KIT – Die Forschungsuniversität in der Helmholtz-Gemeinschaft **www.kit.edu**

 $HIDDeU$ Hunting Invisibles: Dark sectors, Dark matter and Neutrinos

Decoherence in neutrino oscillations and the Gallium anomaly

EuCAPT Astroneutrino Theory Workshop 2024 Prague, Czech Republic, Sept. 2024

- reactor experiments
- A QFT calculation of standard decoherence effects in reactor and radioactive source experiments w. Raphael Krüger, arXiv:2303.15524
- decoherence without sterile neutrinos w. Yasaman Farzan, arXiv:2306.09422

• An explanation of the gallium anomaly in terms of new physics quantum

• Motivation: reactor and gallium anomalies, general decoherence effects in

Outline

The gallium anomaly

 \blacksquare Farzan, TS, 2306.09422 \csc sections CS1, CS2 from \cosh Haxton et al., 2303.13623 **Paramental areas experimental**

electron capture decay: ${}^{51}Cr \rightarrow {}^{51}V + \nu_e$ *Eν* = 750 keV (90%) & 430 keV (10%)

combined with the correlated uncertainty due to the correlated uncertainty due to the cross sections from eq. (
To test sections from eq. (10). To test sections from eq. (10). To test sections from eq. (10). To test sectio *R* = observed detection rate / predicted rate

 R_{S} + R_{S} +

see also Berryman, Coloma, Huber, TS, Zhou, 2111.12530; Goldhagen, Maltoni, Reichard, TS, 2109.14898; Brdar, Gehrlein, Kopp, 2303.05528

- Arguelles, Bertolez-Martinez, Salvado, Impact of Wave Packet Separation in Low-Energy Sterile Neutrino Searches [2201.05108]
- Arguelles, Conrad et al., New Clues About Light Sterile Neutrinos: Preference for Models with Damping Effects in Global Fits [2211.02610]
- Akhmedov, Smirnov, Damping of neutrino oscillations, decoherence and the lengths of neutrino wave packets, [2208.03736]; Jones, Comment on... [2209.00561], Akhmedov, Smirnov, Reply to comment... [2210.01547]

• Jones, Marzec, Spitz, The Width of a Beta-decay-induced Antineutrino Wavepacket [2211.00026]

Can quantum decoherence have an effect on the gallium/reactor tension?

• High-precision reactor experiment JUNO coll., 1507.05613

• decoherence effects in JUNO? Gouvea, Romeri, Ternes, 2005.03022; Wang et al. (JUNO) 2112.14450; Marzec, Spitz, 2208.04277

Can quantum decoherence effects show up in future **reactor experiments?**

JUNO 100k IBD Events

decoherence eects in JUNO? Gouvea, Romeri, Ternes, 2005. Gouvea, 2005. Gouvernement in JUNO? Gouvernement in J
1980. Gouvernement in JUNO? Gouvernement in JUNO? Gouvernement in JUNO? Gouvernement in JUNO? Gouvernement in

Th. Schwetz - Prague Sept 2024 *^E* energy resolution is assumed. Wang et al. Schwetz – Prague Sept 2024.

Wang terminologie

• perform a QFT calculation of the oscillation amplitude, taking into account localization of external particles for reactor and gallium experiments

R. Krüger, T. Schwetz, 2303.15524 (EPJC)

•, first principle calculation of decoherence effects

Decoherence in neutrino oscillations large literature (very incomplete selection): large literature (very incomplete selection):

• S. Nussinov, Solar Neutrinos and Neutrino Mixing, PLB 63 (1976) 201; • B. Kayser, On the Quantum Mechanics of Neutrino Oscillation, PRD 24 (1981) 110; • C. Giunti, C. W. Kim, U. W. Lee, When Do Neutrinos Really Oscillate?: Quantum Mechanics of Neutrino Oscillations, PRD 44 (1991) 3635; • J. Rich, The Quantum Mechanics of Neutrino Oscillations, PRD 48 (1993) 4318; • K. Kiers, S. Nussinov, N. Weiss, Coherence Effects in Neutrino Oscillations, PRD 53 (1996) 537; • W. Grimus and P. Stockinger, Real Oscillations of Virtual Neutrinos, PRD 54 (1996) 3414; • C. Giunti, C.W. Kim, U.W. Lee, When Do Neutrinos Cease to Oscillate?, PLB 421 (1998) 237; • C. Giunti and C. W. Kim, Coherence of Neutrino Oscillations in the Wave Packet Approach, PRD 58 (1998) 017301; • L. Stodolsky, The Unnecessary Wave Packet, PRD 58 (1998) 036006; • W. Grimus, P. Stockinger, and S. Mohanty, The Field Theoretical Approach to Coherence in Neutrino Oscillations, PRD 59 (1999) 013011; • C. Y. Cardall, Coherence of Neutrino Flavor Mixing in Quantum Field Theory, PRD 61 (2000) 073006; • M. Beuthe, Oscillations of Neutrinos and Mesons in Quantum Field Theory, Phys. Rept. 375 (2003) 105; [hep-ph/0109119]. • E. K. Akhmedov and A. Y. Smirnov, Paradoxes of Neutrino Oscillations, Phys. Atom. Nucl. 72 (2009) 1363; [0905.1903]. • E. K. Akhmedov and J. Kopp, Neutrino Oscillations: Quantum Mechanics vs Quantum Field Theory, JHEP 04 (2010) 008; • D. Hernandez and A. Yu. Smirnov, Active to sterile neutrino oscillations: Coherence and MINOS results, PLB706 (2012) 360; • E. Akhmedov, D. Hernandez, and A. Smirnov, Neutrino Production Coherence and Oscillation Experiments, JHEP 04 (2012) 052;. • B. J. P. Jones, Dynamical Pion Collapse and the Coherence of Conventional Neutrino Beams, PRD 91 (2015), no. 5 053002

The "standard oscillation formula" *|‹–*Í = *U*^ú *–ⁱ|‹i*^Í *^e*≠*i*(*Eit*≠*pi ^x*) *[|]‹—*^Í ⁼ *^U*^ú oscillation amplitude:

 $A_{\nu_{\alpha} \to \nu_{\beta}} = \langle \nu_{\beta}|$ propagation $|\nu_{\alpha}\rangle$ $=$ \sum *i,j* $U_{\beta j} \langle \nu_j | e^{-i(E_i t - p_i x)} | \nu_i \rangle U_{\alpha i}^* = \sum_{\alpha}$

-
- *i* $U_{\beta i} U_{\alpha i}^* e^{-i(E_i t - p_i x)}$

The "standard oscillation formula" *|‹–*Í = *U*^ú *–ⁱ|‹i*^Í *^e*≠*i*(*Eit*≠*pi ^x*) *[|]‹—*^Í ⁼ *^U*^ú oscillation amplitude: Neutrino oscillations in vacuum

 $A_{\nu_{\alpha} \to \nu_{\beta}} = \langle \nu_{\beta}|$ propagation $|\nu_{\alpha}\rangle$ $=$ \sum *i,j* $U_{\beta j} \langle \nu_j | e^{-i(E_i t - p_i x)} | \nu_i \rangle U_{\alpha i}^* = \sum_{\alpha}$ *i* $U_{\beta j}\langle\nu_j|$ $e^{-i(E_i t - p_i x)}$ $|\nu_i\rangle U_{\alpha i}^* = \sum U_{\beta i}U_{\alpha i}^* e^{-i(E_i t - p_i x)}$ \sqrt{a} $\sqrt{ }$ $\langle E_i t - p_i x \rangle$ $|U_i \rangle U_{\alpha i}^* = \sum U_{\beta i} U_{\alpha i}^* e^{-i(E_i t - p_i t)}$ $\mathcal{D}_i X$

 $\mathcal{A}_{\nu_{\alpha} \rightarrow \nu_{\beta}}$ - $\begin{array}{c} \hline \end{array}$ 2 $\left| \mathcal{A}_{\nu_{\alpha} \rightarrow \nu_{\beta}} \right|^{-1}$

2

 $\left| \mathcal{A}_{\nu_{\alpha} \rightarrow \nu_{\beta}} \right|^{2} \quad = \sum |U_{\beta i}U_{\alpha i}^{*}|^{2} + \sum U_{\beta j}U_{\alpha j}^{*}U_{\beta i}^{*}U_{\alpha i} \mathrm{e}^{-1}$ $=$ \sum *i* $|U_{\beta i} U_{\alpha i}^*|$ $2 + \sum$ $i \neq j$ $U_{\beta j}U_{\alpha j}^*U_{\beta i}^*U_{\alpha i}e^{-i\phi_{ji}}$ **Construction of the construction of the c**

interference terms

The "standard oscillation formula" α atomdered eealletien ferminie^{ll} oscillation amplitude: le "stanuaru Neutrino oscillations in vacuum

2

$$
\mathcal{A}_{\nu_{\alpha} \to \nu_{\beta}} = \langle \nu_{\beta} | \text{propagation } |\nu_{\alpha} \rangle
$$

=
$$
\sum_{i,j} U_{\beta j} \langle \nu_{j} | e^{-i(E_{i}t - p_{i}x)} |\nu_{i} \rangle U_{\alpha i}^{*} = \sum_{i} U_{\beta i} U_{\alpha i}^{*} e^{-i(E_{i}t - p_{i}x)}
$$

$$
\rightarrow \quad P_{\nu_{\alpha} \to \nu_{\beta}} = |A_{\nu_{\alpha} \to \nu_{\beta}}|^2
$$

with phase differences:

$$
\phi_{ji}=(E_j-E_i)t-(p_j-p_i)x \quad \text{with} \quad E_i^2
$$

after some hand waving: ϕ $\sum_{i=1}^{n}$ after some hand waving: $\phi_{ji} \approx$

$$
= \sum_{i} |U_{\beta i} U_{\alpha i}^{*}|^{2} + \sum_{i \neq j} U_{\beta j} U_{\alpha j}^{*} U_{\beta i}^{*} U_{\alpha i} e^{-i\phi_{ji}}
$$

$$
p_i)x \quad \text{with} \quad E_i^2 = p_i^2 + m_i^2
$$

ving:
$$
\phi_{ji} \approx \frac{\Delta m_{ji}^2 L}{2E}
$$
 with $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$

interference terms

The "standard oscillation formula" *|‹–*Í = *U*^ú *–ⁱ|‹i*^Í *^e*≠*i*(*Eit*≠*pi ^x*) *[|]‹—*^Í ⁼ *^U*^ú oscillation amplitude: Neutrino oscillations in vacuum

2

$$
\rightarrow \quad P_{\nu_{\alpha} \to \nu_{\beta}} = |A_{\nu_{\alpha} \to \nu_{\beta}}|^2
$$

2-flavour: $P = \frac{1}{2} \sin^2 2\theta$

with phase dierences: with phase diependent and the phase diependent and the phase diependent and the phase di
The phase diependent and the phase diependent and the phase diependent and the phase diependent and the phase

$$
\mathcal{A}_{\nu_{\alpha} \to \nu_{\beta}} = \langle \nu_{\beta} | \text{ propagation } |\nu_{\alpha} \rangle
$$

=
$$
\sum_{i,j} U_{\beta j} \langle \nu_j | e^{-i(E_i t - p_i x)} |\nu_i \rangle U_{\alpha i}^* = \sum_i U_{\beta i} U_{\alpha i}^* e^{-i(E_i t - p_i x)}
$$

$$
= \sum_{i} |U_{\beta i} U_{\alpha i}^{*}|^{2} + \sum_{i \neq j} U_{\beta j} U_{\alpha j}^{*} U_{\beta i}^{*} U_{\alpha i} e^{-i\phi_{ji}}
$$

interference terms

$$
n^2 2\theta \left(1 - \cos \frac{\Delta m^2 L}{2E}\right)
$$

10 Th. Schwetz - Prague Sept 2024 *S*CIIWELZ - Prague Sept 2024

naive approach is problematic at least for the following reasons:

- production and detection regions are localised in space inconsistent with plane wave ansatz for neutrino propagation → ∝ *e*−*i*(*Ei t*−*pi x*)
- plane waves correspond to states with exact energy/momentum neutrino mass states are distinguishable particles why is the sum in the amplitude coherent (inside modulus)? →

naive approach is problematic at least for the following reasons:

- assume wave-packets for neutrinos
- QFT approach, neutrino as internal line, wave-packets for external particles
- relation of the two approaches e.g., Akhmedov, Kopp, JHEP (2010) [1001.4815]
- production and detection regions are localised in space inconsistent with plane wave ansatz for neutrino propagation → ∝ *e*−*i*(*Ei t*−*pi x*)
- plane waves correspond to states with exact energy/momentum neutrino mass states are distinguishable particles why is the sum in the amplitude coherent (inside modulus)? →

Two approaches:

naive approach is problematic at least for the following reasons:

Decoherence ananan

 $\overbrace{\qquad \qquad \text{intraff} \qquad \qquad \text{intraff}}$ interference terms

12 Th. Schwetz - Prague Sept 2024 U *<u>x* $\frac{1}{2}$ *= <i>L*, $\frac{1}{2}$ = *L*, $\frac{1}{2}$ =</u>

$$
P_{\nu_{\alpha}\to\nu_{\beta}} = \sum_{i} |U_{\beta i} U_{\alpha i}^{*}|^{2} + \xi \sum_{i \neq j} U_{\alpha i}
$$

decoherence: $0 \le \xi \le 1 \rightarrow$ damping of interference terms

 $U_{\beta j}U_{\alpha j}^*U_{\beta i}^*U_{\alpha i}e^{-i\phi_{ji}}$

Decoherence ananan Neutrino oscillations – the naive approach

*m*²

jiL

 $U_{\beta j}U_{\alpha j}^*U_{\beta i}^*U_{\alpha i}e^{-i\phi_{ji}}$ *i*

 $\overbrace{\qquad \qquad \text{intraff} \qquad \qquad \text{intraff}}$ $interference$ *terms* $\frac{1}{\pi}$ ce t decoherence: 0 Æ *›* Æ 1 æ damping of interference terms

 $\xi < 1$ **In "Classical" decoherence:** $\xi < 1$ due to averaging of the probability: I "Classical" decoherence: $\frac{1}{2}$ **1** due to averaging of the probability:

$$
|\mathcal{A}|^2 = \sum_{ij} \mathcal{A}_j^* \mathcal{A}_i
$$

› < 1 due to averaging of the probability:

$$
P_{\nu_{\alpha} \to \nu_{\beta}} = \sum_{i} |U_{\beta i} U_{\alpha i}^{*}|^{2} + \xi \sum_{i \neq j} U_{\beta j} U_{\alpha j}^{*} U_{\beta i}^{*} U_{\alpha i} e^{-i\phi_{ji}} \qquad \phi_{ji} \approx \frac{\Delta m_{ji} L}{2 E}
$$

interference terms

decoherence: $0 \leq \xi \leq 1 \rightarrow$ damping of interference terms $\sum_{i=1}^{n}$ $\mathbf{r} \rightarrow \mathbf{q}$ and $\mathbf{r} \rightarrow \mathbf{r}$ interference terms ence: $0 < \xi < 1 \rightarrow$ dar $i\circ\cup\leq\zeta\leq\tau-1$ amping of interference terms

\mathbf{r} $\mathbf{$ /el: I "Quantum" decoherence: I "Quantum" decoherence: $\xi < 1$ appears already at amplitude level: ζ < 1 appears already at an

jiL

I "Classical" decoherence:

$$
\overline{P} \propto \int dx \, |A(x)|^2 \, , \qquad x = L, E
$$

- Feynman diagram for joint process of production, propagation, detection eynman diagra
- early papers: We papers: who move to the amplitude relevant for $\mathcal P$ ch. 1993: Giun
- Phys. Pupon. Rept. Bound, Pryor. 10pm of phose

Rich,1993; Giunti,Kim,Lee,Lee,1993; Grimus,Stockinger,1996; Kiers,Weiss,1998 • review paper: M. Beuthe, Phys. Rept. 375 (2003) 105 [hep-ph/0109119] neutrino, *A* 1+2+¯, and anti-neutrino detection via the process *B* + ¯ 3+4. We have $\frac{1}{2}$

Th. Schwetz - Prague Sept 2024

in mind reactor neutrinos, where the production process corresponds to the beta decay of a

QFT approach to neutrino oscillations Joint process of neutrino production and detection

in mind reactor neutrinos, where the production process corresponds to the beta decay of a

• macroscopic separation of the two vertices • wave packets for external particles 3 Neutrino oscillation amplitude and event rate We now move to the discussion of the amplitude relevant for neutrino oscillation experiments **Consider the neutrino production production production production and detection and detection and detection consider the specific consider the constant of the specific consider the constant of the specific consider the co** neutrino production by the decay of a particle *A* into two final state particles and an anti- $R_{\rm eff}$ Giunti, $R_{\rm eff}$ Grimus, $R_{\rm eff}$ Grimus, $R_{\rm eff}$ (see, 199 review paper: M. Beuthe, Oscillations of Neutrinos and Mesons in Quantum Field Theory,

QFT approach to neutrino oscillations Joint process of neutrino production and detection

Figure 1: Feynman diagram for the total process in an oscillation experim Figure 1: Feynman diagram for the total process in an oscillation experiment.

