Nonaccelerator Physics Reach for LBNE Reconfiguration Options

- Proton decay
- Atmospheric neutrinos
- Supernova burst neutrinos

Work in progress...

Kate Scholberg, Duke University

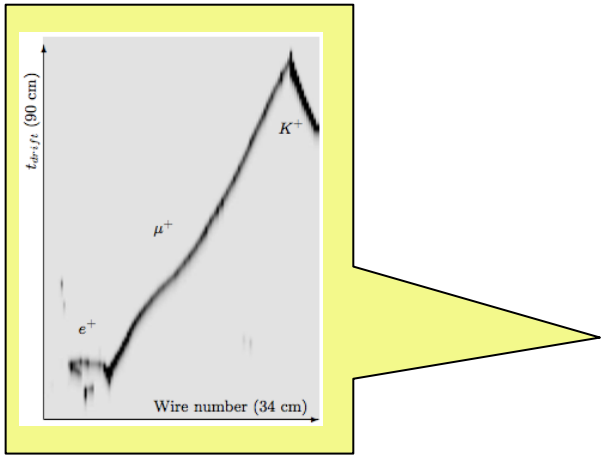
Thanks to:
Dongming Mei, Jen Raaf

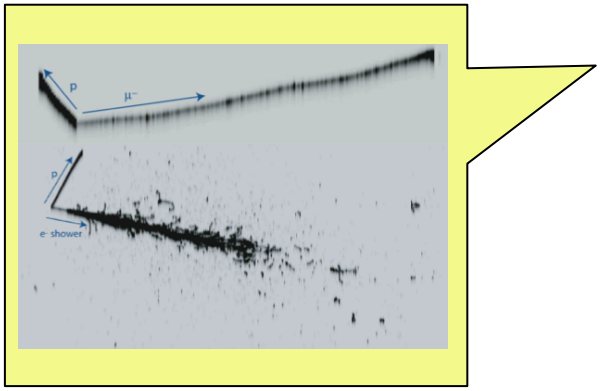
Signal	Energy range	Expected Signal Rate per kton of LAr (s^{-1} $kton^{-1}$)
Proton decay	~ GeV	$< 2 \times 10^{-9}$
Atmospheric neutrinos	0.1-10 GeV	$\sim 10^{-5}$
Supernova burst neutrinos	few-50 MeV	~3 @ 10 kpc in ~30 secs
Supernova relic neutrinos	20-50 MeV	$< 2 \times 10^{-9}$

For all these:

- **assume sufficient photon collection, appropriate triggering**
- **baseline irrelevant (all surface options degenerate)**
- **event rate proportional to mass**
- **depth critical for signal/bg:**

how shallow is really OK?





handsome, distinctive events

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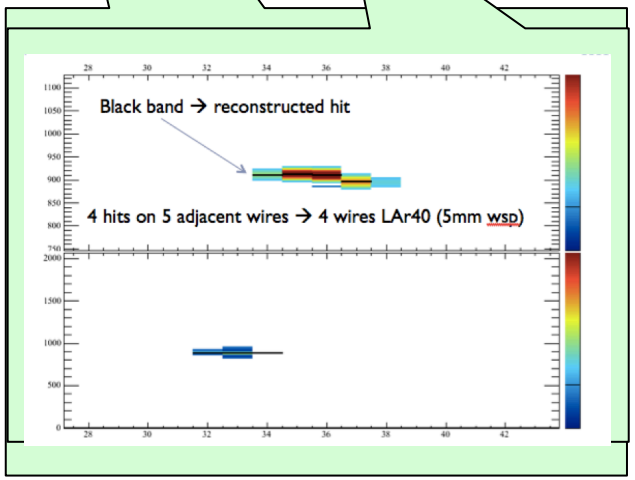
crummy little stubs



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Easy to pick from bg, but highly intolerant of bg

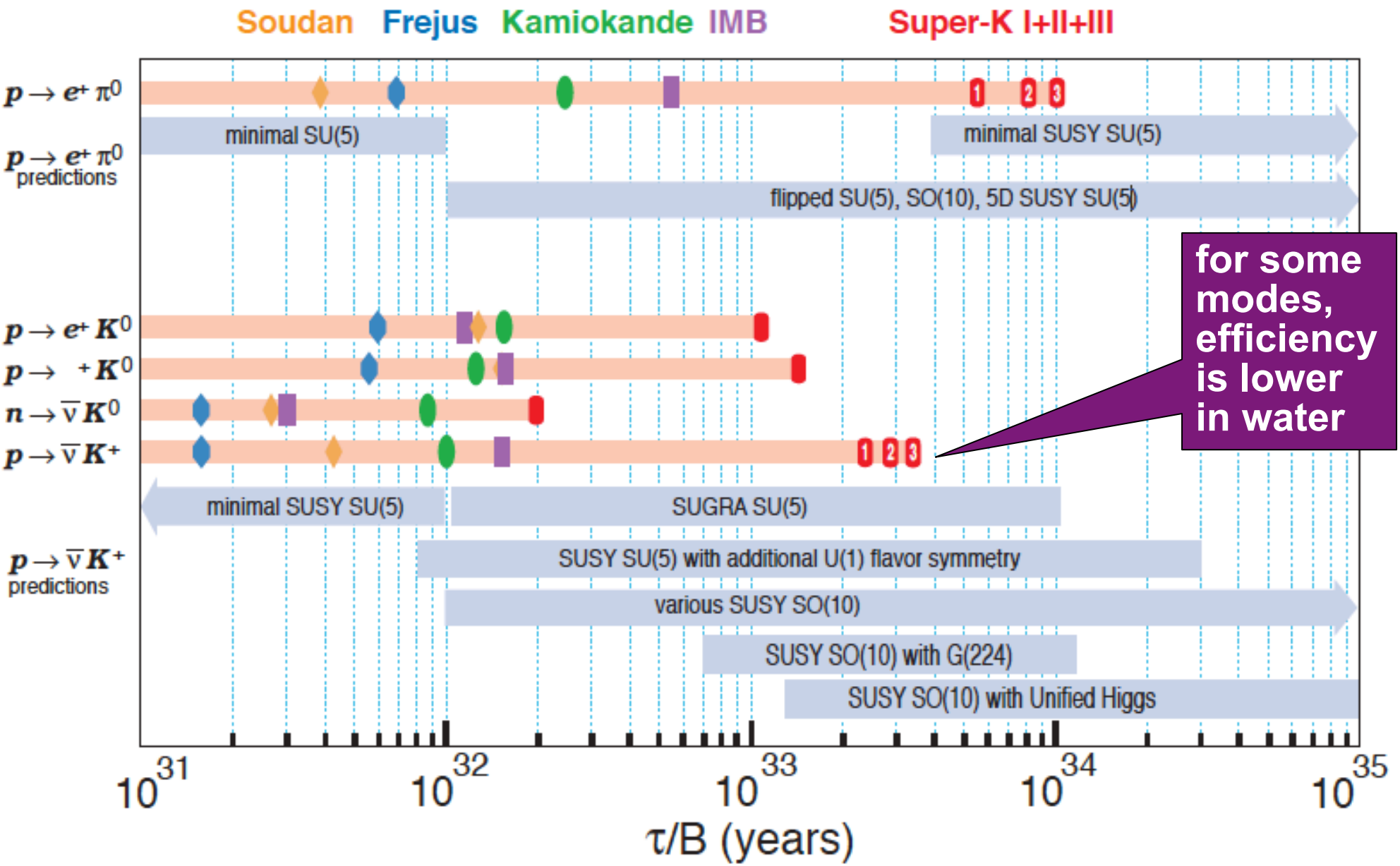
Easy to pick, somewhat more tolerant of bg

Potentially harder to select (esp. low energy end) *but arrive in a burst* (and bg can be well known)

Hard to select *and* intolerant of bg

Baryon number violation

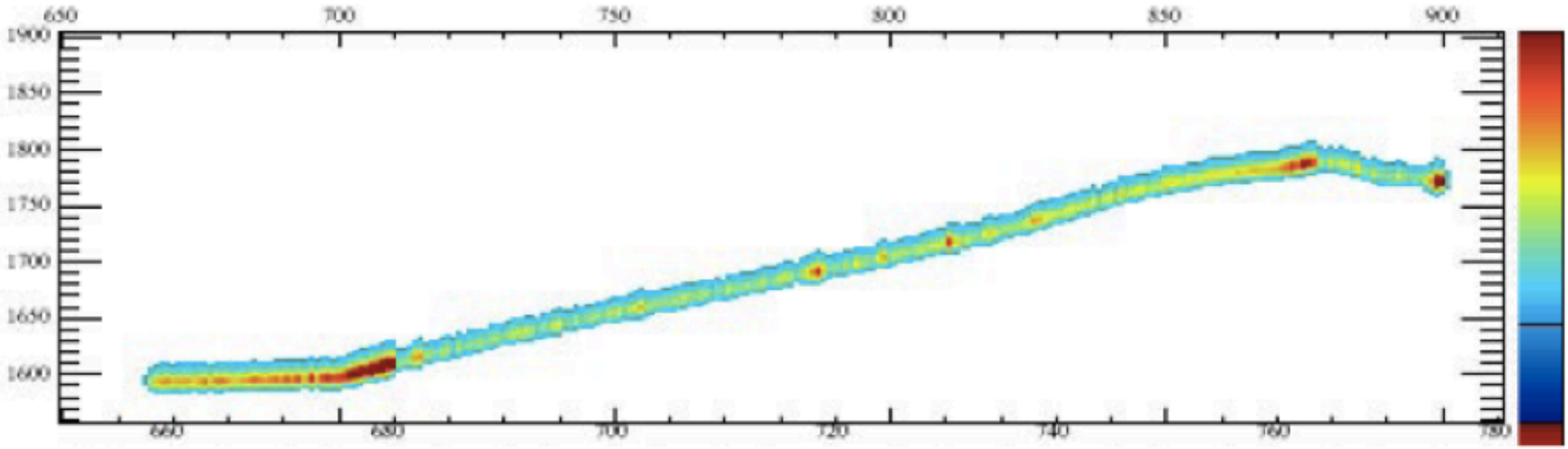
Strongly motivated by GUTs (w or w/o SUSY)



for some modes, efficiency is lower in water

Proton decay in LAr

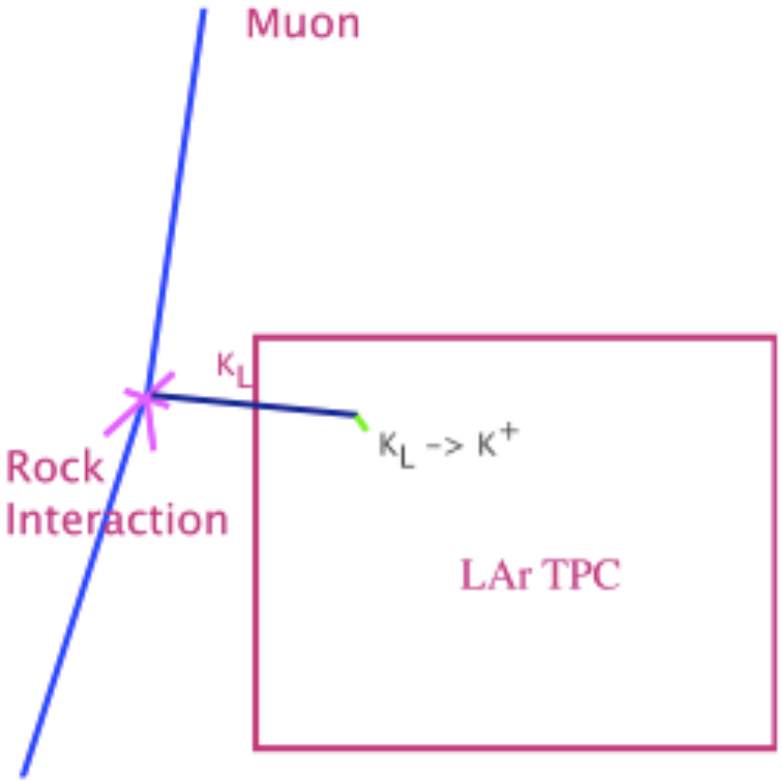
Competitive modes: e.g. $p \rightarrow K^+ \bar{\nu}$

