Fundamental Physics Opportunities from Quantum Technologies

UNIVERSITY OF OXFORD

Edward Hardy

ECFA-UK Meeting

Situation

Standard Model of particle physics + ΛCDM are spectacularly successful!

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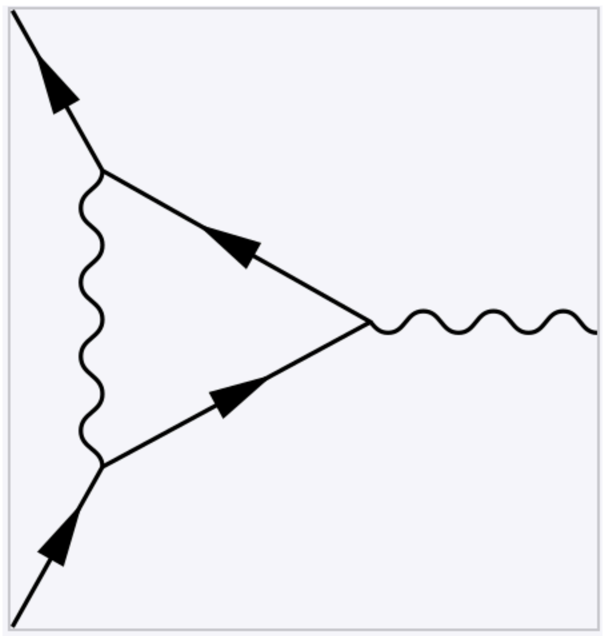
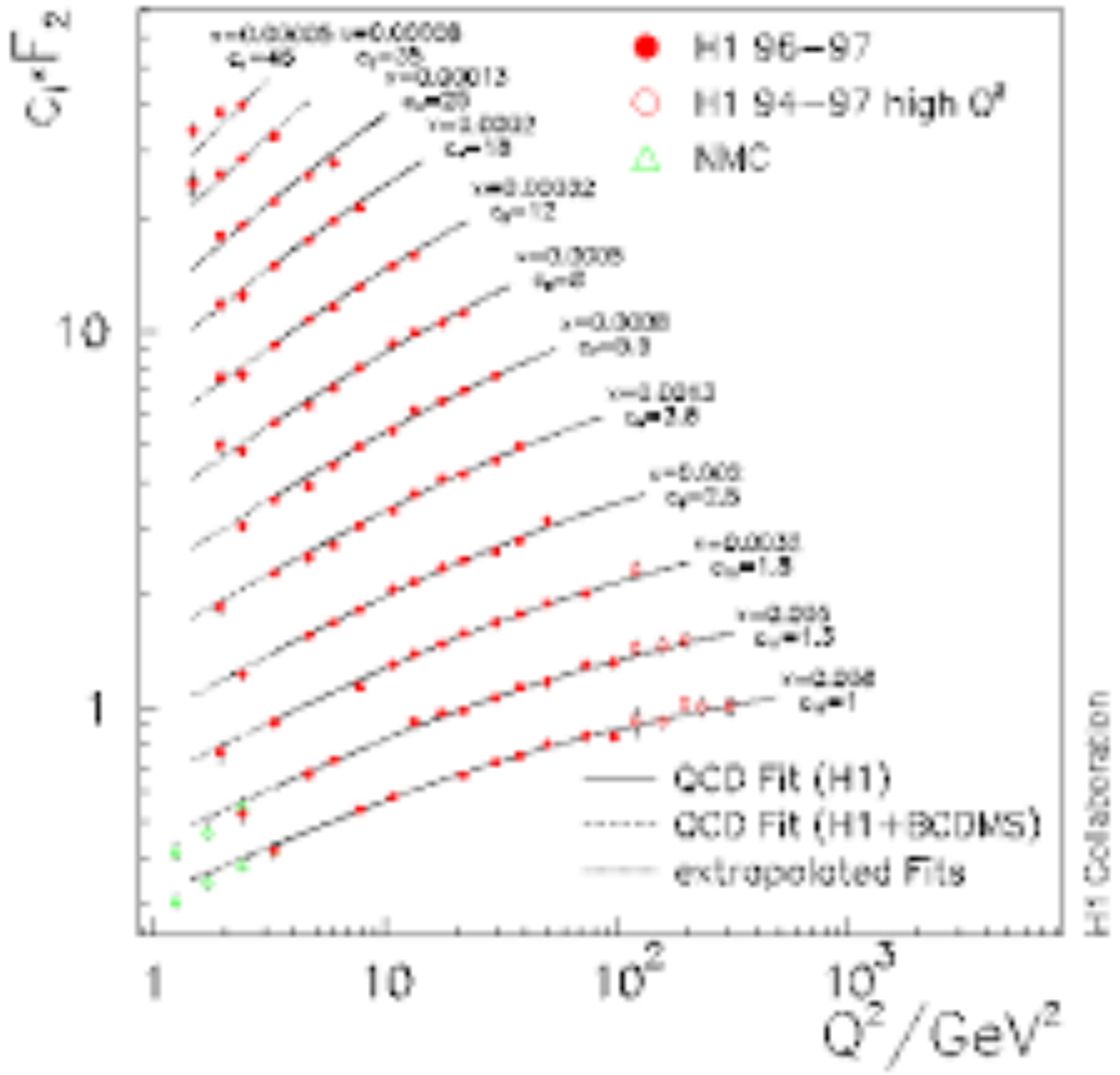
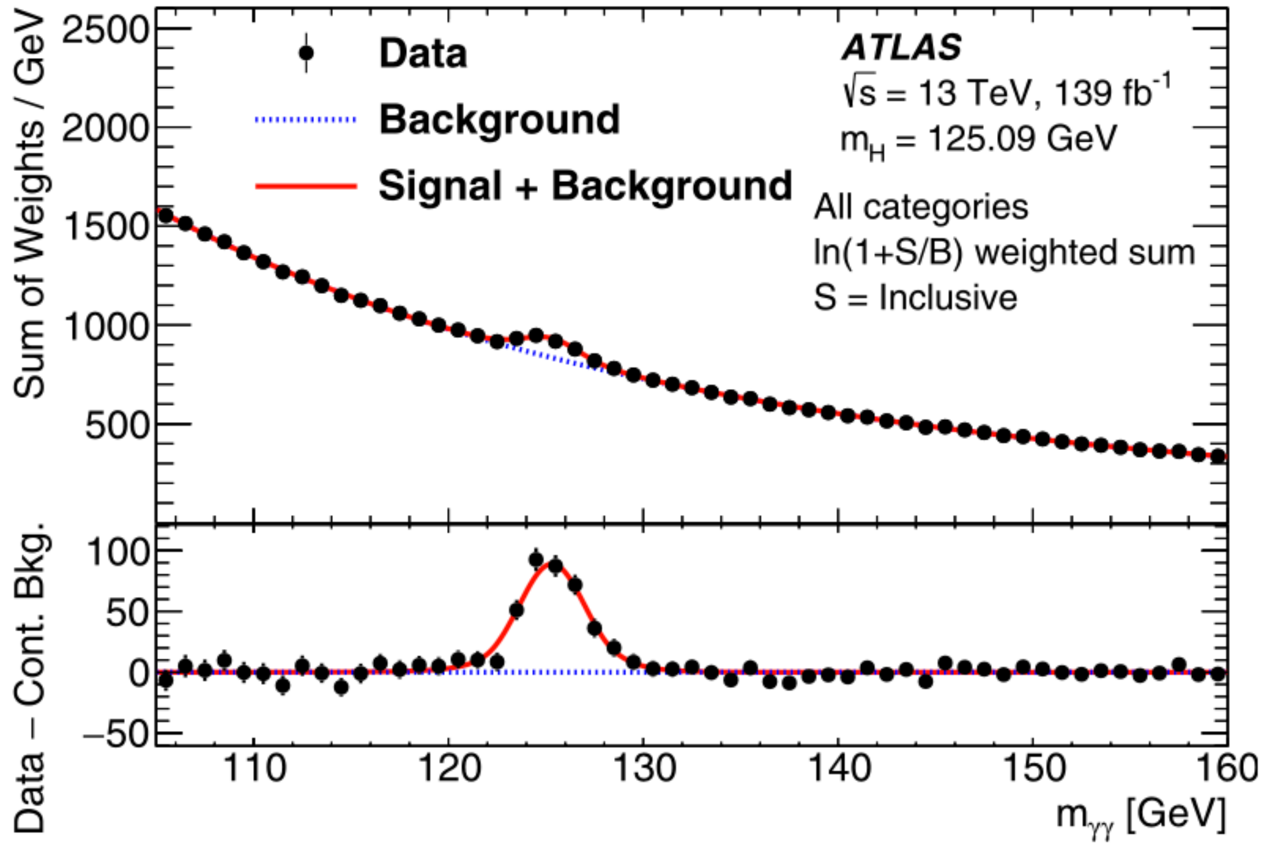
$$a_e = 0.001\,159\,652\,181\,643(764)$$

