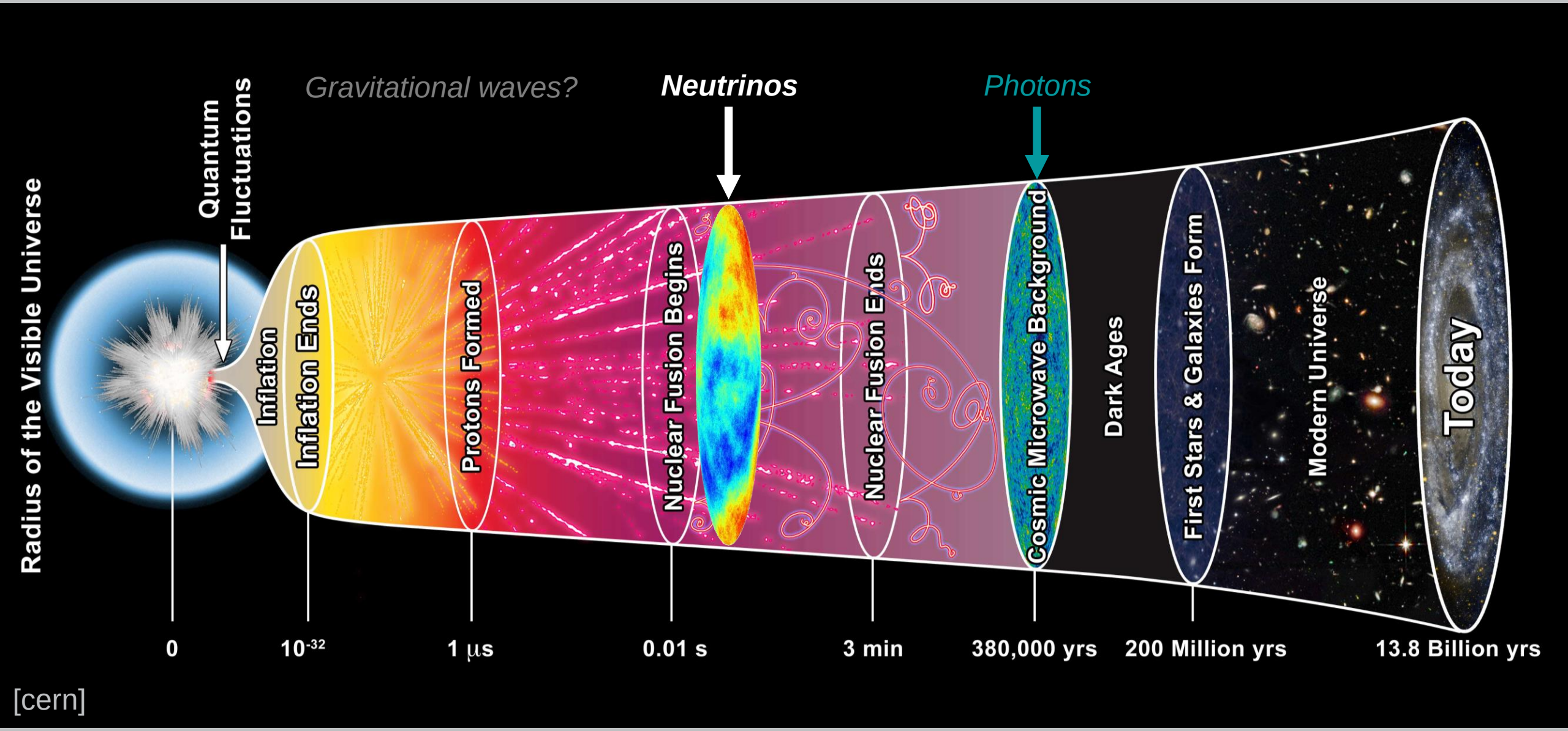
PTOLEMY:
one second after the Big Bang

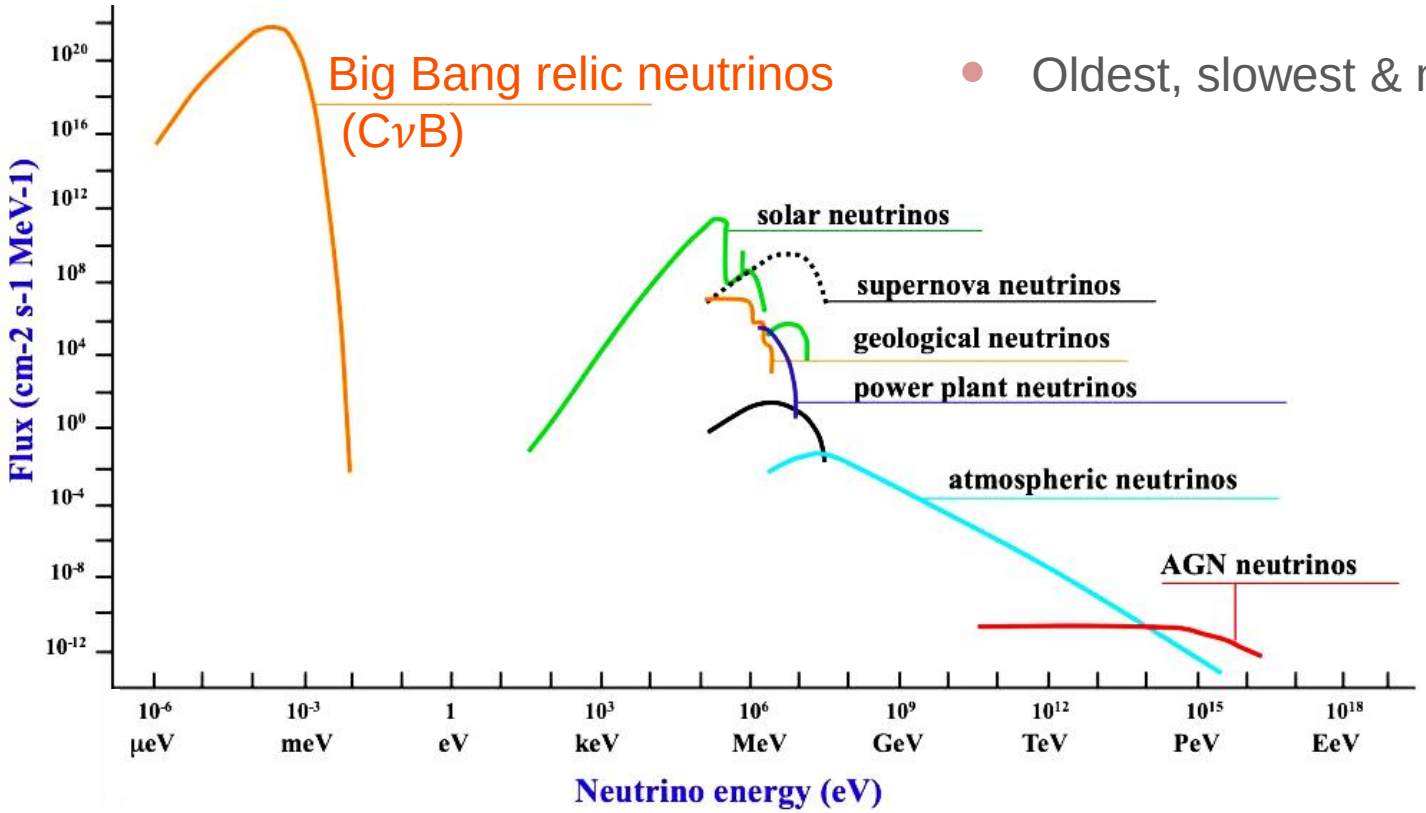
James Vincent Mead

Decoupling in the early universe



[cern]

Cosmic neutrino background



- Oldest, slowest & most abundant neutrinos in the universe

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

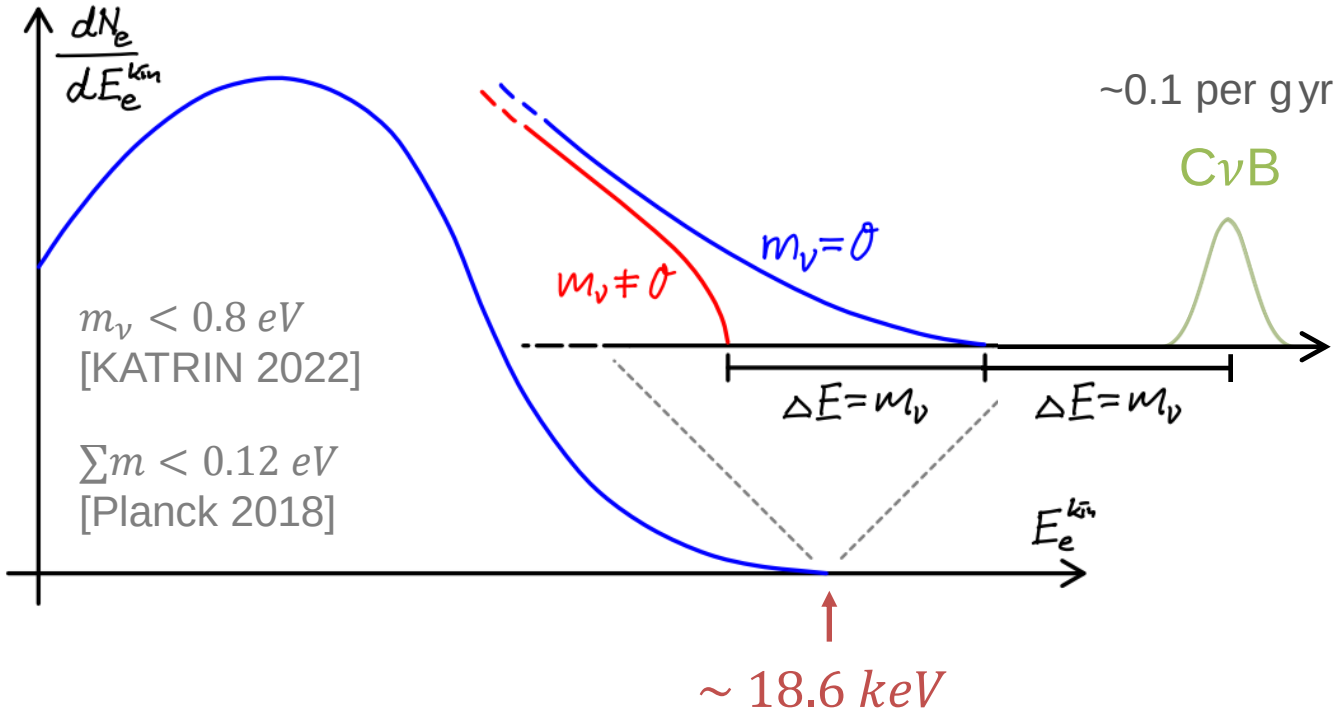
$$\langle v_{rms} \rangle \propto \frac{T}{m_\nu} > \mathbf{160\ km/s}$$

