Possibilities for terrestrial detection of kev-mass 'sterile' neutrinos

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Brief review of

Direct detection of sterile ν dark matter

- Inverse beta decay
- electron scattering

Detecting rare sterile ν events in beta decay

- End point of Tritium beta spectrum
- ν mass reconstruction in K-capture events

Galactic dark matter may be keV-mass sterile neutrinos

(1) Existing neutrino family looks incomplete

text book list of weak couplings to Z boson show missing RH ν current (and LH $\bar{\nu}$)

leptons	$g_L^{\nu}\ \bar{\nu}_e\ \gamma_\mu (1-\gamma_5)\nu_e$		
	$g_L^{e}\ \bar{e}\ \gamma_\mu (1-\gamma_5) e$	+	$g_R^{e}\ \bar{e}\ \gamma_\mu (1+\gamma_5) e$
quarks	$g_L^{u}\ \bar{u}\ \gamma_\mu (1-\gamma_5) u$	+	$g_R^{u}\ \bar{u}\ \gamma_\mu (1+\gamma_5) u$
	$g_L^{d}\ \bar{d}\ \gamma_\mu (1-\gamma_5) d$	+	$g_R^{d}\ \bar{d}\ \gamma_\mu (1+\gamma_5) d$

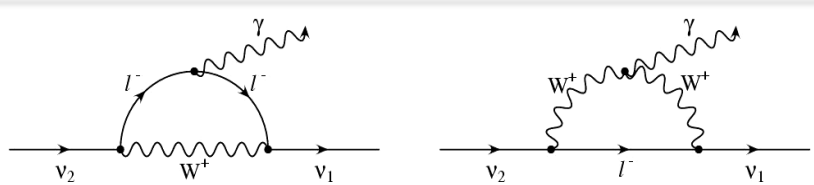
(2) Theoretical studies for > 20 years show keV-mass ν_s is a convincing DM candidate

1994: Dodelson &Widrow, propose ~ 30 – 300 eV sterile ν as dark matter

1999 : Shi & Fuller propose 0.1 – 10 keV sterile ν as dark matter

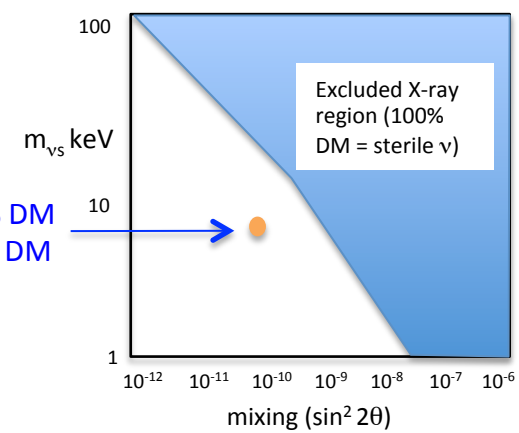
2000 – 2010: > 40 papers & reviews confirming that a keV-mass sterile ν matches DM requirements

(3) Possible galactic 3.5 X-ray signal could be decaying 7 keV ν_s



2014 Boyarsky et al , Bulbul et al

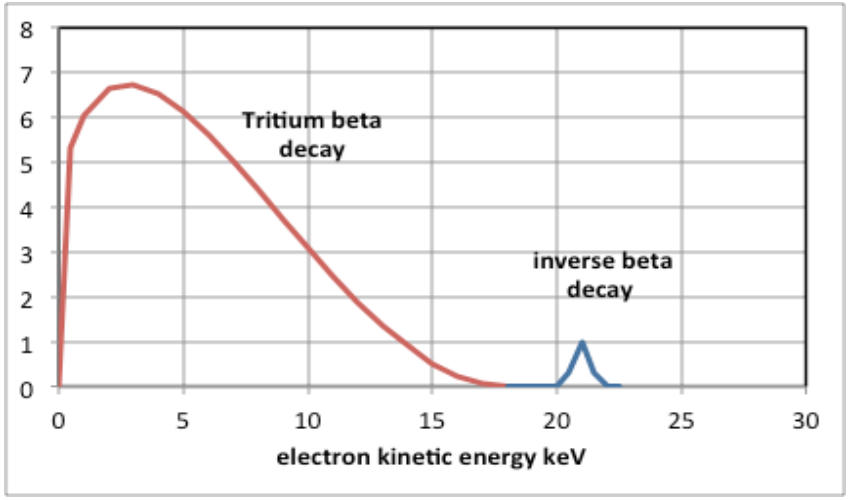
$\sin^2 2\theta \sim 10^{-10}$ if 100% DM
$\sim 10^{-9}$ if 10% DM



Direct detection of dark matter sterile neutrinos by inverse beta decay ?

Example:
normal β decay $^3H \rightarrow {}^3He^+ + e^- + \nu$
implies inverse $\bar{\nu}_s + {}^3H \rightarrow {}^3He + e^-$

Would give events beyond the β decay end point separated by an energy $m_{\nu s}$



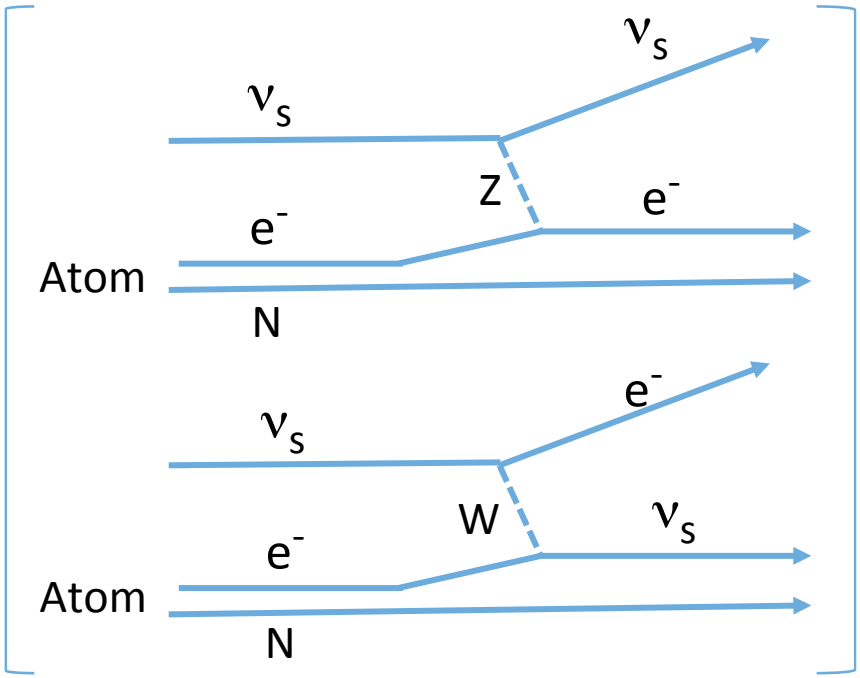
Proposed 30 years ago to detect relic neutrino background, but needed large tritium target (now aim of PTOLEMY)
Same principle would detect sterile ν dark matter

For 7 keV, Li & Xing PLB2011 find 10 events/year
for 10 kg ^3H ($t_{1/2}$ = 12y)
or 1 ton ^{106}Ru ($t_{1/2}$ = 1y) needs replenishment !

