Determination of Absolute Neutrino Mass Using Quantum Technologies

A collaboration of particle, atomic and solid state physicists, electronics engineers and quantum sensor experts

presented by

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Stephen Hogan — Cold Atoms and Molecules, Quantum Optics/Information
Stafford Withington — Quantum Sensors and Quantum Electronics

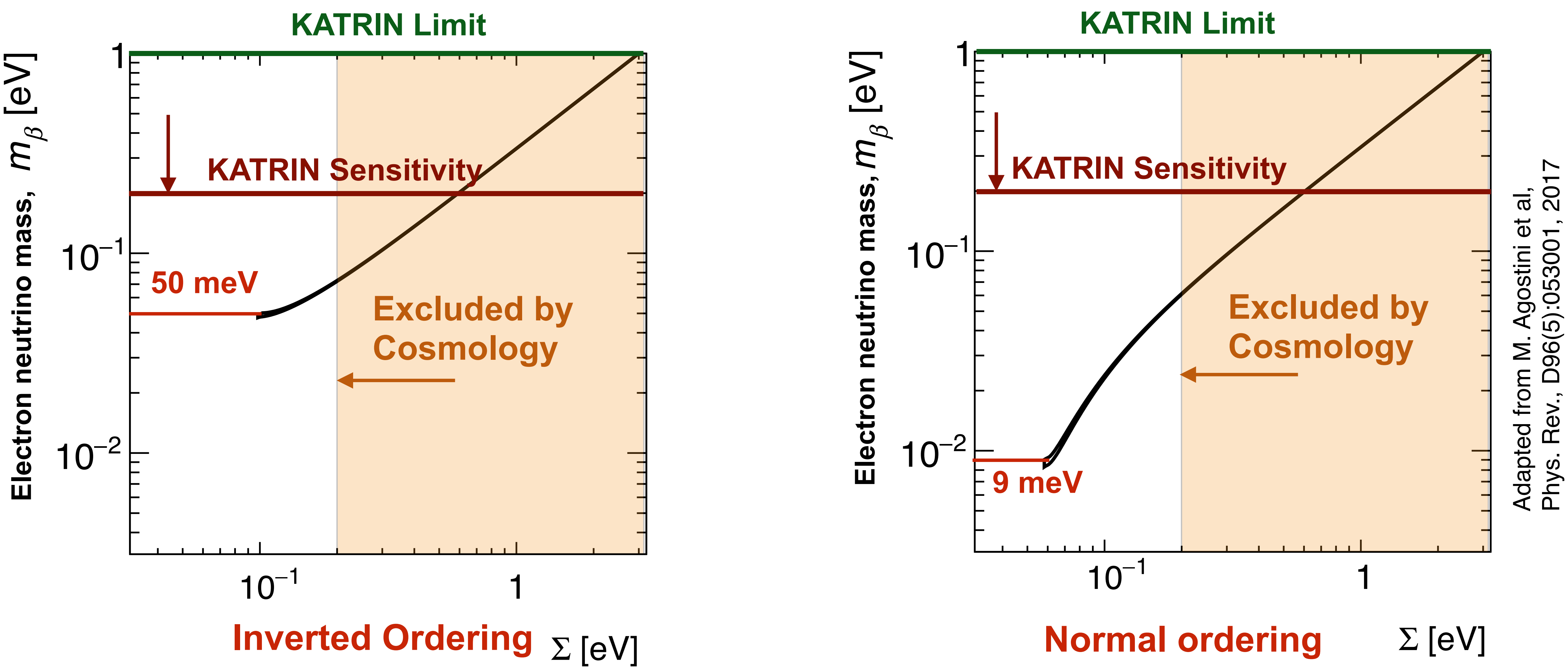
on behalf of the QTNM* Consortium

1-Apr-2020

*Quantum Technologies for Neutrino Mass

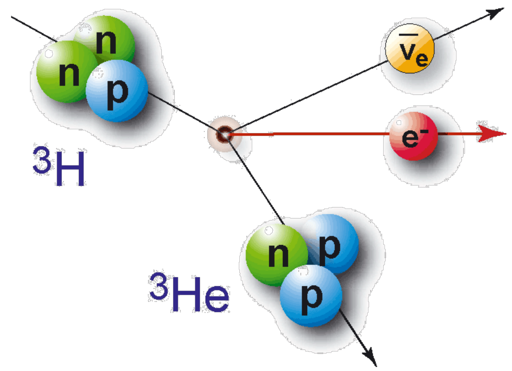
Neutrinos:

- **Most abundant particle of matter in the Universe**
- **Absolute mass not known → window to new physics**

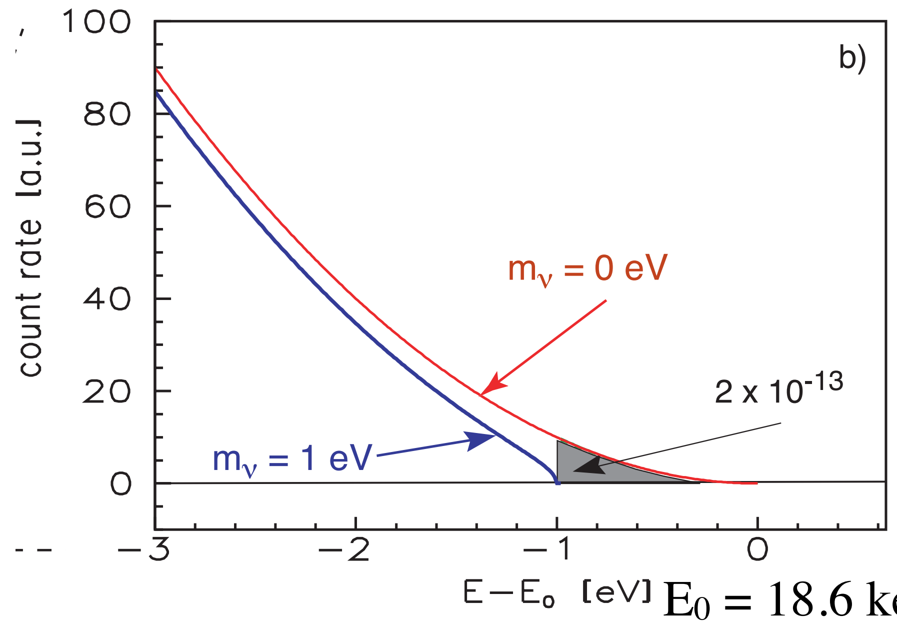


- Powerful constraints from cosmology but cannot replace **lab measurements**
- "Kinematic" measurement of β-decay spectrum is the **only model independent method**
- Two clear sensitivity goals: **50 meV** for **I.O.** and **9 meV** for **N.O.**

"Guaranteed" observation if technology demonstrated



$T_{1/2} = 12.3$ yr



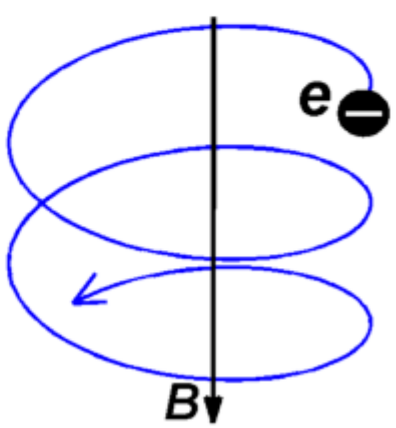
$E_0 = 18.6$ keV

Retarding Potential technology employed by **KATRIN** cannot explore region below *O*(0.1 eV)

Overcome technology limitations with:

Cyclotron Radiation Emission Spectroscopy (CRES) pioneered by **Project-8**

^{3}H decays in magnetic trap



- *non-destructive* full spectrum sampling
- trap *transparent* to radiation
- *frequency* measurement

$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\text{kin}}/c^2}$$

For $B = 1T \;\Rightarrow f \sim 27$ GHz

$$\frac{\Delta E}{E} = \frac{\Delta f}{f} \leq 10^{-6}$$

Key Challenges of CRES:

- **Trapping *O*(10^{20}) T-atoms**
- **Uncertainty on B-field uniformity <1ppm**
- **Quantum limited microwave detection systems**
- **Particle interaction and cyclotron radiation modelling**

Perfect match to UK expertise
Subject of this proposal

Quantum Technologies for Neutrino Mass Proposal

WP1. Simulation and Analysis
Inform Design
CRES modelling and trap simulations
Sensitivity and scale-up studies

WP2. Atomic Source and Magnetic Trap
Supersonic source
Zeeman decelerator
Trap loading and characterisation

