HEP and QIS

Berkeley P5 Town Hall

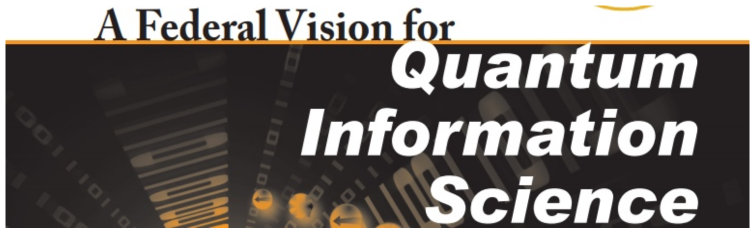
Feb. 2023

M. Garcia-Sciveres, LBNL

(acronyms key in backup)

HEP QIS based on National Quantum Initiative (NQI)

- NQI material drawn mainly from doi 10.1088/2058-9565/ab0441
- 2009:



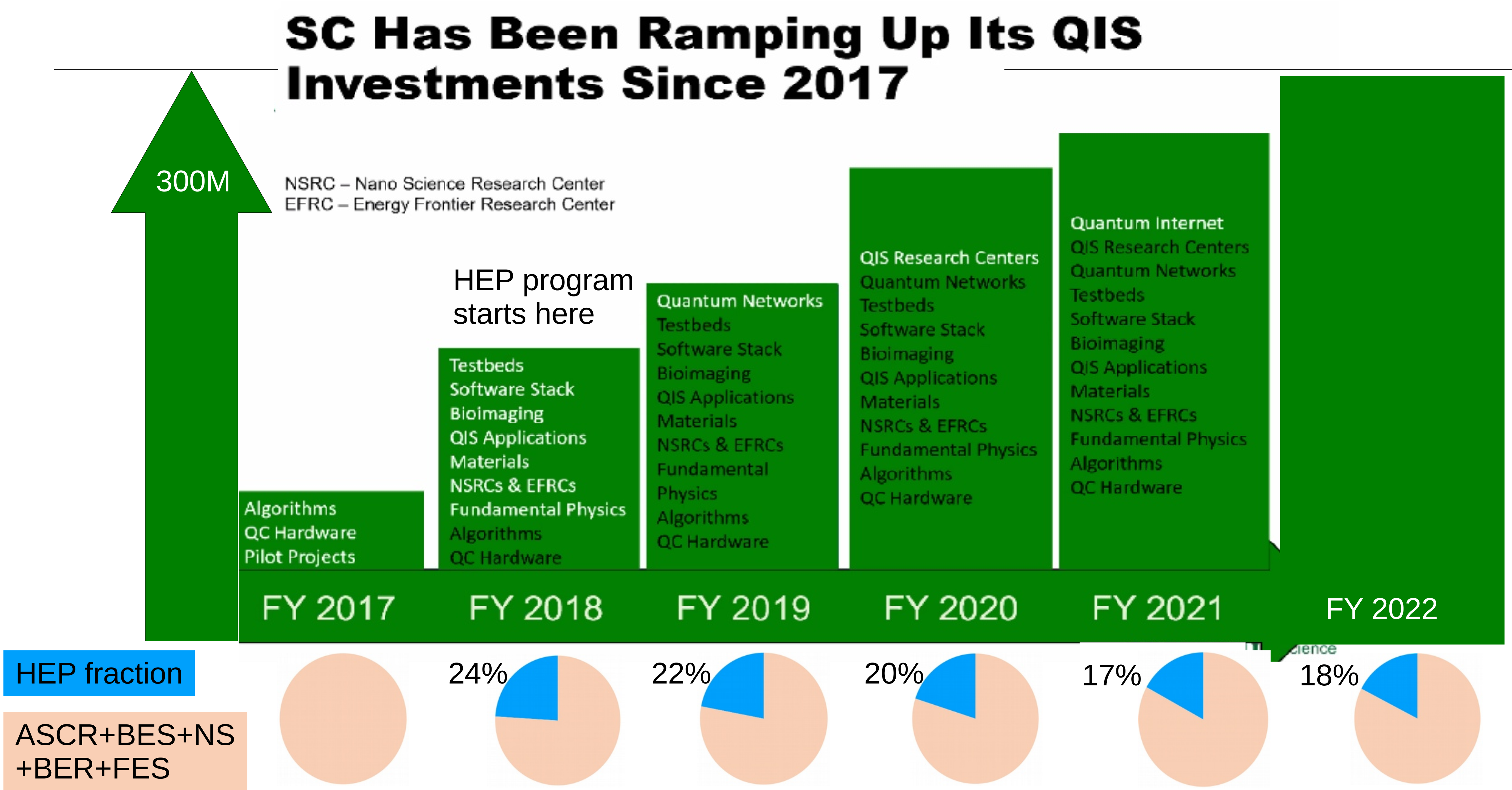
https://www.calyptus.caltech.edu/qis2009/documentsFederalVisionQIS.pdf

- 2016: Office of Science and Technology Policy forum on QIS held at the White House
- 2017:

- June 2018 – Senate bill S.3143 NQI Act passed
- Sept 2018 – House bill H.R.6227 NQI Act passed.

NQI:quantum.gov

National Quantum Initiative



Where HEP fits into NQI

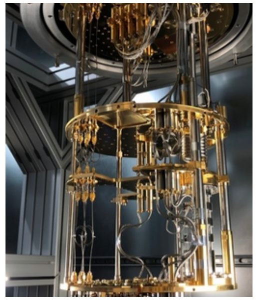
Computing

- Unique nails for the new QC hammer
- QC is great for fundamental physics problems mentioned later
- Message: Please keep building QC so we can solve the mysteries of the universe

Foundations

- Connections between quantum information, quantum field theory, and gravity
- HEP theory makes Unique contributions
- Metrology straddles theory and sensing

Sensing



- HEP is an early adopter of new technology
- A single qubit can't be a computer, but it can be a sensor.
- HEP sensing is a valuable spin-off of the QIS technology ecosystem. No different than HEP solid state detectors and DAQ were possible only because there is a microelectronics industry.
- Message: Please keep growing the QIS technology ecosystem so we can discover the mysteries of the universe.

Quantum Computing

- Development of quantum computers is motivated by high profile problems (national security, material science, …)
- HEP provides additional motivation with problems that cannot be solved on classical computers
- Quantum computers allow to numerically simulate phenomena with large entanglement
- Will give insight into fundamental quantum field theory phenomena
- Some questions studied are Scrambling of quantum information, traversable wormholes, duality of QG in bulk and QFT on boundary
- With a QC can directly compute quantities that traditionally are not accessible numerically

- Significant research is required to harness this potential
- Radically new way of thinking about QFT problems
- Opening up field to young scientists with interest in these problems and engaging with other domain sciences that use similar quantum algorithms
- Critical to have HEP Collaboration with AdvancedScientificComputingRes. QIS programs

HEP Quantum Computing Work

- Generic frameworks can include full quantum entanglement in very large Hilbert spaces
- Examples are scattering in strongly interacting QFTs, non-perturbative quantities such as PDFs, collective evolution in dense media, ...
- Can eventually make predictions of experimentally accessible phenomena that are currently unthinkable
- Need to identify the right questions to address on present-day NISQ* systems
  - Obtain appropriate theory formulation
  - Develop efficient quantum algorithm
  - Obtain results on realistic quantum computers

* Noisy Intermediate Scale Quantum computing

- Quantum computing research is multifaceted, requires
  - Phenomenological insights
  - Formal theory developments
  - Algorithmic developments
  - Software and hardware interactions

Collaborate with ASCR

NQI - HEP Sensing Synergy

- NQI core motivation:
  Entangled qubits will perform certain computations unimaginably faster

