Nonaccelerator Physics Reach for LBNE Reconfiguration Options

- Proton decay
- Atmospheric neutrinos
- Supernova burst neutrinos

Kate Scholberg, Duke University

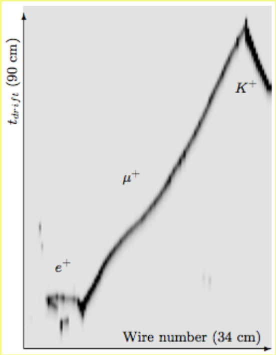
Thanks to:
Dongming Mei, Jen Raaf, Hugh Gallagher

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

For all these:

- **assume sufficient photon collection (required), 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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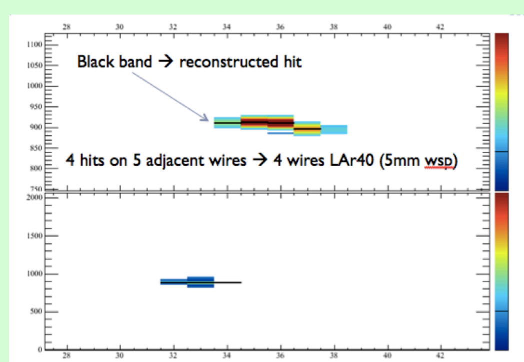


crummy little stubs

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	$< 2 \times 10^{-9}$

Easy to pick from bg, but highly intolerant of bg

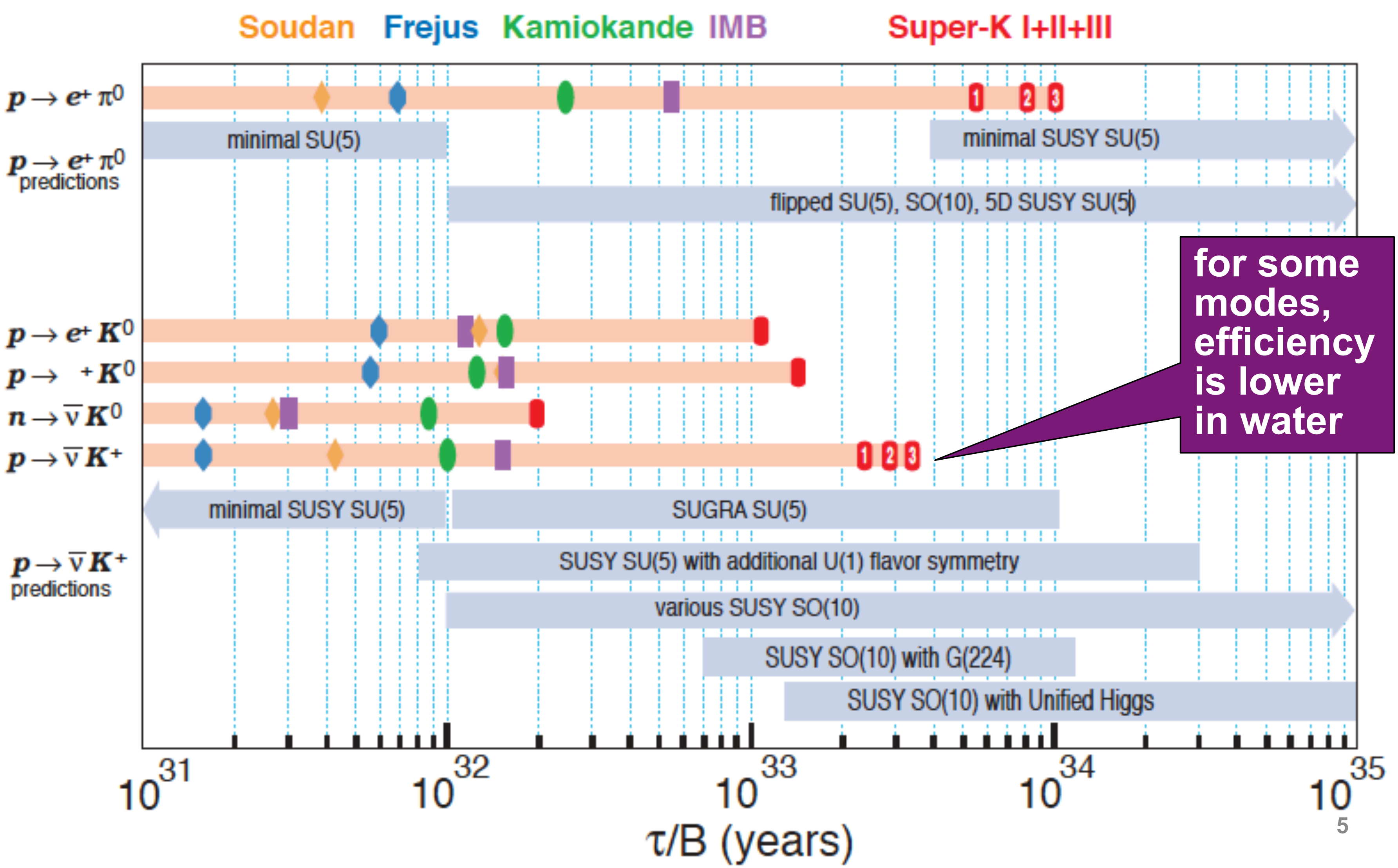
Easy to pick, somewhat more tolerant of bg

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

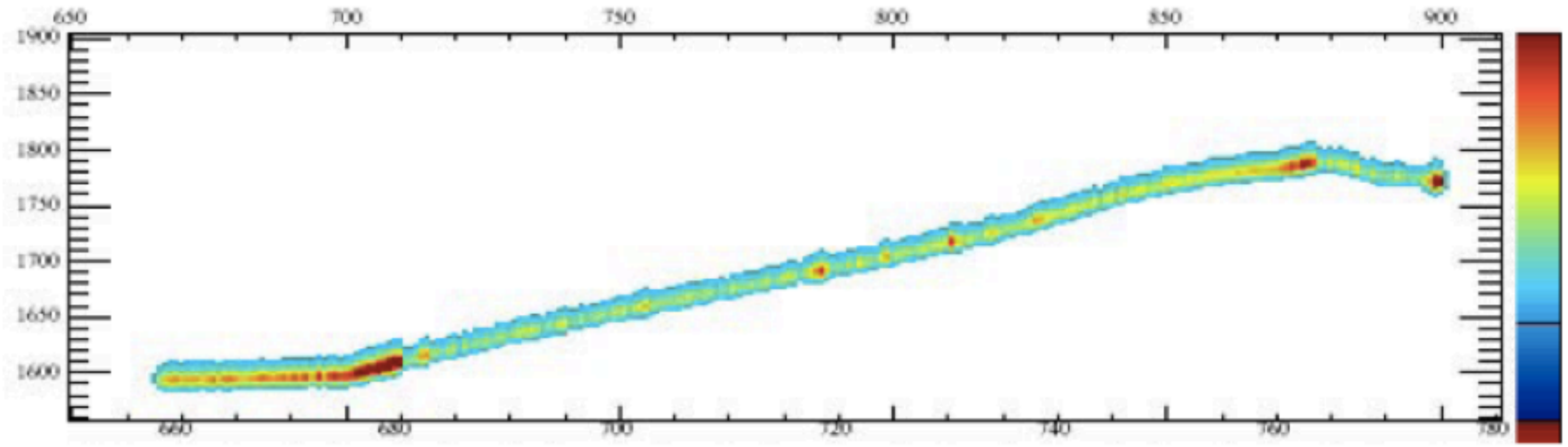
Baryon number violation

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



Proton decay in LAr

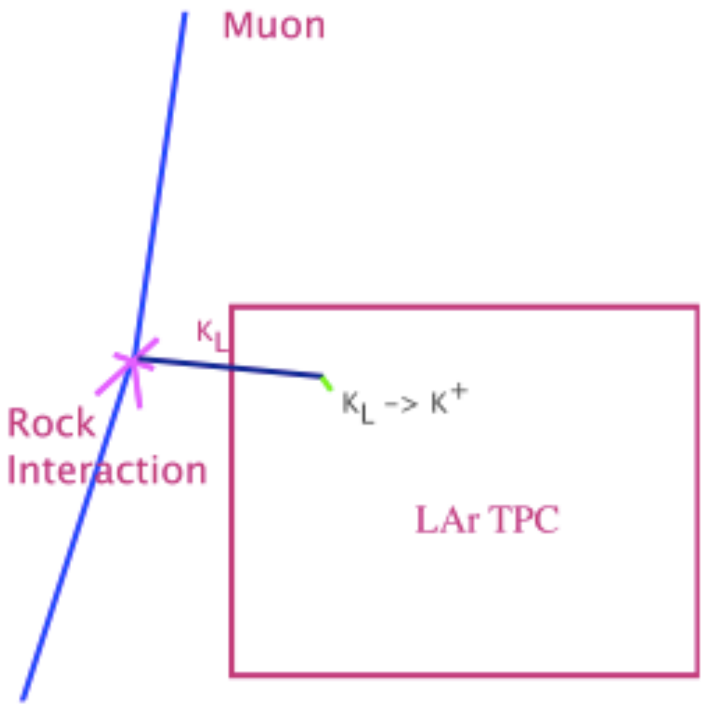
Competitive modes: e.g. $p \rightarrow K^{+}\bar{\nu}$

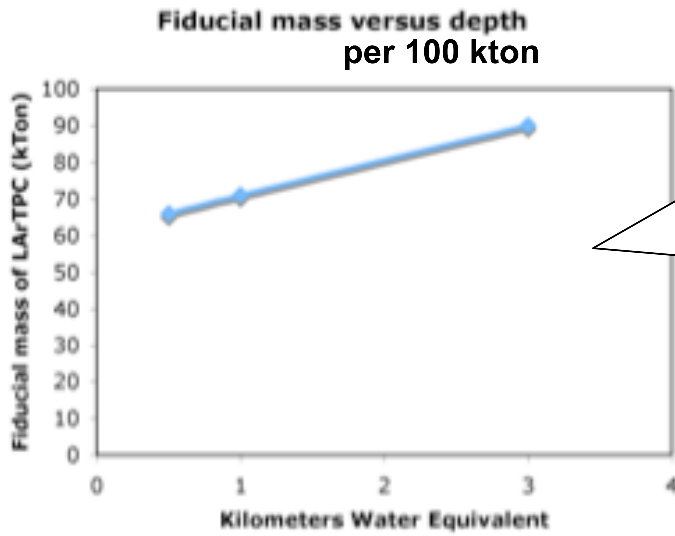


- **At depth, main background is misreconstructed atmnus**
- **Cosmogenic kaons matter if shallow;**
  can be mitigated by veto

How shallow is OK for pdk in LAr?

