Study/Reduce atmospheric neutrino backgrounds for detecting DSNB in Super-Kamiokande

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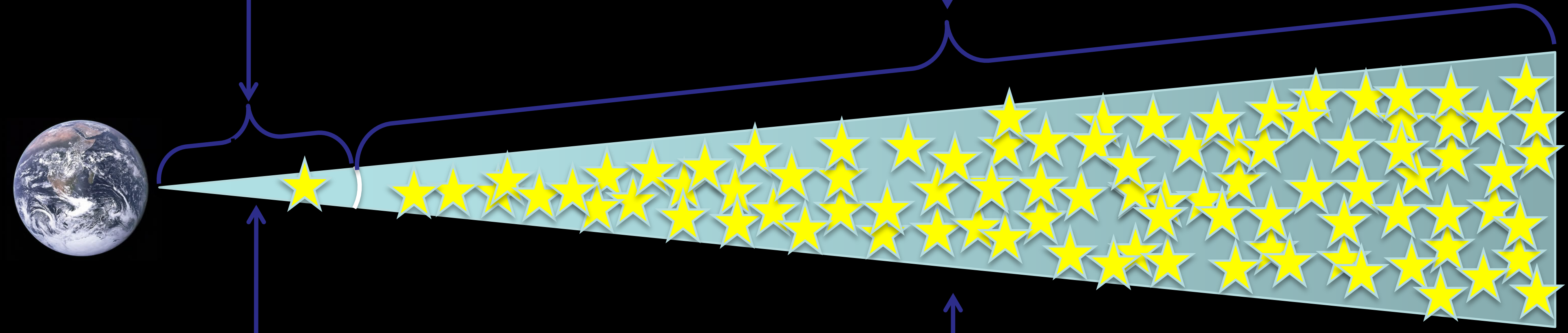
CCAPP, The Ohio State University

6th PIKIO Meeting @ University of Notre Dame, IN

Diffuse Supernova Neutrino Background (DSNB)

Galactic Supernova | DSNB

Detected ν per burst: N >> 1 | N << 1



(Figure credit: John Beacom)

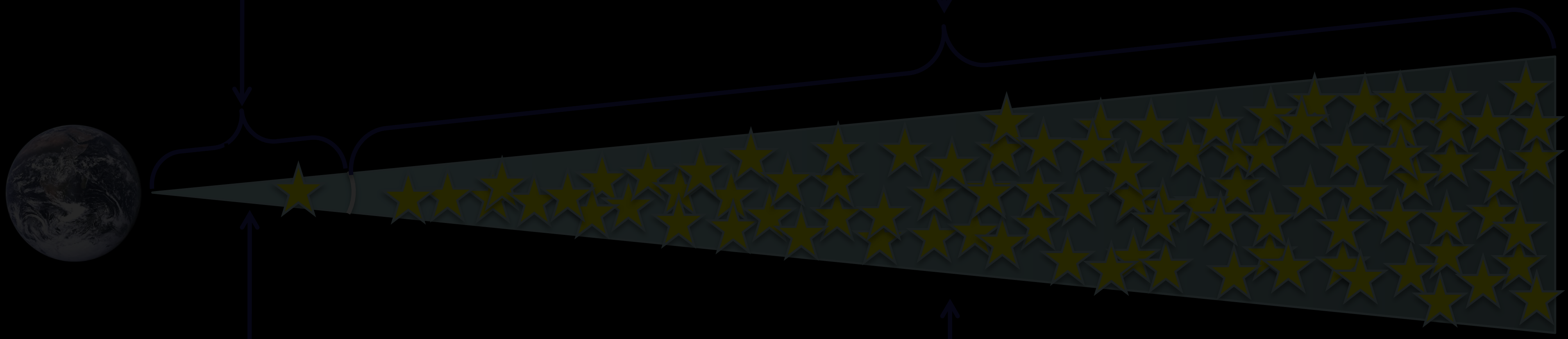
Burst rate: ~ 0.01/yr | $\sim 10^8$/yr

Guaranteed steady neutrino flux

($\sim 10\ \mathrm{cm^{-2}s^{-1}}$)

Diffuse Supernova Neutrino ~~Background~~ Signal (DSNB)

	Galactic Supernova	DSNB
Detected ν per burst:	N >> 1	N << 1



(Figure credit: John Beacom)

Burst rate:	~ 0.01/yr	~ 10^8/yr

Guaranteed steady neutrino flux

(~ 10 $cm^{-2}s^{-1}$)

Why Detecting DSNB is so Important?

- (Almost) Same physics as galactic supernova
    i. Particle physics: neutrino properties & BSM
       (electric dipole/magnetic moment, BSM involving neutrinos, …)
    ii. Astrophysics: lots of supernova physics unreachable by photons
- More than galactic supernova
    i. Rate of star formation, core collapse, and dark collapse, …
- Pushing neutrino frontiers to cosmic distance!!

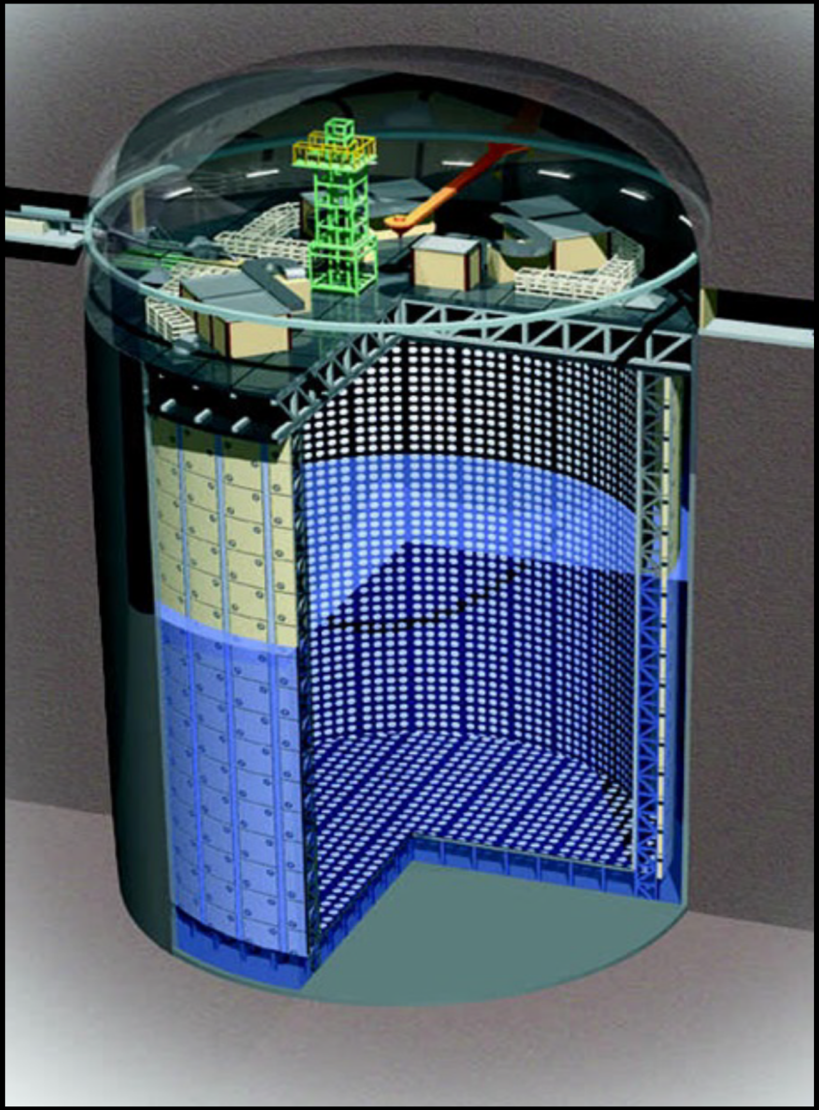
(More about DSNB: Beacom, Ann.Rev.Nucl.Part.Sci. 2010, arXiv:1004.3311)

DSNB Detection

- Super-Kamiokande (SK)
  Water Cherenkov Detector

- Detection process
  $\bar{\nu}_e + p \rightarrow n + e^+$ (Inverse Beta Decay)

- ~ 5 events/yr (theory prediction)
  So ~ 100 events collected so far,
  but not identified.



