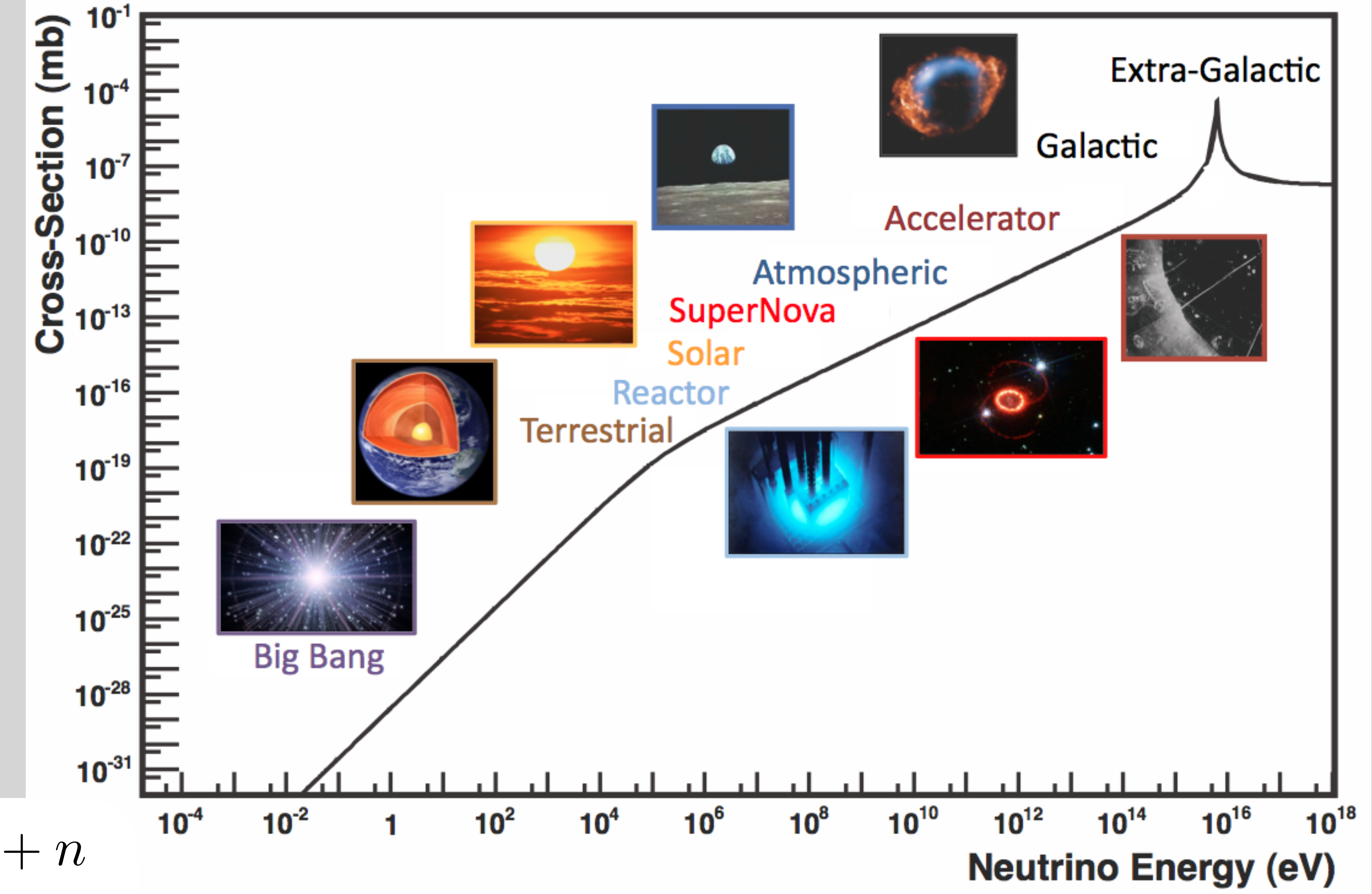
Coherent neutrino-nucleus scattering at SNS: Particle physics

Louis E. Strigari
Texas A&M University

Neutrino cross sections



$$\bar{\nu}_e + p \rightarrow e^+ + n$$

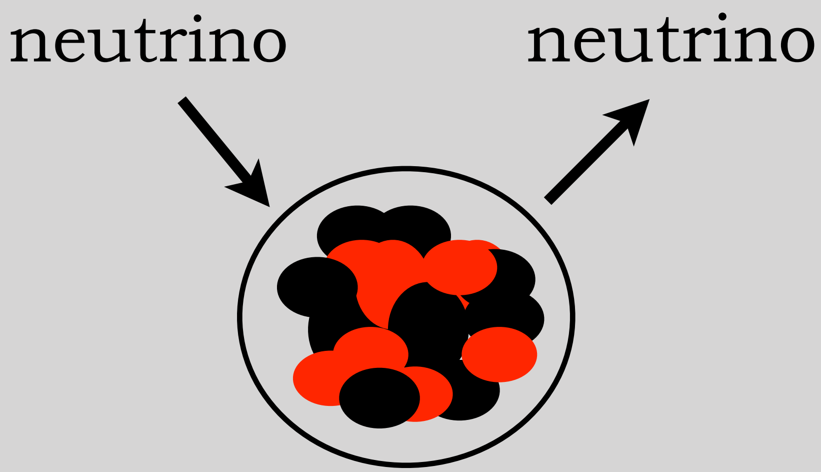
$$\nu_e + {}^{37}\mathrm{Cl} \longrightarrow {}^{37}\mathrm{Ar} + e^-$$

$${}^{37}\mathrm{Ar} + e^- \longrightarrow {}^{37}\mathrm{Cl}^* + \nu_e$$

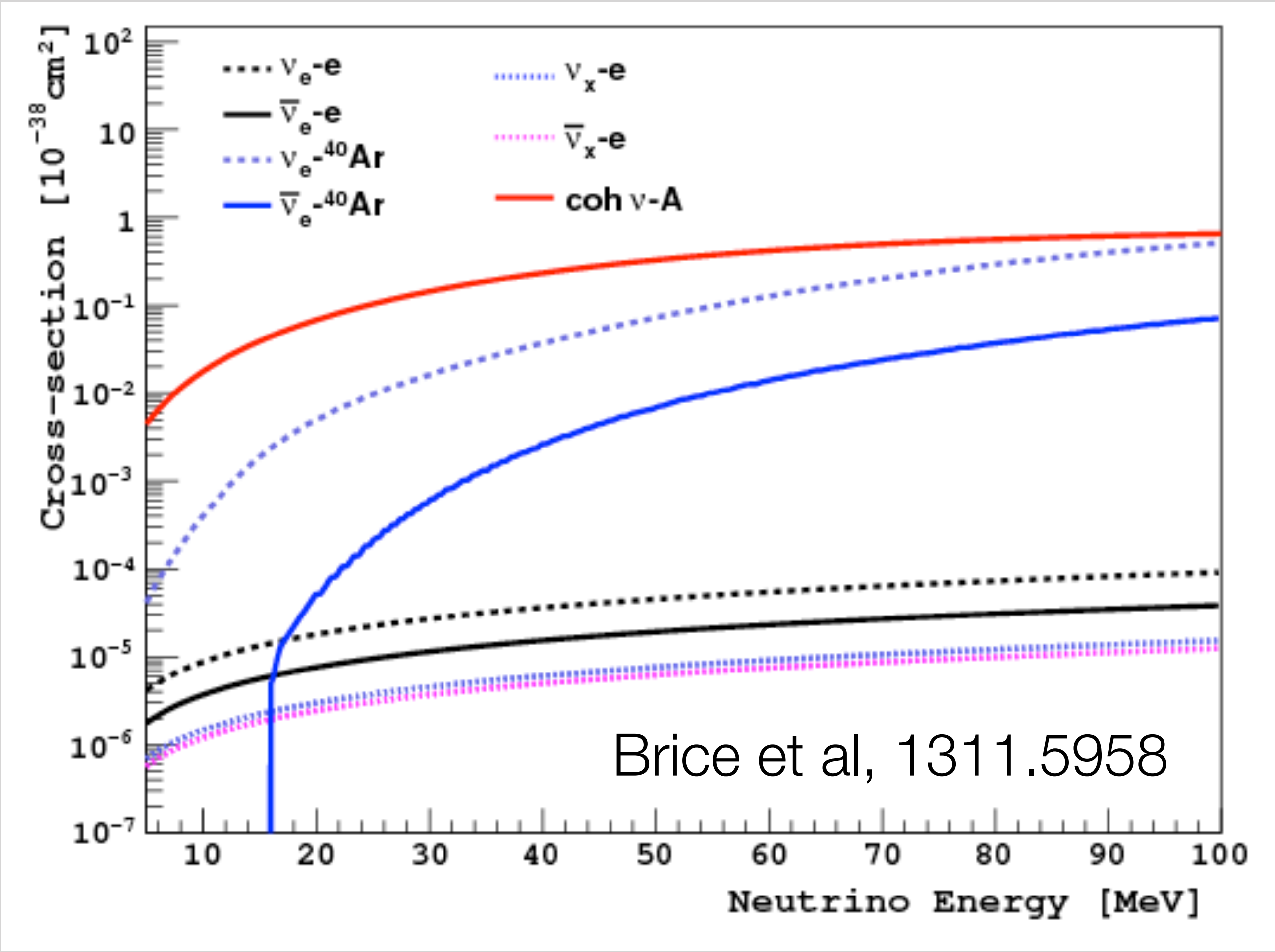
$$\nu + e^- \rightarrow \nu + e^-$$

Formaggio & Zeller 2012

Coherent neutrino-nucleus scattering (CEνNS)



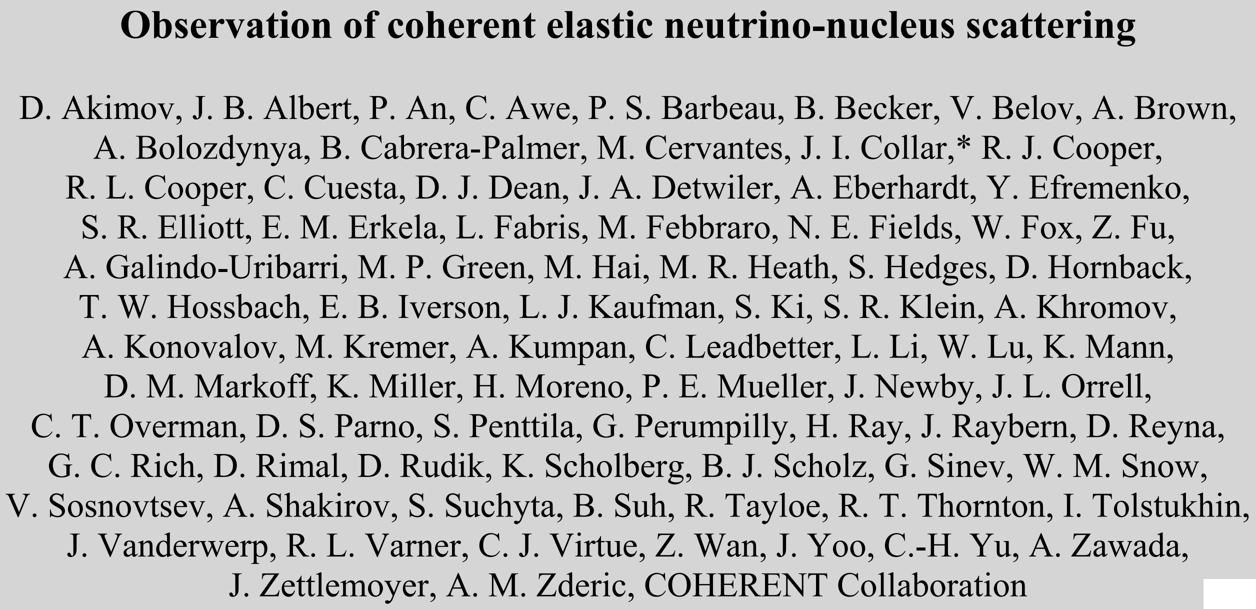
- Neutral current interaction; Total scattering amplitude sum of that on constituent nucleons
- Small momentum transfer wrt to the target size implies coherent enhancement
- Due to Standard Model couplings coherent enhancement due to neutrons
- Low energy recoil distribution implies difficult to detect



Brice et al, 1311.5958

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m}{2\pi}\left((g_v+g_a)^2 + (g_v-g_a)^2\left(1-\frac{E_R}{E_\nu}\right)^2 + (g_a^2-g_v^2)\frac{mE_R}{E_\nu^2}\right)$$

