QUEST
DMC

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

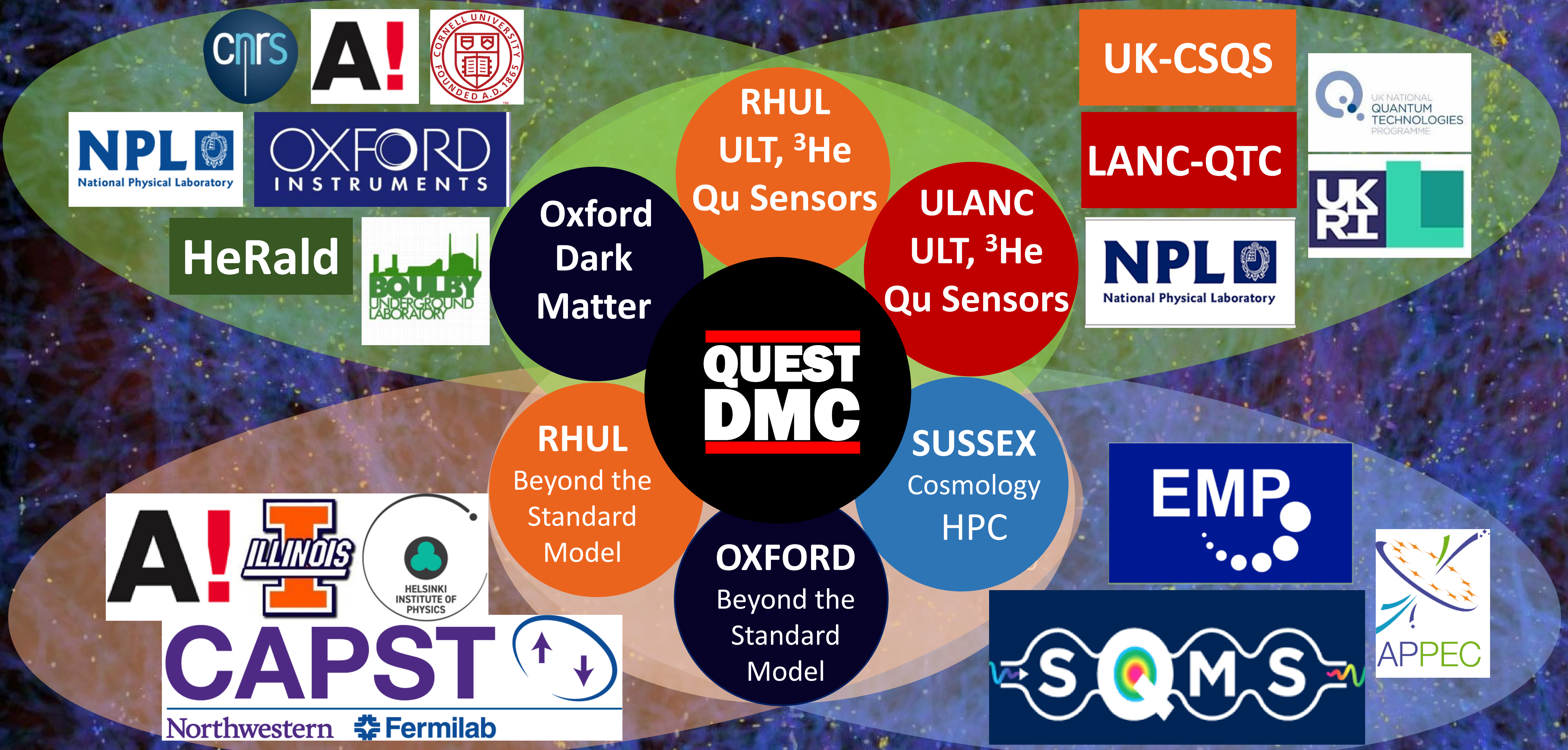
- Phase transitions in extreme matter
- Detection of sub-GeV dark matter with a quantum-amplified superfluid ^{3}He calorimeter

Linked through an experimental approach of combining quantum sensors with ^{3}He at ultralow temperatures and theoretically through beyond-standard model physics.

ROYAL HOLLOWAY UNIVERSITY OF LONDON
Lancaster University
University of Sussex
UNIVERSITY OF OXFORD
UNIVERSITY OF LIVERPOOL

UKRI Engineering and Physical Sciences Research Council
UKRI Science and Technology Facilities Council

Andrew Casey, SQMS Quantum for Science, 22/03/24



QUEST DMC

Oxford
Dark
Matter

RHUL
ULT, ^{3}He
Qu Sensors

ULANC
ULT, ^{3}He
Qu Sensors

RHUL
Beyond the
Standard
Model

OXFORD
Beyond the
Standard
Model

SUSSEX
Cosmology
HPC

Quantum Enhanced Superfluid Technologies for Dark Matter and Cosmology, QUEST –DMC

QUEST-DMC superfluid ^{3}He detector for sub-GeV dark matter.

S. Autti[1], A. Casey[2], N. Eng[2], N. Darvishi[2] , P. Franchini[1],[2], R. P. Haley[1], P. J. Heikkinen[2], A. Jennings[3], A. Kemp[2], E. Leason[2], L. V. Levitin[2], J. Monroe[2], J. March-Russel[4], M. T. Noble[1], J. R. Prance[1], X. Rojas[2], T. Salmon[1], J. Saunders[2], R. Smith[2], M. D. Thompson[1], V. Tsepelin[1], S. M. West[2], L. Whitehead[1], V. V. Zavjalov[1], D. E. Zmeev[1],
Eur. Phys. J. C 84, 248 (2024).

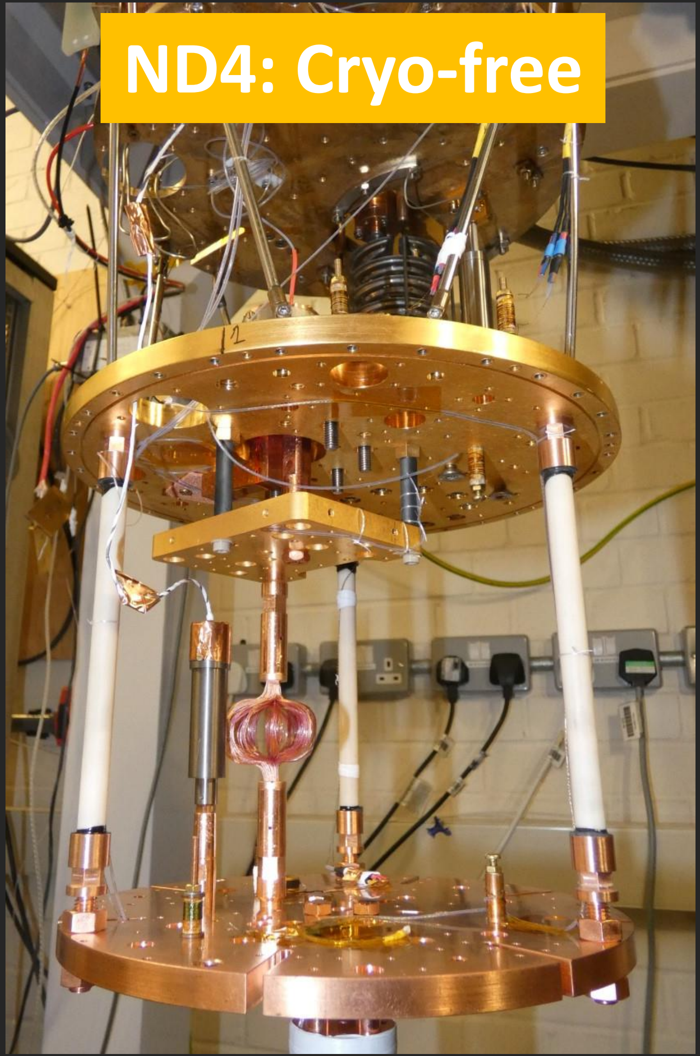
Nanofluidic platform for studying the first-order phase transitions in superfluid helium-3,

Petri J Heikkinen, Nathan Eng, Lev V Levitin, Xavier Rojas, Angadjit Singh, Samuli Autti, Richard P Haley, Mark Hindmarsh, Dmitry E Zmeev, Jeevak M Parpia, Andrew Casey, John Saunders,
arXiv:2401.06079 (2023)

A-B transition in superfluid ^{3}He and cosmological phase transitions,

Mark Hindmarsh, J.A. Sauls, Kuang Zhang, S.Autti, Richard P. Haley, Petri J. Heikkinen, Stephan J. Huber, Lev V. Levitin, Asier Lopez-Eiguren, Adam J. Mayer, Kari Rummukainen, John Saunders, Dmitry Zmeev,
arXiv:2401.07878 (2023)

Quantum sensors operated in ultralow temperatures regime, 100 μK

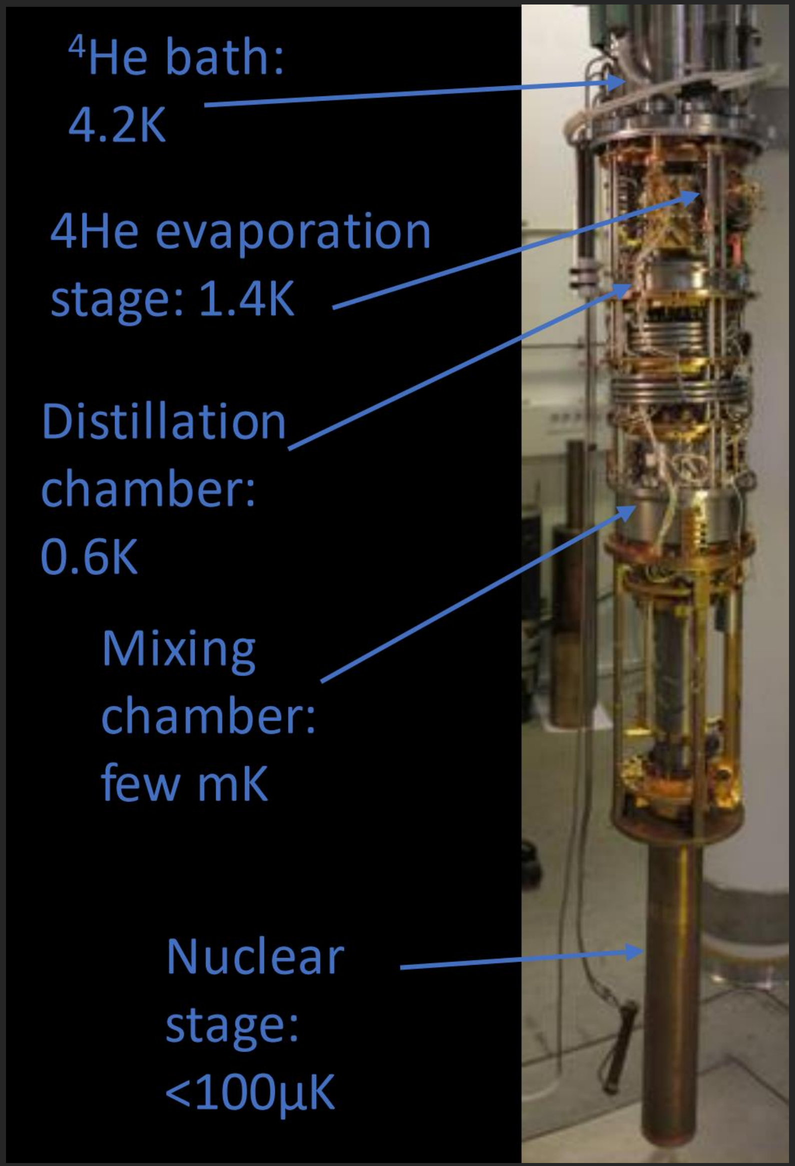


ROYAL
HOLLOWAY
UNIVERSITY
OF LONDON

Lucas, M., Danilov, A.V., Levitin, L.V. *et al.* Quantum bath suppression in a superconducting circuit by immersion cooling. *Nat Commun* **14**, 3522 (2023)

Quantum sensors operated in ultralow temperatures regime, 100 μK

Lancaster University



^{4}He bath: 4.2K

4He evaporation stage: 1.4K

Distillation chamber: 0.6K

Mixing chamber: few mK

Nuclear stage: <100μK

Nanofabrication Facilities

UK CSQS-Centre for Superconducting and Hybrid Quantum Systems, RHUL

Quantum Technology Centre, ULANC

Nanofabrication Facilities

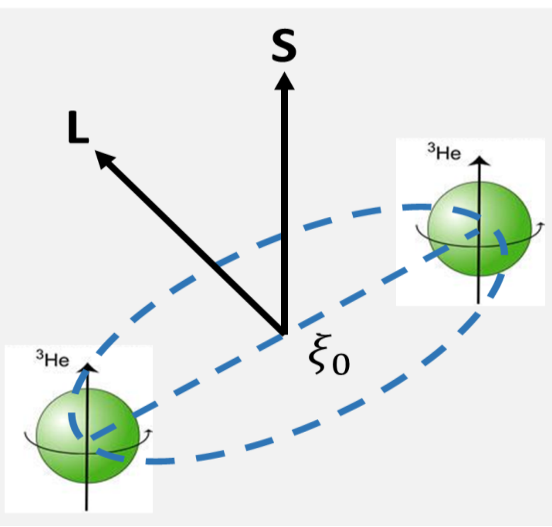
CNF
Cornell NanoScale
Science and Technology Facility

PTB
Physikalisch-Technische Bundesanstalt
Braunschweig und Berlin

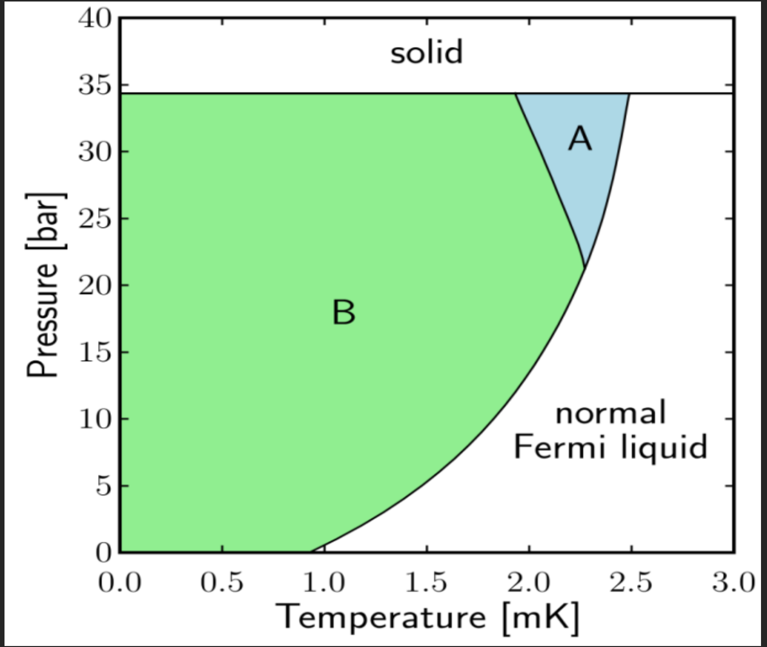
MICHIGAN ENGINEERING
LURIE NANOFABRICATION FACILITY