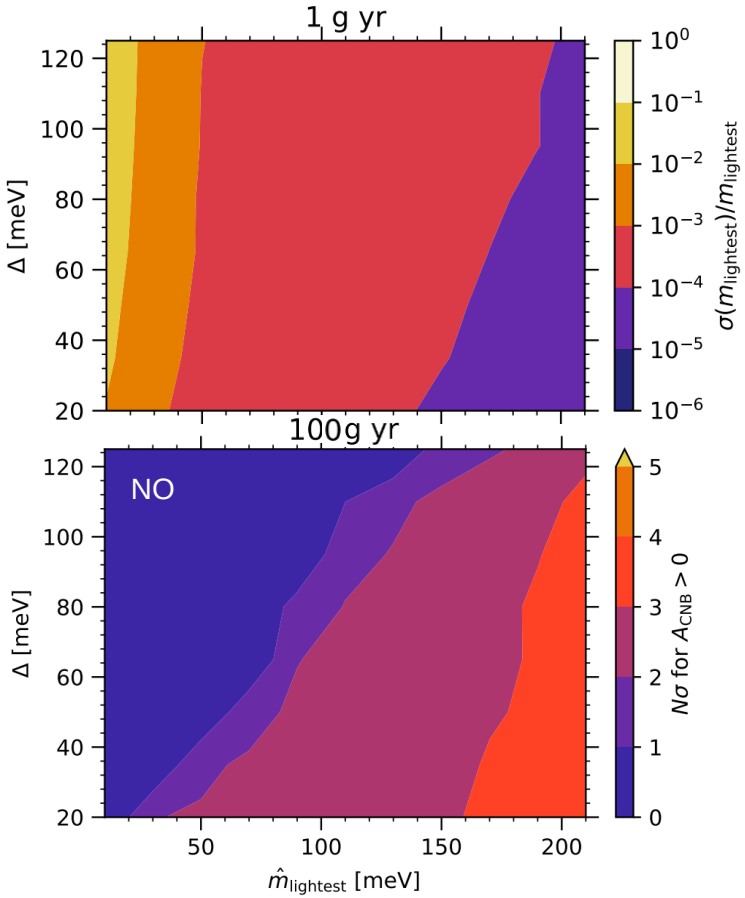
$$T_\nu(t) = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_{CMB} \Rightarrow \sim \mathbf{1.92K}$$

[arXiv:1910.11878v3]

- Principles established by Steven Weinberg in 1962

[PhysRev.128.1457]

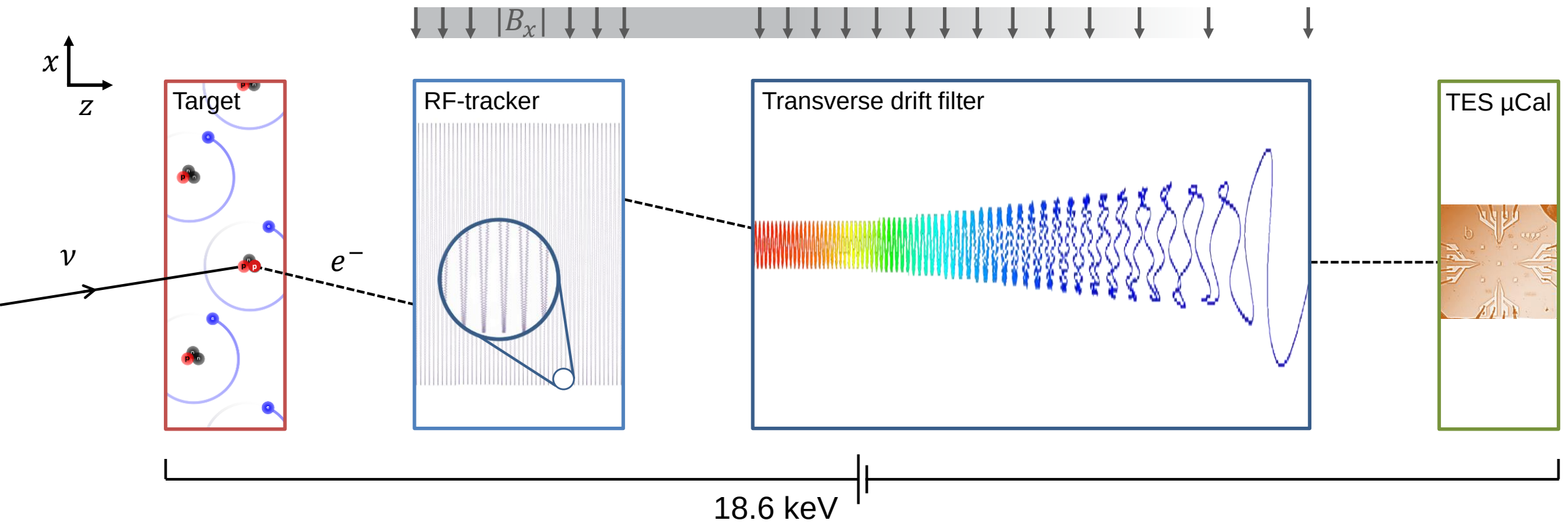




[978-1-64327-680-9]

[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 across the Netherlands

RU

Nicolo de Groot

Inge van Rens

Particle physicists

Nicoleta Laurenciu

Electronic engineering

Oleksandr Zheliuk

Uli Zeitler

High Field Magnet Lab

Leiden

Vadim Cheianov

Oleksii Mikulenko

Alexey Boyarsky

Yevheniia Cheipesh

Theorists

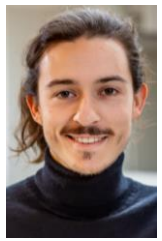
PTOLEMY – UvA / Nikhef

AP Colijn

Saad El Morabit

Particle physicists

Fabian Zimmer



Shin’ichiro Ando

Theorists (GRAPPA)

Pascal Bosch

Michael Naafs

Guido Visser

Electronics engineers

Tony Damen

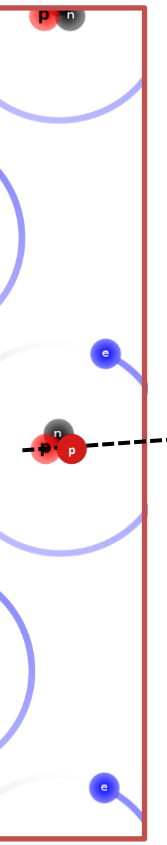
Vincent van Beveren

Software engineers

Martin Adams

Mechanical engineers

RF cavity



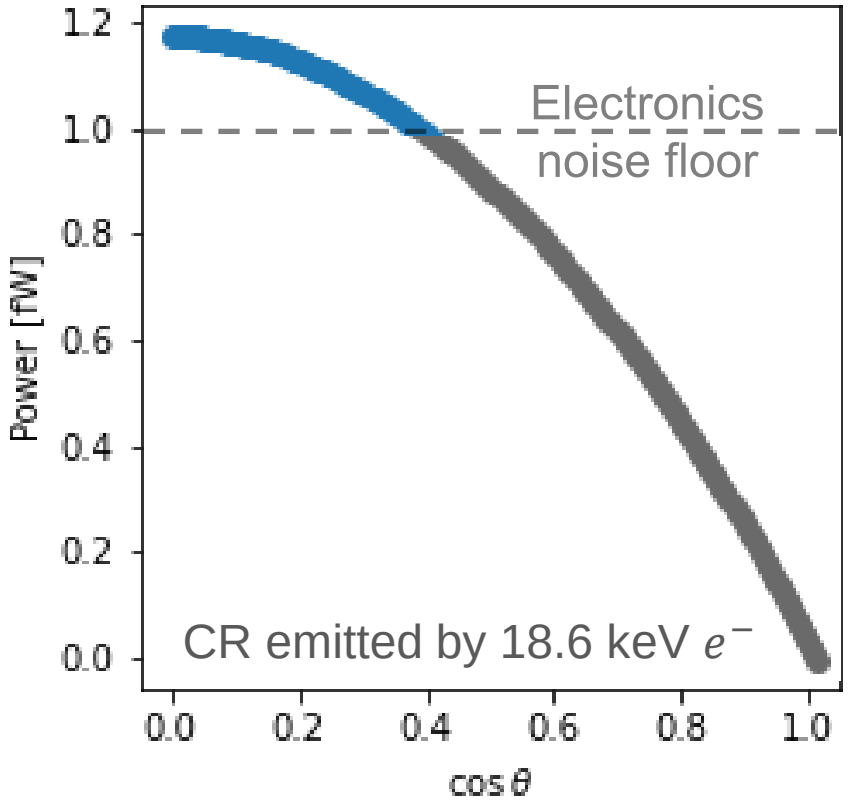
1T uniform B-field
Cyclotron motion (y,z)-plane

