SEARCHING FOR SOLAR KK AXIONS WITH A GASEOUS DETECTOR

Francisco Vazquez de Sola

PATRAS

Hamburg, June 2018

OVERVIEW

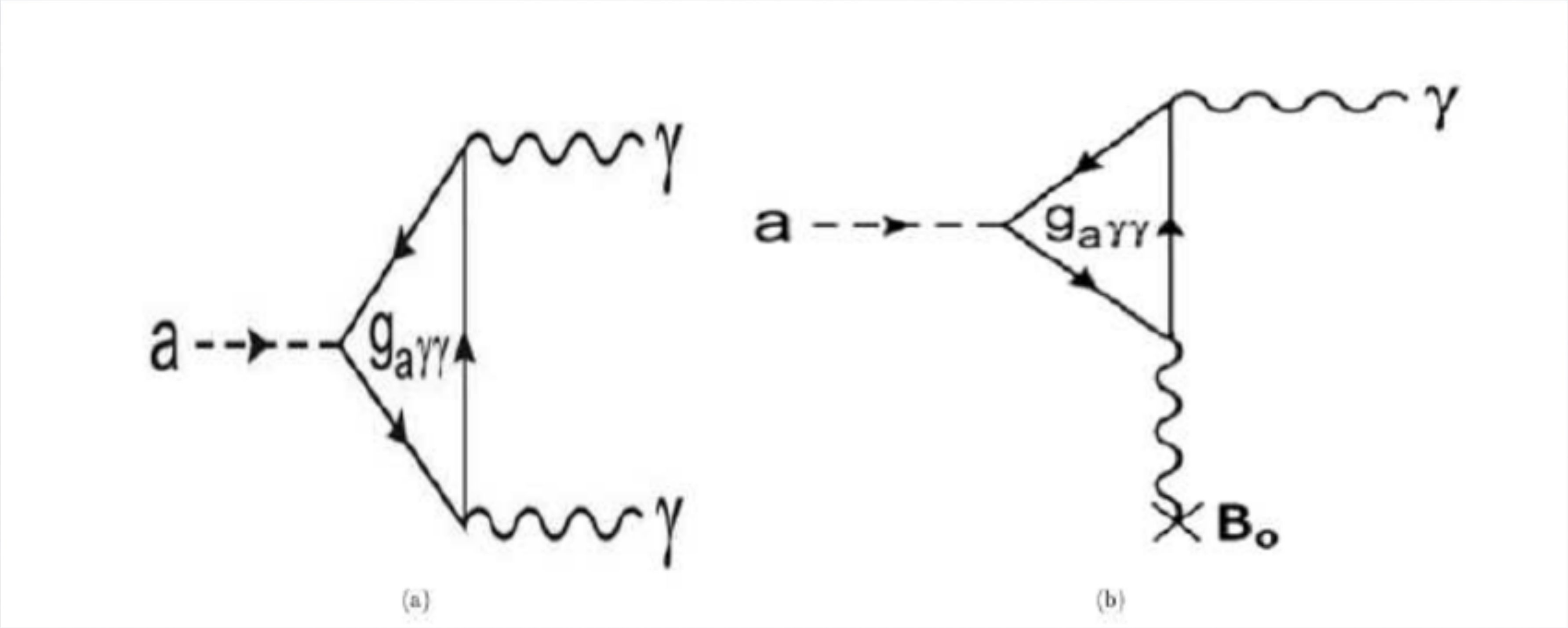
- Solar KK axions (and where to find them)
- NEWS-G detector and signal
- Data analysis, simulations, and preliminary results

QCD AXION

- Peccei-Quinn solution to strong CP problem
  - Problem: QCD Lagrangian contains a CP violating term, but no CP violation is observed in the strong interaction.
  - Hypothesis: new spontaneously broken symmetry is introduced to "remove" the CP violating term, giving rise to a new pseudo-scalar particle, the QCD axion.
  - The characteristics of this particle depend mainly on the symmetry breaking scale (constrained by cosmological observations).

If Dark Matter is QCD axion, its mass ~ 10^{-6} -10^{-3} eV

AXION (AND AXION-LIKE PARTS) COUPLING TO PHOTONS



Decay into two photons

Expected decaytime ~10^{30} - 10^{45} days.
Compare with age of Universe: ~10^{13} days

Primakoff effect

Only in presence of magnetic field
(includes that of an atom)

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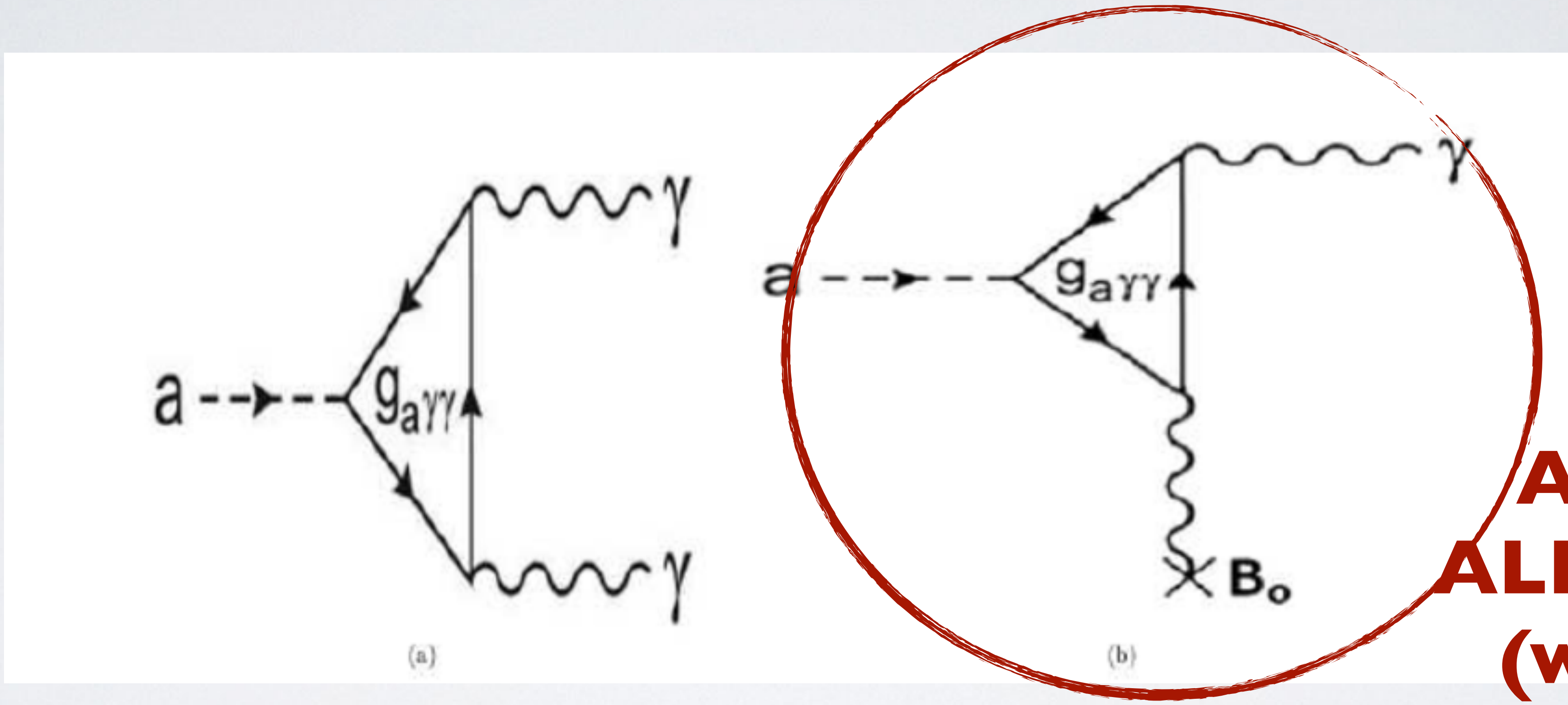

Axion and ALPs searches (with ~10T magnets)

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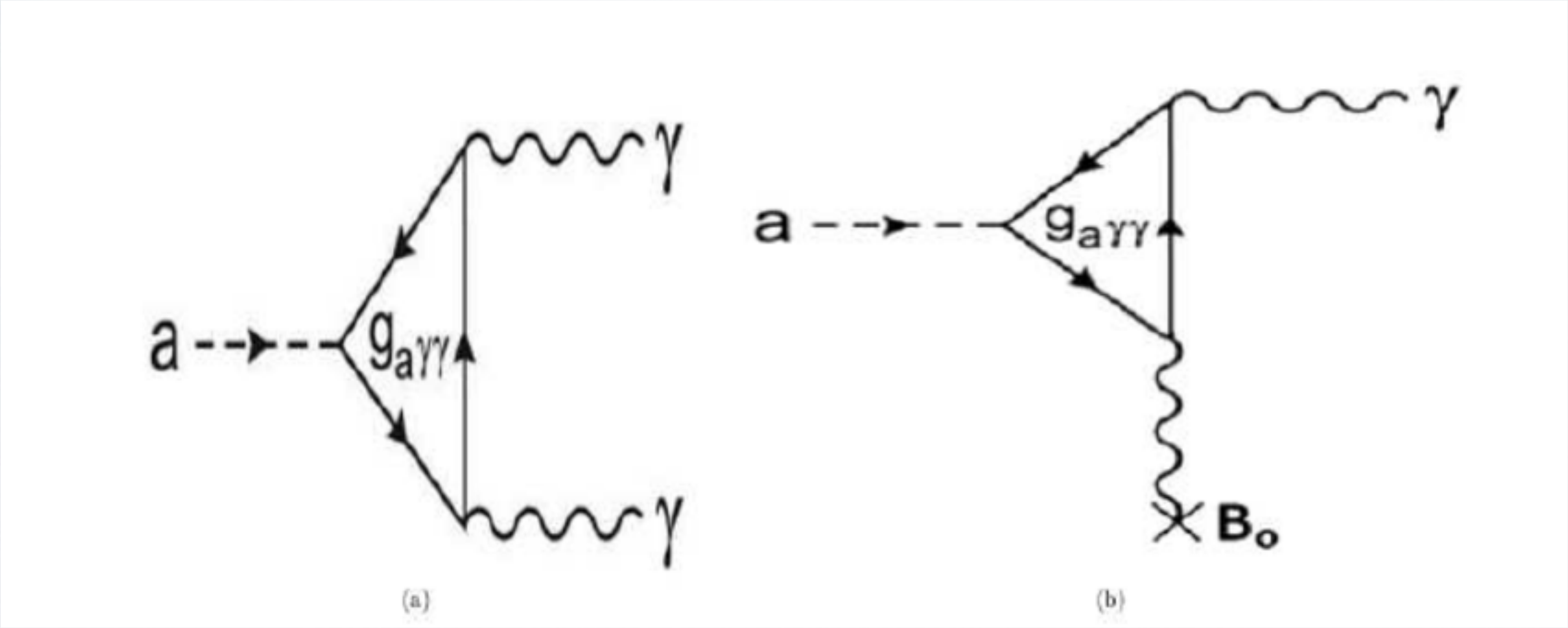
KALUZA-KLEIN AXION

- Extra dimensions theories have been proposed to solve the gauge hierarchy problem.
- In such theories, the QCD axion gains a tower of excitations with heavier masses.
- For two extra dimensions and a quantum gravity scale of 100 TeV, the spacing between excitations is $\sim$1eV.
- **High mass, low decaytime "axions" are possible without changing the symmetry breaking scale.**

AXION (AND AXION-LIKE PARTs) COUPLING TO PHOTONS



Decay into two photons

1 keV axion decaytime ~10^{12} - 10^{18} days.
Observable for large densities

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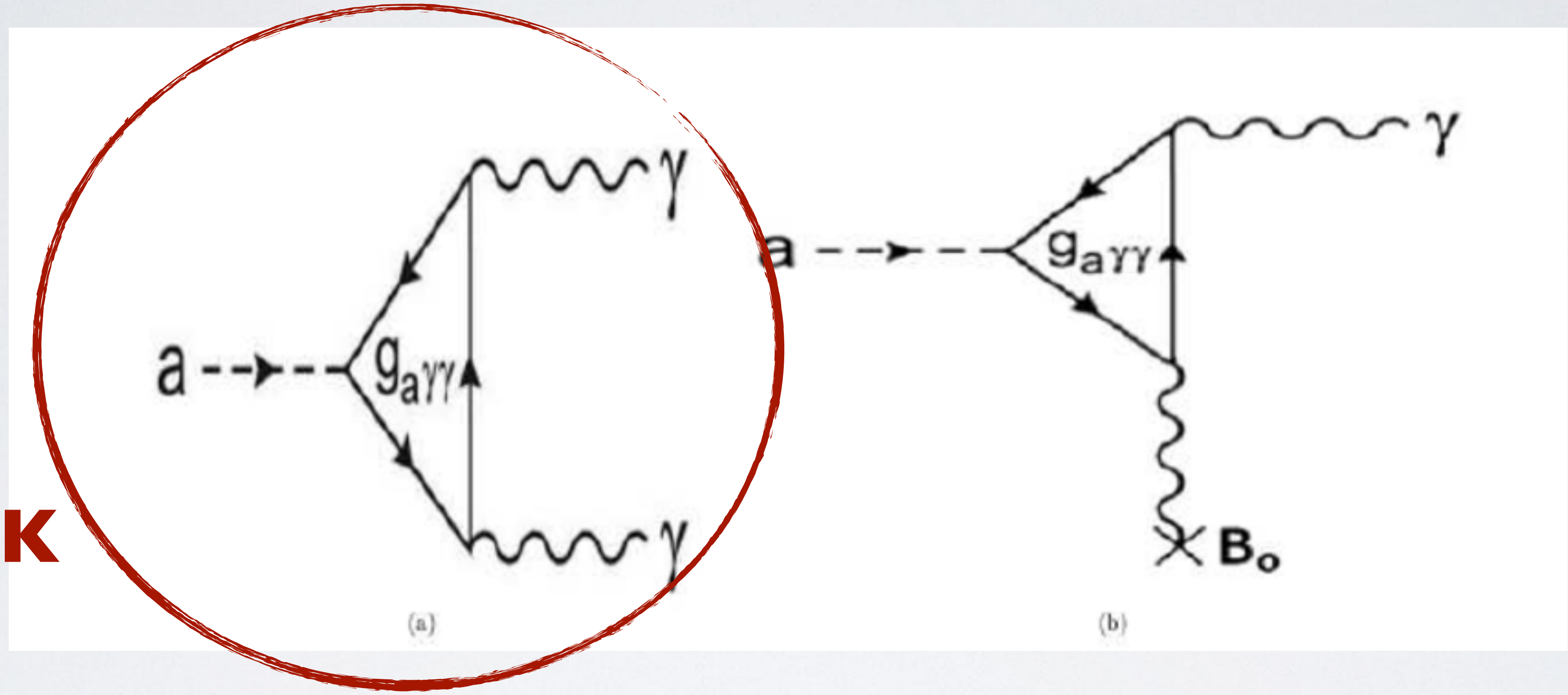

Heavy KK axions?

Decay into two photons

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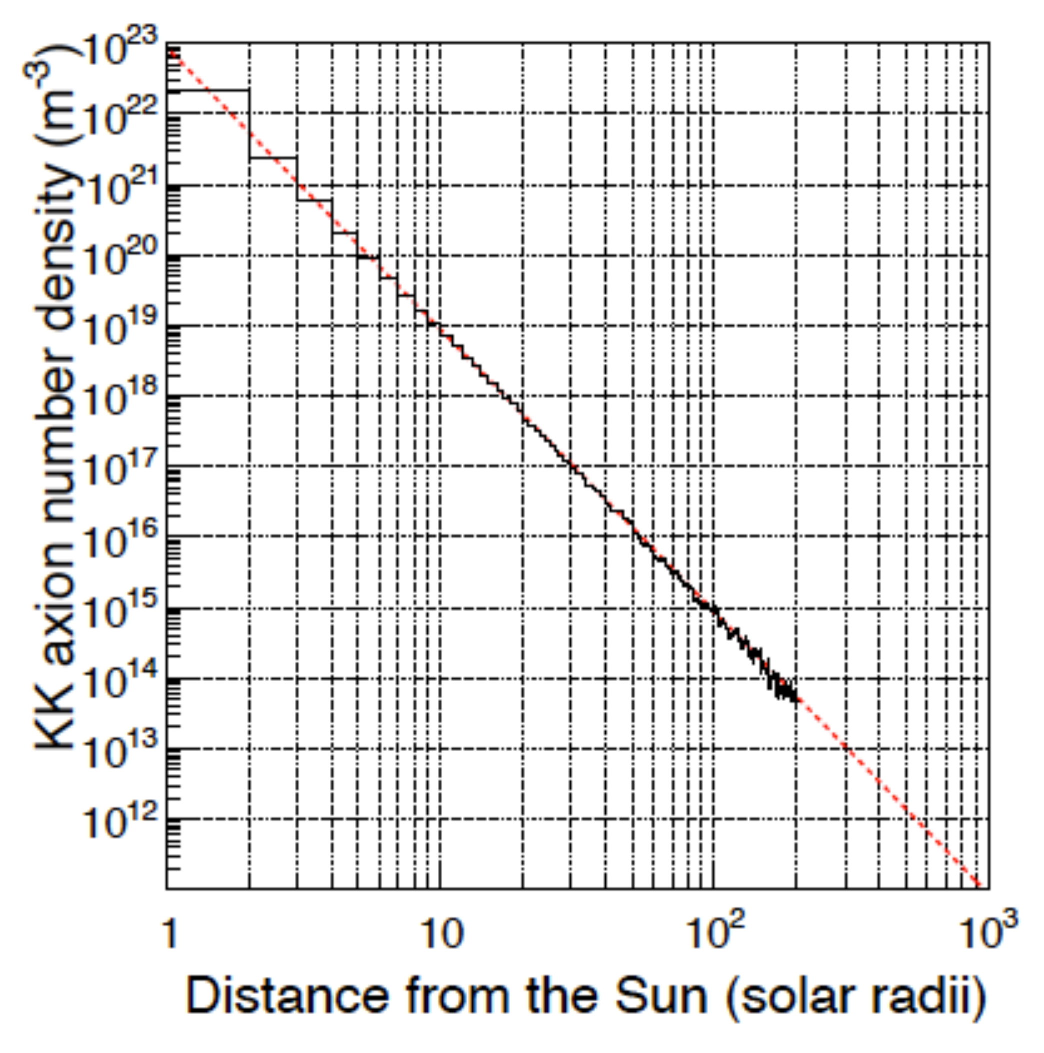
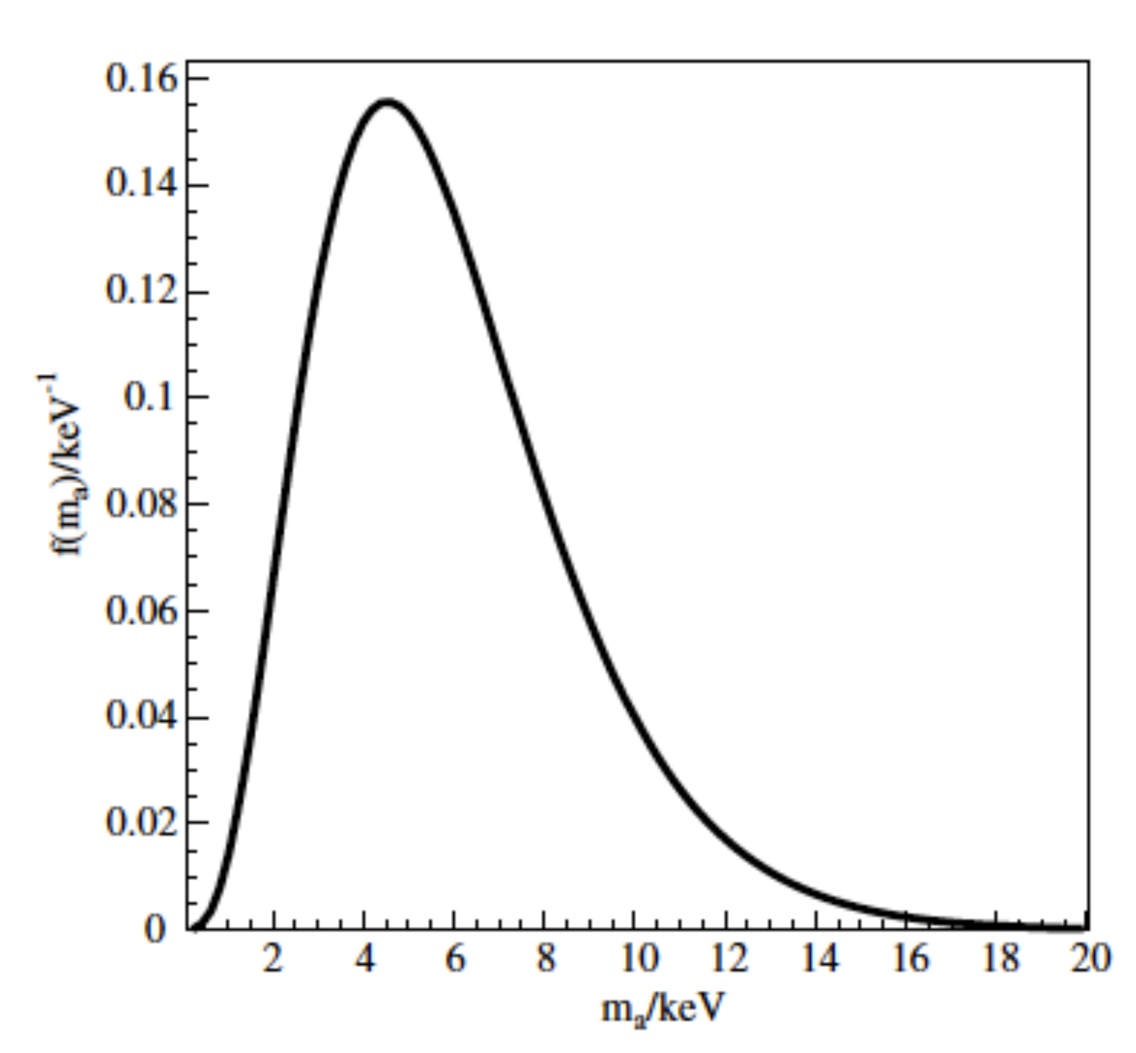
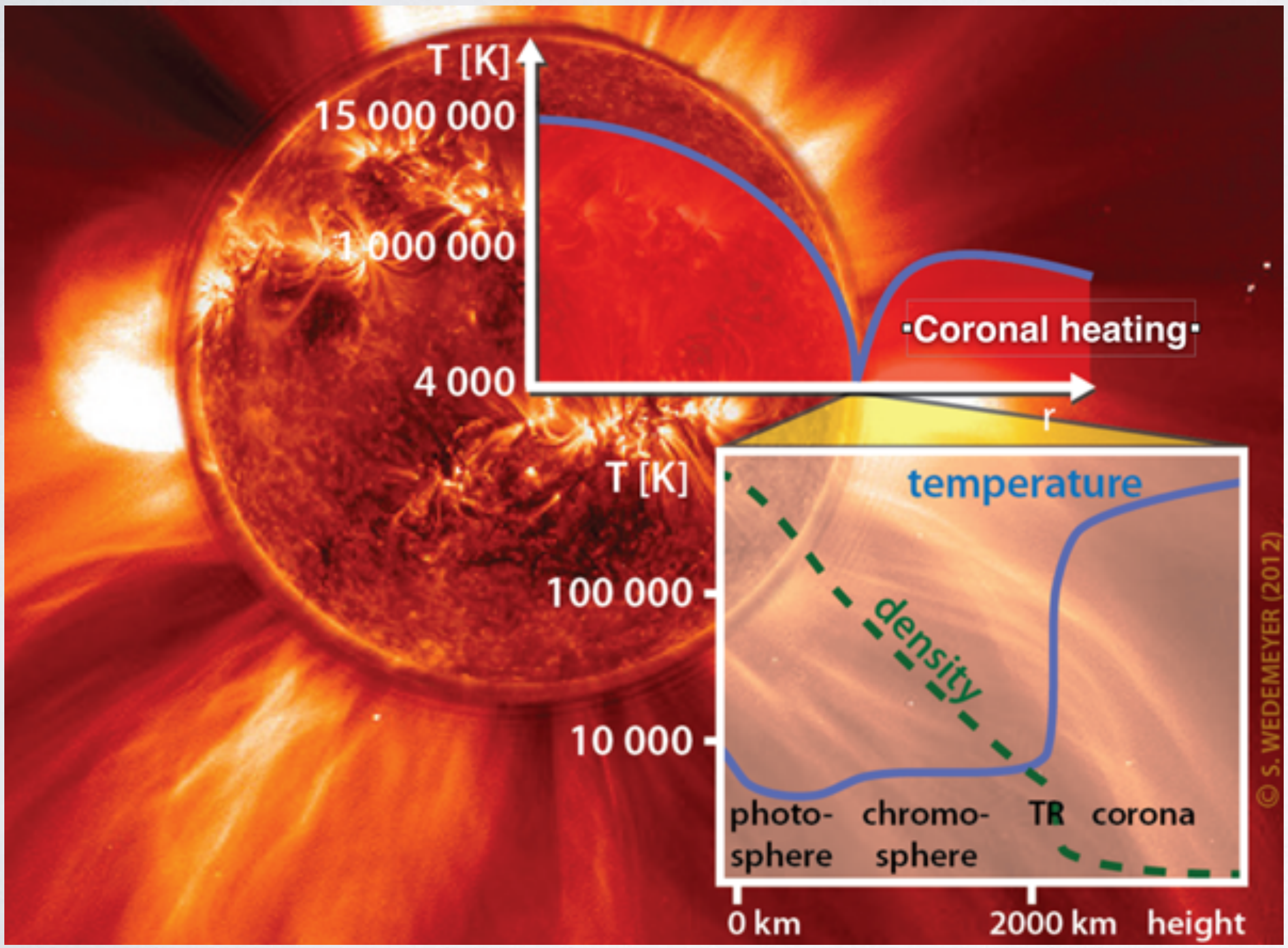
SOLAR KK AXION

- For heavier masses of the axion, a proportion of solar axions are trapped in the gravitational field of the Sun.
- **The density of trapped axions in the Solar System is then large enough to be detected.**
- Expected density and distribution of trapped axions simulated by DiLlela and Zioutas in 2003:





CASE FOR KK AXION



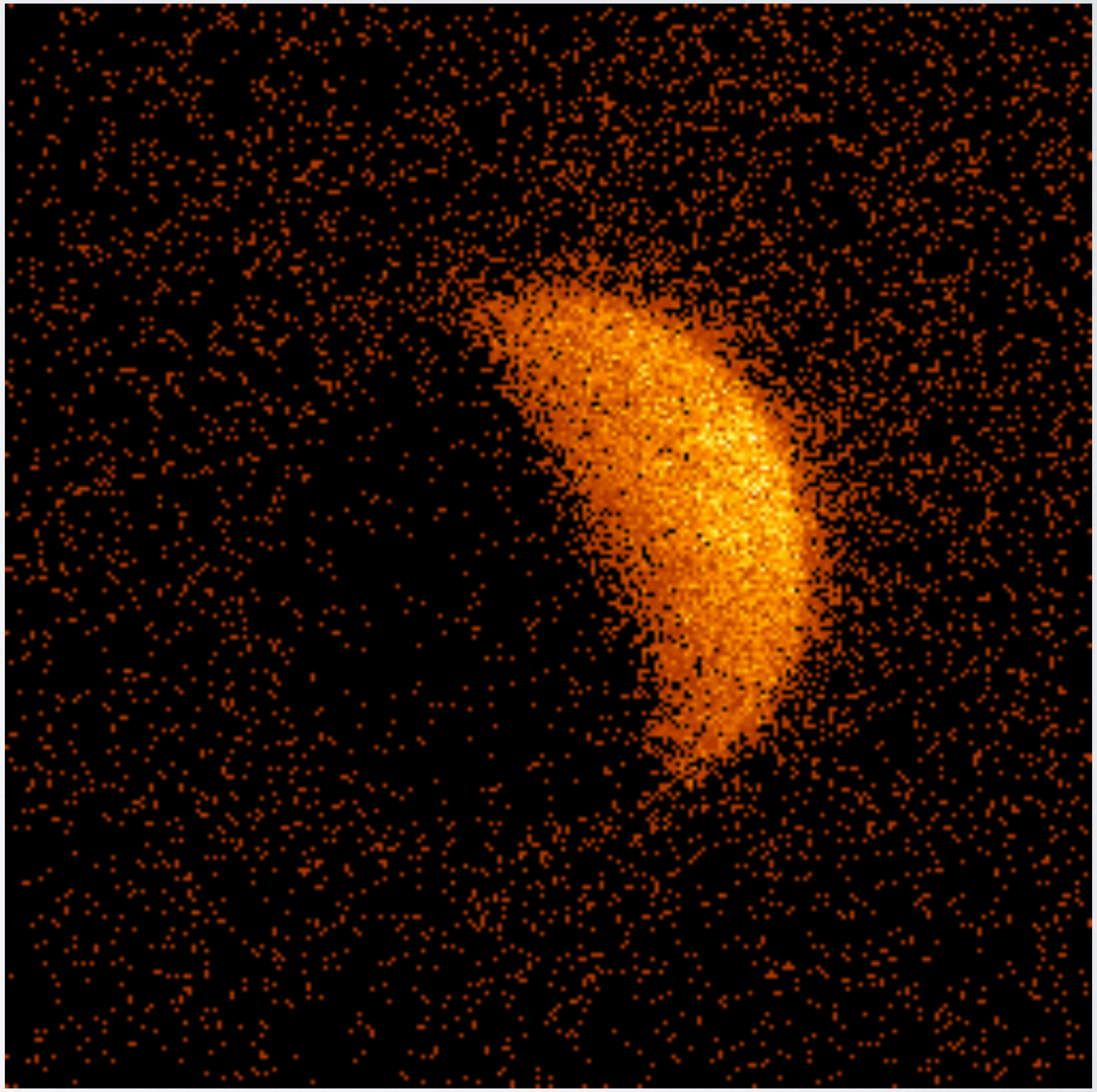
http://www.mn.uio.no/astro/english/research/projects/solaralma/

- **Corona heating problem:** Solar corona hotter than Chromosphere. External irradiation of the Sun?
- **Hypothesis:** KK axions decay in solar orbit, heating up the corona.
- KK axion mass > 1 keV

CASE FOR KK AXION

- **X-rays from dark side of the Moon:** interaction between Solar wind and surface of the Moon not enough to justify these emissions.

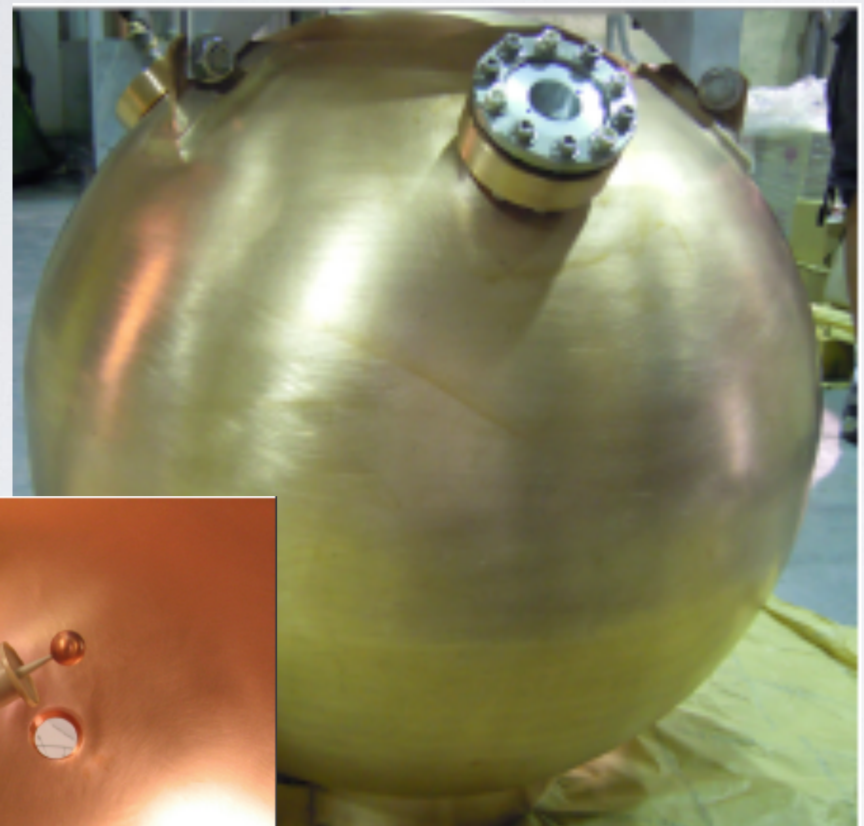
- **Hypothesis:** solar KK axions decaying between the Moon and ROSAT.

