Testing GAGG scintillator for HERMES detector

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HERMES TP/SP - PL meeting, UniUD

Summary

1. Introduction and the Trento Campaign
2. Trento Data and Analysis
3. Calibration: from PMT to SDD
4. The impact of GAGG:Ce Afterglow on the HERMES PL

GAGG:Ce scintillator

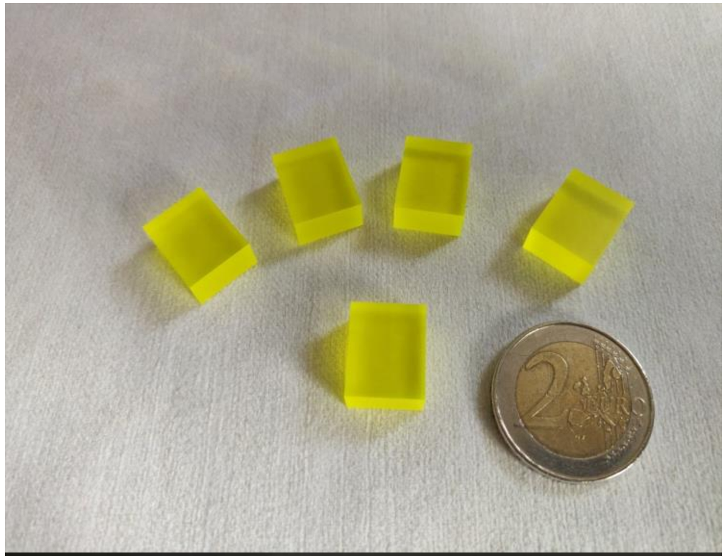
Cerium-doped Gadolinium Aluminium Gallium Garnet,
GAGG:Ce for his friends.

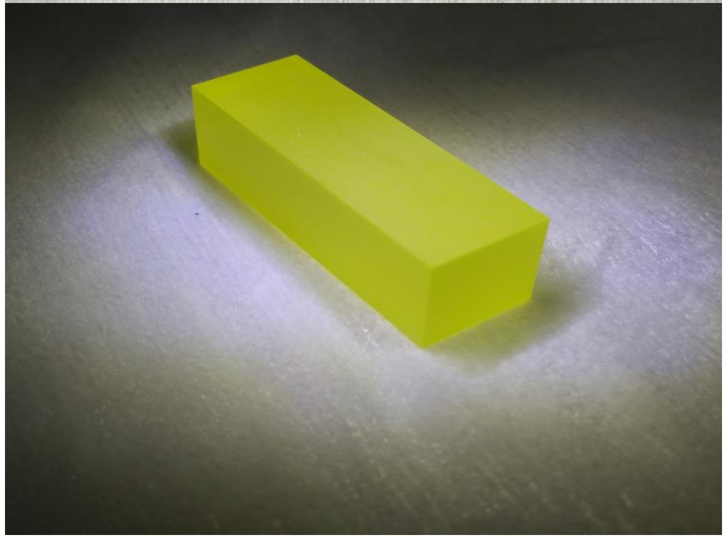
PROS

- High light output ~ 50 ph KeV^{-1}
- Fast prompt emission decay
- Peak emission around 520 nm
- Mechanically robust, high melting point, not hygroscopic, not radioactive..

CONS

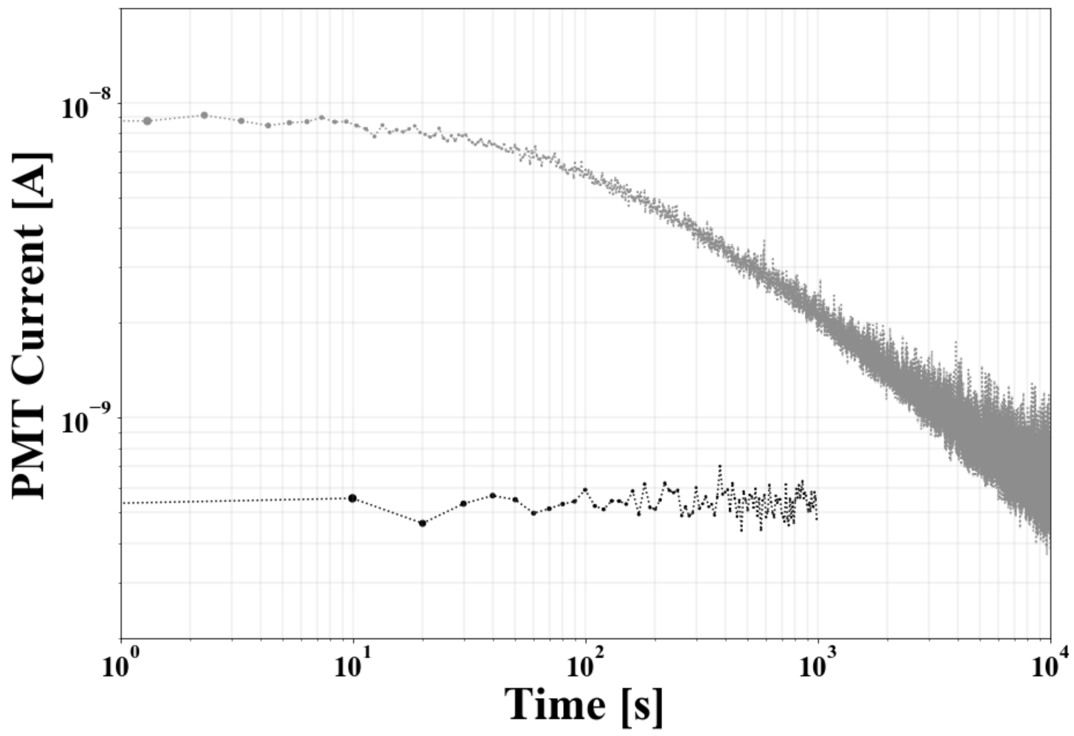
- Lacking literature.
- Worrying delayed emission: **afterglow**





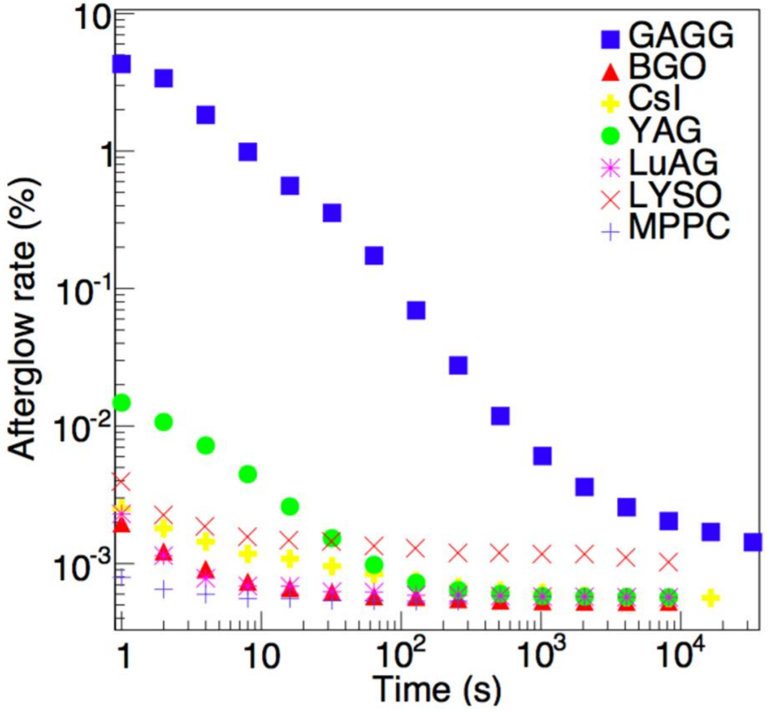
What do you mean with afterglow?

Udine 2019:
Afterglow light activated vs. silent.



