# Destabilizing Matter through a Long-Range Force

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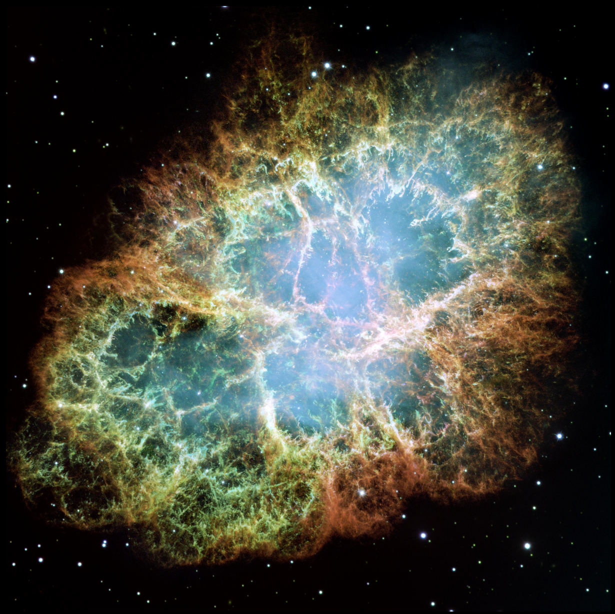

Based on: H.D., Phys.Rev.D 108 (2023) 1, 015023; 2304.06071 [hep-ph]

H.D. and P.Denton, work in progress

The 2024 International Workshop on Baryon and Lepton Number Violation (BLV2024)

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Brookhaven National Laboratory

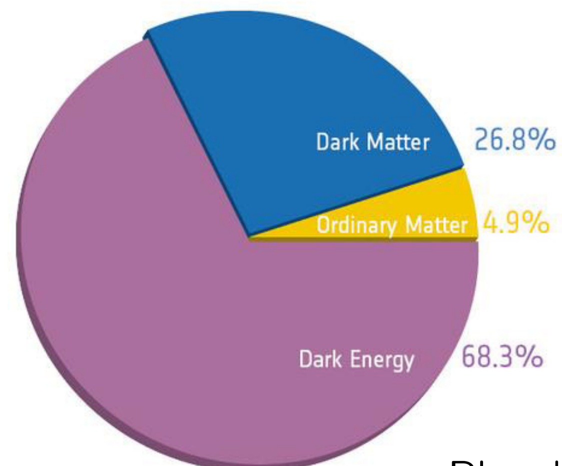
# Introduction

- Ordinary matter ($\sim 5\%$) made of nucleons $(p, n)$ is very stable:
  - Over far longer than cosmological time scales ($\sim 10^{10}$ years)
  - Searches have only yielded strong bounds, *e.g.*

$$\tau(p \to \pi^0 \ell^+) > 2.4\,(1.6) \times 10^{34}\ \text{yr, for } \ell = e\ (\mu)\text{, at 90\% CL}$$

Super-Kamiokande Collaboration; PDG

- Dark matter ($\sim 27\%$): requires new physics
  - Perhaps a new sector with its own forces



Planck

- This talk: a new long-range force
  - Ultralight scalar $\phi$
  - Can be sourced by astronomical objects
- Long range force: local background effects
  - Like an electric or gravitational field

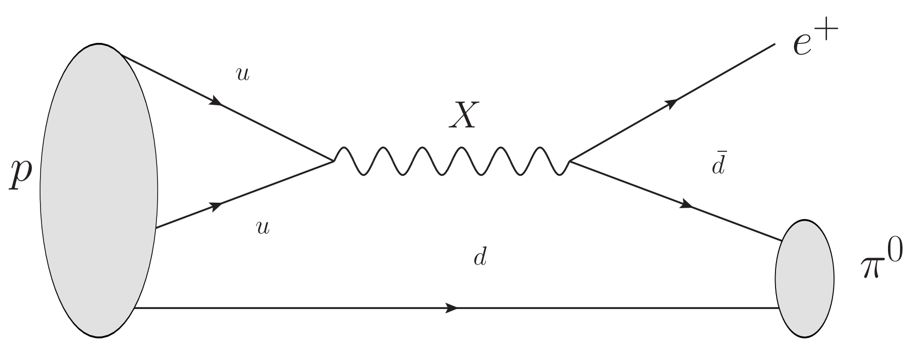
# Baryon Number Violation (BNV)

