Neutrino oscillations and very light dark photons

Gonzalo Alonso-Álvarez

based on [2107.07524] & [2204.04224] with Jim Cline
[2301.04152] with Katarina Bleau & Jim Cline

McGill UNIVERSITY

Chicago Workshop on Dark Matter and Neutrino Physics
Loyola University Chicago, 9 March 2023

Neutrinos change flavor

- Atmospheric neutrinos (Super-Kamiokande)

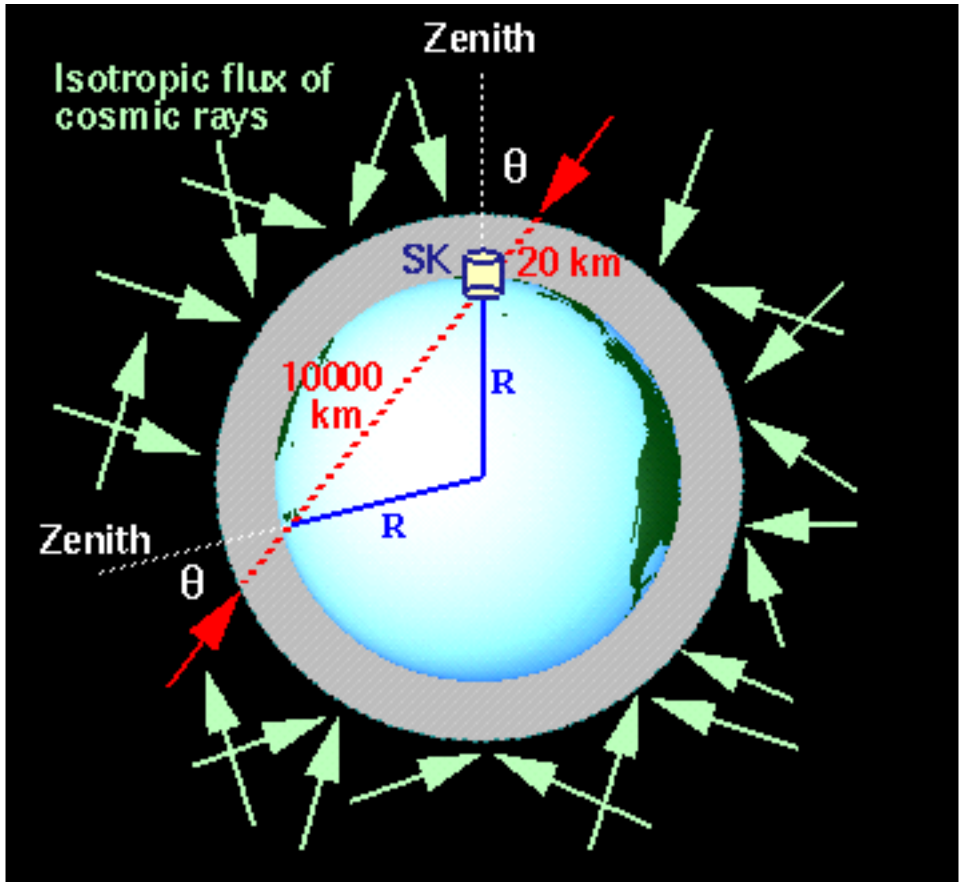
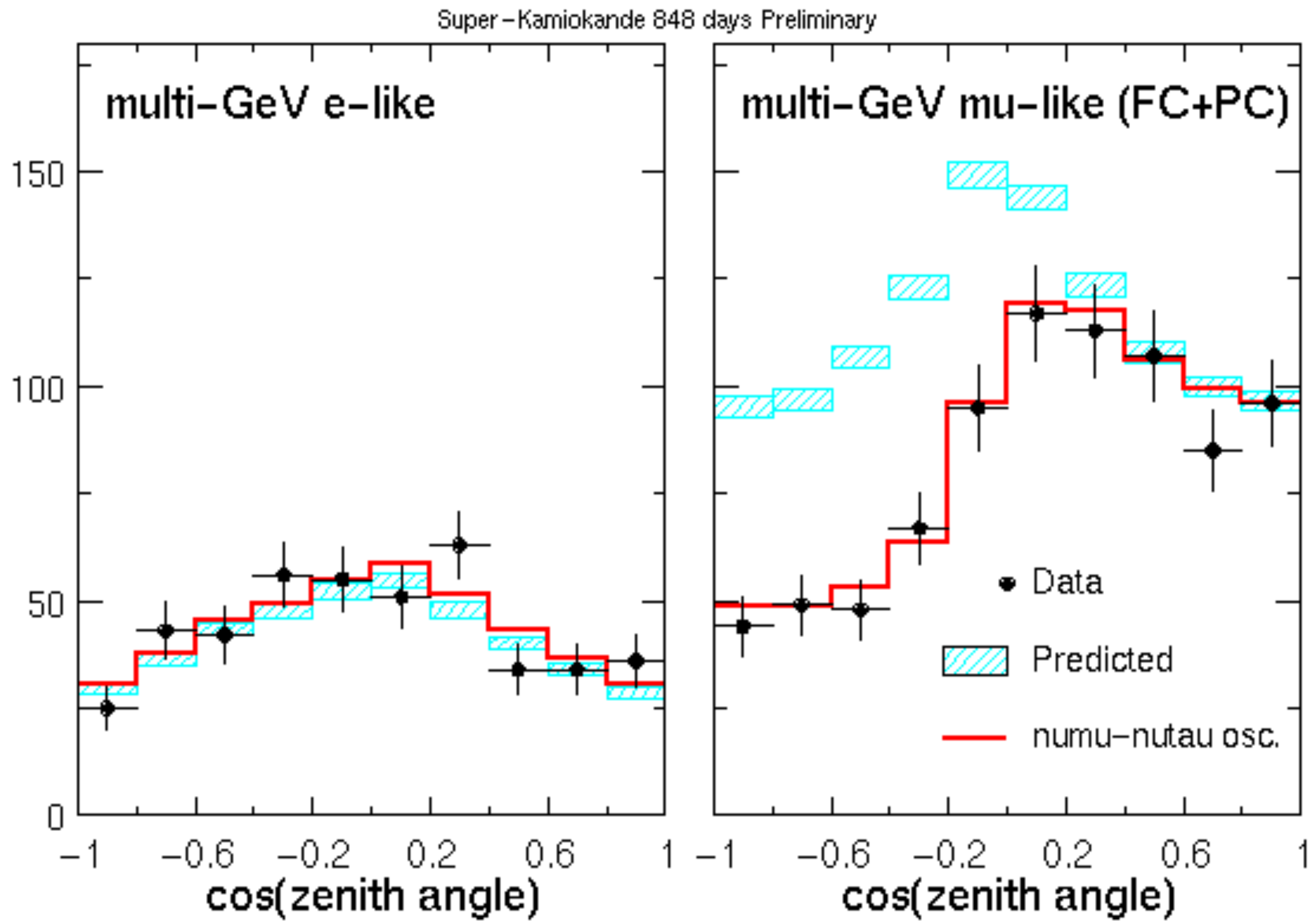


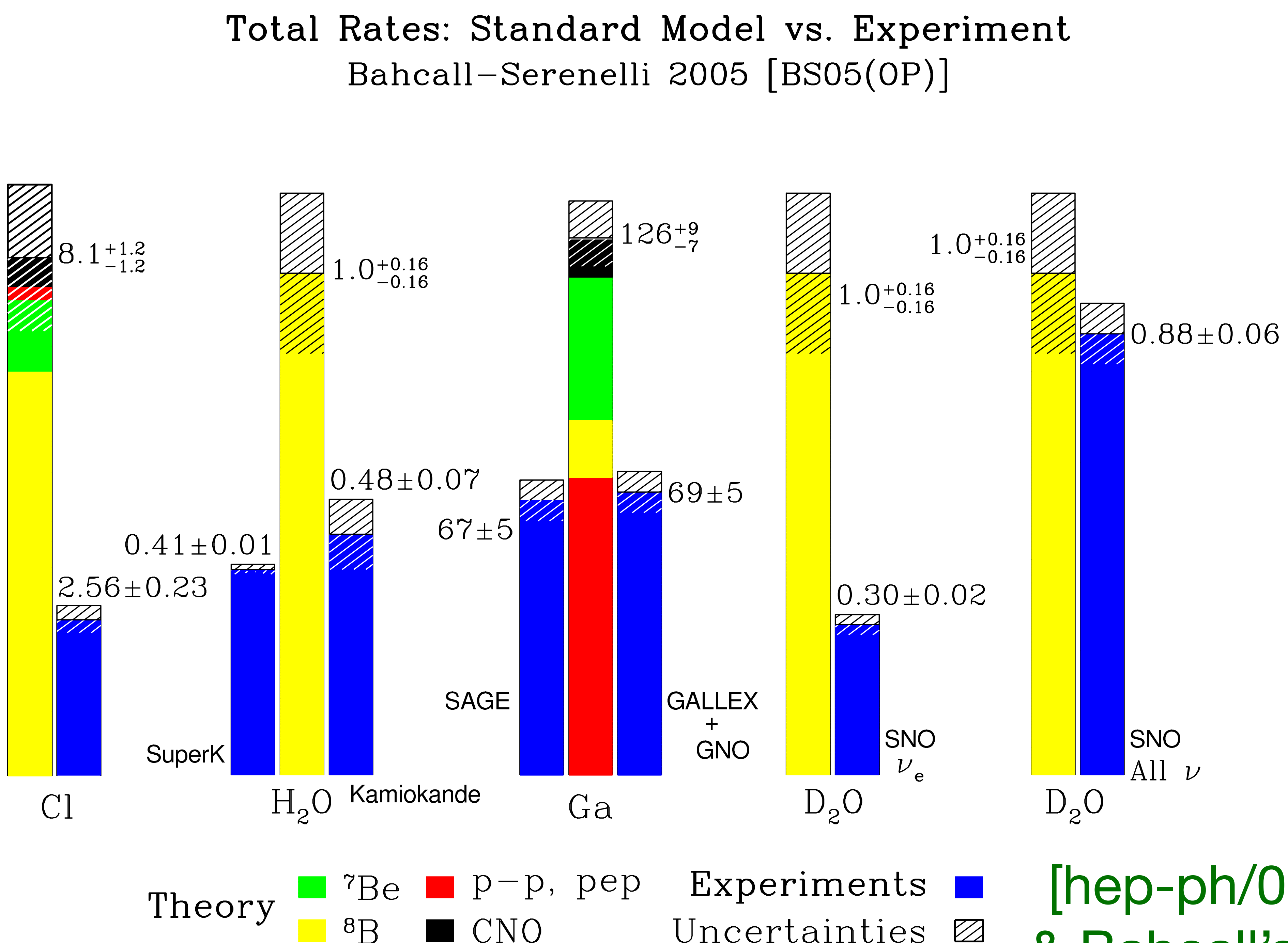
Image credit: Super-K at Boston U.

[hep-ex/9805006] & updates



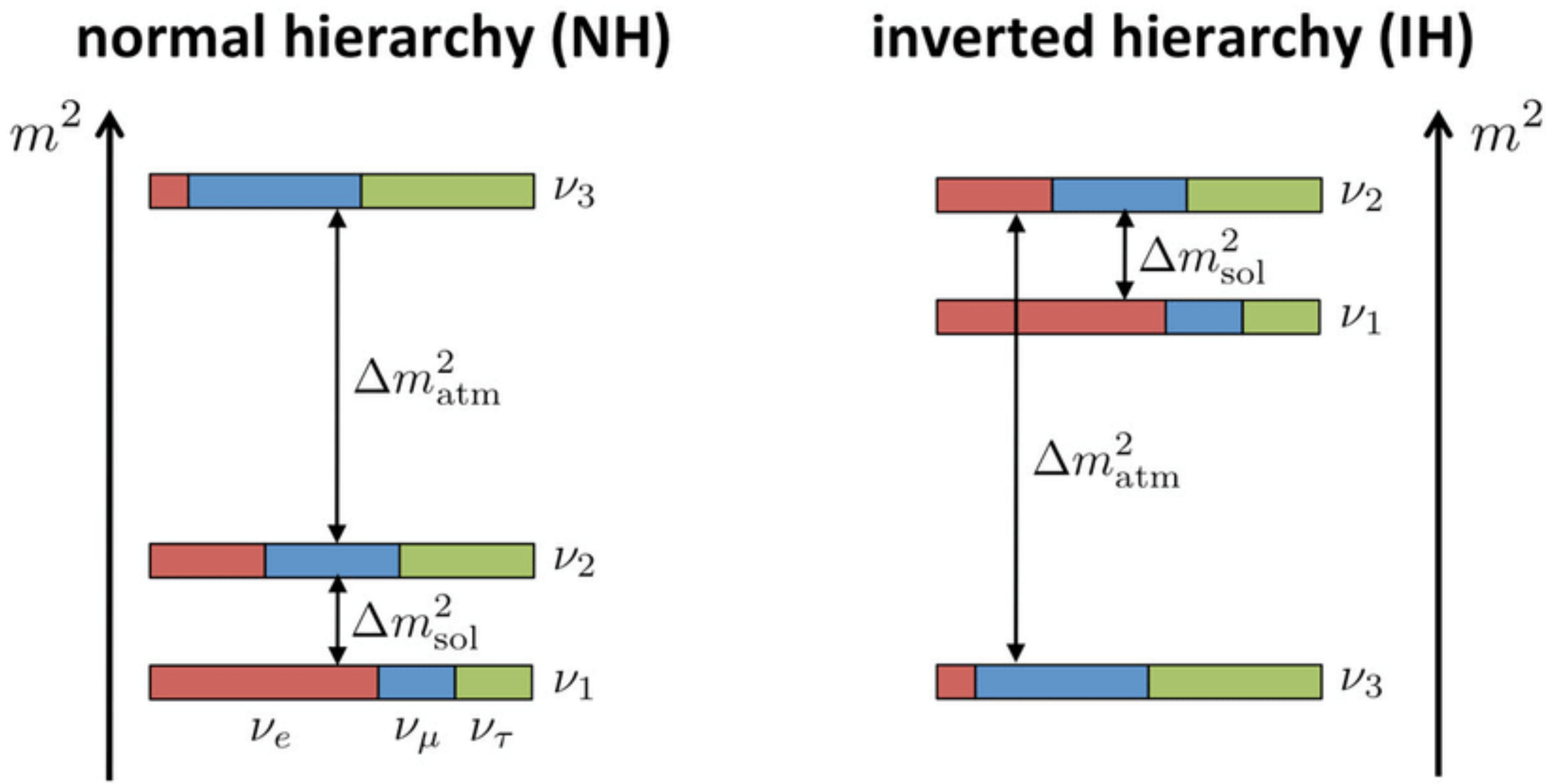
Neutrinos change flavor

- Solar neutrinos (Sudbury Neutrino Observatory)



[hep-ph/0412068]
& Bahcall's website

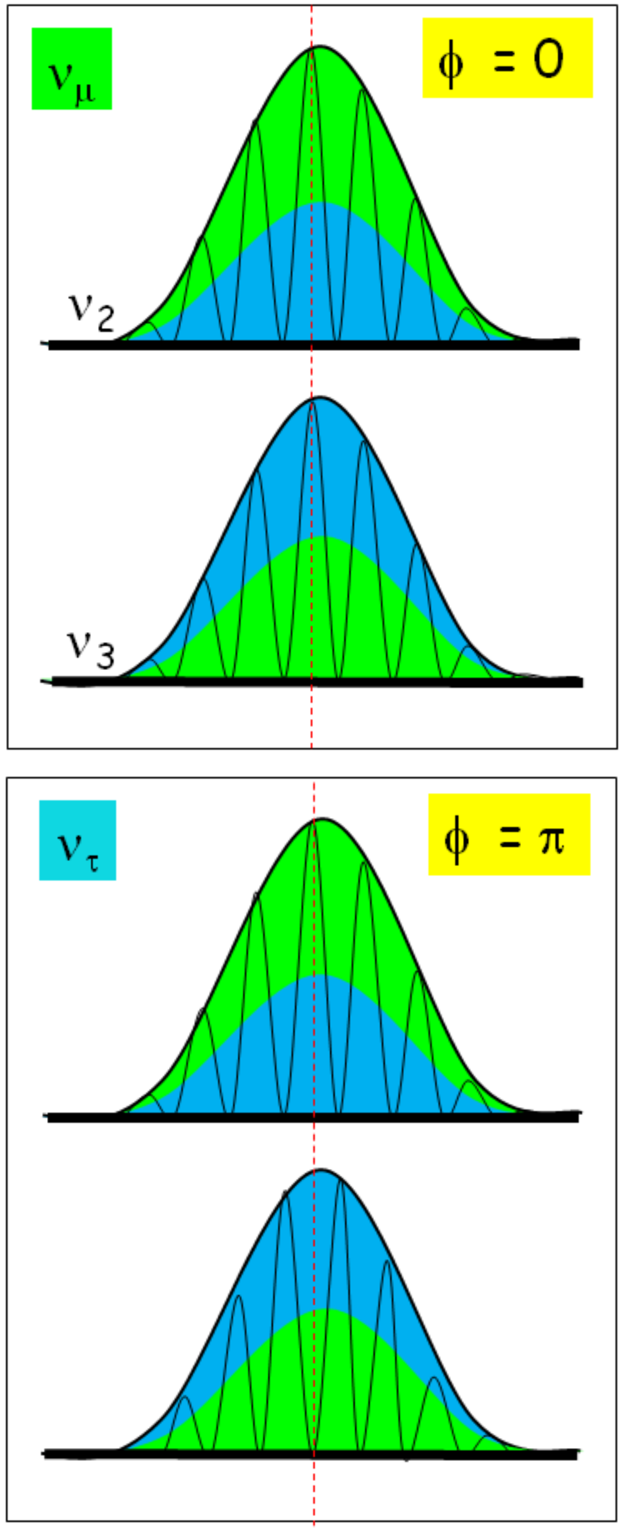
Neutrino mixing



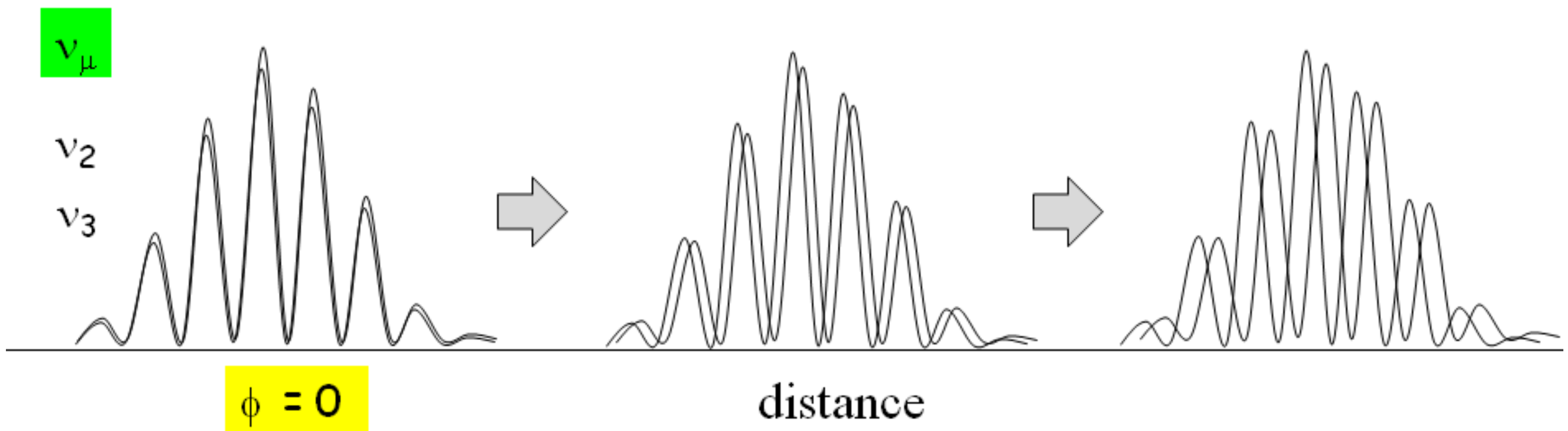
Adapted from Vagnozzi (2019)

