Theory

interface with experiment

Theoretical issues related to:
LHC experiments
(future colliders)
other ongoing laboratory experiments
neutrino experiments
dark matter and other astroparticle experiments

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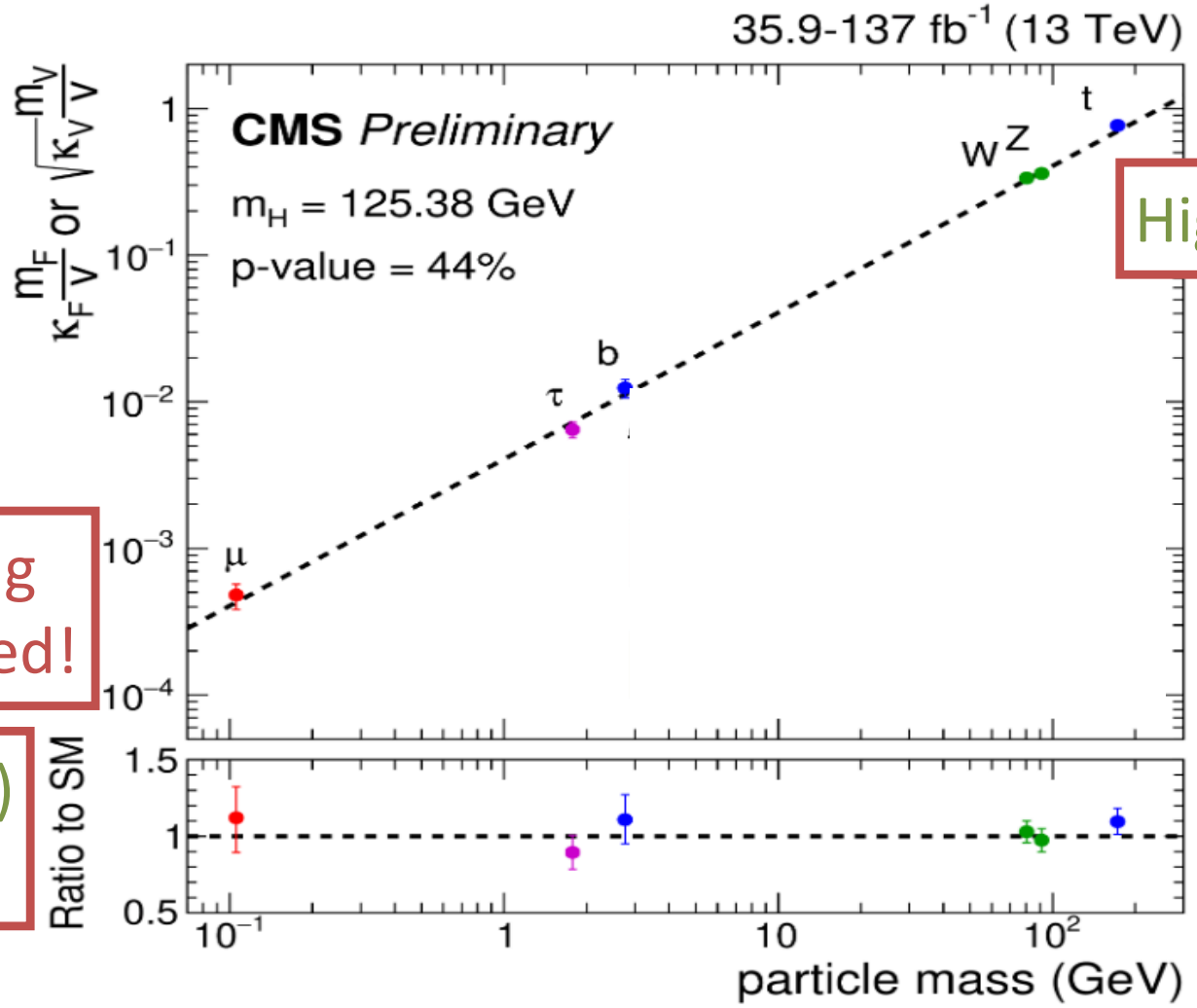
Everything about Higgs is Puzzling

$$\mathcal{L} = yH\psi\overline{\psi} + \mu^2|H|^2 - \lambda|H|^4 - V_0 + \ldots$$

- Pattern of Yukawa couplings y:
  - **Flavour problem**
- Magnitude of mass term μ:
  - **Naturalness/hierarchy problem**
- Magnitude of quartic coupling λ:
  - **Stability of electroweak vacuum**
- Cosmological constant term V_0:
  - **Dark energy**

Higher-dimensional interactions?

Current Measurements of Higgs Couplings

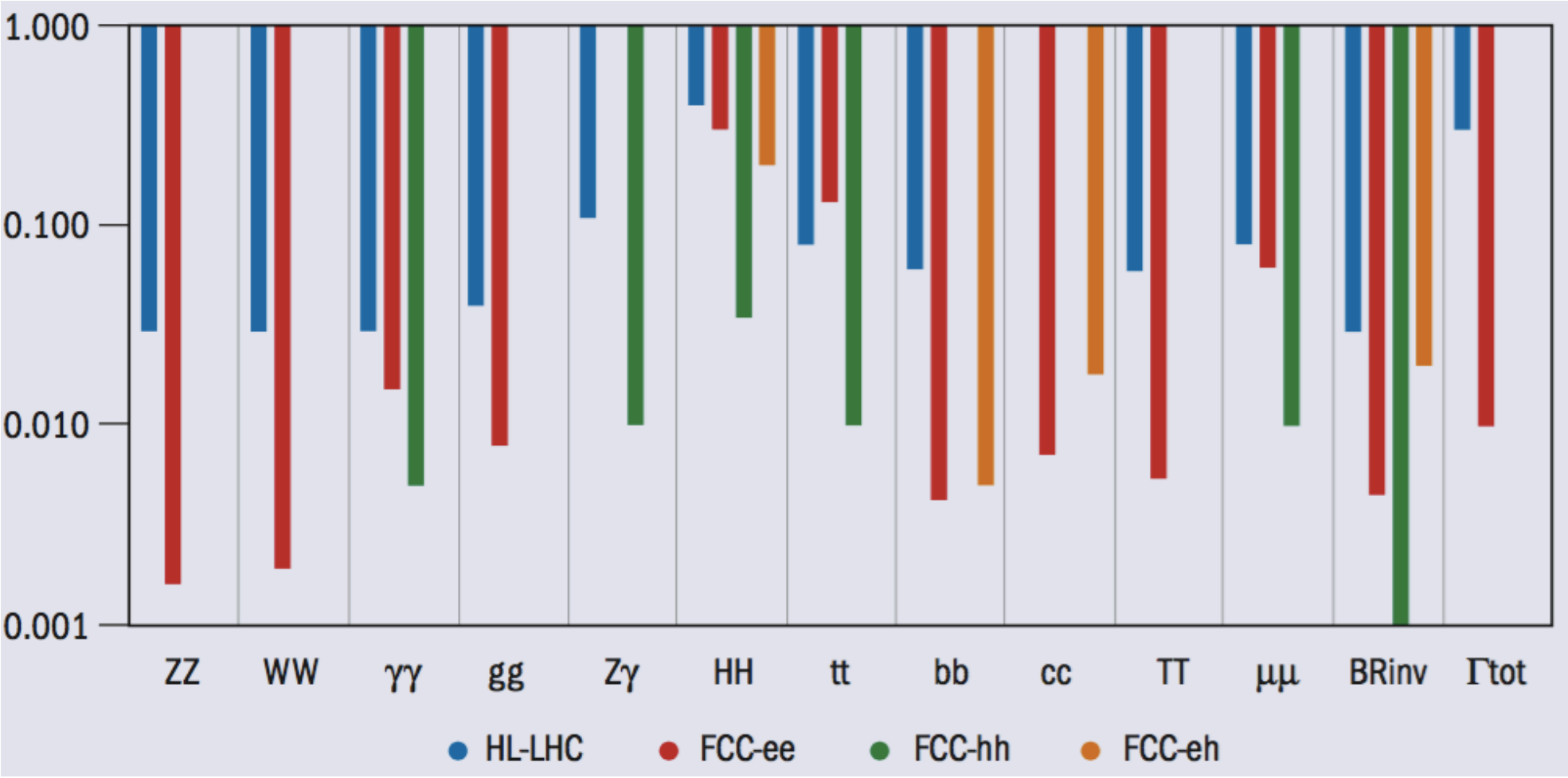


Higgs missing!

