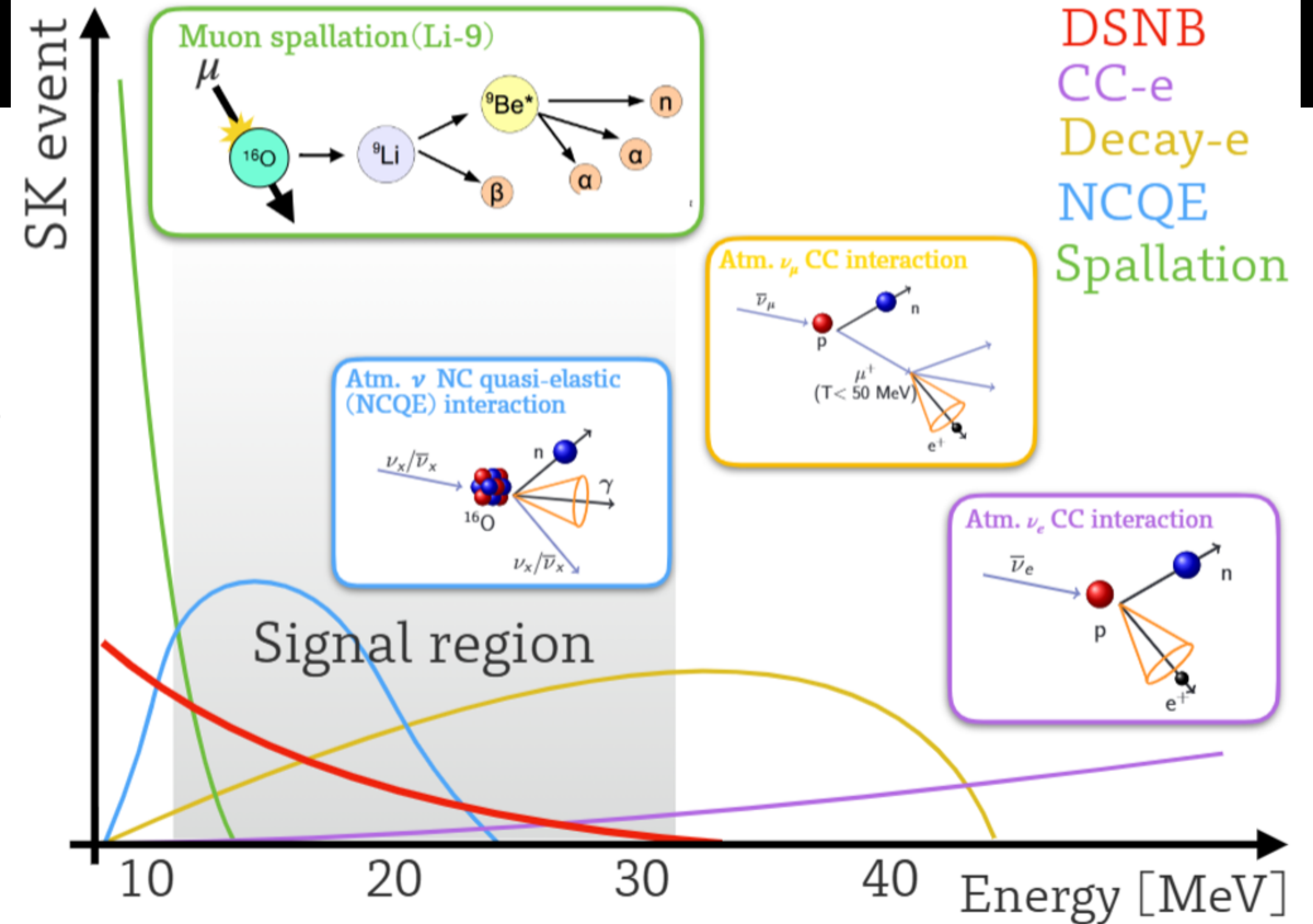
- Capture Xsec: 0.33 barn $\rightarrow$ **~ 49 kbarn**
- γ energy: 2.2 MeV $\rightarrow$ **~ 8 MeV**
- 0.011% (SK-VI), 0.033% (SK-VII~)



Analysis Overview

- **Additional dataset** (5003 days in total)
- **Refined event selections** (ML-based)
- **Lowered threshold** ($E_\nu = 17.3 \text{ MeV} \rightarrow 13.3 \text{ MeV}$)
- **Improvements on systematic uncertainties**
- **Joint fit for SK-IV through SK-VIII**

**New analysis with a 5003-day dataset =
~3350-day pure water + ~1650-day Gd water**

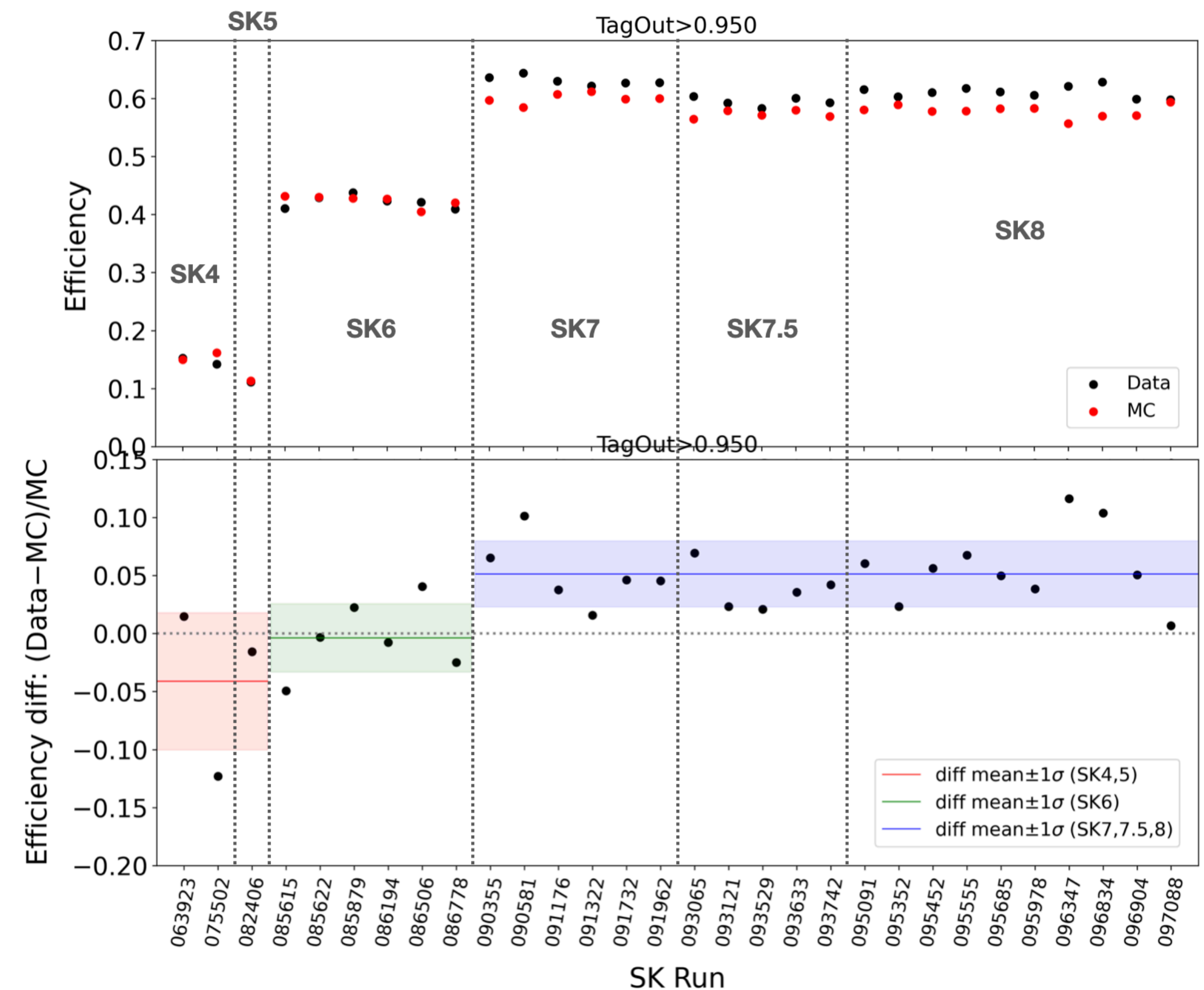
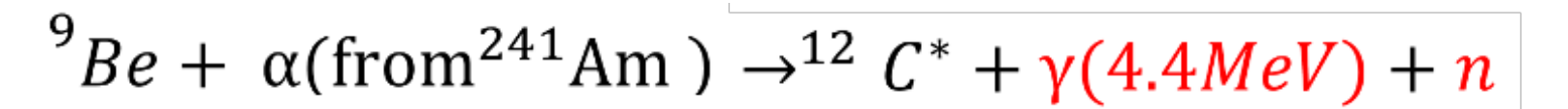
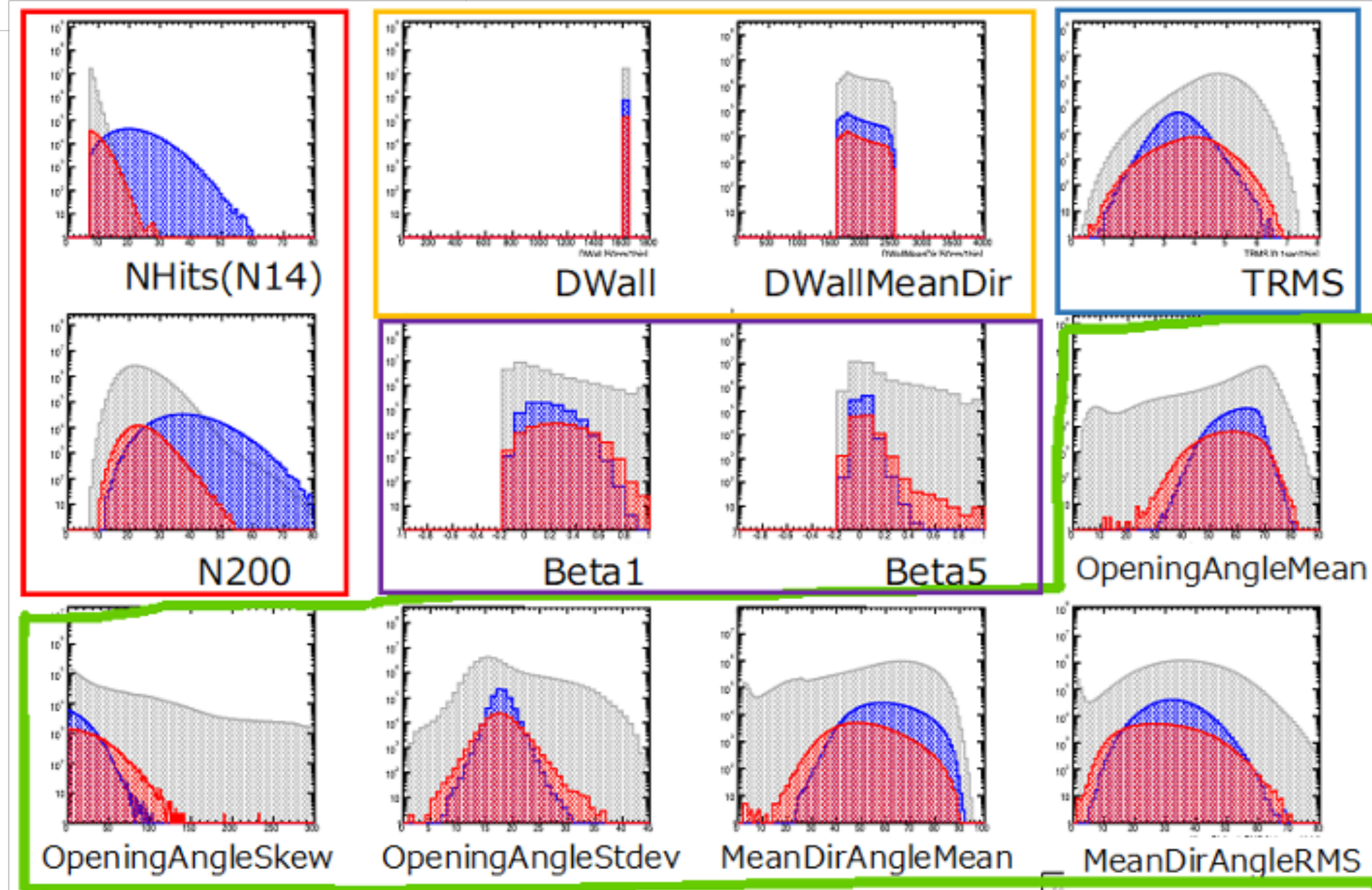


Phase	Period	Livetime [days]	Water Status
SK-IV	Oct. 2008 - Feb. 2018	2970.1	Pure-water
SK-V	Feb. 2019 - Jul. 2020	379.2	Pure-water
SK-VI	Aug. 2020 - Jun. 2022	552.2	Gd-water (0.01w%)
SK-VII	Jul. 2022 - Oct. 2023	404.0	Gd-water (0.03w%)
SK-VII.5	Dec. 2023 - Jul. 2024	191.8	Gd-water (0.03w%)
SK-VIII	Sep. 2024 - Mar. 2026	505.7	Gd-water (0.03w%)

Neutron Tagging

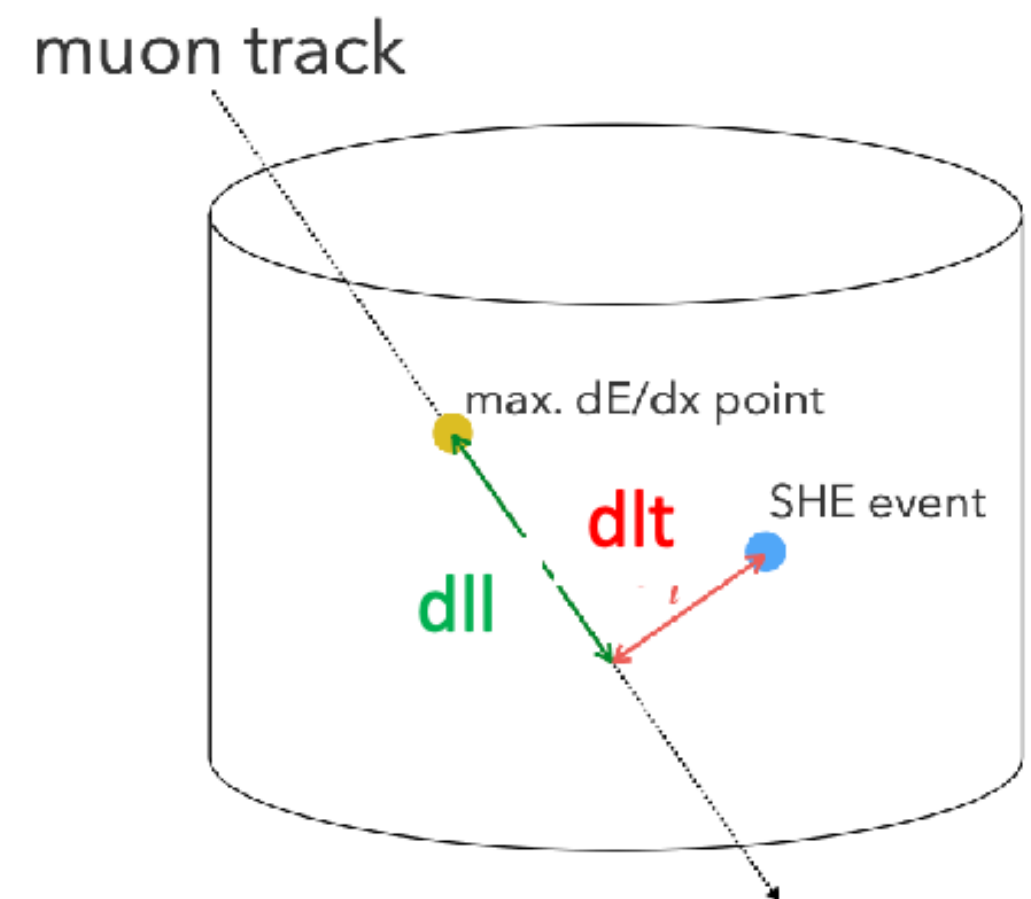
- **Neural Network** (TMVA-MLP) structured based on 12 variables with **spacial and temporal hit patterns**.
- **Am/Be** neutron source is used to validate the employed method.
 - **SK-IV, V:** (sig eff) ~10%, (syst) $\pm 10\%$
 - **SK-VI:** (sig eff) ~40%, (syst) $\pm 3\%$
 - **SK-VII, VII.5, VIII:** (sig eff) ~60%, (syst) $\pm 5\%$

PMT hits
Mean direction/Distance from SK ID
Timing info
Harmonic Beta parameters
Hit patterns

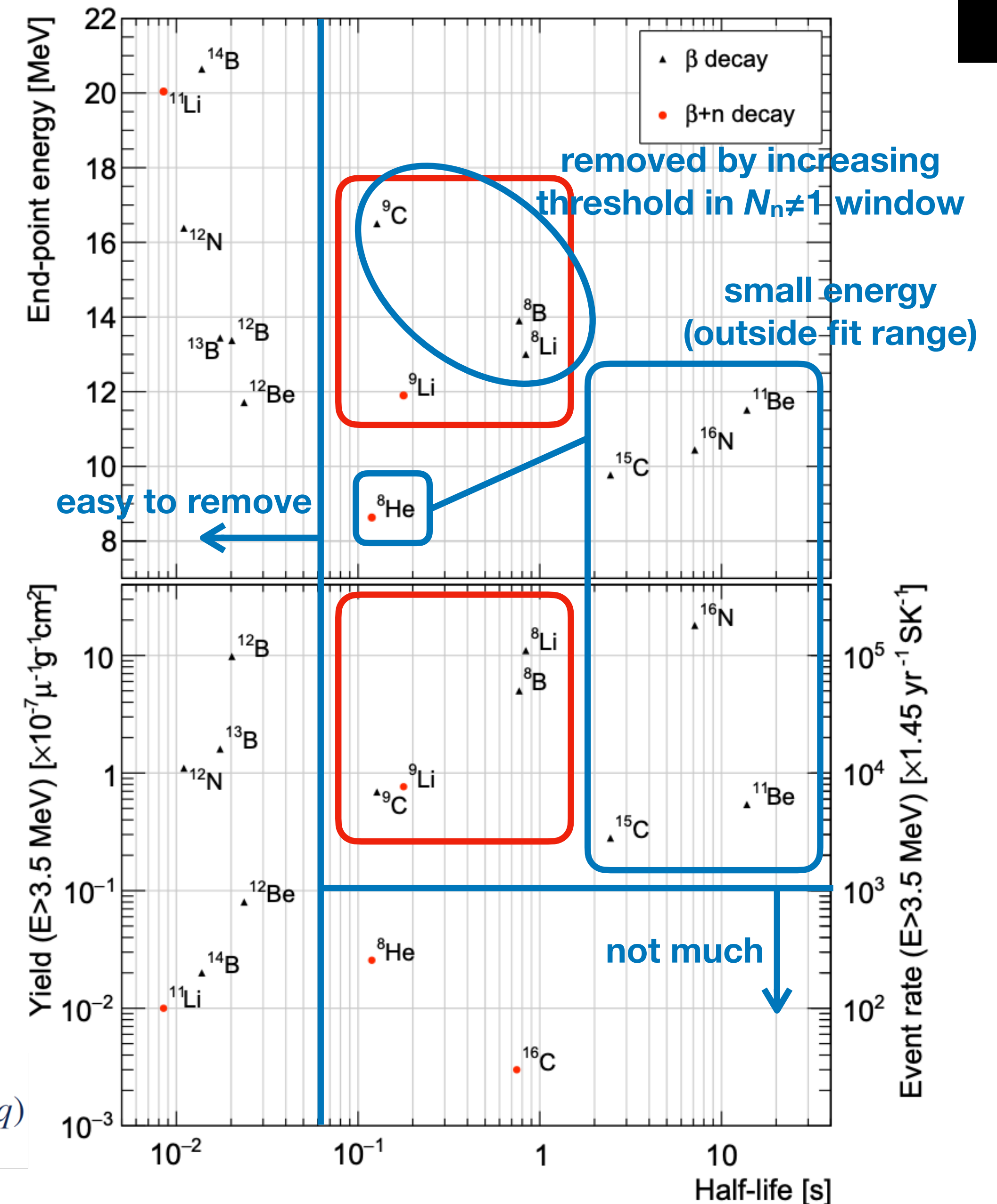


Spallation Reduction

- Optimized selection in a **data-driven** way, by calculating spallation likelihood for muons collected *before/after* each candidate event.
- In the golden window ($N_n=1$), consider ${}^9\text{Li}$ and accidental coincidence events.
 - ${}^9\text{Li}$: estimated by toy samples with replaced dt
 - acc**: estimated by mistag rate
- Higher energy threshold was set in $N_n \neq 1$ so that we don't need to worry about spallation.



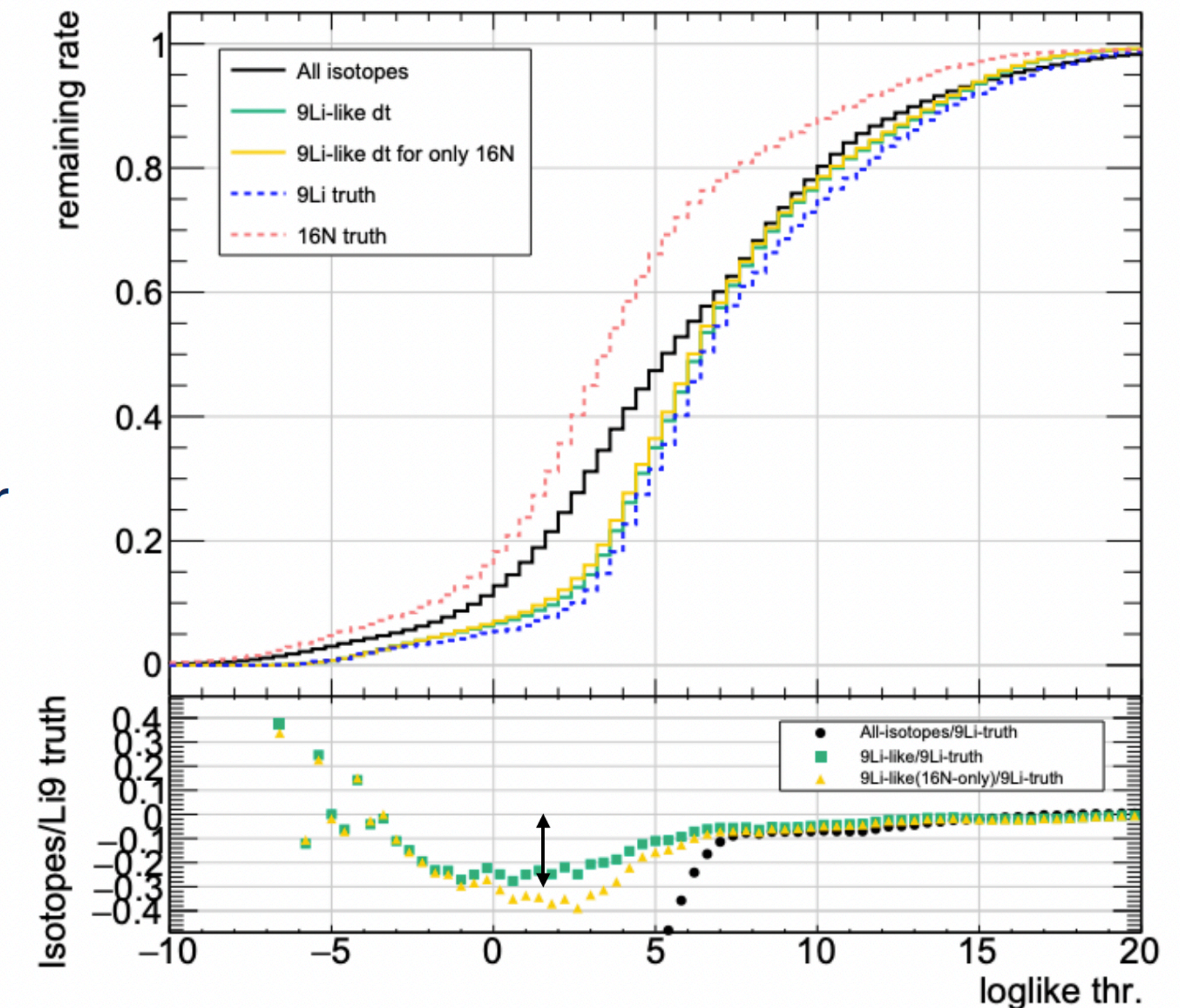
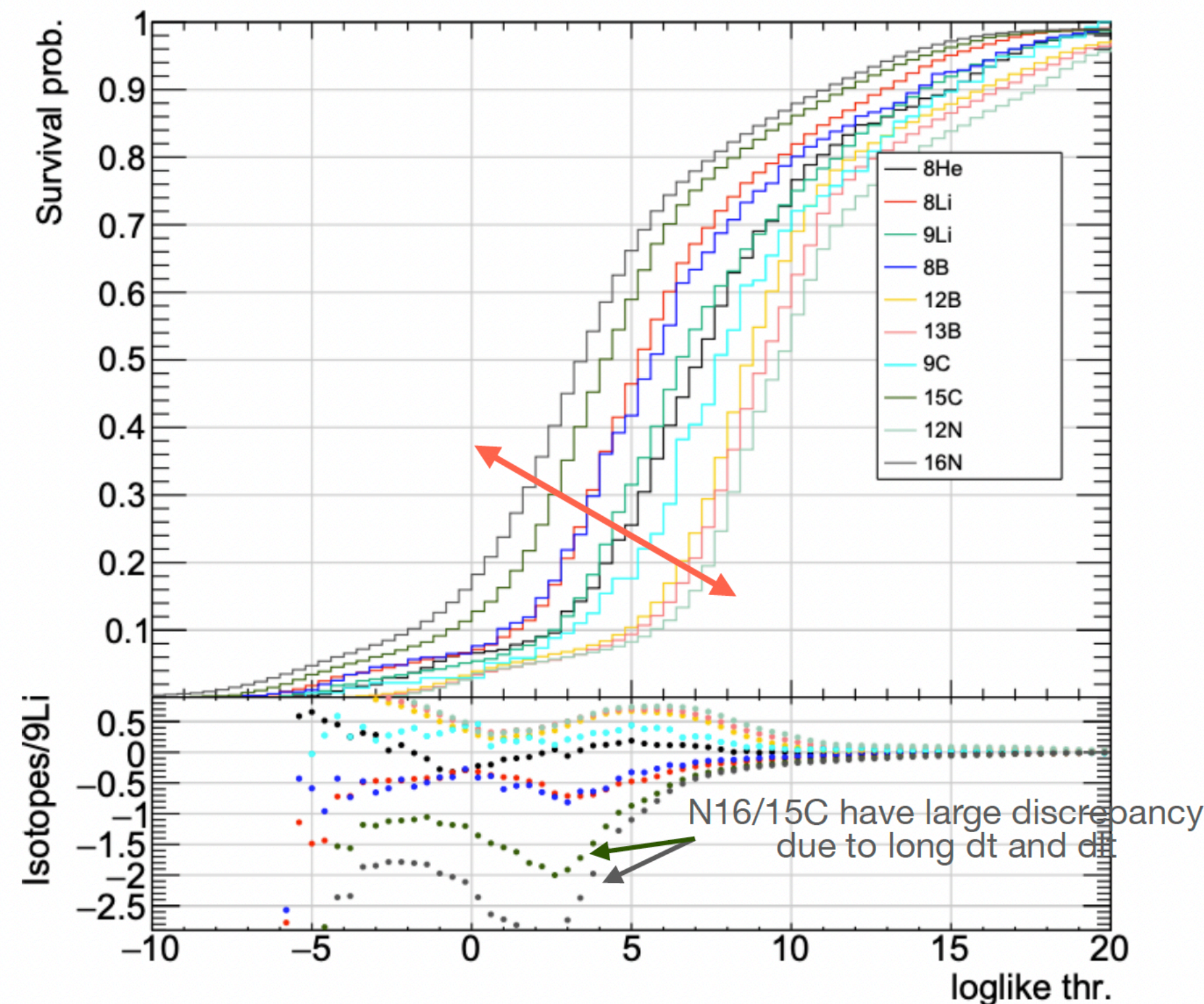
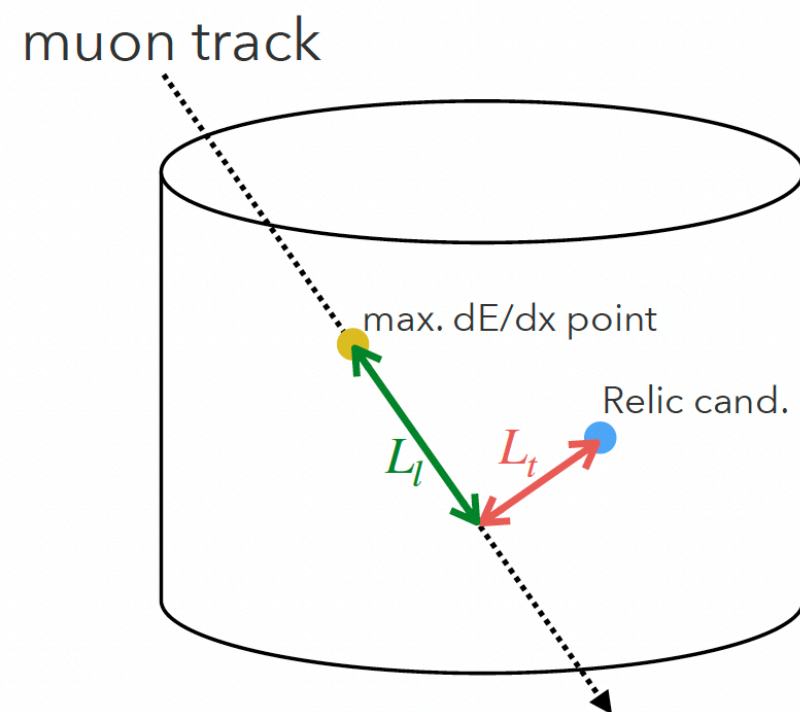
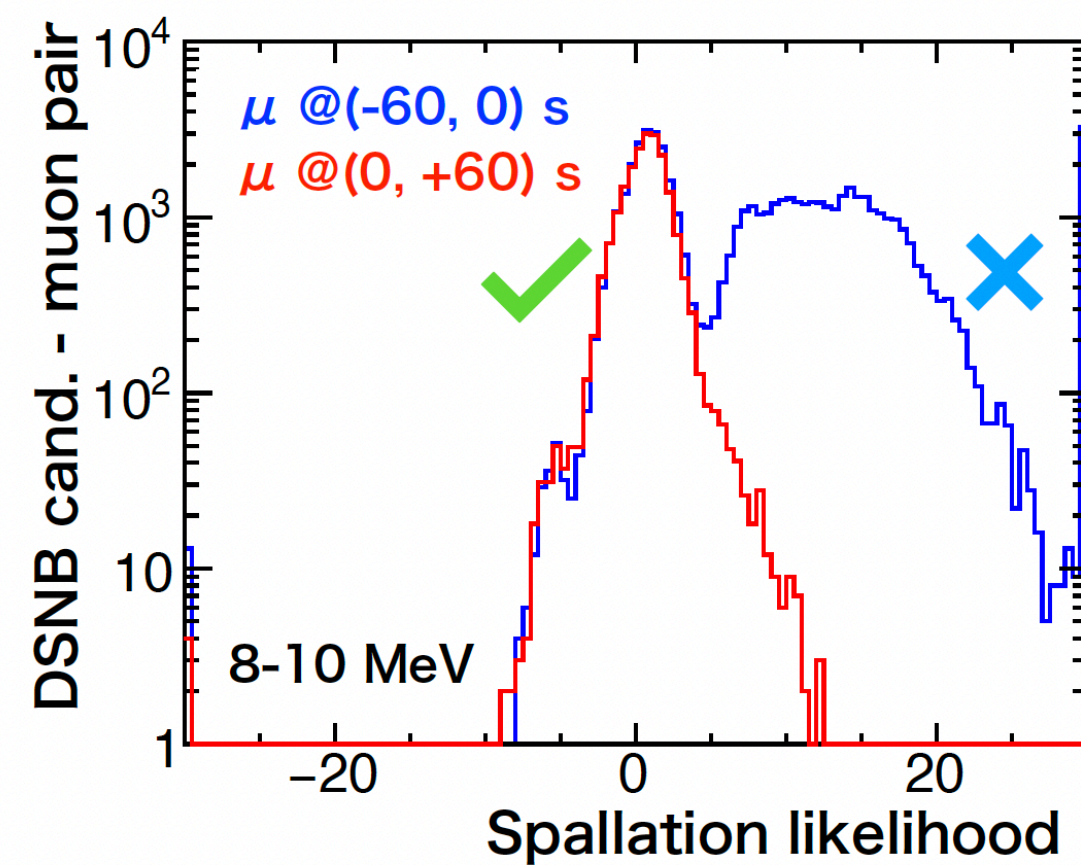
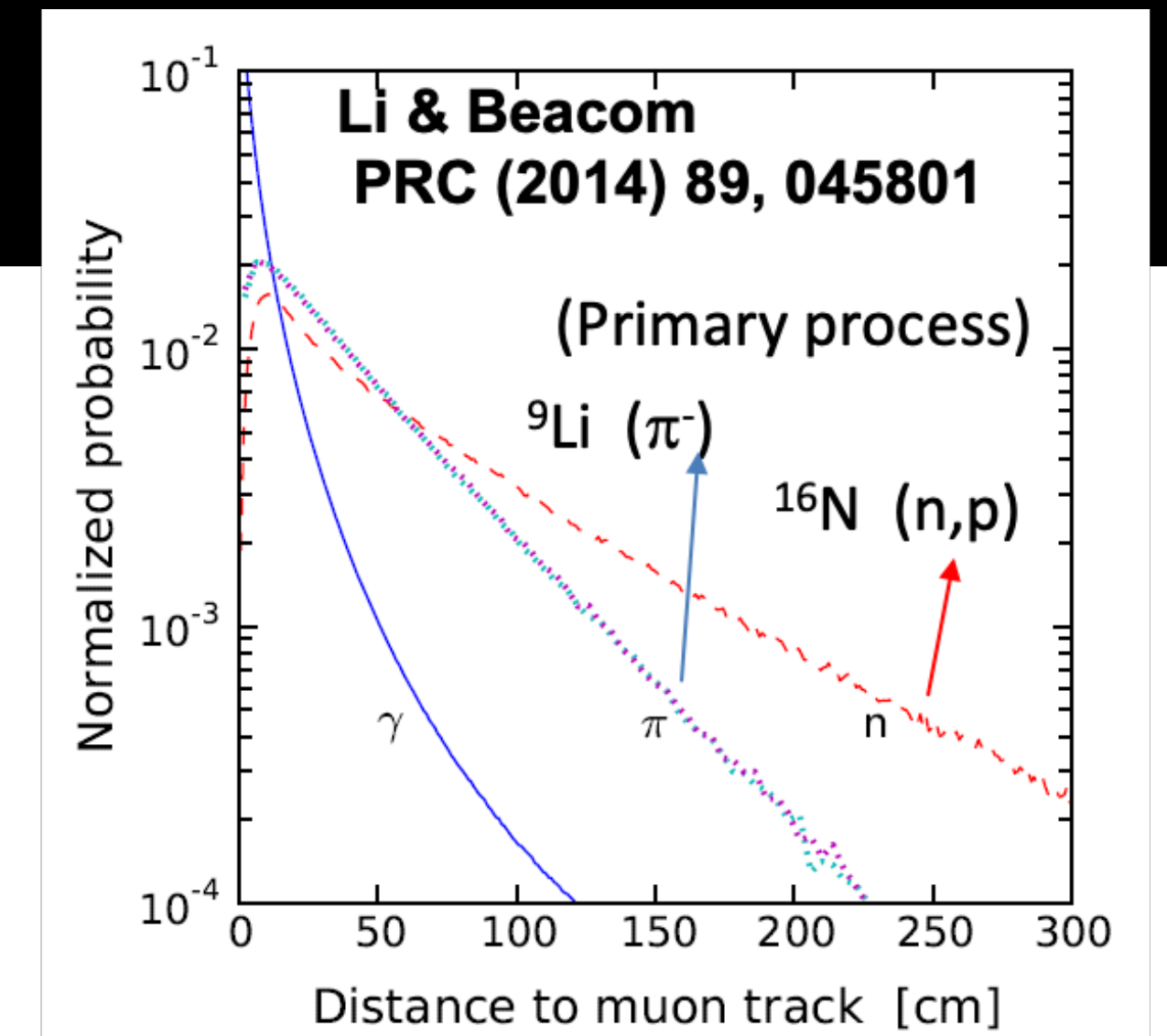
$$\mathcal{L} = \log \prod_{i \in \text{vars}} \frac{\text{PDF}_i^{\text{spall}}(x)}{\text{PDF}_i^{\text{random}}(x)} \quad (\text{vars} = dt, dlt, dll, qtot, resq)$$