Neutrino oscillations

Interference in the propagation of mixed states (wave packets)



Phase velocities: $v_2^{\mathrm{ph}} = \dfrac{E_2}{p_2} \neq \dfrac{E_3}{p_3} = v_3^{\mathrm{ph}}$



$$P_{\nu_\mu\to\nu_\mu}(L) = 1 - \sin^2 2\theta_{23} \sin^2\left(L\,\frac{\Delta m^2_{23}}{4p} \right)$$

figures from [1609.02386]

Mixing in matter

Dispersion relation of neutrinos in matter (refraction)

"Effective potential" $$n - 1 = \frac{V}{p}$$

The mixing angle differs from the one in vacuum

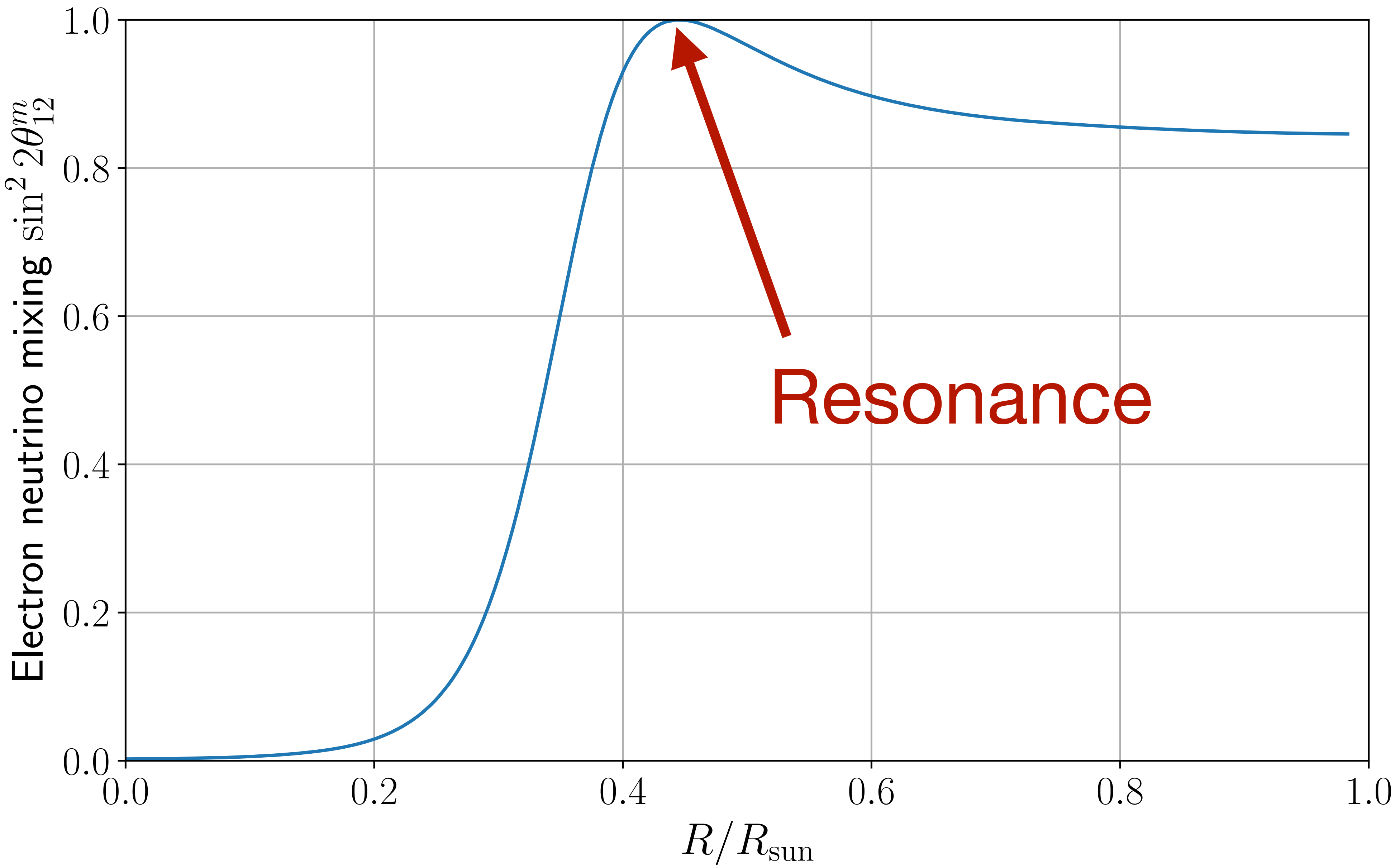
$$\tan 2\theta_m = \frac{\Delta m^2 \sin 2\theta}{\Delta m^2 \cos 2\theta - 2pV}$$

Resonance when $$V = \frac{\Delta m^2 \cos 2\theta}{2p}$$

Neutrino mixing in the Sun

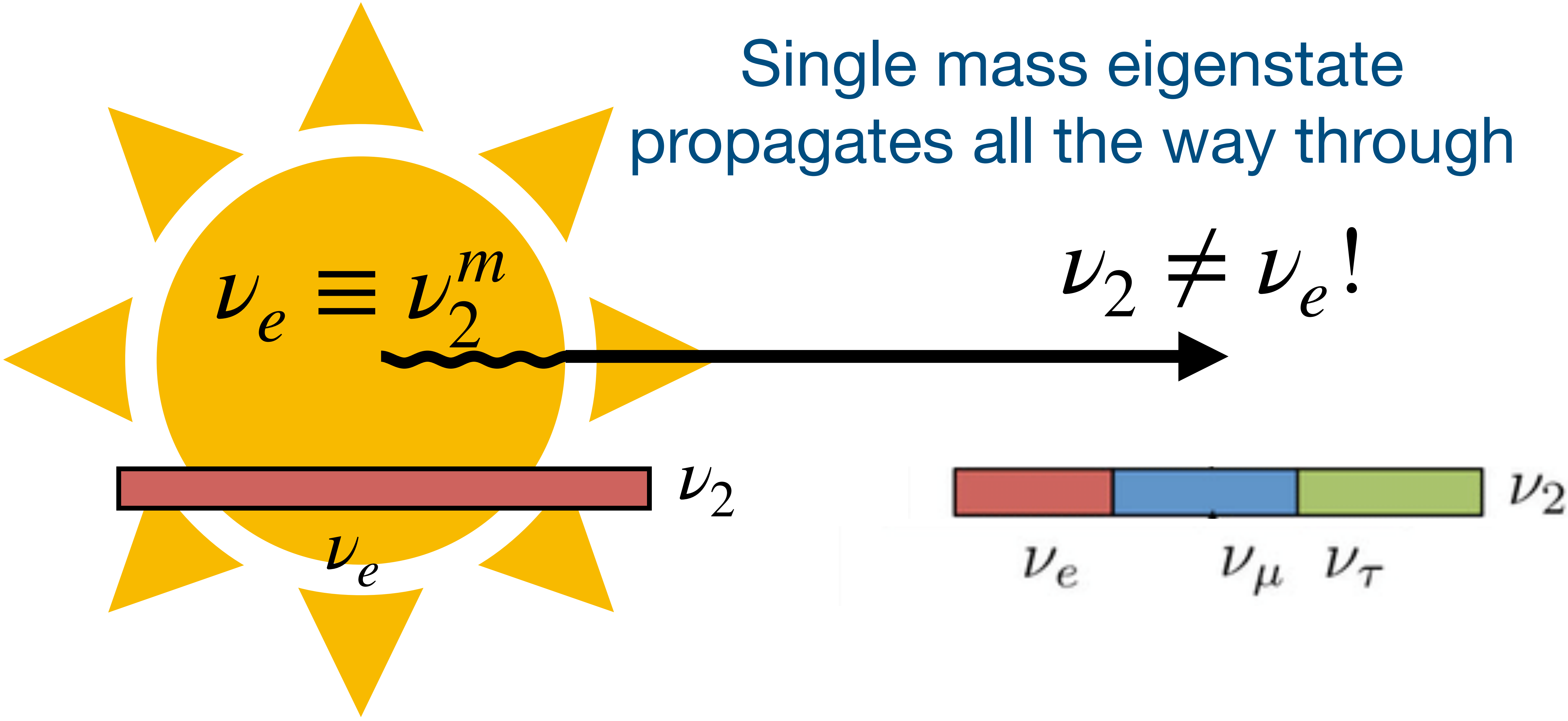
In the Sun, ν_e feel an effective potential

$$V(r) = \sqrt{2}\, G_F\, n_e(r)$$



Adiabatic flavor conversions

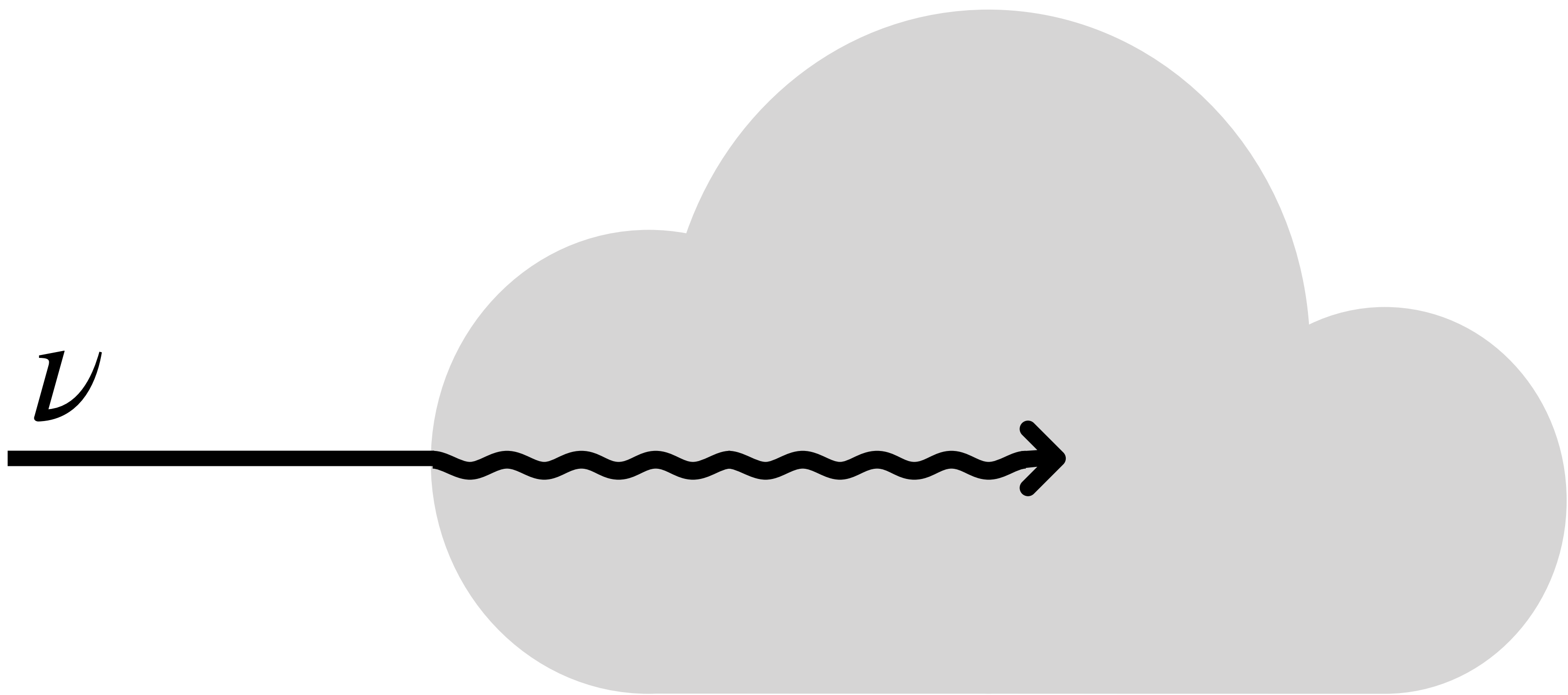
V changes slowly as the neutrino travels out of the Sun



$$P_{ee} \approx |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta_{12} \simeq 0.31$$

Mixing in (dark) matter

Effective potential generated by dark matter



Signatures in neutrino experiments & cosmology

Neutrino gauge interactions

Gauge the anomaly-free lepton number symmetries

$U(1)_{B-L}$, $U(1)_{L_e-L_\mu}$, $U(1)_{L_e-L_\tau}$, $U(1)_{L_\mu-L_\tau}$

$\xrightarrow{\text{SSB}}$ A' becomes massive ($m_{A'} \ll 1\,\mathrm{eV}$)

A' (dark photon) can be dark matter

—> modifies the dispersion relation of neutrinos

$$\omega_{\mathbf{p}_\nu}^2 - \mathbf{p}_\nu^2 = \Pi(\omega_{\mathbf{p}_\nu}, \mathbf{p}_\nu, A') \longrightarrow V_a$$

See [2212.05073] for a recent study in a similar direction

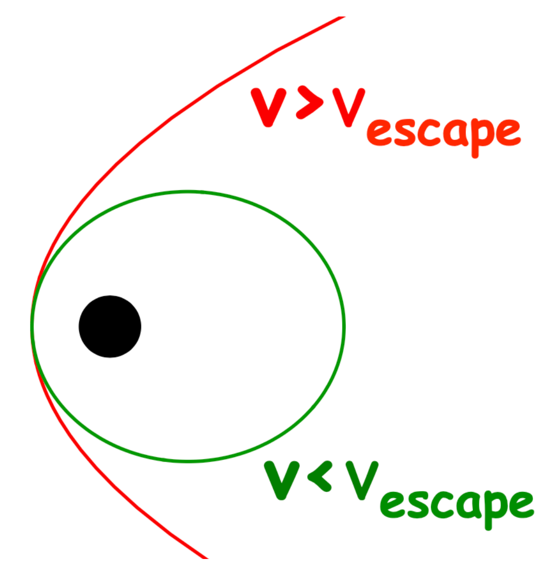
Light bosonic dark matter

Prejudice: dark matter has to be heavy, $m_{\mathrm{DM}} > \mathrm{keV}$

Based on 1) thermal production $v_{\mathrm{DM}} \sim \frac{T}{m_{\mathrm{DM}}} \cdot c$

and / or

2) fermionic dark matter



Dark photons **1) can be produced non-thermally**

and

2) are bosons

$v_{\mathrm{DM}} \ll c$

Dark photon dark matter

Light bosonic field

↓

Large occupation number

↓

Classical field

EOM of vector field in an expanding universe:

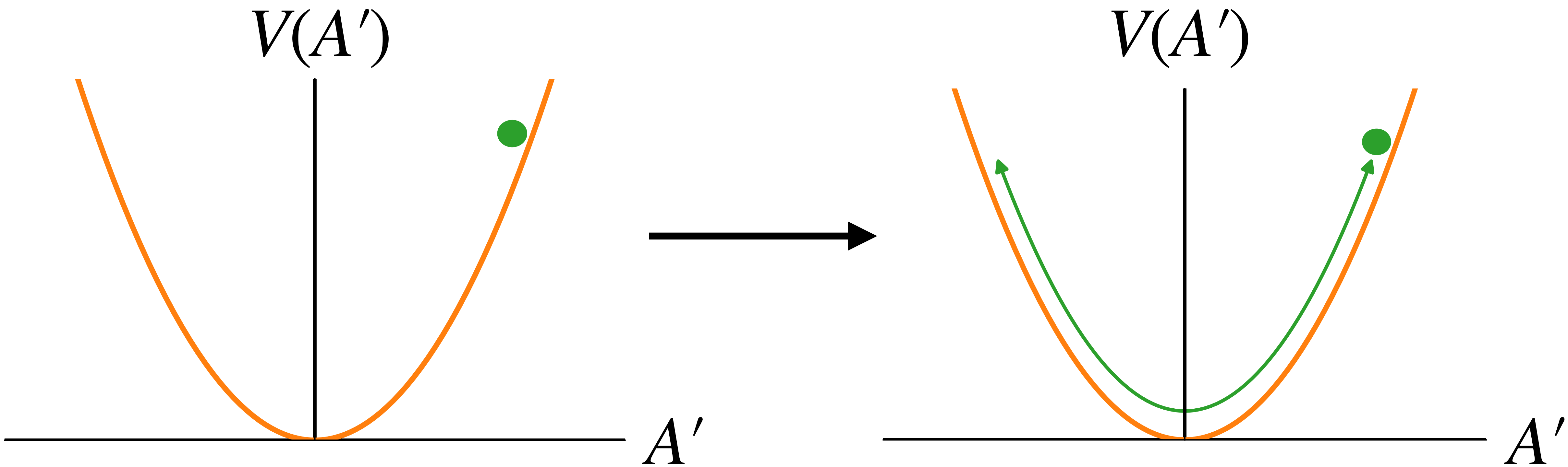
$$\ddot{A}' + 3H\dot{A}' + m_{A'}^2 A' = 0$$

Arias *et al* [1201.5902]

