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."

The HUNTER Sterile Neutrino Search

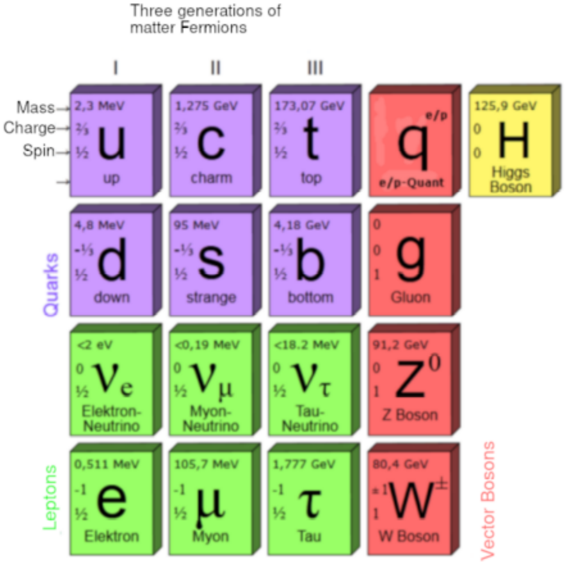
Temple University: C.J. Martoff, V. Palmaccio
UCLA: E. Hudson, P. Hamilton, P.F. Smith, E. Chang, S. Khamis
Princeton U.: P. Meyers
Hebrew Univ. of Jerusalem: G. Ron, A. Prosnyakov
U. Houston: A. Renshaw, F. Malatino

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

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

W.M. KECK FOUNDATION
GORDON AND BETTY MOORE FOUNDATION

Sterile Neutrinos & the Standard Model

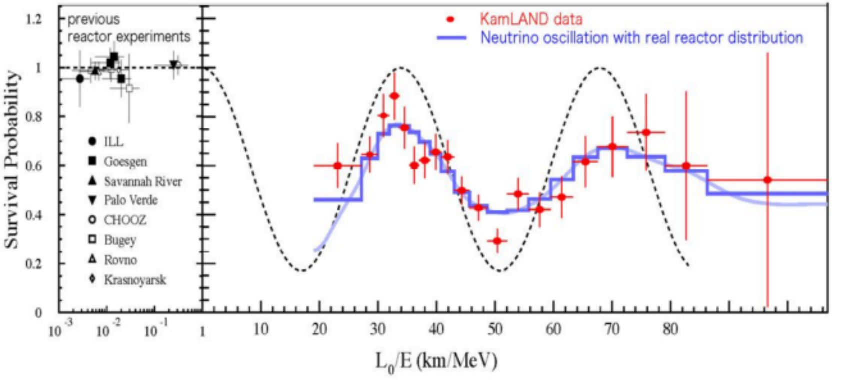


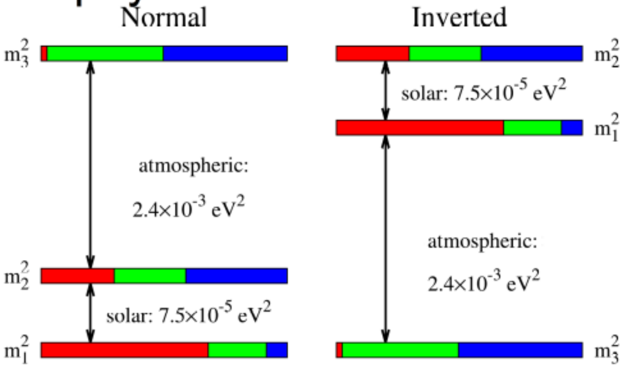
Standard Model is a wonderful thing...

- Unifies weak, EM, strong interactions in a mathematically consistent way
- PREDICTED its gauge boson content before discovery
- Allows sub-ppb calculation of some particle properties
- Accounts for almost all particle phenomenology

The Problem of Non-zero Neutrino 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.

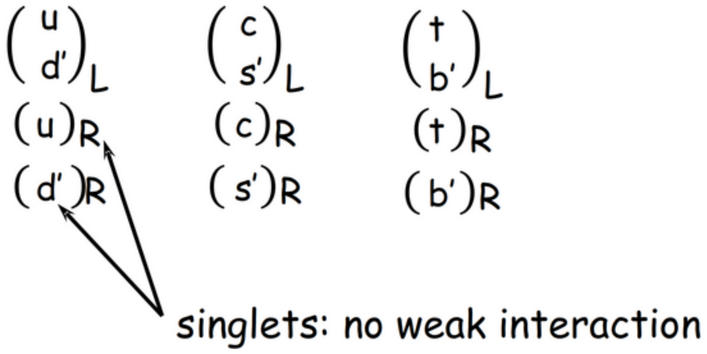
- Phenomenologically implies nonzero active neutrino masses.

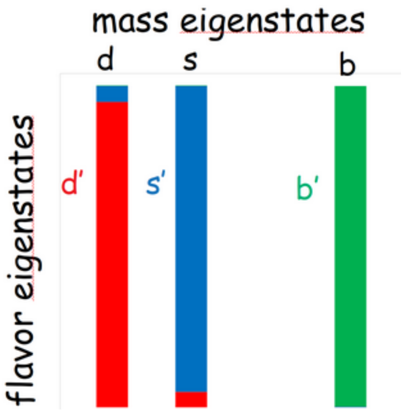
HOWEVER...

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.

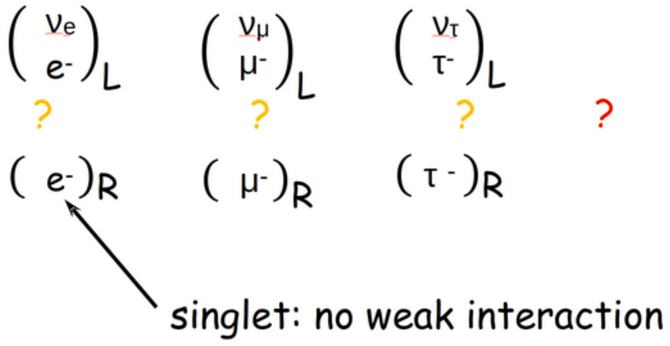
Standard Model Weak Interactions

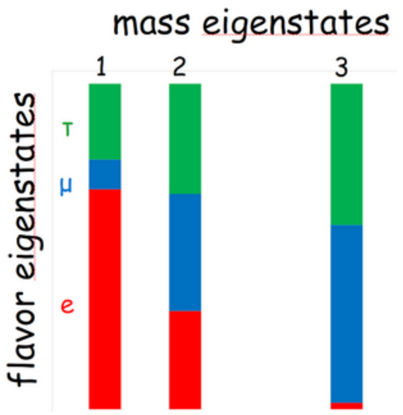
Quarks:





Leptons:

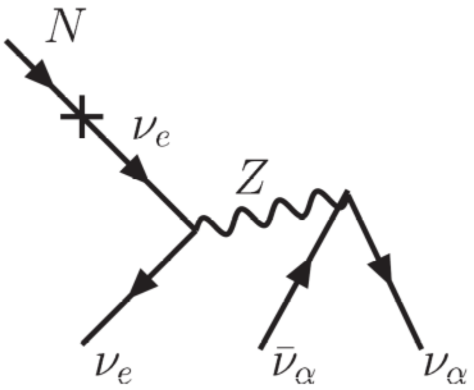




- Strong lepton-quark analogy
- But no “Sterile” (right handed singlet) neutrinos (Sν) in SM!
- Needed for ν mass terms!
- Sν can also allow to explain matter-antimatter asymmetry
- And provide a “warm dark matter” candidate

Sterile Neutrino Interactions

- Simplest assumption: interact ONLY via mixing with active neutrinos
- This still implies decays:



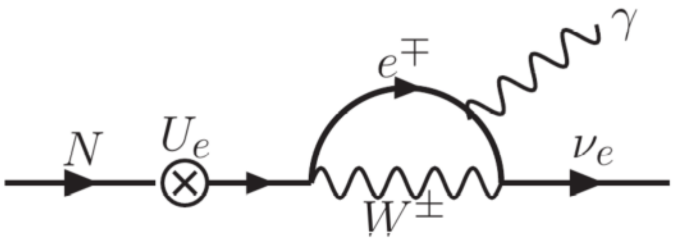
- Main decay: $\nu_s \rightarrow \nu_a + \nu_{a'} + \overline{\nu_{a'}}$
- Basically invisible but determines lifetime:

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

- Present day dark matter candidate Sν can't be too heavy, or mix too strongly (in minimal models)

Sterile Neutrino Interactions II

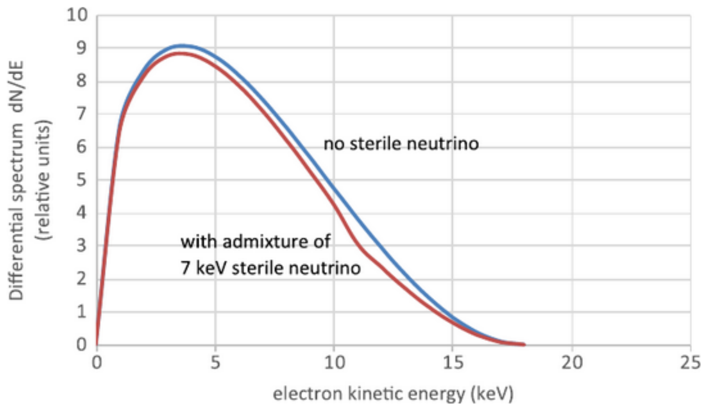
- There is also a visible decay!



