Enabling BSM Studies with Neutrino Data

Joachim Kopp (CERN & JGU Mainz)

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CERN

Neutrino PLATFORM

QUANTUM TECHNOLOGY INITIATIVE

JG|U JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Neutrino Physics Beyond the Standard Model

Sterile Neutrino Oscillations

Heavy Neutral Lepton Decay

Non-standard Neutrino Interactions

Axion Portal

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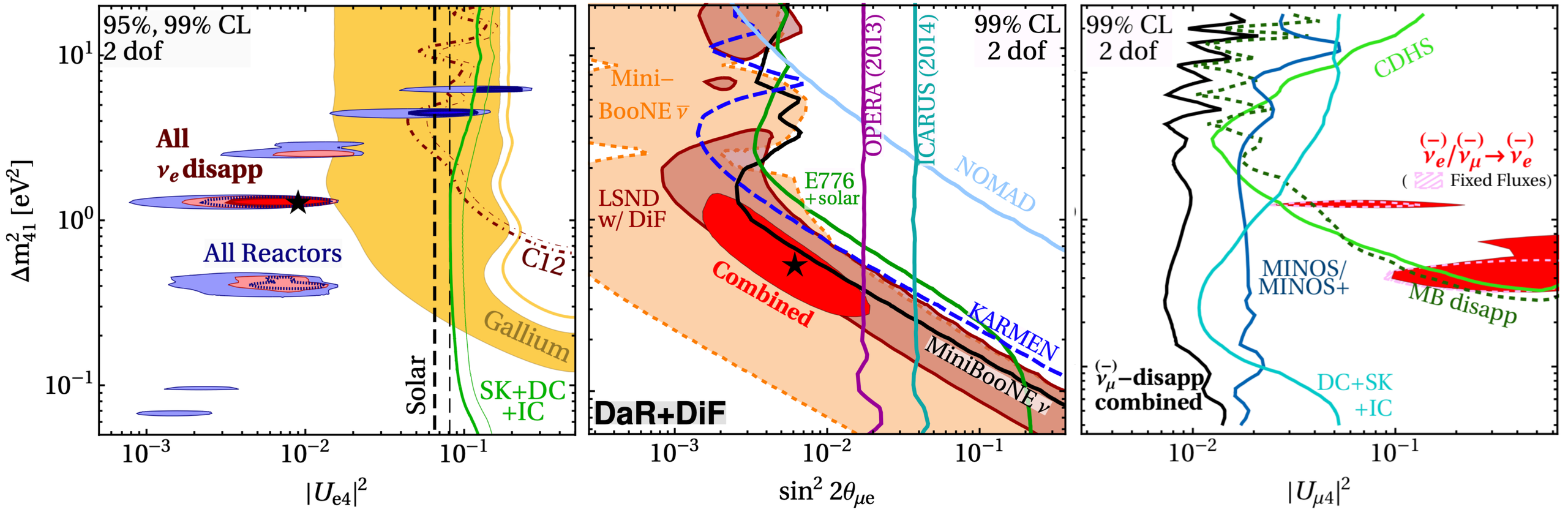
Sterile Neutrino Oscillations – Enabling Global Fits

