Low energy physics at Hyper-Kamiokande

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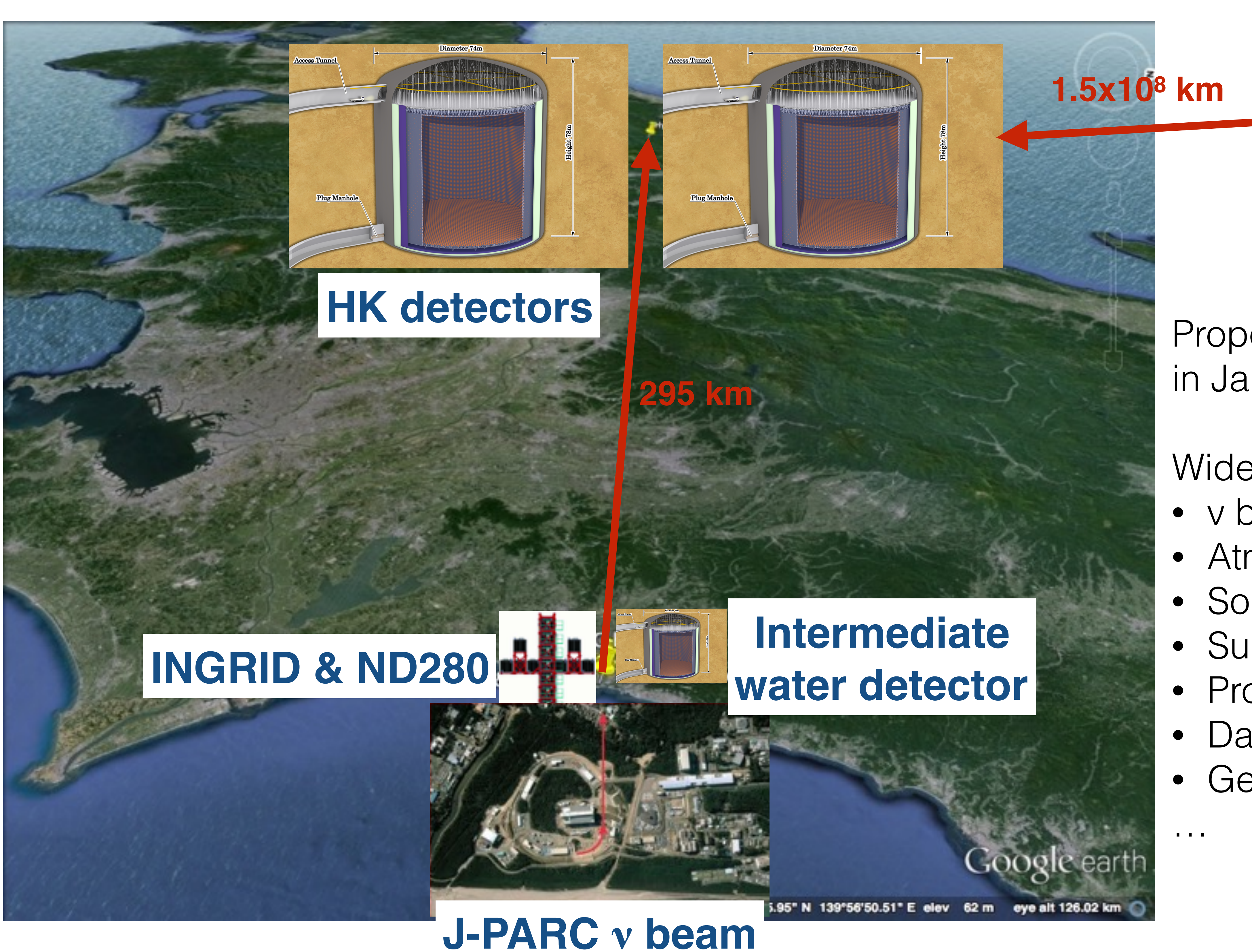
Outline

- The Hyper-Kamiokande (HK) experiment
- Low energy physics at HK
- Low energy triggering

Hyper-Kamiokande (HK)



Proposed experiment in Japan

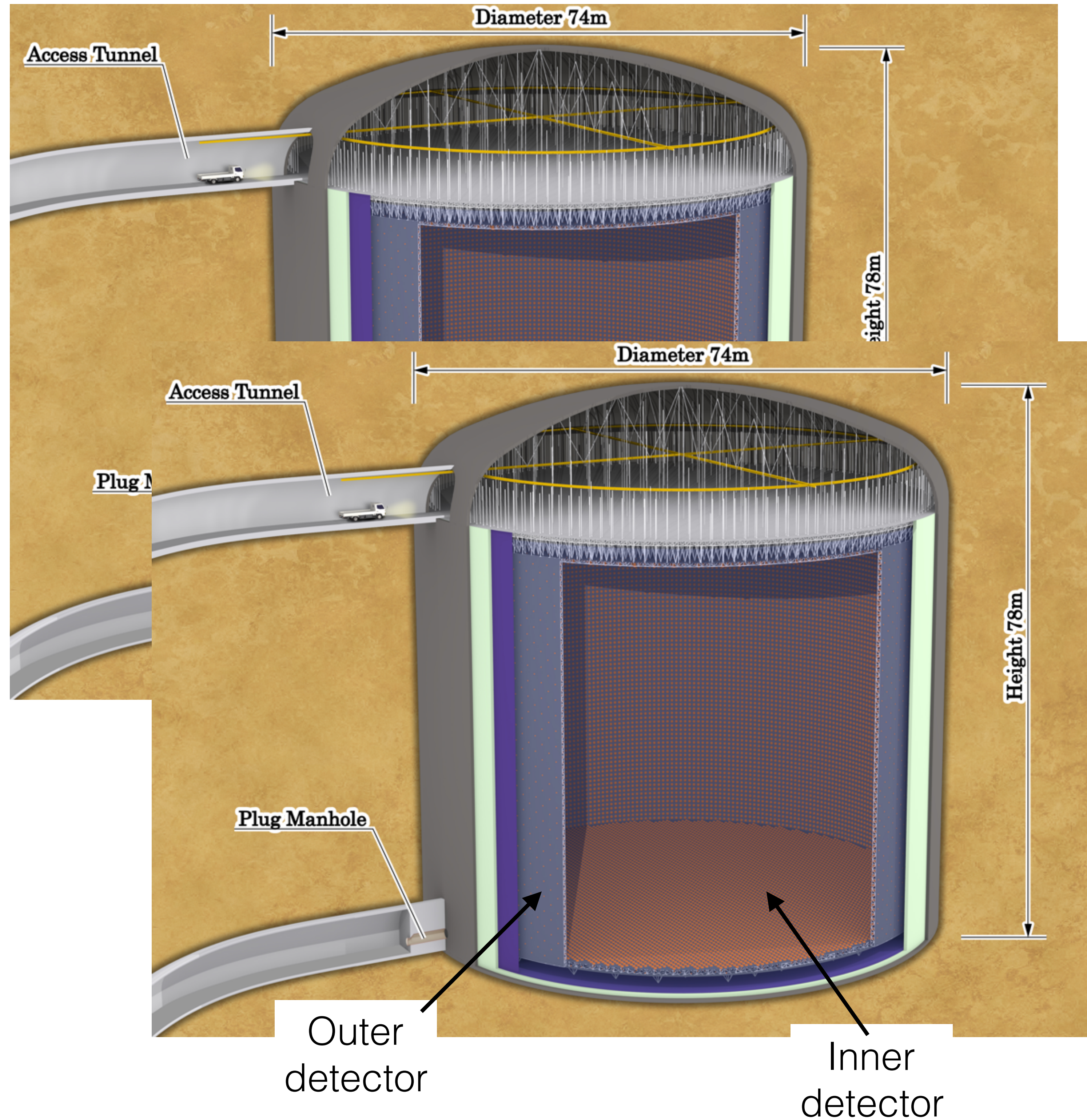
Wide range of physics

- ν beam
- Atmospheric ν
- Solar ν
- Supernova ν
- Proton decay
- Dark matter
- Geophysics

