Oklo: case study in extracting information on fundamental interactions from CN processes

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Outline

Introduction
- What is Oklo?
- Why is Oklo interesting?

Interpretation of Oklo
- Unified treatment
- Earlier estimate of sensitivity to quark mass

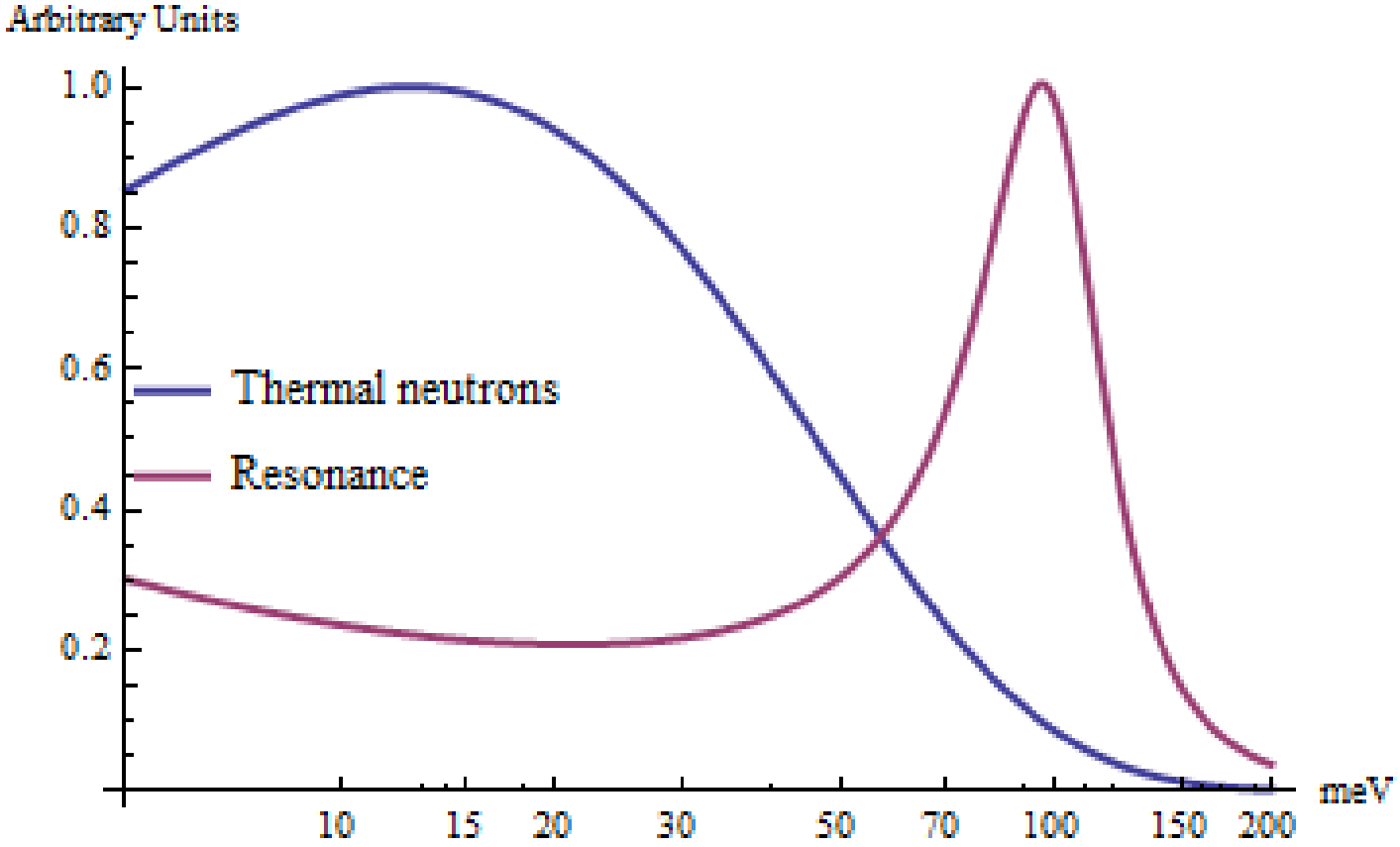
Interpretation of Oklo within many-body chiral EFT model
- Ingredients of model
- Sensitivity to quark mass: approximations & results

Comparisons with epithermal TRNI studies
- Analysis in epithermal regime
- Final result
- Final thoughts

What is Oklo?