Harmonic oscillator

Cosmological dark photon field

Early times $H \gg m_{A'}$:
overdamped oscillator



Late times $H \ll m_{A'}$:
damped oscillations

$$\rho_{A'} \propto a^{-3}$$

<u>(very) cold dark matter!</u>

Neutrino effective potential

- $U(1)_{L_\mu - L_\tau}$ gauge interaction:

$$\mathcal{L} = -g' A'_\mu \left[\bar{L}_\mu \gamma^\mu L_\mu - \bar{L}_\tau \gamma^\mu L_\tau \right]$$

- Neutrino dispersion relation:

$$E_i \to \left((\vec{p} \mp g' \vec{A}')^2 + m^2 \right)^{1/2}$$
$$\cong |\vec{p}| \mp g' \hat{p} \cdot \vec{A}' + \frac{m^2}{2p} + O(g'^2 A'^2)$$

- Effective matter potential

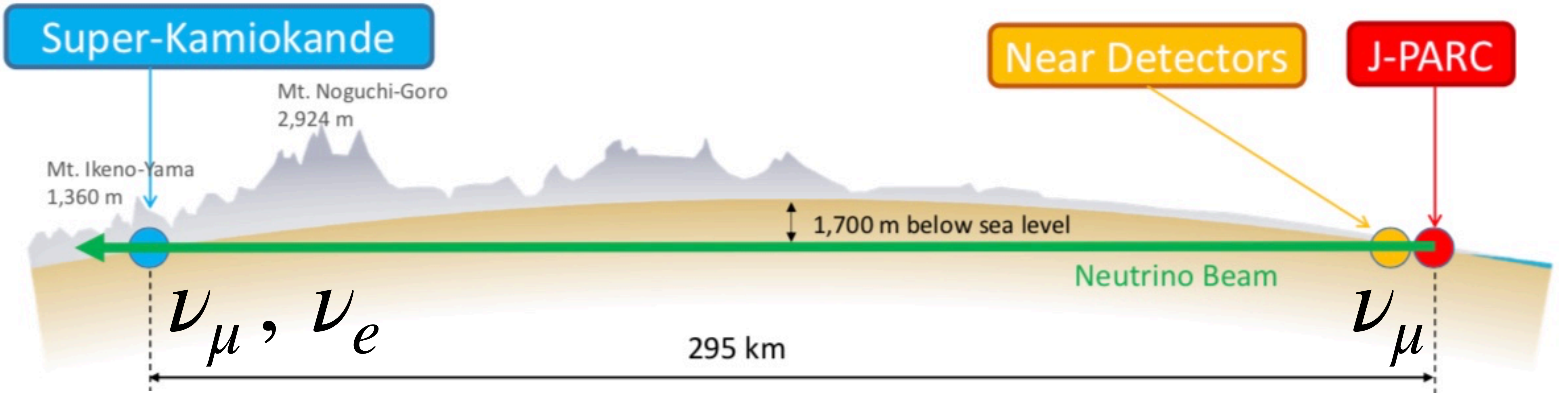
$$V = \mp g' \hat{p} \cdot \overrightarrow{A} = \mp g' A'_\odot \cos(m_{A'} t)$$

Rest of the talk

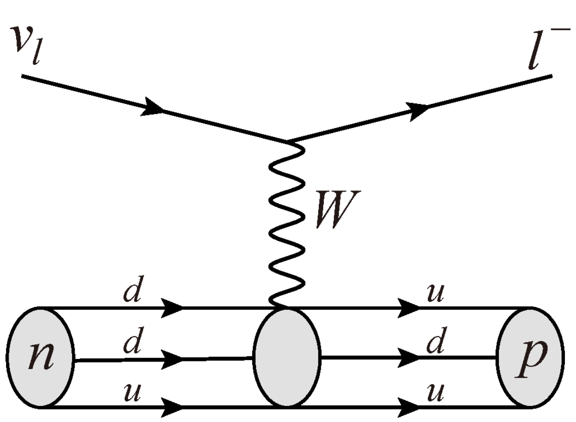
Study the impact of the dark photon field on:

- Long baseline neutrino oscillations (T2K)
- Solar adiabatic flavor conversions (SNO + Super-K)
- Sterile neutrino production in the early universe

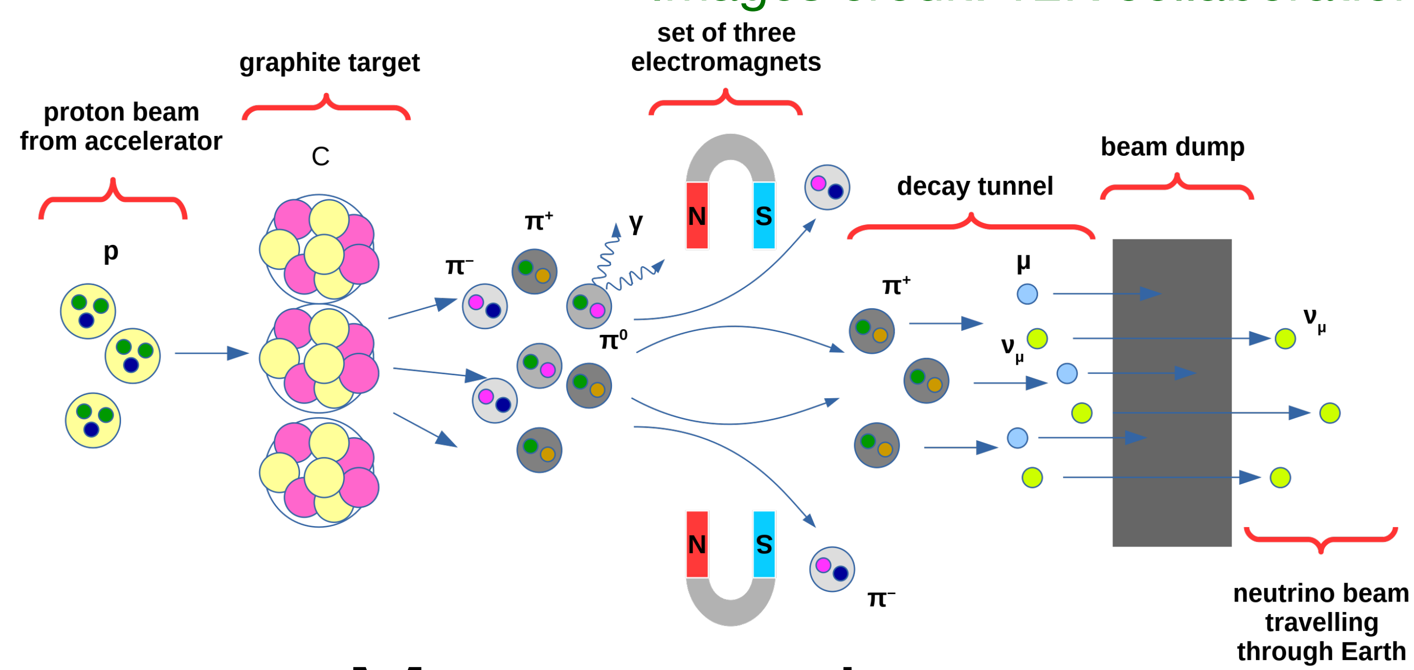
Long baseline - T2K



Images credit: T2K collaboration

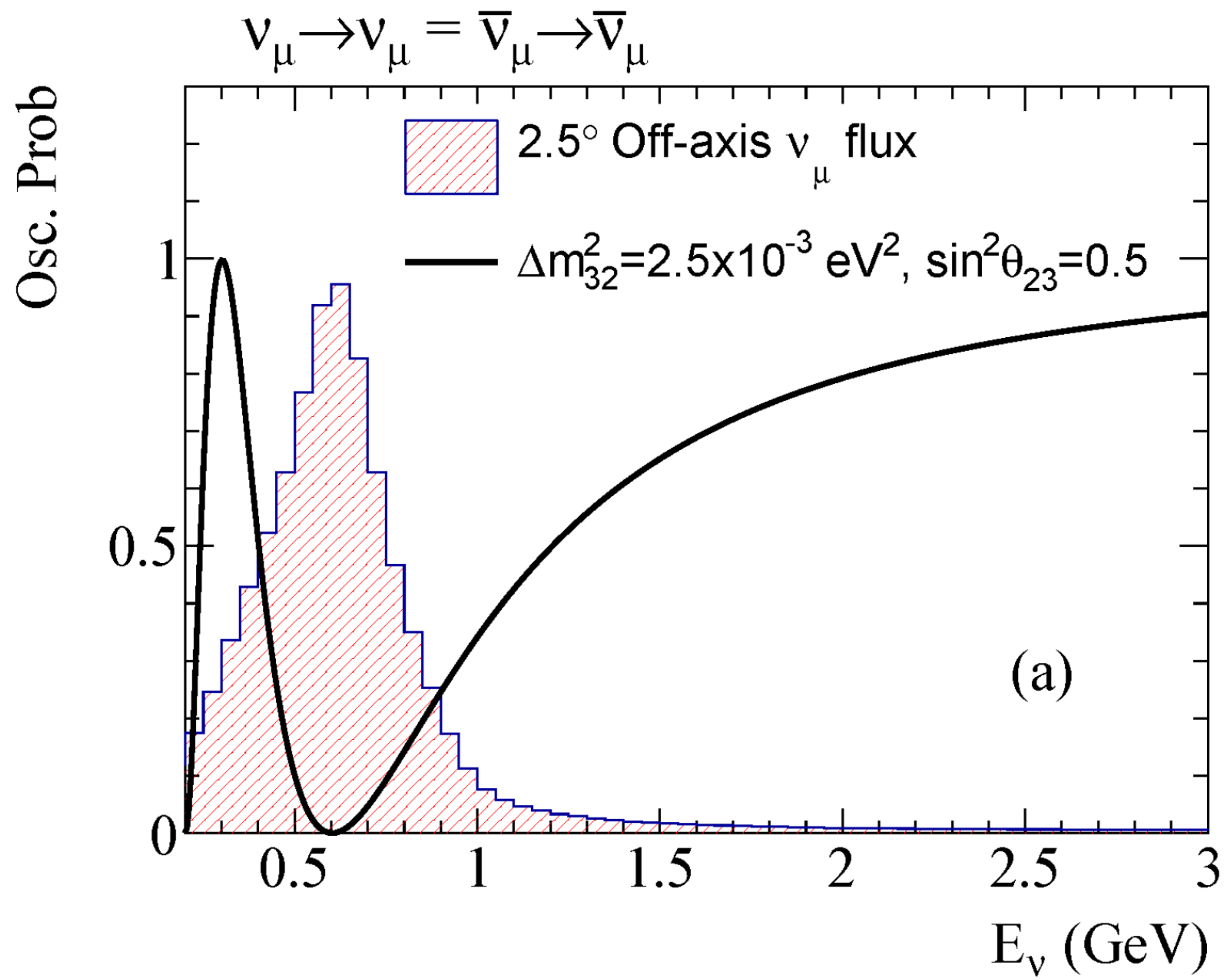


Detection via charged-current interaction



Muon neutrino beam production

2-flavor description of $P_{\nu_\mu \to \nu_\mu}$



$$P_{\nu_\mu \to \nu_\mu} \cong 1 - \boxed{4|U_{\mu 3}|^2(1-|U_{\mu 3}|^2)} \sin^2(L \boxed{\Delta m^2_{\text{eff}}}/4p)$$

$\simeq \sin^2 2\theta_{23}$ $\simeq \Delta m^2_{23}$

Two-state Hamiltonian

- Solve the Schrödinger eq:

$$i\frac{d\Psi}{dt} = H\Psi \qquad \Psi = \begin{pmatrix} \nu_\mu \\ \nu_\tau \end{pmatrix}$$

- With the Hamiltonian:

$$H = E_0 + \frac{\Delta m_{23}^2}{4p}\begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} + g' A'_\odot \cos(m_{A'} t)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

Vacuum mixing — Dark photon

- Solve for: $P_{\mu\to\mu}(t) = |\langle\Psi(0)|\Psi(t)\rangle|^2$

- Initial condition: $\Psi(0) = (1, 0)^T$

Two-state Hamiltonian

- Solve the Schrödinger eq:

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Vacuum mixing

Dark photon

- Solve for: $P_{\mu\to\mu}(t) = |\langle \Psi(0) | \Psi(t) \rangle|^2$

- Initial condition: $\Psi(0) = (1, 0)^T$

⚠ **Fast oscillations**

Analytic approximations

$$H = E_0 + \frac{\Delta m^2_{23}}{4p}\begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23}\end{pmatrix} + g' A'_\odot \cos(m_{A'} t)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- Low frequency $m_{A'} \ll \Delta m^2_{23}/4p$:

Adiabatic correction of vacuum parameters

$$\Delta m^2_{23} \longrightarrow \Delta m^2_{23} \cdot f(g' A'_\odot)$$

$$\sin 2\theta_{23} \longrightarrow \sin 2\theta_{23} \,/\, f(g' A'_\odot)$$

slowly modulated by $\cos(m_{A'} t)$

Analytic approximations

$$H = E_0 + \frac{\Delta m_{23}^2}{4p}\begin{pmatrix} -\cos 2\theta_{23} & \sin 2\theta_{23} \\ \sin 2\theta_{23} & \cos 2\theta_{23} \end{pmatrix} + g' A'_\odot \cos(m_{A'} t)\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

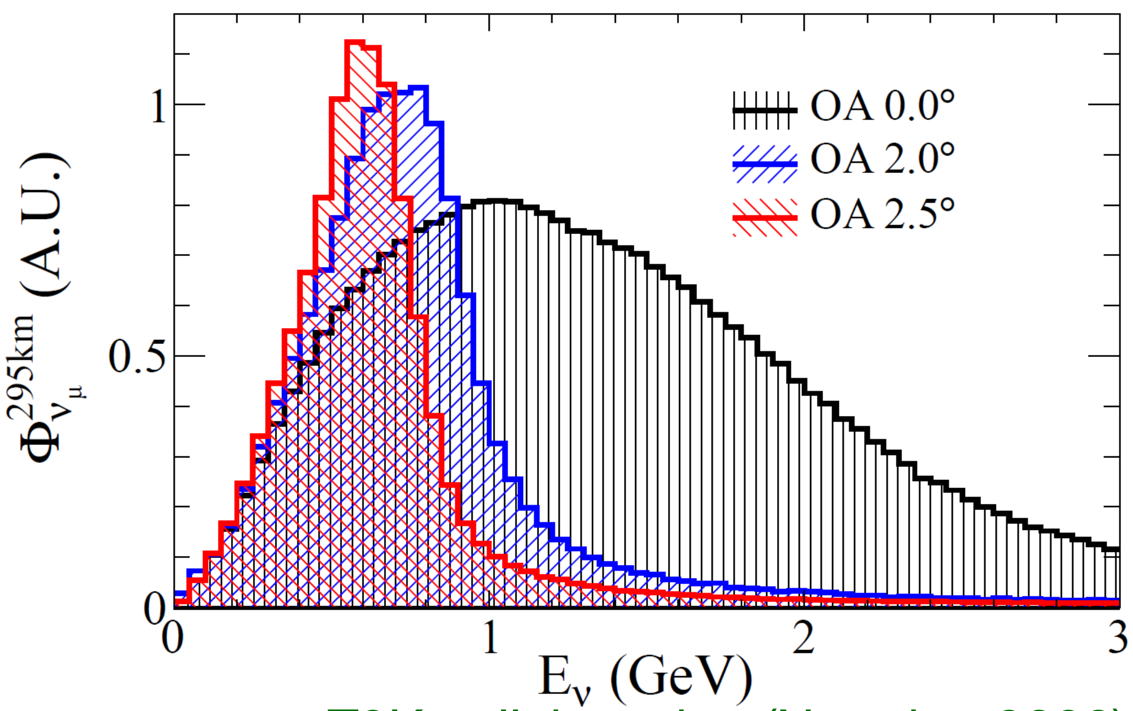
- High frequency $m_{A'} \gg \Delta m_{23}^2/4p$:

Perturbation theory -> shift in Δm^2

$$\Delta m_{23}^2 \longrightarrow \Delta m_{23}^2 \left(1 - \left(\frac{g' A'_\odot \sin 2\theta_{23}}{2 m_{A'}}\right)^2\right)$$

Comparison with T2K data

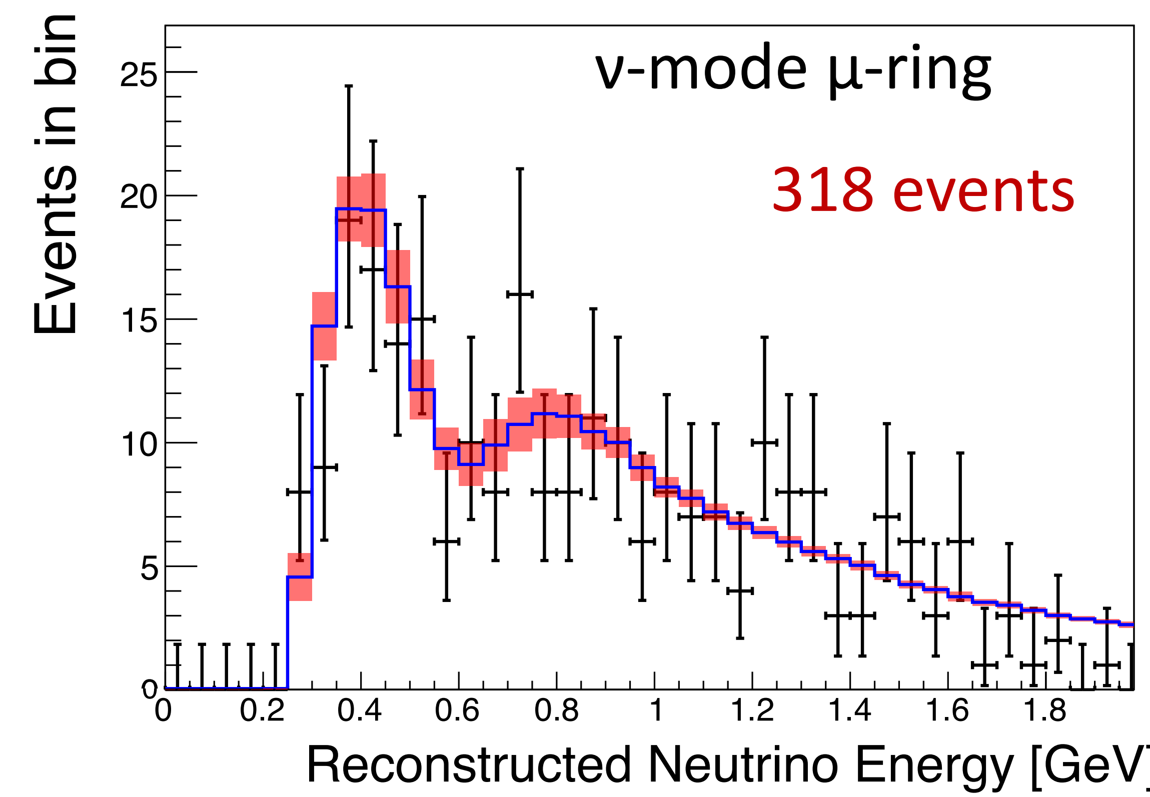
$$P_{\nu_\mu \to \nu_\mu}(E_i, L)$$



T2K collaboration (Neutrino 2020)