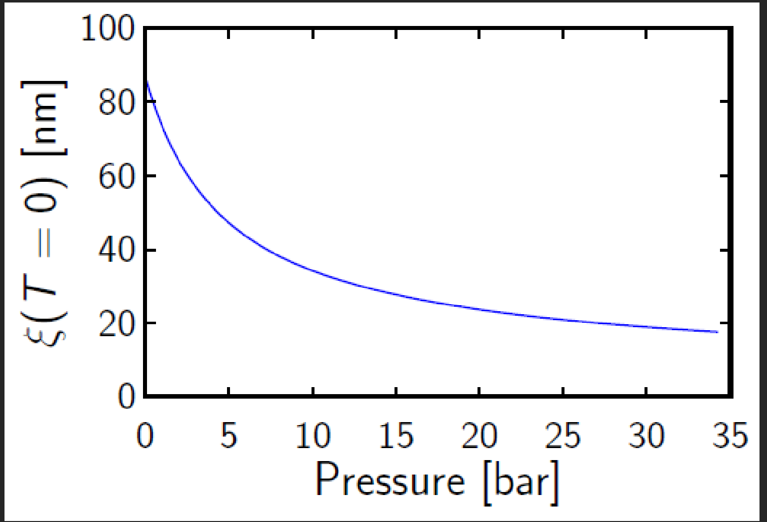
Superfluid Helium, ^{3}He

- Cooper pairs with $L = S = 1$

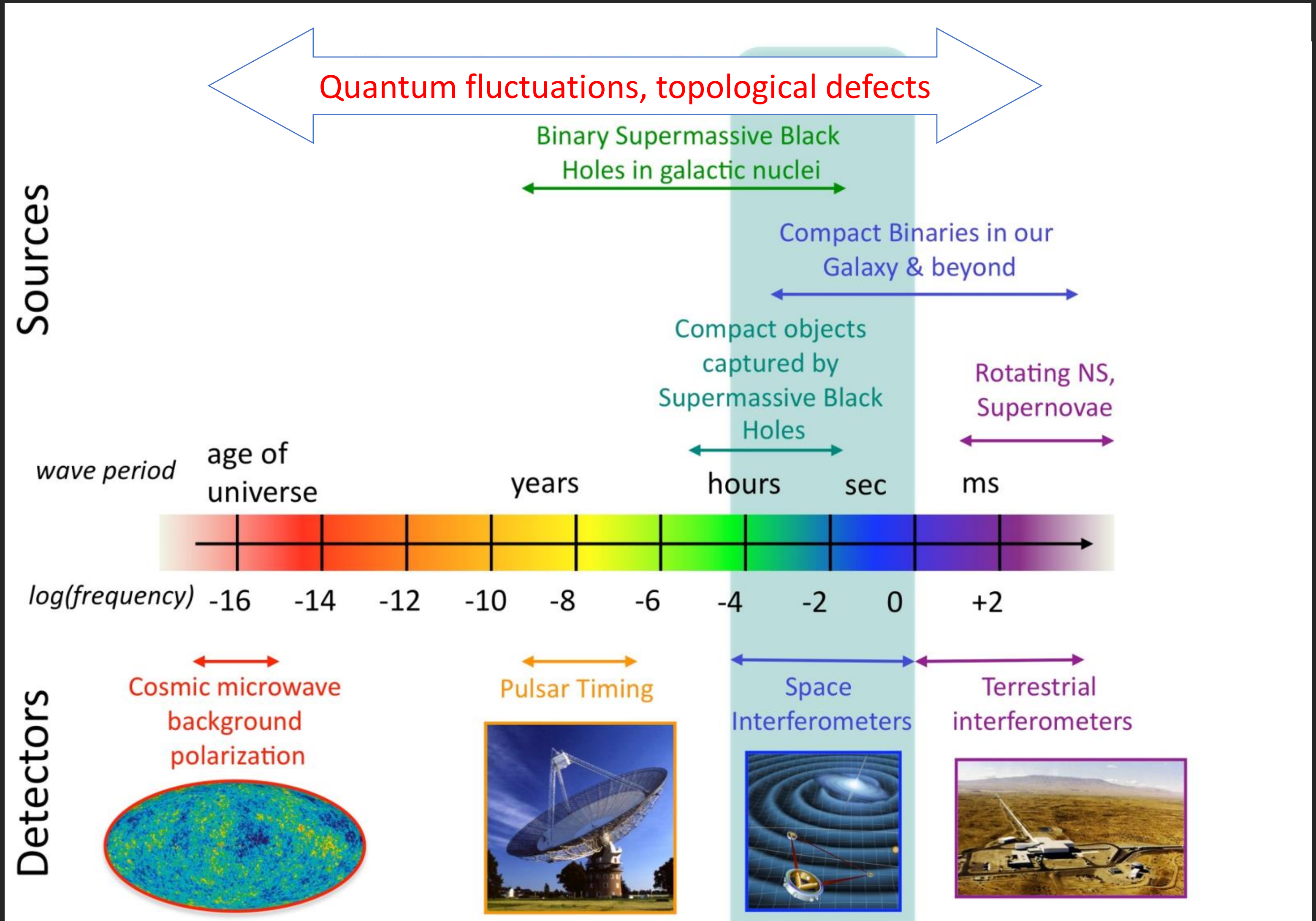


- 18-component order parameter
  - $L_z = -1, 0, 1$
  - $S_z = -1, 0, 1$
- Multiple superfluid phases
  - A-phase: Anderson-Brinkman-Morel
  - B-phase: Balian-Werthamer
- Broken Cooper pairs = thermal excitations with energy $\Delta \sim 10^{-7}$ eV

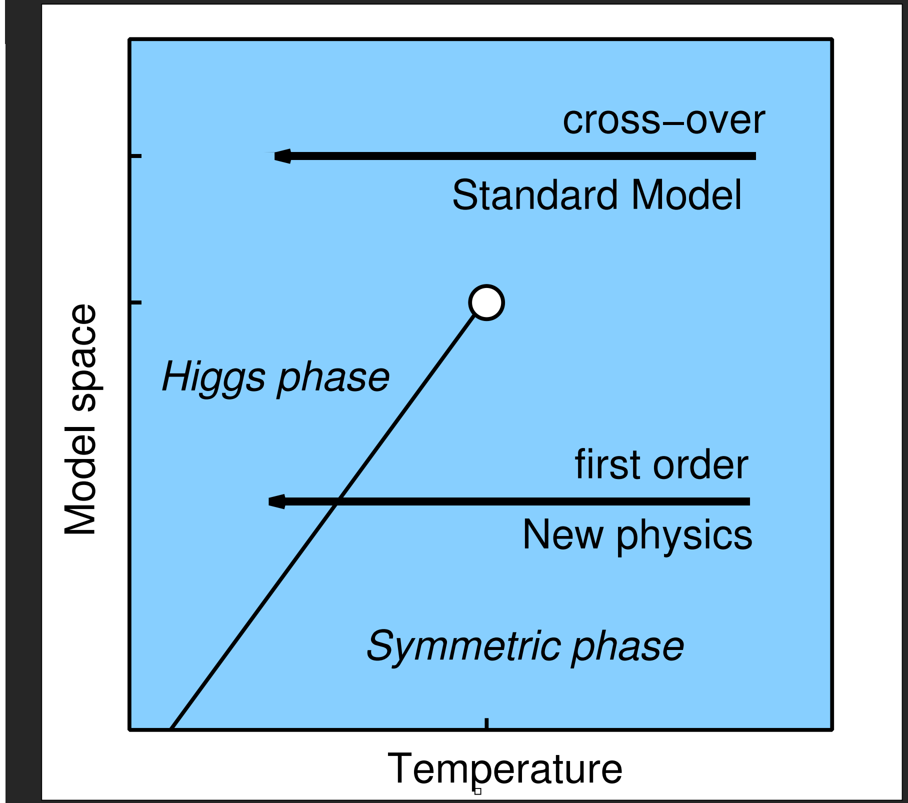


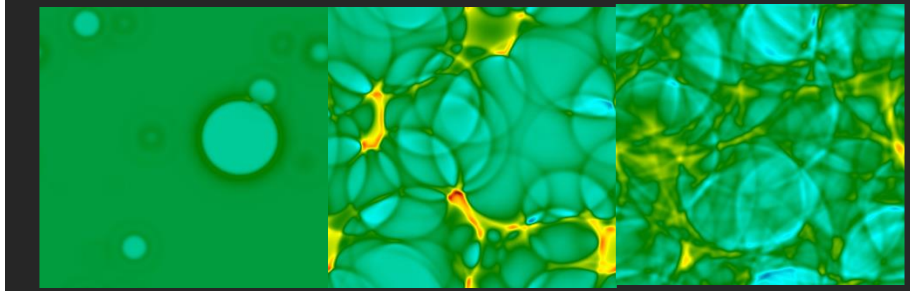


How did the early universe evolve?



Gravitational waves ESA mission LISA (2037)

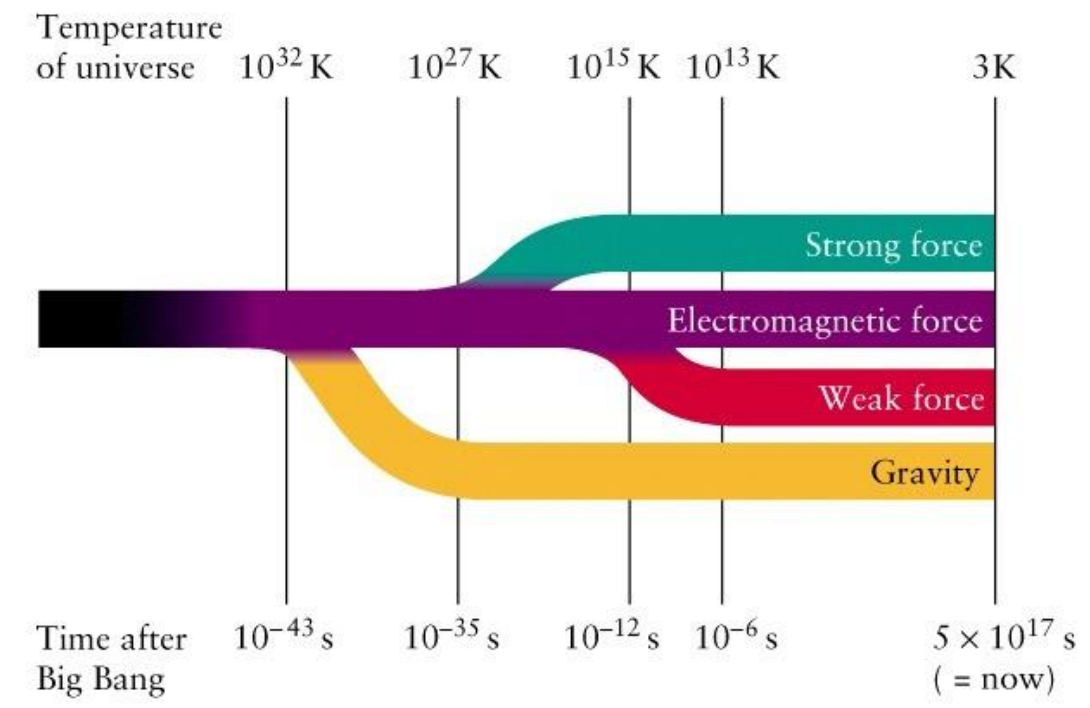


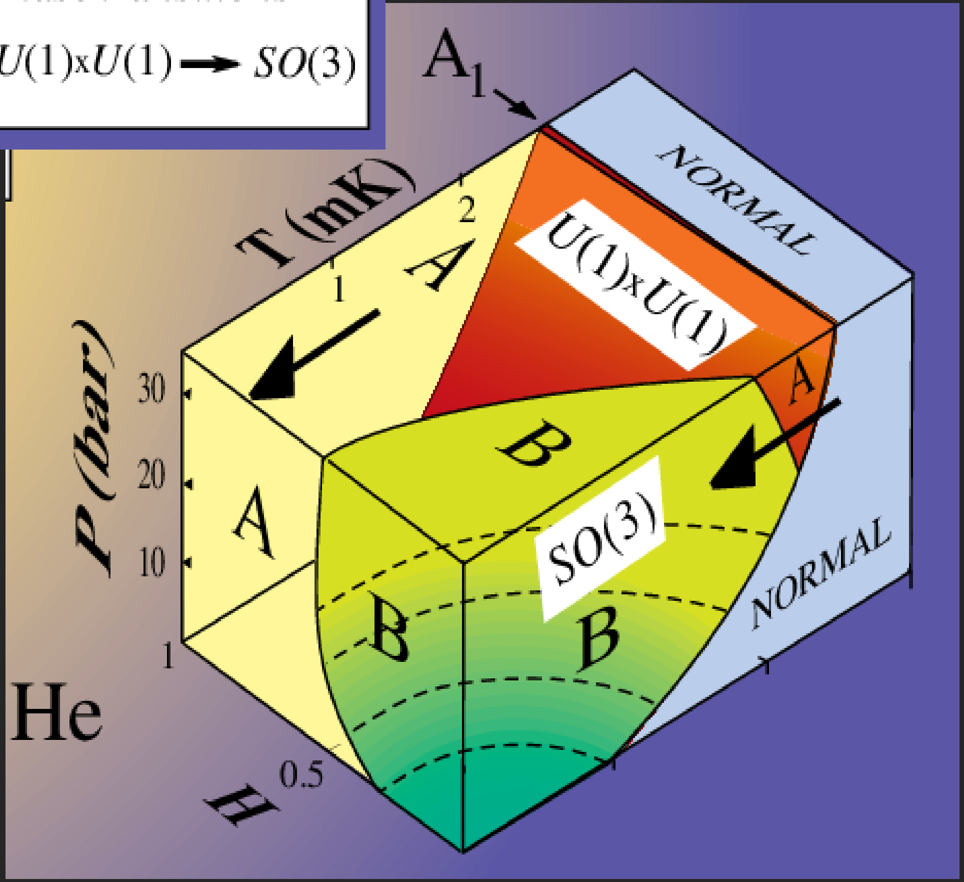


Phase transitions in extreme matter

GUT in Standard Model
symmetry breaking phase transitions
$SO(10) \rightarrow SU(3) \times SU(2) \times U(1) \rightarrow SU(3) \times U(1)$

GUT in superfluid ^{3}He
symmetry breaking phase transitions
$SO(3) \times SO(3) \times U(1) \rightarrow U(1) \times U(1) \rightarrow SO(3)$

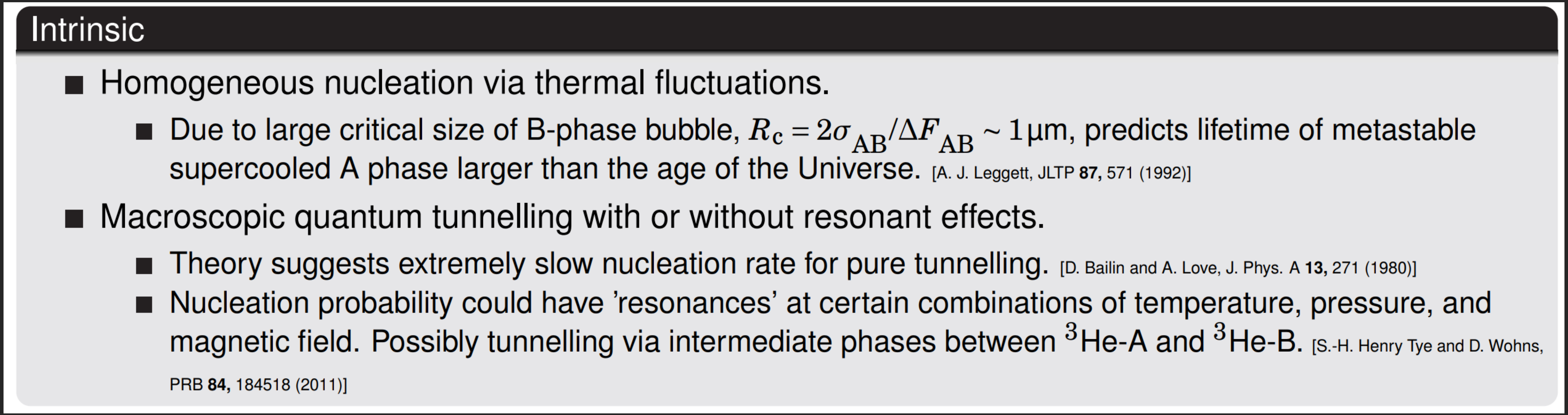




Precise control of Quantum analogue system, Superfluid ^{3}He & dynamics of phase transitions
open gravitational wave window to physics beyond the Standard Model in the early universe

Models for the AB phase transition

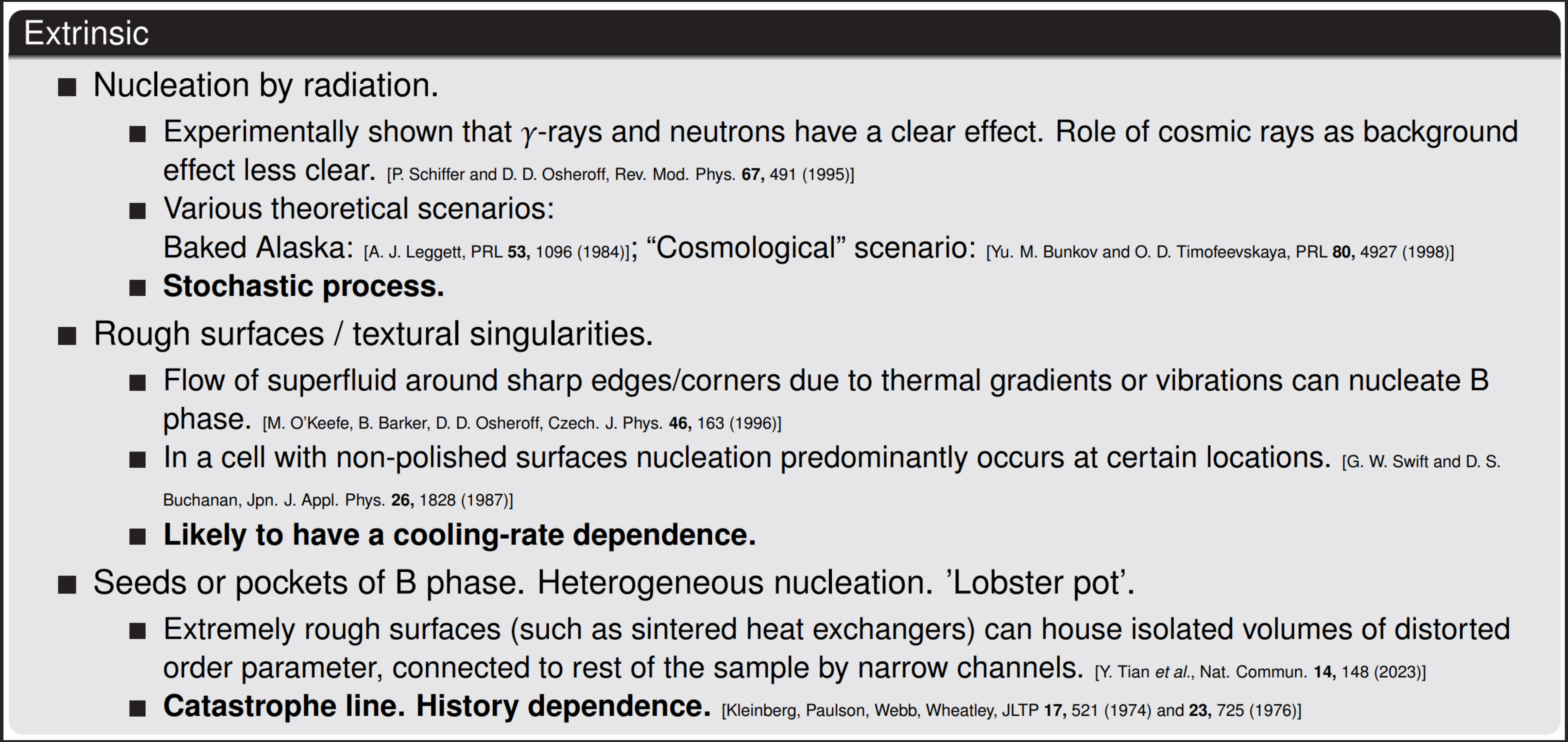
Intrinsic and extrinsic factors controlling nucleation