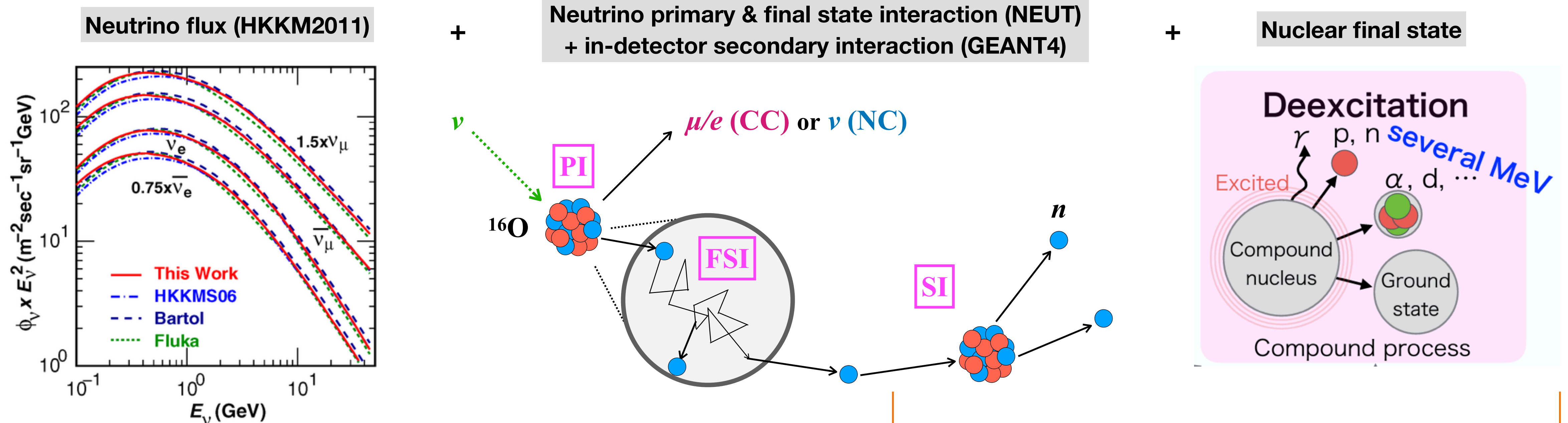
Systematic Uncertainty on ^9Li Efficiency

27

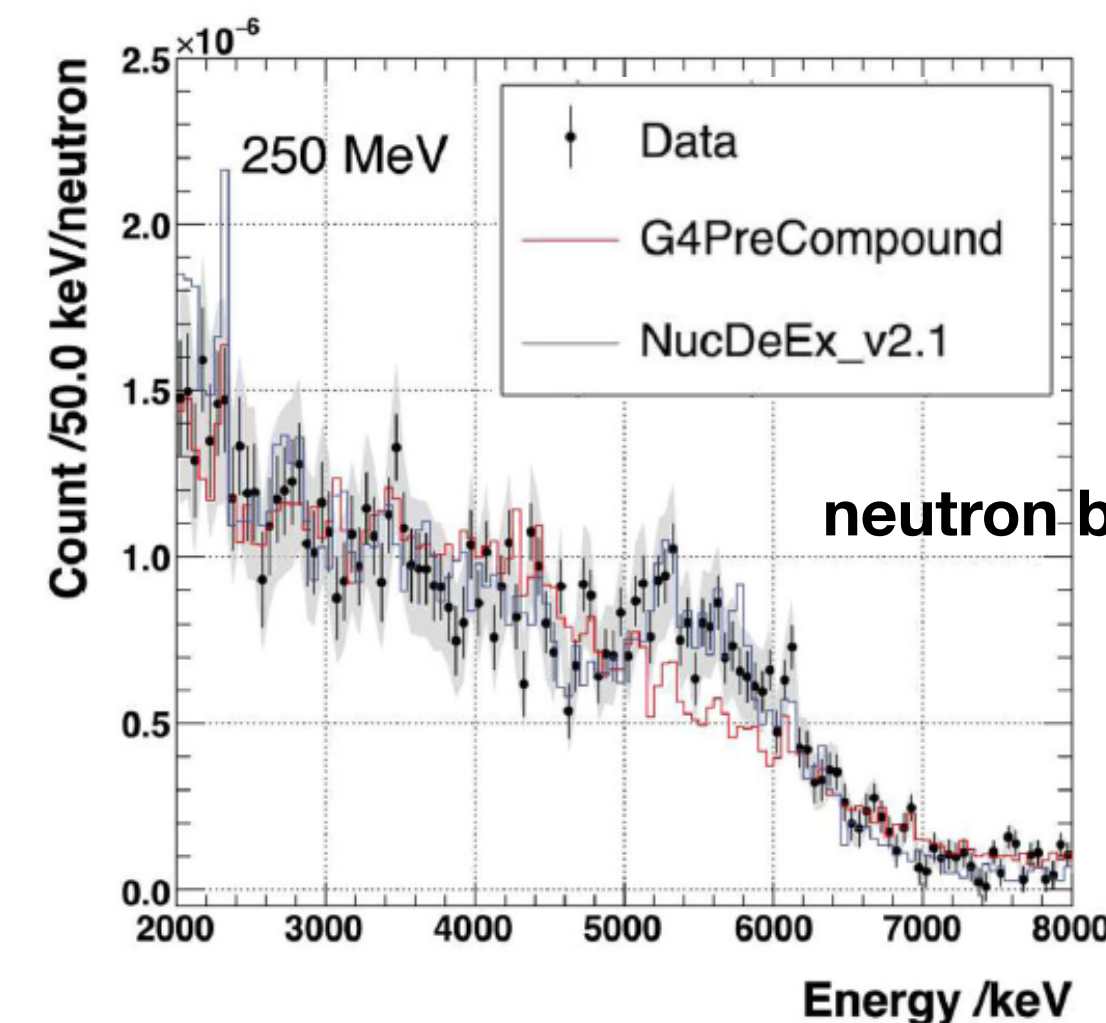
- The current method (dt replacement) may involve bias on other variables.
- Produced simulation samples for each isotope and applied the same analysis to check this effect.
- From this, assign a 30% uncertainty on the ^9Li spectral shape.



Atmospheric Neutrino Background



- **Flux:** Honda flux (HKKM2011)
- **Interaction** (xsec, final state kinematics)
 - Model choice based on various external information.
 - CC: NEUT xsec + GEANT4 simulation
 - NC: T2K measurement for xsec + final state gamma
 - Neutron multiplicity: Super-K measurement



Choose a better model based on external beam tests etc.

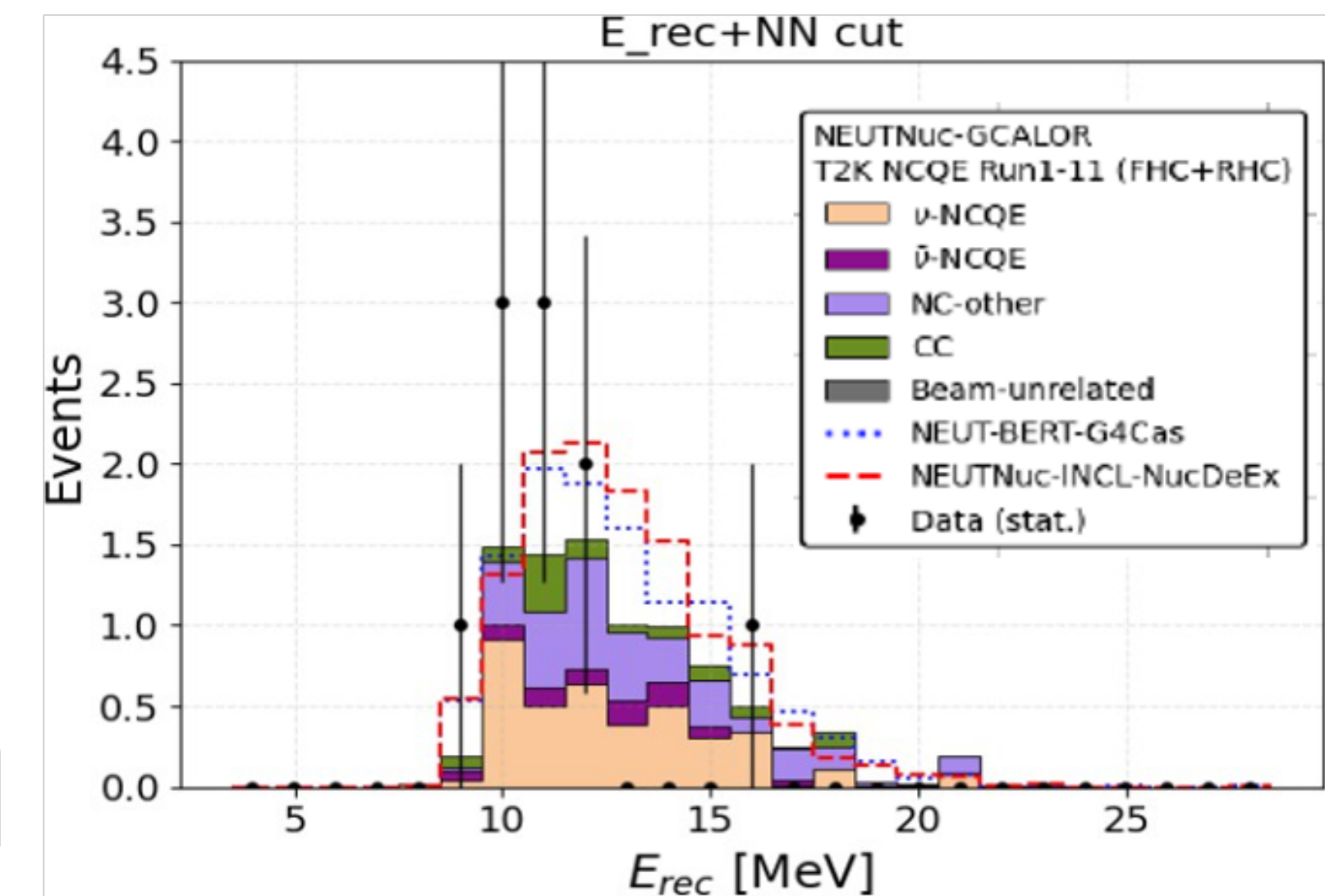
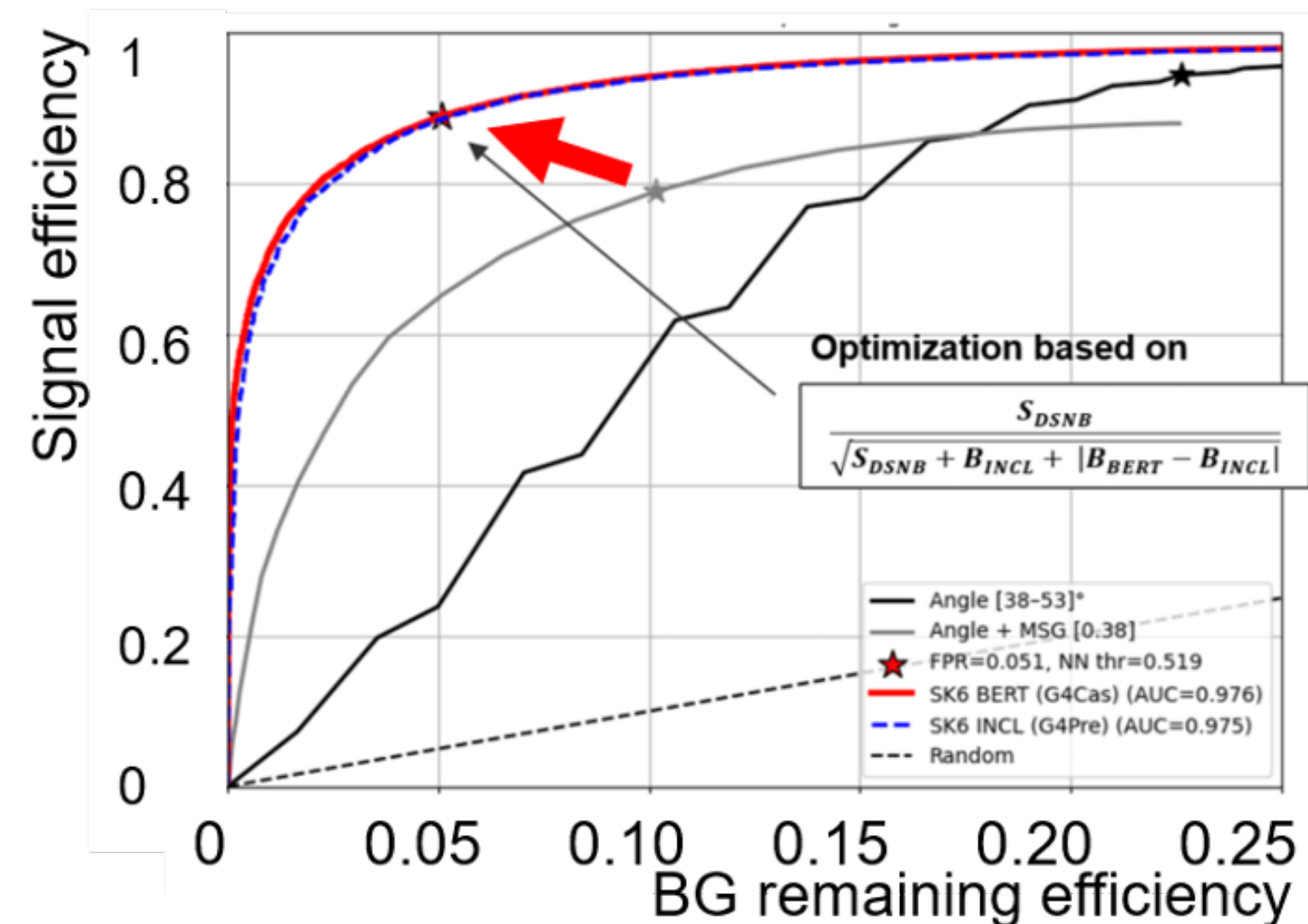
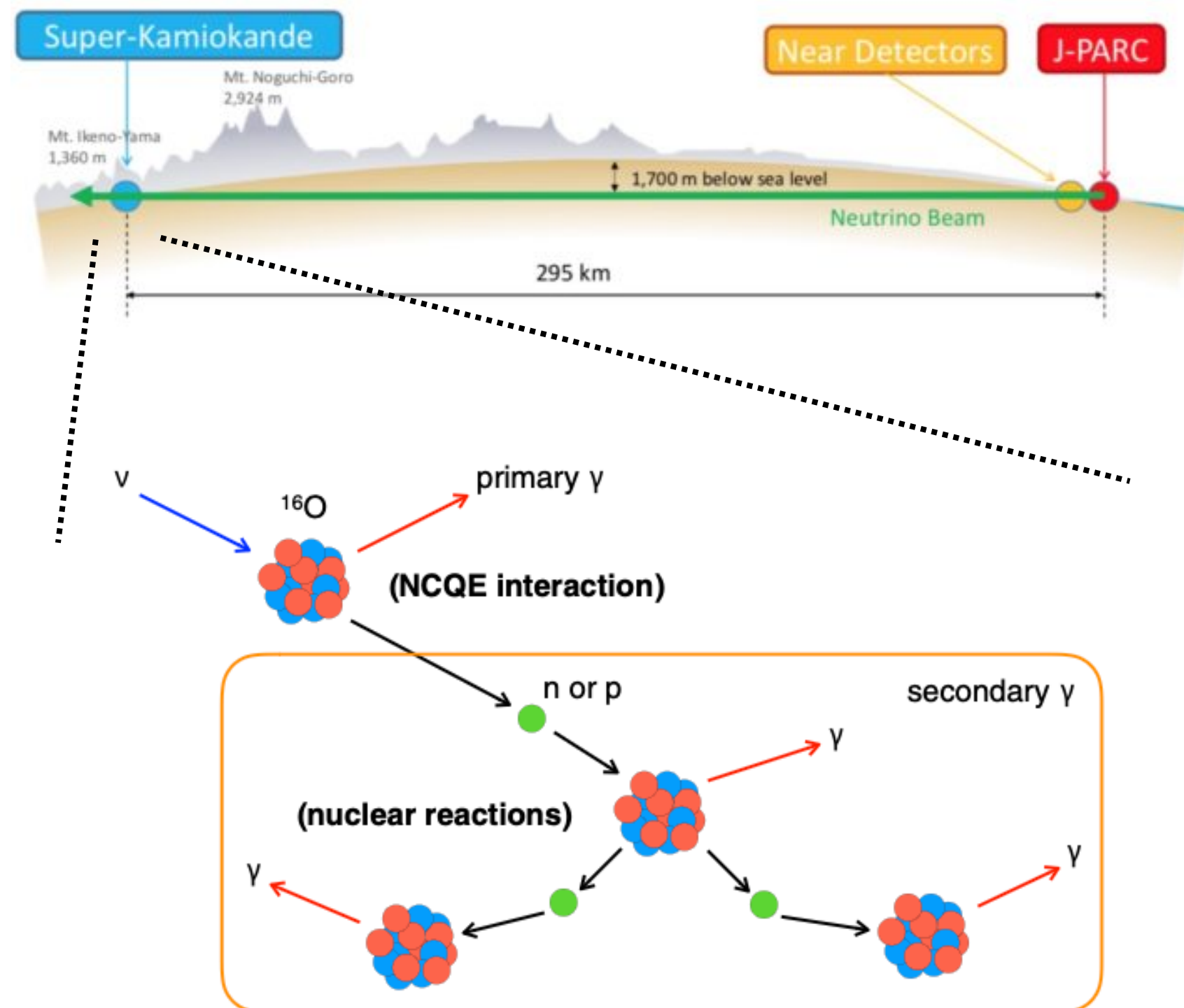
[Y. Ashida et al., PRC 109, 014620 \(2024\)](#)

[T. Tano et al., PTEP 113D01 \(2024\)](#)

[Y. Hino et al., EPJC 86, 148 \(2026\)](#)

NCgamma Validated by T2K Beams

- Developed an NN-based e-gamma discriminator (**10% signal gain + half background**).
- Measured using T2K neutrino beams to measure NCgamma events after DSNB event selections.
- Comparison between Data and MC (our model choice) give a NN validation as well as a direct systematics estimation (smaller systematics than previous: **71% → 45%**).

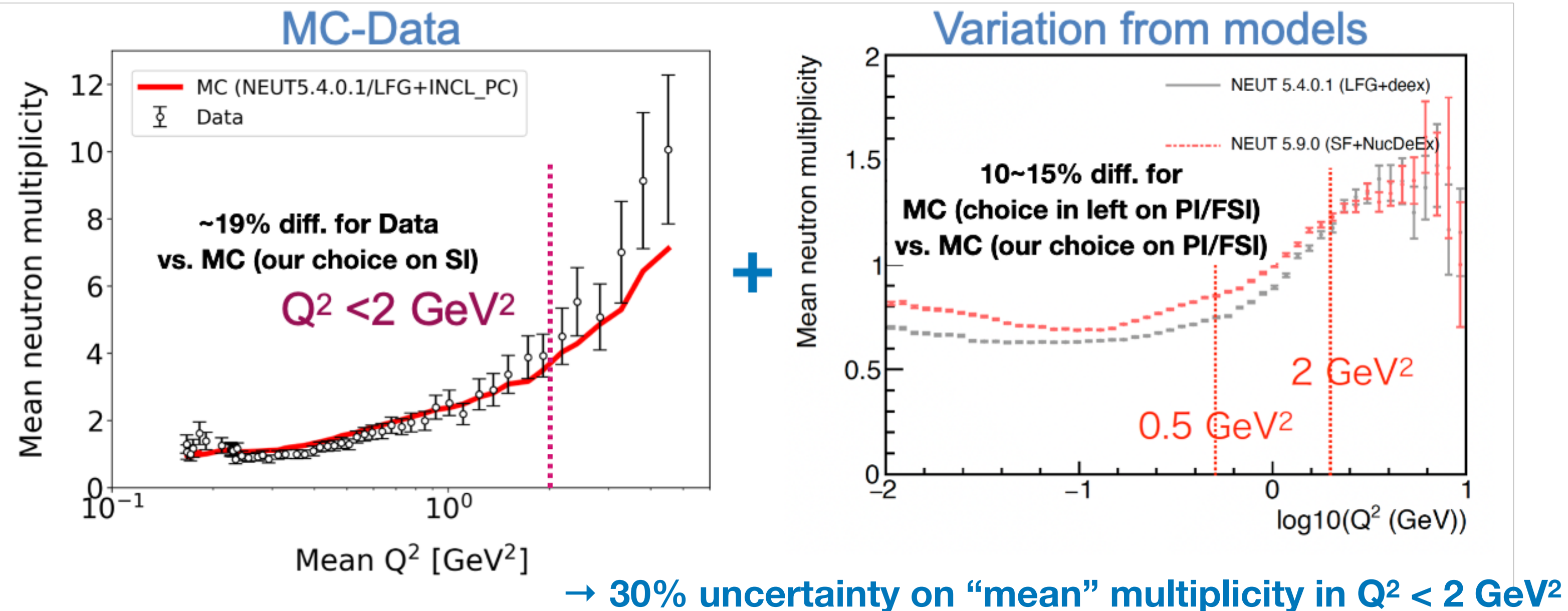
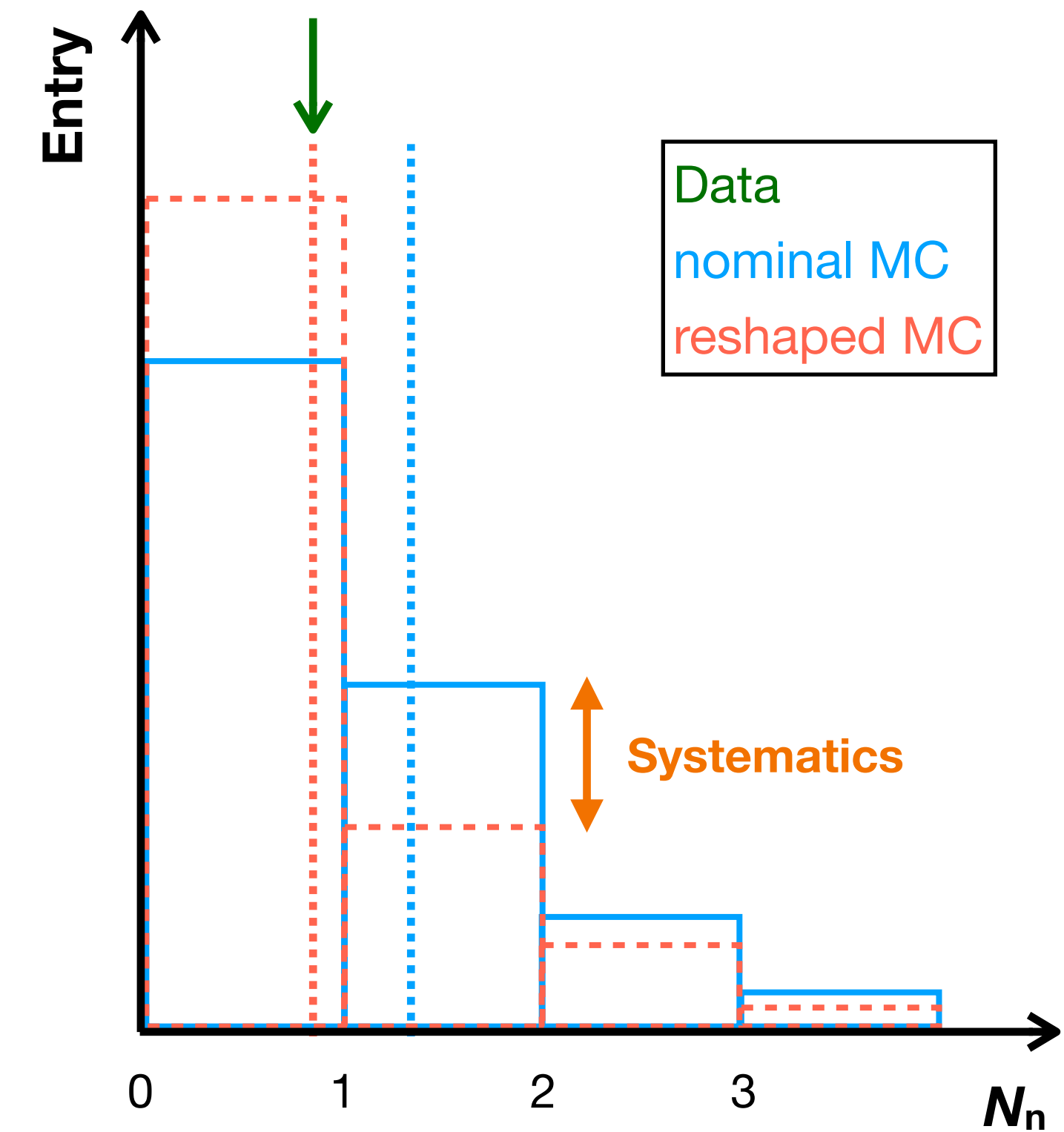


Neutron Multiplicity

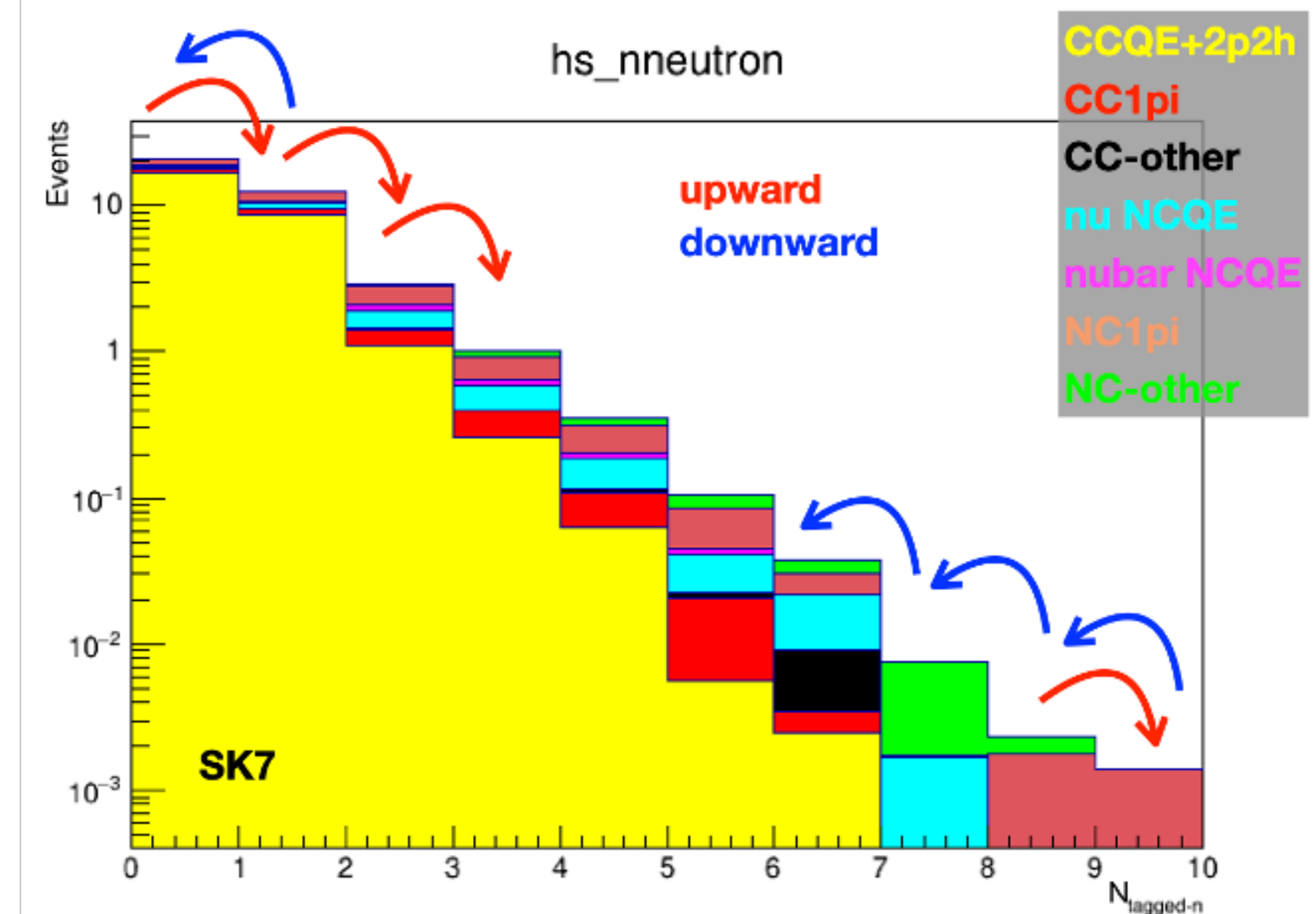
S. Han et al., Phys. Rev. D 112, 012004 (2025)

- Super-K's independent analysis on neutron multiplicity is referred.
- Q^2 is more directly related to outgoing nucleons critical for SI.
- Use a **single-ring** sample to keep QE framework.
- Systematic uncertainties have been improved from $\pm 40\%$.
 - SK-IV, V: $-30/+27\%$
 - SK-VI: $-31/+18\%$
 - SK-VII, VII.5, VIII: $-32/+12\%$

Improved by ntag efficiency!



→ 30% uncertainty on “mean” multiplicity in $Q^2 < 2 \text{ GeV}^2$



Spectral Fitting

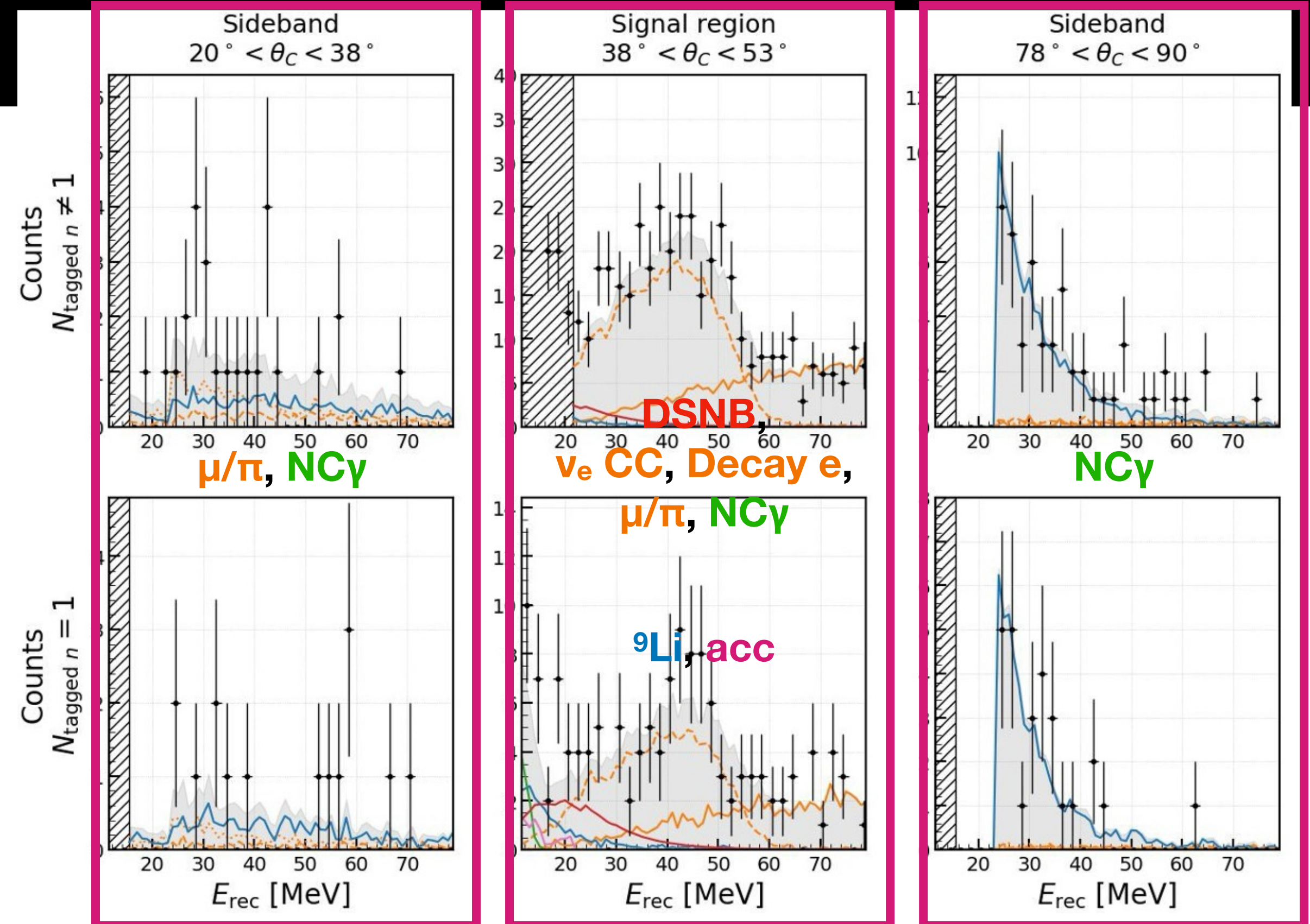
31

- 1 signal + 6 background components considered.
- 6 panels prepared based on θ_C and N_n .

