Physics reach with DUNE FD3

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DUNE FD3 mini-workshop toward a combined photon detection and field cage system

Stony Brook, 26-29 June, 2023

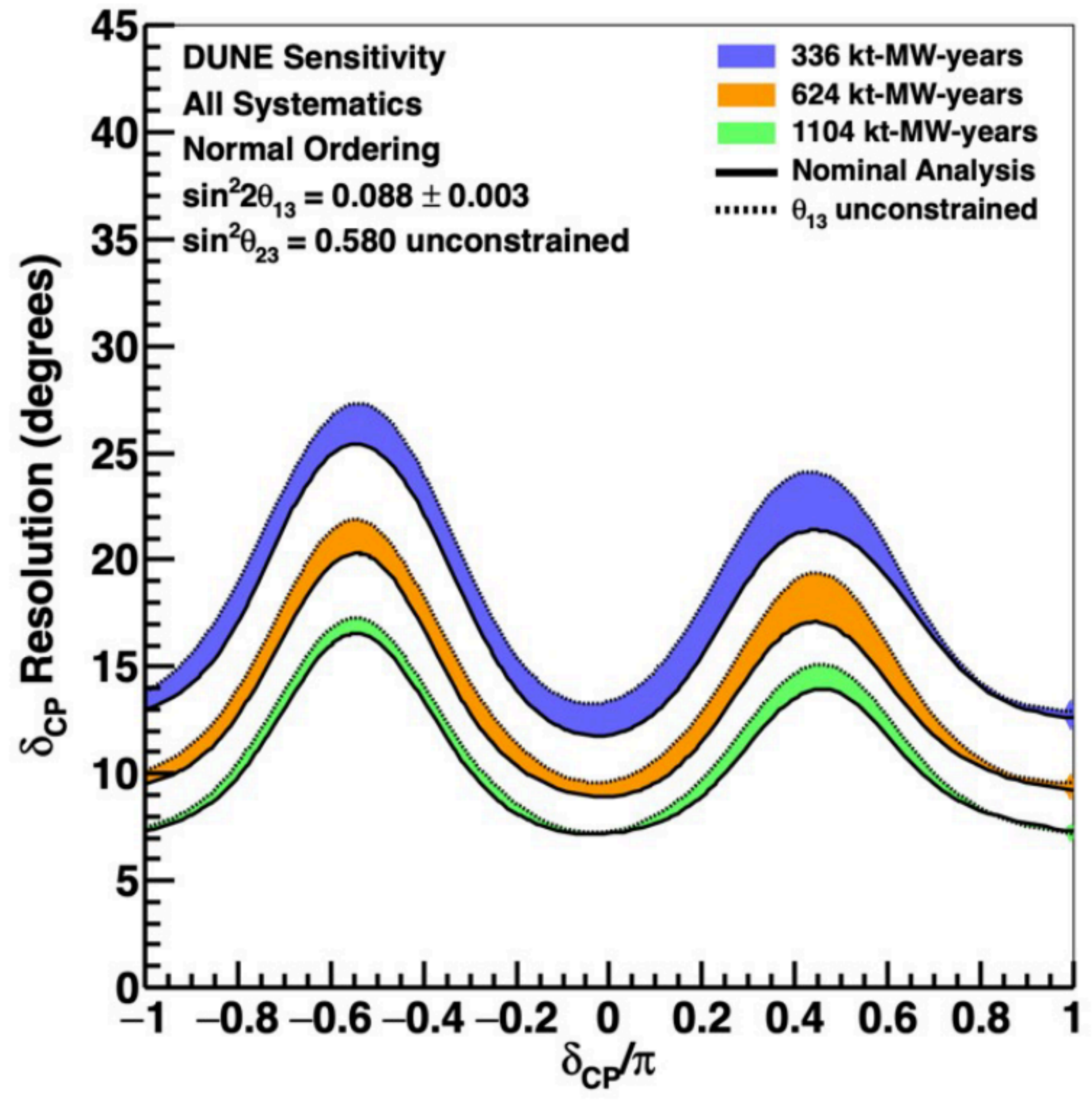
Outline

- DUNE Physics goals
  - LBL neutrino oscillations
  - Beyond Standard Model searches
- Detection of low energy events with LAr TPCs
- Astrophysical neutrinos
  - Solar neutrinos
  - Supernova neutrinos
  - Diffuse Supernova Neutrino Background
- Main detector challenges
- Other low-energy neutrino physics

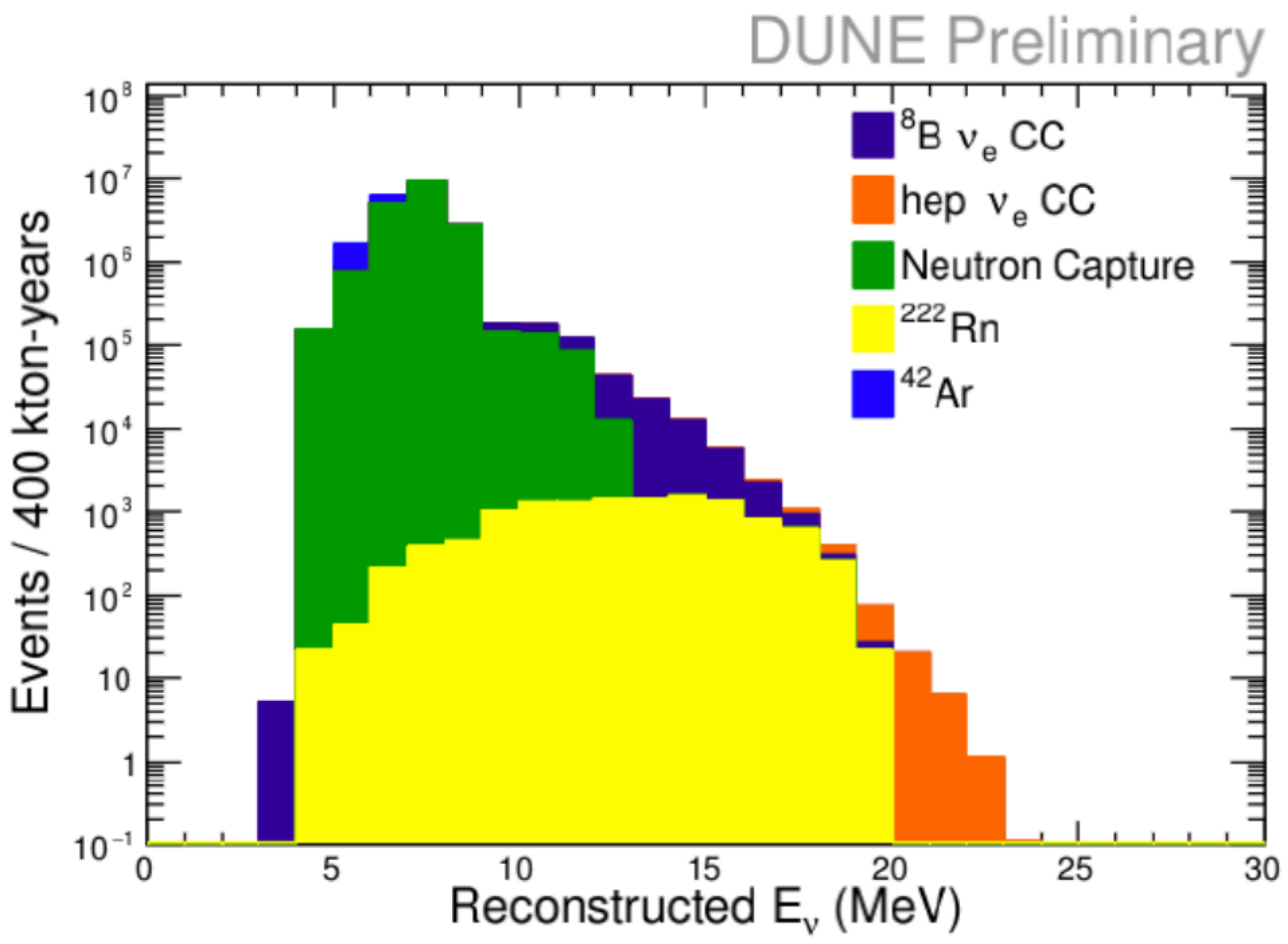
DUNE physics goals

- DUNE has a broad and compelling physics program: long-baseline neutrino oscillations, low-energy neutrino physics, and BSM searches

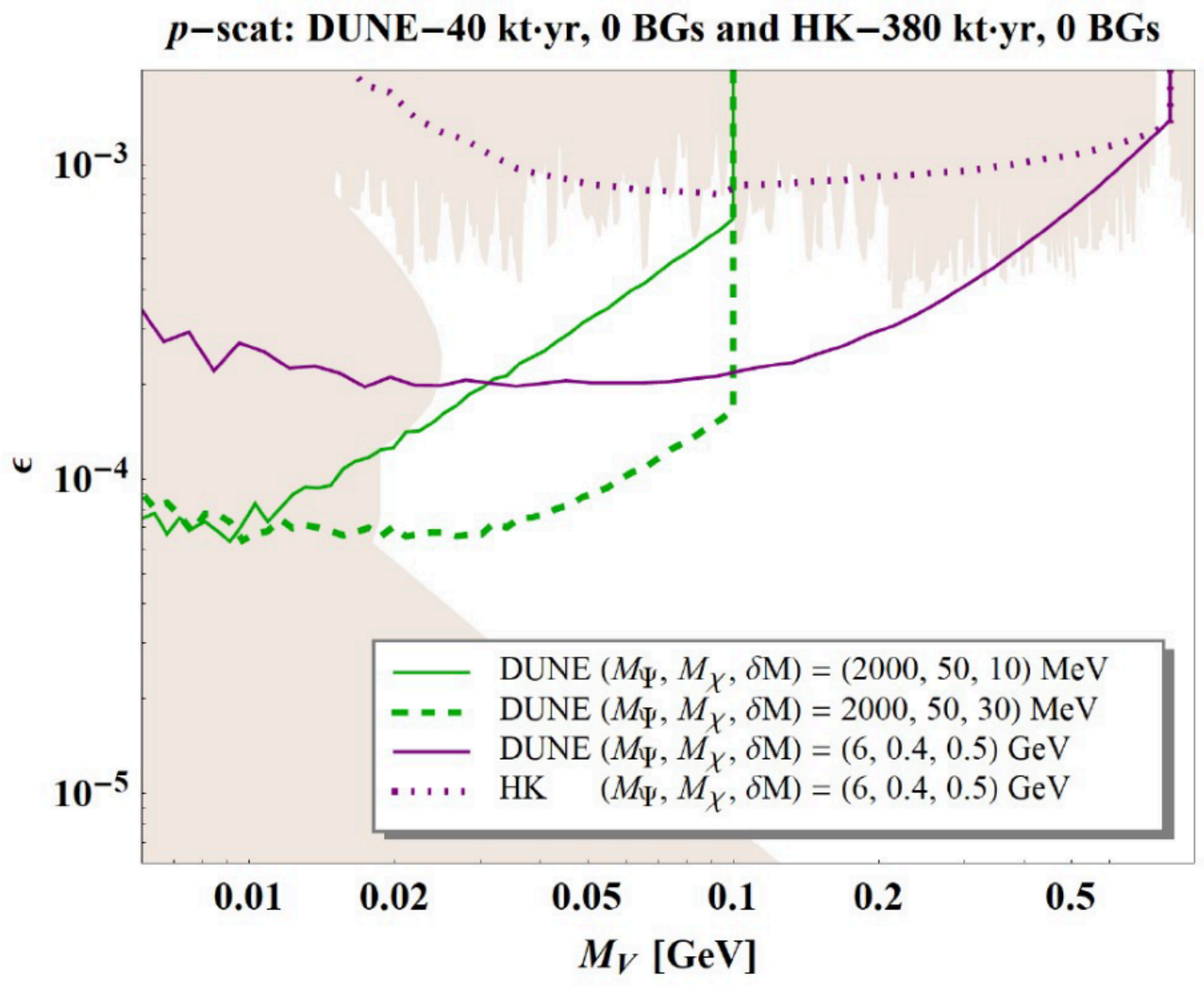
δ_{CP} resolution



Solar neutrinos



Inelastic BDM

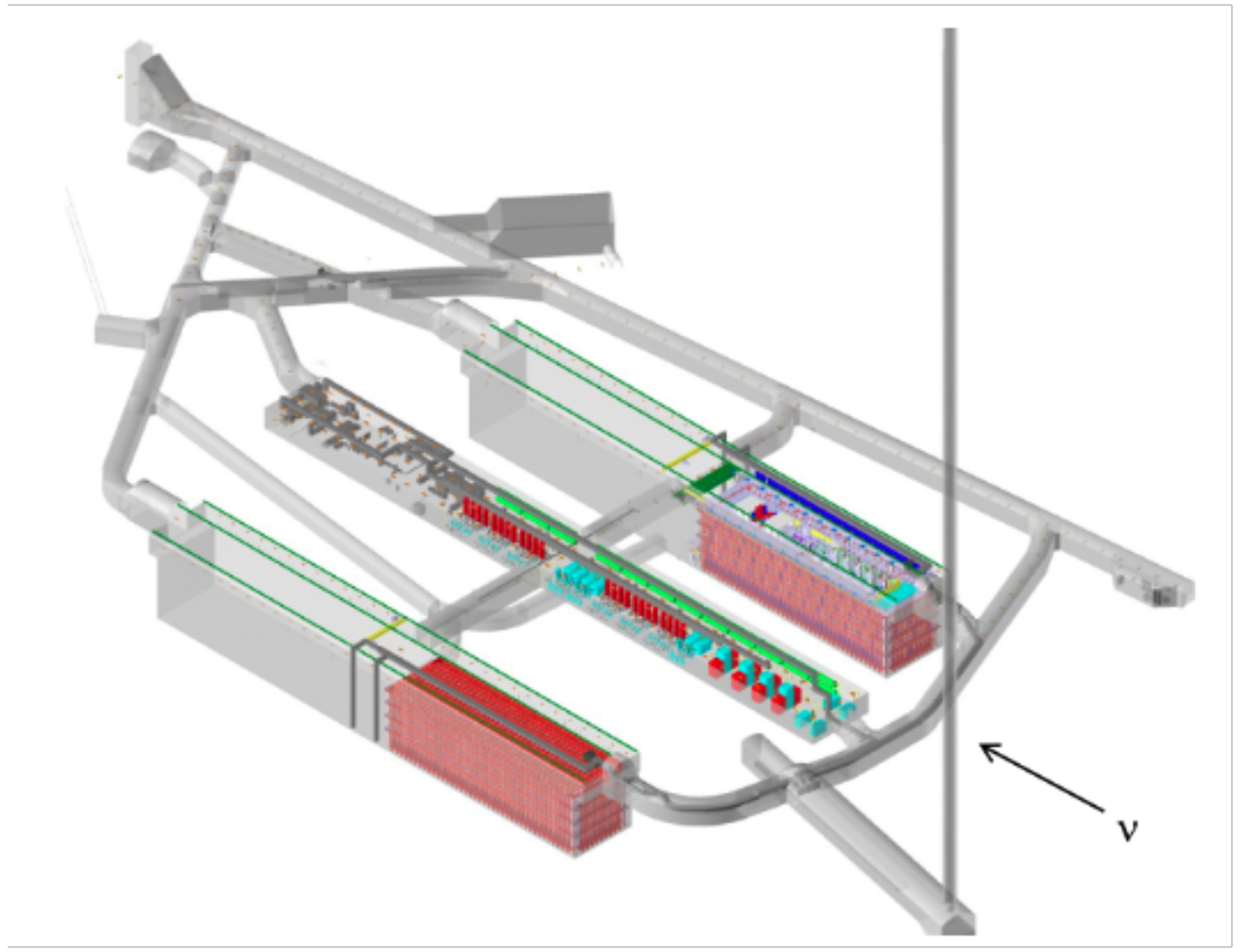


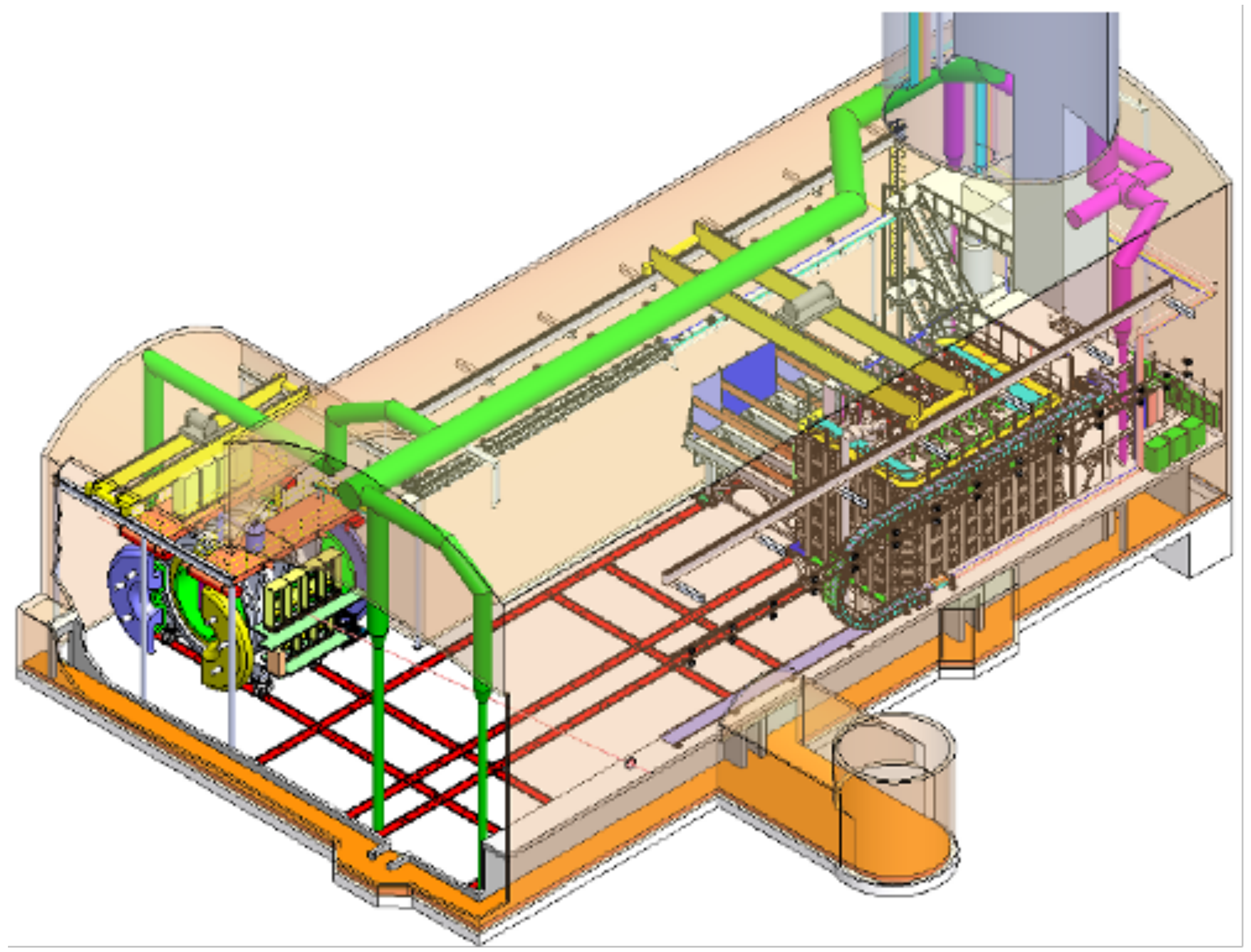
DEEP UNDERGROUND NEUTRINO EXPERIMENT

- **DUNE Phase I:**
  - Full near + far site facility and infrastructure
  - Upgradeable 1.2 MW beam
  - Two 17 kt LArTPC modules
  - Movable LArTPC near detector with muon catcher
  - On-axis near detector
- **DUNE Phase II:**

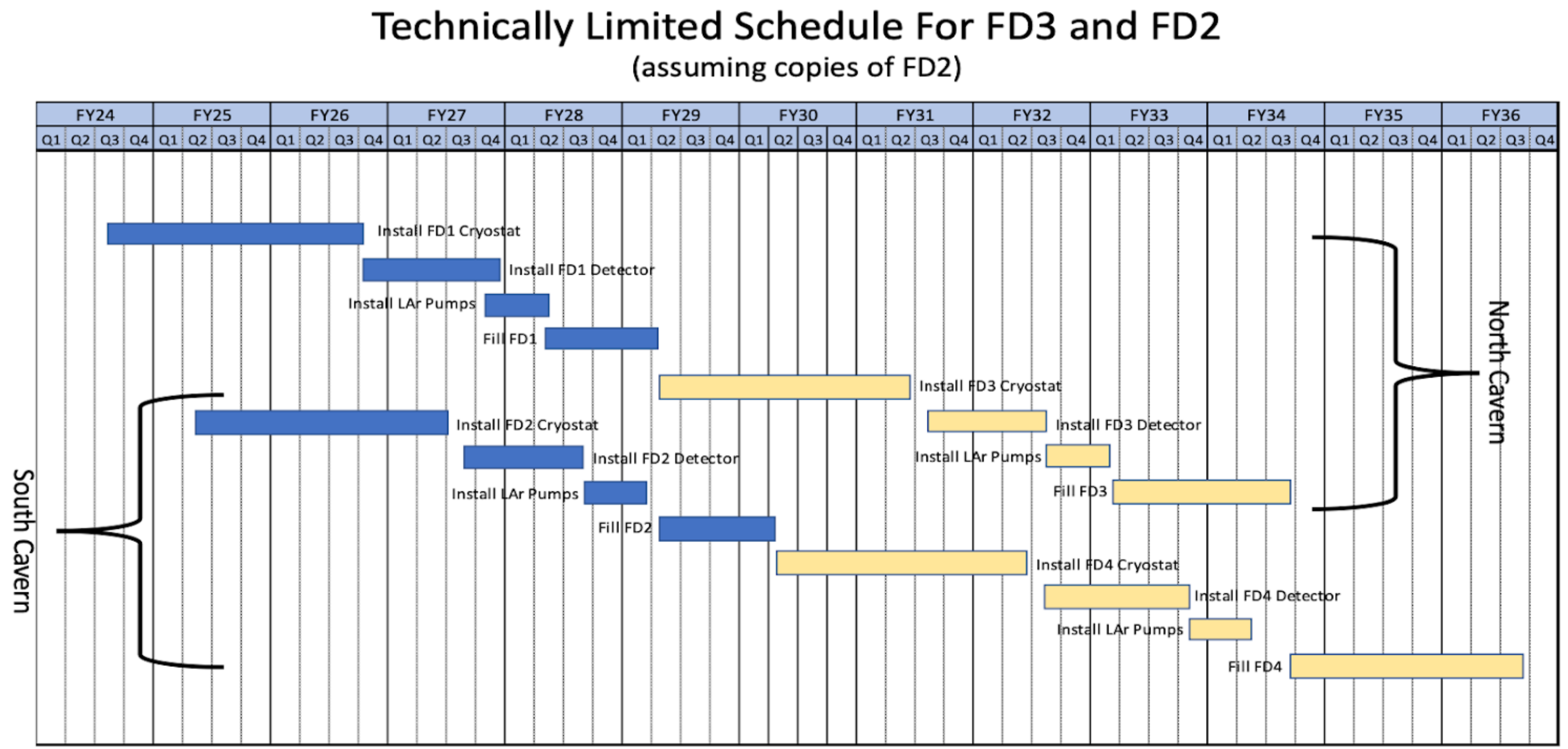
CRITICAL TO ACHIEVE DUNE PHYSICS GOALS

  - Two additional FD modules (≥40 kt fiducial in total)
  - Beam upgrade to >2 MW
  - More capable Near Detector





FD3 and FD4 timeline

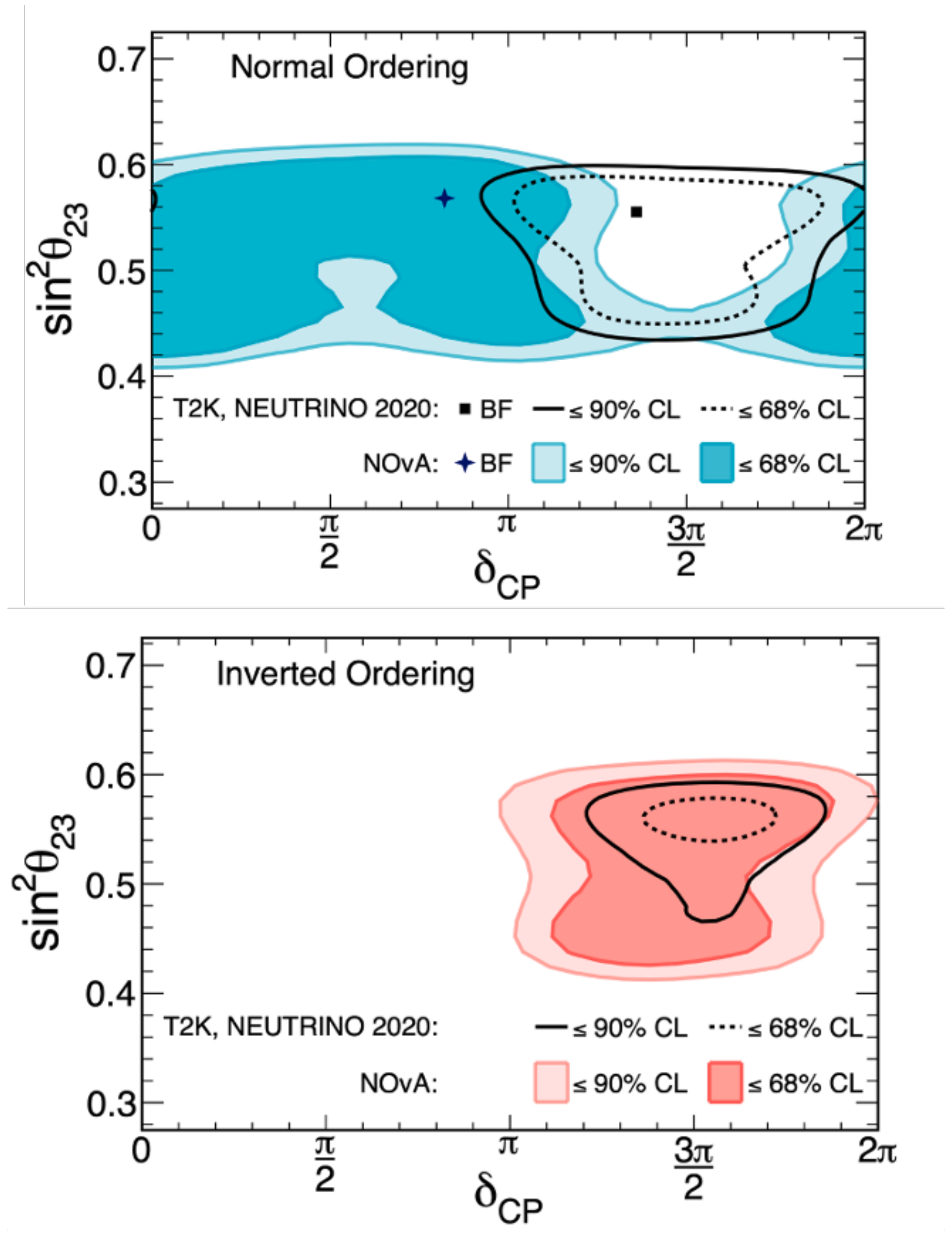


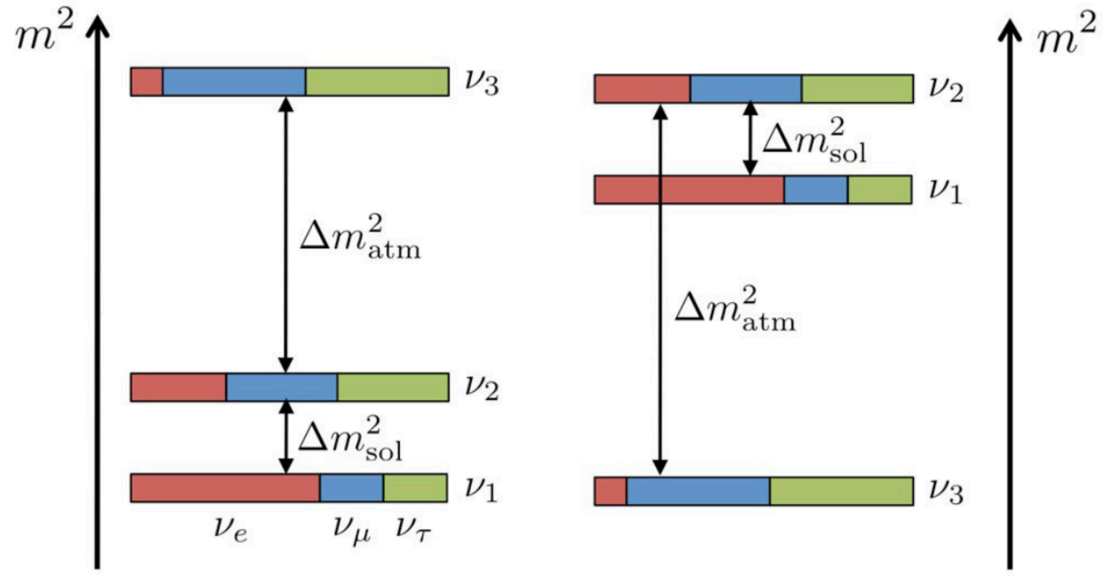
Earliest installation starts in 2029 with FD3 completed in Q4-FY34 and FD4 in Q4-FY36

LBL neutrino oscillation physics goals

- Measure neutrino mixing:
  - Is there CP violation? How large is it?
  - Are there symmetries? Is $U_{\mu3} = U_{\tau3}$?
  - Is the PMNS matrix unitary?
  - What is Δm^2_{32}? Is it positive or negative?
- Search for new physics: Is this three-flavor picture complete?
- We really do not know the mass ordering or δ_{CP} → we need definitive experiments

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \underbrace{\begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{pmatrix}}_{U_{\mathrm{PMNS}}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$



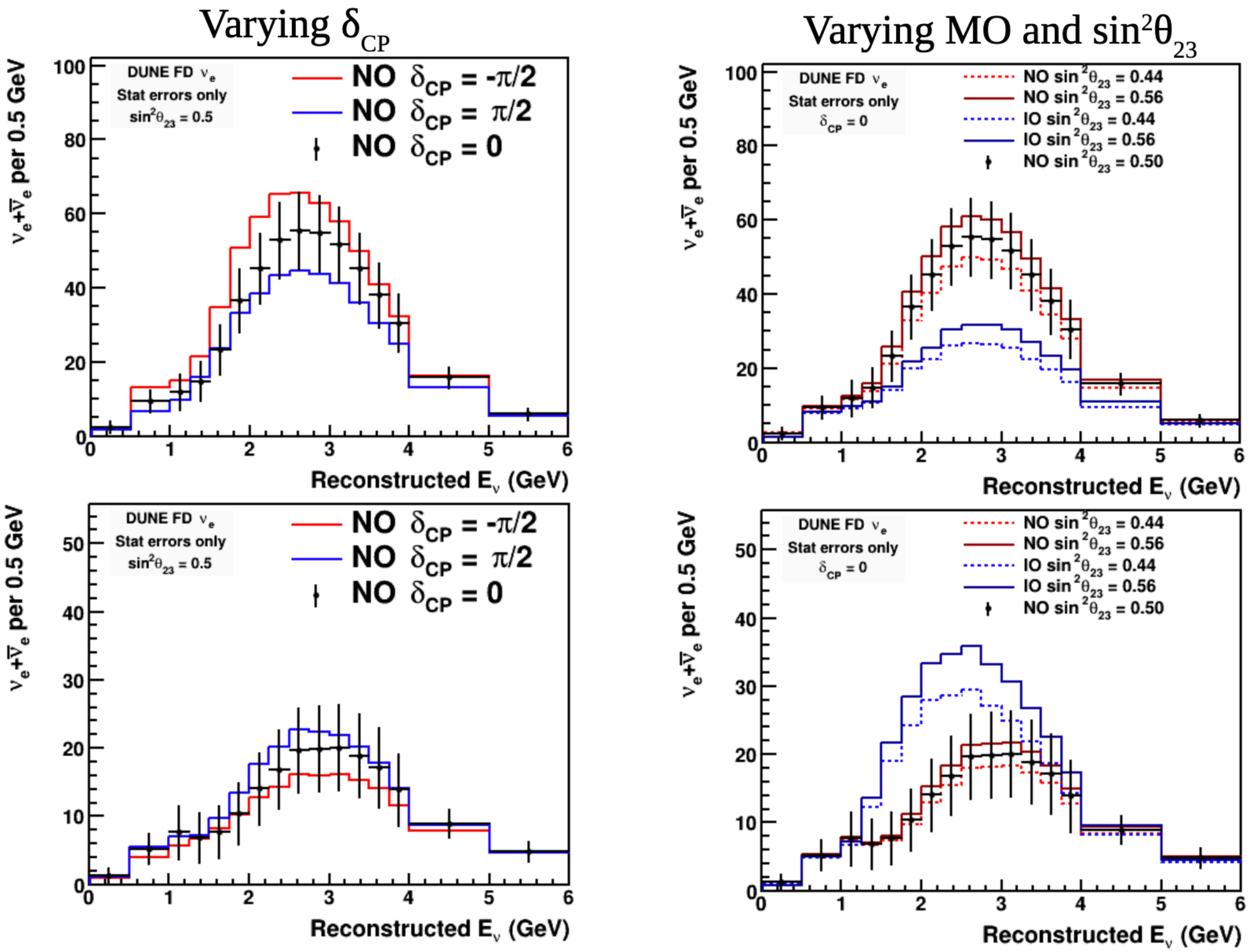


DUNE can distinguish MO in Phase I

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

Neutrino mode

Antineutrino mode



DUNE can measure δ_{CP}, θ_{13} octant in Phase II

Data points show NO, $\delta_{CP} = 0$, $\sin^2\theta_{23} = 0.5$

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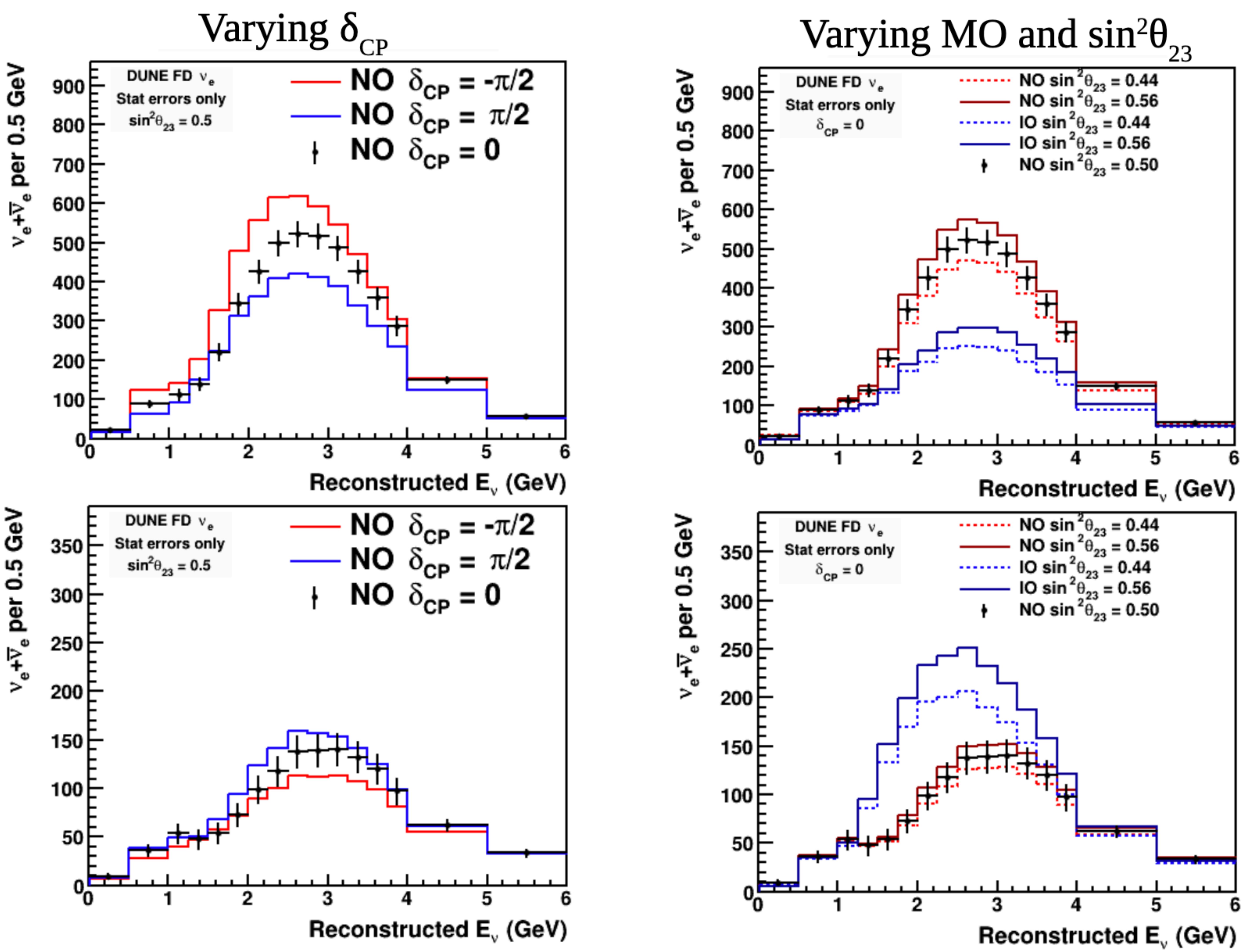
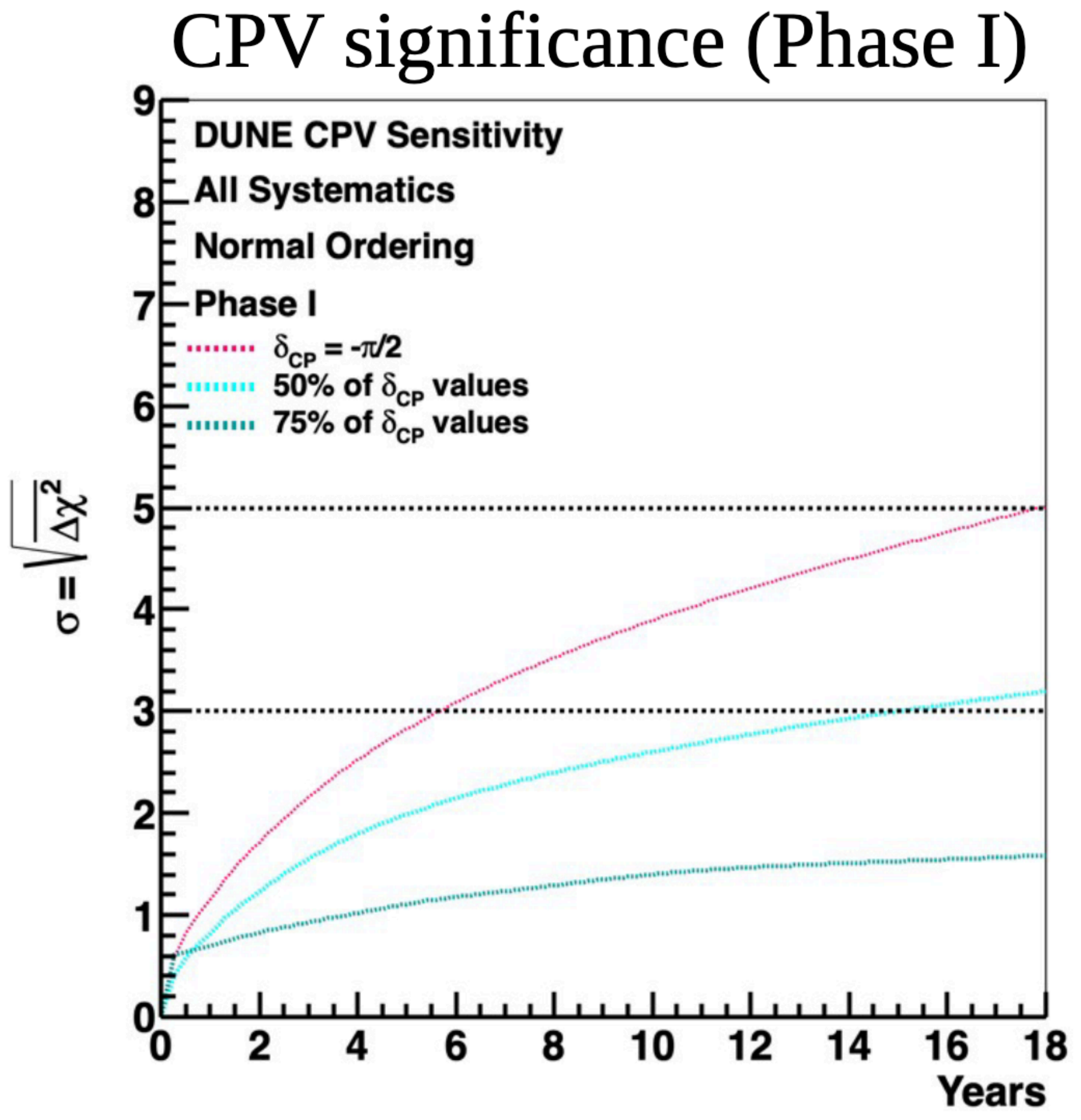
Neutrino mode

