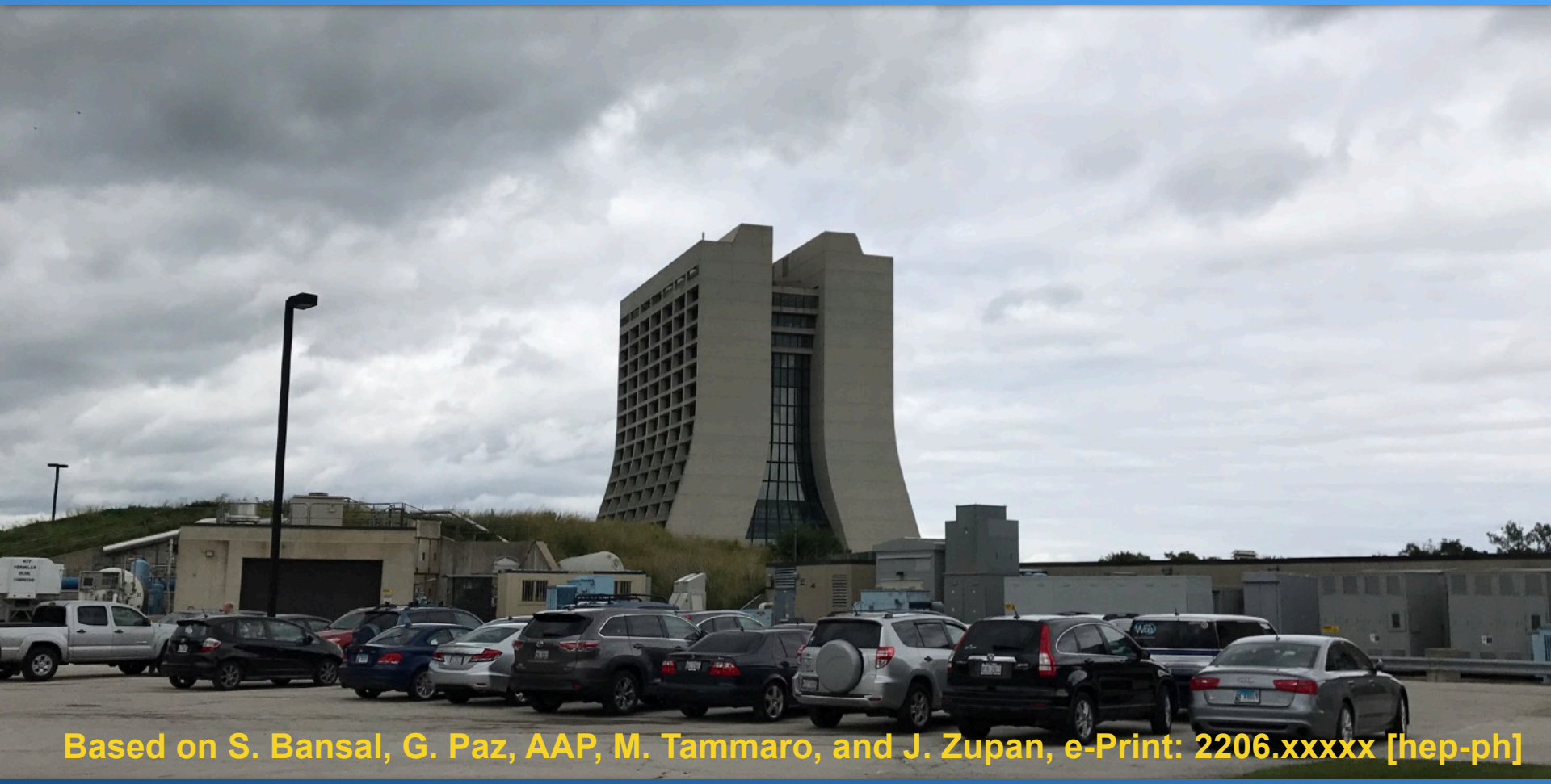
Neutrino polarizability



Based on S. Bansal, G. Paz, AAP, M. Tammaro, and J. Zupan, e-Print: 2206.xxxxx [hep-ph]

