Laser spectroscopy of a nucleus

Eric R. Hudson, UCLA
Department of Physics and Astronomy
Center for Quantum Science and Engineering

The Goal is control

Forty years in the wilderness

- Th-229
- Mössbauer to the rescue

Let there be light!

- Th:LiSAF
- Synchrotrons & Lasers

Let the SNSPD guide you!

- New detectors & Approaches

Th-229 doped $LiSraAlF_6$ crystal

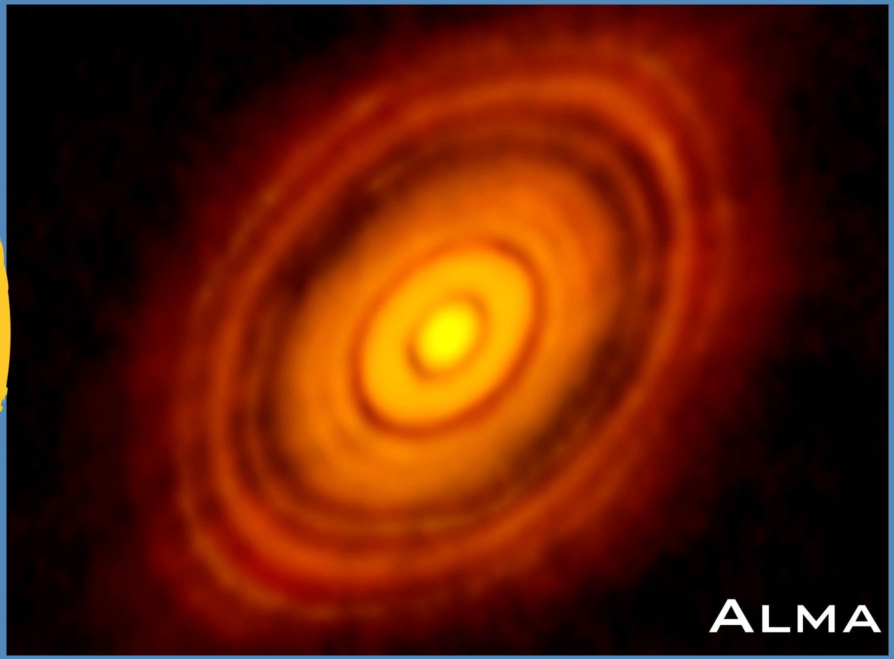
This work was funded by the NSF, ARO, and DARPA

Quantum control for advancing science

Molecular ions

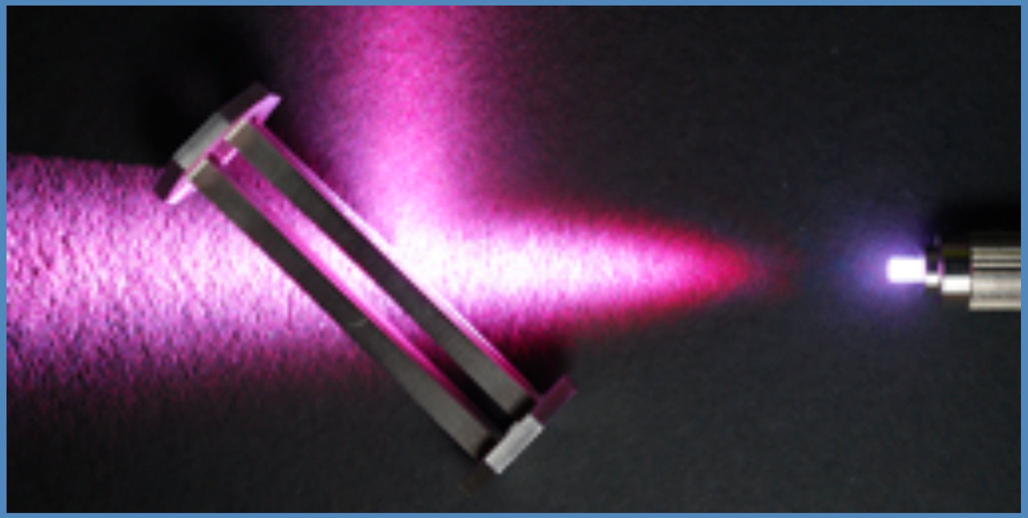
Nuclear Clock

ISM 'Simulator'



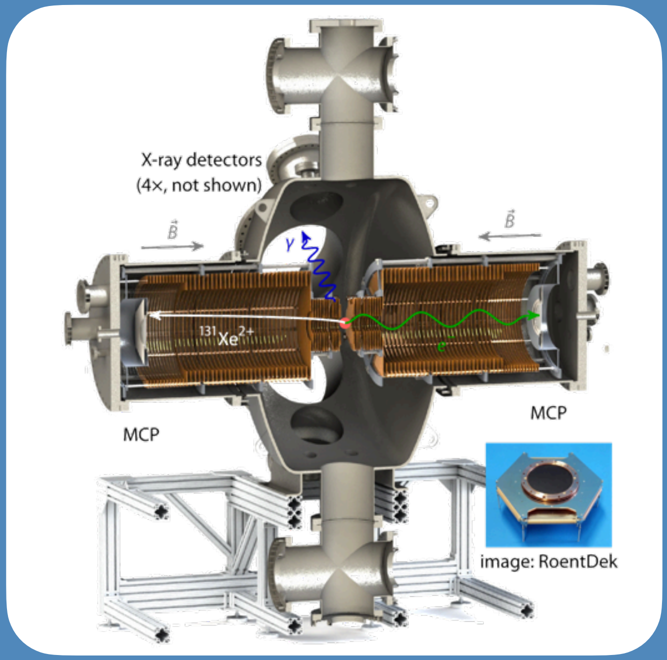
w/ Wes Campbell

Radioactive Qubits
(Ba-133)



w/ Wes Campbell

Sterile Neutrino search



Hunter Collaboration

Paul Hamilton & Christian Schneider @ UCLA

The heroes of our story

Dr. Christian Schneider

Dr. Justin Jeet

Richard Elwell

NIF

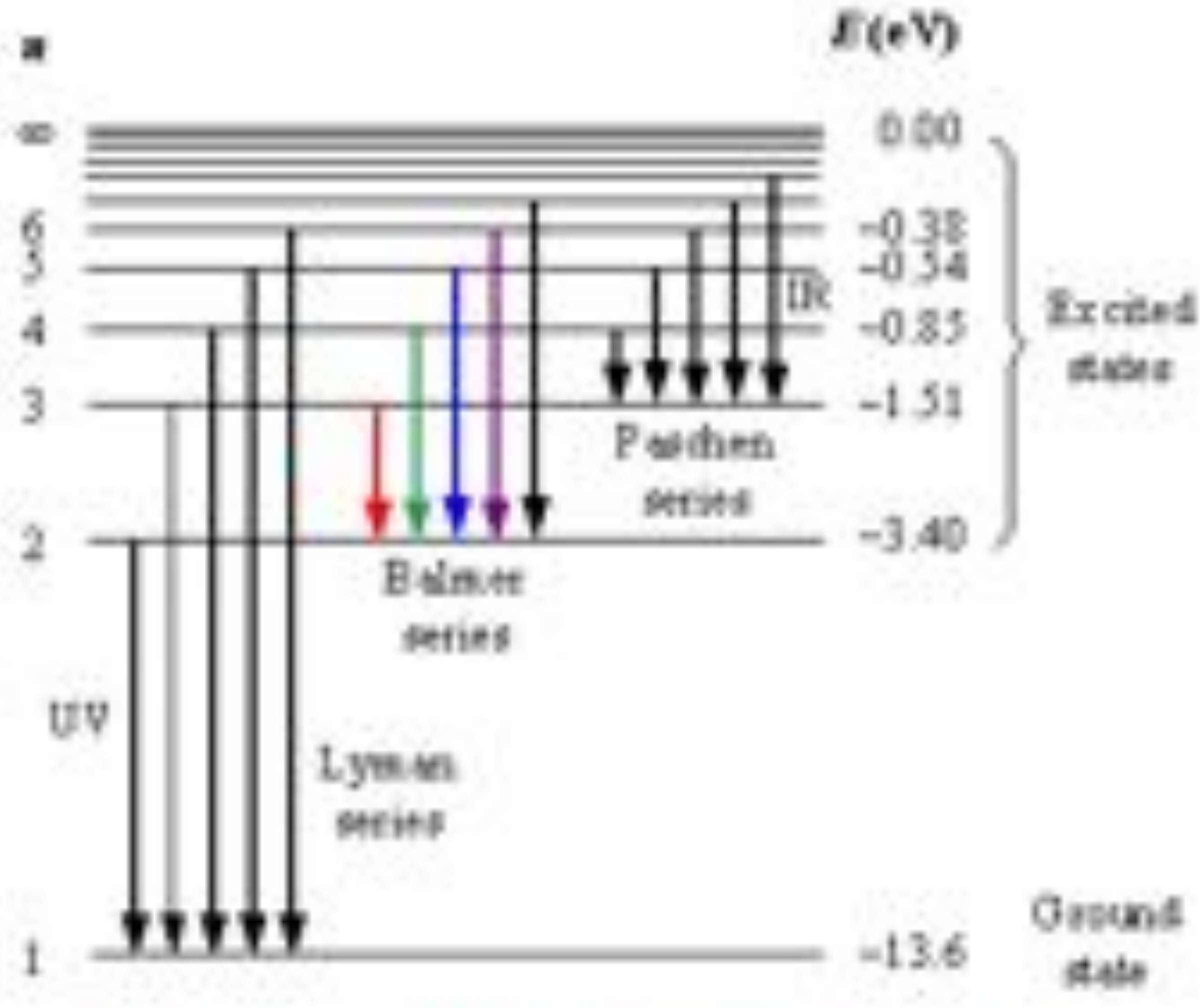
NUCLEAR STRUCTURE

H atom:

$E = -13.6/n^2$ [eV]

Nuclei:

$E = E_o(N,n_z) + C\Lambda\Sigma + D\Lambda^2$



Energy levels of the hydrogen atom with some of the transitions between them that give rise to the spectral lines indicated.

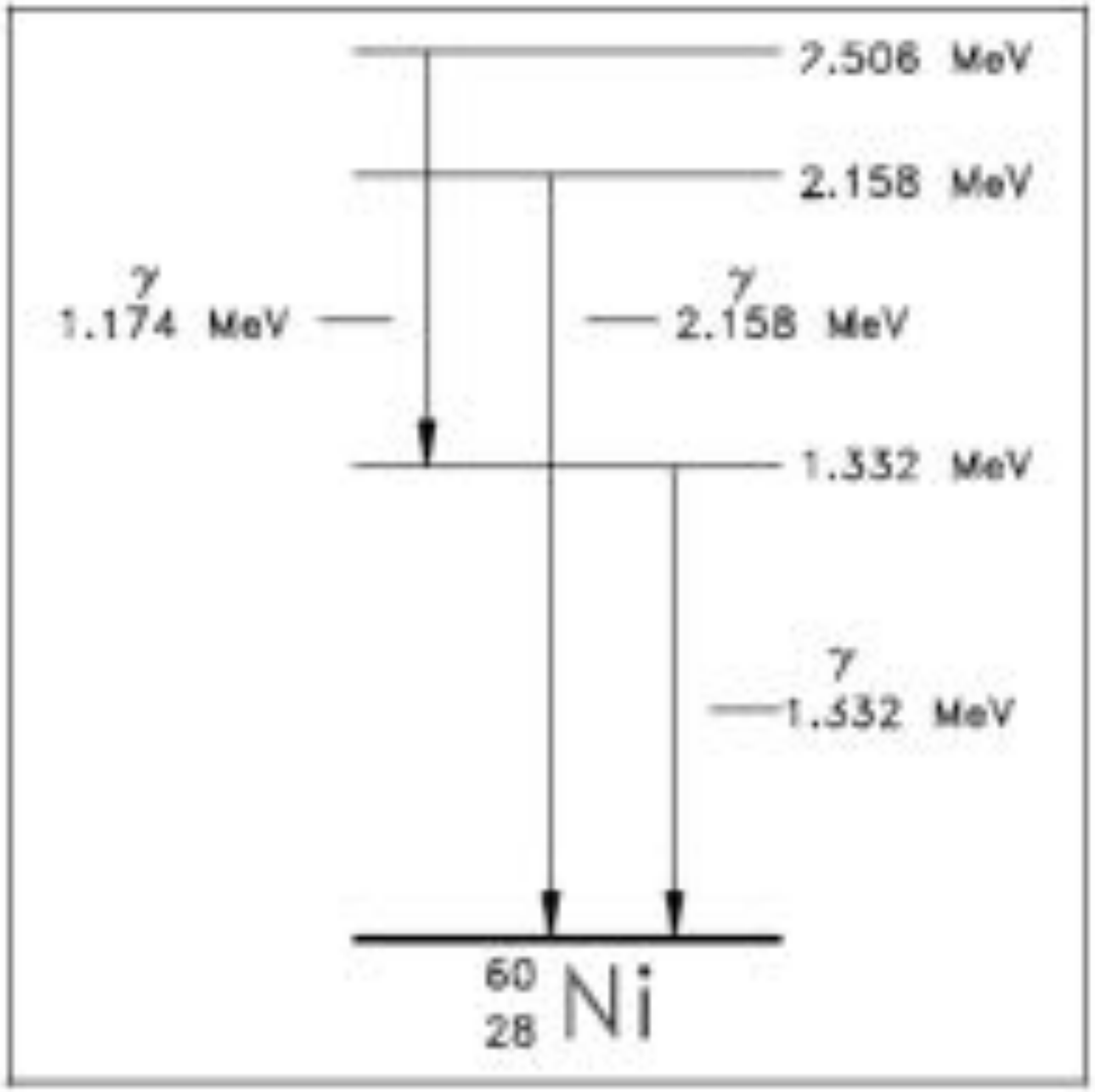


Figure 7 Energy Level Diagram - Nickel-60

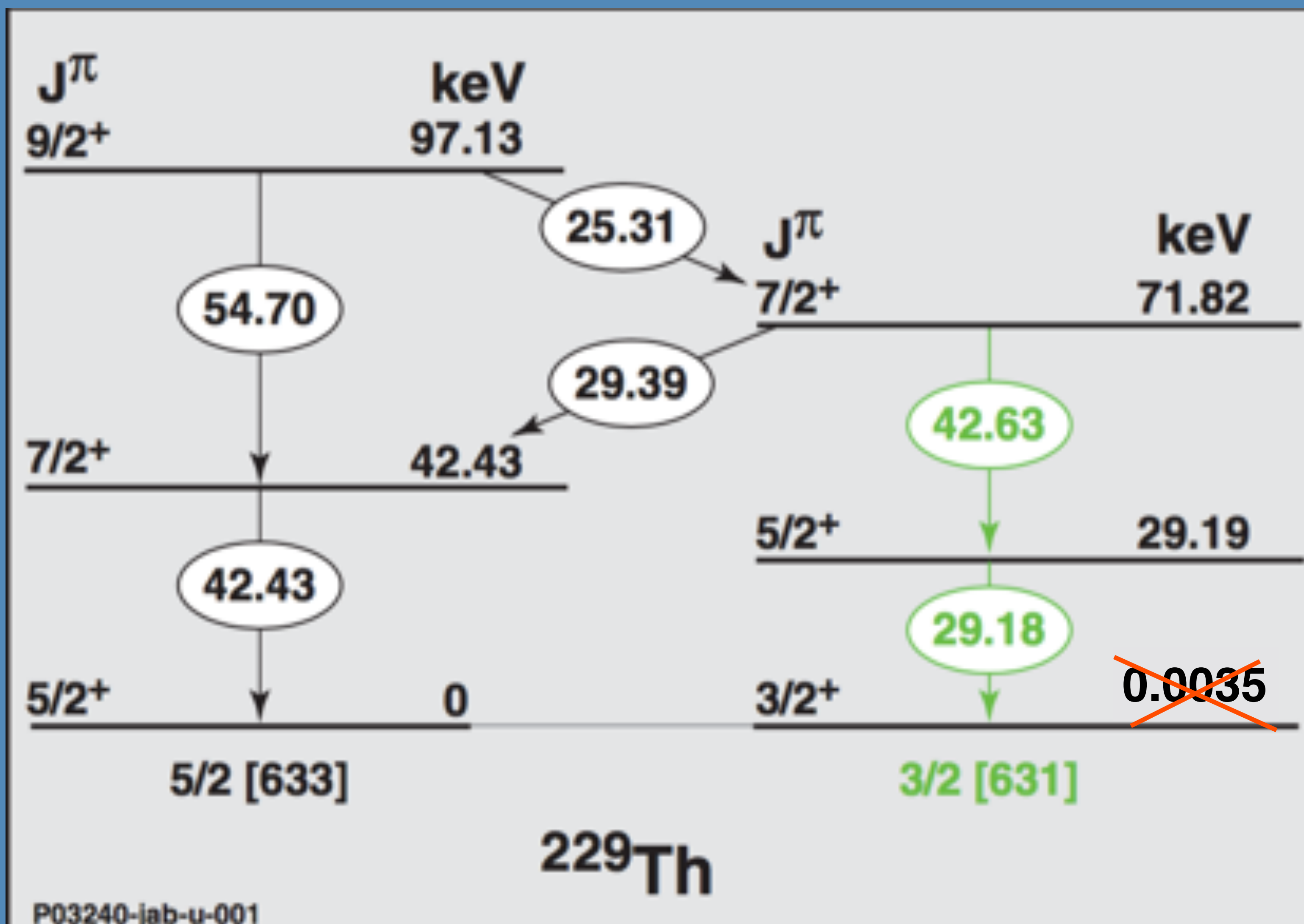
Alpha Decay of a Uranium-233 nucleus

Parent nucleus

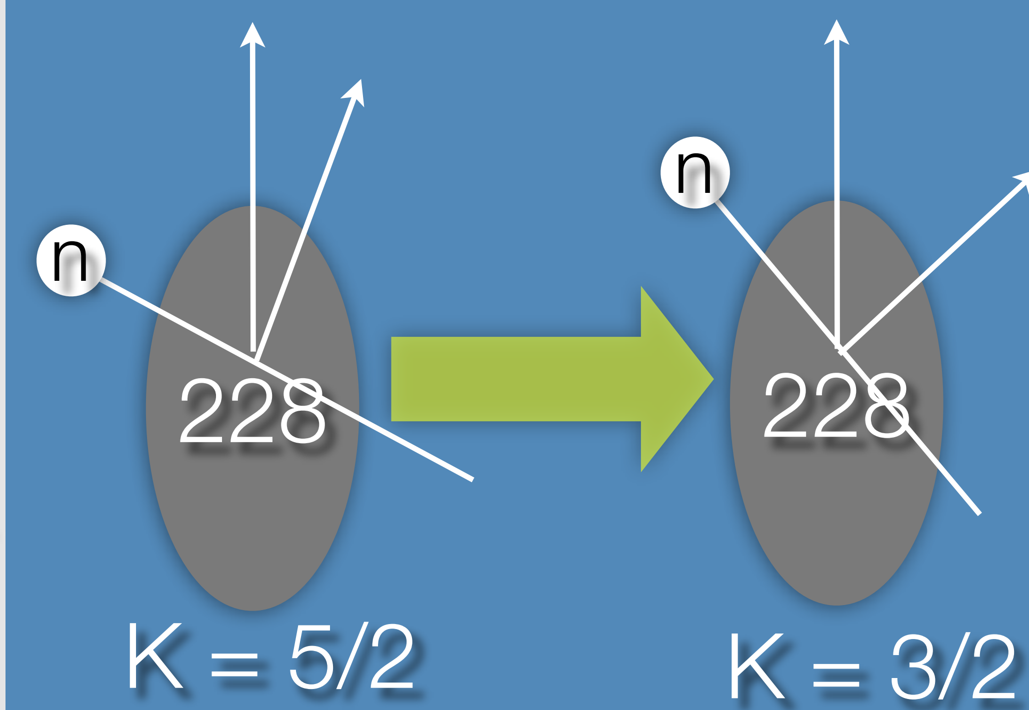
$^{233}_{92}U$

• The ^{229}Th nuclear isomeric transition

First on the scene: L. A. Kroger and C. W. Reich, Nucl. Phys. A 259, 29 (1976).



$$^{229}\mathrm{Th} = {}^{228}\mathrm{Th} + n$$



Spin-orbit and orbit-orbit interactions nearly cancel

$$\lambda = \frac{7.8(5)\ \mathrm{eV}}{160(10)\mathrm{nm}} \qquad \Gamma = 100\ \mu\mathrm{Hz}$$

B.R. Beck et al., PRL 98, 142501 (2007); ibid., LLNL-PROC-415170 (2009).

