(UNWANTED) RADIATION EVENTS IN ASTRONOMICAL CCD IMAGES

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(Presented for Al Smith *et al.*)

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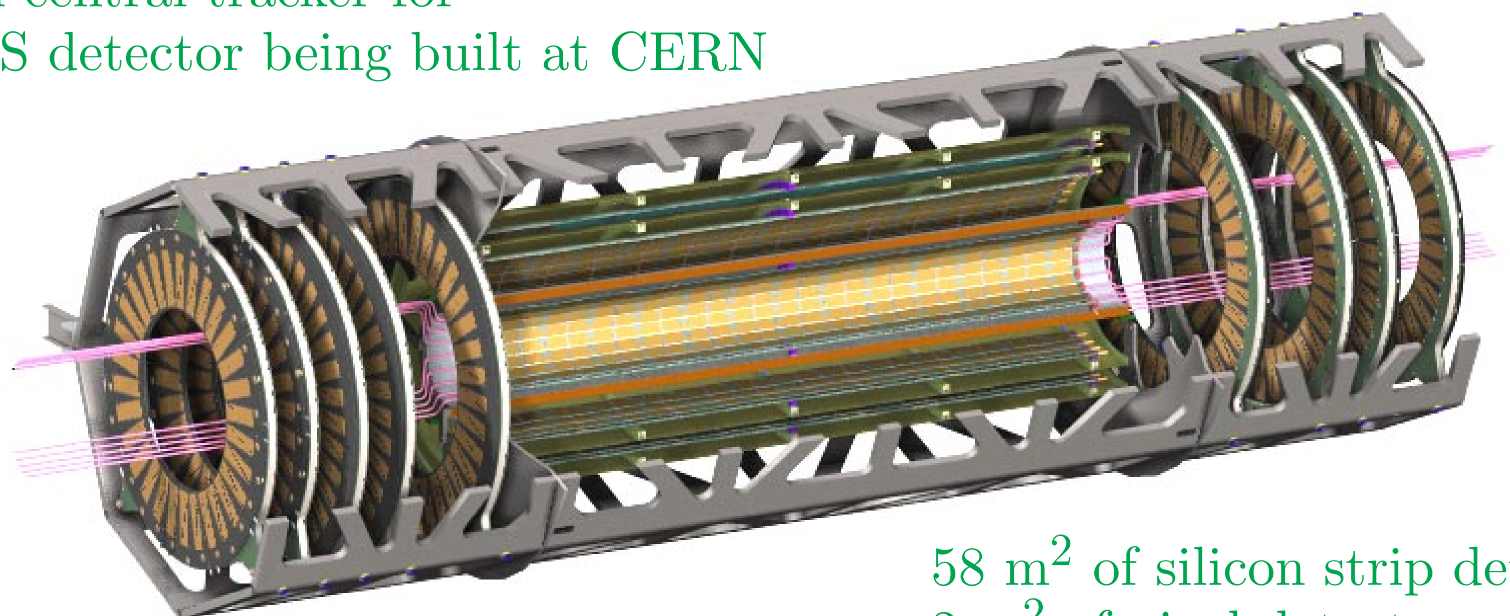
THE OTHER GUYS

Our friends in particle physics use silicon for particle detection

Silicon central tracker for
ATLAS detector being built at CERN



58 m^2 of silicon strip detectors
2 m^2 of pixel detectors

$\Longrightarrow$ They have to worry about keeping light out!

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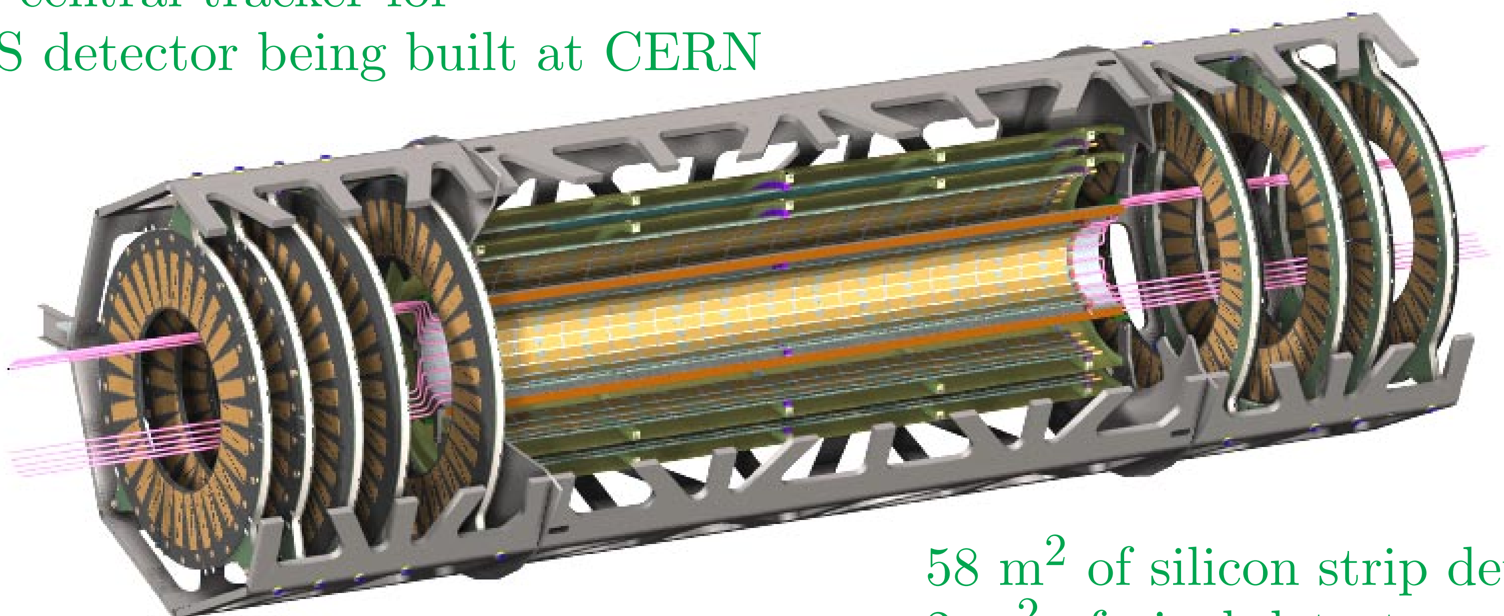
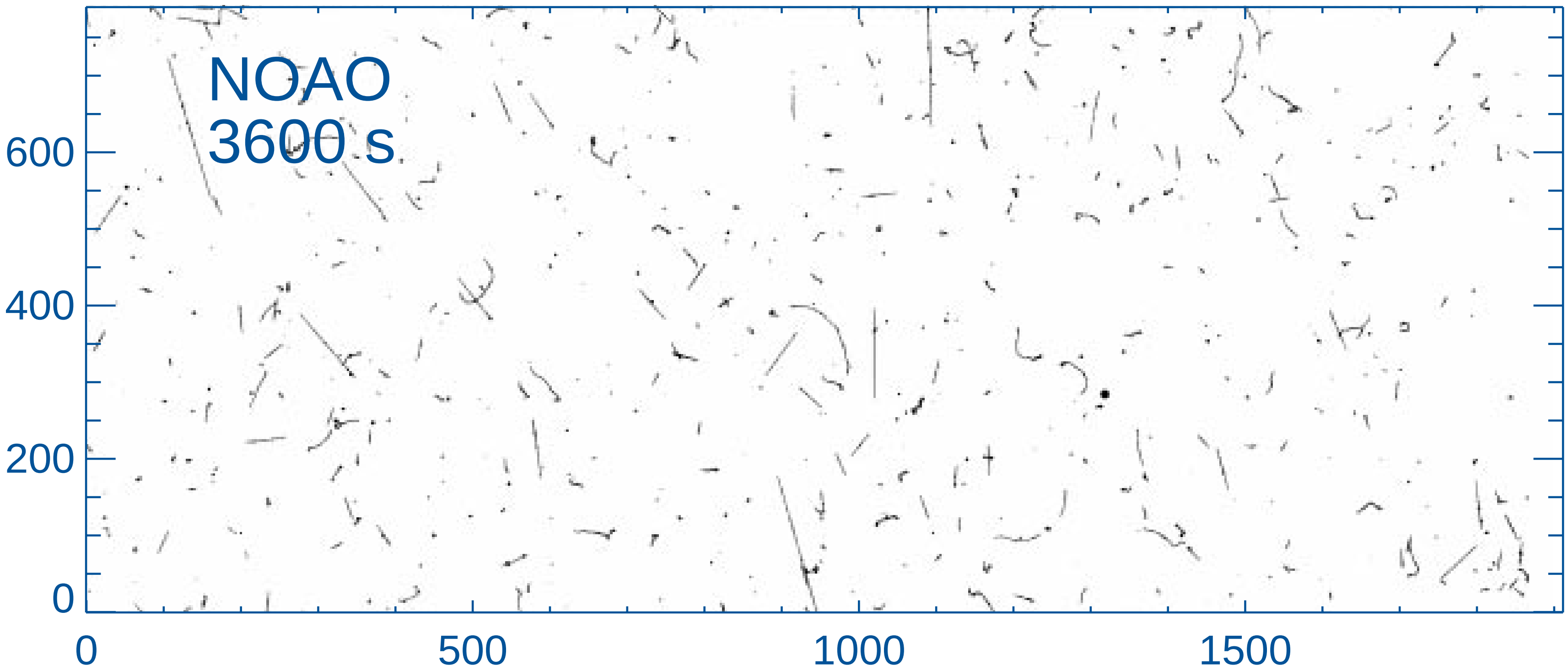


58 m^2 of silicon strip detectors
2 m^2 of pixel detectors

$\Longrightarrow$ They have to worry about keeping light out!

$\Longrightarrow$ Our problem is the opposite! We're trying make good light detectors, and the unwanted particle detection is a royal pain

NOAO lab in Tucson, CCD vertical (on edge) —the dirtiest lab so far!



Our 300-μm thick depleted CCD gives us the great advantage (curse?) that we can see the events in new detail

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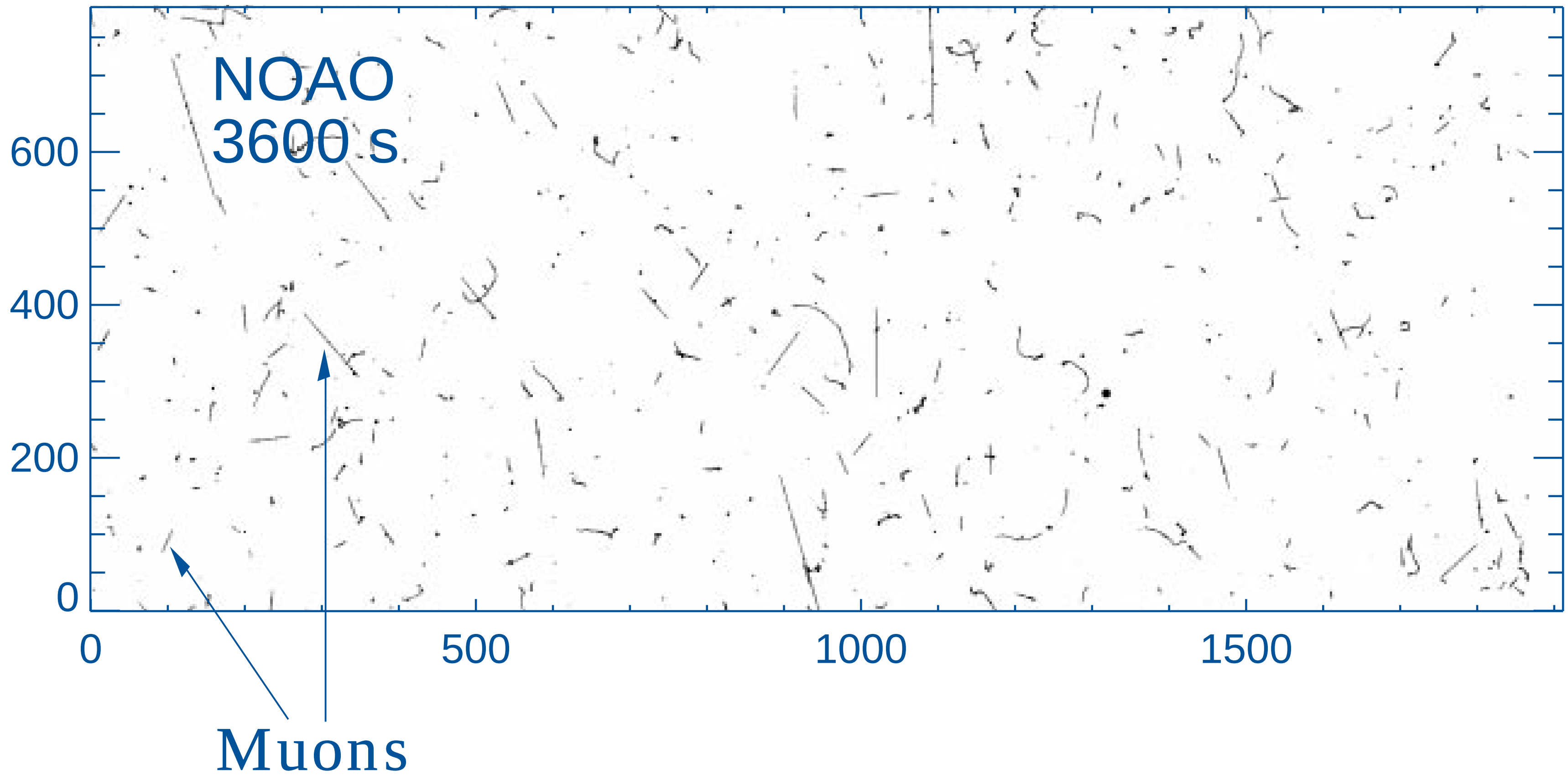