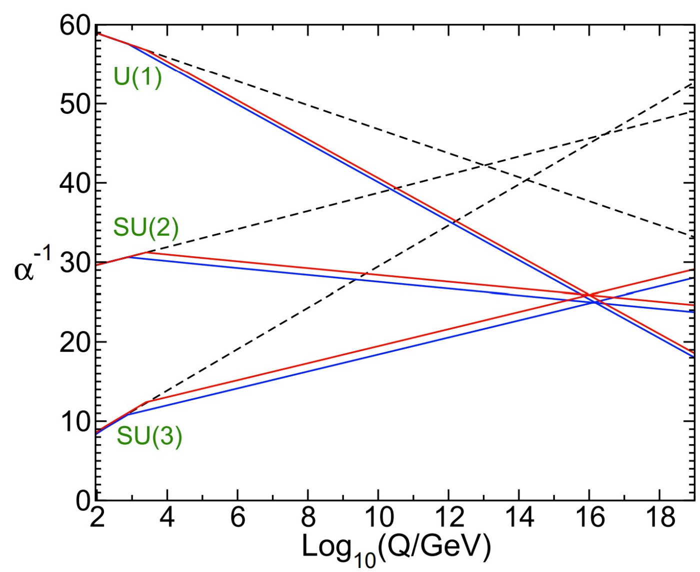
- In the SM, proton decay naturally suppressed, *e.g.*:

$$O_6 = \frac{(uud\ell)_R}{M^2}$$

  - $M$ could be large, maybe near $M_{\text{P}} \approx 1.2 \times 10^{19}$ GeV
  - A consequence of gauge invariance
  - Baryon number: *accidental symmetry*

- Current bounds $M \gtrsim 10^{16}$ GeV
  - Consistent with a GUT interpretation
  - SM (dashed) ; MSSM (solid)




From S. Martin, hep-ph/9709356

# New Physics and Nucleon Decay

- New light physics can affect nucleon decay

*E.g.*, HD 2013; Heeck 2020; Fajfer and Susic 2020

- Consider a light new scalar $\phi$ from a different sector

- One can write down, for example, a dim-7 operator

$$O_7 = \frac{\phi\,(uud\,\ell)_R}{\Lambda^3}$$

- For $m_\phi < m_p - m_e$ one can have $p \to \phi\, e^+$

- However, if $\langle\phi\rangle \neq 0$, dim-7 $\to$ dim-6: $\frac{\phi\,(uud\,\ell)_R}{\Lambda^3} \to \left(\frac{\langle\phi\rangle}{\Lambda}\right)\frac{(uud\,\ell)_R}{\Lambda^2}$
    - Effectively, the coefficient of a dim-6 operator becomes a *background field*

# A New Scalar Force

- Assume an ultralight scalar $\phi$ of mass $\boxed{m_\phi = 10^{-16}\ \text{eV}}$
  - Can arise in a variety of contexts (CPV axions, string moduli,. . . )
  - Sun's radius $R_\odot \approx 7 \times 10^5$ km $\sim (10^{-16}\ \text{eV})^{-1}$
- Possible coupling to nucleons $N$: $g_N\, \phi\, \bar{N} N$
  - $g_N \lesssim 8.0 \times 10^{-25}$ $(2\sigma)$ Microscope Collaboration 2022; Fayet 2017
- We will use reference value $\boxed{g_N = 10^{-25}}$
- Astronomical objects can *coherently* source significant $\langle\phi\rangle$ values

$$\langle \phi_* \rangle \approx -\frac{g_N (M_*/m_N)}{4\pi\, R_*}$$

($m_N$: nucleon mass)

- We will focus on

$$\boxed{O_7 = \frac{\phi\,(u u d\, \ell)_R}{\Lambda^3}}$$

  - As an example, other choices possible
  - Can lead to environment-dependent nucleon decay rates $\propto \langle \phi_* \rangle^2$