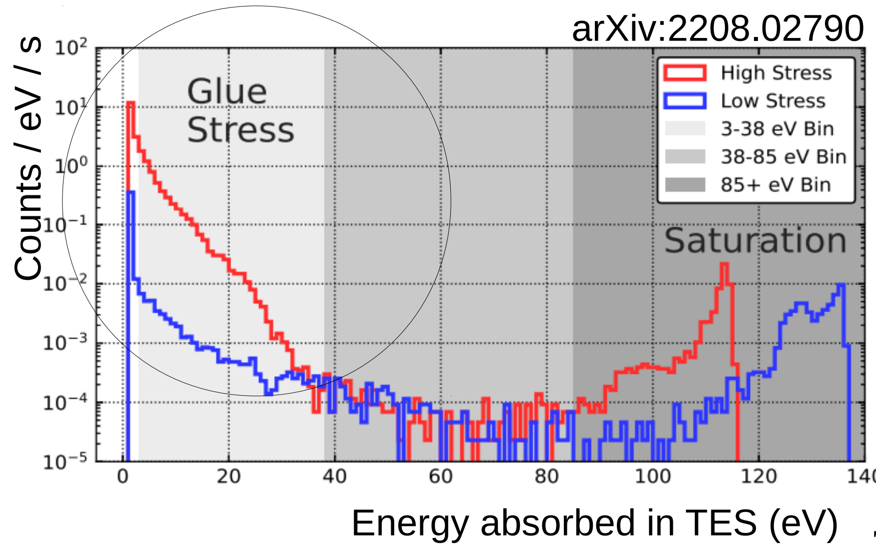
- OK, so we build qubits and entangle them
- Immediately we find what?
- They decohere. They don't stay entangled very long. They have readout errors.
  They have operation errors. NISQ in short.
- Is this due to some fundamental mystery?
- Nope. Just noise, TLS, 1/f
  material imperfections, etc.

- Much of NQI is aimed at solving these non-fundamental, practical, classical problems to get out of NISQ.

- HEP core motivation:
  Need to observe extremely feeble effects: gravity, dark matter, cosmic neutrinos...

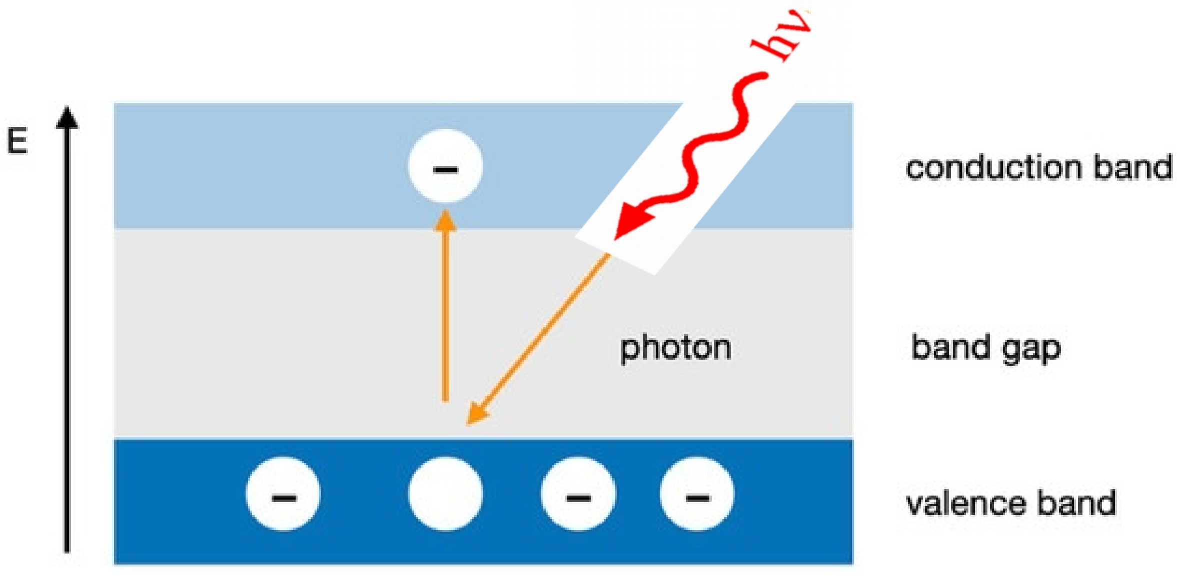
- OK, so we build quantum sensors to measure super small energies with no sensor noise
- Immediately we find what?
- All sorts of background low energy processes that have nothing to do with dark matter.
  Materials are teaming with not-so-tiny energy blips all the time

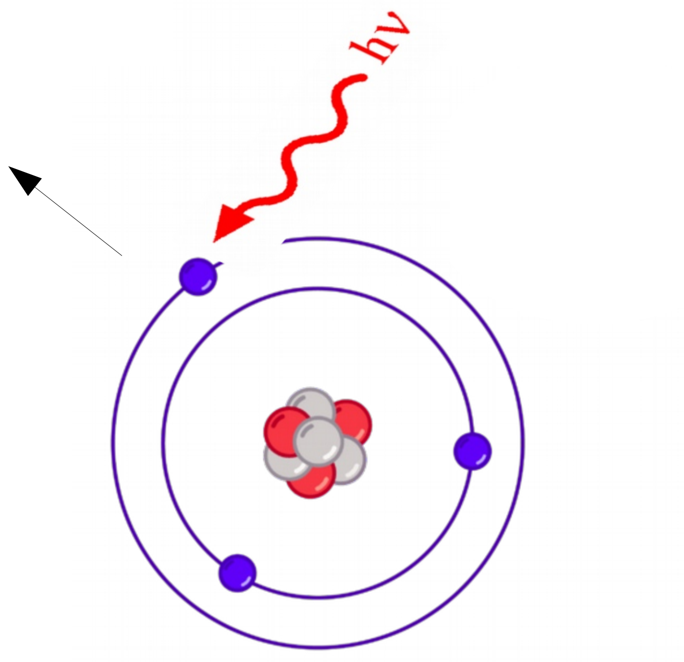
This is basically all
the same stuff qubits
need to get rid of
to get out of NISQ

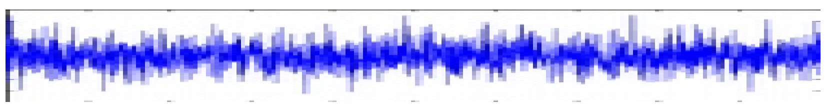


Measuring small energy signals

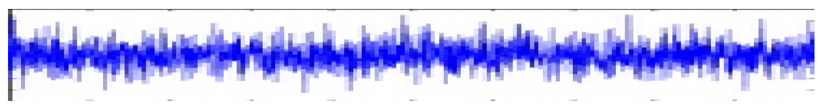
- Traditionally we take advantage quantum effects in materials, followed by classical amplification
- Examples of sensing materials: semiconductor, scintillator, gas





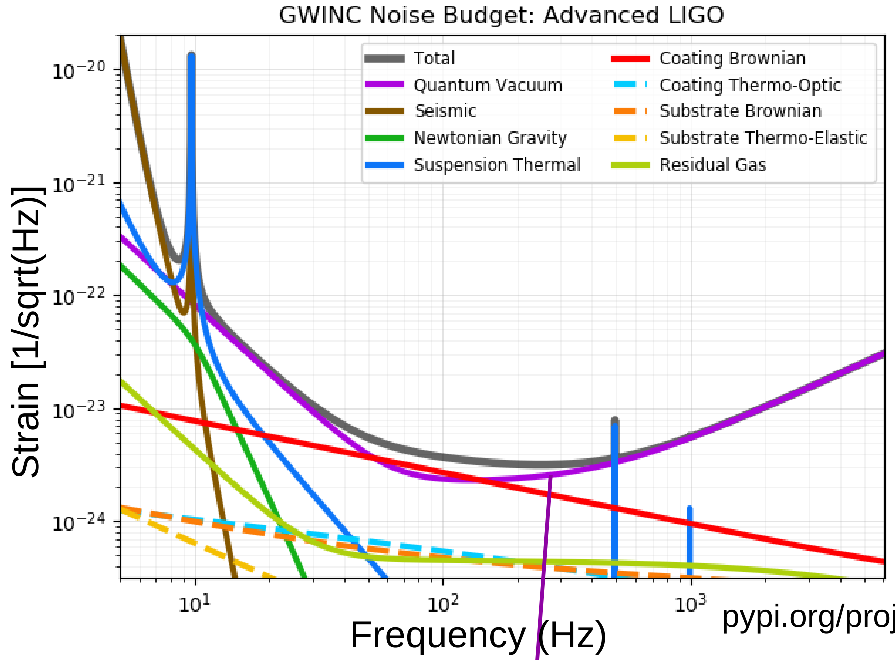


Noise < bandgap
Or < ionization
is hidden from us
(digital electronics analogy)