The nuclear clock

$\lambda = $ 7.8(5) eV / 160(10)nm Γ = 100 μHz → $Q \sim 10^{19}$

PRL **104**, 200802 (2010)   PHYSICAL REVIEW LETTERS   week ending 21 MAY 2010

Constraining the Evolution of the Fundamental Constants with a Solid-State Optical Frequency Reference Based on the ^{229}Th Nucleus

Wade G. Rellergert,[1] D. DeMille,[2] R. R. Greco,[3] M. P. Hehlen,[3] J. R. Torgerson,[3] and Eric R. Hudson[1]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
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(Received 4 June 2009; published 20 May 2010)

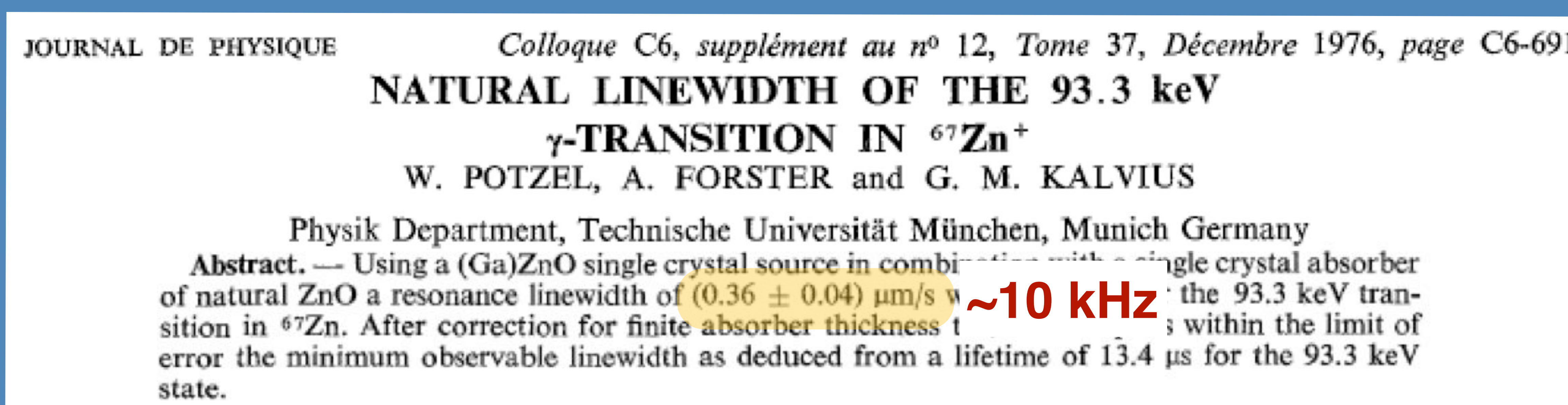
A NUCLEAR CLOCK AT THESE LEVELS WOULD LOSE
<40 MS OVER THE AGE OF THE UNIVERSE

THE SOLID-STATE VERSION WOULD LOSE
<3NS/YEAR AND BE HIGHLY PORTABLE

Nuclear clock @ UCLA

NIST F-1 Clock

Nuclear clock based on rare thorium-229 isotope



JOURNAL DE PHYSIQUE *Colloque C6, supplément au n° 12, Tome 37, Décembre* 1976, *page* C6-691

NATURAL LINEWIDTH OF THE 93.3 keV γ-TRANSITION IN $^{67}Zn^{+}$

W. POTZEL, A. FORSTER and G. M. KALVIUS

Physik Department, Technische Universität München, Munich Germany

Abstract. — Using a (Ga)ZnO single crystal source in combi… …ingle crystal absorber of natural ZnO a resonance linewidth of (0.36 ± 0.04) µm/s w… the 93.3 keV transition in ^{67}Zn. After correction for finite absorber thickness t… …s within the limit of error the minimum observable linewidth as deduced from a lifetime of 13.4 µs for the 93.3 keV state.

~10 kHz

Finding the isomeric transition

The challenge (~40 yrs):

The needle:
γ~ 10 μHz – 100 μHz

The haystack:
140 nm < λ < 180 nm

Finding the isomeric transition

The challenge (~40 yrs):

The needle:

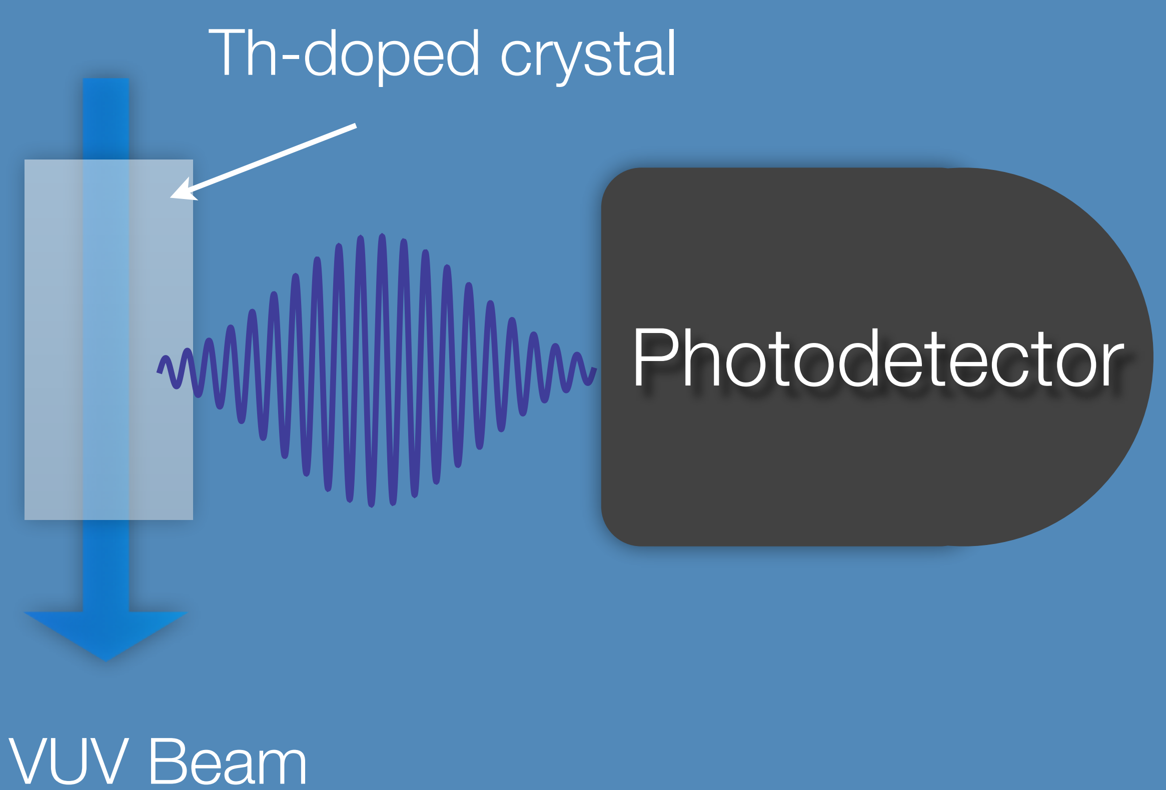
γ~ 10 μHz – 100 μHz

The haystack:

150 nm< λ < 170 nm

Only possible because of the high Th-229 density in a solid

$$N_e \approx \frac{2}{3}\left(\frac{\lambda^2}{2\pi}\right)\frac{\Gamma_n}{\Gamma+\Delta}\frac{1}{1+4\left(\frac{\omega_o-\omega_L}{\Gamma+\Delta}\right)^2}\Phi_\gamma N_g \Delta t$$



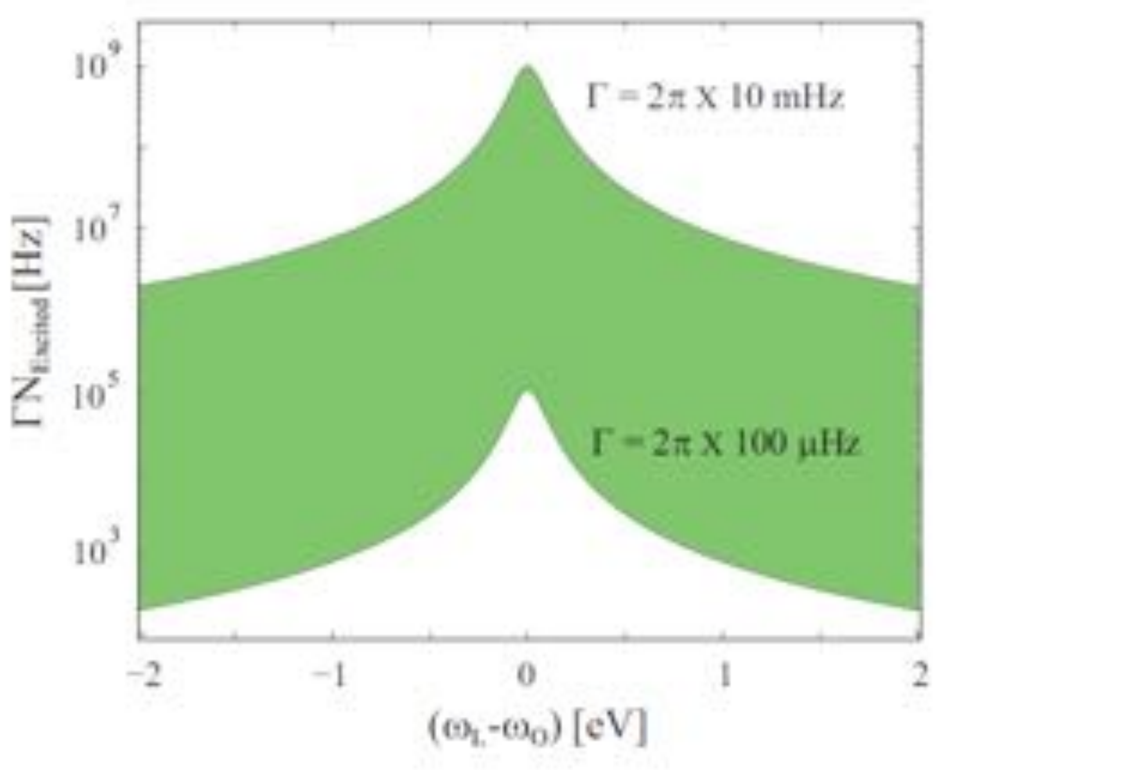


FIG. 1: (color online). Total fluorescence rate after sample illumination for 1000 s with the ALS is indicated by the shaded region. This region is bounded by the upper and lower limit expected for the excited state decay rate, Γ.

Just need a magic crystal!

Requirements:

1. Accepts Th as dopant
2. VUV transmissive
3. Low phosphorescence background
4. Radiation resistant

Procuring Th-229:

TPPA16502	Th-229 Standardized Solution Activity 150 μCi (5.55 MBq) Calibrated, NIST Traceable 5 mL Th-229 Nitrate in 0.5M HNO3 in 10 mL Flame Sealed Ampoule	1	7,200.00 per μCi	1,080,000.00

3 mg = 6 Million Dollars

Thank you for your continued business.

This quotation is good for 60 days.

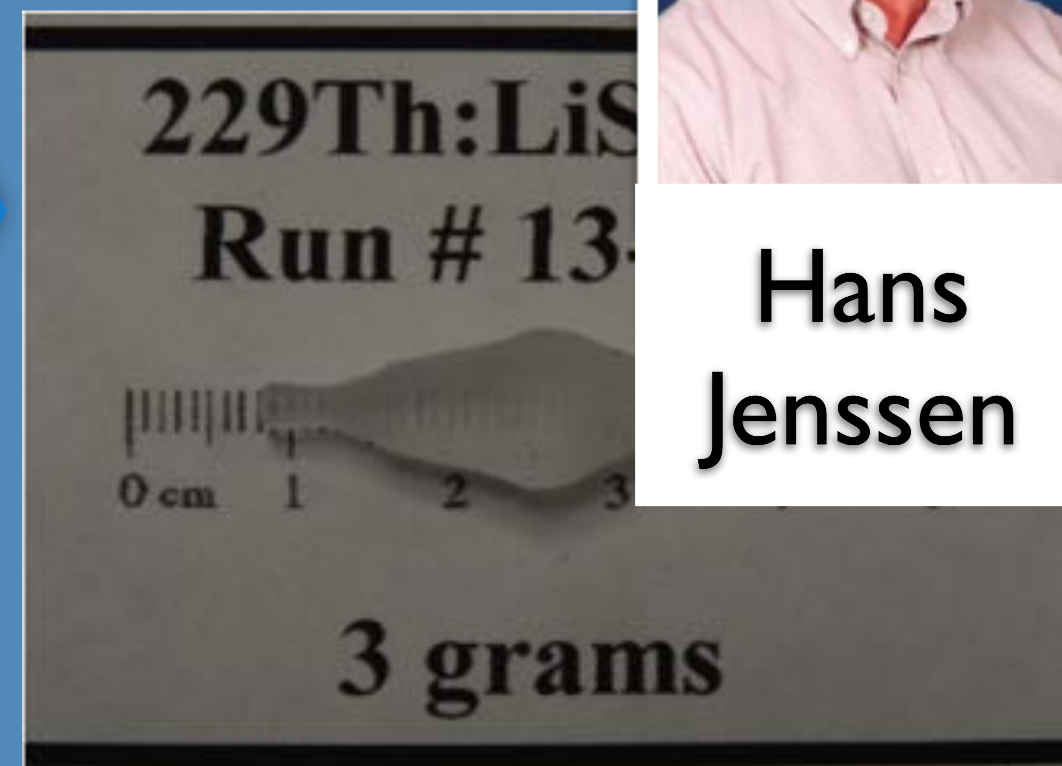
Fabrication of first ^{229}Th:$LiSrAlF_6$ crystal

Saed Mirzadeh

Th nitrate from ORNL converted to ThF_4

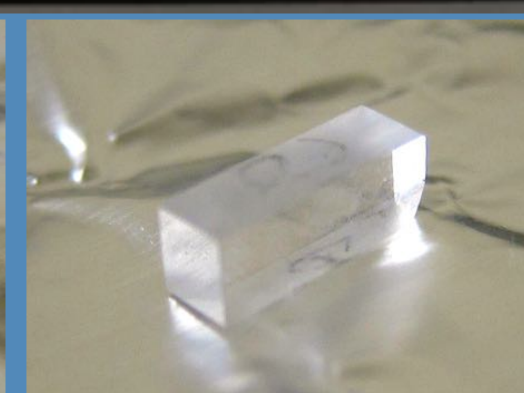
^{232}Th work

Second batch



Hans Jenssen

3×10^{16}/cc



1×10^{17}/cc

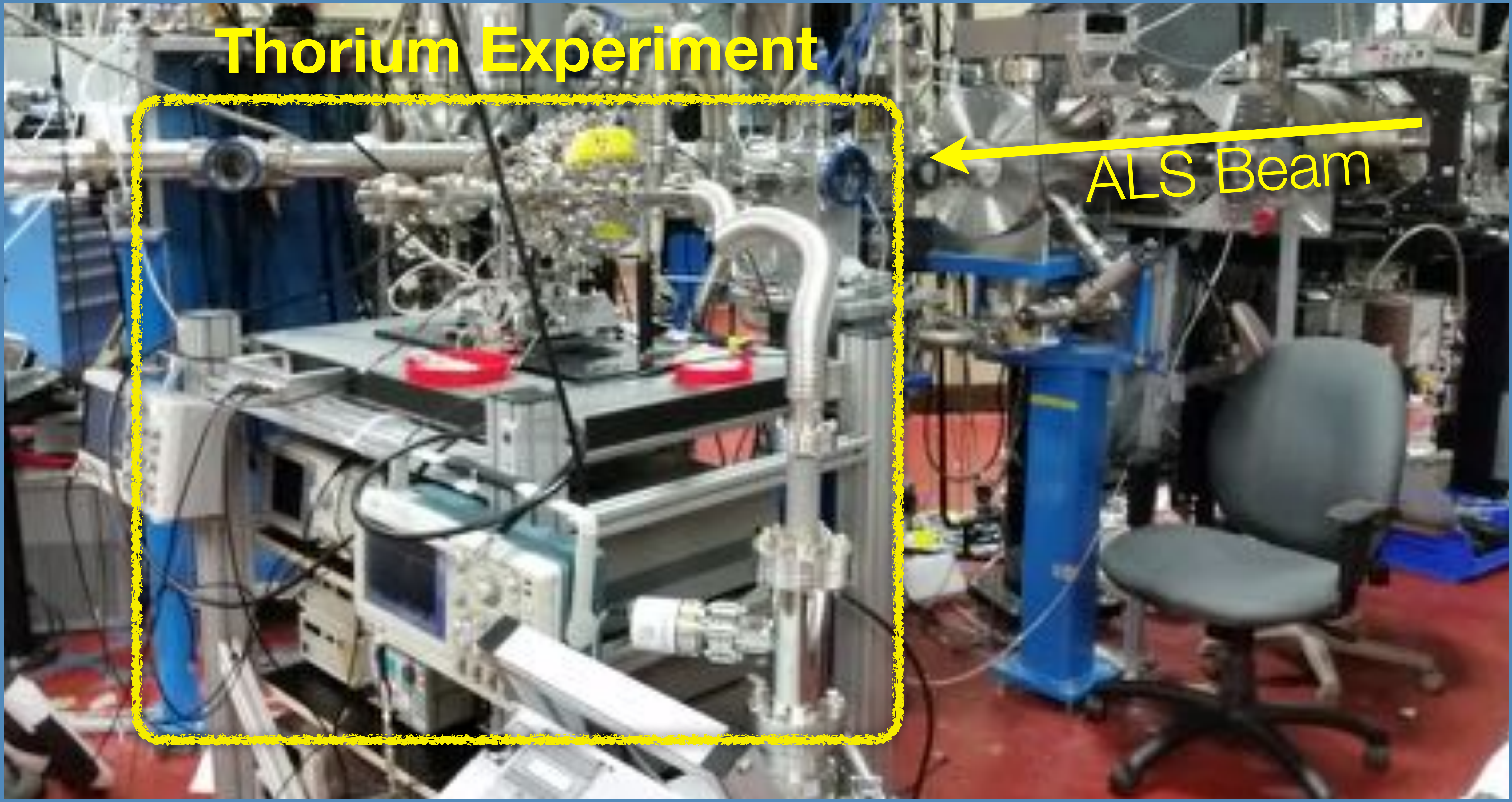
5 years of work, culminated in:

- Ability to grow **small** crystals
- Three 3 mm X 3 mm X 10 mm xtals
- Stable and contains thorium-229.