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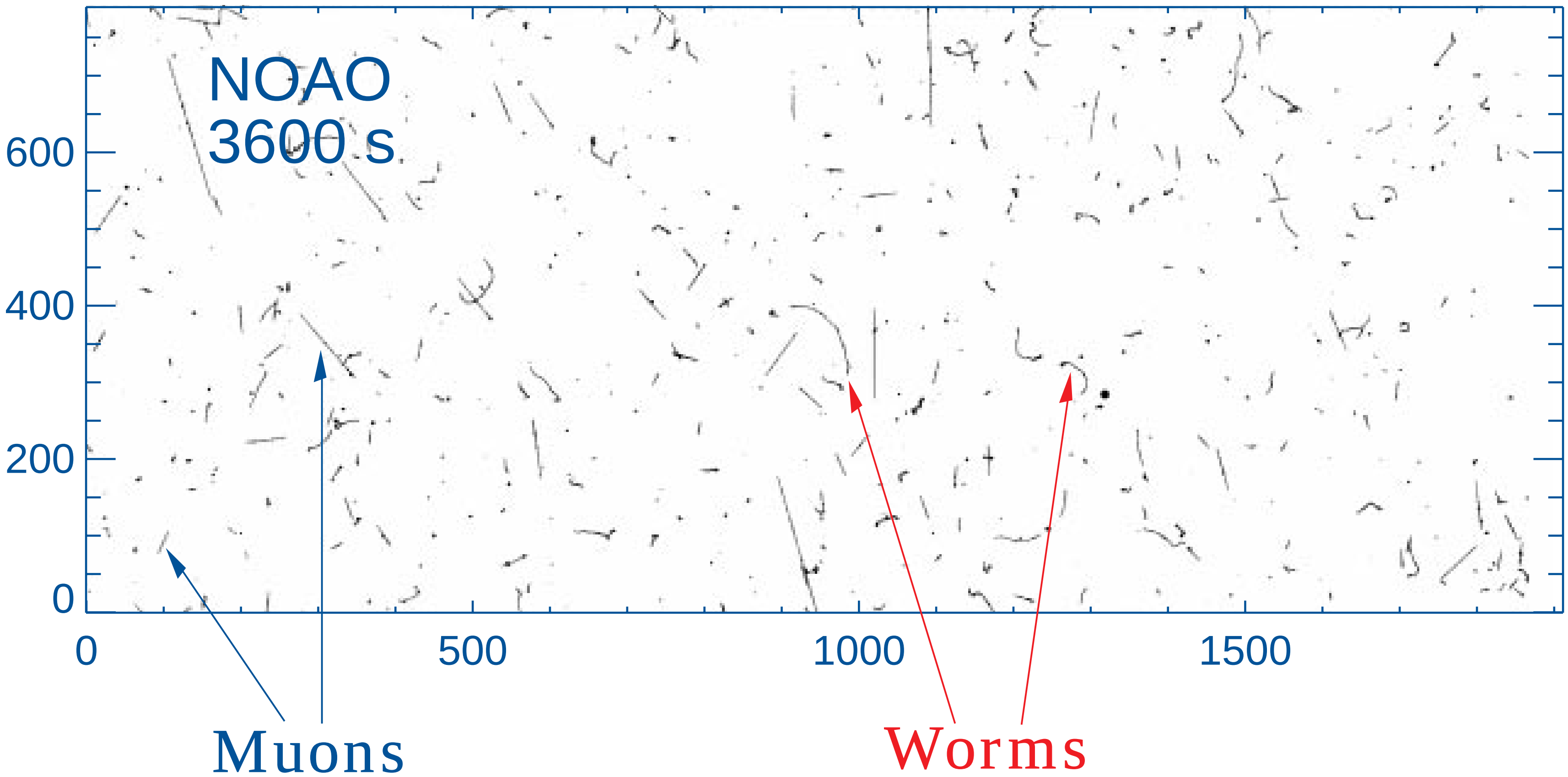

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MUONS, WORMS, SPOTS

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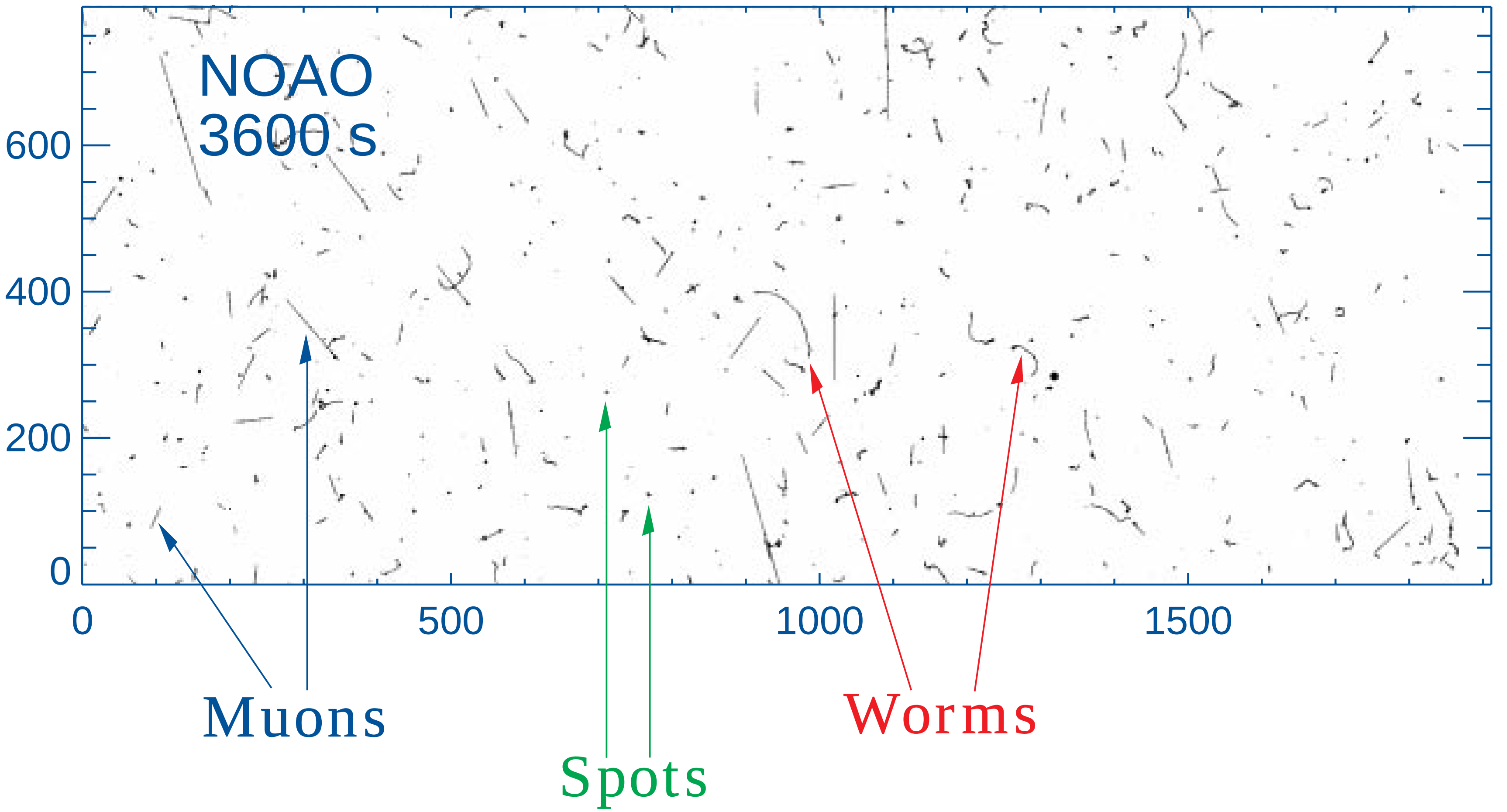

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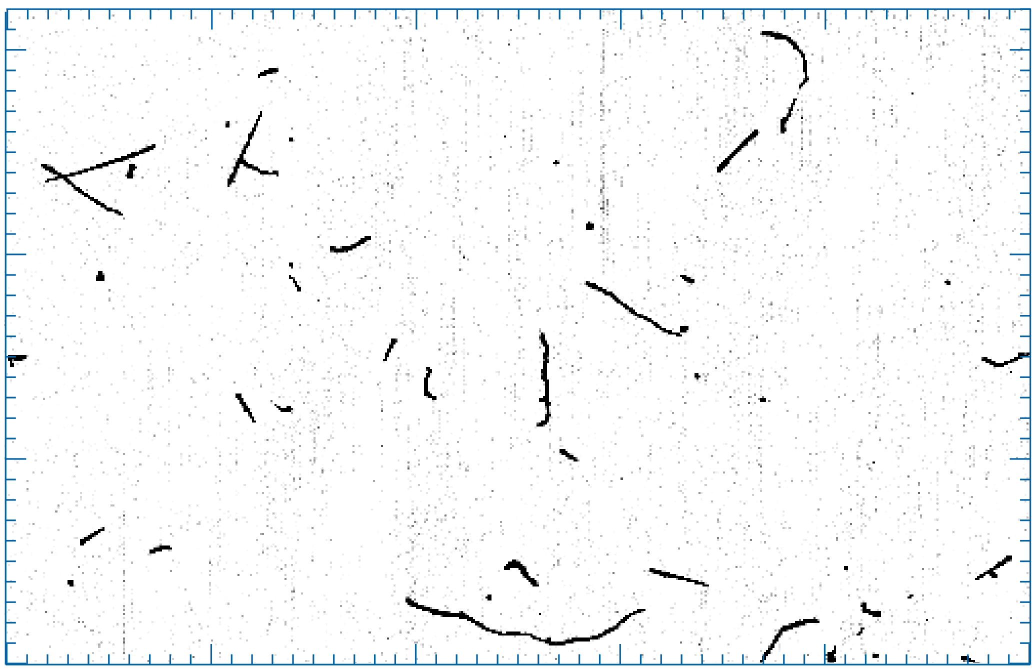
GOALS

Get rid of anything which can be gotten rid of

First we have to figure out what we're seeing and where they come from—

- Isolate, classify, and count events
- Demonstrate nature of muons, worms, and spots