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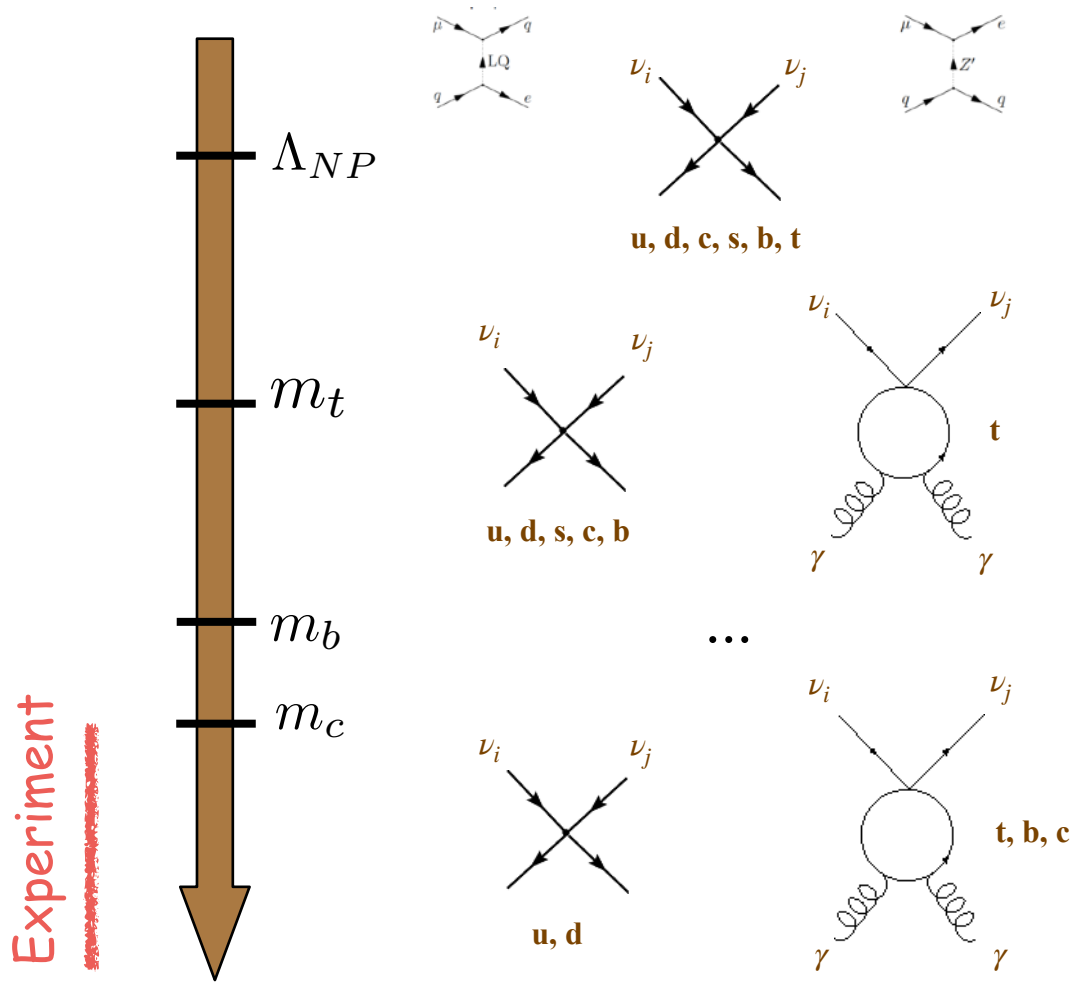
1. Introduction: neutrino EM interactions (EFT)

★ Modern approach to flavor physics calculations: effective field theories

★ It is important to understand ALL relevant energy scales for the problem at hand



New Physics generates lepton FCNC

Scales associated with heavy SM particles (quarks, leptons)

...

heavy quarks decouple

...

