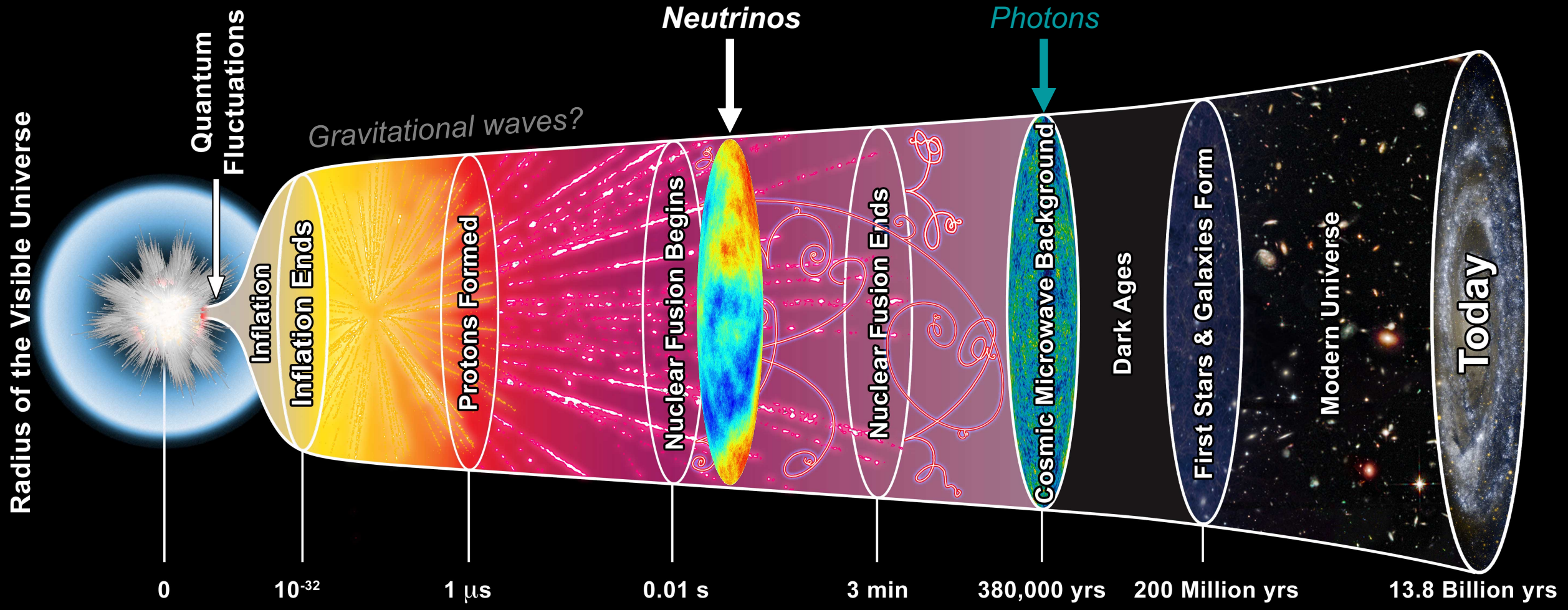
PTOLEMY:

Resolving relics from the early universe

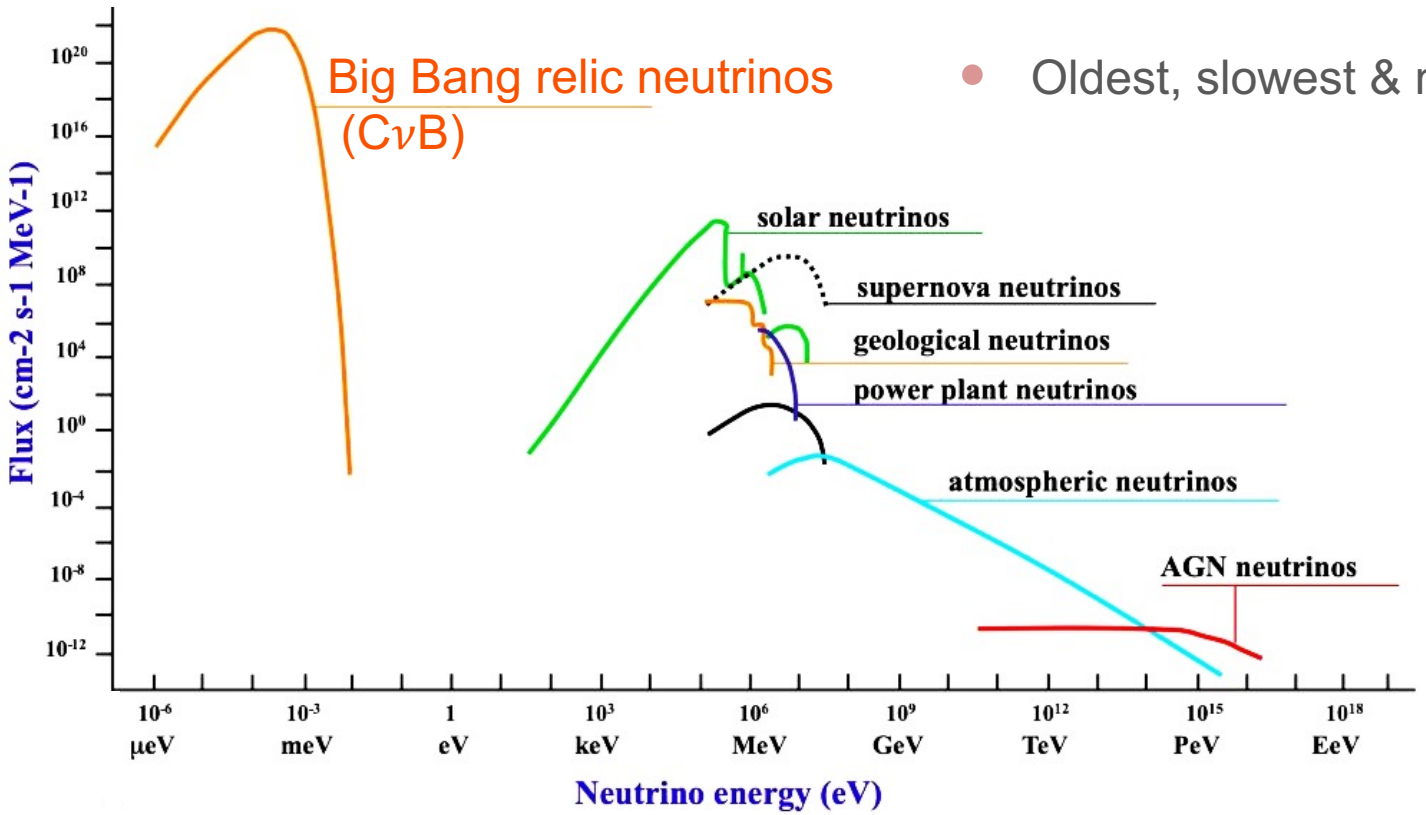
James Vincent Mead

Decoupling in the early universe



[cern]

Cosmic neutrino background



- Oldest, slowest & most abundant neutrinos in the universe

$$N_\nu = N_f \frac{3}{11} N_\gamma \Rightarrow \sim \mathbf{300/cm^3}$$

$$\langle v_{rms} \rangle \propto \frac{T}{m_\nu} > \mathbf{160\ km/s}$$

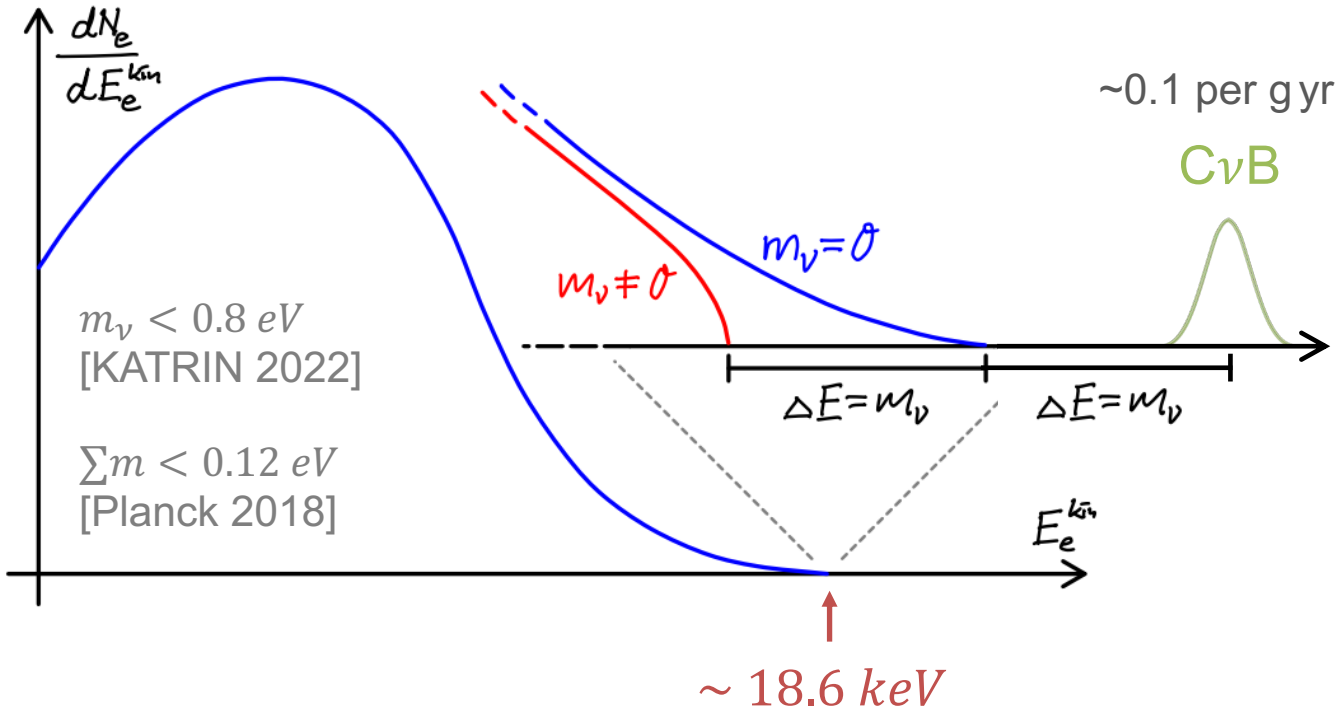
$$T_\nu(t) = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_{CMB} \Rightarrow \sim \mathbf{1.92K}$$

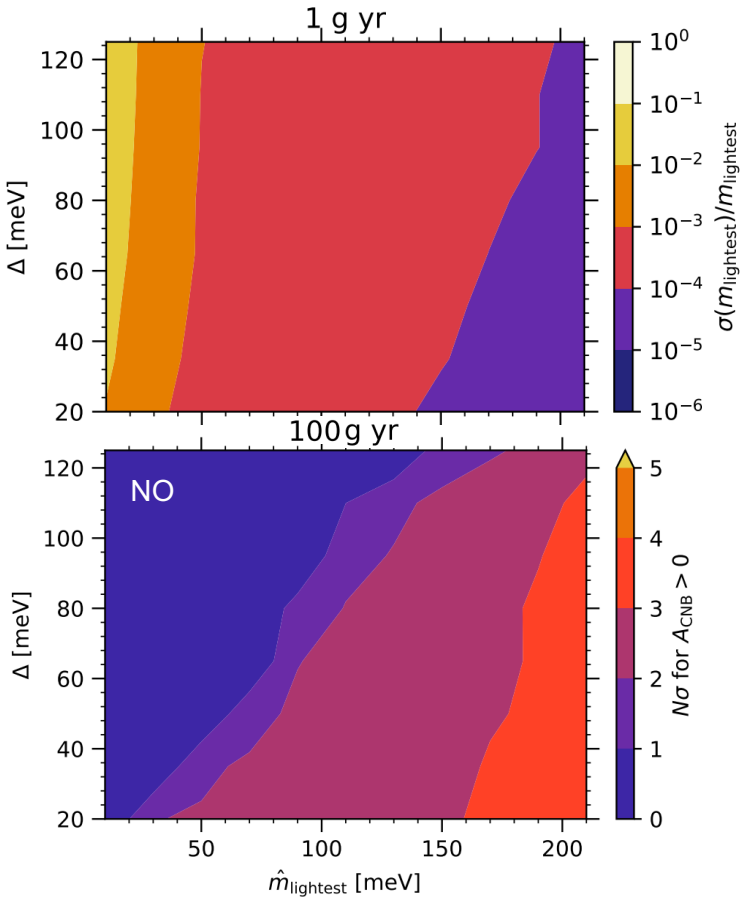
[arXiv:1910.11878v3]