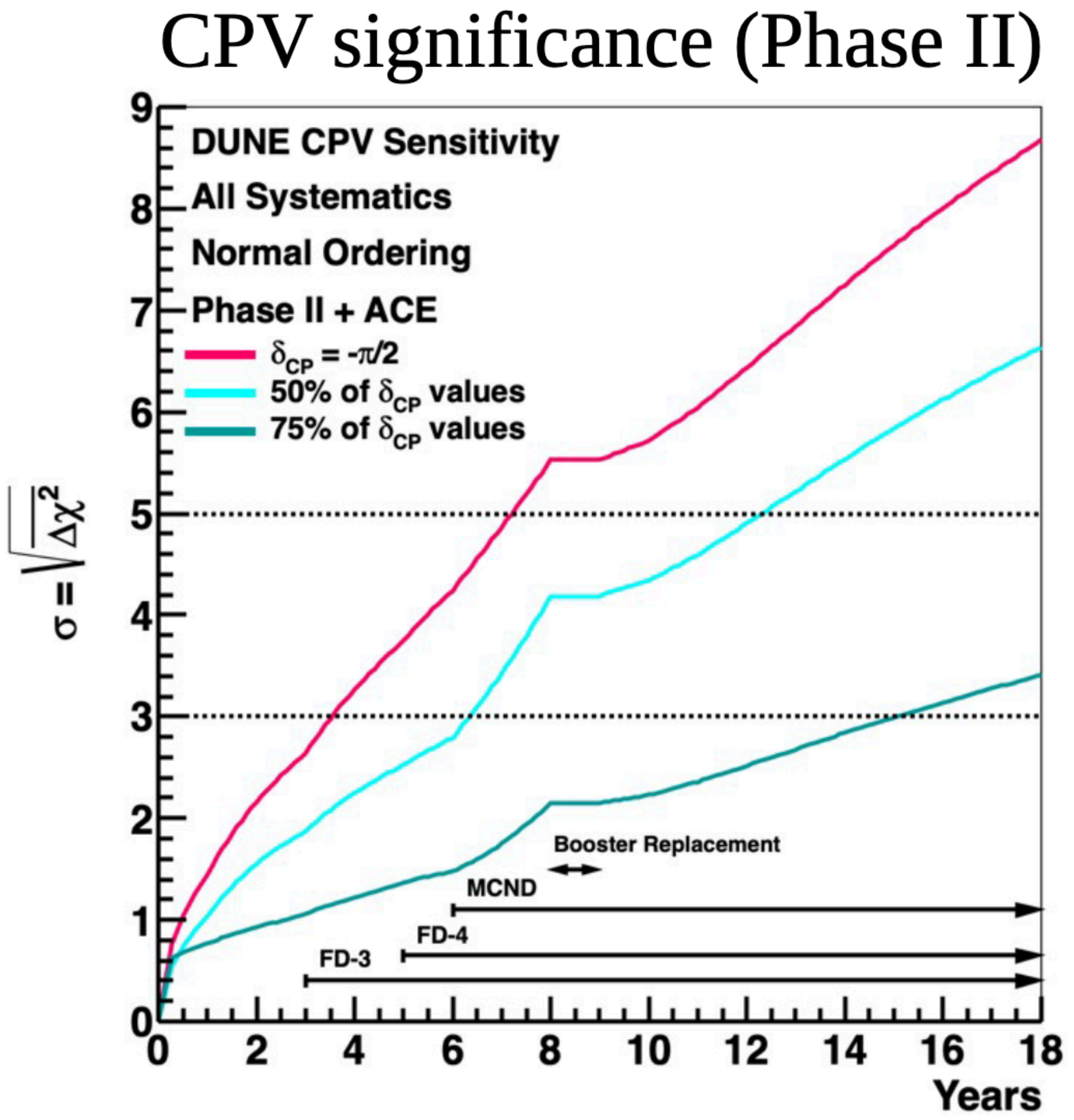
Antineutrino mode



LBL neutrino oscillation physics goals

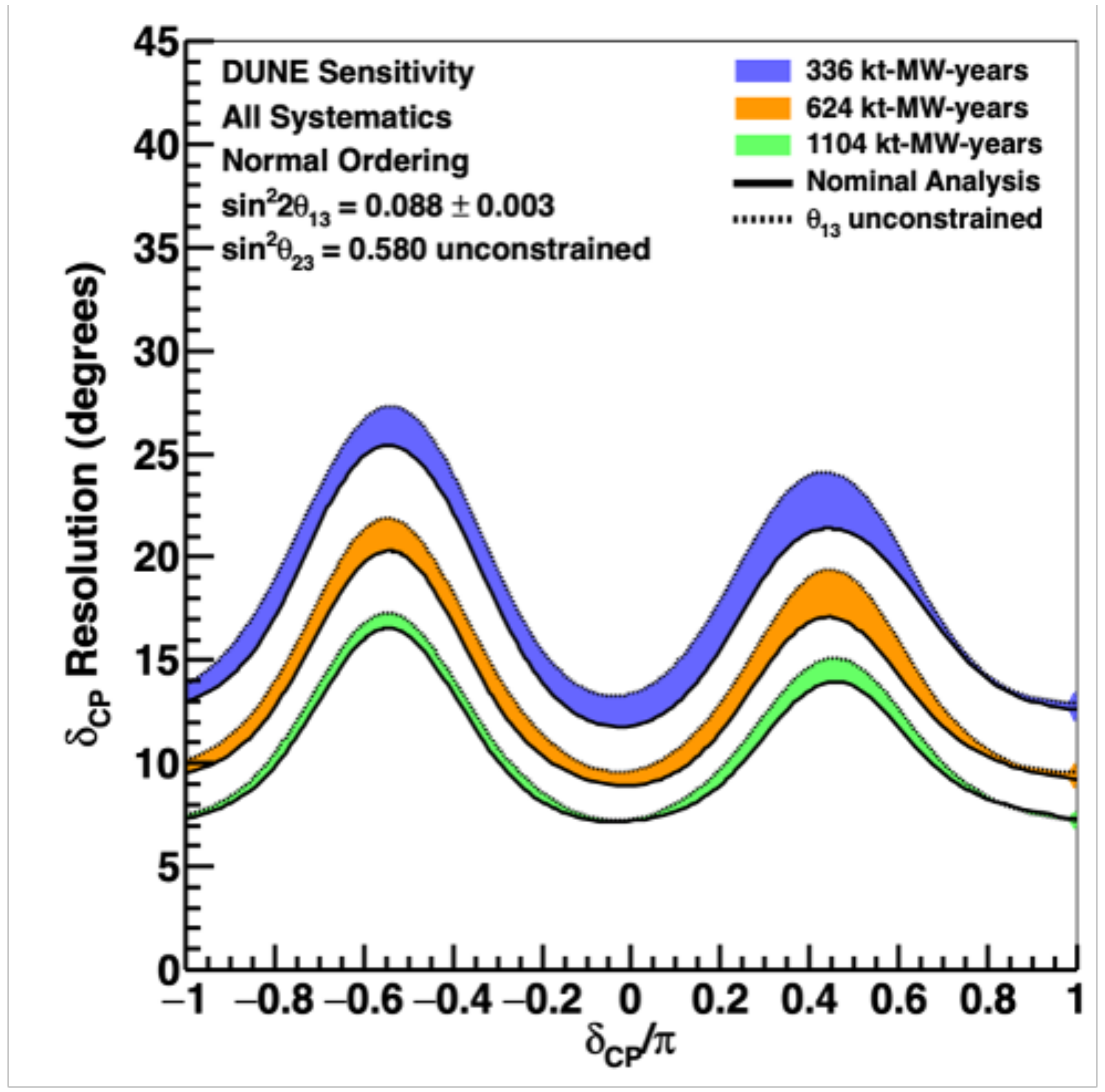
- DUNE **Phase II is required** to achieve the physics goals: beam upgrade to >2 MW, additional FD mass to >40 kt, near detector upgrade

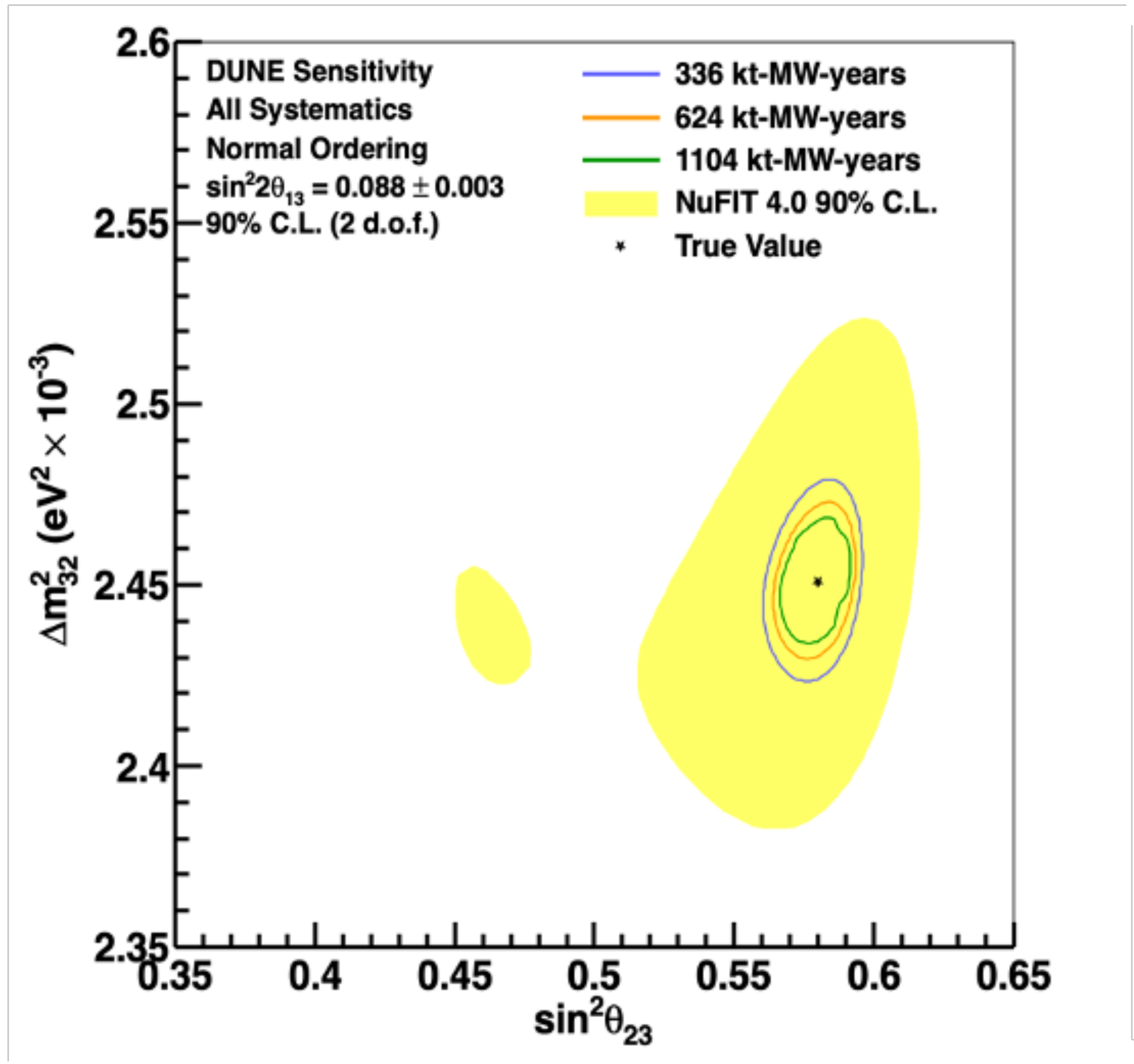


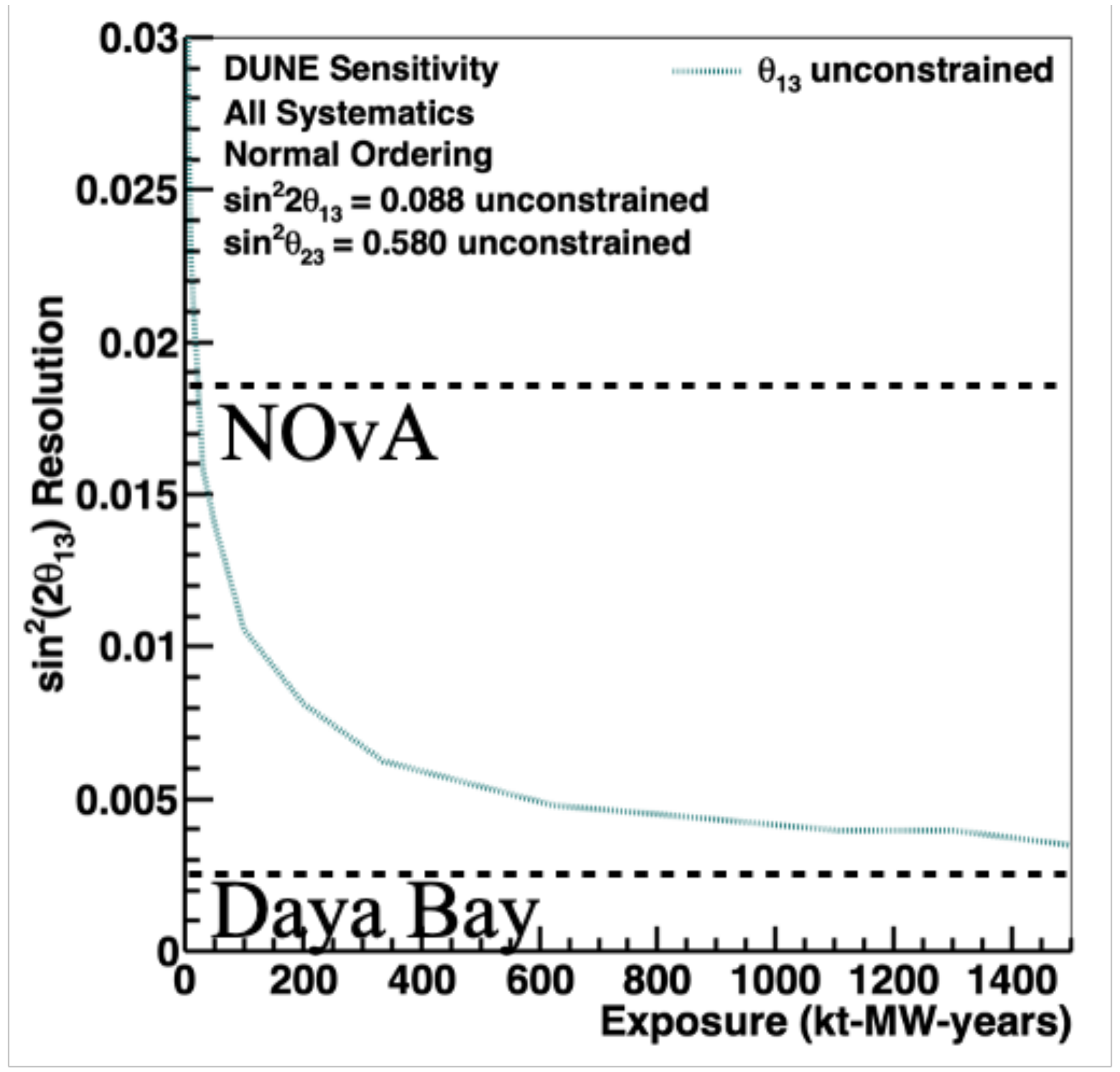


DUNE Phase II precised osc. measurements

- Resolution to δ_{CP} is ~6-16° depending on true value, and sensitivity to CPV even if Nature is relatively unkind
- Excellent resolution to θ_{23}, including octant discovery potential
- Resolution to θ_{13} approaches Daya Bay → DUNE-reactor comparison is sensitive to new physics





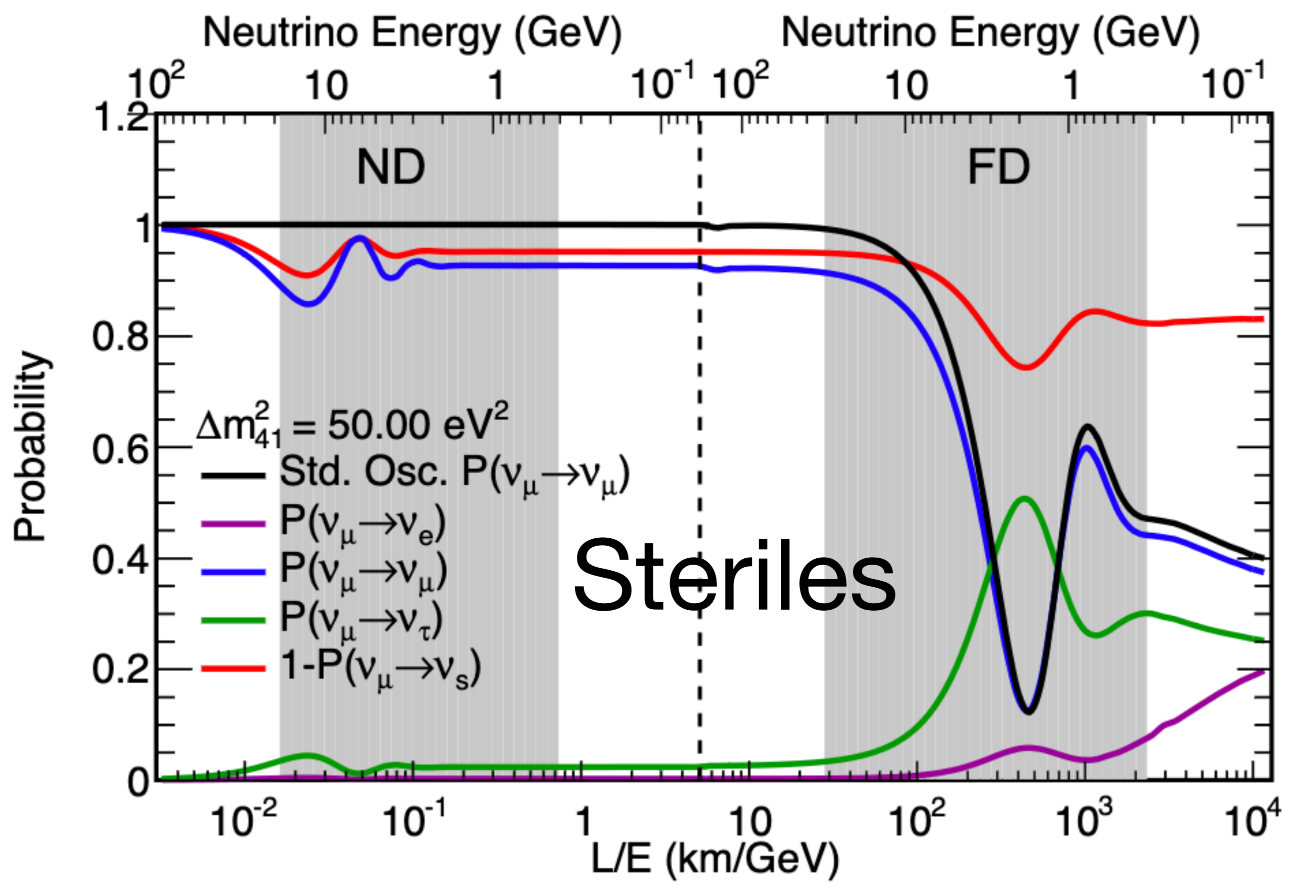


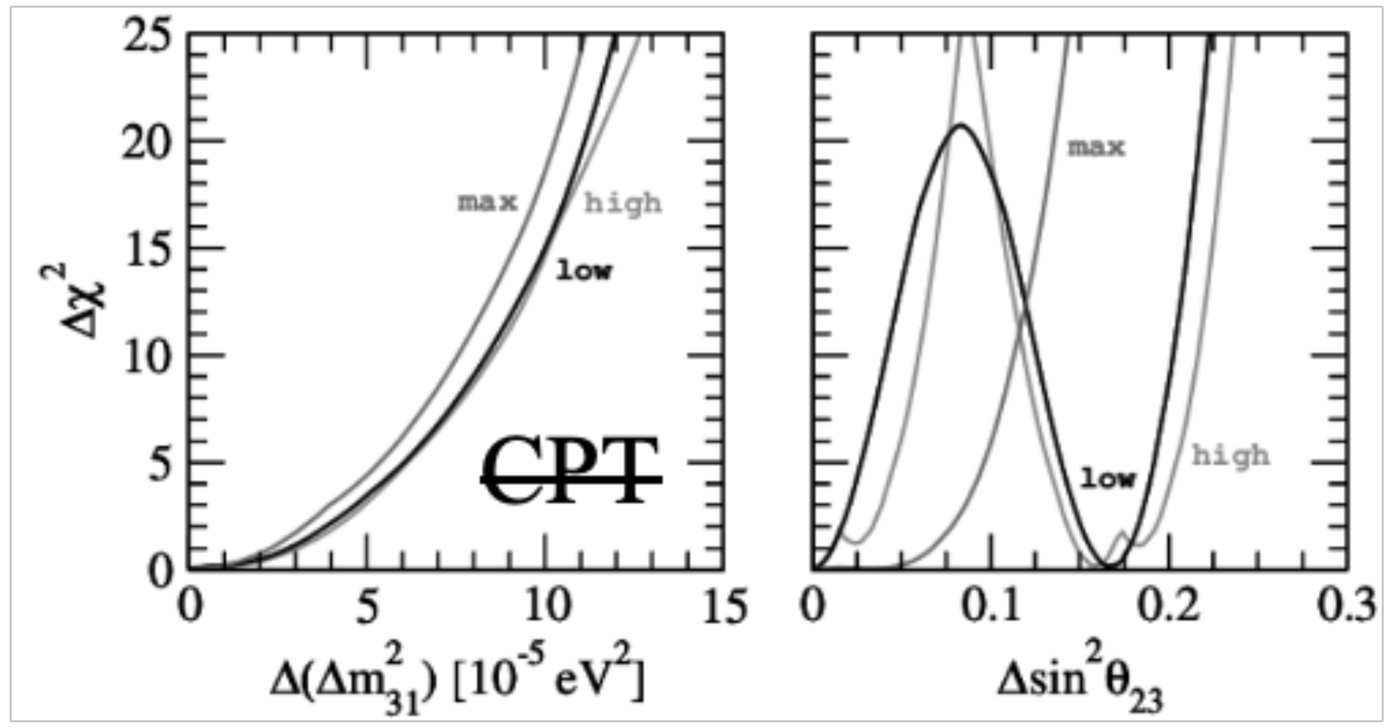
Search for BSM physics (not ordered)

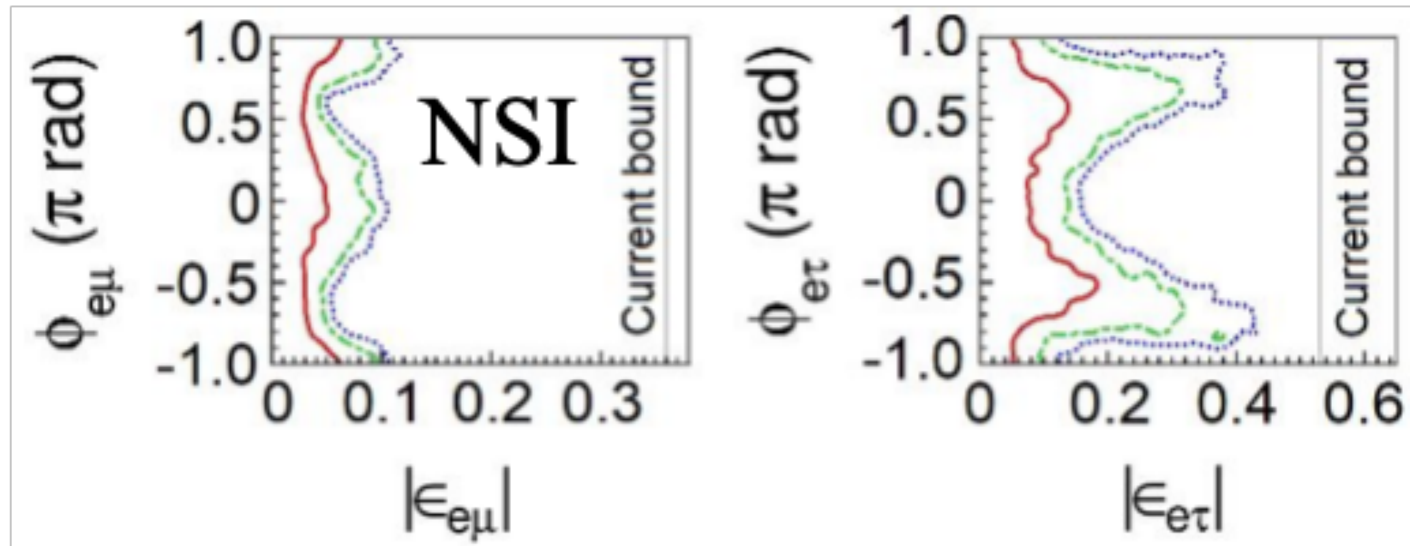
- Neutrino magnetic moment (ND + FD) - signal discrimination, backgrounds…
- Sterile neutrinos (ND + FD)
- Large-extra dimensions (FD)
- Neutrino tridents (ND)
- Baryon number violating processes (FD) - backgrounds…
- Dark matter/axions (ND + FD) - spatial resolution, backgrounds…
- Millicharged particles (ND)
- Tau neutrinos (FD)
- …

New physics in neutrino oscillations

- If ν and $\bar{\nu}$ spectra are inconsistent with three-flavor oscillations, it could be due to sterile neutrinos, CPT violation, NSI…
- DUNE covers a very broad range of L/E at both the ND and FD
- DUNE can measure parameters like Δm^2_{32} with neutrinos and with antineutrinos
- DUNE has unique sensitivity to NSI matter effects due to long baseline
- Characterizing new physics will be challenging: **precise measurements** with large matter effect in DUNE Phase II likely required







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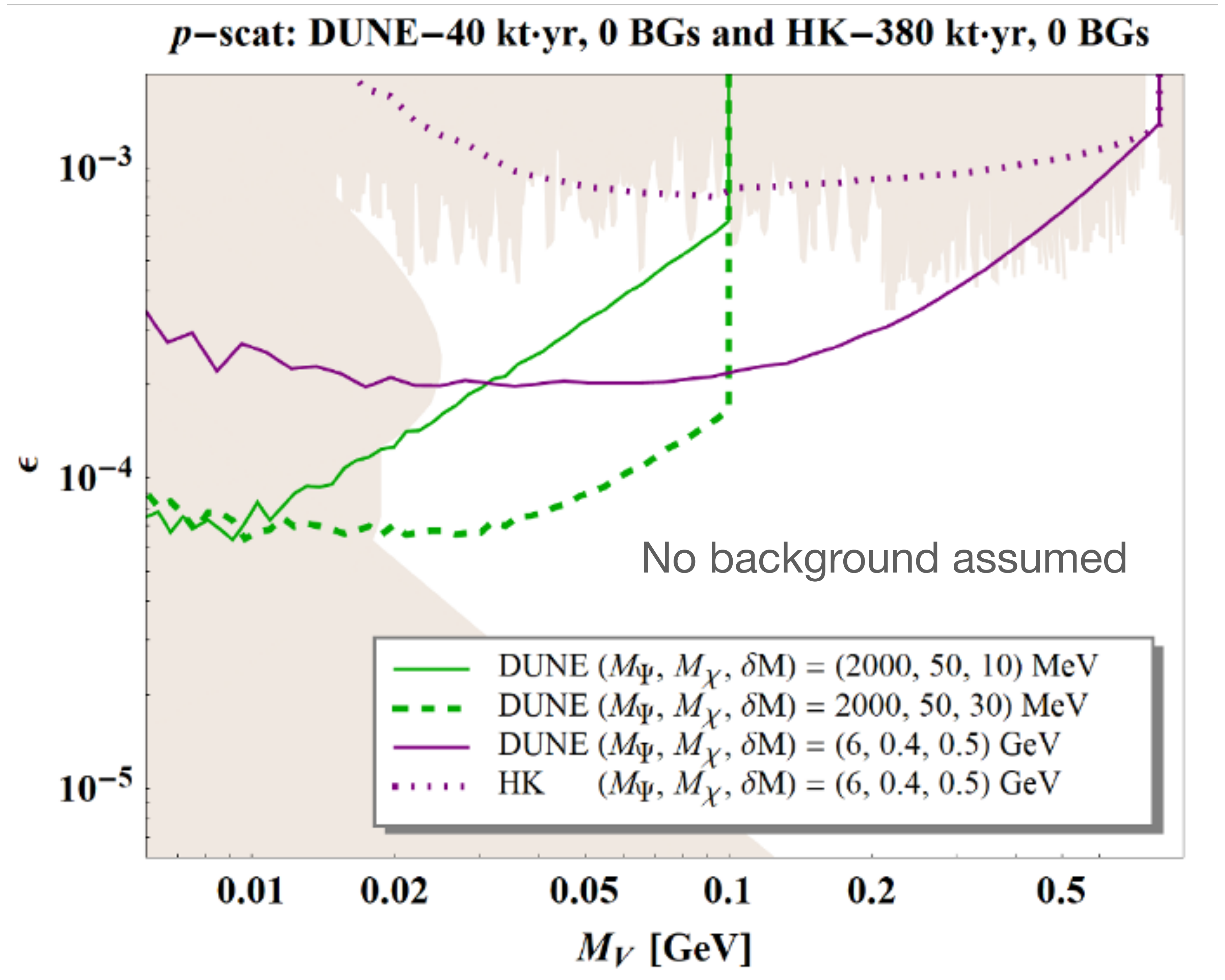
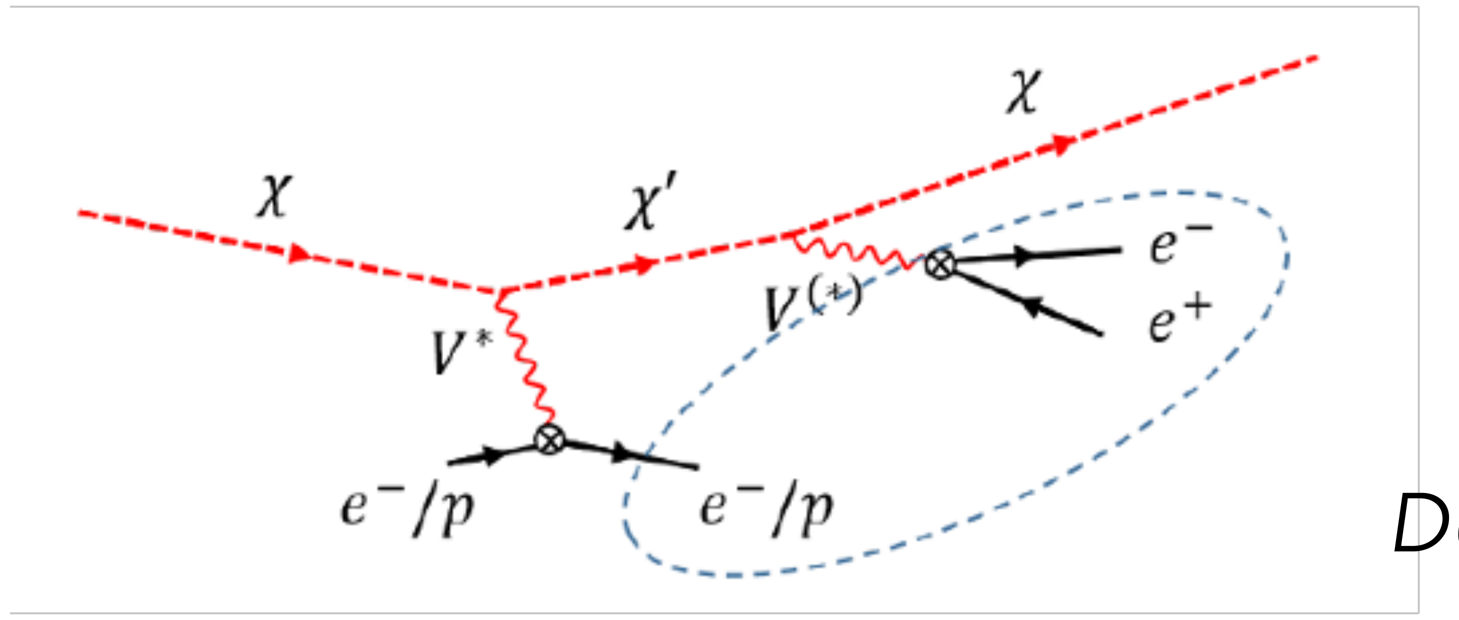
BSM physics in the FD (a few examples)





