



Monopole Phenomenology from the Electroweak Anomaly

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Based in part on work with Nathaniel Craig, Dan Sehayek

Phenomenology
2026
5/11/2026

Review Callan–Rubakov for $\Delta B = 1$

- Global symmetry breaking in fermion–monopole scattering - baryon number violation
- Historical SU(5) Callan–Rubakov picture:
- SU(5) monopole core restores unified symmetry - quark–lepton violating channels
- Lowest angular momentum fermion mode reaches the core - effective boundary condition
- Catalysis is geometric / hadronic scale

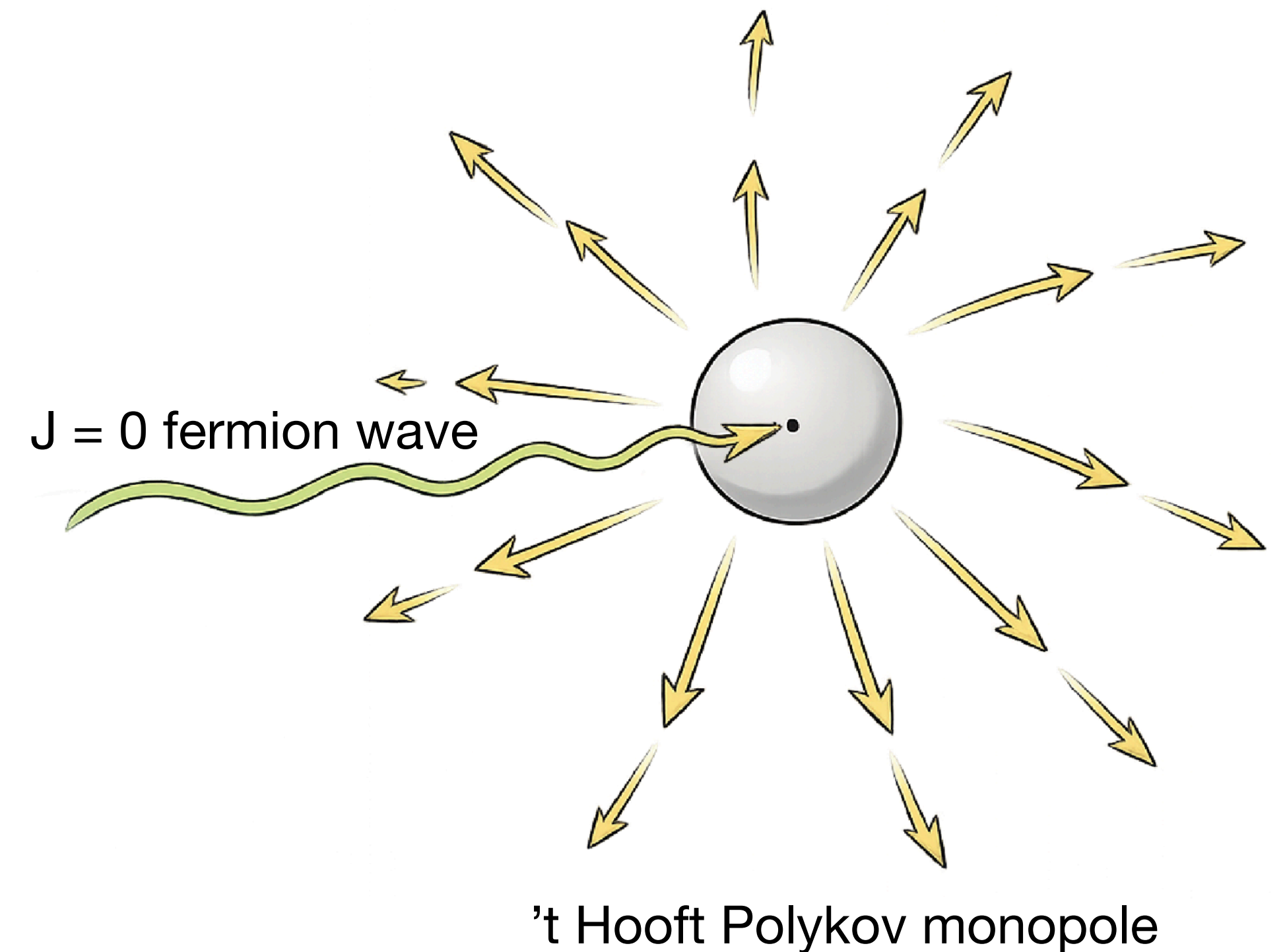


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Anomalous Callan–Rubakov

- Classical core B-violation - not necessary
- Weak anomaly can catalyze B+L violation $SU(2)_L^2 - U(1)_{B+L}$ [Wilczek '1982]
- Full mechanism - anomaly + monopole-sector topology
- Modern picture: $U(1)_Y^2 - U(1)_{B+L}$ [Thorngren '2019] [Wang '2019]
- Electroweak anomalies interested: $SU(2)_L^2 - U(1)_{B+L}$ and $U(1)_Y^2 - U(1)_{B+L}$

Electroweak Anomaly with Selection Rule

- $U(1)_{B+L} \rightarrow Z_6$ for 3 generations in Standard Model