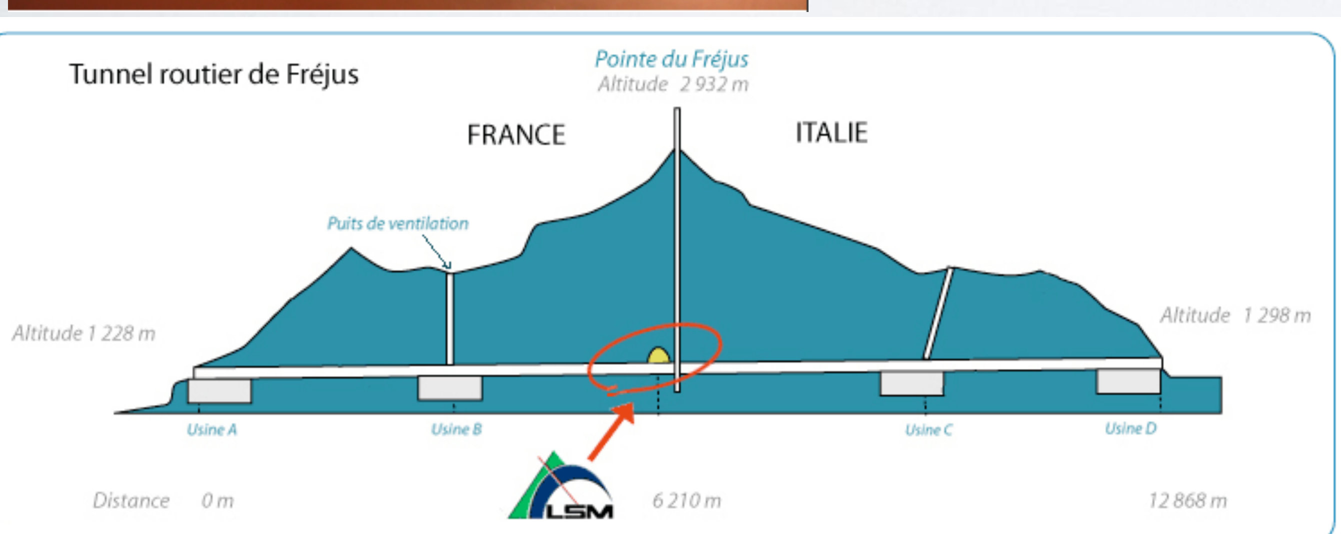


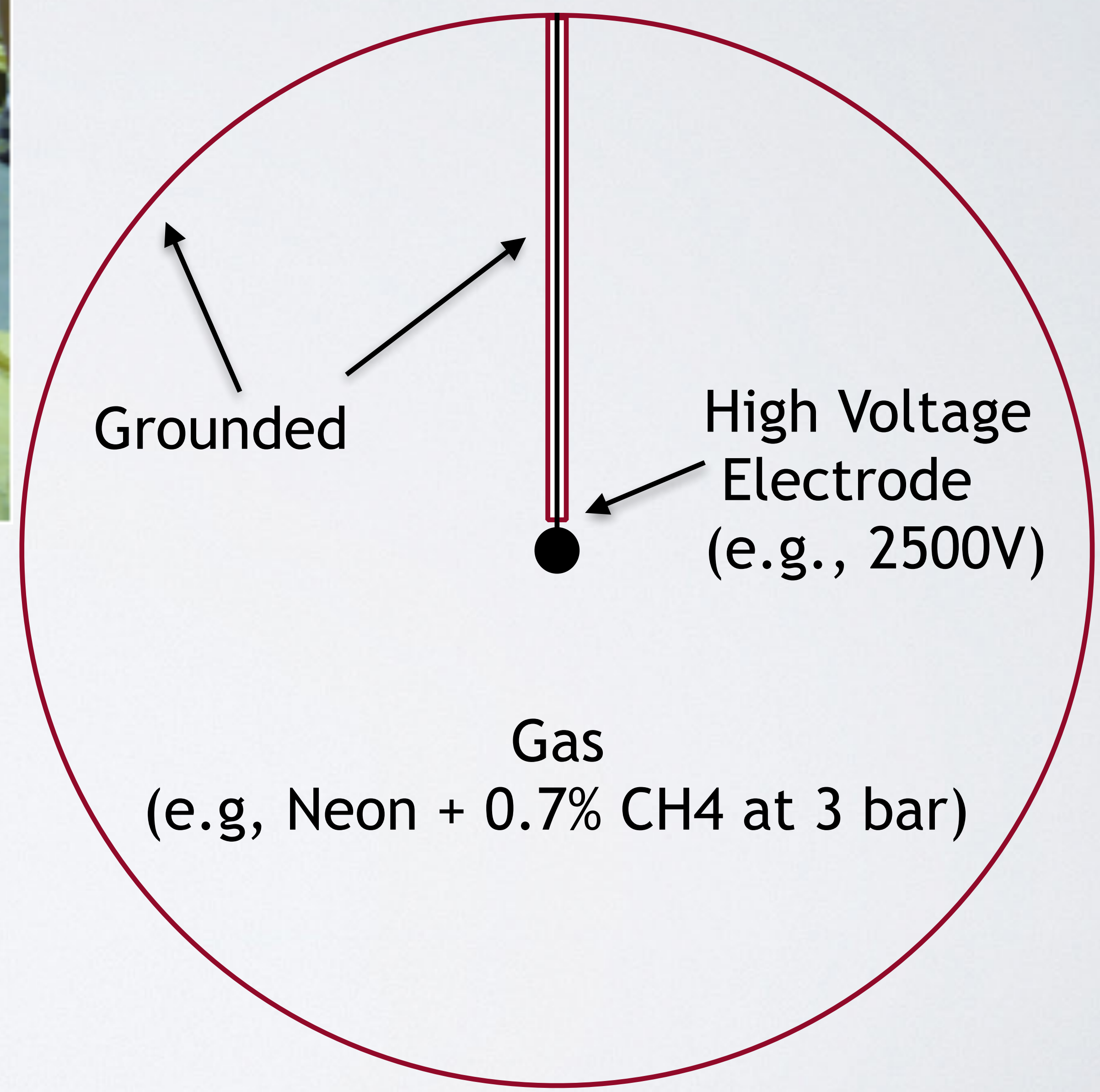
Nature 349 (1991) 583.

NEWS-G :THE DETECTOR

SEDINE
60 cm copper vessel detector at LSM

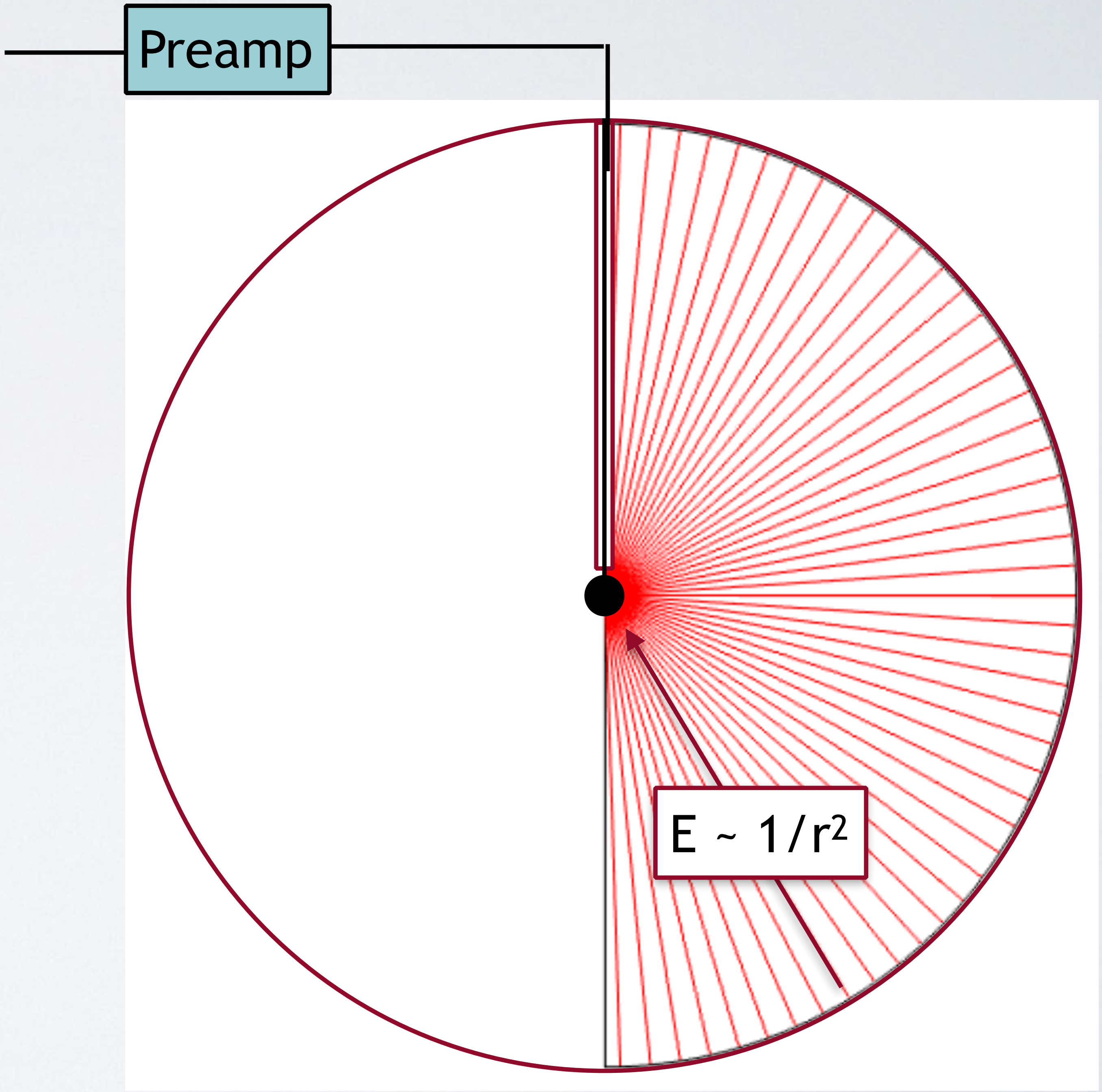






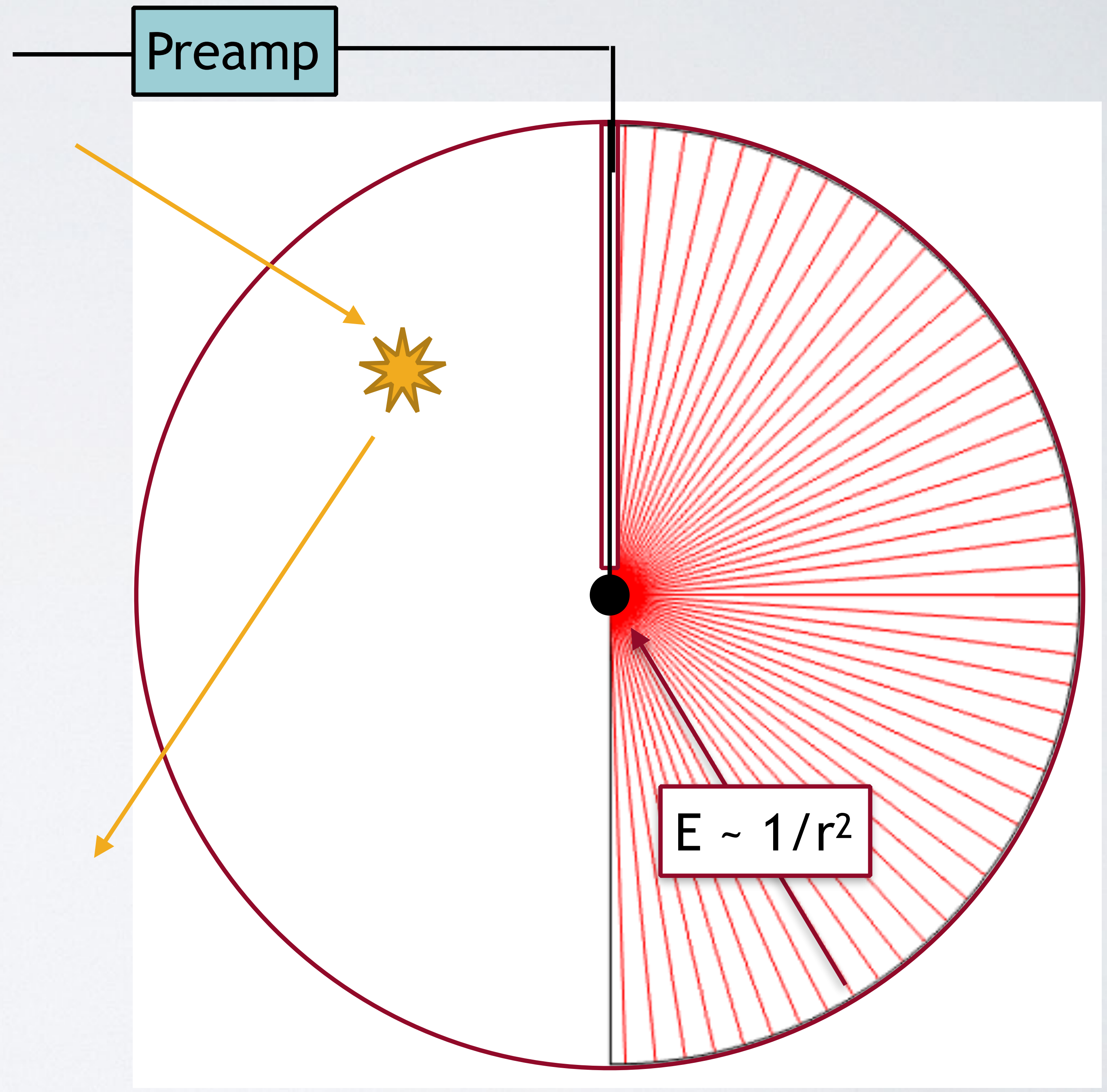
Spherical Proportional Counter

NEWS-G : WORKING PRINCIPLE



NEWS-G : WORKING PRINCIPLE

- Primary Ionisation
  - for Neon, average of 1 electron per 36eV



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- Primary Ionisation
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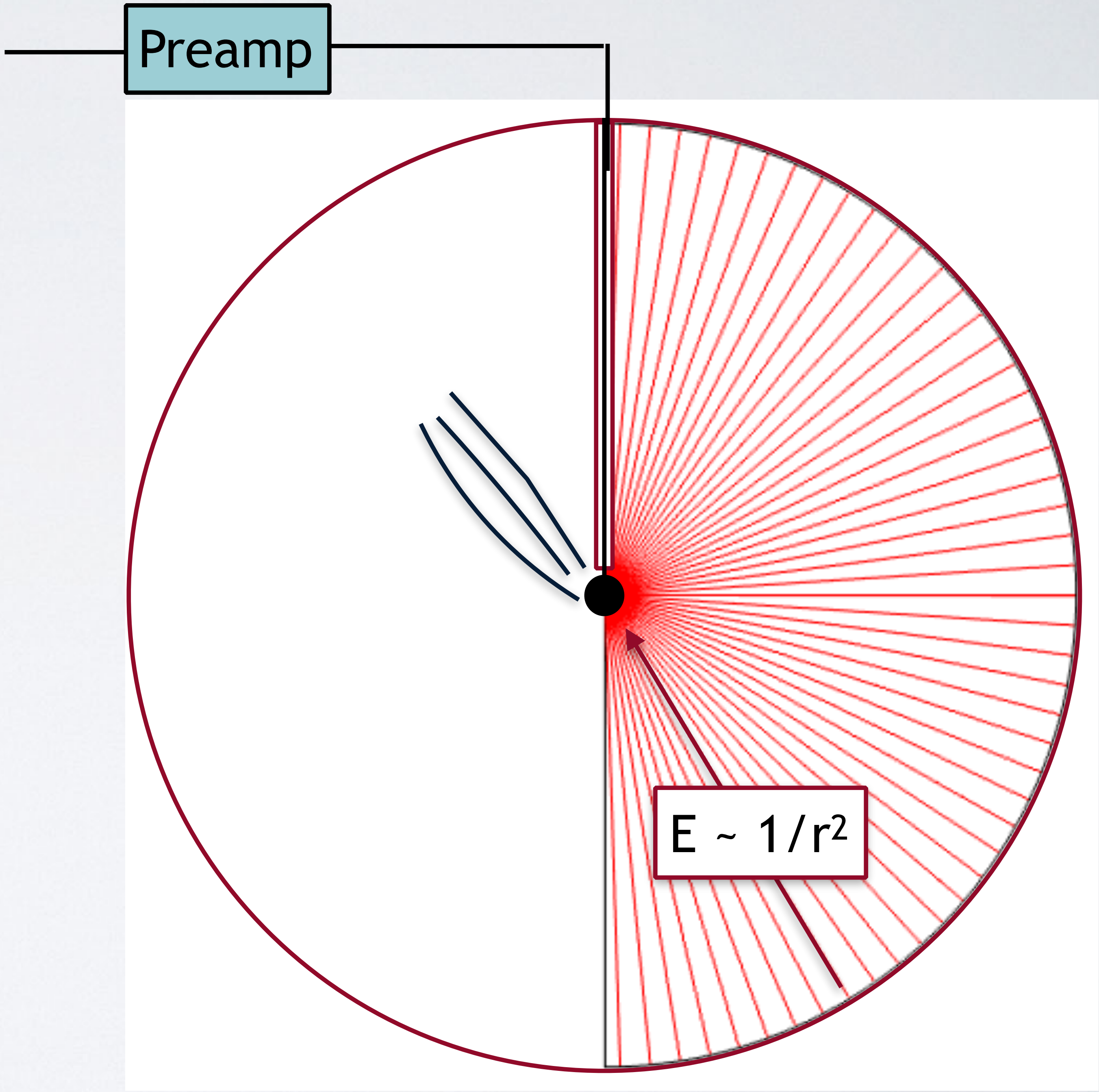
- Electron Drift
  - Drift time, up to ~ 500 μs
  - Diffusion ("spread"), up to ~ ±20 μs



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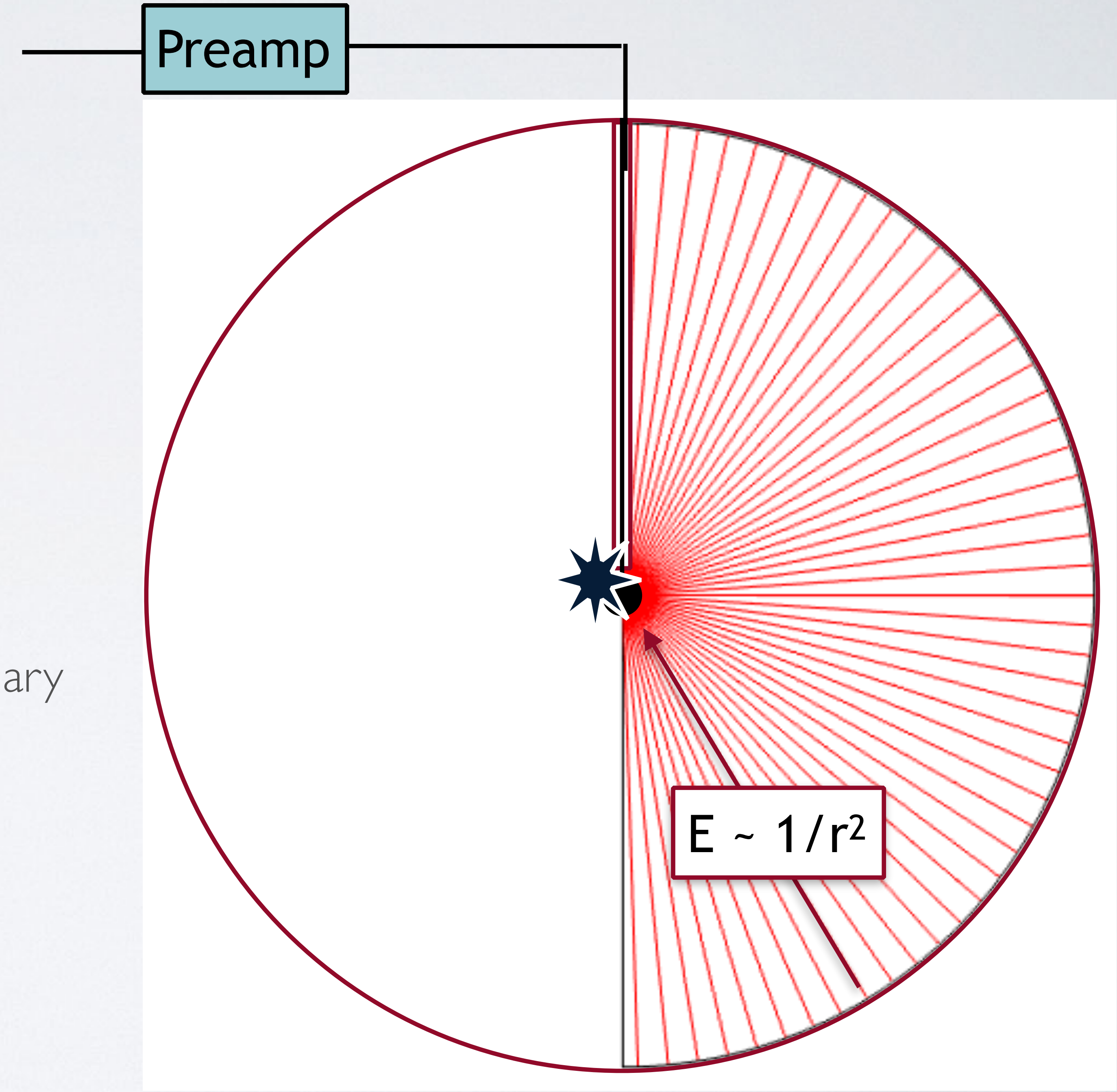

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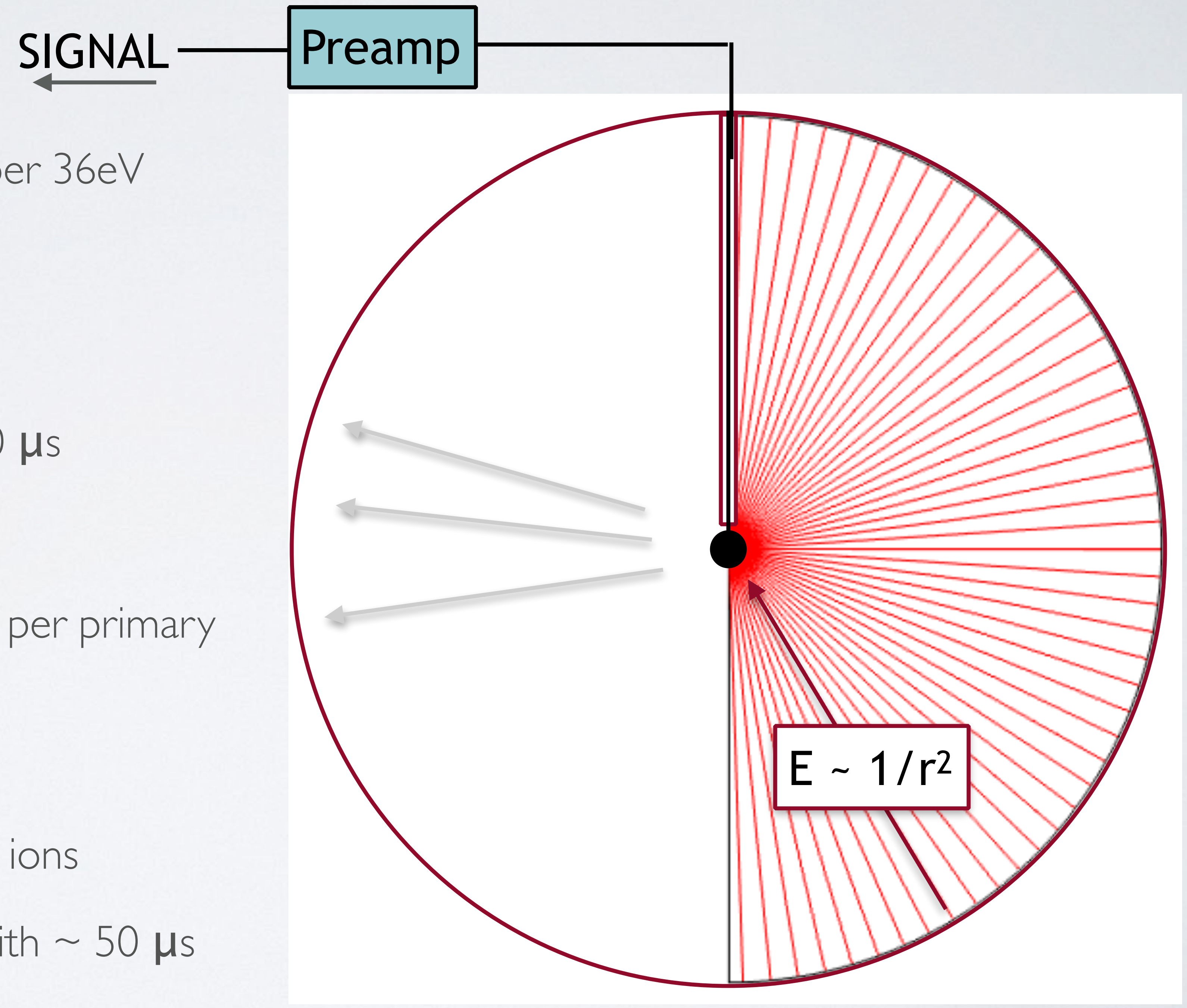
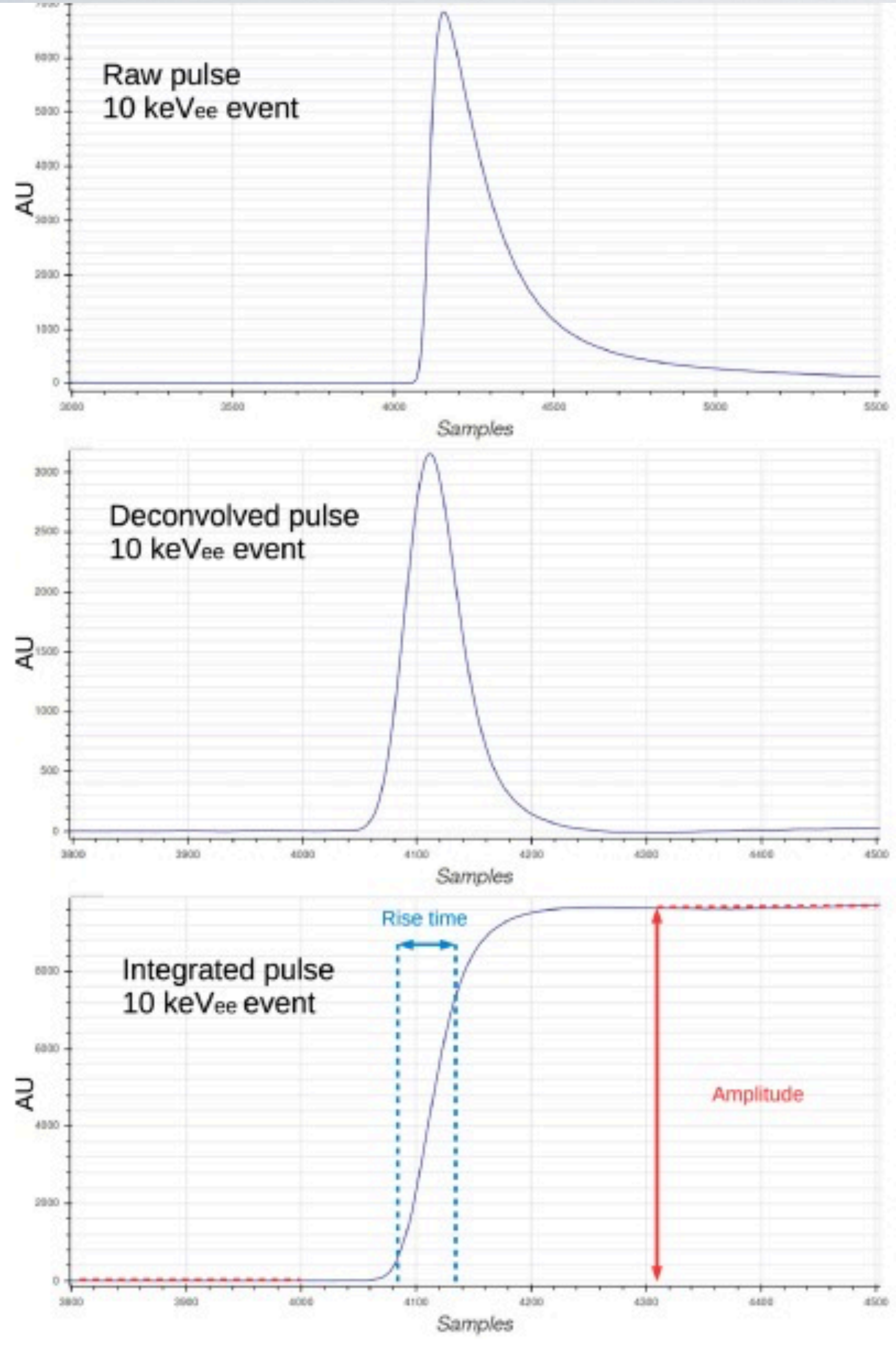
- Signal Formation
  - Current induced on electrode by ions
  - Preamplifier integrates current, with ~ 50 μs decay



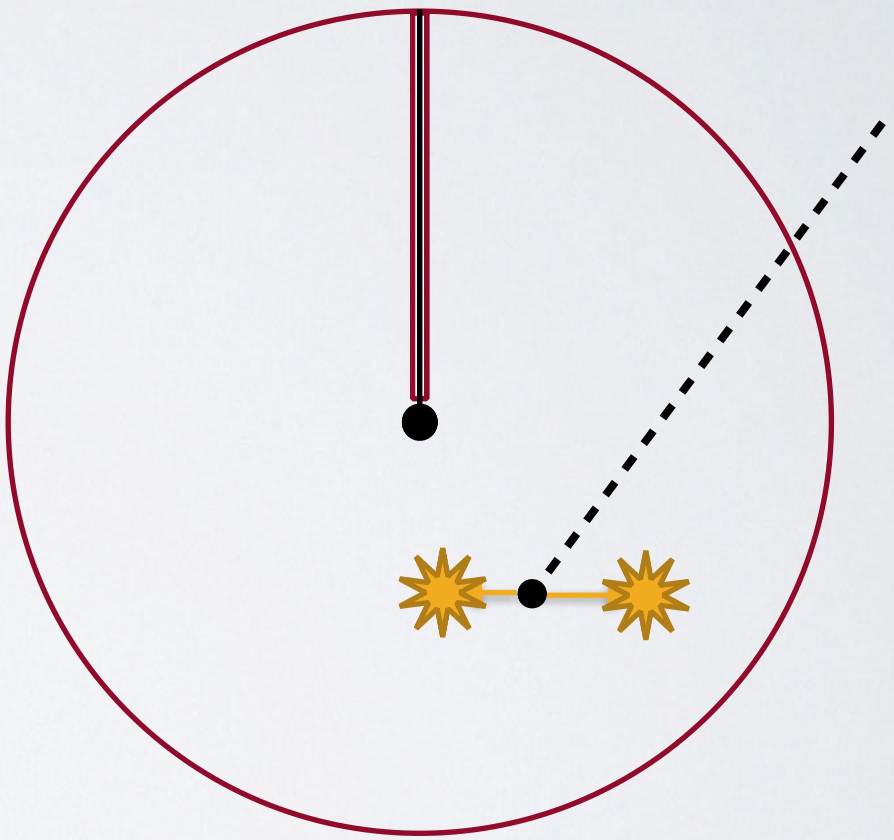


DATA PROCESSING

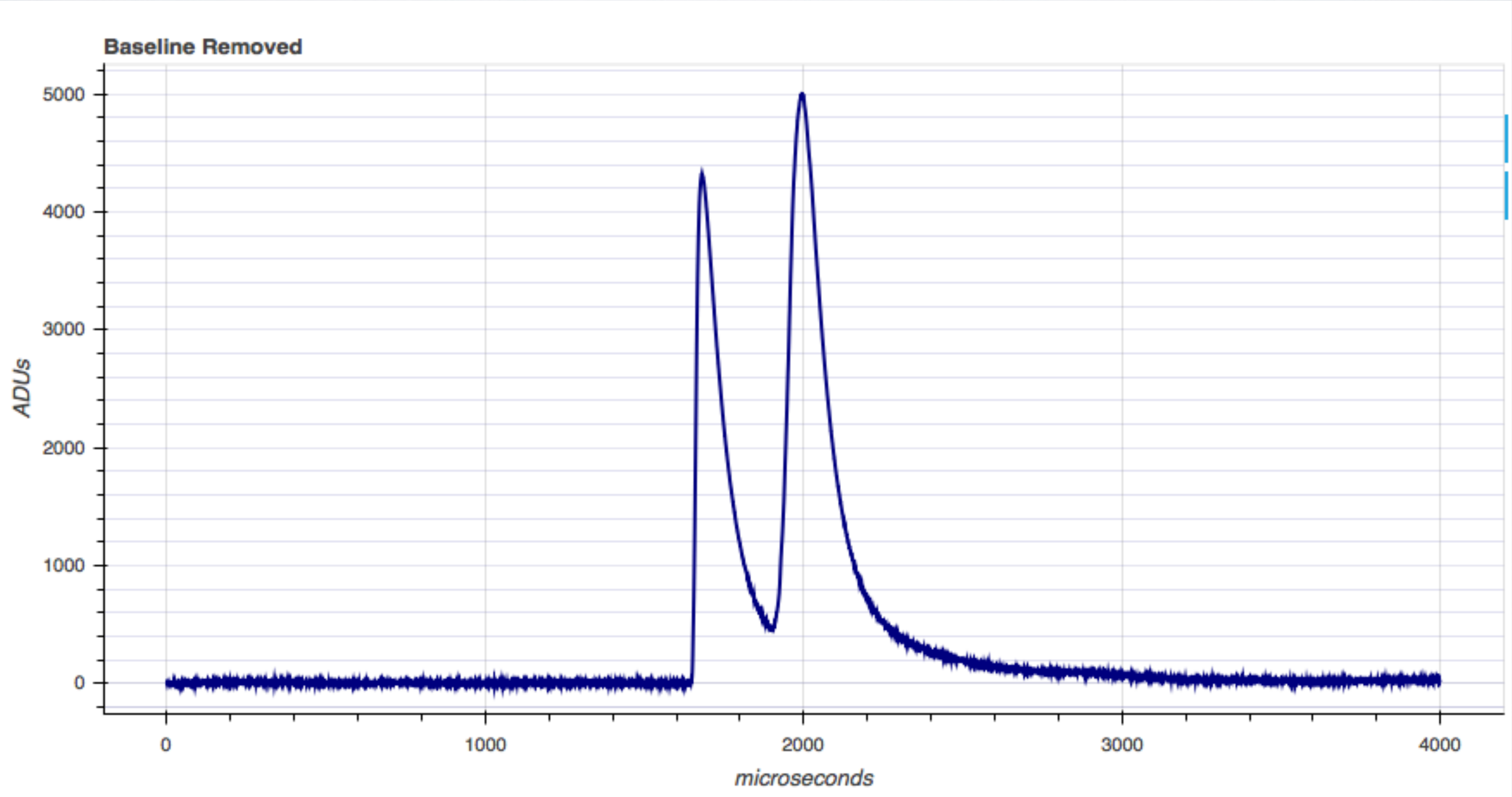
- Pulse as recorded on top. Raw pulse amplitude is biased for longer events.
- From understanding of the ion-induced current and preamplifier response, deconvolve raw pulse, then integrate it. This removes bias.
- Amplitude is an estimator of the energy of the event. Risetime is an estimator of the distance between the sensor and the energy deposition.