Long (> 10^4 s!) delayed emission

Yoneyama 2018:
Afterglow in majour scintillators

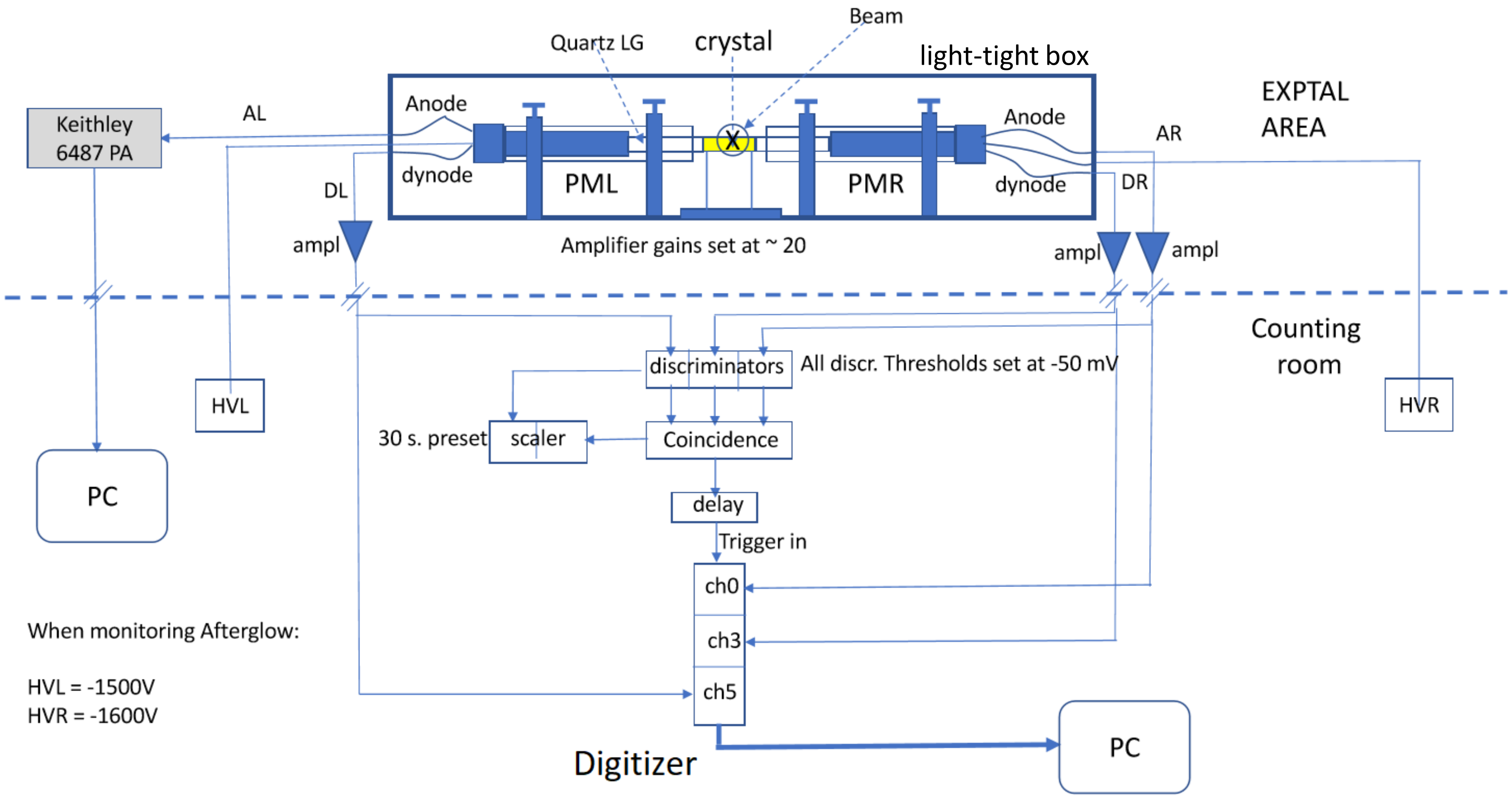


Peculiar feature.

GAGG:Ce Irradiation Campaign

When?	29/01/2019 – 31/01/2019
Who?	Bologna, Trieste, Udine HERMES nodes (roughly).
Where?	Trento Proton Therapy Center
What?	GAGG scintillator crystals.
Why?	**Afterglow will lead to some level of performance degradation**.
	Hopefully small but better be safe than sorry
How?	Irradiation with space-relevant particles relevant to the
	the LEO-environment i.e. tenths of MeV-range protons.

Experimental Setup



Schematic view of the experimental setup employed for the Trento irradiation campaign.

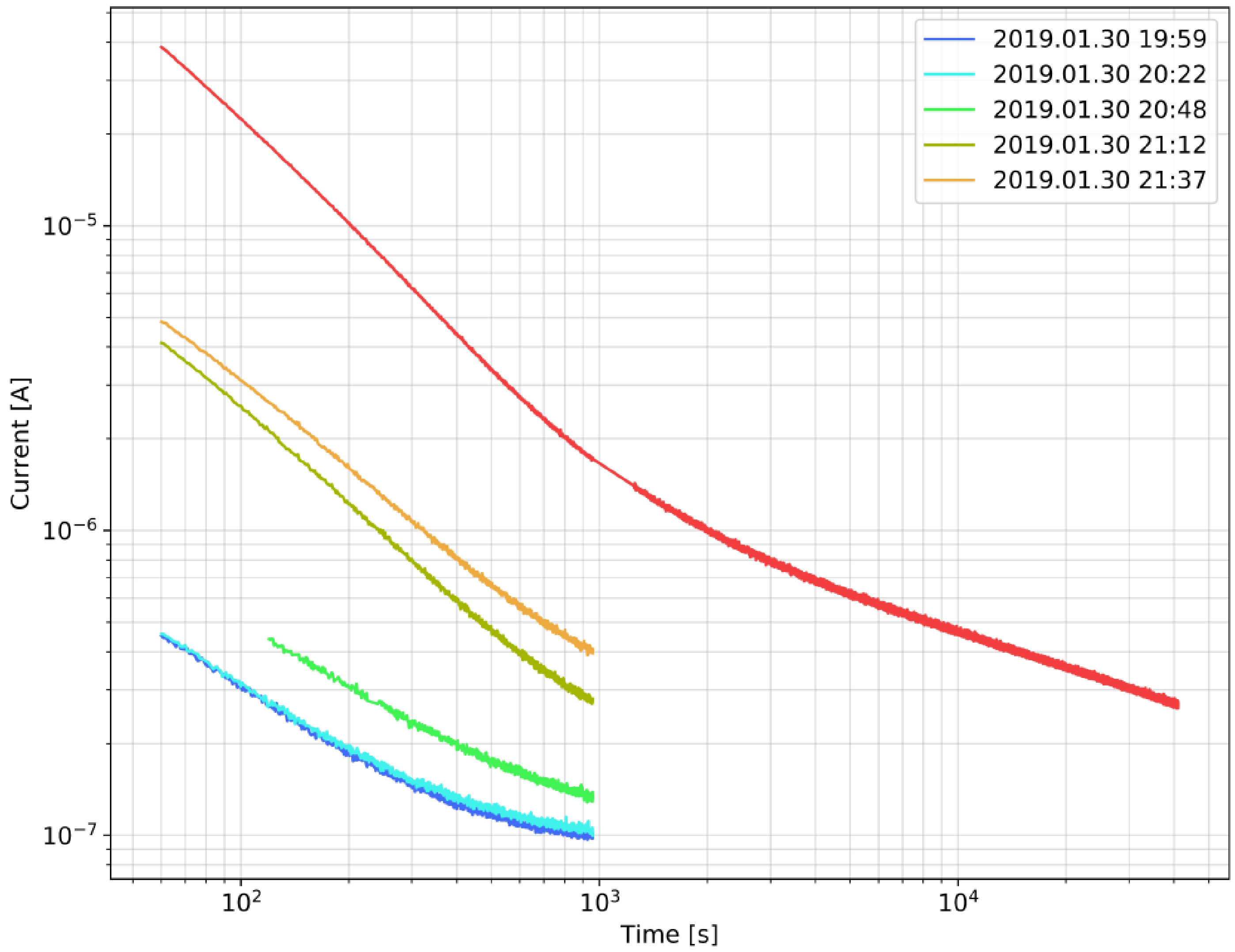
A glimpse to the logbook

Temperature in range $21 \pm 0.5\,^{\circ}\mathrm{C}$

repeat for every irradiation step

1. Cyclotron extraction current is called in 'dark mode' (low protons beam count, <10 p s^{-1}). PM HV set 'low'.
2. Beam on@dark. Data for ~ 5k scintillation waveform are collected.
3. Beam off. Beam operation is requested with irradiation step parameters. pg 9 .
4. Beam on. Crystal is irradiated cf. pg 9.
5. Beam off. Start chronometer (t=+0s). PM HV is set to 'high'.
6. At time t = + 60 s the following measurement starts: a. single PMT anode current, signal count above threshold counter in b. single and c. coincidence mode. Data collection lasts for ~ 15 min.

						Misure		
		Cristallo	Durata[1]	Dose [p/cm^2]	P.O.E.[2]	Corrente	Conteggi	Waveform
2019.01.29 20:52 (O)		J1	20min	1.09×10^8	6m EQ	✓	✓	✓
2019.01.29 21:20 (v)		J1	20min	1.35×10^{10}	5y SS	✓	✓	✓
2019.01.29 22:05 (q)		J1	11h	–	5y SS	✓	×	✓
2019.01.30 09:39 (N)	●	J2	6h	—	–	✓	×	✓
2019.01.30 19:59 (r)	●	J2	15min	2.31×10^8	1y EQ	✓	✓	✓
2019.01.30 20:22 (U)	●	J2	15min	2.32×10^8	2y EQ	✓	✓	✓
2019.01.30 20:48 (E)	●	J2	15min	6.90×10^8	5y EQ	✓	✓	✓
2019.01.30 21:12 (Q)	●	J2	15min	2.66×10^8	10y EQ	✓	✓	✓
2019.01.30 21:37 (b)	●	J2	15min	3.78×10^9	2y SSO	✓	✓	✓
2019.01.30 22:02 (I)	●	J2	15min	2.94×10^{10}	10y SSO	✓	✓	✓
2019.01.30 22:22 (x)	●	J2	11h	–	10y SSO	✓	×	✓
2019.01.31 09:41 (u)		UK	6h	–	—	✓	×	✓
2019.01.31 20:04 (F)		UK	15min	1.11×10^8	6m EQ	×	✓	✓
2019.01.31 20:29 (x)		UK	15min	1.08×10^{10}	5y SSO?	×	✓	✓
2019.01.31 23:14 (S)		UK	10h	–	5y SSO?	×	×	✓
2019.02.27 09:33 (u)	●	J2	$\sim$ 36h	—	10y SSO	✓	×	✓



30 January anode current measures map. GAGG sample JPN#2.

The question:

Which question should this study answer?