…

HK detector

- Water Cherenkov detector
- 258 kton (187 kton fiducial) × 2
  - ~8 × SK × 2
- ~40,000 PMTs × 2
  - ~4 × SK × 2
- 40% photosensitive coverage
  - Same as SK
- Improved PMTs
  - ~2 × SK single photoelectron hit efficiency
  - ~2 × SK dark noise
- Plan to take data from 2026 for at least 20 years
- 2 Tanks
  - Staged approach

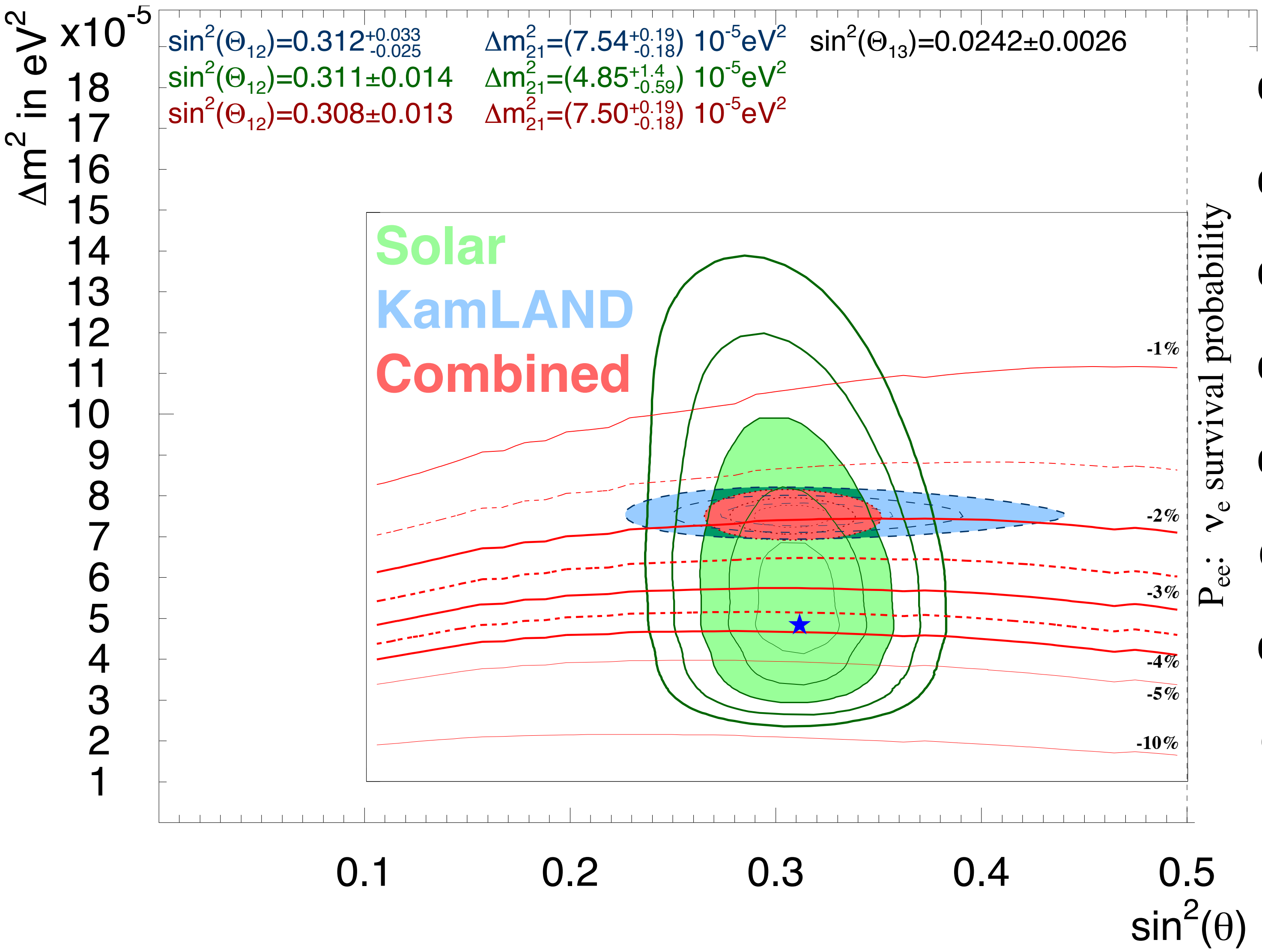


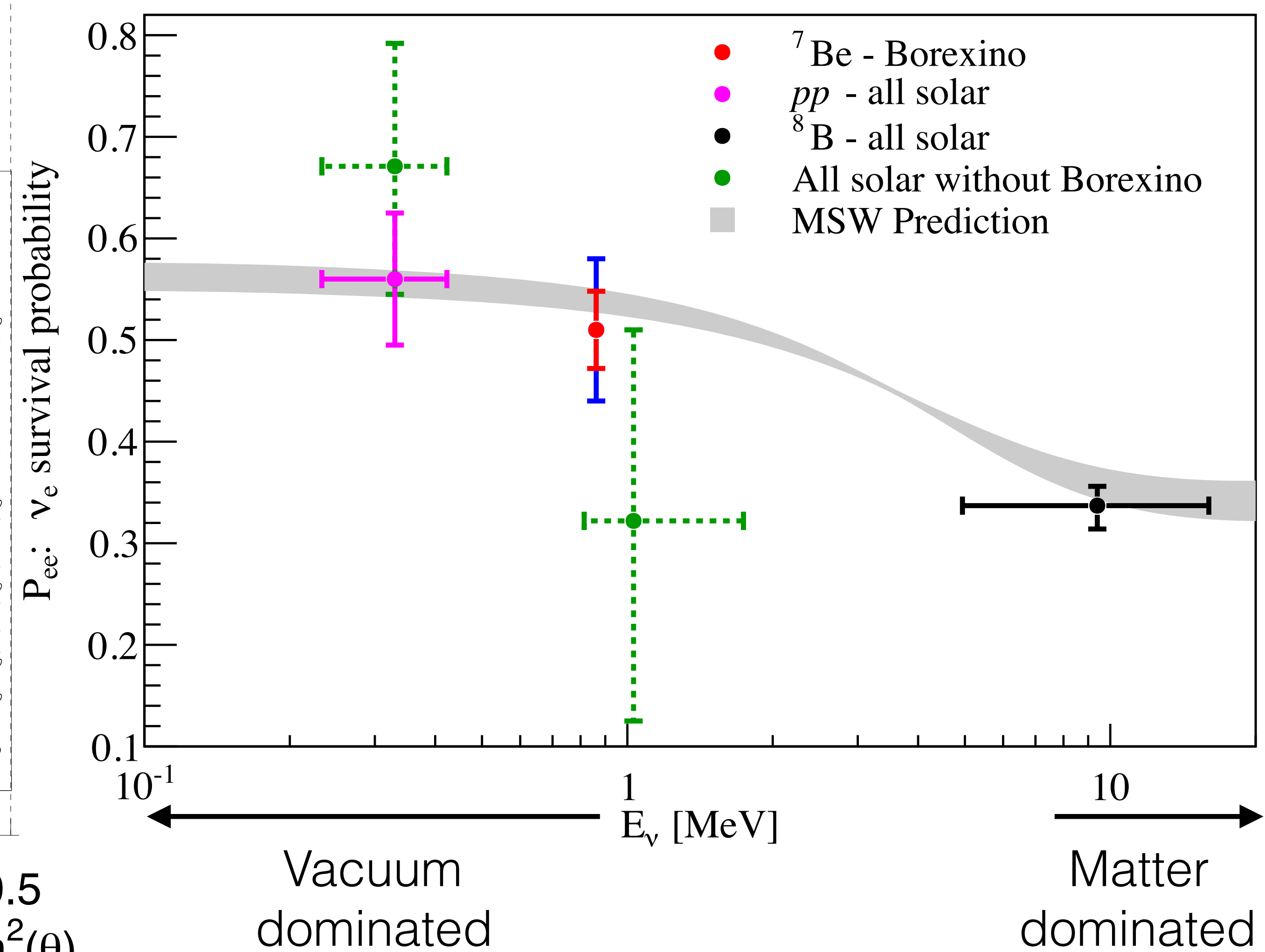
Neutrino oscillations

$$\underbrace{\begin{pmatrix}1 & 0 & 0\\ 0 & \cos\theta_{23} & \sin\theta_{23}\\ 0 & -\sin\theta_{23} & \cos\theta_{23}\end{pmatrix}}_{\text{Atmospheric}}\underbrace{\begin{pmatrix}\cos\theta_{13} & 0 & \sin\theta_{13}e^{-i\delta_{CP}}\\ 0 & 1 & 0\\ -\sin\theta_{13}e^{+i\delta_{CP}} & 0 & \cos\theta_{13}\end{pmatrix}}_{\text{Interference}}\underbrace{\begin{pmatrix}\cos\theta_{12} & \sin\theta_{12} & 0\\ -\sin\theta_{12} & \cos\theta_{12} & 0\\ 0 & 0 & 1\end{pmatrix}}_{\text{Solar}}$$

- PMNS matrix
  - Relates neutrino mass eigenstates to neutrino flavour eigenstates
  - Analogous to quark CKM matrix
- Two-flavour oscillation formula:
  - $P_{\alpha\to\beta,\alpha\neq\beta} \approx \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$
    - L propagation length, E neutrino energy, Δm^2 mass-squared splitting
  - Propagation through matter modifies this (MSW effect)
- "L/E" of experiment determines which oscillations dominate
  - HK can measure all six parameters:
    - 3 mixing angles, CP phase, 2 independent mass-squared splittings

