Very Short Baseline Searches for Sterile Neutrinos with Reactors and Sources

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Outline

- Sterile Neutrino Physics
- Experimental Prospects
- Source Production
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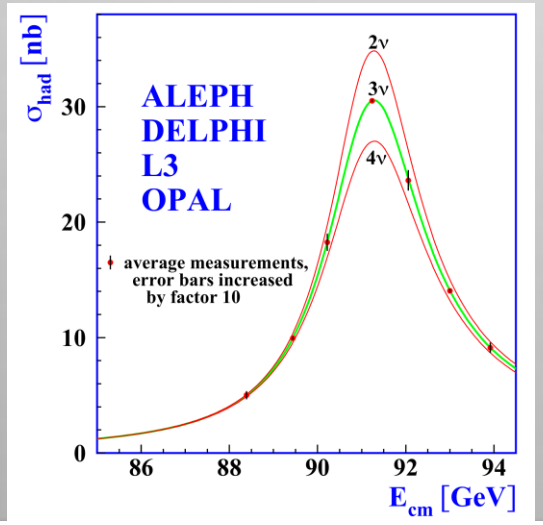
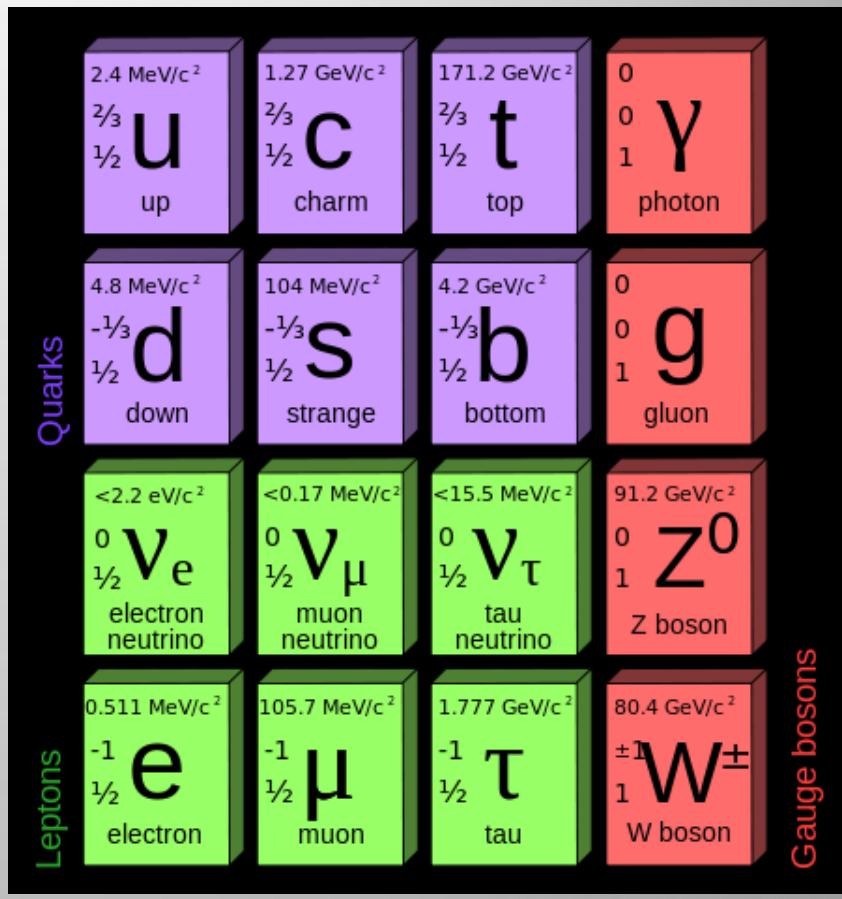
Sterile Neutrino Primer – Neutrinos and the Standard Model

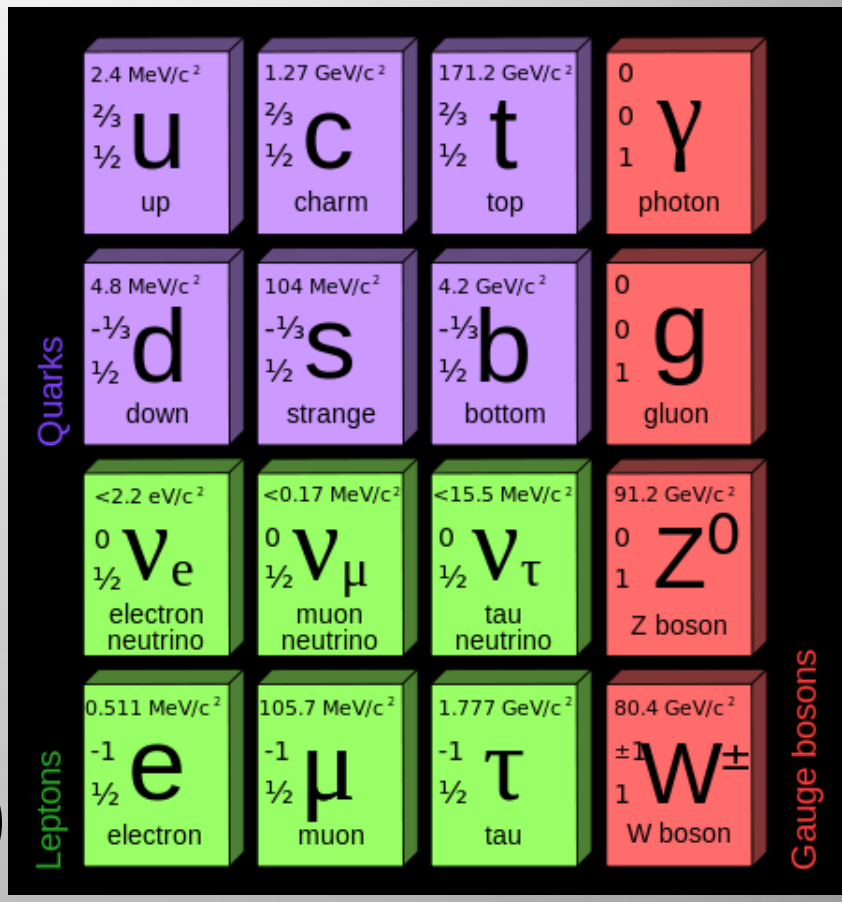
- Neutrinos are the neutral leptons
  - Flavors corresponding to charged leptons (e, μ, τ)
- Three flavors measured by LEP:





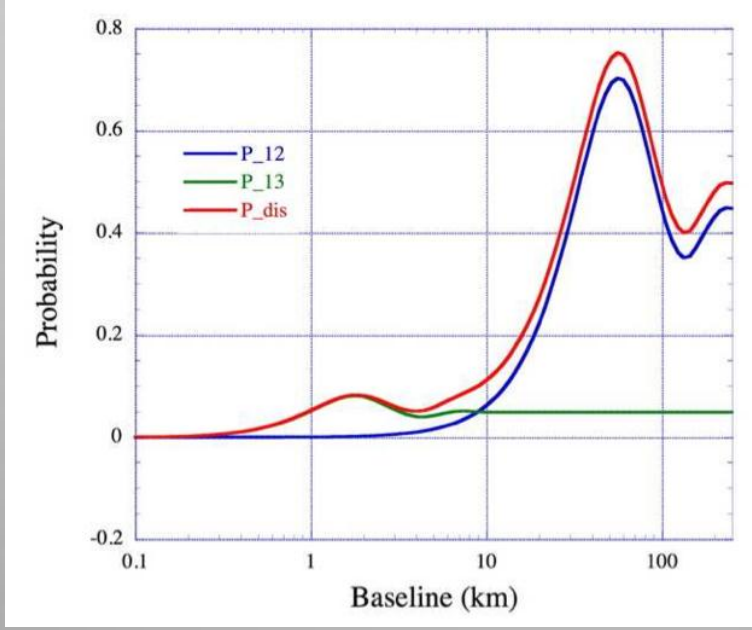
Sterile Neutrino Primer – Neutrino Oscillations

- Neutrinos have non-zero mass
  - Interaction states are not the same as mass states
    - $|\nu_\alpha\rangle = \sum_i U_{\alpha i} |\nu_i\rangle$
  - Neutrinos produced in definite flavor state have probability of oscillating into another state:
    - $P_{\alpha\to\beta} = \left|\langle \nu_\beta | \nu_\alpha(t)\rangle\right|^2$
    - $P_{\alpha\to\beta} \approx \sin^2(2\theta)\,\sin^2\left(1.267\,\frac{\Delta m^2 L}{E}\right)$



Sterile Neutrino Primer – Neutrino Oscillations

- $P_{\alpha\to\beta} \approx \sin^2(2\theta)\,\sin^2\left(1.267\,\frac{\Delta m^2 L}{E}\,\frac{MeV}{eV^2\cdot km}\right)$
  - $\sin^2(2\theta)$: sets amplitude of disappearance probability
  - Δm^2: sets length scale of disappearance maximum

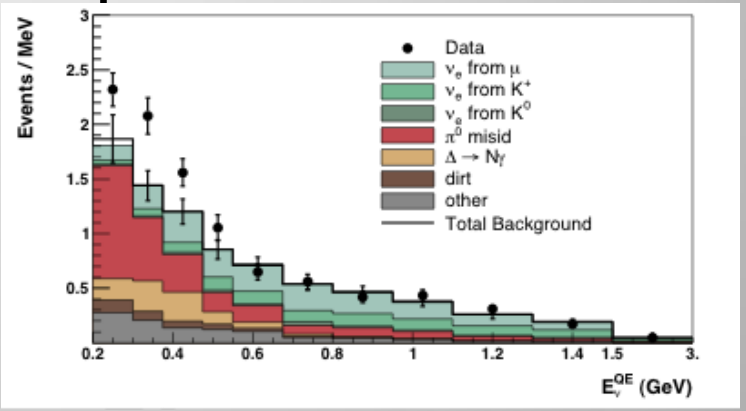


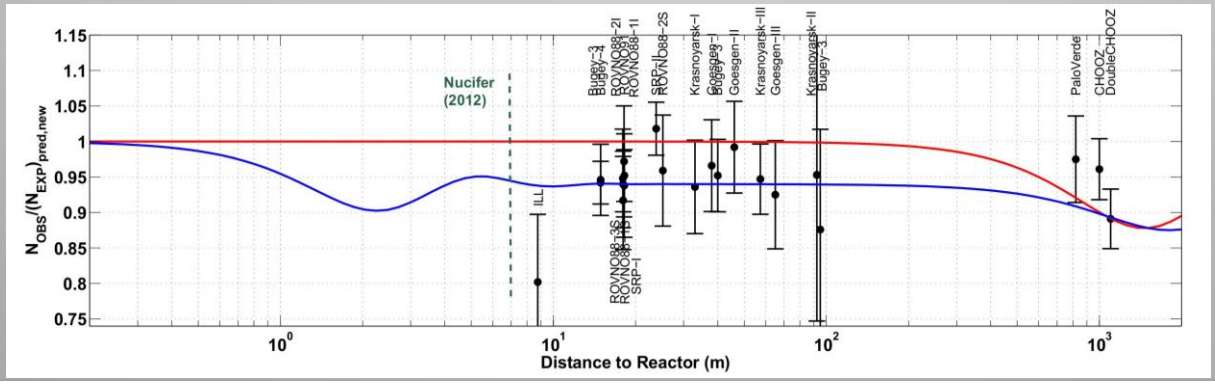
Disappearance probability for reactor antineutrinos

➢ relevant oscillation changes with distance

Sterile Neutrino Primer – Neutrino Anomalies/Sterile Hints

- Recent experiments have observed signals inconsistent with three-flavor picture
  - Accelerator
    - — LSND, MiniBooNE
  - Gallium/Source
    - — GALLEX, SAGE
  - Reactor





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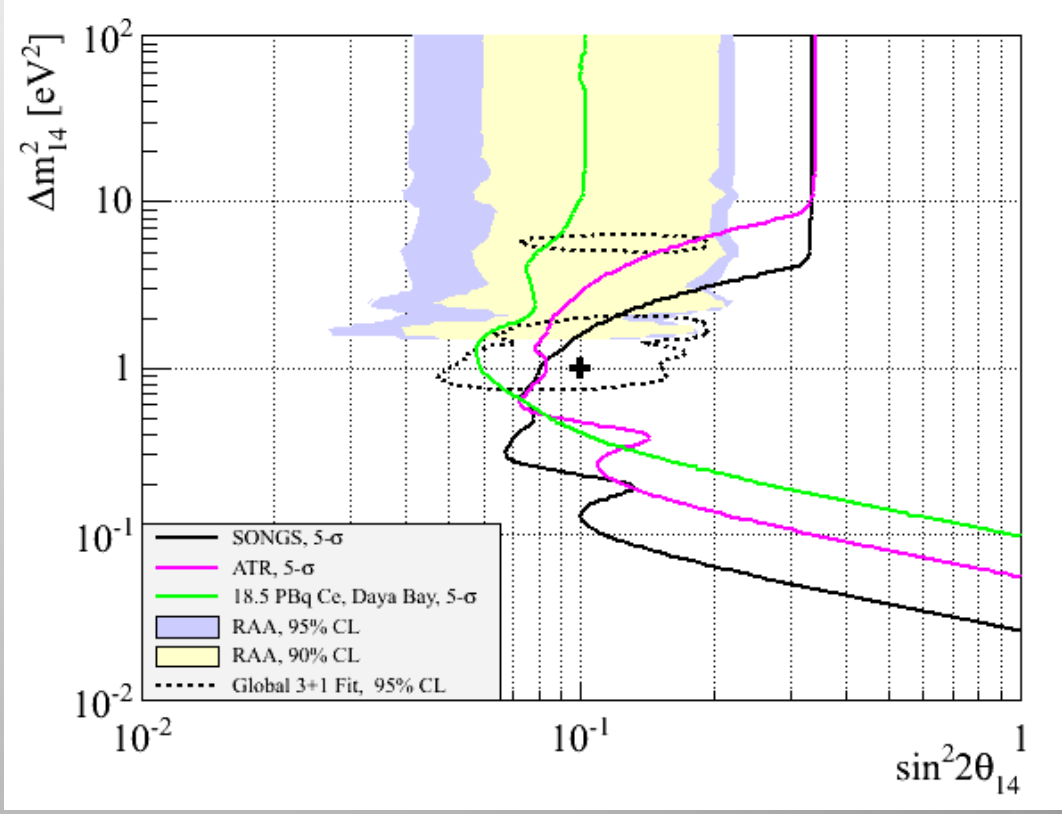
Experimental Prospects – Sterile Parameters