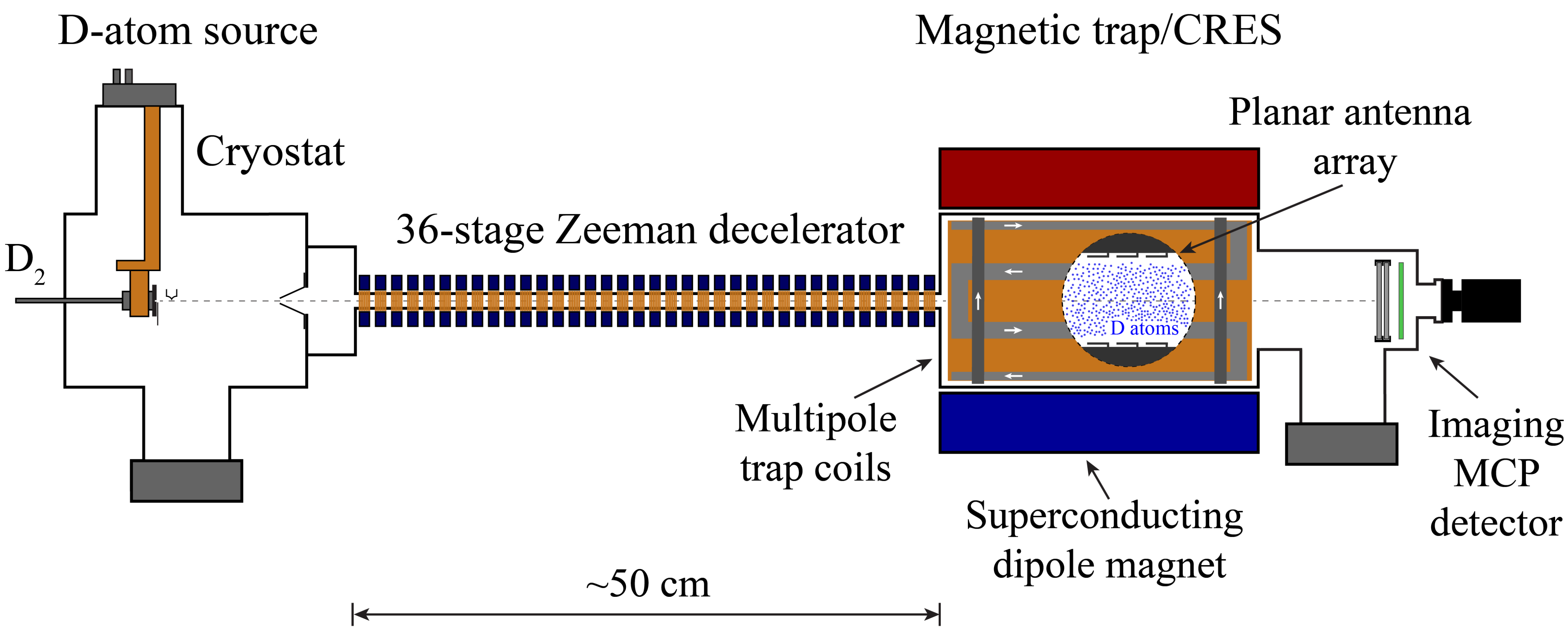
WP3. 3D Magnetic Trap Mapping
In-situ mapping with D atoms as quantum sensors
Rydberg states and Ramsey spectroscopy

CRESDA
(CRES Demonstration Apparatus with Deuterium)

WP4. Cyclotron Radiation Detection
Cryogenic HEMT amplifier
SLUG or JTWPA preamp (downselect)
From devices to quantum limited integrated system

WP5. Geonium Atom Detector
Proof of principle demonstration
Scalability study

CRESDA. Atomic Source and Magnetic Trap.

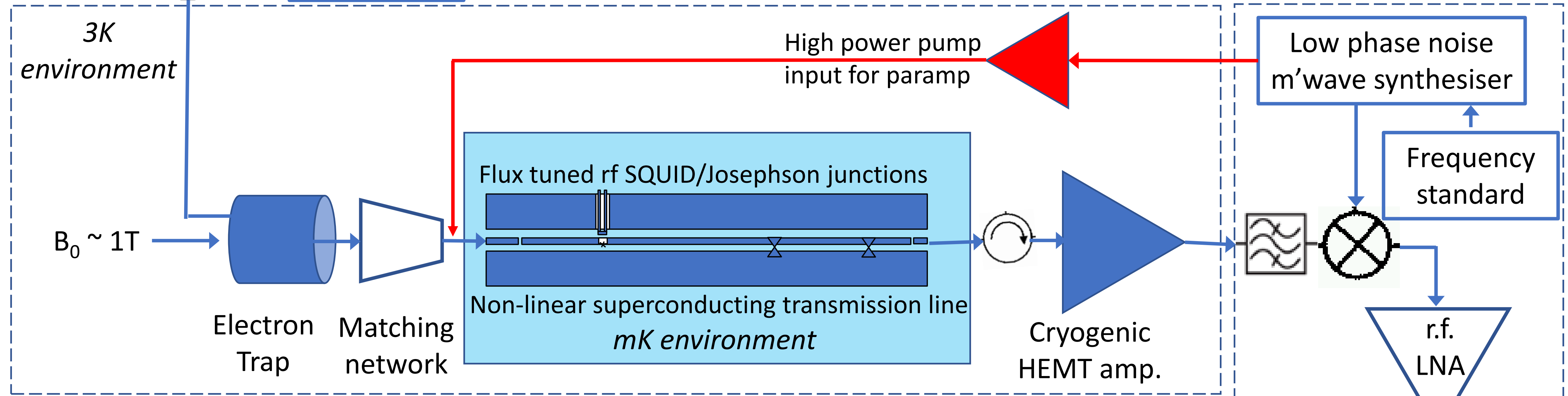


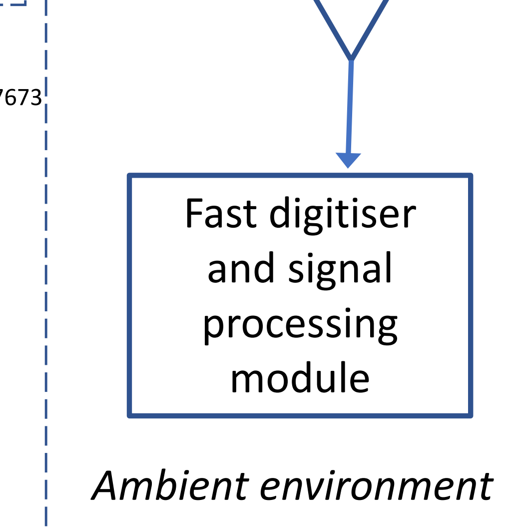
Goals for 3 year proposal

- Trapping 10^{14} D-atoms in 1L tap at T = 1K, $\rho \sim 10^{14}$ cm^{-3} : WP2
- Mapping B-field uniformity in a trap with ≤ 1ppm precision: WP3
- Atomic beam line, trap and scaling up simulations: WP1

Pathway to 10^{20} T-atoms

Ultralow Noise Superconducting Quantum Limited CRES Detector

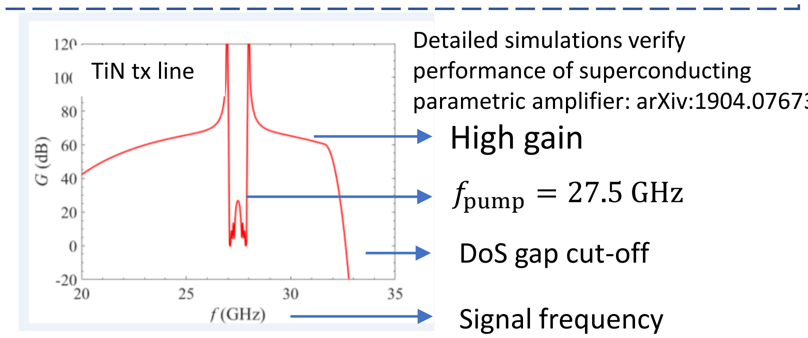


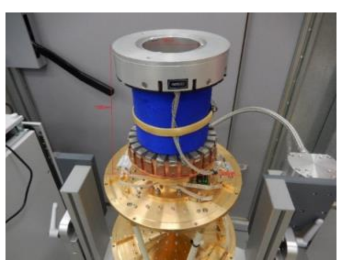


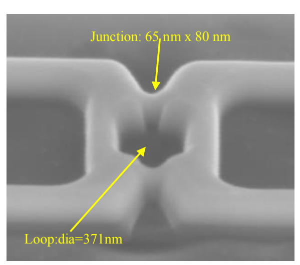
Challenge of millimetre-wave (25-30 GHz) ultra-low-noise amplifiers:

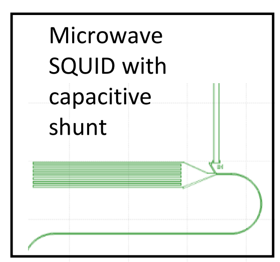
- Push superconducting microwave SQUID amplifiers up in frequency
- Push superconducting parametric amplifiers down in frequency
- High gain quantum-limited noise performance possible

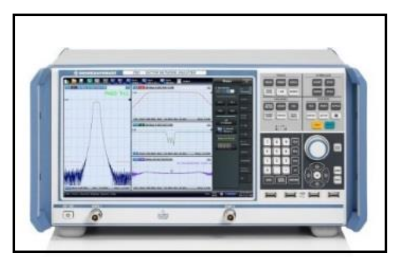
Draws heavily on major investments by funding agencies in establishing superconducting device processing and measurement labs











Goals for 3 year proposal

- **From devices to quantum limited m'wave detection systems: WP4**
- **Cyclotron Radiation Spectroscopy: P ~0.01 fW, $\Delta f/f \leq 10^{-6}$. : WP4 and WP5**
- **CRES signal and background simulations, readout optimisation: WP1**