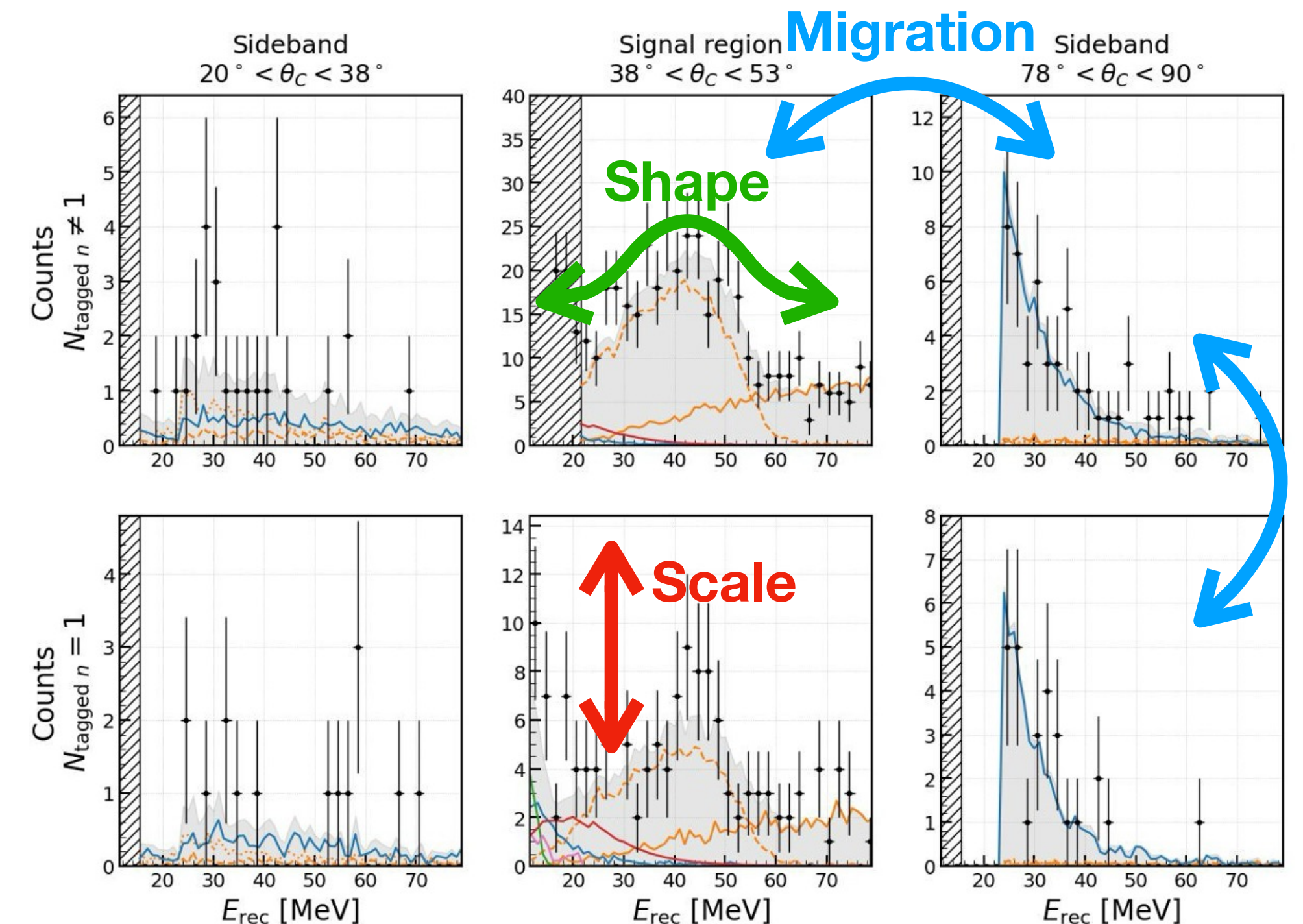
$$\mathcal{L}(\text{Data} | N_s, \vec{N}_b, \eta_s, \vec{\eta}_b) = \mathcal{L}(\vec{0} | \eta_s, \vec{\eta}_b) \leftarrow \text{pull term for nuisance parameters} \right. \\ \times e^{-(\varepsilon_s(\eta_s)N_s + \sum_{j \in \vec{b}} N_j)} \\ \times \prod_{i=1}^{N_{\text{data}}} \left[\varepsilon_s(\eta_s)N_s \cdot \text{PDF}_s(E^i, \theta_C^i, N_n^i) \right. \\ \left. + \sum_{j \in \vec{b}} N_j \cdot \text{PDF}_j(E^i, \theta_C^i, N_n^i | \vec{\eta}_b) \right] \left. \begin{array}{l} \text{Signal-related PDF} \\ + \\ \text{BG-related PDFs} \\ \text{Shape depending on} \\ \text{nuisance parameters.} \end{array} \right.$$

An unbinned maximum likelihood fit

- **Signal:** Horiuchi+09, 6 MeV Max (“**DSNB**”)
- **Background**
 - atmospheric ν_e CC (“ **ν_e CC**”)
 - invisible muon/pion from atmospheric ν_μ CC, NC1 π etc (“**Decay e**”)
 - visible muon/pion from atmospheric ν CC, NC1 π etc (“ **μ/π** ”)
 - nuclear deexcitation gamma rays from atmospheric ν NCQE, NC1 π etc (“**NC γ** ”)
 - atmospheric muon spallation induced isotope with neutron (“**spall ^9Li** ”)
 - accidental coincidental events (“**acc**”)



- **Scale** [pull term]: one value for each sig/bkg component; commonly applied for all panels.
- **Shape** [e.g., Gaussian smearing]: distortion along E_{rec} in one panel.
 - Physics model origin: flux/xsec energy dependent error, final state gamma multiplicity, etc
 - Detector response origin: energy reconstruction uncertainty (scale, resolution) → found to be *negligible* impact then NOT included in fit.
- **Migration** $[1-\varepsilon, 1+\varepsilon]$: transition between panels.
 - mid angle $\leftrightarrow$ high angle: NCgamma multiplicity (NOT considered in this analysis)
 - $n=1 \leftrightarrow n \neq 1$: tagging efficiency, neutron multiplicity



Shared parameters (correlated over phases)

- Signal and background scales
- Atmospheric neutron multiplicity
- ^9Li spectrum shape

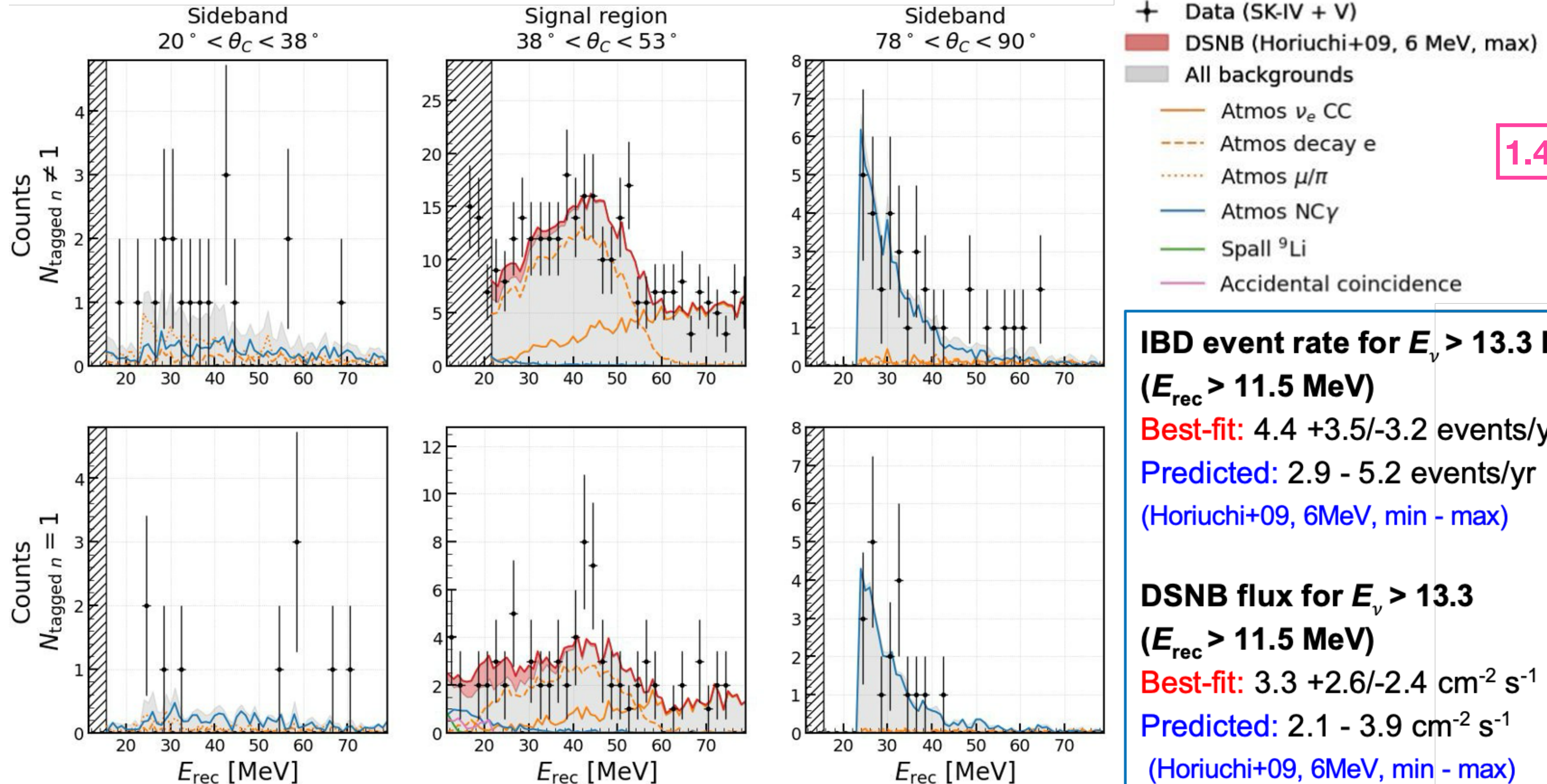
Per-phase parameters (independent)

- Accidental coincidence scale
- Signal efficiency
- Ntag efficiency

$$9 + (3 \times 6 \text{ phases}) = 27 \text{ parameters}$$

	Parameters	Sharing
Signal	DSNB signal rate	Shared
Backgrounds	atmospheric ve CC scale on MC	Shared
	atmospheric decay-e scale on MC	Shared
	atmospheric NCy scale on MC	Shared
	atmospheric μ/π scale on MC	Shared
	^9Li spallation scale on MC	Shared
	accidental coincidence rate	Per-phase
Nuisances	atmospheric bkg ntag migration (CC)	Shared
	atmospheric bkg ntag migration (NCy)	Shared
	ntag efficiency uncertainty	Per-phase
	signal efficiency uncertainty	Per-phase
	^9Li spectral shape	Shared

Fit Result for SK-IV~V (Pure Water Period)



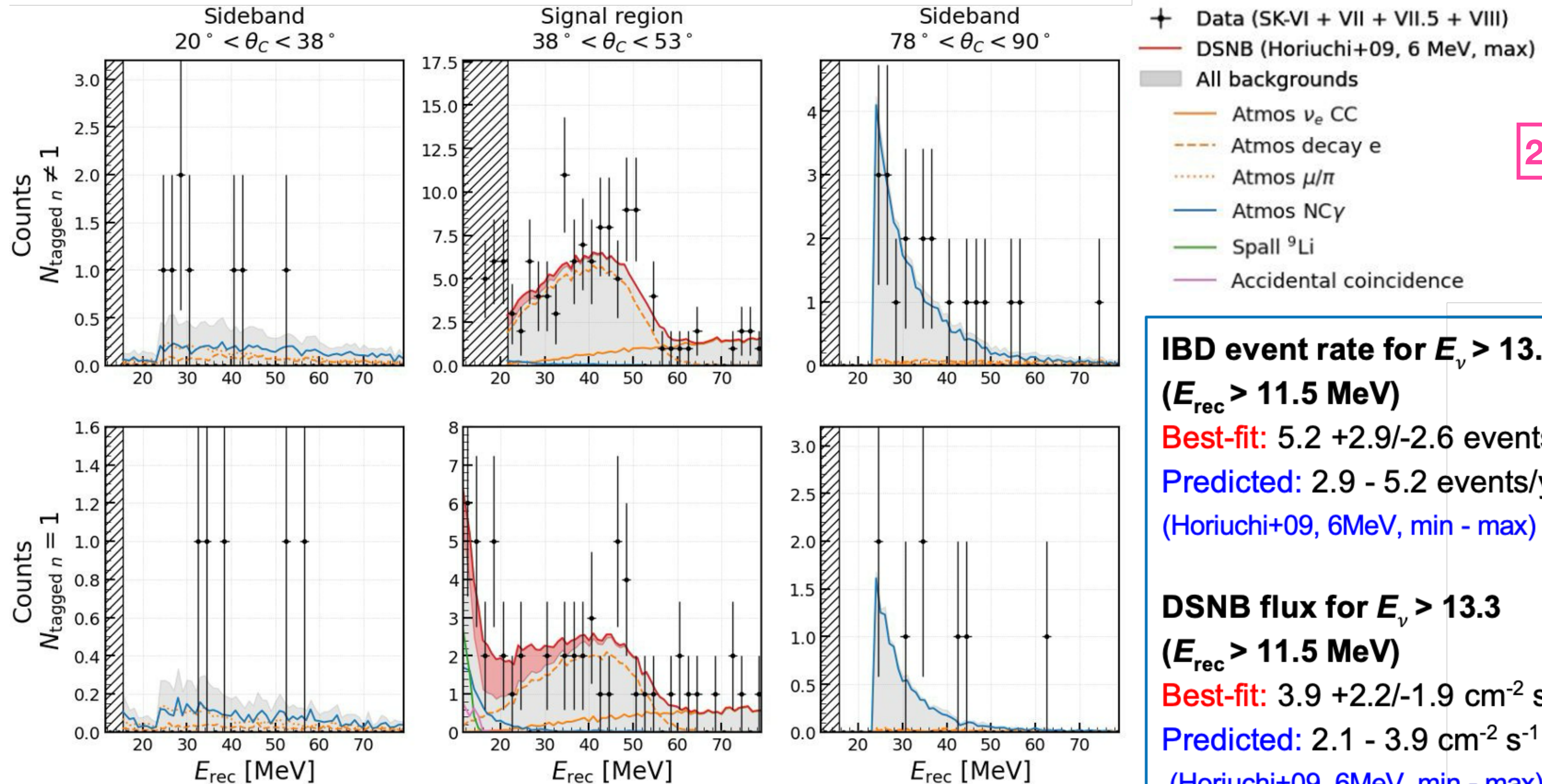
**IBD event rate for $E_\nu > 13.3$ MeV
($E_{\text{rec}} > 11.5$ MeV)**

Best-fit: $4.4^{+3.5}_{-3.2}$ events/yr
Predicted: 2.9 - 5.2 events/yr
 (Horiuchi+09, 6MeV, min - max)

**DSNB flux for $E_\nu > 13.3$
($E_{\text{rec}} > 11.5$ MeV)**

Best-fit: $3.3^{+2.6}_{-2.4}$ $\text{cm}^{-2} \text{s}^{-1}$
Predicted: 2.1 - 3.9 $\text{cm}^{-2} \text{s}^{-1}$
 (Horiuchi+09, 6MeV, min - max)

Fit Result for SK-VI~VIII (Gd Water Period)



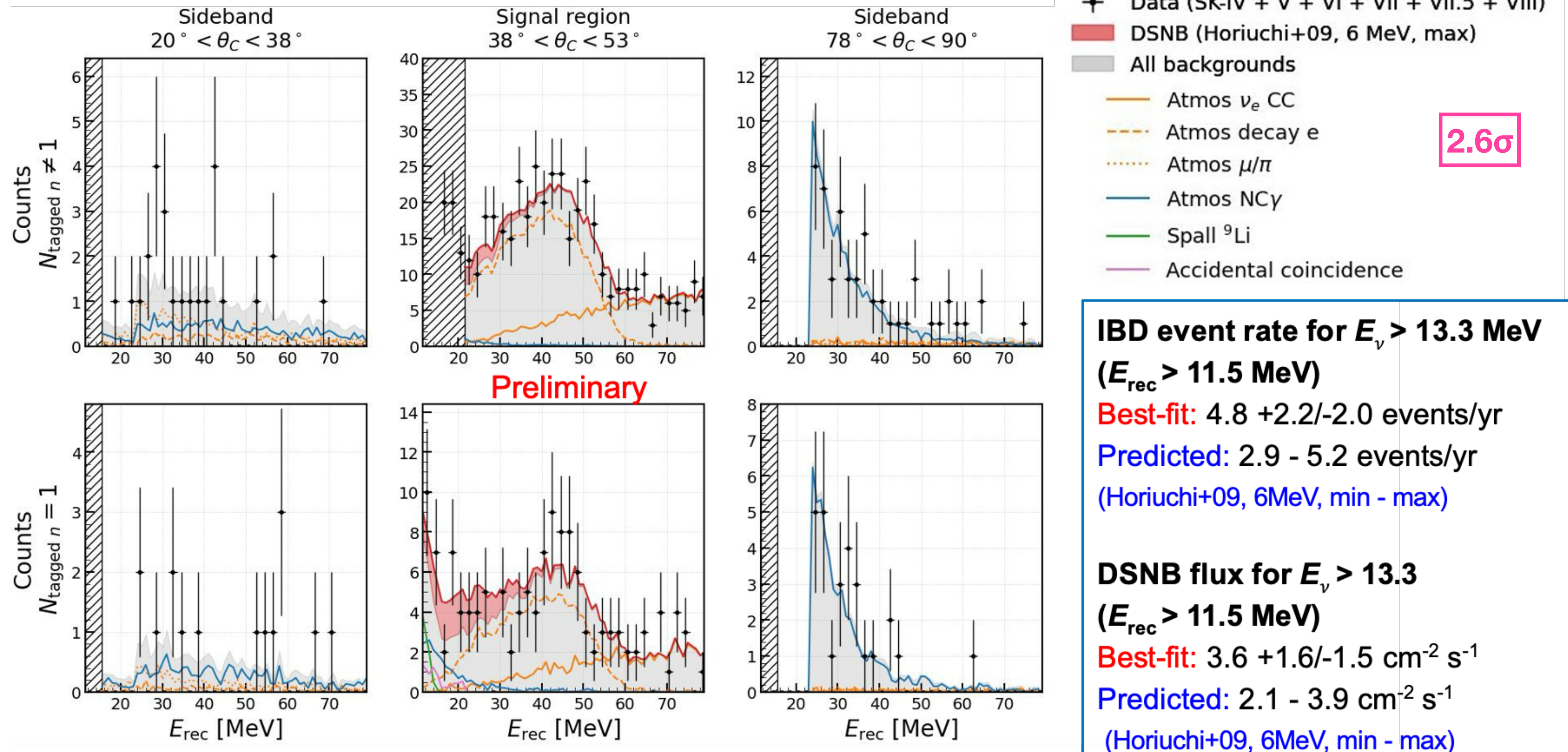
IBD event rate for $E_\nu > 13.3$ MeV
($E_{\text{rec}} > 11.5$ MeV)

Best-fit: $5.2^{+2.9}_{-2.6}$ events/yr
Predicted: 2.9 - 5.2 events/yr
 (Horiuchi+09, 6MeV, min - max)

DSNB flux for $E_\nu > 13.3$
($E_{\text{rec}} > 11.5$ MeV)

Best-fit: $3.9^{+2.2}_{-1.9} \text{ cm}^{-2} \text{ s}^{-1}$
Predicted: 2.1 - 3.9 $\text{cm}^{-2} \text{ s}^{-1}$
 (Horiuchi+09, 6MeV, min - max)

Fit Result for SK-IV~VIII (Entire NTag Period)



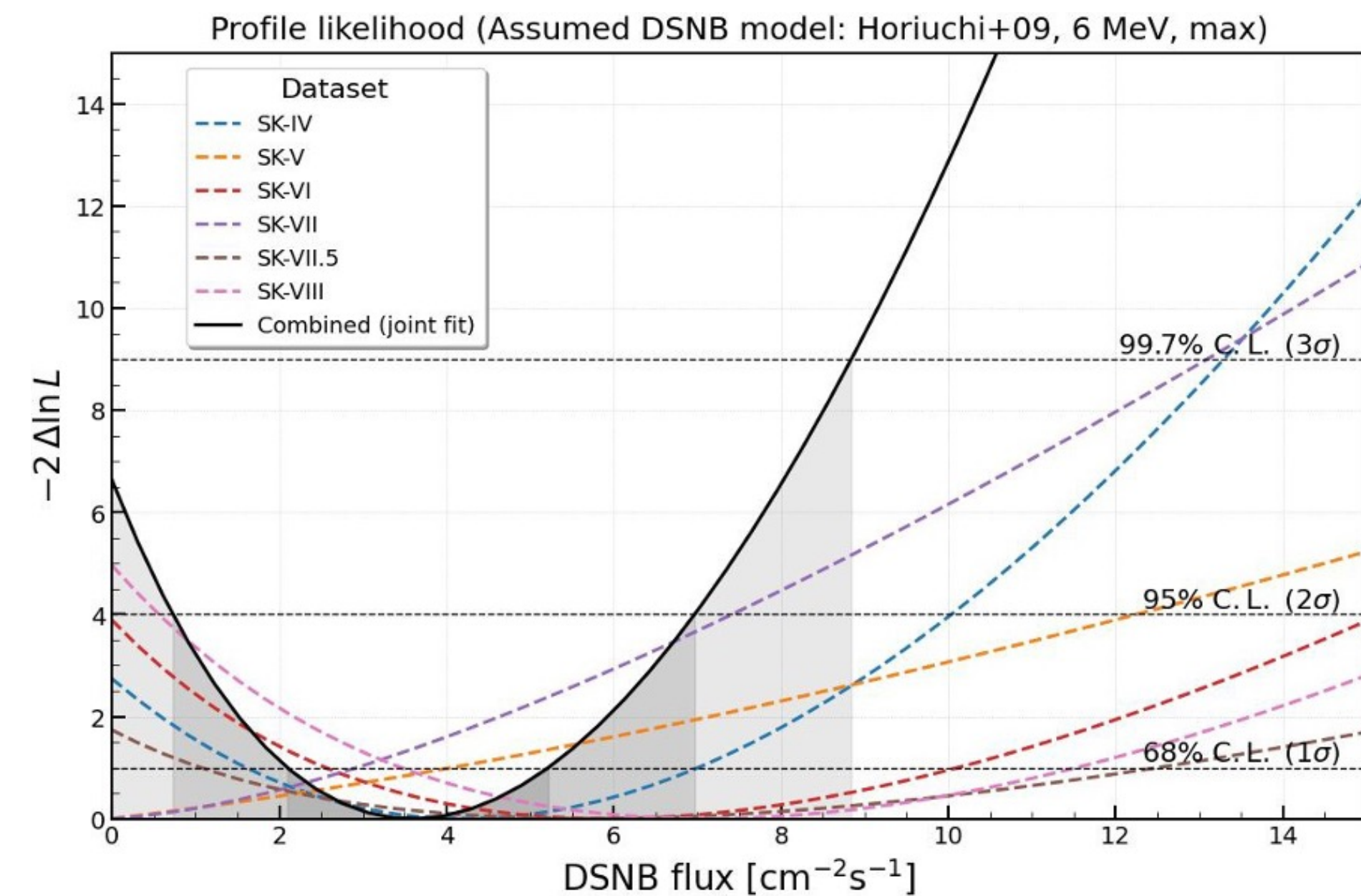
Fit Summary

- Joint fit result gives a **2.6 σ** significance (excludes a null DSNB hypothesis at **99.5% C.L.**).
- Most significant phase is SK-VIII ($\sim 2.2\sigma$).
- 1.4 σ (pure water phase only), 2.2 σ (Gd water phase only)
- This is the first *indication* of the DSNB signature!**

shared parameters

separate parameters

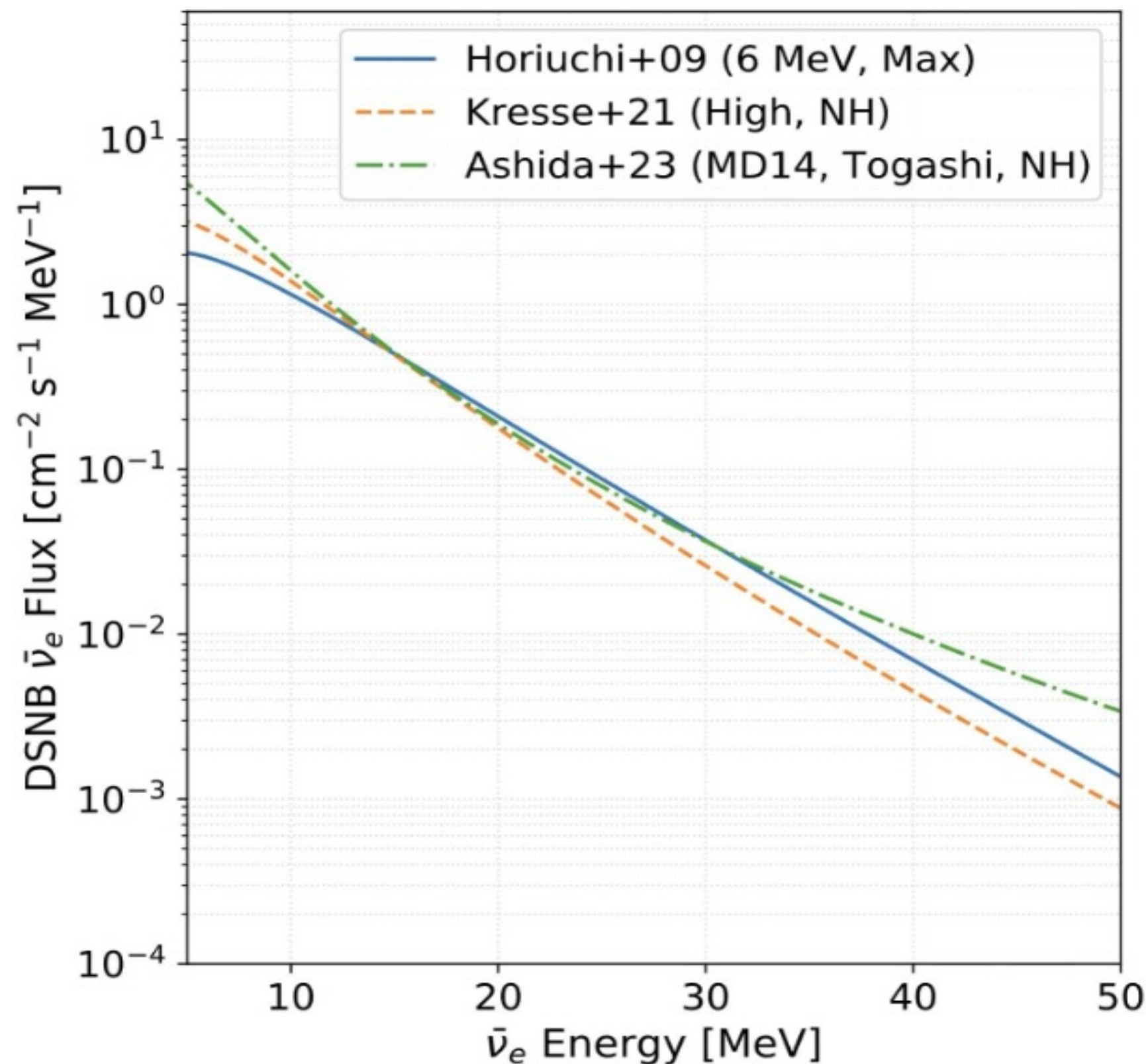
	Parameter	Units	Joint	SK-IV	SK-V	SK-VI	SK-VII	SK-VII.5	SK-VIII
Signal	N_s	rate	4.8	5.6	0	7.9	0	7.6	9.5
Background: atmospherics	N_nue (ve CC)	scale on MC	1.1	1.3	1.3	0.8	0.8	1.0	0.8
	N_numu (decay-e)	scale on MC	1.2	1.2	1.2	1.2	1.3	1.2	1.0
	N_mupi (μ/π)	scale on MC	1.2	1.3	1.0	1.0	0.9	1.1	1.1
	N_ncqe (NCγ)	scale on MC	1.1	1.0	1.2	1.1	1.3	0.9	0.9
Background: spallation	N_spall ($^9\text{C}/^8\text{B}/^8\text{He}$)	scale on MC	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)
	N_li9 (^9Li)	scale on MC	1.1	1.0	1.0	1.0	1.0	1.0	1.0
Background: accidentals	N_acc_coinc	rate	Per-phase	0.2	0.5	0.2	0.3	0.3	0.1
Nuisances	epsilon_ntag_cc	σ units on unc	-0.2	0.0	-1.1	-1.3	-0.9	0.0	1.1
	epsilon_ntag_nc	σ units on unc	0.8	0.2	0.7	0.3	0.4	0.0	0.2
	epsilon_ntag_sig	σ units on unc	Per-phase	0.2	0.0	0.1	0.0	0.0	0.2
	epsilon_eff_sig	σ units on unc	Per-phase	0.0	0.0	0.0	0.0	0.0	0.0
	f0_spall	iso fraction	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)
	f1_spall	iso fraction	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)	0 (inactive)
	epsilon_li9	σ units on unc	0.1	0.1	0.0	0.0	0.0	0.0	-0.1



Fitting with Other DSNB Models

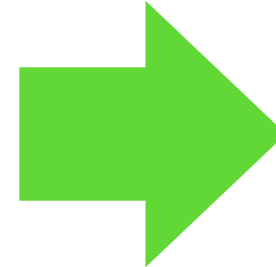
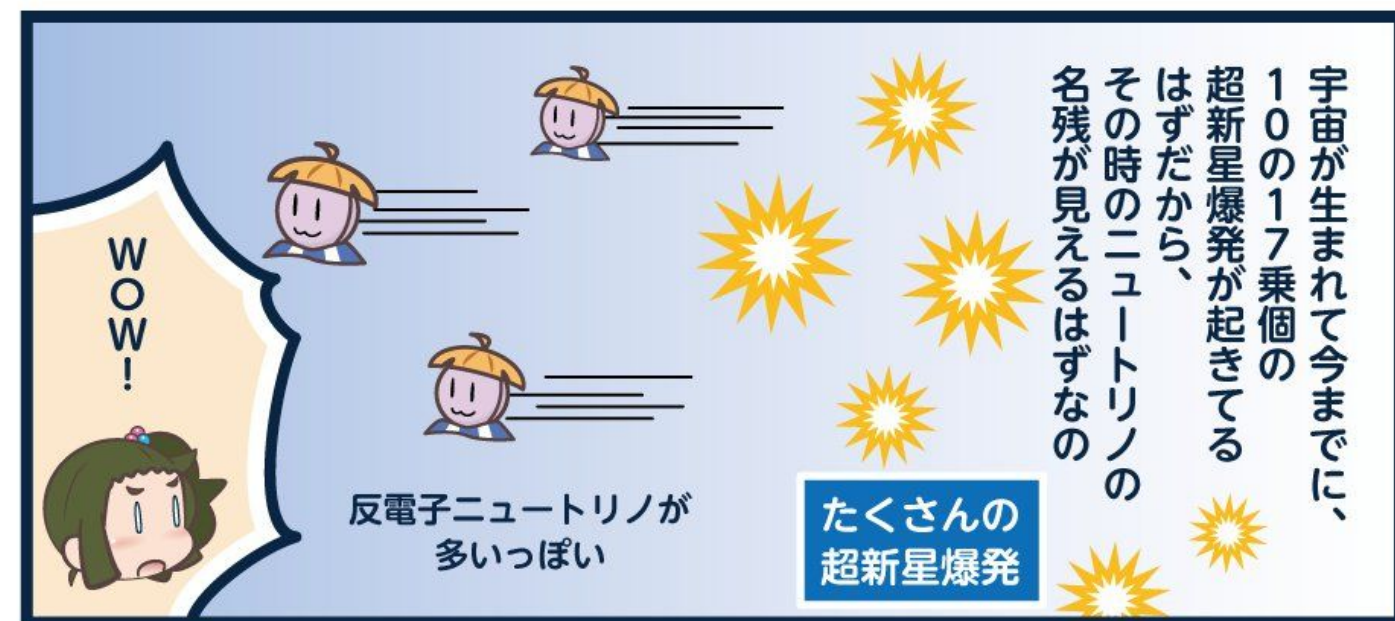
- Three models (which have different shapes) were tested.
- The fitting consistently shows a significance of $\sim 2.6\sigma$ against the null DSNB hypothesis.
- Our analysis is not capable of model discrimination.