Advance Light Source

96 hours of beam

August 20th - September 5th 2014:



PRL 114, 253001 (2015) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2015

Results of a Direct Search Using Synchrotron Radiation for the Low-Energy ^{229}Th Nuclear Isomeric Transition

Justin Jeet,[1] Christian Schneider,[1] Scott T. Sullivan,[1,*] Wade G. Rellergert,[1,†] Saed Mirzadeh,[2] A. Cassanho,[3] H. P. Jenssen,[3] Eugene V. Tkalya,[4,5] and Eric R. Hudson[1]
[1]*Department of Physics and Astronomy, University of California, Los Angeles, California 90095, USA*
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[3]*AC Materials, Inc., 756 Anclote Road, Tarpon Springs, Florida 34689, USA*
[4]*Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Leninskie gory, Moscow 119991, Russia*
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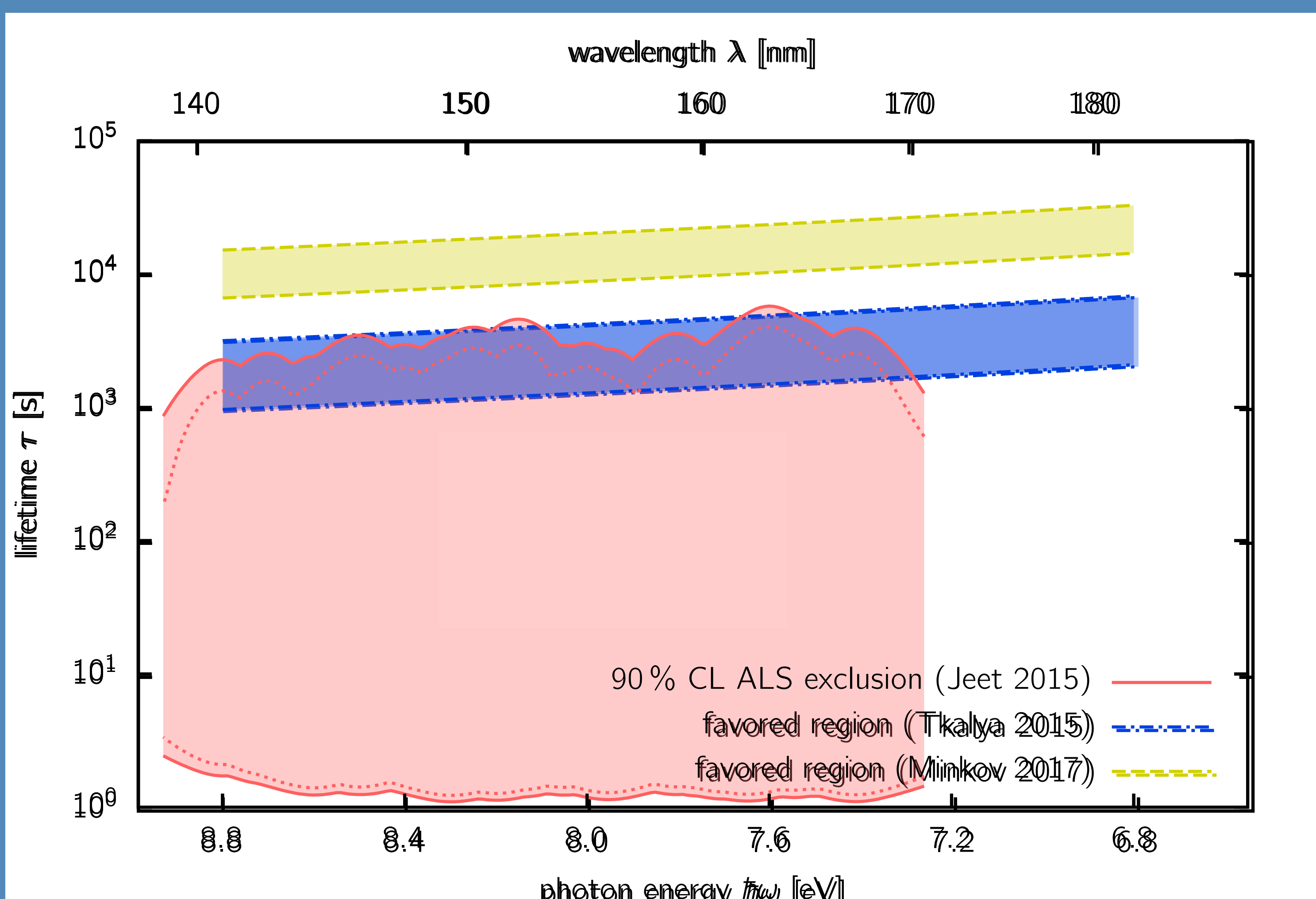
(Received 7 February 2015; revised manuscript received 2 April 2015; published 23 June 2015)



EXCLUSION LIMITED BY:

ALS TUNABILITY

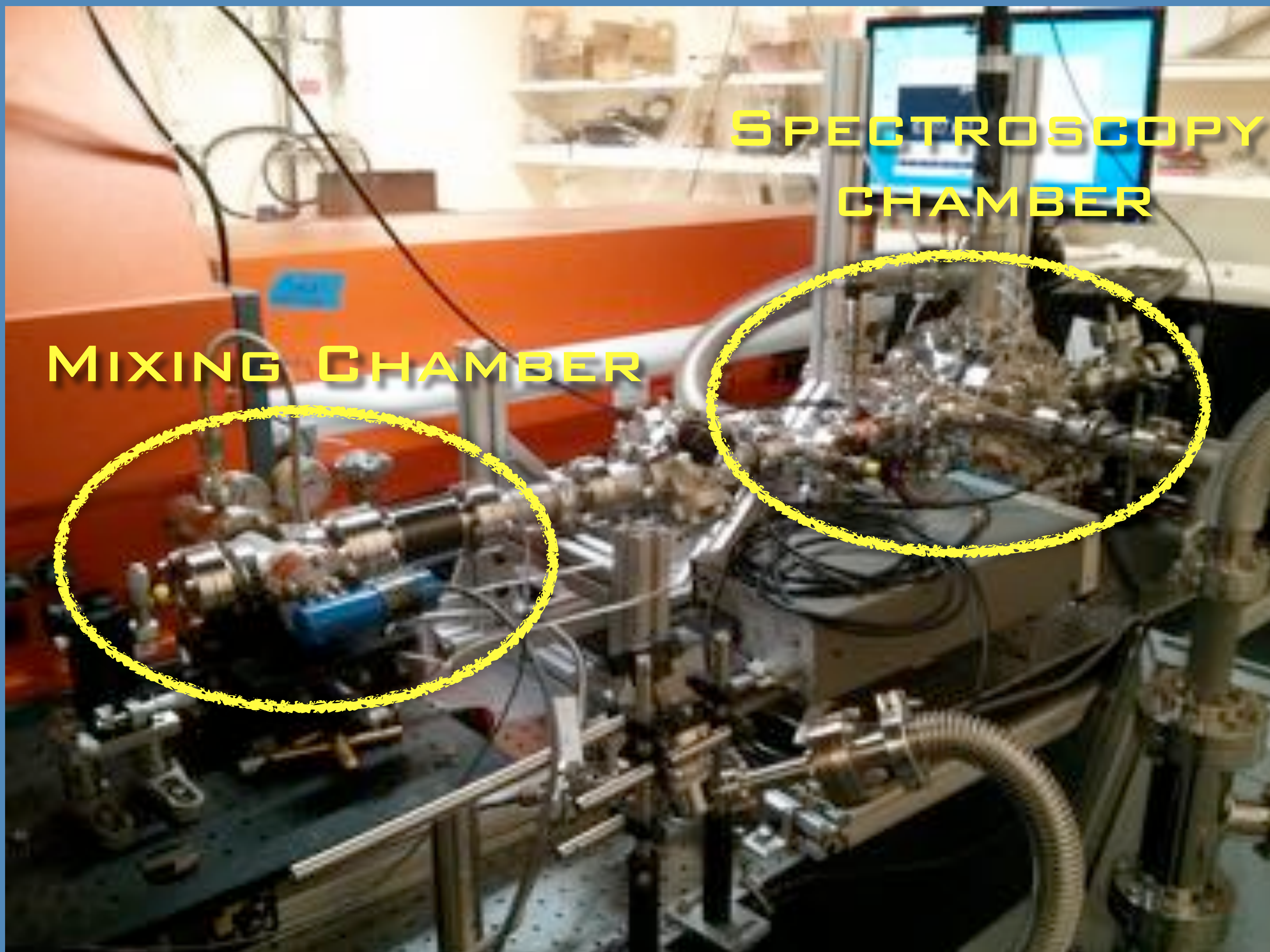
ALS FLUX

TKALYA ET AL., PRC 92 054324 (2015)

MINKOV & PALFFY PRL 118 212501 (2017)

UCLA VUV laser system

4-wave mixing VUV source: Pulsed dye laser + Xe cell



~20,000x brighter than ALS

'unlimited' beam time

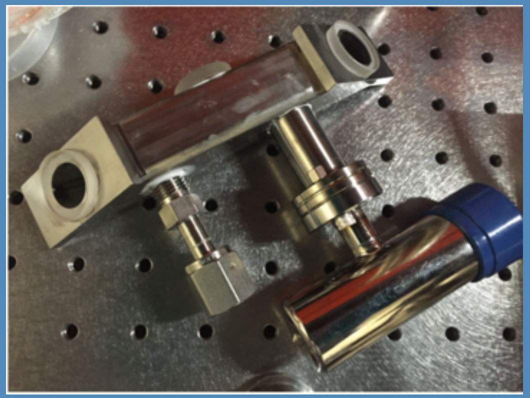
Realtime monitoring:

Spectrum
Wavelength
Energy

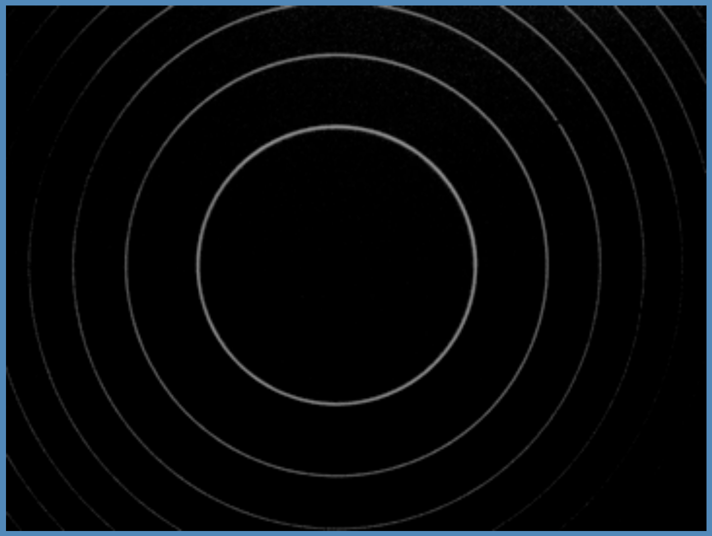
Nearly autonomous operation

VUV Power monitoring

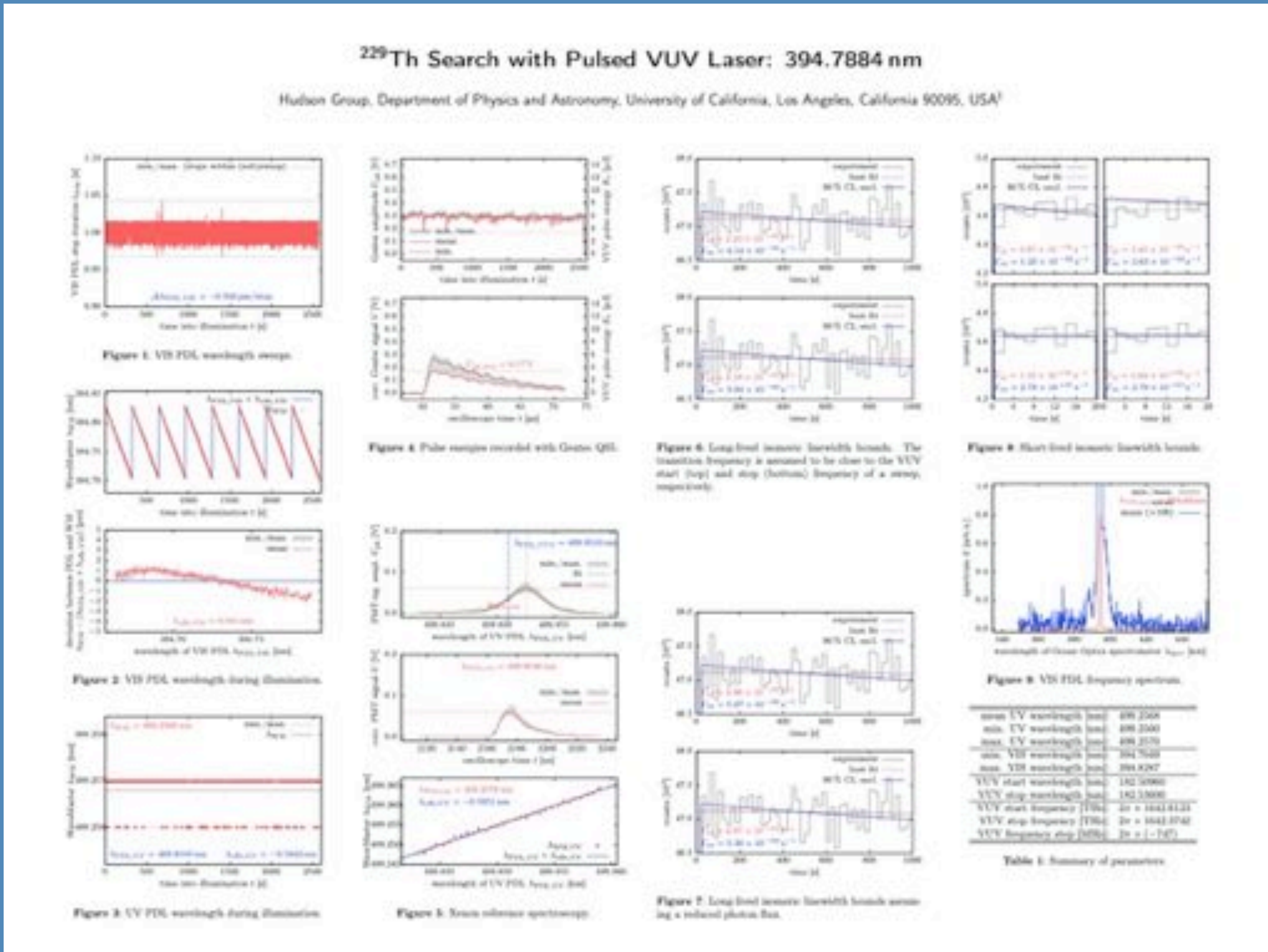
Frequency monitoring



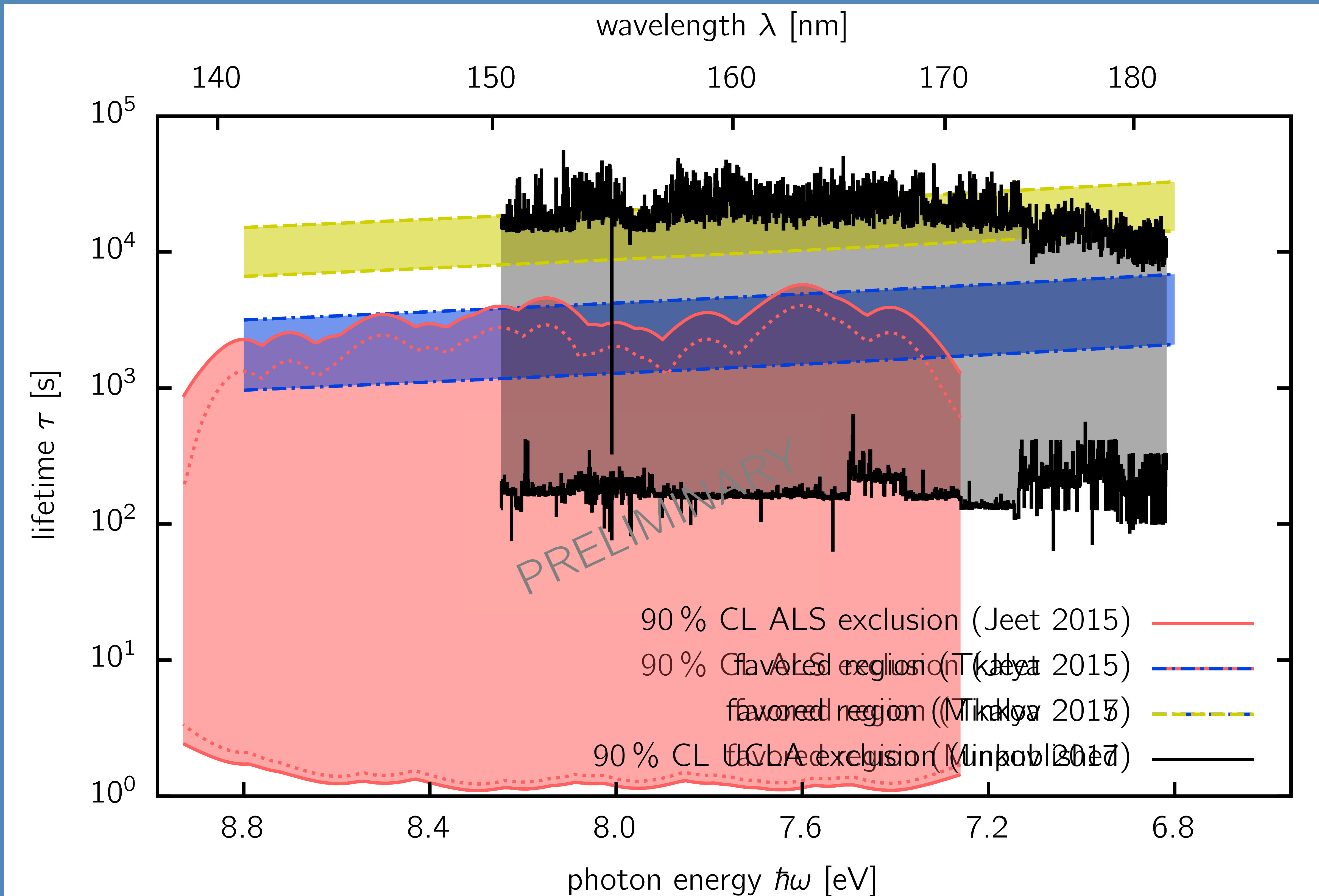
Laser spectrum monitoring



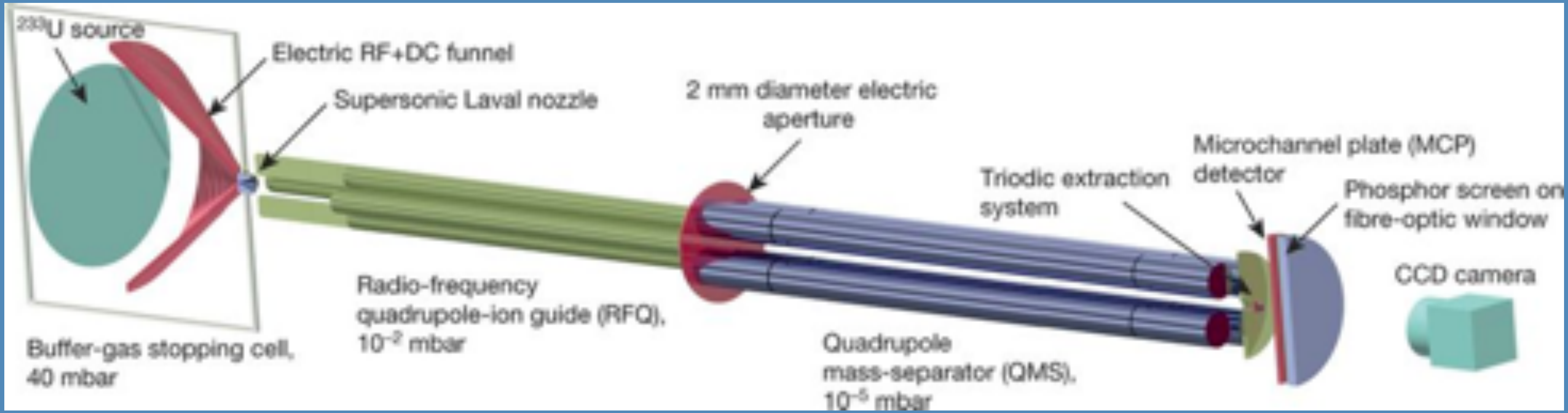
UCLA VUV laser system



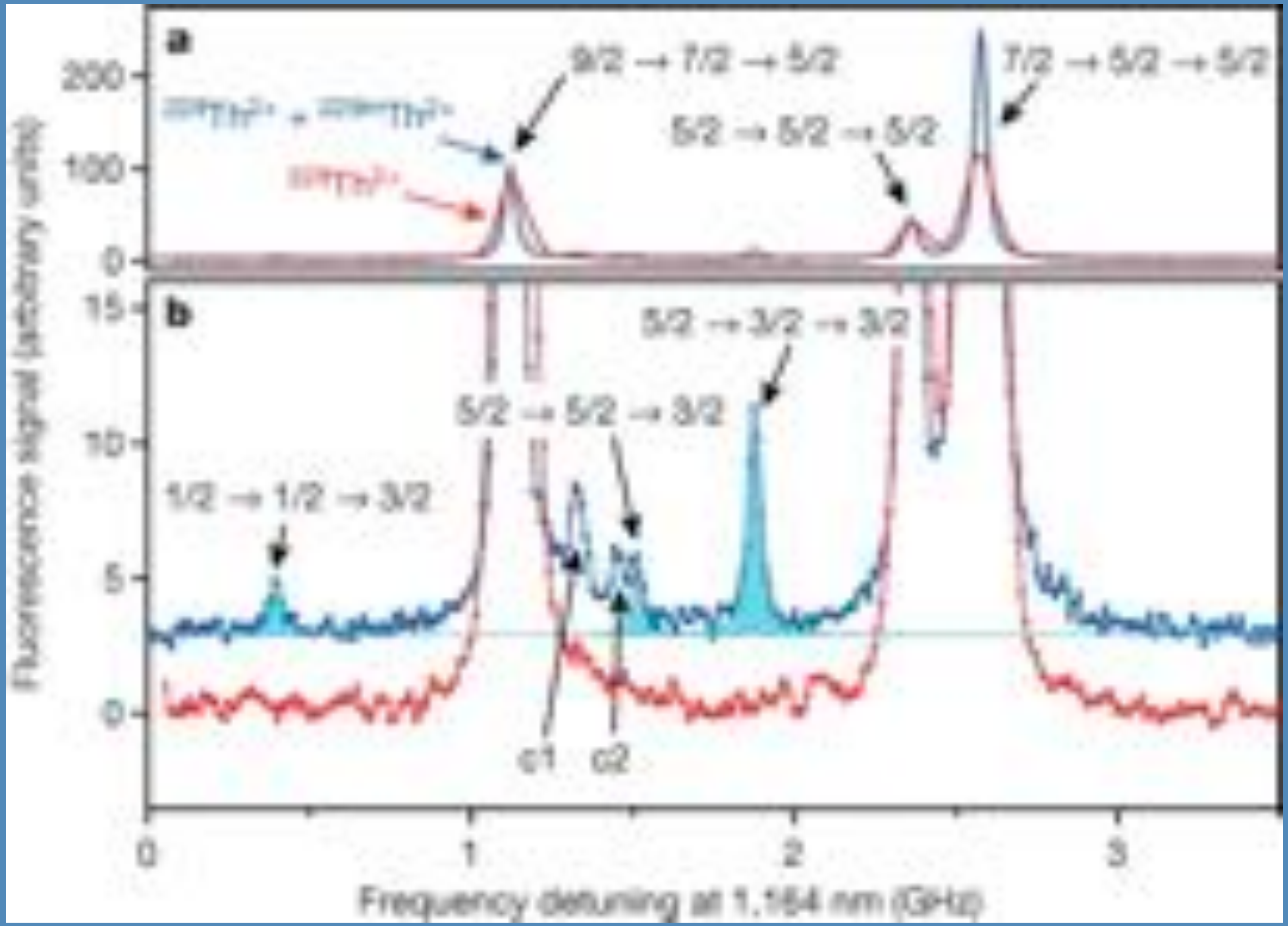
UCLA VUV laser search



Confirmation in Munich



L. Von der Wense et al., Nature 533, 47 (2016)
B. Seiferle et al., PRL 118, 042501 (2017)

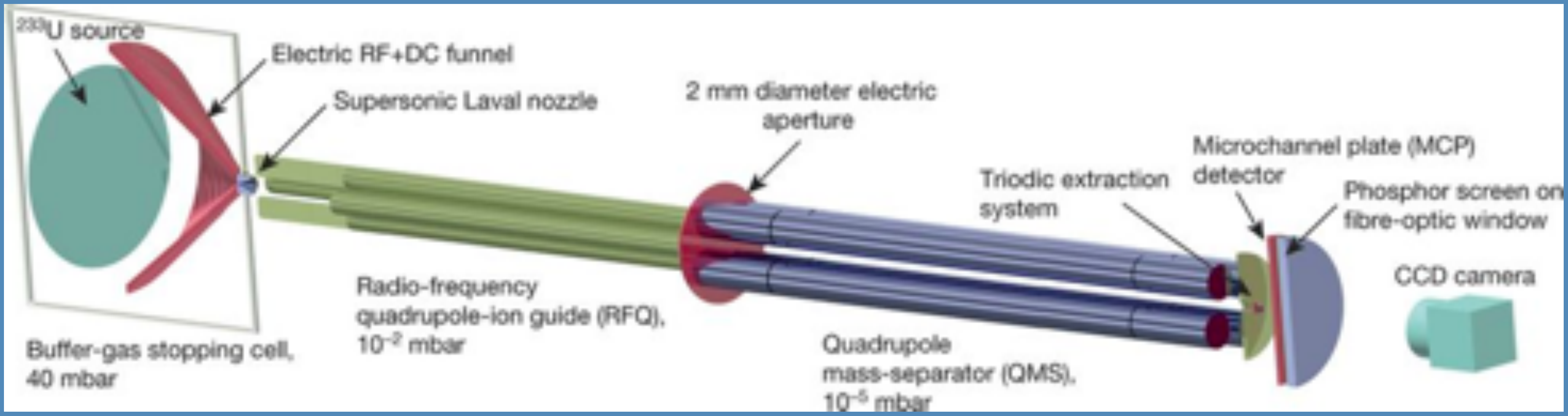


Energy consistent with Beck et al.

Confirmed existence, 2% isomeric produced in decay, and IC Decay channel

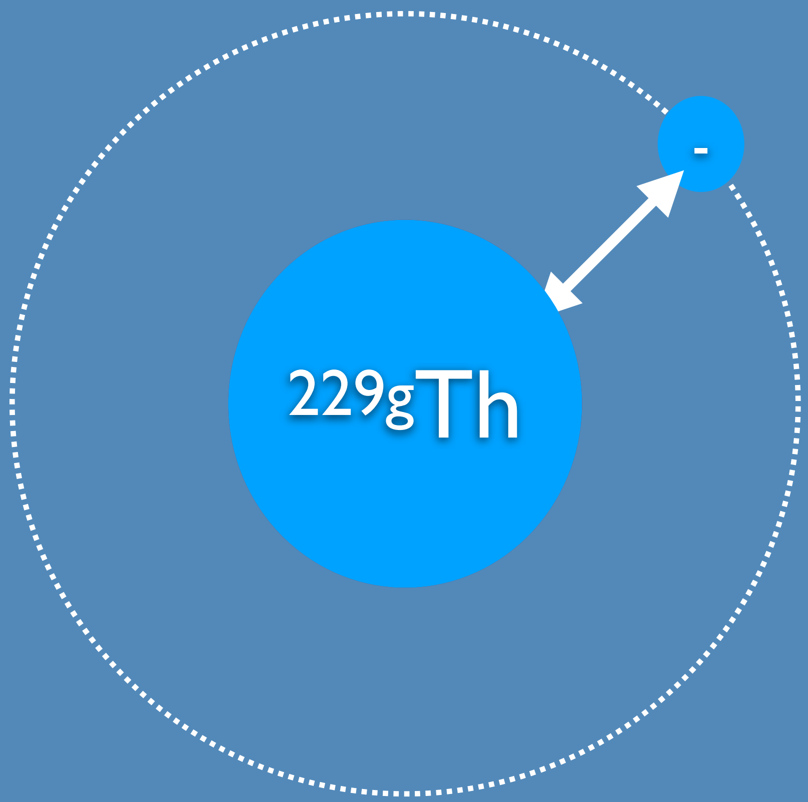
J. Thinking et al., Nature 556, 321 (2018)

Internal Conversion



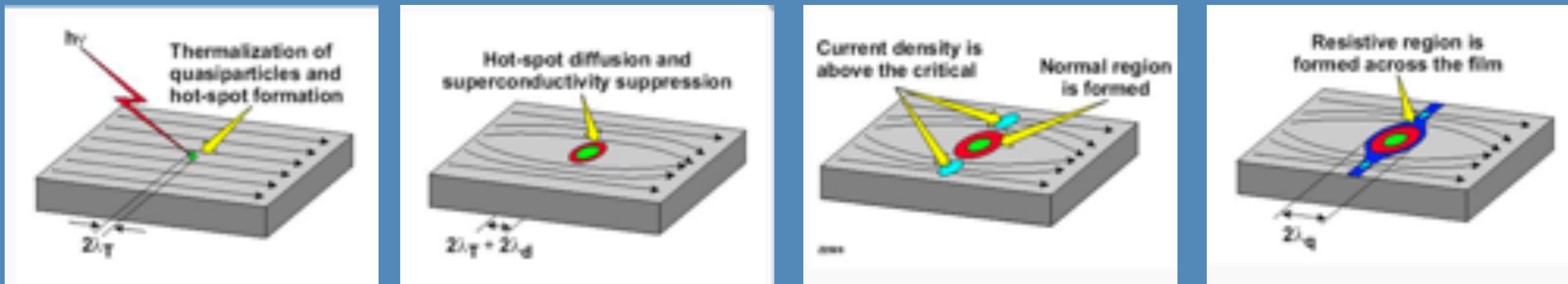
Confirmed existence, 2% isomeric produced in decay, and IC Decay channel

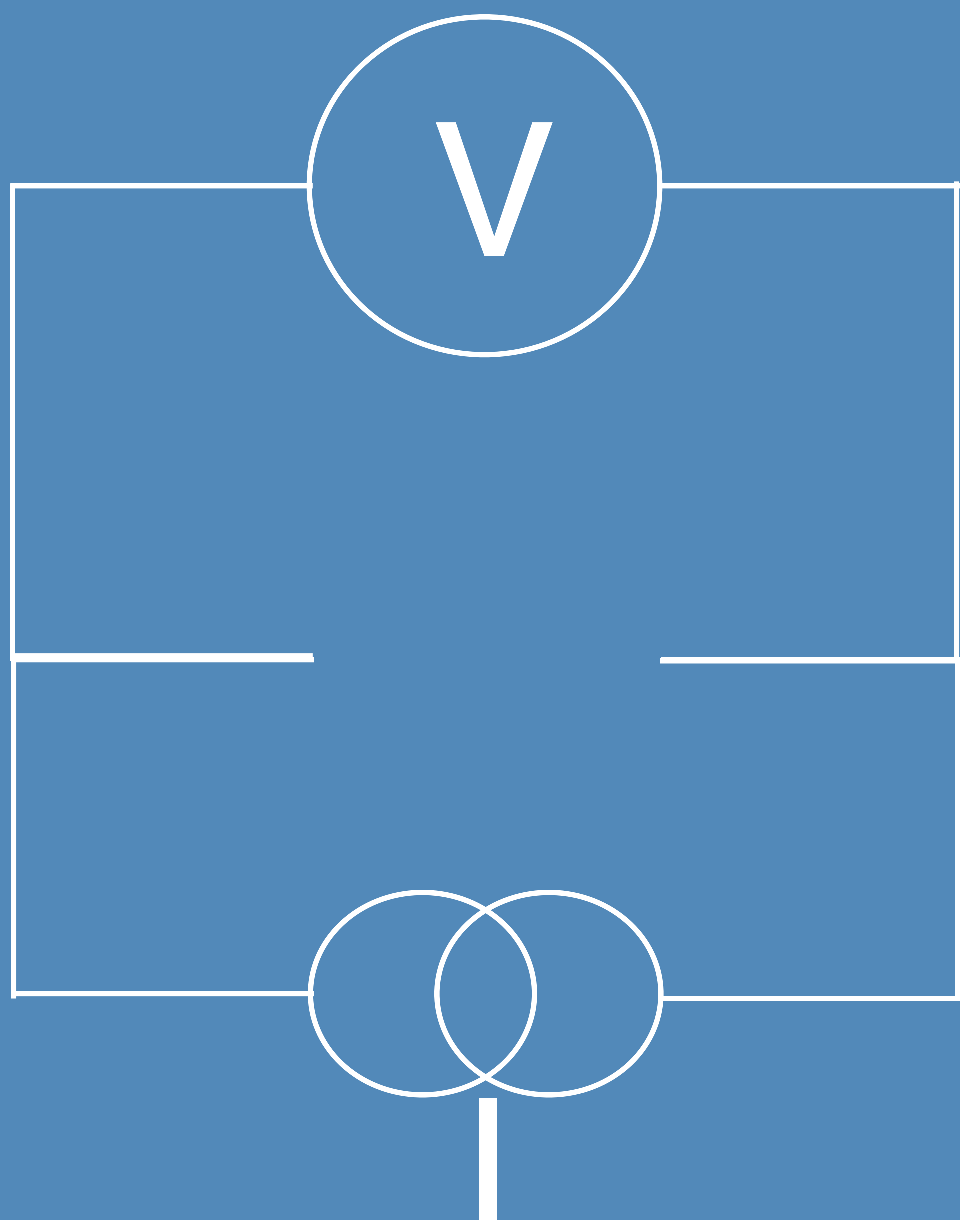
IC lifetime ~ 10 us




Lars
Peter
Benedict
Ekkehard
STAR WARS
A NEW HOPE
EPISODE IV

SNSPD operation Principle





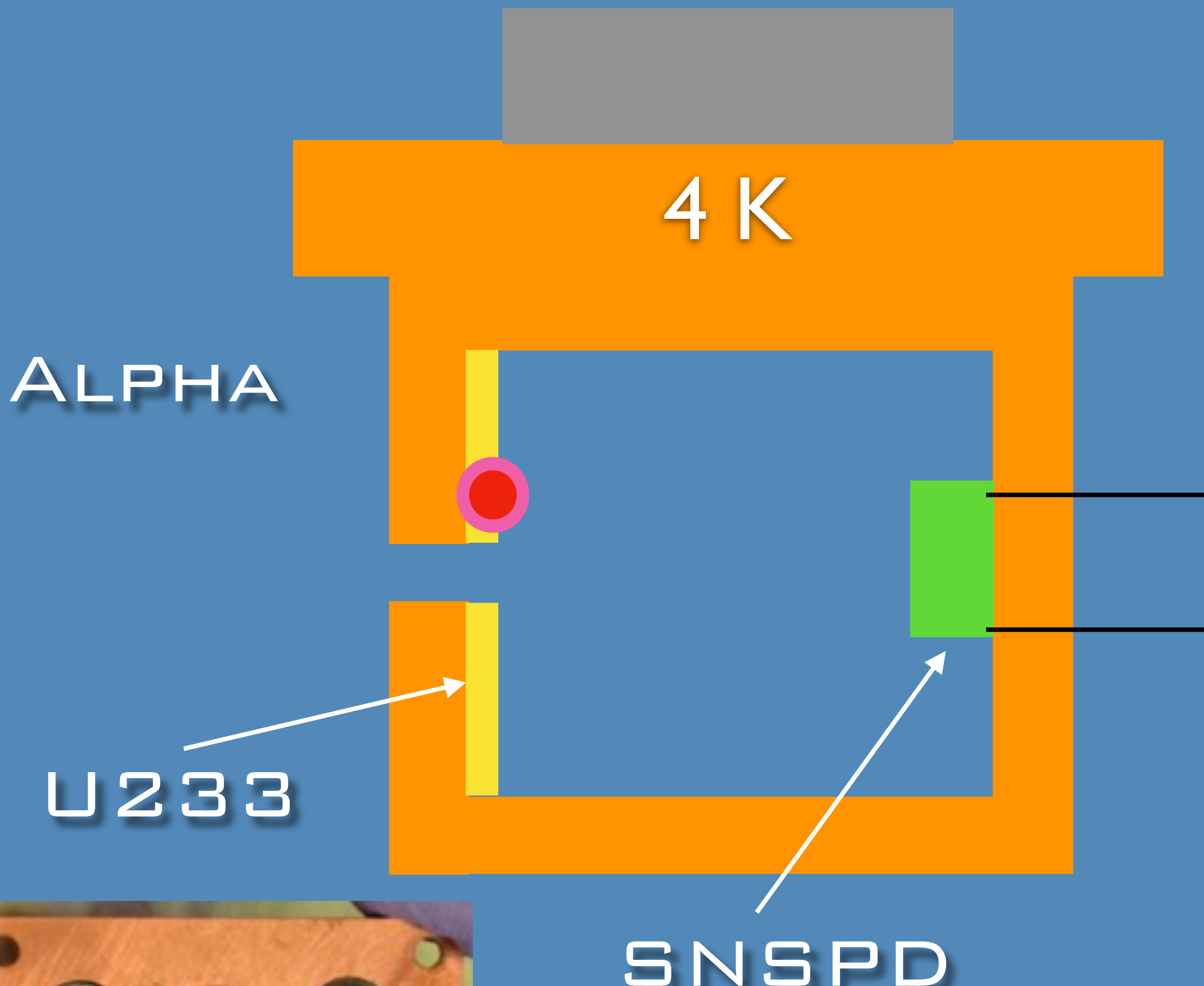
In collaboration with:

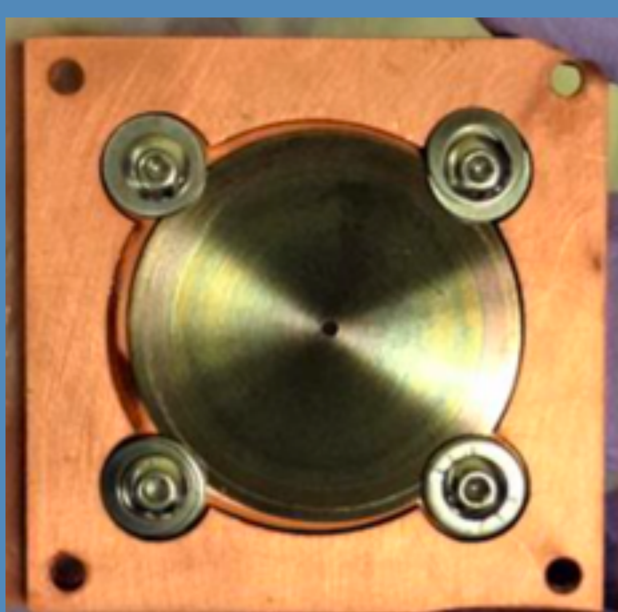
NIST

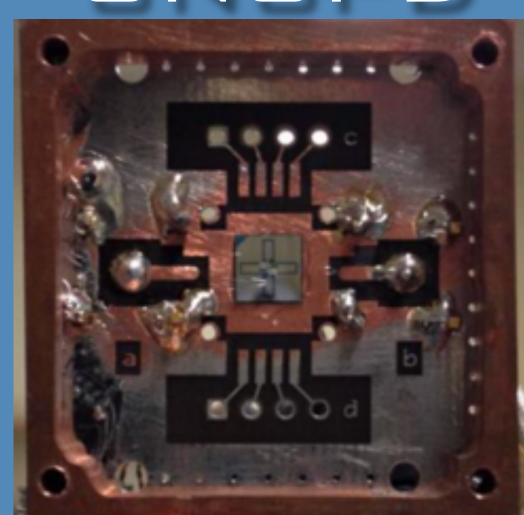
Sae Woo Nam Galen O'Neil

Varun Verma and Dileep Reddy

SNSPD IC Detection







In collaboration with:

Sae Woo Nam Galen O'Neil

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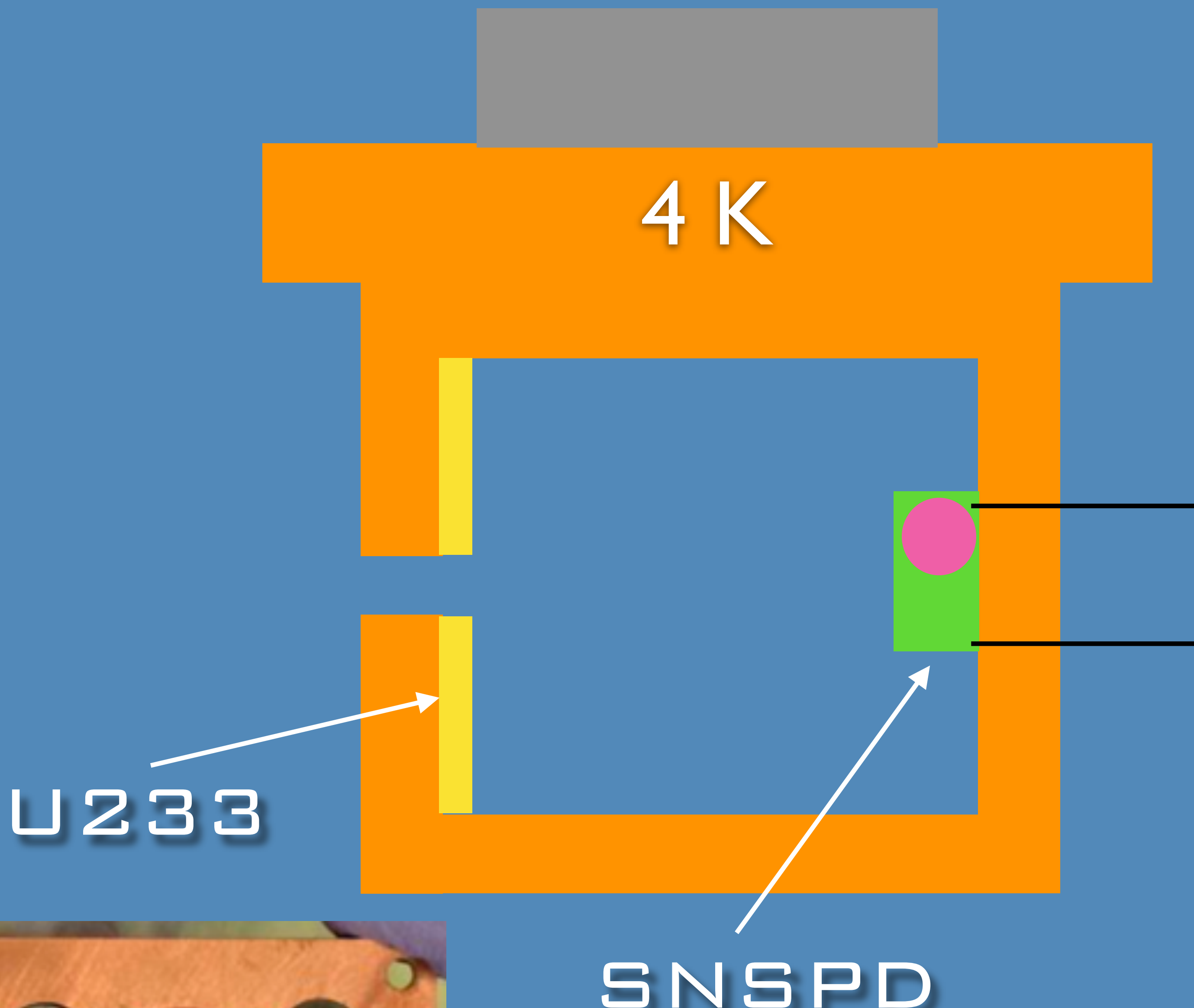
SNSPD IC Detection

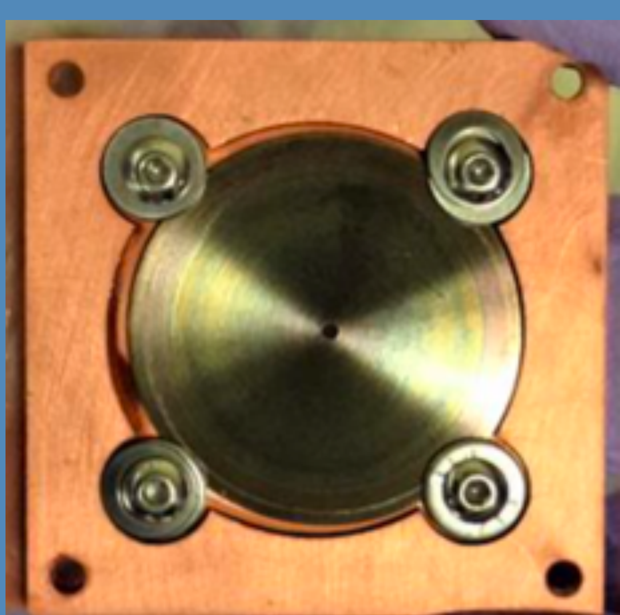


2% of the time:
Th-229m produced

Clicks again!

