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Searches for new physics with neutrino experiments

Seminar at Helsinki Institute of Physics
University of Helsinki
4 March 2020

Based on Phys. Rev. D98 (2018) 075018, Phys. Rev. D 100, no. 9, 095010 (2019), Phys. Rev. D 100, no. 3, 035032 (2019) in collaboration with D. Aristizabal, N. Rojas, P. Machado, K. Kelly, M. Tórtola, M. Hirsch, C. Ternes, G. Anamiati

Outline

1) Introduction: physics beyond the Standard Model

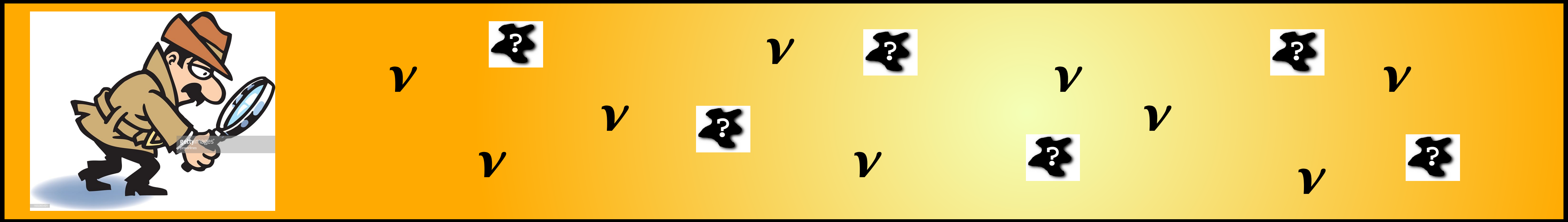
2) Coherent Elastic Neutrino-Nucleus Scattering (CEνNS)

- CEνNS
- The COHERENT experiment
- CEνNS and new physics interactions
- Neutrino generalised interactions (NGI)
- COHERENT constraints on NGI

3) Hunting for light Dark Matter with DUNE

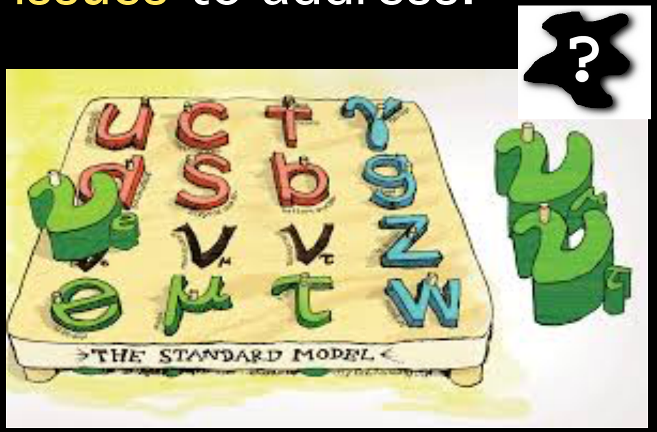
- Light dark matter at DUNE
- Constraints
- Sensitivities at DUNE

4) (Quasi-Dirac neutrinos at DUNE)



New physics beyond the SM?

- The Standard Model can explain most of the experimental results.
  However, there are some theoretical and observational issues to address:
  - neutrino oscillations
  - dark matter
  - baryon asymmetry of the Universe



Symmetry Magazine

- Neutrino oscillations provide 1st laboratory evidence of New Physics
- The Standard Model must be extended (or embedded in larger framework)
  Many candidate models...
- New Physics actively searched for in many fronts:

- High energy colliders direct searches of new states
- High intensity facilities indirect searches (rare processes, deviations from SM)
- Cosmology & astroparticle physics observations (dark matter, inflation, ...)
- Neutrino experiments

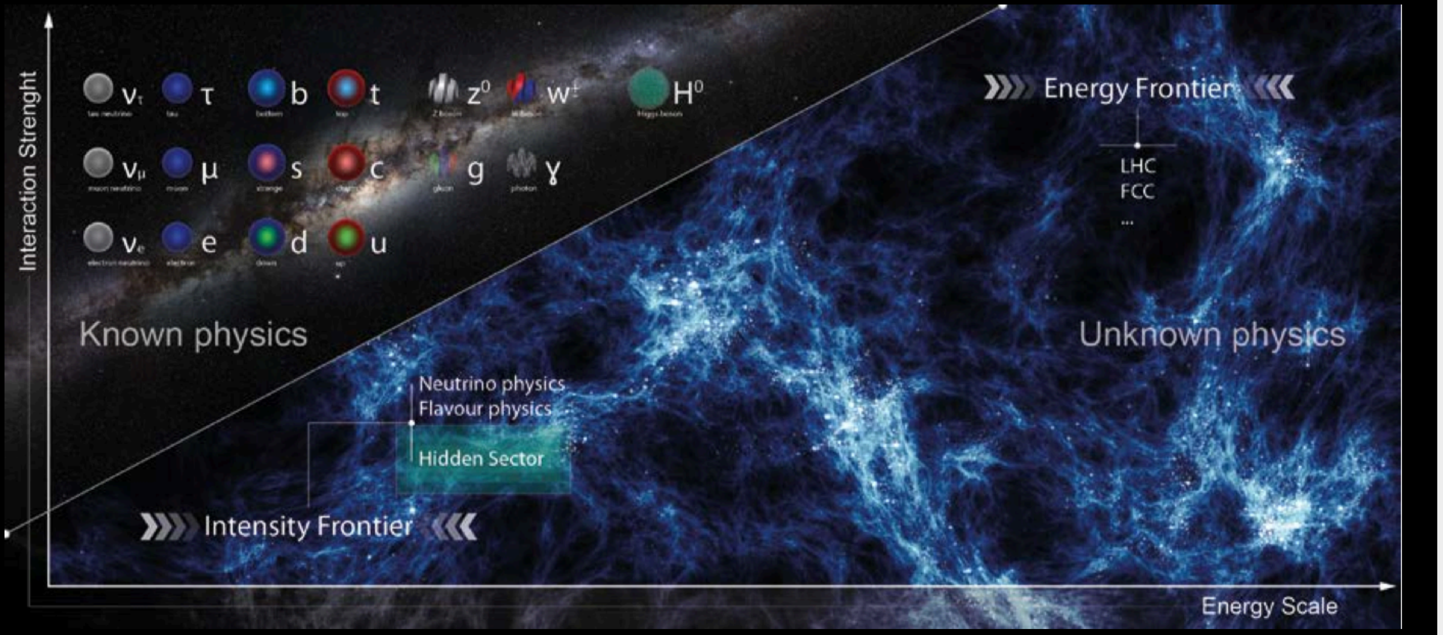
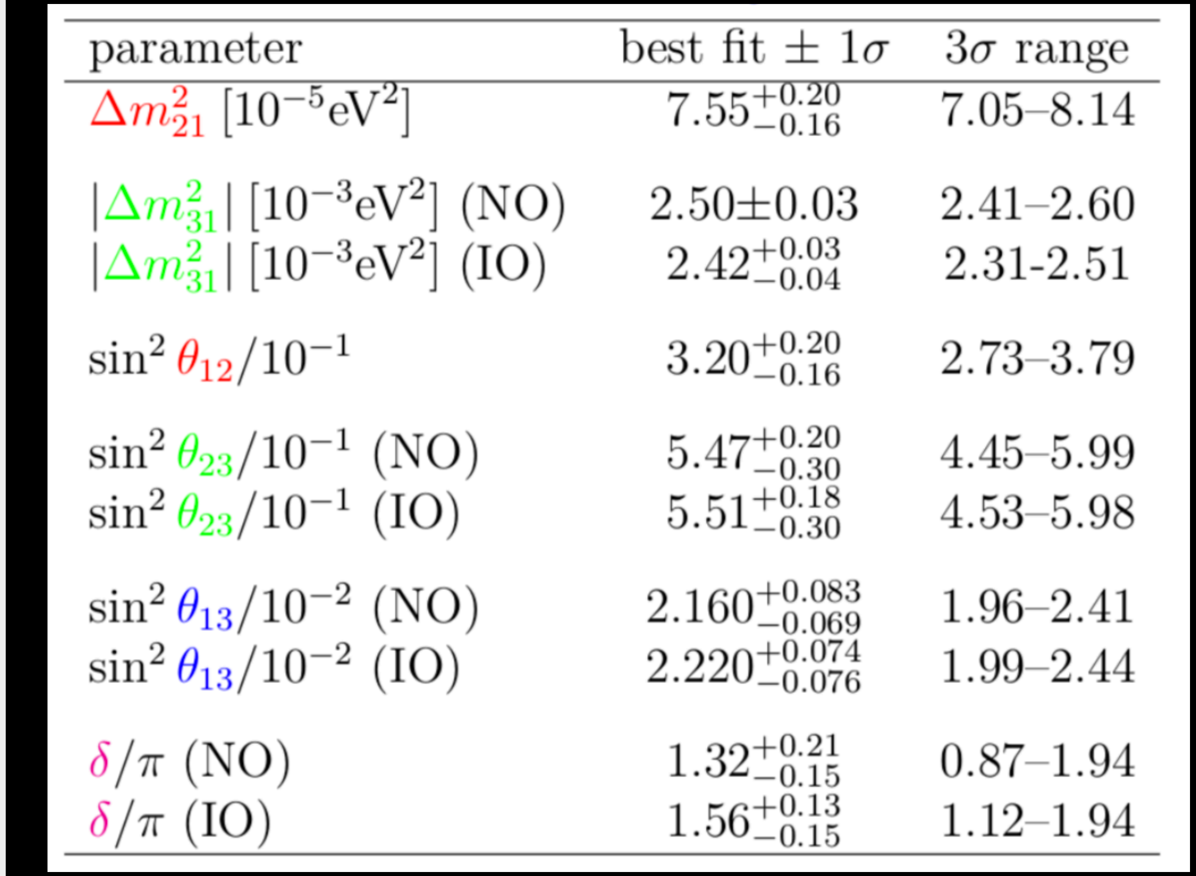


Image from CERN courier 2/2016

Lepton mixing and neutrino physics

- As of today, data favour a three-active neutrinos oscillation framework.
- Neutrino oscillation parameters have been inferred by detecting neutrinos coming from the Sun, the Earth's atmosphere, nuclear reactors and accelerator beams.



parameter	best fit ± 1σ	3σ range
Δm^2_{21} [10^{-5}eV^2]	$7.55^{+0.20}_{-0.16}$	7.05–8.14
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (NO)	2.50±0.03	2.41–2.60
$\|\Delta m^2_{31}\|$ [10^{-3}eV^2] (IO)	$2.42^{+0.03}_{-0.04}$	2.31-2.51
$\sin^2\theta_{12}/10^{-1}$	$3.20^{+0.20}_{-0.16}$	2.73–3.79
$\sin^2\theta_{23}/10^{-1}$ (NO)	$5.47^{+0.20}_{-0.30}$	4.45–5.99
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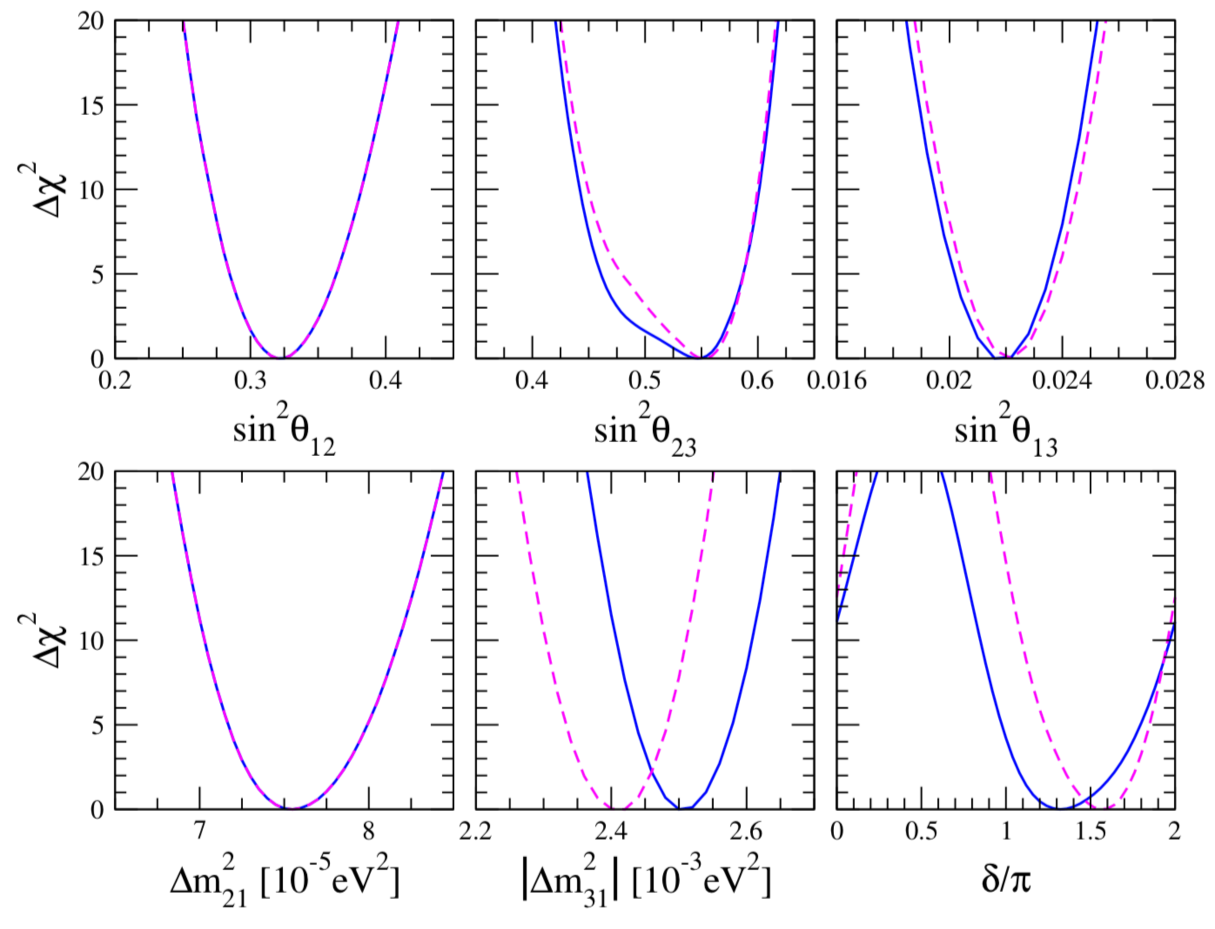
$\sin^2\theta_{13}/10^{-2}$ (NO)	$2.160^{+0.083}_{-0.069}$	1.96–2.41
$\sin^2\theta_{13}/10^{-2}$ (IO)	$2.220^{+0.074}_{-0.076}$	1.99–2.44
δ/π (NO)	$1.32^{+0.21}_{-0.15}$	0.87–1.94
δ/π (IO)	$1.56^{+0.13}_{-0.15}$	1.12–1.94



Phys.Lett. B782 (2018) 633-640, P.F. de Salas et al.,
https://globalfit.astroparticles.es/

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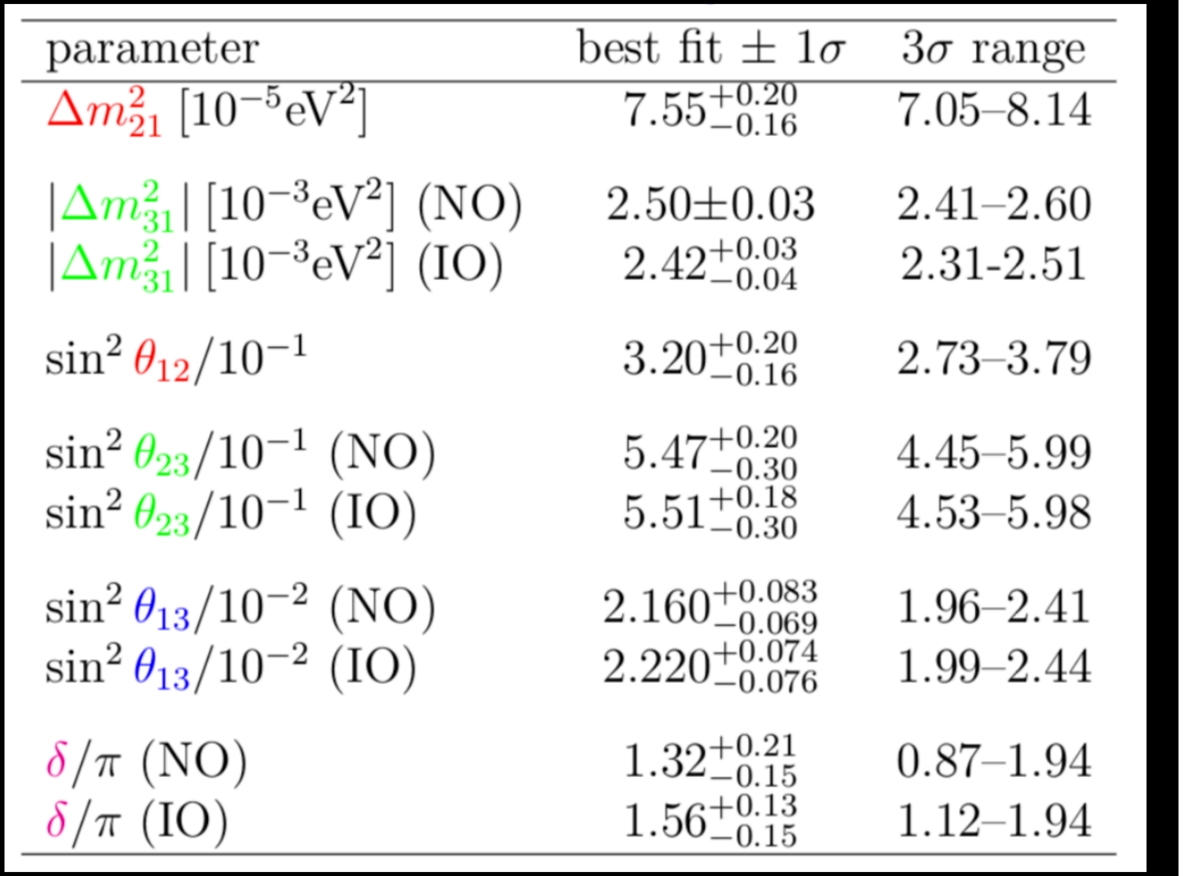

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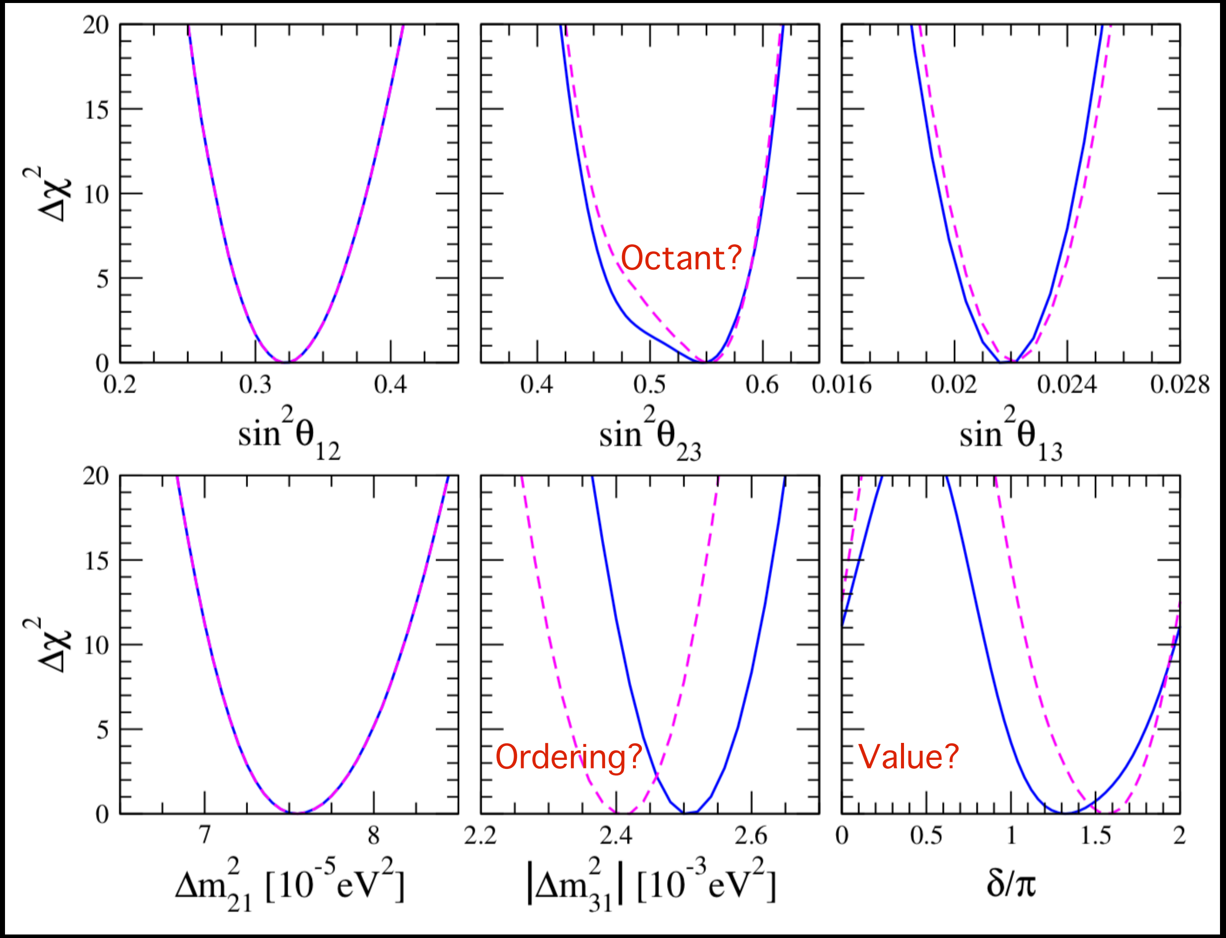

Phys.Lett. B782 (2018) 633-640, P.F. de Salas et al.,
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Open questions in neutrino physics

We are in the PRECISION ERA for neutrino physics.

- only three oscillation parameters unknown: θ_{23} octant, δCP, ν mass ordering
- What about (absolute) neutrino masses?
- Do sterile neutrinos exist?
- What is the mechanism responsible for neutrino masses?

