DISTORTION OF NEUTRINO OSCILLATIONS BY DARK PHOTON DARK MATTER

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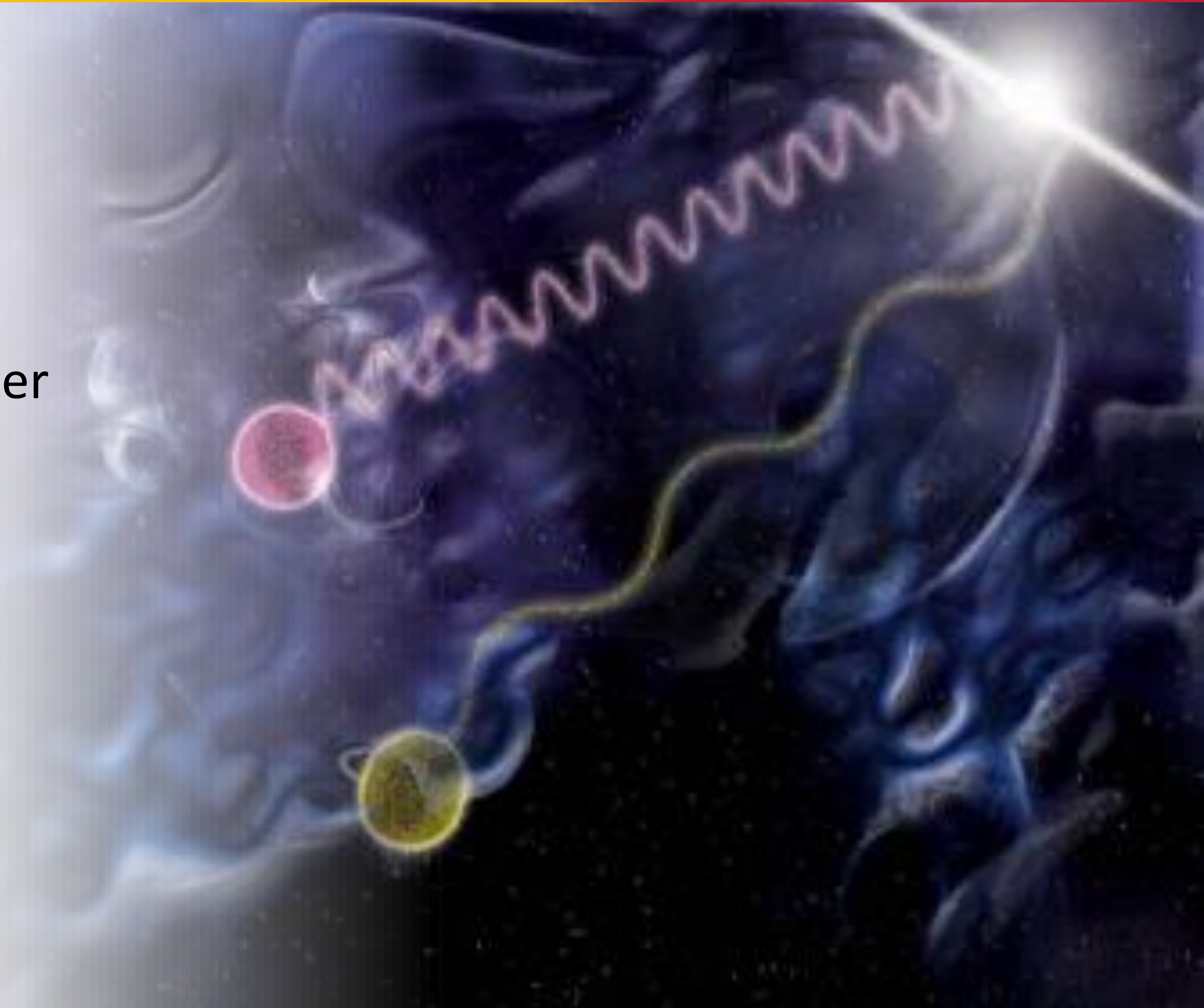
Introducing the Dark Photon

- Candidate for dark matter
- Field is locally polarized (has fixed direction)
- Couples to $L_\mu - L_\tau$
- Modifies dispersion relation of ν_μ and ν_τ
  - ➢ Modifies Hamiltonian describing neutrino oscillations



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Goal: Place bounds on dark photon gauge coupling and mass, and on neutrino vacuum oscillation parameters

- Solve Schrödinger equation for modified Hamiltonian
- Compare prediction to experimental data