Scales associated with experiment

ν electromagnetic interactions

- Neutrino electromagnetic interactions: signs of New Physics?
  - ν electromagnetic interactions are described by operators of dim ≥ 5

$$\mathcal{L}_{\rm EFT} \supset \sum_{i>j} \frac{C^{(5)}_{1,ij}}{\Lambda} \frac{e}{8\pi^2} (\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu}$$

dipole moment

$$+ \sum_{i,j} \frac{C^{(6)}_{F,ij}}{\Lambda^2} \bar{\nu}_i \gamma^\mu \gamma_5 \nu_j \partial^\nu F_{\mu\nu}$$

anapole moment

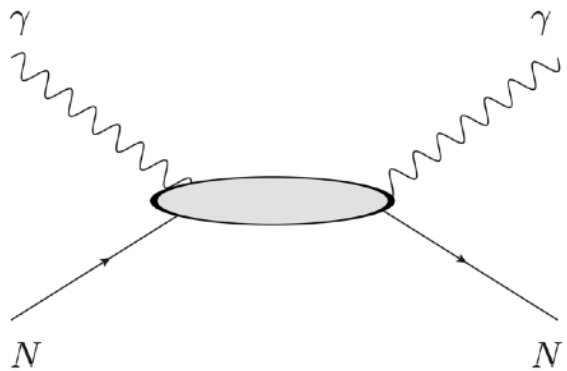
$$+ \frac{1}{2} \sum_{i,j} \left[\frac{C^{(7)}_{1,ij}}{\Lambda^3} \frac{\alpha}{12\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3} \frac{\alpha}{8\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} \tilde{F}^{\mu\nu} \right] + \cdots$$

polarizability

  - For Majorana neutrinos the flavor conserving dipole moments vanish because the dipole is antisymmetric in flavor indices $(\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) = -(\bar{\nu}_j \sigma^{\mu\nu} P_L \nu_i)$
  - The dim-7 Rayleigh operators are symmetric: flavor diagonal transition possible

Neutrino polarizability

- Polarizability: reaction to external EM field
  - Example: nucleon polarizabilities are extensively studied in Compton scattering



$$H_{scal} = -2\pi \left(\alpha_{E1} \vec{E}^2 + \beta_{M1} \vec{H}^2 \right)$$

Hagelstein, Miskimen, Pascalutsa

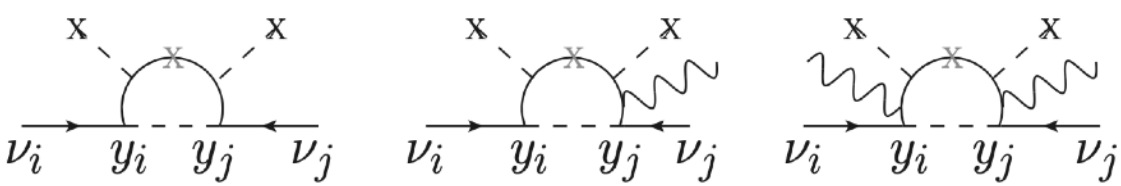
- Neutrino polarizability
  - neutrino polarizability is encoded in dim-7 Rayleigh operators

$$\mathcal{L} = \frac{1}{2} \sum_{i,j} \left[\frac{C^{(7)}_{1,ij}}{\Lambda^3} \frac{\alpha}{12\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3} \frac{\alpha}{8\pi} (\bar{\nu}_i P_L \nu_j) F_{\mu\nu} \tilde{F}^{\mu\nu} \right] + \cdots$$

  - … which are related to polarizability, as, e.g. $F_{\mu\nu} F^{\mu\nu} = \vec{H}^2 - \vec{E}^2$

Naive dimensional analysis: masses and EM interactions

- Neutrino masses: scale of New Physics?
  - Majorana: Weinberg terms (dim-5): $y'_{\alpha\beta}\left(\bar{L}^c_\alpha H^{c\dagger} H^\dagger L_\beta\right)/\Lambda$
  - Dirac: Yukawa terms (dim-4): $y_{\alpha\beta}\left(\bar{L}_\alpha H \nu_{R\beta}\right)$
  - need experiment, e.g. neutrinoless double beta decay



- Neutrino electromagnetic interactions: scale of New Physics?
  - Dipole moment: $c_6\left(\bar{L}_\alpha H \sigma^{\mu\nu} \nu_{R\beta}\right) F_{\mu\nu}/\Lambda^2$
  - Rayleigh operators: $c_8\left(\bar{L}_\alpha H \nu_{R\beta}\right) F_{\mu\nu} F^{\mu\nu}/\Lambda^4$
  - Both types of interaction flip chirality, so we naively expect

$$c_6 v/\Lambda^2 \sim c_6 m_\nu/\Lambda^2 \quad \text{or} \quad c_8 v/\Lambda^4 \sim c_8 m_\nu/\Lambda^4$$

  - … which is tiny and unobservable (similar for Majorana). So, why bother?