- Do neutrinos have non-standard interactions?

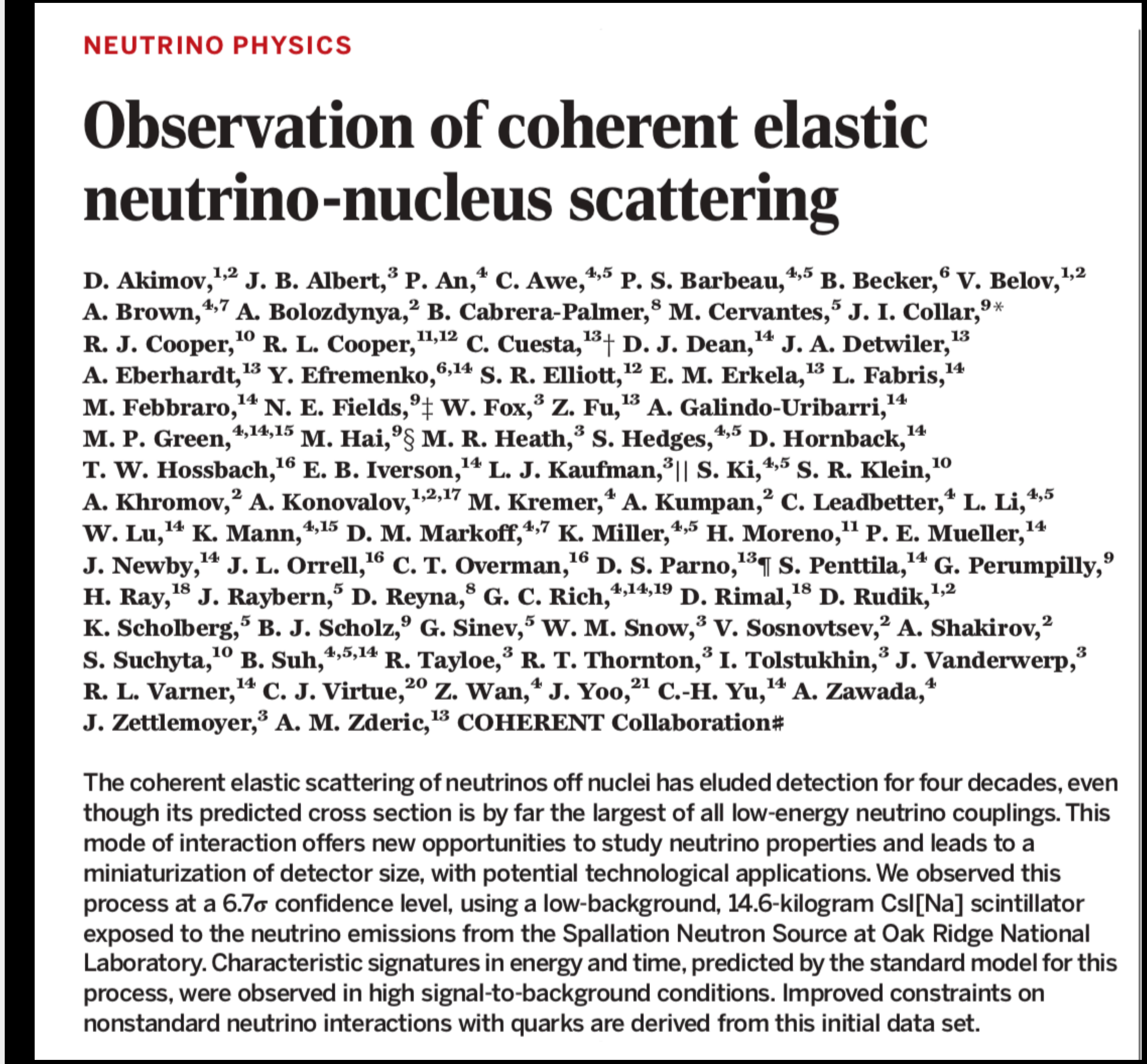
- Exciting experimental roadmap ahead!!

Illustration: © Johan Jarnestad/The Royal Swedish Academy of Sciences

Coherent Elastic Neutrino-Nucleus Scattering (CEvNS) and Neutrino Generalized Interactions

D. Aristizabal, VDR, N. Rojas, Phys.Rev. D98 (2018) 075018

Observation of CEνNS at COHERENT (2017)



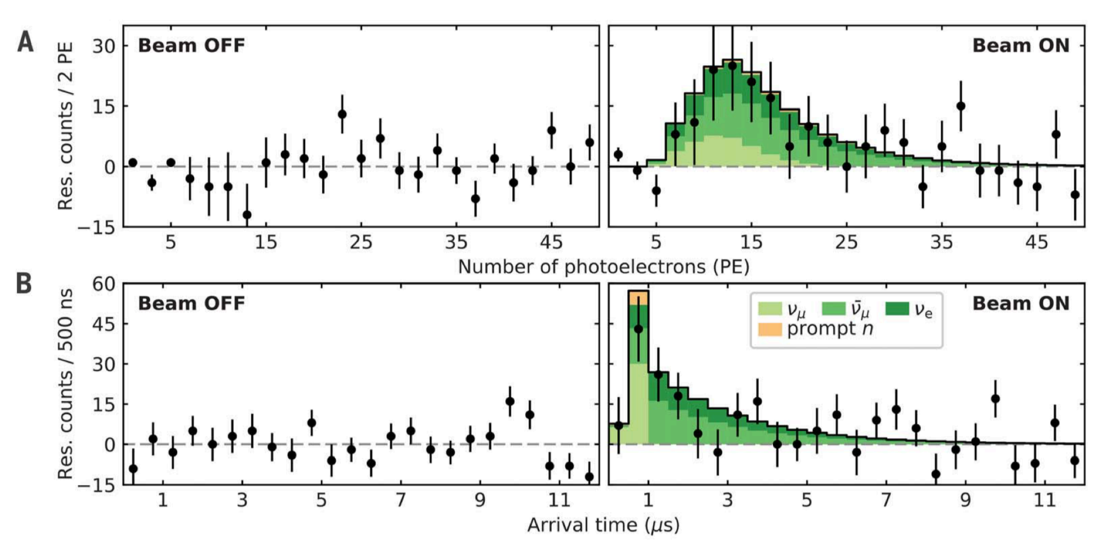
NEUTRINO PHYSICS

Observation of coherent elastic neutrino-nucleus scattering

D. Akimov,[1,2] J. B. Albert,[3] P. An,[4] C. Awe,[4,5] P. S. Barbeau,[4,5] B. Becker,[6] V. Belov,[1,2] A. Brown,[4,7] A. Bolozdynya,[2] B. Cabrera-Palmer,[8] M. Cervantes,[5] J. I. Collar,[9]* R. J. Cooper,[10] R. L. Cooper,[11,12] C. Cuesta,[13]† D. J. Dean,[14] J. A. Detwiler,[13] A. Eberhardt,[13] Y. Efremenko,[6,14] S. R. Elliott,[12] E. M. Erkela,[13] L. Fabris,[14] M. Febbraro,[14] N. E. Fields,[9]‡ W. Fox,[3] Z. Fu,[13] A. Galindo-Uribarri,[14] M. P. Green,[4,14,15] M. Hai,[9]§ M. R. Heath,[3] S. Hedges,[4,5] D. Hornback,[14] T. W. Hossbach,[16] E. B. Iverson,[14] L. J. Kaufman,[3]|| S. Ki,[4,5] S. R. Klein,[10] A. Khromov,[2] A. Konovalov,[1,2,17] M. Kremer,[4] A. Kumpan,[2] C. Leadbetter,[4] L. Li,[4,5] W. Lu,[14] K. Mann,[4,15] D. M. Markoff,[4,7] K. Miller,[4,5] H. Moreno,[11] P. E. Mueller,[14] J. Newby,[14] J. L. Orrell,[16] C. T. Overman,[16] D. S. Parno,[13]¶ S. Penttila,[14] G. Perumpilly,[9] H. Ray,[18] J. Raybern,[5] D. Reyna,[8] G. C. Rich,[4,14,19] D. Rimal,[18] D. Rudik,[1,2] K. Scholberg,[5] B. J. Scholz,[9] G. Sinev,[5] W. M. Snow,[3] V. Sosnovtsev,[2] A. Shakirov,[2] S. Suchyta,[10] B. Suh,[4,5,14] R. Tayloe,[3] R. T. Thornton,[3] I. Tolstukhin,[3] J. Vanderwerp,[3] R. L. Varner,[14] C. J. Virtue,[20] Z. Wan,[4] J. Yoo,[21] C.-H. Yu,[14] A. Zawada,[4] J. Zettlemoyer,[3] A. M. Zderic,[13] COHERENT Collaboration#

The coherent elastic scattering of neutrinos off nuclei has eluded detection for four decades, even though its predicted cross section is by far the largest of all low-energy neutrino couplings. This mode of interaction offers new opportunities to study neutrino properties and leads to a miniaturization of detector size, with potential technological applications. We observed this process at a 6.7σ confidence level, using a low-background, 14.6-kilogram CsI[Na] scintillator exposed to the neutrino emissions from the Spallation Neutron Source at Oak Ridge National Laboratory. Characteristic signatures in energy and time, predicted by the standard model for this process, were observed in high signal-to-background conditions. Improved constraints on nonstandard neutrino interactions with quarks are derived from this initial data set.

Akimov et al., Science 357, 1123–1126 (2017)



Coherent Elastic Neutrino-Nucleus Scattering

- NC (flavour-independent) process: $\nu + A \rightarrow \nu + A$
- CEνNS occurs when the neutrino energy E_ν is such that nucleon amplitudes sum up coherently (up to $E_\nu \sim 100$ MeV):

  cross section enhancement
- Total cross section scales approximately like N^2

$$\frac{d\sigma}{dE_R} \propto N^2$$

- Can be few orders of magnitude larger than inverse beta decay process used to first observe neutrinos

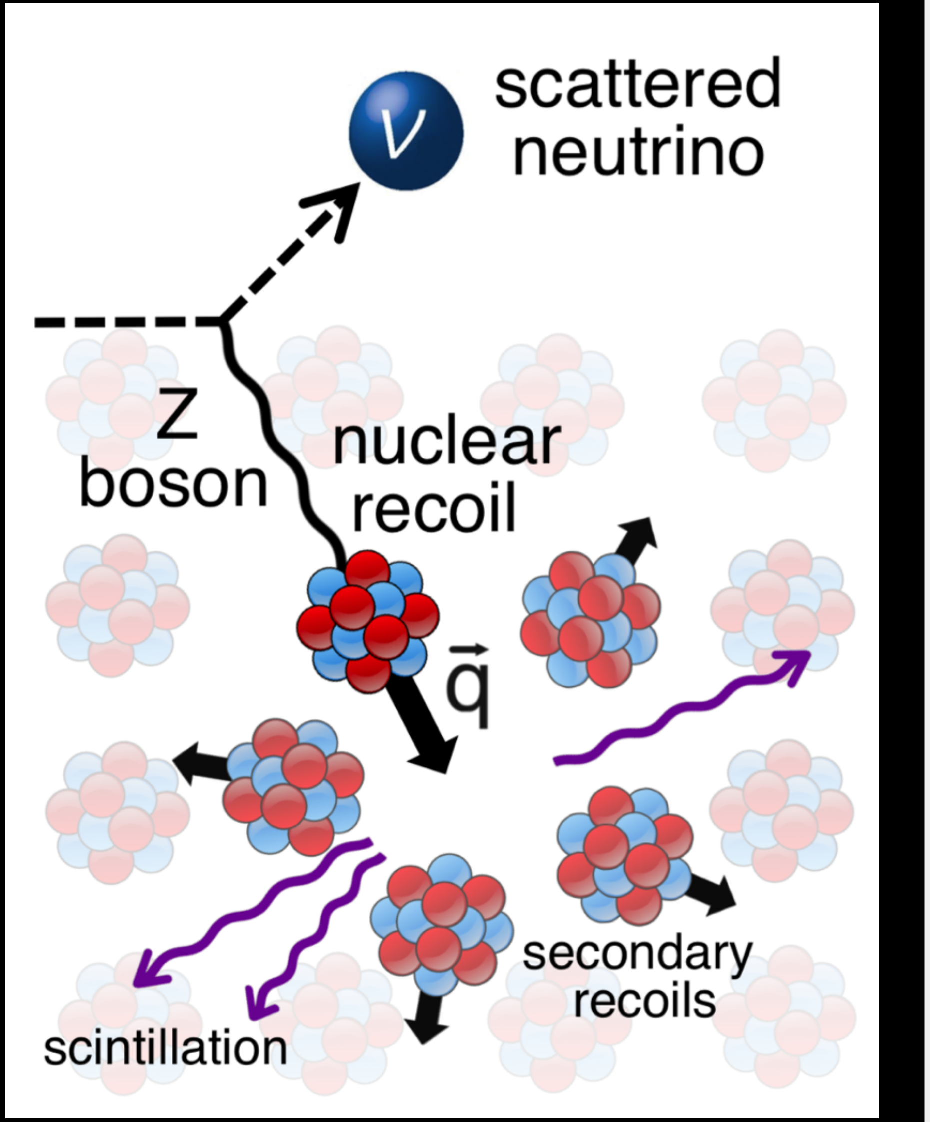
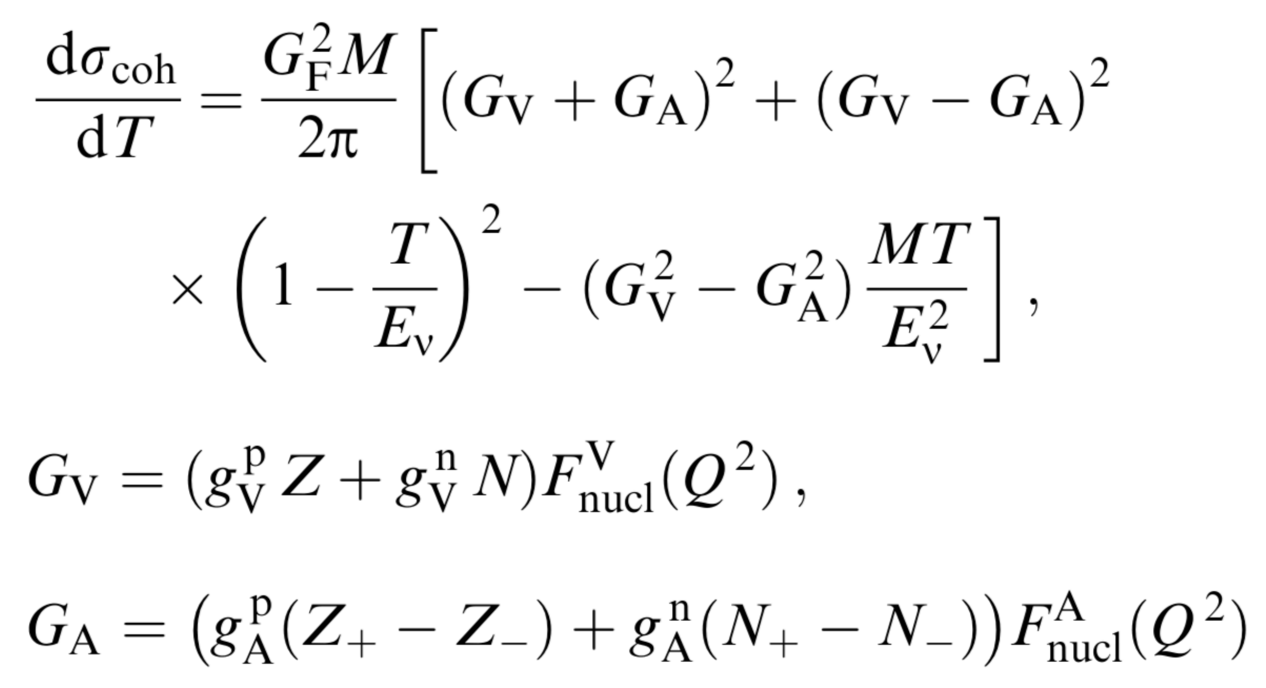


Image from COHERENT exp.

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

Coherent Elastic Neutrino-Nucleus Scattering

CEνNS has a well-calculable cross-section in the SM



$$\frac{\mathrm{d}\sigma_{\mathrm{coh}}}{\mathrm{d}T} = \frac{G_{\mathrm{F}}^2 M}{2\pi}\left[(G_{\mathrm{V}}+G_{\mathrm{A}})^2 + (G_{\mathrm{V}}-G_{\mathrm{A}})^2 \times \left(1-\frac{T}{E_\nu}\right)^2 - (G_{\mathrm{V}}^2 - G_{\mathrm{A}}^2)\frac{MT}{E_\nu^2}\right],$$

$$G_{\mathrm{V}} = (g_{\mathrm{V}}^{\mathrm{p}} Z + g_{\mathrm{V}}^{\mathrm{n}} N) F_{\mathrm{nucl}}^{\mathrm{V}}(Q^2),$$

$$G_{\mathrm{A}} = \left(g_{\mathrm{A}}^{\mathrm{p}}(Z_+ - Z_-) + g_{\mathrm{A}}^{\mathrm{n}}(N_+ - N_-)\right) F_{\mathrm{nucl}}^{\mathrm{A}}(Q^2)$$

T: recoil energy

$Z_\pm$ $N_\pm$: number or protons and neutrons with opposite spins

F_{nucl}: nuclear form factors (close to 1 at low Q^2)

For heavy nuclei the axial contribution is small because is determined only by unpaired protons and neutrons.

D.Z. Freedman, Phys. Rev. D 9 (1974)
V.B. Kopeliovich and L.L. Frankfurt, ZhETF Pis. Red. 19 (1974)

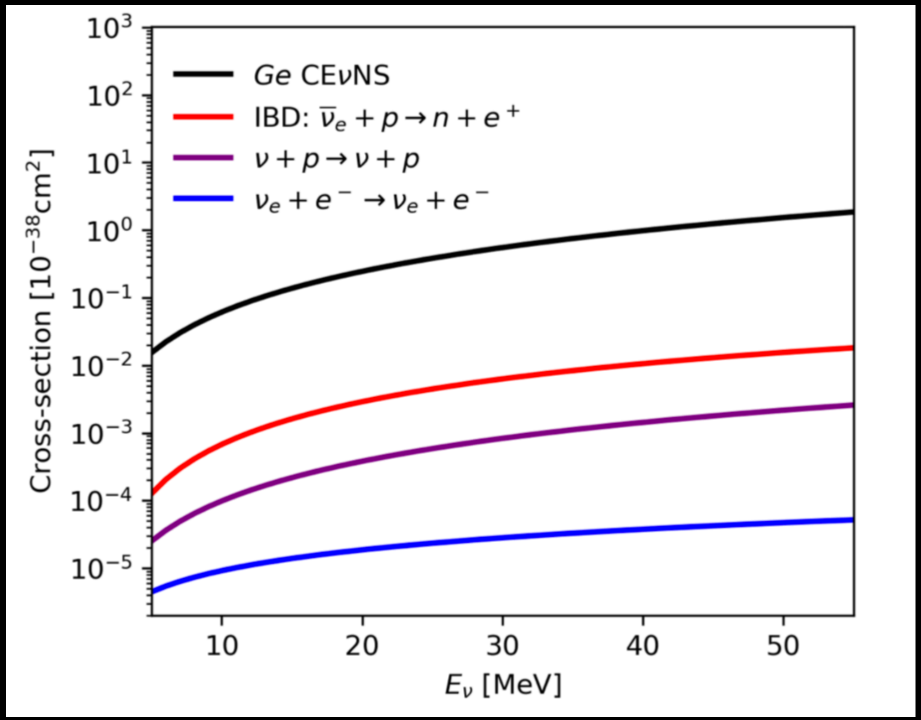
Coherent Elastic Neutrino-Nucleus Scattering

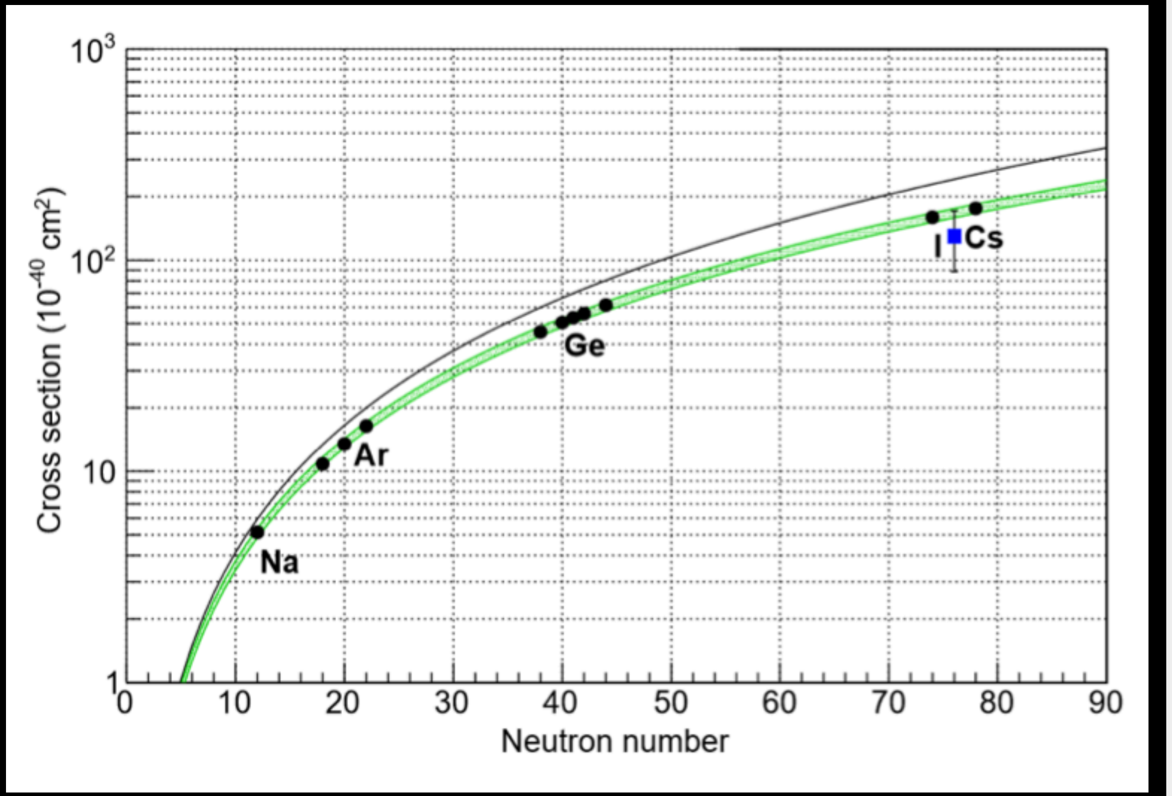
CEνNS has a well-calculable cross-section in the SM