- Surviving generator $g = e^{i\frac{2\pi}{6}(B+L)}$
- Process: $\Delta(B + L) \xrightarrow{\text{picks up phase}} e^{i\frac{2\pi}{6}\Delta(B+L)} \rightarrow \Delta(B + L) \in 6\mathbb{Z}$
- $\Delta(B - L) = 0$
- $\Delta B = \Delta L = 3n$
- Minimal nontrivial event $\rightarrow n = 1, \Delta B = \Delta L = 3$
- $SU(2)_L^2 - U(1)_{B+L}$ and $U(1)_Y^2 - U(1)_{B+L}$

$\Delta B = 3$ Catalysis Rate

Strong vs. Weak

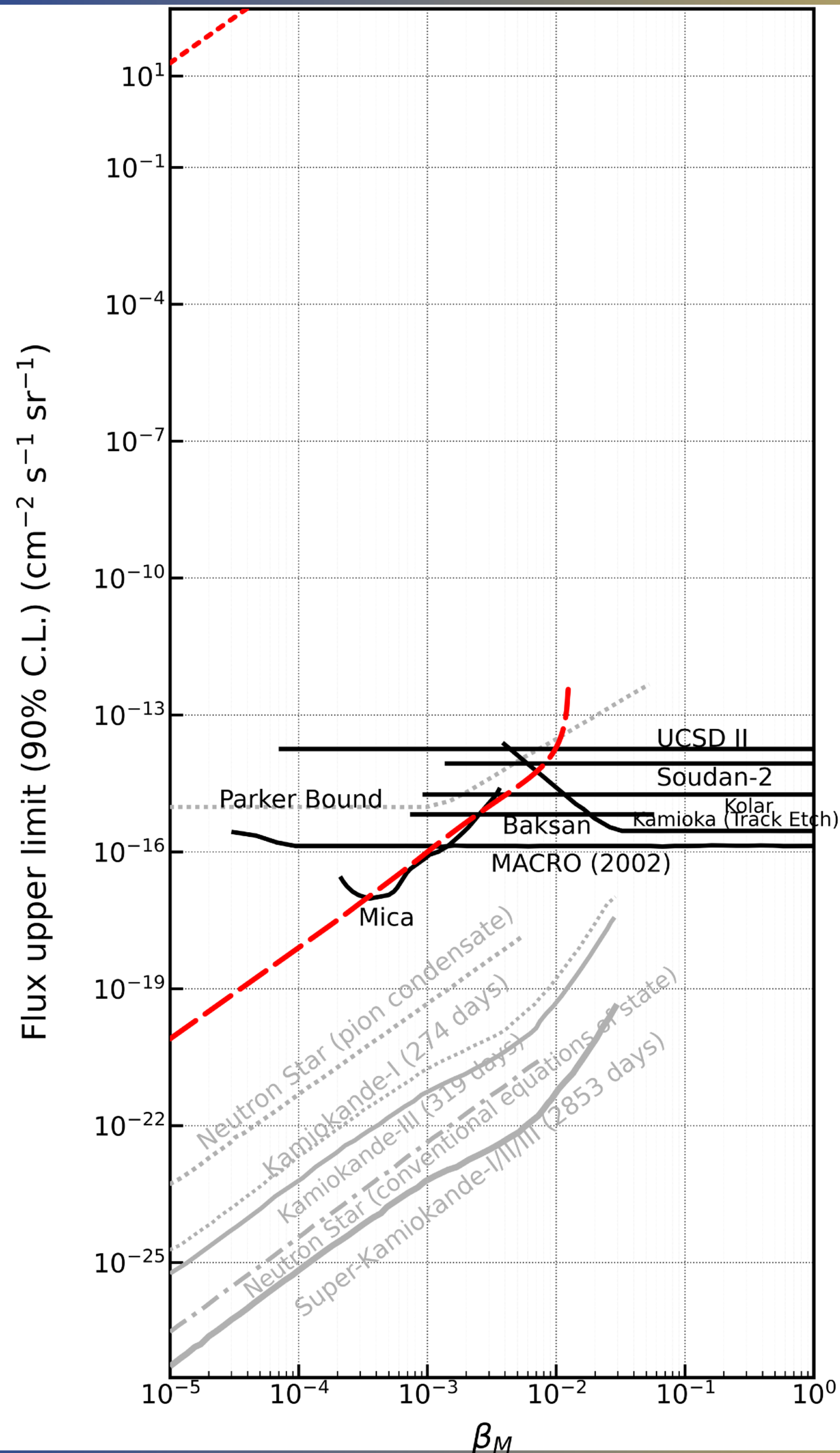
- **First layer:** Weak expectation: after EWSB, relevant weak sector is massive \Rightarrow local weak-scale process [Wilczek '1983]
- Localized scattering picture: the final state conserve the gauge charge + violate anomalous baryon charge [Sen '1984]
- **Second layer:** 3-generation from $\Delta B = 3 \rightarrow$ possible mixing suppression
- Large RH rotation can evade CKM suppression [Sen '1985]
- Maximal RH rotation: 3rd-gen gauge states \rightarrow light mass states
- Weak scale: electroweak-anomaly vertex $\xrightarrow[\text{charged-current flavor conversions}]{\text{off shell W bosons}}$ light nuclear states
- Conservative view: $\sigma_{\text{weak}} \lesssim \sigma_{\Delta B=3} \lesssim \sigma_{\text{strong}}$