- Best fit parameters for 3+1 scenario are:
  - $\Delta m^2 \sim 1\ eV^2$
  - $\sin^2(2\theta) \sim 0.1$
- First oscillation max at ~1m for 1 MeV neutrino

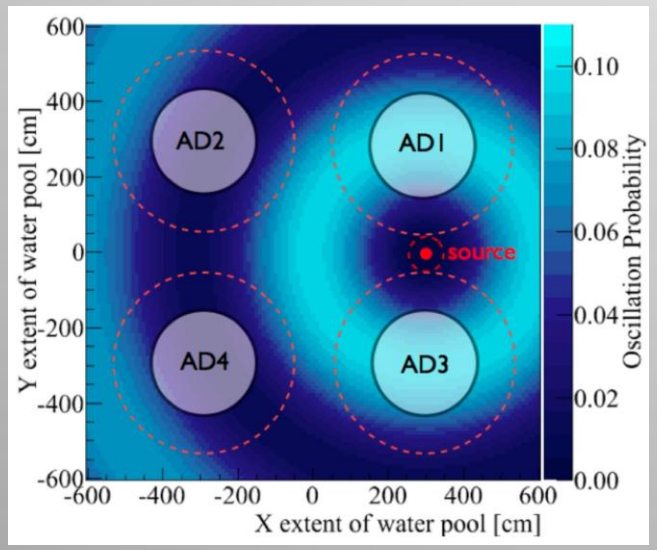


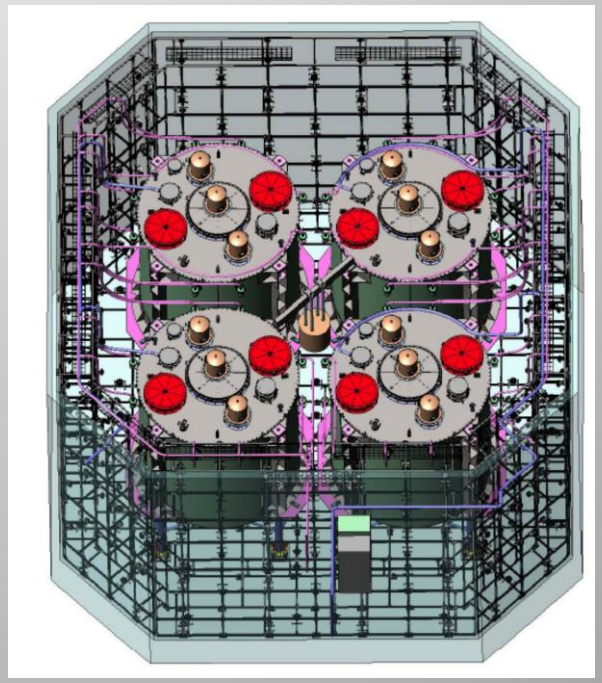
Experimental Prospects – Source Experiments

- Concept: Can an existing large liquid scintillator detector be of use?
- Problem: Need long lived, high Q-value beta
  - E_{th} = 1.8 MeV
- Possible with paired decay:
  - $^{144}Ce \rightarrow {}^{144}Pr \rightarrow {}^{144}Nd$
    - $t_{1/2}$ = 285 days, Q = 0.319 MeV (^{144}Ce)
    - $t_{1/2}$ = 17.3 min, Q = 2.998 MeV (^{144}Pr)
- Proposed Experiments:
  - CeLAND, SNO+Cr, SOX, Daya Bay Ce

Experimental Prospects – Source Experiments: Daya Bay

- 18.5 PBq (=500 kCi) ^{144}Ce in Daya Bay far hall
  - — 157g ^{144}Ce
  - 880 m.w.e overburden
  - 20 tons/detector

