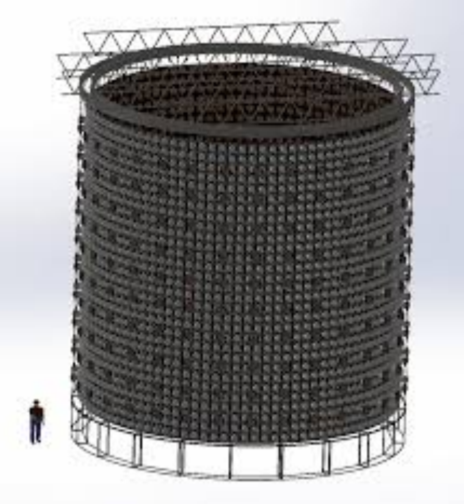
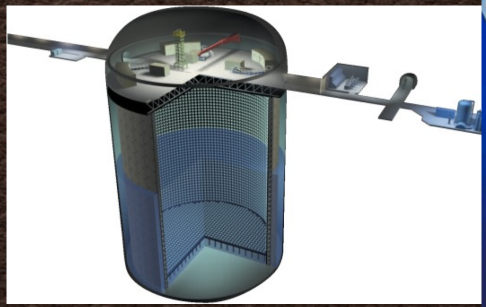
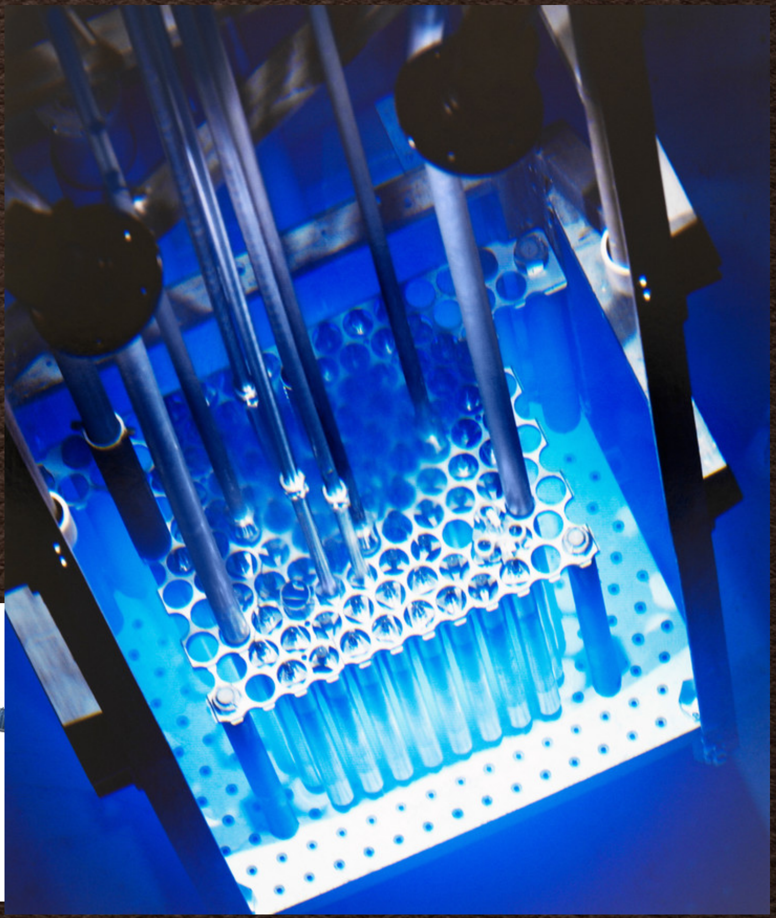
Reactor Neutrino Detection via Elastic Scattering

WoNDRAM Meeting 6/24/2021 Michael Smy, UC Irvine







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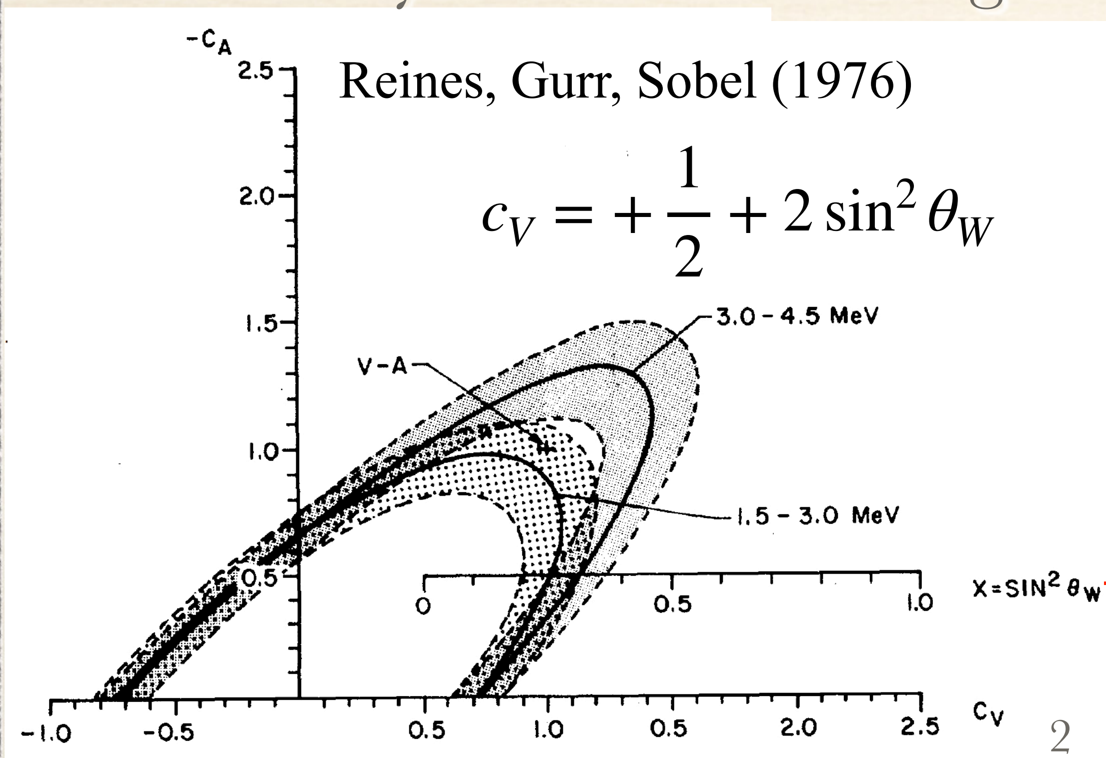
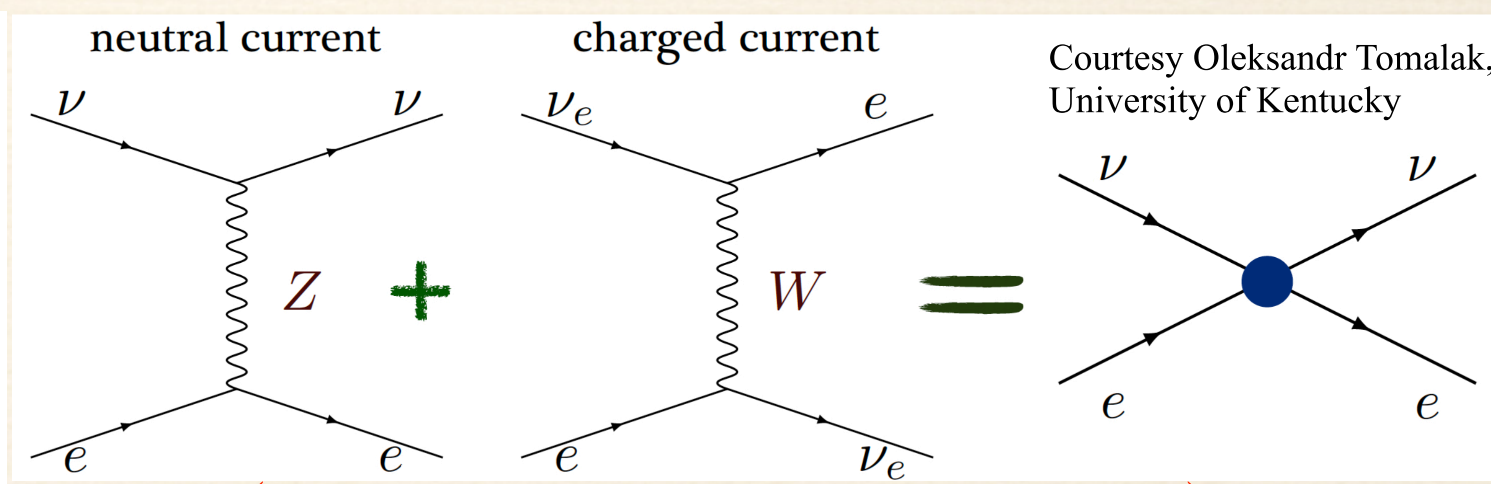
Neutrino-electron Elastic Scattering

- well-defined cross section 🙂
- recoil electrons point in neutrino direction 🙂
- sensitive to all active flavors 🙂
- higher energy signal than coherent scattering (MeV vs. keV) 🙂
- small cross section 🙁
- difficult to reconstruct neutrino energy 🙁
- no delayed coincidence signature 🙁





$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left((c_V - c_A)^2 + (c_V + c_A)^2\left(1 - \frac{T}{E_\nu}\right)^2 + (c_A^2 - c_V^2)\frac{m_e T}{E_\nu^2}\right)$$

$g_V = I_3 - 2Q\sin^2\theta_W,\ g_A = I_3 \qquad c_V = g_V + 1,\ c_A = -(g_A + 1)$

