Response linearity and natural background studies

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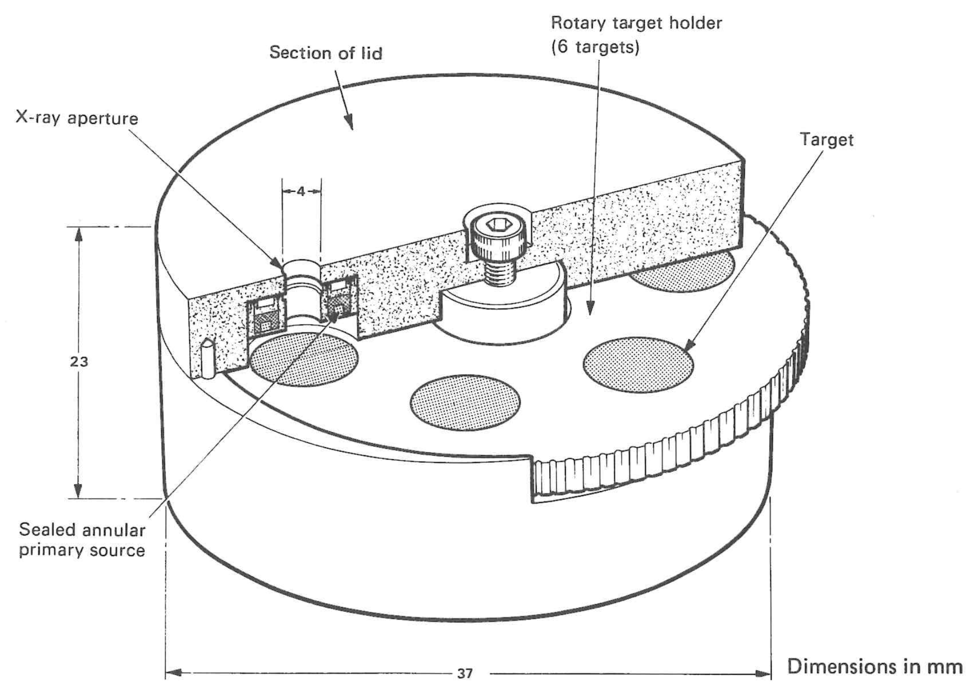
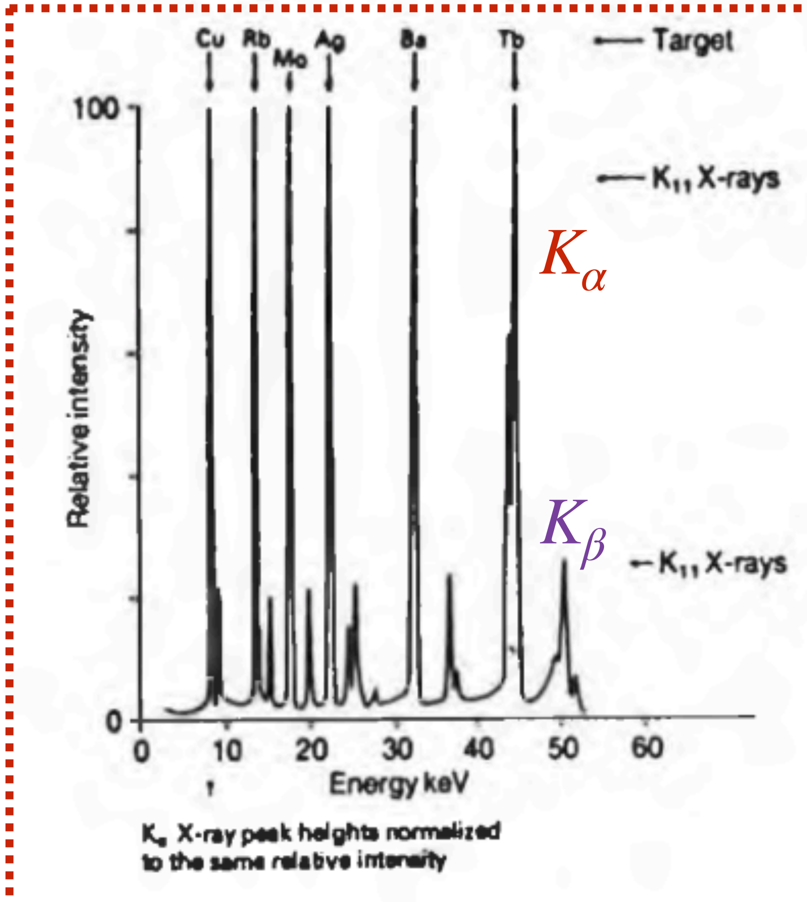
Episode 1:

Response linearity with LNF data

The variable X-ray source

- At LNF high statistics data taken with X-ray sources of different energies
  - Large dataset (40k events) acquired with Amersham ^{241}Am source impinging on different material targets which produces X-rays at different energies:





Material	Energy K_α [keV]	Energy K_β [keV]
Cu	8.04	8.91
Rb	13.37	14.97
Mo	17.44	19.63
Ag	22.10	24.99
Ba	32.06	36.55

Table 2. X-ray emitted by the multi-target source.

Each targets emits mainly 2 lines:

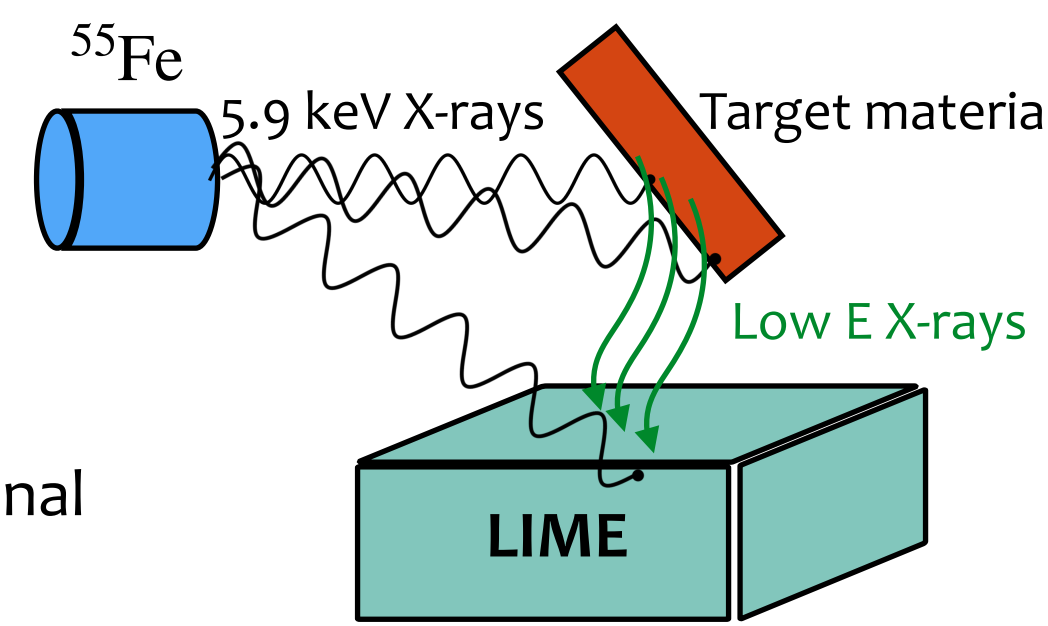
- K_α + ~20% at a slightly higher K_β
- The $\Delta E = E_{K_\beta - K_\alpha}$ increases with E.

  For lower E's cannot be resolved in CYGNO

The home-made sources

- In addition we have our **main candle from ^{55}Fe: E=5.9 keV (+ 6.5 keV 2nd line)**
- physics interest in low energy response of CYGNO (E<6 keV):
  - ⇒we can use ^{55}Fe source to induce X-rays emissions from targets with $K_{\alpha,\beta} < 5.9\,\mathrm{keV}$
- Not an easy task:
  - X-rays yield lowers a lot when lowering energy. Eg: LY(8keV) ≈ 3% LY(46 keV)
  - Absorption by the LIME PMMA window increases at lower energies
- ⇒ a lot of data taken with Ti and Ca to be able to see something

Material	Energy K_α [keV]	Energy K_β [keV]
Ti	4.51	4.93
Ca	3.69	4.01



N.B. Even in "reflection mode", something of the original 5.9 keV X-rays arrives to LIME

