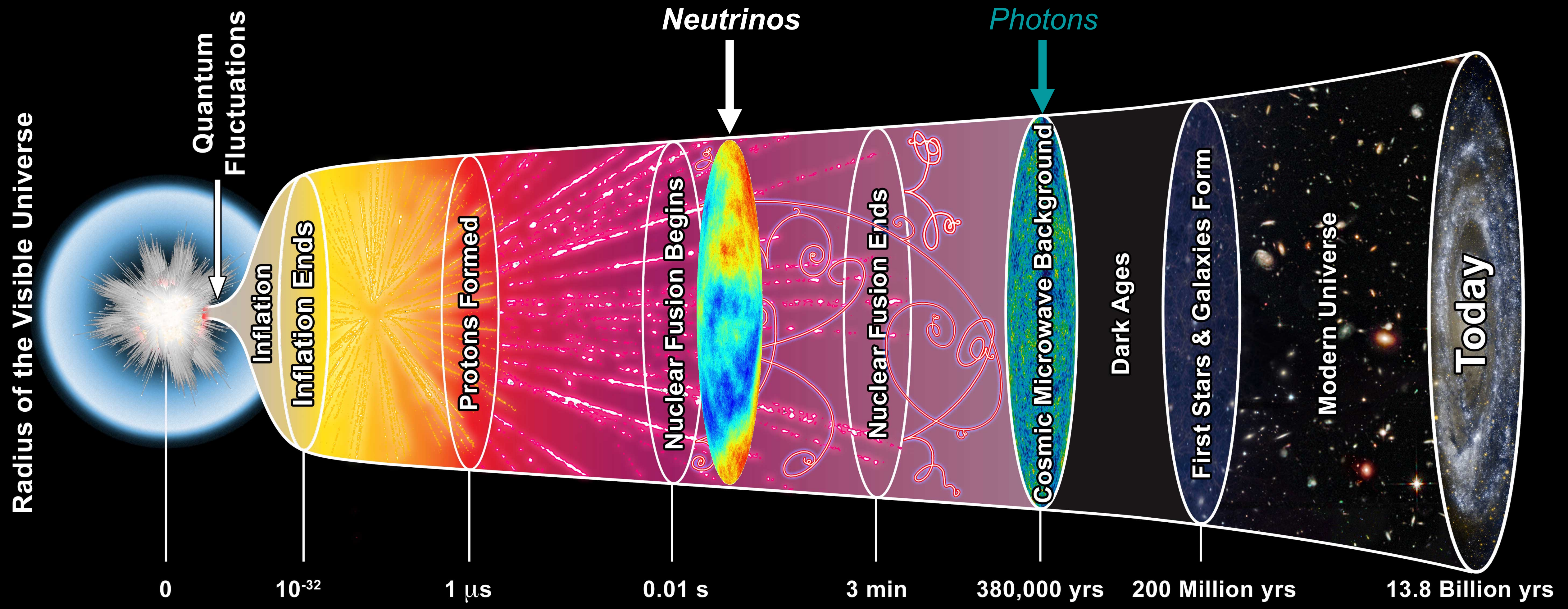
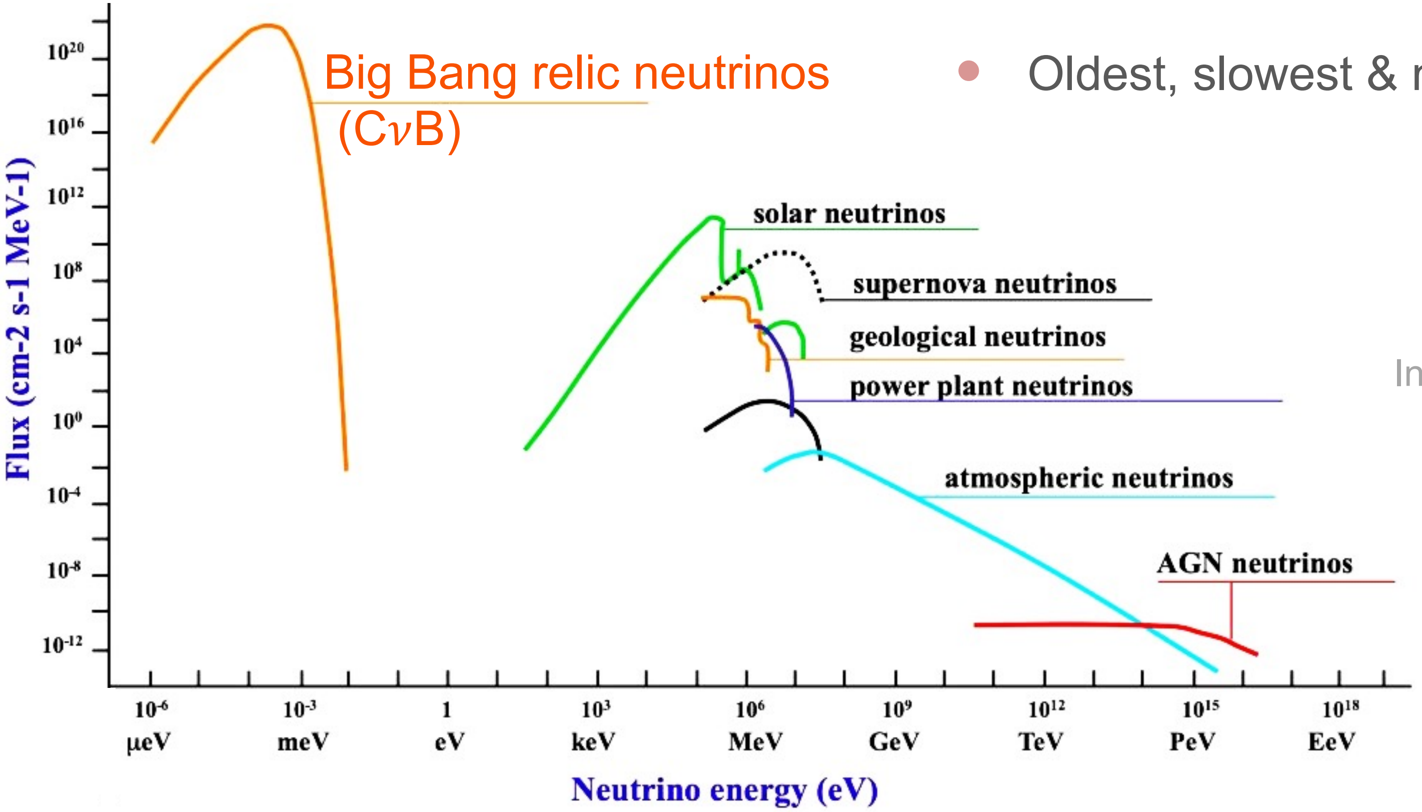
PTOLEMY:
Relic neutrino direct detection

James Vincent Mead

Decoupling in the early universe



[cern]



- Oldest, slowest & most abundant neutrinos in the universe

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

Influence of local structure…' [Zimmer et al (2023)]

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

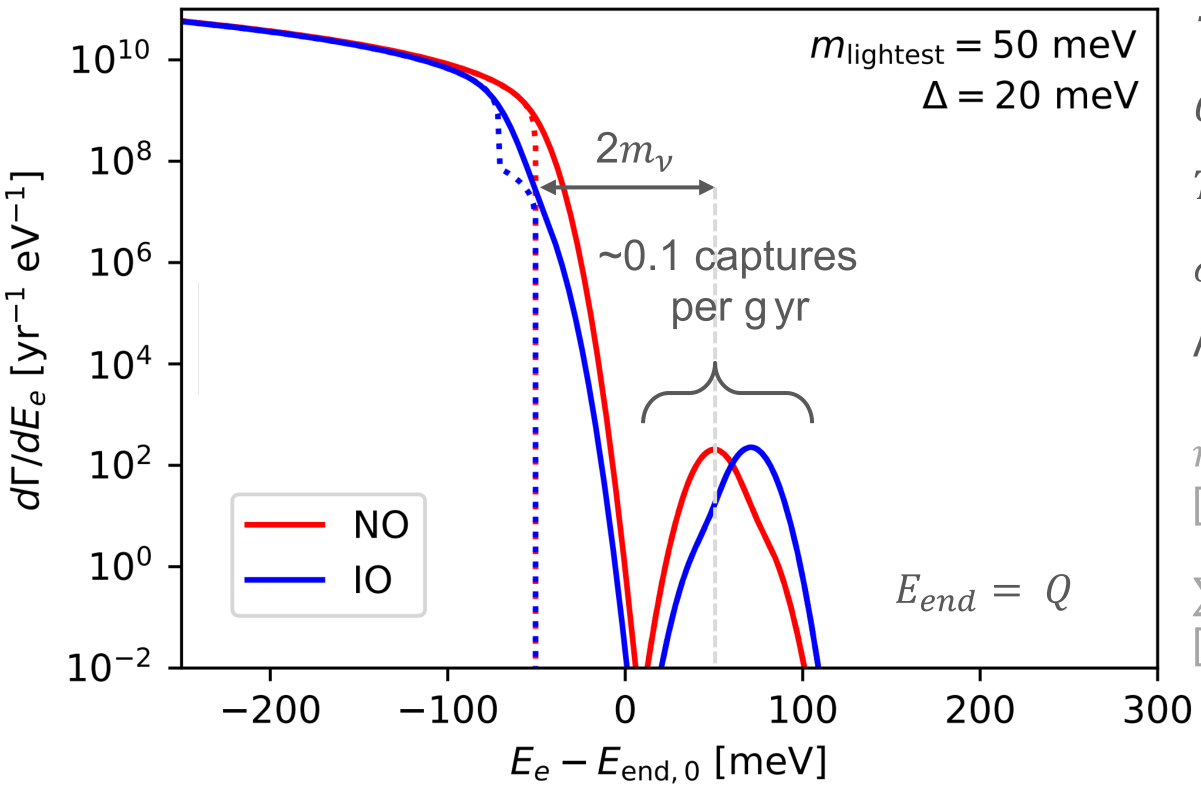
$$T_\nu(t) = \left(\frac{4}{11}\right)^{\frac{1}{3}} T_{CMB} \Rightarrow \sim \mathbf{1.92K}$$

[arXiv:1910.11878v3]

[arXiv:2306.16444]

Concept

- Principles established by Steven Weinberg (1962) revisited (2007)