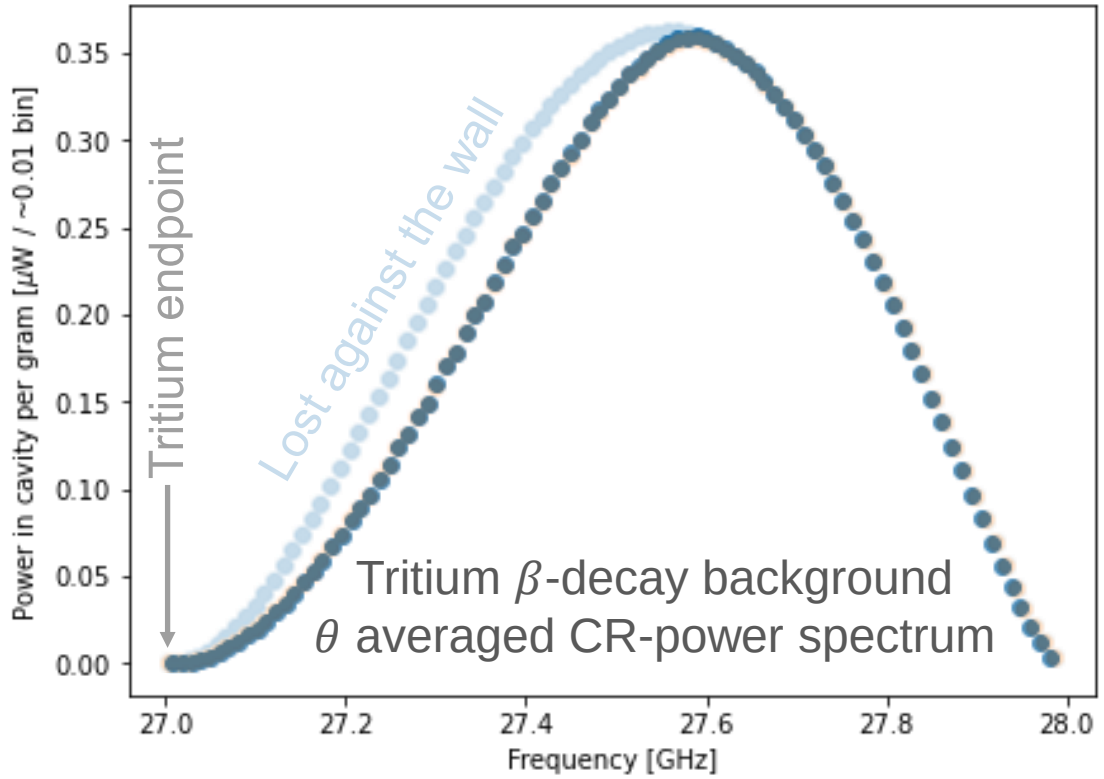
Perpendicular E-field
Drift velocity along z-axis

'Bathtub' bounce potential
Constrains electron

Tritium RF-power spectrum

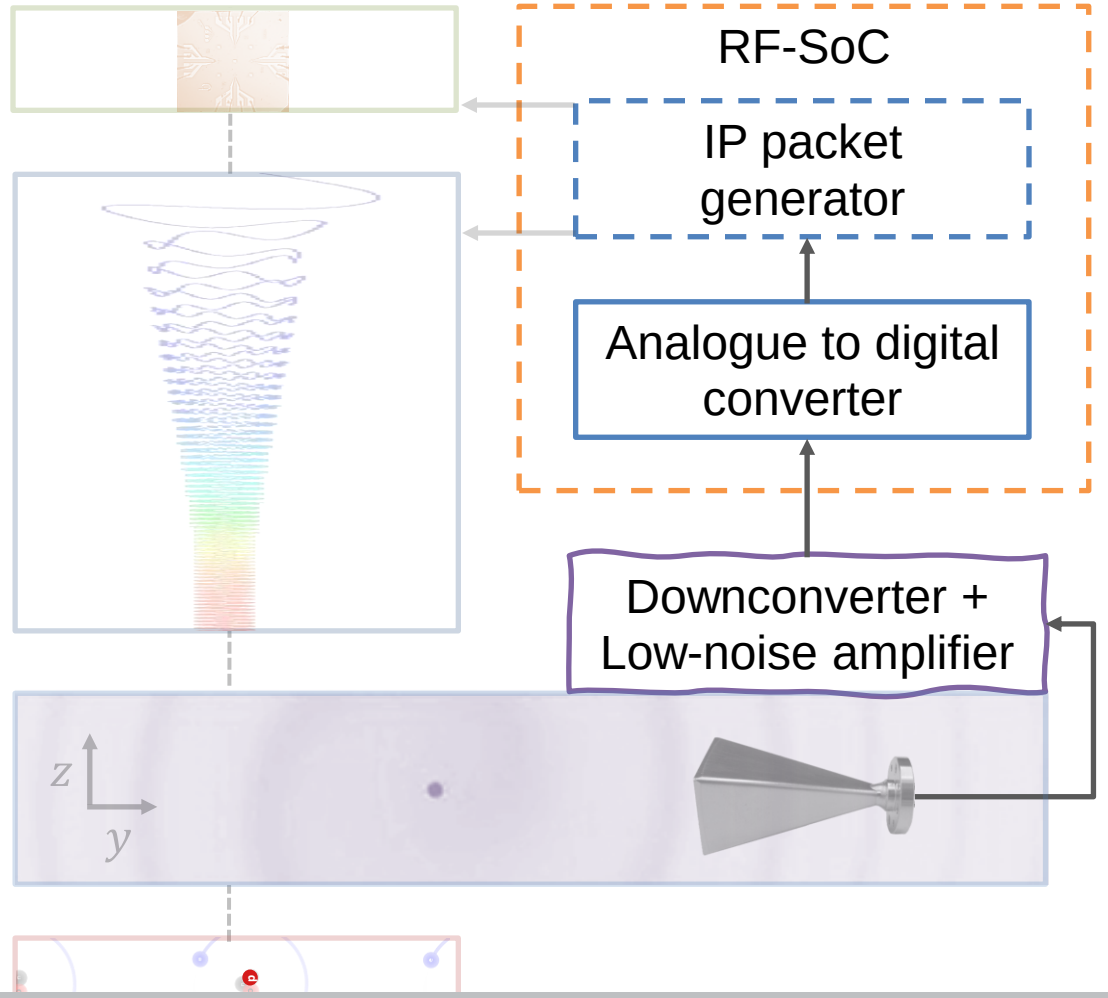
- Angle between B-field and electron's motion is the pitch, θ





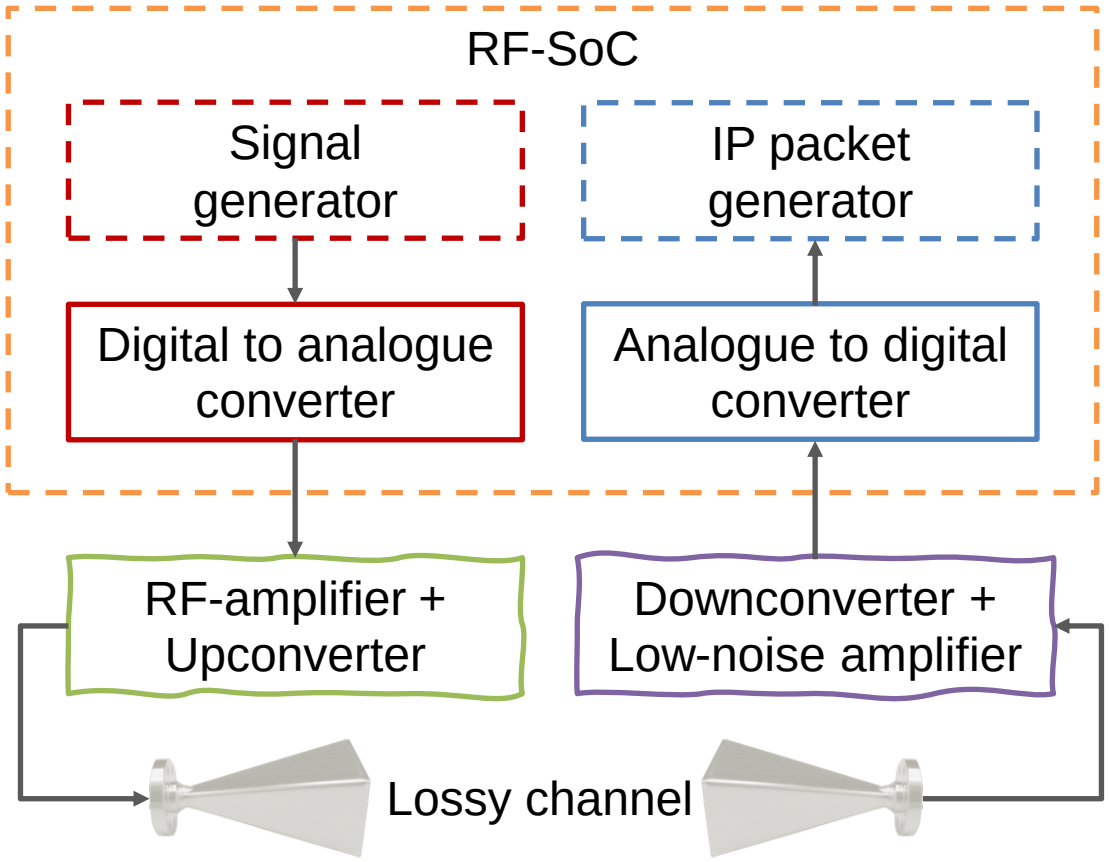
Readout & Electronics

- ***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



Readout & Electronics

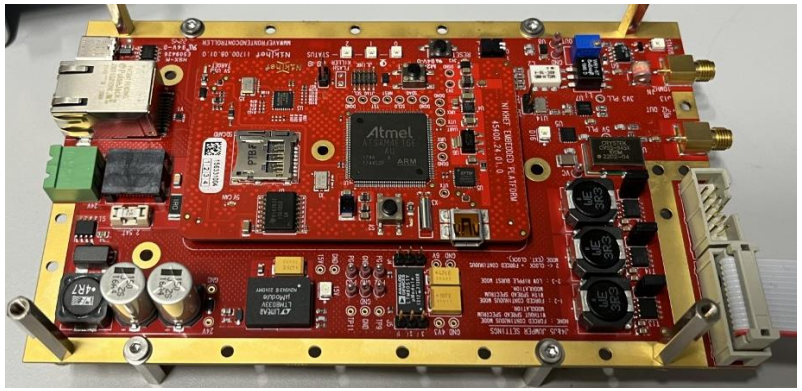
- ***Synthetic signal***
  - 27 GHz central freq., fW emission, $\mathcal{O}$(μs) length
  - Approximate CR to test electronics & antennas
- ***Loop test***
  - FPGA transmits & receives simultaneously
  - Testing shielding & characterising noise
  - Measuring losses and interference
- ***Baseline for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



