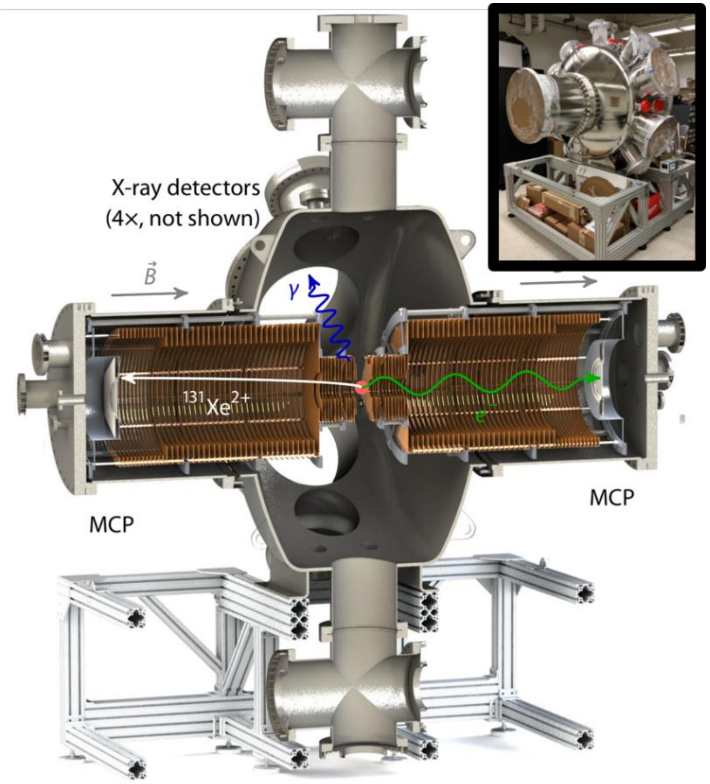
UCLA



The HUNTER Sterile Neutrino Search

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S. Khamis, C. Schneider (now JPL)
Princeton U.: P. Meyers
Hebrew Univ. of Jerusalem: G. Ron, A. Prosnyakov
U. Houston: A. Renshaw, F. Malatino

Theory Collaborators:
UCLA: G. Gelmini, A. Kusenko;
UCI: K. Abazajian

See details in C. J. Martoff et al, Quantum Sci. Technol. 6, 024008 (2021)

W.M. KECK FOUNDATION

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HUNTER

CERN COURIER MARCH/APRIL 2022 CERNCOURIER.COM

FEATURE NEUTRINOS

Neutrino kinks
Precise measurements of β-decay spectra using the KATRIN experiment are potentially sensitive to keV-scale heavy neutral leptons.

TURNING THE SCREW ON RIGHT-HANDED NEUTRINOS

Extending the elementary-particle inventory with heavy neutral leptons could solve the key observational shortcomings of the Standard Model, explain Alexey Boyarsky and Mikhail Shaposhnikov, with some models placing the new particles in reach of current and proposed experiments.

"... many astrophysical observatories, however,... will not be able to determine the particle origin of this signal. Thus, complementary laboratory searches are needed. One experimental proposal that claims a sufficient sensitivity to enter into the cosmologically relevant region is **HUNTER**, based on radioactive atom trapping and high-resolution decay-product spectrometry."

Outline

1. **Why heavy neutrinos?**

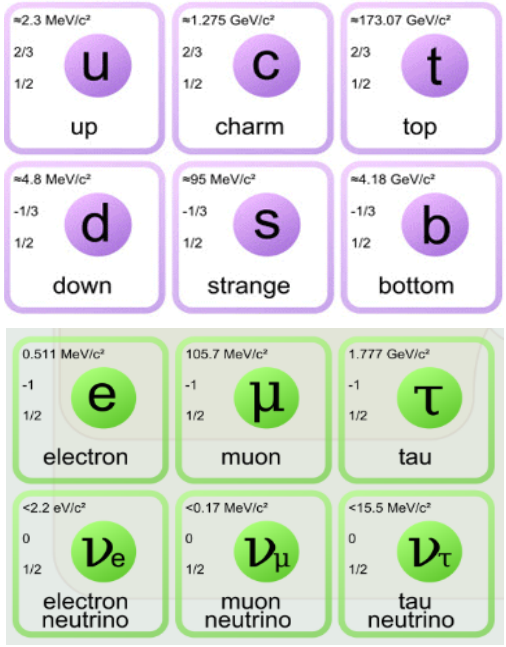
2. HUNTER concept

3. Current status / future reach

Two weird facts about neutrinos

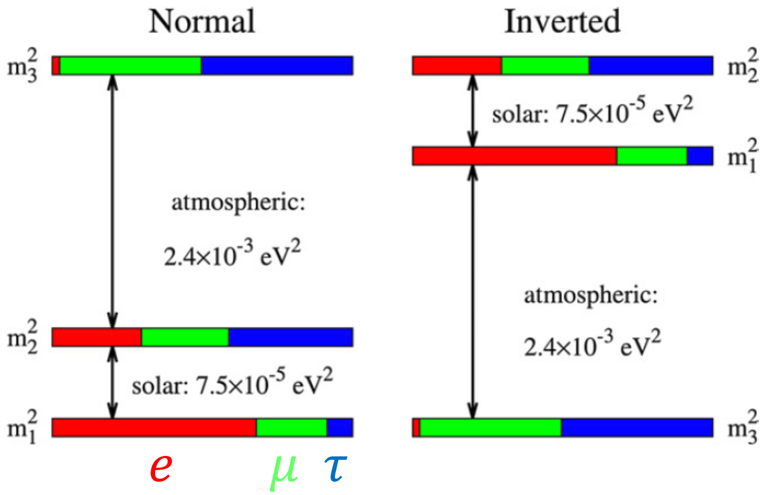
Where art thou right-handed neutrinos?

Left handed	right handed
✓	✓
✓	✓
✓	✓
✓	**MISSING**



Unseen in existing neutrino interactions

Flavor eigenstates aren't mass eigenstates

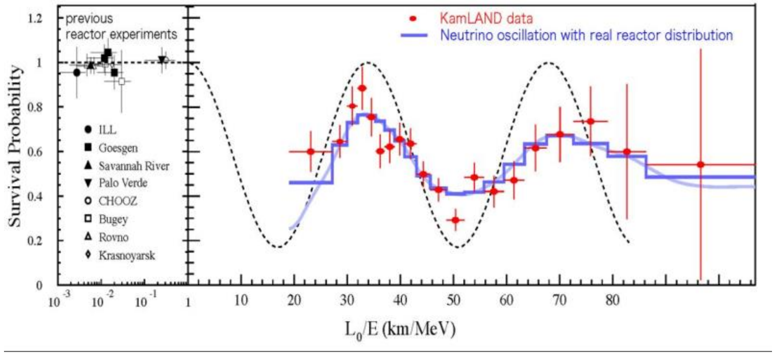


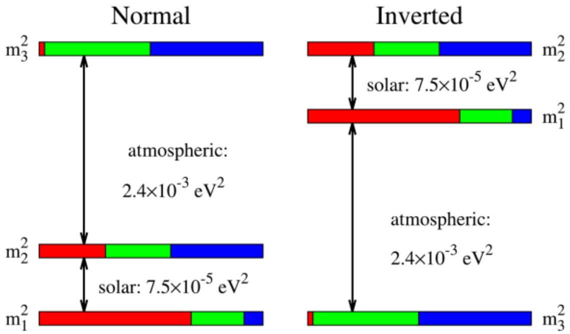
"Mixing" matrix

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{e1} & c_{e2} & c_{e3} \\ c_{\mu 1} & c_{\mu 2} & c_{\mu 3} \\ c_{\tau 1} & c_{\tau 2} & c_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