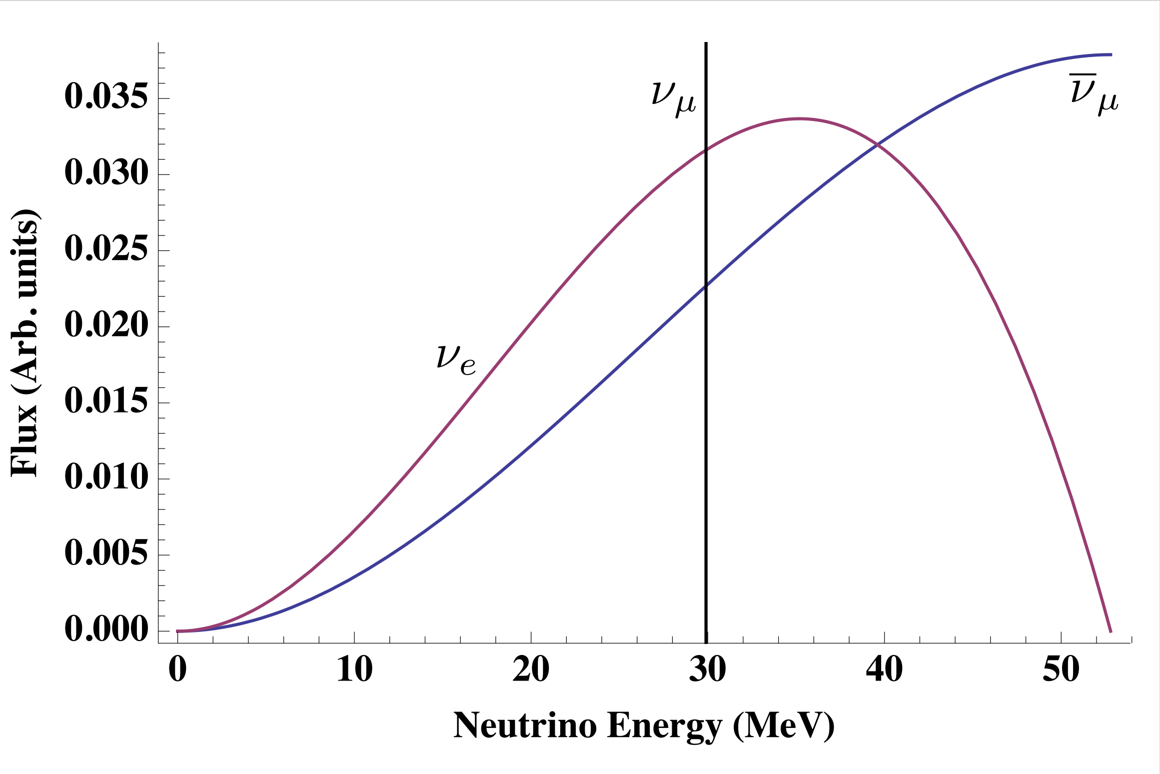
COHERENT



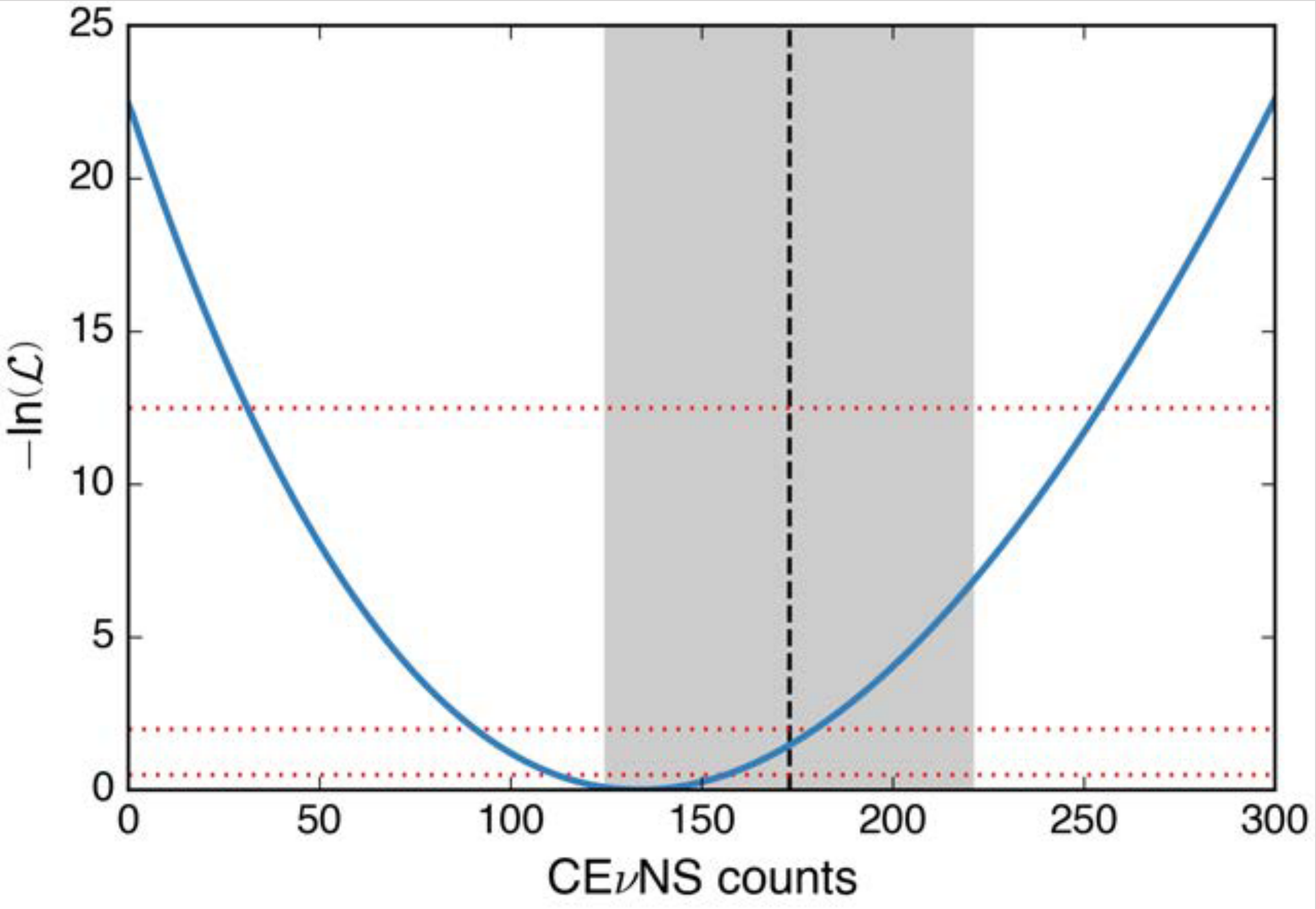
Observation of coherent elastic neutrino-nucleus scattering

D. Akimov, J. B. Albert, P. An, C. Awe, P. S. Barbeau, B. Becker, V. Belov, A. Brown,
A. Bolozdynya, B. Cabrera-Palmer, M. Cervantes, J. I. Collar,* R. J. Cooper,
R. L. Cooper, C. Cuesta, D. J. Dean, J. A. Detwiler, A. Eberhardt, Y. Efremenko,
S. R. Elliott, E. M. Erkela, L. Fabris, M. Febbraro, N. E. Fields, W. Fox, Z. Fu,
A. Galindo-Uribarri, M. P. Green, M. Hai, M. R. Heath, S. Hedges, D. Hornback,
T. W. Hossbach, E. B. Iverson, L. J. Kaufman, S. Ki, S. R. Klein, A. Khromov,
A. Konovalov, M. Kremer, A. Kumpan, C. Leadbetter, L. Li, W. Lu, K. Mann,
D. M. Markoff, K. Miller, H. Moreno, P. E. Mueller, J. Newby, J. L. Orrell,
C. T. Overman, D. S. Parno, S. Penttila, G. Perumpilly, H. Ray, J. Raybern, D. Reyna,
G. C. Rich, D. Rimal, D. Rudik, K. Scholberg, B. J. Scholz, G. Sinev, W. M. Snow,
V. Sosnovtsev, A. Shakirov, S. Suchyta, B. Suh, R. Tayloe, R. T. Thornton, I. Tolstukhin,
J. Vanderwerp, R. L. Varner, C. J. Virtue, Z. Wan, J. Yoo, C.-H. Yu, A. Zawada,
J. Zettlemoyer, A. M. Zderic, COHERENT Collaboration

Spallation Neutron Source



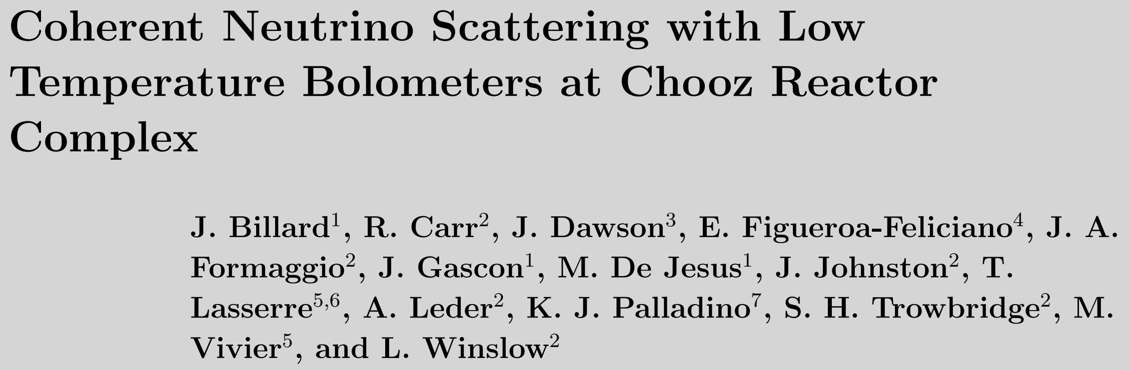
Anderson et al., 1201.3805



CEnuNS at Reactors

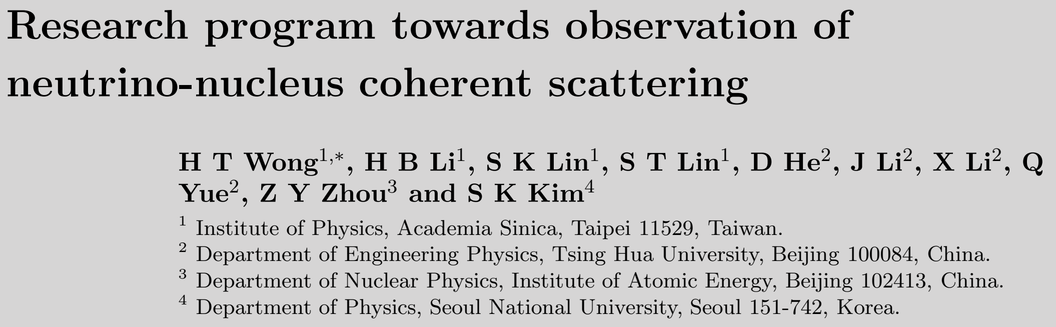
The CONNIE experiment

A. Aguilar-Arevalo[1], X. Bertou[2], C. Bonifazi[3], M. Butner[4],
G. Cancelo[4], A. Castaneda Vazquez[1], B. Cervantes Vergara[1],
C.R. Chavez[5], H. Da Motta[6], J.C. D'Olivo[1], J. Dos Anjos[6],
J. Estrada[4], G. Fernandez Moroni[7,8], R. Ford[4], A. Foguel[3,6],
K.P. Hernandez Torres[1], F. Izraelevitch[4], A. Kavner[9],
B. Kilminster[10], K. Kuk[4], H.P. Lima Jr.[6], M. Makler[6], J. Molina[5],
G. Moreno-Granados[1], J.M. Moro[11], E.E. Paolini[7,12], M. Sofo Haro[2],
J. Tiffenberg[4], F. Trillaud[1], and S. Wagner[6,13]



Coherent Neutrino Scattering with Low Temperature Bolometers at Chooz Reactor Complex

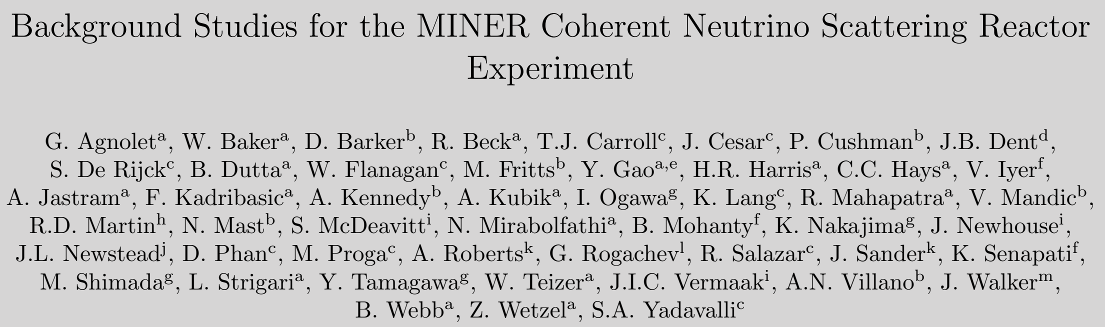
J. Billard[1], R. Carr[2], J. Dawson[3], E. Figueroa-Feliciano[4], J. A. Formaggio[2], J. Gascon[1], M. De Jesus[1], J. Johnston[2], T. Lasserre[5,6], A. Leder[2], K. J. Palladino[7], S. H. Trowbridge[2], M. Vivier[5], and L. Winslow[2]



Research program towards observation of neutrino-nucleus coherent scattering

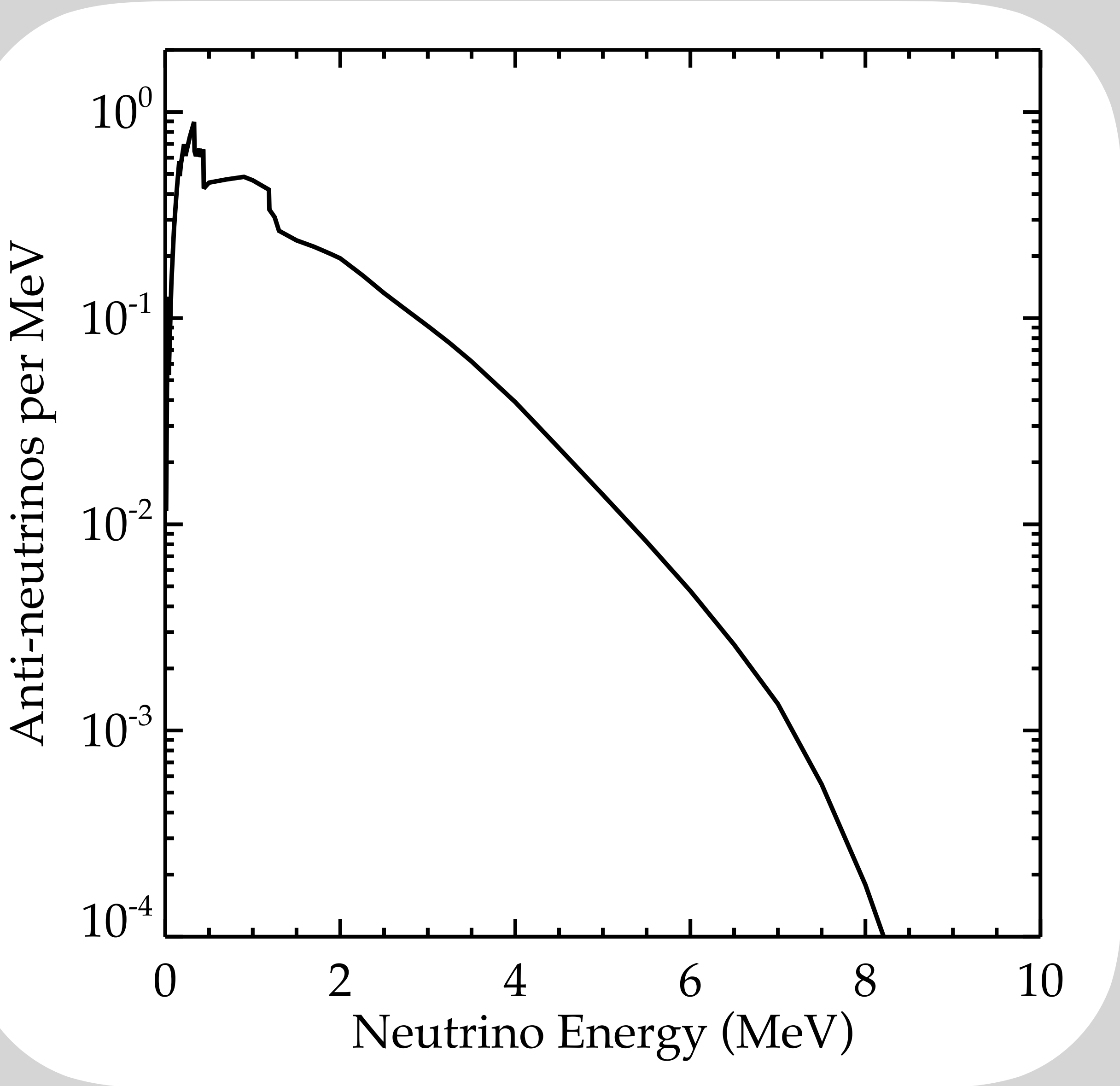
H T Wong[1,*], H B Li[1], S K Lin[1], S T Lin[1], D He[2], J Li[2], X Li[2], Q Yue[2], Z Y Zhou[3] and S K Kim[4]

[1] Institute of Physics, Academia Sinica, Taipei 11529, Taiwan.
[2] Department of Engineering Physics, Tsing Hua University, Beijing 100084, China.
[3] Department of Nuclear Physics, Institute of Atomic Energy, Beijing 102413, China.
[4] Department of Physics, Seoul National University, Seoul 151-742, Korea.