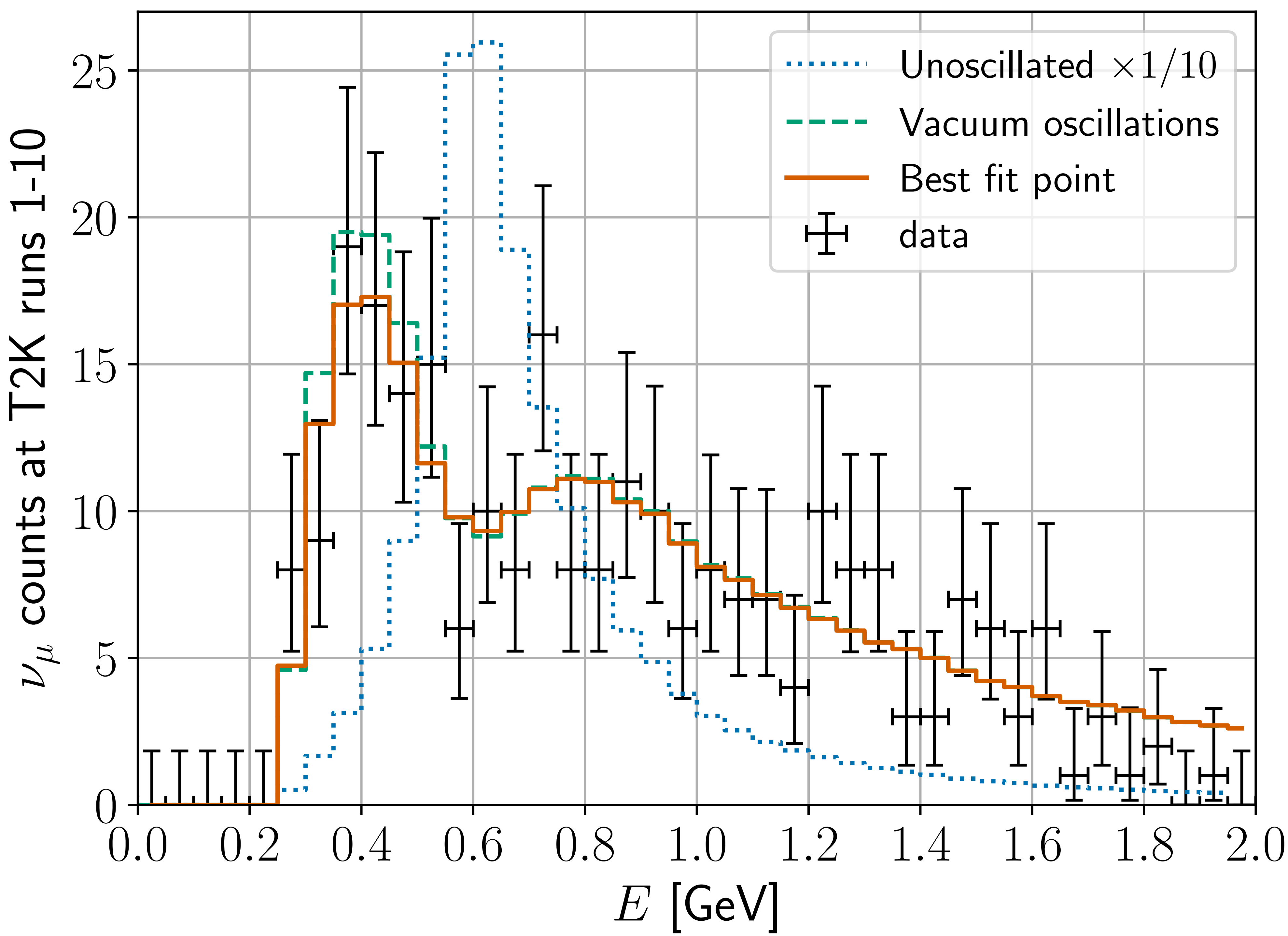
detector response

T2K Run 1-10 Preliminary



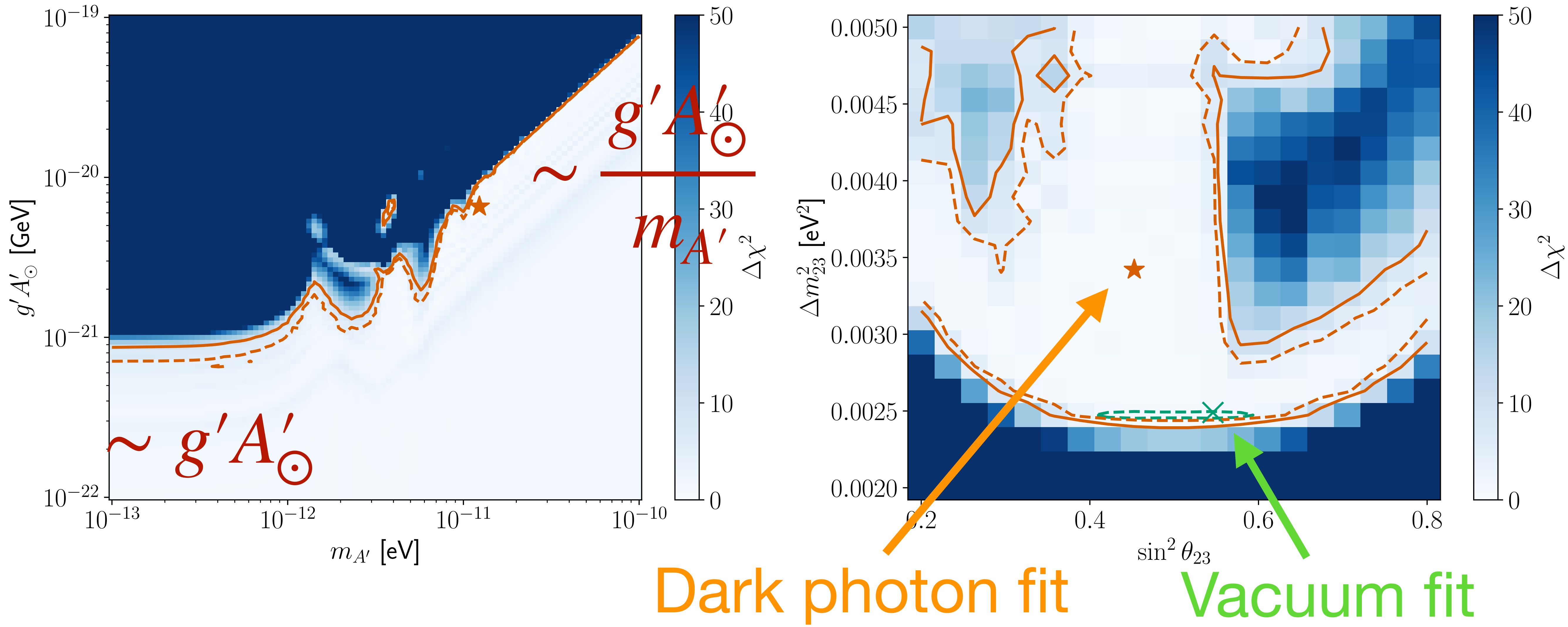
T2K collaboration (Neutrino 2020)

Observed counts at T2K



Maximum likelihood test

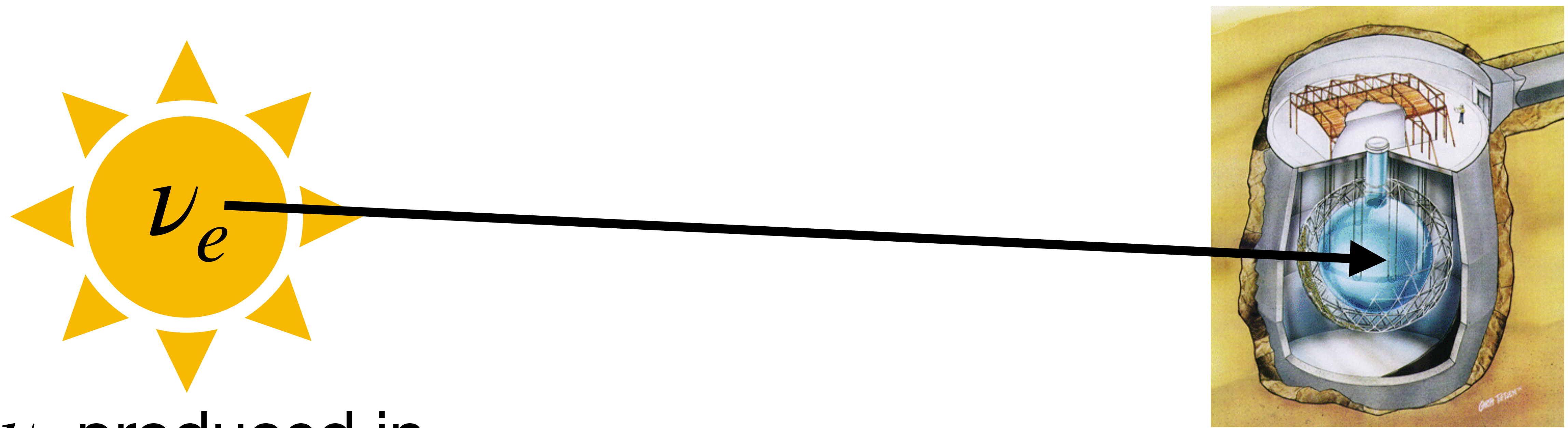
Vary 4 parameters: $\Delta m^2_{23}\,,\ \sin^2\theta_{23}\,,\ m_{A'}\,,\ g'A'_\odot$



Degeneracies with vacuum oscillation parameters

Enlarged allowed region for $\Delta m^2_{23}\,,\ \sin^2\theta_{23}$

Solar experiments - SNO & Super-K

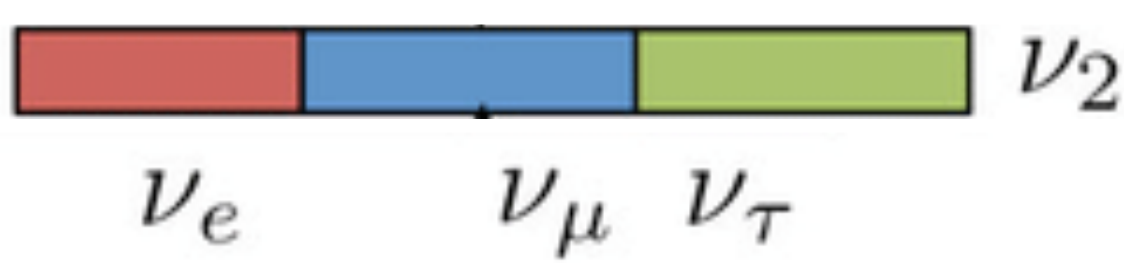


ν_e produced in nuclear reactions

ν_e , ν_μ , ν_τ detected via CC/NC interactions

Mostly adiabatic conversions (MSW effect)

$$P_{ee} \approx |\langle \nu_e | \nu_2 \rangle|^2 = \sin^2\theta_{12} \simeq 0.31$$



Hamiltonian

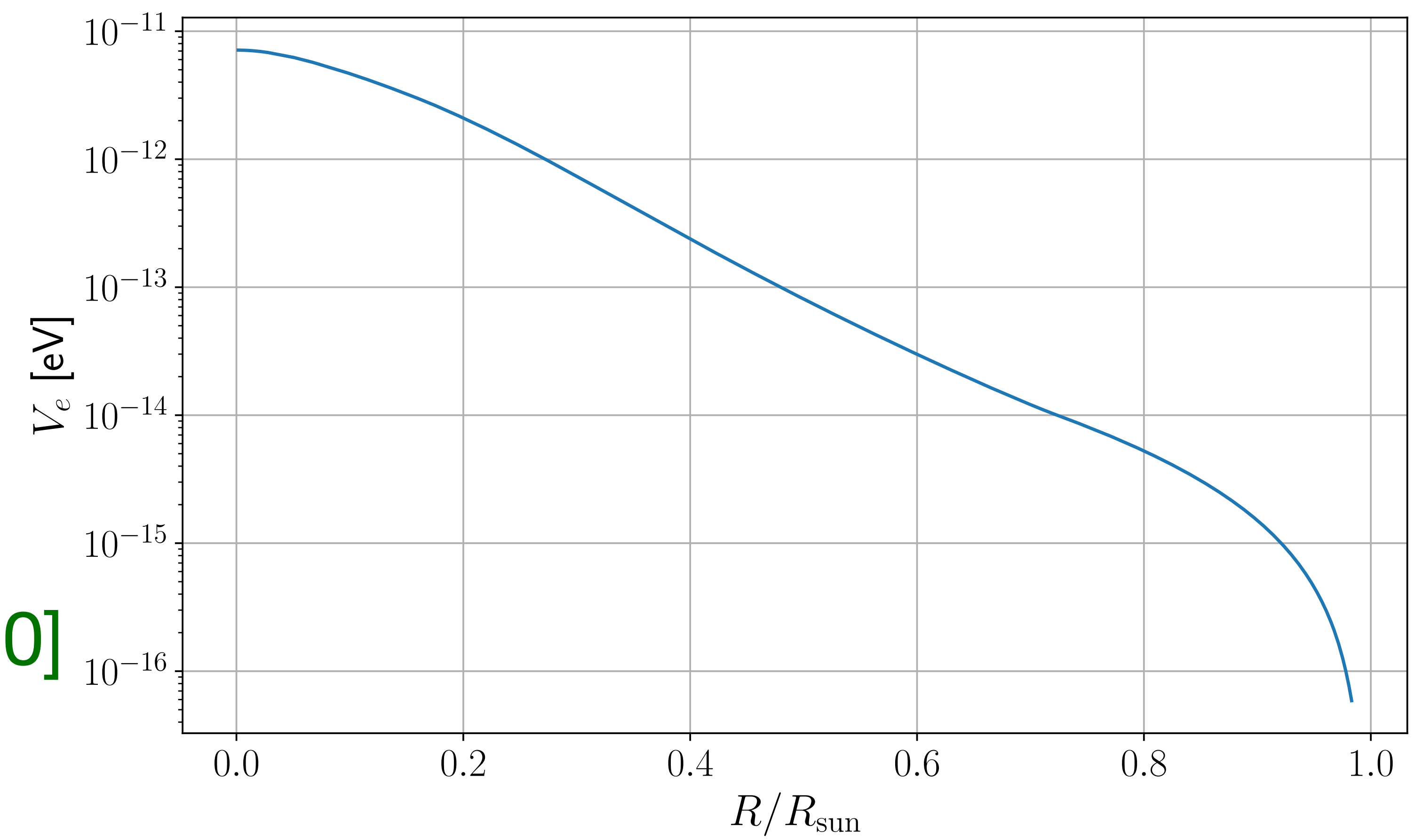
$$H = \frac{\Delta m_{12}^2}{4p}\begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12}\end{pmatrix} + \begin{pmatrix} \sqrt{2}G_F n_e & 0 \\ 0 & 0\end{pmatrix}$$

$$+ g' A'_\odot \cos(m_{A'} t)\begin{pmatrix} 0 & 0 \\ 0 & 1\end{pmatrix}$$

Vacuum mixing

Dark photon

Sun matter potential



[astro-ph/0412440]
& web updates

Analytic approximations

$$H = \frac{\Delta m_{12}^2}{4p} \begin{pmatrix} -\cos 2\theta_{12} & \sin 2\theta_{12} \\ \sin 2\theta_{12} & \cos 2\theta_{12} \end{pmatrix} + \begin{pmatrix} \sqrt{2} G_F n_e & 0 \\ 0 & 0 \end{pmatrix}$$

$$+ g' A'_{\odot} \cos(m_{A'} t) \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

