Antineutrinos From Neutron Capture

Patrick Jaffke

Virginia Tech
Applied Antineutrino Physics 2015

December 8, 2015

Sources of Corrections

NEUTRONS FOR SCIENCE vs. Daya Bay θ_{13}

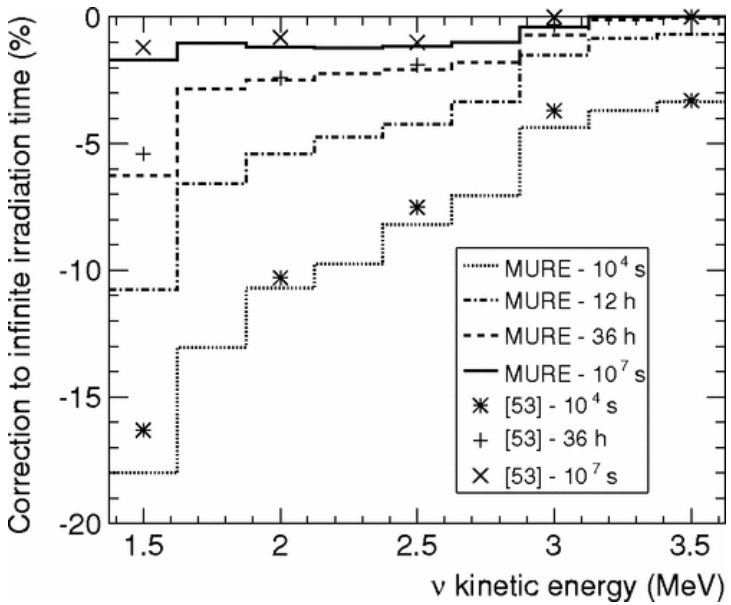
- Used 'single' fissile spectra
- Operated at high flux: $\mathcal{O}(10^{14}\,\mathrm{n/cm^2/sec})$
- Low irradiation time: $\leq 2\,\mathrm{d}$
- Measured beta-spectrum

- Mixture of all fissiles
- Operate at lower fluxes: $\mathcal{O}(10^{13}\,\mathrm{n/cm^2/sec})$
- **Much** higher irradiation times: $\sim 1\,\mathrm{yr}$

Non-equilibrium Correction

1. Mueller *et al.* conducted study in 2011 (PRC **83** 054615) ✓

- Long-lived nuclides building up in reactor environment
- Primarily from ^{90}Sr, ^{106}Ru, and ^{144}Ce

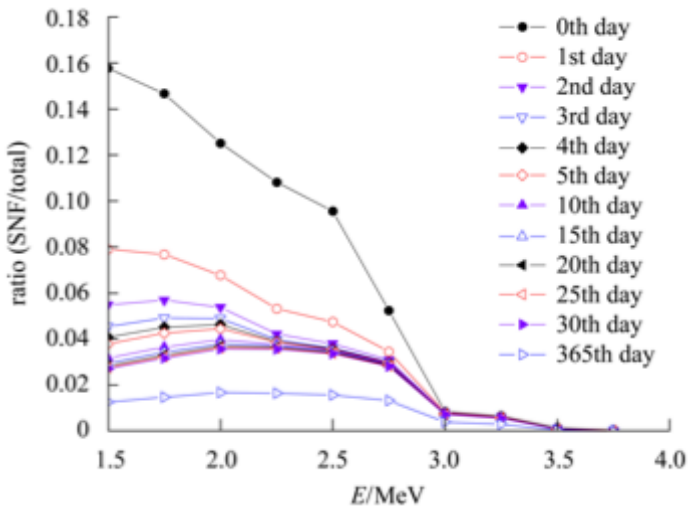


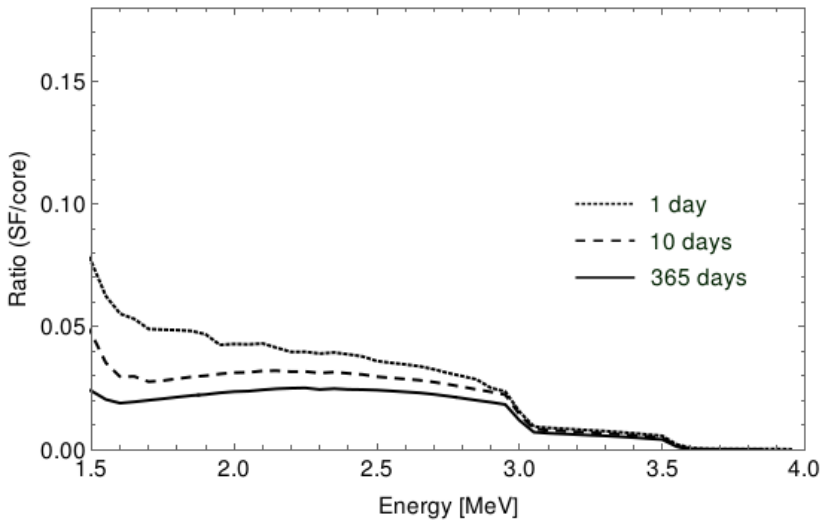
  - Low-E neutrino correction
  - ~ 1 – 4% correction for PWRs and typical irradiation periods

Spent Nuclear Fuel Correction

2. Zhou Bin *et al.* conducted study in 2012 (Chin.Phys. C **36** 1-5) and indepedently verified by PJ ✓

- Long-lived nuclides in nearby spent fuel pools
- Primarily from ^{90}Sr, ^{106}Ru, and ^{144}Ce (again)