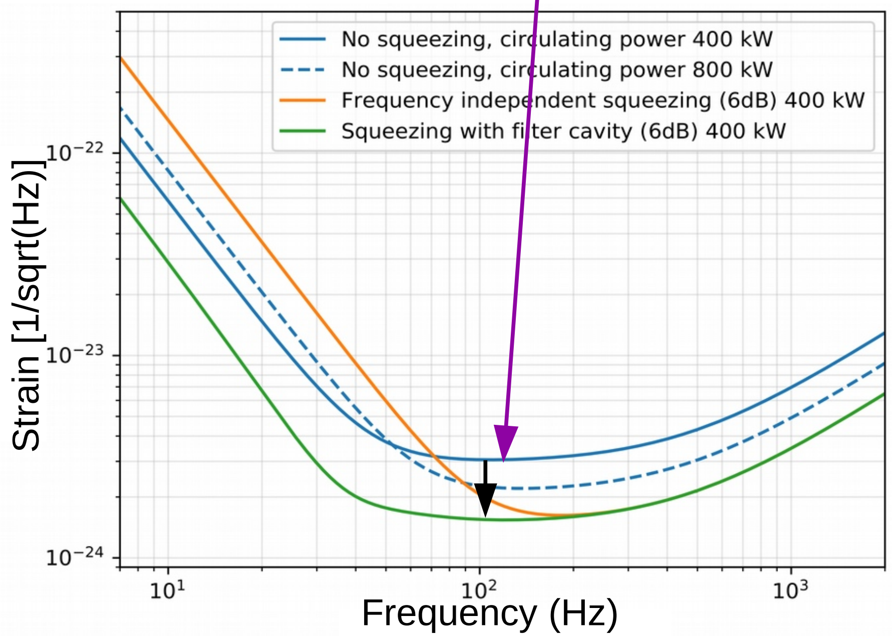
- Now we want to explore this low energy regime that was previously hidden. This has a lot in common with QC development because superconducting qubits are susceptible to this low energy stuff
- Collaboration between HEP and BES on material research needed at the multiple PI “center” level rather than single PI proposals

Quantum measurement for HEP



pypi.org/project/gwinc/

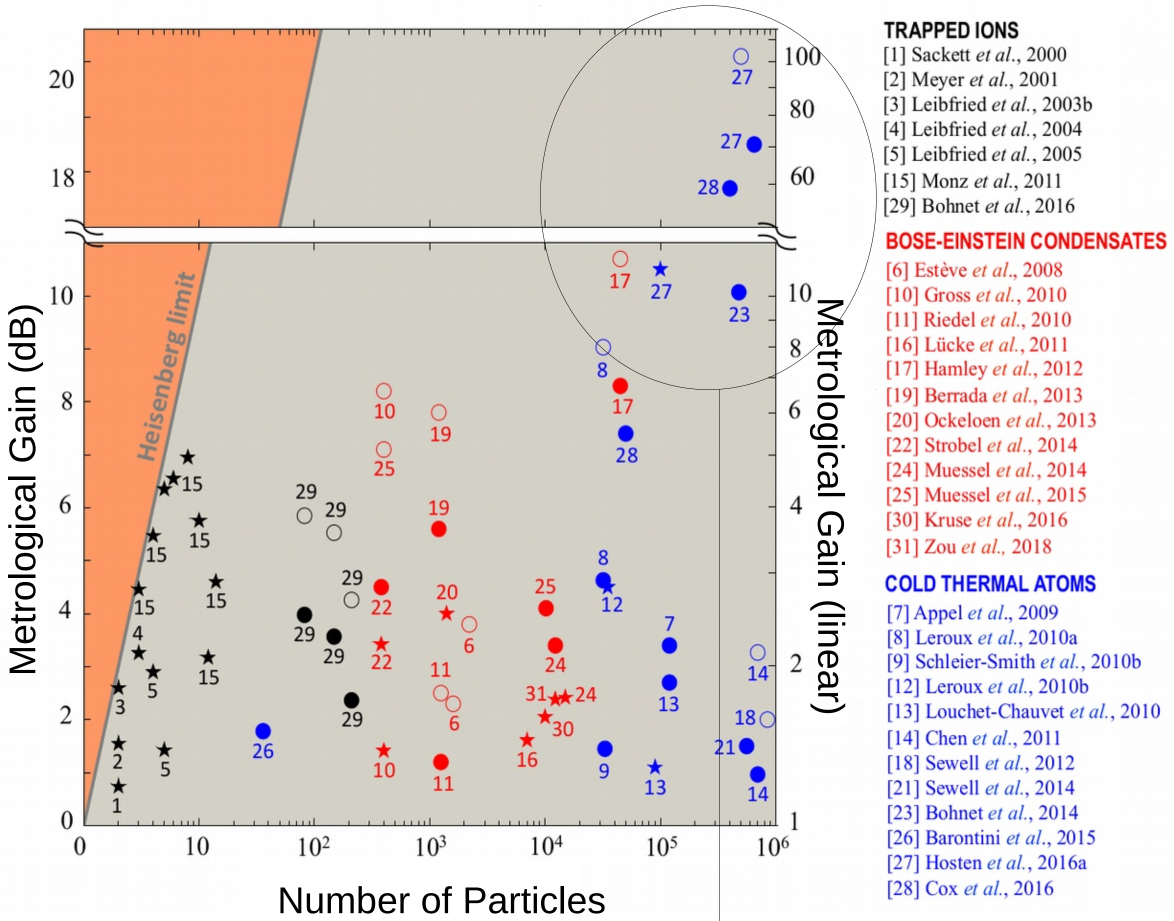
LIGO nicely shows quantum as one of many noise sources, not a fundamental limit



www.mdpi.com/2075-4434/10/2/46

Measurement techniques can Reduce quantum noise.

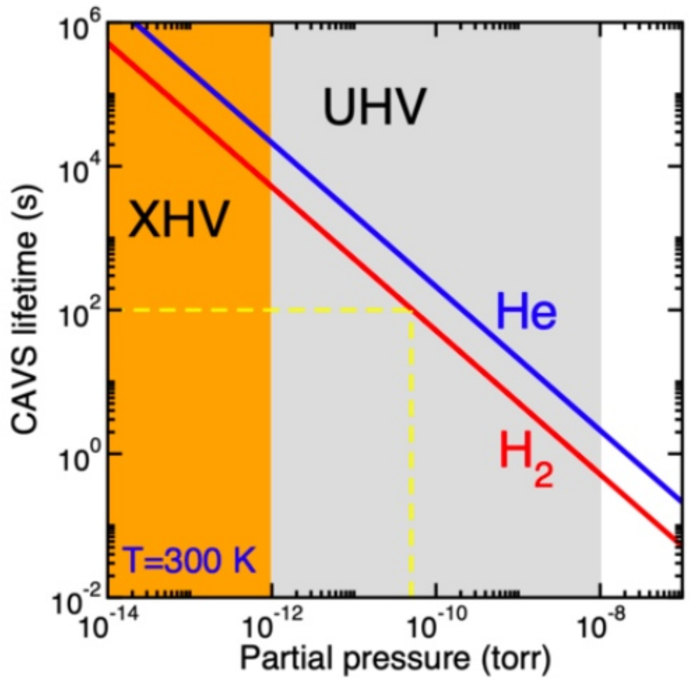
Compilation of noise squeezing applied to atomic ensembles (arxiv:1609.016093)