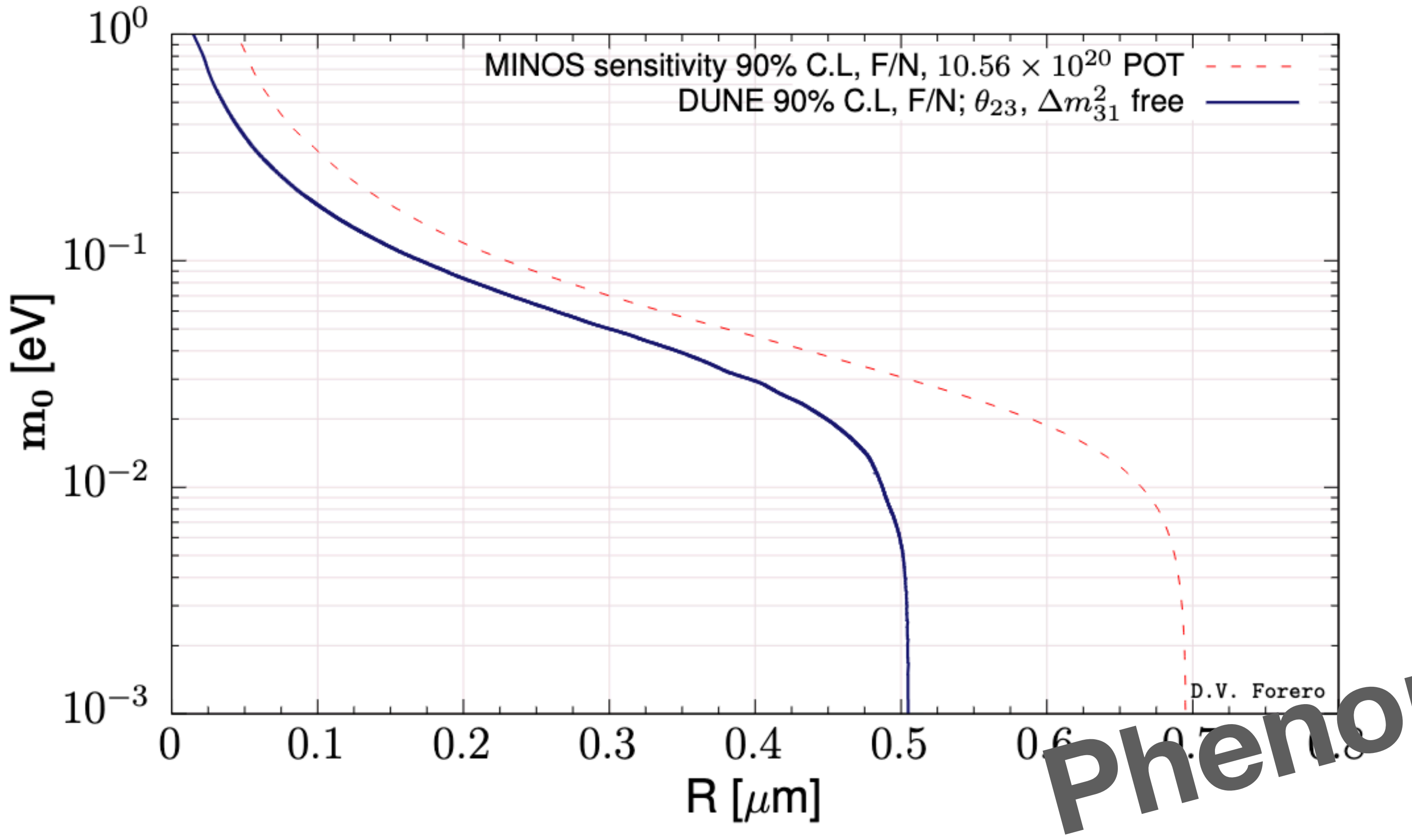
- DUNE's **imaging** and **spatial resolution** are critical for some signals
- **Inelastic dark matter scattering** gives a signature of two low-energy electron tracks, and a detached low-energy electron or proton
  - DUNE can see all of these tracks, and the displacement → world leading sensitivity at low mass already in Phase I

DUNE, Eur. Phys. J. C 81 (2021) 4, 322

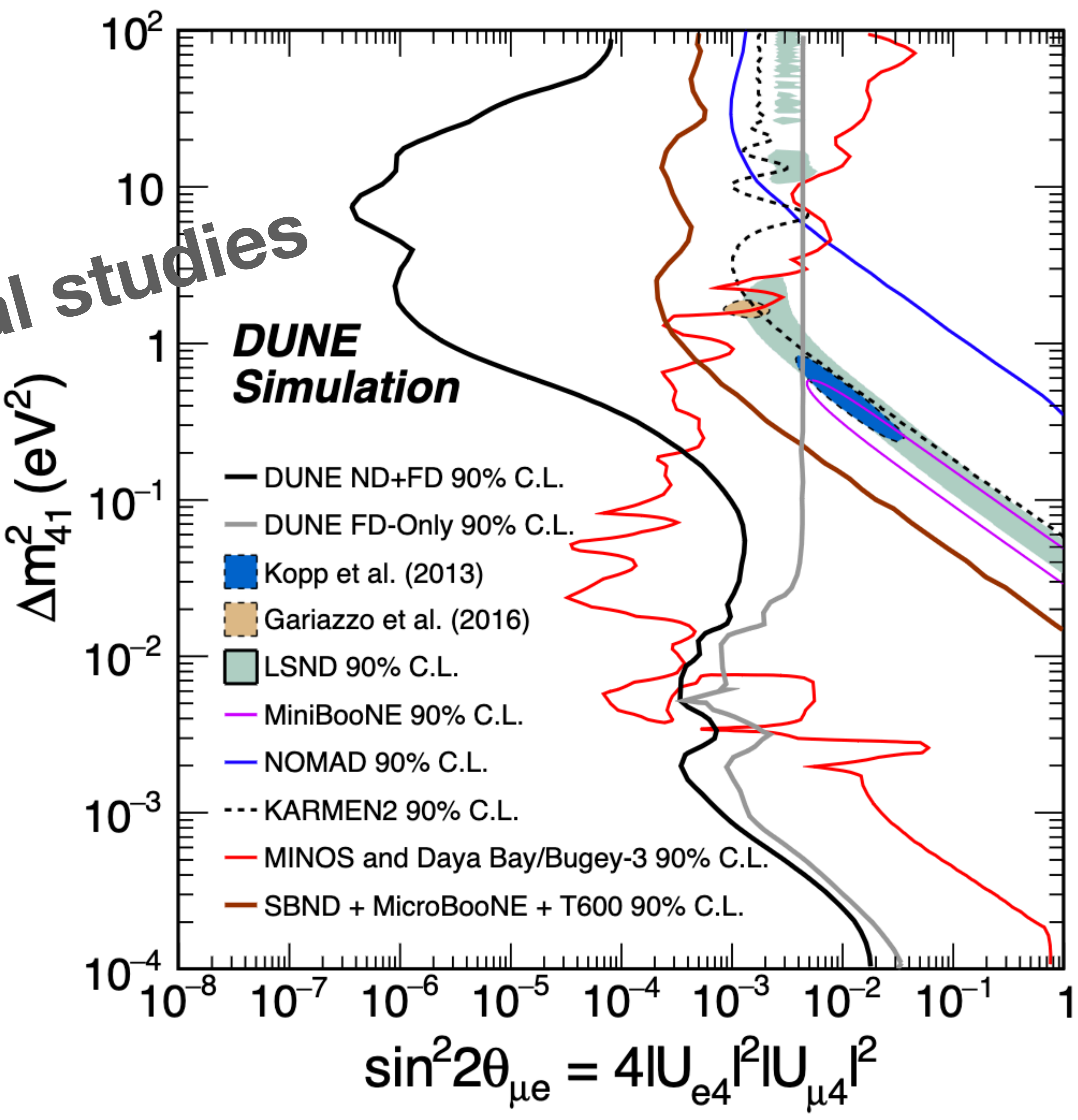
BSM physics in the FD (a few examples)

Constraining the size of large extra-dimensions

DUNE, Eur. Phys. J. C 81 (2021) 4, 322

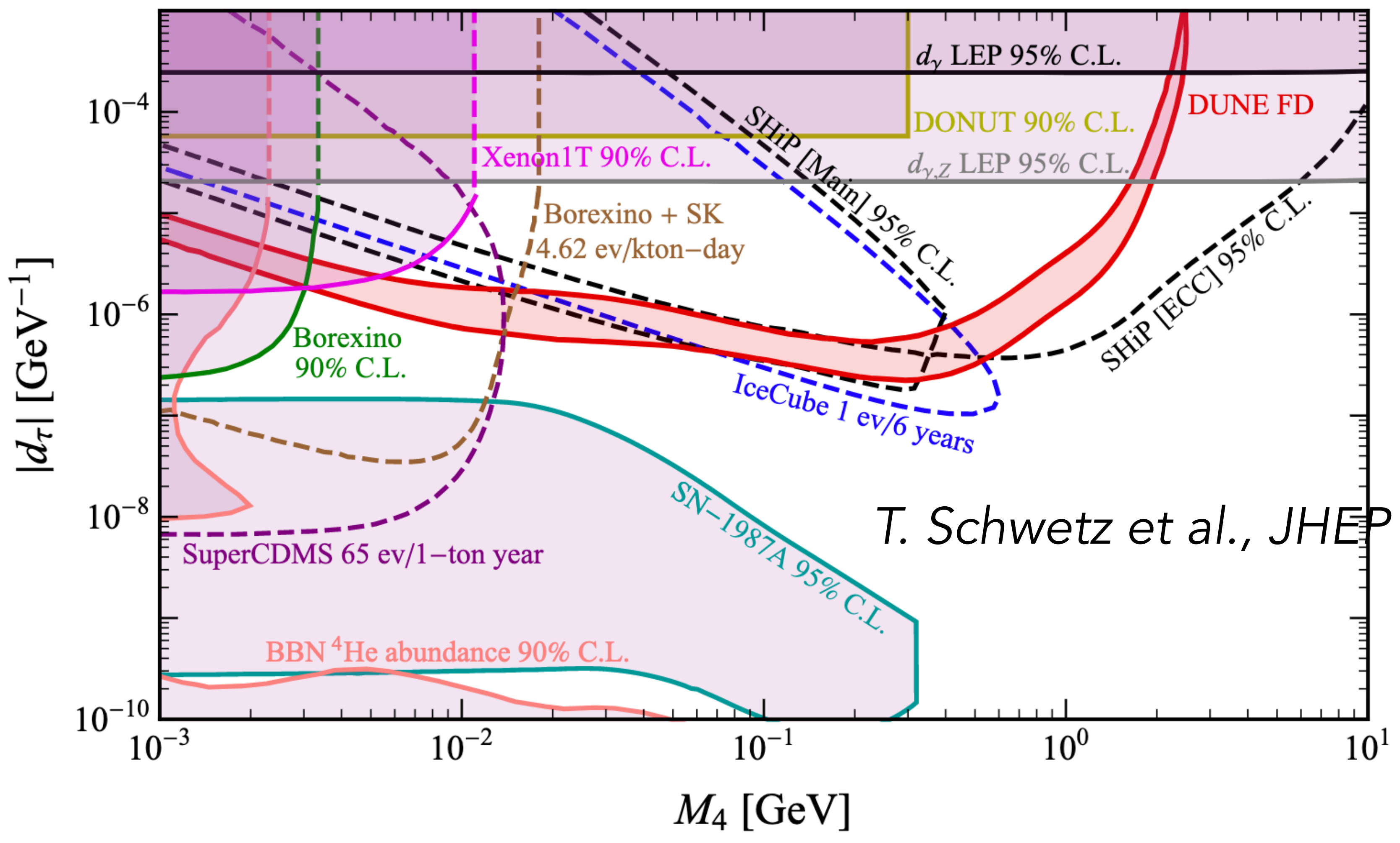


Sterile neutrino mixing



Phenomenological studies

Constraining active-sterile neutrino transition magnetic moments



T. Schwetz et al., JHEP 200 (2021)

Astrophysical neutrinos - physics program

Expand neutrino physics capabilities at low-energy (~MeV) range in LAr TPCs

- **Solar neutrinos**:
  - Improve the precision on the solar neutrino oscillation parameters (solar-reactor tension?)
  - First observation of the hep solar neutrino flux
- **Supernova neutrinos**:
  - First measurement of SN burst neutrinos in all flavors in real time
  - Neutrino oscillations
  - Information about star collapse mechanism

A possibility??

- **Diffuse Supernova Neutrino Background**
  - First measurement of the neutrino flux from old supernovae in the Universe

Low energy neutrino signal in LAr

I.Gil-Botella & A.Rubbia
hep-ph/0307222
JCAP 10 (2003) 009
JCAP 08 (2004) 001

- Elastic scattering (ES) on electrons

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

- Charged-current (CC) interactions on Ar

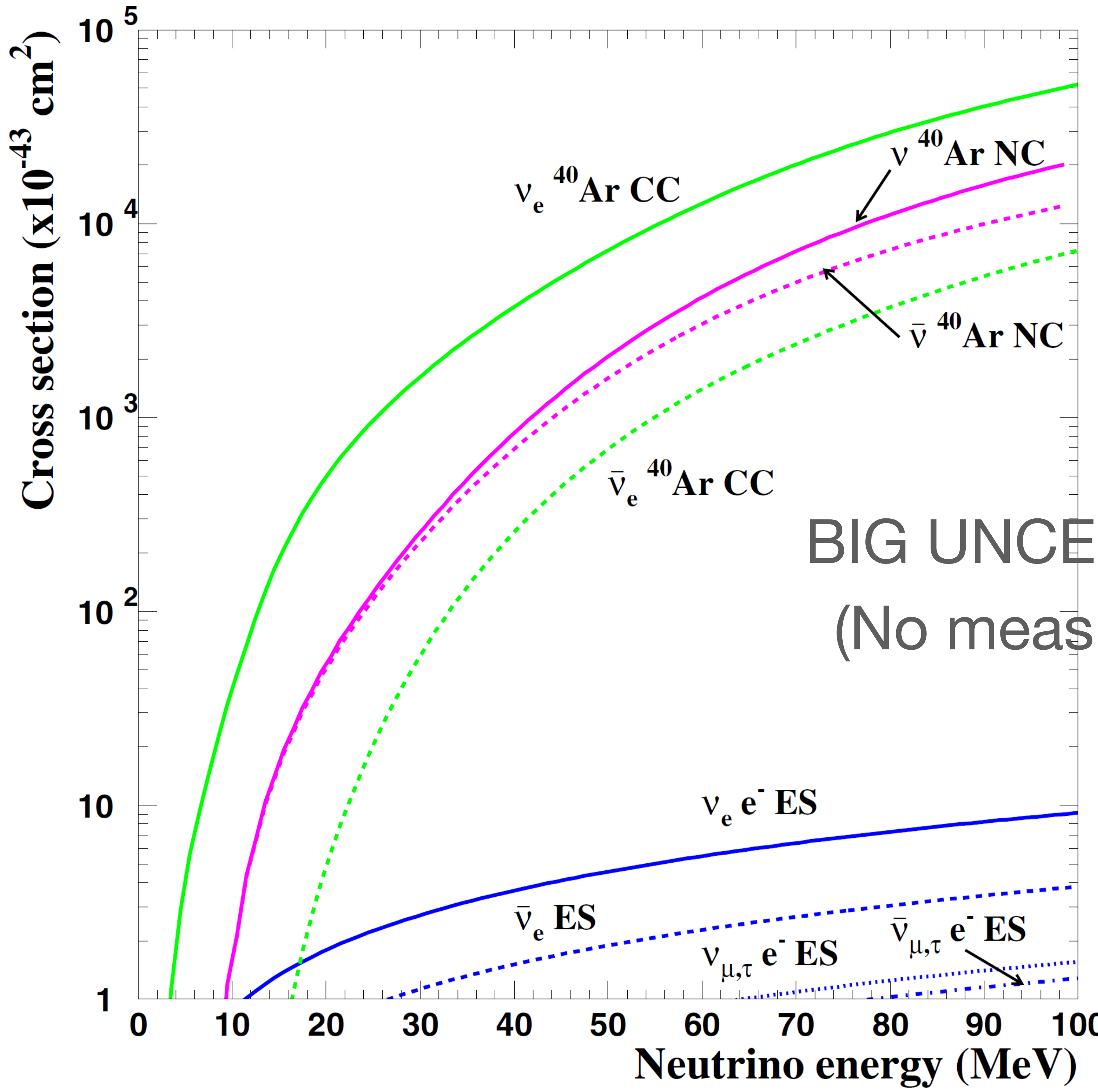
$\nu_e + {}^{40}Ar \rightarrow {}^{40}K^* + e^-$ $E_{\nu e} > 1.5$ MeV

$\bar{\nu}_e + {}^{40}Ar \rightarrow {}^{40}Cl^* + e^+$ $E_{\bar{\nu} e} > 7.48$ MeV

- Neutral current (NC) interactions on Ar

$\nu + {}^{40}Ar \rightarrow \nu + {}^{40}Ar^*$ $E_\nu > 1.46$ MeV

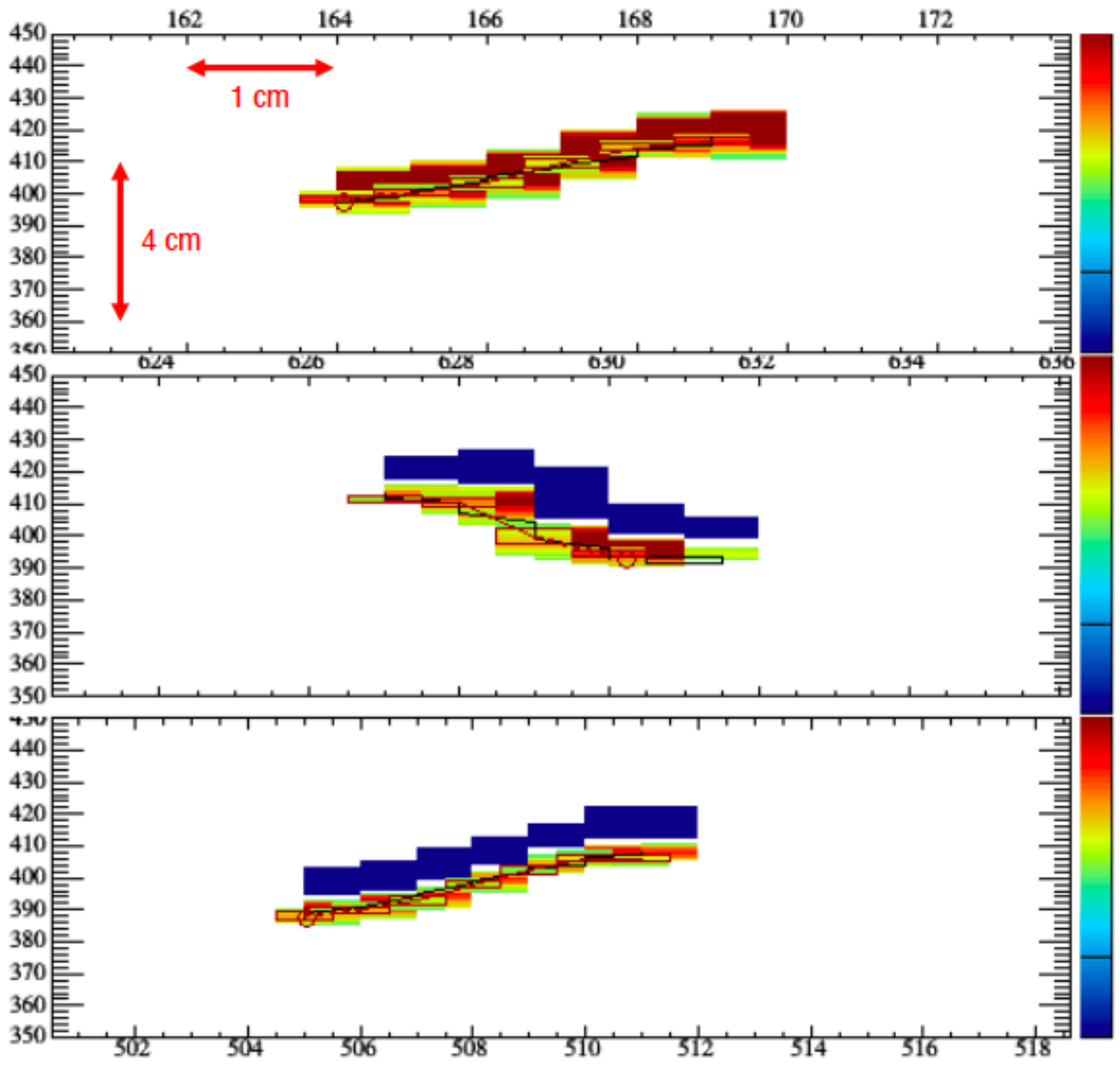
SN ν cross sections on Ar



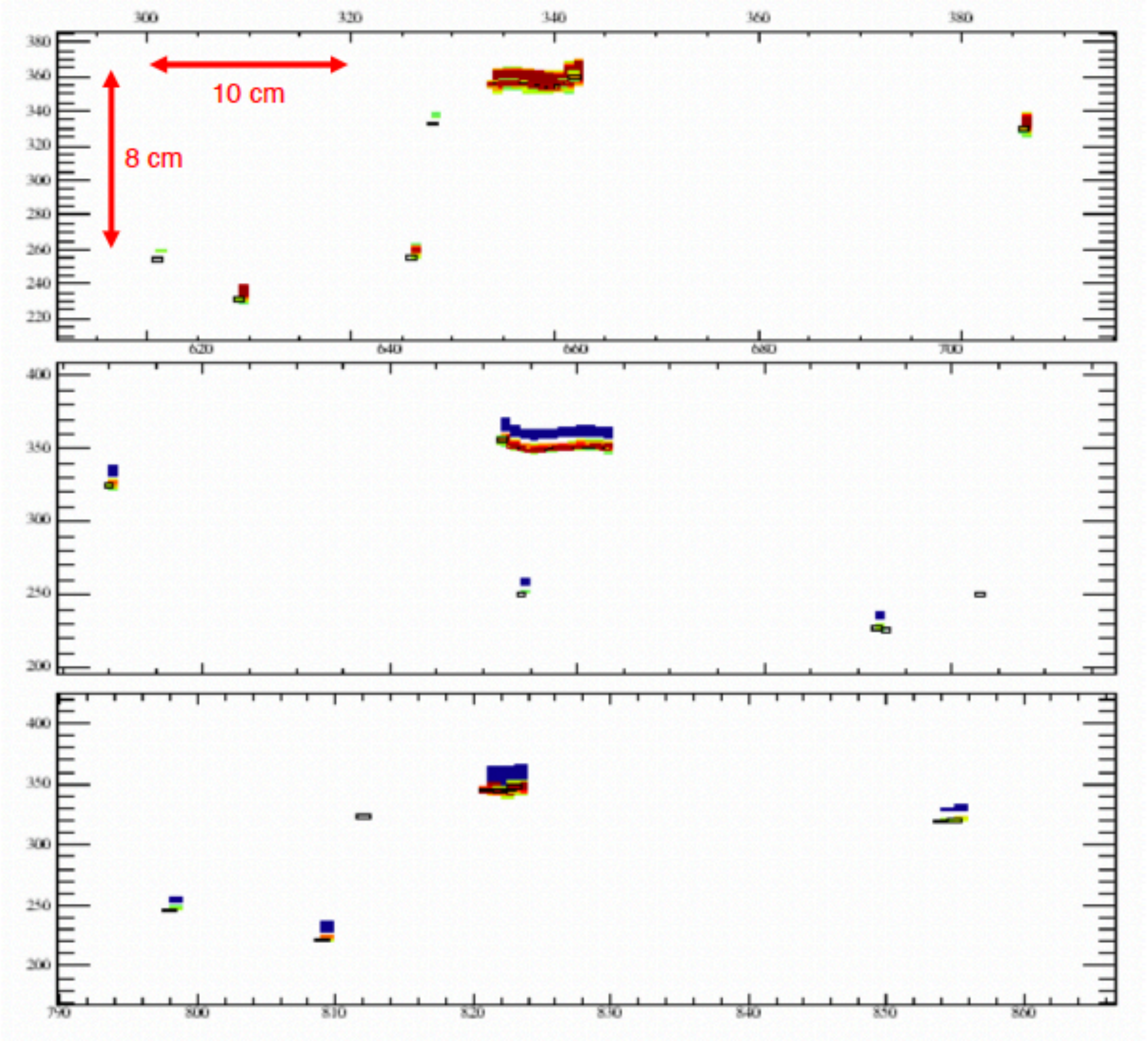
BIG UNCERTAINTIES
(No measurements)

Possibility to separate the different channels by a classification of the associated photons from the K, Cl or Ar de-excitation (specific spectral lines for CC and NC) or by the absence of photons (ES)

Neutrino interactions in LAr

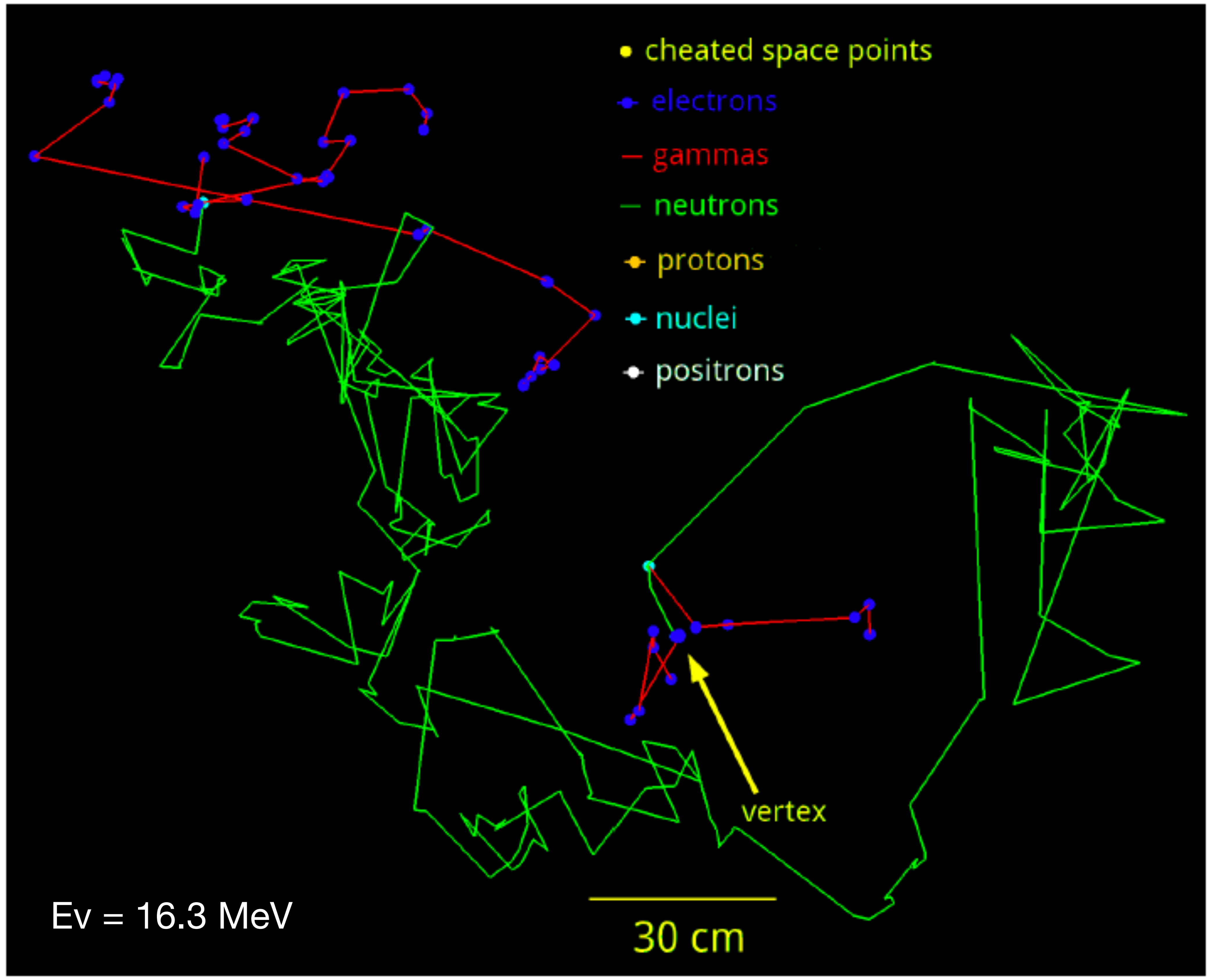


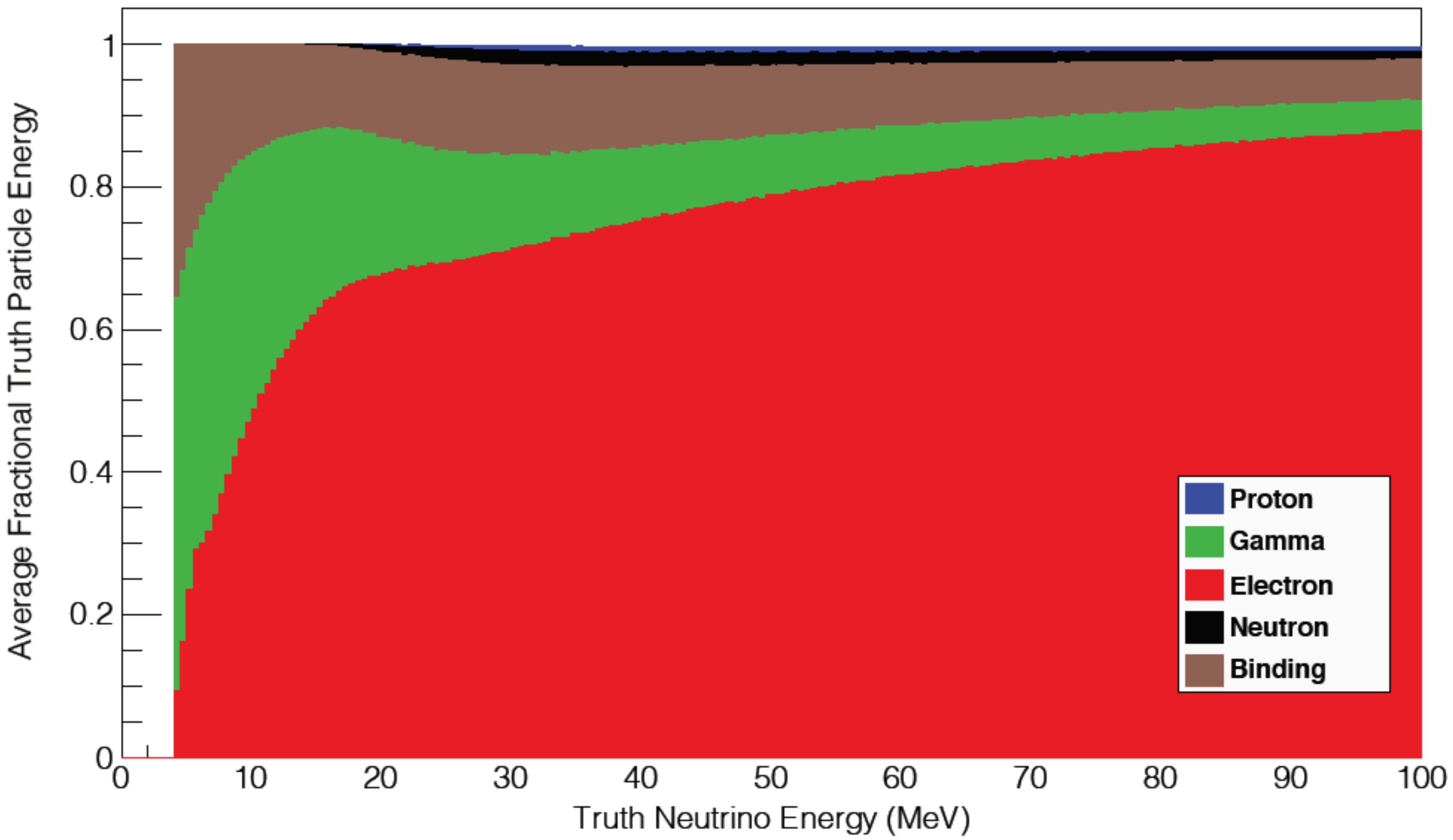
Pointing capabilities ES



CC

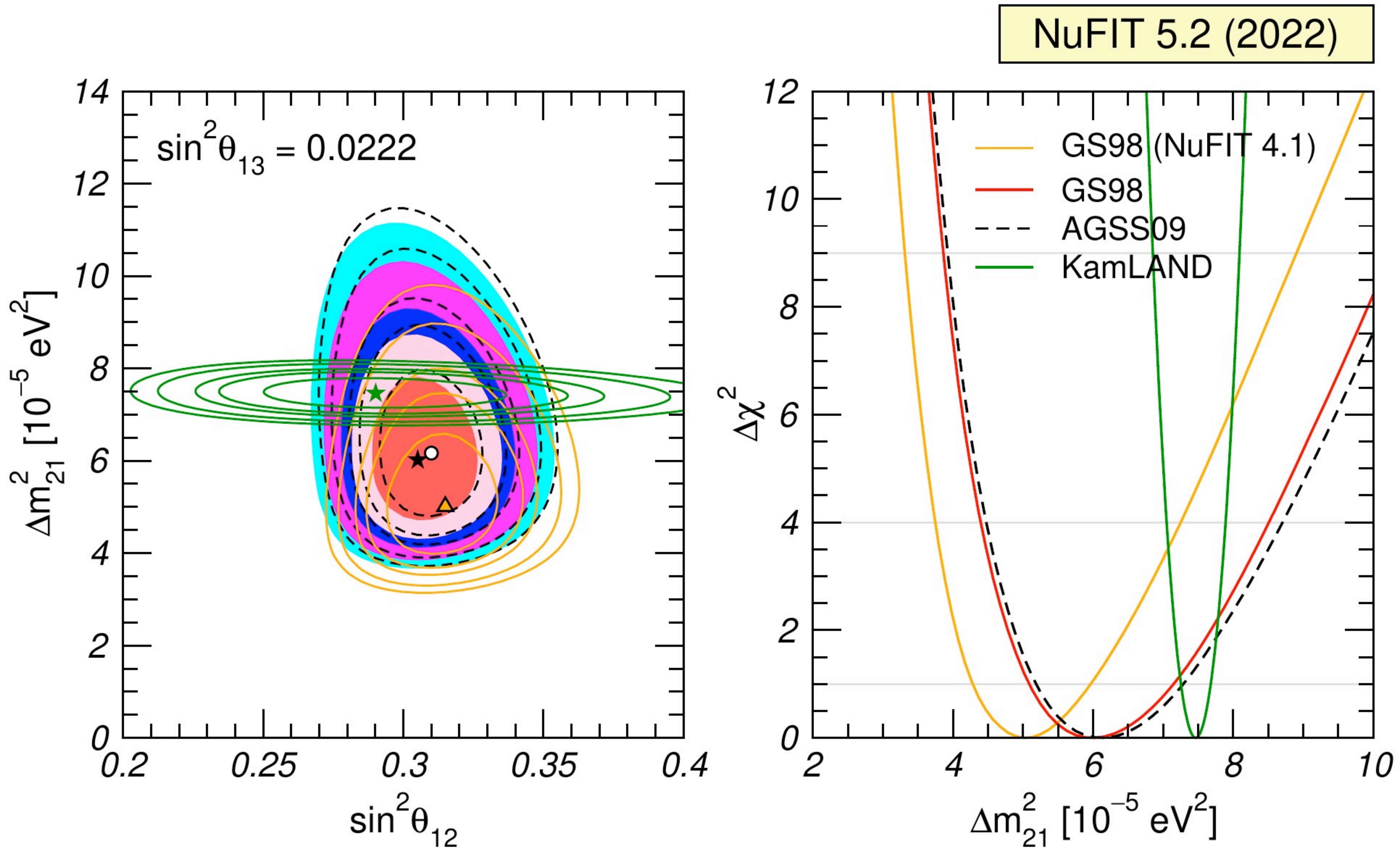
Neutrino interactions in LAr





Current status solar neutrinos

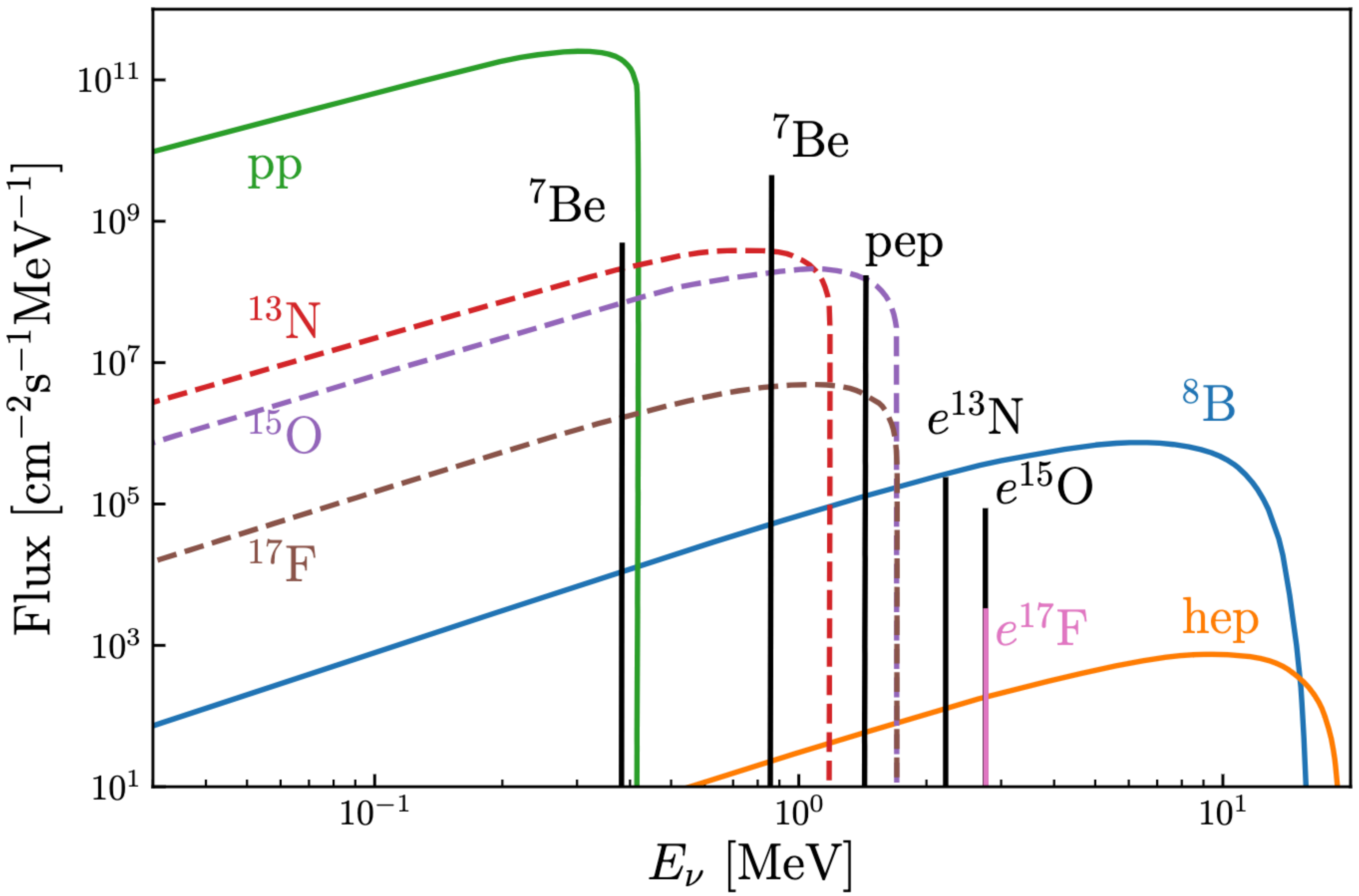
- **^{8}B flux** has been used to extract the solar neutrino oscillation parameters
  - Slight tension (~1σ) between the solar and KamLAND experiments
  - Need of more precise measurements (JUNO, HK, DUNE)
- Neutrinos from **hep fusion**:
  $^3He + p \rightarrow {}^4He + e^+ + \nu_e$
  have not been observed yet
  - Stellar astrophysics



	bfp $\pm 1\sigma$
$\sin^2\theta_{12}$	$0.303^{+0.012}_{-0.012}$
$\frac{\Delta m^2_{21}}{10^{-5}\ \text{eV}^2}$	$7.41^{+0.21}_{-0.20}$