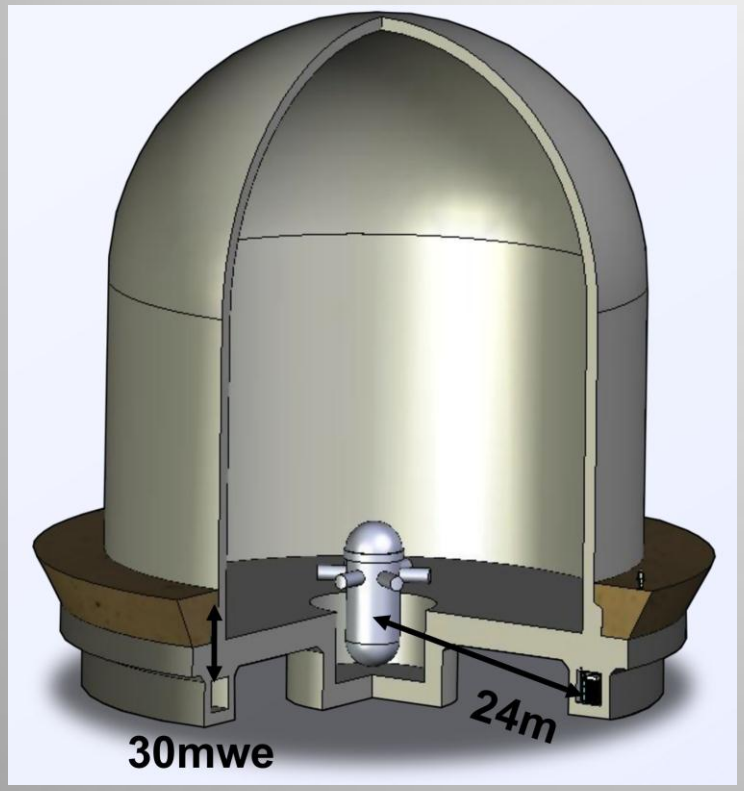




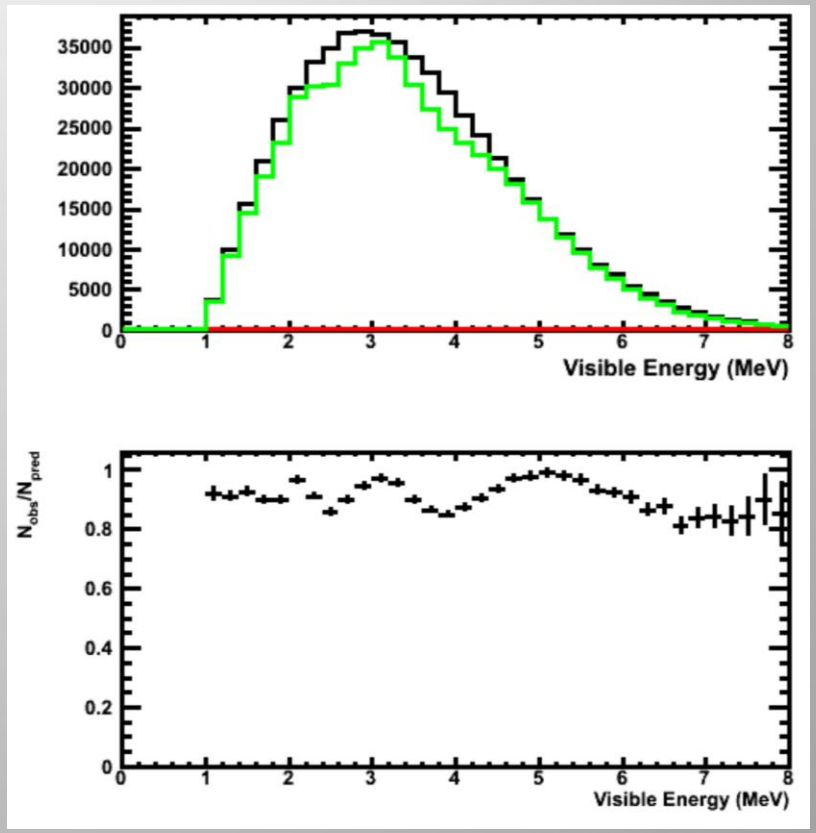
Experimental Prospects – Reactor Experiments

- Concept: Can an existing reactor core be used as the antineutrino source?
- Problem: Commercial reactors have 3-4m diameter cores.
  - (First oscillation max at ~2m for 3 MeV antineutrino)
- Proposed Experiments:
  - NUCIFER, SCRAAM, STEREO

Experimental Prospects – Reactor Experiments: SCRAAM



Signal for $\Delta m^2 = 1.2\ eV^2$



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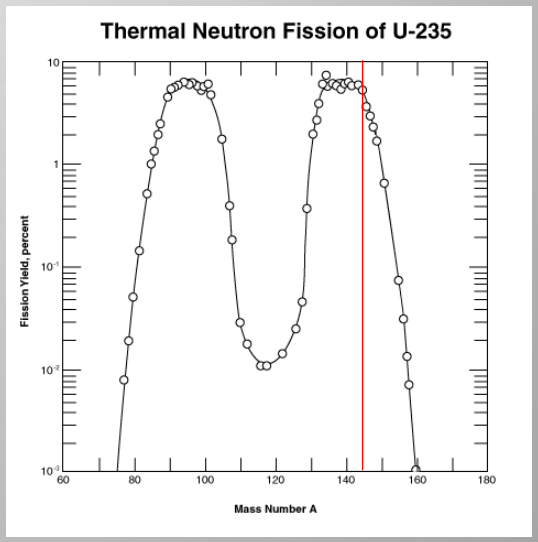
Source Production – Cerium from fission

- ^{144}Ce has $t_{1/2}$ = 285 days
  - Need artificial production
  - Experiments call for 16 – 160g
- Mass 144 is near peak of fission yield curve
  - Produced in 5.5% of ^{235}U fissions

decay

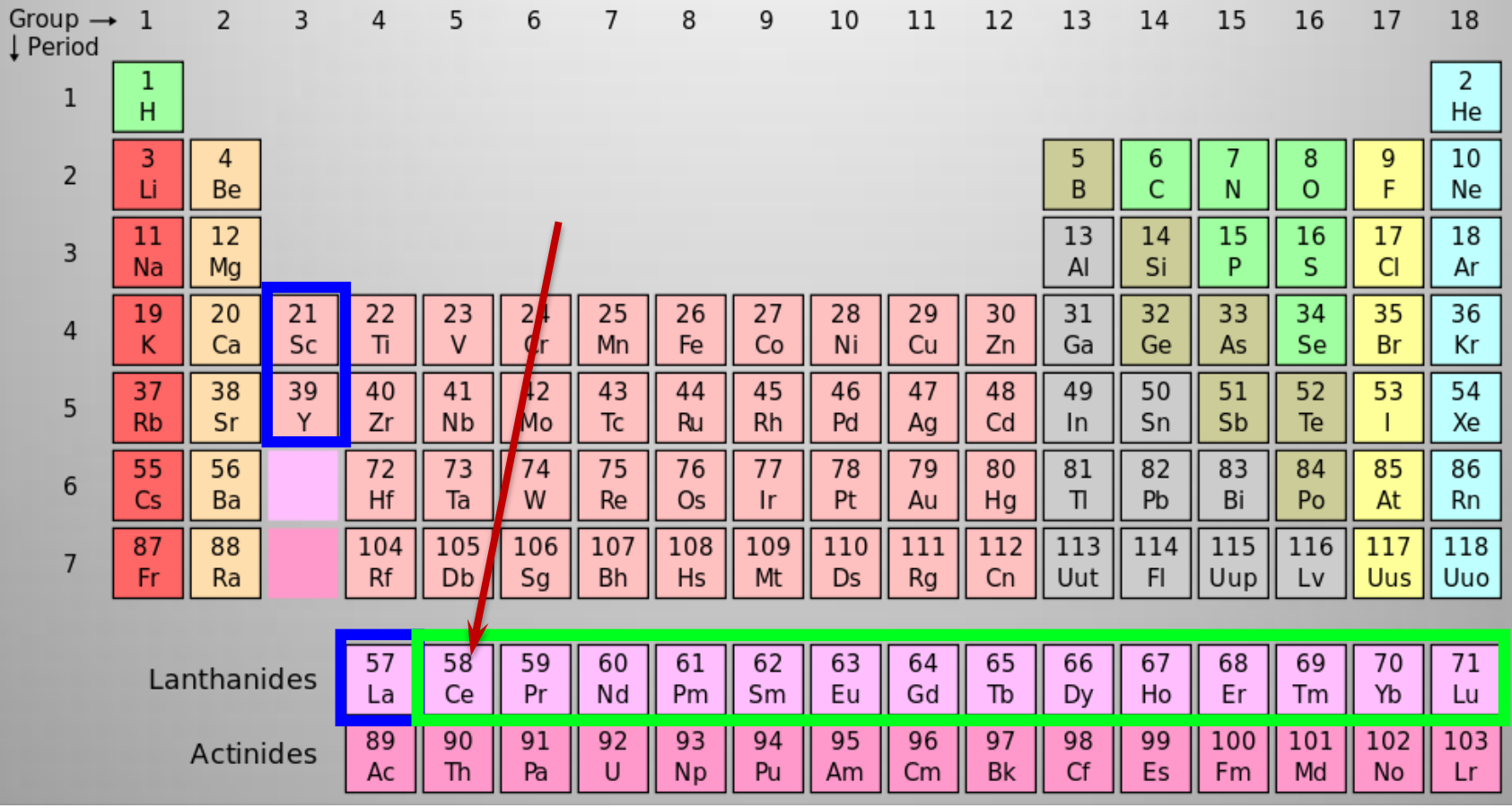
^{144}Xe (.00605%)
^{144}Cs (0.418%)
^{144}Ba (3.98%)
^{144}La (1.07%)
^{144}Ce (0.0345%)