Muon coupling almost measured!

Other 2nd (1st) generation?

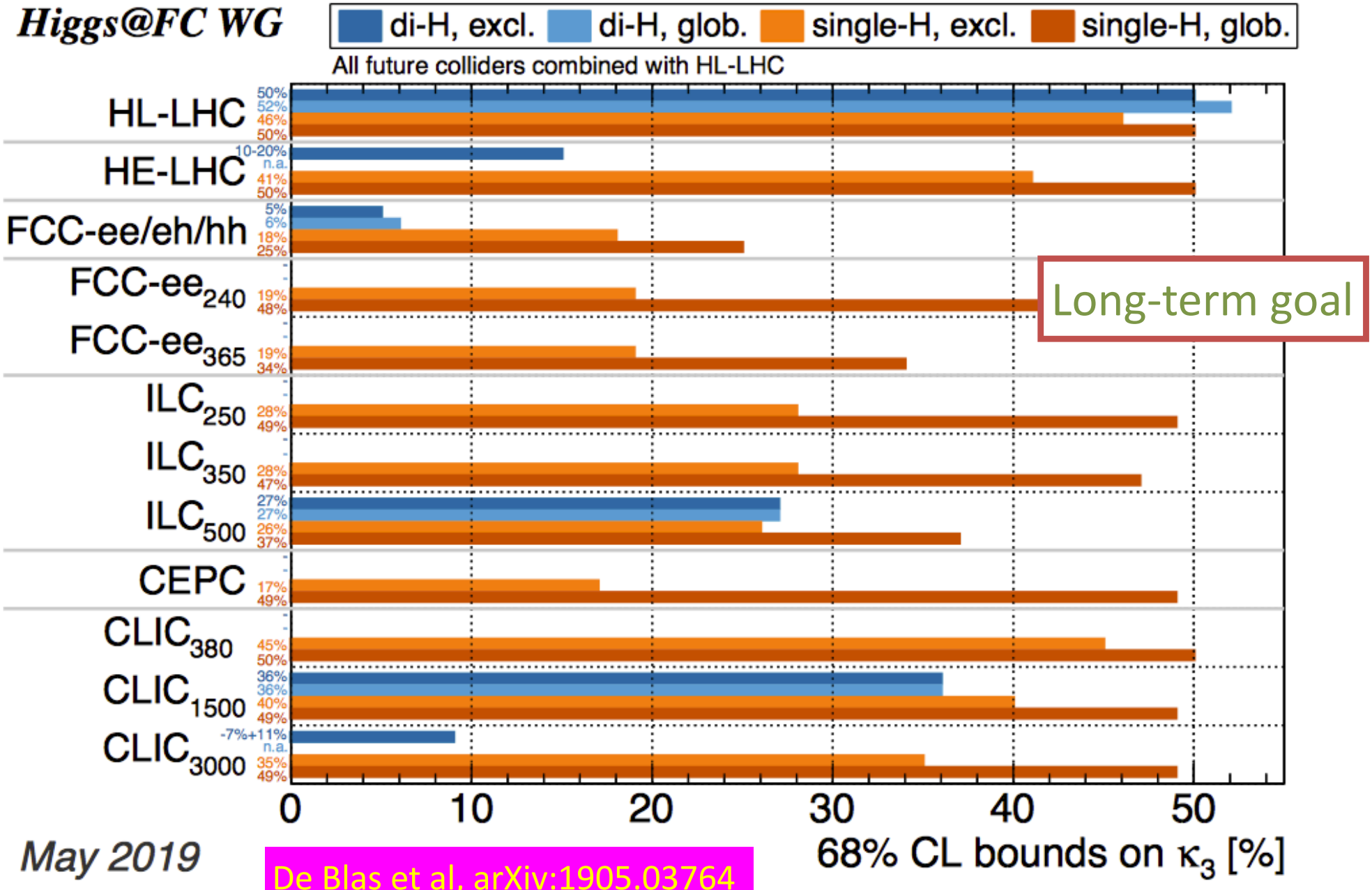
Possible Future Higgs Measurements



- Will need to reduce theoretical uncertainties (QCD, EW) to match experimental errors
  - Needed for BSM interpretation

High precision at FCC-ee/CEPC
Big statistics at FCC-hh/SppC

Triple-Higgs Coupling Analyses



Effective Field Theories (EFTs)

a long and glorious History

- 1930's: "Standard Model" of QED had d=4
- Fermi's four-fermion EFT of the weak force

- Dimension-6 operators: form = S, P, V, A, T?
  - Due to exchanges of massive particles?
- V-A → massive vector bosons → gauge theory
- Yukawa's meson theory of the strong N-N force
  - Due to exchanges of mesons? → pions

- Chiral dynamics of pions: $(\partial\pi\partial\pi)\pi\pi$ clue → QCD

Powerful indirect way to look for BSM physics

Standard Model Effective Field Theory

- Higher-dimensional operators as relics of higher-energy physics, e.g., dimension 6:

$$\mathcal{L}_{\text{eff}} = \sum_n \frac{f_n}{\Lambda^2} \mathcal{O}_n$$

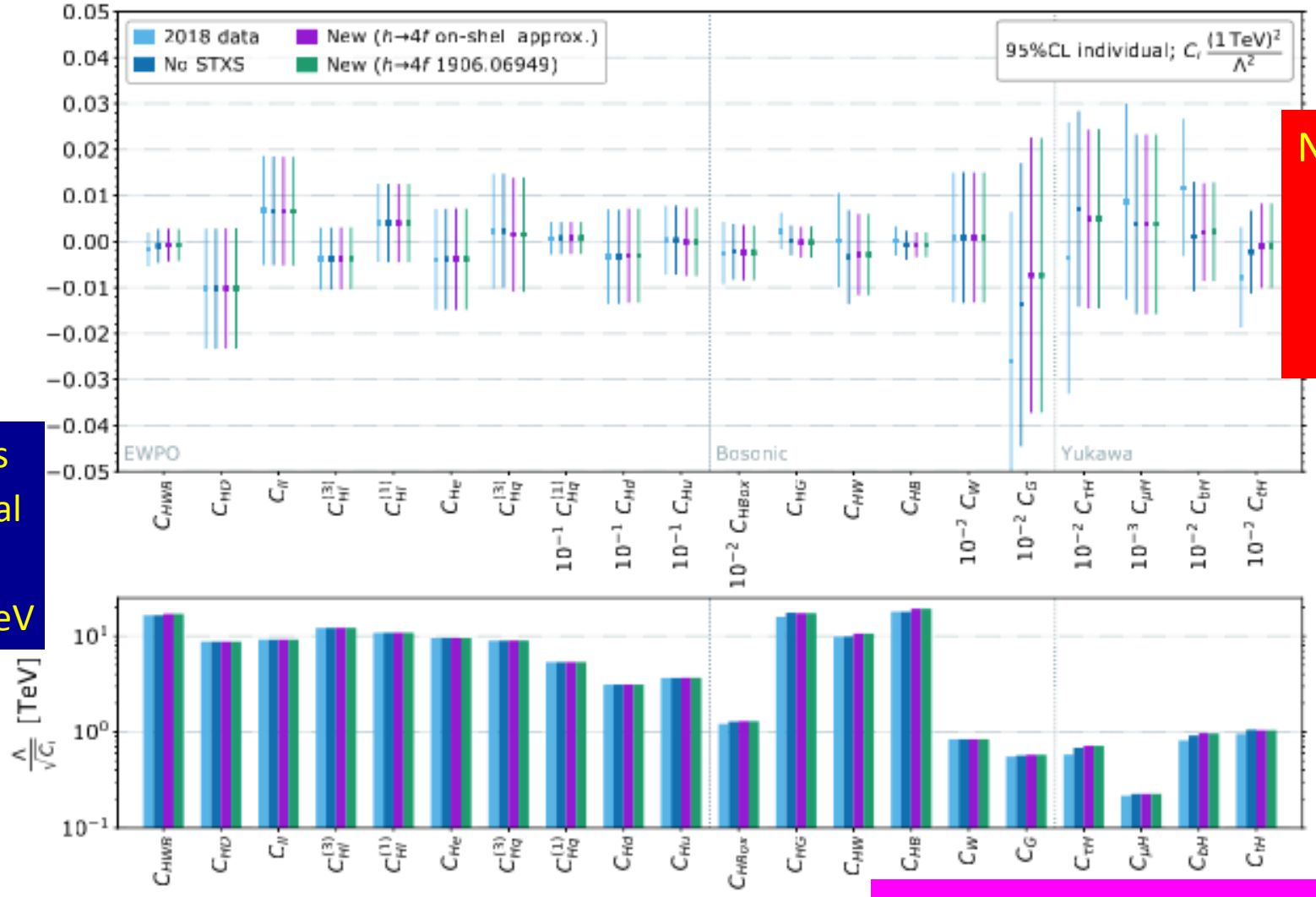
- Operators constrained by SU(2) × U(1) symmetry:

$$\begin{aligned}
\mathcal{L} \supset\ & \frac{\bar{c}_H}{2v^2}\partial^\mu\left[\Phi^\dagger\Phi\right]\partial_\mu\left[\Phi^\dagger\Phi\right] + \frac{g'^2\,\bar{c}_\gamma}{m_W^2}\Phi^\dagger\Phi B_{\mu\nu}B^{\mu\nu} + \frac{g_s^2\,\bar{c}_g}{m_W^2}\Phi^\dagger\Phi G^a_{\mu\nu}G_a^{\mu\nu} \\
& + \frac{2ig\,\bar{c}_{HW}}{m_W^2}\left[D^\mu\Phi^\dagger T_{2k} D^\nu\Phi\right]W^k_{\mu\nu} + \frac{ig'\,\bar{c}_{HB}}{m_W^2}\left[D^\mu\Phi^\dagger D^\nu\Phi\right]B_{\mu\nu} \\
& + \frac{ig\,\bar{c}_W}{m_W^2}\left[\Phi^\dagger T_{2k}\overleftrightarrow{D}^\mu\Phi\right]D^\nu W^k_{\mu\nu} + \frac{ig'\,\bar{c}_B}{2m_W^2}\left[\Phi^\dagger\overleftrightarrow{D}^\mu\Phi\right]\partial^\nu B_{\mu\nu} \\
& + \frac{\bar{c}_t}{v^2}y_t\Phi^\dagger\Phi\ \Phi^\dagger\cdot\bar{Q}_L t_R + \frac{\bar{c}_b}{v^2}y_b\Phi^\dagger\Phi\ \Phi\cdot\bar{Q}_L b_R + \frac{\bar{c}_\tau}{v^2}y_\tau\ \Phi^\dagger\Phi\ \Phi\cdot\bar{L}_L\tau_R
\end{aligned}$$

- Constrain with precision EW, Higgs data, TGCs ...

Updated Fit including Top Data

- Over 200 EW, H, diboson & top LHC Runs 1 + 2 measurements, allow top flavour non-universality



No significant indications of non-zero operators

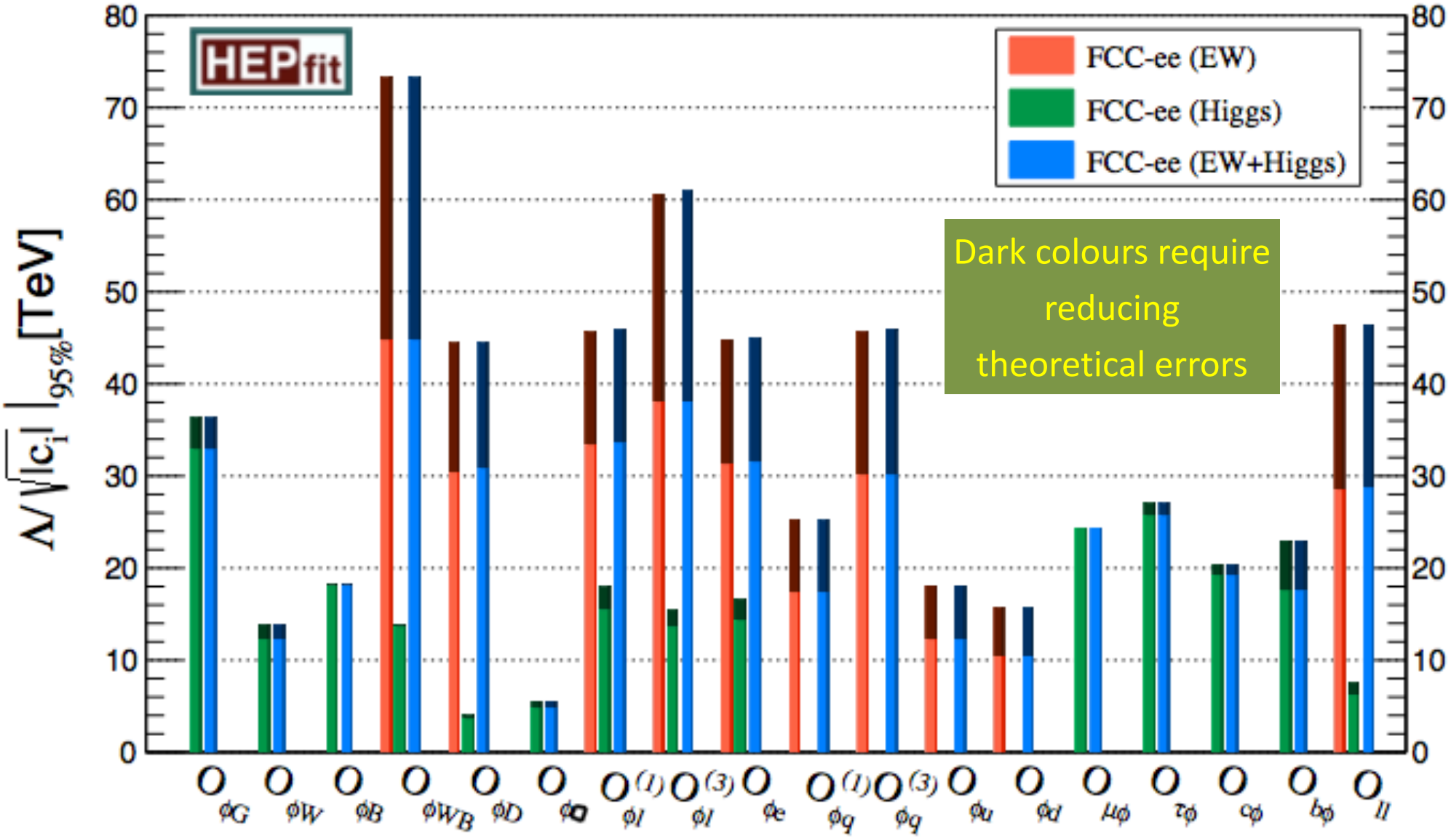
Constraints on individual operators: some > 10 TeV