AXIONS IN SPC

- Axion decays into two back-to-back photons. Photons are captured at different sites, which will be seen as two different pulses within the same event window (unlike for solid or liquid detectors!).
- Axion decay rate depends only on volume of detector, not mass! Having a gas detector is not a drawback for exposure.



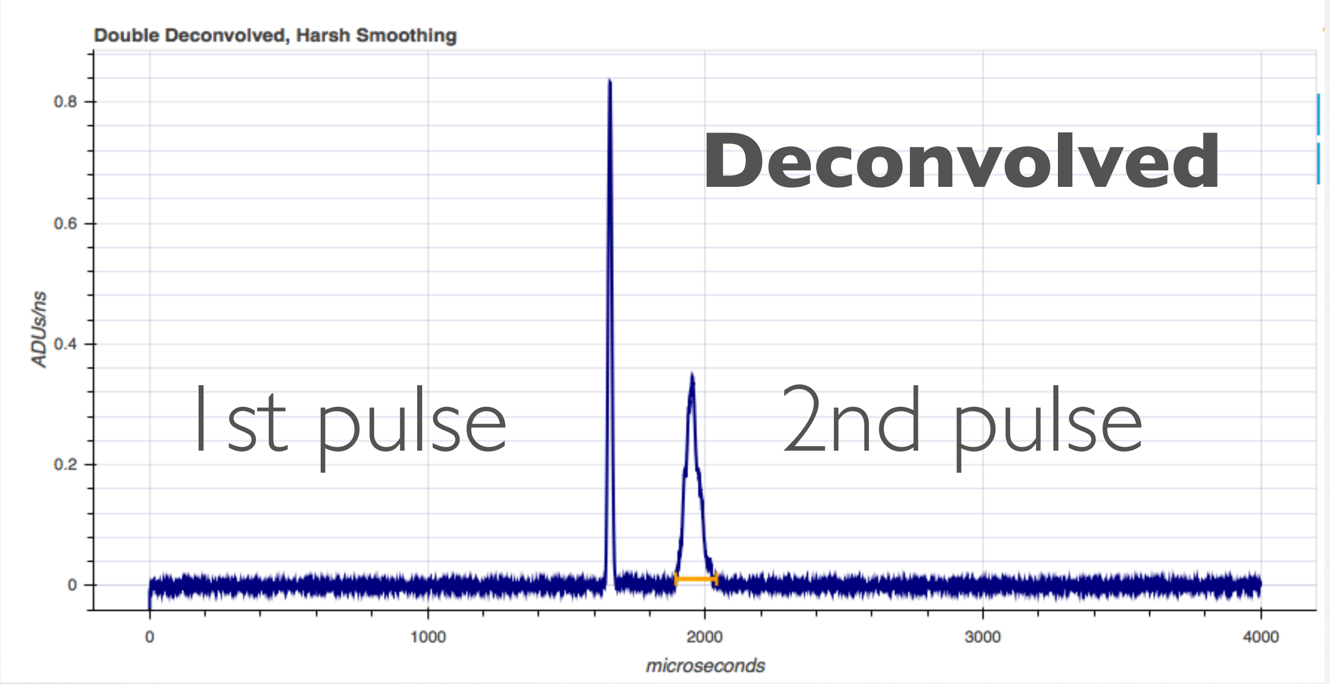
DOUBLE EVENT EXAMPLE

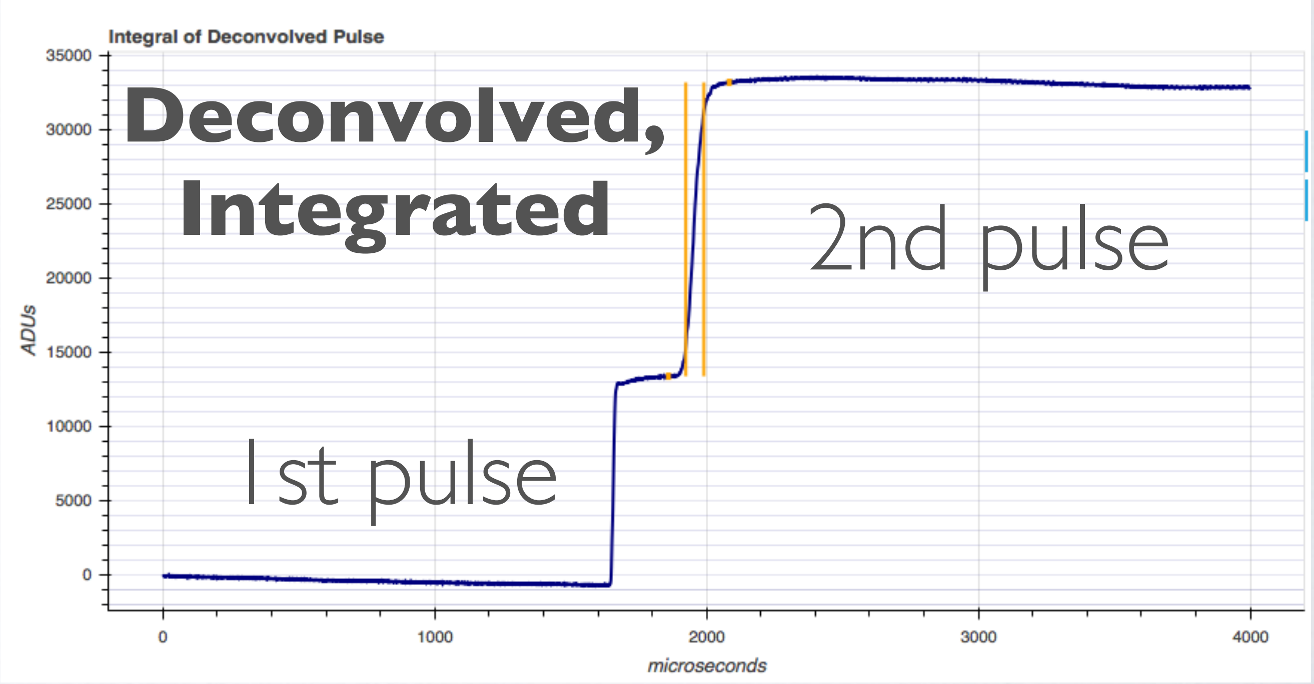


Run: pd02b000 , evt: 73162

ADAPTED PROCESSING: MULTIPLE PULSE ANALYZER

- Deconvolve response of detector from event.
- Separate full window into smaller windows where a pulse was found.
- Get the amplitude, risetime, width, etc. for each window.





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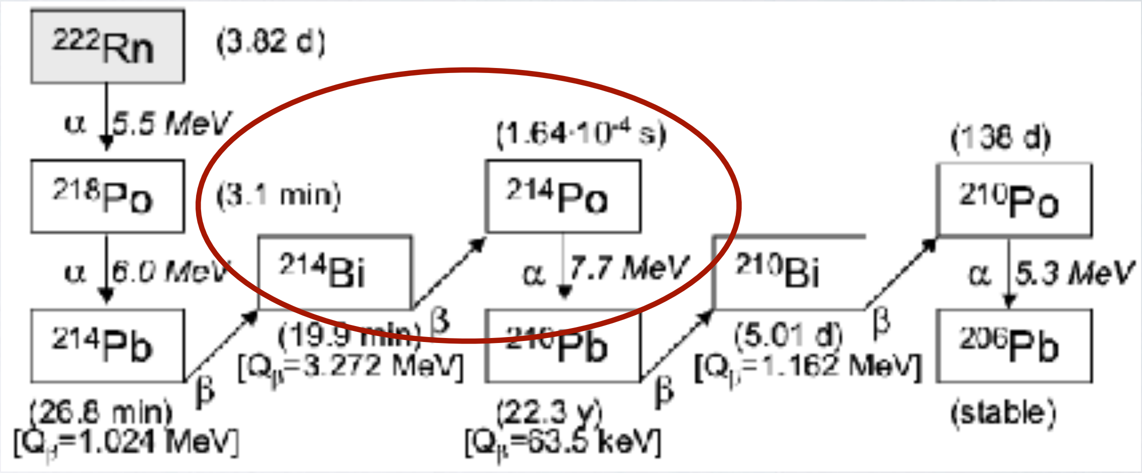
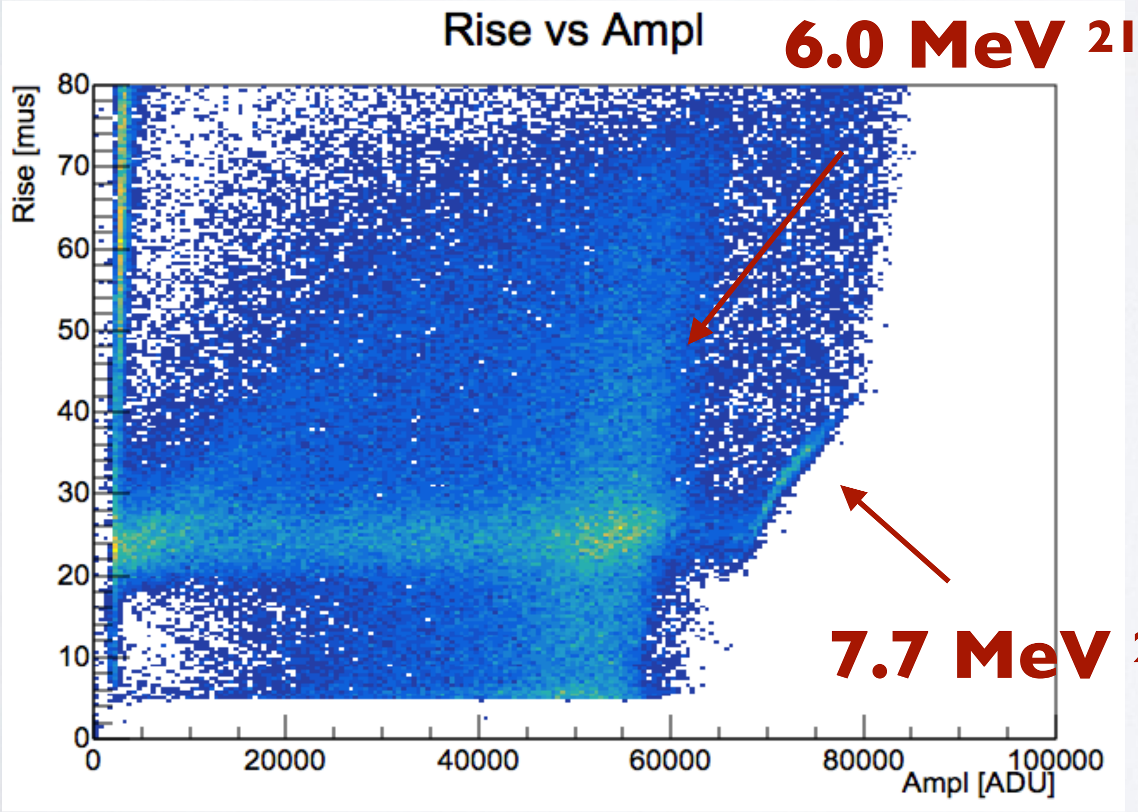
MPA: PROOF OF CONCEPT

- Bi-Po 214, half-life of Polonium is 160 microseconds, **we expect to see both events in the same window.**
- Calibration run with ^{222}Rn:



5.5 MeV ^{222}Rn
6.0 MeV ^{218}Po



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All events: 141281

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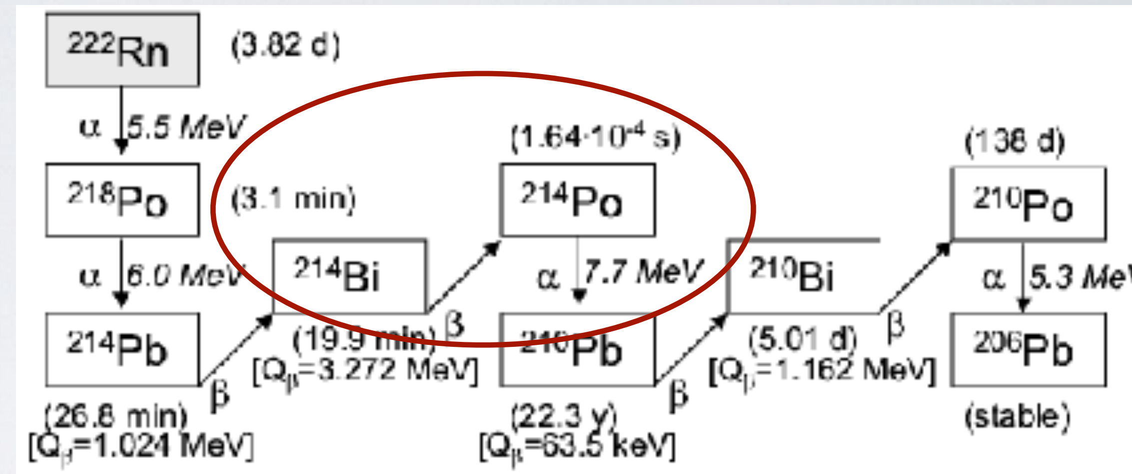

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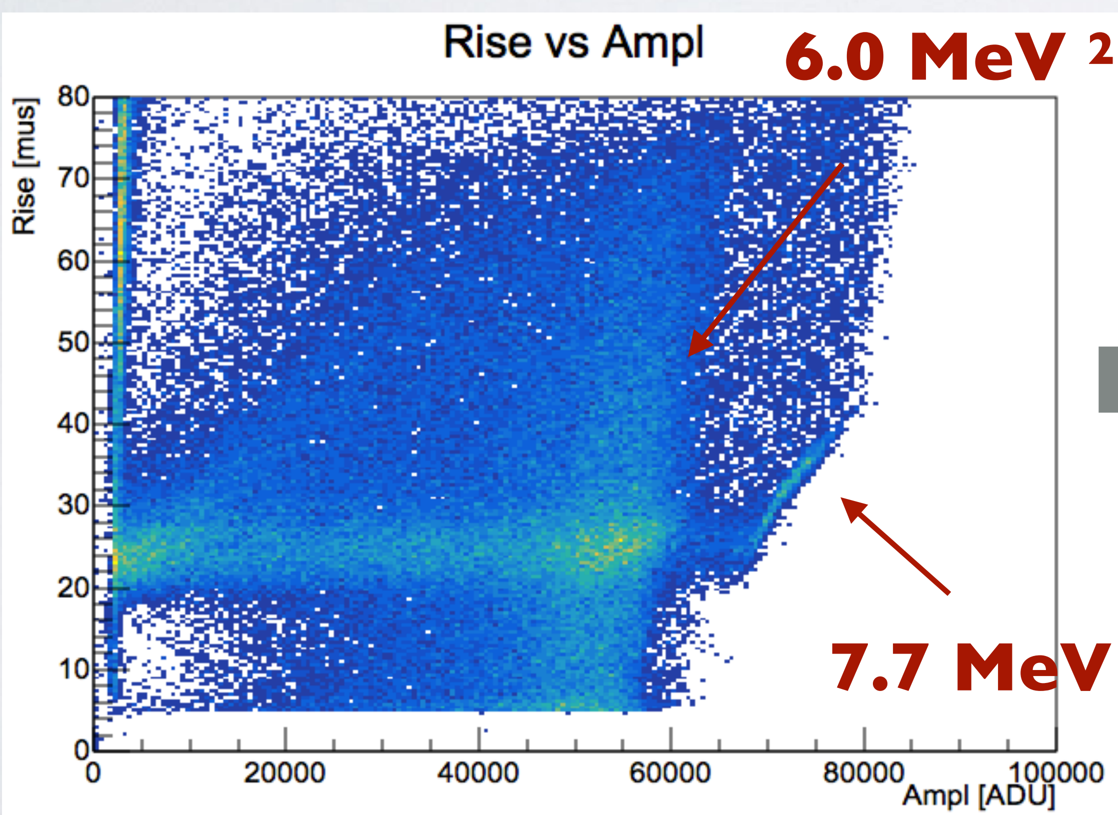

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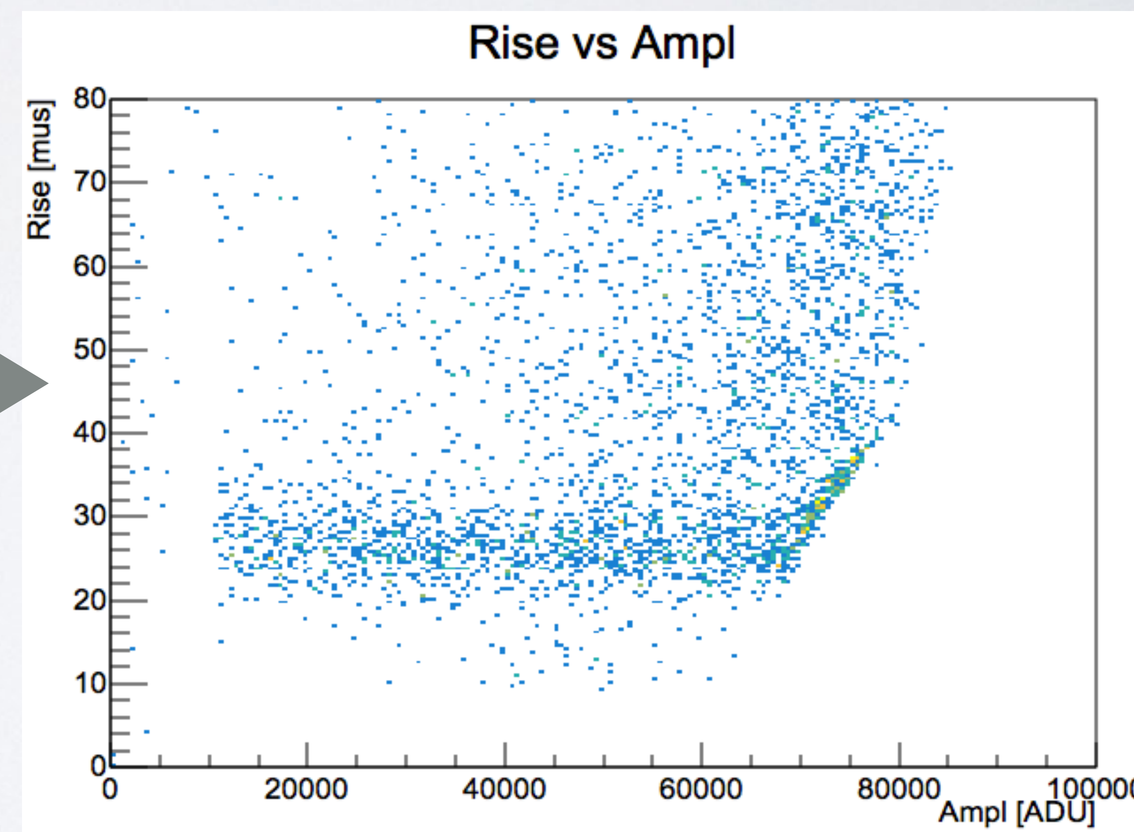

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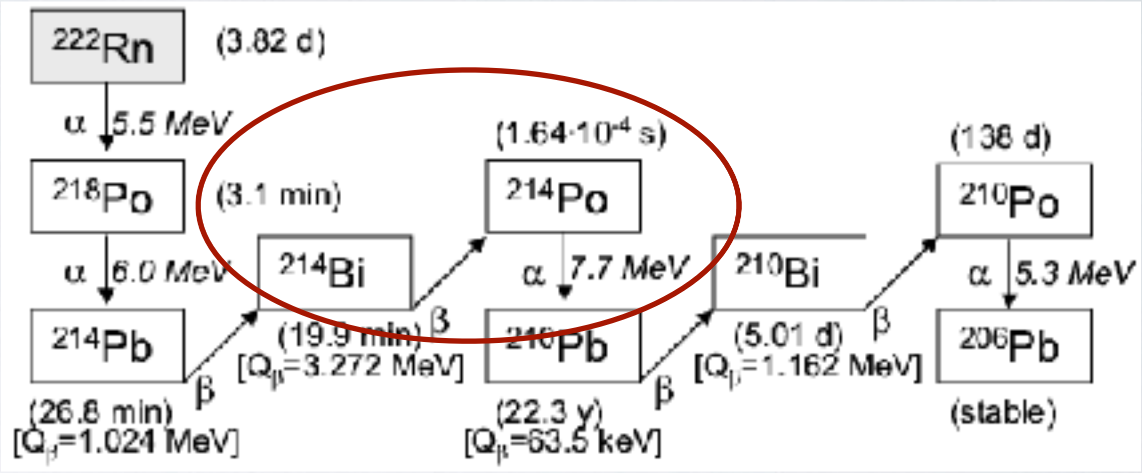

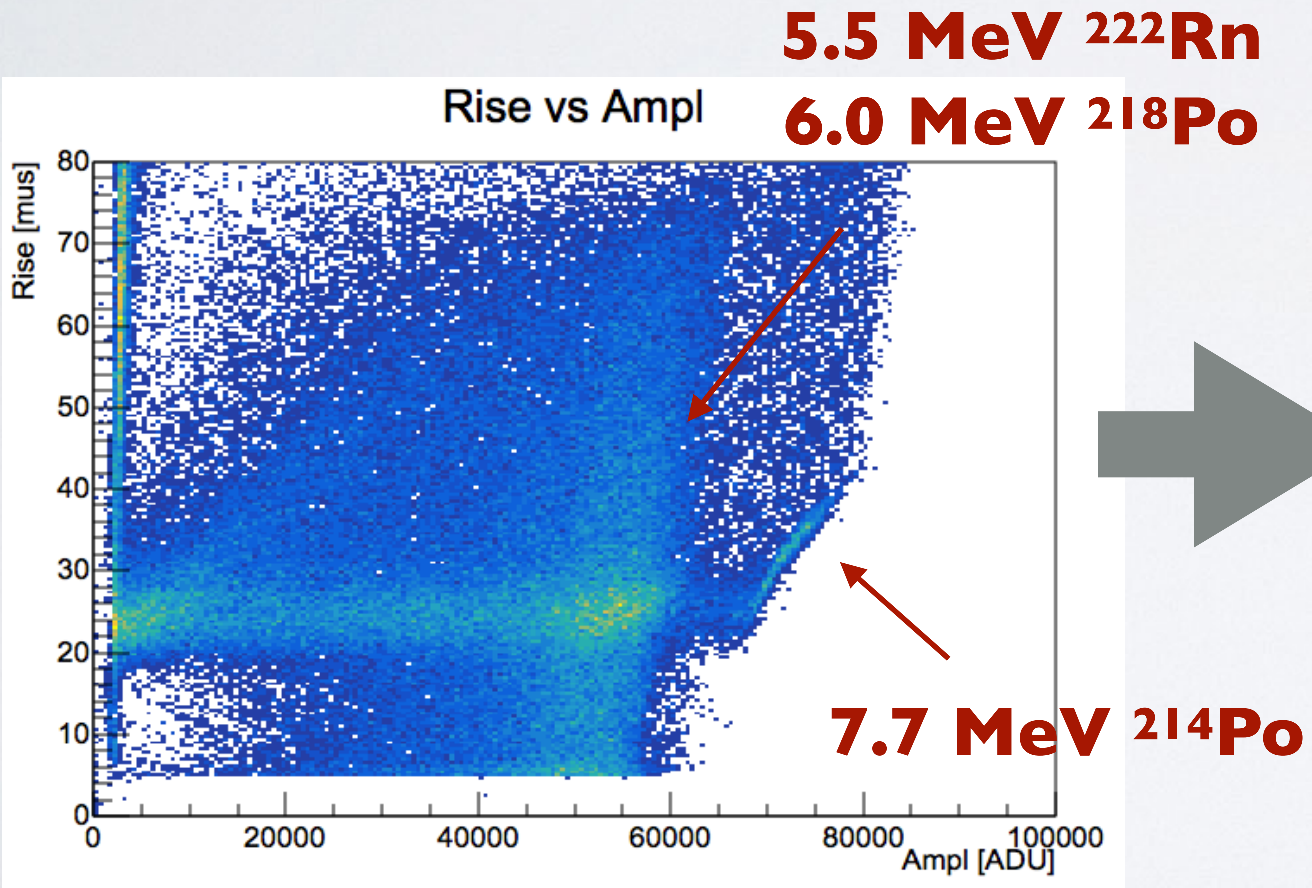

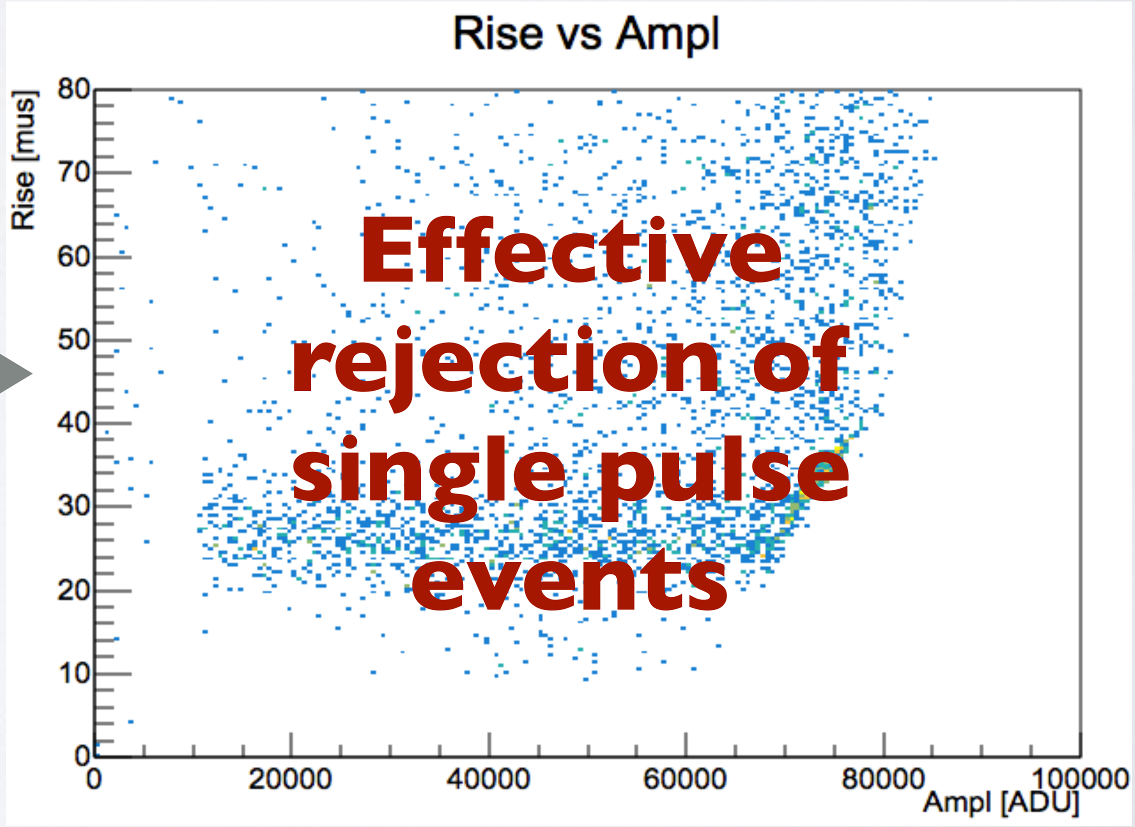

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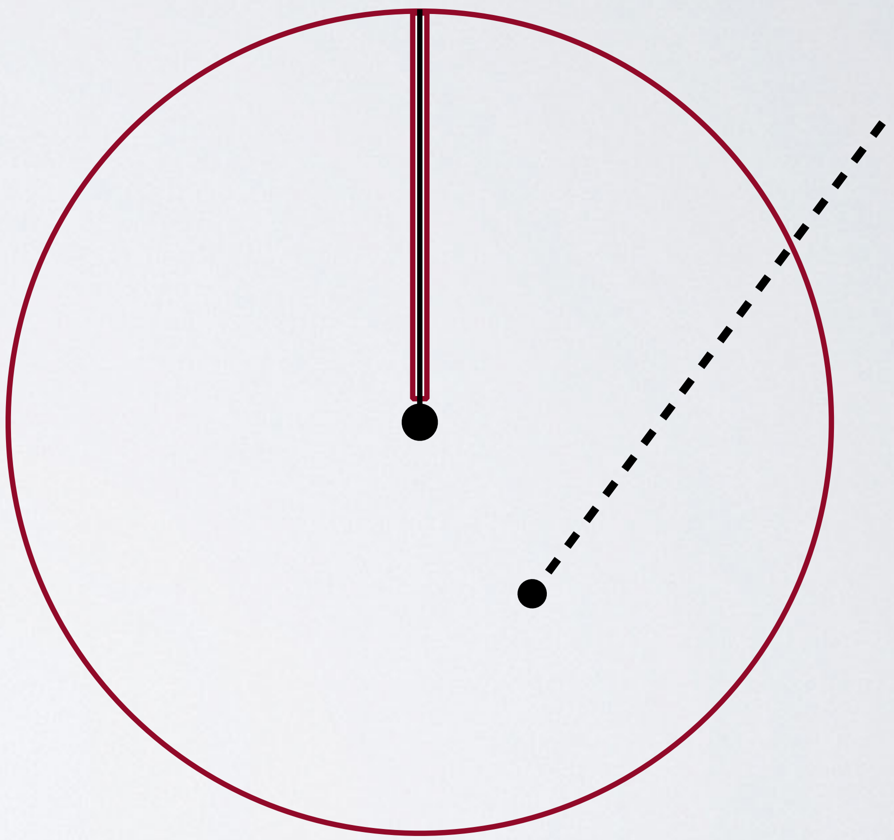
SEDINE PHYSICS DATA

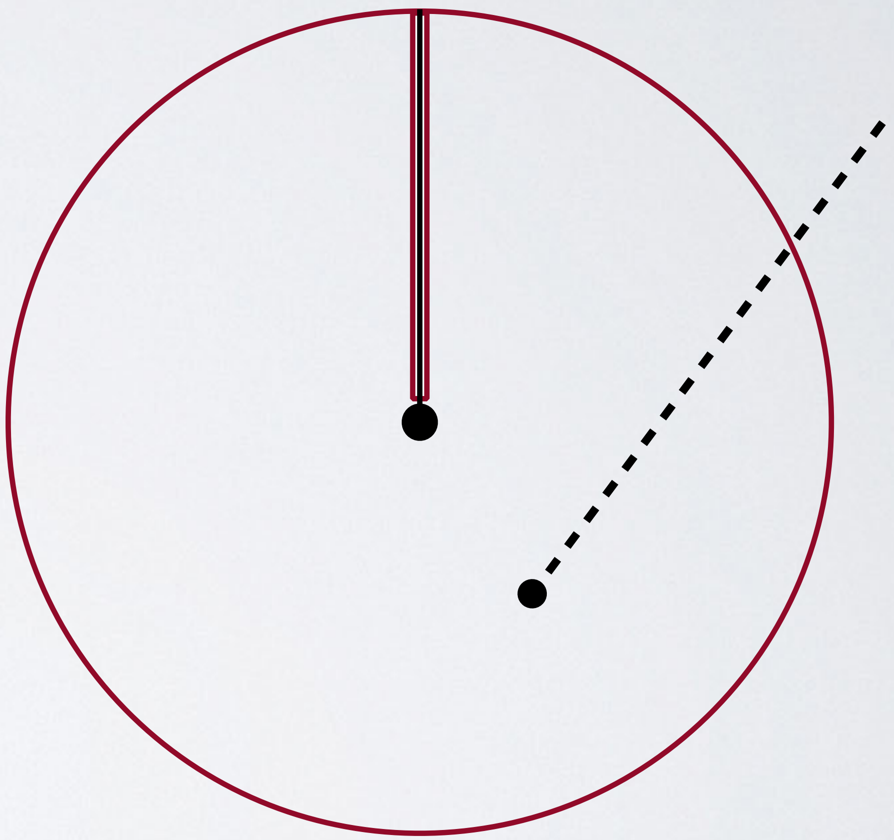
- 42 day long background run with 3.1 bar of Neon
- 60 cm diameter, for ~0.113 m^3, or ~4.75 m^3•day
- Total number of events before cuts ~ 1,640,000
- Data was already used to produce low mass WIMP exclusion limits (Astropart.Phys. 97 (2018) 54-62)
- Reused now for solar KK axion search:
  - Select events with two pulses of similar energy, with second one being wider than first one.