3 Neutrino oscillation amplitude and event ra reactor exper 3 Neutrino oscillation amplitude and event rate conside tection neutrino production by the decay of a particle A into two final state particles and a neutrino, $A \rightarrow 1 + 2 + \overline{\nu}$, and anti-neutrino detection reactor experiments: P production: $A \rightarrow A' + e^- + \bar{\nu}_e$

Gallium source experiments: \blacktriangleright production: $\overline{\text{Cr}} \rightarrow \overline{\text{V}} + \nu_e$

15 nucleus (A) , and the detection process is the inverse sept 2024 decay reaction on a proton (B) , but We now move to the discussion of the amplitude relevant for neutrino oscillation experiments considerige of oneutrino production, propagation and detection. To be specific, we consider neutrino production by the decay of a particle A into two final state particles and an a neutrino, A^T \rightarrow $1+2+*i*$, and anti-neutrino detection via the process $B + *i*$ \rightarrow $3+4$. We have in mind reactor neutrinos, where the production process corresponds to the beta decay of a in mind reactor neutrinos, where the production process corresponds to the beta decay of a consider production of the neutrino propagation and detection. To be specific, we consider neutrino production by the decay of a particle *A* into two final state particles and an antineutrino, $A \rightarrow 1+2+\bar{\nu}$, and anti-neutrino detection via the process $B+\bar{\nu} \rightarrow 3+4$. We have Insident the university of the uniphrate relation of including the consideration of $\frac{1}{2}$ detection: $\frac{1}{2}$ $\frac{1}{2$ \overrightarrow{A} \overrightarrow{A} \overrightarrow{P} $\overrightarrow{1}$ $\overrightarrow{2}$ \overrightarrow{P} \overrightarrow{r} and anti-neutrino detection via the process $B + \overline{\nu} \rightarrow 3 + 4$. We have

QFT approach to neutrino oscillations \blacksquare

$$
|\phi\rangle = \int d\mathbf{k} \phi(\mathbf{k})|\mathbf{k}\rangle
$$

- coherence properties of oscillation amplitude is determined by localization of external particles and their velocities The Quite and proportions of the control of the set of th perties of os
- · assume Gaussian wave packets in momentum space: È**k**Õ *|***k**Í = 2*E^k* (2*fi*) ³*"*(3) (**k** ≠ **k**^Õ)*,*

⁄ *d*³*k*

$$
\phi(\mathbf{k}) = \left(\frac{2\pi}{\sigma^2}\right)^{3/4} e^{-\frac{(\mathbf{k}-\mathbf{p})^2}{4\sigma^2}}
$$

Th. Schwetz - Prague Sept 2024 \overline{I} h. Schwetz - Prague Sept 2024

": spatial localization, with *‡"* = 1*/*2

The oscillation amplitude

 $\sqrt{ }$

 $U_{\alpha j} U_{\beta j}^*$

 π^2

 $\sigma_{pl}^3 \sigma_{El}$

 $\int d^4p$

 $\frac{d}{(2\pi)^4} i \mathcal{M}$

 exp

j

 \times \prod

˜

P

I=*P,D*

$$
i\tilde{M}_P \frac{\cancel{p}-m_j}{\cancel{p^2-m_j^2+i\epsilon}} i\tilde{M}_D e^{-ip(x_D-x_P)}
$$

$$
-\frac{(\mathbf{p}-\mathbf{p}_I)^2}{4\sigma_{pl}^2} - \frac{(\cancel{p^0}-E_I-\mathbf{v}_I(\mathbf{p}-\mathbf{p}_I))^2}{4\sigma_{El}^2}
$$

kinematic neutrino 4-momenta at production and detection vertices: *p*
pA ≠ *pe*≠ effective momentum and energy spreads for neutrino production and detection processes

 $i\mathcal{A}_{\alpha\beta} \propto$

The oscillation amplitude

 $\sqrt{ }$

 $U_{\alpha j} U_{\beta j}^*$

 $\int d^4p$

 $\frac{d}{(2\pi)^4} i \mathcal{M}$

 exp

j

 \times \prod

˜

P

I=*P,D*

$$
i\tilde{M}_P \frac{\cancel{p}-m_j}{\cancel{p^2-m_j^2+i\epsilon}} i\tilde{M}_D e^{-ip(x_D-x_P)}
$$

$$
-\frac{(\mathbf{p}-\mathbf{p}_I)^2}{4\sigma_{pl}^2} - \frac{(\cancel{p^0-E_I}-\mathbf{v}_I(\mathbf{p}-\mathbf{p}_I))^2}{4\sigma_{El}^2}
$$

• interactions with environment (effect in analogy to collisional line broadening)

generalizations for reactor α gaillum computations. generalizations for reactor & gallium configurations:

 π^2

 $\sigma_{pl}^3 \sigma_{El}$

kinematic neutrino 4-momenta at production and detection vertices: *p*
pA ≠ *pe*≠ effective momentum and energy spreads for neutrino production and detection processes

 $i\mathcal{A}_{\alpha\beta} \propto$

- •finite life-time of decaying particles
-

P perform integral over neutrino momentum $\int d^3p$ taking into account p *F* source and dete macroscopic separation of source and detector: $L = |\mathbf{x}_D - \mathbf{x}_P| \rightarrow \infty$ ˆ **l** $\begin{array}{c} \begin{array}{c} \end{array}$ $p_0^2 - m_j^2$

The oscillation amplitude

$$
i\mathcal{A}_{\alpha\beta} \propto \sum_{j} U_{\alpha j} U_{\beta j}^* \int \frac{d^4 p}{(2\pi)^4} i \tilde{\mathcal{M}}_P \frac{p - m_j}{p^2 - m_j^2 + i\epsilon} i \tilde{\mathcal{M}}_D e^{-ip(x_D - x_P)} \\
\times \prod_{l=P, D} \frac{\pi^2}{\sigma_{pl}^3 \sigma_{El}} \exp\left[-\frac{(\mathbf{p} - \mathbf{p}_l)^2}{4\sigma_{pl}^2} - \frac{(p^0 - E_l - \mathbf{v}_l(\mathbf{p} - \mathbf{p}_l))^2}{4\sigma_{El}^2} \right]
$$