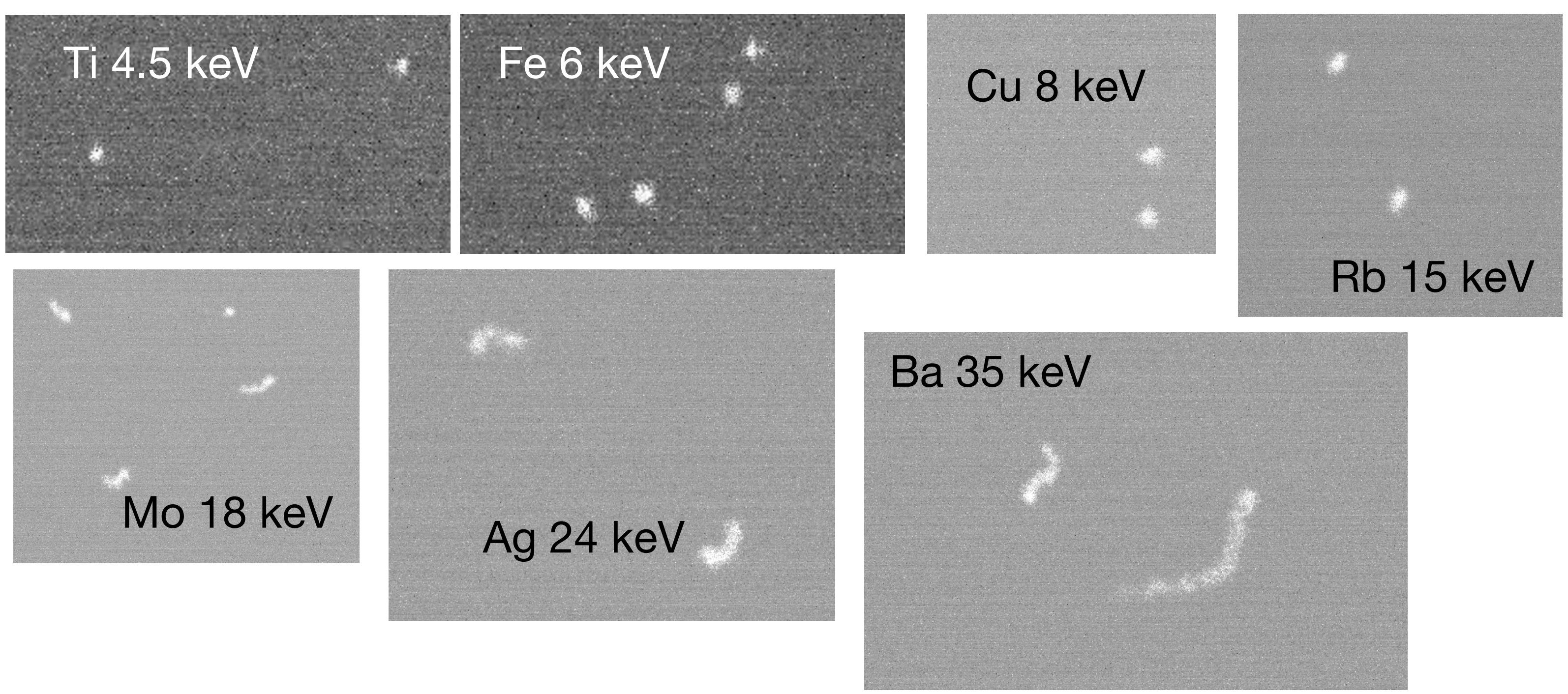
Data taking

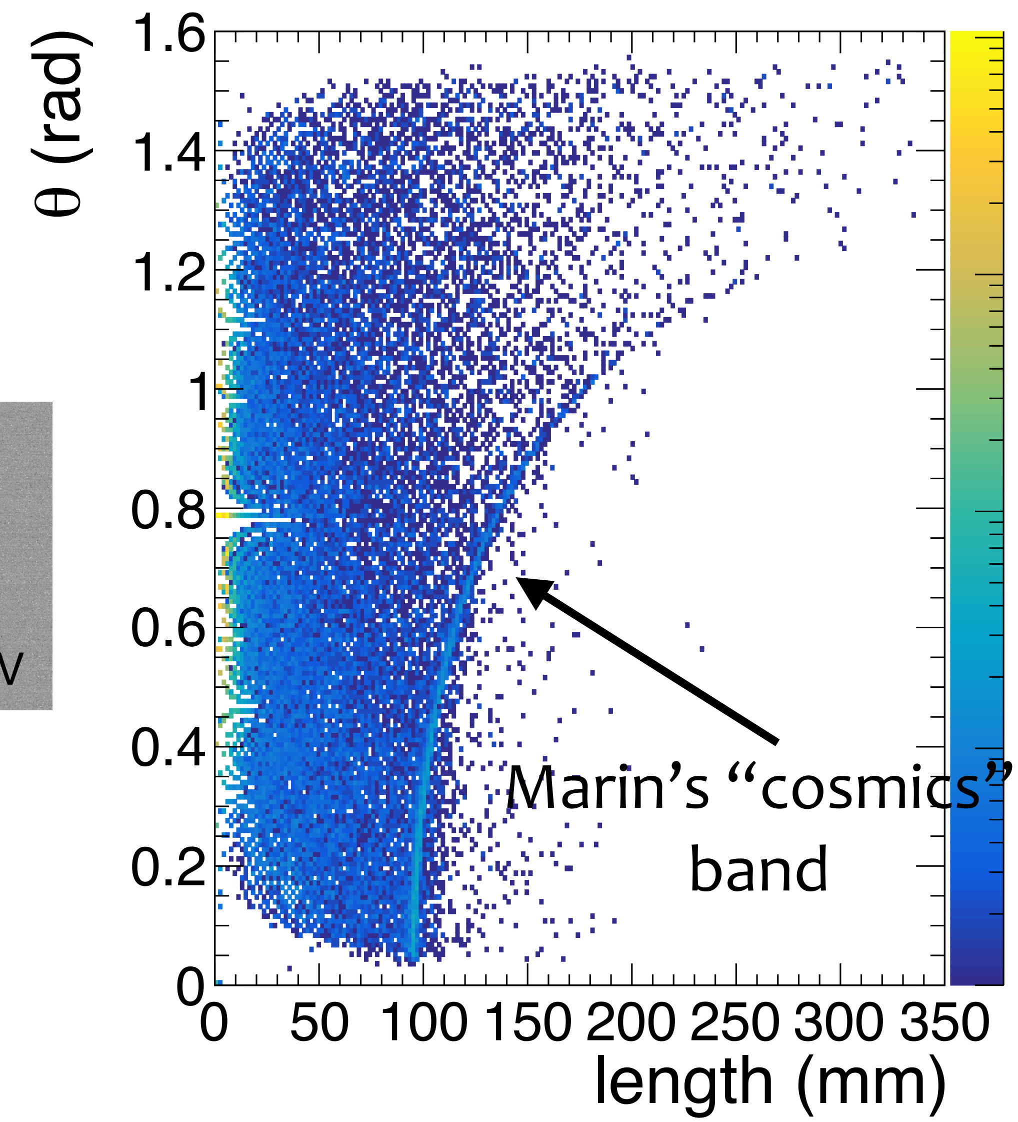
- These are the golden datasets collected in Frascati for the energy calibration

Numbers	Description	PMT
5790-5860	Multi-source High Statistics	No
5861-5911	55Fe: BKG and High Statistics + Water Cooling	No
6121-6141	Titanium + BKG High Statistics	Yes
6143-6290	Calcium + Pedestal Very High Statistics	Yes

Cluster selection

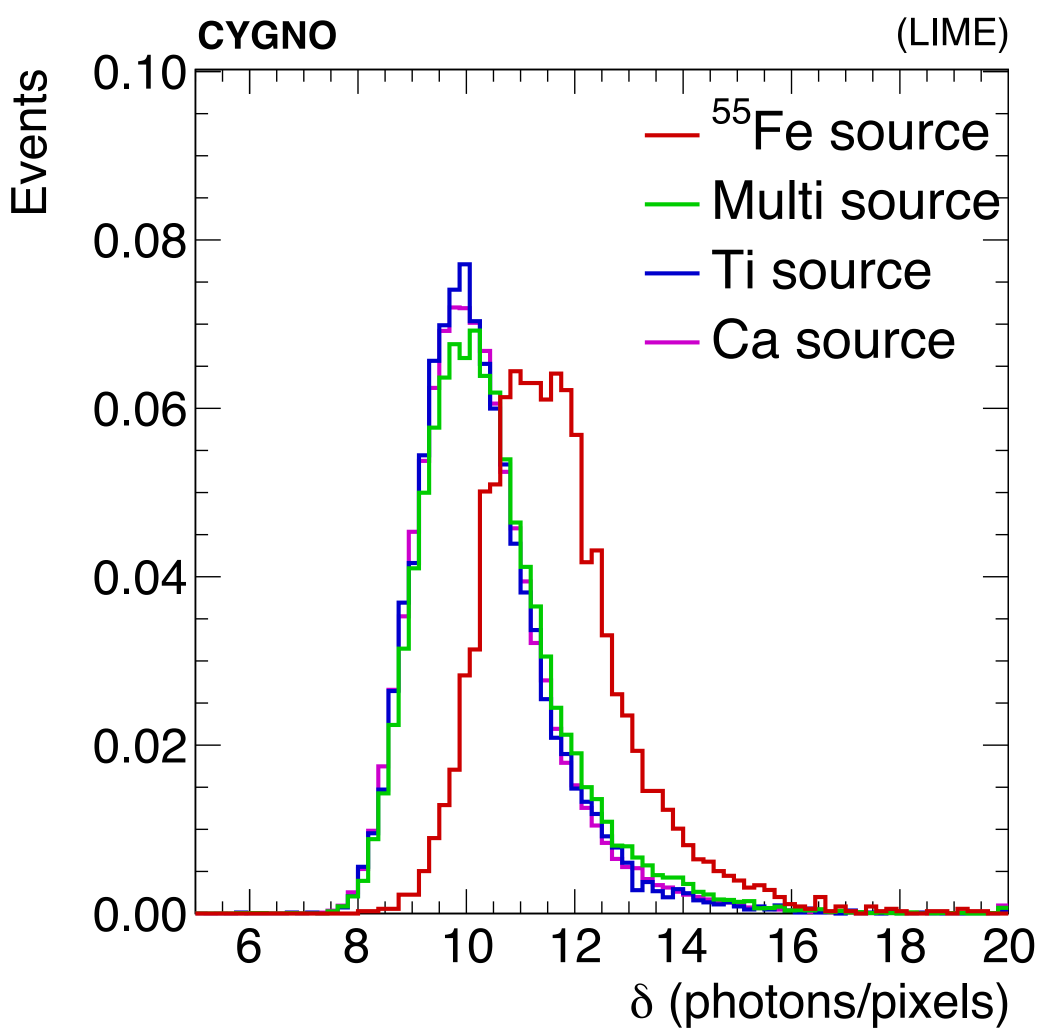
- Clusters are selected to reject very long tracks
  - A useful selection is on the long tracks which saturate the camera exposure window in one direction: correlation among the track-angle and width (D. Marin's presentation on 16 June 2022)
  - RMS of the pixel light yield cluster > 7 to reject more fake clusters (lowered to 6.5 for Ca,Ti in order to not shape too much the background close to a low-E signal)





Run-by-run inter calibrations (ICs)

- Absolute energy calibration with our cleanest candle: high rate ^{55}Fe source
  - At LNF, z = 26cm, standard HV: peak at 8350 ± 10 counts ≡ 5.9 keV
- Conditions (P,T,HV) can move from one data taking to another: to compare multiple runs we need to have something common to all the runs to inter-calibrate them
  - can use the long tracks (at LNF cosmics + ambient radioactivity, at LNGS only the latter): e.g. **the average dE/dx**, energy density $\delta = N_\gamma / N_{pix}$, etc.



Eg. For LNF runs discovered that

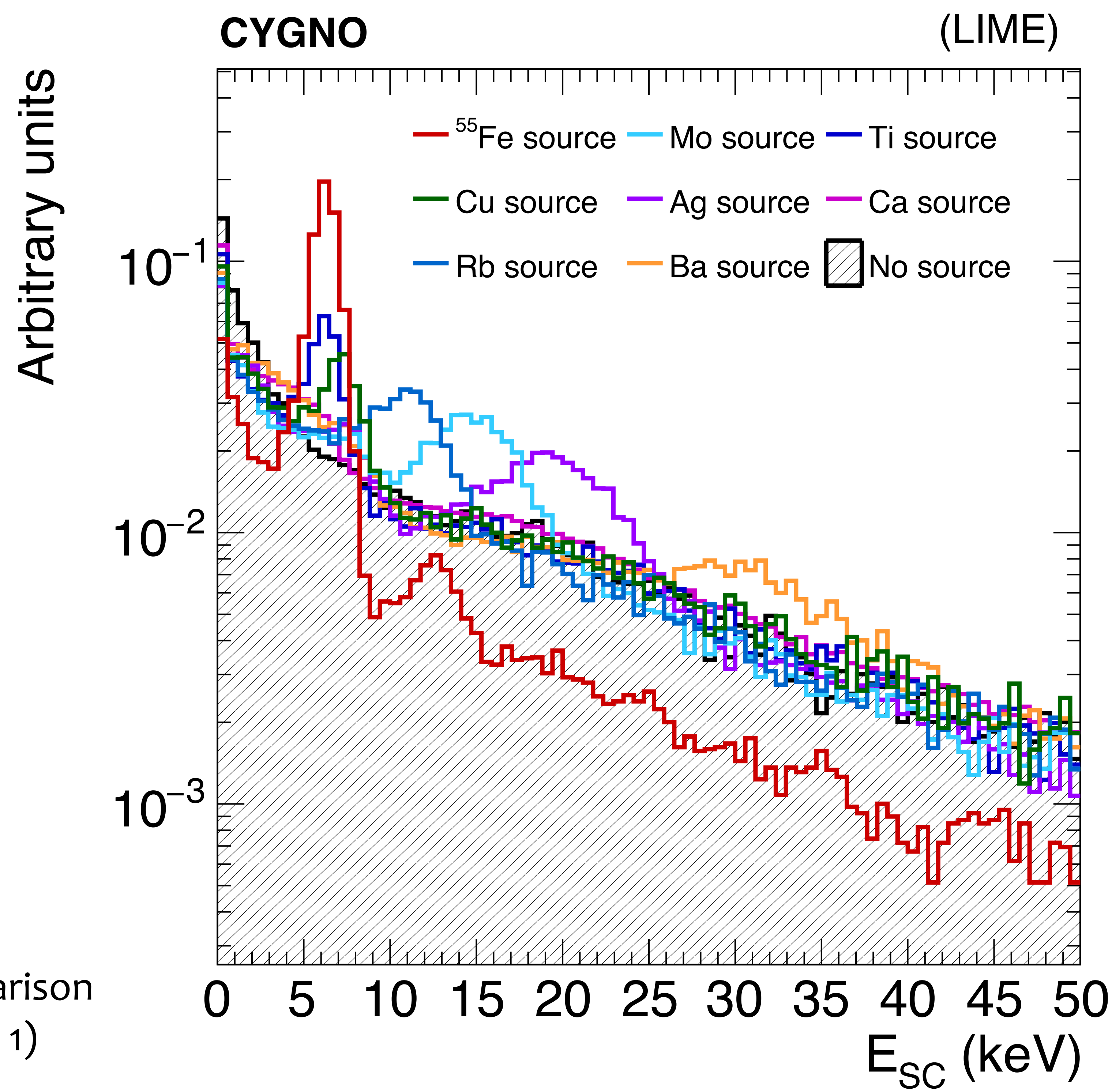
$\mathrm{LY_{Fe}} \approx 1.2 \times \mathrm{LY_{MS,Ti,Ca}}$

- In this particular case we don't know the origin

In general, it is a useful check that we should do routinely

The spectra

- A glimpse to all data together: we can see the contributions of all the source by eye.
  - Except Ti whose line is very close to ^{55}Fe one and has to be taken with caution



Shape-only comparison (normalised to 1)