(Figure credit: SK website)

Large Backgrounds

- **Atm. $\nu_\mu/\bar{\nu}_\mu$ (Dominant)**

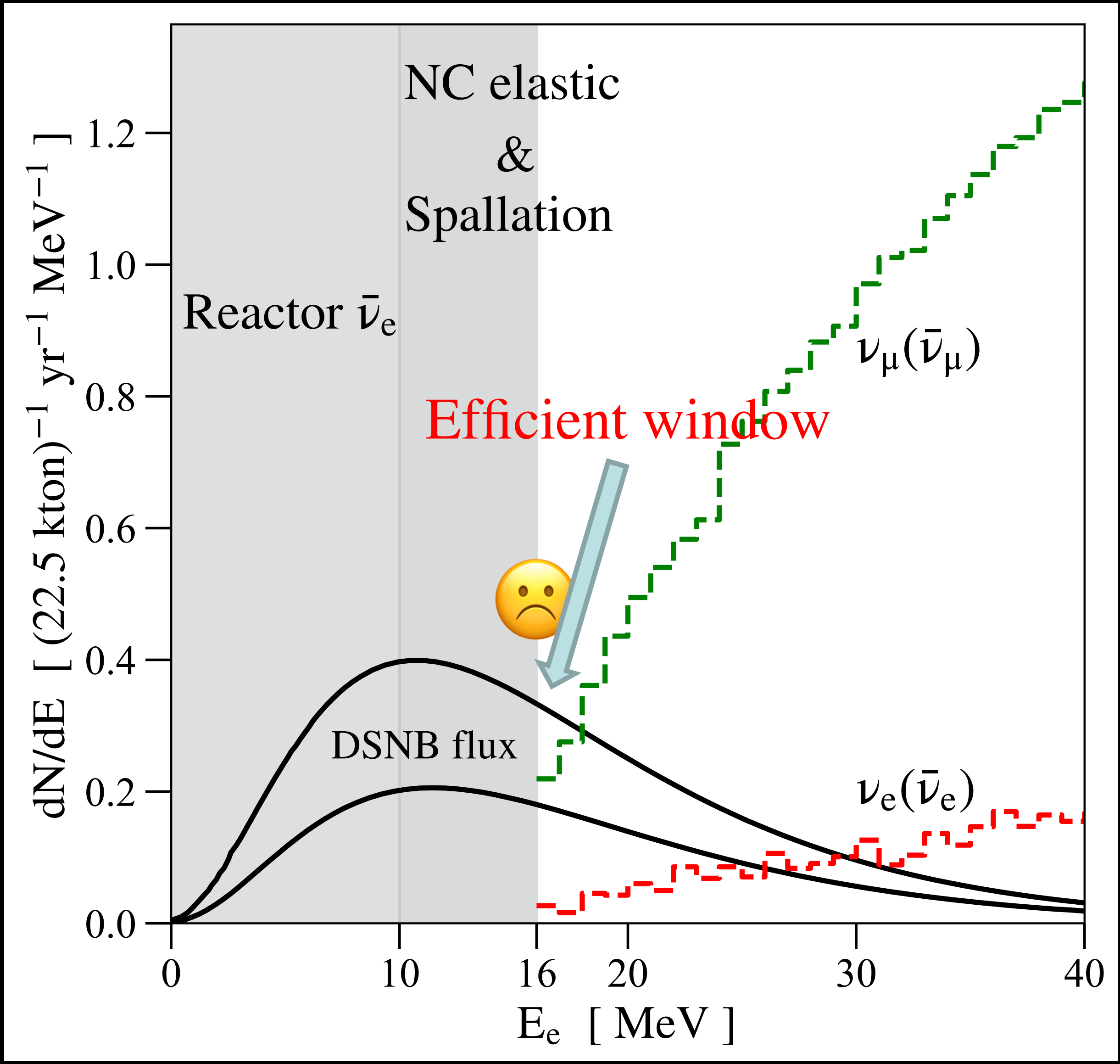
  $\nu_\mu(\bar{\nu}_\mu) + H_2O \rightarrow X + \mu^-(\mu^+)$, etc.

  K_μ< 55 MeV, invisible

  μ decay to e, mimic DSNB events

- **Atm. $\nu_e/\bar{\nu}_e$**

  $\nu_e(\bar{\nu}_e) + H_2O \rightarrow X + e^-(e^+)$



SK-Gd, New Era of DSNB Detection

- Add Gd (Gadolinium) to SK water

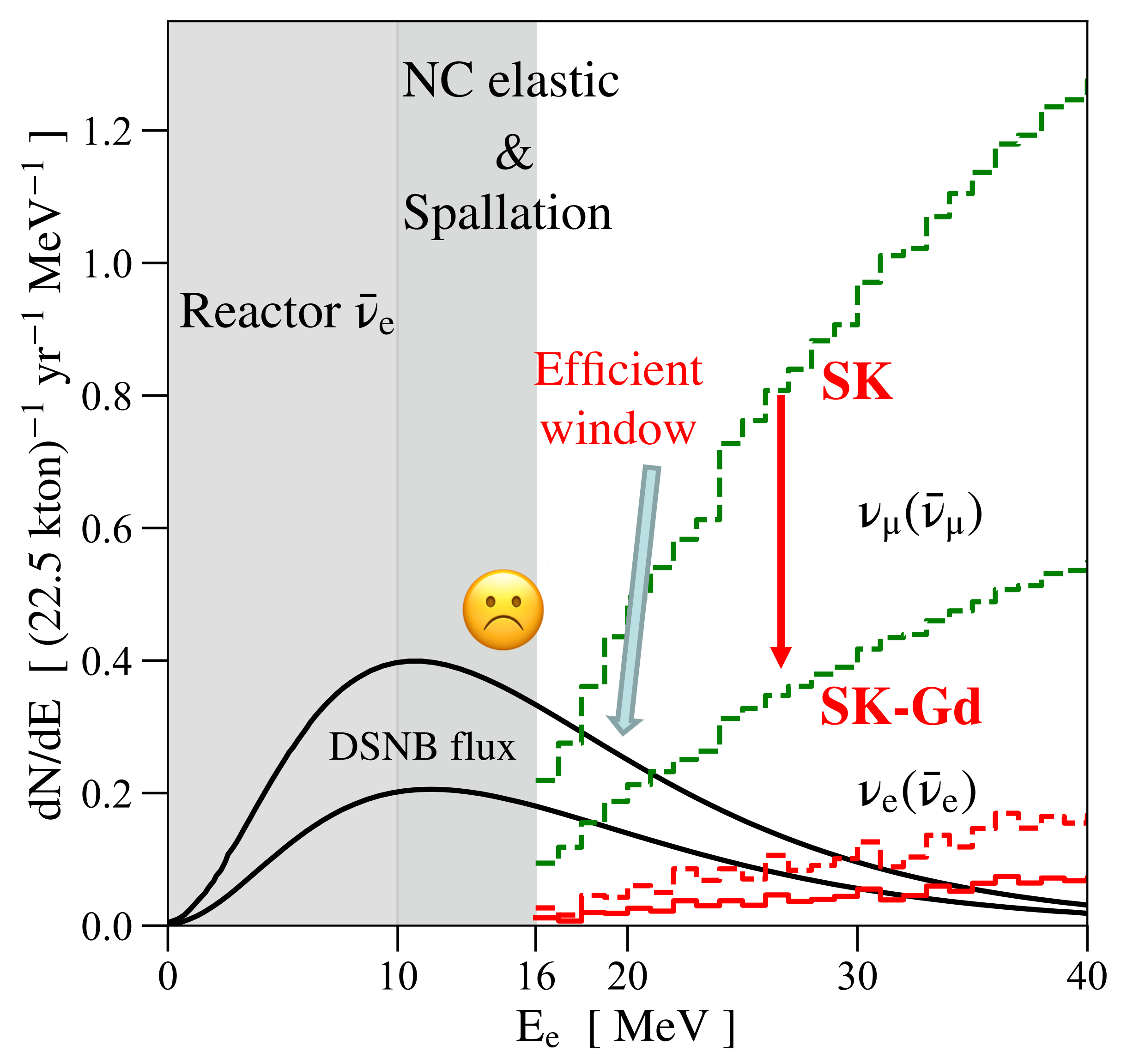
  (Beacom & Vagins, PRL 2004, hep-ph/0309300)

- Enable SK to detect neutrons.
  (neutron tagging)

- SK → SK-Gd, begins soon!!