$$a_e = 0.001\,159\,652\,180\,59(13)$$







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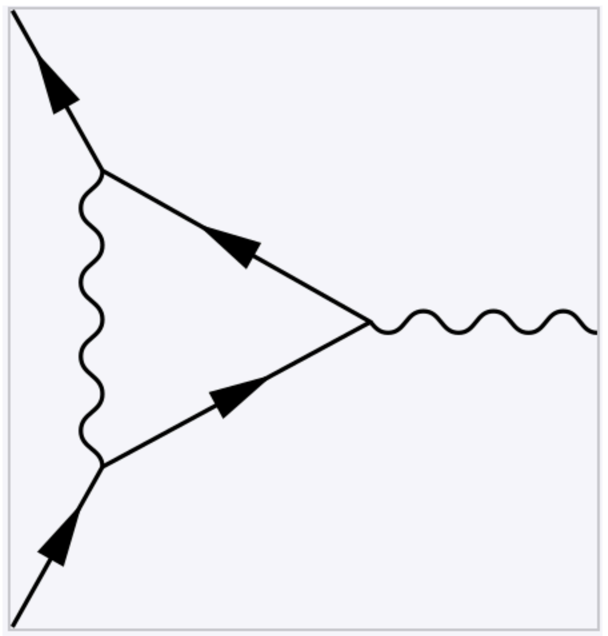
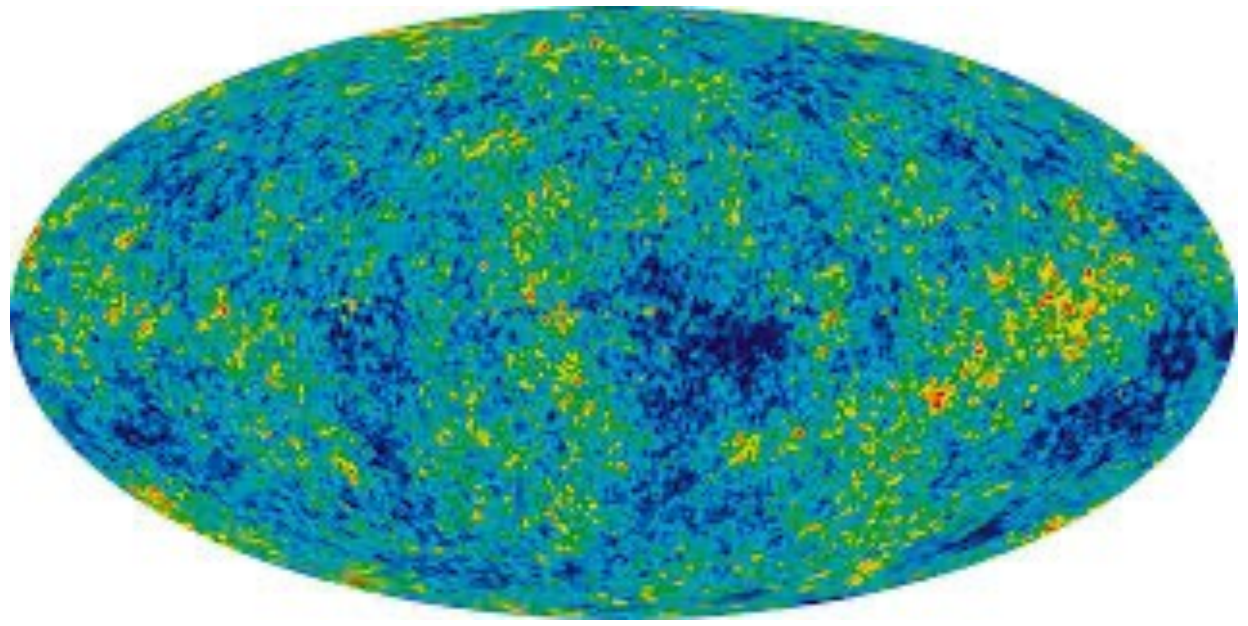
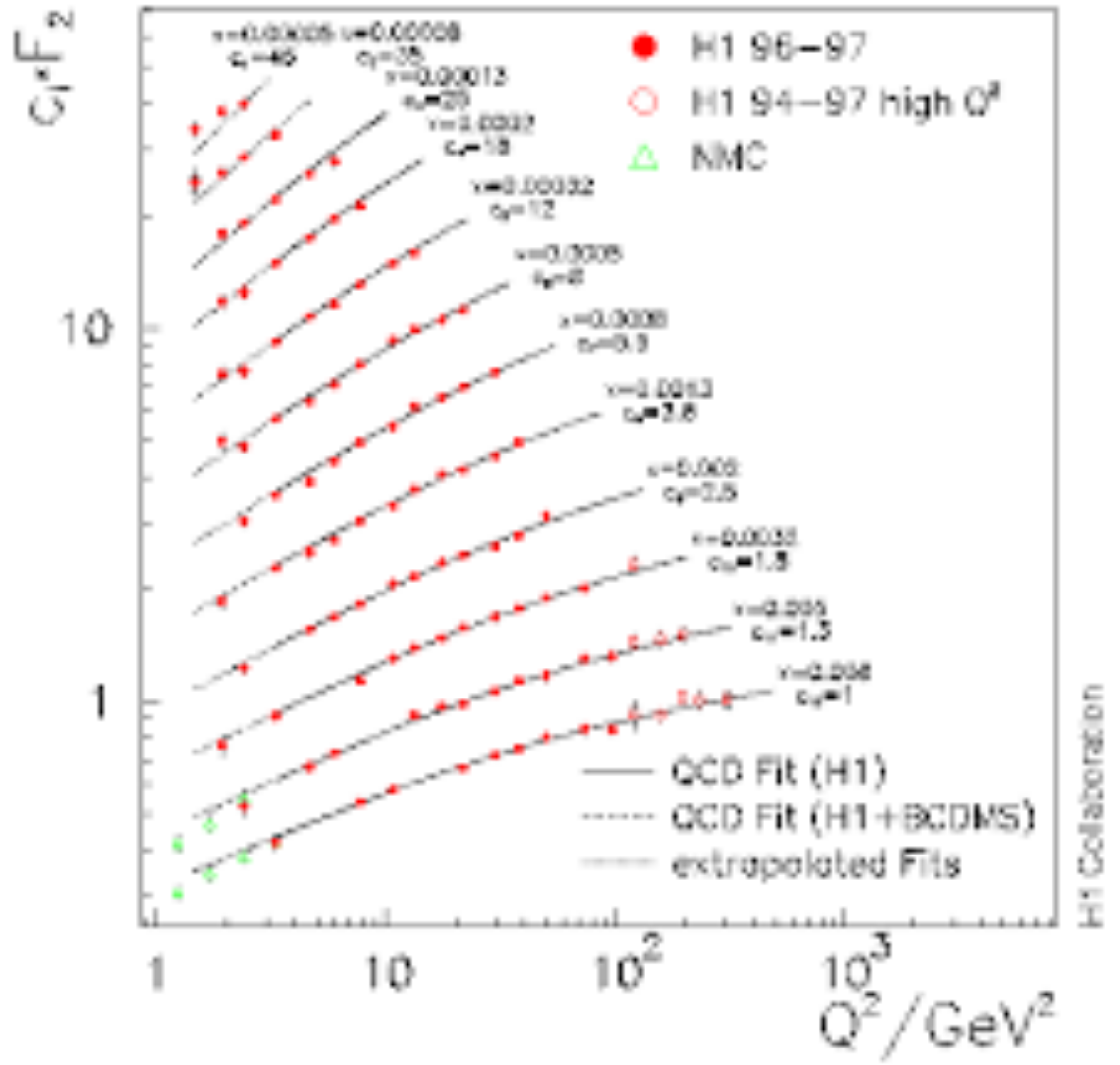
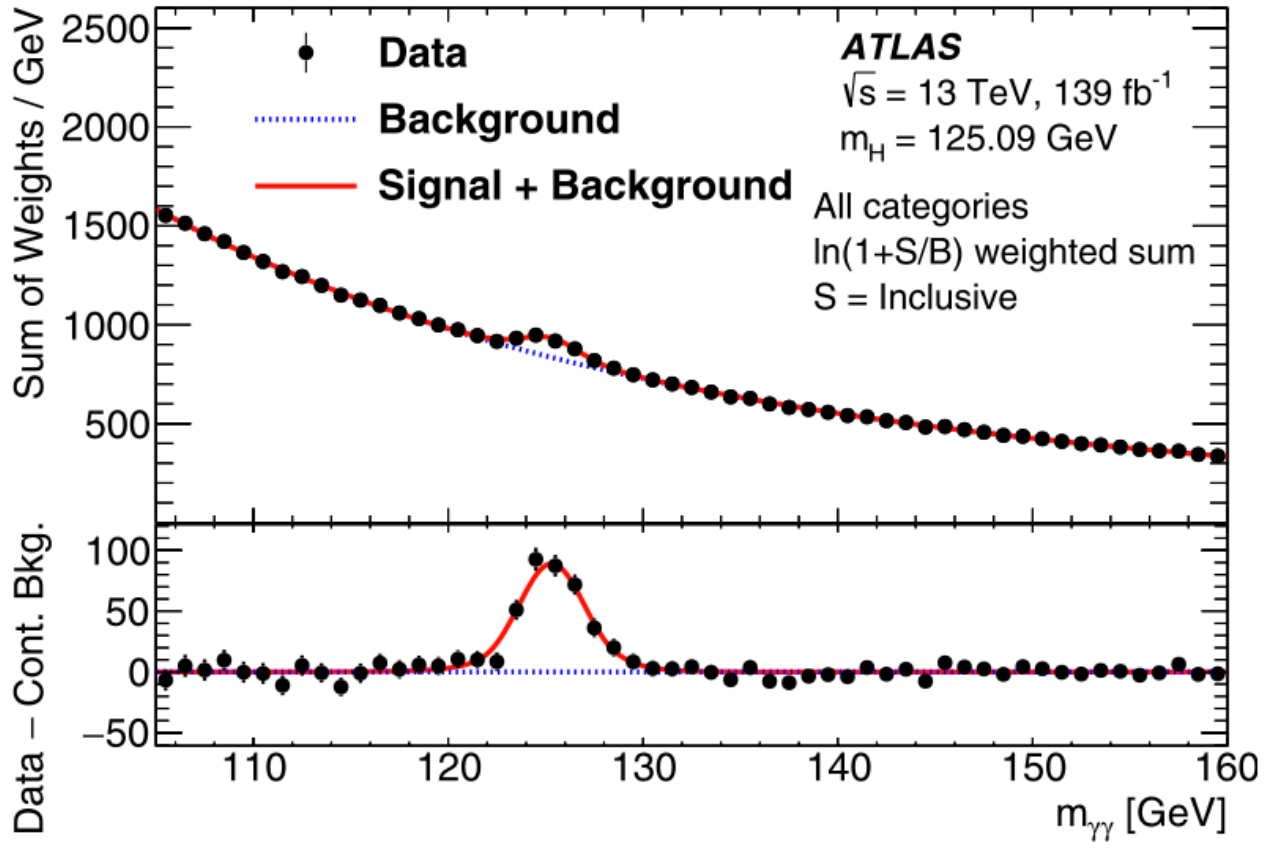
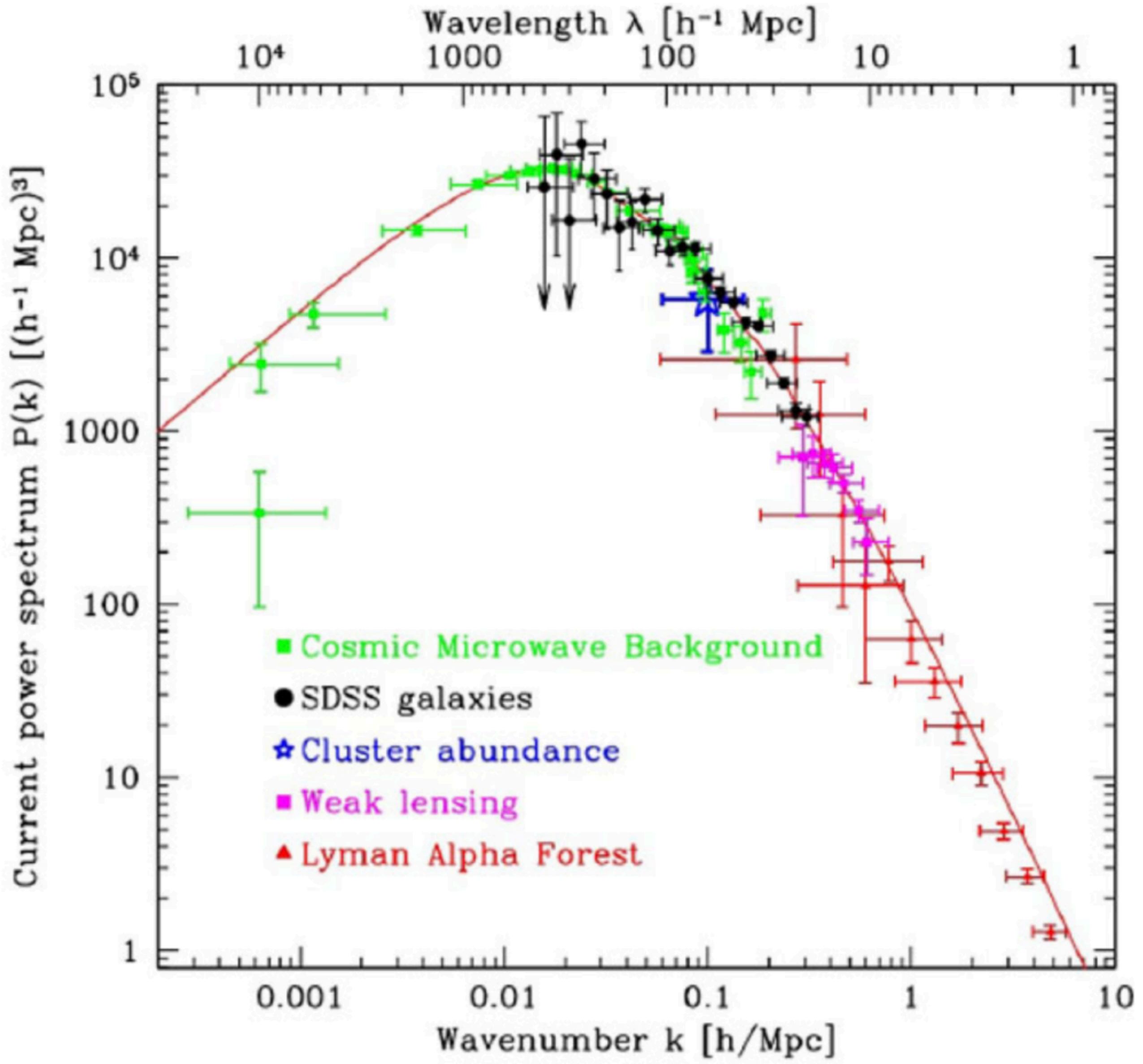
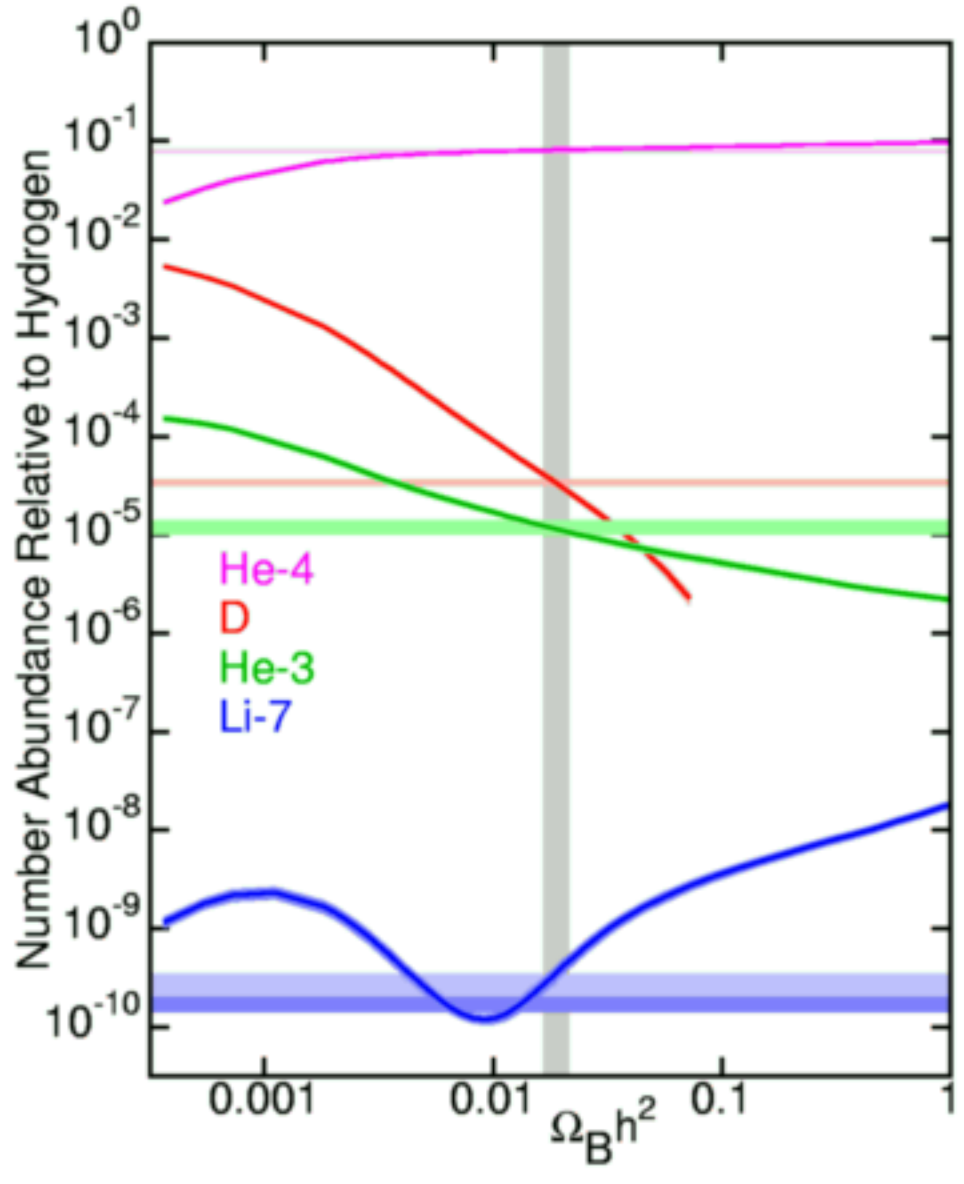