Tritium

Q = 18.57 keV

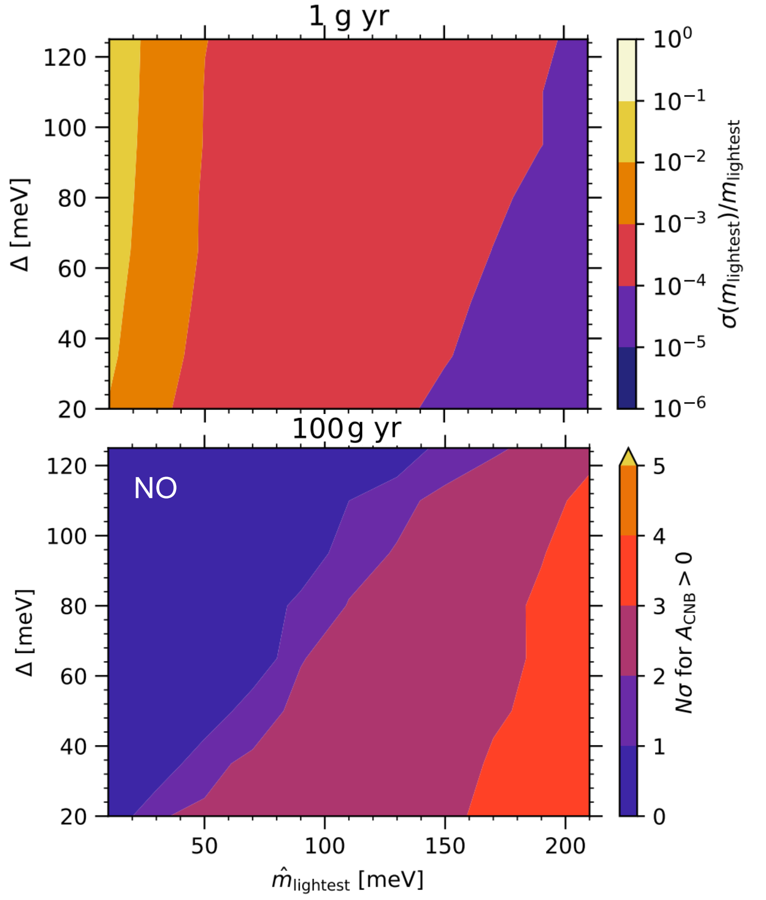
$T_{1/2}$ = 12.32 y

$\sigma \sim 10^{-44}$ cm^2

A $\sim \mathcal{O}(10^{14})$ Bq

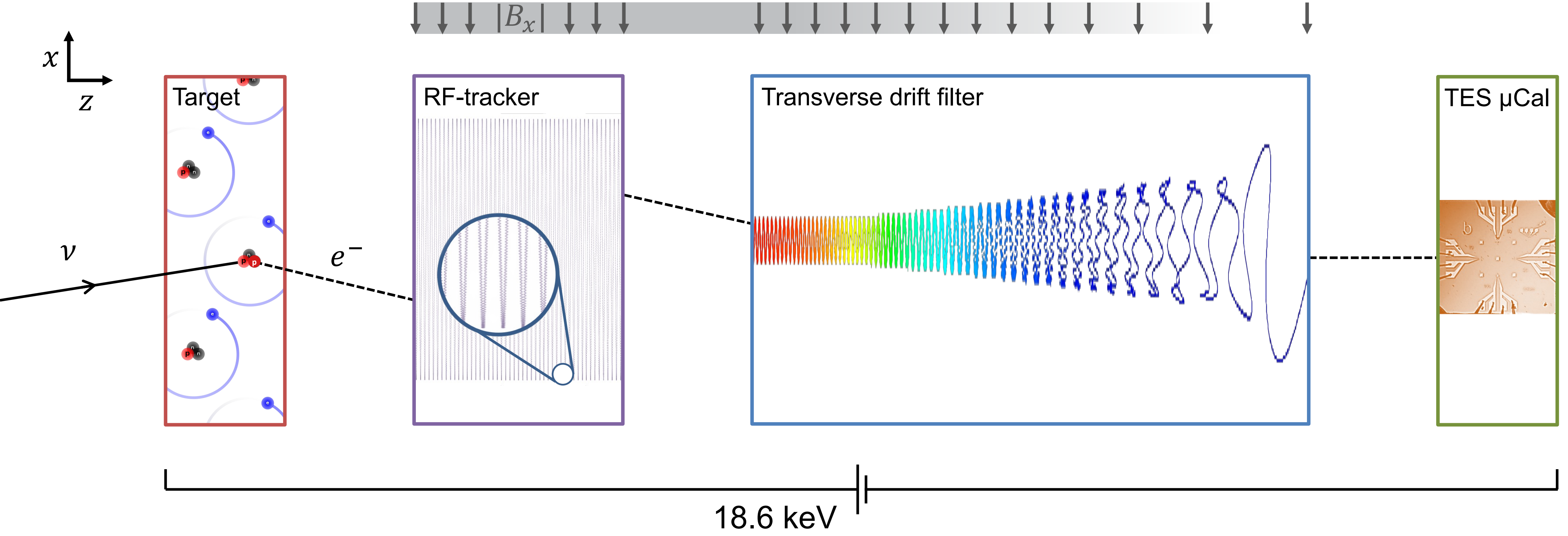
$m_\nu < 0.8$ eV
[KATRIN 2022]

$\sum m < 0.12$ eV
[Planck 2018]



[arXiv:1902.05508]

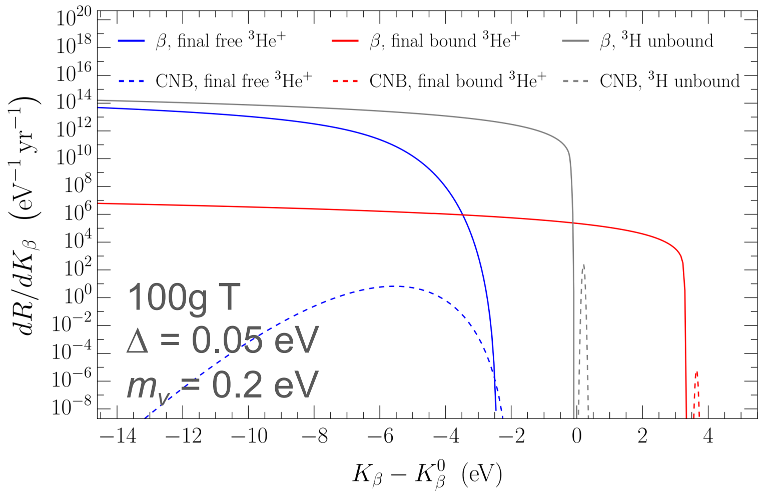
Pon**T**ecorvo **O**bservatory for **L**ight **E**arly-universe **M**assive-neutrino **Y**ield

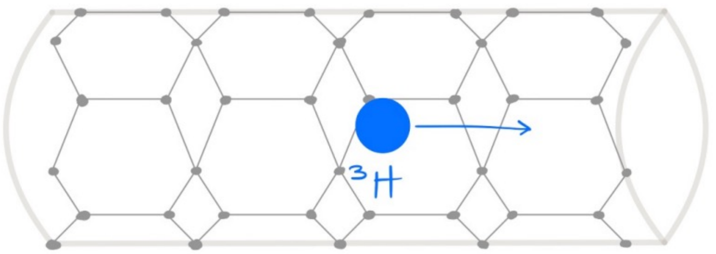


$$E_{total} = q(V_{TES} - V_{target}) + E_{RF} + E_{cal}$$

Solid state tritium target

- ***Solid state target***
  - Atomic T storage avoids molecular excitations from T_2 gas
  - Operate with larger target masses (100g ~ 10^{25} atoms)
- ***Aims for PTOLEMY***
  - Develop target physics predictions (final states & excitations)
  - >90% hydrogen loading on nanoporous graphene (NPG)
  - Demonstrator moving forward with tritiated graphene $\mathcal{O}$(100µg)
- ***Latest news***
  - Localisation on graphene lattice results in quantum spread
  - Hydrogenated carbon nanotubes provide delocalisation, $\mathcal{O}(Å)$
  - External B-field to prevent the formation of molecules

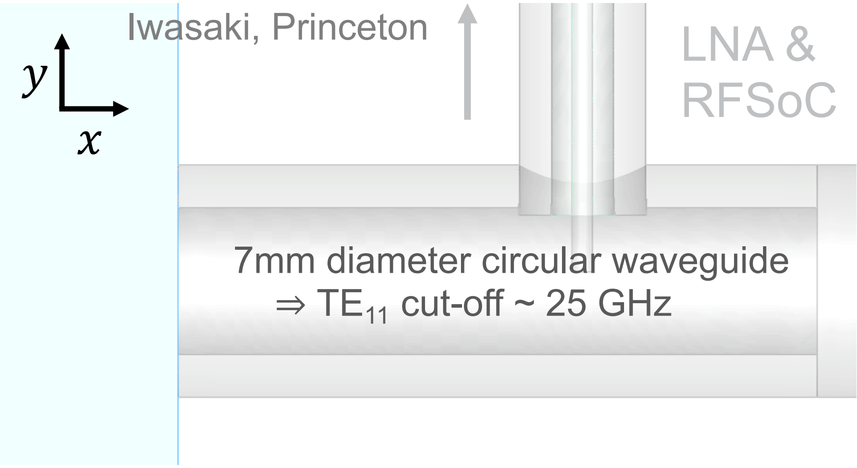




[arXiv:2203.11228]

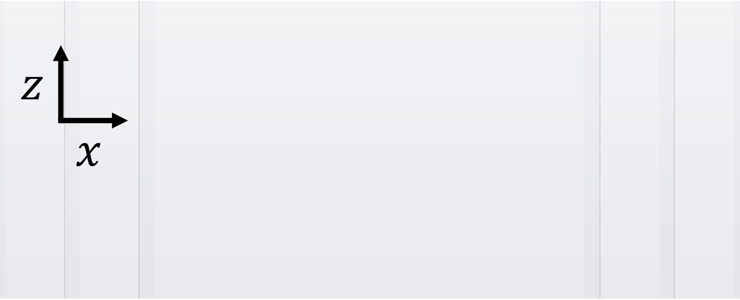
RF-based electron tracking

- ***Cyclotron radiation based $\vec{p}$ reconstruction***
  - 1T field & electron KE at tritium endpoint (~18.6 keV): 27 GHz central frequency with ~1fW emission
  - Explore antenna power threshold & signal integration time
  - Fast $\vec{p}_{\parallel}$ extraction from bkg. dominated data, $\sigma(T_{\parallel}) \sim \mathcal{O}(eV)$