Boards galore

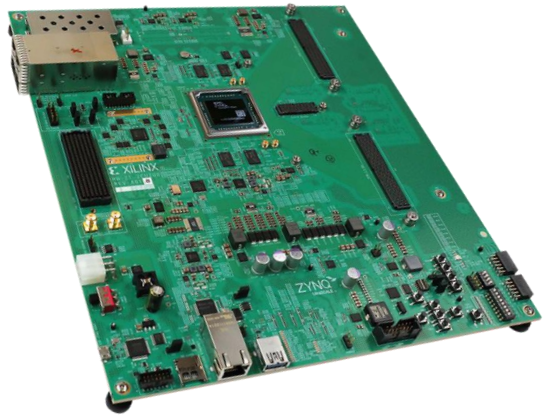
Downconverter board

Front-end control board



Shielding

FPGA evaluation board



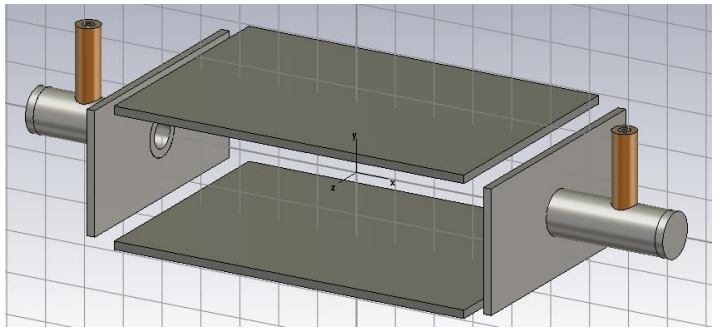
Cases (Nikhef branding included)

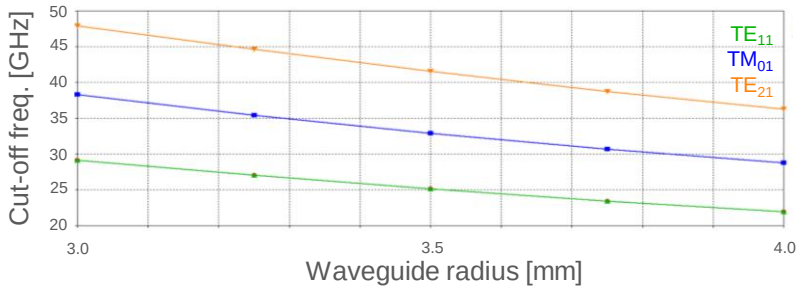
- New control board – Summer
- Enclosure – Fall
- Upconverter – Winter
- Lossy channel – TBC

RF-cavity studies

- Plane-wave producing excitations in side waveguide to coaxial cable

7mm Diam. ⇒ Cut-off freq. 1st mode ~ 25 GHz

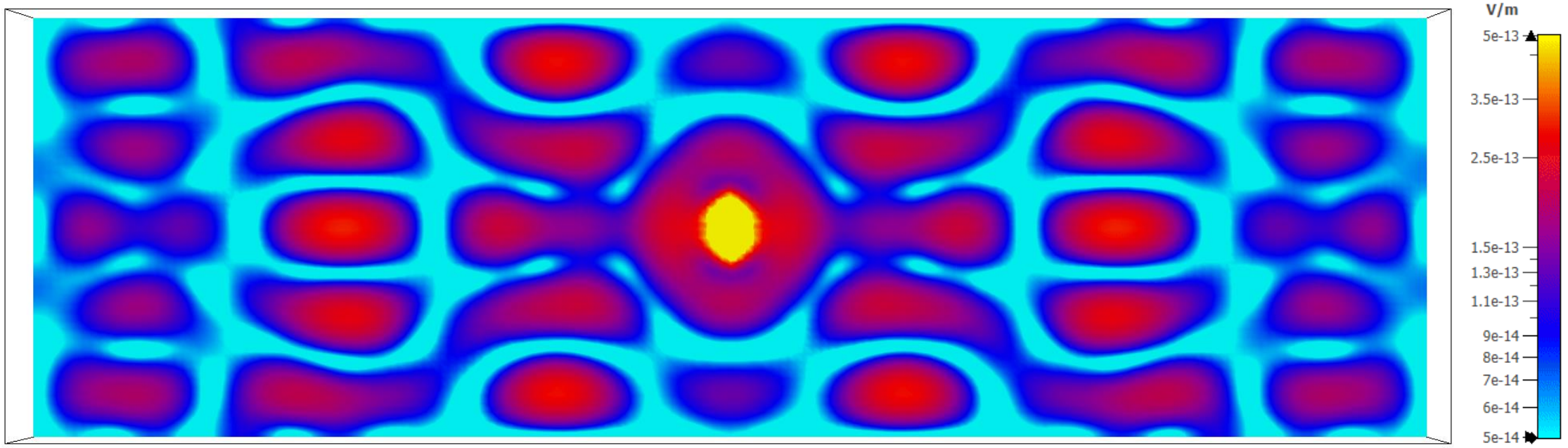




- Dimensions of waveguide chosen to supress background

RF-cavity studies

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

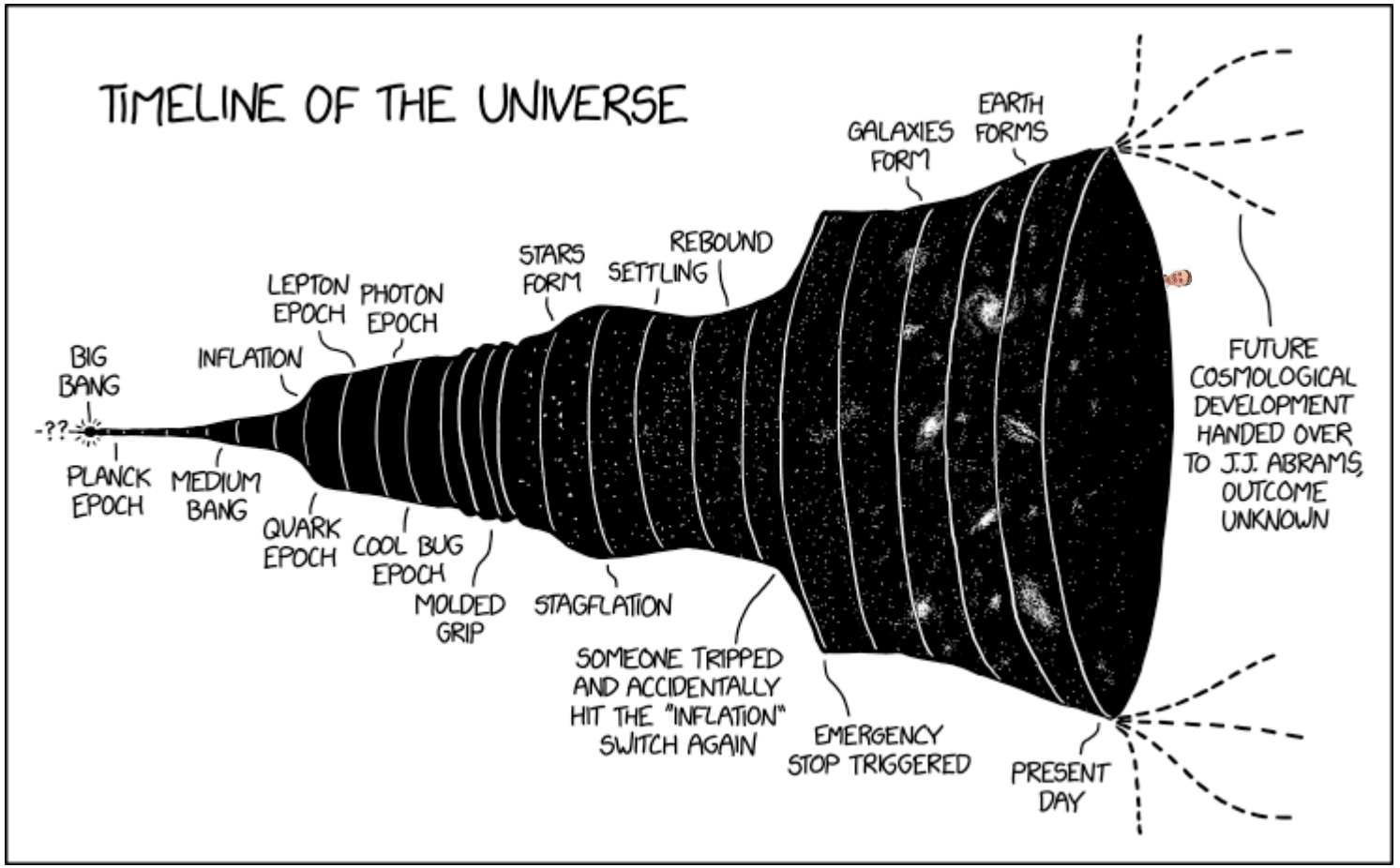


- Mode decomposition will help us optimise cavity & antenna system design

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
  - External collaborators from TNO providing antenna and signal processing expertise
- ***PTOLEMY prototype soon to be based at LNGS***
  - Closer ties being established with KATRIN and Project-8
  - Stay tuned for future developments!