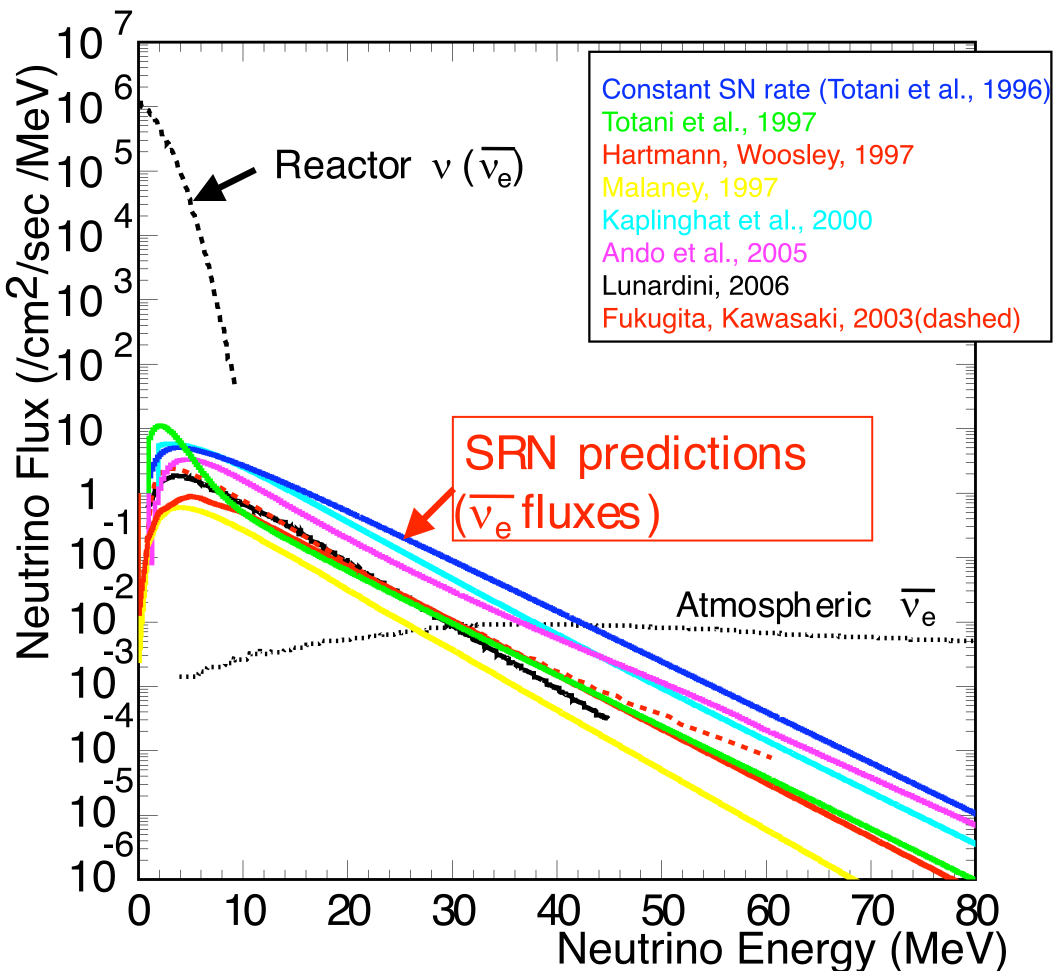
Solar ν physics @ HK

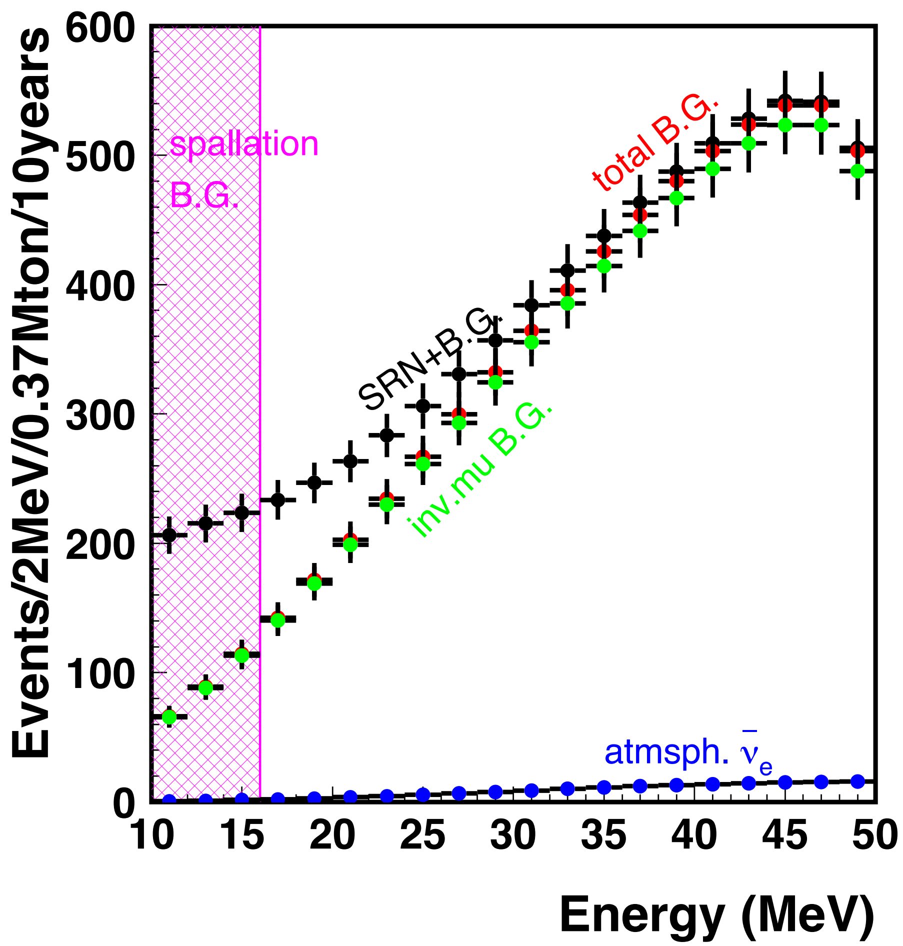




- ~2σ tension between solar experiments & KamLAND in Δm^2_{21}
    - HK can confirm day-night effect (MSW in Earth)
    - This should resolve the tension
- HK can observe the survival probability “upturn”, to confirm MSW prediction
    - Need to reach down to 3 MeV

Supernova relic ν physics @ HK





- Relics: diffuse background of core collapse supernova (ccSN) neutrinos
- Discovery expected at HK