The problem of non-zero mass

Neutrino oscillation (flavor changing via mixing)
is the only firm laboratory observation of BSM physics.





amplitudes → mixing angles

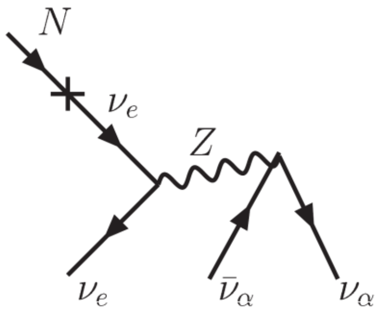
periods → mass^2 differences

Known for 30 years, but the origin is still not explained.

HOWEVER...

PDG “Neutrino Masses, Mixing, and Oscillations”...
14.2 Extending the Standard Model to Introduce Massive Neutrinos; From the above discussion we conclude that it is not possible to construct a renormalizable mass term for the neutrinos with the fermionic content and gauge symmetry of the SM. The obvious consequence is that in order to introduce a neutrino mass in the theory one must extend the particle content of the model, depart from gauge invariance and/or do both.

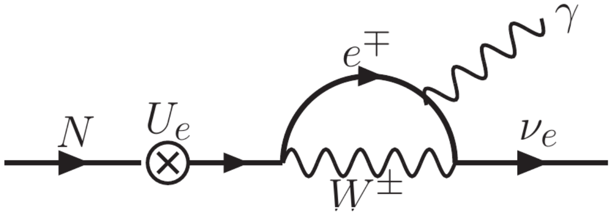
Sterile Neutrino Interactions



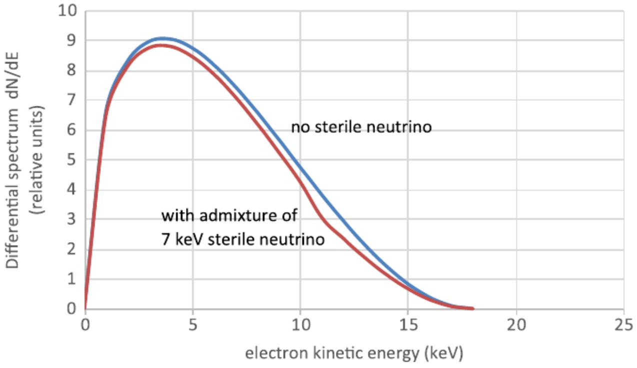
- Main decay is invisible but determines lifetime:

$$\tau = 7.2 \times 10^{29}\,\mathrm{sec}\left[\frac{10^{-8}}{\sin^2(2\theta)}\right]\left[\frac{1\,\mathrm{keV}}{m_{\mathrm{DM}}}\right]^5$$

- To be a dark matter candidate ν_S can't be too heavy, or mix too strongly

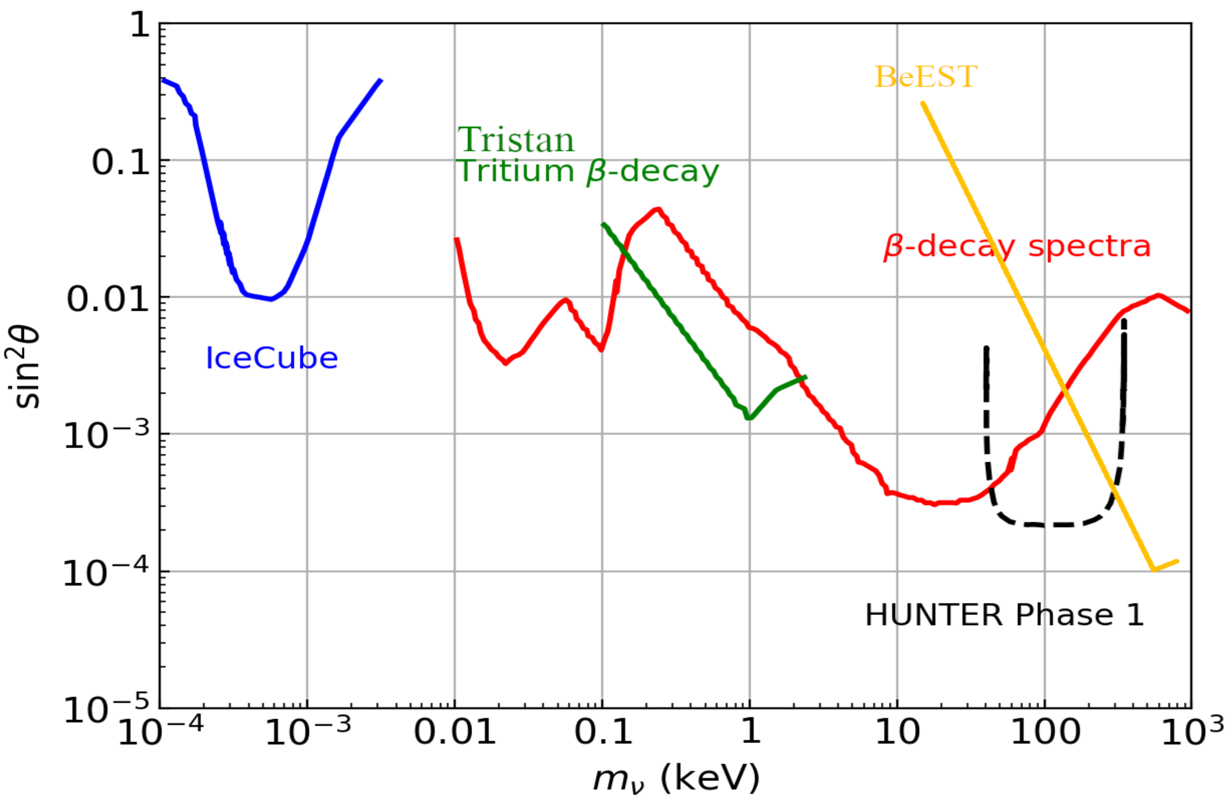


- Gives monoenergetic photons at energy $m_s c^2/2$
- Astrophysical searches for x-ray lines give strong limits (in minimal models)



- Even β decay can be affected.
- Gives a kink in spectrum with amplitude ~ $\sin^2(\theta)$. (see other talks)

Summary of existing lab limits



HUNTER is agnostic about:

- Theory: ν_S just needs to mix and have a mass in our range of ~30-300 keV/c^2
- Whether or not ν_S is part of dark matter