# Formalism

- Using chiral perturbation theory   Claudson, Wise, Hall, 1982

$$\mathcal{L}_{(\Delta B=0)} = \left[\frac{(3F-D)}{2\sqrt{3}f_\pi}\,\partial_\mu\eta + \frac{(D+F)}{2f_\pi}\,\partial_\mu\pi^0\right]\bar{p}\gamma^\mu\gamma_5 p + \frac{(D+F)}{\sqrt{2}f_\pi}\,\partial_\mu\pi^+\,\bar{p}\gamma^\mu\gamma_5 n + \ldots$$

$$\mathcal{L}_{(\Delta B=1)} = \frac{\beta}{\Lambda^3}\,\phi\,\left[\overline{e^c_R}\,p_R - \frac{i}{2f_\pi}(\sqrt{3}\eta + \pi^0)\overline{e^c_R}\,p_R\right] - \frac{\beta}{\Lambda^3}\,\phi\,\left[\frac{i}{\sqrt{2}f_\pi}\pi^+\overline{e^c_R}\,n_R\right] + \text{H.C.}$$

$D = 0.80$, $F = 0.47$, $\beta = 0.01269(107)$ GeV$^3$, Aoki et al., RBC-UKQCD, 2008 ; $f_\pi \approx 92$ MeV

- Focus on 2-body decays; ignore $m_e$   $\mathcal{M} = \pi^0, \eta$

Proton decays: $$\boxed{\Gamma(p\to\phi\, e^+) = \frac{\kappa^2}{32\pi}\,m_p}$$ and $$\boxed{\Gamma(p\to\mathcal{M}e^+) = \frac{\lambda_\mathcal{M}^2}{32\pi}\,m_p\left(1-\frac{m_\mathcal{M}^2}{m_p^2}\right)^2}$$

- Implies $p\to\phi\, e^+$ dominant when $f_\pi \gg \langle\phi\rangle$ (empty space or $g_N\to 0$)

Neutron decay: $$\boxed{\Gamma(n\to\pi^- e^+) = \frac{\lambda_\pi^2}{16\pi}\,m_n\left(1-\frac{m_{\pi^-}^2}{m_n^2}\right)^2}$$

$\kappa \equiv \beta/\Lambda^3$ ; $\mu = \kappa\langle\phi\rangle$ ; $\lambda_\pi \equiv \frac{(D+F+1)\mu}{2f_\pi}$ ; $\lambda_\eta \equiv \frac{(3F-D+3)\mu}{2\sqrt{3}\,f_\pi}$

# “Local” Constraints

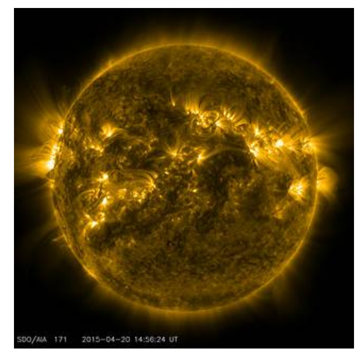
- Laboratory searches *
  - $\tau(p \to e^+\pi^0) > 1.6 \times 10^{34}$ yr (90% CL)      PDG 2022

$$\Rightarrow \boxed{\Lambda \gtrsim 2 \times 10^{11} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}}$$

* PDG 2022 also cites an updated bound, stronger by 3/2, which constrains $\Lambda$ at the same level.

- Search for anomalous flux of $\mathcal{O}(10 \text{ MeV})$ solar neutrinos
  - Super-Kamiokande (SK) search for BNV      Ueno et al., (SK Collab.), 2012

  \- Monopole (GUT) mediated      Rubakov 1981; Callan 1982




  - SK: 176 kton-yr of data, focused on $\pi^+$ from $p$ decays
  - We consider $p \to e^+\eta$ with $\text{Br}(\eta \to \pi^+ X) \approx 27\%$   PDG 2022

$$\phi(r_0) = -\frac{g_N}{2m_N}\int_0^{R_\odot} dr\, r^2\, \rho(r) \int_{-1}^{+1} dx\, \frac{e^{-m_\phi|\vec{r}-\vec{r}_0|}}{|\vec{r}-\vec{r}_0|} y$$