Preliminary

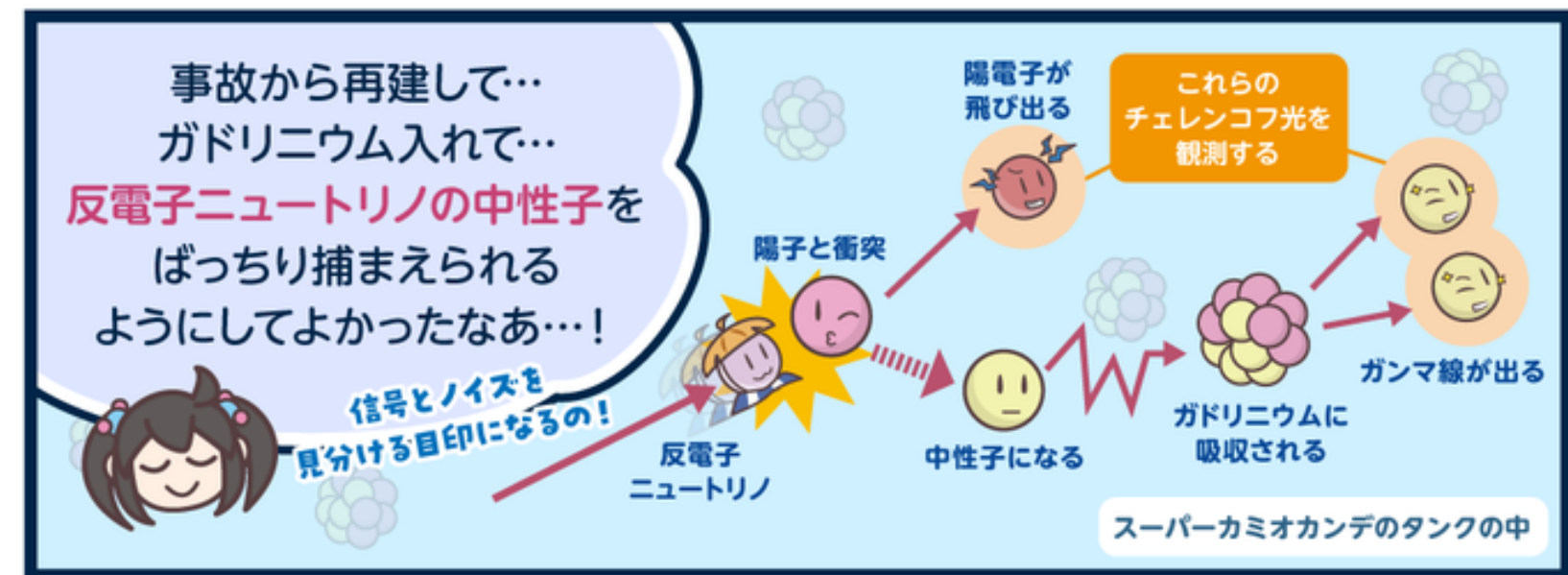


	IBD event rate [events/year]		DSNB flux [cm ⁻² s ⁻¹]		Significance (SK-IV ~ VIII joint fit)	Maximum Likelihood Value
	Best-fit	Pred	Best-fit	Pred		
Horiuchi+09 6 MeV, max	4.8 +2.2/-2.0	5.2	3.6 +1.6/-1.5	3.9	2.6σ	1226.1
Kresse+21	5.1 +2.2/2.0	4.3	4.1 +1.8/-1.6	3.5	2.7σ	1225.3
Ashida+23	5.7 +2.5/-2.3	5.5	4.0 +1.8/-1.6	3.9	2.6σ	1225.9

超新星背景ニュートリノ！



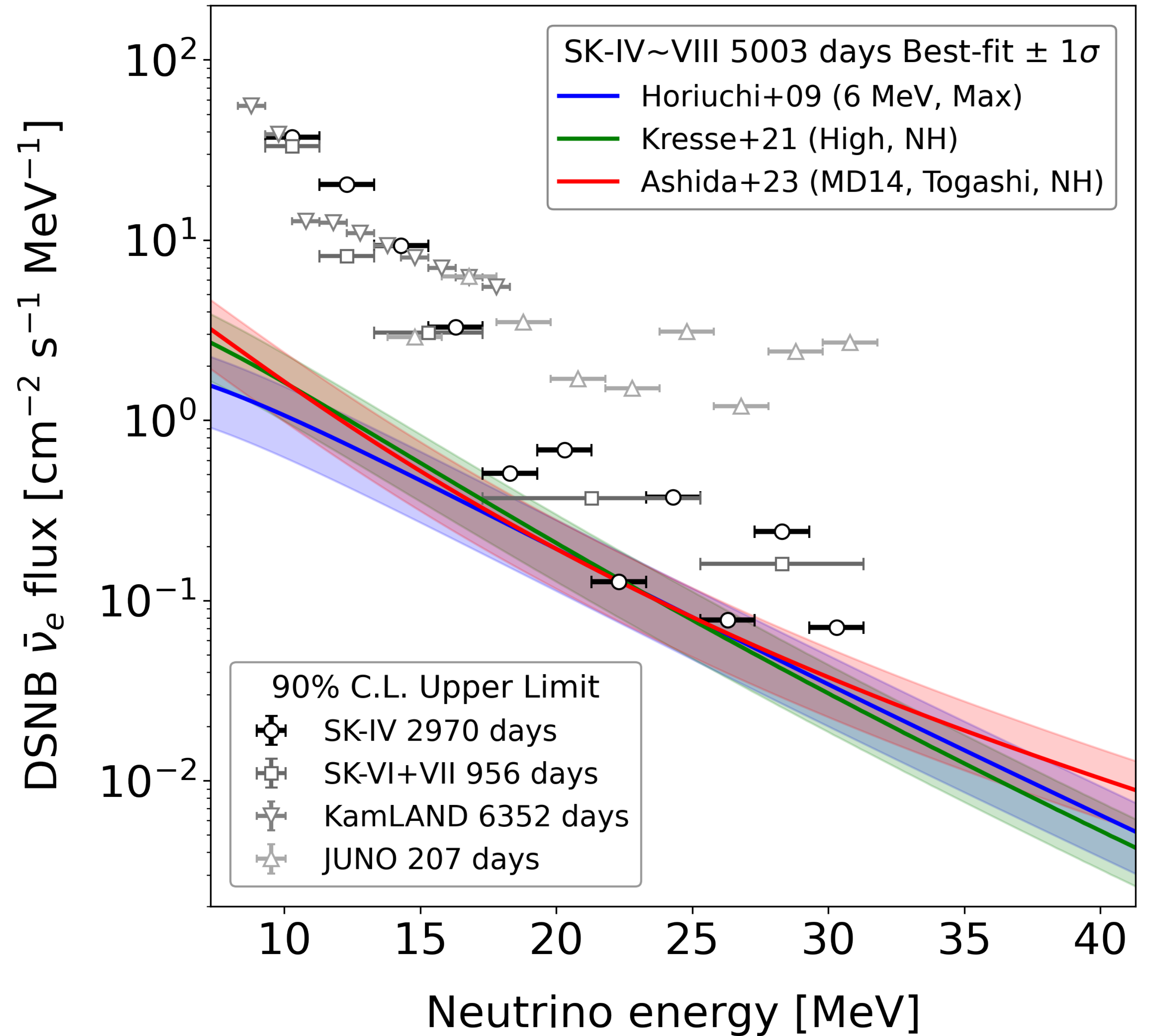
「かすかなささやき」見つけた？ 超新星背景ニュートリノ！



Future Prospects

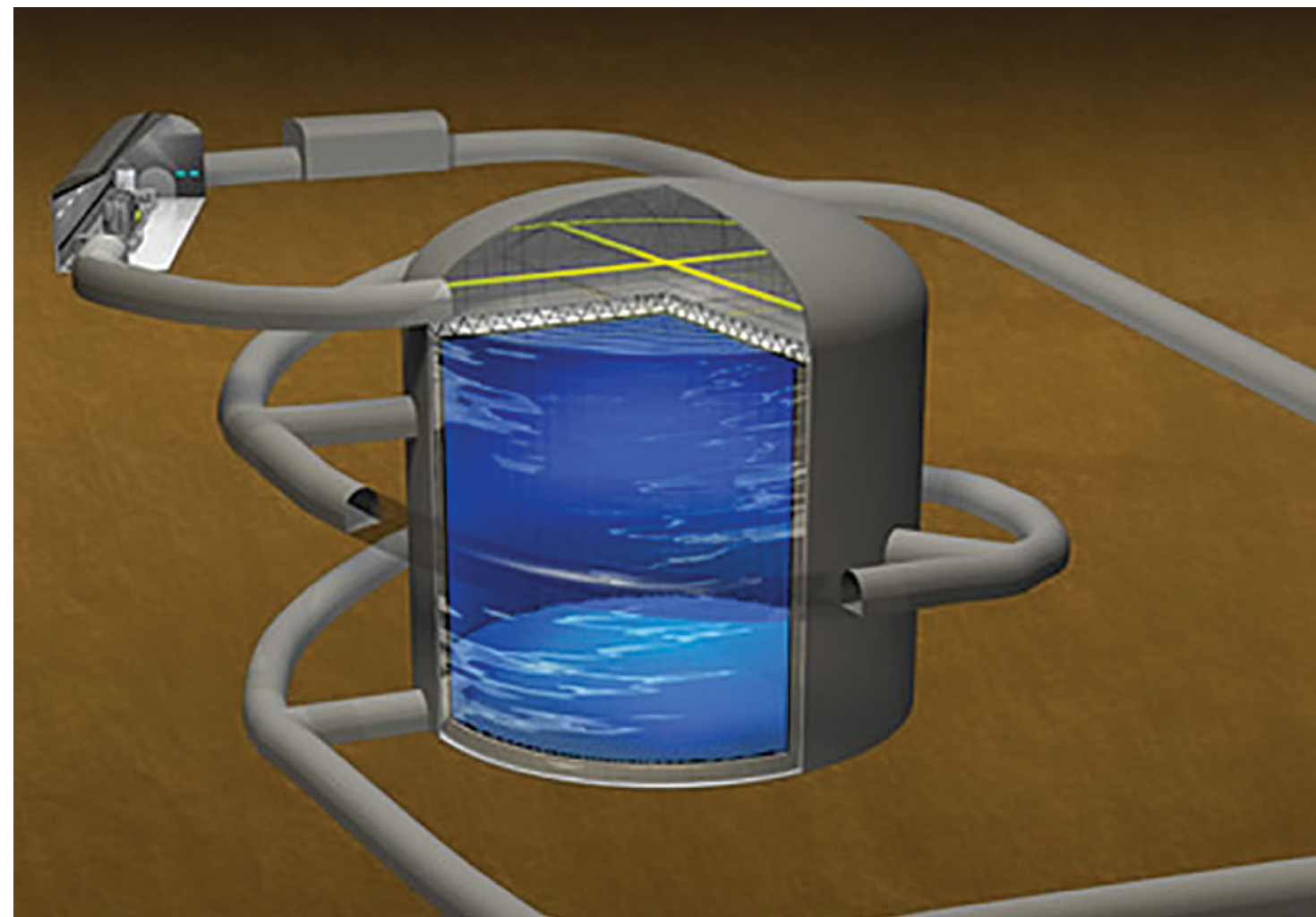
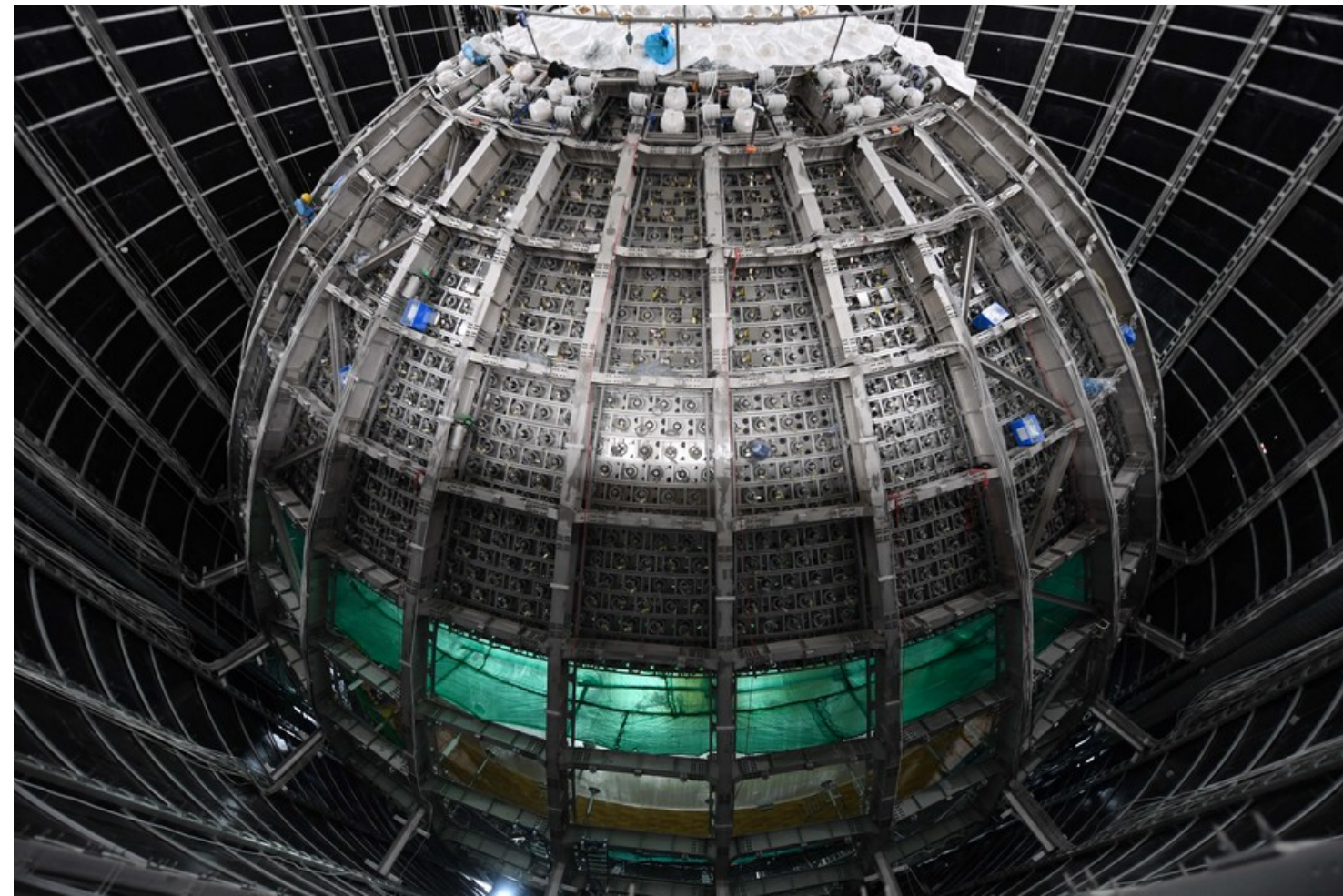


Current Landscape

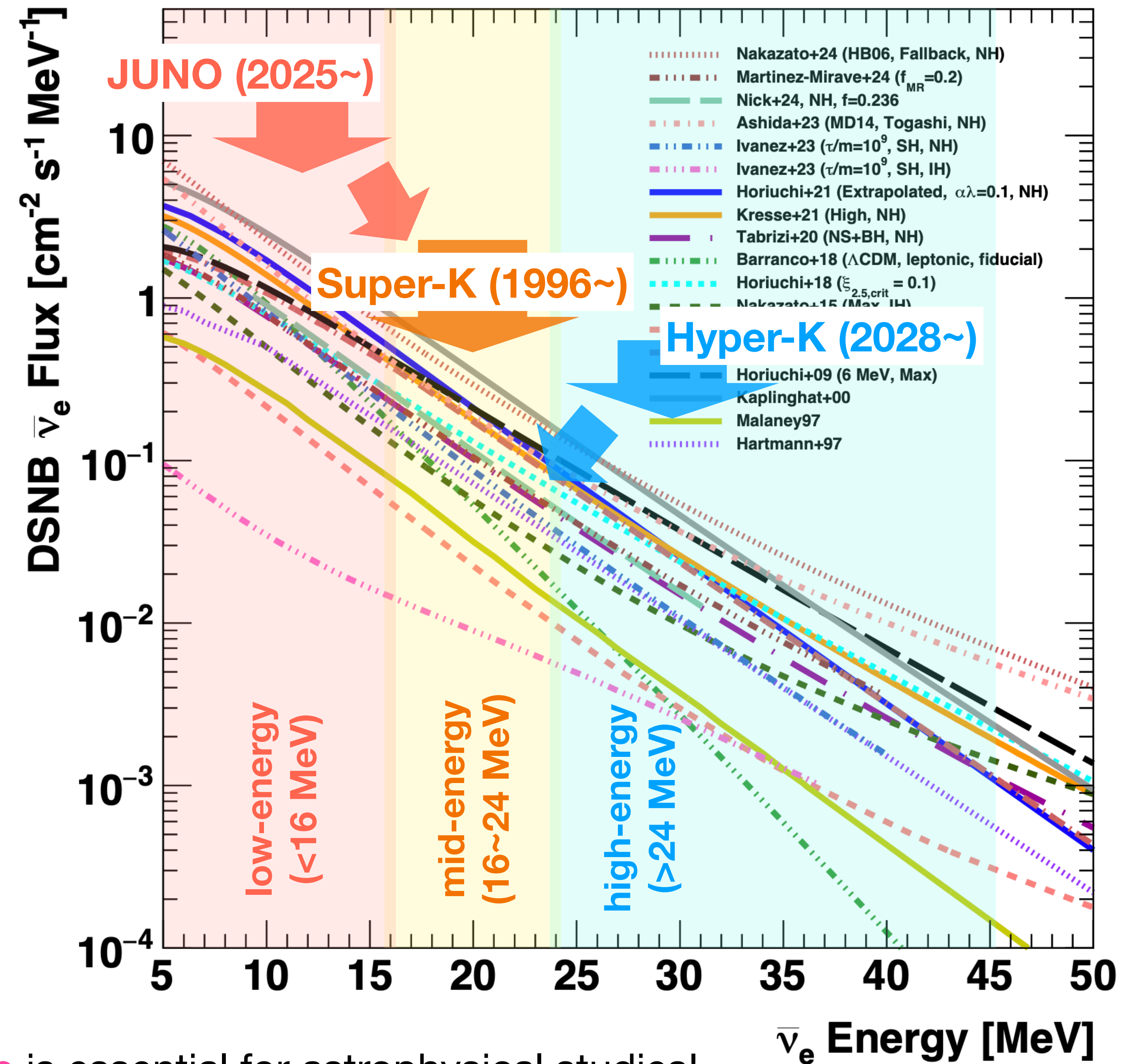


Next Era

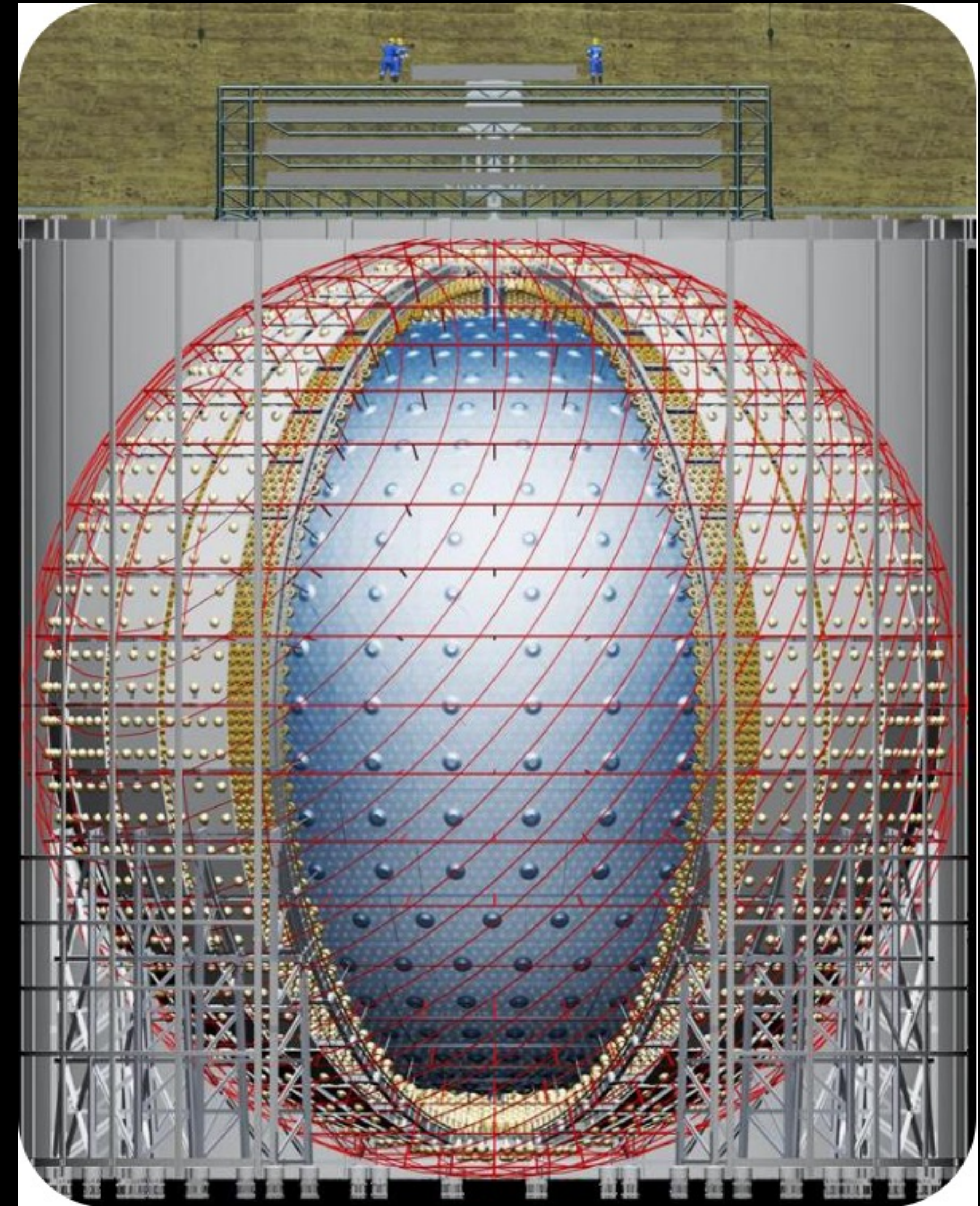
44



DSNB observation over the wide energy range is essential for astrophysical studies!

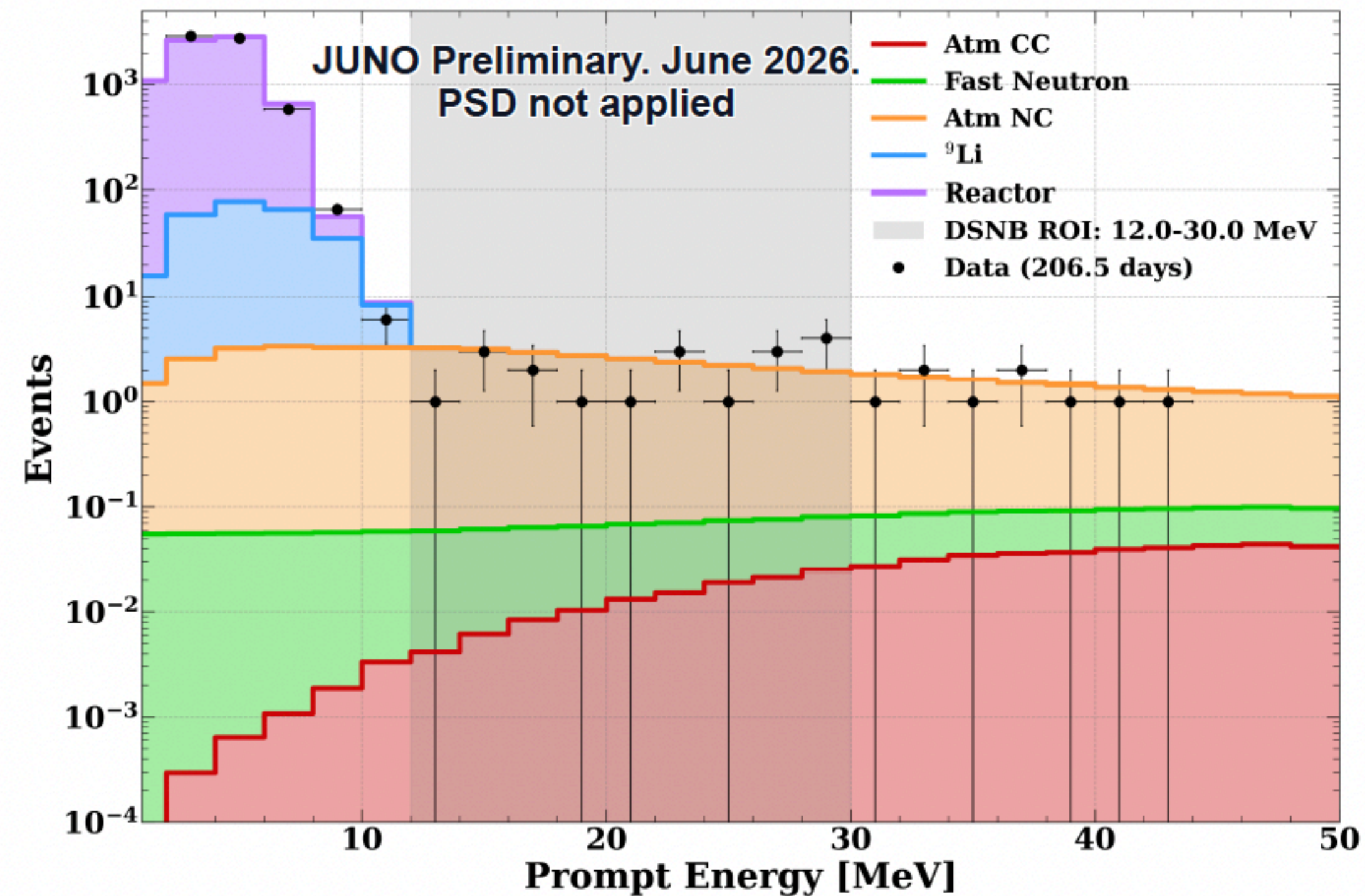


JUNO just kicked off last summer!



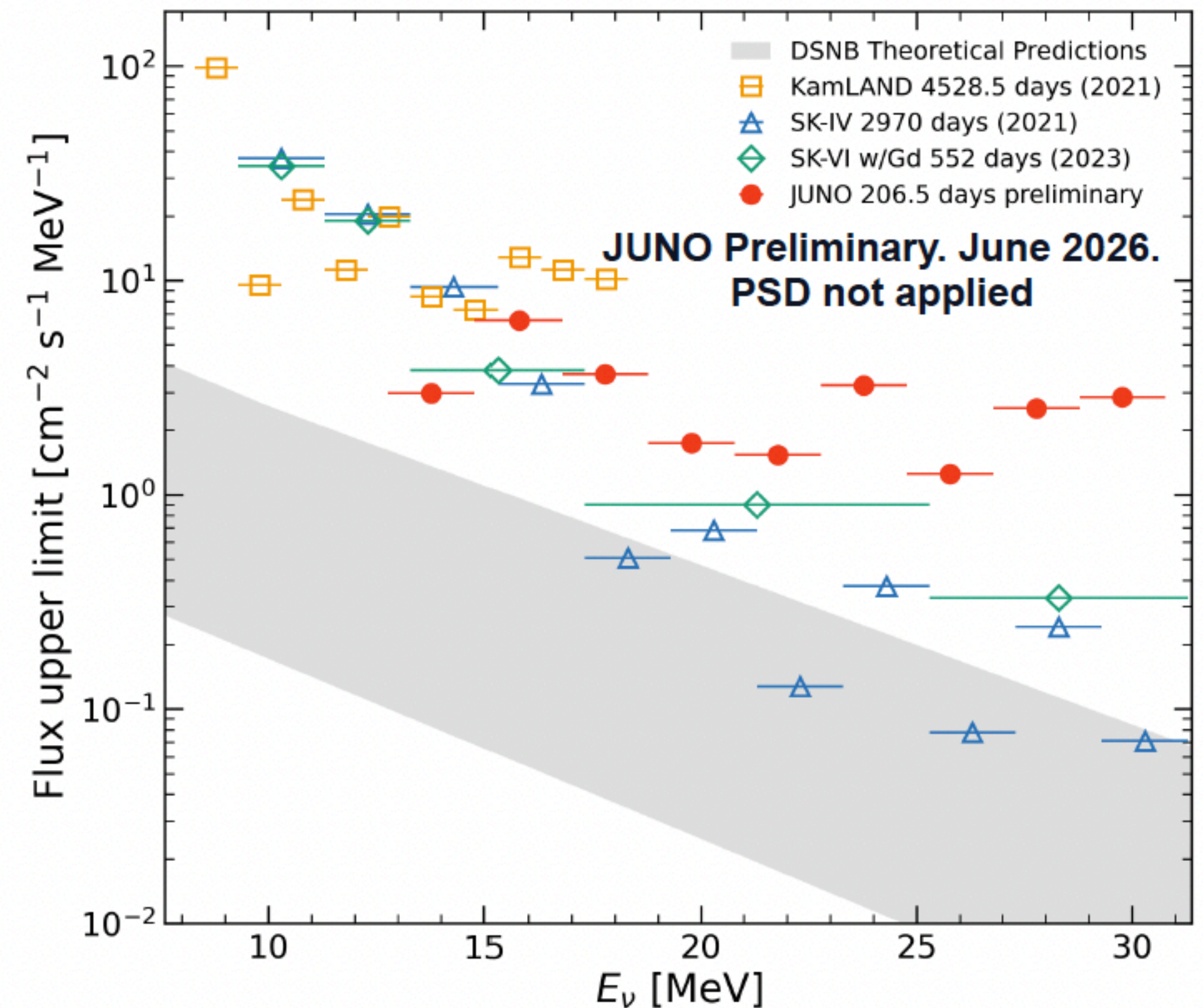
from I. Morton-Blake

- Latest analysis with 207 days of data shows 19 candidates vs. 21.3 ± 10.5 expected background.
- Their upper limit is already better than KamLAND and SK-Gd at low energies.

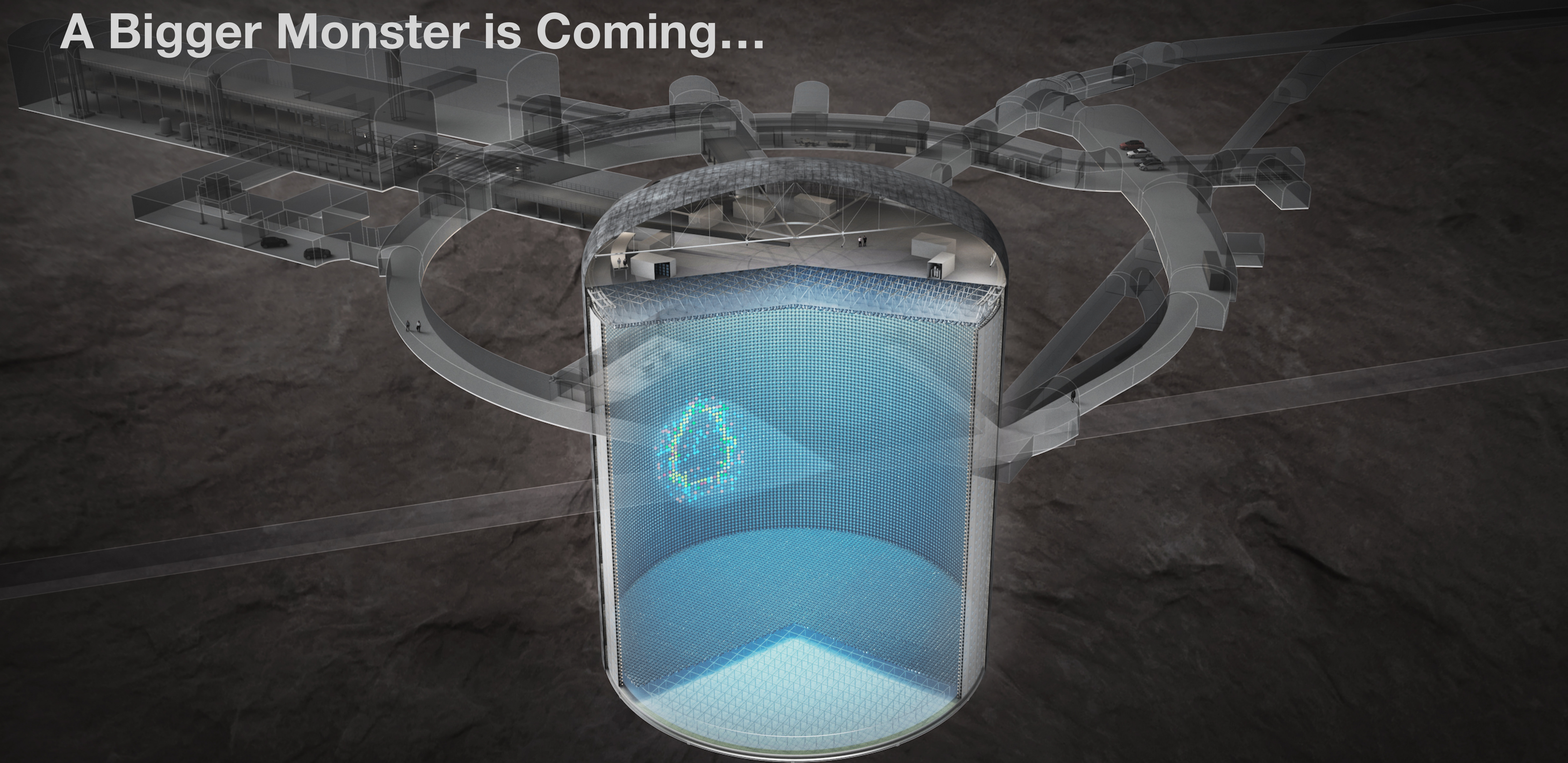


Prompt-energy spectrum; the shaded band marks the DSNB search region.

- 12–30 MeV window: 19 candidates with 206.5-day exposure.
- Total predicted background: 21.3 ± 10.5 events.



A Bigger Monster is Coming...



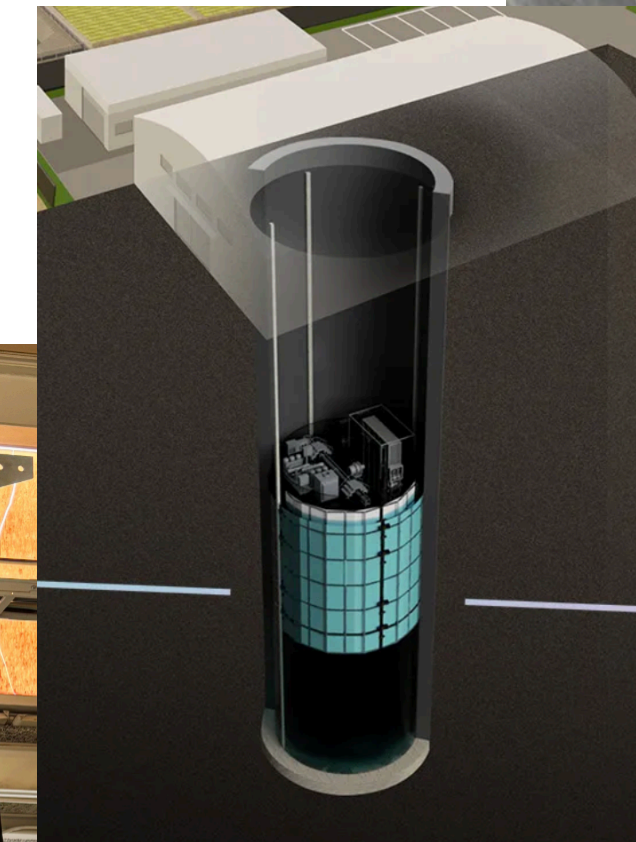
Hyper-Kamiokande, under Construction

A successor of the greatest *parent* and *grandparent* (8.4× Super-K)

- Plenty of physics goals; **MeV to TeV astrophysics** is among the most important missions.
- Plays a key role in the DSNB study to **cover the wide energy range**.
- **IWCD** is a great supportive detector for neutrino interactions.

