Pass the salt: LUX's alternative to blinding

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for the LUX collaboration

Blind Analysis in High-Stakes Survey Science
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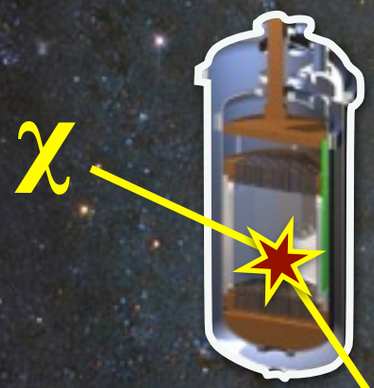
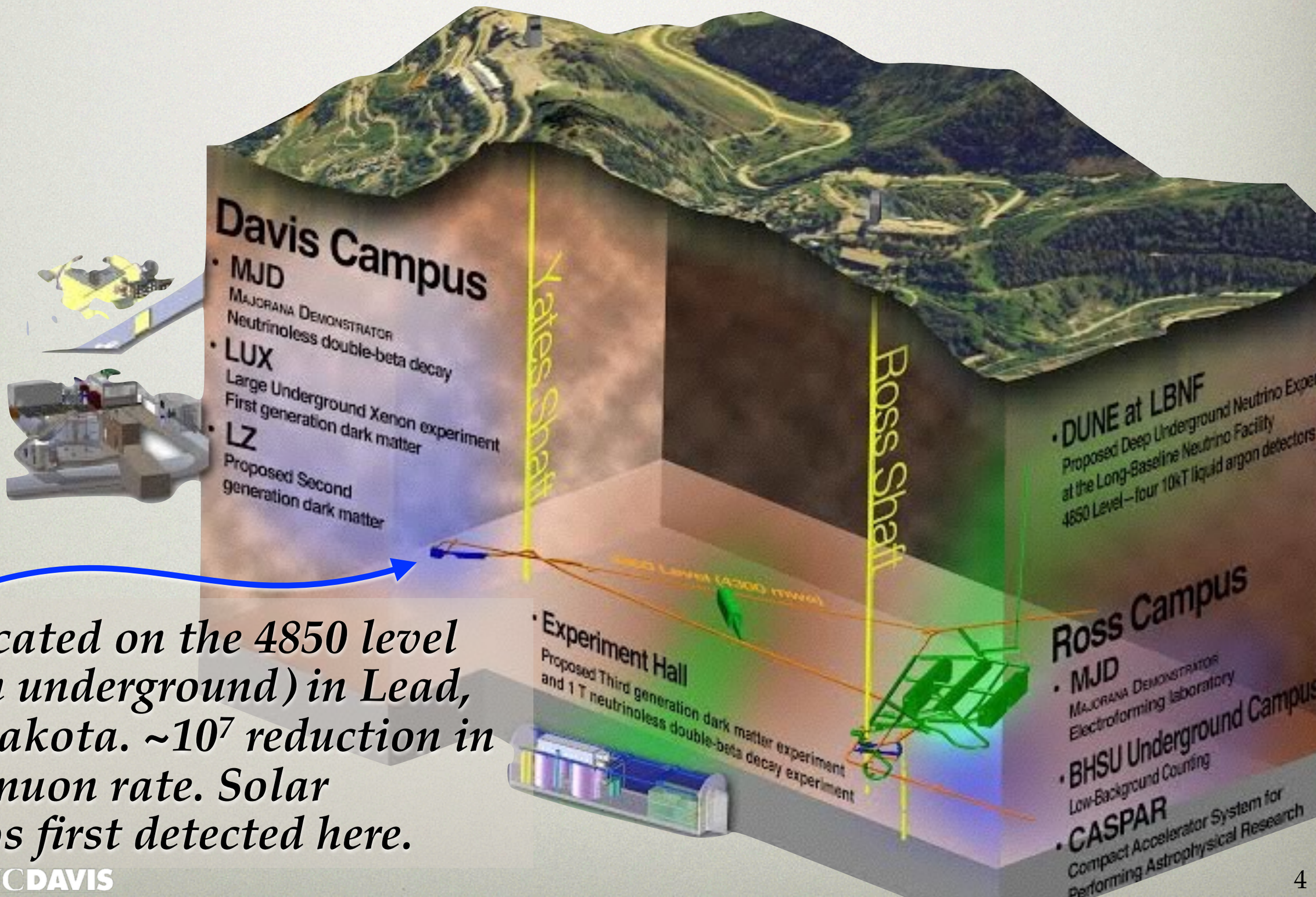
Dark matter direct detection in a nutshell



Sanford Underground Research Facility



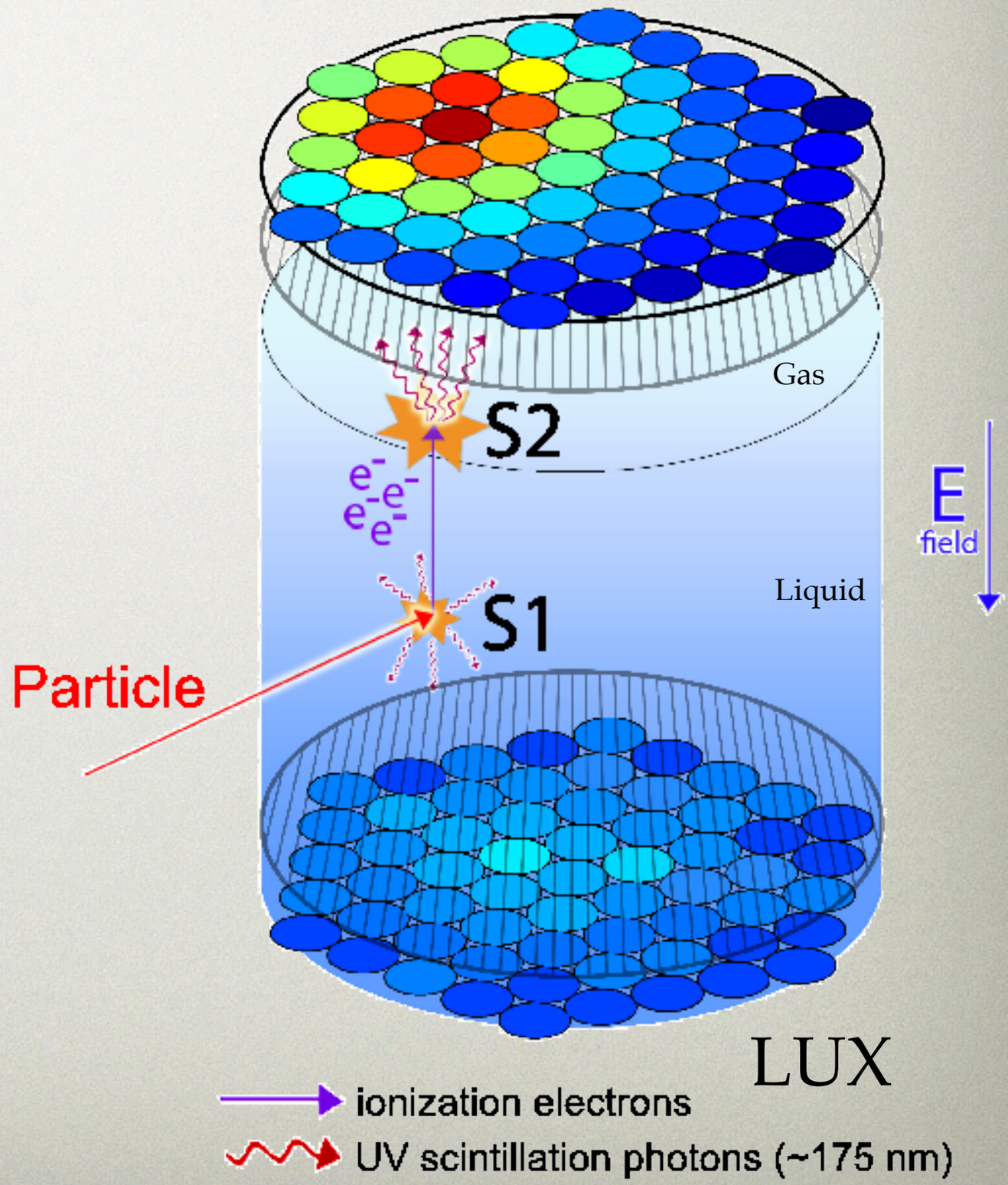
***LUX**, located on the 4850 level (~1.5 km underground) in Lead, South Dakota. ~10^7 reduction in cosmic muon rate. Solar neutrinos first detected here.*

Detection technique

- Dual-phase Xenon Time Projection Chamber (TPC)
- E-dep:
  - primary scintillation (S1)
  - ionization (S2)

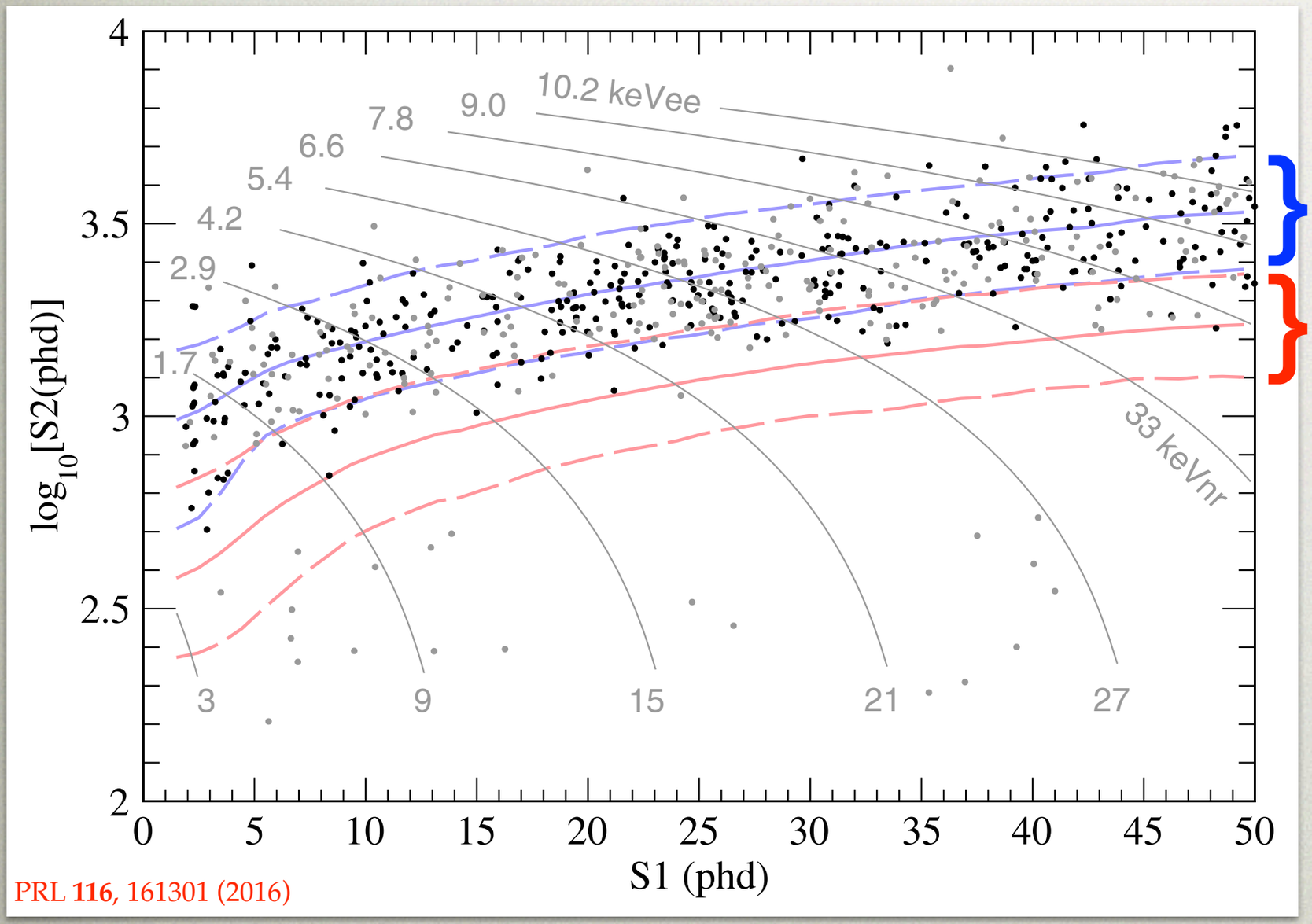
(both measured by PMTs)

- PMT hit-pattern gives *x*-*y* position.
- S1-S2 delay time gives *z* position
- Signal: nuclear recoils
- Background: [mostly] electronic recoils.



Data parameter space

LUX's first science data (95 live days, non-blind)



PRL **116**, 161301 (2016)

Electronic Recoils (BG)

Nuclear Recoils (Signal)

- The two energy variables, scintillation (S1) and ionization (S2), permit distinction between Electronic Recoils and Nuclear Recoils.
- Analysis involves also three position variables.

Data parameter space

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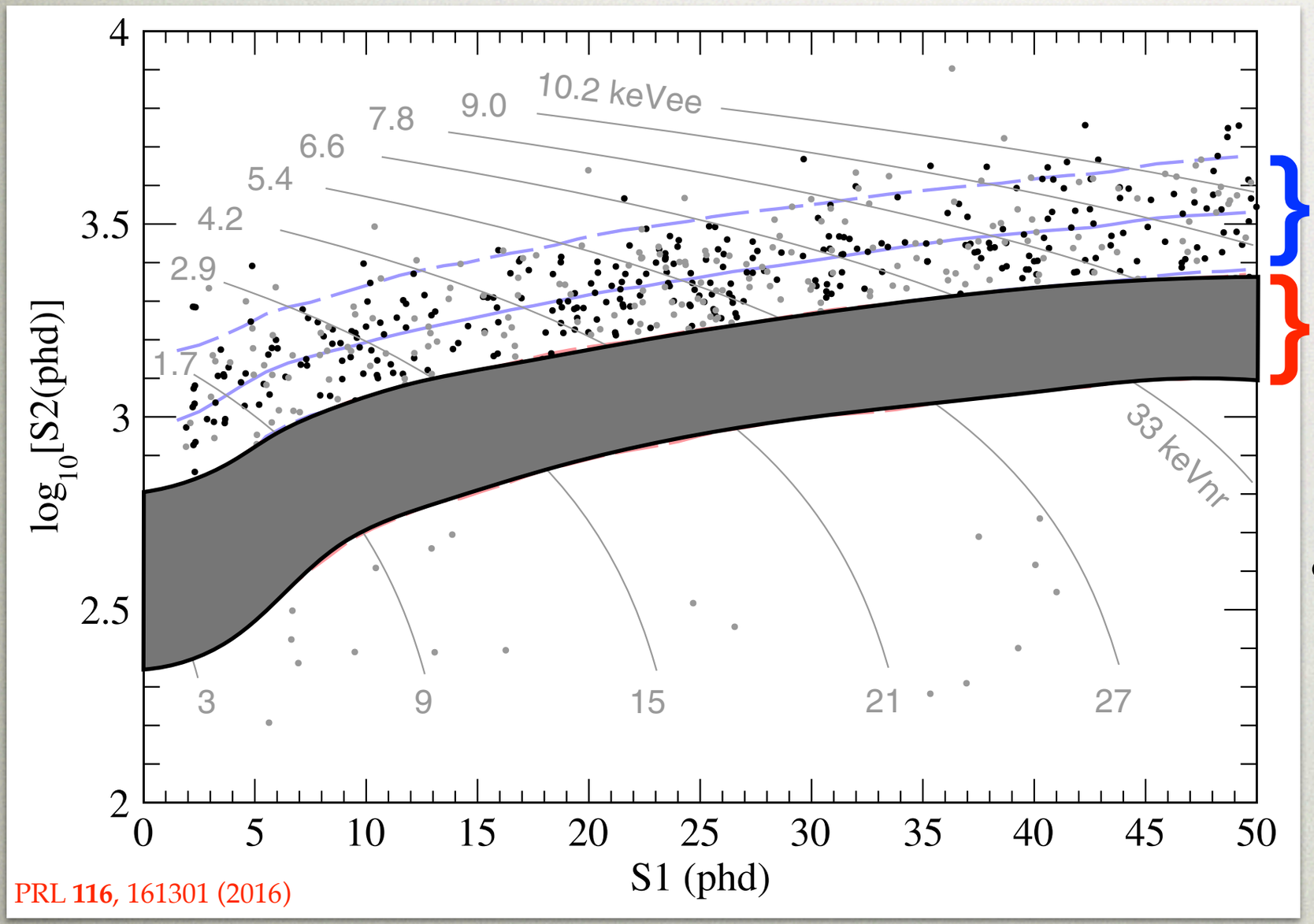

PRL **116**, 161301 (2016)

} Electronic Recoils (BG)

} Nuclear Recoils (Signal)

- Traditional blinding: one masks the signal region from view until analysis is finalized.