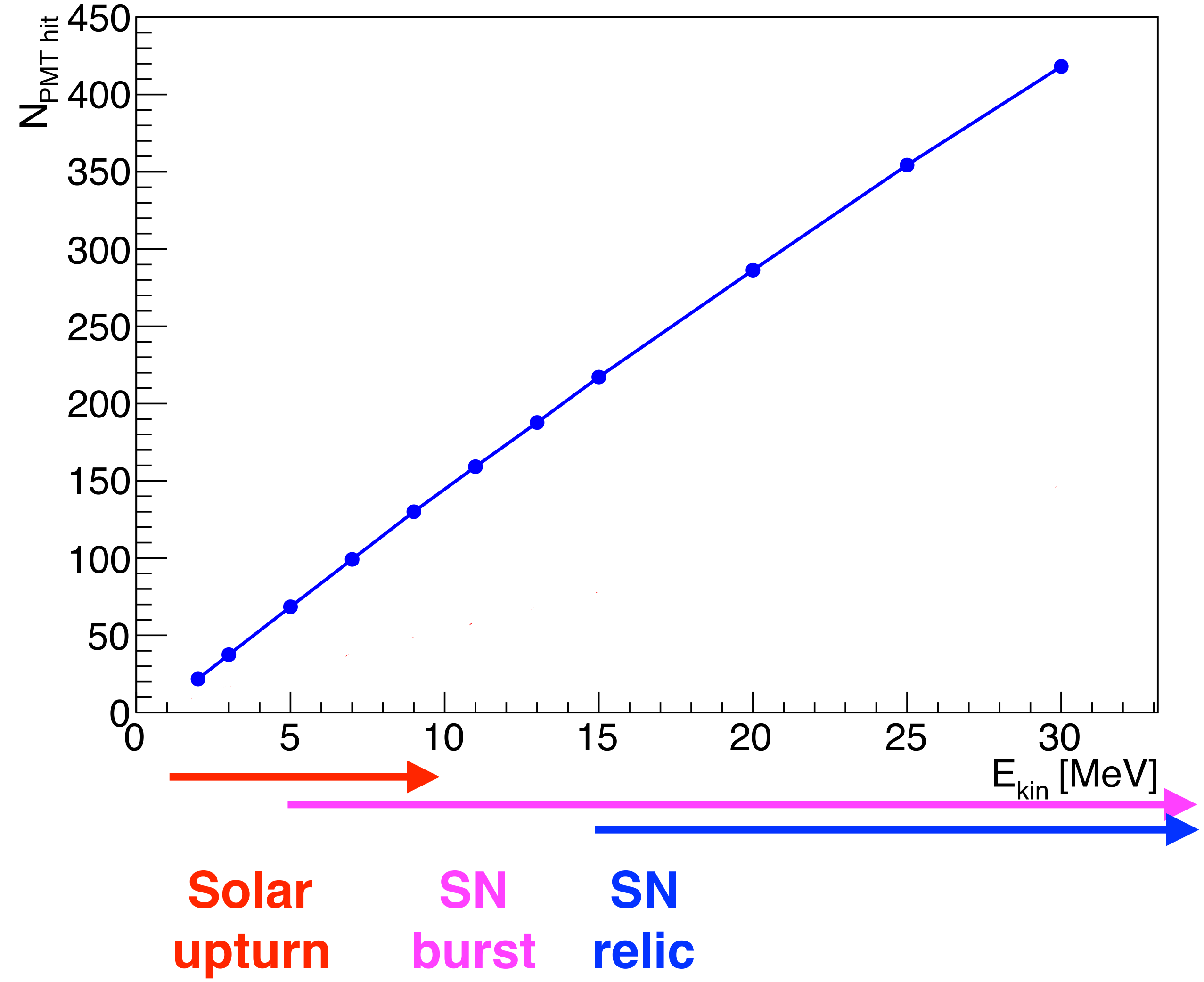
Data rates

Data source	Event rate	Hits / event	Raw data rate
Dark noise	10 kHz	1 (per tube)	5 GB/s
Low energy backgrounds	10 kHz	25	3 MB/s
Cosmic muons	100 Hz	40,000	50 MB/s
Beam	1 Hz	0	0 MB/s
Calibration	2 Hz	40,000	2 MB/s
Pedestal	1 Hz	40,000	2 MB/s

- Dark noise dominates the raw data
  - Want to reduce this as much as possible without sacrificing physics
  - Cheaper system
    - Less hardware: easier to scale
    - Less storage: 5 GB/s is 18 TB/hour and 13 PB/month