Construction status

- Excavation has been completed in **July 2025**.
- Many groups are rushing in parallel towards the operation start in **2028**.



■ Super-K's latest result on DSNB might open the new path in astronomy/astrophysics.

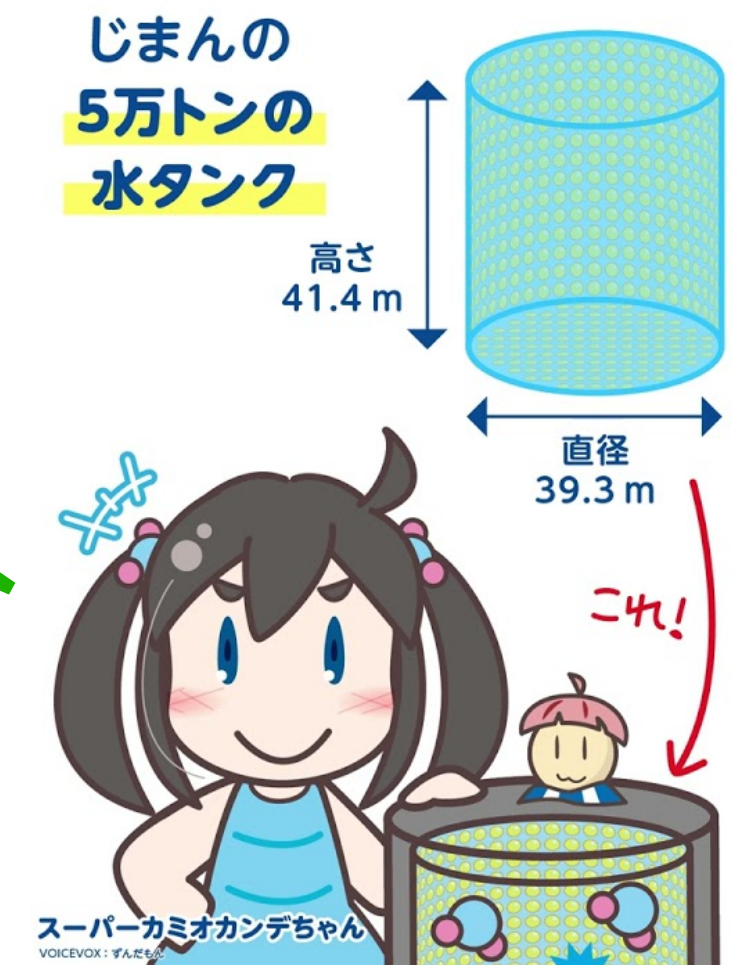
- So many and big improvements have been applied on the 5003-day dataset.
- Lowered energy threshold thanks to better control of background.
- ^9Li efficiency estimation validated by newly produced MC samples.
- NN-based e-gamma discriminator targeting NCQE, and validated by an independent T2K sample.
- Smaller ntag systematics in Gd phases due to thermal boost modification in MC.
- Improved systematics on neutron multiplicity with external inputs.
- etc...

paper in prep

THANK YOU FOR YOUR ATTENTION!

■ Next era is coming...

- Super-K will further improve the analysis, aiming 3σ and more!
- Hyper-K is now under construction; expects to begin its operation in 2028.
- JUNO has kicked-off and showed the initial result.

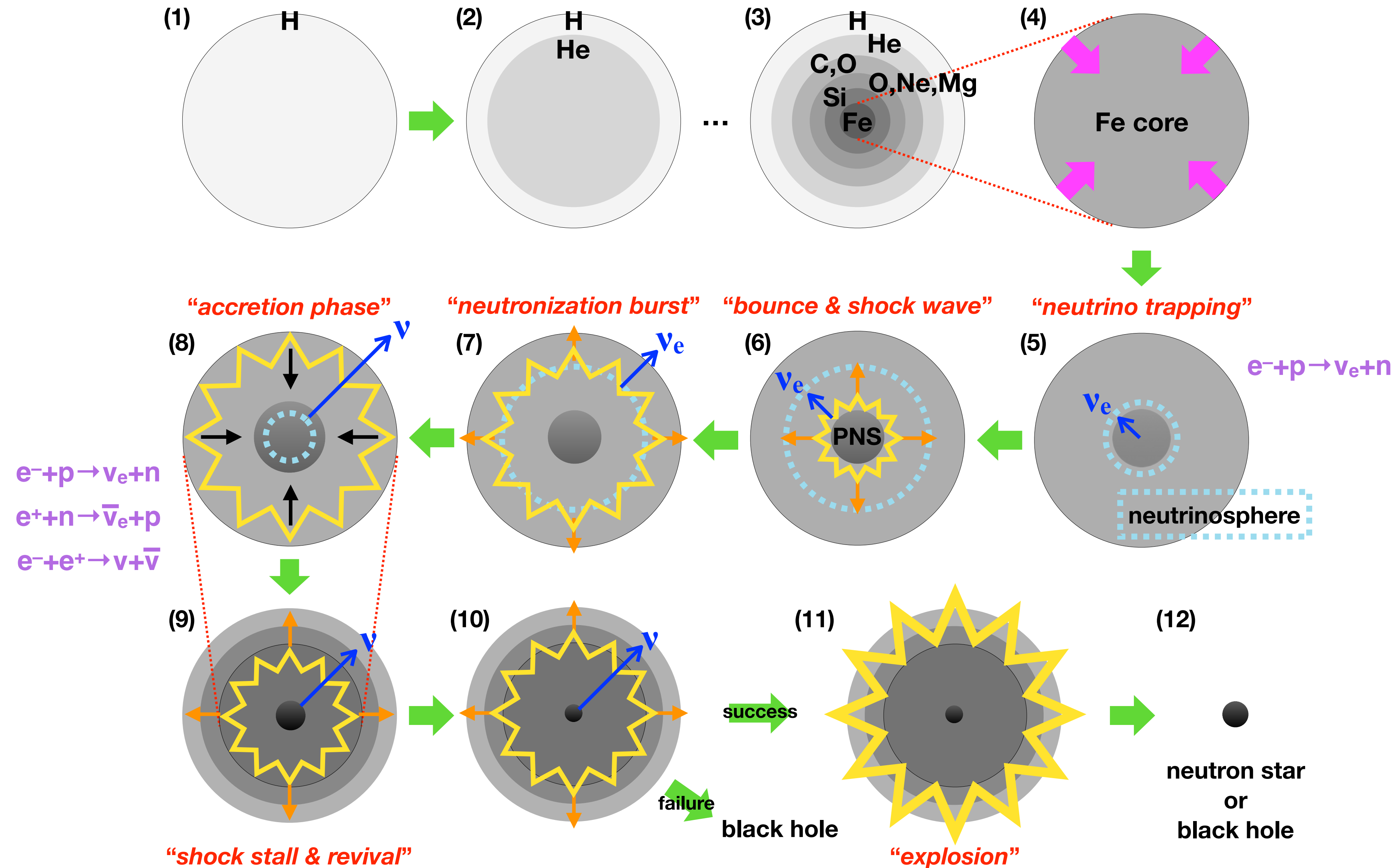


Please feel free to contact me if you are interested to join the related activity!

Supplements

“Neutrino Heating” Scenario

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$$\begin{aligned}\frac{dN_{\bar{\nu}_e}}{dE_\nu} &= |U_{e1}|^2 \frac{dN_{\bar{\nu}_1}}{dE_\nu} + |U_{e2}|^2 \frac{dN_{\bar{\nu}_2}}{dE_\nu} + |U_{e3}|^2 \frac{dN_{\bar{\nu}_3}}{dE_\nu} \\ &= \cos^2 \theta_{12} \cos^2 \theta_{13} \frac{dN_{\bar{\nu}_1}}{dE_\nu} + \sin^2 \theta_{12} \cos^2 \theta_{13} \frac{dN_{\bar{\nu}_2}}{dE_\nu} + \sin^2 \theta_{13} \frac{dN_{\bar{\nu}_3}}{dE_\nu} \\ &\sim 0.68 \cdot \frac{dN_{\bar{\nu}_1}}{dE_\nu} + 0.30 \cdot \frac{dN_{\bar{\nu}_2}}{dE_\nu} + 0.02 \cdot \frac{dN_{\bar{\nu}_3}}{dE_\nu},\end{aligned}$$

$$\Rightarrow \frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim 0.68 \cdot \frac{dN_{\bar{\nu}_e}^0}{dE_\nu} + 0.32 \cdot \frac{dN_{\bar{\nu}_x}^0}{dE_\nu}. \quad \text{Normal: All flavors}$$

$$\Rightarrow \frac{dN_{\bar{\nu}_e}}{dE_\nu} \sim \frac{dN_{\bar{\nu}_x}^0}{dE_\nu}. \quad \text{Inverted: NuMu+NuTau}$$

Contributions from Different Redshifts

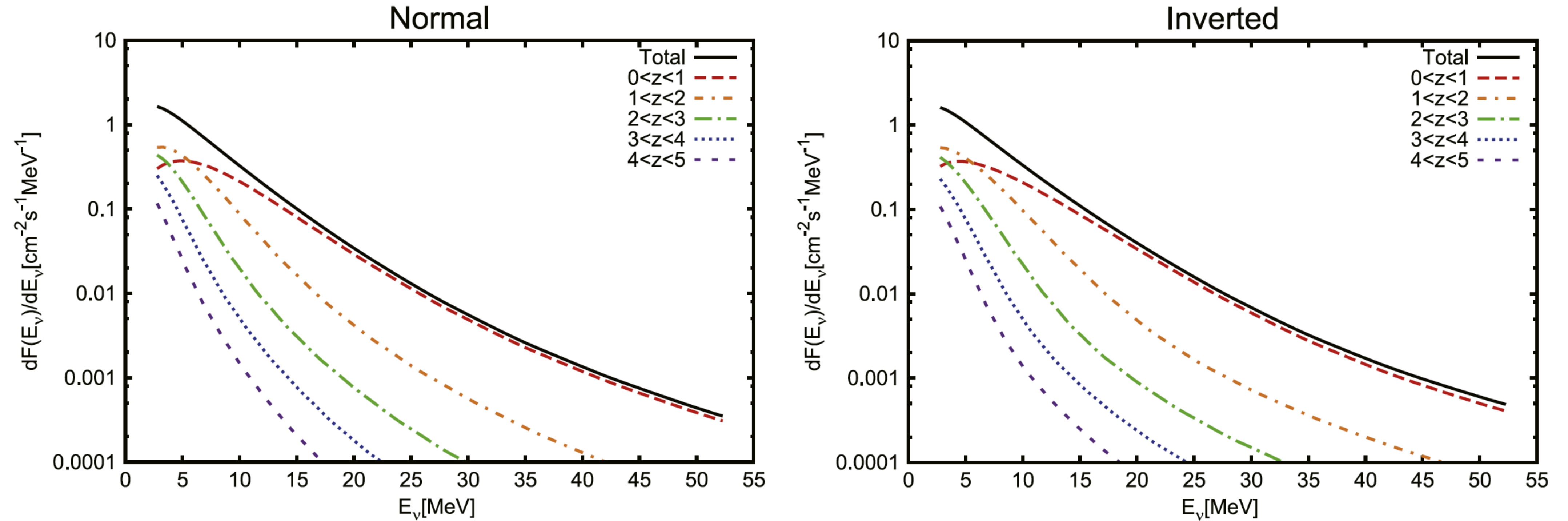
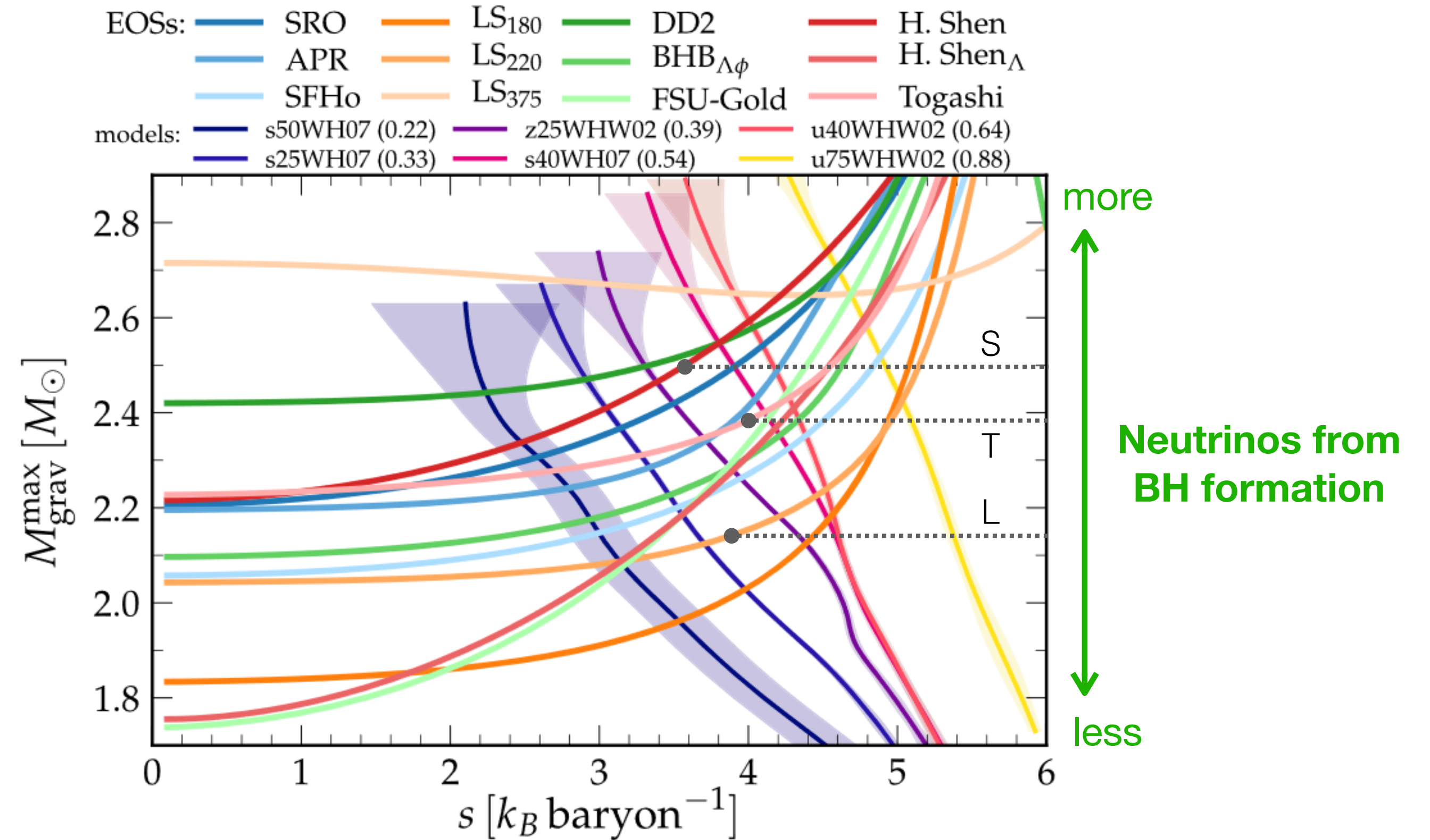
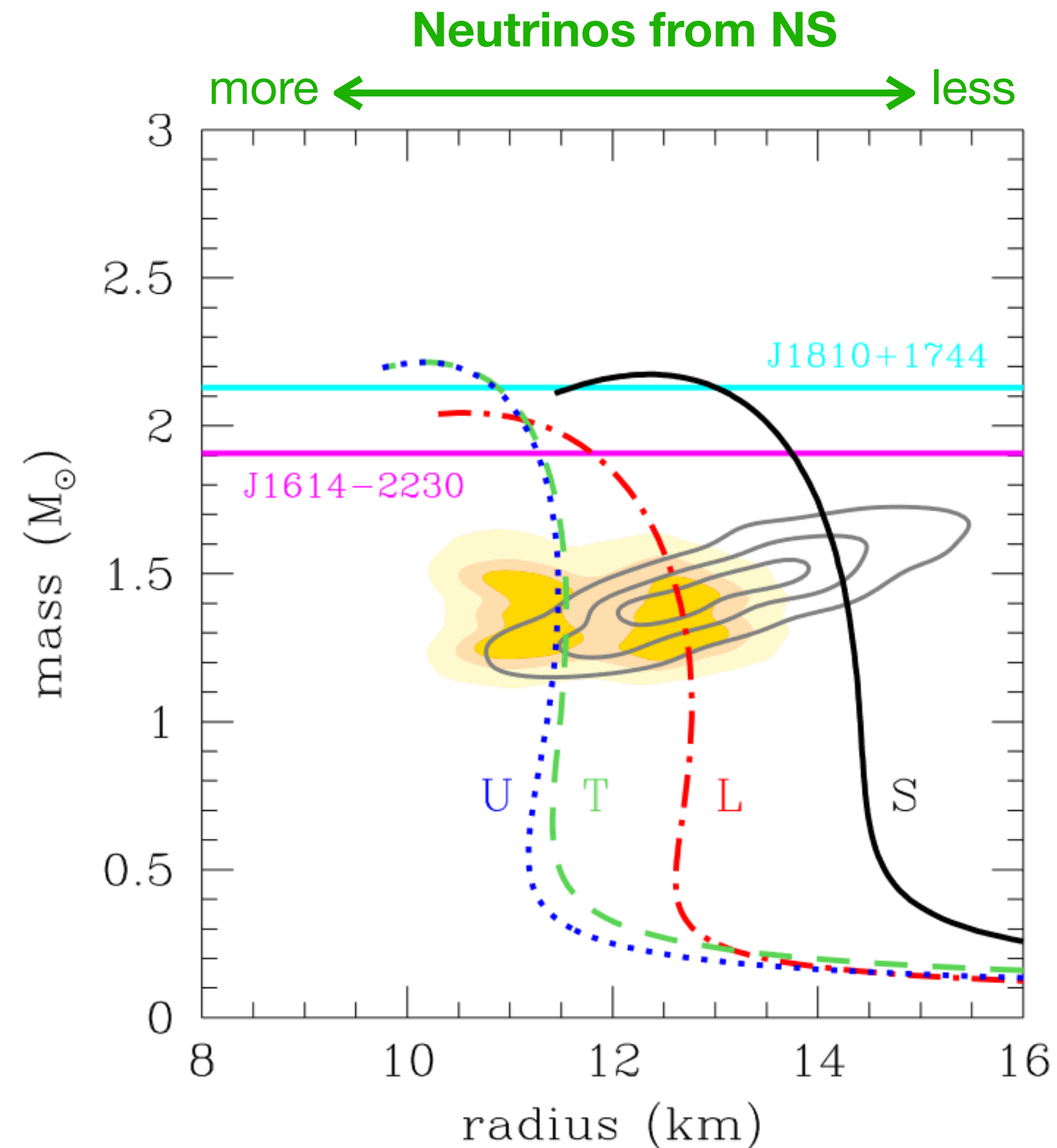


Figure 10. Total fluxes of SRNs (solid) and contributions from various redshift ranges for the reference model. The lines except for the solid line correspond, from top to bottom, to the redshift ranges $0 < z < 1$, $1 < z < 2$, $2 < z < 3$, $3 < z < 4$, and $4 < z < 5$, for $E_\nu > 10$ MeV. The left and right panels show the cases for normal and inverted mass hierarchies, respectively.

Nuclear Equation-of-State Impact

- In the NS case, neutrino emission amount depends on **radius** of proto-NS.
- In the BH case, neutrino emission amount depends on **maximum mass** of proto-NS.



Nuclear EOS Impact (BH Formation Case)

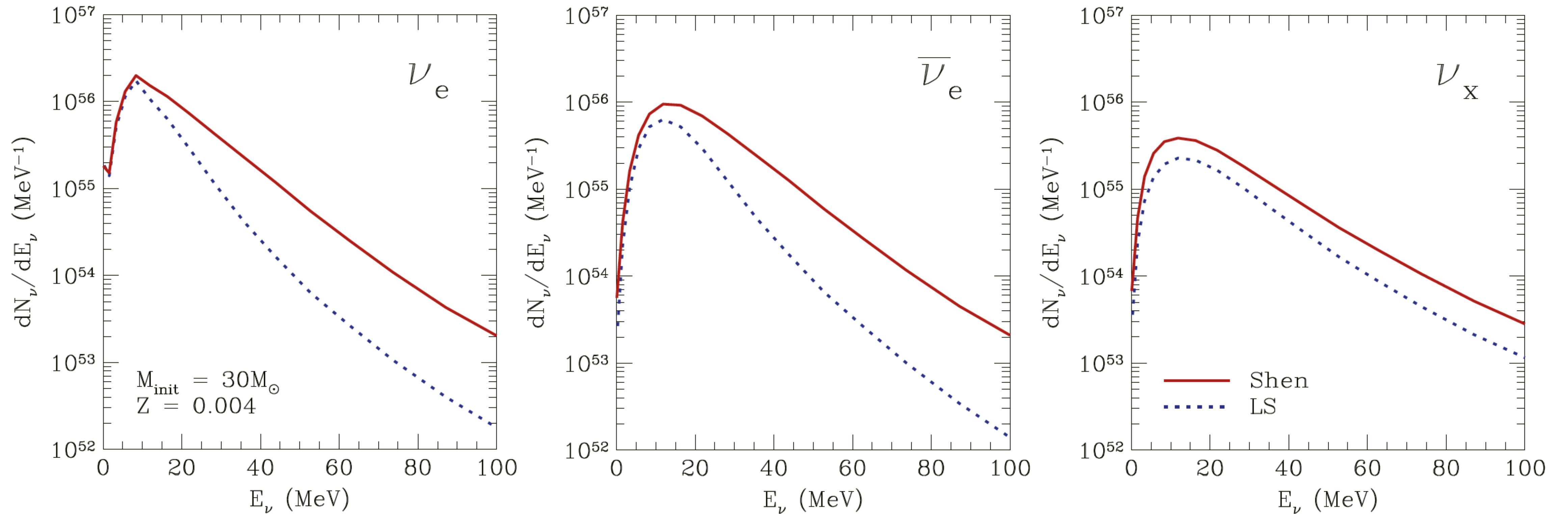


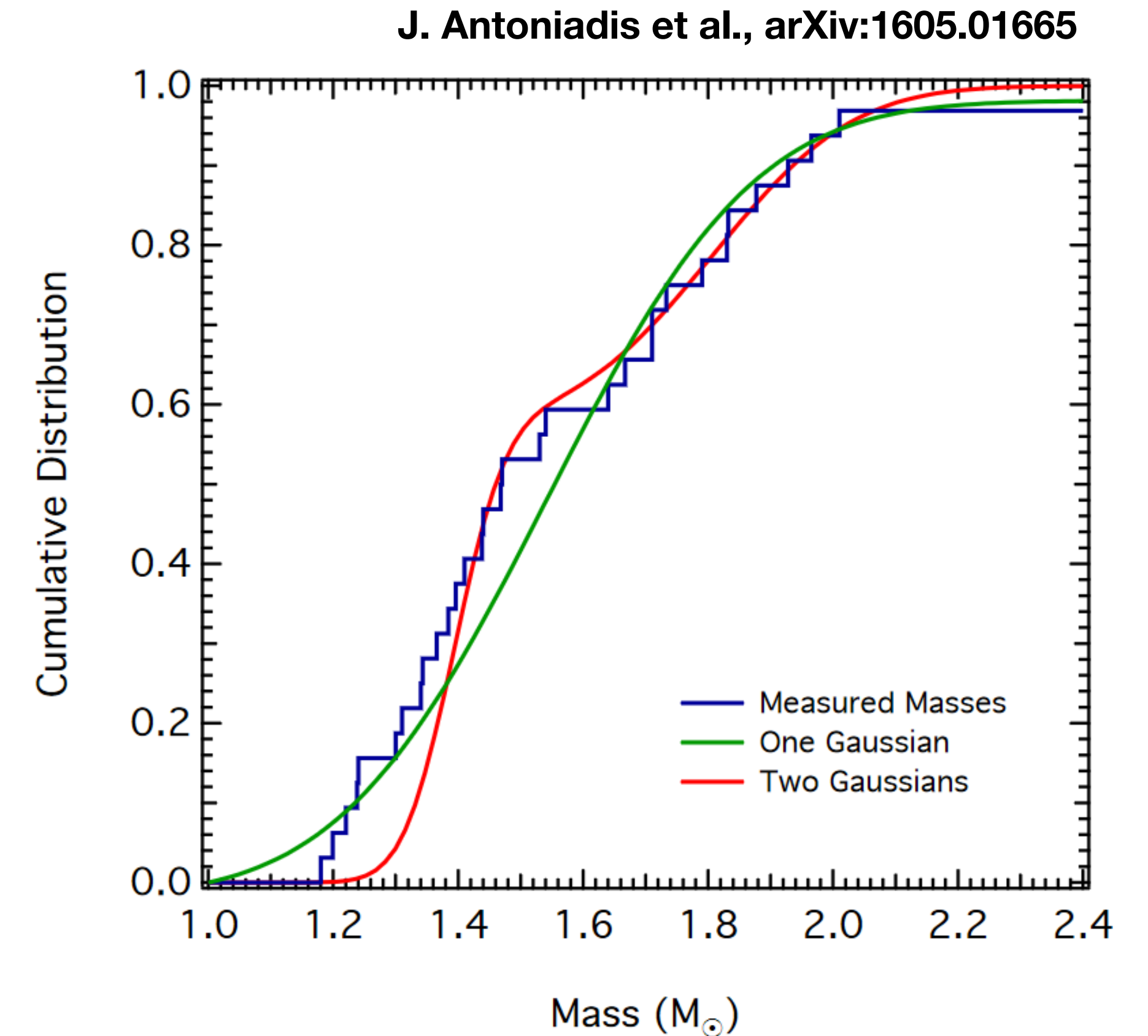
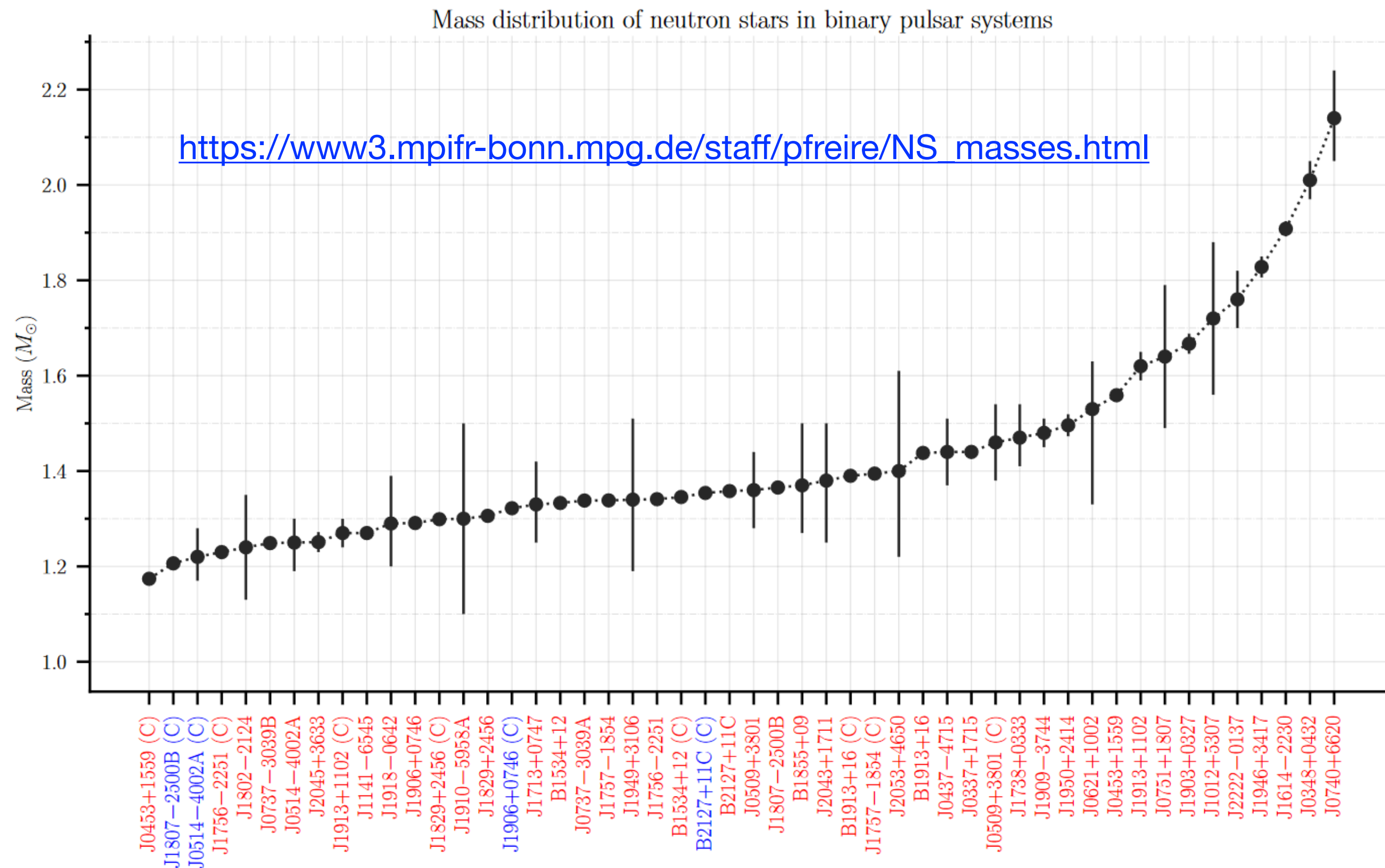
Figure 6. Neutrino number spectra for black hole formation with $30M_\odot$, $Z = 0.004$ and Shen EOS (solid) and LS EOS (dotted). The left, central, and right panels correspond to ν_e , $\bar{\nu}_e$, and ν_x ($=\nu_\mu = \bar{\nu}_\mu = \nu_\tau = \bar{\nu}_\tau$), respectively.

Shen is stiffer than LS (maximum mass of neutron stars is higher).

K. Nakazato et al., ApJ 804, 75 (2015)

Observed Neutron Star Mass

- Neutron mass distribution from optical observations of the binary system shows a peak and higher tail.
- Natural born heavy, *or* gained mass through accretion from companion stars.



Failed SN Fraction

- Monitoring luminous stars gave constraints on a failed SN fraction.
- 2 failed SN candidates (N6946-BH1, M101-OC1) out of 8 SNe.
 - Failed SN fraction $\sim$ **4–39% (90% C.L.)**, assuming $N_{\text{FSN}} = 1$ and $N_{\text{SN}} = 8$.