Background Studies for the MINER Coherent Neutrino Scattering Reactor Experiment

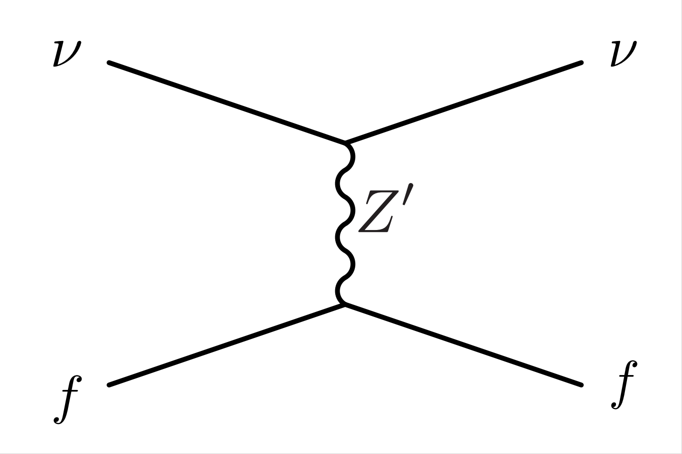
G. Agnolet[a], W. Baker[a], D. Barker[b], R. Beck[a], T.J. Carroll[c], J. Cesar[c], P. Cushman[b], J.B. Dent[d],
S. De Rijck[c], B. Dutta[a], W. Flanagan[c], M. Fritts[b], Y. Gao[a,e], H.R. Harris[a], C.C. Hays[a], V. Iyer[f],
A. Jastram[a], F. Kadribasic[a], A. Kennedy[b], A. Kubik[a], I. Ogawa[g], K. Lang[c], R. Mahapatra[a], V. Mandic[b],
R.D. Martin[h], N. Mast[b], S. McDeavitt[i], N. Mirabolfathi[a], B. Mohanty[f], K. Nakajima[g], J. Newhouse[i],
J.L. Newstead[j], D. Phan[c], M. Proga[c], A. Roberts[k], G. Rogachev[l], R. Salazar[c], J. Sander[k], K. Senapati[f],
M. Shimada[g], L. Strigari[a], Y. Tamagawa[g], W. Teizer[a], J.I.C. Vermaak[i], A.N. Villano[b], J. Walker[m],
B. Webb[a], Z. Wetzel[a], S.A. Yadavalli[c]



New physics searches

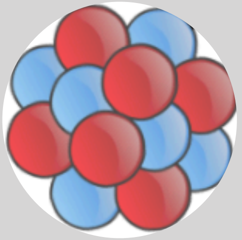
Non-standard/generalized interactions

Scholberg 2005; Barranco 2005; Coloma et al. 2018;
Liao & Marfatia 2017; Aristizabal-Sierra et al. 2018



$$\mathcal{L}_{int} = 2\sqrt{2}G_F\bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L}\left(\epsilon^{fL}_{\alpha\beta}\bar{f}_L\gamma_{\mu}f_L + \epsilon^{fR}_{\alpha\beta}\bar{f}_R\gamma_{\mu}f_R\right)$$

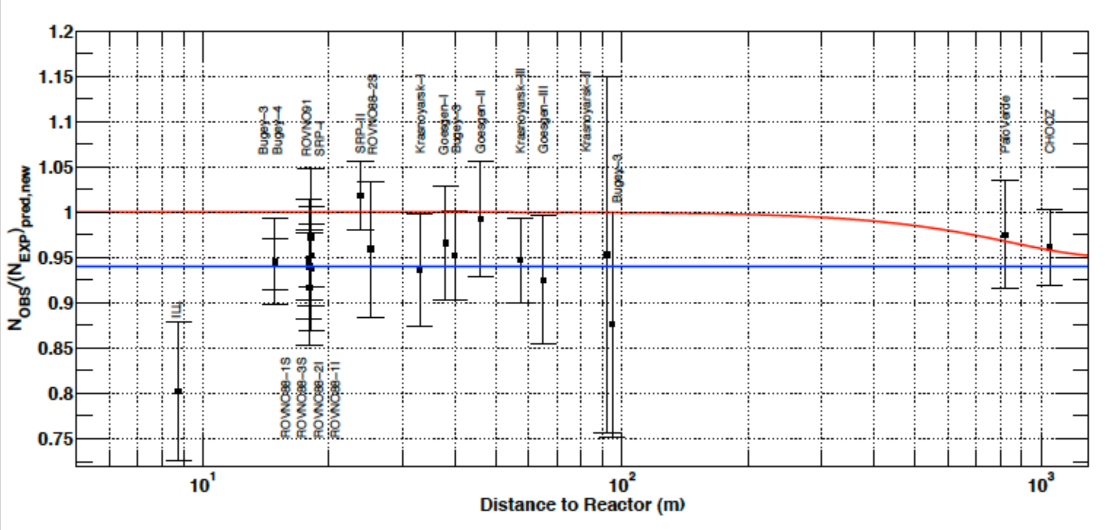
Patton et al. 2013; Cadeddu et al. 2018;
Ciuffoli et al. 2018



Sterile neutrinos

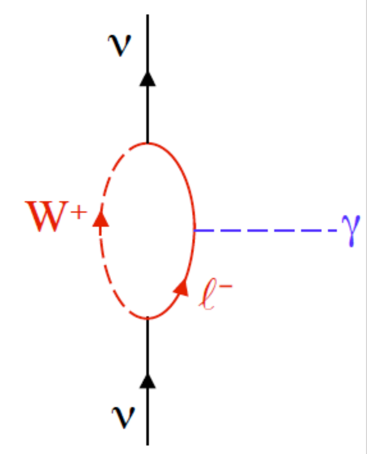
Anderson et al. 2010; Dutta et al. 2015; Kosmas et al. 2017

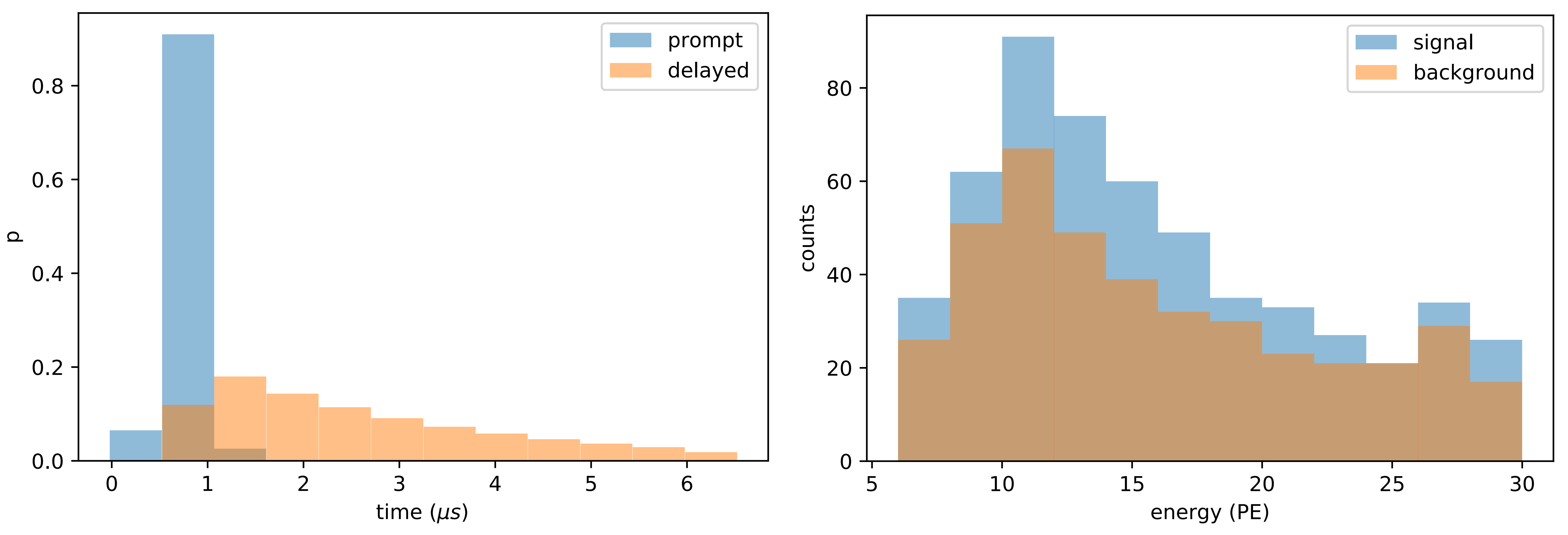
Reactor, Gallium anomalies



Magnetic moment

Vogel & Engel 1989

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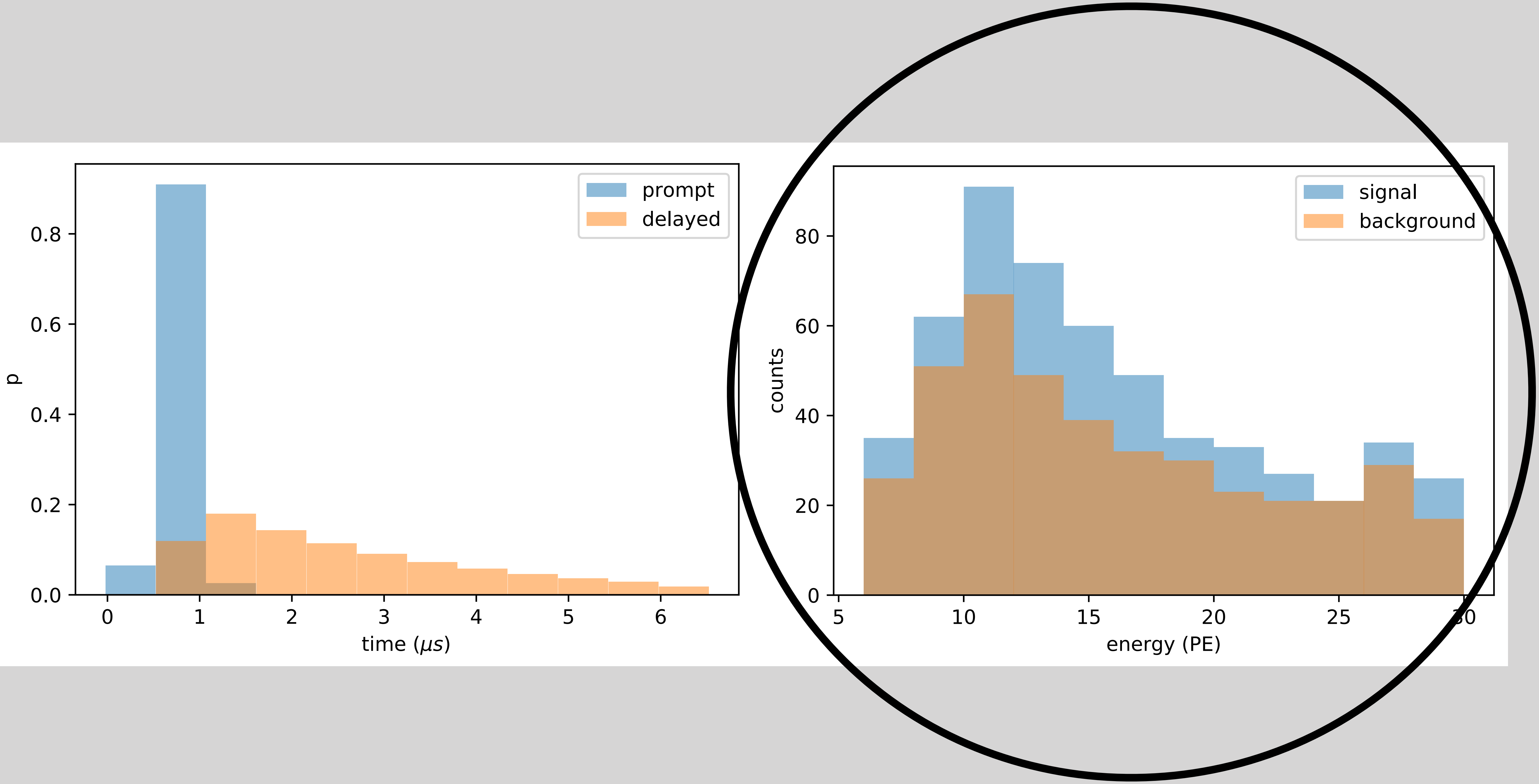
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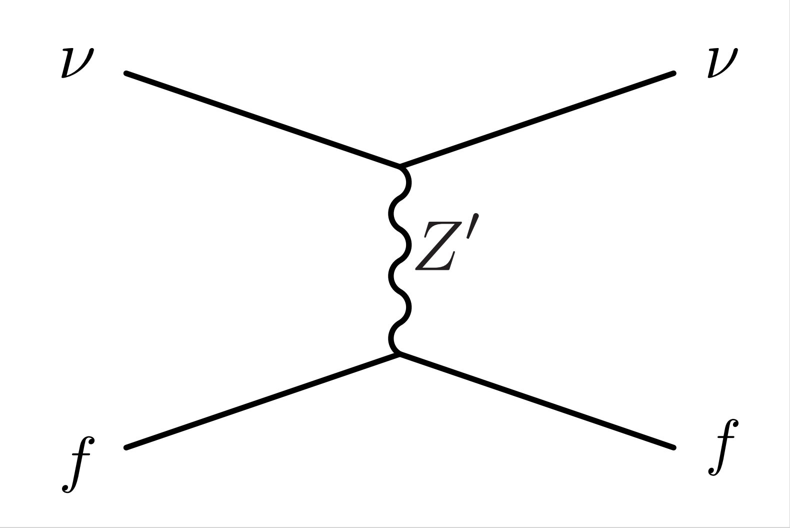
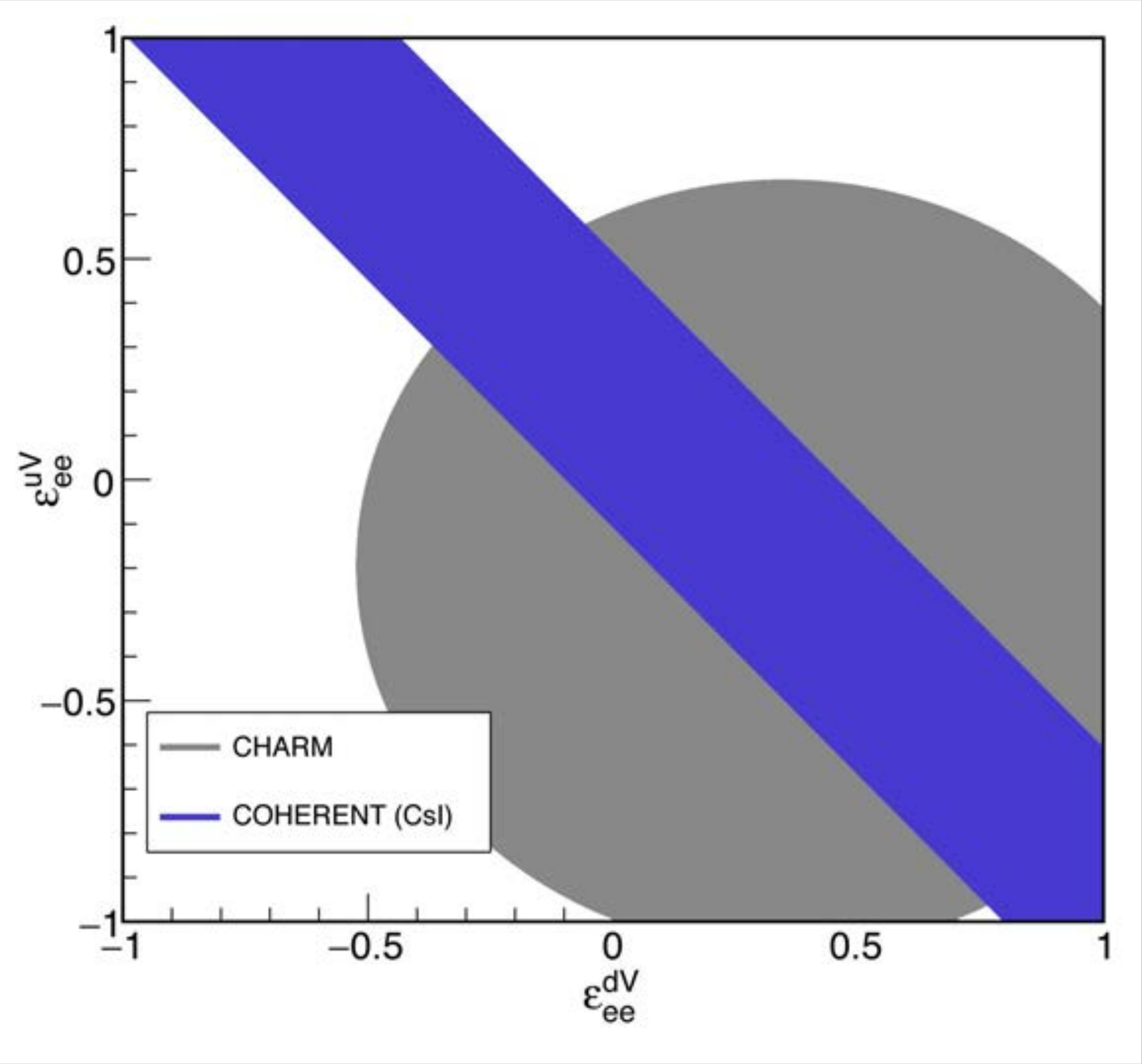
signal
background