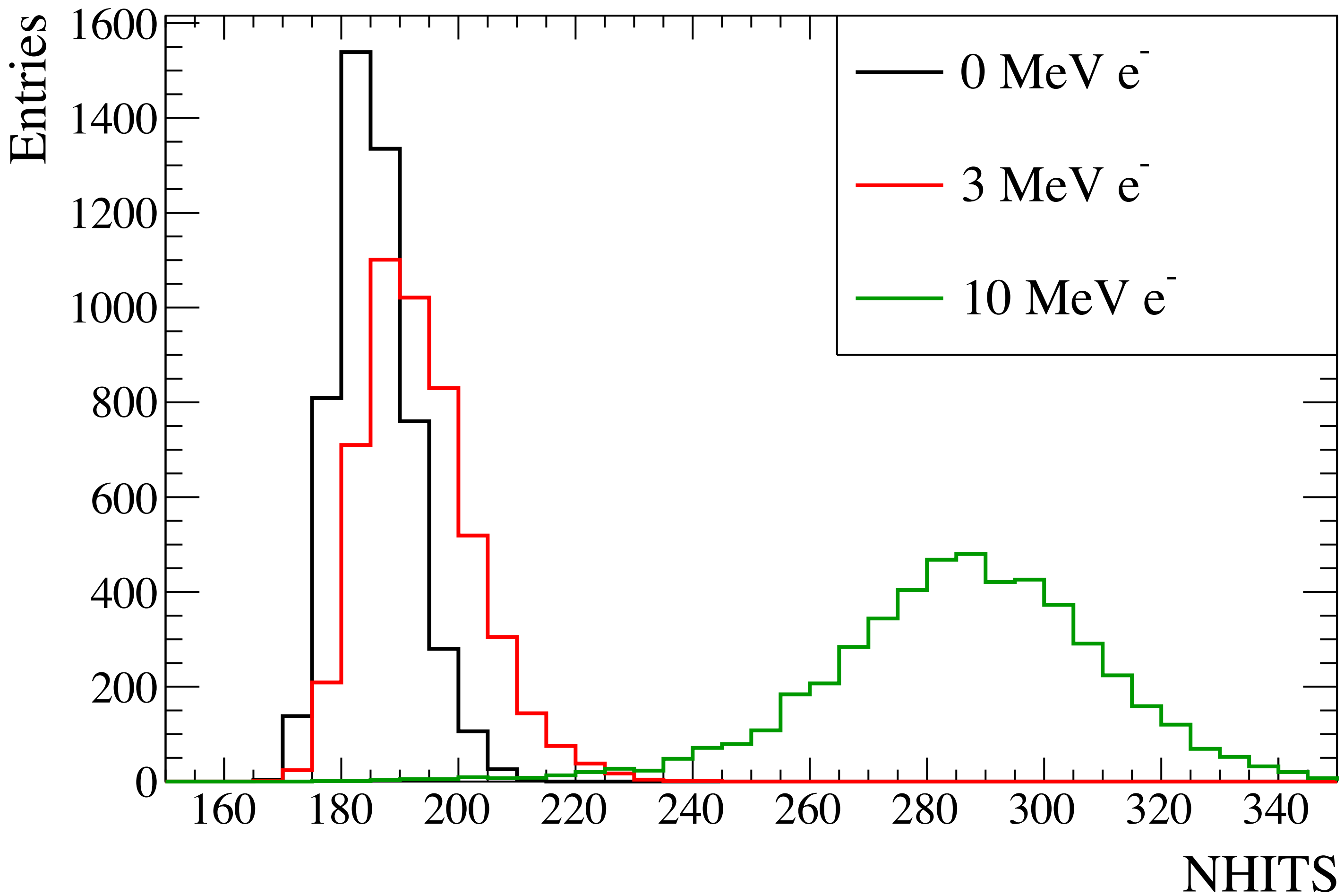
Triggering

- Standard water Cherenkov trigger "NHITS"
  - Count number of hit PMT (hits) in a sliding time window
    - Time window determined by tank size
  - If above a threshold, issue trigger
- HK is big & has lots of high-noise PMTs
  - ~150 dark noise hits in trigger window
  - c.f. ~40 for 3 MeV (kinetic) electron



- NHITS will work for high energy events
  - Need an intelligent trigger to recover low-energy physics

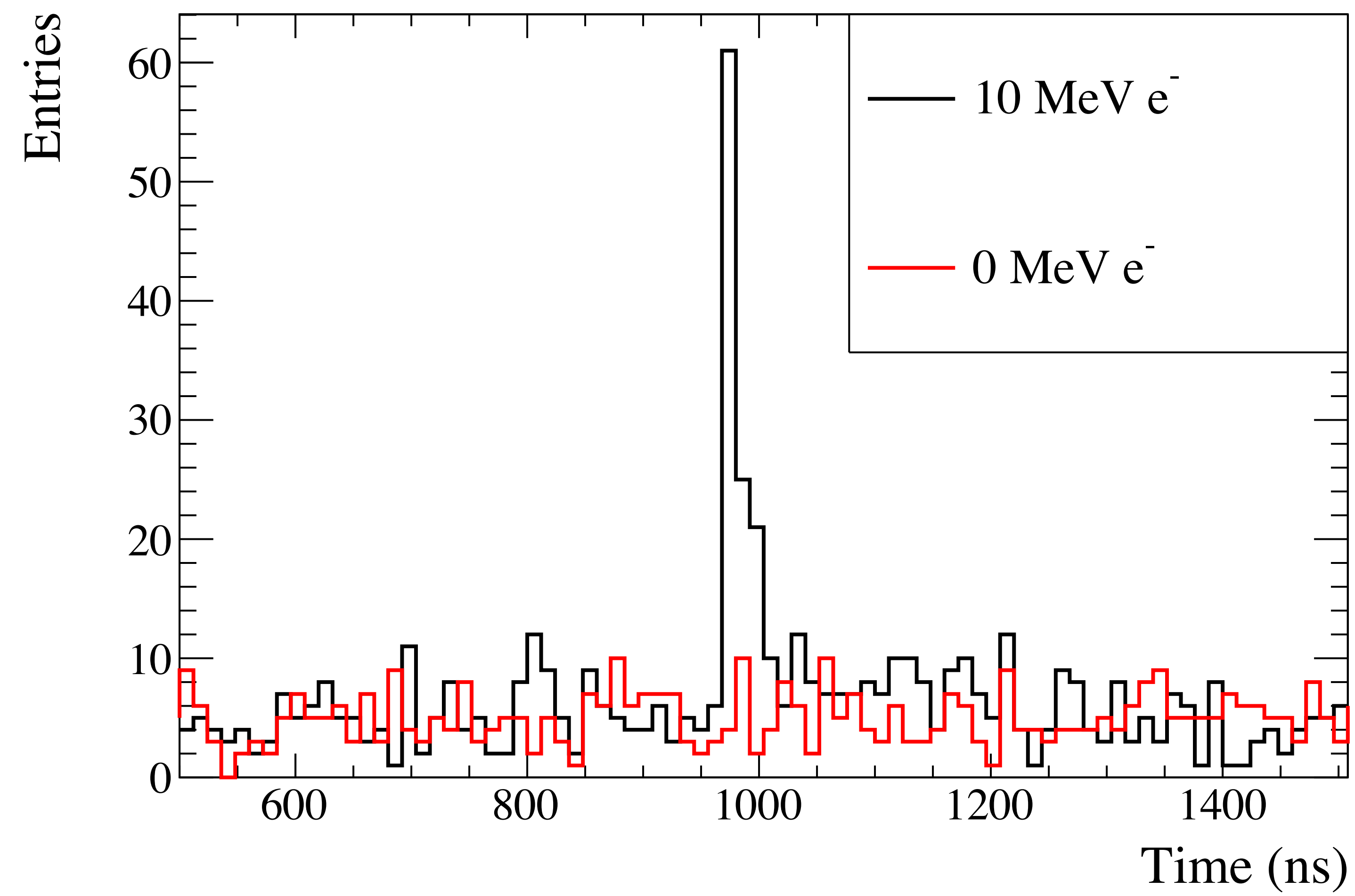
Triggering: NHITS



- Electrons simulated uniformly & isotropically
- Maximum value of NHITS in trigger window