Nuclear Form Factor

$$\frac{d\sigma_{\mathrm{coh}}}{dT} = \frac{G_F^2}{4\pi} M Q_W^2 \left(1 - \frac{MT}{2E_\nu^2}\right) F_{\mathrm{nucl}}^2(Q^2)$$

$$Q_W = \left[Z(1 - 4\sin^2\theta_W) - N\right]$$





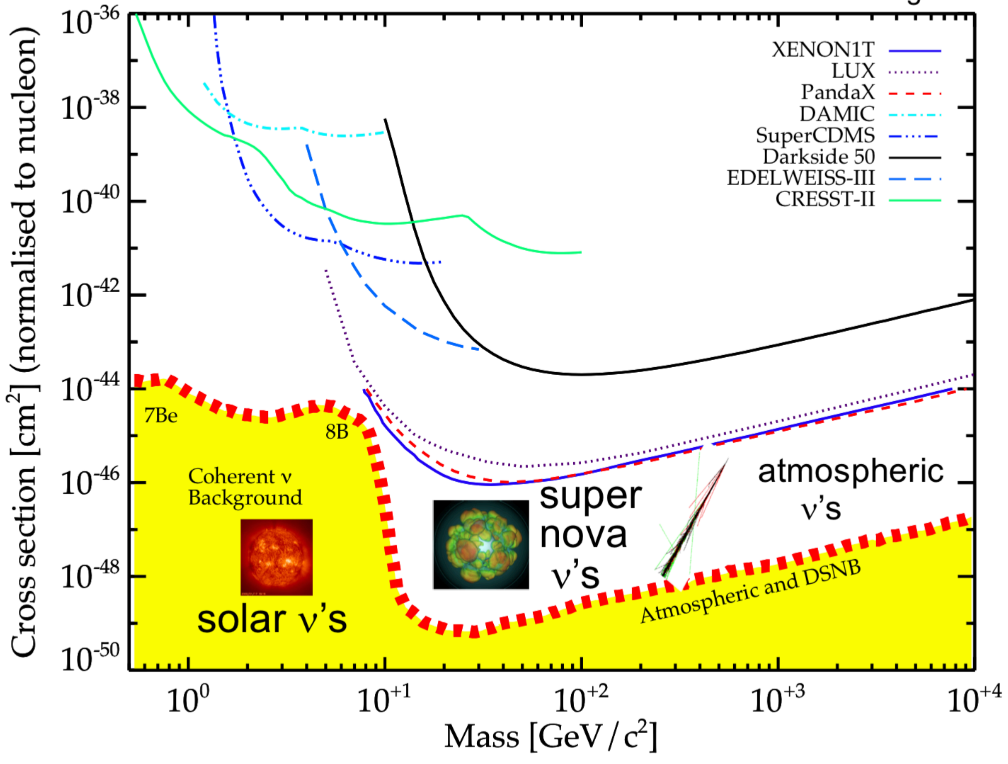
Credit to M. Green @Aspen 2019 Winter Conference

Coherent Elastic Neutrino-Nucleus Scattering

- CEνNS is an exceptionally challenging process to observe
- Despite its large cross section, not observed for years due to tiny nuclear recoil energies
  - Heavier nuclei: higher cross section but lower recoil
  - Both cross-section and maximum recoil energy increase with neutrino energy
  - Max recoil energy: $$E_R^{\text{max}} = \frac{2E_\nu^2}{m_N}$$
- Related to dark matter direct detection experiments:
  - CEνNS from natural neutrinos creates ultimate background for direct DM search experiments

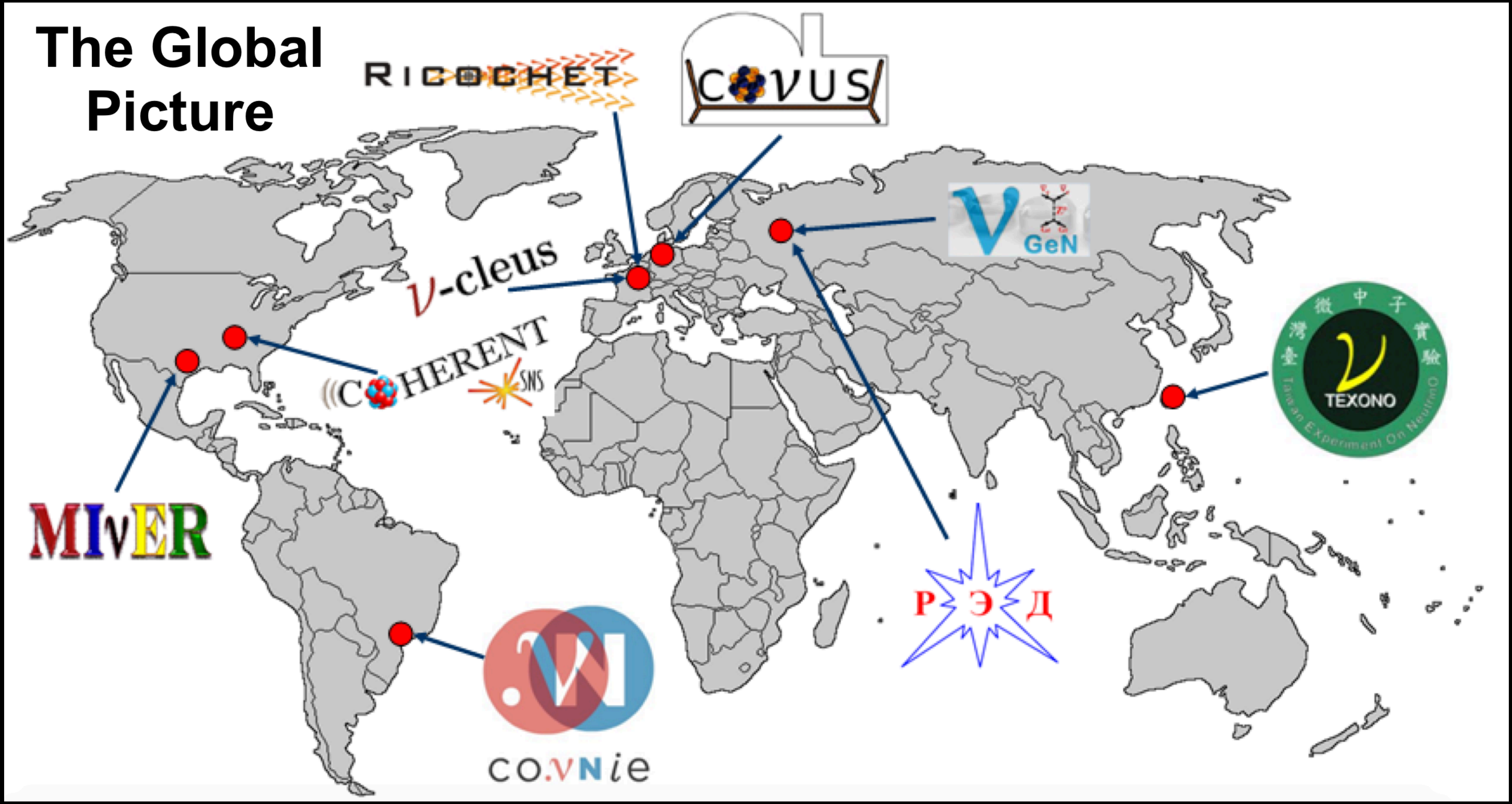
J. Monroe & P. Fisher, 2007 J. Billard, E. Figueroa-Feliciano, and L. Strigari, arXiv:1307.5458v2 (2013).

L. Strigari



D.Z. Freedman, Phys. Rev. D 9 (1974)
M.W. Goodman, E. Witten, Phys Rev D 31 (1985)
Billard et al., Phys. Rev. D89 (2014) 023524

CEvNS experiments worldwide



Credit to M. Green @Aspen 2019 Winter Conference

The COHERENT experiment

- COHERENT collaboration observed CEνNS at a 6.7-sigma confidence level in 2017 (more than 40 years after its prediction)
- Uses intense neutrino source provided by Spallation Neutron Source (SNS) at Oak Ridge National Laboratory
- (~1 GeV) Pulsed protons hit a liquid mercury fixed target
- Neutrinos stem from the decays of stopped pions and muons resulting in flux with well-defined spectral and timing characteristics

$$\pi^+ \to \mu^+ + \nu_\mu$$

monochromatic, prompt

$$\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$$

delayed

- The COHERENT detector uses different nuclear targets to allow for measurement of characteristic N^2 cross-section dependence
- Consists of 14.6 kg of CsI[Na]

Akimov et al., Science (2017), 1708.01294
Asimov et. al, 1804.09459
K. Scholberg, Phys. Rev. D73 (2006) 033005

CEνNS status

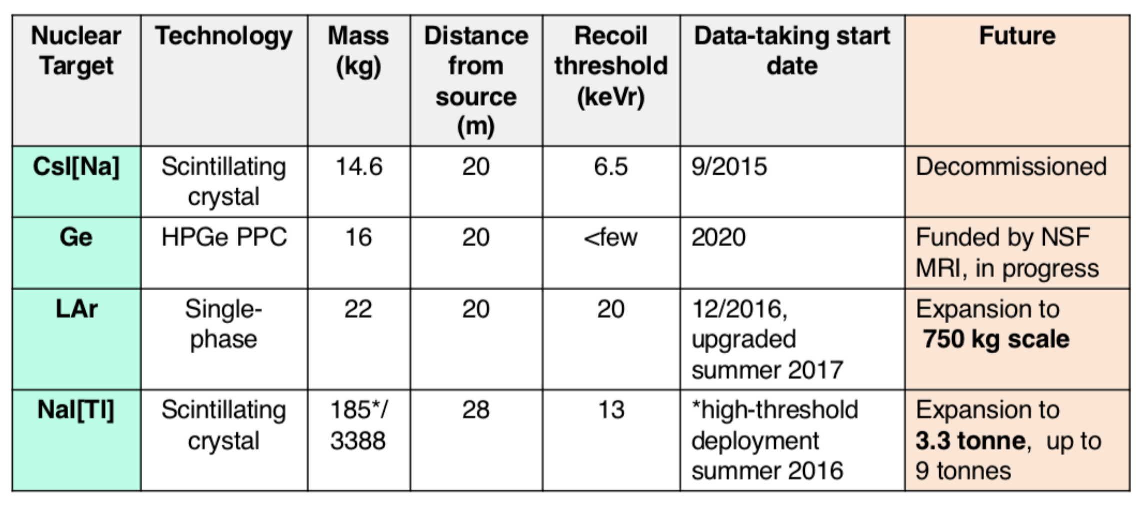
From accelerators:

- The COHERENT detector uses different nuclear targets to allow for measurement of characteristic N^2 cross-section dependence
- Recent result from LAr: <7.4 observed CEνNS events

From nuclear reactors:

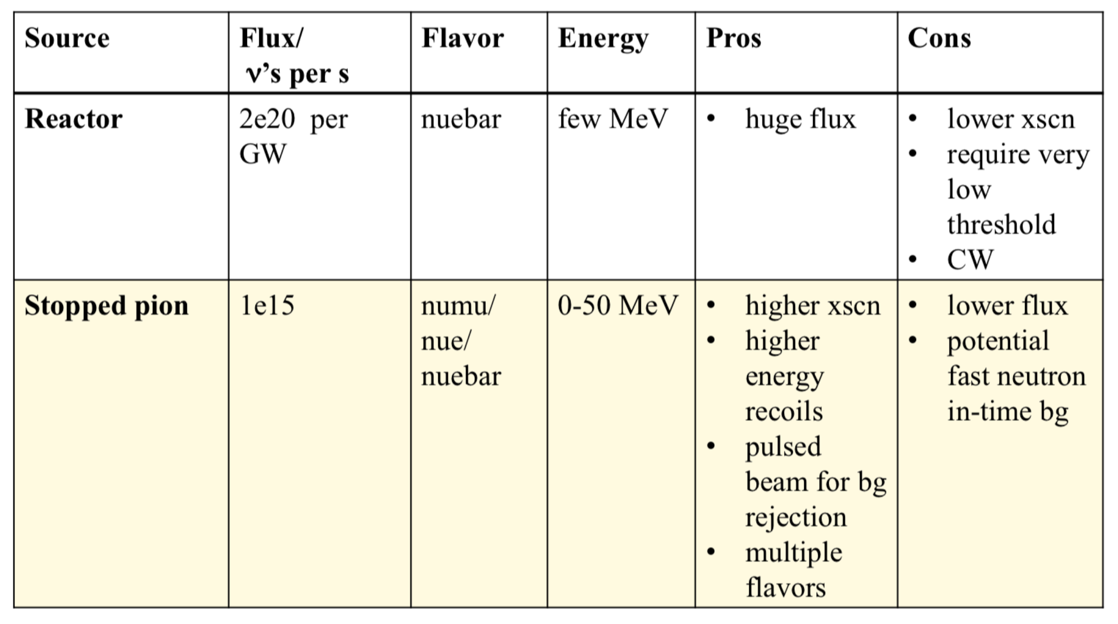
- Anti_ve are produced in fission reactions (single flavor); recoil energies<keV and backgrounds make it very challenging. E.g. CONUS, TEXONO, CONNIE, νCLEUS...
- CONNIE experiment measures low-energy recoils from CEνNS of reactor antineutrinos with silicon nuclei. It has not yet observed CEνNS at recoil energies below 20 keV.

Akimov et al., Science (2017), 1708.01294
Akimov et. al, 1804.09459
Akimov et al. 1909.05913
K. Scholberg, Phys. Rev. D73 (2006) 033005
Aguilar-Arevalo et al. 1906.02200



Nuclear Target	Technology	Mass (kg)	Distance from source (m)	Recoil threshold (keVr)	Data-taking start date	Future
CsI[Na]	Scintillating crystal	14.6	20	6.5	9/2015	Decommissioned
Ge	HPGe PPC	16	20	<few	2020	Funded by NSF MRI, in progress
LAr	Single-phase	22	20	20	12/2016, upgraded summer 2017	Expansion to **750 kg scale**
NaI[Tl]	Scintillating crystal	185*/ 3388	28	13	*high-threshold deployment summer 2016	Expansion to **3.3 tonne**, up to 9 tonnes

Credit to K. Scholberg @ TAUP 2019



Source	Flux/ ν's per s	Flavor	Energy	Pros	Cons
Reactor	2e20 per GW	nuebar	few MeV	• huge flux	• lower xscn • require very low threshold • CW
Stopped pion	1e15	numu/ nue/ nuebar	0-50 MeV	• higher xscn • higher energy recoils • pulsed beam for bg rejection • multiple flavors	• lower flux • potential fast neutron in-time bg

Credit to K. Scholberg @ TAUP 2019

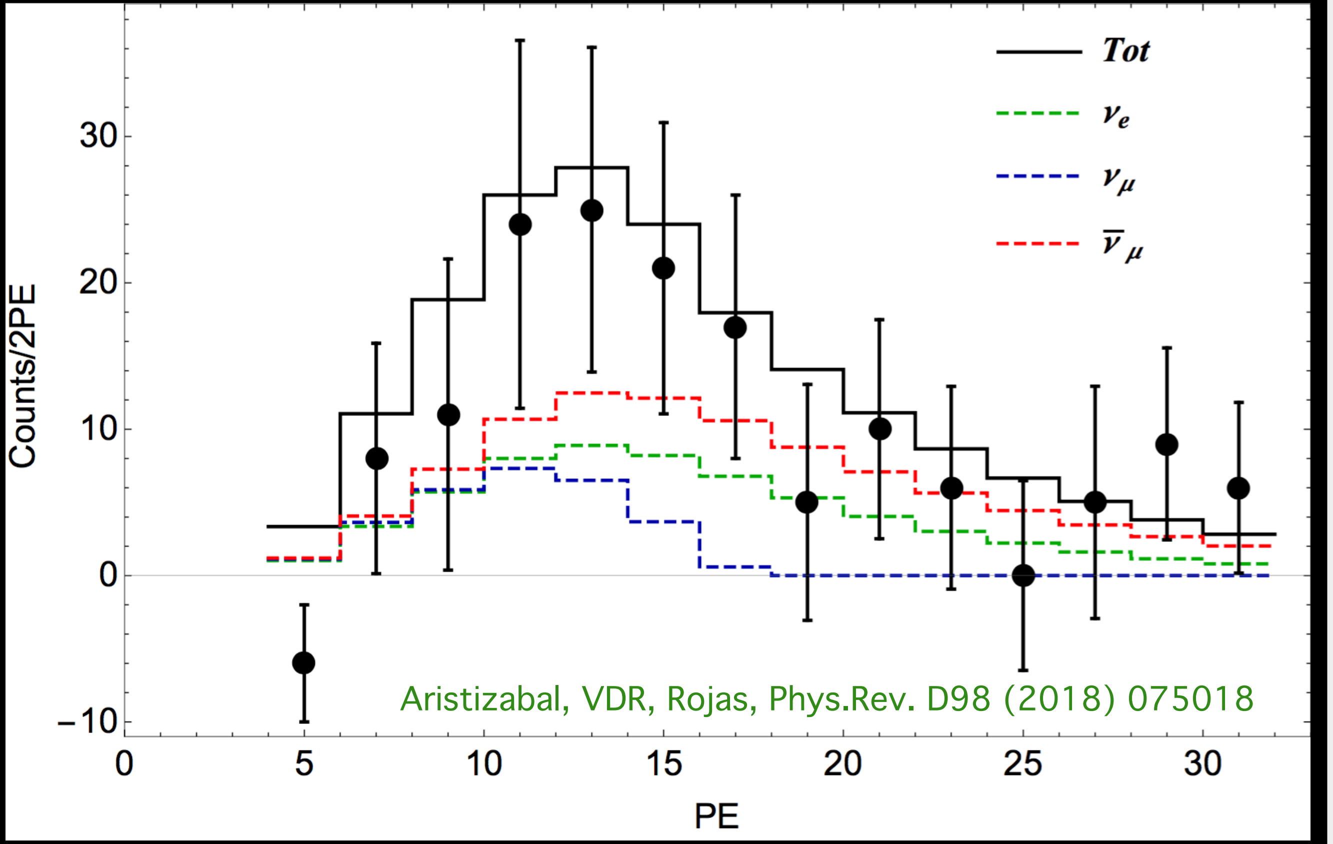
CEνNS physics potential

- CEvNS opens the window to a rich neutrino physics programme
  - Supernovae physics: determination of SN neutrino properties through measurement of the neutrino DSNB or neutrino emission in a single SN explosion
  - Nuclear properties such as: neutron form factor, neutron radius ...
  - Measurement, study and test of the SM axial nuclear current
  - Fundamental neutrino physics (weak mixing angle, effective neutrino charge radius and magnetic moment ...)

- New physics such as: non-standard neutrino interactions, sterile neutrinos, new NC heavy or light mediators ...

- COHERENT measurement consistent with SM at 1σ

- Still open room for new physics



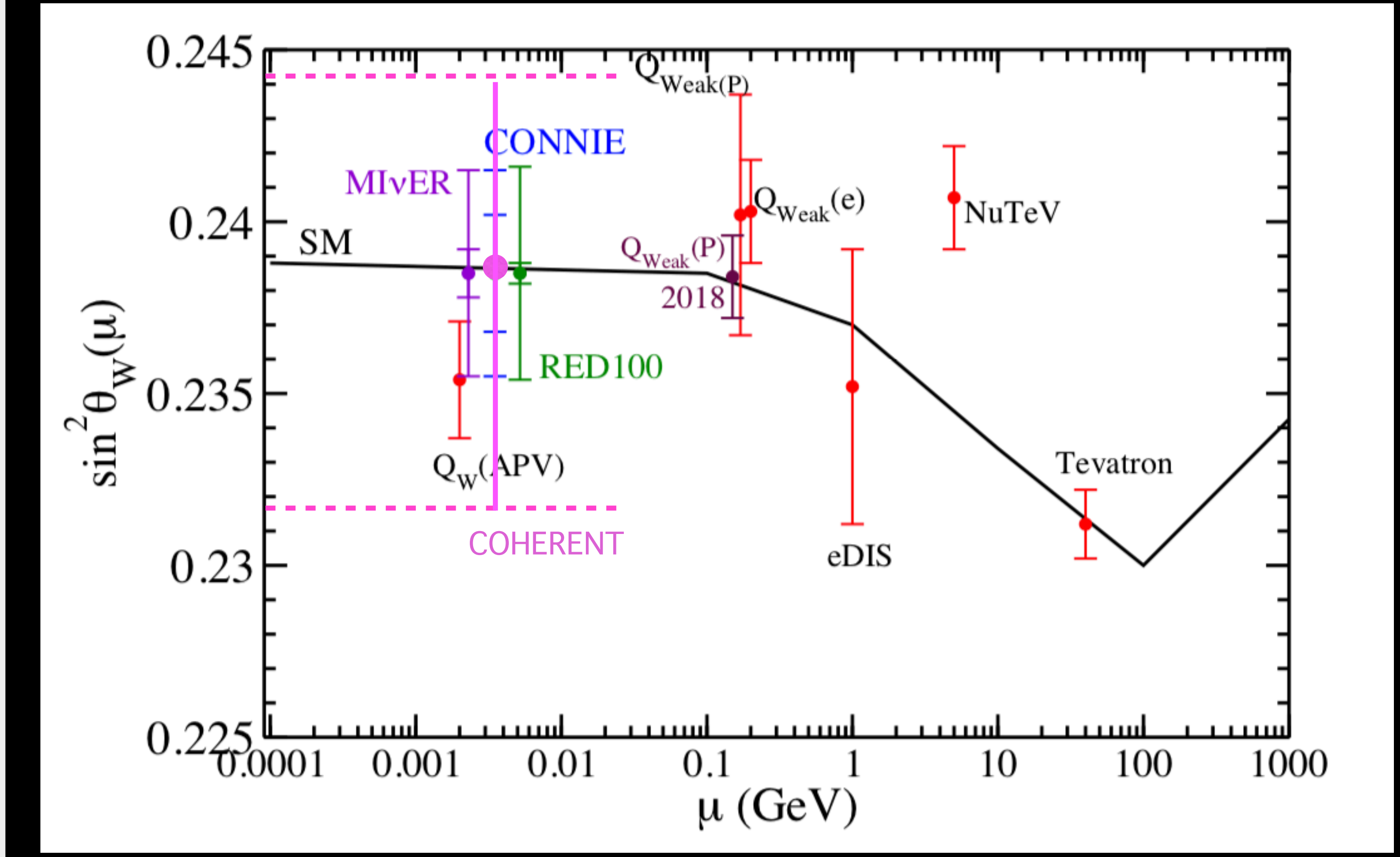
Aristizabal, VDR, Rojas, Phys.Rev. D98 (2018) 075018

D.Z. Freedman, Phys. Rev. D 9 (1974), C. Horowitz et al., Phys. Rev. D 68 (2003), H. Davoudiasl et al., Phys. Rev. D 89 (2014), J. Barranco et al., Phys. Rev. D 76 (2007), K. Patton et al., Phys. Rev. C 86 (2012), C. Horowitz & J. Piekarewicz, Phys. Rev. Lett. 86 (2000), K. Scholberg, Phys. Rev. D 73 (2006), P. Coloma et al., Phys. Rev. D 96 (2017), A.J. Anderson et al., Phys. Rev. D 86 (2012), Coloma et al. Phys. Rev. D 96, 115007, Cadeddu et al Phys. Rev. Lett. 120, 072501, Liao and Marfatia Phys. Lett. B775 (2017) 54–57, Papoulias and Kosmas Phys. Rev. D97 (2018) 033003, Farzan et al. JHEP 05 (2018) 066, ...