Two important calibrations

- **CH_3T** (tritiated methane): Used to define our ER band (i.e. background). After injection, mixes uniformly in the detector in minutes. Removed on a ~8 hr timescale by our purification system.

- **Deuterium-Deuterium** neutron generator: Used to define our NR band (i.e. signal). Monoenergetic, collimated neutron beam.

Blinding problems

Dark matter direct detection searches are:

- low-background
- rare signal event

- **Blinding in this type of search means one is also blind to rare backgrounds.**

- Un-modeled rare BGs are not a showstopper for a 1-sided search (i.e. limit-setting only), but they are quite problematic for a 2-sided search.

∃ plenty of examples in this field of blind searches "discovering" un-modeled, pathological backgrounds. E.g.:

- XENON10: PRL **100** (2008) 021303 (arXiv:0706.0039)
- XENON100: PRL **109** (2012) 181301 (arXiv:1207.5988)
- ZEPLINIII: PRD **80** (2009) 052010 (arXiv:0812.1150)
- SuperCDMS: PRL **112** (2014) 241302 (arXiv:1402.7137)

Blinding

Dark matter direct dete

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- **Blinding in this type o**
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Annu. Rev. Nucl. Part. Sci. 2005. 55:141–63
doi: 10.1146/annurev.nucl.55.090704.151521

BLIND ANALYSIS IN NUCLEAR AND PARTICLE PHYSICS

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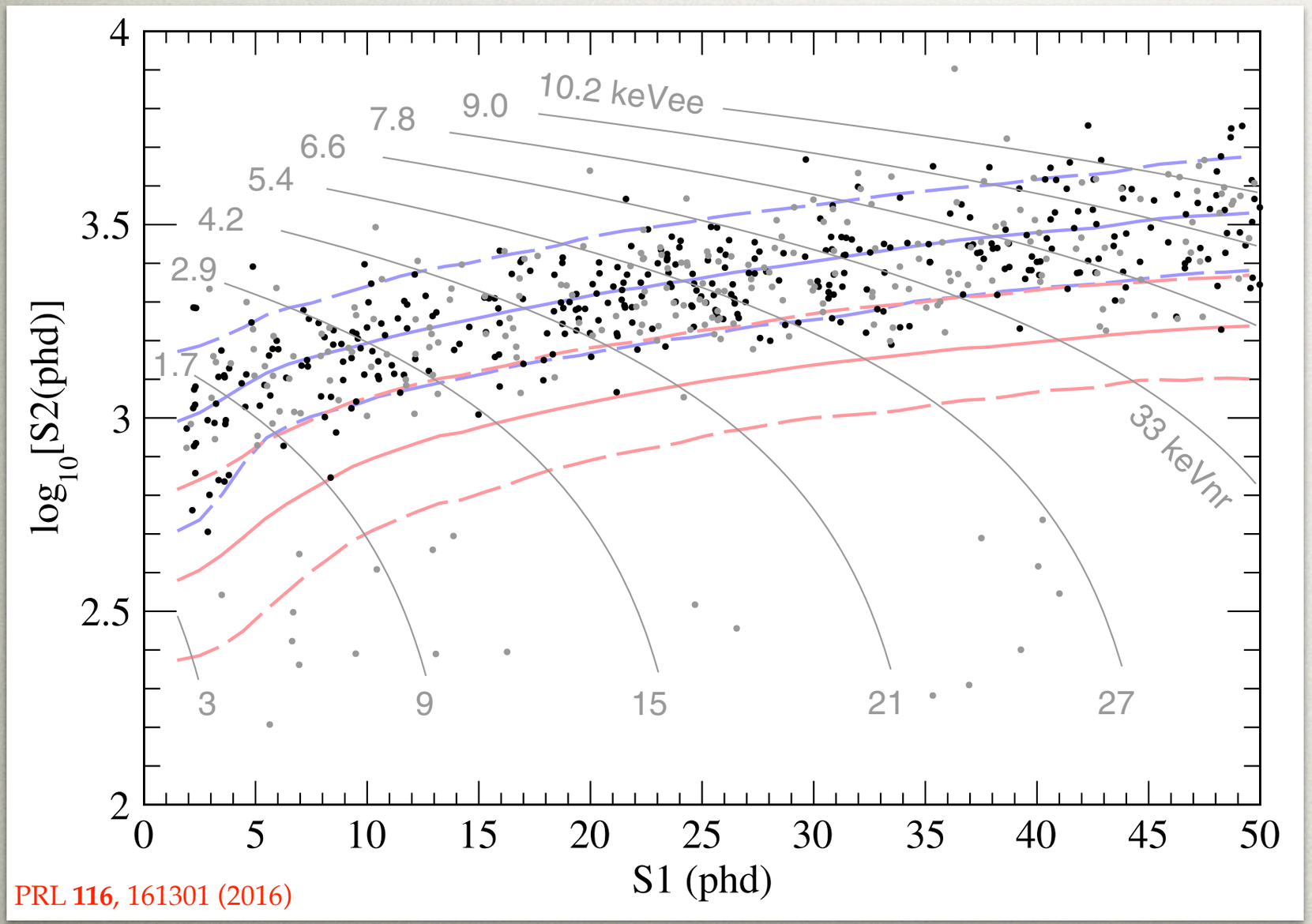
of th [traditional blinding] prevents the experimenter from being able to examine the characteristics of the signal, and hence carries the kind of risk discussed in Section 2: a large and obvious signal can be missed while the experimenters examine background details that later turn out to have little impact on the measurement. In addition, a hidden signal box approach assumes that the characteristics of the backgrounds are known well enough that nothing unexpected will be discovered when the signal box is opened.

Blinding alternative



PRL **116**, 161301 (2016)

- Blinding is a means, not an end. The end is to mitigate subjective bias.
- Instead, one can leave the data open, but **add fake signal events.** In this case, it might look like sprinkling salt on the plot.
- Other fields sometimes use a similar technique (often called "spiking"), e.g.
  - neutrino searches
  - searches for fractional charge
  - gravitational wave detection

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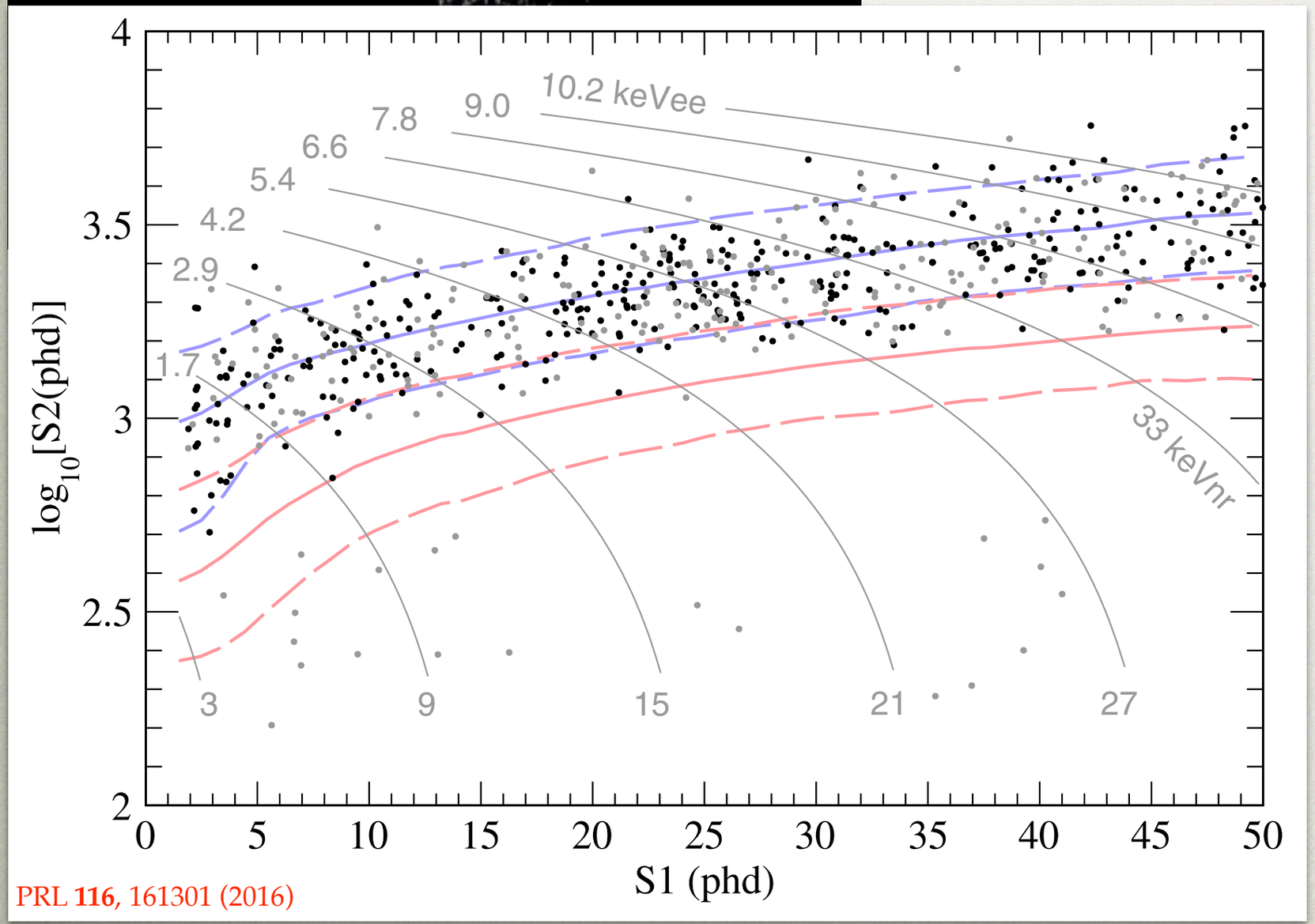

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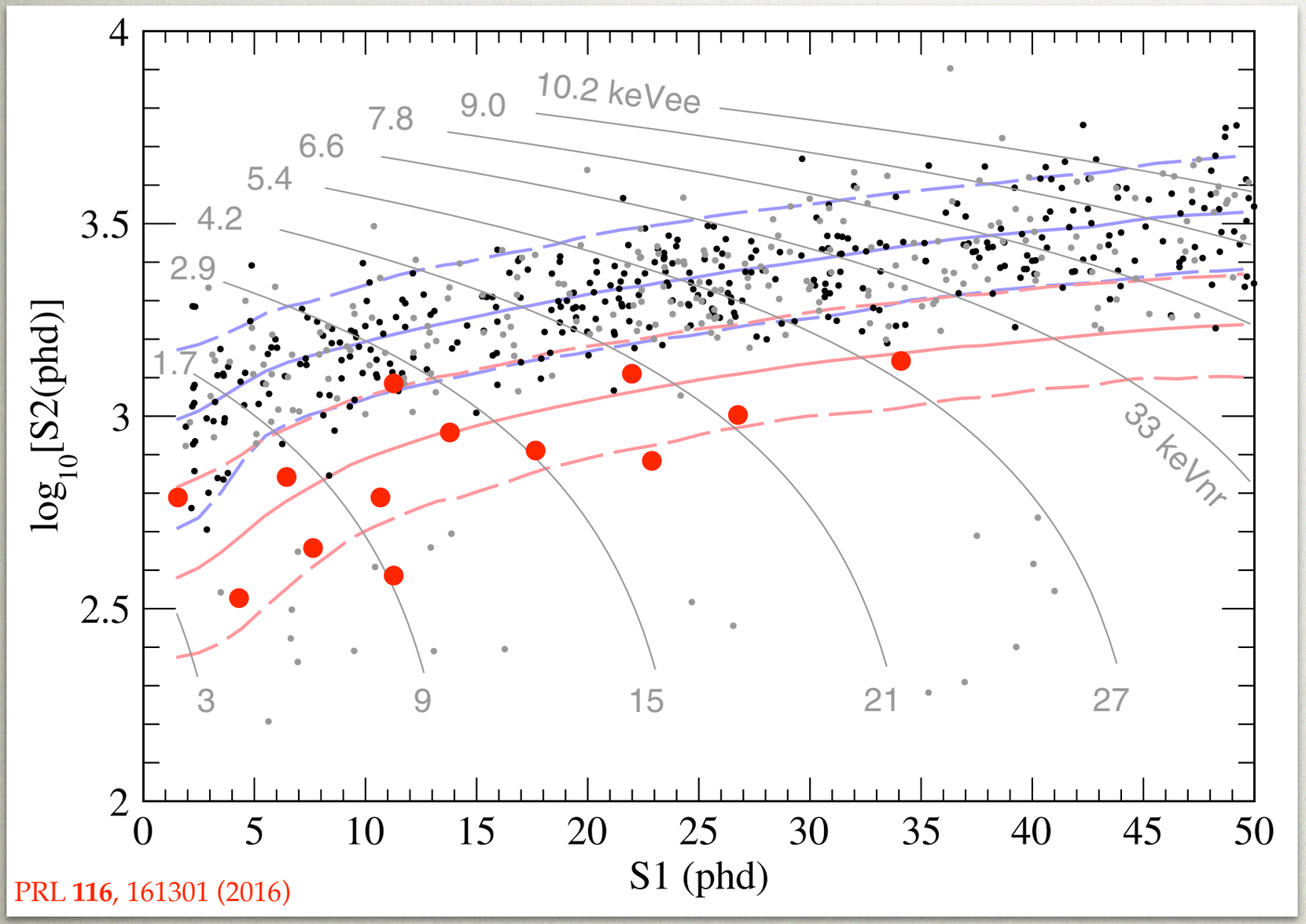

