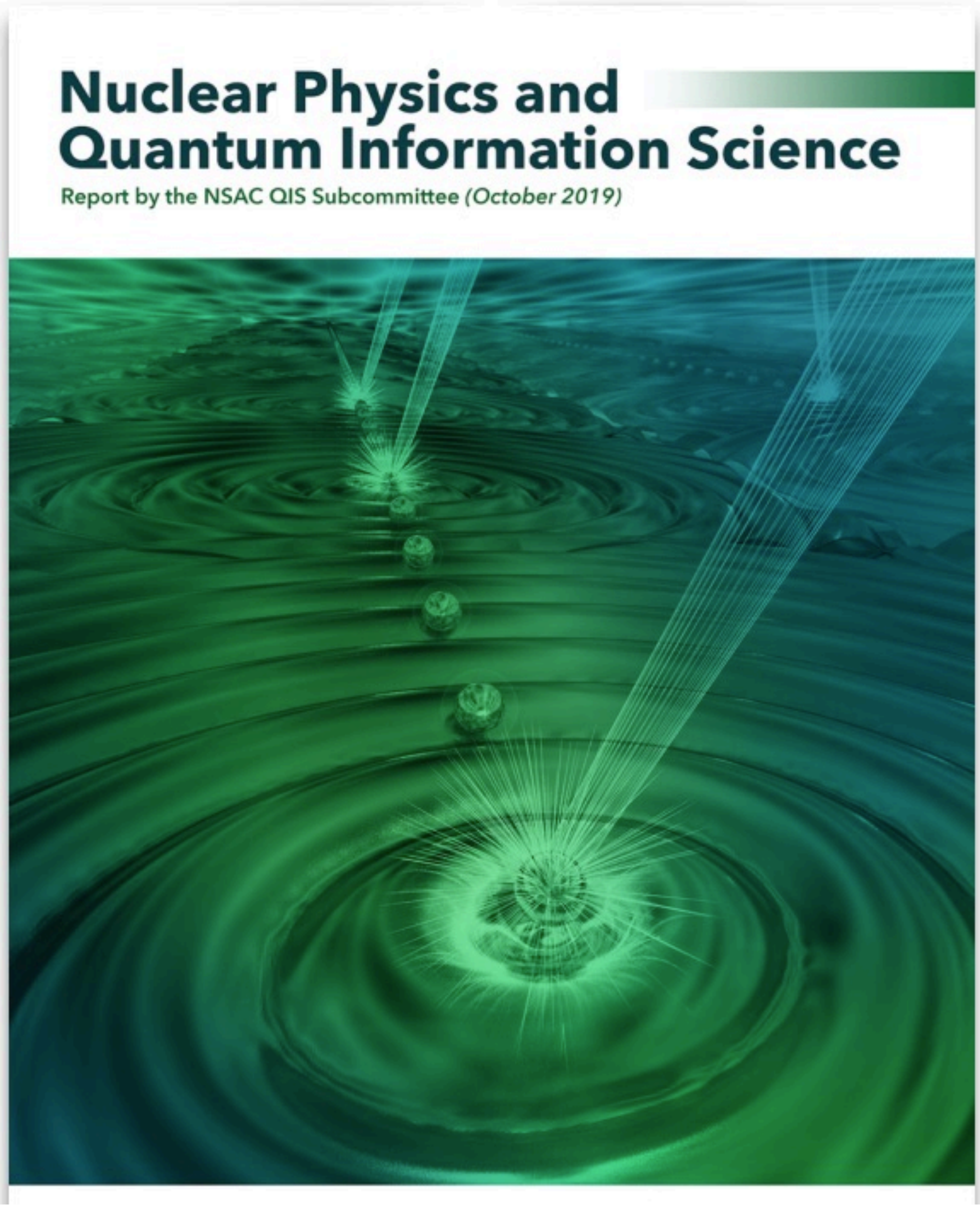
Summary: NSAC QIS Report

Alan Poon
2019.11.19

Most slides from Martin Savage's report at NSAC meeting in October



Final report has not been posted yet. Contact me if you want the pre-printing version.

Douglas Beck (UIUC)
Amber Boehnlein (JLab)
Joseph Carlson (LANL)
David Dean (ORNL)
Matthew Dietrich (ANL) (Co-Chair)
William Fairbanks Jr (CSU)
Joseph Formaggio (MIT)
Markus Greiner (Harvard)

David Hertzog (UW) (NSAC Chair)
Christine Muschik (Waterloo)
Jeffrey Nico (NIST)
Alan Poon (LBNL)
John Preskill (Caltech)
Sofia Quaglioni (LLNL)
Krishna Rajagopal (MIT)
Martin Savage (INT) (Chair)

Timeline

MEETING #1

Bethesda, Maryland

Nuclear Physics Exploration of the Quantum Information Science and Quantum Computing Landscape

March 28-29, 2019

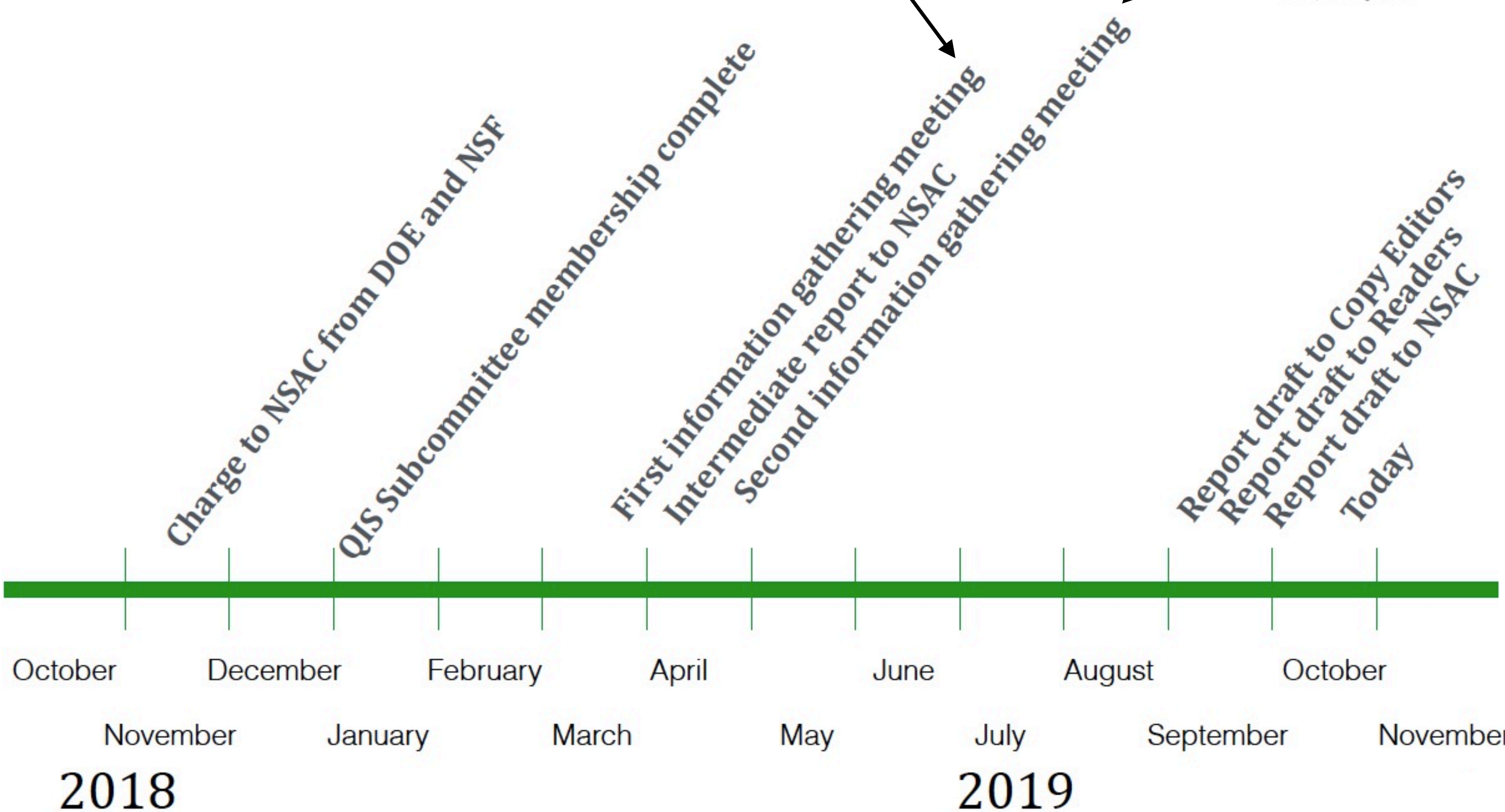
MEETING #2

Seattle, Washington

Quantum Computing and Quantum Information Science: A Deep Dive

April 30 - May 1, 2019

University of Washington, HUB



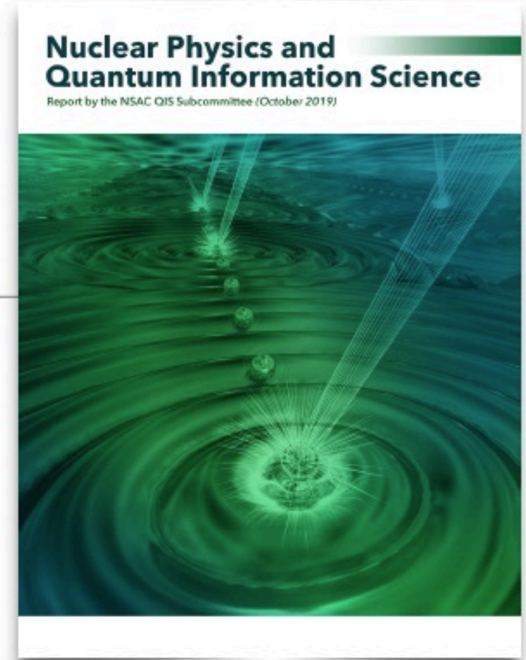
The Charge

… to provide an assessment of both the potential impact that QIS may have on nuclear physics research programs and new opportunities that may arise,

and to identify unique contributions that NP research could make to the development of QIS.

$$\widehat{\text{NQI}}\;|\,\text{NP} > \;\otimes\; |\,\text{QIS} > \;=\; \begin{aligned} &[\,|\,(\text{NP sensing} > \;\otimes\; |\text{QIS}> + \\ &|\,\text{quantum many-body and QFT simulation} > \;\otimes\; |\text{QC}> + \\ &|\,\text{Nuclear Isotopes} > \;\otimes\; |\text{qubits}> + \\ &|\,\text{Low Background Radioactivity} > \;\otimes\; |\text{qubits}> + \\ &|\,\text{NP workforce} > \;\otimes\; |\text{quantum workforce}> + \ldots \\ &\qquad\qquad\qquad]/\sqrt{n} \end{aligned}$$

Report Scope



Addressed the Charge in detail

- **QIS for NP and NP for QIS**
- experiment, theory and computation
- NP-QIS is the focus
  - identified synergies with other domains
- sidebars for highlights and state-of-the-art presentation

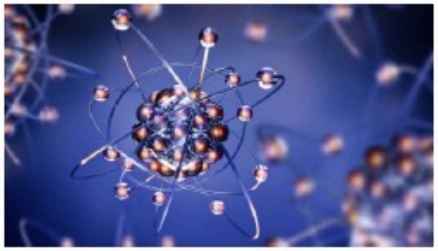
Developed a "vision" for the path forward for NP

- **Recommendations and Comments**
  - agencies, DNP, community, journals, ….
  - did not develop implementation plan
  - aspects could be scaled up to include HEP and BES
  - collaborative, multi-disciplinary efforts beyond what we have seen

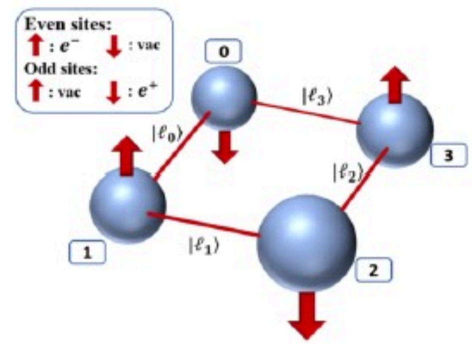
Introduction to QIS and its relationship to NP

- did not discuss/address quantum communication or memory or …

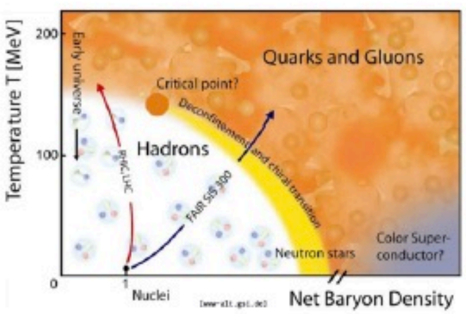
Potential Contributions from **QIS and QC** to **NP**
Simulation



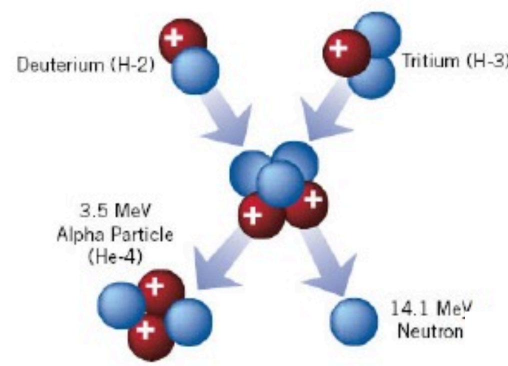
The structure and interactions of medium and large nuclei directly from nuclear forces.
Exponentially large Hilbert spaces