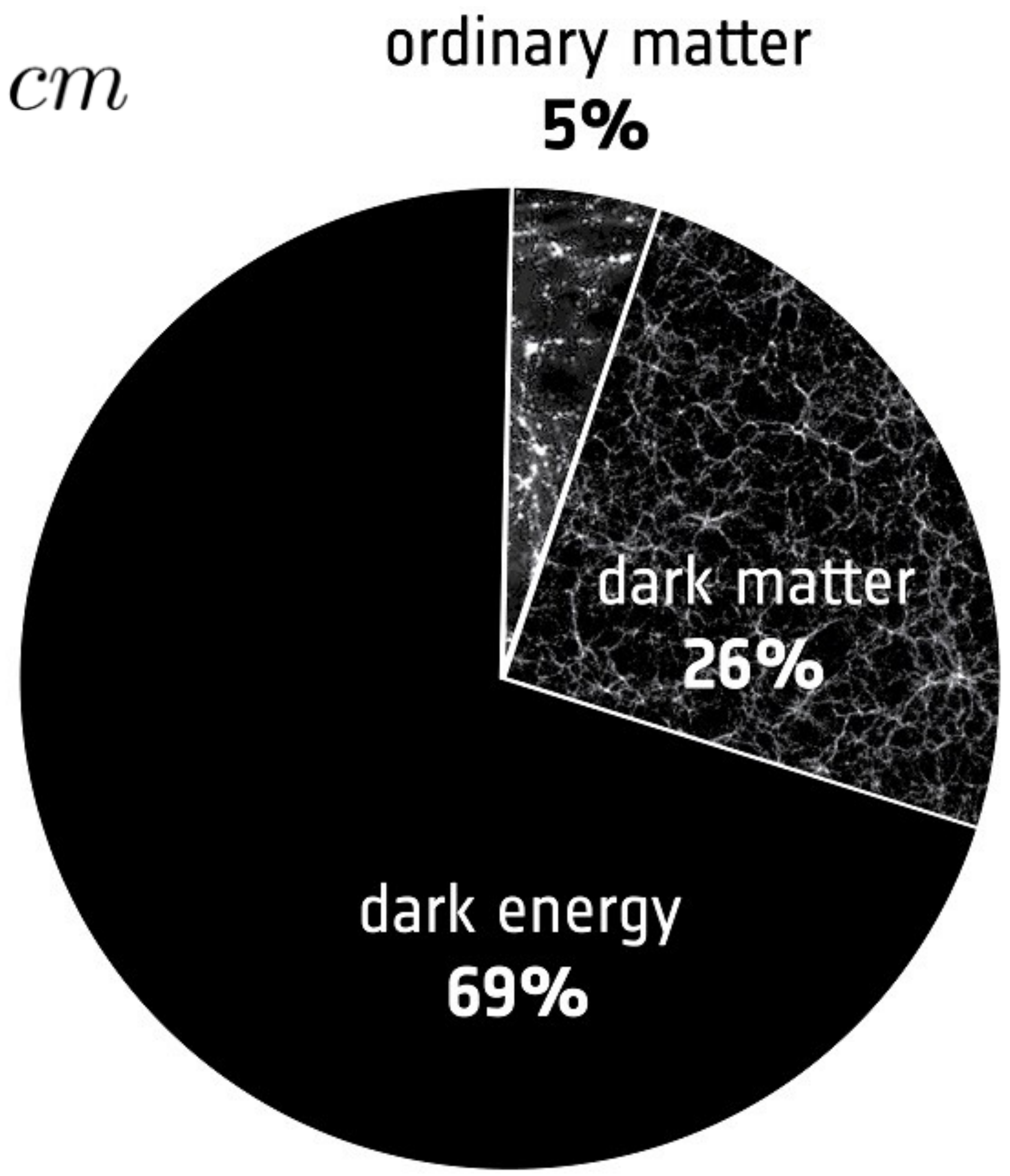


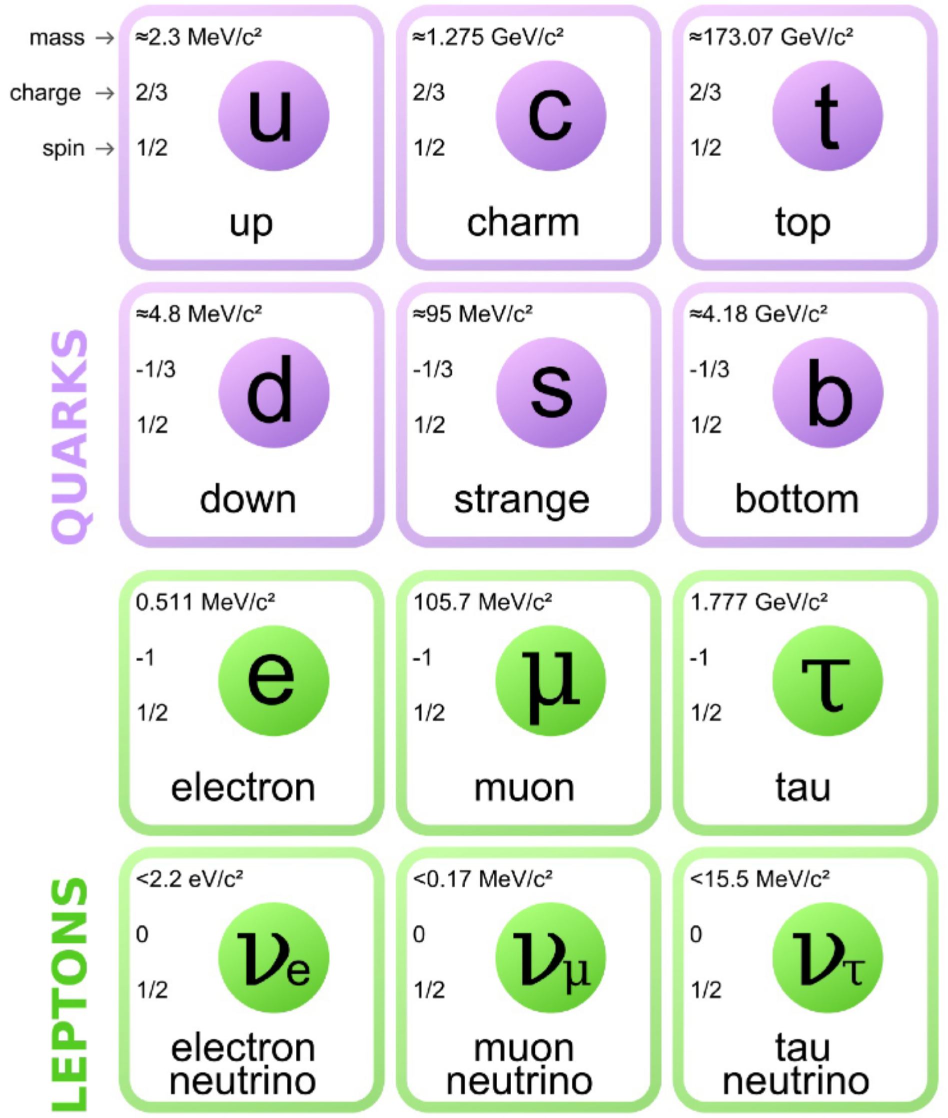


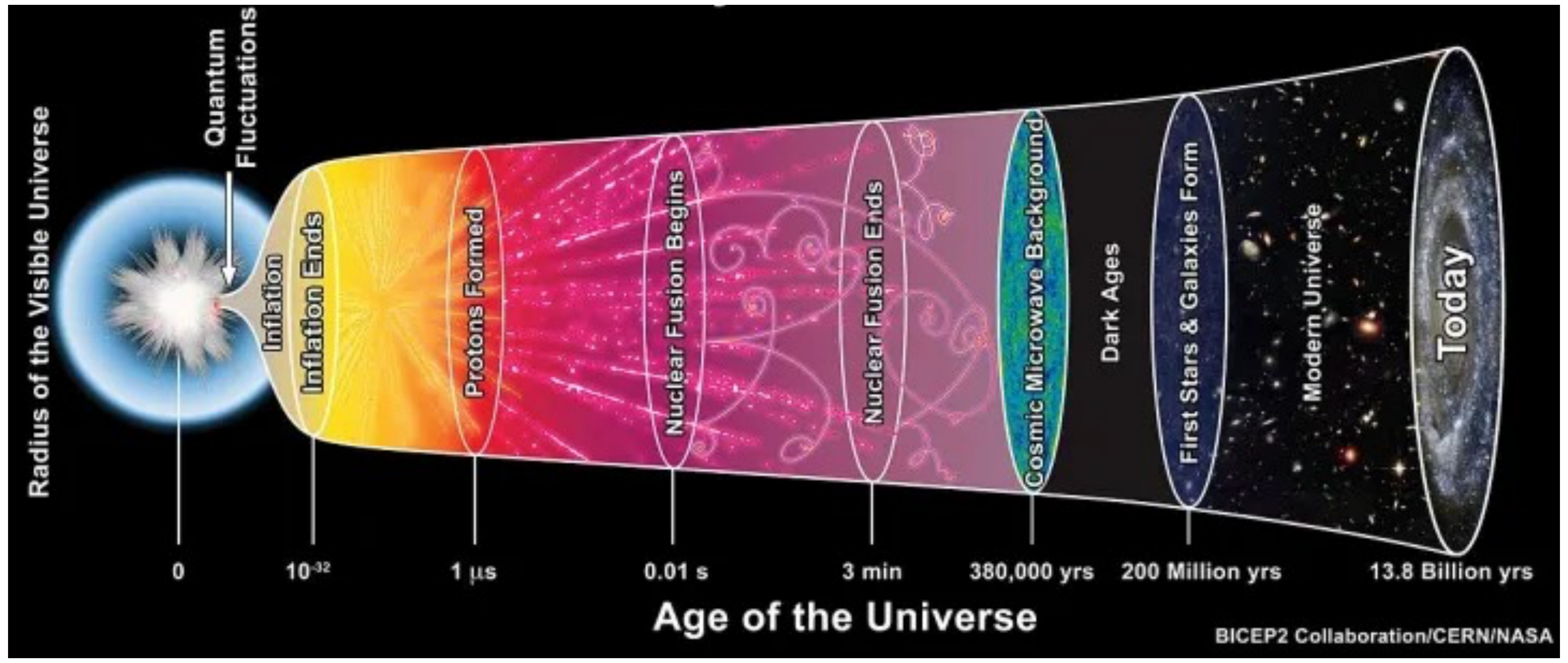


However ...