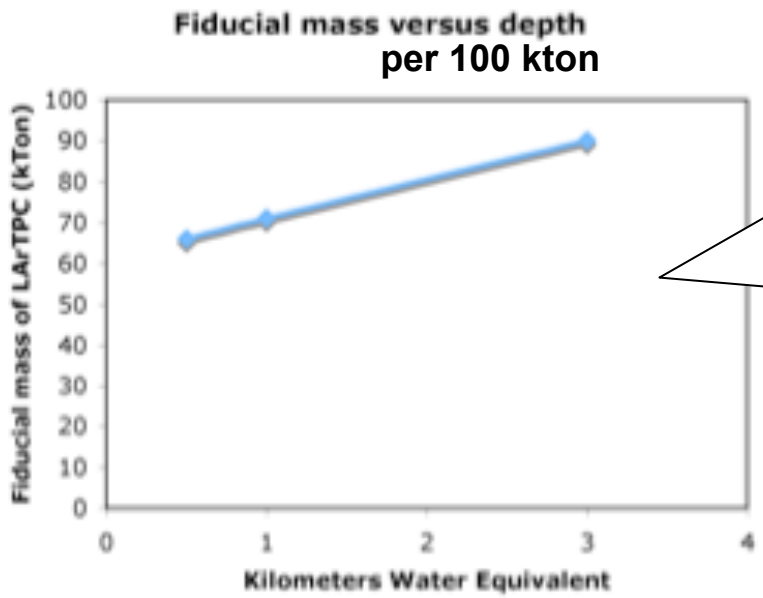


- **At depth, main background is misreconstructed atmnus**
- **Cosmogenic kaons matter if shallow;**
  can be mitigated by veto

How shallow is OK for pdk in LAr?

Bueno et al., arXiv:hep-ph/0701101
Bernstein et al. arXiv:0907.4983 ("Depth document")

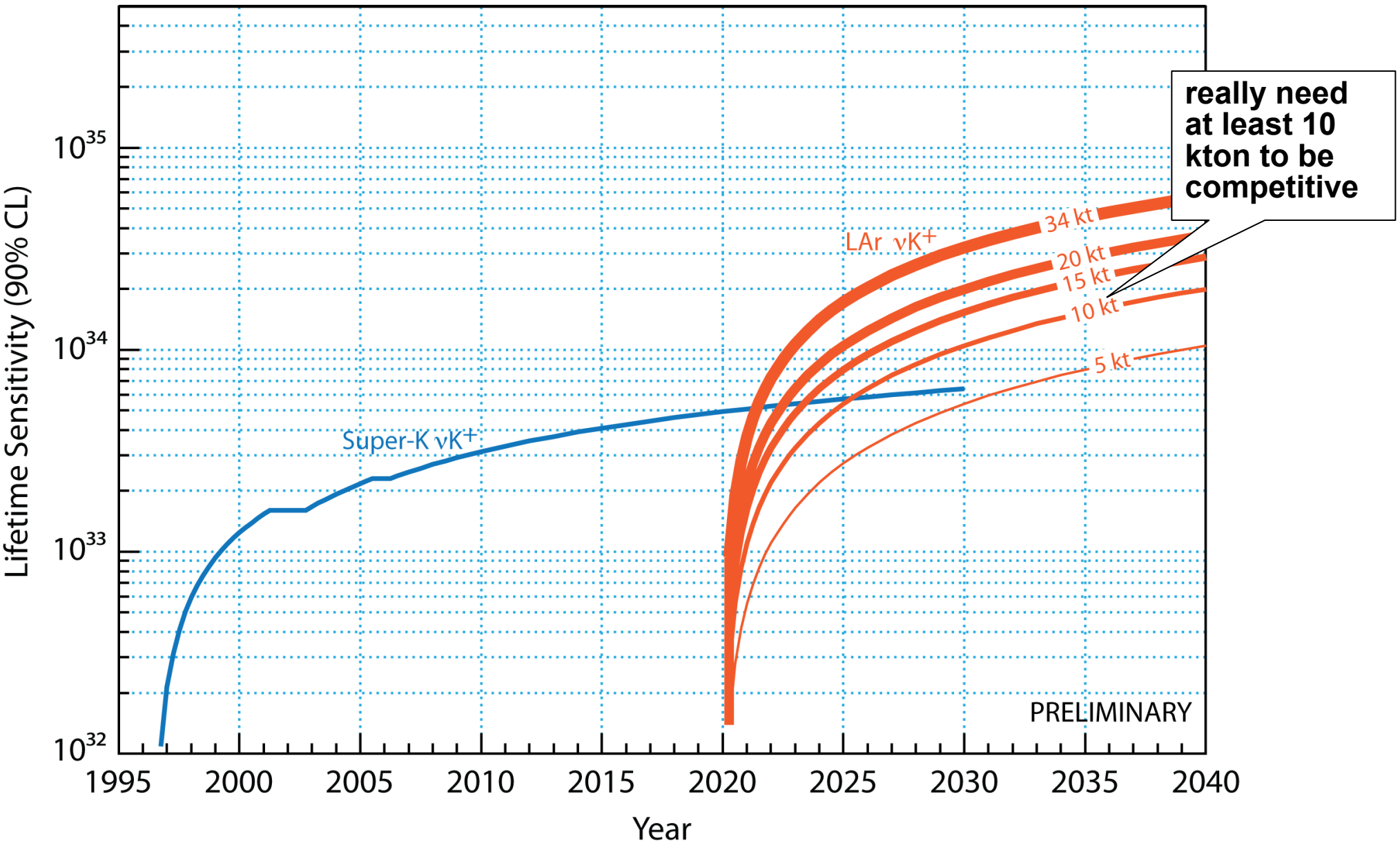




can be somewhat shallow, at cost of fiducial mass

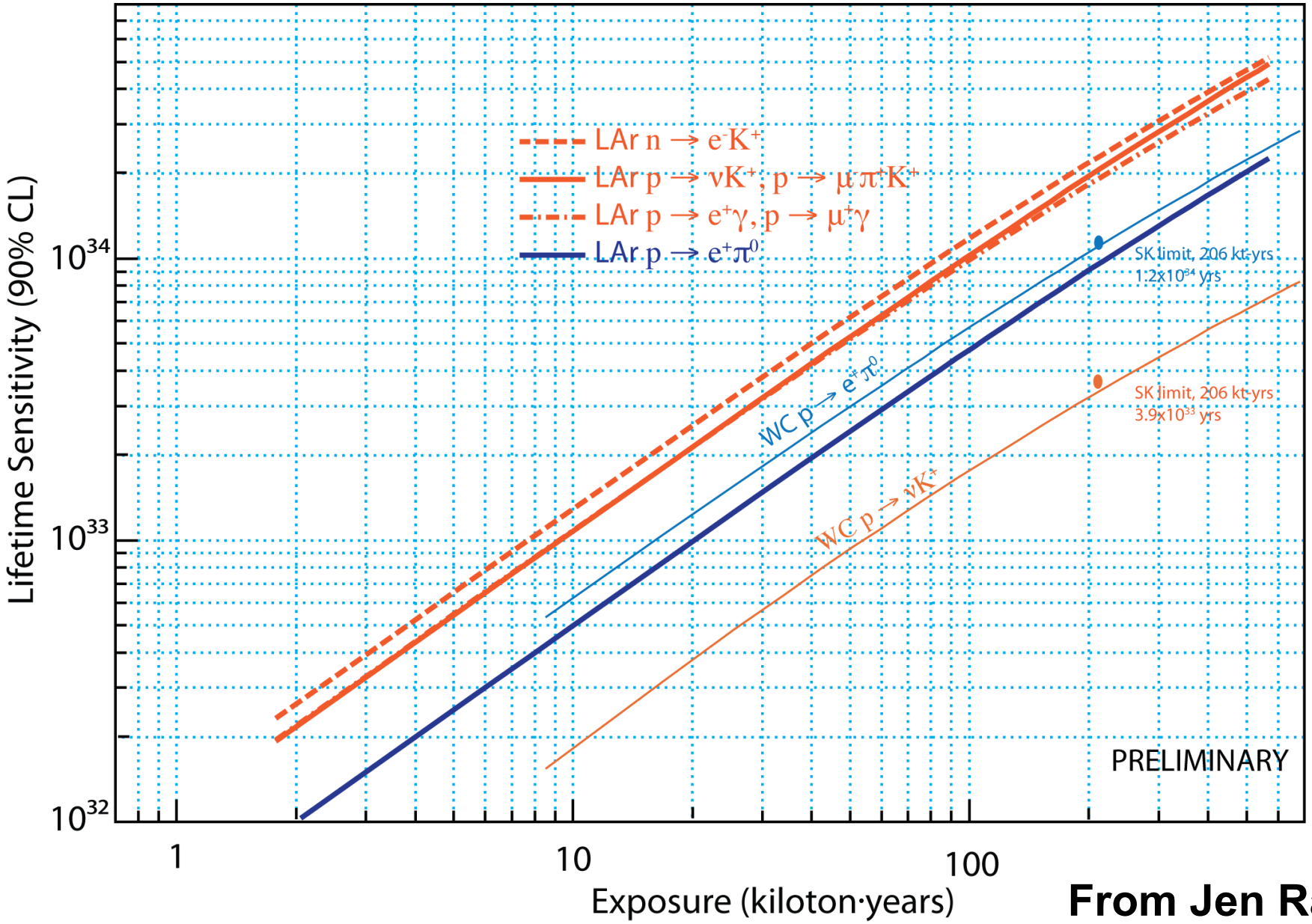
- **surface is likely *not* OK**
- **Soudan depth ~ Homestake depth (no fiducial loss)**