«GAGG:Ce afterglow will affect the detector duty cycle?
How much will it impact detector perfomances?»

The plan:

INPUT >>

Model and parametrize afteglow from Trento proton irradiation

↓

Translate from PMT to SDD.

↓

Estimate leakage current from afterglow emission vs orbital time

OUTPUT <<

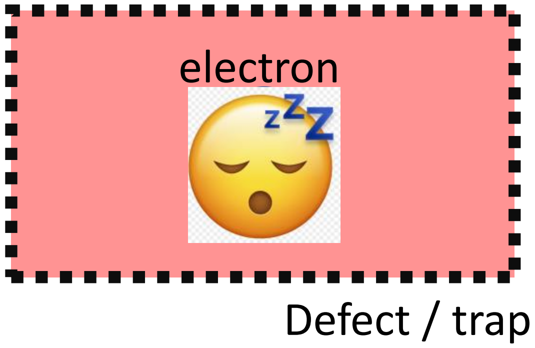
Which model for GAGG:Ce afterglow?

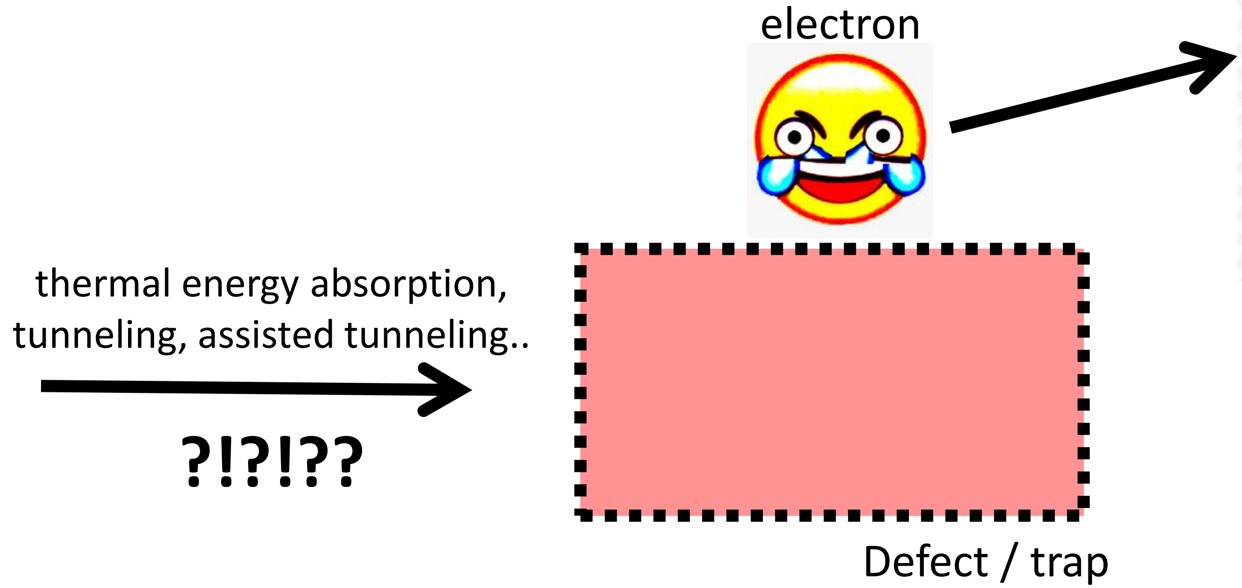
Afterglow ≈ *phosphorescence*.

Different mechanisms can explain prolonged luminescence in solids.

And different mechanisms come with different math.

The basic idea:





We propose: a simple semi-empirical model based on the idea that afterglow emission could result from the presence of traps with different, discrete energetic levels from which electrons can escape through thermal excitation.

Labelling with i the trap species defined by n_i and τ_i, if $P_i(N_i) = P_i$:

$$\frac{dN_i}{dt} = n_i\Phi - \frac{N_i}{\tau_i} \quad ,$$

average trapped electron per incident particle; average lifetime

$$N_i(t) = [N_{i,0}e^{-\frac{\Delta t_I}{\tau_i}} + n_i\Phi\tau_i(1 - e^{-\frac{\Delta t_I}{\tau_i}})]e^{-\frac{t}{\tau}}$$

From which the PMT current:

$$I(t) = -ef\epsilon_V G_V \frac{dN}{dt}$$

elem. charge; PMT quantum eff.

cryst-PMT transmission coef.

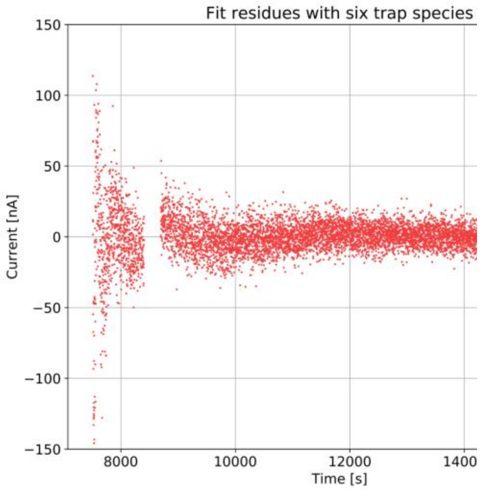
PMT gain

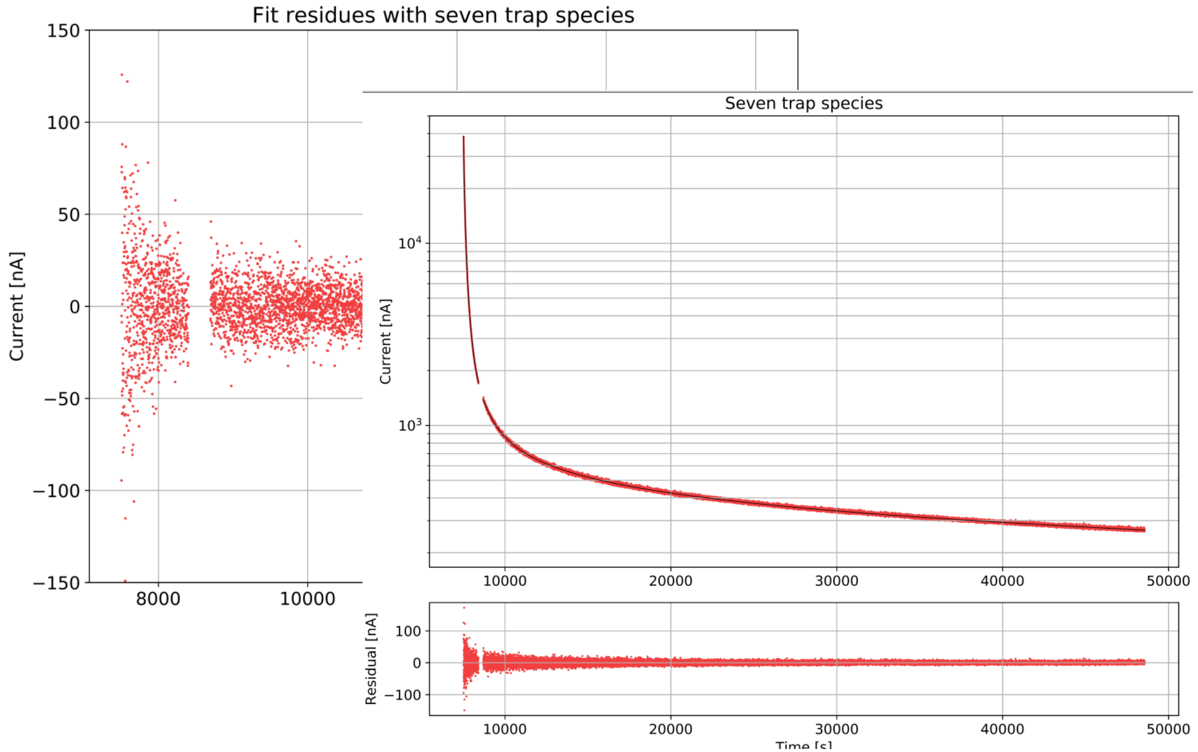
Now we **fit***

*: exps do not go gently in that good night

Q: How many traps?