Must be in the form of gas or surface layers to detect the electrons. Not feasible in near future.

Li & Xing: "may not be hopeless in the long run"

Direct detection of dark matter sterile neutrinos by electron scattering ?



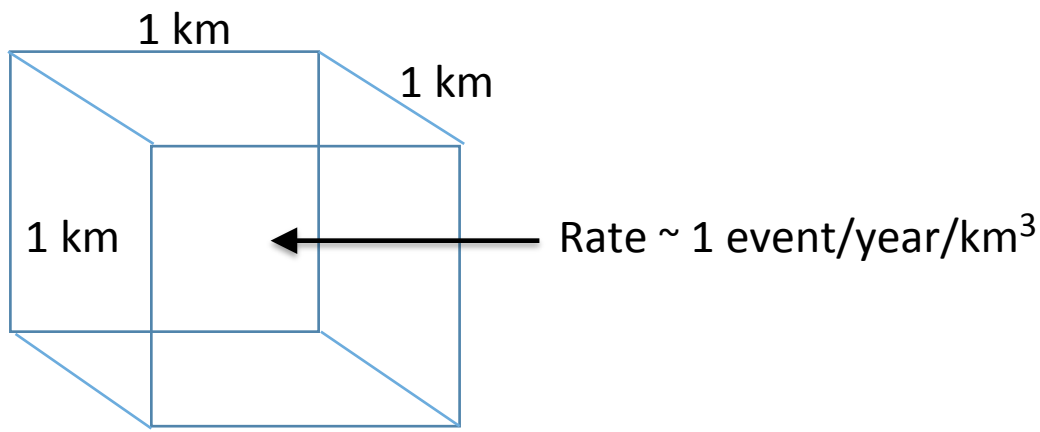
Ando & Kusenko PRD 2010

Sufficient energy transfer to produce ionization

But for m_s ~ 7 keV, coupling ~ 10^{-9}

Rate ~ 1 event/year/kiloton (inc Z^2 coherence)

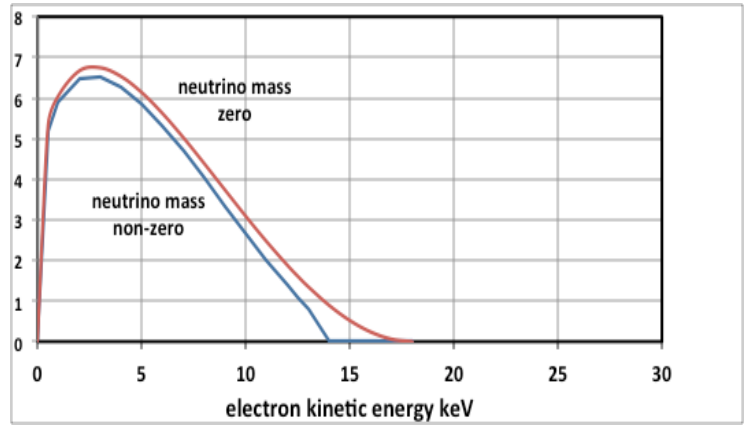
Also ν_s decay to X-ray
In an enclosure



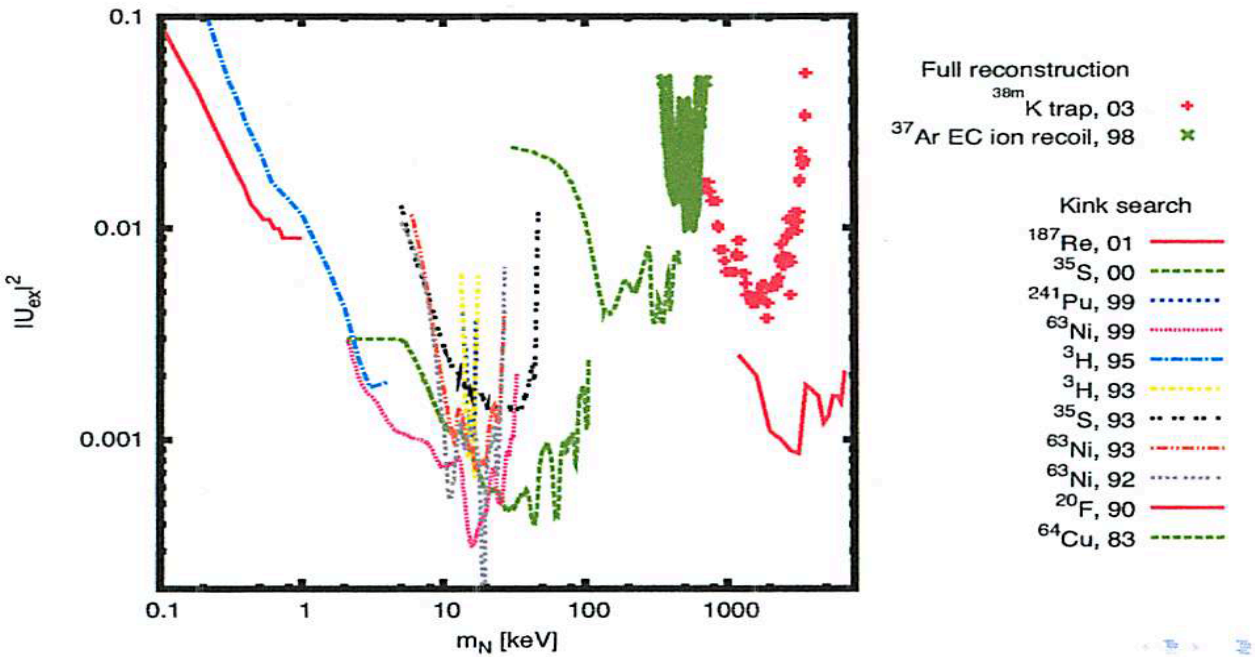
Distortion of beta spectrum by sterile neutrino admixture

Basis of attempts over 30 years to measure ν mass* by its effect on the end point of a beta spectrum.