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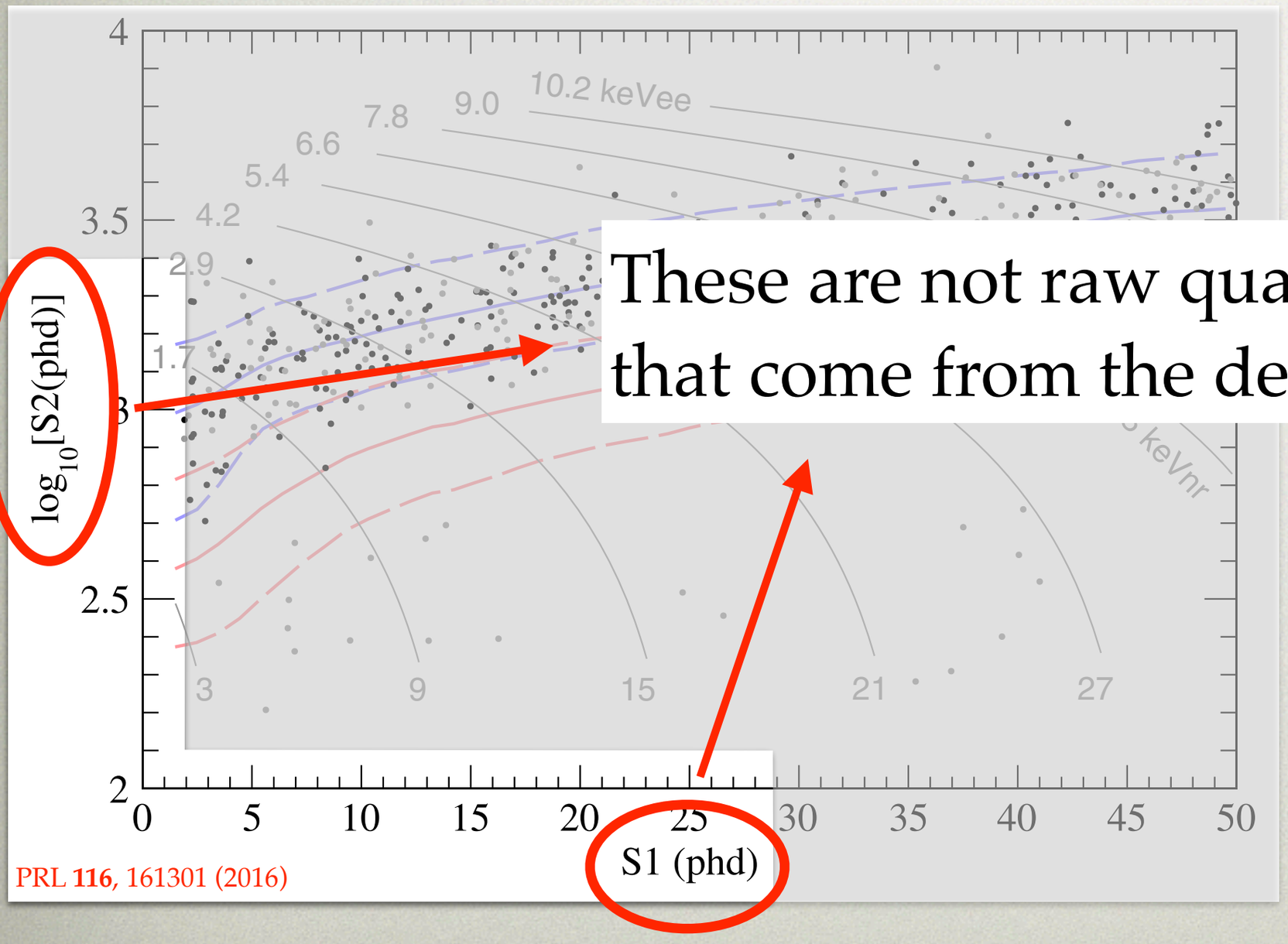
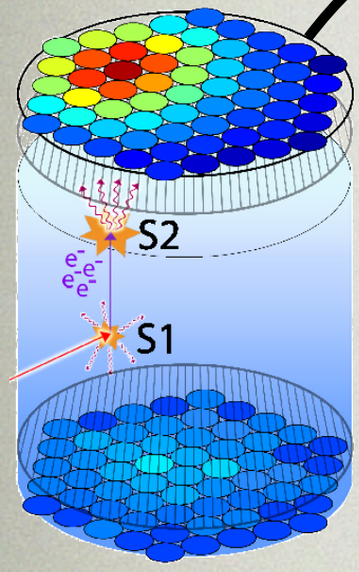
Salty details



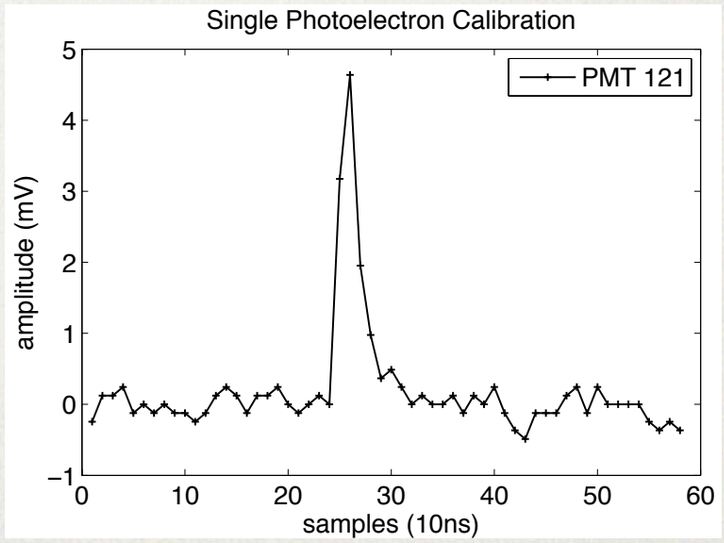
These are not raw quantities that come from the detector.

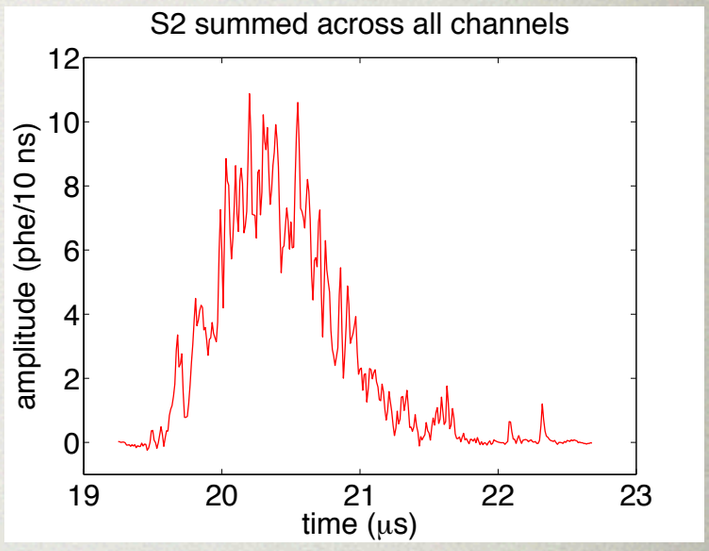
PRL **116**, 161301 (2016)

Salty details



Raw waveforms
(digitized samples)

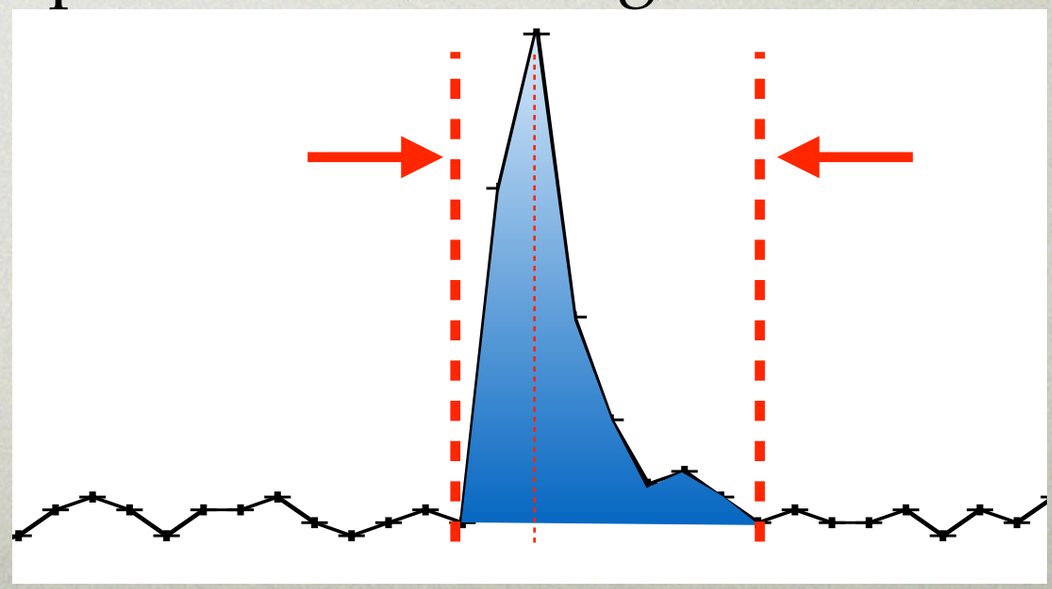




data processing

Reduced quantities
(used in analysis)

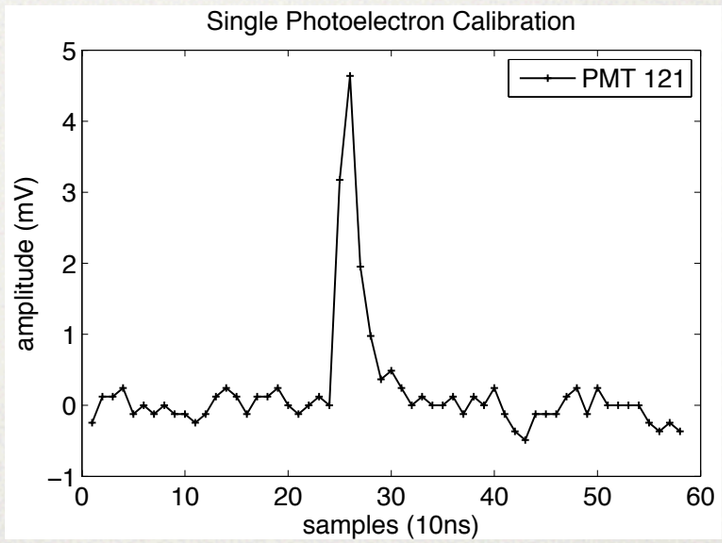
pulse areas, timing, widths, etc.

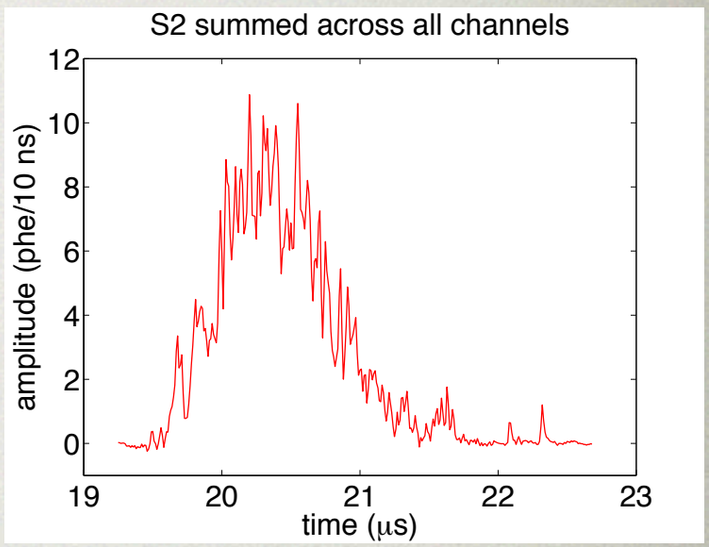


Salty details

At which stage do we add salt?

Raw waveforms
(digitized samples)





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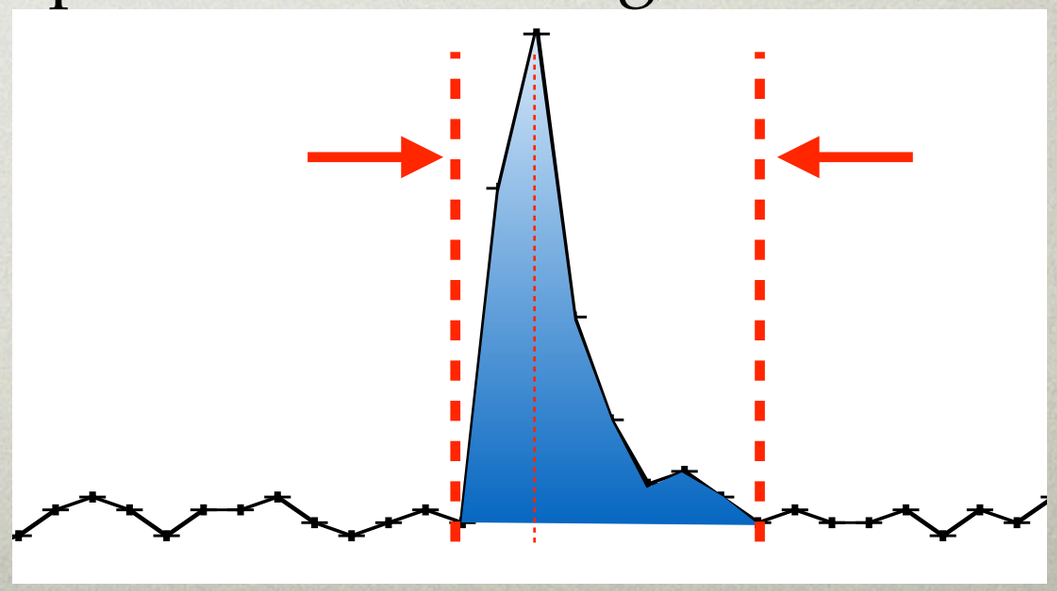