Non-standard neutrino interactions (NSI)

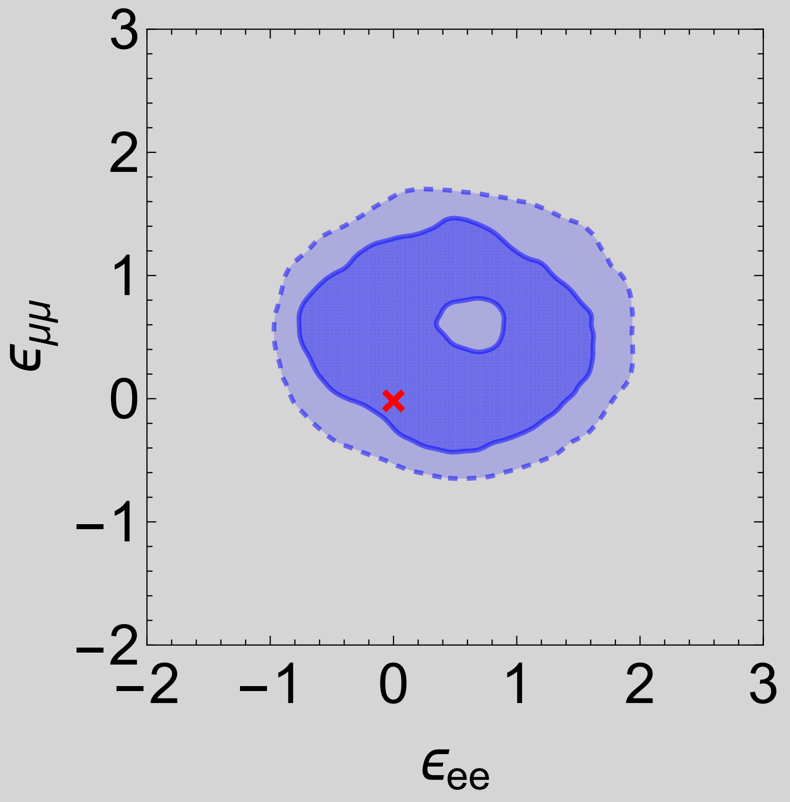




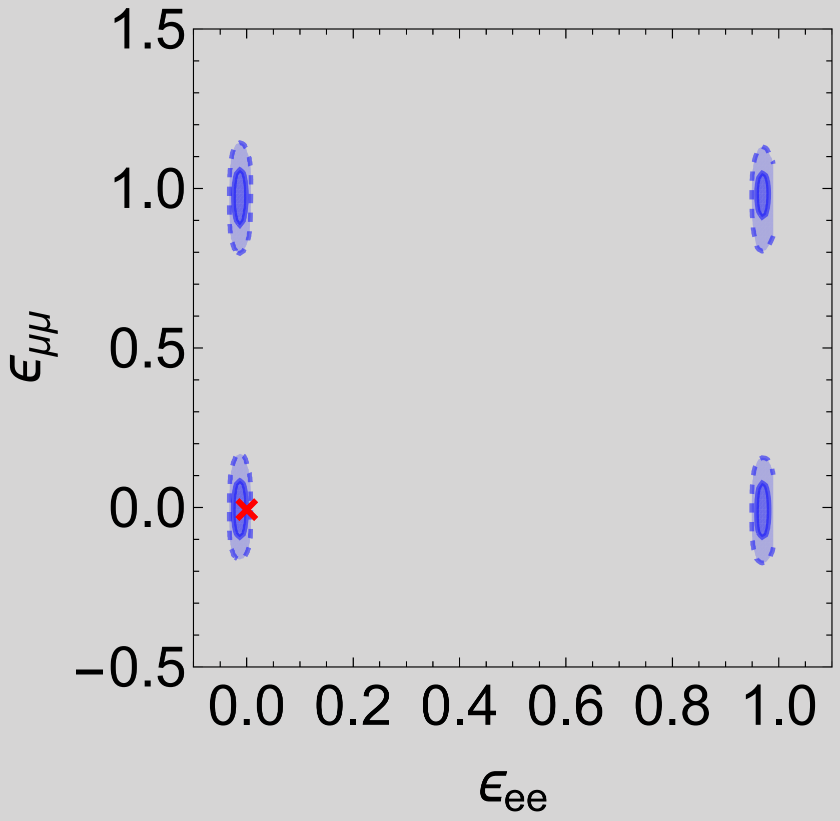
$$\mathcal{L}_{int} = 2\sqrt{2}G_F\bar{\nu}_{\alpha L}\gamma^{\mu}\nu_{\beta L}\left(\epsilon^{fL}_{\alpha\beta}\bar{f}_L\gamma_{\mu}f_L + \epsilon^{fR}_{\alpha\beta}\bar{f}_R\gamma_{\mu}f_R\right)$$

$$\begin{aligned}\frac{d\sigma}{dT}(E_\nu,T) = \frac{G_F^2 M}{\pi}\left(1-\frac{MT}{2E_\nu^2}\right)\times\Big\{&\Big[Z(g_V^p+2\varepsilon^{uV}_{ee}+\varepsilon^{dV}_{ee})+N(g_V^n+\varepsilon^{uV}_{ee}+2\varepsilon^{dV}_{ee})\Big]^2+\\ &\sum_{\alpha=\mu,\tau}\Big[Z(2\varepsilon^{uV}_{\alpha e}+\varepsilon^{dV}_{\alpha e})+N(\varepsilon^{uV}_{\alpha e}+2\varepsilon^{dV}_{\alpha e})\Big]^2\Big\}\end{aligned}$$

Non-standard neutrino interactions (NSI)



Current COHERENT



Future COHERENT + reactor

- Consider mediators with masses that are much larger than the scale of the momentum transfer
- Future COHERENT + Reactor data will be break (and identify new) degeneracies between multiple NSI parameters

Dent et al. PRD 2018, 1711.03521

BSM physics: Light mediators

- Cross section may be modified if a new mediator couples to quarks/leptons
- The interaction with a new vector particle may be described by:

$$\mathcal{L} \supset Z'_\mu (g'_\nu \bar{\nu}_L \gamma^\mu \nu_L + g'_{f,v} \bar{f} \gamma^\mu f + g'_{f,a} \bar{f} \gamma^\mu \gamma^5 f)$$

- The effect of the new field may be accommodated by the redefinition of the couplings:

$$\frac{d\sigma}{dE_R} = \frac{G_F^2 m}{2\pi}\left((g_v + g_a)^2 + (g_v - g_a)^2 \left(1 - \frac{E_R}{E_\nu}\right)^2 + (g_a^2 - g_v^2)\frac{mE_R}{E_\nu^2}\right) \qquad (g_v, g_a) \ \Rightarrow \ (g_v, g_a) + \frac{g'_\nu \,(g'_{f,v}, \pm g'_{f,a})}{2\sqrt{2}G_F \,(q^2 + M_{Z'}^2)})$$

BSM physics: Light mediators

- Consider a model to generate couplings with new U(1)
- Fields mix via the kinetic terms:

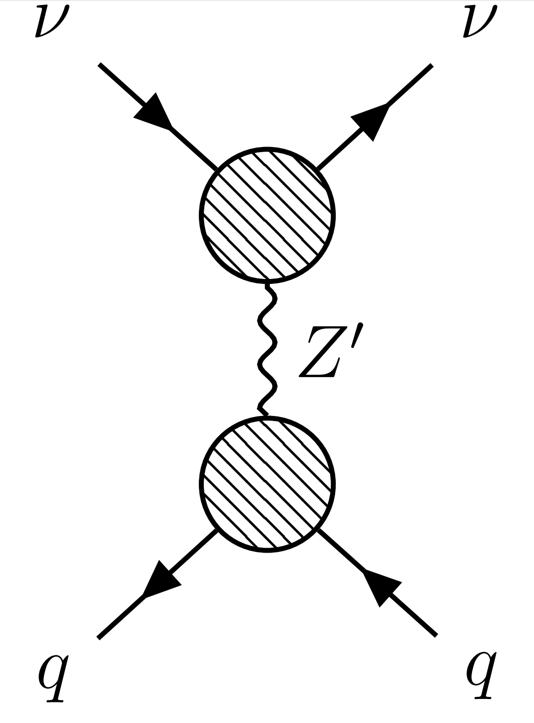
$$L_{gauge} = -\frac{1}{4}F_a^{\mu\nu}F_{a\mu\nu} - \frac{1}{4}F_b^{\mu\nu}F_{b\mu\nu} - \frac{\epsilon}{2}F_a^{\mu\nu}F_{b\mu\nu}$$

- For near similar mediator masses, the bound on the mixing terms is:

$$\epsilon \leq 10^{-2}$$

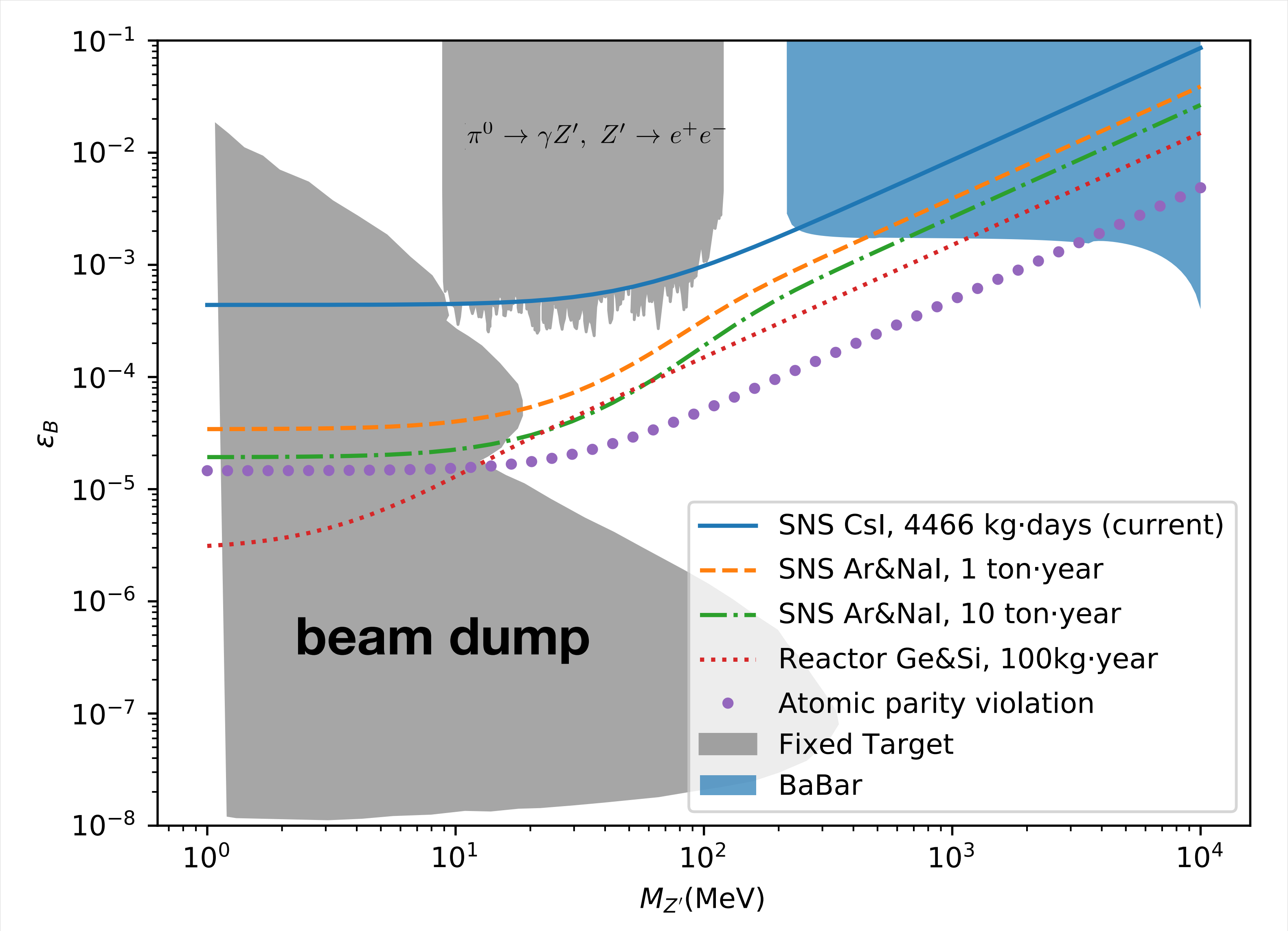
- Consider two limiting cases:
  - Dark hyper charge gauge boson: coupling proportional to SM hyper shares
  - Dark Z boson