- $\sim 1-3\%$ low-E neutrino correction for typical PWRs

Non-linear Correction

3. **Correction arising from neutron-capture in the reactor**

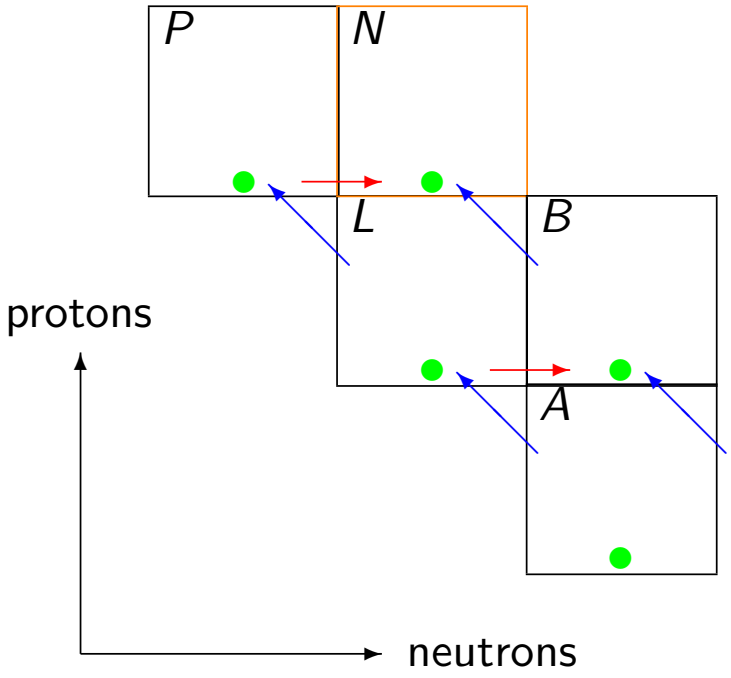
- Neutron capture **usually** small contribution (decay dominates)
- However, some nuclides are dominantly produced by neutron capture!

Goals:

1. Overall size of the non-linear (NL) correction
2. Spectral shape of the correction
3. Dependence on the reactor

Linear Nuclides

- Most nuclide production (destruction) dominated by fission or beta-decays (beta-decays)

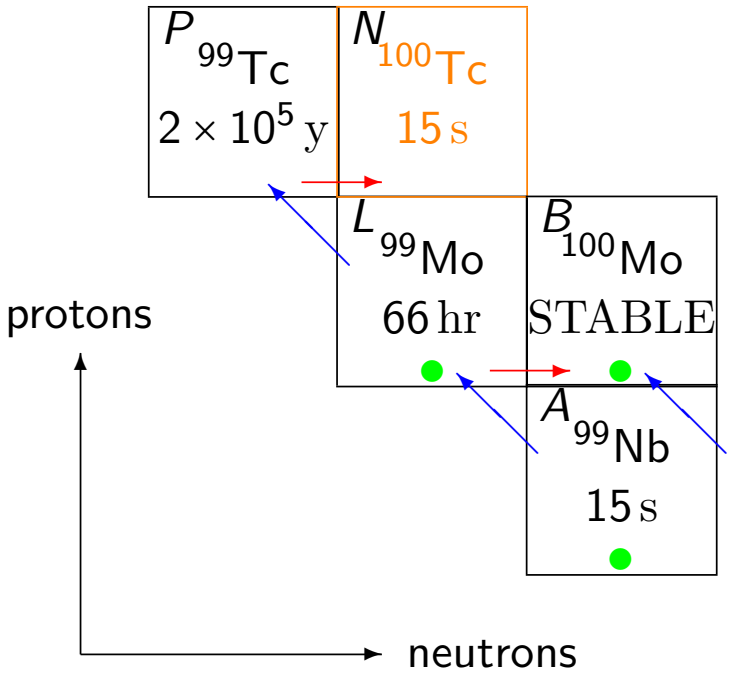


$$\frac{dN_N}{dt} = \vec{Y}_N \cdot \vec{\mathcal{F}} - (\lambda_N + \phi\sigma_N)N_N + \lambda_B N_B + \phi\sigma_P N_p$$

- Equilibrium decay rate linear in ϕ as $\vec{\mathcal{F}} = \phi\vec{\Sigma}_f$

Non-linear (NL) Nuclides

- Non-linear effect arises from nuclides with dominating neutron-capture components ($\phi\sigma_P N_P$)



$$\frac{dN_N}{dt} = \cancel{\vec{Y}_N \cdot \vec{\mathcal{F}}} - (\lambda_N + \cancel{\phi\sigma_N})N_N + \cancel{\lambda_B} N_B + \phi\sigma_P N_p$$

- Now, ^{100}Tc is a non-linear nuclide!

Non-linear Candidates

About 30 nuclides satisfy the format; shorten via...

1. Large precursor cumulative fission yield $\sum_{f=1}^{N_f} Z_P^f \geq 0.025$
2. Large neutron capture cross-section σ_P^c
3. Non-linear nuclide N decays sufficiently quickly
4. Beta-decay of N has $E_0 \geq 1.8\,\mathrm{MeV}$

		^{100}Tc	^{104}Rh	^{110}Ag	^{142}Pr
N E_0 (MeV)		3.2	2.45	2.9	2.15
N $\tau_{1/2}$ (sec)		15.54	42.3	24.6	68830
P Cumul. Fission Yields (atoms/fiss.)	^{235}U(522b)	0.061	0.031	0.00029	0.059
	^{239}Pu(698b)	0.062	0.069	0.017	0.052
	^{241}Pu (950b)	0.056	0.065	0.030	0.049
P σ_P^c (b)		17.0	127	80.9	6.53
L $\tau_{1/2}^L$ (d)		2.75	39.3	0.57	32.5
L σ_L^c (b)		1.57	7.08	18.2	26.7

Non-linear Limits

- First, L must be in equilibrium to produce P, so $T_{irr} > \tau_{L1/2}$
- Next, ϕ must be large enough to promote $P(n,\gamma)N$, but not too large such that $N_L \lambda_L < N_L \phi \sigma_L^c$
  - Critical flux given by $\tilde{\phi} = \frac{\ln 2}{\tau_{L1/2}} \frac{1}{\sigma_L^c}$

$$\hookrightarrow \tilde{\phi} = 9 \times 10^{15} - 2 \times 10^{18}\,\mathrm{n/cm^2/sec} \text{ (unphysical)}$$