Dipole moment

- Neutrino electromagnetic interactions: signs of New Physics?
  - ν electromagnetic interactions are described by operators of dim ≥ 5

$$\mathcal{L}_{\rm EFT} \supset \sum_{i>j} \frac{C^{(5)}_{1,ij}}{\Lambda} \frac{e}{8\pi^2} (\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) F_{\mu\nu}$$

dipole moment

  - For Majorana neutrinos the dipole operator is antisymmetric in flavor indices $(\bar{\nu}_i \sigma^{\mu\nu} P_L \nu_j) = -(\bar{\nu}_j \sigma^{\mu\nu} P_L \nu_i)$, while the mass operator is symmetric
  - Then, any New Physics that is odd under the same flavor exchange will only contribute to the neutrino magnetic moments and not to the neutrino masses.

Voloshin

Neutrino electrodynamics and possible consequences for solar neutrinos

M. B. Voloshin, M. I. Vysotskiĭ, and L. B. Okun'

Institute of Theoretical and Experimental Physics
(Submitted 25 April 1986)
Zh. Eksp. Teor. Fiz. **91**, 754–765 (September 1986)

The neutrino electromagnetic moment matrix and the possibility that some of the elements of this matrix are of the order of 10^{-10} of the Bohr magneton are discussed. Flavor oscillations and spin precession are examined for a neutrino in a magnetic field in the presence of matter. The interaction between solar neutrinos and the magnetic field in the interior of the convective zone of the Sun can lead, in this case, to the 11-year and semiannual variations in the neutrino flux, shown experimentally to be correlated with the magnetic activity of the Sun.

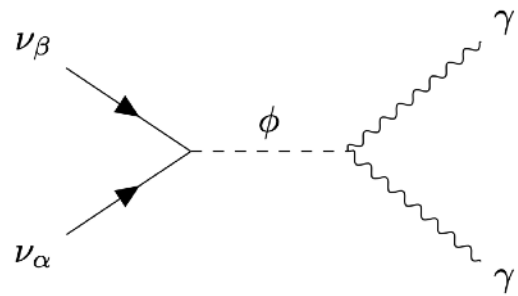
  - Is it possible to find a similar mechanism to enhance Rayleigh operators?

Polarizability: Rayleigh operators

- Neutrino polarizability
  - neutrino polarizability is encoded in dim-7 Rayleigh operators

$$\mathcal{L} = \frac{1}{2}\sum_{i,j}\left[\frac{C^{(7)}_{1,ij}}{\Lambda^3}\frac{\alpha}{12\pi}(\bar{\nu}_i P_L \nu_j)F_{\mu\nu}F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3}\frac{\alpha}{8\pi}(\bar{\nu}_i P_L \nu_j)F_{\mu\nu}\tilde{F}^{\mu\nu}\right] + \cdots$$

  - … which are also symmetric in flavor indices, just like the mass operator
  - But the smallness of the neutrino masses can be compensated:



  - A prototypical example is pNGB interactions: majoron a, which couples to $\Delta L = 2$ interaction as $\bar{\nu}^c_L \nu_L \partial_\mu a / f_a$
  - Majoron would also generically have EM couplings, aFF/Λ_γ
  - Thus, for energies below m_a: $\nu\nu FF \times (m_\nu/f_a)1/(m_a^2\Lambda_\gamma)$

We can study phenomenology of $\nu\nu FF$ interactions to probe New Physics

Phenomenology of neutrino polarizability

- Consider two separate cases
  - heavy mediator: effective operators and constraints on Wilson coefficients/New Physics scale

$$\mathcal{L} = \frac{1}{2}\sum_{i,j}\left[\frac{C^{(7)}_{1,ij}}{\Lambda^3}\frac{\alpha}{12\pi}(\bar{\nu}_i P_L \nu_j)F_{\mu\nu}F^{\mu\nu} + \frac{C^{(7)}_{2,ij}}{\Lambda^3}\frac{\alpha}{8\pi}(\bar{\nu}_i P_L \nu_j)F_{\mu\nu}\tilde{F}^{\mu\nu}\right] + \cdots$$