 $Grimus, Stockinger, 1996 \rightarrow neutrinos go onshell$ $\mathbf{p}_j =$

neutrino production

The oscillation amplitude *iA–—* Ã tio *u*
u am δ (2*fi*)⁴ *ⁱ^M*

$$
i\mathcal{A}_{\alpha\beta} \propto \sum_{j} U_{\alpha j} U_{\beta j}^* \int \frac{d^4 p}{(2\pi)^4} i \tilde{\mathcal{M}}_P \frac{p - m_j}{p^2 - m_j^2 + i\epsilon} i \tilde{\mathcal{M}}_D e^{-ip(x_D - x_P)} \\
\times \prod_{l=P, D} \frac{\pi^2}{\sigma_{pl}^3 \sigma_{El}} \exp\left[-\frac{(\mathbf{p} - \mathbf{p}_l)^2}{4\sigma_{pl}^2} - \frac{(p^0 - E_l - \mathbf{v}_l(\mathbf{p} - \mathbf{p}_l))^2}{4\sigma_{El}^2} \right]
$$

- *p*^{*P*} = *p*^{*e*}≠ *p*² ≠ *p*² ≠ *p*² ≠ *p*² ≠ *p*² *p***d** = $\frac{1}{2}$ + *p***e**+ $\frac{1}{2}$ + $\frac{1}{2}$ + neutrino production
- E_{R} *Portors* the integral over the position energy $\int d\mathbf{r}$ *xP, x^D* space-time coordinates of neutrino production and detection **I** perform the integral over the neutrino energy $\int dp_0$

I square the amplitude and perform a time average due to unobserved time of

…after some algebra: ... after some algebra:

standard oscillation phase Standard Oscillation

localization decoherence ξ_{loc} izati 2*E*⁰ È herence $\varepsilon_{\rm loc}$

energy decoherence $\xi_{\rm en}$ ner \overline{a} ≠1 2 $\overline{\mathcal{A}}$ *m*2*L‡*en 2*E*² 0 Δr ICC ζ_{en}

$$
\frac{|\mathcal{A}_{\alpha\beta}|^2}{|\mathcal{A}_{\alpha\beta}|^2} \propto \exp\left[i\frac{\Delta m^2 L}{2E_0}\right]
$$

$$
\times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_0\sigma_m}\right)^2\right]
$$

$$
\times \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L \sigma_{\text{en}}}{2E_0^2}\right)^2\right]
$$

$\boldsymbol{\omega}_m$, $\boldsymbol{\omega}_{\text{er}}$ $a¹$ particle $\frac{1}{2}$ are calculable from *σm*, *σ*en localization properties of initial and final state particles

m

I=*P,D*

pI

EI B

en

I=*P,D*

*I,*e

• energy/momentum uncertainty be large enough that individual mass states cannot production and detection regions have to be localised much better than certainty be large enough that individual mass st
2 *D* T approach to neutrino oscillations The decoherence terms The dec

• production/detection regions be localized better than oscillation length: $\delta_{\text{loc}} \ll L_{\text{osc}}$

• Localization decoherence:

- be identified: $\sigma_m \gg \Delta m^2/E_\nu$ energy-momentum uncertainty has to be large enough, such that individual mass states cannot be resolved: *‡^m* [∫] *m*2*/E‹*
	-

$$
\xi_{\rm loc} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_{\nu}\sigma_m}\right)^2\right] = \exp\left[-2\pi^2\left(\frac{\delta_{\rm loc}}{L_{\rm osc}}\right)^2\right] \quad \text{with} \quad \sigma_m\delta_{\rm loc} = \frac{1}{2}
$$

I this term can be interpreted as decoherence due to neutrino wave

• Localization decoherence:

² *, ^L*osc ⁼ ²*fi* $\xi_{en} = exp$ $\overline{}$ $\frac{1}{2}$

- energy/momentum uncertainty be large enough that individual mass states cannot be identified: $\sigma_m \gg \Delta m^2/E_\nu$ energy-momentum uncertainty has to be large enough, such that individual mass states cannot be resolved: *‡^m* [∫] *m*2*/E‹*
	-
	- Energy decoherence: [≠]2*fi*² *^L*osc ⁴²

production and detection regions have to be localised much better than certainty be large enough that individual mass st
2 *D* T approach to neutrino oscillations The decoherence terms The dec

• production/detection regions be localized better than oscillation length: $\delta_{\text{loc}} \ll L_{\text{osc}}$

- the oscillation length: *"*loc ^π *^L*osc (note *"*²
	-

$$
\xi_{\rm loc} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2}{4E_{\nu}\sigma_m}\right)^2\right] = \exp\left[-2\pi^2\left(\frac{\delta_{\rm loc}}{L_{\rm osc}}\right)^2\right] \quad \text{with} \quad \sigma_m\delta_{\rm loc} = \frac{1}{2}
$$

\n- the neutrino energy needs to be well defined
$$
\sigma_{\text{en}} \ll E_{\nu}
$$
\n- can be interpreted as neutrino wave packet separation $(v_j \approx 1 - m_j^2 / 2E_{\nu}^2)$
\n

• Energy decoherence:
$$
\xi_{en} = \exp\left[-\frac{1}{2}\left(\frac{\Delta m^2 L \sigma_{en}}{2E_{\nu}^2}\right)^2\right] = \exp\left[-2\pi^2 \left(\frac{L}{L_{osc}}\frac{\sigma_{en}}{E_{\nu}}\right)^2\right]
$$

I this term can be interpreted as decoherence due to neutrino wave

- indistinguishable phenomenologically Kiers, Nussinov, Weiss, 1996; Stodolsky, 1998; Ohlsson, 2001
-
- the quantum level

• Classical averaging of $|\mathcal{A}|^2$ over space and energy has the same effect as intrinsic QM decoherence: \mathcal{A} 2

• quantum mechanical uncertainties provide a fundamental lower bound on the uncertainty

• to observe QM decoherence, classical averaging effects have to be suppressed down to

$$
\delta_{loc}^2 \rightarrow \delta_{loc}^2 + \delta_{clas}^2, \quad \sigma_{en}^2 \rightarrow \sigma_{en}^2 + \sigma_{clas}^2
$$

 $P \propto$ ⁄
∕∕∕ *dx |A*(*x*)*|*

Classical averaging Classical averaging *› <* 1 due to averaging of the probability:

$$
2, \quad x = L, E
$$

- classical averaging due to experimental reasons: size of production region, finite detector resolutions (in space and energy),...
- •fundamental averaging effects due to experimental configuration and physics principles: • phase space integrals of unobserved particles:
	- reactor experiments: momenta of outgoing particles in the source, neutron in the detector gallium: momenta of all outgoing particles (counting experiment)
	- gallium experiments: Doppler broadening of the decay line from $\mathrm{Cr} \rightarrow \mathrm{V} + \nu_e$ due to thermal motion of source particles