(*nowadays $\nu_e \equiv$ sum over three mass eigenstates)



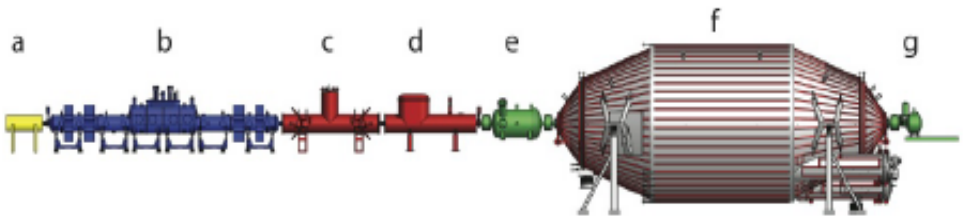
Existing direct limits on mass and coupling (mainly spectrum kink searches)



from F Bezrukov Conf: New Instrumentation for Particle Physics (CERN 2008)

Possible future limits from KATRIN

KATRIN high resolution spectrometer 70m x 10m
Aims to measure sub-eV ν mass from end-point



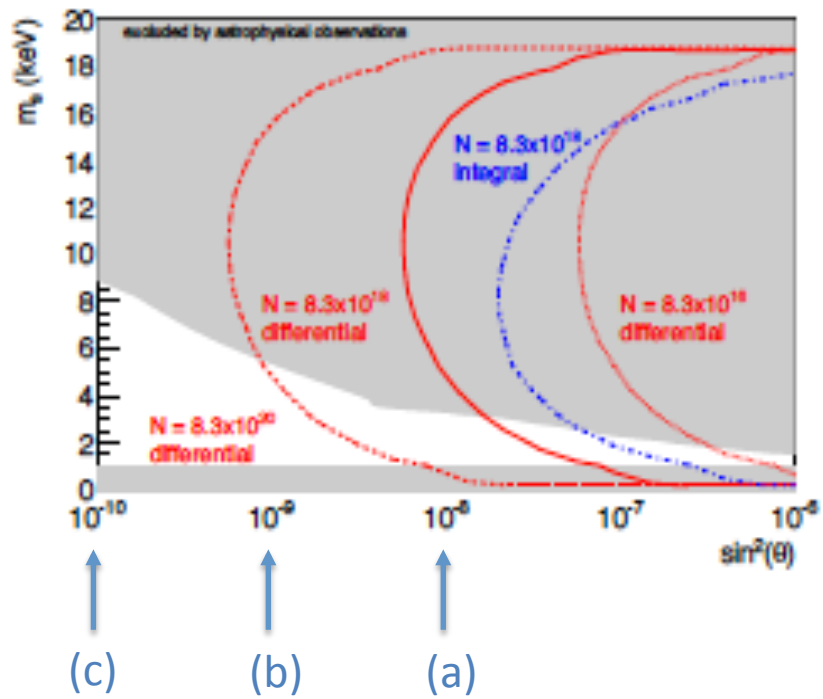
KATRIN also analyzing spectrum for admixture of sterile ν events.

Susanne Mertens et al arXiv:1409.0920v2 (2014):

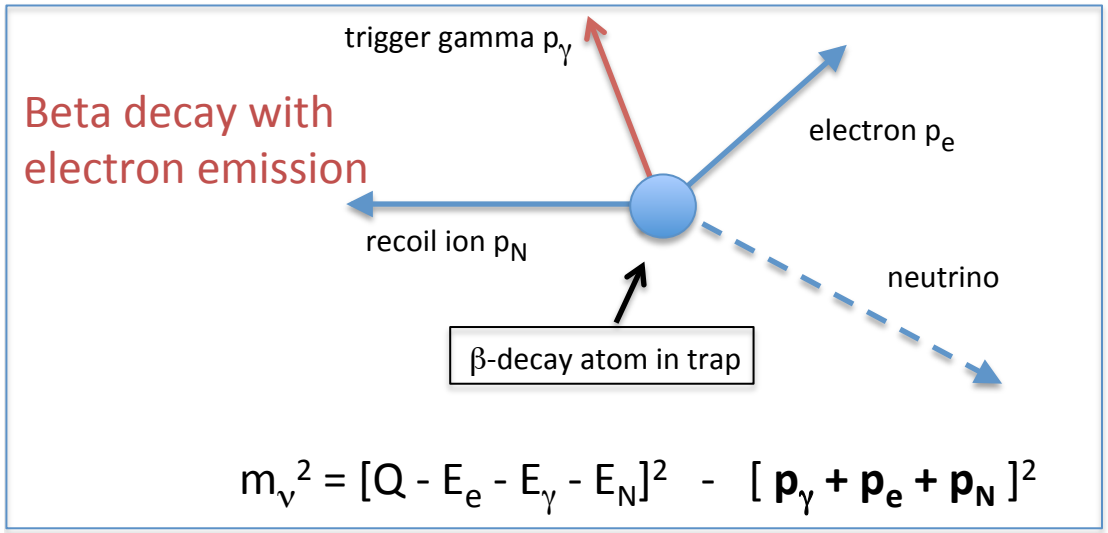
(a) 3-year mixing limit 10^{-7}-10^{-8} for design T source.

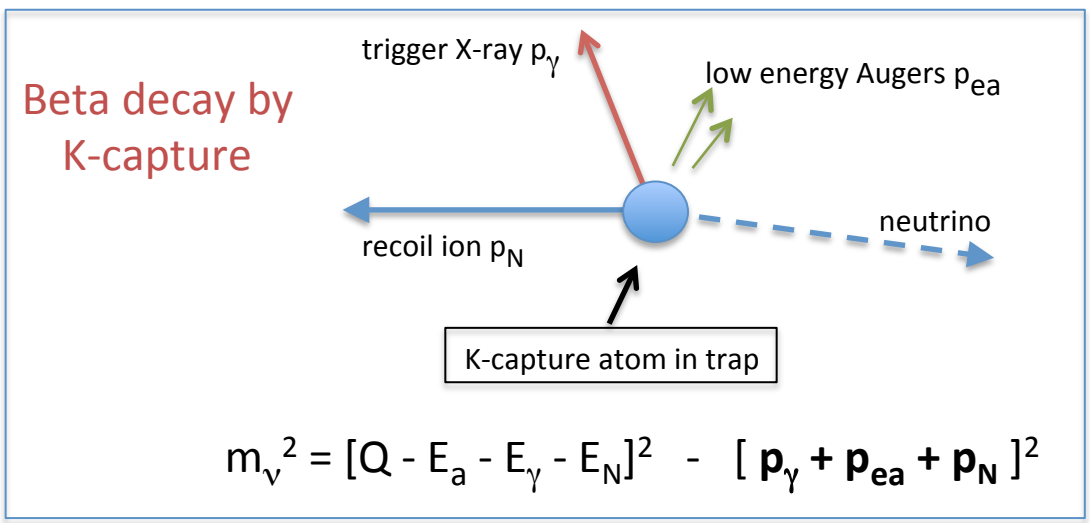
(b) Future limit 10^{-9} (3y) achievable with 10x source.