Still hold locally at each value of $R/R_{\rm sun}$

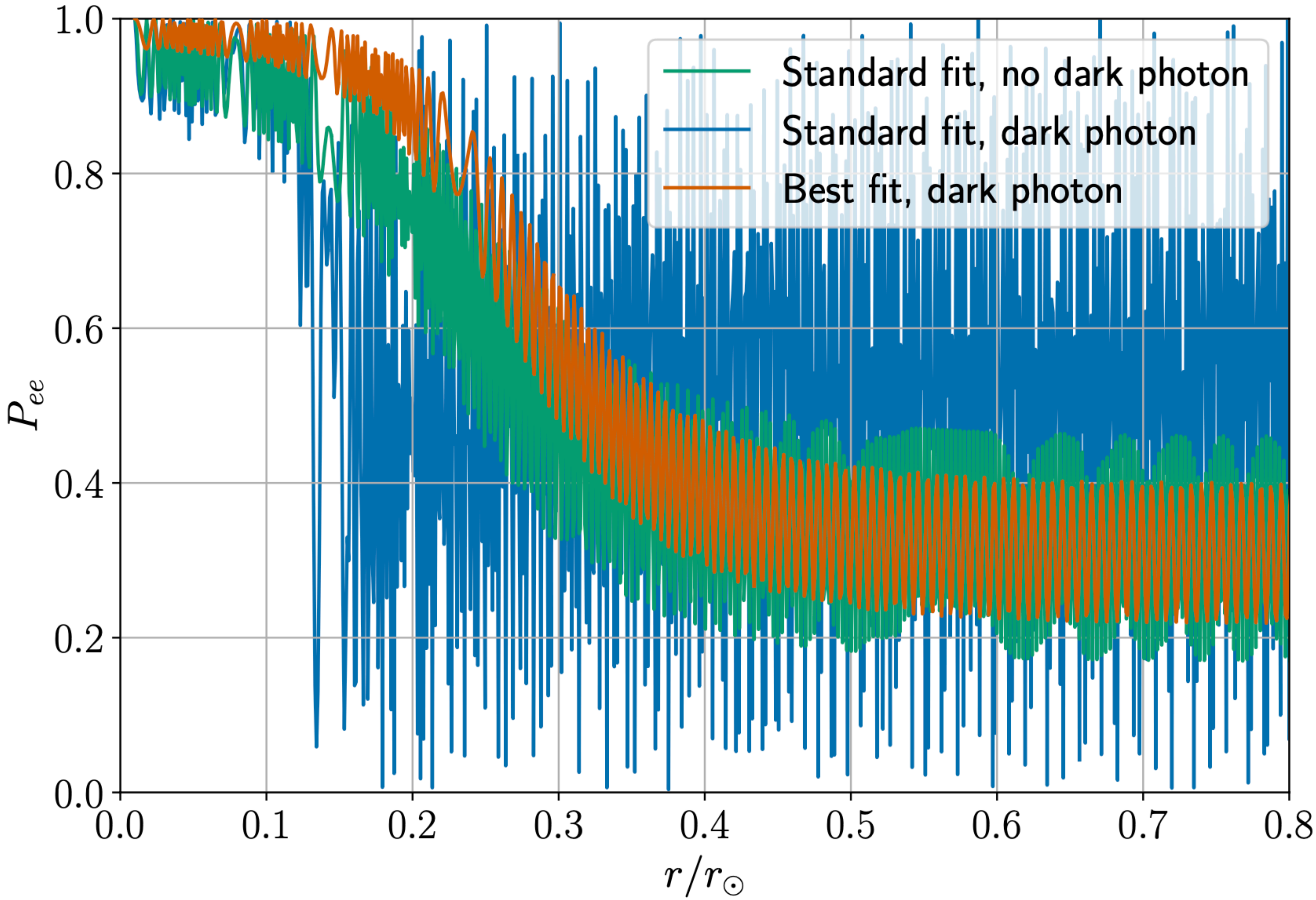
- Low frequency $m_{A'} \ll \Delta m_{12}^2/4p$:

  multiplicative correction of Δm_{12}^2, $\sin 2\theta_{12}$

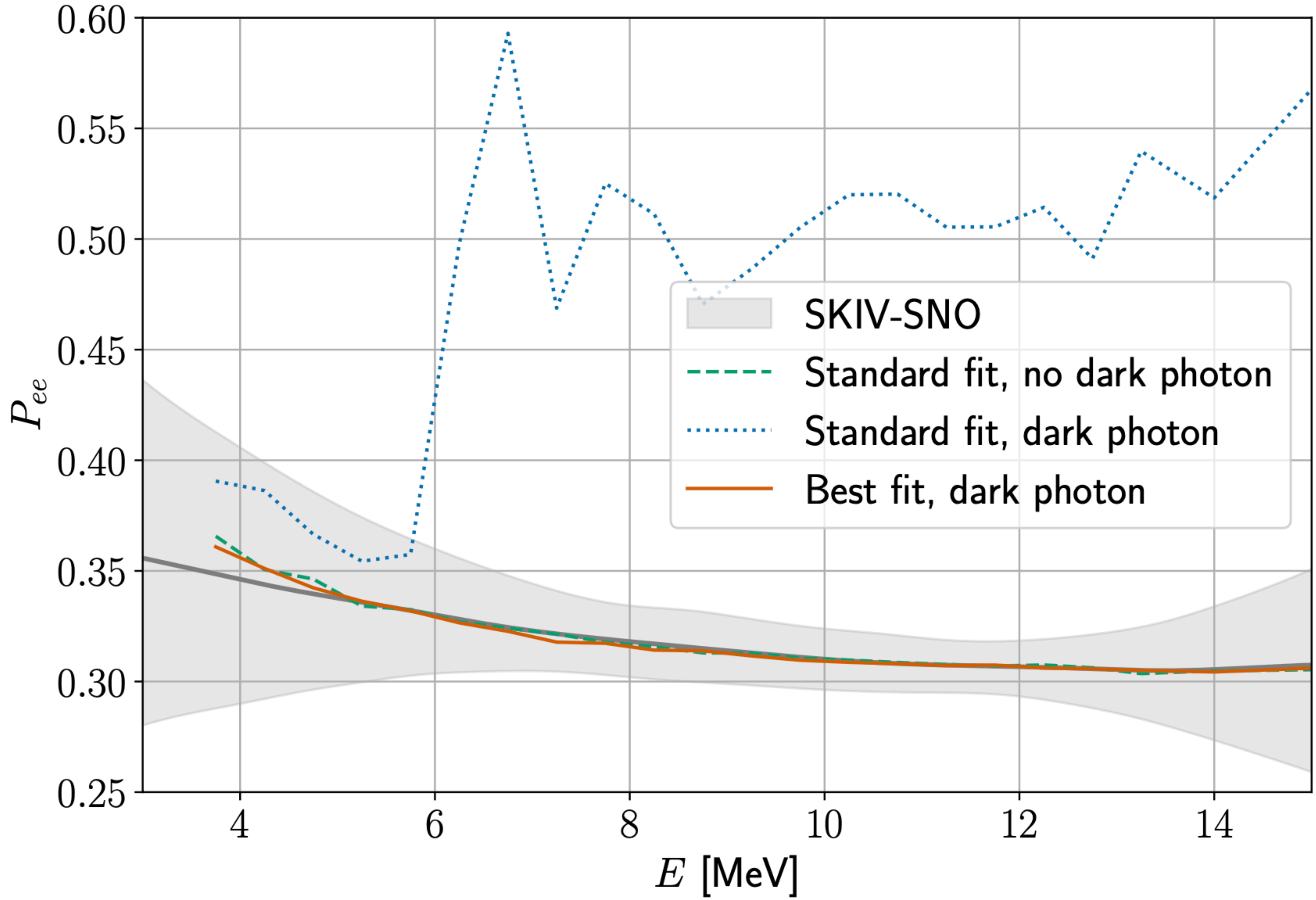
- High frequency $m_{A'} \gg \Delta m_{12}^2/4p$:

  multiplicative shift in Δm_{12}^2

ν_e survival probability along the Sun

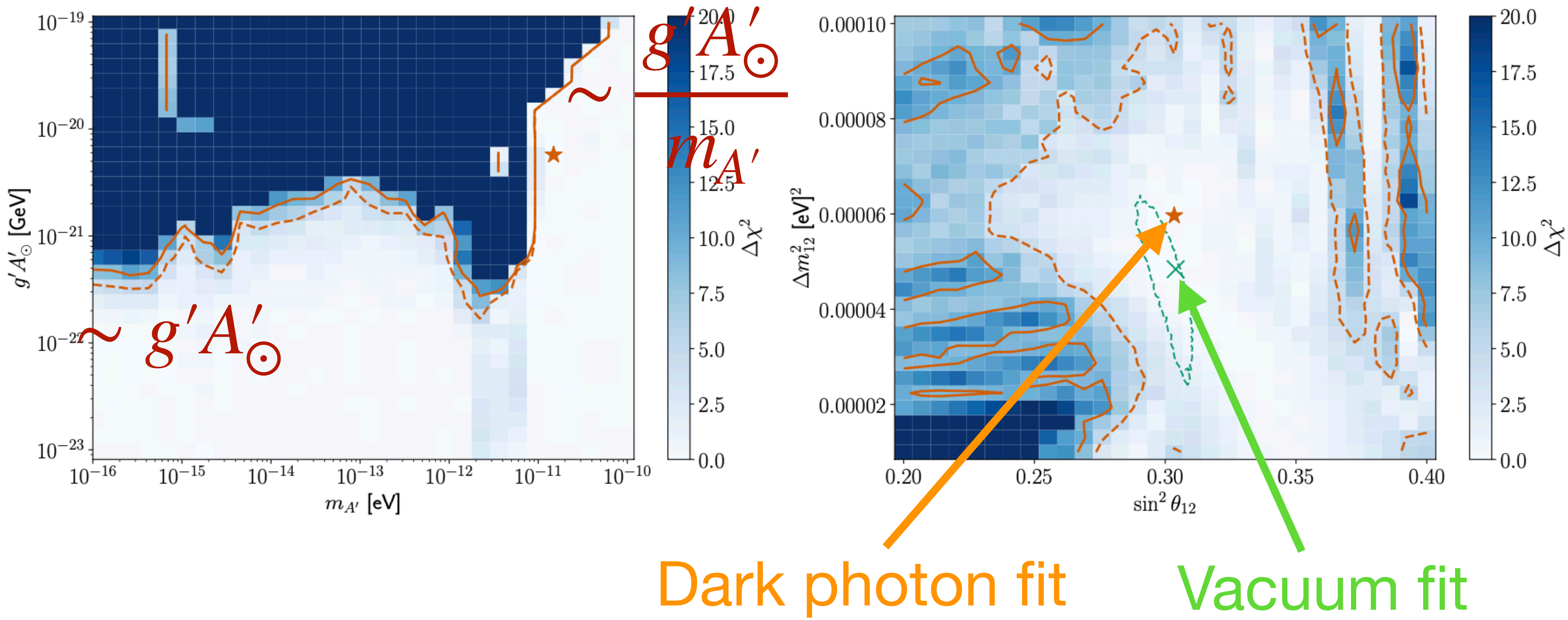


Combined fit to SNO & Super-K



Parameter space

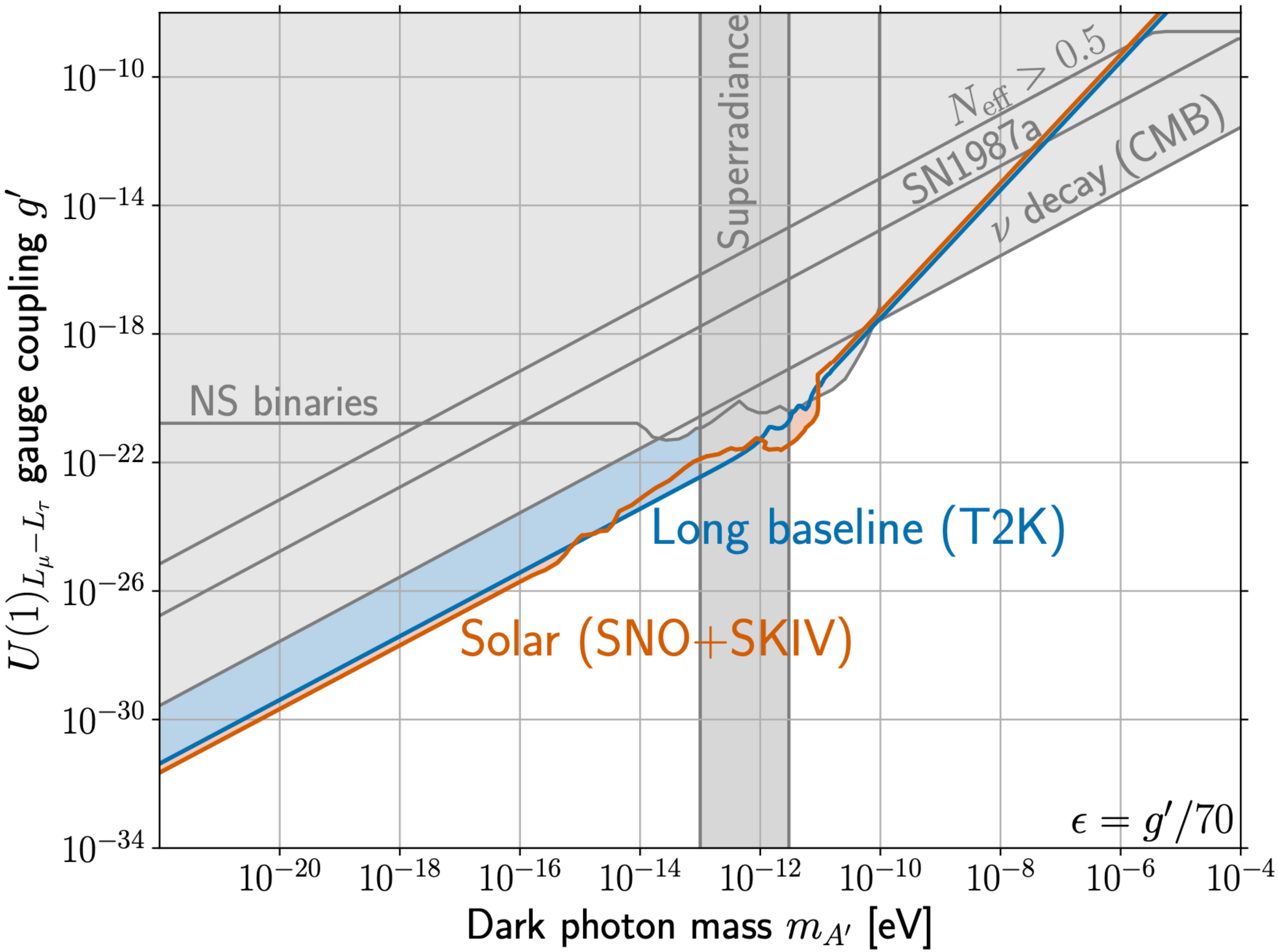
Vary 4 parameters: $\Delta m^2_{12}\,,\ \sin^2\theta_{12}\,,\ m_{A'}\,,\ g'A'_\odot$



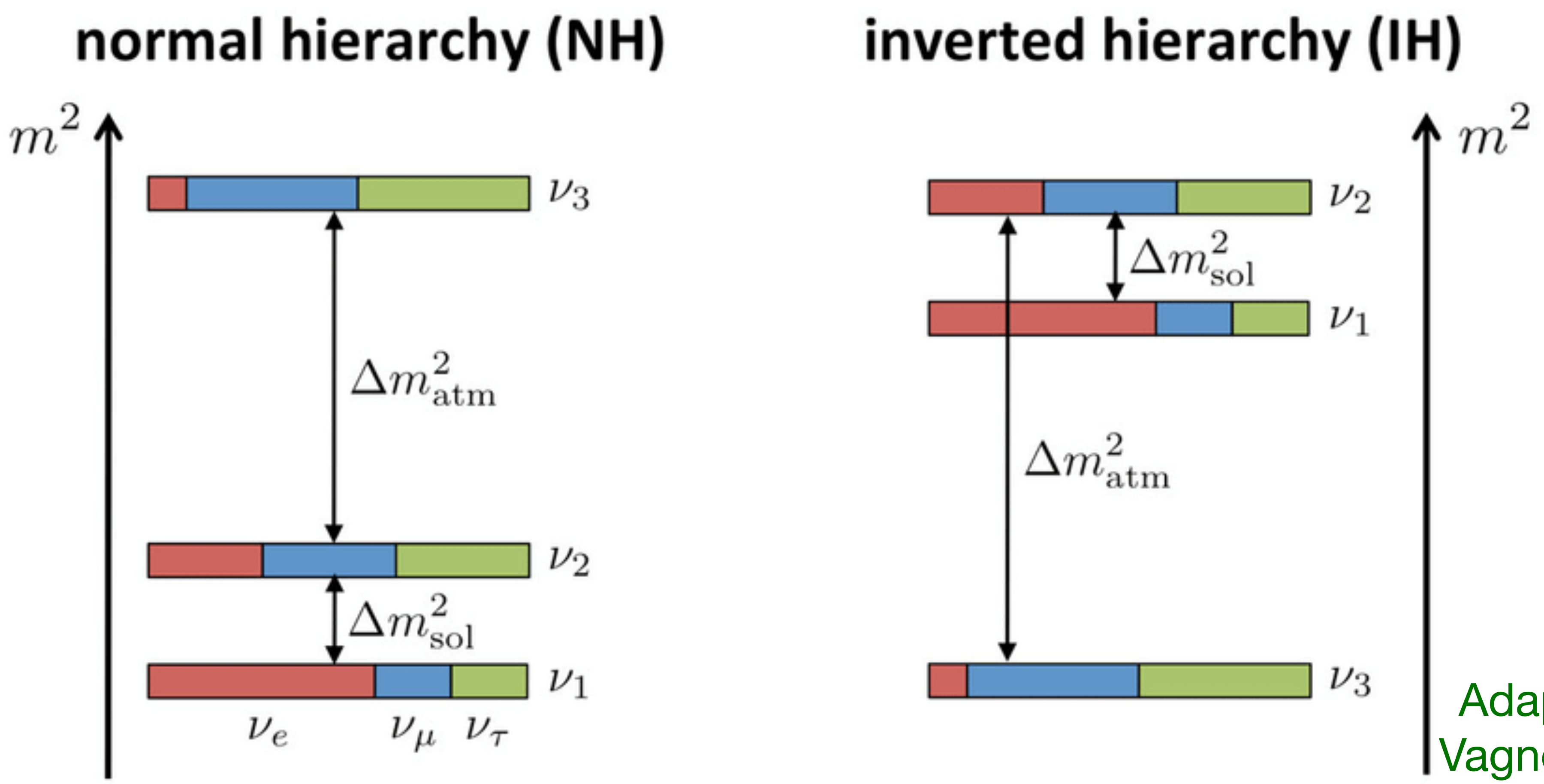
Enlarged allowed region for $\Delta m^2_{23}\,,\ \sin^2\theta_{23}$

E.g. better compatible with results from KamLAND

Dark photon parameter space

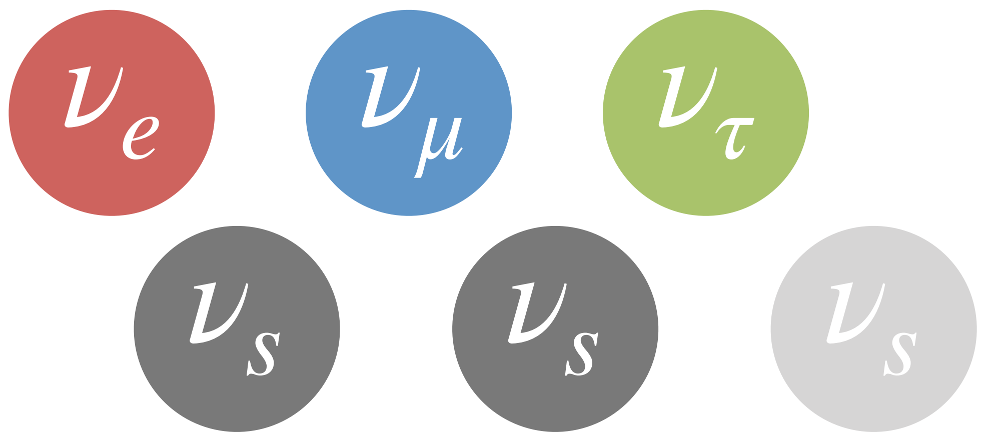


Sterile neutrinos



Adapted from Vagnozzi (2019)