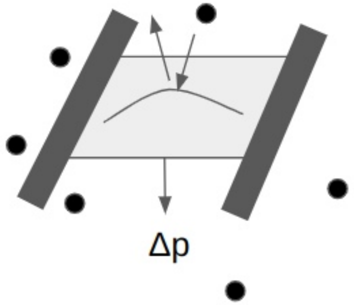
Big improvement possible when N >> √N
Far away from fundamental limit when N is large

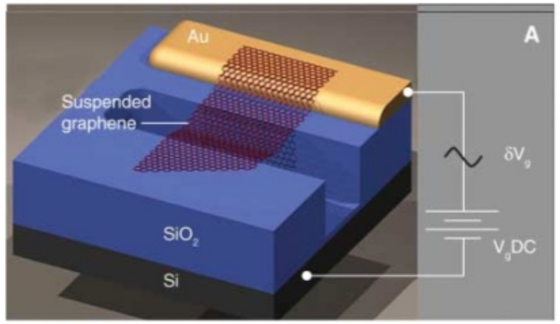
HEP contributes to quantum measurement

- Recent example of XHV pressure sensor following development of sensors to measure low energy recoils of interest to HEP
- Unique HEP problems motivate development that then finds broader application



NIST project: Cold Atom Vacuum Sensor





HEP contribution: membrane system at standard quantum limit offers better performance.

Conclusion & Program Outlook

- HEP can continue to make unique contributions to NQI
- Problems with full quantum entanglement that can be solved on NISQ computers
  - Important HEP – ASCR connections
- Emerging quantum hardware technology can be applied to high profile measurement problems, such as dark matter
  - Large synergy with understanding materials backgrounds that afflict qubit coherence
  - Important connection to materials science- HEP – BES partnerships crucial
- Developments in foundations theory & quantum metrology that can be applied beyond HEP
- Important role training an early adopter workforce

- OUTLOOK: QuantISED grants are soon coming to an end without a clear funding guidance beyond that. Stable funding is needed to retain expertise that has not been easy to build.

Many Other Sensing Topics I didn't Mention

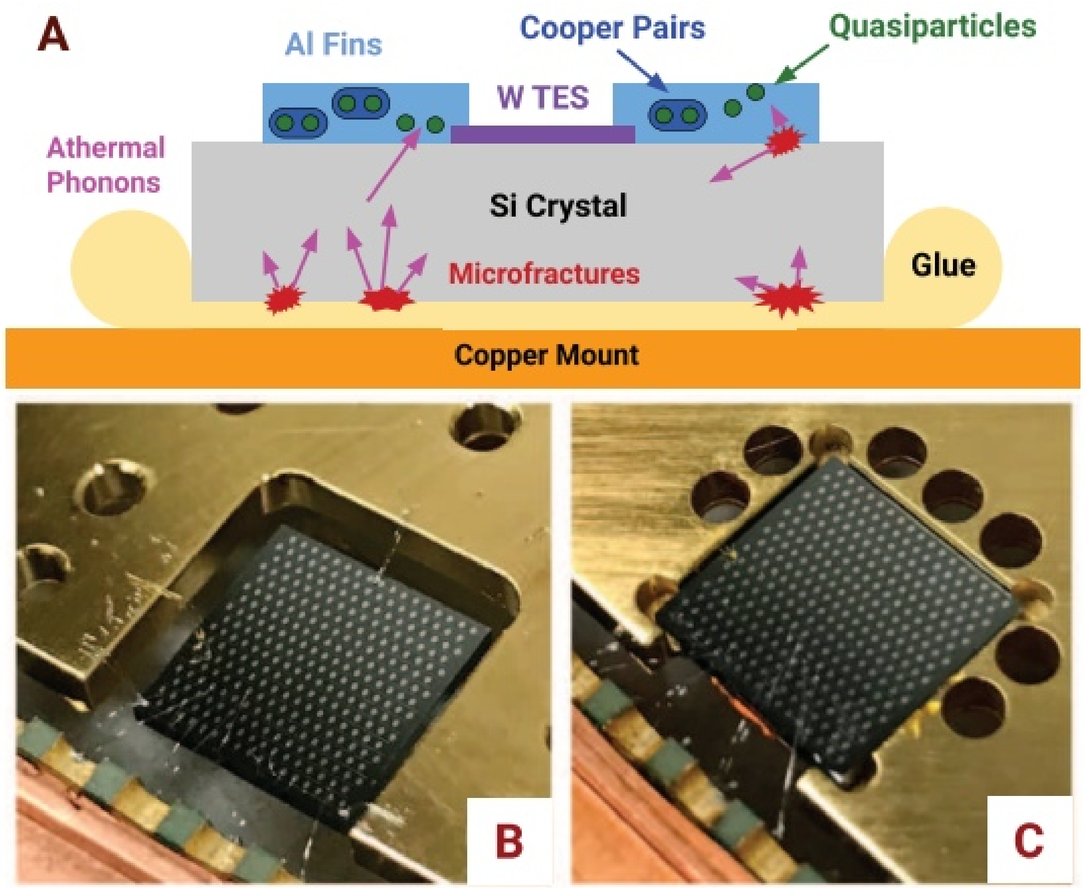
- Axions- assumed topic will be covered at other town halls
  - Significant connection to qubit readout- quantum limited RF signals- squeezing, QND, etc. to bead SQL
  - Same messaging as energy sensing- use of emerging quantum technology for high impact science
- Quantum communications
  - Quantum internet
  - Teleportation technology and application eg. to large baseline optical interferometry
- Atom interferometry
  - Measurement of fundamental constants, gravity probes, etc