Dentler *et al.* 2018



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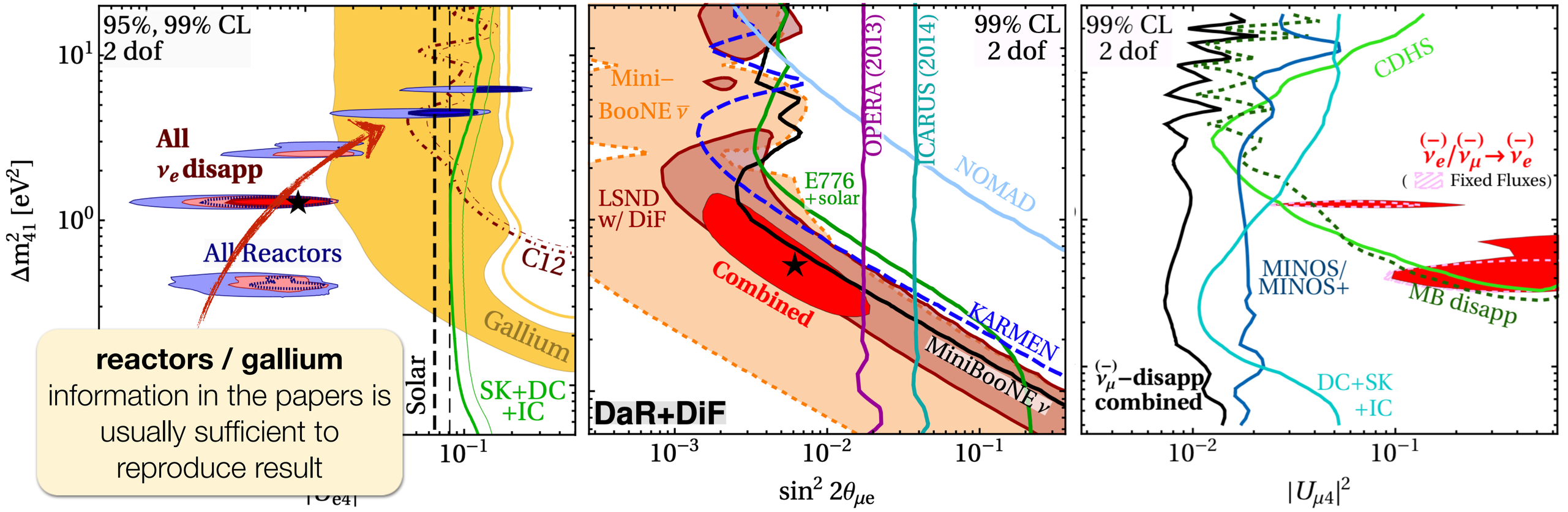

reactors / gallium
information in the papers is usually sufficient to reproduce result

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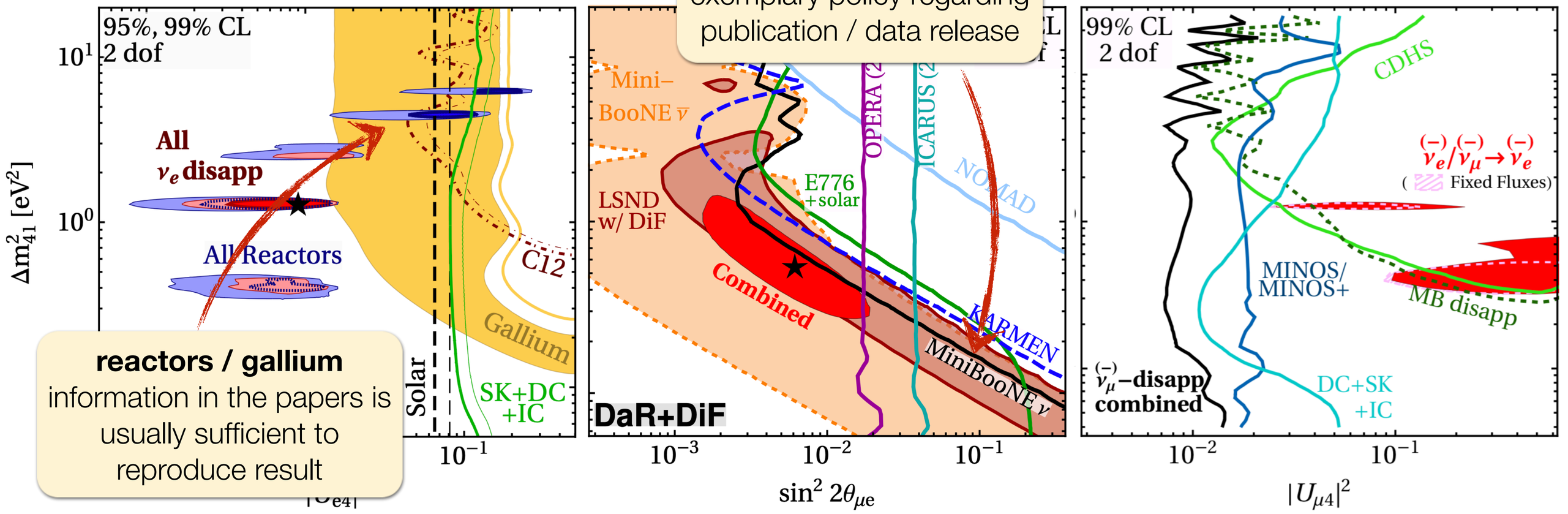