- Improve DSNB detectability

DSNB	Atm. ν bkgd.
100% one neutron	**<~ 50% one neutron**

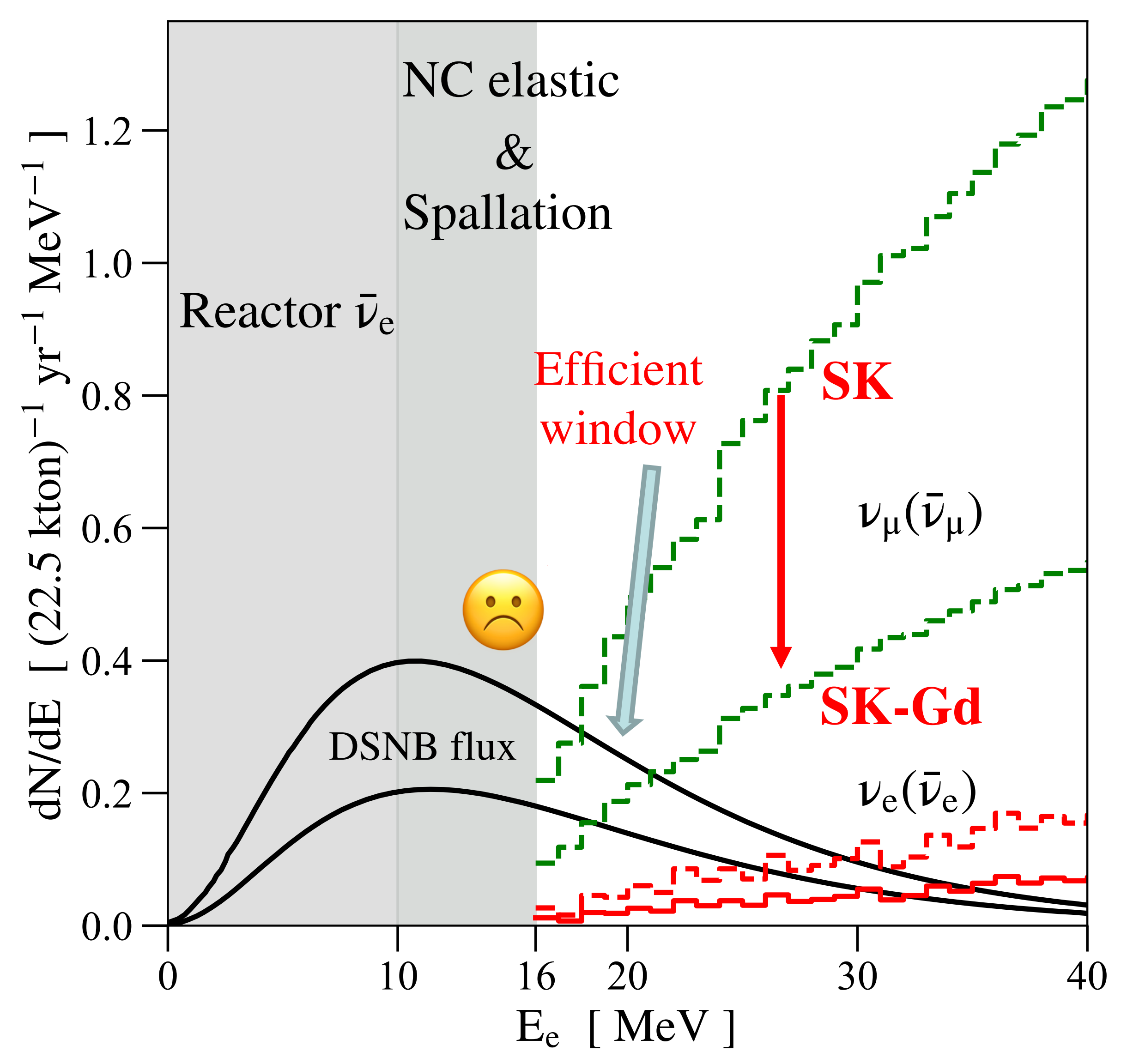


Goal of Our Work

- Further reduce the atm. ν bkgd.

- Need understand the physics here
  - Atm. ν interactions with nuclei
    - *QuasiElasic Scattering*
    - *Resonance production*
    - *Coulomb distortion*
    - *etc.*
  - Propagations/Interactions of secondaries
    - *π/μ/neutron/proton transport and capture, very different physics*
    - *etc.*

(No systematic study before)



Major Inputs and Uncertainties

- Atmospheric ν flux
  Uncertainty: ~ 15%-20% (~ 100 MeV)

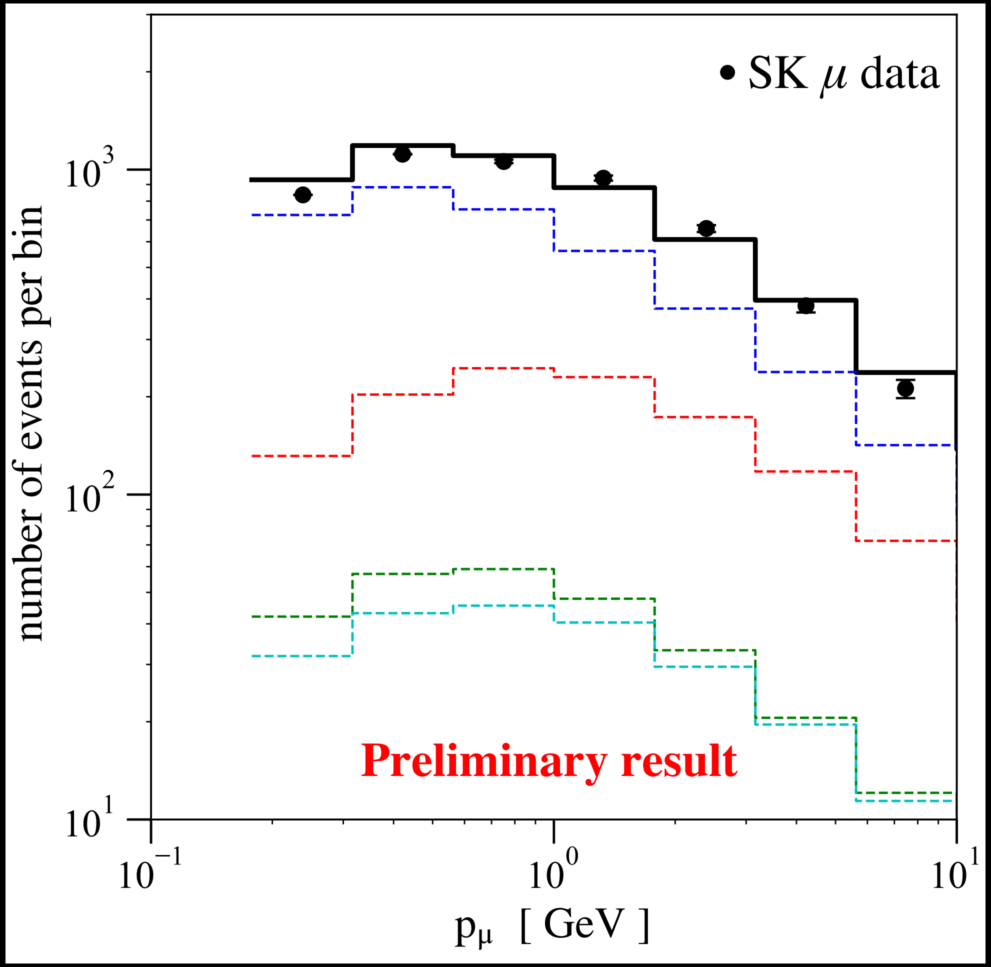
  (Honda et al., PRD 2015, arXiv:1502.03916)
  (Battistoni et al., Astropart.Phys. 2015)

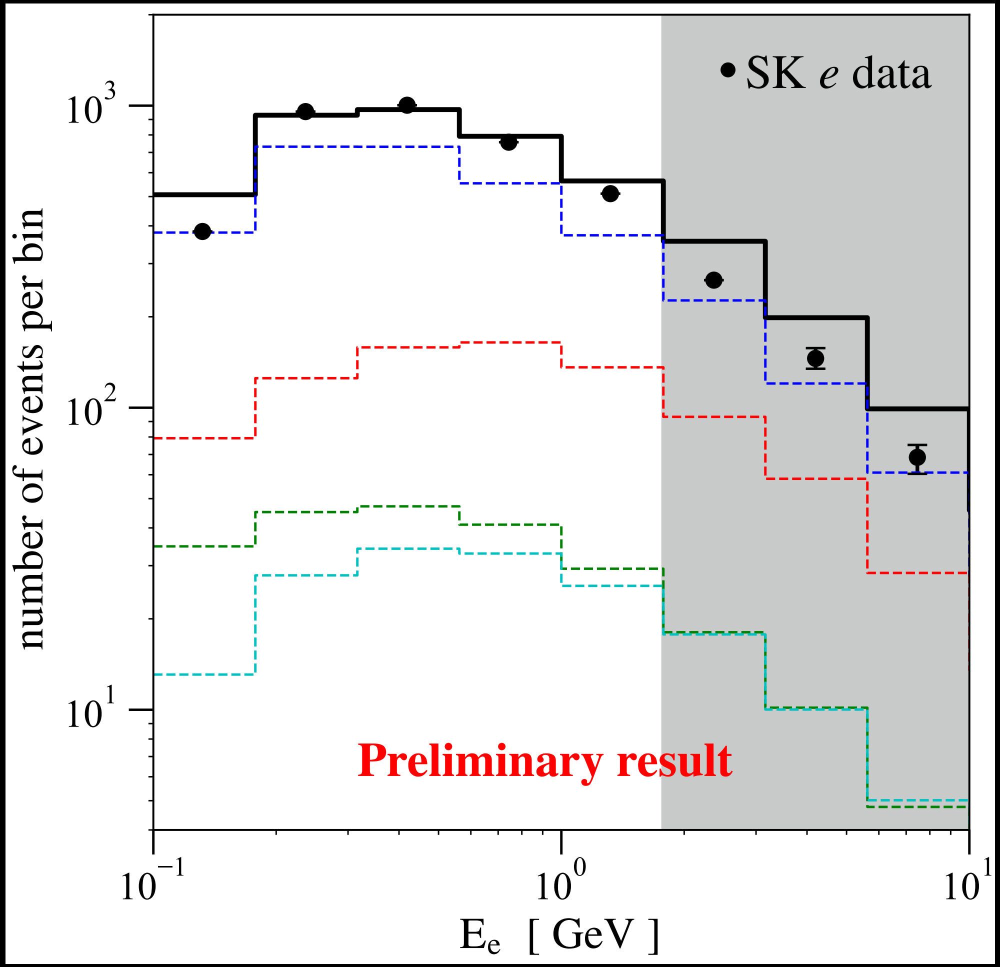
- Neutrino mixing
  3ν framework + matter effect
  Uncertainty is subdominant

- Neutrino interactions ($\nu_\mu/\bar{\nu}_\mu + H_2O$)
  Uncertainty of cross-section calculations: ~ 25% (~ 100 MeV) *(GENIE 2.12.0)*

Definitely needs more theoretical/experimental work for the inputs!