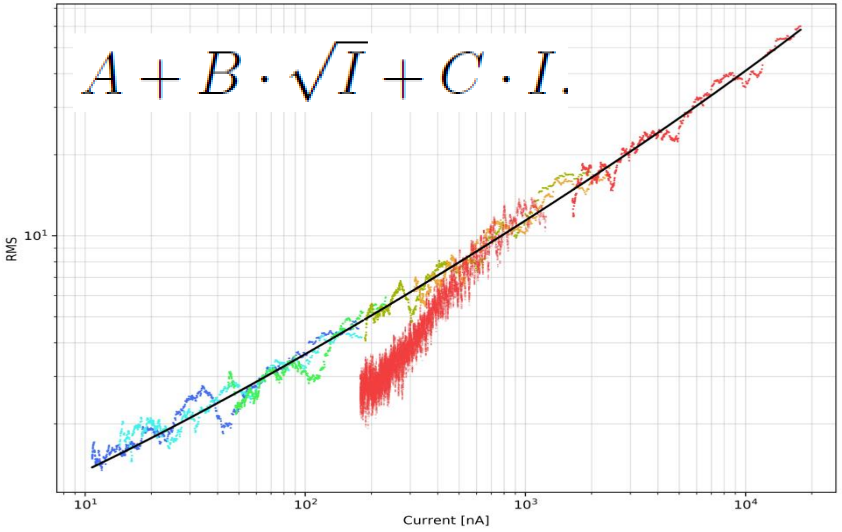
A: 7





Q: What about errors?

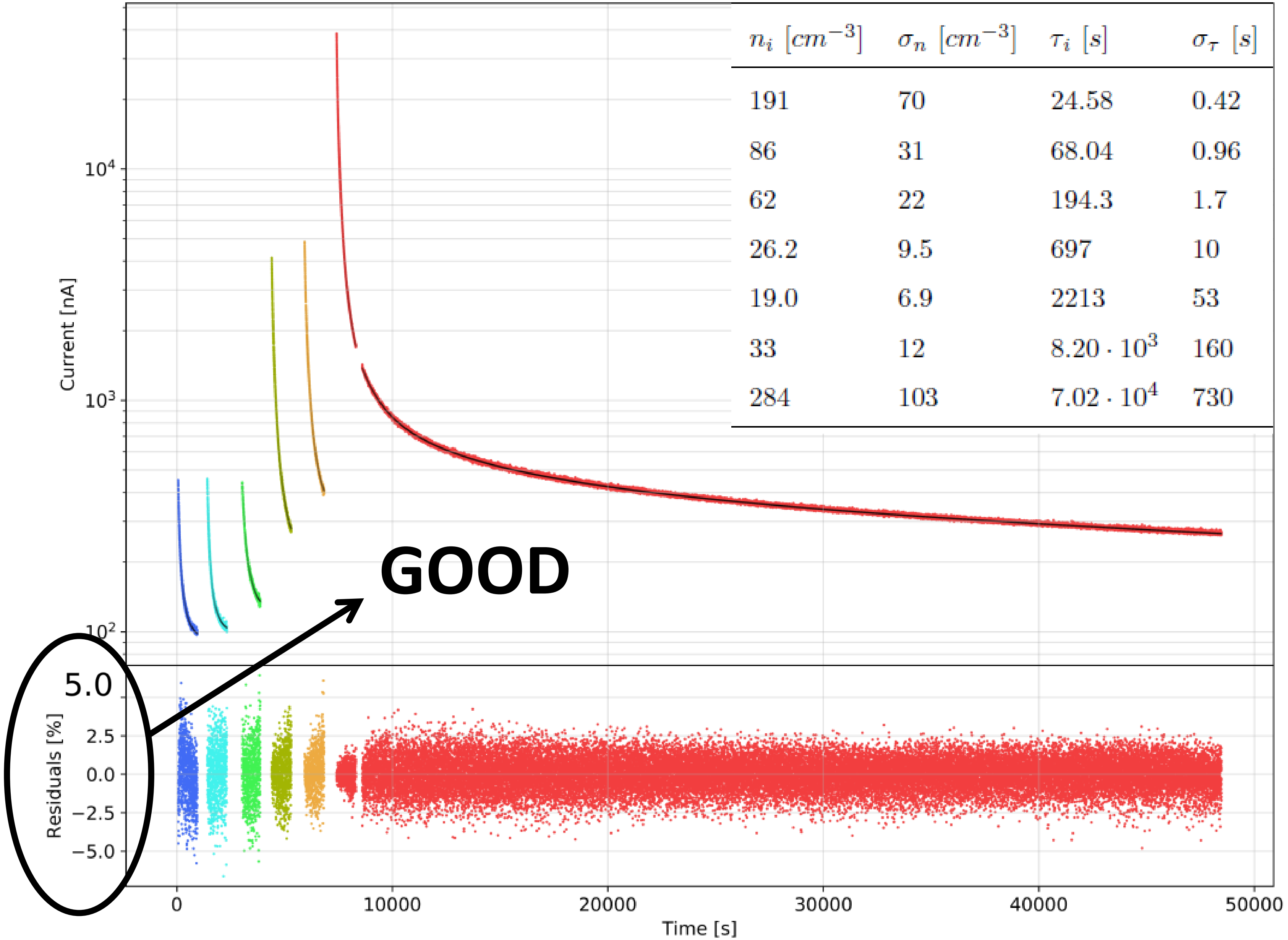
A: RMS weighting from cubic-spline fit




```
def residual(pars, t, scaling, runs_to_fit, measured_values):
    from scipy.constants import elementary_charge as ECHARGE
    GAIN = 1.04 * 10 ** 6
    PMT_EFF = 0.1
    F = 0.31
    CORR_FAC = GAIN * PMT_EFF * F * ECHARGE* scaling

    model = v['Ib']
    for run_index, run in enumerate(runs_to_fit):
        for i in range(v['trap_number']):
            model += heaviside(t - (run.time_since_start - DELAY - v['dT_' + str(
↪ run_index)]), 1)* CORR_FAC * v['fluxN_' + str(run_index)] * (1 - run.
↪ irr_duration / v['exp_t' + str(i)])) * exp(-(t - (run.time_since_start - DELAY -
↪  v['dT_' + str(run_index)])) / v['exp_t' + str(i)])
```

Fit results:



$n_i\ [cm^{-3}]$	$\sigma_n\ [cm^{-3}]$	$\tau_i\ [s]$	$\sigma_\tau\ [s]$
191	70	24.58	0.42
86	31	68.04	0.96
62	22	194.3	1.7
26.2	9.5	697	10
19.0	6.9	2213	53
33	12	$8.20 \cdot 10^3$	160
284	103	$7.02 \cdot 10^4$	730

BAD

!!

$\Phi\ [p \cdot cm^{-2} \cdot s^{-1}]$	$\sigma_\Phi\ [p \cdot cm^{-2} \cdot s^{-1}]$	$\Delta T^m\ [s]$	$\sigma_{\Delta T^m}\ [s]$
$1.524 \cdot 10^6$	$3.2 \cdot 10^3$	20.48	0.28
$1.322 \cdot 10^6$	$3.3 \cdot 10^3$	9.16	0.27
$1.359 \cdot 10^6$	$3.1 \cdot 10^3$	9.58	0.52
$1.37 \cdot 10^7$	0.00	9.754	0.092
$1.315 \cdot 10^7$	$1.3 \cdot 10^4$	8.573	0.094
$1.036 \cdot 10^8$	$7.6 \cdot 10^4$	0.00	0.00

Calibrations

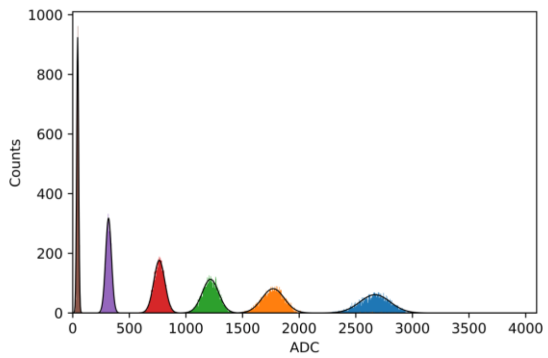
elem. charge;

$$I(t) = -e f \epsilon_V G_V \frac{dN}{dt}$$

cryst-PMT transmission coef.

PMT quantum eff.