Intrinsic

- Homogeneous nucleation via thermal fluctuations.
  - Due to large critical size of B-phase bubble, $R_\mathrm{c} = 2\sigma_{\mathrm{AB}}/\Delta F_{\mathrm{AB}} \sim 1\,\mu\mathrm{m}$, predicts lifetime of metastable supercooled A phase larger than the age of the Universe. [A. J. Leggett, JLTP **87,** 571 (1992)]
- Macroscopic quantum tunnelling with or without resonant effects.
  - Theory suggests extremely slow nucleation rate for pure tunnelling. [D. Bailin and A. Love, J. Phys. A **13,** 271 (1980)]
  - Nucleation probability could have 'resonances' at certain combinations of temperature, pressure, and magnetic field. Possibly tunnelling via intermediate phases between ^{3}He-A and ^{3}He-B. [S.-H. Henry Tye and D. Wohns, PRB **84,** 184518 (2011)]

Models for the AB phase transition



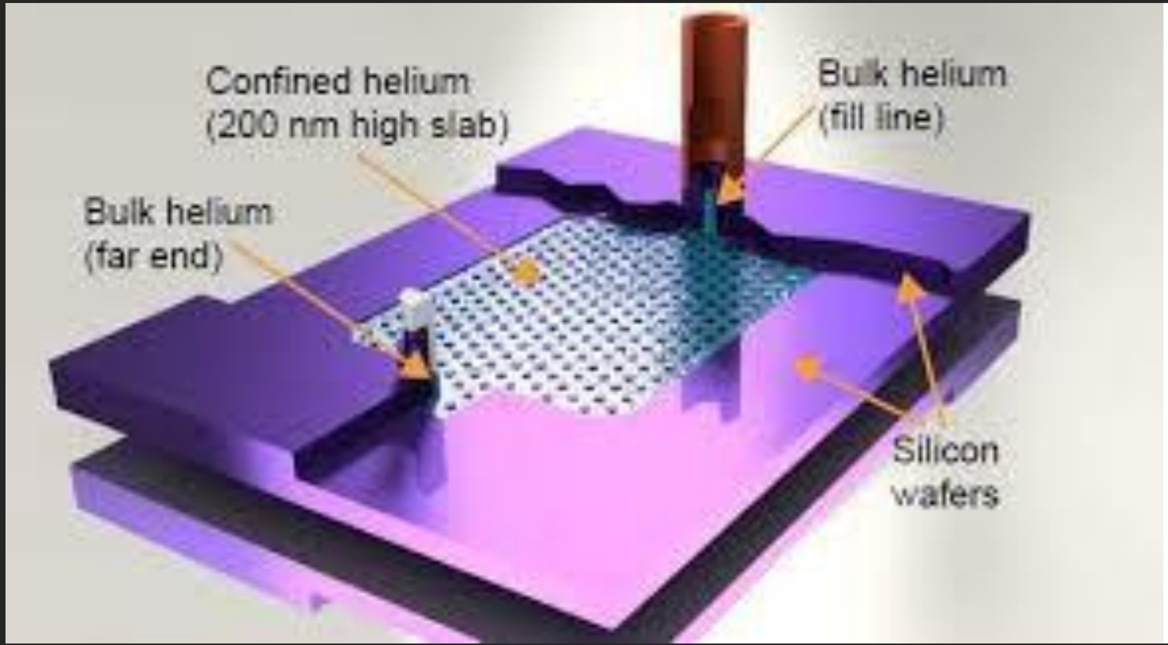
Extrinsic

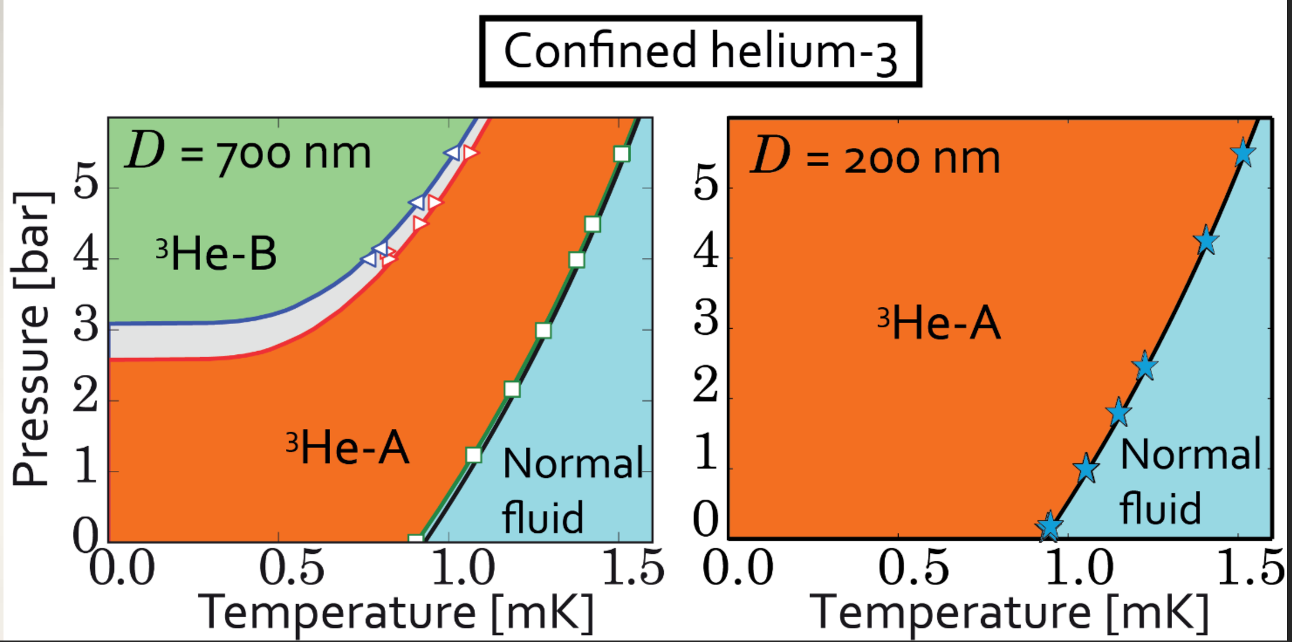
- Nucleation by radiation.
  - Experimentally shown that γ-rays and neutrons have a clear effect. Role of cosmic rays as background effect less clear. [P. Schiffer and D. D. Osheroff, Rev. Mod. Phys. **67,** 491 (1995)]
  - Various theoretical scenarios:
    Baked Alaska: [A. J. Leggett, PRL **53,** 1096 (1984)]; "Cosmological" scenario: [Yu. M. Bunkov and O. D. Timofeevskaya, PRL **80,** 4927 (1998)]
  - **Stochastic process.**
- Rough surfaces / textural singularities.
  - Flow of superfluid around sharp edges/corners due to thermal gradients or vibrations can nucleate B phase. [M. O'Keefe, B. Barker, D. D. Osheroff, Czech. J. Phys. **46,** 163 (1996)]
  - In a cell with non-polished surfaces nucleation predominantly occurs at certain locations. [G. W. Swift and D. S. Buchanan, Jpn. J. Appl. Phys. **26,** 1828 (1987)]
  - **Likely to have a cooling-rate dependence.**
- Seeds or pockets of B phase. Heterogeneous nucleation. 'Lobster pot'.
  - Extremely rough surfaces (such as sintered heat exchangers) can house isolated volumes of distorted order parameter, connected to rest of the sample by narrow channels. [Y. Tian *et al.*, Nat. Commun. **14,** 148 (2023)]
  - **Catastrophe line. History dependence.** [Kleinberg, Paulson, Webb, Wheatley, JLTP **17,** 521 (1974) and **23,** 725 (1976)]

Engineer phase landscape through confinement

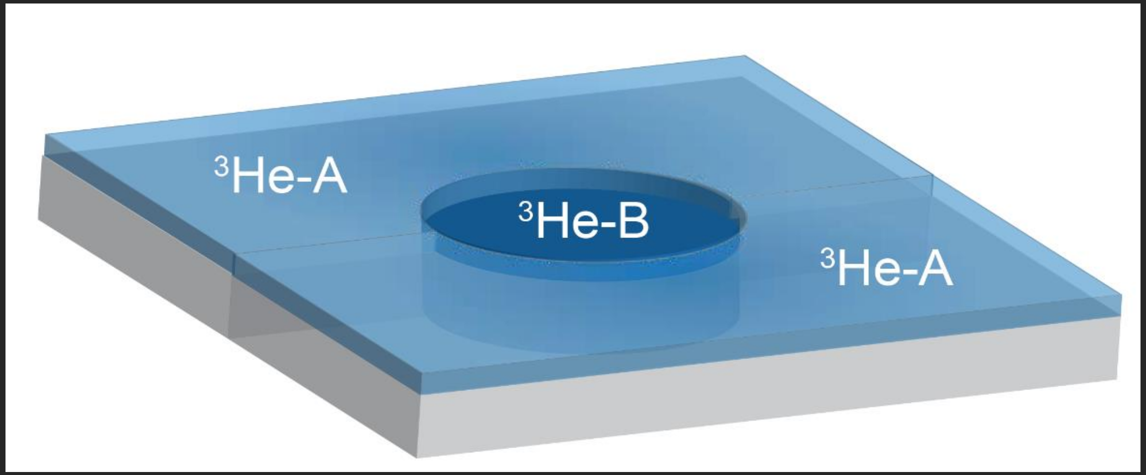
- Engineer phase transitions between superfluid ^{3}He phases of distinct symmetry.
- Control the free energy landscape with tuning parameters. (Temperature, pressure, surface specularity, magnetic field)

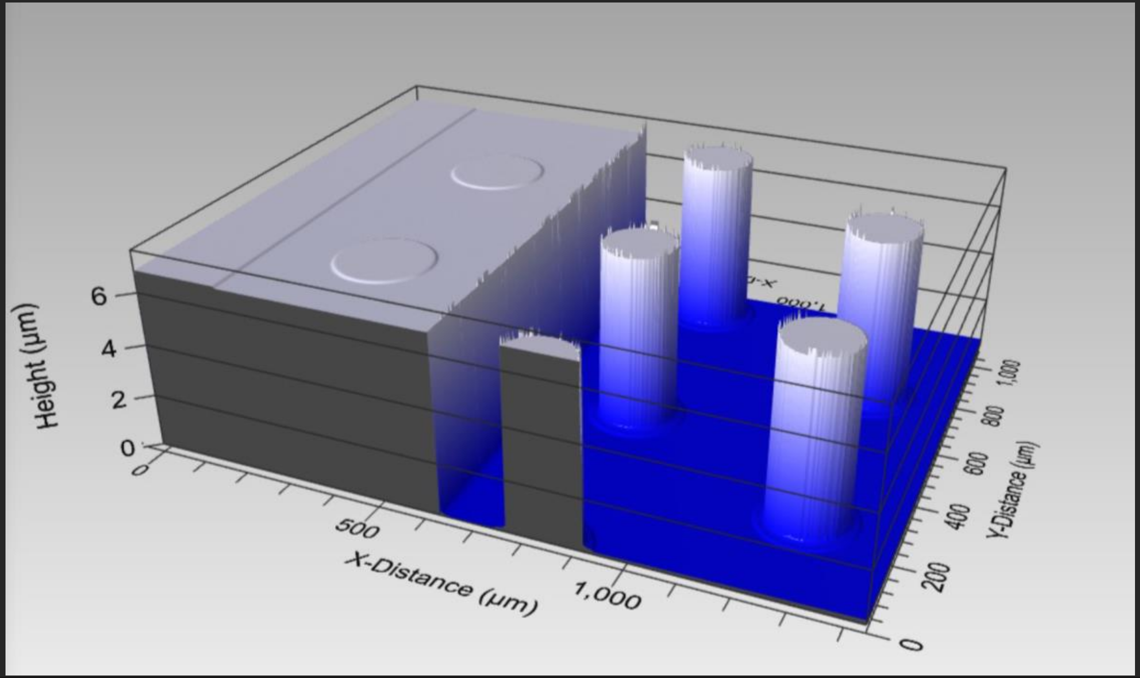
Levitin LV, Bennett RG, Casey A, Cowan B, Saunders J, Drung D, Schurig T, Parpia JM. *Phase diagram of the topological superfluid ^{3}He confined in a nanoscale slab geometry.* Science. **340**, 6134,841-444 (2013). doi:10.1126/science.1233621

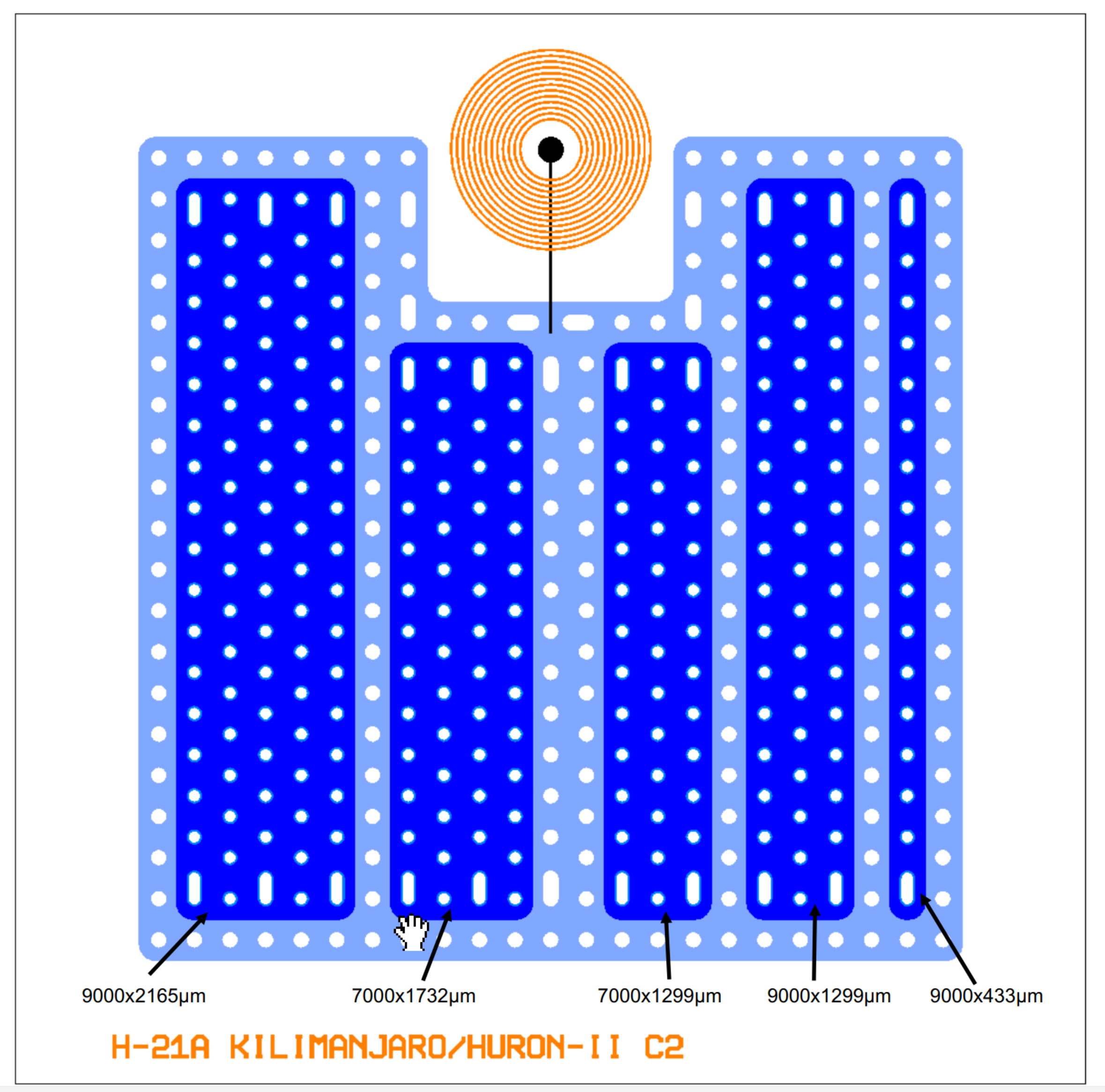




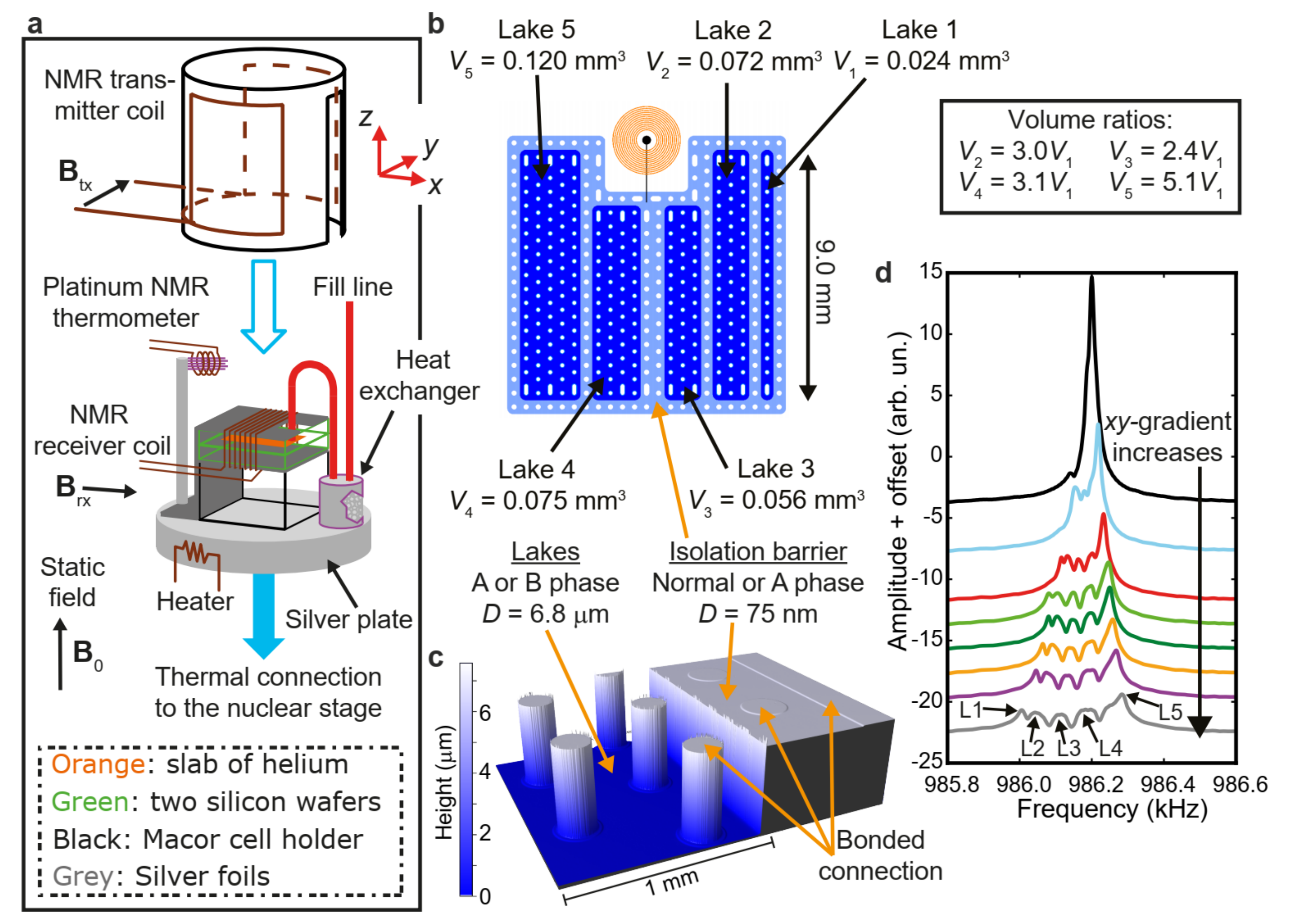
Engineer phase landscape through confinement