Lattice quantum field theories, QCD, EFT,…
Real-time dynamics, inelastic processes
Insights from model theories for NP-related physics



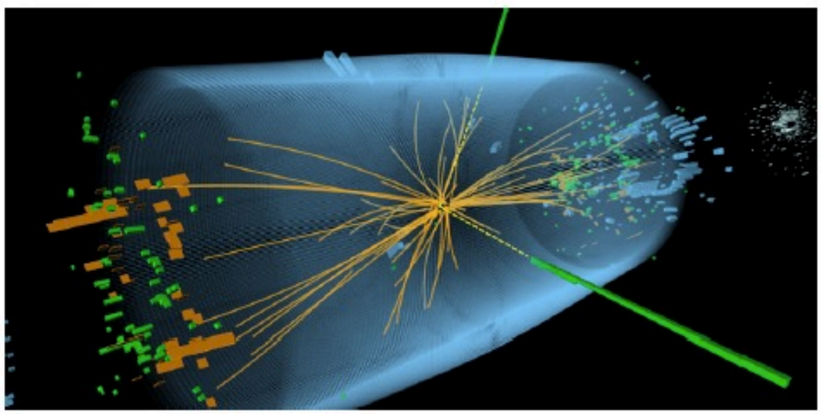
Equation of state of dense matter and neutron stars
The phase diagram of QCD
Conquering some "sign problems"

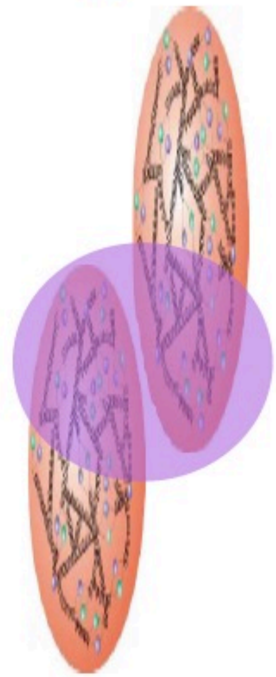


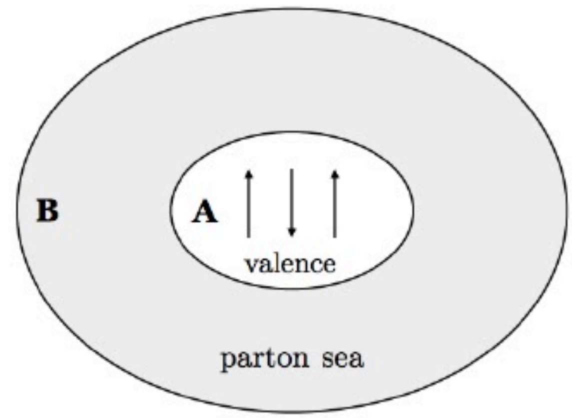
Electroweak processes in nucleons and nuclei
Dynamics of low-energy nuclear reactions and fission
Neutrino dynamics in astrophysical environments

Potential Contributions from NP to QIS and QC
Entanglement

Exploring entanglement with NP experiments







Emergent Symmetries
Spin-Flavor:
Wigner-Symmetry and SU(3)

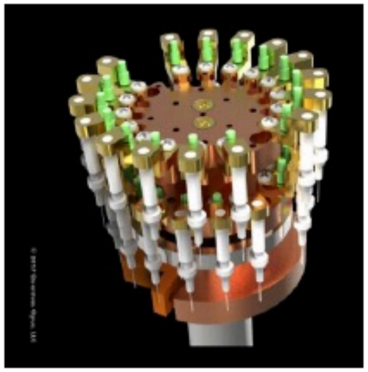
↔

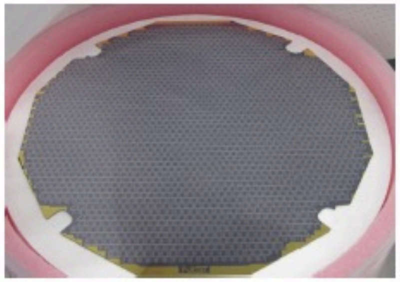
Vanishing Entanglement
Fluctuations by Nuclear
Forces - mean-field

known to eliminate sign problems in simulations

Potential Contributions from **QIS and QC** to **NP**

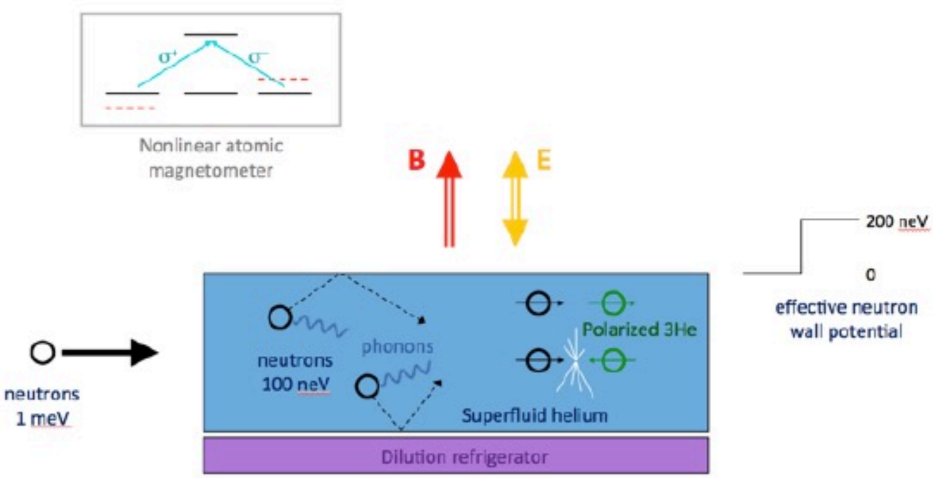
Sensors





Advanced quantum 1.0 sensors continue to be broadly integrated into NP expt. programs.
e.g., SNSPDs, TESs, MKIDs, TWAs, …

Improved capability in sensing both the heat and light will improve sensitivity in the long-sought 0νββ-decay of nuclei in the search for lepton number violation.



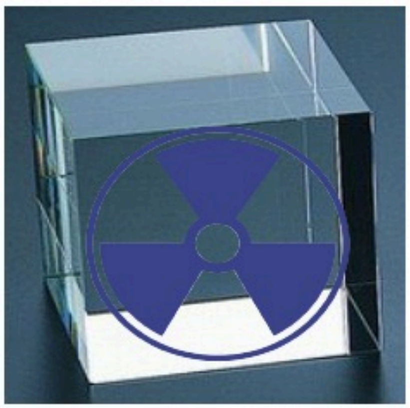
Quantum 2.0 sensors are nascent technologies. Used in nEDM experiments to measure B-fields.

Expected to provide parametrically improved sensitivities in high-sensitivity experiments, searches for new physics, EDM, axions, 0νββ-decay.

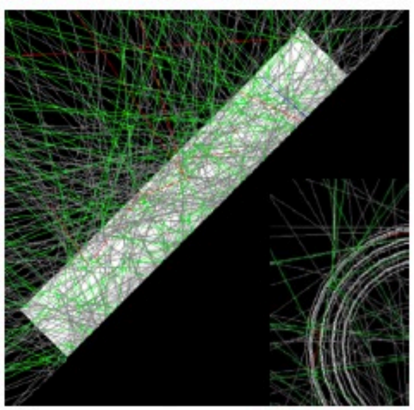
Potential Contributions from **NP** to **QIS and QC**

Sensors

Isotope enrichment and rare isotope development



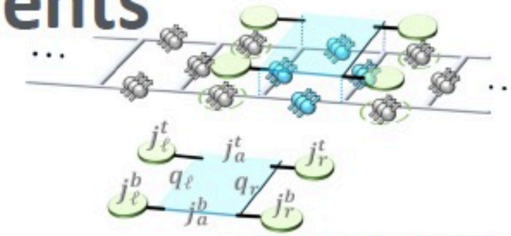
Development of nuclear clocks using radioactive isotopes, e.g., ^{229}Th



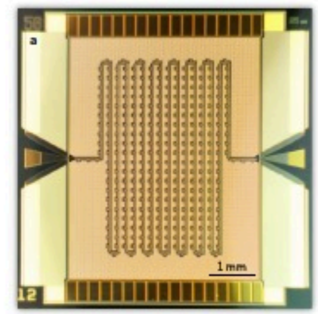
Understanding the impact of radioactive backgrounds on quantum devices

Path Forward for NP

A *Package* of Recommendations and Comments



Recommendation 1A: Quantum Computing, Simulation, and Nuclear Physics



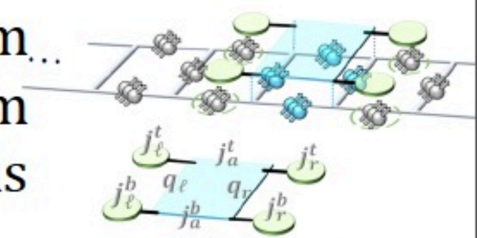
Recommendation 1B: Quantum Sensing in Nuclear Physics

Recommendation 2: Exploratory Techniques and Technologies in Combined NP and QIS Activities

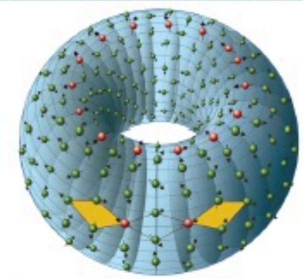
Recommendation 3: A Quantum-Ready Nuclear Physics Workforce

Rec. 1A: Quantum Computing, Simulation and NP

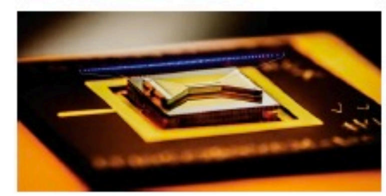
….. the intertwining of quantum device development, algorithm… and application development, classical simulation of quantum devices, QC and simulation, and workforce development is essential in establishing a sustainable NP quantum ecosystem. ……



The NP quantum many-body and quantum field theory problems will help drive the development of QIS.



We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for simulation. These Co-Development Consortia should pursue and facilitate the development of quantum simulation capabilities for NP research and utilize NP expertise in quantum many-body physics and quantum field theory to impact quantum information science and quantum computing.

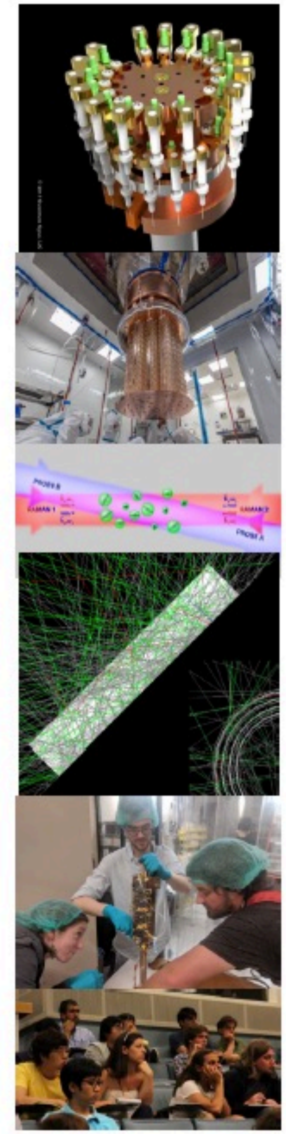


Rec. 1B: Quantum Sensing in NP

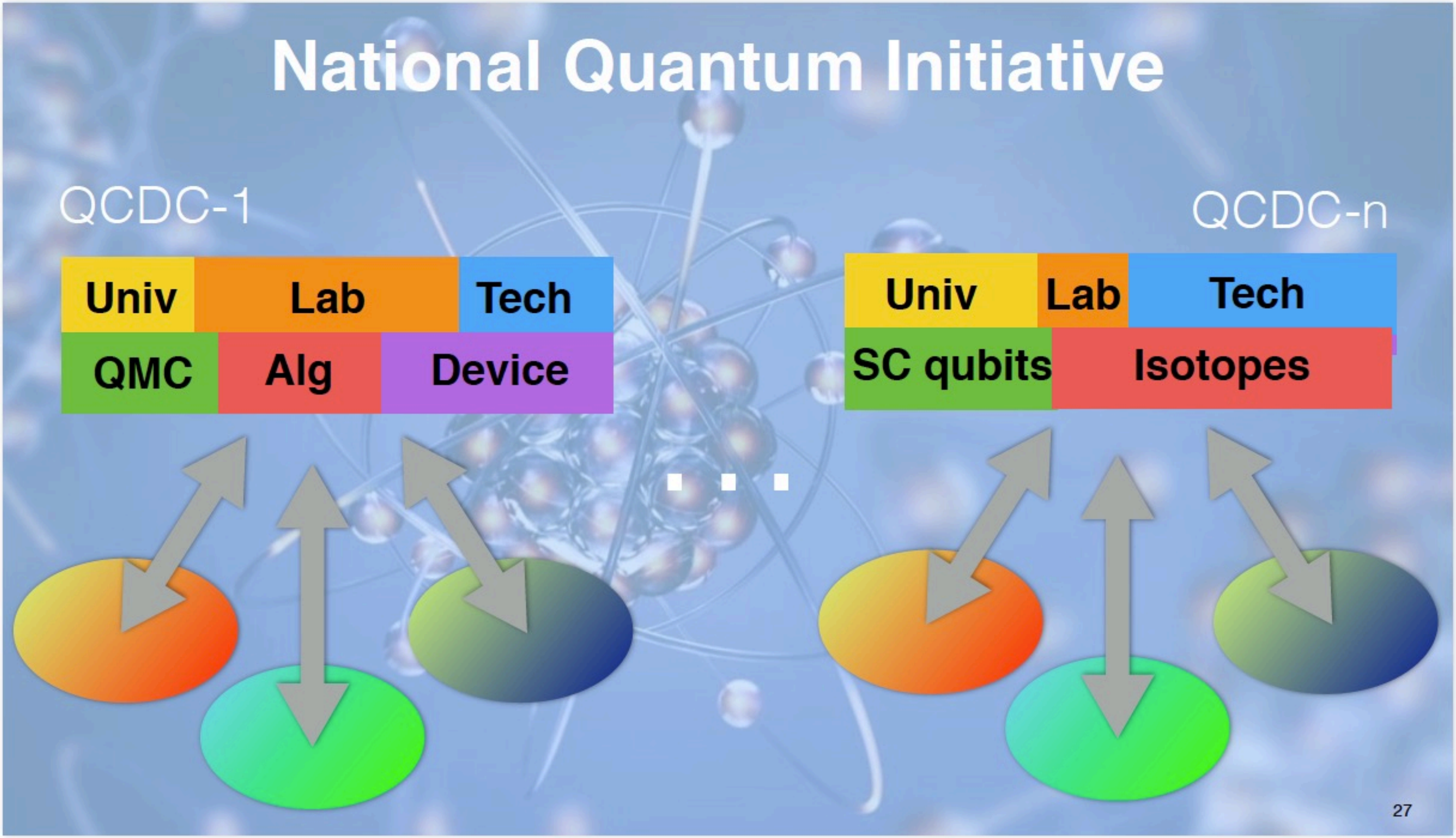
Expertise within the NP community provides opportunities to drive forward the development of quantum sensors and other quantum devices.

