The HUNTER experiment - searching for keV sterile neutrinos by energy-momentum reconstruction of atomic K-capture events

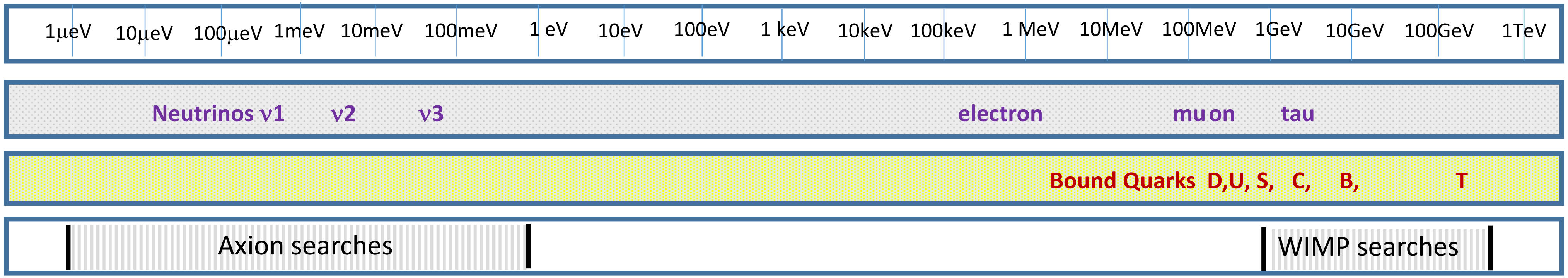
Peter F Smith (UCLA)

- Dark matter could be sterile neutrinos (K N Abazajian, day 1)
- Direct detection not yet feasible (PFS DM2016 & arXiv:1607.06876)
- Could be detected in laboratory K-capture experiments
- Initial demonstration phase (proof of principle) recently funded by Keck Foundation

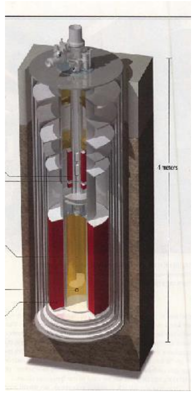
interdisciplinary collaboration (particle physics, nuclear physics, atomic physics):

Jeff Martoff, Francesco Granato, Xunzhen Xu, *(Temple University)*
Andrew Renshaw *(University of Houston)*
Peter D Meyers *(Princeton University)*
Eric Hudson, Paul Hamilton, Christian Schneider, Hanguo Wang, Peter F Smith *(UCLA)*

Wide mass range of known 'elementary' particles and new particle searches

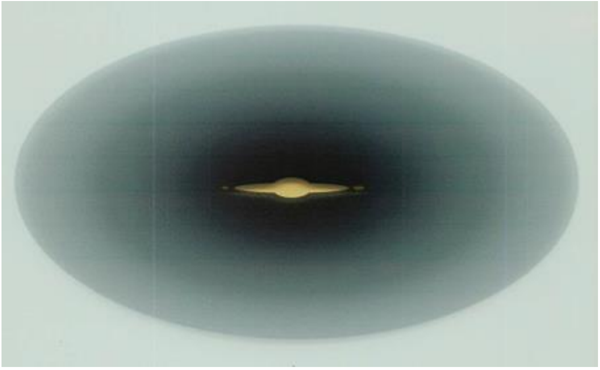


No Axion signals so far

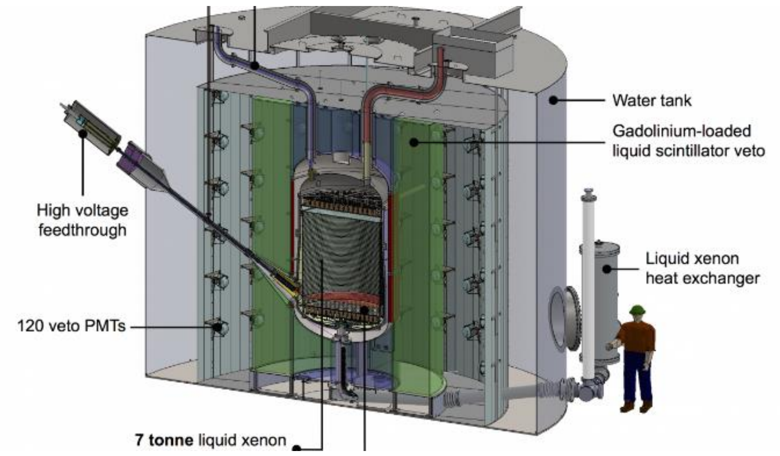


Galactic dark matter Problem

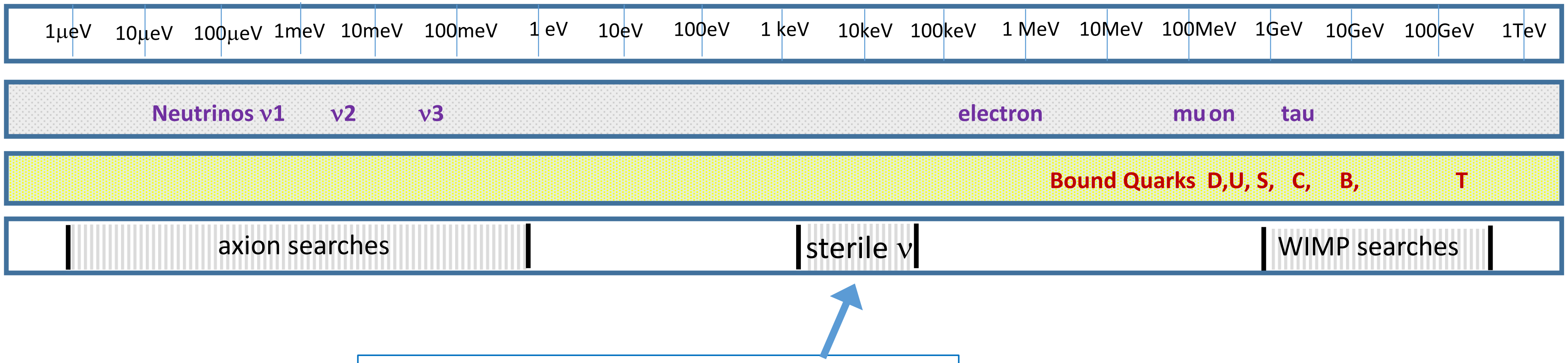
New stable particle needed for dark matter ?