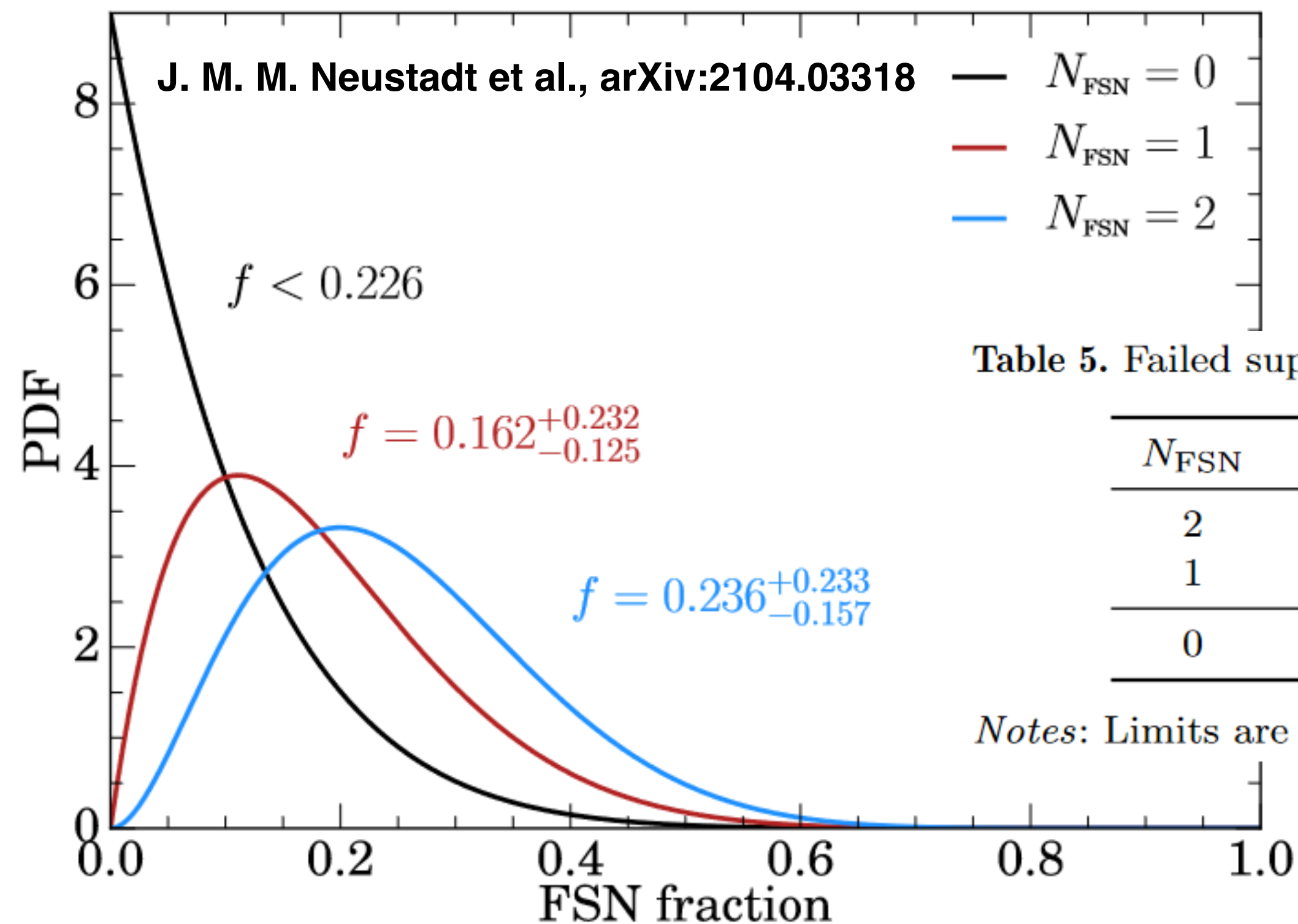
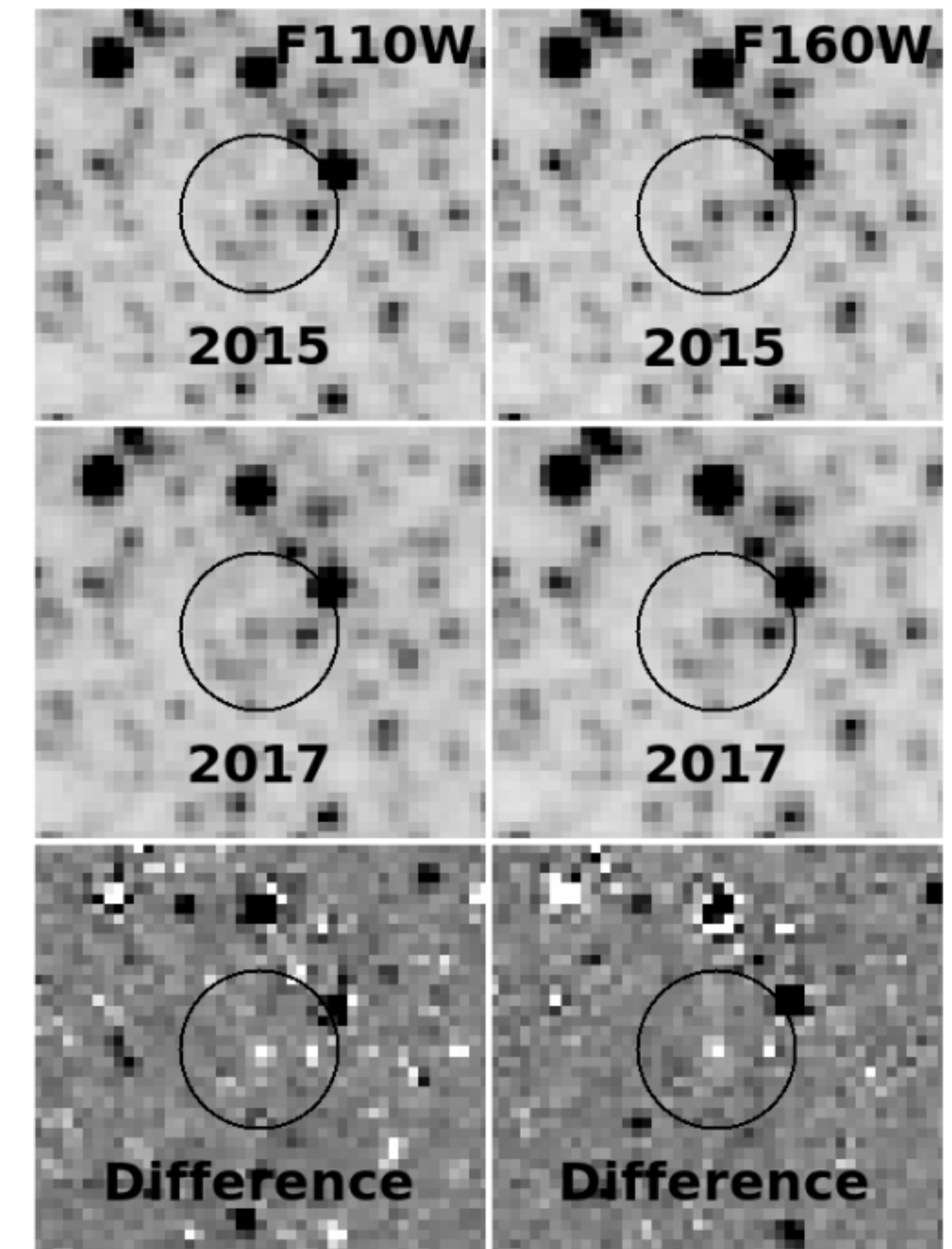


Table 5. Failed supernova/core-collapse fraction

N_{FSN}	Lower limit	Median	Upper limit
2	0.079	0.236	0.470
1	0.037	0.162	0.394
0	—	—	0.226

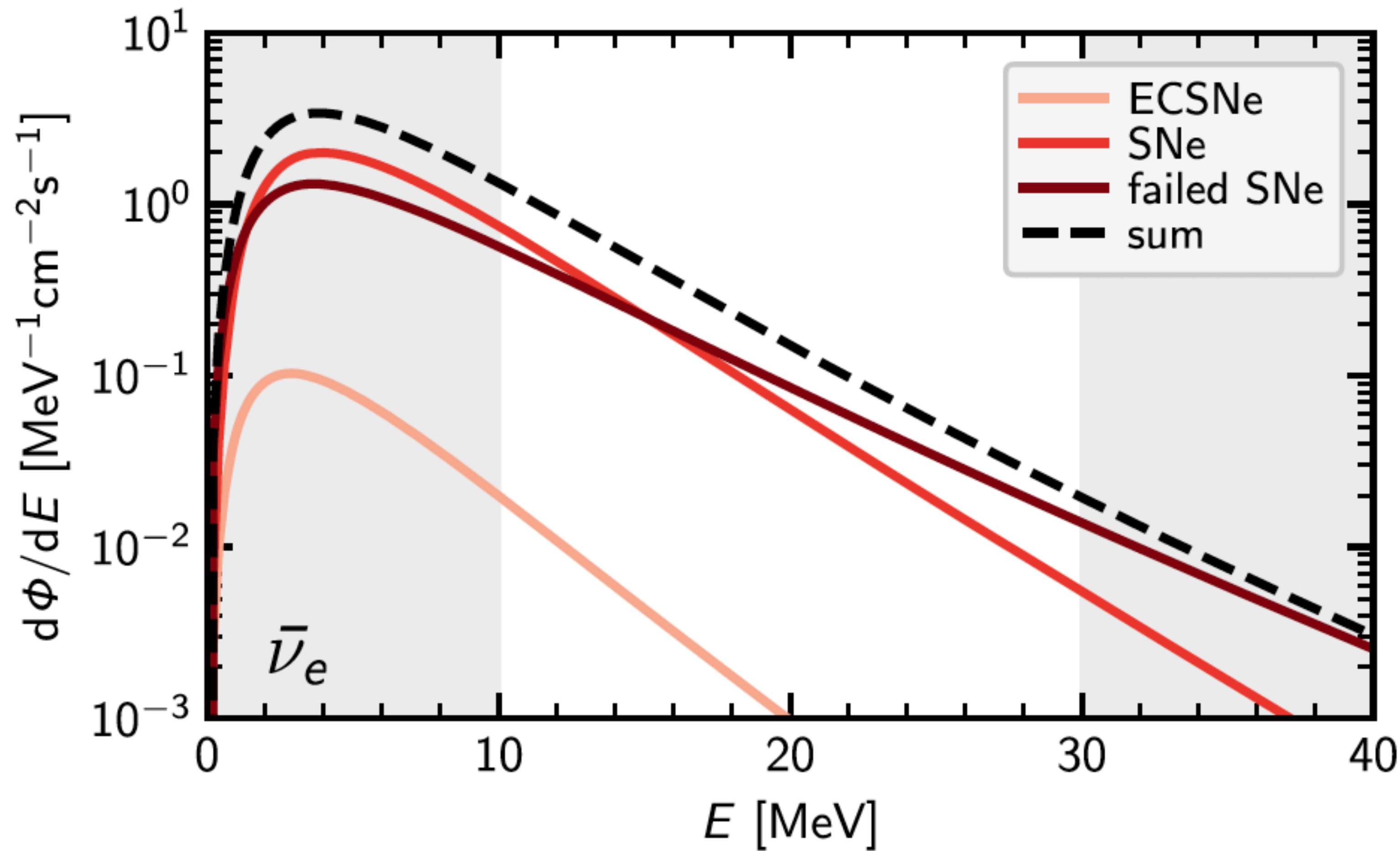
Notes: Limits are presented at the 90 per cent confidence level.

C. M. Basinger et al., arXiv:2007.15658



Failed SN & Electron-Capture SN Contributions

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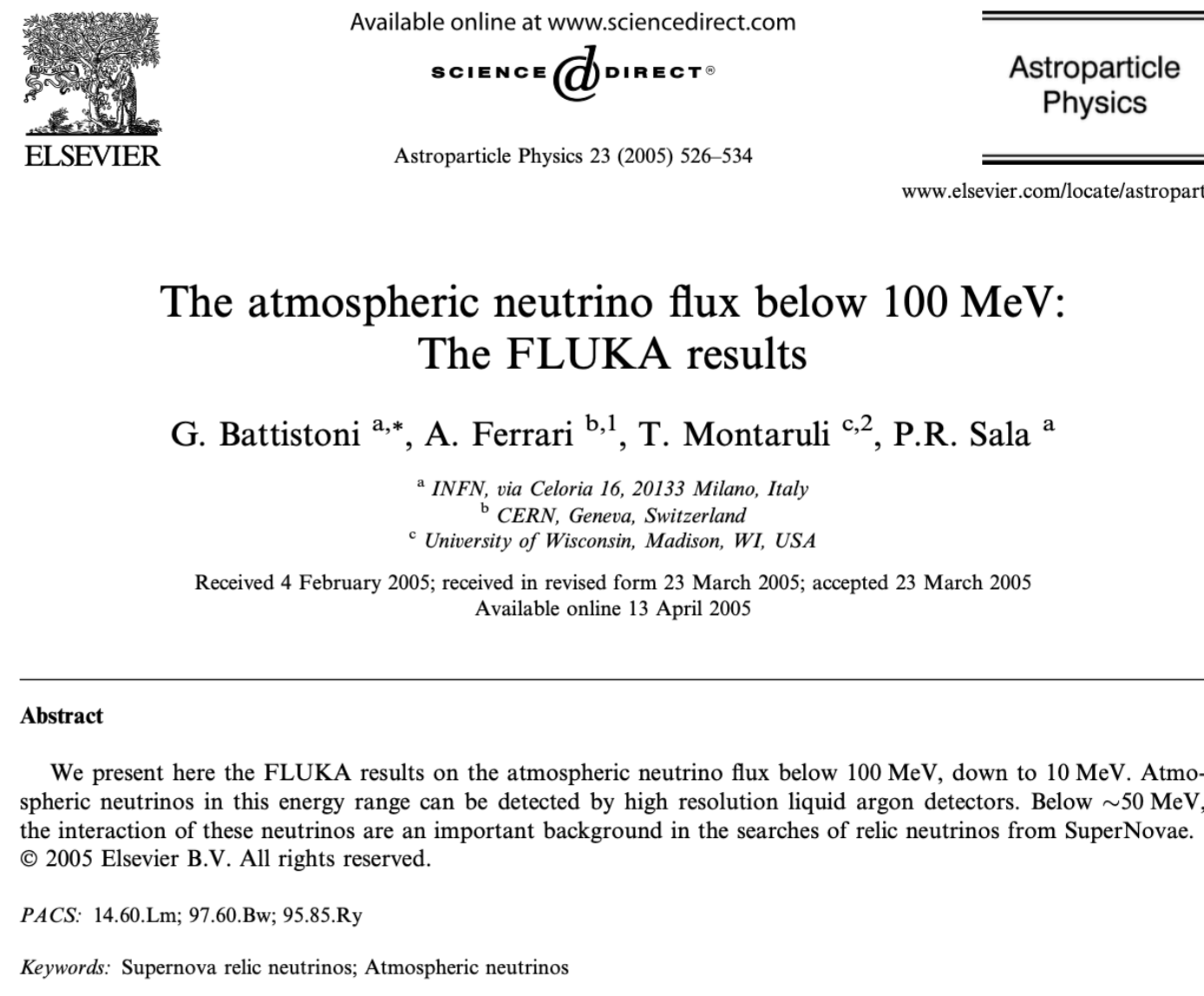


ECSNe = electron-capture supernovae
(marginal one around mass threshold, w/ ONeMg core)

D. Kresse et al., ApJ 909, 169 (2021)

Low Energy Atmospheric Neutrino Flux

- Current MC considers only >100 MeV atmospheric flux.
- Sato-san (ICRR) provided Honda calculation result for <100 MeV so we would like to check its impact.



1. Introduction

When a massive star ($\gtrsim 8M_{\odot}$) collapses as a Type II Supernova (SNII), $\sim 99\%$ of its energy is emitted as $\sim 10^{53}$ erg neutrinos. The neutrinos from all SNII occurred in the Universe should constitute

an isotropic cosmological flux of core-collapse SN Relic Neutrinos (SRN in the following). Recently Super-Kamiokande [1] and KamLAND [2] published their results on SRNs. SNO [3] presented a preliminary measurement of the solar $\bar{\nu}_e$ flux that could easily be adapted to this measurement. Besides SN physics, the SRN measurement can be used to constrain neutrino decay models since this process could substantially alter expected fluxes [4,5].

The main background sources for SRN are solar, atmospheric and possibly reactor neutrinos in the relevant energy range of $\lesssim 50$ MeV. Solar neutrinos

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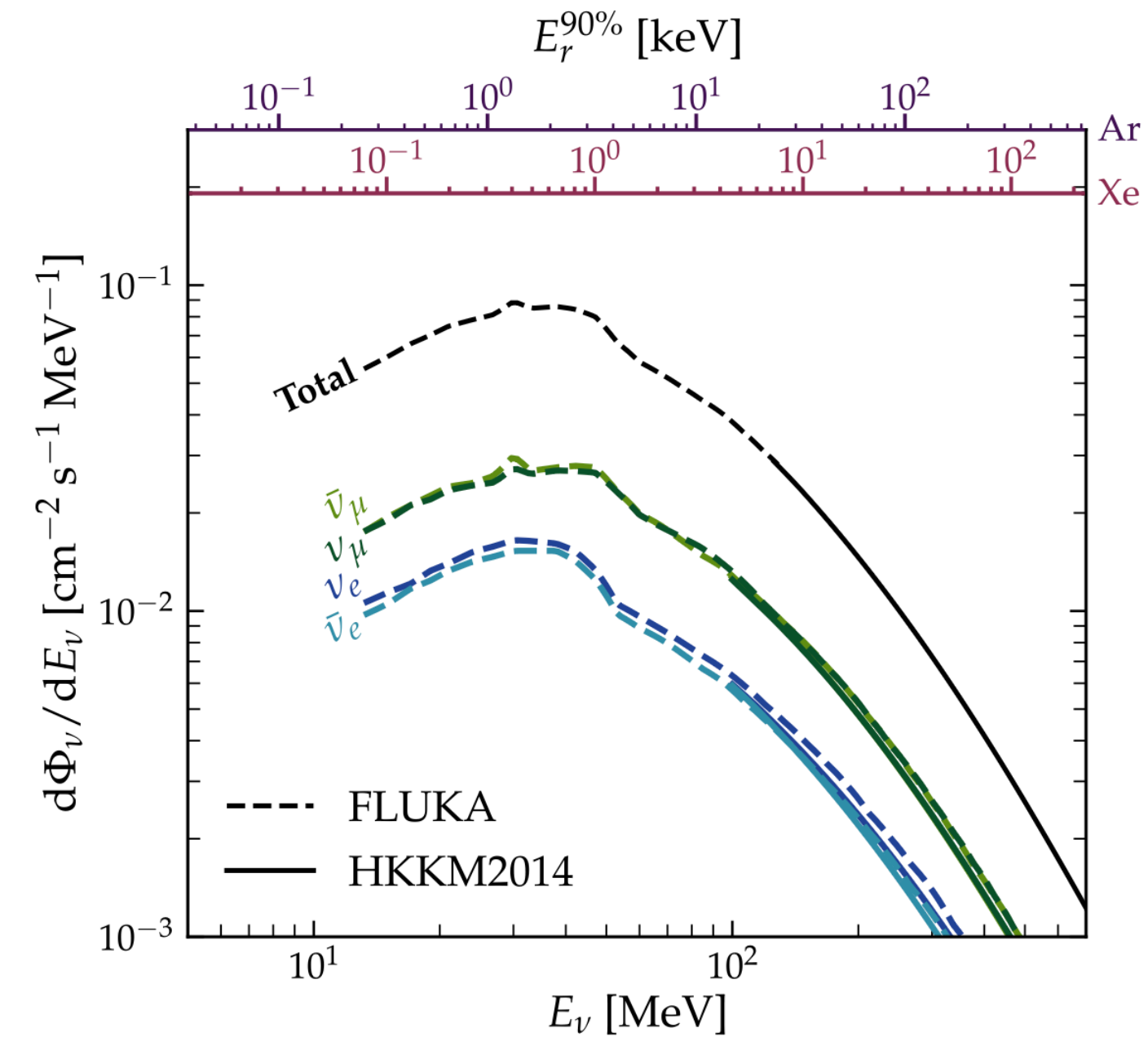
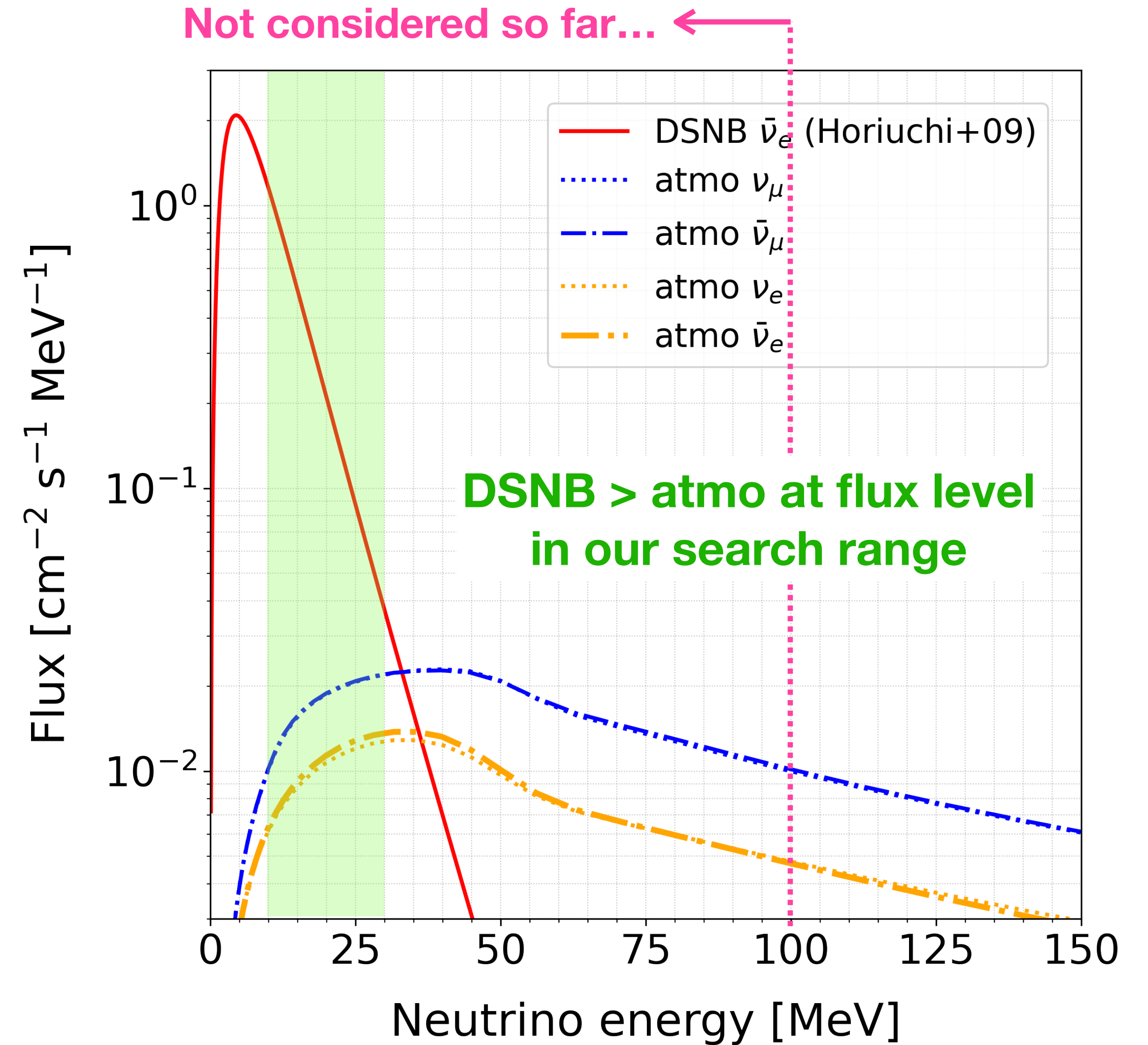
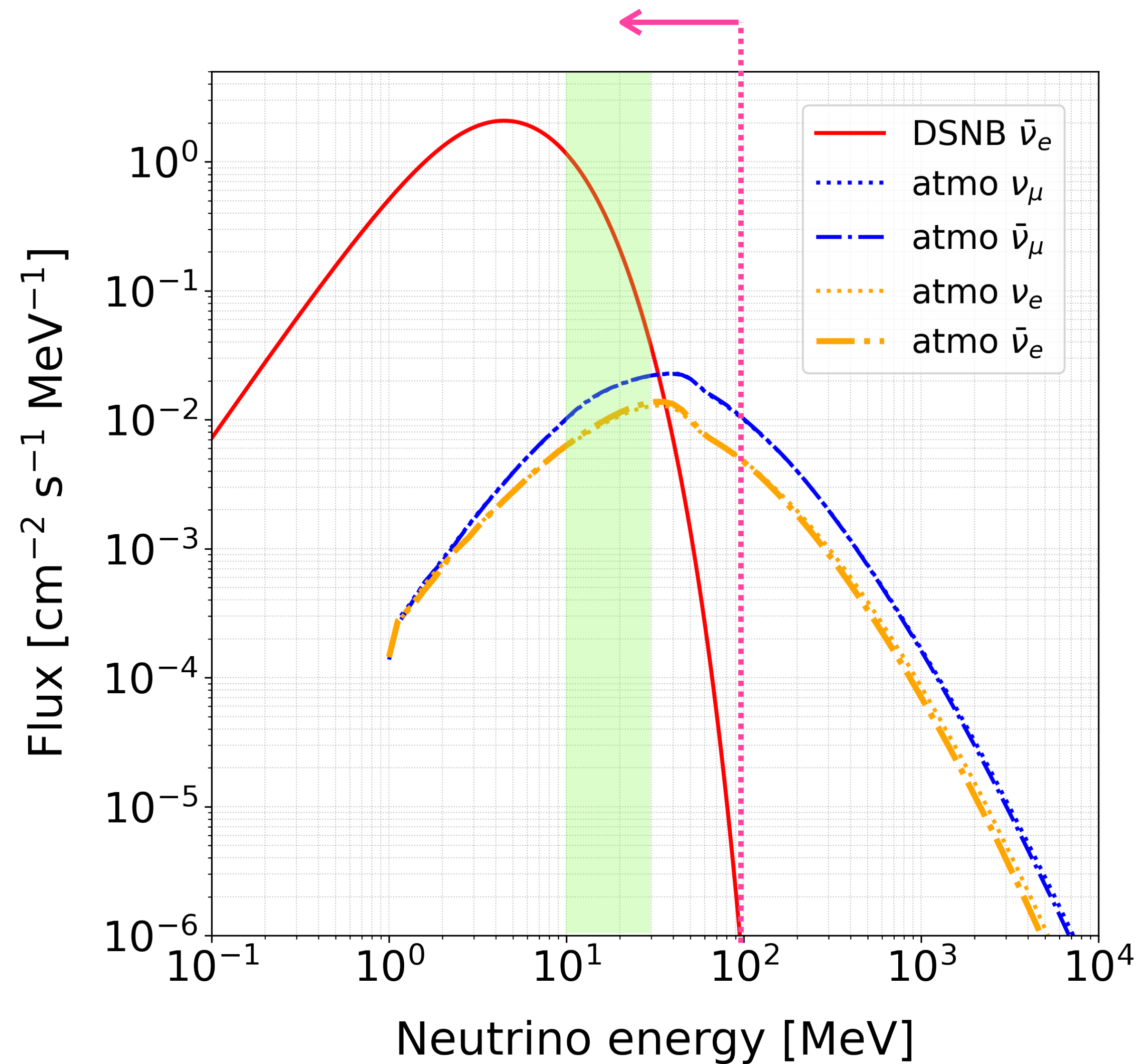
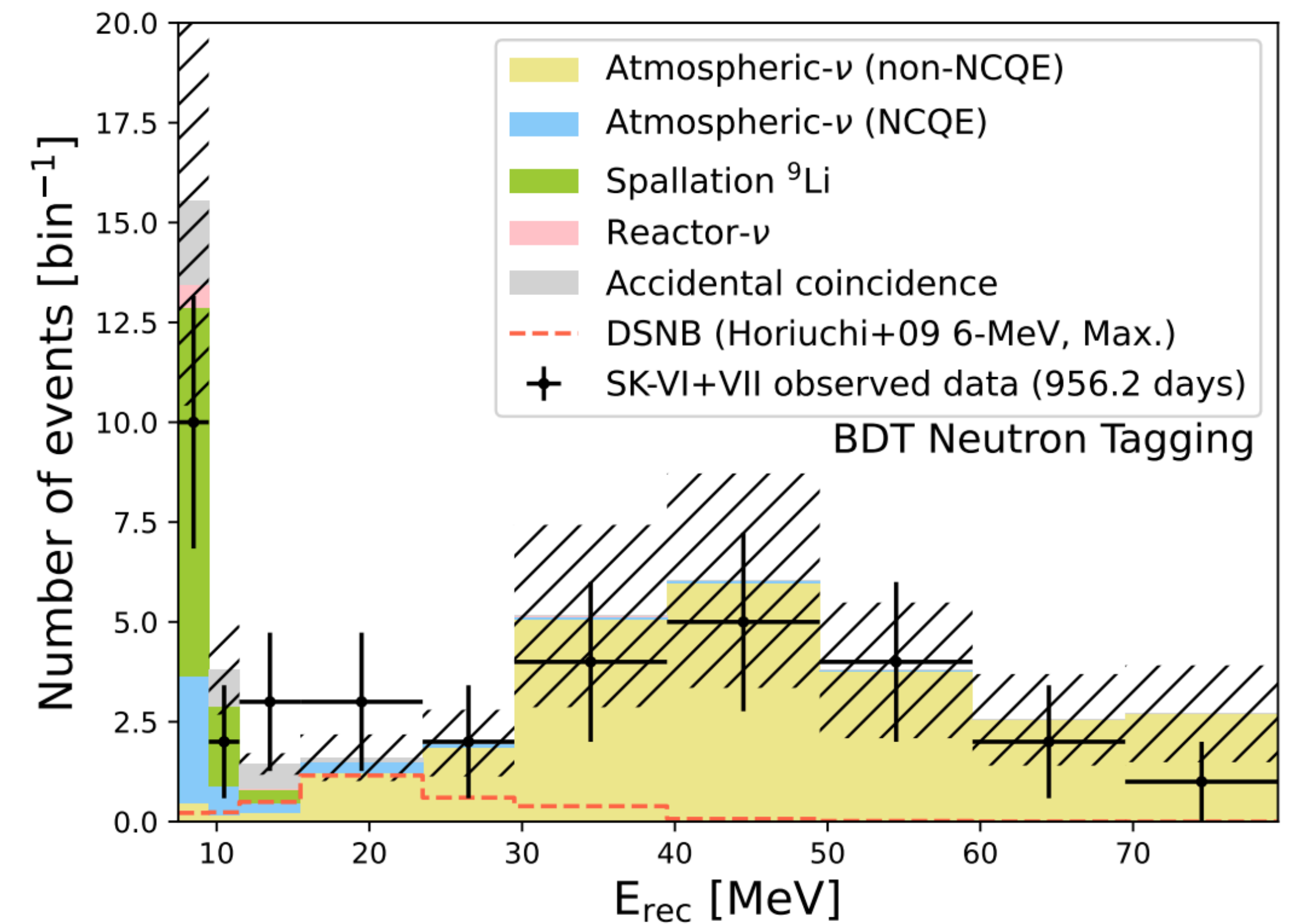
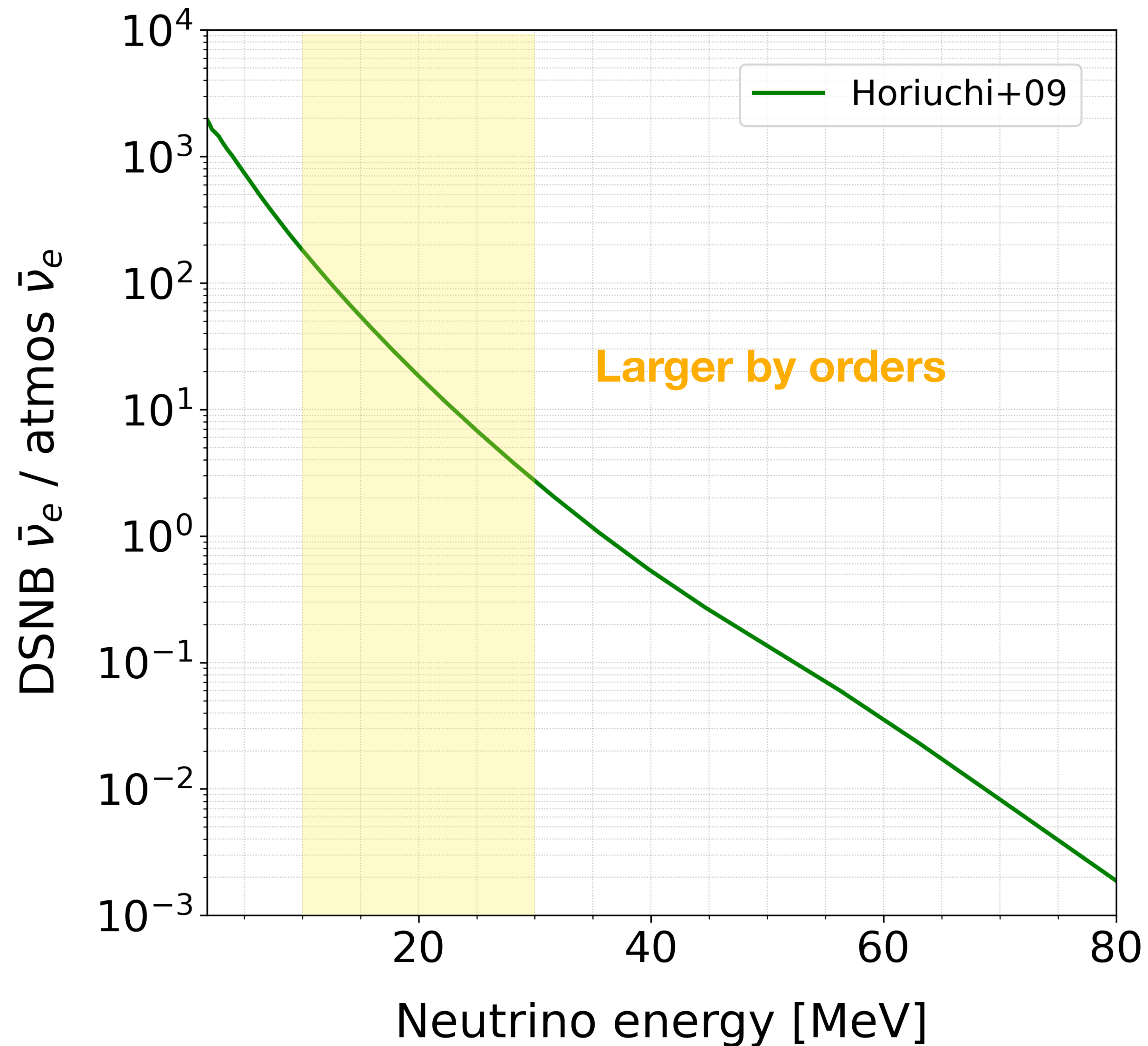


FIG. 1. The low energy atmospheric neutrino flux. The spectra from 13 MeV–1 GeV are taken from the FLUKA simulation [69] (dashed lines), whereas the higher energy components (for which we also have the angular distributions) are from the HKKM2014 simulation [70] (solid lines). We show each individual neutrino species (ν_e and $\bar{\nu}_e$ in blue, and ν_μ and $\bar{\nu}_\mu$ in green) as well as the total spectrum interpolated between the two simulations (black). On the upper horizontal axis we show $E_r^{90\%}$ for xenon and argon, which we define to be the energy above which lie 90% of CE ν NS recoils for the corresponding incoming neutrino energy.

LowE Flux Impact: Flux-level





Current atmo BKG prediction is comparable to DSNB, so low flux impact seems small (covered by systematics).