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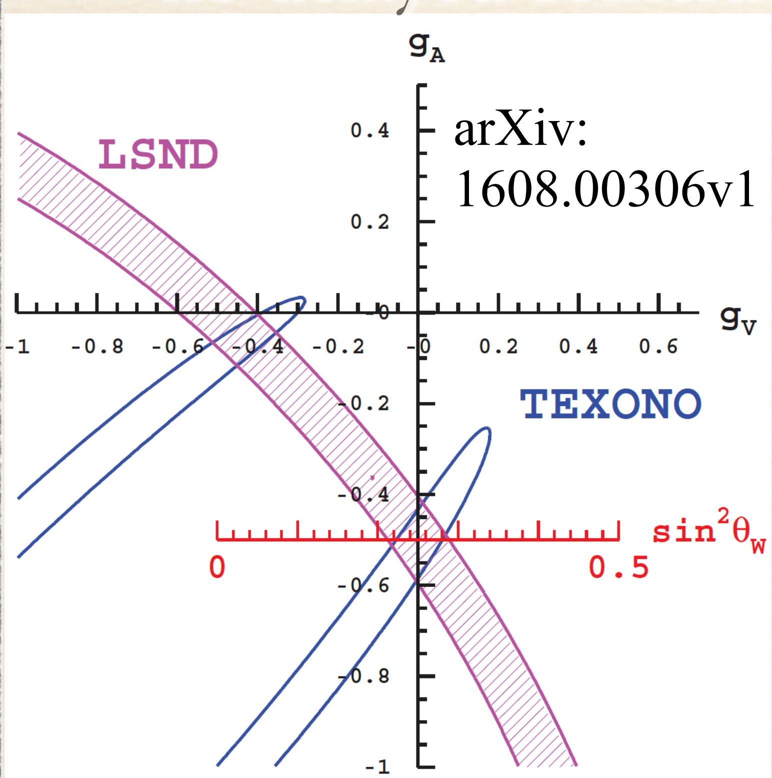
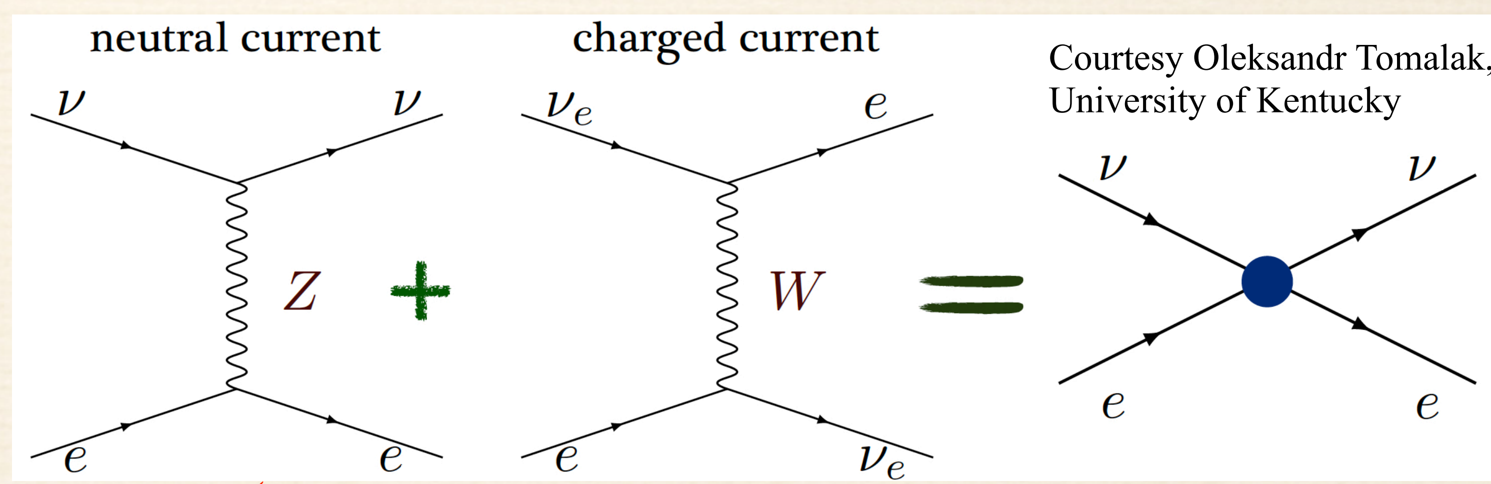
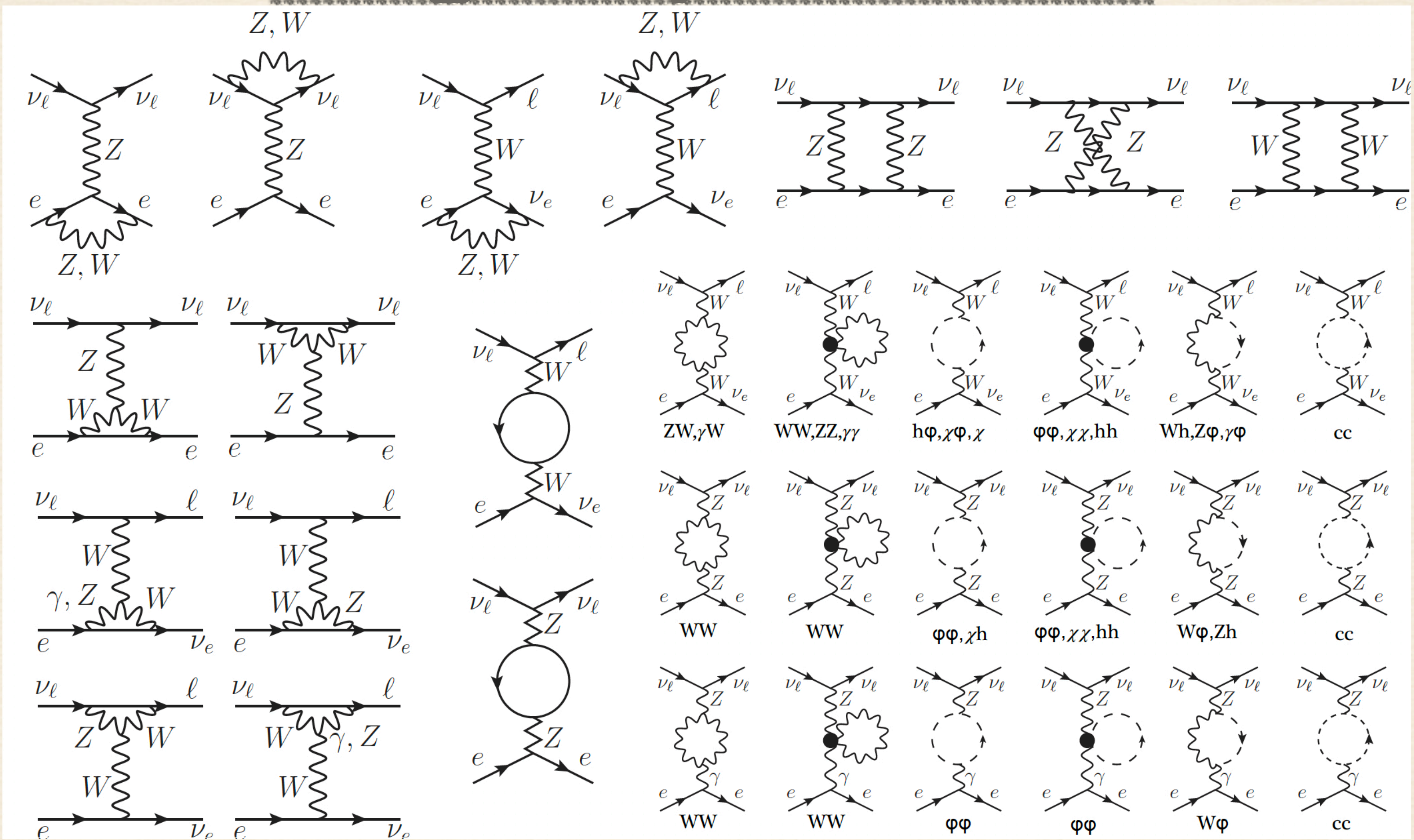




$$\frac{d\sigma}{dT} = \frac{G_F^2 m_e}{2\pi}\left((g_V - g_A)^2 + (g_V + g_A + 2)^2\left(1 - \frac{T}{E_\nu}\right)^2 - (g_V - g_A)(g_V + g_A + 2)\frac{m_e T}{E_\nu^2}\right)$$

2 $g_V = I_3 - 2Q\sin^2\theta_W,\ g_A = I_3 \qquad c_V = g_V + 1,\ c_A = -(g_A + 1)$

Neutrino-electron Elastic Scattering: Beyond Tree Level

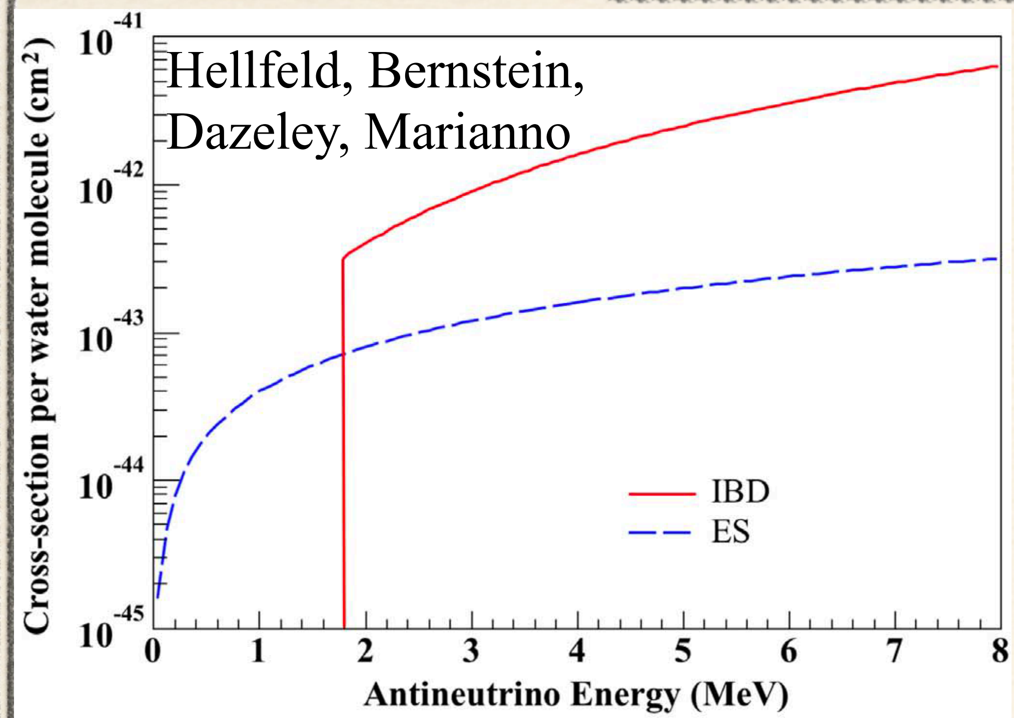


- hadronic uncertainty is the main theory error: 0.2-0.4%

Courtesy Oleksandr Tomalak, University of Kentucky

Neutrino-Electron Elastic Scattering Cross Section

- substantially smaller cross section than IBD
- less different at lower energy
- very directional differential cross section above 4 MeV
- problem: multiple Coulomb scattering of recoil electrons: limits Cherenkov detector "pointing" and background discrimination