CEνNS physics example: Weak Mixing Angle

$$\frac{d\sigma_{\mathrm{coh}}}{dT} = \frac{G_F^2}{4\pi} M Q_W^2 \left(1 - \frac{MT}{2E_\nu^2}\right) F_{\mathrm{nucl}}^2(Q^2)$$

$$Q_W = \left[Z(1 - 4\sin^2\theta_W) - N\right]$$



adapted from Cañas et al., Phys.Lett. B784 (2018) 159-162 and MOLLER collab 1411.4088

- Expected sensitivity of CEνNS experiments to the weak mixing angle compared to the SM prediction.
- Measurements of the weak mixing angle in a region so far not measured.
- e.g. to probe hypothetical dark Z mediator (explanation for g-2 anomaly)

See also Cadeddu et al.,2018
Papoulias et al., 2018

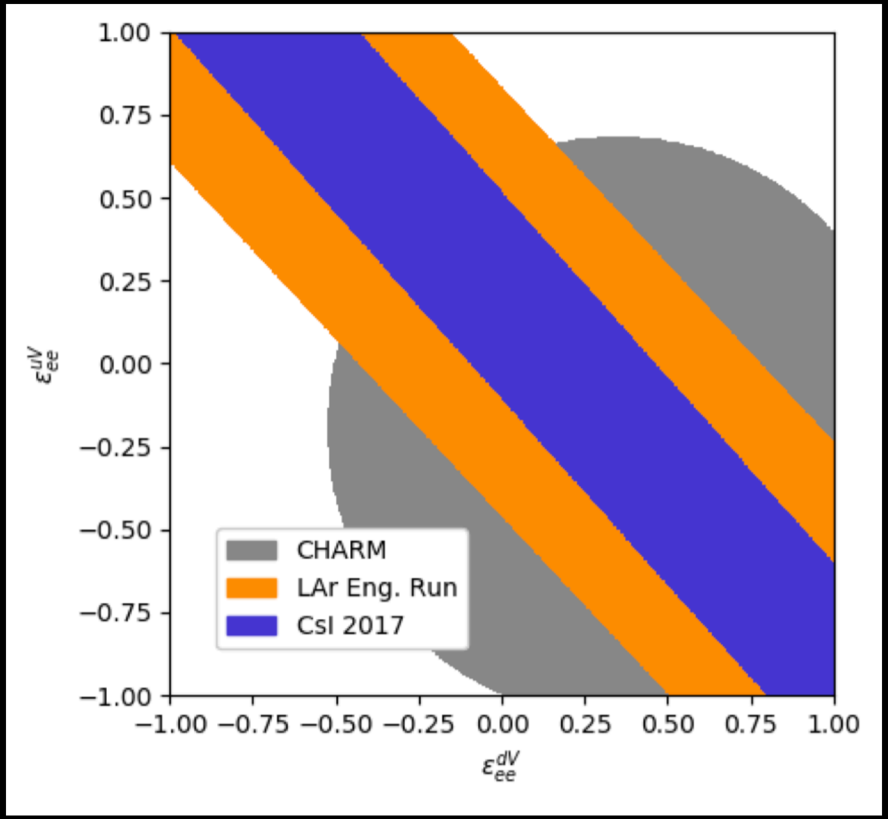
CEνNS and new physics interactions

- Neutrino NSI: non-standard interactions parametrised in a model-independent and phenomenological way

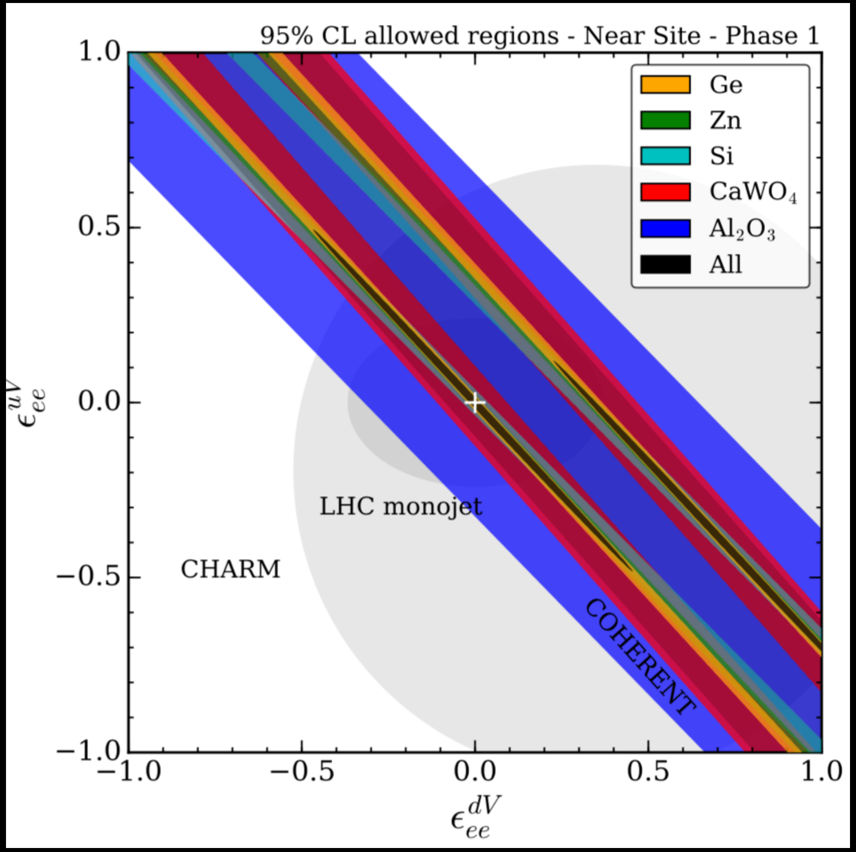
$$\mathcal{L} \sim G_F \sum_{q=u,d} \bar{\nu}_i(1-\gamma_5)\gamma_\mu \nu_j \bar{q}(\epsilon^{qV}_{ij} - \epsilon^{qA}_{ij}\gamma_5)\gamma^\mu q$$

- Pheno constraints from forward coherent scattering (matter potentials), DIS and oscillation data, LHC mono jet …
- For light mediators (mX ≲ 1 GeV) contributions of NSI to DIS are suppressed, COHERENT constraints are important

Coloma et al. Phys. Rev. D 96, 115007, Gonzalez-Garcia et al. 1803.03650

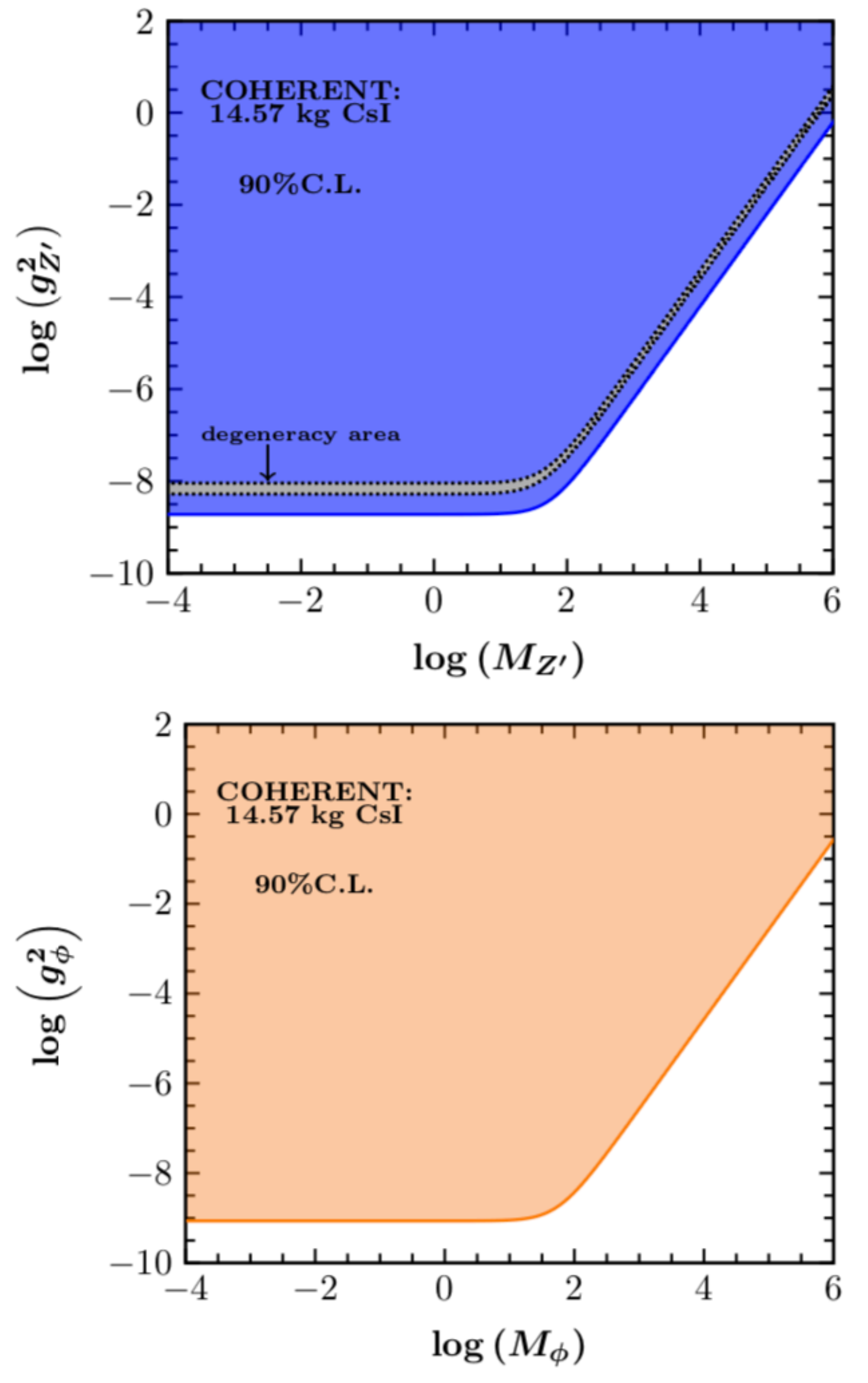


Akimov et al. 1909.05913



Billard et al. 1805.01798

CEνNS and new light mediators



Papoulias and Kosmas, Phys.Rev. D97 (2018) 033003

$$\mathcal{L}_{\rm vec} = Z'_\mu \left(g^{qV}_{Z'} \bar{q}\gamma^\mu q + g^{\nu V}_{Z'} \bar{\nu}_L \gamma^\mu \nu_L \right) + \frac{1}{2} M^2_{Z'} Z'_\mu Z'^\mu \,.$$

$$\mathcal{L}_{\rm sc} = \phi \left(g^{qS}_{\phi} \bar{q}q + g^{\nu S}_{\phi} \bar{\nu}_R \nu_L + \text{H.c.} \right) - \frac{1}{2} M^2_\phi \phi^2$$

See also:
Liao et al. PLB 775 (2017)
Abdullah et al. PRD98 (2018) 015005
Dutta et al. PRD 93 (2016) 013015

Neutrino Generalised Interactions (NGI)

- NSI are a subset of a larger set of neutrino-quark interactions: Neutrino Generalized Interactions (NGI)
- all Lorentz invariant non-derivative interactions of neutrinos with first generation quarks

$$\mathscr{L}^{\mathrm{NGI}}_{\mathrm{eff}} = \frac{G_F}{\sqrt{2}} \sum_X \bar{\nu}\Gamma^X \nu\, \bar{q}\Gamma_X \left(C^q_X + i\gamma_5\, D^q_X\right) q$$

Kayser et al. Phys. Rev. D 20, 87
Lindner et al. JHEP03(2017)097

$$\Gamma_X = \{\mathbb{1}, i\gamma_5, \gamma_\mu, \gamma_5\gamma_\mu, \sigma_{\mu\nu}\}$$

$$\mathscr{L}_S \sim (\bar{\nu}\nu)\left[\bar{q}\left(C^q_S + i\gamma_5 D^q_S\right) q\right]$$

$$\mathscr{L}_P \sim (\bar{\nu}\gamma_5\nu)\left[\bar{q}\left(\gamma_5 C^q_P + i D^q_P\right) q\right]$$

$$\mathscr{L}_V \sim (\bar{\nu}\gamma^\mu\nu)\left[\bar{q}\left(\gamma_\mu C^q_V + i\gamma_\mu\gamma_5 D^q_V\right) q\right]$$

$$\mathscr{L}_A \sim (\bar{\nu}\gamma^\mu\gamma_5\nu)\left[\bar{q}\left(\gamma_\mu\gamma_5 C^q_A + i\gamma_\mu D^q_A\right) q\right]$$

$$\mathscr{L}_T \sim (\bar{\nu}\sigma^{\mu\nu}\nu)\left[\bar{q}\left(\sigma_{\mu\nu} C^q_T + i\sigma_{\mu\nu}\gamma_5 D^q_T\right) q\right]$$

- Constrain dominant spin-independent contributions (C^q_X)
- Neglect Pseudoscalar and Axial interactions (spin-dependent: $Z_\uparrow - Z_\downarrow$, $N_\uparrow - N_\downarrow$)

Freedman et al. Ann. Rev. Nucl. Part. Sci. 27 (1977)

From quark to nuclear currents

- To compute the CEνNS cross section induced by the NGI we assume a fermion nuclear ground state with spin J = 1/2.

$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\text{max}}} + \xi_V^2 \left(1 - \frac{E_r}{E_r^{\text{max}}} - \frac{E_r}{E_\nu}\right) + \xi_T^2 \left(1 - \frac{E_r}{2E_r^{\text{max}}} - \frac{E_r}{E_\nu}\right) - R \frac{E_r}{E_\nu} \right]$$

$$\xi_S^2 = \frac{C_S^2 + D_P^2}{N^2}, \quad \xi_V^2 = \frac{C_V^2 + D_A^2}{N^2}, \quad \xi_T^2 = 8\frac{C_T^2}{N^2}, \quad R = 2\frac{C_S C_T}{N^2}$$

$$E_r^{\text{max}} \simeq 2E_\nu^2/m_{N_a}$$

- ν – N coefficients are written as follows

$$C_S = Z \sum_{q=u,d} C_S^{(q)} \frac{m_p}{m_q} f_{T_q}^p + (A-Z) \sum_{q=u,d} C_S^{(q)} \frac{m_n}{m_q} f_{T_q}^n ,$$

$$C_V = Z \left(2C_V^u + C_V^d\right) + (A-Z)\left(C_V^u + 2C_V^d\right) ,$$

$$C_T = Z \left(\delta_u^p C_T^u + \delta_d^p C_T^d\right) + (A-Z)\left(\delta_u^n C_T^u + \delta_d^n C_T^d\right) .$$

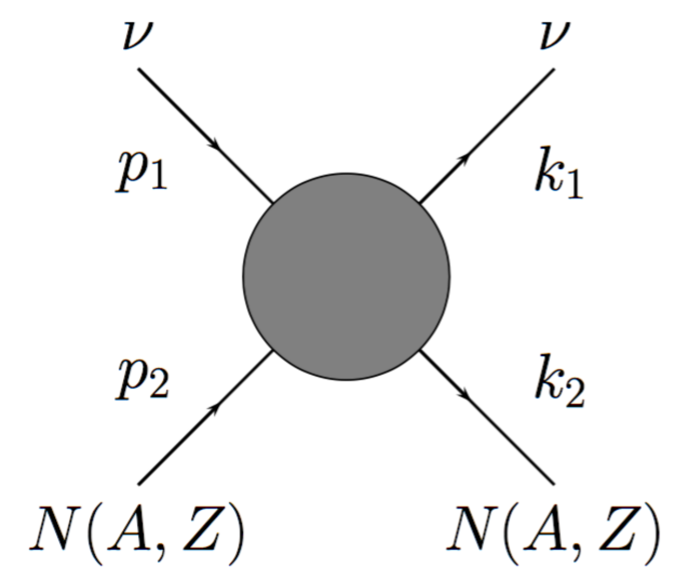
e.g. Dent et al. Phys. Rev. D92 (2015) 063515

NGI and CEvNS

- Cross section parameterised in terms of nuclear currents: Scalar, Vector and Tensor

$$\frac{d\sigma^a(q^2=0)}{dE_r} = \frac{G_F^2}{4\pi} m_{N_a} N_a^2 \left[\xi_S^2 \frac{E_r}{E_r^{\text{max}}} + \xi_V^2\left(1-\frac{E_r}{E_r^{\text{max}}}-\frac{E_r}{E_\nu}\right)+\xi_T^2\left(1-\frac{E_r}{2E_r^{\text{max}}}-\frac{E_r}{E_\nu}\right) - R\,\frac{E_r}{E_\nu}\right]$$

$$E_r^{\max} \simeq 2E_\nu^2/m_{N_a}$$



- Single-parameter scenario
- Two-parameter scenario

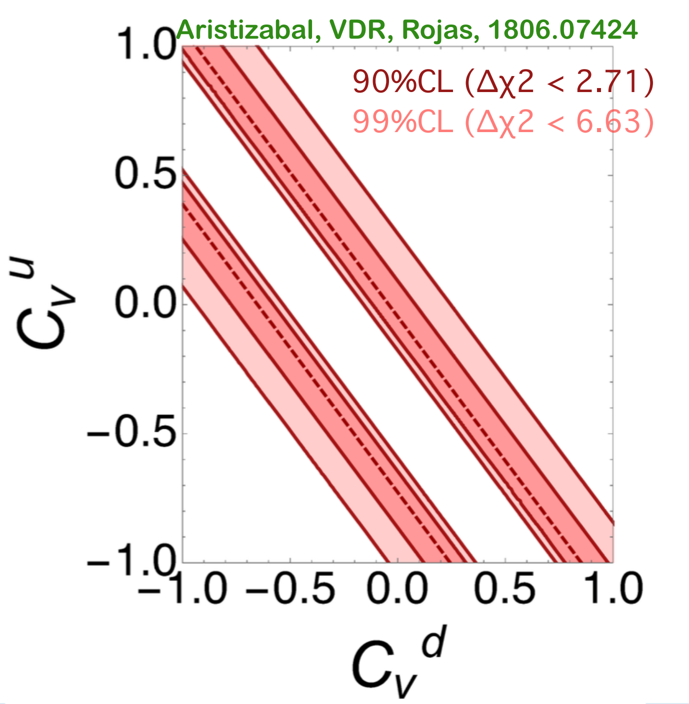
Lindner et al. JHEP03(2017)097
D. Aristizabal, VDR, N. Rojas, Phys.Rev. D98 (2018) 075018

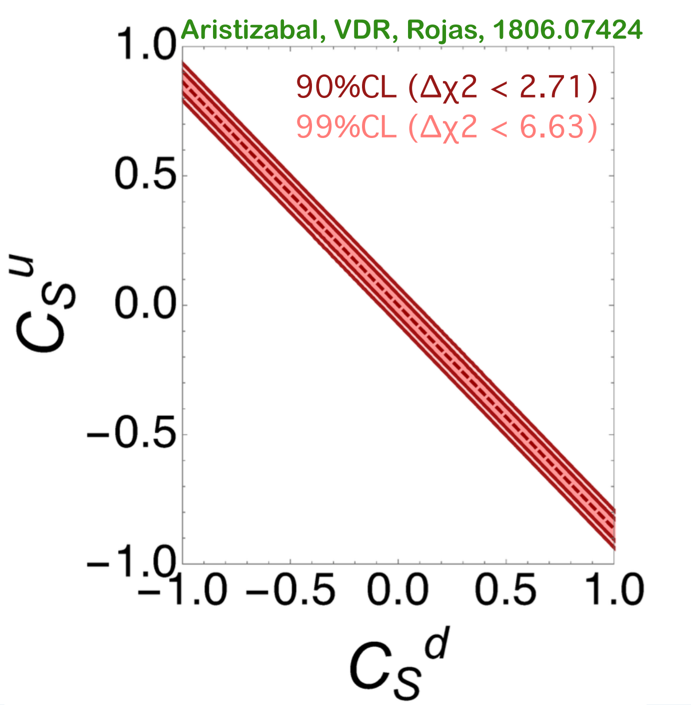
COHERENT constraints on NGI

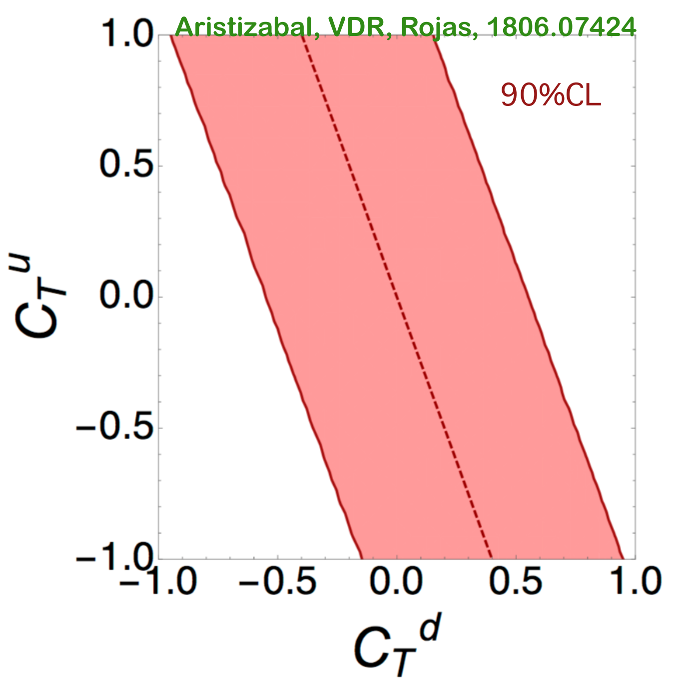
$$\chi^2 = \sum_{i=4}^{16} \left(\frac{N_i^{\text{meas}} - (1+\alpha) N_i^{\text{NGI}}(\mathscr{P}) - (1+\beta) B_i^{\text{on}}}{\sigma_i} \right)^2 + \left(\frac{\alpha}{\sigma_\alpha} \right)^2 + \left(\frac{\beta}{\sigma_\beta} \right)^2$$