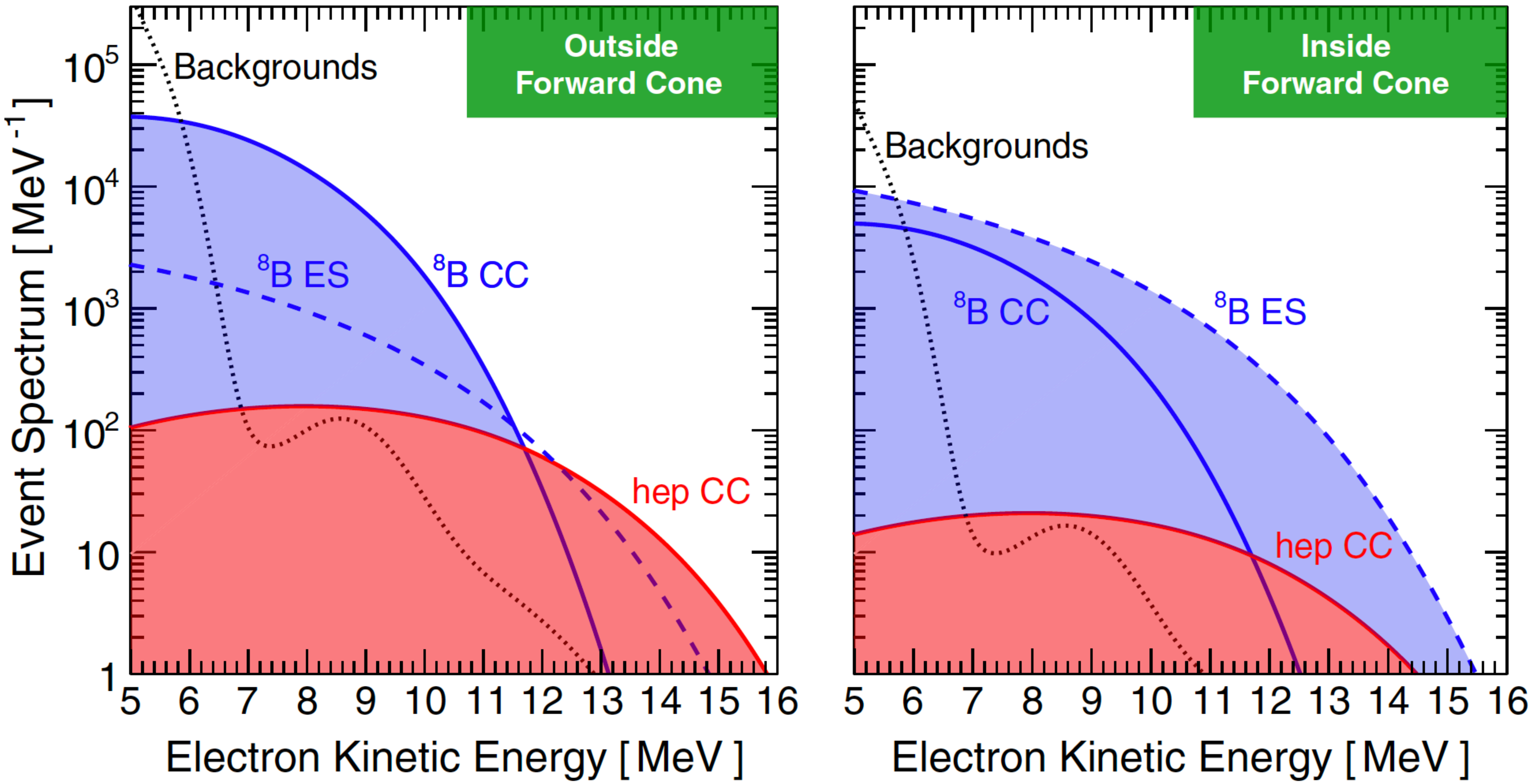
Expected solar neutrinos in DUNE

- DUNE has the potential to record an enormous amount of solar neutrinos
  - Measurement of ^{8}B solar flux and observe hep flux
- For an energy threshold of 5 MeV in a 10 kt FD:
  - **~10000 CC** evts/year
  - **~2000 ν-e scattering** evts/year
- Above 14 MeV, pure hep neutrino sample
  - **Up to 50** evts/year



Expected solar signals and backgrounds

Capozzi et al., PRL 123, 131803 (2019)

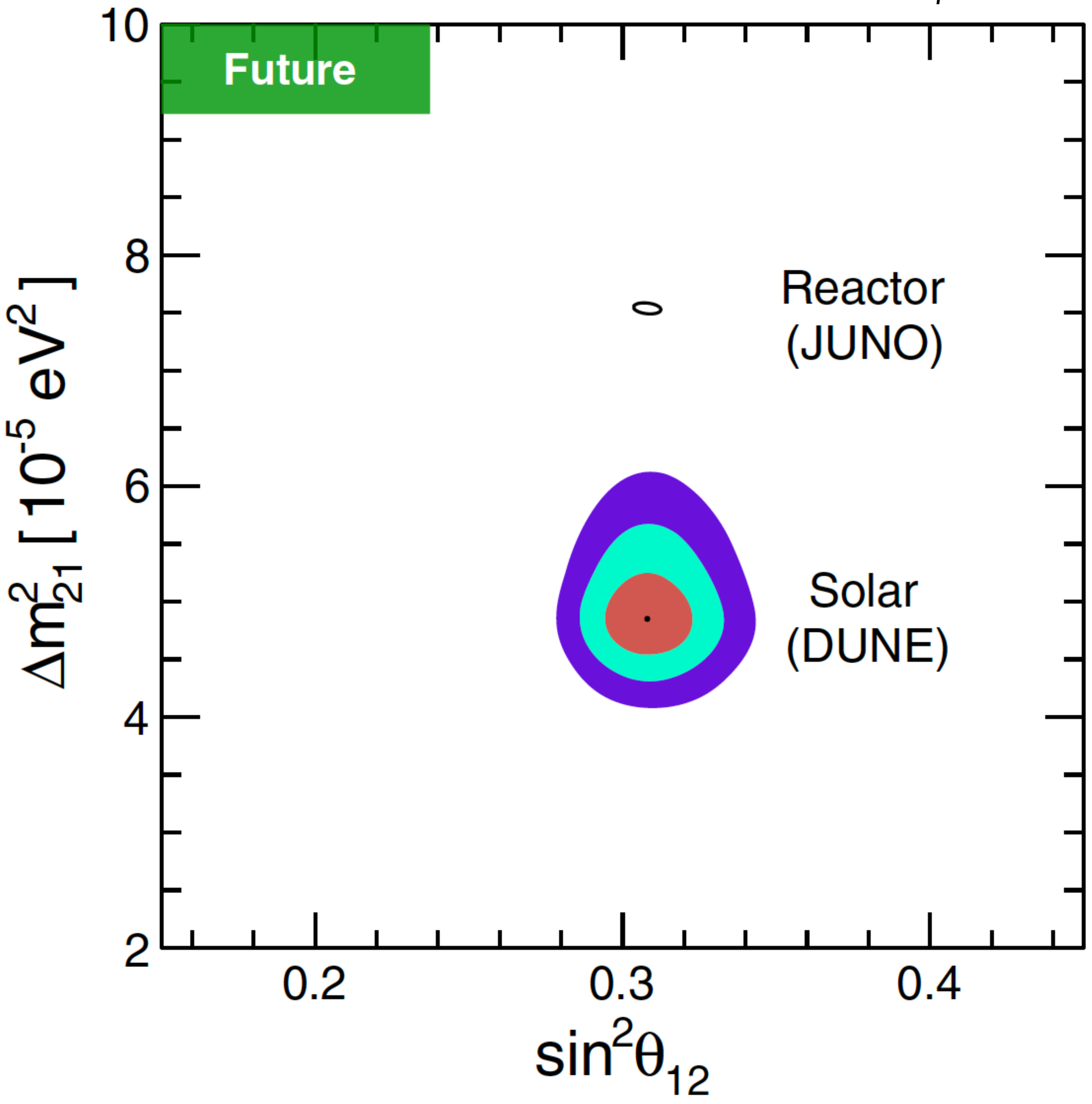


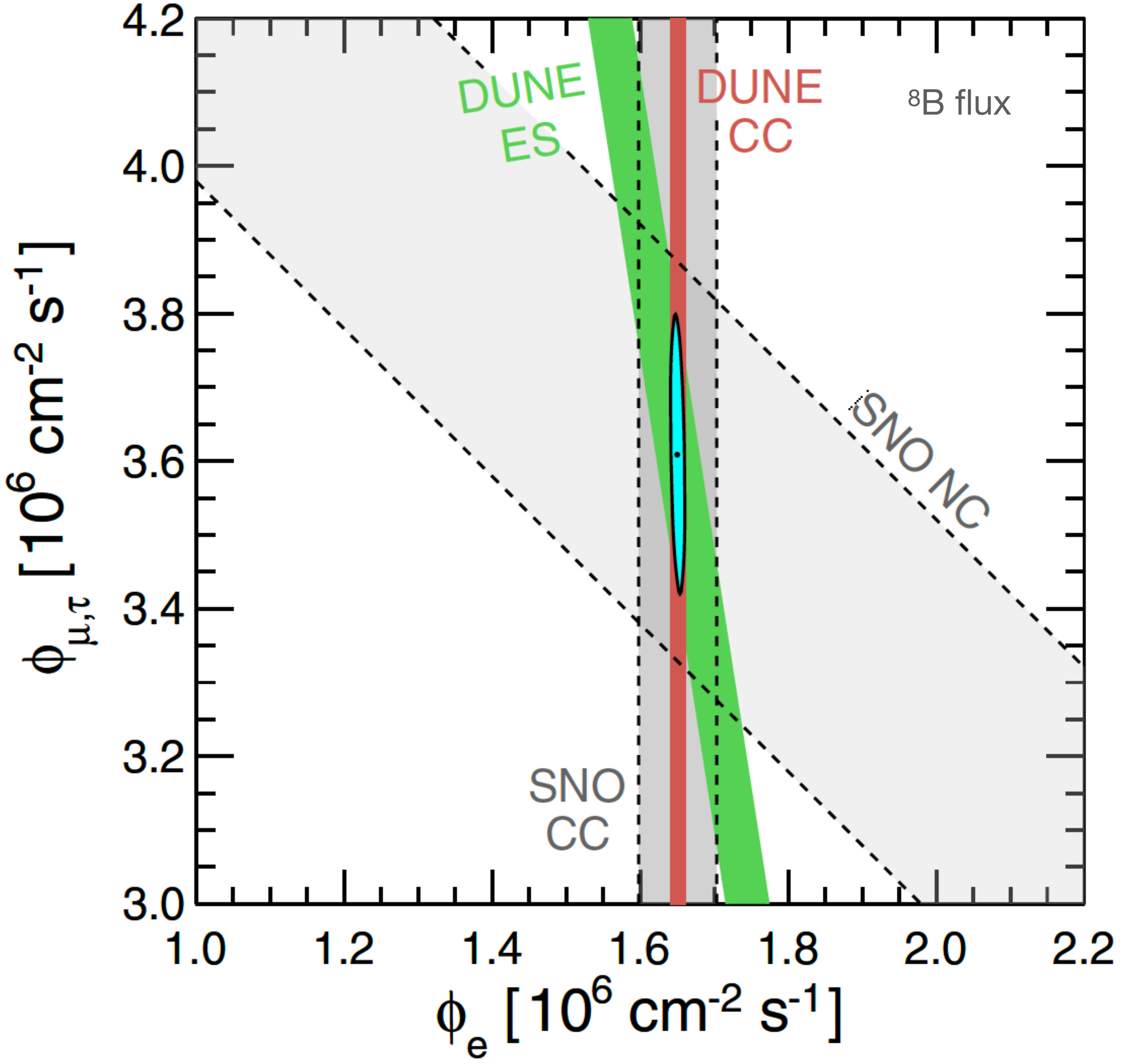
100 kton-yr exposure + 3 flavor mixing + some detector effects

Considered backgs are neutron captures on ^{40}Ar, NC νAr and beta-decaying radioactivities induced by muons

Precision of neutrino mixing and neutrino fluxes

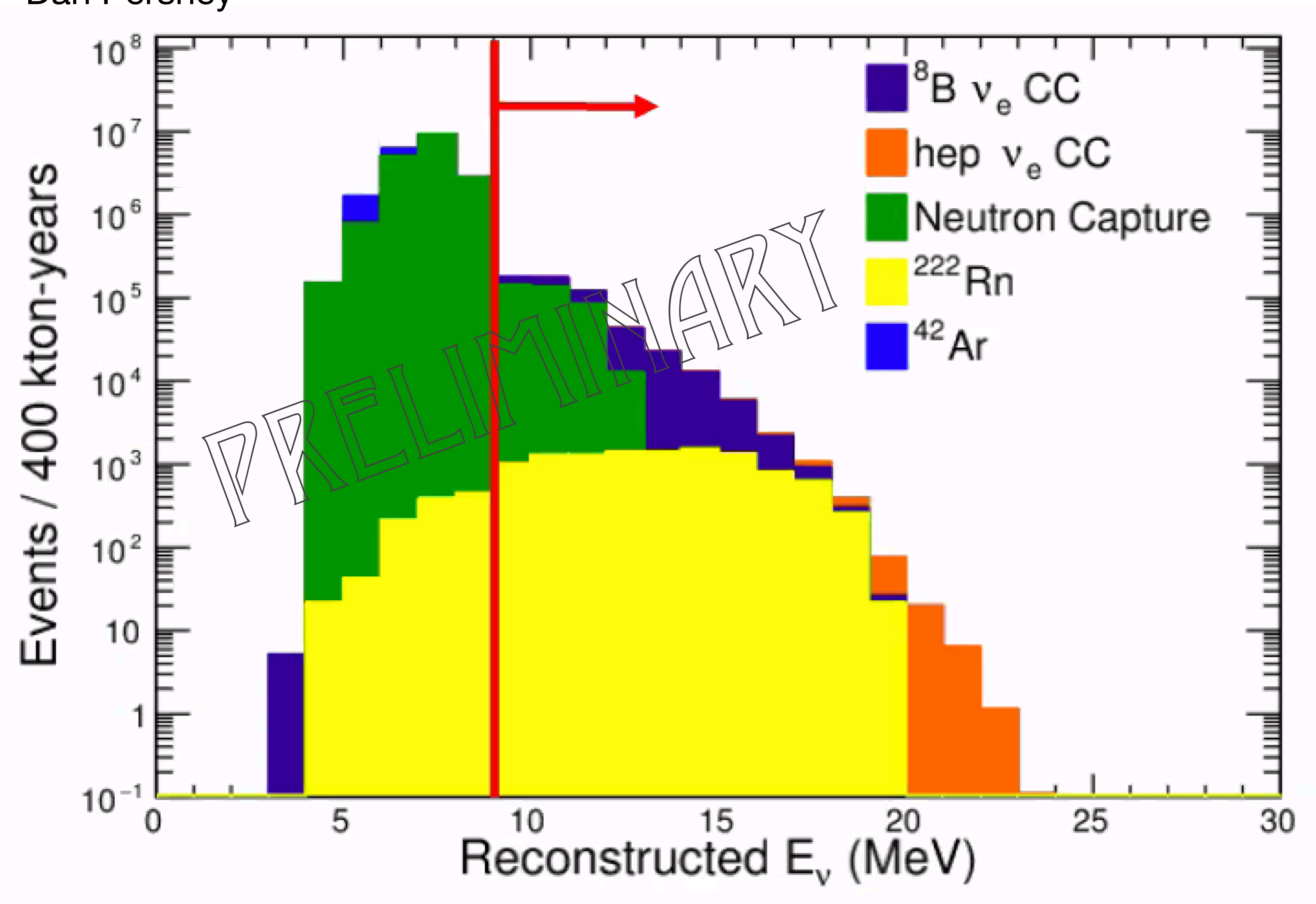
Capozzi et al., PRL 123, 131803 (2019)





Preliminary solar studies in DUNE FD-HD

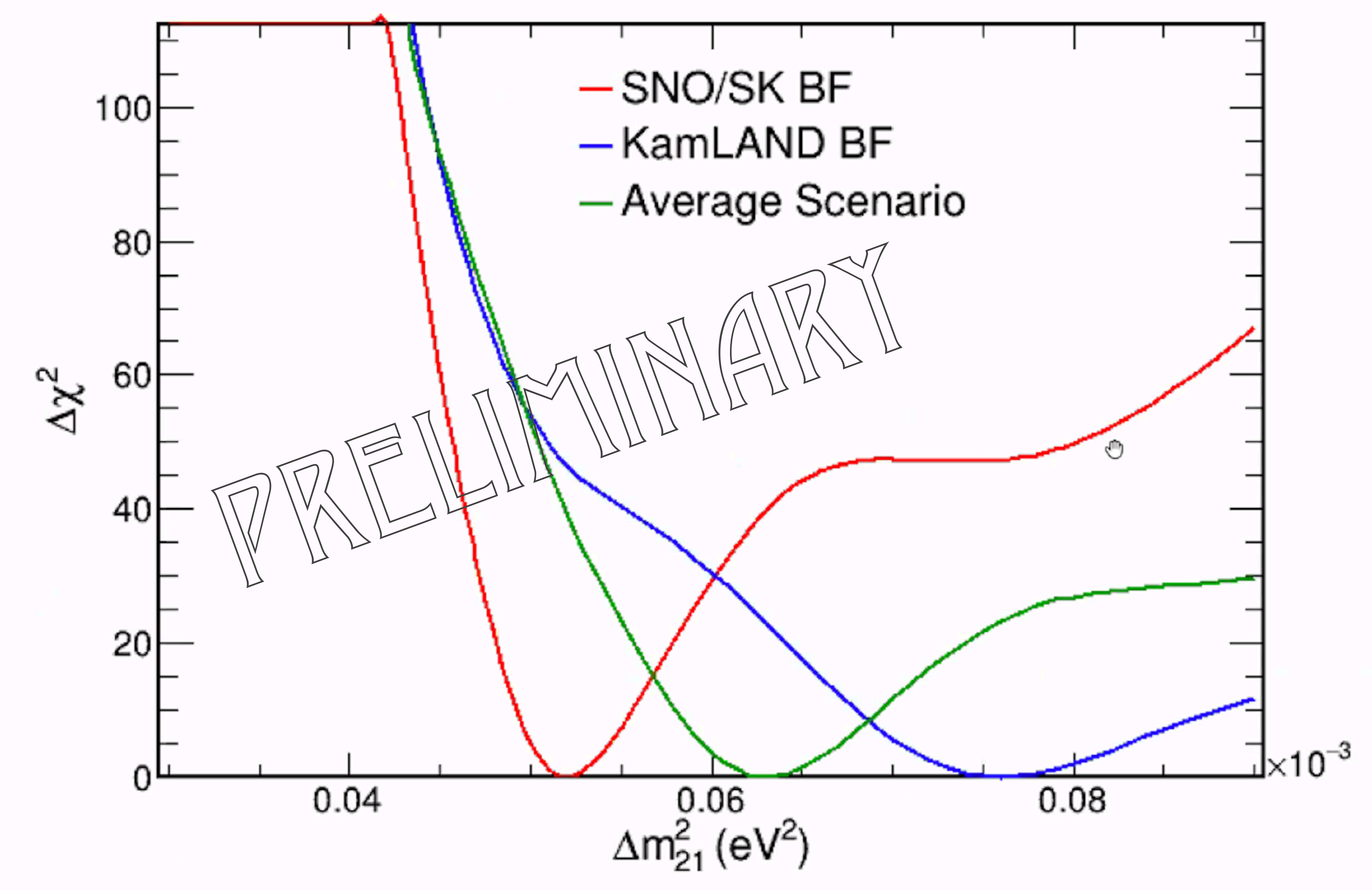
Dan Pershey



- Analysis threshold > 9 MeV
- Folding oscillation and efficiency effects
  - ~7200 evts/module/year (only CC)
- Neutron capture is the dominant background
  - ^{40}Ar(n,ɣ)
  - ^{36}Ar(n,ɣ)
  - ^{40}Ar(α,ɣ) important at higher energy

Preliminary solar studies in DUNE

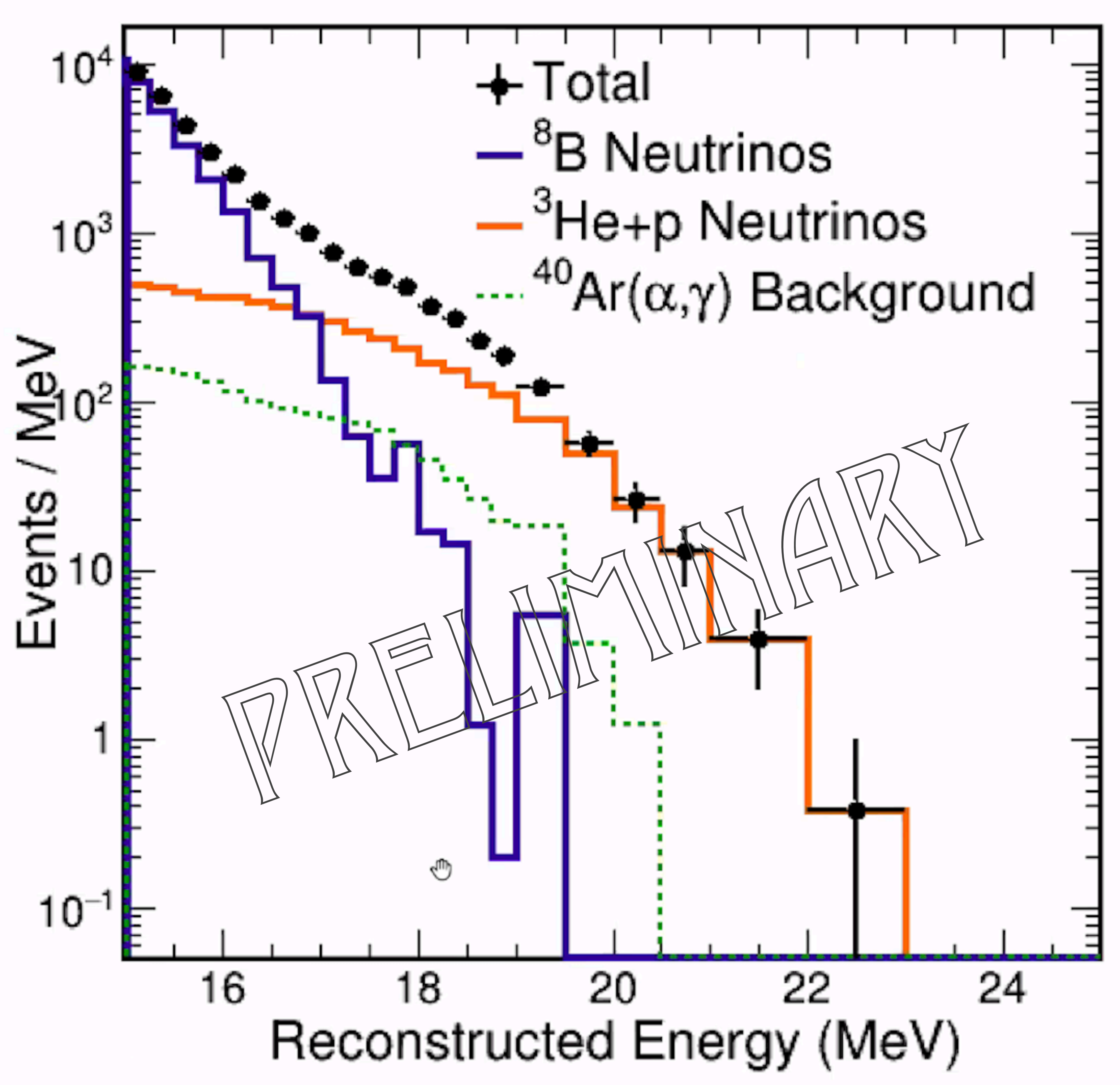
Dan Pershey



- Δm^2_{21} sensitivity for 400 kt-yrs
  - ~5-7σ sensitivity to discern between SNO/SK (2021) and KamLAND best fits
  - 1.8% (3.8%) 1σ errors at the SNO/SK (KamLAND) best fits

Preliminary hep neutrinos in DUNE

Dan Pershey

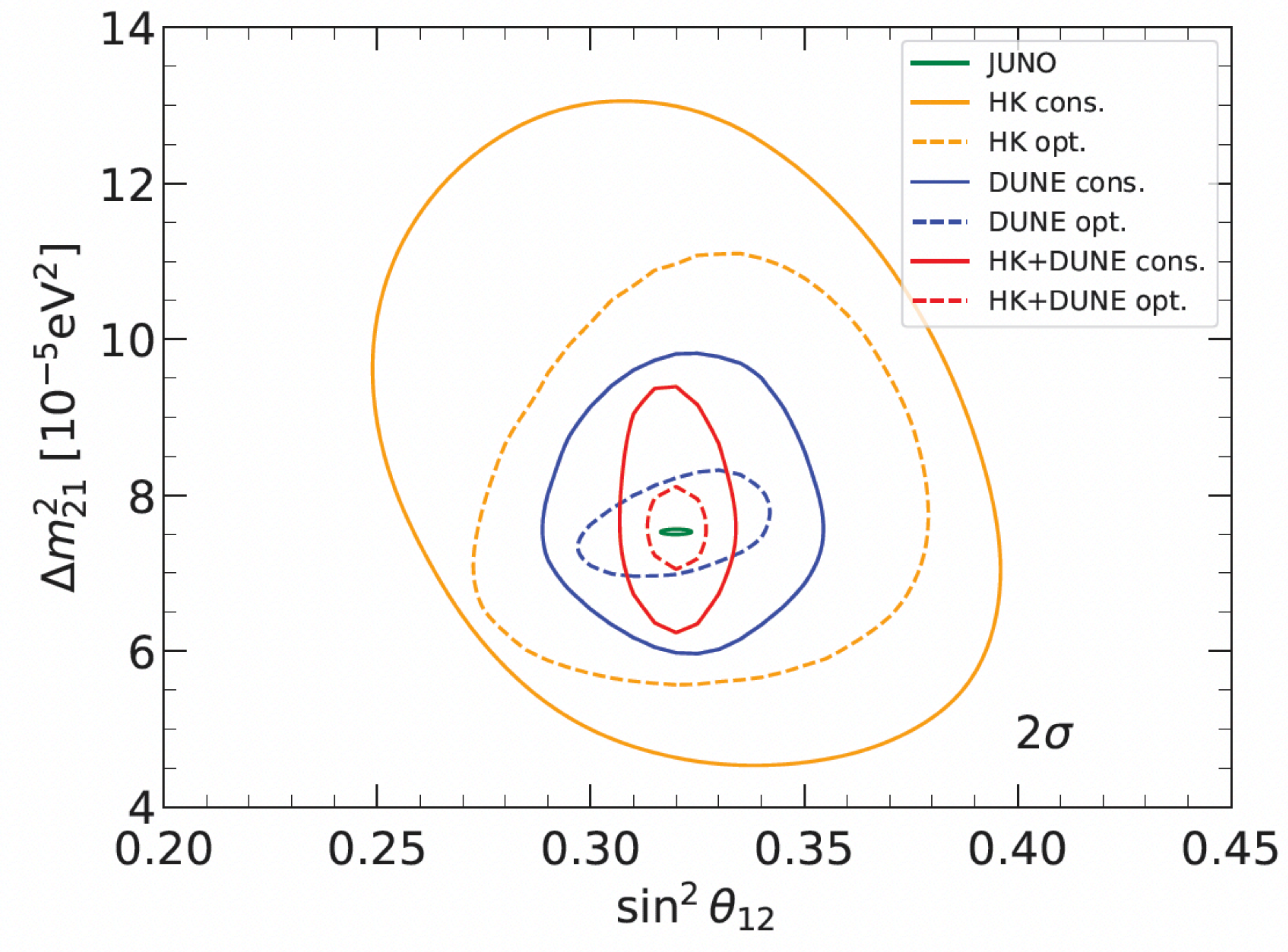


- At 400 kt-yrs, reach is 8.8% measurement of flux ratio
- Background free above 20 MeV
- 30 kt-yrs after first two years of running, above 19 MeV we would expect
  - 10.7 hep neutrinos
  - 2.3 bkg events
  - **7.1σ evidence**
  - 34% measurement of flux, comparable to current theoretical flux errors

Neutrino CPT violation in the solar sector

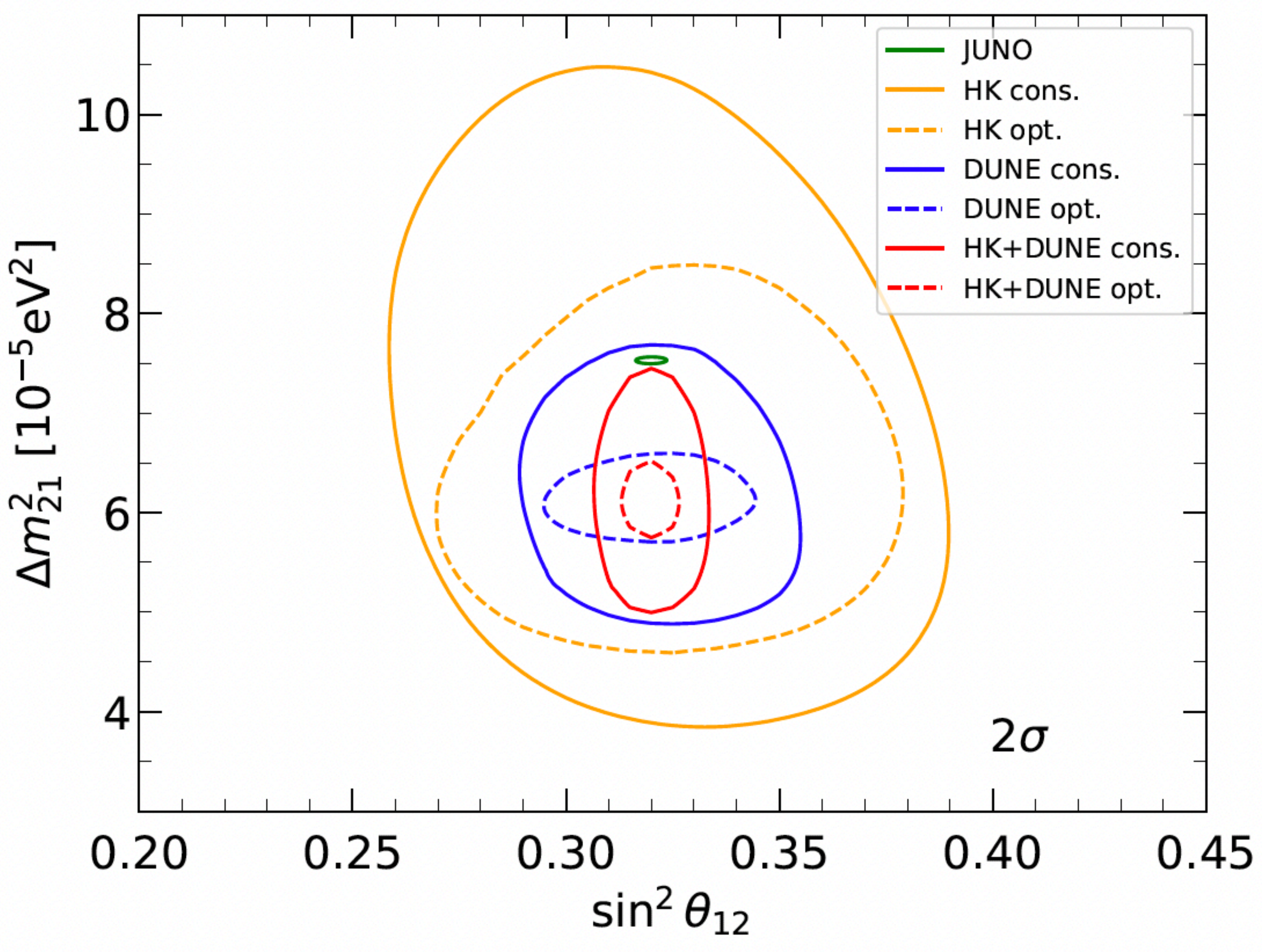
Barenboim et al., arxiv:2305.06384

CPT conserving



Same oscillation parameters for neutrinos and antineutrinos

CPT violation

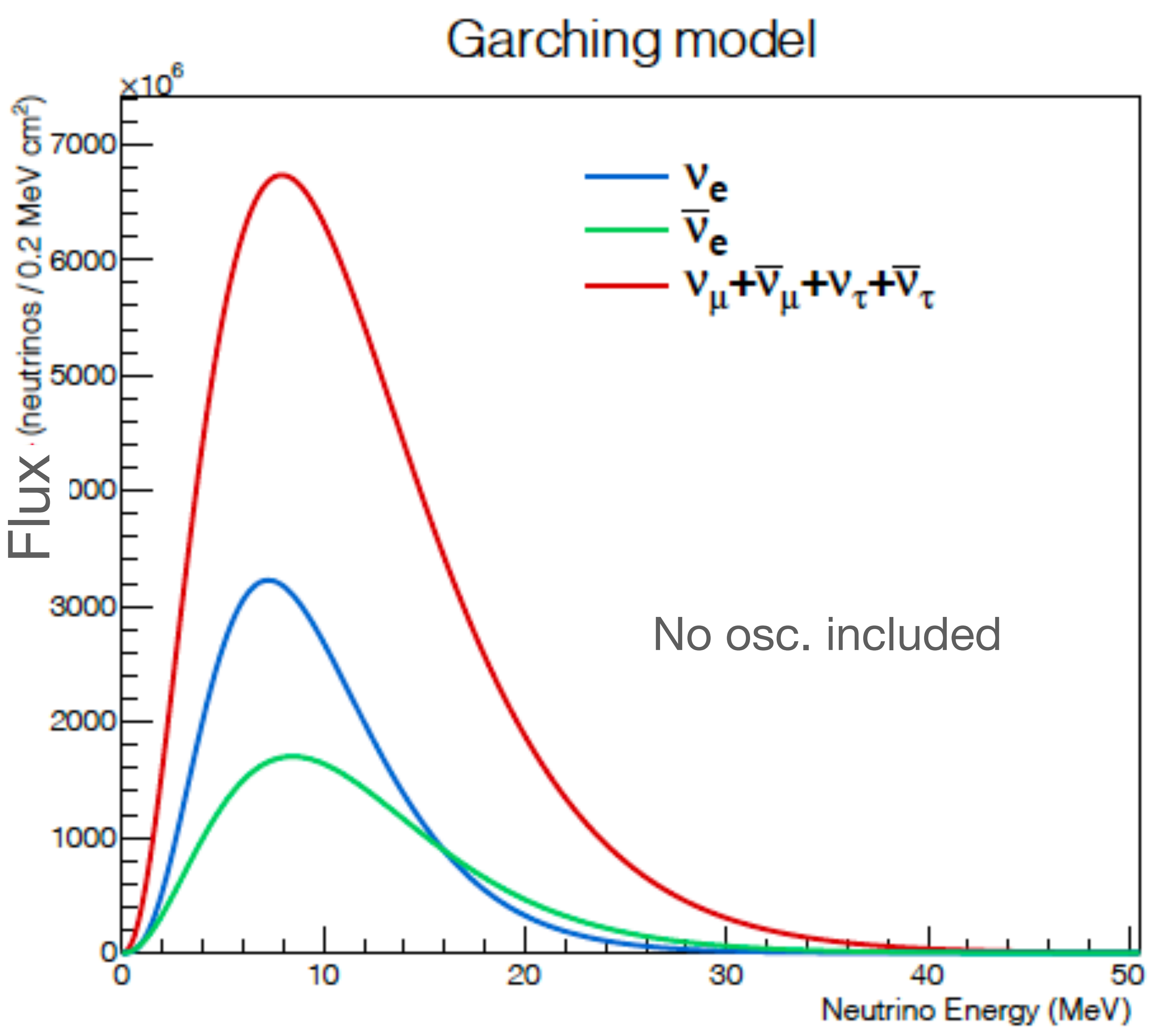


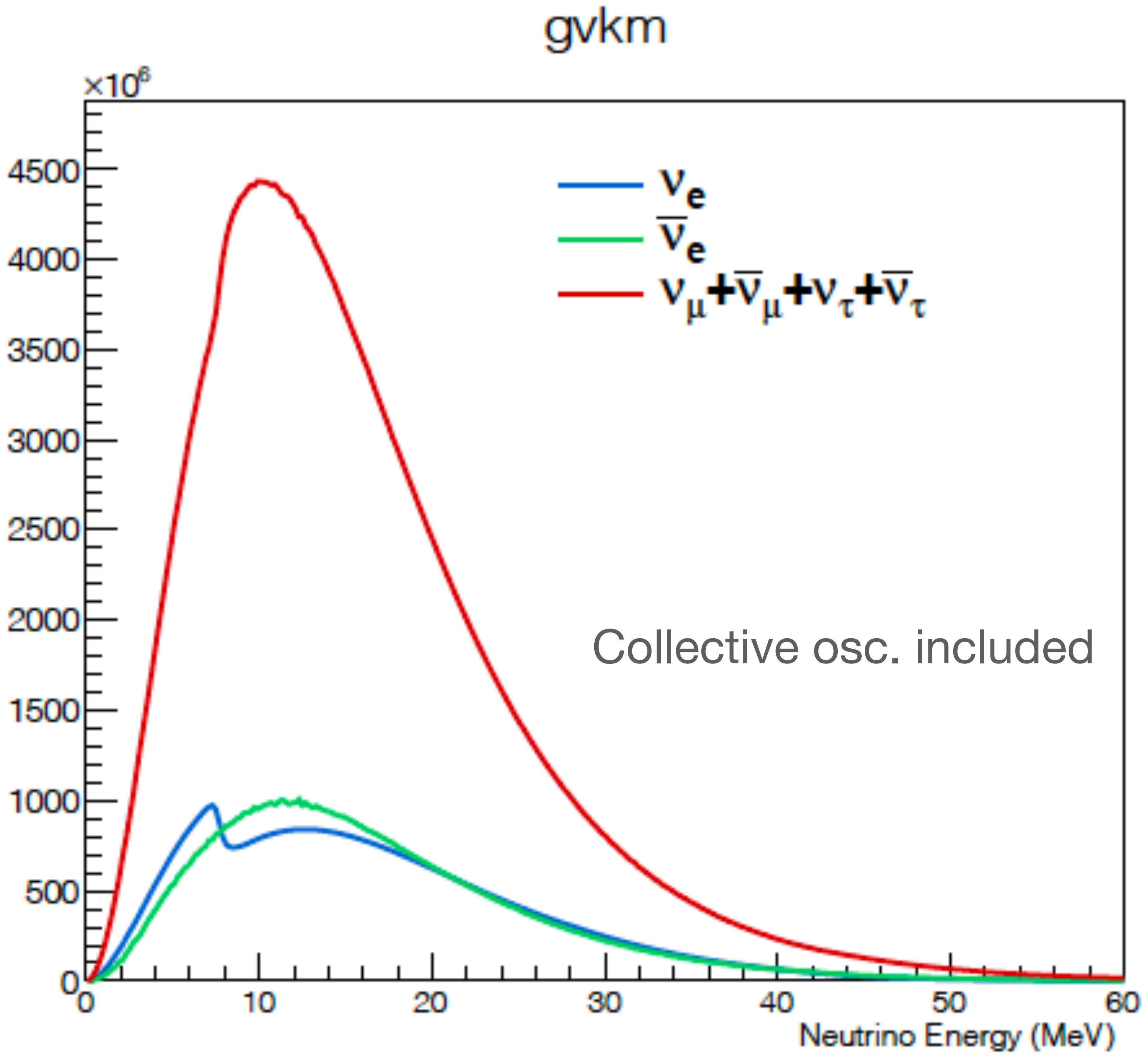
Different oscillation parameters for neutrinos and antineutrinos