Contents

Dark Photon – Neutrino Interaction

- Shift in neutrino dispersion relation:

$$E \rightarrow \sqrt{(\vec{p} \mp g' \vec{A}')^2 + m^2} \cong |\vec{p}| + \frac{m^2}{2p} \mp g' \hat{p} \cdot \vec{A}' + O(g'^2 A'^2)$$

  g' = dark photon gauge coupling

  A' = amplitude of dark photon field

  $\mp$ depends on neutrino flavor

- Approximate A'= constant in solar neighborhood + direction of neutrinos in experiments is constant
  - $\hat{p} \cdot \vec{A}' = A'_{\odot} \cos(m_{A'} t)$
- Background A' field makes up fraction of dark matter of the Universe

Dark Photon – Neutrino Interaction

- Hamiltonian for two-flavor approximation:

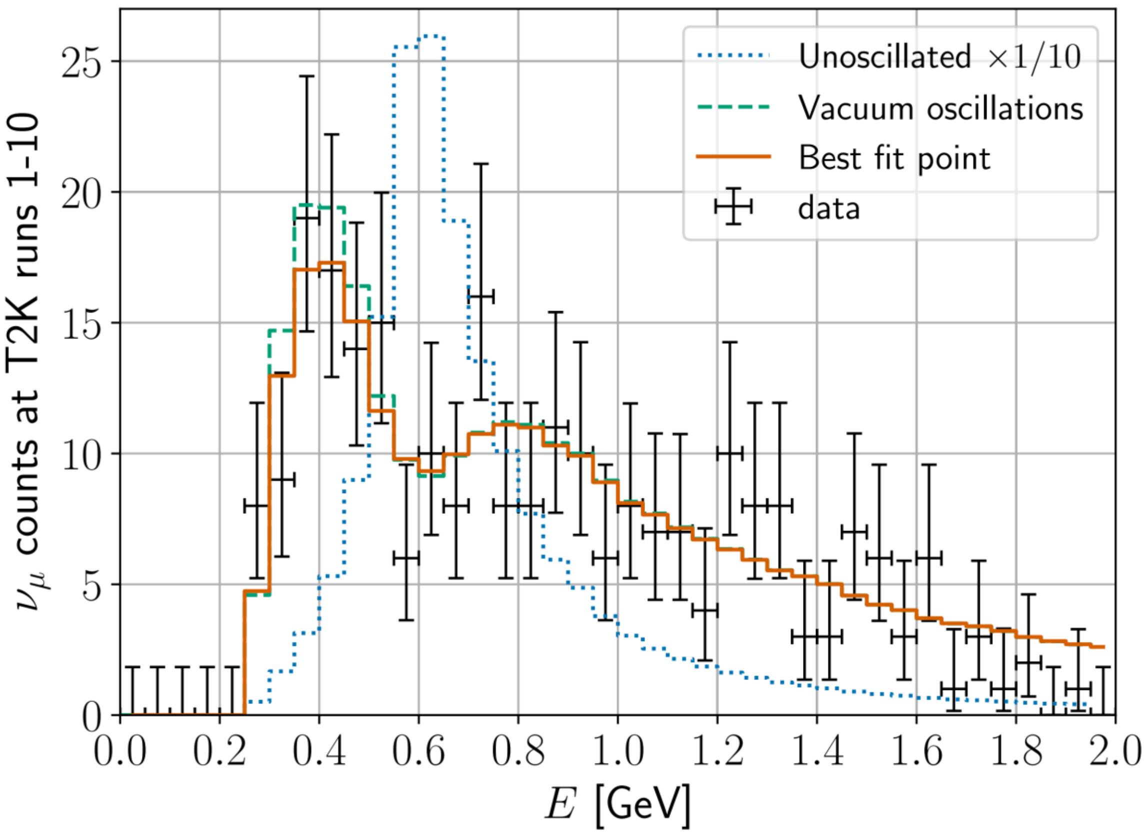
$$H = \begin{cases} \frac{\Delta m_{23}^2}{4p} \begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} + g' A'_{\odot} \cos(m_{A'} t) \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, & \text{atmospheric} \\ \frac{\Delta m_{12}^2}{4p} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + g' A'_{\odot} \cos(m_{A'} t) \begin{pmatrix} 0 & 0 \\ 0 & -1 \end{pmatrix}, & \text{solar} \end{cases}$$

- Numerically solve Schrödinger equation for survival probability of given flavor:

$$i \frac{d\Psi}{dt} = H\Psi \qquad P_{\mu\to\mu}(t) = |\langle \Psi(0) | \Psi(t) \rangle|^2$$