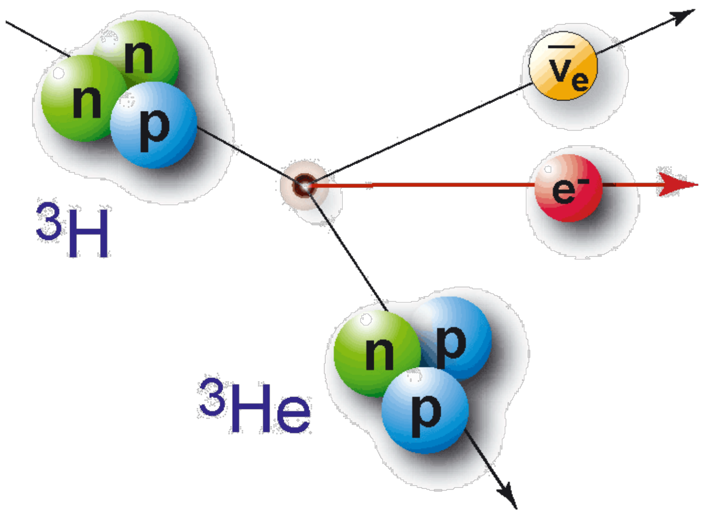
Updates and Outlook

- Visit to **Culham Centre for Fusion Energy**
  - Strong interest in a major **fundamental science project at National Lab**
  - Possible site at **new H3AT facility**
- Absolute Neutrino Mass workshop on 19-Dec-2019 at UCL https://indico.cern.ch/event/849868/
  - Endorsement of proposal and strategy by KATRIN and Project-8
  - Discussions of **joint strategy** with Project-8
  - **Culham**: Willingness to engage through direct support/consulting and H3AT site planning
- Next step: **moving CRESDA to Culham**
  - Commissioning with Tritium at potential ultimate site
  - O(1eV) neutrino mass sensitivity
- Establishing **international collaboration** for ultimate experiment
- TDR and Full Proposal
- Possibility to host **final experiment on UK soil**

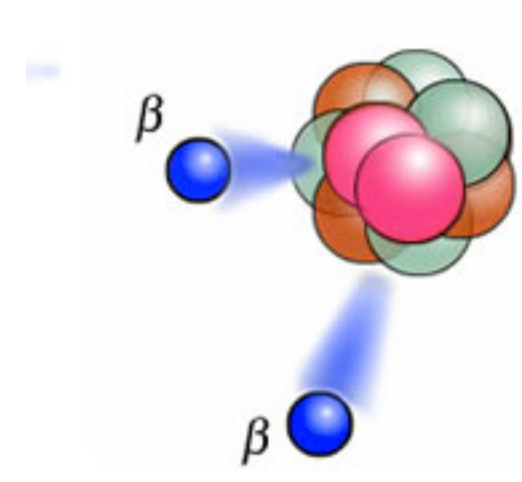
BACKUP

Absolute Neutrino Mass Parameters

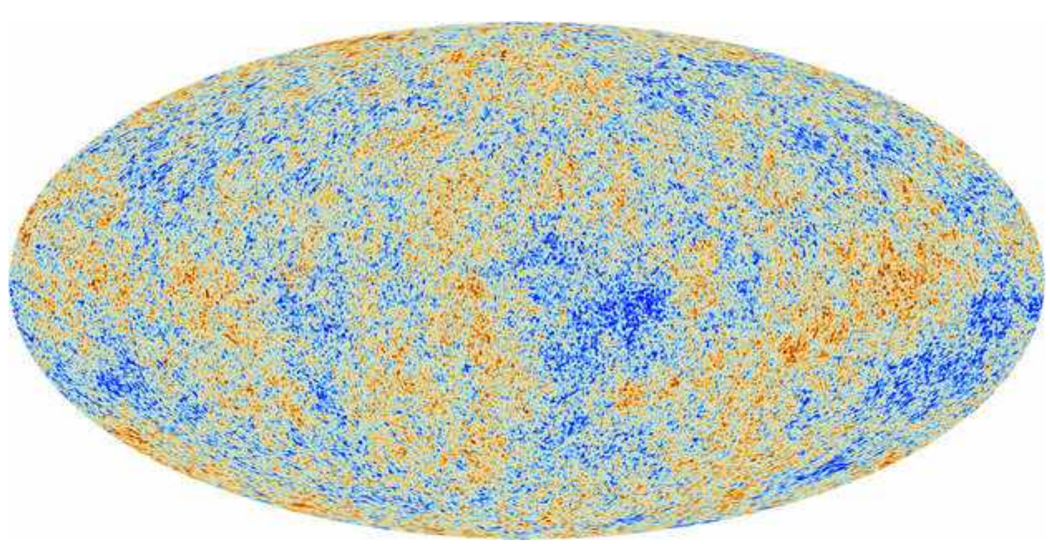
$$m_{\nu_e} = \sqrt{U_{e1}^2 m_1^2 + U_{e2}^2 m_2^2 + U_{e3}^2 m_3^2}$$



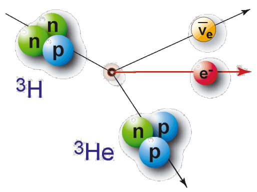
$$\langle m_{\beta\beta}(\nu_e) \rangle = U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}$$