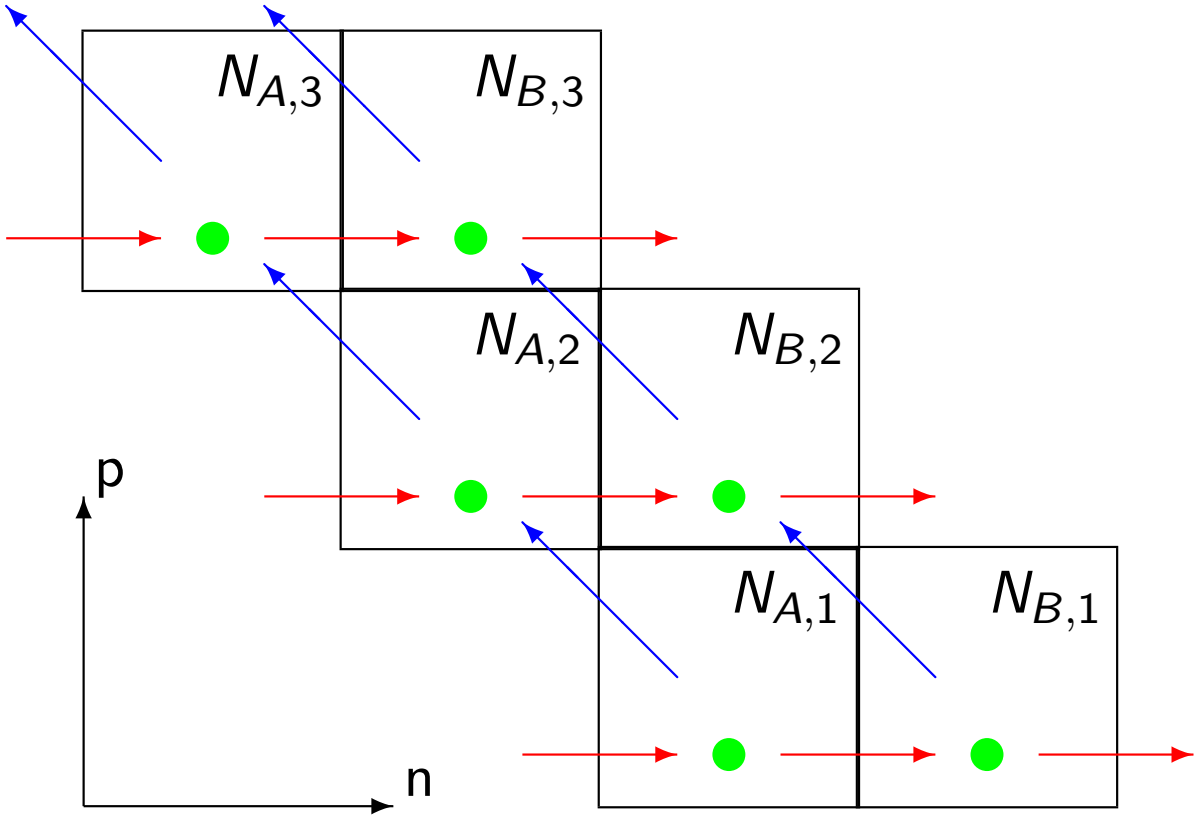
- If $T_{irr} > \tau_{L1/2}$ and $\phi < \tilde{\phi}$ the non-linear decay rate is given by

$$\Gamma_{non-linear} = \underbrace{\sigma^{\mathrm{fiss}} \phi Z_P T_{\mathrm{irr}}}_{\text{atoms } N_P} \sigma_P^c \phi \propto T_{\mathrm{irr}} \phi^2$$

- Decay rate proportional to $\phi^2 T_{irr}$ (non-linear) instead of ϕ (linear)

Set-up

- Start with the famous Bateman equations
- Originally used simple decay-only chain
- Generalize with inclusion of fission and neutron capture



$$\frac{dN_{\alpha,i}}{dt} = \vec{Y}_{\alpha,i} \cdot \vec{\mathcal{F}} + \lambda_{\alpha,i-1} N_{\alpha,i-1} + \sigma_{\alpha-1,j} \phi N_{\alpha-1,j} - \tilde{\lambda}_{\alpha,i} N_{\alpha,i}$$

$$\tilde{\lambda} = \lambda + \sigma\phi \qquad \vec{\mathcal{F}} = \{\mathcal{F}_{\mathrm{U235}}, \mathcal{F}_{\mathrm{Pu239}}, \mathcal{F}_{\mathrm{Pu241}}\} \qquad \vec{Y}_{\alpha,i} = \{Y^{\alpha,i}_{\mathrm{U235}}, Y^{\alpha,i}_{\mathrm{U235}}, Y^{\alpha,i}_{\mathrm{U235}}\}$$