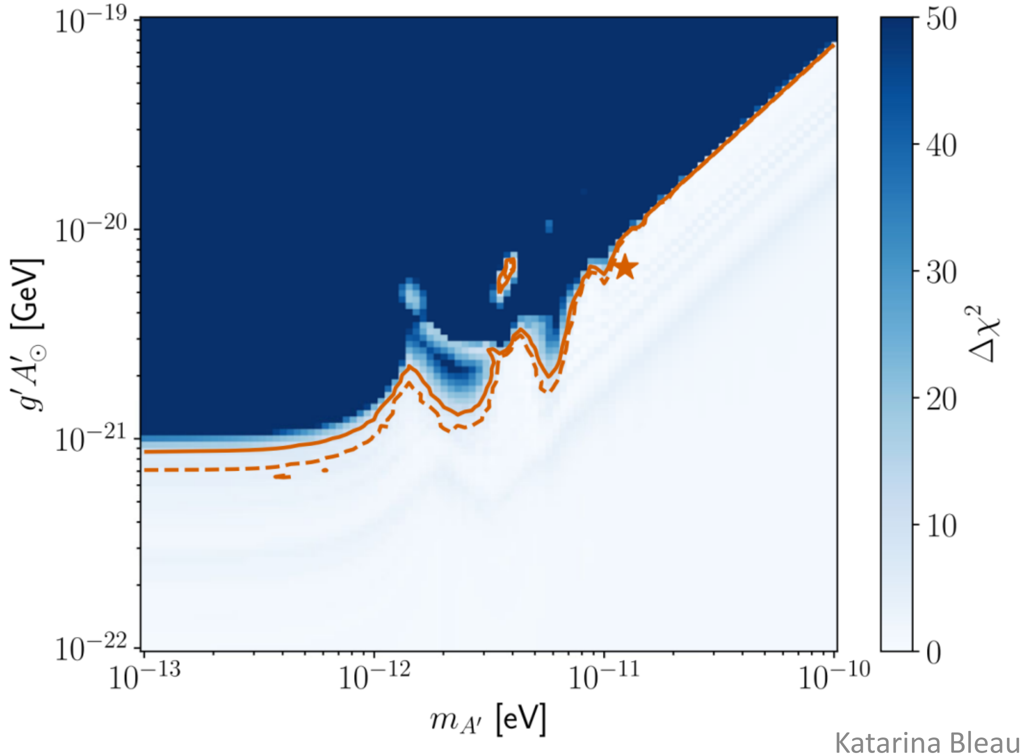
Long Baseline Neutrino Experiments

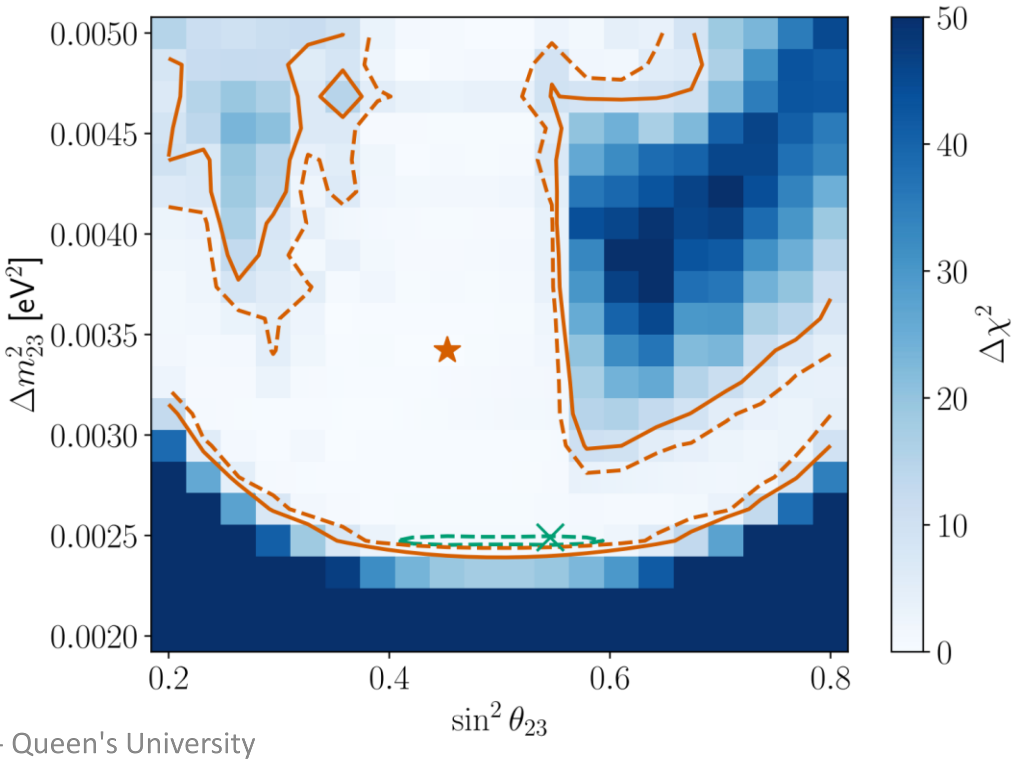
- Atmospheric neutrinos generated by cosmic ray interactions
- **Data:**
  - Tokai-to-Kamioka (T2K) experiment
  - Generate initial beam of ν_μ and observe flavor content at detector at L = 295 km
- **Prediction:**
  - dP/dE spectrum of initial beam
  - $P_{\mu\to\mu}(E, t \cong L)$
  - Detector response