Outline

1. Why heavy neutrinos?

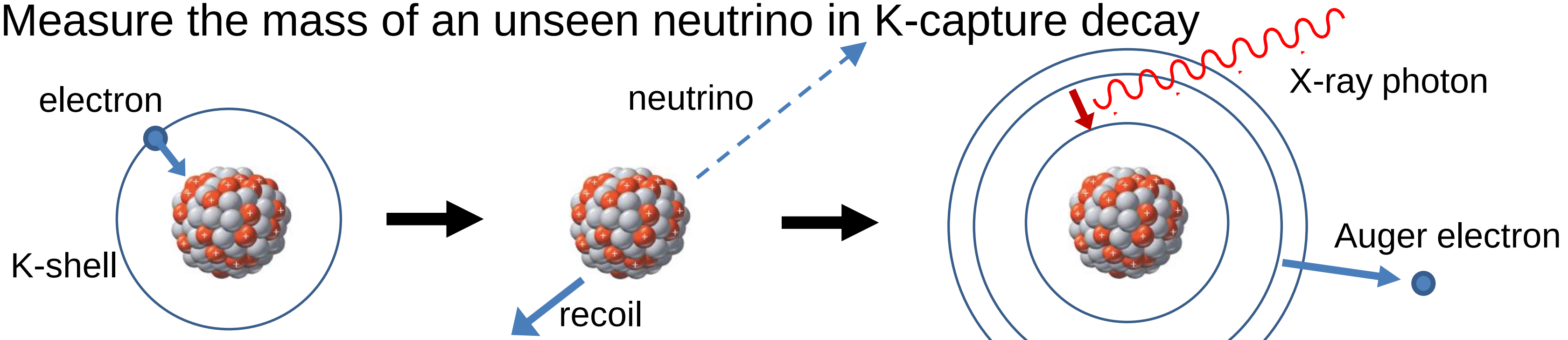
2. **HUNTER concept**

3. Current status / future reach

HUNTER concept

Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction

Measure the mass of an unseen neutrino in K-capture decay



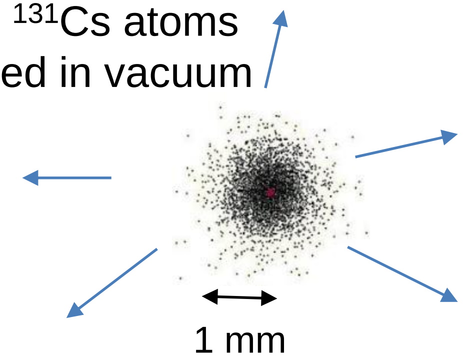
Proton in nucleus
absorbs K-shell
atomic electron

Neutrino emitted
Nucleus recoils

X-ray emitted
Auger electrons emitted

Measure momentum of ion, X-ray, and electron to calculate neutrino momentum and mass

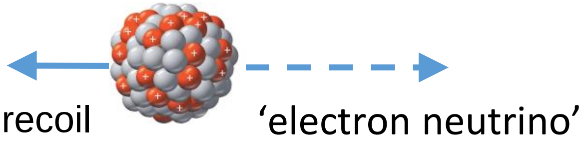
Cloud of ^{131}Cs atoms
laser cooled in vacuum

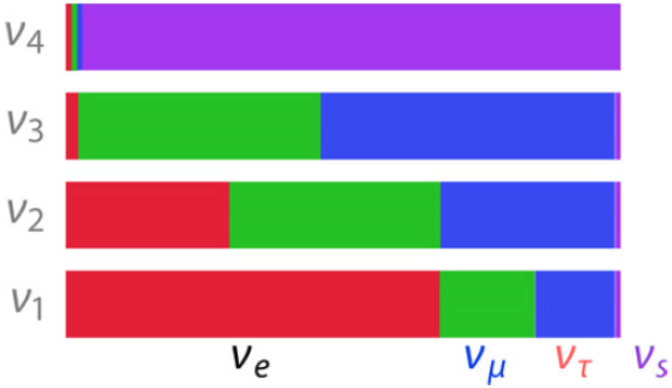


Sterile neutrinos can be produced up to to Q value of decay (350 keV for ^{131}Cs)

Fraction of heavy decays events gives coupling

What does a sterile neutrino look like?





$$\boxed{\nu_e = c_{e1}\nu_1 + c_{e2}\nu_2 + c_{e3}\nu_3 + c_{e4}\nu_4}$$

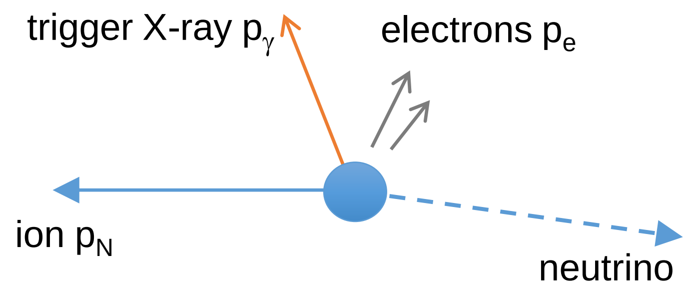
standard neutrino mass states

‘sterile’ neutrino component – $c_{e4} \ll 1$

The amplitude squared is the “coupling strength.”

The “normal” electron neutrino is a superposition of mass states including components of possible sterile neutrinos.

HUNTER concept

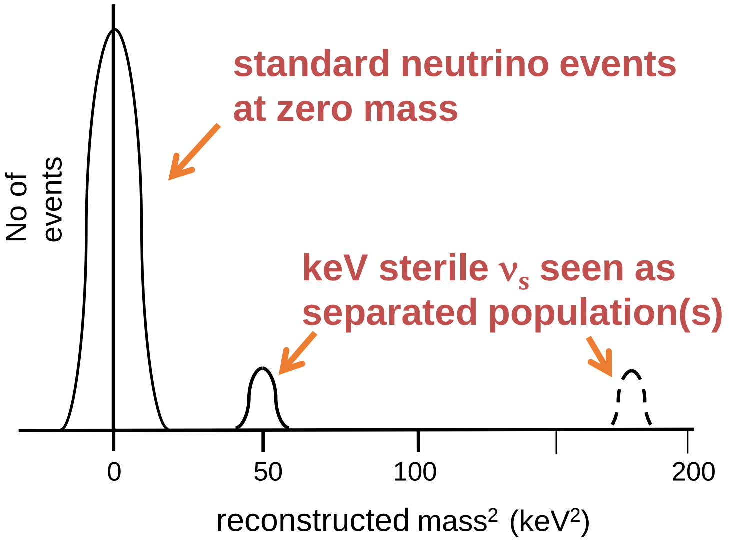


Mass reconstruction formula:

$$m_\nu^2 = [Q - E_e - E_\gamma - E_N]^2 \quad - \quad [\mathbf{p}_\gamma + \mathbf{p}_e + \mathbf{p}_N]^2$$

missing energy   missing momentum

Reconstructed mass spectra:



- Separated population of sterile neutrino events
- Model independent

Kinematic reconstruction idea:
S. Cook et al., PRD 46 R6 (1992)
G. Finocchario and R.E. Schrock, PRD 46 R888 (1992)