First Reproduce SK High-Energy Atm. ν Data





SK *μ* data: SK *e* data:

Calculation matches SK High-Energy data well!

Data from *SK collaboration, PRD, 2005, hep-ex/0501064*

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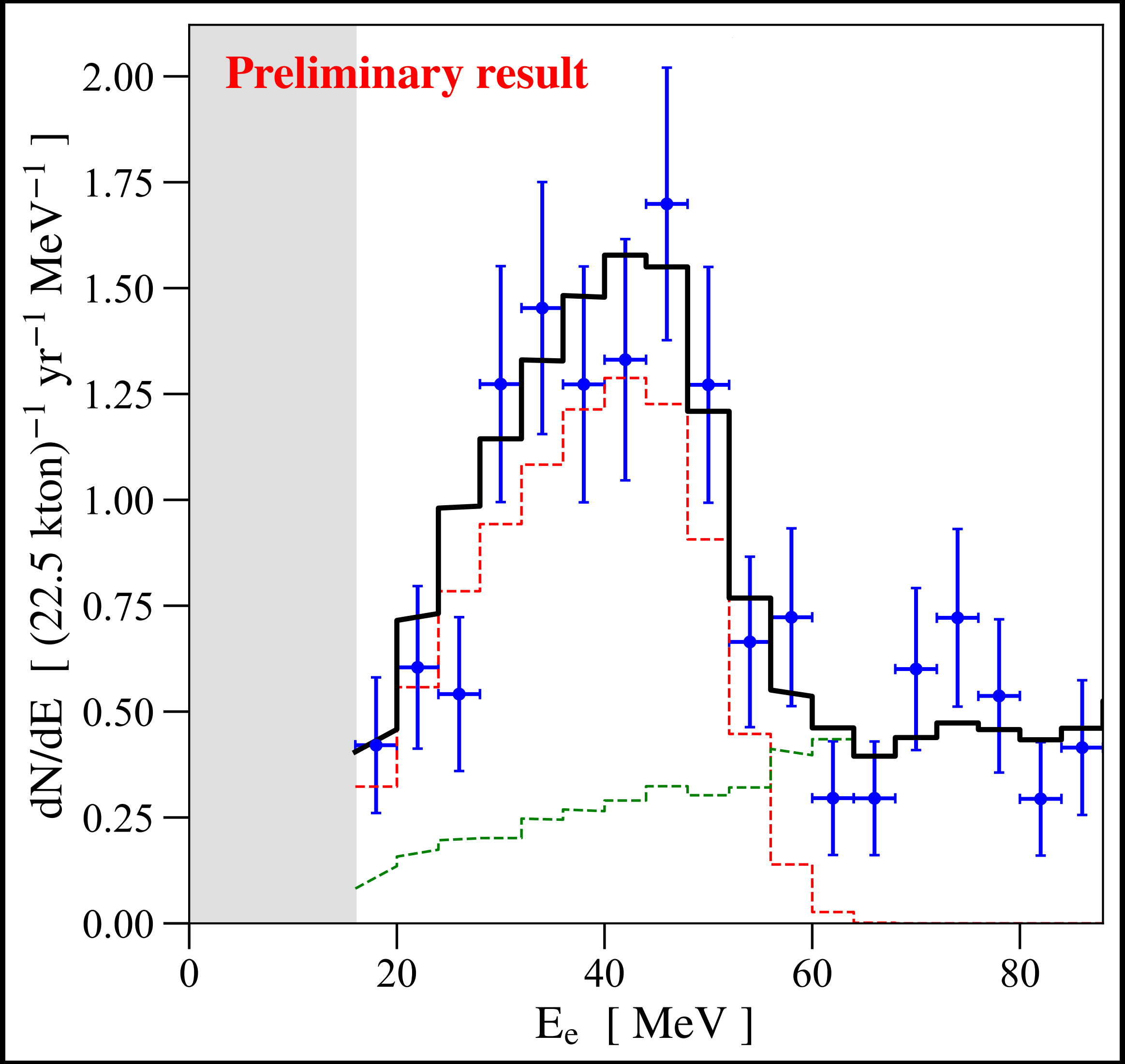


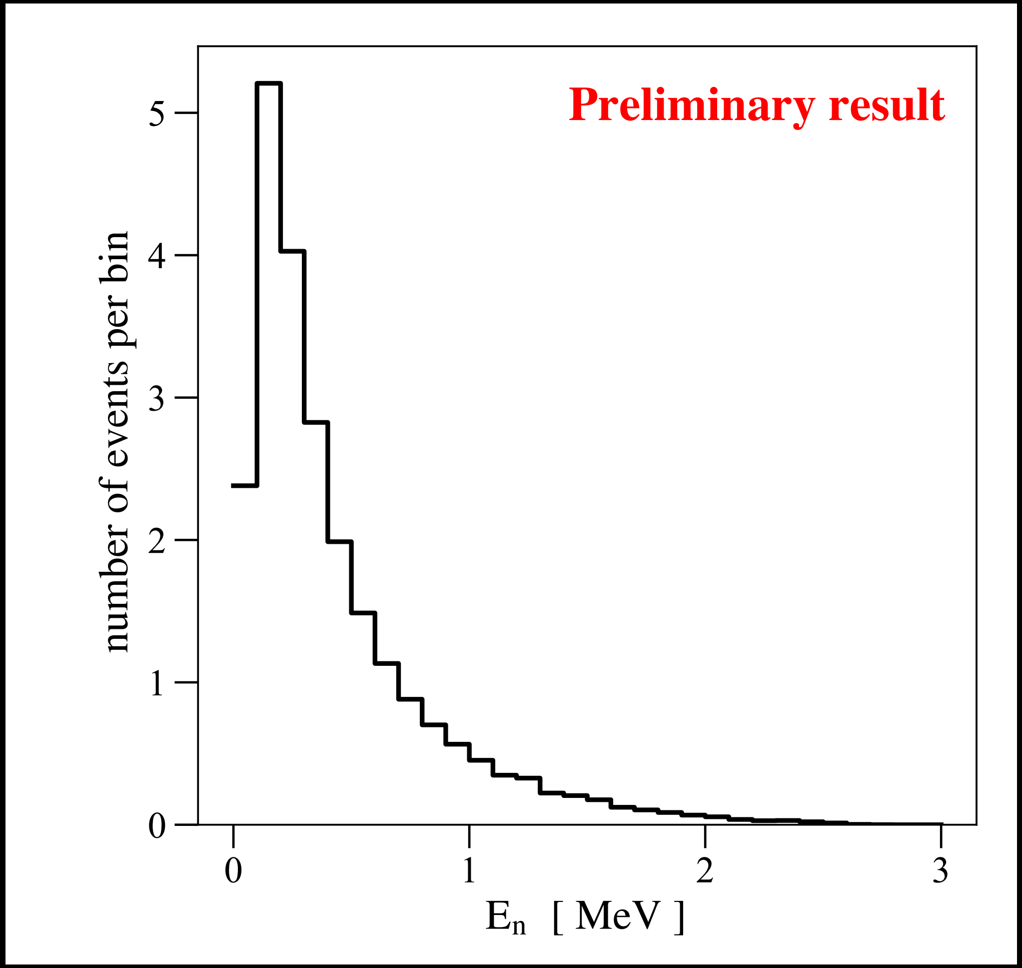
Calculation matches SK Low-Energy data well!