$\Delta m^2_{21} = \Delta \overline{m}^2_{21} = 7.53 \times 10^{-5}\ \mathrm{eV}^2$ $\quad \sin^2\theta_{12} = \sin^2\overline{\theta}_{12} = 0.32$ $\quad \Delta \overline{m}^2_{21} = 7.53 \times 10^{-5}\ \mathrm{eV}^2$ $\quad \Delta m^2_{21} = 6.10 \times 10^{-5}\ \mathrm{eV}^2$

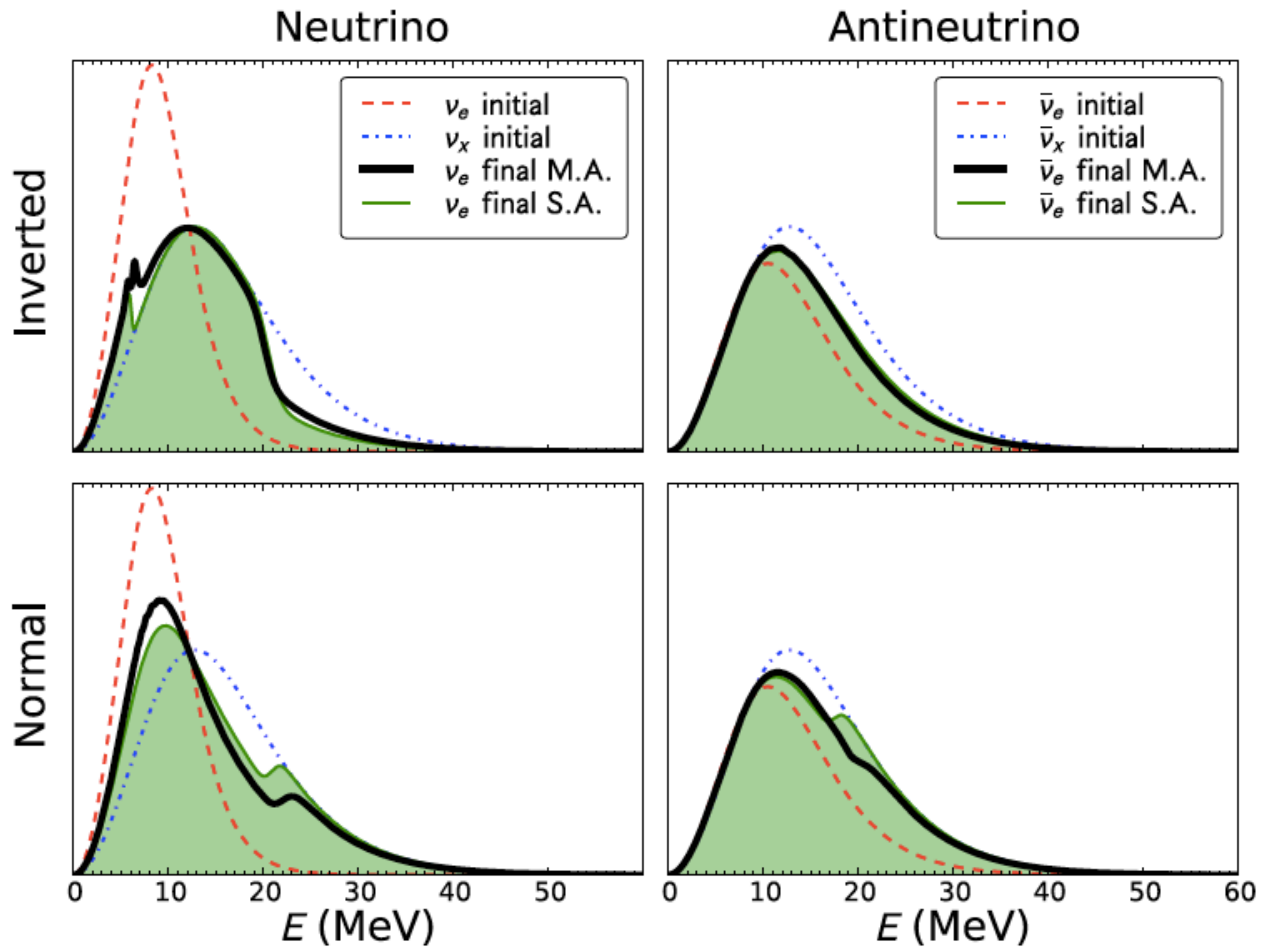
- DUNE **conservative** (solid line) = E > 9 MeV, 400 kt-yr, E resolution = 20%, Eff = 30%(9 MeV) - 60% (21 MeV)
- DUNE **optimal** (dashed line) = 1 order of magnitude n-capture reduction and 100% efficiency

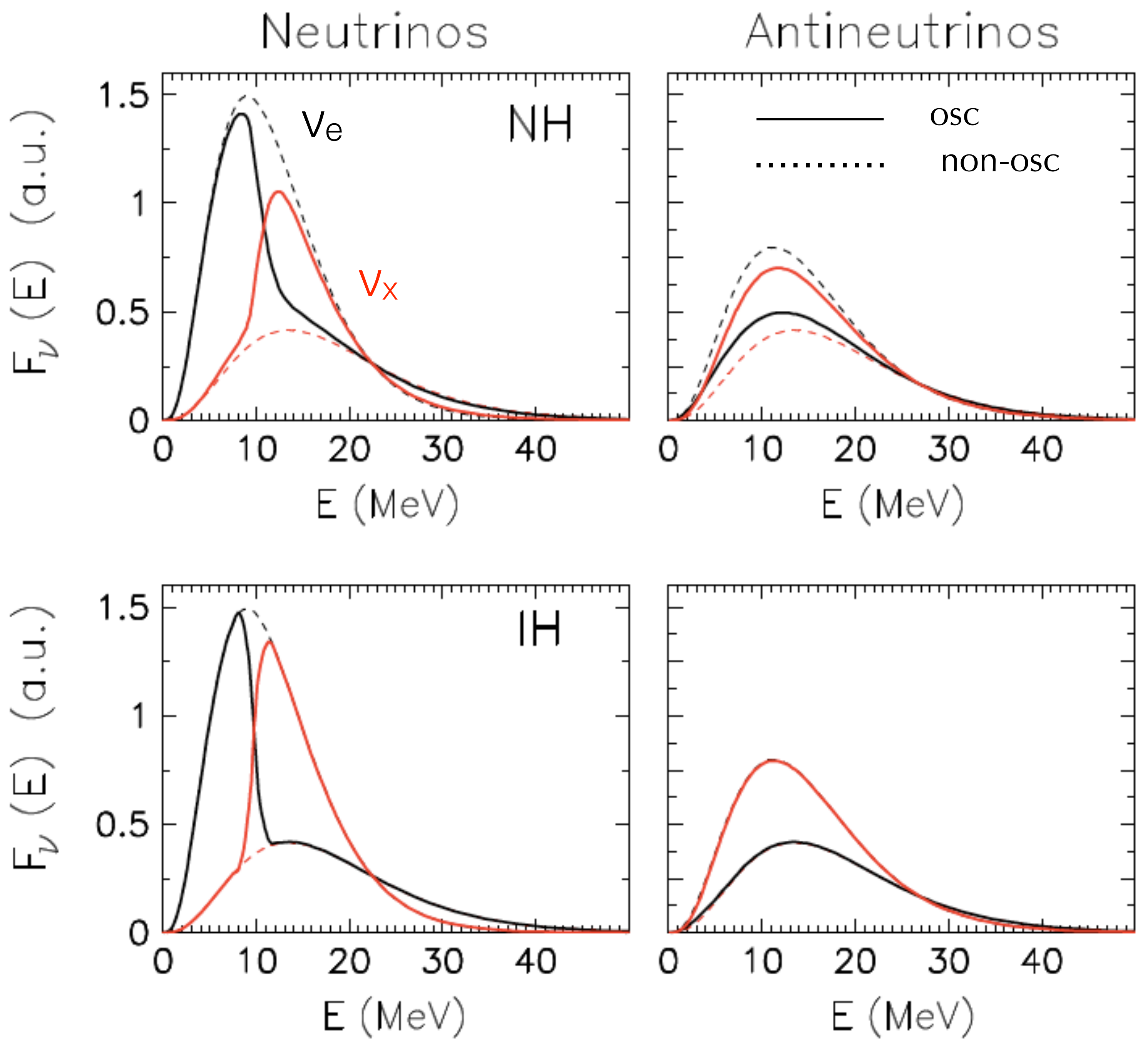
SN neutrino fluxes





Duan & Friedland, Phys. Rev. Lett. 106 (2011) 091101





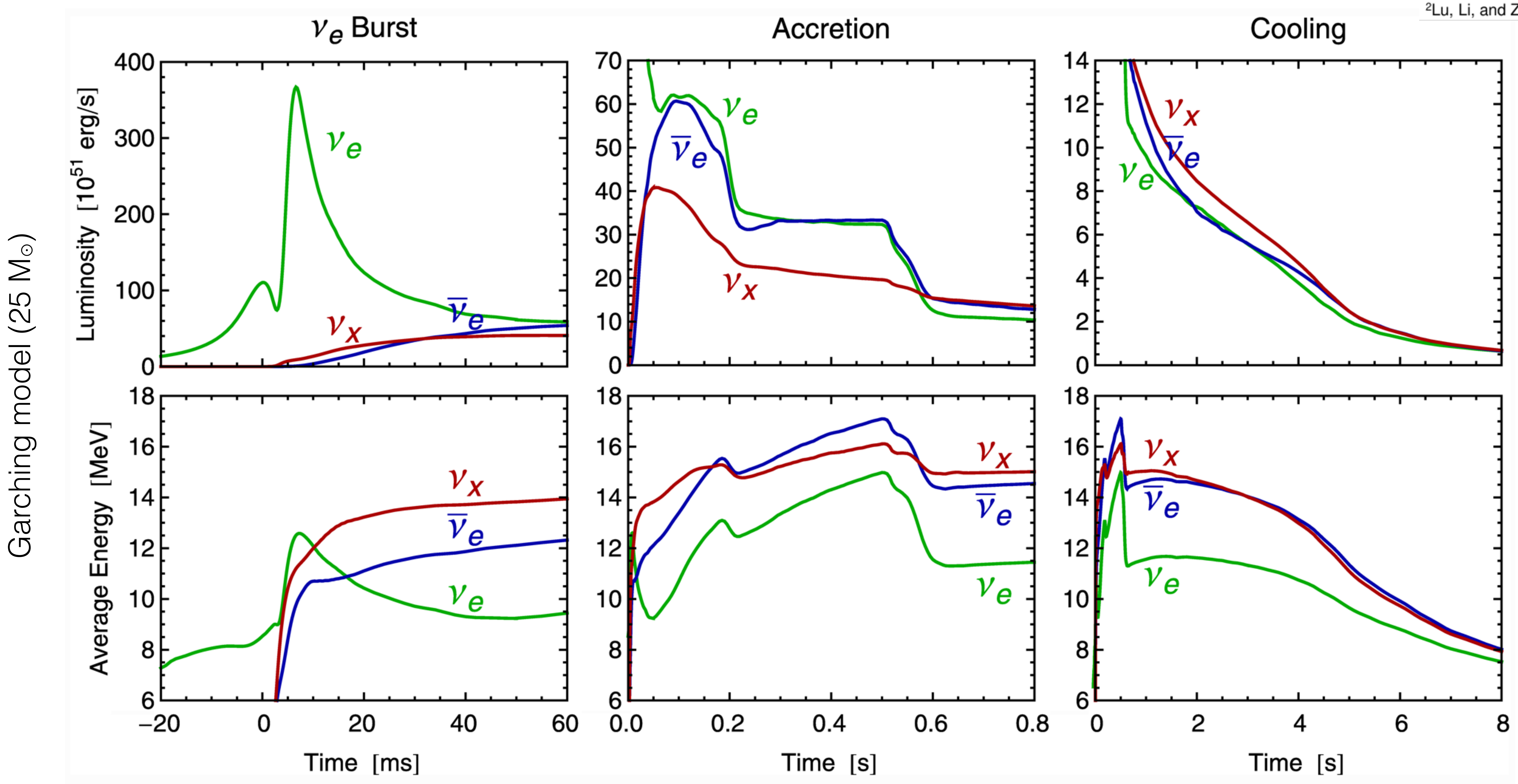
S. Chakraborty and A. Mirizzi, Phys. Rev. D90, 033004 (2014)

- Typical spectra: “pinched” Fermi-Dirac distribution
- Very model-dependent
- Affected by MSW + collective neutrino oscillations

Time evolution (Garching model)

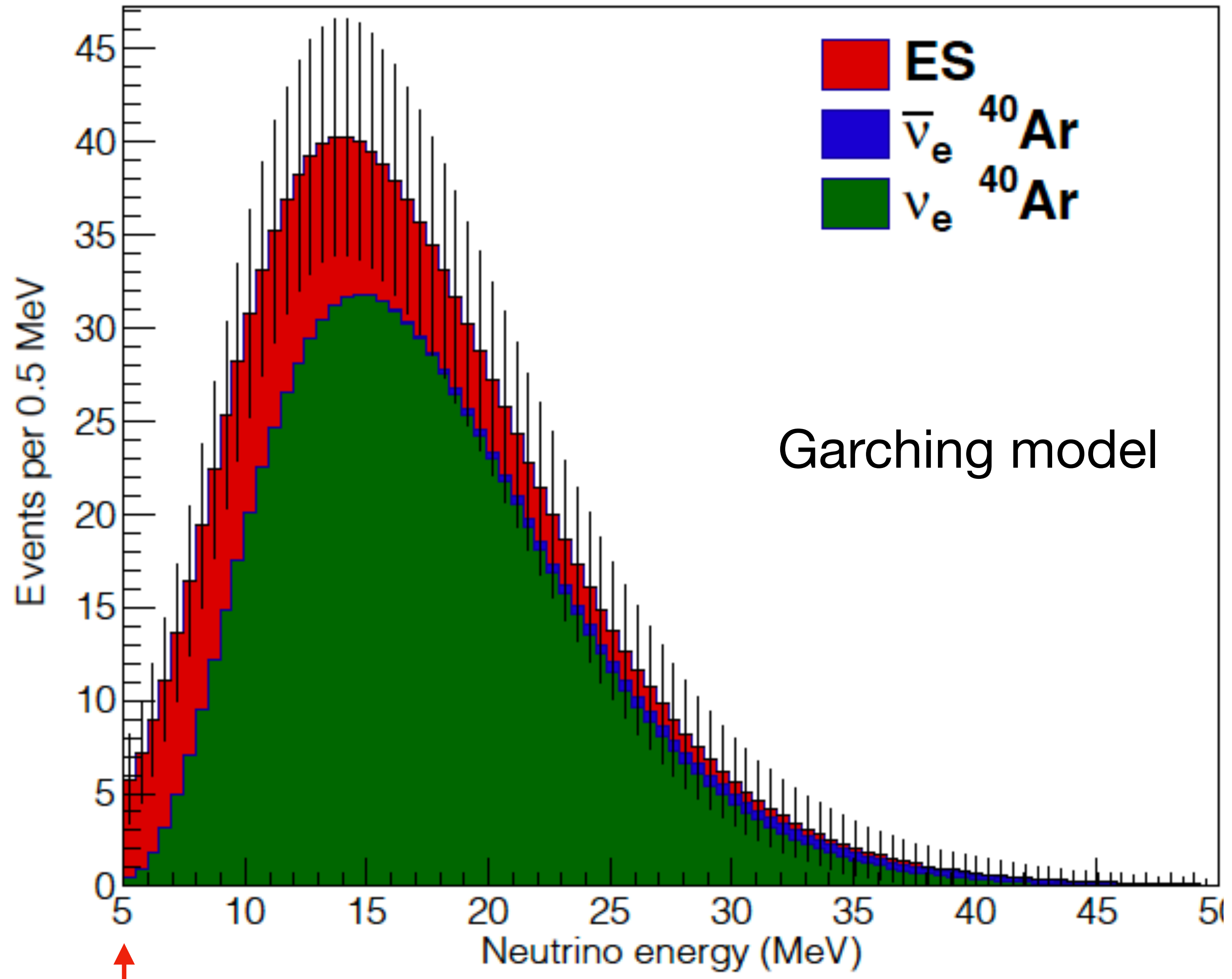
	ν_e	$\bar{\nu}_e$	ν_x
DUNE	89%	4%	7%
SK[1]	10%	87%	3%
JUNO[2]	1%	72%	27%

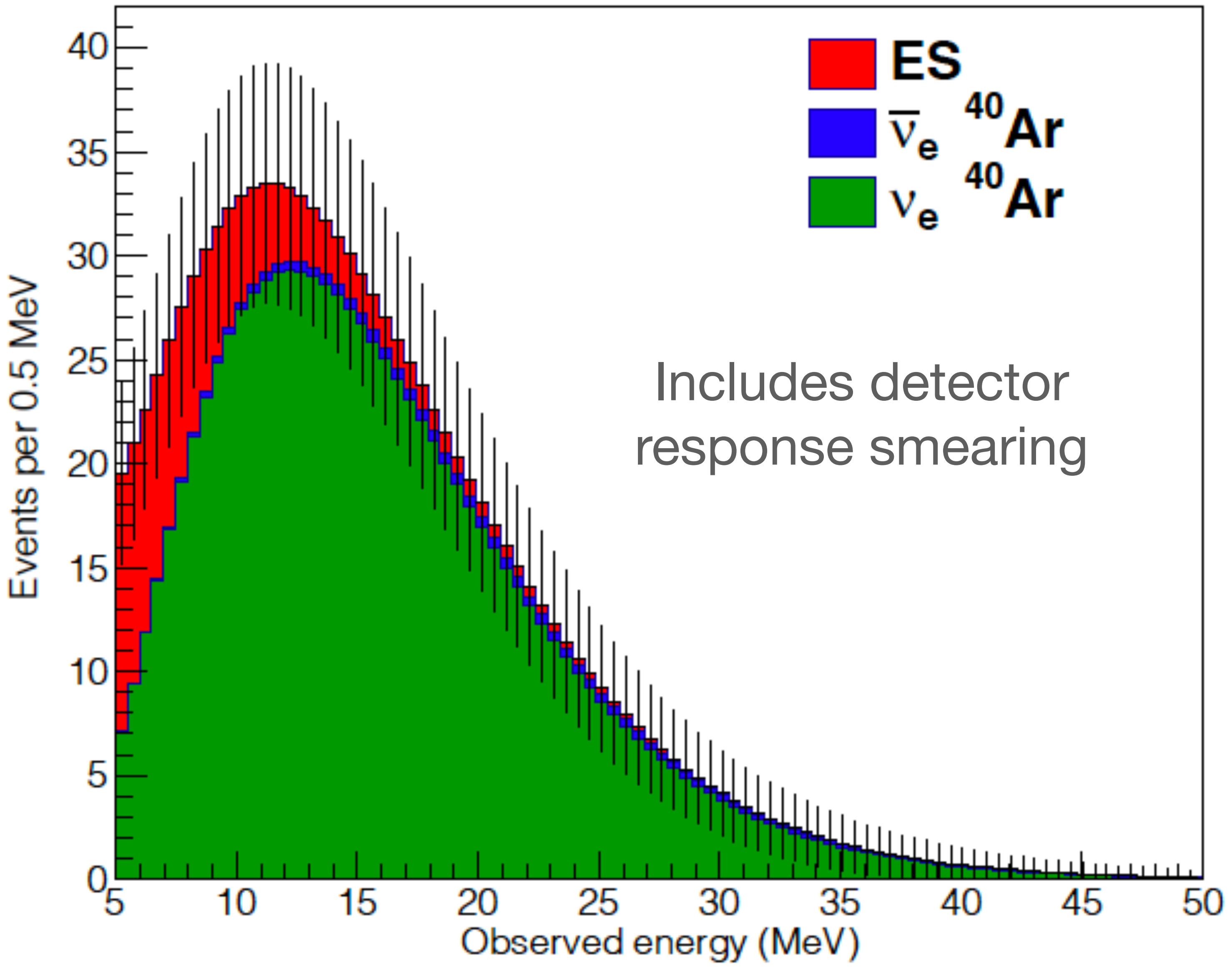
[1]Super-Kamiokande, *Astropart. Phys.* **81** 39-48 (2016)
[2]Lu, Li, and Zhou, *Phys Rev. D* **94** 023006 (2016)

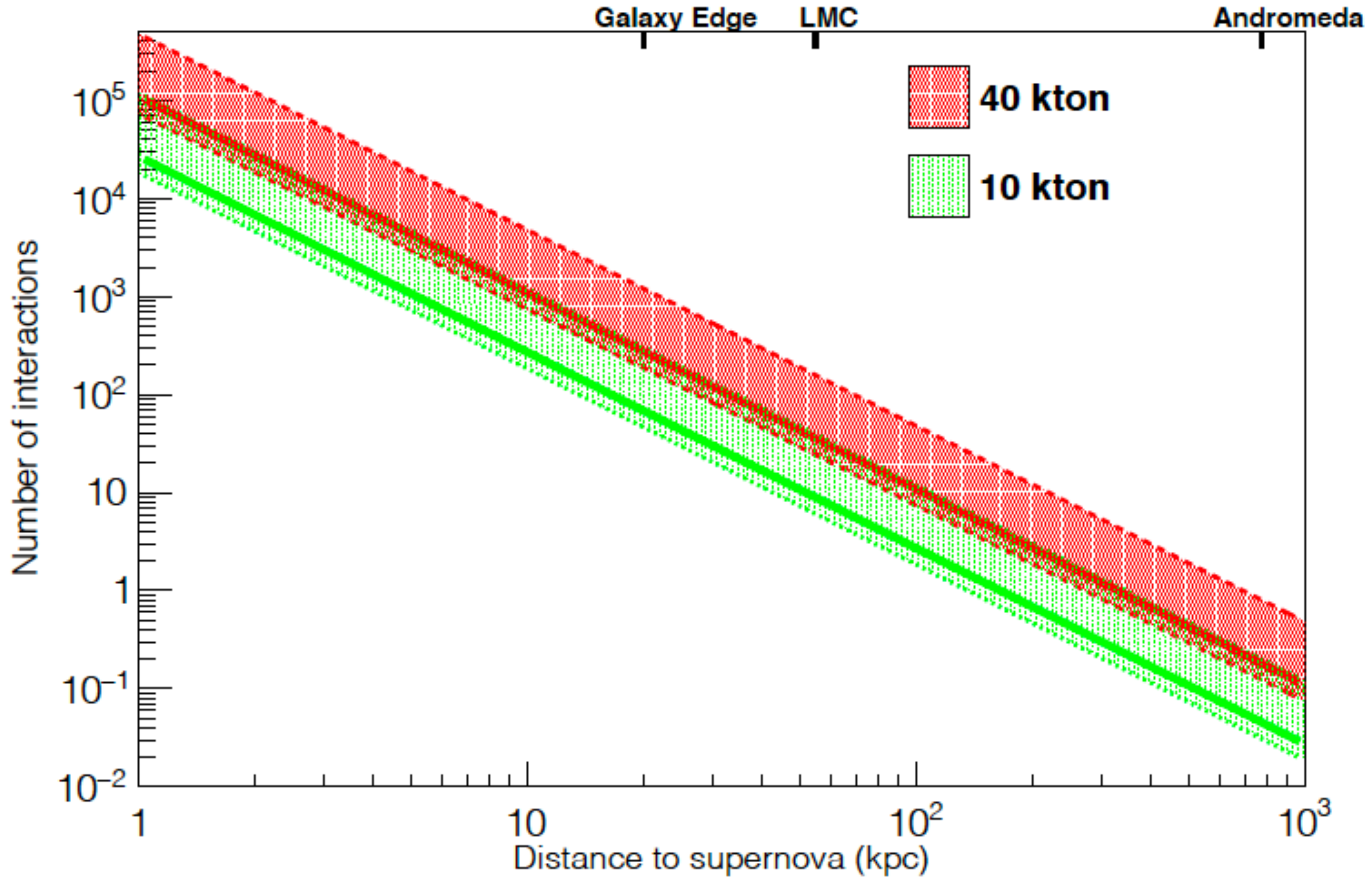


DUNE, Eur. Phys. J. C 81 (2021) 5, 423

Expected SN neutrino events in 40 kt DUNE



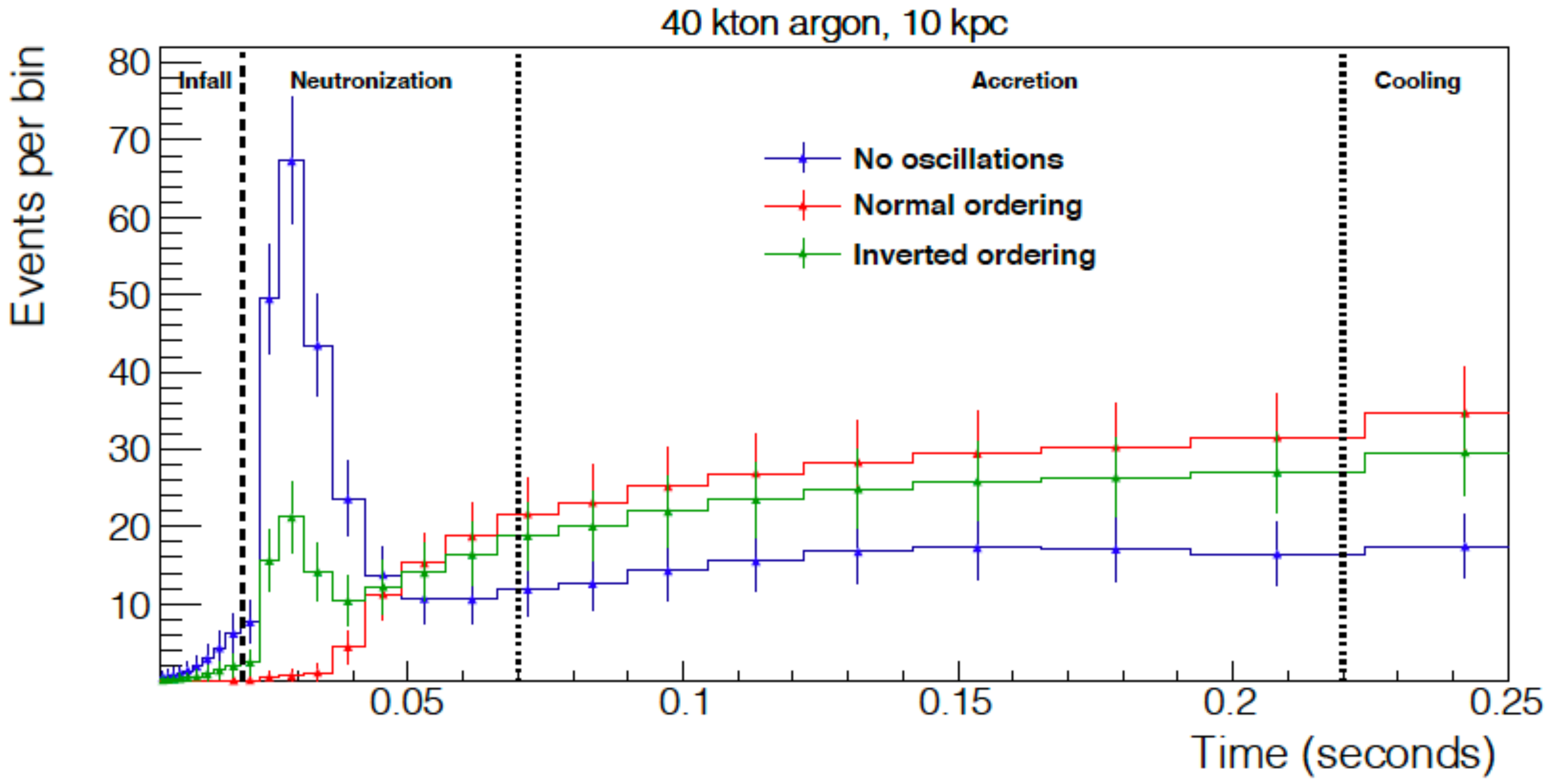




5 MeV threshold

SN at 10 kpc, 40 kt

Channel	Liver-more	GKVM	Garching
$\nu_e + ^{40}\mathrm{Ar} \rightarrow e^- + ^{40}\mathrm{K}^*$	2648	3295	882
$\bar{\nu}_e + ^{40}\mathrm{Ar} \rightarrow e^+ + ^{40}\mathrm{Cl}^*$	224	155	23
$\nu_X + e^- \rightarrow \nu_X + e^-$	341	206	142
Total	3213	3656	1047

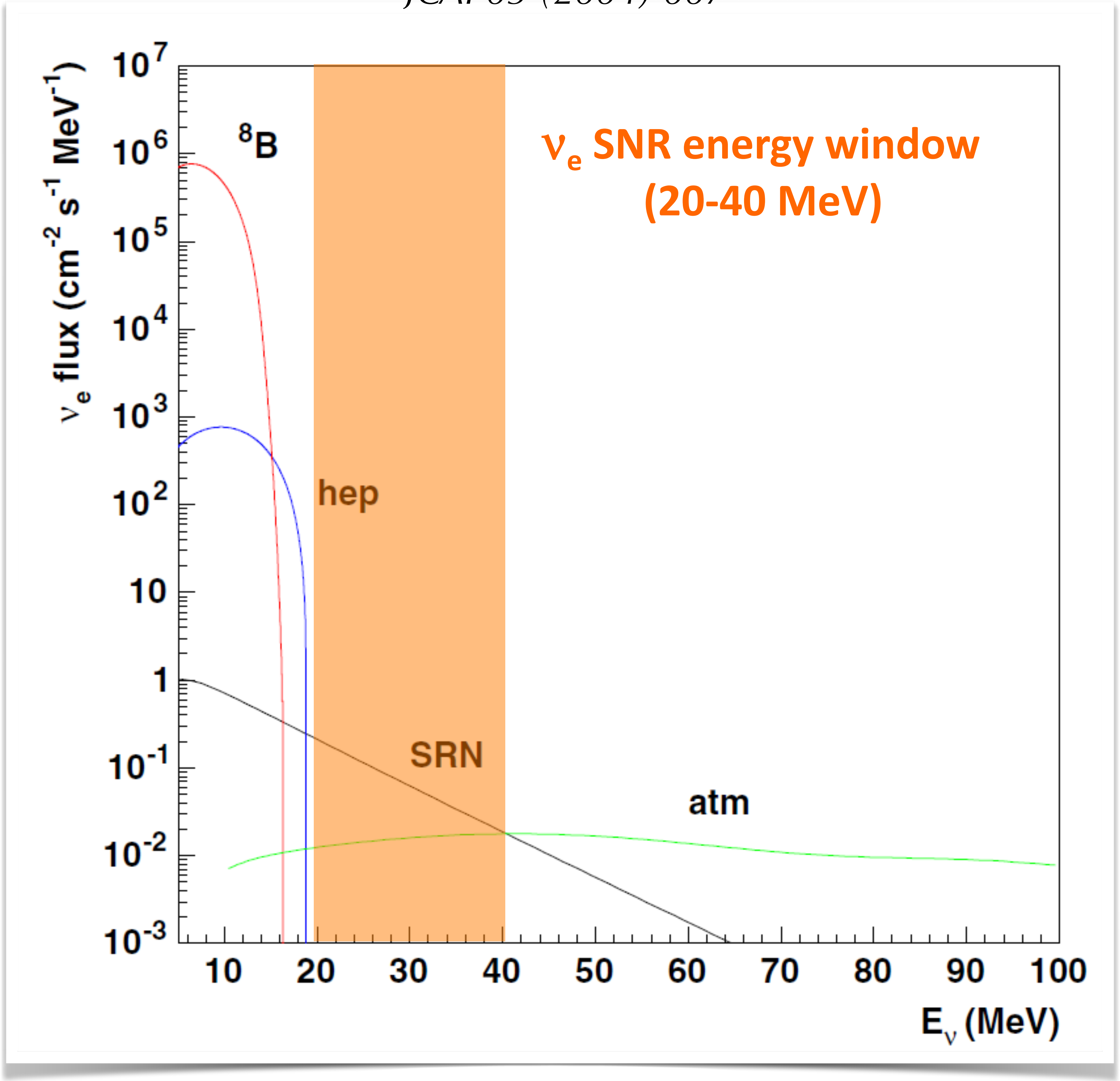


Current status of DSNB

- Guaranteed source of SN neutrinos (averaged neutrino flux from all supernovae)
- Not detected yet
  - Best limit by SK: *Phys. Rev. D 104, 122002 (2021)*