…. Quantum sensors are expected to enable transformative changes in the design of high-priority NP experiments. ….

We recommend establishing one or more multi-institutional Quantum Co-Development Consortia for sensors focused on targeted, prioritized, cross-disciplinary developments in quantum-enhanced sensing for NP research.



QCDC - Quantum Co-Development Consortia



Rec. 2: Exploratory Techniques and Technologies in combined NP and QIS Activities

... at the small scale, support for nascent new techniques and technologies in this domain should enable rapid and flexible NP response to newly apparent opportunities ...

We recommend that DOE and NSF encourage and support selected exploratory technologies and techniques that have promise to be of mutual benefit to NP and QIS or QC research activities.

- experiment, HPC, theory
- independent stand-alone projects critical to the success of QCDCs and NP growth in QIS
- should enable rapid and flexible NP response to new opportunities
- provide intellectual and training support for the overall NP effort
- high-stakes, high-payoff research

Rec. 3: Quantum-Ready NP Workforce

With the expectation of mutual benefit, we recommend strengthening the QIS and QC expertise in the NP workforce.

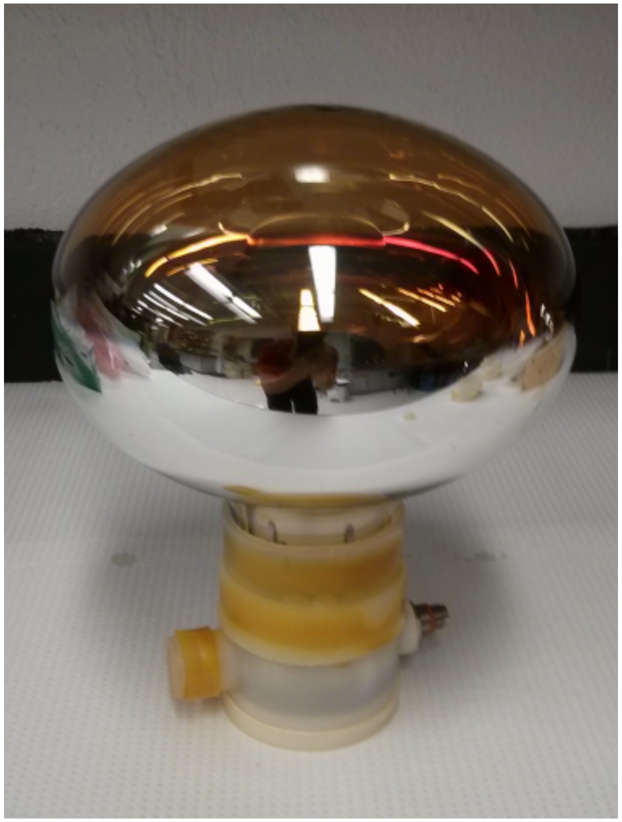
- a quantum-ready workforce is essential to the ecosystem supporting the emerging quantum economy
- includes NP scientists, engineers and developers
- broad engagement of NP with other domains is required
- in-person creative gatherings are essential - translations of languages are required
- co-advising
  - CS researchers now need to know physics and vice versa

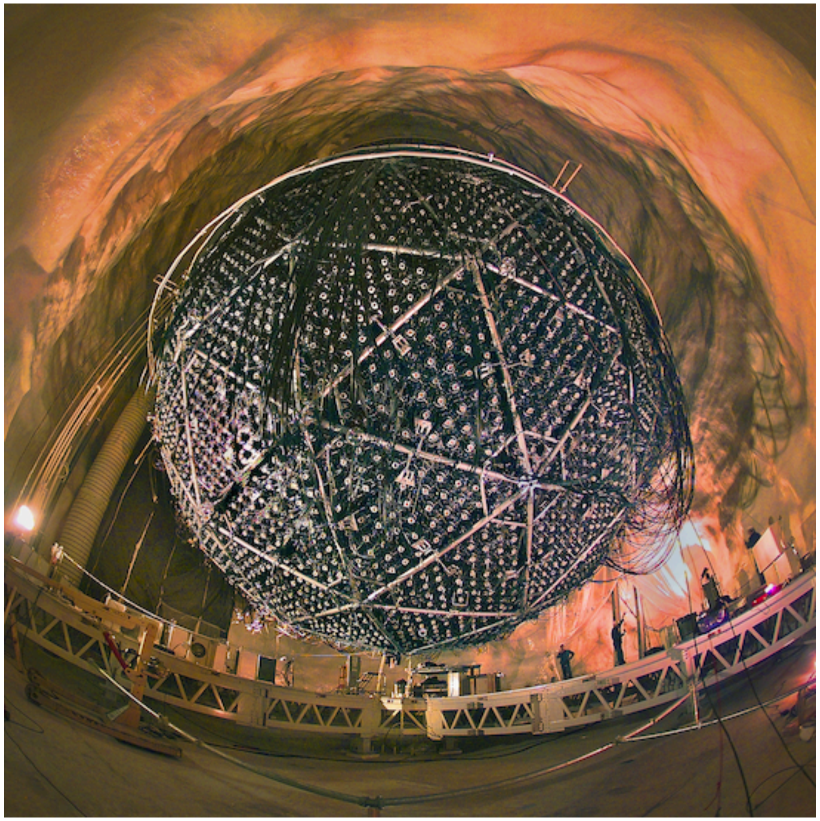
NP could develop this workforce with activities including the following:

- Annual summer schools and training programs
- Annual conferences
- Graduate fellowships
- Recruit postdoctoral fellows with expertise in QIS
- Bridge positions - scientists, engineers, developers, …
- Visiting scholar positions
- Enlarge the scope of the SciDAC program, or establish analogous programs

Workforce Development - Construction ...
constructioncareercollaborative.org

Single photon device

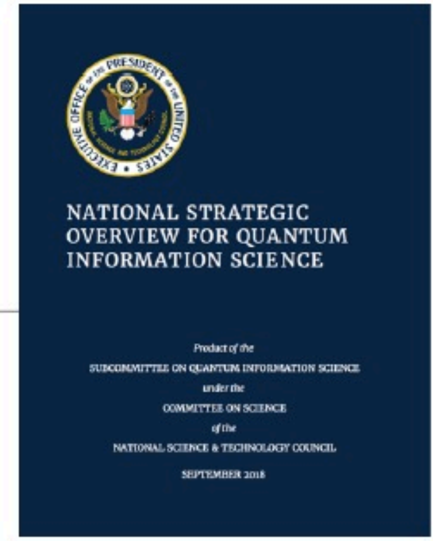




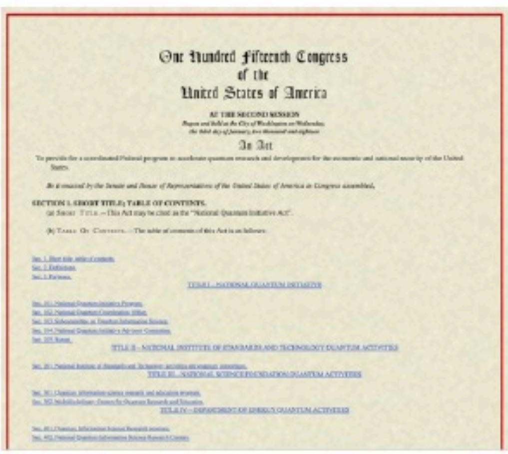
The End

US National Quantum Initiative

https://www.congress.gov/bill/115th-congress/house-bill/6227/text



The National Quantum Information (NQI) Act, passed in 2018.
NQI shall:

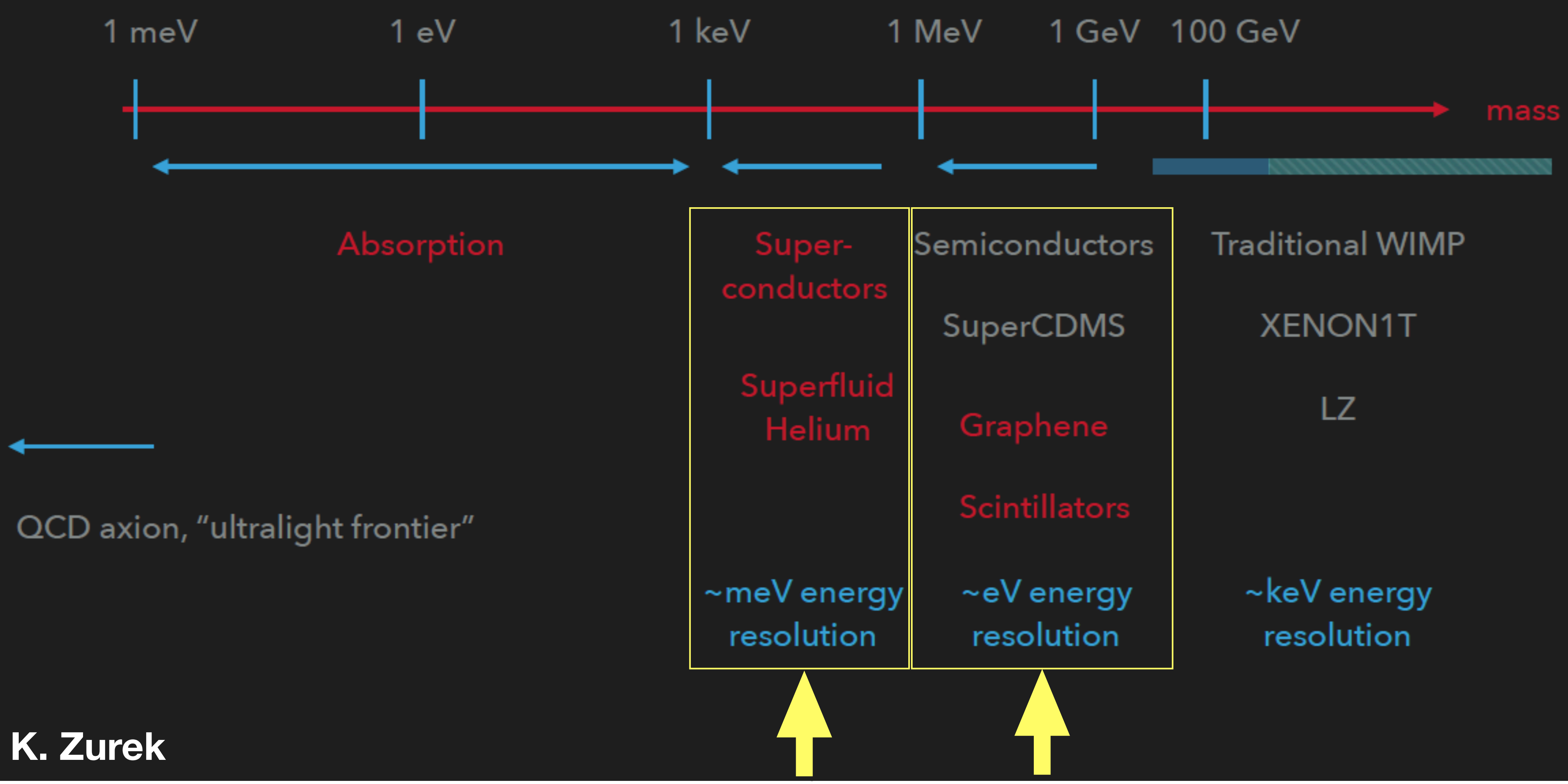

One Hundred Fifteenth Congress
of the
United States of America
An Act

- establish a **10-year plan** to accelerate basic research in QIS and relevant technological applications
- invest in fundamental QIS&T R&D and other to accomplish these goals
- invest in activities to develop a QIS&T worksforce pipeline
- provide for interagency planning and coord. of QIS R&D and other
- partner with industry and universities to leverage knowledge and resources
- leverage existing investments to advance goals and priorities