Data from *SK collaboration, PRD, 2012, arXiv:1111.5031*

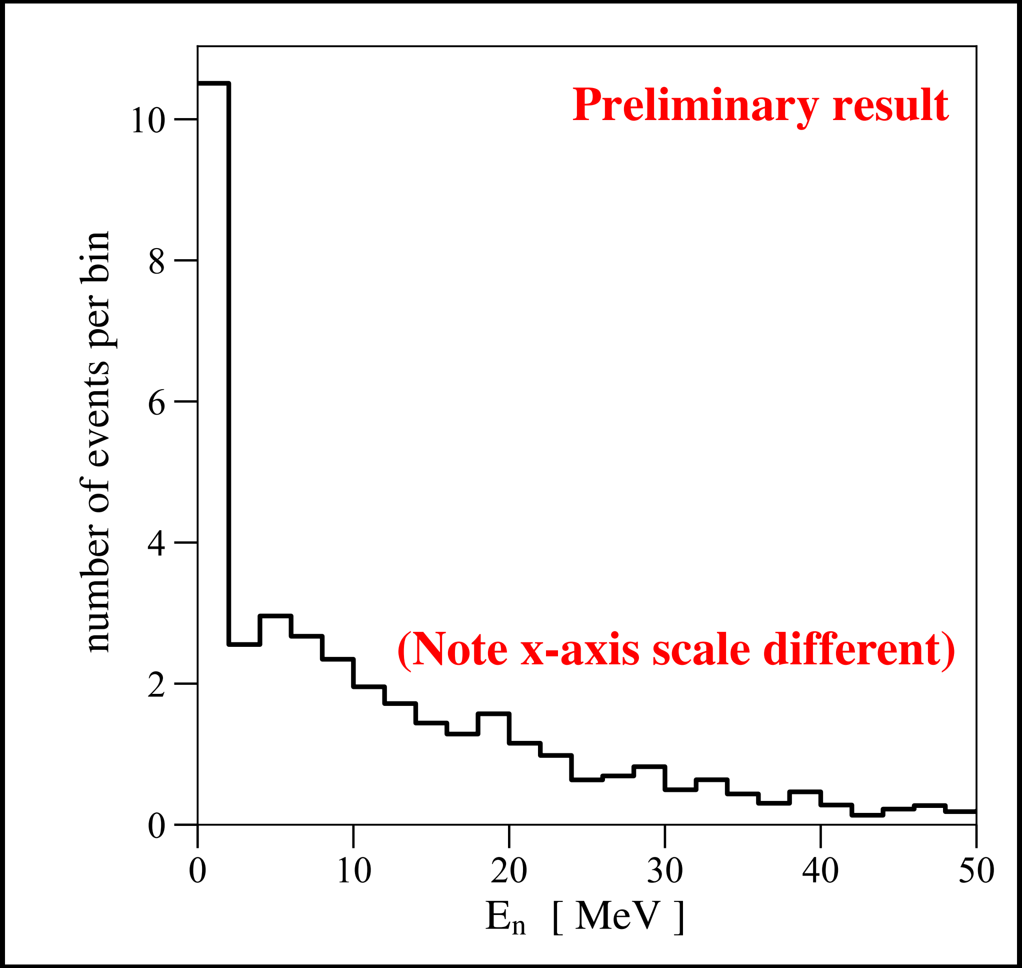
The physics is understood well.

Then, how do we reduce the backgrounds????

One Major Clue: Neutron Energies



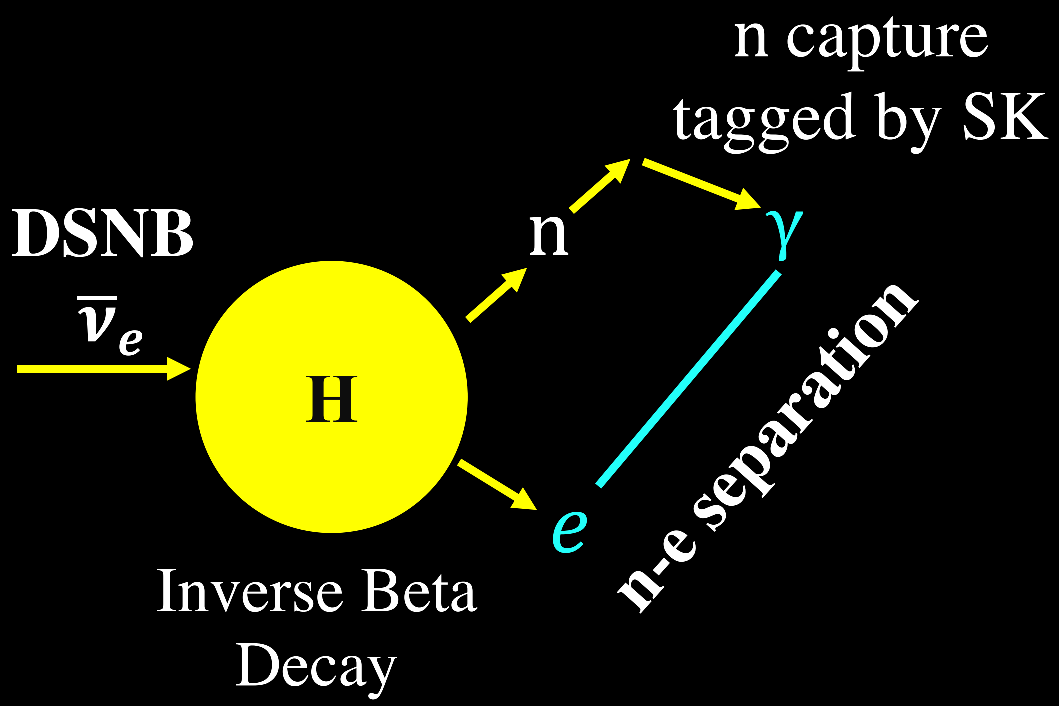
DSNB signals

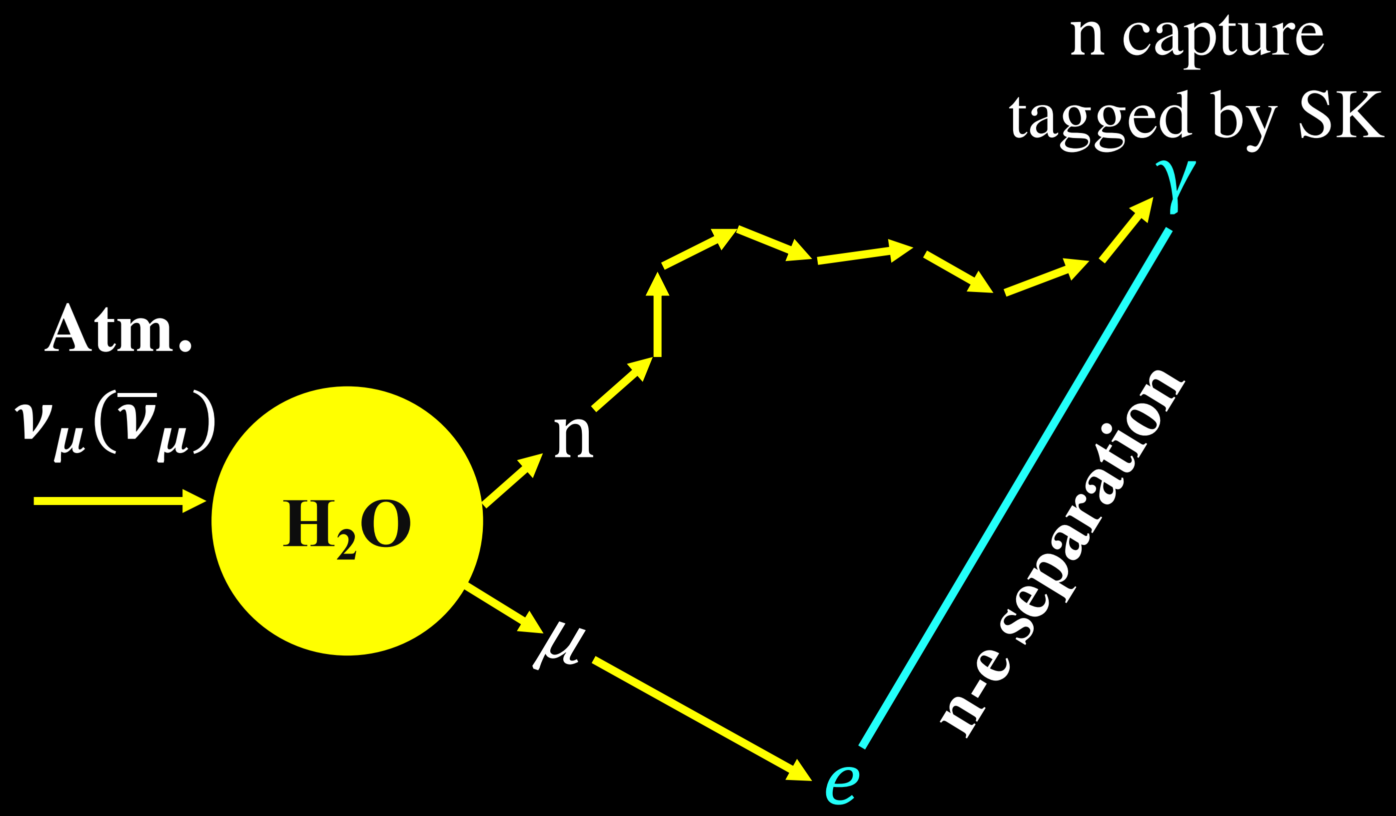


Atm. $\nu_\mu(\bar{\nu}_\mu)$ backgrounds

So neutrons from atm. ν bkgd can propagate much further!