Experimental Signatures

From Solar Core - monopoles accumulated

- Super-Kamiokande (SK) gives a published solar-monopole search [Ueno et.al '2012]
 - SK: 50-kton water Cherenkov detector sensitive to neutrinos
- $\Delta B = 1$ catalysis (proton decay) in Sun $\rightarrow \pi^+, \mu^+$ stop & decay: $\pi^+ \rightarrow \mu^+ \nu_\mu, \mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$
- $\Delta B = 3$ Conservative recast: ${}^4\text{He}$ - only use the stopped π^+/μ^+ neutrino component
- Same experimental bound - total solar catalysis rate f_{max}
- Catalysis cross section: $\sigma_{\Delta B=3} = \frac{\sigma_0}{\beta_{\text{rel}}} F(\beta_{\text{rel}}) P_{3N}$
- $f_{p_3} = N_M \times r_3^{\text{per M}} \leq f_{\text{max}}$

Solar monopole flux limit from free scattering



- SK $\Delta B = 3$ unbound scattering (strong)
- - SK $\Delta B = 3$ unbound scattering (weak)

- Direct terrestrial searches: UCSD-II, Soudan-2, Baksan, Kolar, Kamiola, MACRO, Mica
- Astrophysical searches for $\Delta B = 1$ Callan Rubakov effect: Neutron stars, Kamiokande, Super-Kamiokande
 - Stronger bounds in general due to larger targets and longer exposure time of monopole
- Parker bound: not a detector limit — a magnetic-field survival bound

Neutron-star $\Delta B = 3$ heating bound

- SK $\Delta B = 3$ free scattering (strong)
- - - SK $\Delta B = 3$ free scattering (weak)
- $\Delta B = 3$ Neutron star bound (strong)
- - - $\Delta B = 3$ Neutron star bound (weak)

- Captured monopoles \rightarrow core catalysis \rightarrow heating \rightarrow soft X-ray luminosity [Kolb & Turner '1984]