QIS development (QC, sensing, communications, networking, memory,..) coordinated by NSTC

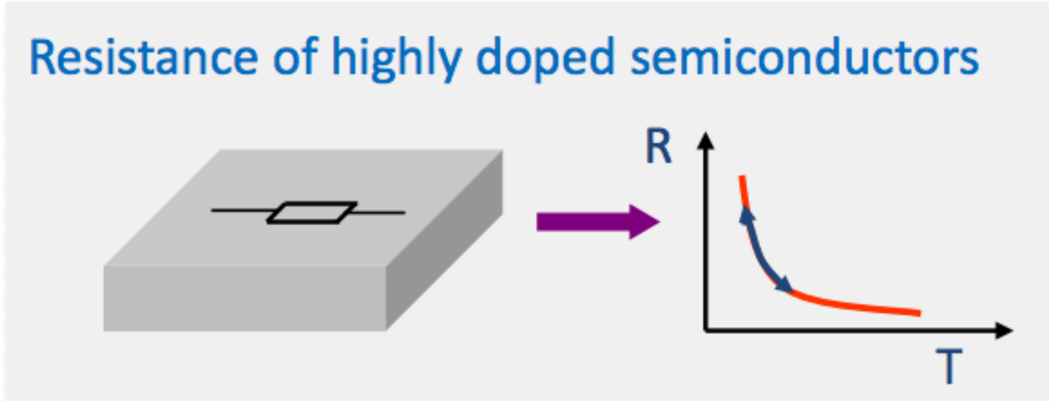
Current R&D efforts organized around 3 pillars: civilian, defense, and intelligence communities

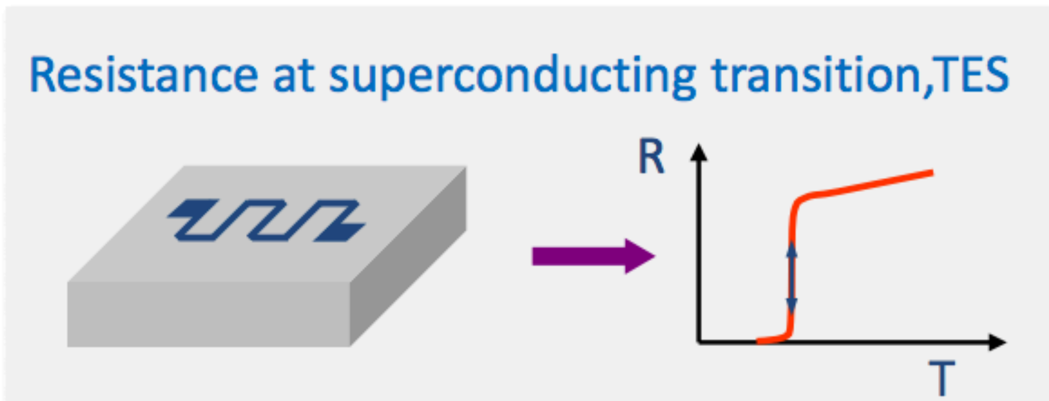
DARK MATTER LANDSCAPE

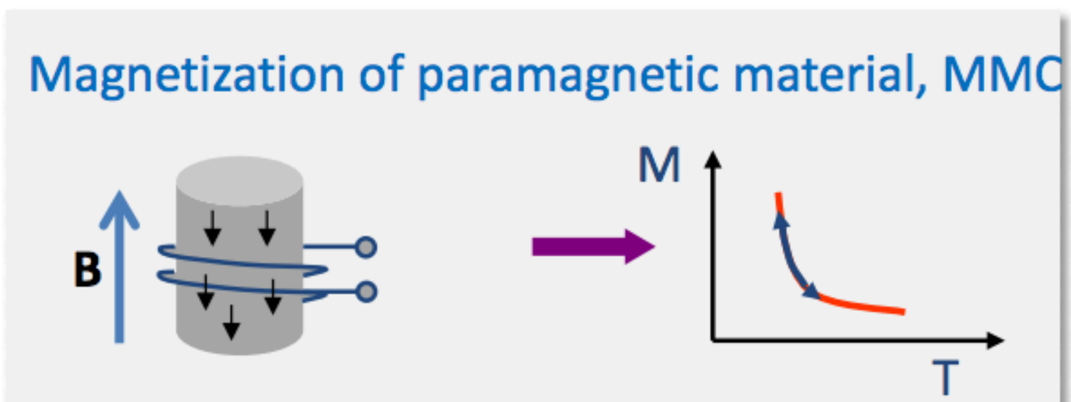


K. Zurek

Calorimetry





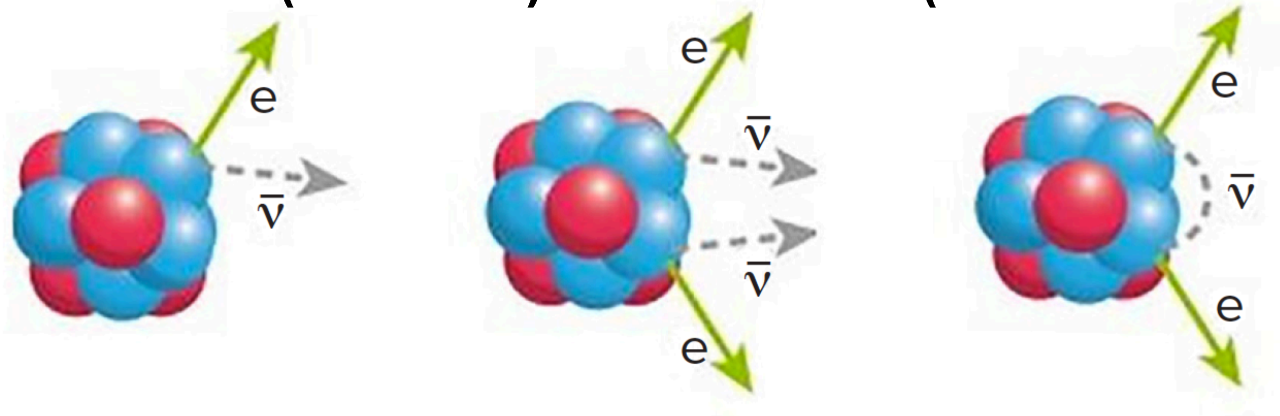


Graphics from Gastaldo

Double-beta decays

Standard physics (measured)

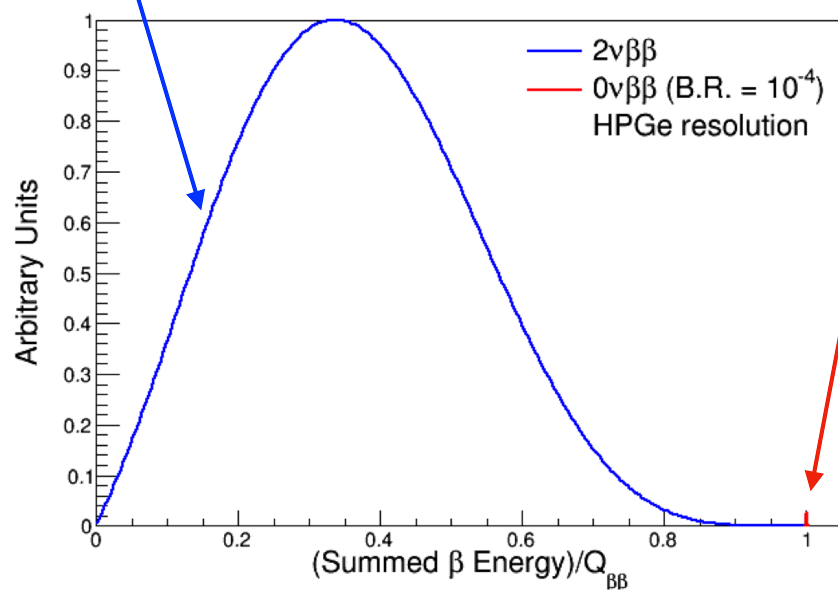
New physics (to be discovered)



$\nu = \bar{\nu}$?

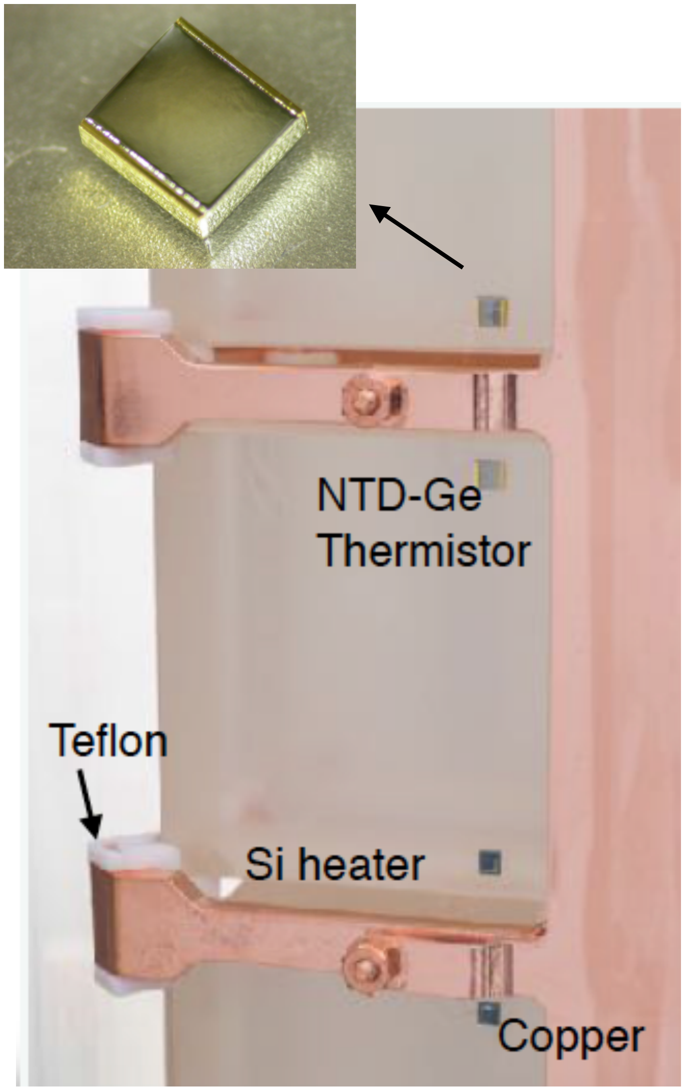
$\Delta L \rightarrow \Delta B$?

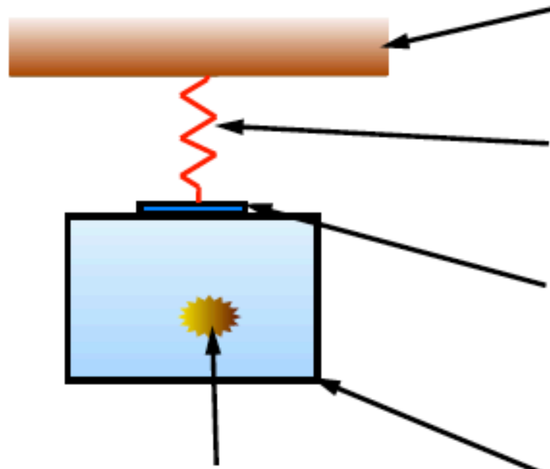
Standard β Decay | Double β Decay | Neutrinoless Double β Decay



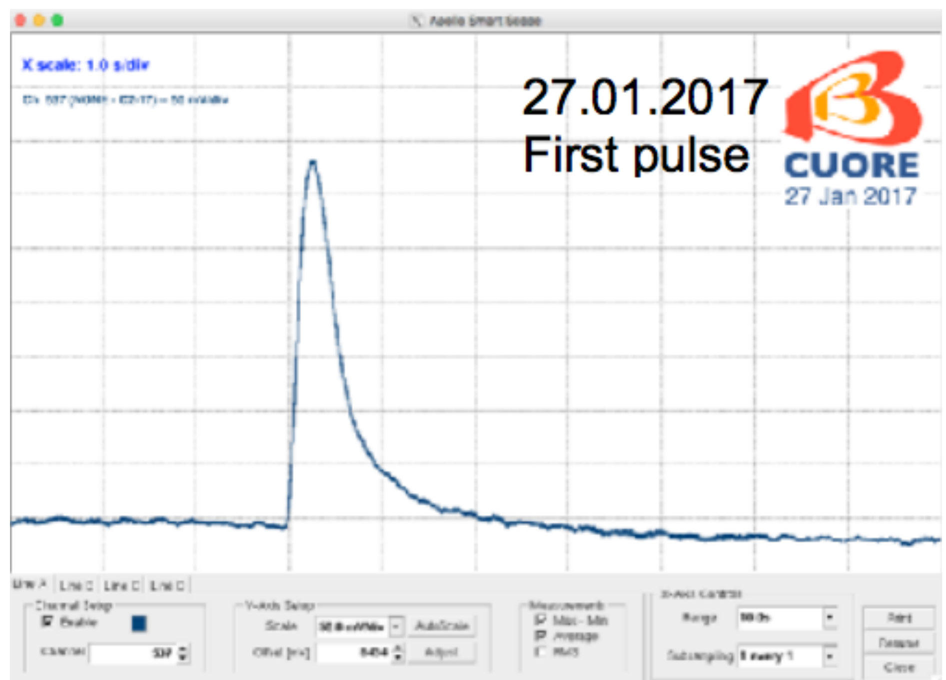
CUORE (heat) bolometer

$$\Delta T = \frac{E}{C}$$





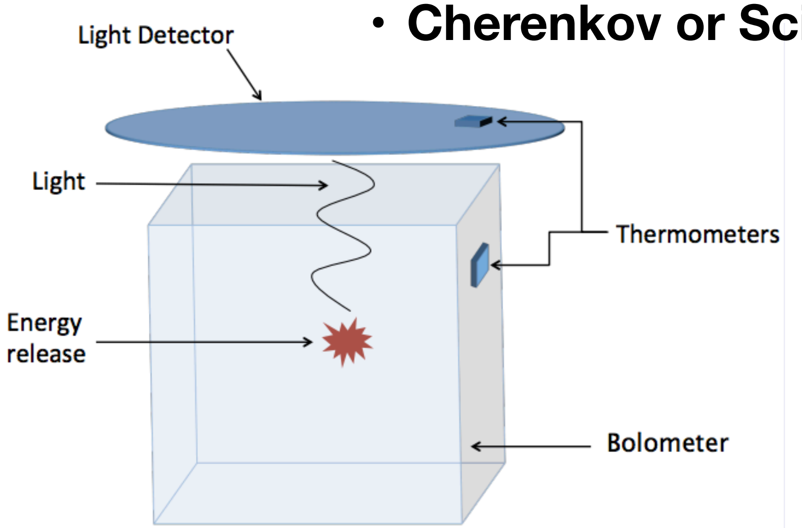
Heat sink:
Cu structure (10 mK)
Thermal coupling:
Teflon (G = 4 pW/mK)
Thermometer:
NTD Ge-thermistor (100 kΩ/μK)
Absorber:
TeO_2 crystal
(C ≅ 2 nJ/K ≅ 1 MeV / 0.1 mK)