- Site (in Gabon) of natural fission reactors
  - active $\sim 2 \times 10^9$ years ago
  - characteristic distribution of isotopes ($\neq$ natural abundances)

- SLOW neutron + HEAVY nucleus = SENSITIVE receiver



Why is Oklo interesting?

- Bounds on shifts in resonances $\Longrightarrow$ Most restrictive bound on $\Delta\alpha = \alpha_{\rm then} - \alpha_{\rm now}$

	z	$\Delta\alpha/\alpha_{\rm now}$	$\dot{\alpha}/\alpha$ (yr^{-1})
Atomic clock (Al^+/Hg^+)	0		$(-1.6 \pm 2.3) \times 10^{-17}$
Oklo ($\mathrm{n} + {}^{149}\mathrm{Sm}$)	0.16	$(-1.0 \mapsto 0.7) \times 10^{-8}$	$(-4 \mapsto 5) \times 10^{-18}$
Meteorites	0.43	$(-0.25 \pm 1.6) \times 10^{-6}$	
Quasar absorption (MM)	$0.2 - 4.2$	$(-5.7 \pm 1.1) \times 10^{-6}$	
Cosmic μwave background	10^3	$-0.013 \mapsto 0.015$	
Big-bang nucleosynthesis	10^9	$< 6 \times 10^{-2}$	

Adapted from ProgTheorPhys.126.993. [Oklo result: ModPhysLettA.27.1250232]

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- Issue: influence of QCD parameters, specifically changes in light quark mass $m_q \equiv \frac{1}{2}(m_u + m_d)$?

Interpretation of Oklo: unified treatment

[IntJModPhysE.23.1430007]

- $\Delta E_r \equiv E_r(\mathrm{Oklo}) - E_r(\mathrm{now}) = k_q \dfrac{\Delta X_q}{X_q} + k_\alpha \dfrac{\Delta\alpha}{\alpha}$ $\left(x_q = \dfrac{m_q}{\Lambda_{QCD}}\right)$
  - k_q independent of mass number A!
    - Conjecture based on study of p-shell nuclei/schematic CN model [PhysRevC.79.034302/PhysRevD.67.063513]
    - k_q susceptible to nuclear matter analysis
  - Order of magnitude estimate for k_q? Model dependent

$k_q \simeq +10\,\mathrm{MeV}$ (Walecka model) $k_q \simeq -40\,\mathrm{MeV}$ (Chiral model)

($k_\alpha \simeq -1\,\mathrm{MeV}$ [NuclPhysB.480.37])

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Interpretation of Oklo: Walecka model estimate of k_q

[PhysRevC.79.034302]

- Shift δE_r (due to δX_q) $\xrightarrow[\text{model}]{\text{CN}}$ Depth U_0 of nuclear mean-field

$$\frac{\delta E_r}{U_0} \approx -\underbrace{\left(\frac{\delta m_N}{m_N} + 2\frac{\delta r_0}{r_0} + \frac{\delta U_0}{U_0}\right)}_{\text{Independent of } A} \qquad (R = r_0 A^{\frac{1}{3}})$$

- Walecka model estimate of U_0-term implies (Ignore δr_0)

$$\frac{\delta E_r}{U_0} \approx 7.50\frac{\delta m_S}{m_S} - 5.50\frac{\delta m_V}{m_V} - \frac{\delta m_N}{m_N} \equiv \left(7.50K_S^q - 5.50K_V^q - K_N^q\right)\frac{\delta X_q}{X_q}$$

- Uncertain microscopic interpretation of *scalar* S and *vector* V bosons $\longrightarrow$ No first principles calculation of K_S^q, K_V^q

- In PhysRevC.79.34302, K_S^q, K_V^q chosen such that $k_q \sim +10\,\mathrm{MeV}$

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- *Plausible* paradigm relating U_0 to QCD?