No heavy particle dark matter signals seen in underground ton-scale detectors or at Large Hadron Collider. Multi-ton detectors planned.



New mass range expected for sterile neutrino dark matter



Theoretical calculations show

- *5 - 30 keV sterile neutrino mass range could give known dark matter density.*
- *Weak relative coupling < 10^{-4} gives stability for universe lifetime.*
- *Not detectable in existing or foreseeable experiments*

Galileo (1564 – 1642):
"Measure what is measurable.
Make measurable what is not so"

How do we 'make measurable' a keV sterile neutrino ?

Search for sterile neutrinos in electron neutrino emission

Electron neutrino is a mixture of mass eigenstates

neutrino flavors (ν_e , ν_μ , ν_τ , ν_{s1} ν_{s2} ν_{s3}) ⟷ mixtures of definite mass (ν_1 , ν_2 , ν_3 , ν_4, ν_5, ν_6)

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \\ \nu_{s1} \\ \nu_{s2} \\ \nu_{s3} \end{vmatrix} = \begin{vmatrix} c_{11} & c_{12} & c_{13} & c_{14} & c_{15} & c_{16} \\ c_{21} & c_{22} & c_{23} & \cdot & \cdot & \cdot \\ c_{31} & c_{43} & c_{33} & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \end{vmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \\ \nu_4 \\ \nu_5 \\ \nu_6 \end{vmatrix}$$

mass eigenstates

beta decay
or K-capture

'electron neutrino'

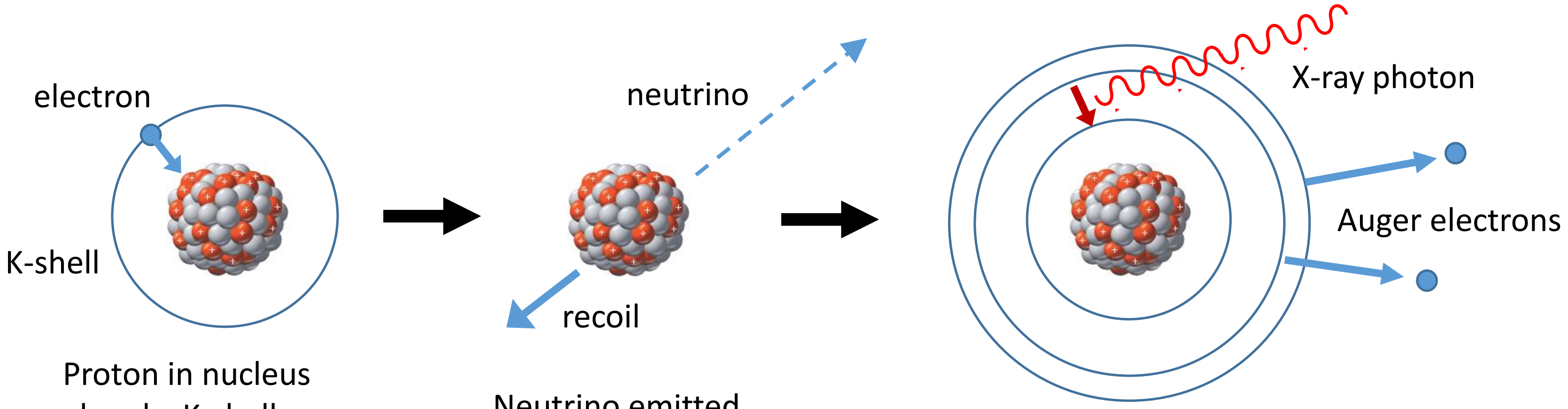
$$\nu_e = c_{11}\nu_1 + c_{12}\nu_2 + c_{13}\nu_3 + c_{14}\nu_4 + c_{15}\nu_5 + c_{16}\nu_6$$

standard neutrino mass states

admixture of 'sterile' neutrinos

lower probability but will be seen as rare events

Proposed K-capture experiment: measuring the mass of an unseen neutrino



Proton in nucleus absorbs K-shell atomic electron

Neutrino emitted
Nucleus recoils

X-ray emitted
Auger electrons emitted

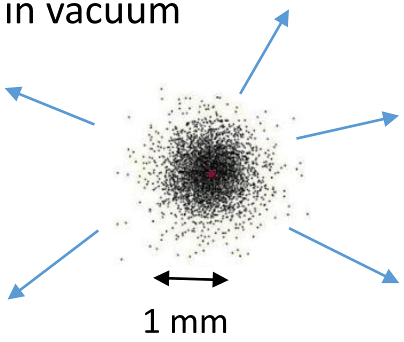
make precision momentum measurements of:

- recoil ion
- X-ray photon
- Auger electrons

↓

calculate missing ν momentum

- Cloud of ^{131}Cs atoms (10 day half-life) suspended in vacuum

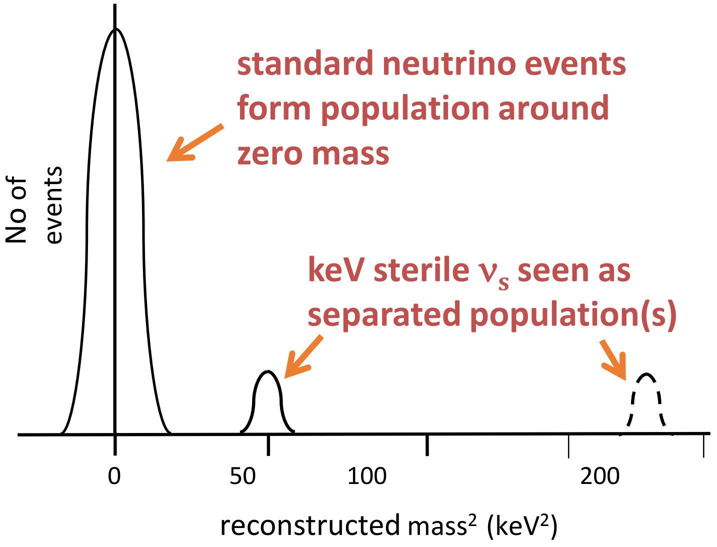


Reconstruct neutrino mass for large number of events

$$m_\nu^2 = [Q - E_a - E_\gamma - E_N]^2 \; - \; [\mathbf{p}_\gamma + \mathbf{p}_{ea} + \mathbf{p}_N]^2$$

missing energy   missing momentum

Reconstructed mass spectra:



Requires advanced versions of two established techniques

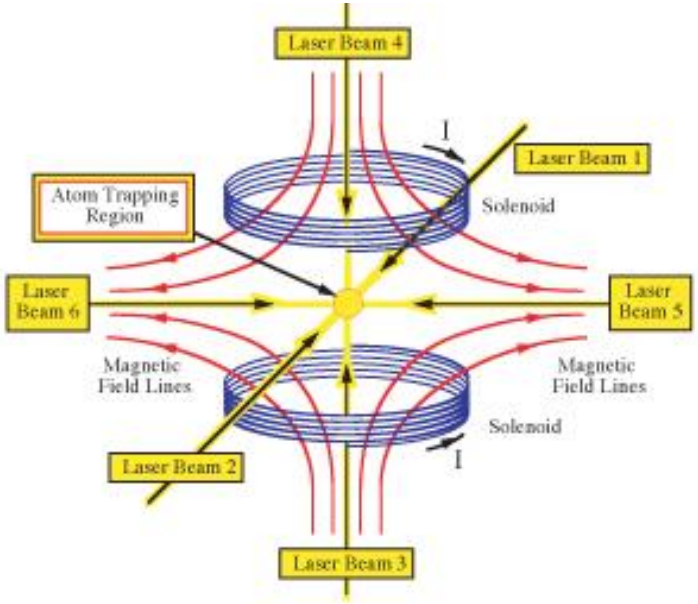
MOT - Magneto-Optical Trap

Developed for over 20 years for cooling and suspension of neutral atoms

No of trapped atoms: 10^6 - 10^{10}

Atom temperature: 10 - 100 μK

(Atomic & Molecular Optics Group UCLA)



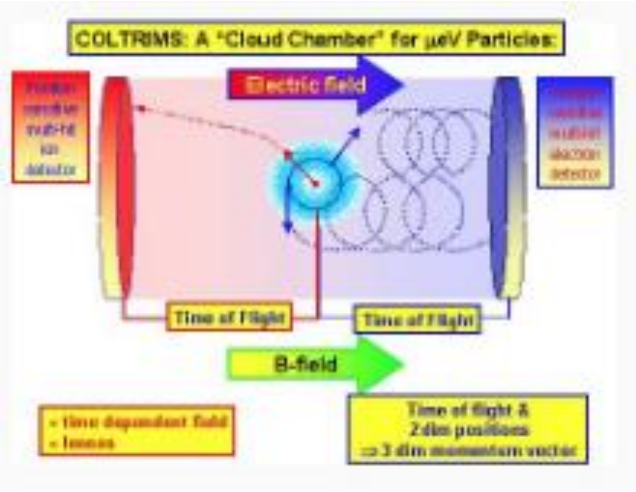
COLTRIMS – COLd Target Recoil Ion Mass Spectroscopy

Used extensively for 20 years for 3-D studies of atom-atom and photon atom collisions