In collaboration with:

NIST

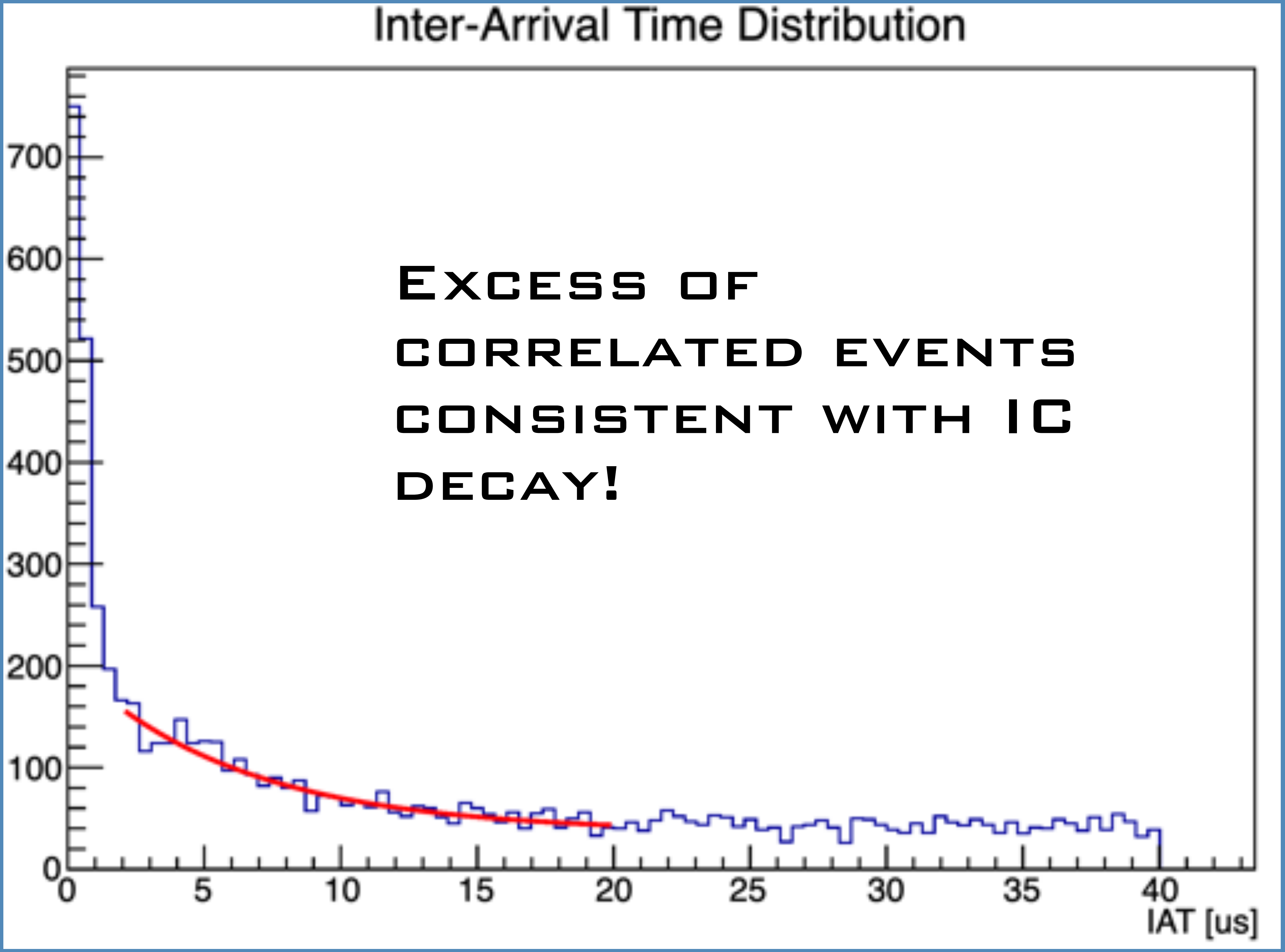


Sae Woo Nam

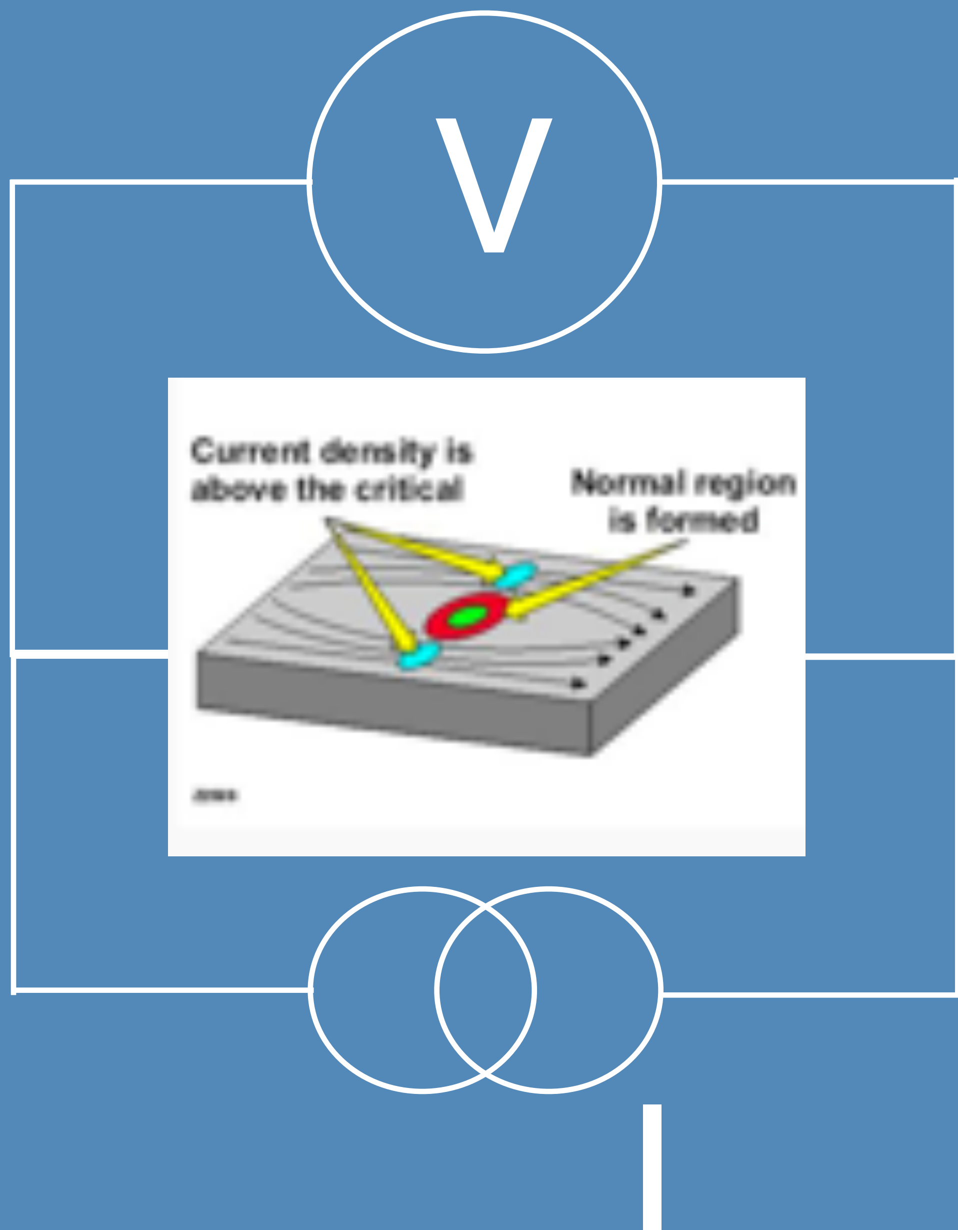
Galen O'Neil

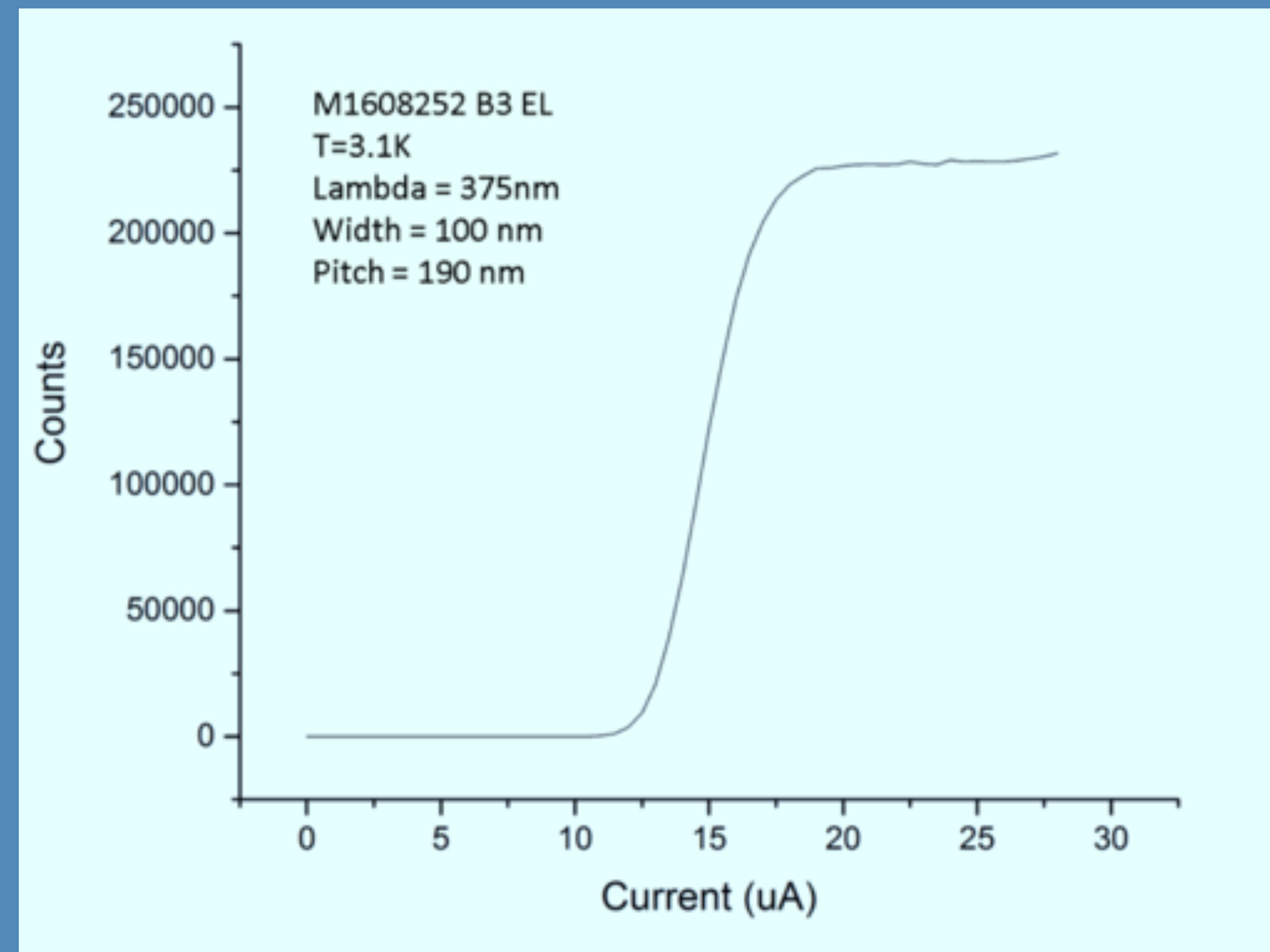
Varun Verma and Dileep Reddy

SNSPD Interarrival time histogram



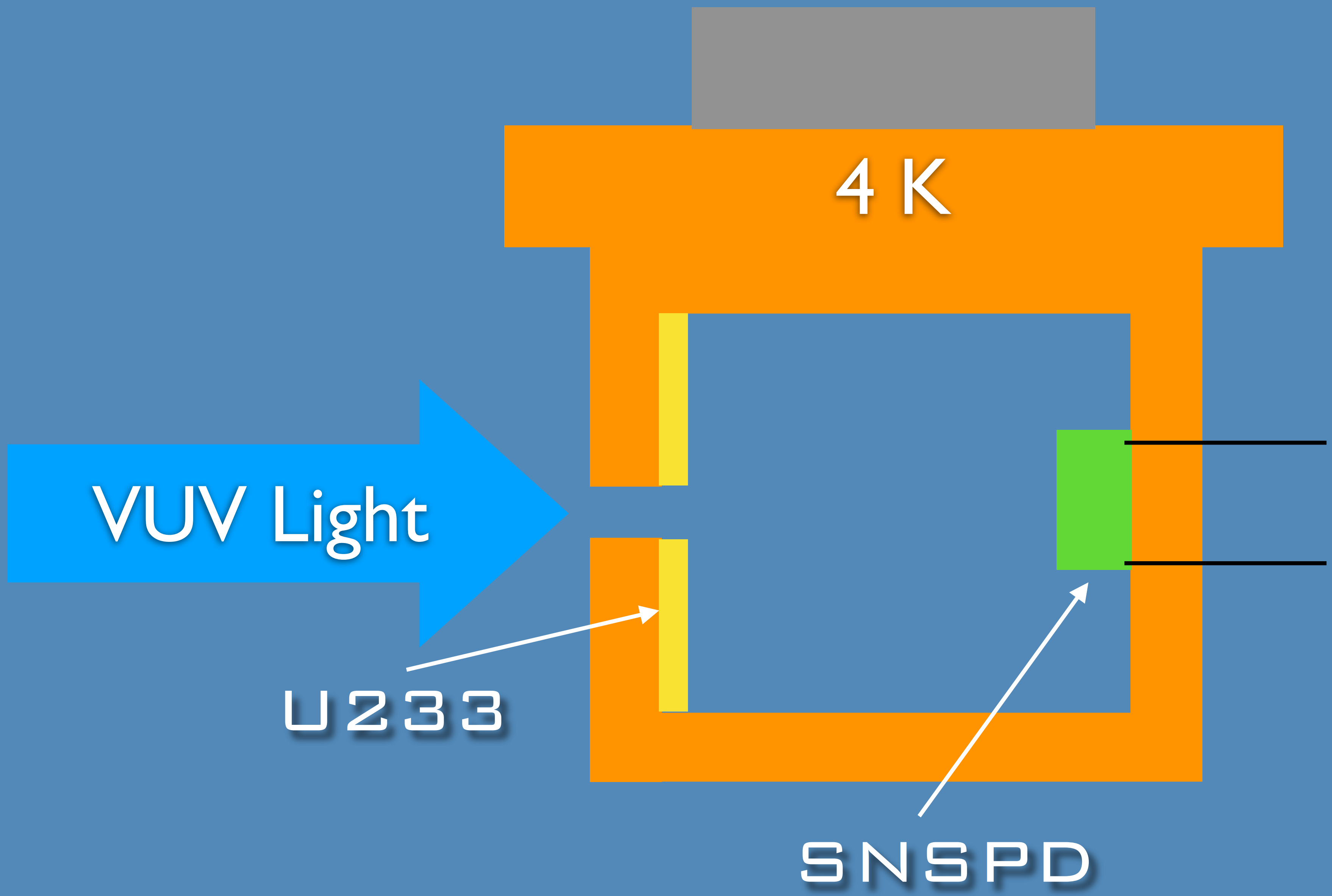
SNSPD IC Detection



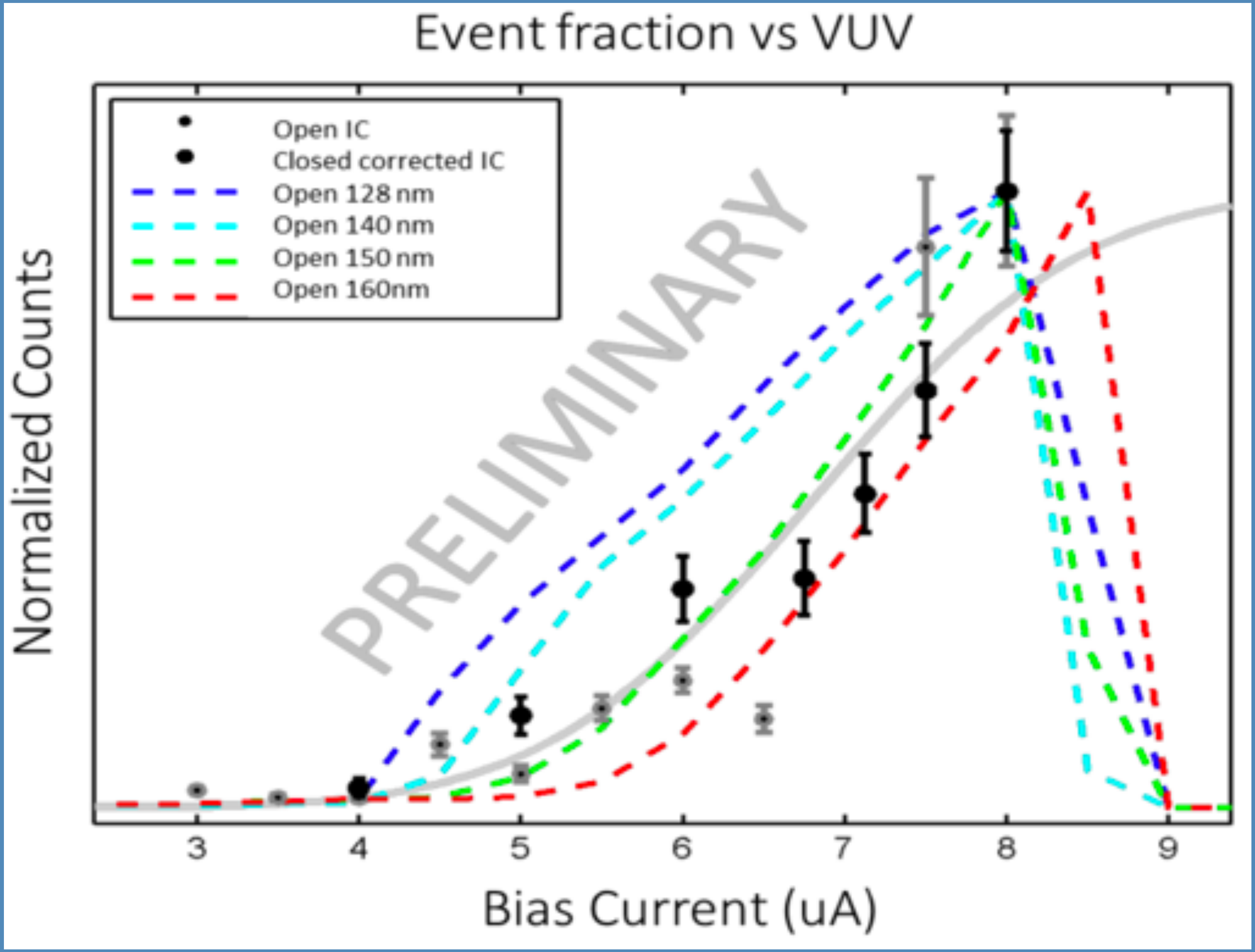


If Bias current is too low the SNSPD never goes 'normal'