Concept

- Principles established by Steven Weinberg in 1962

[PhysRev.128.1457]

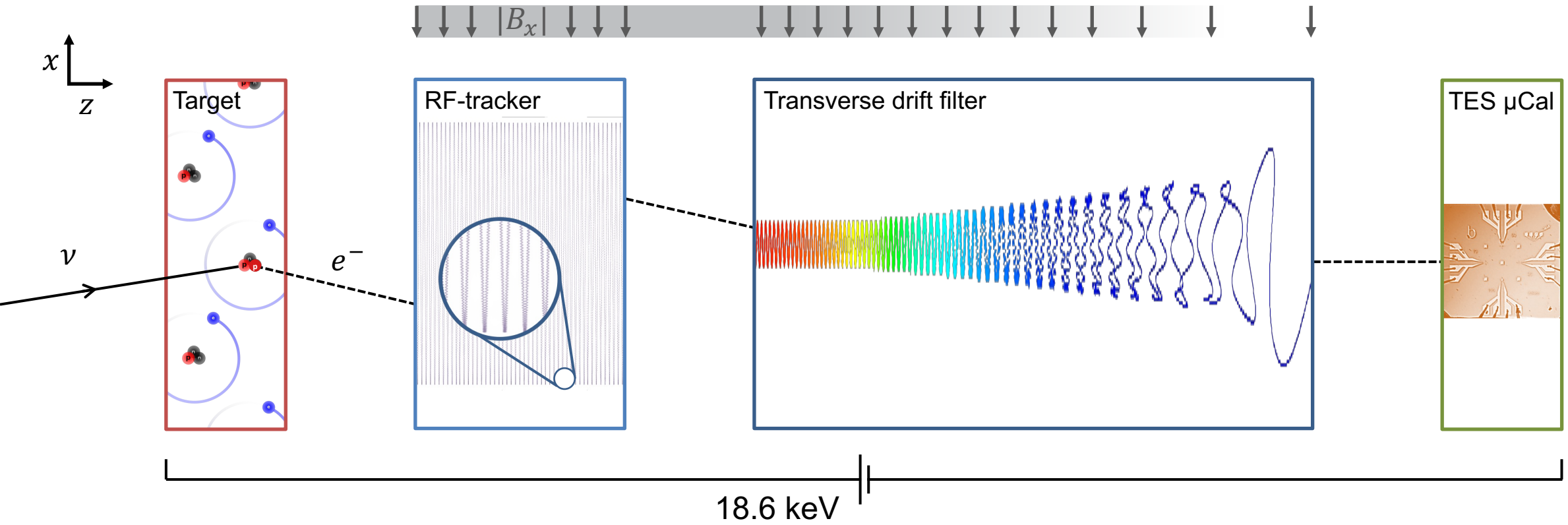




[FF Deppisch 2019]

[arXiv:1902.05508]

Pon**T**ecorvo **O**bservatory for **L**ight **E**arly-universe **M**assive-neutrino **Y**ield



$$E_{total} = q\left(V_{TES} - V_{target}\right) + E_{RF} + E_{cal}$$

Prototype roadmap

- ***Detector concept***
  - Target: Atomic tritium embedded on graphene $m \sim \mathcal{O}(100g)$
  - Trigger: Single-electron CR-based tracking $\sigma(E_x) \sim \mathcal{O}(eV)$
  - Filter: EM ‘transverse-drift’ filter $\Delta E_T \sim \mathcal{O}(100meV)$
  - Calorimeter: Cryogenic transition edge sensor $\sigma \sim \mathcal{O}(10\ meV)$

- ***Aims***
  - Prototype at Gran Sasso National Lab (LNGS) in 2023
  - Intermediate measurement of lowest neutrino mass
  - CνB physics runs in 2030s

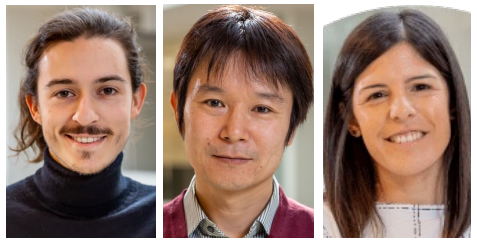
PTOLEMY at GRAPPA / Nikhef

AP Colijn

Saad El Morabit

Particle physicists

Fabian Zimmer Camila Correa

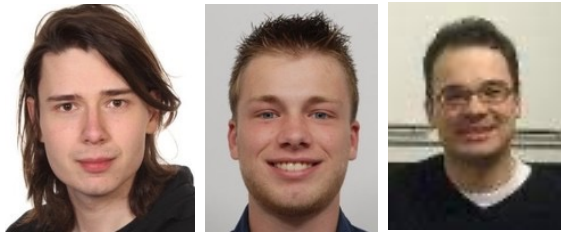


Shin'ichiro Ando

Theorists

Influence of local structure on relic neutrino abundances and anisotropies
[arXiv:2306.16444] – 28/06/2023

Michael Naafs



Pascal Bosch Guido Visser

Electronics engineers

Vincent van Beveren

Tony Damen

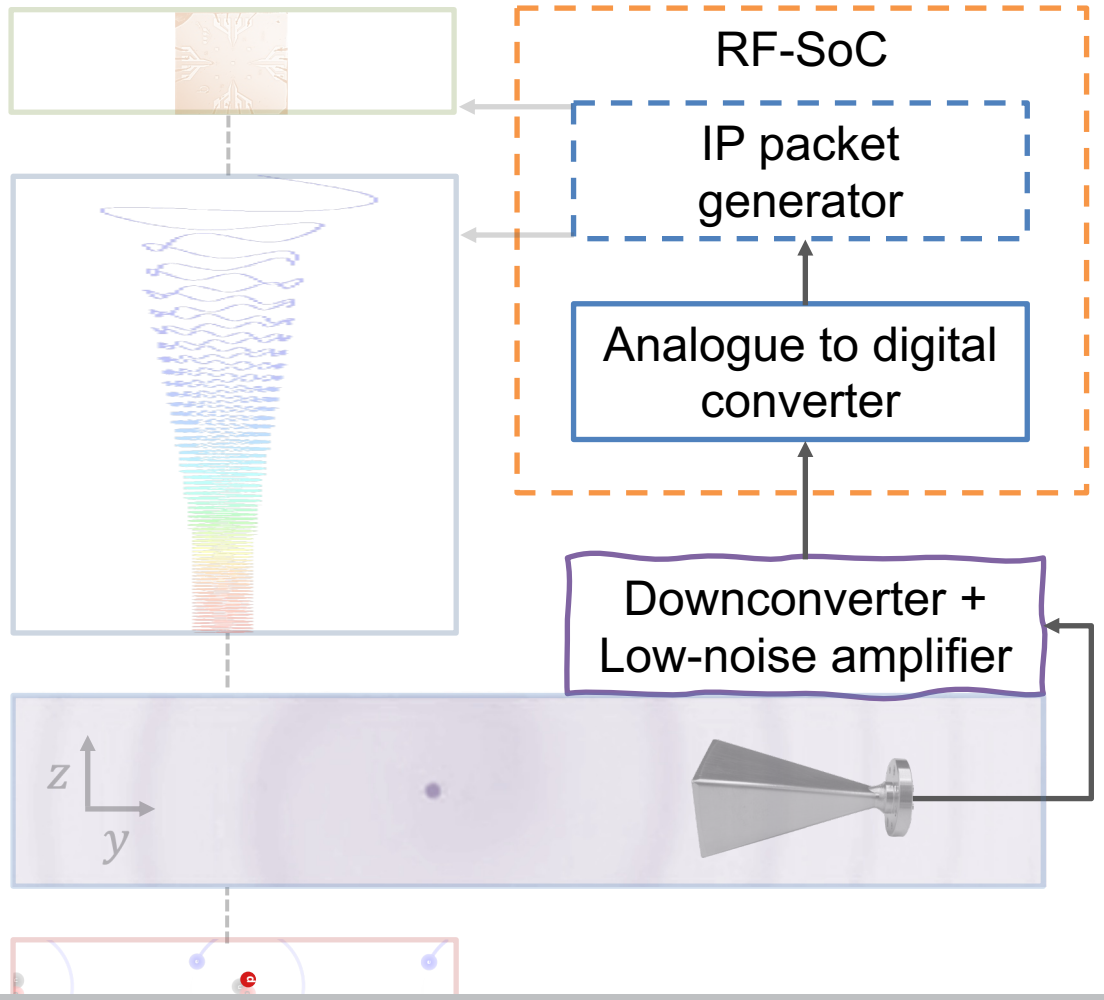
Software engineers

Martin Adams

Mechanical engineers

Readout & Electronics

- ***Synthetic signal***
  - 27 GHz central freq., fW emission, $\mathcal{O}$(μs) length
  - Approximate CR to test electronics & antennas
- ***Loop test***
  - FPGA transmits & receives simultaneously
  - Testing shielding & characterising noise
  - Measuring losses and interference
- ***Baseline for evolving test setup***
  - Explore antenna power feasibility threshold
  - Test impact of cavity and potential-shaping elements on CR-signal



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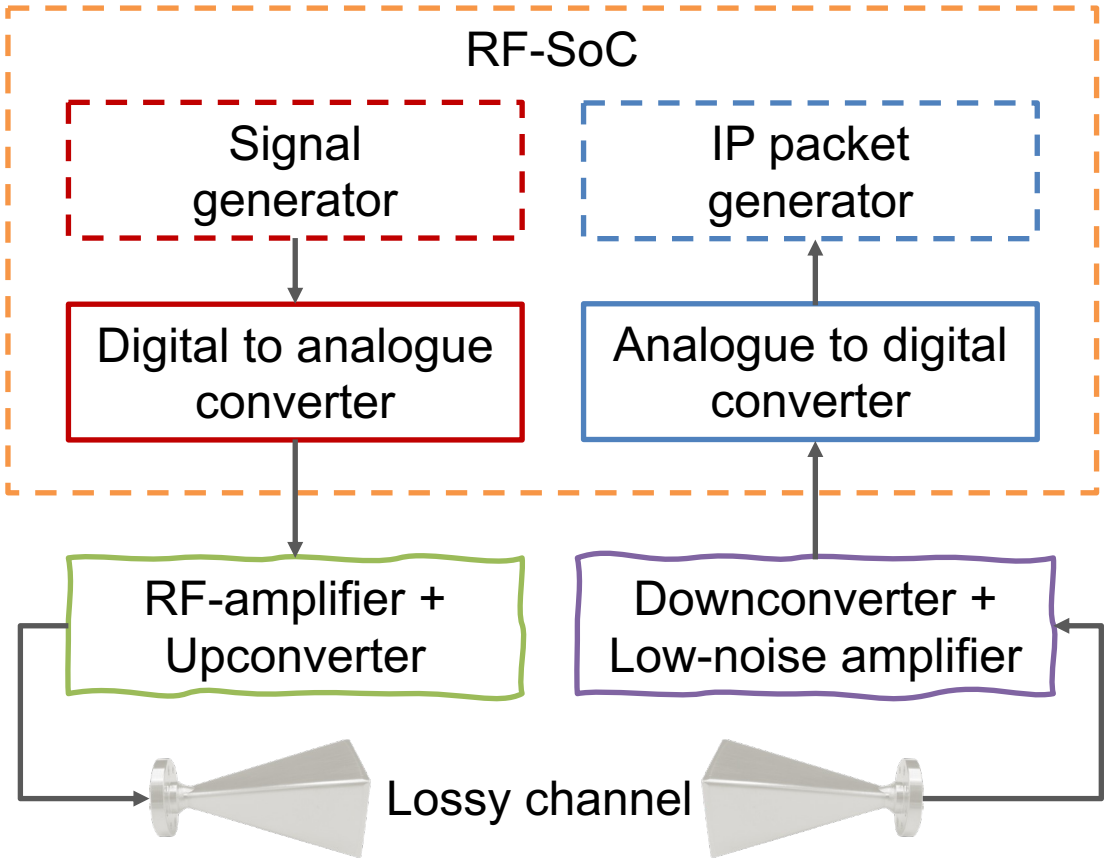
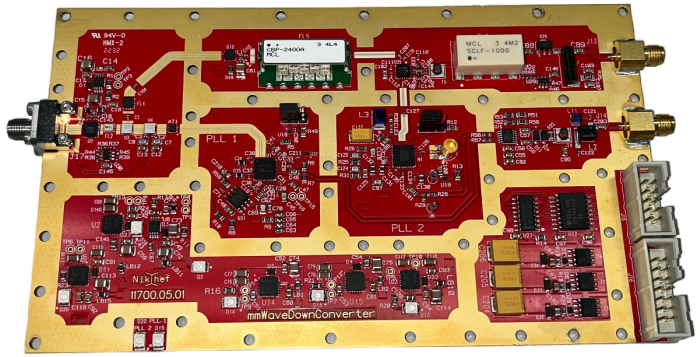
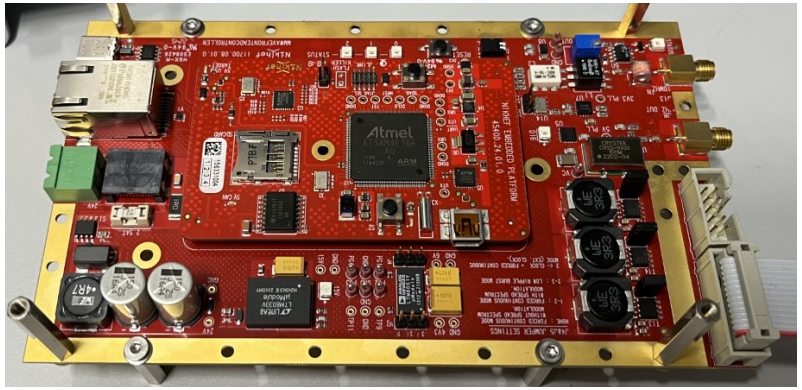