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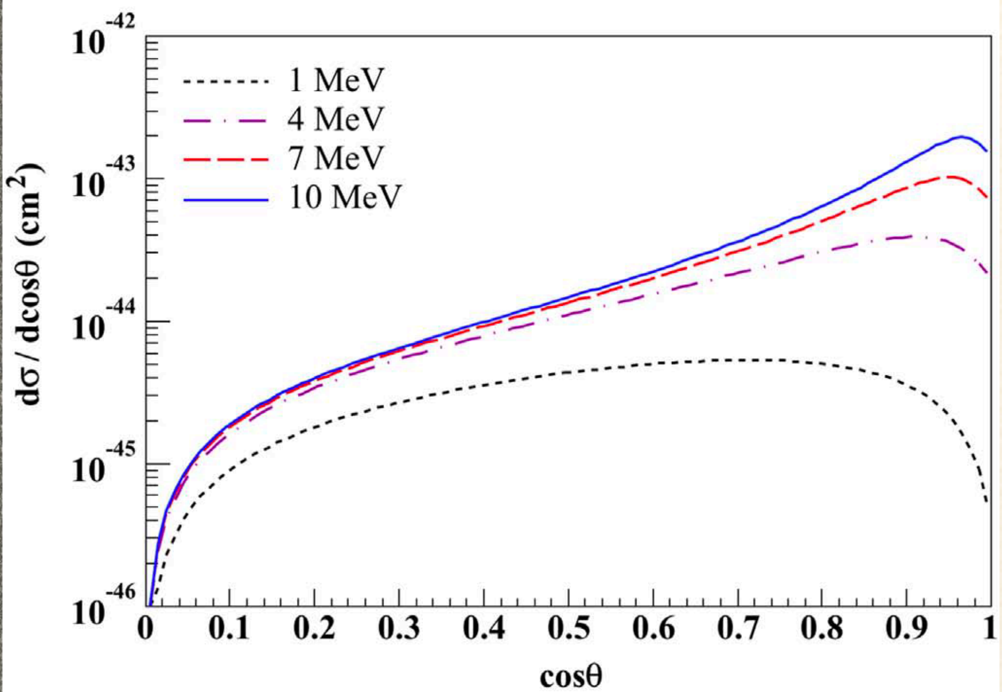

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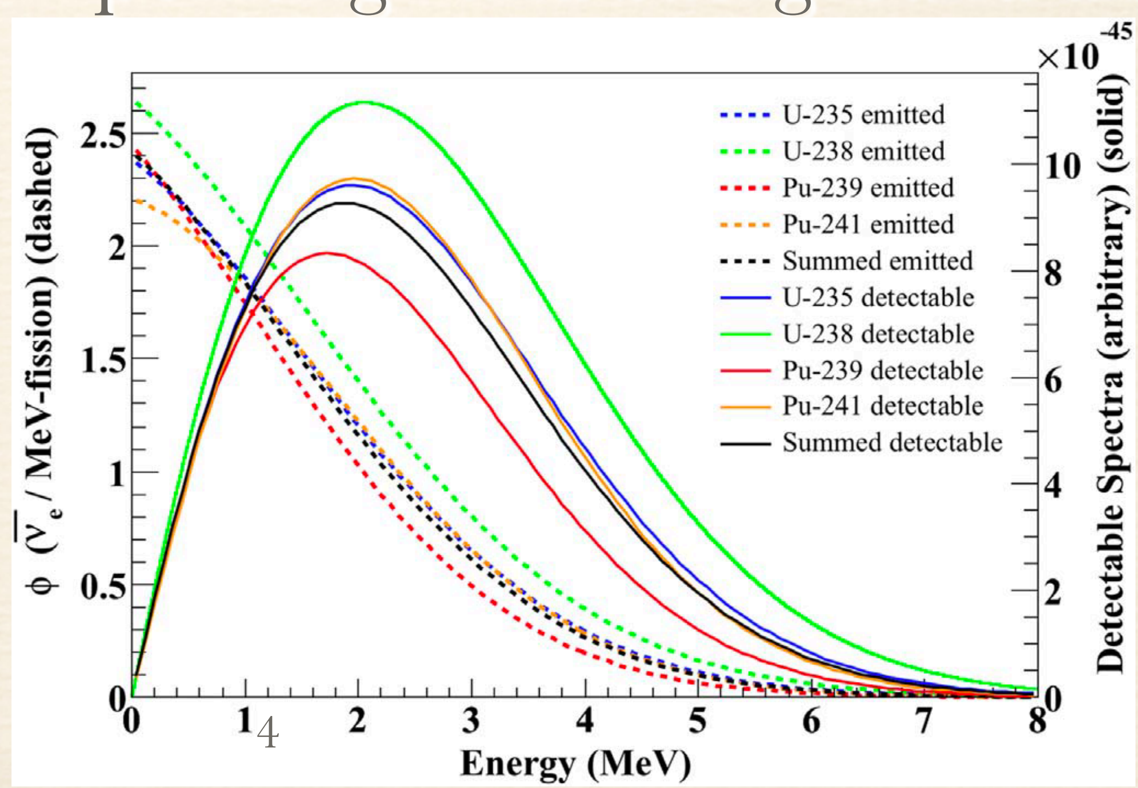
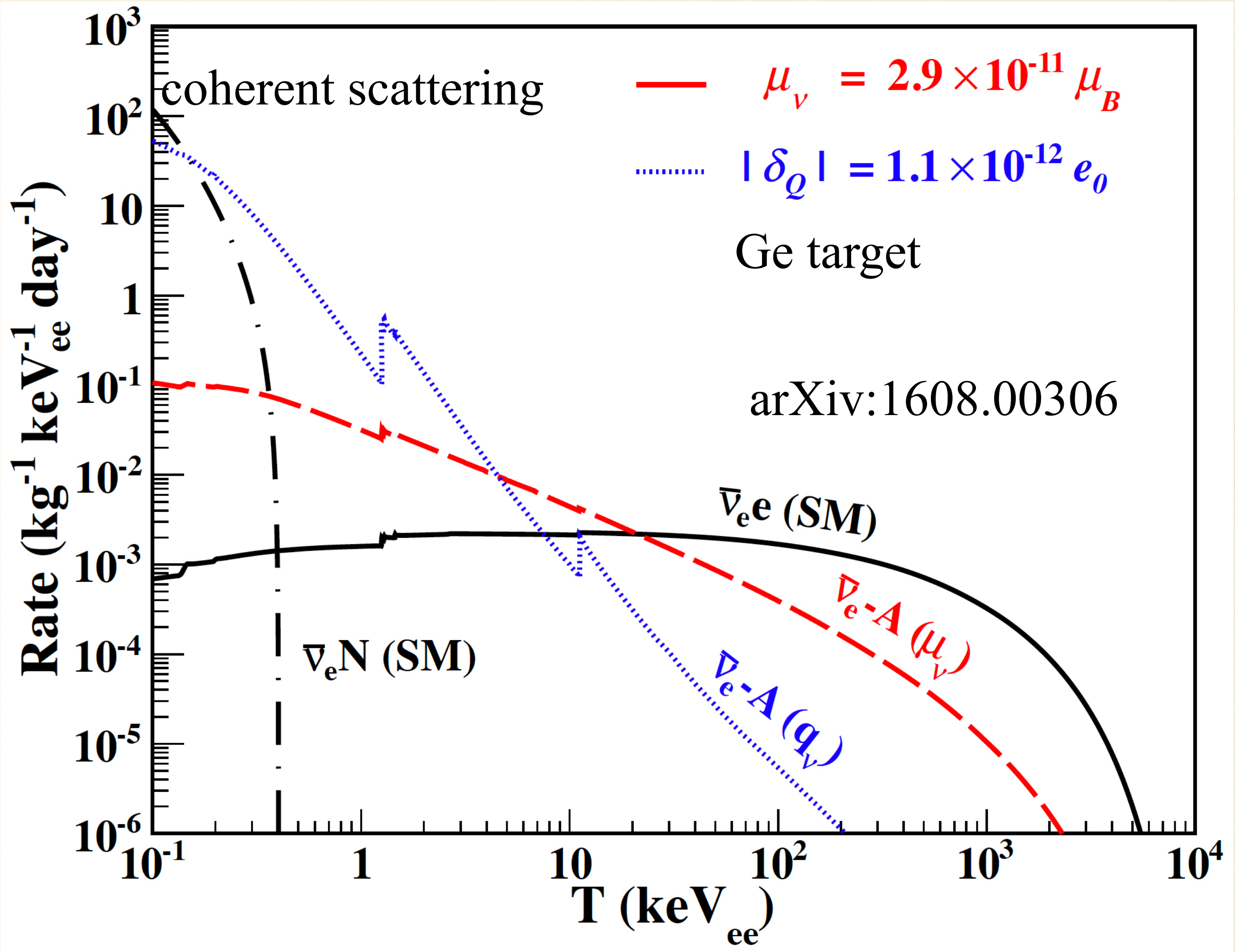