Classical averaging

- nuclei localization: inter-atomic distances in cristal lattice or fluid
- velocities: either thermal velocities or velocities for typical kin. energies of outgoing particles
- electron/positron localization: distance the particle travels until it deposits one mean excitation energy (integrating ⟨*dE*/*dx*⟩ Bethe equation)

Numerical estimates for gallium and reactors Particle localizations and velocities R. Krüger, TS, 2303.15524

Th. Schwetz - Prague Sept 2024 Th. Schwetz - Prague Sept 2024

s. also Akhmedov, Smirnov, 2208.03736

Numerical estimates for gallium and reactors R. Krüger, TS, 2303.15524 1 A

•localization decoherence: ref $^{\circ}$ *I*=*P,D*

for reactor and gallium experiments dominated by hadronic particles

 \Rightarrow QM localization decoherence irrelevant for all practical purposes: $\xi_{\text{loc}} = 1$ Note: classical spatial averaging is relevant and needs to be taken into account

$$
\sigma_m \simeq (400 - 500) \,\text{eV} \,, \qquad \delta_{\text{loc}} = \frac{1}{2\sigma_m} \simeq 0.2 \,\text{nm}
$$
\n
$$
-\ln \xi_{\text{loc}} = \frac{1}{2} \left(\frac{\Delta m^2}{4E_\nu \sigma_m}\right)^2 \approx 1.3 \times 10^{-19} \left(\frac{\Delta m^2}{1 \,\text{eV}^2}\right)^2 \left(\frac{1 \,\text{MeV}}{E_\nu}\right)^2 \left(\frac{500 \,\text{eV}}{\sigma_m}\right)^2
$$

Numerical estimates for gallium and reactors R. Krüger, TS, 2303.15524 *‡*en © S. IGAI stimates f ∠a *m*
Dina masa sa mananganakan dina masa sama dina akan dina masa akan dina masa akan dina akan dan ama

• energy decoherence: \overline{P}

1

T ≠1*/*2

R. Krüger, TS, 2303.15524

 $\sigma_{\rm en} \approx 0.5 \,\text{eV}$, $\delta_{\rm en} \approx 200 \,\text{nm}$

 \Rightarrow QM energy decoherence ("wave packet separation") irrelevant for all practical

including phase space integration and Doppler broadening:

$$
-\ln \xi_{\rm en} = 2\pi^2 \left(\frac{L}{L_{\rm osc}}\frac{\sigma_{\rm en}}{E_\nu}\right)^2 \approx 4.9\times 10^{-12}~\left(\frac{L}{L_{\rm osc}}\right)^2 \left(\frac{1~{\rm MeV}}{E_\nu}\right)^2 \left(\frac{\sigma_{\rm en}}{0.5~{\rm eV}}\right)^2
$$

purposes: $\xi_{en} = 1$

Note: classical energy averaging is relevant and needs to be taken into account

Summary energy decoherence R. Krüger, TS, 2303.15524

• our result: $\sigma_{\rm en} \approx 0.5 \,\text{eV}$, $\delta_{\rm en} \approx 200 \,\text{nm}$

• energy resolution of typical reactor neutrino detectors:

 $(0.03 - 0.06) \,\text{MeV} \sqrt{E/\text{MeV}}$ =

about 6 orders of magnitude larger than $\sigma_{\rm en}$!

• QM decoherence negligible — dominated by classical averaging (holds also for JUNO)

• phenomenological constraint is dominated by classical energy resolution:

s. also Akhmedov, Smirnov, 2208.03736

$$
\Rightarrow \quad \sigma_{\text{clas}} \simeq 0.1 \text{ MeV}
$$

 σ < 0.47 MeV, δ > 2.1 \times 10^{-4} nm [Gouvea, Romeri, Ternes, 2005.03022, 2104.05806]

Barenboim, Mavromatos, Sarkar, Waldron-Lauda, 2006 Fogli, Lisi, Marrone, Montanino, Palazzo, 2007 Farzan, TS, Smirnov, 2008; Bakhti, Farzan, TS, 2015 Guzzo, de Holanda, Oliveira, 2014 Hellmann, Pas, Rani, 2022 Banks, Kelly, McCullough, 2023

…

Any decoherence effect on top of classical averaging will point towards new physics!

Decoherence explanation of the gallium anomaly Y. Farzan, TS, 2306.09422 $e^{\int f(t) \cdot \phi(t)}$ or $e^{\int f(t) \cdot \phi(t)}$ and $e^{\int f(t)}$ should be simple be simple beginning to $f(t)$ \overline{a} oherence explanation of the gallium anomaly **x.** Fa arzan, TS, 2306.09422

 \bullet three SM neutrinos (no steriles) • modified QM evolution: write the Hamiltonian and the *D* matrix in the neutrino mass basis as $\overline{}$ From $H = \frac{1}{2} m^2 m^2 m^2$. With $H = \frac{1}{2} m^2 m^2 m^2$.