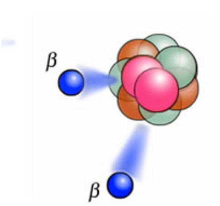


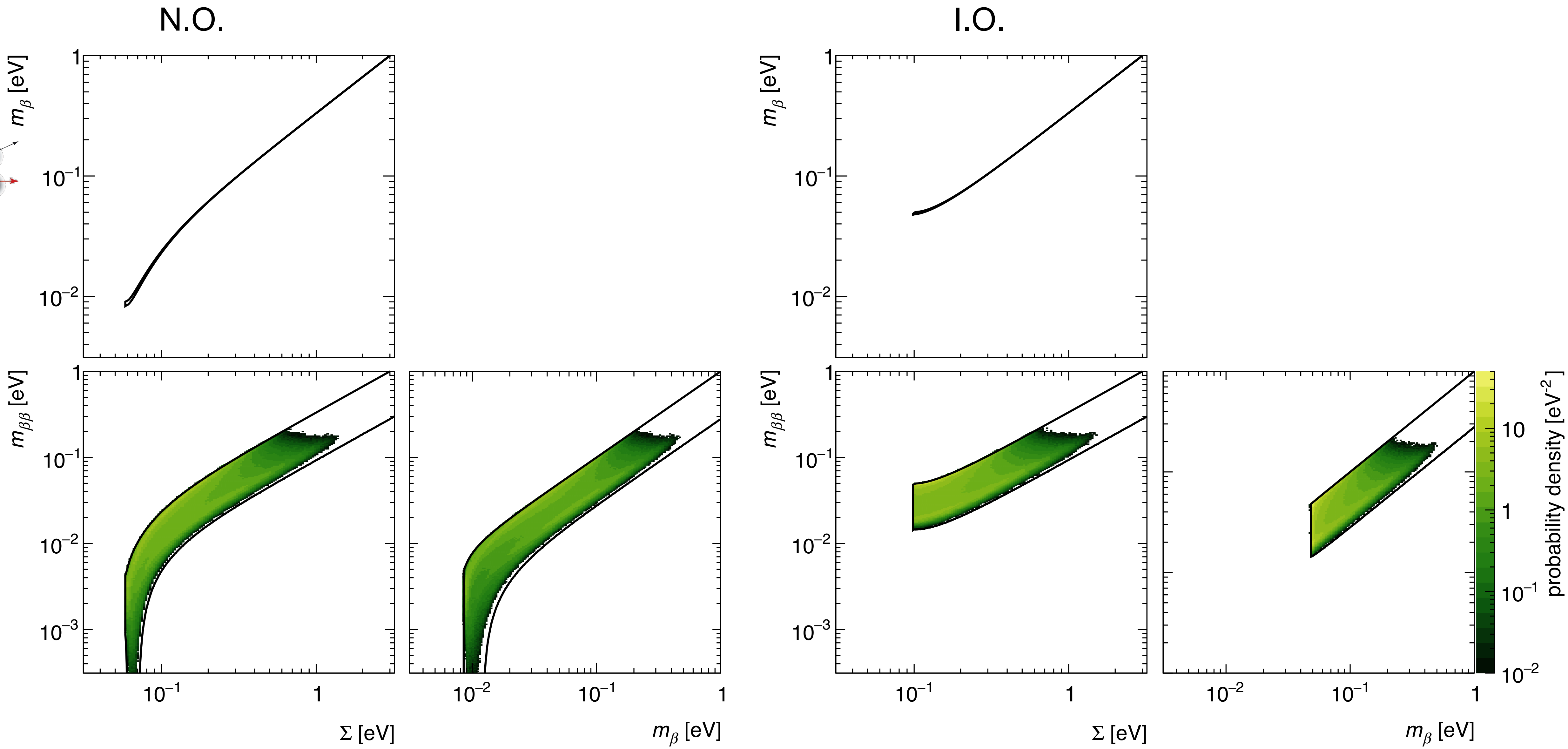
$$\Sigma = m_1 + m_2 + m_3$$



Neutrino masses and their correlations

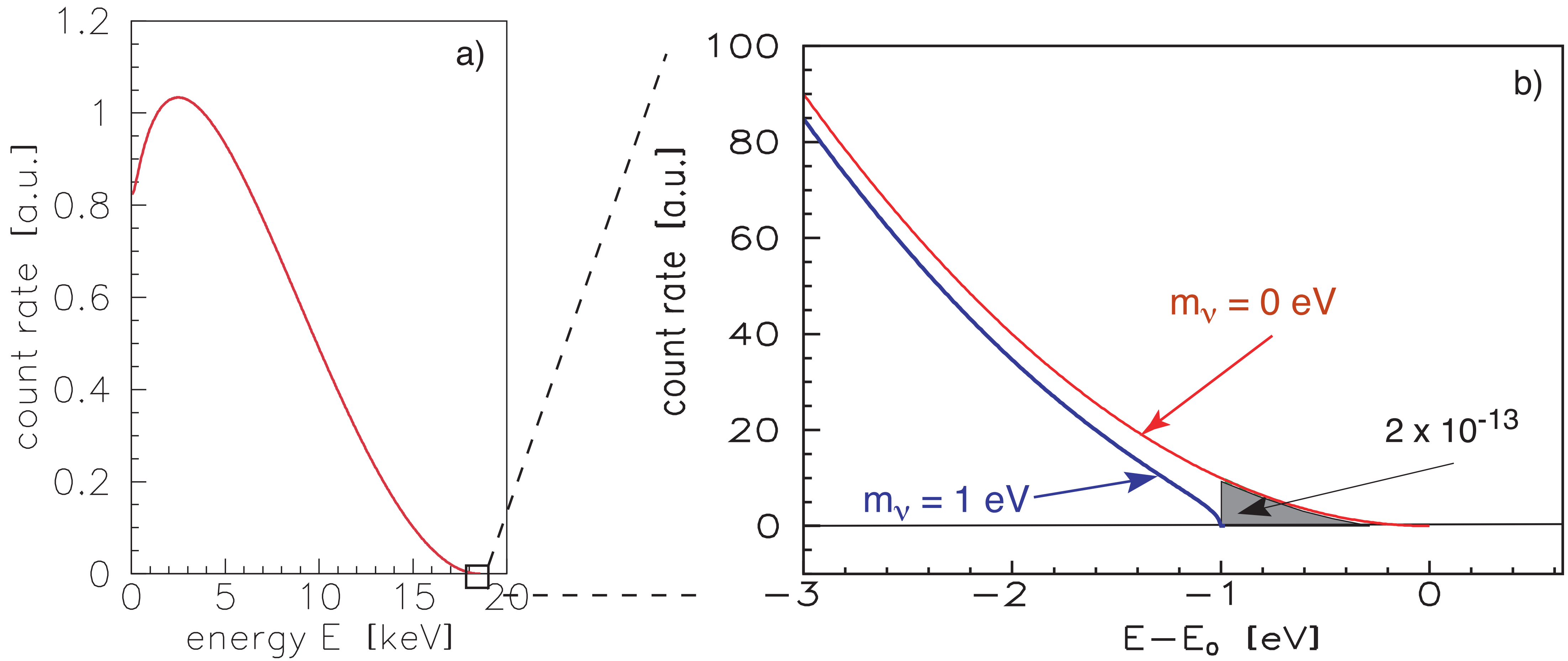






M. Agostini et al, Phys. Rev., D96(5):053001, 2017

- No uncertainties on m_β
- No cancellations with m_β



$$\frac{dN}{dE_e} = 3rt\left(E_0 - E\right)\left[\left(E_0 - E\right)^2 - m_\nu^2\right]^{1/2}$$

r - rate in $\Delta E = 1eV$ with $m_\nu = 0$

b - background rate

$$N_{tot} = rt\left(\Delta E\right)^3\left[1 - \frac{3}{2}\frac{m_\nu^2}{\left(\Delta E\right)^2}\right] + bt\Delta E$$

signal

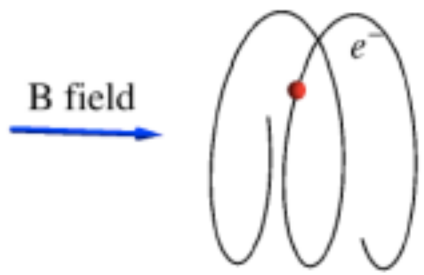
background

$$\sigma_{m_\nu^2} = \frac{2}{3rt\Delta E}\sqrt{N_{tot}} = \frac{2}{3rt}\sqrt{rt\Delta E + \frac{bt}{\Delta E}}$$

$$\Delta E_{opt} = \sqrt{\frac{b}{r}}$$

How to overcome present technology limitations

A. Schawlow: “Never measure anything but frequency!”

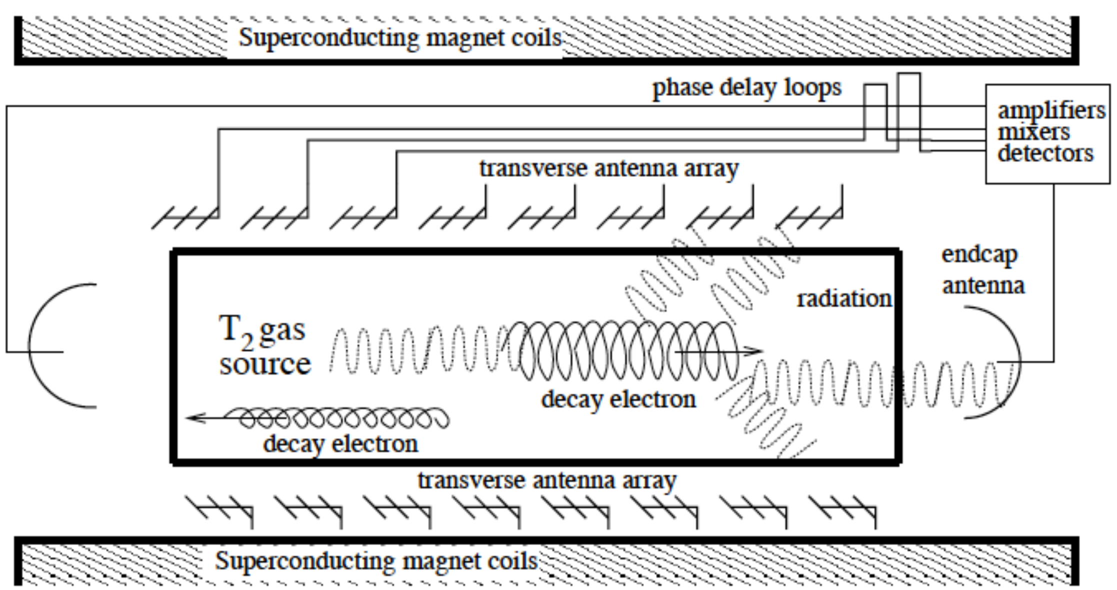


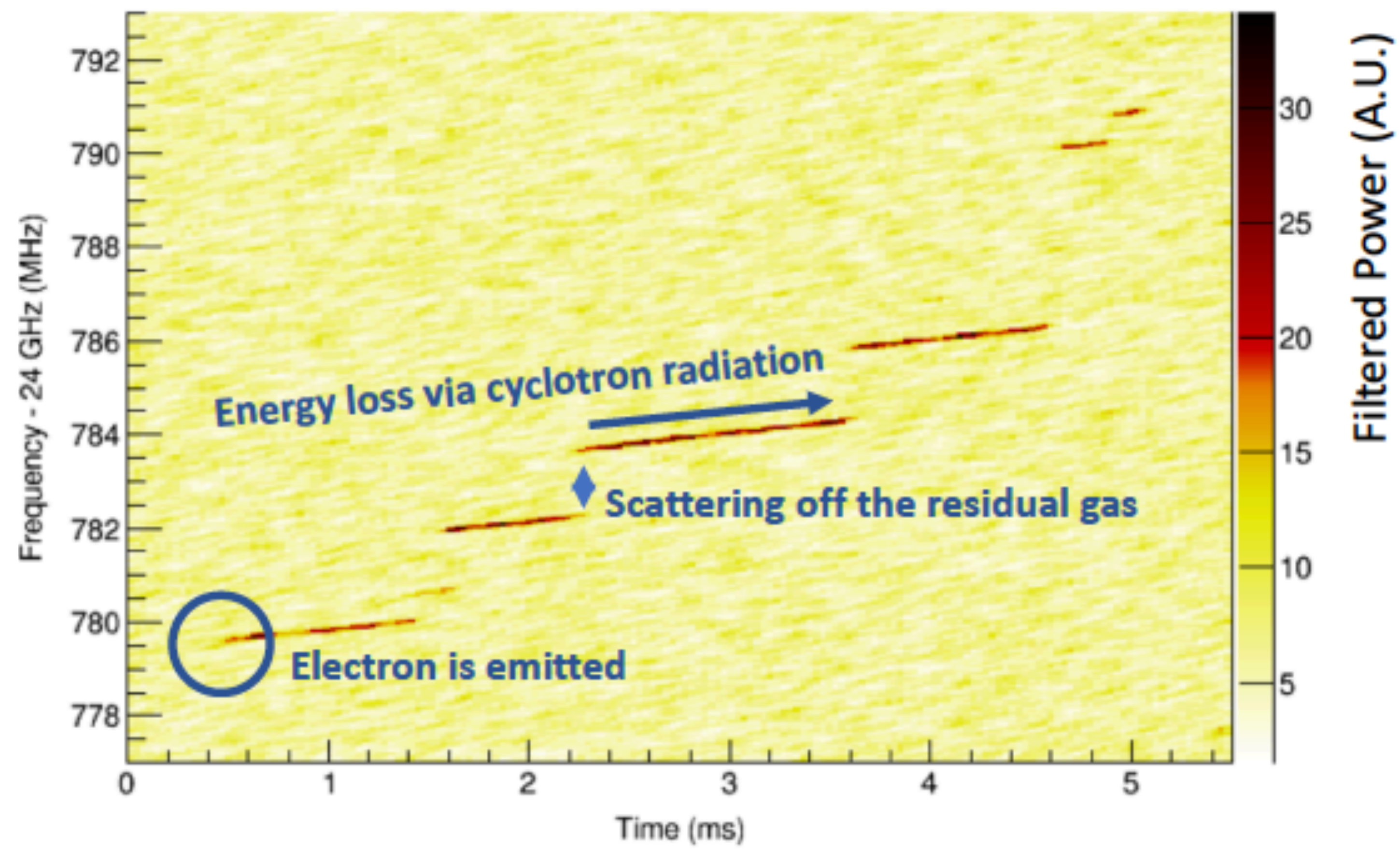
$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\rm kin}/c^2}$$

$$f \cdot \frac{\Delta E}{E} \sim \Delta f; \quad \frac{\Delta f}{f} \sim 10^{-6}$$