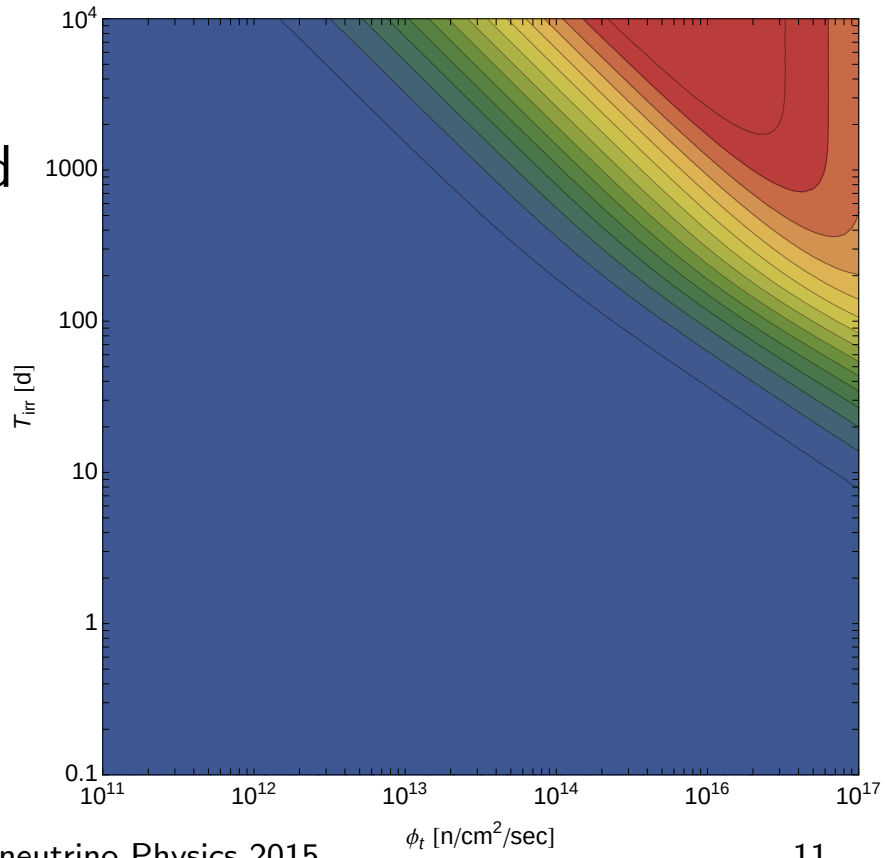
Analytical Solution

- Need to solve 3 linearly coupled non-homogeneous diff. eqn.s

$$\frac{dN_L}{dt} = \vec{Z}_L \cdot \vec{\mathcal{F}} - \tilde{\lambda}_L N_L \qquad \frac{dN_P}{dt} = \vec{Y}_P \cdot \vec{\mathcal{F}} + \lambda_L N_L - \phi \sigma_P^c N_P$$

$$\frac{dN_N}{dt} = \phi \sigma_P^c N_P - \lambda_N N_N$$

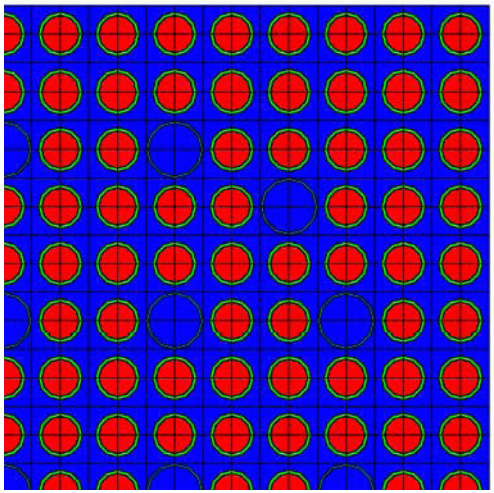
- Analytical solution yields expected limits (turn-off at high flux and increase with T_{irr})
- Abundance peaks for a "sweet-spot" flux



SCALE Intro

- SCALE converts core structure into 0d cross-section object
- Depletes core along power history supplied

$$\frac{dN_i}{dt} = \sum_{j=1}^{m} l_{ij}\lambda_j N_j + \bar{\Phi}\sum_{k=1}^{m} f_{ik}\sigma_k N_k - (\lambda_i + \bar{\Phi}\sigma_i)N_i$$



- w17 × 17 very similar to Daya Bay/Ling Ao cores!
- SCALE provides nuclide abundance and fission rates at all time intervals

Calculating Non-linear Contribution

Use SCALE to compute the non-linear correction:

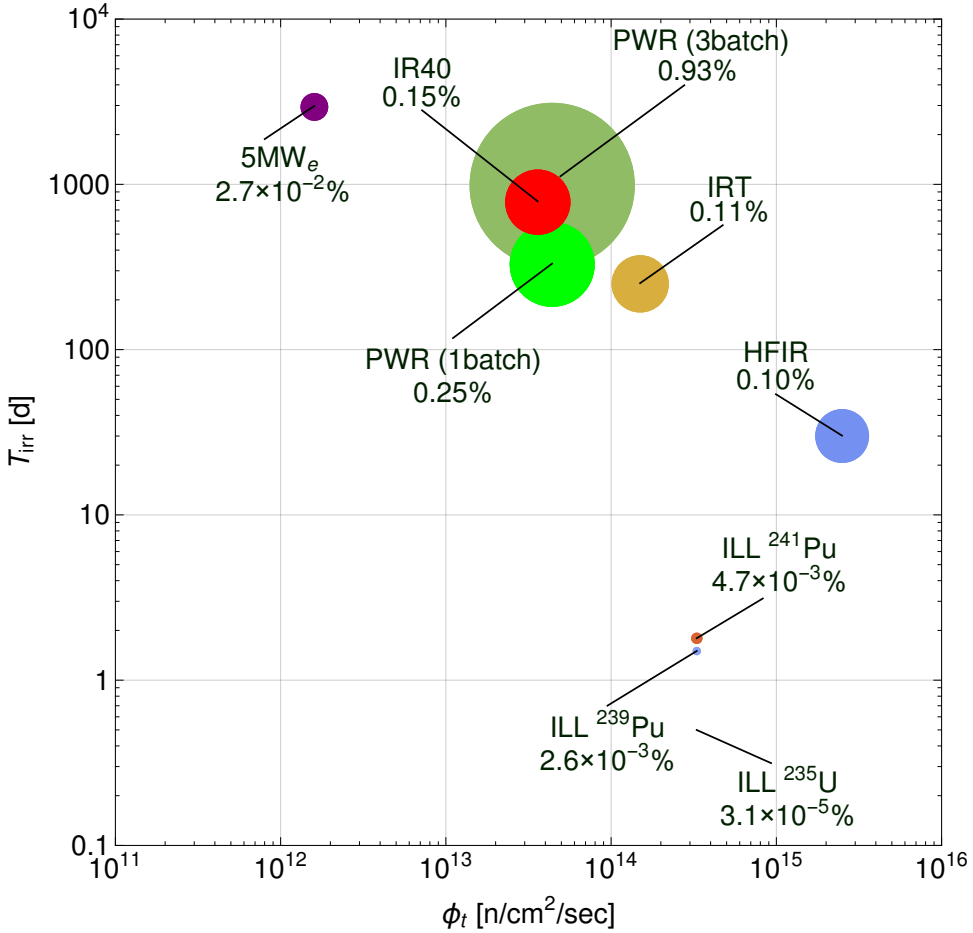
1. Irradiate various reactors to their typical power history
2. Pull non-linear abundances and compute non-linear neutrino spectrum: $\Phi_{NL}(t, E)$
3. Pull fission rates and compute the reactor spectrum: $\Phi_{Rx}(t, E)$
4. Compute time-averaged non-linear correction: $\langle \Phi_{NL}(t, E)/\Phi_{Rx}(t, E) \rangle_{T_{irr}}$