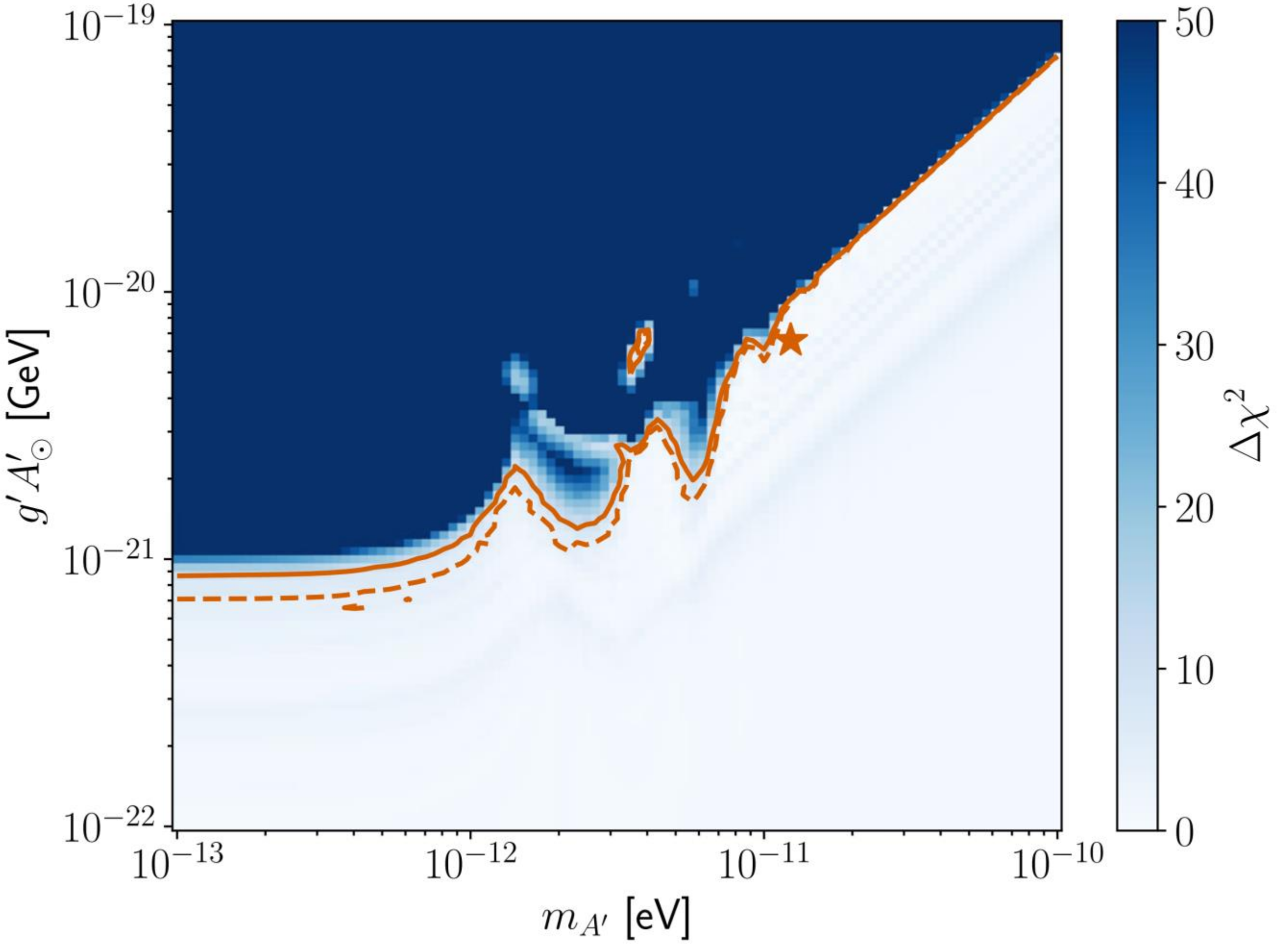
Long Baseline Neutrino Experiments

- χ^2 test comparing data with different predicted spectra, varying four parameters
- Orange star and solid (dashed) lines correspond to best fit point and 95% (68%) confidence line limits
- Green cross and dashed line correspond to best fit point and 68% confidence line limits in absence of dark photon