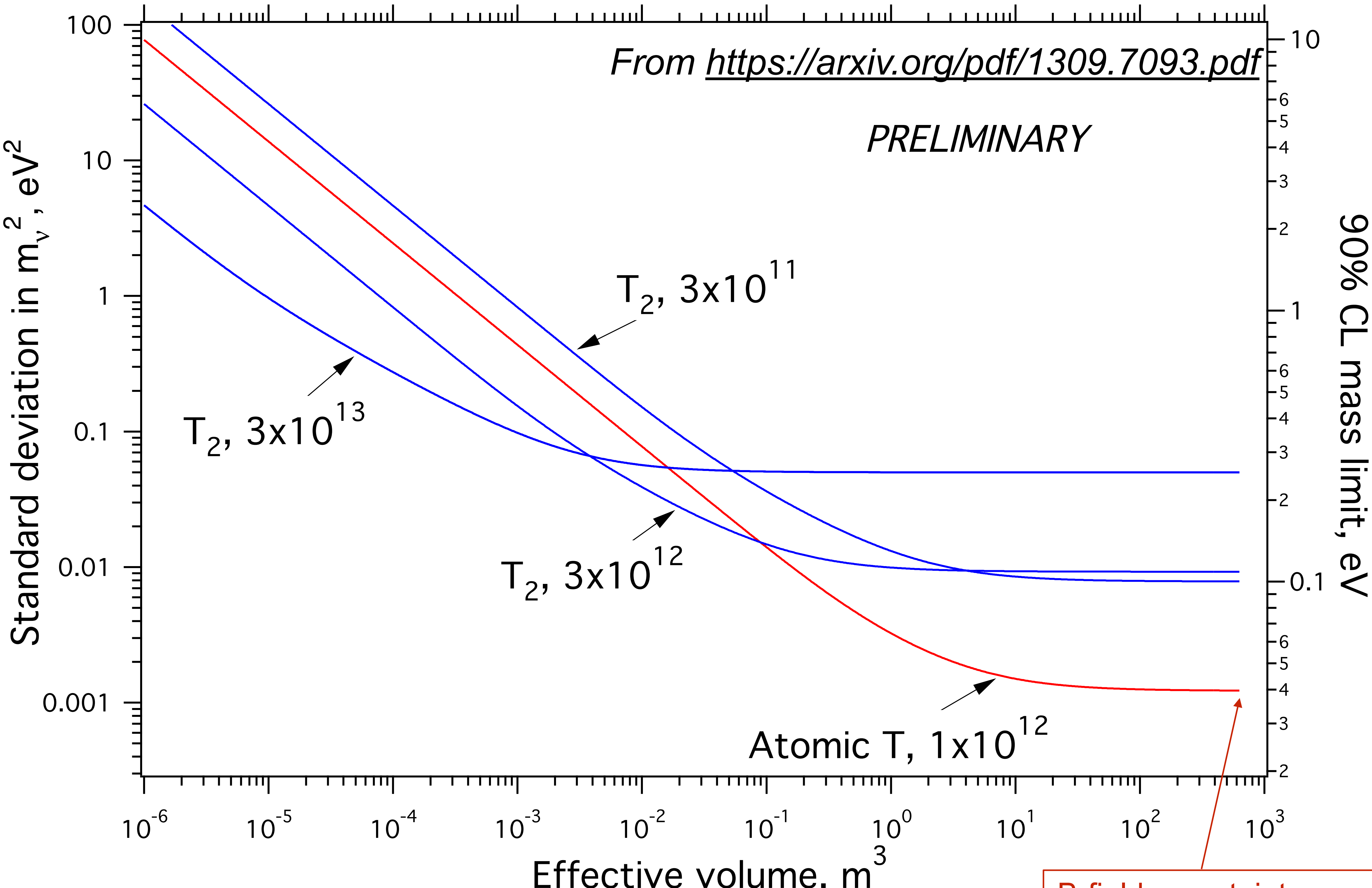
Cyclotron Radiation Emission Spectroscopy (CRES)