Bahcall and Pinsonneault, 2004

  - Rate of $p \to e^+\eta$ in the Sun:

$$\mathcal{R}_{\eta e} = \frac{4\pi}{m_N}\int_0^{R_\odot} dr\, r^2 \rho(r)\, \Gamma(r)_{(p\to\eta\, e^+)} \Rightarrow \boxed{\Lambda \gtrsim 2 \times 10^{10} \left(\frac{g_N}{10^{-25}}\right)^{1/3} \text{ GeV}}$$

# Neutron Star Heating via Nucleon Decay

- Neutron star (NS) mass $M_{\text{NS}} \approx 1.5 M_\odot$ and radius $R_{\text{NS}} \approx 10$ km
  - $n_N \sim 4 \times 10^{38}$ cm$^{-3}$

- Focus on neutron decay $n \to \pi^- e^+$, depositing $E \approx m_n$ in the NS
  - $\sigma_{\nu N} \sim 10^{-42}$ cm$^2$ for $E_\nu \sim 10$ MeV $\Rightarrow \lambda_\nu \sim \mathcal{O}(10 \text{ m}) \ll R_{\text{NS}}$
  - All decay products scatter many times in the NS

- Constant density approximation

$$\rho_{\text{NS}} = \frac{M_{\text{NS}}}{(4\pi/3) R_{\text{NS}}^3} \approx 7 \times 10^{14} \text{ gcm}^{-3}$$

- For $r < R_{\text{NS}}$

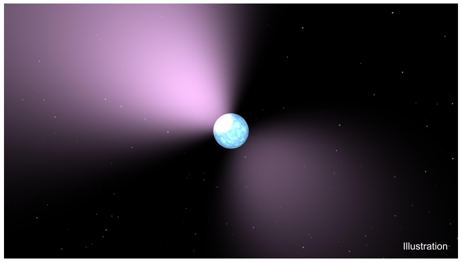
$$\phi_{\text{NS}}(r) \approx -\frac{g_N \, \rho_{\text{NS}}}{6\, m_n} R_{\text{NS}}^2 \left(3 - \frac{r^2}{R_{\text{NS}}^2}\right)$$

- Neutron decay rate in NS

$$\Gamma_n^{\text{NS}} = 4\pi \frac{\rho_{\text{NS}}}{m_n} \int_0^{R_{\text{NS}}} dr\, r^2\, \Gamma(r)_{(n \to \pi^- e^+)}$$

# Observational Bound

- Steady state: $m_n \Gamma_n^{\text{NS}} = 4\pi R_{\text{NS}}^2 \, \sigma_{\text{SB}} \, T_{\text{NS}}^4$
  - Stefan-Boltzmann constant $\sigma_{\text{SB}} = \pi^2/60$
  - Surface temperature: $T_{\text{NS}}$




Credit: NASA

- Coldest known NS: pulsar PSR J2144-3933
  - Hubble Space Telescope (HST) data: $T_{\text{NS}} < 42000$ K  Guillot *et al.*, 2019
  - Distance from Earth $\approx$ 180 pc, estimated to be $3 \times 10^8$ yr old
  - $T_{\text{NS}} \sim \mathcal{O}(100 \text{ K})$ expected without heating  Yakovlev, Pethick, 2004

- The NS heating bound yields*

$$\boxed{\Lambda \gtrsim 7 \times 10^{11} \left( \frac{g_N}{10^{-25}} \right)^{1/3} \text{ GeV}} \quad \text{(HST)}$$