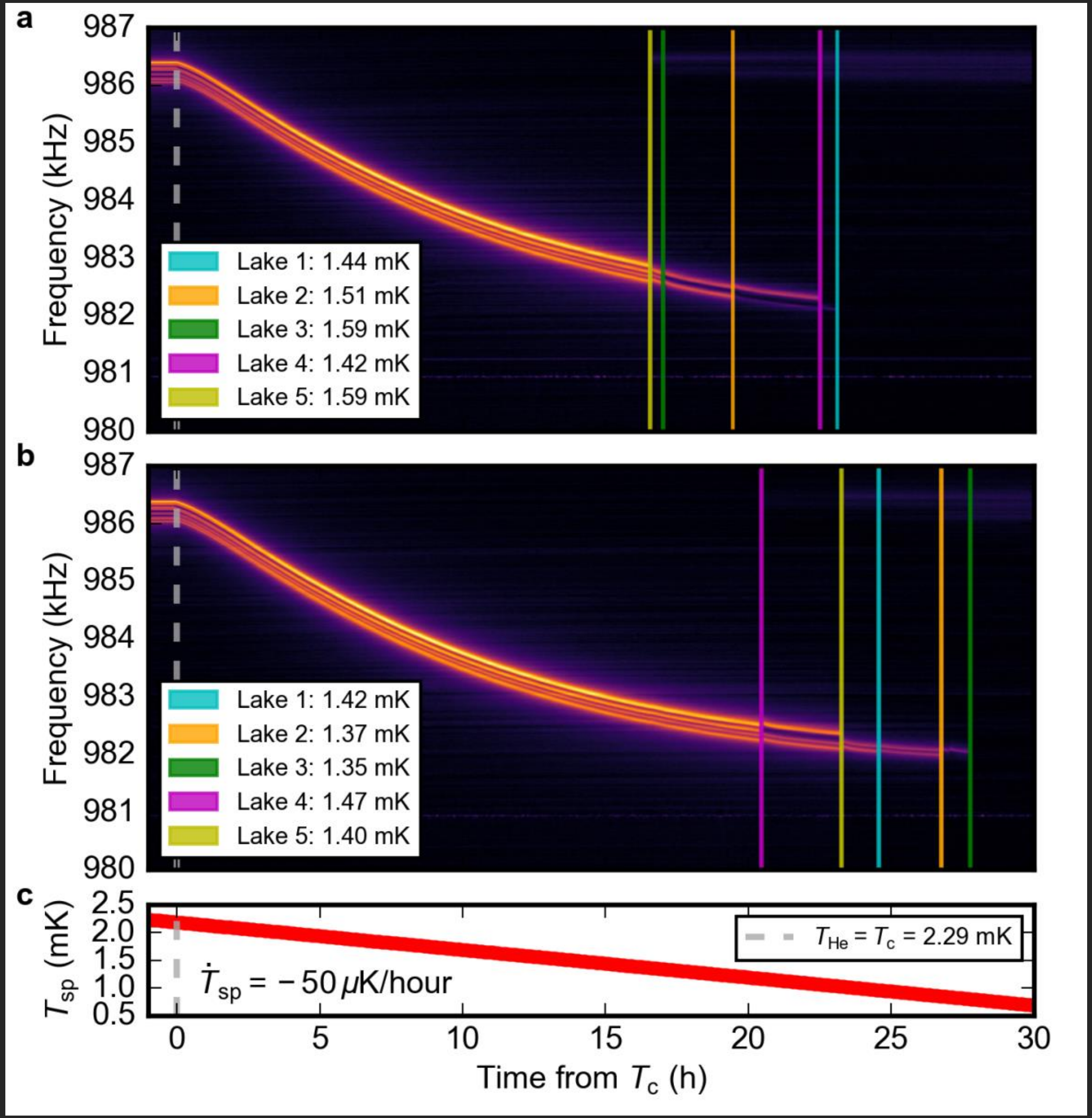


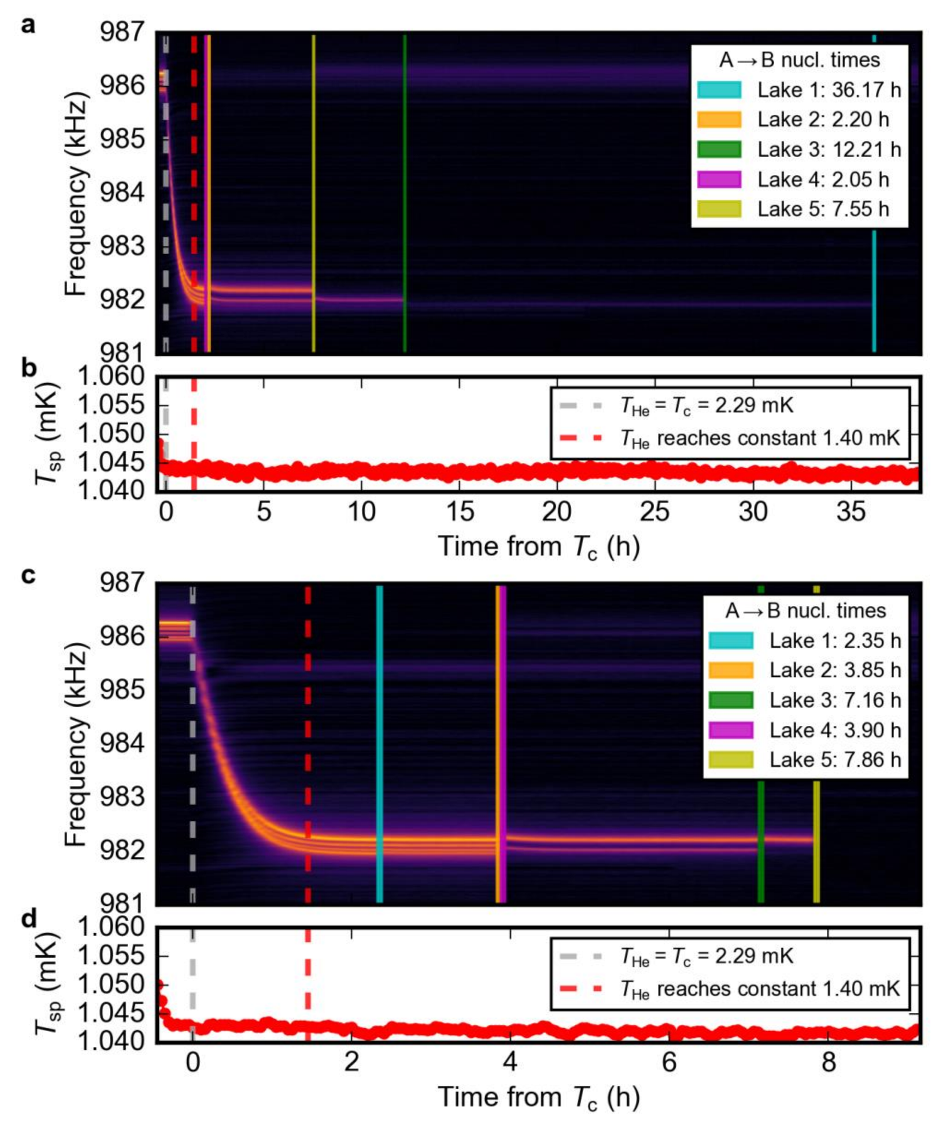


Nanofluidic sample containers and SQUID NMR

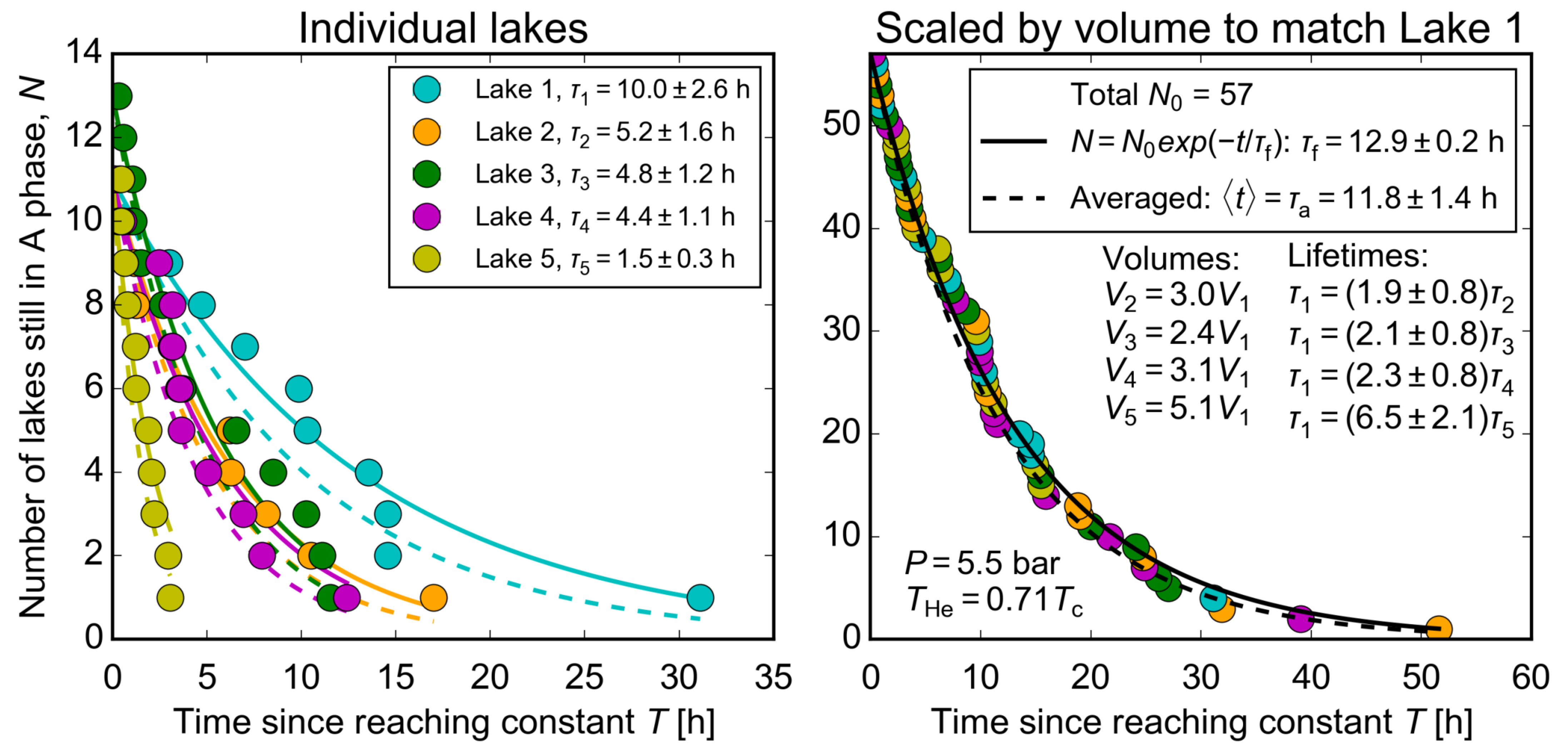


Observations of AB transition from supercooled A phase

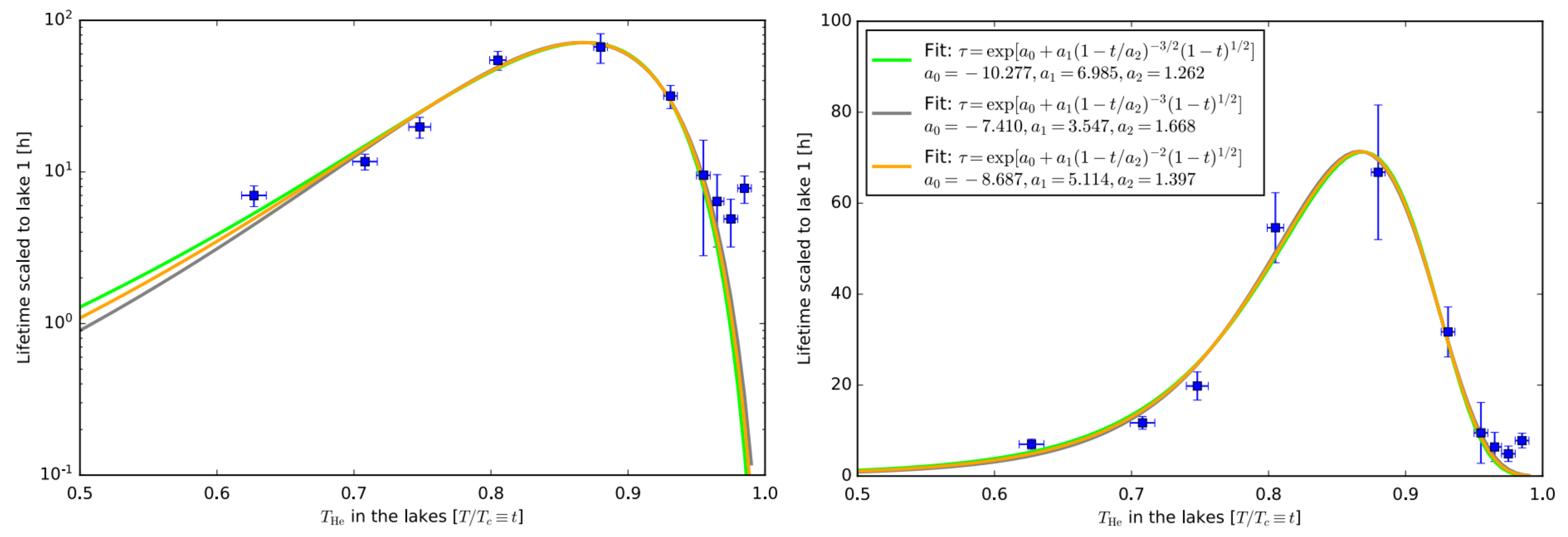




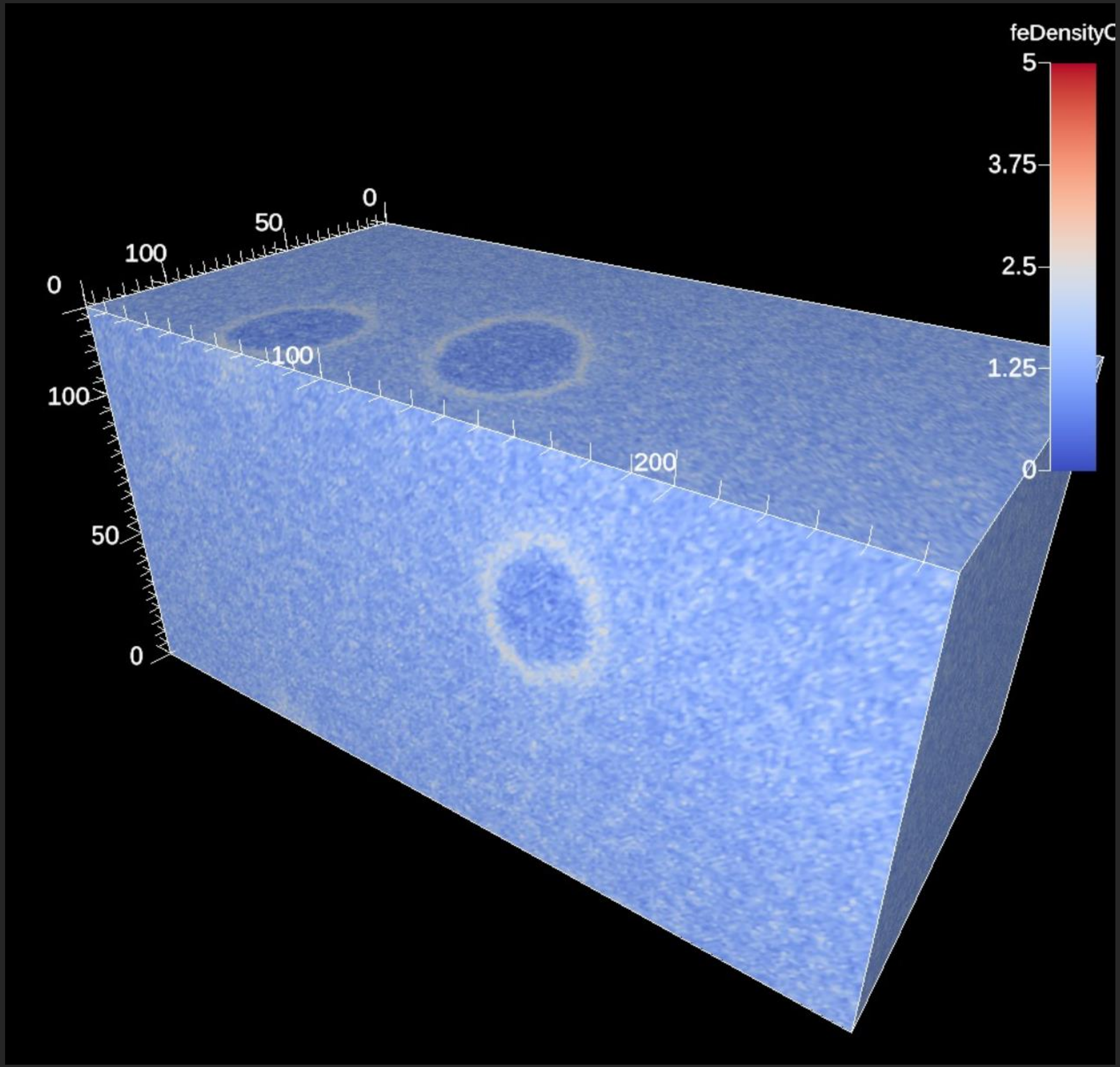
Collection of statistics: lifetime scales with volume