n-e separation: Definition



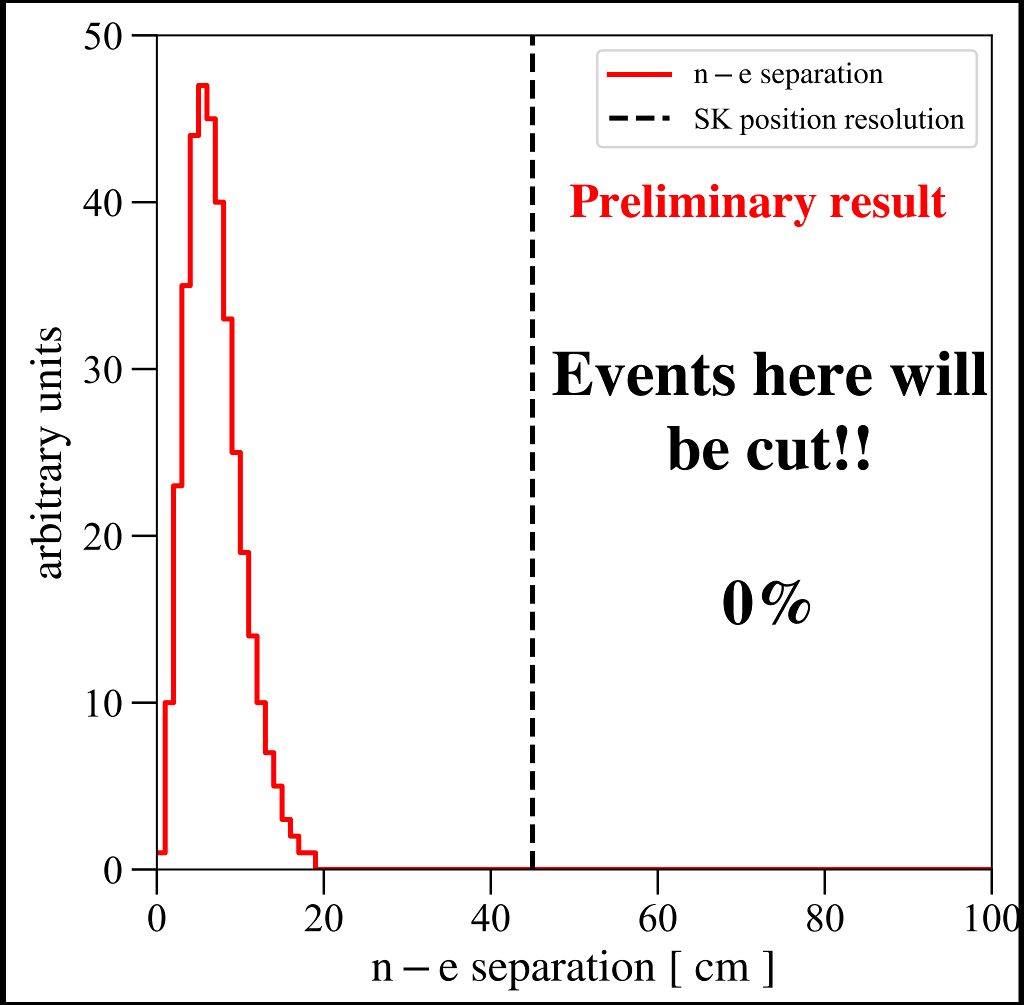


DSNB signals

Atm. $\nu_\mu(\bar{\nu}_\mu)$ backgrounds

(Cartoon credit: Bei Zhou)

n-e separation: Result



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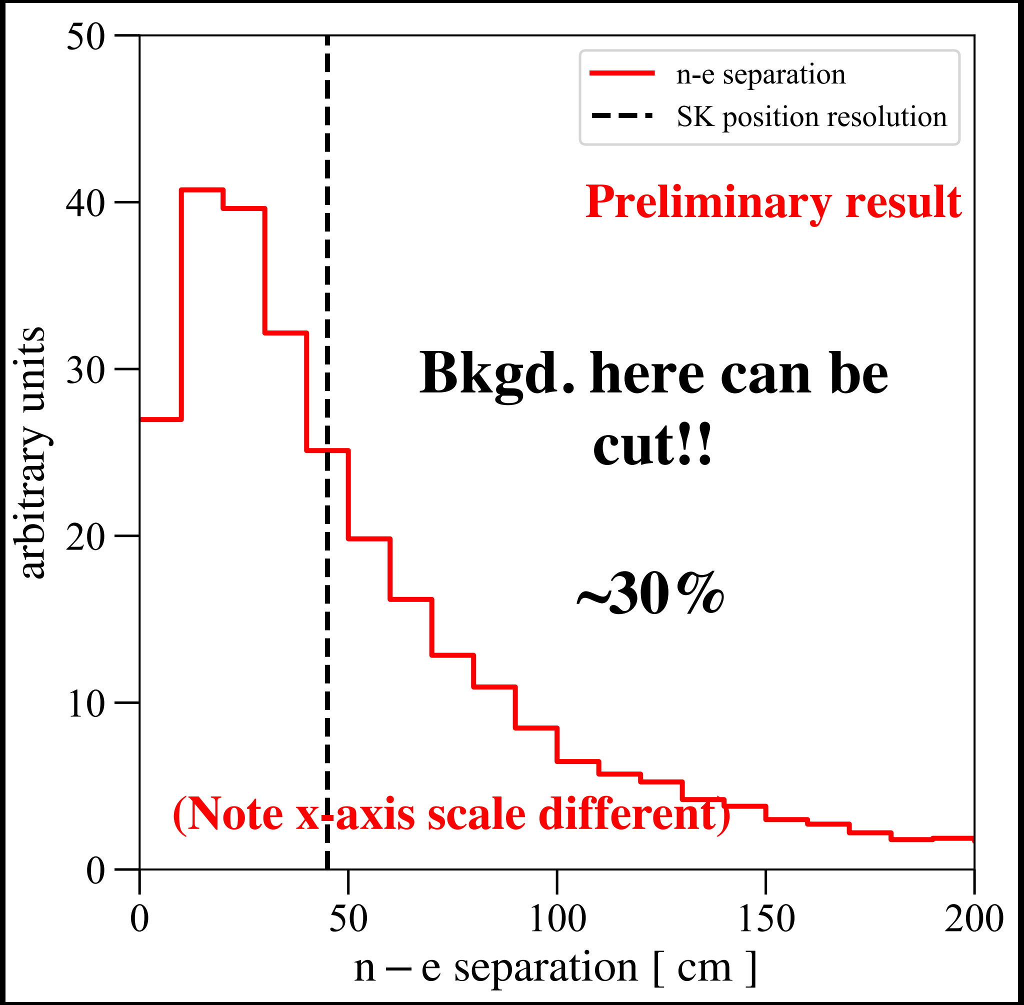
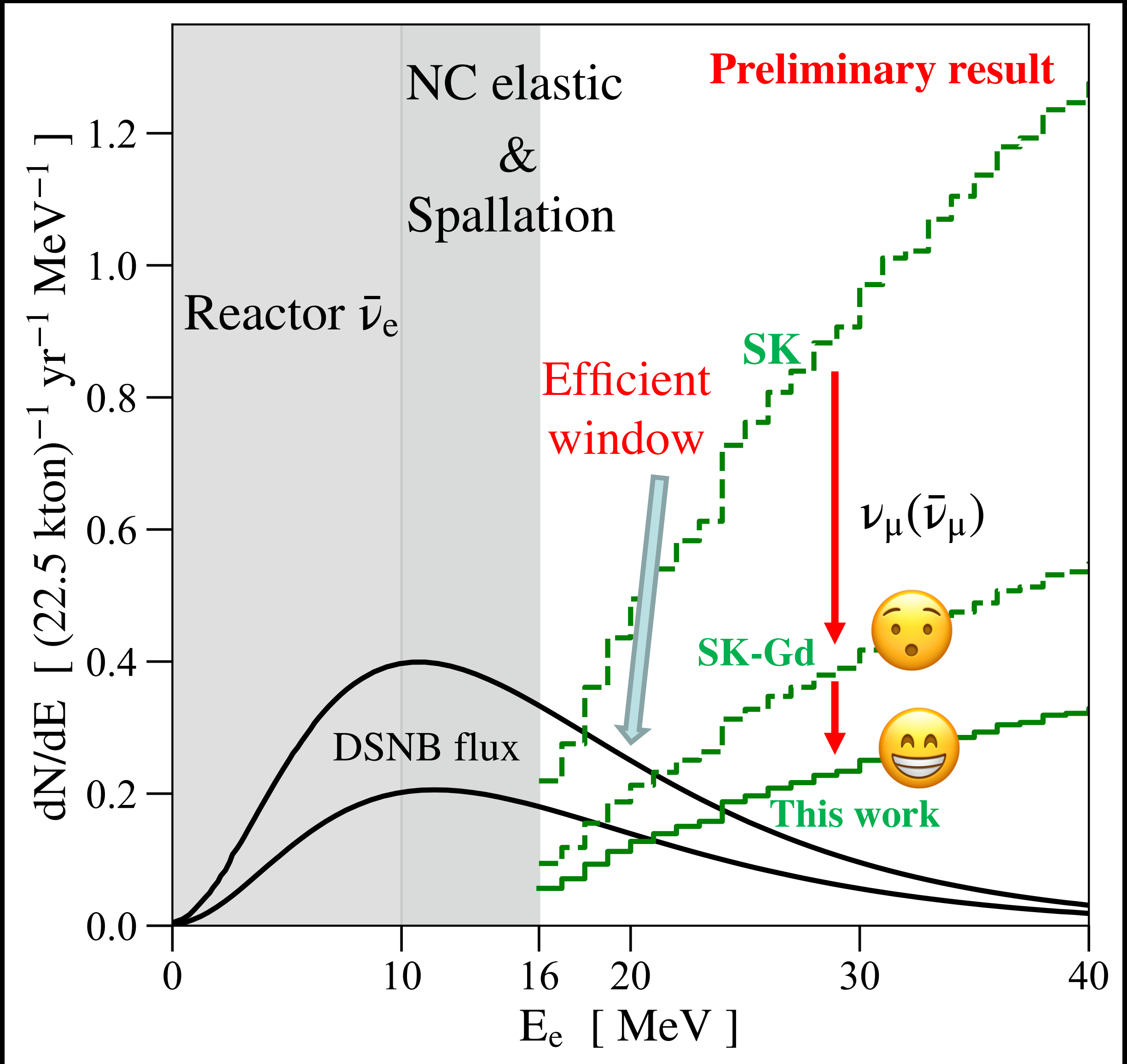