- Radiative two-body decay: $\nu_s \rightarrow \nu_a + \gamma$
- Gives monoenergetic photons at energy $m_s c^2/2$
- Branching ratio ~.01
- Astrophysical searches for x-ray lines give strong limits (in minimal models)

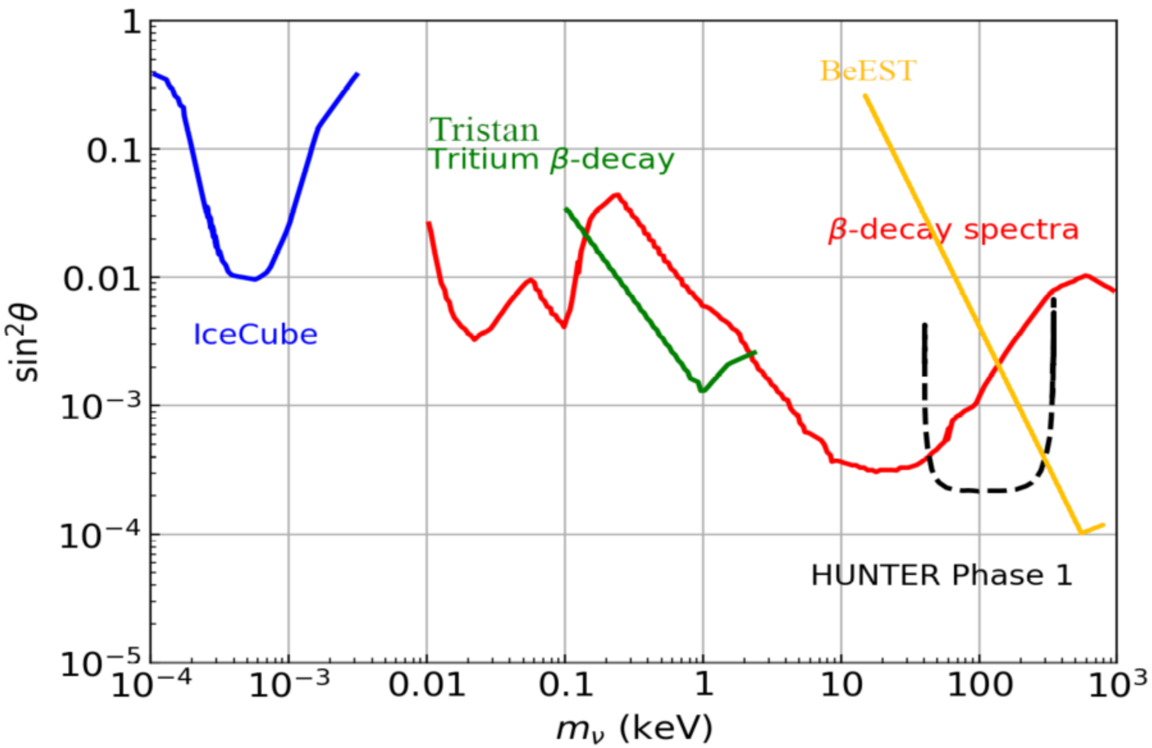
Sterile Neutrino Interactions III

- Even β decay can be affected!



- Oscillation into a massive Sν state => subset of decays with reduced Q_β
- Gives a kink in beta decay spectrum with amplitude ~ $\sin^2(\theta)$.
- Remember the “17 keV neutrino”?
- Laboratory limits in keV mass range $\sin^2(\theta)$>~.01

Summary of Existing Sν Limits

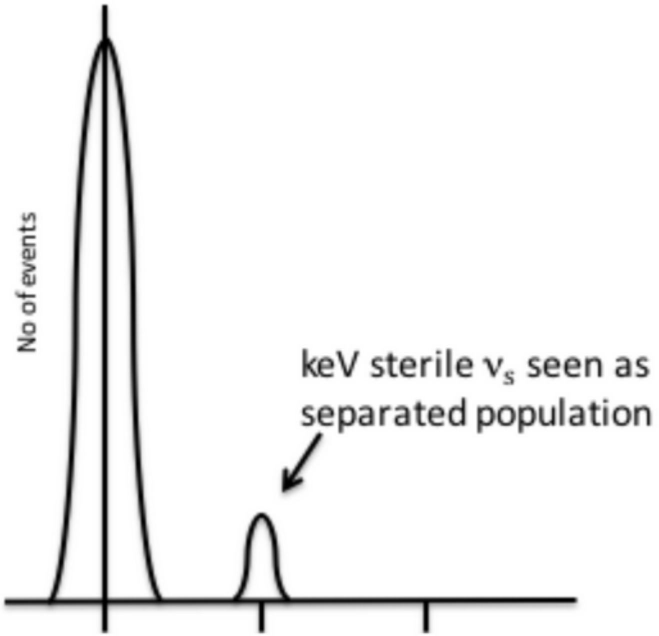


Other Experiments:
Tristan (Katrin extension)
BeEST- ^{7}Be microcalorimeter

HUNTER is agnostic about:

- any particular theory - Sν just needs to mix with active multiplets and have a mass in our range of sensitivity (initally 30-300 keV/c^2)
- whether or not Sν are the dark matter

The HUNTER Experiment



After a venerable suggestion... (R. E. Shrock, Phys. Lett. **B96**, 159 (1980))

Consider the decay $A^+ \rightarrow \ell^+ + \nu_\ell$.

- For a massless neutrino, the produced

lepton has unique $p_0 = \frac{m_A^2 - m_l^2}{2 m_A}$

- If the neutrino can oscillate into a state with small but nonzero mass m_x, a second lepton

  momentum peak appears at $p_x \approx p_0 \left(1 - \frac{m_x^2}{2(m_A - m_B)^2} \right)$

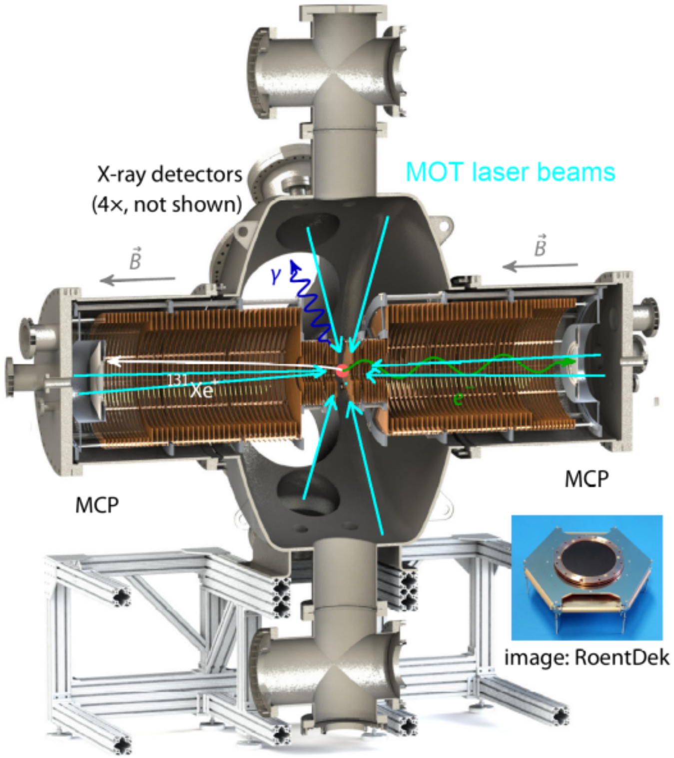
- Classically, A = π+, K+, etc.

- HOWEVER - to discover small m_x, small energy release $Q = m_A - m_B$ is best.

HUNTER:

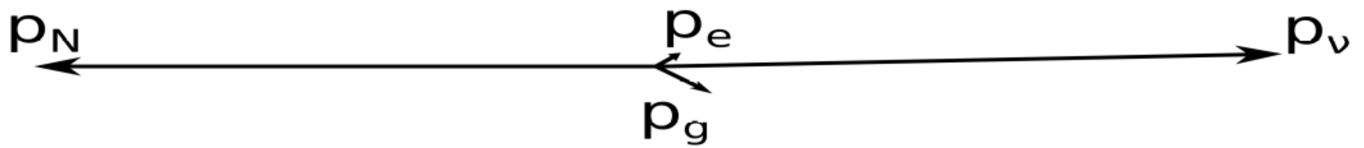
Heavy Unseen Neutrinos by Total Energy-momentum Reconstruction

Kinematic reconstruction of m_ν in individual Electron Capture decays of ^{131}Cs atoms at rest



- EC decay- basic decay is 2-body
- Kinematic reconstruction- not an oscillation experiment. Measure all decay product momenta & reconstruct missing neutrino mass event-by-event
- ^{131}Cs is at rest- held in a Magneto-Optical Trap and laser cooled to 20 μK

Electron-Capture Decay Basic Kinematics



p_N , p_ν ~ 320 keV/c, v_N ~ 800 m/s
p_e ~ 10 keV/c, p_g ~ 30 keV/c
$m_\nu^2 = [Q - E_e - E_g - E_N]^2 - [\mathbf{p}_g + \mathbf{p}_e + \mathbf{p}_N]^2$

- Sadly, atomic x-ray and Auger electron(s) complicate kinematics
- Ignoring e and x-ray, estimate effect of m_ν on p_N:
  accurate lowest-order solution: $p = Q(1 - m_\nu^2/2Q^2)$
- For m_ν =10 keV, effect is dp/p ~.04% ! (~ ^{131}Cs thermal momentum at 150 mK)

This sets the scale of measurement accuracy needed.