Proton decay reach at Soudan



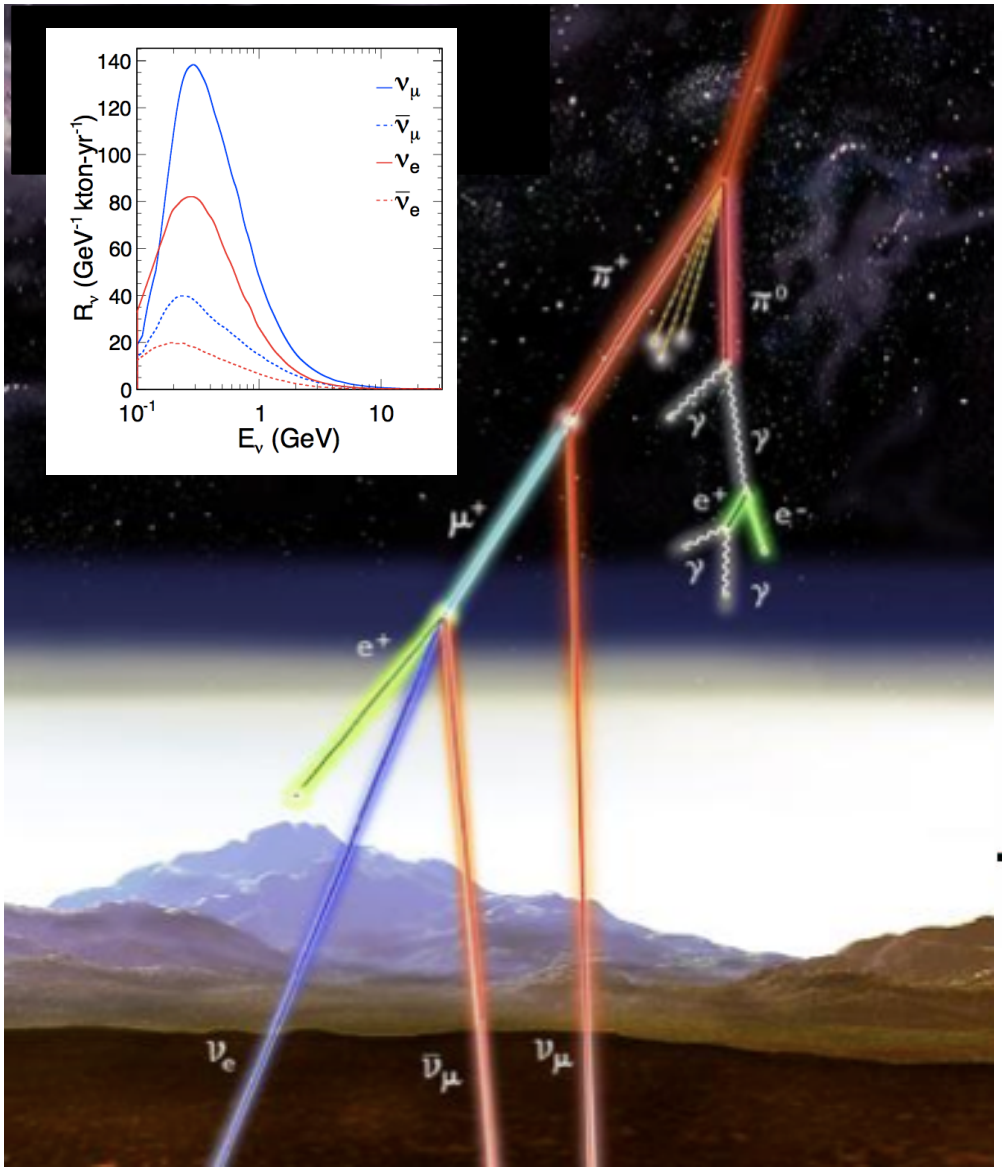
From Jen Raaf

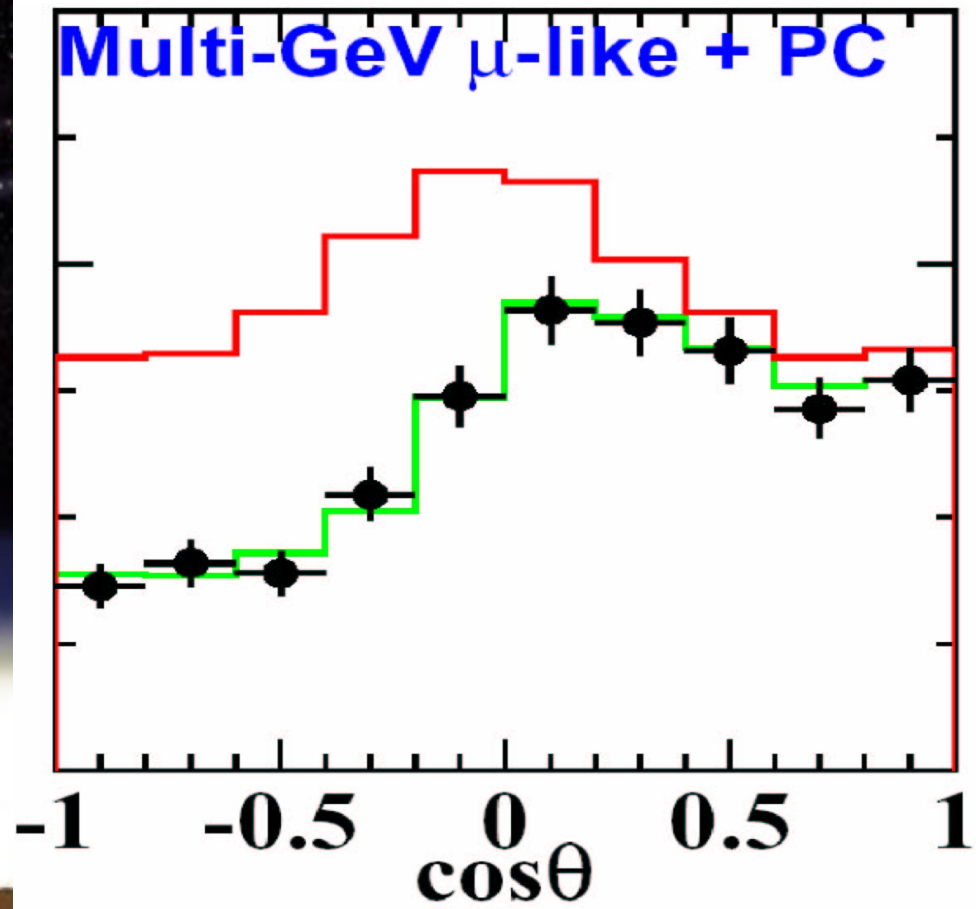
Sensitivity for different pdk modes



From Jen Raaf

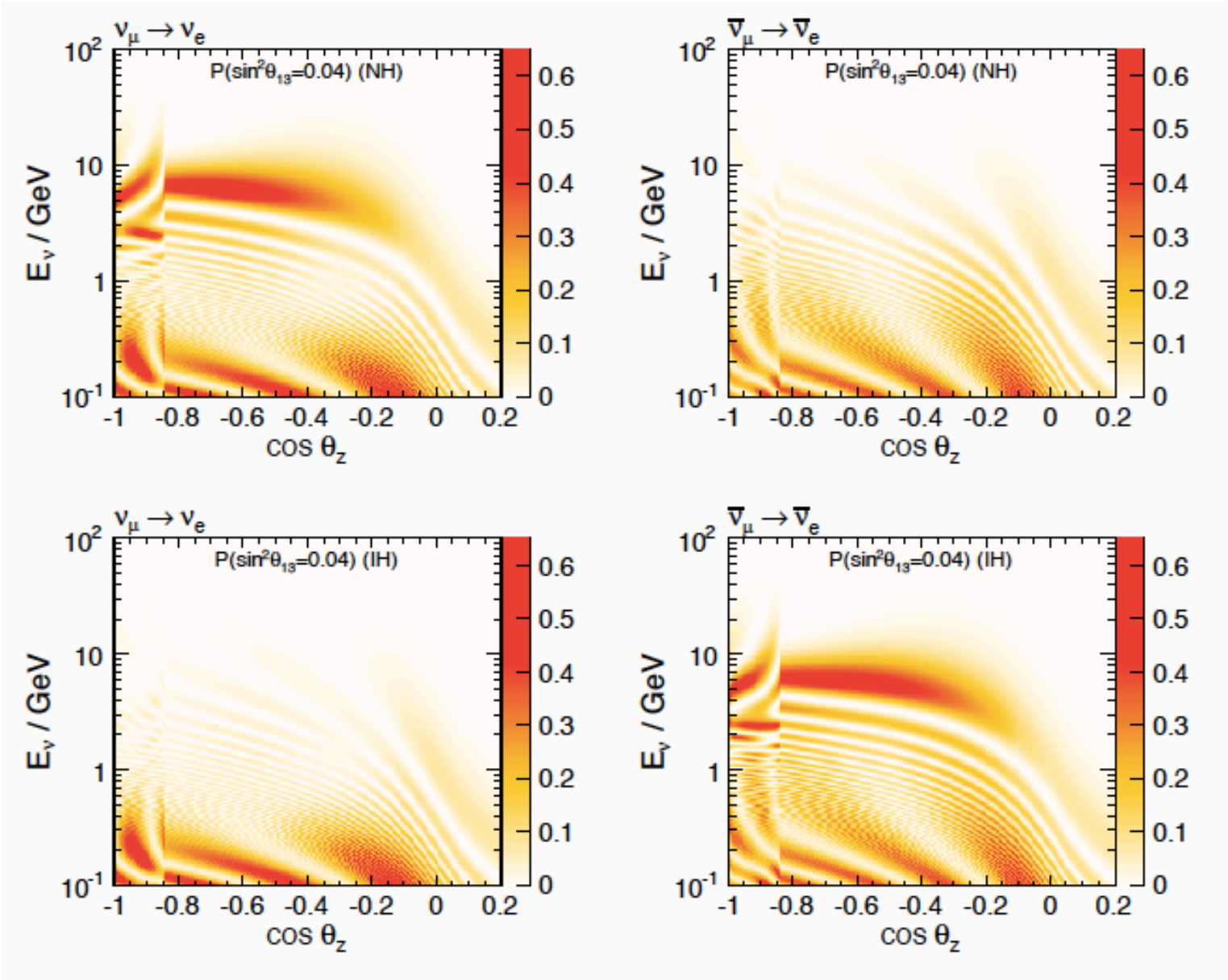
Atmospheric neutrinos





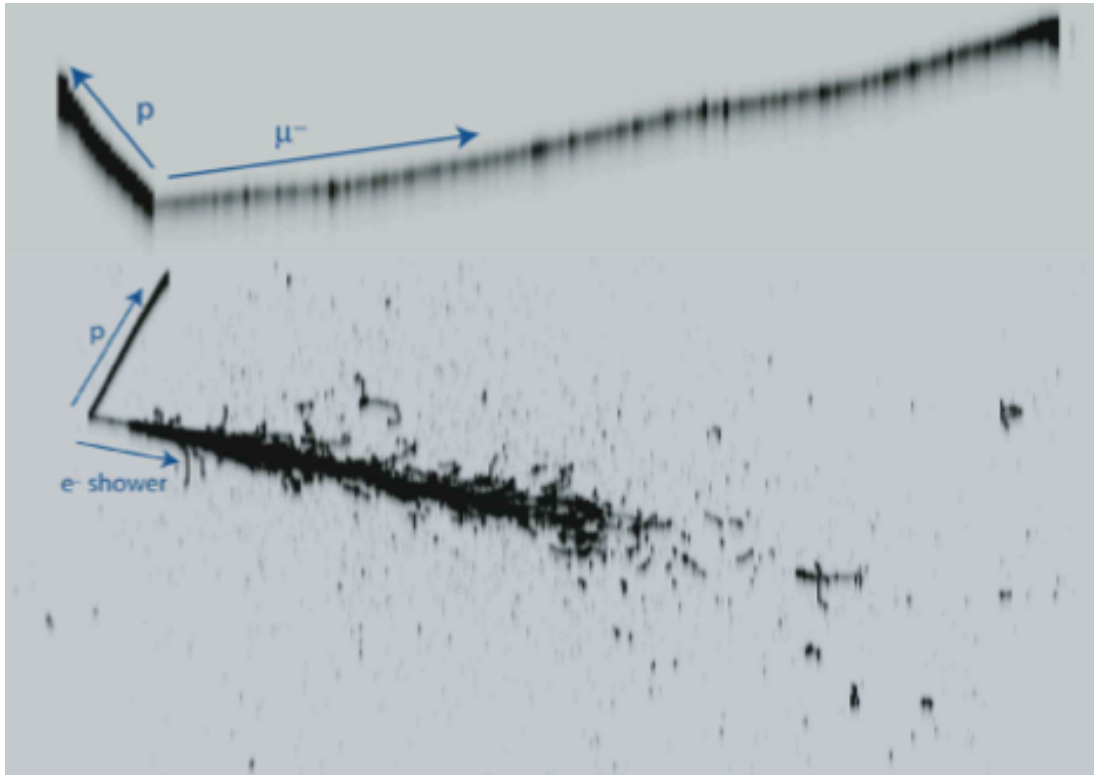
First unambiguous evidence for neutrino mass and oscillations (1998) in Super-K

~0.1 GeV to ~TeV.
10-13,000 km pathlengths



Oscillation probabilities depend on θ_{13}, mass hierarchy, CP δ, θ_{23} octant

Atmospheric neutrinos in LAr

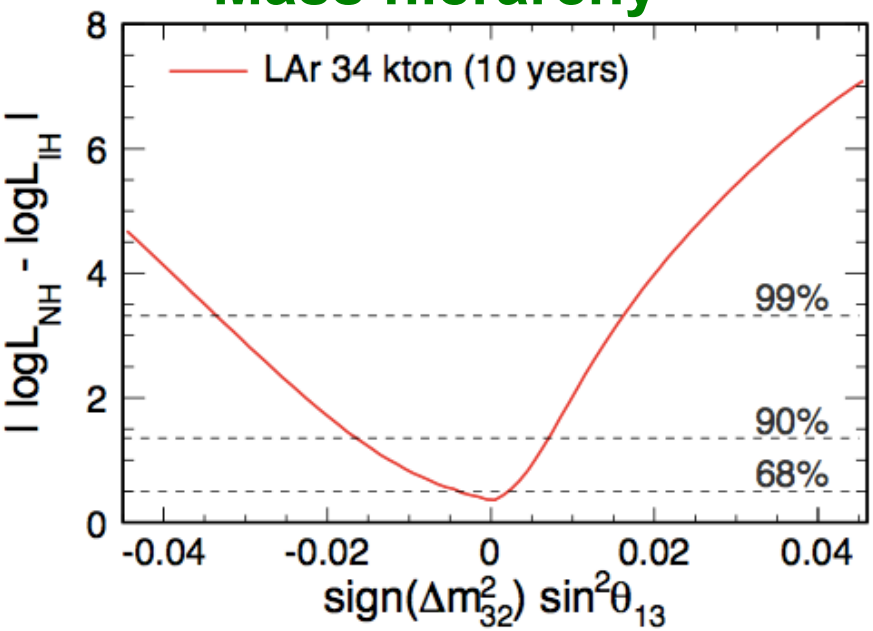