$t_{1/2}$ < 3 min



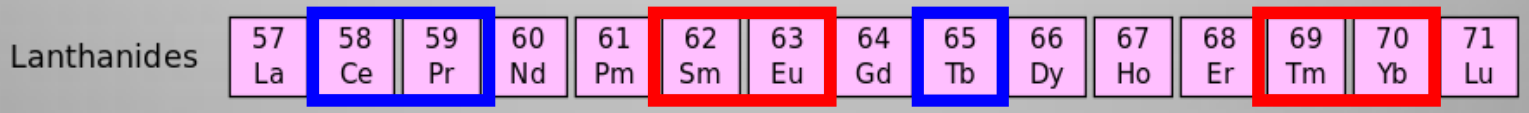
Source Production – Cerium Chemistry

- Classified as a “Rare Earth” or Lanthanoid



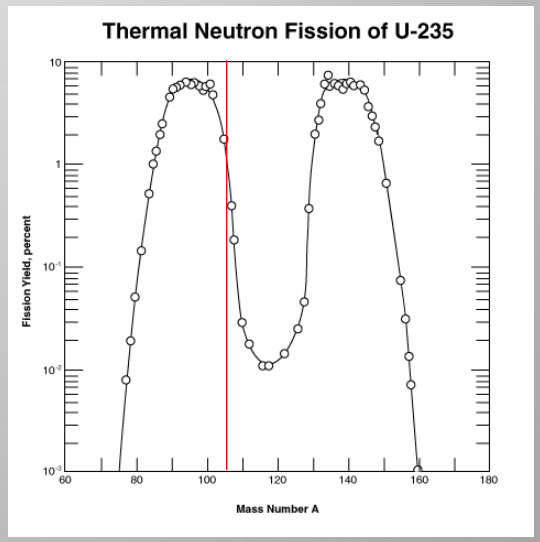
Source Production – Rare Earth Chemistry

- Filling *4f* subshell
- Form trivalent cations (Ln^{3+})
  - Ionic radius decreasing from $_{57}La$ to $_{71}Lu$
  - Only a few can be found in other oxidation states
    - Ln(II): Sm^{2+}, Eu^{2+}, TmI_2, Yb^{2+}
    - Ln(IV): Ce^{4+}, PrO_2, TbO_2
      - Only Ce(IV) in solution



Source Production –Ruthenium from fission

- ^{106}Ru is another fission-product with paired decays yielding long $t_{1/2}$ and high Q
  - $^{106}Ru \rightarrow {}^{106}Rh \rightarrow {}^{106}Pd$
    - $t_{1/2}$ = 374 days, Q = 0.0394 MeV (^{106}Ru)
    - $t_{1/2}$ = 29.8 sec, Q = 3.541 MeV (^{106}Rh)
- Off-peak for ^{235}U fission yield
  - 0.4% fission yield
  - More challenging separation



Source Production – From Spent Power Reactor Fuel

- Spent fuel sits in cooling ponds for 3-5 years before moved to dry storage and reprocessing considered
  - Only 1-7% of initial ^{144}Ce remain
- Requires few hundred kgs fuel processed
  - ~2 fuel assemblies

Source Production – From Irradiated Sources

- Cerium has high fission yield from most actinides
  - Can pick target with good fission cross section/cost

Isotope	Cross Section, σ_f (barns)	Branching to ^{144}Ce	Half-Life
^{227}Th	202	5.97%	18.7 d
^{229}Th	30.8	9.76%	7340 yr
^{232}U	76.8	4.31%	68.9 yr
^{233}U	529.1	4.73%	159,000 yr
^{235}U	581	5.5%	7.04×10^8 yr
^{237}Np	0.0215	4.85%	2.14×10^6 yr
^{239}Pu	748.1	3.74%	24,110 yr
^{240}Pu	0.056	3.93%	6,561 yr
^{241}Pu	1011.1	4.23%	14.3 yr
^{242}Pu	0.2	4.20%	375,000 yr
^{241}Am	3.15	3.49%	432 yr
^{242}Am	2100	4.43%	16 hr

Source Production – From Irradiated Sources

- High Flux Isotope Reactor (HFIR) at Oak Ridge offers irradiation in flux trap center of reactor
  - 23 day fuel cycle
  - $\Phi_{neutron} \approx 2 \times 10^{15}$ n/cm^2/s
- Short cycle has favorable yield, little decay loss:

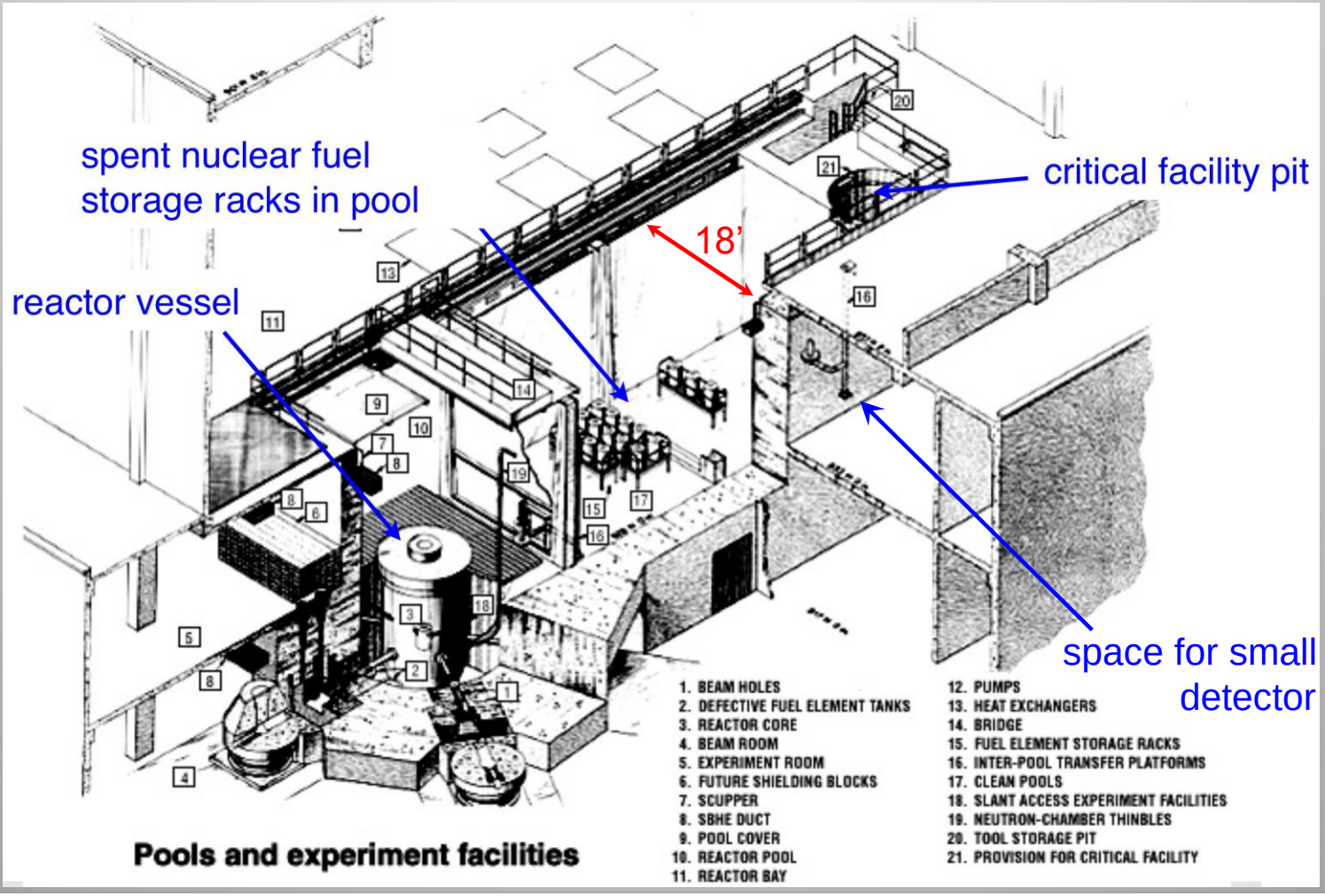
Isotope	Yield (g ^{144}Ce/kg target)
^{232}U	10.0
^{233}U	13.8
^{235}U	30.4
^{239}Pu	21.4
^{241}Am	9.5

- Small target size requires multiple cycles

Source Production – Unprocessed Spent Fuel

- Only source option available
- 10 kg HEU fuel used at HFIR
  - Generates ~75g ^{144}Ce in 23 day cycle with 30% burnup
    - <6 g ^{106}Ru generated in same cycle (clean anti-nu spectrum)
      - Mixed fuel will have significant ^{106}Ru quantity produced
    - Yields known to <1% uncertainty

Source Production – Unprocessed Spent Fuel



Source Production – Unprocessed Spent Fuel

- 9 PBq source in the cooling pool
  - 1 ton detector at 3m standoff gets <1 count/day
    - Size of detector limited by space adjacent to pool
    - Concrete wall of pool forces minimum standoff
  - >11/day events from reactor core in signal region

- Low statistics make this setup unfeasible

Source Production – Unprocessed Spent Fuel

- Option: HFIR fuel element measurement at different location
  - Achieve lower backgrounds
  - Use multiple fuel elements to increase Ce signal
- Must design appropriate shielding against gamma backgrounds from hot source

Source Production – Unprocessed Spent Fuel

- Option: Spent fuel assembly from commercial reactor (at Daya Bay)
  - Mixed fuel will have higher uncertainty on isotopic content
    - More ^{106}Ru present
  - Can use existing detectors

Isotope	Fuel Fraction	^{106}Ru FY		^{144}Ce FY	
^{235}U	55.6%	0.402%	1.0-1.4%	5.500%	0.5-0.7%
^{238}U	7.1%	2.490%	1.0-1.4%	4.548%	1.0-1.4%
^{239}Pu	32.6%	4.350%	1.4-2.0%	3.739%	0.5-0.7%
^{241}Pu	4.7%	4.363%	1.0-1.4%	4.227%	0.7-1.0%

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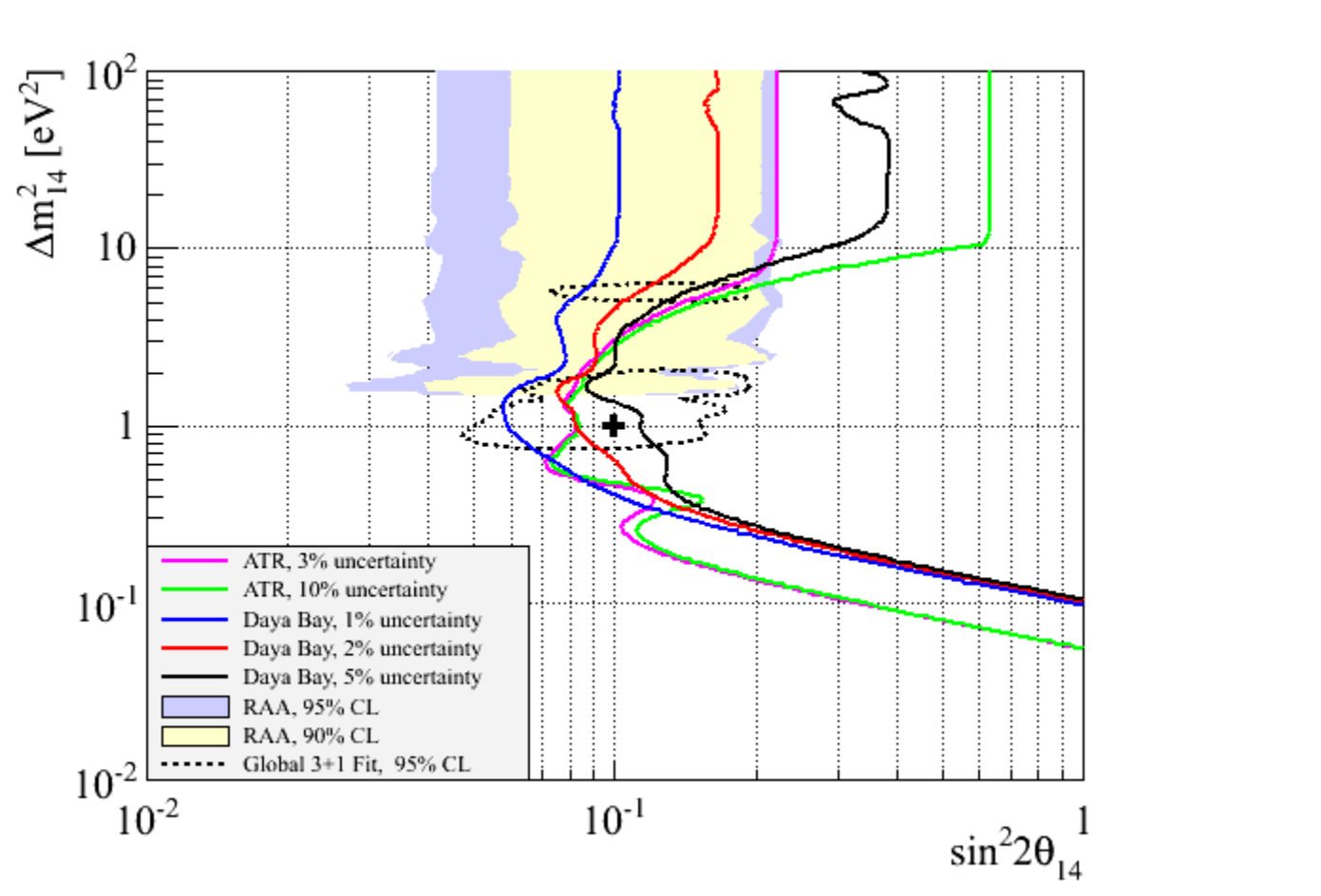
Experiment Simulations – Design