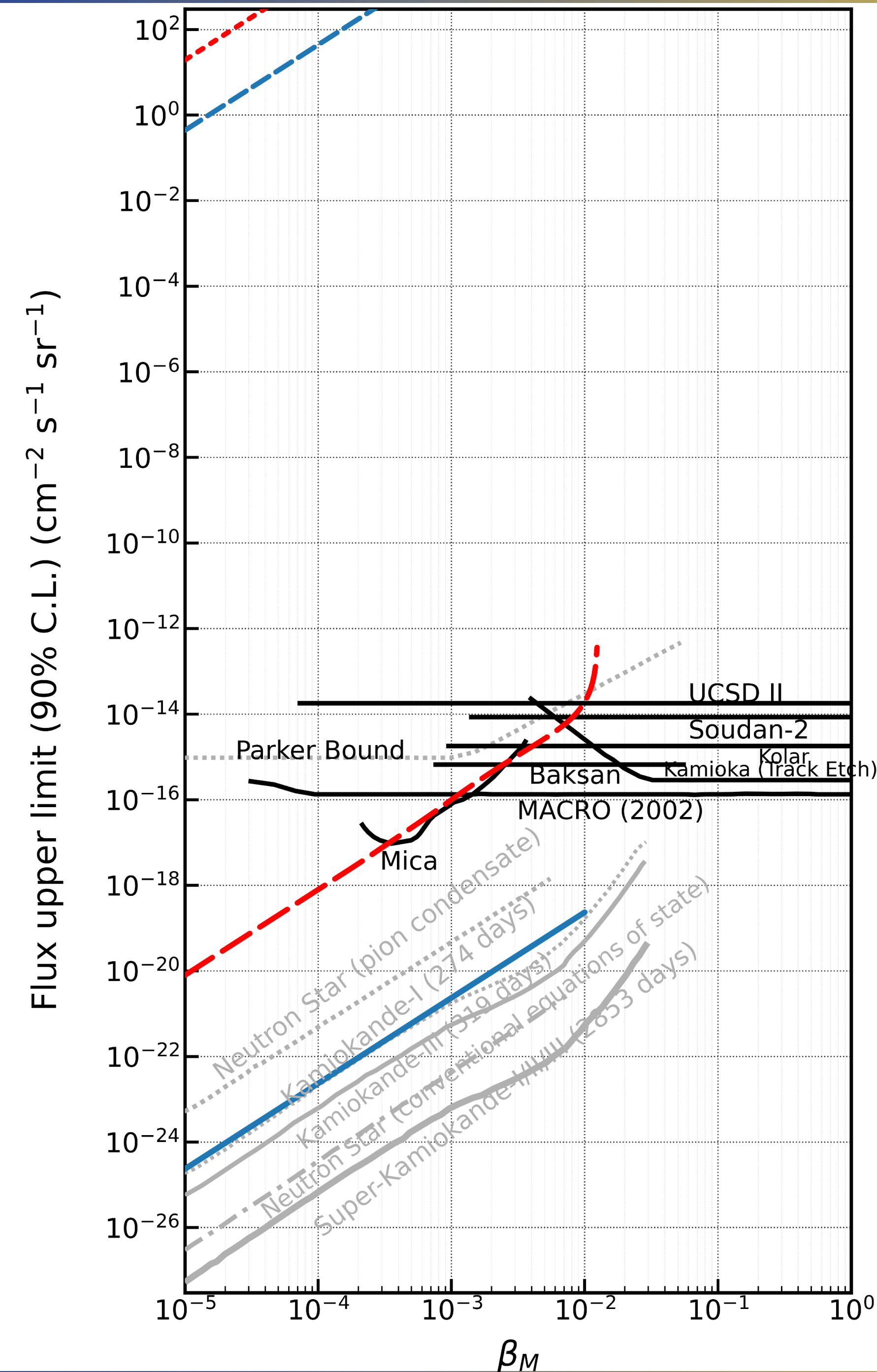
- Non-observation of extra soft X-ray emission \Rightarrow upper bound on monopole flux

- **Per monopole catalysis rate:**

$$r_3 = n_N \sigma_{\text{str}} v_{\text{rel}} P_{3N}$$

- Power deposited by one monopole into the star: $P_3 = r_3 E_{\text{decay}}^{(3)}$

- $L_{M,3} = N_M P_3 \leq L_\gamma$



Future Directions

- General phenomenon - electroweak anomaly

Theory

- Catalysis rate - UV completion
- Generalize beyond Pati–Salam
 - broader space of lighter anomaly-participating monopole

[Sen '1985]

Phenomenology

- Harder vertex neutrinos / kaon-rich channels in solar signal
- Modern soft X-ray data in neutron-star bound