Computational Results

Results:

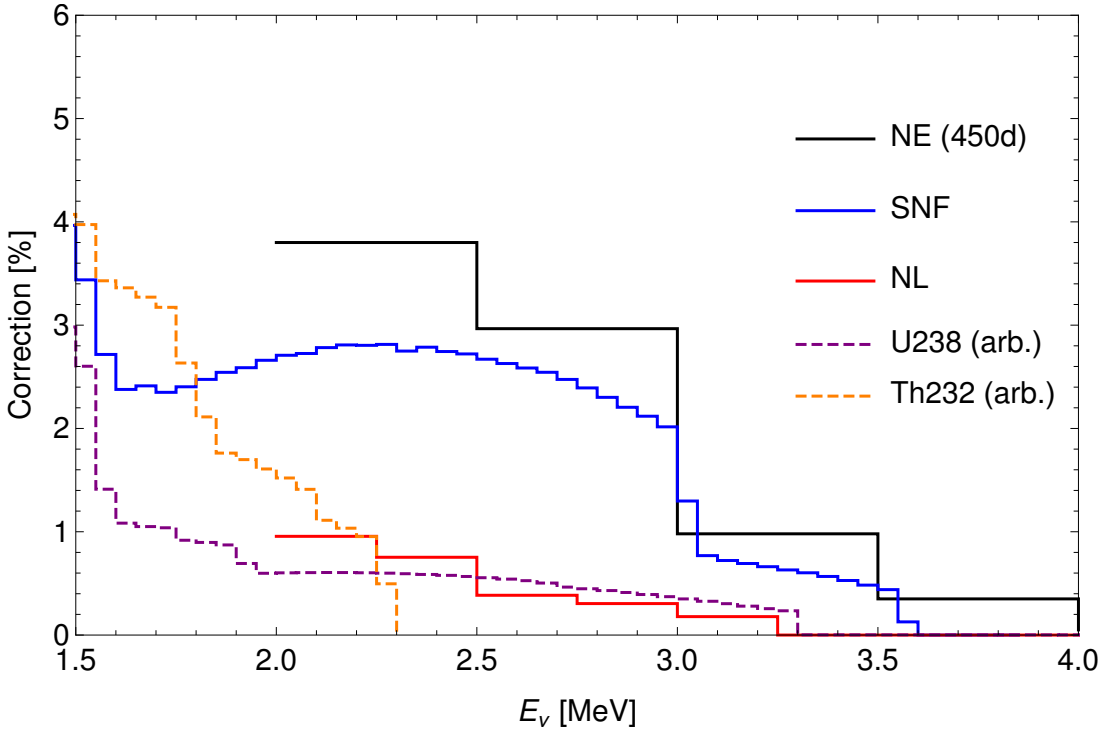
	$5\,\mathrm{MW_e}$	IR40	PWR		IRT	ILL			HFIR
			1-batch	3-batch		^{235}U	^{239}Pu	^{241}Pu	
Fuel/Moderator	NU+C	NU+D_2O	LEU+H_2O		HEU+H_2O	HEU+D_2O			HEU+H_2O
Burn-up [MWd/t]	32380	31200	31510	1890000	2230	7.3×10^{-5}	1.1×10^{-4}	1.7×10^{-4}	2550
$\phi\,[\mathrm{n/cm^2/sec}]$	1.6×10^{12}	3.6×10^{13}	4.4×10^{13}	4.4×10^{13}	1.5×10^{14}	3.3×10^{14}	3.3×10^{14}	3.3×10^{14}	2.5×10^{15}
Max[$\langle \Phi_{\mathrm{NL}}/\Phi_{\mathrm{R}} \rangle_T$] [%]	0.027	0.15	0.25	0.93	0.11	3.1×10^{-5}	2.6×10^{-3}	4.7×10^{-3}	0.10

Non-linear Results



- Larger corrections for "sweet-spot" flux and high T_{irr} (i.e. high burnup)
- Small corrections for $T_{irr} \ll 30\,\mathrm{d}$ (ILL measurements are safe)
- **Commercial reactors** can see a maximum non-linear effect ~ **1%**
- Results in arXiv:1510.08948