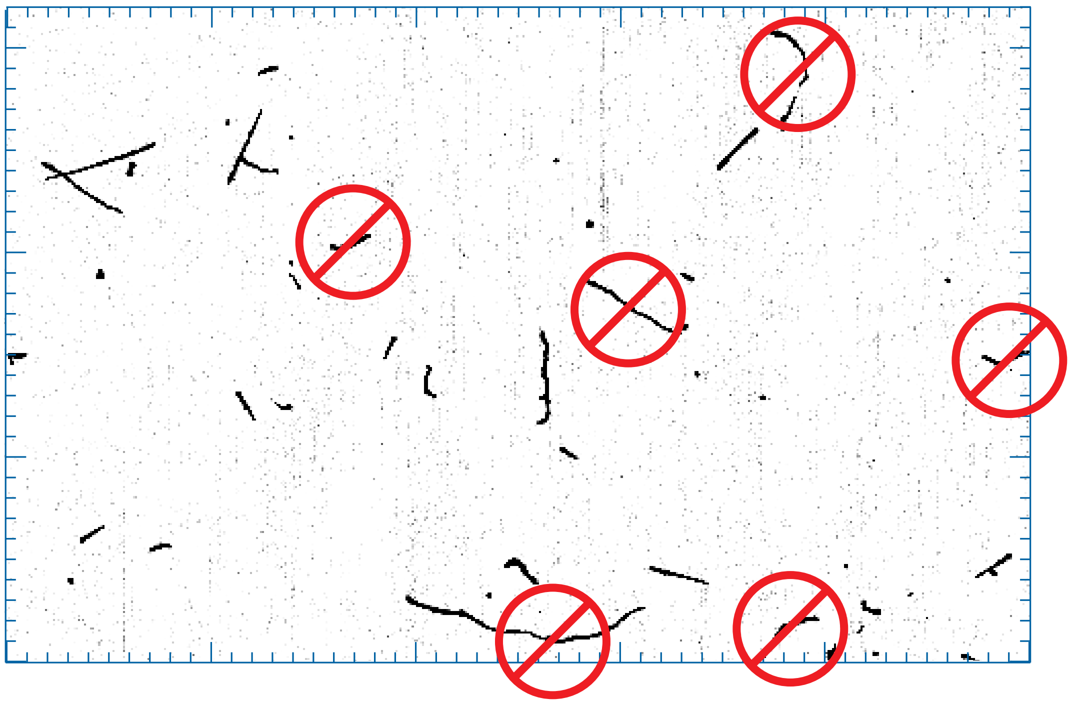
GOALS

Get rid of anything which can be gotten rid of

First we have to figure out what we're seeing and where they come from—

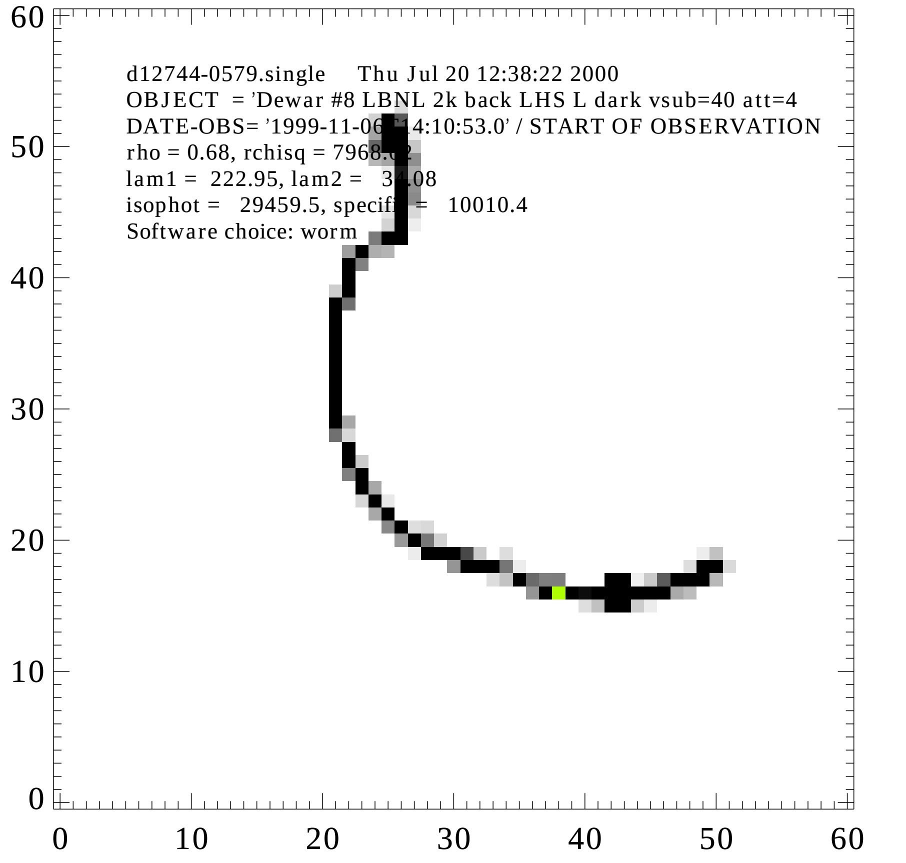
- Isolate, classify, and count events
- Demonstrate nature of muons, worms, and spots

Then, to the extent possible, shield to get rid of the bad guys



ISOLATION would be hard, except that we have astronomy packages for finding "objects," or "events," in images

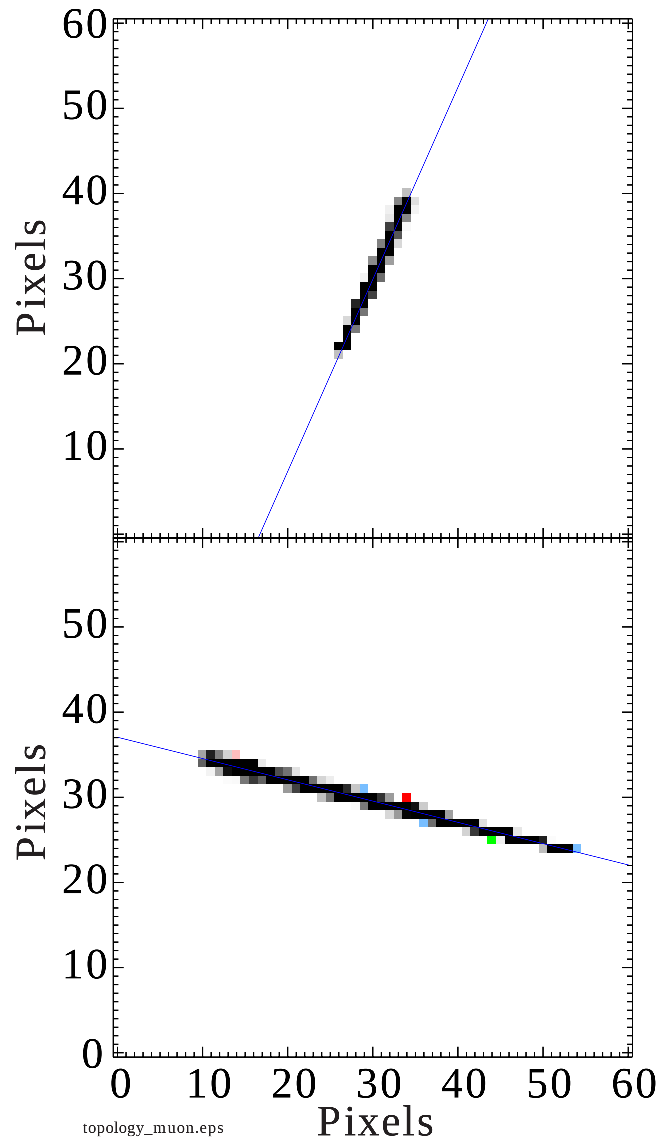
An "object" is a group of connected pixels with counts significantly above background



COSMIC RAYS

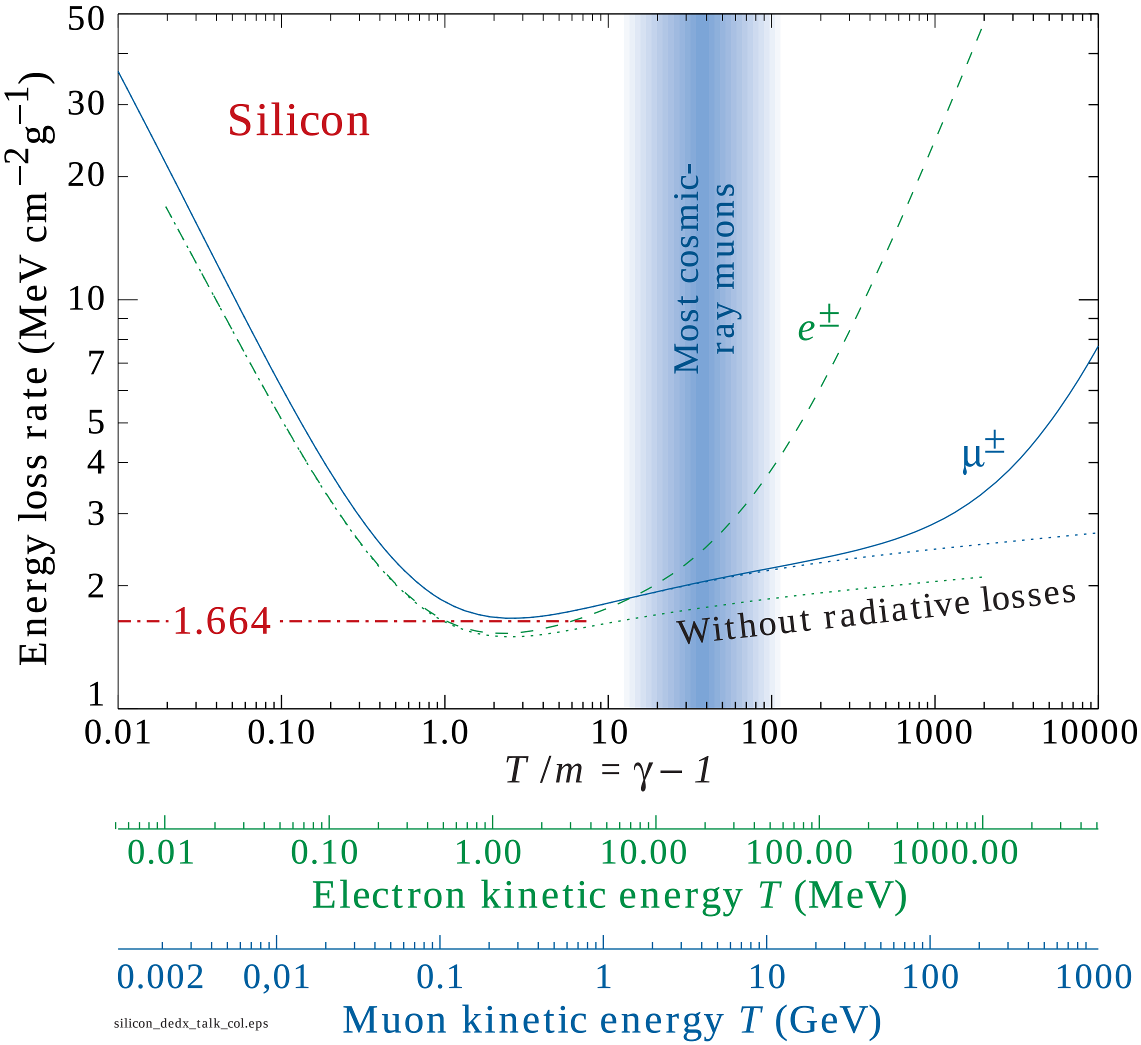
The straight tracks are no great mystery—

- $>$ 95% of sea-level cosmic rays are muons, with mean energy $\sim$ 4 GeV
- For a horizontal detector, the rate is 0.8–1.0 cm^{-2}min^{-1}



topology_muon.eps

COSMIC RAY MUONS



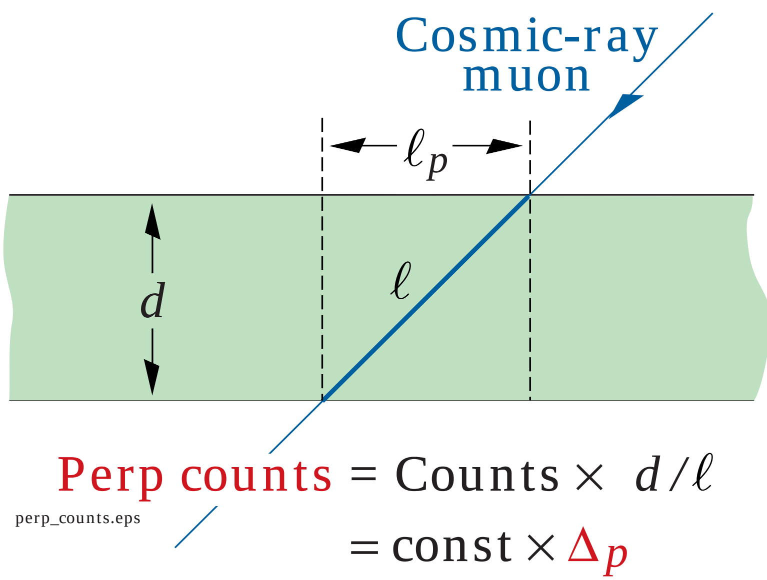
- The mean muon energy is around 4 GeV
- Here the energy loss rate is near the broad minimum $\langle dE/dx \rangle_{\rm min} =$ 1.66 MeV g^{-1}cm^2
- The most probable energy loss is about 66% of this, or

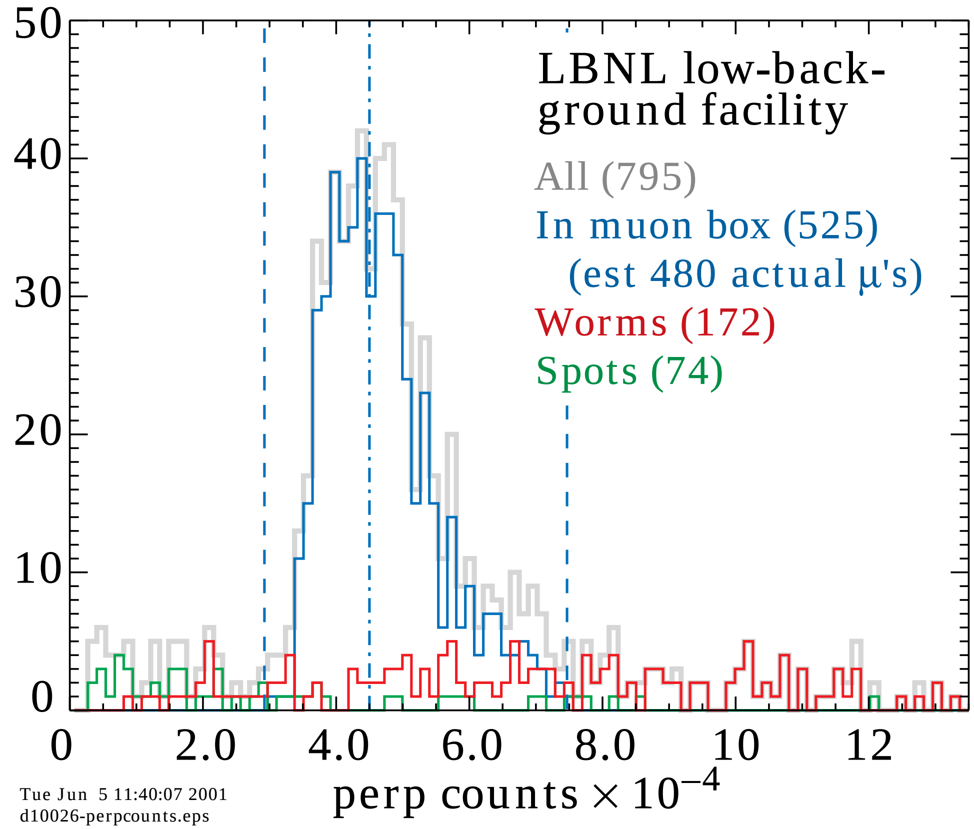
$$\Delta_p \approx 1.10 \text{ MeV g}^{-1}\text{cm}^2$$
$\approx 21,000$ e-h pairs
per 300 μm