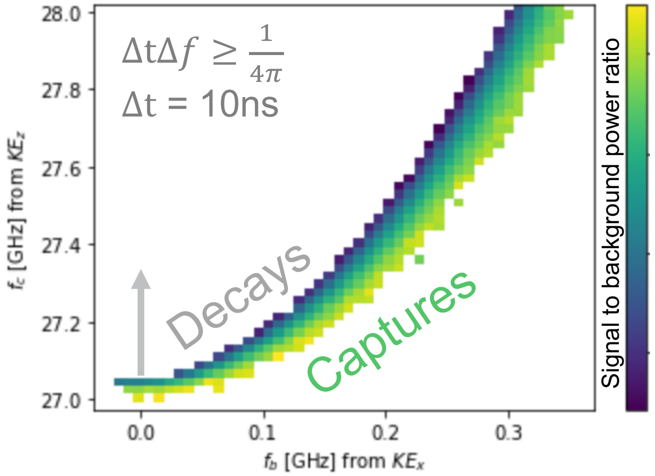


- ***Evolving test setups***
  - Vacuum & LNA cryogenics
  - Emitter & synthetic signal
  - Antennas and/or resonator
  - Potential-shaping elements
  - Source (*e*-gun / *C*-15 / *Kr*-83m)

CST simulation

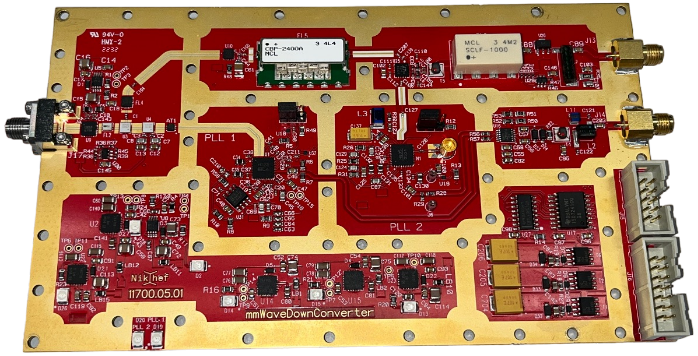


Parallel motion bouncing between electrodes
E_y produces transverse *ExB* drift along z-axis

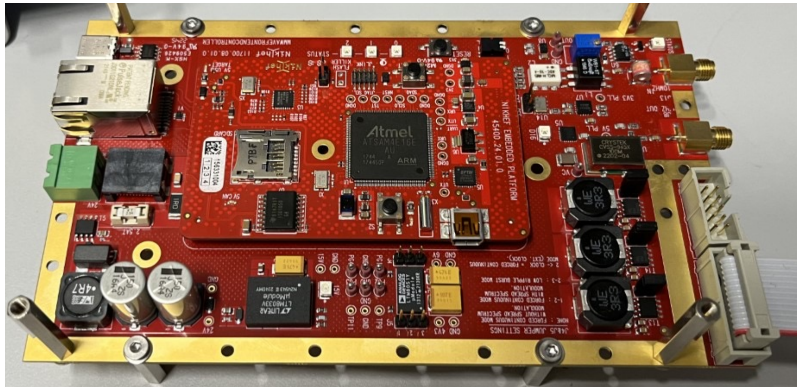


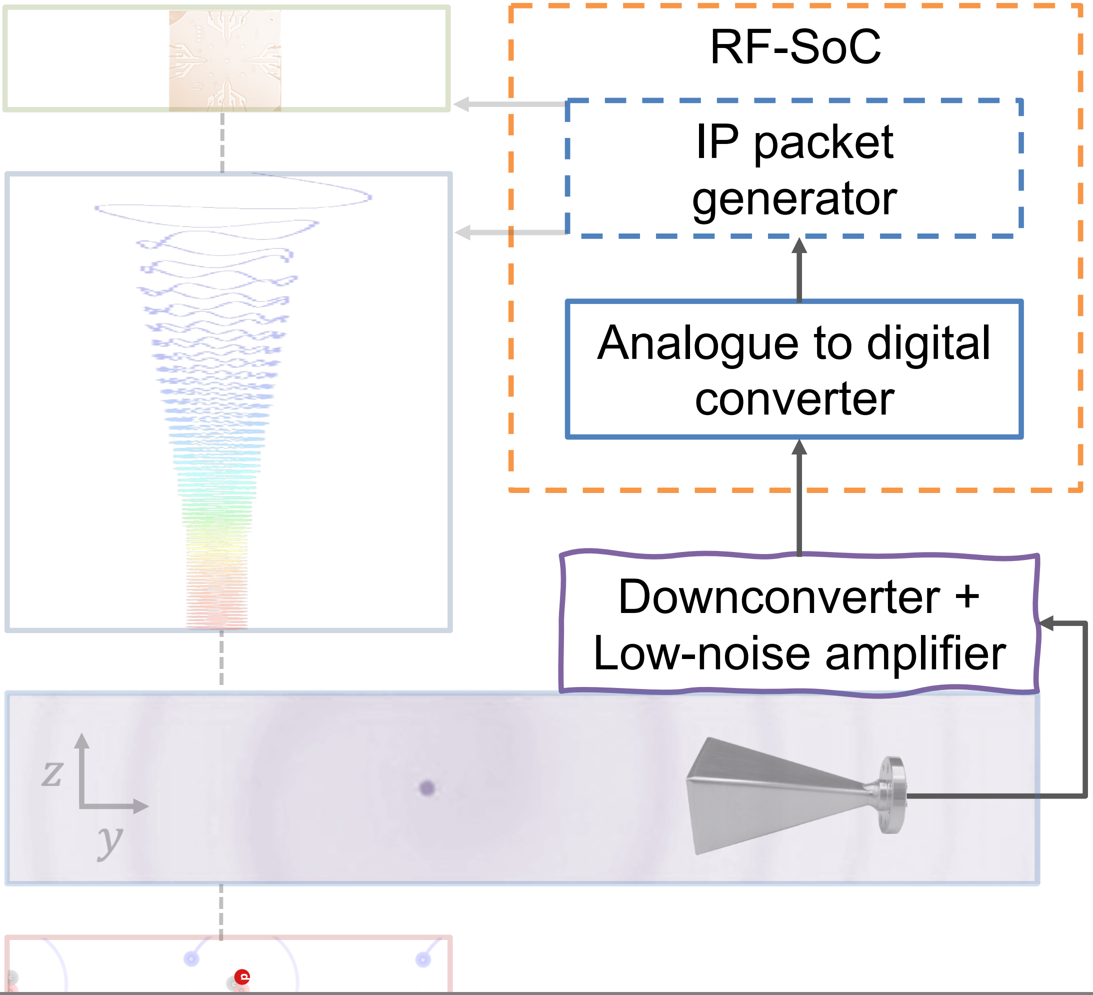
RF readout & electronics

Downconverter board



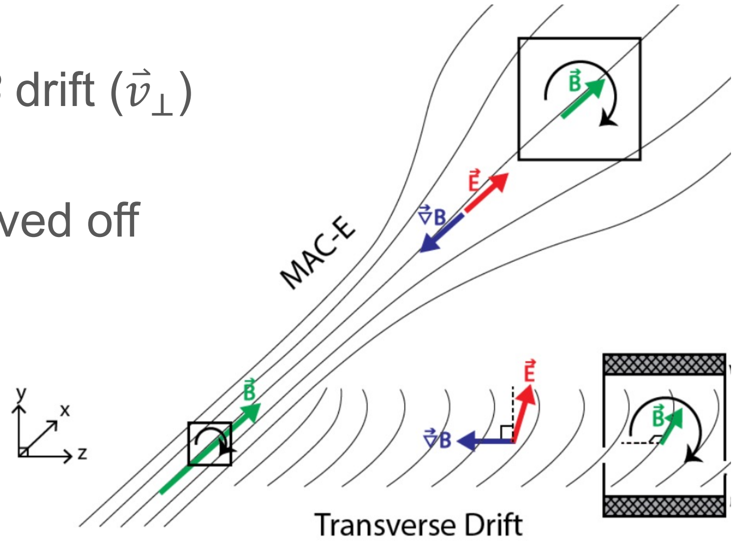
Front-end control board



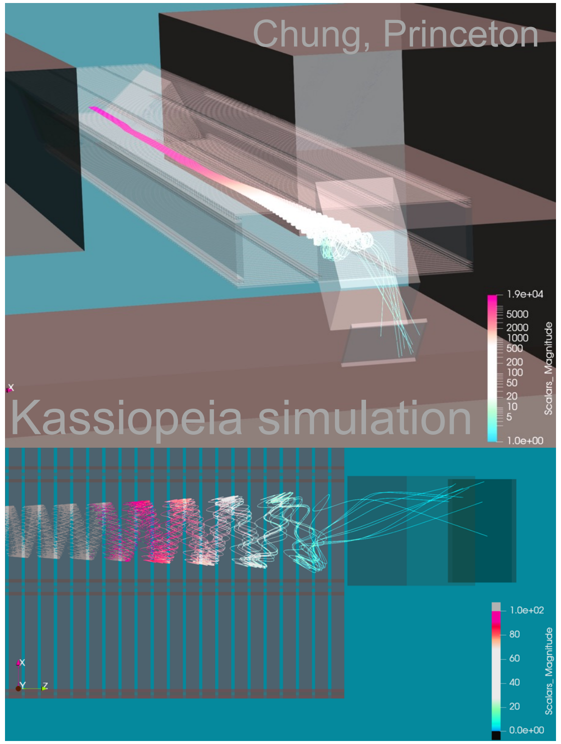


Naafs, NIKHEF

- ***Spin on KATRIN's MAC-E filter***
  - Bounce electrodes trap e⁻ in *ExB* drift ($\vec{v}_\perp$) along -ve ∇*B* in filter region
  - KE transverse to *B*-field ($T_\perp$) shaved off by work done through $E \cdot \vec{v}_\perp$
  - 18.6 keV to 0.01 keV in 0.7 m



$$\frac{dT_\perp}{dt} = \frac{\mu}{B^2}\boldsymbol{E}\cdot(\boldsymbol{\nabla}B \times \boldsymbol{B})$$



- ***Specification***
  - $\Delta T_\perp \sim \mathcal{O}(100meV)$
  - Dynamic setting informed by RF-tracker determination of $T_\parallel$
  - Acceptance of the filter adapts as per pitch of endpoint e⁻
  - Prototype filter magnet completed and tested at Princeton!