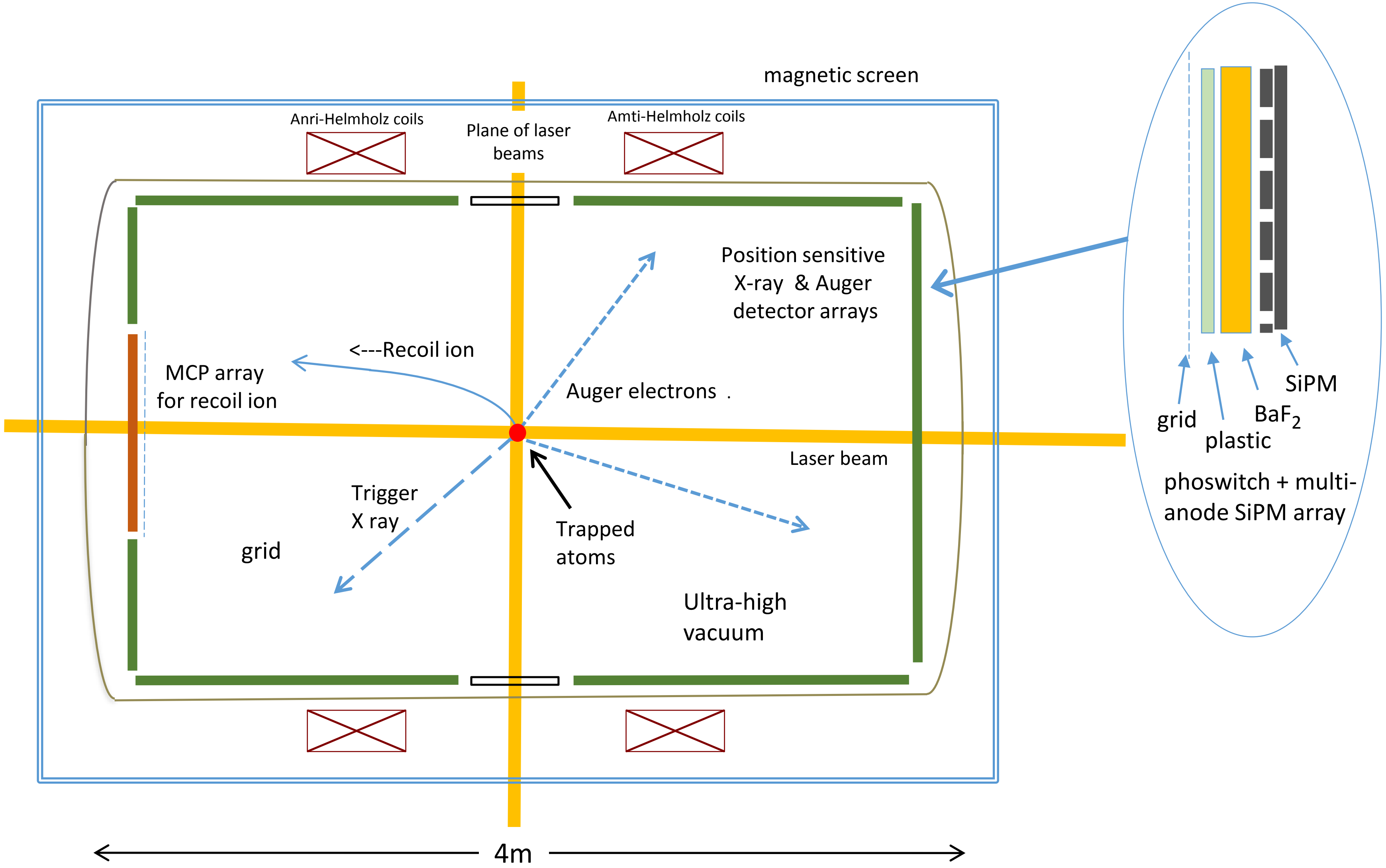
time of flight precision 200 ps

spatial precision (MCP) 40 μm

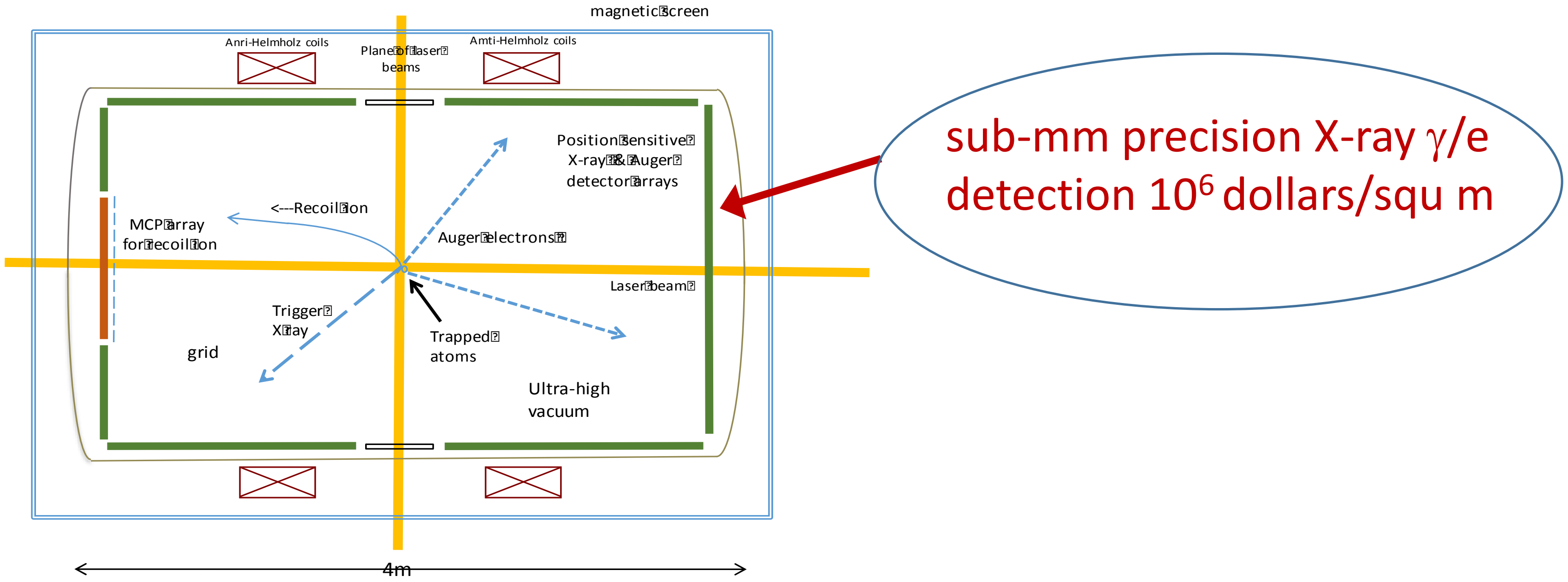
(supplied by Roentdek, Germany)