SNSPD IC Detection



SNSPD IC Detection



Suggested possibility of measurement

SNSPD → SNSPI

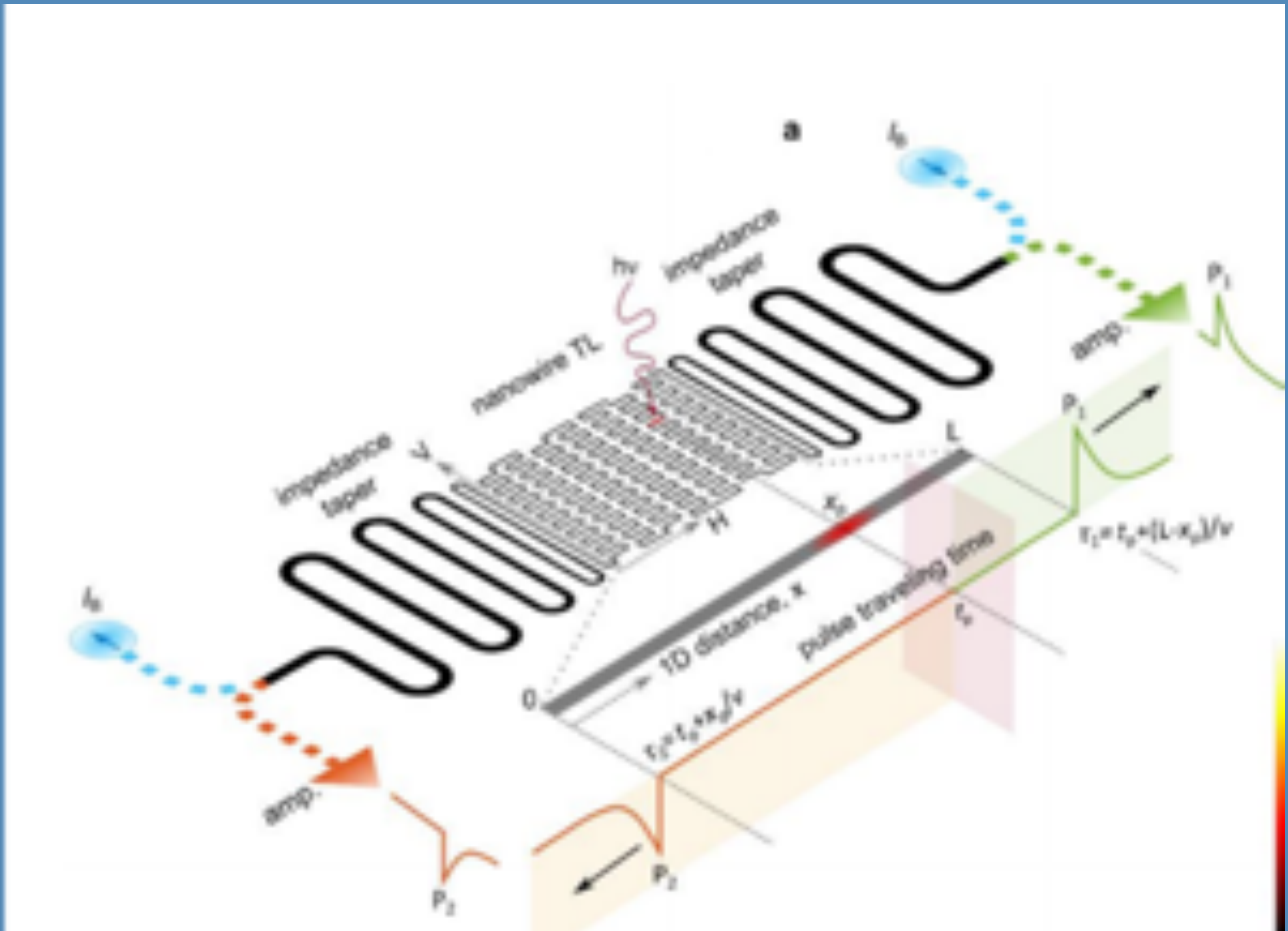
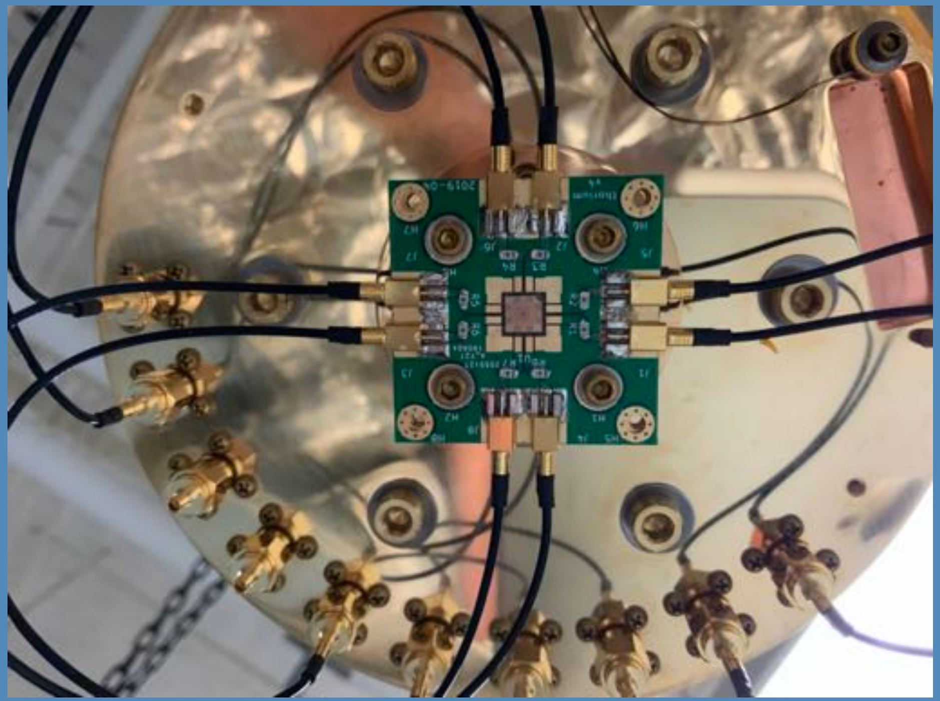


Figure from: Q.Y. Zhao et al., Nature Photonics 11,247-251(2017)



IN COLLABORATION WITH:

NIST

Sae Woo Nam

Galen O’Neil

Varun Verma and Dileep Reddy

SNSPI IC Detection

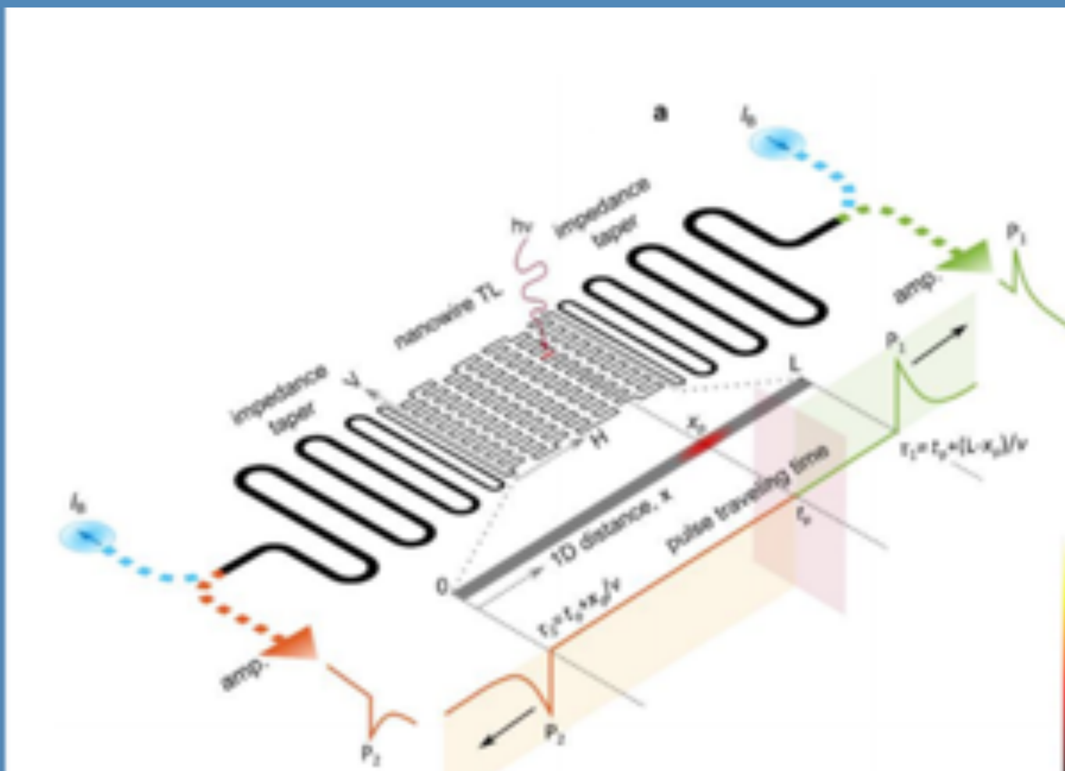
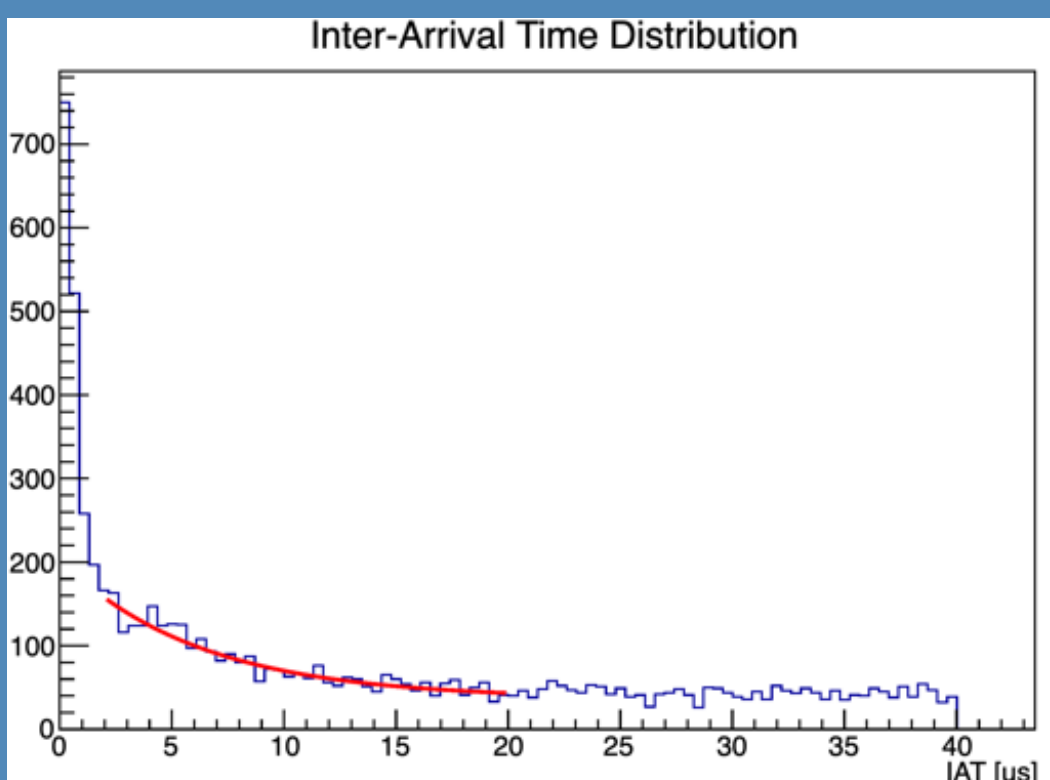
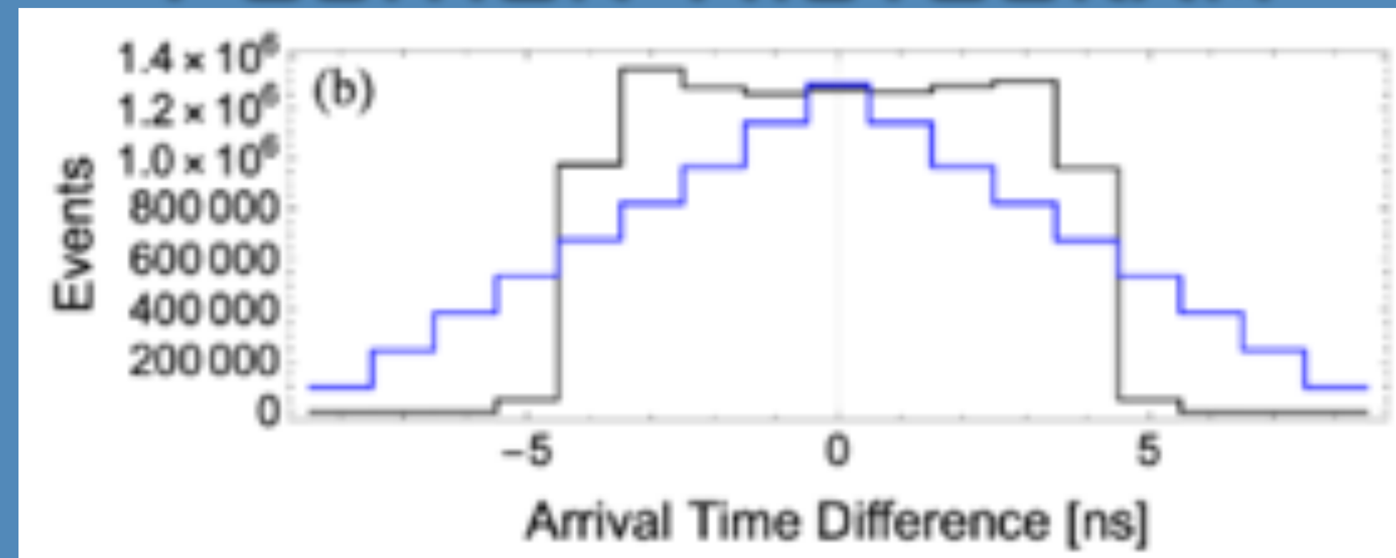


Figure from: Q.Y. Zhao et al., Nature Photonics 11,247-251(2017)



Position Histogram



Black: All Events

Blue: successive events

SNSPI IC Detection

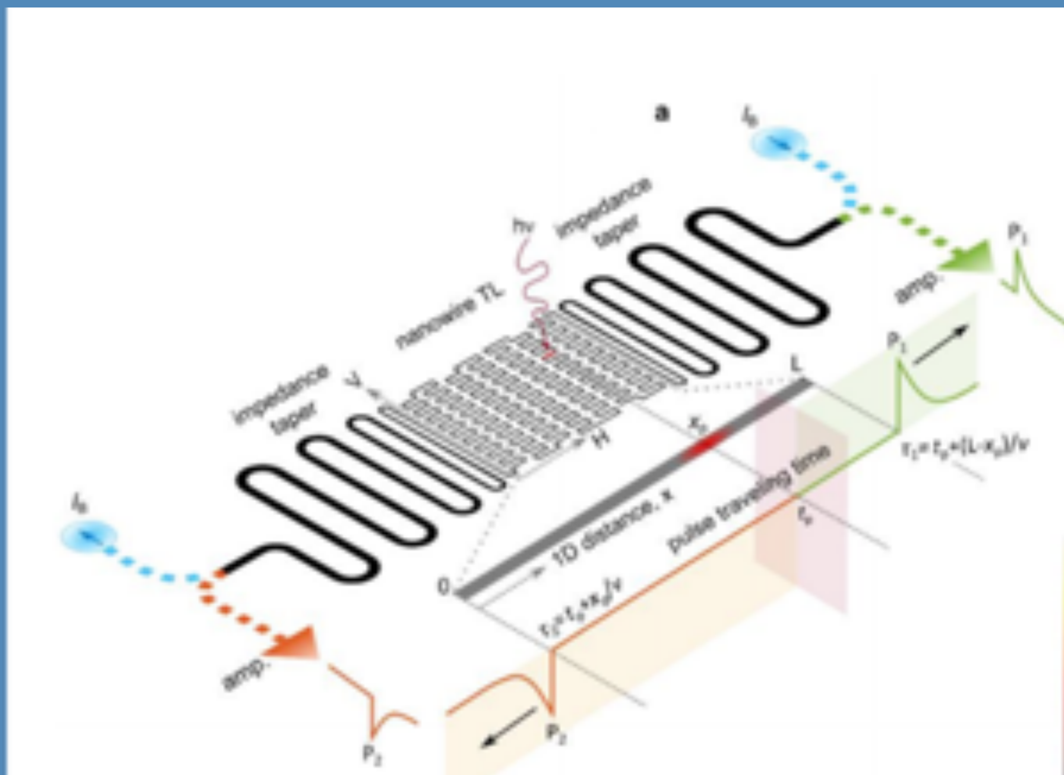
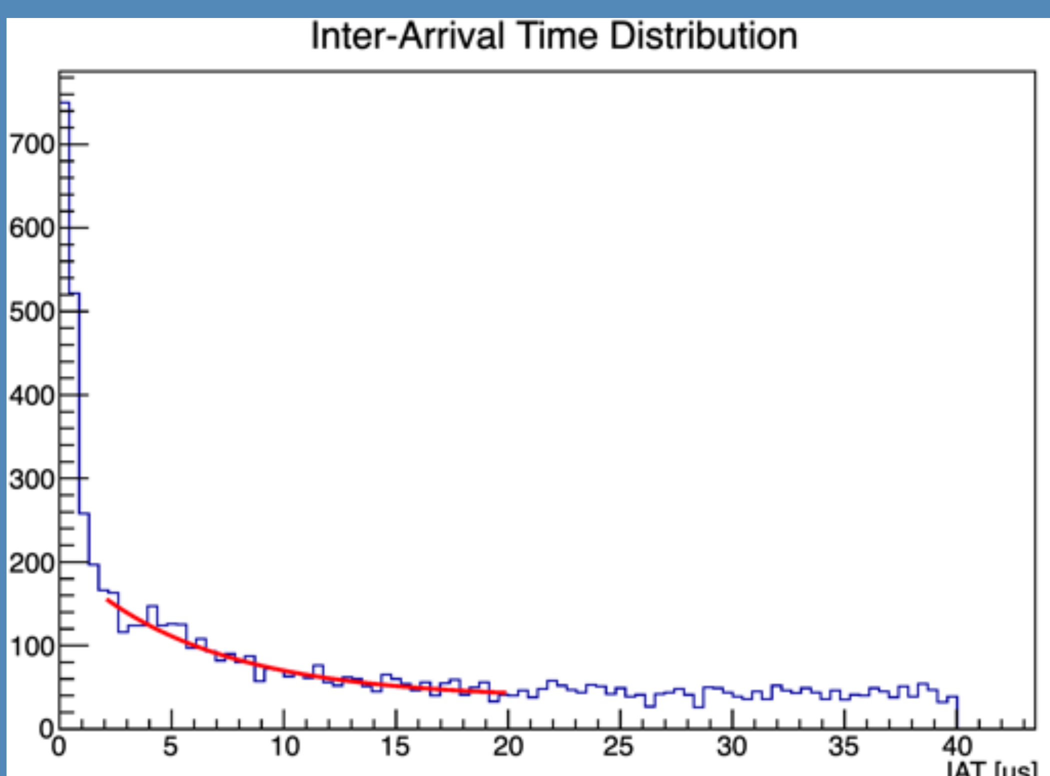
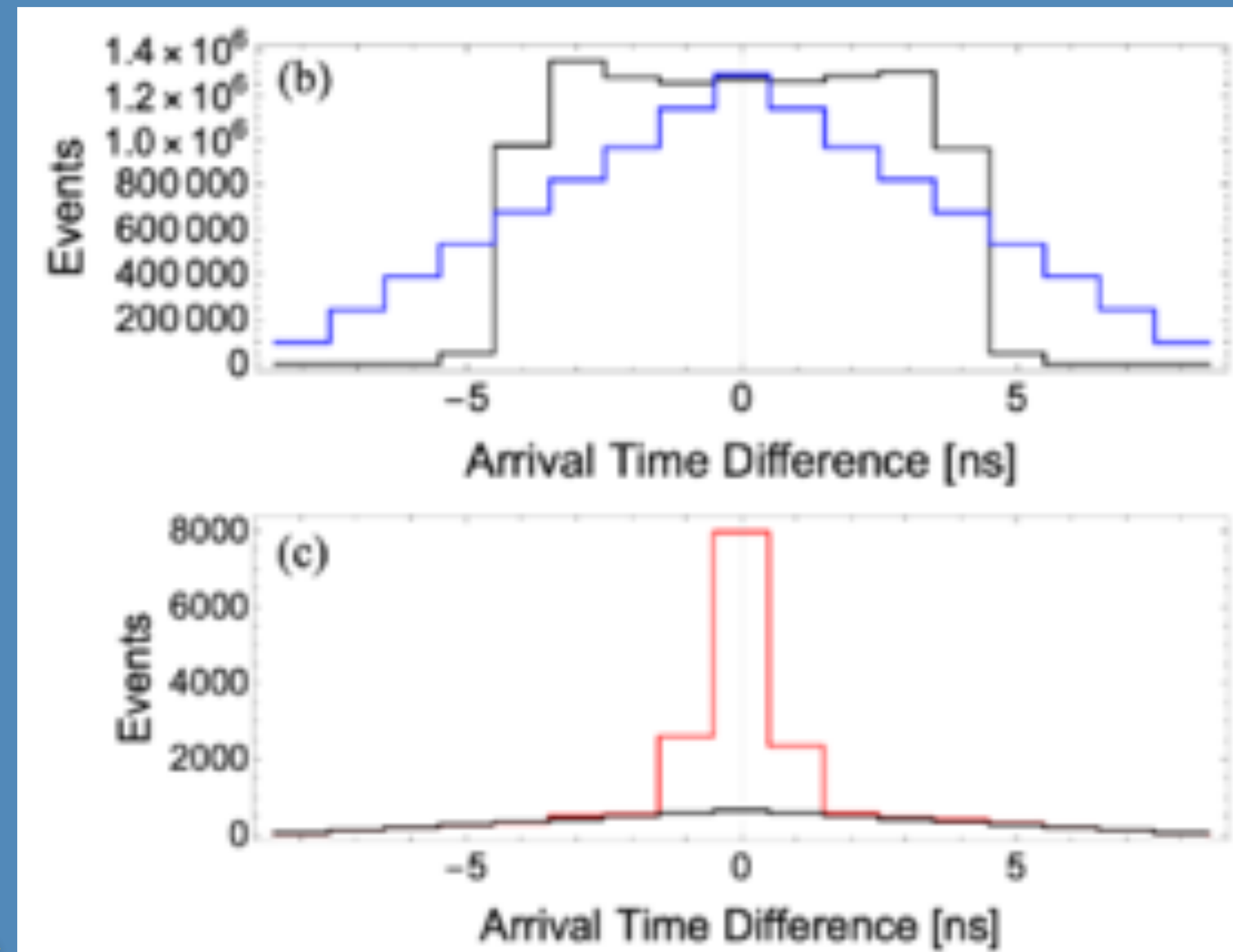