- Origin and stability of the electroweak scale $m_h \simeq 125.5 \text{ GeV} \lll M_{\text{Planck}}$
- Strong CP problem  $d_n < 2.9 \cdot 10^{-26} \, e\, cm$
- Neutrino masses $|\nu_\alpha\rangle = \sum_i U_{\alpha i} \, |\nu_i\rangle$
- Structure of fermion generations and masses
- Dark matter
- Origin of the matter/ antimatter asymmetry
- Dark energy = cosmological constant?
- Cosmological history at $T \gtrsim \text{MeV}$
- Quantum gravity. Inflation. Supersymmetry.







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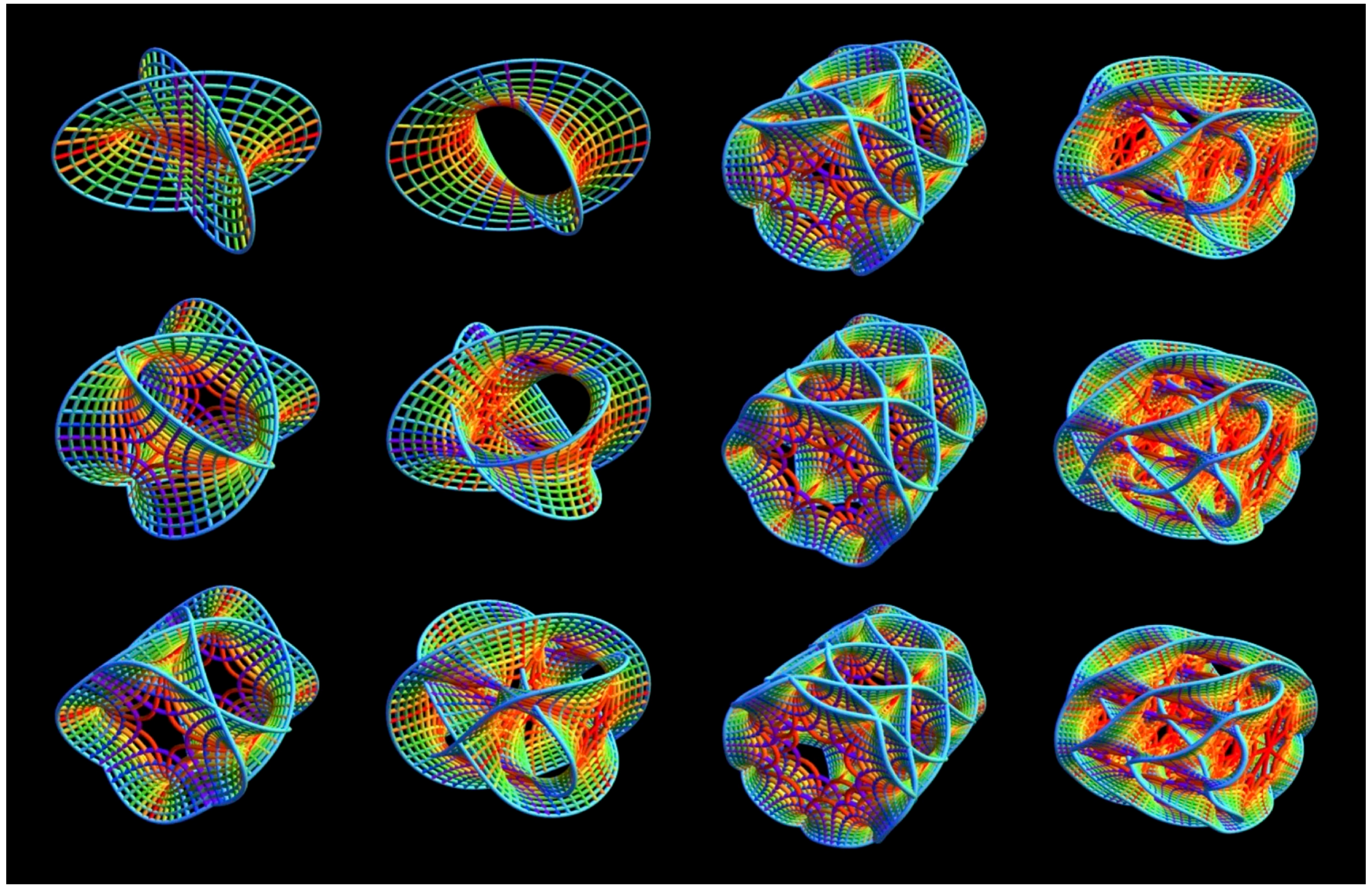


[Quanta]

Computation of Quark Masses from String Theory

Andrei Constantin (Oxford U., Theor. Phys.), Cristofero S. Fraser-Taliente (Oxford U., Theor. Phys.), Thomas R. Harvey (Oxford U., Theor. Phys.), Andre Lukas (Oxford U., Theor. Phys.), Burt Ovrut (Pennsylvania U.)

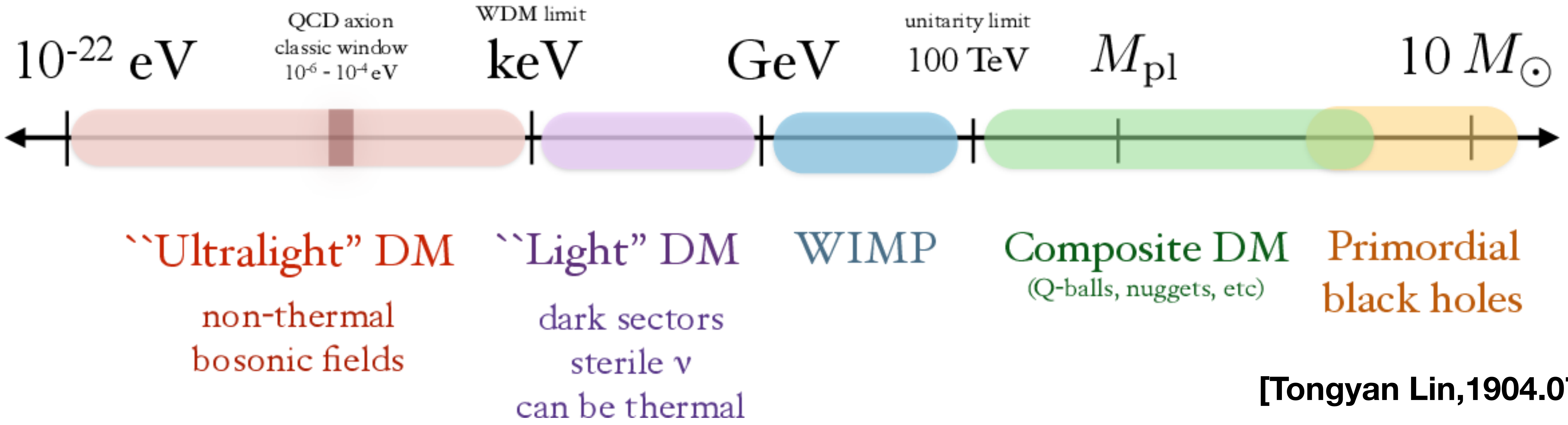
Experimental discoveries are vital!

No single guaranteed way forward

- Major open questions
- No no-lose theorems
- Not even a dominant theoretical expectation