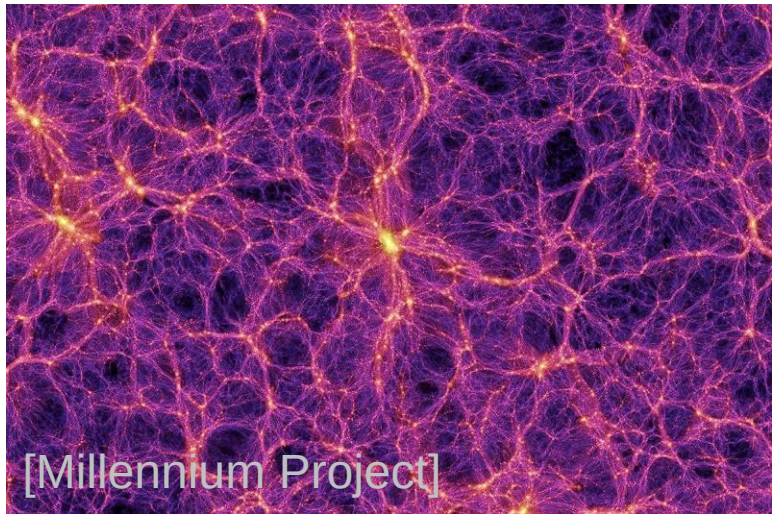
Thanks for listening!

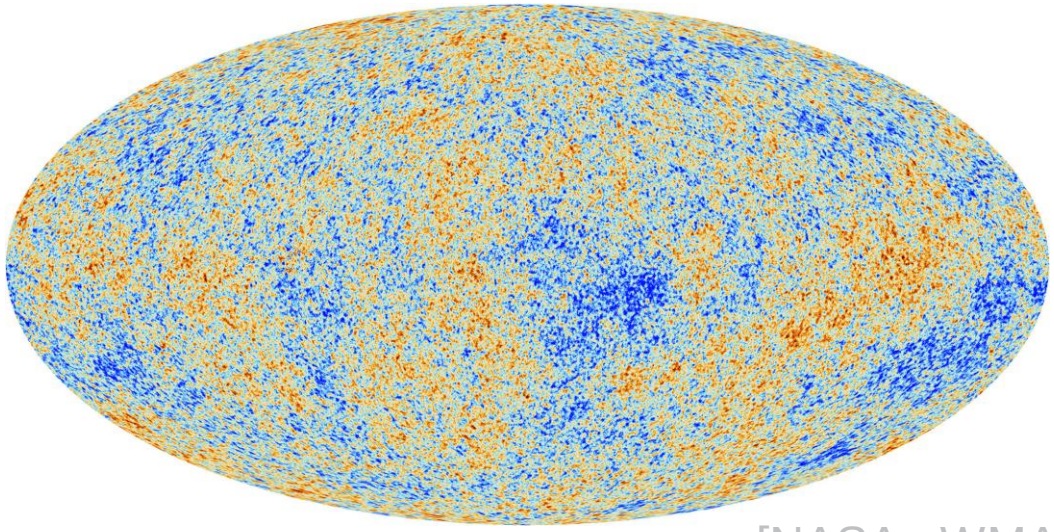


[xkcd.com/2240]

Imprint upon the cosmos

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


[Millennium Project]


[NASA - WMAP]

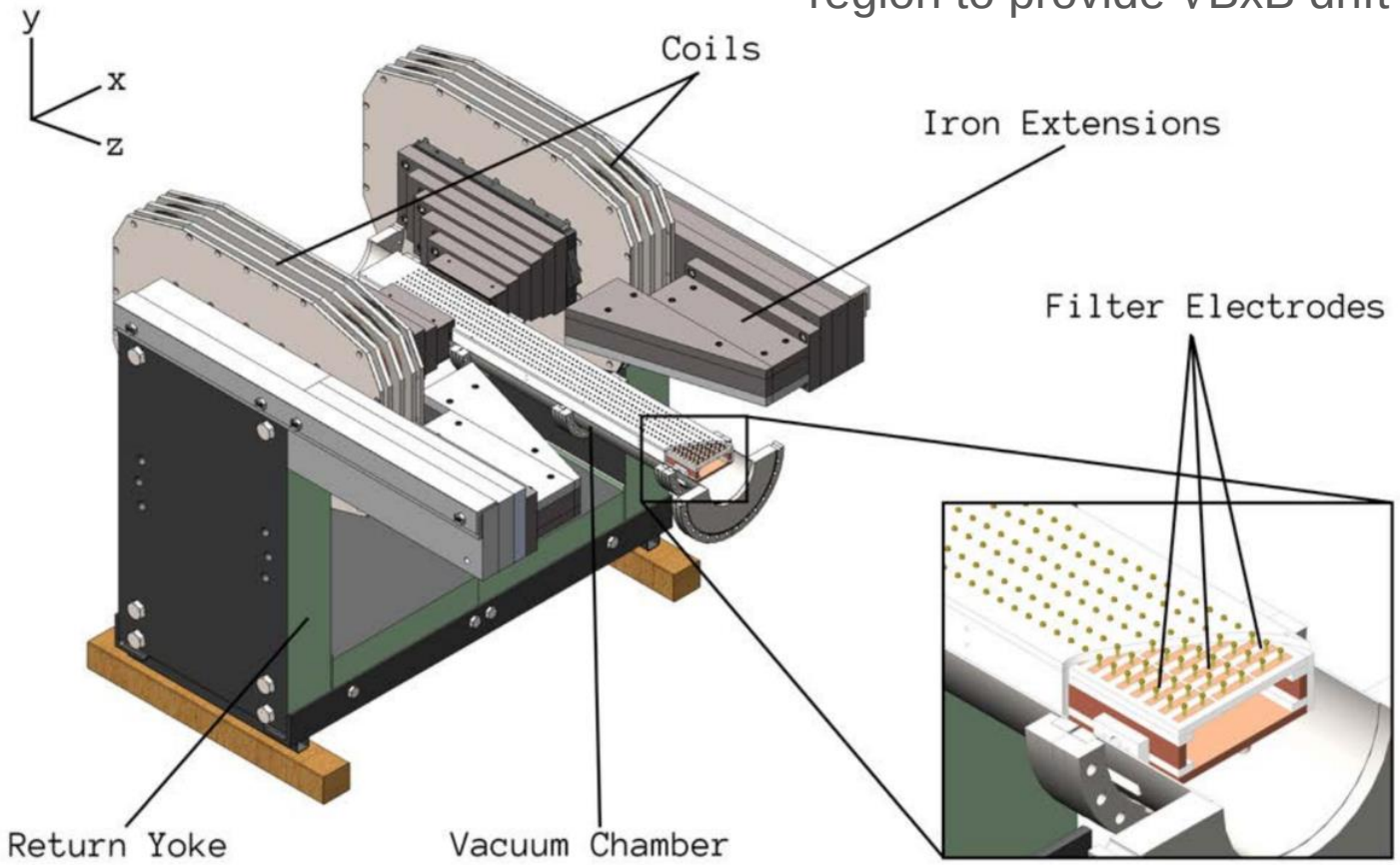
- Anisotropies in the CνB result in phase variations which damp the angular power spectrum of the CMB