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Ingredients	**Nuclear property**
Large scalar & vector self-energies	Spin-orbit interaction
Chiral $\pi N\Delta$-dynamics + Pauli-blocking	Binding & saturation

NuclPhysA.750.259 NuclPhysA.770.1

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In-medium χPT to 3 loops

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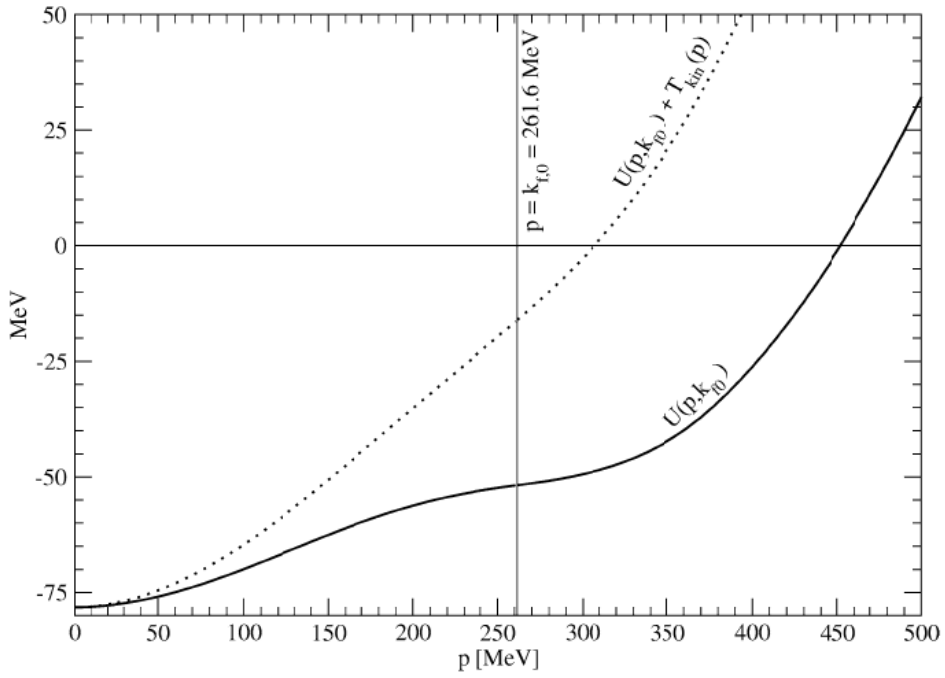
Ensures model phenomenologically satisfactory