  - light mediator: constraints on a simplified model parameters

$$\mathcal{L}_{\rm int} = -\frac{\alpha}{12\pi}\frac{c_\gamma}{f_\phi}\phi F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{8\pi}\frac{c'_\gamma}{f_\phi}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}c^{ij}_\nu(\bar{\nu}_i P_L \nu_j)\phi + {\rm h.c.}$$

where c_γ, c'_γ and c^{ij}_ν are dimensionless couplings, while f_ϕ is a UV scale (e.g. related to pNG symmetry breaking)

  - also, $g_{\phi\gamma} \equiv \frac{\alpha}{2\pi}\frac{c'_\gamma}{f_\phi}$ and

$$\Gamma(\phi\to\gamma\gamma) = \left(\frac{\alpha}{8\pi}\right)^2\frac{m^3_\phi}{4\pi f^2_\phi}\left[\frac{4}{9}(c_\gamma)^2 + (c'_\gamma)^2\right],$$

$$\Gamma(\phi\to\nu\nu') = \frac{m_\phi}{16\pi}\sum_{\alpha\beta}\left|c^{\alpha\beta}_\nu\right|^2,$$

Light mediator phenomenology depends on what is larger, $\Gamma(\phi\to\gamma\gamma)$ or $\Gamma(\phi\to\nu\nu')$

Example: heavy mediator/collider constraints

- Consider invisible decays of scalar/pseudoscalar states (S = π^0, B^0, H)
  - interpreting those decays as decays into a pair of neutrinos, we can use the unitarity relation

$$\mathrm{Im}\ \mathcal{T}(S \to f) = \frac{1}{2i}\left(\langle f|\mathcal{T}|S\rangle - \langle f|\mathcal{T}^\dagger|S\rangle\right) = \frac{1}{2}\sum_I \langle f|\mathcal{T}^\dagger|I\rangle\langle I|\mathcal{T}|S\rangle$$

  - We can use the result above to calculate the rate of the process $S \to \gamma\gamma \to \bar{\nu}\nu$ by considering the discontinuity in the amplitude

$$\mathrm{Im}\ \mathcal{A}(S \to \gamma\gamma \to \bar{\nu}\nu) = \frac{m_S^4}{4\pi}\left[\mathcal{A}_+^S\left(\mathcal{A}_+^R\right)^* + \mathcal{A}_-^S\left(\mathcal{A}_-^R\right)^*\right]$$

  - where $A_\pm^S$ and $A_\pm^R$ are the coefficients of the meson to photon and neutrino to photon interaction Lagrangian

$$\mathcal{L} = \mathcal{A}_+^R(\bar{\nu}^c P_L \nu)F^{\mu\nu}F_{\mu\nu} + \mathcal{A}_-^R(\bar{\nu}^c P_L \nu)\tilde{F}^{\mu\nu}F_{\mu\nu}$$

with $\mathcal{A}_+^R = \frac{1}{2}\left(\frac{\alpha}{12\pi}\right)\frac{C_1}{\Lambda^3}$ and $\mathcal{A}_-^R = \frac{1}{2}\left(\frac{\alpha}{8\pi}\right)\frac{C_2}{\Lambda^3}$

Example: heavy mediator/collider constraints

- Consider invisible decays of scalar/pseudoscalar states (S = π^0, B^0, H)
  - since $|\mathrm{Im}\,\mathscr{A}(S \to \gamma\gamma \to \bar{\nu}\nu)| \leq |\mathscr{A}(S \to \gamma\gamma \to \bar{\nu}\nu)|$, the decay rate calculated using $|\mathrm{Im}\,\mathscr{A}|$ is smaller or equal to the decay rate calculated using $|\mathscr{A}|$, allowing to bound $|\mathscr{A}^R_\pm|$ from the invisible decays of S!

$$\Gamma_{\rm Im} = n_\nu \frac{m_S^9}{256\pi^3}\frac{1}{4}\left(\frac{\alpha}{8\pi}\right)^2 \left|\mathcal{A}^S_+\left(\frac{2}{3}\frac{C_1^*}{\Lambda^3}\right) + \mathcal{A}^S_-\left(\frac{C_2^*}{\Lambda^3}\right)\right|^2 \leq \Gamma(S \to \text{invisible})$$