Framework for analysis of future LHC data

JE, Madigan, Mimasu, Sanz & You, *to appear*

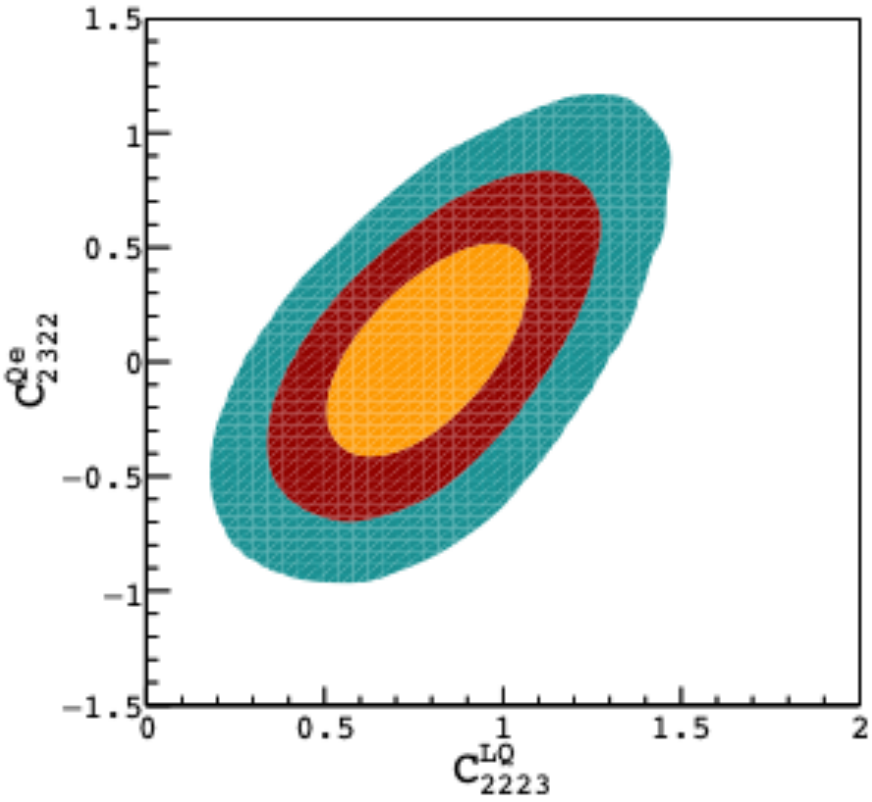
FCC CDR

Future EFT Constraints from Higgs and Electroweak Measurements



Flavour Physics

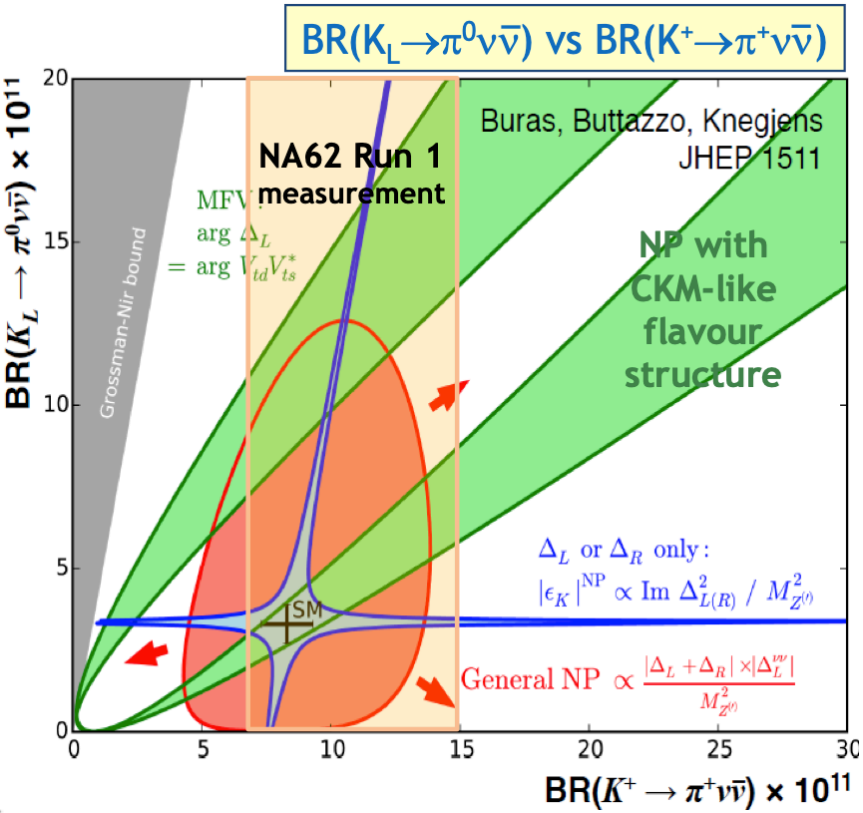
- Indications of new physics in b -> s ll decays
- Ratios of branching ratios with l = e, mu
- Also angular distributions
- Nominal 6-sigma anomaly
- Need optimal theoretical calculations of hadronic effects
- Attractive BSM framework?