Atm. $\nu_\mu(\bar{\nu}_\mu)$ background

After Our n-e separation Method

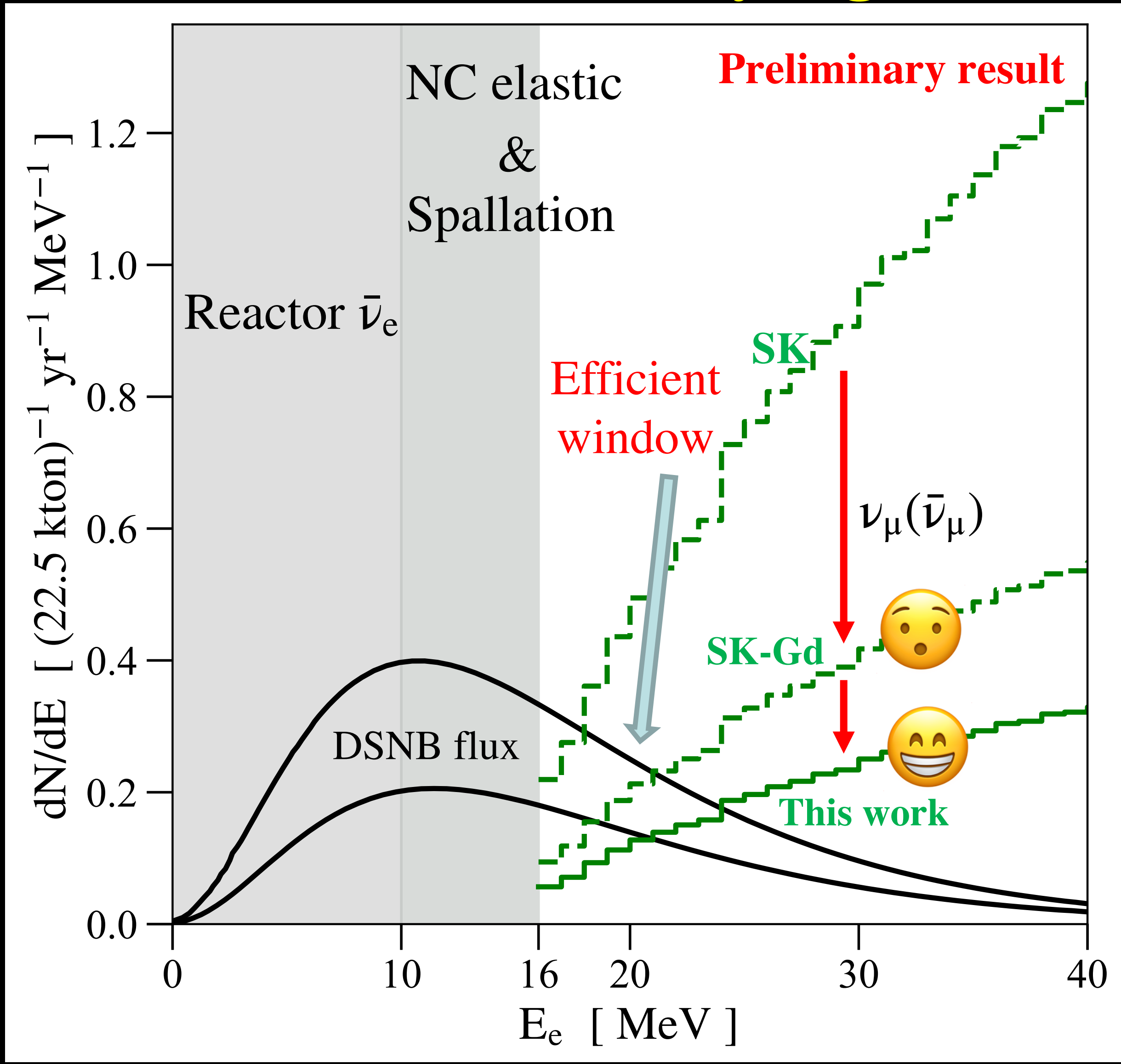


More suggested methods will appear in the coming paper

Conclusion

- (First) detection of DSNB is super important
- First comprehensive study of underlying physics of atm. ν backgrounds for DSNB
- Our methods can significantly speed up the detection of DSNB
- SK-Gd starts ~ 2019, also applies to future Hyper-Kamiokande
- More details, more suggested methods will appear in the forthcoming paper(s)

Take-away Figure



Thanks for your attention!

Why Detecting DSNB is important?

(First) detection of DSNB will be of great importance.

- This may be the first detection of cosmological neutrinos with known source.
- Average emitted neutrino spectrum that reflects the physics of NS or BH formation.
- Help understand core-collapse physics and neutrino mixing, which determine the physics of SNe and their products.
- Open a new window of neutrino astrophysics, probing physics far beyond the lab, which may allow new tests of neutrino properties.
- Etc.

Why Detecting DSNB is Important?

(First) detection of DSNB will be of great importance.

- Probe conditions of core-collapse (incl. supernovae) to NS/BH (average ν spectrum)
- Probe rate of core-collapse (incl. supernovae) events
- Probe neutrino properties
- Etc.

(More about DSNB: Beacom, Ann.Rev.Nucl.Part.Sci. 2010, arXiv:1004.3311)

Major Inputs and Uncertainties

- Atmospheric ν flux

  Use HKKM2014 for > 100 MeV; FLUKA2005 for < 100 MeV

  Uncertainty: ~ 15%-20% (~ 100 MeV)

  (Honda et al., PRD 2015, arXiv:1502.03916)
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- Neutrino mixing

  3ν framework + matter effect

  Uncertainty is subdominant

- Neutrino interactions ($\nu_\mu/\bar{\nu}_\mu + H_2O$)

  Use GENIE 2.12.0 to do the interactions

  Uncertainty of cross sections: ~ 25% (~ 100 MeV)

Definitely needs more theoretical/experimental work for the inputs!