- Single-parameter scenario
- Constraints on scalar-type interactions are the most stringent

Param	**BFP value**	90% CL	99% CL
ξ_S	0	$[-0.62, 0.62]$	$[-1.065, 1.065]$
ξ_V	-0.113	$[-0.324, 0.224]$	$[-0.436, 0.67]$
	-1.764	$[-2.102, -1.554]$	$[-2.545, -1.442]$
ξ_T	0	$[-0.591, 0.591]$	$[-1.071, 1.072]$

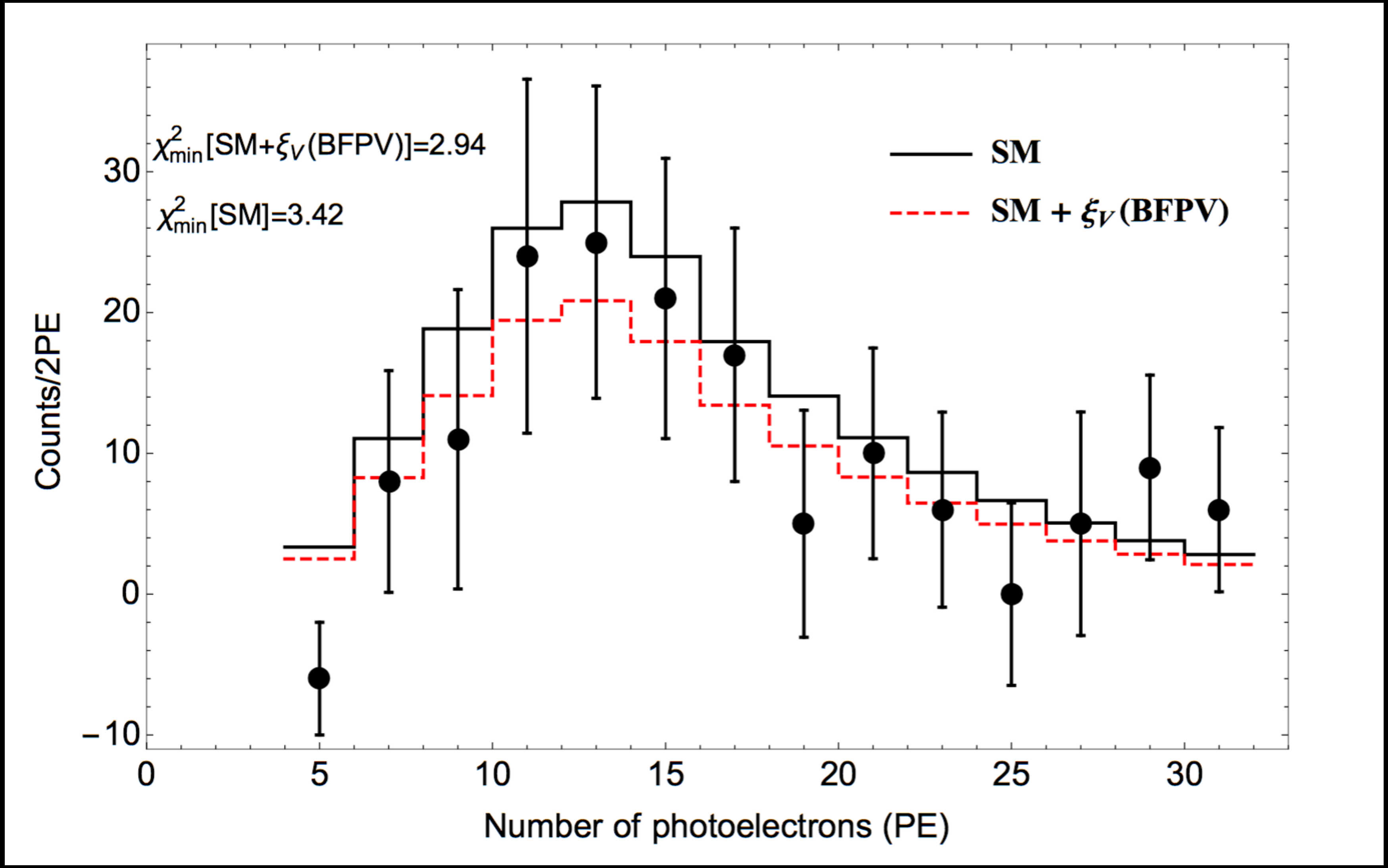






COHERENT constraints on NGI

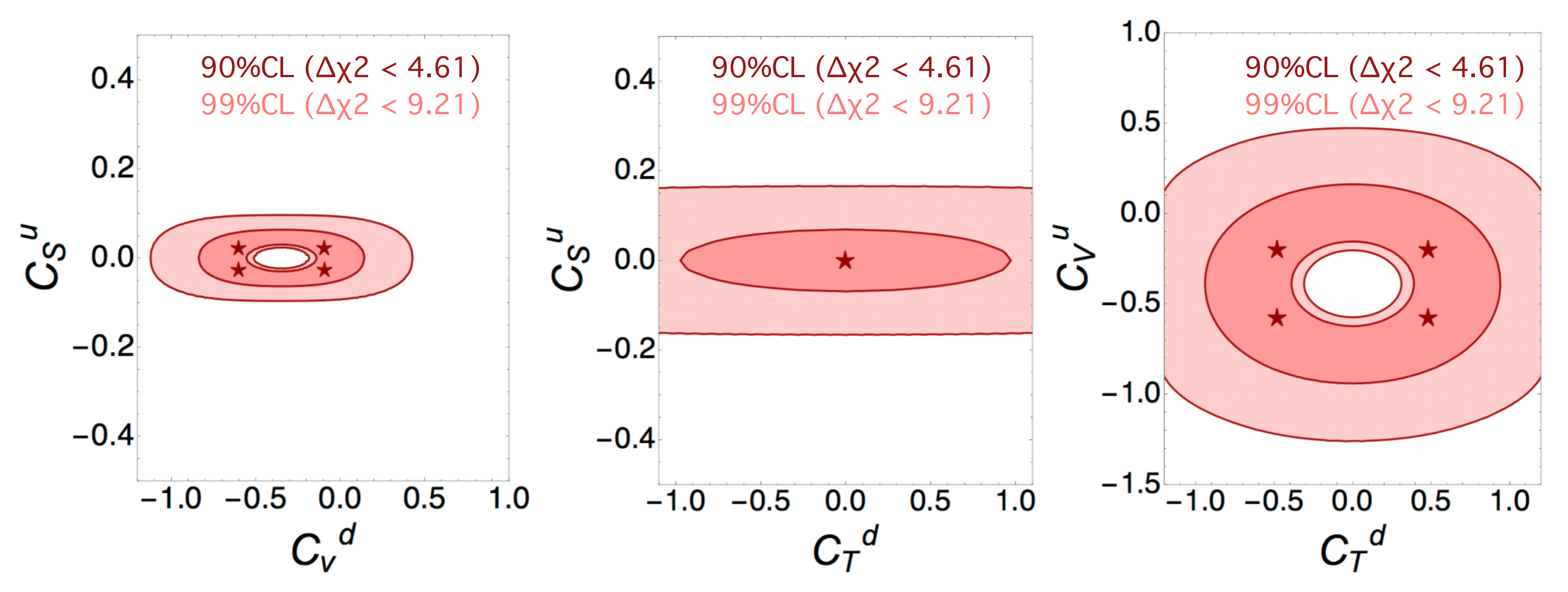
- Single-parameter scenario
- Sizeable NGI (vector interactions) are allowed



$n_{PE} = 1.17(E_R/\text{keV})$

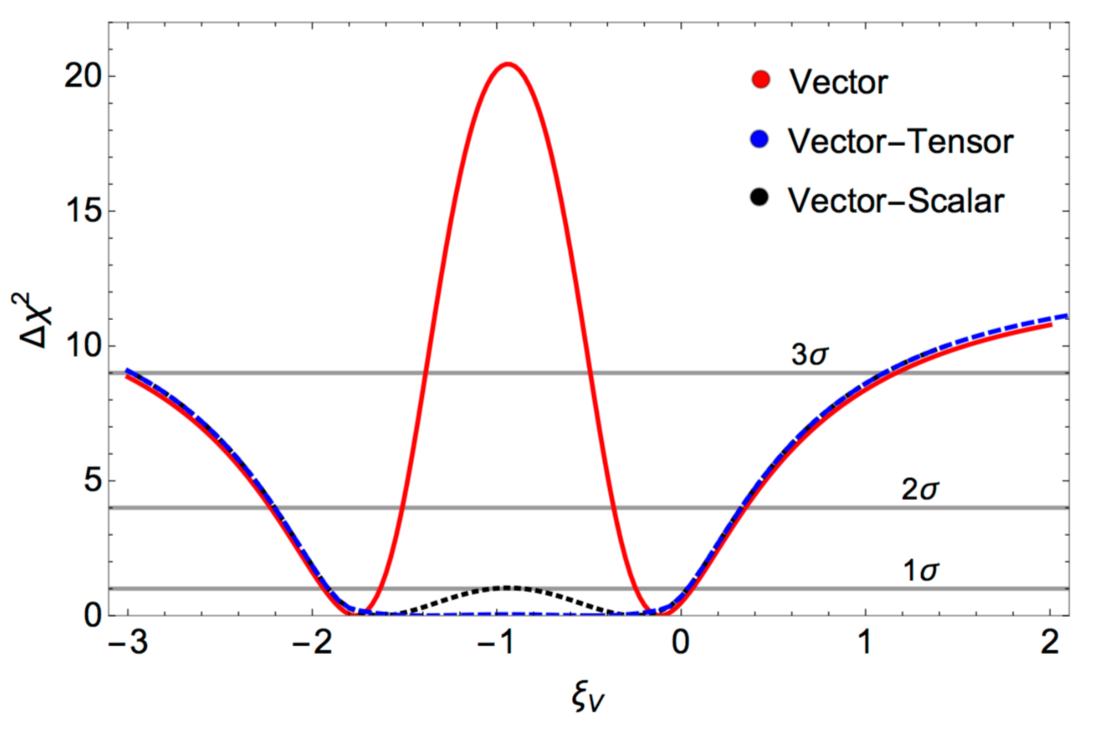
COHERENT constraints on NGI

- Two-parameter scenario



- The presence of an additional interaction at the nuclear level relaxes the bounds on the fundamental neutrino-quark couplings

$$\xi_V = -C_V = -[1-(1-4\sin^2\theta_w)-N/Z] \simeq -0.95$$



Summary of CEνNS constraints on NGI

- We have studied a generic set of effective Lorentz invariant non-derivative neutrino-quark interactions (NGI).

- We have employed the recent COHERENT data to place constraints on the different NGI effective parameters.

- In the single-parameter case, our findings show that the scalar interaction is the most constrained, with the tightest bound found for the Lorentz mixed pseudoscalar-scalar coupling.

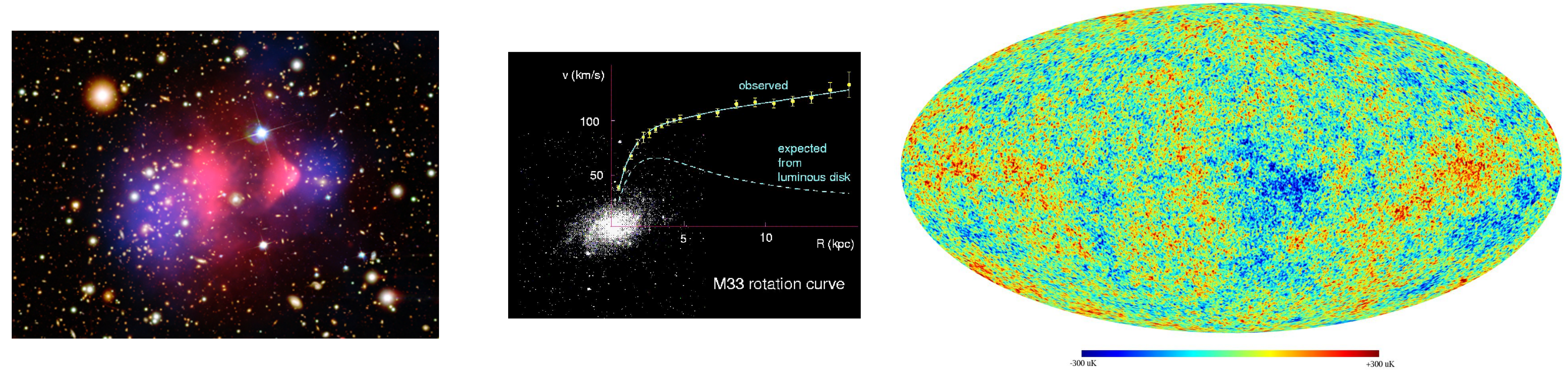
- In the two-parameter case, we have found that the presence of an additional interaction at the nuclear level relaxes the bounds on the fundamental neutrino-quark couplings.

- CEvNS offers a plethora of physics opportunities. Future new COHERENT data and forthcoming data from CONUS and e.g. ν-CLEUS will allow unraveling the presence of new physics.

Hunting for light dark matter with DUNE

VDR, K. Kelly, P. Machado, Phys. Rev. D 100, no. 9, 095010 (2019) +
DUNE Technical Design Report arXiv:2002.03005

There is overwhelming evidence for the existence of dark matter:



CMB anisotropies,
Clusters (X-rays, lensing),
Large Scale Structures,
Galaxies (rotation curves, fits...)

The content of the Universe in terms of paellas (after Planck)

Cosmological
and astrophysical
observations

26.8% Dark Matter
Black Rice Paella

4.9% Ordinary Matter
Valencian Paella

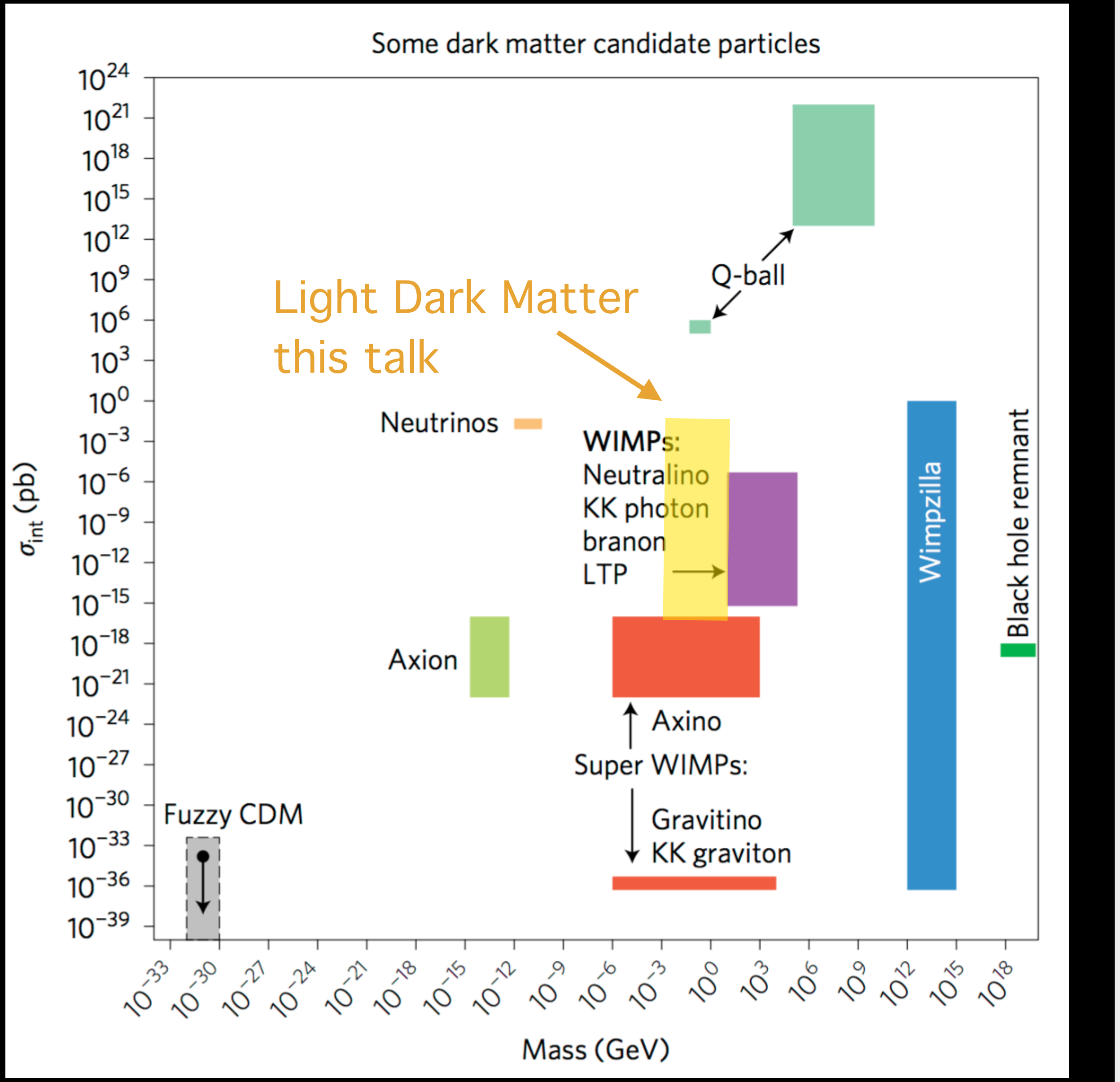
68.3% Dark Energy
Peppers' Paella

credit: R.A. Lineros

$$\Omega_{\rm CDM} h^2 = 0.1186 \pm 0.0020$$

What do we know about DM?

- ▶Non-baryonic (BBN, CMB)
- ▶Collisionless (bullet cluster)
- ▶Stable on cosmological scales (or lifetime >> t_U ~13.8 Gyr)
- ▶Neutral
- ▶Massive
- ▶Cold or Warm (structure formation)
- ▶Not in conflict/excluded by DM experiments and cosmological data



Park, E.-K. DMSAG Report on the Direct Detection and Study of Dark Matter (2007)

not included in the Standard Model

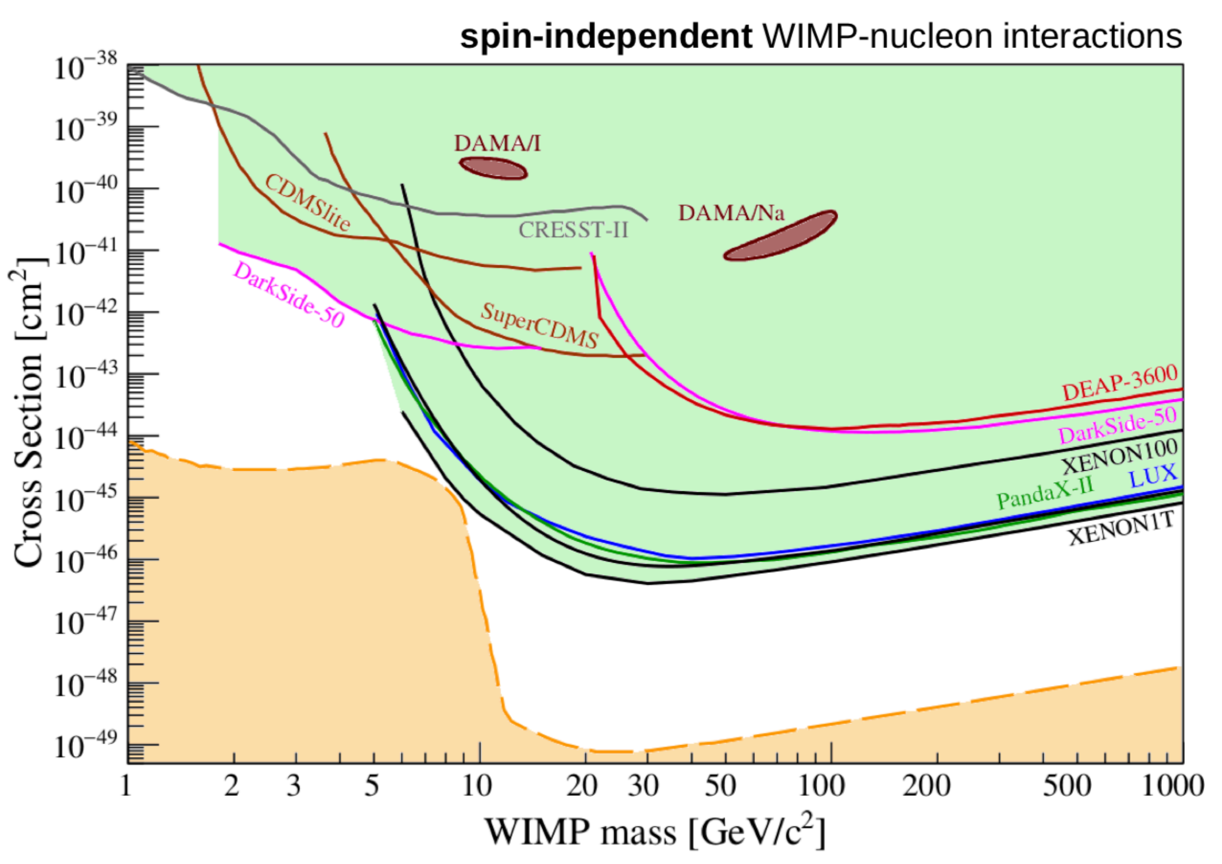
Many candidates in Particle Physics!