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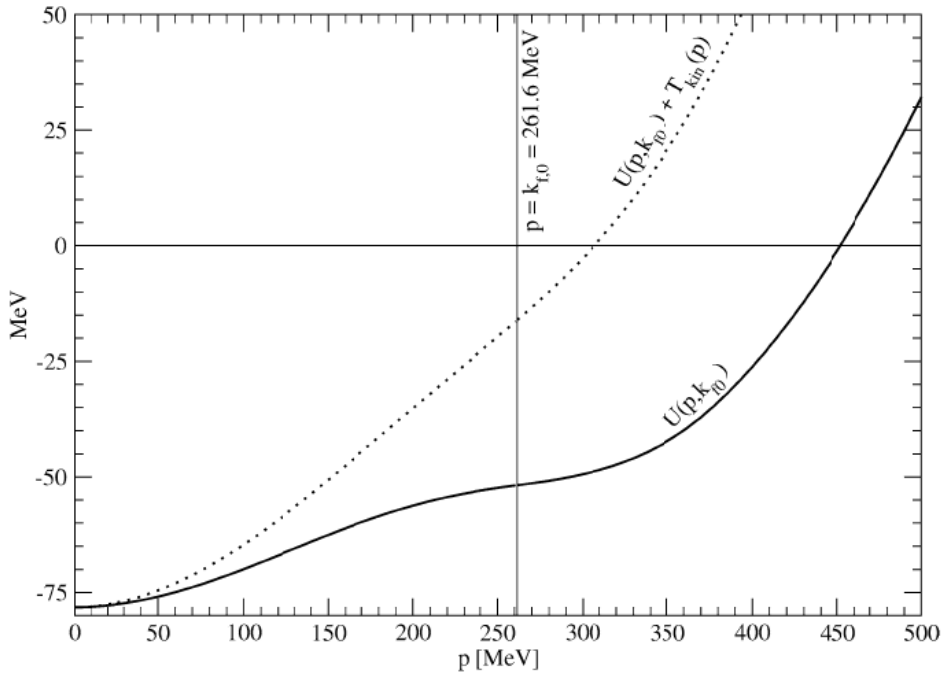
Short range interactions

2 contact-terms
Strengths fitted directly to nuclear matter properties



NuclPhysA.750.259

Sensitivity to quark mass: approximations & results

Long & intermediate range interaction terms $\rightarrow$ $\tilde{U}_0 = \sum_i U_{0i}$

$$\frac{\tilde{U}_0}{m_N} = \underbrace{\frac{\pi}{4}\left(\frac{M_\pi g_A}{2\pi F_\pi}\right)^4 \left[(9+6u^2)\tan^{-1} u - 9u\right]}_{\text{Twice iterated } 1\pi\text{-exchange (2 medium insertions)}} + \ldots \qquad \left(u = \frac{k_F}{M_\pi}\right)$$

- In terms of hadronic parameters P (i.e. M_π, F_π, g_A, m_N & Δ)

$$\frac{\delta \tilde{U}_0}{U_0} = \frac{1}{U_0}\frac{\delta \tilde{U}_0}{\delta m_q}\delta m_q = \left[\sum_{P,i} \frac{U_{0i}}{U_0} \underbrace{\left(\frac{P}{U_{0i}}\frac{\delta U_{0i}}{\delta P}\right)}_{=K^P_{U_{0i}}} \underbrace{\left(\frac{m_q}{P}\frac{\delta P}{\delta m_q}\right)}_{=K^q_P}\right]\frac{\delta m_q}{m_q}$$

- Discard all but $P = m_\pi$ term: $\underbrace{K^q_{M_\pi} \approx \frac{1}{2} \gg \text{other } K^q_P\text{'s}}_{\text{Berengut et al. (2013)}}$

- Result: $\frac{\delta \tilde{U}_0}{U_0} = -0.28\frac{\delta m_q}{m_q} \quad \Longrightarrow \quad k_q \sim 10\,\mathrm{MeV}\ (!)$

Same as PhysRevC.79.034302 but with *controlled* approximations

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- Contributes to part of U_0 linear in density ρ

$$\frac{3\pi}{2m_N}\underbrace{\left[\frac{2\pi}{m_N}B_3+\tfrac{15}{16}\pi^2\left(\frac{g_A}{2\pi F_\pi}\right)^4 m_N^2 M_\pi\right]}_{\xrightarrow{\rho\to 0}\ V^{(^1S_0)}_{\mathrm{low}-k}(0,0)+V^{(^3S_1)}_{\mathrm{low}-k}(0,0)}\rho$$

[$V_{\mathrm{low}-k}$: Bogner, Kuo, Schwenk (2003)]

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- Working assumption: m_q-dependence of $V_{\mathrm{low}-k}$ negligible

$$K^q_{B_3}=0.52K^q_{M_\pi} \quad\Longrightarrow\quad \frac{\delta U_{0B_3}}{U_0}=+1.1\frac{\delta m_q}{m_q} \quad\Longrightarrow\quad k_q\simeq -40\,\mathrm{MeV}$$