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



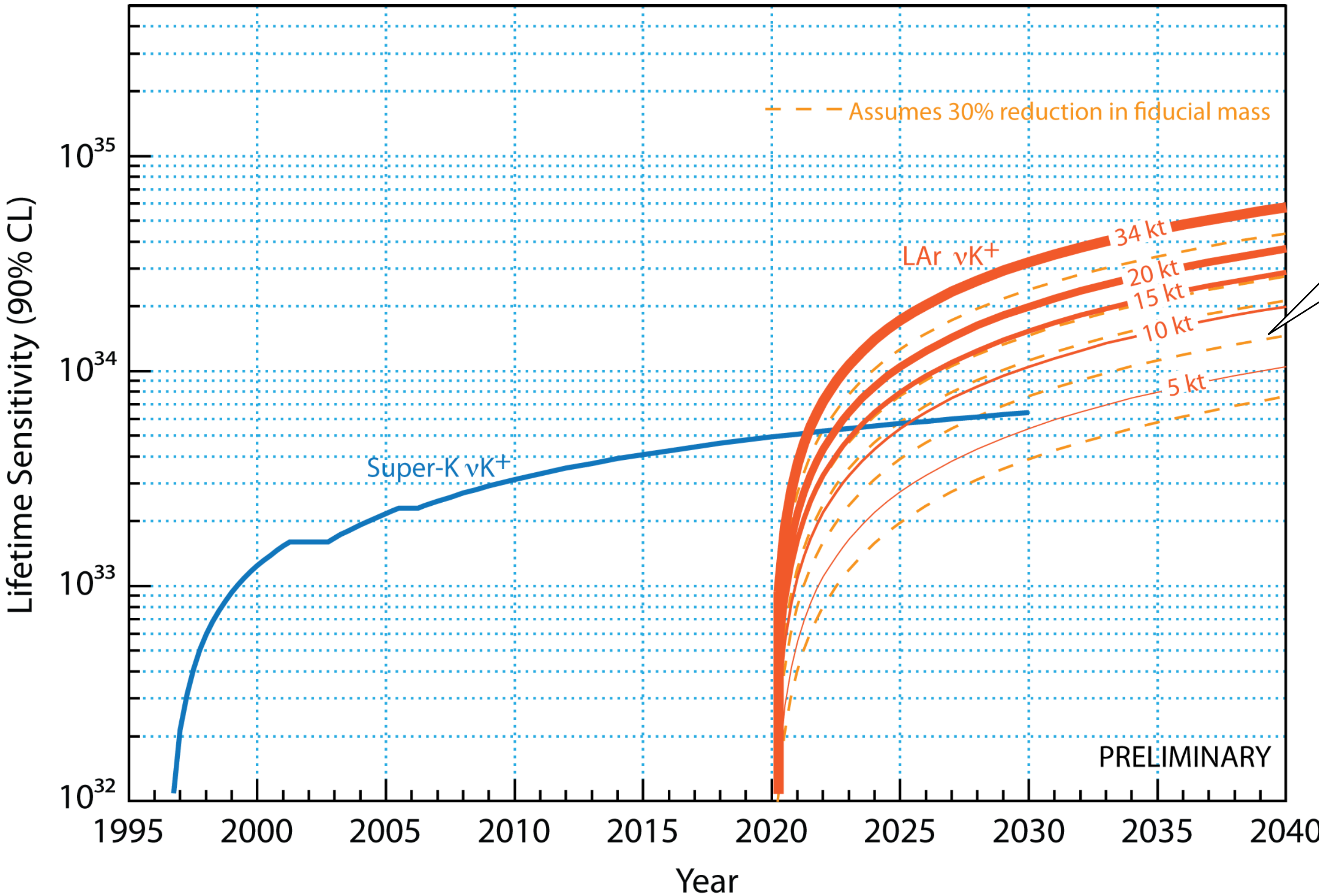


per 100 kton

can be somewhat shallow, at cost of fiducial mass

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

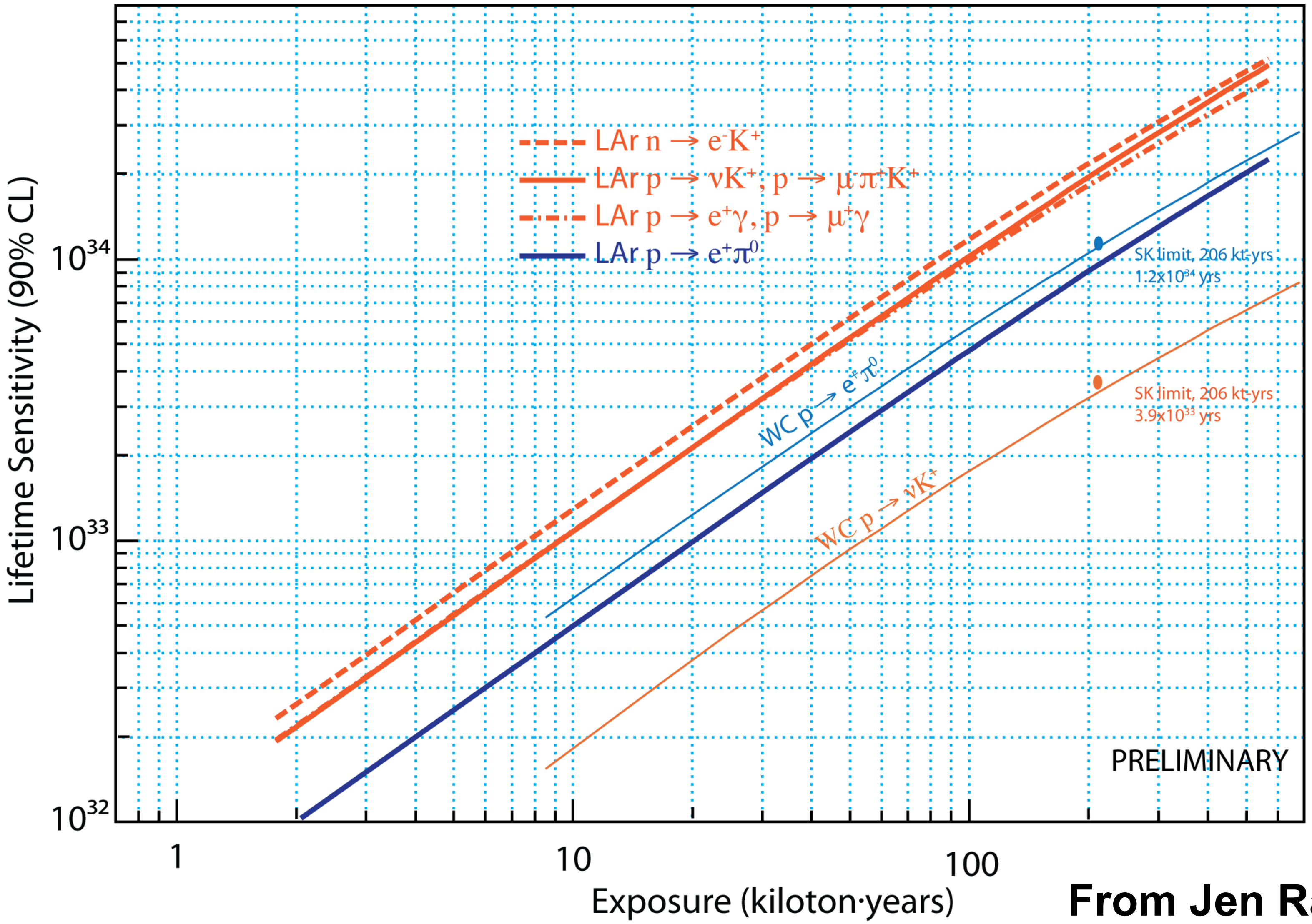
Proton decay reach at Soudan



really need at least 10 kton to be competitive

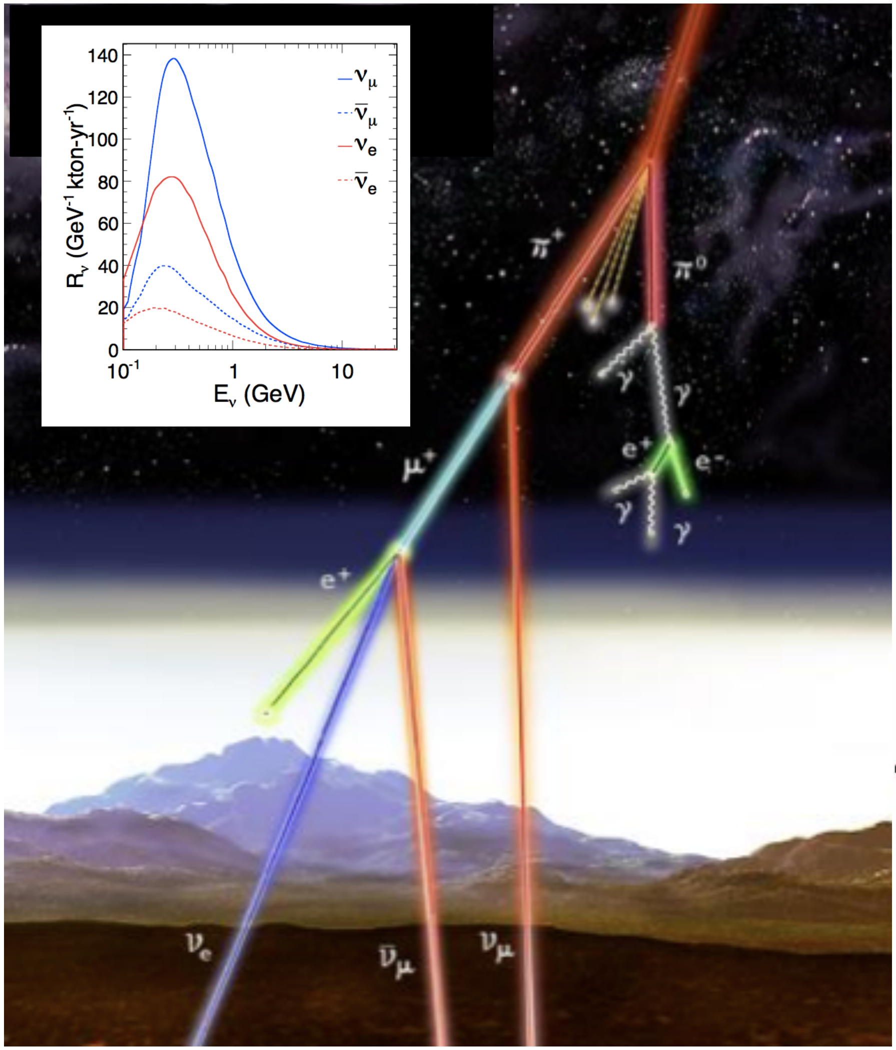
From Jen Raaf

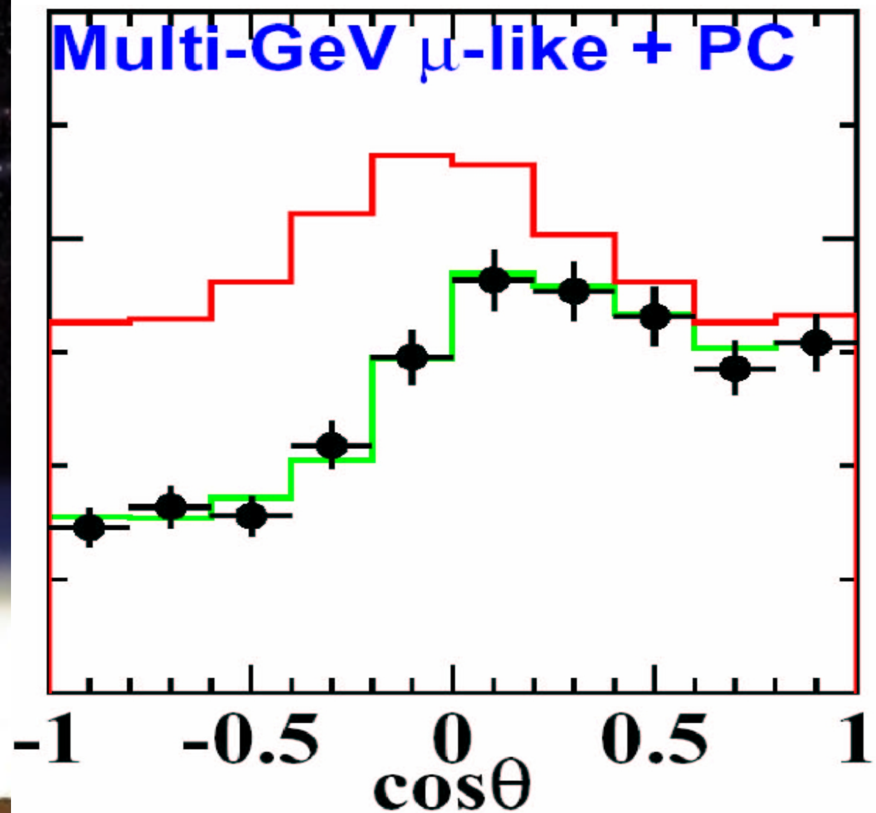
Sensitivity for different pdk modes



From Jen Raaf

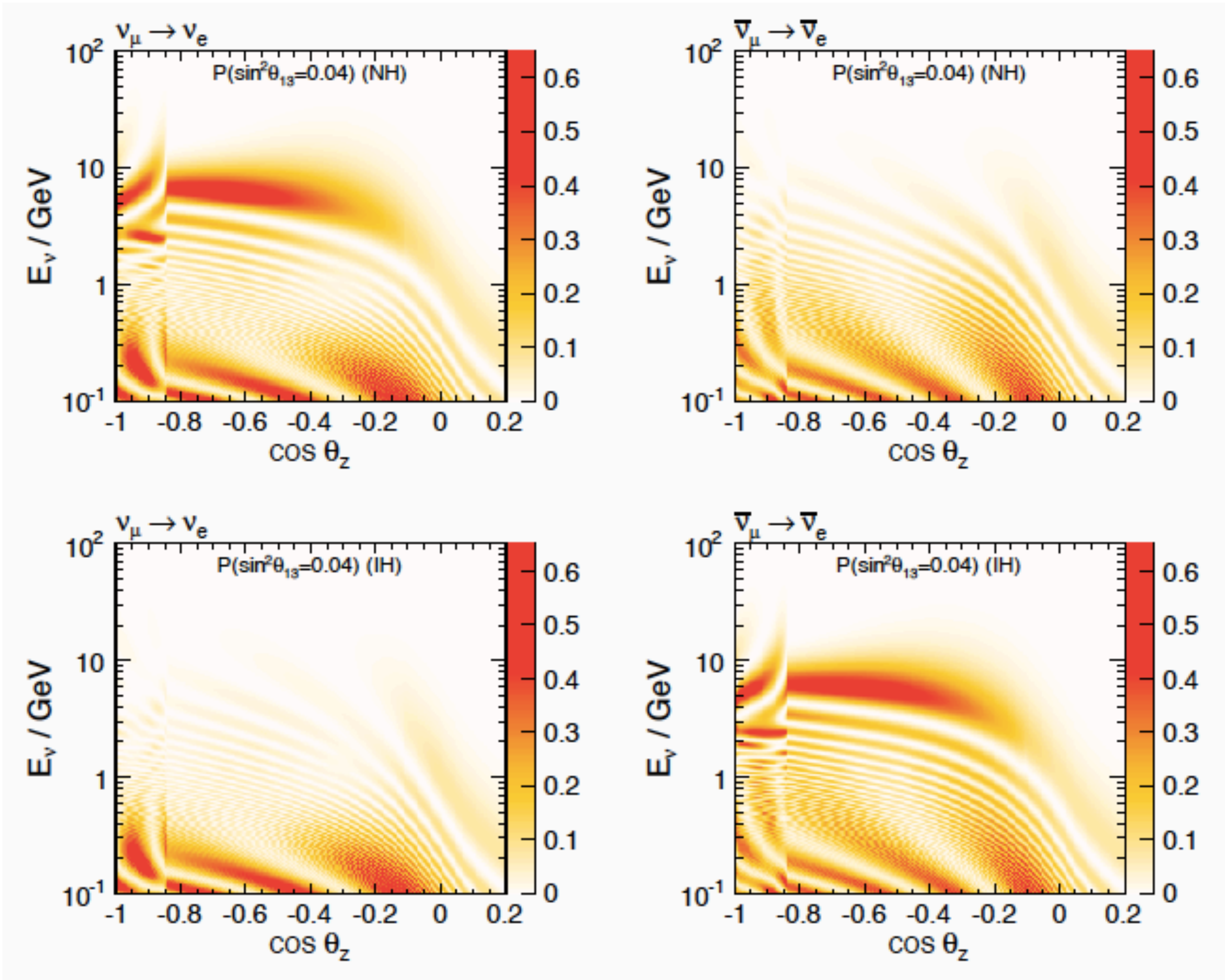
Atmospheric neutrinos





First unambiguous evidence for neutrino mass and oscillations (1998) in Super-K; current best info on θ_{23}

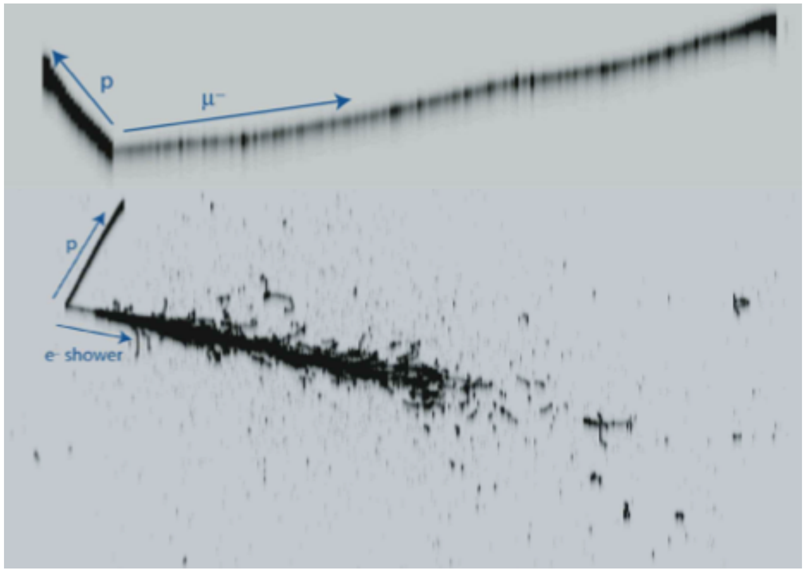