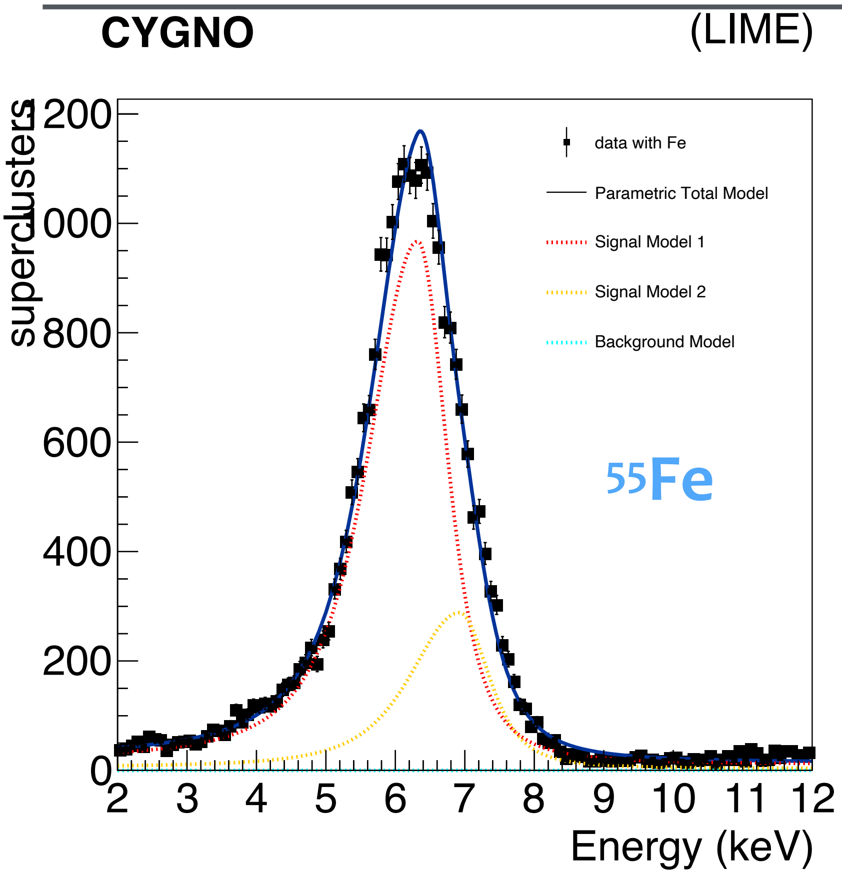
Energy spectrum fits

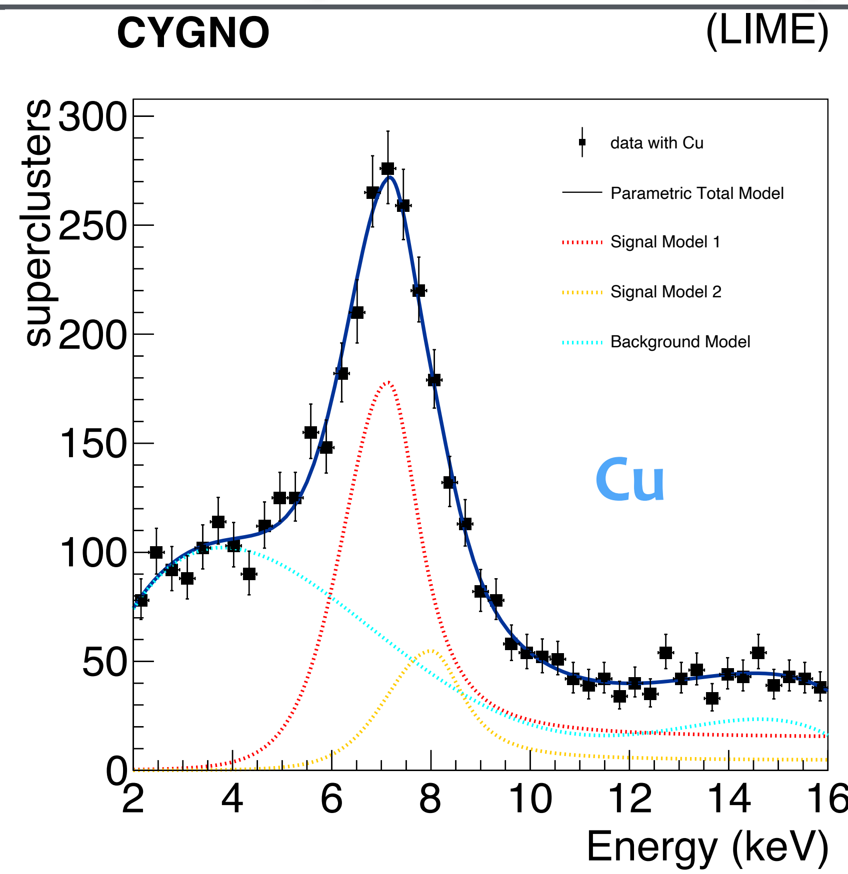
- Each signal line modeled with a **Cruijff function** (a Gaussian with different left-right resolutions and non-Gaussian tails):

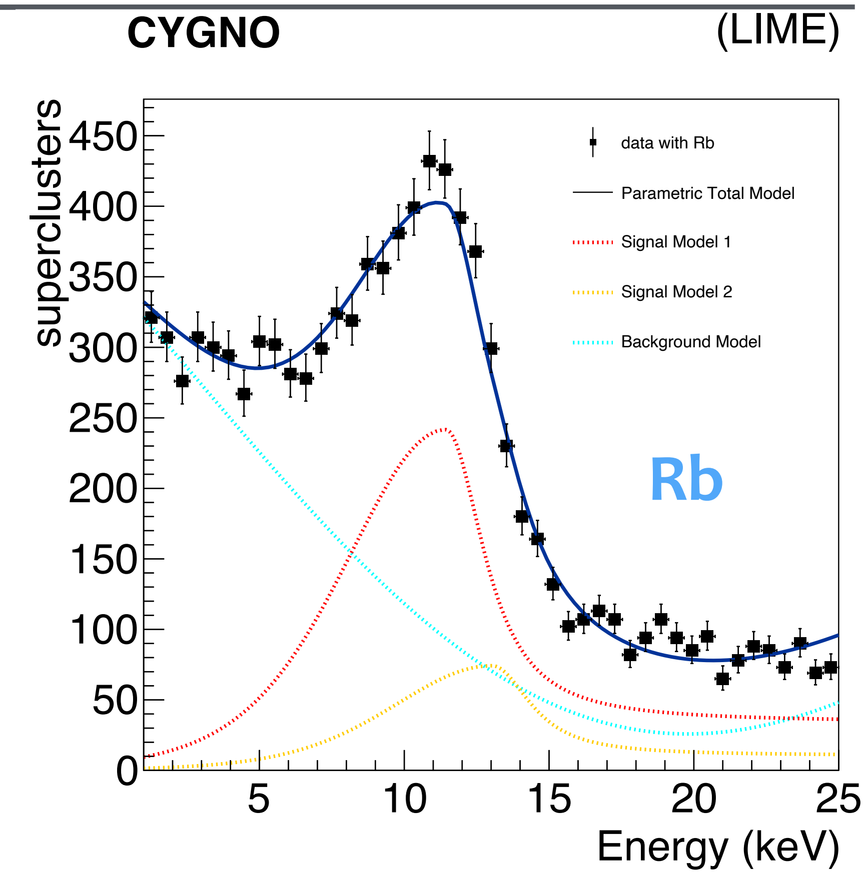
$$f(x) = \exp\left(\frac{(x-m)^2}{2\sigma_{L,R}^2 + \alpha_{L,R}(x-m)^2}\right)$$

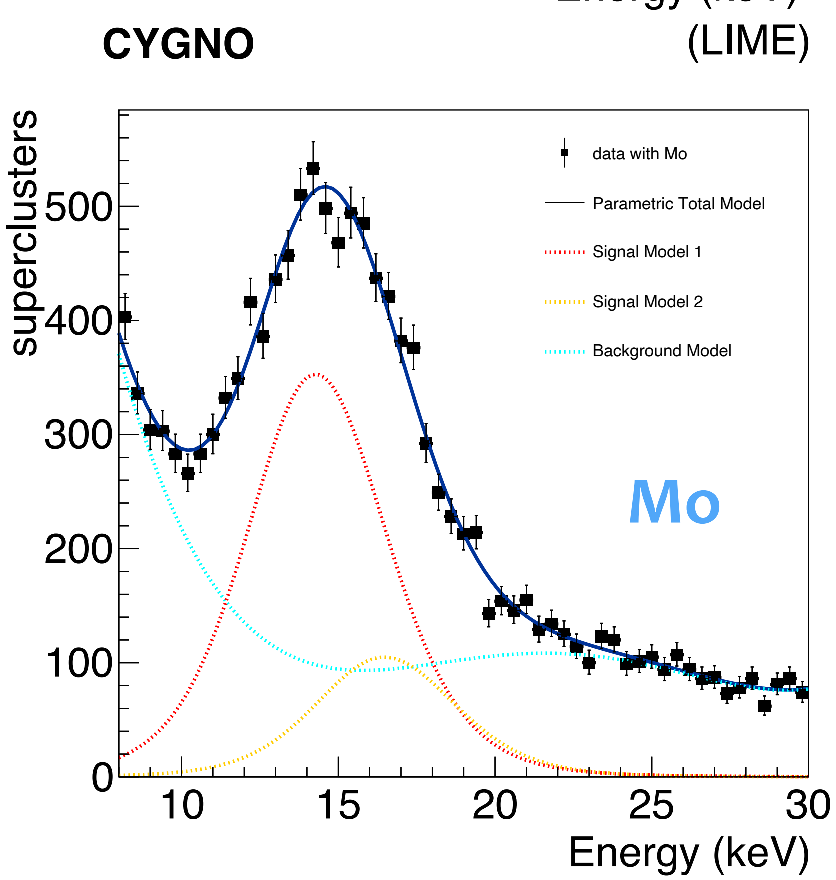
- Each signal model has **2 lines (K_α, K_β)**, with:
  - $\Delta E(K_\alpha, K_\beta)$ fixed to the expected values (i.e. in the fit $m_{K_\beta} \equiv m_{K_\alpha} + \Delta E$)
  - Relative fraction of the two yields free to float in [0-30%] (expected ~20% at emission)
  - Freely floating shape parameters, but the 2 shapes are forced to be the same (neglect $\sigma_{K_\alpha} \neq \sigma_{K_\beta}$)
- Exception for Ca and Ti, where **4 lines expected**, i.e. 2 additional ones from ^{55}Fe X-rays
- Background modelled with a Bernstein polynomial of order n (n up to 5), with parameters fixed to values obtained on no-source data