  - which leads to the constraint

$$\left|\frac{C_i}{\Lambda^3}\right| \leq k_i \frac{128\pi^2}{\alpha m_S^3\sqrt{n_\nu}}\sqrt{\frac{\mathrm{Br}(S \to \text{invisible})}{\mathrm{Br}(S \to \gamma\gamma)}}$$

with $k_1 = 3/2$ and $k_2 = 1$

also, for the B-meson, $\mathscr{A}^{B^0}_+ = \mathscr{A}^{B^0}_- = \frac{G_F}{\sqrt{2}}\frac{\alpha}{3\pi}\frac{f_B}{2}V^*_{td}V_{tb}C_{7\gamma}\frac{m_{B^0}}{\lambda_B}$

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Heavy mediator constraints

- Heavy mediator constraints can be summarized as

Process	$\mathcal{C}/\Lambda^3$ (GeV^{-3})	EFT thr. (GeV)
BBN	X	$\sim 10^{-3}$
ν decay	—	$\sim 10^{-9}$
ν self-interaction	X	$\sim 10^{-6}$
HB star	1.9×10^6	$\sim 10^{-5}$
SN1987a	X	$\sim 10^{-1}$
Borexino	970	$\sim 10^{-4}$
Xenon-nT	751	$\sim 10^{-2}$
MiniBoone	4.5×10^{-2}	$\sim 10^{-1} - 1$
$\pi^0 \to \gamma\gamma \to \bar{\nu}\nu$	1.6×10^4	$\sim 1.4 \times 10^{-1}$
$B^0 \to \gamma\gamma \to \bar{\nu}\nu$	1.725×10^4	~ 5
BaBar	0.34	~ 10
$H^0 \to \gamma\gamma \to \bar{\nu}\nu$	0.35	~ 125

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Light mediator constraints

Process	$m_\phi = \text{eV}$	$m_\phi = \text{keV}$
BBN	$c_\nu \lesssim 4 \times 10^{-5}$	$c_\nu \lesssim 4.4 \times 10^{-6}$
ν self-interaction	$c_\nu < 2.8 \times 10^{-7}$	$c_\nu < 2.8 \times 10^{-4}$
HB star	$g_{\phi\gamma} \in [3.5 \times 10^{-3}, 10^{-11}]$	$g_{\phi\gamma} \in [3.3 \times 10^{-3}, 10^{-11}]$
SN1987a	$g_{\phi\gamma} \in [10^{-2}, 5 \times 10^{-6}]$	$g_{\phi\gamma} \in [10^{-2}, 5 \times 10^{-6}]$
	$c_\nu \in [10^{-3}, 1]$	$c_\nu \in [10^{-6}, 10^{-2}]$
Borexino	$c_\nu g_{\phi\gamma} < 1.1 \times 10^{-8}$	$c_\nu g_{\phi\gamma} < 1.1 \times 10^{-8}$
Xenon-nT	$c_\nu g_{\phi\gamma} < 9 \times 10^{-5}$	$c_\nu g_{\phi\gamma} < 9 \times 10^{-5}$
MiniBoone	$c_\nu g_{\phi\gamma} < 5.2 \times 10^{-7}$	$c_\nu g_{\phi\gamma} < 5.2 \times 10^{-7}$
$\pi^0 \to \gamma\gamma \to \bar{\nu}\nu$	$c_\nu g_{\phi\gamma} < 0.18$	$c_\nu g_{\phi\gamma} < 0.18$
$B^0 \to \gamma\gamma \to \bar{\nu}\nu$	$c_\nu g_{\phi\gamma} < 250$	$c_\nu g_{\phi\gamma} < 250$
BaBar	$c_\nu g_{\phi\gamma} < 4 \times 10^{-2}$	$c_\nu g_{\phi\gamma} < 4 \times 10^{-2}$