Key technologies:

for a sensitive keV-mass sterile neutrino search with low energy nuclear decays:

Magneto Optical Trap (MOT) => thinnest possible radioactive source

- Density $>10^{10}/cm^3$ ($\sim 10^{-15}$ bar within cold atom cloud)
- Radius (1 - few) mm
- 10^8-10^{11} Trapped atoms (10^2-10^5 Bq for $t_{½}$=10 days)
- Trapped atoms temperature ~ few μK to mK

MOT + Reaction Ion Microscope Spectroscopy = MOTRIMS

- Electro-magnetostatic spectrometers, MCP detection
- High accuracy momentum measurements for low-energy charged particles

Large-area x-ray detector with high spatial- and energy-resolution

- Segmented readout of thin YAP scintillators

Choice of Isotope

Important considerations for initial experiment:

- Want EC-only decay
    - low energy visible products (no $\beta^{+/-}$) => E/**p** by TOF
    - no 511 keV or other gammas to disrupt reconstruction or require expensive shielding
- Want 10 days >$t_{1/2}$> 1 day (stock isotope in our own lab)
- Must be MO-Trappable
- Consider isotope availability (medical)

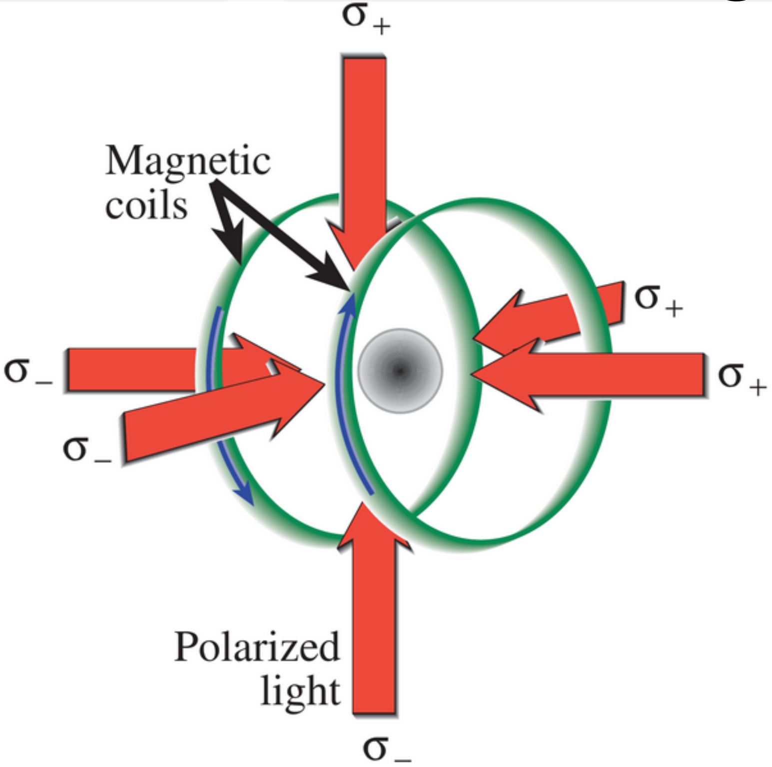
Criteria result in essentially unique choice: **^{131}Cs**.

^{131}Cs

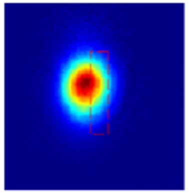
- $t_{1/2}$=9.7 da, EC 100%, Q_{EC}=355 keV
- ^{131}Cs -> ^{131}Xe (stable)
  + x-ray (4-35 keV)
  + Auger e^{-}'s (3-150 eV)
- No penetrating radiation, stable 131-Xe daughter.
- Commercially available

(***IsoRay*** brachytherapy source- mfr will load our atomic beam source!)
$10K/order + $1K/Ci

MOT- Laser Cooling and Trapping



HUNTER Phase 1 goals:
20 μK, 10^8 ^{131}Cs atoms (10^2 Bq) in ~1 mm MOT

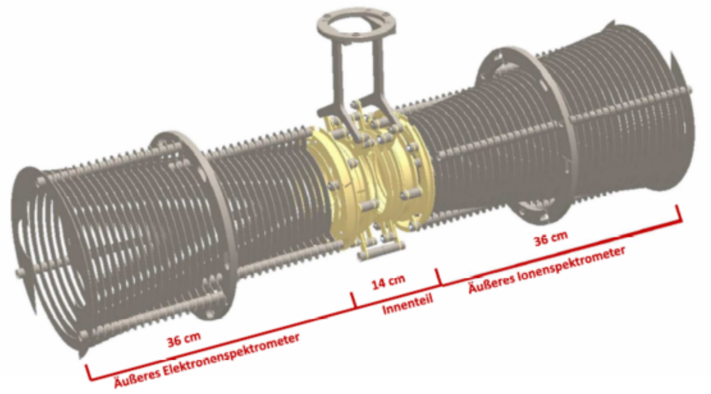


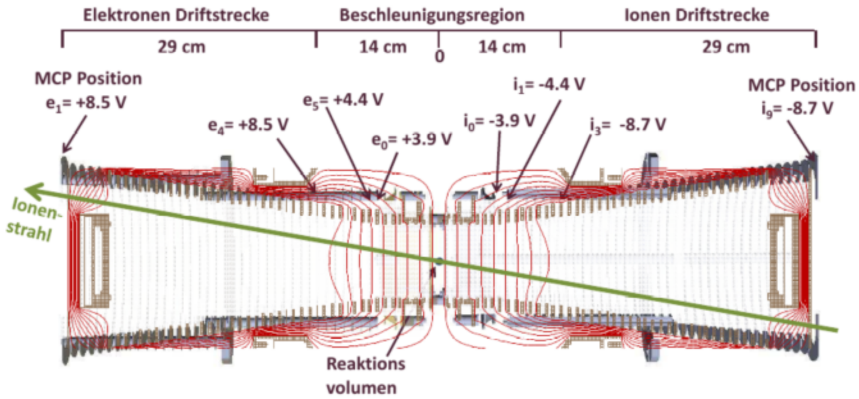
HUNTER UCLA group
CCD image of 10^9 ^{133}Cs atoms
at 20 μK

- 3 red-detuned laser pairs => 3-D damping, cooling
- Add Zeeman-shifting **B**-field gradient and CP light

=> **"MOT"** with 3-D <u>restoring</u> <u>force</u>

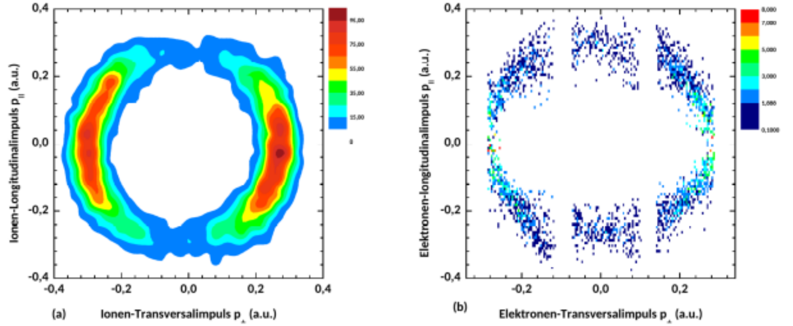
PARTICLE DETECTION: REACTION ION MICROSCOPE SPECTROME





R. Hubele, 2013 dissertation, Ruprecht-Karls Uni. Heidelberg

Invented and refined for chemical physics studies; mapping chemical reactions with 4π acceptance. (Dorner[2000], Ullrich[2003])