Appendix I

Full quantum field theory story of Callan-Rubakov effect (anomaly only)

- Special $J=0$ channel reaches the monopole core
- Full QFT: sum over time-dependent gauge-field histories around the same monopole
- Some core histories have $\int F \widetilde{F} \neq 0$ (equivalently $E \cdot B \neq 0$ near the core)
 - Quantum gauge-field fluctuations E in the monopole sector
 - Saddle-point configurations develop radial E
- Anomaly converts that topological event into $\Delta N_f \neq 0$
- Exact gauge charge is preserved; anomalous/global baryon or fermion number can change

Appendix II

$$U(1)_{B+L} \rightarrow Z_6$$

- For a global $U(1)_{B+L}$ rotation: $\psi_i \rightarrow e^{i\alpha q_i} \psi_i$
- ABJ anomaly - $\partial_\mu j_{B+L}^\mu = A \frac{g^2}{32\pi^2} F_{\mu\nu}^a \widetilde{F}^{a\mu\nu}$
- Topological charge - $\nu = \int d^4x \frac{g^2}{32\pi^2} F_{\mu\nu}^a \widetilde{F}^{a\mu\nu} \in \mathbb{Z}$
- Under a local transformation parameter α , $\delta_\alpha \Gamma = \alpha A \nu$, $Z \rightarrow e^{i\delta_\alpha \Gamma} Z = e^{i\alpha A \nu} Z$
- Symmetry survive only if $e^{i\alpha A \nu} = 1$ for all $\nu \in \mathbb{Z} \rightarrow$ choose $\alpha = \frac{2\pi m}{A}$, $m \in \mathbb{Z}$
- $U(1)_{B+L} \rightarrow Z_A$ - SM: $A = 6$ for 3 generations

Appendix III

From Solar Core - monopoles accumulated

- Super-Kamiokande (SK) gives a published solar-monopole search [\[Ueno et.al '2012\]](#)
 - 50-kton water Cherenkov detector
- $\Delta B = 1$ catalysis (proton decay) in Sun $\rightarrow \pi^+, \mu^+$ stop & decay: $\pi^+ \rightarrow \mu^+ \nu_\mu$,
 $\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$ chain $\rightarrow \nu$ flux at Earth $\rightarrow \nu e + \bar{\nu}_e p \rightarrow$ SK events in 19--55 MeV
- Extract signal from solar angular correlation: $\cos \theta_{\text{Sun}}$
- $N_i^{\text{obs}} = N_i^{\text{sig}}(I_0) + \alpha N_i^{\text{bkg}}$
- $I_0 = 102 \pm 64 \text{ cm}^{-2} \text{ s}^{-1}$, 1.6σ excess
- $I_{90} = 166.6 \text{ cm}^{-2} \text{ s}^{-1}$ from the 90% C.L. upper limit on the fitted neutrino flux

Appendix IV

From SK's neutrino limit to $\Delta B = 3$ monopole flux limit full pipeline

- Bound on the total solar catalysis rate - $f_3^{\max} \sim \frac{4\pi d^2 I_{90}}{3 f_{\nu_e}^{(3)}}$
 - Catalysis cross section: $\sigma_{\Delta B=3} = \frac{\sigma_0}{\beta_{\text{rel}}} F(\beta_{\text{rel}}) P_{3N}$, $F(\beta_{\text{rel}}) = 0.017$ at $\beta = 10^{-3}$
 - Per monopole catalyzed rate: $r_{3,4\text{He}}^{\text{per M}} = \int d^3 r n_{\text{He}}(r) v_{\text{He}}(r) \sigma_{\Delta B=3}(r)$
- $$f_{p_3} = N_M \times r_3^{\text{per M}} \leq f_3^{\max}, \quad N_M = 4\pi^2 R_{\odot}^2 t_{\odot} \left(1 + \frac{\beta_{\text{esc}}^2}{\beta_M^2} \right) \epsilon(M, \beta_M) F_M,$$
- [Ahlen et.al '1997], [Ahlen et.al 1996]
- $F_M^{\max} \propto \frac{I_{90}}{f_{\nu_e}^{(3)} r_3^{\text{per M}} \epsilon(M, \beta_M) (1 + \beta_{\text{esc}}^2 / \beta_M^2)}$

Appendix V

$\Delta B = 3$ monopole flux limit vs mass at $\beta_M = 10^{-3}$