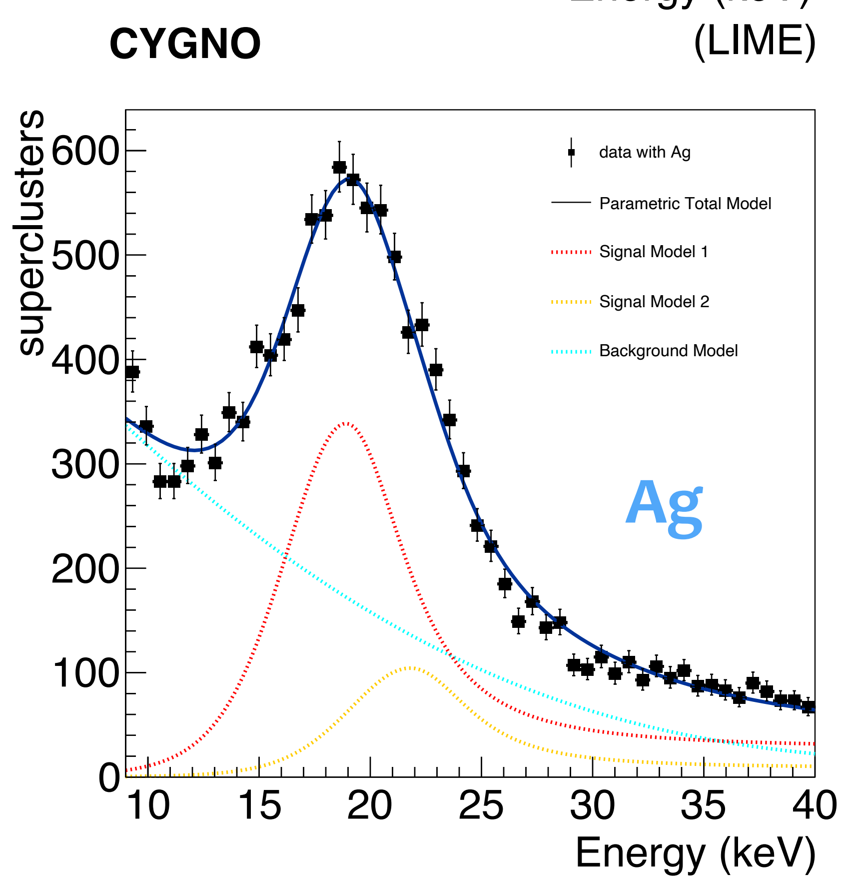
Fits to higher energies

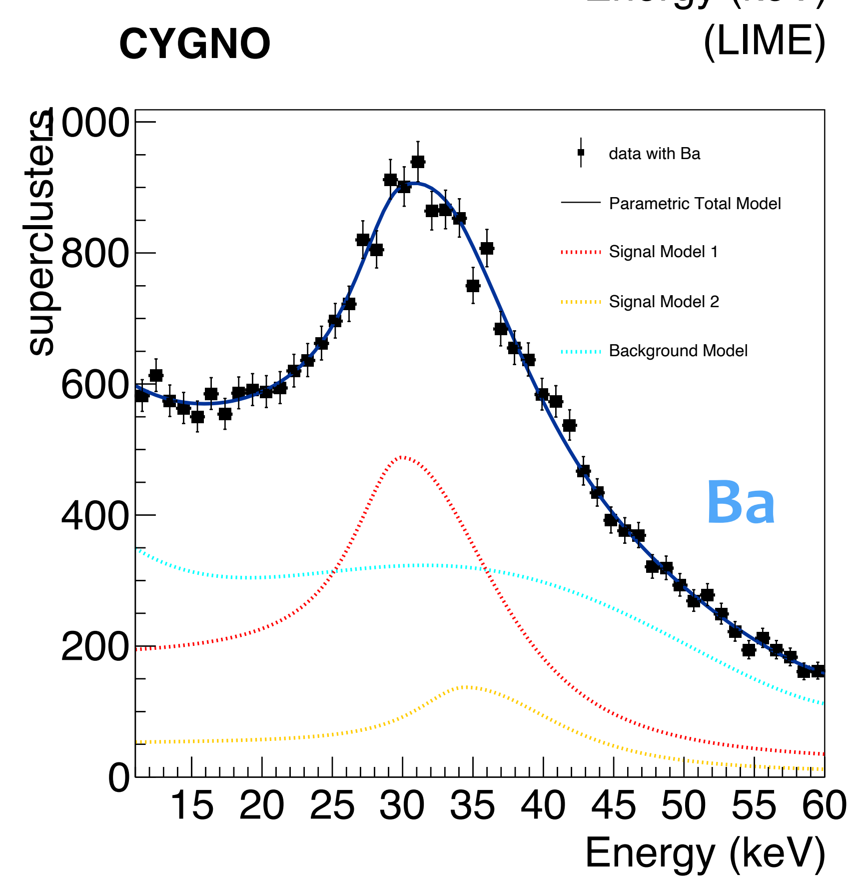






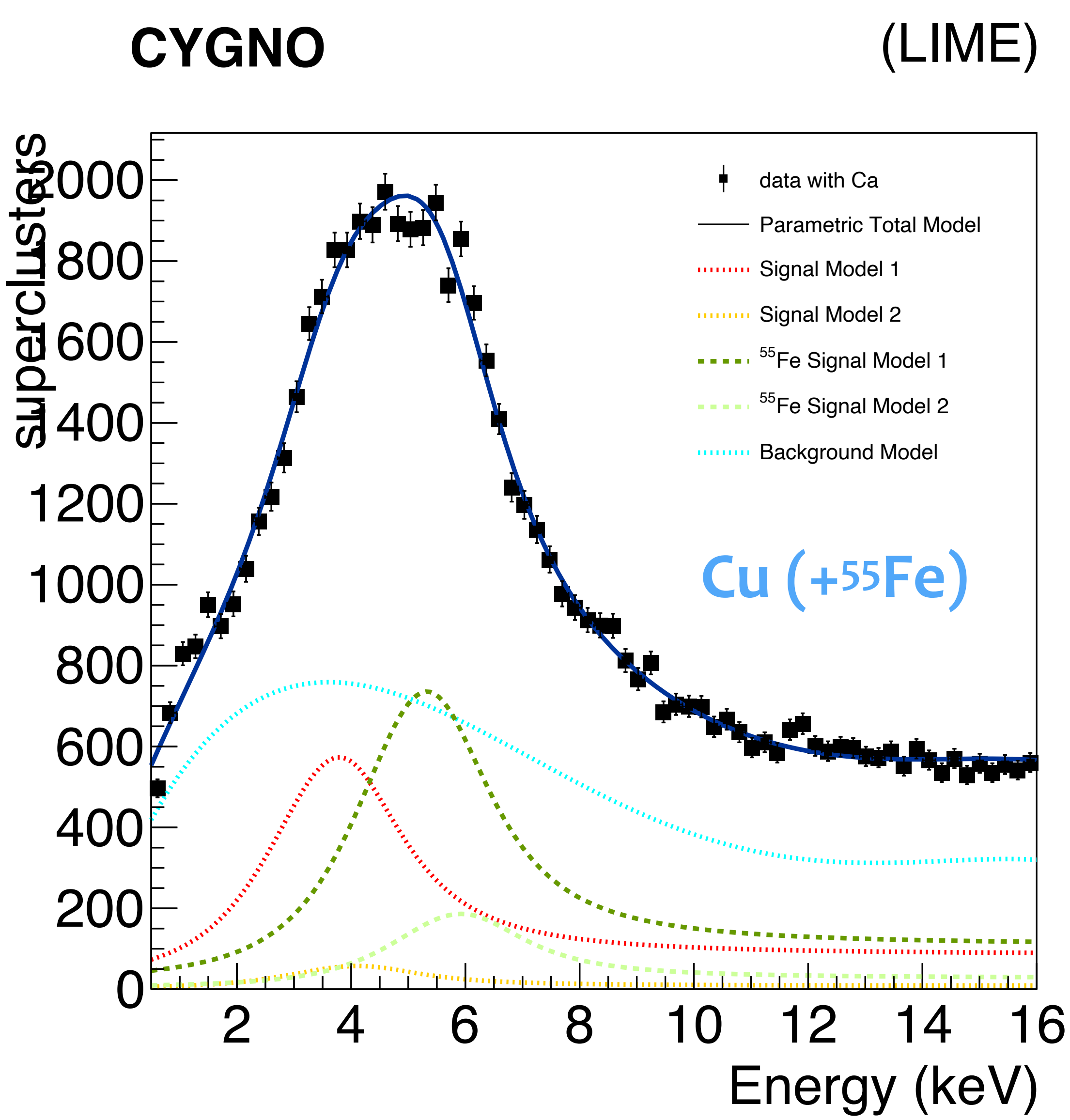


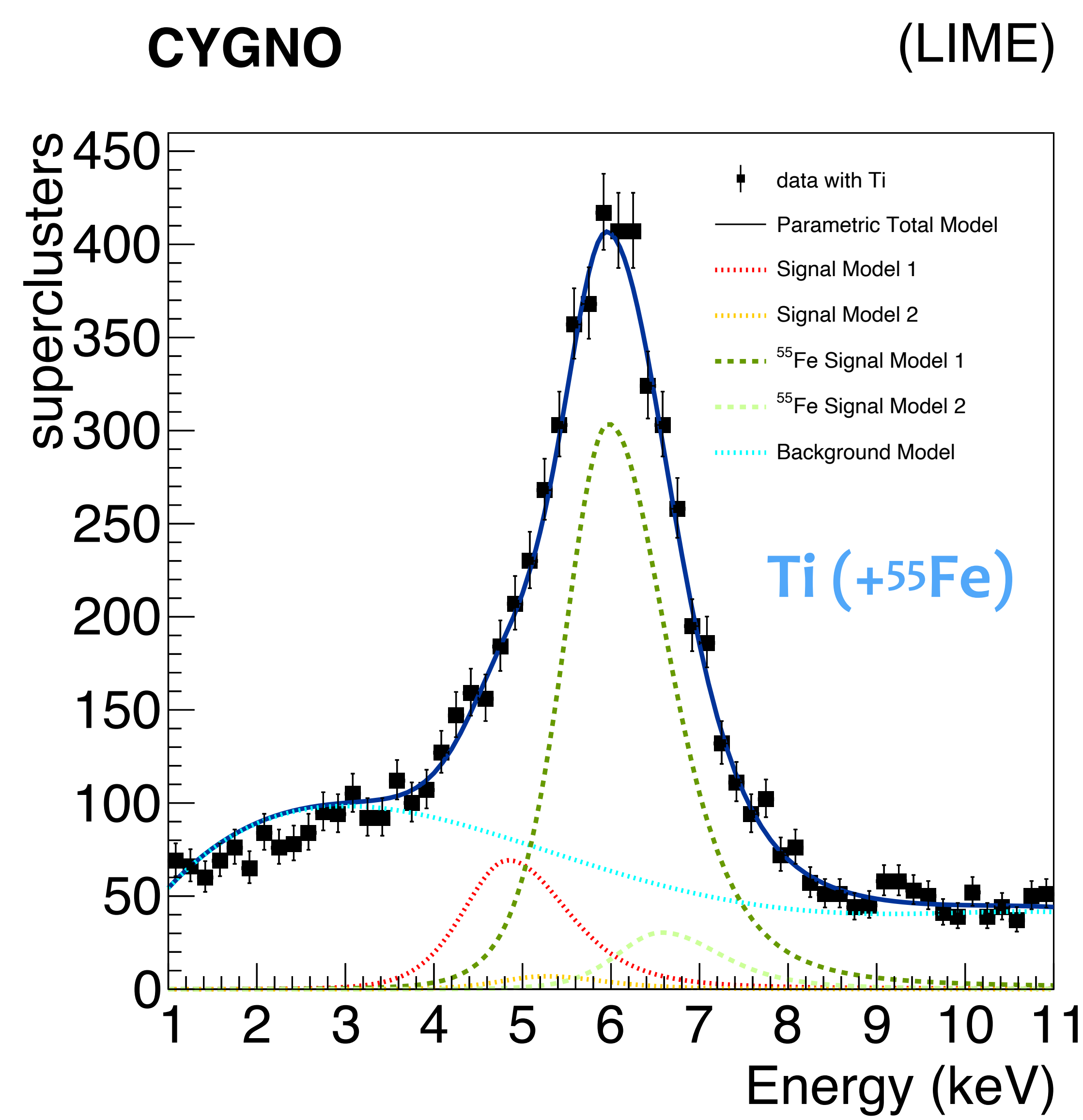




Fits to lower energy X-rays

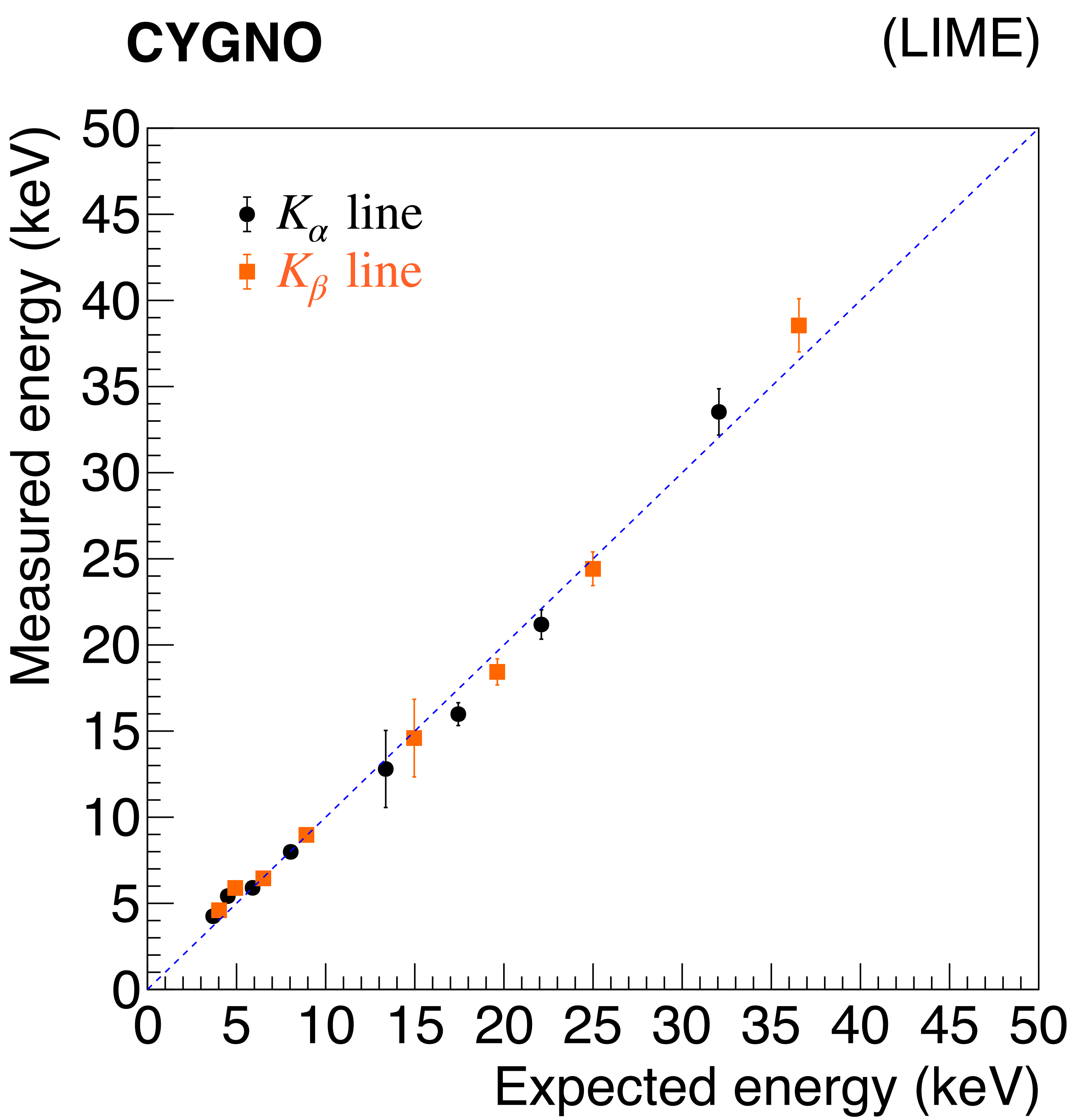
- Calcium: not including the ^{55}Fe component would lead to absurdly high resolution. Including it becomes reasonable and the fit is OK
- Titanium: the Ti component is much smaller than the very close ^{55}Fe: the fit should be taken with some caution (i.e. the main uncertainty is not the stat one)





Results on linearity

- From the z-scan, the LY changes of about $\Delta E / \Delta z \approx 2\,\% / \mathrm{cm}$. Included the uncertainty on the z position of $\pm 1 \mathrm{cm}$.