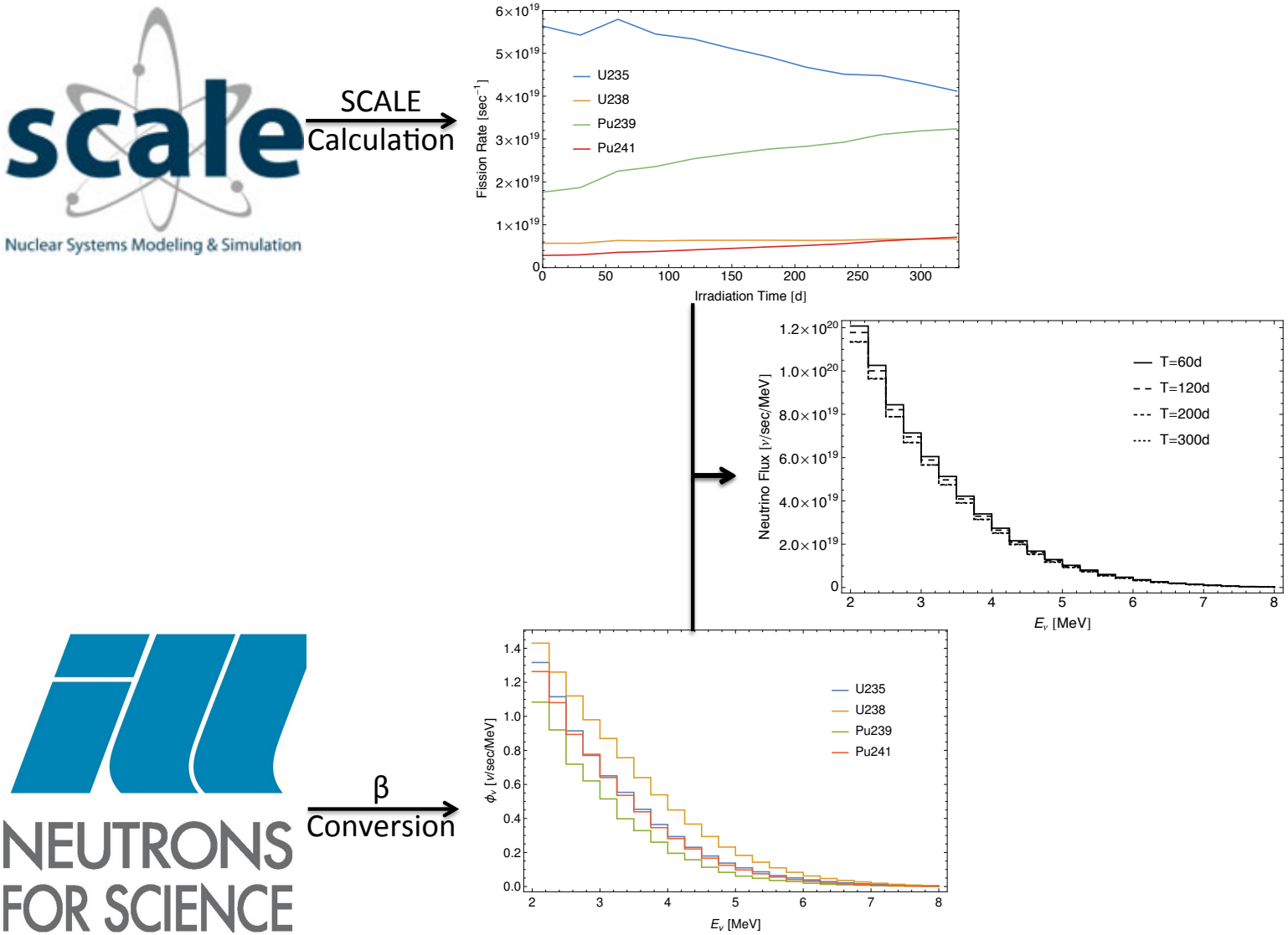
Correction Summary



- Three corrections all with $\mathcal{O}(1\%)$ effects
- All corrections require detailed reactor simulations (and could be more!)
- Directly impacts geoneutrino searches

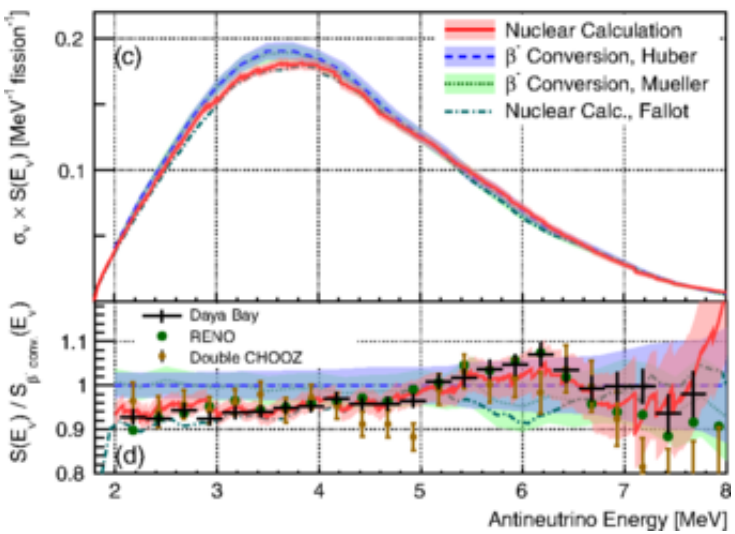
Thank you!

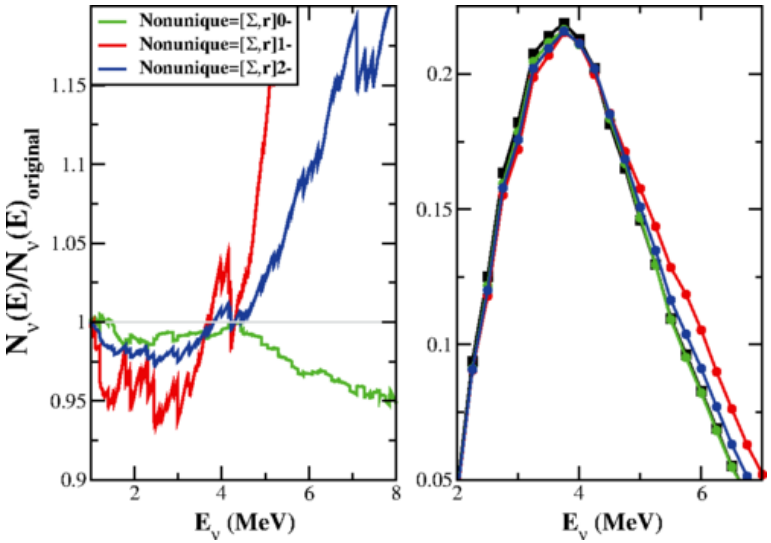
Producing a Reactor Spectrum



Other Corrections?