Less controlled but still plausible? (More details: DOI 10.1007/s00601-014-0909-0)

Comparisons with epithermal TRNI studies

- Oklo (in summary):

$$\text{Reactor data} \xrightarrow[\text{model}]{\text{Reactor}} \Delta E_r \text{ bound} \xrightarrow[\text{model}]{\text{“CN”}} \delta U_0 \xrightarrow[\text{model}]{\chi\text{EFT}} \delta m_q$$

- Epithermal TRNI:

$$\text{Reaction data} \xrightarrow[\text{model}]{\text{Reaction}} \underbrace{\langle s|\widehat{V}_{\text{PT}}|p\rangle}_{=V_{sp}} \text{ bound} \xrightarrow[\text{model}]{\text{CN}} \underbrace{\text{RMS } V_{sp}}_{\text{Average over } p\text{'s}} \xrightarrow{?}$$

- All not well with Random Matrix Theory (RMT)?
  - “Anomalous fluctuations of s-wave reduced neutron widths of ^{192,194}Pt resonances” PhysRevLett.105.072502
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Analysis in epithermal regime

$$\text{Reaction data} \xrightarrow[\text{model}]{\text{2-level}} V_{sp} \text{ and } E_p \text{ (Already know } E_s\text{'s)}$$

- Invoke $\underbrace{\textit{Eigenstate Thermalization Hypothesis}}_{\text{Nature.452.854}}$? $\longleftrightarrow$ Chaotic $|\psi\rangle$

  Eigenstate expectation values "almost do not fluctuate at all between eigenstates that are close in energy"

  Consequence: for any weights w_α in small energy window ΔE

$$\sum_\alpha w_\alpha \langle\psi_\alpha|\widehat{O}|\psi_\alpha\rangle = \frac{1}{N_{\Delta E}} \sum_\alpha \langle\psi_\alpha|\widehat{O}|\psi_\alpha\rangle = \langle\widehat{O}\rangle_{\mu\text{can}}$$

- Introduce *fig leaf* average (Weight $w_s \propto \frac{1}{(E_p - E_s)^2}$ maybe)

$$\underbrace{\sigma_p^2 = \sum_s w_s V_{ps} V_{sp}}_{\text{Average over } s} \xrightarrow[\text{hypothesis}]{\text{ET-like}} \frac{1}{\mathcal{N}_{\text{PsC}}} \sum_s V_{ps} V_{sp} \approx \frac{1}{\mathcal{N}_{\text{PsC}}} \langle p|\widehat{V}_\square^2|p\rangle$$

$\mathcal{N}_{\text{PsC}}$: number of principle s-wave components of $\widehat{V}_\square|p\rangle$

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Analysis in epithermal regime: final result

- Use ETH on σ_p^2!

$$\sigma_p^2 \approx \frac{1}{\mathcal{N}_{\mathrm{PsC}}} \langle \widehat{V}_{\square}^2 \rangle_{\mu\mathrm{can}} \approx \frac{1}{\mathcal{N}_{\mathrm{PsC}}} \langle \widehat{V}_{\square}^2 \rangle_{\mathrm{can}}$$

Canonical ensemble averages calculable within chiral model for nuclear matter!

- Discard fig leaf of average (Weighting such that $\sigma_p \approx |V_{sp}|$)

$$|V_{sp}| \approx \frac{1}{\sqrt{\mathcal{N}_{PsC}}} \langle \widehat{V}_{\square}^2 \rangle^{\frac{1}{2}}{}_{\mathrm{can}}$$

Parallels with PhysRevLett.70.4051

- Issues:
  - Order of magnitude of $\mathcal{N}_{PsC}^{-\frac{1}{2}}$? $\sim 10^{-3}$ or ~ 1?
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Shell model studies of issue 1?
Address issue 2 with EGOE(1+2)-π or tractable many-body system

Analysis in epithermal regime: final result

- Use ETH on σ_p^2!