MiniBooNE / MINOS
exemplary policy regarding publication / data release

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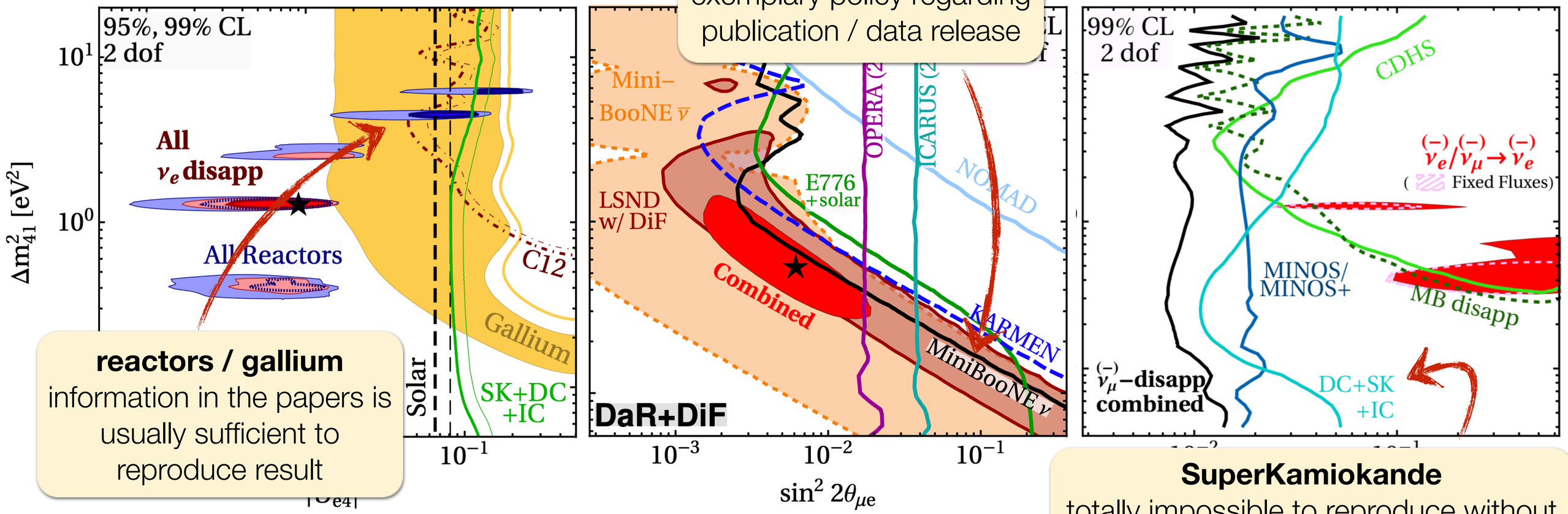