Th. Schwetz - Prague Sept 2024

 ^d^ρ dt $i[\rho, H] - {\rho, D^2} + 2D\rho D$ $\sqrt{2}$ 2*E*⌫ $+2D\rho D$

$$
H = \frac{1}{2E_{\nu}} \text{diag}(m_1^2, m_2^2, m_3^2),
$$

 $D = diag(d_1, d_2, d_3)$,

Decoherence explanation of the gallium anomaly Y. Farzan, TS, 2306.09422 $e^{\int f(t) \cdot \phi(t)}$ or $e^{\int f(t) \cdot \phi(t)}$ and $e^{\int f(t)}$ should be simple be simple beginning to $f(t)$ \overline{a} oherence explanation of the gallium anomaly **x.** Fa arzan, TS, 2306.09422

 \bullet three SM neutrinos (no steriles) • modified QM evolution: write the Hamiltonian and the *D* matrix in the neutrino mass basis as $\overline{}$ From $H = \frac{1}{2} m^2 m^2 m^2$. With $H = \frac{1}{2} m^2 m^2 m^2$. ● three SM neutrinos (no steriles) • modified QM evolution: $\frac{1}{\pi}$ and $\frac{2}{\pi}$ and $\frac{2}{\pi}$

 ^d^ρ dt $i[\rho, H] - {\rho, D^2} + 2D\rho D$ • damping of interference terms: $\sqrt{2}$ 2*E*⌫ $+2D\rho L$ $\{ \rho, D^2 \}$ + 2 **• damping of interference terms:** m_{1} are $\{ \rho, D^{2} \} + 2D\rho D$ and $D = \text{diag}(d_{1}, d_{2}, d_{3})$, α mass. The decoherence terms lead to exponential damping of the o 4 diagonal elements of the o 4 the density matrix, $\frac{1}{2}$, with a rate set $\frac{1}{2}$, with a rate set $\frac{1}{2}$

• modified QM evolution:
$$
H = \frac{1}{2E_{\nu}} \text{diag}(m_1^2, m_2^2, m_3^2),
$$

$$
\rho \boldsymbol{D}
$$

$$
D \rho D \qquad \qquad D = \text{diag}(d_1, d_2, d_3) \,,
$$

$$
P_{ee} = \sum_{i=1}^{3} |U_{ei}|^4 + \sum_{i \neq j} |U_{ei}|^2 |U_{ej}|
$$

*m*²

$$
\gamma_{ij}=(d_i-d_j)^2
$$

Th. Schwetz - Prague Sept 2024 **Schwetz - Prague Sept 2024**
 1898 *P*^e = X^ee = Xee = X

|Uei| $4 + \sum$ $i \neq j$ *|Uei|* 2 $|U_{ej}|$ $\left\{e^{-\gamma_{ij}L}\right\}e^{-i\phi_{ij}}$

phenomenological ansatz:

is close to the dominant neutrino energies from a Cr source.

 $\gamma_{ii} = -$ 1 E_r $\sqrt{2}$ *.* (6) Deviations from the standard oscillation formula are controlled by the decoherence param-1 *λij* (*E*ref *E^ν*) −*r*

|Uei| $4 + \sum$ $i \neq j$ *|Uei|* 2 $|U_{ej}|$ $\left\{e^{-\gamma_{ij}L}\right\}e^{-i\phi_{ij}}$

phenomenological ansatz:

- \bullet $r \neq 1$ violates Lorentz invariance $r \neq 1$ $\tau \neq 1$ violates Lorentz invariance.
-
- $\bullet r = -2$: quantum gravity models $r = -2$ $\cdot = -2$: qu
- $\bullet r = -1$: cross section like behaviour $r = -1$
- $\bullet r = 2$: light cone fluctuations $r = 2$
- \bullet $r = 1$: phenomenologically similar to invisible neutrino decay $r = 1$: phenomenologically similar to invisible neutrino decay

 $\gamma_{ii} = -$ 1 E_r $\sqrt{2}$ *.* (6) Deviations from the standard oscillation formula are controlled by the decoherence param-1 *λij* (*E*ref *E^ν*) −*r*

\bullet localization and energy decoherence $r=$ 2 or 4, but have different L dependence $(L^0$ or $L^2)$ $r=2$ or 4, but have different L dependence $(L^0$ or L^2 ocalization and energy decoherence $r=$ 2 or 4, but have different L dependence (L^0 or L^2)

is close to the dominant neutrino energies from a Cr source.

best fit points, the 2 to the 2 to the 2 to the number of two-sided Gaussian standard deviations when the number of
The number of two-sided Gaussian standard deviations when the number of two-sided Gaussian standard deviat

Decoherence explanation of the gallium anomaly Y. Farzan, TS, 2306.09422

for ¹³ is in all cases at 0.04 m, which corresponds to the lower boundary of the considered range.

best fit points, the 2 to the 2 to the 2 to the number of two-sided Gaussian standard deviations when the number of
The number of two-sided Gaussian standard deviations when the number of two-sided Gaussian standard deviat

A ₁₂ = 1.44 m, λ_{13} = 0.04 r						
A ₁₂ = 1.44 m, λ_{13} = 0.04 r						
BEST						
$\frac{\chi_{min}^2/dof}{2.2/1}$	0.14	32.5	5.4	1.44	$BEST$ (inner)	
all	$9.2/5$	0.10	29.2	5.0	1.74	$SAGE$ (Ar)
SAGE	SAGE					

$$
P_{ee}^{\text{gal}} \approx 1 - \frac{1}{2} \sin^2 2\theta_{13} - \frac{1}{2} \cos^4 \theta_{13} \sin^2 2\theta_{12} (1 - e^2)
$$

Decoherence explanation of the gallium anomaly Y. Farzan, TS, 2306.09422

33 Th. Schwetz - Prague Sept 2024 for ¹³ is in all cases at 0.04 m, which corresponds to the lower boundary of the considered range. τ sponding to the last term in eq. (111, SCIIWEL - FIGULE SEPT ZUZ4 $\overline{111}$

Consistency with other oscillation data

34 Th. Schwetz - Prague Sept 2024 Figure 3: Comparison of relevant length scales at di↵erent neutrino energies. Lines in black show the

Consistency with other oscillation data

^ν , *r* ≳ 10 − 12

- solar and reactor neutrinos require steep energy dependence of decoherence effects: *γ* ∝ *E*−*^r*
	- ⇒ other oscillation evidences not affected

- solar and reactor neutrinos require steep energy dependence of decoherence effects: *γ* ∝ *E*−*^r ^ν* , *r* ≳ 10 − 12
	- ⇒ other oscillation evidences not affected
- predict distance dependence in gallium exps. (still compatible with BEST) slightly modified MSW transition region in $P_{\rho\rho}(E_{\nu})$ for solar neutrinos