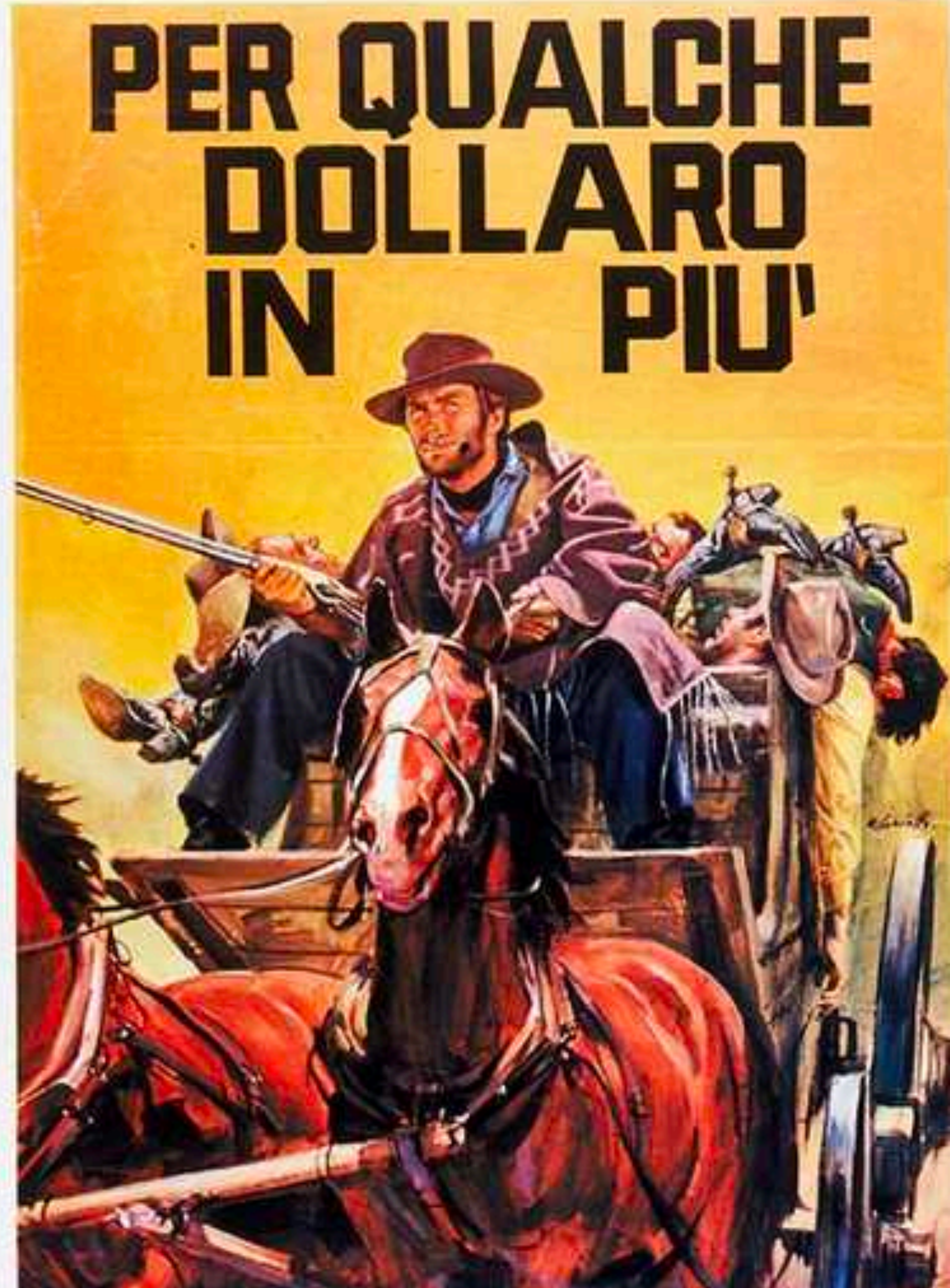


Points for both K_{α} (1st) and K_{β} (2nd) line shown in the plot:

- The two are not independent, since for each fit $\Delta E(K_{\alpha}, K_{\beta})$ is fixed to the expectation
- Still, both contribute to the fit of a unique scale parameter

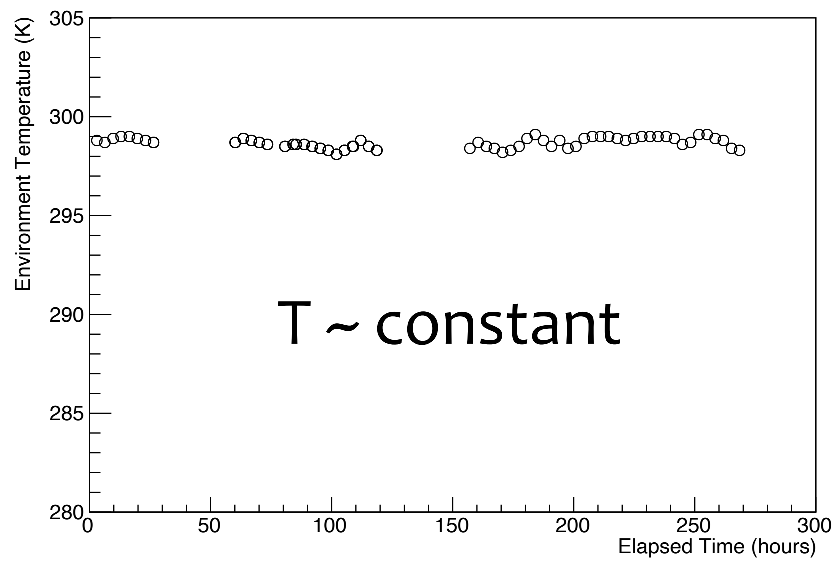
Episode 2:

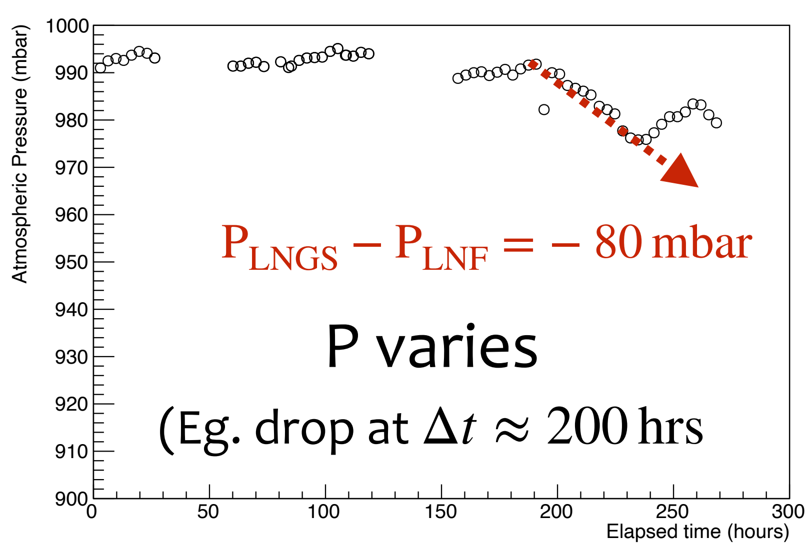
From LNF to LNGS

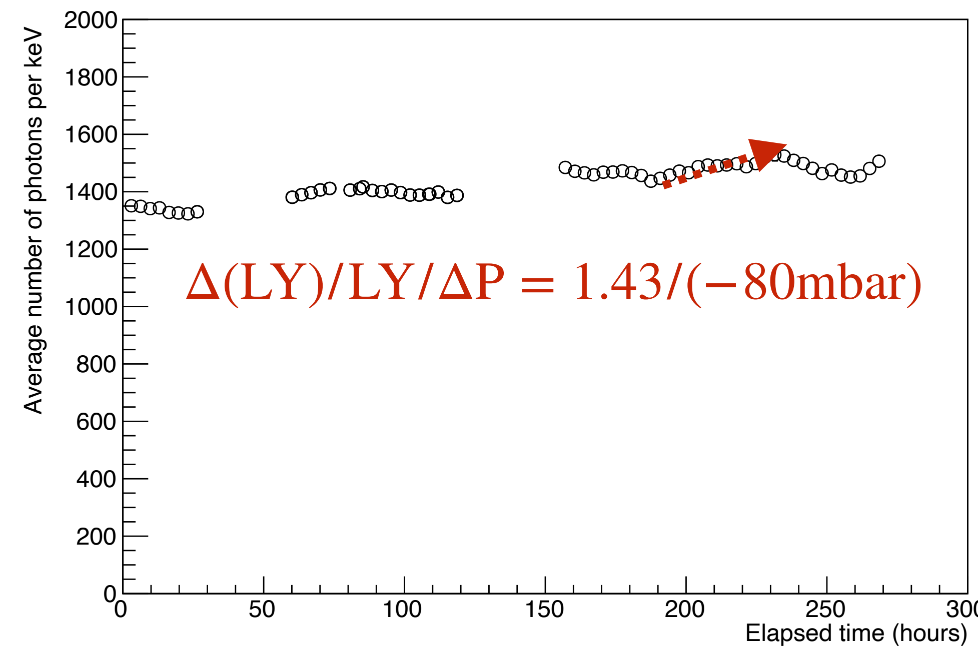


Gain vs gas density

- Long term stability measurements show the dependency of the light yield in response to 5.9 X-rays to gas conditions.
  - In particular the gain G = G(ρ) = G(P/T $\propto \alpha_{\mathrm{Townsend}}$)