SIMULATIONS



SIMULATIONS

- Attenuation length of photon depends on energy, gas type, and pressure. Need sufficient separation to discriminate both positions, but not so much that photons leave the detector.



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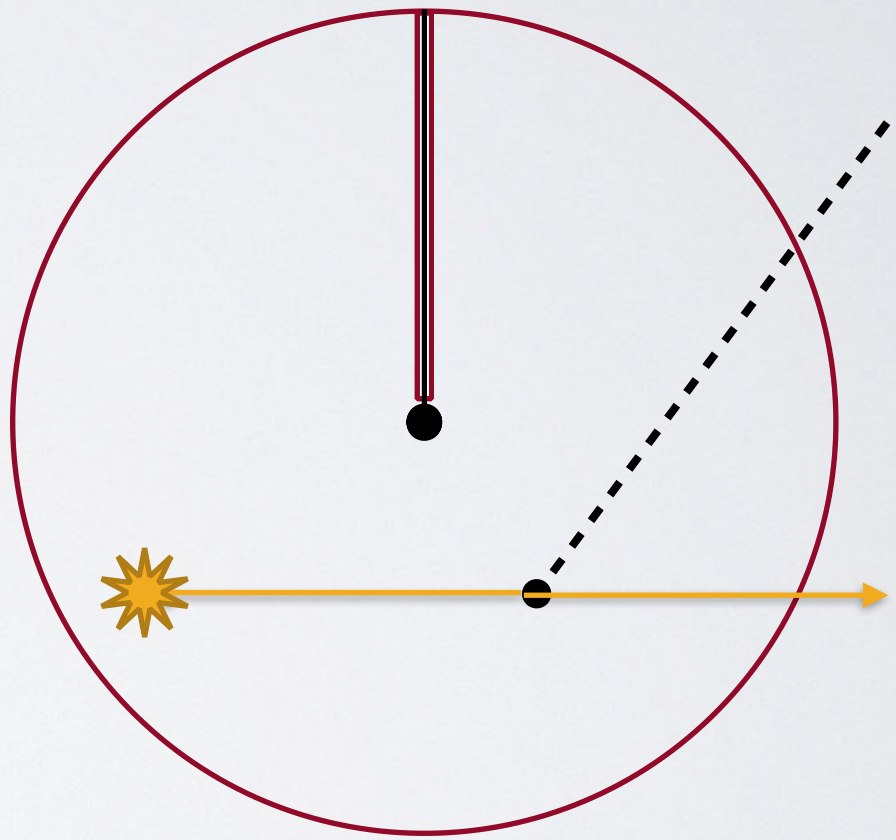

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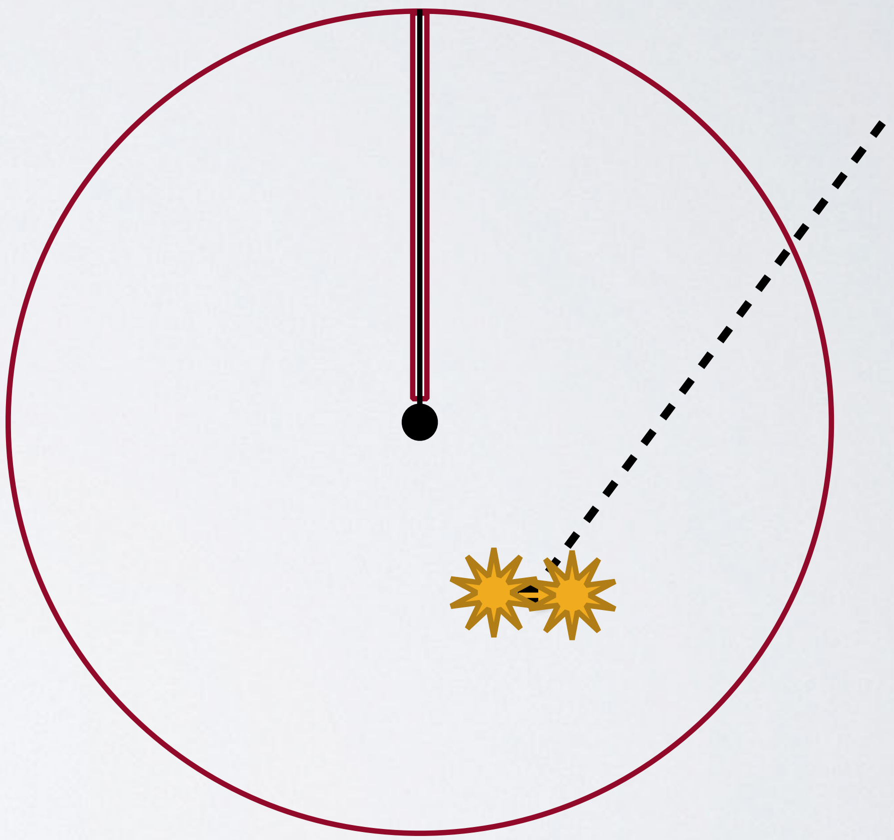

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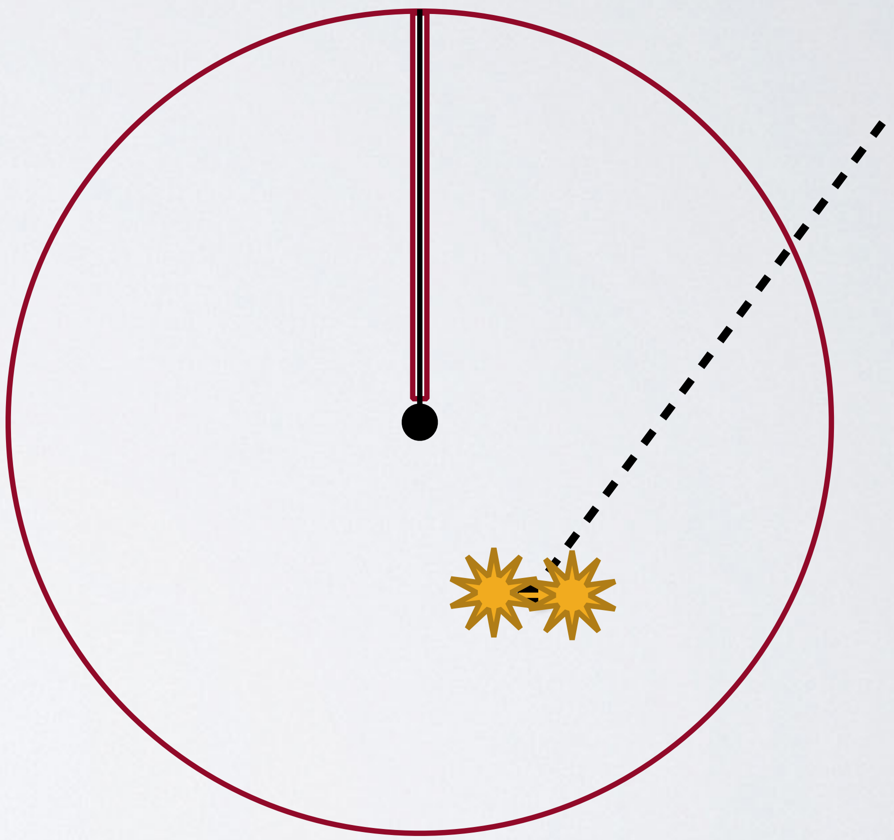
- We can simulate axion events, from attenuation length of photons (NIST data), drift time and diffusion of electrons (COMSOL + Magboltz), and finally response function of detector.
- Simulations allow determination of detector sensitivity, choice of parameter cuts, and of optimal run conditions.



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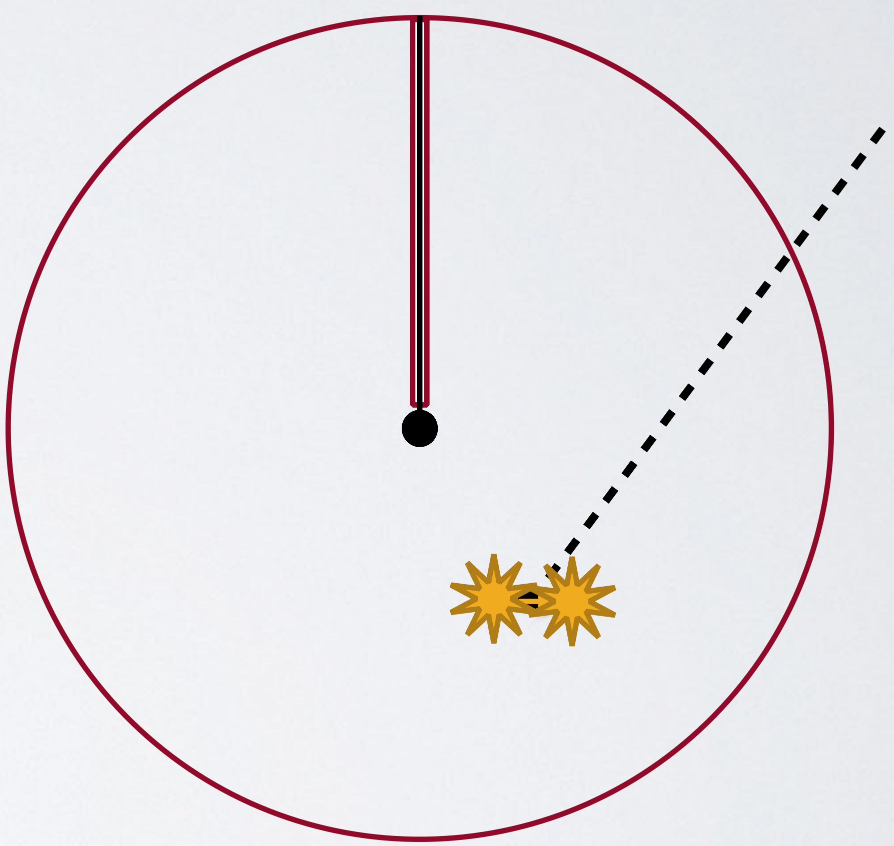
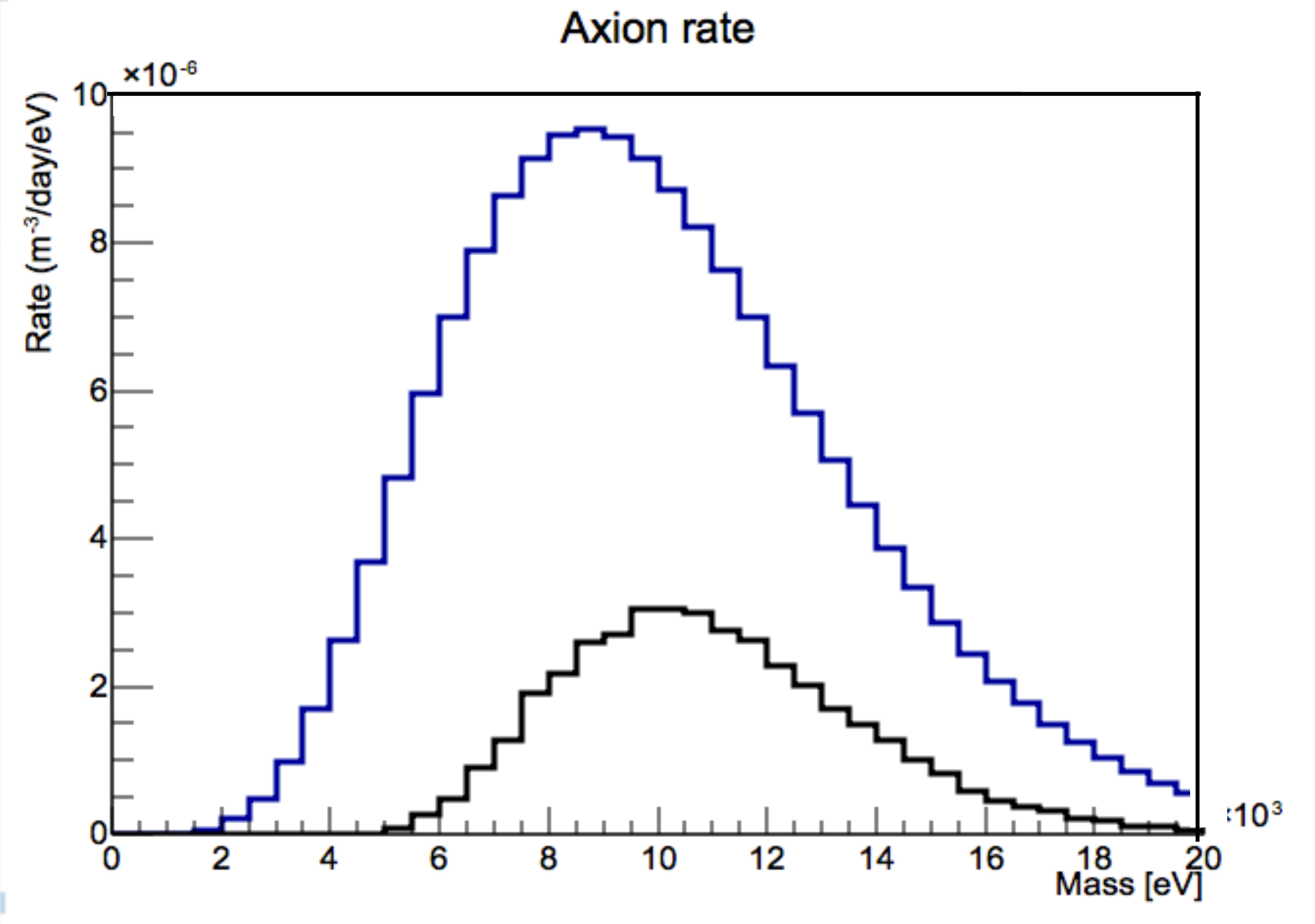


Minimum radius difference ~ 2.5 cm (from simulations)

SEDINE SOLAR KK AXION EXPECTED SIGNAL



Blue: total axion decay rate (Morgan et al, 2005)
Black: rate accounting for detector sensitivity, ~25% total

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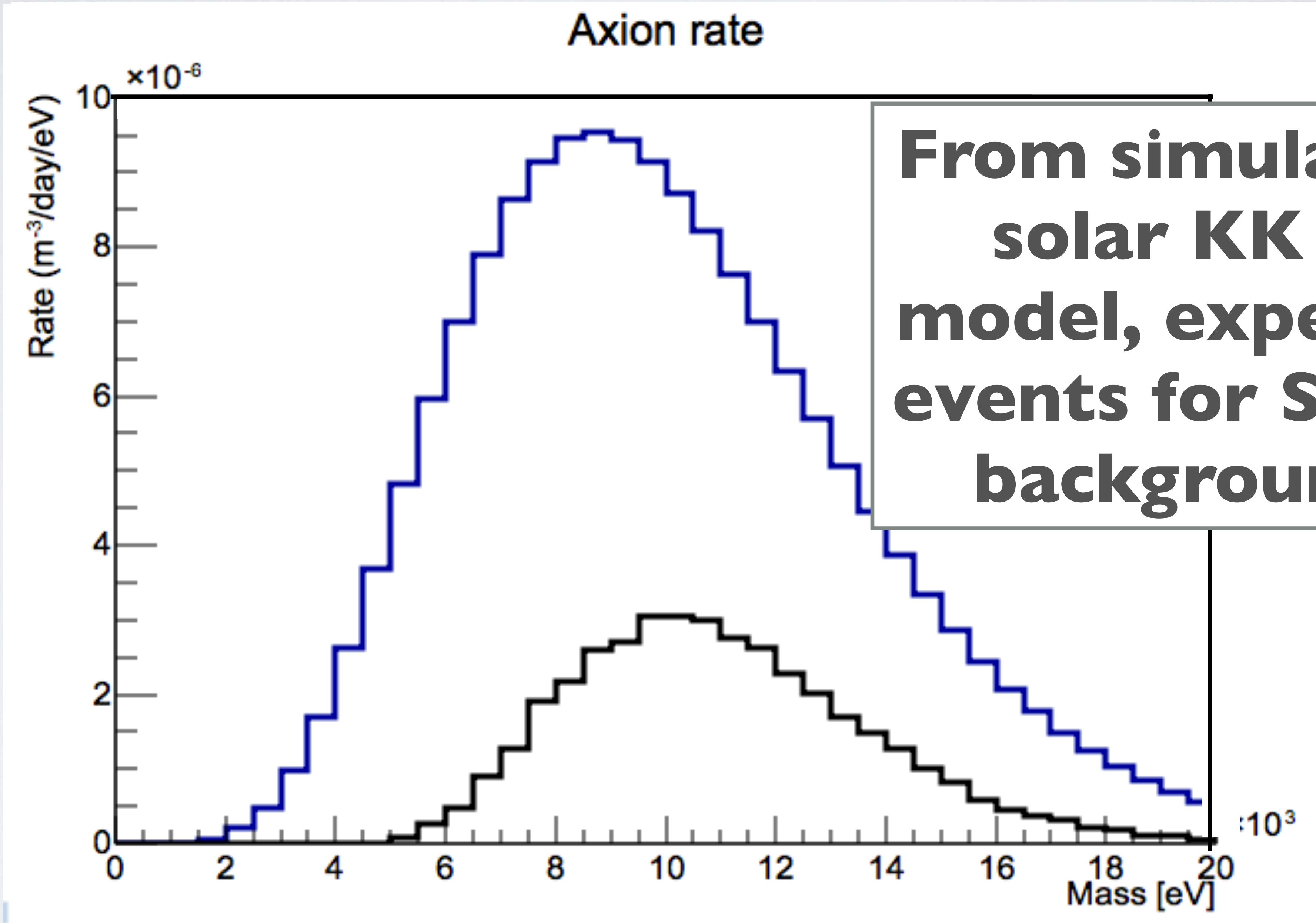

From simulations of solar KK axion model, expect 0.095 events for SEDINE's background run

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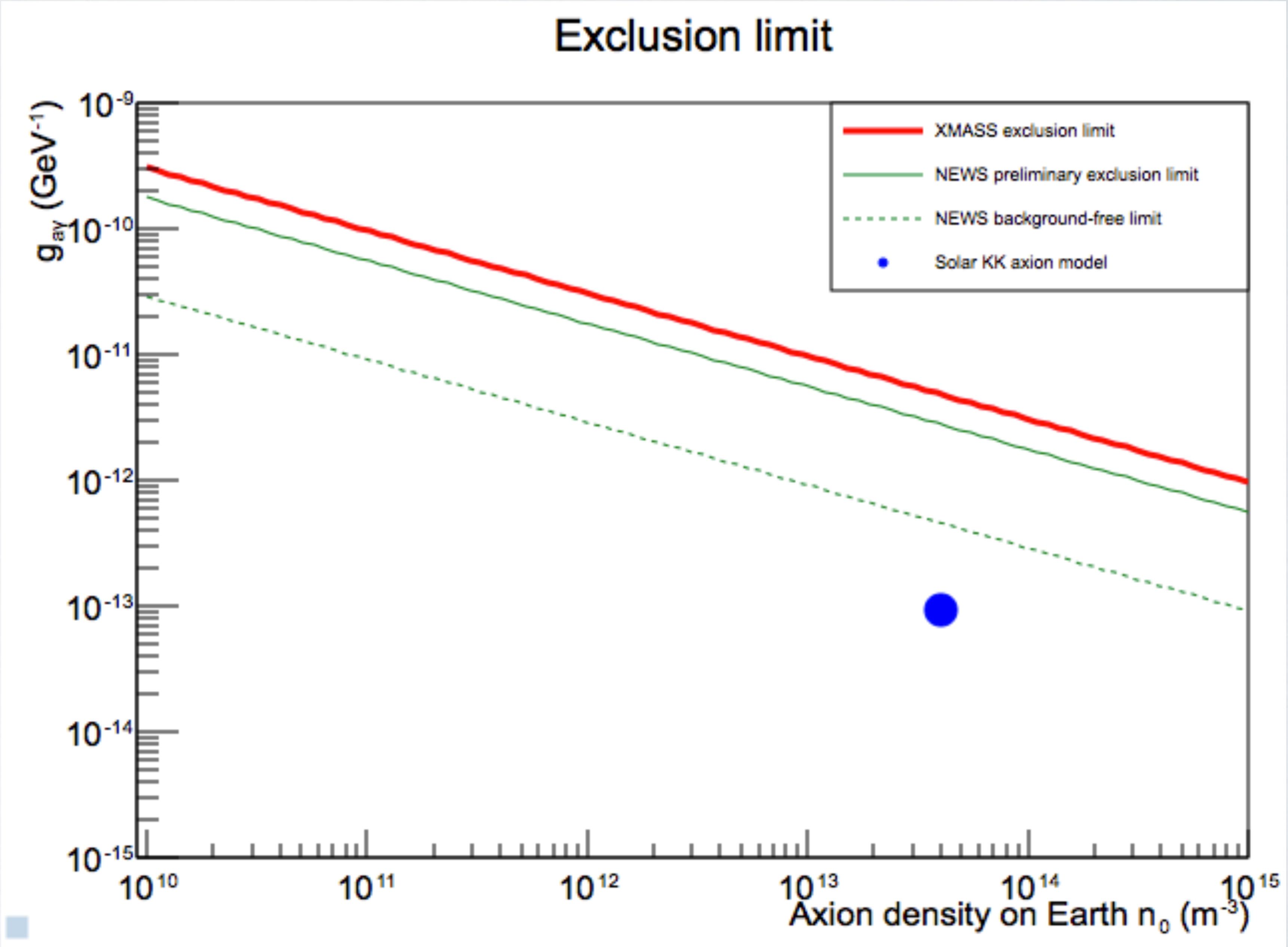
Black: rate accounting for detector sensitivity, ~25% total

SEDINE SENSITIVITY

- We can use simple Poisson statistics to derive both the background-free and the preliminary exclusion limits based on number of observed events.
- We use the MPA on the background run, and find 73 events.
- We expect these events to be non-axion background, but a detailed study is necessary before performing background subtraction.



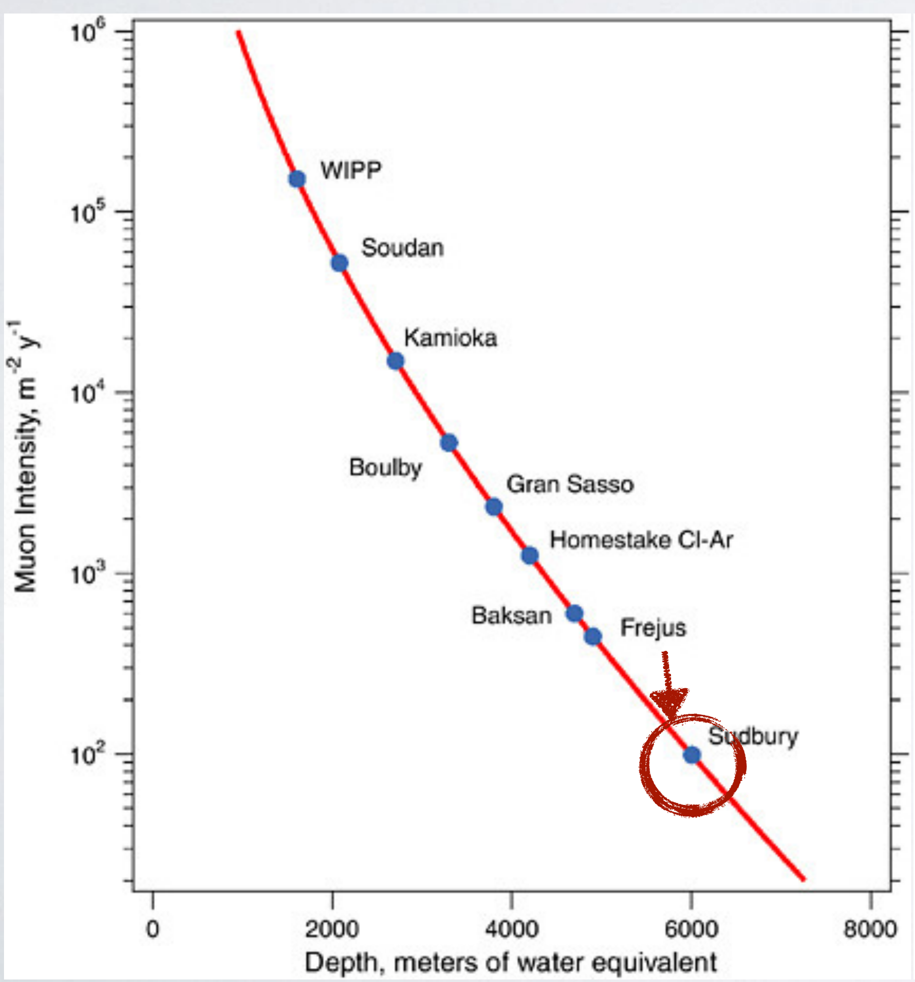
NEWS@

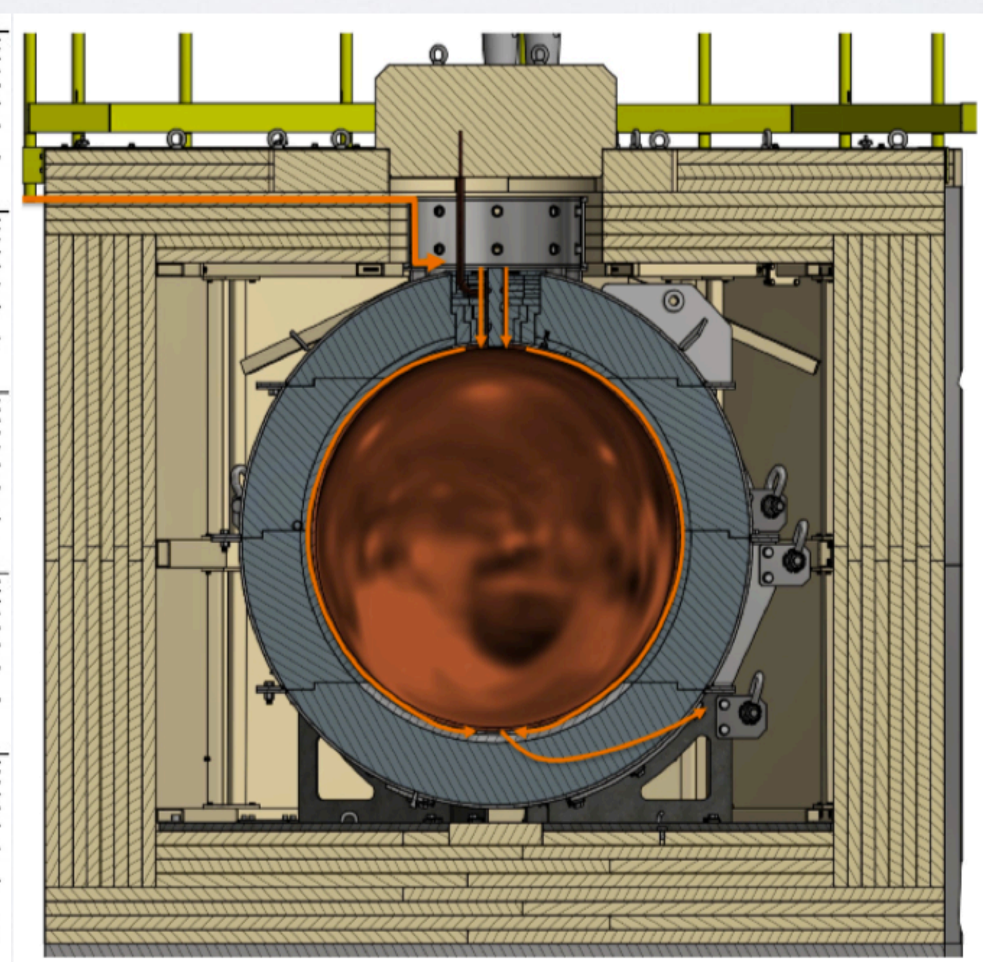
UPCOMING NEW DETECTOR
Exposure improvement:

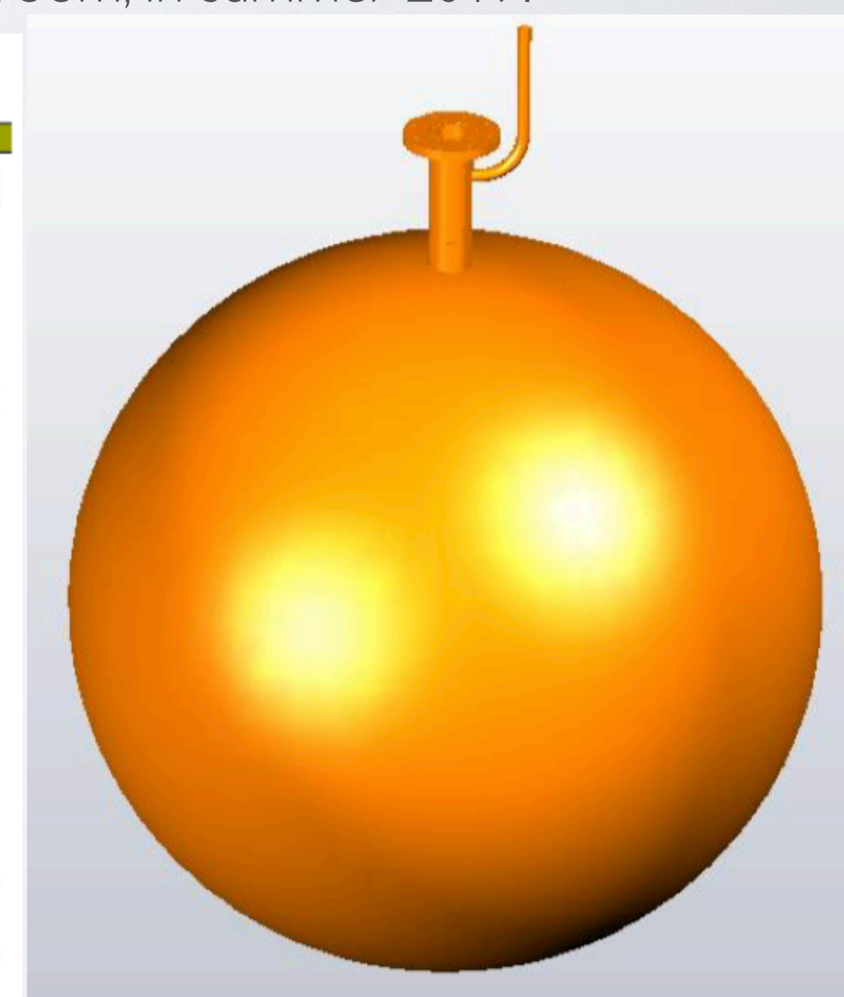
- 140 cm diameter (instead of 60) ~12.5 times more volume!

Background improvement:

- 25 cm of lead shielding, 34 cm of polyethylene shield (instead of 15 and 28, respectively).
- The inside of the sphere will be electroplated before data taking for higher surface purity.
- Will be installed at SNOLAB (Sudbury, Canada), World's deepest clean-room, in summer 2019.