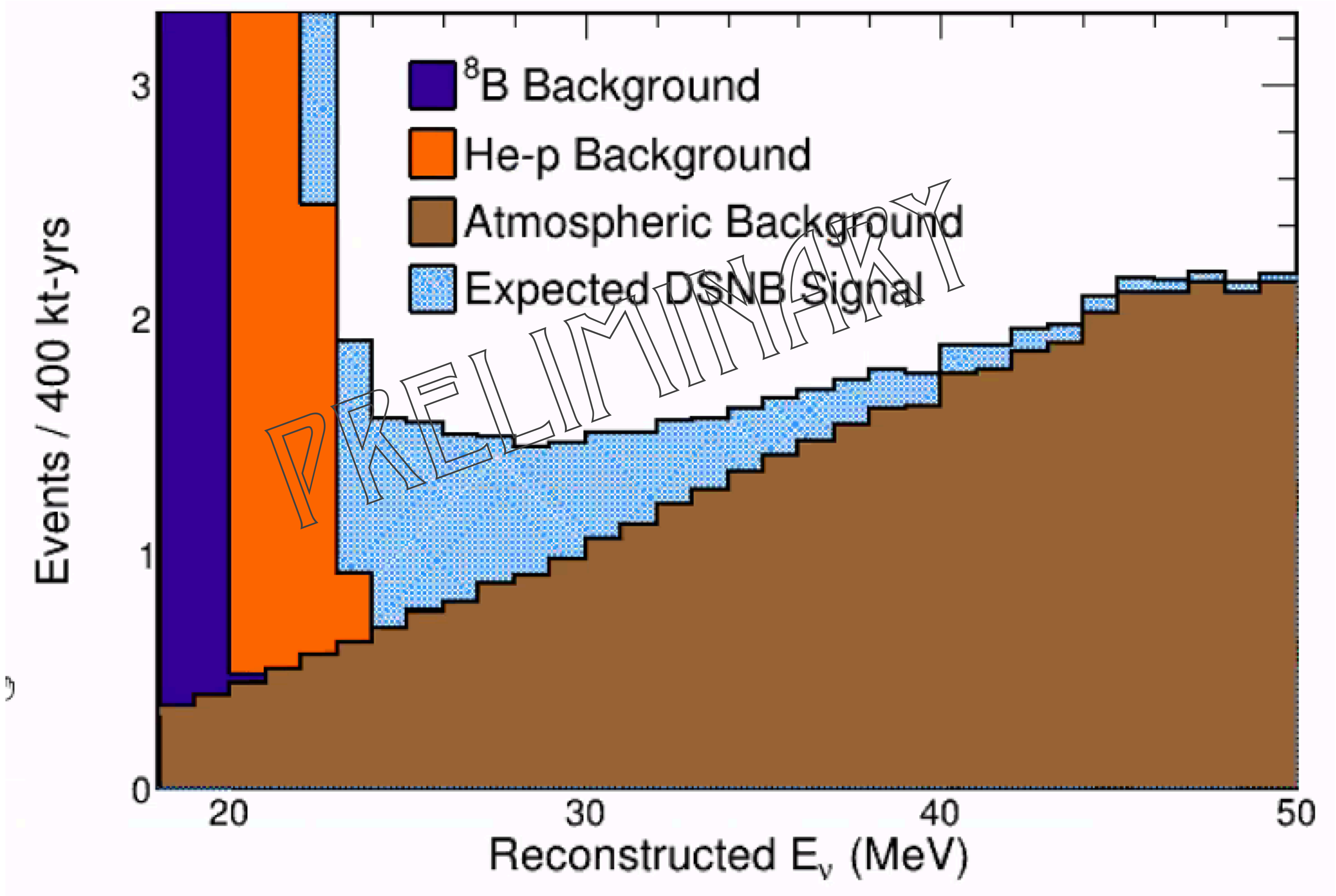
    $\Phi(\bar{\nu}_e) < 2.7\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for $E_\nu > 17.3$ MeV
- WC and LSc experiments detecting antineutrinos while DUNE will uniquely constrain the neutrino flux
- Main backgrounds for ν_e channel: solar and atmospheric neutrinos
- Look for an energy window where signal dominates over backgrounds
- **DUNE**, in 10 years, n.h. (from DUNE Physics TDR)
  - $N_{DSNB} = 46 \pm 10$ (16 MeV $\leq E_e \leq$ 40 MeV)

SNR flux prediction based on Strigari et al., JCAP03 (2004) 007



Diffuse Supernova Neutrino Background

Dan Pershey

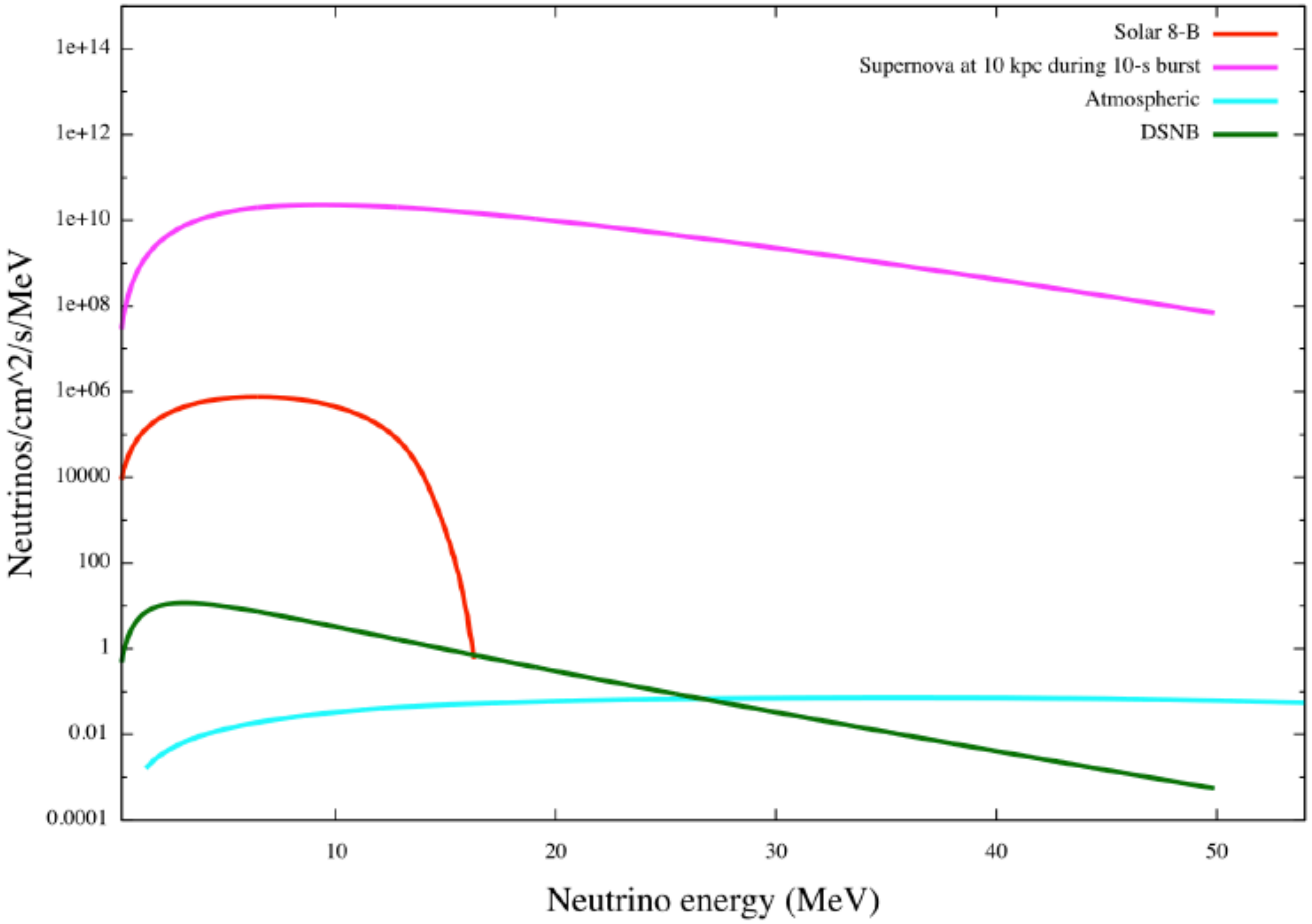


- Region between 22 and 33 MeV
- After 400 kt-yr
  - 2.2σ significance can be obtained (6 events)
  - 8.8% measurement of $\phi(hep)/\phi(^8B)$
- Can we improve it?

Main detector challenges

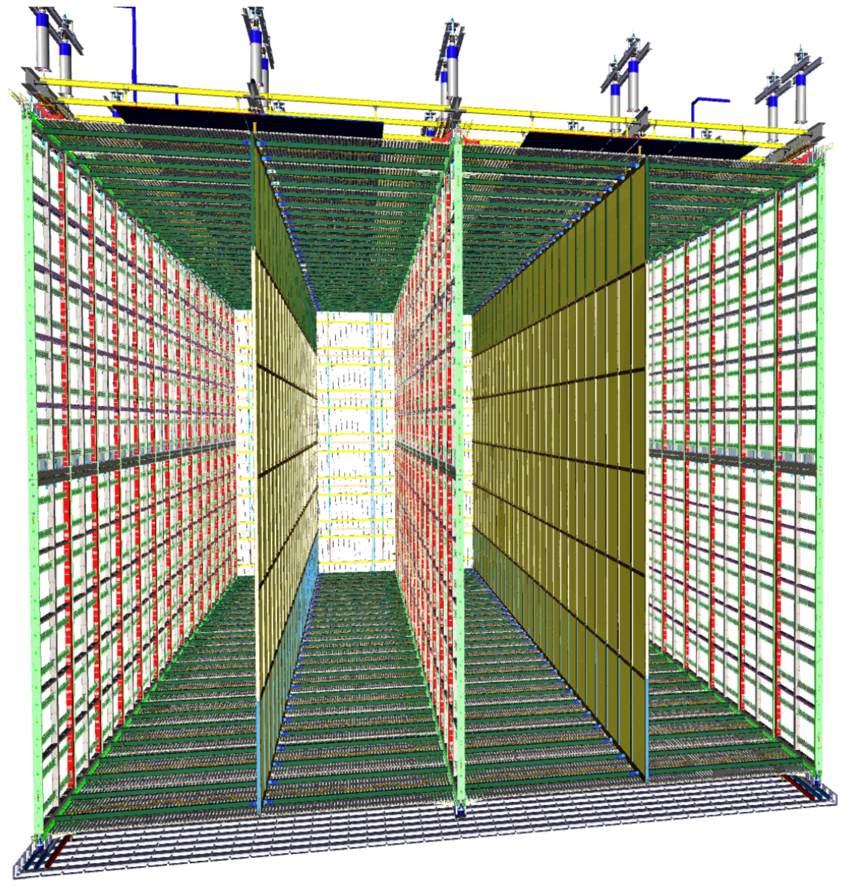
- Large **detector mass**
- Develop an **efficient event reconstruction** (including de-excitation gammas) and **particle ID**
- Identify **neutrino direction** (angular resolution)
- Tag different **neutrino flavors**
- Achieve an excellent **energy resolution**
- Reduce low-energy **backgrounds**
- Lower **energy thresholds**
- Good **calibration** at MeV energies across the detector volume

Energy range of interest

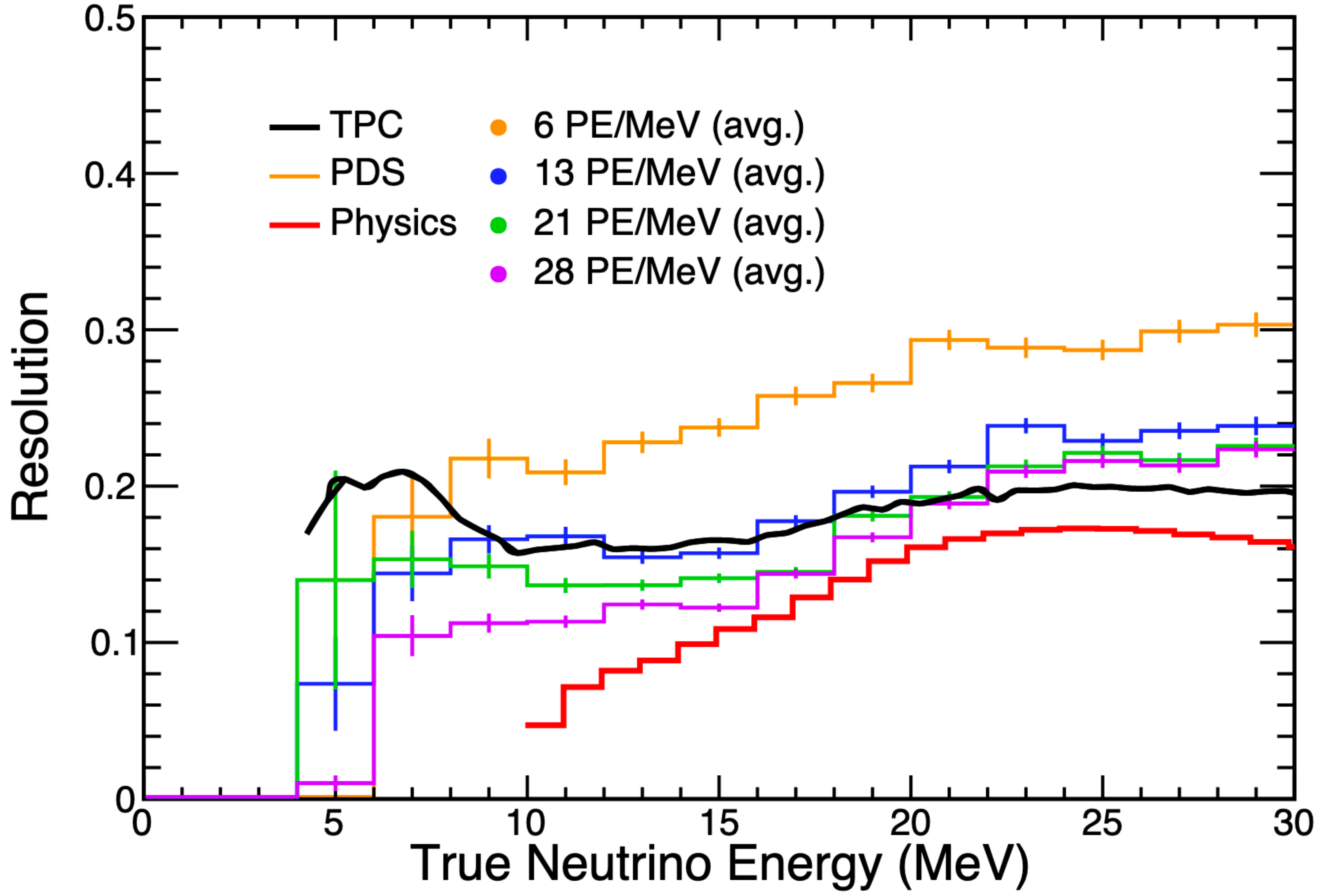


- Up to ~100 MeV

Energy resolution FD1-HD

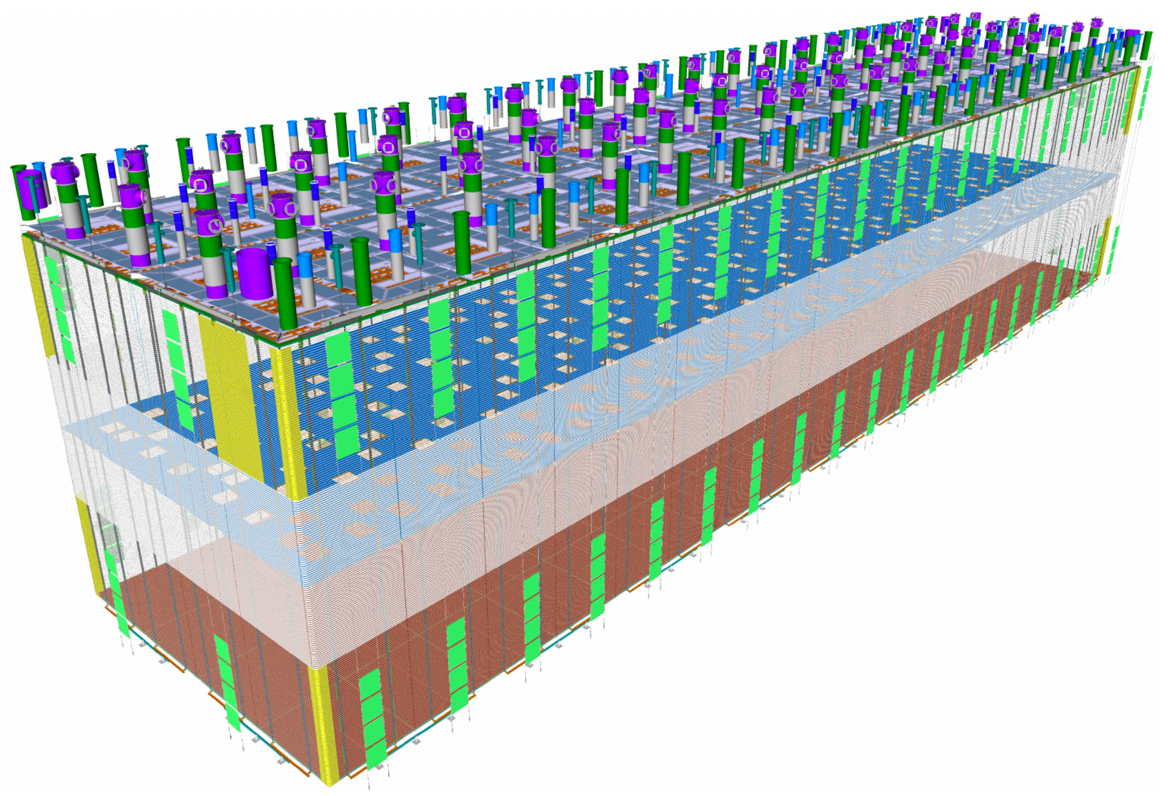


DUNE FD1-HD TDR
(For SN neutrino events)

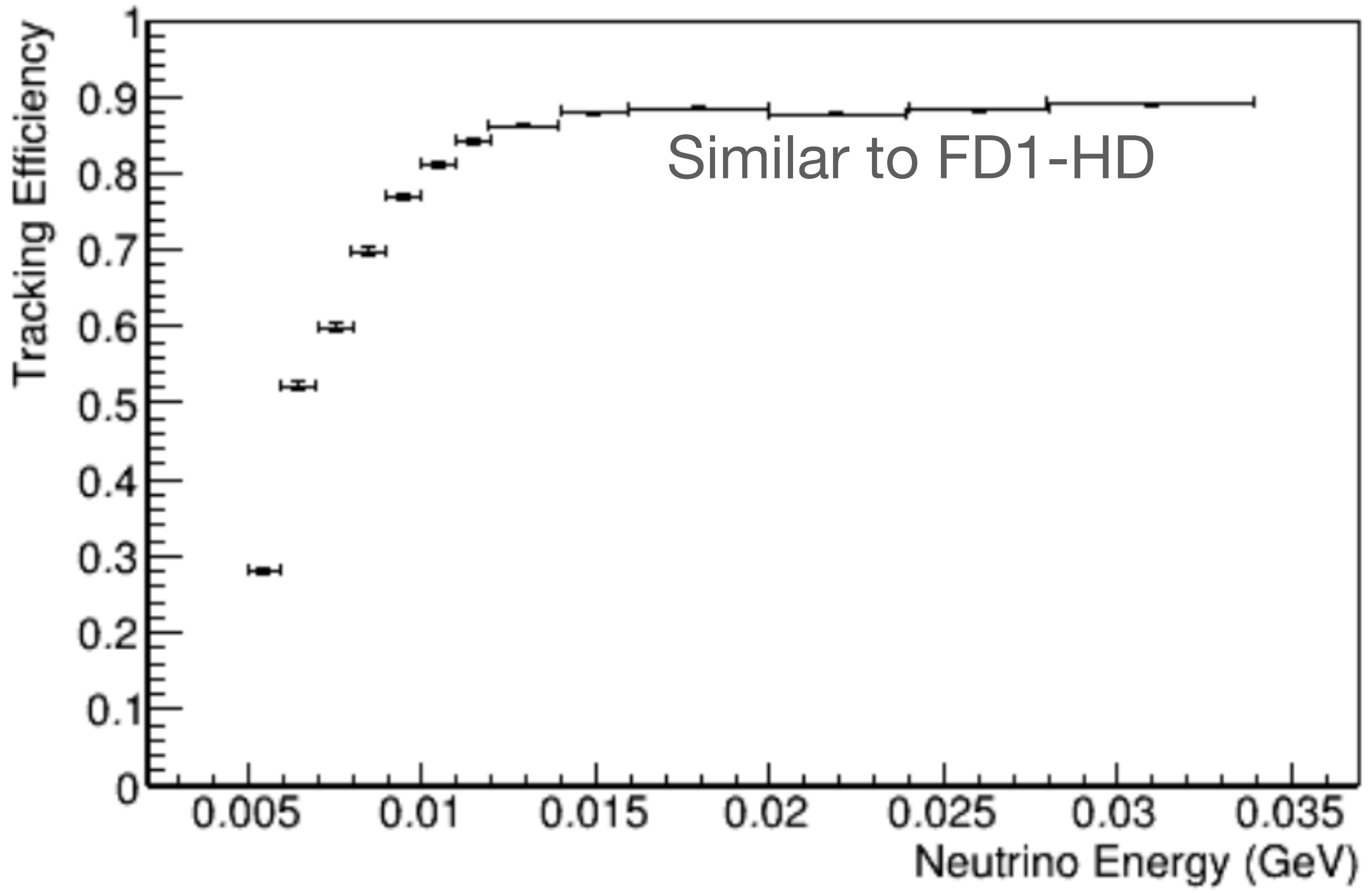


- Energy resolution for true energy
- PD and TPC similar energy resolution for ~20 PE/MeV light yield
- Can we improve it?

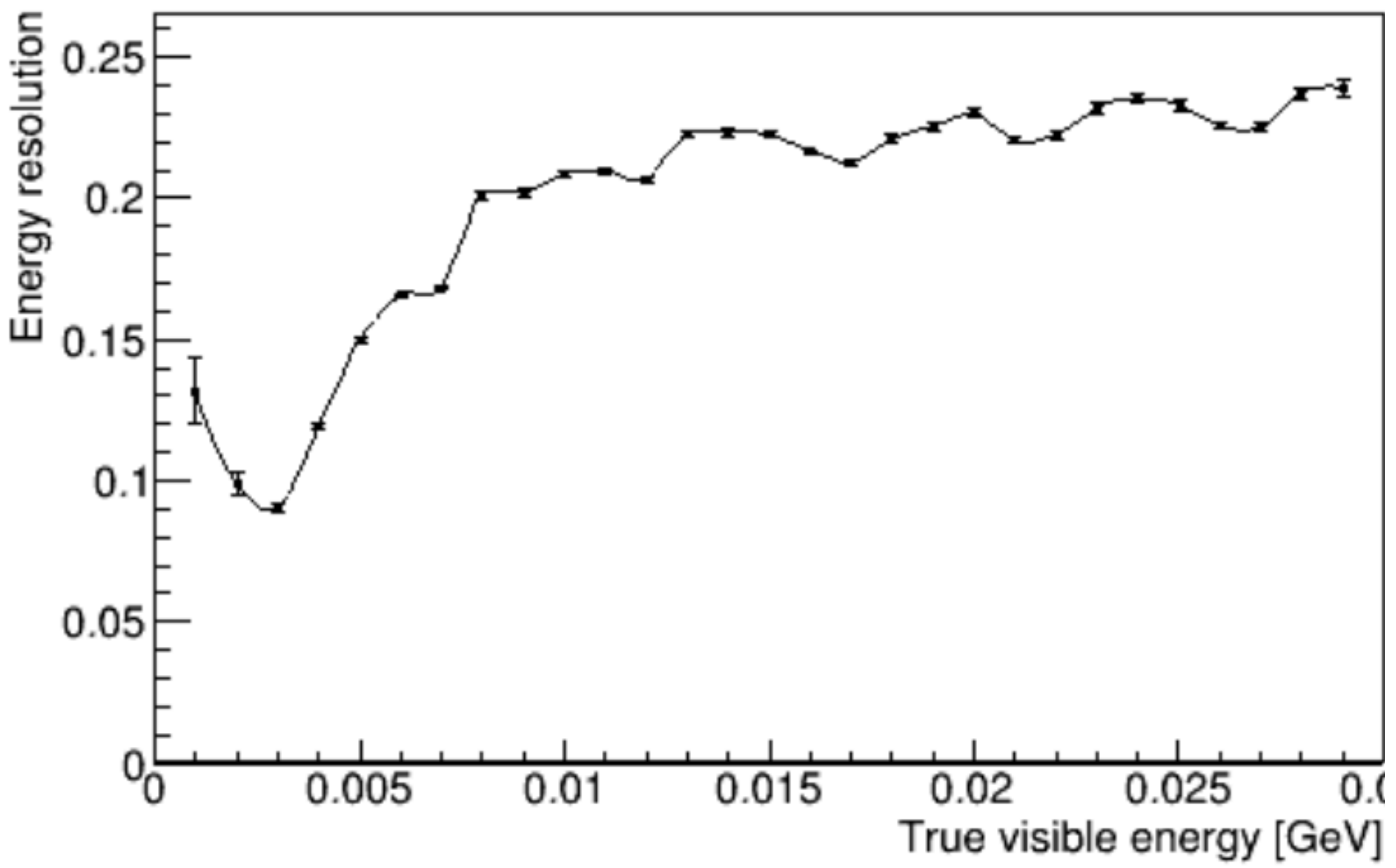
Energy resolution FD2-VD



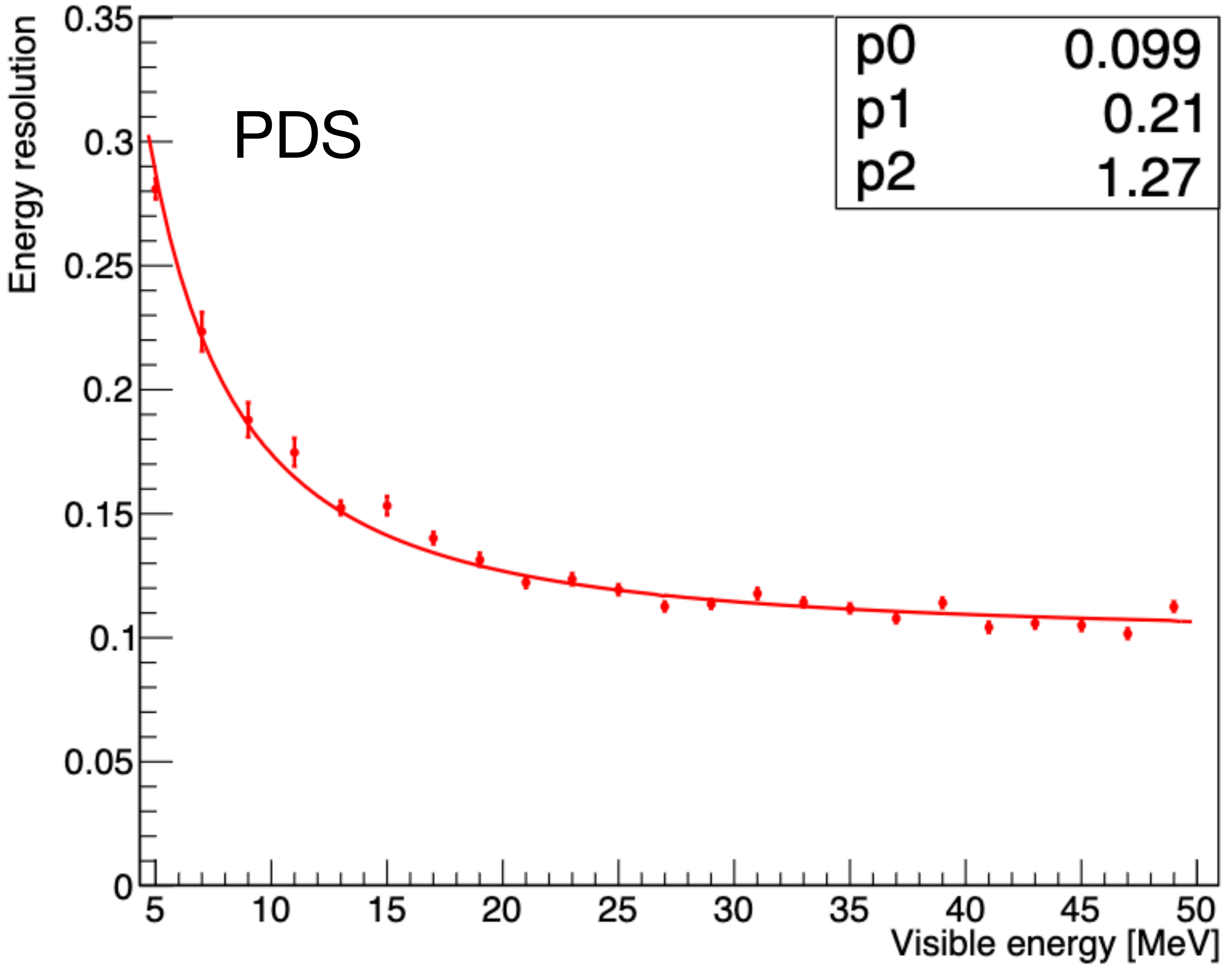
DUNE FD2-VD TDR
ve CC signal sample



TPC



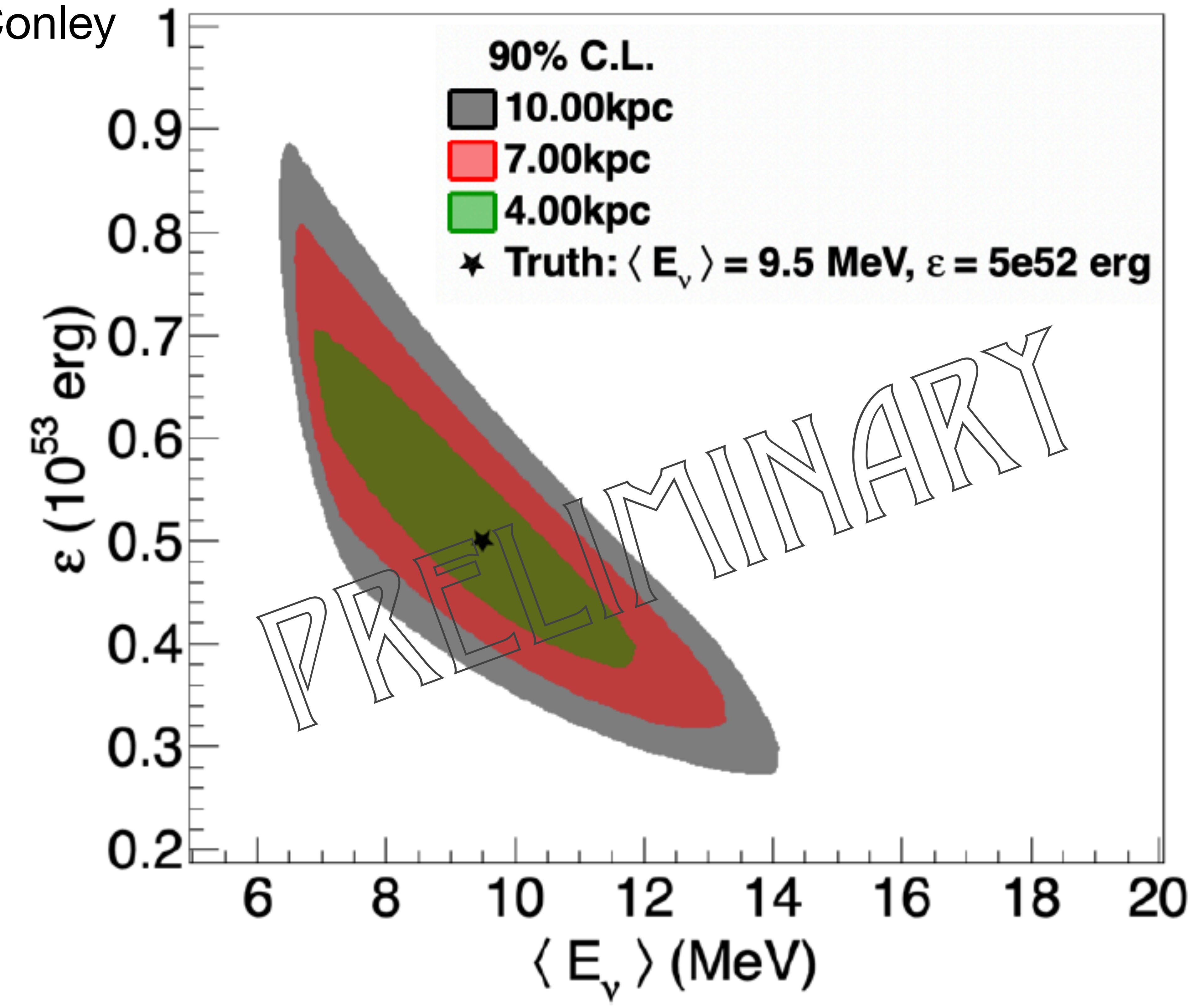
Assuming neutrino's true position in the detector
Statistical-only uncertainties

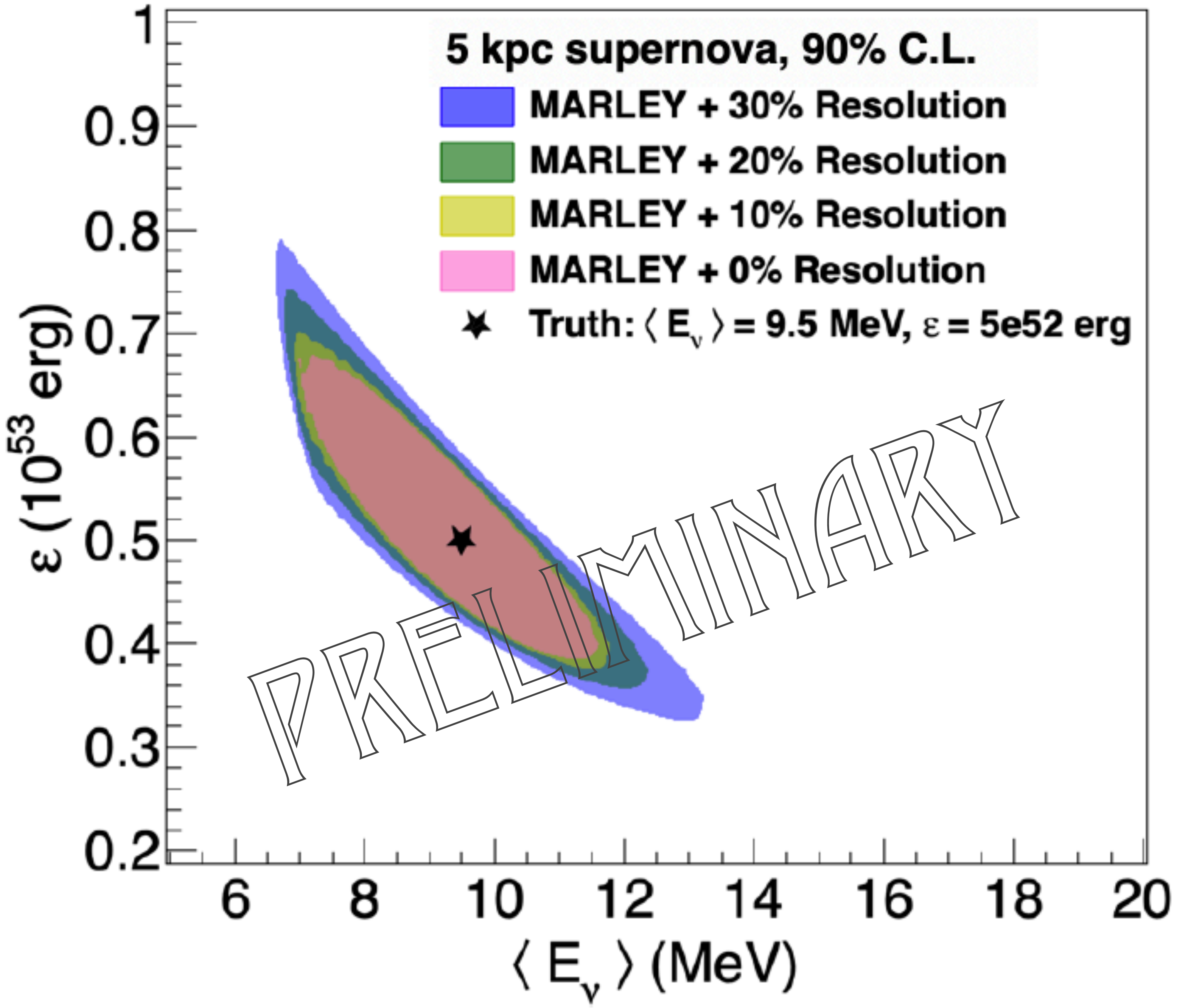


- Can we improve it?