PMT gain



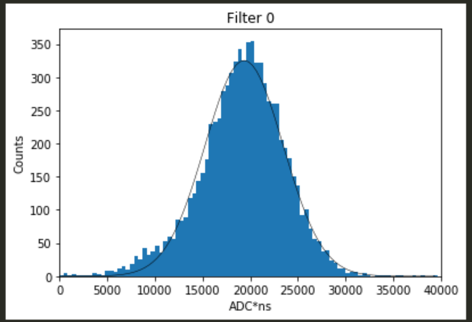
$$\sigma^2 = \sigma_{noise}^2 + (k\sqrt{N_{pe}})^2 + \alpha(kN_{pe})^2$$

$$G_V = c \cdot k_V / e$$

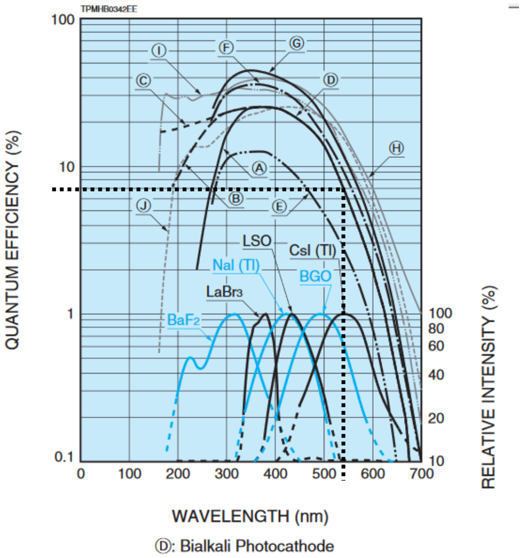
```
Filter 0
[[Model]]
    Model(gaussian)
[[Fit Statistics]]
    # fitting method   = leastsq
    # function evals   = 25
    # data points      = 91
    # variables        = 3
    chi-square         = 225.895431
    reduced chi-square = 2.56699354
    Akaike info crit   = 88.7383551
    Bayesian info crit = 96.2709336
[[Variables]]
    sigma:      4097.07201 +/- 56.2771408 (1.37%) (ini
    center:     19574.6422 +/- 75.9209884 (0.39%) (ini
    amplitude:  3340323.88 +/- 61080.5695 (1.83%) (ini
    fwhm:       9647.86710 +/- 132.522537 (1.37%) == '
    height:     325.255814 +/- 7.43212423 (2.29%) == '
[[Correlations]] (unreported correlations are < 0.100)
    C(sigma, center) = -0.154
```

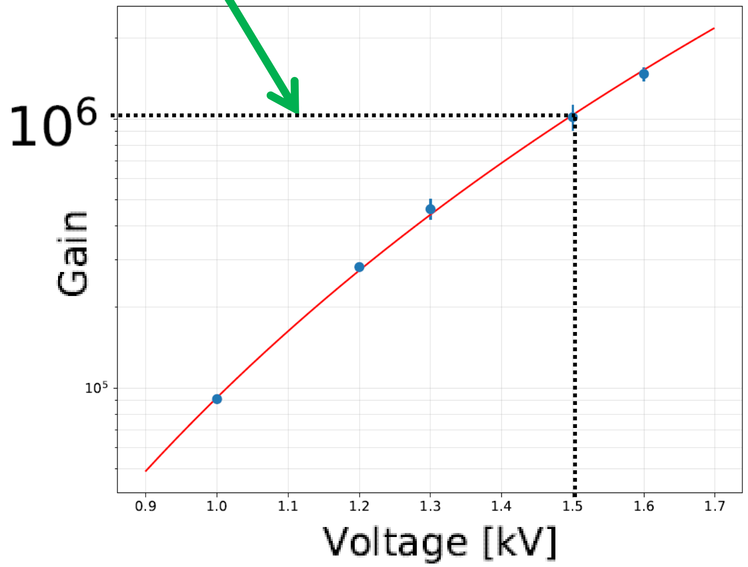
Cs-137

Cesium-137 (Caesium-137)




```
Measured light output = 31+/-9 photons/keV
Coupling efficiency = 64+/-19%
```





Impact of GAGG:Ce afterglow on SDDs

Since SDD detectors have no (= 1) intrinsic gain, a cell coupled to a scintillator won't be able to resolve the dim afterglow photons into full-blown signals. However the afterglow will contribute to the detector leakage current leading to degradation in detector performance.

How do we estimate leakage current increase due to afterglow from LEO radiation?

The recipe:

1. Simulate an orbit trajectory and calculate with some timesteps.
2. Evaluate protons and electrons differential fluxes along the orbit.
3. Convert differential fluxes to 70 MeV equivalent

   To accomplish this we scale the particle differential fluxes at energy E (expressed in MeV) by a factor $70/E$. This means that a 70 $p/cm^2/s$ flux of protons with energy 1 MeV, will input our afterglow model as a 1 $p/cm^2/s$ equivalent flux.

4. Apply the afterglow model above with Δt_I = orb. timesteps and Φ as in 3., integrated over five crystal faces.

Trapped radiation models

We can apply our afterglow model to simulated orbits.

Proton and electron fluxes are calculated via

AE9/AP9 VARB models.

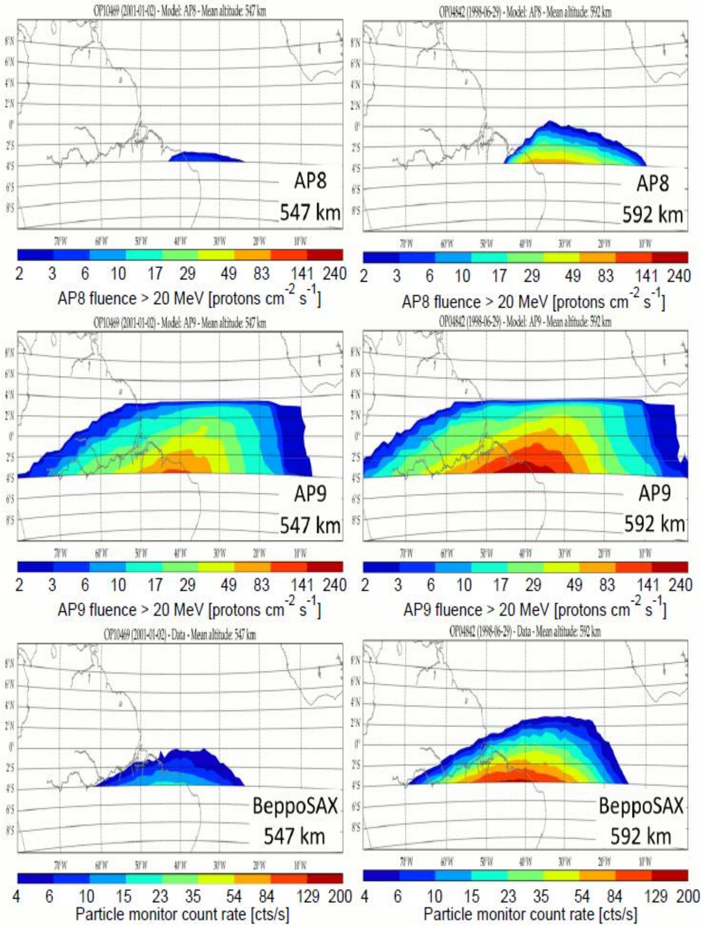
Developed by a collaboration led by AFRL (US military people).

Intended to succeed to the de-facto industry standard NASA AE8/AP8.

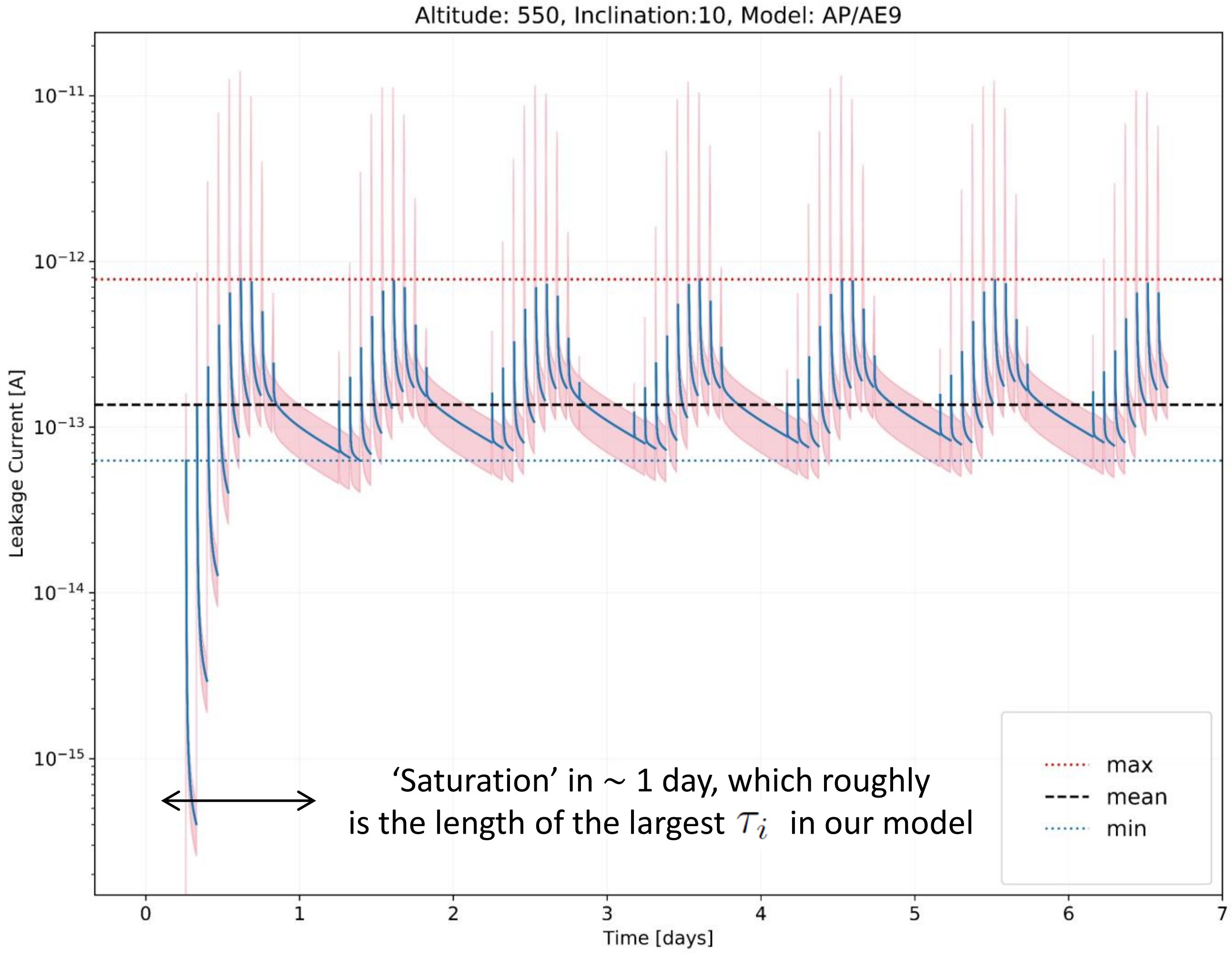
Why using AE9/AP9 instead of its predecessor?