If DM is made of particles that interact among themselves and with SM particles we may hope to detect it. Two strategies:

1. DIRECT DETECTION (looks for energy deposited within a detector by the DM-nuclei scattering)

2. INDIRECT DETECTION (looks for WIMP annihilation (or decay) products)

+ complementary searches at colliders



M. Schumann ZPW 2019

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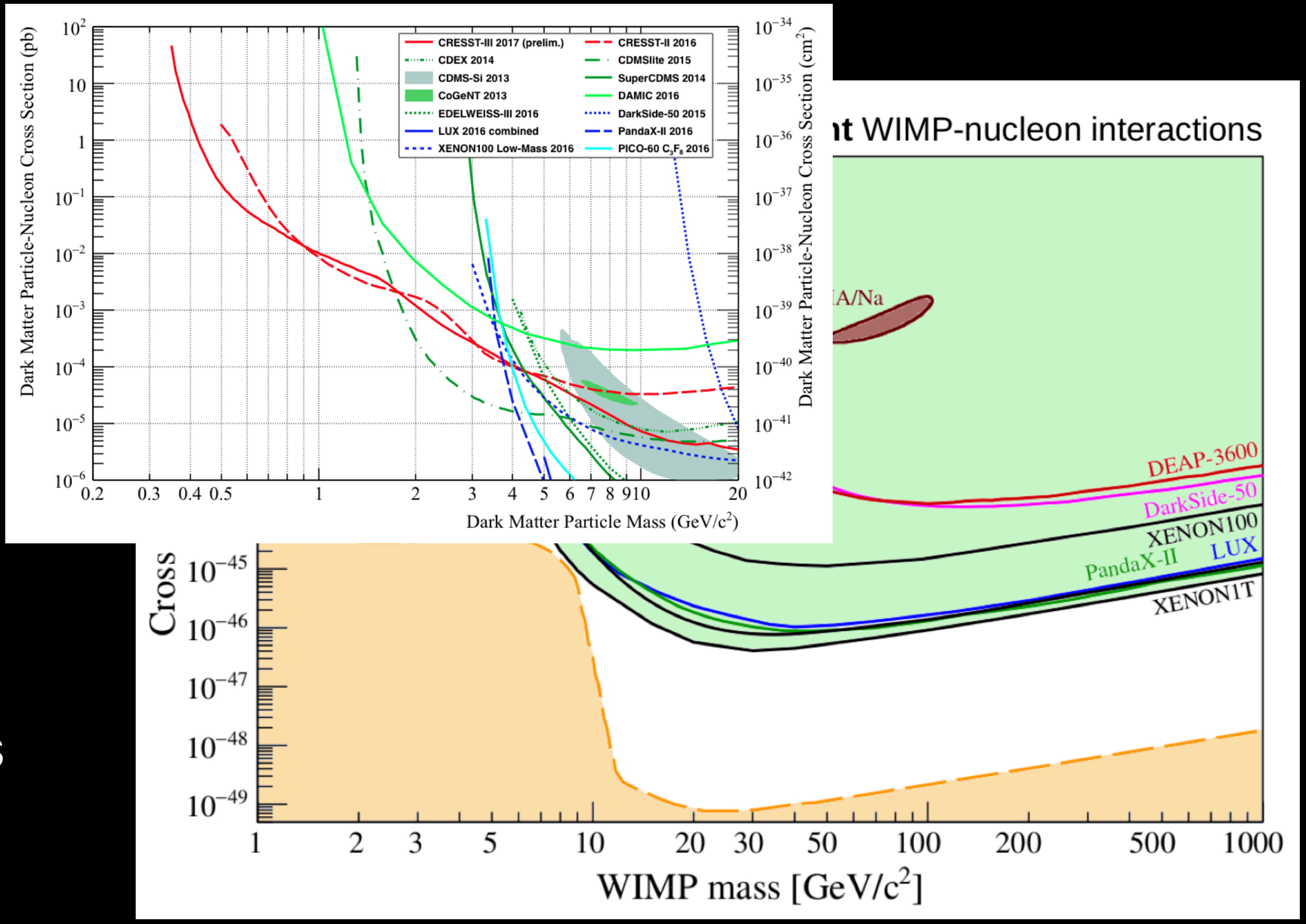

M. Schumann ZPW 2019, CRESST-III exp

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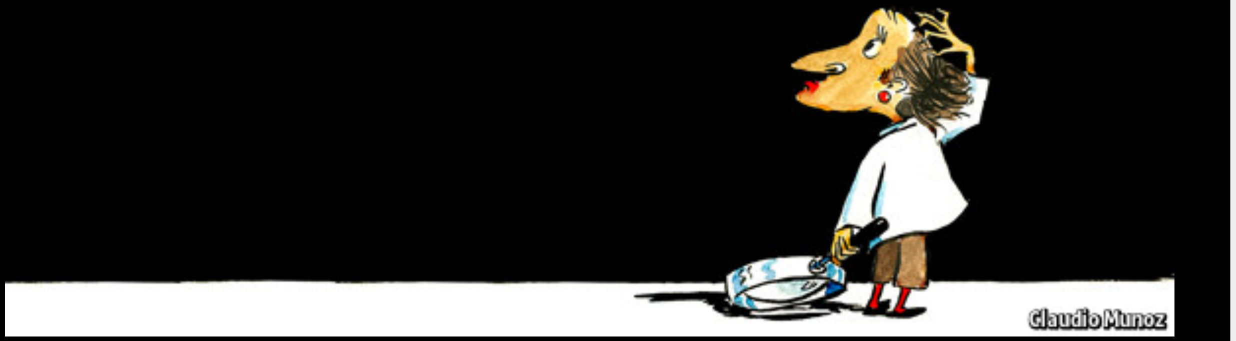

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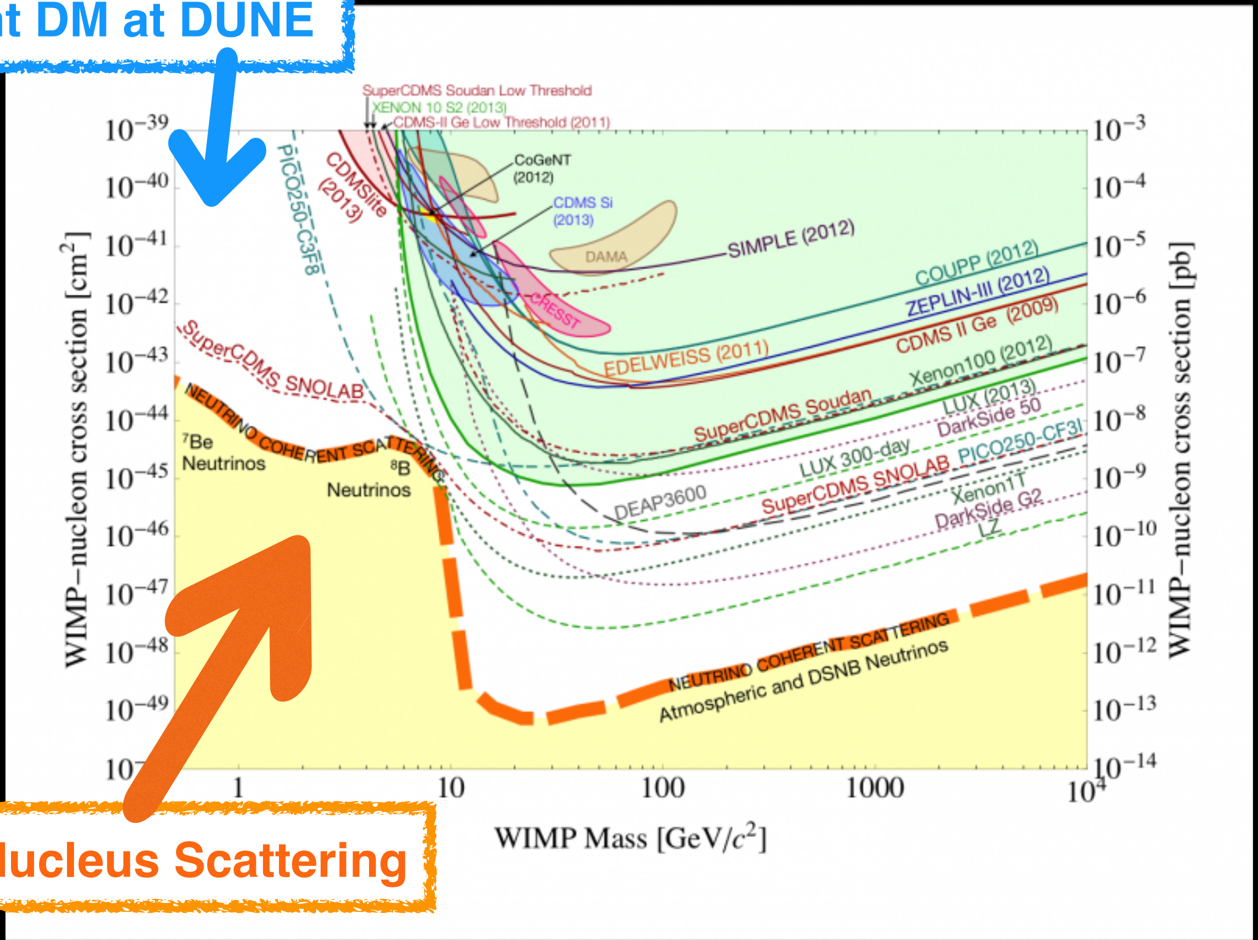
Light DM at DUNE

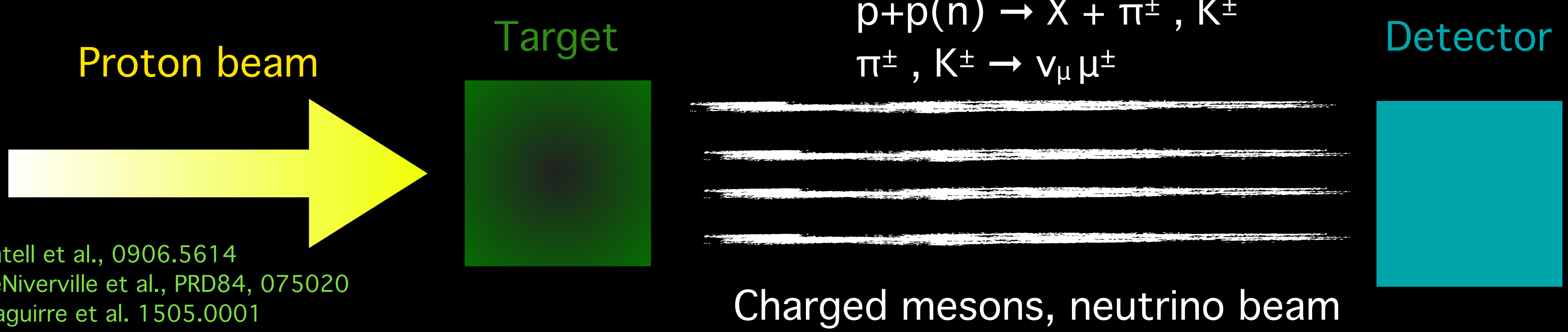


Coherent Elastic Neutrino-Nucleus Scattering

Snowmass CF1 Final Summary Report 2013

Light dark matter signals in neutrino detectors

- Need of new experimental strategies
- Traditional direct detection experiments and the LHC have limited sensitivity to sub-GeV DM
- Neutrino facilities to probe light dark matter-nucleon interactions
- Experiments impact a target with ~10^{21} protons/yr to produce a high intensity neutrino beam.
- Neutrinos produced from decays of charged mesons propagating through subsequent decay volume
  - Can select for neutrino or antineutrino beams through the use of magnetic focusing horns.
  - Non-neutrinos are removed from the beam before it reaches the detector to reduce background.


Proton beam

Target

$p+p(n) \rightarrow X + \pi^\pm , K^\pm$

$\pi^\pm , K^\pm \rightarrow \nu_\mu \mu^\pm$

Detector

Charged mesons, neutrino beam

Batell et al., 0906.5614
deNiverville et al., PRD84, 075020
Izaguirre et al. 1505.0001
deNiverville et al., PRD95 035006
deNivervile, Frugiuele 1807.06501
++ ...

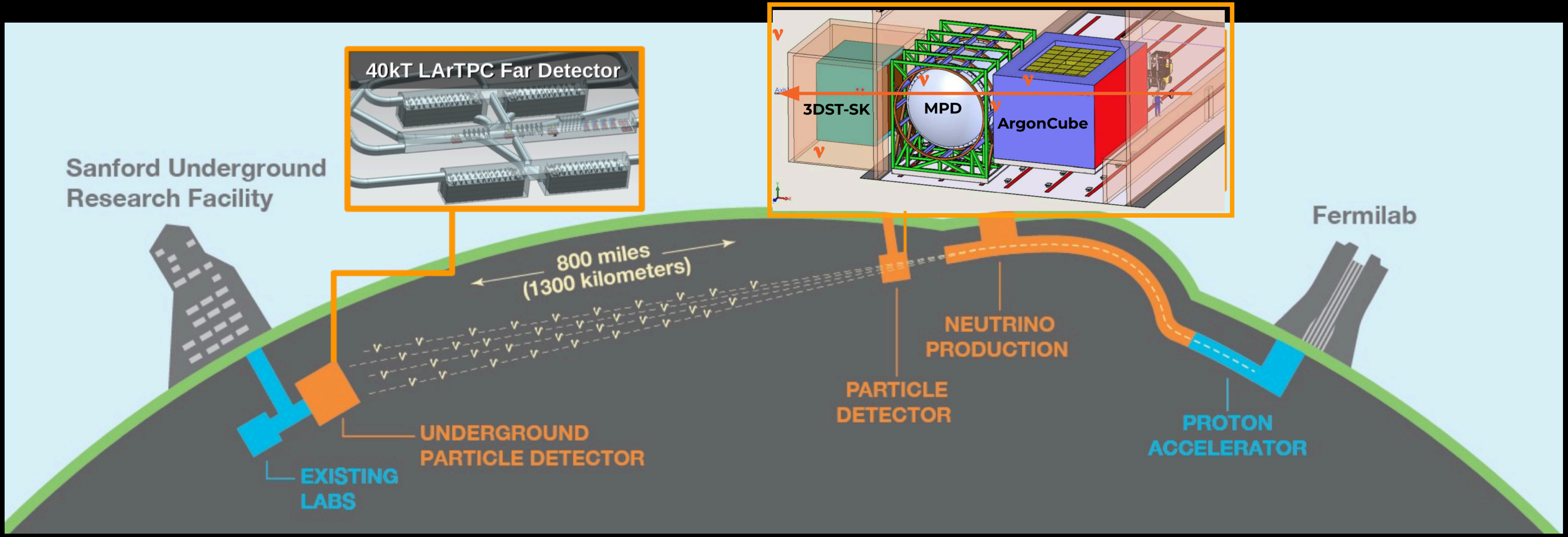
Light dark matter @ DUNE

- To search for DM with high mediator mass (1-10 GeV), we need high proton energy.

- The Deep Underground Neutrino Experiment (DUNE) is the next generation long baseline neutrino experiment to provide a broad neutrino physics programme. It will consist of:

    - Far Detector: 40 kton (fiducial) liquid argon time-projection chamber (LArTPC) installed (on-axis) 1475 meters underground at the Sanford Underground Research Facility in Lead, South Dakota, 1300 km away from the source.
    - Hybrid Near Detector: integrated system composed of multiple detectors placed at a distance of ~574 m from the beam line. LArTPC and MPD (GAr TPC) designed to be moved for off-axis measurements.

- Fermilab's Main Injector accelerator as a powerful 60-120 GeV proton beam (1.2MW upgradeable to 2.4MW) to make highest intensity neutrino beam.



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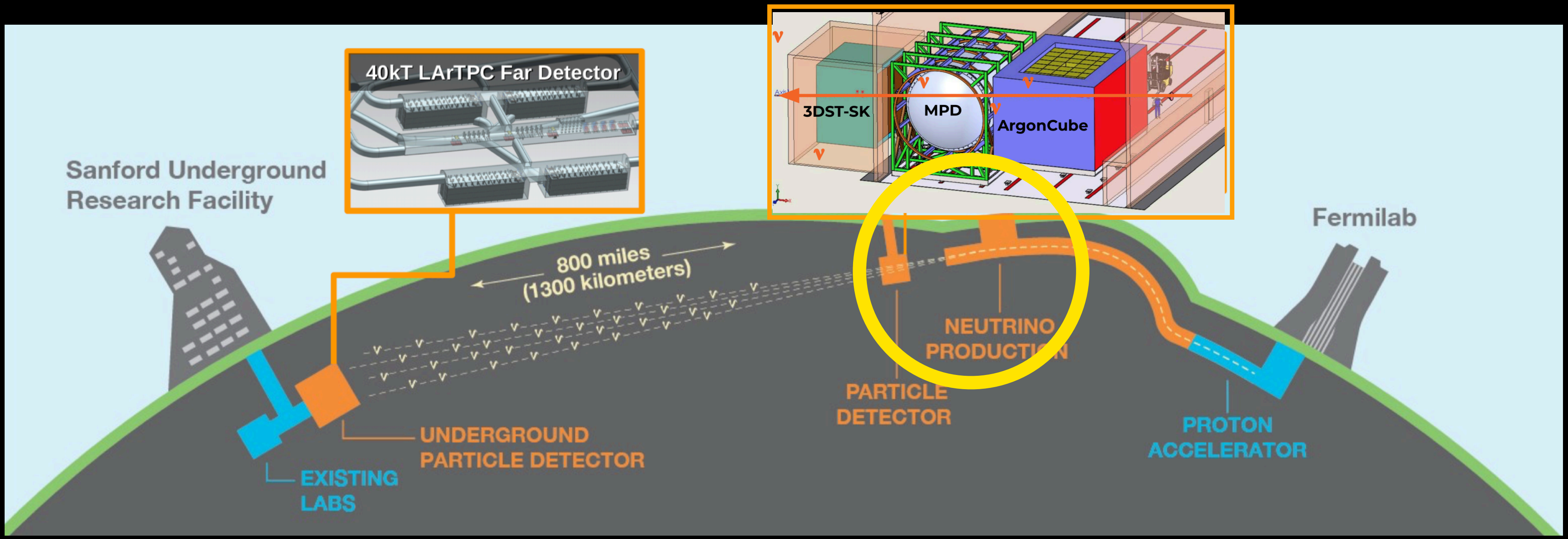
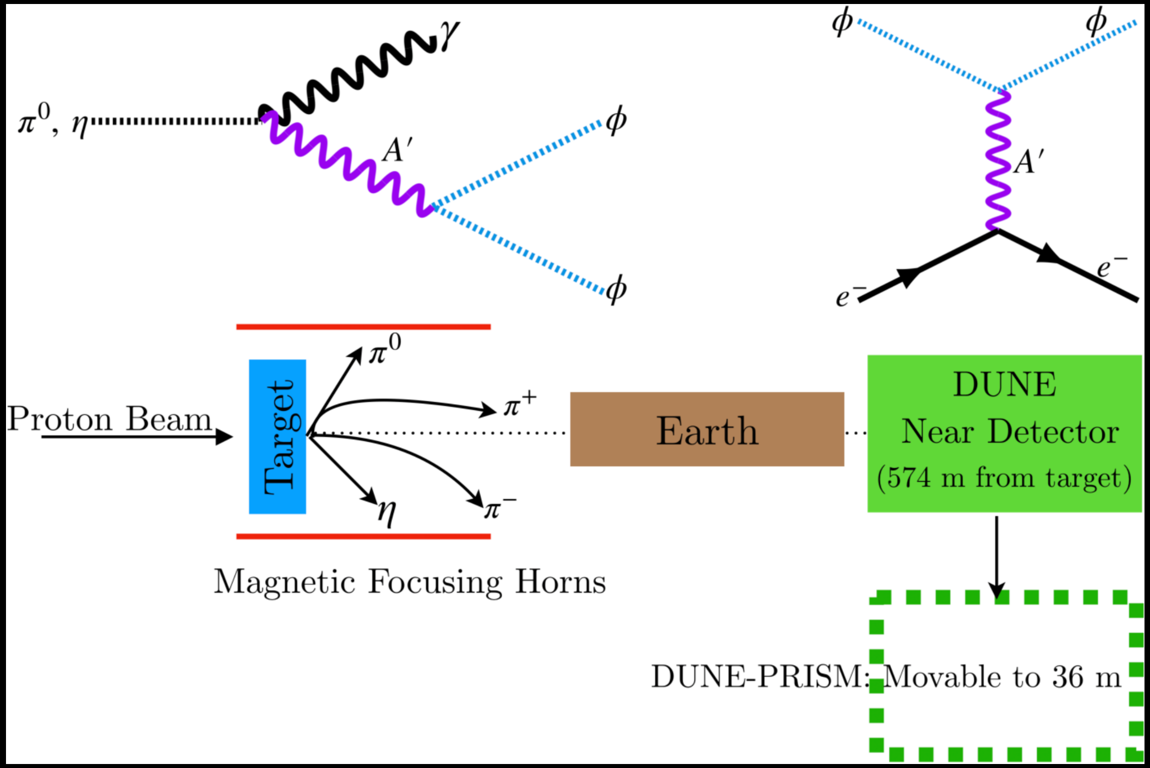


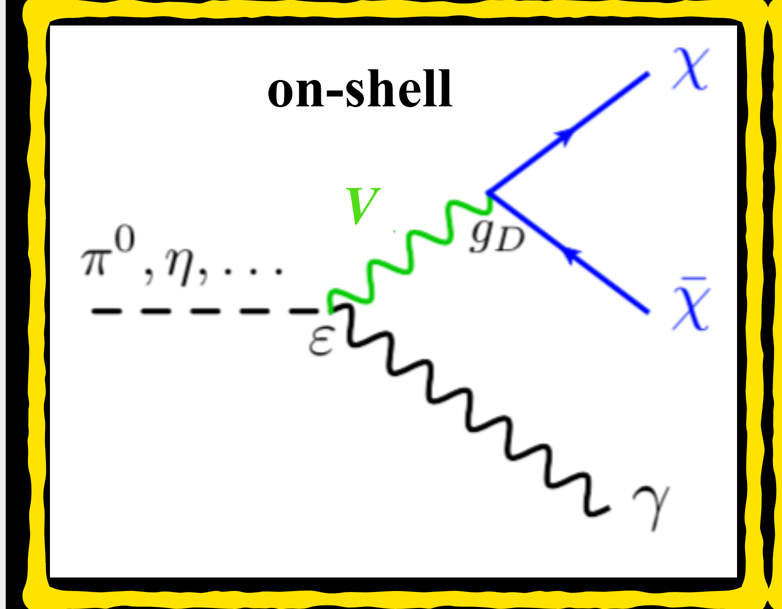
Light dark matter @ DUNE

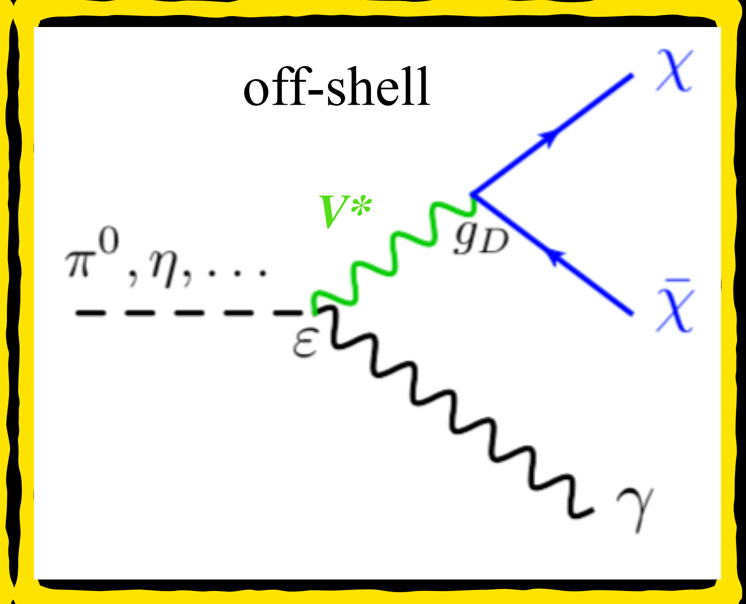
DUNE near detector can perform as a high intensity beam dump experiment.