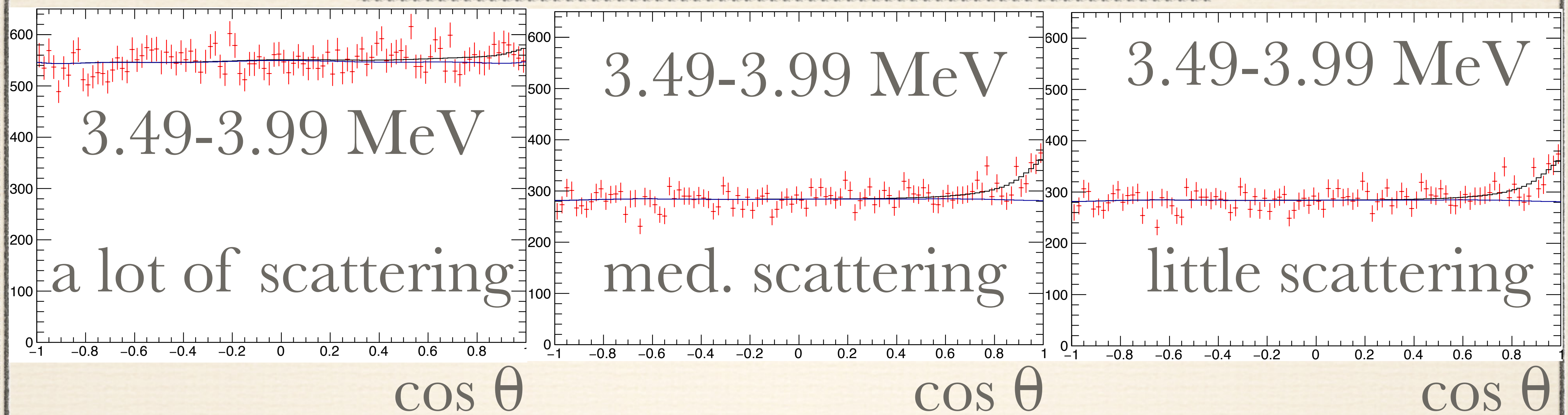
Hellfeld, Bernstein, Dazeley, Marianno

Possible Reasons to Use Electron ES

- detect near or below IBD threshold
- probe electroweak physics
- search for non-zero neutrino magnetic moment or milli-charge
- oscillation measurements?
- directional remote monitoring of reactors (this talk)
  - need huge detectors (small cross section)
  - need recoil electron directional reconstruction



Pointing: Estimate Multiple Coulomb Scattering in Super-K Solar ν Data



- angular resolution and multiple Coulomb scattering reconstruction checked with an electron LINAC at 4.5 MeV
- most of the angular tail is from events with a lot of scattering
- ^{208}Tl and ^{214}Bi tend to have more effective scattering (due to lower energy and/or multiple electrons)
- perhaps LArTPC can do a lot better than this

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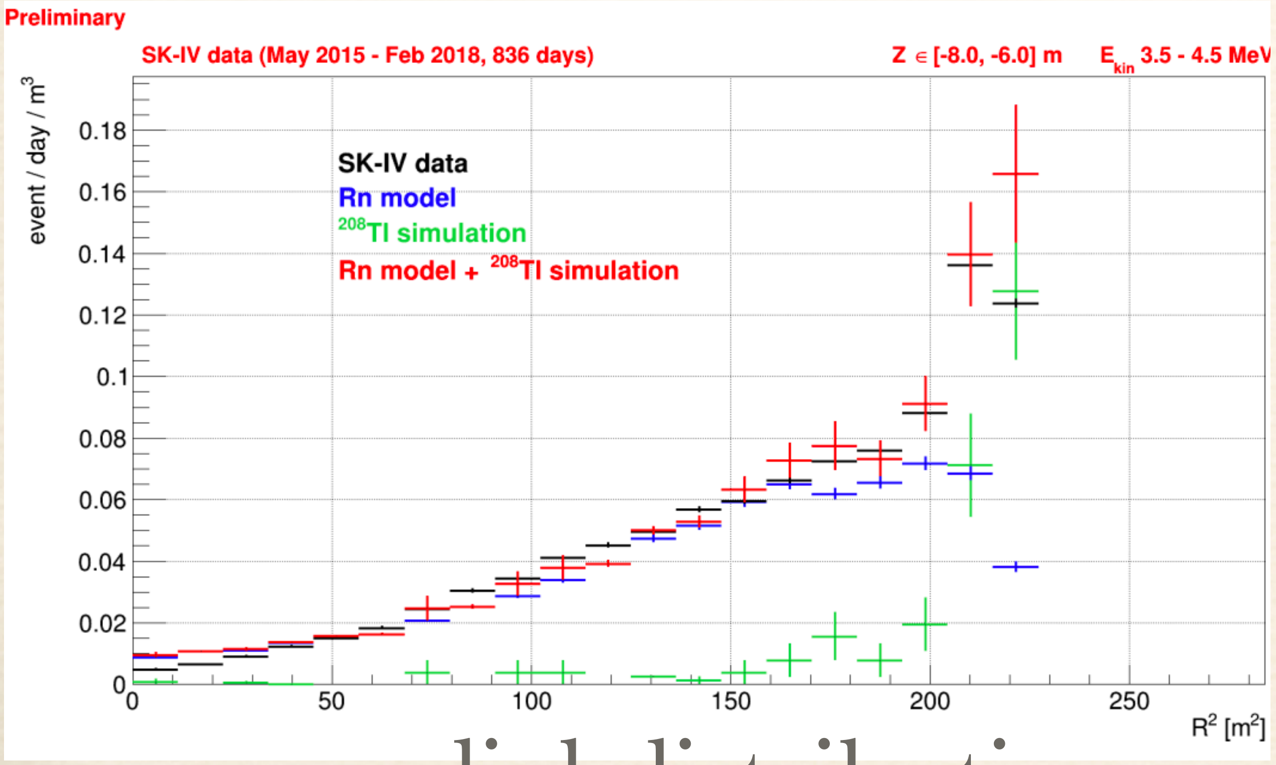
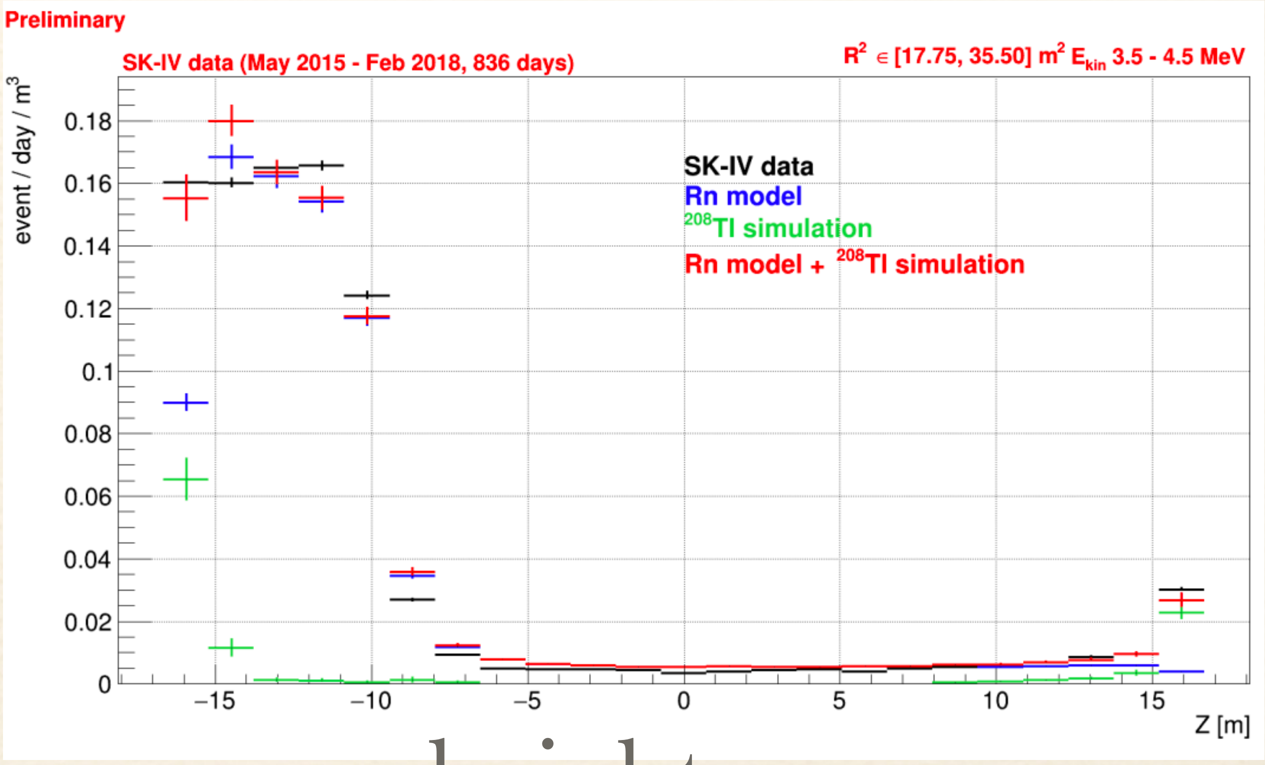
Radioactive Backgrounds

- lots of detectors have electrons that can serve as target for the signal …
- …but all have different radioactive background
- choose here: water target (either water Cherenkov or water-based liquid scintillator)
- … as it can make use of directionality in large detectors
- here's an example of a background model for Super-K