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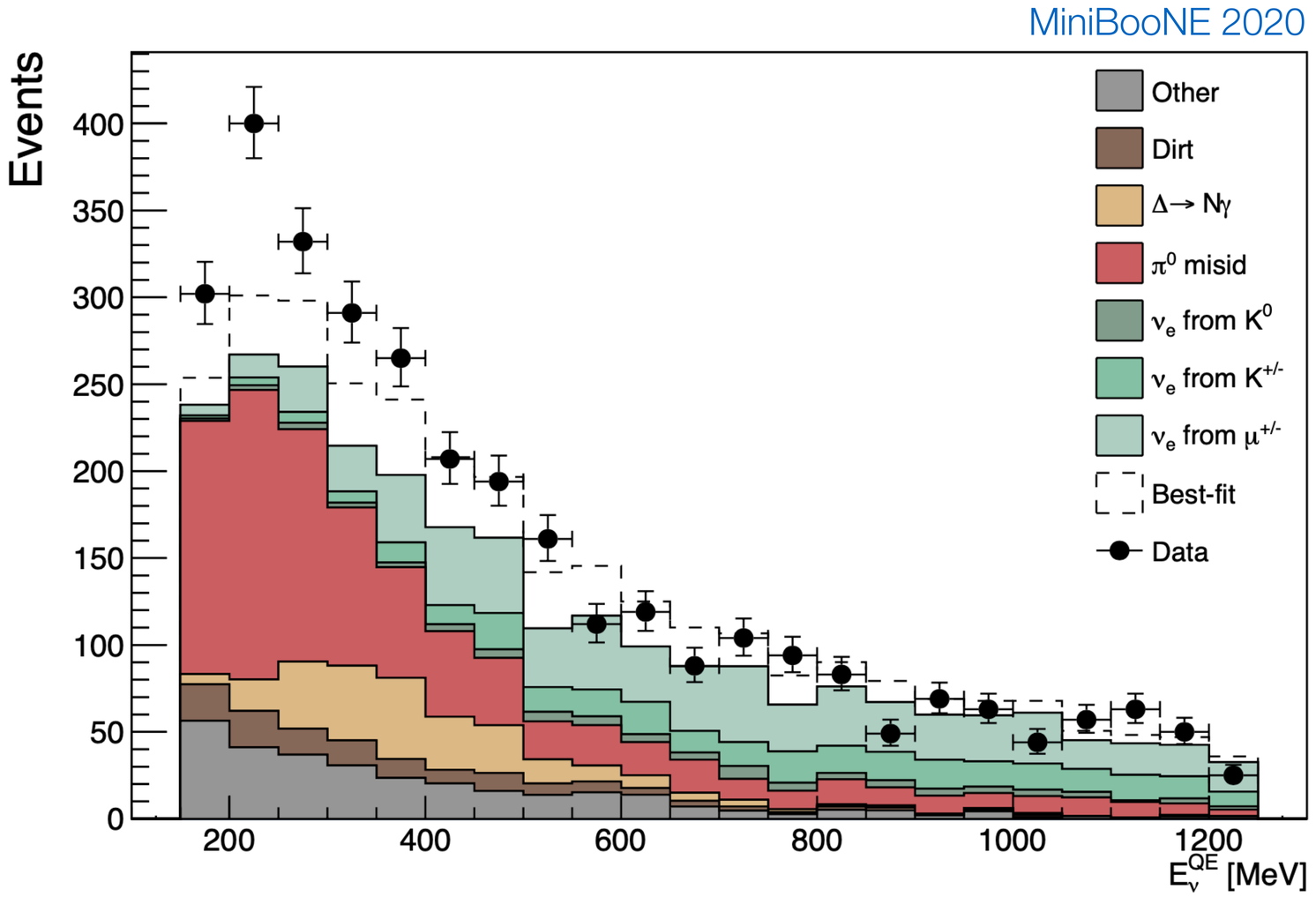
SuperKamiokande
totally impossible to reproduce without investing years of work
(or collaborating with Michele Maltoni who has invested years of work)

Sterile Neutrino Oscillations – MiniBooNE



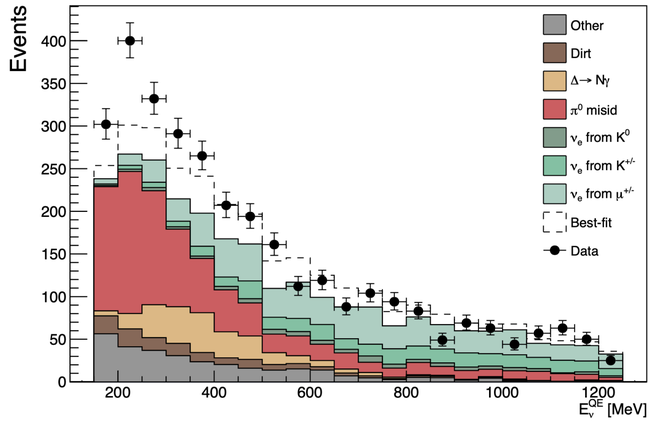
- Unexplained Excess (4.8σ)
- L/E too short for standard oscillations

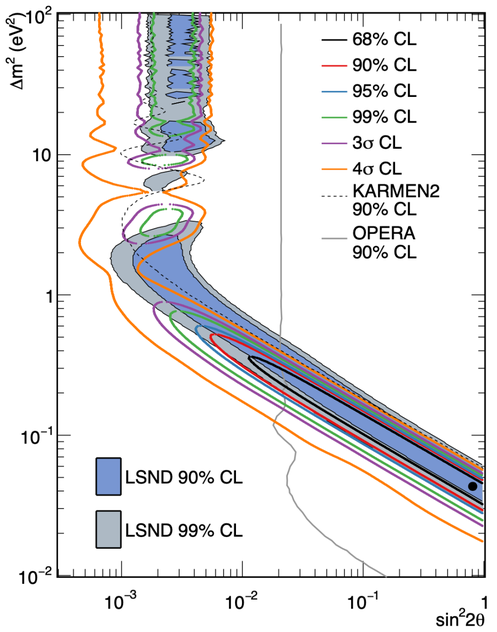
Usefulness of MiniBooNE's Data Releases

MiniBooNE’s oscillation data releases feature

- ☐ data shown in plots in machine-readable form
- ☐ flux tables
- ☐ efficiencies
- ☐ MC event samples (E_{true} vs E_{reco})
  - can be reweighted to match any BSM oscillation scenario
  - can be used to extract detector / analysis response function
- ☐ Covariance matrices
- ☐ Detailed instructions on how to reproduce the official results
- ☐ A very approachable collaboration
  - real interest in outside input
  - ability to share information without too much red tape