R. Hubele, 2013 Dissertation, Rubrecht-Karls Uni. Heidelberg

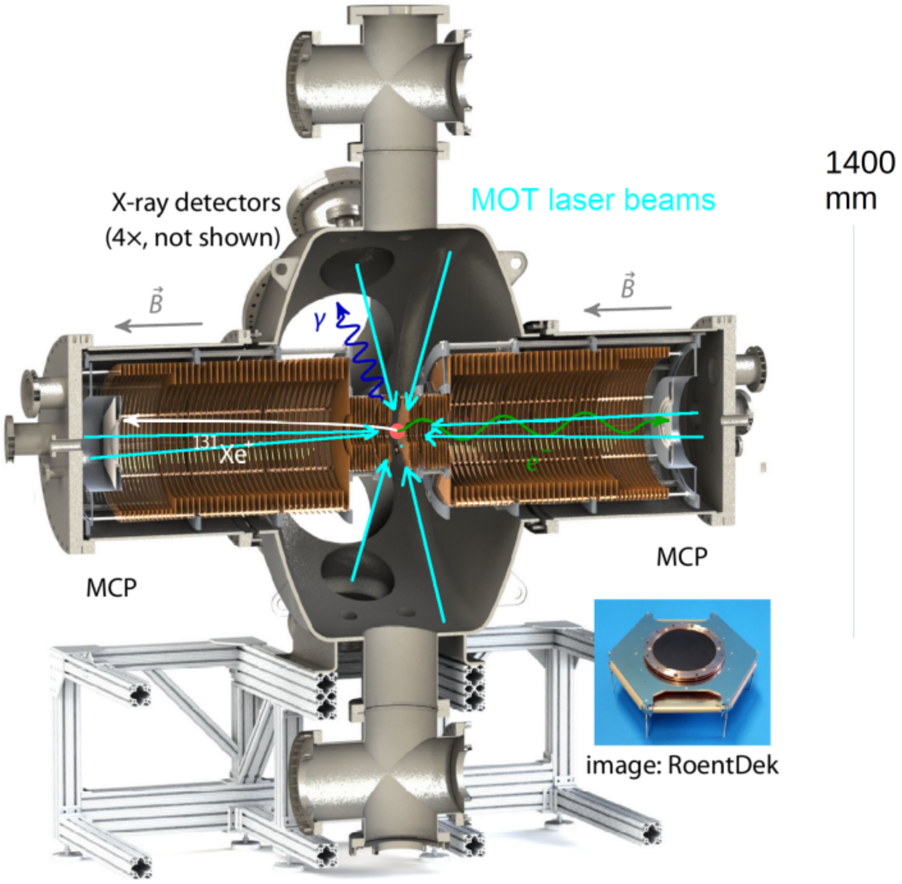
Abbildung 5.6.: Schnitt durch den dreidimensionalen Impulsraum für (a) Rückstoßionen und (b) Elektronen der Photoionisation. Die Polarisation des UV-Lasers ist in x-Richtung orientiert.

Transverse momentum distribution of $^7Li^+$ ions (left) / electrons(right) from ^7Li ionized by linearly polarized 266 nm photons

Overview of Apparatus

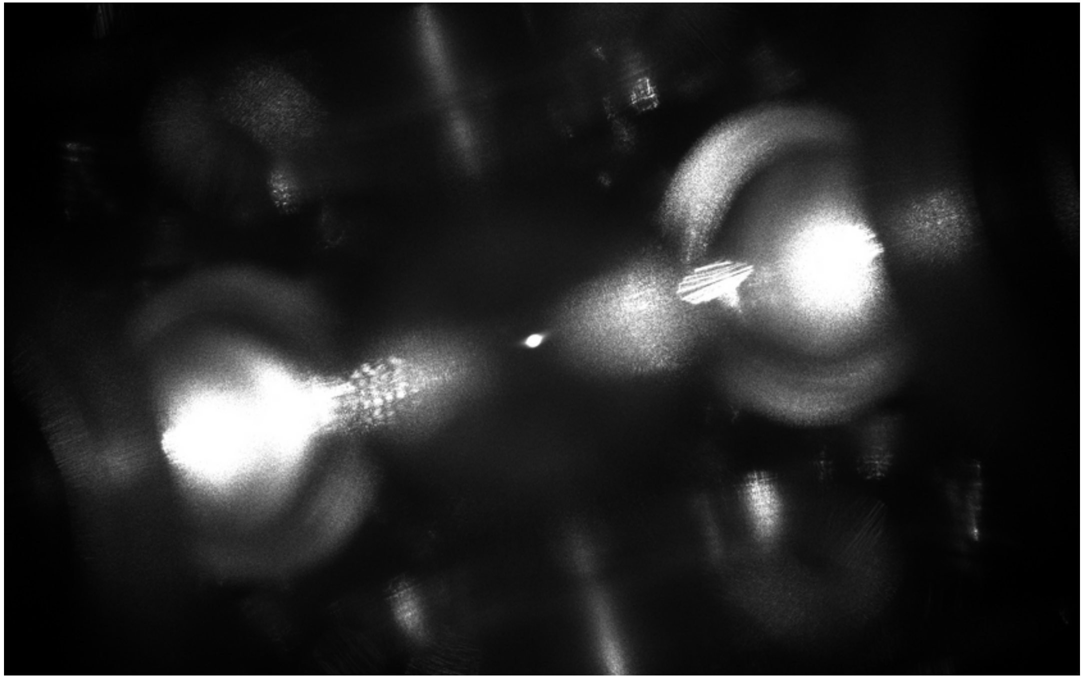
- MOT trapped & cooled atom target
  at temperature < 1 mK
- Axial (magneto-)electrostatic spectrometers
  with 4π(1.6π) ion(electron) acceptance.
- Accurate p_L and p_T from high TOF and spatial
  resolution of MCPs
- x-ray vector momentum and TOF start from
  pixelated scintillator panels

A lot of details must be mastered to achieve the desired accuracy.



Not just on paper...

<-- Preparing to pump out (now at 1e-7 mbar)



133Cs in HUNTER loading MOT

MOTRIMS for HUNTER

- MOT lasers require 62 mm gap between central electrodes **BUT** ion resolution depends on uniform “extraction” field

- Lasers also preclude grid between “extraction” and “drift” regions

- Laser nearly collinear with spectrometer axis requires large ID and hence large OD

- Ion resolution requires weak extraction field **BUT** 4π electron acceptance requires strong field.

- Designed using automated SIMION optimization and GEANT4 for particle tracking (https://doi.org/10.1016/j.nima.2020.163511)

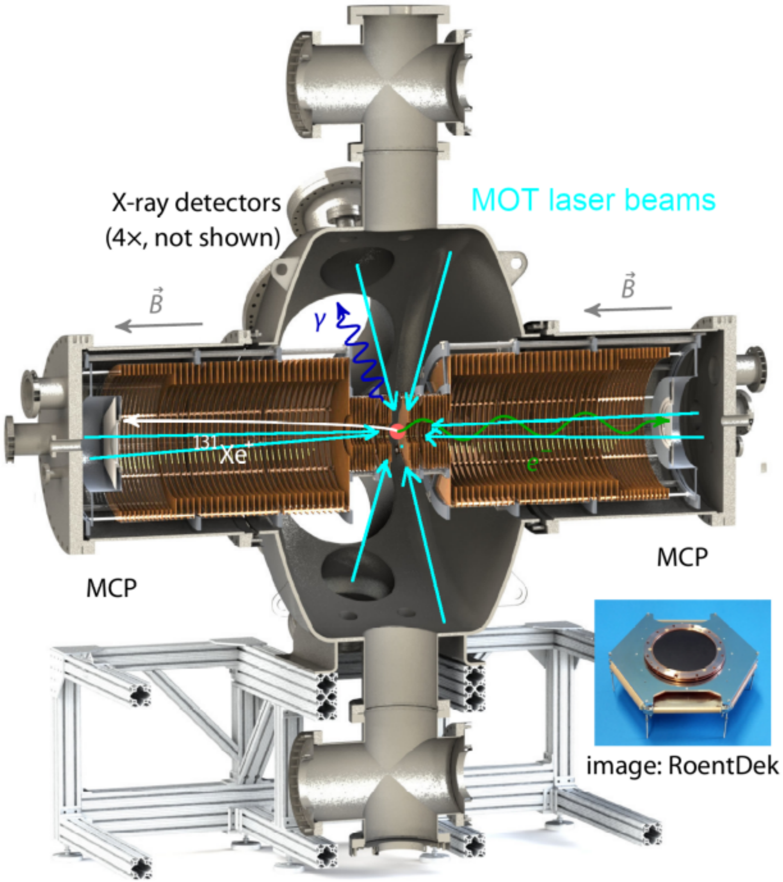
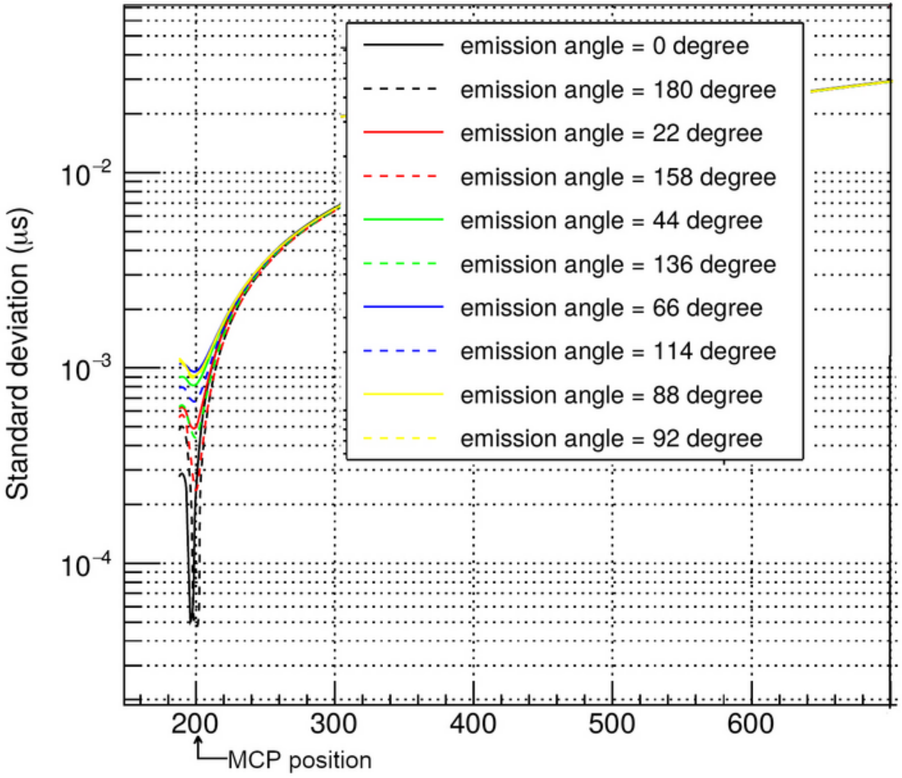