NEWS@SNOLAB

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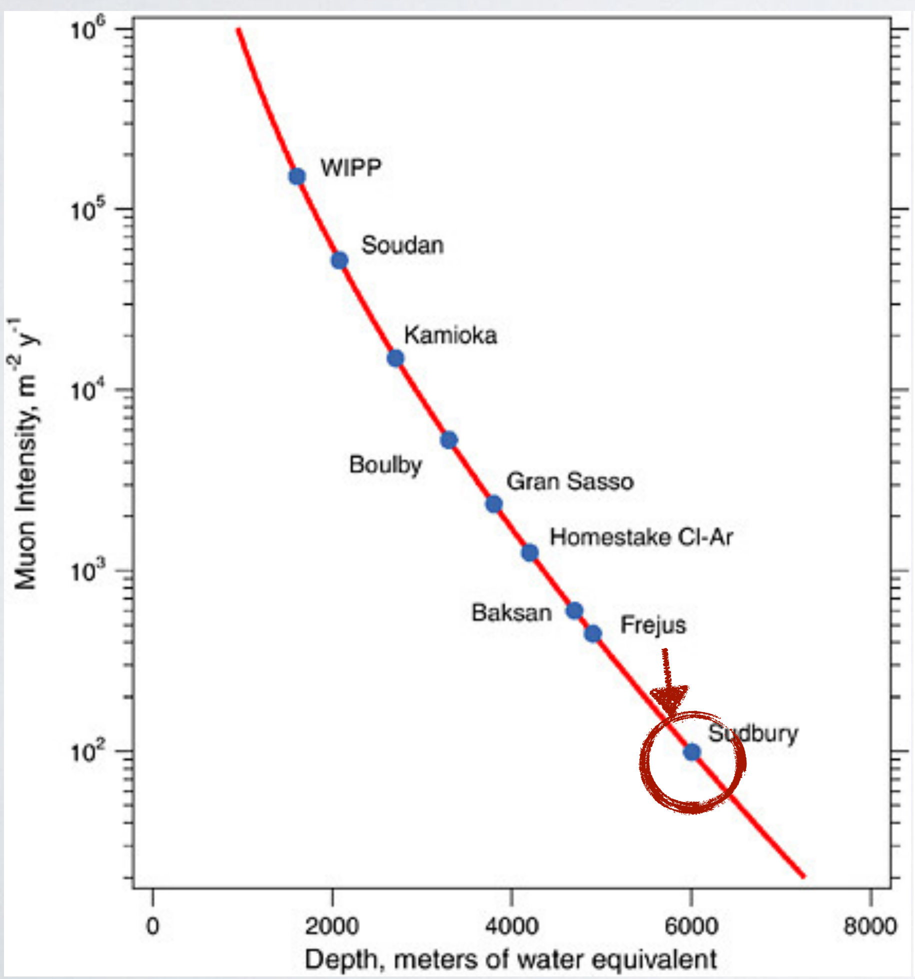
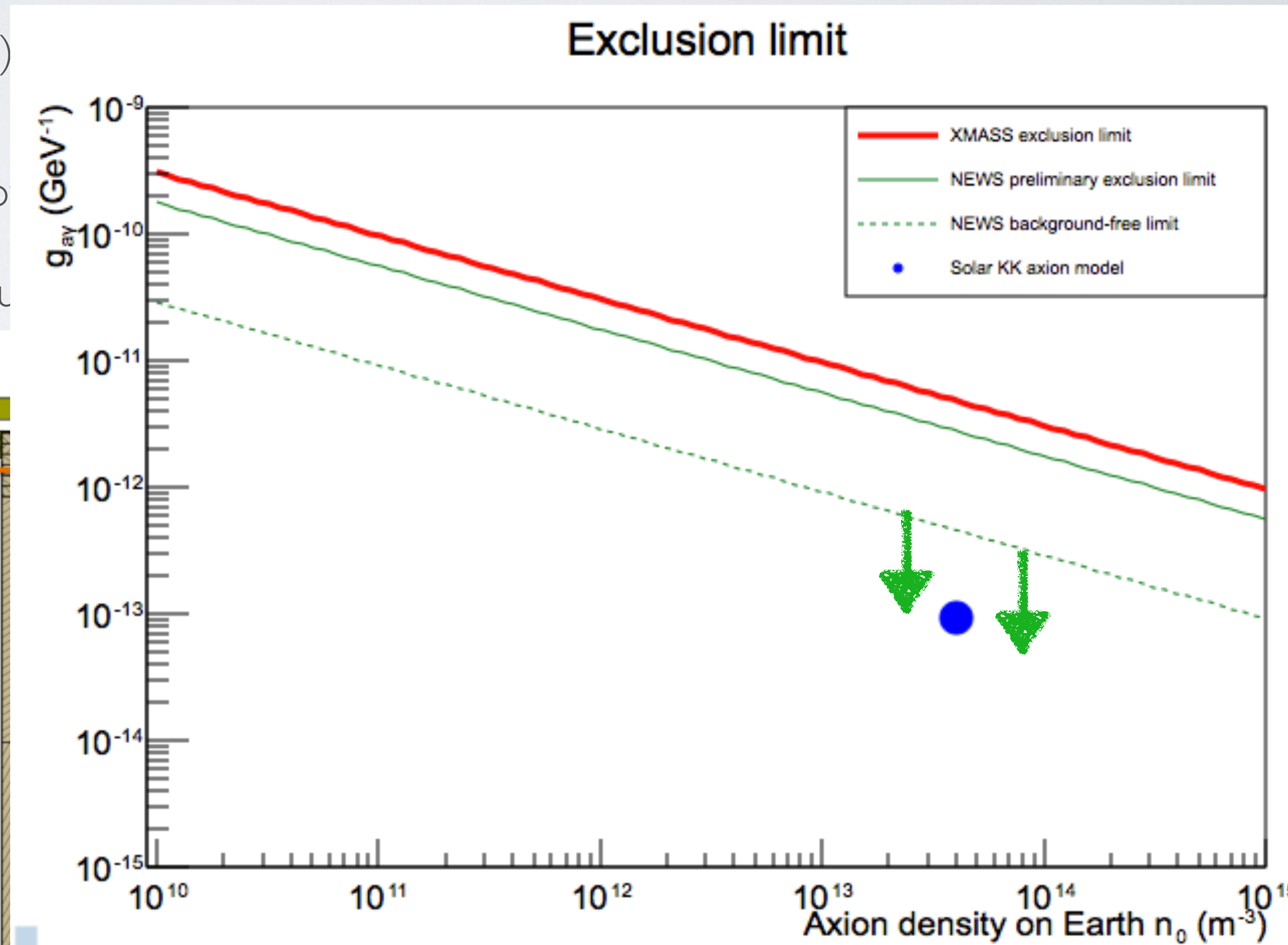




CONCLUSION

- Axions, and their extension, KK axions, have compelling arguments in favour of their existence, and trapped solar KK axions could be detected with SEDINE.

- Preliminary results based on existing data suggest NEWS-G can set leading exclusion limits on solar KK axions. Further analysis required before definitive results.

- The new, larger NEWS-G detector at SNOLAB will likely be able to probe the preferred parameter space of the solar KK axion model.

Thank you for your attention!

- **Queen's University Kingston –** G Gerbier, P di Stefano, R Martin, G Giroux, T Noble, D Durnford, S Crawford, M. Vidal, A Brossard, F Vazquez de Sola, Q Arnaud, K Dering, J McDonald, M Clark, M Chapellier, A Ronceray, P Gros, J Morrison, C. Neyron
  - Copper vessel and gas set-up specifications, calibration, project management
  - Gas characterization, laser calibration, on smaller scale prototype
  - Simulations/Data analysis

2018 Summer : +
C. Garrah, A. Goodman, W. Salmon, T. Ward

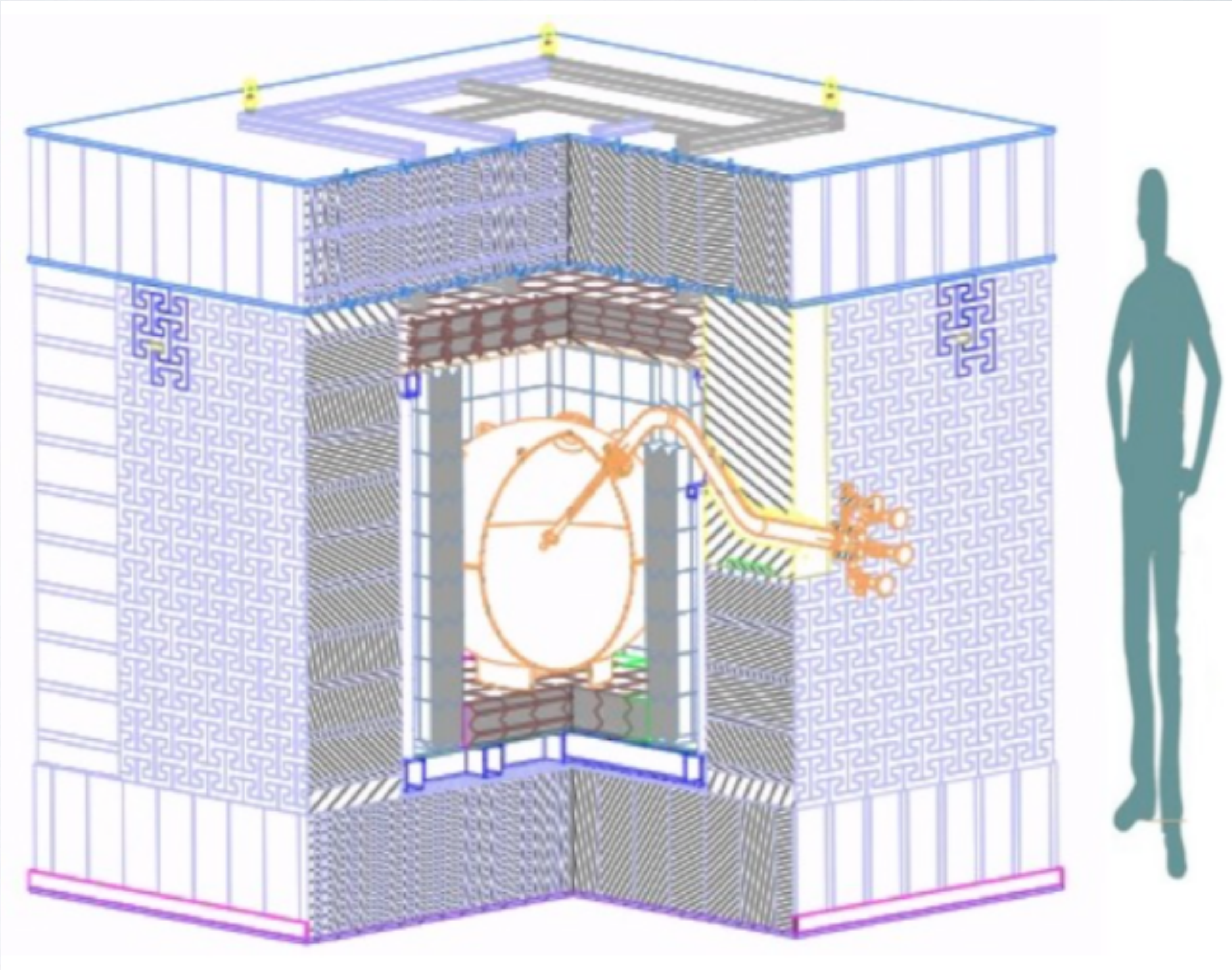
- **IRFU** (Institut de Recherches sur les Lois fondamentales de l'Univers)**/CEA Saclay** - I Giomataris, M Gros, C Nones, I Katsioulas, T Papaevangelou, JP Bard, JP Mols, XF Navick,
  - Sensor/rod (low activity, optimization with 2 electrodes)
  - Electronics (low noise preamps, digitization, stream mode)
  - DAQ/soft
- **LSM** (Laboratoire Souterrain de **Modane**), IN2P3, U of Chambéry **-** F Piquemal, M Zampaolo, A Dastgheibi-Fard
  - Low activity archeological lead
  - Coordination for lead/PE shielding and copper sphere
- **Thessaloniki University –** I Savvidis, A Leisos, S Tzamarias
  - Simulations, neutron calibration
  - Studies on sensor
- **LPSC** (Laboratoire de Physique Subatomique et Cosmologie) **Grenoble** - D Santos, JF Muraz, O Guillaudin
  - Quenching factor measurements at low energy with ion beams
- **Pacific National Northwest Lab–** E Hoppe, R. Bunker
  - Low activity measurements, Copper electroforming
- **RMCC** (Royal Military College Canada) **Kingston –** D Kelly, E Corcoran
  - 37 Ar source production, sample analysis
- **SNOLAB –Sudbury –** P Gorel
  - Calibration system/slow control
- **University of Birmingham–** K Nikolopoulos, P Knights, R Ward
  - Simulations, analysis, R&D
- **Associated lab : TRIUMF** - F Retiere
  - Future R&D on light detection, sensor

(A BUNCH OF) EXTRA SLIDES

NEWS-G : BACKGROUND

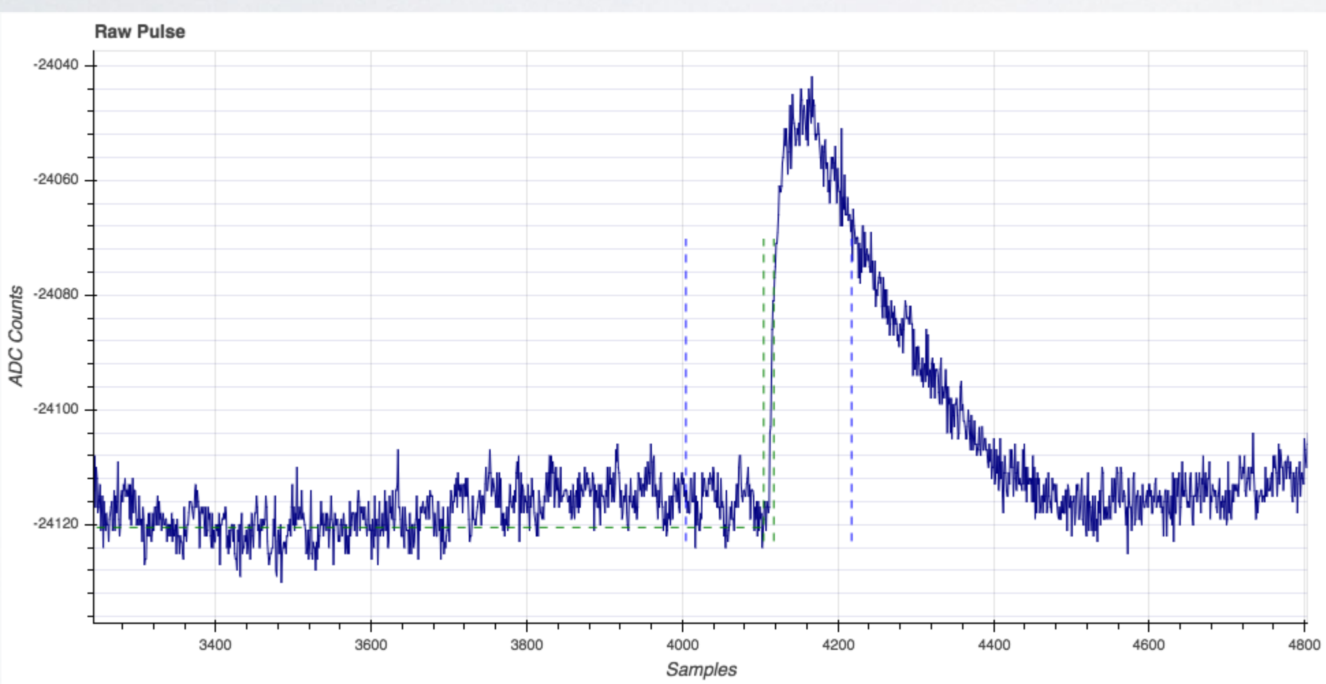
- <u>Sources:</u>
  - Cosmic radiation
  - Cosmic-activated copper
  - Uranium and Thorium decay chains
- Generate alphas, gammas, neutrons and electrons

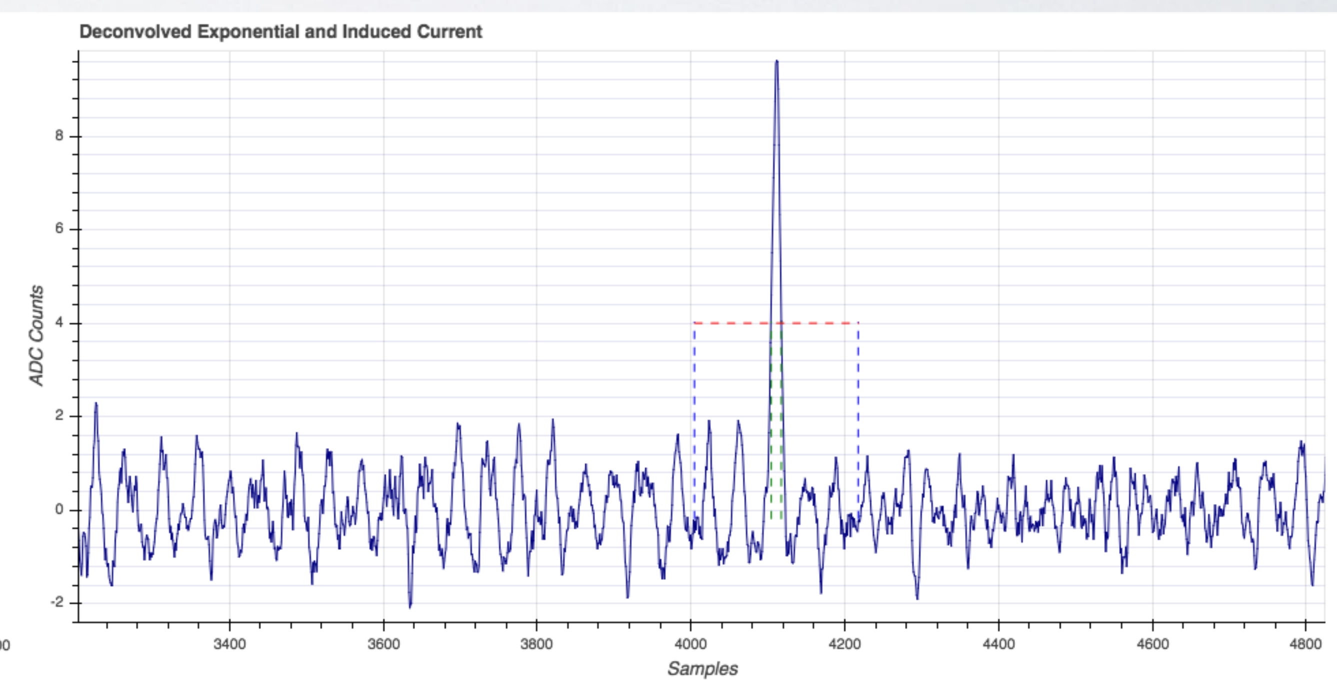
- <u>Shielding:</u>
  - Polyethylene (n)
  - Lead (gammas)
  - Copper (radiation from lead)



PARAMETER EXTRACTION : DDEC

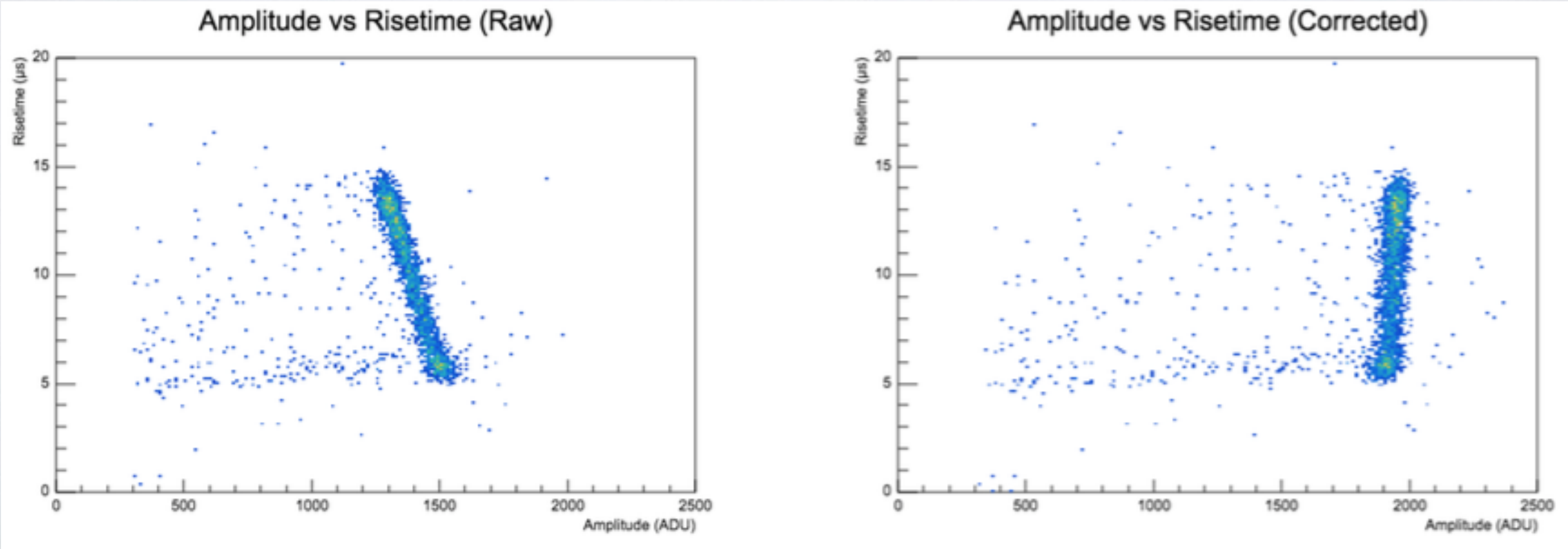
- After DDec, we recover a signal that goes back to (flat) baseline in a few tens of μs at most: model consistent with data!
- Integral of deconvolved pulse gives amplitude and risetime of event
- Applying the DDec method to data also corrects the ballistic deficit
- Problem: DDec method greatly amplifies noise





PARAMETER EXTRACTION : DDEC

- After DDec, we recover a signal that goes back to (flat) baseline in a few tens of μs at most: model consistent with data!
- Integral of deconvolved pulse gives amplitude and risetime of event
- Applying the DDec method to data also corrects the ballistic deficit
- Problem: DDec method greatly amplifies noise



STRONG CP PROBLEM

- The QCD Lagrangian contains a CP violating term:

$$\mathscr{L}_\theta = \bar{\theta}\,\frac{g^2}{32\pi^2}\,G^{a}_{\mu\nu}\,\widetilde{G}^{a\mu\nu}$$

- A non-zero value of theta gives rise to an electric dipole moment for the neutron $d_n \sim 10^{-16}$ e*cm

- However, current measurements of $d_n < 10^{-27}$ e*cm. That implies theta $< 10^{-9}$. Why such a small value?

PECCEI-QUINN SOLUTION

- Introduce a new $U_{PQ}(1)$ symmetry, spontaneously broken at some scale f_{PQ}.
- The breakdown of the symmetry leads to the existence of a pseudo-Goldstone boson, the axion, which couples to gluons. The new QCD Lagrangian becomes:

$$\mathcal{L}_\theta = \left(\bar{\theta} - \frac{a(x)}{f_{\mathrm{PQ}}}\right) \frac{g^2}{32\pi^2} G^{\mathrm{a}}_{\mu\nu} \widetilde{G}^{\mathrm{a}\mu\nu}$$

- The potential for the axion field has a minimum at $f_{\mathrm{PQ}}\bar{\theta}$, cancelling the CP-violating term, and solving the strong CP problem

QCD AXION PROPERTIES

Model dependent, order ~1

- Mass $m_a \simeq 0.6\ \text{eV}\,\frac{10^7\ \text{GeV}}{f_{PQ}}$
- Coupling constant to photons $g_{a\gamma\gamma} = \frac{\alpha_{EM}}{\pi}\frac{C_a}{f_{PQ}}$
- Decaytime $\tau = \frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3}$
- Only one parameter, the symmetry-breaking scale!

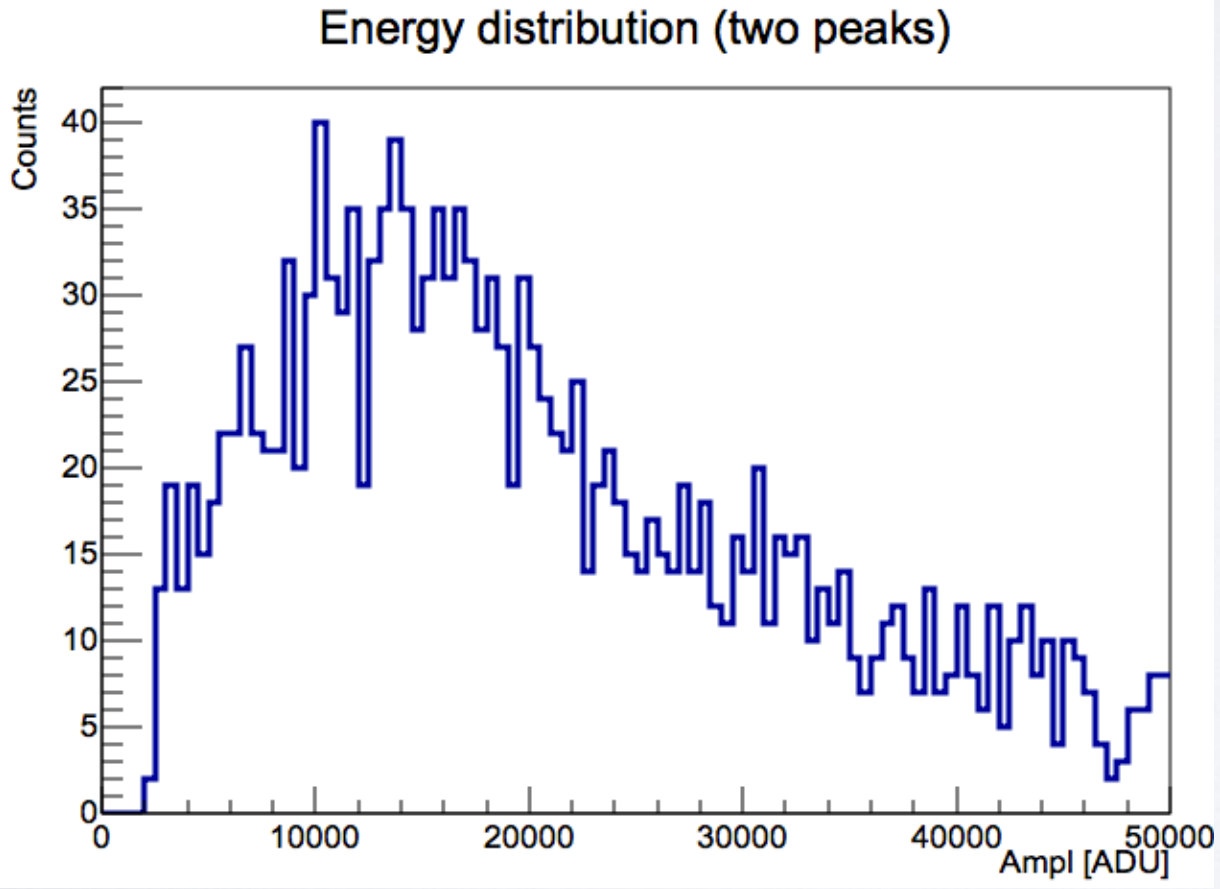
For Axion-like Particles (ALPs), only the decaytime relationship is still valid (others are model-dependent)

AXION SEARCH: MPA CUTS

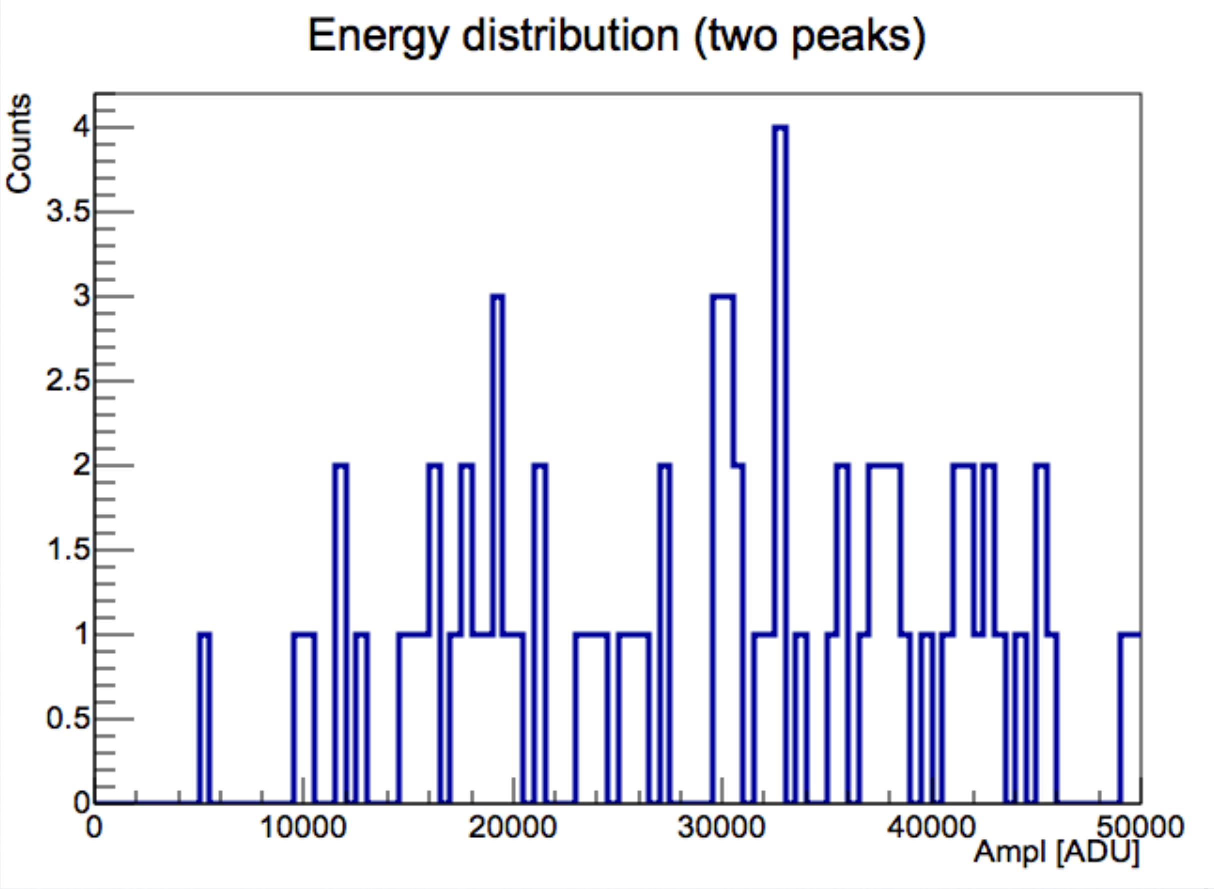
- Round 1:
  - Two pulses or more, both of amplitude larger than 1000 ADUs (~400 eV)
- Round 2, also add:
  - Amplitude of both pulses are "close" (highest is not more than twice the lowest + 10000 ADUs)
  - Sum of both pulses is greater than 5000 ADUs (~2 keV) and lower than 50000 ADUs (~20 keV)
  - Risetime of both pulses smaller than 70 mus
  - Risetime of second pulse is longer than of first
  - "width" of both deconvolved pulses are less than 150 mus
  - Centre of both pulses within 500 microseconds of each other