Original (2016) suggestion for 4π collection and time-of flight measurement

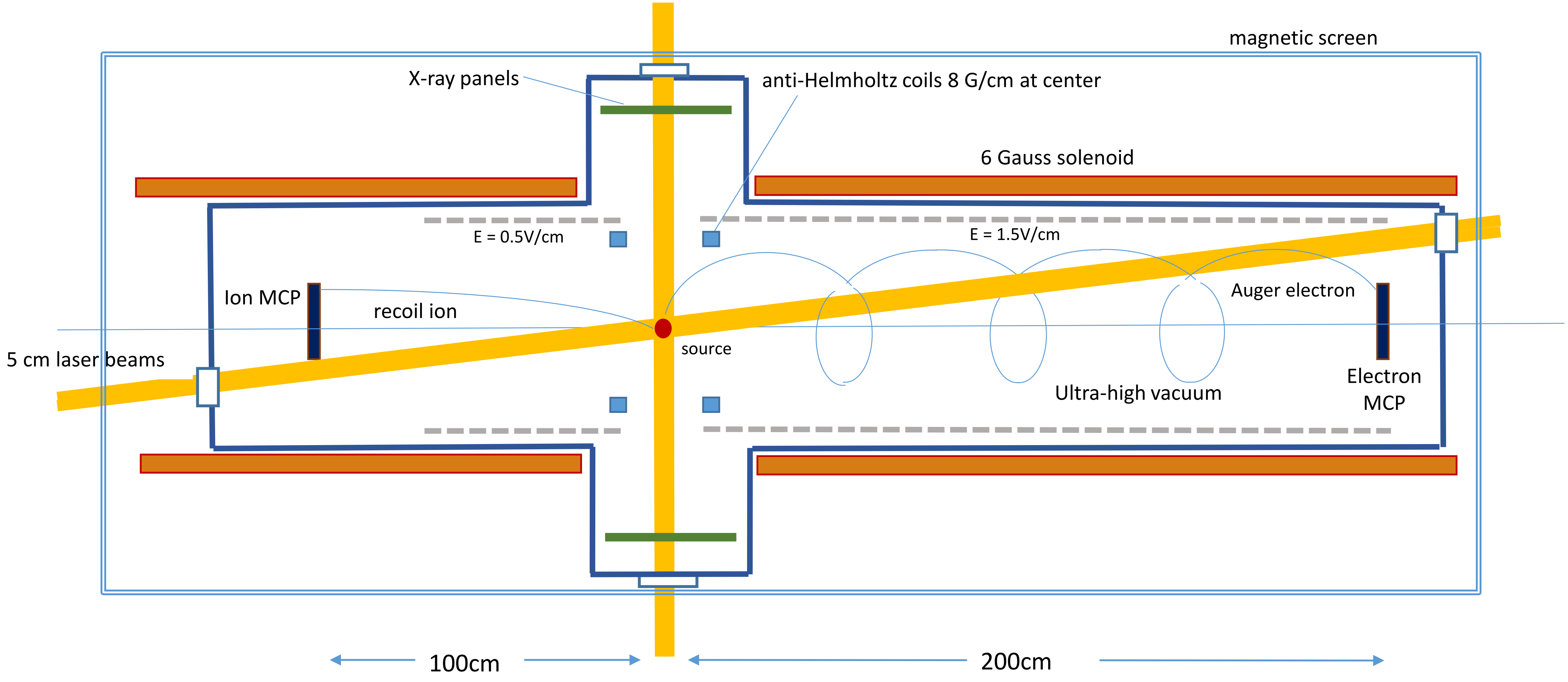


Original proposal for 4p collection and time-of flight measurement

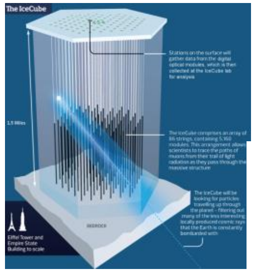


HUNTER experiment (**H**eavy **U**nseen **N**eutrinos by **T**otal **E**nergy-momentum **R**econstruction)

Phase 1 (proof of principle) funded by Keck Foundation

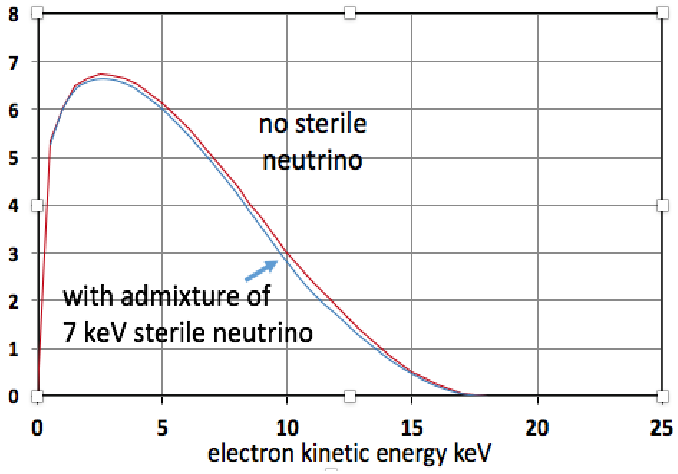


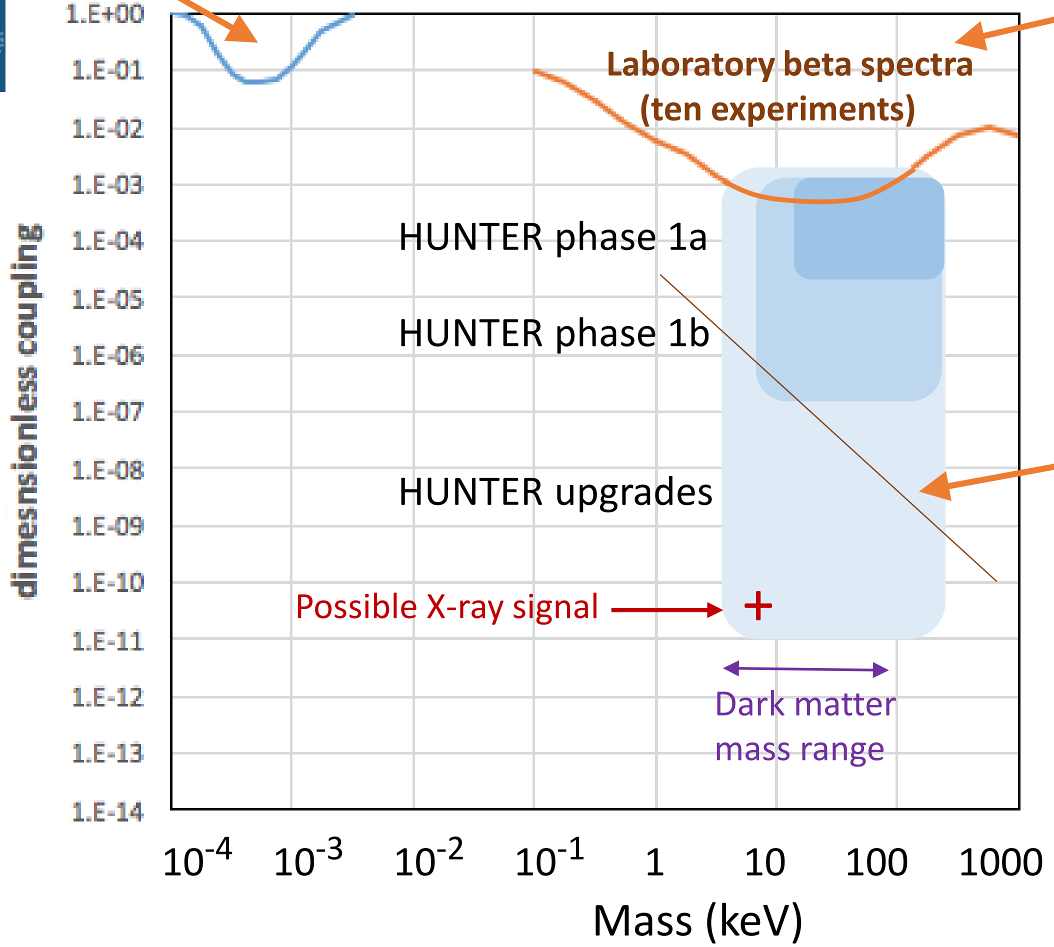
Existing limits and future coverage of HUNTER experiment