Light mediators



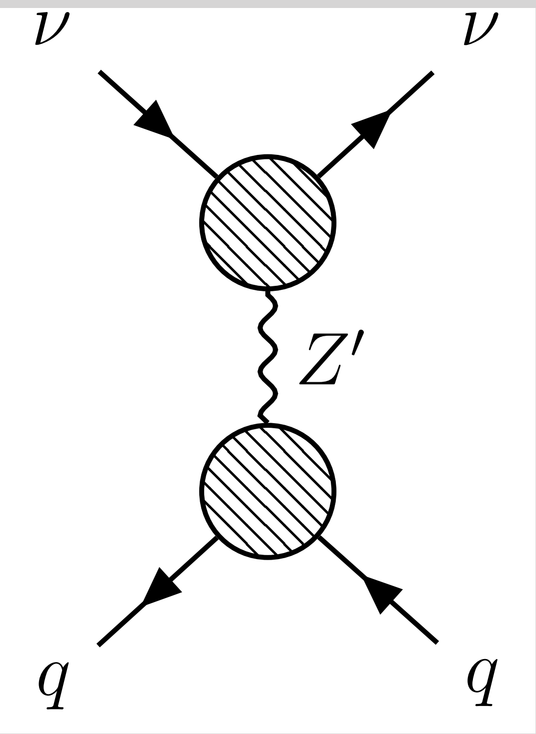
Dark hypercharge gauge boson

$$ig\tan\theta_w\,(Y_f/2)\,\epsilon_B$$



M. Abdullah et al. PRD 2018, 1803.01224

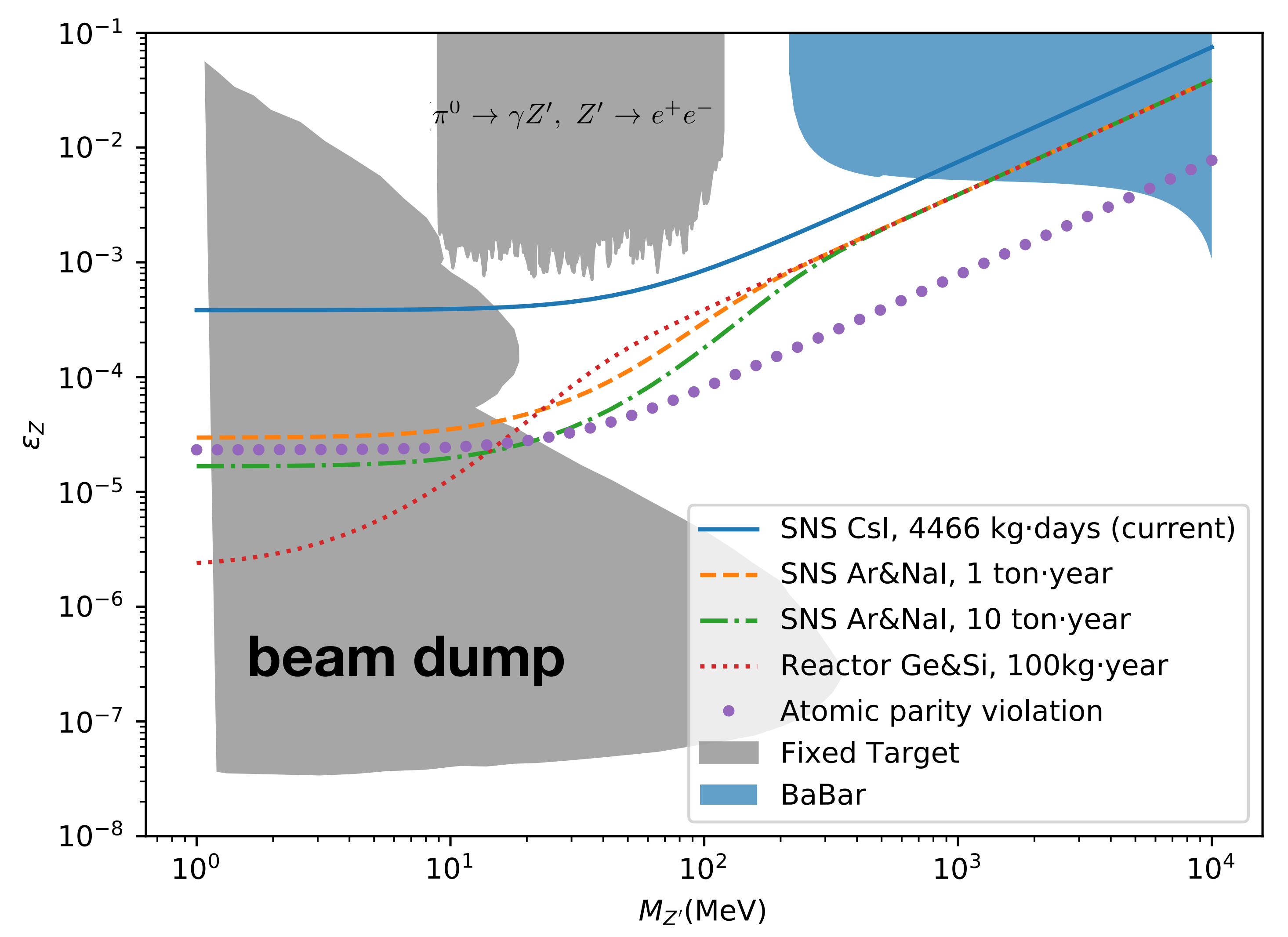
Light mediators



M. Abdullah et al. PRD 2018, 1803.01224

Dark Z boson

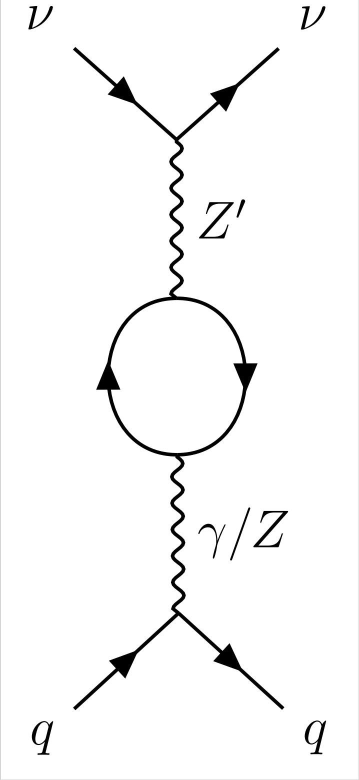
$$\frac{-ig}{\cos\theta_w}\,\epsilon_z\,\left[T_L^3 - \sin\theta_w^2 Q\right]$$

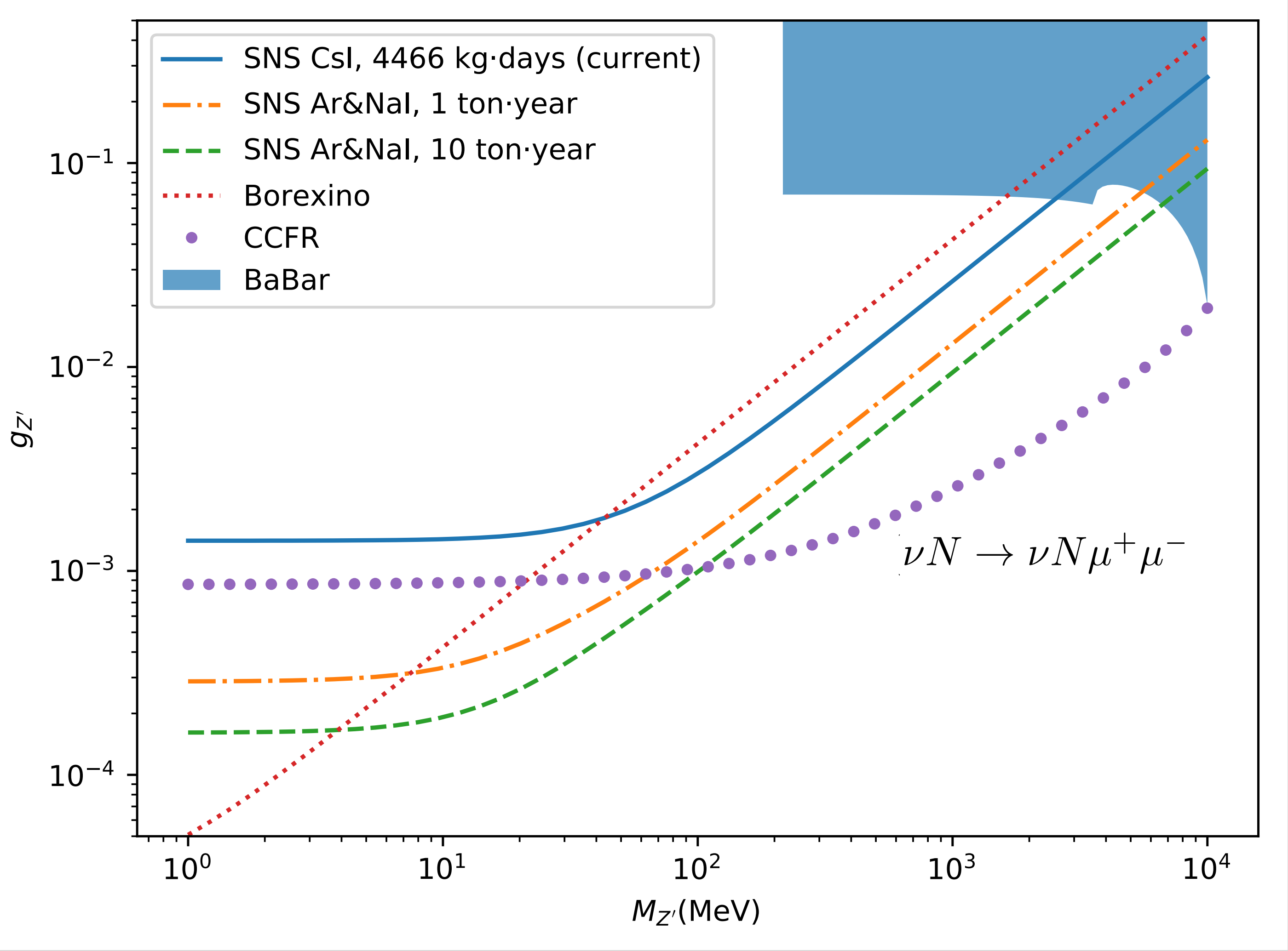


Light mediators

- **Can also consider new universal symmetry, i.e. on that only operates in the mu/tau sector**
- **New gauge boson couples to neutrino, but to first generation quarks via lepton loops**

$$\mathcal{L}_{int} \supset g_{Z'} Q_{\alpha\beta}(\bar{l}_\alpha \gamma^\mu l_\beta + \bar{\nu}_{L\alpha}\gamma^\mu \nu_{L\beta}) Z'_\mu$$

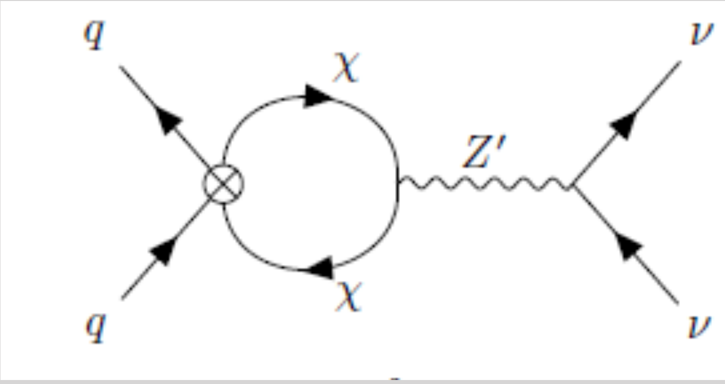


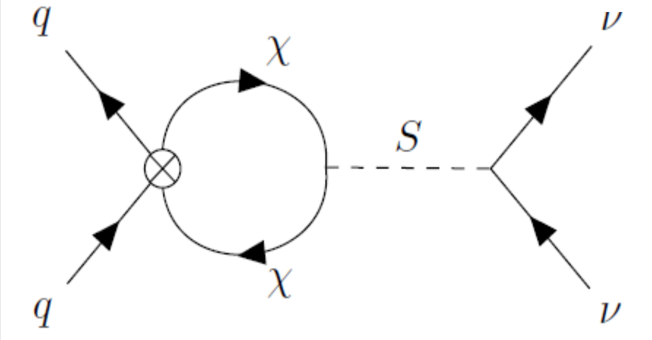


M. Abdullah et al. PRD 2018, 1803.01224

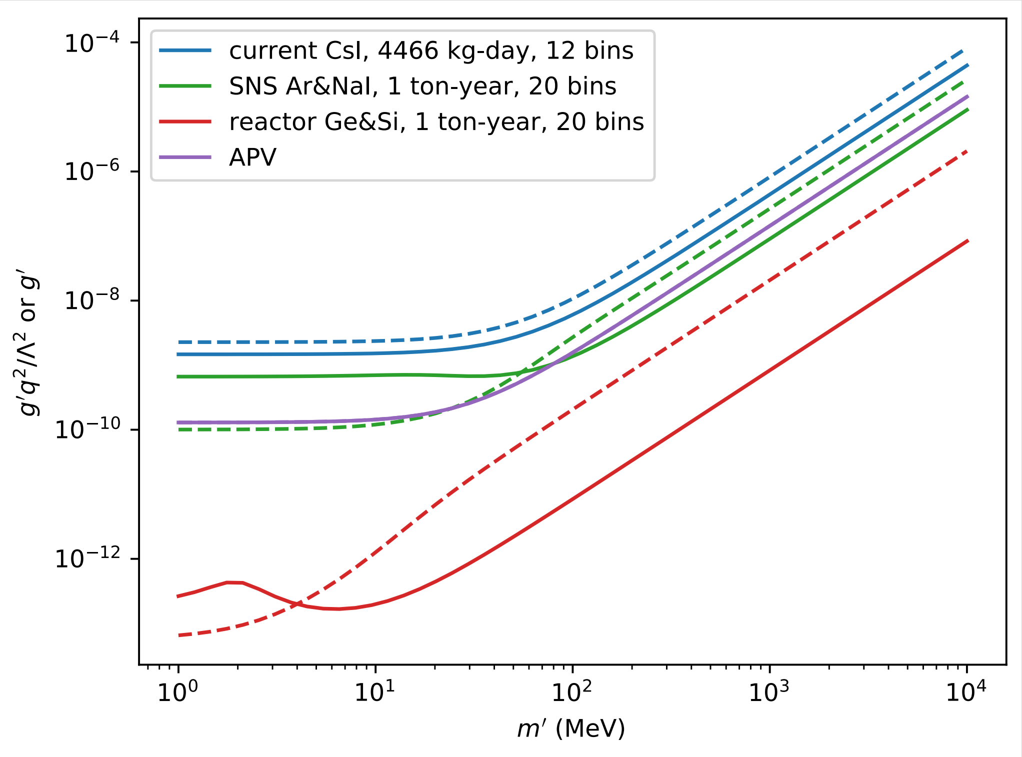
Hidden sectors fermions

- **Consider if the Z’ couples to hidden sector fermions and leptons**
- **Quarks couple to the hidden sector fermions**