Hardware progress

Downconverter board

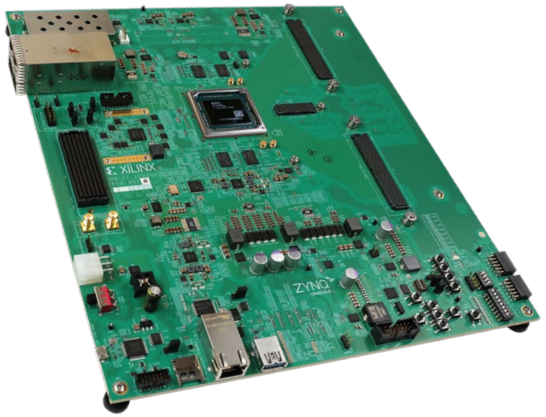


Front-end control board



Shielding

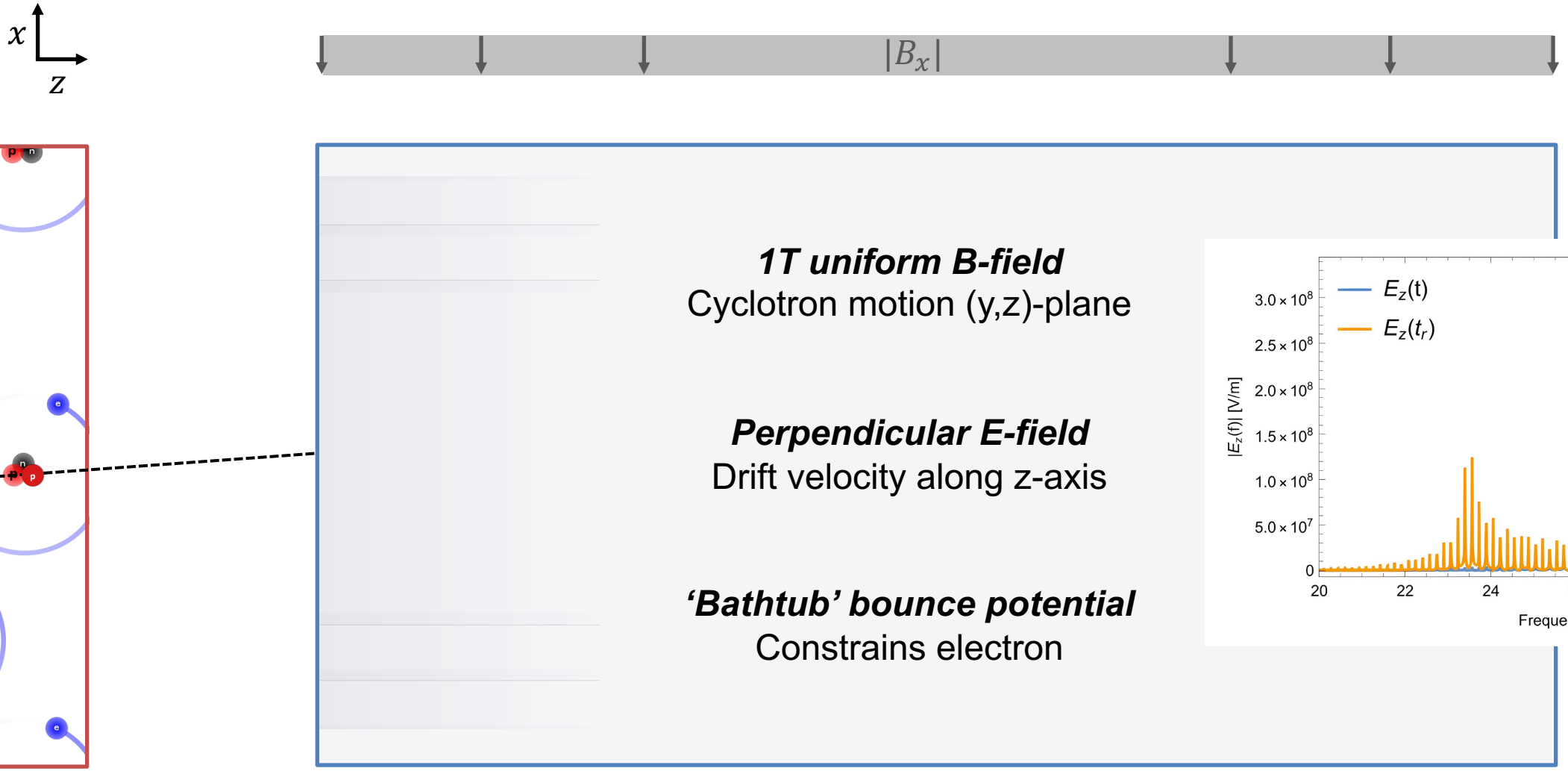
FPGA evaluation board



Cases (Nikhef branding included)

- New control board – Summer
- Enclosure – Autumn
- Upconverter – Autumn
- ‘Lossy channel’ – Investigating
- Vacuum chamber – Investigating
- Cryogenics – Investigating

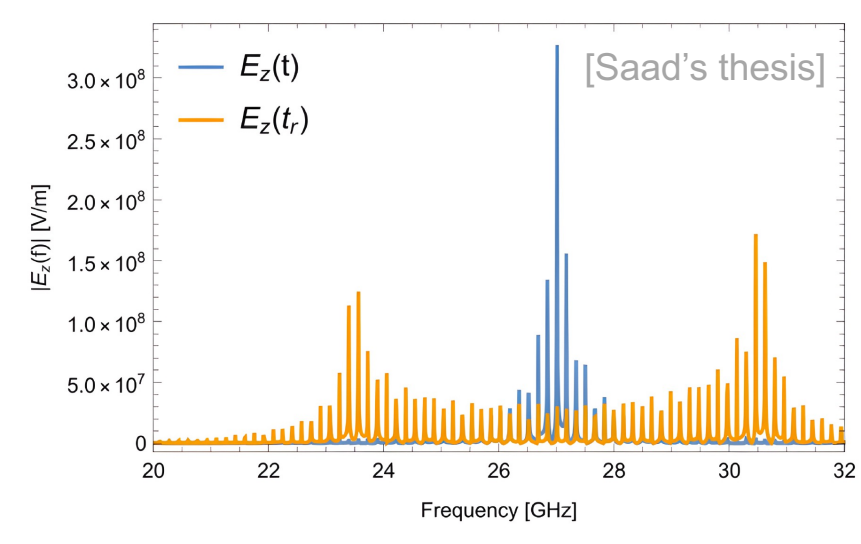
RF cavity



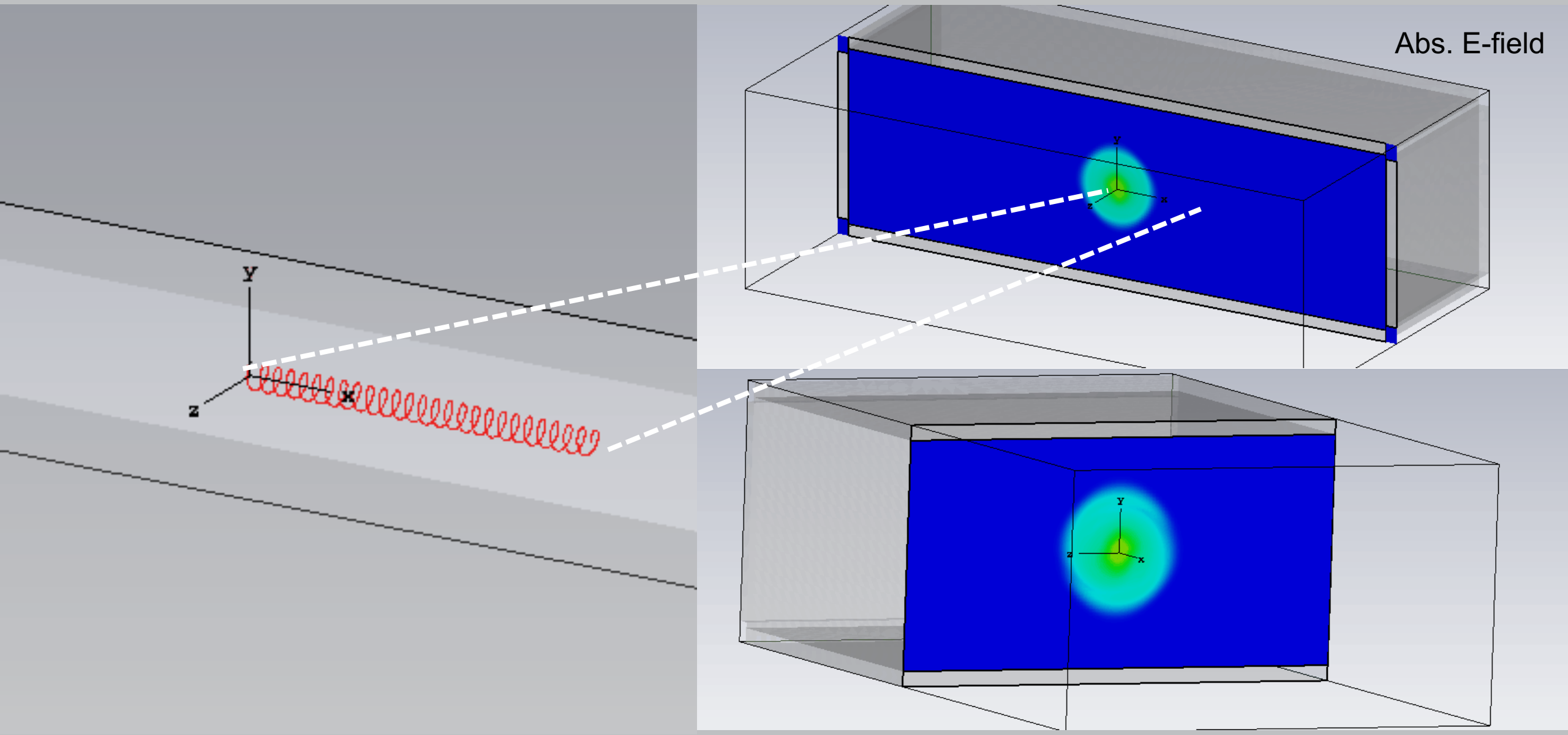
1T uniform B-field
Cyclotron motion (y,z)-plane