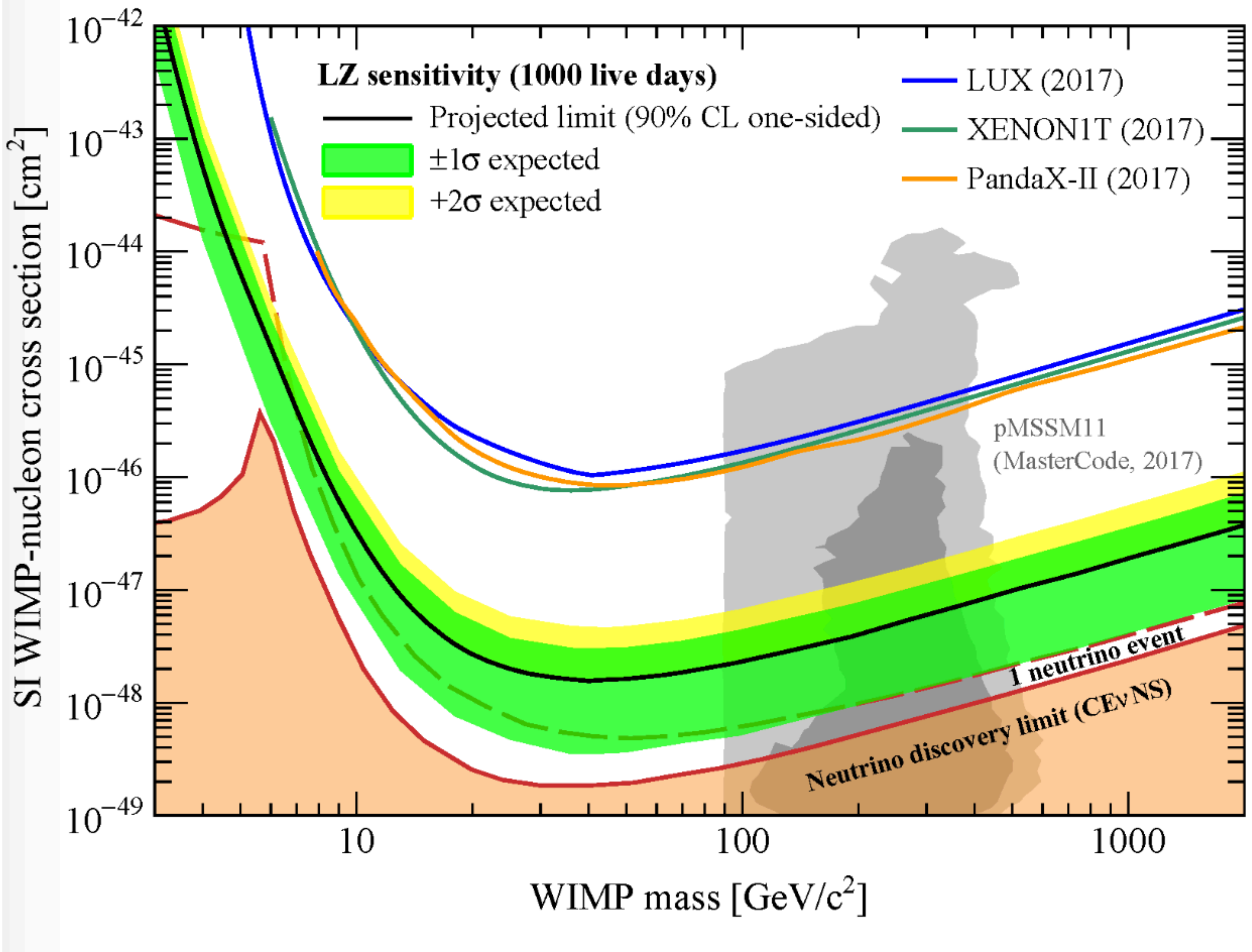
} Challenging but also exciting

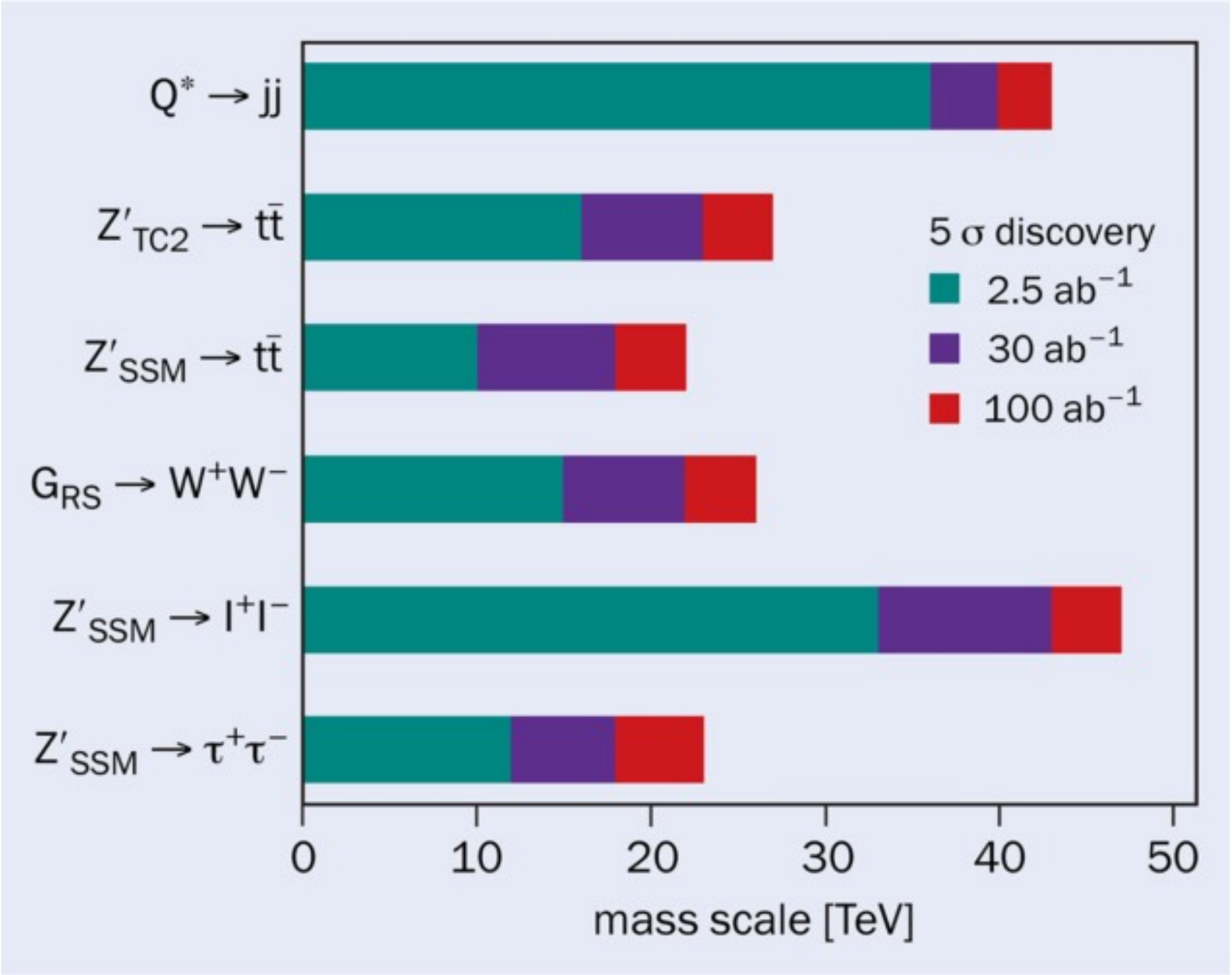
E.g. dark matter



[Tongyan Lin,1904.07915]

Well-established strategies have impressive reach





LZ projections

https://doi.org/10.3390/universe5030073

FCC-ee

https://cerncourier.com/a/fcc-the-physics-case/

Quantum technologies open up new opportunities

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NQTP

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Quantum Technologies for Fundamental Physics

In late 2020, seven projects were funded with a £31 million investment to demonstrate how quantum technologies could solve some of the greatest mysteries in fundamental physics.

https://uknqt.ukri.org/our-programme/qtfp/

Quantum sensors for the hidden sector

Principal investigator: Ed Daw

$$\theta' = \theta_0 + \arg\left(\mathrm{Det} M_q\right) \lesssim 10^{-10}$$

$$\frac{a}{f_a}\frac{\alpha_s}{8\pi}G_{\mu\nu}\tilde{G}^{\mu\nu}$$

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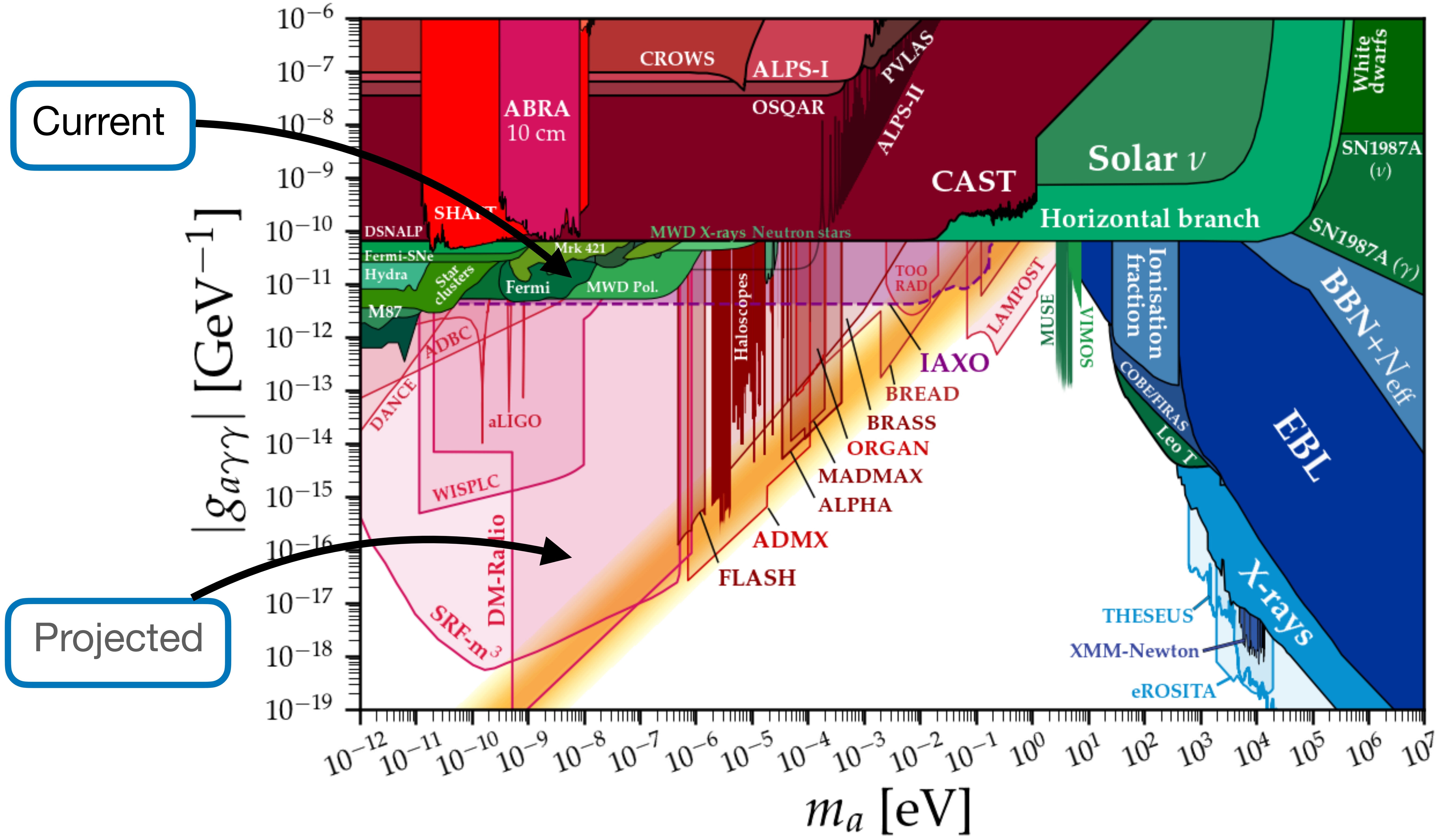