MUONS

A muon leaves a track with a known number of e-h's per unit length

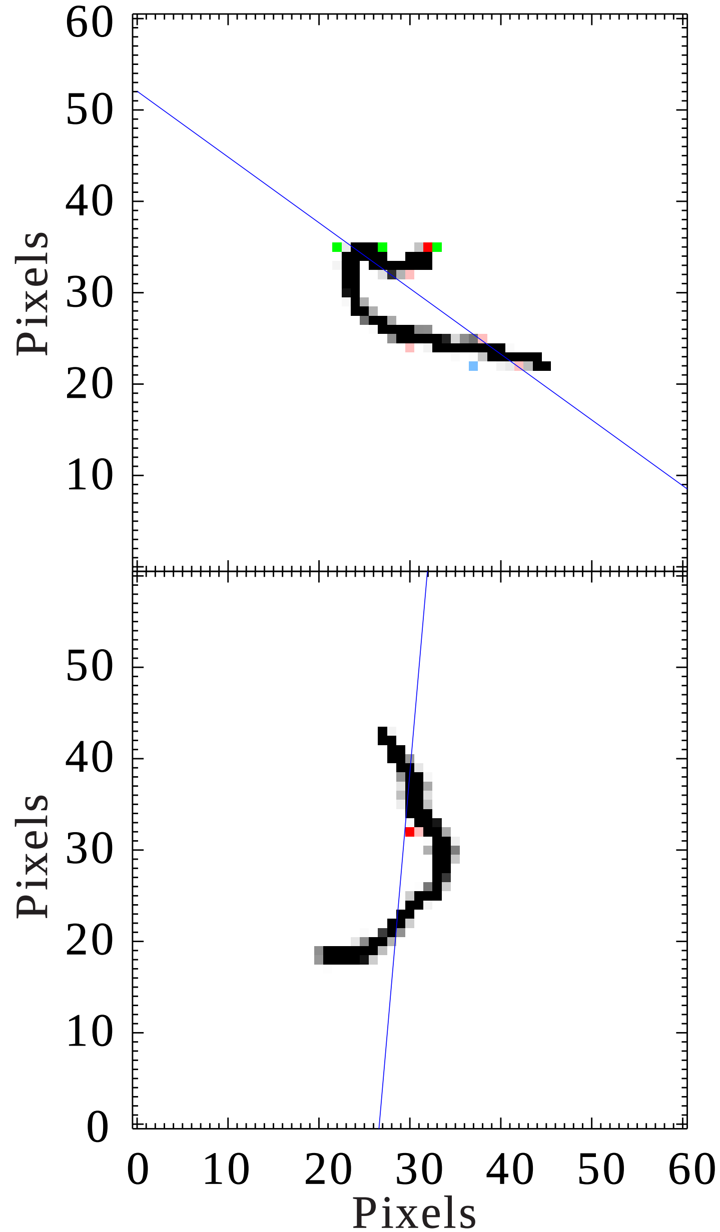
So the idea is to use the projected length ℓ_p to scale the number of counts to the number of counts per sensitive-region thickness d





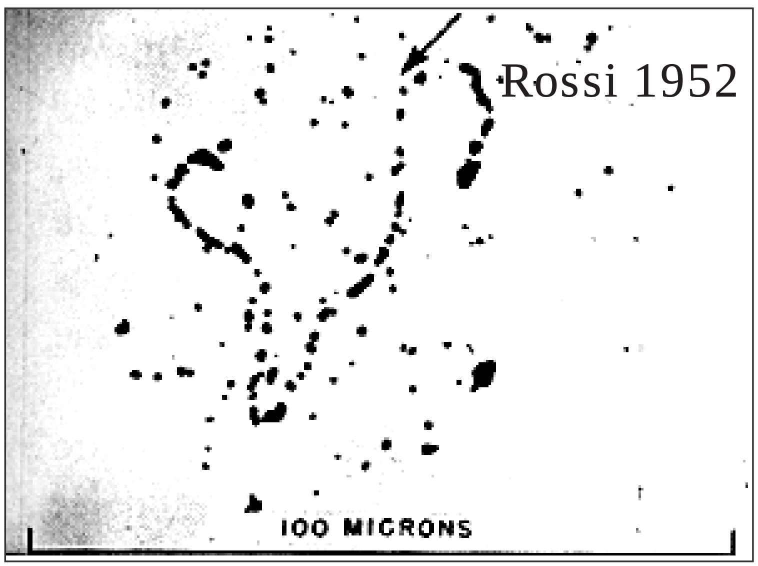
WORMS

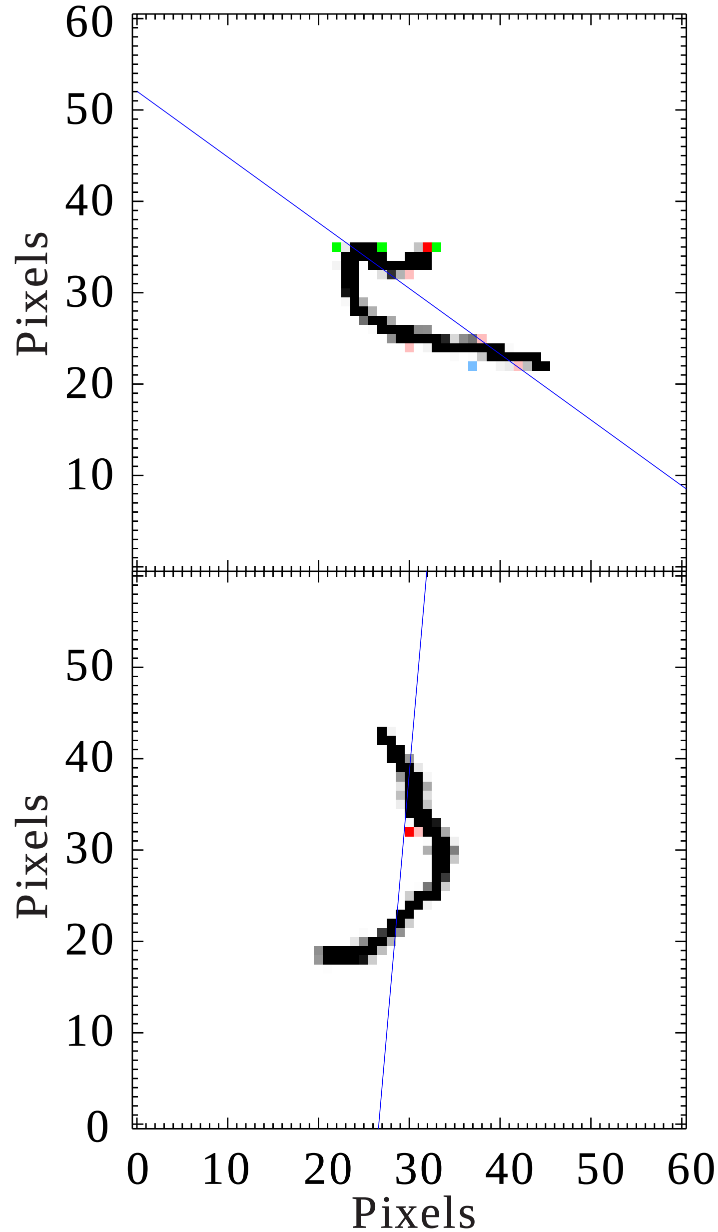
- We are still left with worms, wandering tracks of various lengths and energy deposition



WORMS

- We are still left with worms, wandering tracks of various lengths and energy deposition
- These are not unfamiliar to elderly physicists who used nuclear emulsions a half-century ago, and frequently saw these multiply-scattering electrons





STRAIGHTNESS

One more factoid:

Muon tracks are *straight*
(By contrast, worms are *fat*)

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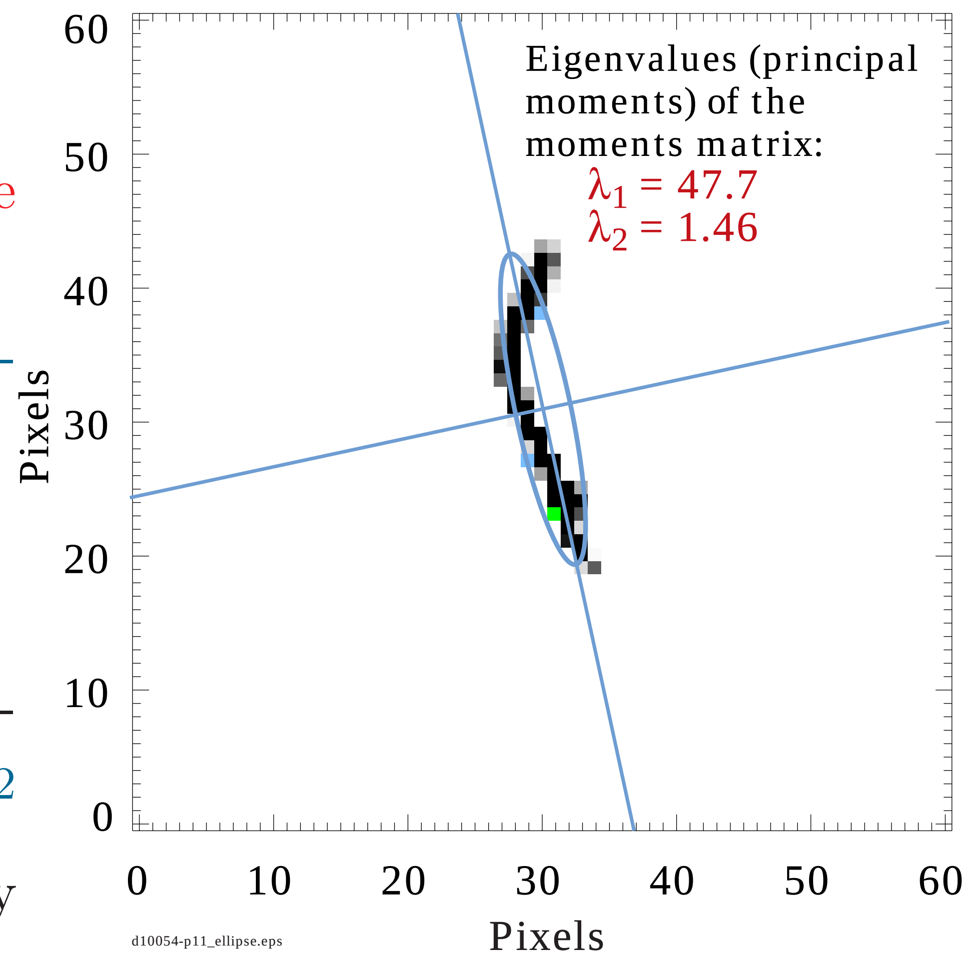
The only other really good cut we've found is a measure of *straightness*.

The data reduction finds the moments of the "object:"

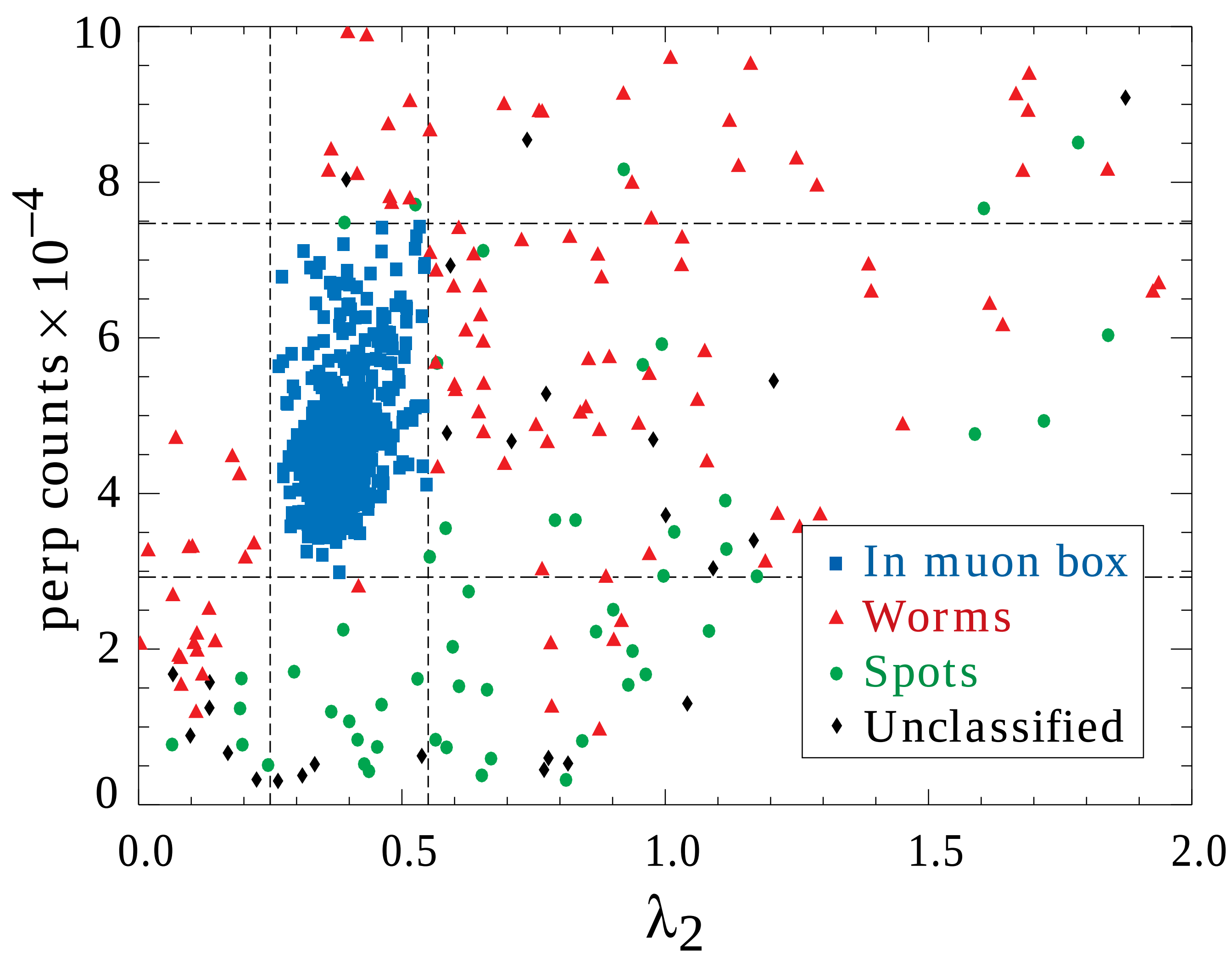
$$\begin{pmatrix} m_{xx} & m_{xy} \\ m_{xy} & m_{yy} \end{pmatrix} \xrightarrow{\text{rotate}} \begin{pmatrix} \lambda_1 & 0 \\ 0 & \lambda_2 \end{pmatrix}$$

with eigenvalues (the matrix after rotation to the principal axes) $\lambda_1 > \lambda_2$