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Light mediator constraints

Process	$m_\phi =$ MeV	$m_\phi =$ GeV
BBN	$c_\nu \lesssim 5 \times 10^{-9}$	X
ν self-interaction	$c_\nu < 2.8 \times 10^{-1}$	$c_\nu < 2.8 \times 10^{2}$
HB star	X	X
SN1987a	$g_{\phi\gamma} \in [10^{-2}, 5 \times 10^{-6}]$	X
	$c_\nu \in [10^{-9}, 10^{-5}]$	X
Borexino	$c_\nu g_{\phi\gamma} < 1.1 \times 10^{-6}$	$c_\nu g_{\phi\gamma} < 1.1$
Xenon-nT	$c_\nu g_{\phi\gamma} < 9 \times 10^{-5}$	$c_\nu g_{\phi\gamma} < 0.87$
MiniBoone	$c_\nu g_{\phi\gamma} < 5.2 \times 10^{-7}$	$c_\nu g_{\phi\gamma} < 5.2 \times 10^{-5}$
$\pi^0 \to \gamma\gamma \to \bar{\nu}\nu$	$c_\nu g_{\phi\gamma} < 0.18$	$c_\nu g_{\phi\gamma} < 18$
$B^0 \to \gamma\gamma \to \bar{\nu}\nu$	$c_\nu g_{\phi\gamma} < 250$	$c_\nu g_{\phi\gamma} < 250$
BaBar	$c_\nu g_{\phi\gamma} < 4 \times 10^{-2}$	$c_\nu g_{\phi\gamma} < 4 \times 10^{-2}$

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Conclusions and takeaways

- Neutrino polarizabilities provide interesting tools for BSM studies
- Heavy mediators: effective operator description of polarizabilities
  - polarizabilities are encoded by Rayleigh operators
  - they are known to be important in explaining SM phenomena
  - they could be seen to probe effects in BSM-SM couplings
- Light mediators: simplified models
  - a mechanism that could provide enhancement for the process
  - explicit model building is possible

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The Evening
EXTRA!
FROM THE WIRES

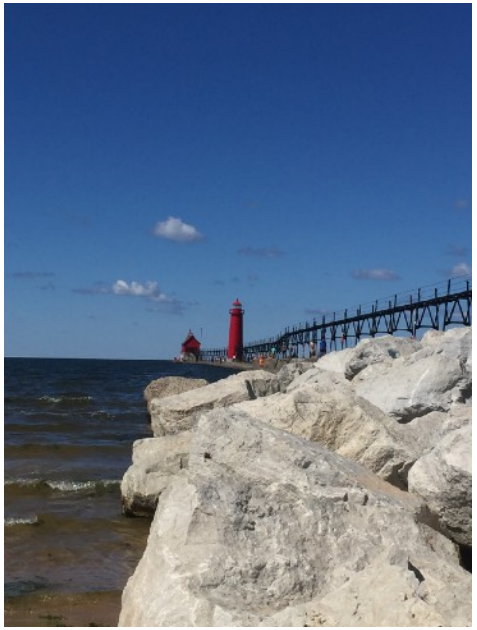
Why is the sky blue?

- Why is the sky blue?
  - stronger scattering of shorter wavelengths (blue) compared to longer wavelengths (red)

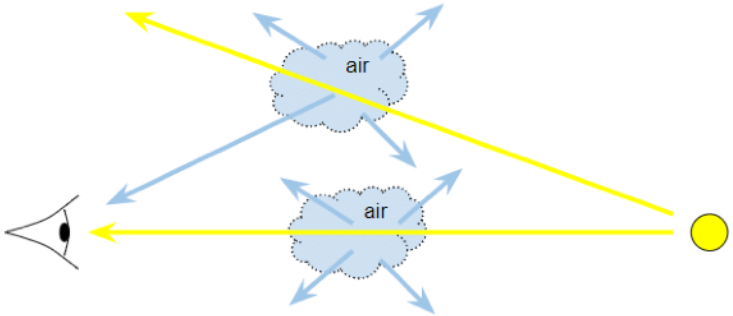
$$\sigma_{\rm R} = \frac{2\pi^5}{3}\frac{d^6}{\lambda^4}\left(\frac{n^2-1}{n^2+2}\right)^2$$

where n is the refractive index,
d is the scatterer size, and
λ is the wavelength

  - this is the so-called Rayleigh scattering cross section
  - blue (430 nm) scatters about a factor of 6 more efficient than red (680 nm)!



Lake Michigan lighthouses



Why is the sky blue (EFT version)?