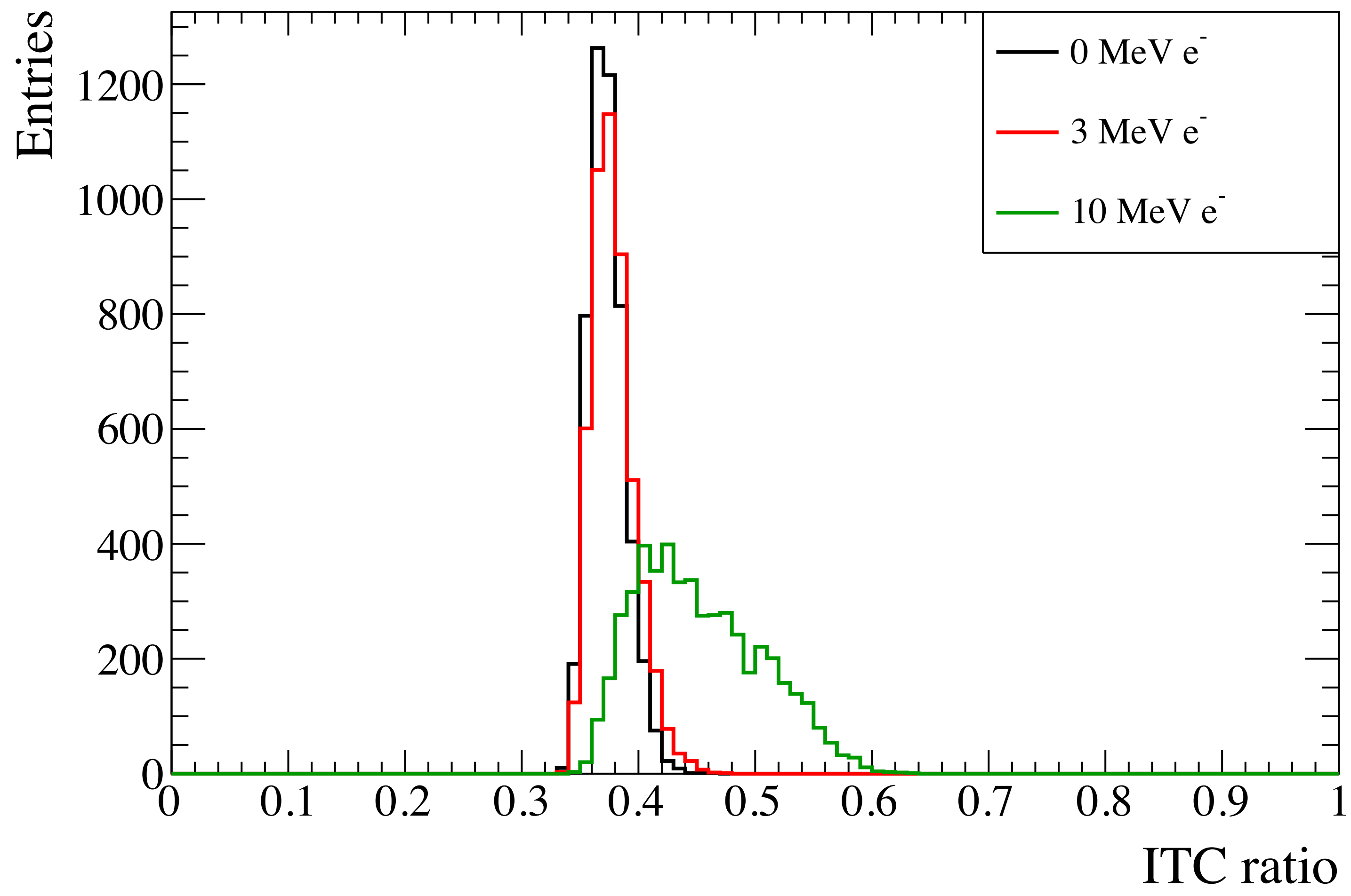
- e.g. cut @ 200 NHITS
  - Dark noise efficiency 2%
    - ~100 MB/s data rate; much more manageable
  - <1% sacrifice @ 10 MeV
  - But, 80% sacrifice @ 3 MeV
- Need a more intelligent trigger to do solar physics & reject dark noise

Triggering: ITC ratio



- Based on in-time channel (ITC) cut used by SNO (post-trigger)
  - M. Neubauer, SNO-STR-2000-012
- Algorithm
  1. Count number of hits in 2 co-sliding time windows
     - 'Big window'
     - 'Small window'
  2. If 'Small window' / 'Big window' > threshold, issue trigger
- If 'big window' ≈ 'NHITS window'
  - Looking for spike in time distribution
- If 'big window' >> 'NHITS window'
  - Looking for increase in average noise rate

Triggering: ITC ratio



- Electrons simulated uniformly & isotropically
- Maximum value of ITC ratio

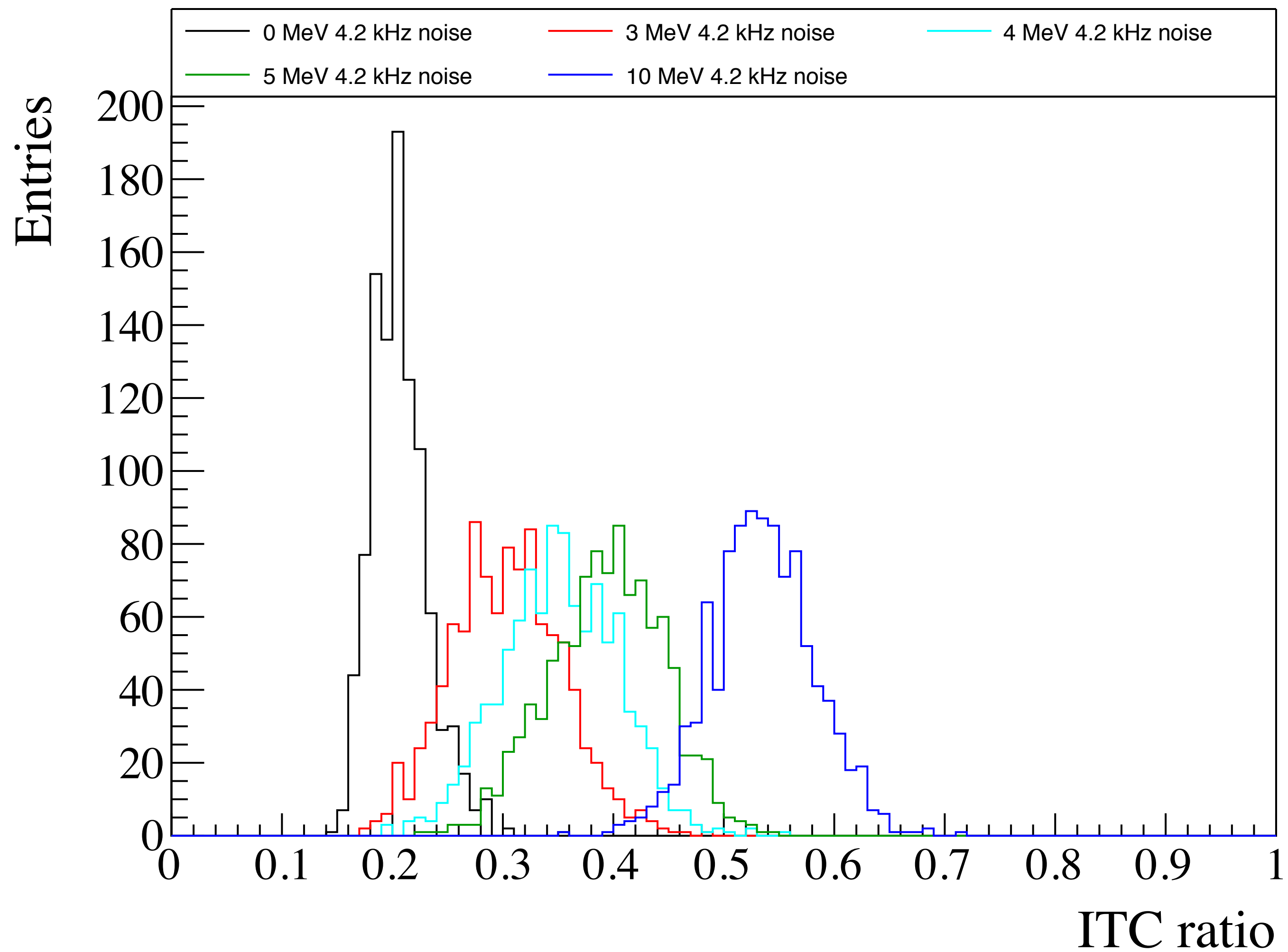
- Appears less efficient than the NHITS trigger
  - Currently performing window size tuning to confirm
    - Works well inside the SK geometry
- May be useful in conjunction with other variables
  - e.g. 2D cut on NHITS & ITC ratio