Right-handed (sterile) neutrinos to generate masses



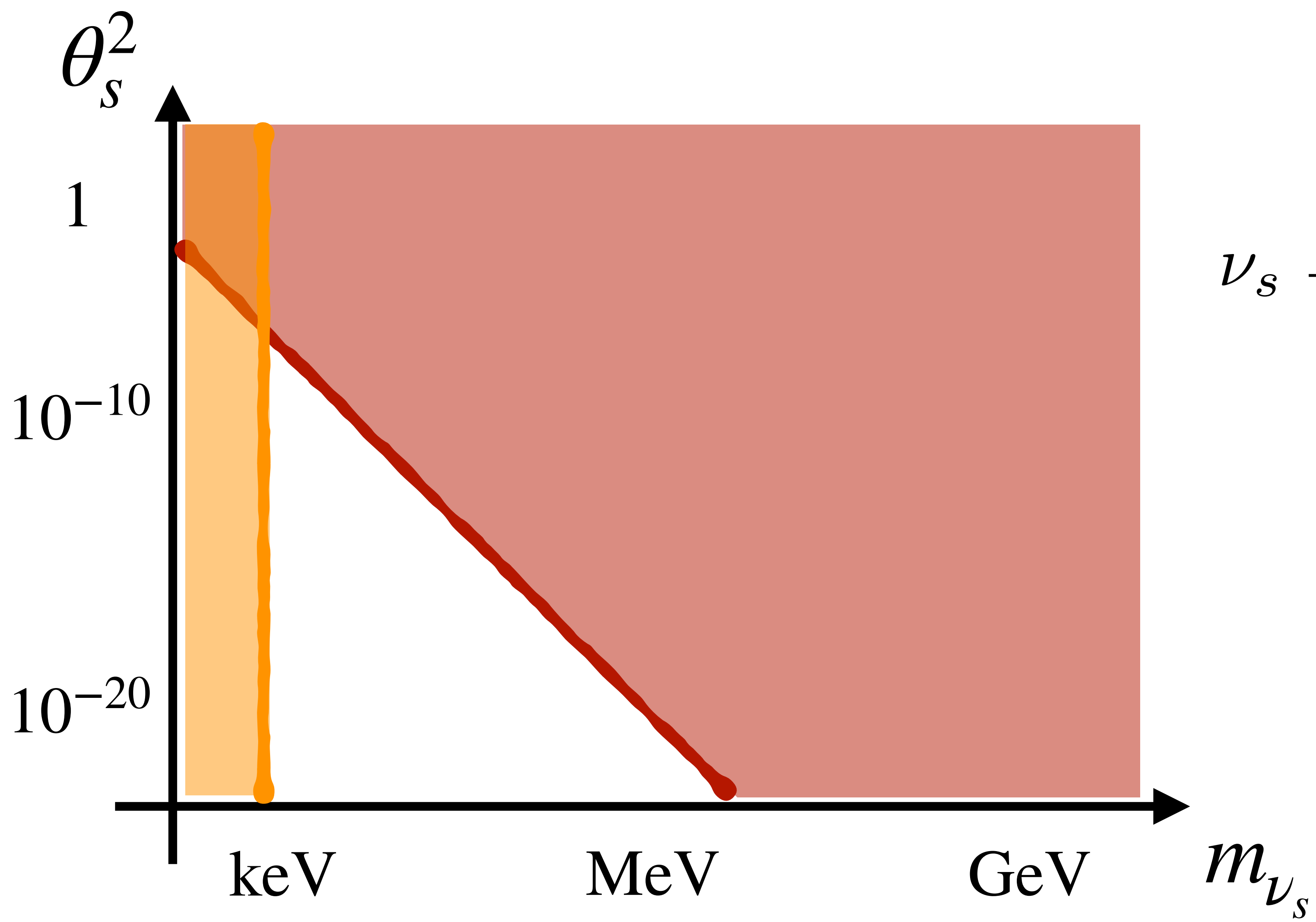
Sterile neutrino dark matter

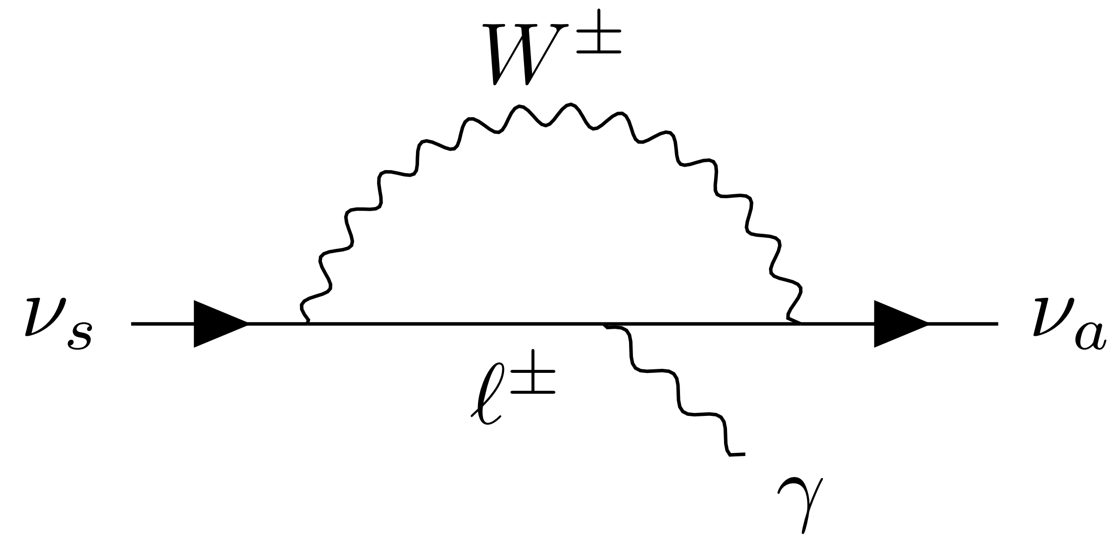
- Warm dark matter

$m_{\nu_s} \gtrsim 1\,\mathrm{keV}$

- Decay into X/Gamma-rays

$\Gamma_{\nu_s \to \nu_a \gamma} \propto \theta_s^2\, m_{\nu_s}^5$





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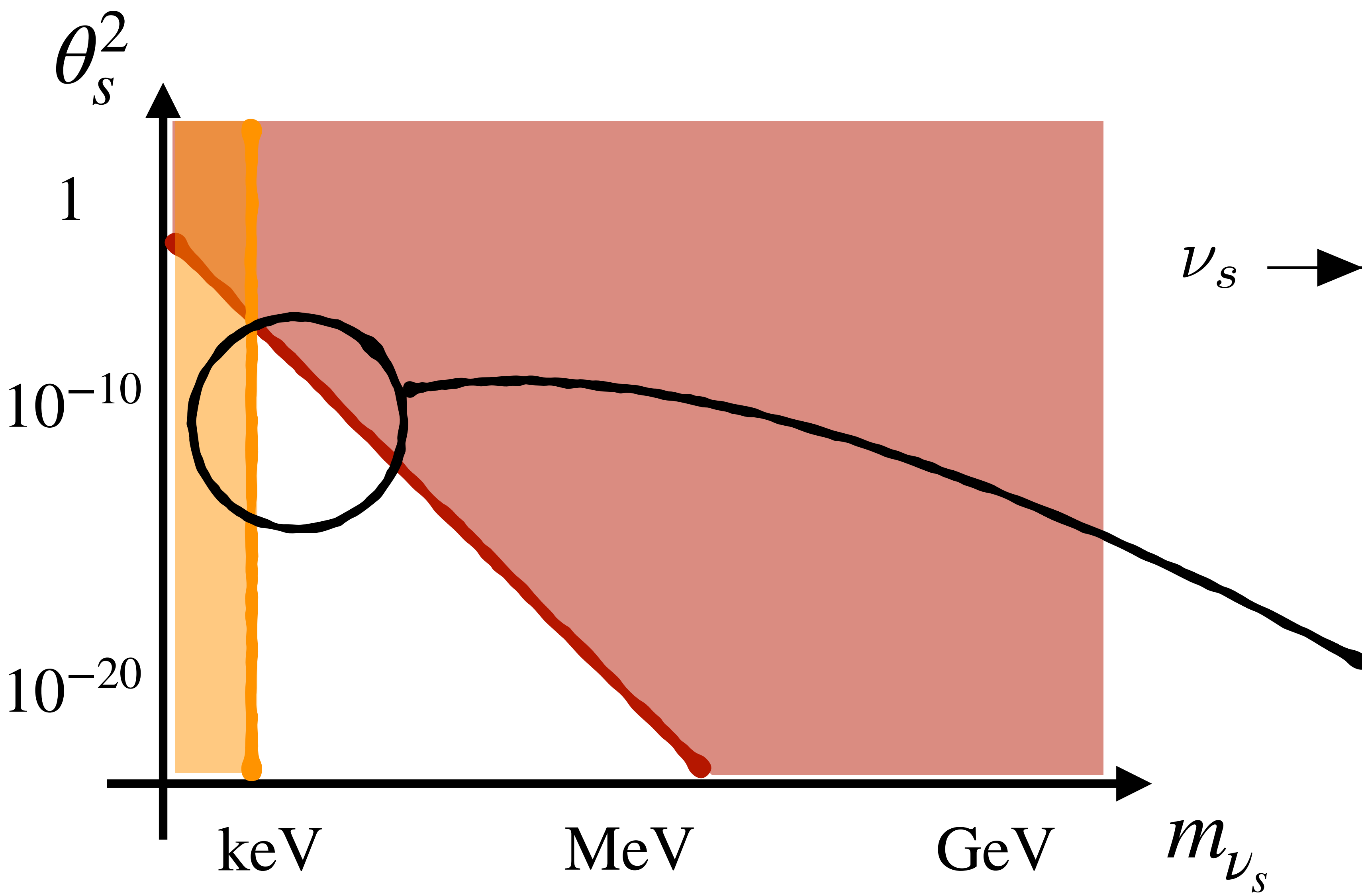
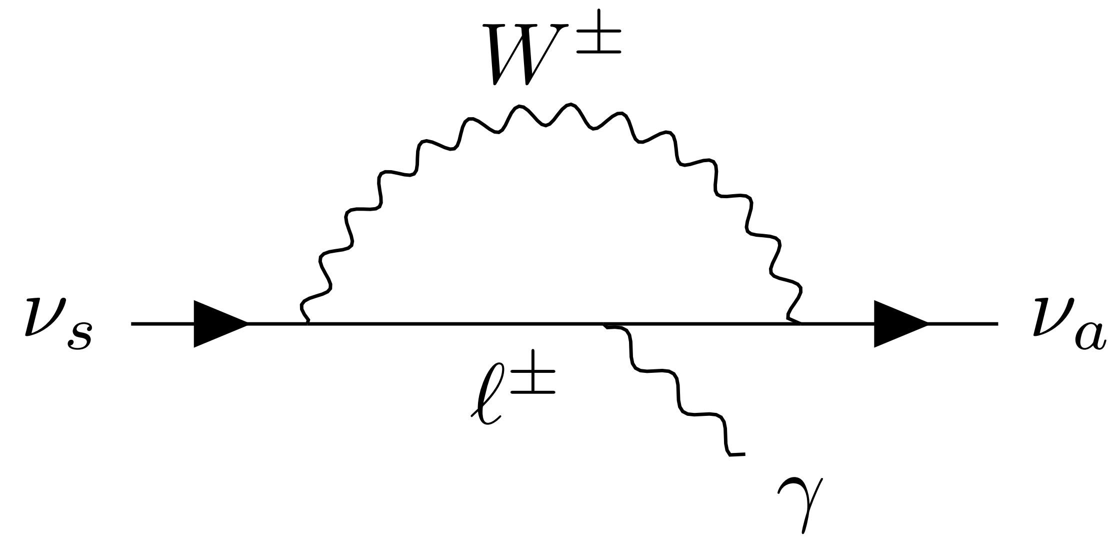
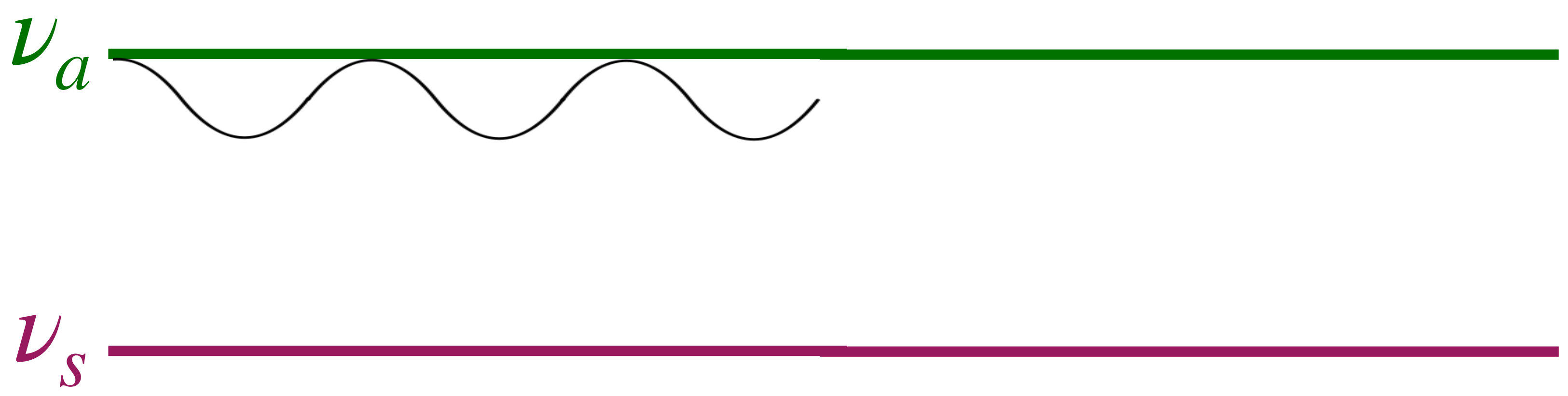




Non-resonant production



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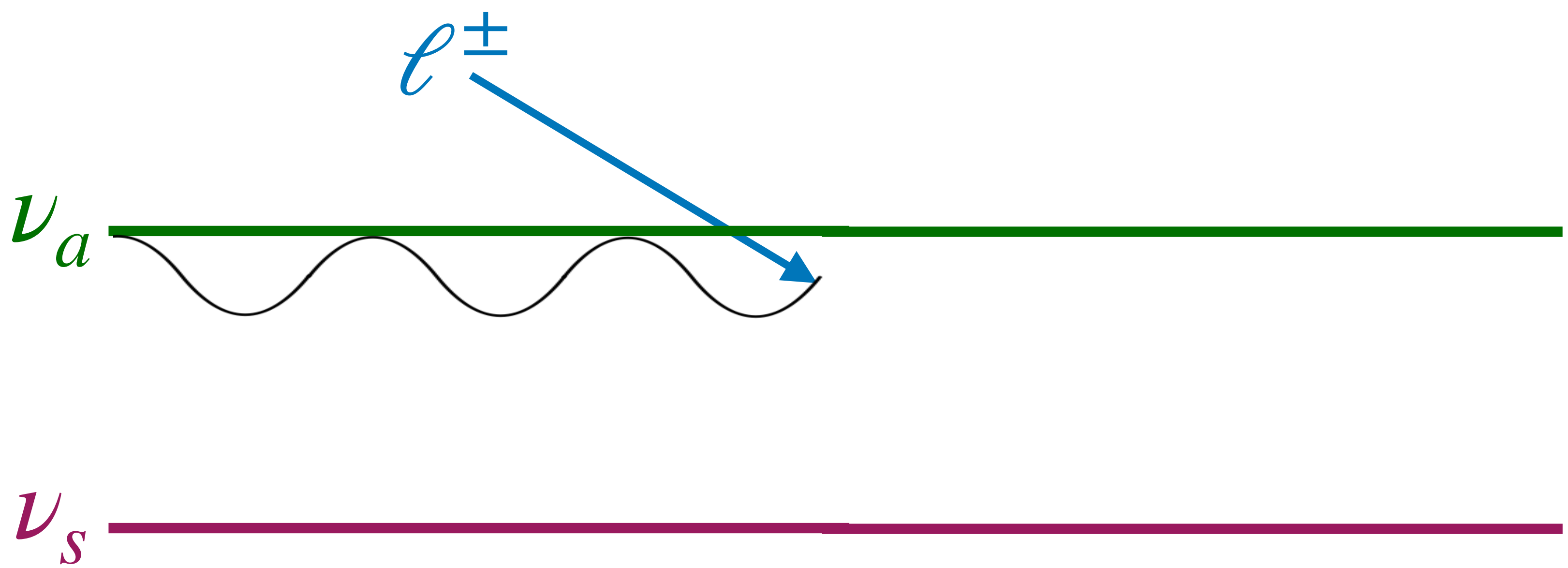
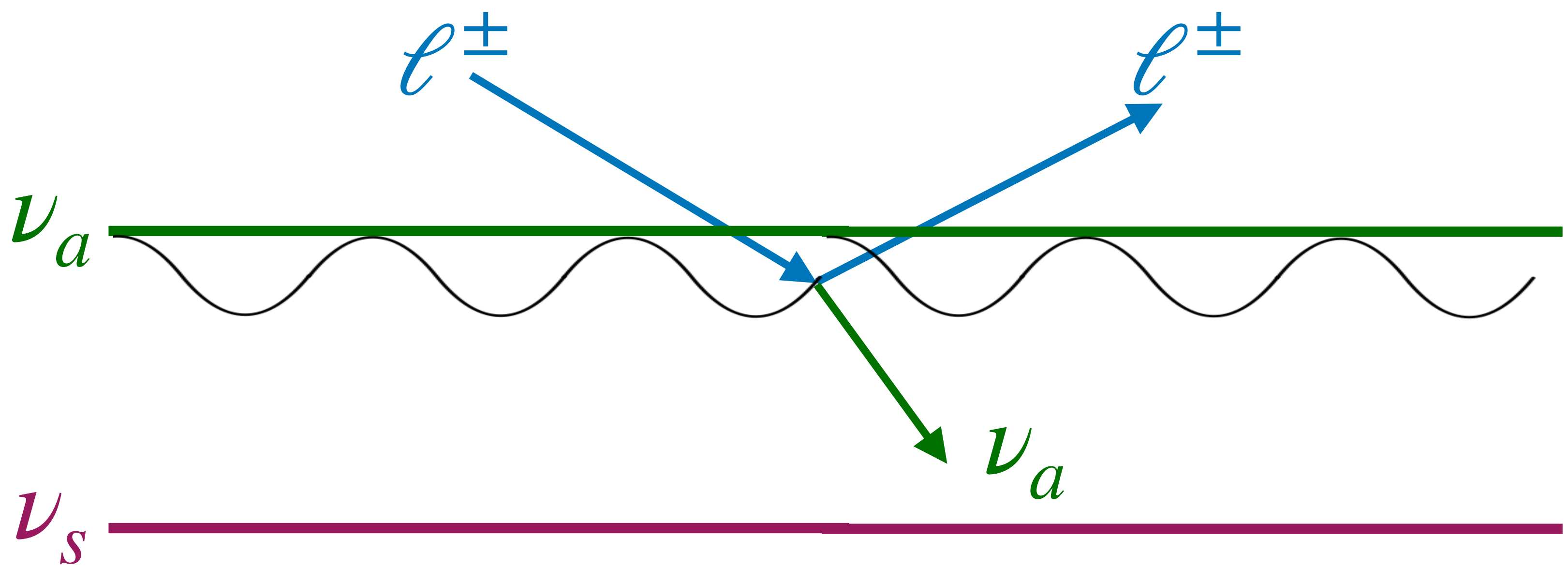
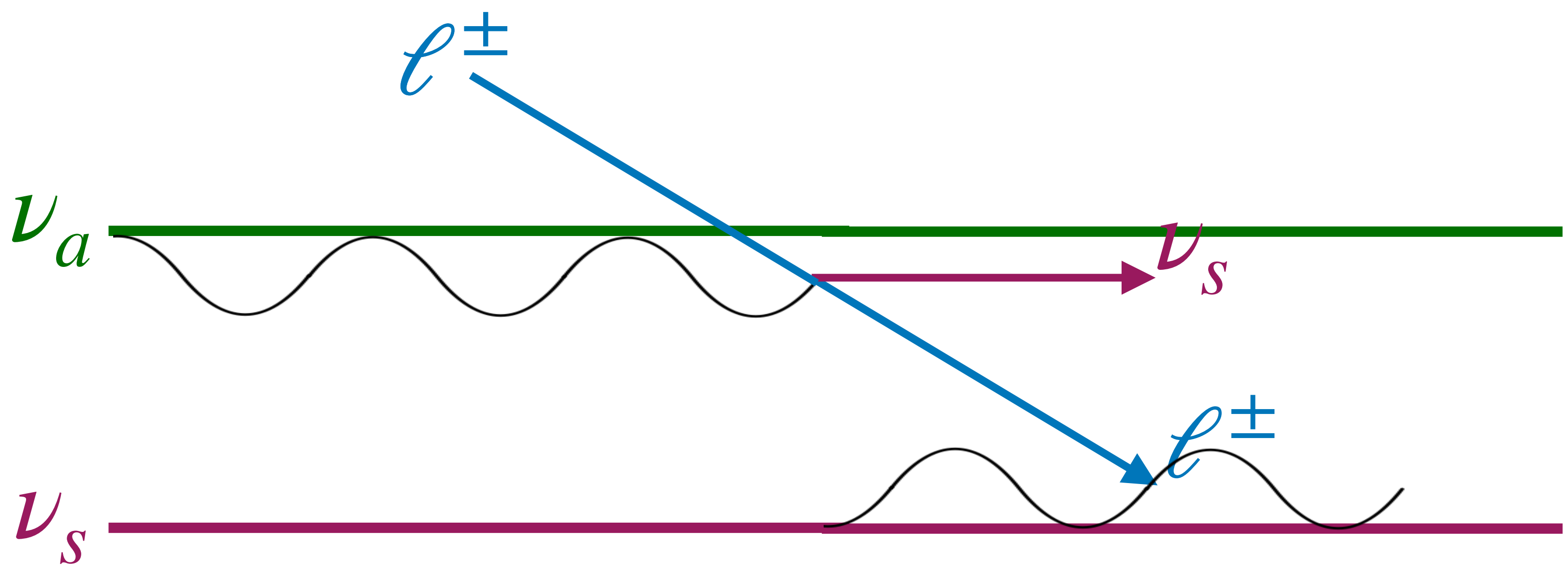