[arXiv:2108.10388]

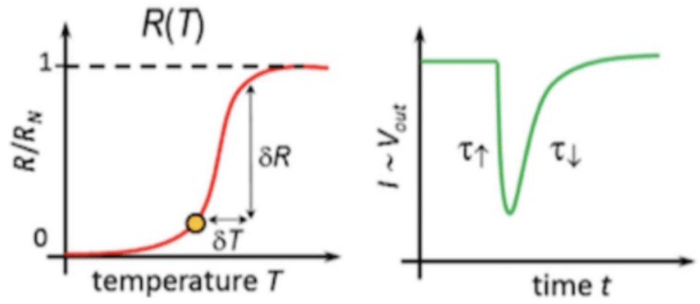
[arXiv:1810.06703]

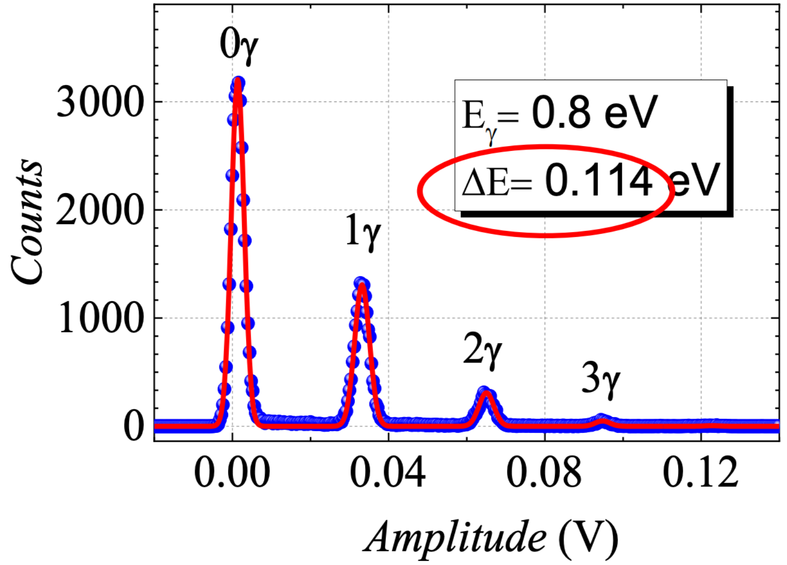
TES micro-calorimeter

[arXiv:1808.01892]

- ***Transition edge sensor***
  - Superconducting film held just below T_c (~100mK)
  - Near unit quantum efficiency
  - Resolution, $\Delta E \propto T^{3/2}$
  - Response time, $\tau_{eff} \propto T_c^{-3}$
  - Saturation energy, $E_{sat} \propto T_c$

- ***Energy resolution***
  - Requires ΔE_e = 0.05 eV at E_e = 10 eV
  - 20x20 μm pixels at 52 mK → ΔE_e ~100 meV with photons
  - Extrapolate down to 15x15 μm² pixels → ΔE_e ~ 50 meV
  - Soon testing with electrons!





Garrone, INRiM

PTOLEMY Demonstrator

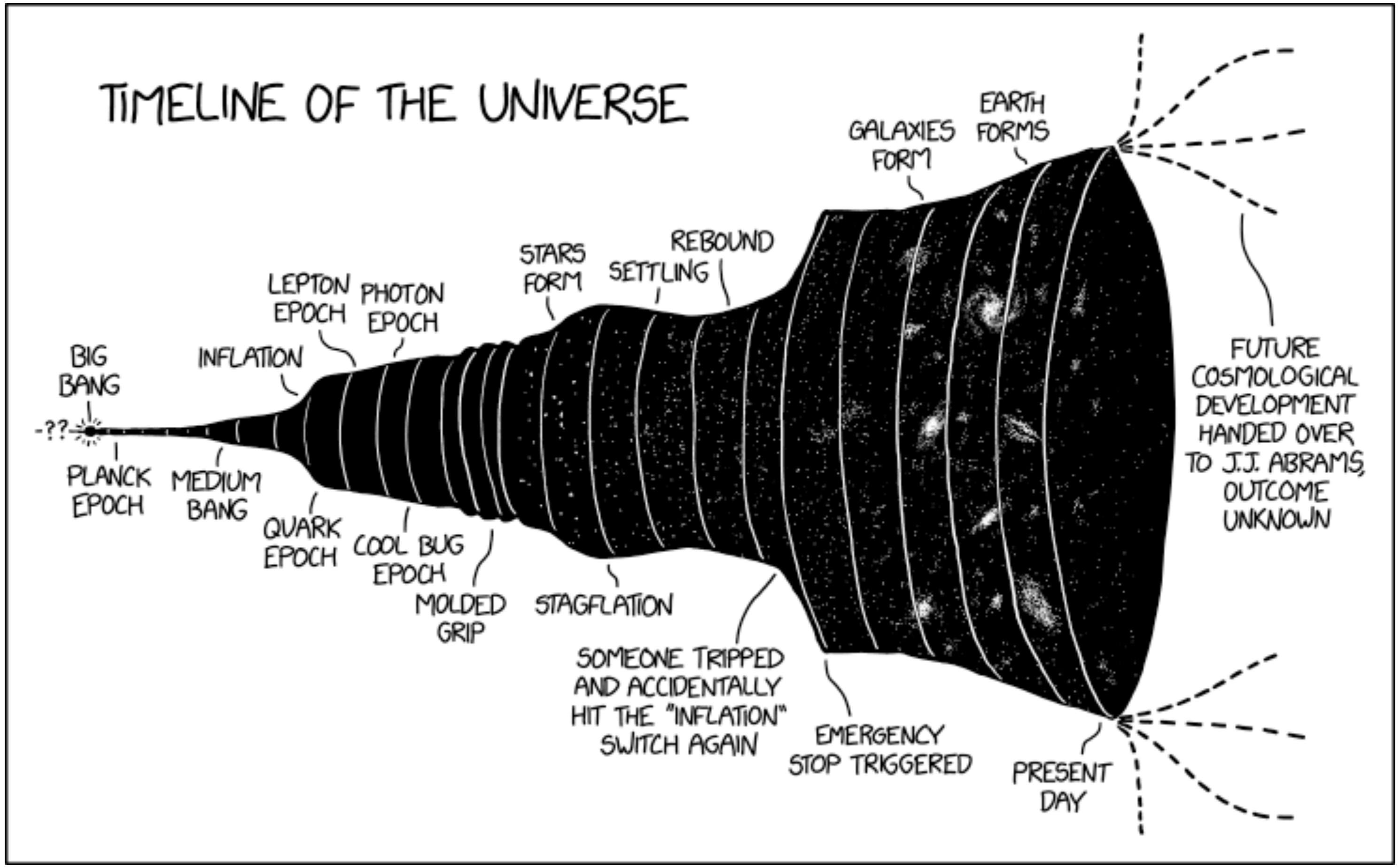
- ***Phase-0: 2023* – Proof of principle**
  - Calibration e^- source & silicon drift detector calorimeter
  - Electron transport from target to calorimeter
  - Filter selecting electrons $\Delta \sim 100 meV$ around endpoint
  - Efficiency study using electrons near E_{end}
- ***Phase-1: 2025 – Lowest neutrino mass***
  - >90% tritium loading on graphene – $\mathcal{O}(100\mu g)$ target
  - Transition edge sensor implemented as μ-calorimeter
- ***Aims for PTOLEMY***
  - ST: Develop target physics predictions (final states & excitations)
  - LT: Operate with larger target masses (up to 100g ~ 10^{25} atoms)

INFN LNGS

Conclusion

- ***High risk, high reward***
  - Array of novel R&D challenges yet to overcome
  - First observation of the CνB with intermediate determination of the lowest neutrino mass
- ***Single electron tracking using CR***
  - RF-system & readout electronics from HF-analogue systems experts
  - Amsterdam test setup: 0.95T magnet and $\mathcal{O}(10K)$ cold head vacuum chamber WIP
  - Kassiopeia end-to-end electron transport simulation & rapid solver for RF cavity excitations
- ***PTOLEMY prototype soon to be based at LNGS***
  - Closer ties being established with neutrino mass experiments and quantum sensor groups
  - New magnet commissioning 2023 (ANSALDO Co.) and installation at Gran Sasso
  - Demonstrator setup for 2025 – full setup for CνB runs in 2030s

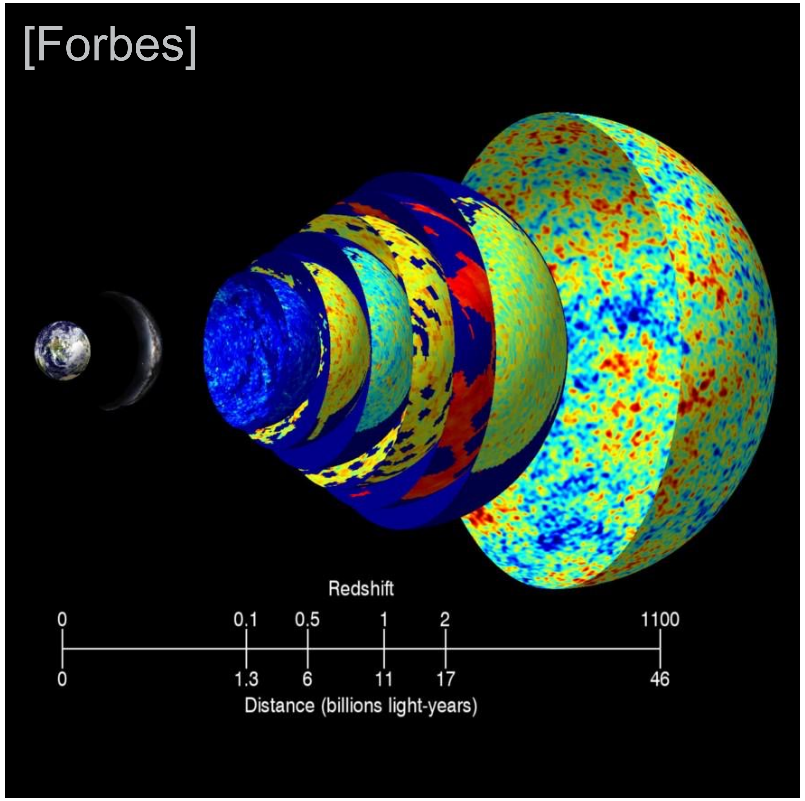
Thanks for listening!