HUNTER spectrometer

Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction

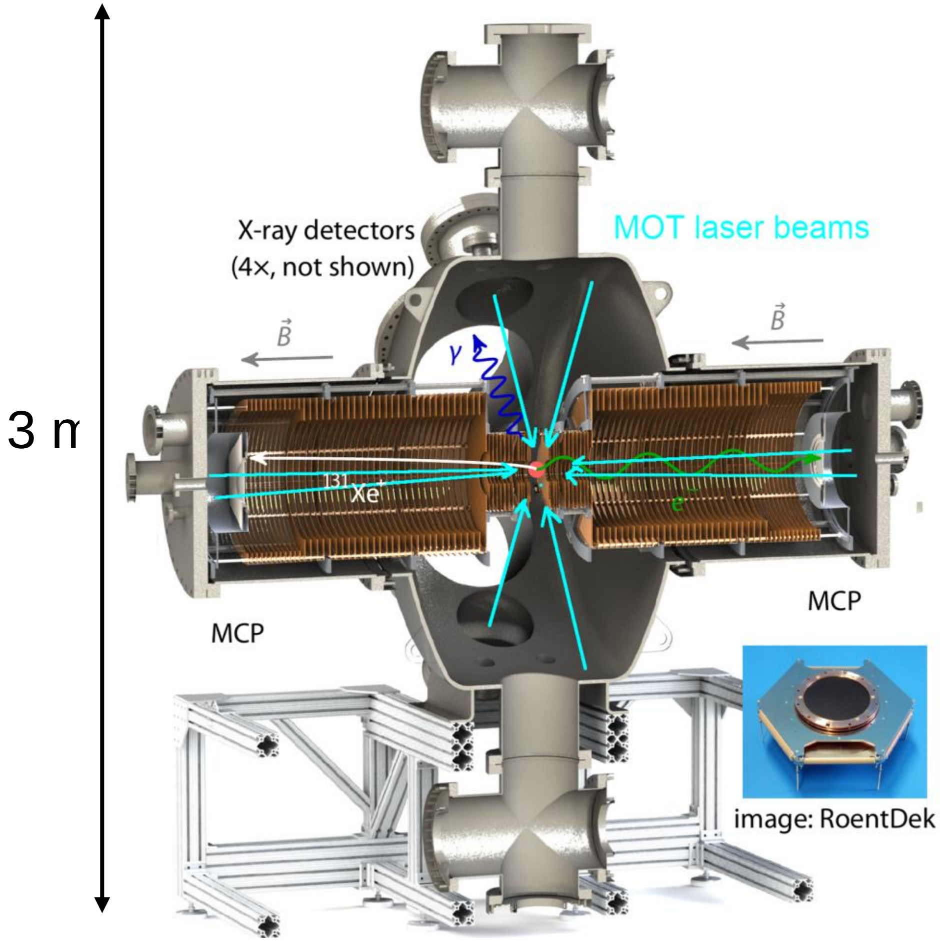


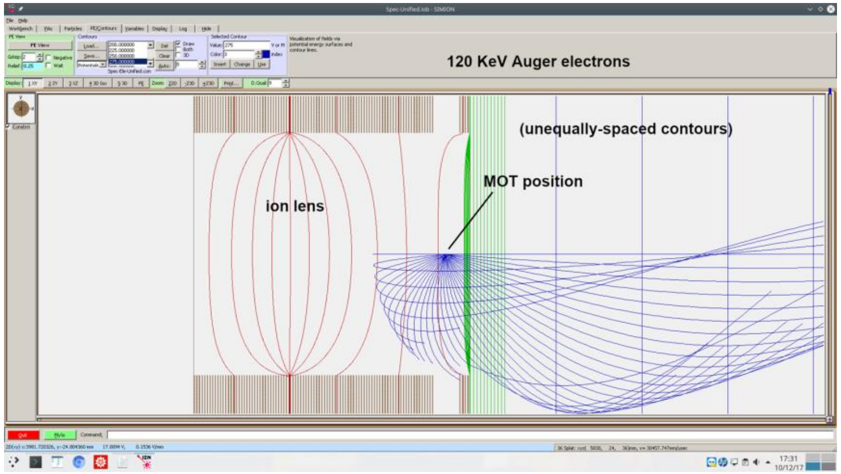
image: RoentDek

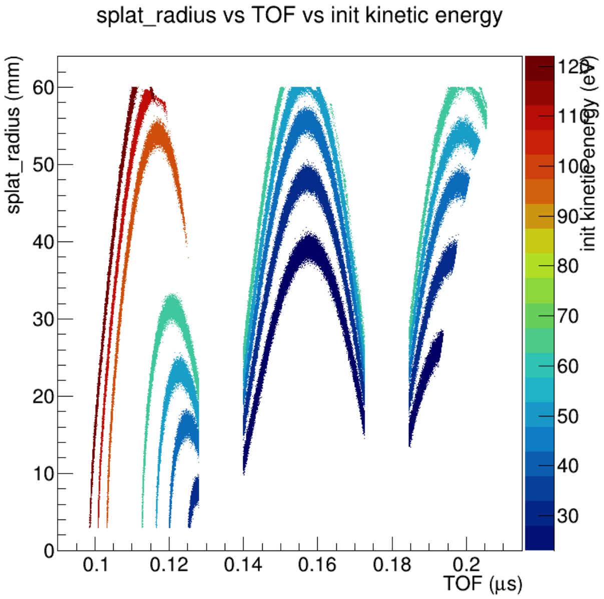
- Kinematic reconstruction of “2-body” EC decay
  - Measure all decay product momenta
  - Reconstruct missing neutrino mass event-by-event

- ^{131}Cs is held in a magneto-optical trap and laser cooled to 20 µK

- Reaction Ion Microscopes measure recoil nucleus and Auger electron momenta with high efficiency & resolution 0.1-1%