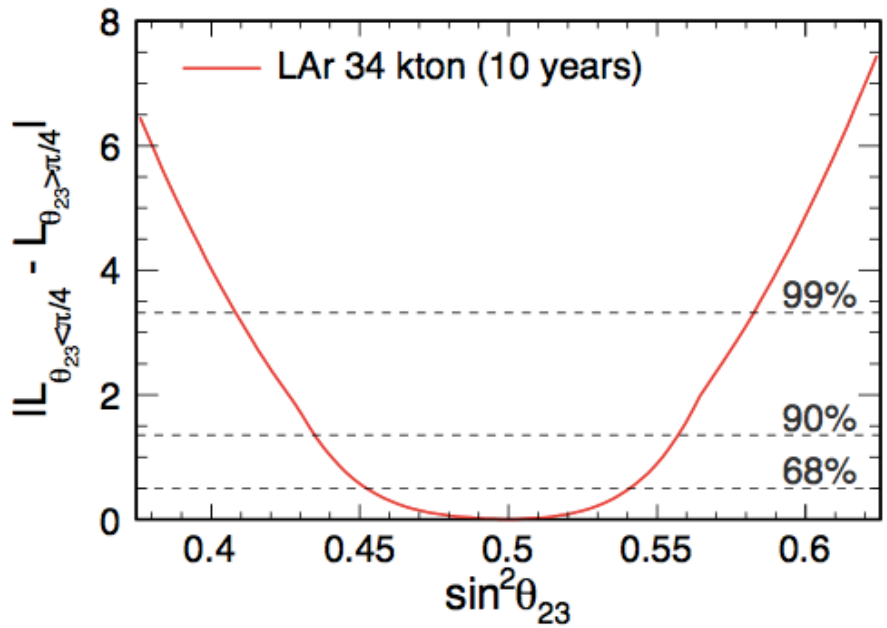
Excellent resolution and lack of Cherenkov threshold enable high efficiency, precision angle & energy reconstruction

- **~280 events/kton/yr**
- **presumably easy to select from cosmic bg**
- **if depth OK for pdk, should be OK for atmnus**
- **is surface OK? probably not...**

Oscillation sensitivity from atmnus in LAr

Mass hierarchy



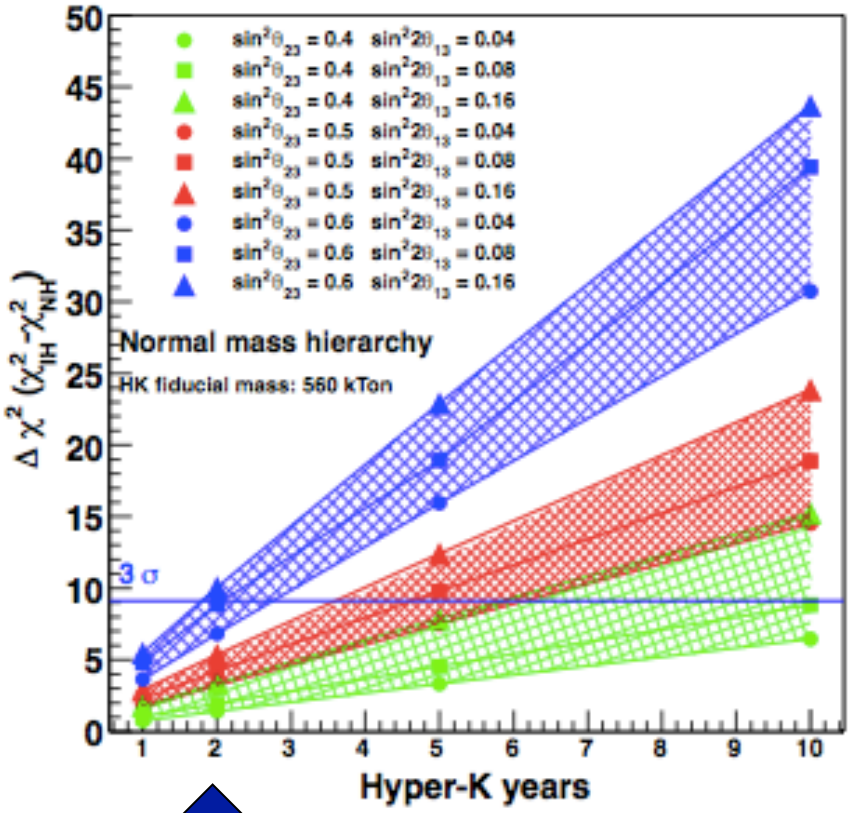


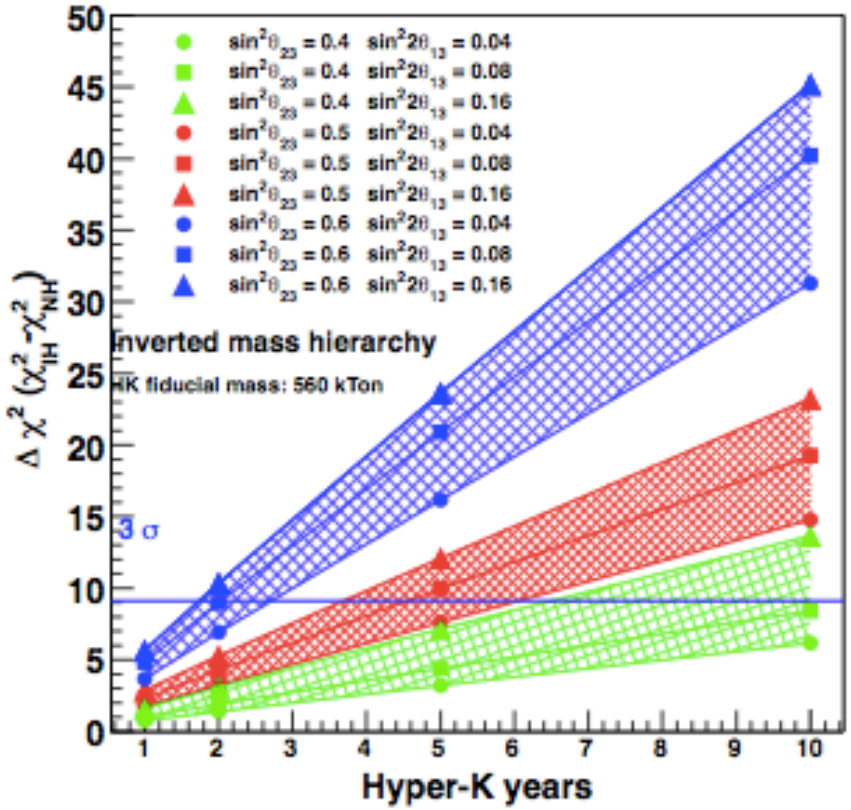
More studies underway of sensitivity as a function of exposure & depth (Hugh Gallagher)