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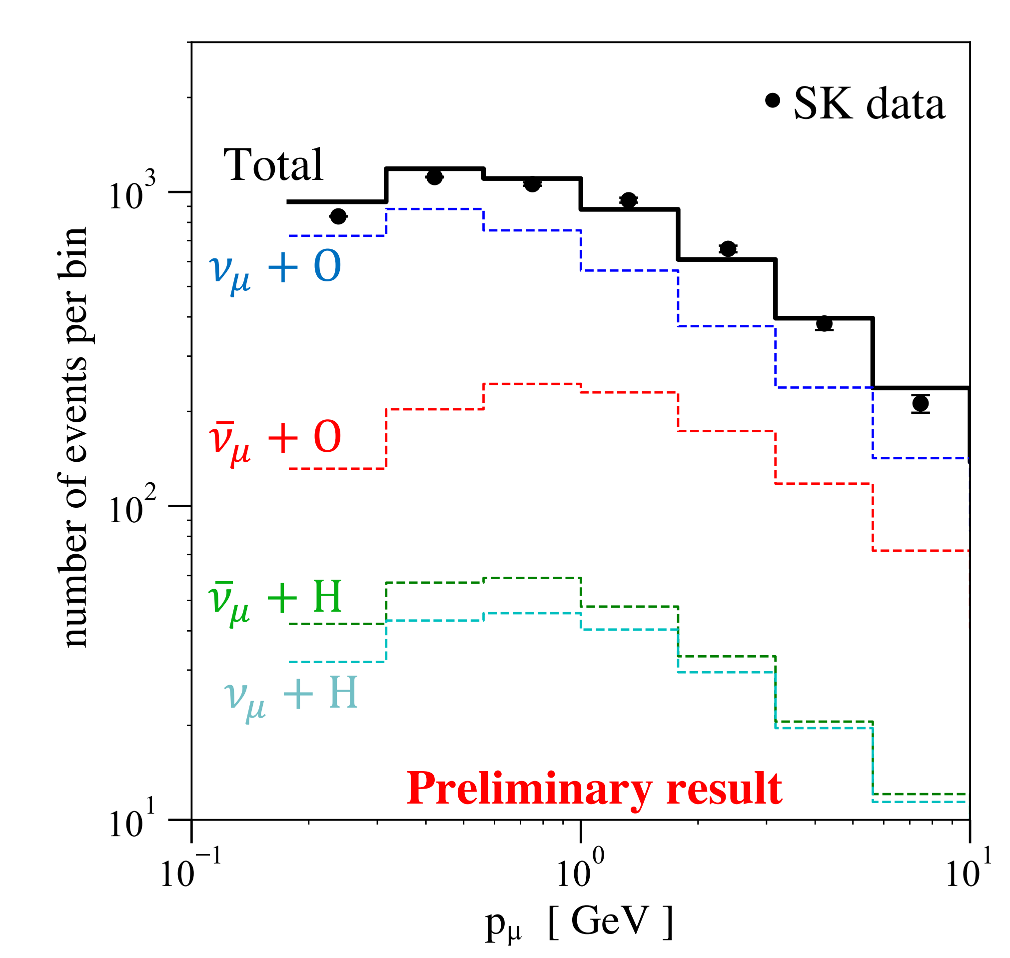
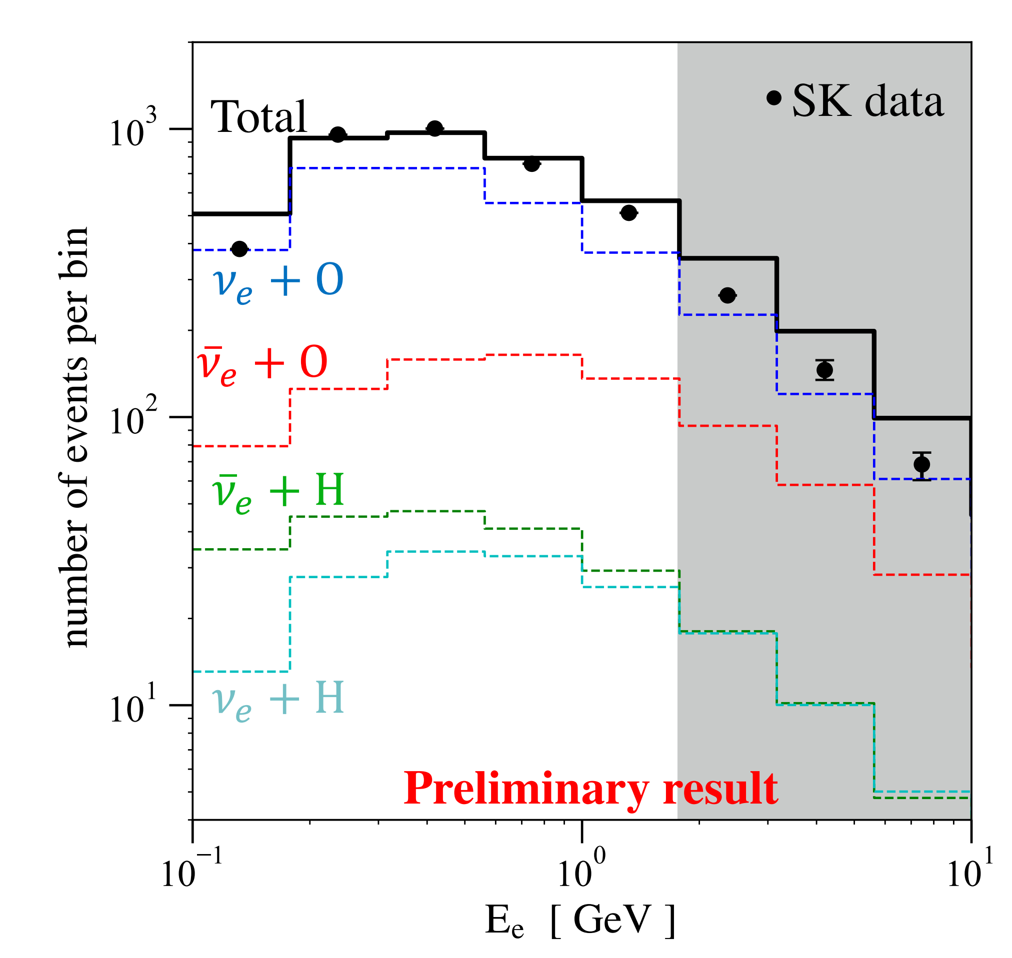


SK μ data:
single ring + multi-ring + partially contained events



SK *e* data:
single ring events only

Our calculation matches SK High-Energy data well!

Data from *SK collaboration, PRD, 2005, hep-ex/0501064*

However, huge background

- Atm. $\nu_\mu/\bar{\nu}_\mu$

$$\nu_\mu + \mathrm{p} \rightarrow \mathrm{n} + \mu^+$$
$$\nu_\mu + \mathrm{O}^{16} \rightarrow \mathrm{N}^{15} + \mathrm{p} + \mu^-, \text{ etc.}$$
$$\bar{\nu}_\mu + \mathrm{O}^{16} \rightarrow \mathrm{O}^{15} + \mathrm{n} + \mu^+, \text{ etc.}$$

K_μ< 55 MeV not Cherenkov light, invisible

$\mu^+(\mu^-)$ decay to $e^+(e^-)$, mimic DSNB events

- Atm. $\nu_e/\bar{\nu}_e$

$$\nu_e + \mathrm{p} \rightarrow \mathrm{n} + e^+$$
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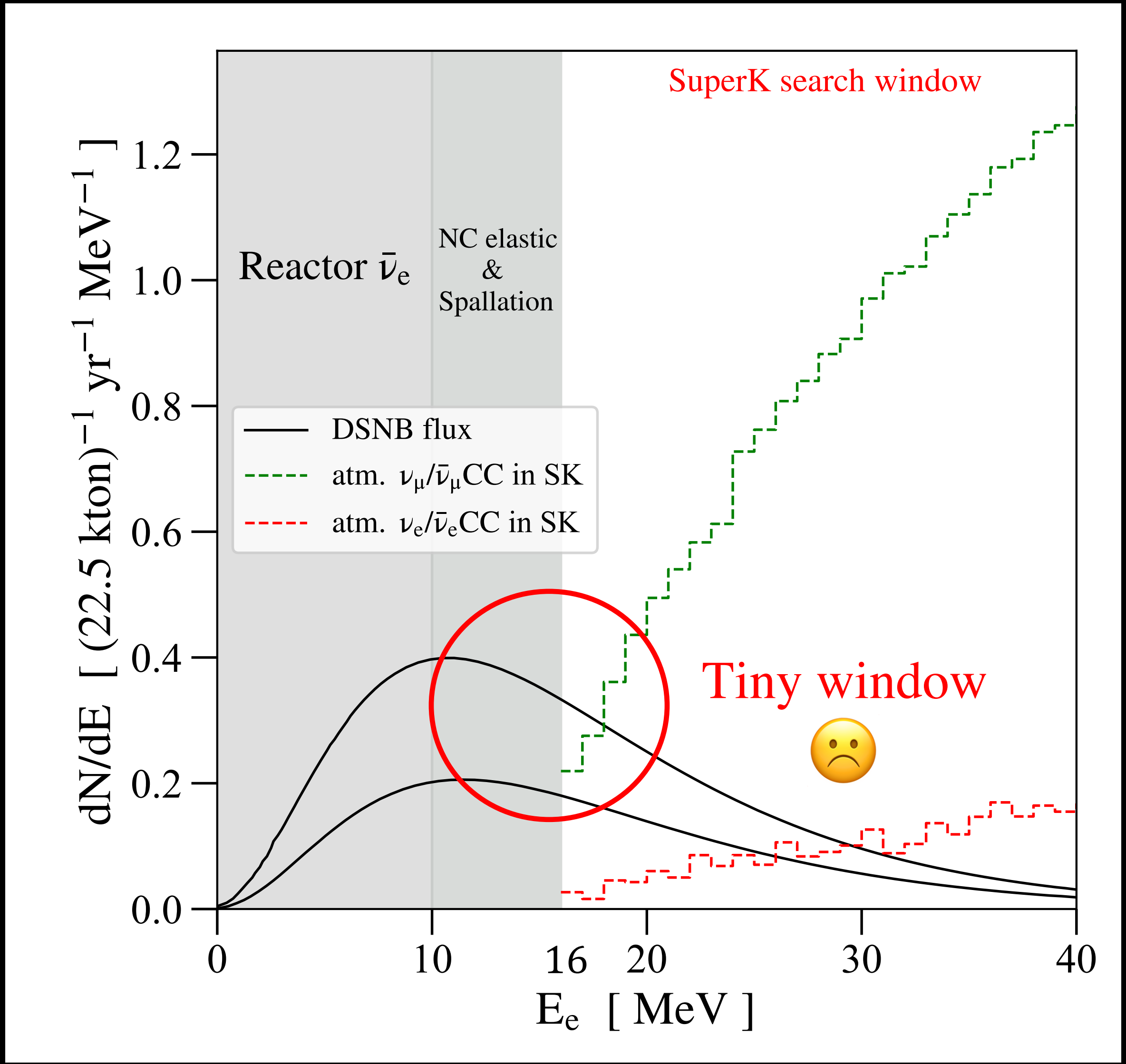

GADZOOKS! SK → SK-Gd with n-tagging

- Add 0.1% Gd (Gadolinium) to SK
  (Beacom & Vagins, PRL 2004, hep-ph/0309300)
  SK-Gd begins in late 2018.

- SK: LE n's captured on H, produce 2.2 MeV γ, hard to detect
  SK-Gd: 90% LE n's captured on Gd, produce 8.0 MeV γ, easy to detect

- DSNB $\bar{\nu}_e$ always give one n
  Atm. bkgd, ≃55% give no n or multiple n.
  → Mostly killed by n-tagging