Different Interaction Picture

- Electron antineutrinos are probably okay, but how about others? We would like to make **a direct estimate in a reconstructed energy frame, considering the final state.**
- NEUT is not available for <100 MeV interactions because it assumes *at least one* nucleon recoil; however, **at low energies, neutrinos are more likely to interact with nucleus.**
- We are evaluating the impact using **SKSNSim.**

THE ASTROPHYSICAL JOURNAL, 965:91 (6pp), 2024 April 10

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<https://doi.org/10.3847/1538-4357/ad344e>



Supernova Burst and Diffuse Supernova Neutrino Background Simulator for Water Cherenkov Detectors

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Received 2024 January 31; revised 2024 March 8; accepted 2024 March 11; published 2024 April 10

Abstract

If a Galactic core-collapse supernova explosion occurs in the future, it will be critical to rapidly alert the community to the direction of the supernova by utilizing neutrino signals in order to enable the initiation of follow-up optical observations. In addition, there is anticipation that observation of the diffuse supernova neutrino

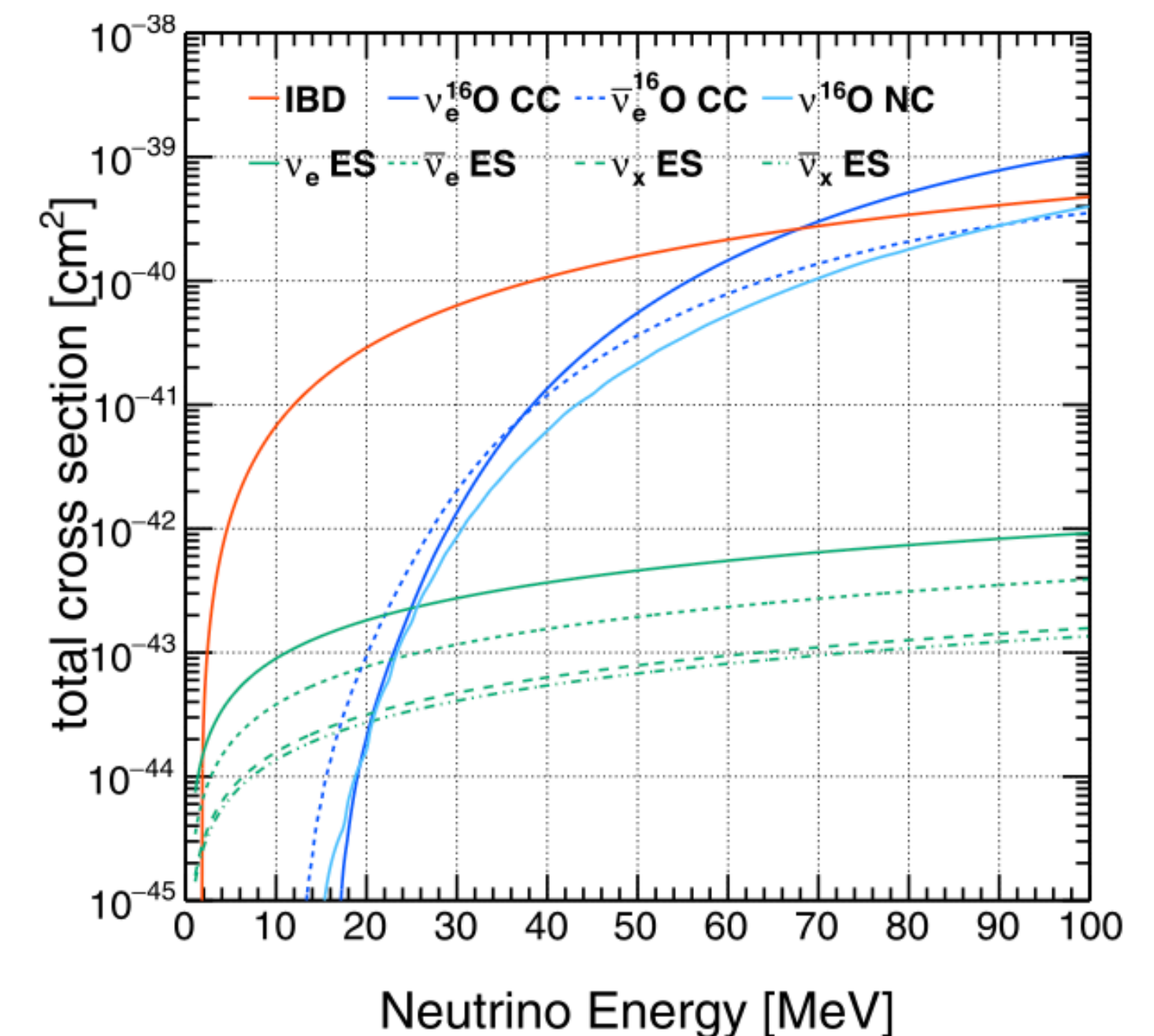
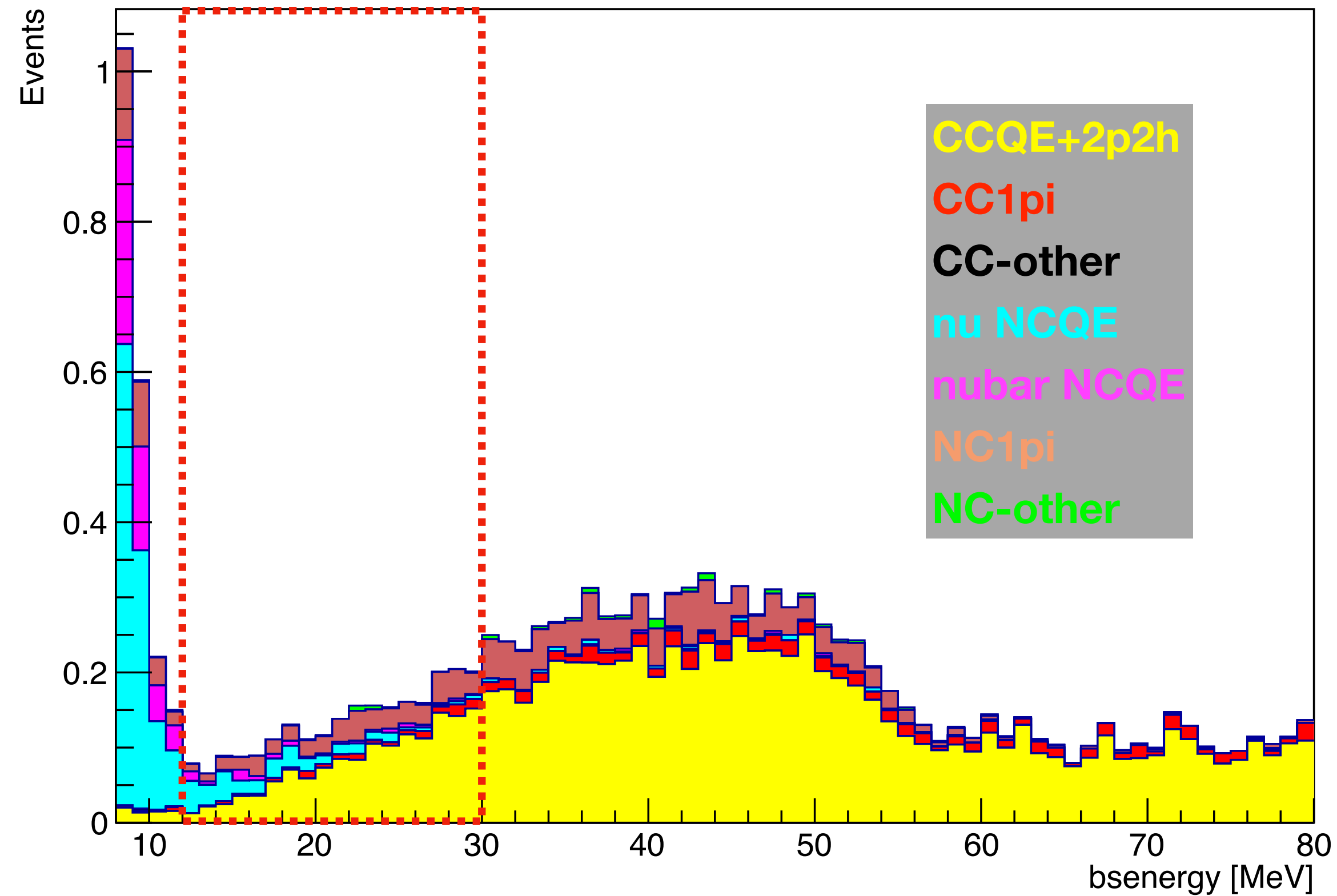


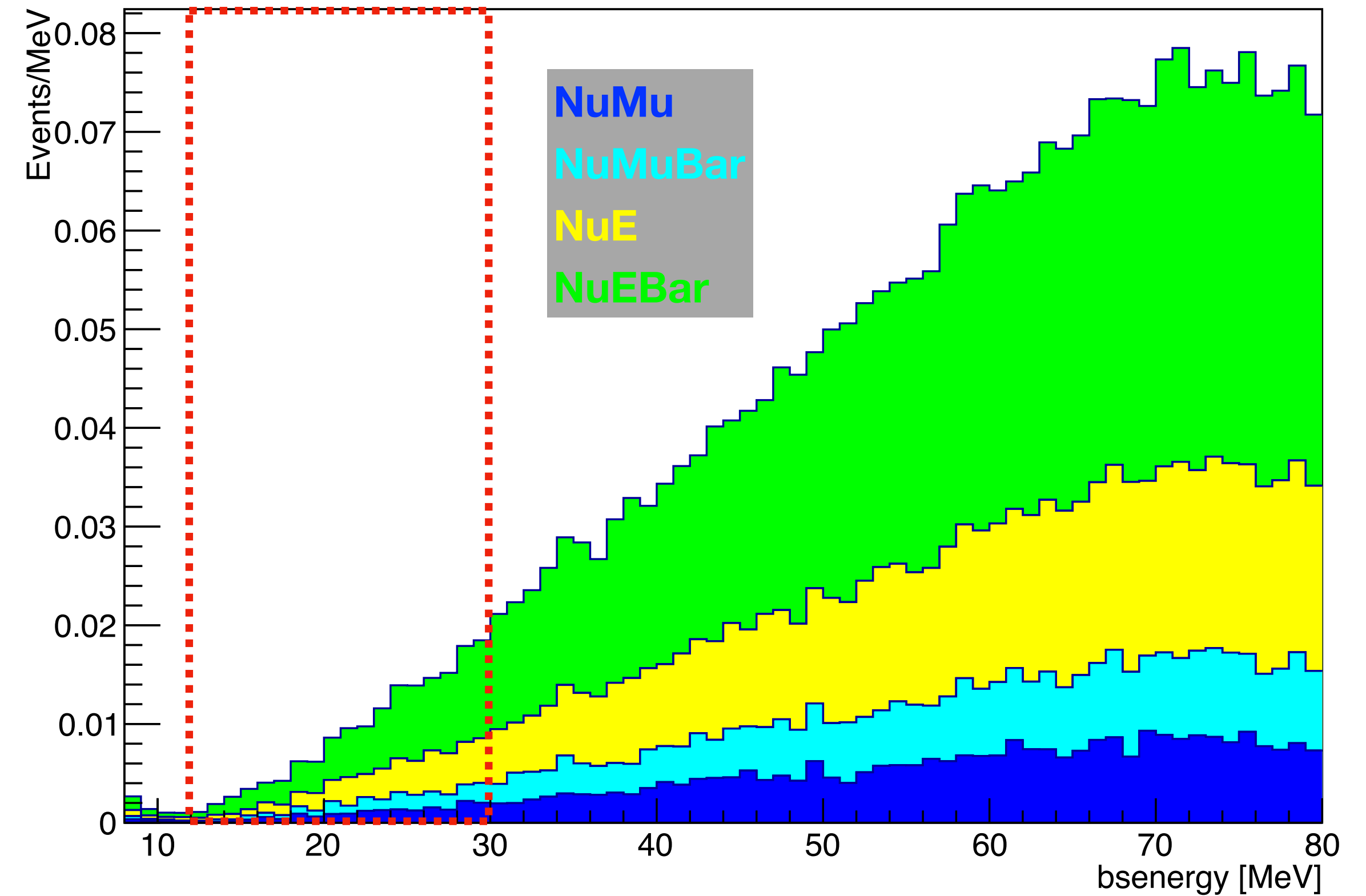
Figure 1. Total cross sections of neutrinos with water as a function of neutrino energy. The solid red line indicates IBD, and the green lines represent ES with a neutrino flavor: ν_e (solid), $\bar{\nu}_e$ (dotted), ν_x (dashed), and $\bar{\nu}_x$ (dotted-dashed). The solid blue and dashed blue lines represent ^{16}O CC ν_e and $\bar{\nu}_e$, respectively. The dotted-dashed light blue line indicates ^{16}O NC interaction. The cross sections are calculated according to Strumia & Vissani (2003) for IBD, Bahcall et al. (1995) for ES, Nakazato et al. (2018) for ^{16}O CC interaction, and Langanke et al. (1996) and Kolbe et al. (2002) for ^{16}O NC interaction.

Result (SK7 w/ thetaC, MSG, NTag)

>100 MeV + NEUT



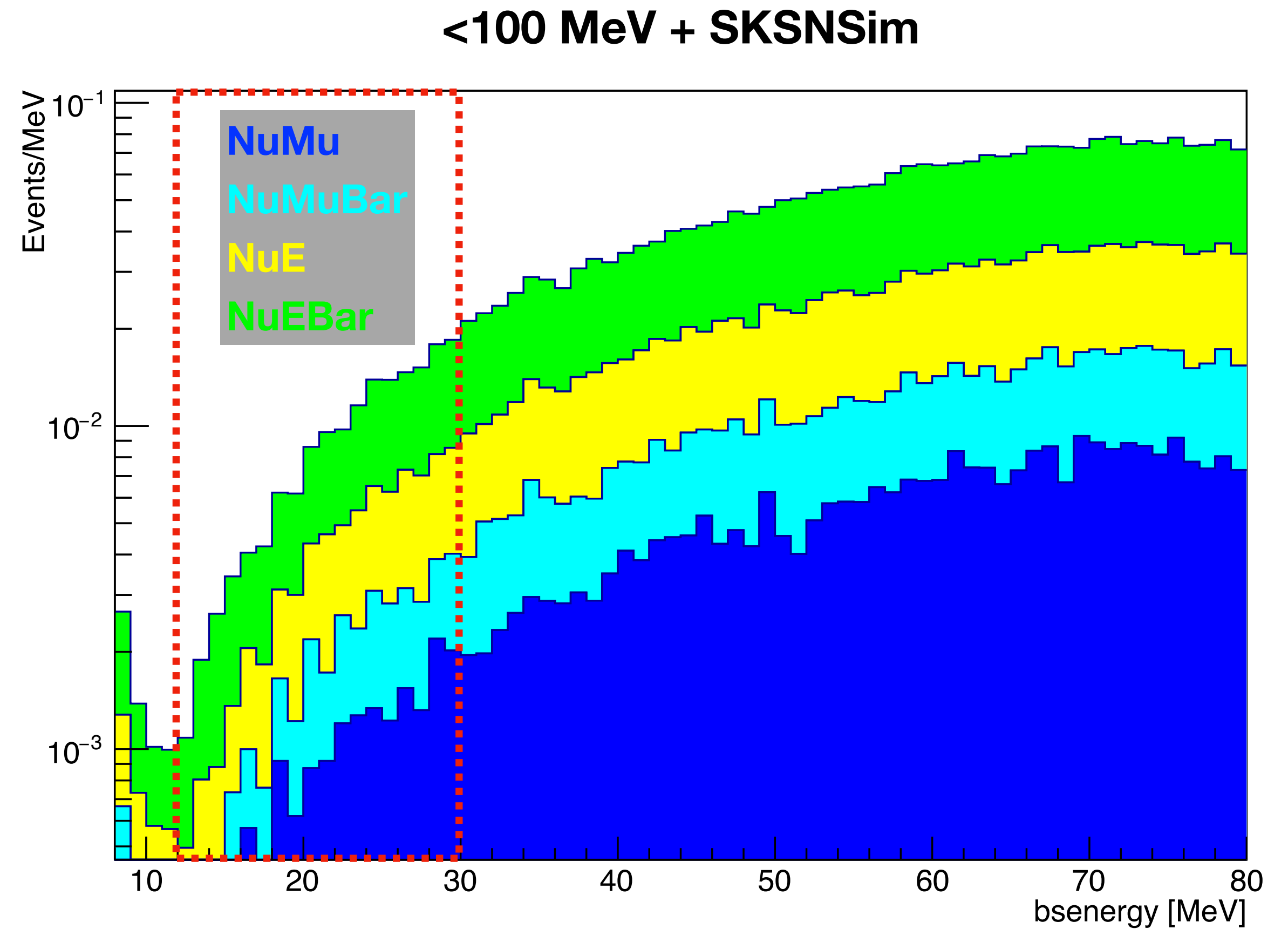
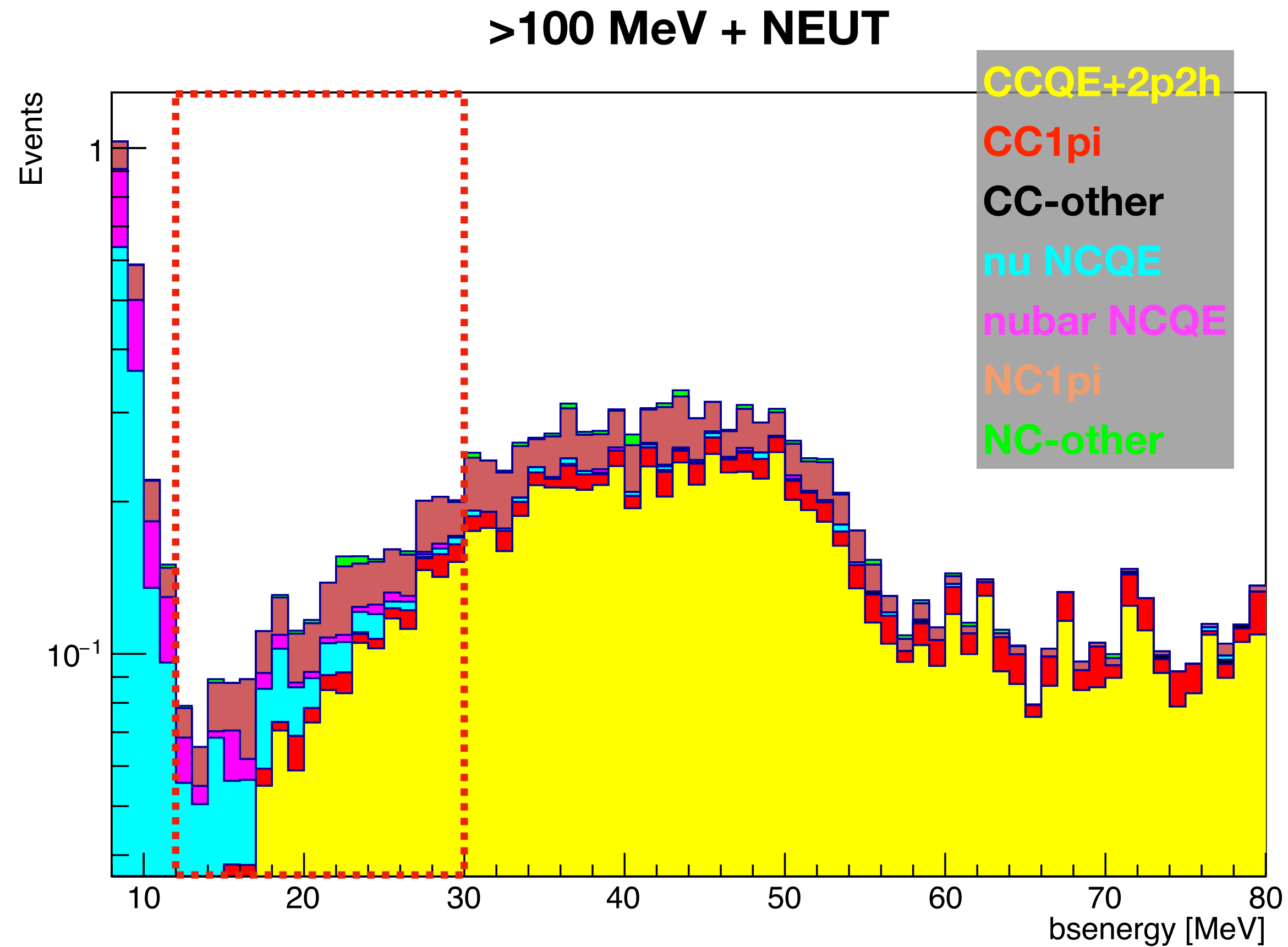
<100 MeV + SKSNSim



a few ~ 10% contribution in the signal region.

This is well covered by the currently assigned systematics (36% scale etc).

Result (SK7 w/ thetaC, MSG, NTag)

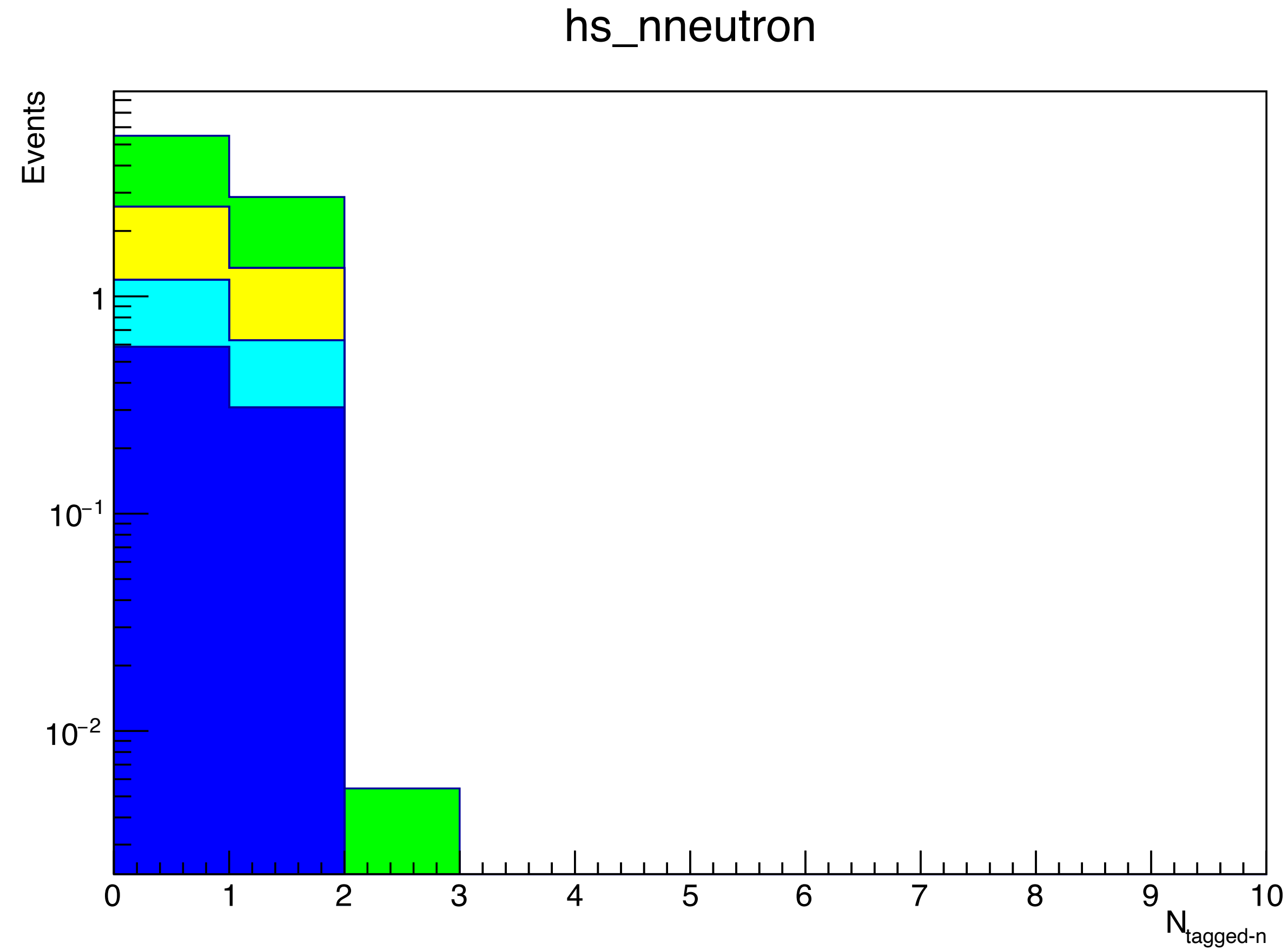


a few ~ 10% contribution in the signal region.

This is well covered by the currently assigned systematics (36% scale etc).

LowE ATM Flux Distributions (w/ thetaC, MSG, NTag)

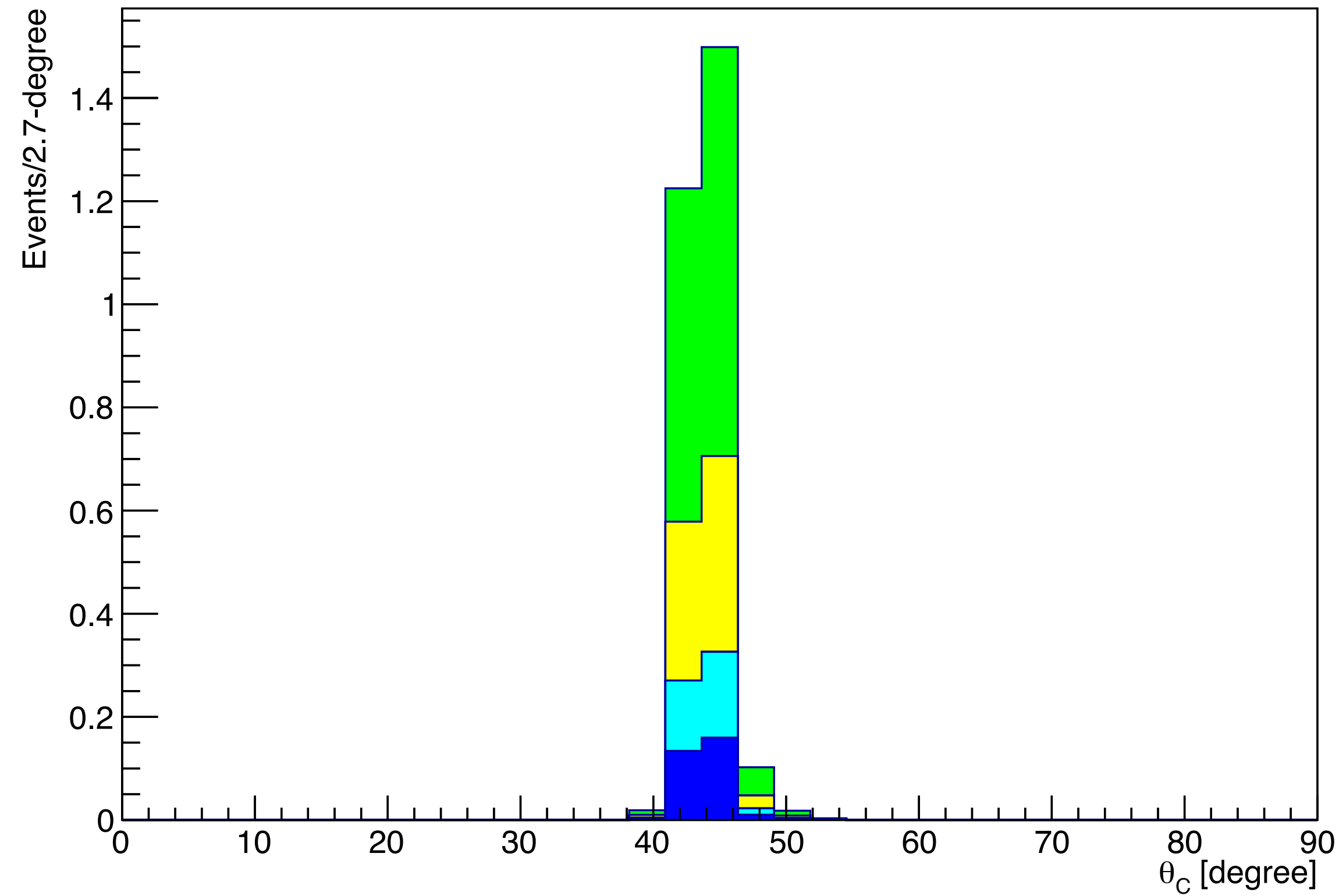
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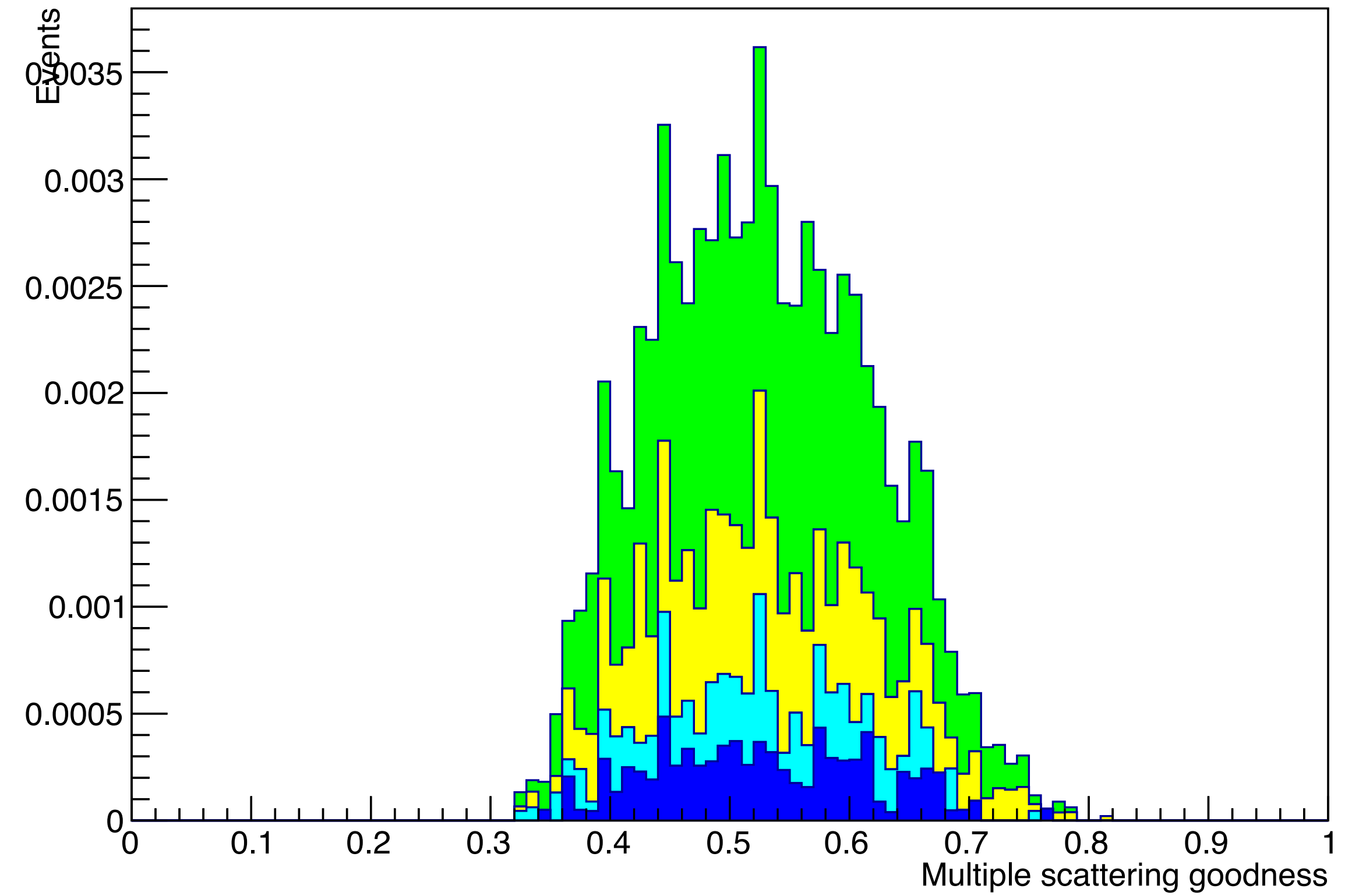
LowE ATM Flux Distributions (w/ thetaC, MSG, NTag)

66

hs_angle_ntag



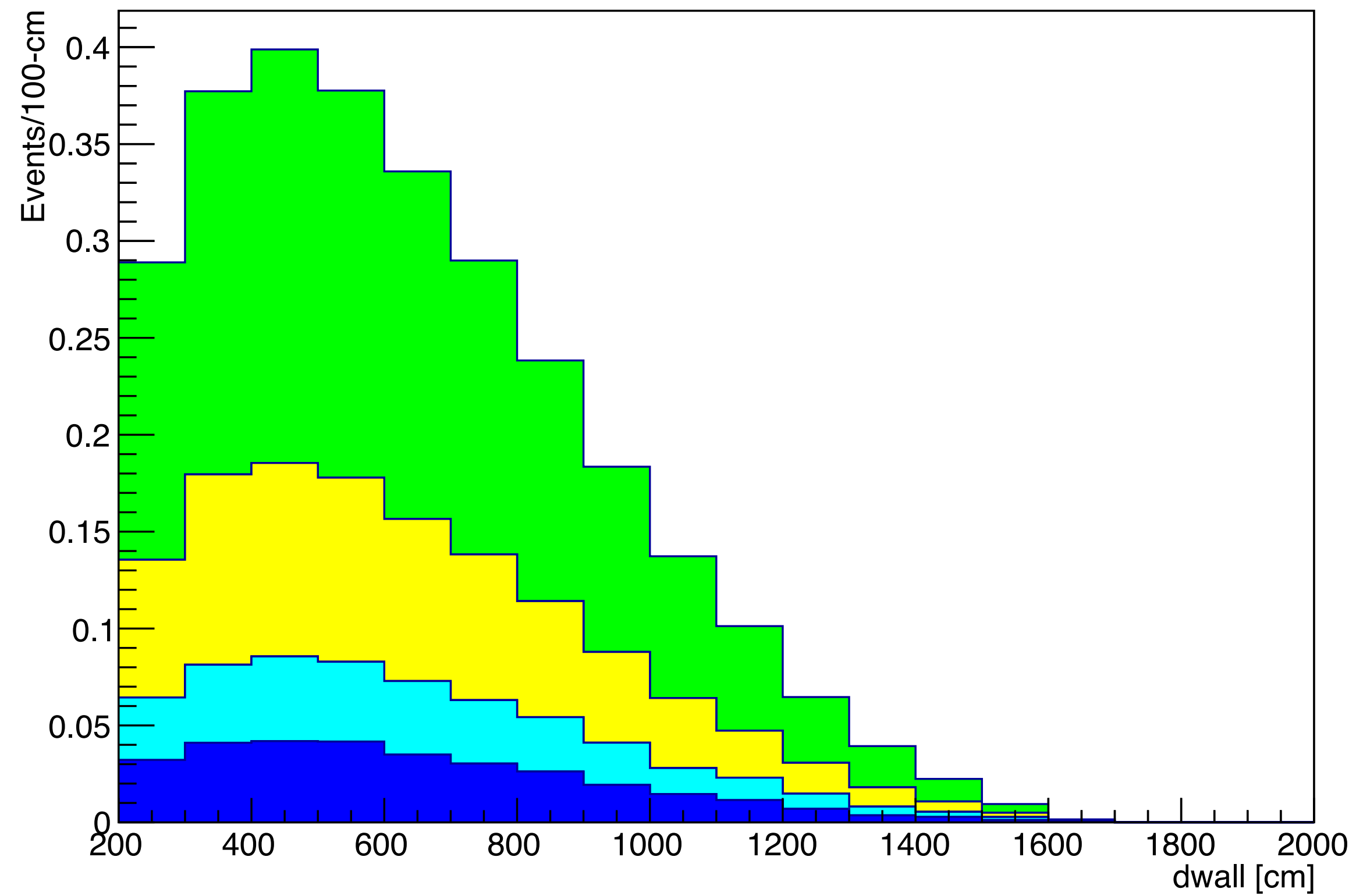
hs_msg_ntag



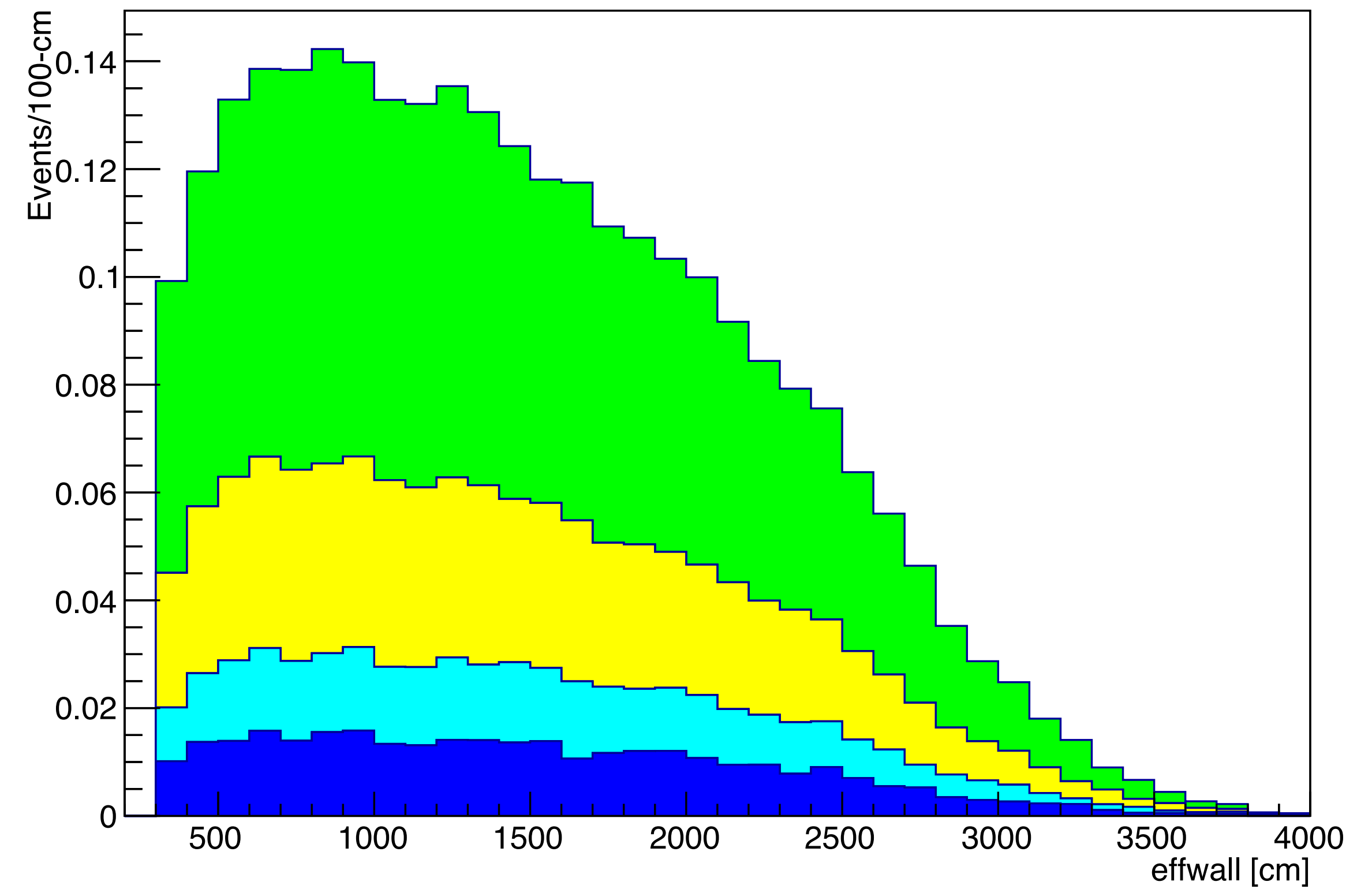
LowE ATM Flux Distributions (w/ thetaC, MSG, NTag)