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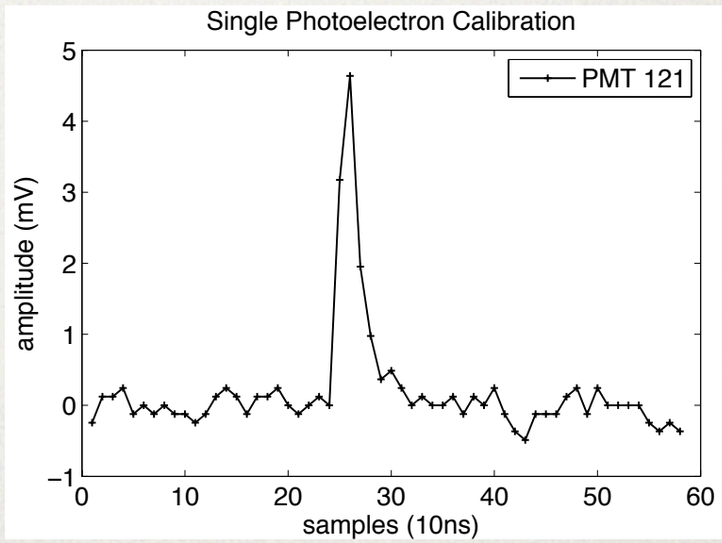

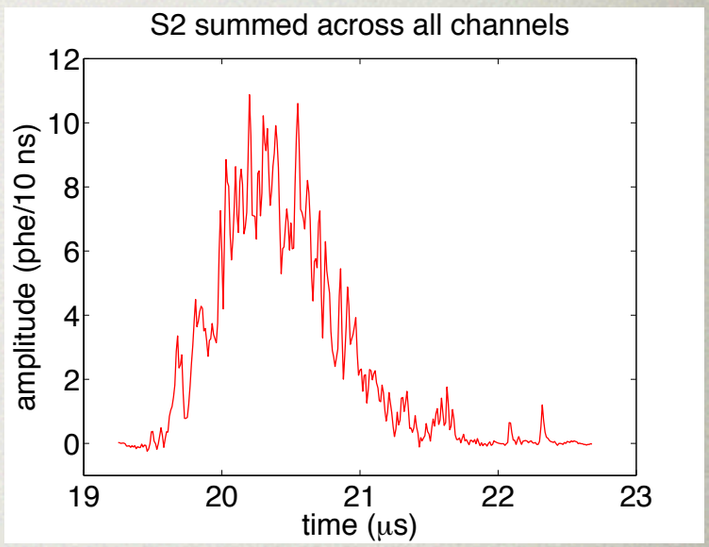

data processing

Easy, insufficient

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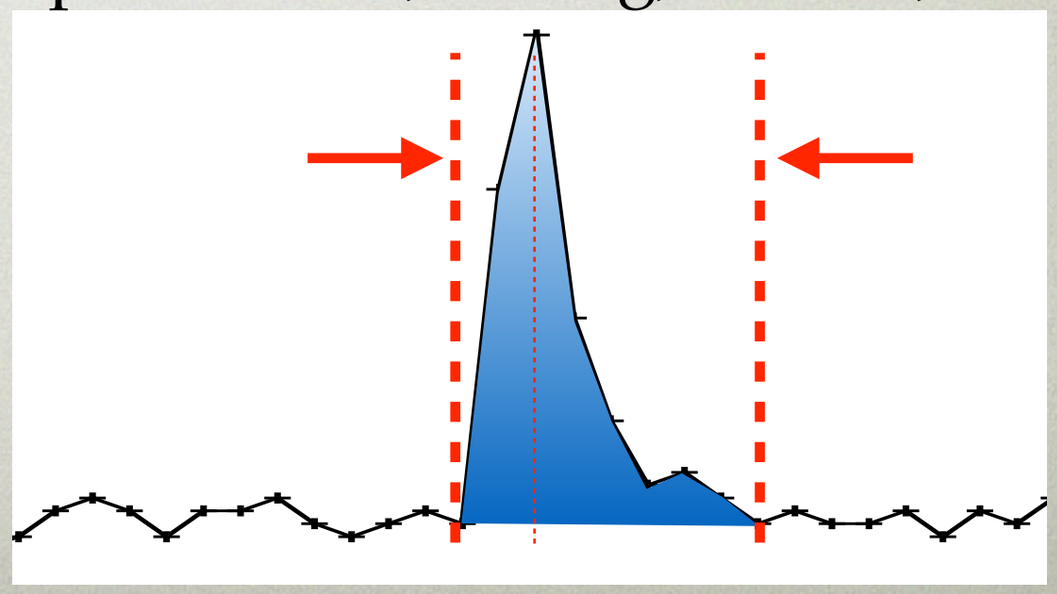

Salty details

At which stage do we add salt?

Difficult, necessary

Raw waveforms
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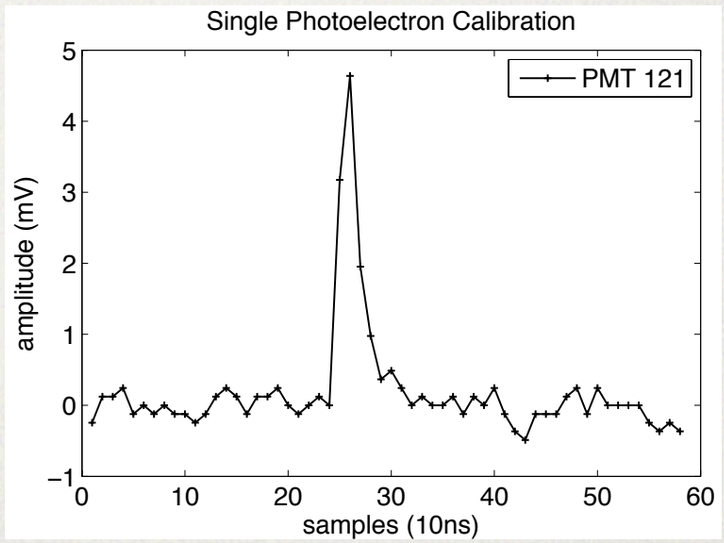

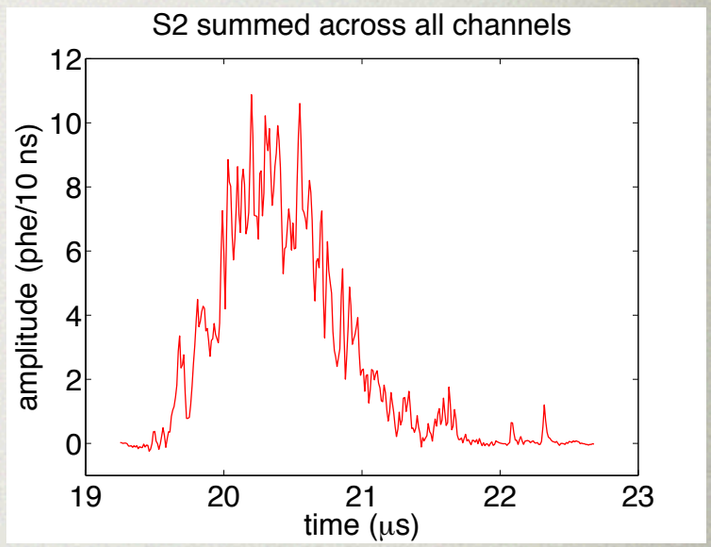

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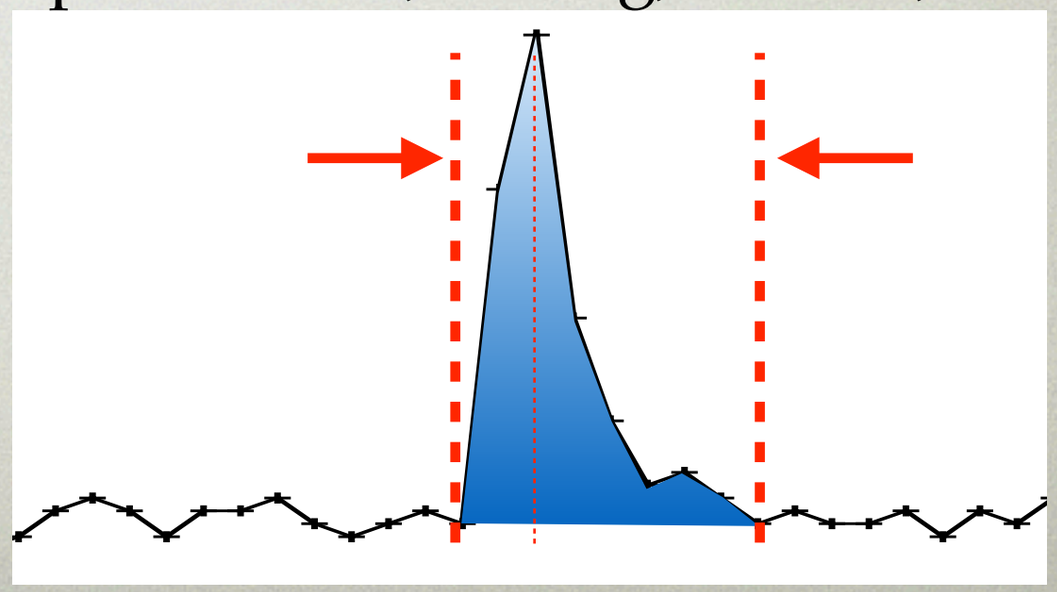

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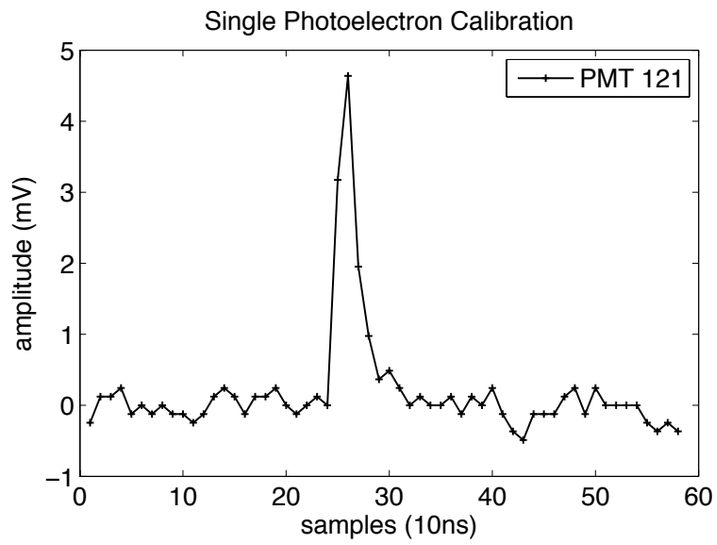

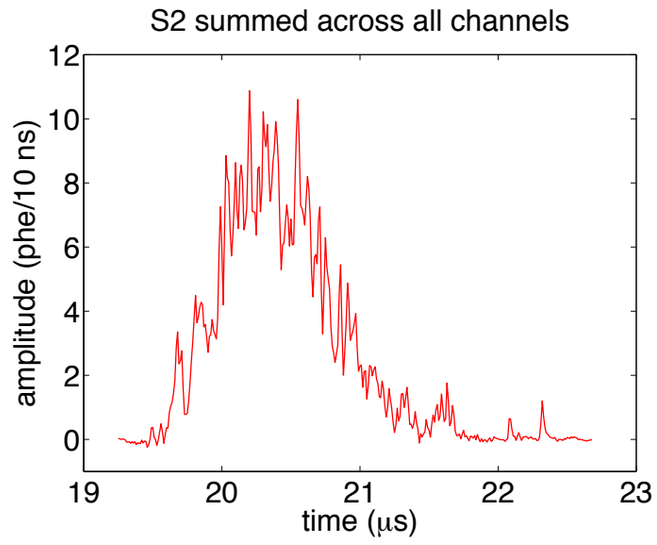

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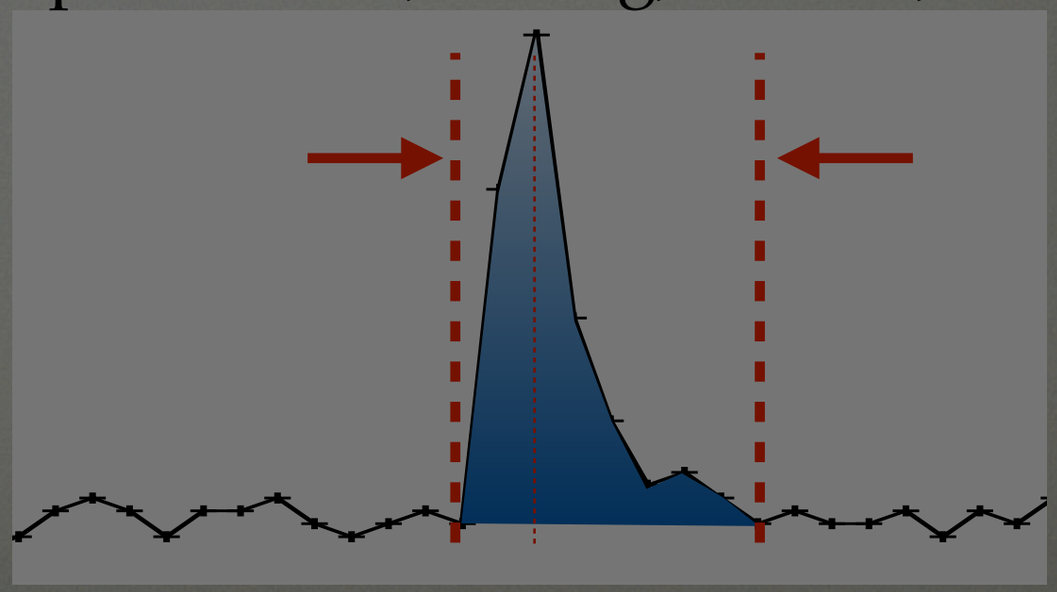

How to construct salted waveforms?