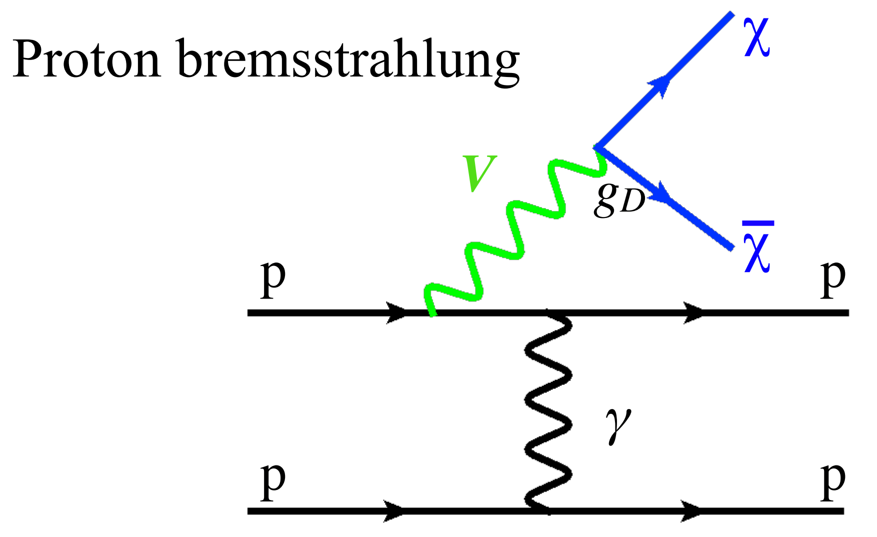
- High luminosity available (10^{21} POT/year)
- Allows for the production of a sizeable relativistic DM beam
- DM produced in the radiative decay of neutral hadrons, proton bremsstrahlung processes or direct parton-level production



VDR et al. Phys.Rev. D100 (2019) no.9, 095010







Light dark matter: dark photon portal

Extend the SM gauge group by including a new U(1)$_D$, spontaneously broken in a hidden sector.

A dark matter particle χ (or Φ) interacts with the SM particles through a massive dark photon A′ and its kinetic mixing with the photon.

- DM is a light WIMP
- stable because new interactions are such that the DM can only be pair produced.

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + \overline{\chi} i \gamma^\mu \left(\partial_\mu - i g_D A'_\mu\right) \chi - M_\chi \overline{\chi} \chi$$

- Fermionic DM

$$\mathcal{L} \supset -\frac{\varepsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{M_{A'}^2}{2} A'_\mu A'^\mu + |D_\mu \phi|^2 - M_\phi^2 |\phi|^2$$

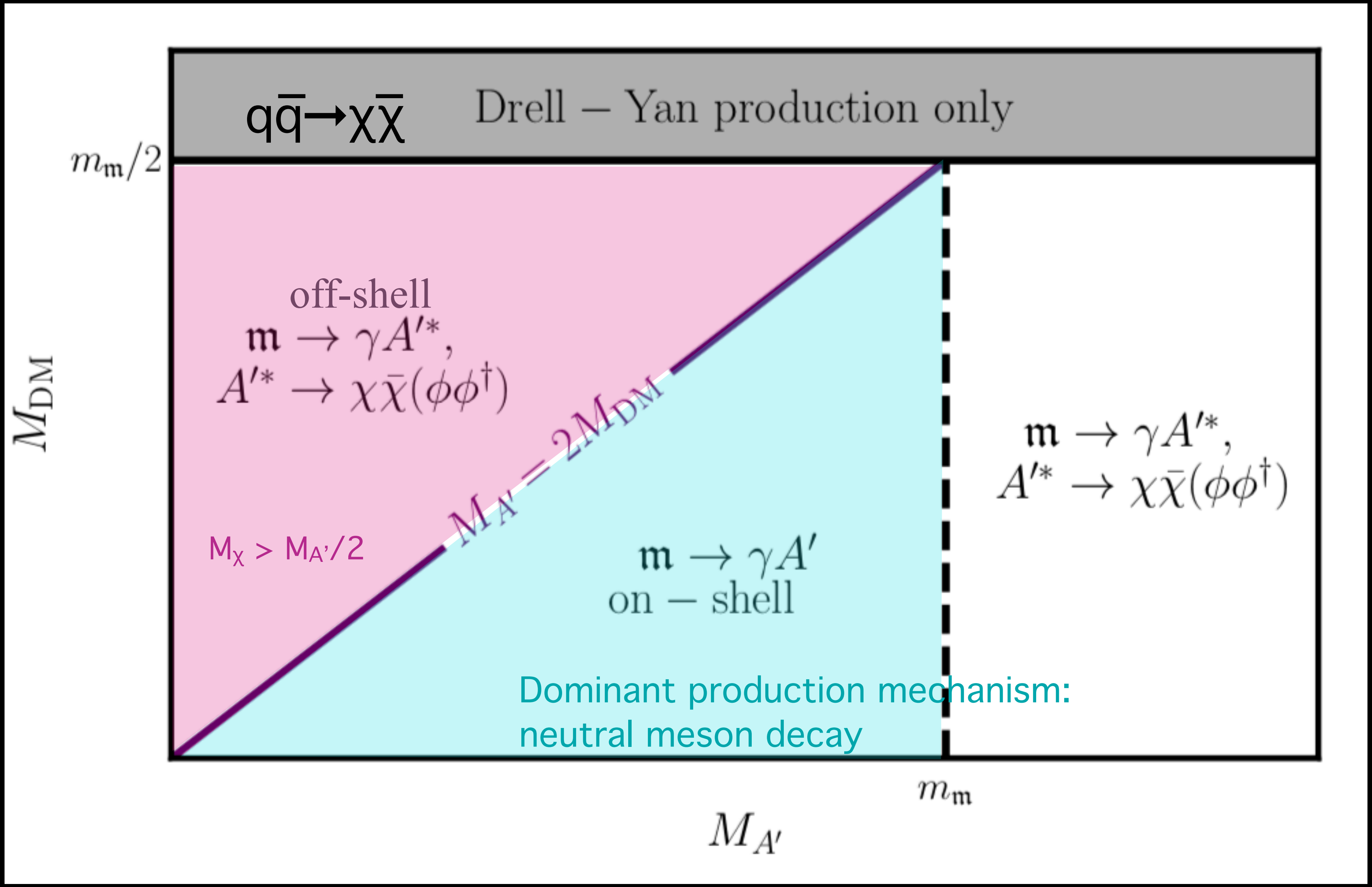
- Scalar DM

- ε kinetic mixing parameter between the SM U(1)$_Y$ and the new U(1)$_D$
- g_D gauge coupling associated to the dark U(1)$_D$
- $\alpha_D \equiv g_D^2/(4\pi)$, dark fine structure constant

Okun Sov. Phys JTEP 56, 502
Holdom PLB 166 196
Pospelov et al. Phys. Lett. B662 (2008) 53–61
Pospelov Phys. Rev. D80 (2009) 095002

Light dark matter @ DUNE

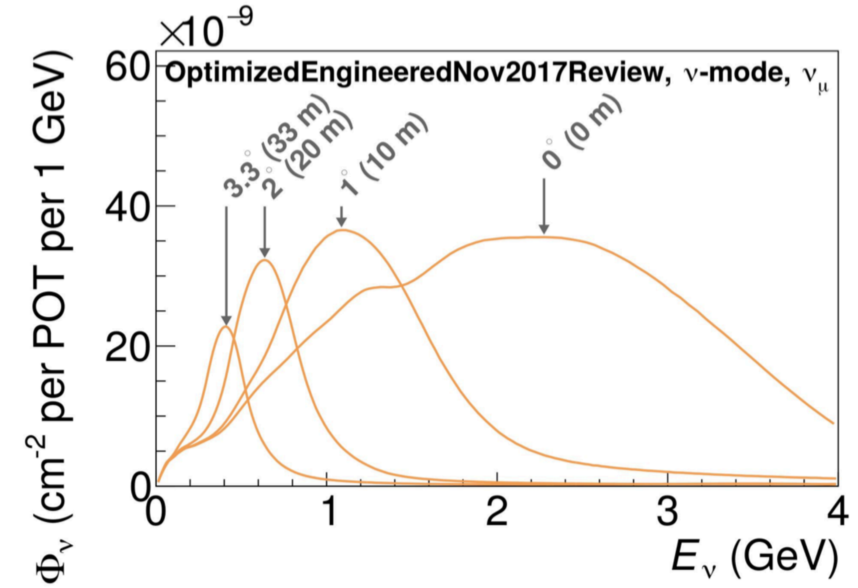
Any process in which photons participate at a neutrino facility can lead to A’ or DM production.



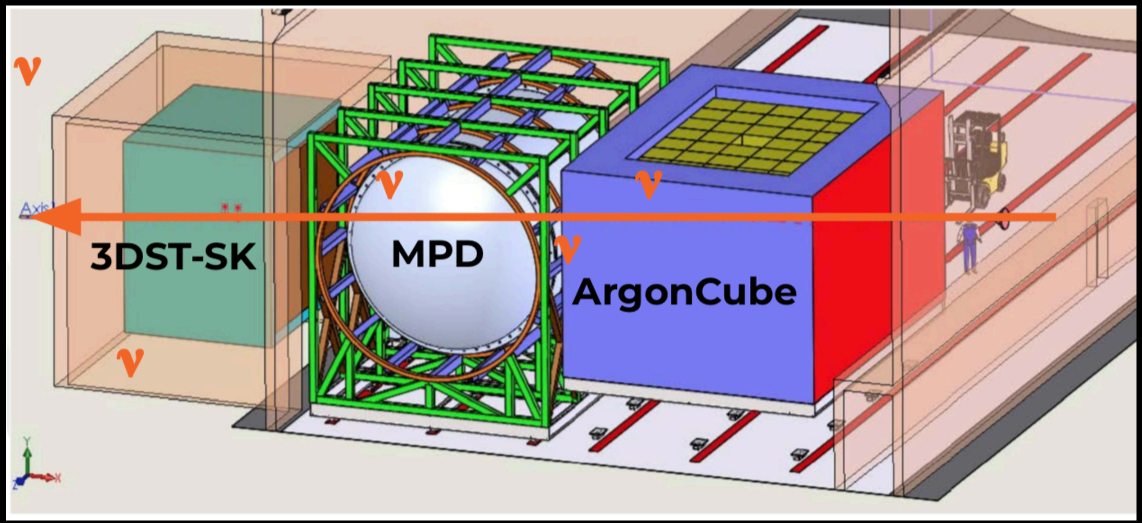
Dominant production mechanism: neutral meson decay

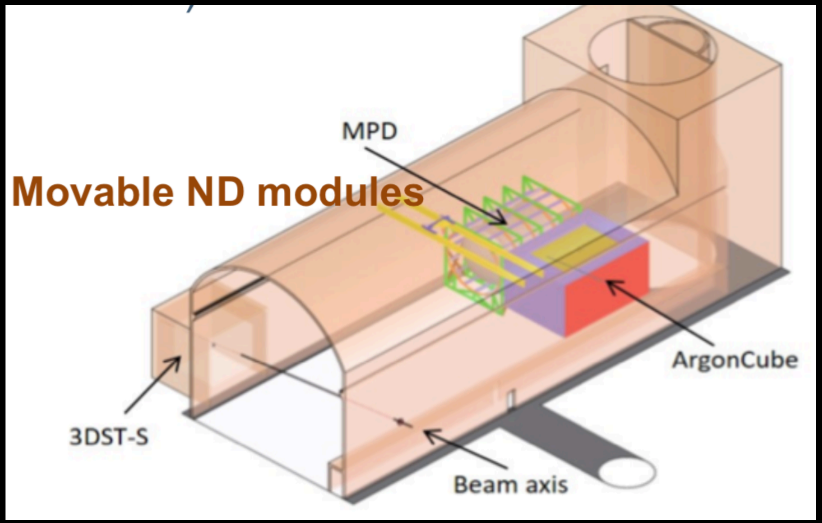
DUNE PRISM

- The DUNE Precision Reaction-Independent Spectrum Measurement (PRISM) concept proposes to move the near detector between 0 and 36 m transverse to the beam direction.
- By moving the detector off-axis, can measure increasingly lower Ev spectra.
  - Advantage: reduce systematic uncertainties related to neutrino cross sections.
  - Interaction observed at different off-axis angles can be combined to mimic what would be observed with a different Ev spectrum.
- DM beam is broader than the neutrino beam: detectors located away from the proton beam axis will have larger signal to background ratio.



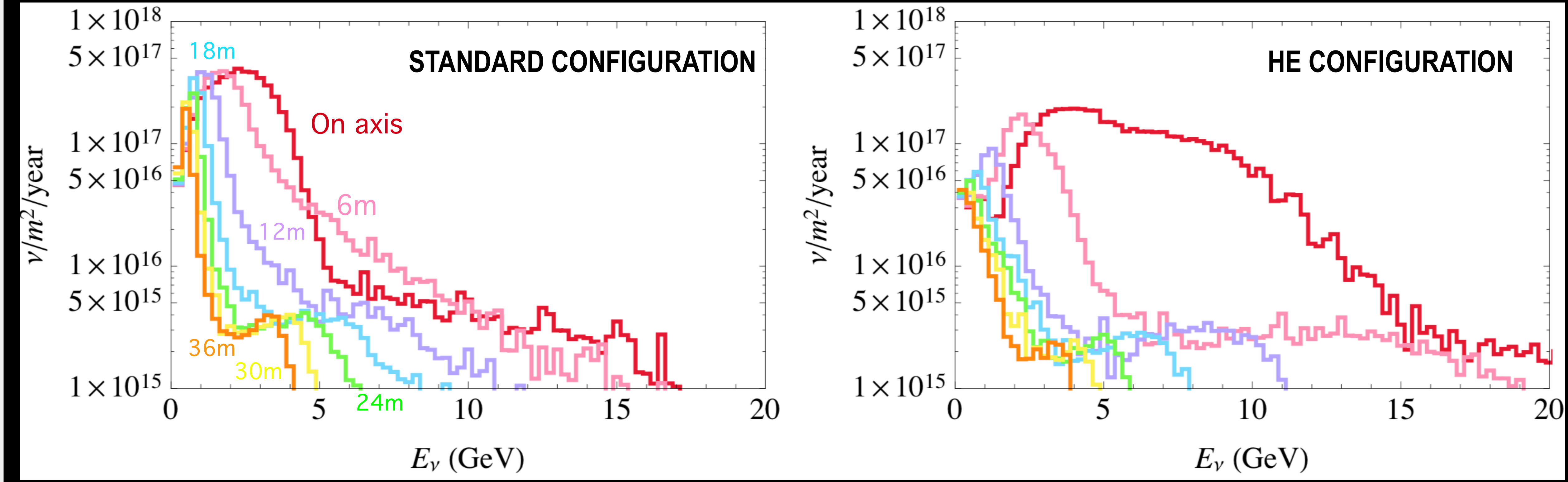
credit: L. Pickering and M. Wilking, DUNE PRISM design group





DUNE HE configuration

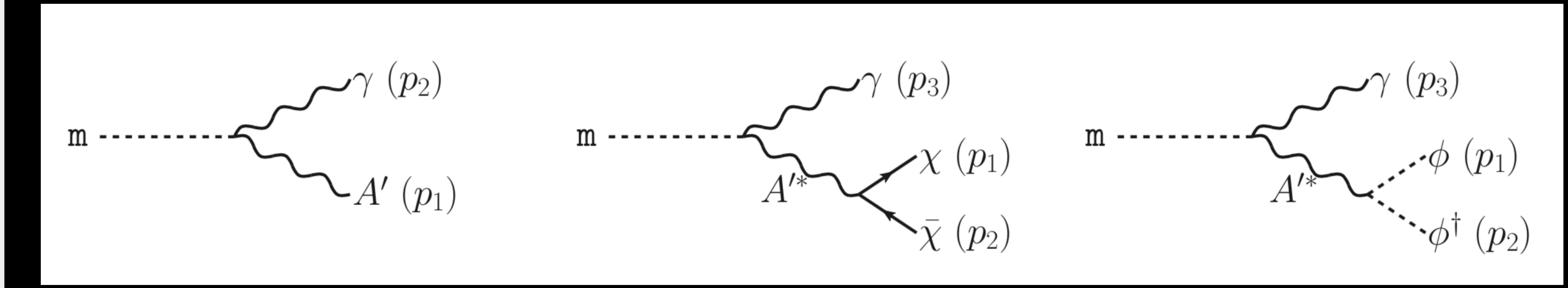
- DUNE will operate in two horn currents, focusing positive and negative mesons that produce mostly neutrinos and antineutrinos
- Additionally, a HE configuration has also been considered mainly for the study of tau neutrinos at the far detector.



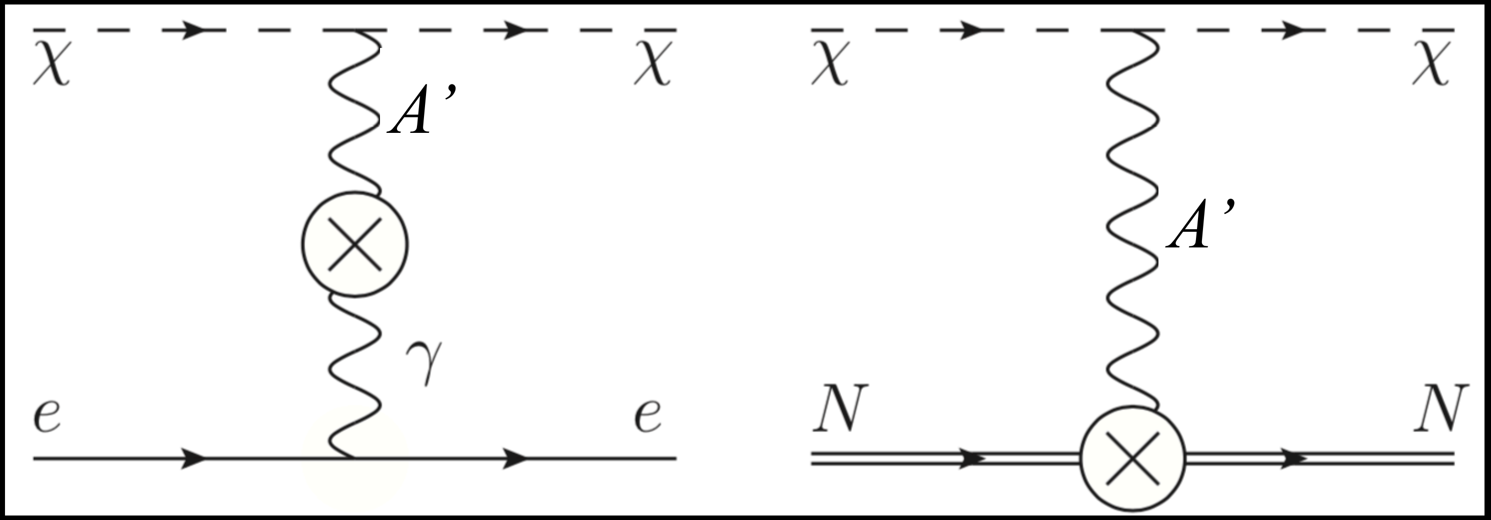
fluxes from Laura Fields http://home.fnal.gov/~ljf26/DUNEFluxes/

Detecting Dark Matter with DUNE

- We consider a 120 GeV proton beam striking a graphite target and simulate the production of meson m = π^0, η using PYTHIA8.
- We simulate the DUNE DM angular distributions and energy spectra from π^0, η decays on an event-by-event basis.