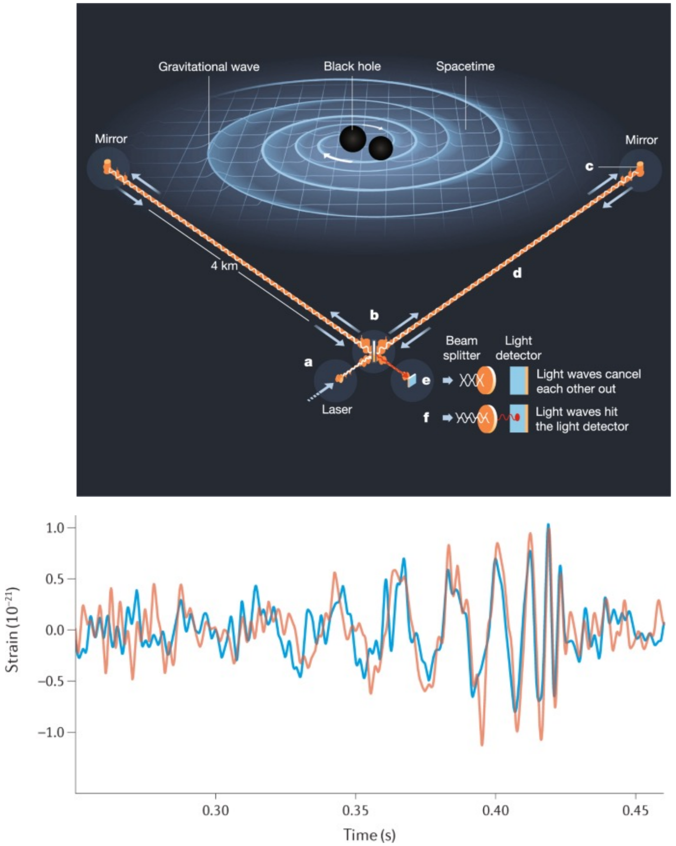
[xkcd.com/2240]

[APOD]

Wikipedia, Pablo

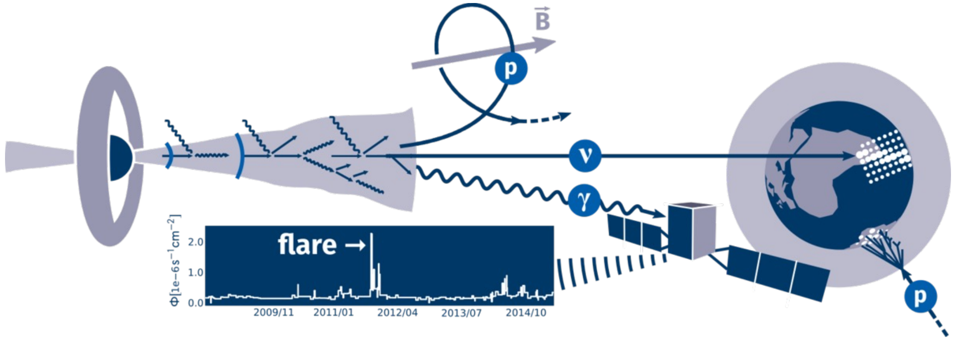


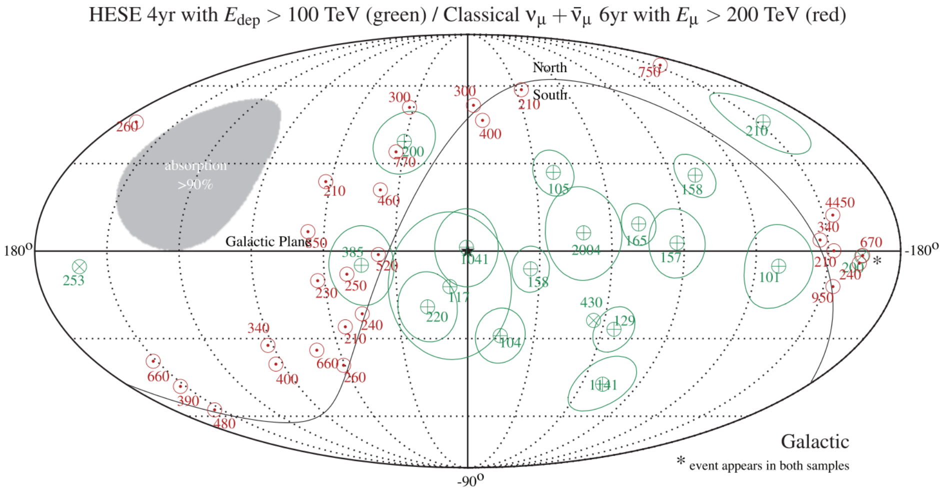
Gravitational waves



[10.1038/s41586-019-1129-z]

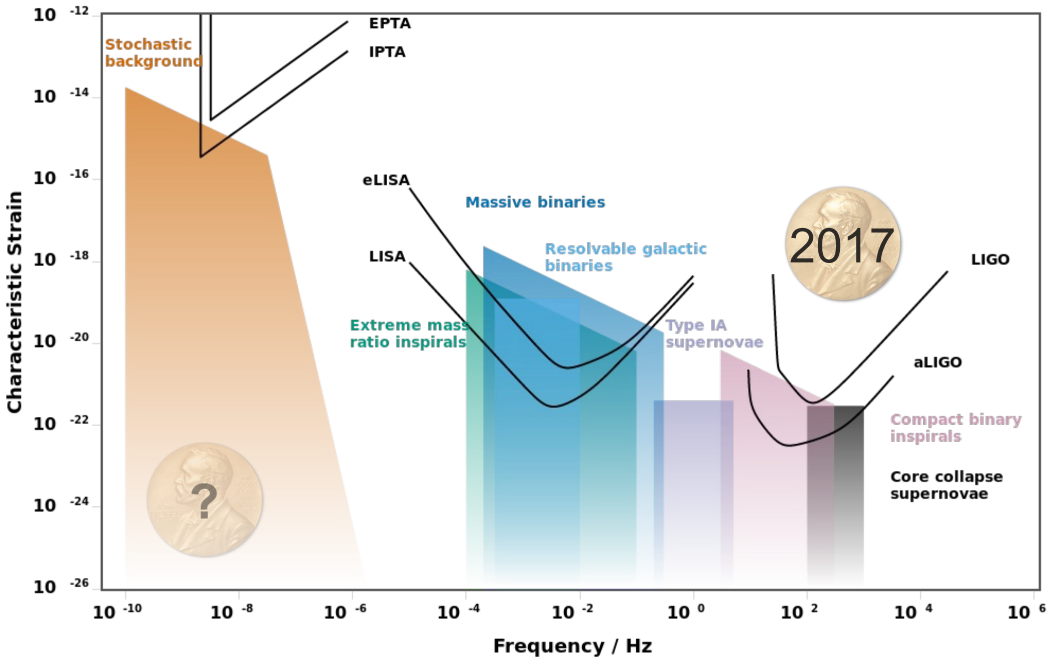
Neutrinos



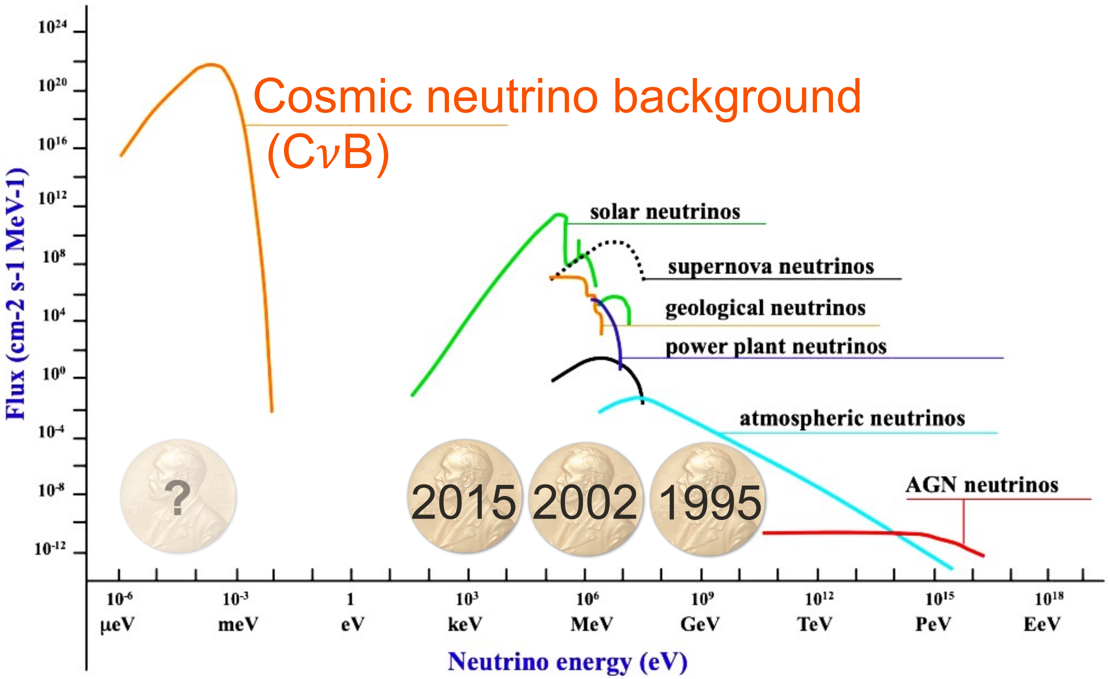


[arXiv:1805.11112v1]