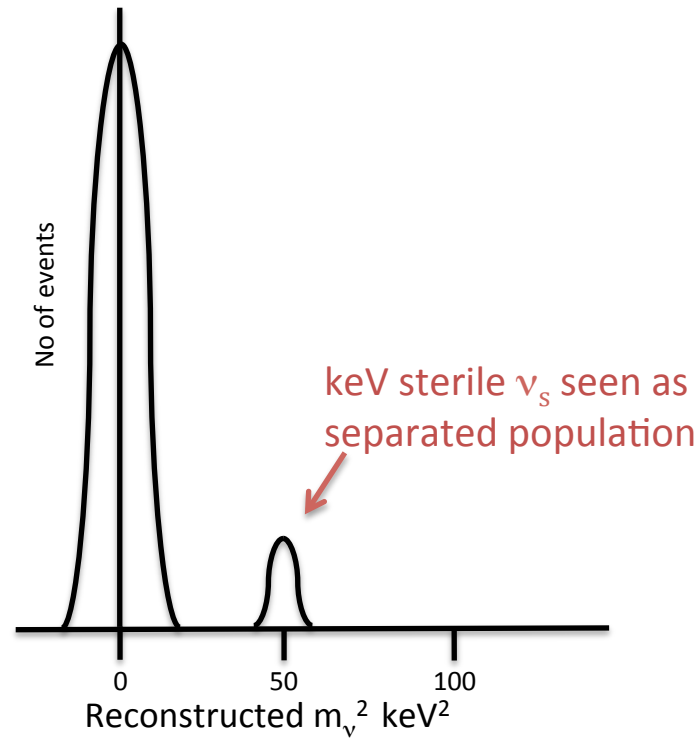
(c) Thus 10^{-10} (3y) achievable with 100x source.



Detection of sterile ν in beta decay by total energy-momentum reconstruction







High precision time of flight measurements needed to achieve 6σ separation from zero mass peak

Recent studies show this may now be feasible

Not a new idea - suggested for over 20 years.

but reaching masses < 100 keV and < 10^{-4} mixing is very difficult ('challenging')

PHYSICAL REVIEW D VOLUME 46, NUMBER 3

1992

Suggestion for an experiment to search for a massive admixed neutrino in nuclear beta decay by complete kinematic reconstruction of the final state

Guido Finocchiaro*
Physics Department, State University of New York, Stony Brook, New York 11794

Robert E. Shrock†
Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11794
(Received 2 March 1992)

Proposed ^{3}H decay reconstruction for 17 keV neutrino with mixing ~ 10^{-2}

PHYSICAL REVIEW C VOLUME 58, NUMBER 4

1998

Search for the admixture of heavy neutrinos in the recoil spectra of ^{37}Ar decay

M. M. Hindi,[1] Recep Avci,[2] A. H. Hussein,[3] R. L. Kozub,[1] P. Miočinović,[1,*] and Lin Zhu[2,†]

Used ^{37}Ar K-capture reconstruction to set limit ~ 10^{-2} at 300-600 keV

VOLUME 90, NUMBER 1 PHYSICAL REVIEW LETTERS

2003

Novel Search for Heavy ν Mixing from the β^+ Decay of ^{38m}K Confined in an Atom Trap

M. Trinczek,[1,*] A. Gorelov,[1] D. Melconian,[1] W. P. Alford,[2] D. Asgeirsson,[3] D. Ashery,[4] J. A. Behr,[3] P. G. Bricault,[3] J. M. D'Auria,[1] J. Deutsch,[5] J. Dilling,[6,3] M. Dombsky,[3] P. Dubé,[1] S. Eaton,[3] J. Fingler,[3] U. Giesen,[3] S. Gu,[3] O. Häusser,[1,†] K. P. Jackson,[3] B. Lee,[3] J. H. Schmid,[6] T. J. Stocki,[1] T. B. Swanson,[1] and W. Wong[3]

Used ^{38m}K decay reconstruction to set limit ~ 10^{-2} at 0.7-3.5 MeV

PHYSICAL REVIEW D 75, 053005

2007

Searching for dark matter sterile neutrinos in the laboratory

Fedor Bezrukov[1,2] and Mikhail Shaposhnikov[1]

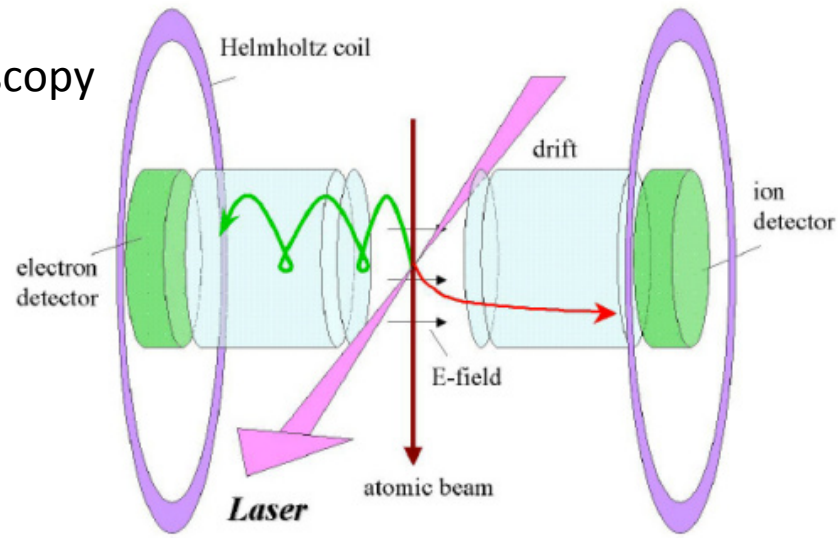
Discussion of ^{3}H decay reconstruction for keV masses & mixing < 10^{-6}

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)