Three options for generating salt

- **Monte Carlo**
  - Pro: One is flexible to choose pulse parameters
  - Con: will probably miss some features of a real-world waveform, allowing identification of salt
- **DD Neutron calibration data**
  - Pro: WIMP-like S2/S1 ratio
  - Pro: actual detector data
  - Con: Not super clean (may contain multiple scatters)
  - Con: Events only exist at a fixed z position
- **Tritium calibration data**
  - Pro: Clean events (single scatter, low-energy)
  - Pro: actual detector data
  - Pro: Spatially uniform (physically)
  - Con: Wrong S2/S1 ratio

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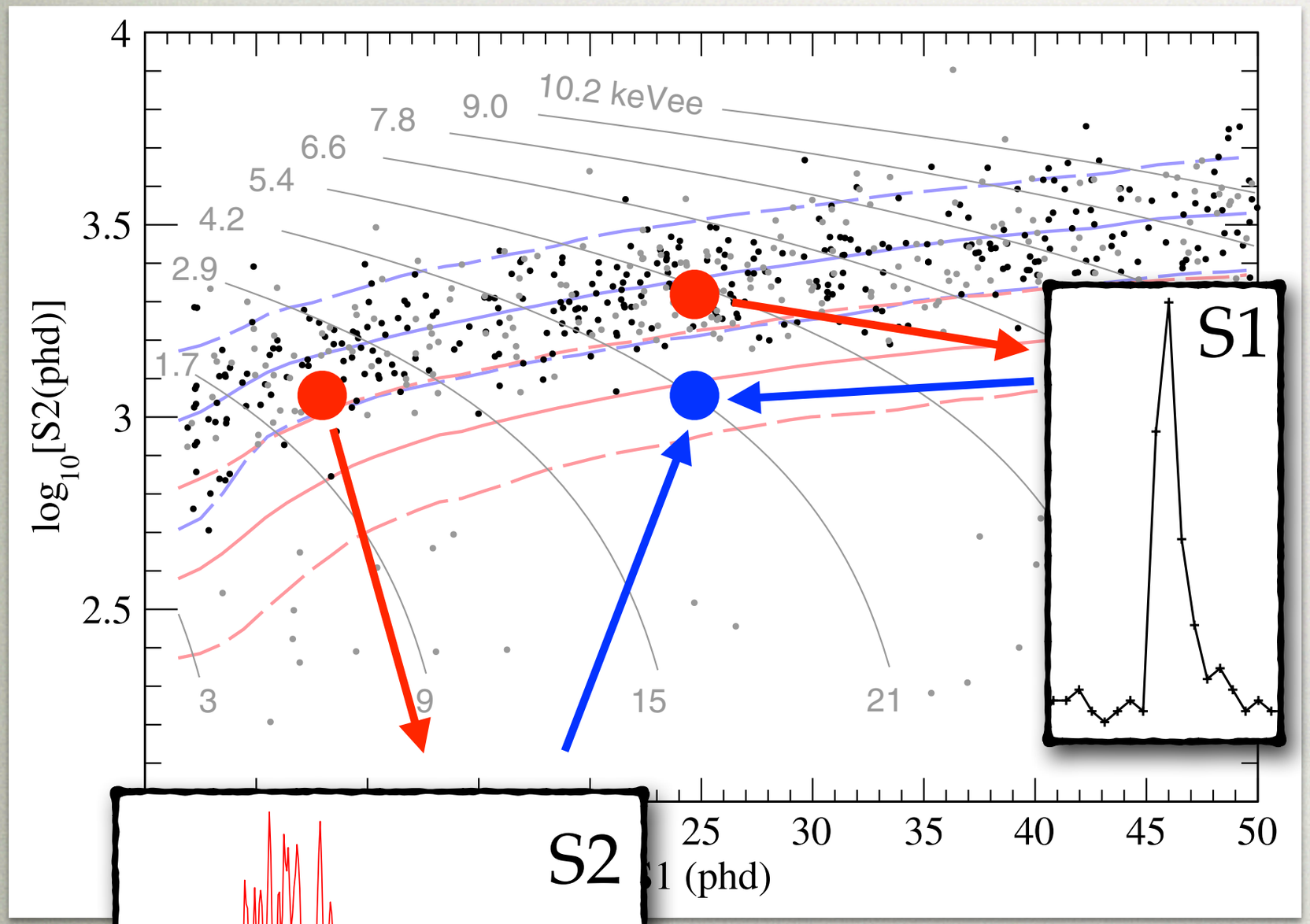
Turning tritium into salt

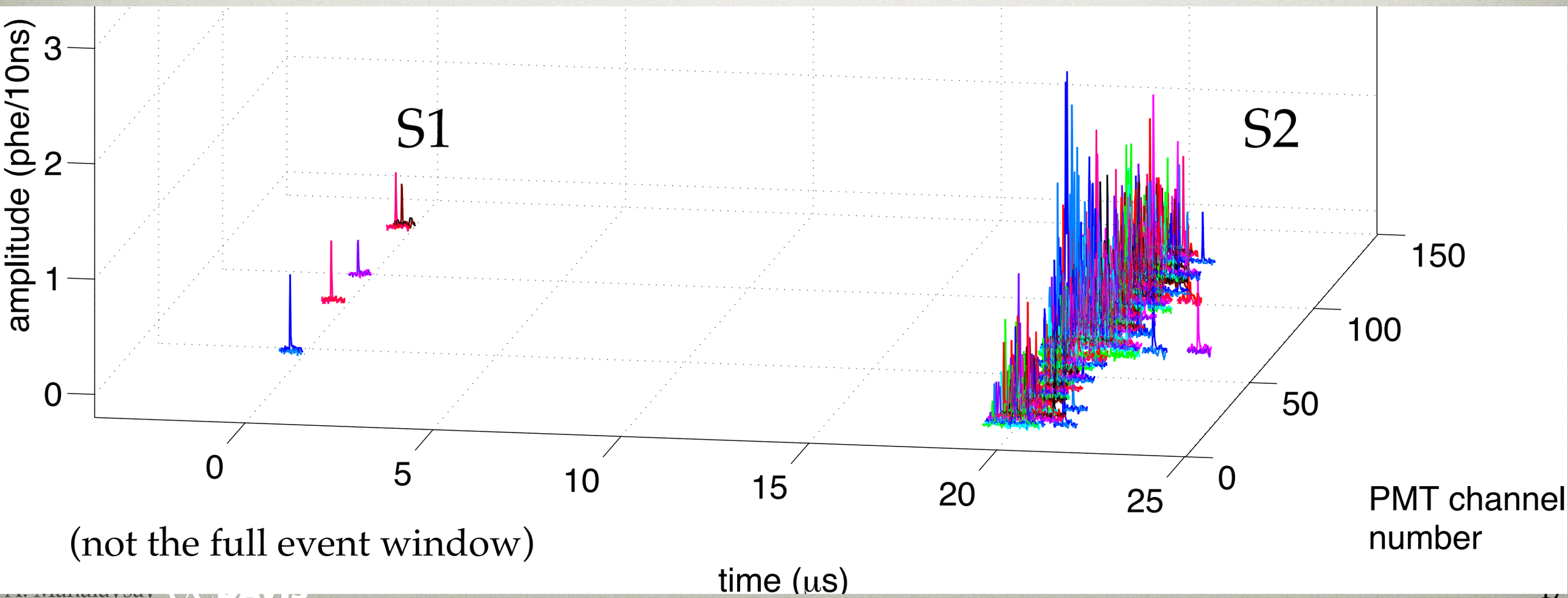


- By splicing together two ^{3}H events, we can create a chimera event whose S2-S1 proportion is consistent with a WIMP event.

Turning tritium into salt

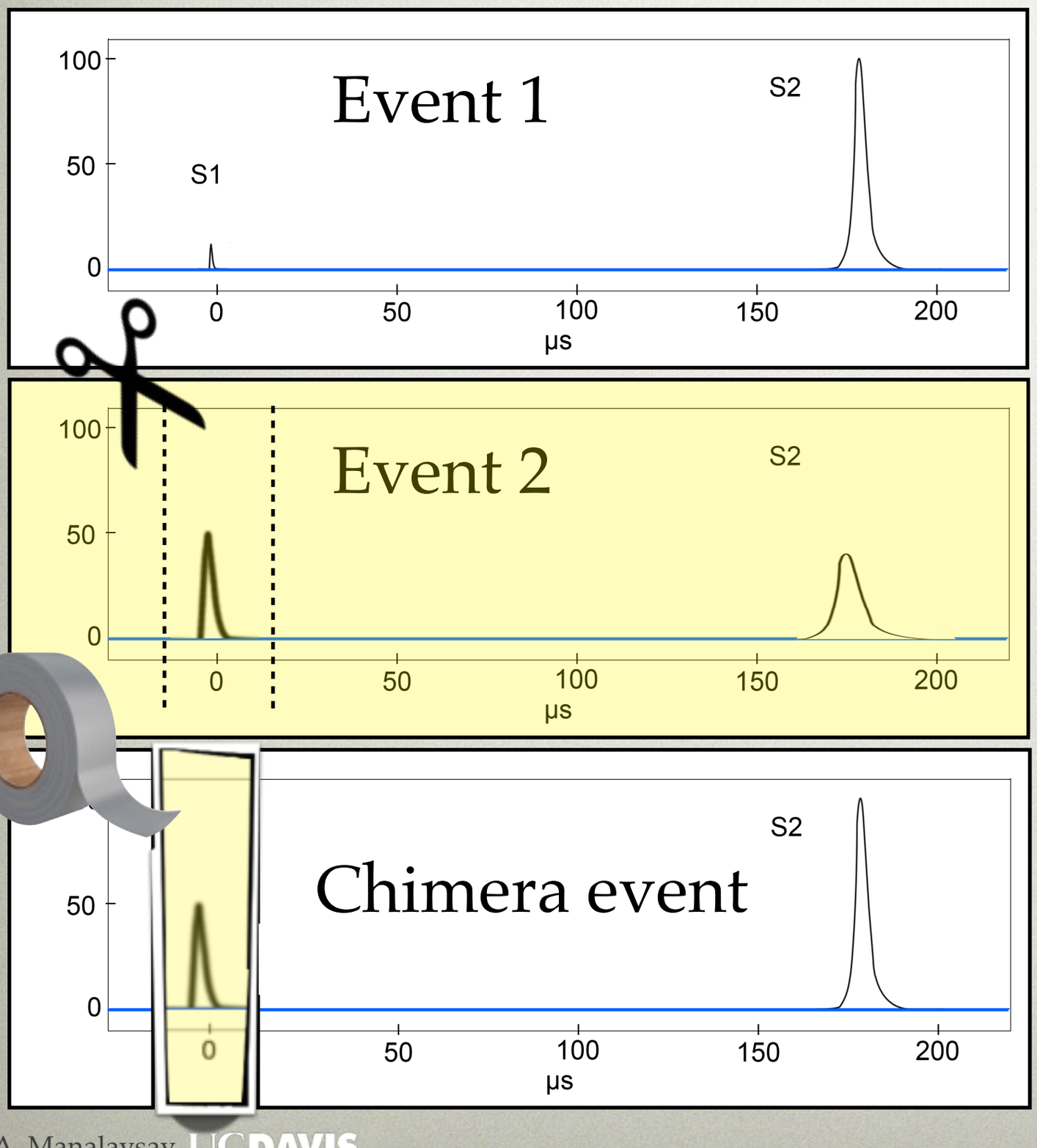
- The LUX DAQ records waveforms of pulses only (no baseline recorded between)

  ➡ simple to splice together bits from different pulses



(not the full event window)

Turning tritium into salt

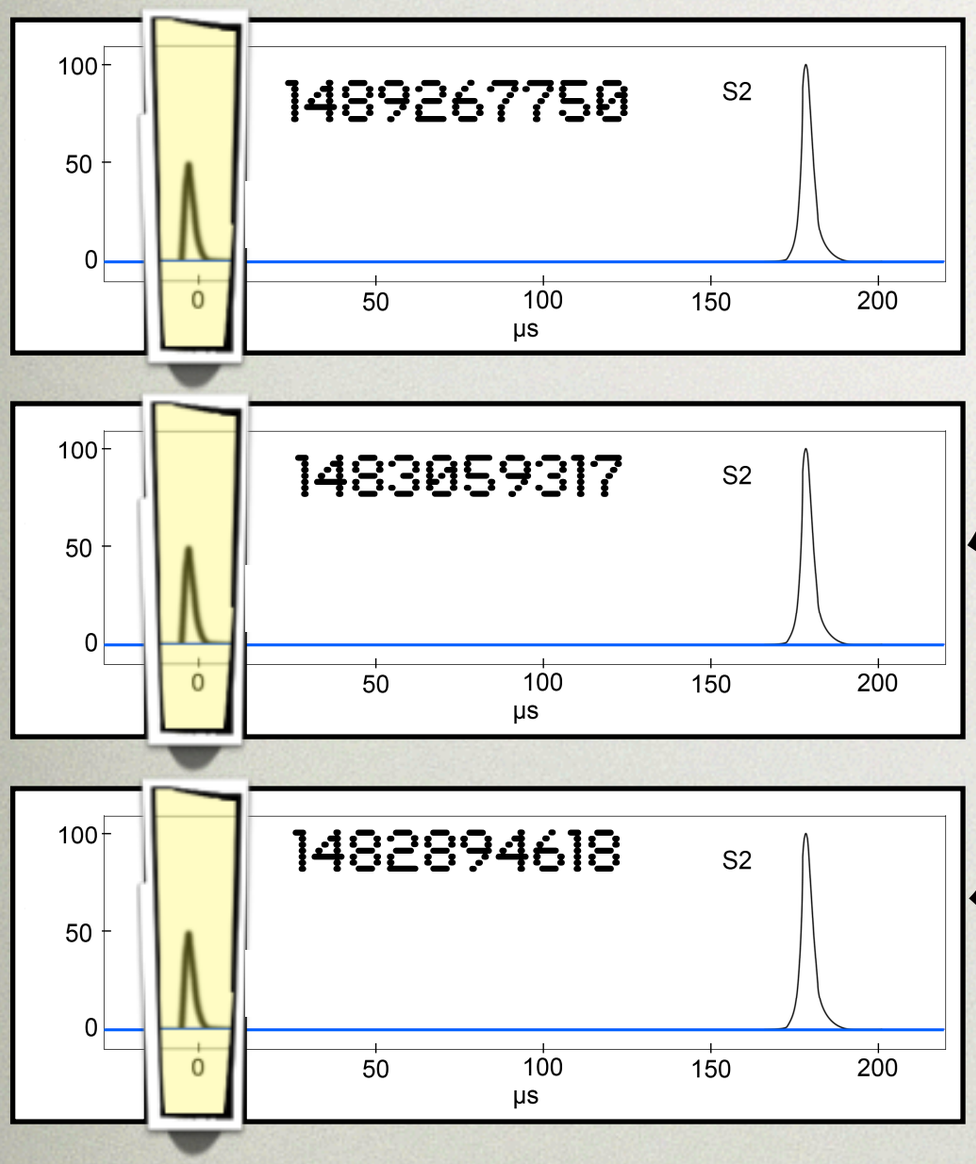


- Generate targeted S1 and S2 pulse areas with MC.
- Collect sequestered, blind ^{3}H data set.
- Find a ^{3}H event with the targeted S2 size (Event 1)
- Find a ^{3}H event with the targeted S1 size (Event 2), from a similar position as Event 1.
- Rip out the S1 from Event 1, implant the S1 from Event 2.
- New event contains all the detector quirks/features from Event 1.

Salt development

Before implementing the salt in the real data stream, we created several sets of "known" salt, and presented these data to the data-analysis group in a series of "salt Turing tests" to see if analyzers could identify which events are real and which are salt.