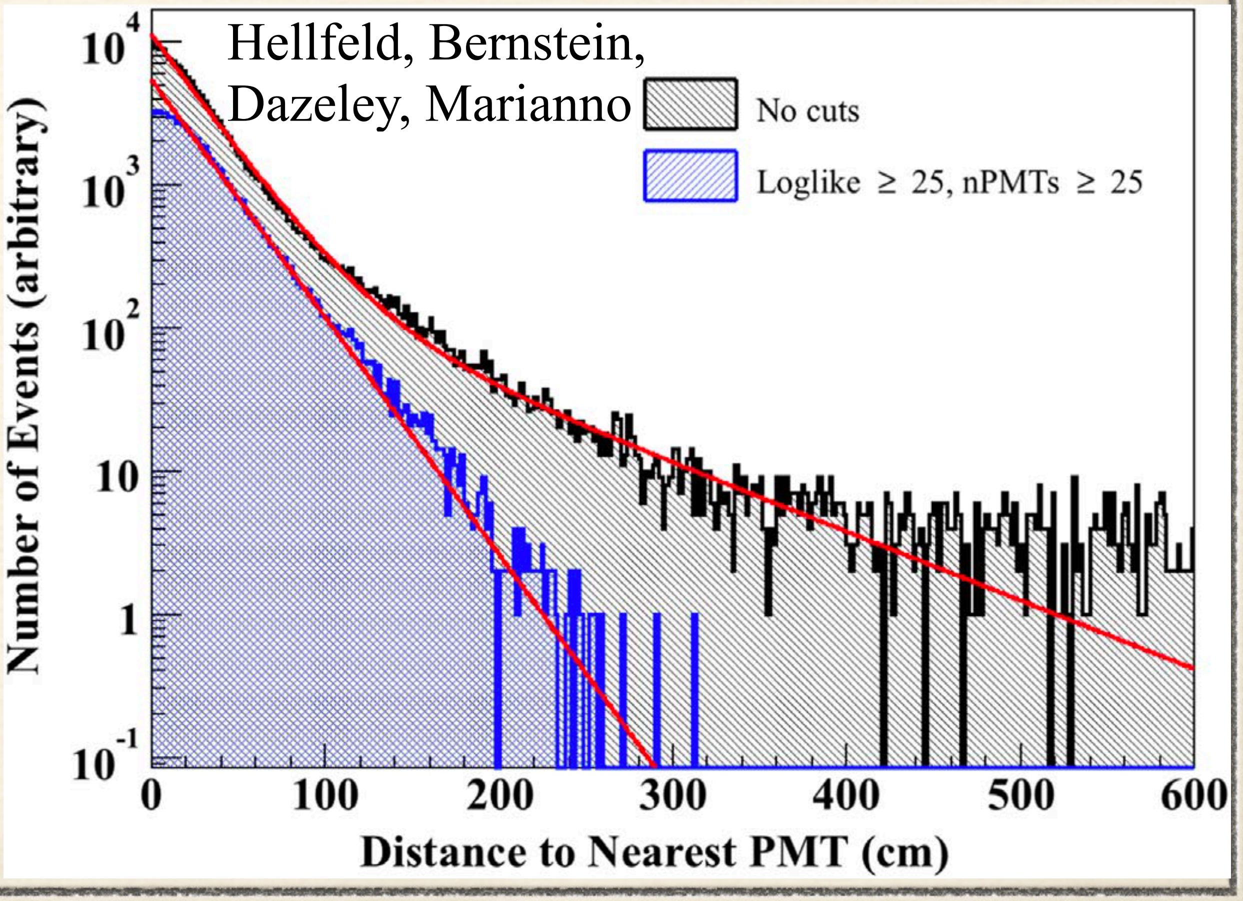
radial distribution



height

Radioactive Backgrounds: From the Detector Materials

- ^{214}Bi is a Radon daughter and is therefore found everywhere
- ^{208}Tl (and ^{40}K) are produced by the detector boundaries; not much will be in the water (or scintillator) ⟹remove by self-shielding
- calculate required radiopurity for a given detector size
- similar for scintillator (but should consider α's as well)
- liquid noble gases is a different case, however



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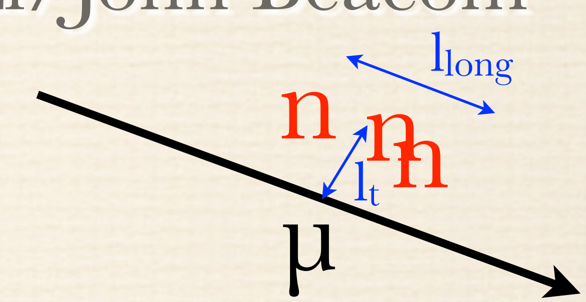
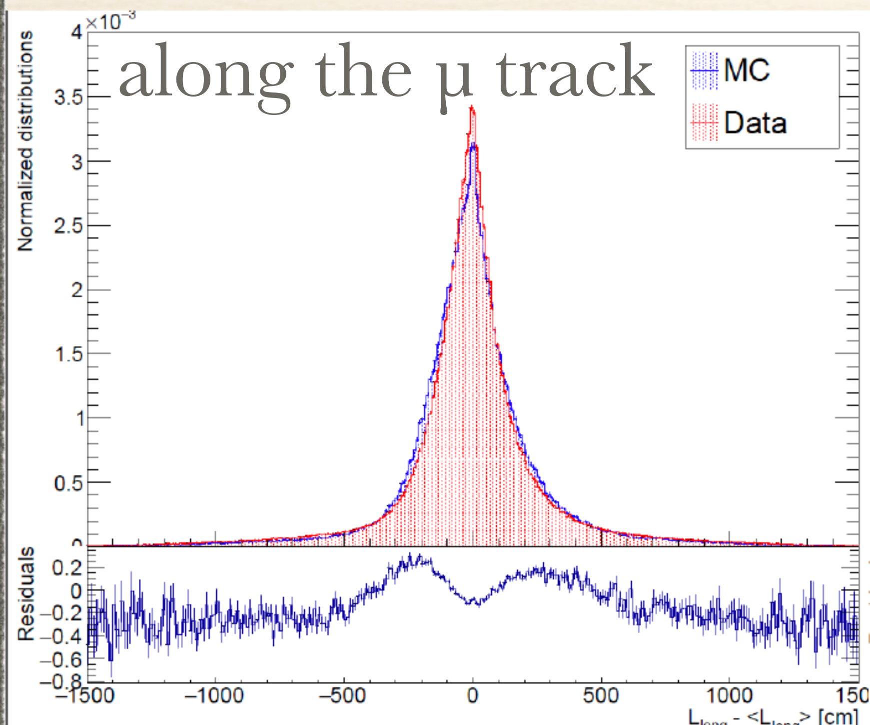
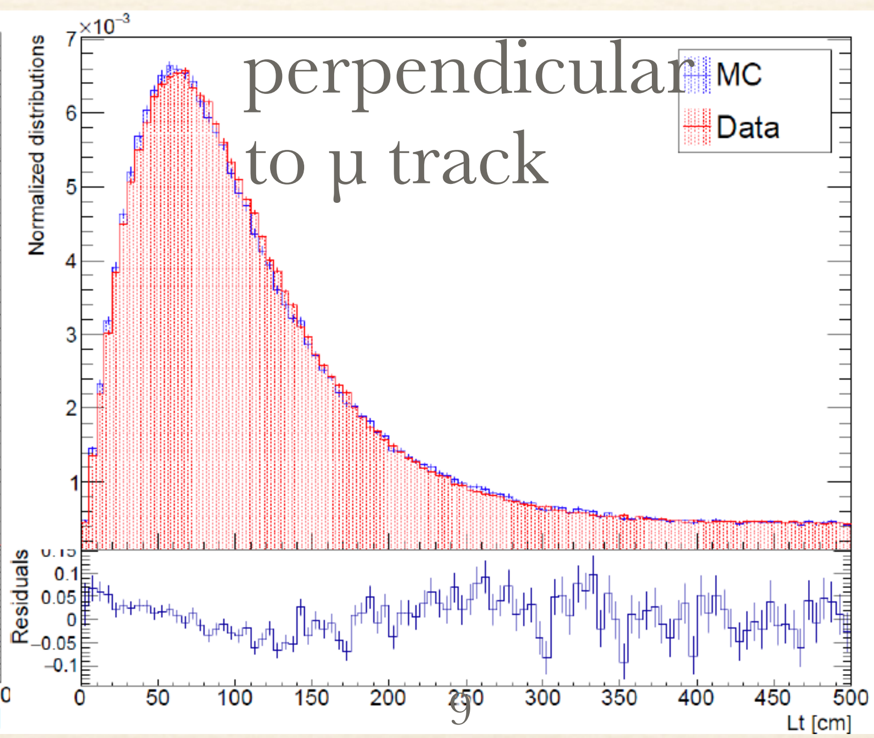
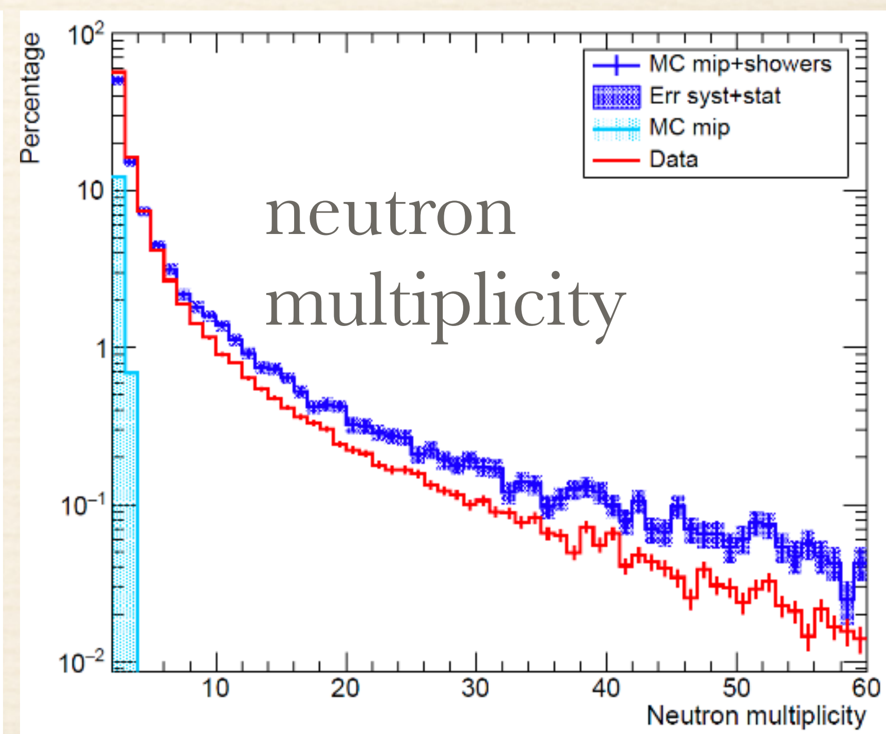
Cosmogenic Radioactive Backgrounds

- basically just ^{16}O spallation for water (or ^{12}C for scintillator)
- most of the spallation from showering muons, in particular hadronic showers
- FLUKA simulations in water by Super-K and Shirley Li/John Beacom
- use neutron tagging to measure hadronic showers
- more data will come from Super-K-Gd