Based on up-to-date measurements, stochastic approach,

better at space weather…, more conservative estimates.



Thanks Riccardo and Jakub!



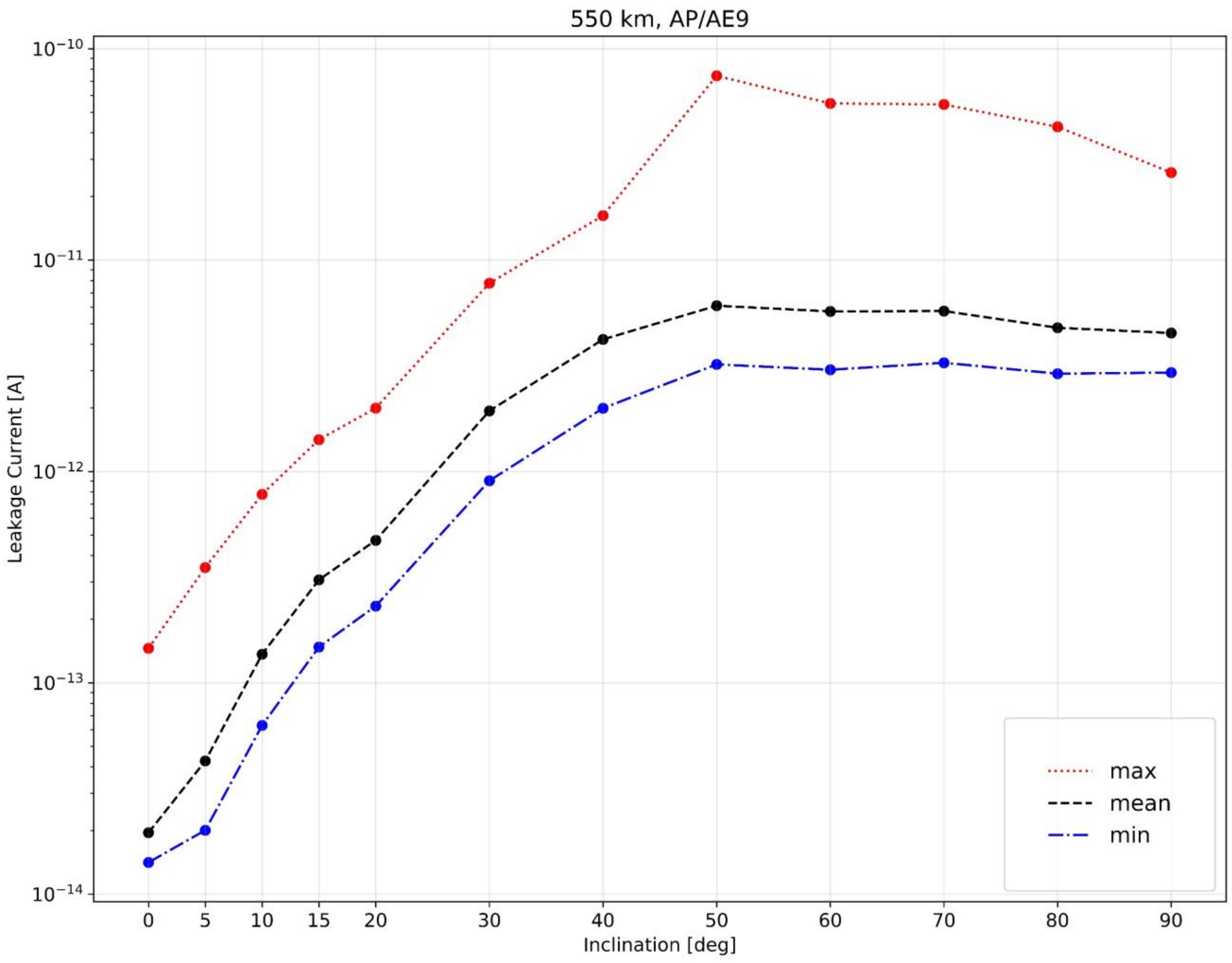
Afterglow leakage current versus orbital lifetime. Orbit inclination 10 deg, altitude 550 km. Estimated max, mean and min are calculated between 1 and 7 days of orbital lifetime.

Warning label:

1. 550 km, 10 deg orbit.
2. AE9/AP9 flux estimates.
3. Naked scintillator $1.21 \times 0.69 \times 1.45\ \mathrm{cm}^3$
   Five exposed, reflective faces.
   Looks at two SDDs.
4. Temperature $21 \pm 0.5\ °\mathrm{C}$
5. All particle E_K converted to ionization energy in scintillator.
6. No data inside SAA and $60\ \mathrm{s}$ after.
7. No radiation damage for both SDD and scintillator.

Danger zone = $100\ \mathrm{pA}$

..but we really want to be < $1\ \mathrm{pA}$



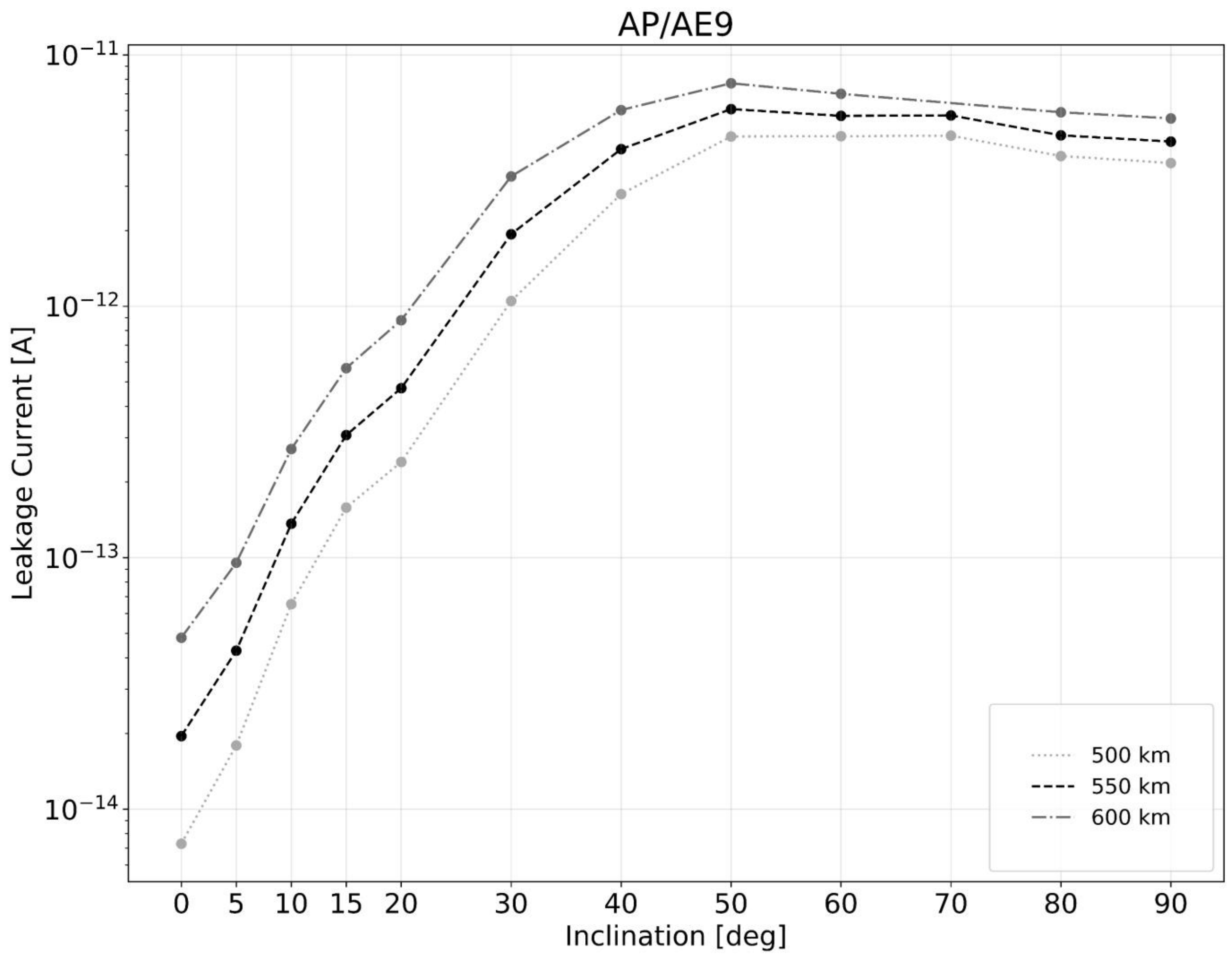
Estimated max, mean and min of leakage current versus orbital inclination. Altitude 550 km. Values are calculated between 1 and 7 days of orbital lifetime.