- Goal: Flexible simulation to give side-by-side comparison of reactor and source experiments
- Multiple sources: HEU, Mixed fuel, ^{144}Ce source
  - Finite source size to smear spectrum
- Multiple backgrounds
  - Reactor, flat, exponential, user-input
- Energy and Position Resolution of detector
- Chi-Square Minimization
  - $\chi^2 = \sum \frac{\left(N_{obs} - N_{exp}(1+\alpha_s) - N_{bg}\alpha_{bg}\right)^2}{N_{exp} + N_{bg} + \sigma_{b2b}\left(N_{exp} + N_{bg}\right)^2} + \sum_k \left(\frac{\alpha_k}{\sigma_k}\right)^2$

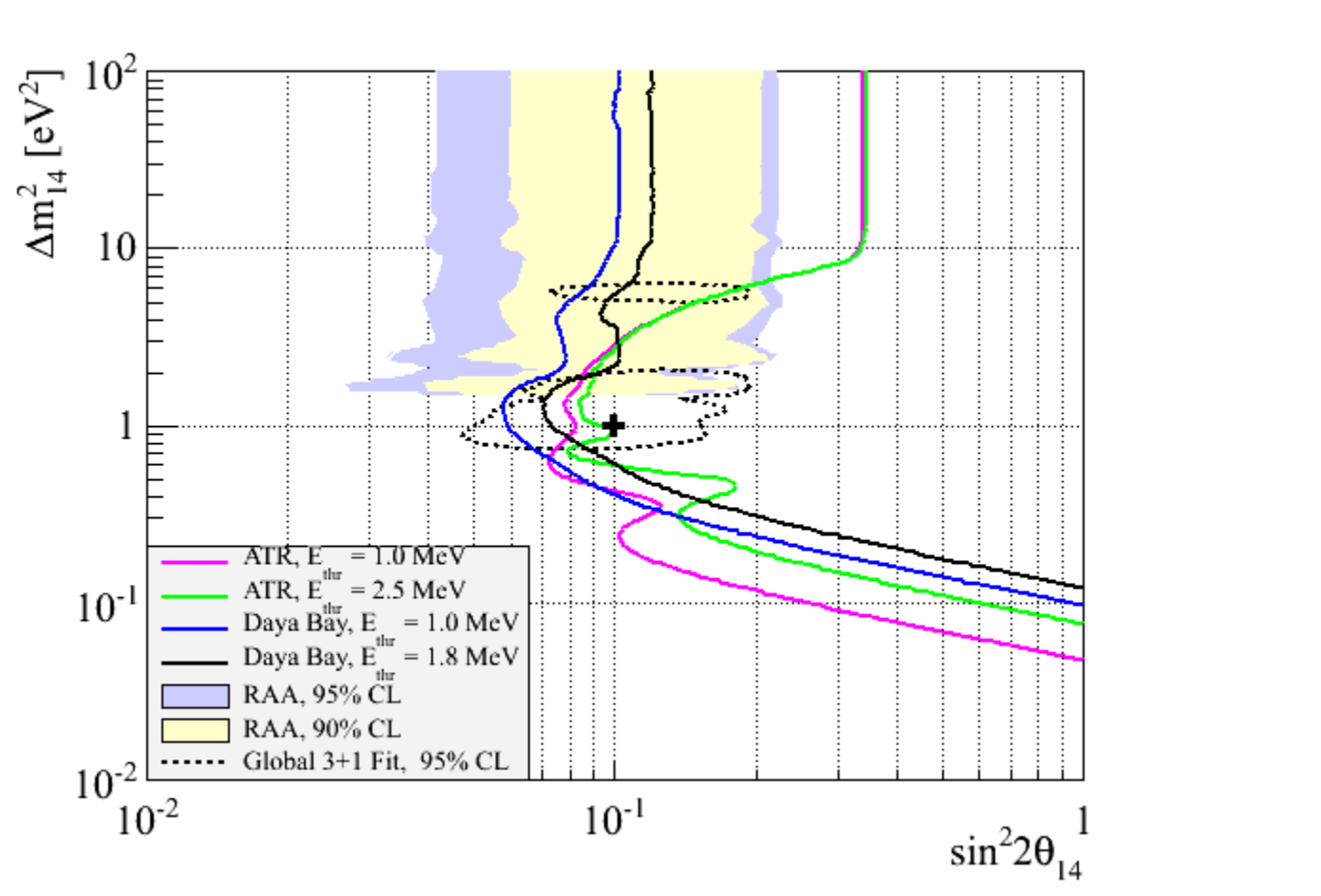
Experiment Simulations – Comparison

- ATR
  - Reactor experiment, 12 m baseline
- Daya Bay
  - ^{144}Ce Source experiment, 1.5 – 8 m baseline