Antarctic 'ICE CUBE'
Detector + CR muons

Sterile neutrinos would
produce minute distortions
In beta decay spectra



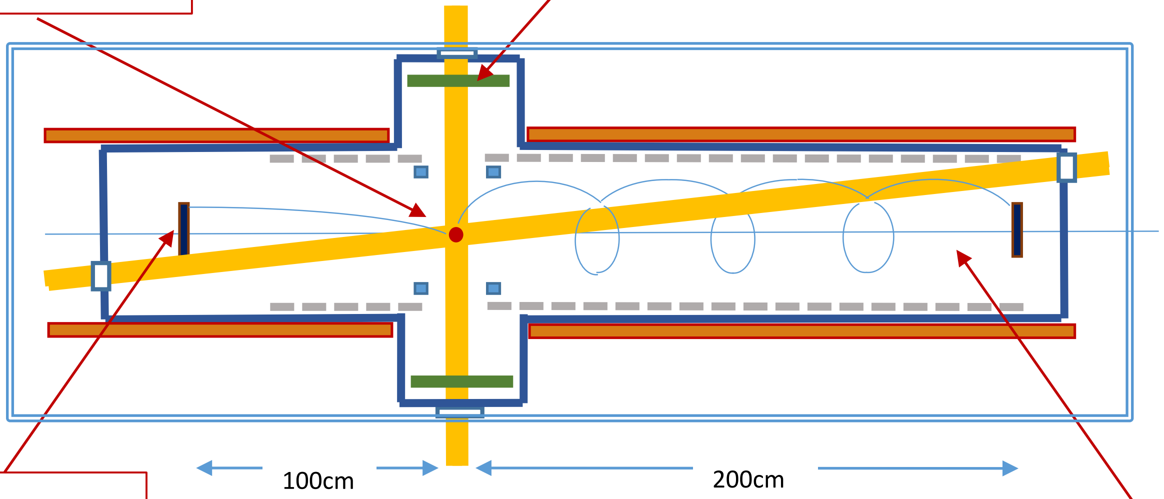


X-ray astronomy limits
If significant sterile ν
component of DM

Principal technical challenges !!

- MOT 10^7 - 10^8 ^{131}Cs atoms in 1-2mm volume
- MOT scalable to 10^9 - 10^{10} atoms
- MOT magnet coils aligned to 0.5mm precision
- Constant replenishment with 10 day half life
- Pulsed MOT operation with 20ms cycle
- Compensation for eddy currents in vessel
- Ultra-high vacuum 10^{-11} tor
- Minimum loss loading
- Periodic uv desorption of lost atoms

- LYSO/SiPM detector panel selects N-shell X-ray photons
- Gives event trigger time to 0.5ns
- Requires X-ray photon angle to 5.10^{-3} radian
- Requires spatial calibration relative to source to < 0.3mm
- LN2 cooling for low electronic noise

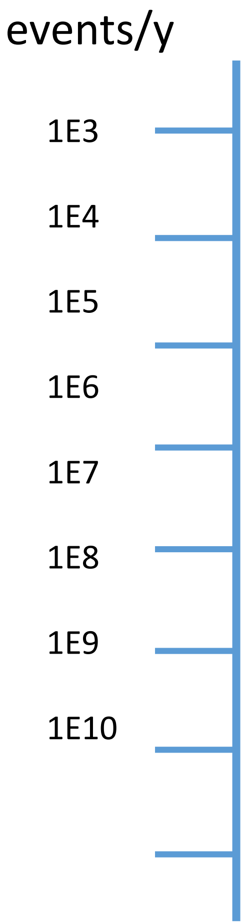


- MCP 60 micron spatial precision
- Time of flight < 1ns precision
- Recoil ion momentum 0.02% precision
- Recoil angle precision 2.10^{-3} radians
- Axial time-focusing of source axial size
- Electrostatic focusing of lateral source size