Back-of-the-envelope for smaller detector:

560 kton WC ~ 100 kton LAr

For 20 kt LAr: 5 years ~ 1 year of HK



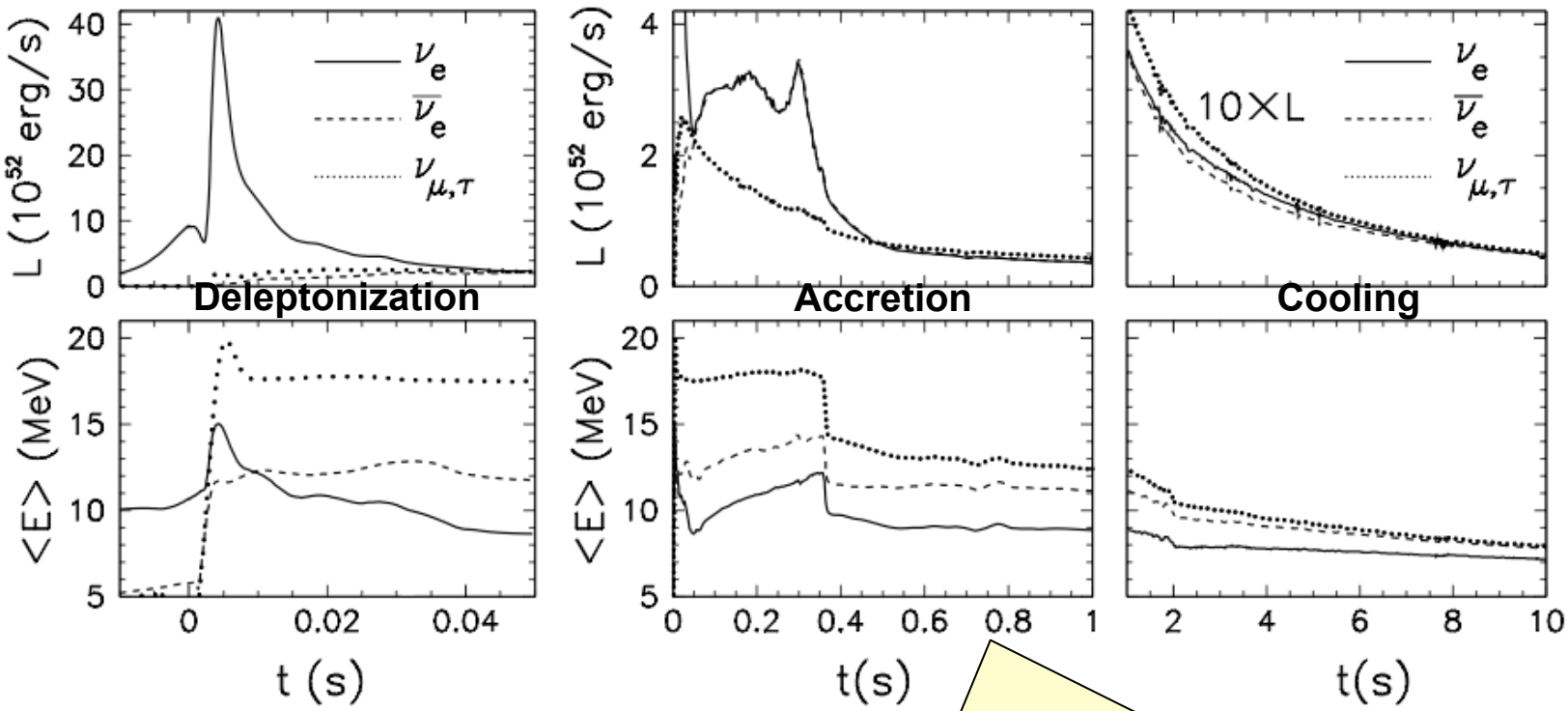


20 kton LAr, 10 years

Core collapse supernova neutrinos

Timescale: *prompt* after core collapse, overall Δt~10's of seconds

~few SNae per century



Detection would yield enormous particle physics & astro-physics info

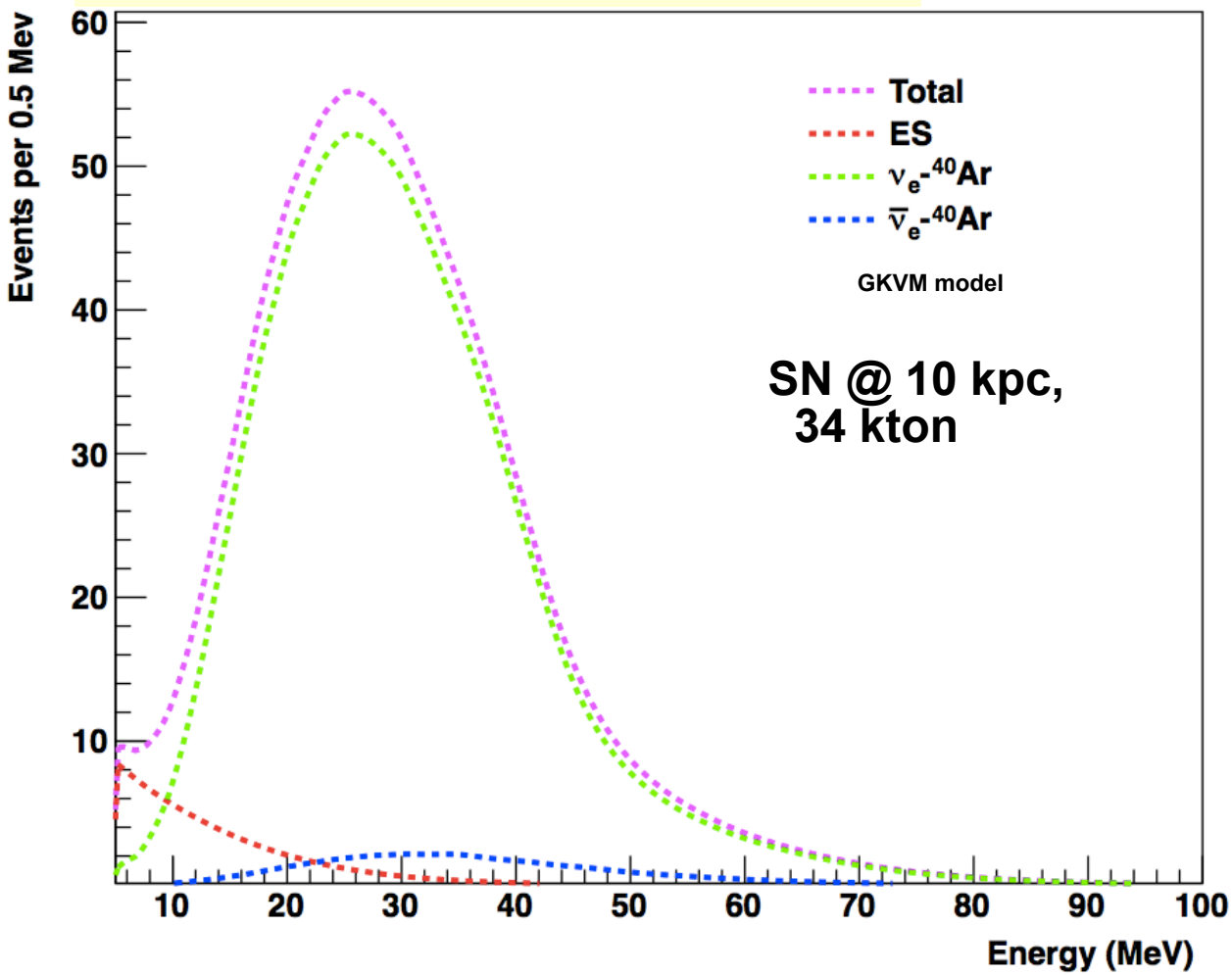
Fischer et al., arXiv:0908.1871
'Basel' model