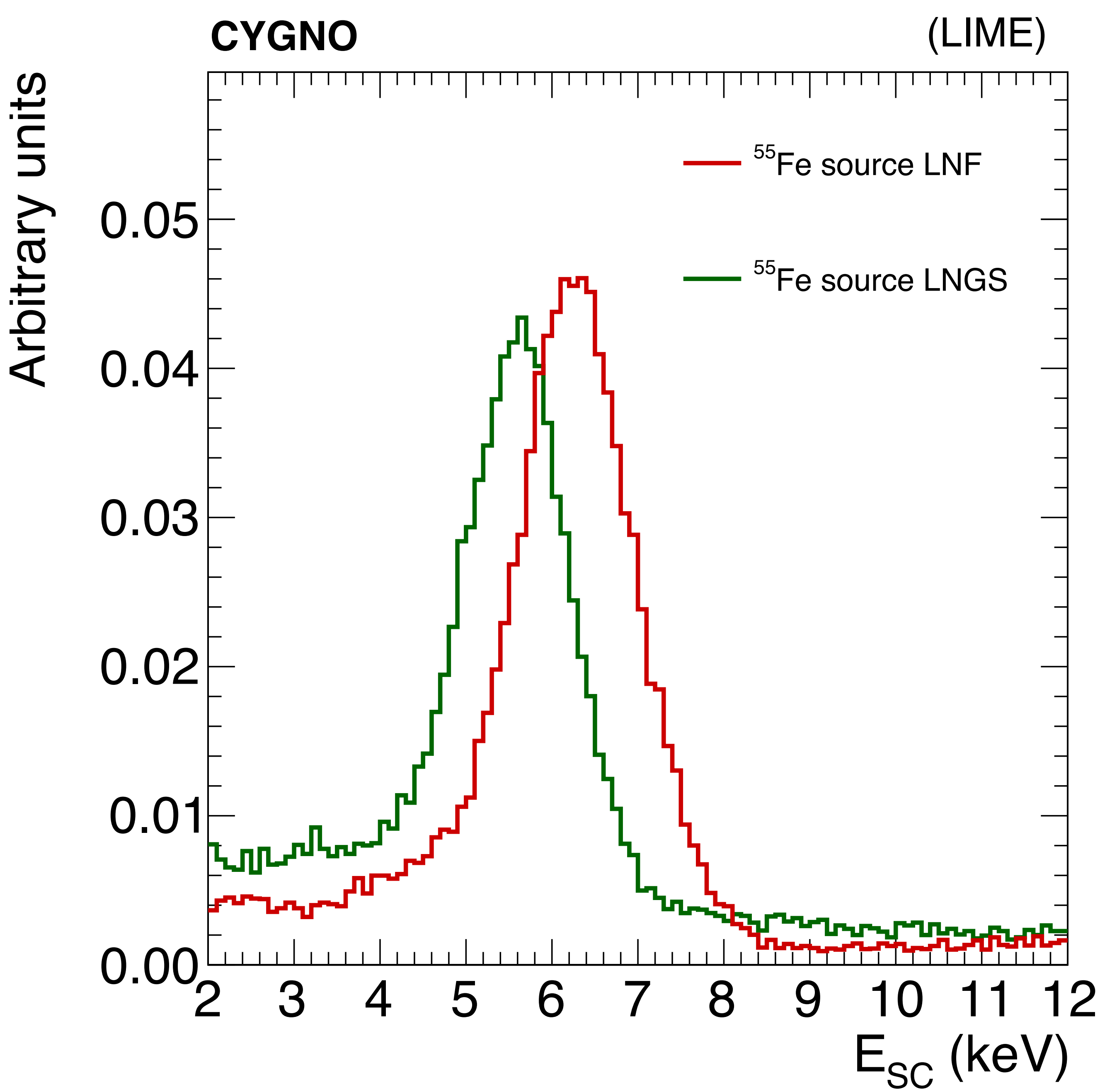
So:

- Light yield increases for lower pressure:
  $\Rightarrow LY_{LNGS}/LY_{LNF} = 143\,\%$
- Electron Gain for Lower GEM HV ($\Delta V = -20V \times 3$):
  $\Rightarrow G_{LNGS}/G_{LNF} = 64\,\%$ (D. Pinci, G. Mazzitelli, X-ray gun)

Expect final LNGS/LNF light yield ratio ~ 90%

LY LNGS / LNF comparison

- LNGS: runs 5694 - 5730



Gaussian mean (LNGS) = 7420 ± 21

Gaussian mean (LNF) = 8350 ± 9

$$\frac{LY_{LNGS}}{LY_{LNF}} \approx 89\,\%$$

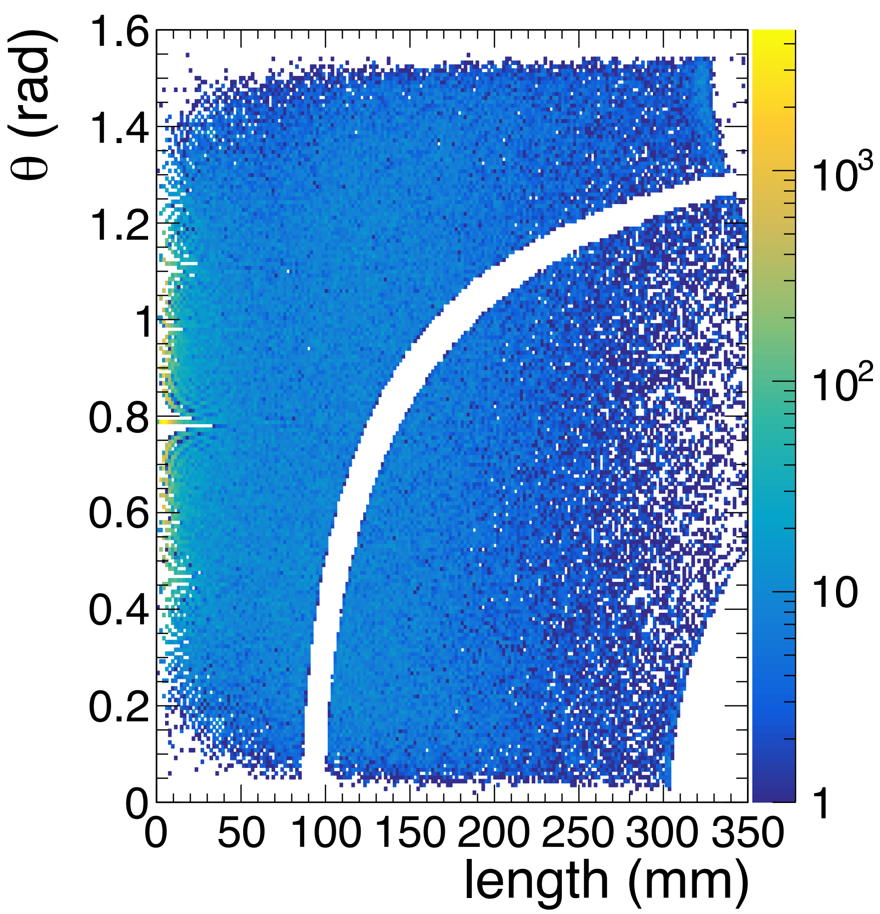
confirms the expectations

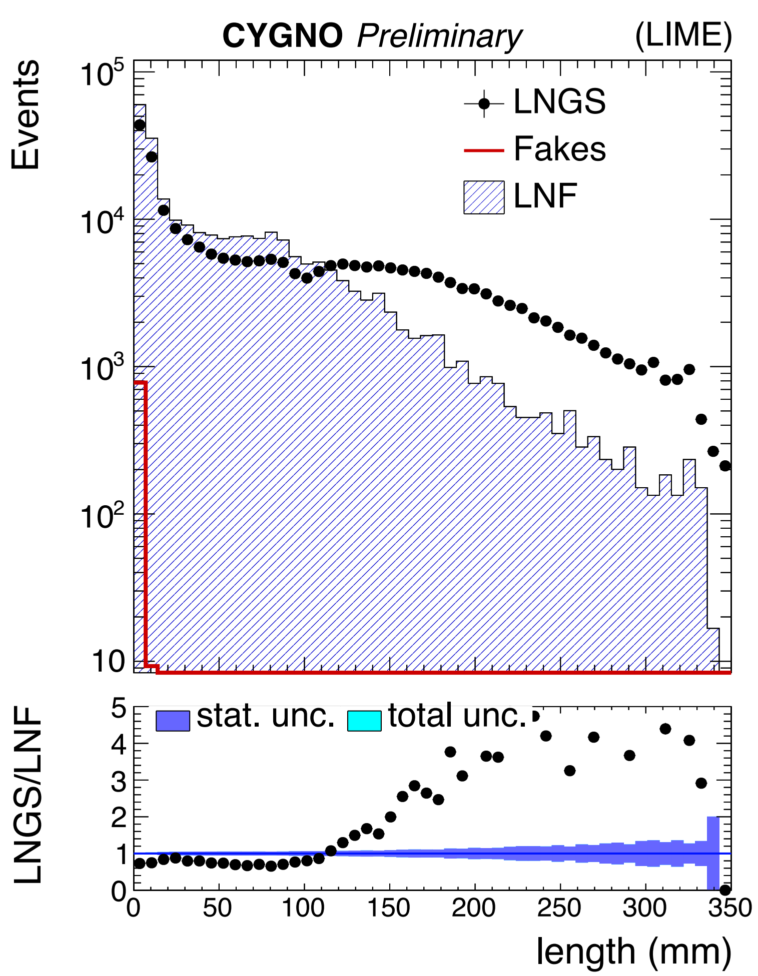
Episode 3:

Background studies at LNGS

Bagkround: LNF vs LNGS

- Reconstructed few no-source runs at LNF with exactly the same code / thresholds as for LNGS to compare the two datasets
  - a full re-reco of LNF with “autumn22” is not useful, since the occupancy of LNF>>LNGS makes the “winter22” version better for LNF
- LNF and LNGS data taking have two main differences:
  - Overground the cosmic component is much larger - apply D. Marin selection to both
  - Different exposure: 50 (=140 real) ms (LNF) vs 300 (=390 real) ms. The latter mitigates the cutting of long tracks because of the global exposure time saturation limit a lot => length comparison not really fair

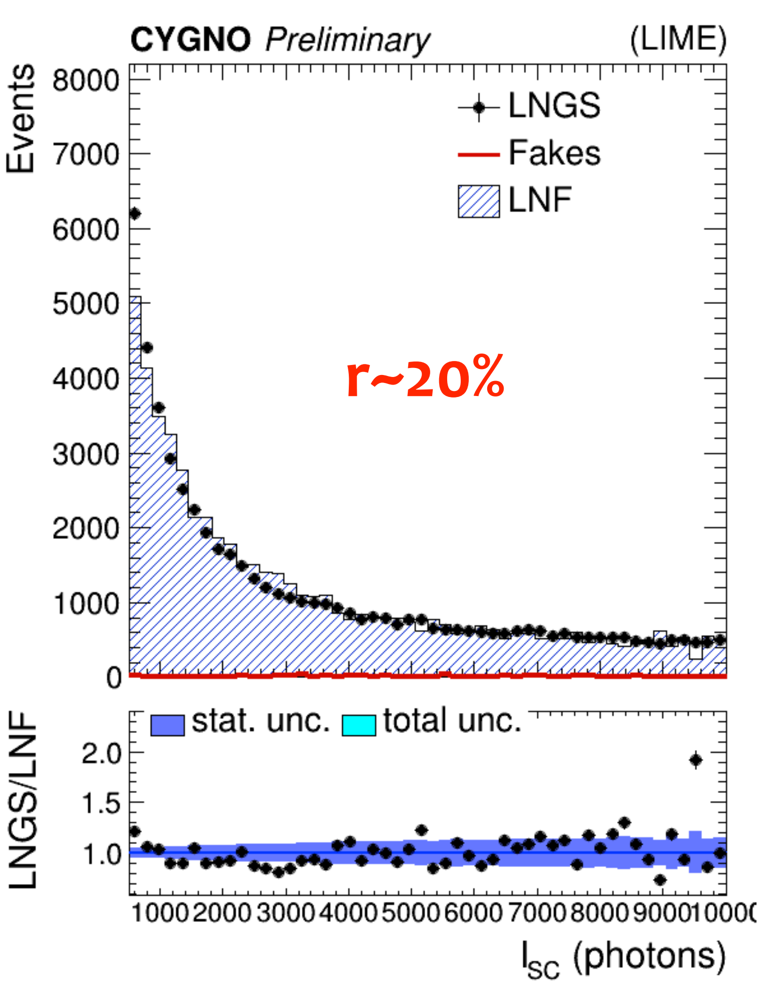




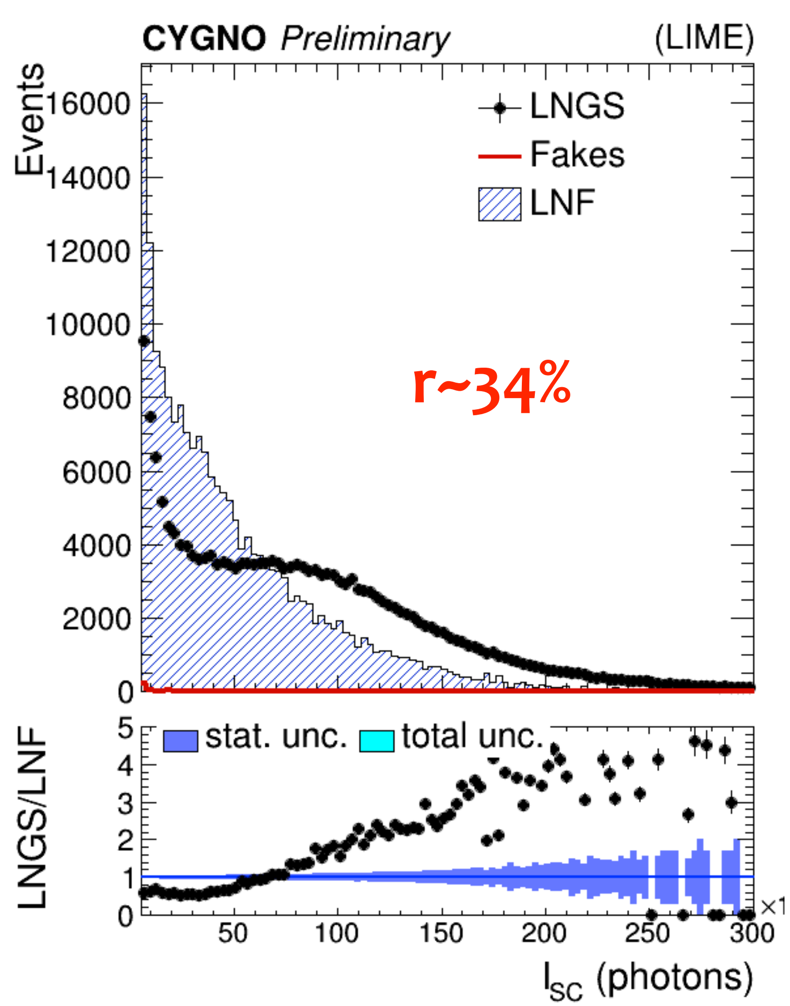
Uncalibrated energy spectra

- Components normalization:
  - LNGS: number of reconstructed clusters
  - Fakes: clusters reconstructed on pedestal runs, normalized to LNGS livetime (1% for $E \lesssim 6$ keV)
  - LNF: clusters reconstructed with exactly the same LNGS reco, few runs (5862-5867), normalized to LNGS livetime
    - Further normalization to fit LNGS rate, with no on energy selection : **r=NGS / LNF = 31%**