Spectrometer simulation



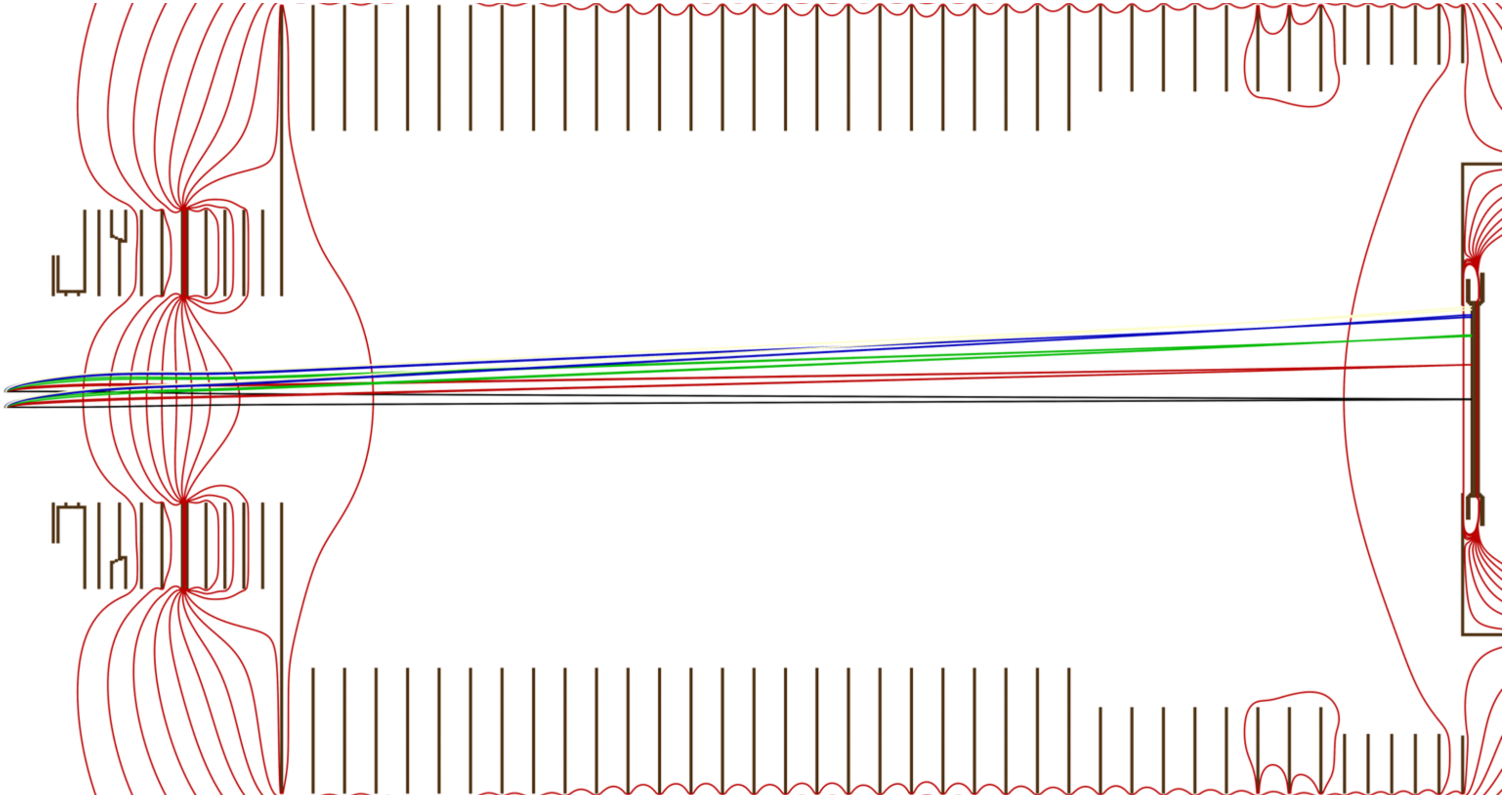

splat_radius vs TOF vs init kinetic energy

To satisfy resolution requirements, HUNTER double-focusing RIMs are perhaps the world's largest.

Design process based on full 3-D simulations done at Temple:

- 3-D E maps from SIMION
- 3-D B maps from COMSOL
- Particle tracking by GEANT4
- Analysis with ROOT

Example: Transverse focusing



Groups of ions with p_t denoted by color

Source locations separated by 10 mm focus to same detector position.

Radioactive isotope choice

Desired properties of nuclear isotope:

- Electron capture: Simple kinematics allow reconstruction
- Laser coolable species: Low initial kinetic energy
- $t_{1/2}$> 1 day (no accelerator beam – for now)
- Isotope availability (medical – for now)

From >60 possible nuclides to essentially only one meets requirements:

$^{131}\mathrm{Cs}$

Ref: Peter F Smith 2019 New J. Phys. 21 053022

^{131}Cs Decay

$t_{1/2}$=9.7 days, 100% electron capture,
Q_{EC}=355 keV

131-Cs -> 131-Xe (stable)
+ ν
+ x-rays (4-35 keV)
+ Auger e^{-}'s (3-150 eV)

No penetrating radiation, no radioactive daughter.

Commercially available

$10K/order + $1K/Ci

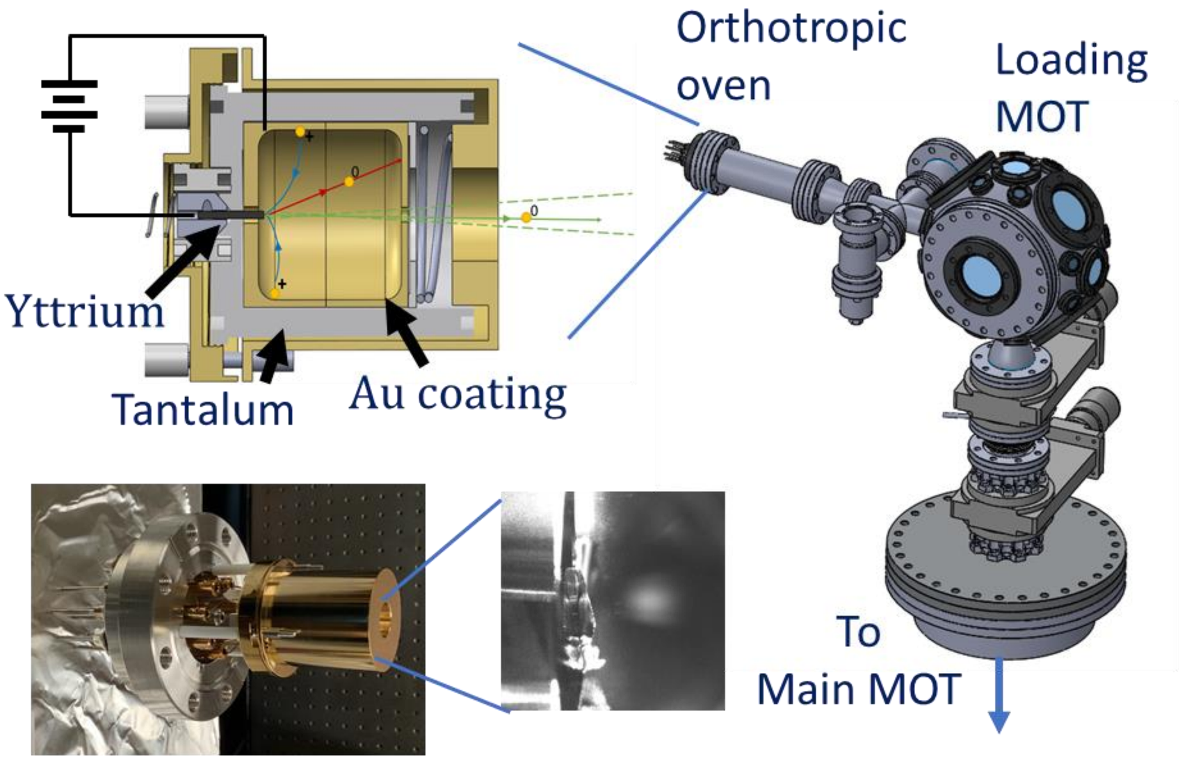
Outline

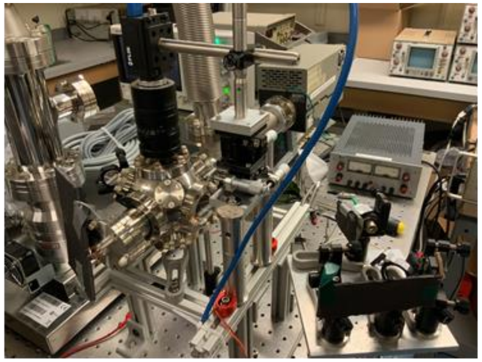
1. Why heavy neutrinos?