image: RoentDek

Simulation Results

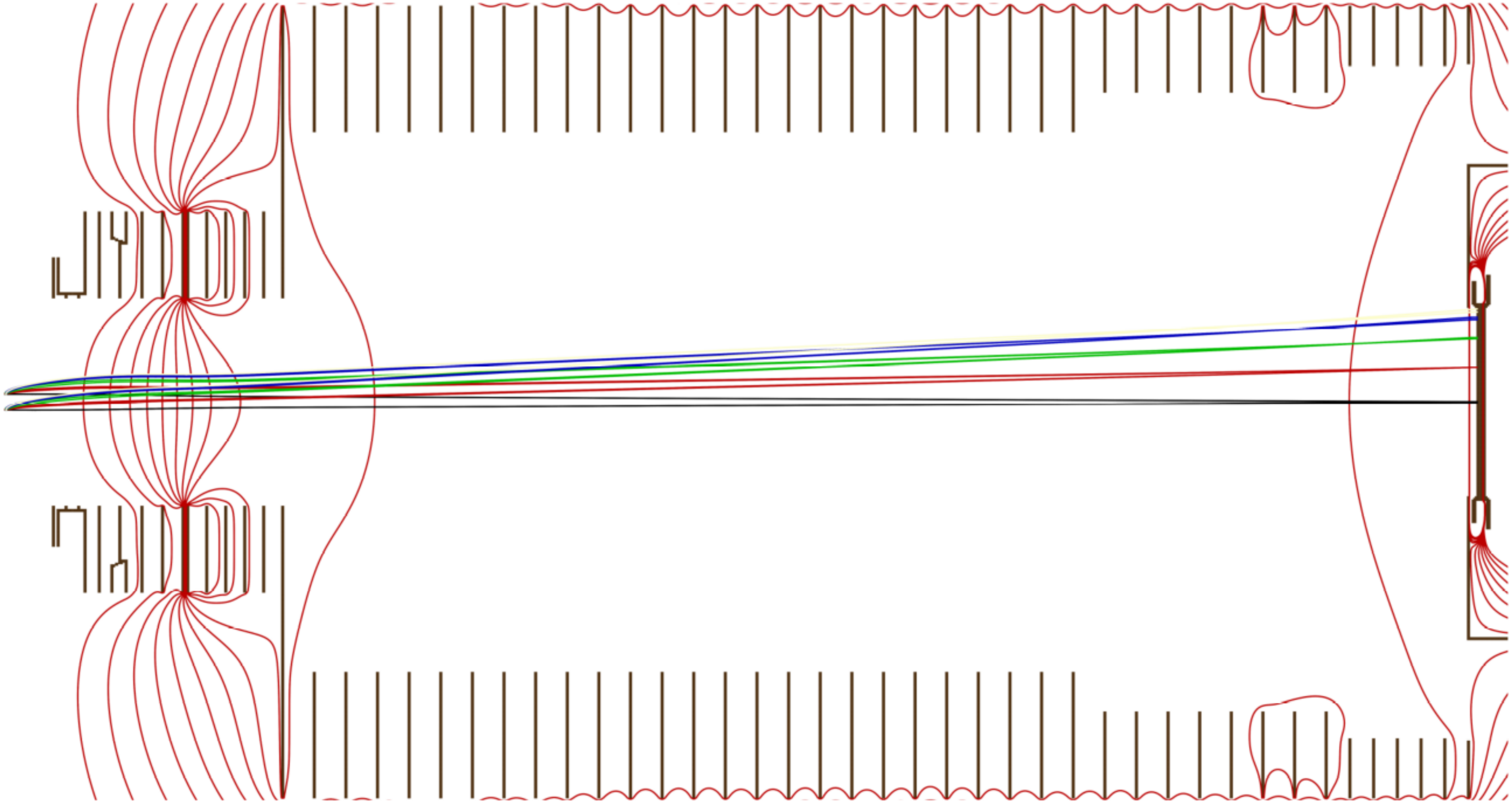


- Plot shows std dev of TOF for tracks originating at random points within a 1 mm radius MOT, with varying elevation angles.

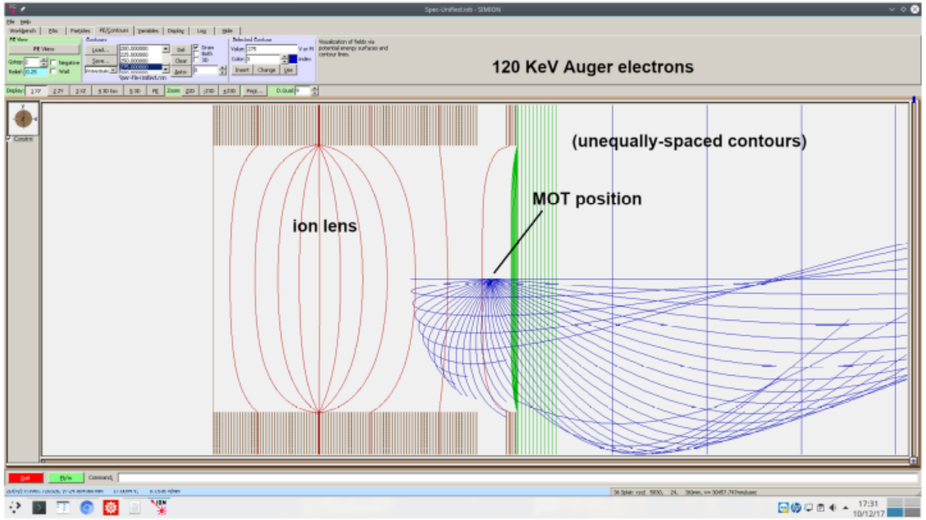
- Note: minimum timing width ("time focus") occurs at the same position for all angles and is not greatly broadened by MOT size. ("double focusing" not easy to achieve)

- Timing width matches 1 ns resolution of x-ray detectors.

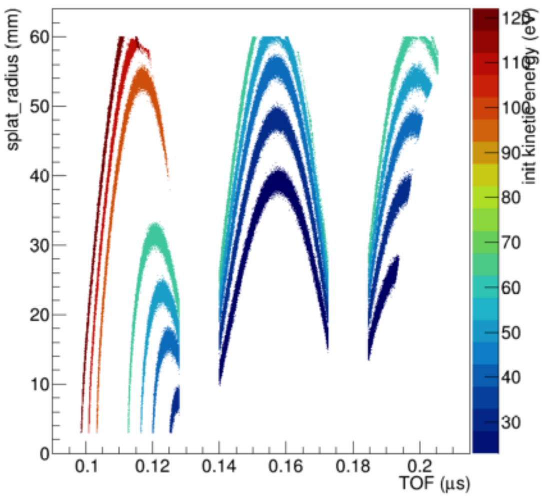
Simulated Transverse ("spatial") Focusing



Groups of ions with p_t coded by color, transverse origins separated by 10 mm!

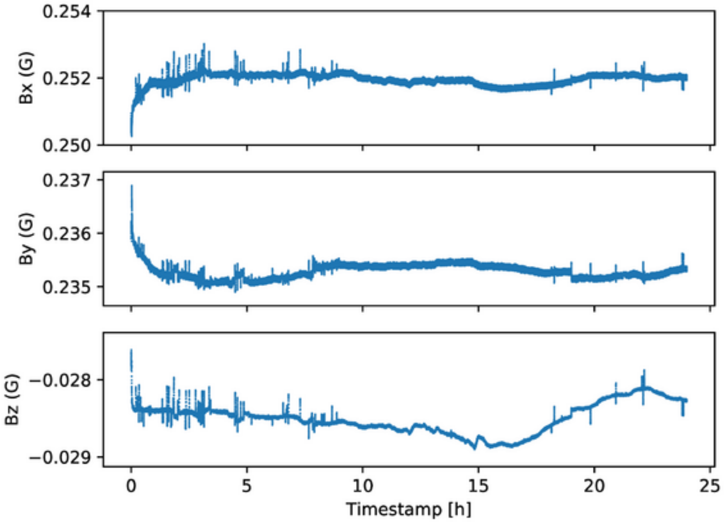


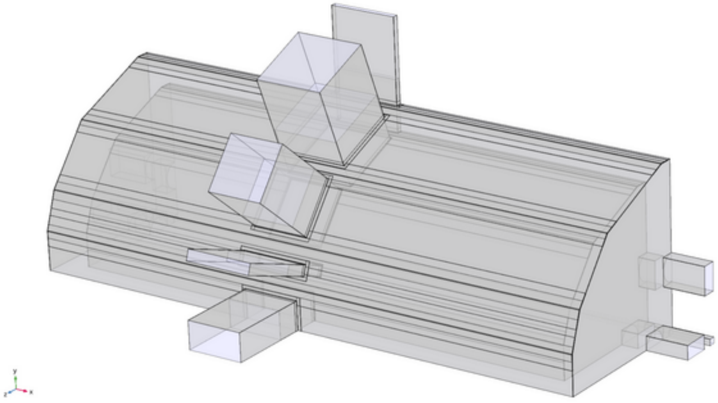
splat_radius vs TOF vs init kinetic energy