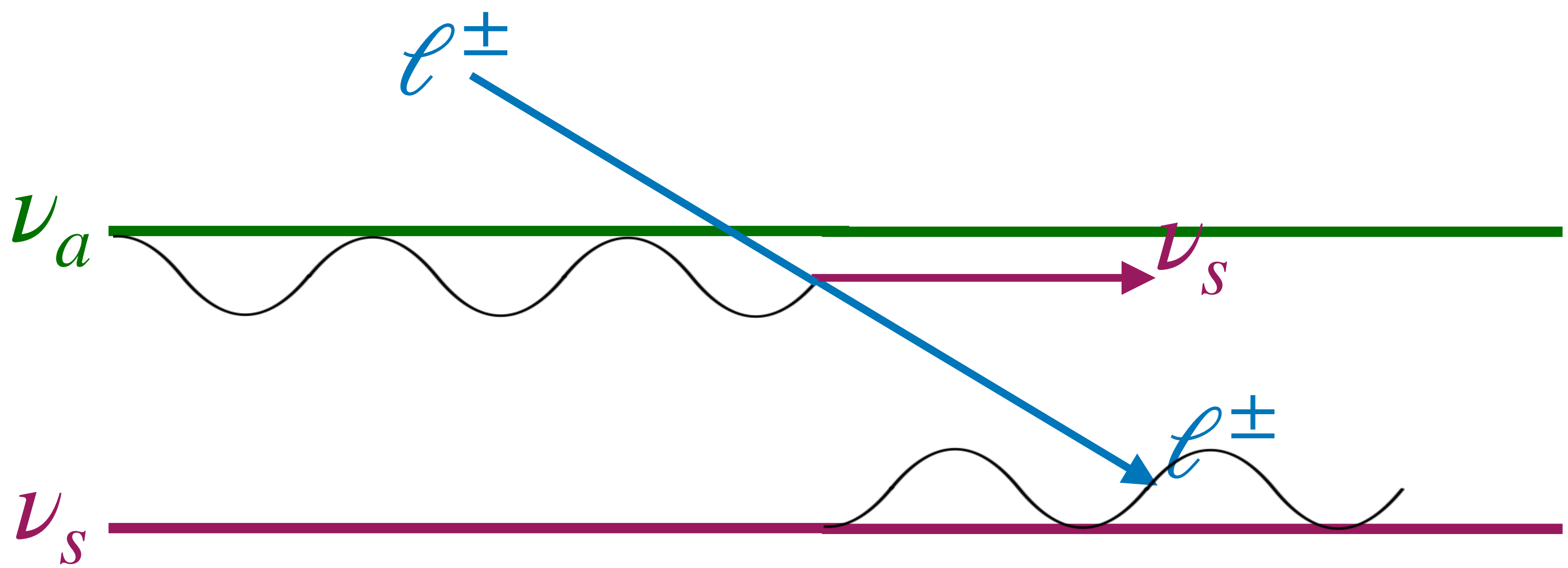
Non-resonant production



Non-resonant production



Non-resonant production



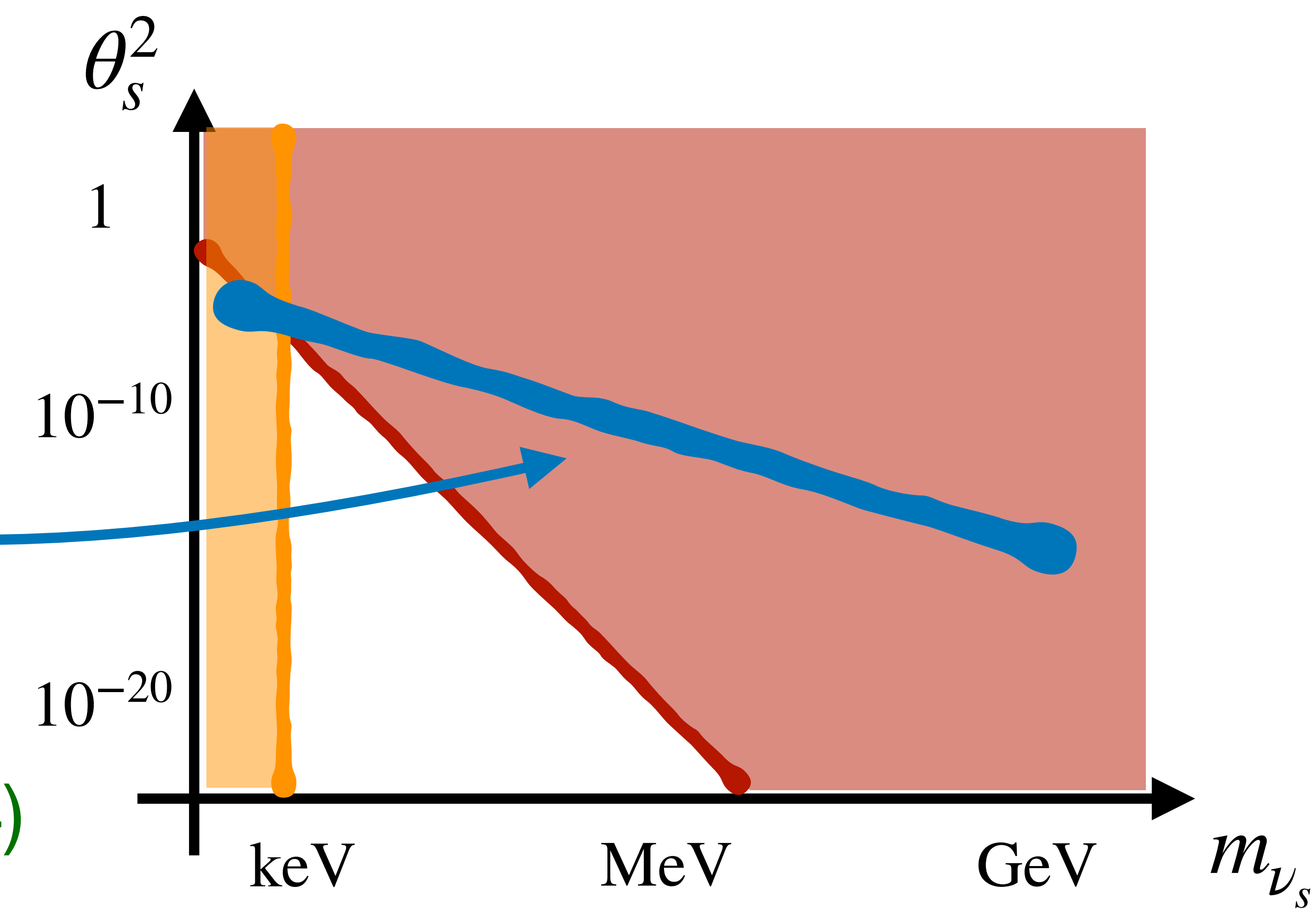
Production rate

$$\Gamma_s = \Gamma_a(T) \cdot < \mathrm{P}_{a\to s} >$$

where

$$\mathrm{P}_{a\to s} = \left| 2\theta_s \sin(\omega t) \right|^2$$

Dodelson & Widrow (1994)



Resonant production

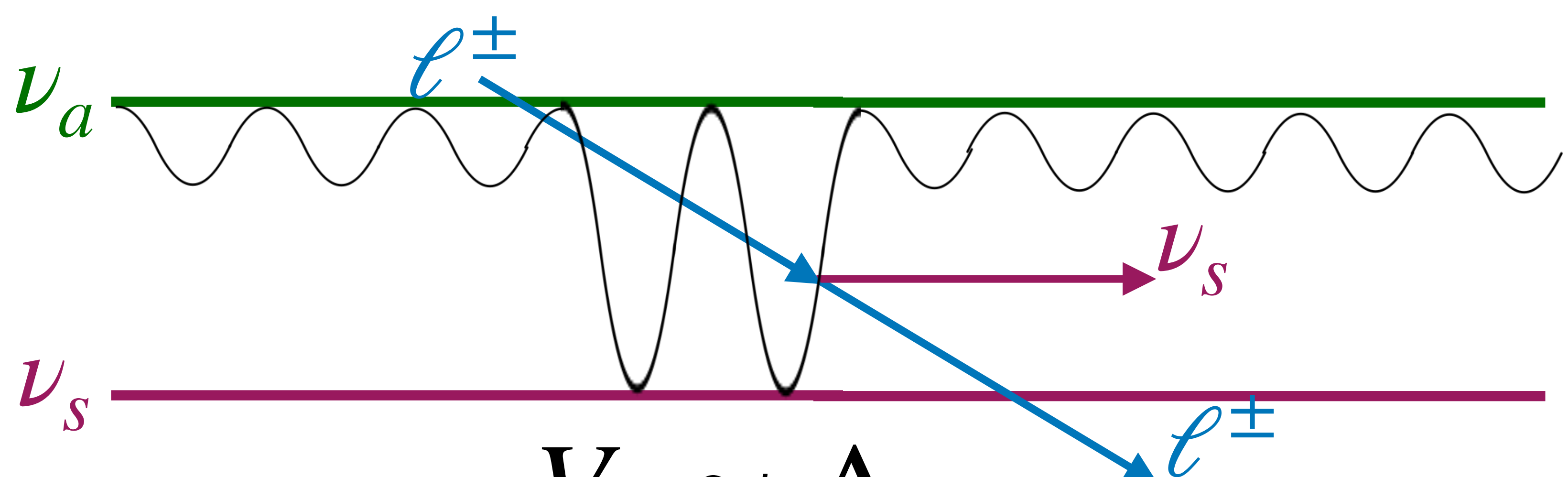
In the presence of matter effects

$$< P_{a\to s} > \simeq \frac{1}{2}\frac{4\Delta^2\theta_s^2}{4\Delta^2\theta_s^2 + \Gamma_a^2/4 + (V_a - \Delta)^2}$$