$$P_{a\gamma\gamma} = 5.0 \times 10^{-23}\ \mathrm{w}$$

QTNM — Quantum Technologies for Neutrino Mass

Determination of absolute neutrino mass using quantum technologies

Principal investigator: Ruben Saaykan

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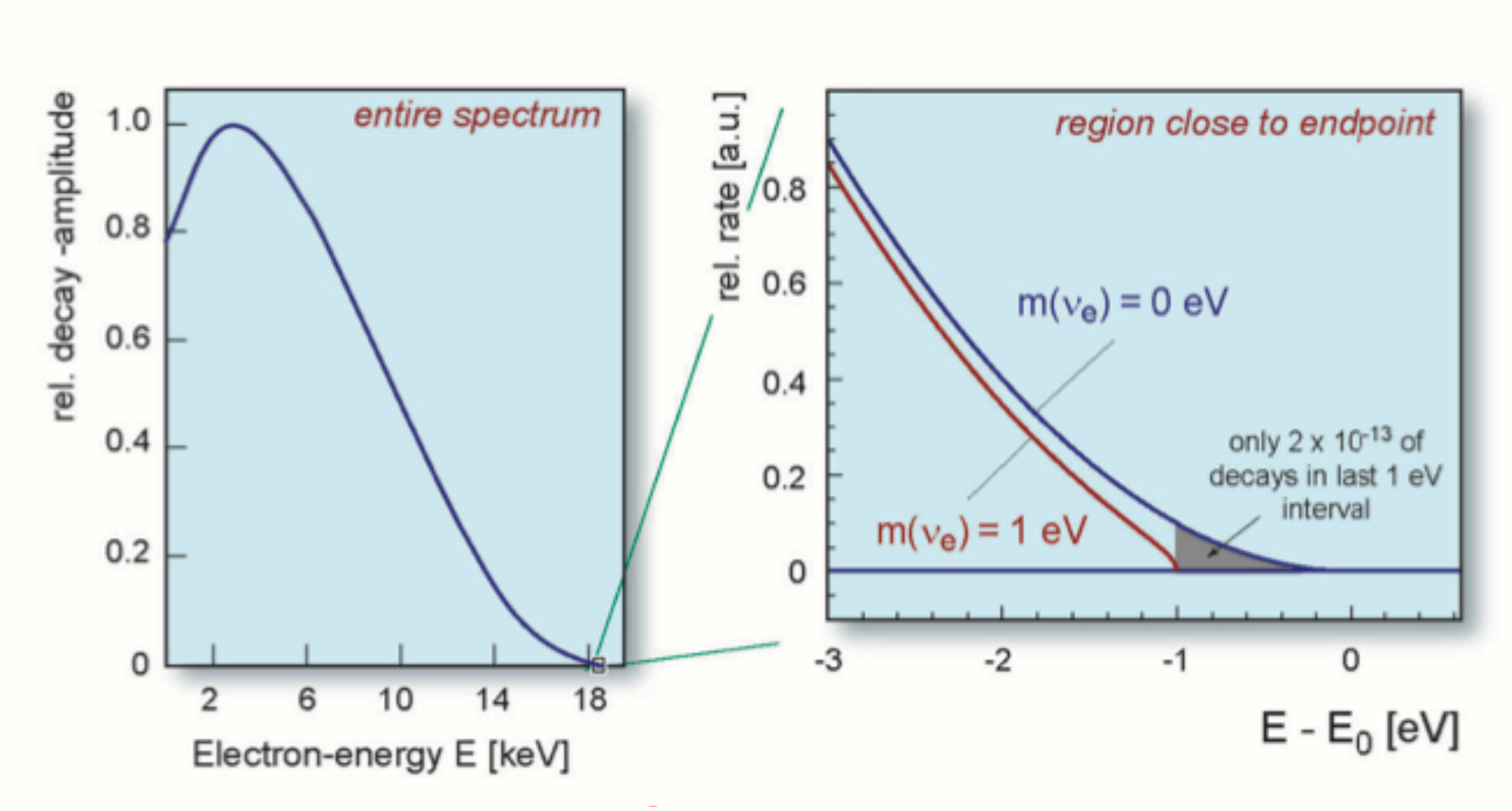
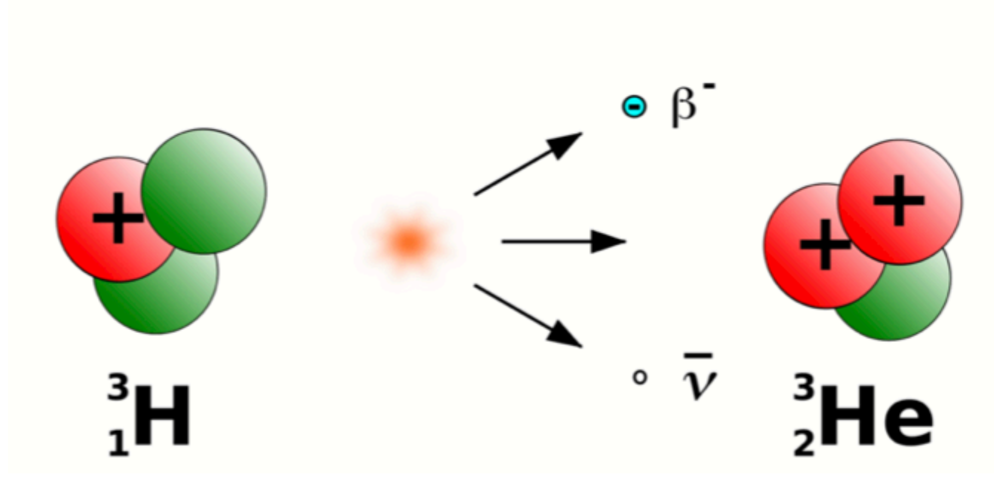
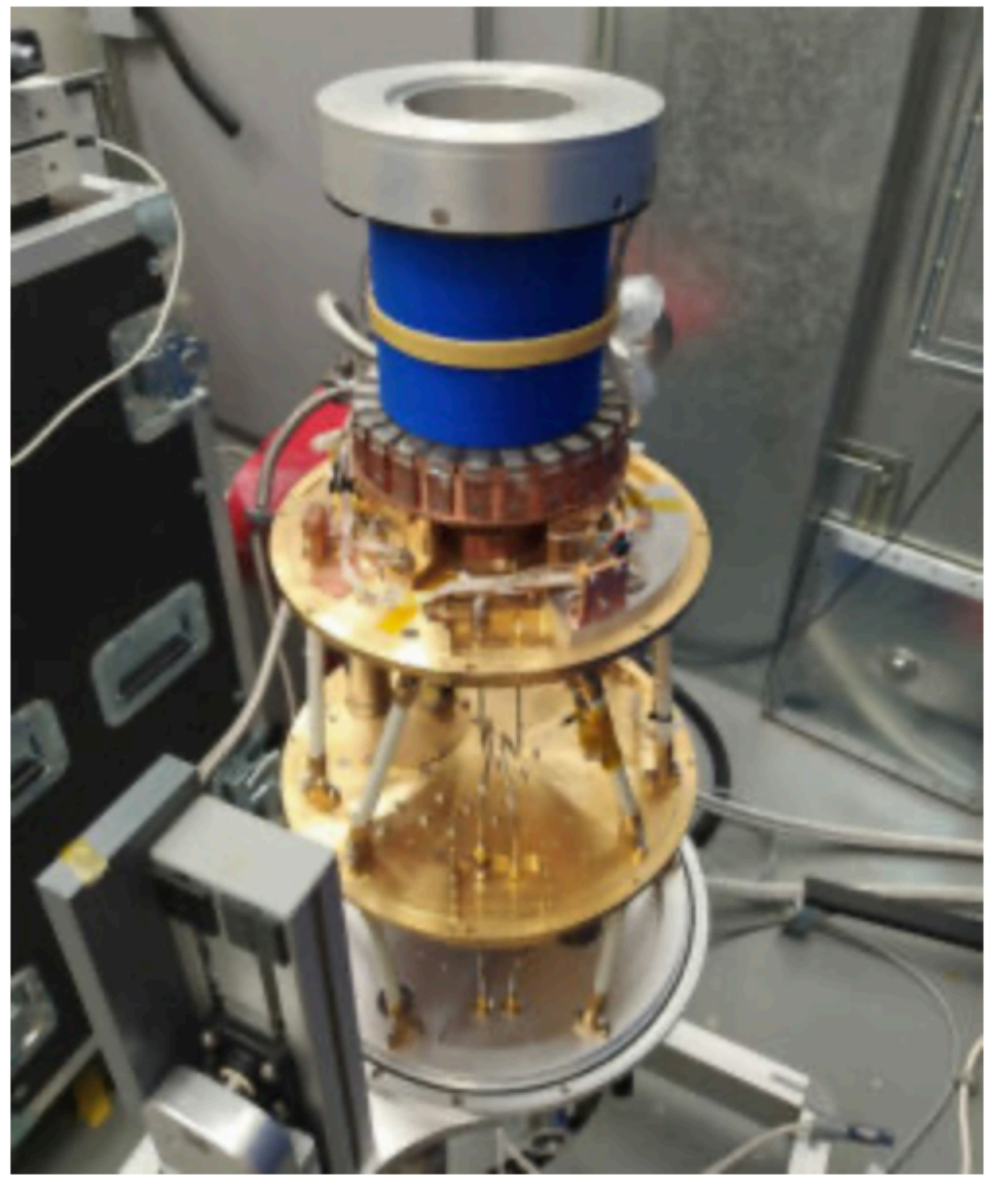




- $E_{\text{kin}} = Q_\beta = 18.6\,\text{keV},\ B = 1\,\text{T}$
- $f = 27\,\text{GHz},\ \lambda \sim 1\,\text{cm} \rightarrow$ microwaves



- Basic technology demonstration (2021–2025)
- Tritium demonstration at Culham (2025–2030+)
- Final neutrino mass experiment with $\sim 10 - 50$ meV sensitivity at Culham or similar facility (2030–2040)

https://indico.cern.ch/event/1261135/contributions/5333590/attachments/2622745/4535157/iopApril2023.pdf

A UK atom interferometer observatory and network

Principal investigator: Oliver Buchmuller

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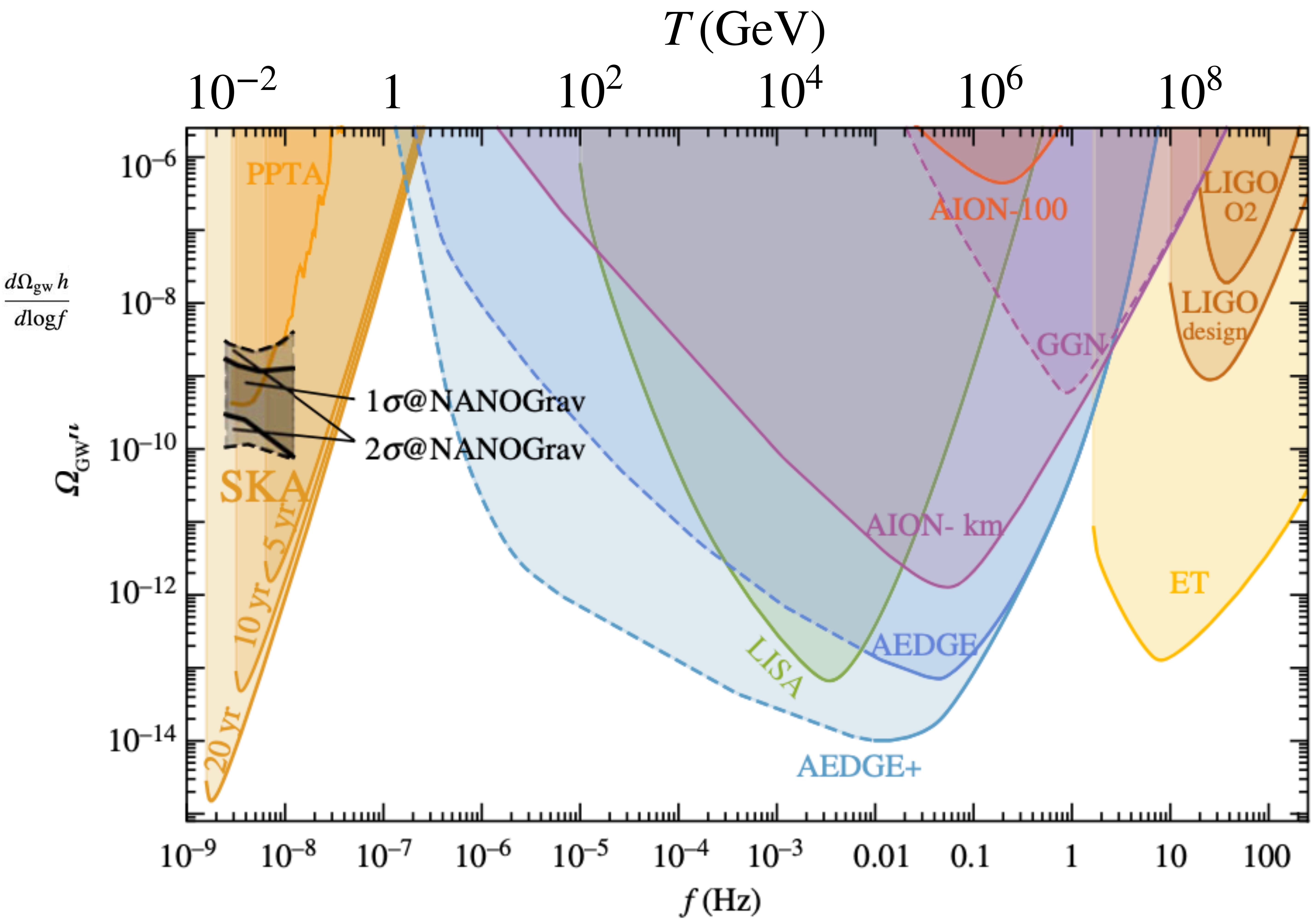