Implementation



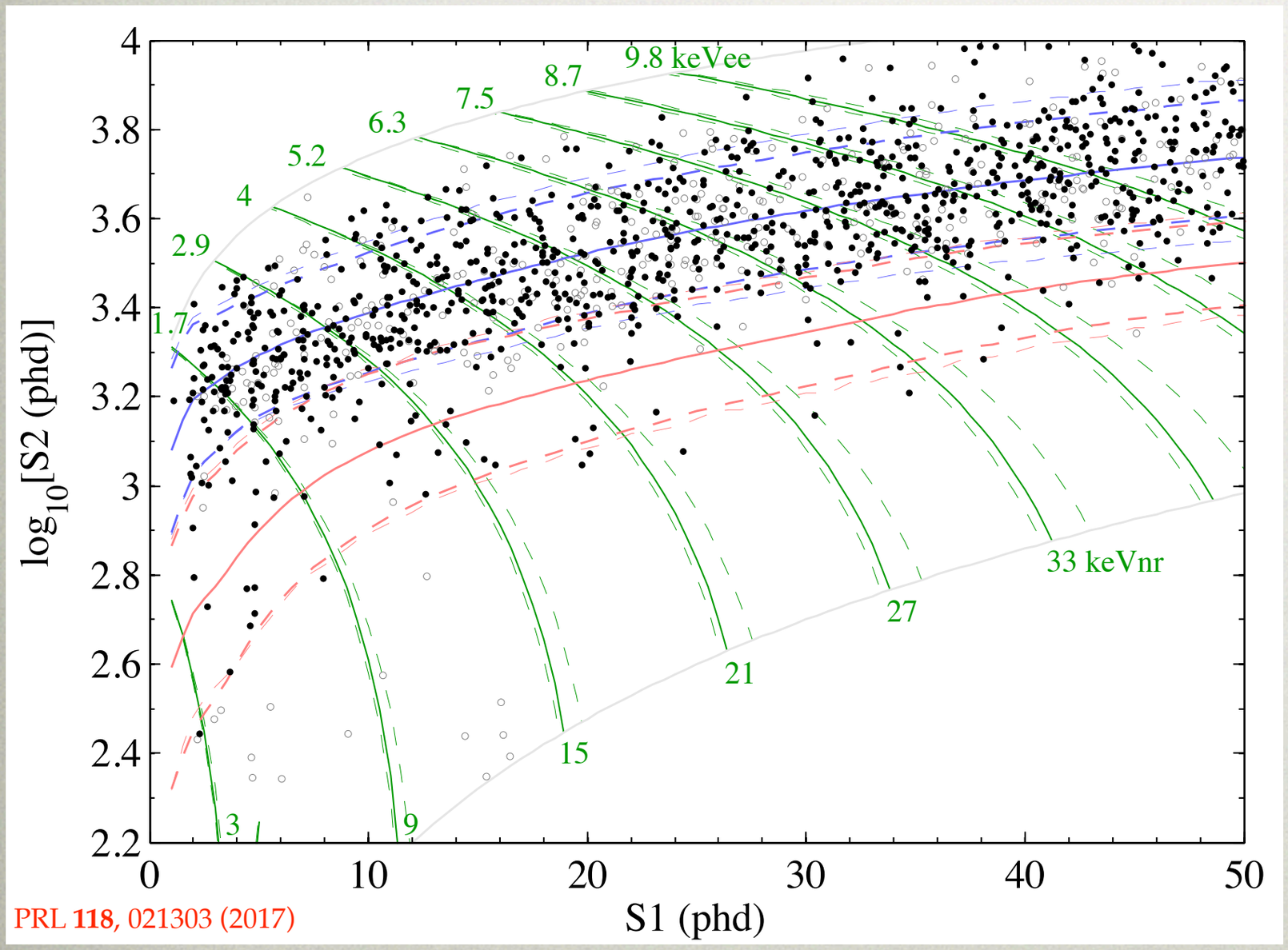
SaltDB

- Each generated salt waveform is given a random TIME STAMP and loaded into a database ("SaltDB").
- SaltDB is locked; it injects salt waveforms into our data stream.
- A sysadmin (not on LUX) at one of our data centers has access to SaltDB. This person is "salt keeper"
- Un-salting: we give a timestamp list to the salt keeper, they identify which on the list are salt.

the results…

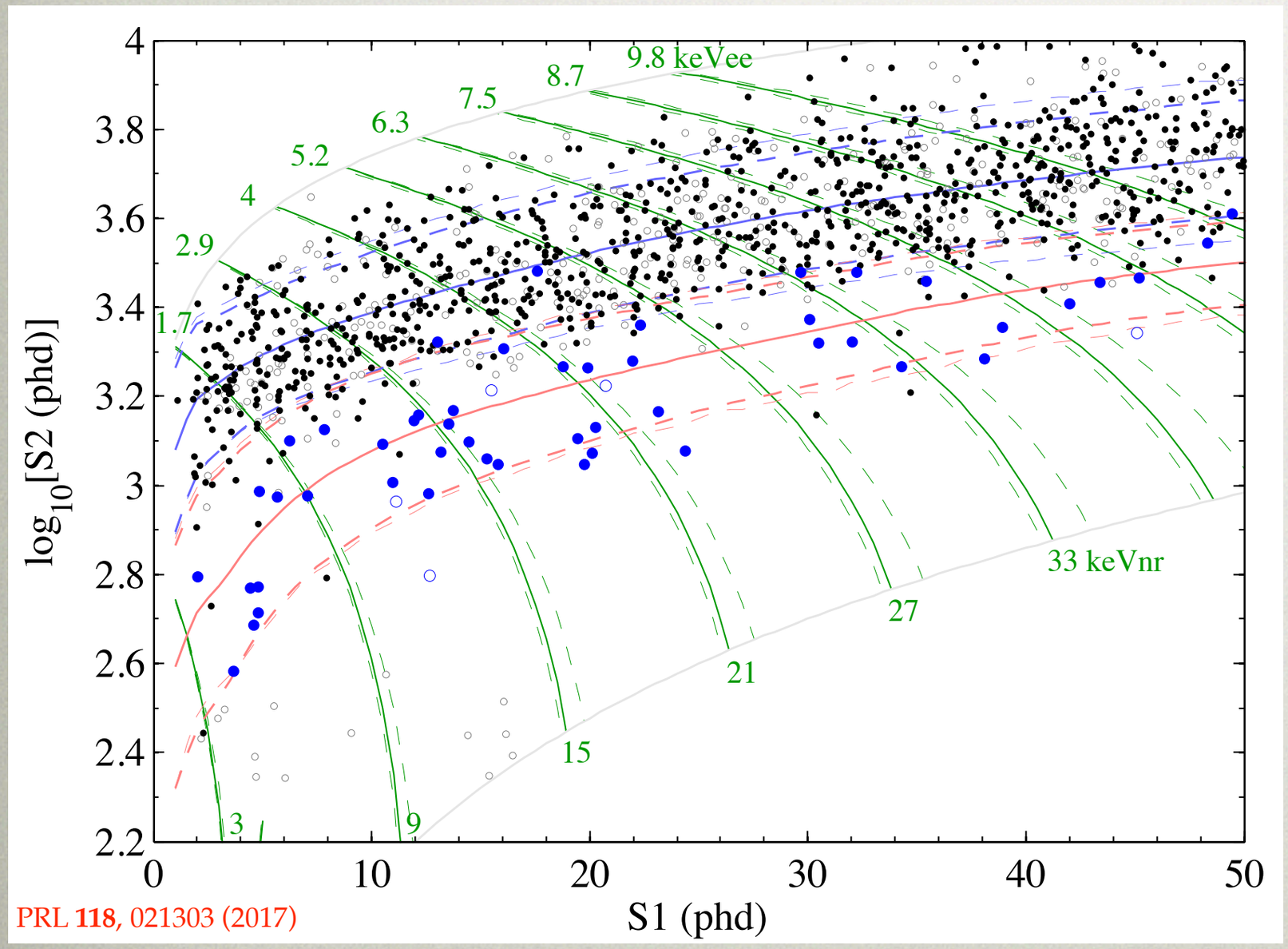
LUX's second science run (with salt)

LUX's second science data (332 live days, with salt)



- These are the data with salt still un-tagged.
- Salting was quite useful: it enabled us to identify a number of rare pathologies that contributed events to the signal band.

LUX's second science run (with salt)



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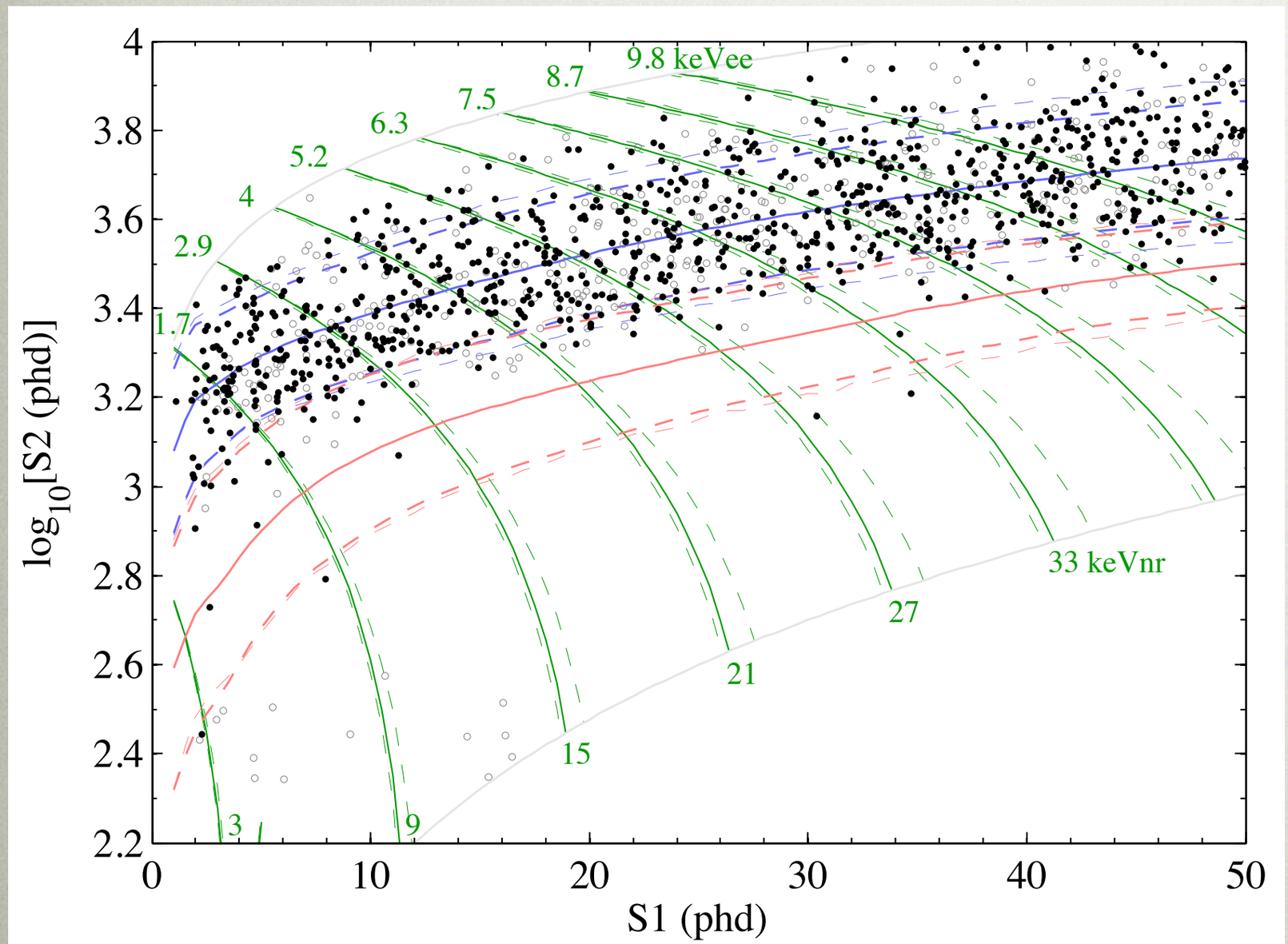
- Salt events identified in blue.
- These lie in the signal band, as expected.

Scrutiny after the salt removal



- After un-salting, events outside the ER band were scrutinized again.
- Three events were identified away from the BG region that were found to be clearly pathological.

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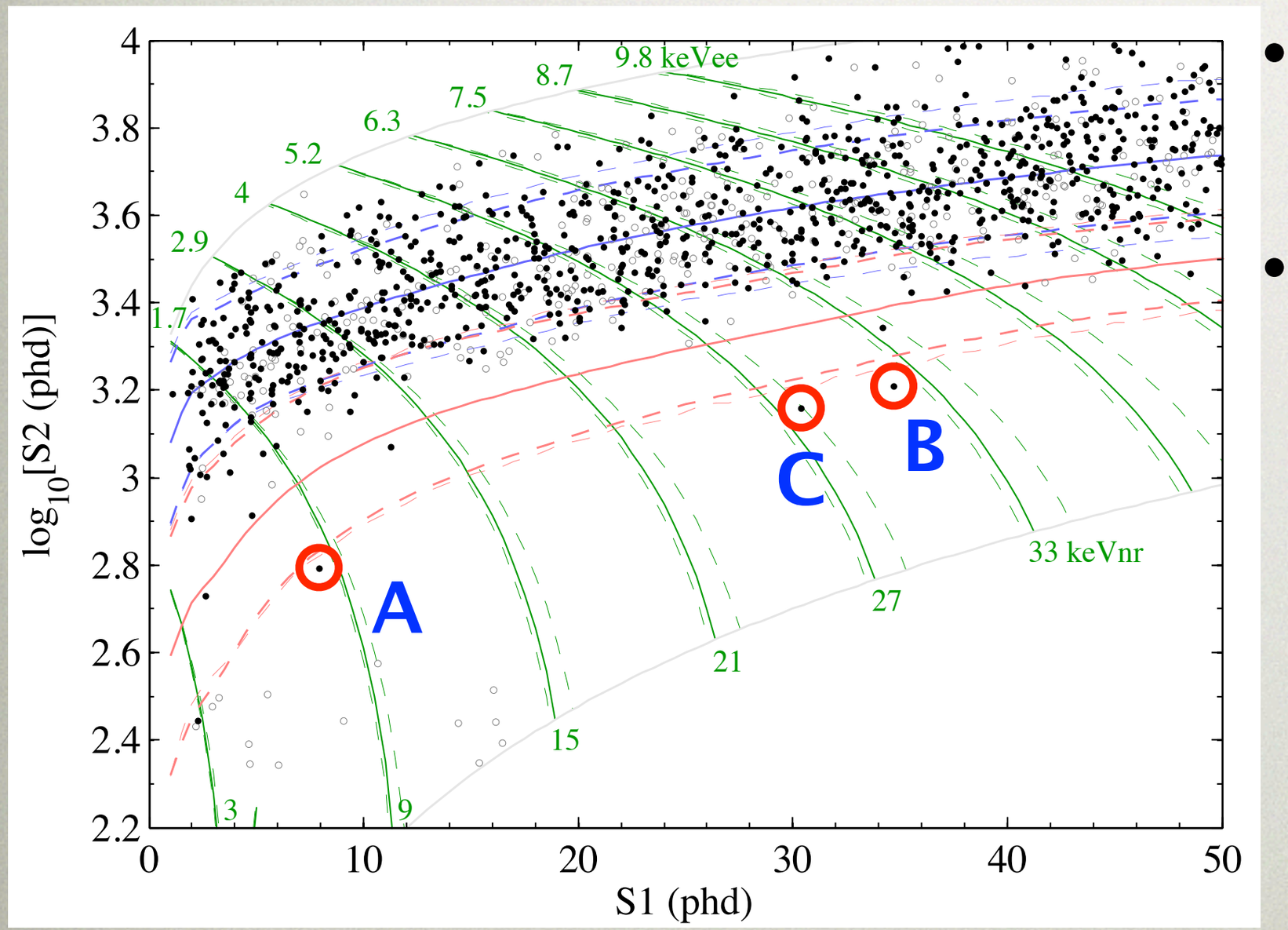