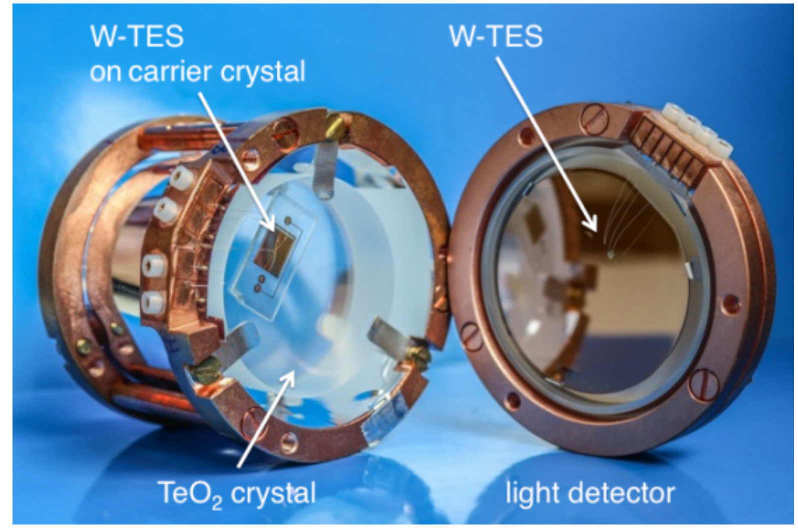


CUORE with heat & light bolometer (CUPID/CALDER…)

To distinguish ββ decays from backgrounds

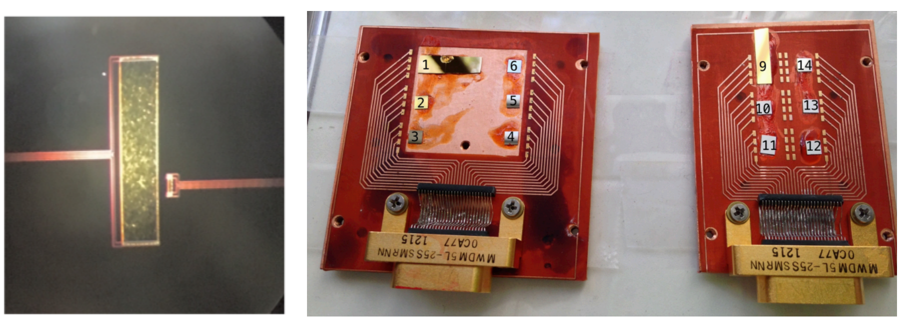
- **TeO_2, $Zn^{82}Se$, $Li_2{}^{100}MoO_4$**
- **Cherenkov or Scint. light**





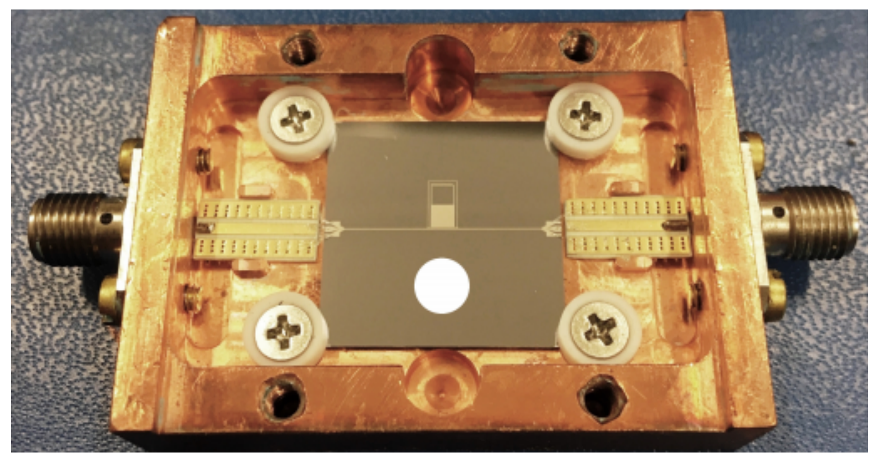
W-TES

K. Schaeffner et al, Astrop. Phys. 69, 30 (2015)



Au/Ir/Au trilayers and Ir/Pt bilayers TES development

arXiv:1711.036



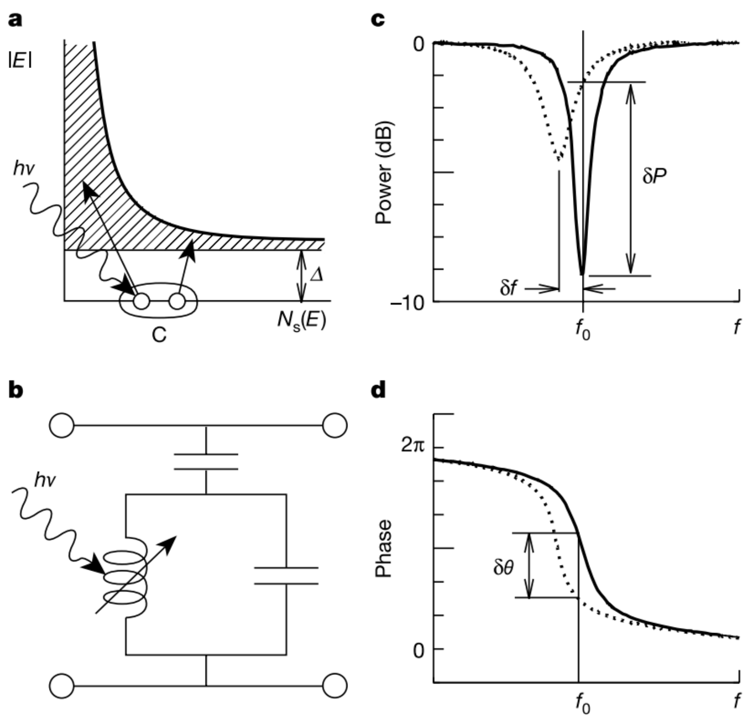
CALDER: Kinetic Inductance Detectors (KIDs)

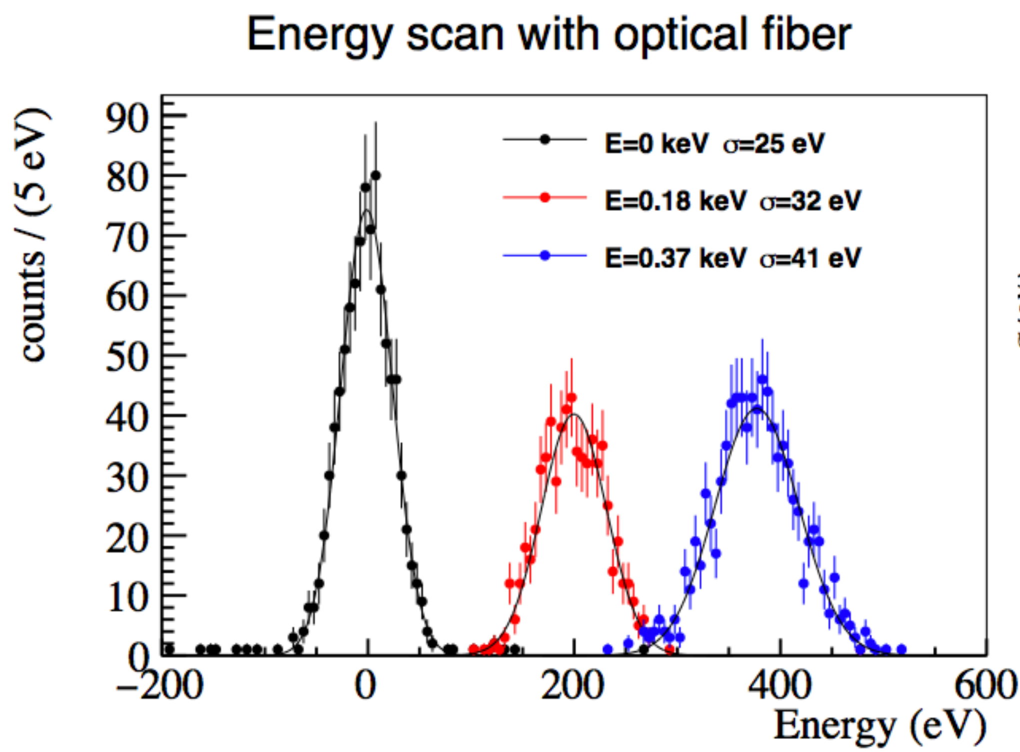
arXiv:1801.08403

BERKELEY LAB

Kinetic Inductance Detectors (KIDs)

Nature 425, 817–821 (2003)





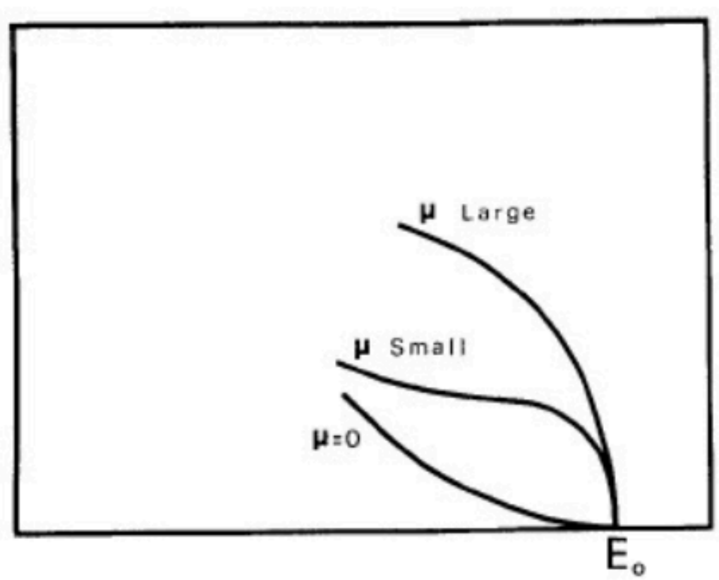
M. Vignati @TAUP 2017

a. photon breaks up Cooper pairs
b. quasiparticles cause increase in inductance L_S and R_S; LC increases
c. LC increase causes shift and broadening in resonance
d. causes change in the phase of probe

Measuring the neutrino mass (via β-decay kinematics)

"Hence, we conclude that the rest mass of the neutrino is either zero, or, in any case, very small in comparison to the mass of the electron."