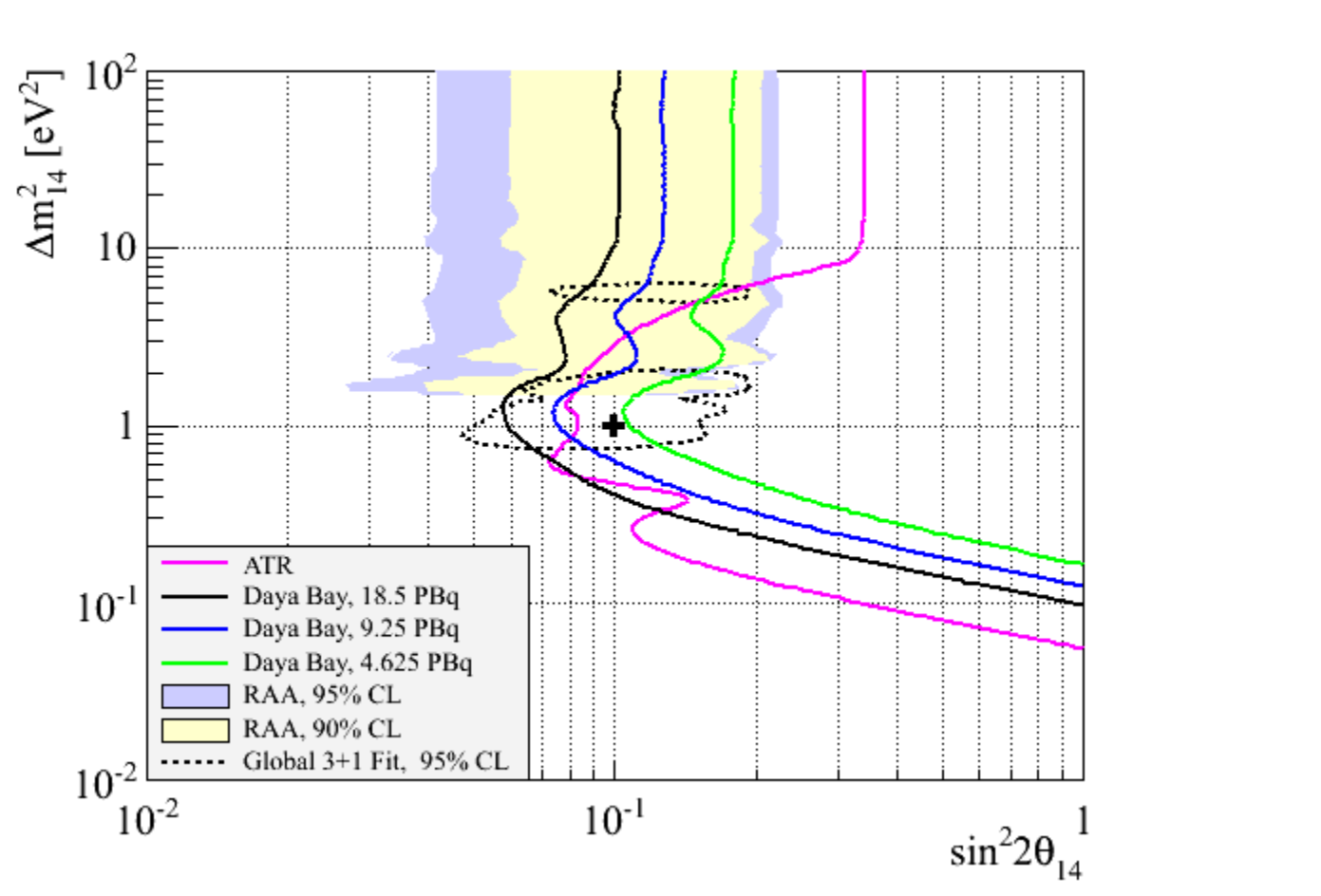
Experiment Simulations – Signal Uncertainty



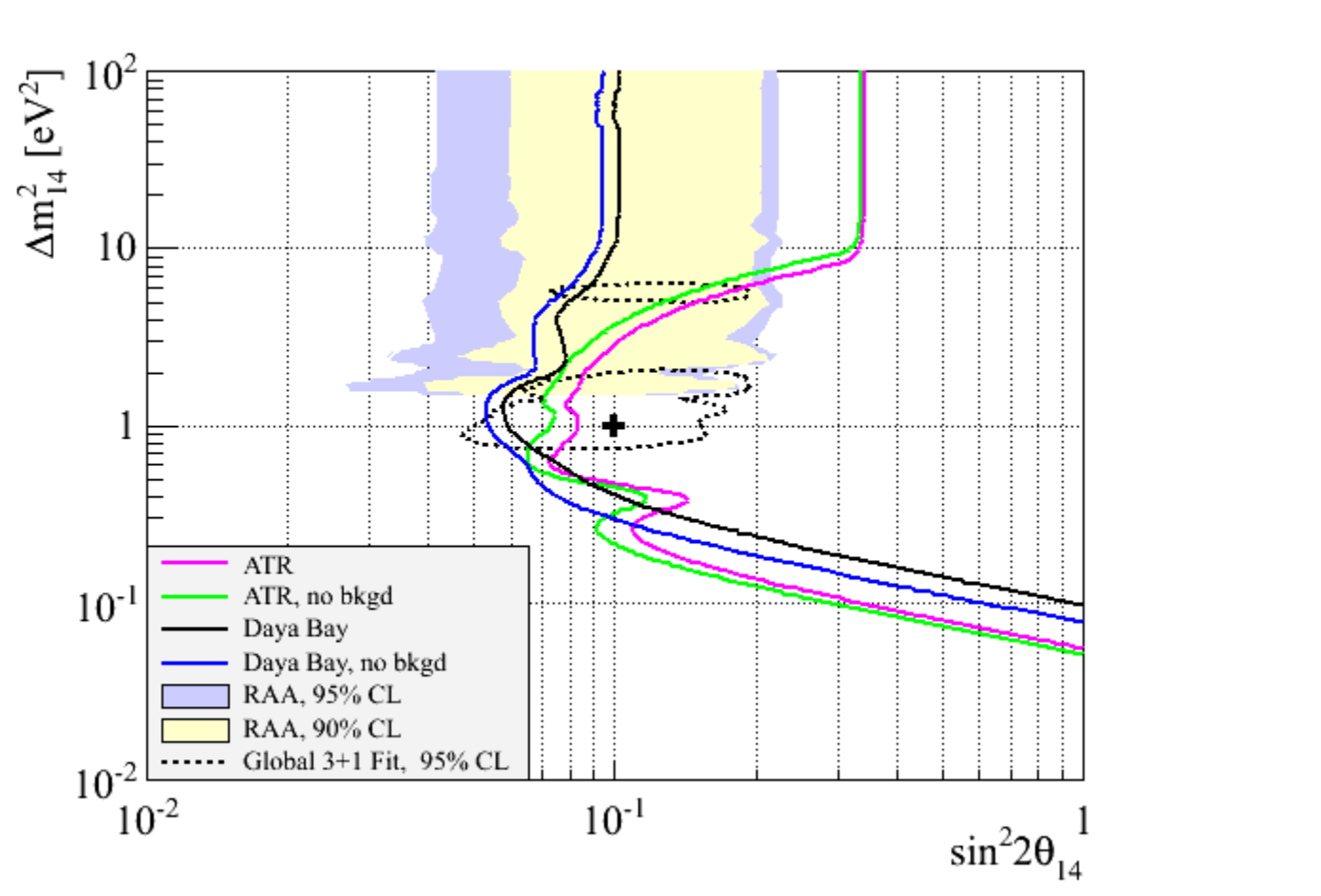
Experiment Simulations – Threshold



Experiment Simulations – Source Power



Experiment Simulations – Backgrounds



Conclusions

- Source experiments hold precarious edge over reactor experiments
  - Target activity is critical
  - Precise knowledge of source strength needed
- Prospects for unprocessed spent nuclear fuel experiments uncertain