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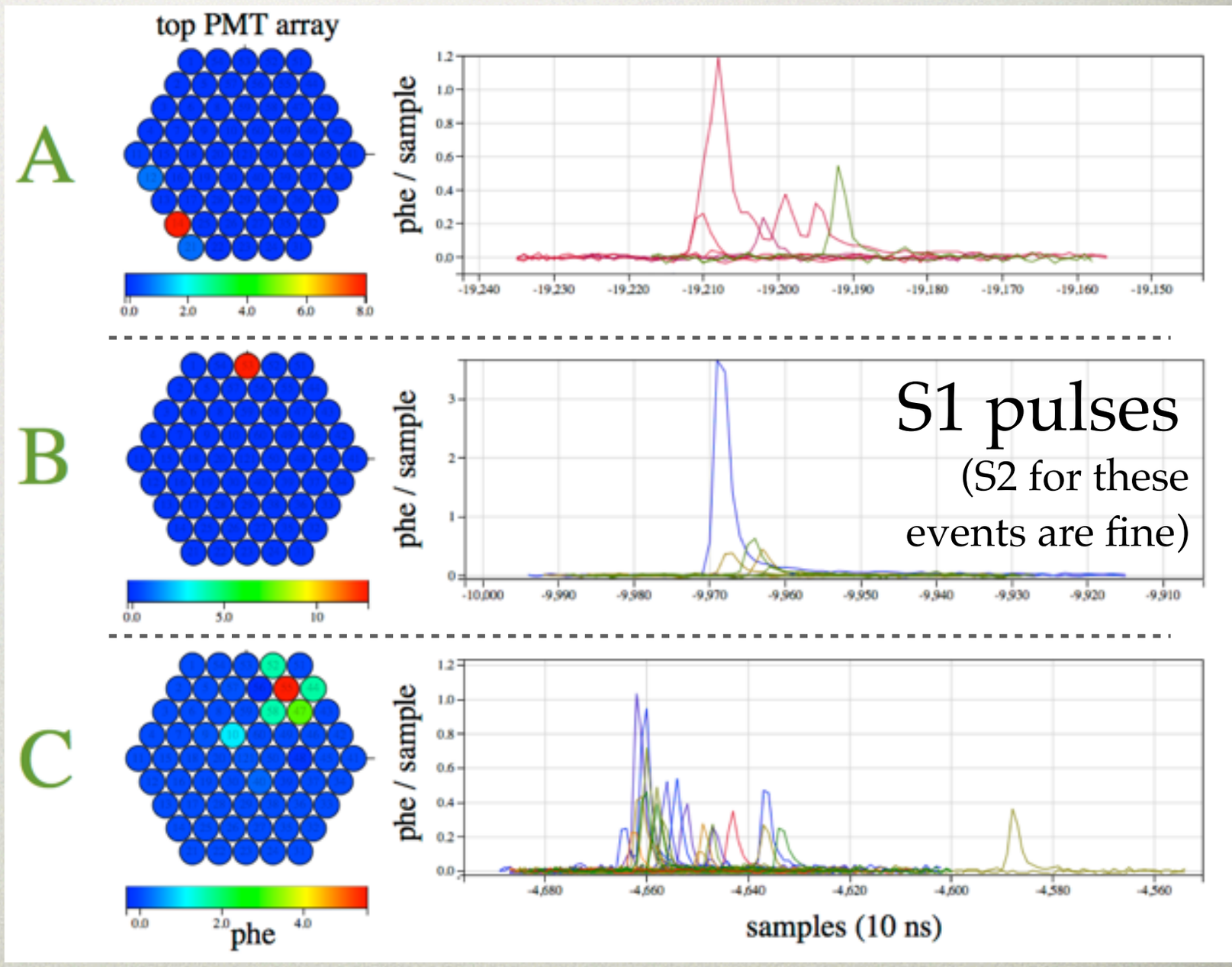
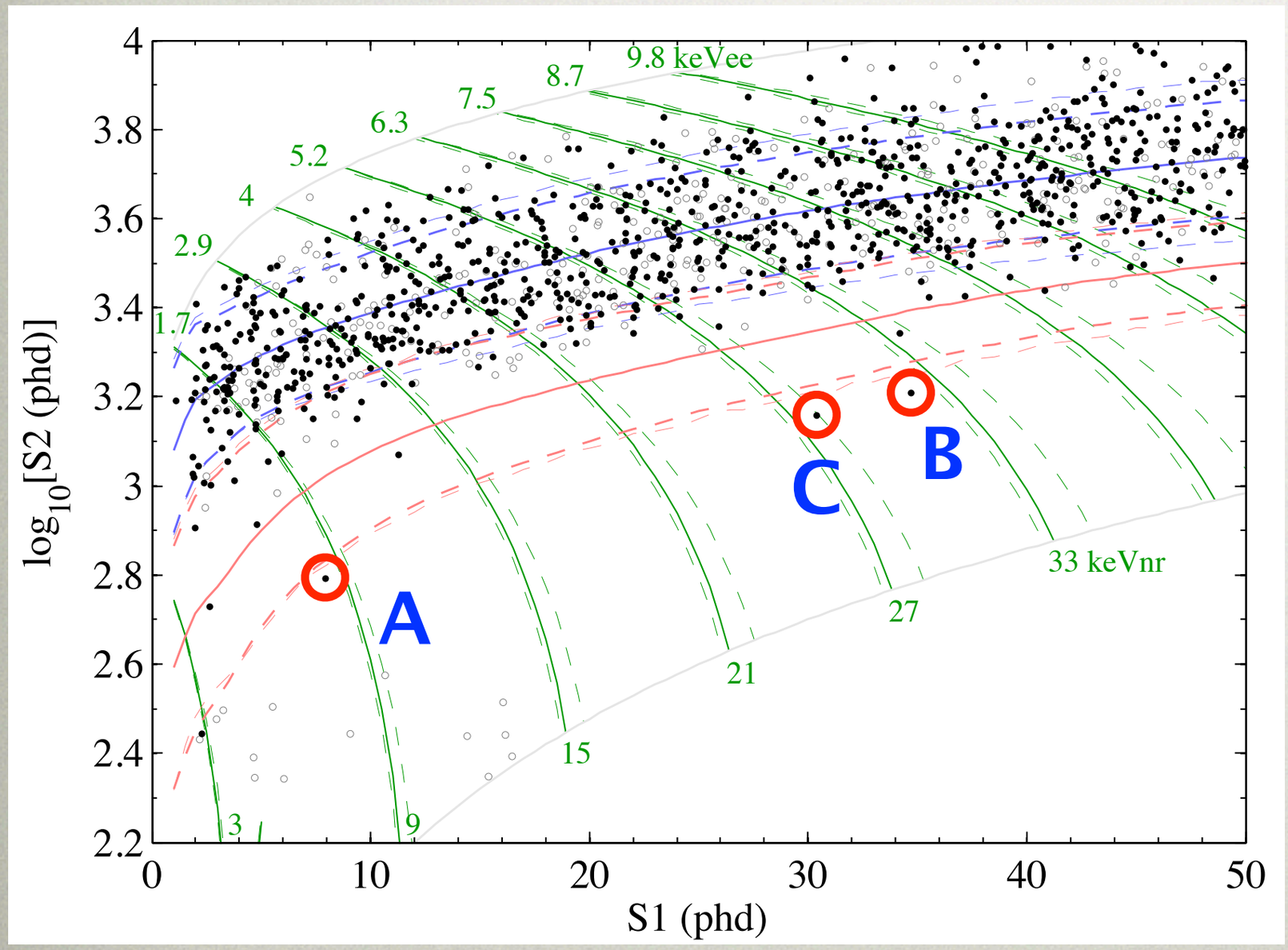
Pathological events

- Events **A** and **B** have ~80% of the light in a single top-edge PMT. Consistent with energy deposited outside the TPC, and light leaking through a gap near the edge of the PMT array. p of $O(10^{-9})$ and $O(10^{-10})$ for A and B, respectively.
- Event **C** is highly concentrated under a few top PMTs and has a time structure consistent with gas scintillation emission. Event came after high rate in preceding 1 second.
- Since these events do not correspond to interactions in the TPC, we develop cuts [post-un-salting] to target them.



Scrutiny after the salt removal



Two important points:

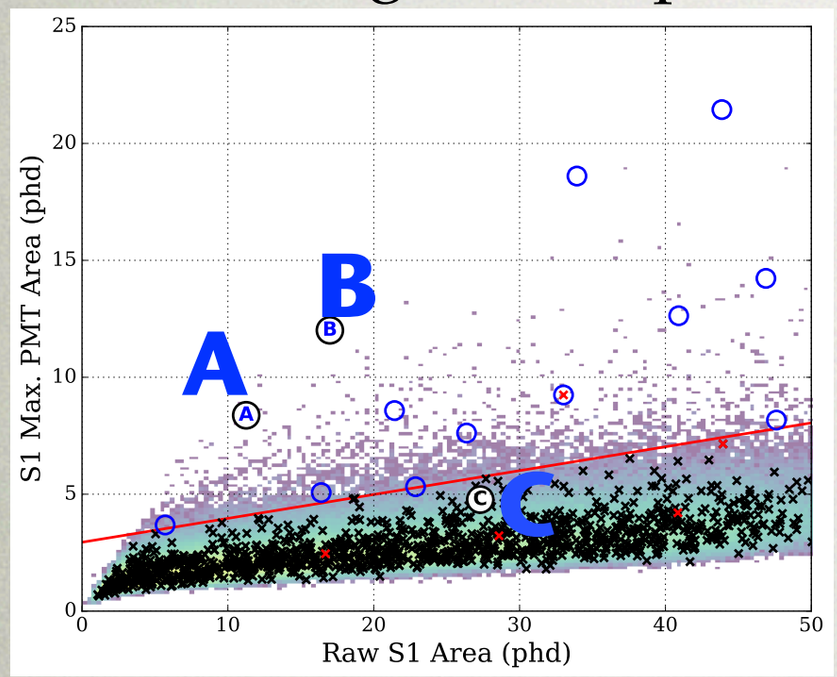
1. These events are clearly pathological: they do not correspond to interactions within the TPC.
2. These events have a very low background likelihood.

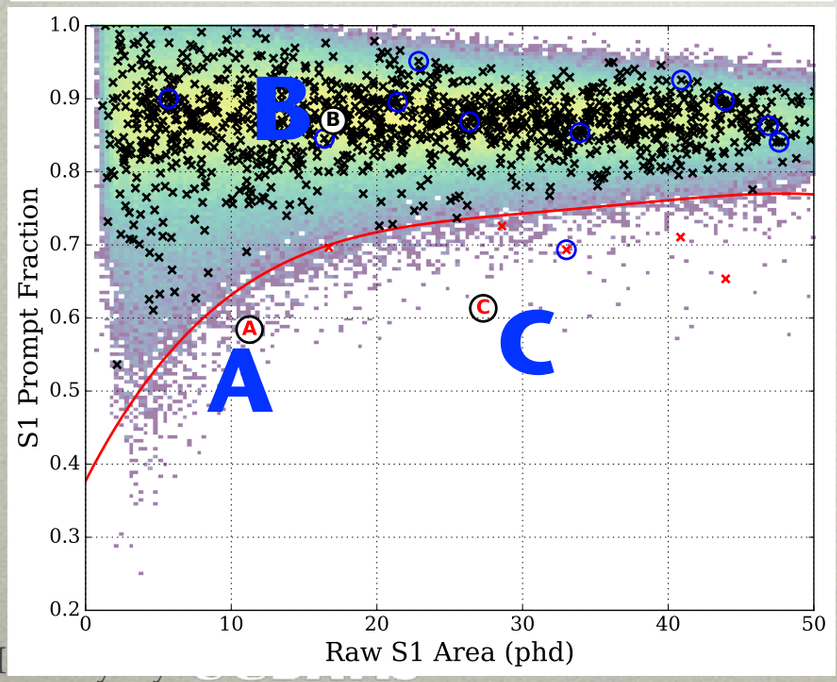
To be clear, these events COULD HAVE BEEN identified prior to un-salting (it was an oversight on our part).

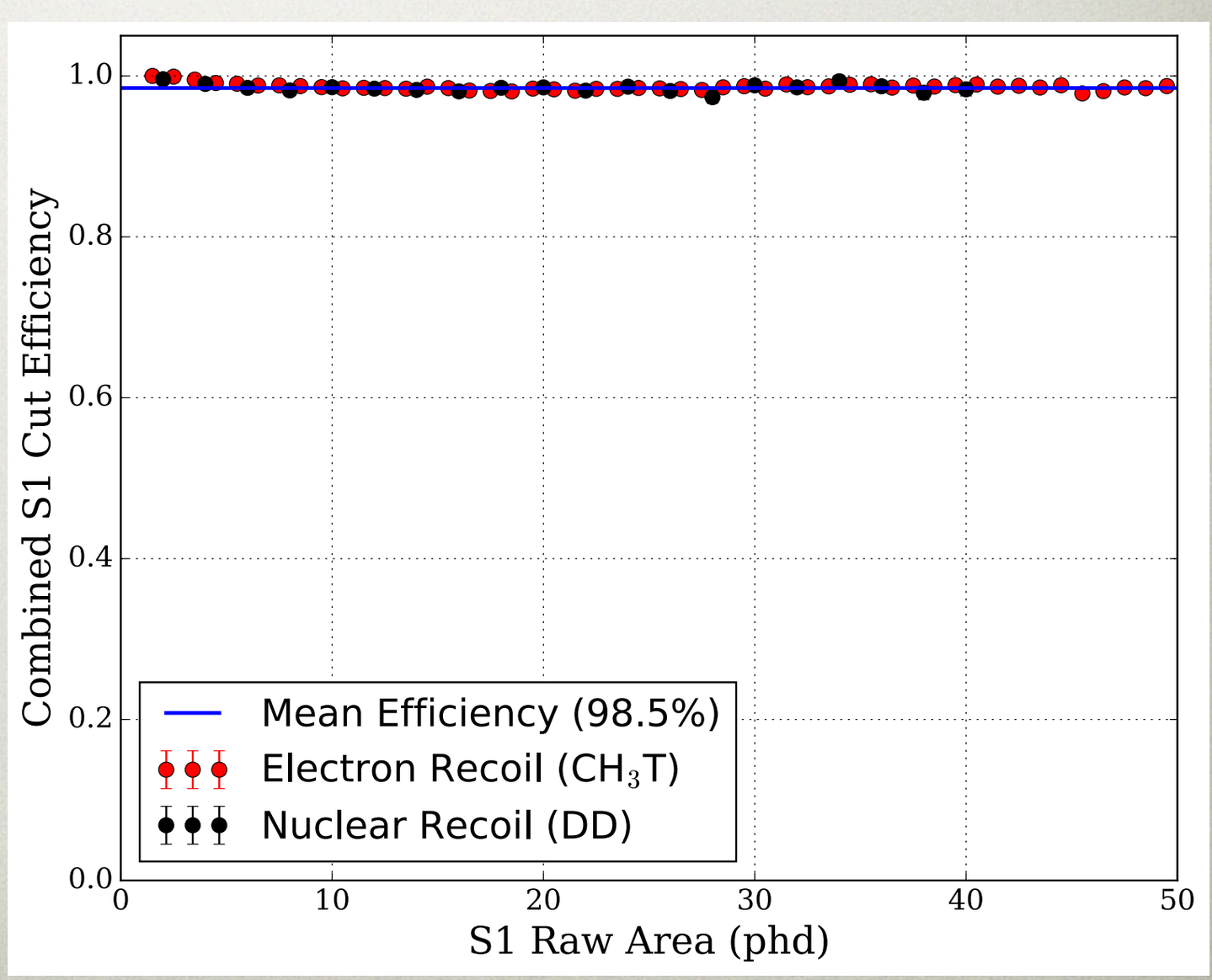
As a collaboration, we decided these two facts warranted us to take steps to remove these pathologies.