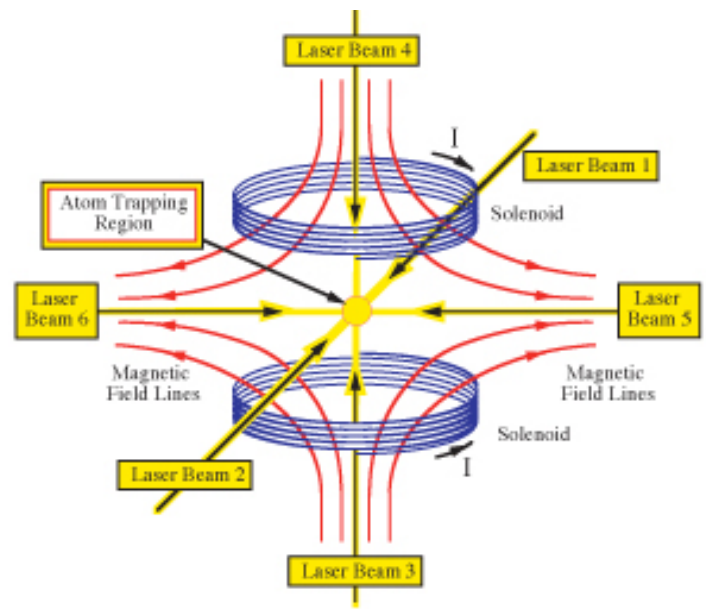


MOT - Magneto-Optical Trap

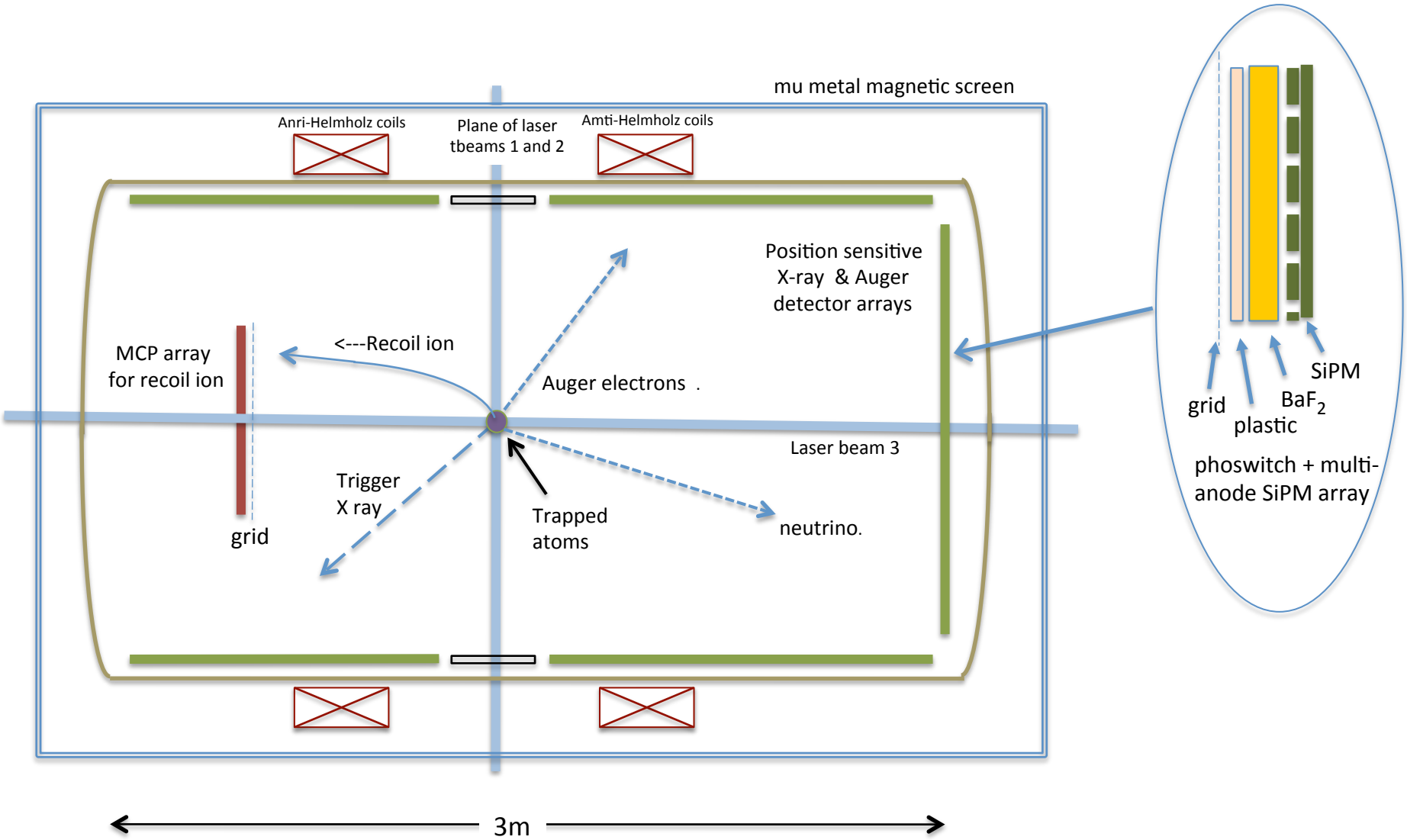
Developed for over 20 years for
Cooling and suspension of neutral atoms