Impact of energy resolution in SN physics

Erin Conley





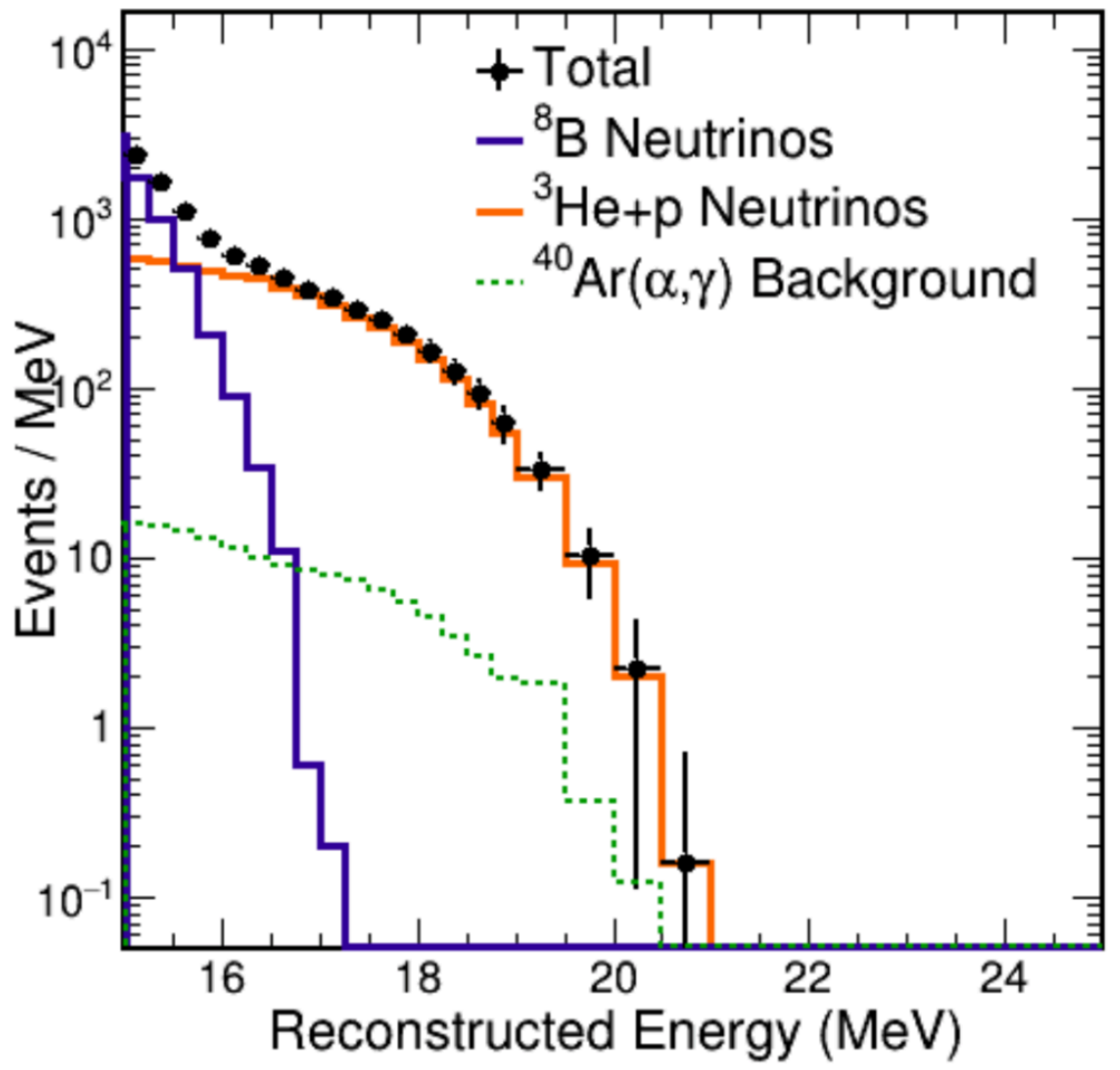
Precision of the measurement of SN spectral parameters is **limited more strongly by statistics than by energy resolution**

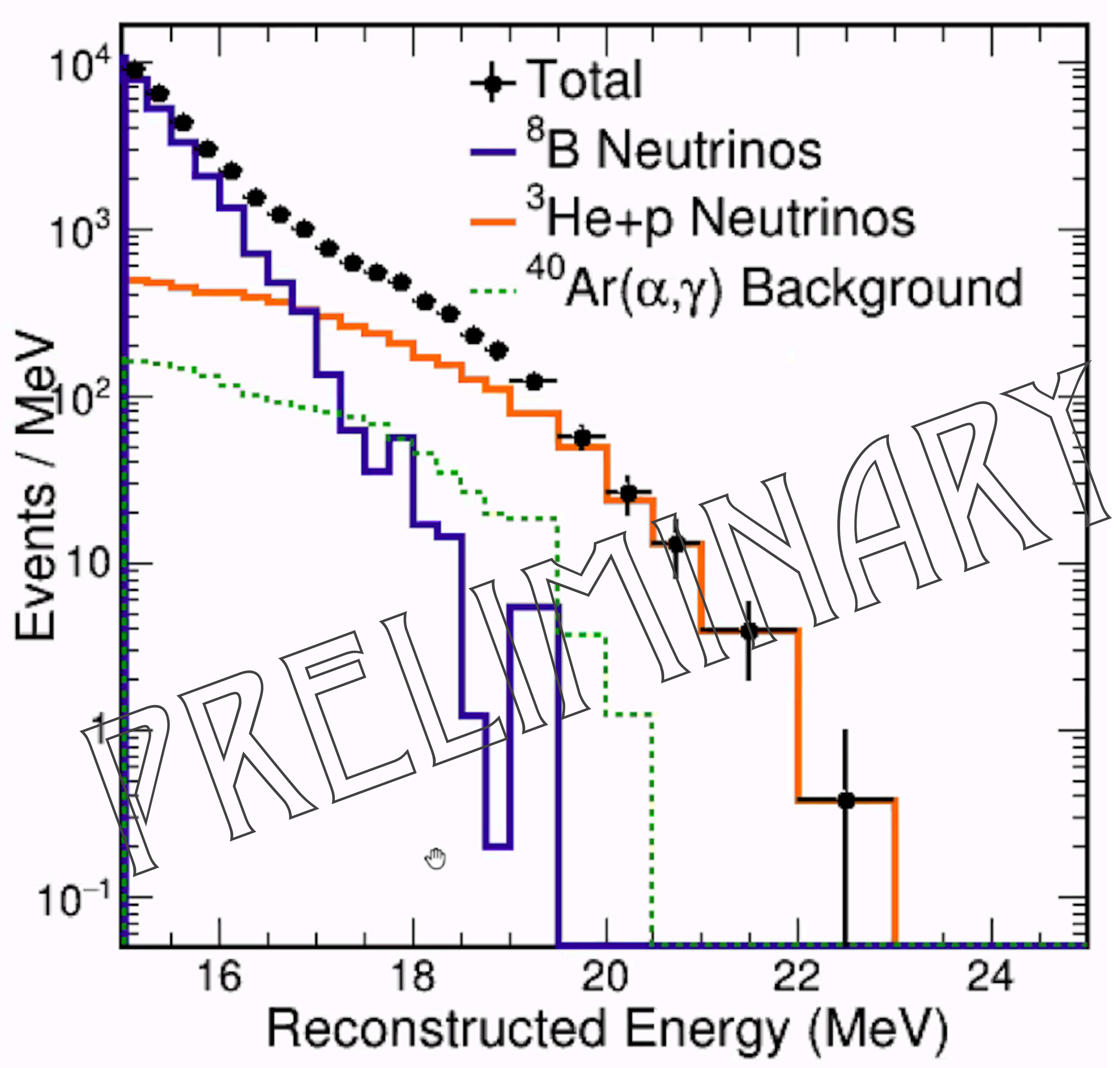
Impact of energy resolution in solar neutrinos

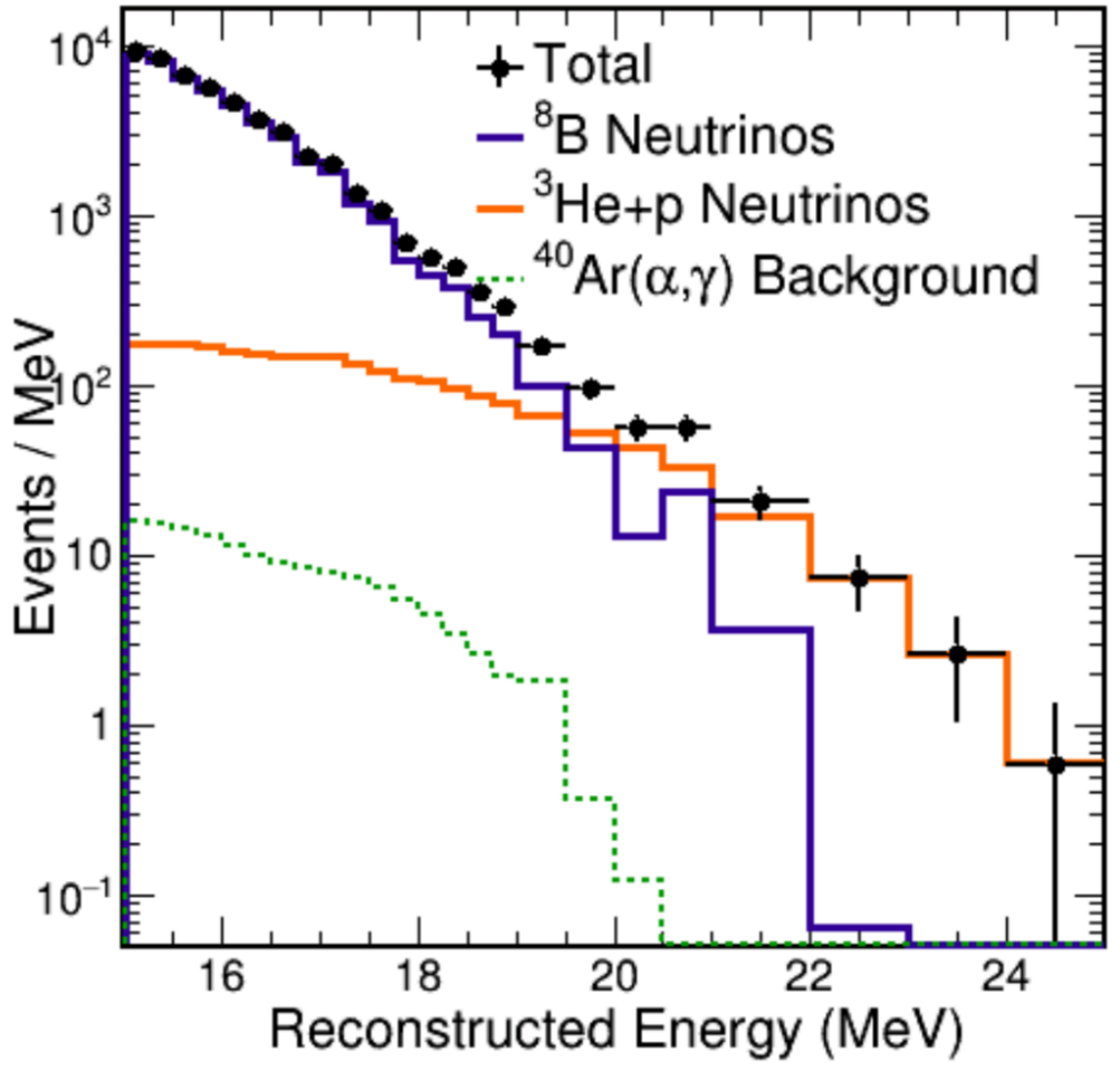
Dan Pershey

α backg x1/10
Optimistic smearing -50%

α backg x1/10
Pessimistic smearing +50%







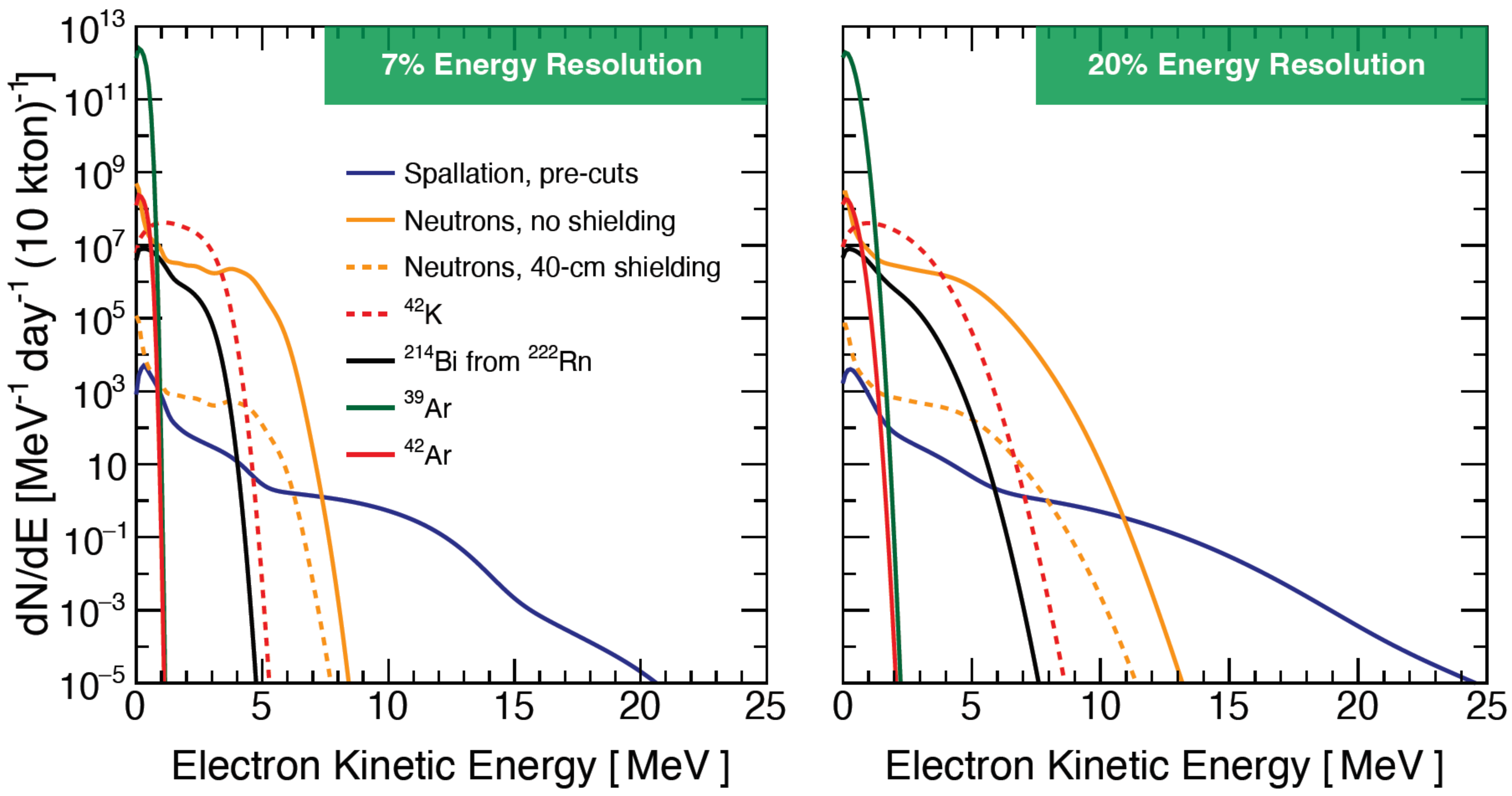
- 4-5% flux measurement
- 7σ after 10 kt-yr

- 9% flux measurement
- 7σ after 30 kt-yr

- 12% flux measurement
- 5σ after 30 kt-yr

Impact of energy resolution in solar neutrinos

Capozzi et al., PRL 123, 131803 (2019)



- Impact on backgrounds
- Needed to distinguish the ^{8}B shoulder from the hep neutrinos

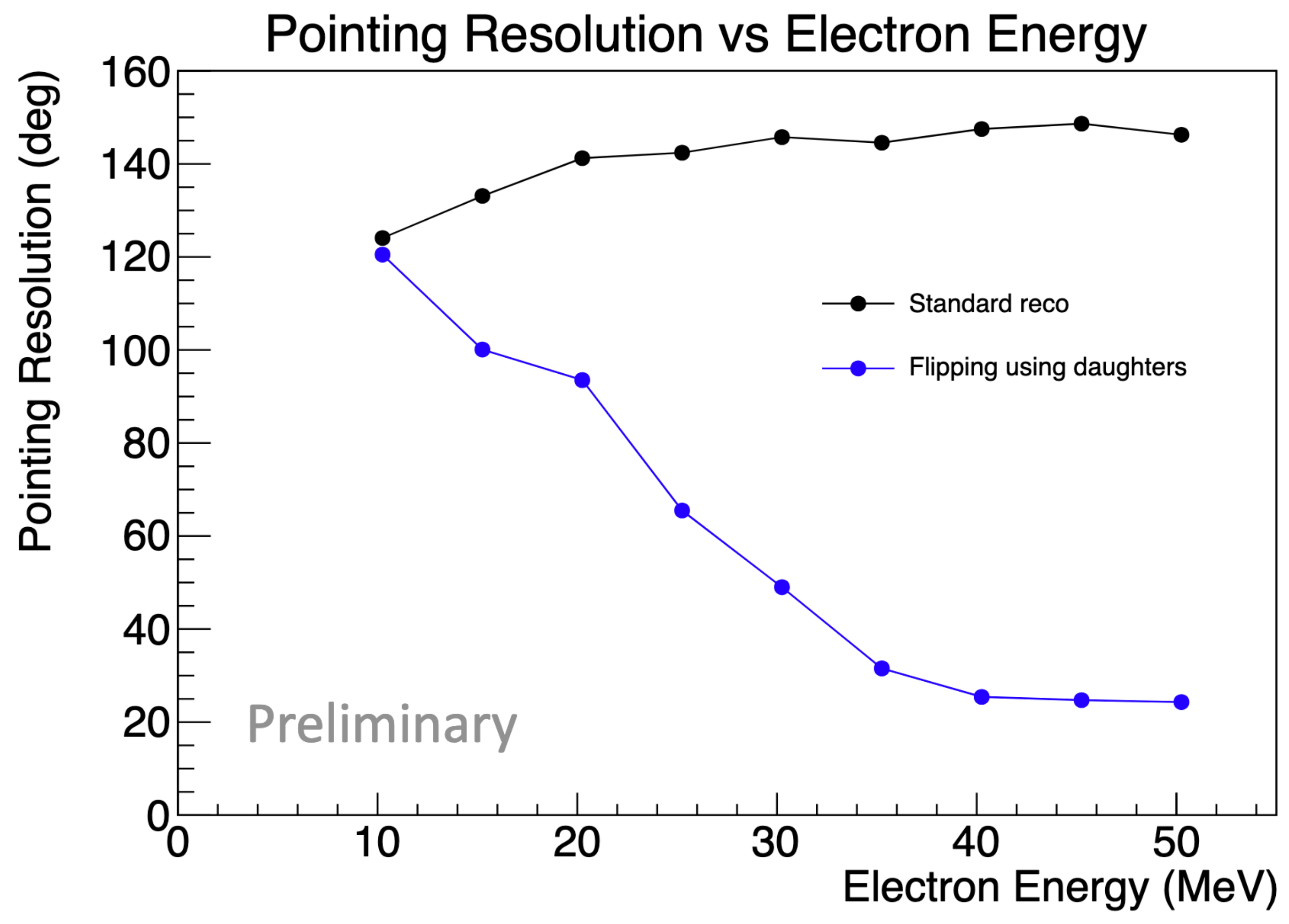
Background model

- Build a complete background model including:
  - Gammas from the rock
  - External neutrons
  - Cryostat and detector background
  - Liquid Argon background (Ar-42, Ar-39, Kr-85, Rn-222, …)
- Develop reduction techniques:
  - Pulse shape discrimination
  - Self-shielding capabilities
  - …

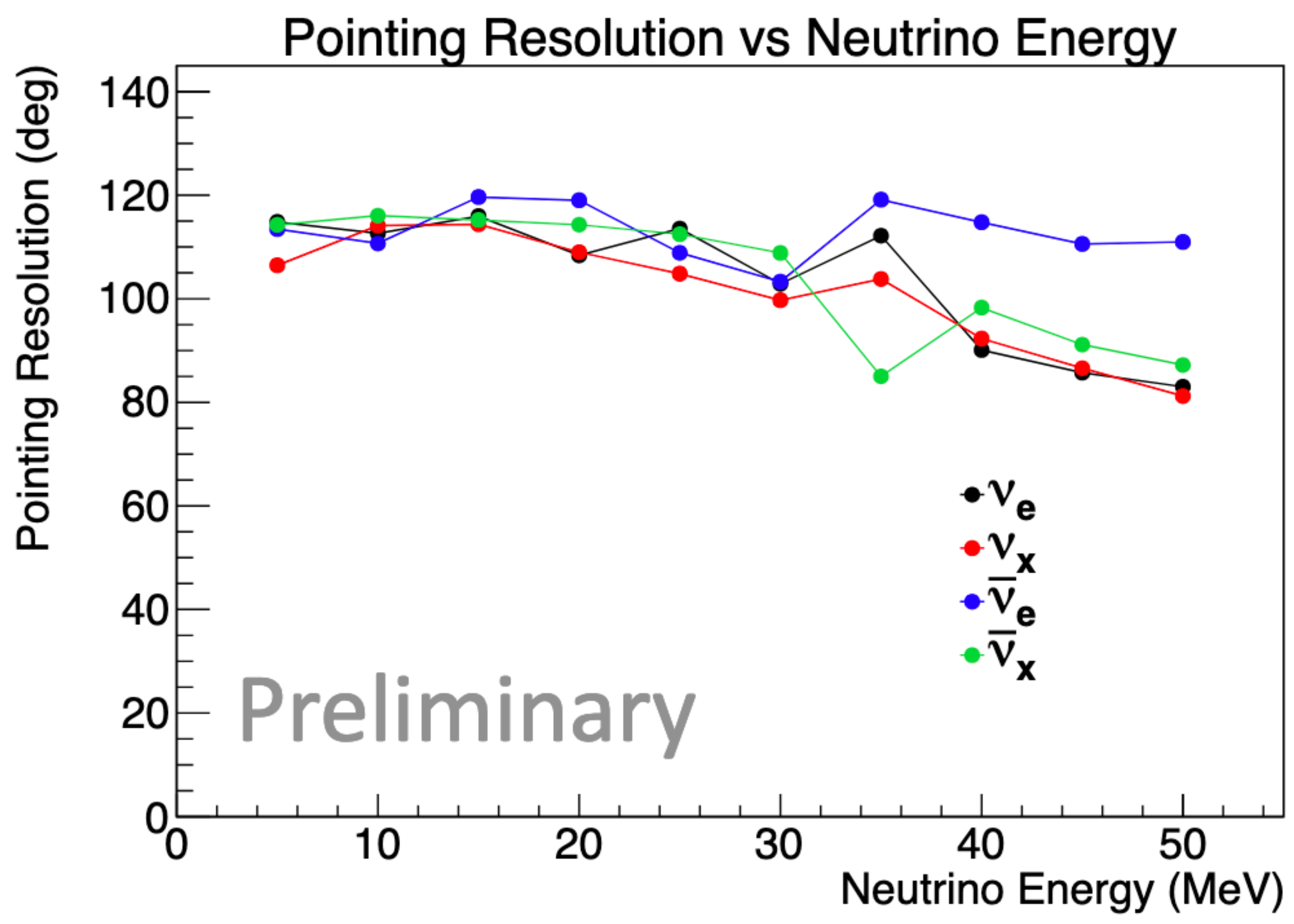
Pointing resolution studies in DUNE

- Event by event resolution limited by **statistics** and **reconstruction**
- Use statistical ensemble to point to supernova
- Pointing resolution = angle at which 68% of events are closer to truth

AJ Roeth



Single electron pointing resolution



ES reconstructed electron direction wrt neutrino direction

Reconstructed SN direction (from all electron directions and energies)

SN pointing resolution = **~5 (11) degrees** (10 kpc, 40kt (10 kt), GVKM model, ES + CC events)

- Can we use directionality for solar neutrinos?

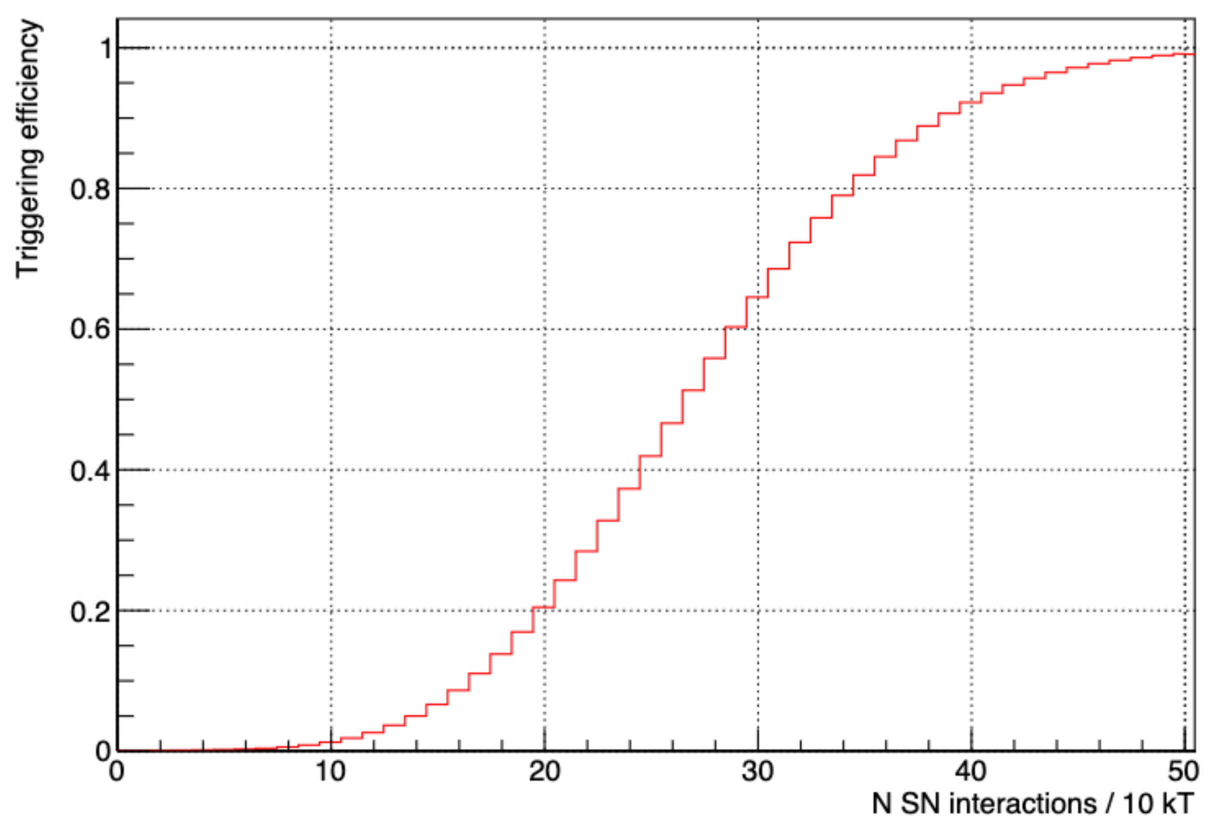
Timing resolution

- From SN physics point of view: **sub-ms** timing enough to identify time features
  - SASI oscillations: ~10 ms
  - Trapping of neutrinos in the stellar core before the neutralization burst: ~1-2 ms
- From the event reconstruction point of view:
  - During the first 50 ms of a 10-kpc-distant supernova, the mean interval between the successive neutrino interactions is **0.5-1.7 ms** depending on the model
  - Closer SN will produce higher neutrino rates (x10-100 higher)
  - **< 1us** to assign a unique event time for a minimal energy deposition (10 MeV), spatial separation (1 m) and temporal separation (1 ms) - 1 mm position resolution

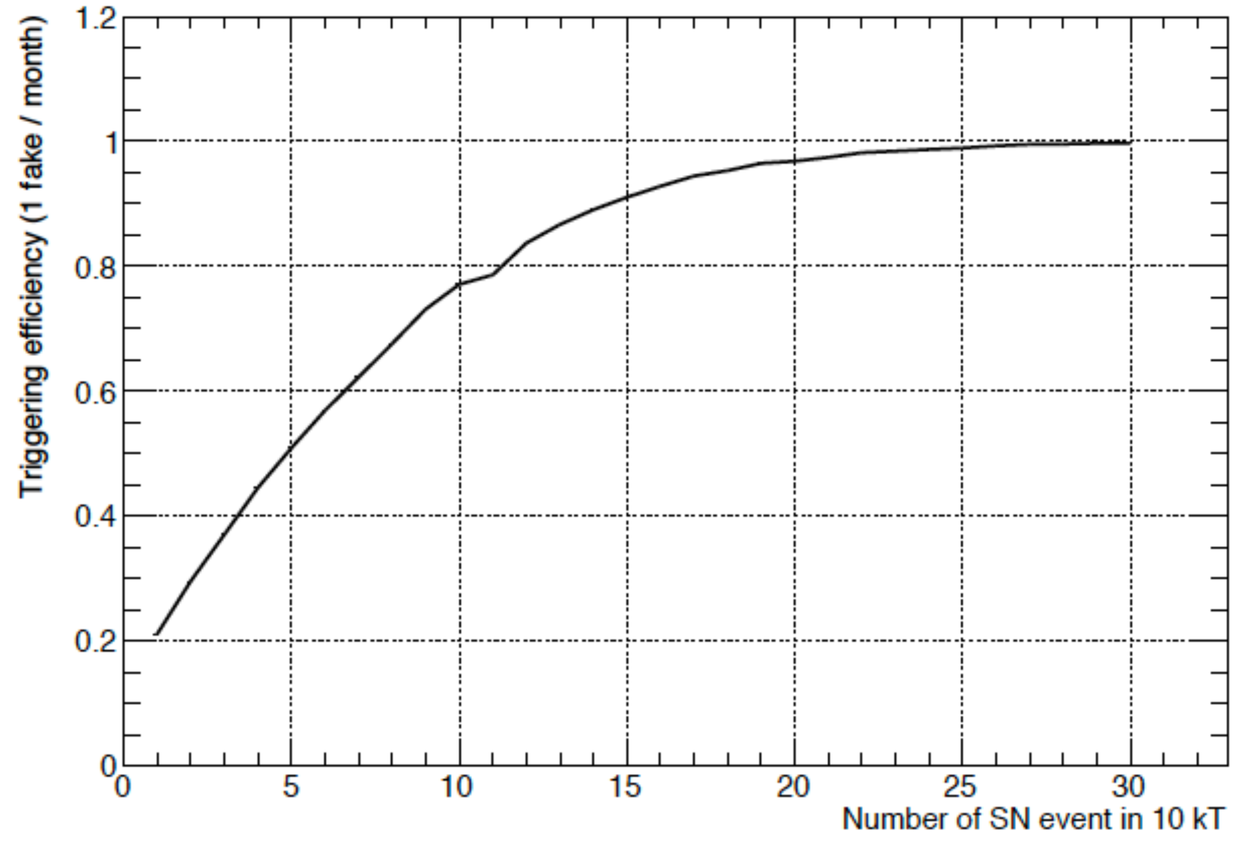
SN burst trigger

- Identification of the burst (time coincidence of multiple signals in the SNB timescale) with:
  - TPC trigger:
    - based on Trigger Primitives (hits from the collection wires) → Trigger Candidates (hit clusters based on correlation in **time** and **channel space**) → Trigger decision
  - PDS trigger:
    - Hits in photodetectors → Optical clusters (**time/spatial information**)
- Requirement: **>99% trigger efficiency in the whole detector for 50 interactions in 10 kt** (far side of our Galaxy) with false positive trigger rate less than 1/month (noise and radiological background)