Perpendicular E-field
Drift velocity along z-axis

'Bathtub' bounce potential
Constrains electron

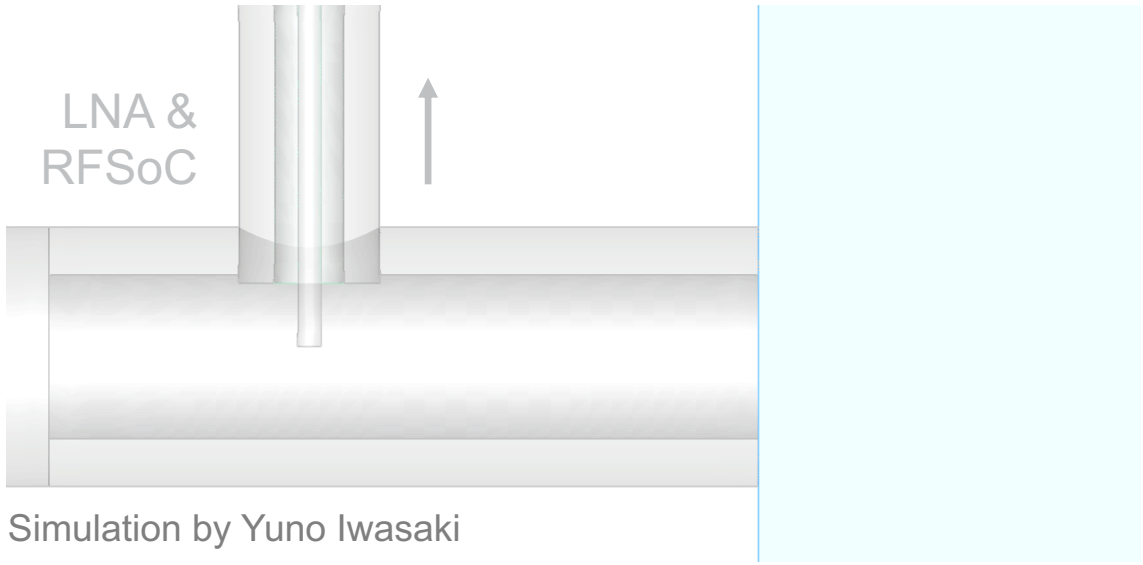


Cyclotron radiation in a rectangular waveguide

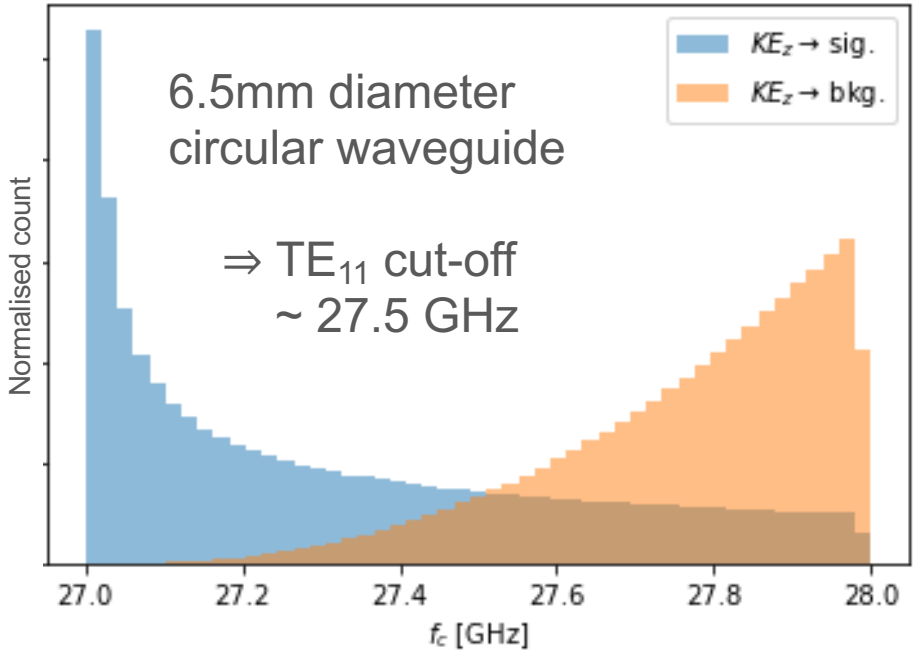


RF-cavity studies

- Plane-wave producing excitations in the x-facing waveguide to coaxial cable



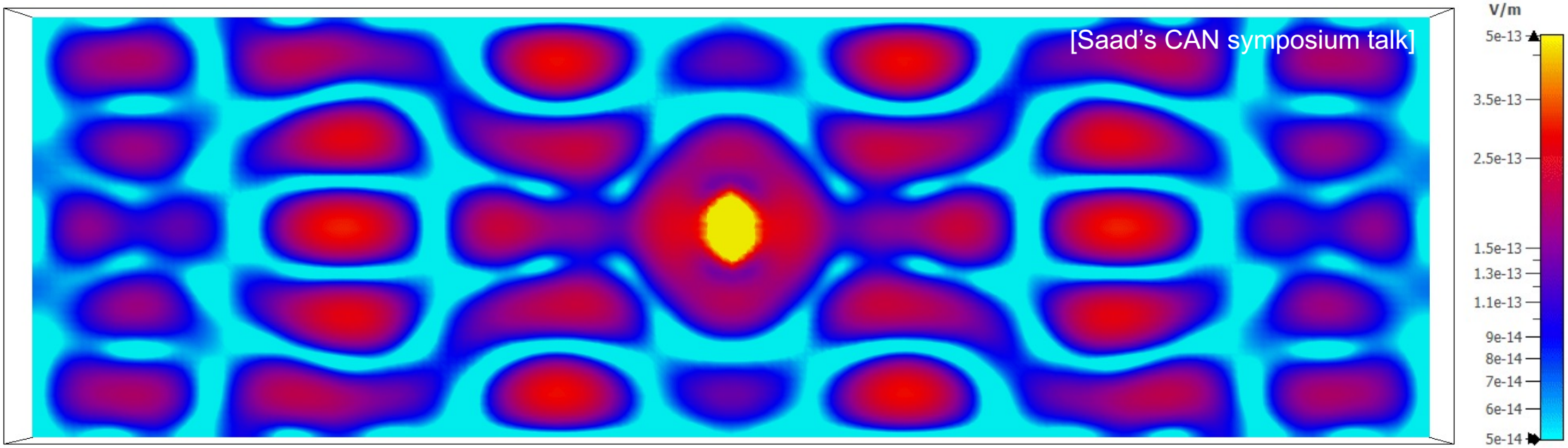
Simulation by Yuno Iwasaki



- Dimensions of waveguide may be chosen to supress decay-event cyclotron emissions

RF-cavity studies

- *E*-field excitations in a rectangular cavity (x,y)-plane from 18.6 keV e^- orbiting [0,0,0]

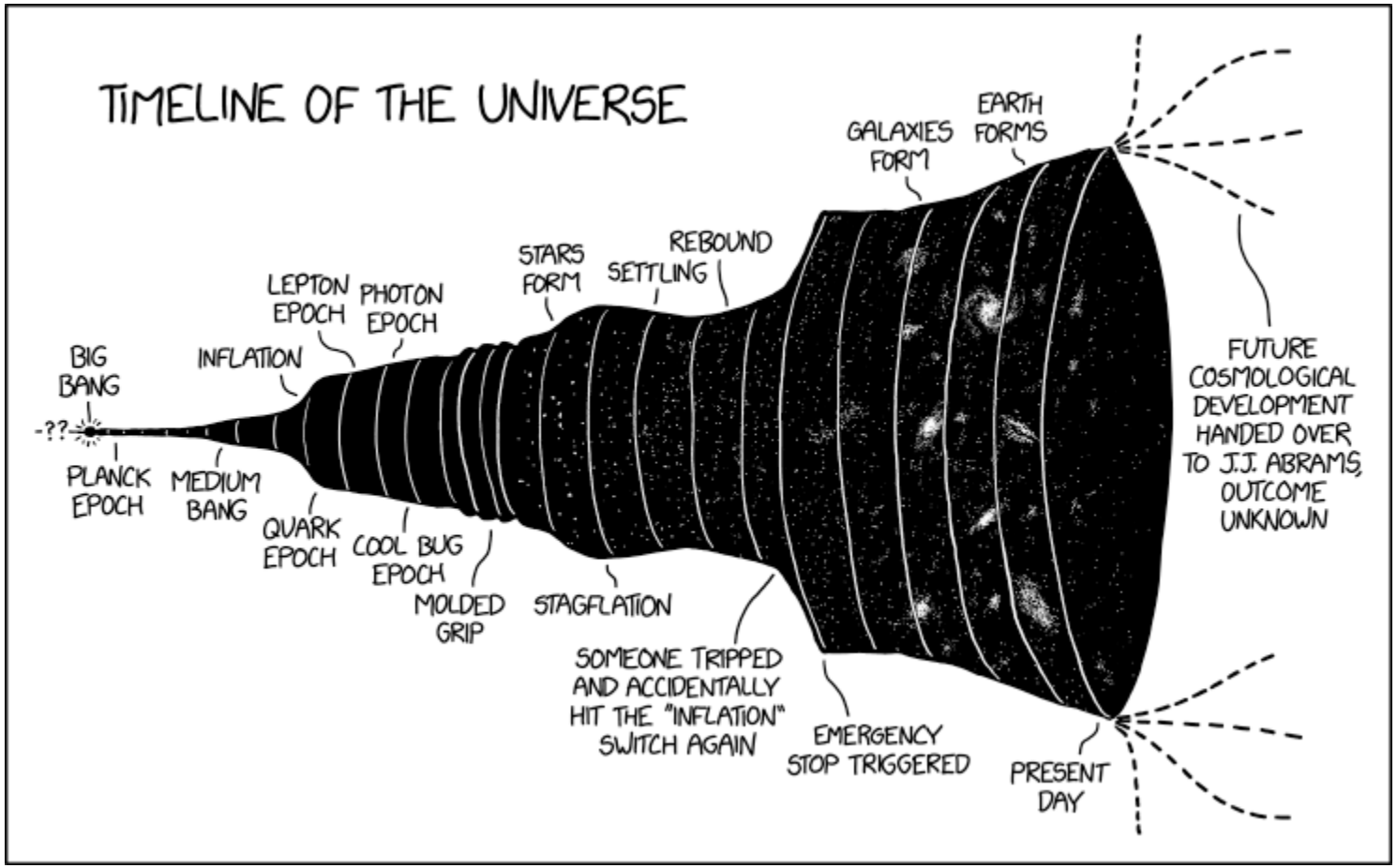


- Mode decomposition will help us optimise cavity & antenna system design

Conclusion

- ***High risk, high reward***
  - Array of novel R&D challenges yet to overcome
  - Intermediate determination of the lowest neutrino mass
  - First observation of the CνB
- ***Nikhef have critical involvement on the RF-system***
  - Local expertise of the electronic engineers for HF-analogue systems invaluable
  - Investigating status of 1T magnet at Nikhef and vacuum chamber $\mathcal{O}(10K)$ cooling system
  - External collaborators from TNO providing antenna and signal processing expertise
- ***PTOLEMY prototype soon to be based at LNGS***
  - Closer ties being established with KATRIN, Project-8 and QNTM - CRESDA
  - Stay tuned for future developments!

Thanks for listening!

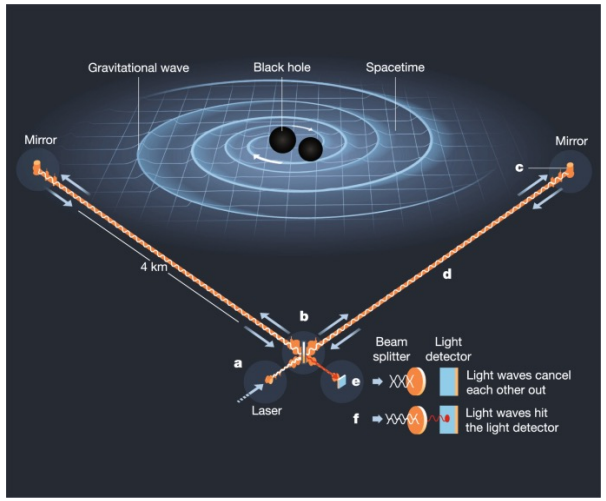


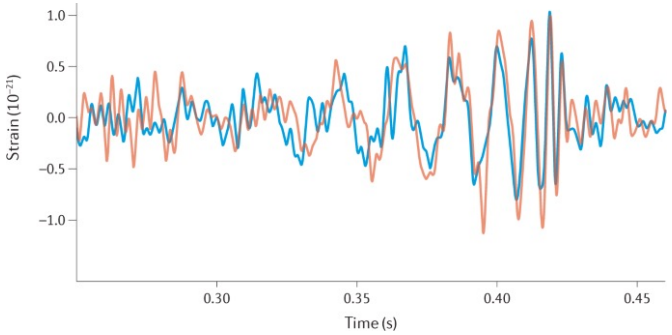
[xkcd.com/2240]