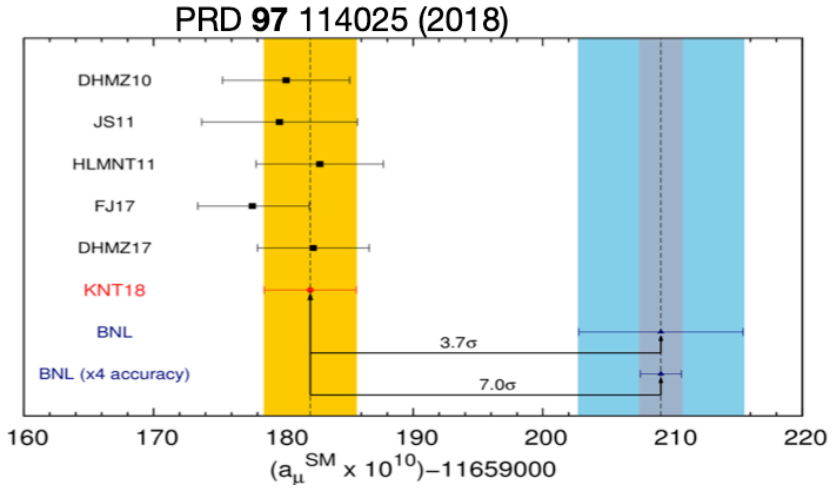


Ciuchini et al., arXiv: 2011.01212

Low-Energy Precision Measurements

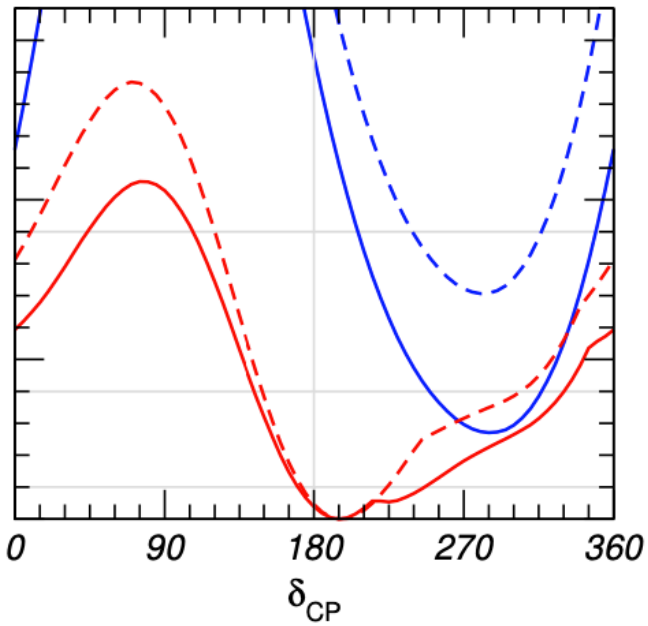
- NA62: **BR=(11±4)×10^{-11}**
- K+ -> pi+ nu nubar is key test of CKM & probe of BSM
- K0 -> pi0 nu nubar would be just as interesting
- g-2: $a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 279(76) \times 10^{-11}$
- Confirmation of BNL result would indicate BSM < TeV scale, but trigger check of SM calculation!



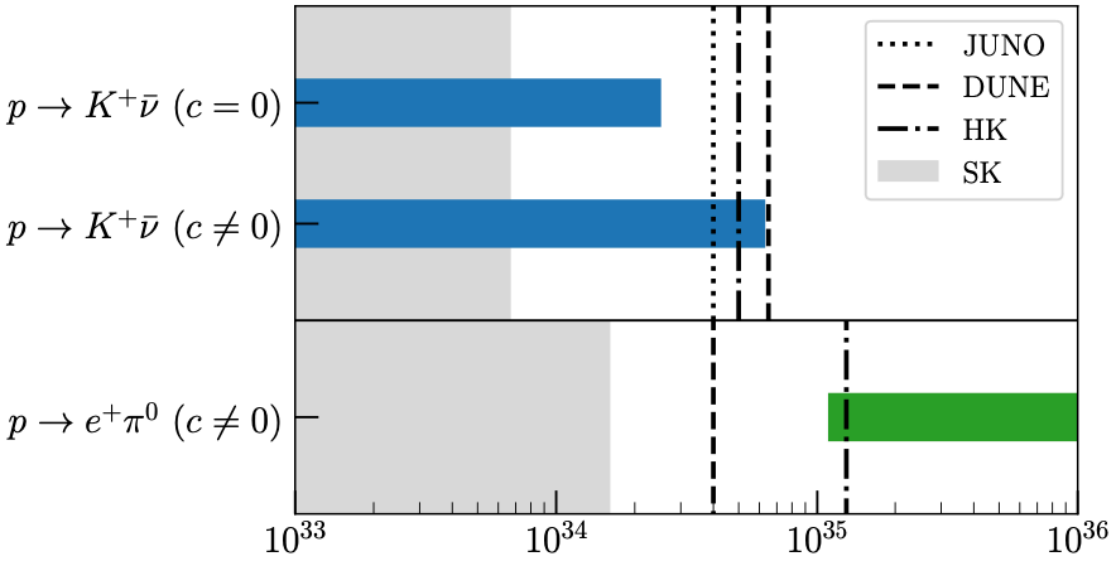


Neutrinos *& Proton Decay*

- Mass ordering and CP still unclear: need >1 experiment
- Complementary experimental capabilities for proton decay