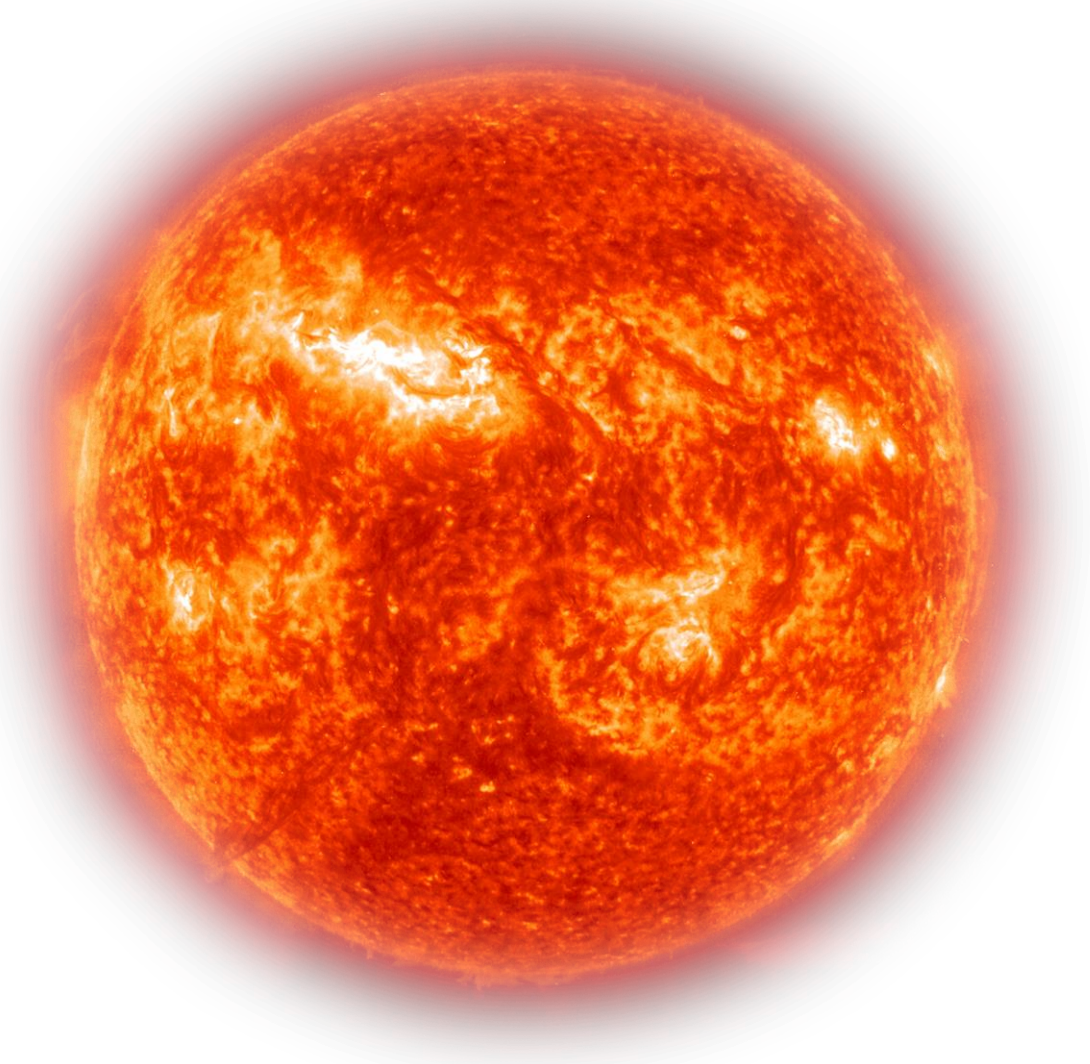
Long Baseline Neutrino Experiments



- $m_{A'} \ll \frac{\Delta m^2}{4p} \sim 10^{-12} eV$:
  - Asymptotically independent of $m_{A'}$
- $m_{A'} \gg \frac{\Delta m^2}{4p} \sim 10^{-12} eV$:
  - Shift in $\Delta m^2 \propto \frac{g' A'_{\odot}}{m_{A'}}$ (perturbation theory)
- $m_{A'} \sim 10^{-12} - 10^{-11}\ eV$:
  - Interplay between neutrino and dark photon oscillation times

Solar Neutrino Oscillations

- ν_e produced in the Sun
- As they travel through the Sun, matter potential changes with varying electron density
- Generates adiabatic conversions of ν_e into predominantly ν_μ
- **Data:**
  - Sudbury Neutrino Observatory (SNO) and Super-Kamiokande Phase IV (SK-IV)
  - Detect solar ν_e flux on Earth
- **Prediction:**
  - $P_{e\rightarrow e}(E, t \cong R_\odot)$
- Need to add term to Hamiltonian to account for varying matter potential



$$H = \frac{\Delta m_{12}^2}{4p}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \begin{pmatrix} \sqrt{2}G_F n_e & 0 \\ 0 & 0 \end{pmatrix} + g' A'_\odot \cos(m_{A'}t)\begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