  - Potential improvements from James Webb Space Telescope

E.g., Chatterjee *et al.*, 2022; Raj, Shivanna, Rachh, 2024

*Note: The bound implies $\tau_p \gtrsim 10^{20}$ yr near the NS

# Ultralight Dark Matter

- Alternative assumptions can make $\phi$ viable DM
- Example: allow for electron coupling $g_e \phi \bar{e} e$ with $g_e \sim 10^{-25}$
  - $g_e \lesssim 1.4 \times 10^{-25}$ at $2\sigma$ Microscope collaboration 2022; Fayet 2017
- $\phi \sim g_e n_e m_\phi^{-2}$ by "thermal misalignment" Batell, Ghalsasi, 2020
- $\phi$ starts oscillating once $H \sim m_\phi$ corresponding to $T \sim$ MeV, $n_e \sim T^3$
- For $m_\phi \sim 10^{-16}$ eV we find $\phi_i \sim 10^{25}$ eV
- Initial energy density $\rho_i \sim m_\phi^2 \phi_i^2 \sim 10^{18}$ eV$^4$ redshifts like $T^{-3}$
- At $T \sim$ eV (matter-radiation equality): $\rho_i \to \mathcal{O}(\text{eV}^4) \Rightarrow \phi$ could be DM
- For $\rho_{\text{DM}} \sim 0.3 - 0.4$ GeV cm$^{-3}$ (nearby): $\phi_{\text{DM}} \sim 10^{13}$ eV, $\mathcal{O}(10)$ larger than $\phi_\oplus$
  - Would not lead to stronger constraint from nucleon decay data than from NS heating
  - Introduces time variation due to wavelike nature of $\phi$ DM
  - Further phenomenology beyond the scope of this talk

# How fast can protons decay?

H.D., P. Denton; work in progress

- NS heating: aside from laboratory bounds, proton decay can be much faster

- Can this be a local effect?

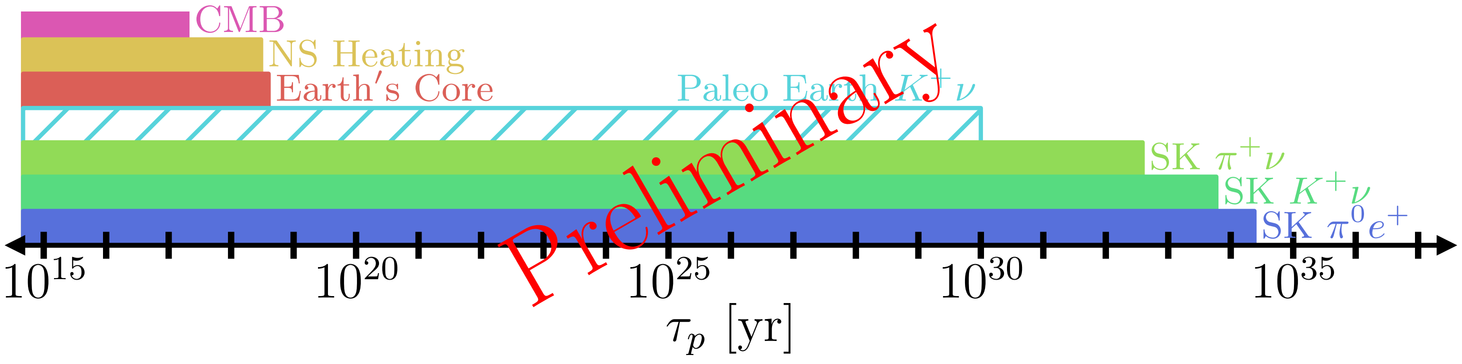
- $udd\psi/M^2$, with dark fermion $\psi$: fast $p \to \pi^+\psi$ if kinematically allowed
- Consider: $m_\psi$ set by $\mathcal{O}$(kpc) range scalar background sourced by DM
- No fast proton decay near Earth, but could be allowed where DM low density
- Local DM density evolution: proton decay rate modulation on Galactic time scales

- Can search for such effects, akin to DM decay

- Anti-correlated with DM density, in the above picture

- Maybe a global effect: $m_\psi$ governed by an evolving cosmic modulus

- Proton decay faster everywhere in the Universe, billions of years ago
- Can we look for its imprints?



# Concluding Remarks

- We considered the effect of an ultralight scalar $\phi$ on BNV
- Besides providing a final state, $\phi$ may be sourced by matter
- Our discussion focused on a particular operator, as an example
- This can enhance standard operators mediating BNV near astronomical bodies
  - $\langle\phi\rangle(x)$ as a Wilson coefficient in the EFT
- We examined laboratory bounds, as well as solar neutrino emission and neutron star heating via BNV
- Current HST observations of the coldest known pulsar seem to provide the strongest bounds on our setup
  - Data from JWST could provide improved bounds
- Depending on choice of parameters, $\phi$ could be an ultralight DM candidate
- More generally: Can proton decay be faster in the past, elsewhere?

- Proton longevity may be a local effect: could look for its decay far away from us

- Alternatively, could be governed by a cosmic modulus, much faster in the past

- What would be the imprints on Earth?