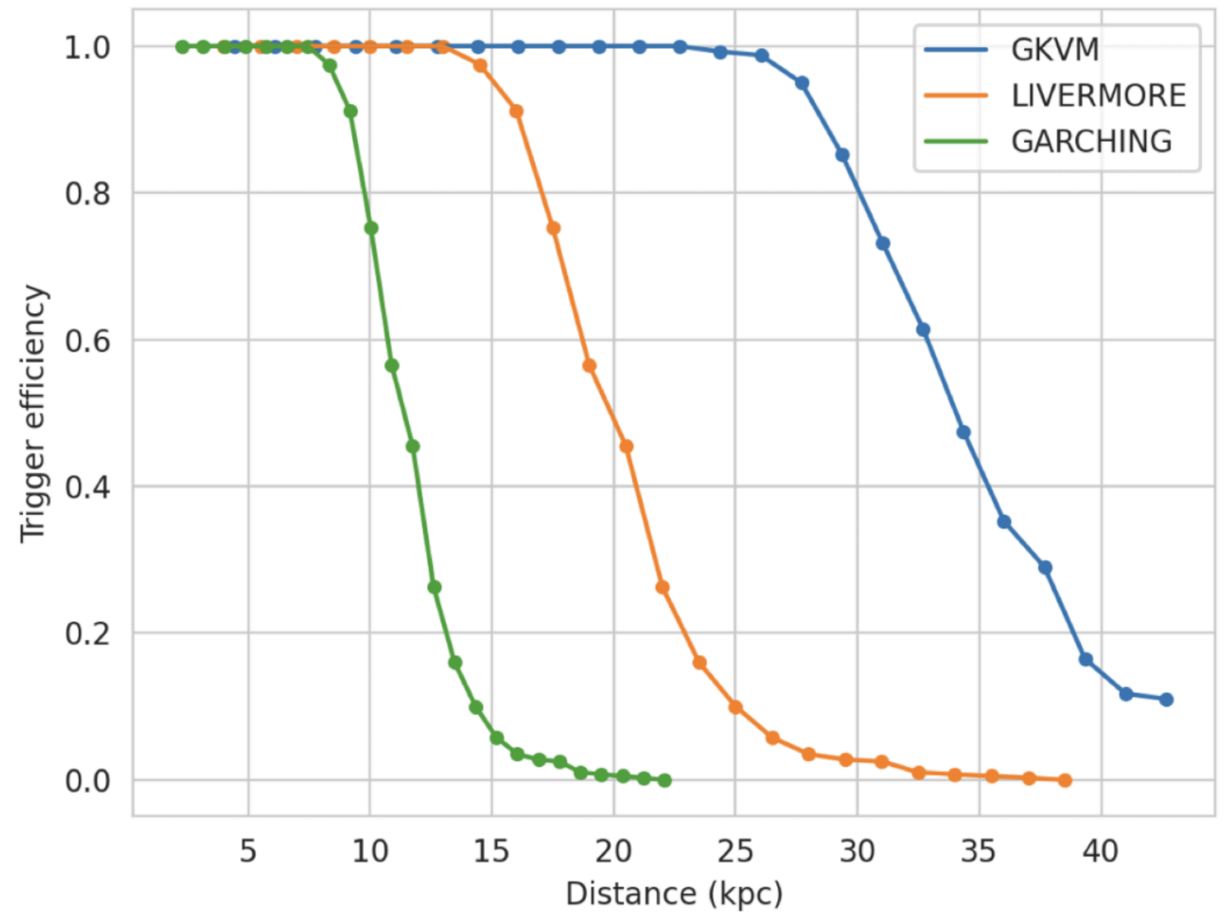
TPC trigger efficiency in FD-VD



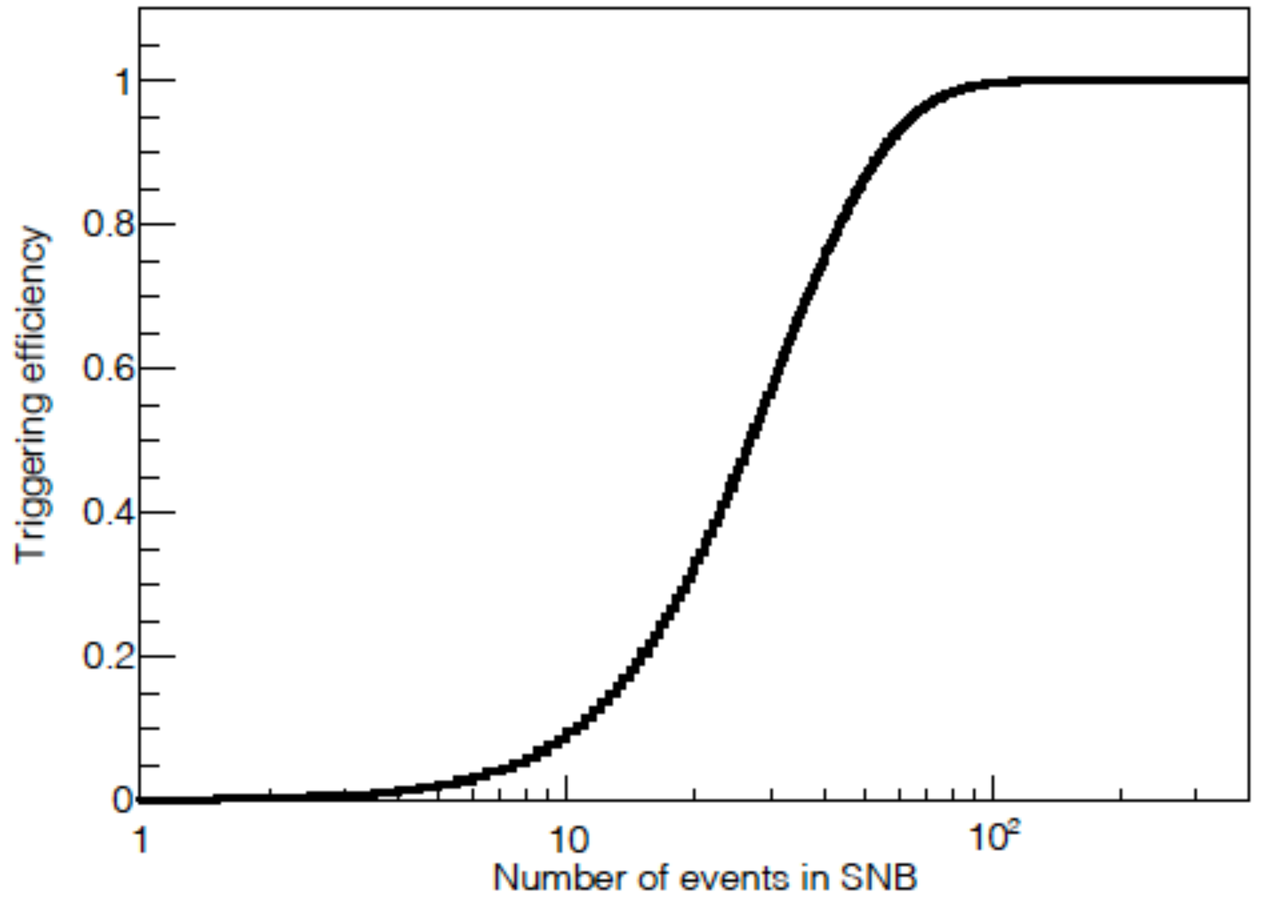
TPC trigger efficiency in SP FD



PDS trigger efficiency in FD-VD



PDS trigger efficiency in DP FD

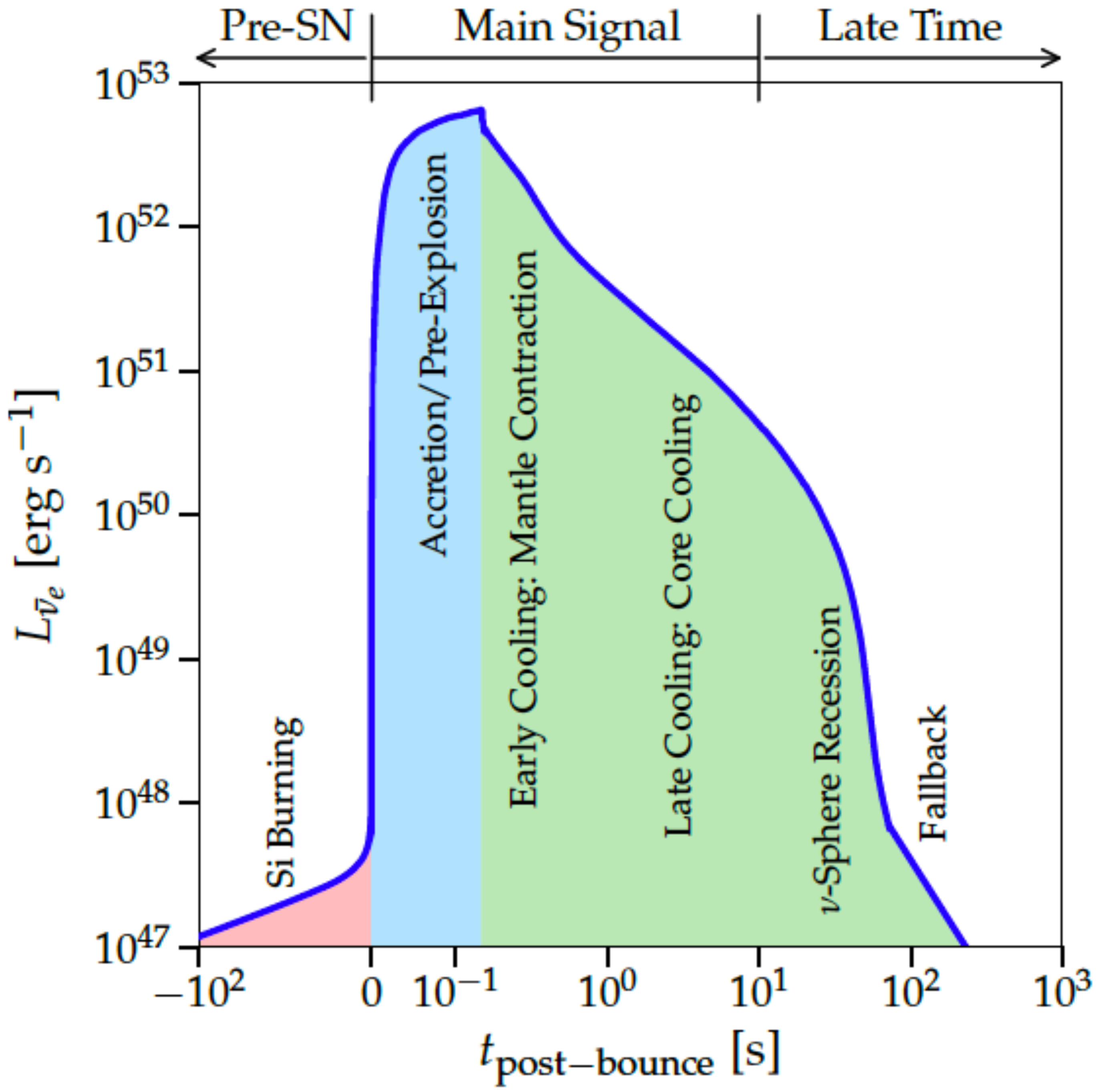


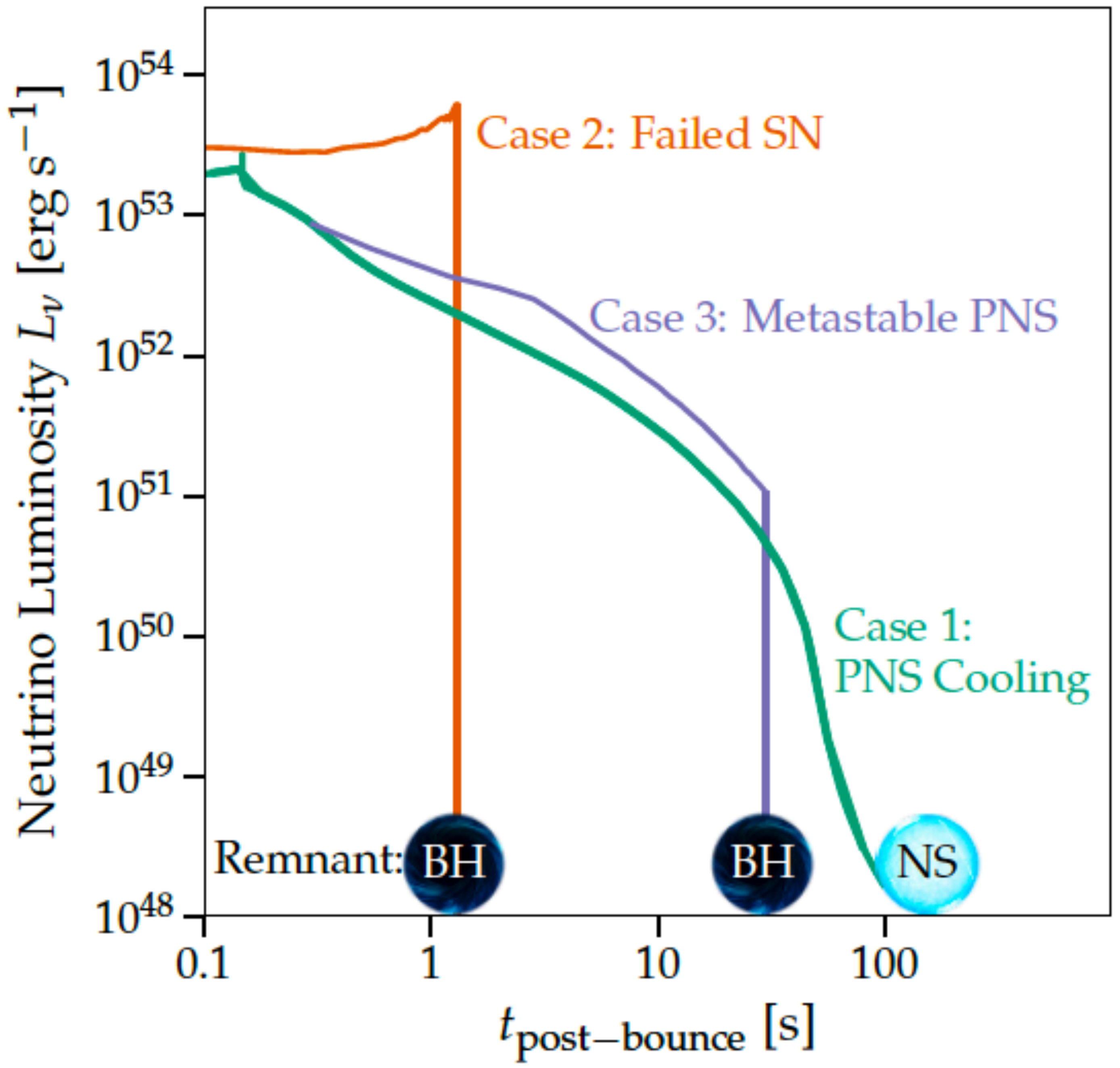
Solar Neutrino Trigger not studied yet in DUNE

Readout time

- By default, we considered 10 seconds as SNB readout time (mainly because the limitations from current theoretical models).
- However, interesting physics may happen at later stages ("as long as possible")

Phase	Physics Opportunities
Pre-SN	early warning, progenitor physics
Neutronization	flavor mixing, SN distance, new physics
Accretion	flavor mixing, SN direction, multi-D effects
Early cooling	equation of state, energy loss rates, PNS radius, diffusion time, new physics
Late cooling	NS vs. BH formation, transparency time, integrated losses, new physics

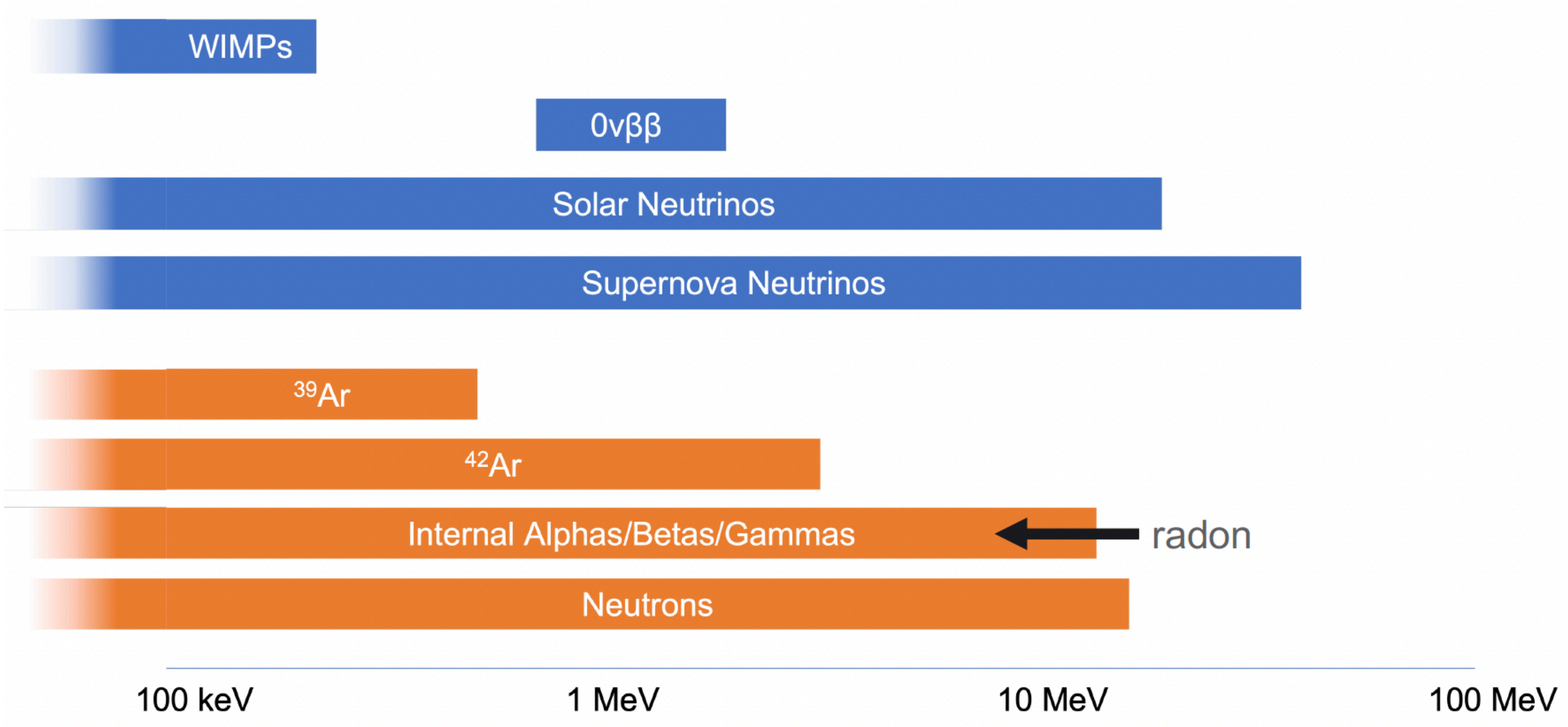




- Current goal is to store full raw data **up to 100 seconds for full readout**

Other low energy (< 5 MeV) neutrino physics

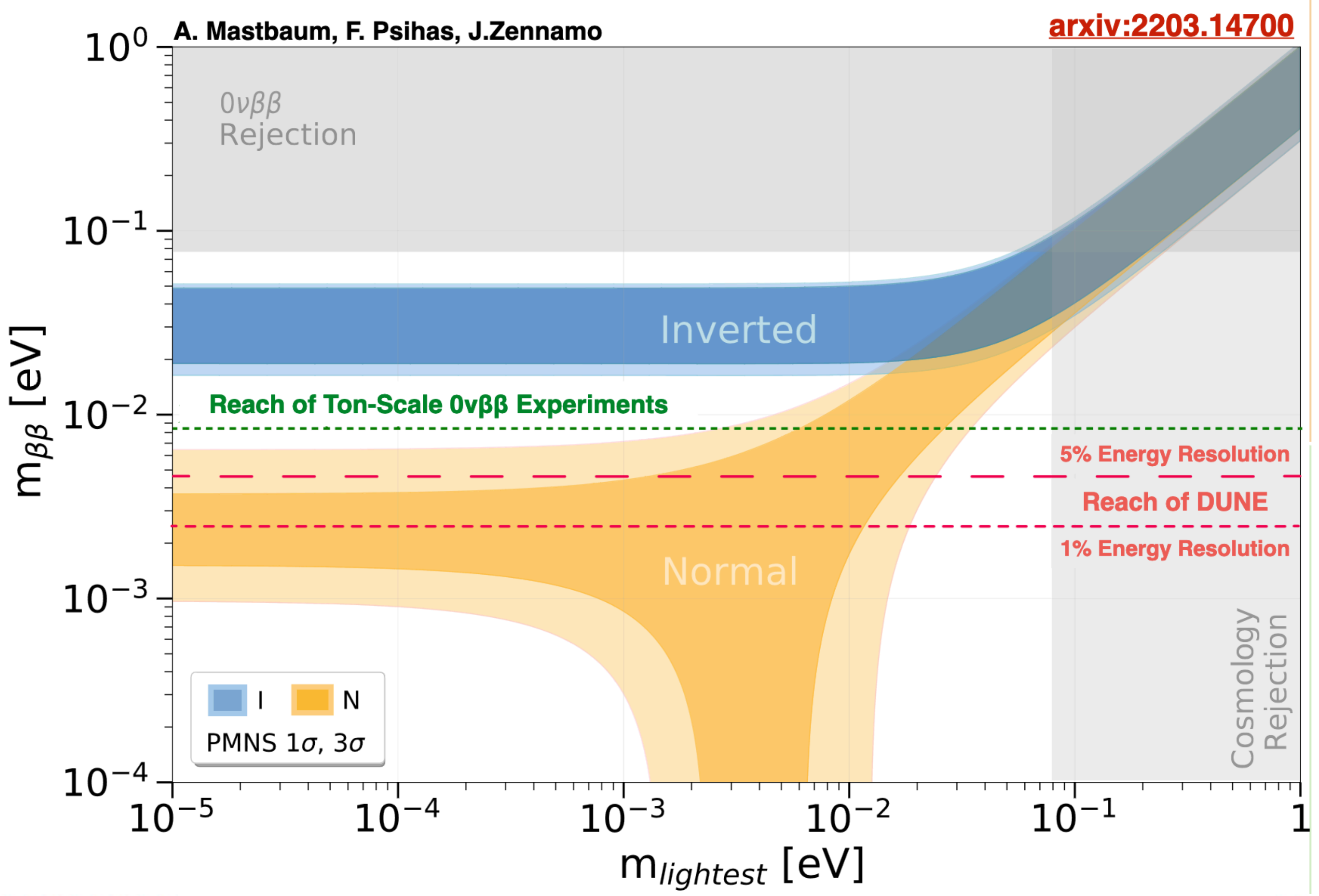
- Possible physics goals:
  - Measurement of lower-energy neutrinos in real time with high statistics
  - 0νββ
  - WIMP dark matter
  - CEvNS…
- Technologies ready for FD3?

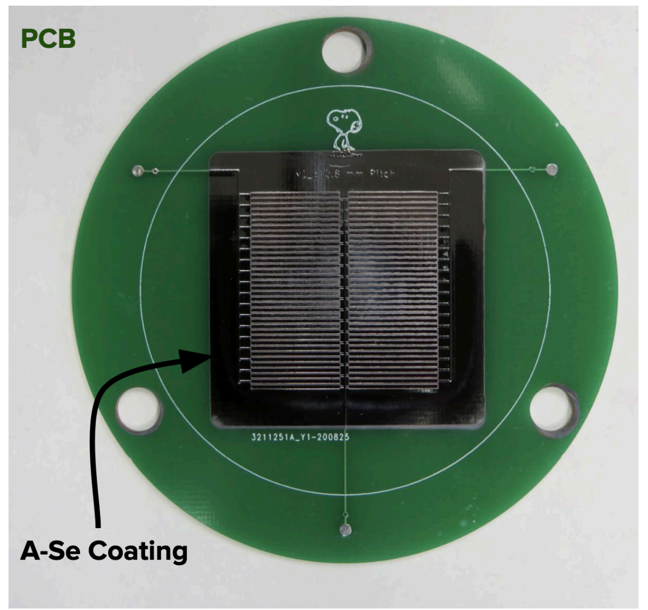


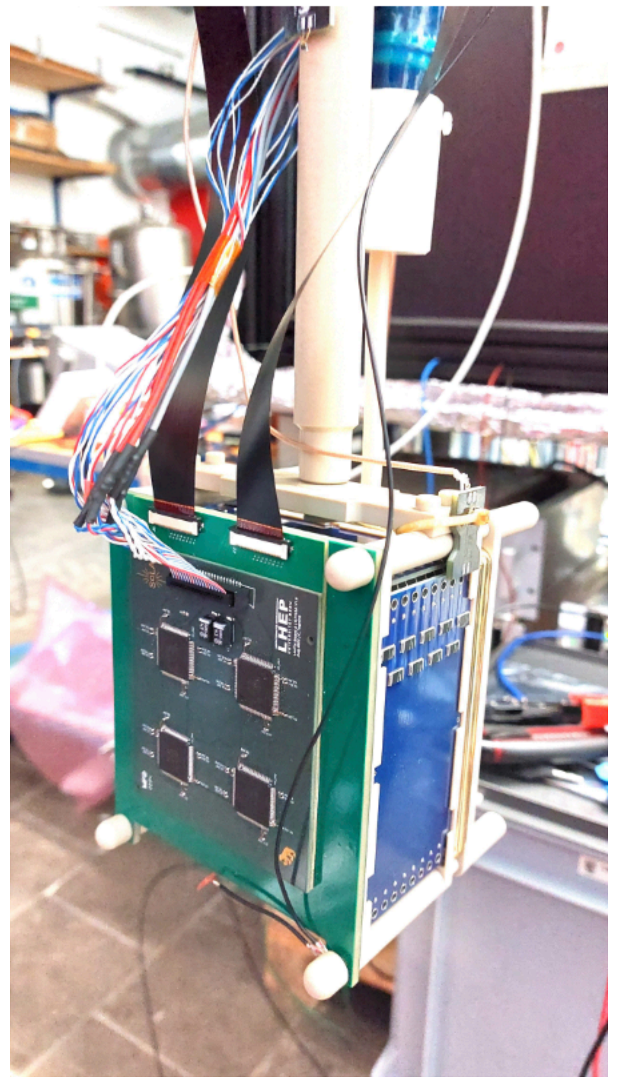
From C. Jackson

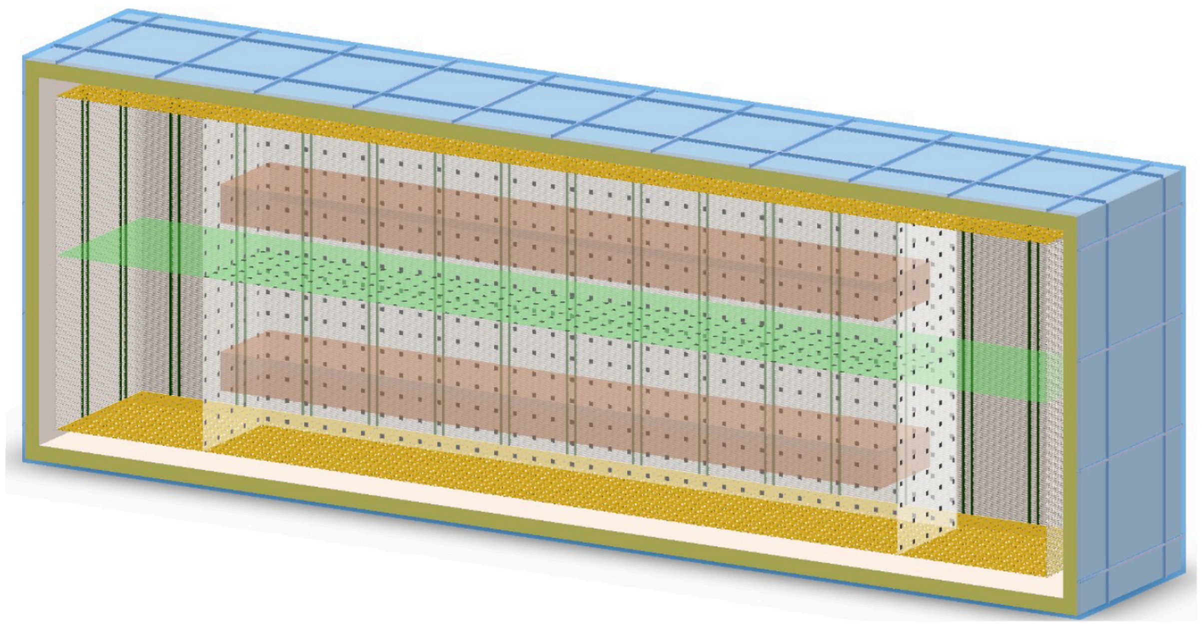
Higher detector challenges (depending on the technology)

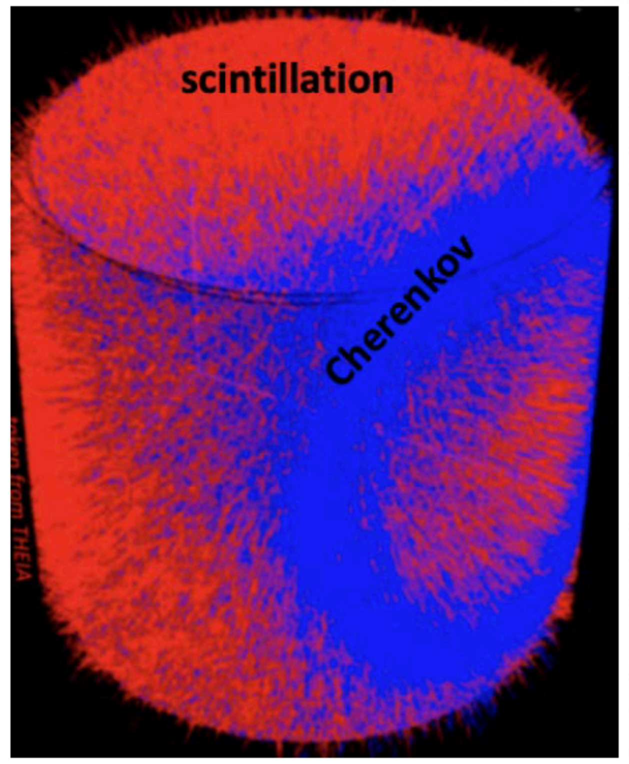
- External shielding
- Materials selection QA/QC
- Radon reduction
- Low-radioactivity underground argon
- % level energy resolution
- % level Xe-doping
- Photosensitive dopants
- …

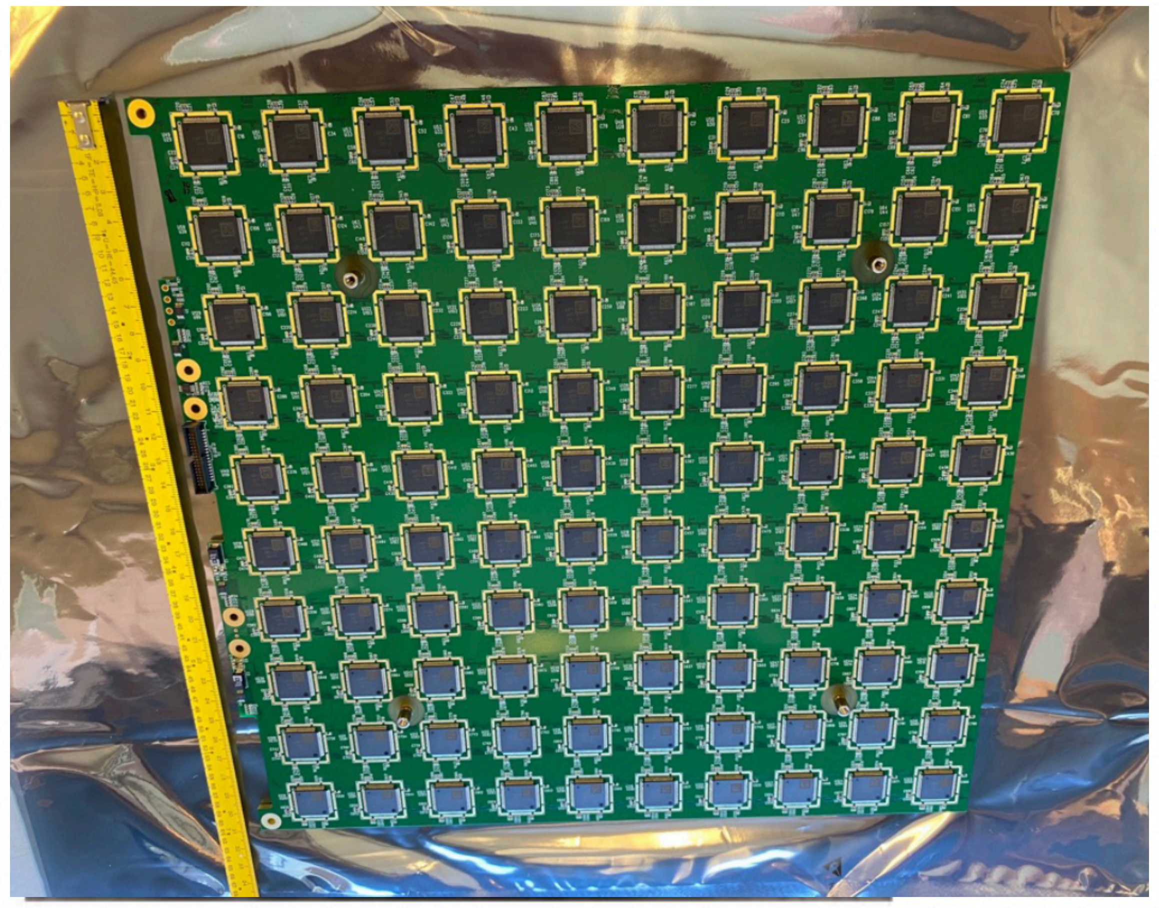












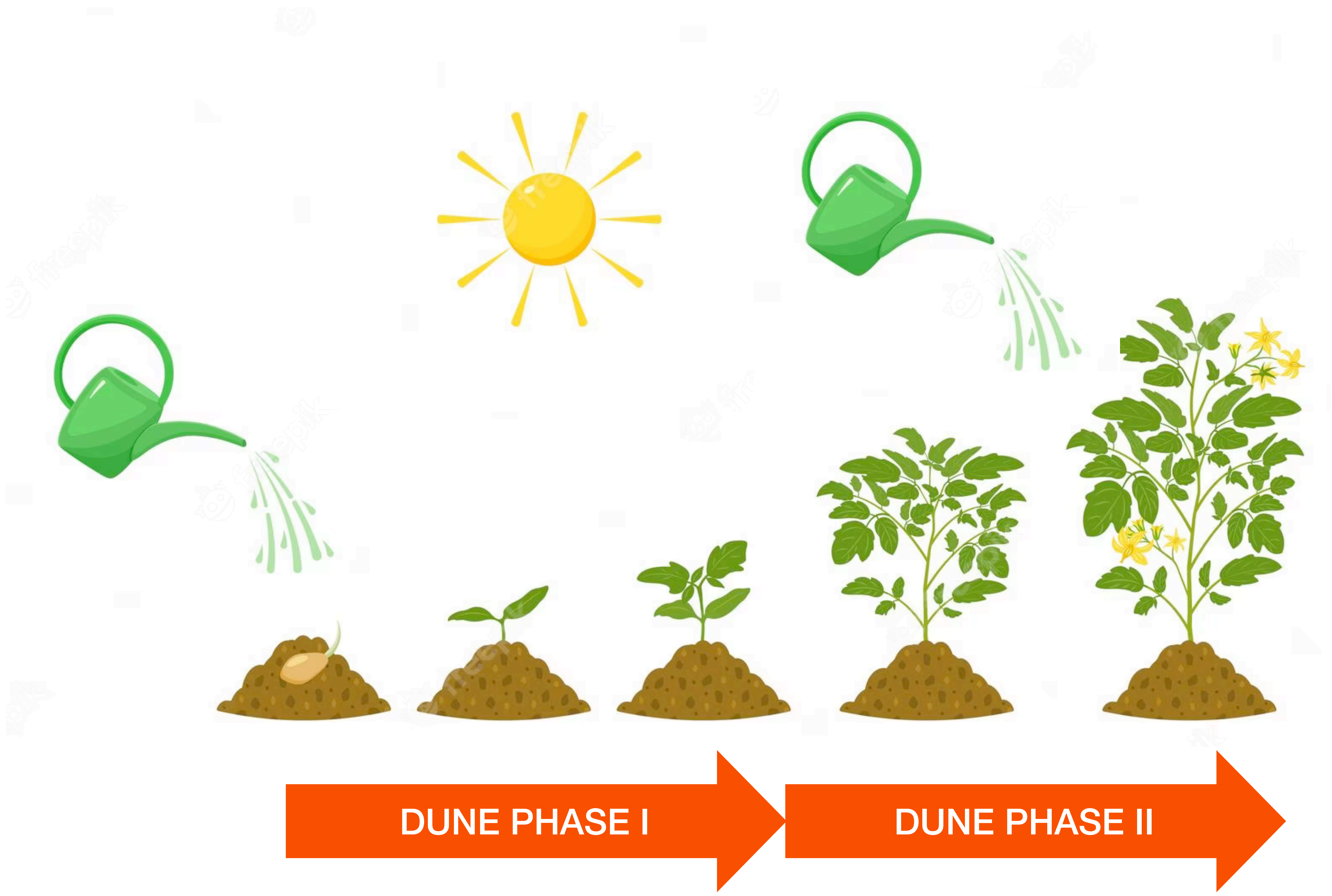
Conclusions

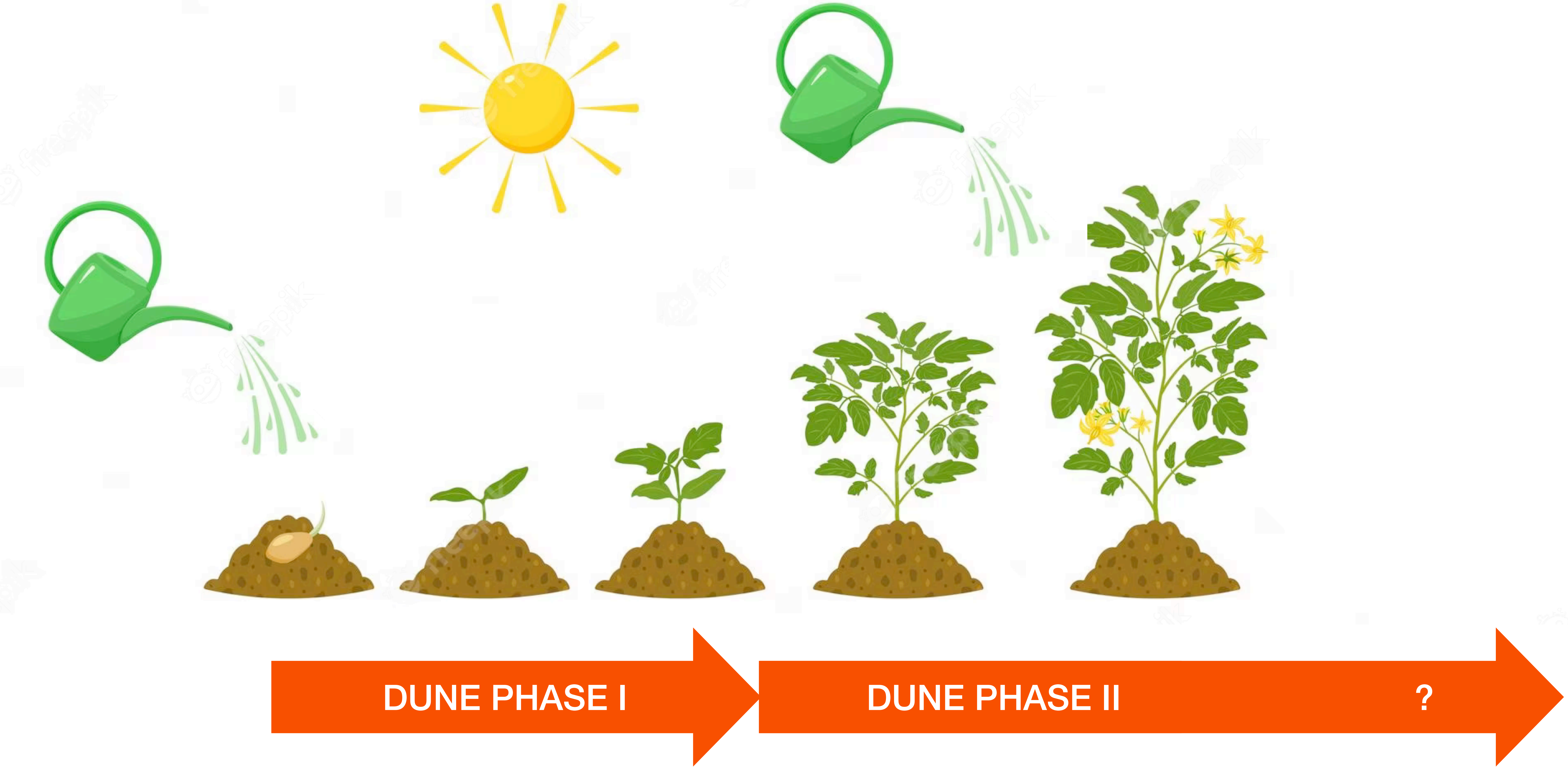
- DUNE is a best-in-class **long-baseline neutrino oscillation** experiment
  - Mass ordering and initial measurements in Phase I
  - CP violation, precision measurements, and search for new physics in Phase II
- DUNE has unique sensitivity to **MeV-scale neutrinos**
  - Only experiment sensitive to supernova ν_e
  - Detection of hep solar flux and measurement of solar parameters
  - Opportunities to greatly enhance LE reach in Phase II
- DUNE has a rich and broad **BSM program**
  - BSM oscillations with large L/E range and large matter effect
- DUNE is both **competitive** with, and **complementary** to the global experimental program

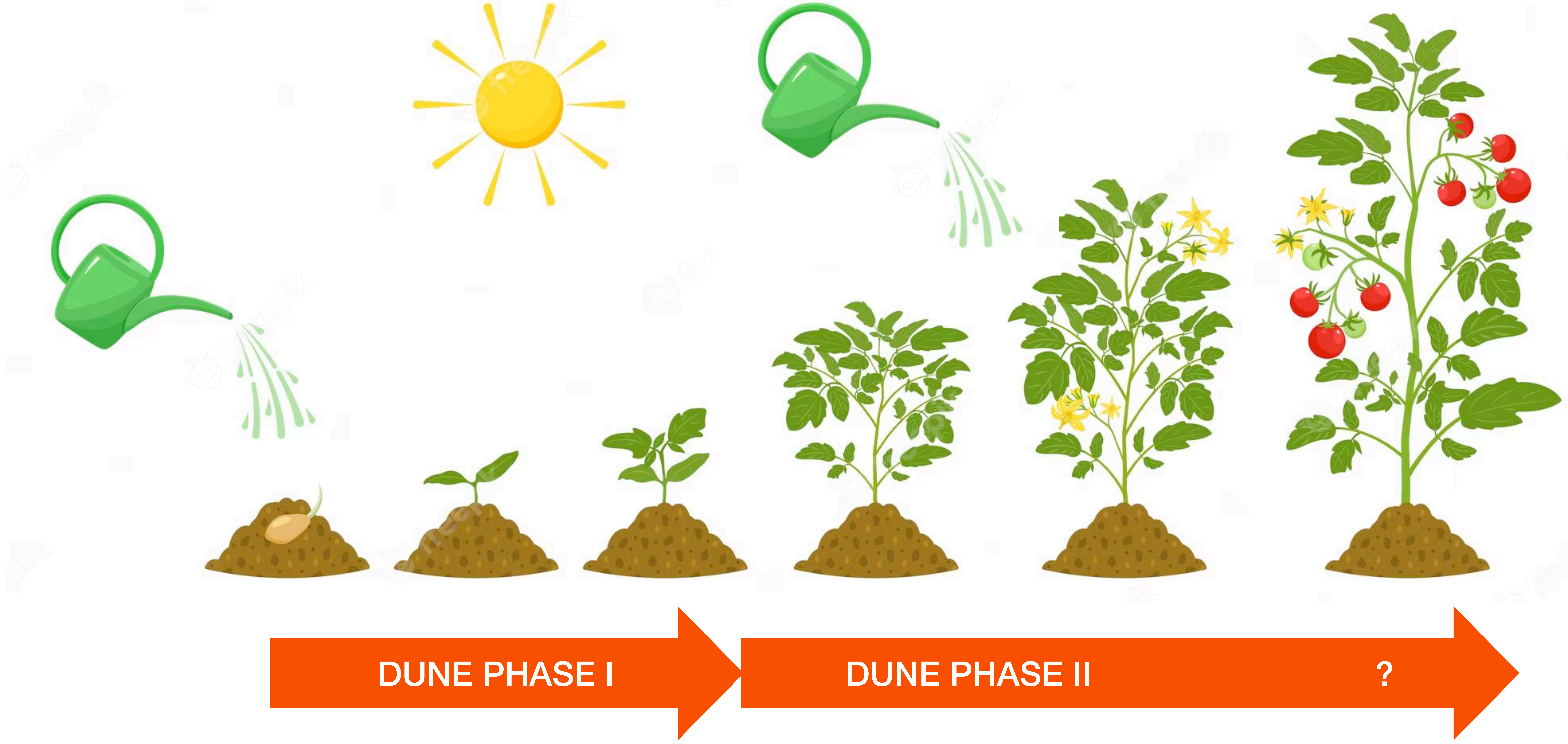
DUNE PHASE I

DUNE PHASE I

DUNE PHASE II


DUNE PHASE I
DUNE PHASE II


DUNE PHASE I
DUNE PHASE II
?


DUNE PHASE I
DUNE PHASE II
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