E. Fermi



F. Wilson, Am. J. Phys. 36, 1150 (1968)

Courtesy of H. Robertson

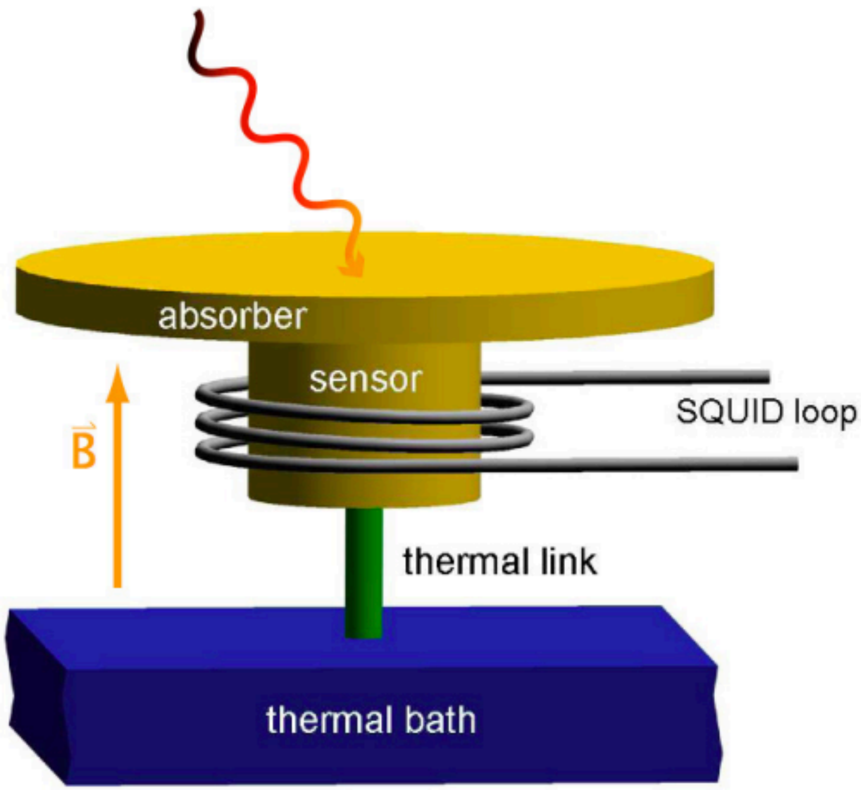
Measuring the neutrino mass (via β-decay kinematics)

$$^{3}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

Metallic Magnetic Calorimeters (MMC)

A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

- Paramagnetic Au:Er sensor
  Ag:Er



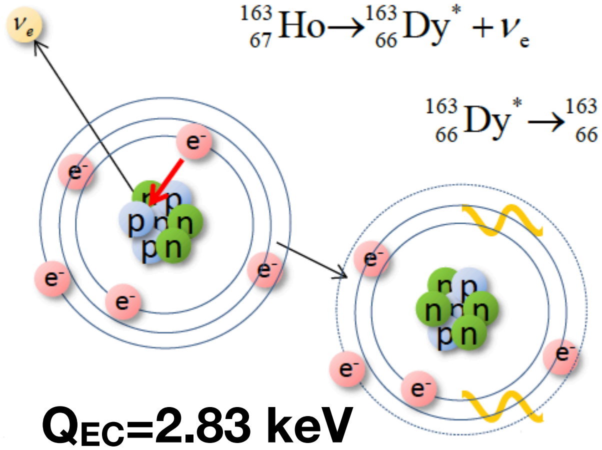
$$\Delta\Phi_s \propto \frac{\partial M}{\partial T}\Delta T \quad \rightarrow \quad \Delta\Phi_s \propto \frac{\partial M}{\partial T}\frac{E}{C_{sens}+C_{abs}}$$

Graphics from Gastaldo

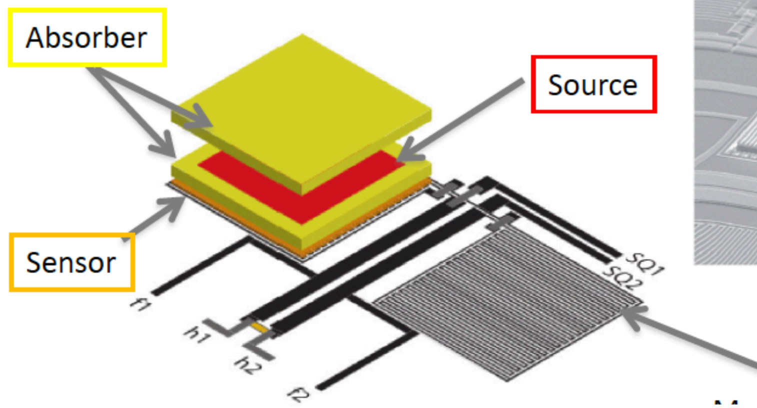
ECHO - EC in ^{163}Ho

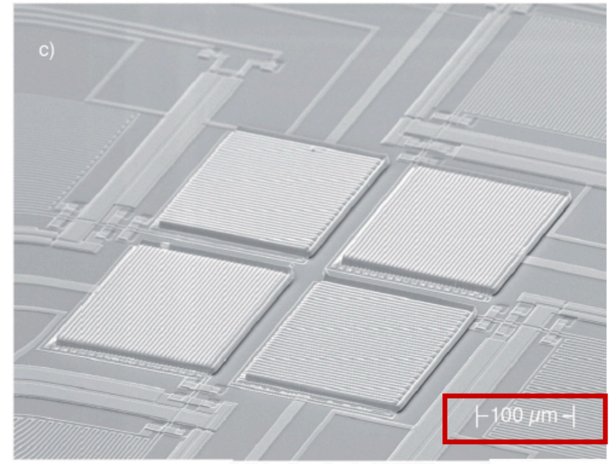
$$^{163}_{67}\mathrm{Ho} \rightarrow ^{163}_{66}\mathrm{Dy}^{*} + \nu_e$$

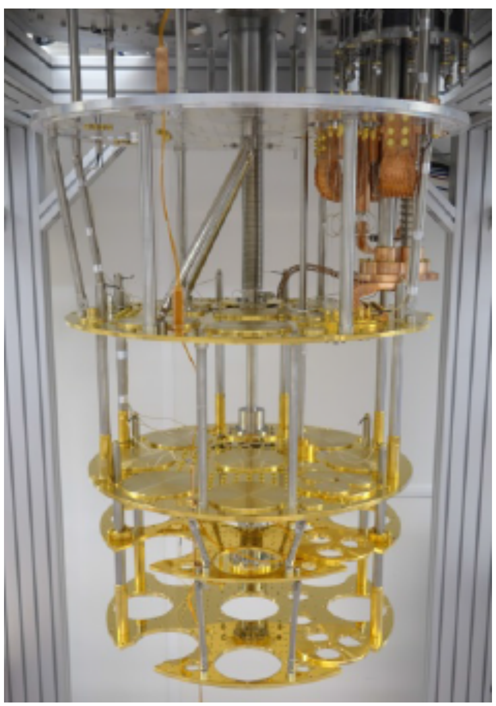
$$^{163}_{66}\mathrm{Dy}^{*} \rightarrow ^{163}_{66}\mathrm{Dy} + E_C$$

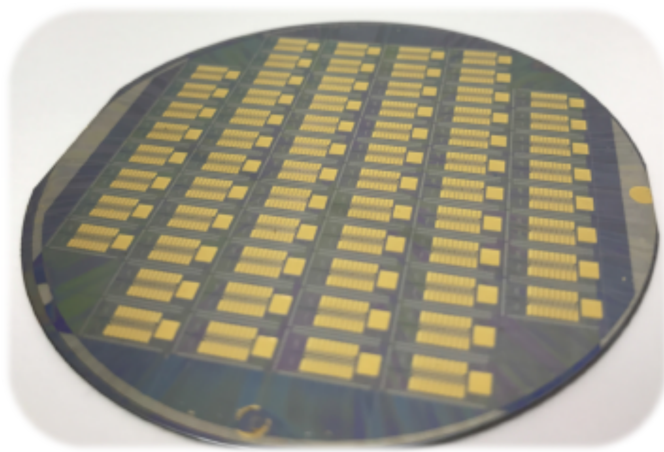


Q_{EC}=2.83 keV



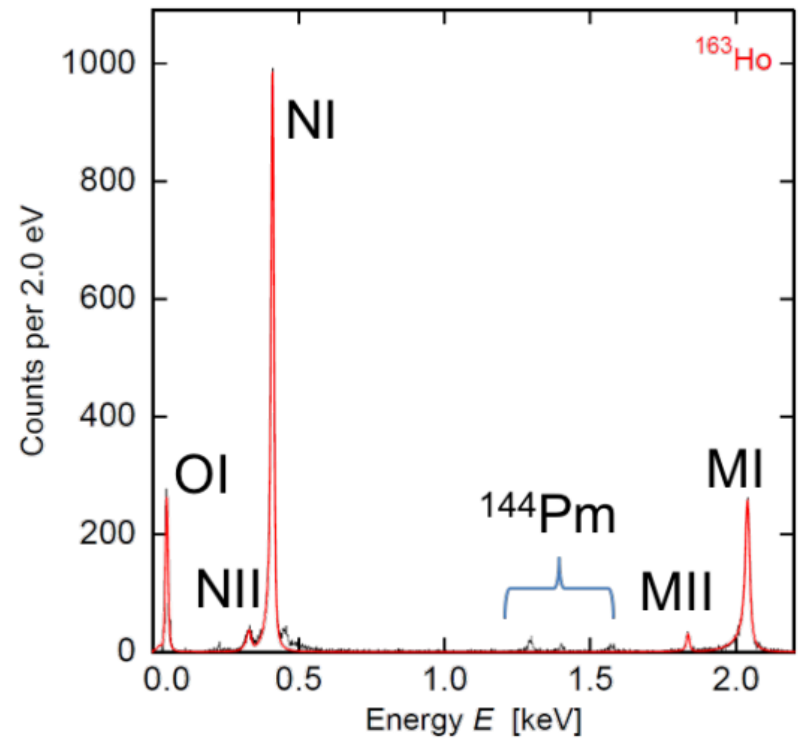






ECHO-1k

First calorimetric OI-line measurement



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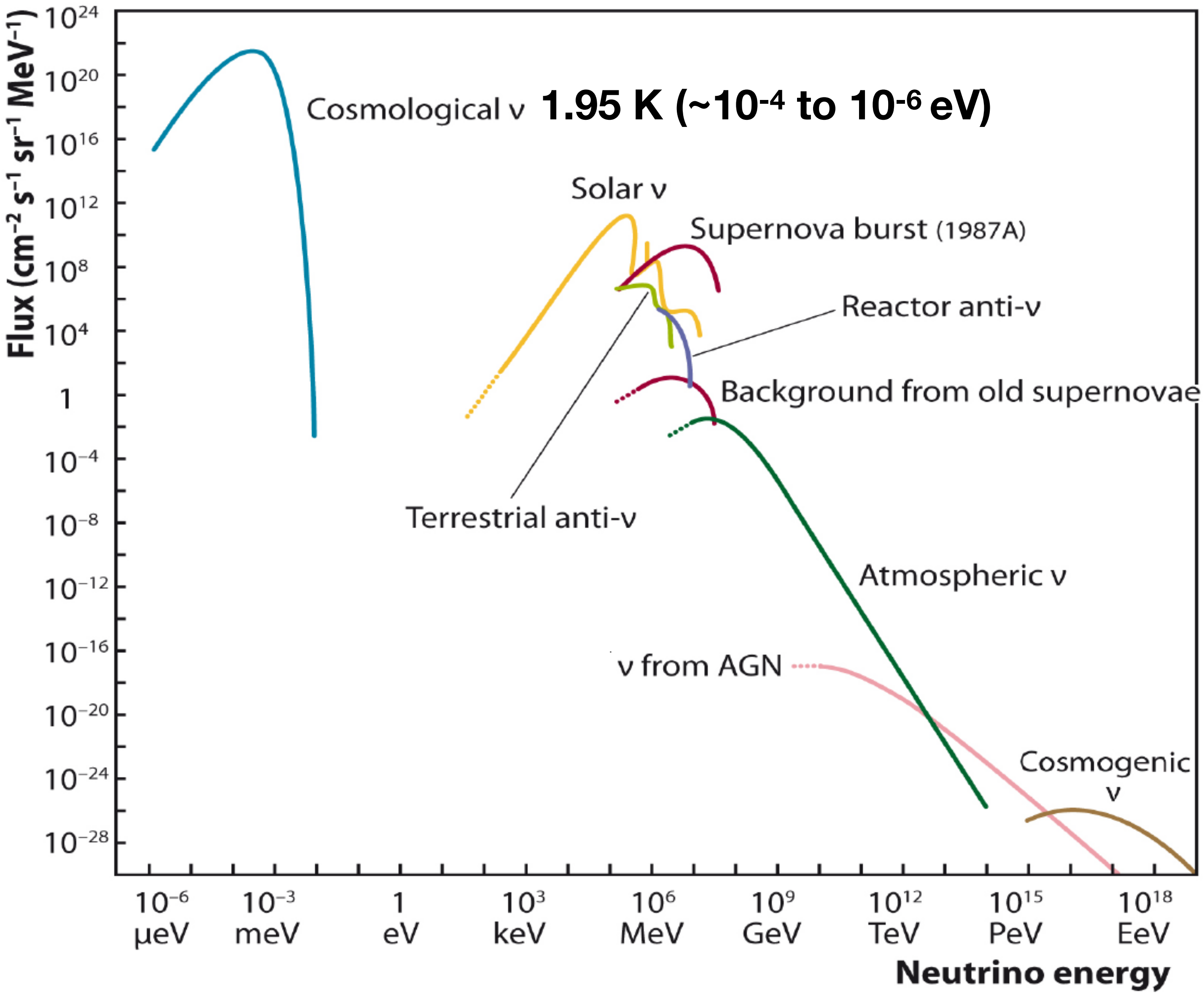
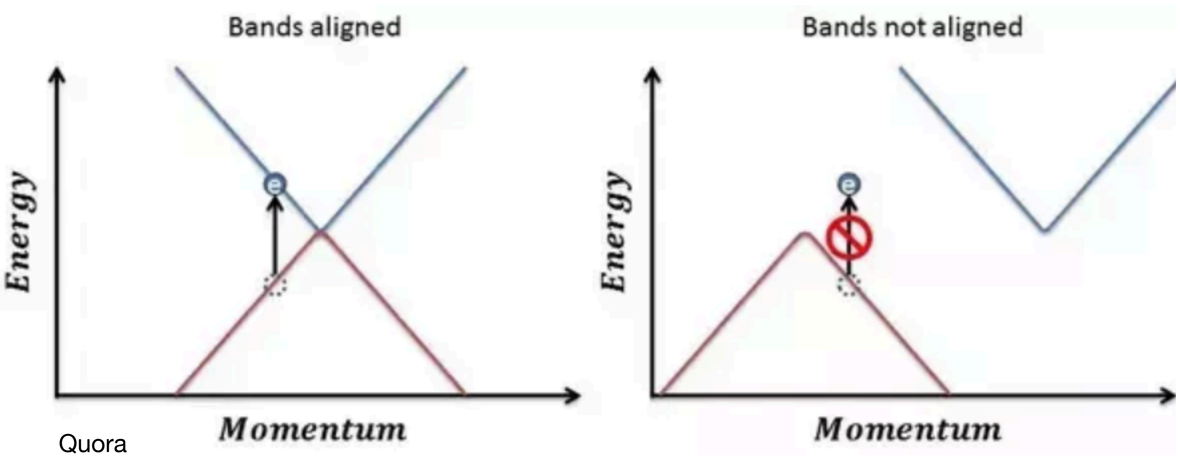
Neutrino sources