Removal of new pathologies

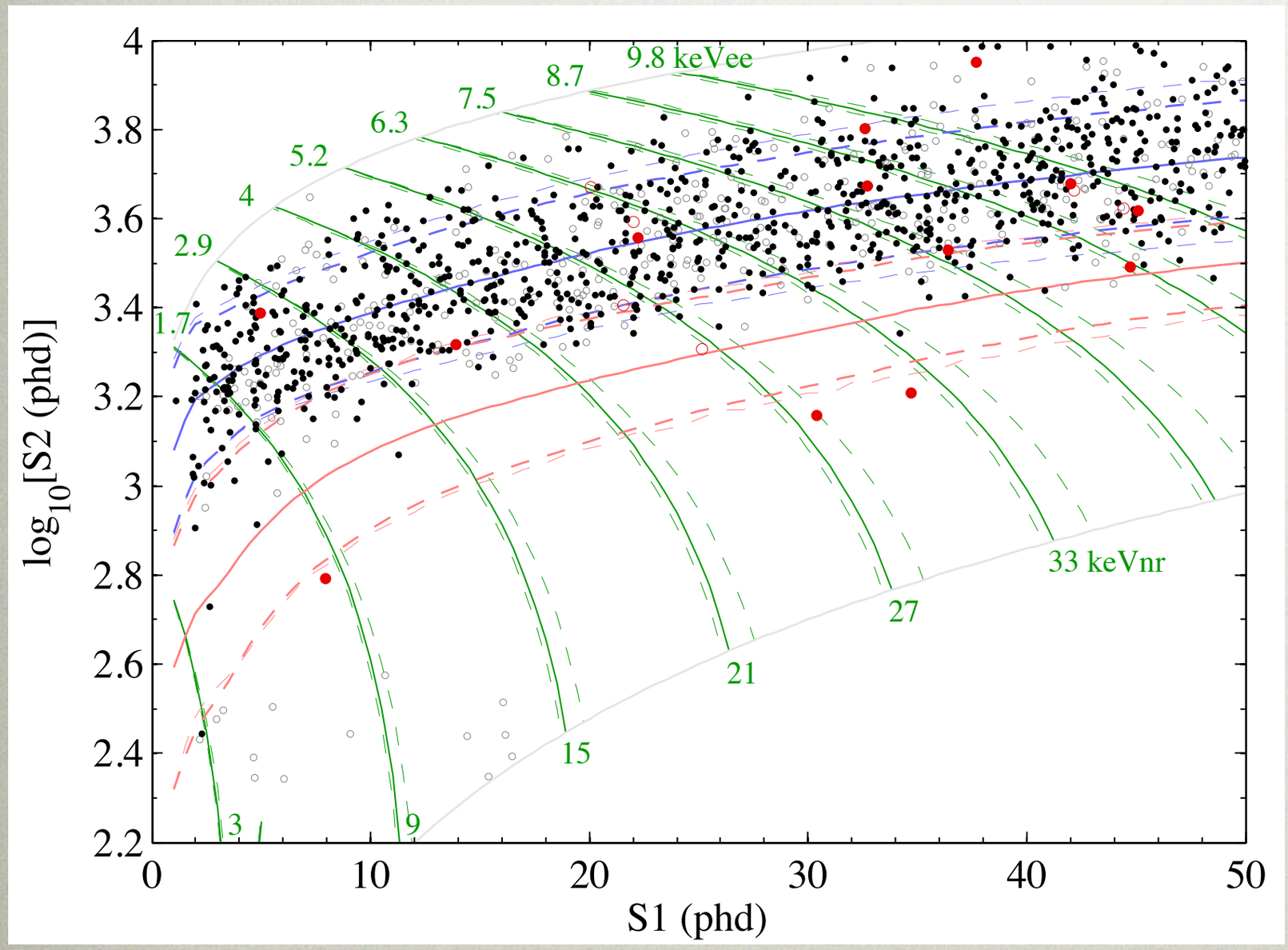
- Post-un-salting cuts: (pre-existing cuts left untouched)
  - Loose cuts (high signal acceptance), defined on calibration data.
  - Flat signal acceptance.





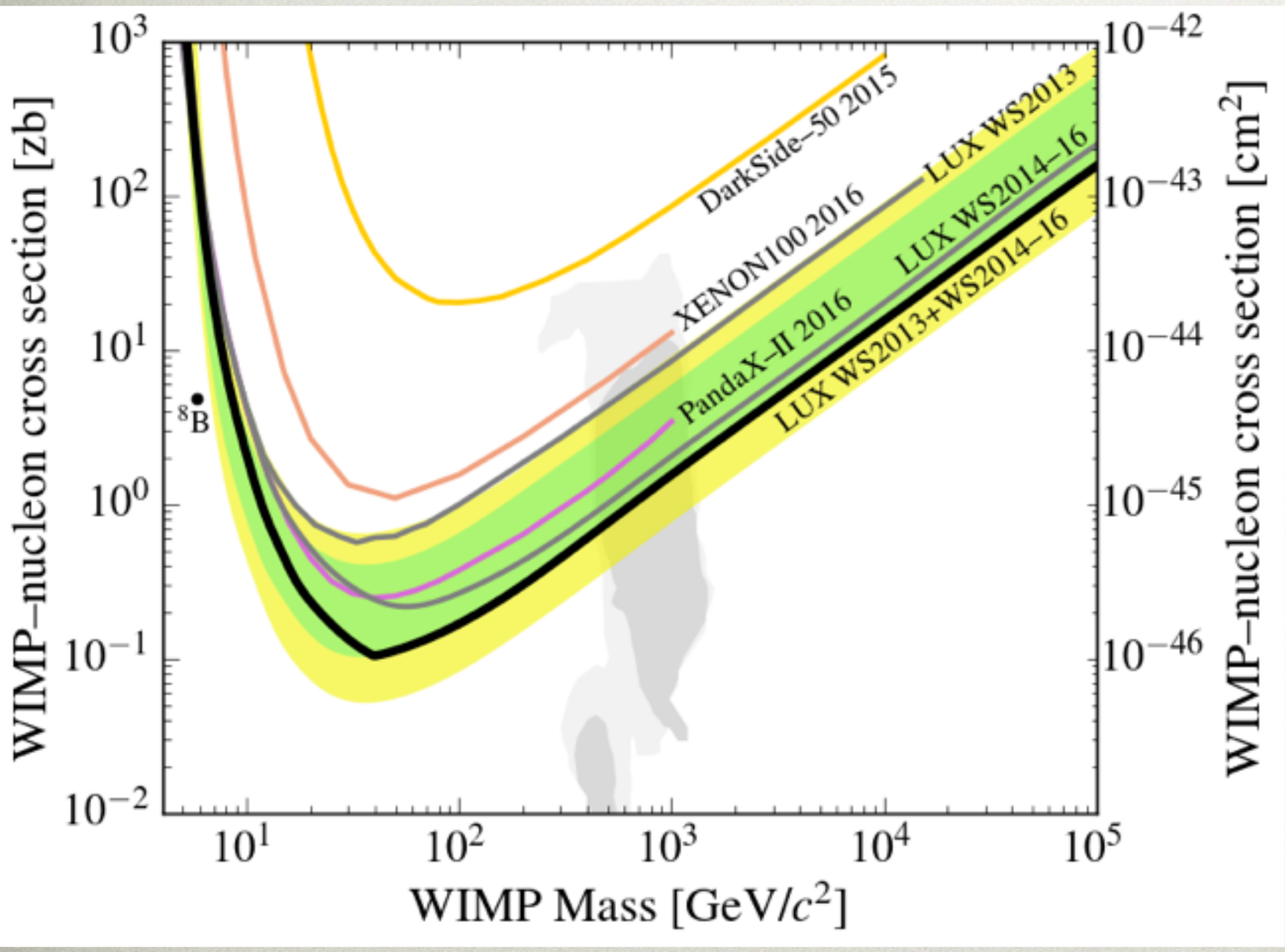


Pathological events



- Red indicates events that are removed by these additional post-unsalting cuts. There are a few more that we missed, living in the background band.

Results



- Sets world's-best limits on spin-independent WIMP-nucleon scattering over wide range of masses*!*

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Summary

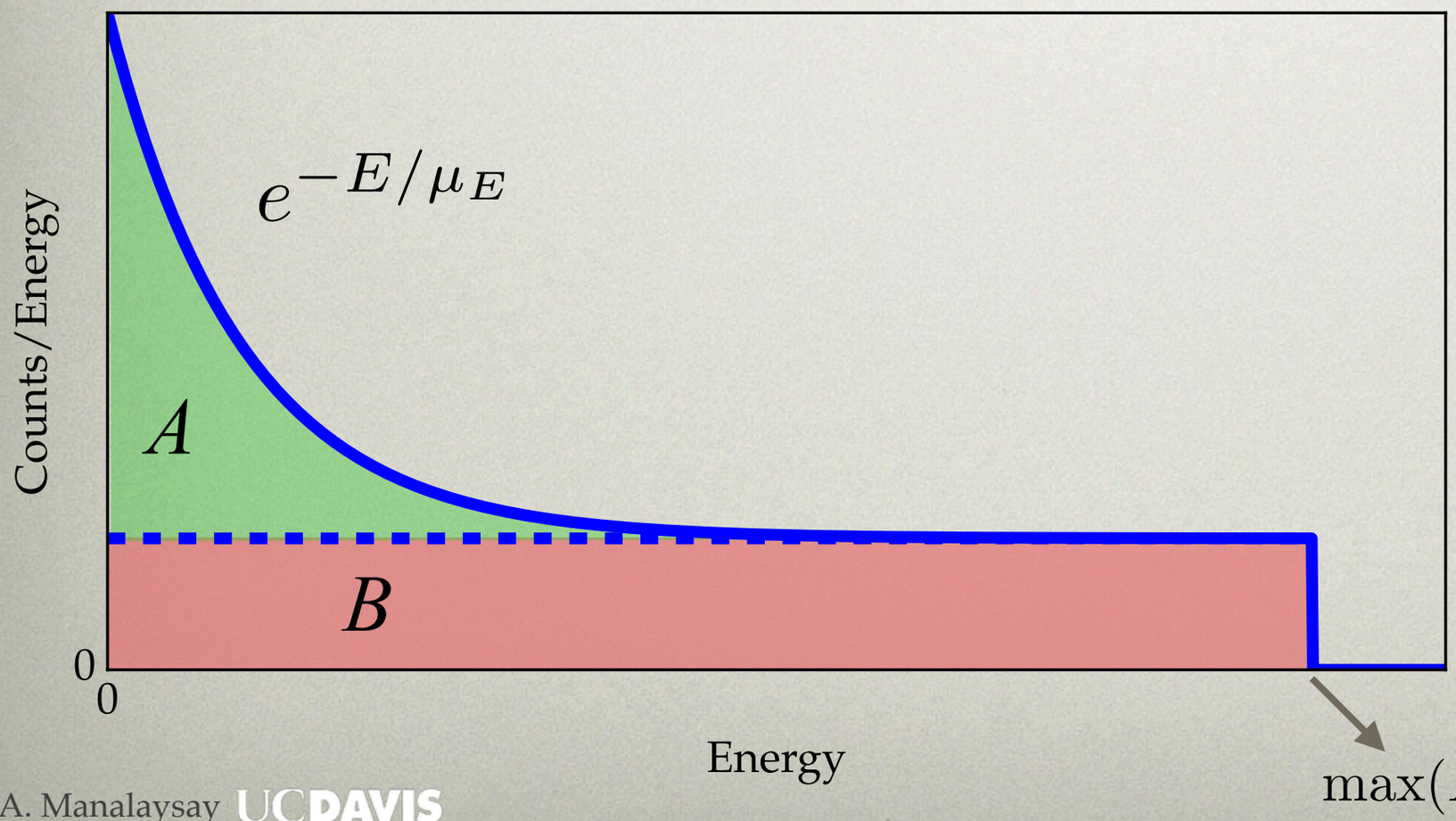
- Traditional blinding is problematic in a low-background, rare-event search.
- LUX implemented a method of adding fake "salt" signal events to the data stream.
- This method allowed a number of pathological events to be identified (which would have been missed in a traditional blind search). A few rare undetected pathologies were not caught before un-salting the data, but could have been.
- LUX has had an overall positive experience with this technique. Implementation details are very experiment specific.

Backup slides

Salt energy distribution

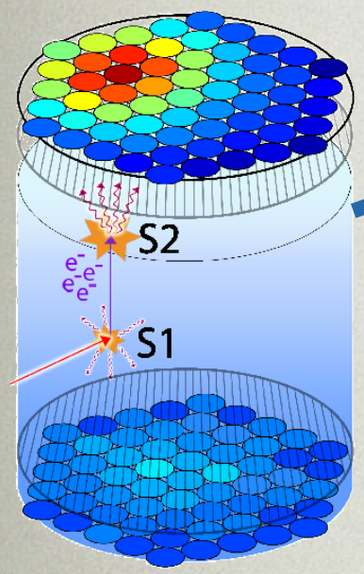
- Exponential + uniform distribution
- 4 free parameters:
- Similar to a low-mass and high-mass WIMP recoil spectrum.

μ_E
$\max(E_{\text{flat}})$
$f_{\text{exp}} = A/(A+B)$
$N_{\text{tot}} = A + B$



- Exact values for these four distributions are chosen at [uniform] random, and are kept blind to analyzers.

Salt injection



ADC

Un-triggered raw waveforms

.raw0

Software event builder

Waveforms bundled in "events"

.raw1

Hardware trigger

(trigger signal is digitized on equal footing with PMT signals)

Salt DB

Data processing

.rq

Reduced quantities (pulse areas, times, etc.) "RQ files"

- Each fake waveform is assigned a random timestamp and saved in a database ("saltDB"). The event builder queries the saltDB for any appropriate salt timestamps and adds them to raw1 if they do not conflict with the timestamps of existing. Our waveform viewer works on raw1 files.