67

hs_dwall_ntag

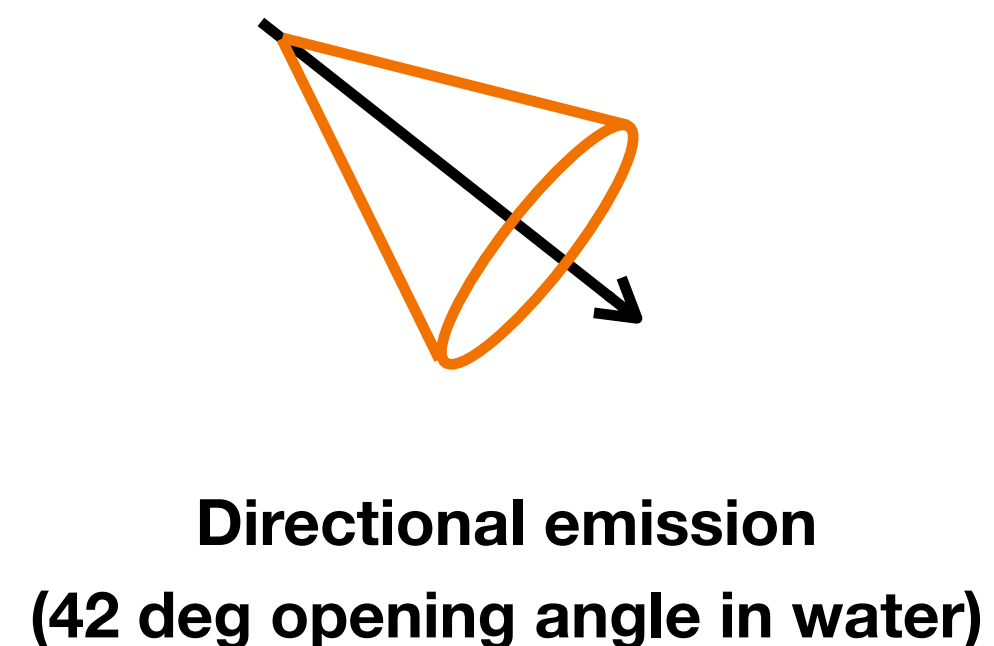
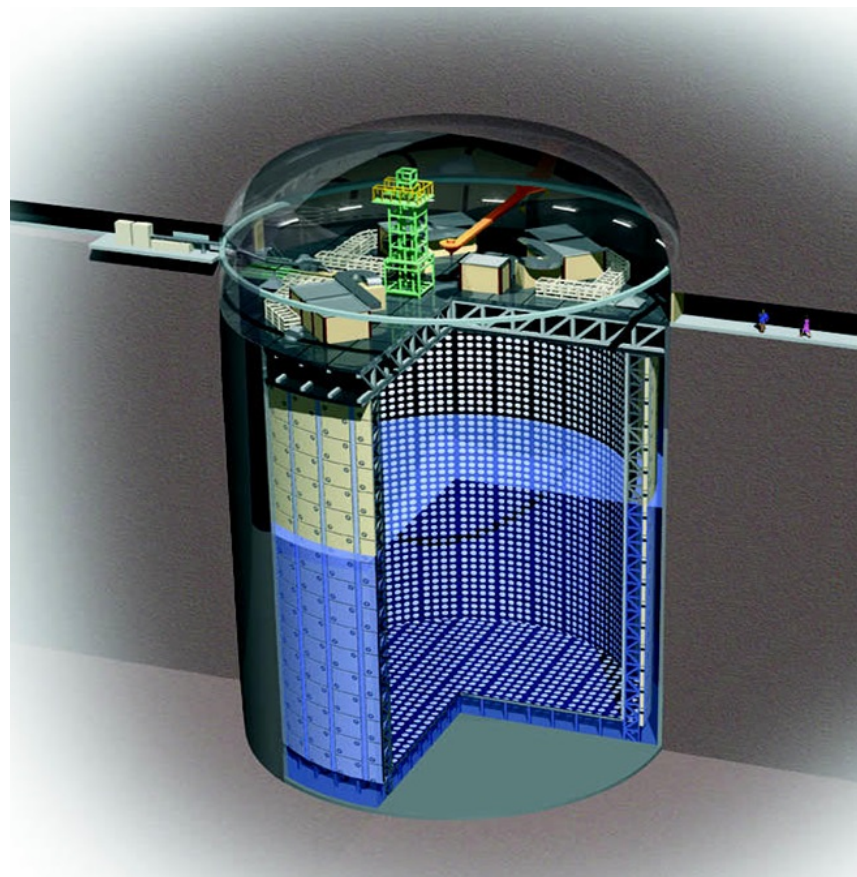


hs_effwall_ntag



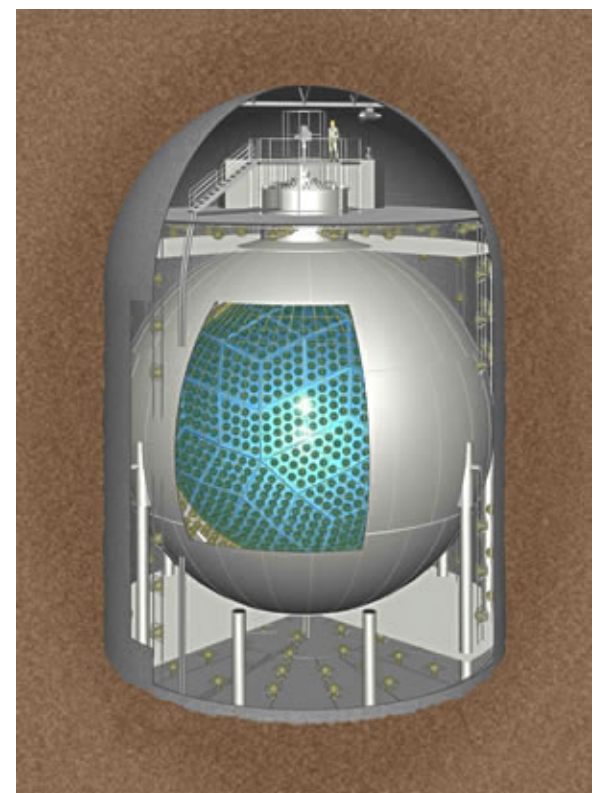
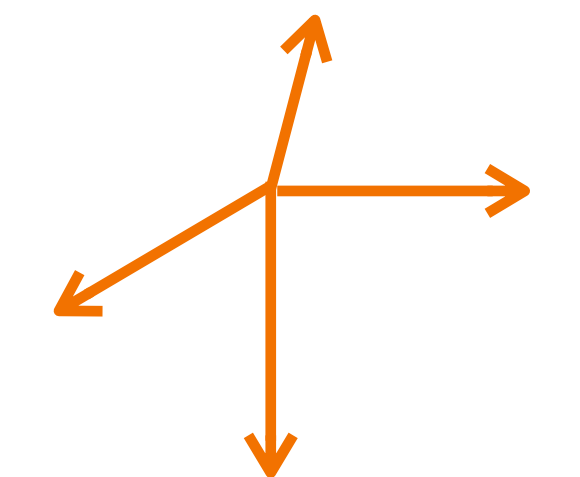
Water Cherenkov

- **Good scalability** ($O(10)$ kton $\rightarrow$ $O(100)$ kton)
- **Small light yield**
 - higher energy threshold
 - worse reconstruction performance
- Background modeling
 - Insensitive to low energy hadronic particles
 - More chains for muon spallation isotopes
 - Smaller reference dataset for neutrino interactions



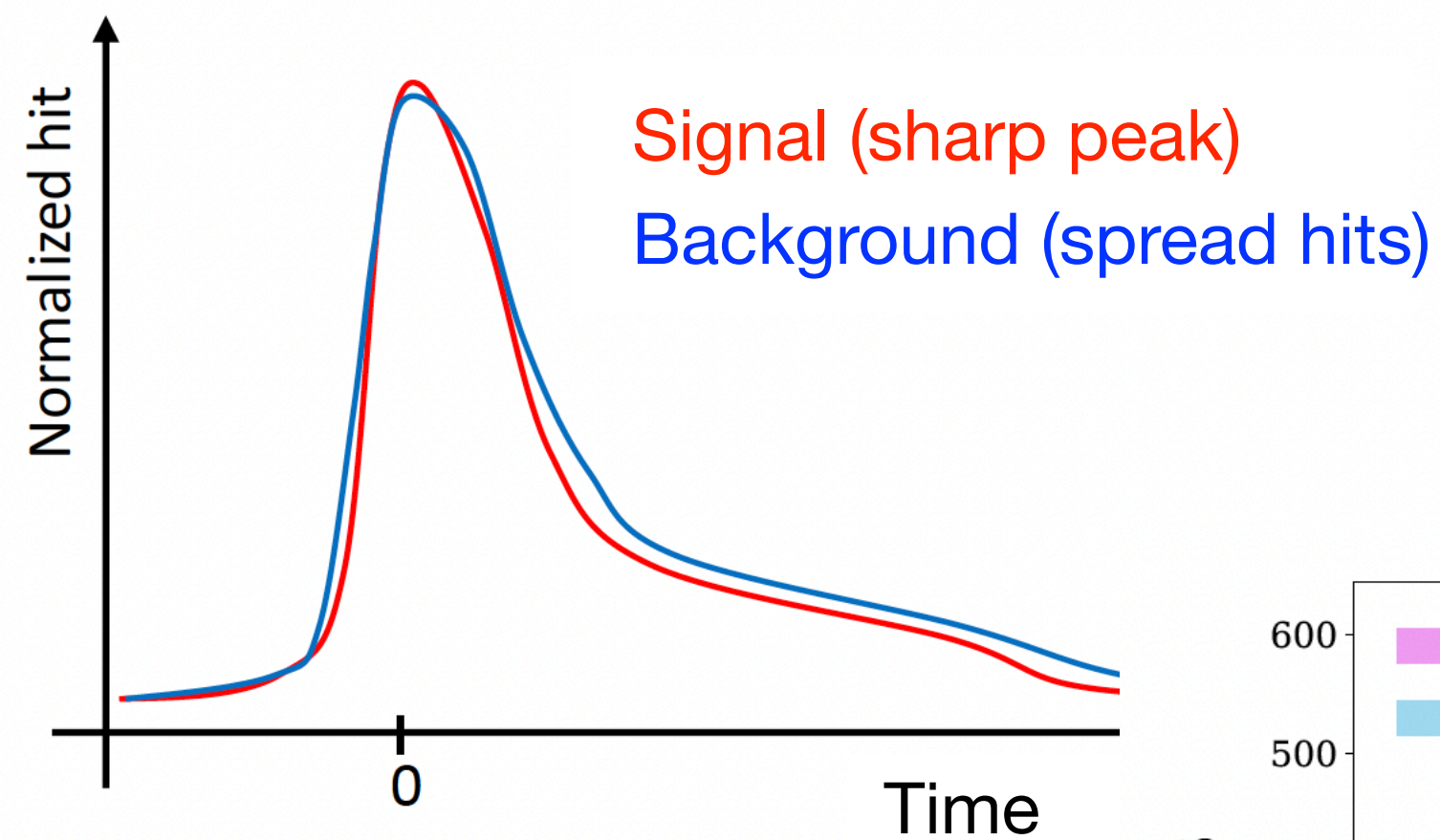
Liquid Scintillator

- **Worse scalability** ($O(1)$ kton $\rightarrow$ $O(10)$ kton)
- **Large light yield**
 - lower energy threshold
 - good reconstruction performance
- Background modeling
 - Sensitive to almost any particles
 - Less chains for muon spallation isotopes
 - A lot of scintillation-based neutrino cross section measurement results available

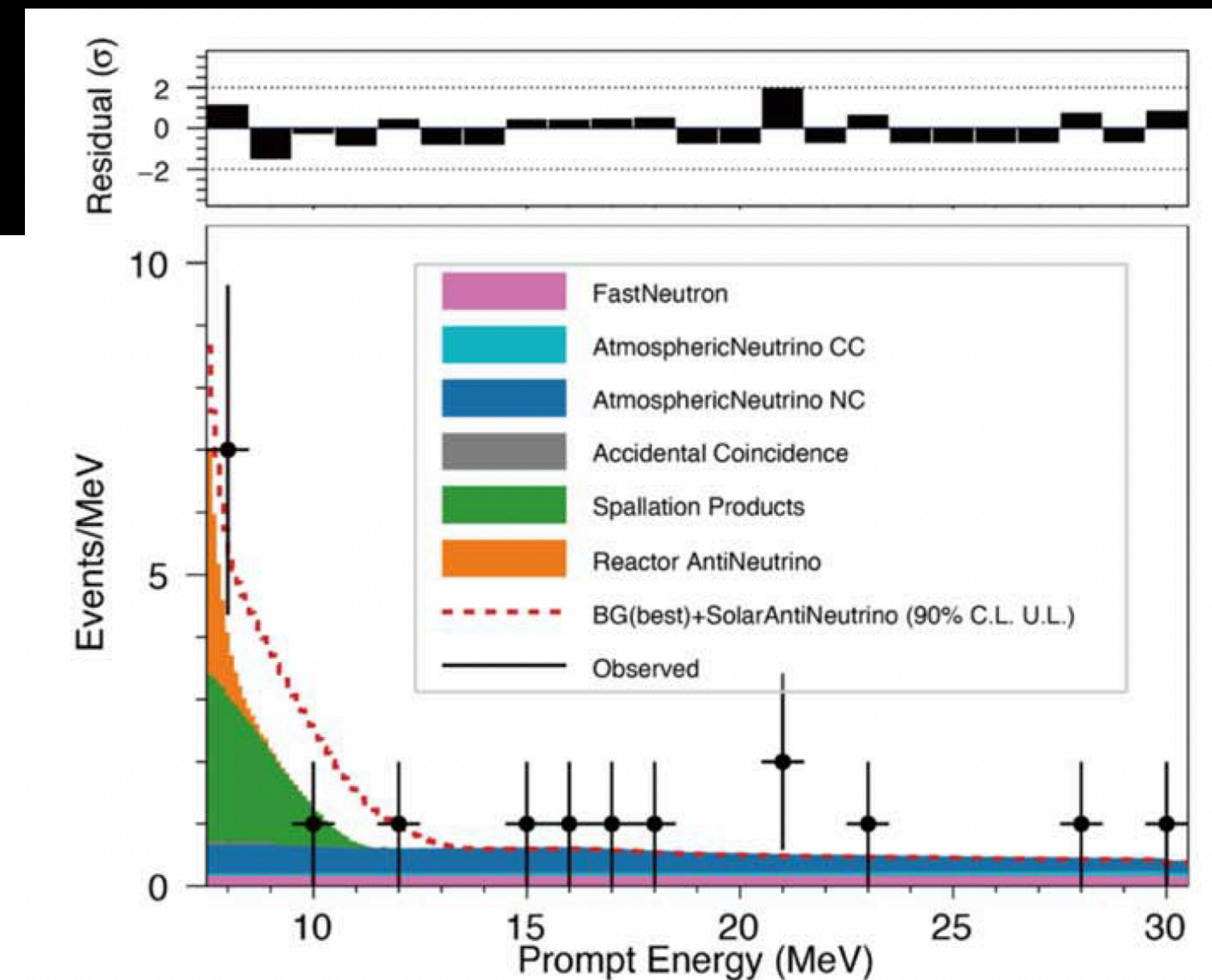
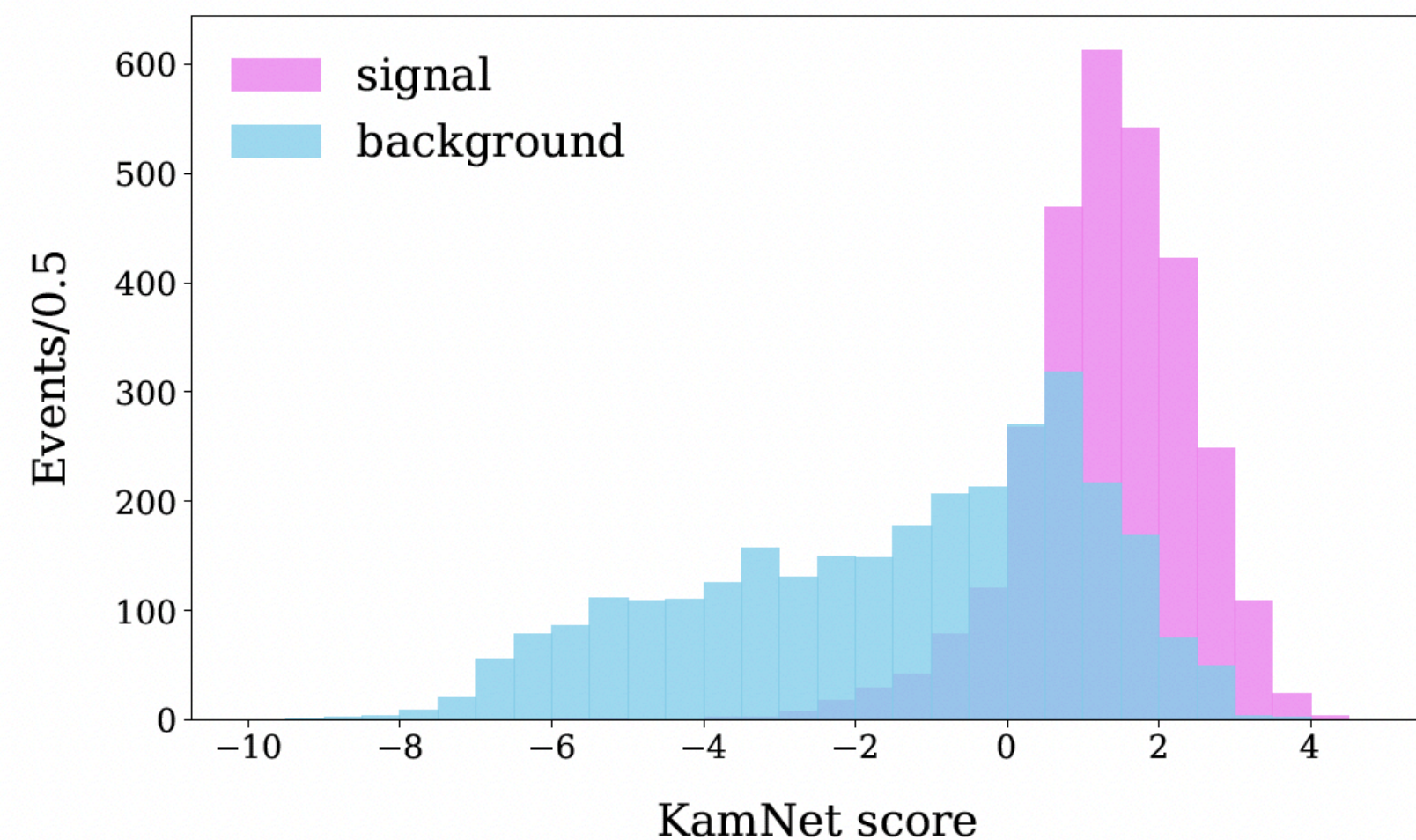


Search at KamLAND

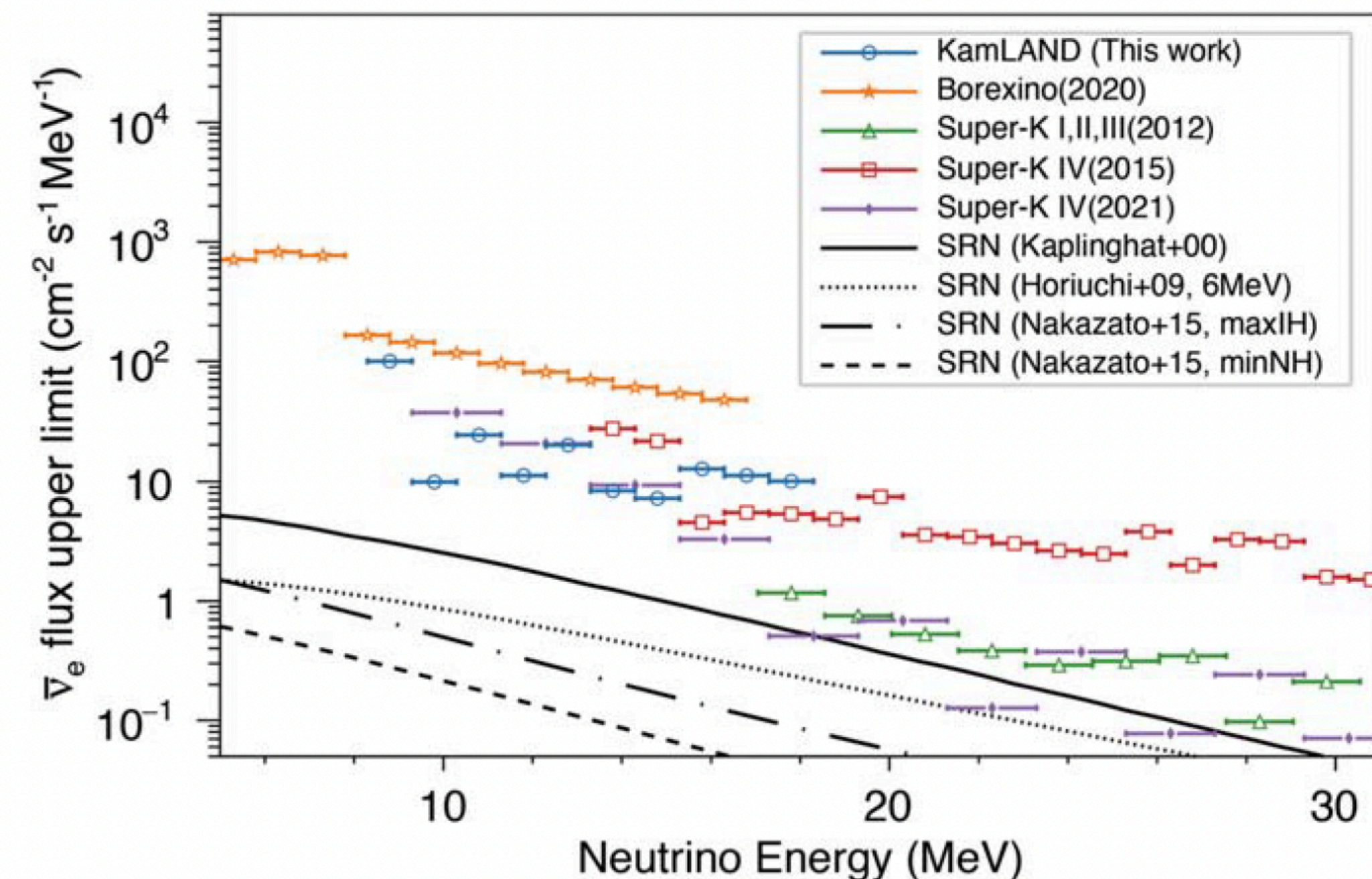
- KamLAND performed a search in 2022 using its reactor-off period.
- They are now introducing DNN to capture signal/background difference in *space* and *time* distributions — a new result with this discriminator will be shown soon!



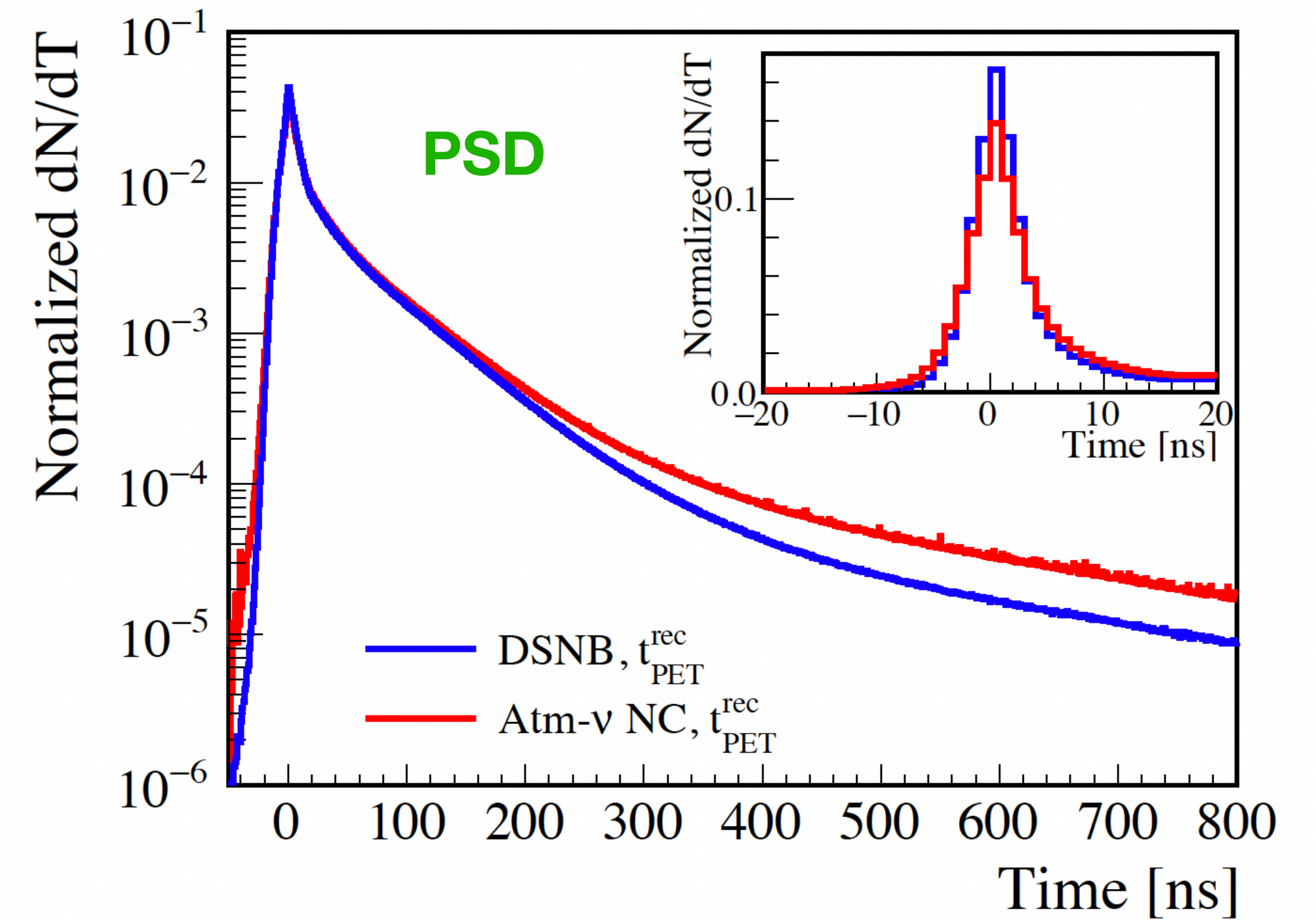
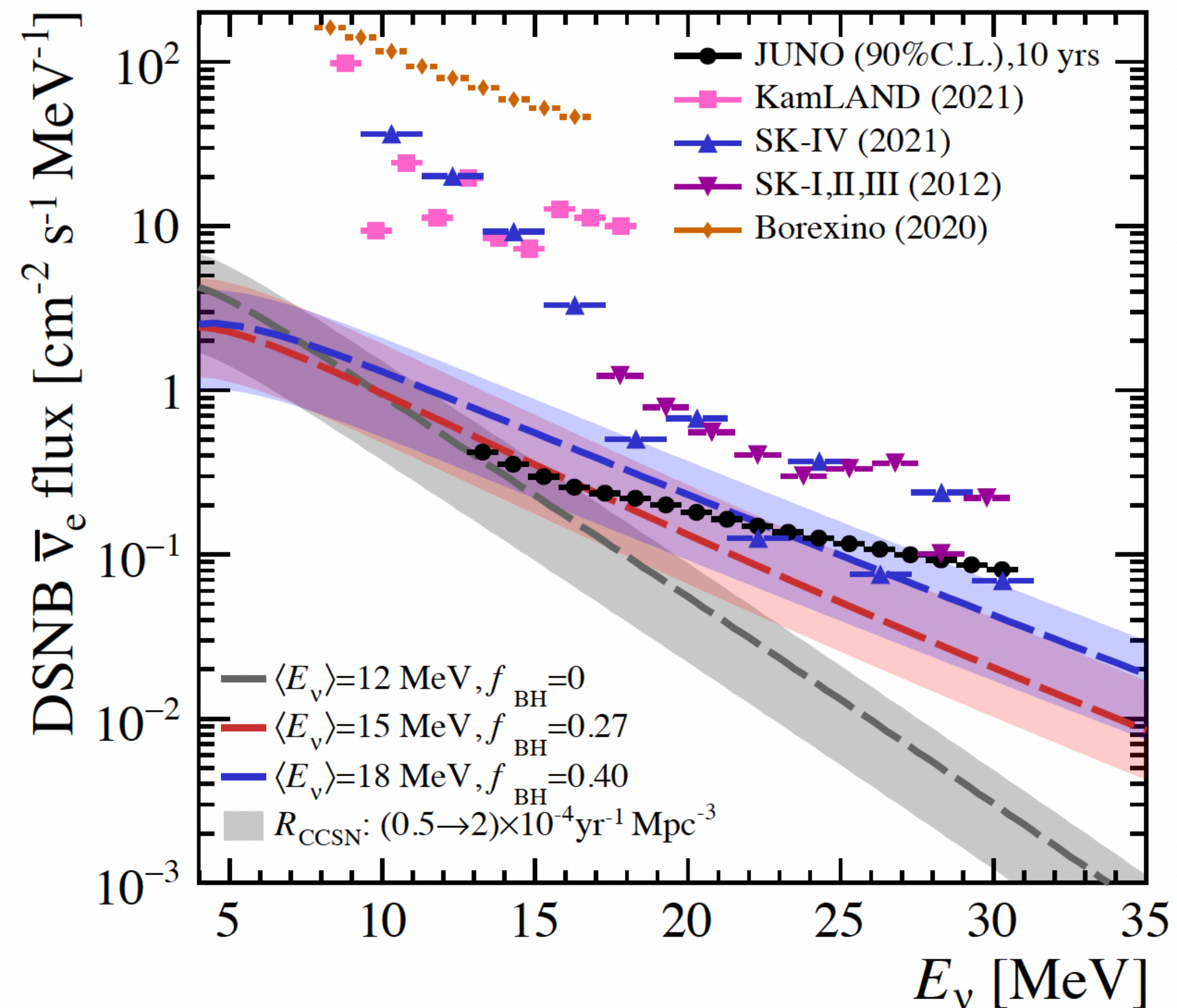
[M. Eizuka, PoS \(ICRC2025\) 1036](#)



[S. Abe et al. \(KamLAND Collaboration\), ApJ 925, 14 \(2022\)](#)



With benefits of their large volume (~ 14.7 kton) + strong background rejection based on the pulse shape, they expect to achieve good reach to DSNB models after 10 years.



[A. Abusleme et al. \(JUNO Collaboration\), JCAP 10, 033 \(2022\)](#)

[J. Cheng et al., arXiv:2311.16550 \[hep-ex\]](#)