Gravitational waves



Neutrinos

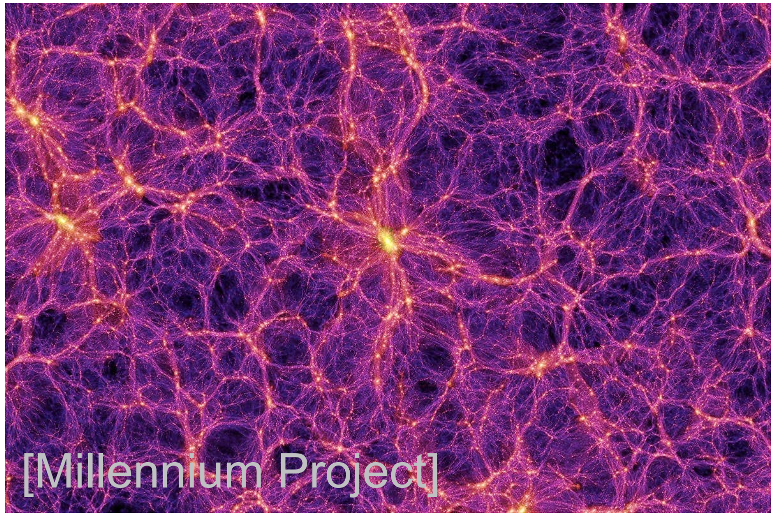


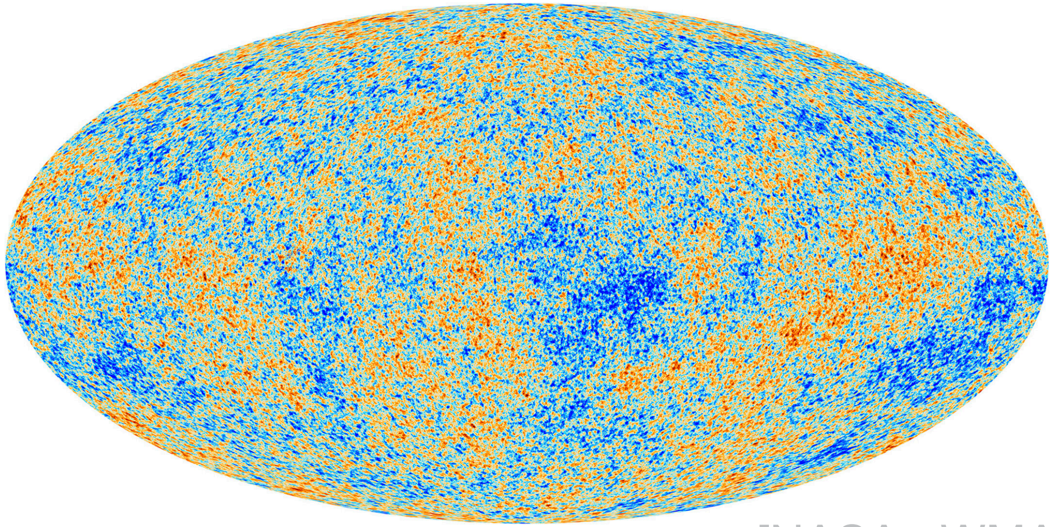
[arXiv:1408.0740v2]

[arXiv:1910.11878v3]

Imprint upon the cosmos

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





[NASA - WMAP]

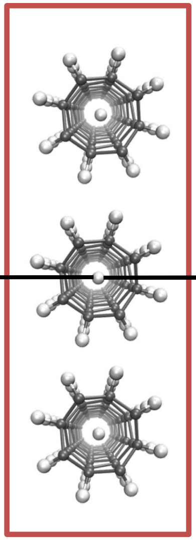
- Anisotropies in the CνB result in phase variations which damp the angular power spectrum of the CMB

Frankenstein's monster

Solid state ^3H

[arXiv:2203.11228]

Target



ν-capture on 100g tritium

Project 8

[arXiv:1703.02037]

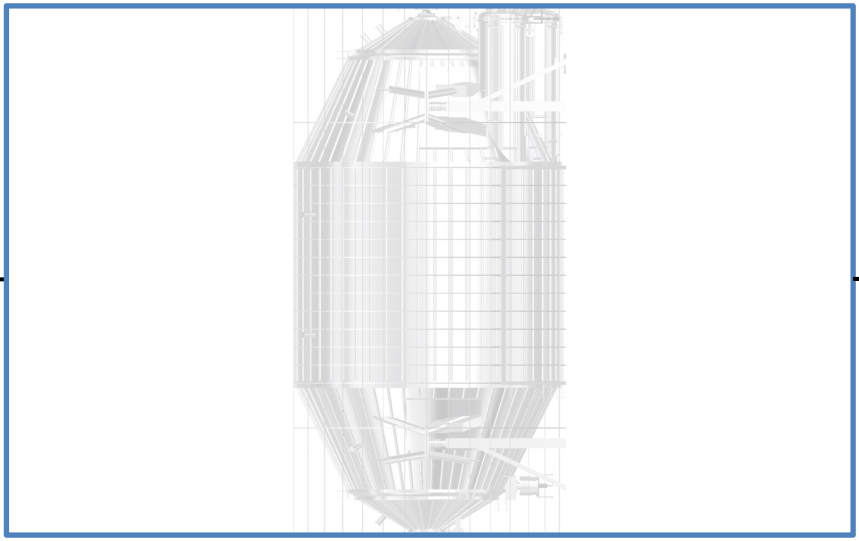
CRES

RF-tracking
$\sigma(E_x) \sim \mathcal{O}(eV)$

KATRIN

[katrin.kit.edu]

MAC-E filter

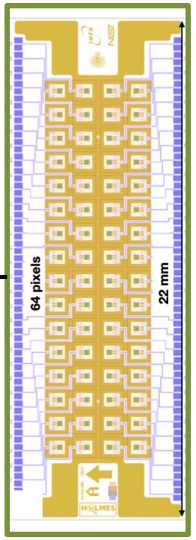


EM filter
$\Delta E_z \sim \mathcal{O}(100meV)$

HOLMES

[Gerone et al (2022)]