SEDINE BACKGROUND: RUN PD02B000

- Total number of events: 1639360

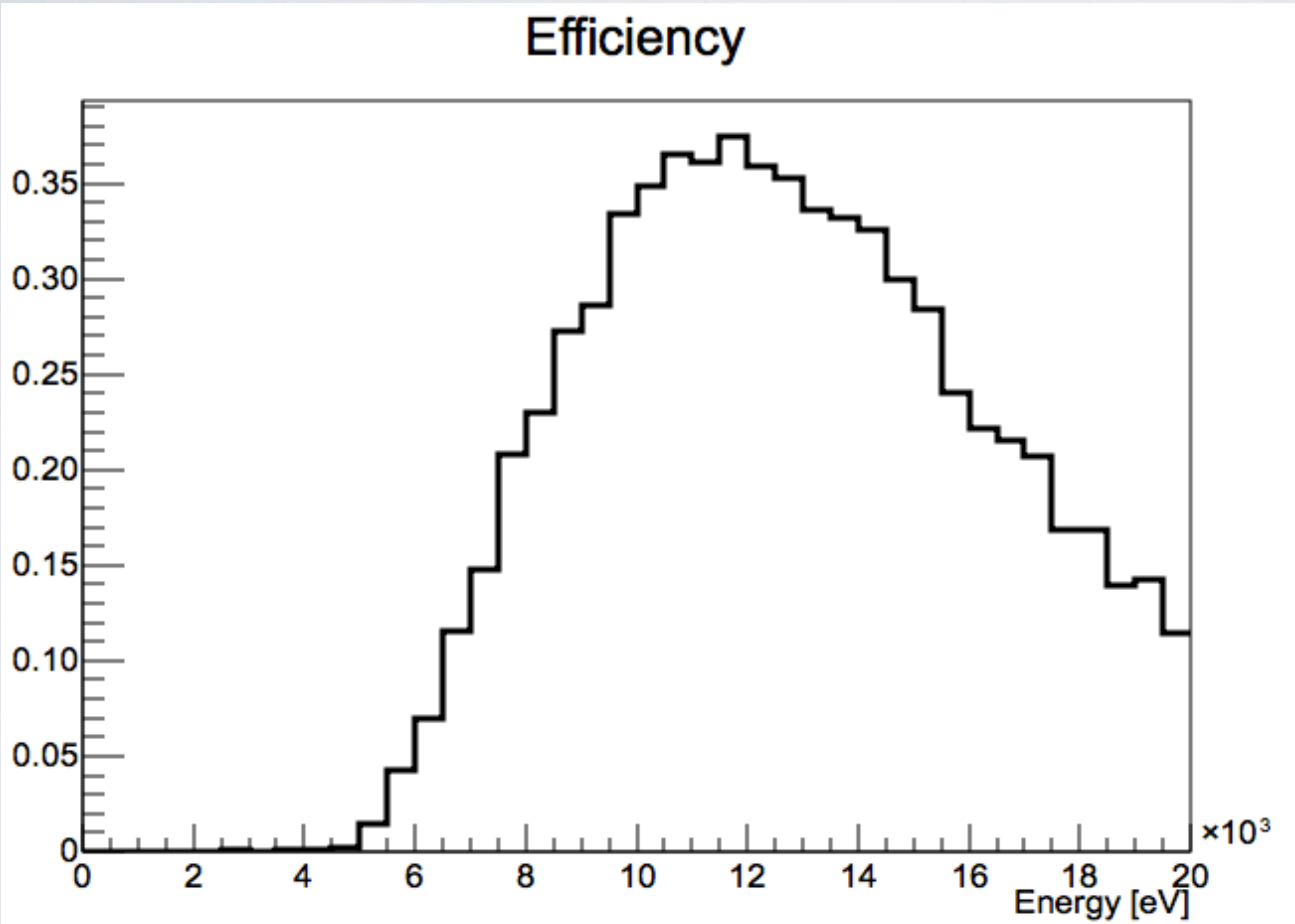


Round 1 cuts:
1677 events



Round 2 cuts:
73 events

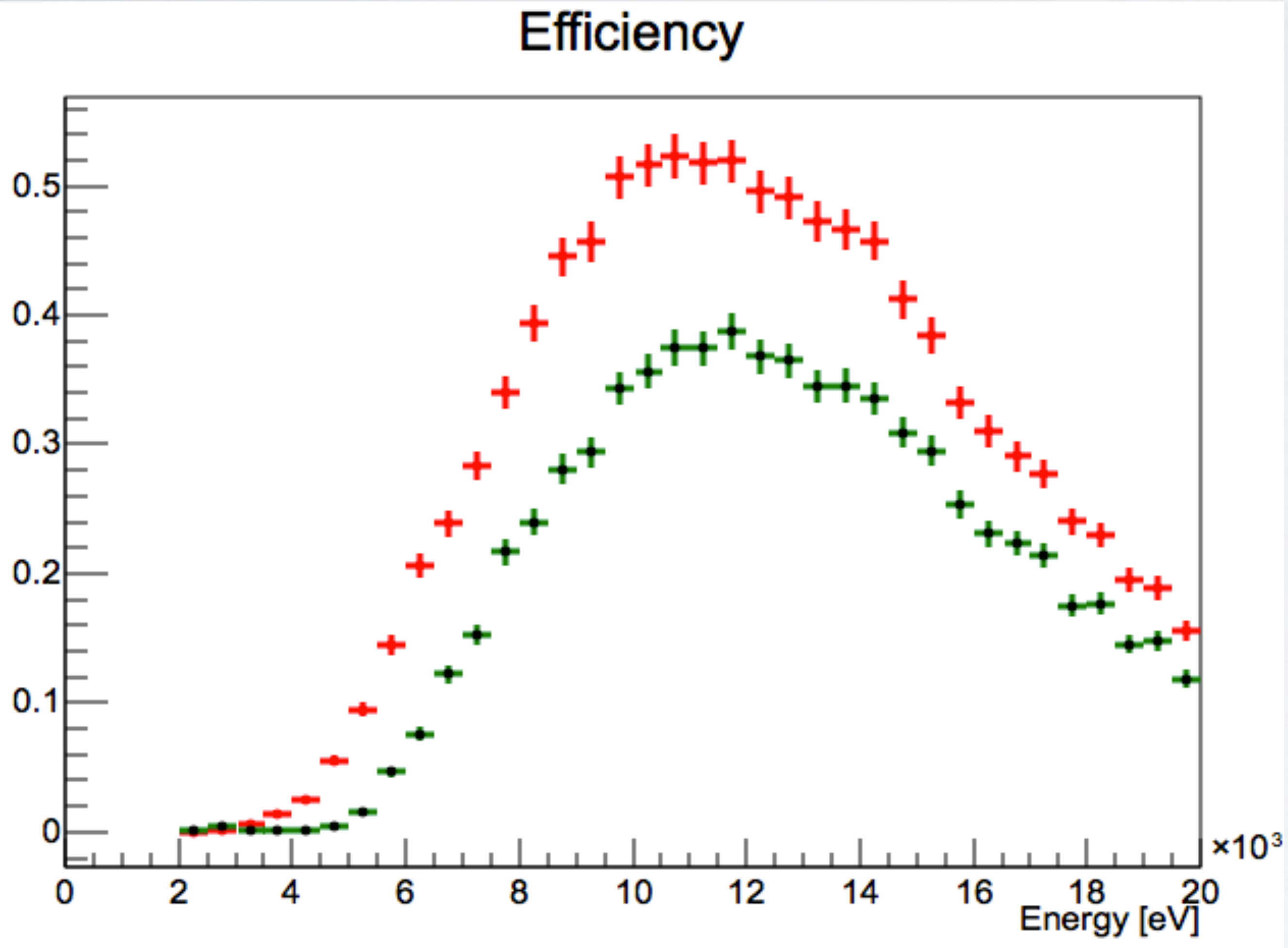
SEDINE EFFICIENCY

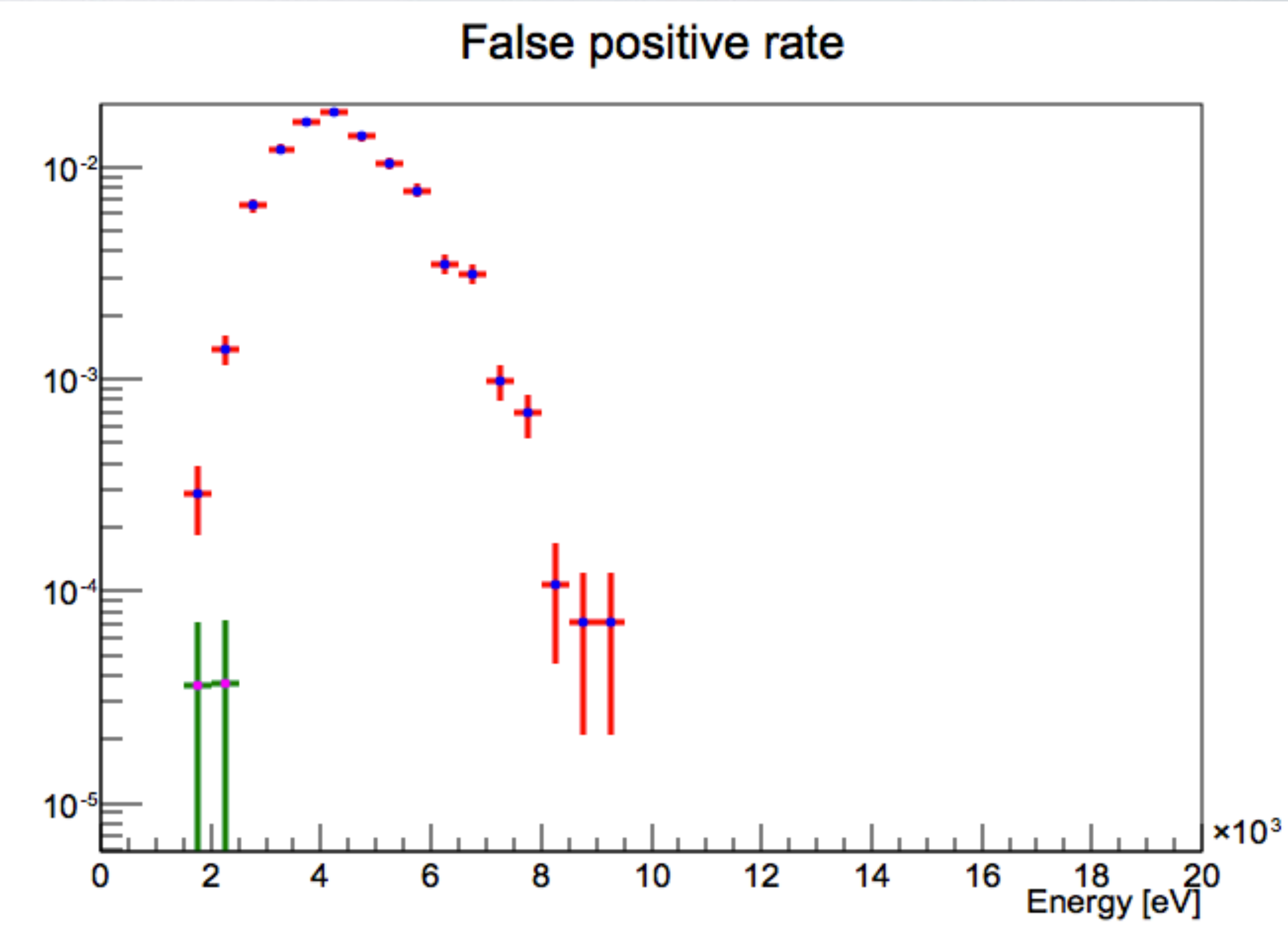


- Simulate axion events at different energies, see how many pass the cuts, to figure out efficiency.
- When maximizing efficiency, at the analysis level, have to be careful not to increase false positive rate, i.e. non-coincident events reconstructed as such (right now, 2 in a million pointlike events pass the cuts)

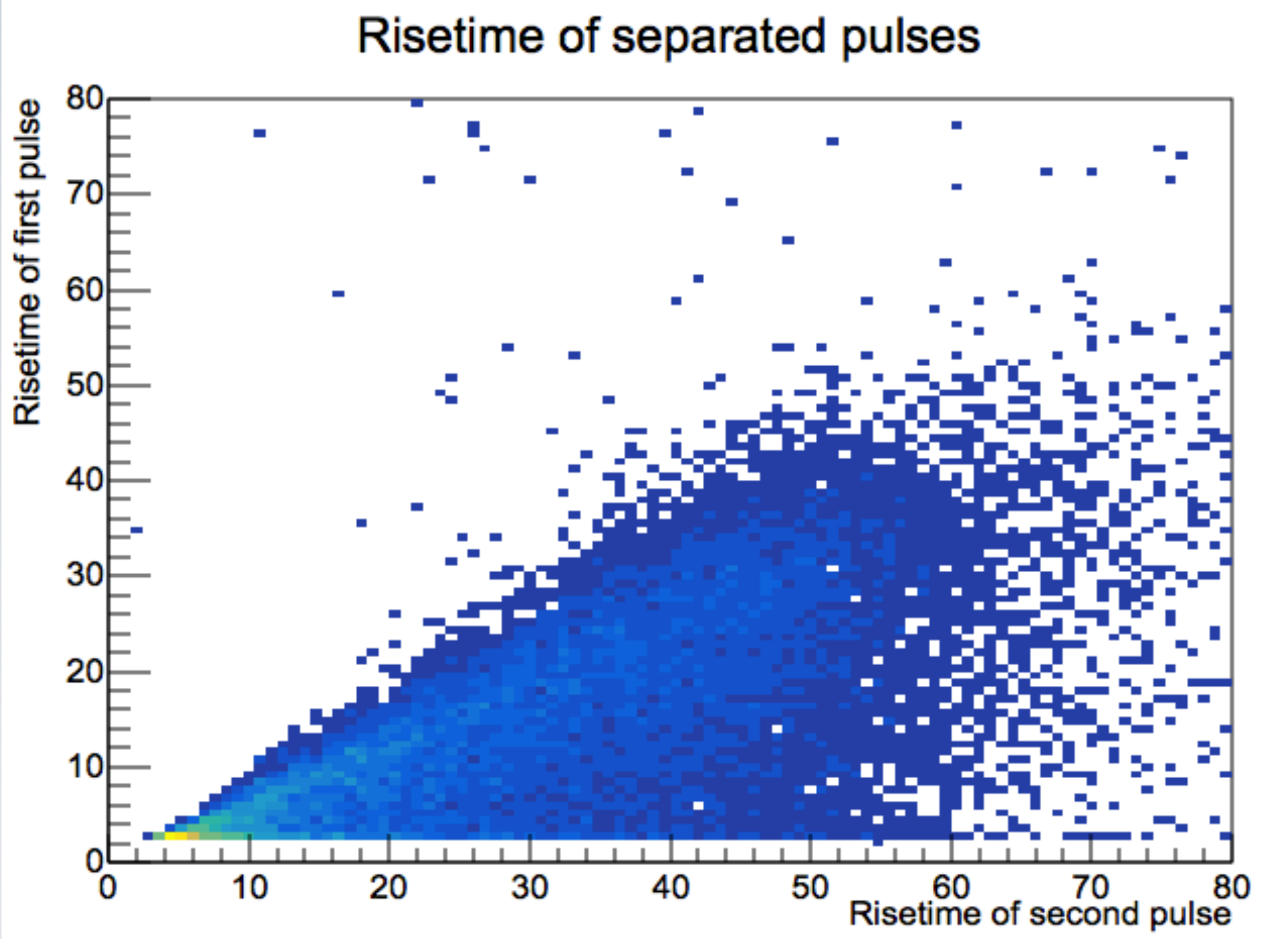
Maximum efficiency for an attenuation length of 4-9 cm for the photons. → Compare to radius of sphere, 30 cm

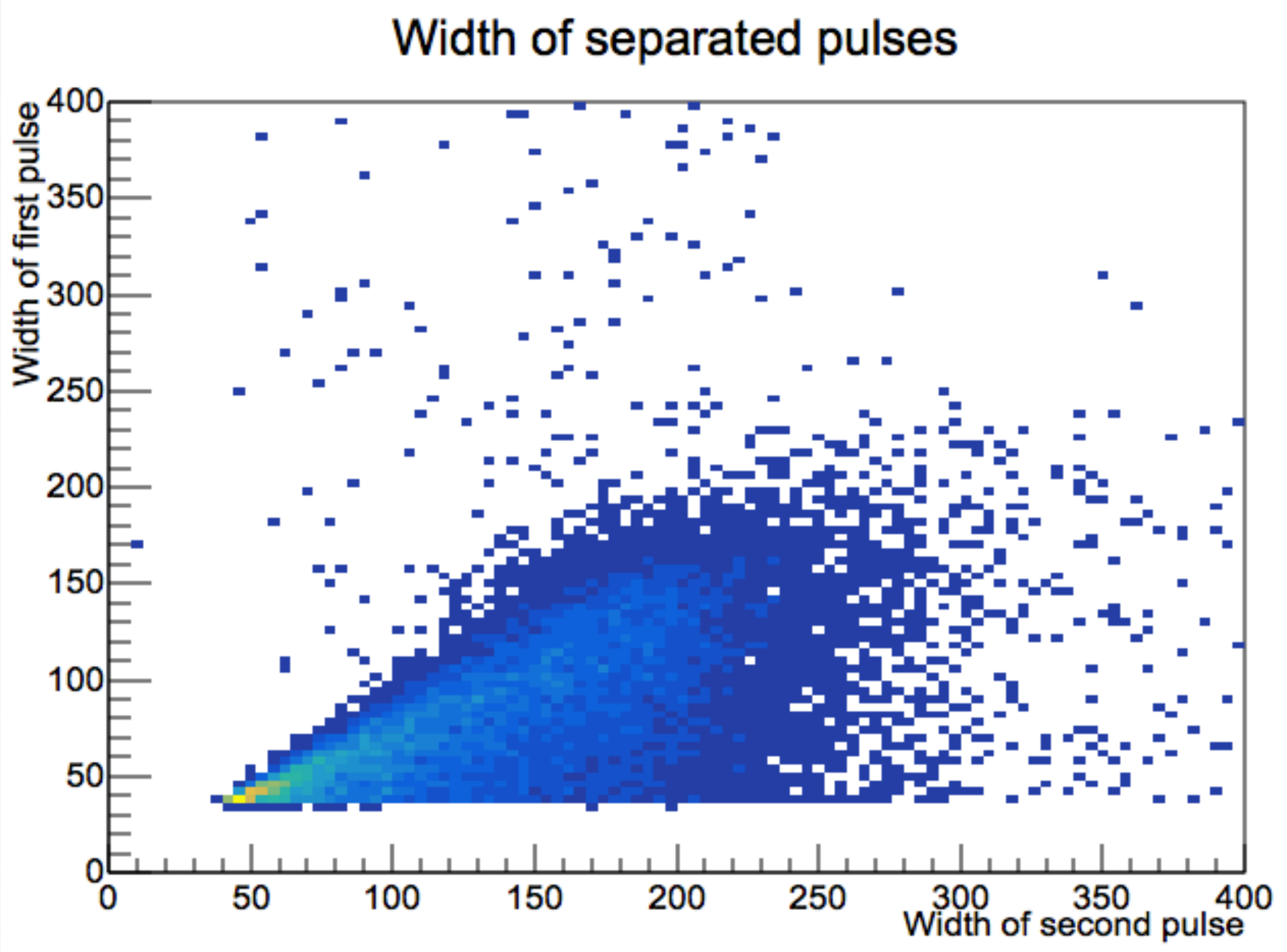
SEDINE EFFICIENCY

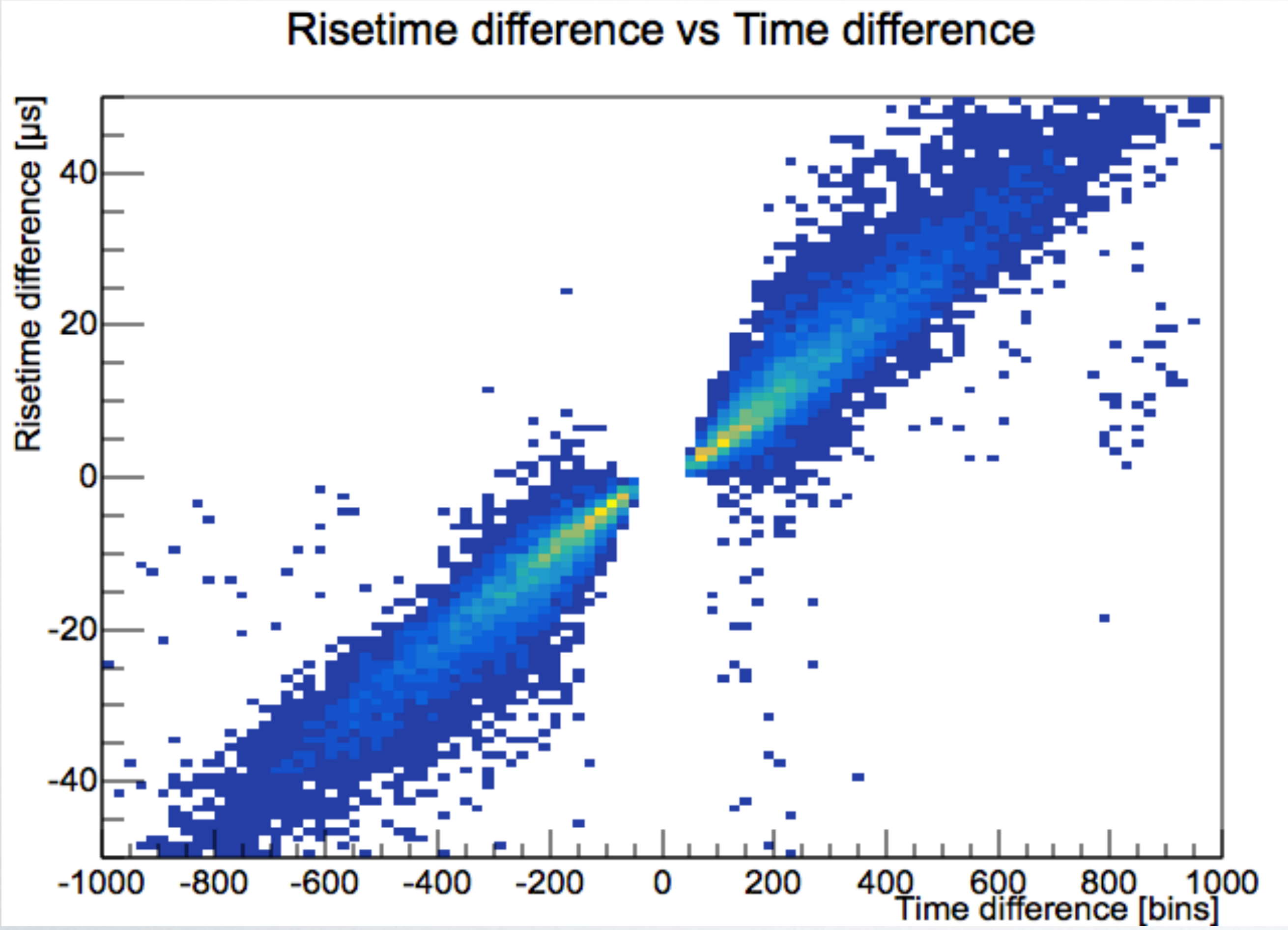




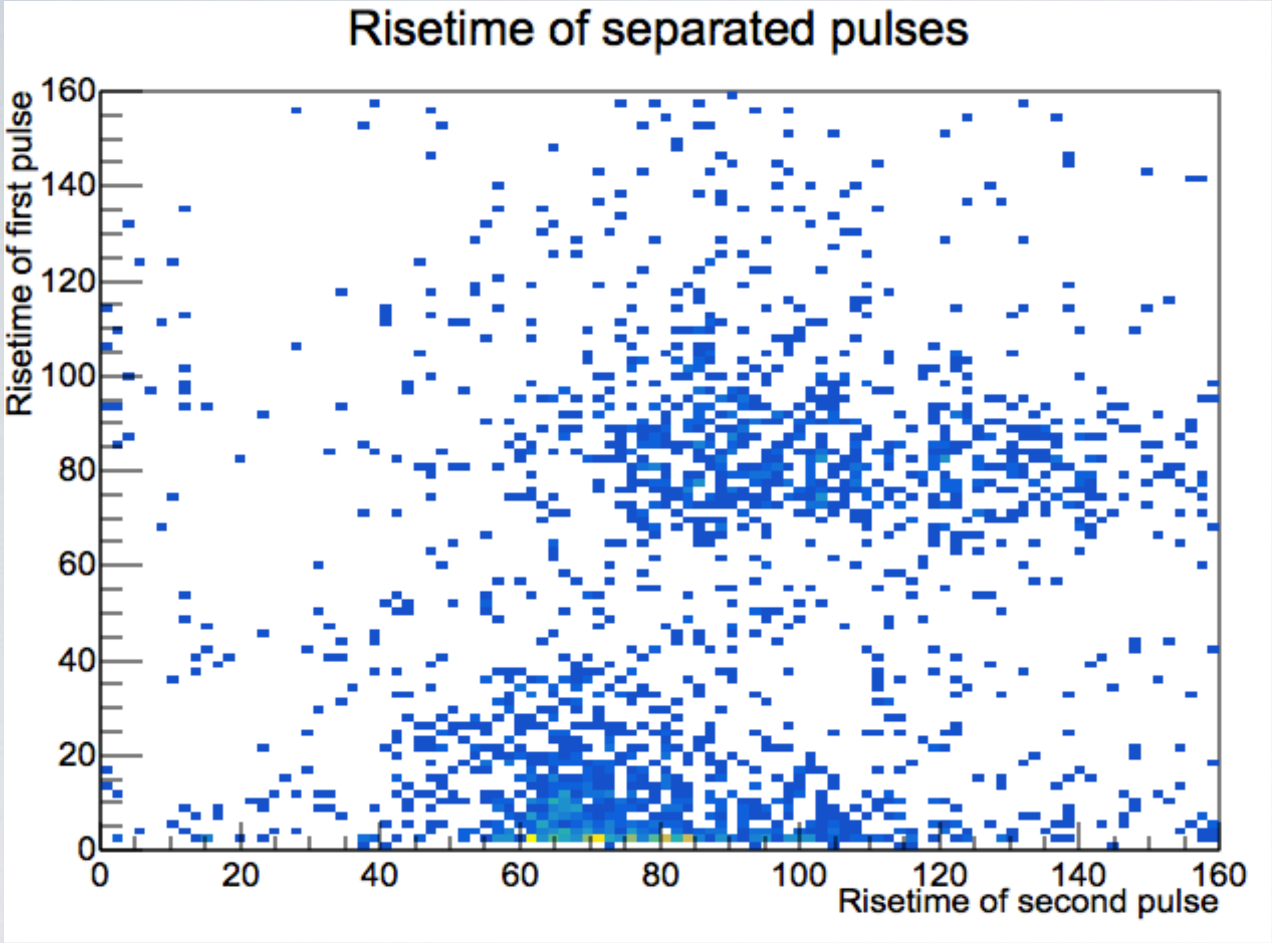
Green curve: low MPA threshold
Red curve: high MPA threshold

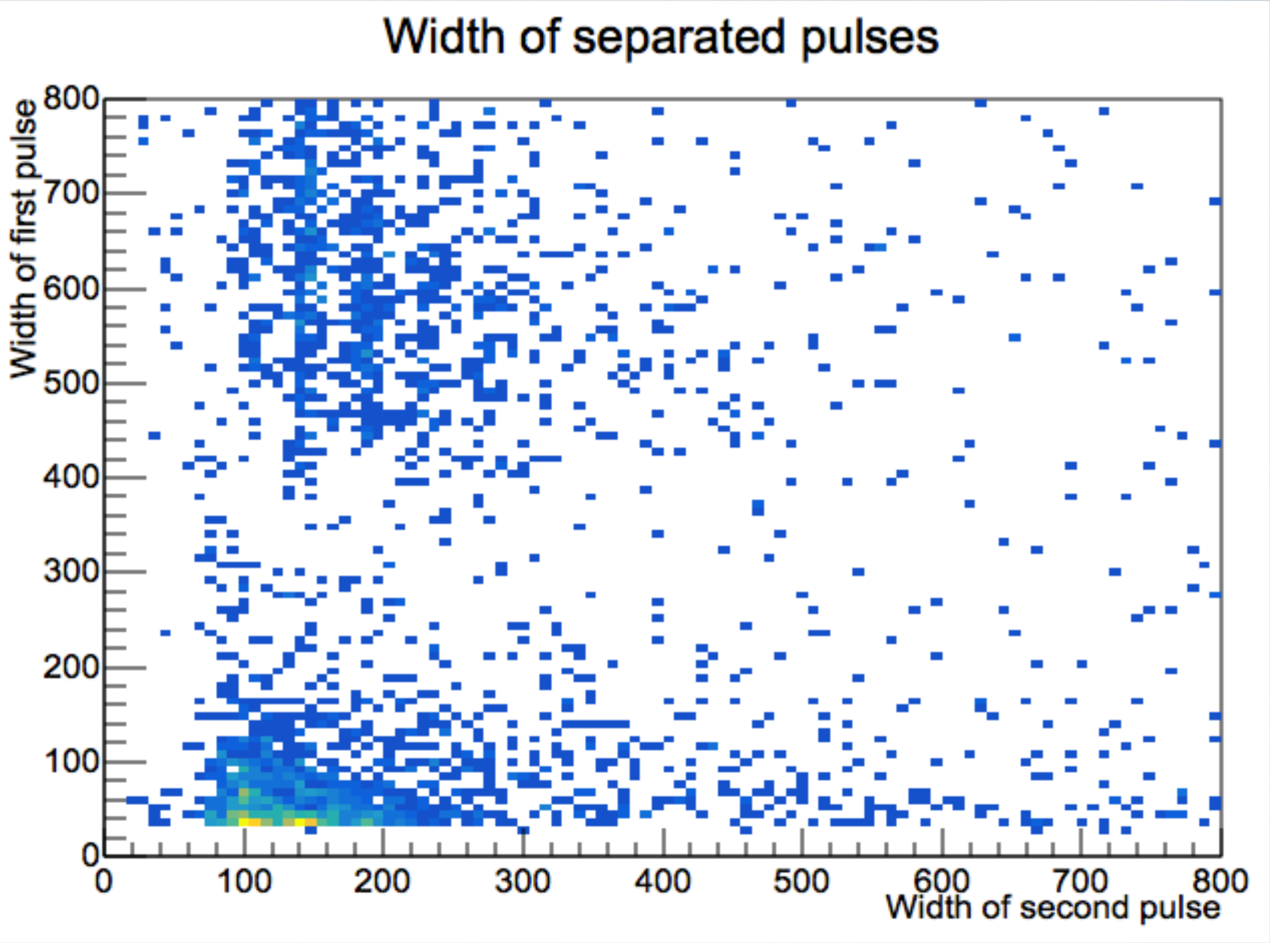


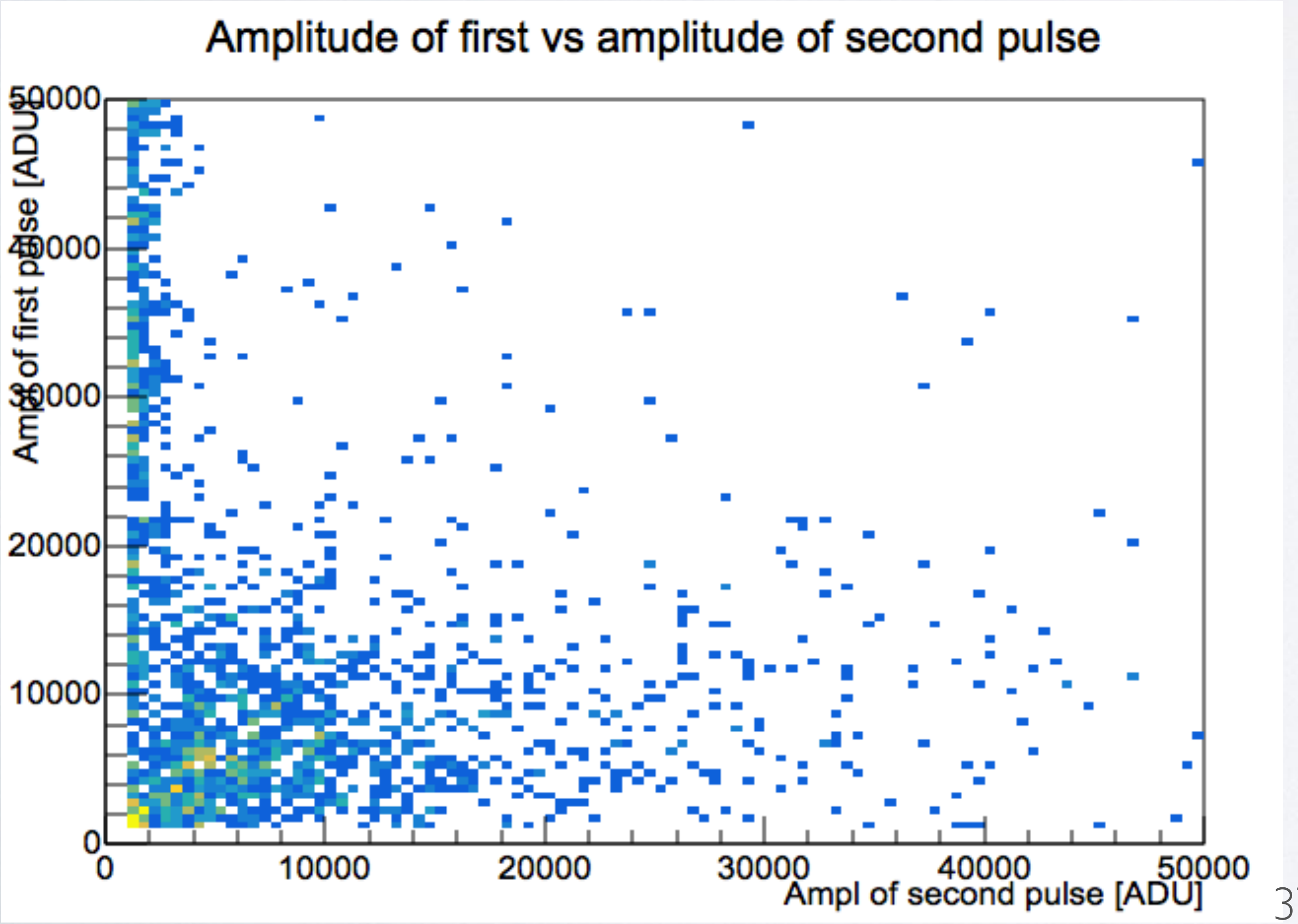




PLOTS (SIMULATED PULSES)