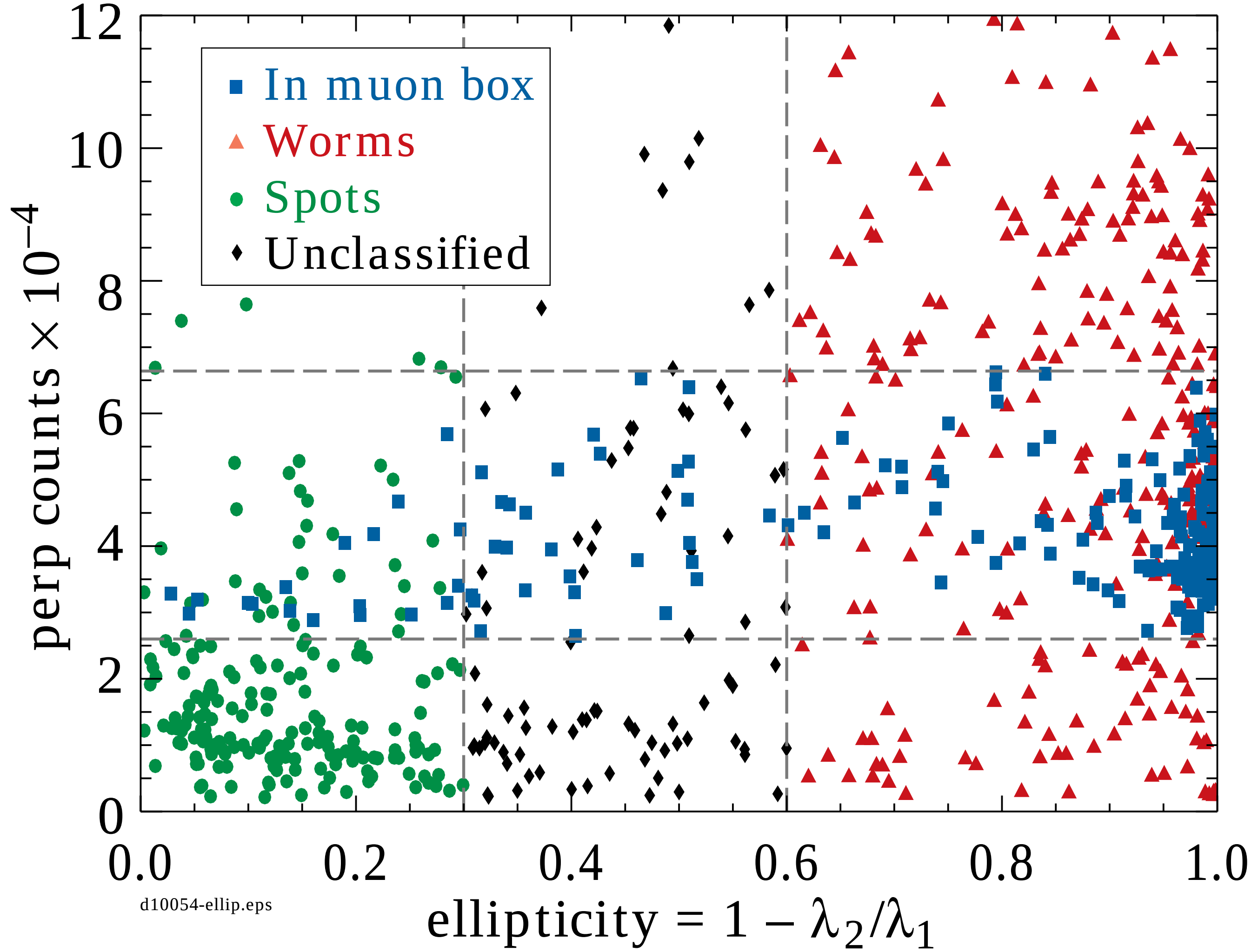
λ_2 is *small* for a muon, otherwise any size



SMALLEST EIGENVALUE

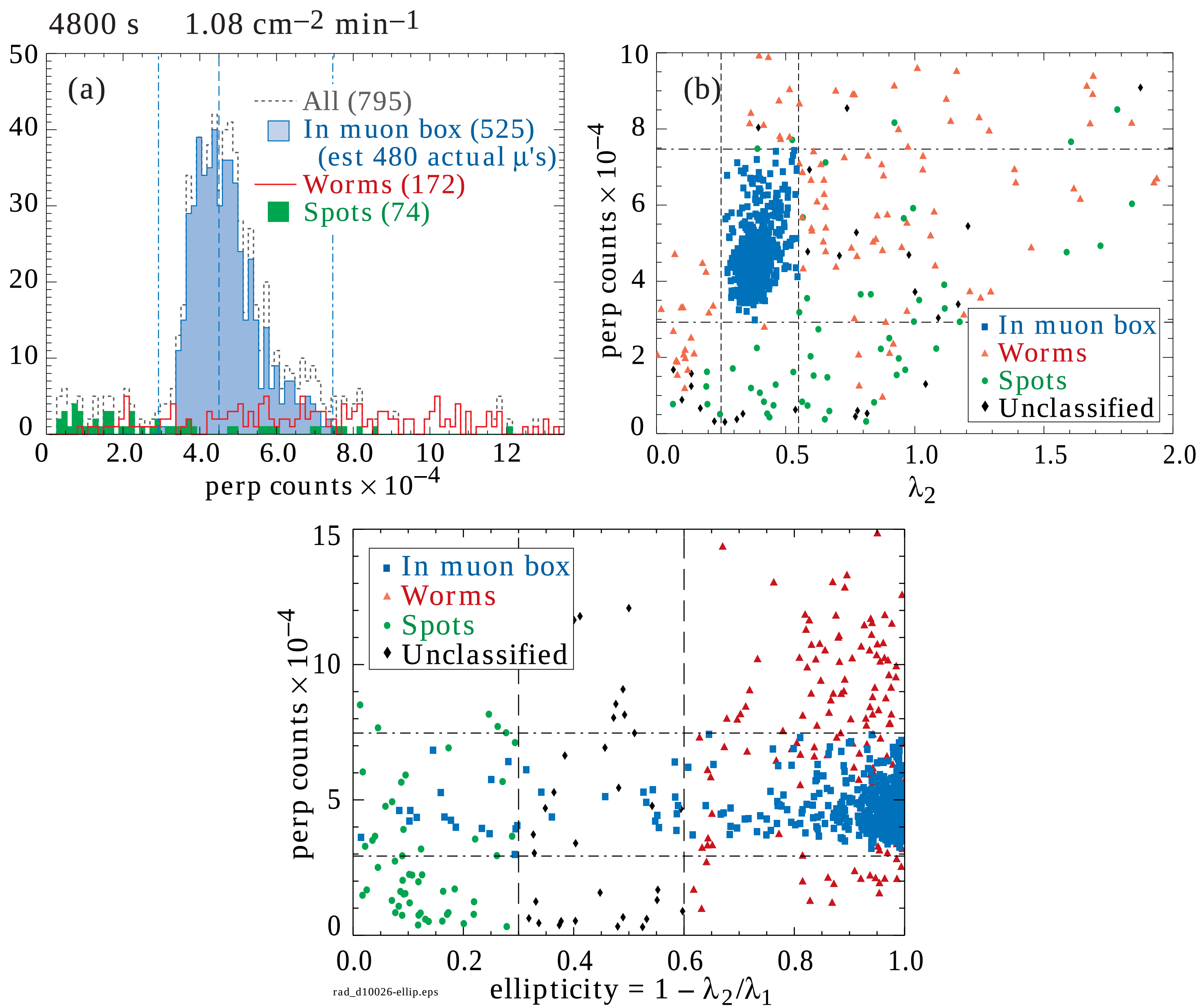


"Ellipticity" is also a somewhat useful idea



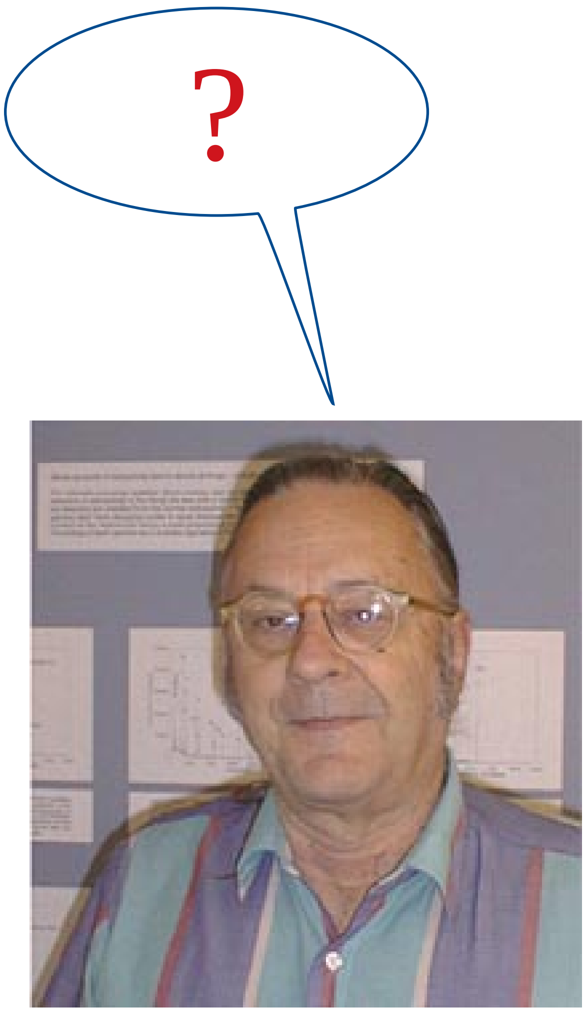
(2000 s dark, Lick 3-m spectrometer room)

SELECTION SUMMARY



WORMS AND SPOTS?

WHAT causes the worms and spots?