Figure from: Q.Y. Zhao et al., Nature Photonics 11,247-251(2017)

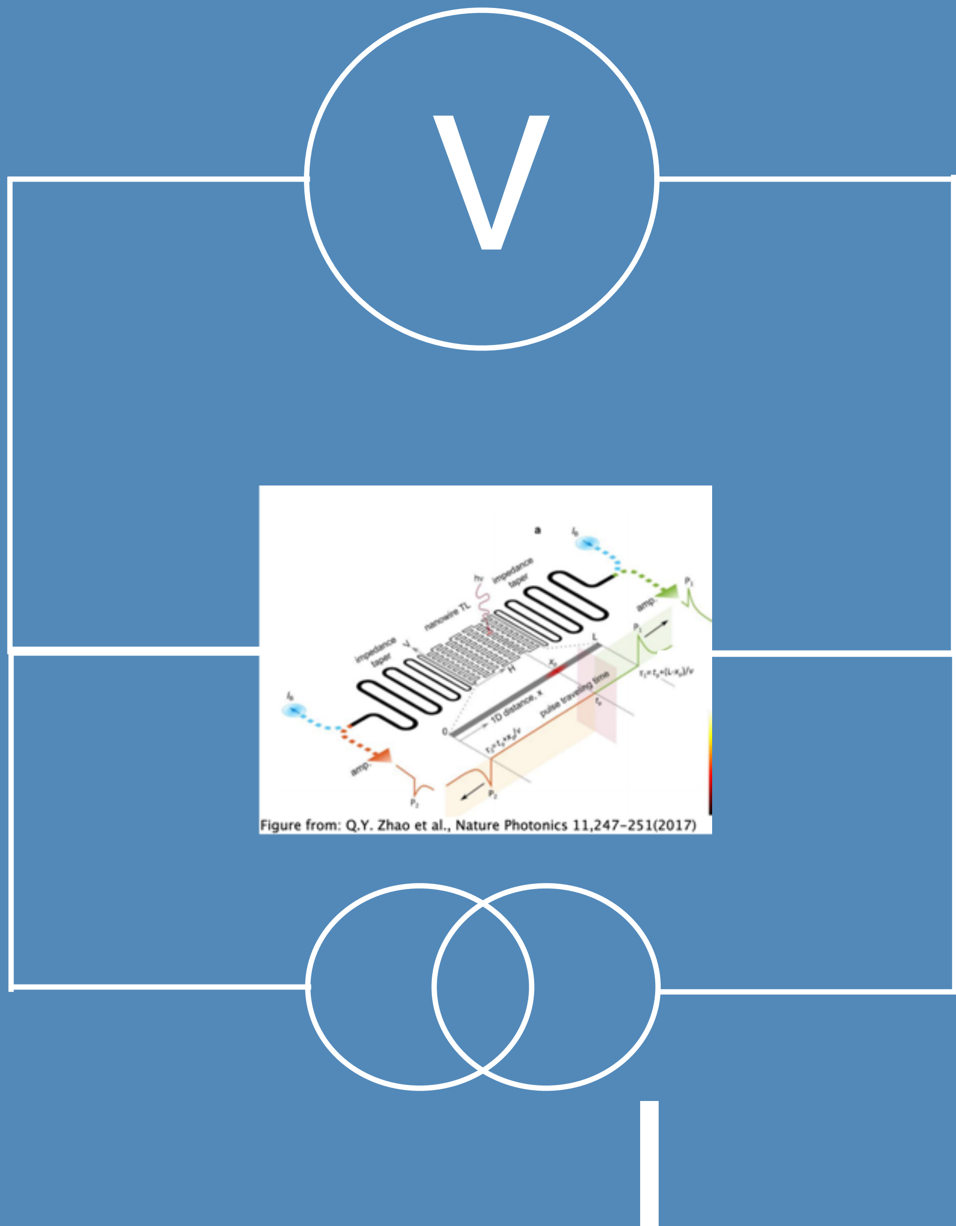




Red: Events within 30 us

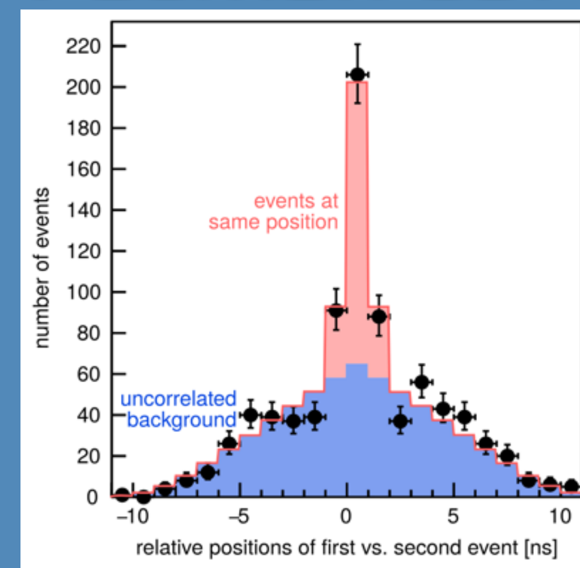
Black: expected bgnd

SNSPI IC Detection

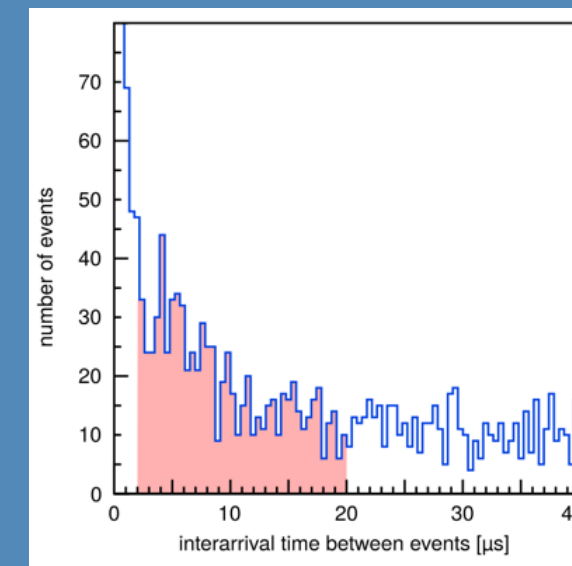


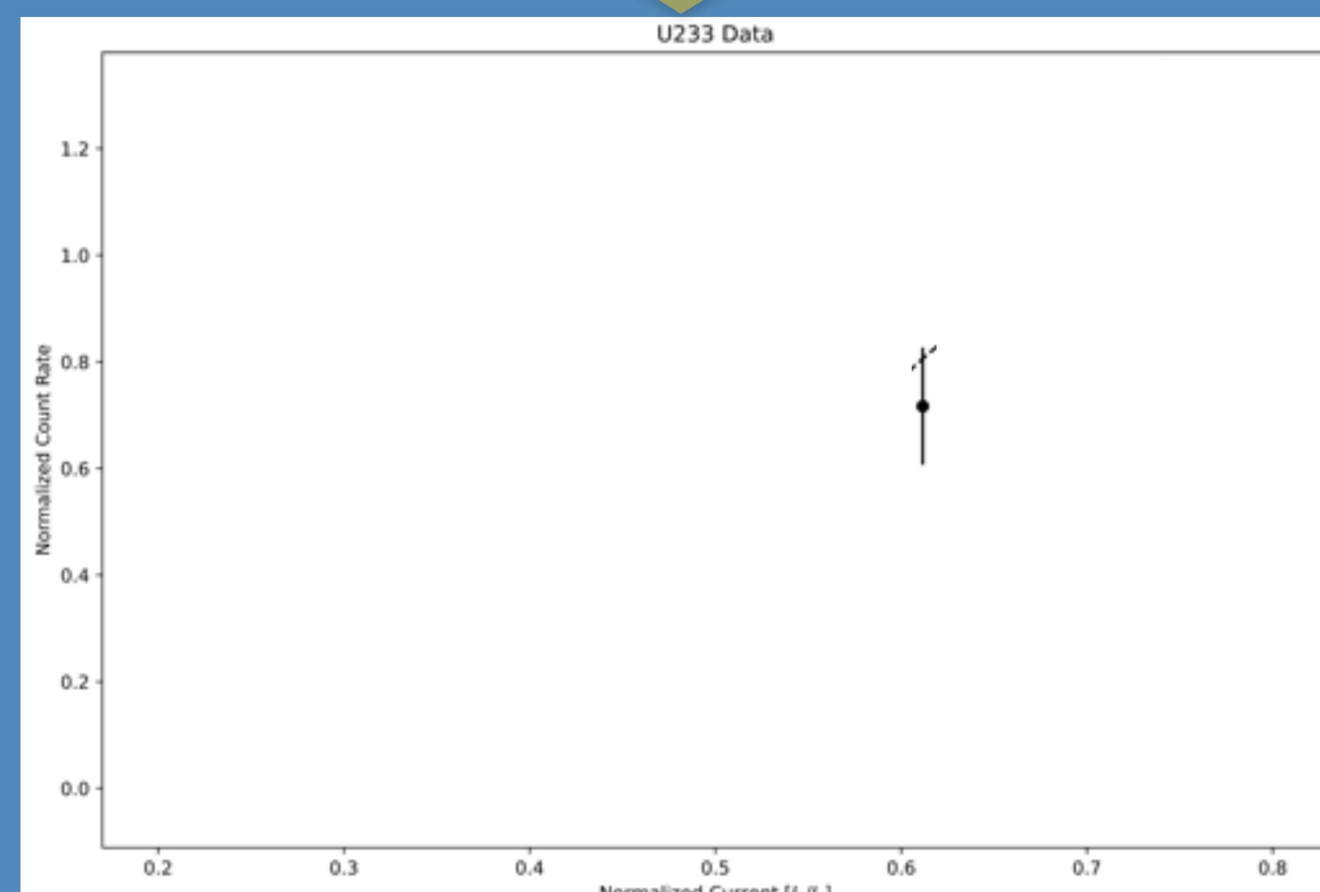
For each I_{BIAS}:

Position cut

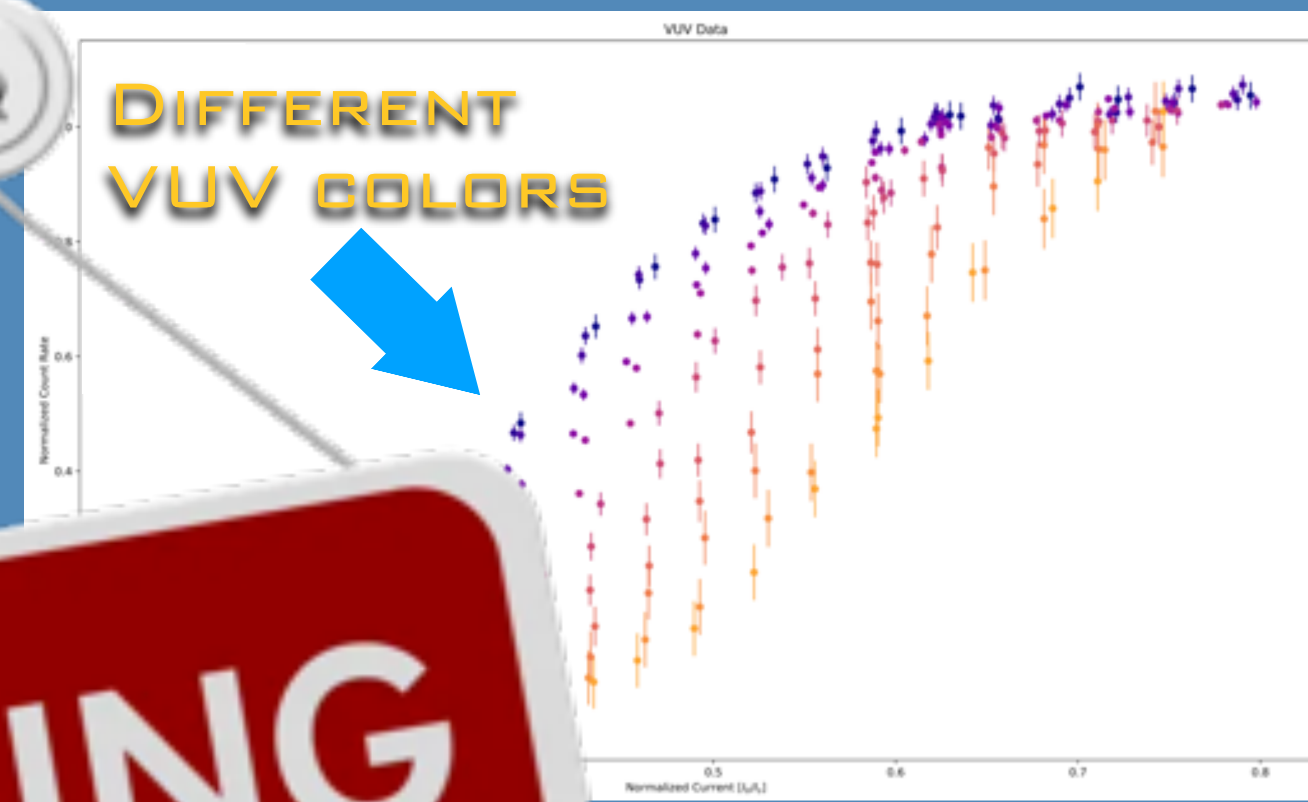


Time cut





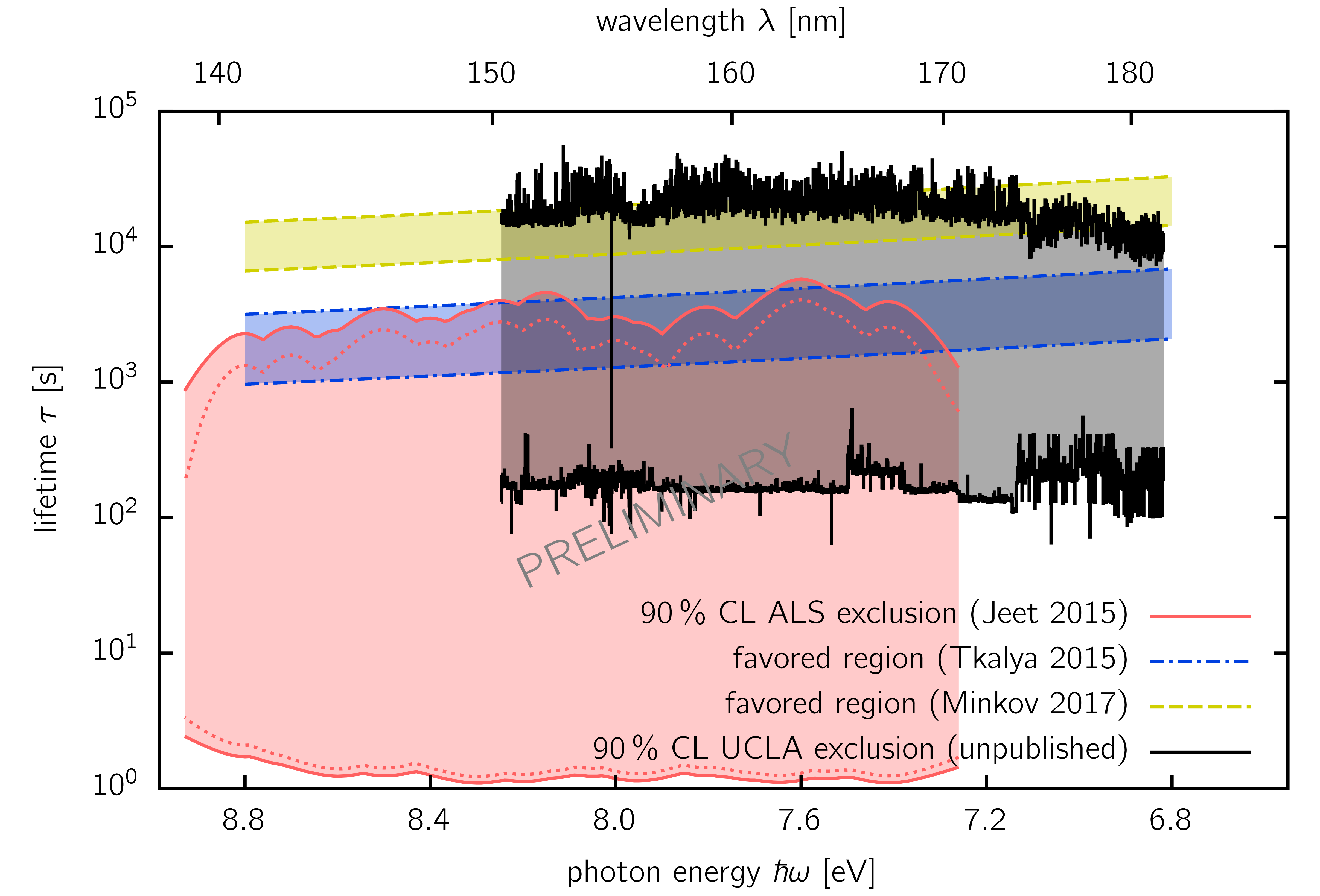
SNSPI IC Calibration



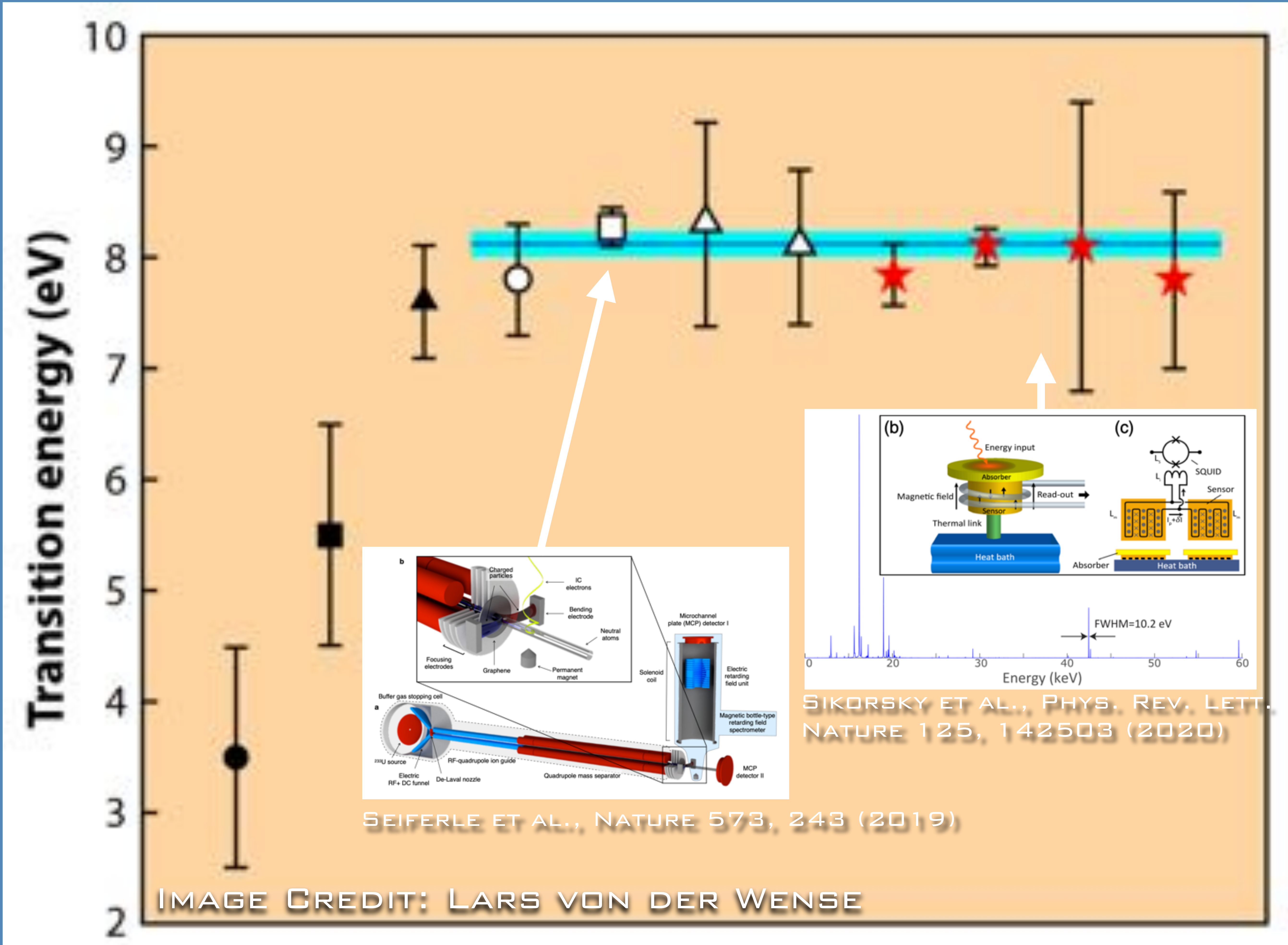
Comparison of
to thorium IC Decay

Measure IC Energy

What's next?