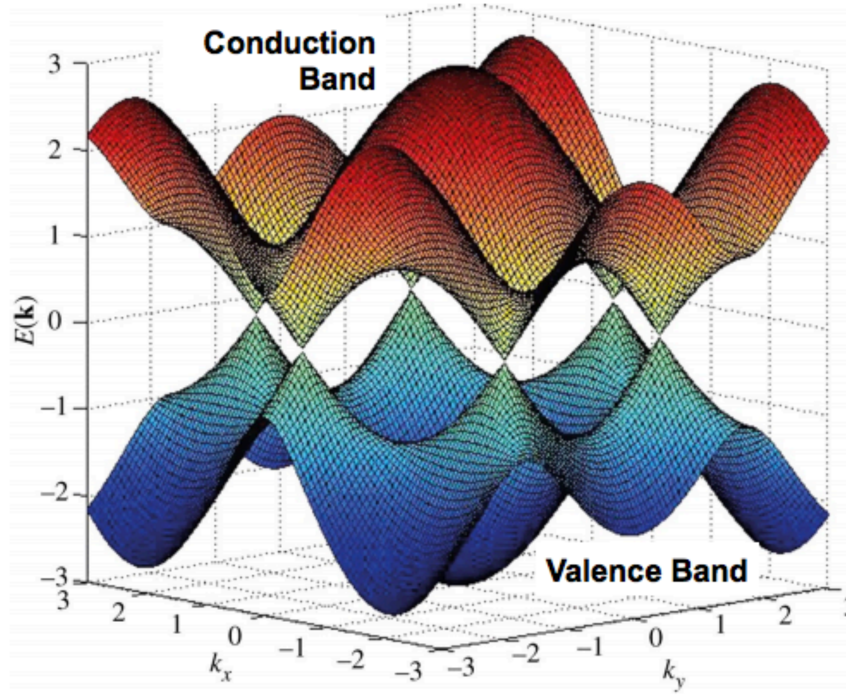


Graphene

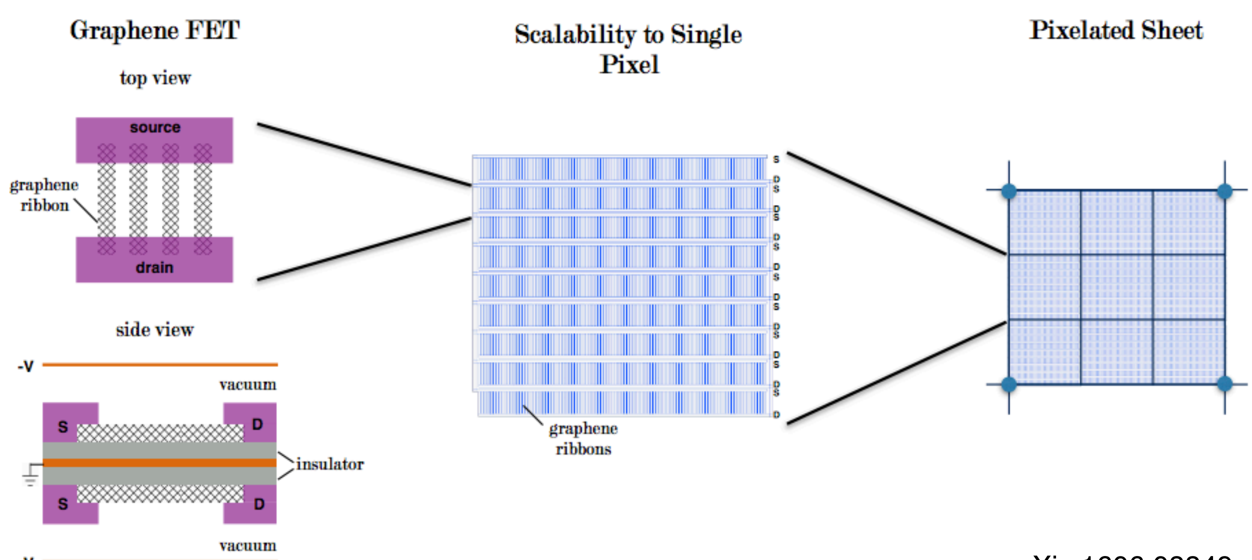
- Symmetry structure leads to overlap points (Dirac point) where there is no band gap



Quora

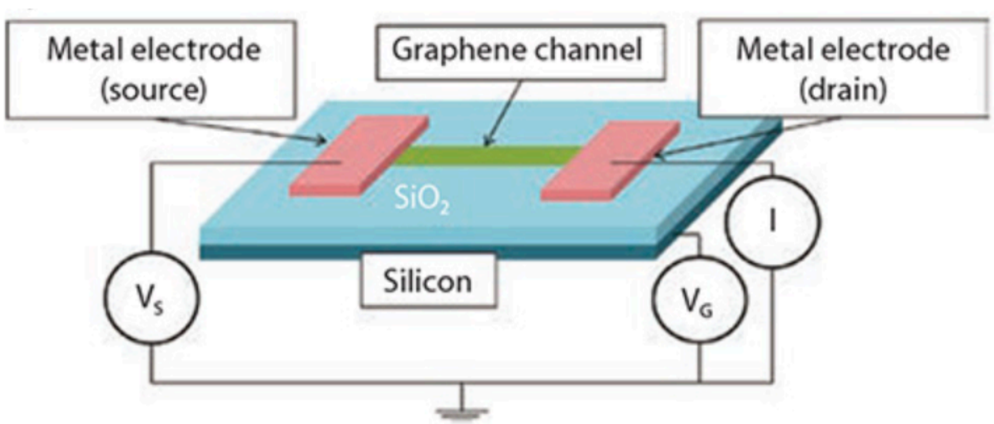


M. Lisanti



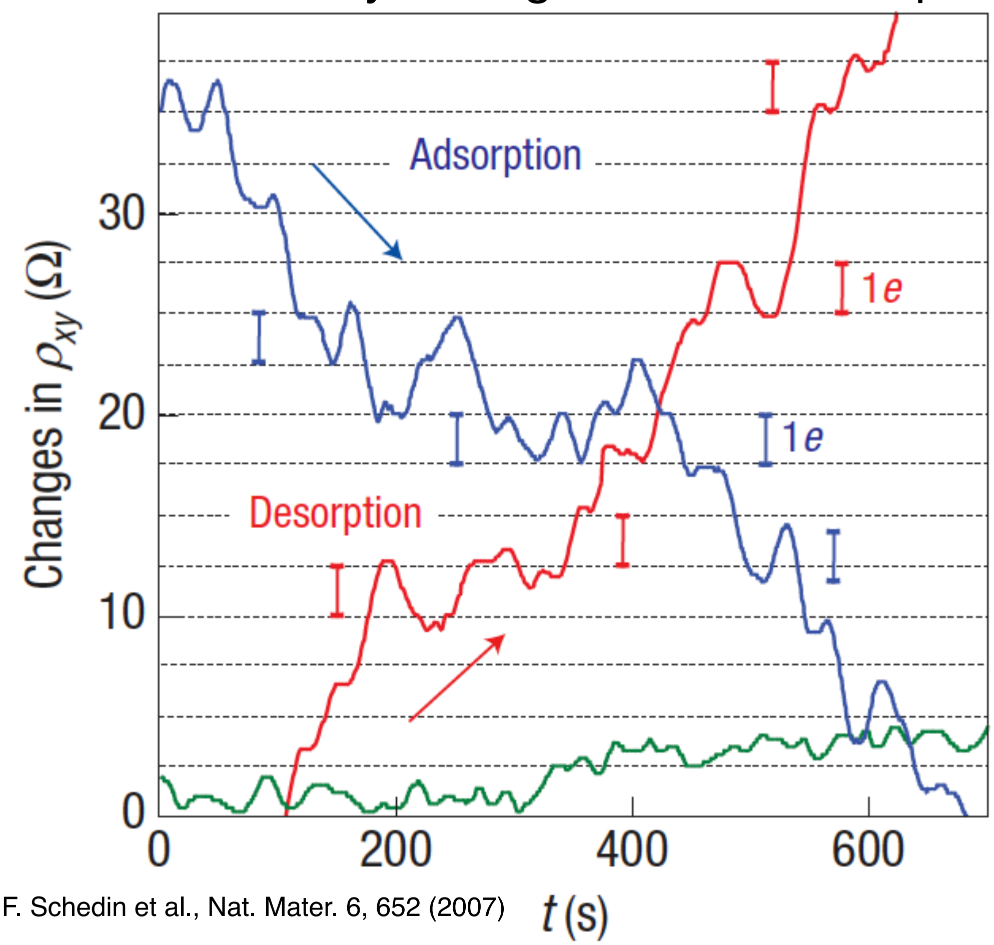
arXiv:1606.08849

Graphene FET



Sigma-Aldrich website

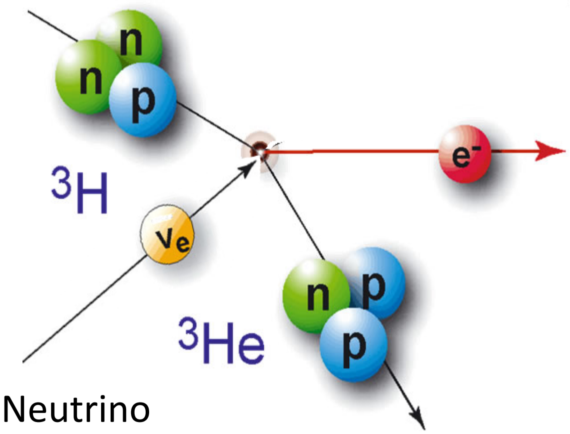
Sensitivity to singe e$^-$ at room temp.



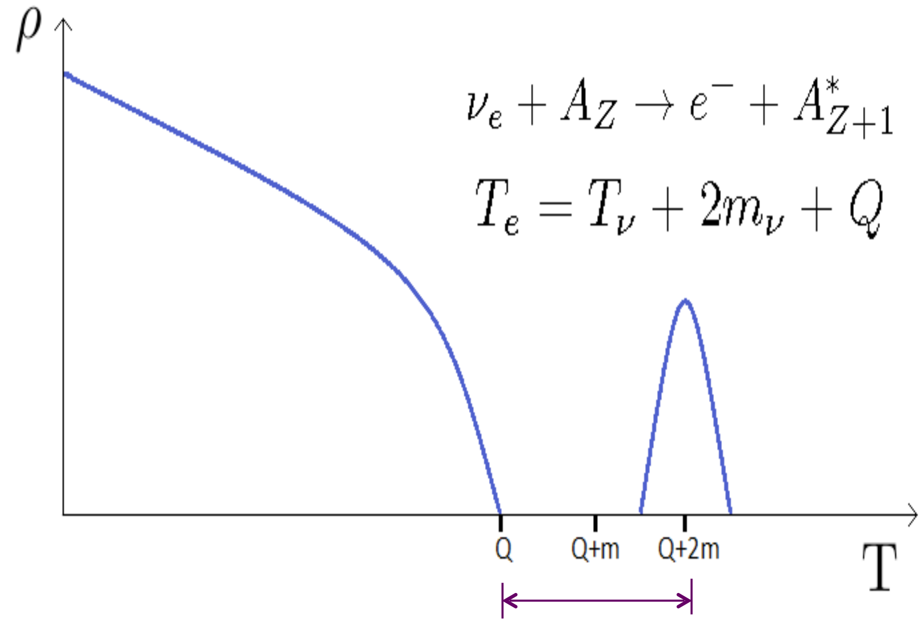
F. Schedin et al., Nat. Mater. 6, 652 (2007)

Neutrino mass & relic neutrinos

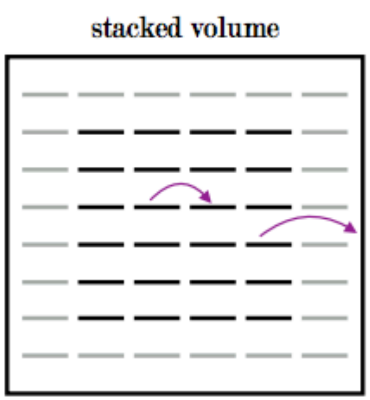
PTOLEMY Collaboration, S. Betts *et al.*, arXiv:1307.4738 (astro-ph)