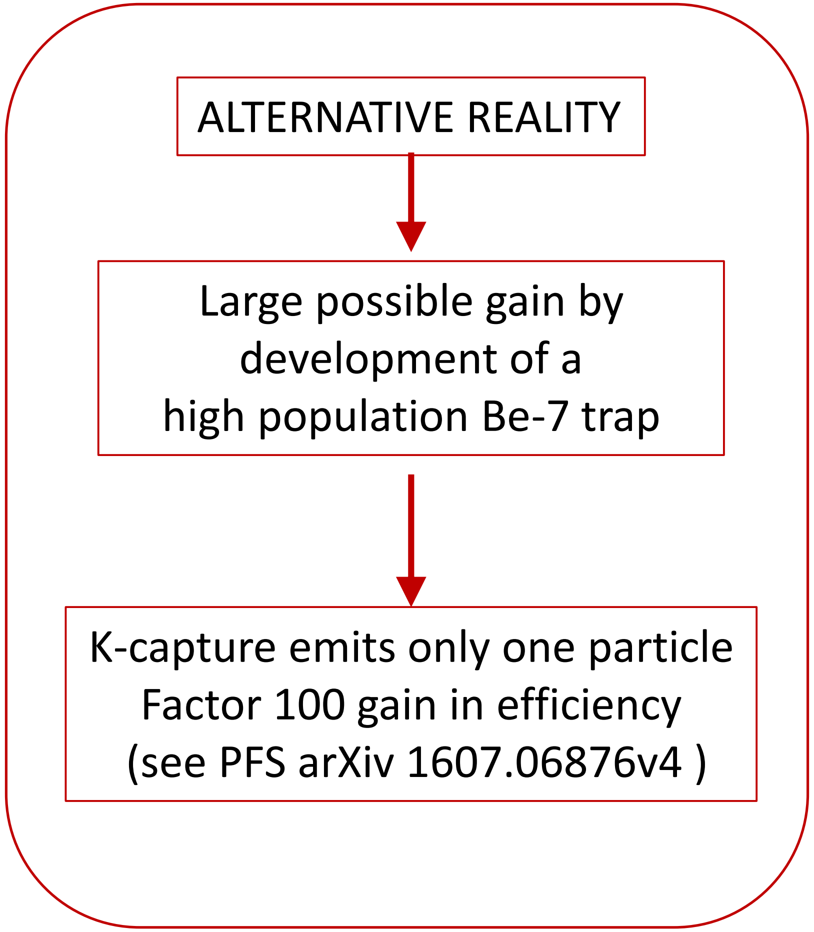
- External magnetic fields shielded to 0.1mGauss
- Non-magnetic vacuum vessel material
- Simultaneous detection of 1 or 2 Auger electrons
- Energy precision 3.10^{-3} for 20 – 120 eV energy
- Directional precision 2.10^{-3} radians each electron
- Rejection of 'shake-off' electrons from Cs -> Xe transition
- Timing rejection of electron background from ^{131}Cs & X-rays
- Computed relation between MCP signals and initial angles
- Photo-ionization calibration of residual transverse field correction

Conclusions :

- sterile neutrino masses in range 7 – 300 keV detectable with Cs-131
- lower mass limit depends on achieved momentum precision
- coupling sensitivity governed by no of events/y, increasing with upgrades



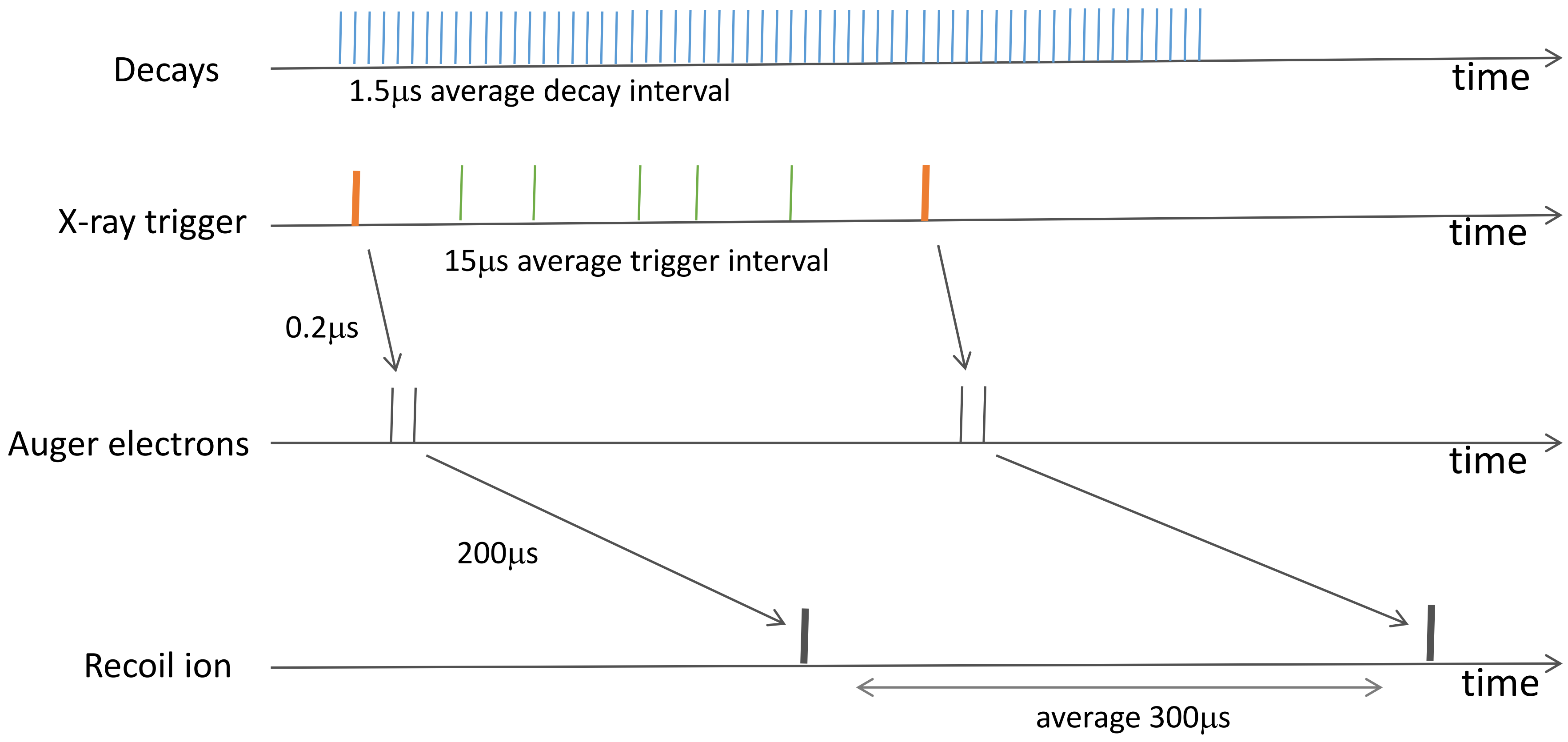
- Phase 1a Keck funding (3-y) from Jan 2018
  Source 1E7 atoms
  demonstrate mass reconstruction,
  assess backgrounds, optimize analysis.
- Phase 1b: Source 1E9 atoms
  Detector improvements
  Analysis improvements
- Phase 2a: Source 1E10 atoms
  larger detector coverage
- Phase 2b: Upgrade to multiple sources ?