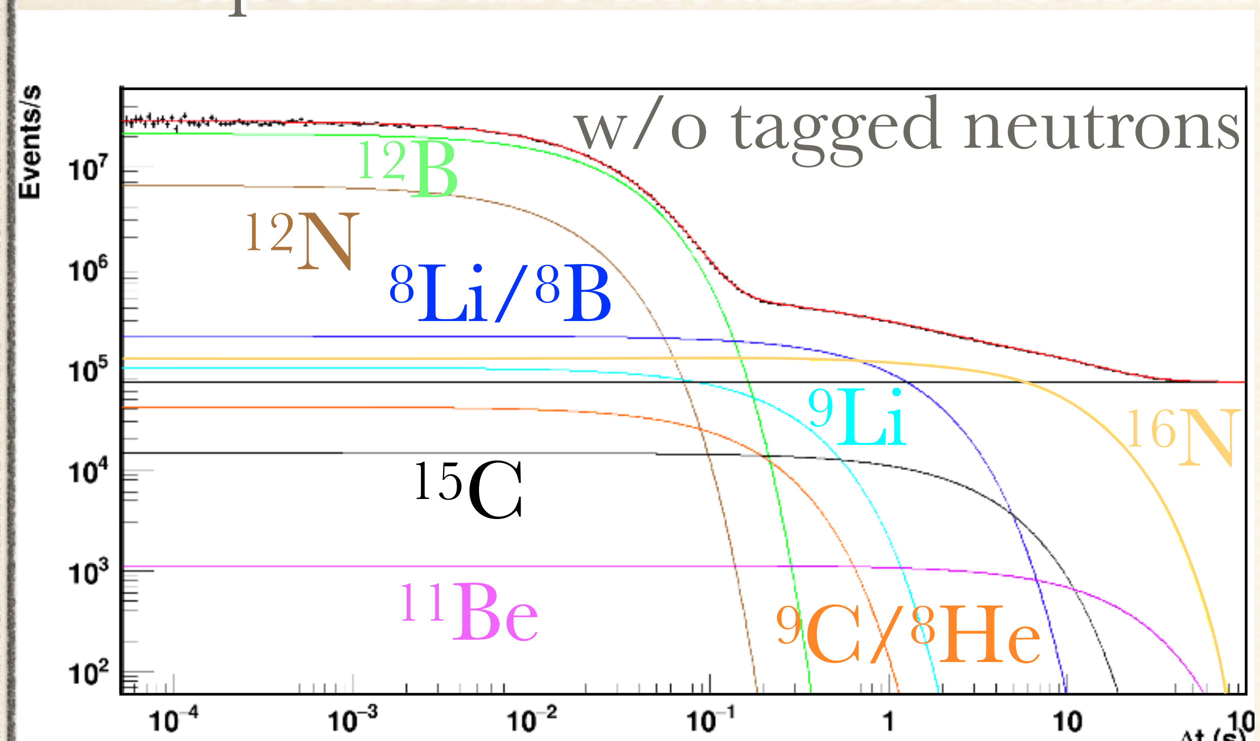


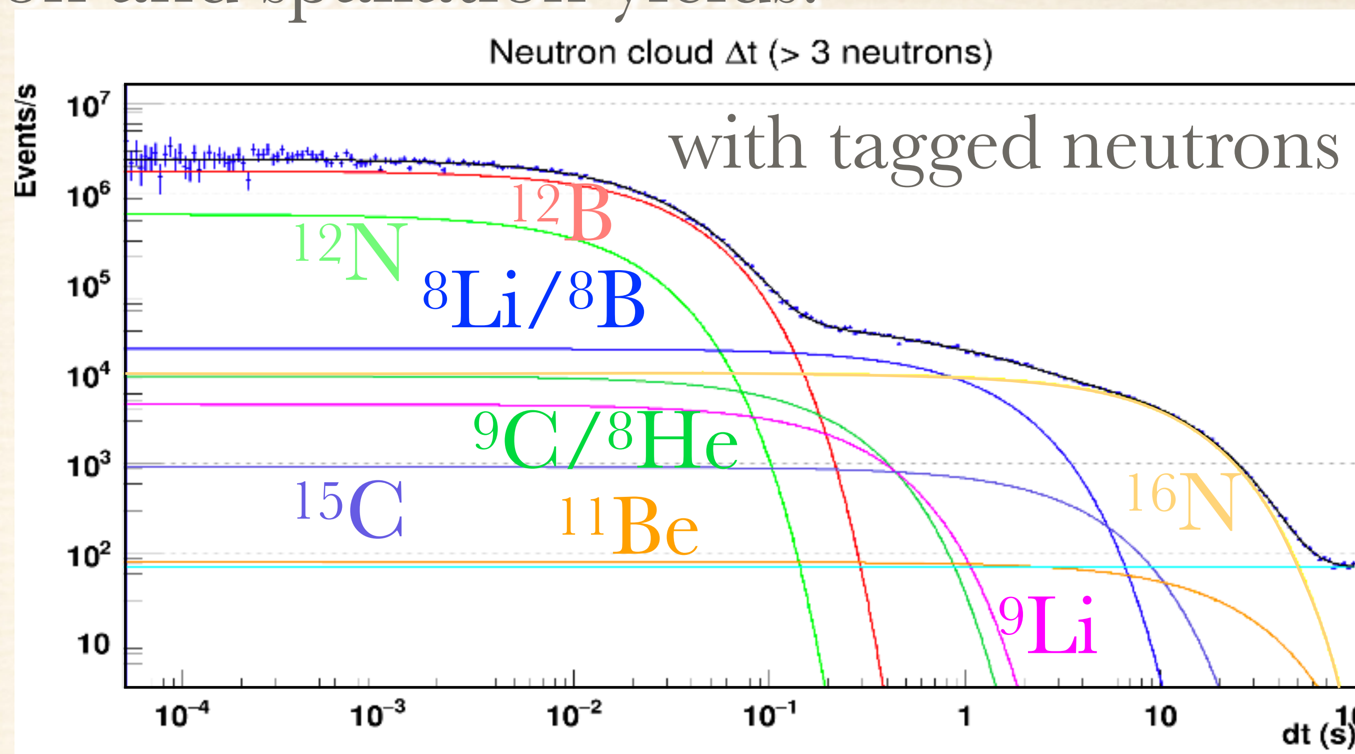


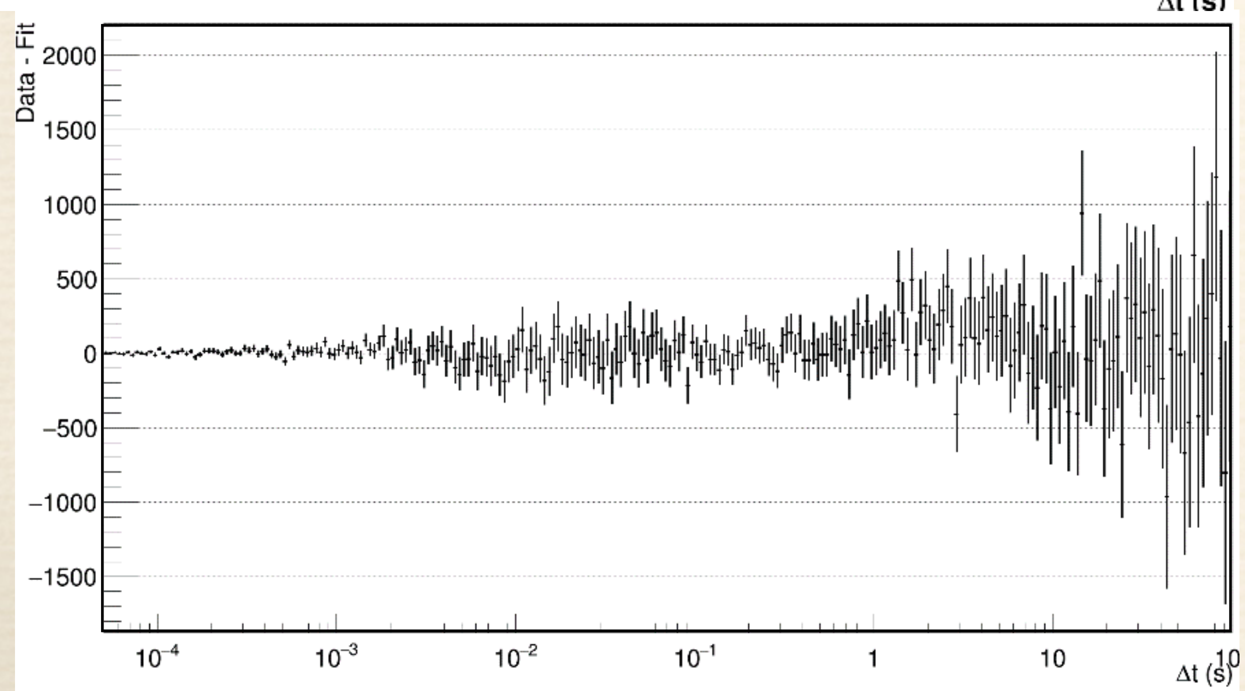


Cosmogenic Radioactive Backgrounds

- Super-K also measures the neutron and spallation yields:



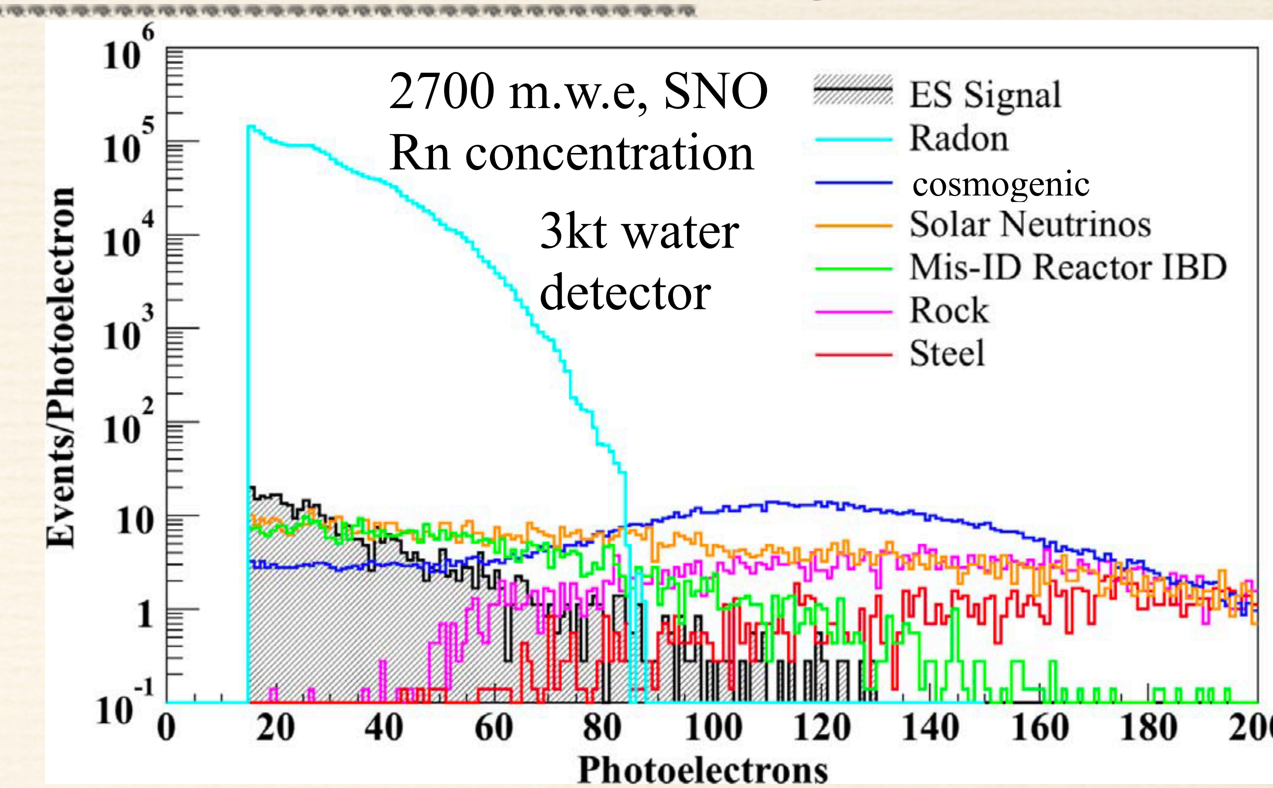


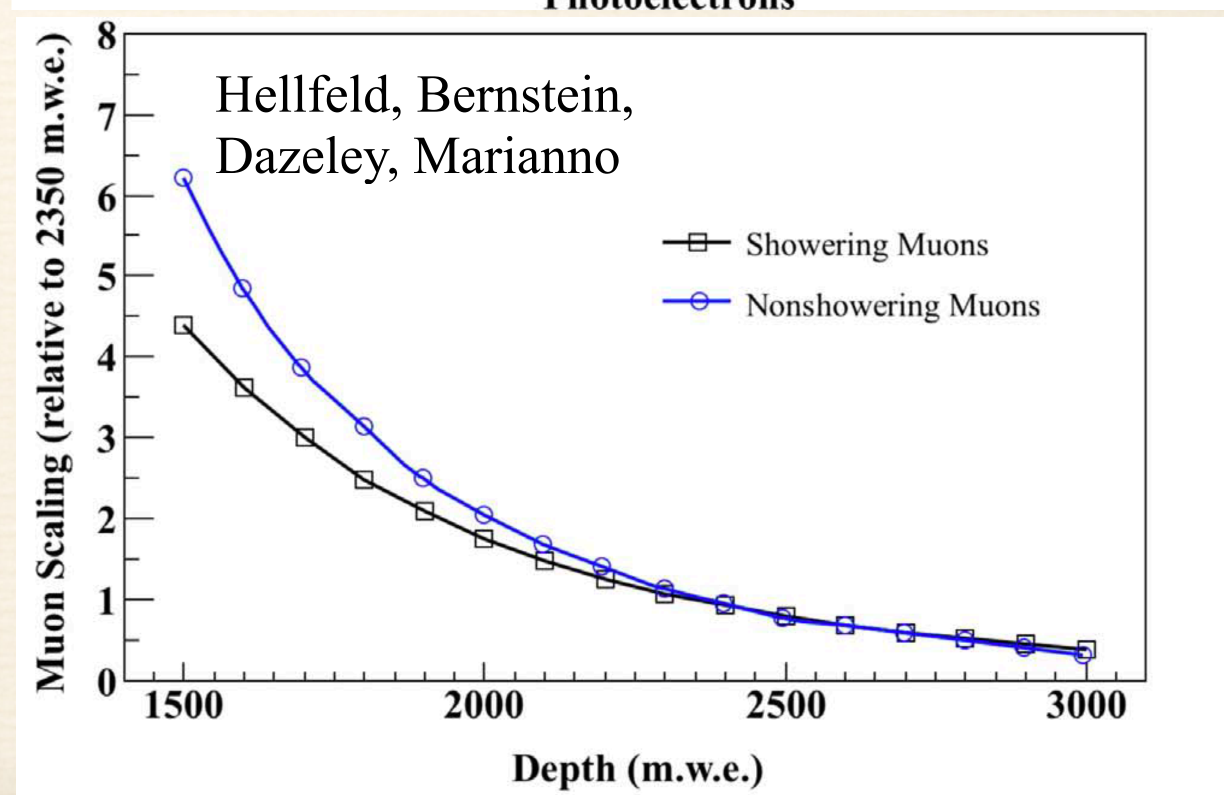


Isotope	Yield ($10^{-7}cm^2/g\mu$)	E
^{16}N	27.35±0.34±0.28	10.4
^{12}B	12.91±0.06±0.12	13.4
^{8}Li/^{8}B	5.11±0.10±0.50	~13.5
^{12}N	1.717±0.036±0.01	16.4
^{15}C	1.57±0.26±0.02	9.8
^{9}Li	0.67±0.19±0.01	13.6/10

Cosmogenic Radioactive Backgrounds: Depends on μ Flux

- IBD background assumes 20% mistag rate of neutrons
- assumed depth is the same as Super-K
- detector wall materials subdominant by self-shielding, PMTs are omitted
- Rn (^{214}Bi) is the main problem
- need to reduce contamination from SNO equivalent to 0.01 of SNO
- maybe using tight water flow control, similar to Super-K?





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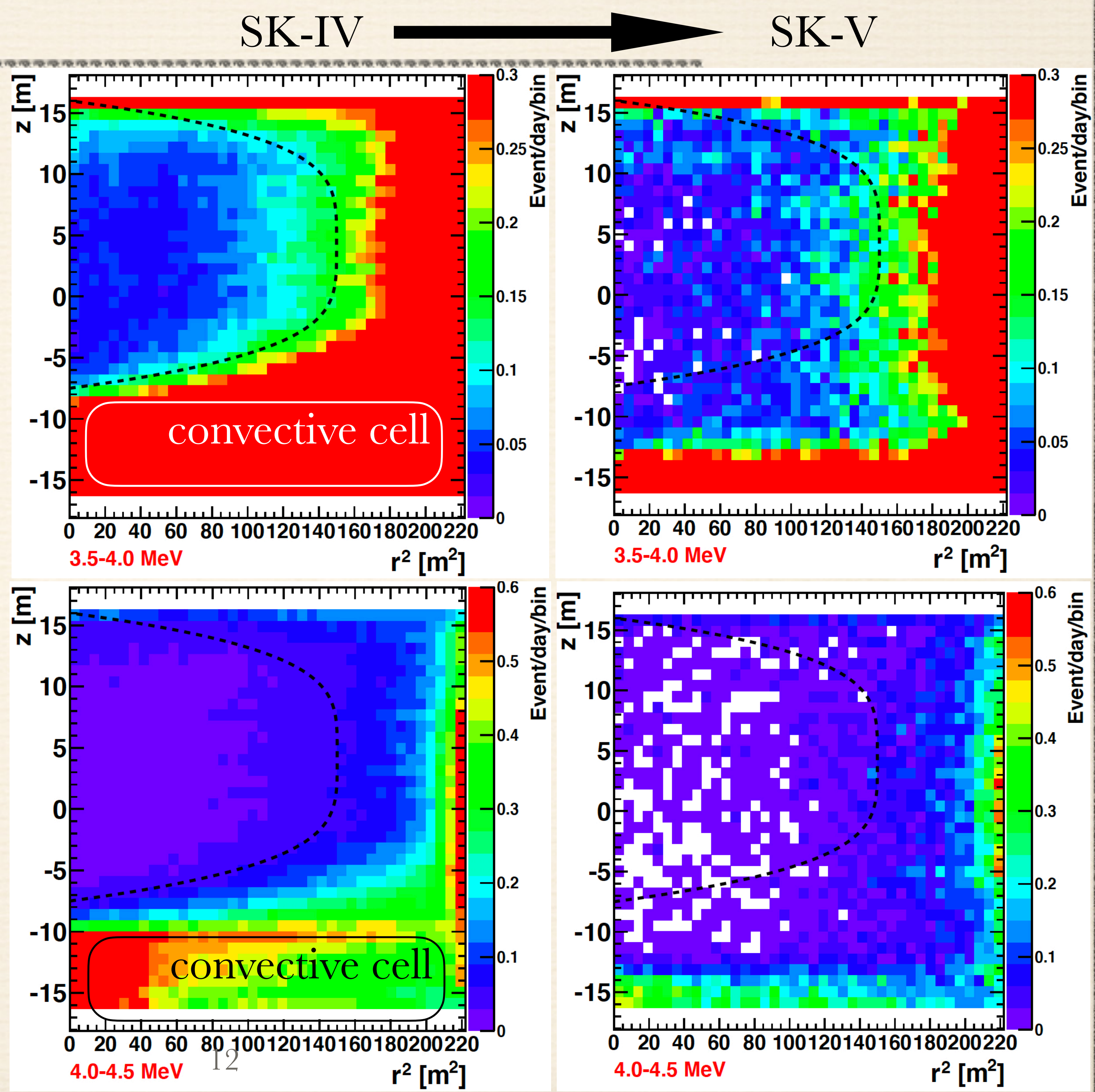
Water Flow Control in Super-K

- when Super-K fixed the water leak in 2018, water piping was also upgraded
- using carefully chosen injection and draining points as well as temperature control of injection water, convective cells are suppressed
- sometimes you need hydrodynamic data, not nuclear data!