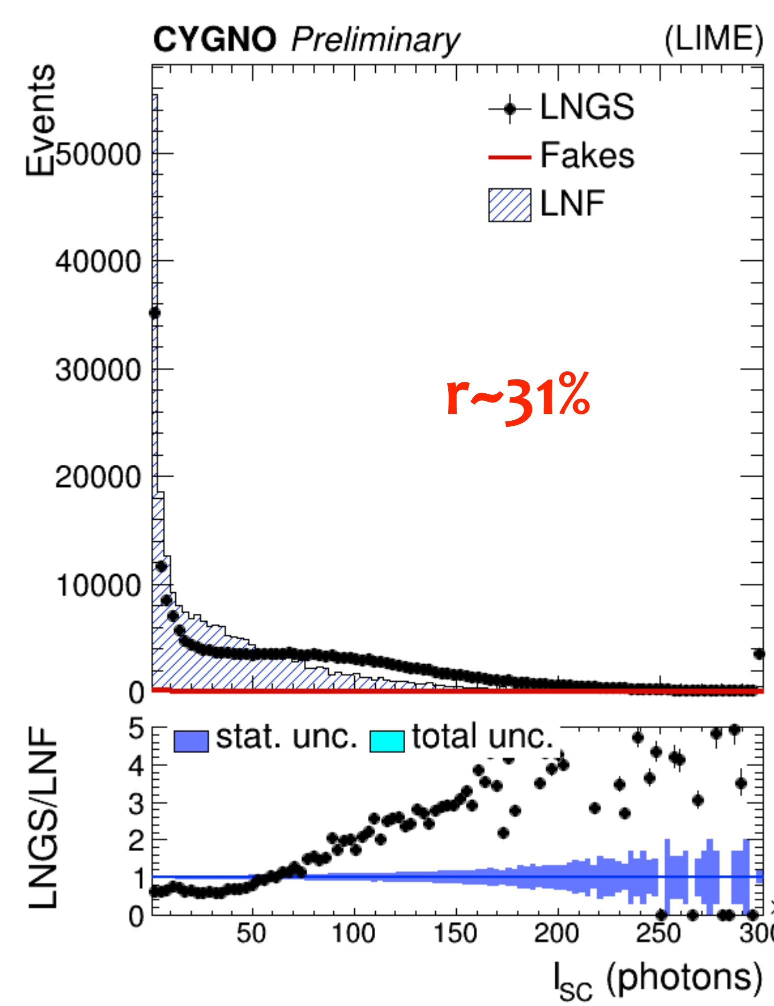
$0.3 \lesssim E \lesssim 6$ keV



$6 \lesssim E \lesssim 200$ keV

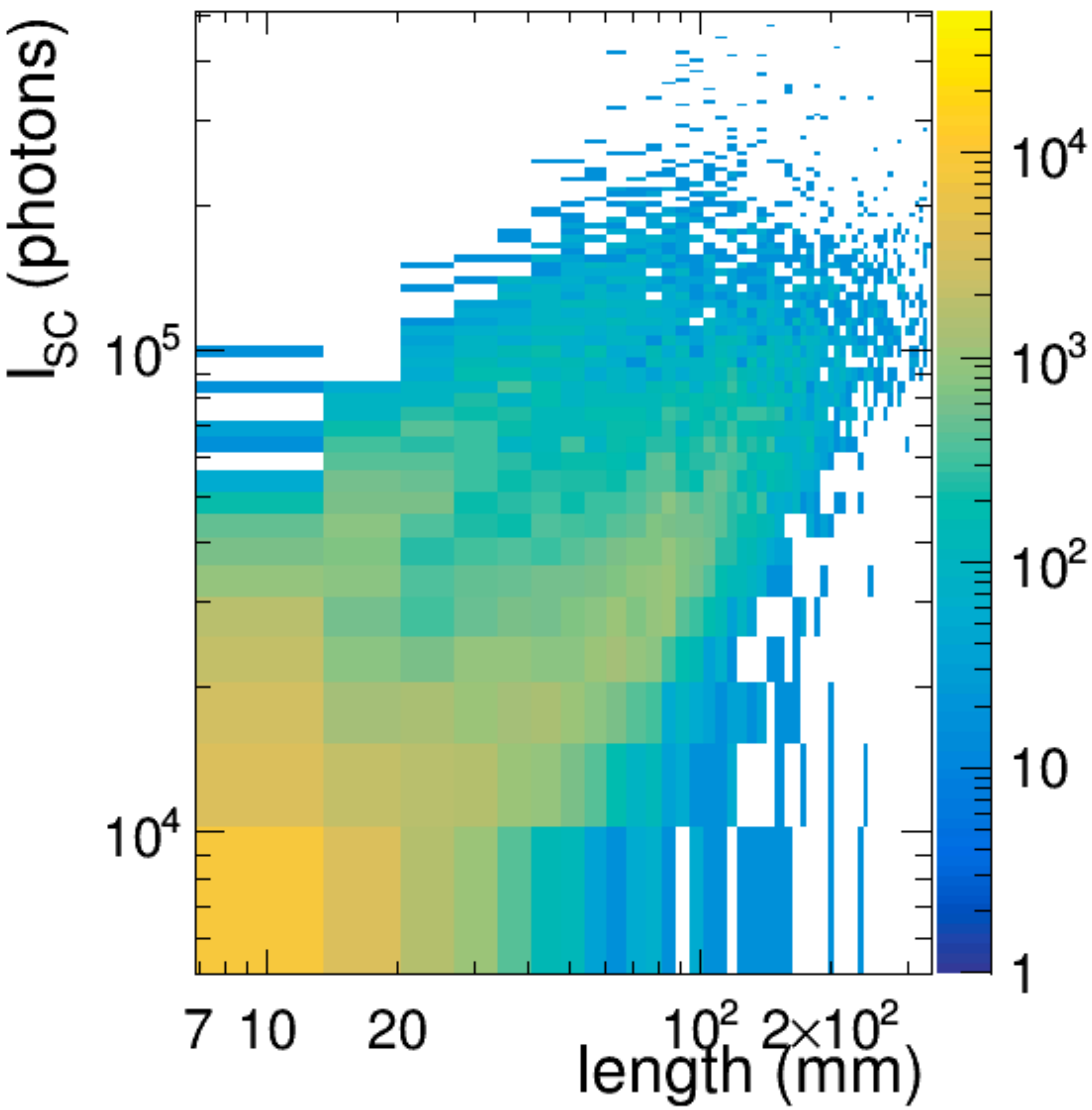


$0.3 \lesssim E \lesssim 200$ keV

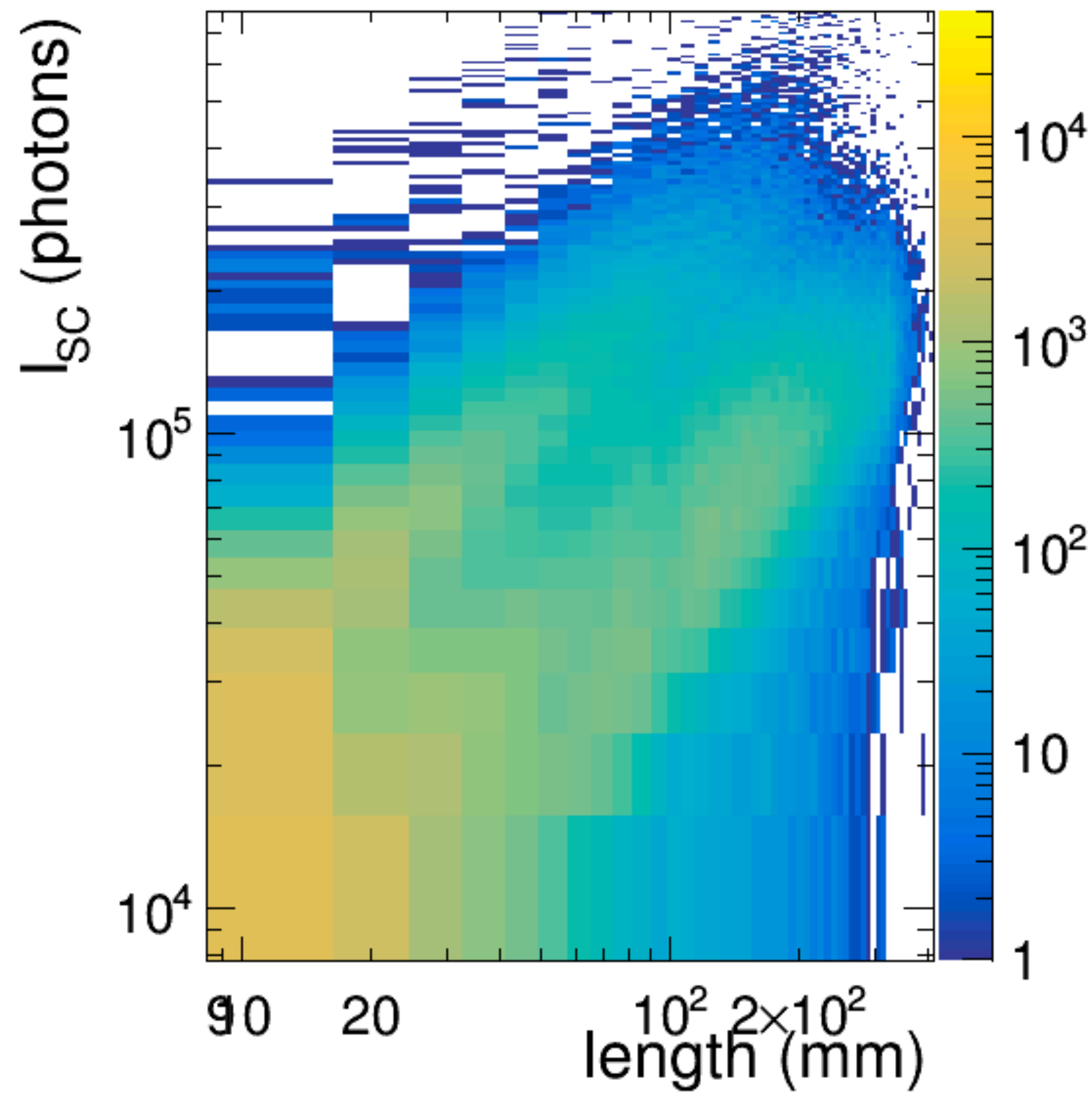


Energy vs length

- Two components of clusters with E proportional to length, with different coefficients (same for LNGS and LNF)