Spare slides for questions

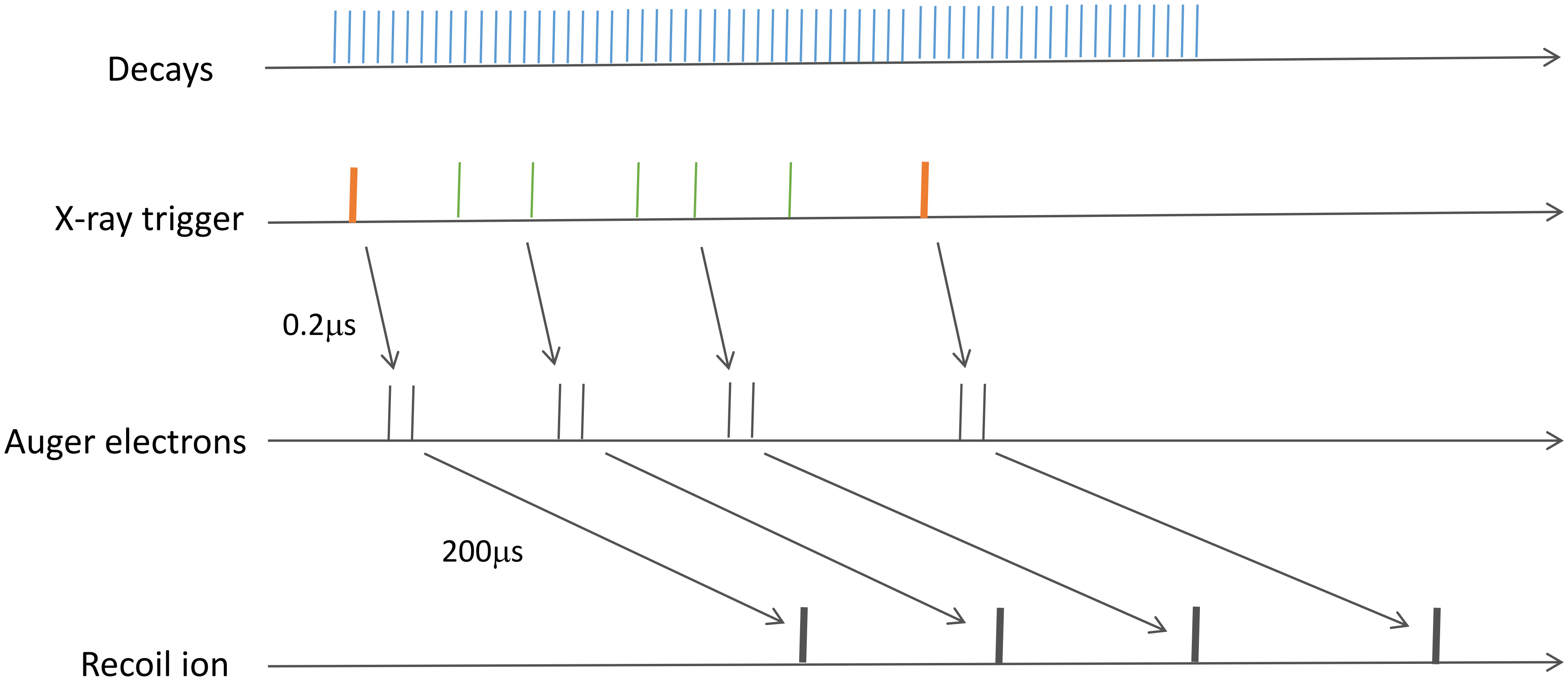
Background reduction by event timelines

- find trigger with matching Auger and ion signals
- wait for completion of event before searching for next matching set



Faster event processing by overlapping timelines

- search for overlapping events by matching corresponding Auger and ion signals
- majority of events are incomplete (Auger and/or ion signals missing)
- thus overlap allows more analyzed events/year, but software analysis complex



(shown timescales not linear)

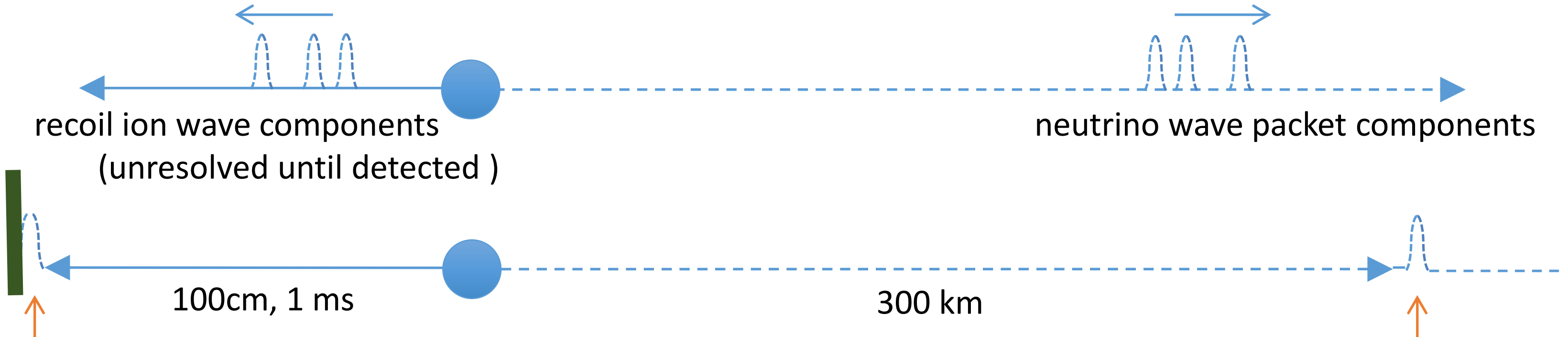
K-capture provides excellent example of wave packet collapse

$$\begin{vmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{vmatrix} = \begin{vmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{23} \\ c_{31} & c_{43} & c_{33} \end{vmatrix} \begin{vmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{vmatrix}$$

Mass eigenstates

$$\nu_e = c_{11}\nu_1 + c_{12}\nu_2 + c_{13}\nu_3$$

different masses -> different momenta and speed



Detection selects one component of wave function

Single neutrino mass state becomes defined as it passes over Las Vegas !