~0.1 GeV to ~TeV
10-13,000 km pathlengths



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

➔ **want high statistics, good angle and energy resolution**

Atmospheric neutrinos in LAr

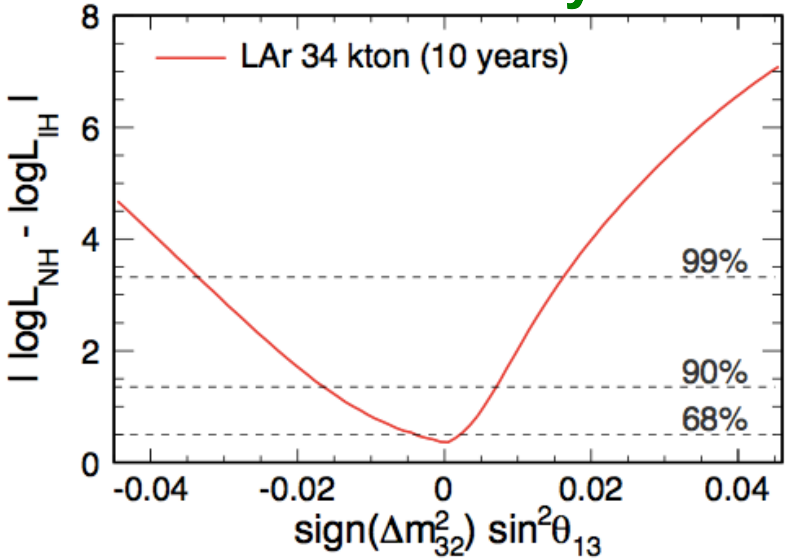


Excellent resolution and lack of Cherenkov threshold enable high efficiency, precision angle & energy reconstruction

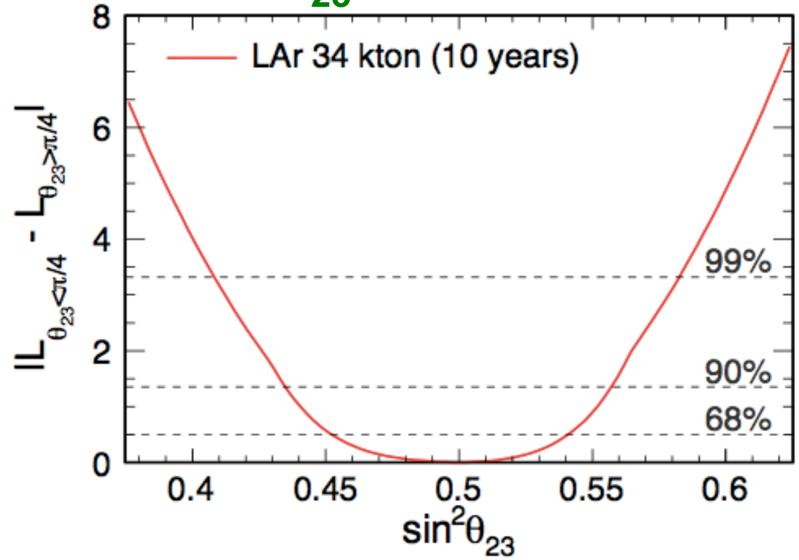
- ~280 events/kton/yr
- presumably easy to select from cosmic bg
- if depth OK for pdk, should be OK for atmnus
- Depth issues:
  - surface probably not OK
  - if OK for pdk, OK for atmnu
  - from Soudan 2 experience (Hugh Gallagher): Soudan depth requires ~0.5 m fiducial cut