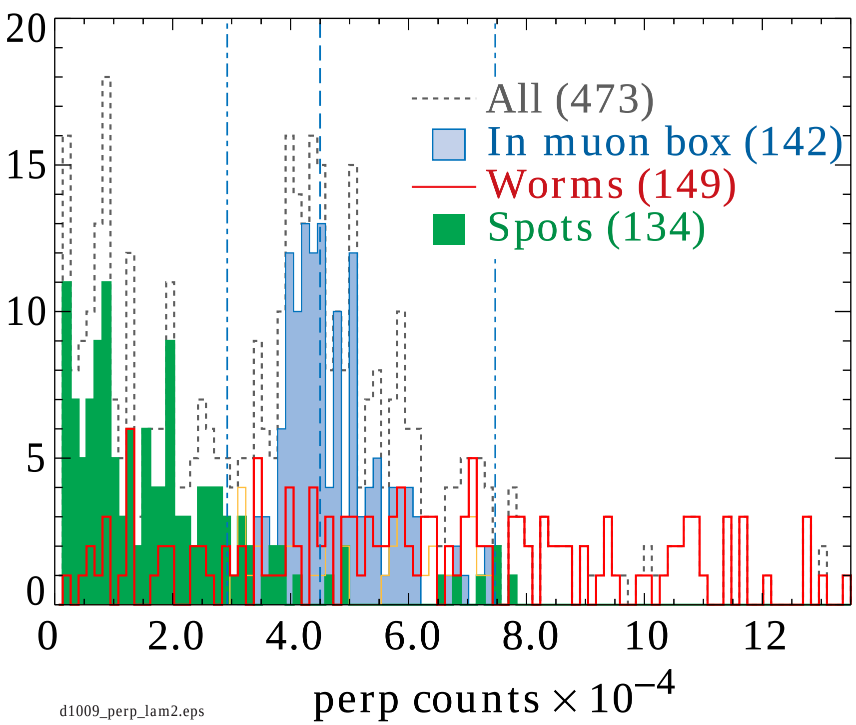
Al Smith and Dick McDonald, LBNL low-level radiation experts, (along with Steve Holland, Richard Stover and Mingzhi Wei) suggested and carried out a series of long dark exposures at different places

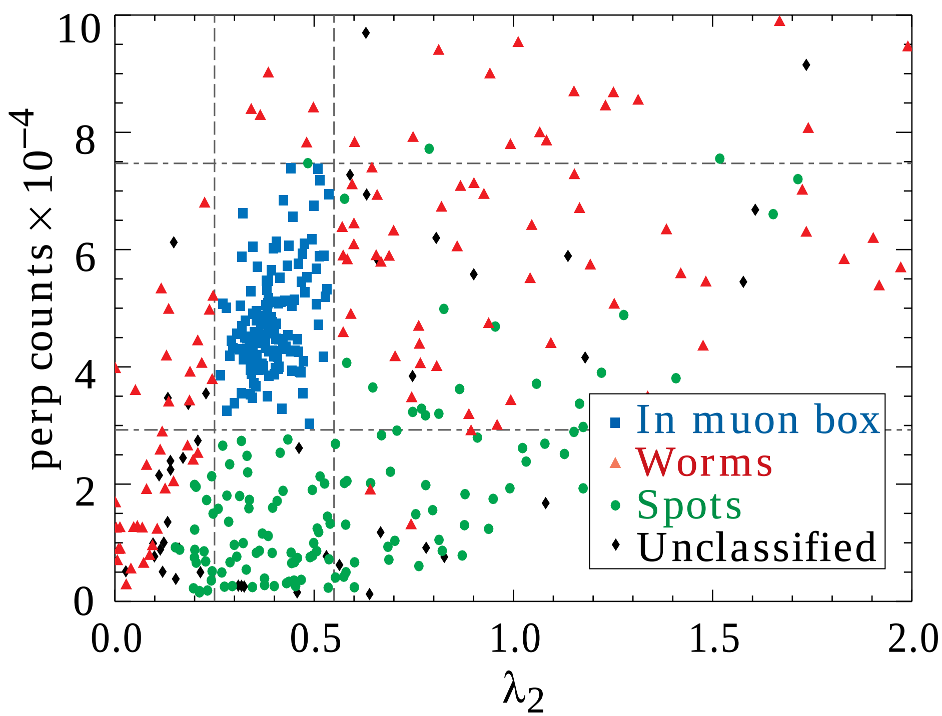
⟹Four experiments show what's happening:

Al Smith

1. In the basement of a building in Santa Cruz—the UCO/Lick CCD lab
   ⟹ muons (about 30%), worms, and spots

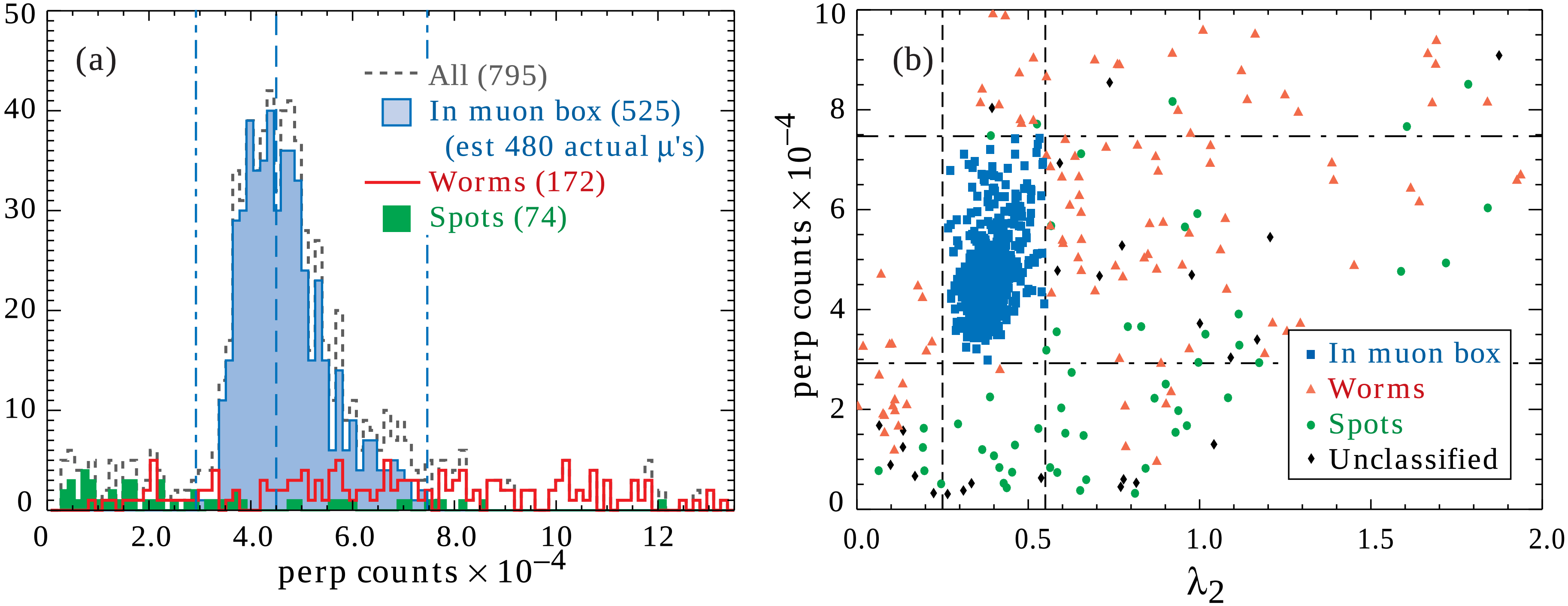
1000 s 3.1 cm^{-2} min^{-1}





2. In the low-background facility (LBF) at LBNL (a room with 1.5 thick concrete walls; the concrete has very low radioisotope content)
$\Longrightarrow$ 66% muons

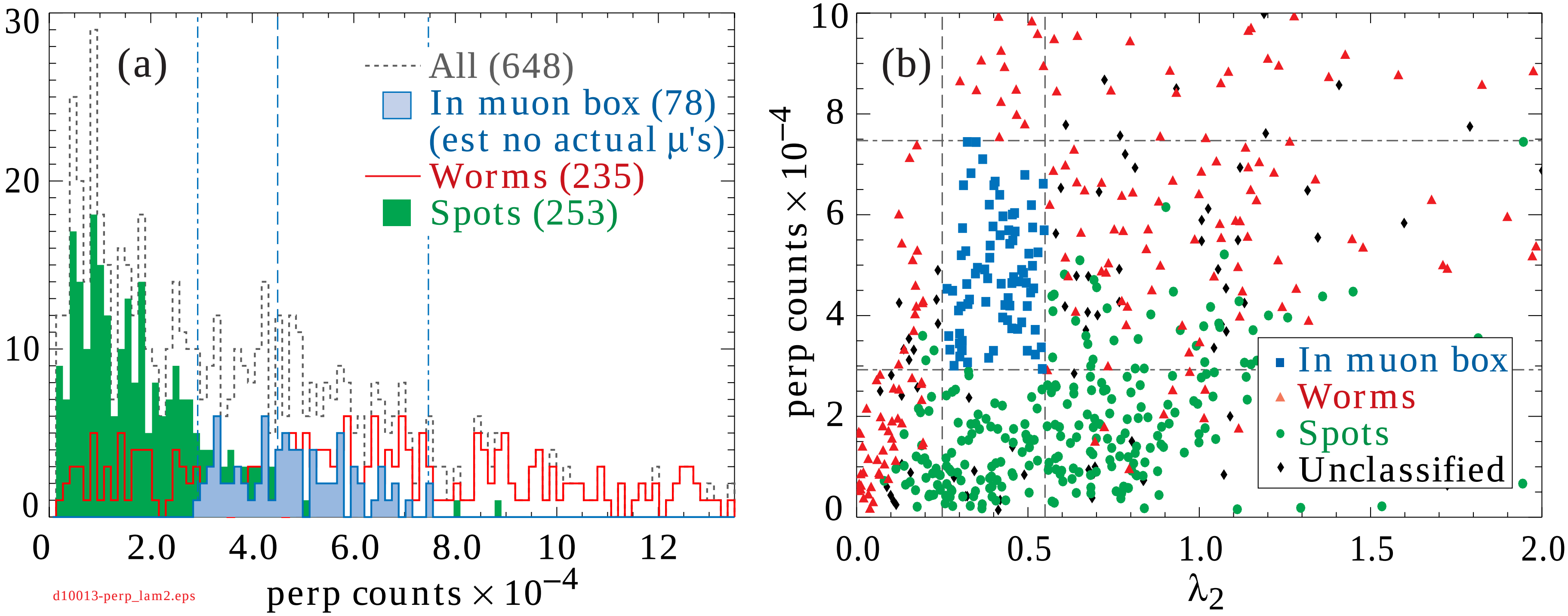
4800 s   1.08 $\mathrm{cm}^{-2}\,\mathrm{min}^{-1}$



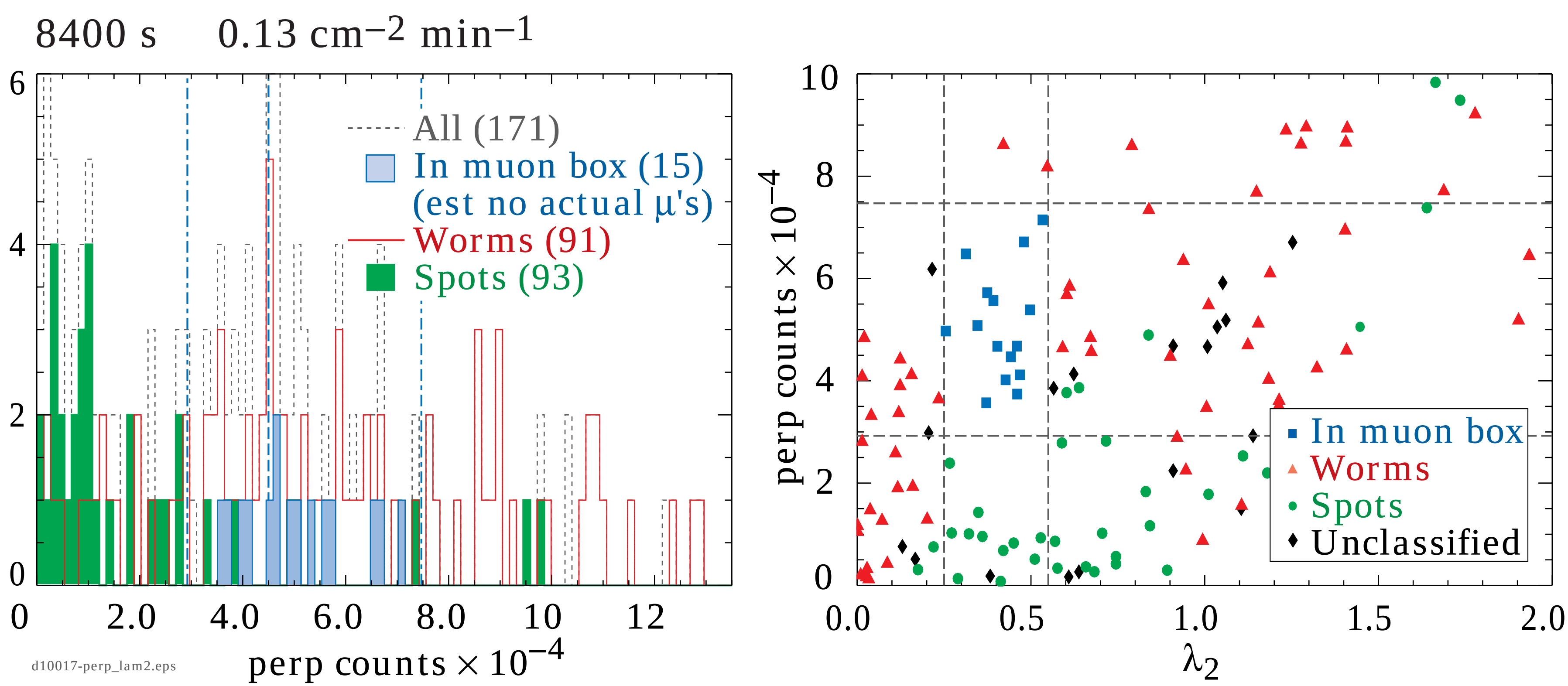
OROVILLE OUTSIDE VAULT

3. At the power plant of the Oroville (California) dam, 160 m under rock, where cosmic rays are attenuated by 10^3
$\Longrightarrow$ worms and spots, no muons