Project-8



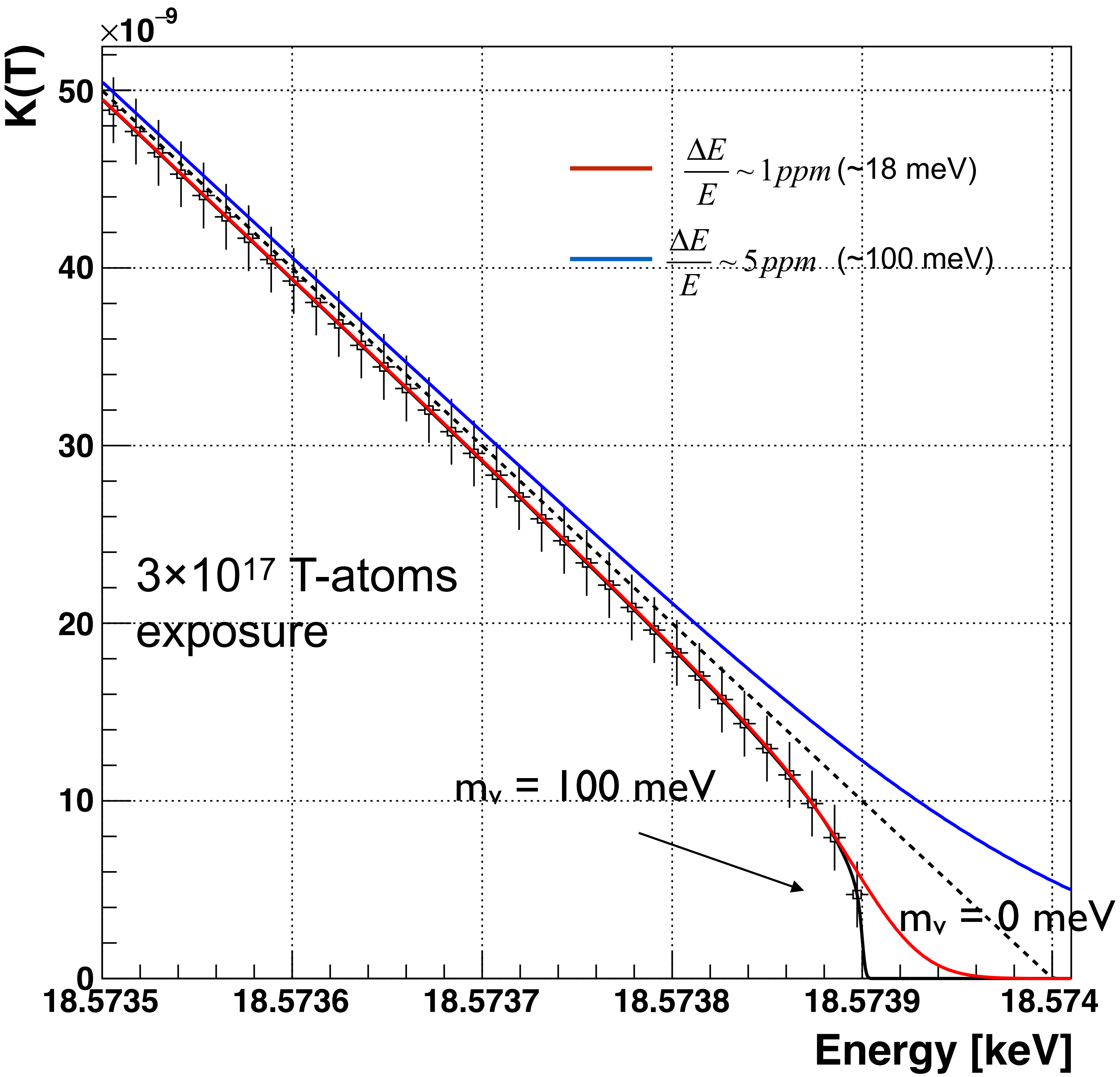


Project-8 Sensitivity



B-field uncertainty
T_2 background

WP1. Simulation and Analysis

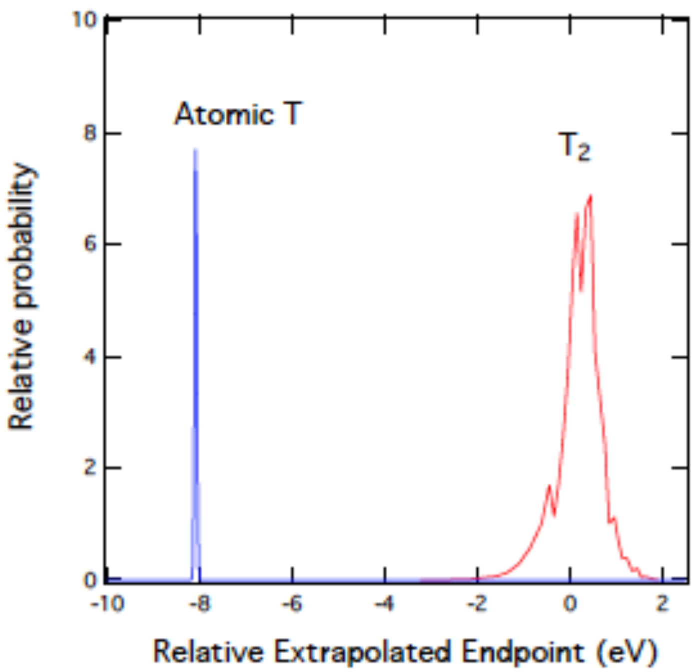


For *O(10meV)* sensitivities >10^{20} T-atoms exposures required

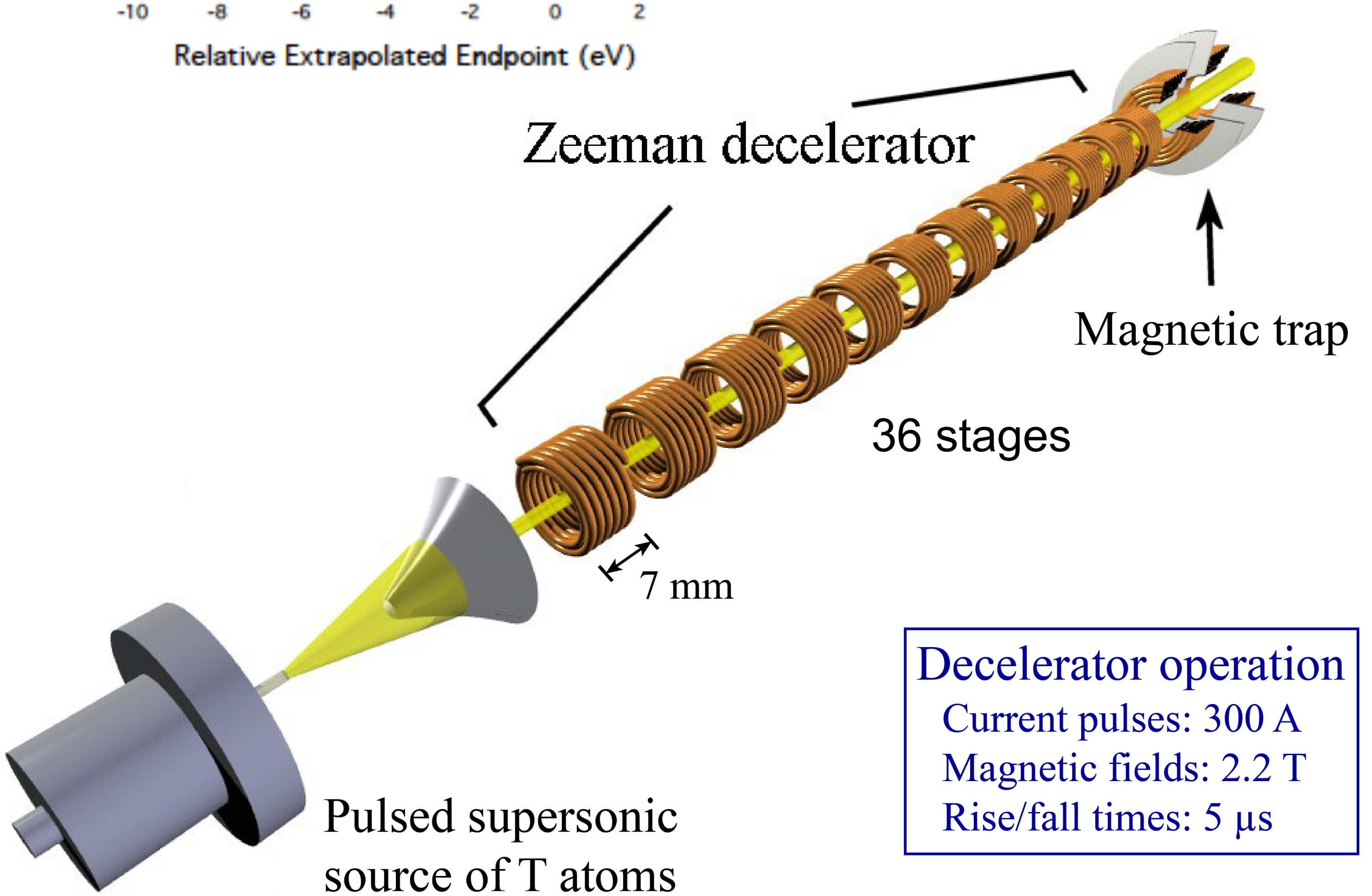
Tasks

- 3D atomic beam simulations. Input to WP2 to interpret TOF measurements from Zeeman decelerators
- Cyclotron emission and detection modelling. Input to WP4 and 5.
- Atomic Trap simulations. Modelling large ensemble of T-atoms with long residence time. Electron-gas interactions. Link to WP2.
- CRES Analysis and Sensitivity. Spectrogram analysis with ML techniques to extract maximum information (inc. e.g. spatial distribution of decays). Scale-up modelling and ultimate sensitivity.

WP2. Atomic Beam Source and Magnetic Trapping



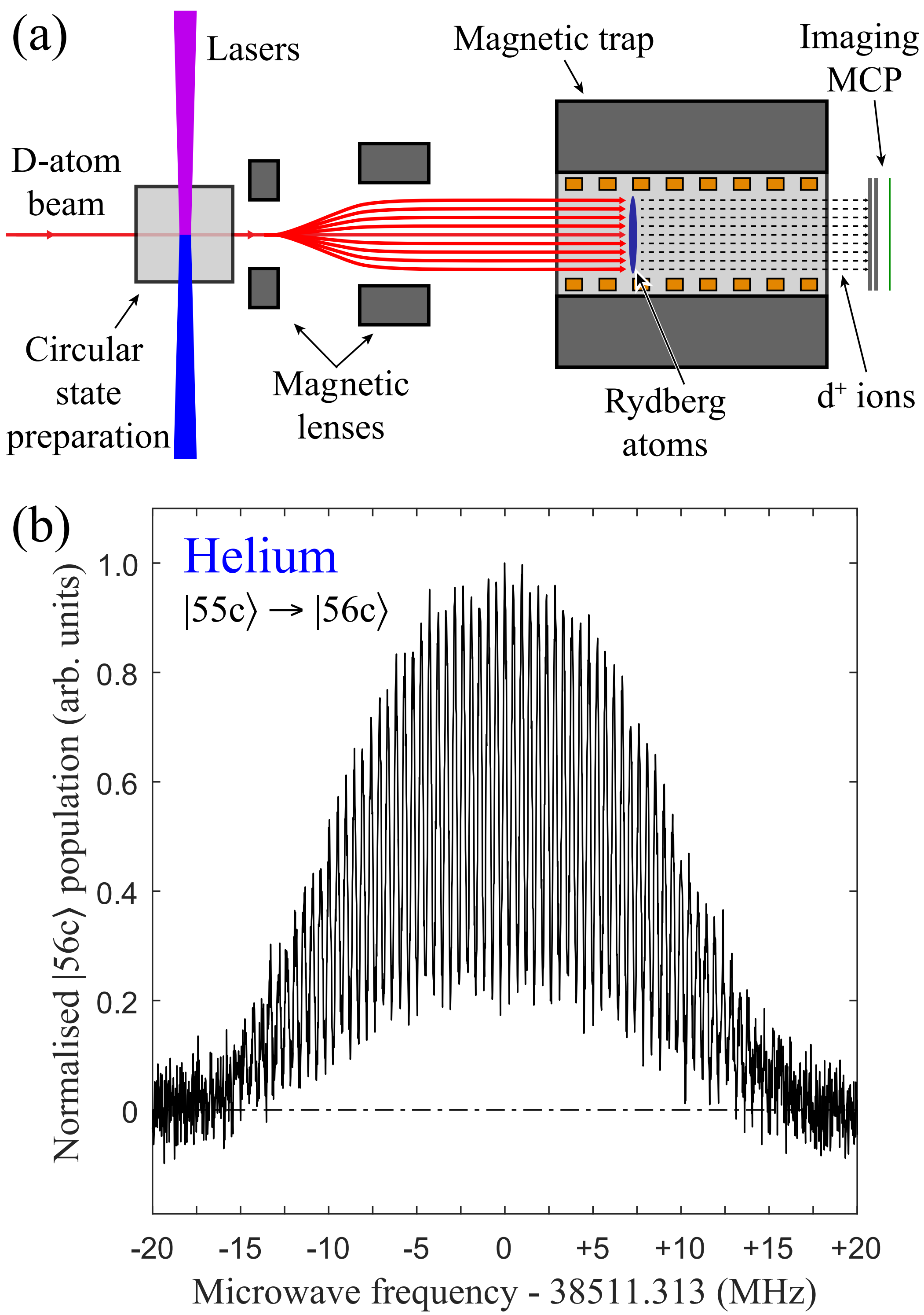
Need atomic T due to uncertainties in final states of molecular T_2



Tasks

- D-atom Source. Cryo-cooled supersonic source based on electric discharge of D_2. Output: D-atoms with 650±50 m/s, 10^{14}-10^{15} cm^{-3}.
- Zeeman Decelerator. Successfully demonstrated for D-atoms and suitable for high densities. Output D-atoms with 50m/s, T~0.1K.
- Magnetic Trap. 1L multipole superconducting magnetic trap. Optimisation of loading technologies. Density characterised by laser and MW spectroscopy. Identify traces of D_2 by comparing REMPI spectra of D_2 and D.