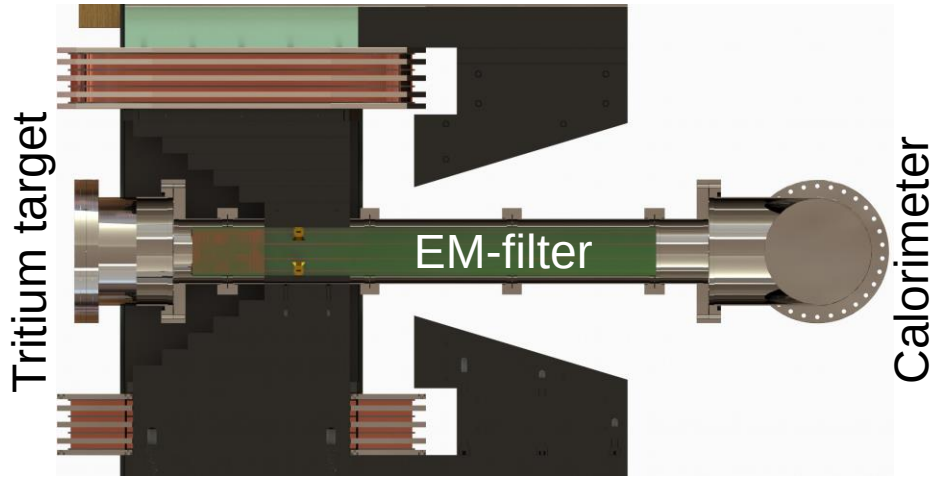
Tritium target

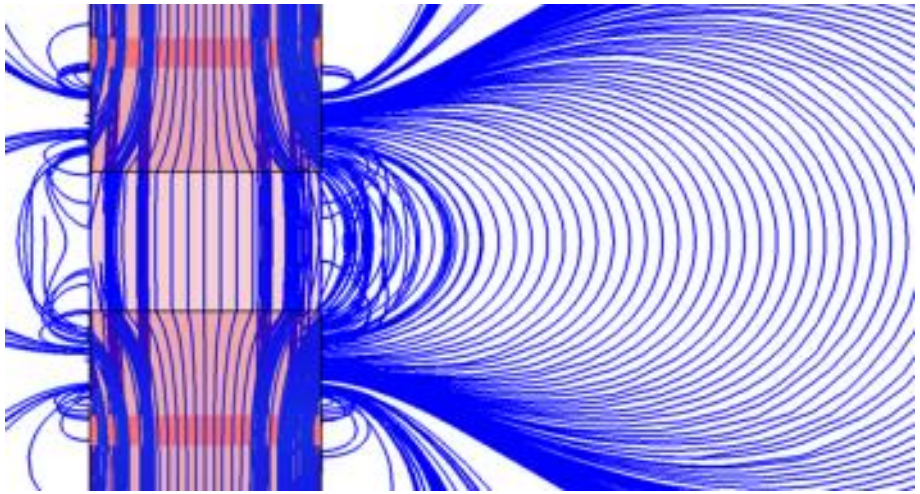
- ***ν-capture on tritium*** (^{3}H)
  - Long-lived β-decay nuclei, half-life ~ 12 years
  - Low emitter Q-value, endpoint at 18.6 keV
  - $\sigma \sim 10^{-44} cm^2$, known to < 0.5%

Continuous magnetic field

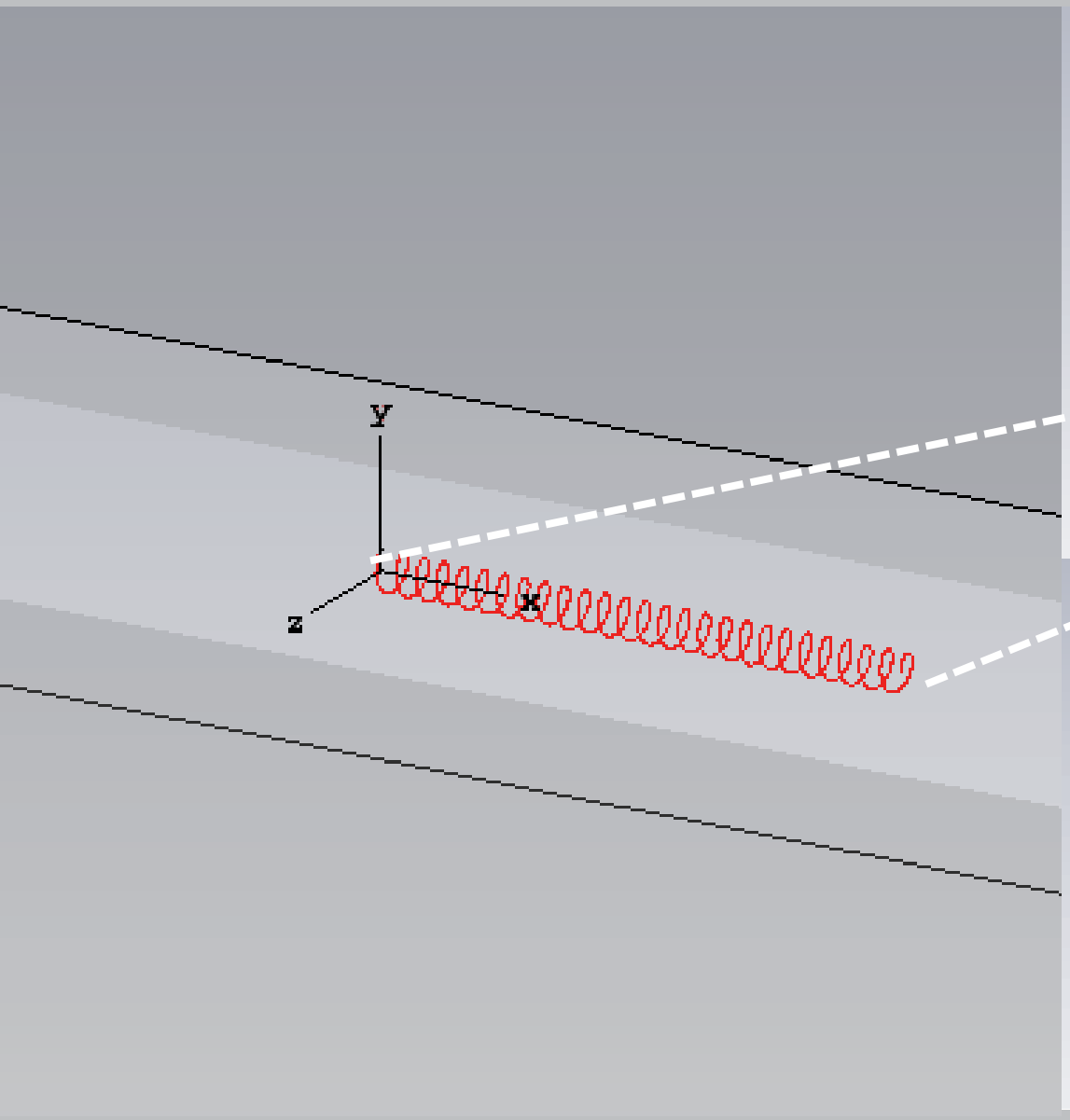
- B-field in RF region is constant while extending over EM-filter region to provide ∇BxB drift