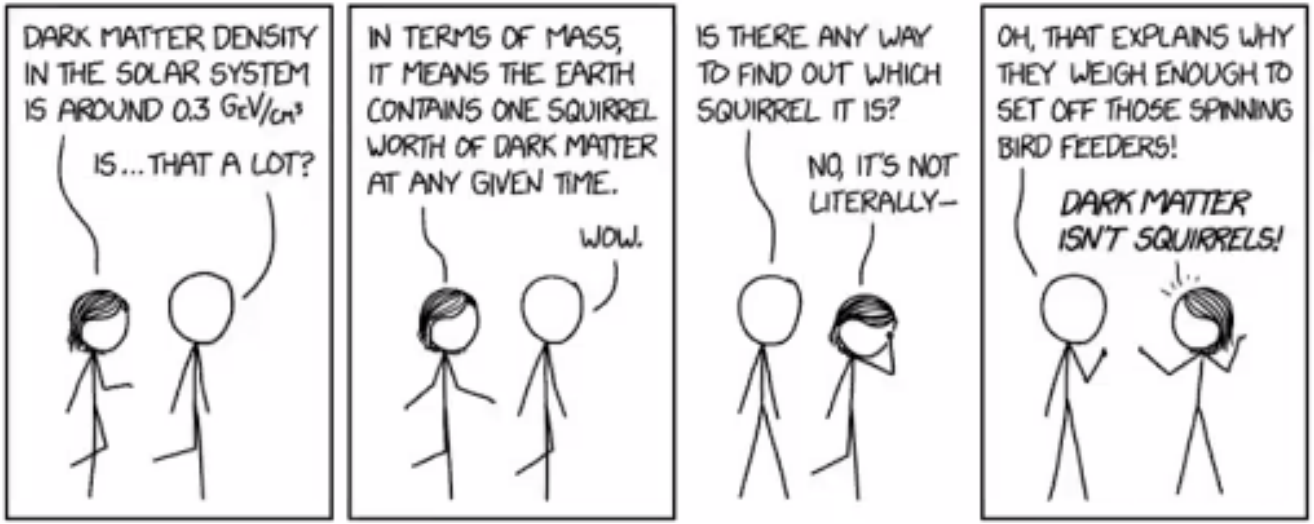


NuFit

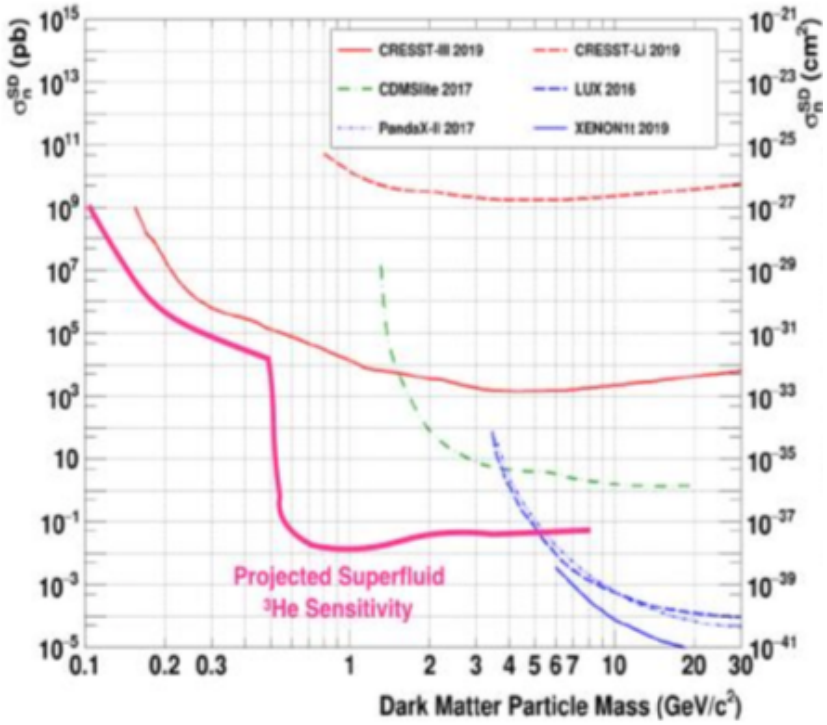


JE, Evans, Nagata, Olive & Velasco-Sevilla, arXiv:1912.04888

Dark Matter *isn't Squirrels*

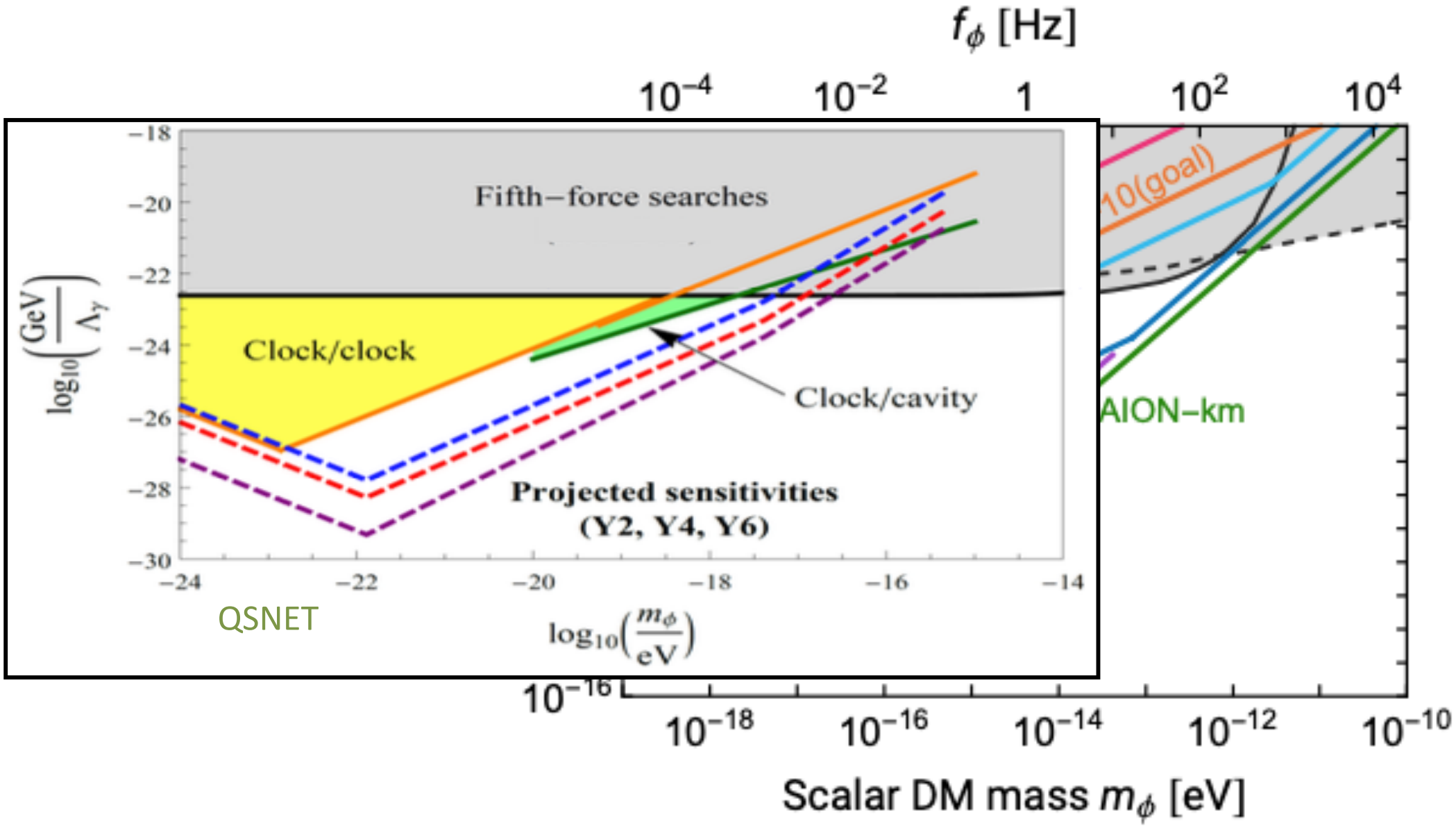


- Is it a particle or a wave?
- WIMP (LZ) or
- sub-GeV (QUEST-DMC) or
- ultralight dark matter?
- via UKRI/STFC/EPSRC initiative:
- Quantum Technologies for Fundamental Physics programme



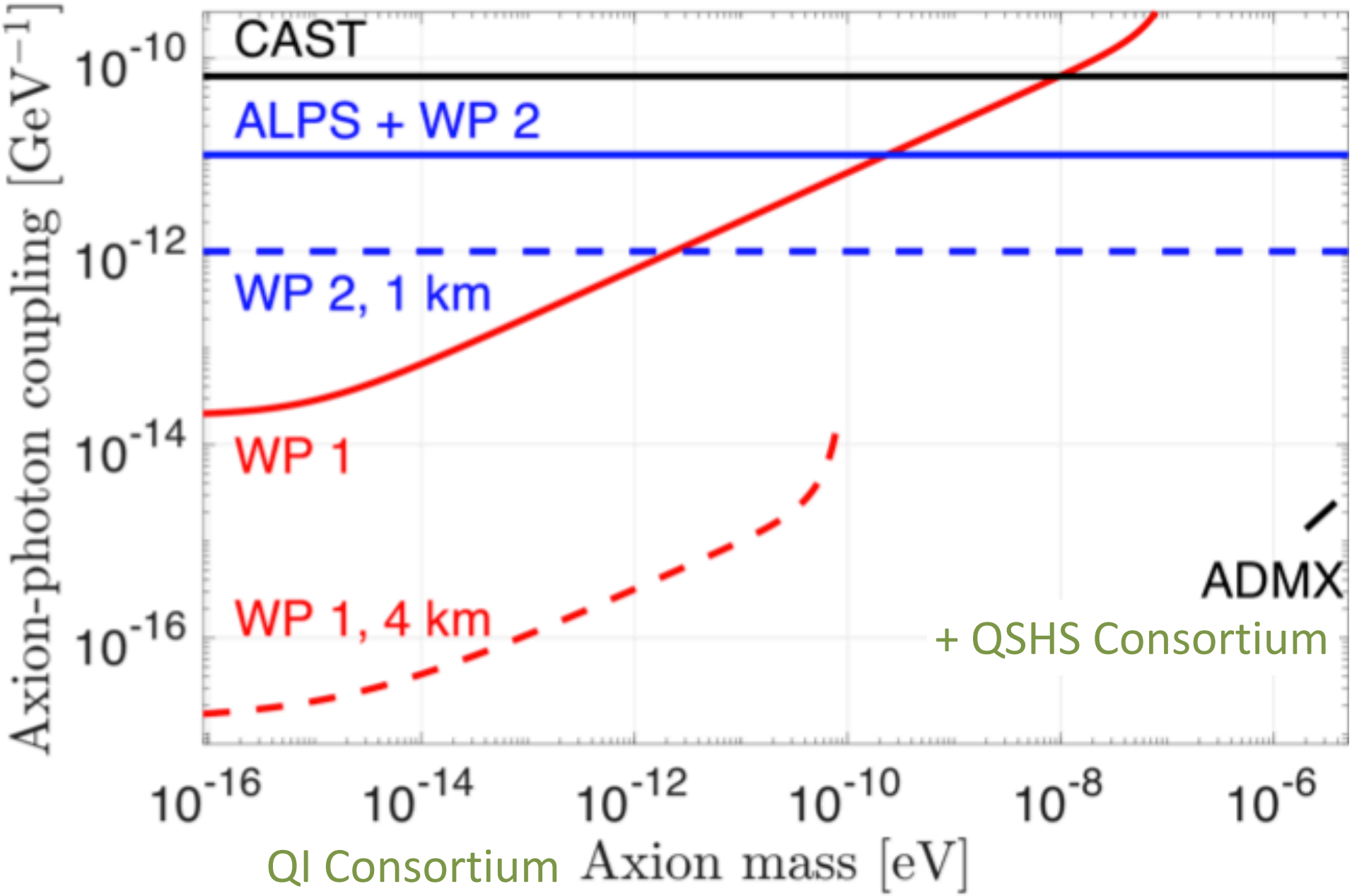
Quantum Technologies for Fundamental Physics:

Ultralight Scalar Dark Matter Searches



Quantum Technologies for Fundamental Physics:

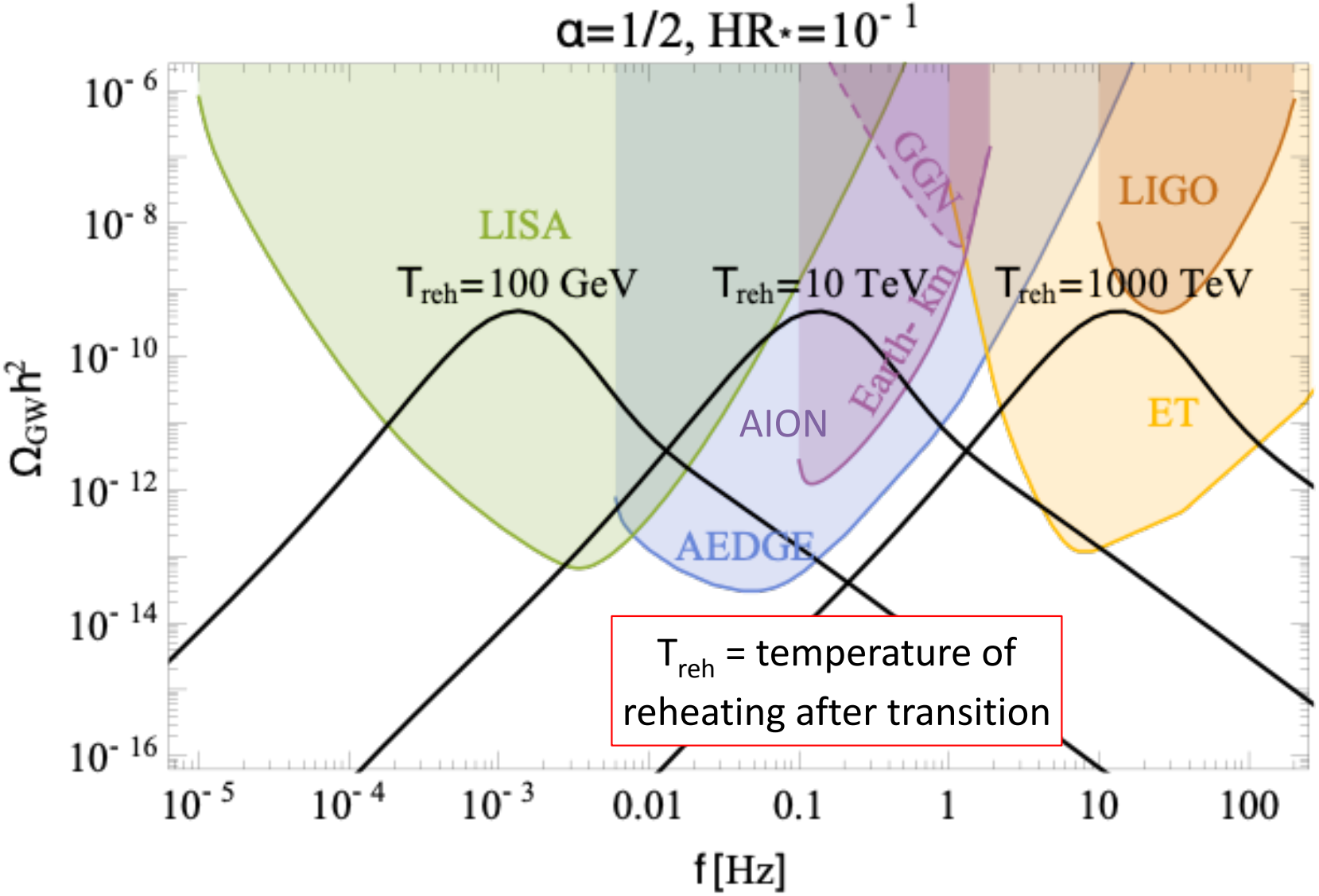
Axion-Like Particles



QI Consortium

Quantum Technologies for Fundamental Physics:

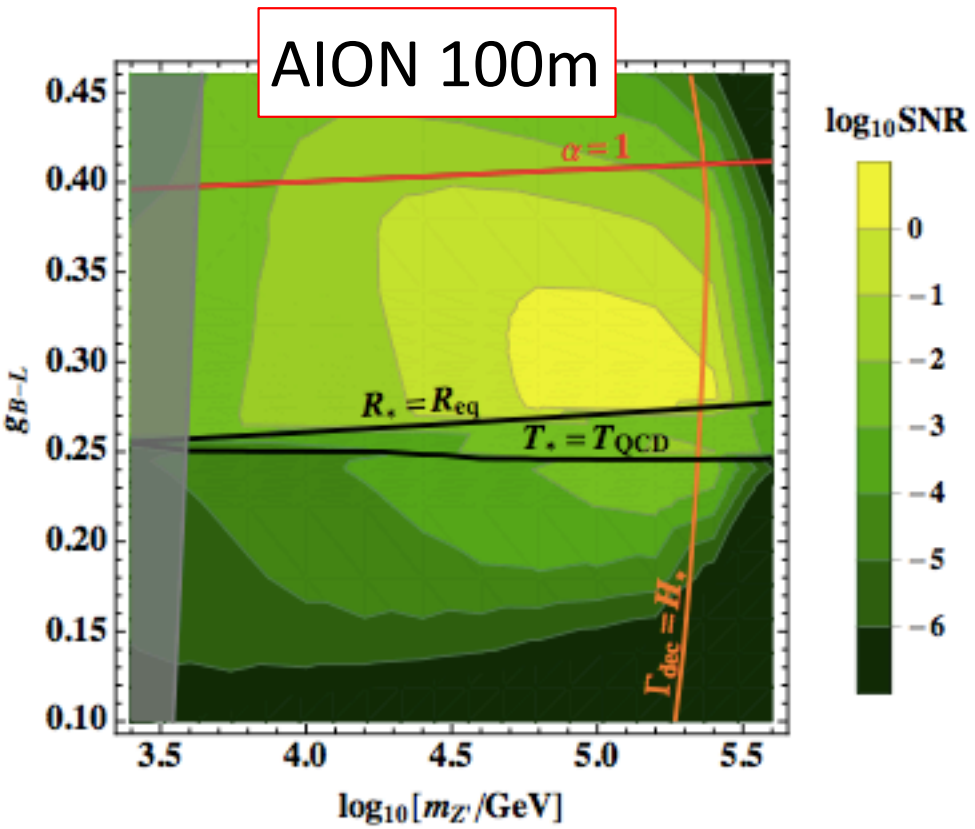
Gravitational Waves from $U(1)_{B-L}$ Phase Transition