No of trapped atoms: 10^8- 10^{12}

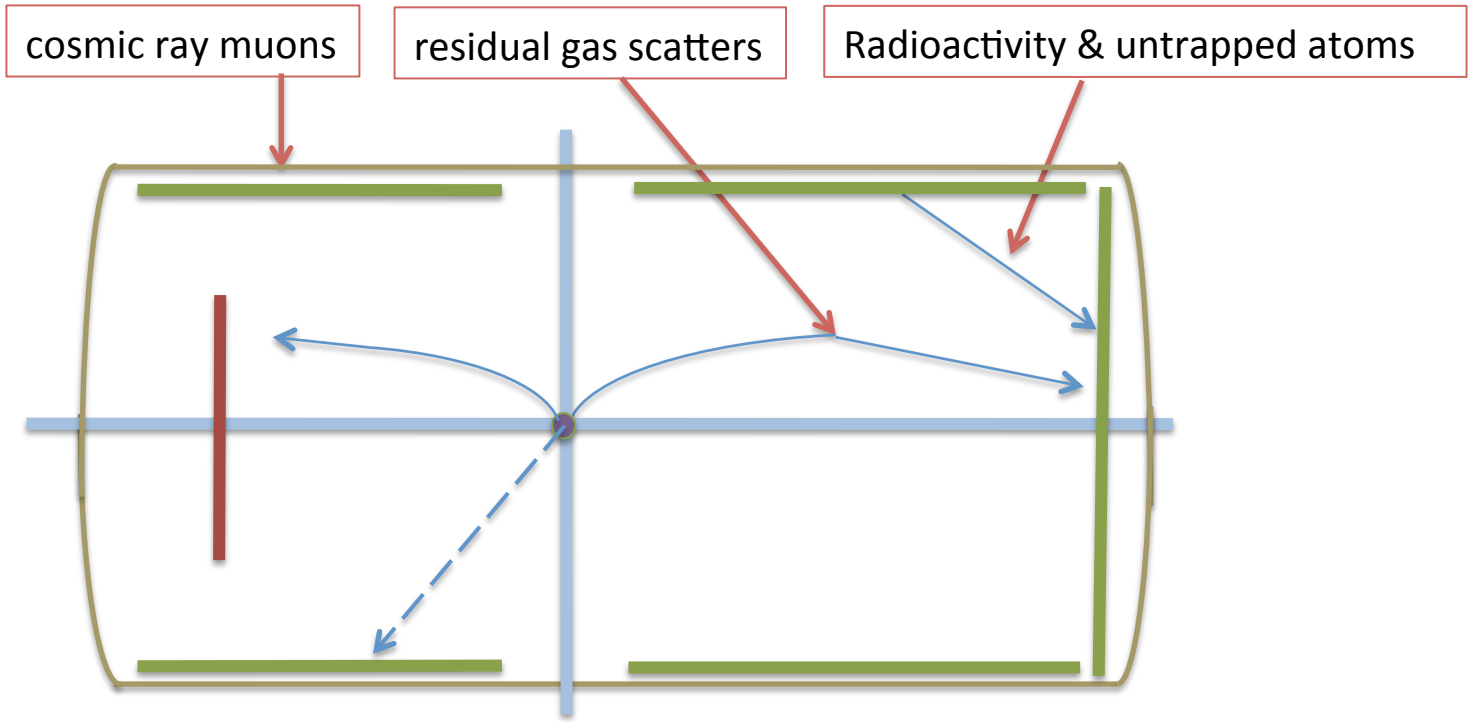
effective temperature: 10 - 100 μK



Basic geometry for 3-D time-of flight measurements



Some backgrounds



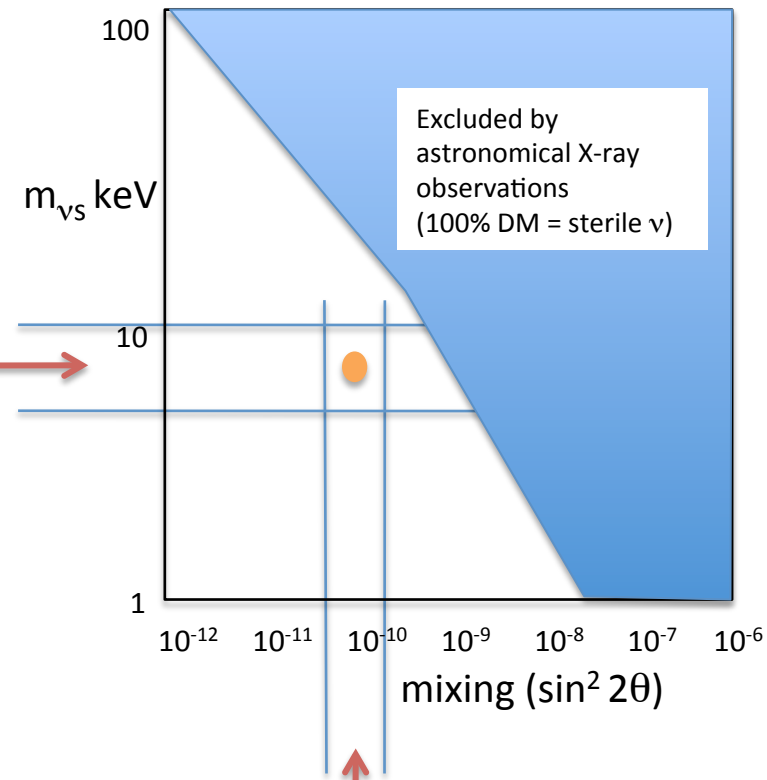
Reject by real time tests - most self-vetoing:

- Signals not in correct time window
- Signal pulses wrong size or shape
- X-Ray triggers not followed by Augers in 200ns
- Mass reconstruction $m_\nu^2=[Q- E_e- E_\gamma -E_N]^2 - [\mathbf{p_\gamma}+\mathbf{p_e}+\mathbf{p_N}]^2$ negative or wrong magnitude

Backgrounds found tolerable in published MOT atomic experiments

Requirements to reach mass and coupling levels of the X-ray signal ?

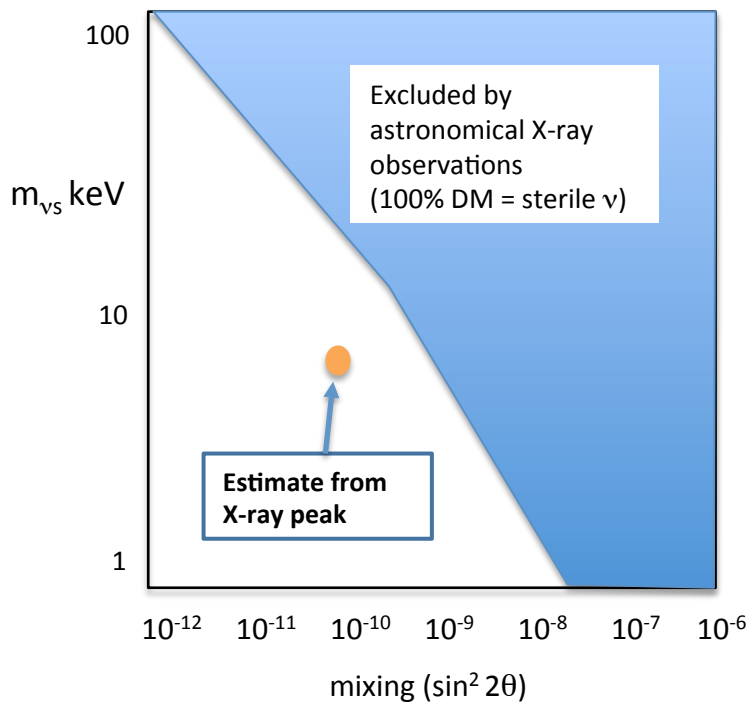
- need > 6 sigma separation of signal from zero mass peak
- kinematic simulations show possible with ± 0.2 ns timing and ± 0.1 degrees X-ray direction

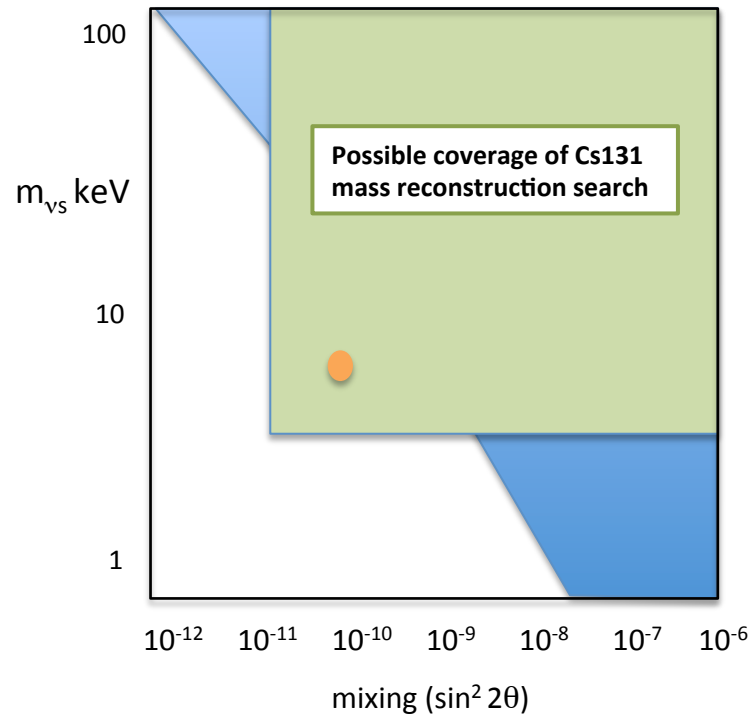


feasible in principle

- needs 10^{11} reconstructed decays/y for 5-10 events/y
- analysis of 3000 events/s – achieved in COLTRIMS expts
- fast decaying isotope: eg Cs131 ($t_{1/2}$=10 days) good for MOT