Temperature dependence of the lifetime at 5.5 bar



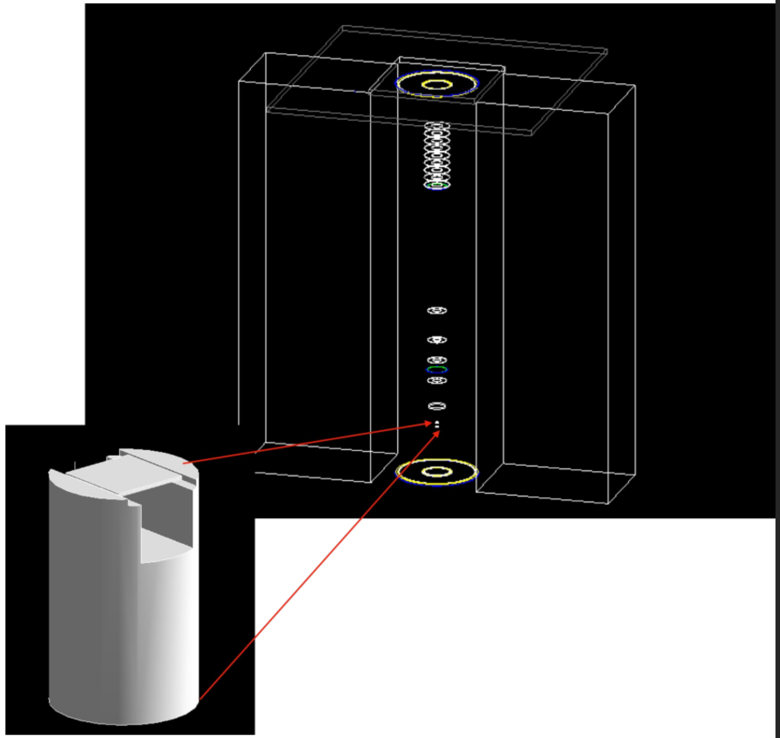
“Cosmological” simulations of 3He

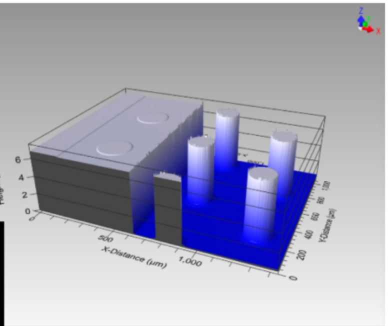


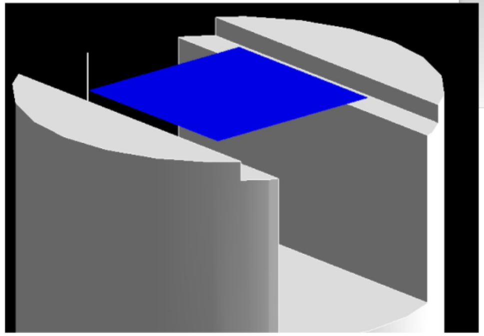
Geant4 modelling of ND2

ND2 in Geant4

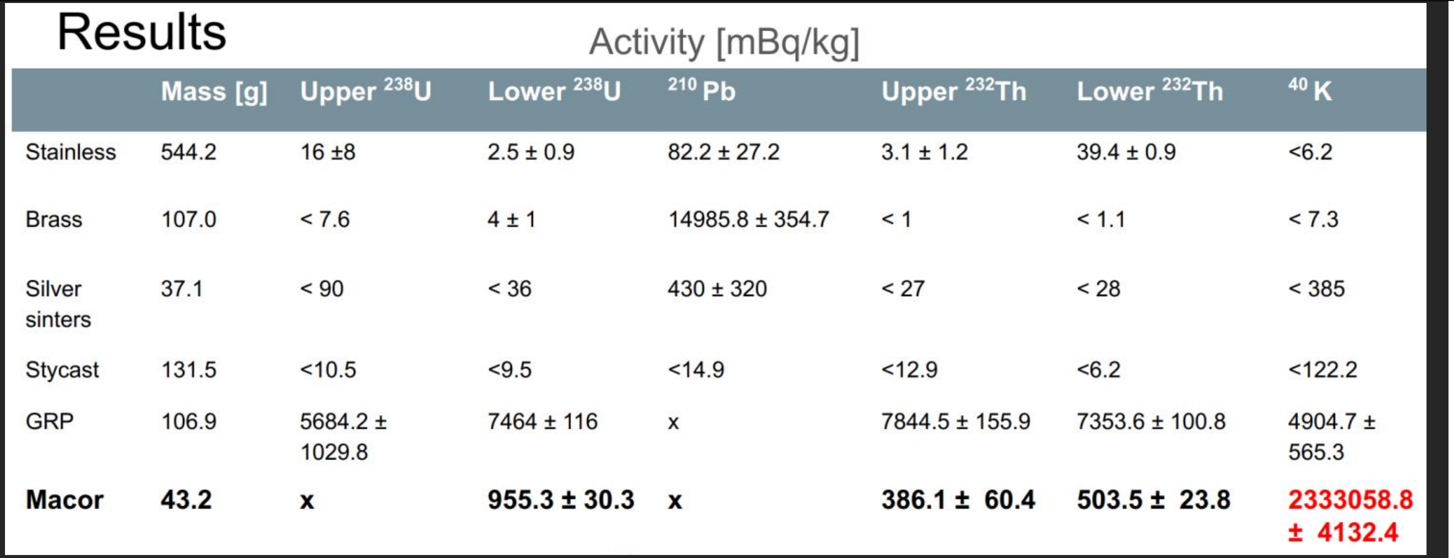
- Modelled as 42 separate active volumes
- Github repo for ND2: https://github.com/QUEST-DMC/QUEST-ND2-Simulation.git (feel free to use/ask for help getting set up)
- One singular volume of helium 3 10mmx10mmx0.007mm







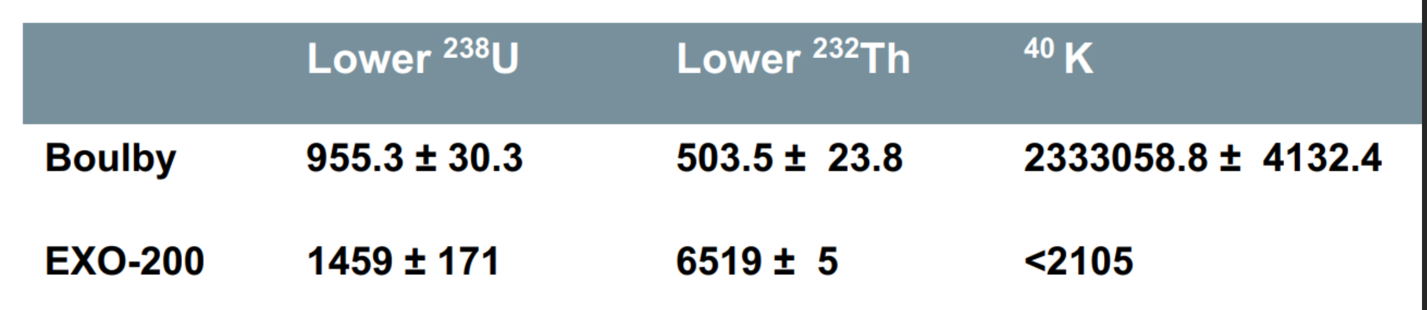
Boulby Radioassays



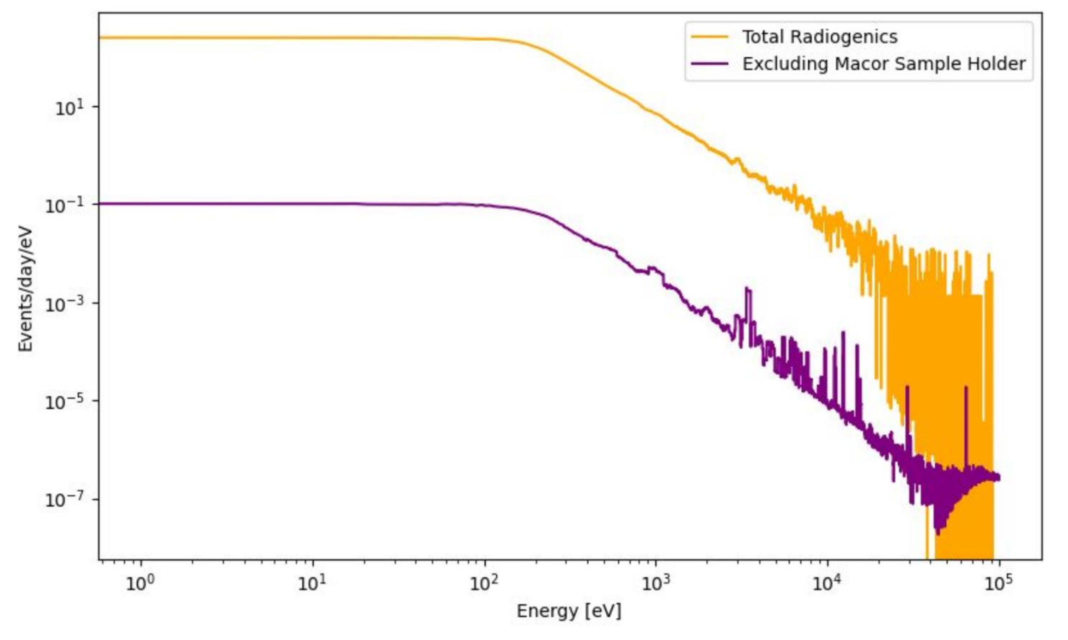
Results

Activity [mBq/kg]

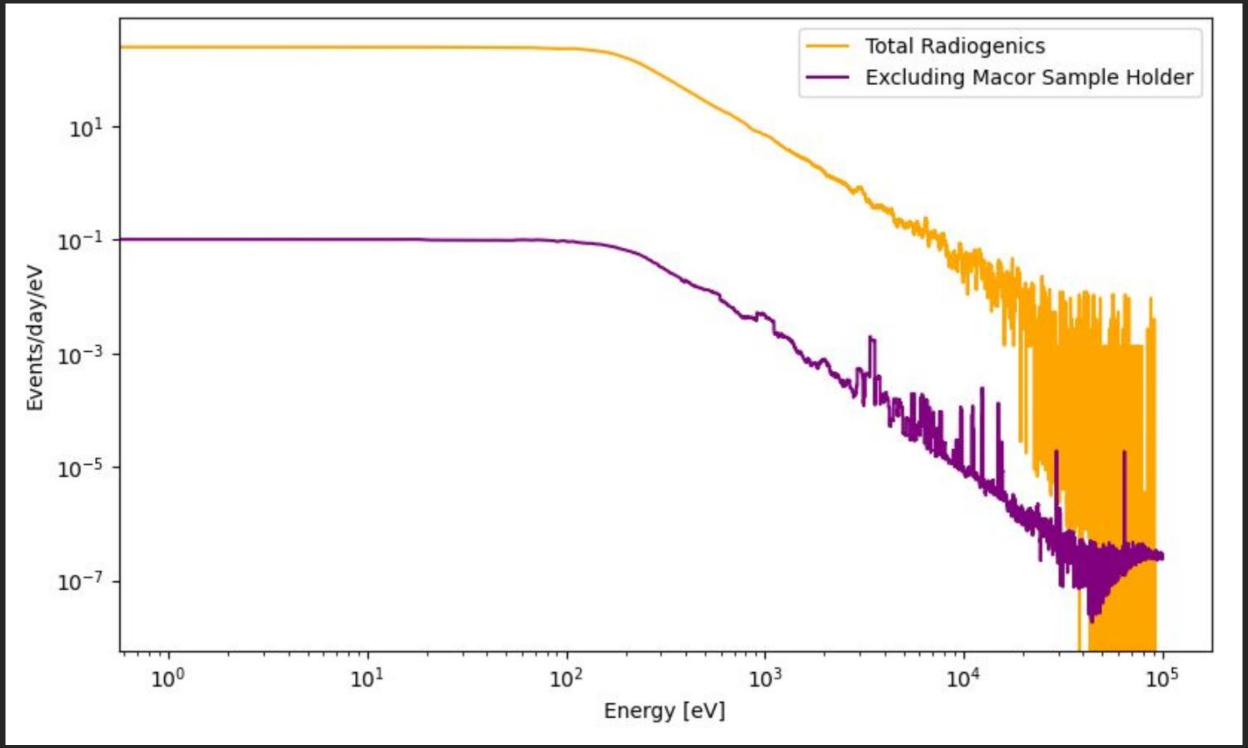
	Mass [g]	Upper ^{238}U	Lower ^{238}U	^{210}Pb	Upper ^{232}Th	Lower ^{232}Th	^{40}K
Stainless	544.2	16 ±8	2.5 ± 0.9	82.2 ± 27.2	3.1 ± 1.2	39.4 ± 0.9	<6.2
Brass	107.0	< 7.6	4 ± 1	14985.8 ± 354.7	< 1	< 1.1	< 7.3
Silver sinters	37.1	< 90	< 36	430 ± 320	< 27	< 28	< 385
Stycast	131.5	<10.5	<9.5	<14.9	<12.9	<6.2	<122.2
GRP	106.9	5684.2 ± 1029.8	7464 ± 116	x	7844.5 ± 155.9	7353.6 ± 100.8	4904.7 ± 565.3
Macor	**43.2**	**x**	**955.3 ± 30.3**	**x**	**386.1 ± 60.4**	**503.5 ± 23.8**	**2333058.8 ± 4132.4**

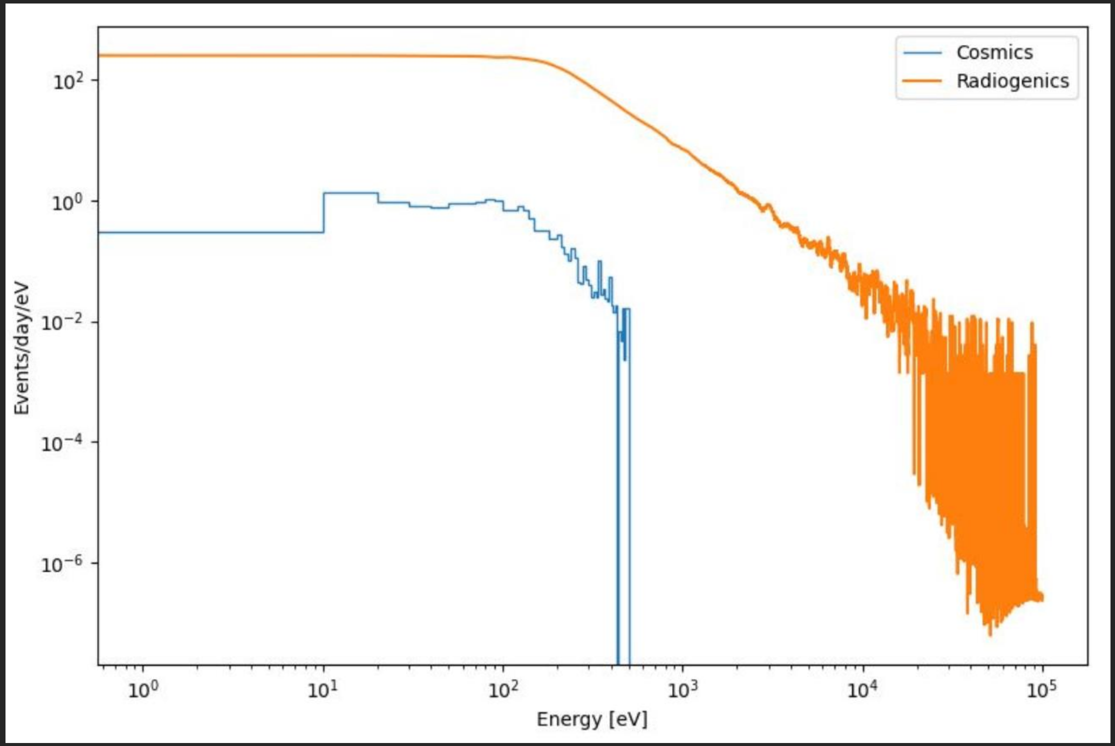


	Lower ^{238}U	Lower ^{232}Th	^{40}K
Boulby	**955.3 ± 30.3**	**503.5 ± 23.8**	**2333058.8 ± 4132.4**
EXO-200	**1459 ± 171**	**6519 ± 5**	**<2105**