- solar and reactor neutrinos require steep energy dependence of decoherence effects: *γ* ∝ *E*−*^r ^ν* , *r* ≳ 10 − 12
	- ⇒ other oscillation evidences not affected
- predict distance dependence in gallium exps. (still compatible with BEST) slightly modified MSW transition region in $P_{\rho\rho}(E_i)$ for solar neutrinos
- no effect predicted in MiniBooNE or SBL reactors

- solar and reactor neutrinos require steep energy dependence of decoherence effects: ⇒ other oscillation evidences not affected *γ* ∝ *E*−*^r ^ν* , *r* ≳ 10 − 12
- predict distance dependence in gallium exps. (still compatible with BEST) slightly modified MSW transition region in $P_{\rho\rho}(E_i)$ for solar neutrinos
- no effect predicted in MiniBooNE or SBL reactors
- expect standard three-neutrino neutrino cosmology

Bakhti, Farzan, TS [1503.05374] assume Gaussian energy $10⁷$ dependence:

Can be combined with decoherence explanation of LSND

$$
d_1 \approx 0
$$

\n
$$
d_{2,3} = \frac{1}{\sqrt{\lambda_i}} \exp\left[-\frac{(E_{\nu} - E_i)^2}{2(0.1E_i)^2}\right] \quad \stackrel{\text{10}^3}{=} \quad \frac{10^3}{4} \quad \frac{1}{10^1}.
$$

 $\lambda_2 = 2$ m, $E_2 = 0.75$ MeV

 $\lambda_3 = 300 \text{ m}, E_3 = 35 \text{ MeV}$

 $\gamma_{ij} = (d_i - d_j)^2$

 10^{-1}

 10^{-3}

- BEST results make gallium anomaly highly significant difficult to explain without being in conflict with other data
- QFT framework to study decoherence effects standard QM localization/wave packet effects are negligible
- presented an explanation in terms of new-physics decoherence, with an LSND explanation

consistent with oscillation data, cosmology, and potentially compatible

≈ 5*σ*

Summary

- BEST results make gallium anomaly highly significant difficult to explain without being in conflict with other data
- QFT framework to study decoherence effects standard QM localization/wave packet effects are negligible
- presented an explanation in terms of new-physics decoherence, with an LSND explanation

consistent with oscillation data, cosmology, and potentially compatible

≈ 5*σ*

Summary

Than^k you for your attention

Backup

Single vertex case Single vertex case

transition probability $i \rightarrow f$:

 $P_{if} = |\langle \phi_f | i \rangle$

$$
T|\phi_i\rangle|^2 \equiv |iA|^2
$$

definition of the matrix element for momentum states:

$$
\left(\prod_f \langle \mathbf{k}_f | \right) i \mathcal{T} \left(\prod_i |\mathbf{k}_i\rangle \right) = (2\pi)^4 \delta^{(4)} \left(\sum_f k_f - \sum_i k_i\right) i \mathcal{M},
$$

transition amplitude:

$$
i\mathcal{A} = \prod_f \int d\tilde{\mathbf{k}}_f \phi_f^*(\mathbf{k}_f) \prod_i \int d\tilde{\mathbf{k}}_i \phi_i(\mathbf{k}_i) (2\pi)^4 \delta^{(4)} \left(\sum_f k_f - \sum_i k_i \right) i\mathcal{M}
$$

Single vertex case Single vertex case

transition probability $i \rightarrow f$:

 $P_{if} = |\langle \phi_f | i \rangle$

$$
T|\phi_i\rangle|^2 \equiv |iA|^2
$$

definition of the matrix element for momentum states:

$$
\left(\prod_f \langle \mathbf{k}_f | \right) i \mathcal{T} \left(\prod_i |\mathbf{k}_i\rangle \right) = (2\pi)^4 \delta^{(4)} \left(\sum_f k_f - \sum_i k_i\right) i \mathcal{M},
$$

transition amplitude:

$$
i\mathcal{A} = \prod_{f} \int d\tilde{\mathbf{k}}_{f} \phi_{f}^{*}(\mathbf{k}_{f}) \prod_{i} \int d\tilde{\mathbf{k}}_{i} \phi_{i}(\mathbf{k}_{i}) (2\pi)^{4} \delta^{(4)} \left(\sum_{f} k_{f} - \sum_{i} k_{i} \right) i\mathcal{M}
$$

=
$$
\int d^{4}x \prod_{f} \int d\tilde{\mathbf{k}}_{f} \phi_{f}^{*}(\mathbf{k}_{f}) e^{ik_{f}x} \prod_{i} \int d\tilde{\mathbf{k}}_{i} \phi_{i}(\mathbf{k}_{i}) e^{-ik_{i}x} i\mathcal{M}
$$

Single vertex case Single vertex case for f and f and f

$$
iA \propto iM \frac{\pi^2}{\sigma_p^3 \sigma_e} \exp \left[
$$

$$
-\frac{(\Delta p)^2}{4\sigma_p^2} - \frac{(\Delta E - \Delta p v)^2}{4\sigma_e^2}
$$

with $\Delta p \equiv \sum$ *i* $\mathbf{p}_i - \sum$ *f*

and effective momentum and energy spreads:

$$
\mathbf{p}_f, \qquad \Delta E \equiv \sum_i E_{p_i} - \sum_f E_{p_f}
$$

$$
\sigma_{p}^{2} \equiv \sum_{i,f} \sigma_{i,f}^{2}, \qquad \sigma_{e}^{2}
$$

$$
\sigma_e^2 \equiv \sigma_p^2(\Sigma - \mathbf{v}^2)
$$

and a weighted velocity and velocity-squared:

$$
\mathbf{v} \equiv \frac{1}{\sigma_p^2} \sum_{i,f} \sigma_{i,f}^2 \mathbf{v}_{i,f}, \qquad \Sigma \equiv \frac{1}{\sigma_p^2} \sum_{i,f} \sigma_{i,f}^2 \mathbf{v}_{i,f}^2, \qquad \mathbf{v_i} \equiv \left. \frac{\partial E_i}{\partial \mathbf{k}_i} \right|_{\mathbf{k}_i = \mathbf{p}_i}
$$