B A C K U P

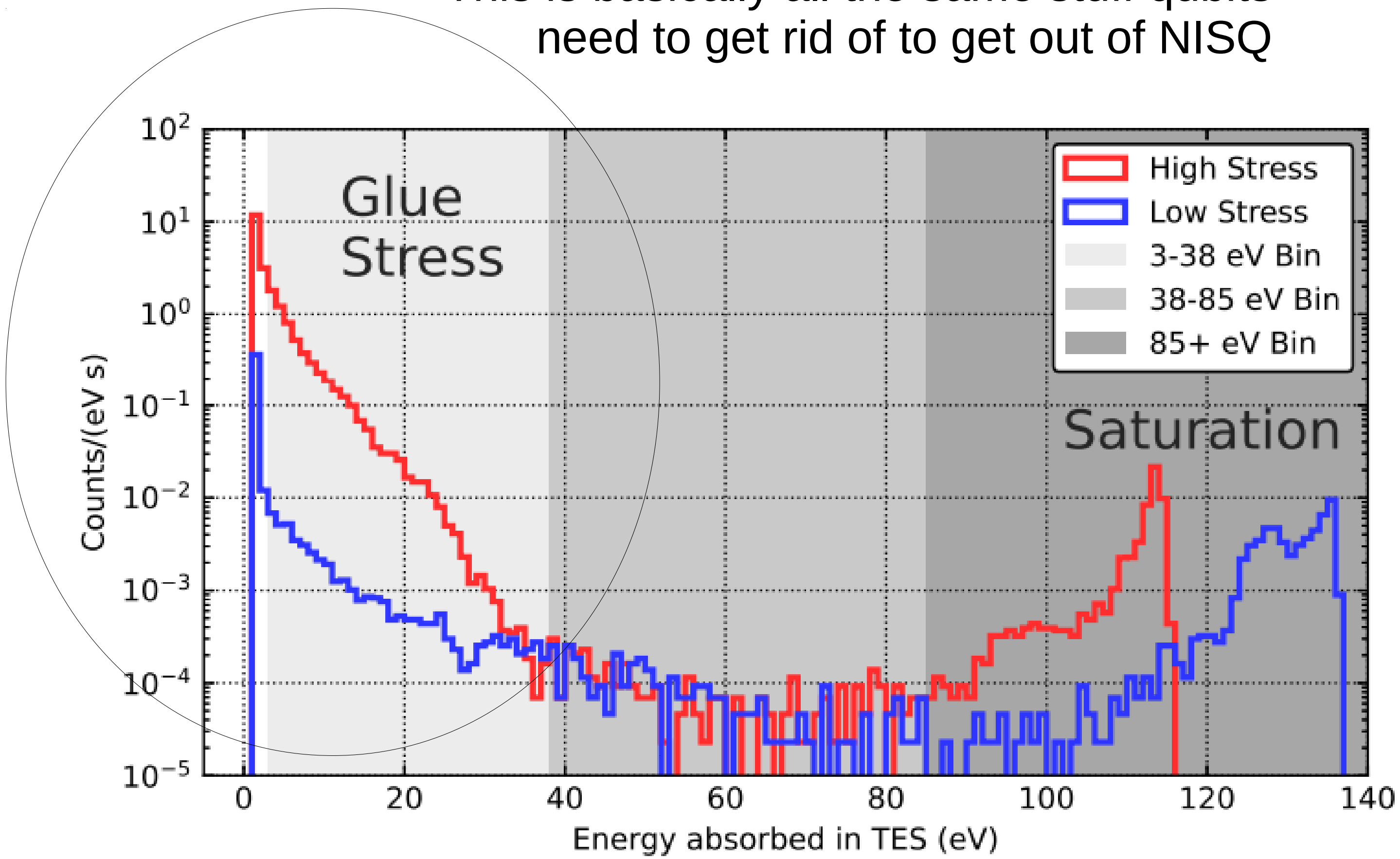
Acronyms

- QIS – Quantum Information Science
- NQI – National Quantum Initiative
- SC – DOE office of Science
- HEP – High Energy Physics
- ASCR – Advanced Scientific Computing Research
- BES – Basic Energy Sciences
- NS – Nuclear Science
- BER – Biological and Environmental Research
- FES – Fusion Energy Sciences
- QC – Quantum Computing
- DAQ – Data AcQuisition system
- QG – Quantum Gravity
- QFT – Quantum Field Theory
- NISQ – Noisy Intermediate Scale Quantum
- TLS – Two-Level System noise
- TES – Transition Edge Sensor
- PI – Principal Investigator
- XHV – Extreme High Vacuum
- NIST – National Institute of Standards

Microfracture background



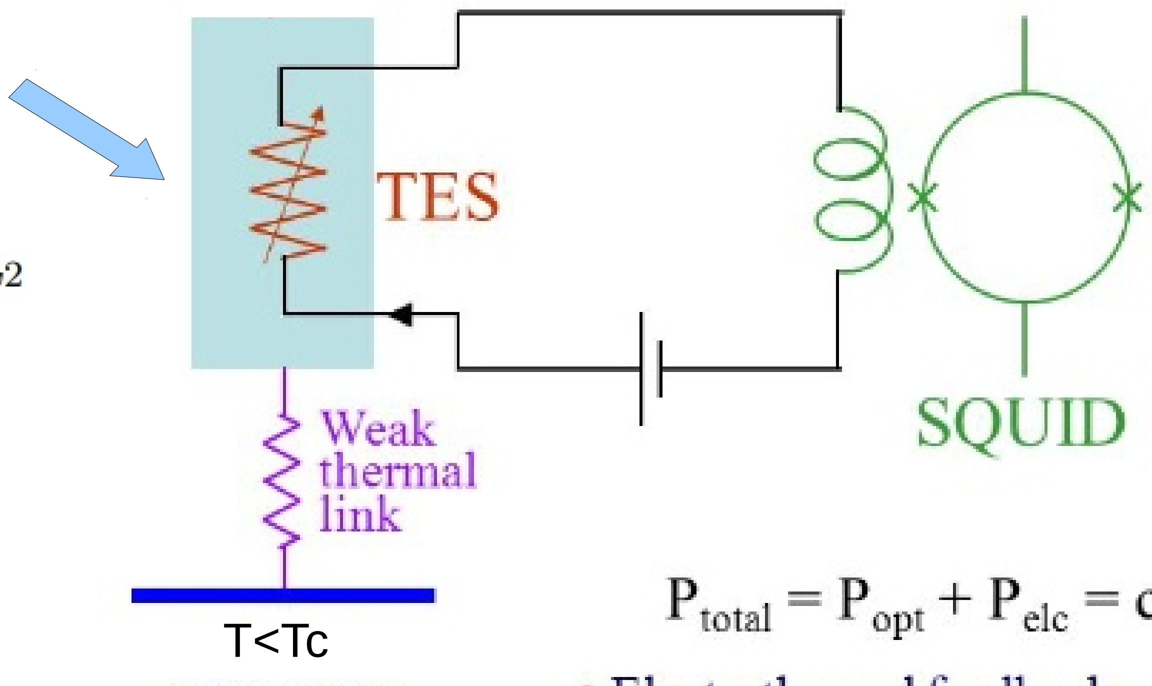
This is basically all the same stuff qubits need to get rid of to get out of NISQ

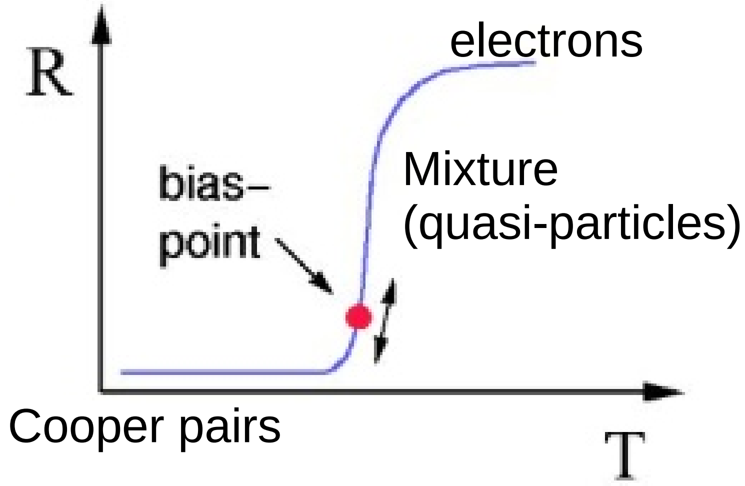


HEP low energy sensors: TES

- Transition Edge Sensors are the current workhorse of for low mass particle DM searches
- Probably the oldest superconducting circuit- invented in 1938/9
- But technology as used today not perfected till 1995
  - Kent D. Irwin (1995). An application of electrothermal feedback for high resolution cryogenic particle detection. Applied Physics Letters 66
- They are read out with DC SQuID amplifiers

$$\sigma^2_{<E>} = C k_b T^2$$





$$P_{total} = P_{opt} + P_{elc} = \text{constant}$$

- Electrothermal feedback: fast, linear response
- Low power dissipation (~1 nW)
- Sensitivity limited by fluctuations in the photon arrival rate