7840 s 0.54 $\text{cm}^{-2}\ \text{min}^{-1}$

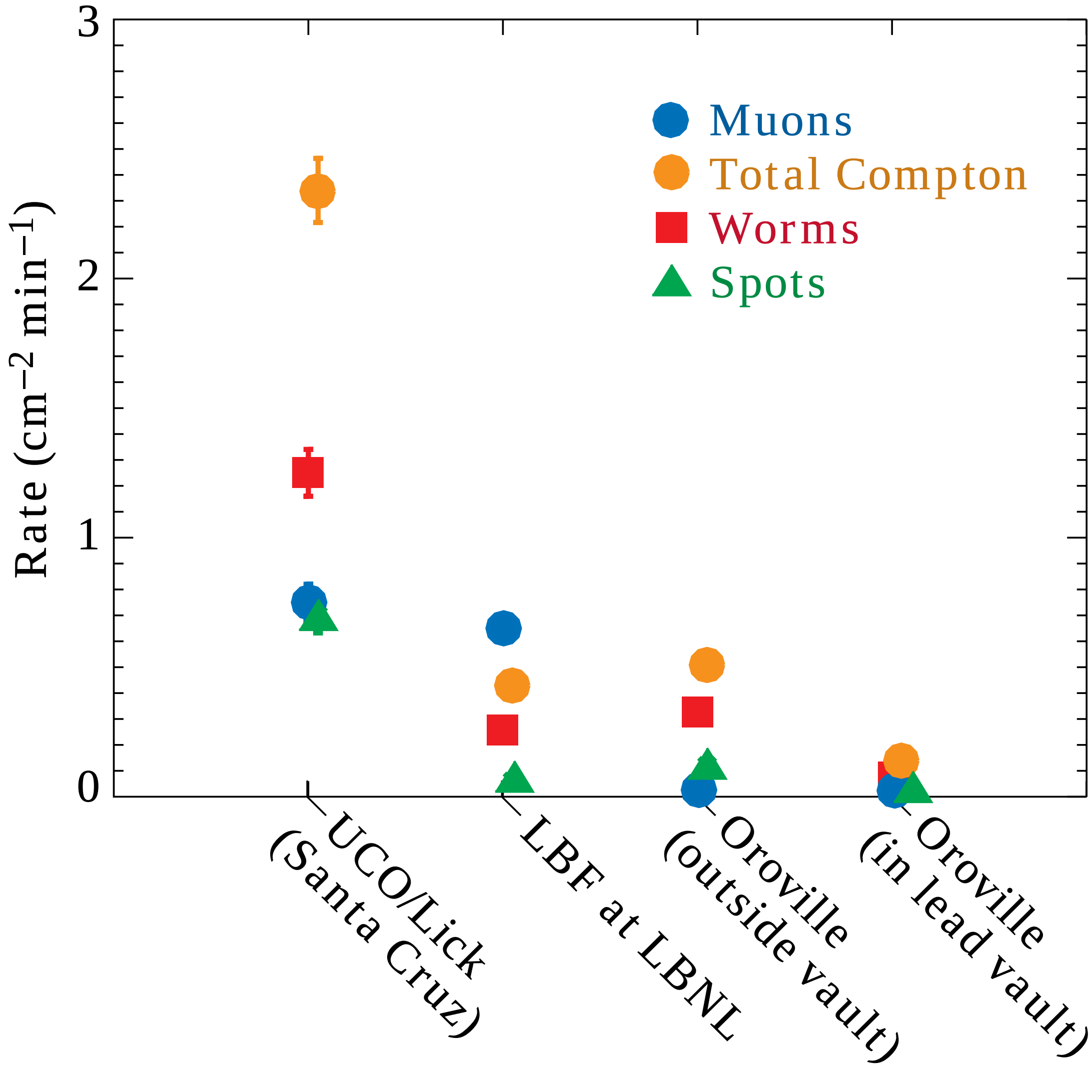


4. Again at Oroville, but this time in a lead vault built for exotic low-level experiments
   ⟹ almost nothing—171 events in 8400 s



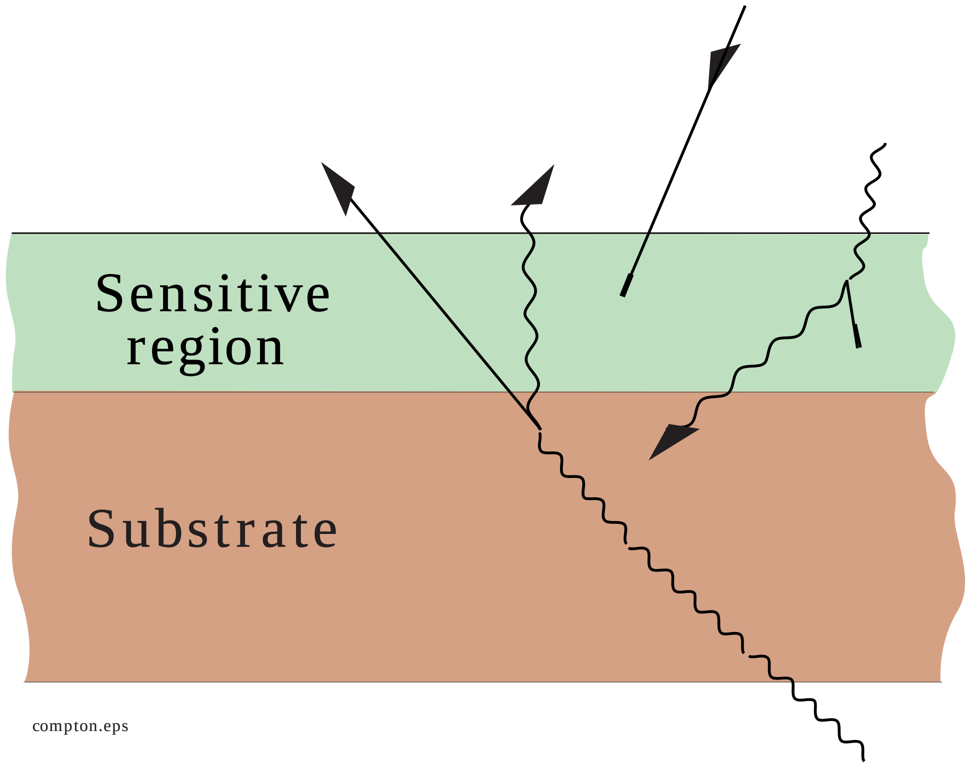
AMBIENT GAMMA SOURCES

Summary:



MORAL: Operate the CCD in a lead vault deep underground

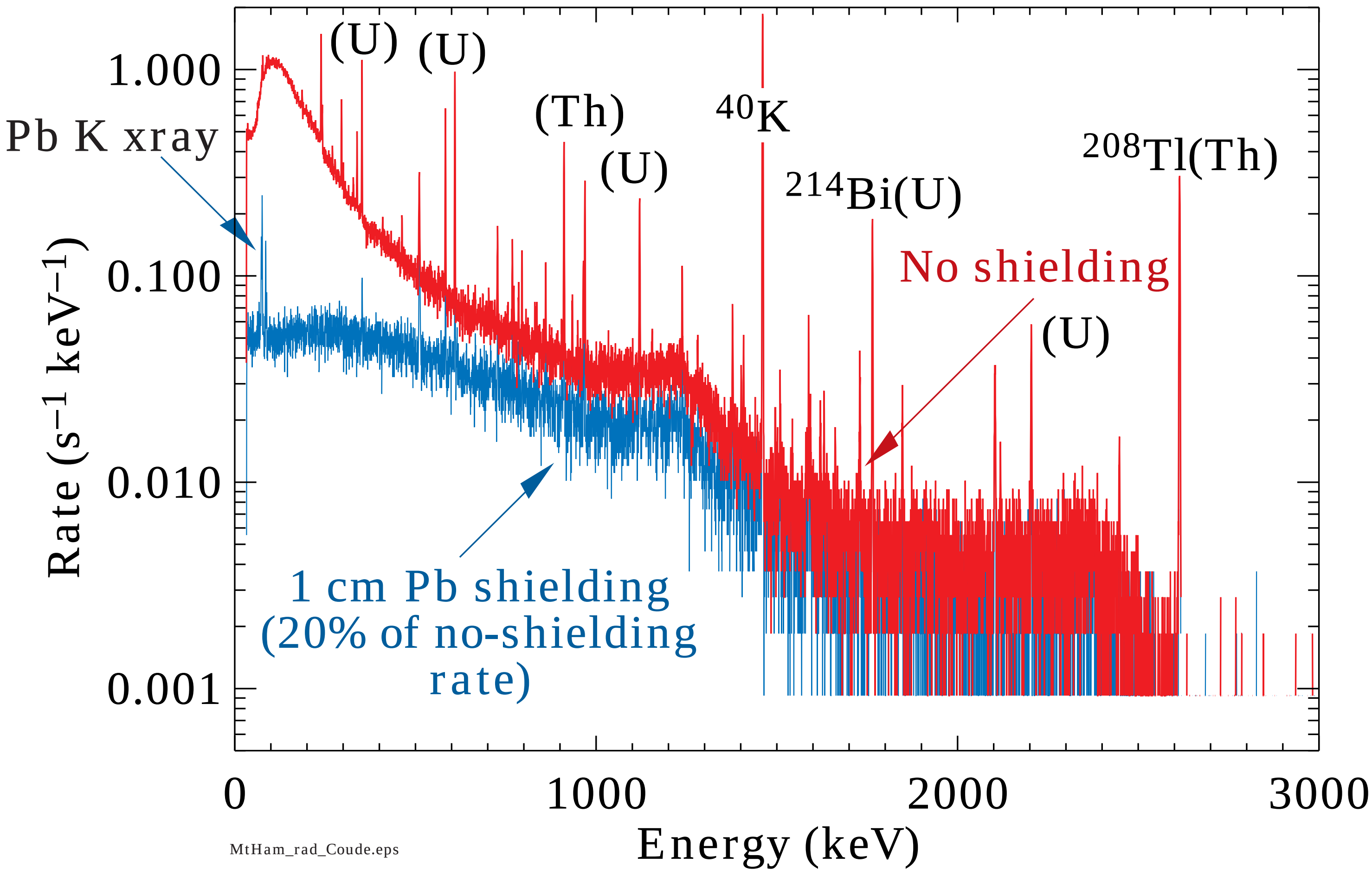
The worms and spots are almost certainly recoil electrons from Compton scattering of environmental γ rays



compton.eps

The γ's are from ^{40}K decay to ^{40}Ar, plus the U and Th decay chains, some degraded by multiple Compton scattering

Spectrum at the Lick 3-m spectrometer, observed in a Ge γ-ray spectrometer:



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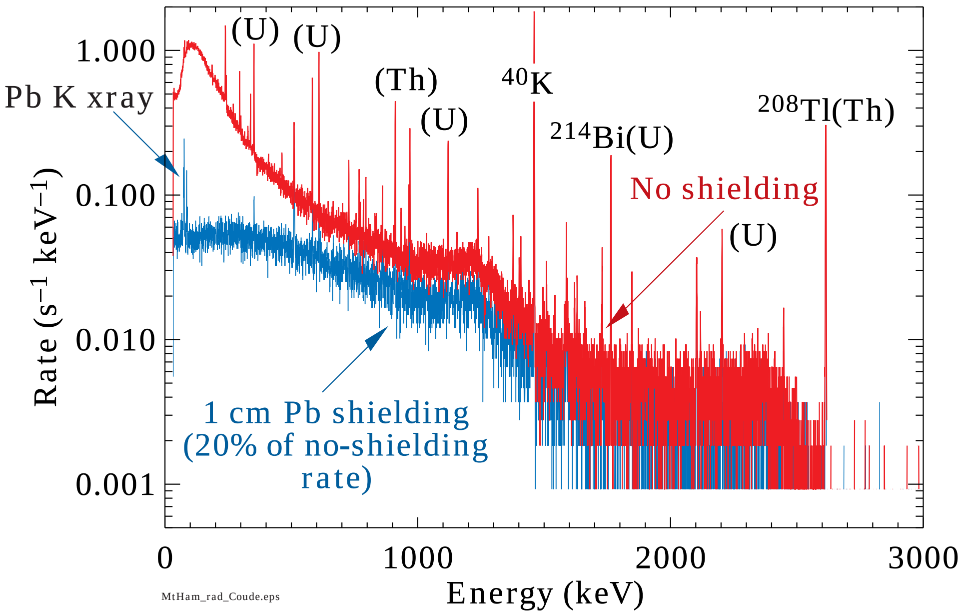
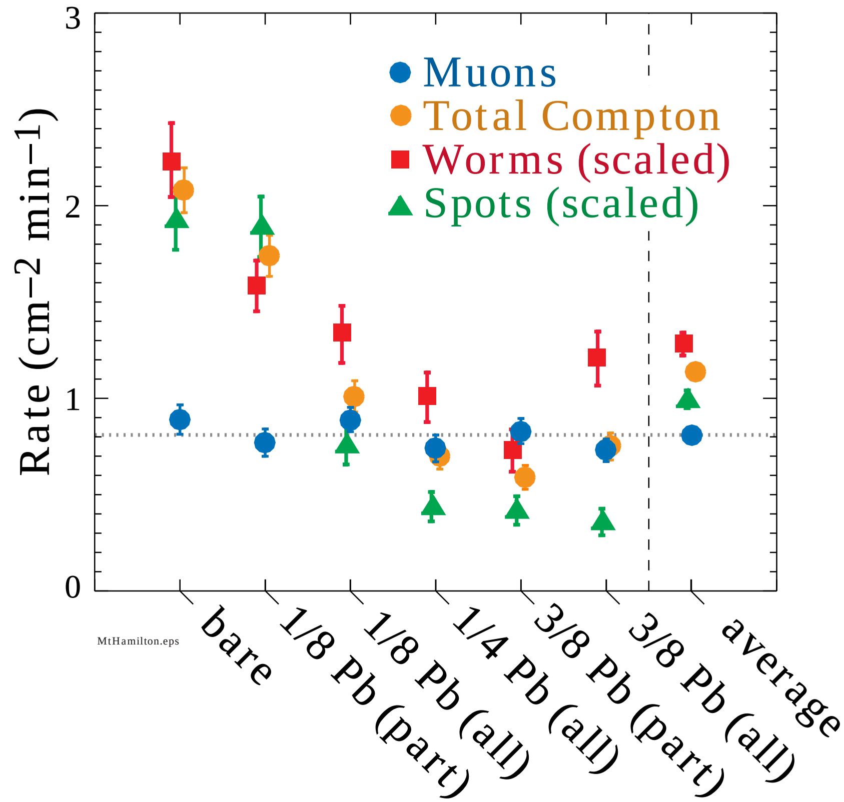