https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2021.0060

QUEST DMC

Quantum enhanced superfluid technologies for dark matter and cosmology

Principal investigator: Andrew Casey

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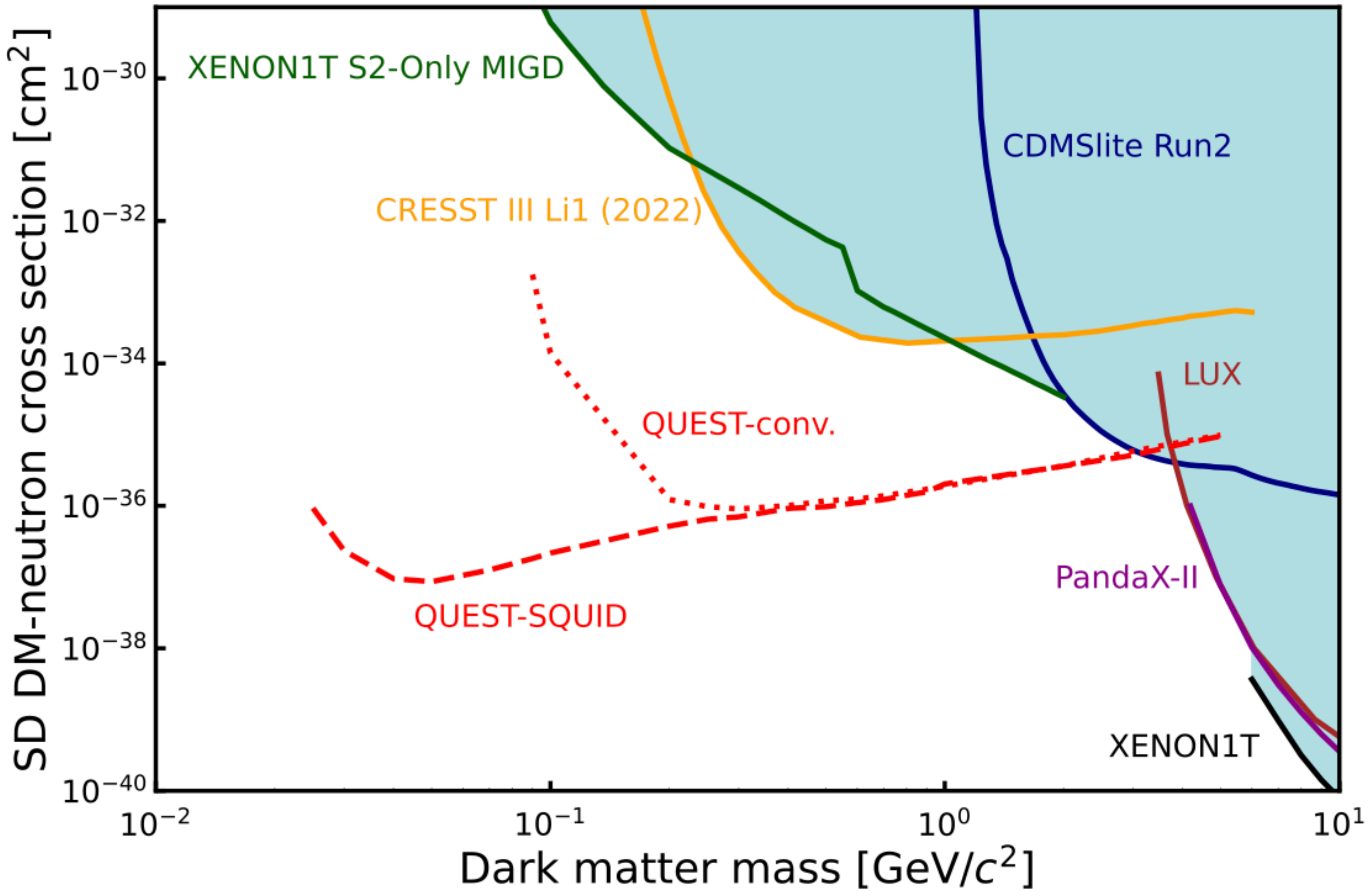
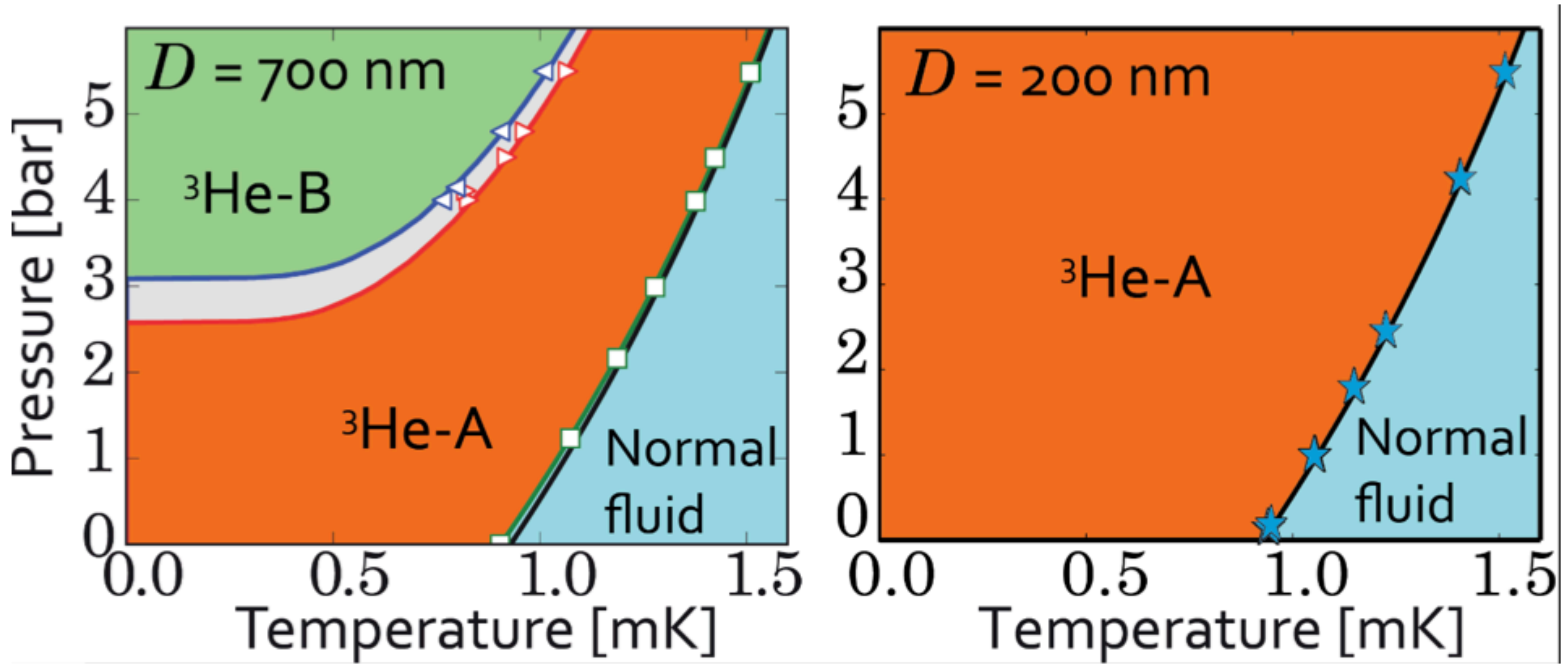


https://arxiv.org/pdf/2310.11304

UK HEP forum 2020 slides, Andrew Casey



Quantum-enhanced Interferometry for new physics

Principal investigator: Hartmut Grote

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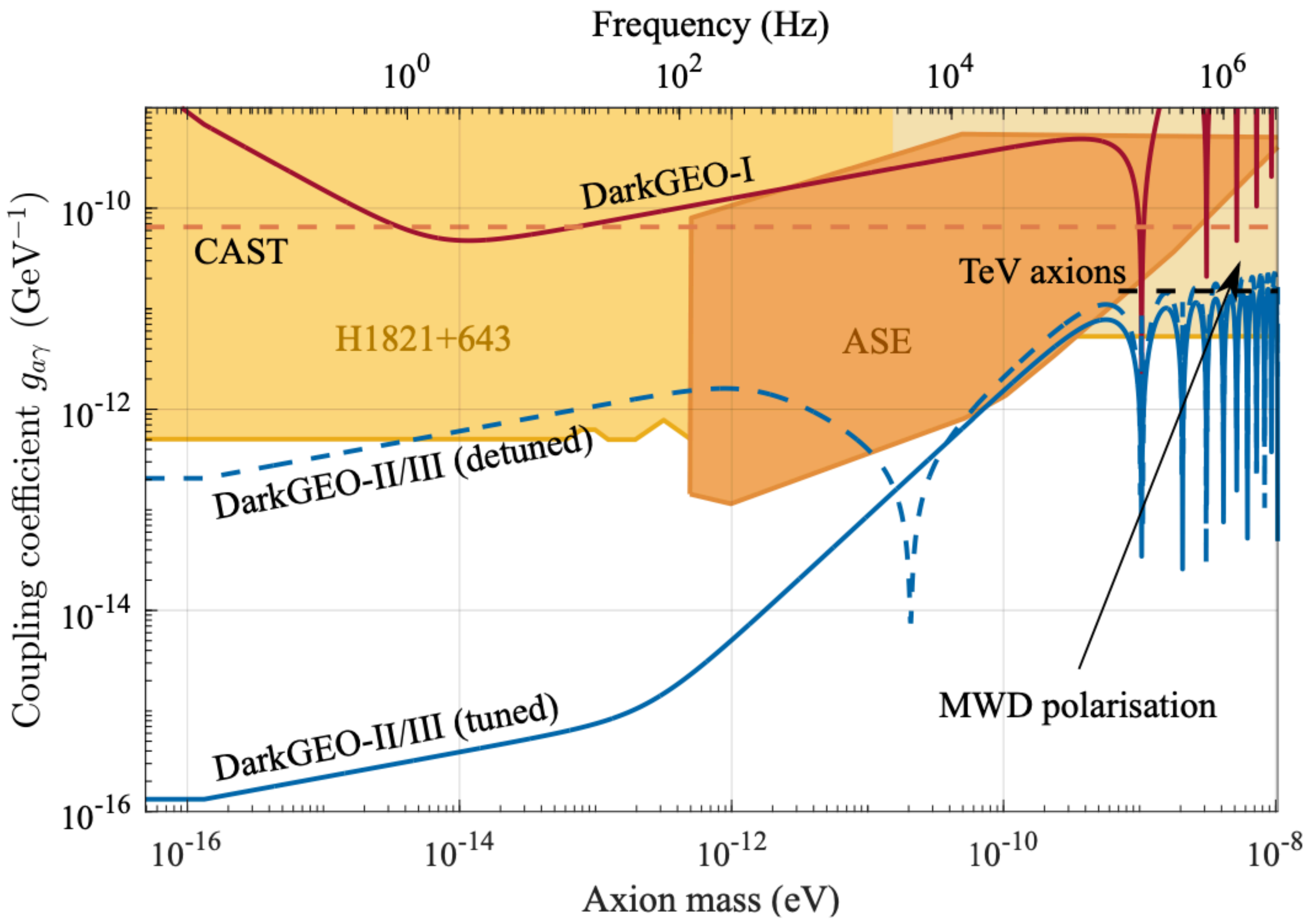
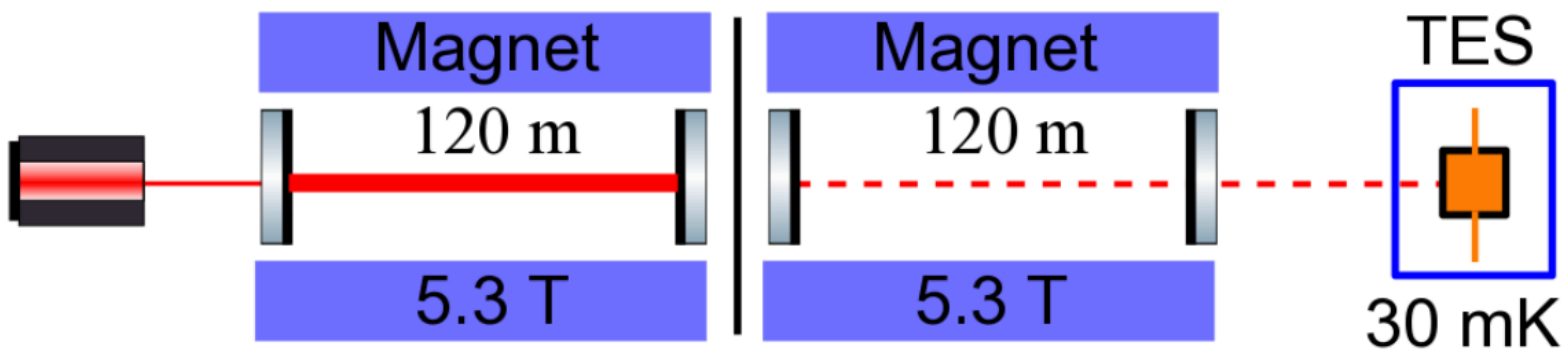


https://arxiv.org/pdf/2401.11907



ALPS II

WP 3: QUantum-Enhanced Space-Time experiment (QUEST)