MiniBooNE 2020





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Sterile Neutrino Oscillations

Heavy Neutral Lepton Decay

Non-standard Neutrino Interactions

Axion Portal

Non-Standard Neutrino Interactions

- new dimension-6 operators
  - NC: new oscillation effects
  - CC: new production / detection effects

$$\mathcal{L}_{\mathrm{NSI,NC}} = \sum_{f,\alpha,\beta} 2\sqrt{2} G_F \varepsilon^{f,P}_{\alpha\beta} (\bar{\nu}_\alpha \gamma_\mu P_L \nu_\beta)(\bar{f} \gamma^\mu P f) + \mathrm{h.c.}$$

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- Production / propagation / detection effects should be considered together
  (EFT needs SU(2) invariant UV completion, e.g. SMEFT)

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lepton current

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quark or **charged lepton** current

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Non-Standard Neutrino Interactions

- ne rs
  - o
  - o ction effects

dimensionless coefficient
strength of the new interaction relative to SM weak interactions

lepton current

quark or **charged lepton** current

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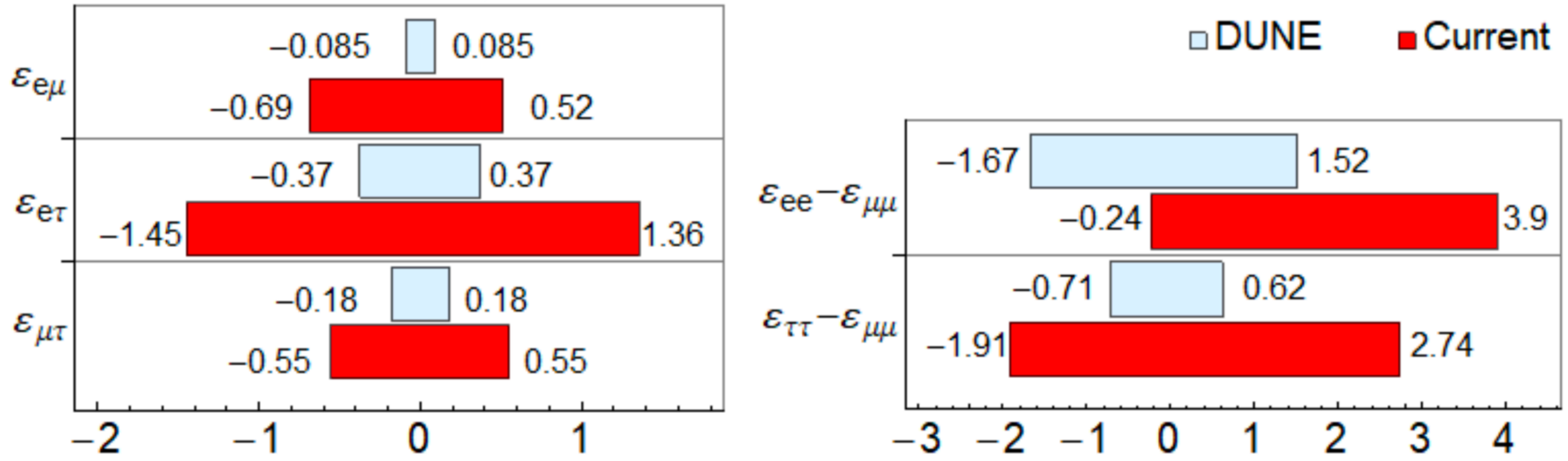
Non-Standard Neutrino Interactions

DUNE FD TDR – Vol II – Physics



- For quark flavor-universal V–A interactions (as in the SM):
  - straightforward implementation in terms of modified oscillation probabilities
- For interactions with different Lorentz / flavour structures:
  - modified meson decays ➠ need **production MC events** to re-decay mesons