3. Shape/Forbiddenness Corrections (Hayes + Dwyer)?

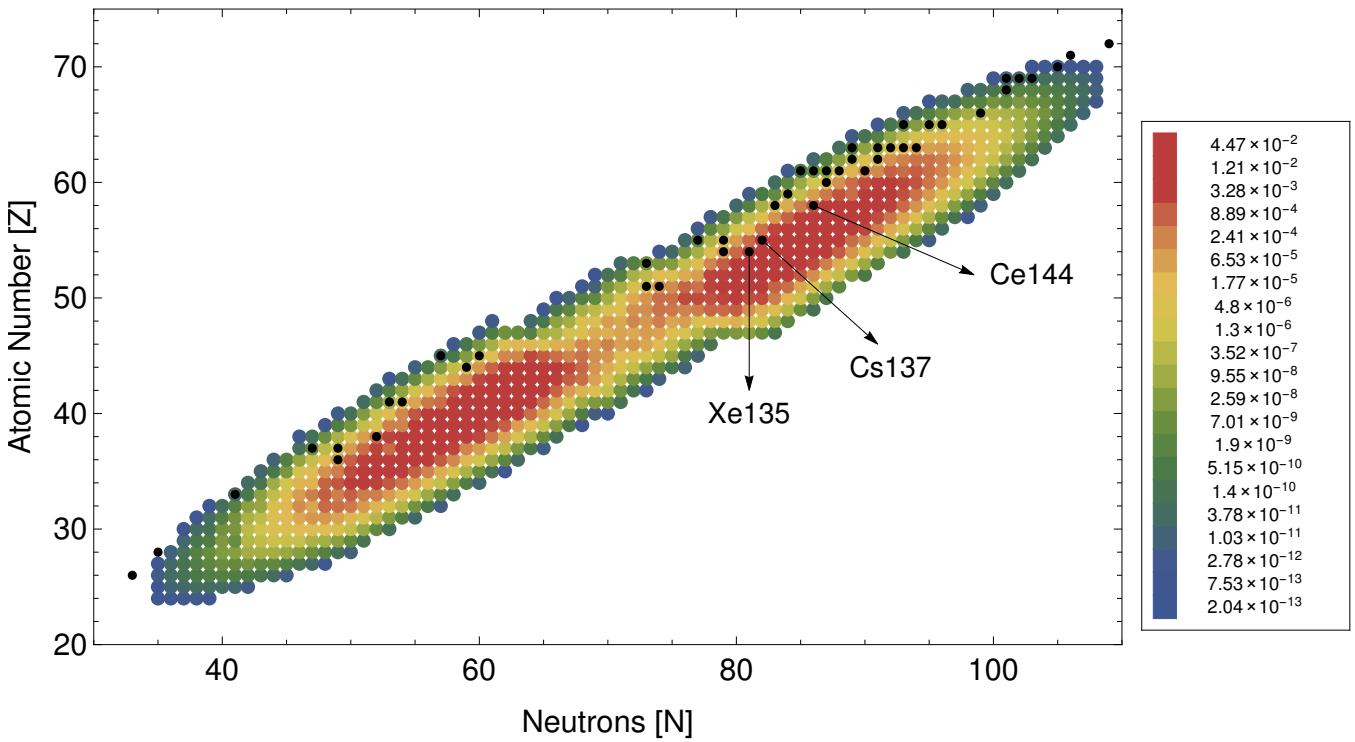




4. **Neutron-capture (i.e. Non-linear) Correction?**
5. ???

Non-linear Nuclides

- Test all nuclides in JEFF yields (900) for their linearity
- Those with $\lambda \sim \tilde{\phi}\sigma_c$ for $\tilde{\phi} \leq 10^{17}\,\mathrm{n/cm^2/sec}$ given in black



Analytical Solution

- Solutions for L and P are...

$$N_L(t) = \left[\frac{\vec{Z}_L \cdot \vec{\mathcal{F}}}{\tilde{\lambda}_L}\right]\left(1 - e^{-\tilde{\lambda}_L t}\right)$$

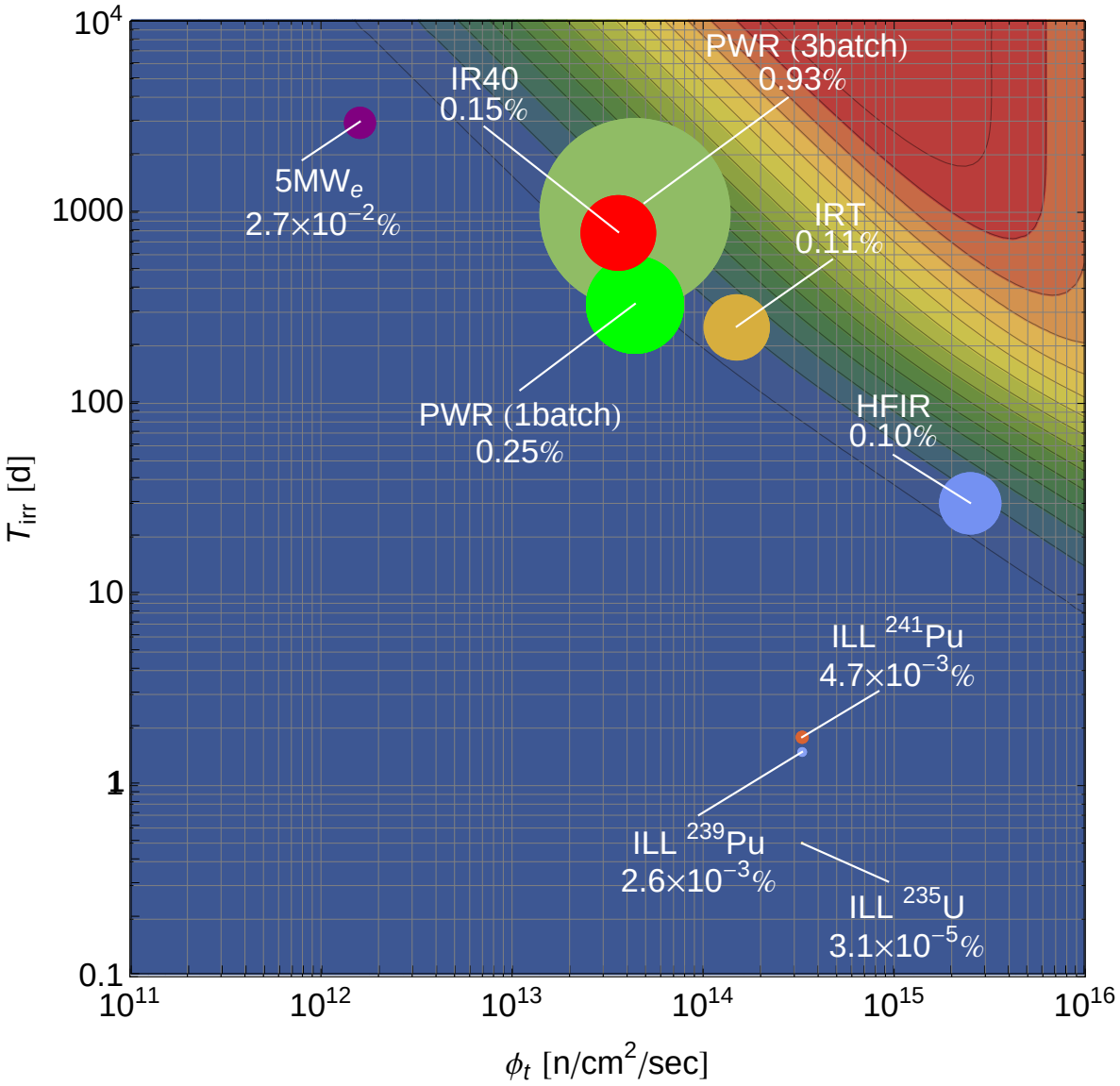
$$N_P(t) = \left[\frac{\lambda_L \vec{Z}_L \cdot \vec{\mathcal{F}} + \tilde{\lambda}_L \vec{Y}_P \cdot \vec{\mathcal{F}}}{\phi\sigma_P \tilde{\lambda}_L}\right]\left(1 - e^{-\phi\sigma_P t}\right) - \left[\frac{\lambda_L \vec{Z}_L \cdot \vec{\mathcal{F}}}{\tilde{\lambda}_L(\phi\sigma_P - \tilde{\lambda}_L)}\right]\left(e^{-\tilde{\lambda}_L t} - e^{-\phi\sigma_P t}\right)$$