$$\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_x} \rangle$$

Supernova burst neutrinos in LAr

Expect ~100/kton within few tens of seconds

Events seen, as a function of observed energy



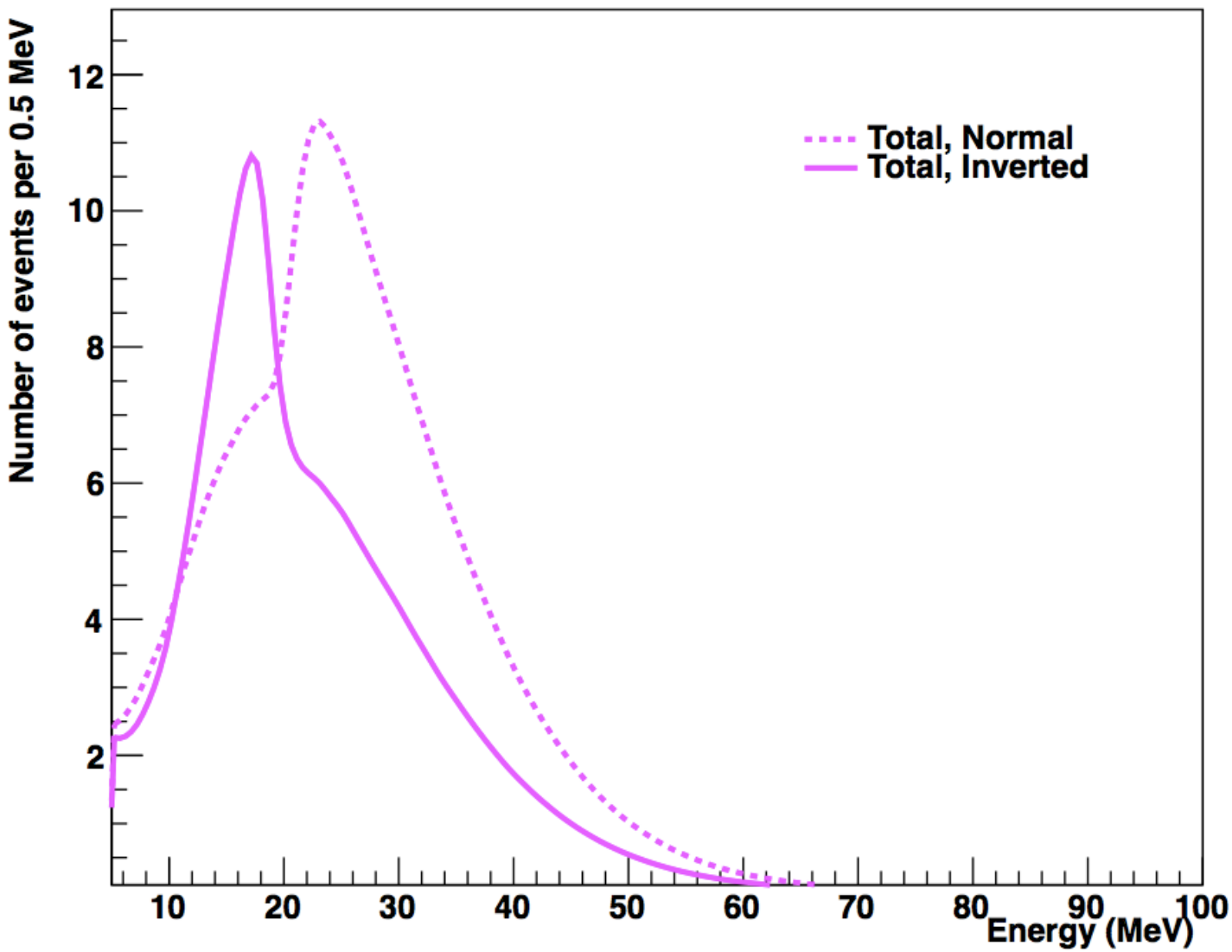
Dominated by ν_e

In LAr this is a *unique sensitivity*; most other detectors see anti-ν_e

Example: Can we tell the difference between normal and inverted hierarchies?

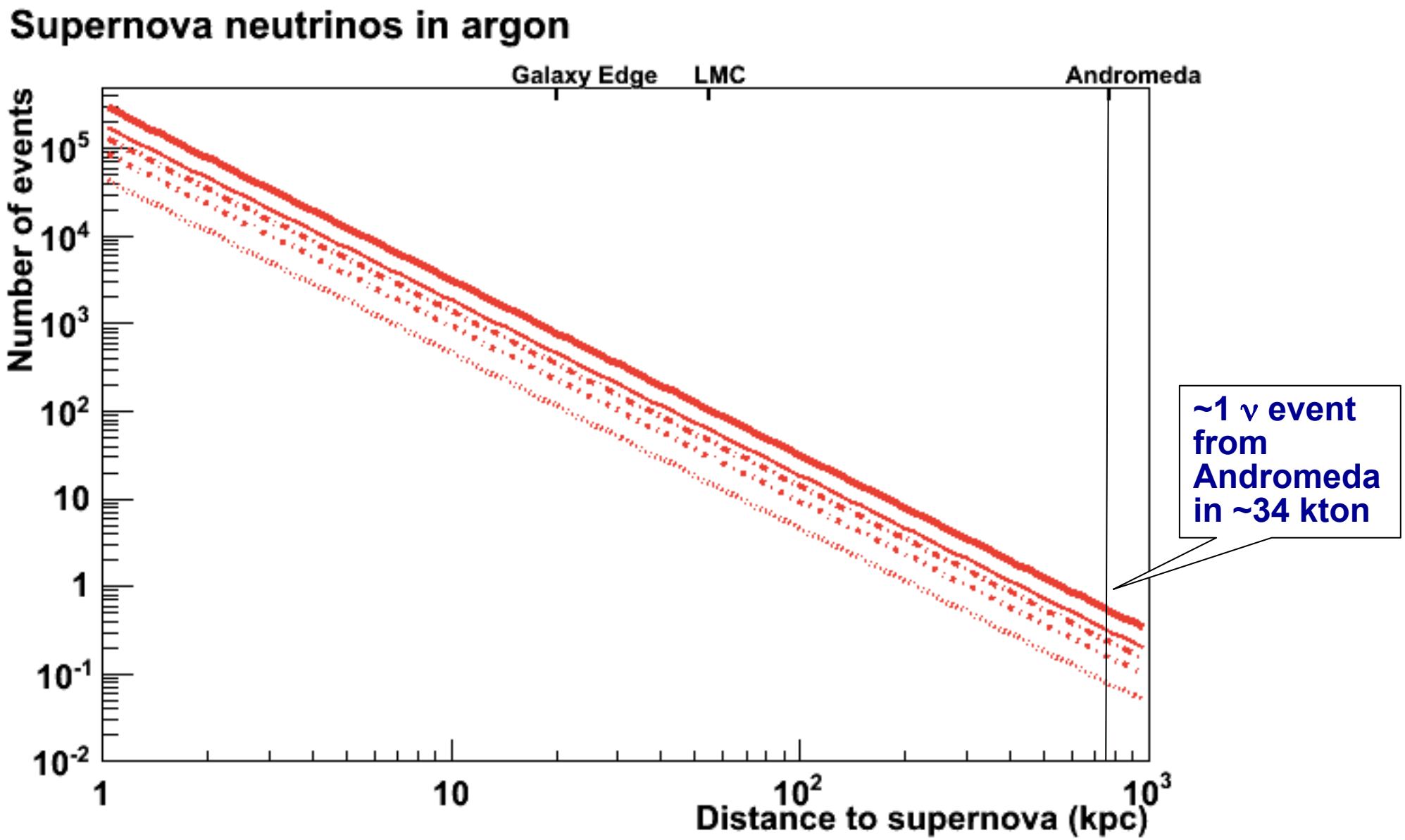
(1 second late time slice from Huaiyu Duan flux with 'multi-angle' collective effects)

Caveat: *this is just one model*



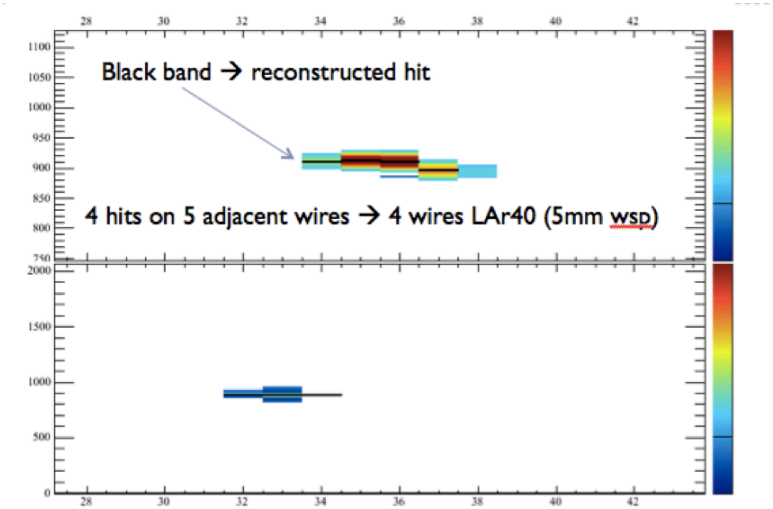
A decent fraction of events have > 20 MeV, but note there may be useful information at low energies

Signal rates vs distance



5, 10, 15, 20, 34 kton

Backgrounds for SN in LAr



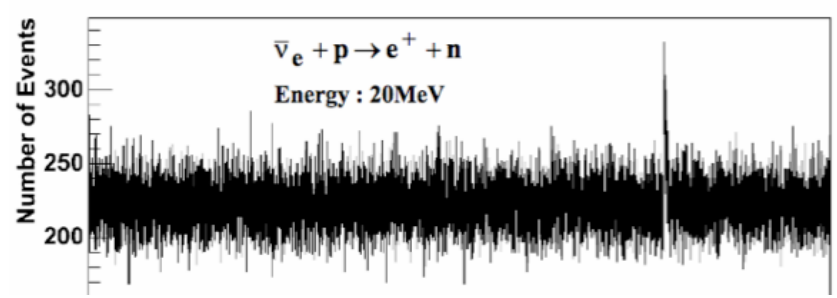
Note:

may also have γ tag for CC interactions

- **muons & associated Michels: should be identifiable**
- **radioactivity: mostly < 5 MeV**
- **cosmogenics**

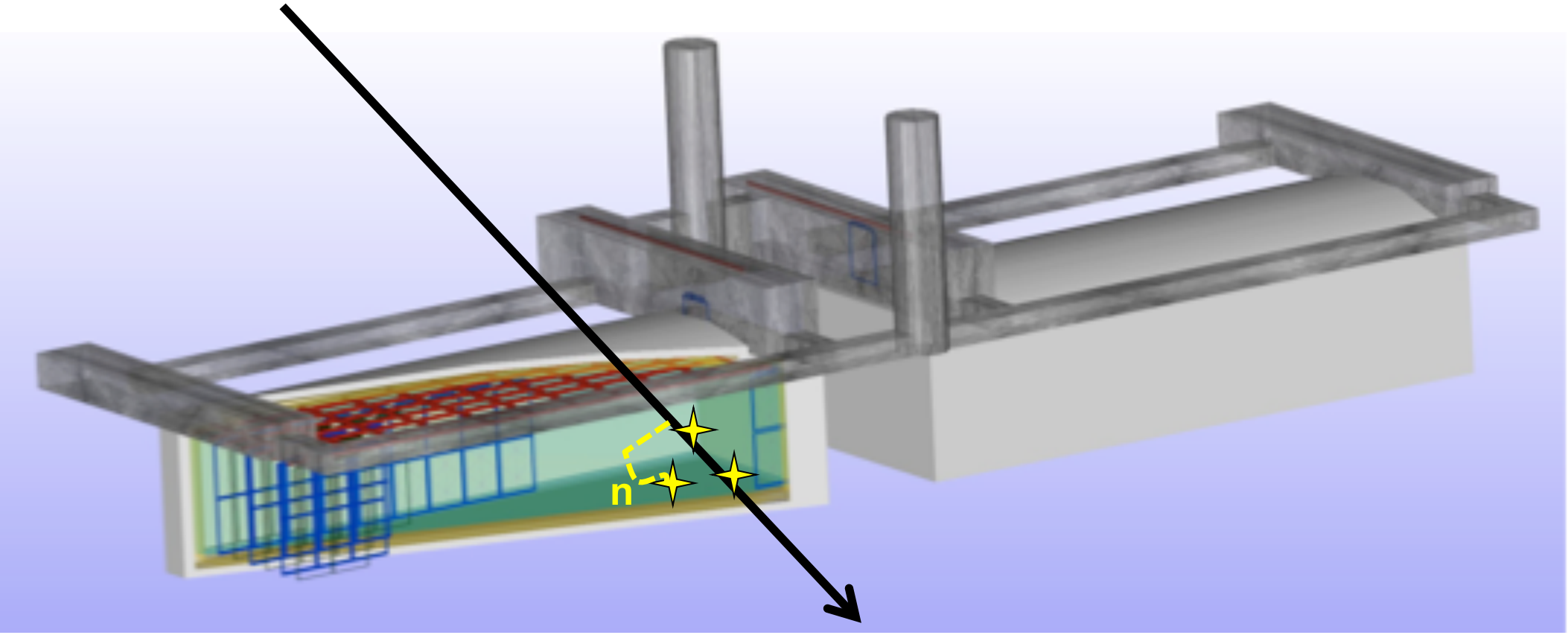
How shallow is OK?