Warning label:

1. 550 km, 10 deg orbit.
2. AE9/AP9 flux estimates.
3. Naked scintillator $1.21 \times 0.69 \times 1.45 \text{ cm}^3$
   Five exposed, reflective faces.
   Looks at two SDDs.
4. Temperature $21 \pm 0.5\,^{\circ}\mathrm{C}$
5. All particle E_K converted to ionization energy in scintillator.
6. No data inside SAA and 60 s after.
7. No radiation damage for both SDD and scintillator.

Danger zone = 100 pA

..but we really want to be < 1 pA



Estimated mean and min of leakage current versus inclination at different altitudes.
Values are calculated between 1 and 7 days of orbital lifetime.

Warning label:

1. 550 km, 10 deg orbit.
2. AE9/AP9 flux estimates.
3. Naked scintillator $1.21 \times 0.69 \times 1.45\ \mathrm{cm}^3$
   Five exposed, reflective faces.
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Danger zone = $100\ \mathrm{pA}$

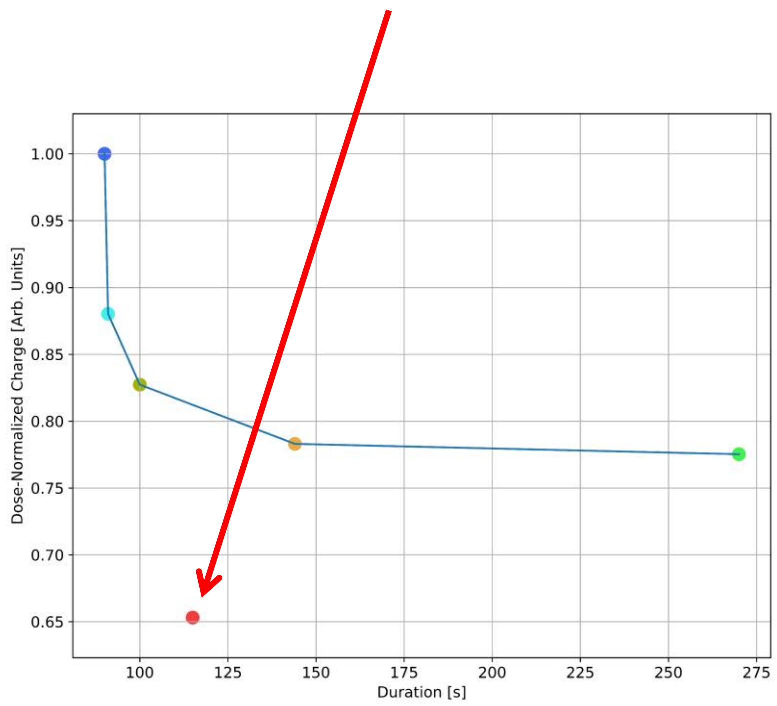
..but we really want to be < $1\ \mathrm{pA}$

Notes of concern

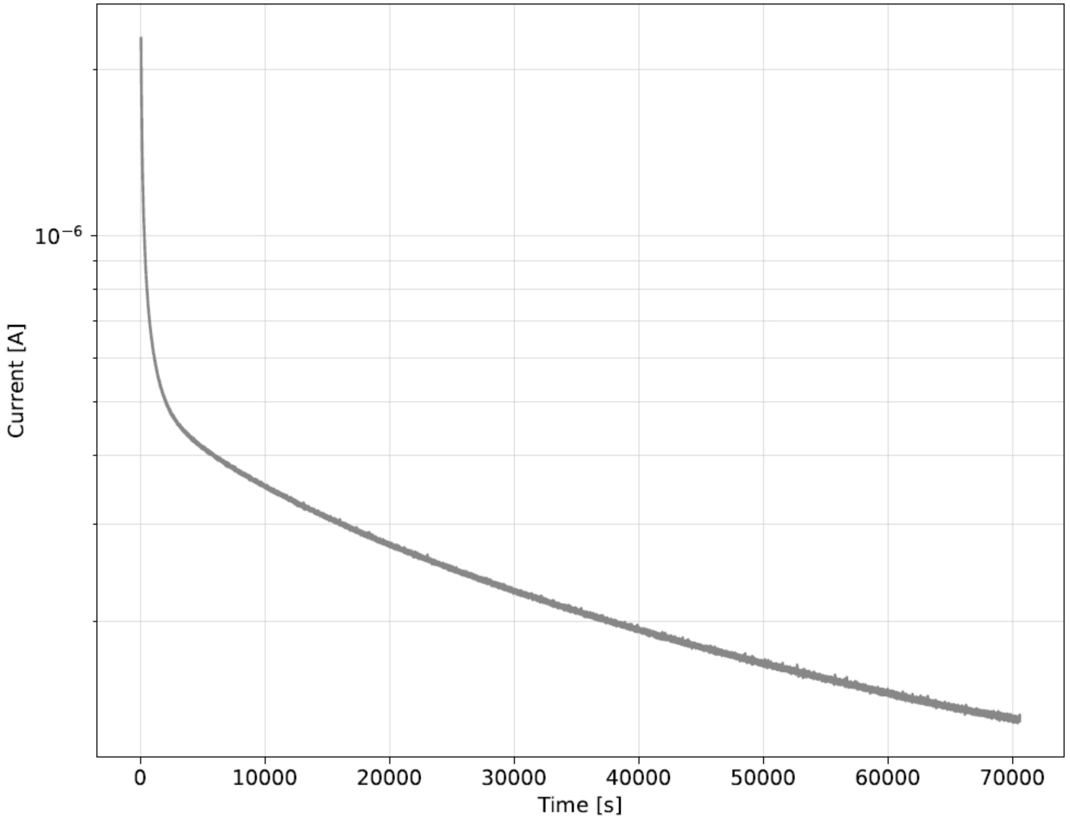
1. The longest irradiation measure we have is the last one, which was obtained at highest proton fluence.
   Fit estimates of the largest τ_i depend on this measure.
   For reasons this run resulted in comparatively less afterglow than others.
2. Where is the activation?

In one line:

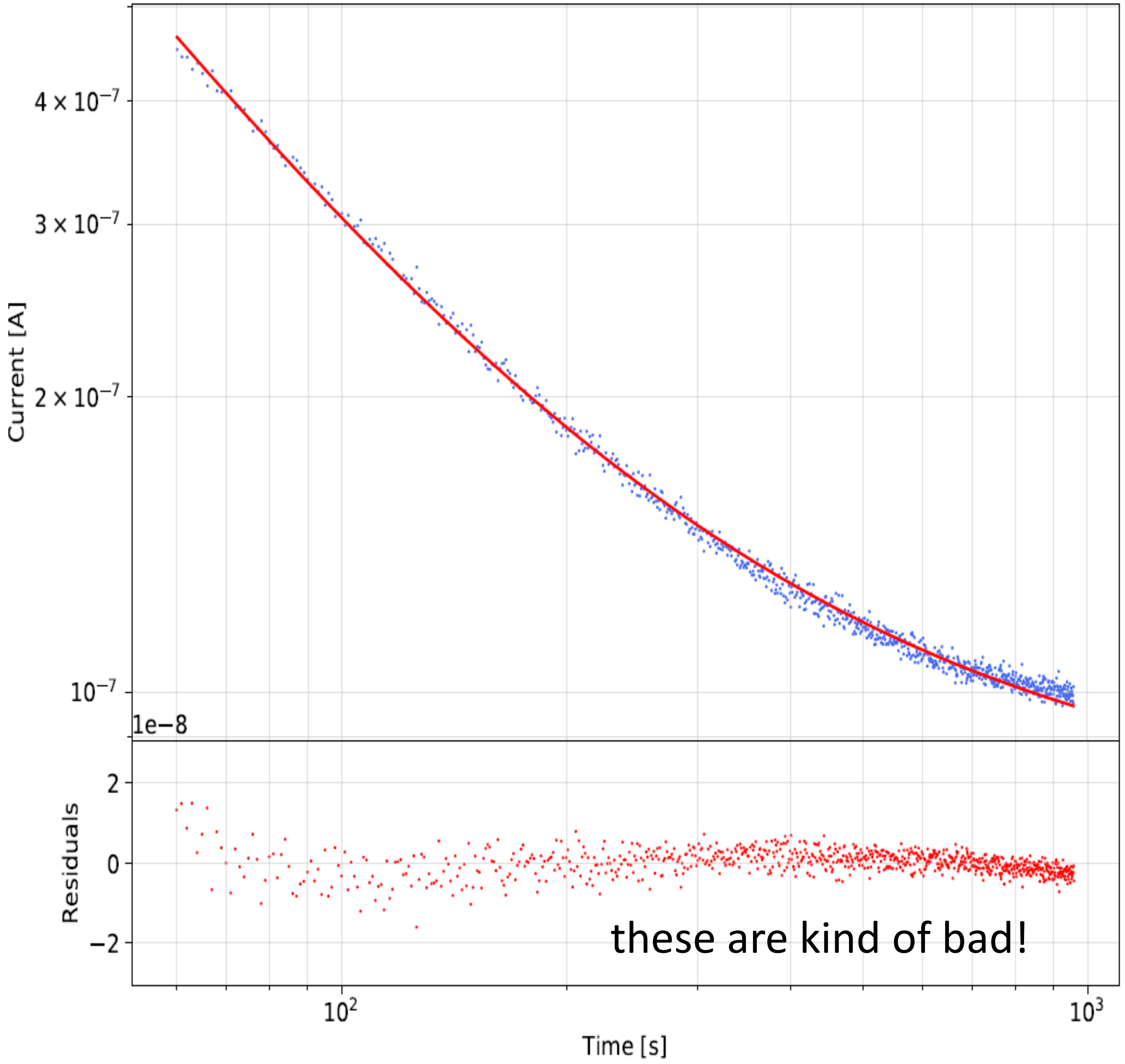
Hopefully afterglow will not be a problem for HERMES SP/TP. However, when the HERMES fleet will be enlarged to higher inclinations the impact of afterglow on detector performance will demand further, more accurate investigations.