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Heavy Neutral Leptons

- Just another word for sterile neutrino, typically used if mass ~ MeV–GeV
- coupled via the neutrino portal

$$\mathcal{L} \supset y\, \bar{L}\, (i\sigma^2 H^*)\, N$$

- leads to mixing between *ν* and *N*
  - ➠ any process that makes *ν* in the SM can also make *N* (suppressed by a mixing angle)
  - ➠ meson decays
  - ➠ need **ability to re-decay mesons**

Heavy Neutral Leptons

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  typically used i –G
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SM Higgs doublet

SM lepton doublet

Heavy Neutral lepton
(singlet fermion = sterile ν
= right-handed ν)

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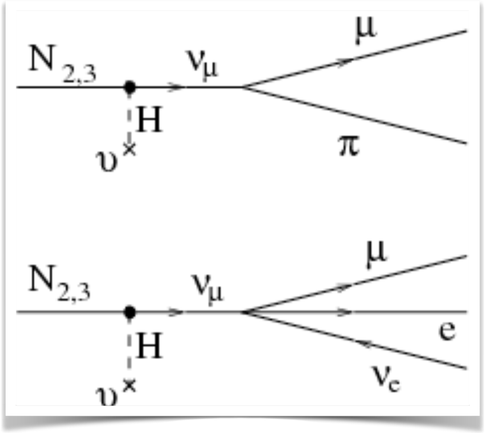
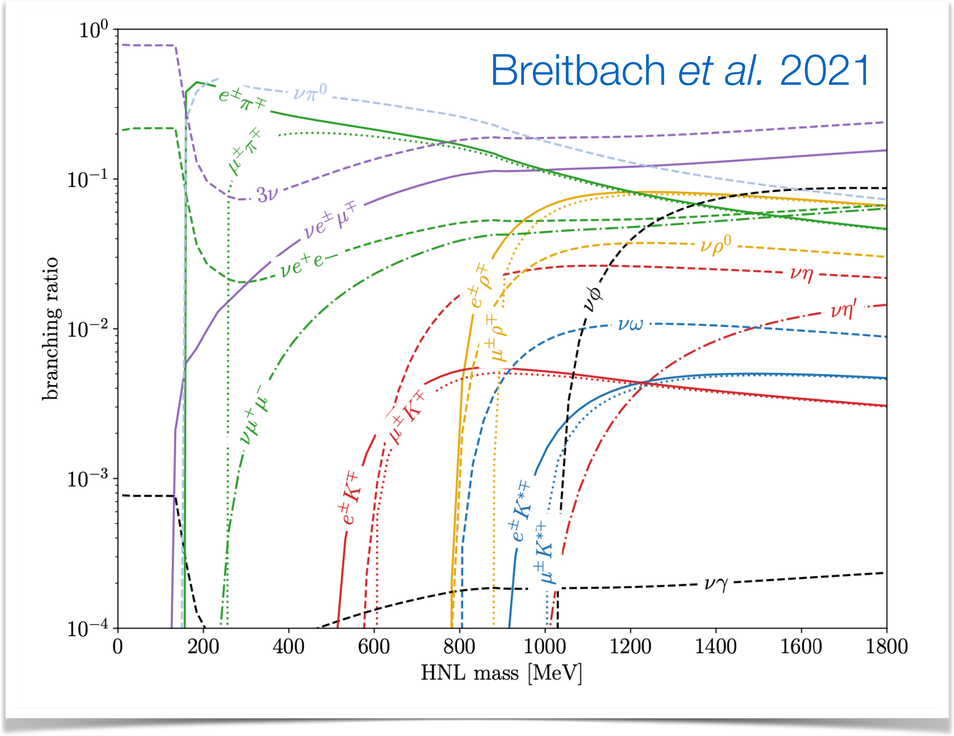
- Very generic extension of SM
  - leftovers of GUT multiplets?
- Useful phenomenological tool
  - ν masses (seesaw mechanism)
  - cosmic baryon asymmetry (leptogenesis m≫100 GeV (thermal) or m<100 GeV (ARS))
  - dark matter (m ~ keV)
  - mediator to a dark sector

Heavy Neutral Leptons

- decay inside the detector into a variety of modes
  - very hard to extract without dedicated searches by the experiments
  - best chance would probably be with **event-by-event information** on
    - **particle IDs** (with probability of correctness)
    - **4-momenta** (with errors)
  - systematic uncertainties?
- backgrounds from SM neutrino interactions