Summary

- HK can access a wide variety of low energy ν physics
  - Solar, SN burst, SN relic, …
- Requires an efficient trigger down to (at least) 3 MeV
  - Pre-trigger dark noise raw data rate is 13 PB/month
- Studies show simple NHITS trigger is insufficient
- New ideas are being looked at
  - Effect of radioactive background (both in PMTs and water) will be included

Backups

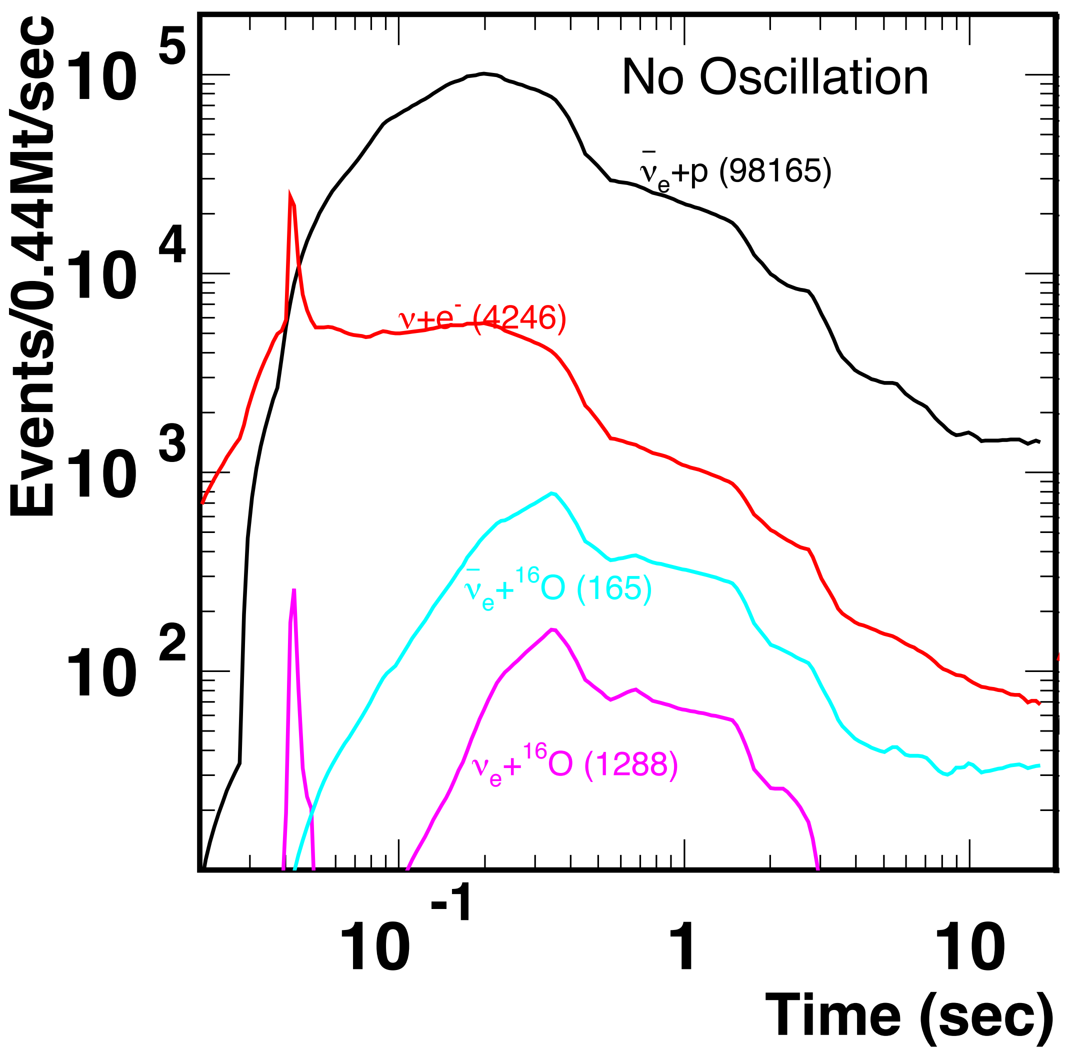
Triggering: ITC ratio @ SK

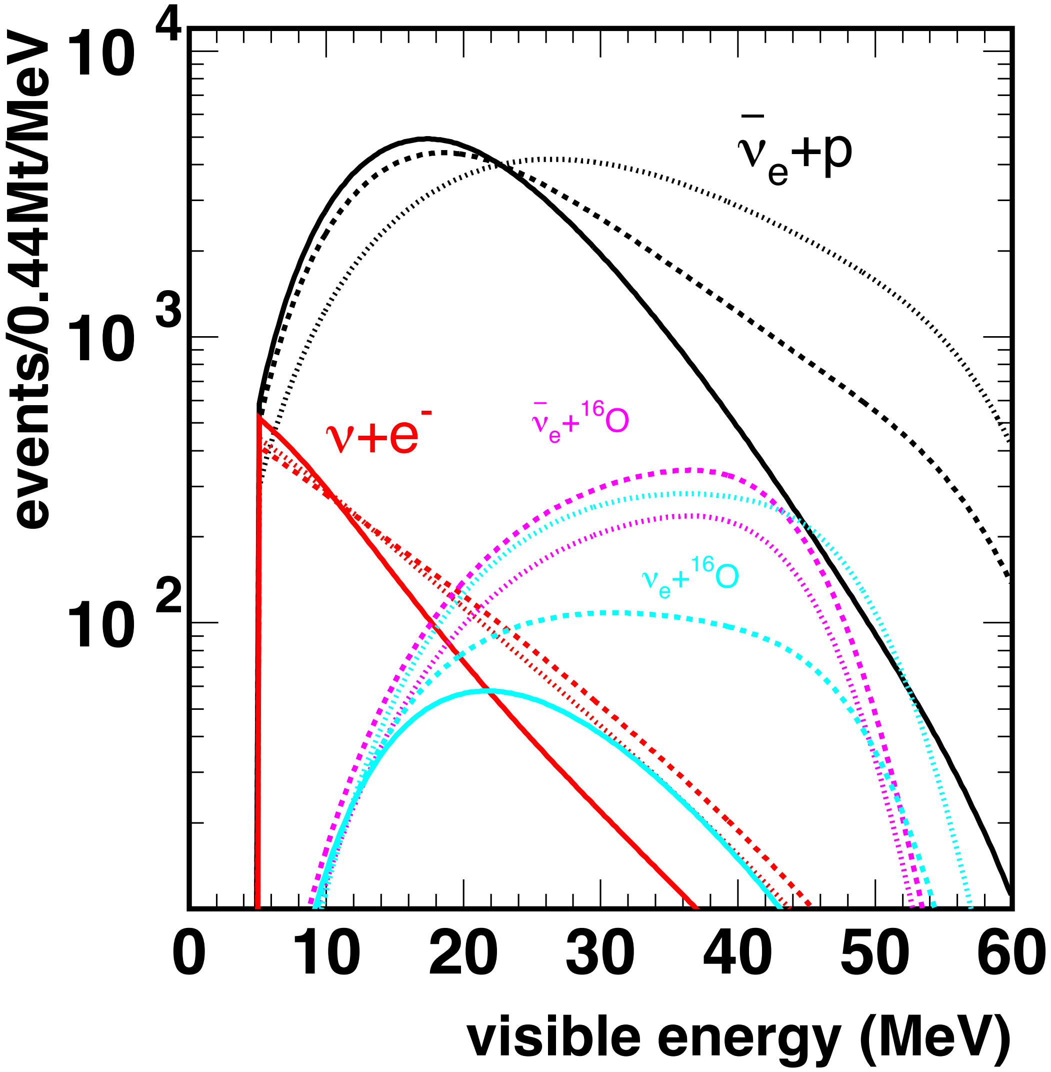


- Electrons simulated uniformly & isotropically inside Super-K
- Maximum value of ITC ratio

- SK *easier* to trigger
  - Fewer, less noisy PMTs
- 100% rejection of dark noise for 0% sacrifice @ 10 MeV

Supernova burst ν physics @ HK



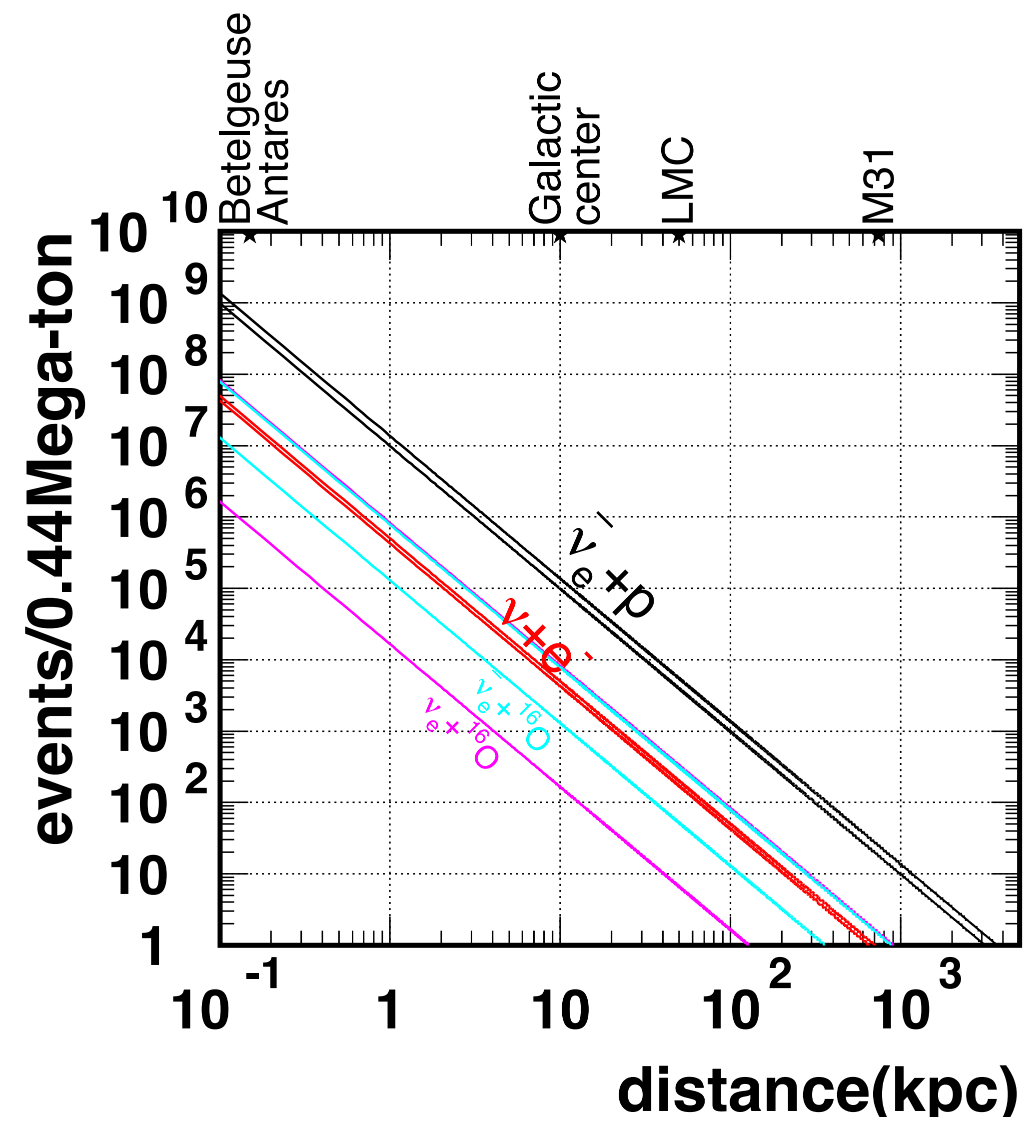


- ~50% probability of ccSN in galaxy in 20 years
- 52,000~79,000 events @ 10 kpc
- Not observed a SN with ν since SN1987a
  - Gave us limits on ν mass, ν charge, number of ν, …
  - Large number of events can test ν oscillation & SN models

Triggering: supernova burst

- Primary DAQ architecture
  - Rare events; we don't want to miss them

1. Self trigger
   - If trigger rate increases above a threshold, issue SN burst trigger
   - For SN @ 10 kpc
     - Data rate peaks @ ~500 MB/s
       - Dark noise still dominates
     - ~60,000 events in 10 seconds
       - Average individual PMT hit rate ~45 Hz



2. External trigger
   - Store **all** hits for a few hours in a large circular buffer
     - 100 TB = 5 hours
   - For SN @ 1 Mpc
     - ~10 events in 10 seconds
     - Require external observation (e.g. photon telescope) after the neutrinos arrive