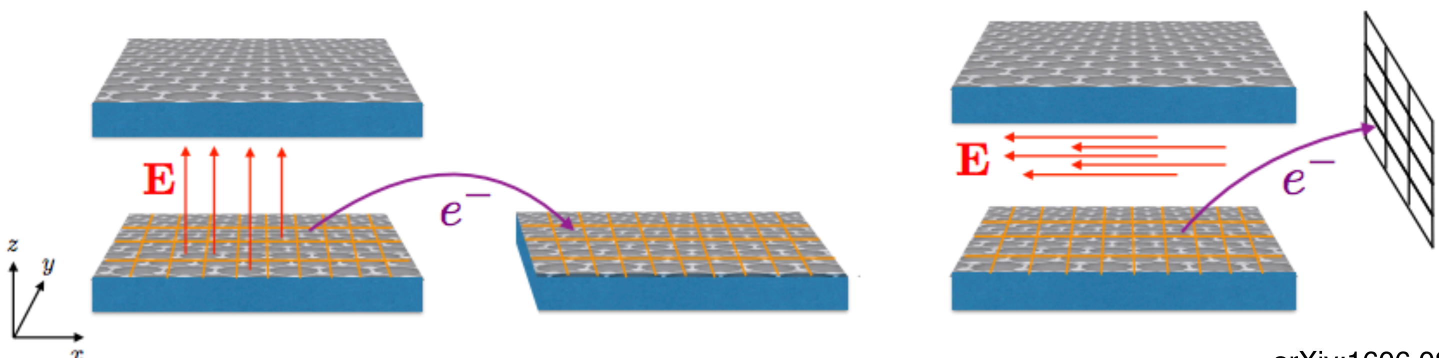


Relic Neutrino Capture on Tritium



Original idea: Steven Weinberg in 1962 [*Phys. Rev.* 128:3, 1457]
JCAP 0706 (2007)015, hep-ph/0703075, Cocco, Mangano, Messina



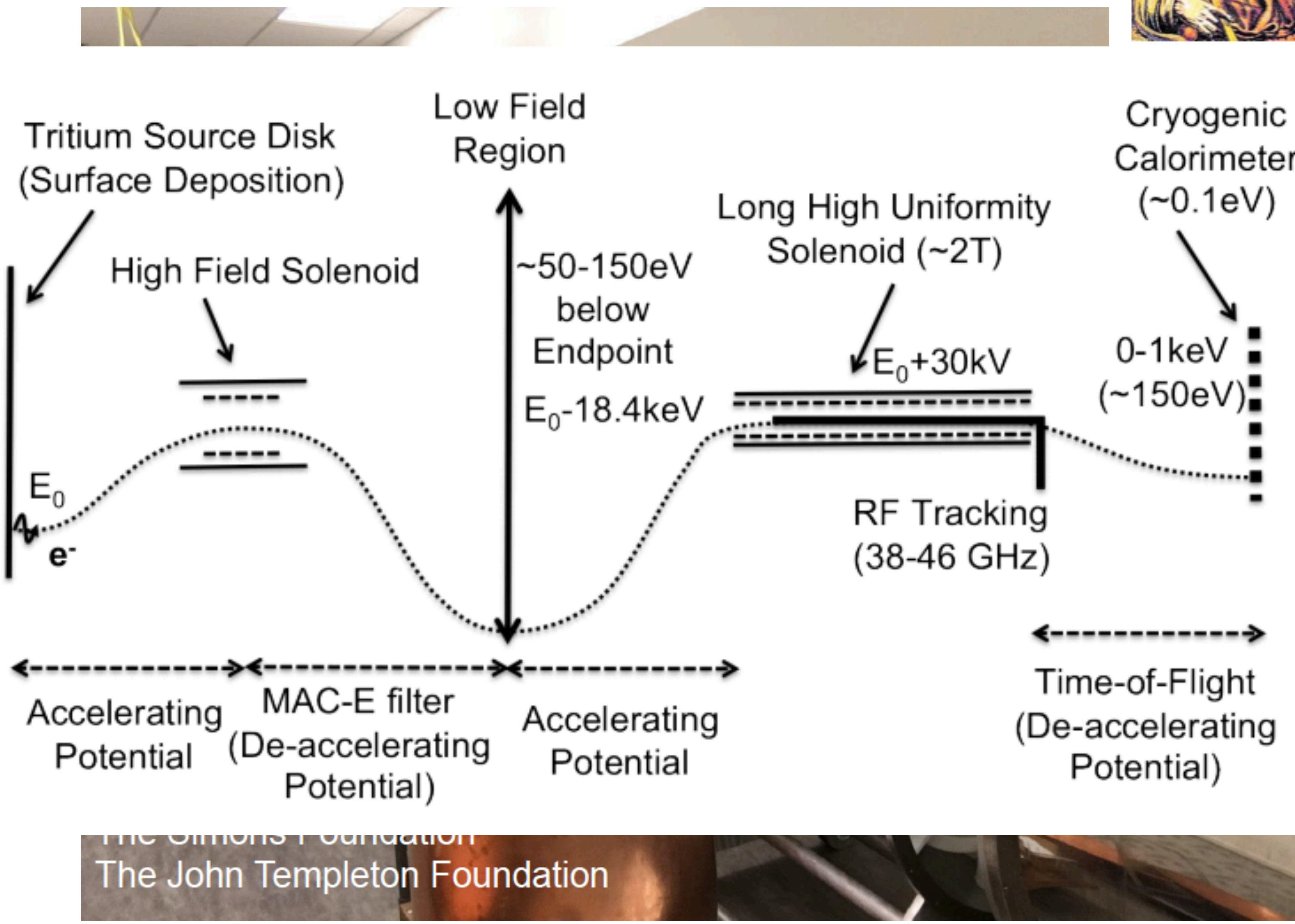


arXiv:1606.08849

Courtesy of C. Tully

PTOLEMY

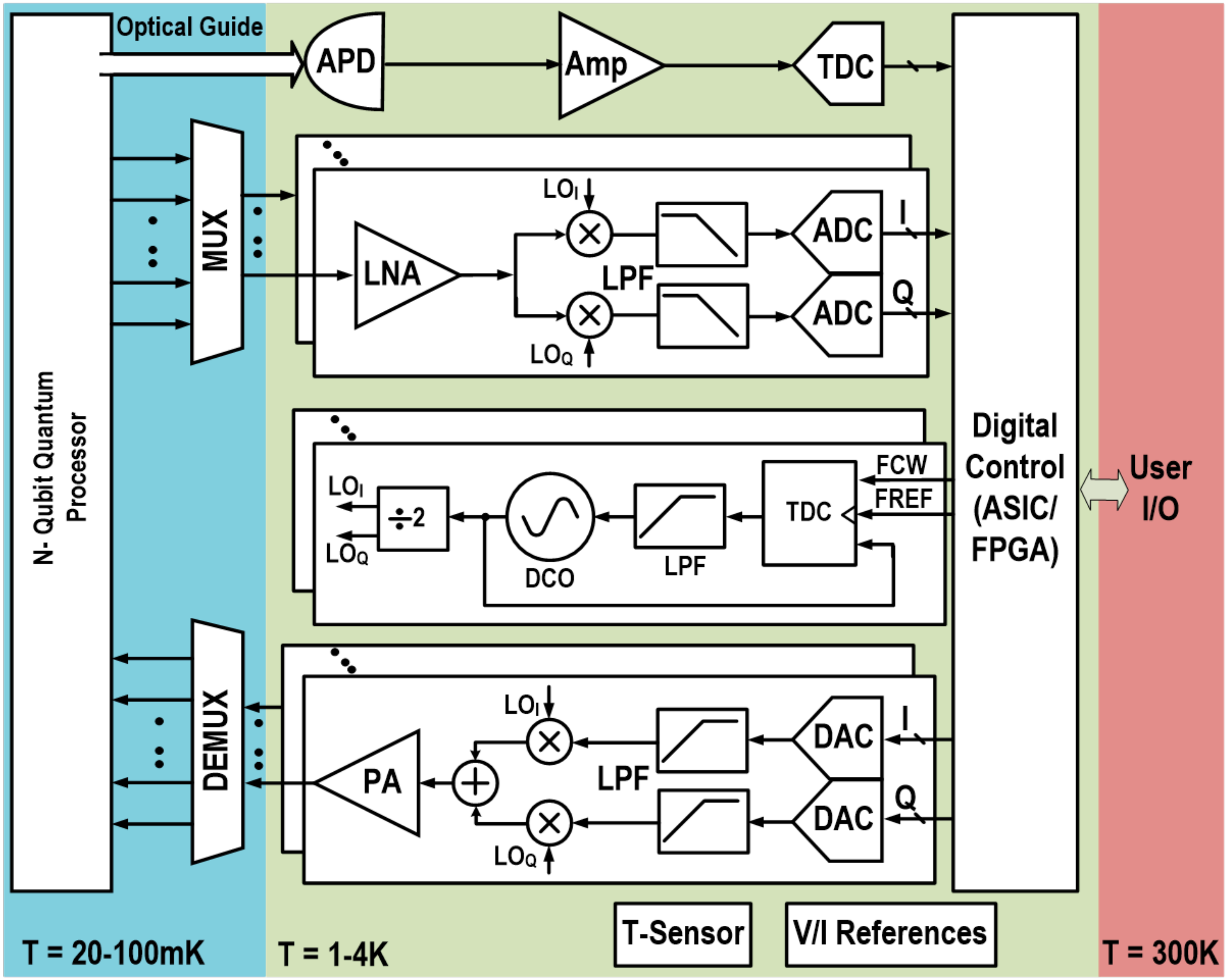
P rinceton
T ritium
O bservatory for
L ight,
E arly-universe,
M assive-neutrino
Y ield



Opportunity for low-background counting community: ^{14}C background in graphene

Cryo-electronics

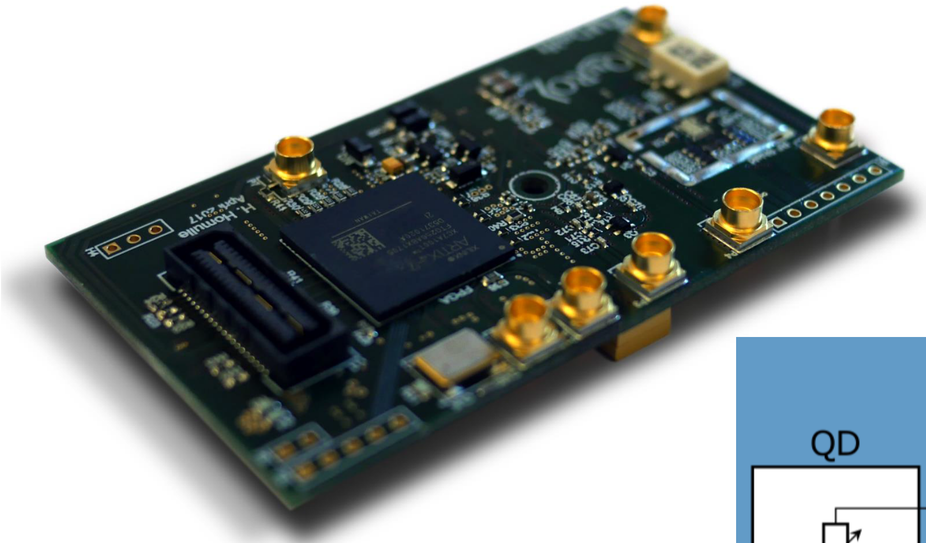
Classical interface to a quantum computer



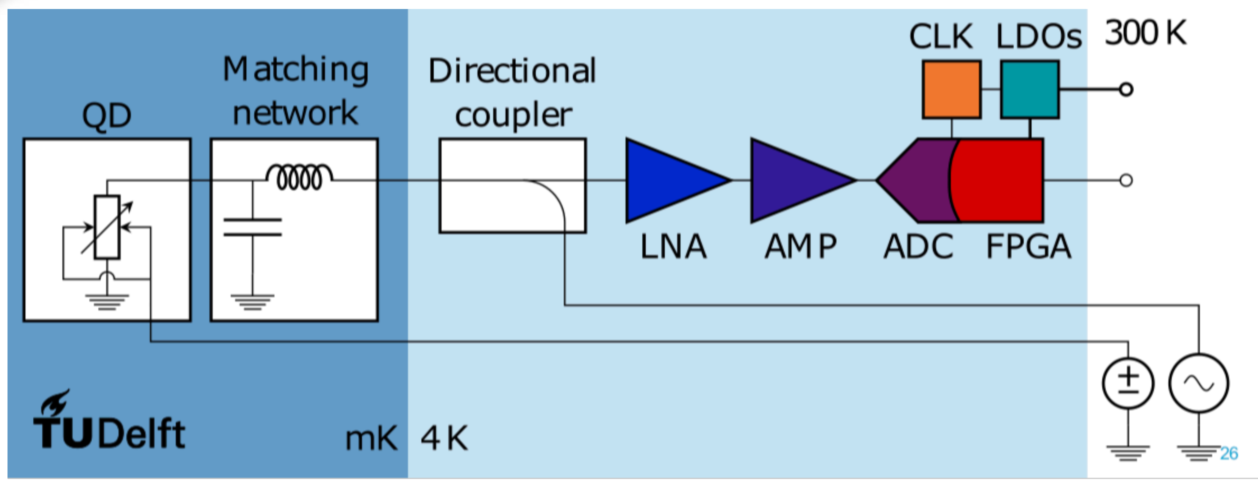
E. Charbon

QuRO

QuRO: The first entirely cryogenic interface between silicon spin qubits and a programmable classical system



H. Homulle 2018



Opportunities for NP detector/CMOS designers to develop integrated cryo-electronics systems for future NISQ/QC, SC magnet controls and cryogenic fundamental symmetry experiments?

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