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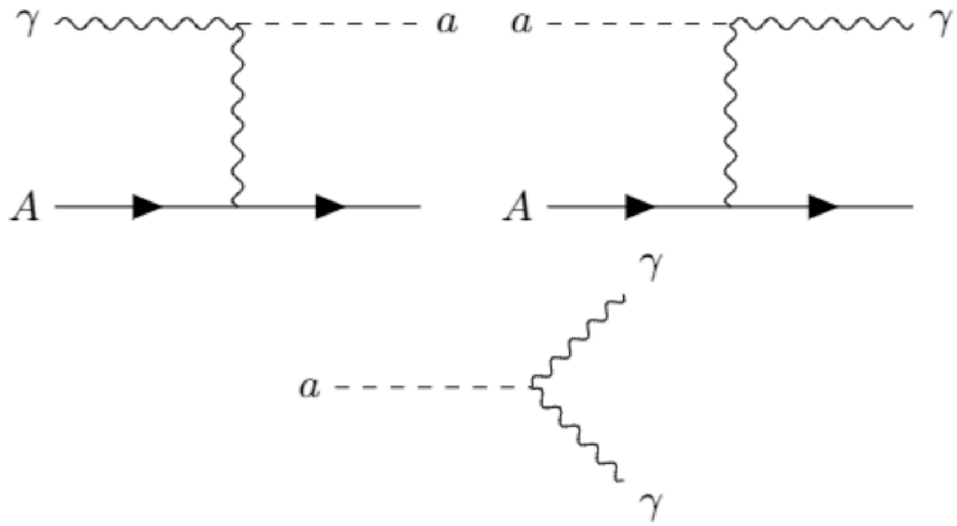
Axion-Like Particles

- a new pseudoscalar particle with a shift symmetry $a \to a + \text{const.}$
  - if sub-eV: possible solution to the strong CP problem (“axion”)
    → non-accelerator searches (astrophysics, quantum sensors)
  - frequent occurrence in string compactifications
  - dark matter candidate



e.g. Dent *et al.* 2020

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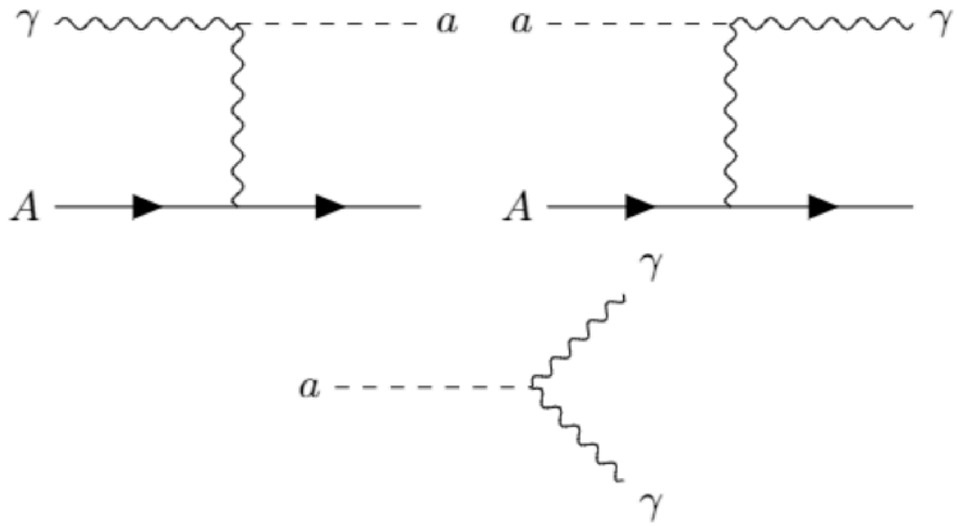

e.g. Dent *et al.* 2020

$$\mathcal{L}_a = \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{\alpha_s}{4\pi f_a}\, a\, \mathrm{tr}\, G^{\mu\nu}\tilde{G}_{\mu\nu} + \frac{s\alpha}{8\pi f_a}\, a\, F^{\mu\nu}\tilde{F}_{\mu\nu} + \mathcal{L}_a^{\mathrm{int}}\left[\frac{\partial_\mu a}{f_a}; \psi\right]$$