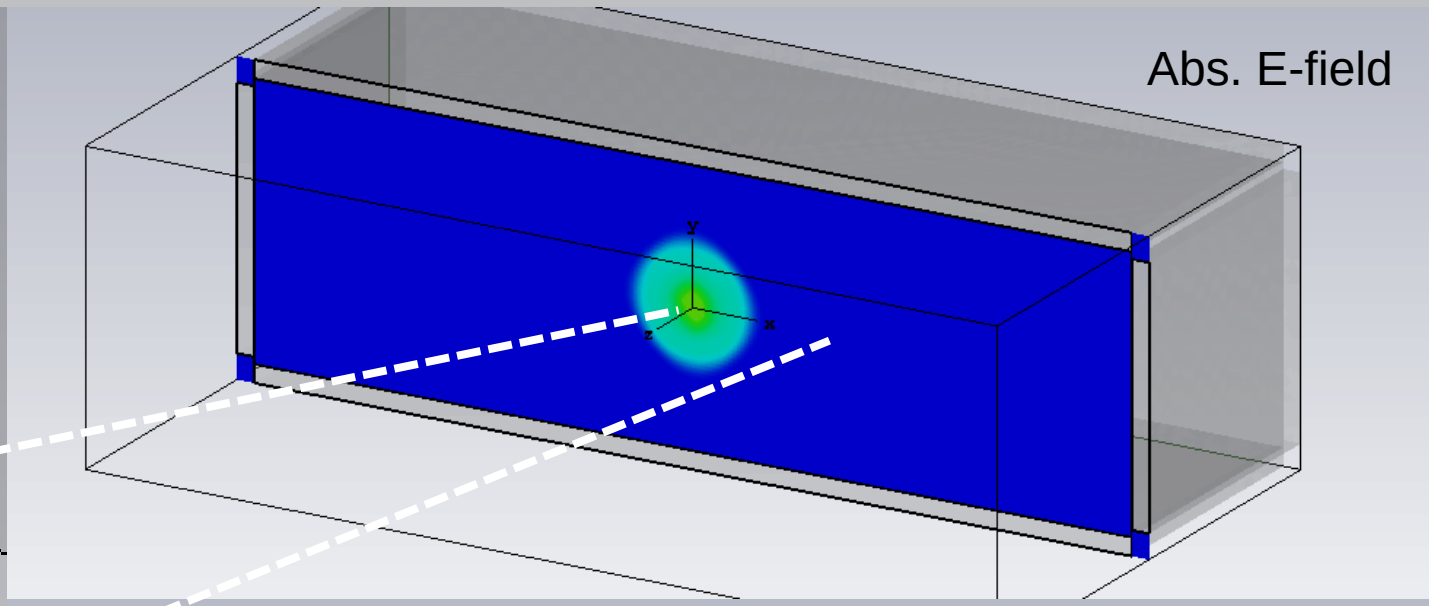


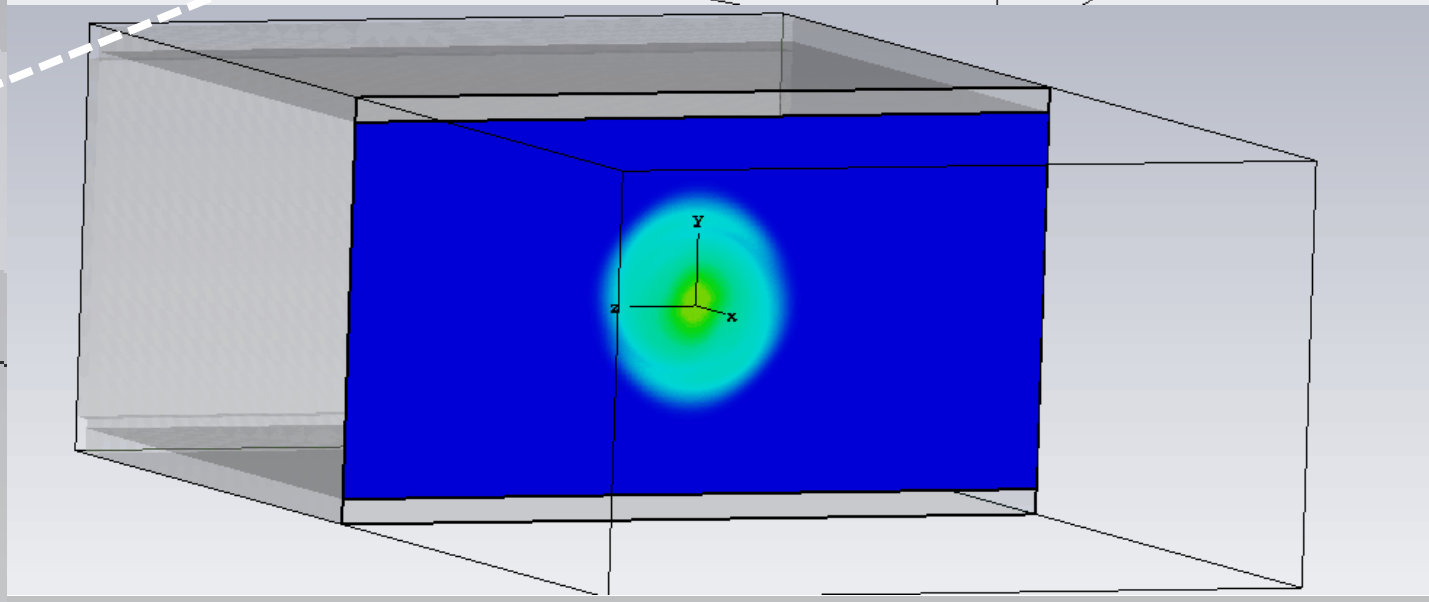




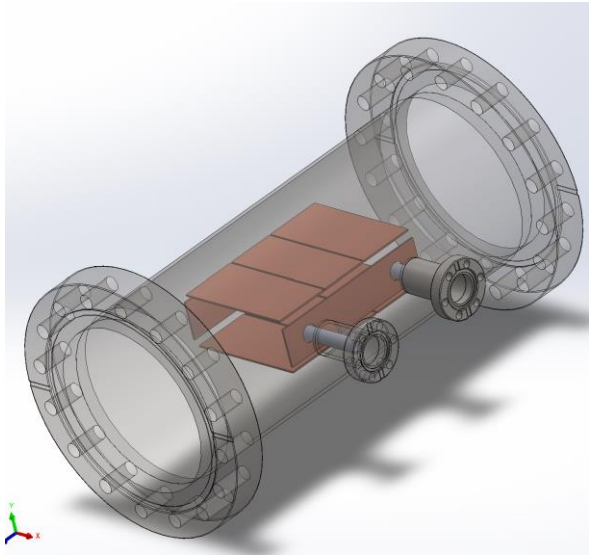
Cyclotron radiation in a rectangular waveguide