NOνA, MiniBooNE, μBooNE get *something*, if background-ridden (and bg can be *known*)



NOνA

Cosmogenic backgrounds



- cosmic rays can rip apart nuclei, leaving radioactive products that can decay on ms-hour (day, year..) timescales
- neutrons, muon capture can also be problematic
- fairly well understood in water & scintillator, but few studies in argon

- in principle can be associated with parent muons (need photons...)
- in principle mitigation strategies exist (e.g. γ tagging) but efficiency currently unknown

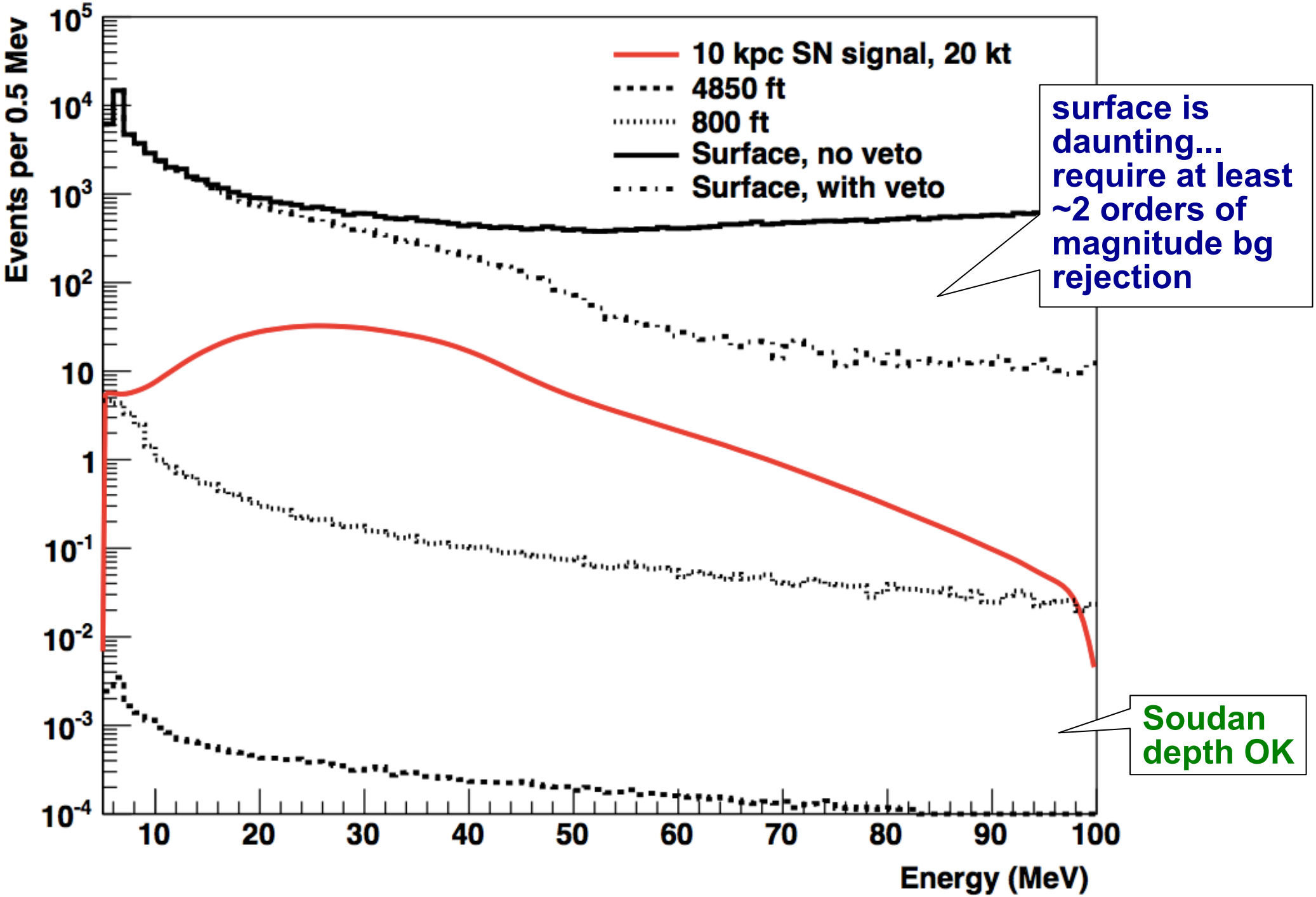
Recent work by Barker, Mei & Zhang, arXiv:1202.5000

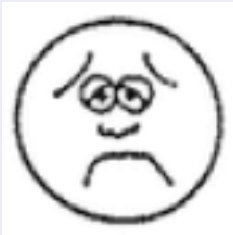
Muon-Induced Background Study for an Argon-Based Long Baseline Neutrino Experiment

D. Barker,[1] D.-M. Mei,[1,*] and C. Zhang[1,2]

- Geant4 study w/ 20 kton LAr detector @ 800 ft & 4850 ft
- Muon & muon-induced neutron spectra from Mei & Hime 2006
- Backgrounds considered:
  - muon-induced fast neutrons
  - ^{40}Cl from muon capture, neutrons, secondaries
  - radioactive isotopes from spallation & hadronic interactions

Muon-induced fast neutron background



Signal	Surface	Soudan, 2600 ft	Homestake, 4850 ft
Proton decay			
Atmospheric neutrinos	 ?		
Supernova burst neutrinos	 ?		

Wong-Baker FACES Pain Rating Scale

Summary

- Homestake depth is excellent and
  Soudan depth is fine for any of this physics

- Proton decay is best understood situation:
  - surface is no good
  - need 10 kt or more to be competitive
- Atmospheric neutrinos
  - unclear if OK on surface, probably hard
  - need 20 kt or more to be competitive
- Supernova neutrinos
  - may get something on surface, but very difficult;
    highly degraded in best case
  - unique ν_e flavor signal even for 5 kt,
    but more mass is better

Backups

Low energy neutrino interactions in argon

Charged-current absorption

$$\nu_e + {}^{40}Ar \rightarrow e^- + {}^{40}K^*$$

Dominant

$$\bar{\nu}_e + {}^{40}Ar \rightarrow e^+ + {}^{40}Cl^*$$

Neutral-current excitation

$$\nu_x + {}^{40}Ar \rightarrow \nu_x + {}^{40}Ar^*$$

Insufficient info in literature; find out more?

Elastic scattering

$$\nu_{e,x} + e^- \rightarrow \nu_{e,x} + e^-$$

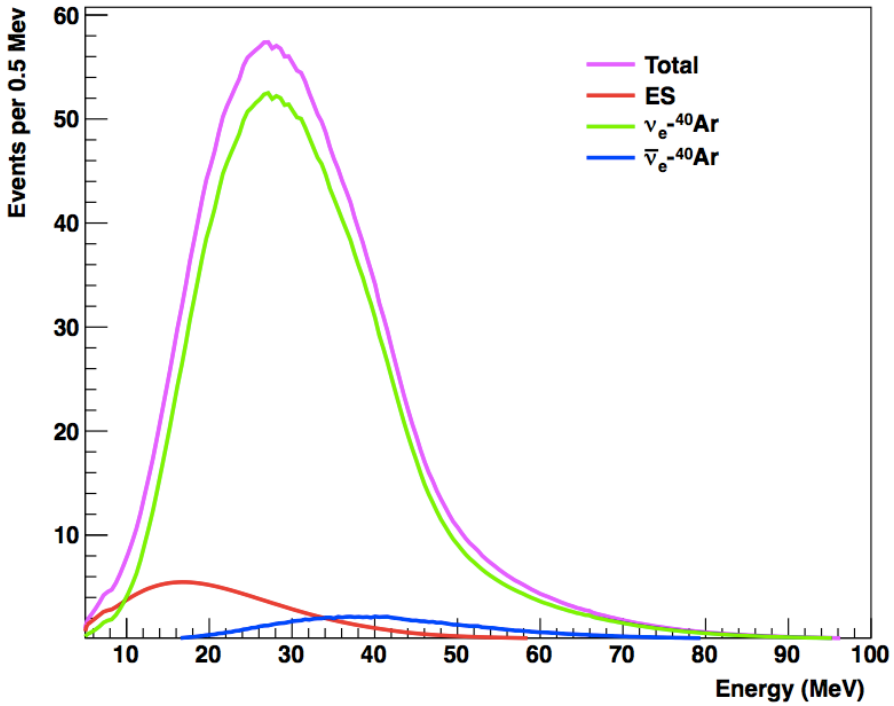
Can use for pointing

- In principle can tag modes with
- deexcitation gammas (or lack thereof)...
- however no assumptions made about this so far