WP 4: searches for semiclassical gravity

A network of clocks for measuring the stability of fundamental constants

Principal investigator: Giovanni Barontoni

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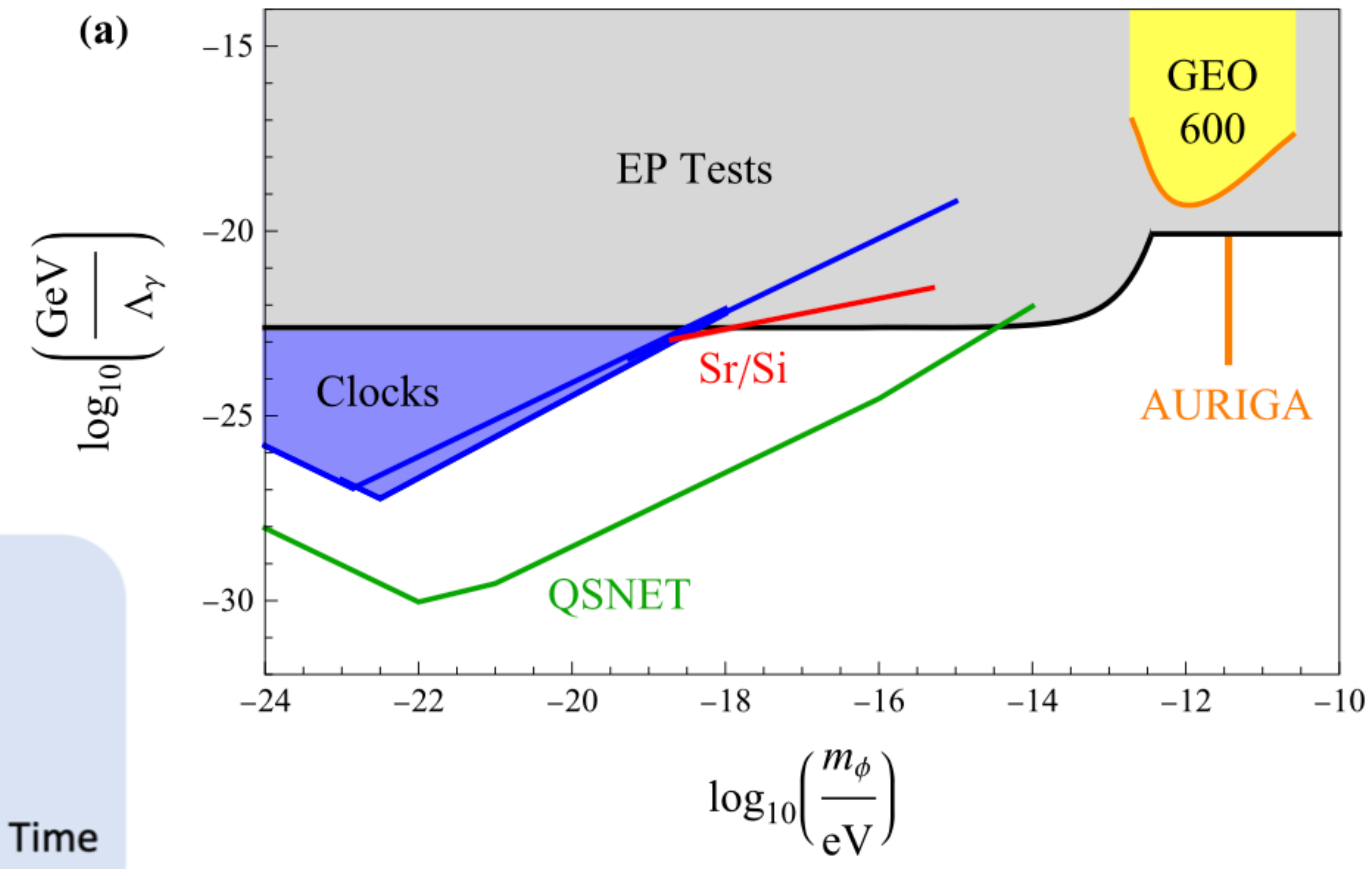
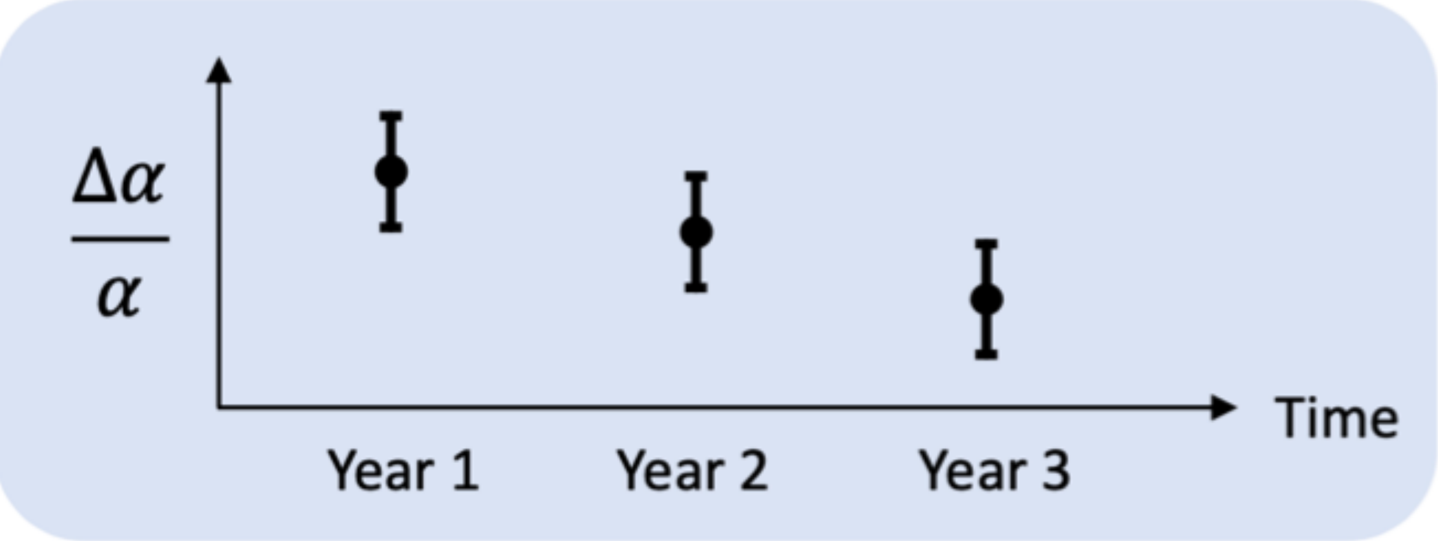
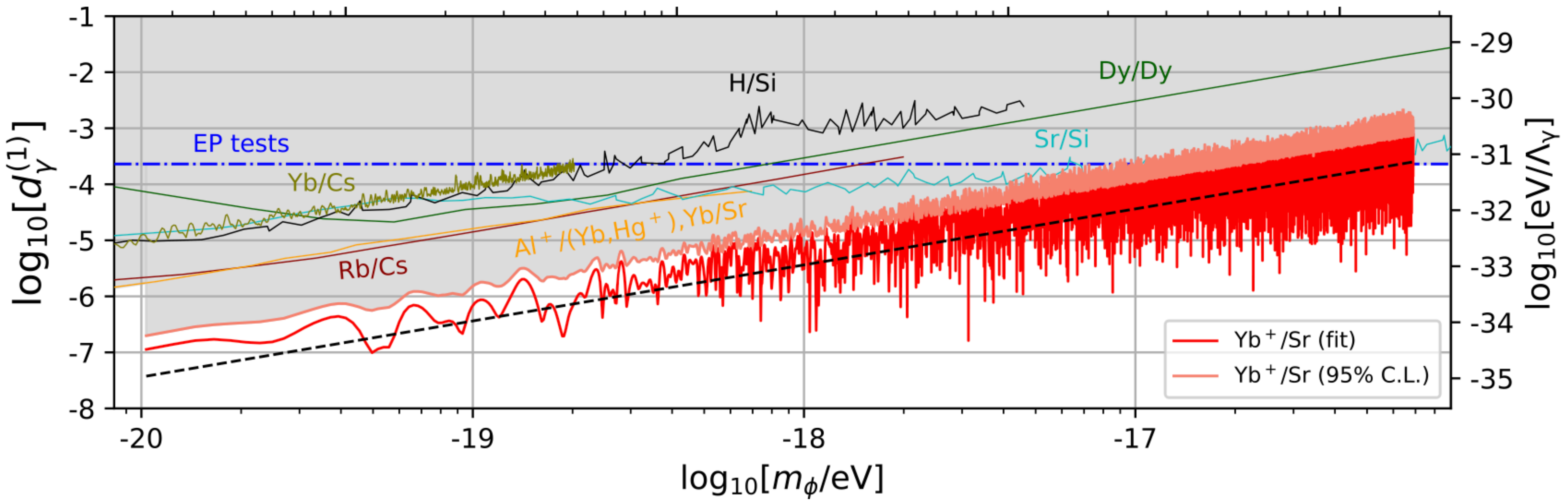
$$\mathcal{L} = \frac{\phi}{\Lambda_\gamma} \frac{F_{\mu\nu}F^{\mu\nu}}{4}$$



Also slow drifts:





https://arxiv.org/pdf/2302.04565

QSimFP — Quantum simulators for fundamental physics

Principal investigator: Silke Weinfurtner

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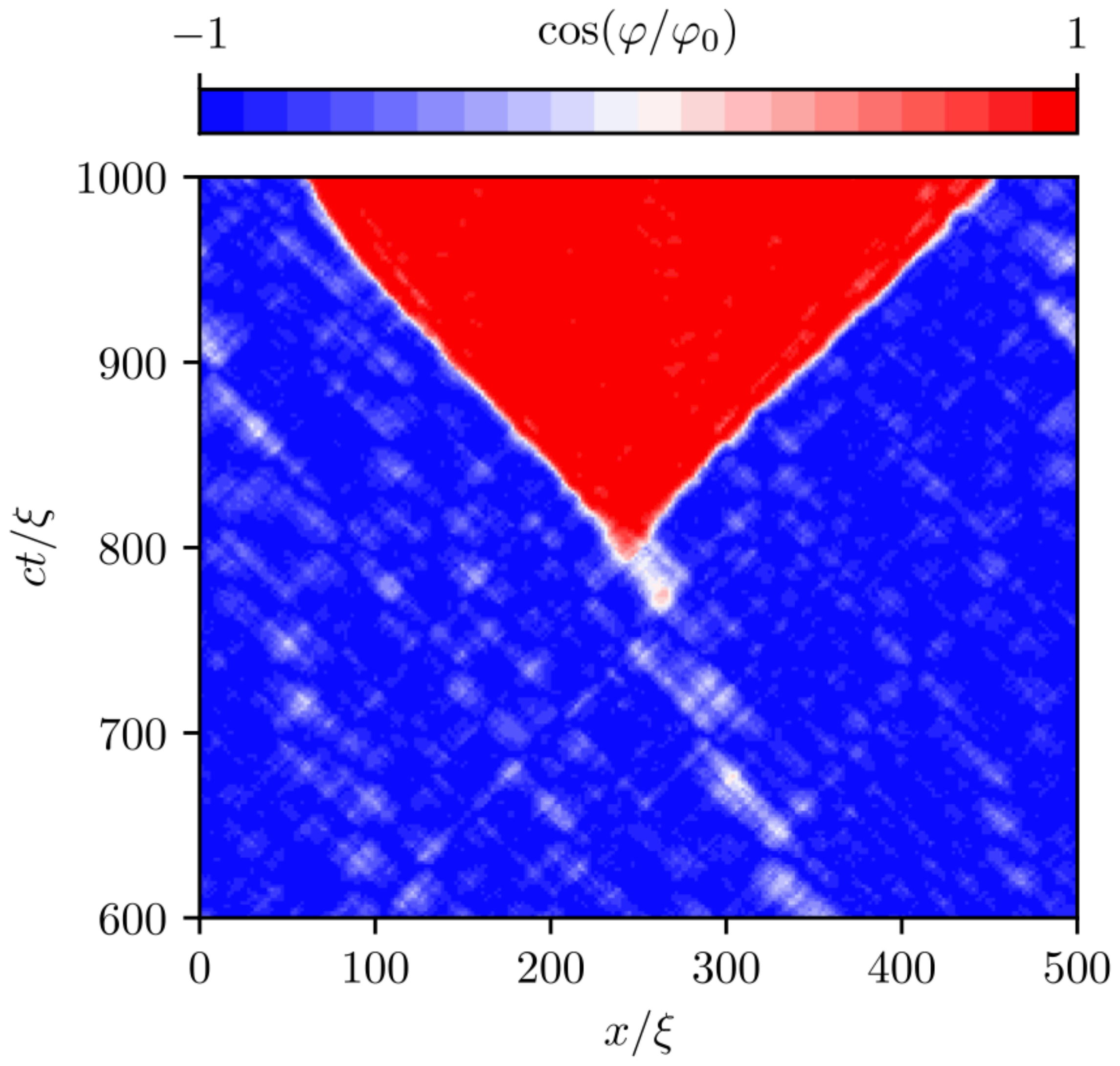
Quantum Vacuum:
- False Vacuum Decay

Analog vacuum decay from vacuum initial conditions

Alexander C. Jenkins,[1,*] Jonathan Braden,[2] Hiranya V. Peiris,[1,3] Andrew Pontzen,[1] Matthew C. Johnson,[4,5] and Silke Weinfurtner[6,7]



False vacuum decay via bubble formation in ferromagnetic superfluids

A. Zenesini, A. Berti, R. Cominotti, C. Rogora, I. G. Moss, T. P. Billam, I. Carusotto, G. Lamporesi, A. Recati & G. Ferrari

Nature Physics **20**, 558–563 (2024) | Cite this article

Quantum Black Hole:
- Black hole ring-down

1+1-Dimensional Black Hole Simulator
- Fibre-optical solitons
- Quantum Light Detectors
- **Black Hole Spectral Stability**

2+1-Dimensional Black Hole Simulator
- Biggest Quantum Vortex Flows
- Off-axis Holography Detectors
- **Black Hole Bound states and Instabilities**

2+1-Dimensional Black Hole Simulator
- State-of-the-art nanotechnology facilities
- Superconducting microwave micro-structures
- Quantum Fields Dynamics & Quantised Rotation

[Ian Shipsey's slides ECFA-UK physics kick off]

Conclusions

- Beyond SM physics might take an enormous range of forms
- Quantum assisted searches are complementary to other approaches
- Potentially sensitive to some of the best “theoretically-motivated” scenarios
- Automatic links to technology developments

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Thanks!