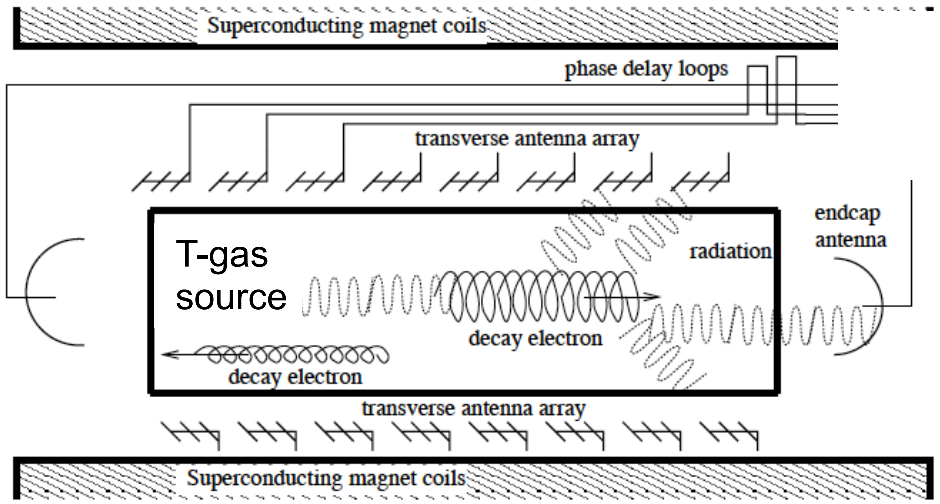
WP3. 3D B-field Mapping by Quantum Sensing.



$$f = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2} \Rightarrow \frac{\Delta f}{f} \sim 10^{-6} \Rightarrow \frac{\Delta B}{B} \sim 10^{-6}$$

- High-res MW spectroscopic measurement of transitions between circular Rydberg states by Ramsey spectroscopy.
- State selective ionisation and ion imaging
- Measuring B-field with precision 0.1ppm possible.
- Spatial resolution at a level of 0.1mm
- Scheme can be used for precise determination of Rydberg constant ⟹ possible contribution to “proton radius puzzle”

WP4. Cyclotron Radiation Detection



→ Quantum-limited Preamplifier → Baseline Detector

Baseline Detector:
Cryogenic HEMT amplifier and heterodyne receiver coupled via waveguide
Antenna structures to match trap and receiver

- CRES signal: 27GHz, sub-fw, only 100's of MW photons in receiver
- Resolution $\Delta f/f \sim 10^{-6}$ or better!
- Requires amplifiers at quantum noise limit (0.6K)

Quantum-noise limited pre-amplifier before **B.D.** to improve S/N

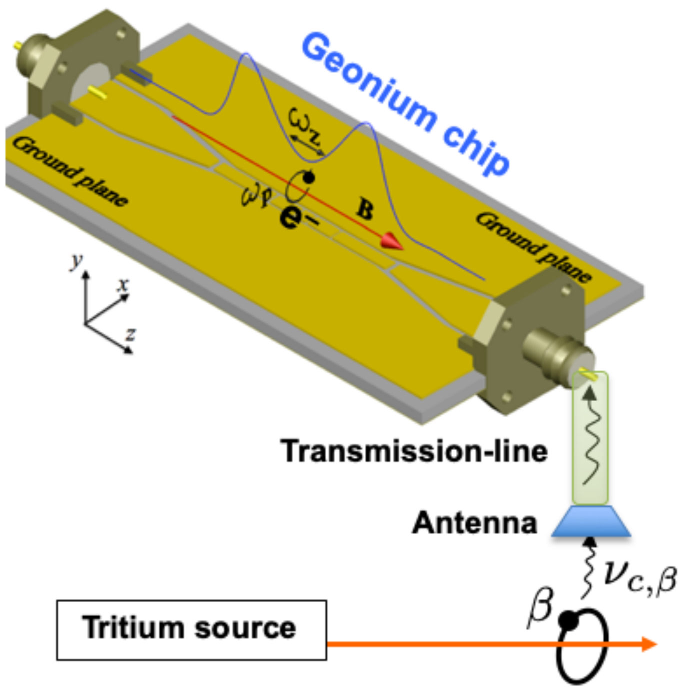
SLUG Amplifier at quantum limit (NPL)

Josephson Travelling Wave Parametric Amplifier (Cambridge)

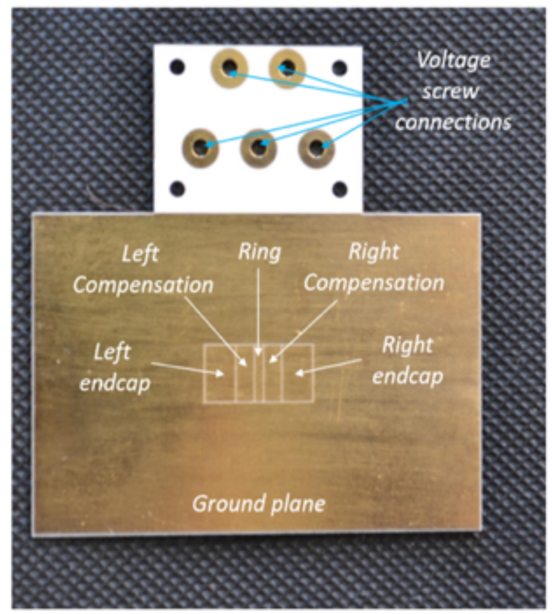
Down-selection and integration into quantum limite m'wave detection **system**

- Installation on CRESDA
- Performance characterisation with monochromatic e-sources:
  - photoionisation of confined D-atoms (eV scale)
  - radioactive sources ^{83m}Kr (keV scale).

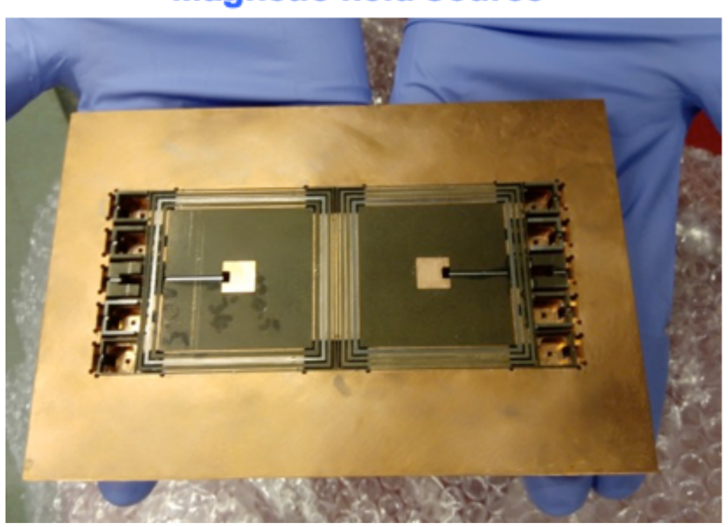
WP5. Geonium Atom CRES Detector.



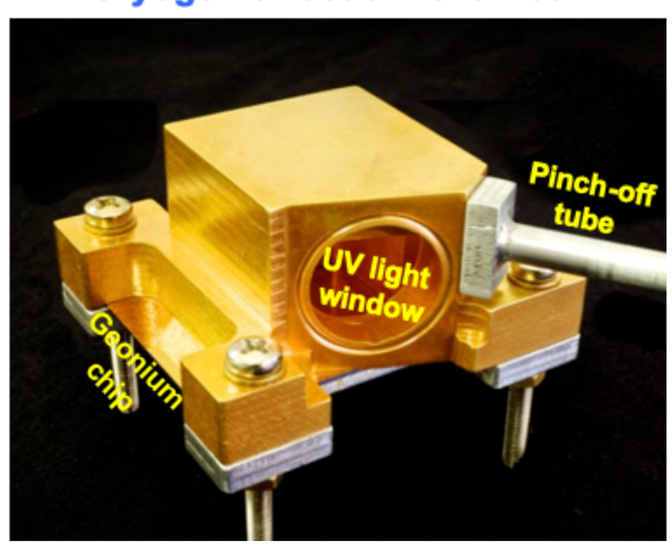
Geonium chip



Magnetic field source



Cryogenic vacuum chamber



- Single electron captured in a planar Penning trap (“geonium atom” on a chip).
- A quantum resonator with a Q-value of 10^9. Possibility to reach sub-meV resolution
- Tuning to a specific frequency with very narrow bandwidth (e.g 25Hz for 25GHz of CRES in 1T field) — “one detector per energy bin”
- Fabrication of “geonium chip”
- Installation on CRESDA
- Characterisation with monochromatic e-source