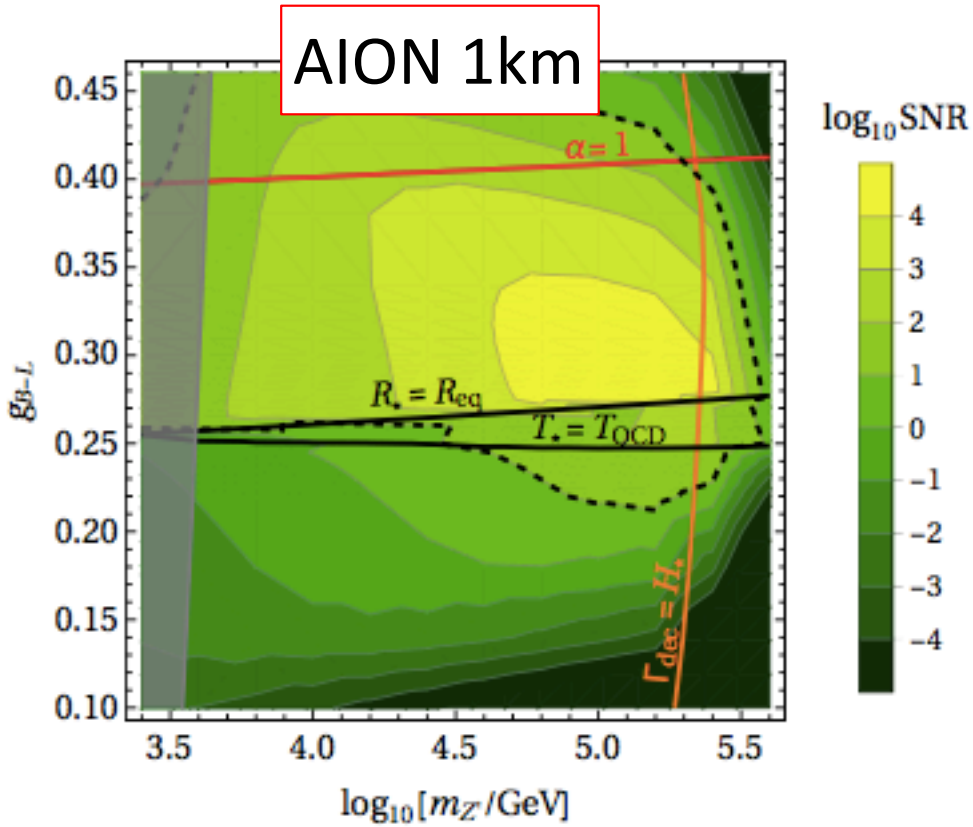


AEDGE: Bertoldi, ..., JE et al: arXiv:1908.00802

Quantum Technologies for Fundamental Physics:

AION GW SNR in $U(1)_{B-L}$ Model





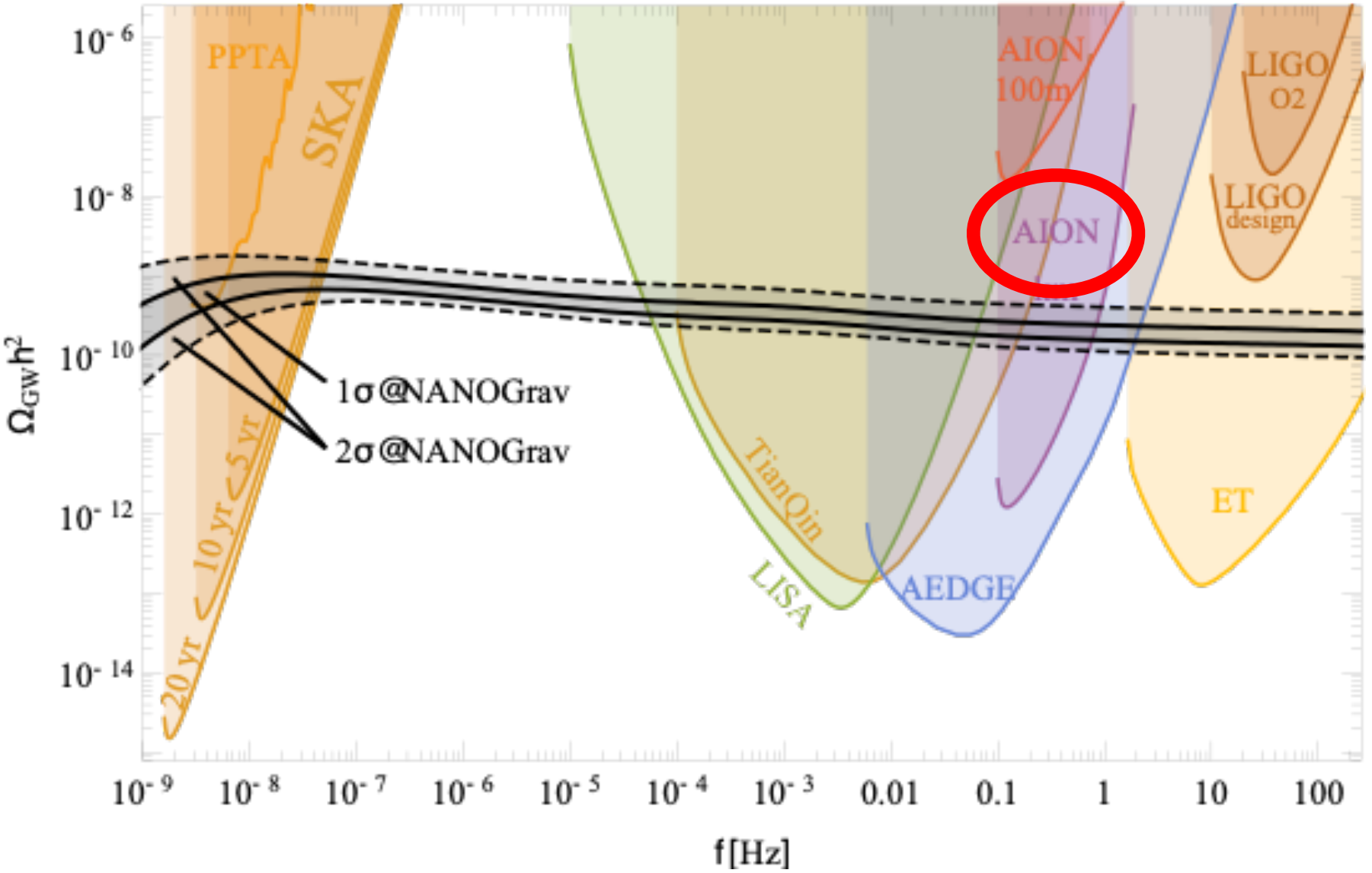
Discovery of GW possible with AION 1km (100m)

Above red line: transition before vacuum energy dominates
Right of orange line: period of matter domination

JE, Lewicki, No & Vaskonen, arXiv:1903.09642

Quantum Technologies for Fundamental Physics:

Gravitational Waves from Cosmic Strings?



NANOGrav-inspired cosmic string prediction can be tested in AION

JE & Lewicki: arXiv:2009.06555

How to progress beyond the SM?

"...the direct method may be used...but indirect methods will be needed in order to secure victory."

"...there are not more than two methods of attack – the direct and the indirect; ...Who can exhaust the possibilities of their combination?"

Sun Tzu, *The Art of War*