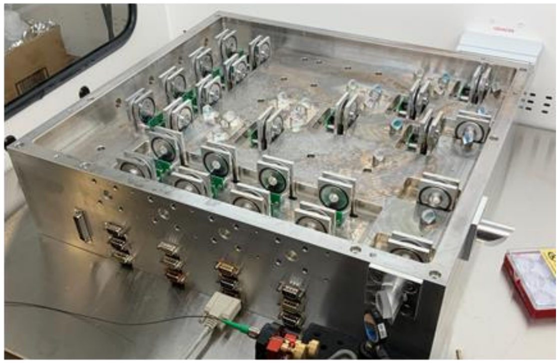
2. HUNTER concept

3. **Current status / future reach**

^{131,133}Cs magneto-optical trapping

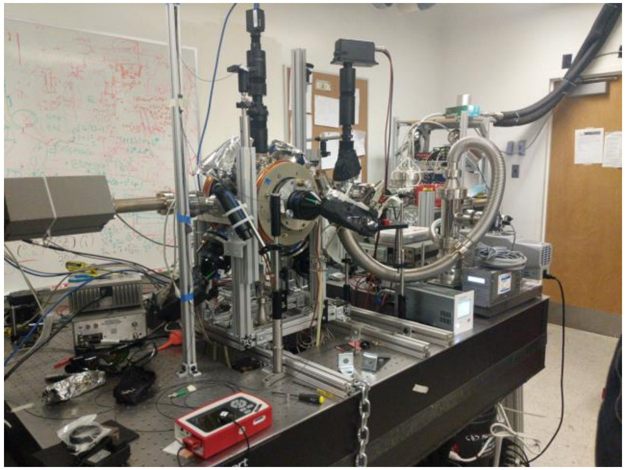






- Modular oven design complete for easy reloading.
- Ultrastable laser system with complete amplitude / polarization control for MOT control.

HUNTER assembly at UCLA



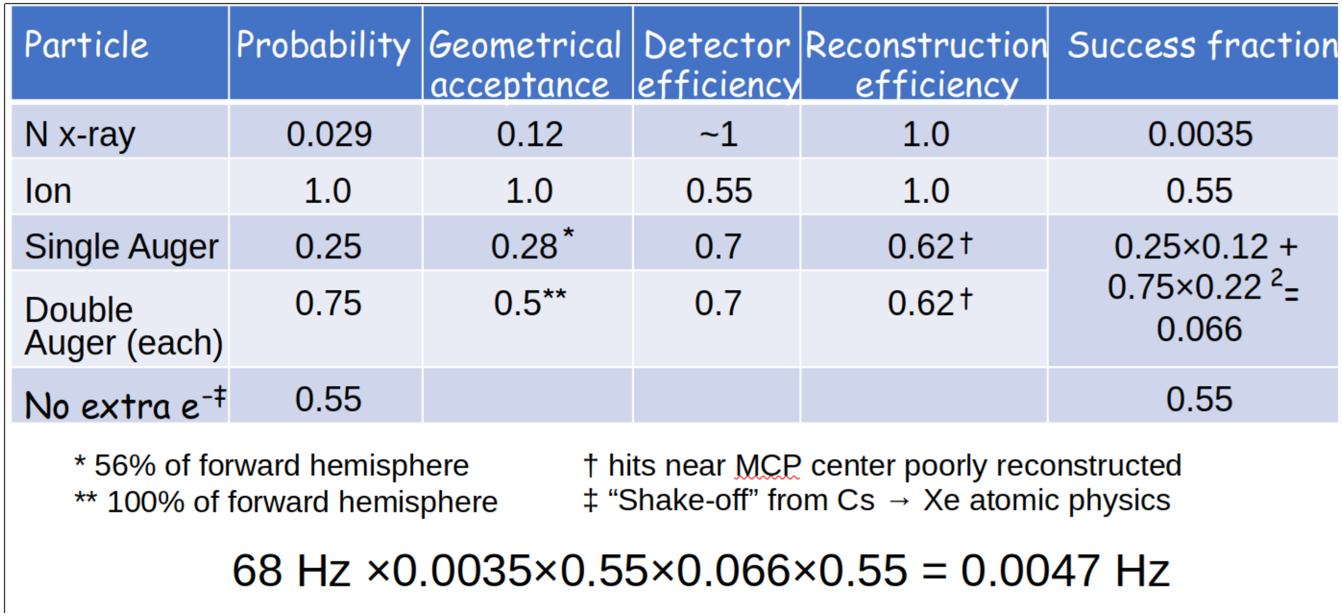
Loading MOT w/ $10\,\mu g$ of ^{133}Cs

Vacuum vessel- now < 1e-8 mbar

Spectrometer assembly

Projected ^{131}Cs rates & efficiency

10^8 trapped atoms, τ = 14 d → 80 Hz of decays => 0.85x80 = 68 Hz of K-captures



Particle	Probability	Geometrical acceptance	Detector efficiency	Reconstruction efficiency	Success fraction
N x-ray	0.029	0.12	~1	1.0	0.0035
Ion	1.0	1.0	0.55	1.0	0.55
Single Auger	0.25	0.28*	0.7	0.62†	$0.25\times0.12 + 0.75\times0.22^{2} = 0.066$
Double Auger (each)	0.75	0.5**	0.7	0.62†	
No extra e^-‡	0.55				0.55

* 56% of forward hemisphere
** 100% of forward hemisphere

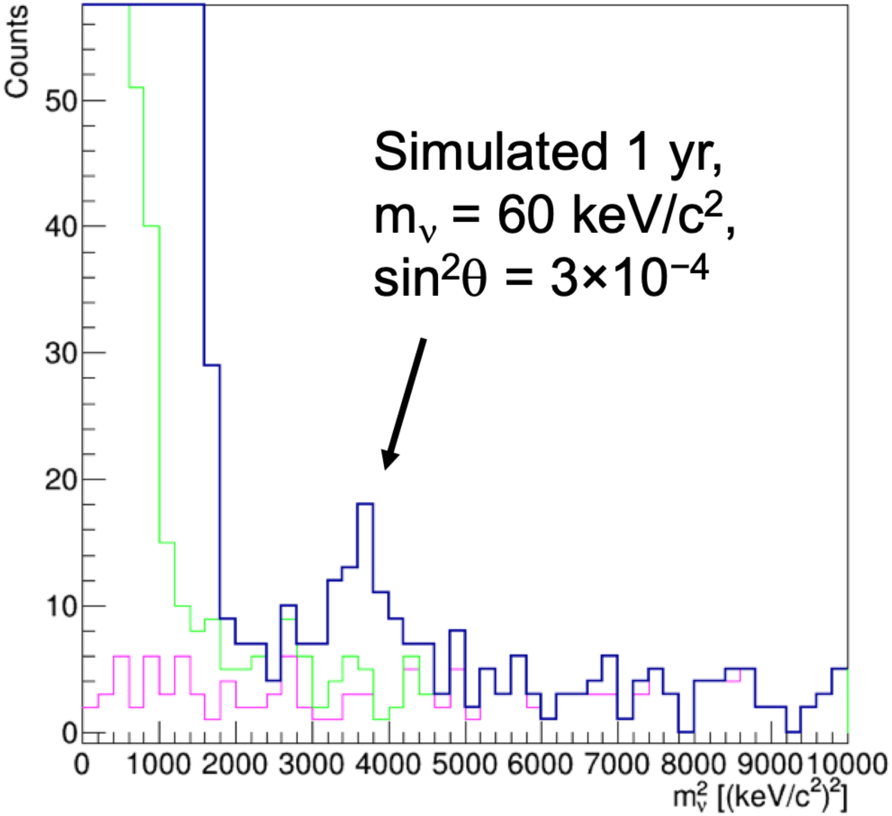
† hits near MCP center poorly reconstructed
‡ “Shake-off” from Cs → Xe atomic physics

$$68\ \text{Hz} \times 0.0035\times0.55\times0.066\times0.55 = 0.0047\ \text{Hz}$$