A small amount of shielding is effective—



ACTIVITY NEAR OUR CCD

The next step is to assay the radioisotope content of the nearby concrete, plus everything near the CCD

	Sample	U (ppm)	Th (ppm)	K (%)
	Lick 3-m core	1.35	4.0	0.72
	UCO/Lick lab core	1.2	1.2	0.72
	Mauna Kea lava	1.5	4.7	1.52
⟹	CCD black socket	0.64(4)	1.38(6)	0.011(1)
	Si wafers (3 in box)	0.025(6)	0.16(2)	ND
	Aluminum nitride	0.010(2)	0.019(5)	ND
	Aluminum sputter	ND	0.044(14)	ND
	Circuit boards (Lick)	0.064(4)	2.07(8)	0.016(2)
	Epoxy (Lick)	0.012(3)	0.010(3)	ND
	INVAR, bar stock	ND	ND	ND
	Molybdenum, bar stock	0.020(3)	0.020(3)	ND
⟹	Sn/In alloy	5.0(1)	4.6(1)	ND

—In all cases, the concrete/rock activity is dominated by $^{40}K \rightarrow {}^{40}Ar + \gamma$, by a factor of about 10

SUMMARY SO FAR

What we've learned so far in this talk:

- The worms are Compton recoil electrons; the spots are little worms
- The rates are about twice that of cosmic ray muons in most lab or spectrometer room situations we've looked at
- Simple lead shielding (1 cm) can reduce the Compton to below that of cosmic rays

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$\Longrightarrow$ BUT MURPHY ABHORS SIMPLICITY $\Longleftarrow$

Cautionary tale number one:

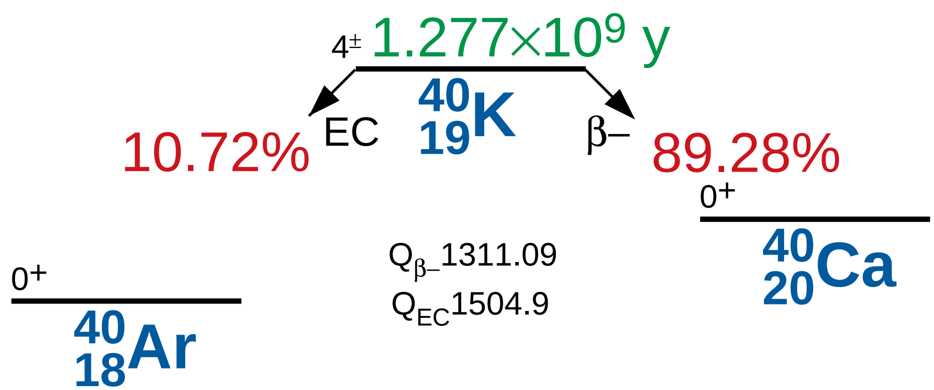
- At NOAO in Tucson, Arjun Dey and Rich Reed found an atrocious event rate *when a field lens was in the dewar*

$\Longrightarrow$ When it was outside the dewar, even close to it, there was no problem

$\not\gamma$ $\not\alpha$ β ? ?

Is Schott BK7 low-radiation optical glass a β *emitter*?

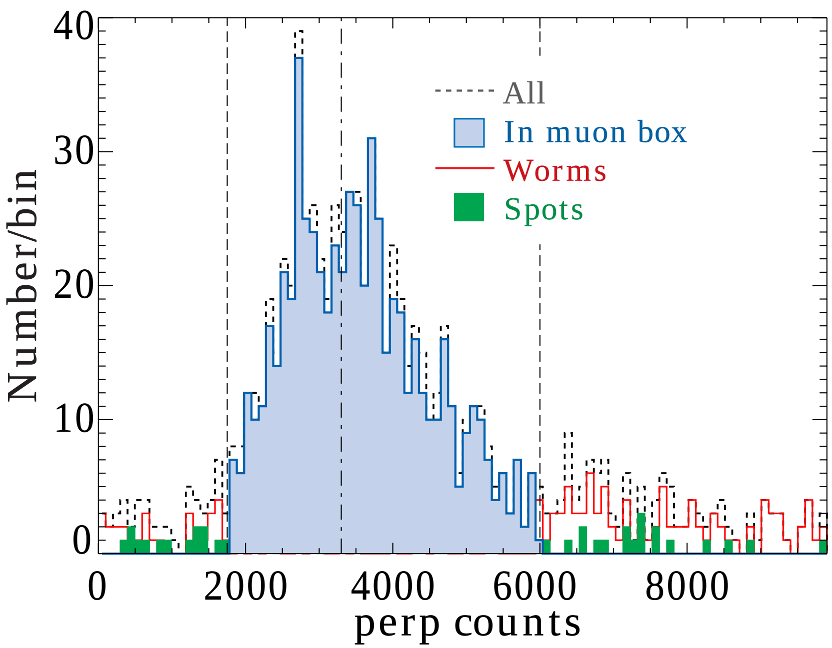
$\Longrightarrow$ This lens is 11% potassium!

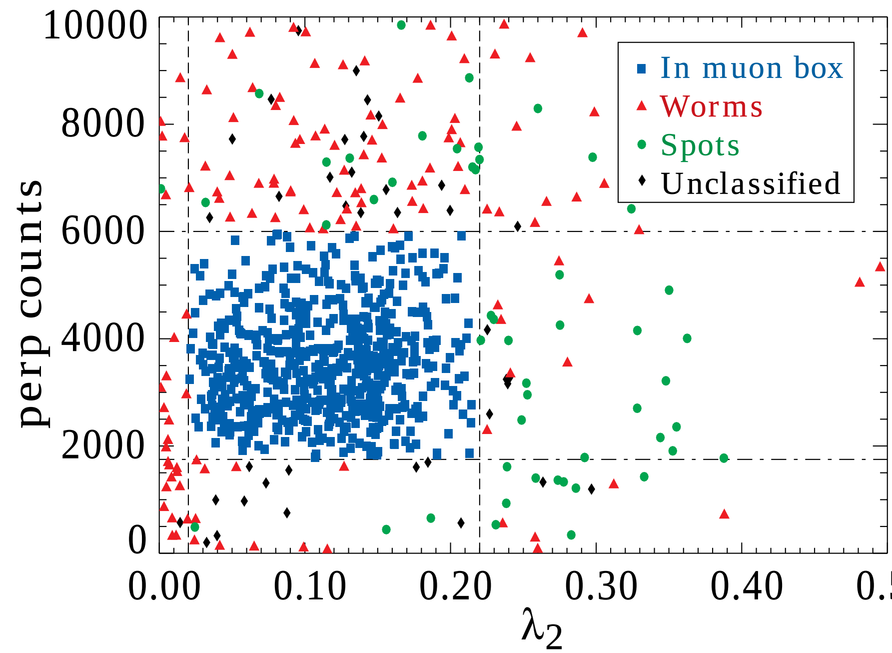


AVOID glass containing potassium. Also watch out for rare-earth containing glasses. *Think quartz.*

Cautionary tale number two:

- Richard Stover & Mingzhi Wei obtained long darks for a deep-depletion 2k $\times$ 4k LL/MIT CCD destined for DEIMOS. The tracks are too short for a good muon/worm separation, but with shielding, most of the events fall into the minimum-ionization peak





LL/MIT THICK CCD

A careful comparision of shielded/unshielded rates gives results *consistent with the same worms/spot rate + cosmic-ray rate observed with the LBNL CCD's under the same conditions*

The LL/MIT thick CCD sensitive region is 40 μm, rather than our 300 μm

$\Longrightarrow$ The Compton rate is *NOT* a (strong) volume effect

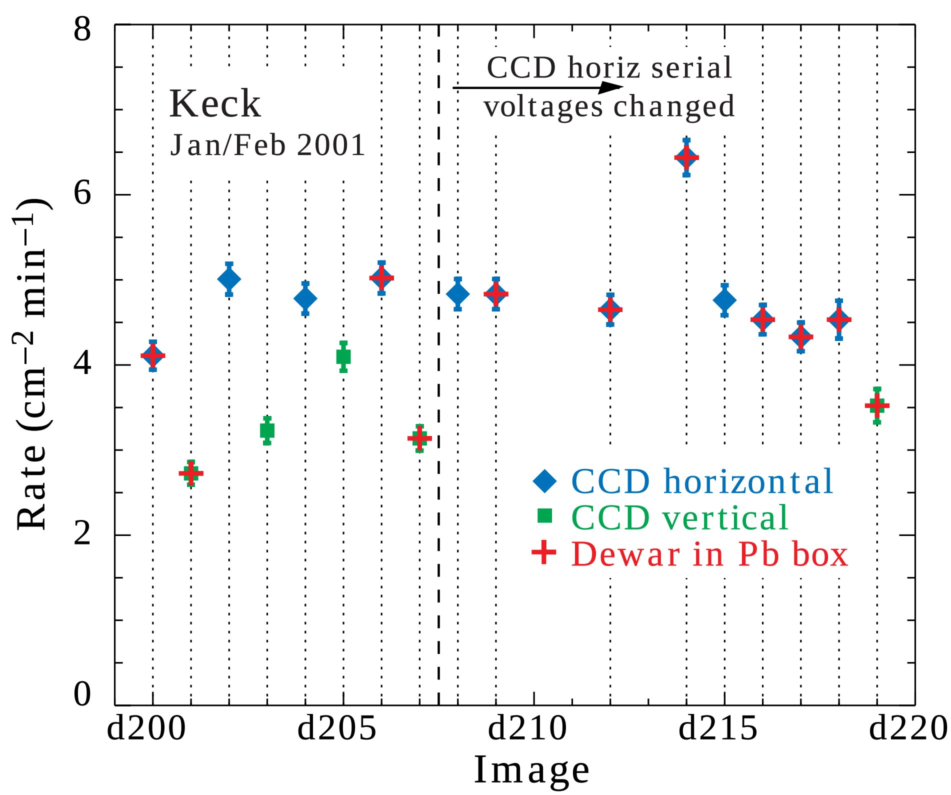
$\Longrightarrow$ The Compton recoils come from other places than just the active region

Everybody's CCD's have these problems

Cautionary tale number three:

Kirk Gilmore (UCO/Lick) obtained long darks in the Keck dome floor. A CCD controller problem limited the analysis, but

- Results are consistent with a cosmic ray rate 2$\times$ sea level rate, as expected
- As *NOT* expected, the lead box didn't make any difference



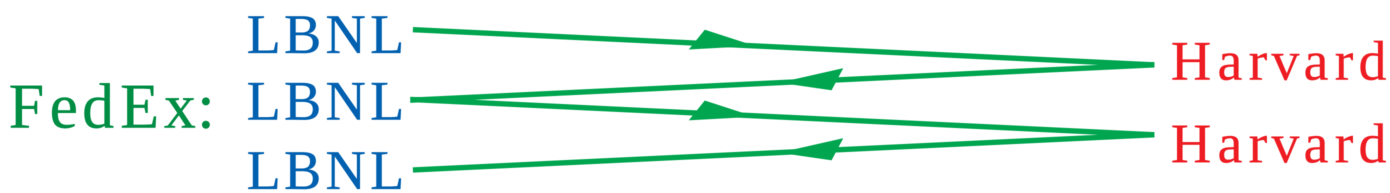
KECK MYSTERY

Grasping at straws

- Well, the proton/neutron intensity in a jet is 30 times that at sea level
- The CCD in its dewar had just been flown to Hawaii. Cosmogenic activation of the stainless at 11 km, say to the level ordinary concrete?

⟹ To test this crazy idea, we got 7 kg of stainless plate (same recipe),

- Counted it at the LBNL LBF at Oroville, then



- Took it immediately to the LBNL-LBF in Oroville for counting.

We in fact found cosmogenic isotopes not there before the flight:

$$^{44m}\mathrm{Sc},\ ^{51}\mathrm{Cr},\ ^{52}\mathrm{Mn},\ ^{54}\mathrm{Mn},\ ^{56}\mathrm{Co},\ ^{58}\mathrm{Co},\ ^{60}\mathrm{Co}$$

—but these together produce about 0.15 decays/min/kg

⟹ and in the meantime, Richard Stover's lead box at the Lick 3-m spectrometer failed to shield.

ADVICE—

- Avoid potassium
- Get lots of exercise
- Use lead
- Be careful of your neighbors