Analytical Solution

- Solution for N is...

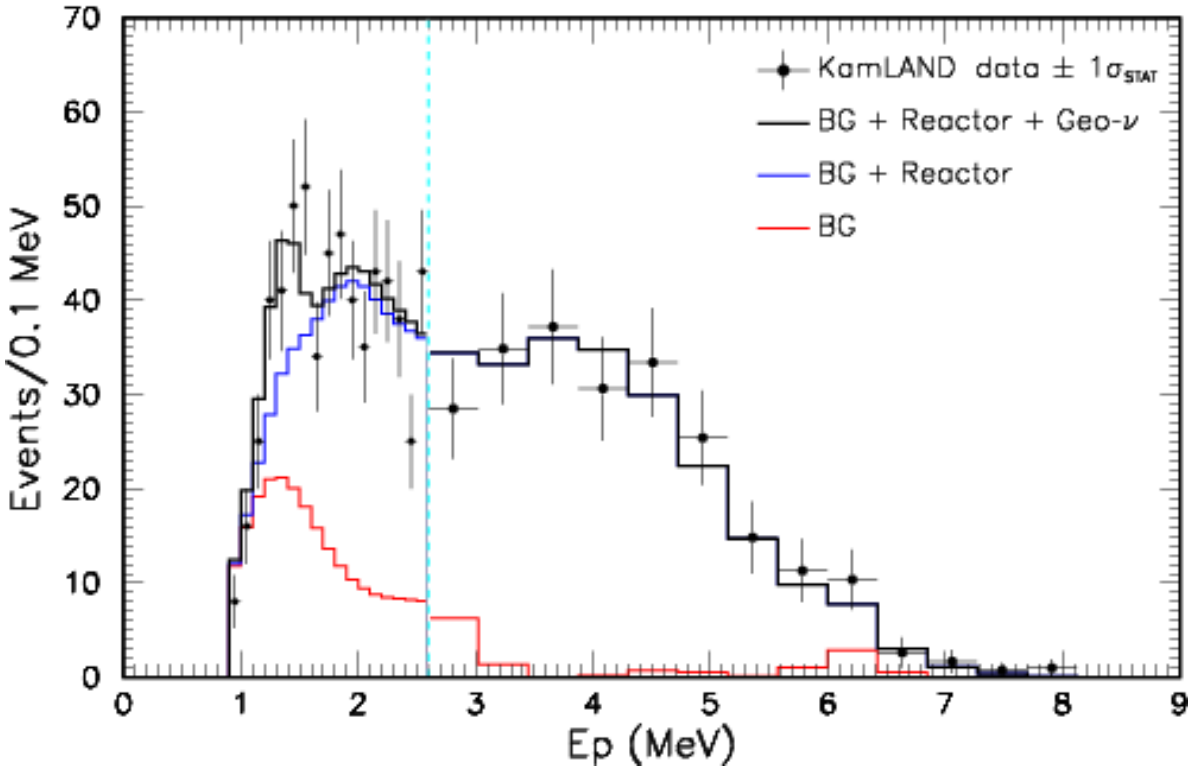
$$
\begin{aligned}
N_N(t) = &\left[\frac{\tilde{\lambda}_L \vec{Y}_F \cdot \vec{\mathcal{F}} + \lambda_L \vec{Z}_L \cdot \vec{\mathcal{F}}}{\tilde{\lambda}_L \tilde{\lambda}_N}\right]\left(1 - e^{-\tilde{\lambda}_N t}\right) \\
&+ \left[\frac{\lambda_L \phi \sigma_F \vec{Z}_L \cdot \vec{\mathcal{F}}}{\tilde{\lambda}_L(\tilde{\lambda}_L - \phi\sigma_F)(\tilde{\lambda}_N - \tilde{\lambda}_L)}\right]\left(e^{-\tilde{\lambda}_L t} - e^{-\tilde{\lambda}_N t}\right) \\
&- \left[\frac{(\tilde{\lambda}_L - \phi\sigma_F)\vec{Y}_F \cdot \vec{\mathcal{F}} + \lambda_L \vec{Z}_L \cdot \vec{\mathcal{F}}}{(\tilde{\lambda}_L - \phi\sigma_F)(\tilde{\lambda}_N - \phi\sigma_F)}\right]\left(e^{-\phi\sigma_F t} - e^{-\tilde{\lambda}_N t}\right)
\end{aligned}
$$

Analytical vs. Computational



Correction Result

- 1 – 8% correction for low-E reactor $\bar{\nu}_e$ could swamp geoneutrino signal



PRD 82 093006 (2010)