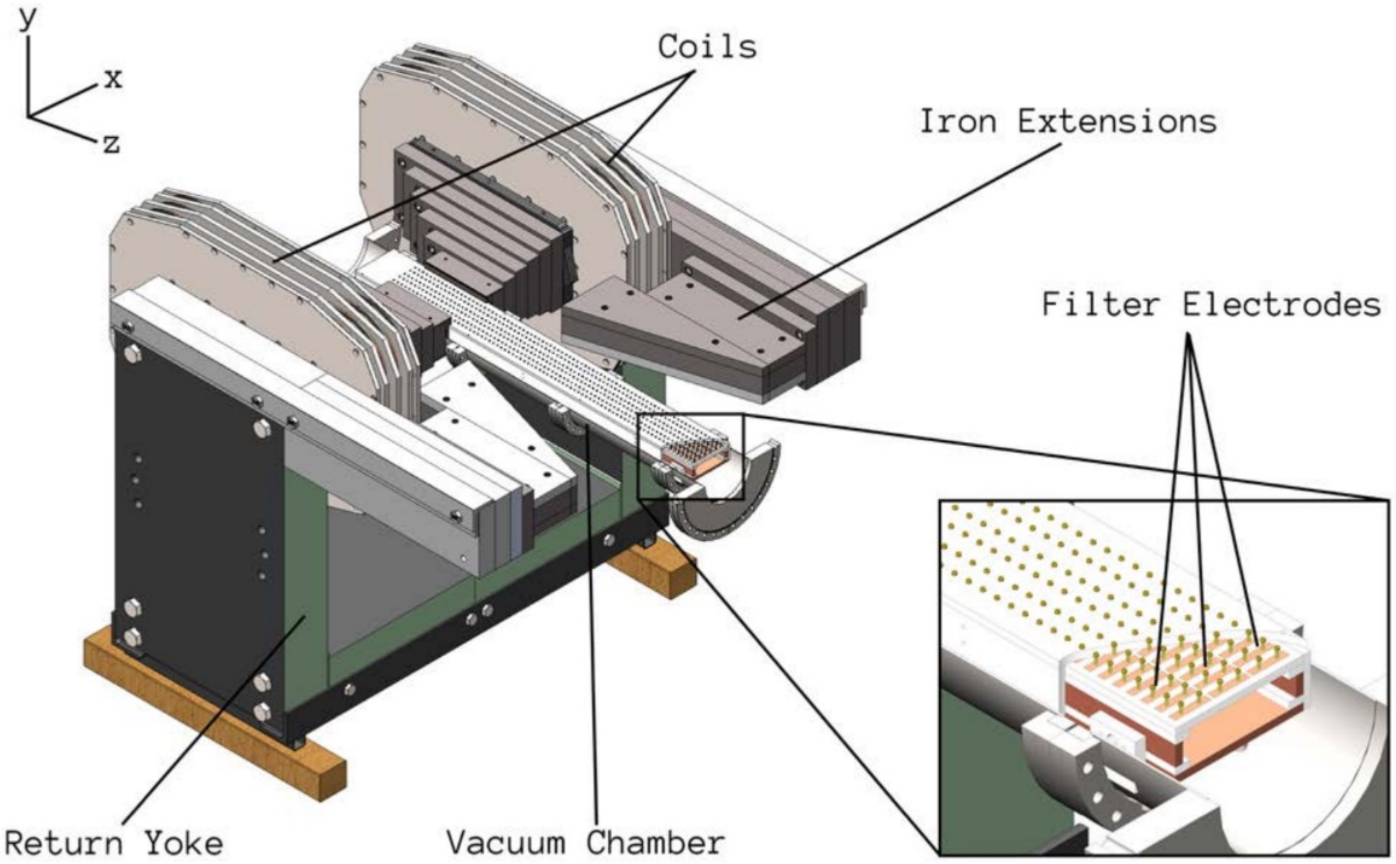
μ-cal



TES
$\mathcal{O}(10\ meV)$

ν → e^-

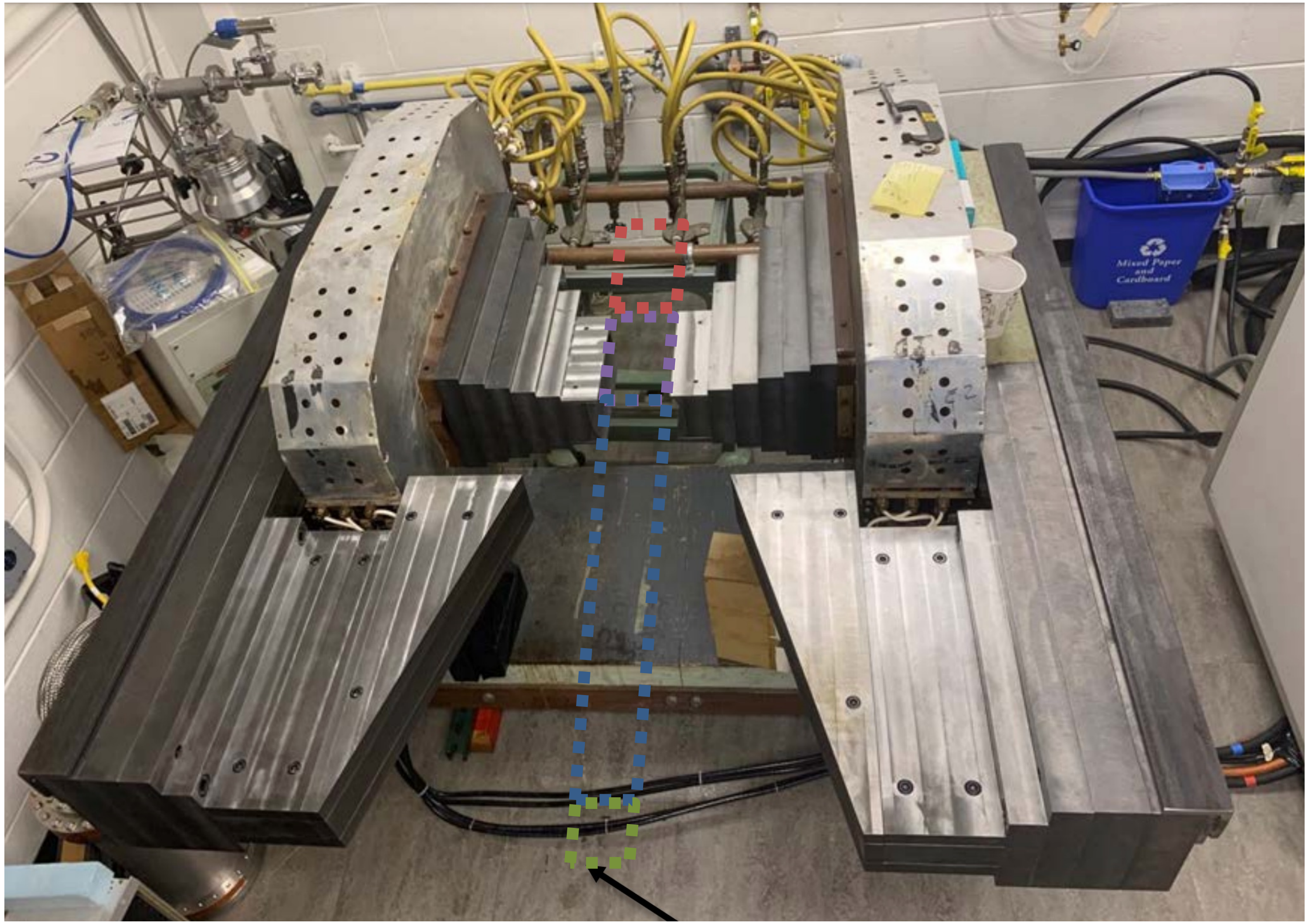
- *B*-field in RF region is constant; extends over EM-filter region for ∇*B*x*B* drift