Windows onto the cosmos

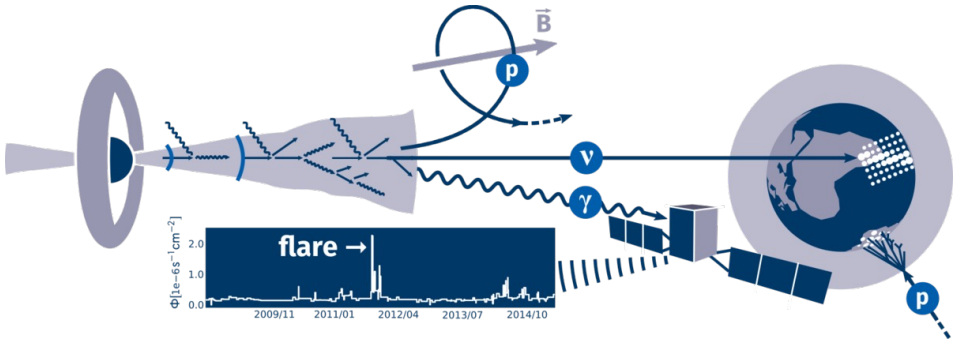
Gravitational waves

[10.1038/s41586-019-1129-z]

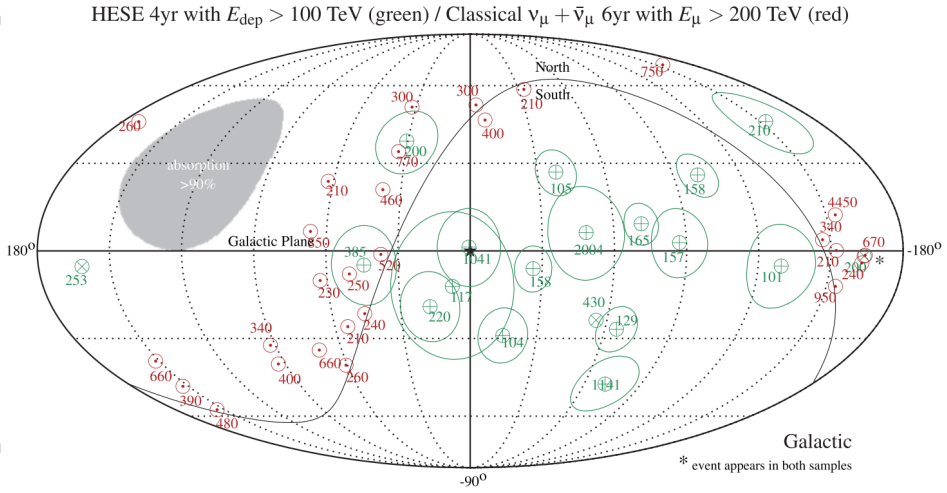




Neutrinos

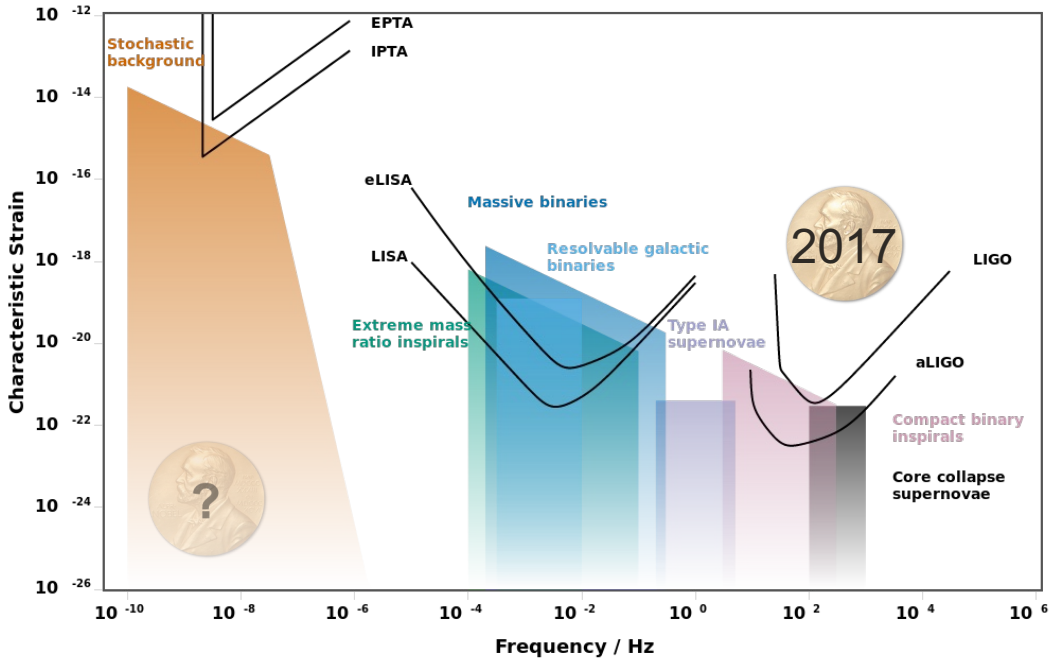


[arXiv:1805.11112v1]



Ancient and in abundance

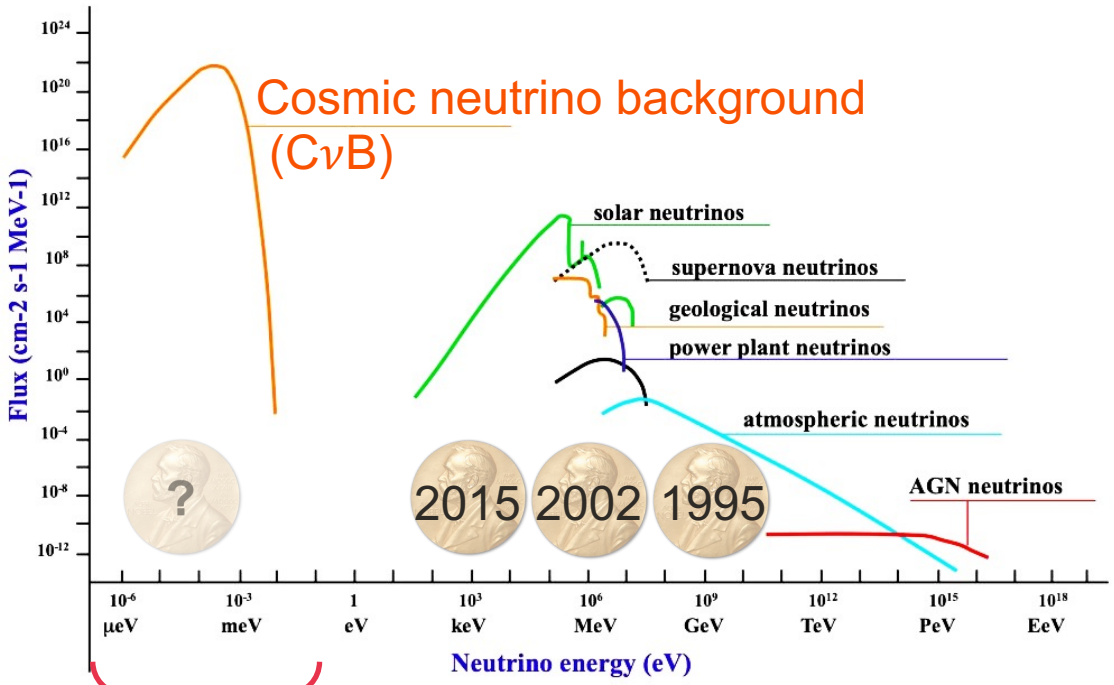
Gravitational waves



Primordial gravitational waves

[arXiv:1408.0740v2]

Neutrinos

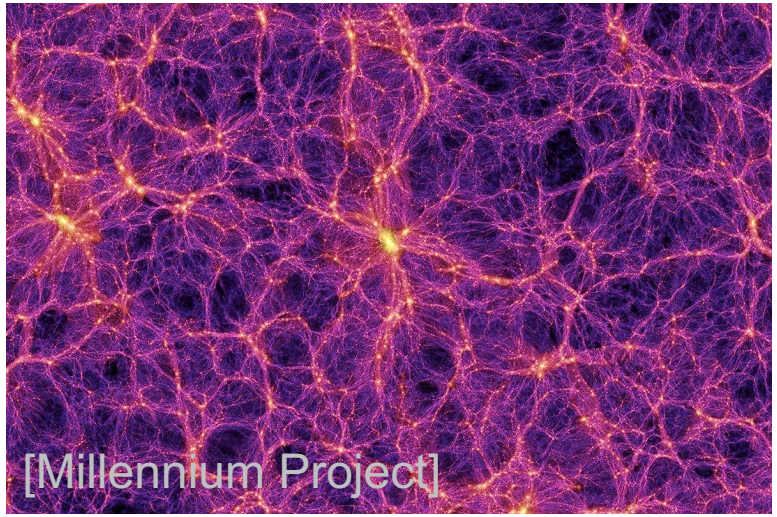


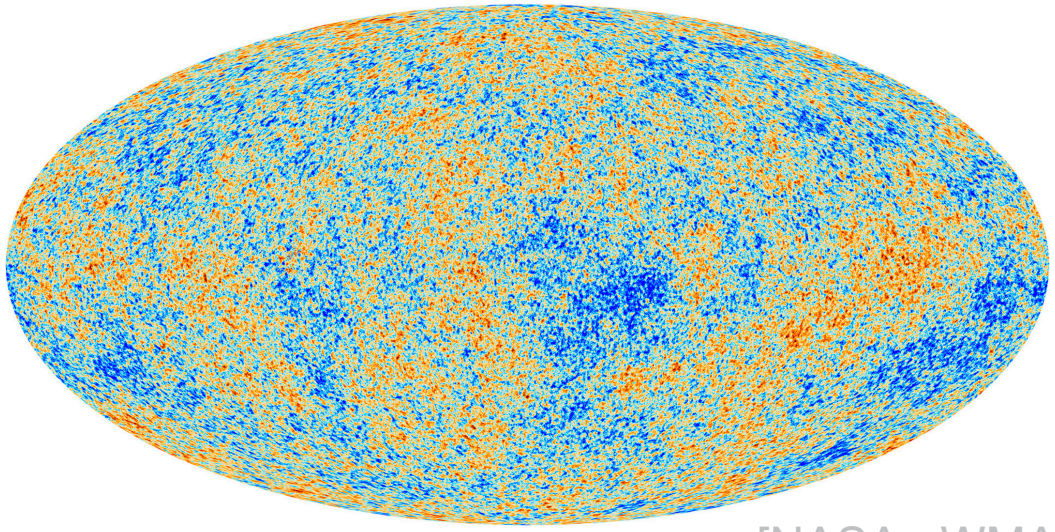
Big Bang relics

[arXiv:1910.11878v3]

Imprint upon the cosmos

- Primordial sound waves (baryon acoustic oscillations) seed large scale structure reflected in the CMB





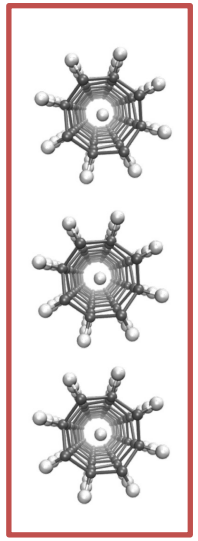
[NASA - WMAP]

- Anisotropies in the CνB result in phase variations which damp the angular power spectrum of the CMB