n_e = electron density

G_F = Fermi constant

Solar Neutrino Oscillations

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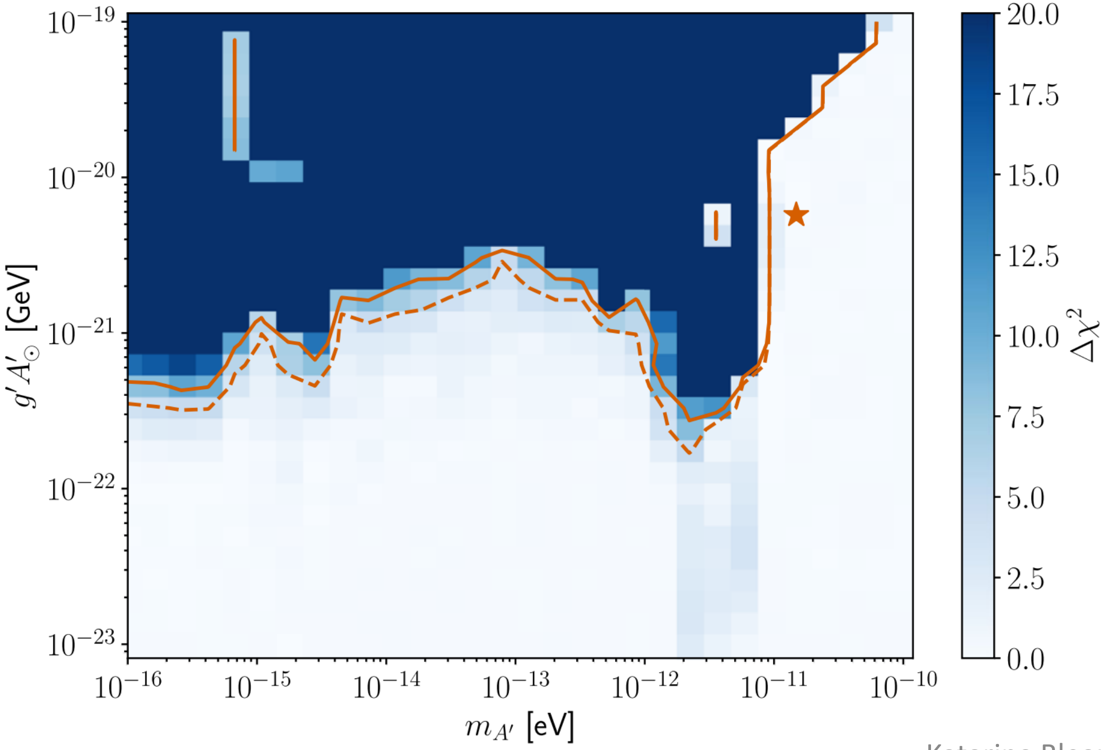
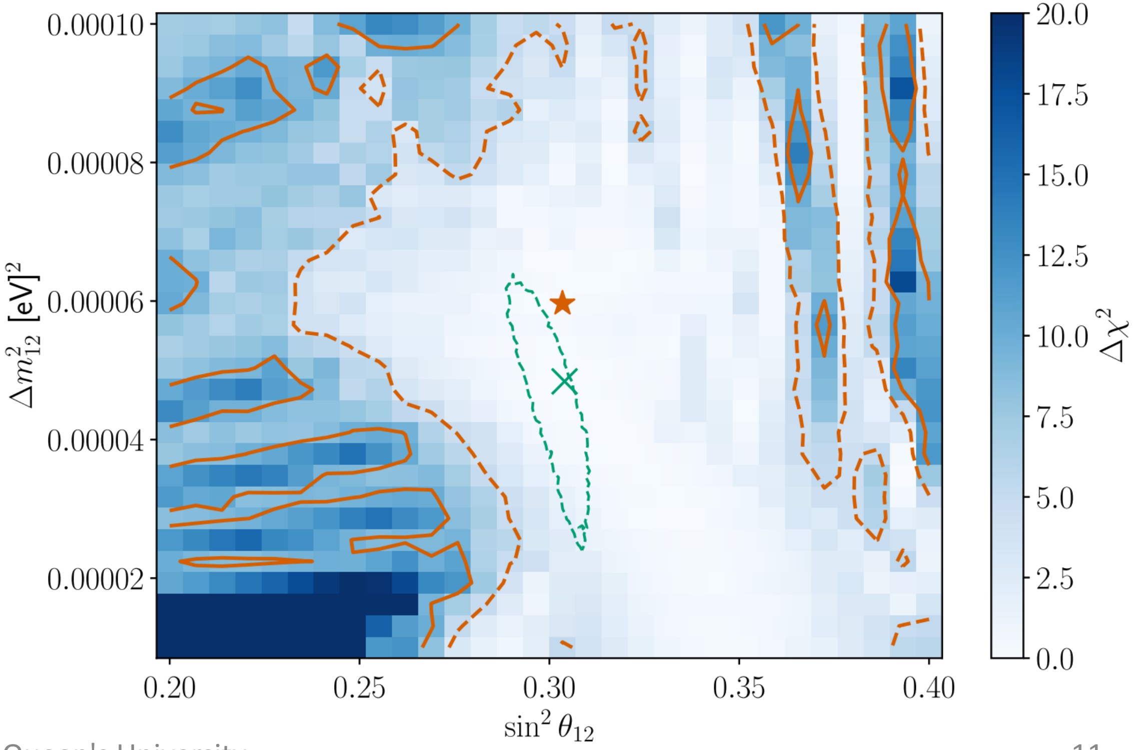
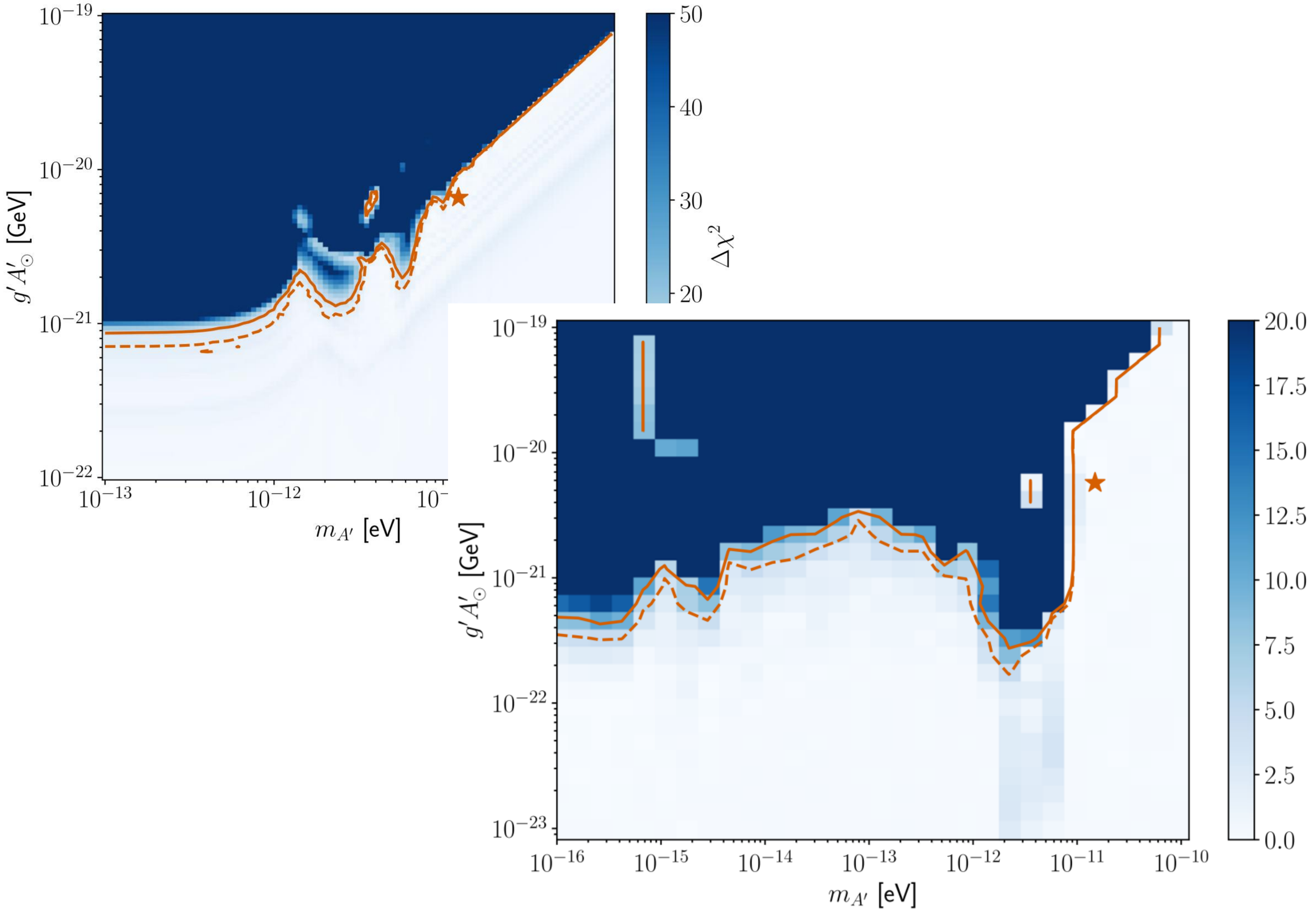