Oscillation sensitivity from atmnus in LAr

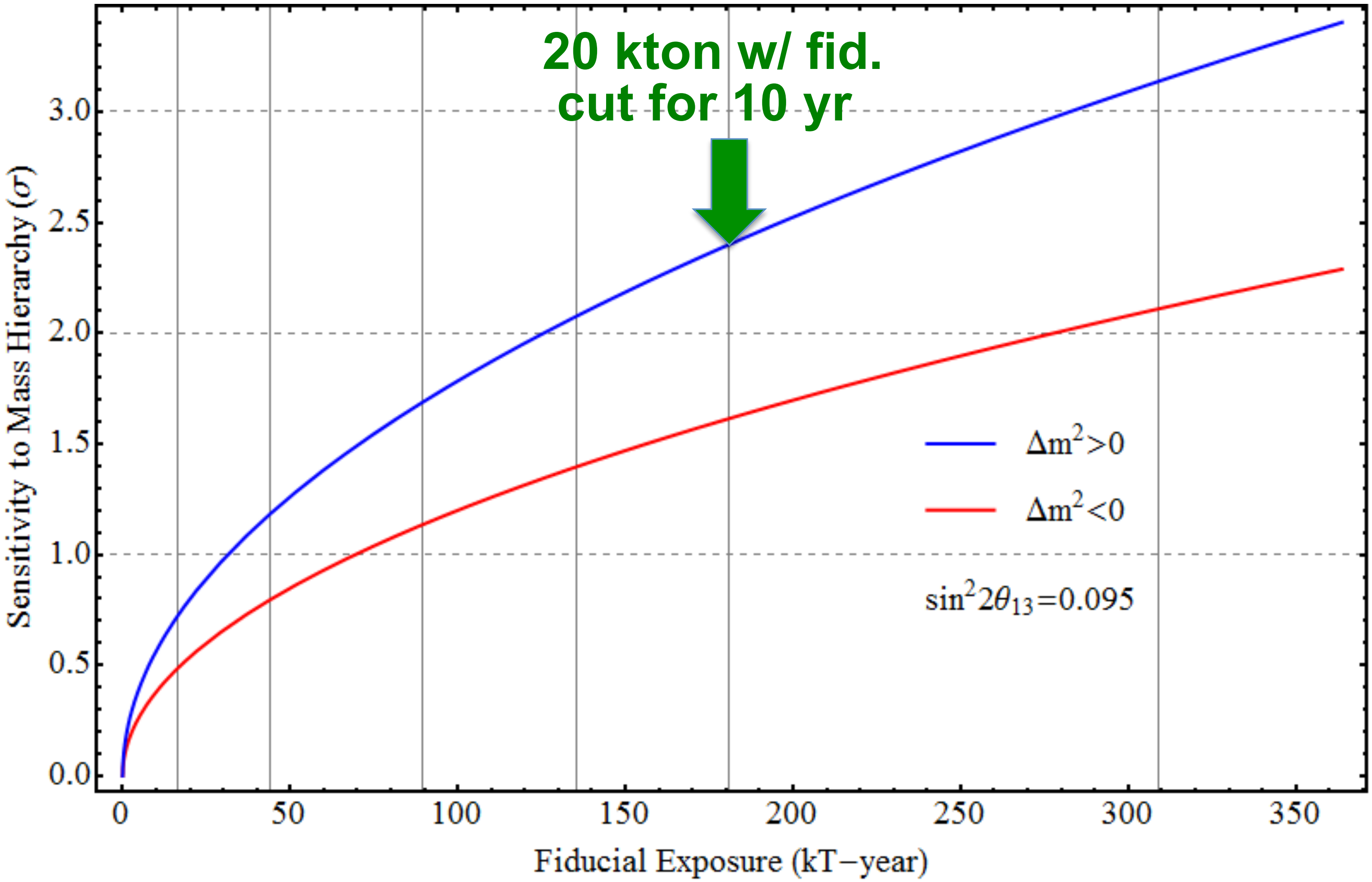
Mass hierarchy



θ_{23} octant



Hierarchy sensitivity as a function of exposure

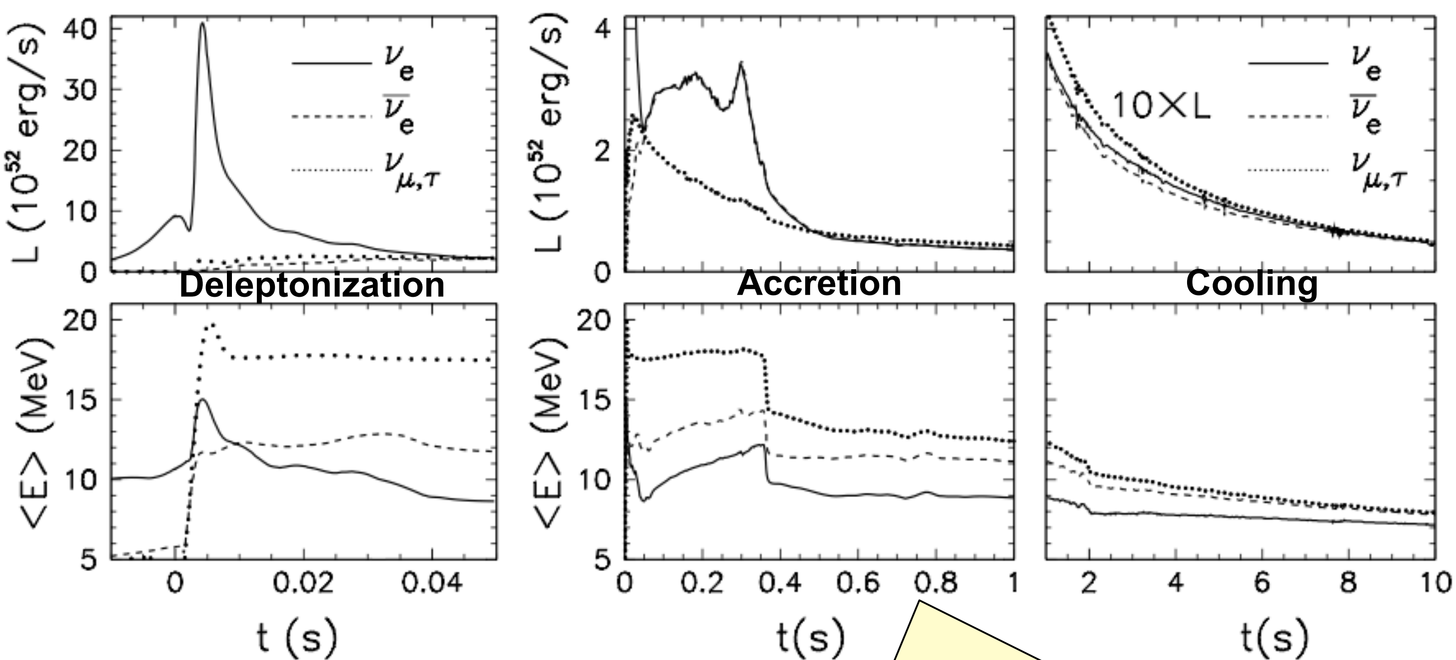


From Hugh Gallagher, Andy Blake, Joao Coelho

Core collapse supernova neutrinos

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

~few SNae per century



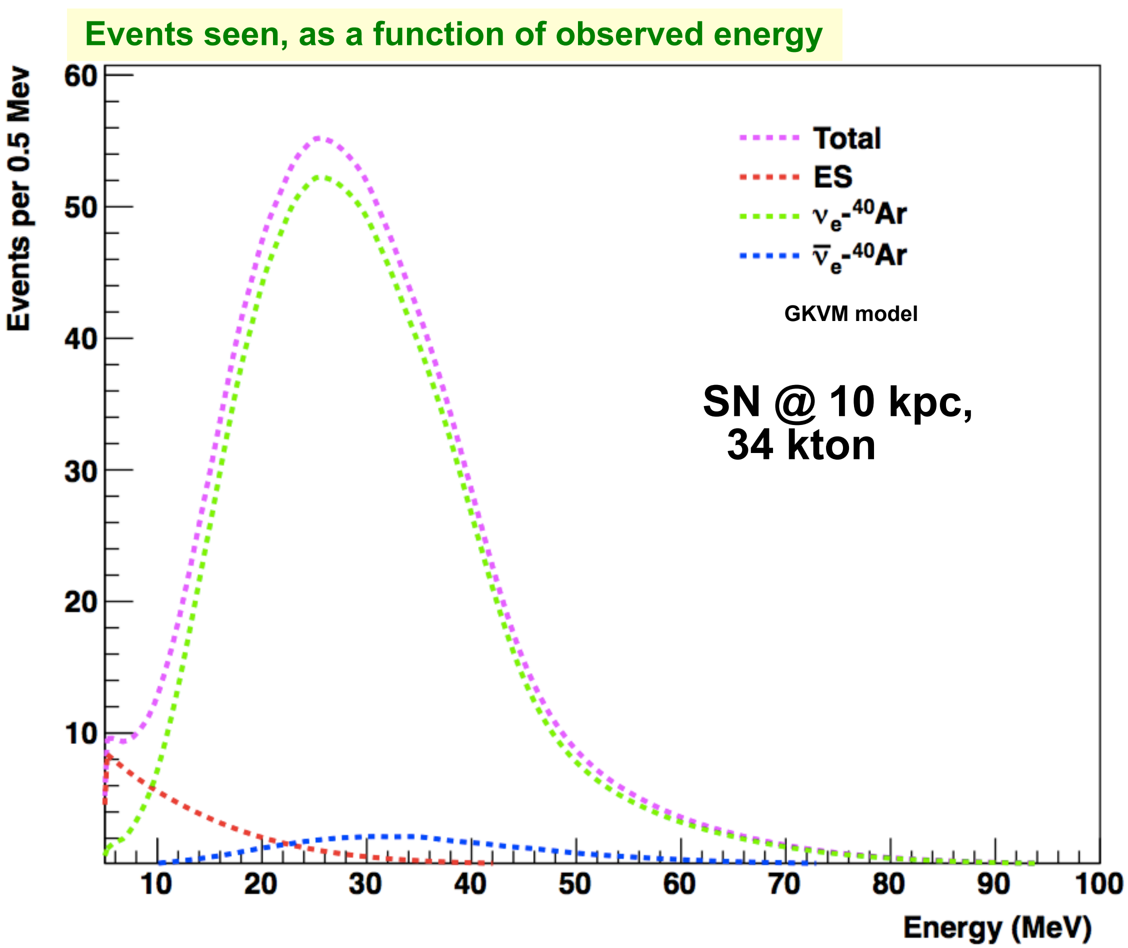
Detection would yield enormous particle physics & astro-physics info