Athermal Phonon Detector

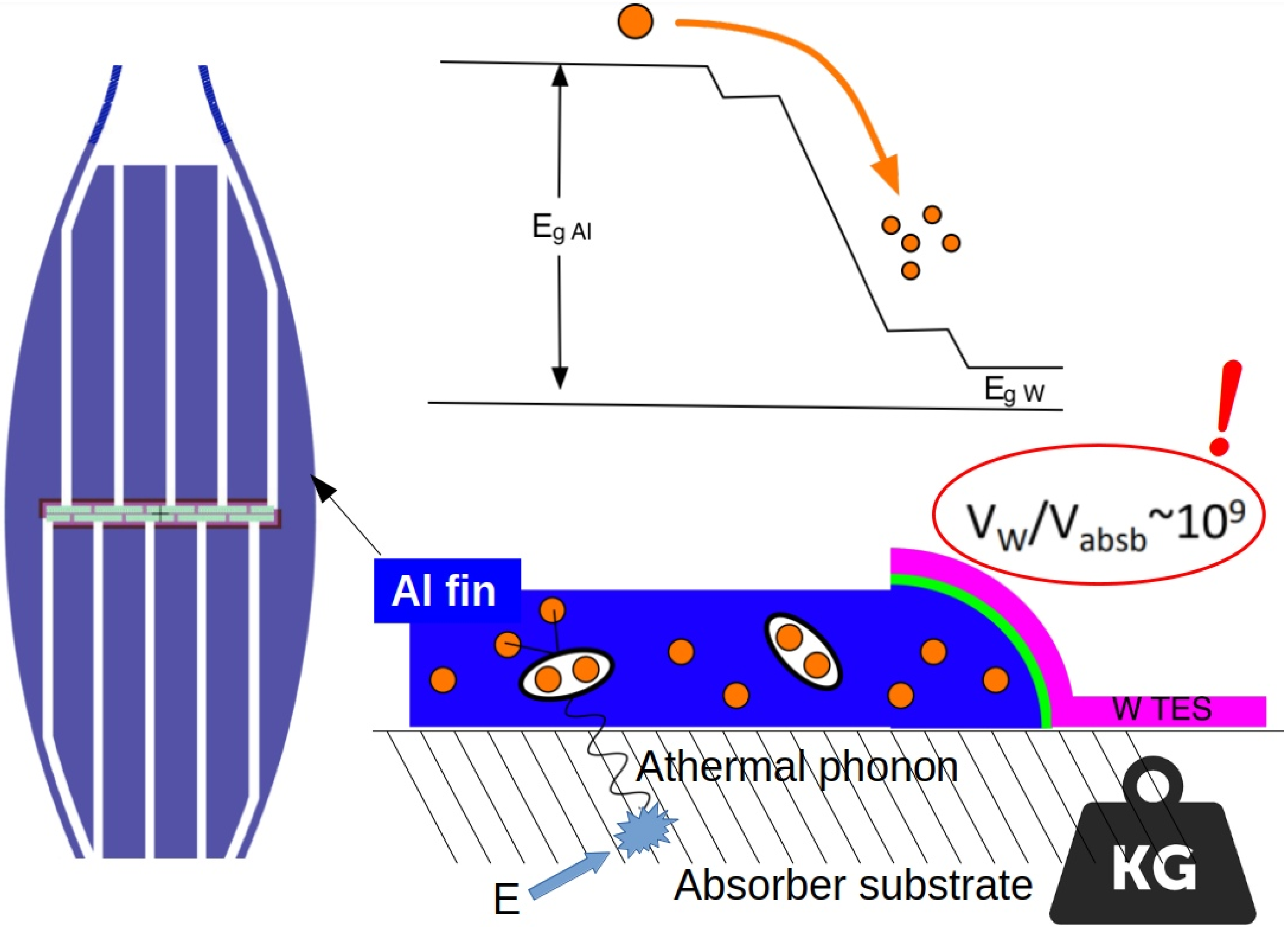
Clever scheme to decouple the target mass (the bigger the better for dark matter interactions) from the TES mass (the smaller the better for noise)

An E blip produces phonons with energy > thermal energy.

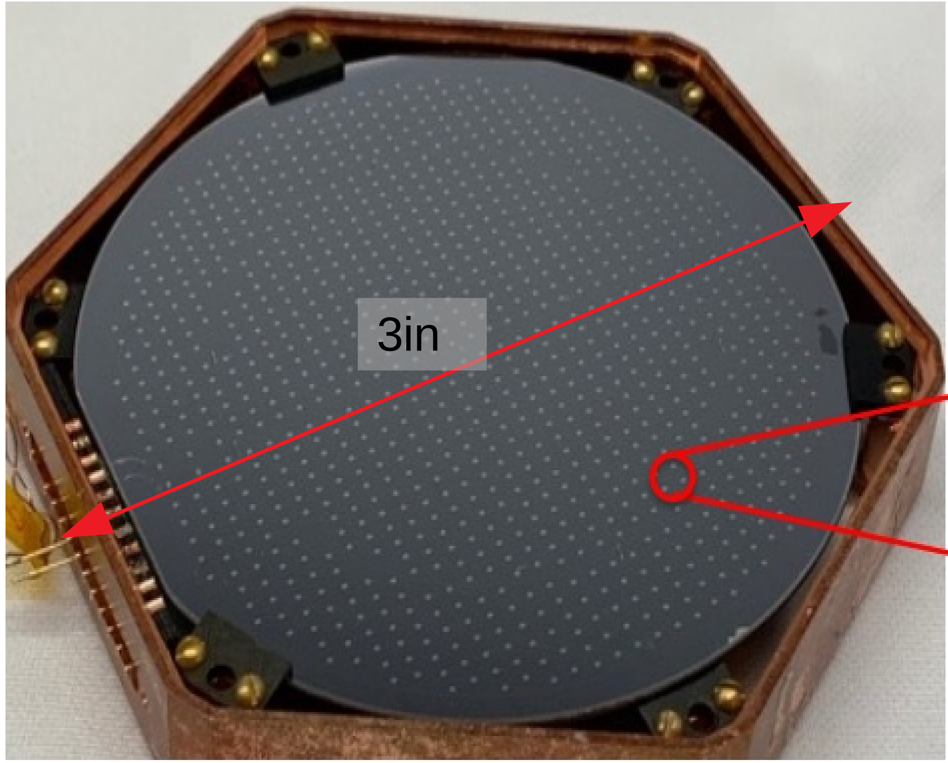
These live a while before they thermalize

Cooper pairs can absorb them and break (make quasiparticles). This is bad for qubits BTW ("quasiparticle poisoning")

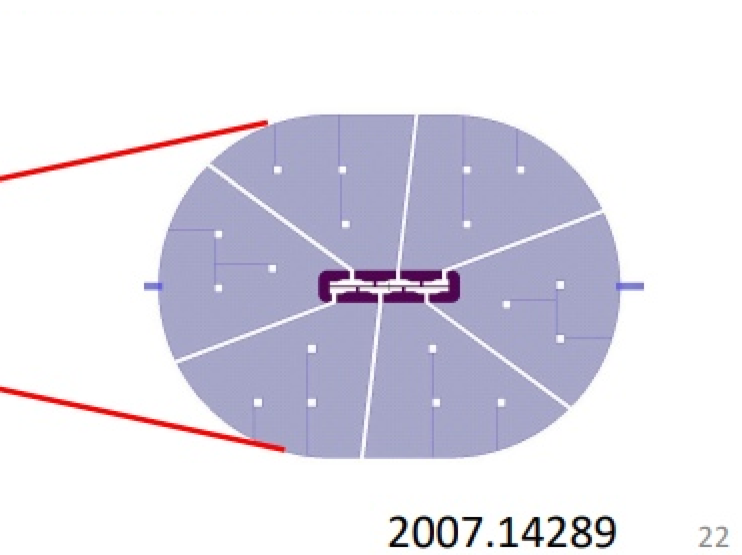
Quasiparticles diffuse and when they reach the TES they get trapped there and raise the TES temperature



Transition Edge Sensor based Athermal Phonon Detectors
are the present low noise workhorse



A large mass single channel with eV energy resolution



R&D keeps going to:

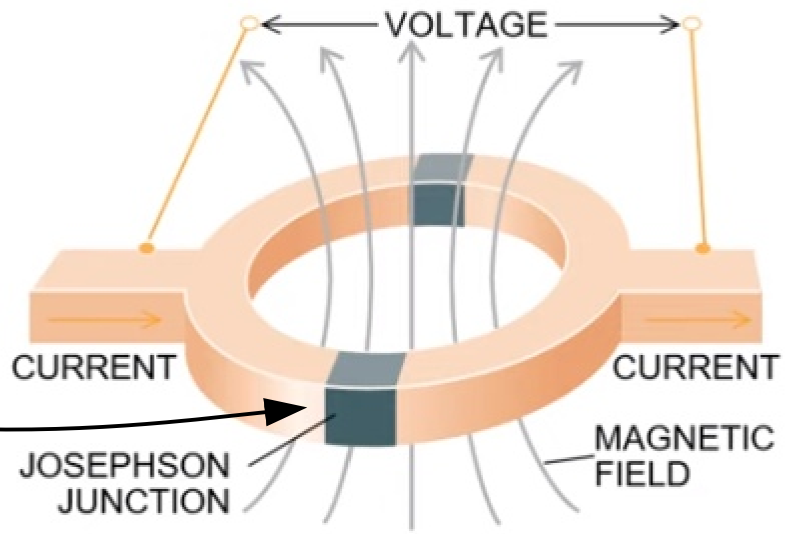
- Lower transition temperature to achieve lower noise
- Improve collection efficiency- which will give lower noise for same area
- Understand and lower environmental noise (strong connection to SC qubit tech.)
- Improve readout

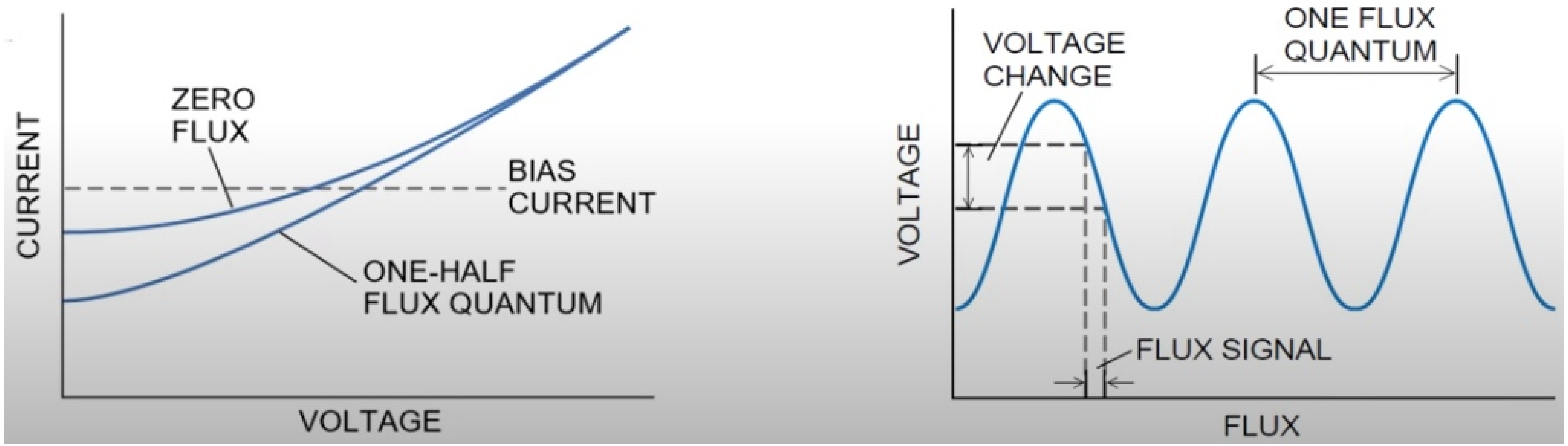
Other quantum energy sensors besides TES

- TES's are dissipative devices so there is no real way to enhance measurements with coherence tricks
- Other sensor of interest to the problem of detecting tiny energy blips are not dissipative
  - Microwave kinetic inductance detectors (MKIDs) (dispersive)
  - Opto-mechanical resonators as phonon detectors (resonant)
  - He quantum evaporation and detection with spin system (spin-spin coupling)
  - Superconducting Nanowire Single Photon Detectors (SNSPD) (next talk)
- Today, TES athermal phonon detectors are the best (lowest noise, can see the smallest blips), quantum sensing tricks or not.
- But we're still a long way form meV E blip sensitivity.
- Quantum enhancement may be needed to get there
- (Always remembering that first we have to "get out of NISQ" = control material noise that is no longer hidden by bandgaps, etc)

SQuID

Tunneling exploited
(annoying quantum effect turned into an asset- think back to entanglement in Irfan's opening talk)





Aside on annoying tunneling

(in case you didn't believe me it was annoying)

- Whole chip industry Trillion $ transition to high-K metal gates was purely to mitigate annoying quantum tunneling. And remember the gate oxide technology was the MVP enabler of CMOS integrated circuits in the first place!

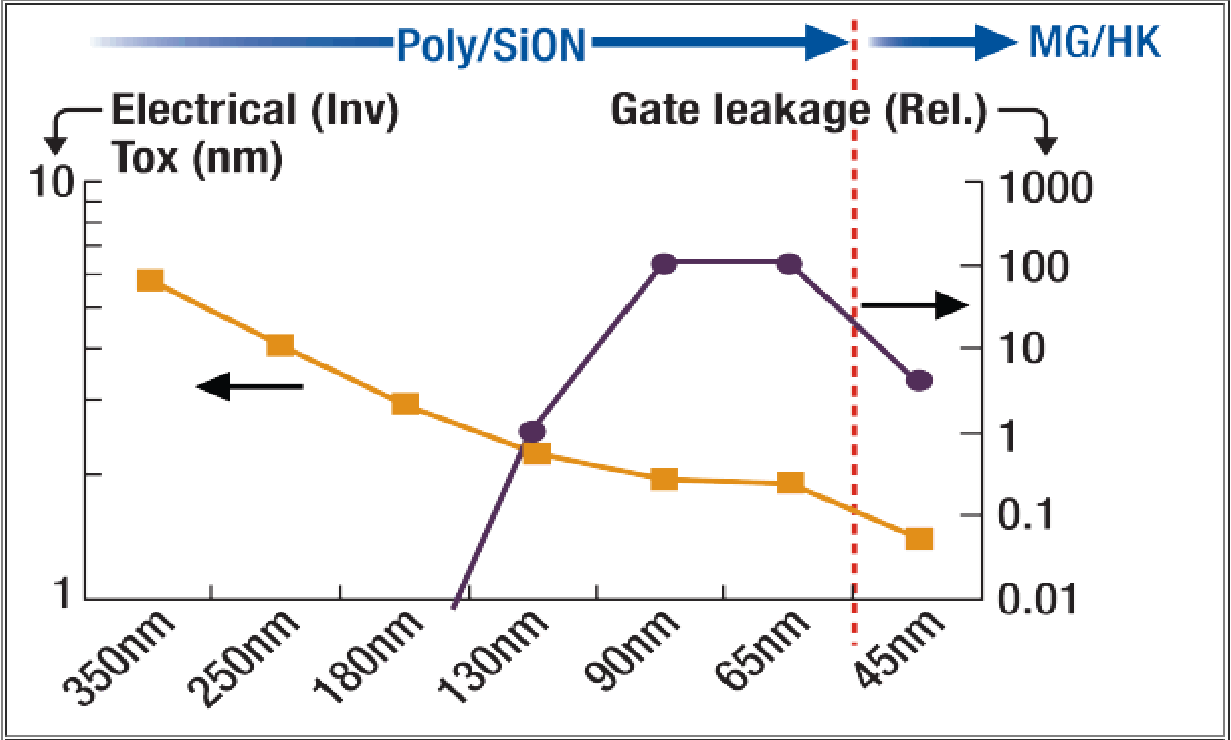
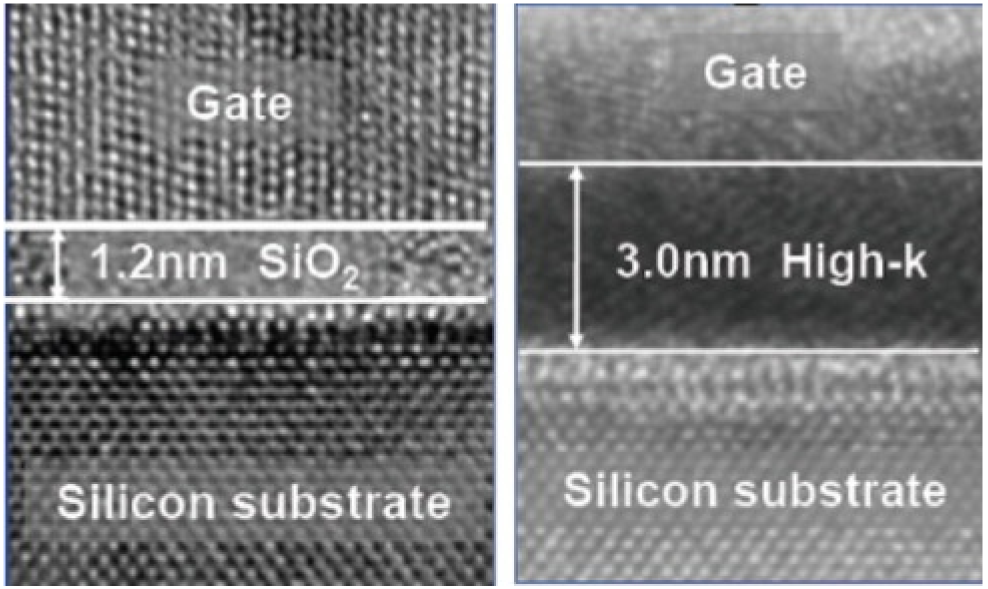