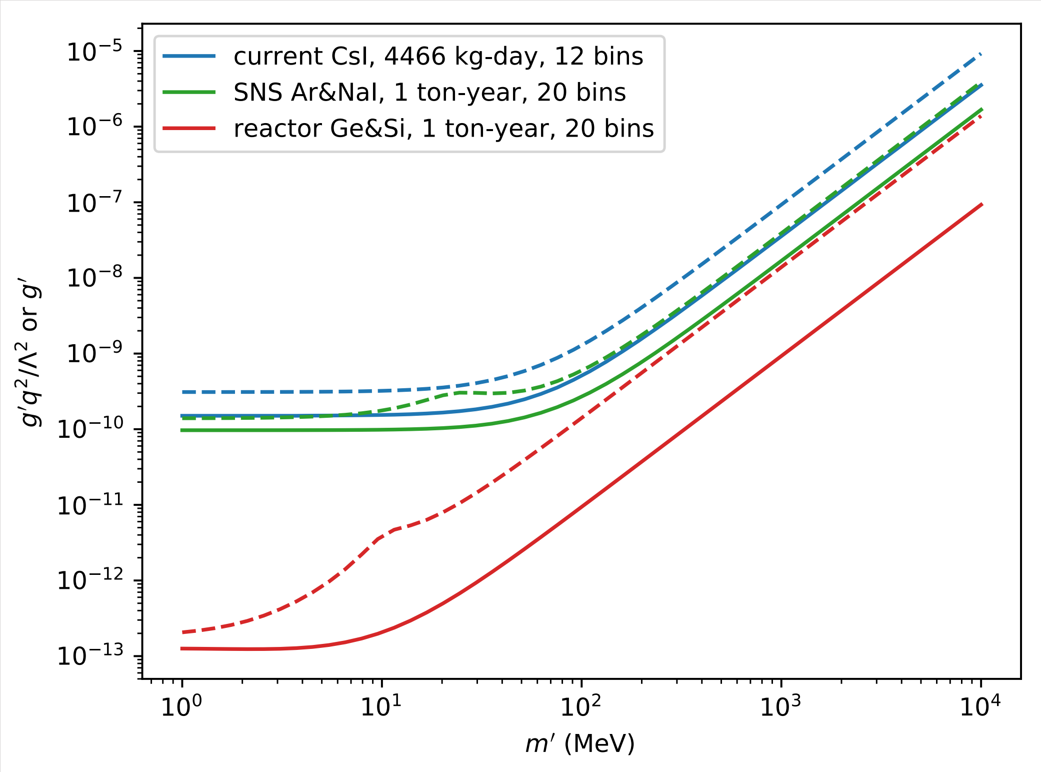




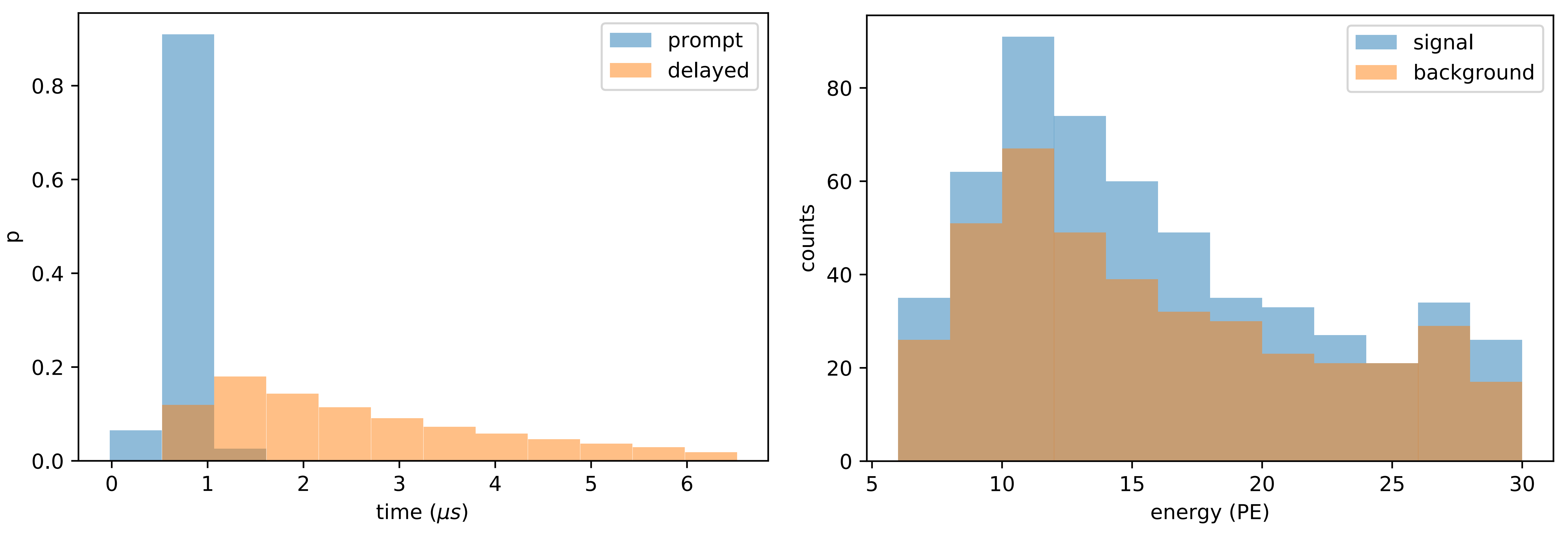
Vector



Scalar



Datta et al JHEP 2019, 201808.02611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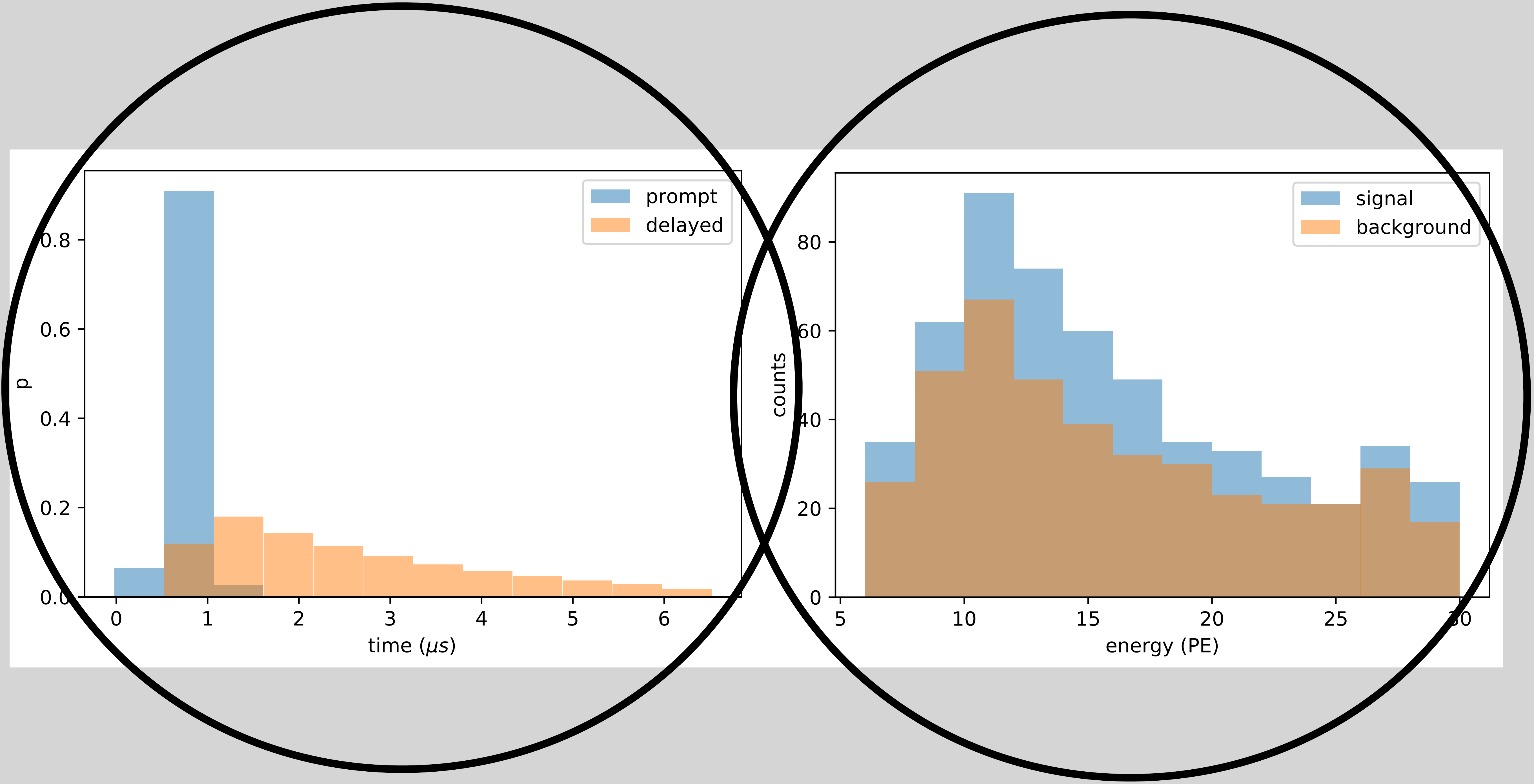
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energy (PE)

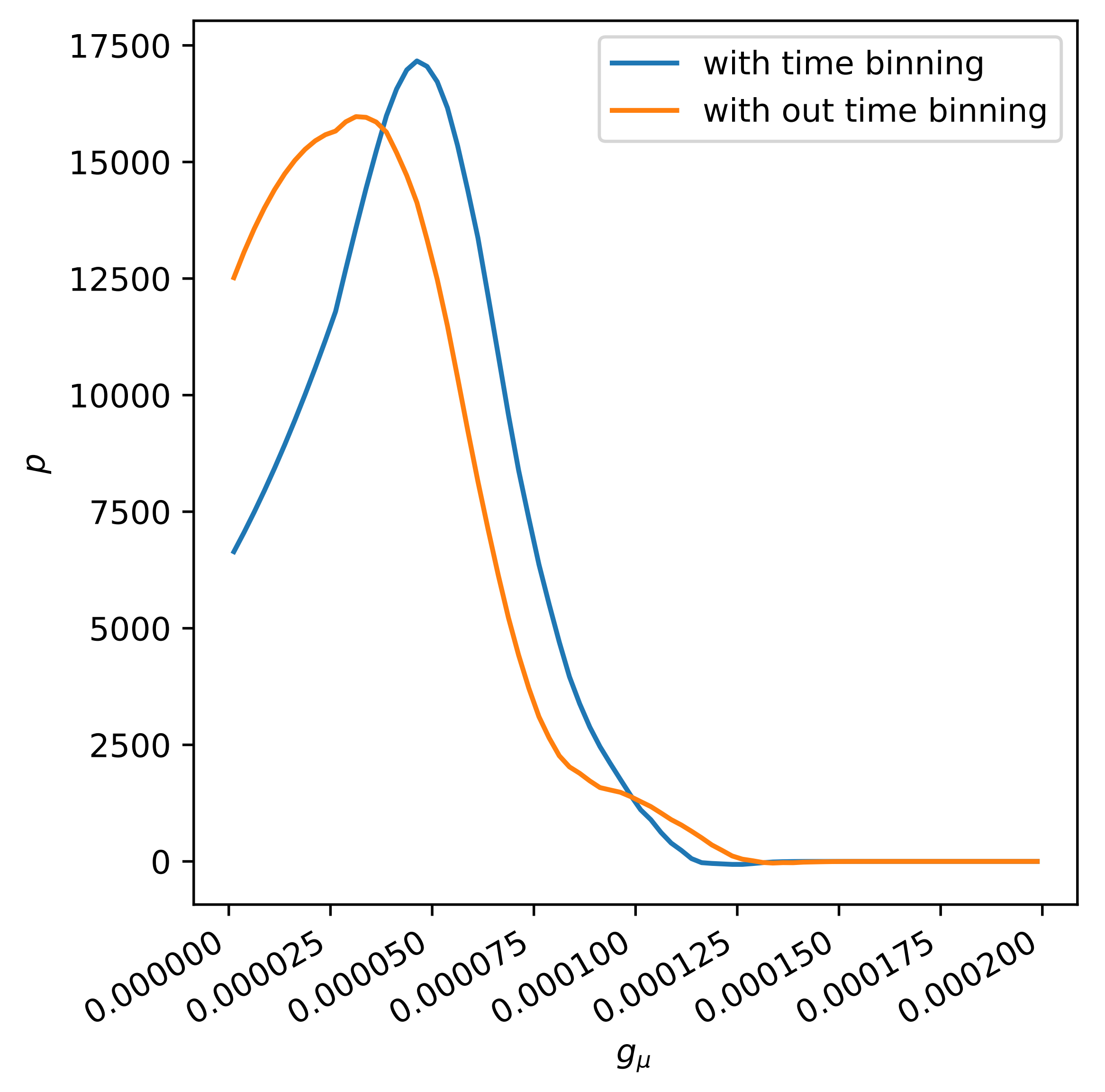
Energy + Timing Analysis

Light (1-1000 MeV) mediators

$$\mathcal{L} \supset Z'_\mu (g'_\nu \bar{\nu}_L \gamma^\mu \nu_L + g'_{f,v} \bar{f} \gamma^\mu f + g'_{f,a} \bar{f} \gamma^\mu \gamma^5 f)$$

- Important issue: how to statistically handle steady-state background
- Define a poisson model in energy/time bins and integrate out unknown parameters

Dutta, Liao, Sinha, LS PRL 2019



Energy + Timing Spectra

Light (1-1000 MeV) mediators

$$\mathcal{L} \supset Z'_\mu (g'_\nu \bar{\nu}_L \gamma^\mu \nu_L + g'_{f,v} \bar{f} \gamma^\mu f + g'_{f,a} \bar{f} \gamma^\mu \gamma^5 f)$$

- Important issue: how to statistically handle steady-state background
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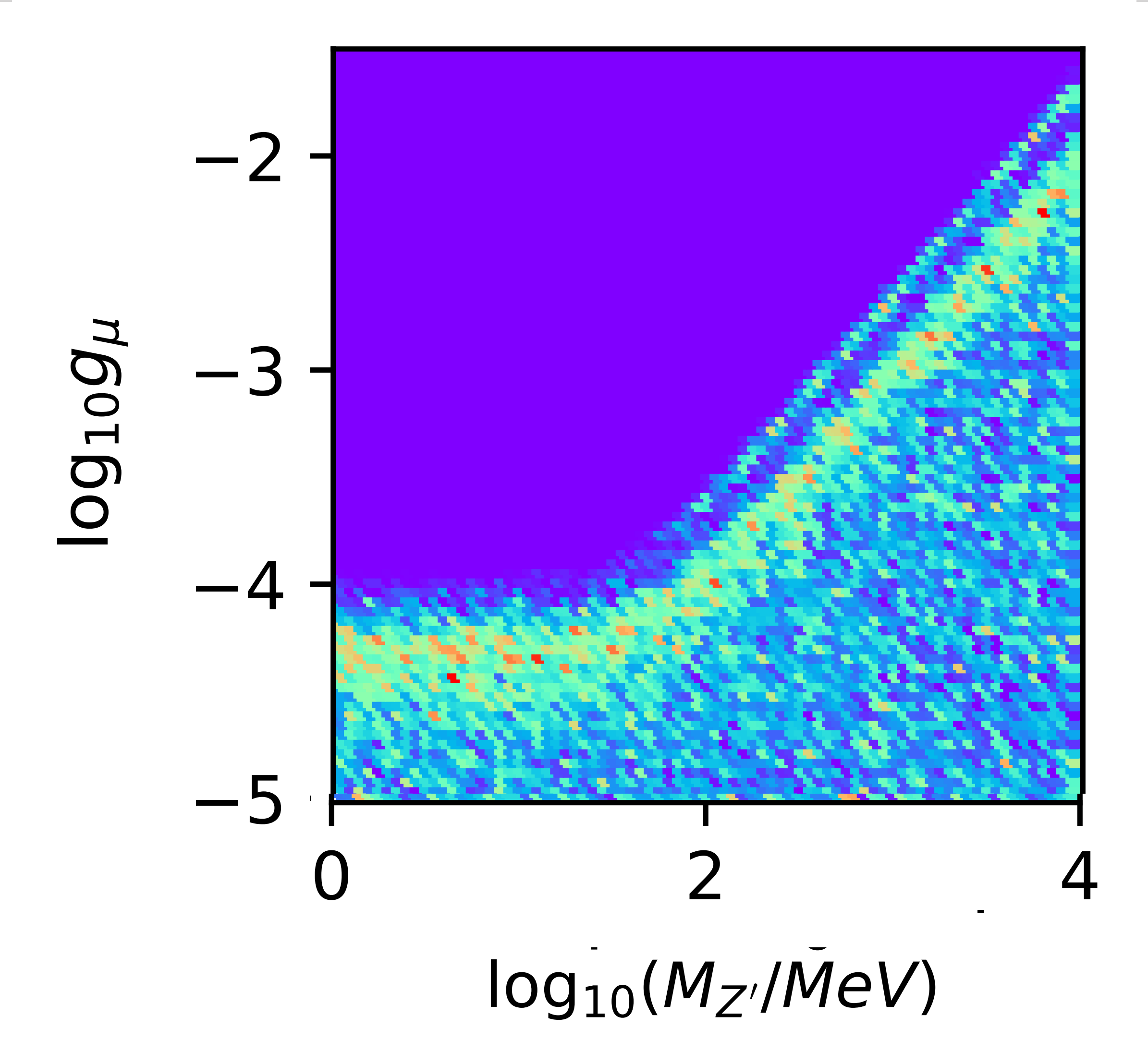
Dutta, Liao, Sinha, LS PRL 2019