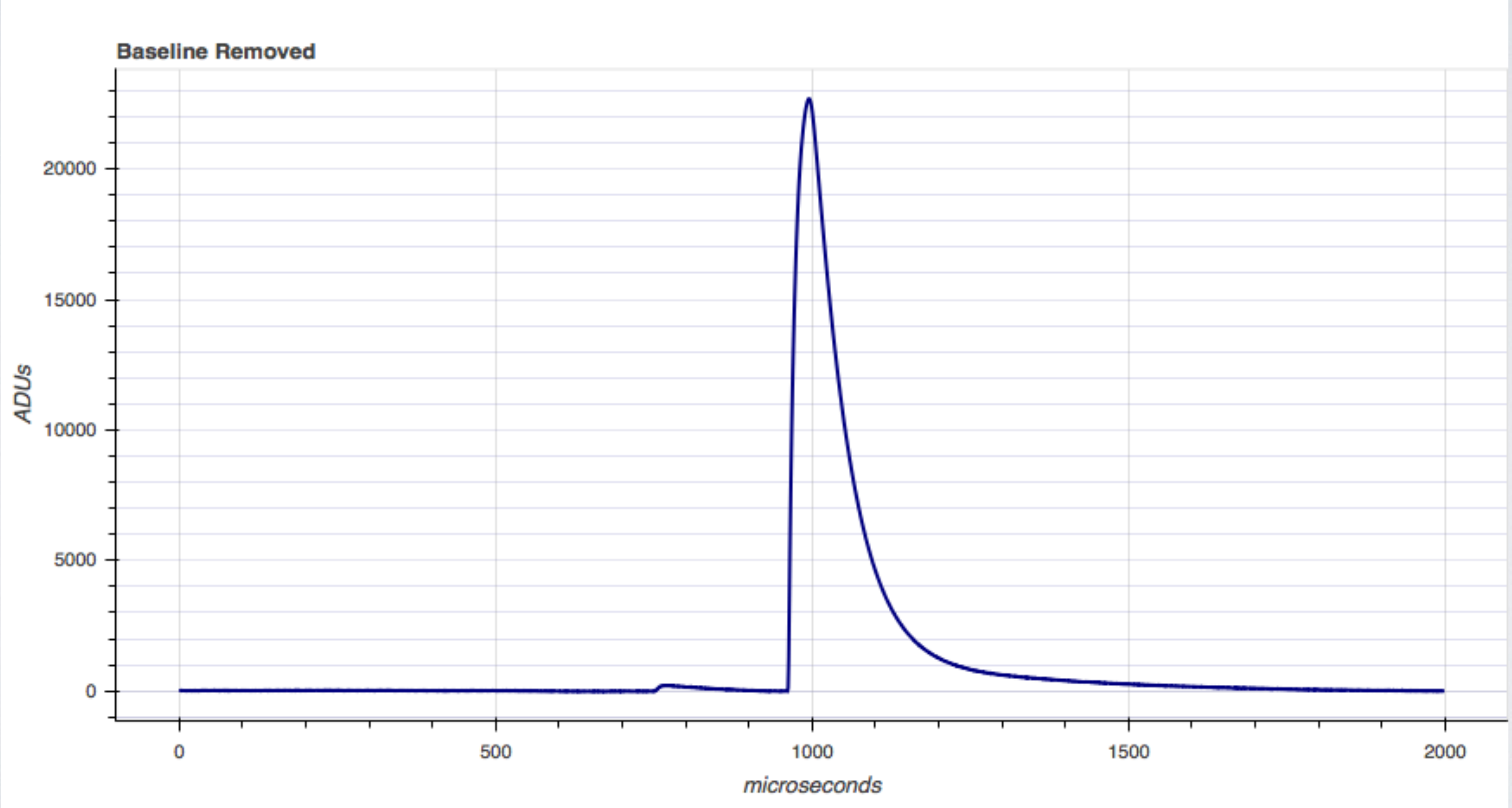




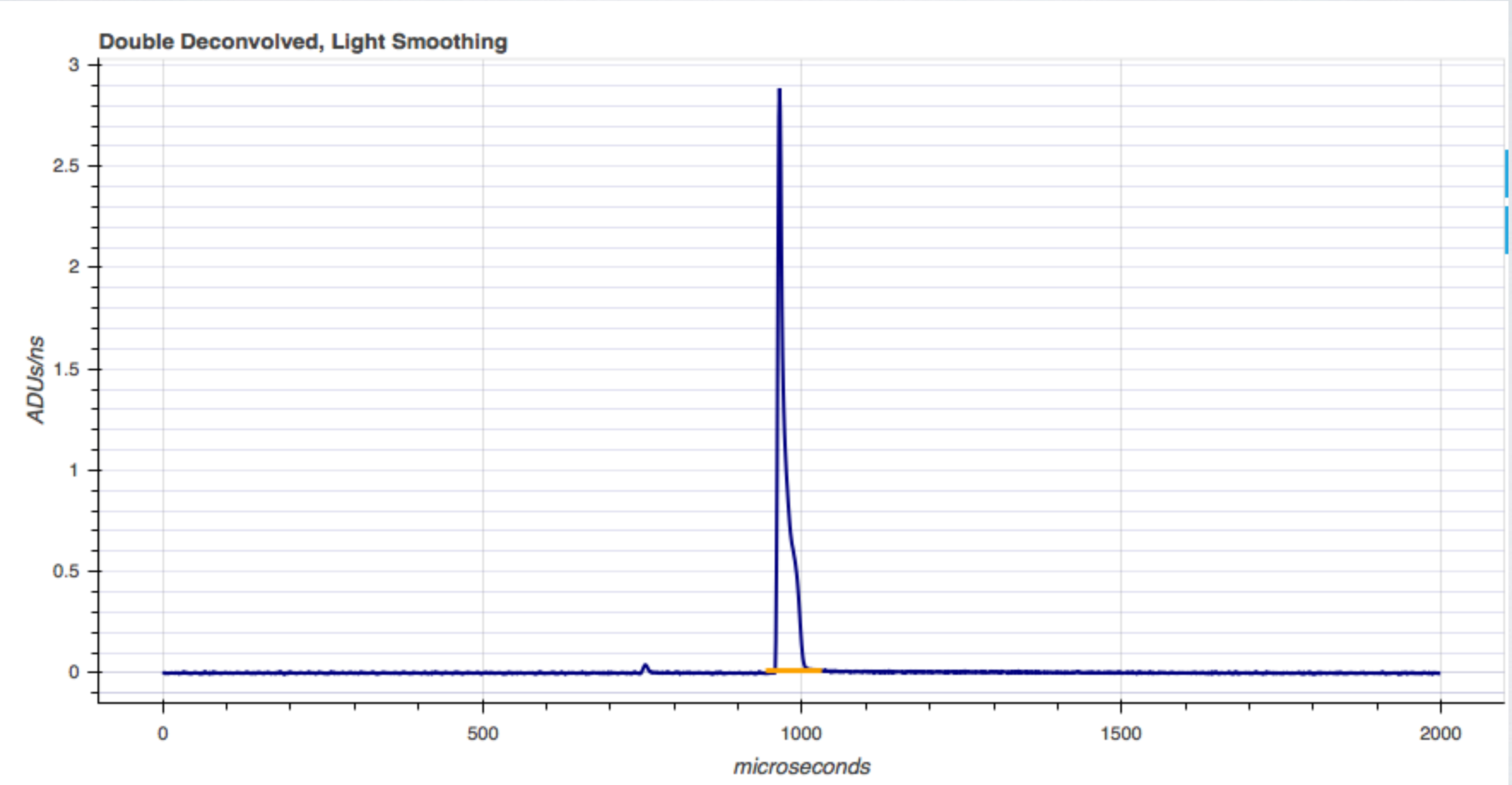


PLOTS (PD02B000)

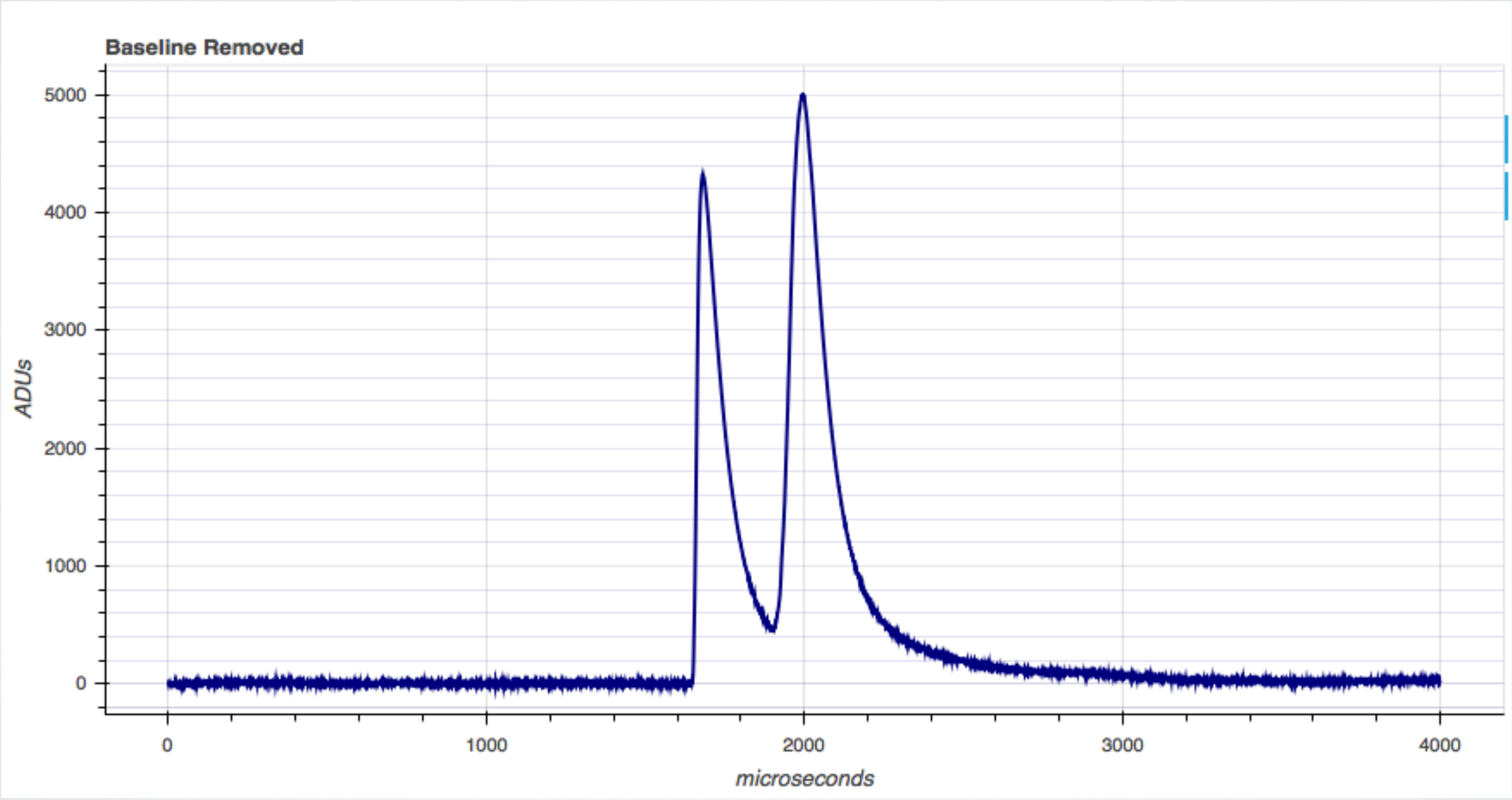
BIPO 214 EVENT



BIPO214 EVENT



PD02B000 DOUBLE EVENT



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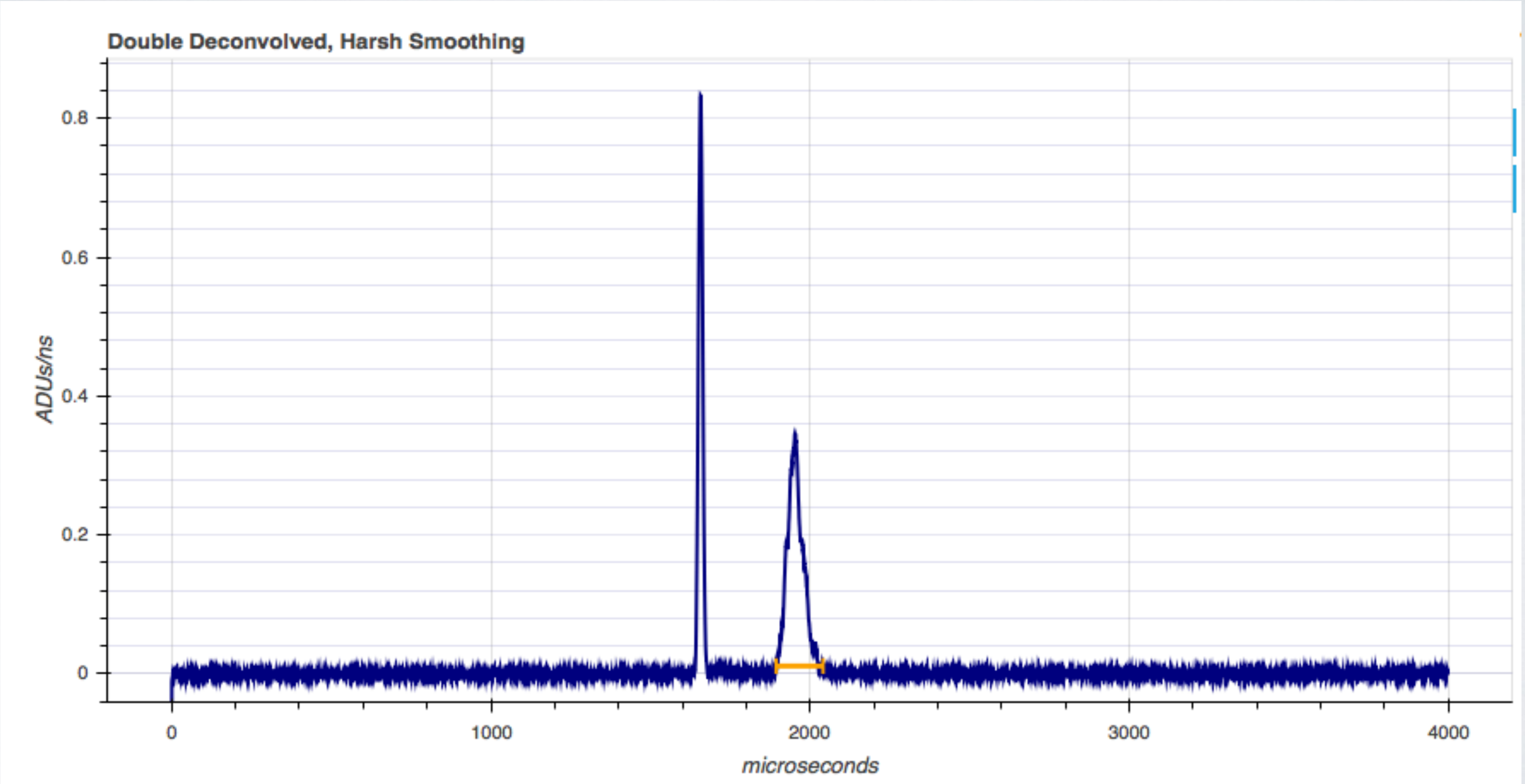

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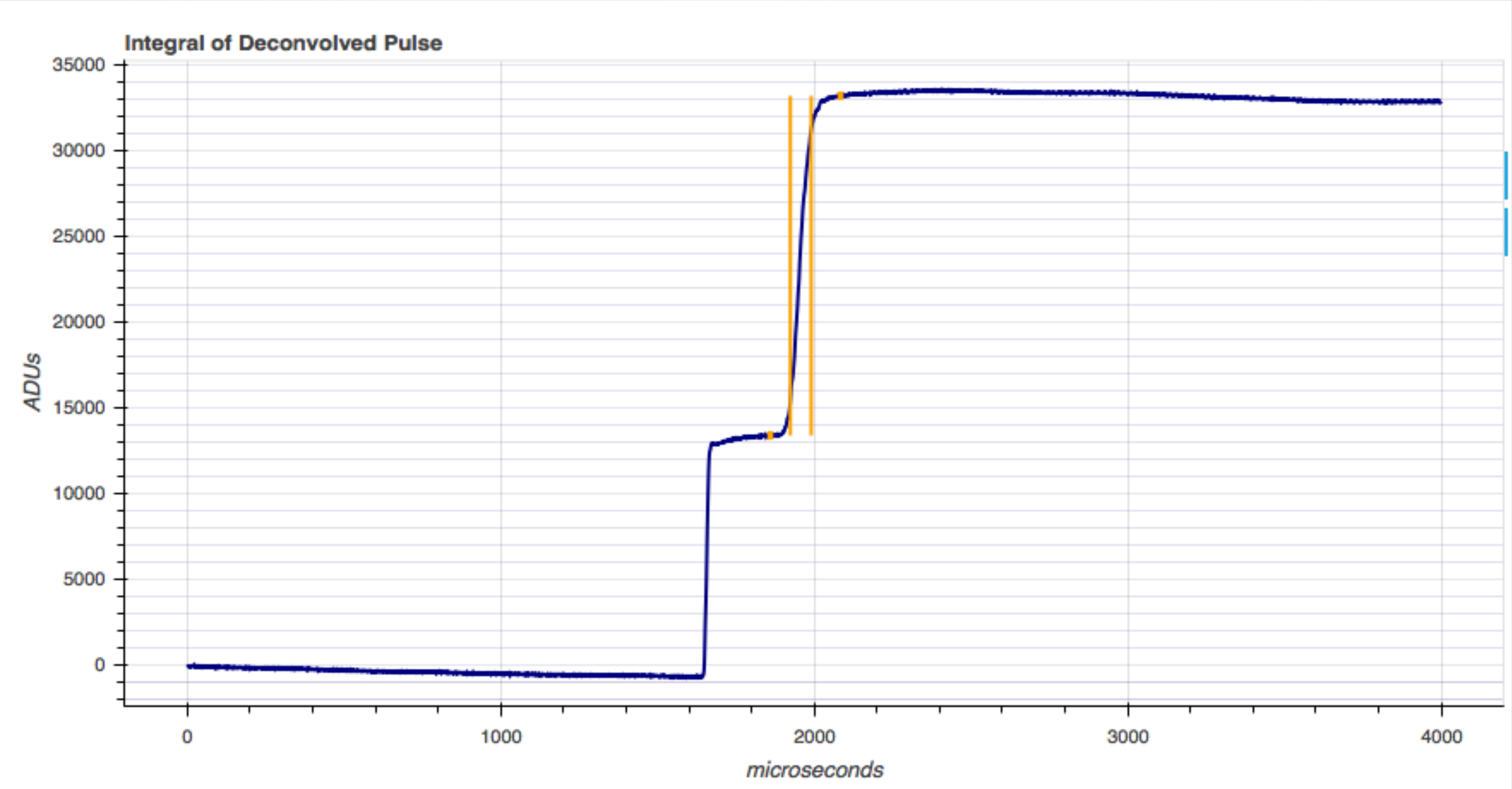
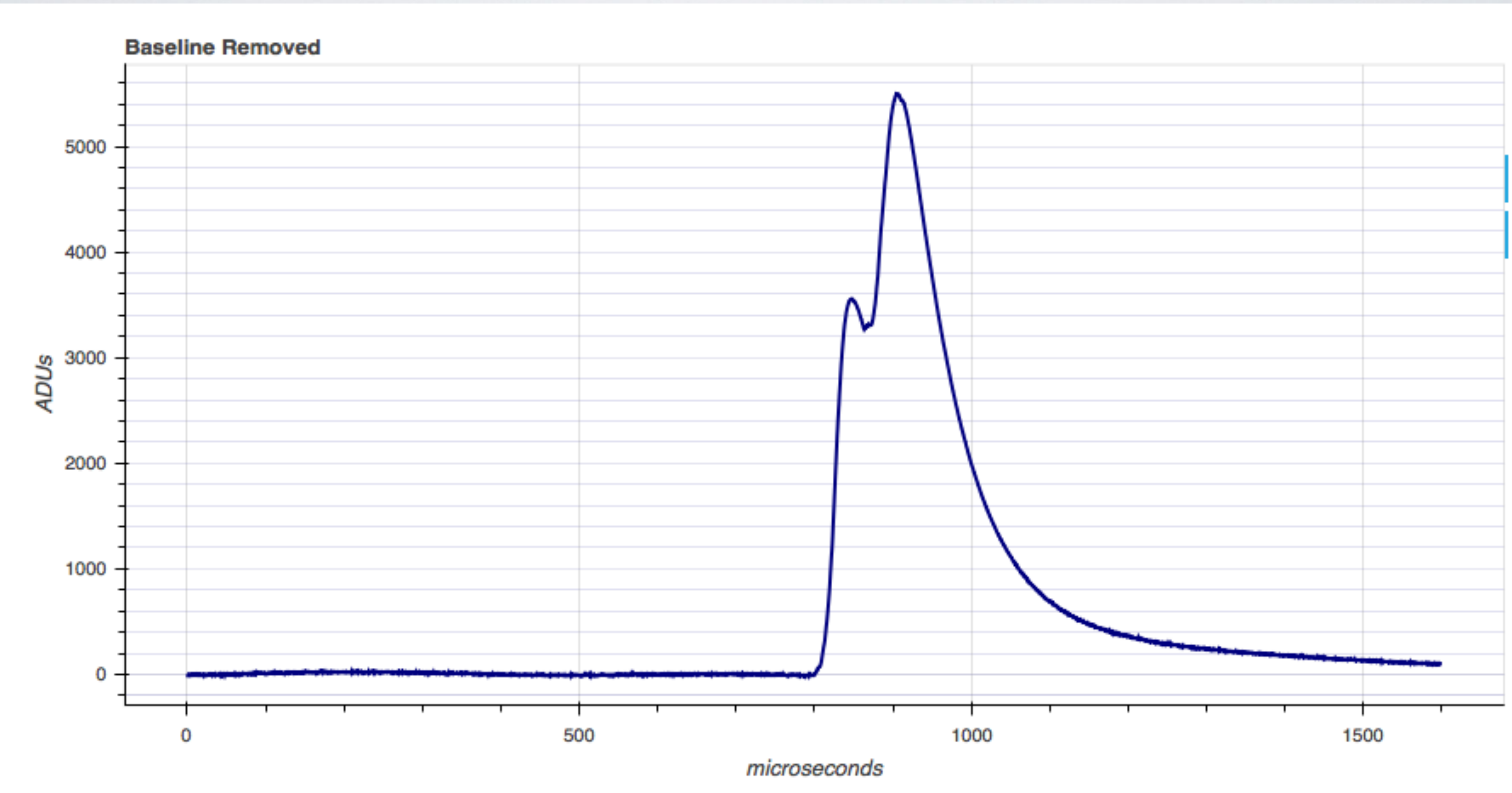


PD02B000 SIMULATED AXION



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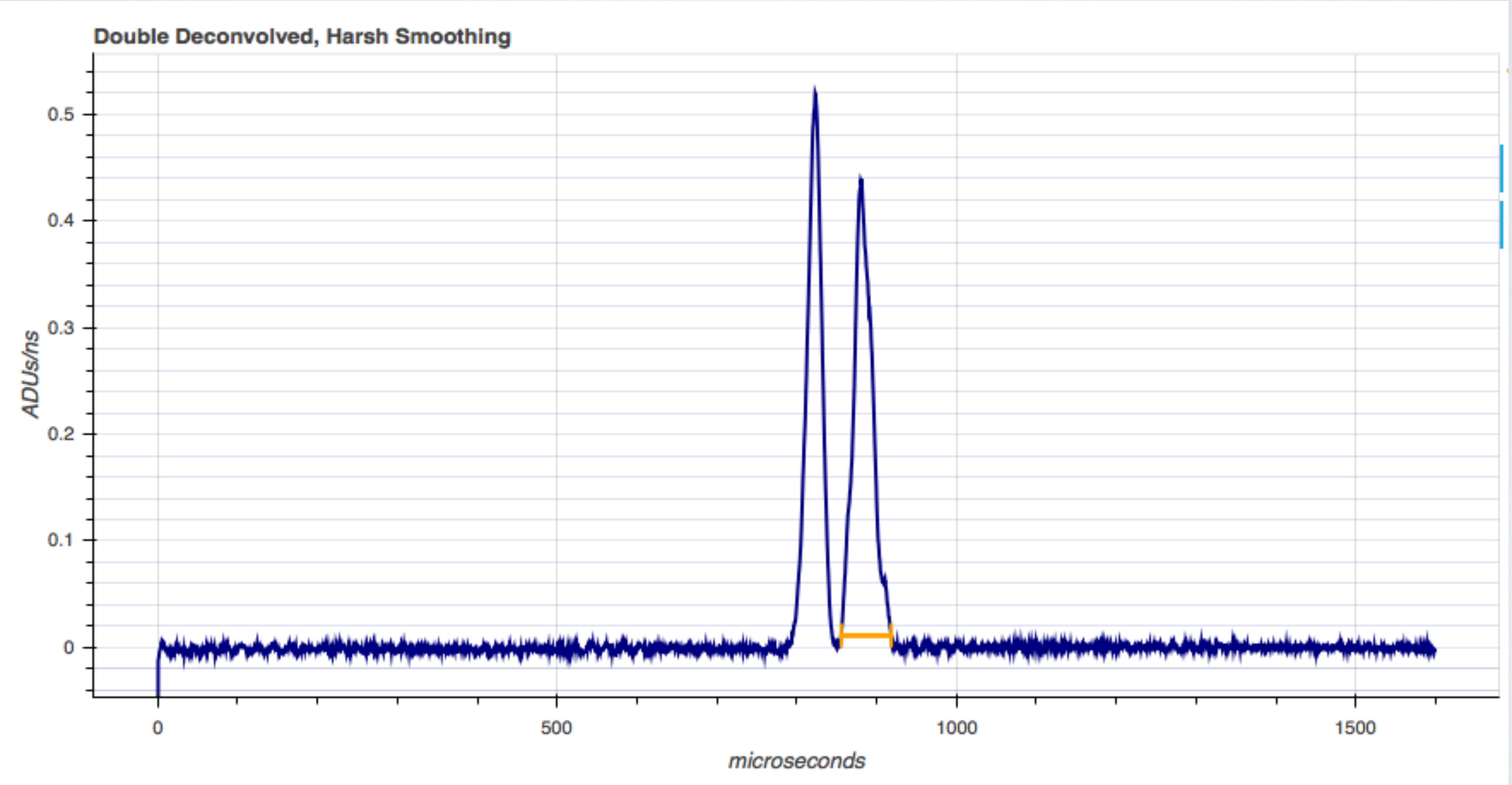

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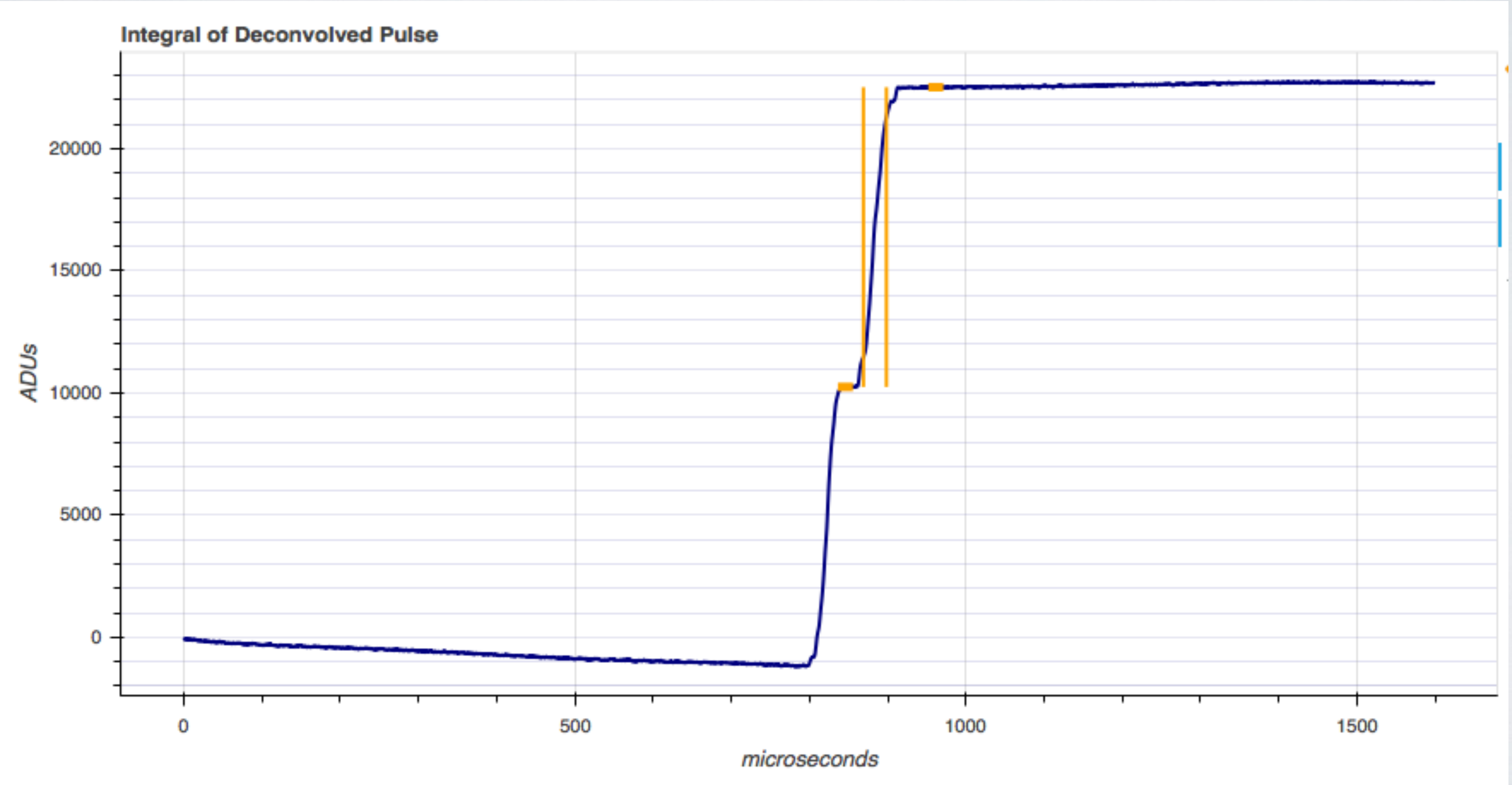

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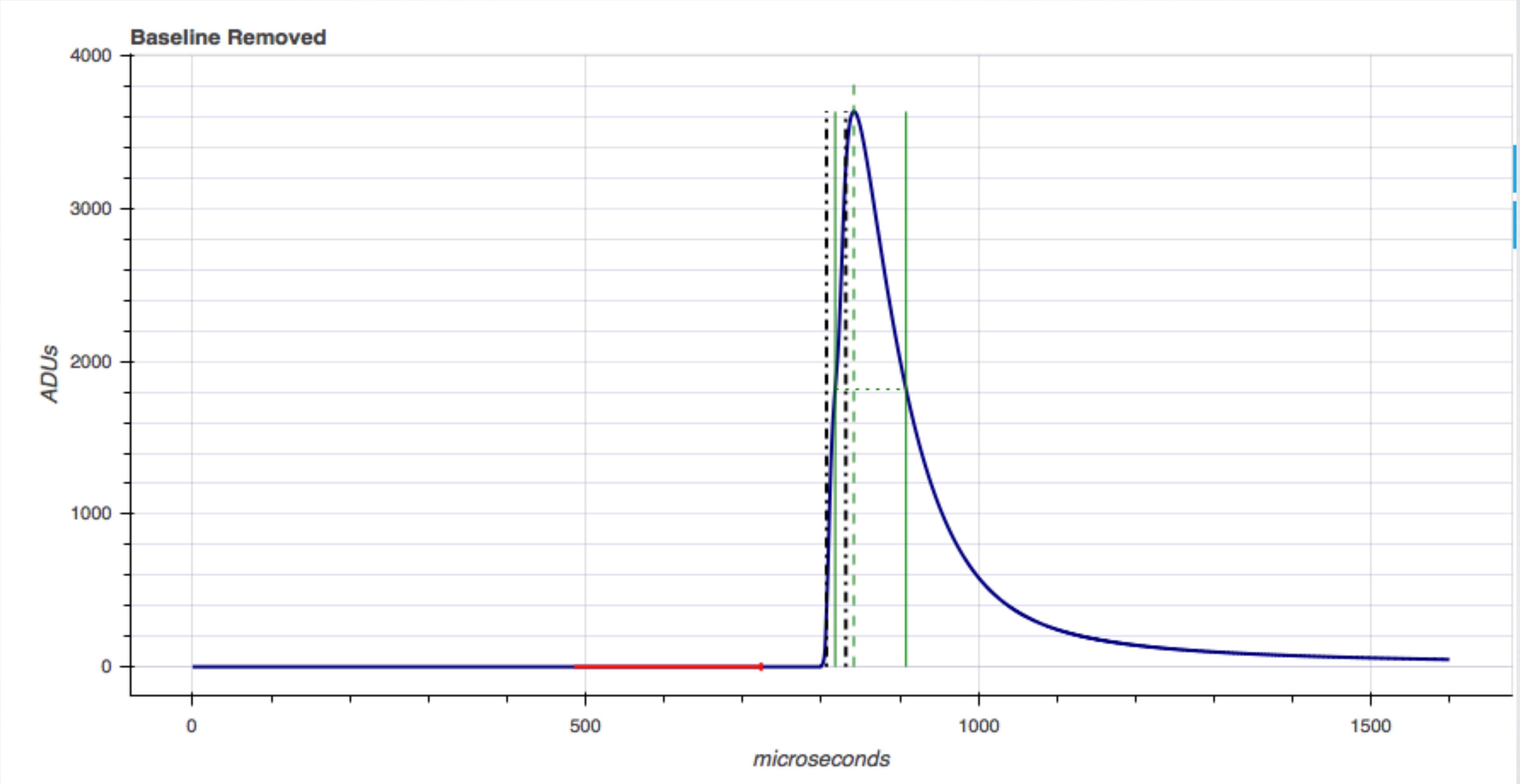