^{131}Cs K-capture has Q = 352 keV - allows sterile mass range 5 -350 keV

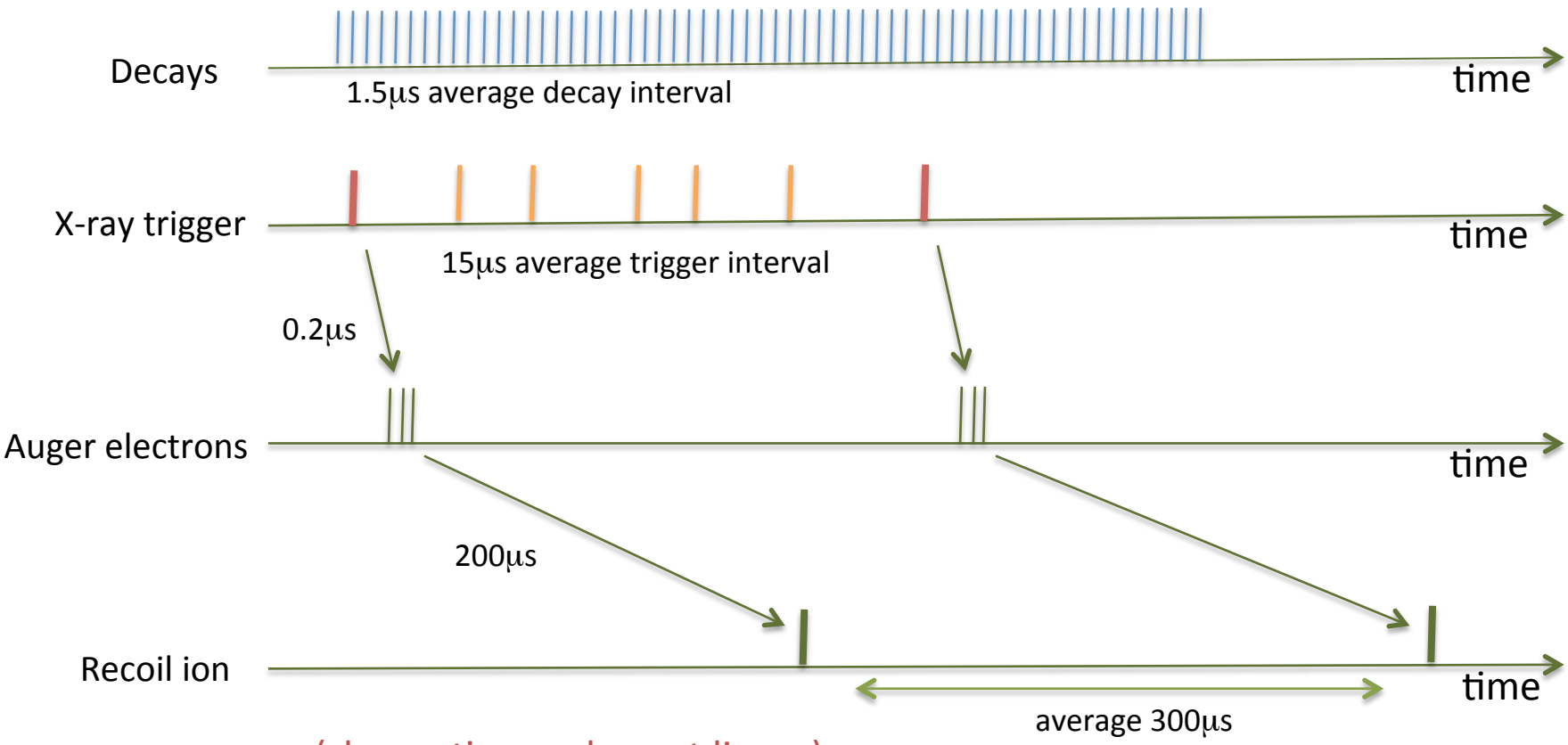




all masses searched at the same time – several peaks could be seen)

Event timelines – no overlapping

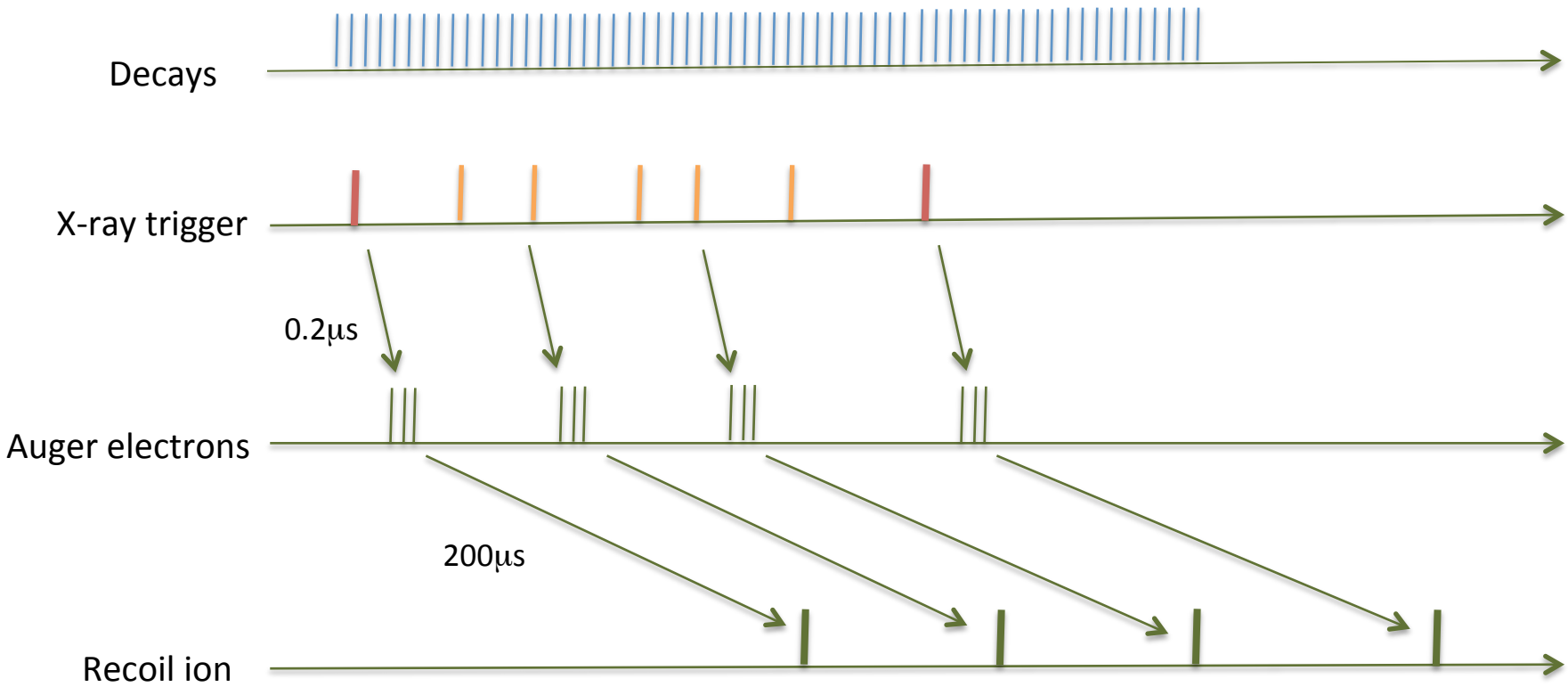
- find trigger with matching Auger and ion signals
- wait for completion of event before searching for next matching set