Simulation software stack:

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



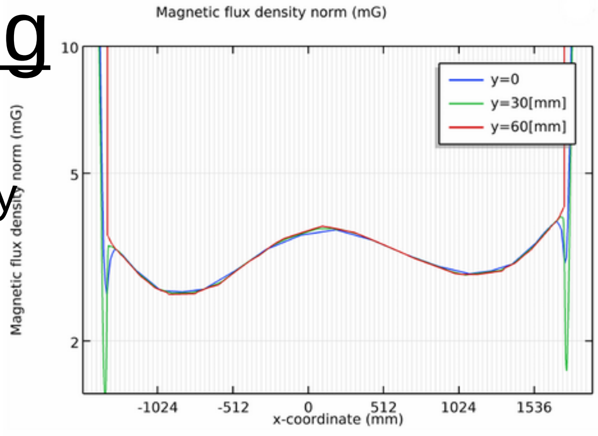


Magnetic Shielding

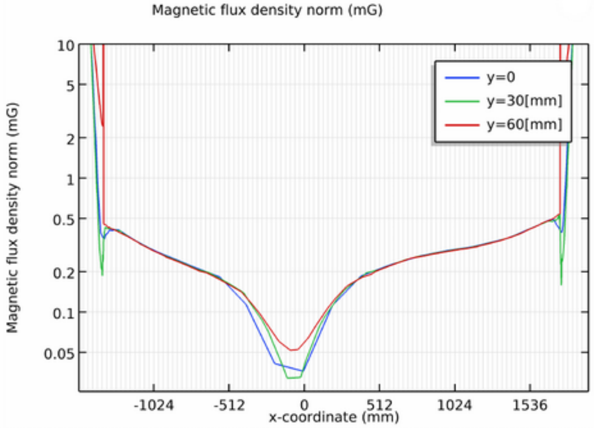
- Electrons must be confined by 6G axial field **and** protected from lab stray fields.

- Borrowed octagonal design from E. Wodey et al 2020* (all flat parts)

- 2-layer shield gives reduction factor > 200 while carrying return flux of 6G solenoid.



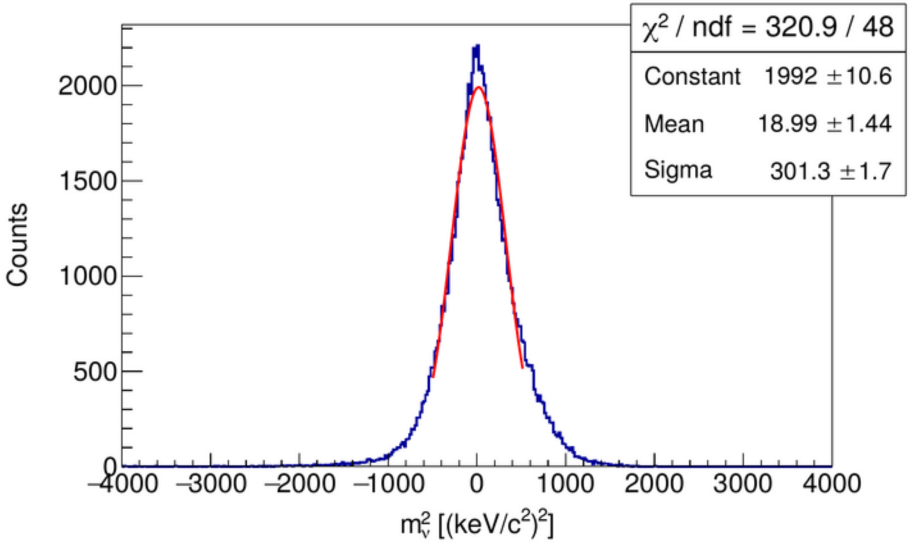
(a)



*http://arxiv.org/abs/https://doi.org/10.1063/1.5141340 (b)

Simulated m_ν^2 Reconstruction

- This is “high acceptance” mode (4π for ions onto 120 mm MCP)
- A “high resolution” mode also exists with σ=100 $(keV/c^2)^2$ and 1/8 the acceptance
- Limit arises from resolution/diameter of MCP- larger ones becoming available.



Reconstructed neutrino mass spectrum.
(Simulation)

Physics Backgrounds

- Many physics backgrounds discussed at more length in https://doi.org/10.1088/1367-2630/ab1502 and Quantum Sci. Tech. **6**, 024008 (2021)
- Most important is ion-atom scattering of Xe+ by Cs (induced dipole- Langevin)
  - Broadens zero-mass peak and contributes flat-ish background

Rates, acceptance, efficiency

10^8 trapped atoms, $t_{1/2}$ = 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 Hz ×0.0035×0.55×0.066×0.55 = 0.0047 Hz

⟹ ~150,000 events per year of livetime

Simulated discovery spectrum

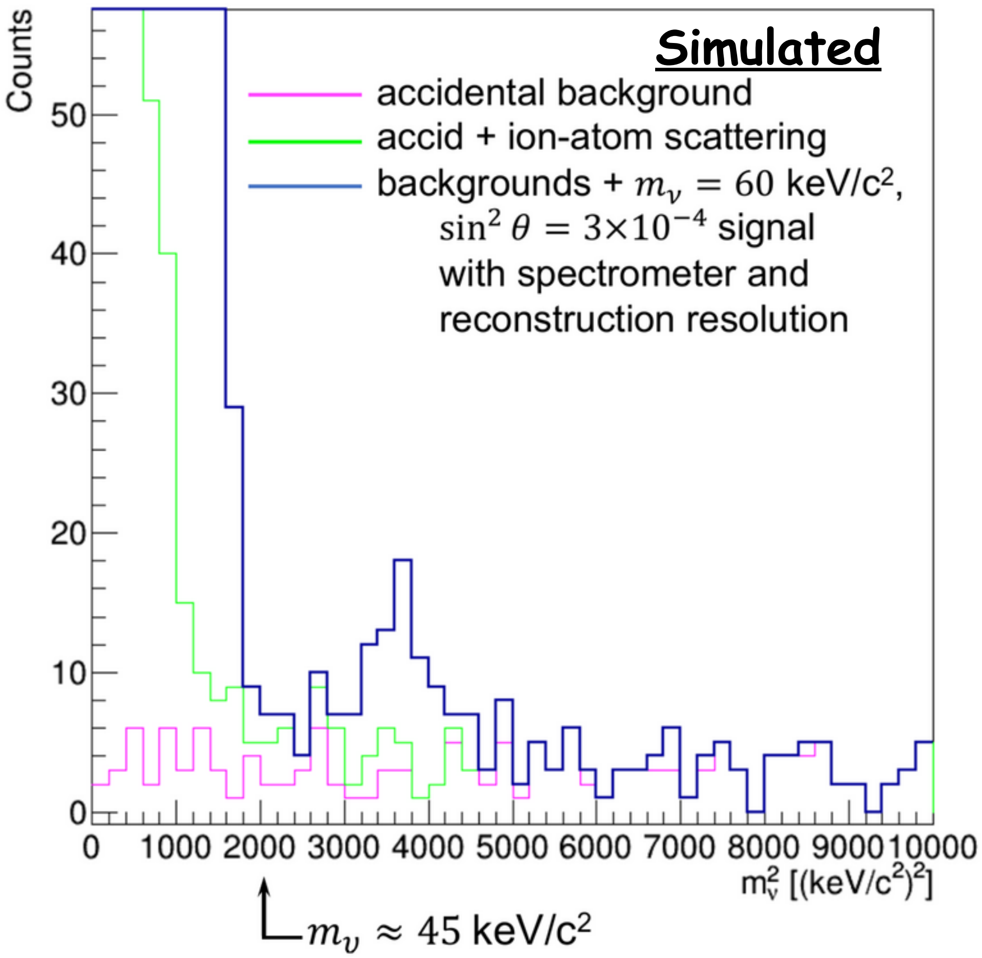
40 sterile neutrino events giving a 5σ peak at m_ν = 60 keV/c² with $\sin^2\theta = 3\times10^{-4}$, using the best estimates of backgrounds and a 1-year-livetime data sample.