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Canonical ensemble averages calculable within chiral model for nuclear matter!

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Final thoughts

"[I]s it possible to interpret the neutron data in terms of the elementary weak interaction and mesonic couplings?

The problem is usually decomposed into two fairly independent parts. In a first step, the effective parity-violating nucleon-nucleon interaction is calculated from the elementary weak interaction by taking into account the nuclear medium surrounding the two interacting nucleons. In a second step, this effective interaction is propagated into the huge shell-model spaces typical for compound-nucleus states at neutron threshold ... it is possible to determine the rms matrix element v and the spreading width ... The spreading width is found to lie in the expected range of 10^{-6} eV." (RevModPhys.71.445)

Since the 1980's, most PV calculations have been expressed in terms of the DDH parameters. More recently EFT descriptions, both with and without explicit pion degrees of freedom, have been adopted to ensure consistency between PC and PV interactions and currents. Finally, instead of using the Lagrangian directly, hybrid calculations use a potential derived from the EFT Lagrangian combined with models for the PC interactions. ... we attempt to create a dictionary, to the extent possible ... There are some inherent uncertainties involved, particularly when cutoffs and subtraction points in one scheme are not compatible with another, so some of these translations cannot be considered exact and should be interpreted carefully. (ProgPartNuclPhys.72.1)

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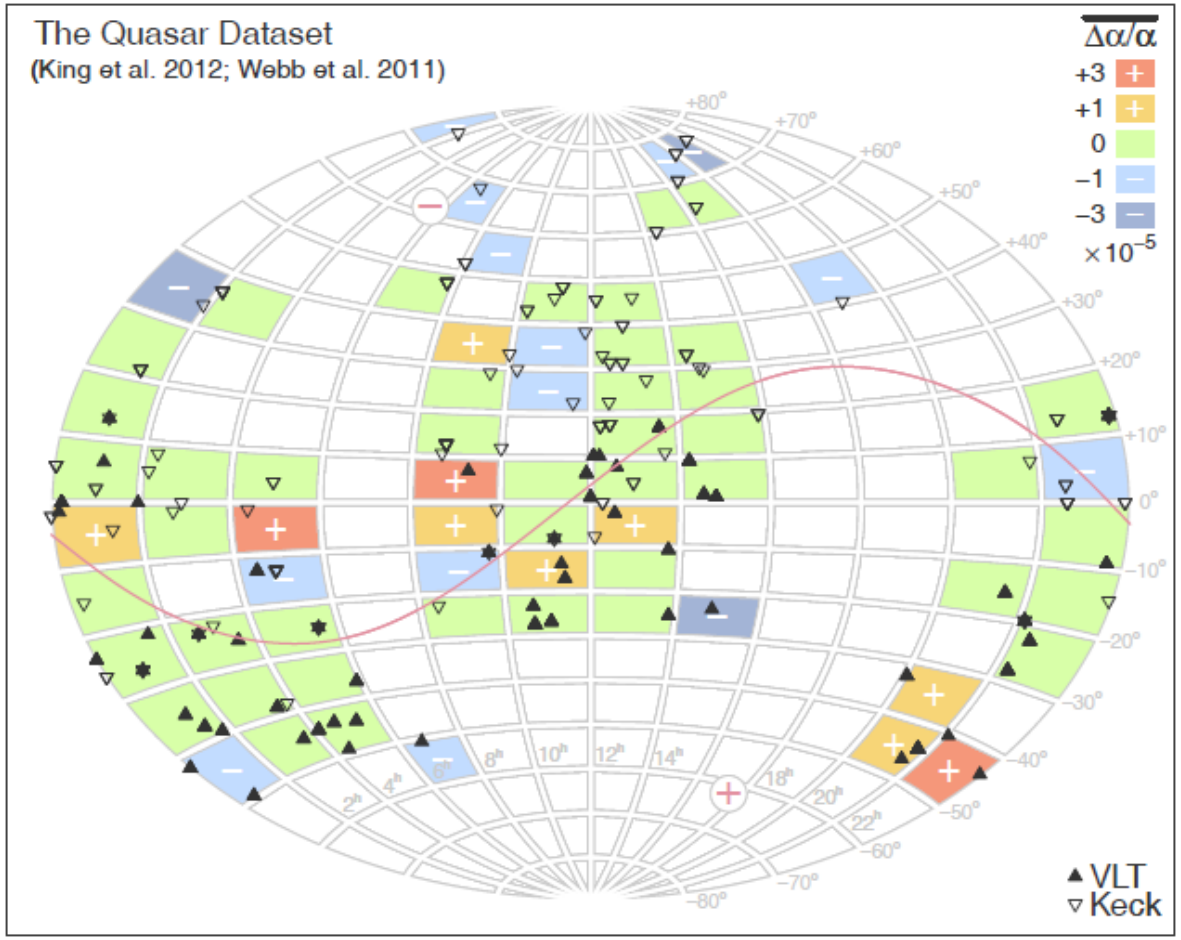
Issue: time dependence of parameters in SM Lagrangian