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 @ 10 kpc



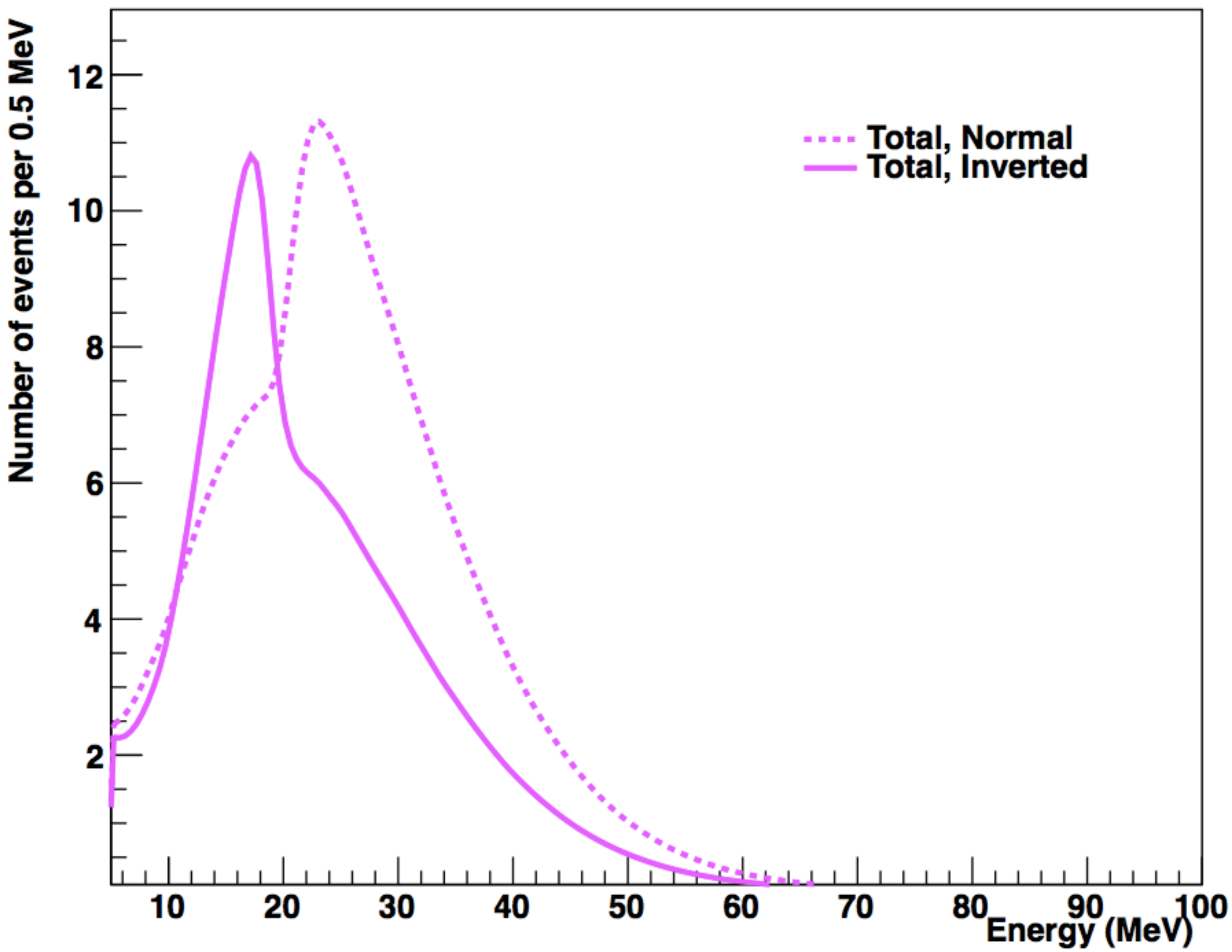
Dominated by ν_e

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?

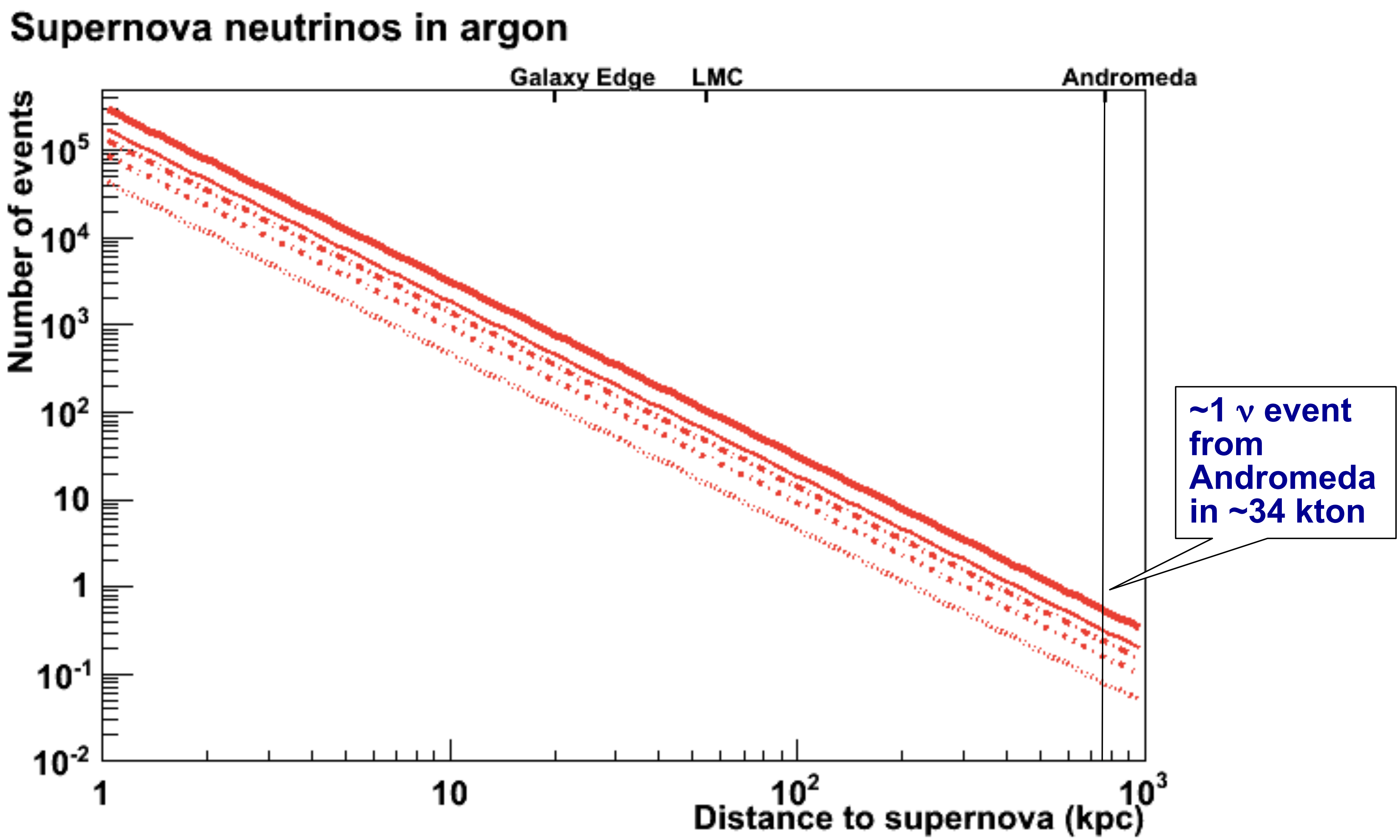
(1 second late time slice from Huaiyu Duan flux with 'multi-angle' collective effects)

<u>Caveat</u>: *this is just one model*



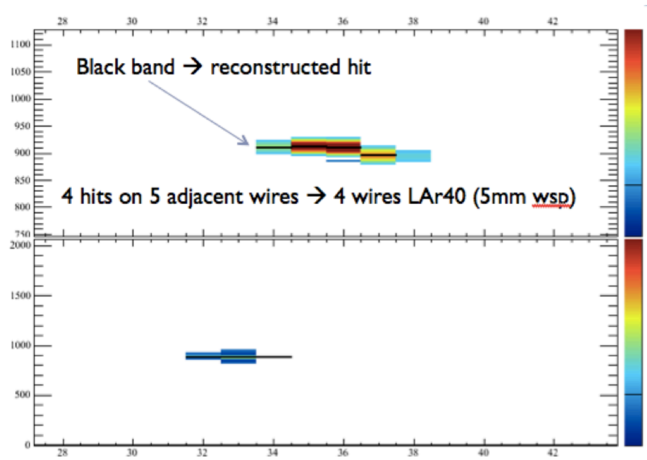
A decent fraction of events have > 20 MeV, but note there may be useful information at low energies

Signal rates vs distance



5, 10, 15, 20, 34 kton

Backgrounds for SN in LAr



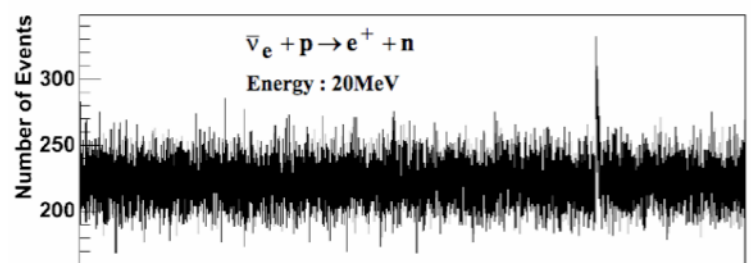
Note:

may also have γ tag for CC interactions

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

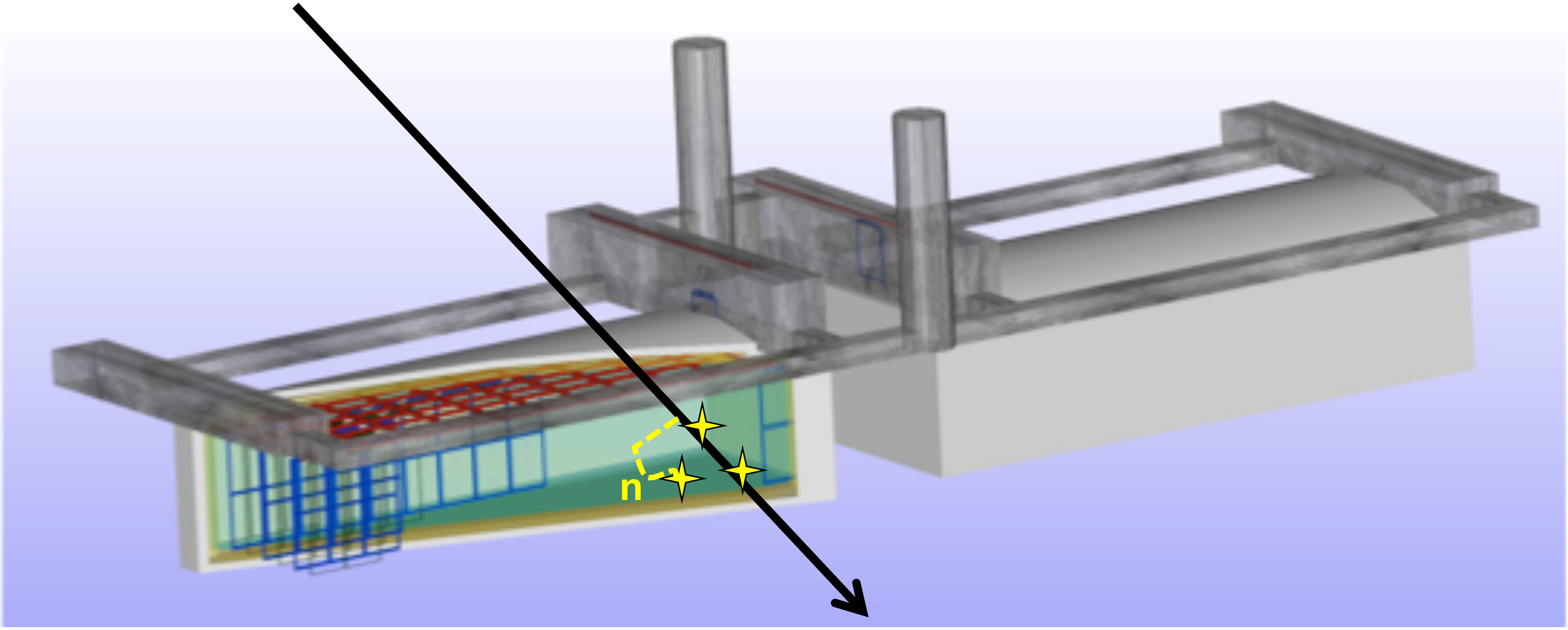
How shallow is OK?