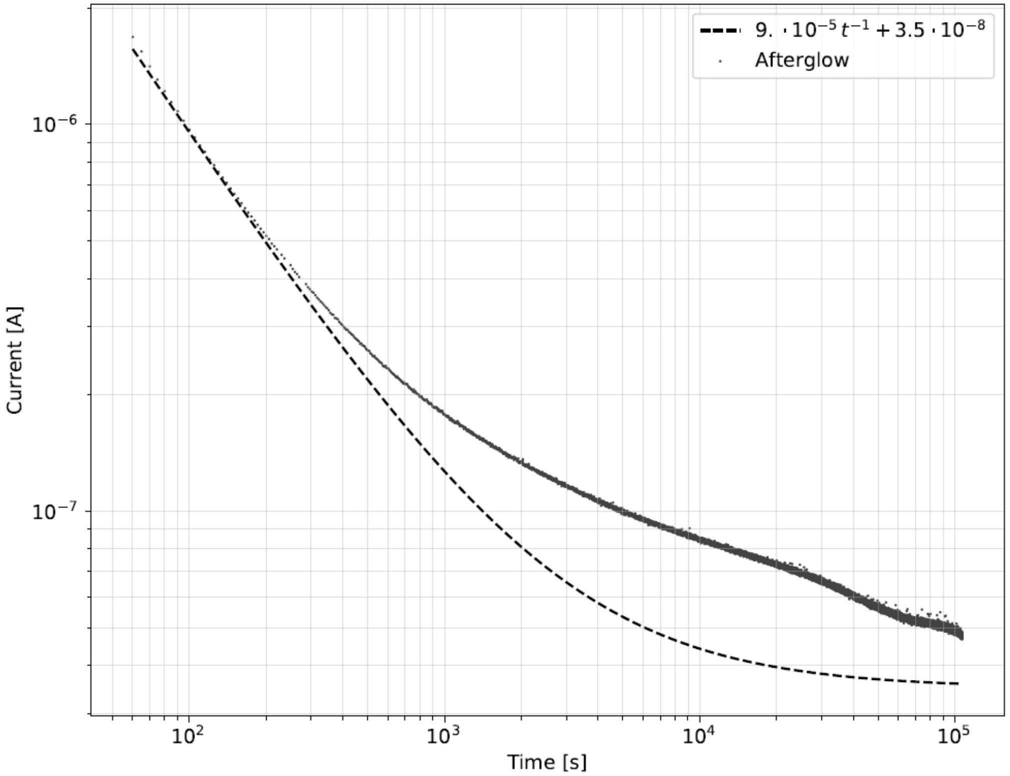
BACK-UP SLIDES



Light-activated afterglow. Note scale being nat-log.
Long timescales behaviours ~ exponential!



these are kind of bad!



many traps and **many** electrons

↓

some kind of **power-law** behavior.

Some escape mechanisms (tunnelling) natively predict inverse power-law emission intensity.

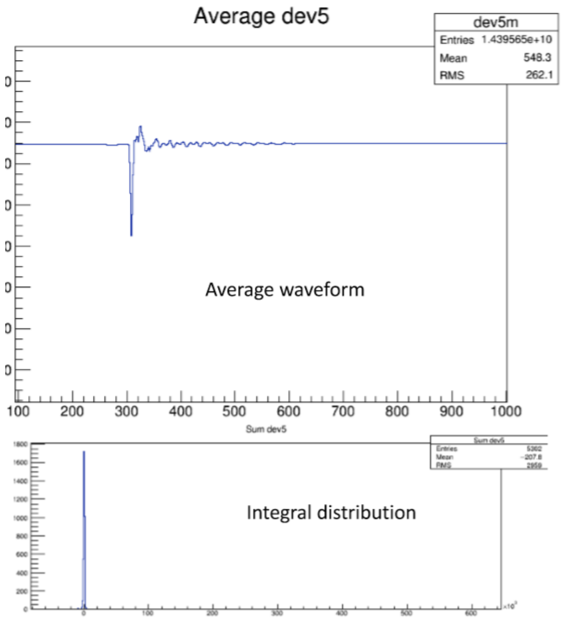
but

1. Power-laws do not fully describe GAGG:Ce afterglow emission
2. Power-laws are analytically bad-tempered while we need an analytical model

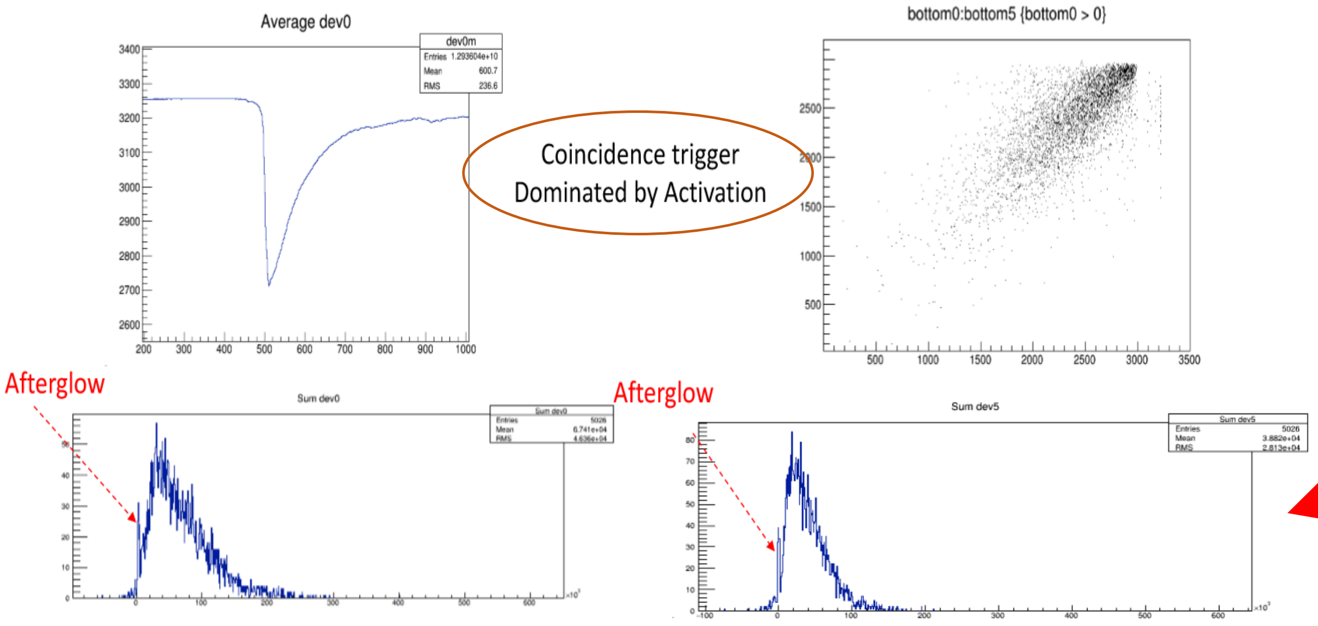
Why? Remember at Trento we worked with protons fluences much larger than we expect over typical orbital period.

A couple facts preliminary to data analysis

1. We expect most of the afterglow to be emitted after SAA passage.
2. Min irradiation fluence > 10^2 times expected fluence from SAA passage.
3. Beside afterglow, irradiation results in activation of the crystal sample.



From ‘clean’ afterglow acquisition



From waveforms acquired after irradiation of JP#1 (no beam!)

L’intensità di fascio puo variare da 1 a 320 nA, che corrisponde a flusso di protoni 70 MeV da 3.8E6 a 3.8E8 p/sec.
il beam spot è gaussiano con sigma dipendente da energia