Is this an issue?

- Quasar absorption spectra $\Longrightarrow$ Space-time variation of α?



Cameron & Pettitt, arXiv:1207.6223

What is Oklo?

The Oklo Fossil Natural Reactors

Relative magnitudes of $\left|\frac{\Delta\alpha}{\alpha}\right|$ and $\left|\frac{\Delta X_q}{X_q}\right|$

- Unification at some scale implies

$$\left|\frac{\Delta X_q}{X_q}\right| \sim \underbrace{\left|\left(R - \lambda - 0.8\kappa\right)\frac{\Delta\alpha}{\alpha}\right|}_{\text{Langacker et al. (2001)}}$$

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$$\left.\begin{array}{c}\Delta\left(\ln\frac{m_p}{m_e}\right) \sim (R-\lambda-0.8\kappa)\,\Delta\left(\ln\alpha\right) \\ \text{Experimental results for } \Delta\left(\ln\frac{m_p}{m_e}\right),\ \Delta\left(\ln\alpha\right)\end{array}\right\} \Longrightarrow \left|\frac{\Delta X_q}{X_q}\right| \sim \left|\frac{\Delta\alpha}{\alpha}\right|$$

Interpretation of Oklo: earlier estimates of a (in MeV)

[Flambaum & Wiringa (2009)]

- Estimate 1: VMC study (with AV18+UIX) of "a" in light nuclei

$\frac{m_q}{m_V}\frac{\Delta m_V}{\Delta m_q}$	^{6}He	^{6}Li	^{7}He	^{7}Li	^{7}Be	^{8}Be	^{9}Be	"a"
0.03	9.92	9.52	11.7	15.4	15.5	17.2	16.2	14
0.06	0.60	1.39	2.01	−0.23	0.62	−1.67	3.94	1.0

- Estimate 2: Walecka model with Fermi gas model estimate for shift Δ'_r due to ΔX_q

$$\frac{\Delta'_r}{U_0} \approx -\underbrace{\left(\frac{\Delta m_N}{m_N} + 2\frac{\Delta r_0}{r_0} + \frac{\Delta U_0}{U_0}\right)}_{\text{Independent of } A} \qquad (R = r_0 A^{\frac{1}{3}})$$

Focus on potential well depth or U_0-term (Ignore Δr_0)

$$\frac{\Delta'_r}{U_0} = 7.50\frac{\Delta m_S}{m_S} - 5.50\frac{\Delta m_V}{m_V} - \frac{\Delta m_N}{m_N} \implies a = \begin{cases} 6 \\ 12 \end{cases}$$

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