- Let's construct EFT for low-energy elastic photon-atom scattering
  - photon energy E_γ is smaller that atom's excitation energy ΔE and (inverse) atomic Bohr radius a^{-1}

$$E_\gamma \ll \Delta E \ll a^{-1} \ll M_{\rm atom}$$

  - $\mathscr{L}_{\rm eff}$ should respect Lorentz, gauge, etc. invariance; need:
    - two photons (from $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$) with $\left[A_\mu\right] = 1$
    - two atomic fields ϕ_v with NR scaling $\left[\phi\right] = 3/2$

$$\mathcal{L}_{\rm eff} = \frac{c_1}{\Lambda^3}\ \phi_v^\dagger \phi_v\ F_{\mu\nu}F^{\mu\nu} + \frac{c_2}{\Lambda^3}\ \phi_v^\dagger \phi_v\ v^\alpha F_{\alpha\mu} v_\beta F^{\beta\mu} + \ldots$$

where c_i are $\mathcal{O}(1)$ and $\Lambda \sim a^{-1}$ (as low energy photons cannot feel inside the atom)

also, $v_\mu v^\mu = 1,\ v^\mu = (1,0,0,0)$ in ϕ_v rest frame

Why is the sky blue (EFT version)?

- Let's estimate the cross section ($\sigma \sim \Lambda^{-6}$)
  - in principle, we can match to QED to obtain c_i
  - order-of-magnitude: as $[\sigma] = -2$ and $\Lambda \sim a^{-1}$ we expect

$$\sigma \sim E_\gamma^4 a^6 \left[1 + \mathcal{O}\left(E_\gamma/\Delta E\right)\right]$$

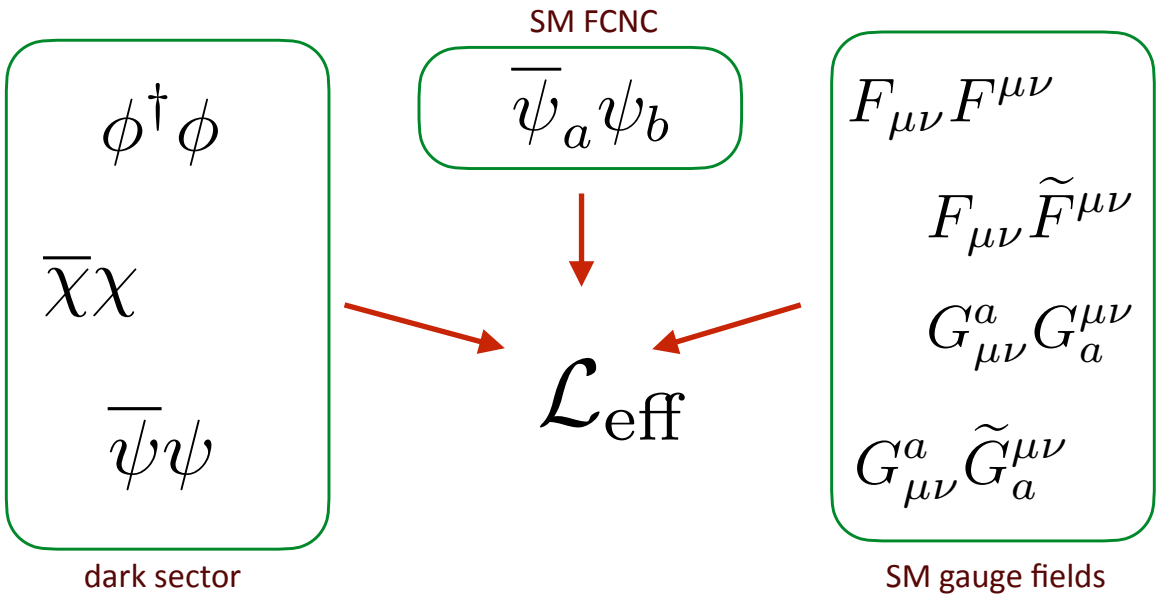
  - this is Rayleigh scattering: higher energy blue light scatters more than the low energy red light
  - expect corrections $\mathcal{O}(E_\gamma/\Delta E)$
  - results from Rayleigh operators

- Why is the sky red on Mars? Is it red?
- What about the night sky?

Mars Pathfinder picture

Rayleigh operators: EFT

- Rayleigh operators are built out of singlets (SM gauge + others)
  - ideal for studies of portal-type of SM-NP interaction models



  - also ideal for studies of FCNC effects in the SM
  - can represent leading effect for NP interactions with SM gauge fields

We will consider two such effects today: lepton FCNC/gluons and DM/photons interactions