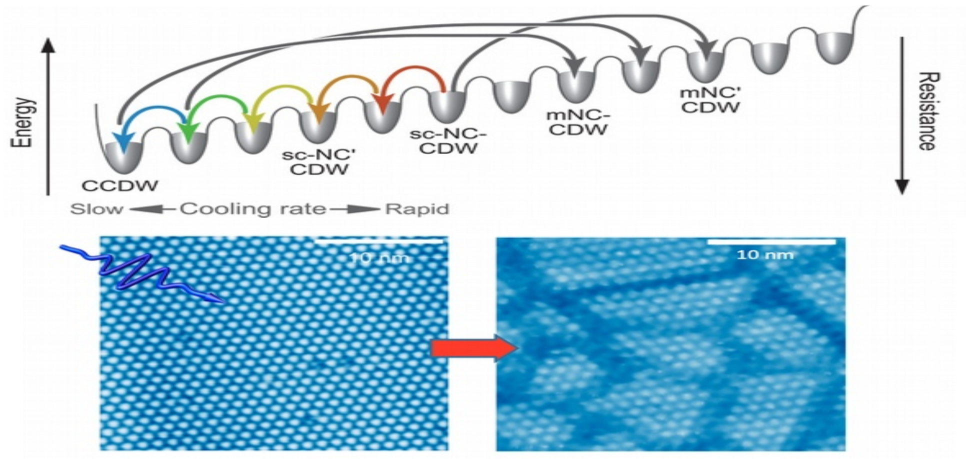
Figure 1. Intel's technology roadmap illustrating how migrating from Poly/SiON to metal gate/high-k (MG/HK) enabled the resumption of electrical Tox scaling, while containing gate leakage [1].



Quantum Materials for DM Detection

- Axion insulators -
  - Antiferromagnetic topological insulators; Magnetic TIs MnBi2Te4;
    flat band Kagome materials

- Correlated systems with Metastable states
  - Mott/CDW Metastable states in 1T-TaS2 & 1T-TaSe2
  - Metastable magnetic states in manganates and other oxides



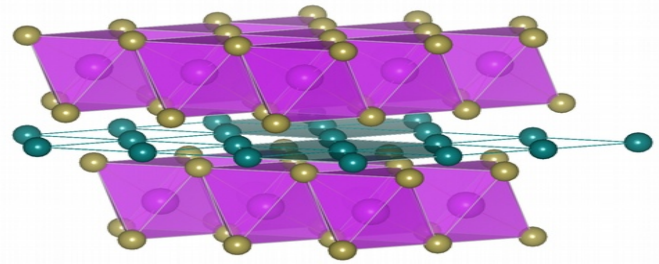
Letter | Published: 06 January 2020

Robust axion insulator and Chern insulator phases in a two-dimensional antiferromagnetic topological insulator

Chang Liu, Yongchao Wang, Hao Li, Yang Wu, Yaoxin Li, Jiaheng Li, Ke He, Yong Xu, Jinsong Zhang & Yayu Wang

Nature Materials **19**, 522–527(2020) | Cite this article

$MnBi_2Te_4$



Crystal Defects: A Portal To Dark Matter Detection

Fedja Kadribasic, Nader Mirabolfathi
Department of Physics and Astronomy, Texas A&M University, College Station, TX, USA

Kai Nordlund and Flyura Djurabekova
Helsinki Institute of Physics and Department of Physics, PB 43, University of Helsinki, Finland
(Dated: February 12, 2020)

PHYSICAL REVIEW LETTERS **124**, 201801 (2020)

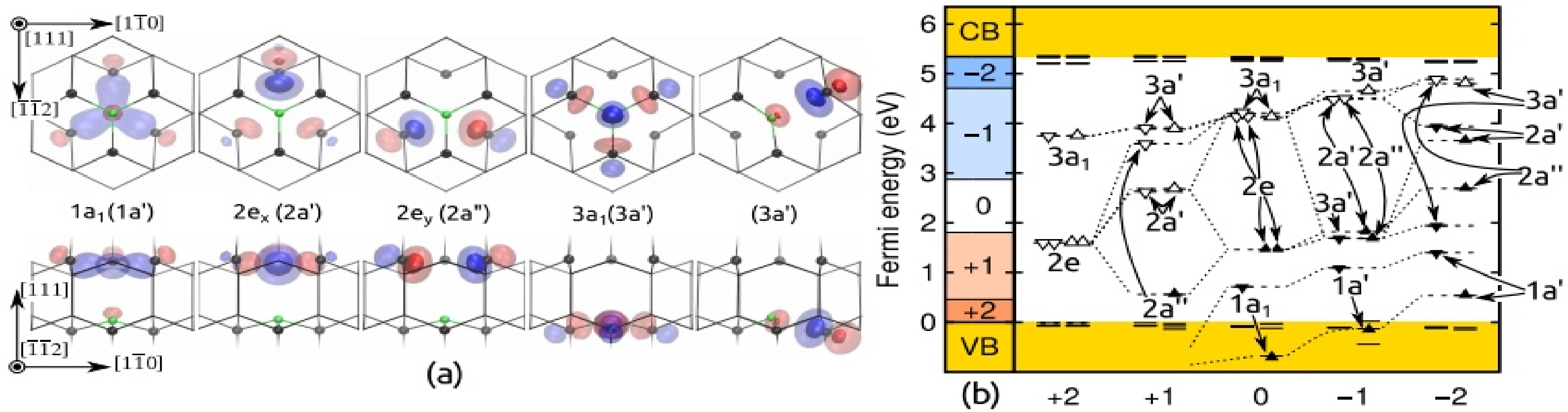
Detecting Light Dark Matter with Magnons

Tanner Trickle,[1,2,3] Zhengkang Zhang,[3,1,2] and Kathryn M. Zurek[3,2,1]
[1]*Department of Physics, University of California, Berkeley, California 94720, USA*
[2]*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
[3]*Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena, California 91125, USA*

Illustration of Quantum Materials – HEP connection

- Oxygen vacancies on diamond are an important qubit platform
- Extensive theory framework developed to understand and predict them

“Characterization of oxygen defects in diamond by means of density functional theory calculations” – cond-mat/1606.03859



- Same framework can be used to study response of diamond lattice to interactions from DM models.
- (Diamond was an classic example, but same analysis can be done for any material given enough HPC hours)

“Multi-Channel Direct Detection of Light Dark Matter: Target Comparison” – hep-ph/1910.10716 (2020)