Frankenstein's monster

Atomic Tritium

Target

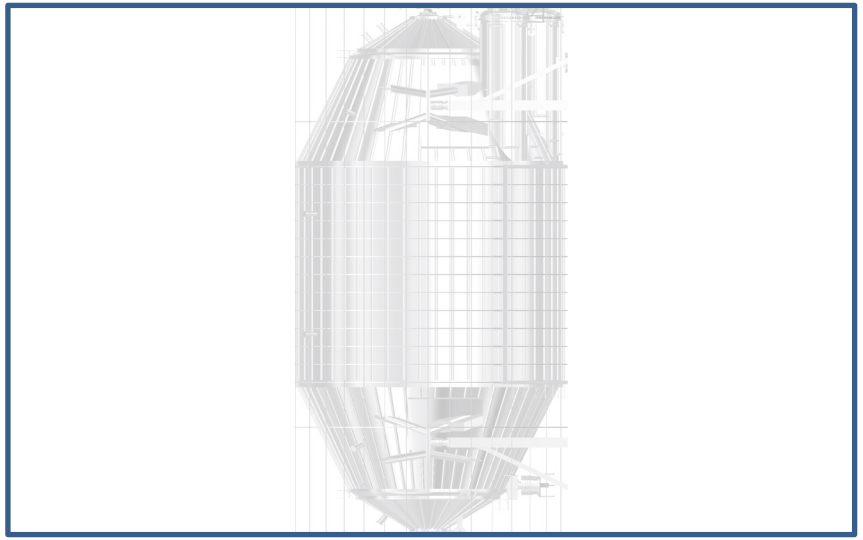


Project 8

CRES

KATRIN

MAC-E filter

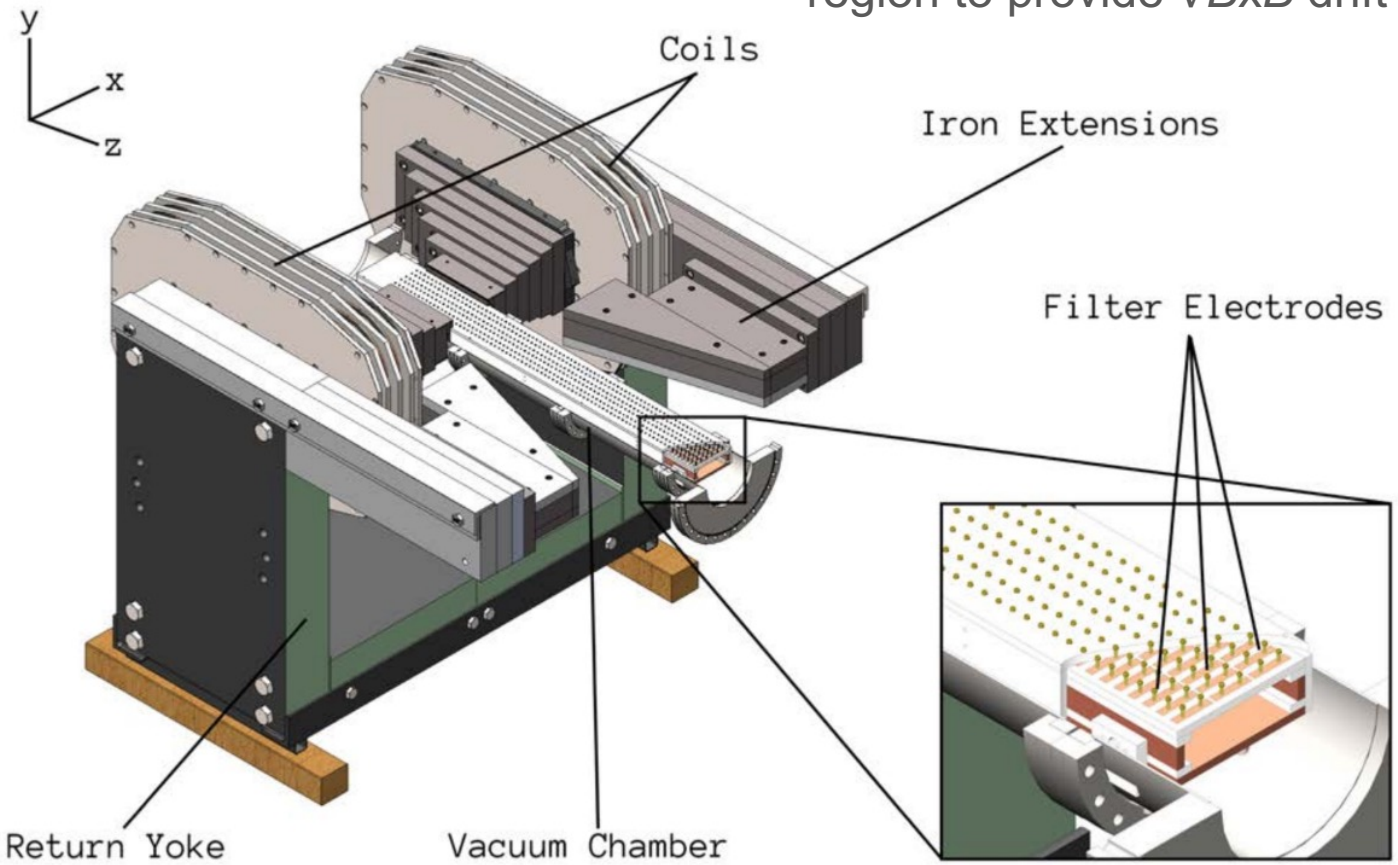


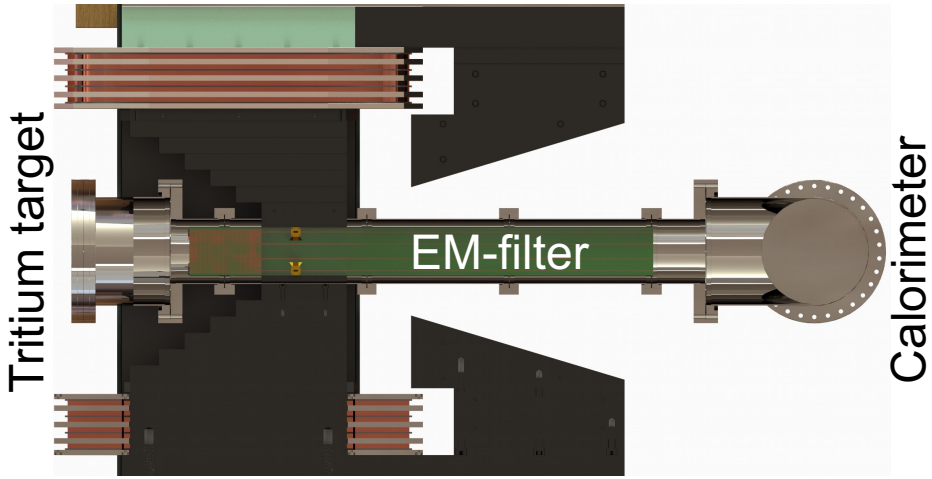
HOLMES

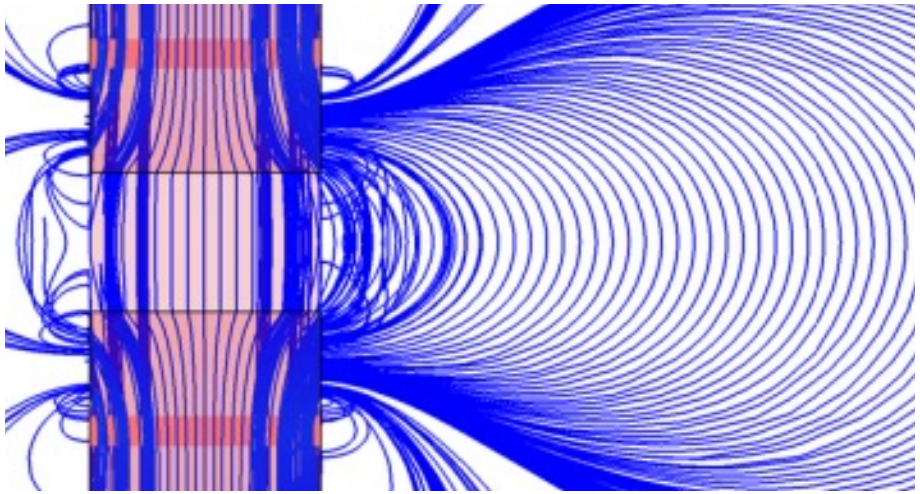
Cryo-calorimeter

Continuous magnetic field

- *B*-field in RF region is constant while extending over EM-filter region to provide ∇*B*x*B* drift