Production

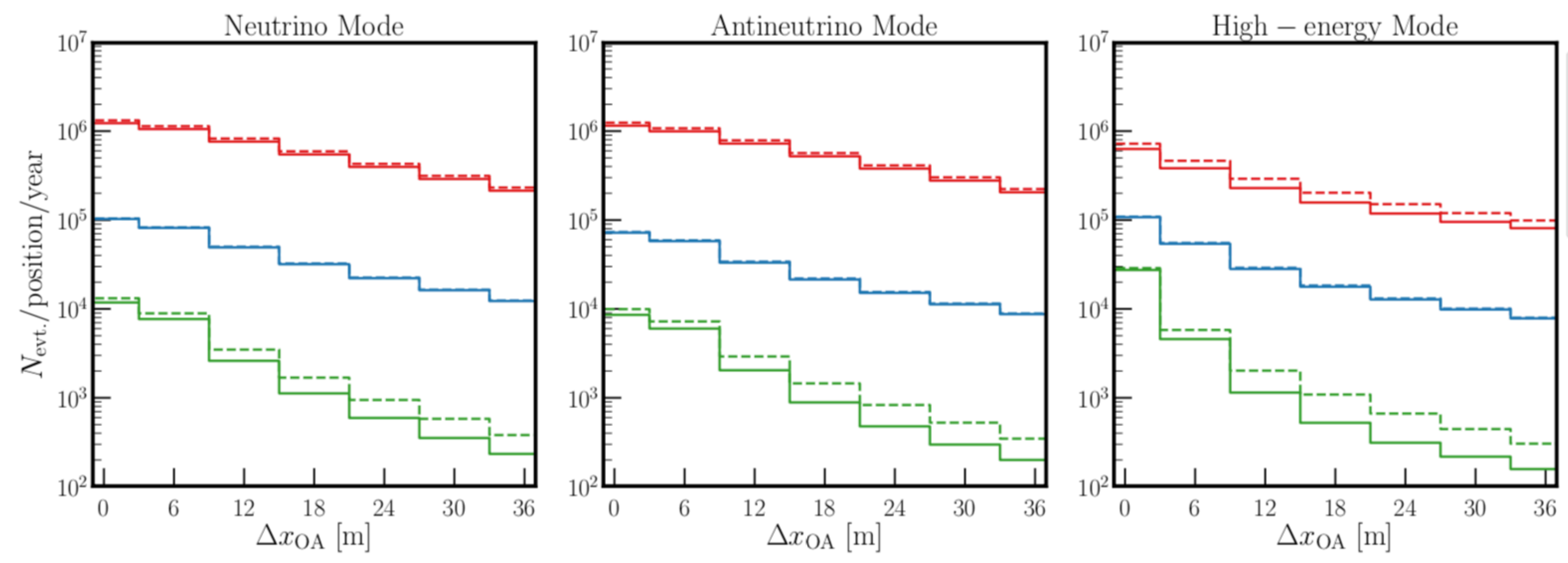


Signatures

- Nucleon scattering (NCQE)
- Electron scattering

Detecting Dark Matter with DUNE

- Expected number of events per year of data collection



- Expected NS Background Events
- $M_{A'} = 90$ MeV $= 3M_\chi$, $\alpha_D = 0.1$, $\varepsilon^2 = 10^{-6}$
- Expected ES Background Events
- $M_{A'} = 90$ MeV $= 3M_\chi$, $\alpha_D = 0.1$, $\varepsilon^2 = 10^{-7}$
- ES Background Events ($\nu_e n \to e^- p$ vetoed)
- $M_{A'} = 90$ MeV $= 3M_\chi$, $\alpha_D = 0.1$, $\varepsilon^2 = 10^{-7}$

Three backgrounds:

- neutrino-nucleon scattering (NC) $\nu\ N \to \nu\ N$

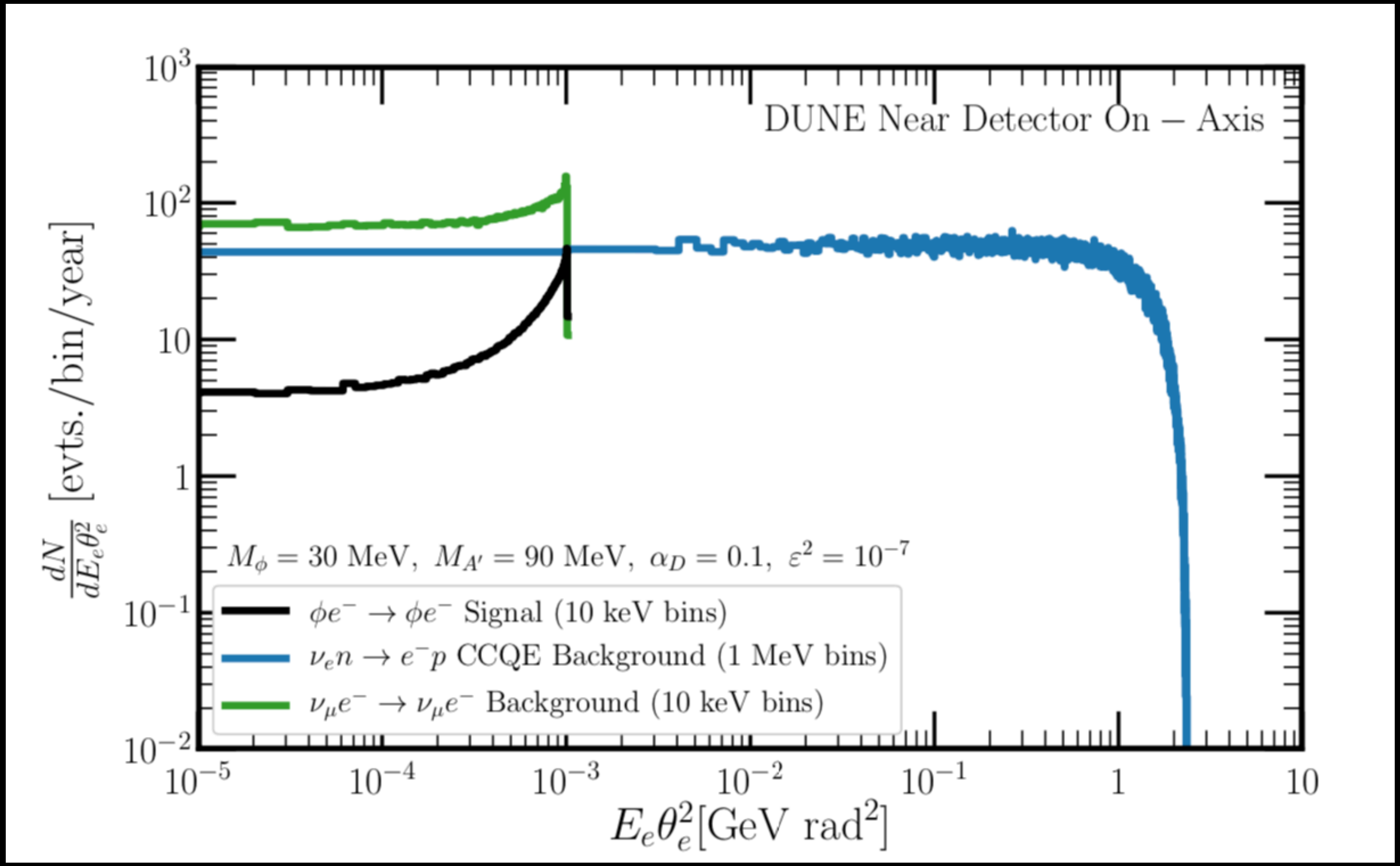
- neutrino-electron scattering (NC) $\nu_\mu\ e^- \to \nu_\mu\ e^-$
- neutrino-nucleon scattering (CC) $\nu_e\ n \to e^-\ p$

Background reduction for CCQE scattering

Performing solely a counting experiment:
largest background from electron neutrino beam contamination with CCQE scattering,
$\nu_e n \to e^- p$ or $\nu_e p \to e^+ n$ (final-state hadronic system is unidentified).

Initial and final states are distinct (and nucleons) → the electron will scatter at large angles.

- Place a cut on the outgoing energy and angle of the final electron → less than 0.1% of the CCQE background.



Statistical analysis

Combine all channels and beam configurations as independent experiments.
7 years total running time.

- On-axis: all data collected on axis, 3.5 yr nu mode, 3.5 yr anu mode.
- DUNE-PRISM: data collected at equal time for each off-axis position, 3.5 yr nu mode, 3.5 yr anu mode.
- DUNE-PRISM-HE: data collected at equal time for each off-axis position, 3 yr nu mode, 3 yr anu mode, 1yr HE mode.

$$-2\Delta\mathcal{L} = \sum_i \frac{r_i^m \left(\left(\frac{\varepsilon}{\varepsilon_0}\right)^4 N_i^\chi + (A-1)N_i^\nu\right)^2}{A\,(N_i^\nu + (\sigma_{f_i} N_i^\nu)^2)} + \frac{(A-1)^2}{\sigma_A^2}.$$

Benchmarks	$r^{\nu}_{\rm on}$	$r^{\bar{\nu}}_{\rm on}$	$r^{\nu}_{{\rm off},i}$	$r^{\bar{\nu}}_{{\rm off},i}$	$r^{{\rm HE}\nu}_{k}$
On-axis	3.5	3.5	0	0	0
DUNE-PRISM	0.5	0.5	0.5	0.5	0
DUNE-PRISM-HE	3/7	3/7	3/7	3/7	1/7

Three sources of uncertainty: statistical, correlated systematic (σ_{f_i} =1%) and uncorrelated systematic (σ_A =10%).

Nüisance parameter A (different for each mode) modifies the number of nu-related background events in each bin (with Gaussian uncertainty = 10%).
Any single-position measurement will be systematic-limited.

Sensitivity improvement from e- kinematics

Sensitivity can be improved by including information about the final-state electron kinematics for the signal and background distributions.

Depending on the DM/A′ masses, the DM-electron scattering spectrum can appear significantly different than the $\nu_\mu e^- \to \nu_\mu e^-$ background.

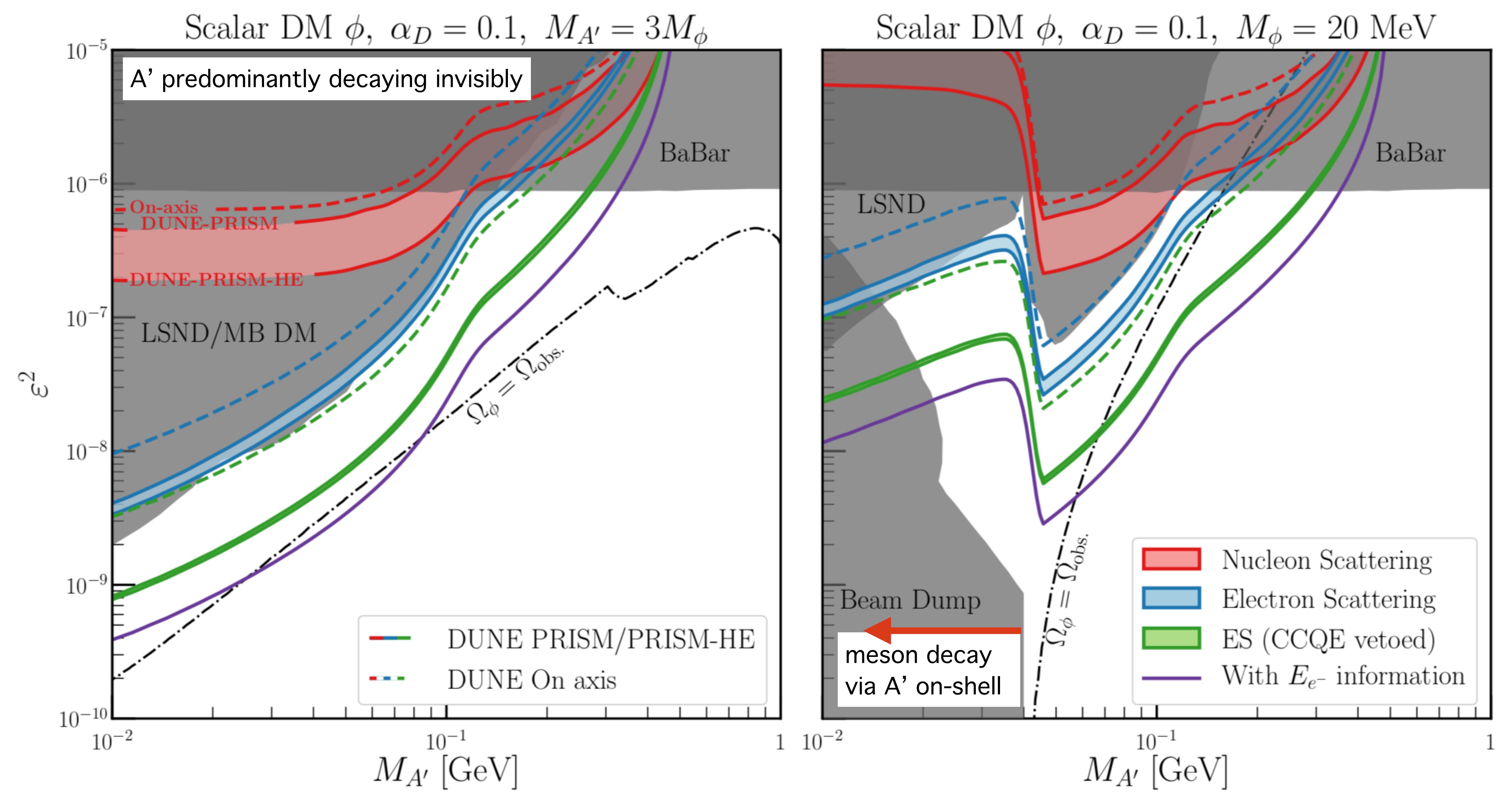
$$\mathcal{L}_{ij} \to -A * f_i \left(\left(\frac{\varepsilon}{\varepsilon_0}\right)^4 N^{\chi}_{ij} + N^{\nu}_{ij}\right) + N^{\nu}_{ij} \ln\left(A * f_i \left(\left(\frac{\varepsilon}{\varepsilon_0}\right)^4 N^{\chi}_{ij} + N^{\nu}_{ij}\right)\right) - \ln\left(N^{\nu}_{ij}!\right),$$

$$-2\Delta\mathcal{L} = \sum_{i=1}\left[\sum_{j=1}(-2\mathcal{L}_{ij}) + \frac{(f_i-1)^2}{\sigma^2_{f_i}}\right] + \frac{(A-1)^2}{\sigma^2_A}.$$

i: position
j: energy bin

The improvement leads to roughly a factor of 2 stronger limits on ε^2 are expected for A′ and χ masses of interest.

Results: scalar DM



A’ predominantly decaying invisibly

meson decay via A’ on-shell

Summary of LDM searches at DUNE

- We have studied the prospects for detecting light dark matter at DUNE. Great complementarity to direct detection experiments and LHC searches.

- We have assumed a light dark matter (fermionic or scalar) (sub-GeV) with dark photon mediator.

- We investigated the impact on sensitivity limits at DUNE with both the DUNE-PRISM option and the HE configuration.

- Role of DUNE-PRISM:
  - neutrino induced backgrounds decrease faster than the DM signal
  - the on-axis measurement, being signal-rich, serves to constrain the neutrino flux with high statistics
  - → extend the reach in sensitivity on ε^2.

- Electron scattering allows for better sensitivity (compared to nucleon scattering) especially if the ν_e CCQE background can be removed.

- Competitive with dedicated experiments in probing light dark matter scenarios!!

Quasi-Dirac neutrino oscillations at DUNE

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Quasi-Dirac neutrino oscillations

A pair of quasi-Dirac neutrinos is a pair of Majorana neutrinos with a small mass splitting and a relative CP-sign between the two states.

We begin with a pair of active-sterile neutrinos.
This pair has mass matrix:

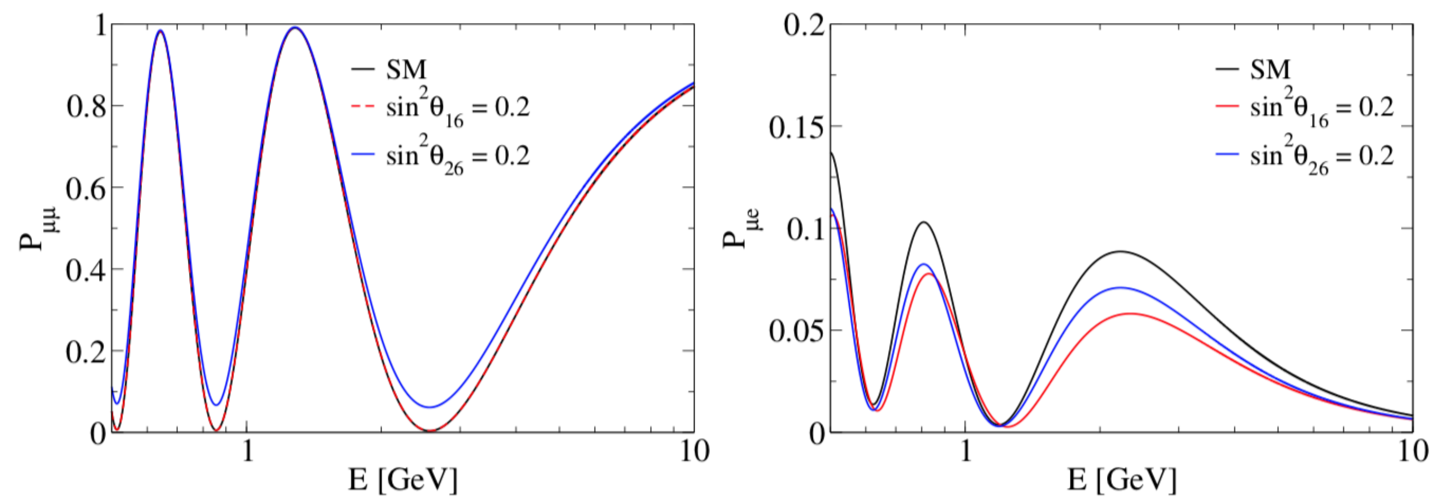
$$m_\nu = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

If these are zero, neutrinos are Dirac particles.
If they are not zero, but very small we are left with a pair of quasi-Dirac neutrinos.

The charged current SM Lagrangian is modified and a new mass term is allowed

$$\mathcal{L}_{CC} = -\frac{g}{\sqrt{2}} W_\mu^- \sum_{l=1}^{3} \sum_{j=1}^{6} \mathbf{V}_{lj} \bar{\ell}_l \gamma^\mu P_L \nu_j + \text{h.c.}$$

$$\mathcal{L}_{\text{mass}} = \frac{1}{2} \bar{\nu}_\alpha M_{\alpha\beta} \nu_\beta + \text{h.c.}$$



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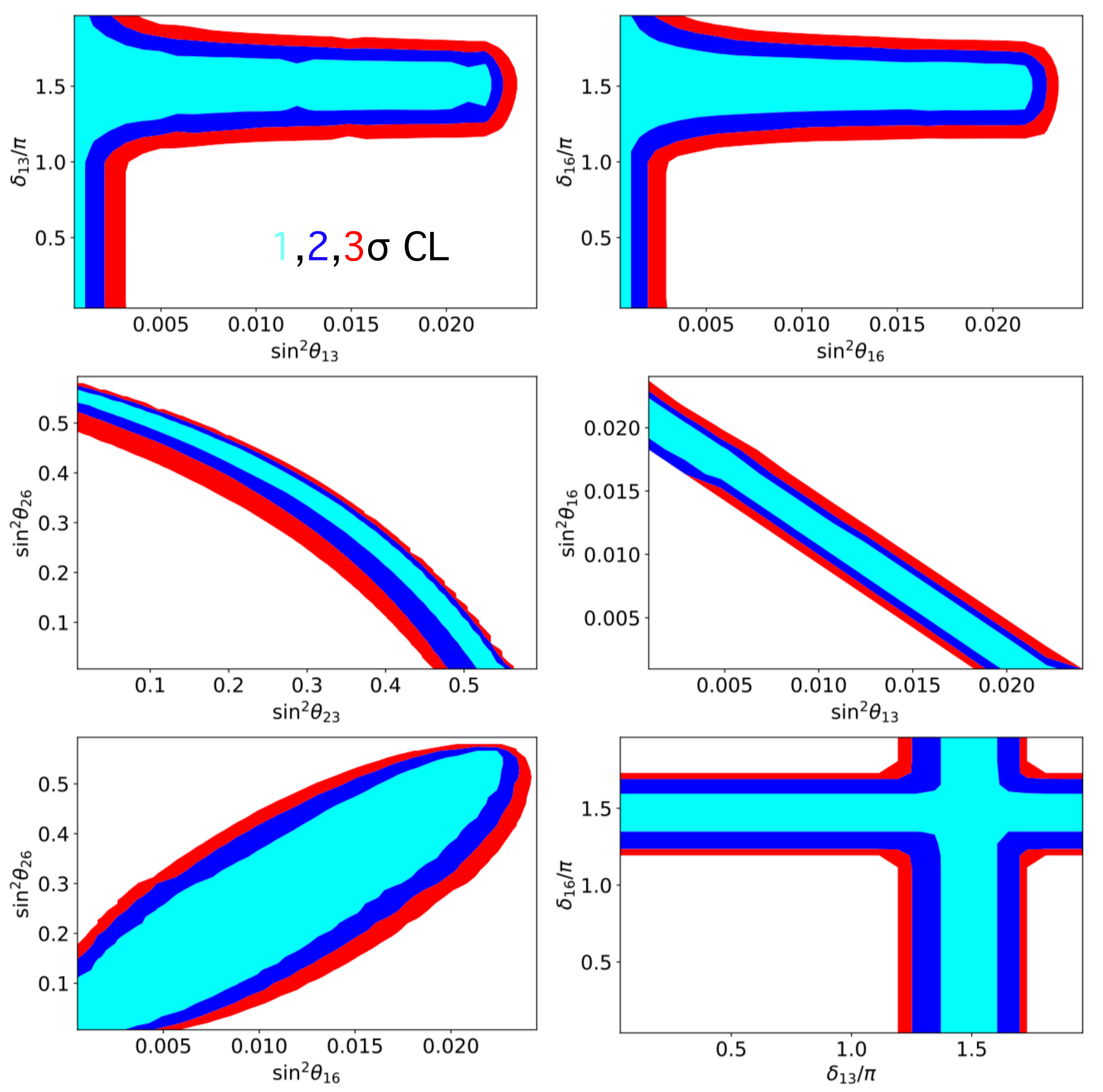
Quasi-Dirac neutrino oscillations



We assume DUNE to run 3.5 years in neutrino mode and other 3.5 years in antineutrino mode.
Total exposure of 300 kton-MW-years (equivalent to 1.47 × 1021 POT per year).

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Thank you!