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

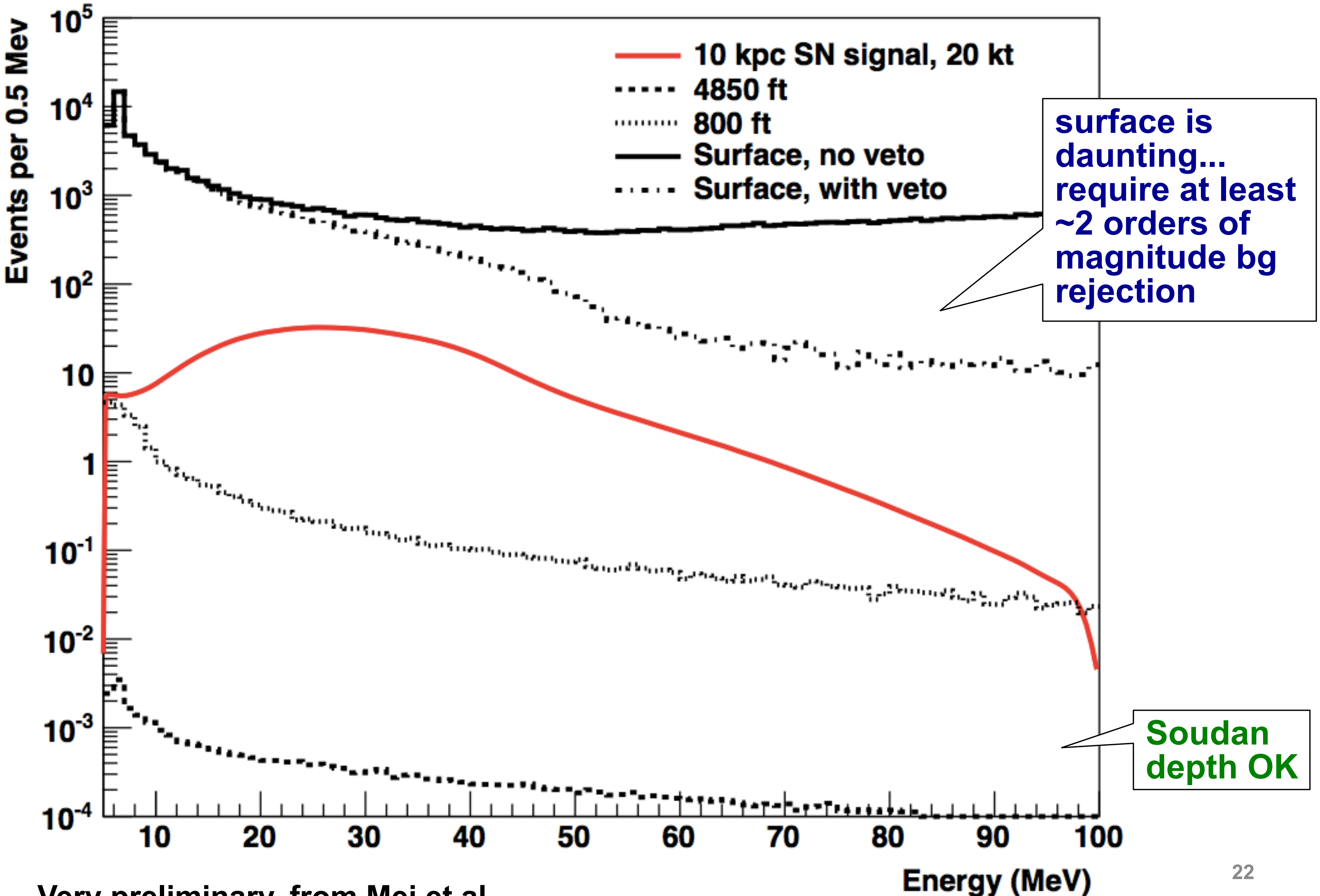
Recent work by Barker, Mei & Zhang, arXiv:1202.5000

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

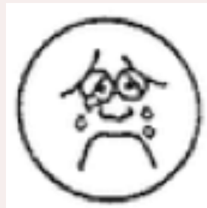
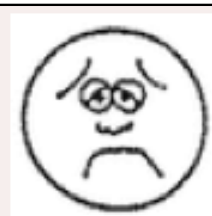
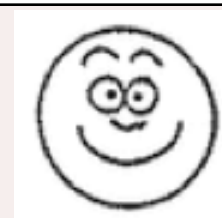
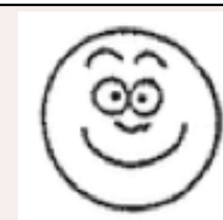
D. Barker,[1] D.-M. Mei,[1,*] and C. Zhang[1,2]

- 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



Very preliminary, from Mei et al.

Signal	Surface	Soudan, 2350 ft	Homestake, 4850 ft
Proton decay			
Atmospheric neutrinos	 ?		
Supernova burst neutrinos	 ?		

Summary: reconfiguration options for non-beam physics

- Homestake depth is excellent and
  Soudan depth is fine (no veto) 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 very 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

Surface options are highly disfavored

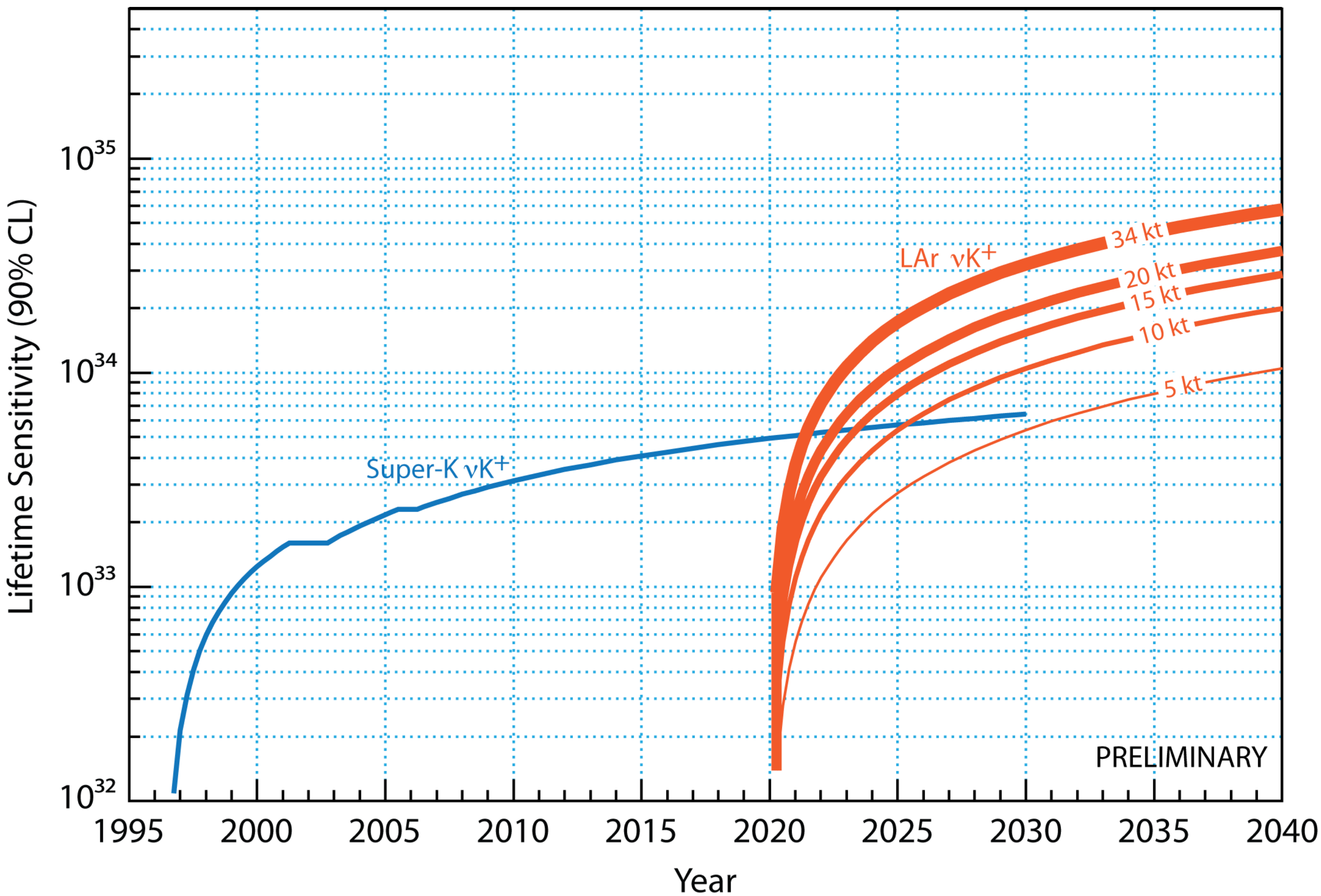
Backups

From Bueno paper

Depth		Code	All muons		$E_\mu > 1$ GeV		Effective
Water equiv.	Standard rock		Particles/s	Particles/10 ms	Particles/s	Particles/10 ms	mass
Surface detector		FLUKA	1700000	17000	1300000	13000	–
$\simeq$ 0.13 km w.e.	50 m	FLUKA	11000	110	10000	100	50 kton
$\simeq$ 0.5 km w.e.	188 m	FLUKA	330	3.3	320	3.2	98 kton
	200 m	GEANT4	–	–	420	4.2	98 kton
$\simeq$ 1 km w.e.	377 m	FLUKA	66	0.66	65	0.65	100 kton
$\simeq$ 2 km w.e.	755 m	FLUKA	6.2	0.062	6.2	0.062	100 kton
$\simeq$ 3 km w.e.	1.13 km	FLUKA	0.96	0.01	0.96	0.01	100 kton
Under the hill (see figure 4)		GEANT4	–	–	960	9.6	96 kton

Table 3: Computed average number of muons entering the detector per unit time for various geographical configurations. The effective mass corresponds to the mass of Argon that can be used when, in both 2D readout views, a slice of size 10 cm around each crossing muon is vetoed.