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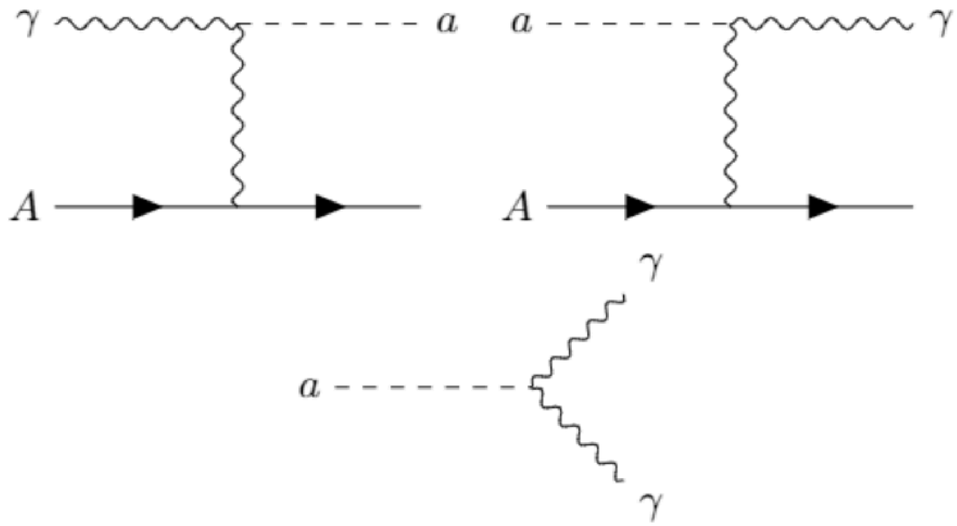

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- signatures with **one or two electromagnetic showers** very important
  - also relevant for e.g. dark photon decay to e^+e^-

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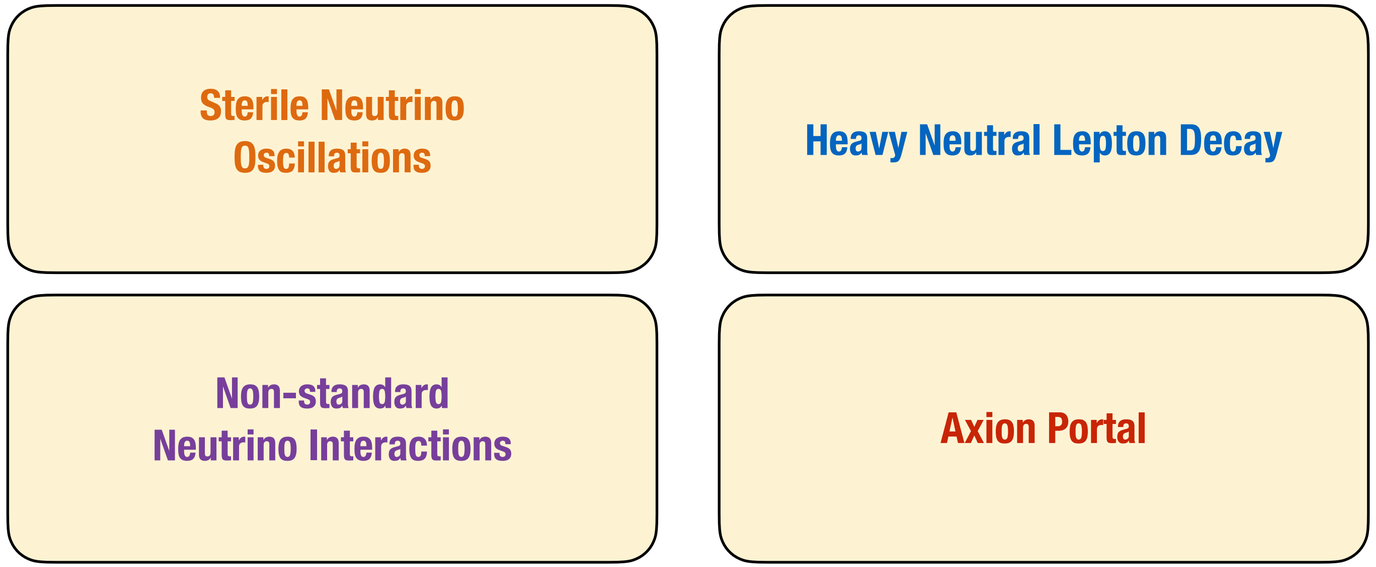

Wish List

- ☐ beam Monte Carlo events (with full decay history)
- ☐ detector Monte Carlo events (true energy ↔ reconstructed energy)
- ☐ covariance matrices
- ☐ efficiencies

Thank You!

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