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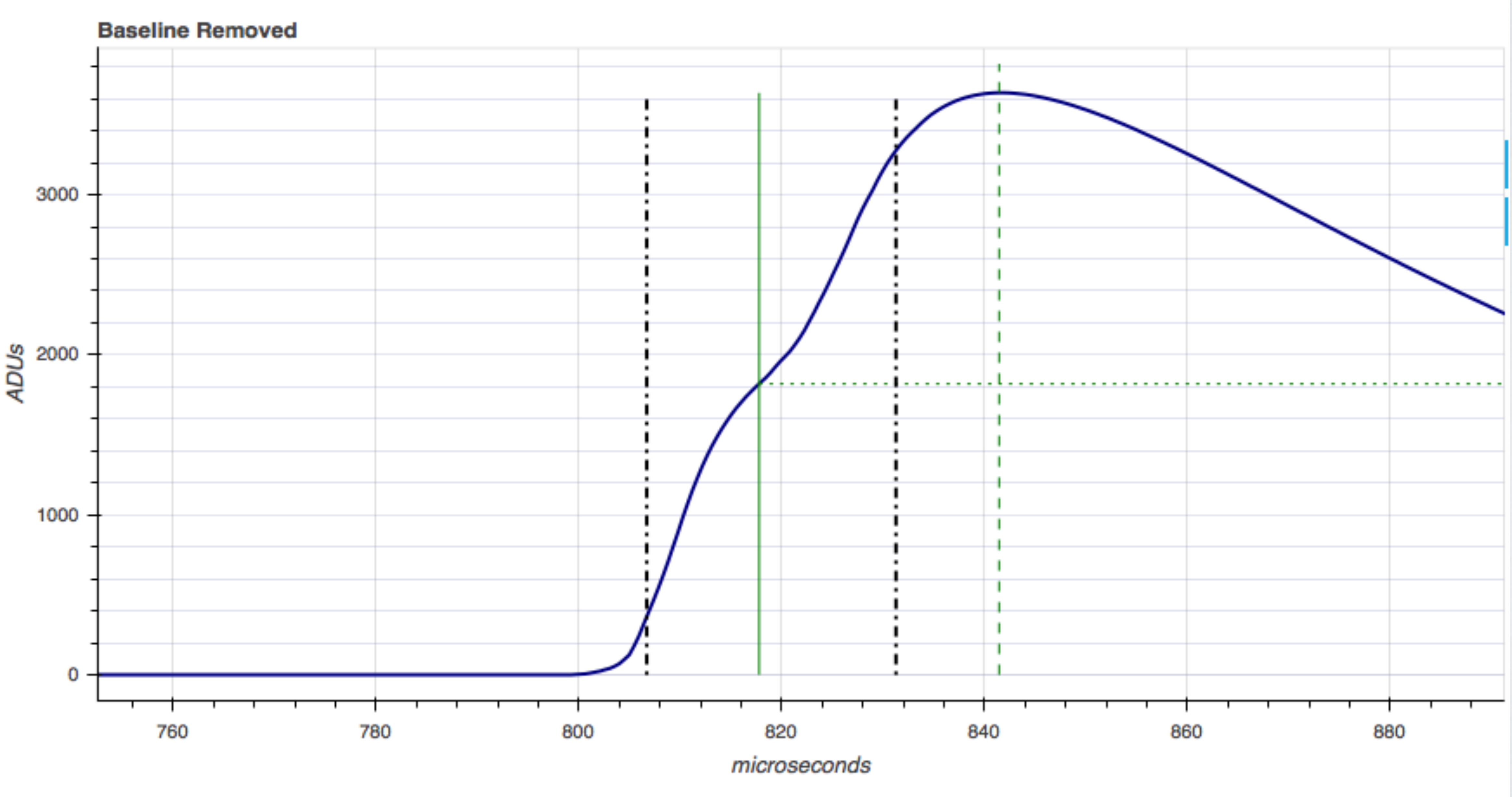

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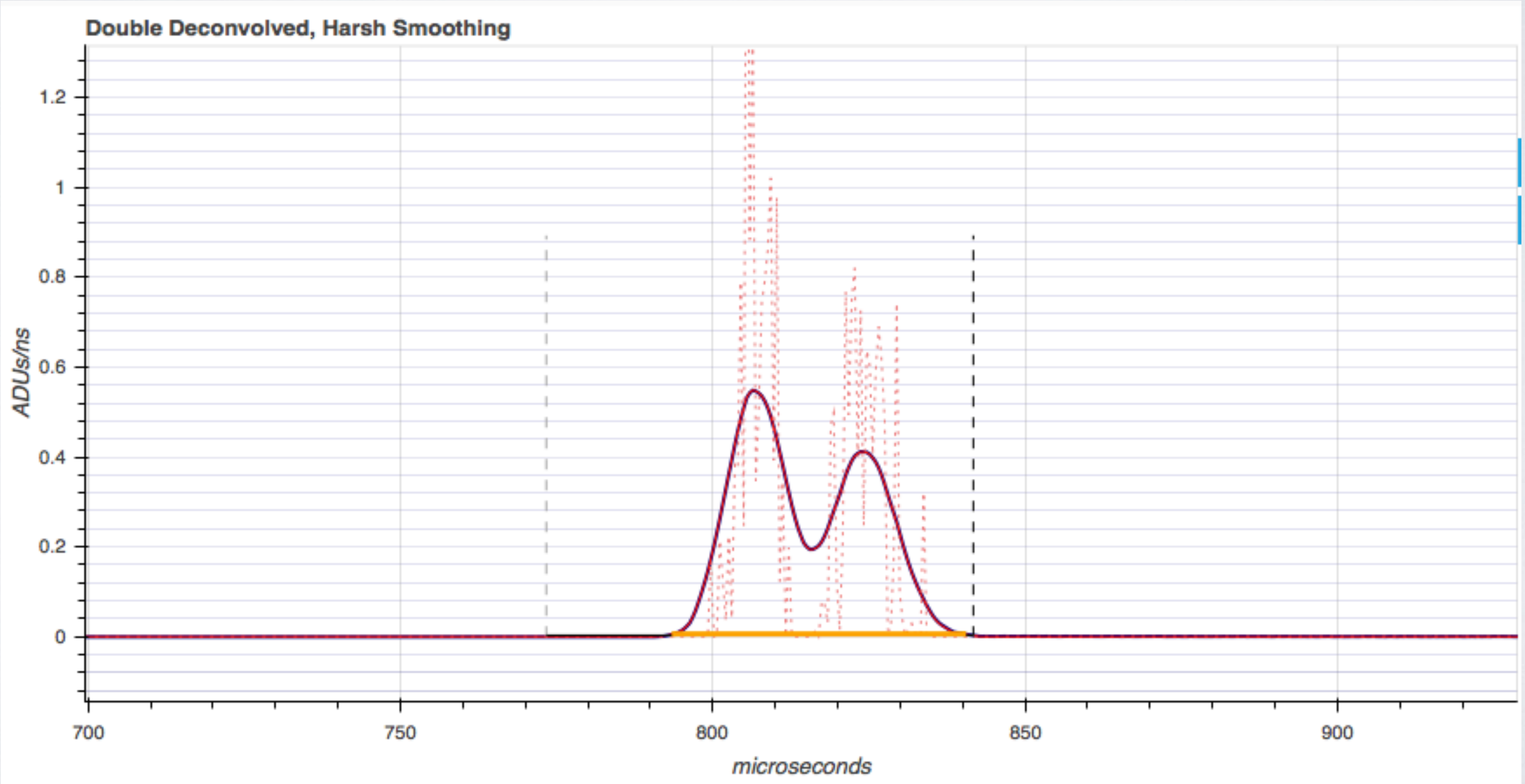


PHYSICS CASE FOR AXIONS

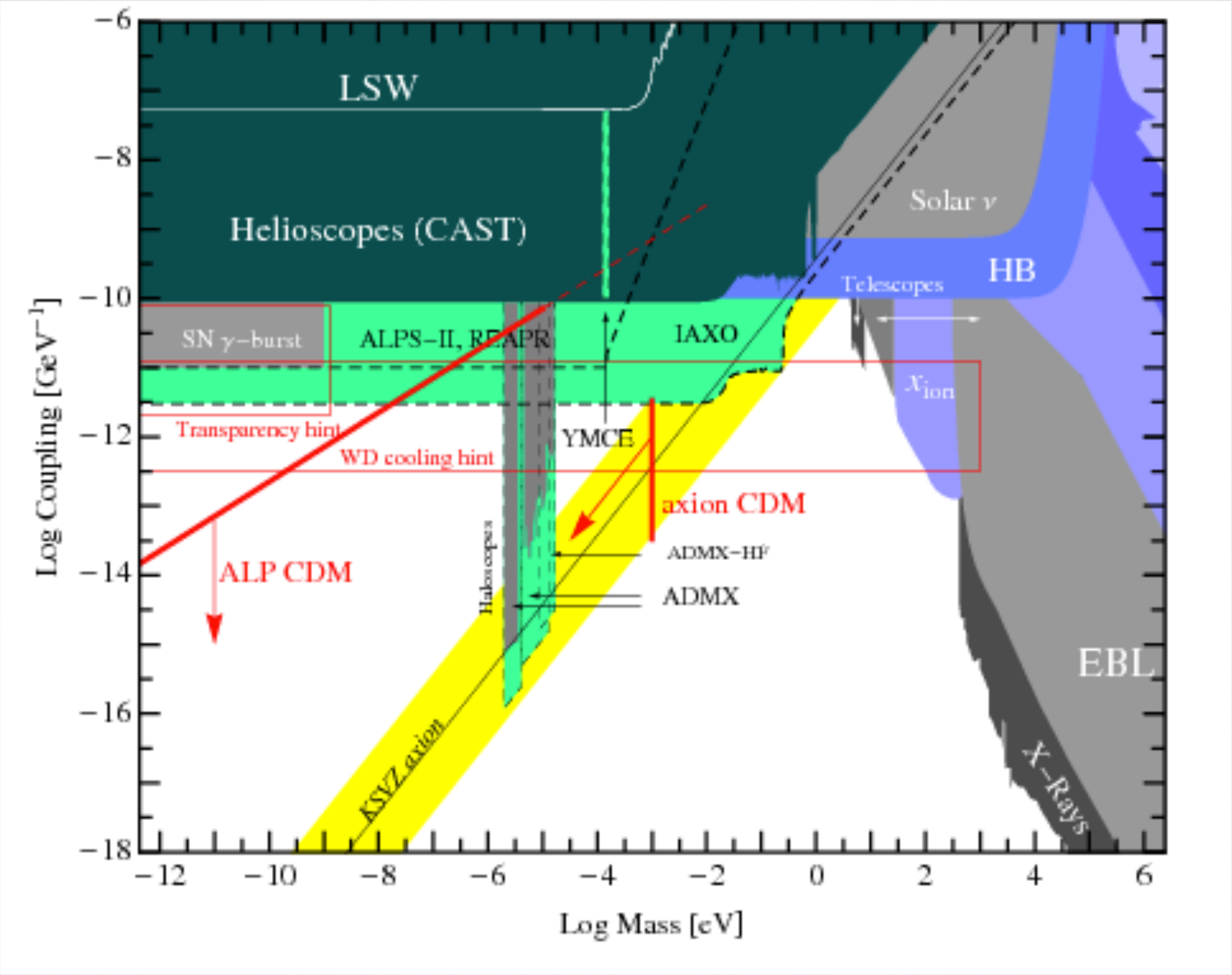
- **As Cold Dark Matter:** created by the vacuum realignment mechanism. For all DM to be axionic, $m_a \sim 10^{-6}$ - 10^{-3} eV. Lower masses are ruled out by density of DM, higher masses mean DM is mostly something else.

- **Gamma transparency of the Universe:** there is an anomalous transparency of the Universe to TeV gamma-rays at large optical depth. Could be explained by axion-photon oscillations. This would need $m_a < 10^{-7}$ eV

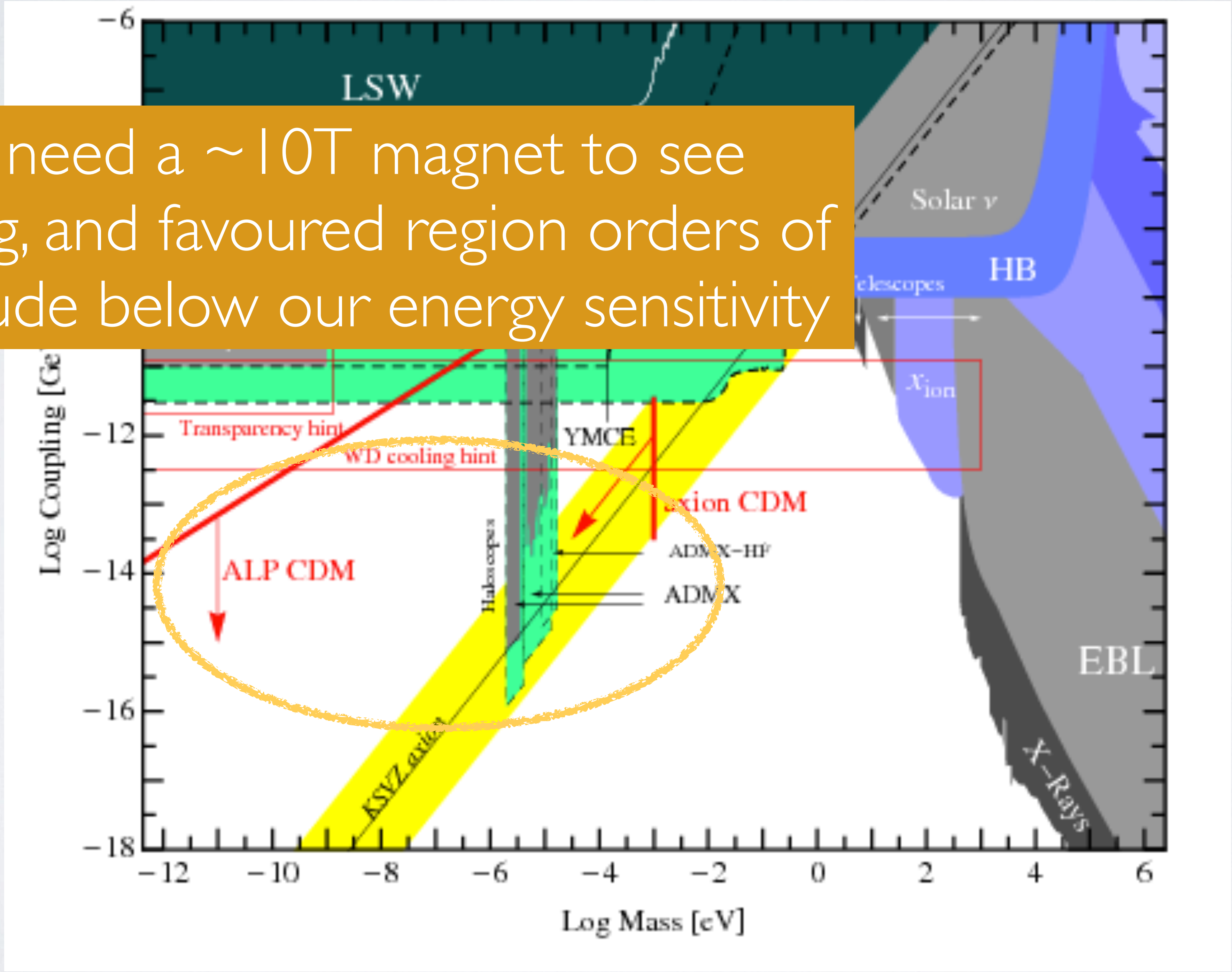
- **Cosmic ALP background radiation:** observed X-ray excess from the Coma cluster could come from the conversion of such background in the magnetic field of the cluster. This would need $m_a < 10^{-12}$ eV

- **White Dwarf cooling:** some hints of stars cooling faster than expected could be explained by them radiating extra energy as axions.

ALPs EXCLUSION LIMIT



ALPs EXCLUSION LIMIT



We need a ~10T magnet to see anything, and favoured region orders of magnitude below our energy sensitivity

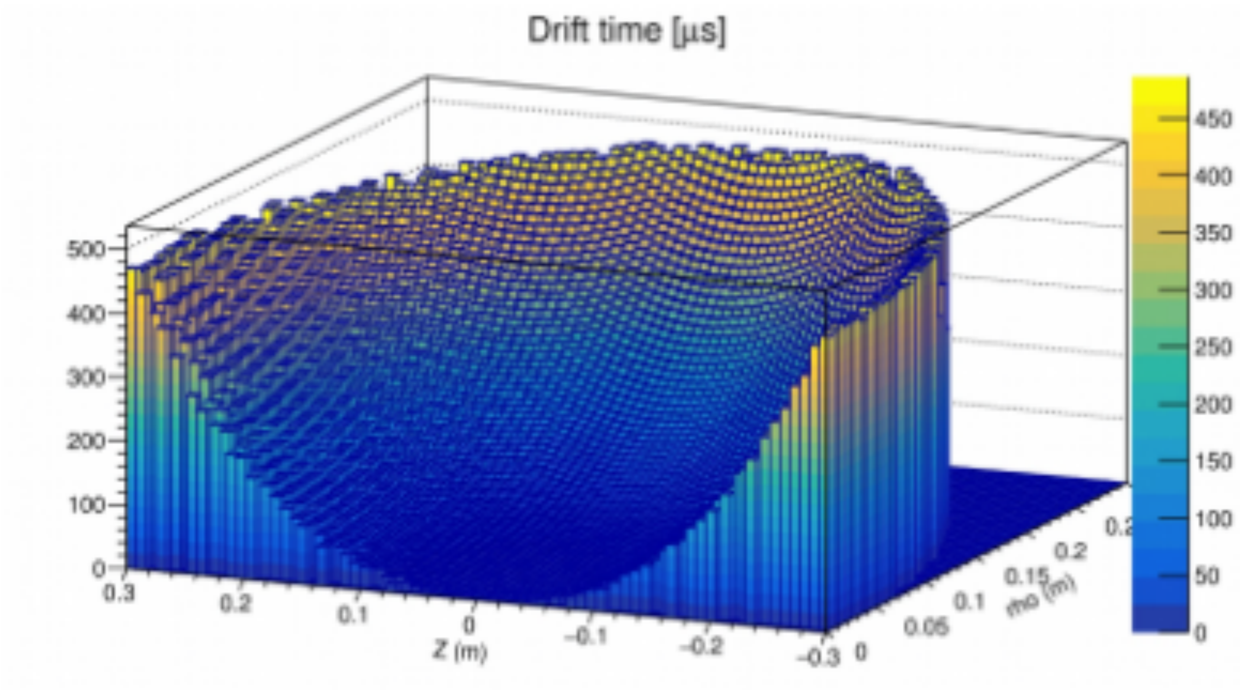
A NOTE ON THE COMPETITION

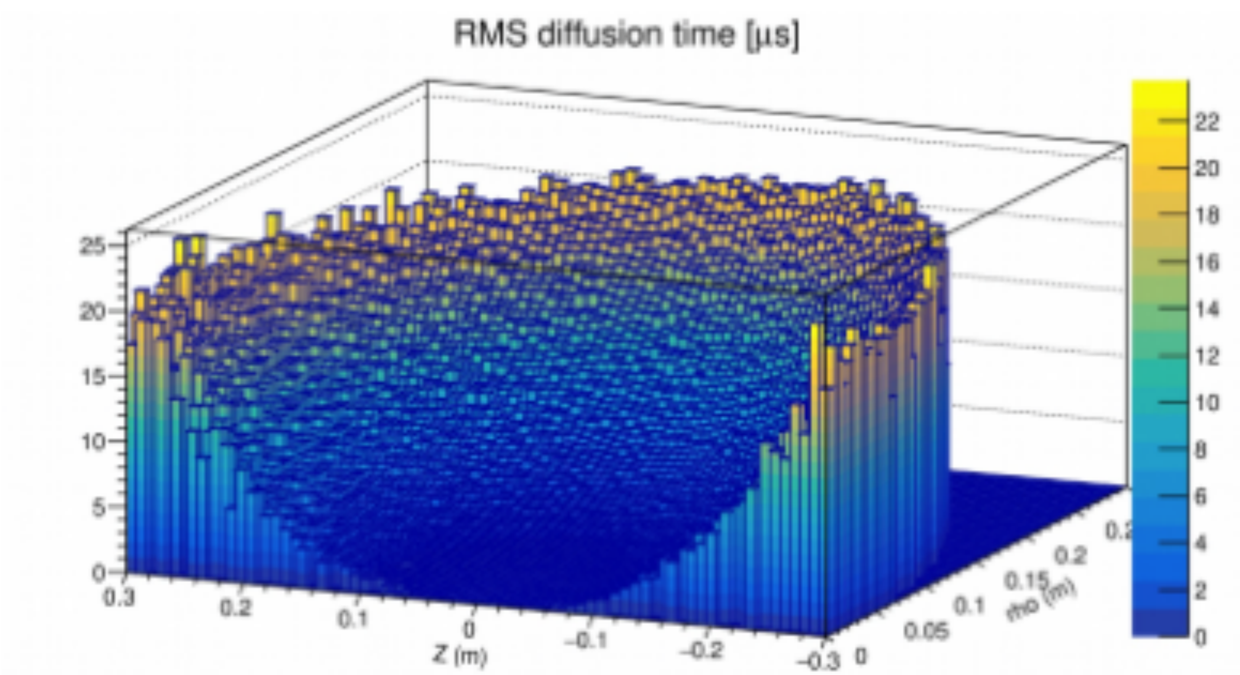
- XMASS-I (Kamioka)
  - 2018 paper setting first limits on solar KK axions.
  - 832 kg liquid Xenon tank surrounded by PMTs.
  - No coincidence discrimination, instead rely on annual signal modulation due to change in distance from the Earth to the Sun, over 500 days.

- DRIFT (University of Sheffield)
  - Low pressure gas TPC (0.05 bar).
  - No results papers yet, but presentation mentioning they can do exposure of $1m^3$*year, and with the addition of a lead shield (currently absent) to reduce gamma background. Their projected sensitivity with the shield is much better than ours.

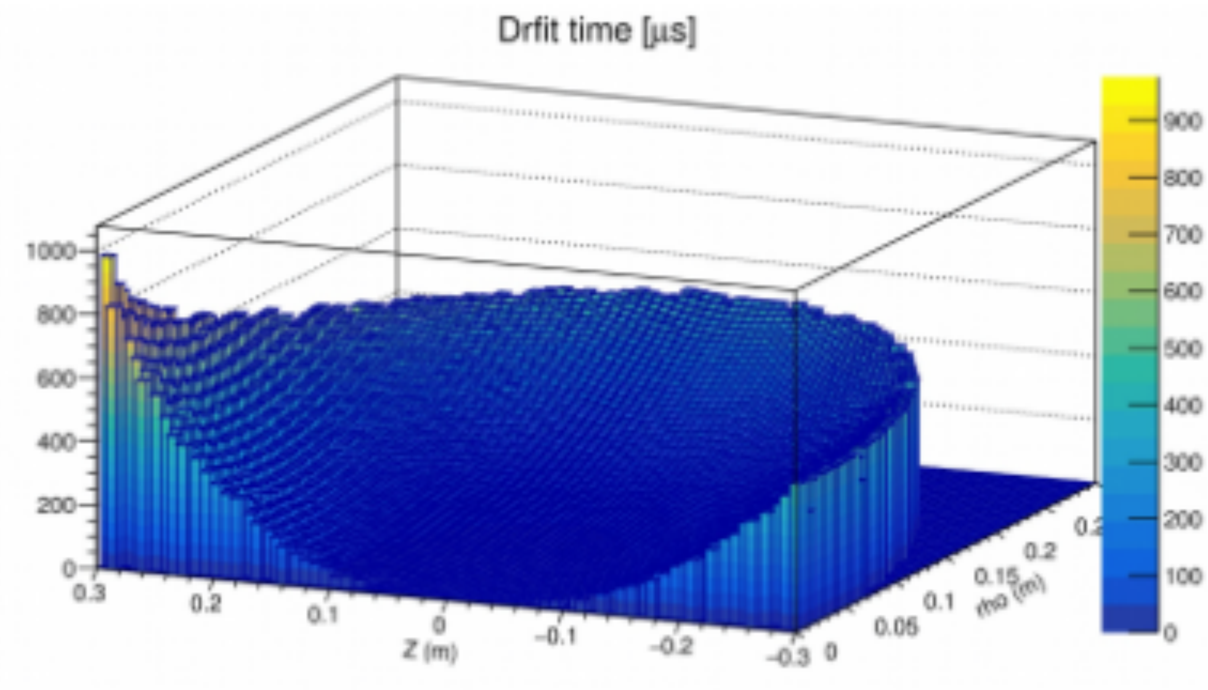
- Other TPCs?

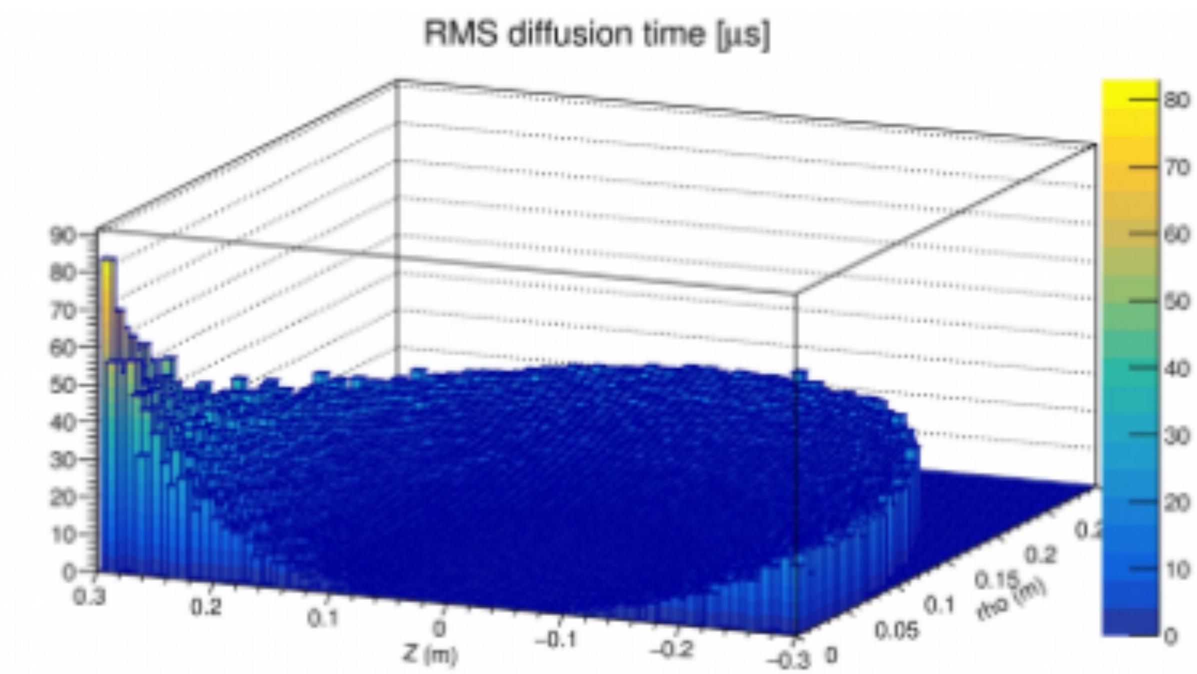
Ideal Geometry



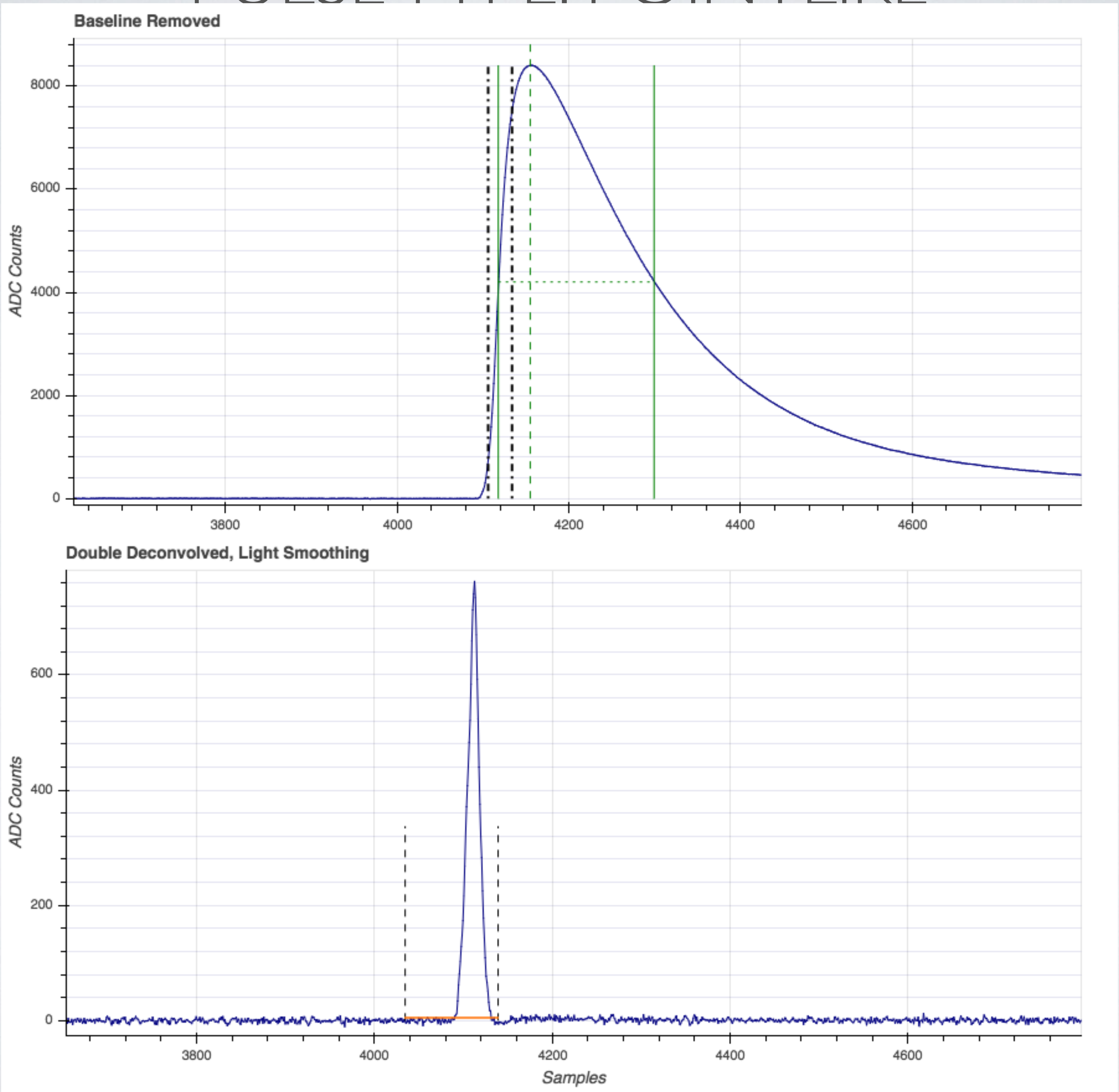


Real Geometry

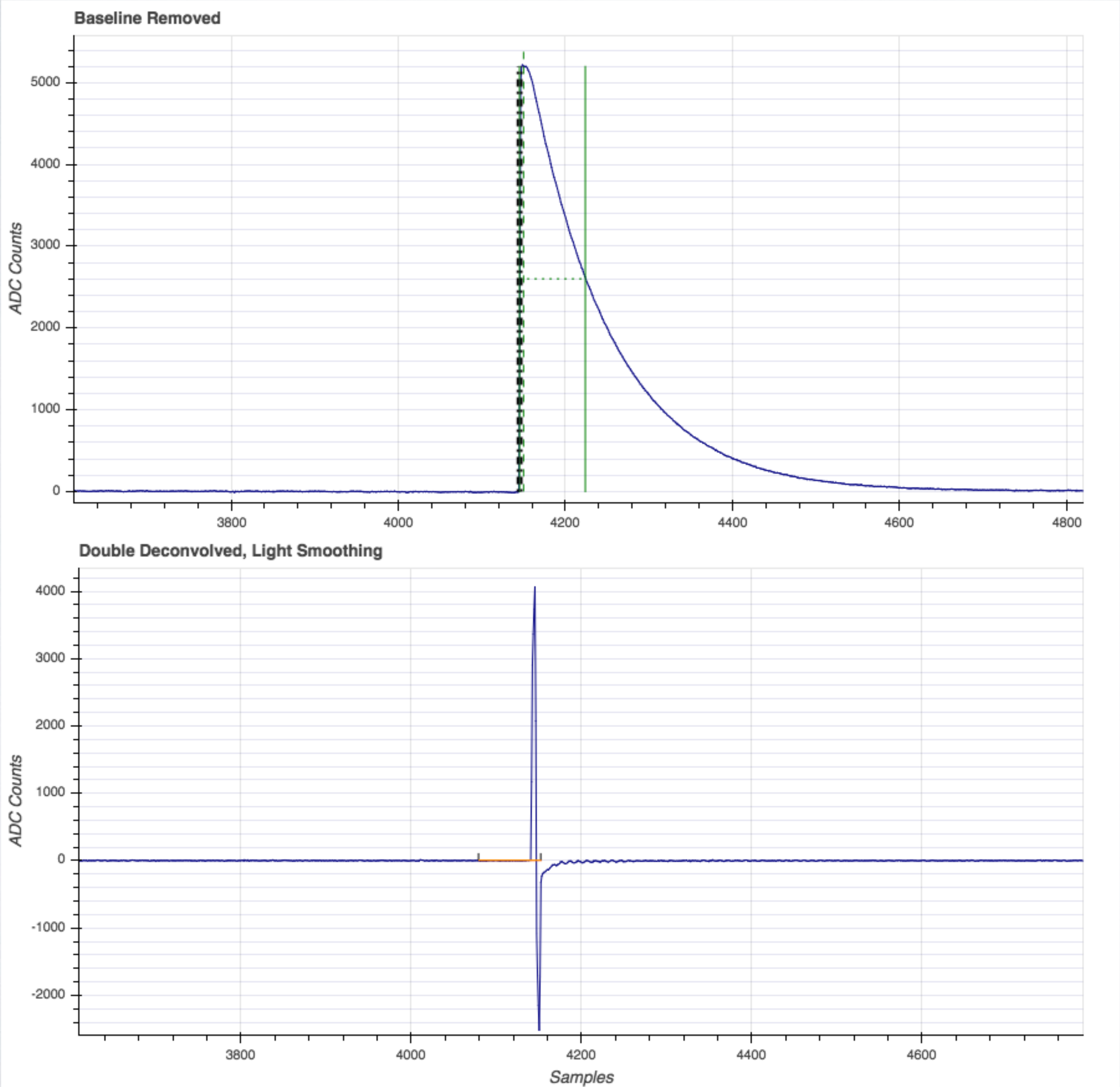




PULSE TYPE: POINTLIKE



PULSE TYPE: "ELECTRONIC" EVENTS



PULSE TYPE: TRACK