HUNTER mass range:

$20 < m_\nu < 300$ MeV/c²

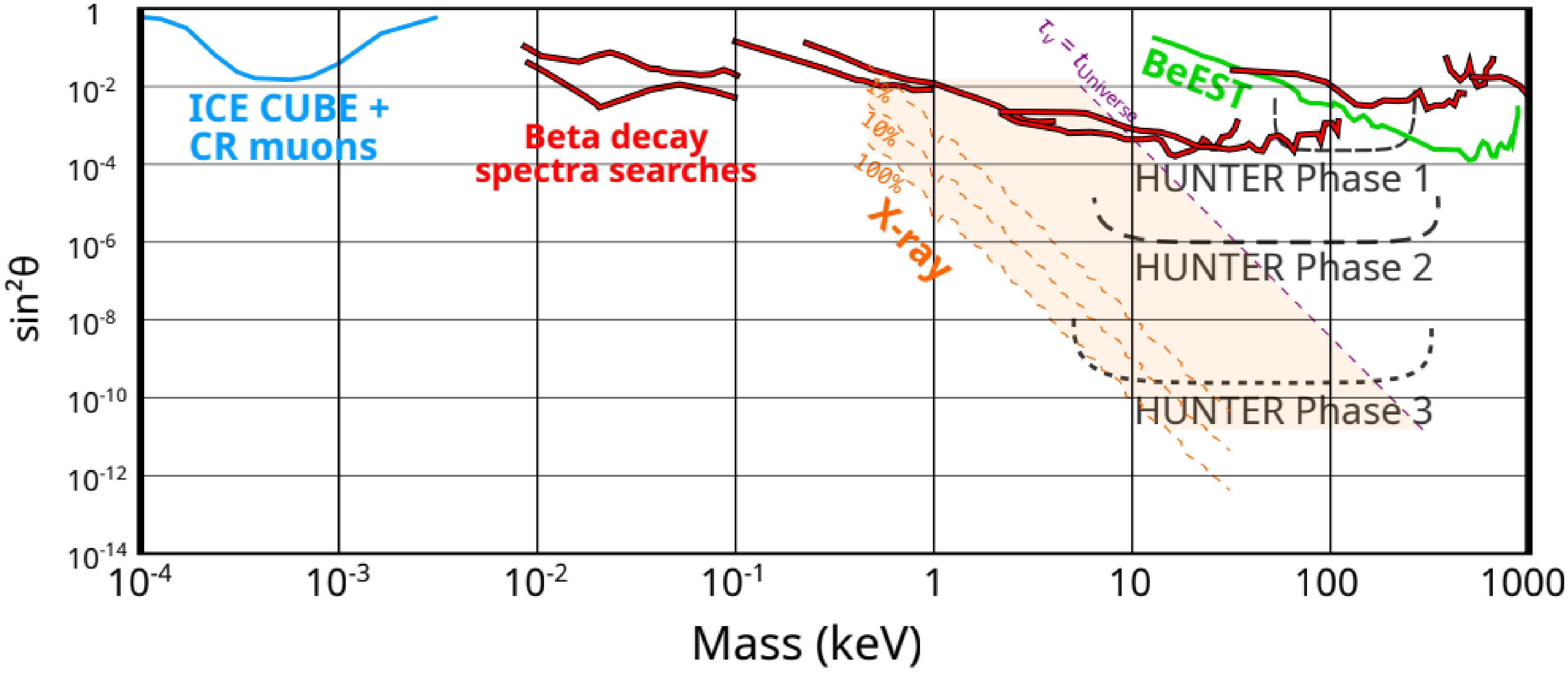
resolution

Q-value



Anticipated Results: Phase I and Upgrades

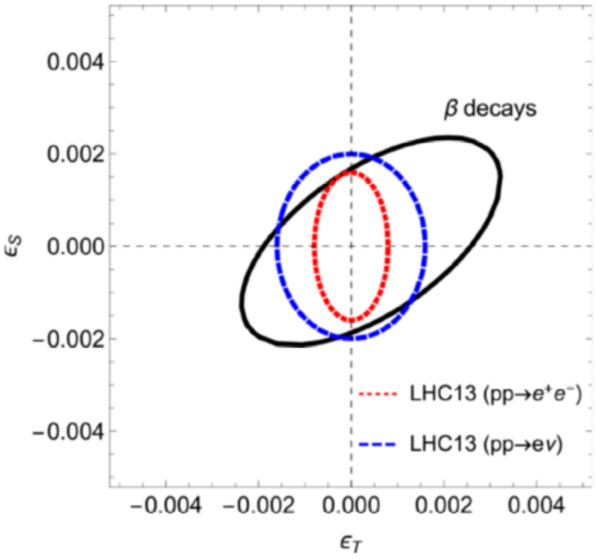
$\sin^2\theta_{e4}$ = probability that ν_e is measured as ν_4



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)

Can access essentially all beta decay correlations and eventually the Fierz term



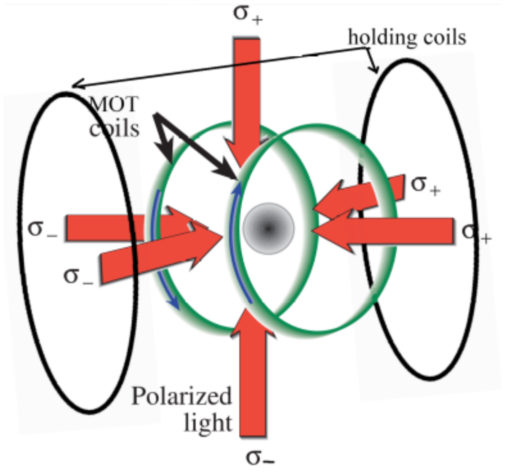
(Falkowski et al, JHEP04(2021)126)

EC Spin Asymmetry:

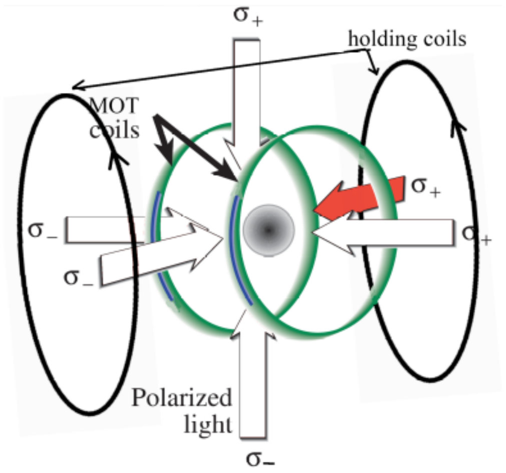
EC decay of polarized nuclei (Triemann 1958):

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

B+ = beta decay neutrino spin asy. parameter
b = beta decay Fierz term
combination is linear in $C_T^{(')}$



Trapping



Polarizing

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

Lorentz Violation in EC

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

- Lorentz and CPT invariance violated in some unifying theories
- Parametrize Lorentz violation by adding a complex tensor $\chi_{\mu\nu}$ to the metric
- Results in additional spin asymmetries
- Some terms of $\chi_{\mu\nu}$ are experimentally unconstrained

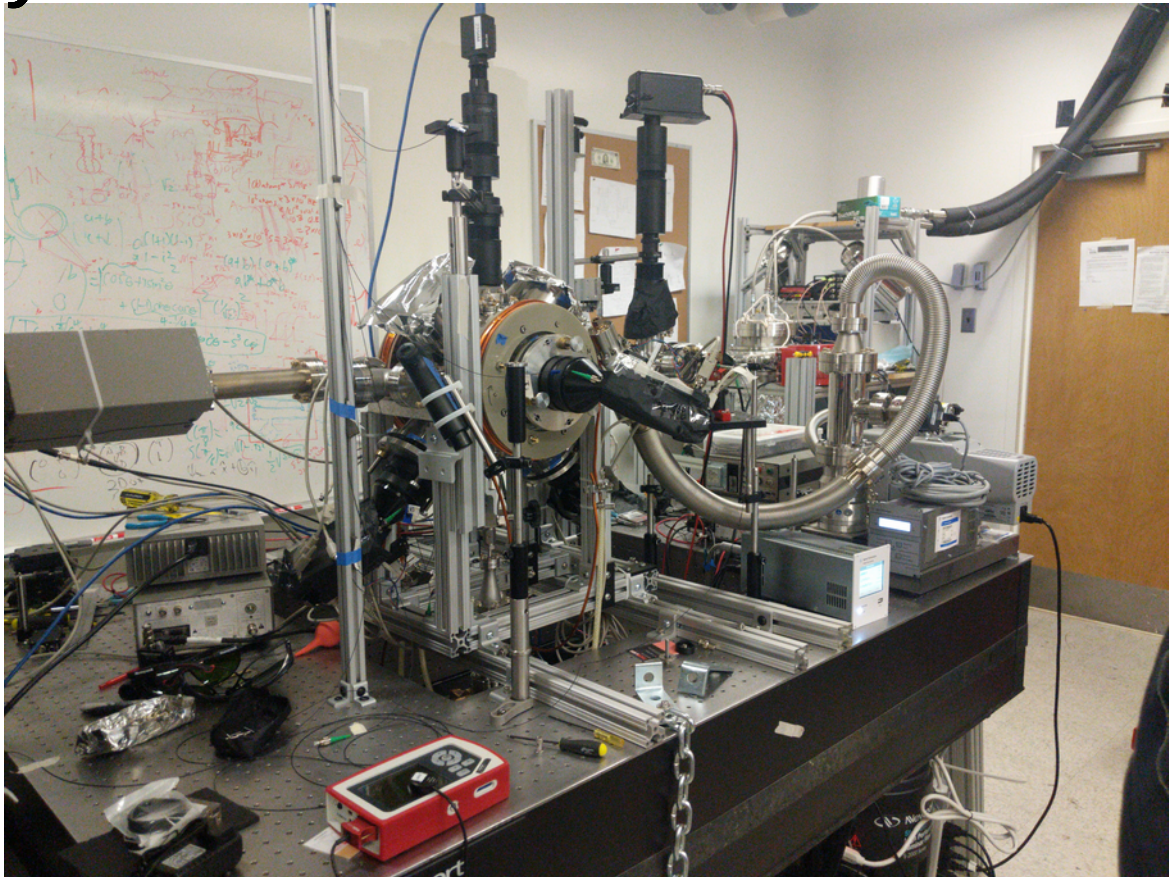
$$dW \propto \left[\left(1 - P\hat{k}\cdot\hat{I}\right) - P\chi_i^{s0}\left(\hat{k}\times\hat{I}\right)\right]^{s},$$

k = neutrino momentum
I = initial nuclear spin
P $\propto$ Polarization, B

An azimuthal asymmetry that rotates at sidereal rate!