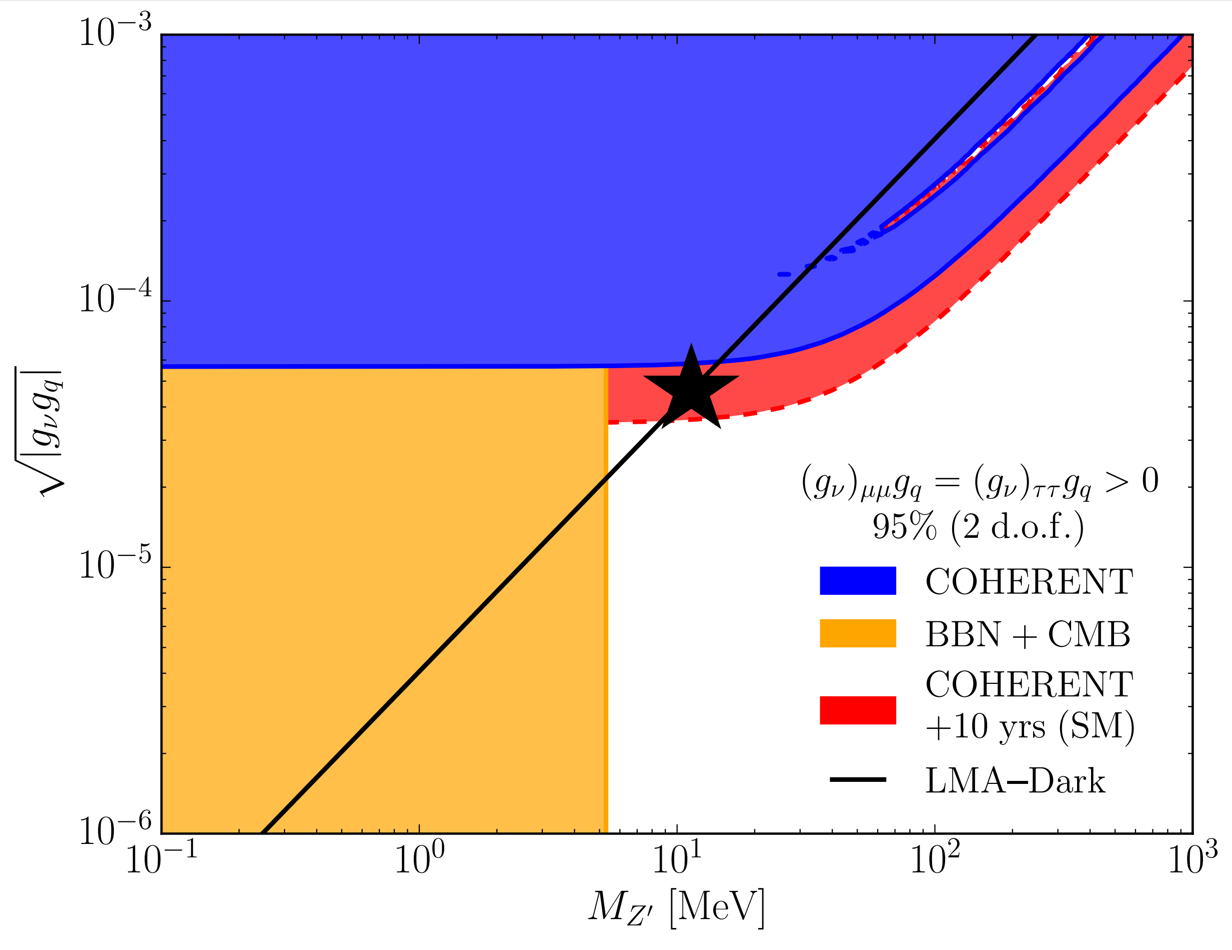
LMA-Dark Solution

- Possible to have a `dark side' solution for the Solar mixing angle with large NSI, and mixing angle > 45 degrees

- For light mediators a possible model is:

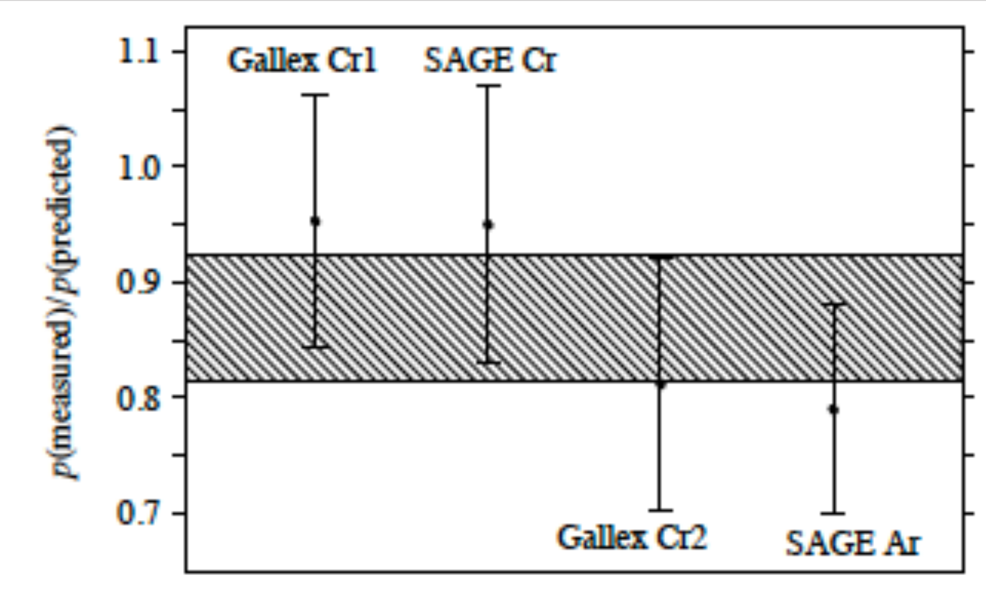
$$\mathscr{L} \supset \sum_{q\in\{u,d\}} g_q Z'_\mu \bar{q}\gamma^\mu q + \sum_{\alpha,\beta\in\{e,\mu,\tau\}} (g_\nu)_{\alpha\beta} Z'_\mu \bar{\nu}_\alpha \gamma^\mu \nu_\beta.$$