$$\Delta = \frac{m_s^2 - m_a^2}{2p} > 0$$

Decoherence by scatterings

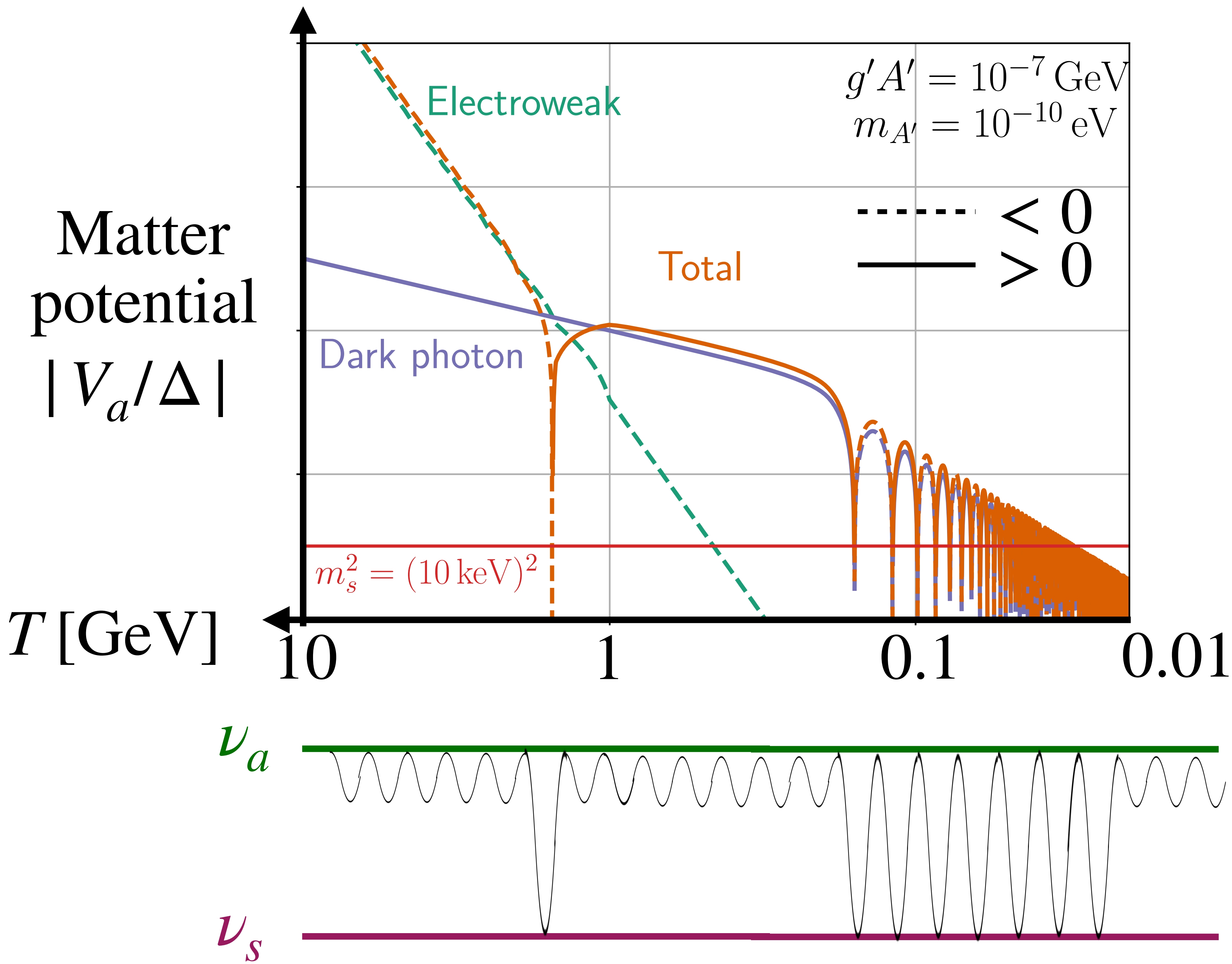
Matter potential



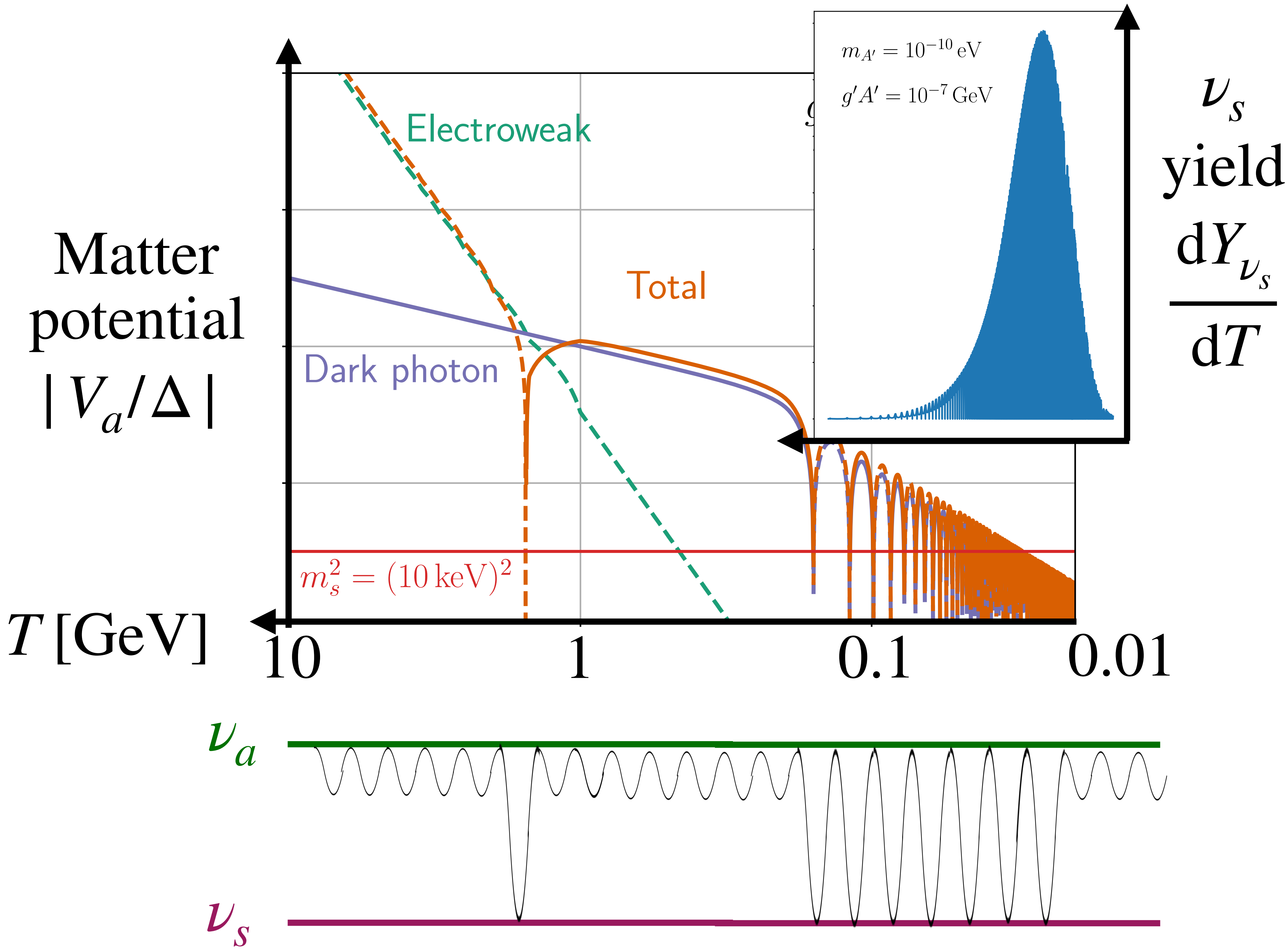
$$V_a \simeq \Delta$$

Caveat: $V_a < 0$ unless there is a huge lepton asymmetry $L \sim 10^5\, B$

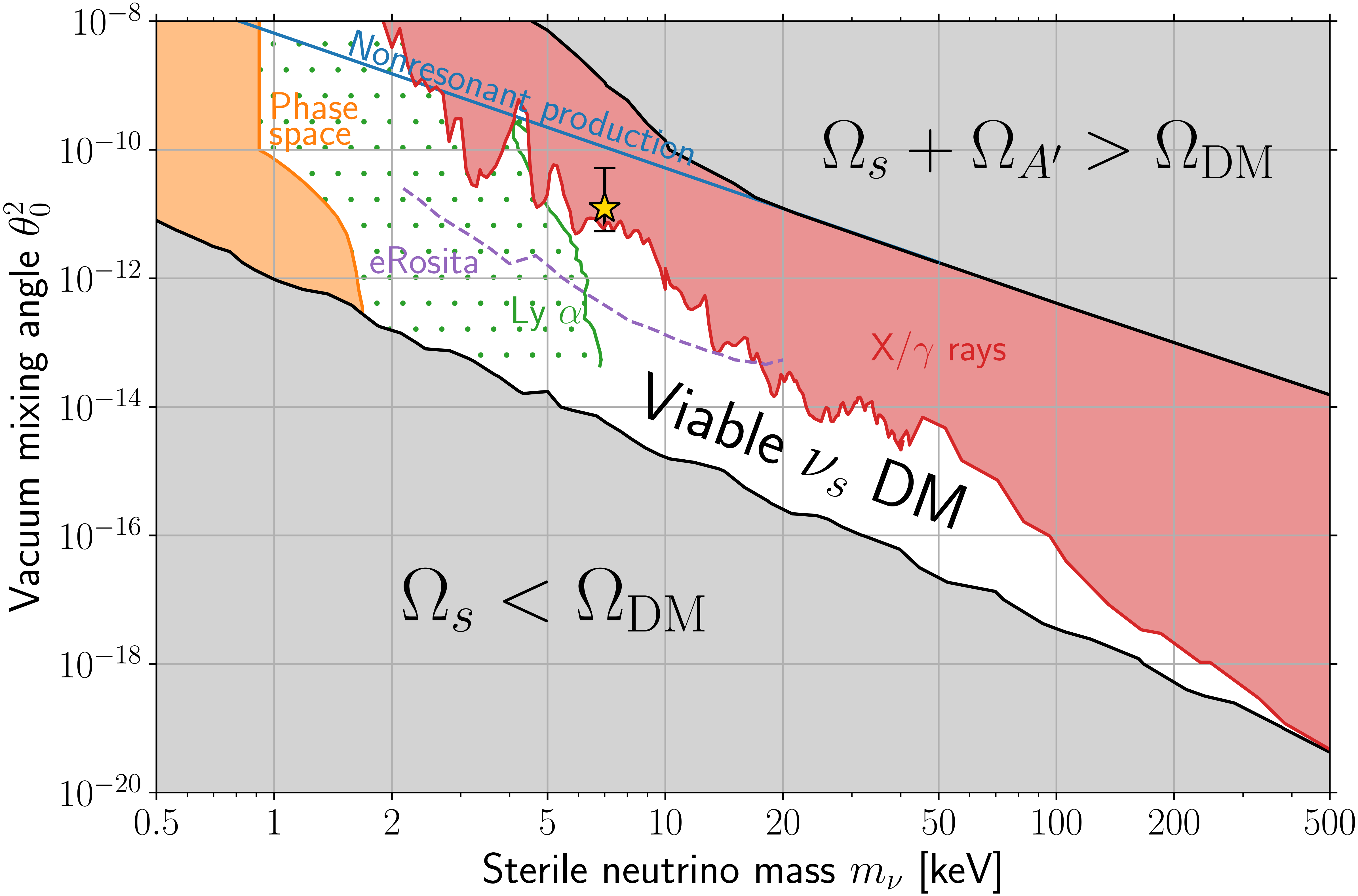
(Multi-)resonant production



(Multi-)resonant production



Sterile neutrino parameter space



Conclusions & outlook

- A background of very light $L_\mu - L_\tau$ dark photons can modify neutrino flavor conversions

- Other things to look at:
  - Full 3-flavour setup in long baseline
  - Directional dependence
  - Reactor experiments
  - Cosmological history
  - …

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  - Full 3-flavour setup in long baseline
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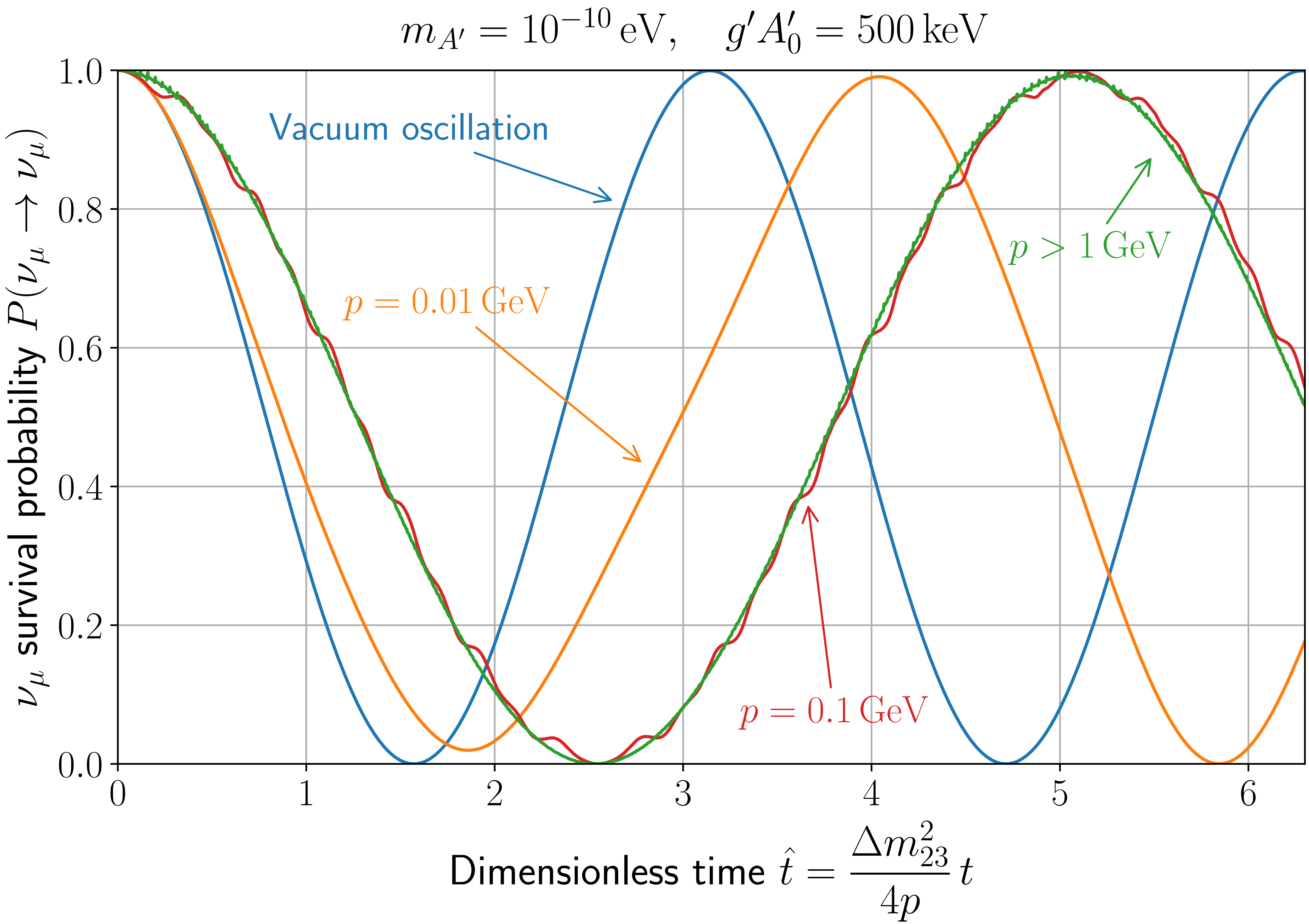
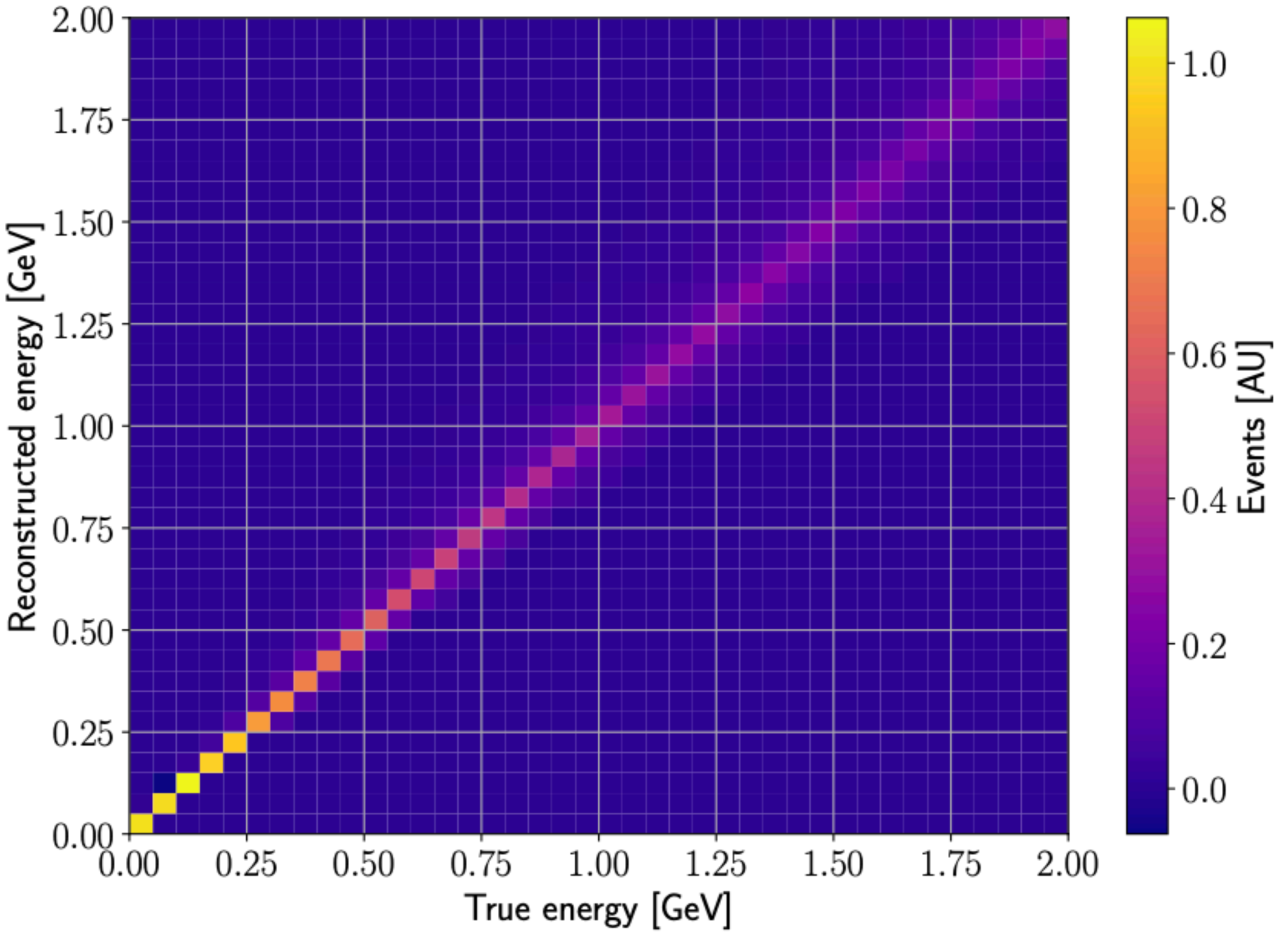
Thanks!

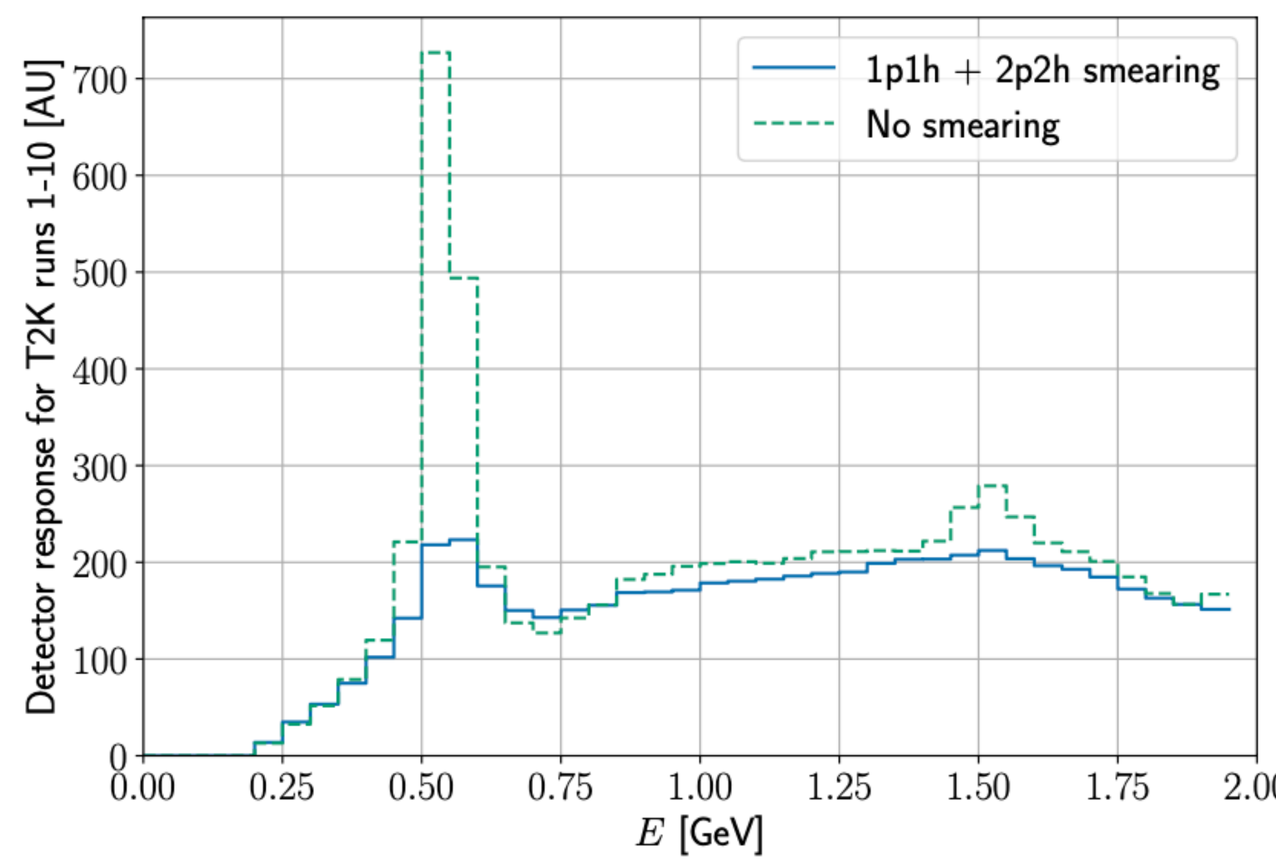
Backup

Numerical validation



T2K detector response





Standard fit - T2K