Proton decay reach at Soudan: no FV cut



From Jen Raaf

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

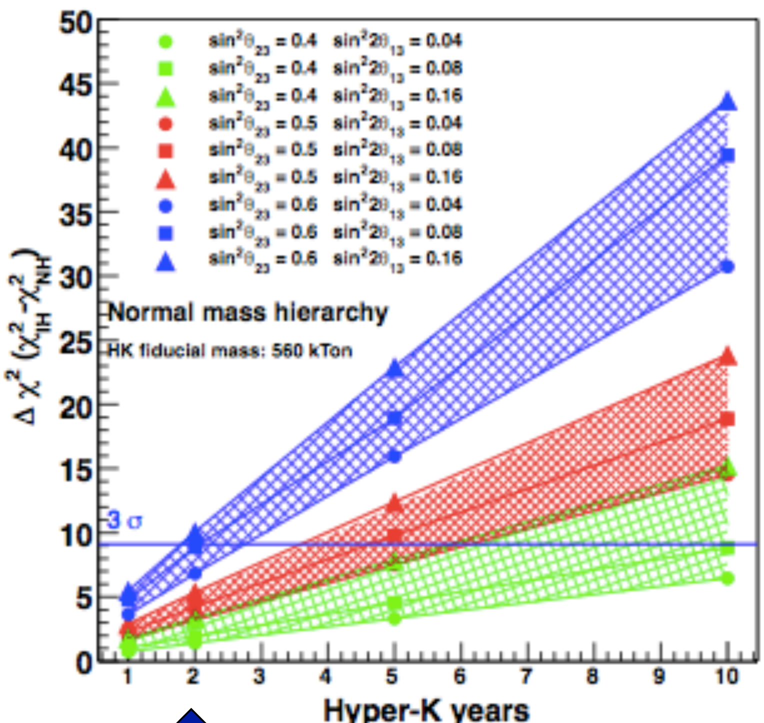
where we call the first, second, and third terms the "solar term", "interference term", and "θ_{13} resonance term", respectively. P_2 is the two neutrino transition probability of $\nu_e \to \nu_{\mu,\tau}$ which is driven by the solar neutrino mass difference Δm^2_{21}. R_2 and I_2 represent oscillation amplitudes for CP even and odd terms. For anti-neutrinos, the probabilities P_2, R_2, I_2 are obtained by replacing the matter potential $V \to -V$, and the sign of the δ (see [64] for details). r is the ν_μ/ν_e flux ratio as a function of neutrino energy; $r \approx 2$ at sub-GeV energies, starts deviating from 2 at 1 GeV, and reaches to ~ 3 at 10 GeV. The $\tilde{\theta}_{13}$ is an effective mixing angle in the Earth; $\sin^2\tilde{\theta}_{13}$ could become large at $5 \sim 10$ GeV neutrino energy due to the matter potential [65–67]. This MSW resonance

HK LOI

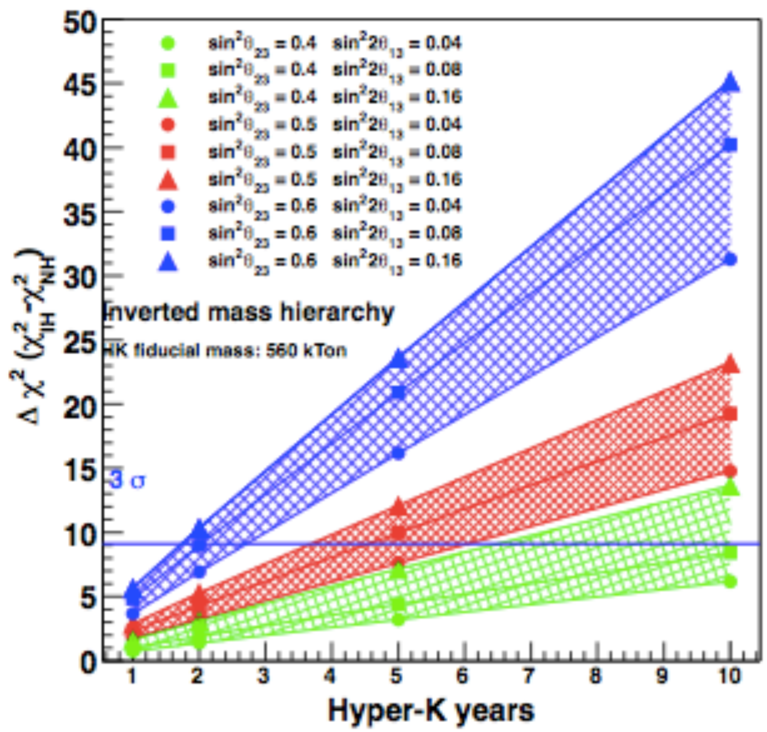
Back-of-the-envelope for smaller detector:

560 kton WC ~ 100 kton LAr

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

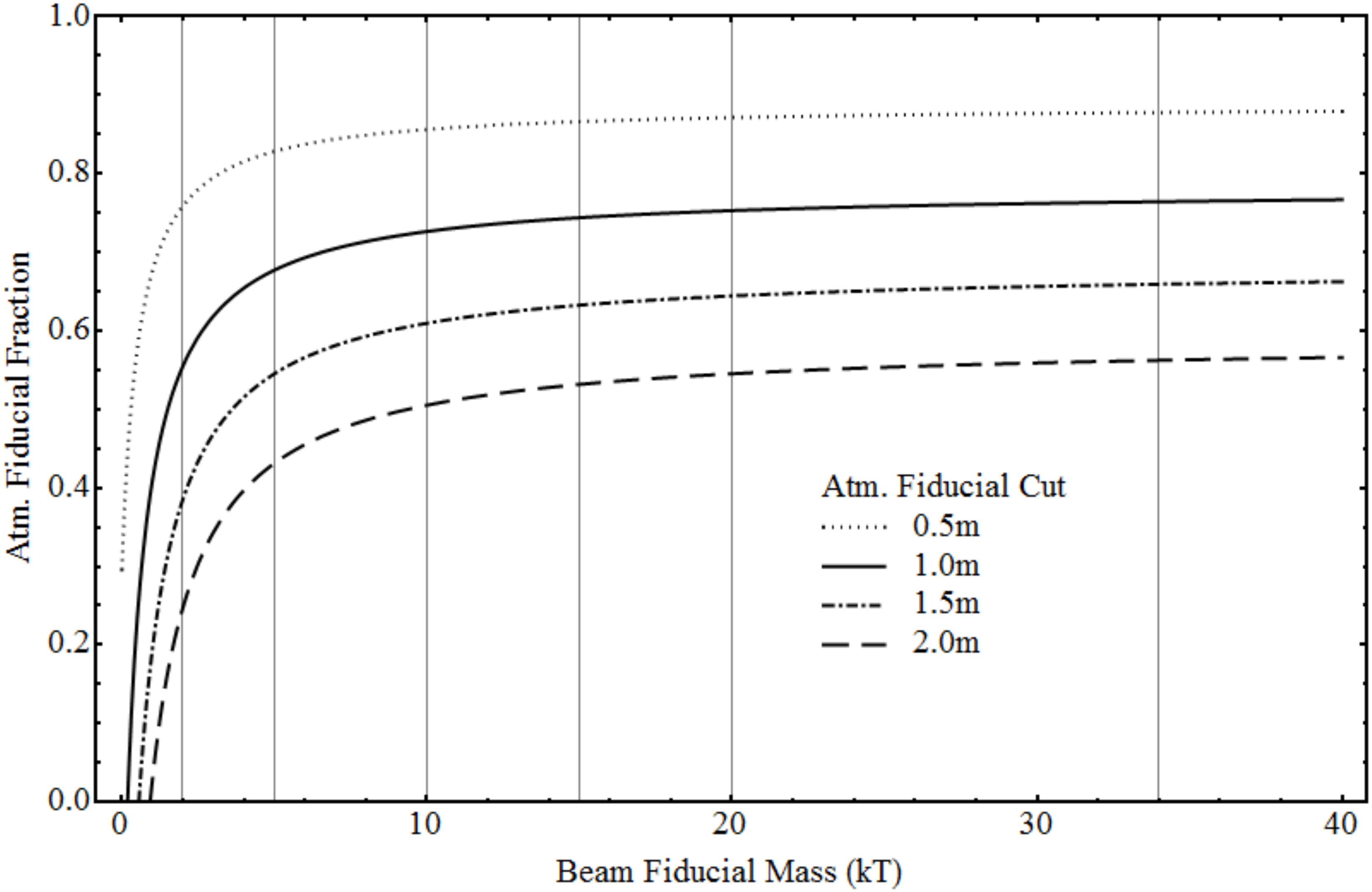


20 kton LAr, 10 years



From HK LOI

Mass for atmnus with fiducial cut



From Hugh Gallagher, Joao Coelho

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

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

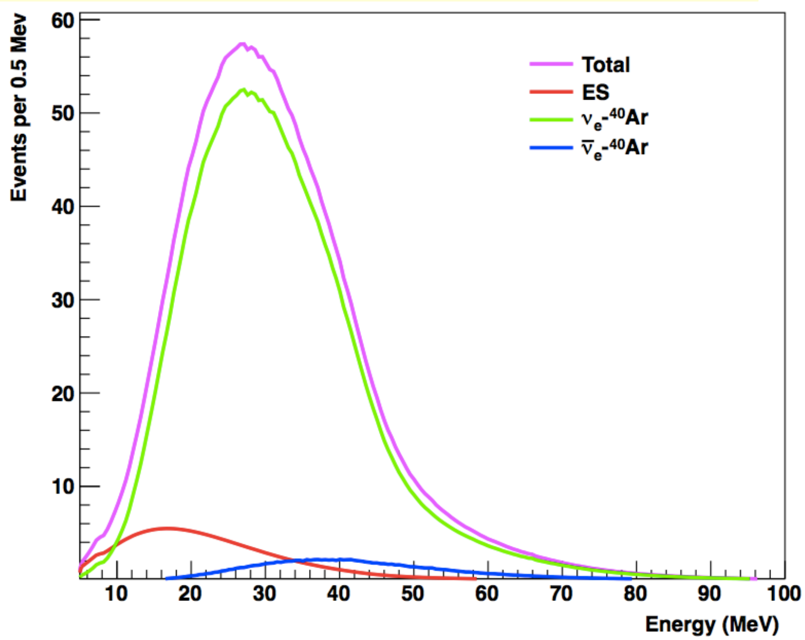
Can use for pointing

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

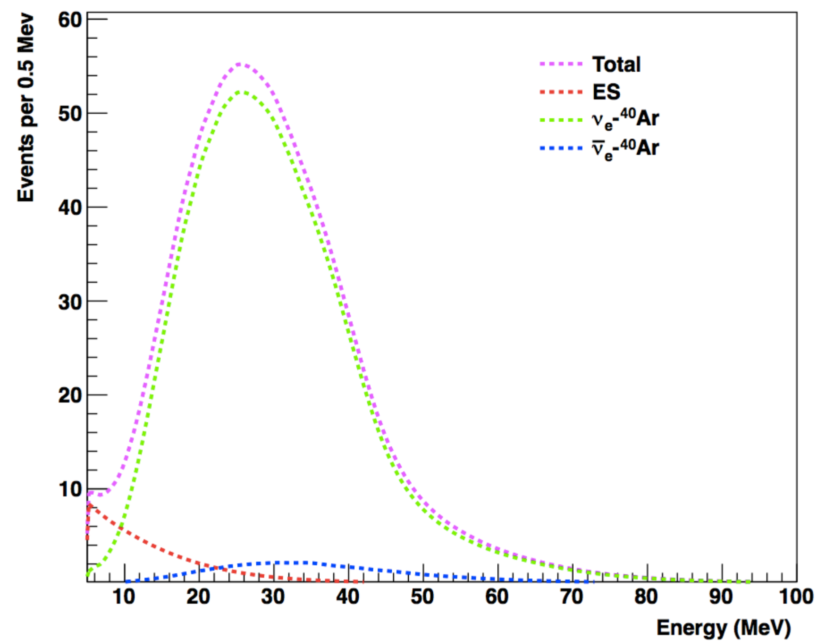
Event rates for 34 ktons of LAr

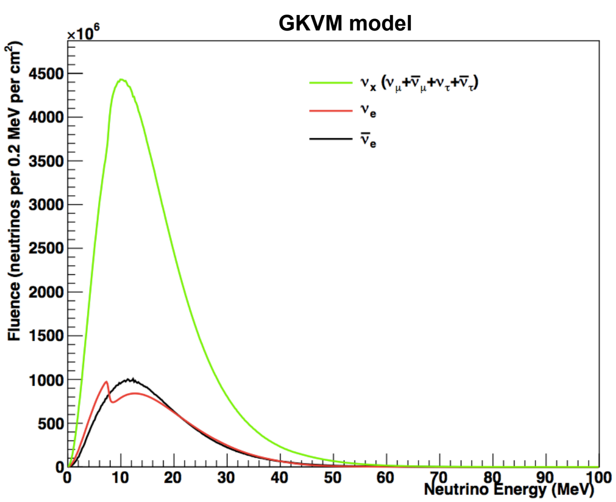
SN @ 10 kpc

Interactions, as a function of neutrino energy



Events seen, as a function of observed energy

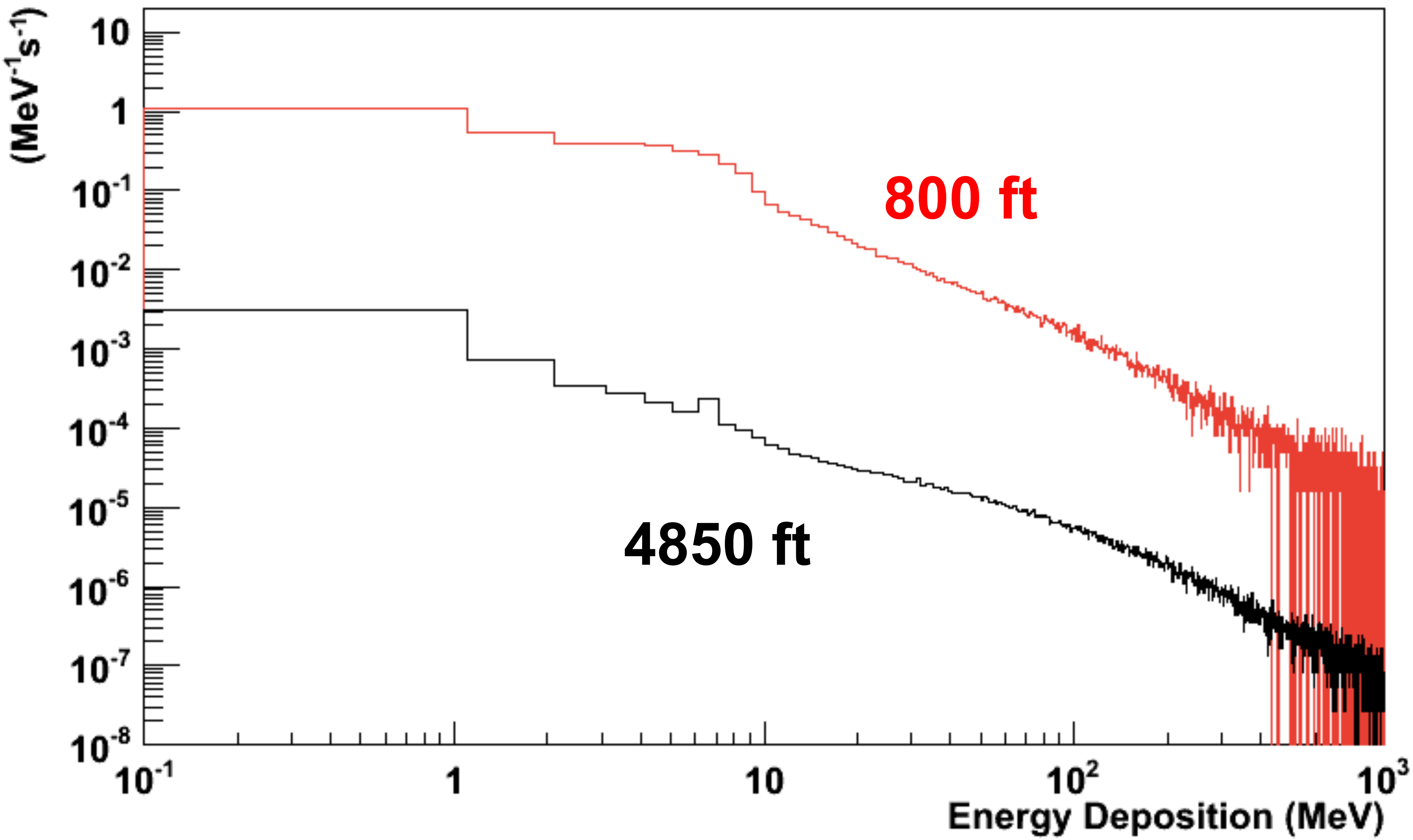




Channel	No of events (observed), GKVM	No. of events (observed), Livermore
Nue-Ar40	2848	2308
Nuebar-Ar40	134	194
ES	178	296
Total	**3160**	**2798**

Dominated by ν_e

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

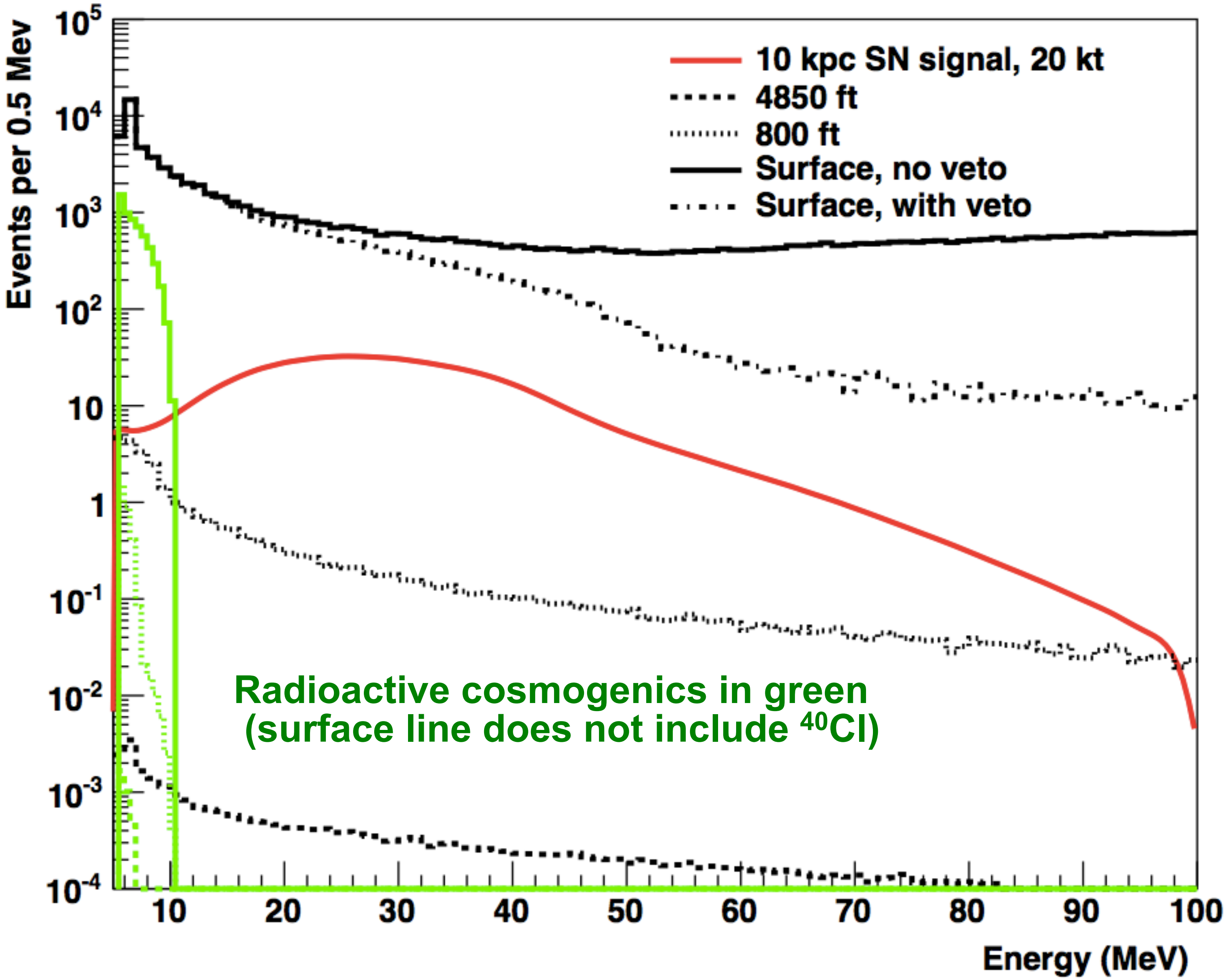
TABLE II: Additional significant cosmogenic production rates in the detector (20 kton) at the 800-ft level.

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?)



10 kpc SN signal, 20 kt
4850 ft
800 ft
Surface, no veto
Surface, with veto
Events per 0.5 Mev
Energy (MeV)
Radioactive cosmogenics in green
(surface line does not include 40Cl)