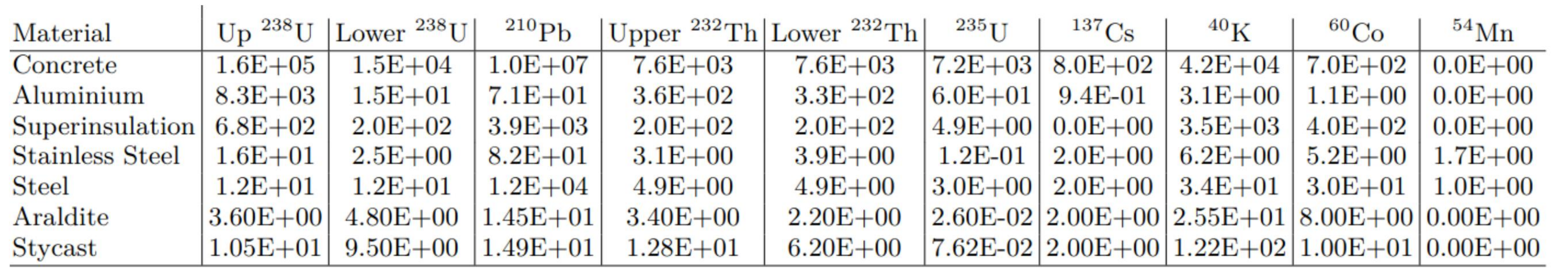


Boulby Radioassays

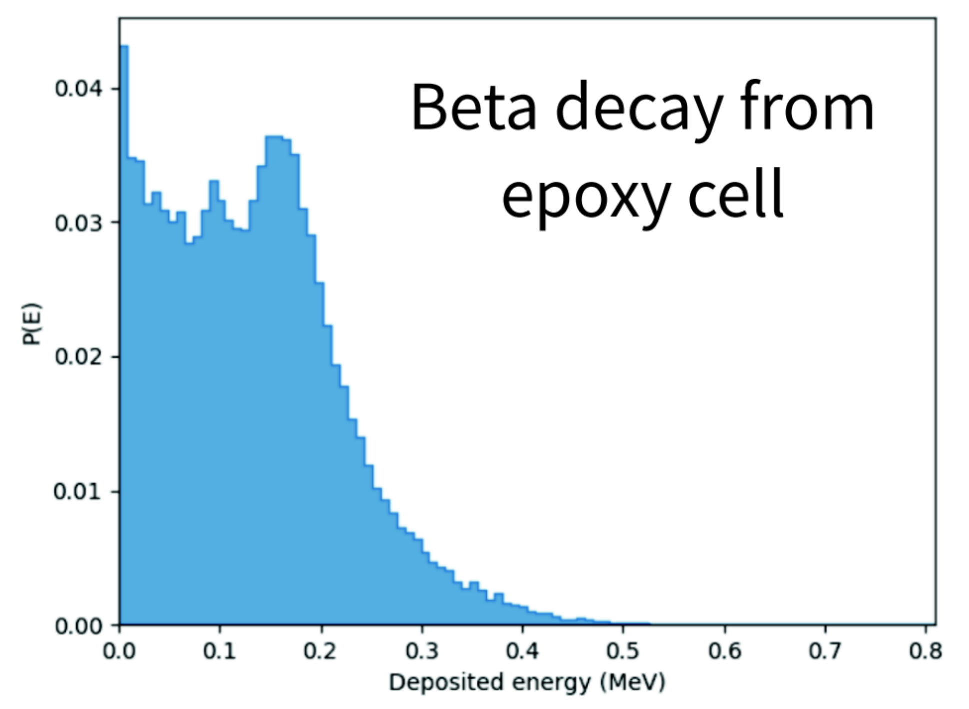




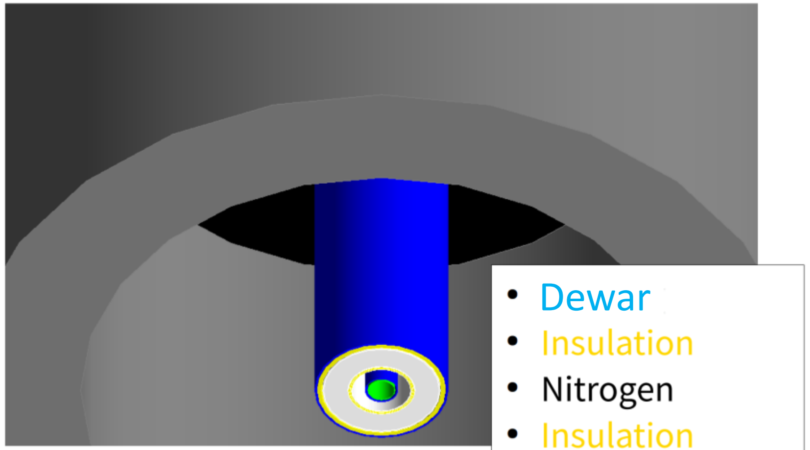
Simulation of decays, radiopurity screening (Boulby, database)



Material	Up ^{238}U	Lower ^{238}U	^{210}Pb	Upper ^{232}Th	Lower ^{232}Th	^{235}U	^{137}Cs	^{40}K	^{60}Co	^{54}Mn
Concrete	1.6E+05	1.5E+04	1.0E+07	7.6E+03	7.6E+03	7.2E+03	8.0E+02	4.2E+04	7.0E+02	0.0E+00
Aluminium	8.3E+03	1.5E+01	7.1E+01	3.6E+02	3.3E+02	6.0E+01	9.4E-01	3.1E+00	1.1E+00	0.0E+00
Superinsulation	6.8E+02	2.0E+02	3.9E+03	2.0E+02	2.0E+02	4.9E+00	0.0E+00	3.5E+03	4.0E+02	0.0E+00
Stainless Steel	1.6E+01	2.5E+00	8.2E+01	3.1E+00	3.9E+00	1.2E-01	2.0E+00	6.2E+00	5.2E+00	1.7E+00
Steel	1.2E+01	1.2E+01	1.2E+04	4.9E+00	4.9E+00	3.0E+00	2.0E+00	3.4E+01	3.0E+01	1.0E+00
Araldite	3.60E+00	4.80E+00	1.45E+01	3.40E+00	2.20E+00	2.60E-02	2.00E+00	2.55E+01	8.00E+00	0.00E+00
Stycast	1.05E+01	9.50E+00	1.49E+01	1.28E+01	6.20E+00	7.62E-02	2.00E+00	1.22E+02	1.00E+01	0.00E+00

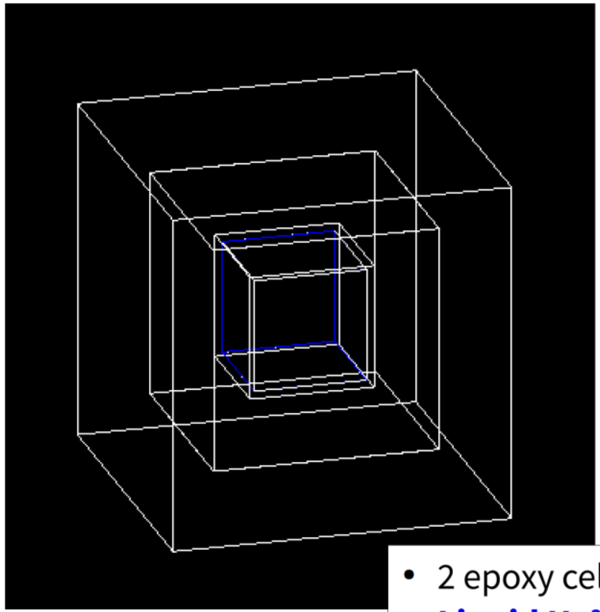


- Geant4 simulation



- Dewar
- Insulation
- Nitrogen
- Insulation
- Liquid He^4
- Vacuum can
- Radiation shield

Paolo Franchini



- 2 epoxy cells
- **Liquid He^3 cm^3**

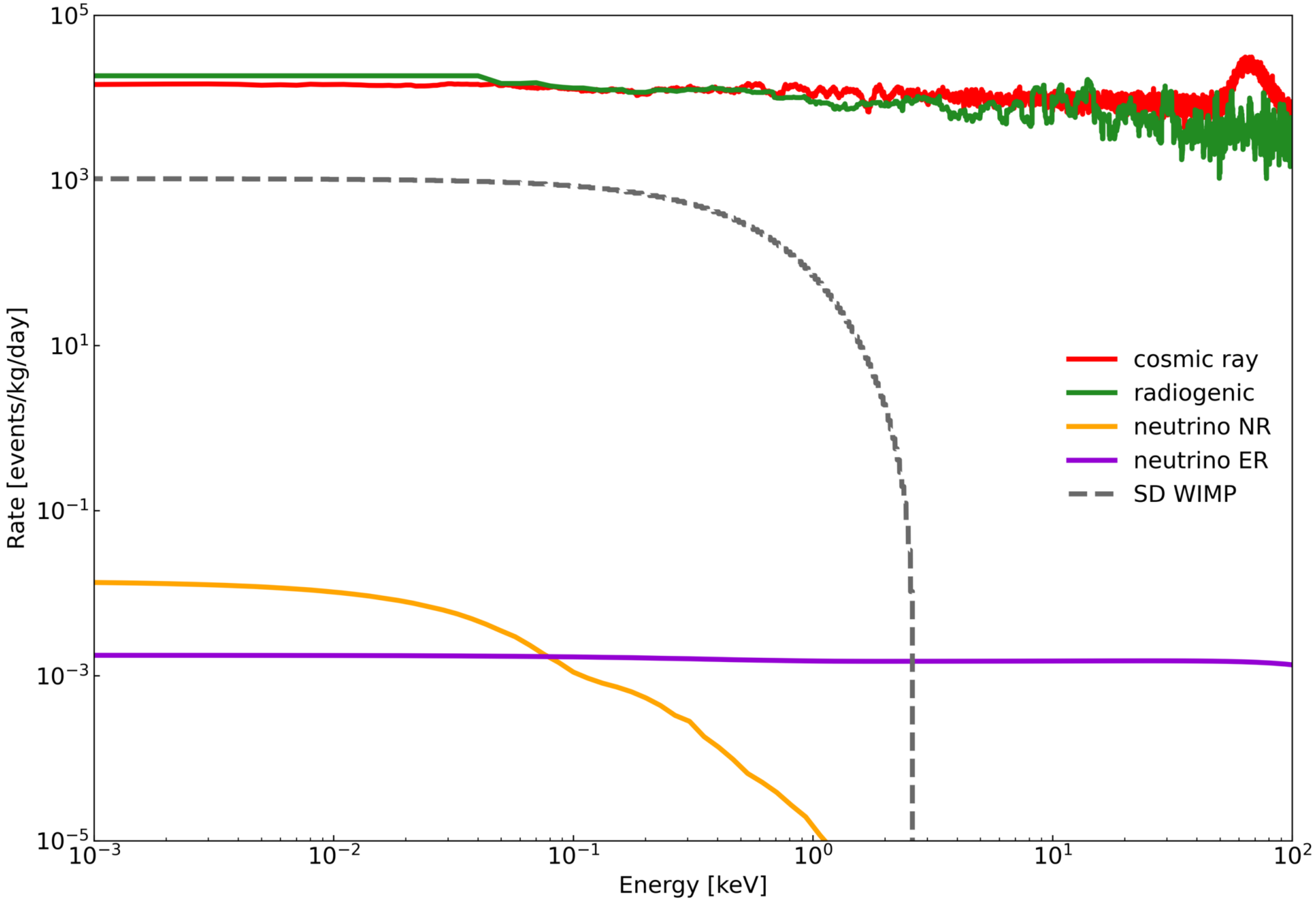
Dark Matter search ULANC cryostat modelling

Background	Events/cell/day [all energies]
Cosmic rays	162.4
Radiogenic	32.8
PP neutrino	0.01
CN neutrino	0.0003

Cosmic ray detector around the target (90% veto efficiency).

Even better – go underground!

UKRI preliminary infrastructure bid

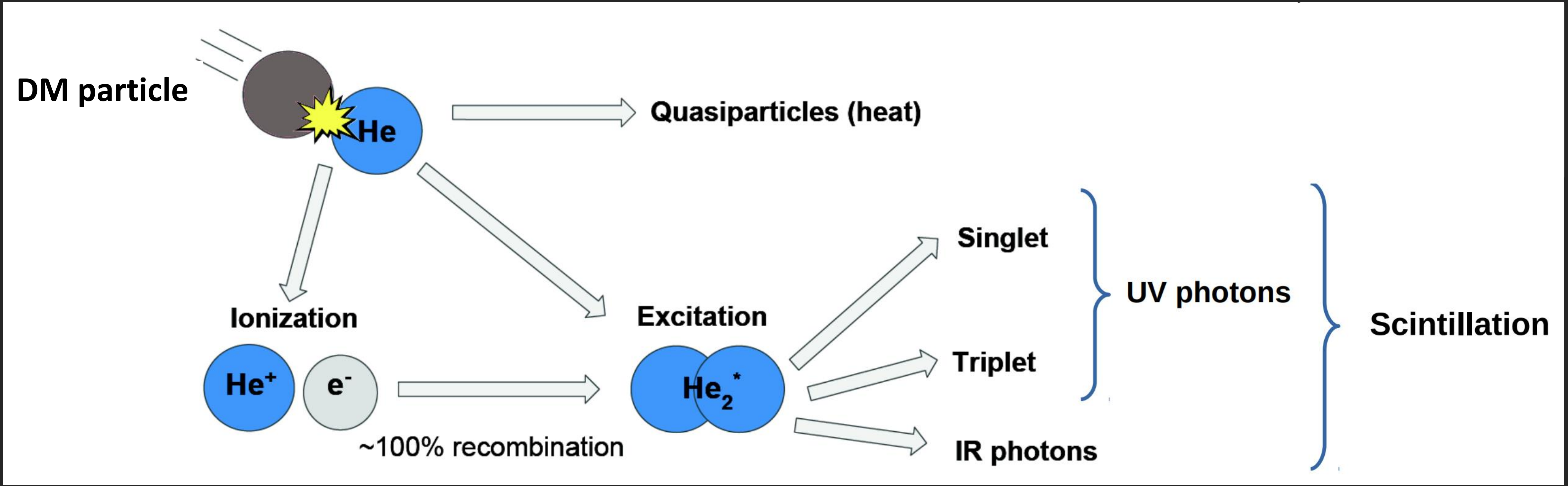


Superfluid ^{3}He as a Dark Matter target

Collision WIMP - ^{3}He atom (mass 3 versus argon - 39.948, xenon -131.293)

– Heat as quasiparticle excitations

– Light from de-excitation, threshold for ionization is ~ 20 eV



ULTIMA: D.I. Bradley, et al., Nucl. Instrum. Methods A 370, 141 (1996); C.B. Winkelmann, et al., Nucl. Instrum. Methods A 559, 384 (2006); C.B. Winkelmann, et al., Nucl. Instrum. Methods A 574, 264 (2007).