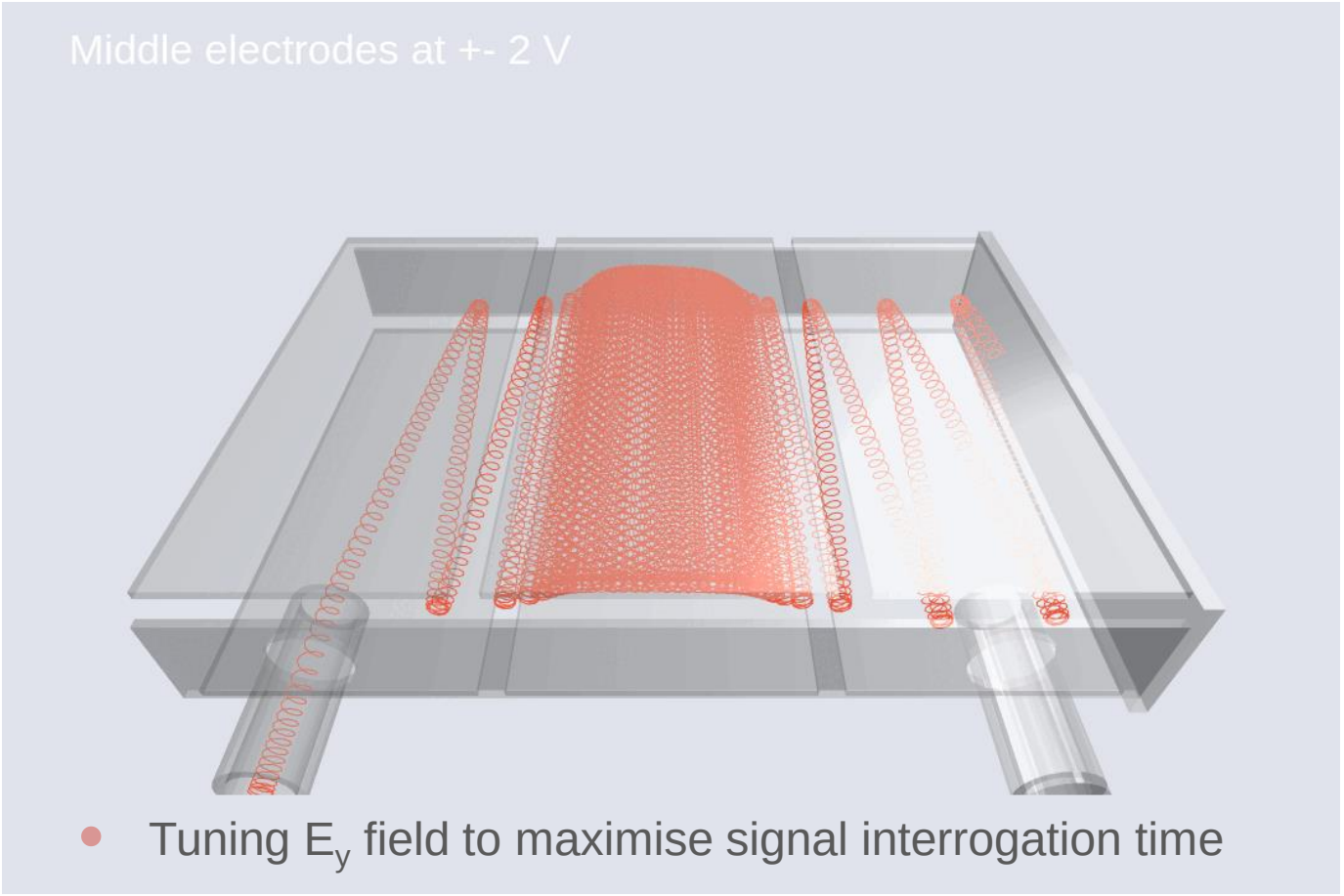






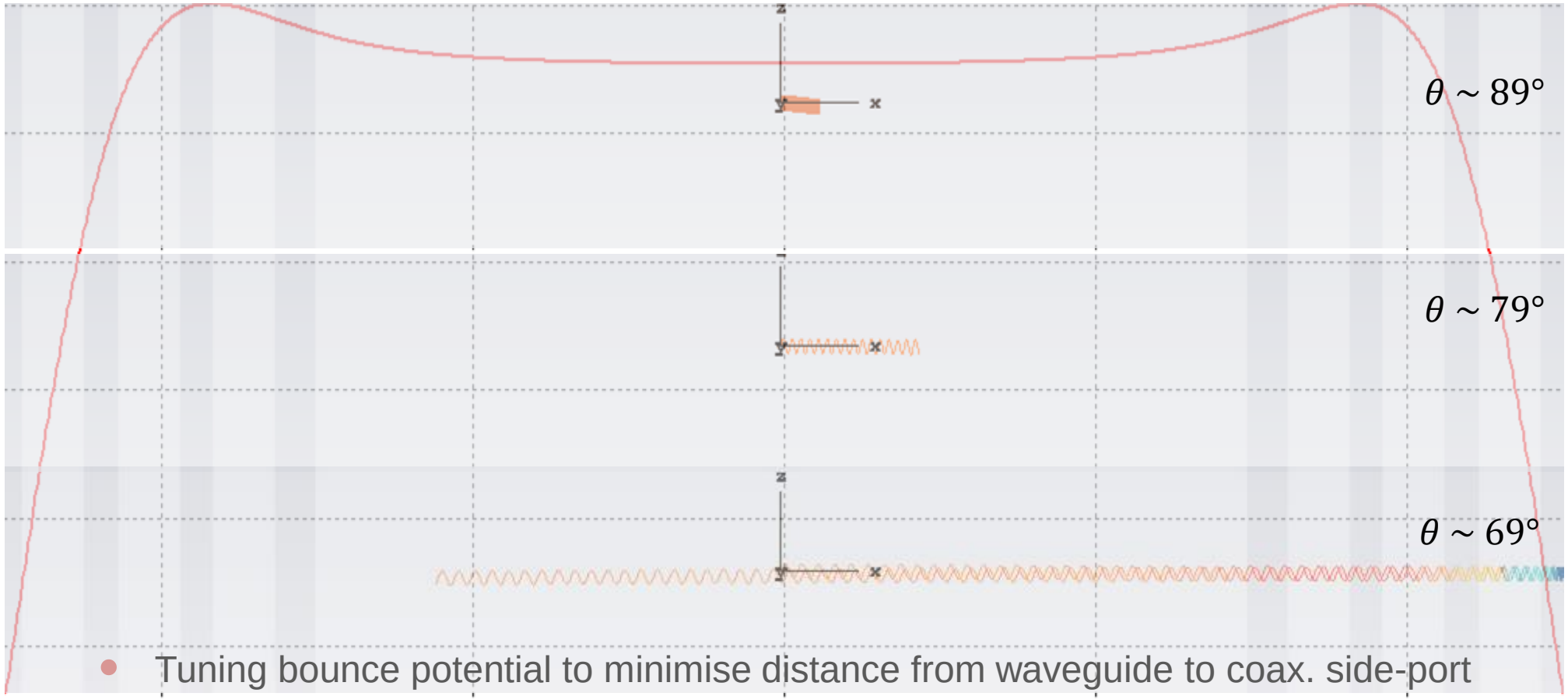
Slow ExB drift region





- Tuning E_y field to maximise signal interrogation time

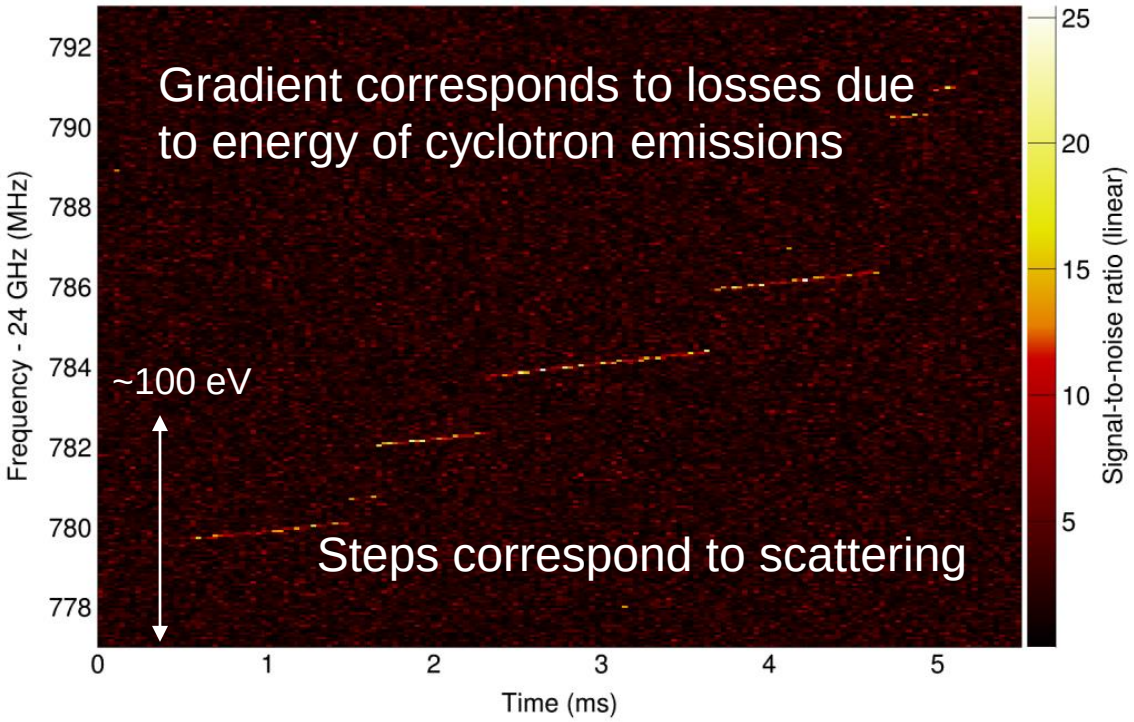
Potential shaping for high pitch electrons



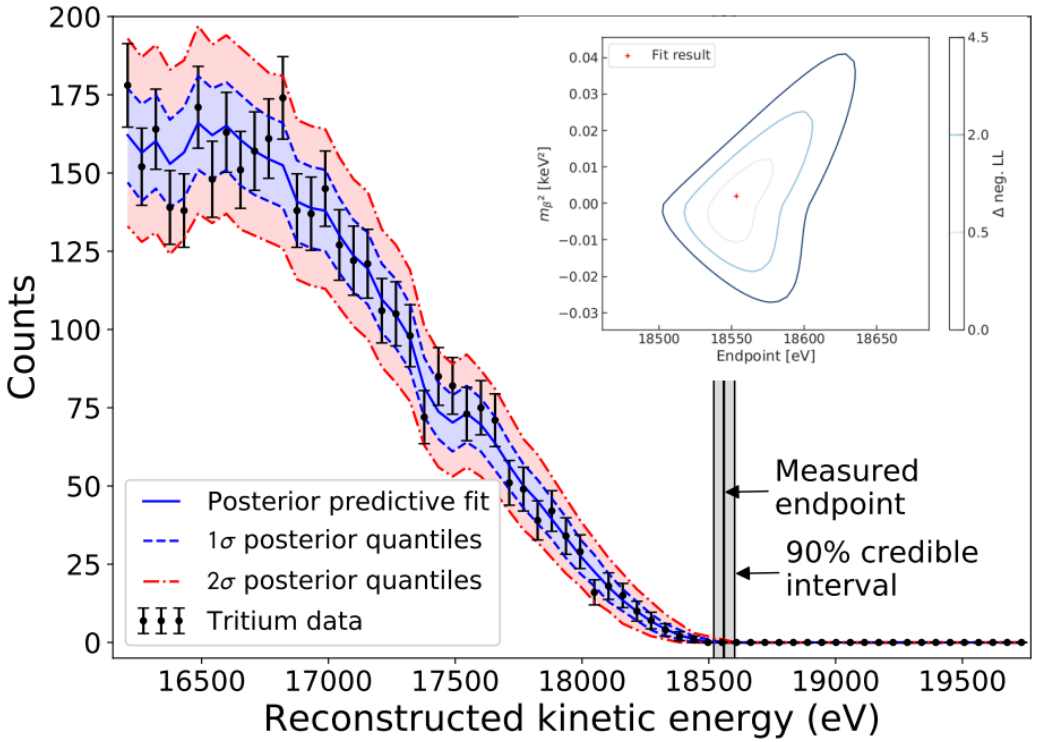
- Tuning bounce potential to minimise distance from waveguide to coax. side-port

Project 8's proof-of-principle

- Using CR emission spectroscopy to interrogate trapped tritium gas

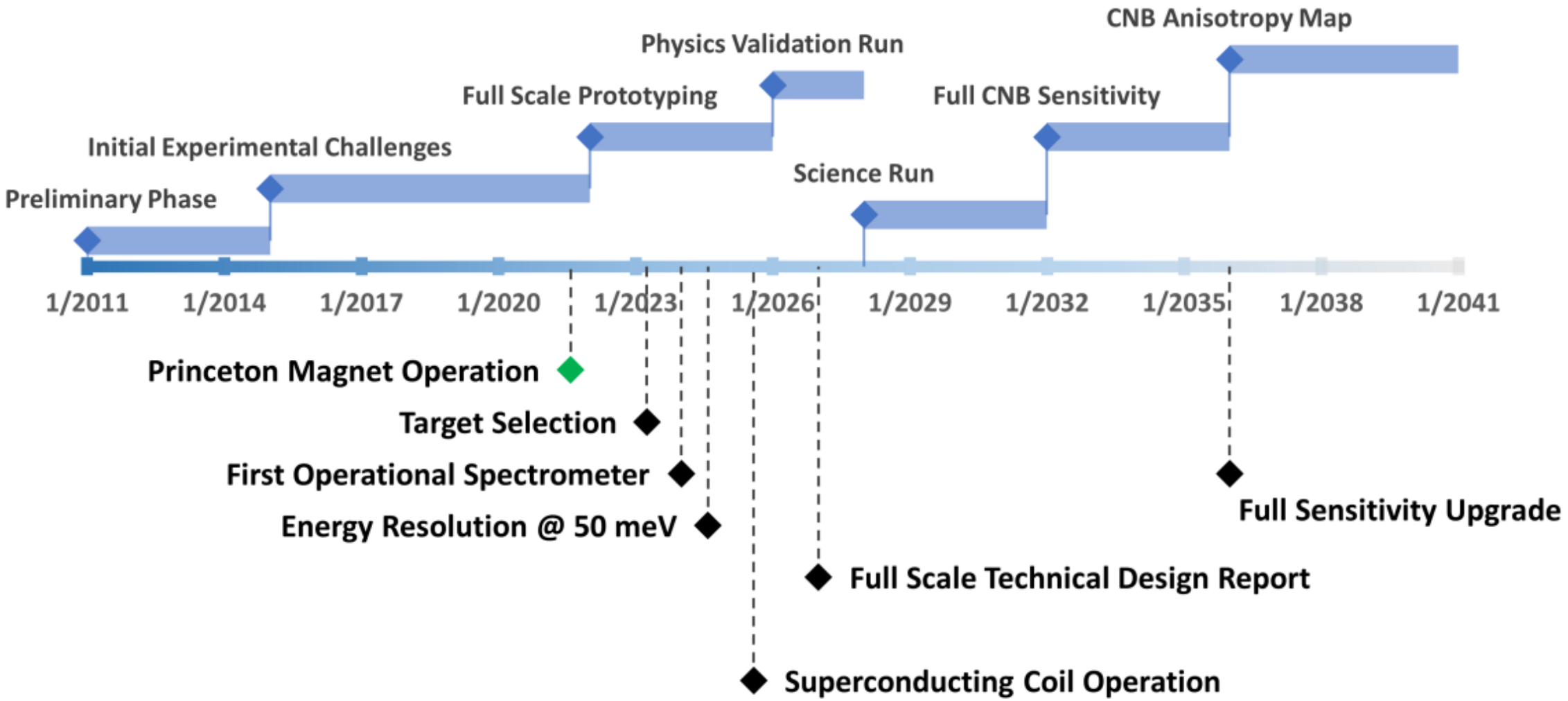


[arXiv:2203.07349]



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

PTimeline


CNB Anisotropy Map
Physics Validation Run
Full CNB Sensitivity
Full Scale Prototyping
Initial Experimental Challenges
Science Run
Preliminary Phase
1/2011
1/2014
1/2017
1/2020
1/2023
1/2026
1/2029
1/2032
1/2035
1/2038
1/2041
Princeton Magnet Operation
Target Selection
First Operational Spectrometer
Energy Resolution @ 50 meV
Full Sensitivity Upgrade
Full Scale Technical Design Report
Superconducting Coil Operation