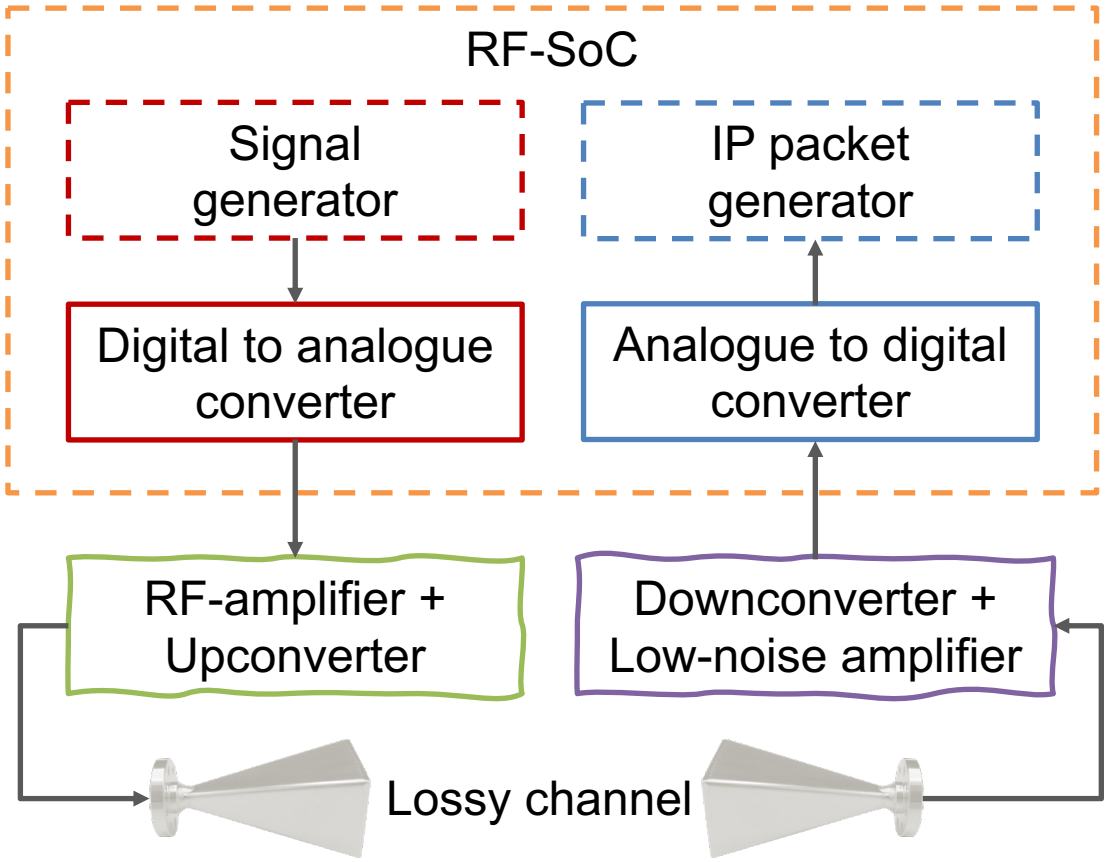






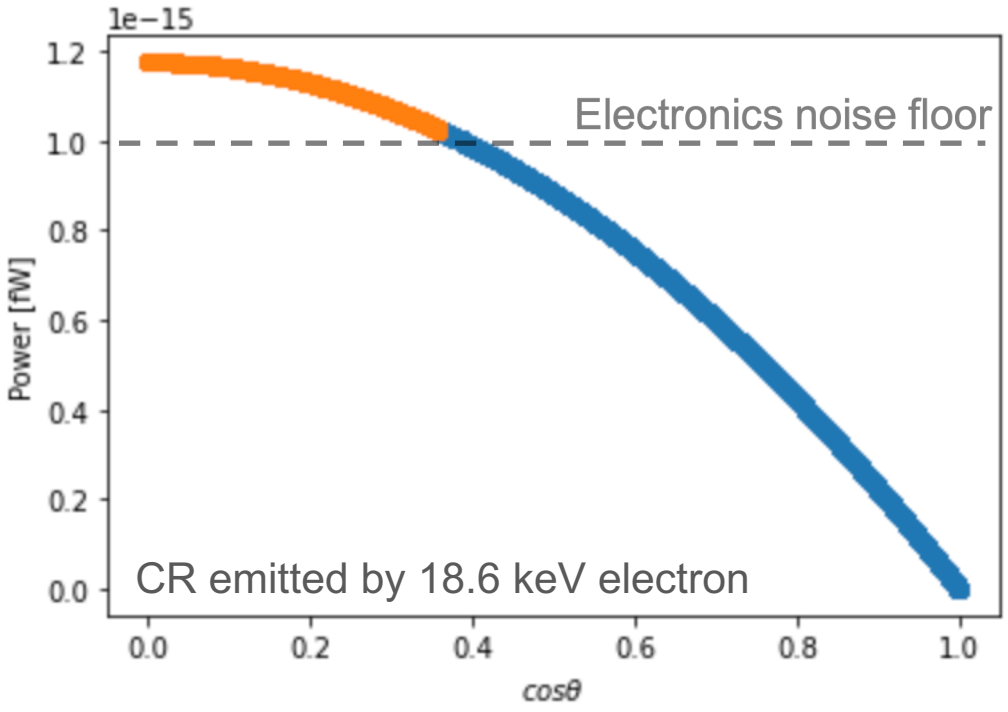
RF-SoC roadmap

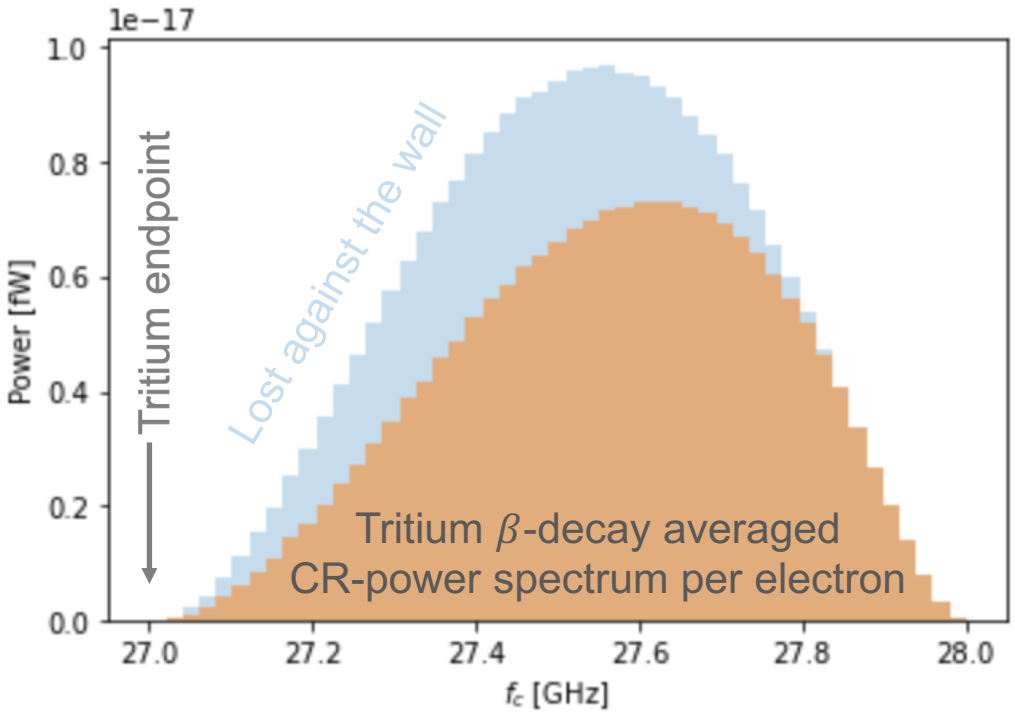
- ***Loop test requirements***
  - Upconverter + attenuators
  - Transmitter & receiver
- ***Vacuum chamber R&D***
  - Feed-throughs (coax & LNA)
  - Cooling for LNA & vacuum chamber O(10K)
- ***Ambitions***
  - High-power test in air
  - Characterise electronics noise
  - Gain measurement for LNA
  - Test noise figures (incl. thermal noise)



Tritium RF-power spectrum

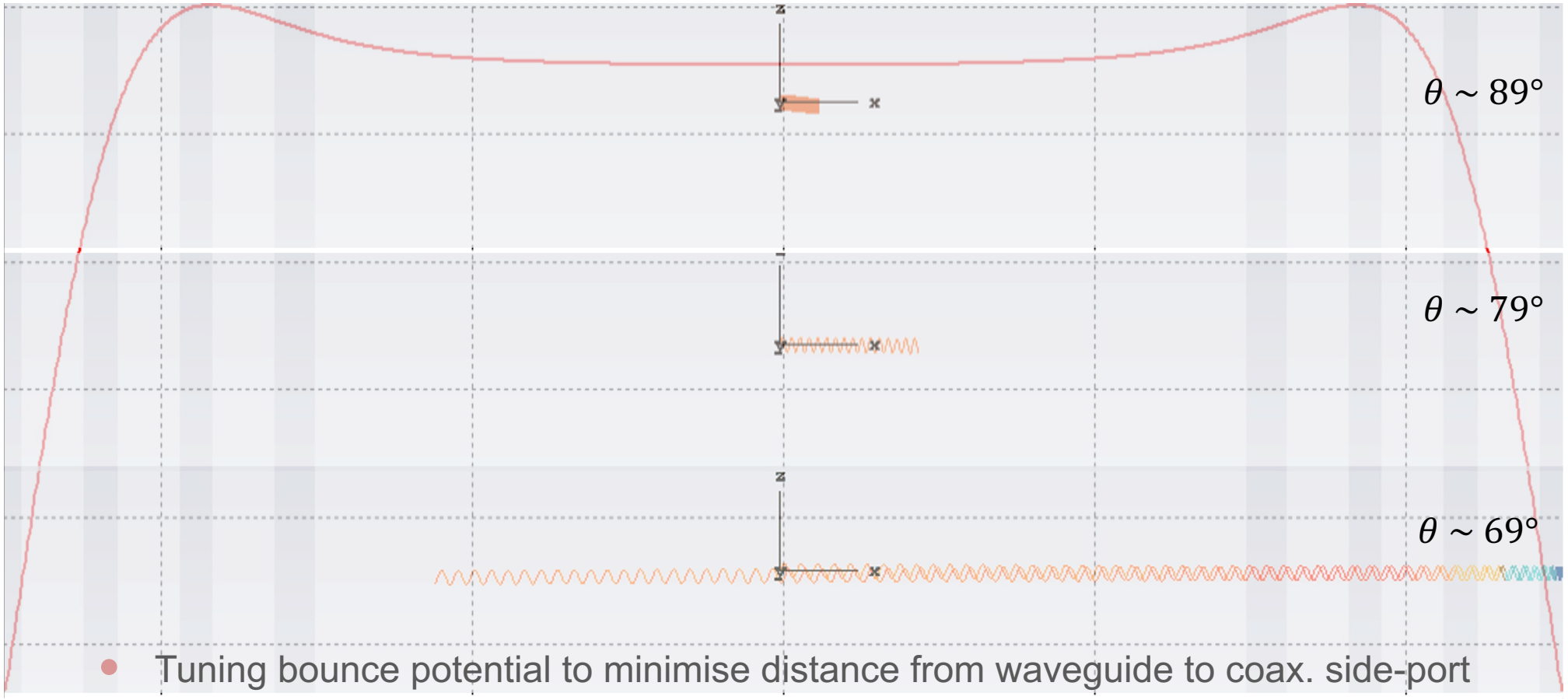
- Angle between *B*-field and electron's motion is the pitch, θ





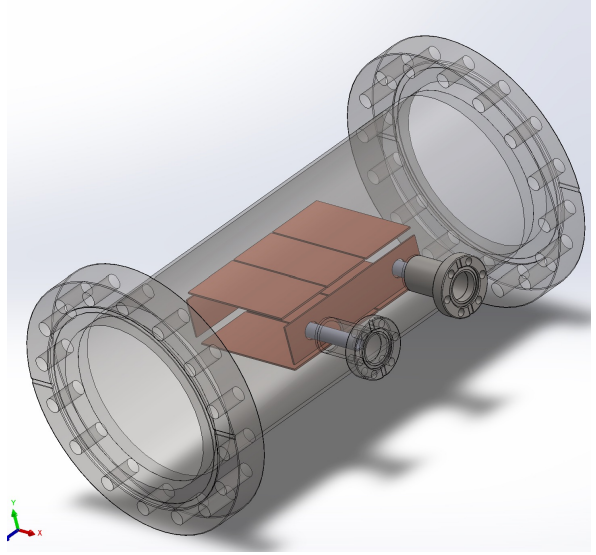
- Bounce potential can be used to discard some fraction of background on 1st bounce

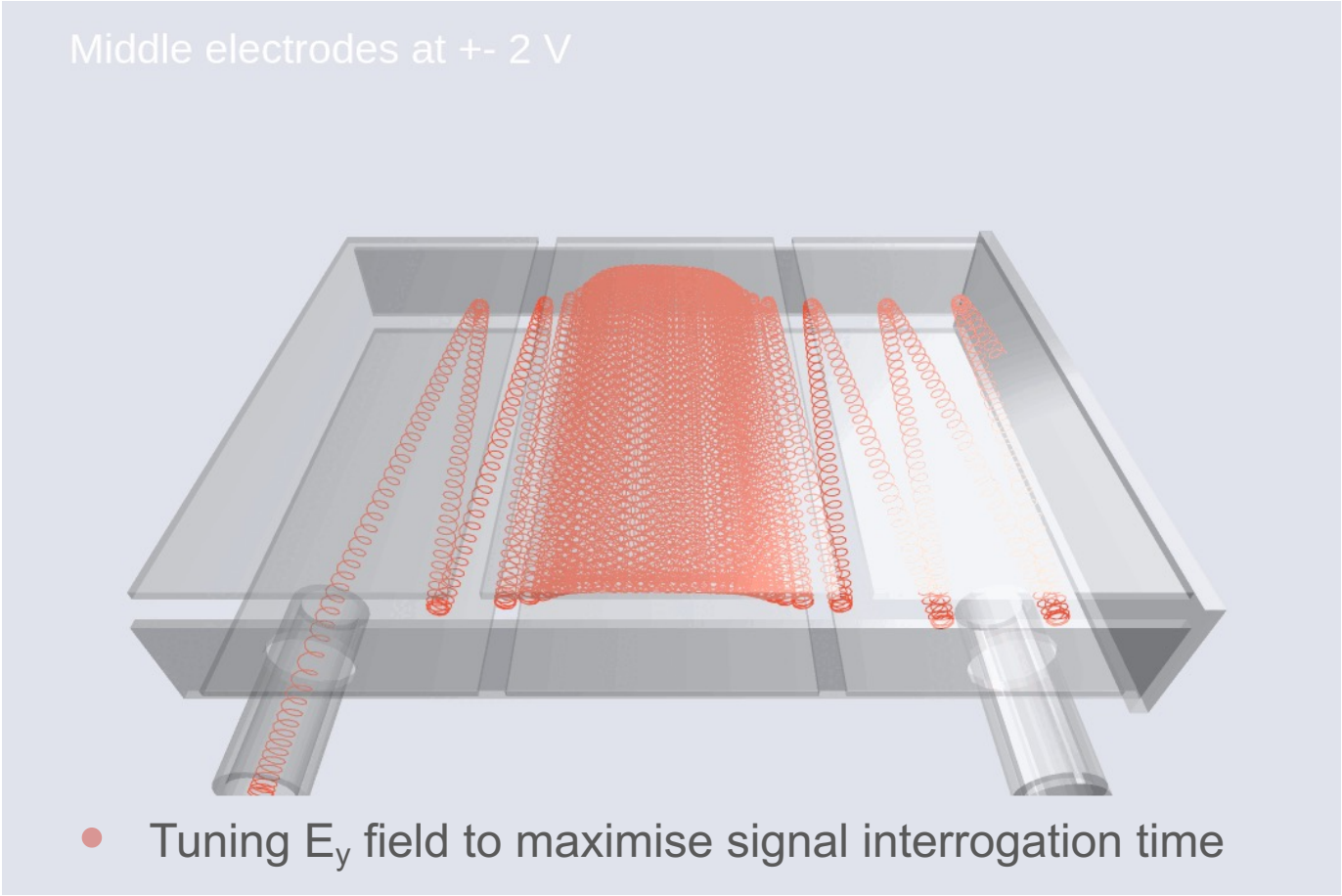
Potential shaping for high pitch electrons