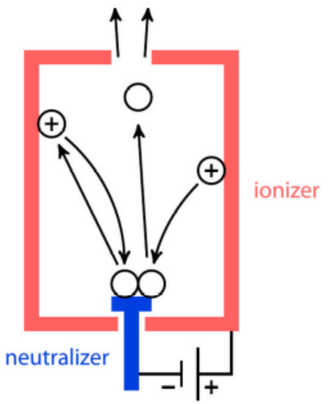
HUNTER assembly at UCLA

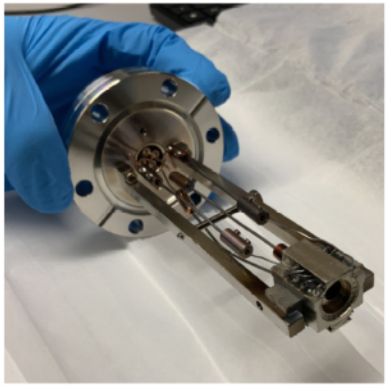
Vacuum vessel- now at 1e-7 mbar



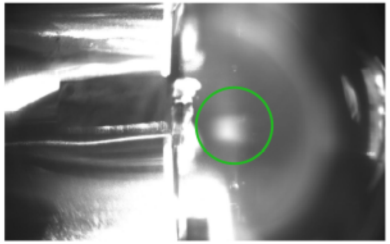
Loading MOT- now trapping ^{133}Cs

Radioactive Atom Source: Orthotropic Oven

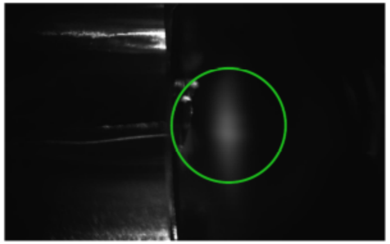




prototype oven



orthotropic ^{133}Cs emission

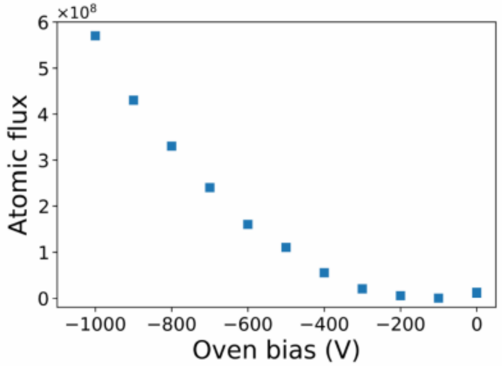


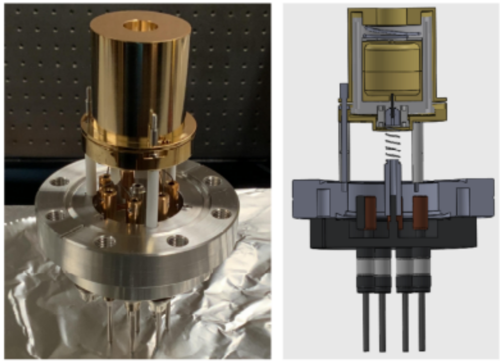
thermal ^{133}Cs emission

orthotropic oven T. Dinneen et al.: Rev. Sci. Instrum. **67**, 752 (1996)
H. Kawamura et al.: arXiv **1908.10686v1**, 1 (2019)

cesium: ionization potential I_{Cs} = 3.9 eV
ionizer: high workfunction (e.g. Φ_{Re} = 4.7 eV)
neutralizer: low workfunction (e.g. Φ_Y = 3.1 eV)

Langmuir-Saha Eq.: $$\frac{n_+}{n_0} = \frac{1}{2}\exp\left(\frac{e(\Phi - I)}{k_B T}\right)$$





"quick-load" oven

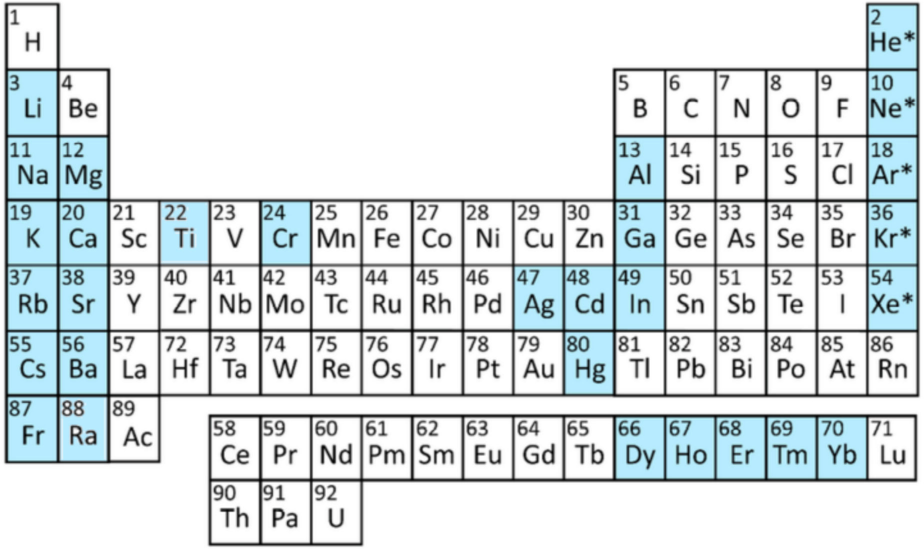
Upgrades for later Phases of HUNTER:

- More atoms in trap 10^7 -> 10^{11}
- More x-ray detector coverage 8.5% -> 45%
- Accept more x-ray transitions 2.5% -> 15%
- ***Different isotope with shorter halflife-***

requires online operation at isotope separator

Elements/Isotopes for Advanced HUNTER

Trappable atoms:



Candidates for advanced HUNTER as well as other beta decay studies.

Suitable EC isotopes:

(NNDC Database -thanks Alejandro Sonzogni)

Looked for isotopes with
- EC with < 25% β+ BR -> 258 nuclides
- halflife < 10 days
- < 25% nuclear γ following EC
- Z < 55 for Auger multiplicity

Results in order of preference:
121-Cs (15 sec), 128-Cs (220 sec)
130-Cs (1750 sec), 105-Cd (3300 sec)

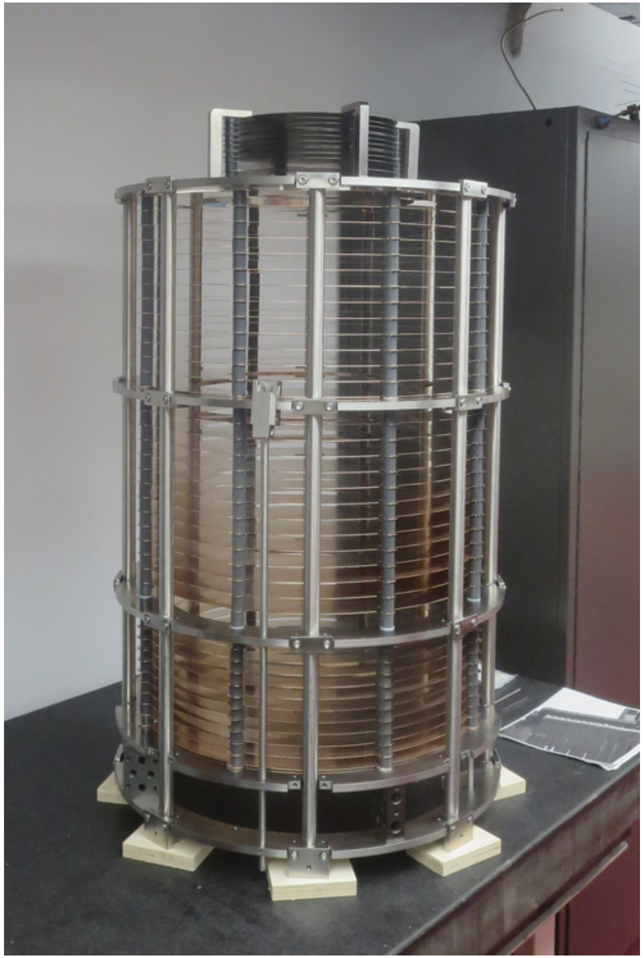
Not without challenges- nuclear γ and β+ backgrounds must be flagged & excluded

Current Plan:

Preliminary leak-check & pumpdown now underway
July-September: Clean, assemble, insert spectrometers,
x-ray detector, main MOT
September-October Bake-out
October-November Add coils & magnetic shield
December 2022- first stable ^{133}Cs fill & calibration,
then ^{131}Cs fill

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

We are always seeking additional collaborators with expertise and new ideas!



Note: why don't we use ^{7}Be?

- No one has MO-Trapped Be
  - the only possible cycling transition is in UV- hard to generate & handle
  - two-photon absorption on cycling-transition => ionization & escape from trap

- No x-ray for t=0 TOF trigger
  - 478 keV gamma I=10% but hard to detect with requisite angle resolution
  - could possibly develop an Auger or shake-off trigger

- Not commercially available in mCi quantities