$\Longrightarrow$ ~150,000 events per year of livetime

Projected HUNTER Reach

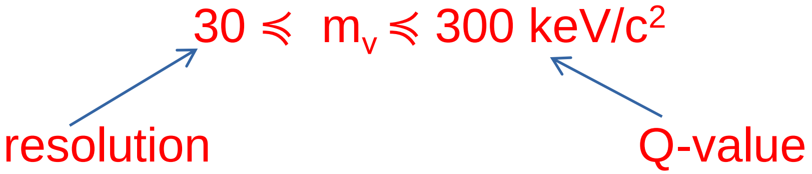
Phase 1: Cost-limited Proof-of-principle and Science



Simulated 1 yr,
$m_\nu = 60$ keV/c^2,
$\sin^2\theta = 3\times10^{-4}$

- 40 sterile neutrino events gives 5σ peak
- Using best estimates of backgrounds and a 1-year sample.

HUNTER mass range:



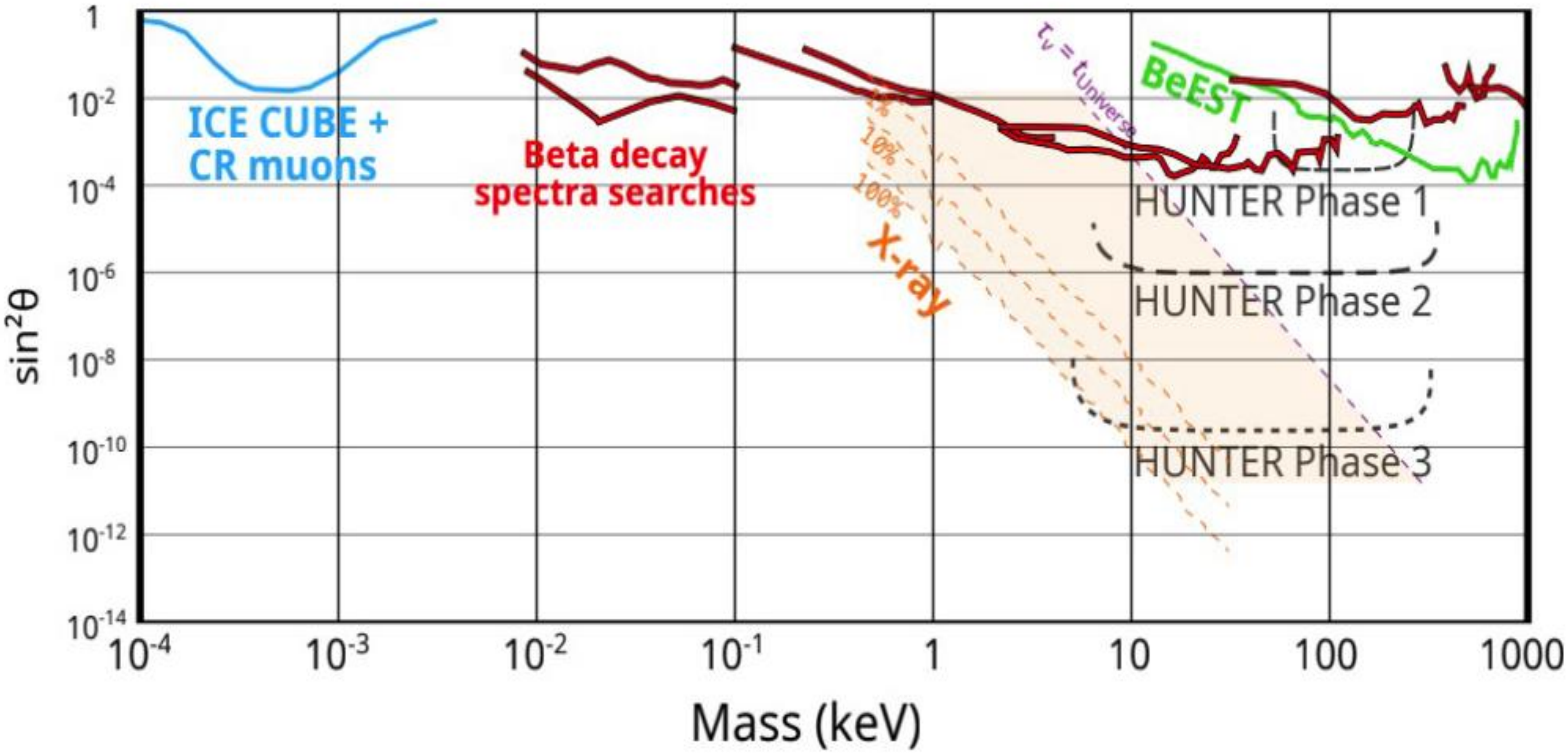
$30 \lesssim m_\nu \lesssim 300$ keV/c^2

resolution

Q-value

Backgrounds discussed in Quantum Sci. Tech. 6, 024008 (2021)
Leading background: Scattering of Xe+ by Cs broadens zero-mass peak and contributes flat-ish background shown in green

Projected sensitivity



Later phases increase acceptance with more detector coverage and progressive increases in trap population.