- Tuning bounce potential to minimise distance from waveguide to coax. side-port

Slow ExB drift region

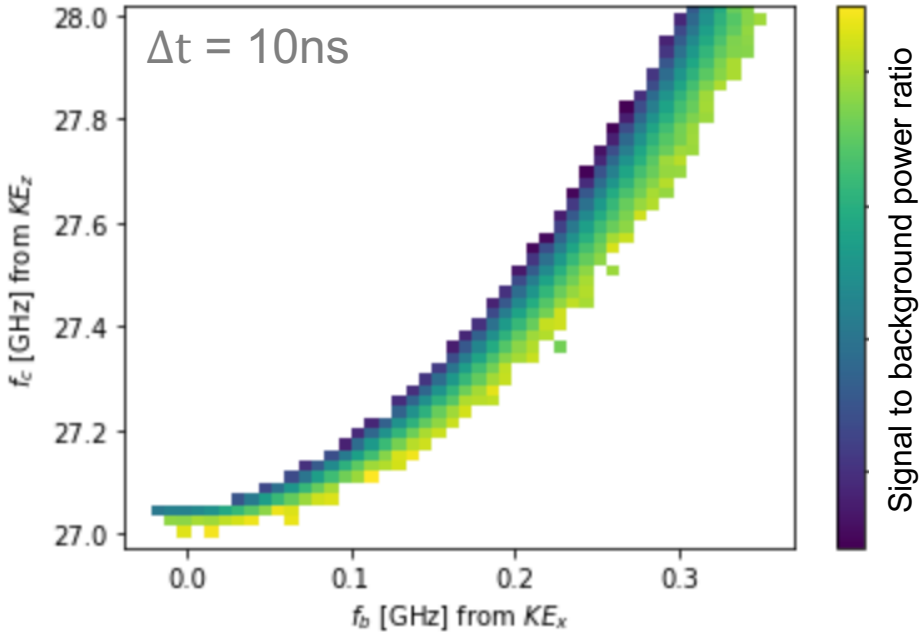


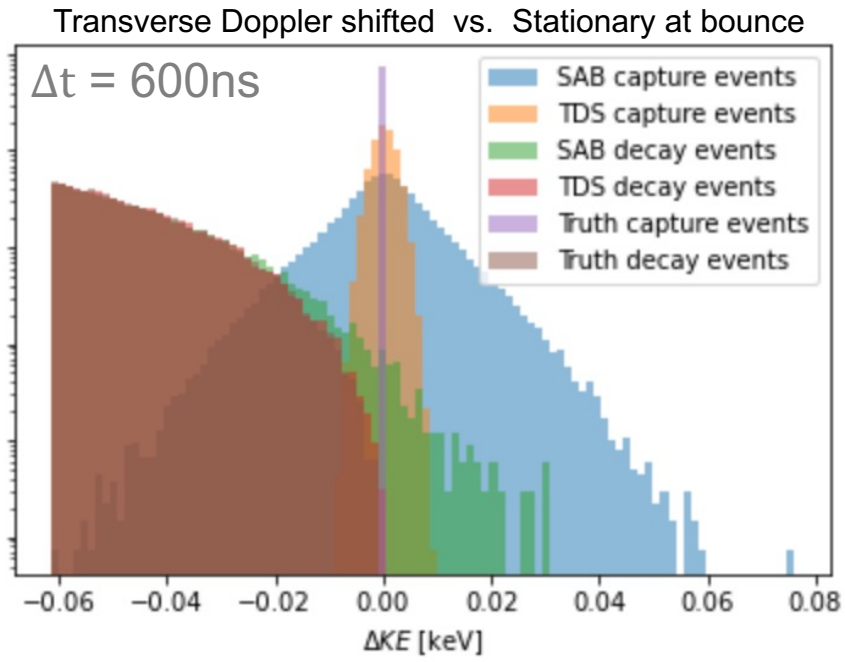


- Tuning E_y field to maximise signal interrogation time

Extracting signal & determining kinematics

- Signal has restriction on f_c to f_b interrelationship not shared by majority of decays



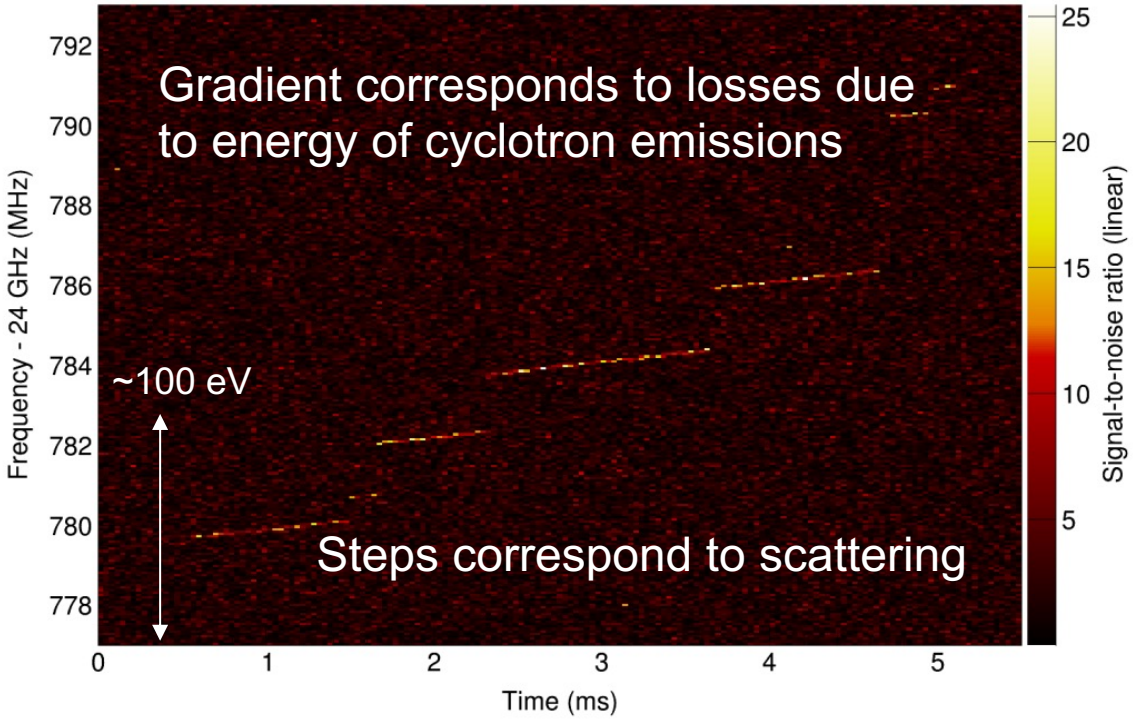


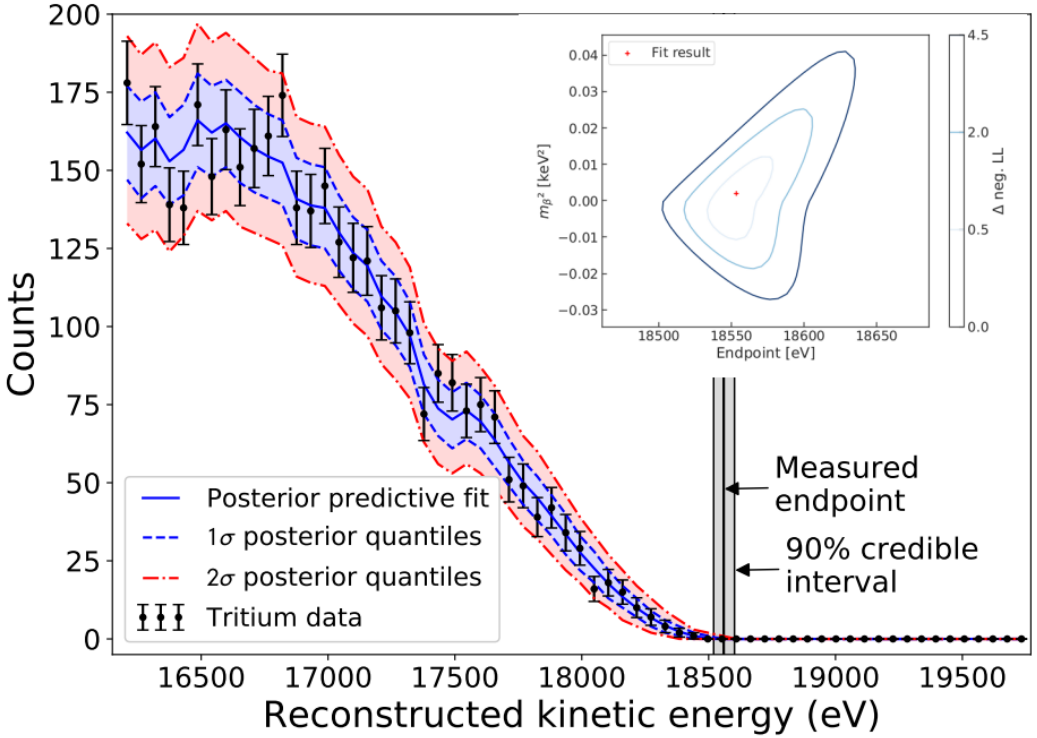
- Precision limit $\Delta t \Delta f \geq \frac{1}{4\pi}$ where, assuming a coherent source, Δt between first & last bounce

Project 8's proof-of-principle

- Using CR emission spectroscopy to interrogate trapped tritium gas

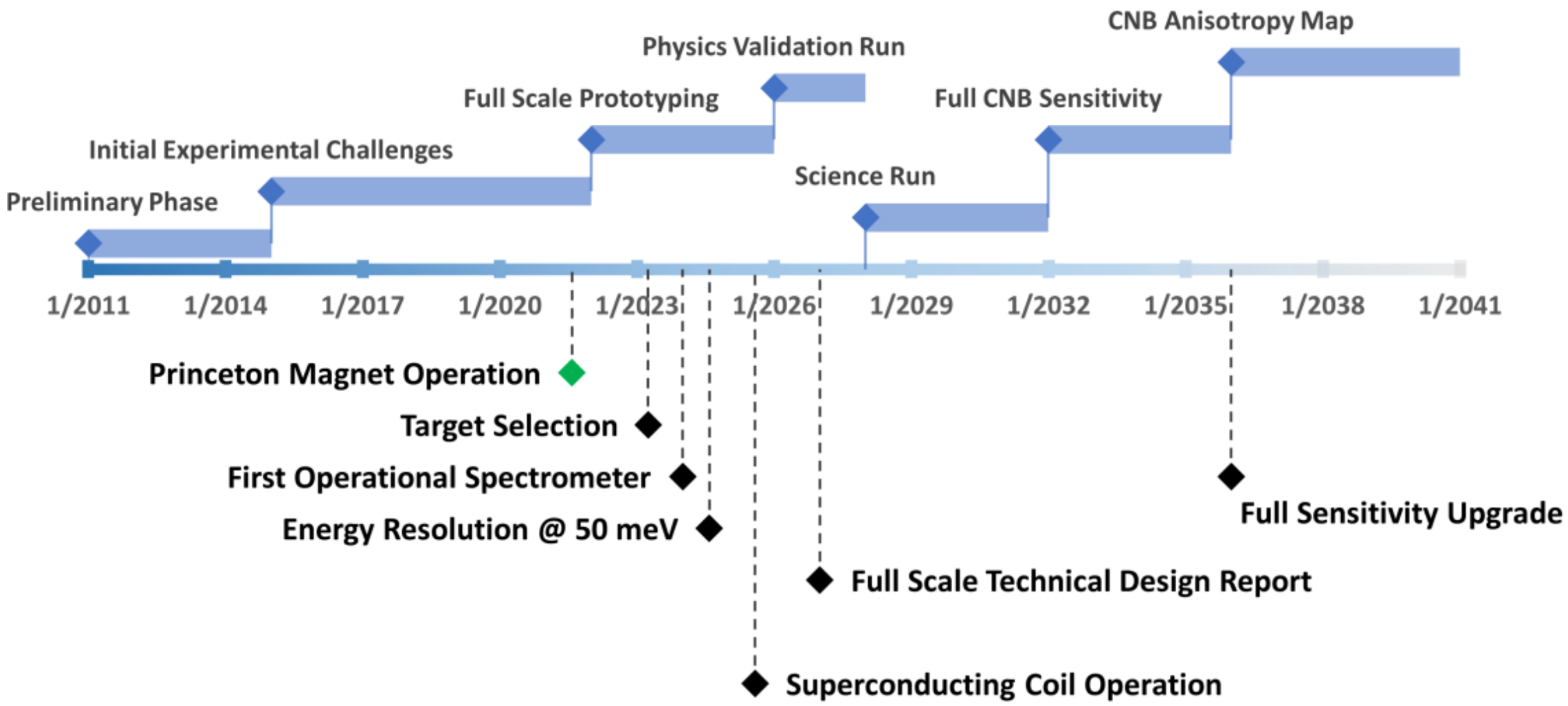
[arXiv:2203.07349]





- Constraint of $m_\nu < 0.04\ eV$ expected by Phase IV

Optimistic Ptimeline



PTOLEMY across the Netherlands

RU

Nicolo de Groot

Inge van Rens

Nicoleta Laurenciu

Oleksandr Zheliuk

Uli Zeitler

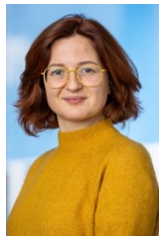
Particle physicists

Electronic engineering

High Field Magnet Lab

Leiden

Vadim Cheianov



Oleksii Mikulenko

Alexey Boyarsky

Yevheniia Cheipesh

Theorists

PTOLEMY around the world