^{4}He target HeRald: S. A. Hertel, A. Biekert, J. Lin, V. Velan, and D. N. McKinsey Phys. Rev. D **100**, 092007 (2019)

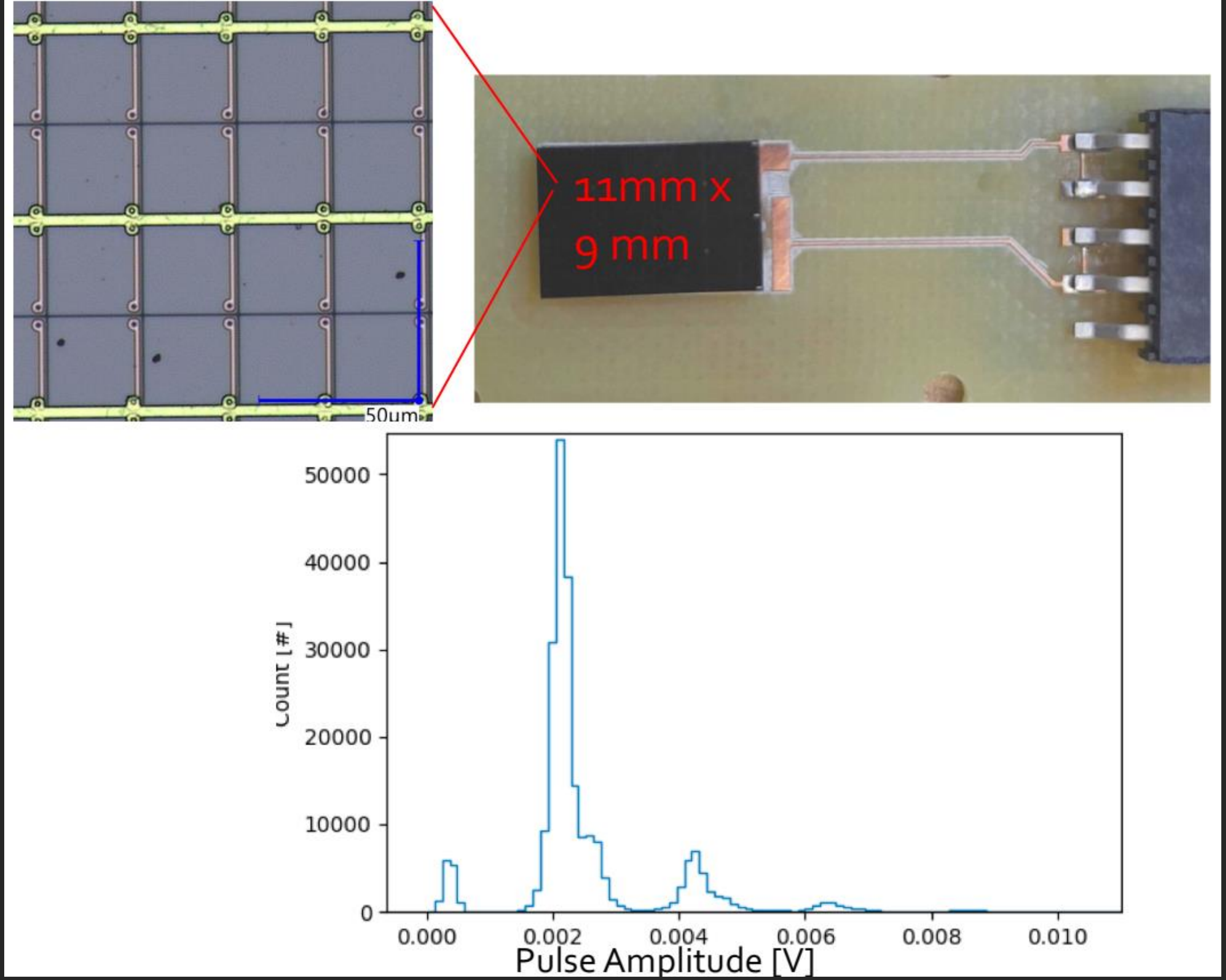
Ionisation energy channel

Test of SiPMs at 4K

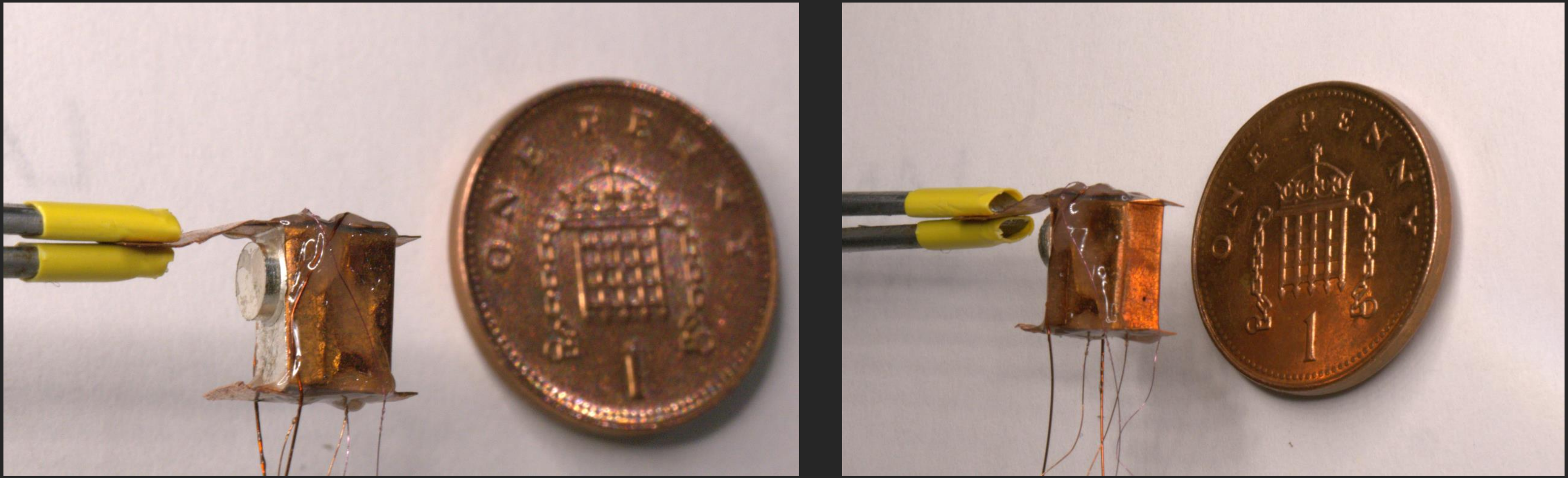
- Superconducting devices:
- TES, Nanowires, mKIDs

- SiPMs (developed for Darkside) normally operated at LN2 consists of matrix of single photon avalanche diodes. High gain and single photo-electron resolution.

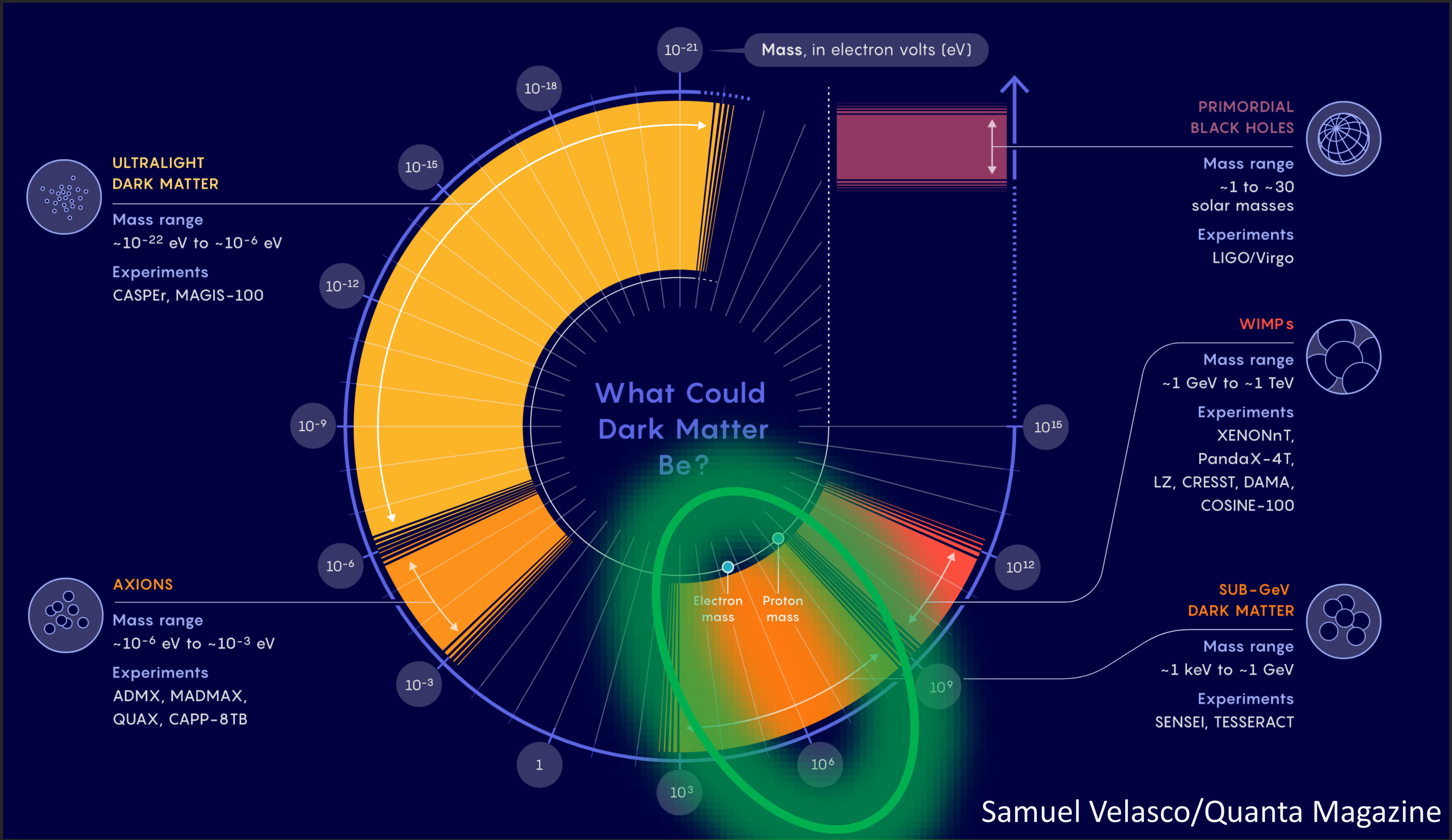
- In the first instance use as Veto rather than measure energy partition fraction.



Bolometer for quasiparticle detection



What mass range are we searching for?



ULTRALIGHT DARK MATTER

Mass range
~10^{-22} eV to ~10^{-6} eV

Experiments
CASPEr, MAGIS-100

AXIONS

Mass range
~10^{-6} eV to ~10^{-3} eV

Experiments
ADMX, MADMAX, QUAX, CAPP-8TB

PRIMORDIAL BLACK HOLES

Mass range
~1 to ~30 solar masses

Experiments
LIGO/Virgo

WIMPs

Mass range
~1 GeV to ~1 TeV

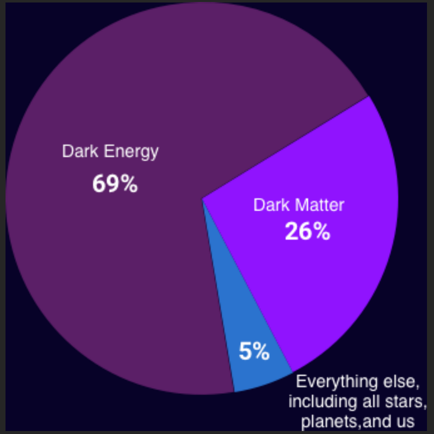
Experiments
XENONnT, PandaX-4T, LZ, CRESST, DAMA, COSINE-100

SUB-GeV DARK MATTER

Mass range
~1 keV to ~1 GeV

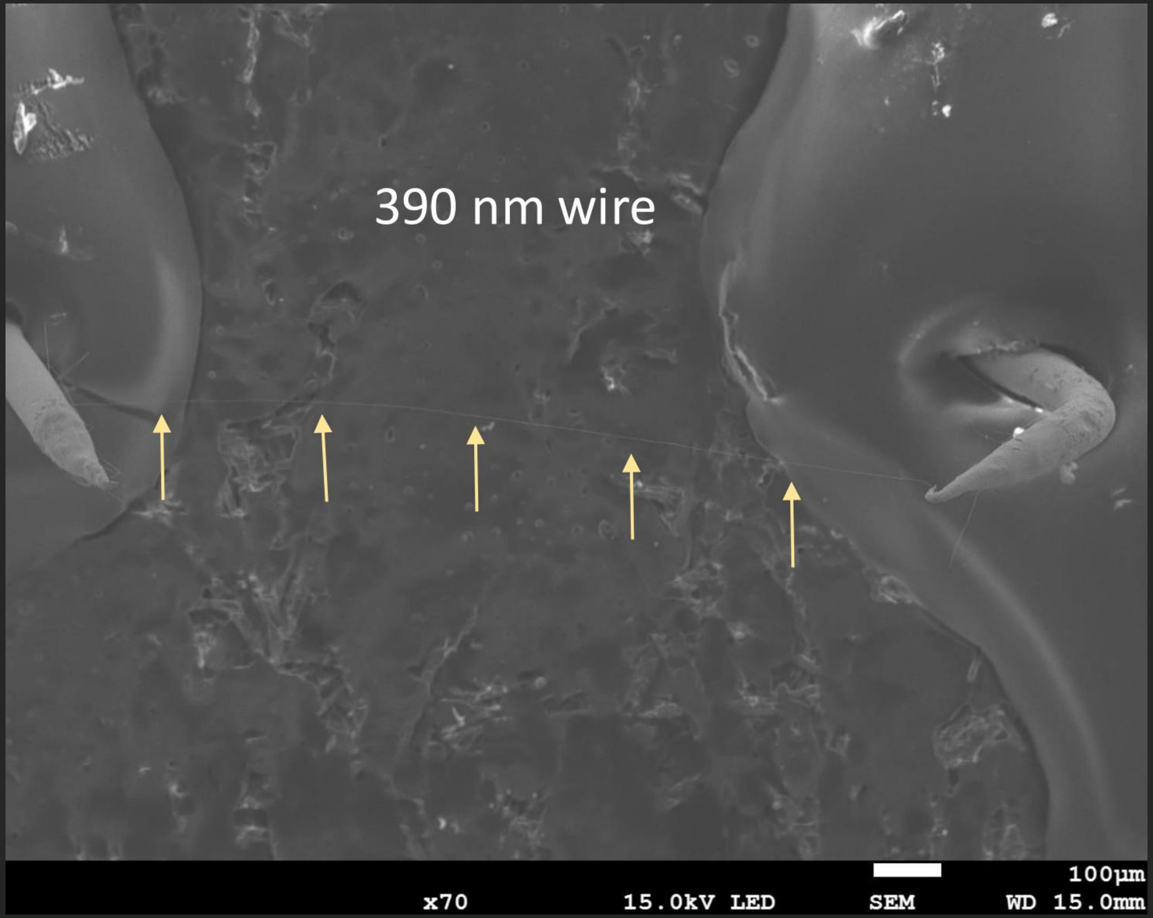
Experiments
SENSEI, TESSERACT

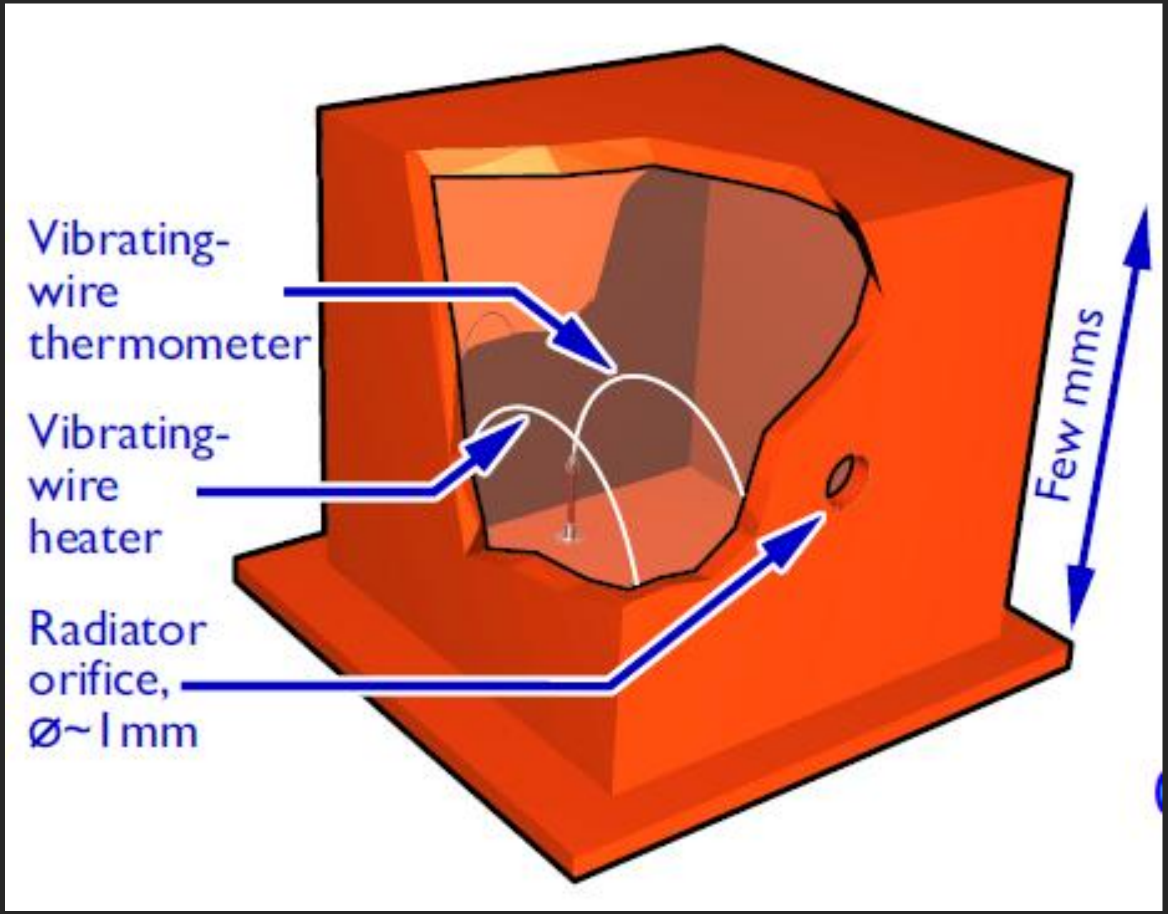
Samuel Velasco/Quanta Magazine



Mass range of the order GeV theoretically motivated by *Asymmetric dark matter models*