(shown timescales not linear)

Faster processing with overlapping events

.• search for overlapping events by matching corresponding Auger and ion signals
• BUT 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)

Proposal submitted based on Cs131:

CACHE (Cesium Atomic-electron Capture with Heavy neutrino Emission)

C J Martoff, J Napolitano (Temple) E R Hudson, H Wang, P F Smith (UCLA)
A Renshaw (Houston), G M Fuller (UCSD, theory), E Grohs (Michigan, theory)

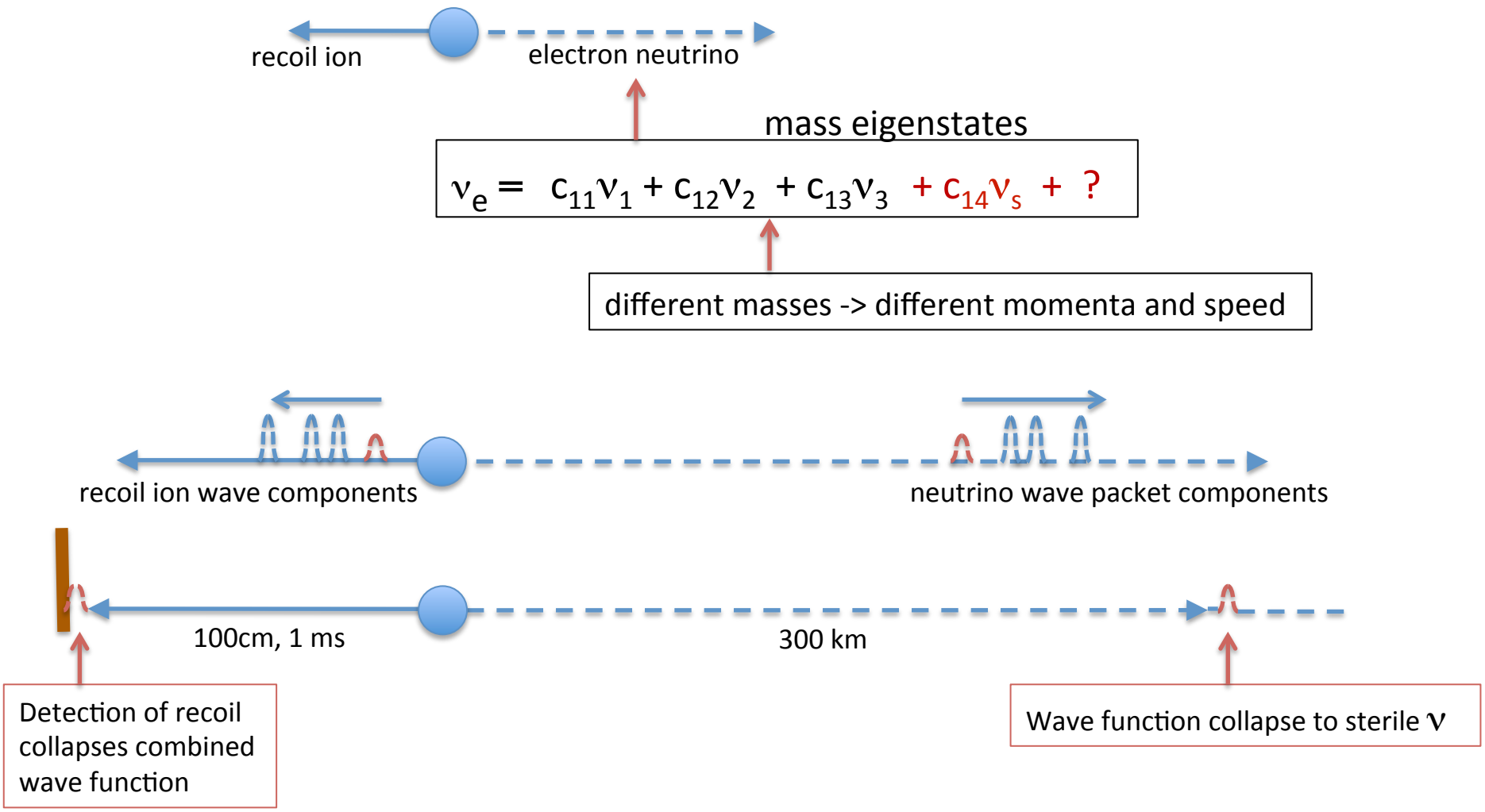
Smaller-scale phase 1 experiment
confirming mass reconstruction & background rejection

Initial objectives

- 100 processed events/h
- coupling sensitivity ~ 10^{-6} in 400d running
- mass sensitivity ~ 30-300 keV

Could be upgraded to a fully instrumented phase 2
reaching sensitivity < 10^{-10} and 7 keV mass

K-capture provides example of wave packet collapse and 'EPR paradox'



Summary

- keV mass sterile neutrinos are a strong dark matter candidate
- Detecting keV sterile neutrinos in the laboratory will be feasible

Auger electrons

- X-ray leaves another vacancy, producing a cascade of electron transitions, including Auger electron emission

- Choice of N-shell X-ray as trigger gives only 1 or 2 Augers of 60-120 eV, whose momentum and direction must be measured.