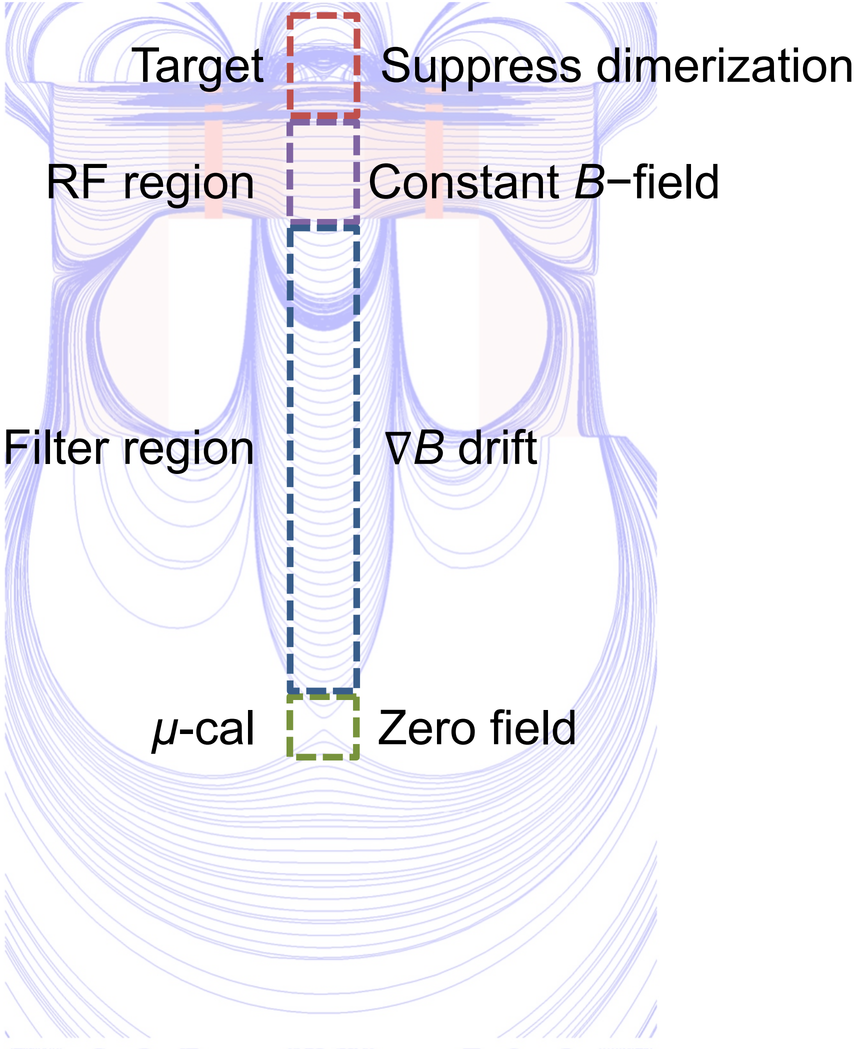


Tritium target

Tan, Princeton

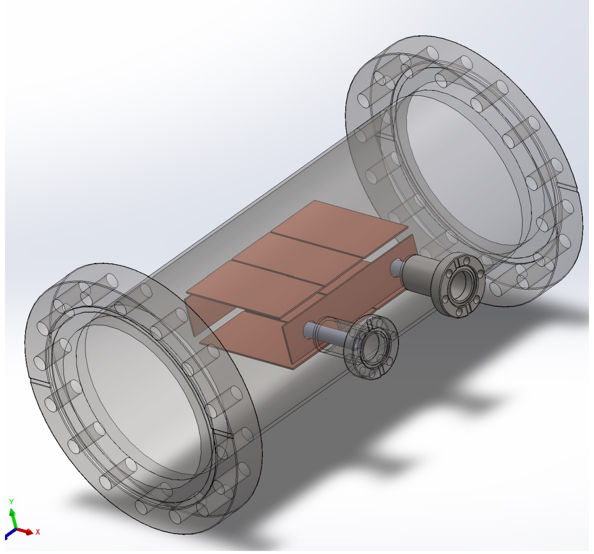
Continuous magnetic field

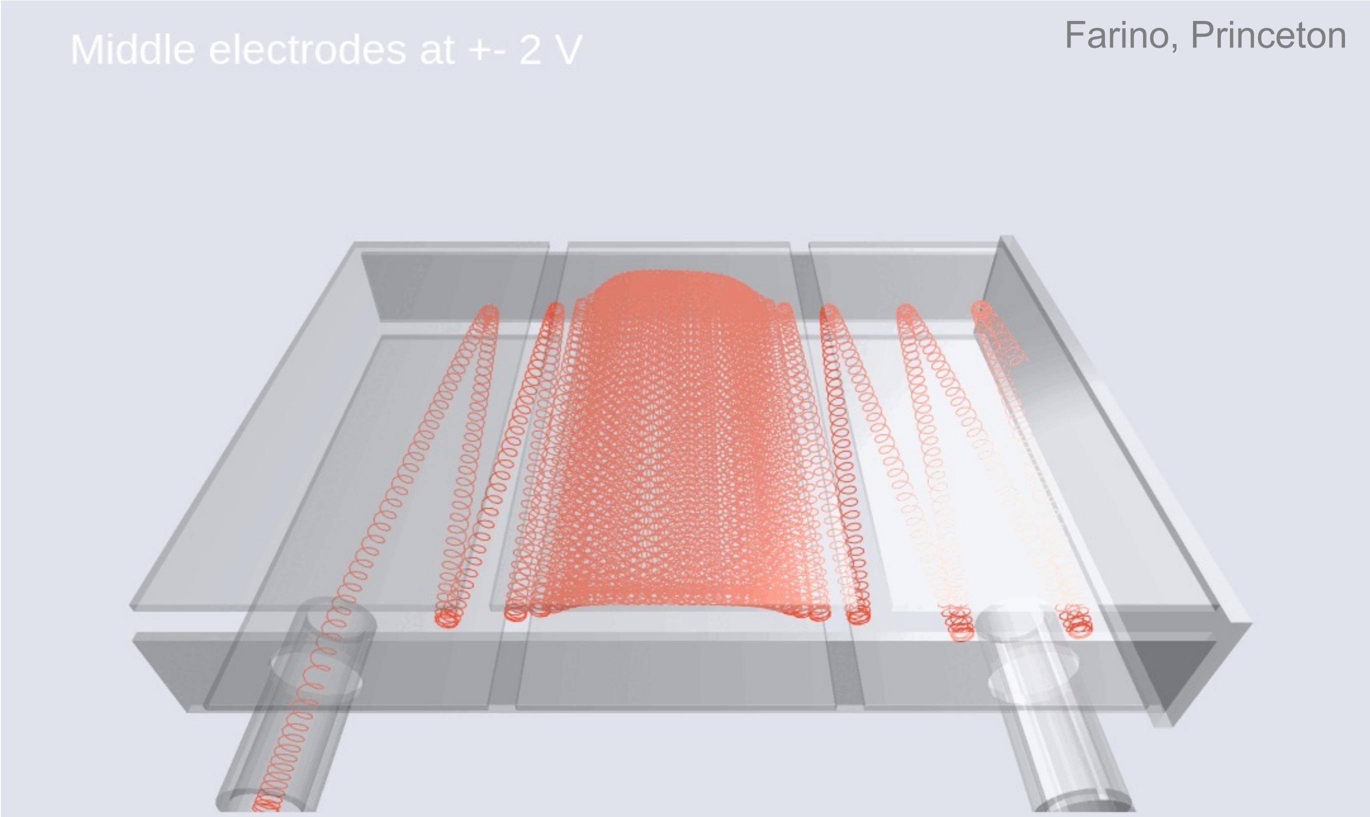




Chung, Princeton

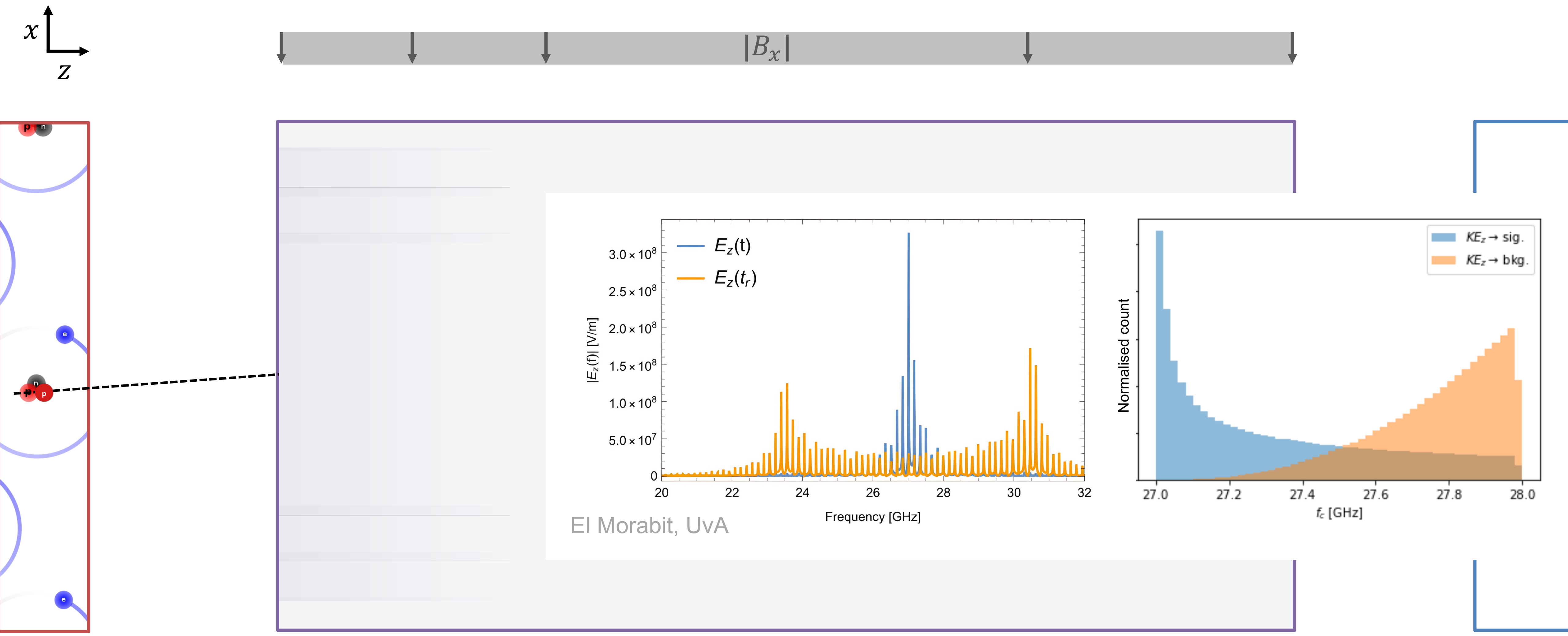
Slow *ExB* drift region

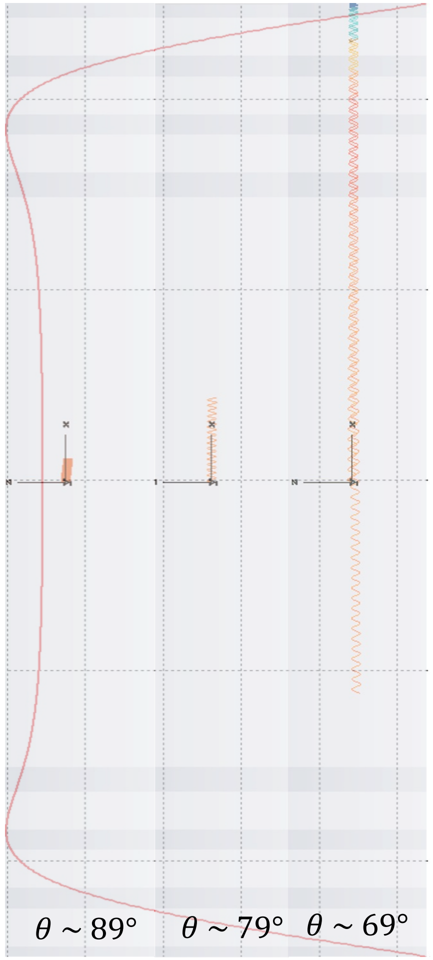




- Tuning E_y field to maximise signal interrogation time

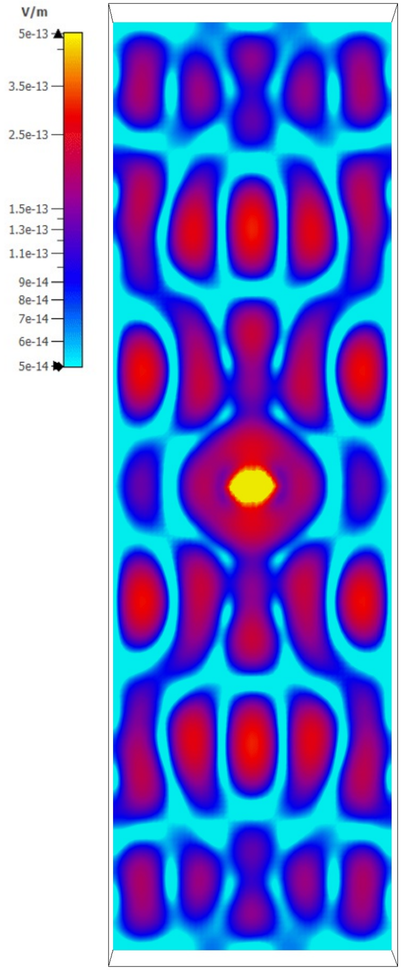
RF trigger & tracking





- Potential shaping for high-pitch electrons to maximise signal for proximity-based antennas
- Tuning bounce potential to minimise distance from waveguide to coax. side-port increasing solid angle of ~1fW CR emissions received

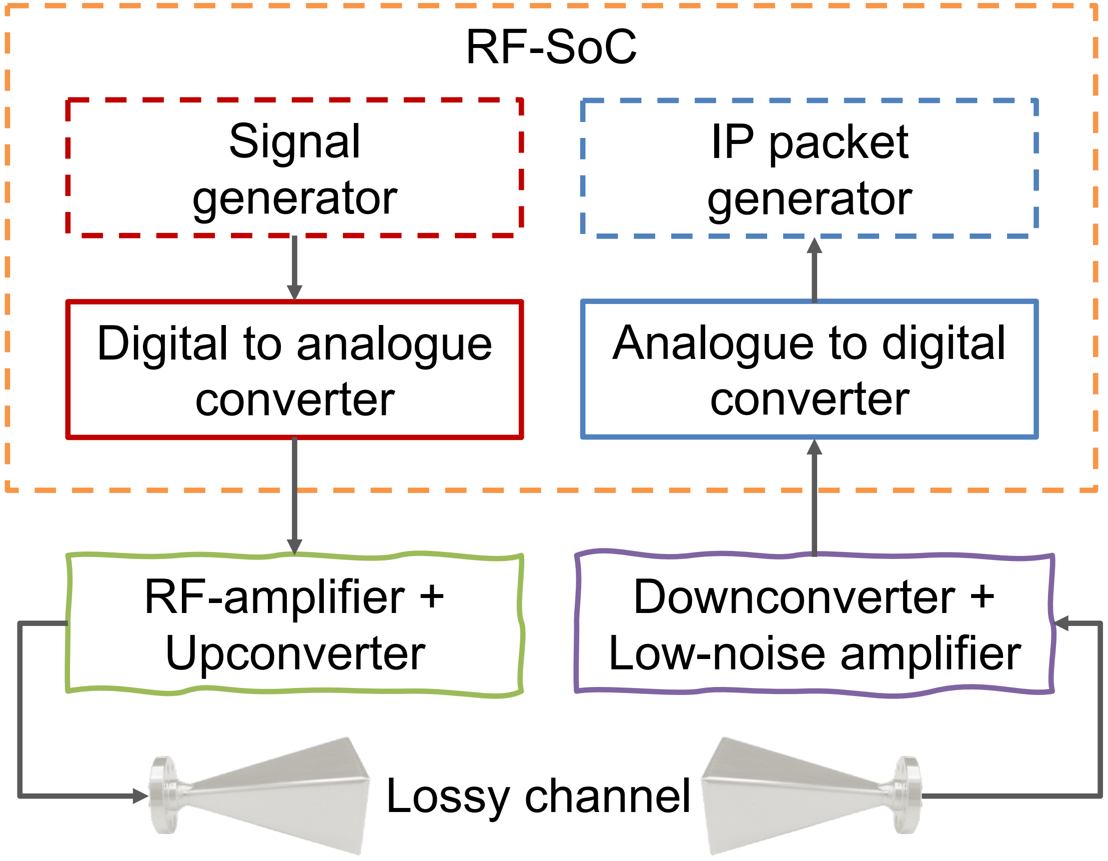
- *E*-field excitations in a rectangular cavity (x,y)-plane from 18.6 keV e^- orbiting [0,0,0]
- Mode decomposition will help us optimise cavity & antenna system design
- Mode filtering elements to be investigated



El Morabit, UvA

RF 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



Naafs, NIKHEF