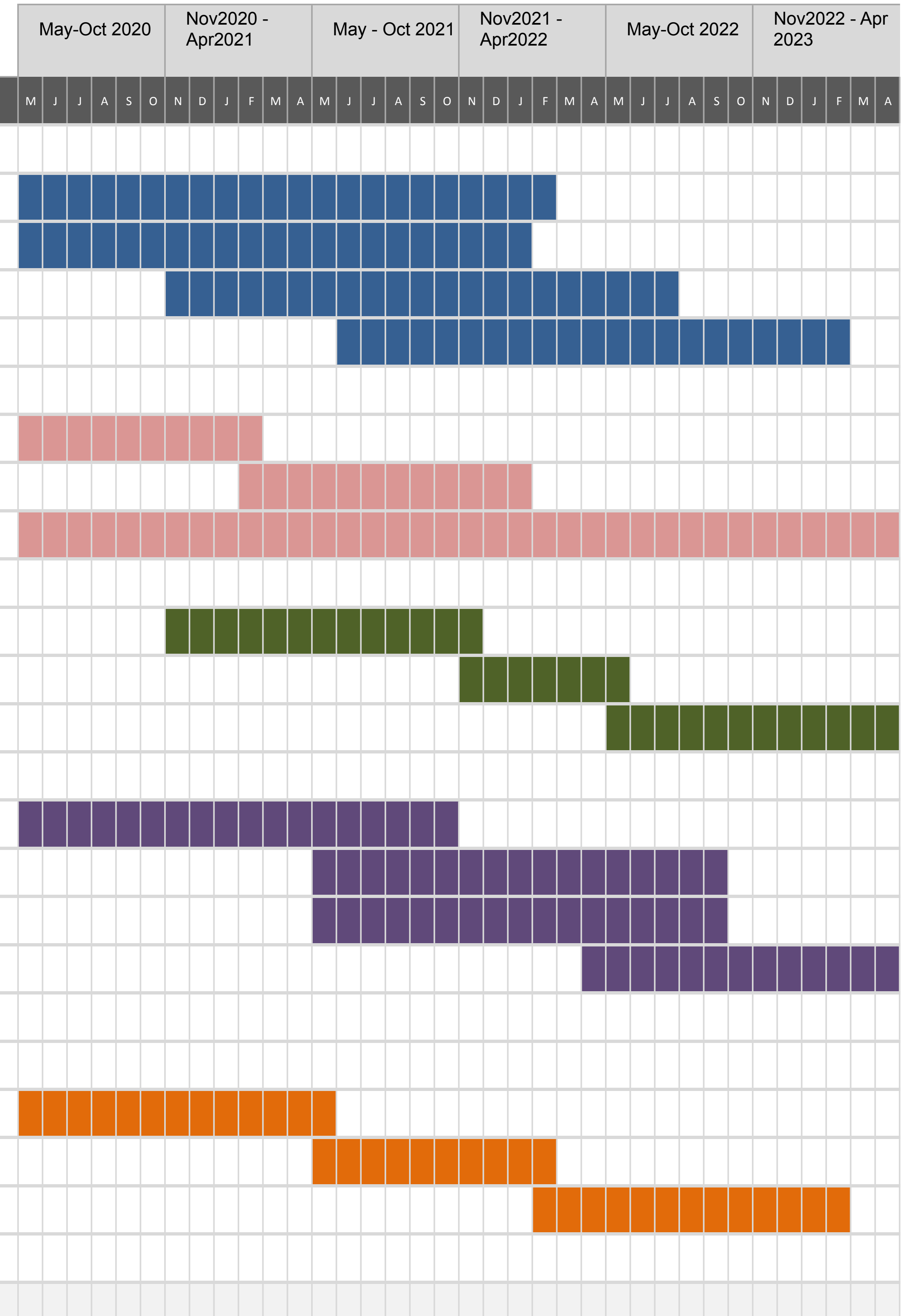
QTNM Proposal Timeline

Quantum Technologies for Neutrino Mass

Project Start: Fri, 5/1/2020

Display Week:

TASK	Name	START	END
WP1 Simulations and Analysos			
Task 1	Atomic Beamline Simulations	5/1/20	3/3/22
Task 2	CRES Module	5/1/20	2/7/22
Task 3	Trap Simulations	11/2/20	8/9/22
Task 4	CRES Analysis and Sensitivity	6/8/21	2/13/23
WP2. Atomic Beam Source and Magnetic Trapping			
Task 1	D-Beam construction and characteris.	5/4/20	2/3/21
Task 2	Zeeman consr. And characters.	2/2/21	1/5/22
Task 3	Magnetic Trap	5/11/20	4/7/23
WP3. 3D B-map			
Task 1	D- and MW Spectrosopy	11/2/20	11/3/21
Task 2	D-motion control	11/1/21	5/3/22
Task 3	1D and 3D mapping	5/2/22	4/4/23
WP4. CRES Detection			
Task 1	Baseline Detector	5/1/20	11/1/21
Task 2	SLUG pre-Amp	5/3/21	9/6/22
Task 3	JTWPA pre-Amp	5/3/21	9/6/22
Task 4	Down-sel., Integr, Run	4/25/22	4/13/23
Task 5		date	date
WP5. Geonium Detector			
Task 1	Geonium chip in B-field	5/20/20	5/24/21
Task 2	Integration with trap and calib.	4/26/21	2/18/22
Task 3	CRES Run with Geonium	5/3/21	9/6/22



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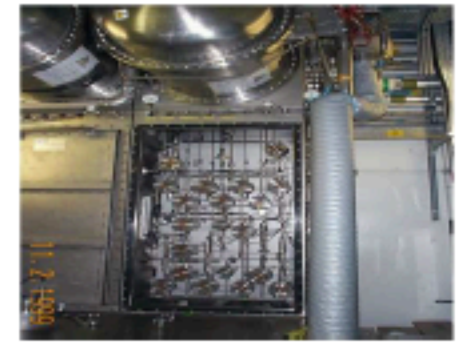
H3AT

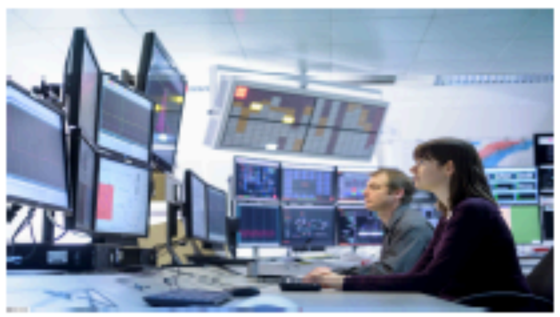
Building

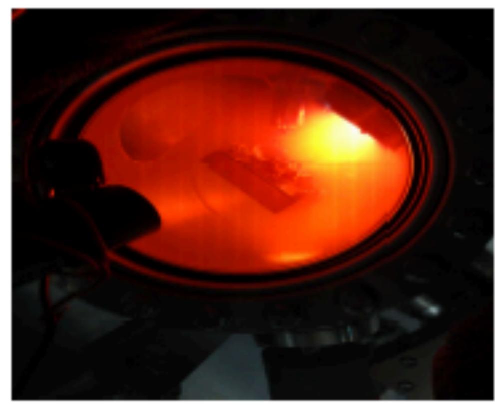
Experiments

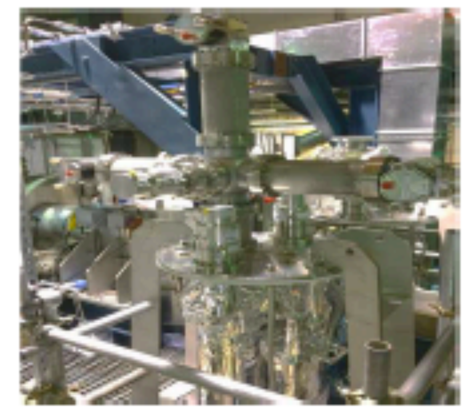
Tritium Systems

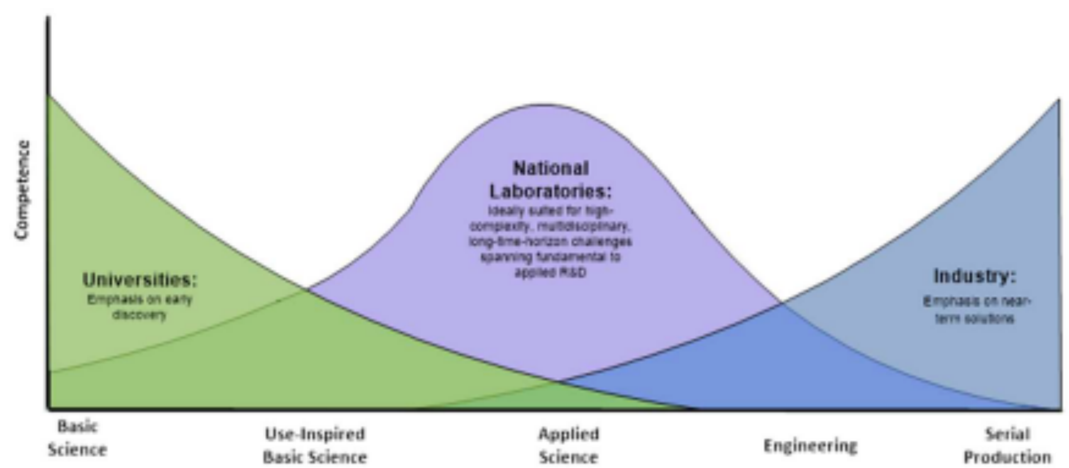


Control and Safety
systems









H3AT

- A £40M state of the art facility
- Up to 100g T2 inventory. No increase in site discharge authorisation.
- ITER like tritium fuel cycle able to operate in closed loop. Uranium bed storage and delivery, Impurity Separation, Cryogenic Distillation, Water Detritiation Systems.
- Fuel cycle feeds flexible test cells/gloveboxes for experiments/component qualification.
- Also contains tritium wet chemistry, solid waste detritiation and C-14 laboratory
- Inactive test space, office and training facilities.
- Interim H3AT in the Culham MRF. Target: H3AT facility open 2022.

Timeline