Solar Neutrino Oscillations



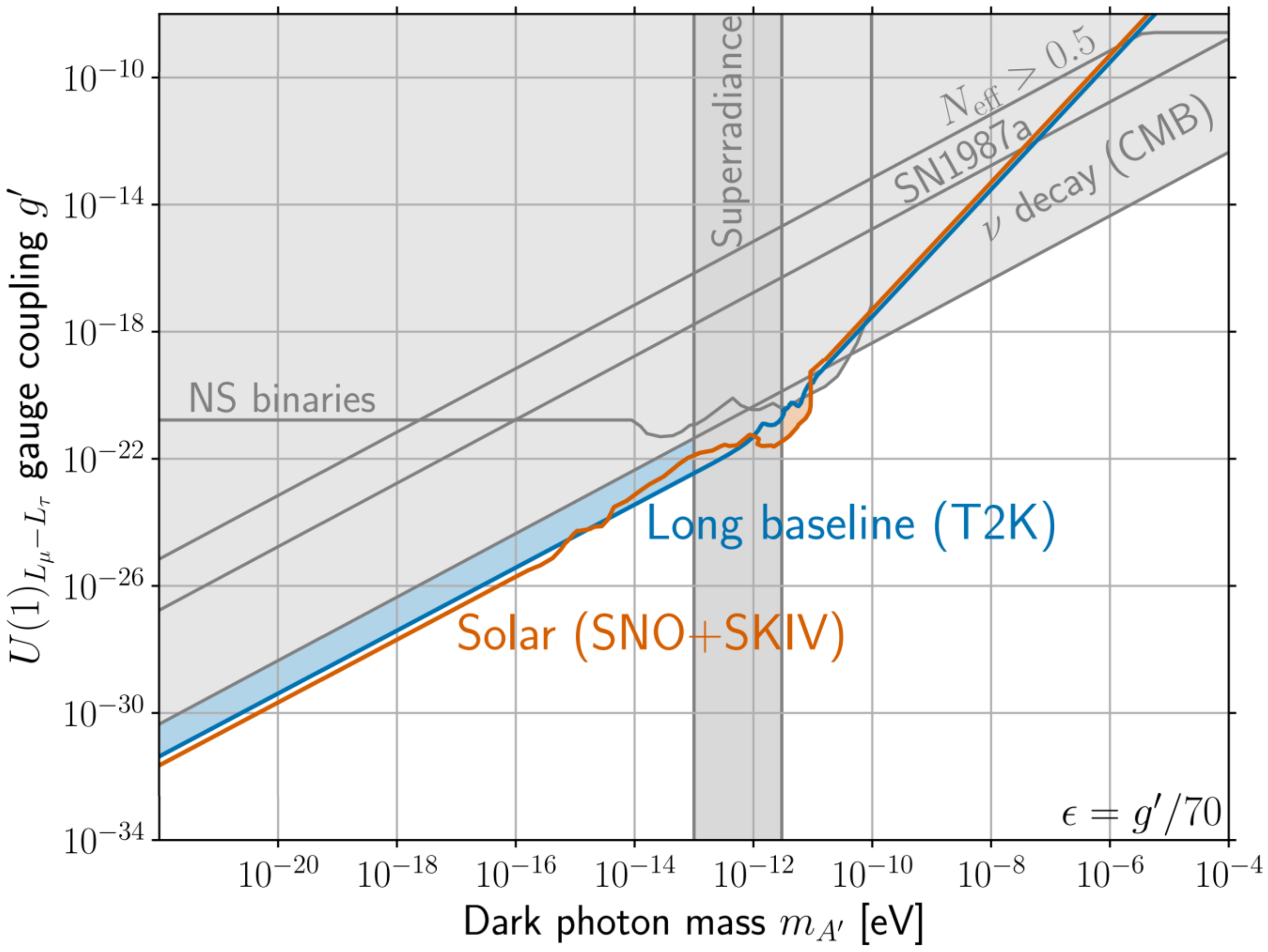
- Similar limits as for atmospheric neutrinos at low and high frequencies
- Main difference:
  - Two characteristic frequencies
    - ➢ $\frac{\Delta m^2}{4p} \sim 10^{-12} - 10^{-11}\ eV$
    - ➢ $\frac{1}{R_{\odot}} \sim 3 \times 10^{-16}\ eV$

Dark Photon Parameter Space

- Using known dark matter concentration factor to relate A' and $A'_{\odot}$:

$$A'_{\odot} \simeq 25\ \text{MeV} \left(\frac{10^{-10}\ \text{eV}}{m_{A'}}\right) \sqrt{\frac{\Omega_{A'}}{\Omega_{\text{DM}}}}$$

- Find limits on g' and $m_{A'}$, assuming dark photon is totality of dark matter



Conclusion

1. Studied effect of background oscillating $L_\mu - L_\tau$ dark matter gauge field on long baseline experiments and solar neutrino oscillations
2. Strongest limits on g’ for $m_{A'} \lesssim 10^{-11}\ eV$
3. Dark photon introduces degeneracies with neutrino vacuum oscillation parameters, which increases amount of allowed values