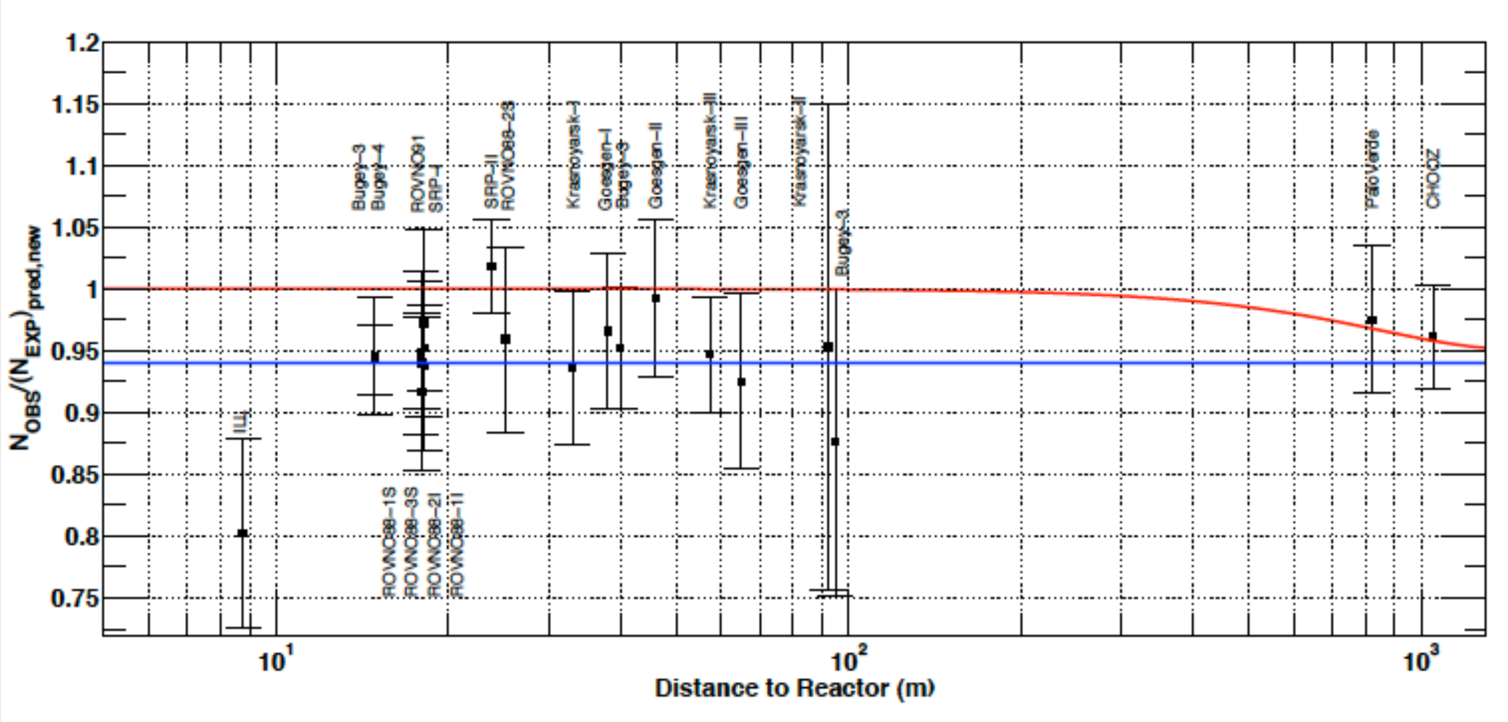
- Viable solution with COHERENT data



Denton, Farzan, Shoemaker 2019

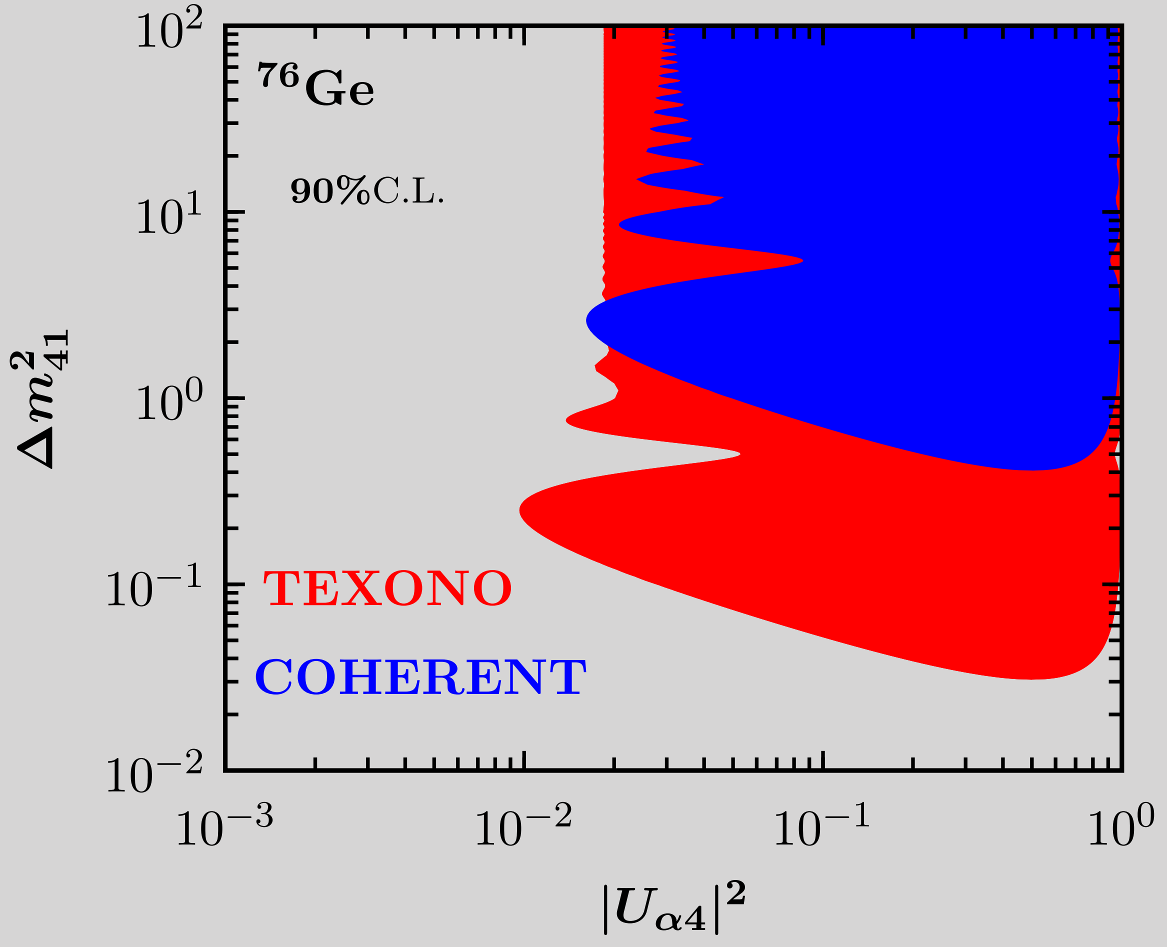
Sterile neutrinos



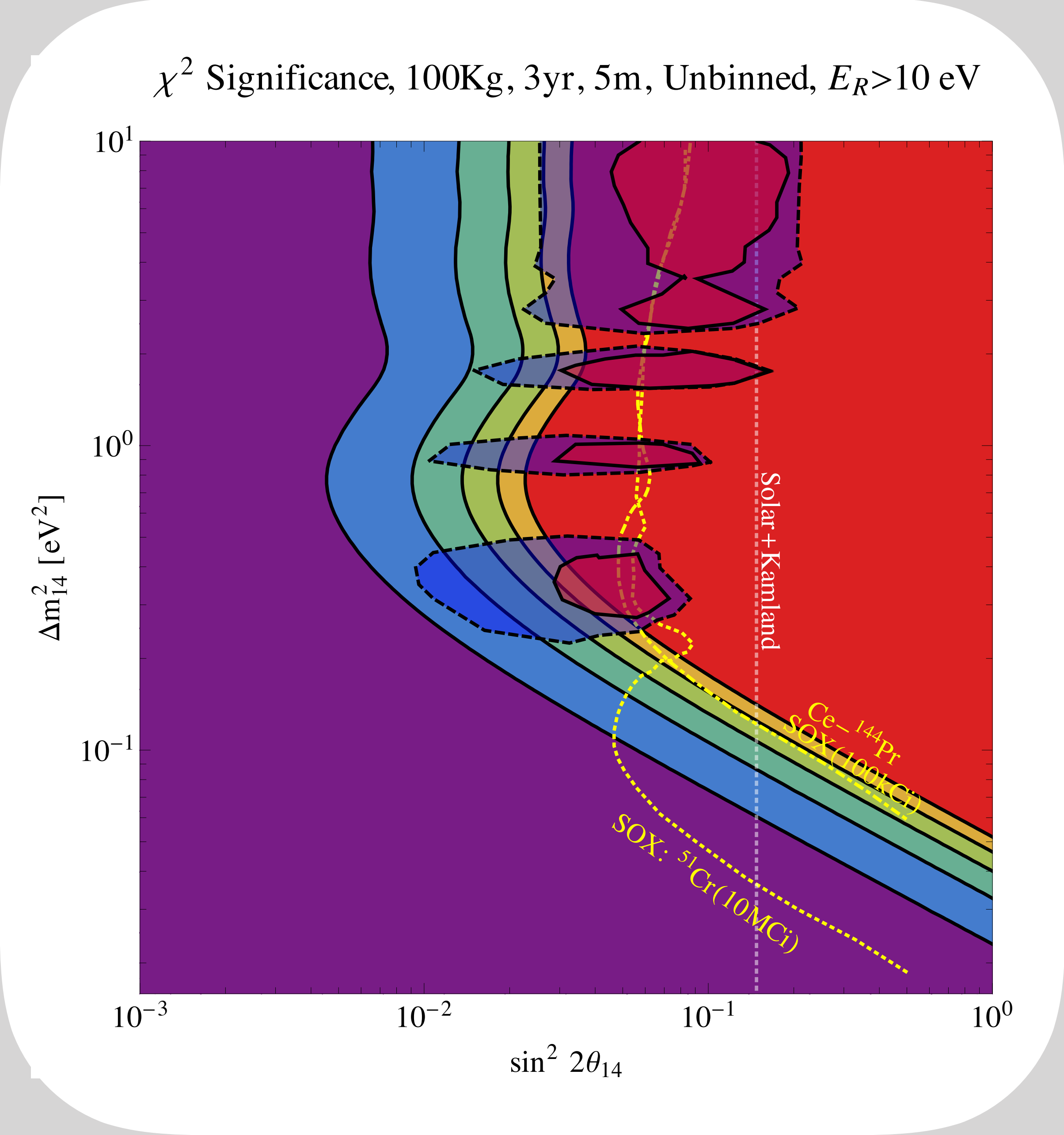


- Combined with ‘reactor anomaly’, gallium results may hint at new physics, i.e. ~ eV sterile neutrino (Giunti & Laveder 2010; Mention 2011)

Sterile neutrinos



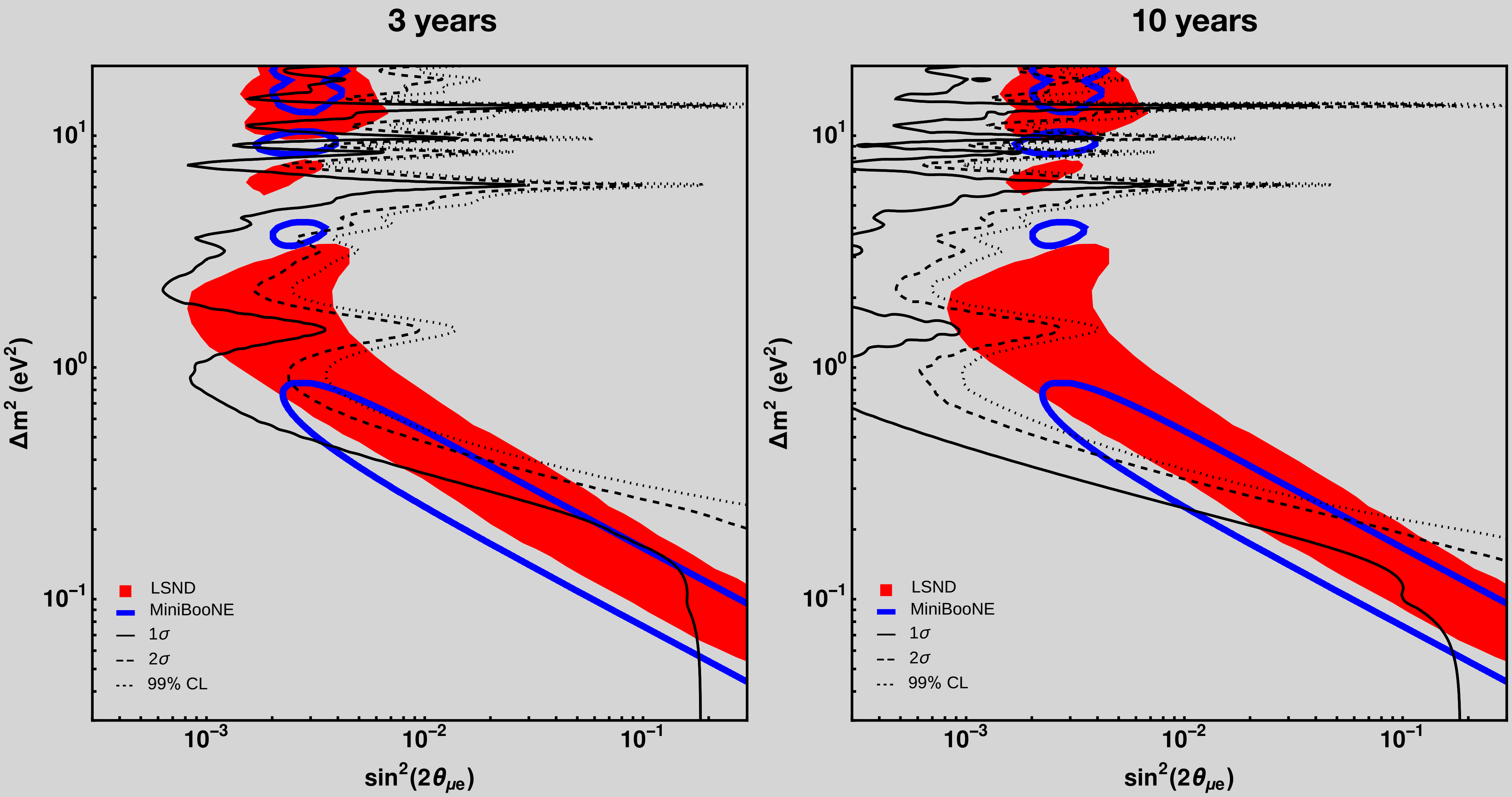
Kosmas et al. 2017



Dutta et al. 1511.02834

$$P(\nu_\alpha \to \nu_{\not{\alpha}}) = 4|U_{\alpha 4}|^2(1-|U_{\alpha 4}|^2)\sin^2(1.27\Delta m^2_{41} L/E)$$

Sterile neutrinos



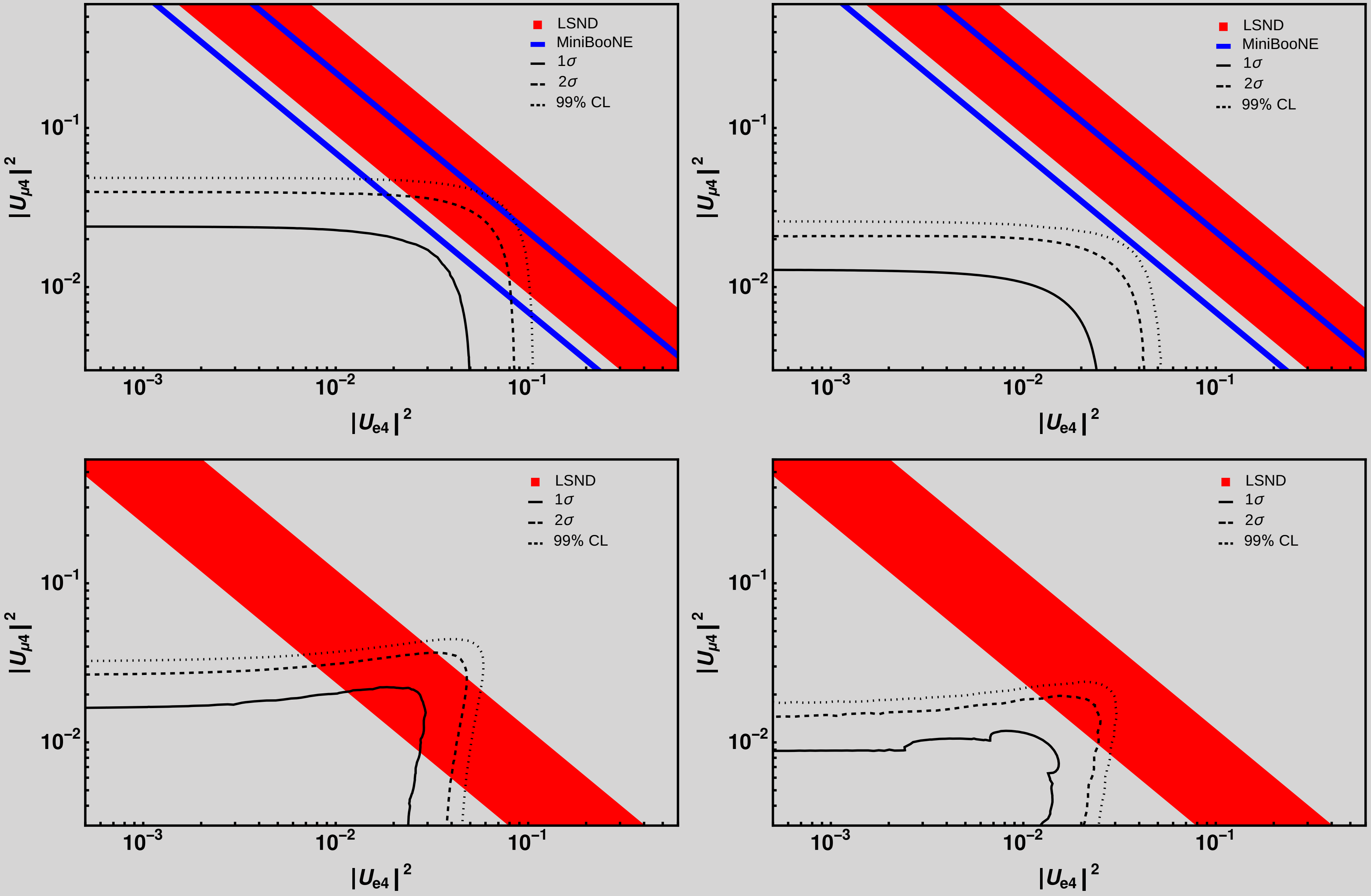
Blanco, Machado, Hooper 2019

Sterile neutrinos

3 years **10 years**

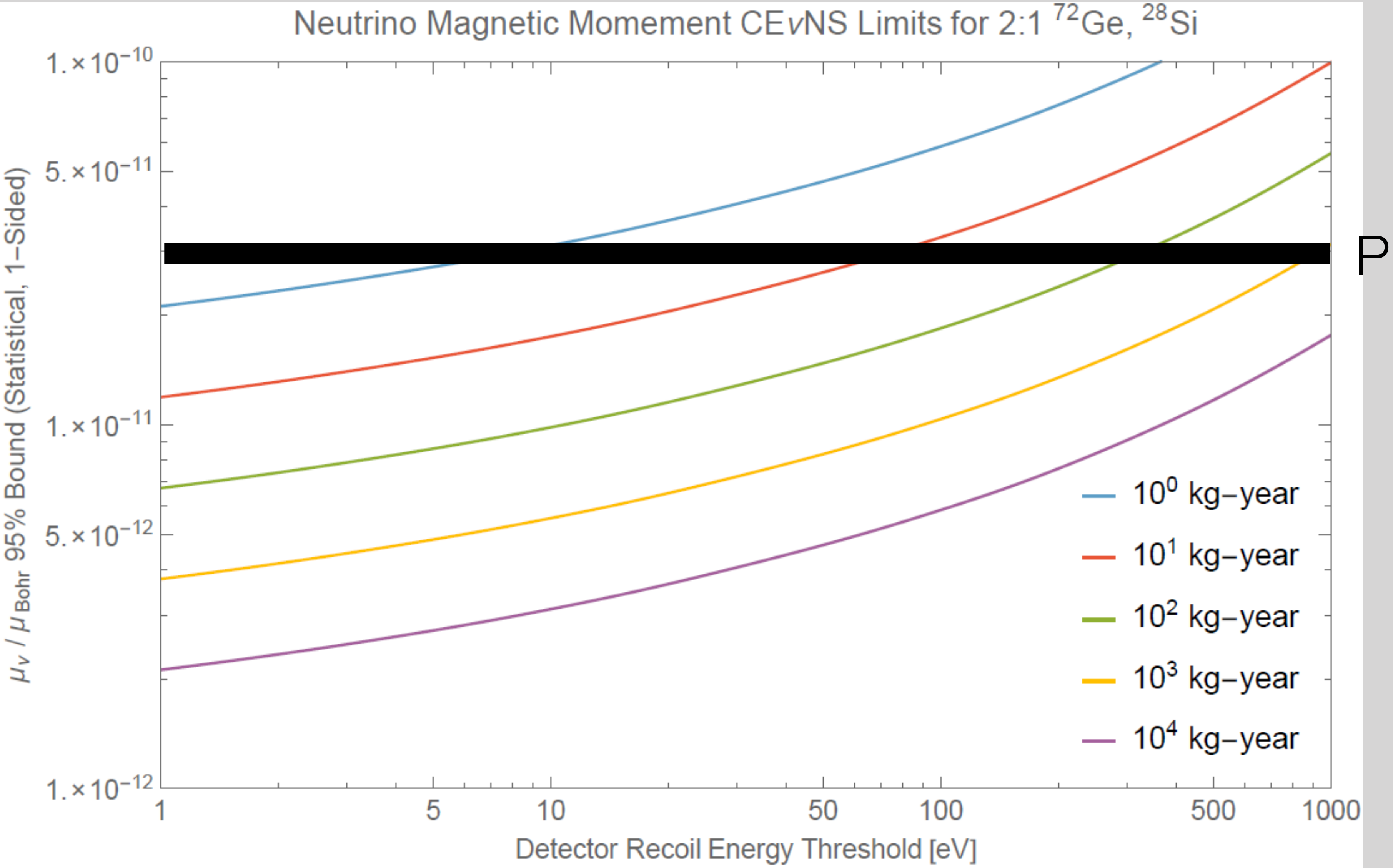
0.55 eV

1.2 eV



Blanco, Machado, Hooper 2019

Neutrino magnetic moment



Present limit

projected limits

recoil threshold $T_{\mathrm{R}}^{\mathrm{th}} = 10$ eV

kg-year, 3×10^{-11} Bohr magneton

10^4 kg-years, 3×10^{-12} Bohr magneton

Future prospects for CEνNS