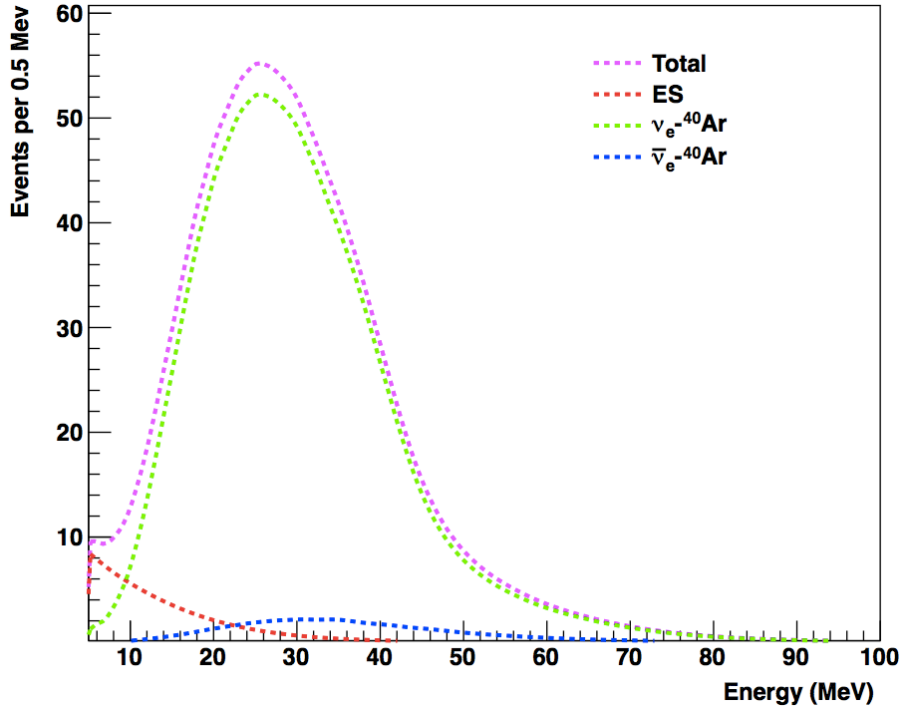
Event rates for 34 ktons of LAr

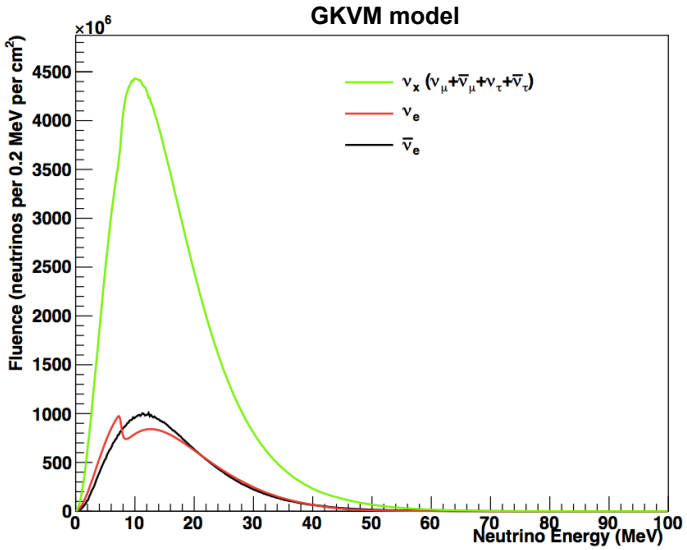
SN @ 10 kpc

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy



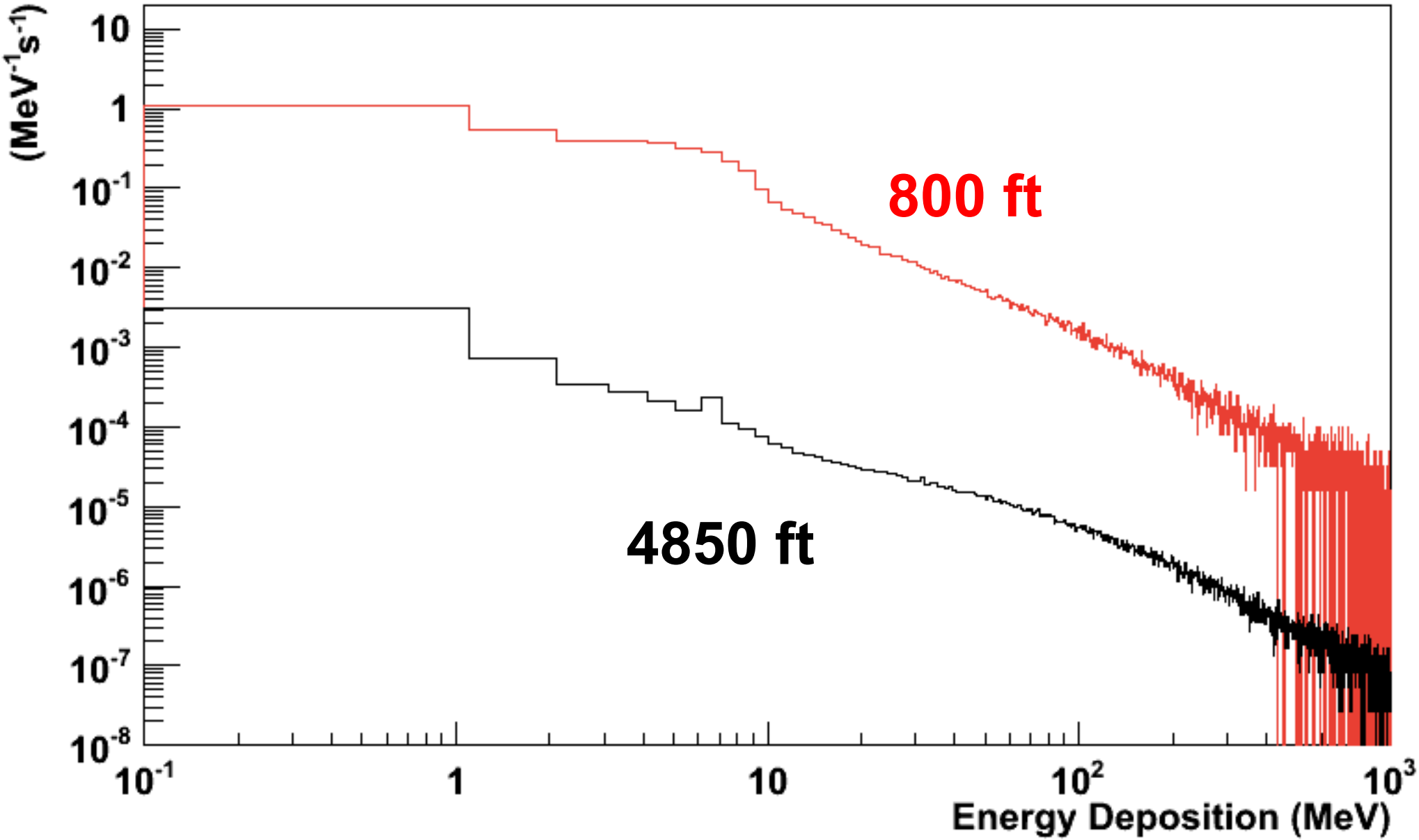


Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

Dominated by ν_e

$$
\begin{aligned}
\frac{\Phi(\nu_e)}{\Phi_0(\nu_e)} - 1 \approx\ & P_2 \cdot (r \cdot \cos^2\theta_{23} - 1) \\
& -r \cdot \sin\tilde{\theta}_{13} \cdot \cos^2\tilde{\theta}_{13} \cdot \sin 2\theta_{23} \cdot (\cos\delta \cdot R_2 - \sin\delta \cdot I_2) \\
& +2\sin^2\tilde{\theta}_{13} \cdot (r \cdot \sin^2\theta_{23} - 1)
\end{aligned}
$$

Muon-induced fast neutrons



^{40}Cl production by cosmics

endpoint 7.5 MeV, half-life 1.35 min

TABLE I: ^{40}Cl production rates in the detector (20 kton) at the 800-ft level.

From μ simulation		From n simulation	
Produced by	Rate per day	Produced by	Rate per day
Muon Capture	27344	Secondary μ	45
Secondary n	40587	Neutrons	3667
Pions	249	Pions	1.4
Others	83	Others	< 1
Total	68163	Total	3714

TABLE III: ^{40}Cl production rates in the detector (20 kton) at the 4850-ft level.

From μ simulation		From n simulation	
Produced by	Rate per day	Produced by	Rate per day
Muon Capture	17.5	Secondary μ	0.43
Secondary n	54.4	Neutrons	9.3
Pions	0.33	Pions	0.016
Others	0.04	Others	0.002
Total	72.3	Total	8.41

Other cosmogenic products

TABLE II: Additional significant cosmogenic production rates in the detector (20 kton) at the 800-ft level.

Isotope	Produced by	Rate per day	Q (MeV)	$t_{1/2}$
^{30}P	Spallation	9020	4.23	2.5 m
^{32}P	Spallation	20900	1.71	14. 3 d
^{33}P	Spallation	30100	0.25	25.3 d
^{34}P	Spallation	12090	5.4	12.4 s
^{35}P	Spallation	7500	4.0	47. 2 s
^{36}P	Spallation	1190	10.4	5.6 s
^{37}P	Spallation	550	7.9	2.3 s
^{31}S	Spallation	5500	5.4	2.6 s
^{35}S	Spallation	215500	0.17	87.5s
^{37}S	(n,α)	31500	4.9	5.1 m
^{38}S	Spallation	11500	2.9	170 m
^{39}S	Spallation	850	6.6	11.5 s
^{33}Cl	Spallation	670	5.6	2.5 s
^{34}Cl	Spallation	8700	5.6	32 m
^{36}Cl	Spallation	1005000	0.7	3.1×10^{5} y
^{38}Cl	Spallation	110000	4.9	37.24 m
^{35}Ar	(n,6n′)	7100	6.0	1.8 s
^{37}Ar	(n,4n′)	21000	0.8	35 d
^{39}Ar	(n,2n′)	91000	0.57	269 y
^{41}Ar	capture	45100	2.5	109 m
^{38}K	Spallation	650	5.9	7.6 m
^{40}K	(p,n)	6500	1.3	1.28×10^{9} y
Total		1641920		

TABLE IV: Additional significant cosmogenic production rates in the detector (20 kton) at the 4850-ft level.

Isotope	Produced by	Rate per day	Q (MeV)	$t_{1/2}$
^{30}P	Spallation	9.6	4.23	2.5 m
^{32}P	Spallation	22.2	1.71	14. 3 d
^{33}P	Spallation	31.9	0.25	25.3 d
^{34}P	Spallation	12.8	5.4	12.4 s
^{35}P	Spallation	8.0	4.0	47. 2 s
^{36}P	Spallation	1.3	10.4	5.6 s
^{37}P	Spallation	0.6	7.9	2.3 s
^{31}S	Spallation	5.8	5.4	2.6 s
^{35}S	Spallation	228.5	0.17	87.5s
^{37}S	(n,α)	33.4	4.9	5.1 m
^{38}S	Spallation	12.2	2.9	170 m
^{39}S	Spallation	0.9	6.6	11.5 s
^{33}Cl	Spallation	0.7	5.6	2.5 s
^{34}Cl	Spallation	9.2	5.6	32 m
^{36}Cl	Spallation	1065.7	0.7	3.1×10^{5} y
^{38}Cl	Spallation	116.6	4.9	37.24 m
^{35}Ar	(n,6n′)	7.5	6.0	1.8 s
^{37}Ar	(n,4n′)	22.3	0.8	35 d
^{39}Ar	(n,2n′)	96.5	0.57	269 y
^{41}Ar	capture	47.8	2.5	109 m
^{38}K	Spallation	0.69	5.9	7.6 m
^{40}K	(p,n)	6.9	1.3	1.28×10^{9} y
Total		1741		

(are G4 cross-sections OK?)

Background for SN burst from Barker, Mei & Zhang

Background	800 ft	4850 ft
Direct muons	88 Hz	0.05 Hz
Fast neutrons, > 5 MeV	0.28 Hz	0.001 Hz
Fast neutrons > 20 MeV	0.02 Hz? (by eye)	0.0001 Hz? (by eye)
^{40}Cl	0.83 Hz	0.001 Hz
^{40}Cl > 20 MeV	~0	~0
Other cosmogenics	19 Hz	0.02 Hz
Other cosmogenics, > 20 MeV	~0	~0

Compare to ~few tens of Hz signal @ 10 kpc; furthermore many strategies can mitigate this bg

this is for 20 kton, but both signal & bg scale with mass

Work underway by Mei & collaborators to evaluate surface & Soudan depths