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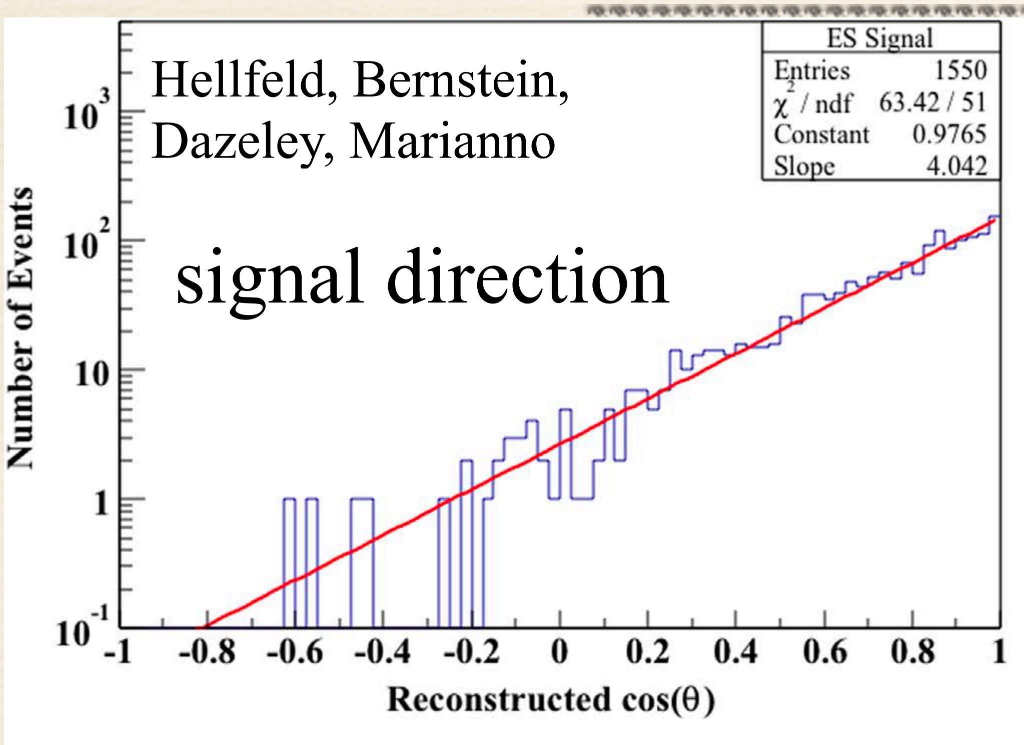
Example: 2000 m.w.e, 0.01 SNO Radon Concentration in Water



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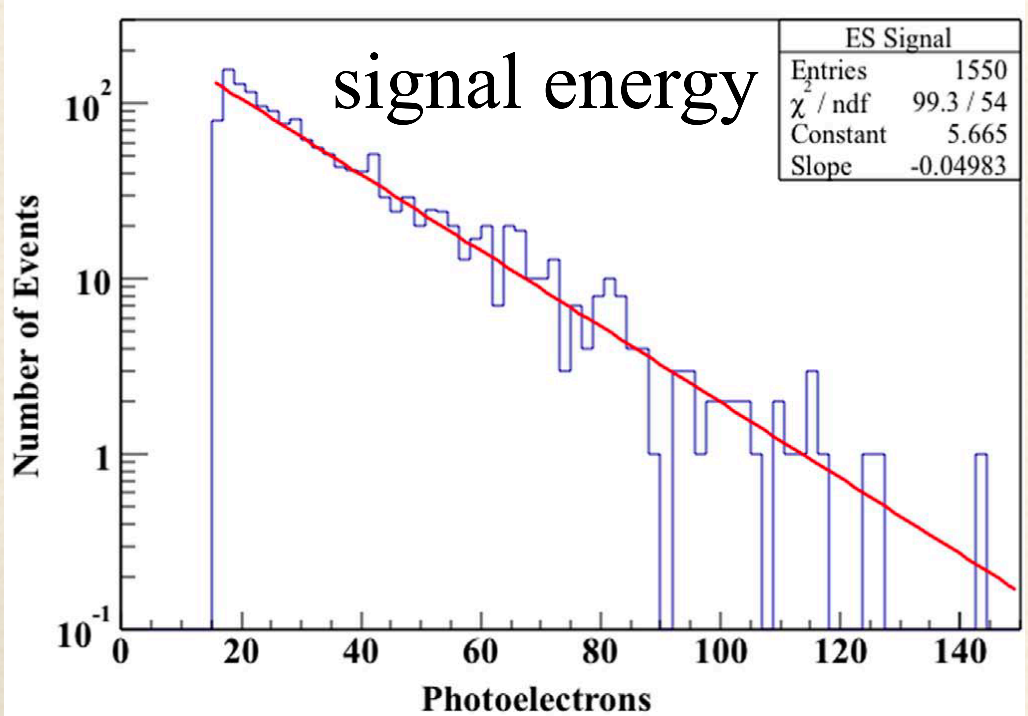

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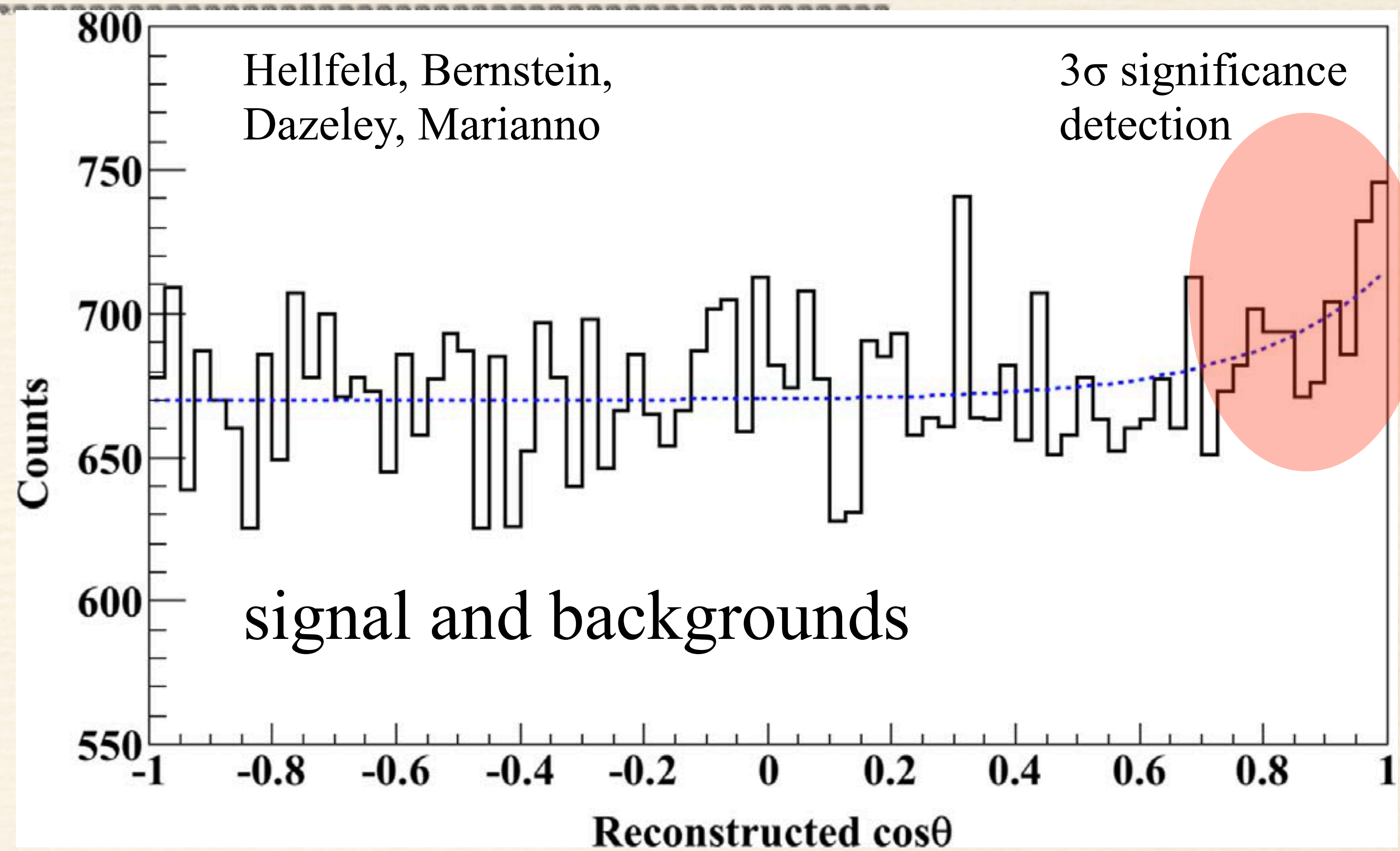

- simulated signal of a ~1kton fiducial mass detector from a 3.8 GW reactor 13 km away from the detector, observed for five years
- uses BONSAI event reconstruction (as does Super-K)

Liquid Argon TPCs

- no reactor IBDs (high threshold for anti-neutrinos)
- detailed tracking may result in superior pointing
- similar detector mass as water possible (within a factor of two or so)
- similar number of electrons/g (20/(40g/mol) compared to 10/(18g/mol))
- may need a different detector design than DUNE to get the best tracking and low energy threshold, high signal/noise (e.g. two-phase and/or pixel readout); would probably need some R&D
- need to know detector performance for ~2-8 MeV electrons, radioactivity (e.g. ^{39}Ar or ^{42}Ar, Radon daughters, neutron captures, cosmogenic)
- some data exists (to estimate DUNE solar neutrino sensitivity)

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Summary

- not the easiest way to detect reactor neutrinos from a distance!
- main advantage: directional detection (although coherent scattering may be able to this also)
- needs huge detectors
- realistically, this means either water (or water-based) detectors or liquid Argon TPCs (no IBD background there!)
- a lot of the required data already exists for water; (I don't know how much data exists for LArTPCs, but some does)