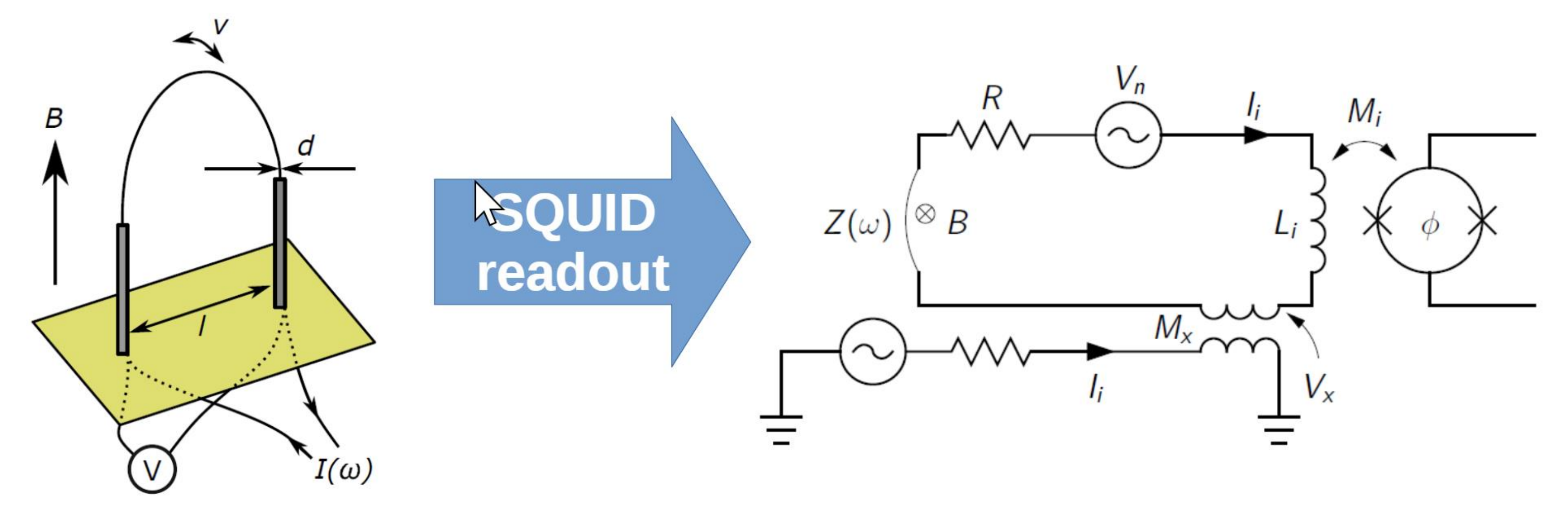
Optimising beam/wire geometry for and both He and SQUID response





Long nanomechanical resonators with circular cross-section, D. Zmeev et al. arXiv:2311.02452 (2023)

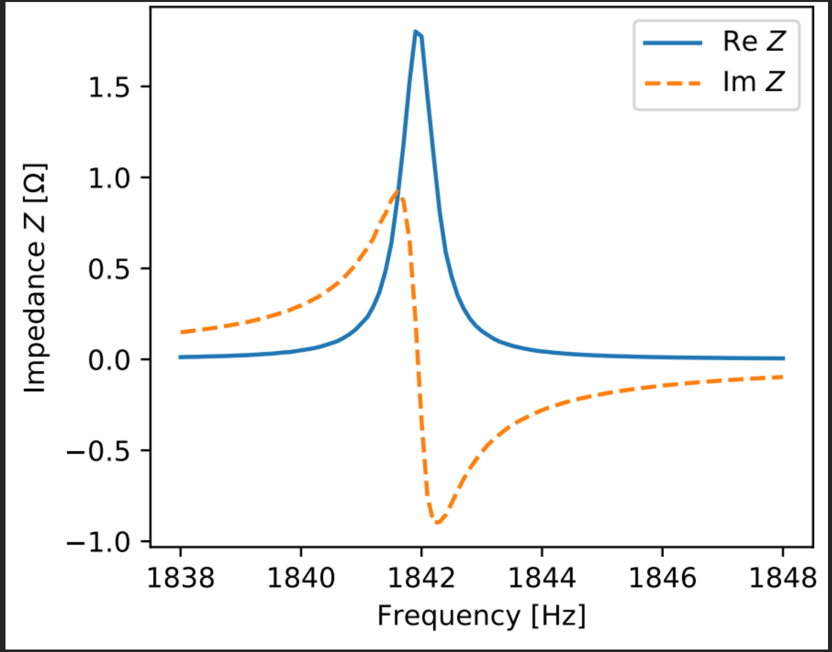
SQUID readout of nanowire

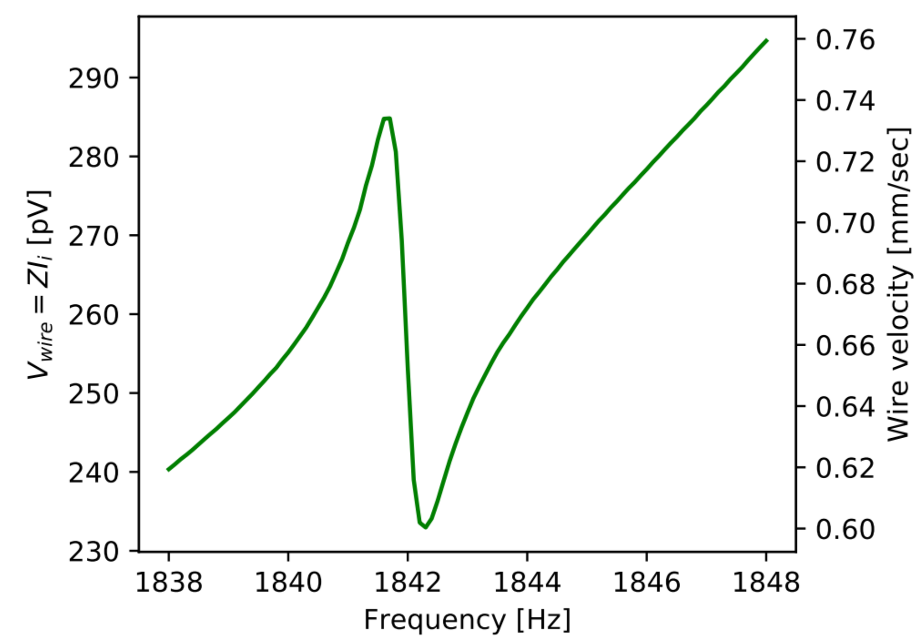


2-stage SQUID amplifier (PTB)
IEEE Trans. Appl. Supercond. 17 (2007)

Vacuum characterisation of SQUID nanowire readout. 315 nm wire, 8.5 mT, 4.2 K

$$\Delta Q = \alpha(T_0, P)\Delta(\Delta f)$$



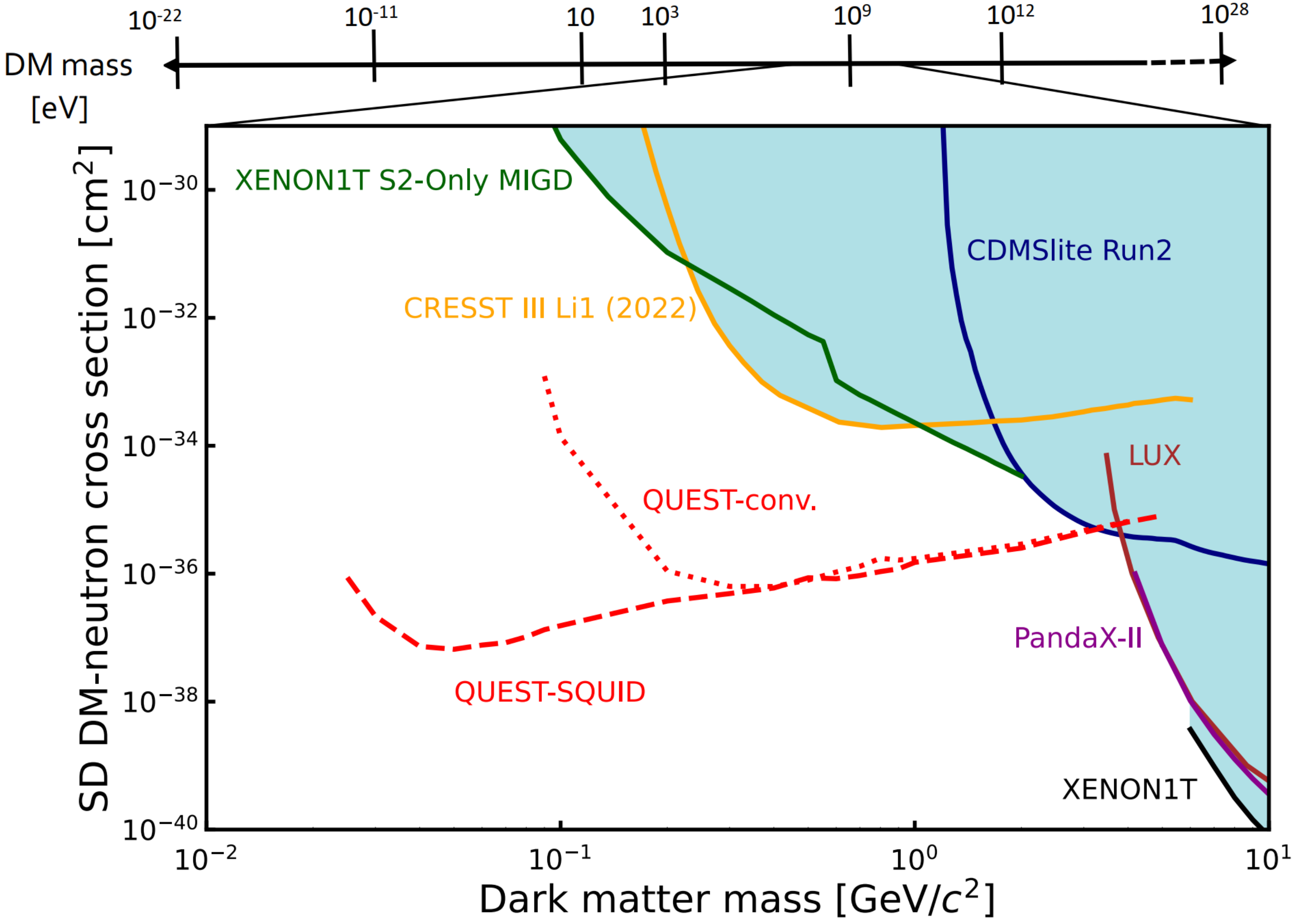


Optimising beam/wire geometry for and both He and SQUID response

Spin dependent sensitivity projection for:

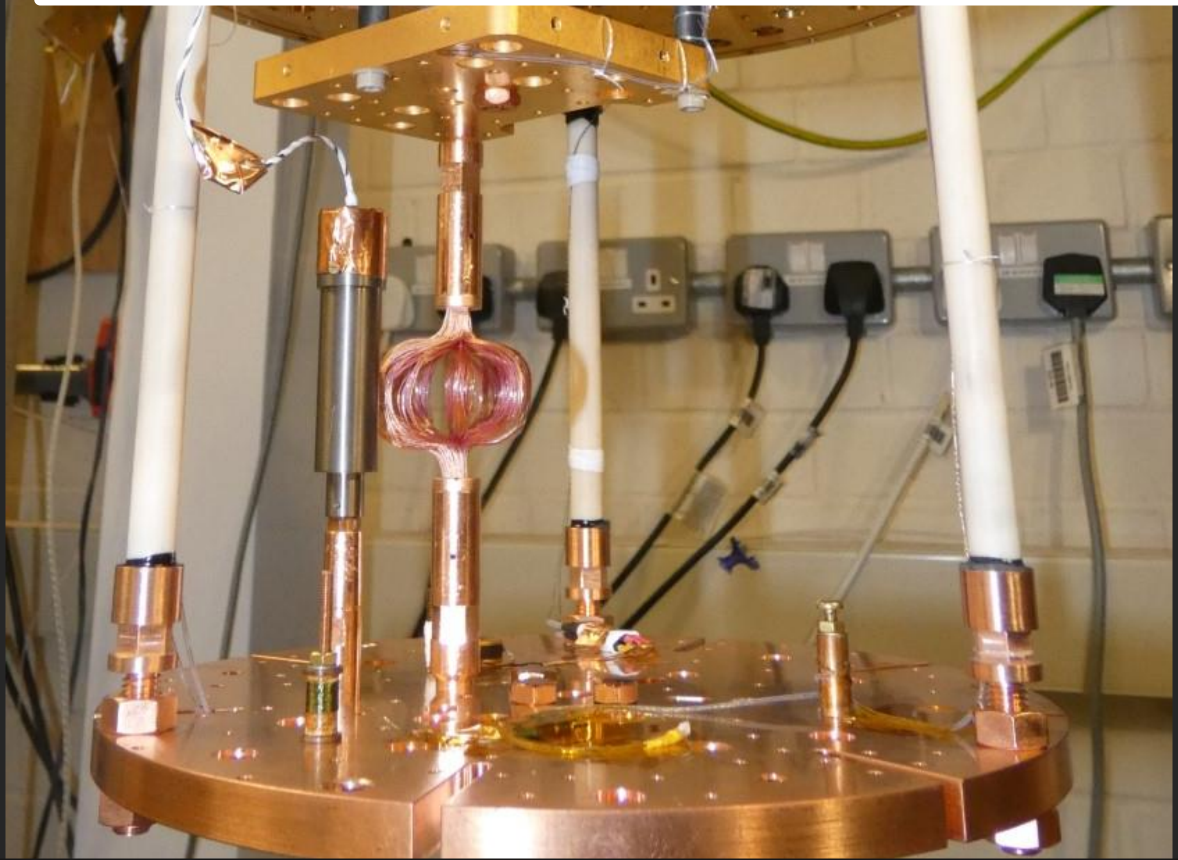
- 5 x 0.3 cm^3 cells
- 6 month run with 50% duty cycle

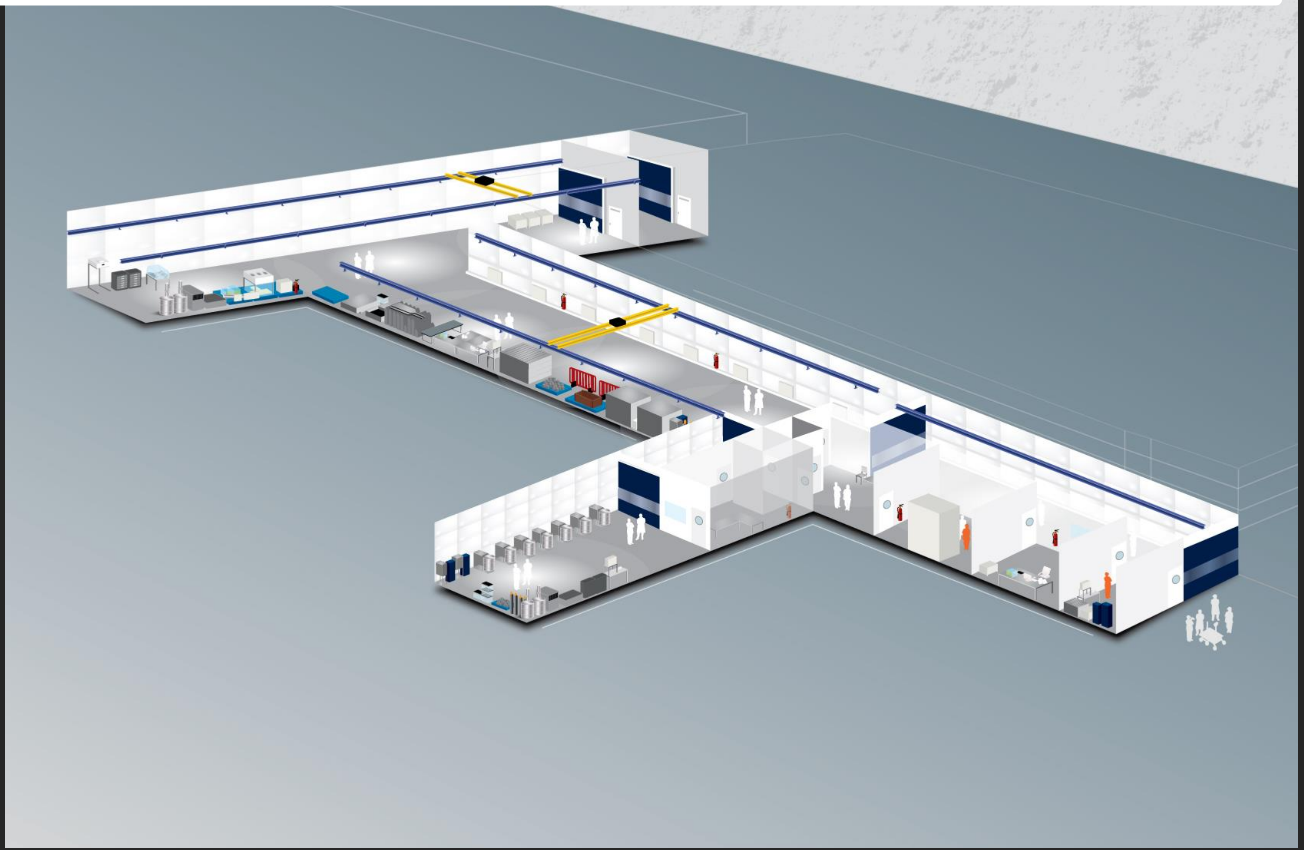
Systematics: background rate, energy scale and galactic escape velocity.



Future Prospects: ULT Underground

UltraDark: Sub mK Cryo-free, low radiogenic background, shielded low vibration underground laboratory for high coherence quantum phenomena and rare event searches





Andreev Scattering

- P wave superfluid, Retroreflection, reverses velocity but not momentum (Fermi Momentum)
- When the superfluid is in motion (around beam), canting of the dispersion curve results in a strong damping term.