See: C J Martoff *et al* 2021 *Quantum Sci. Technol.* 6 024008

Other physics with HUNTER

HUNTER allows:

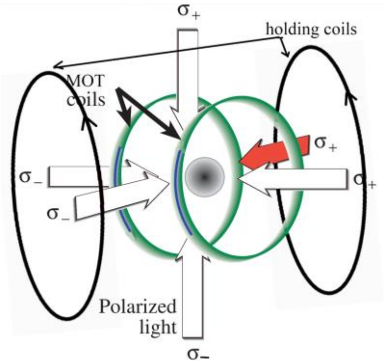
- High resolution nuclear recoil detection
- 4π solid angle for angle-resolved detection of recoil ions
- Large solid angle for low energy electrons
- Nuclear polarization in the trap
- Angle-resolved measurement of x-rays and electrons up to several hundred keV (energy range is upgradable)

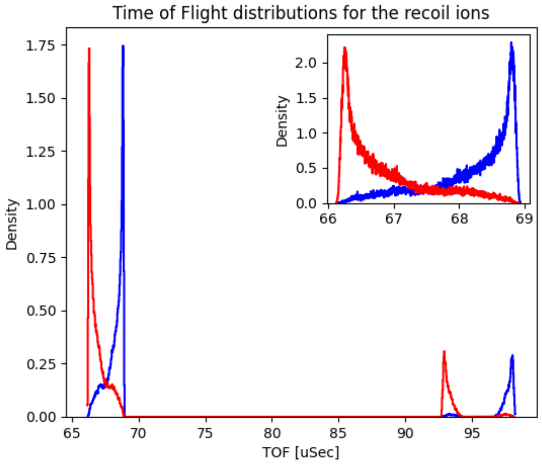
EC spin asymmetry

EC decay of polarized nuclei (Triemann 1958):

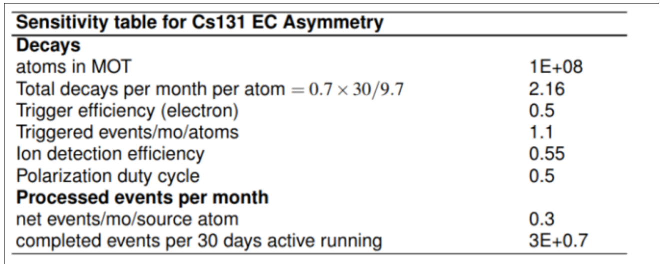
$$w(\theta)d(\cos\theta) = \frac{\langle J_z\rangle}{J}\left[1 - \frac{B_+}{1+b}\cos\theta\right] d(\cos\theta)$$

B_+ = beta decay spin asy. parameter
b = beta decay Fierz term





- Polarize by optical pumping
- Measure polarization optically
- Shake-off e- trigger
- Measure recoil nuclei only
- Asymmetry by TOF or position
- Alternate polarization axis/sense



Sensitivity table for Cs131 EC Asymmetry	
Decays	
atoms in MOT	1E+08
Total decays per month per atom $= 0.7 \times 30/9.7$	2.16
Trigger efficiency (electron)	0.5
Triggered events/mo/atoms	1.1
Ion detection efficiency	0.55
Polarization duty cycle	0.5
Processed events per month	
net events/mo/source atom	0.3
completed events per 30 days active running	3E+0.7

Lorentz violation in EC

(K. K. Vos, H. W. Wilschut, and R. G. E. Timmermans, Phys. Rev.C 91, 038501 (2015))

Parametrize Lorentz violation by adding a complex tensor $\chi_{\mu\nu}$ to the metric.

Some terms of $\chi_{\mu\nu}$ are experimentally unconstrained.

Decay rate w/ Lorentz violation:

$$dW \propto \left[\left(1 - P\hat{k}\cdot\hat{I}\right) - P\chi_i^{s0}\left(\hat{k}\times\hat{I}\right)^{s}\right],$$

k = neutrino momentum
I = nuclear spin
P ∝ polarization

Leads to an azimuthal asymmetry that rotates at sidereal rate!

Current Plan:

Source chamber:

- Summer: MOT & precision hyperfine measurements of ^{131}Cs
- Fall: Decay asymmetry measurement

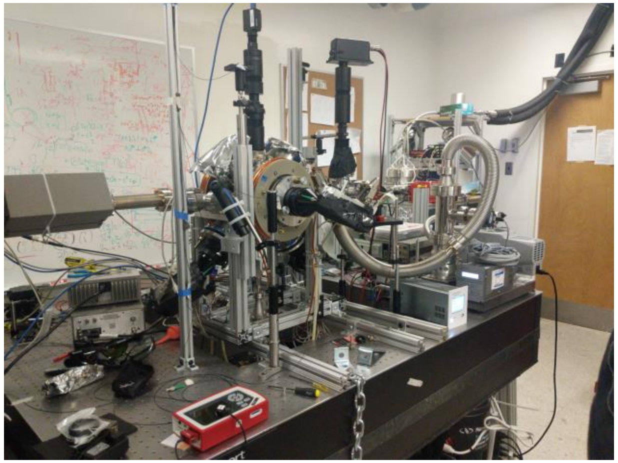
Main chamber:

- Leak-check & pump-down complete
- Summer: Mounting of spectrometers, x=ray detectors, coils & magnetic shield

End of year: first stable ^{133}Cs fill & calibration, then ^{131}Cs fill

This mounting & integration time is an exciting time for HUNTER.

<u>We are always seeking additional collaborators with expertise and new ideas!</u>



Improving Sensitivity

1. Increase detection efficiency (rate and coupling)

- Scale the number of detectors to increase surface coverage
- New detector technology to detect X-ray and Auger e$^-$ in same device
- Increase number of atoms in MOT (higher radioactivity limits)

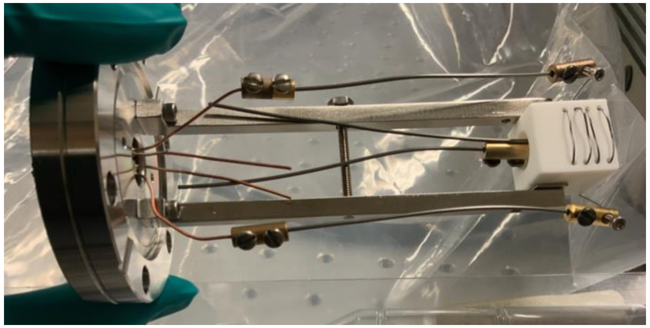
2. Improve timing resolution (mass resolution)

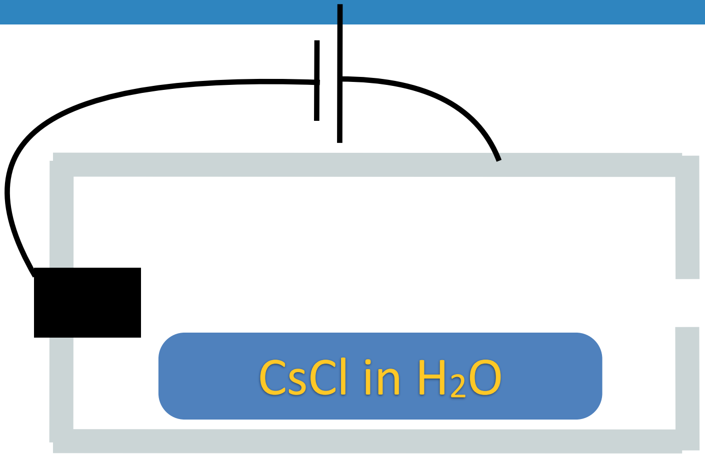
- Faster electronics: Digitize all channels with sub-nanosecond resolution, commercial device ($1,000s per channel)
- Or home-built DAQ system from UH, spin-off from ongoing PET scanner project (~$50 per channel!)

3. Improve position resolution (mass resolution)

- SiPM arrays with smaller individual SiPM sizes available
- Readout individual SiPMs instead of rows and channels
- Less effective than above, since limited by source size

Cs-131 MOT: High Efficiency source





Prototype oven:

Loaded with “Fake” radioactive solution

Atomic Cs flux measured w/RGA

Bias controls flux