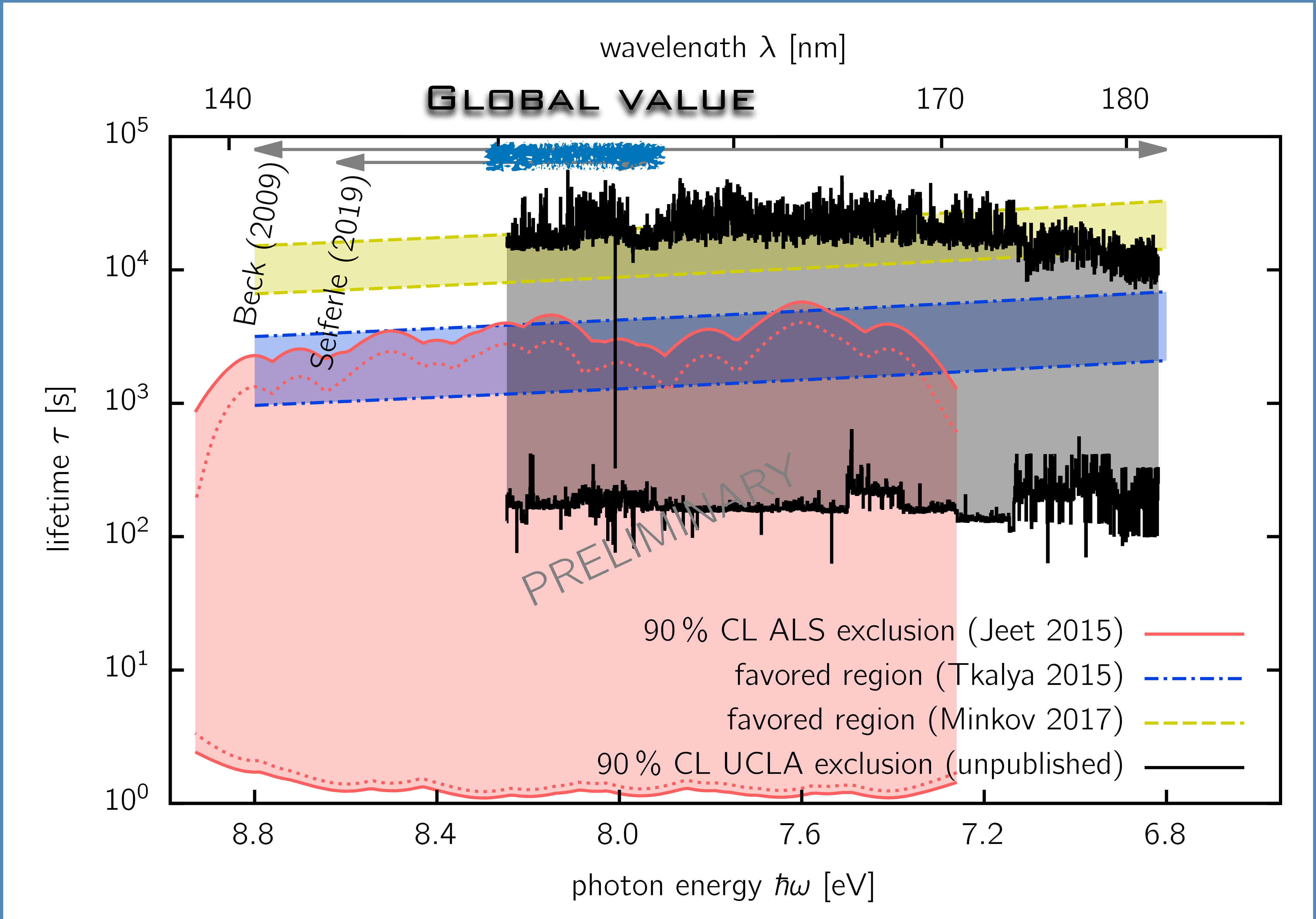


wavelength λ [nm]
140
150
160
170
180
10^5
10^4
10^3
10^2
10^1
10^0
lifetime τ [s]
PRELIMINARY
90 % CL ALS exclusion (Jeet 2015)
favored region (Tkalya 2015)
favored region (Minkov 2017)
90 % CL UCLA exclusion (unpublished)
8.8
8.4
8.0
7.6
7.2
6.8
photon energy ℏω [eV]

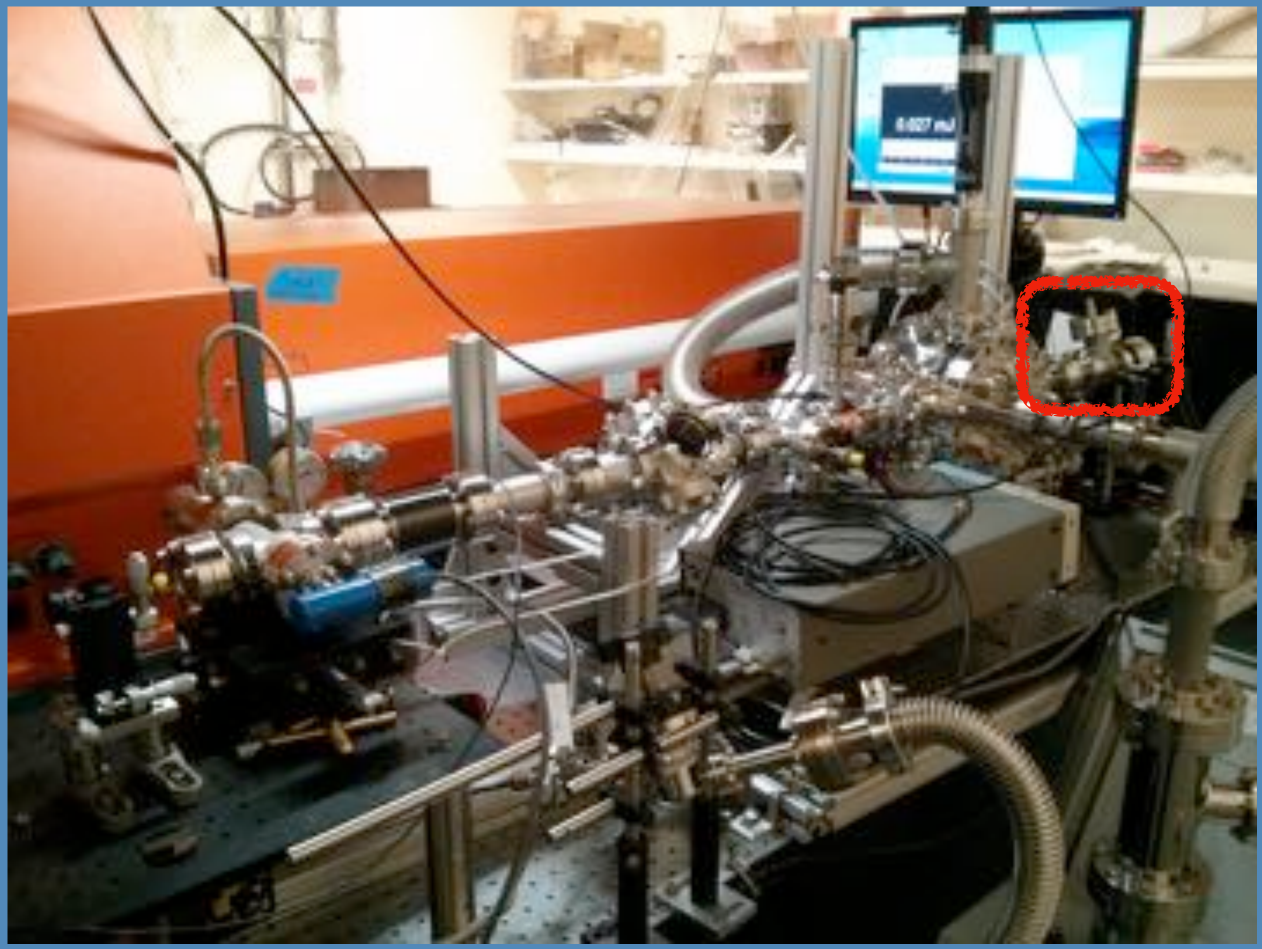


Transition energy (eV)
10
9
8
7
6
5
4
3
2
(b)
Energy input
Absorber
Magnetic field
Read-out
Sensor
Thermal link
Heat bath
(c)
SQUID
Sensor
Absorber
Heat bath
FWHM=10.2 eV
0
20
30
40
50
60
Energy (keV)
Sikorsky et al., Phys. Rev. Lett.
Nature 125, 142503 (2020)
b
Charged particles
IC electrons
Bending electrode
Neutral atoms
Focusing electrodes
Graphene
Permanent magnet
Microchannel plate (MCP) detector I
Solenoid coil
Electric retarding field unit
Magnetic bottle-type retarding field spectrometer
Buffer gas stopping cell
a
^{233}U source
RF-quadrupole ion guide
Electric RF+ DC funnel
De-Laval nozzle
Quadrupole mass separator
MCP detector II
Seiferle et al., Nature 573, 243 (2019)
Image Credit: Lars von der Wense

Status of the search

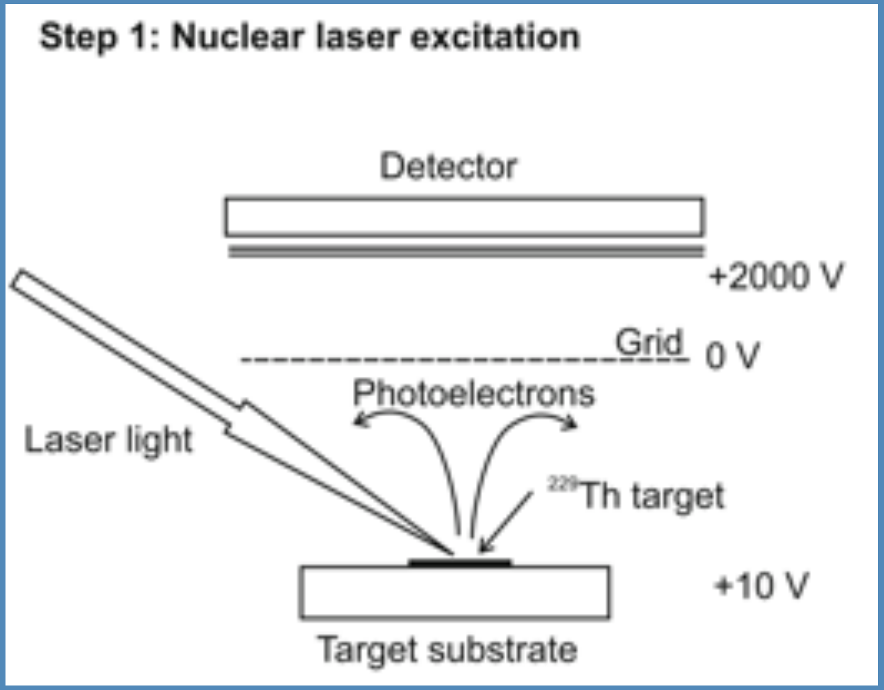


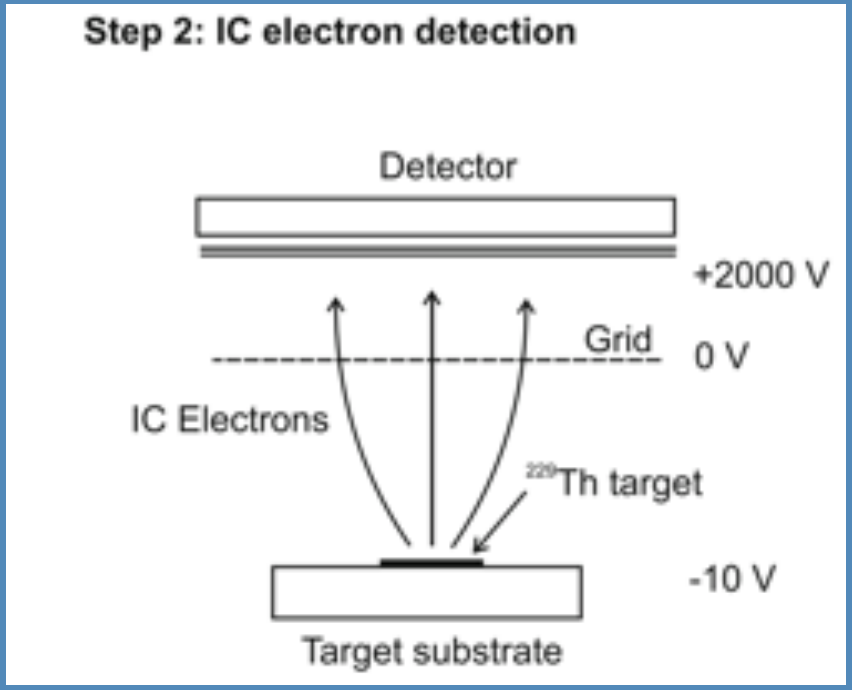
The Search Continues with an Upgrade



In collaboration with:

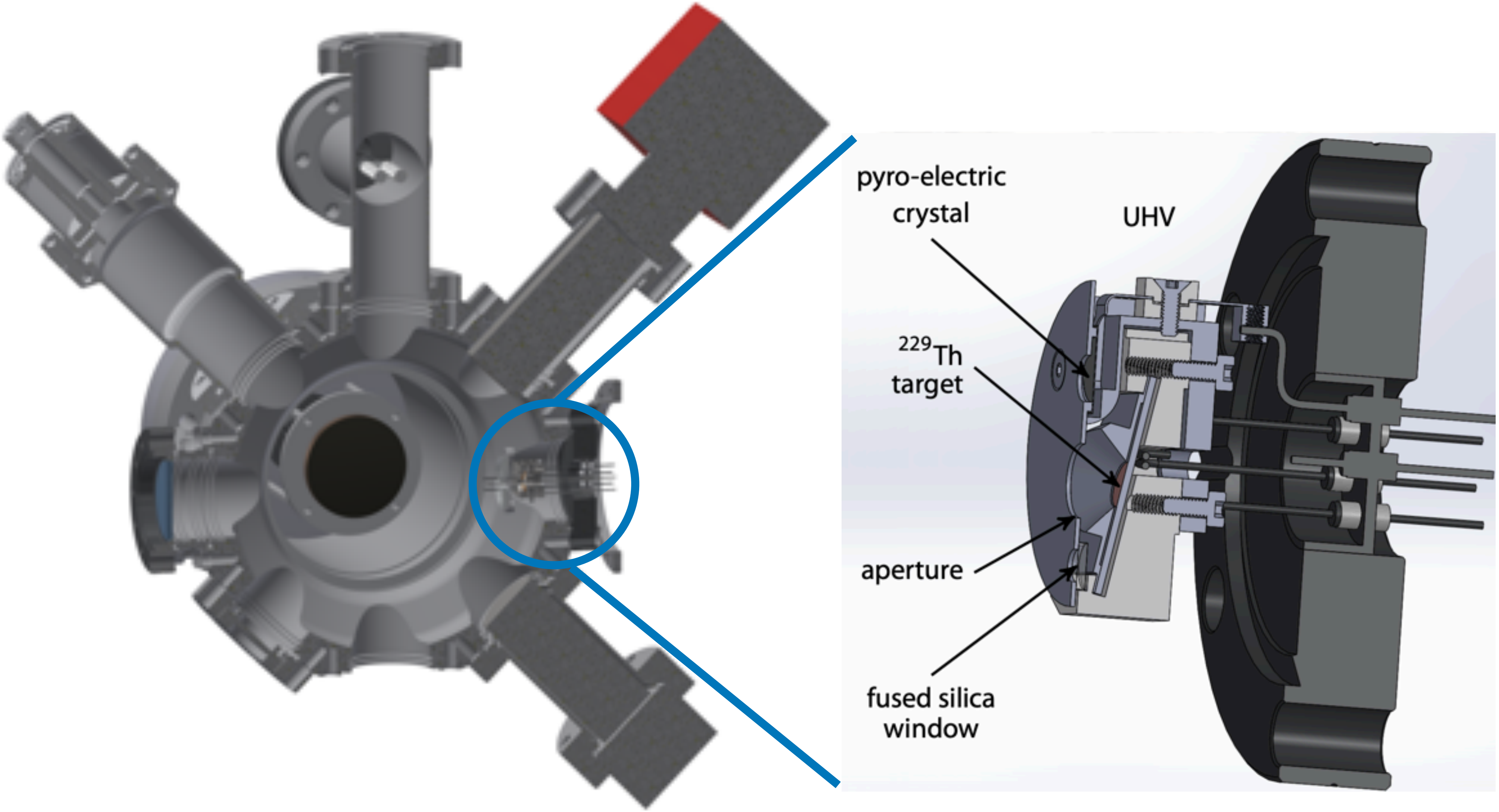
Thorium metal Target





THE SEARCH CONTINUES WITH AN UPGRADE

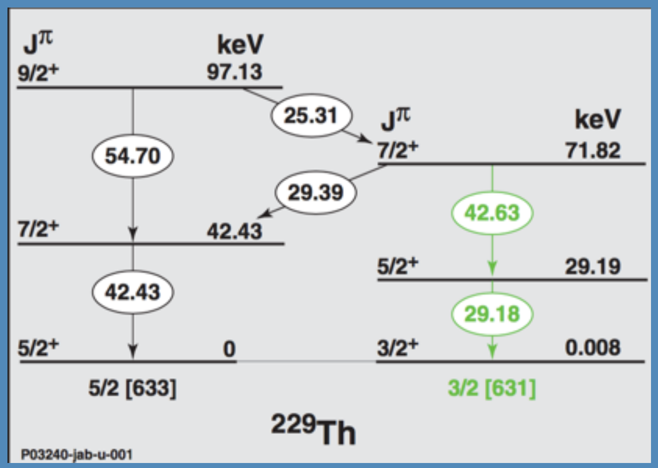
Laser-Based Search with Thorium Metal



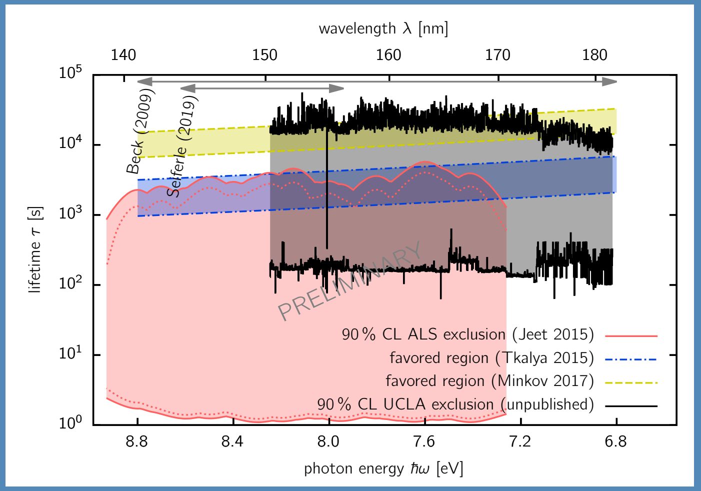
L. C. von der Wense, B. Seiferle, CS, J. Jeet, ..., E. R. Hudson and P. G. Thirolf: Hyperfine Interact. **240**, 23 (2019)
in collaboration with the groups of: P. Thirolf (LMU Munich), C. Düllmann (U Mainz/GSI), U. Morgner (U Hannover)

Summary

Forty years in the wilderness



Crystal-based search



New detections