LNF



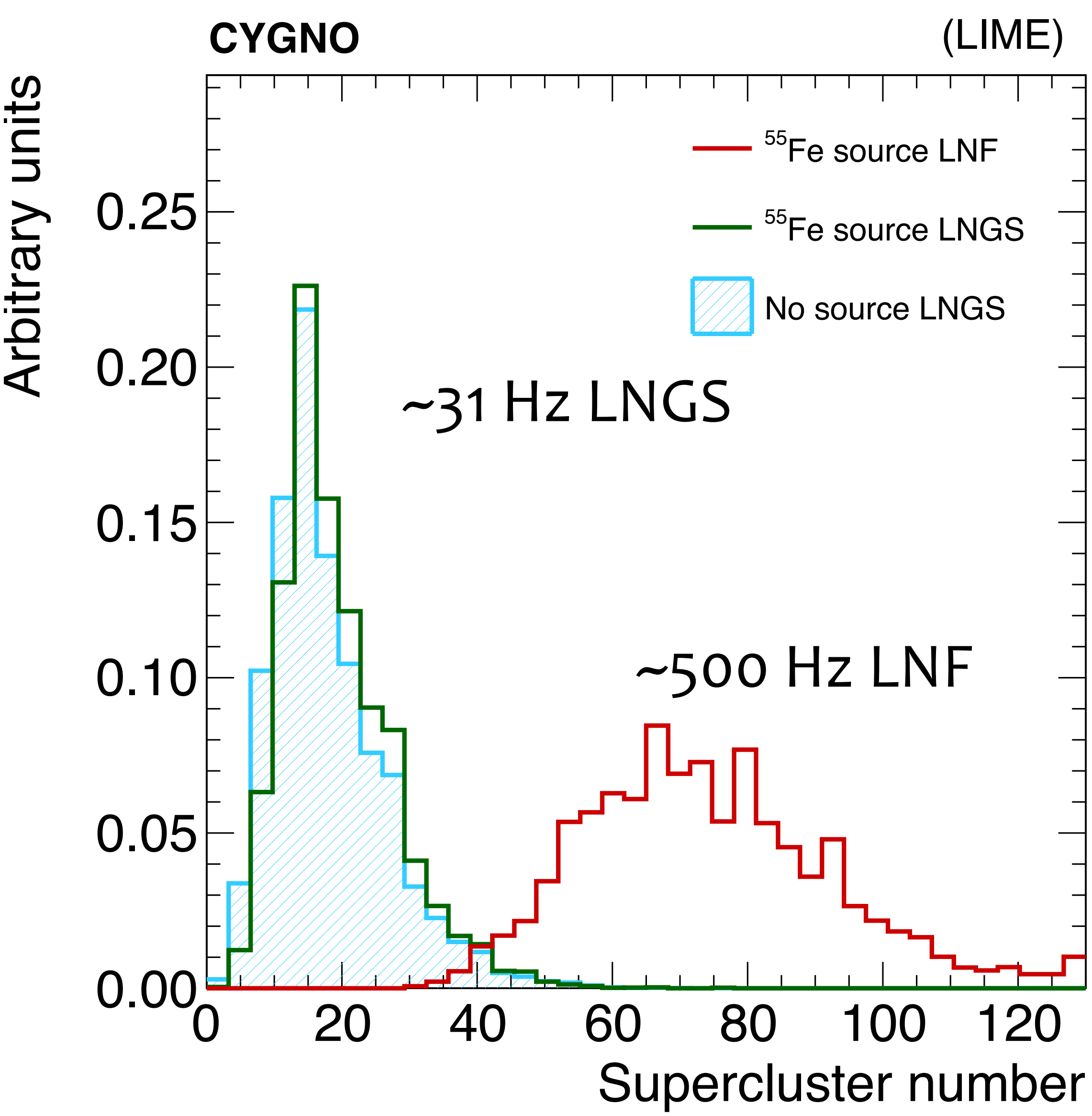
LNGS

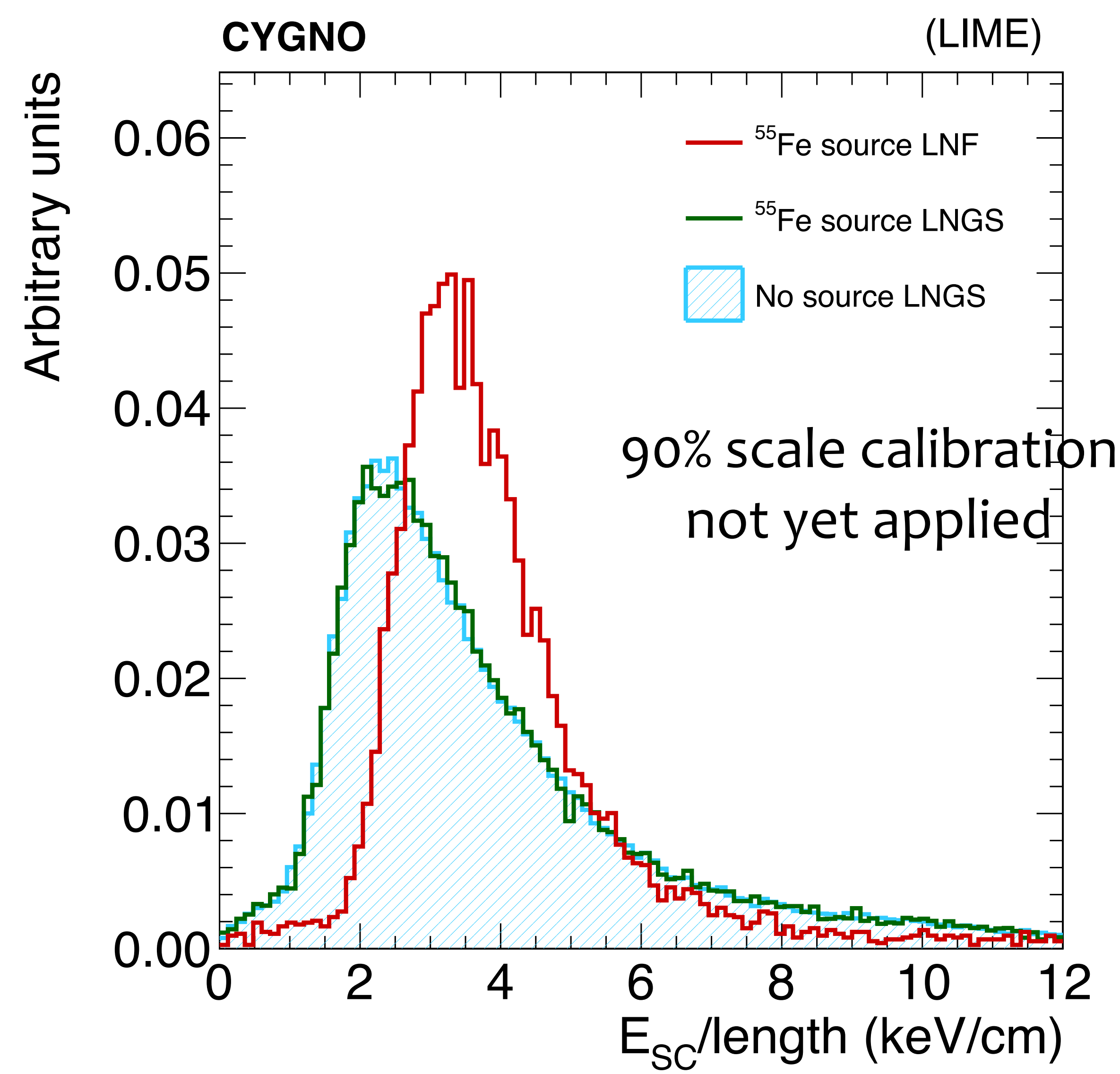
All these data are reconstructed

Numbers	Description	PMT	Source	Gas Flux	PMT Thr
3000-3003	Scan HV PMT	Yes	None	20 l/h	15 mV
3009-3116	stability while flushing gas (Z=5cm)	Yes	55Fe	20 l/h	15 mV
3125-3160	stability while flushing gas (Z=25cm)	Yes	55Fe	20 l/h	15 mV
3161-3201	BKG: first study, crashed after 40 runs	Yes	None	20 l/h	15 mV
3358-3551	BKG	Yes	None	20 l/h	15 mV
3554-3568	BKG: first study, crashed after 18 runs	Yes	None	20 l/h	15 mV
3569-4128	BKG	No	None	20 l/h	15 mV
4141-4143	scan HVGEM All	Yes	55Fe	20 l/h	15 mV
4145-4201	scan Z, scan VGEM1	Yes	55Fe	20 l/h	15 mV
4257-4266	scan Z, scan VGEM1	Yes	55Fe	20 l/h	15 mV
4271-4302	scan Z, scan VGEM1	Yes	55Fe	20 l/h	15 mV
4202-4256	stability (Z=25cm)	Yes	55Fe	20 l/h	15 mV
4314-4365	stability (Z=25cm)	Yes	55Fe	20 l/h	15 mV
4366-4381	Test Trigger	Yes	55Fe	20 l/h	15 mV
4391-4468	stability (Z=25cm), thr 15 mV	Yes	55Fe	20 l/h	15 mV
4469-4475	stability (Z=25cm), thr 5 mV	Yes	55Fe	20 l/h	5 mV
4475-4492	BKG: 5 mV	Yes	None	20 l/h	5 mV
4493-4512	stability (Z=25cm), thr 5 mV	Yes	55Fe	20 l/h	5 mV
4513-4780	55Fe: stability (Z=25cm), thr 5 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4782-4935	BKG: stability (Z=25cm), thr 5 mV, flux 3l/h	Yes	None	3 l/h	5 mV
4936-4947	55Fe: 100 ms exposure, thr 5 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4949-4963	55Fe: (Z = 5 cm) thr 5 mV, flux 3l/h, test equalization	Yes	55Fe	3 l/h	5 mV
4964-4972	55Fe: (Z = 25 cm) thr 100 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4973-4977	55Fe: (Z = 25 cm) thr 75 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4978-4982	55Fe: (Z = 25 cm) thr 50 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4983-4987	55Fe: (Z = 25 cm) thr 200 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4988-4992	55Fe: (Z = 25 cm) thr 255 mV, flux 3l/h	Yes	55Fe	3 l/h	5 mV
4993-5000	55Fe: (Z = 25 cm) thr 5 mV, flux 3l/h, scan drift field	Yes	55Fe	3 l/h	5 mV
5001-5106	BKG: 5 mV, thr 5 mV, flux 3l/h	Yes	None	3 l/h	5 mV
5107-5162	55Fe: (Z = 25 cm) thr 5 mV, flux 20l/h, after operations on gas system	Yes	55Fe	20 l/h	5 mV
5163-5174	55Fe: (Z = 25 cm) thr 5 mV, flux 1l/h, after operations on gas system	Yes	55Fe	1 l/h	5 mV
5175-5178	WARNING: the sequencer was on while the cap was removed, the data of these runs could be thrash	Yes	55Fe	1 l/h	5 mV
5179-5366	55Fe: (Z = 25 cm) thr 5 mV, flux 1l/h	Yes	55Fe	1 l/h	5 mV
5377-5491	55Fe: (Z = 25 cm) thr 5 mV, flux 1l/h - new PMT HV (part 1)	Yes	55Fe	1 l/h	5 mV
5507-5650	55Fe: (Z = 25 cm) thr 5 mV, flux 1l/h - new PMT HV (part 2)	Yes	55Fe	1 l/h	5 mV
5652-5692	55Fe: (Z = 25 cm) thr 5 mV, flux 10 l/h - new PMT HV - to study the effect of new gas	Yes	55Fe	10 l/h	5 mV
5694-5730	55Fe: (Z = 25 cm) thr 5 mV, flux 10 l/h - new PMT HV - stable	Yes	55Fe	10 l/h	5 mV
5732-5740	55Fe: (Z = 25 cm) thr 2 mV, flux 10 l/h - new PMT HV - Drift Field Scan	Yes	55Fe	10 l/h	2 mV
5741-5908	BKG: thr 2 mV, flux 10 l/h - new PMT HV - (part 1)	Yes	None	10 l/h	2 mV
5910-5921	55Fe: (Z = 25 cm) thr 2 mV, flux 10 l/h - new PMT HV - PMT HV Scan	Yes	55Fe	10 l/h	2 mV
5922-6287	BKG: thr 2 mV, flux 10 l/h - new PMT HV - (part 2)	Yes	None	10 l/h	2 mV
6288 - 6744	BKG: thr 2 mV, flux 10 l/h - new PMT HV - (part 2) - no DGTZ	Yes	None	10 l/h	2 mV

Long tracks comparison

- Dominated by natural radioactivity (+cosmics at LNF).
  - Remember $\Delta t_{LNGS} = 3.4 \Delta t_{LNF}$





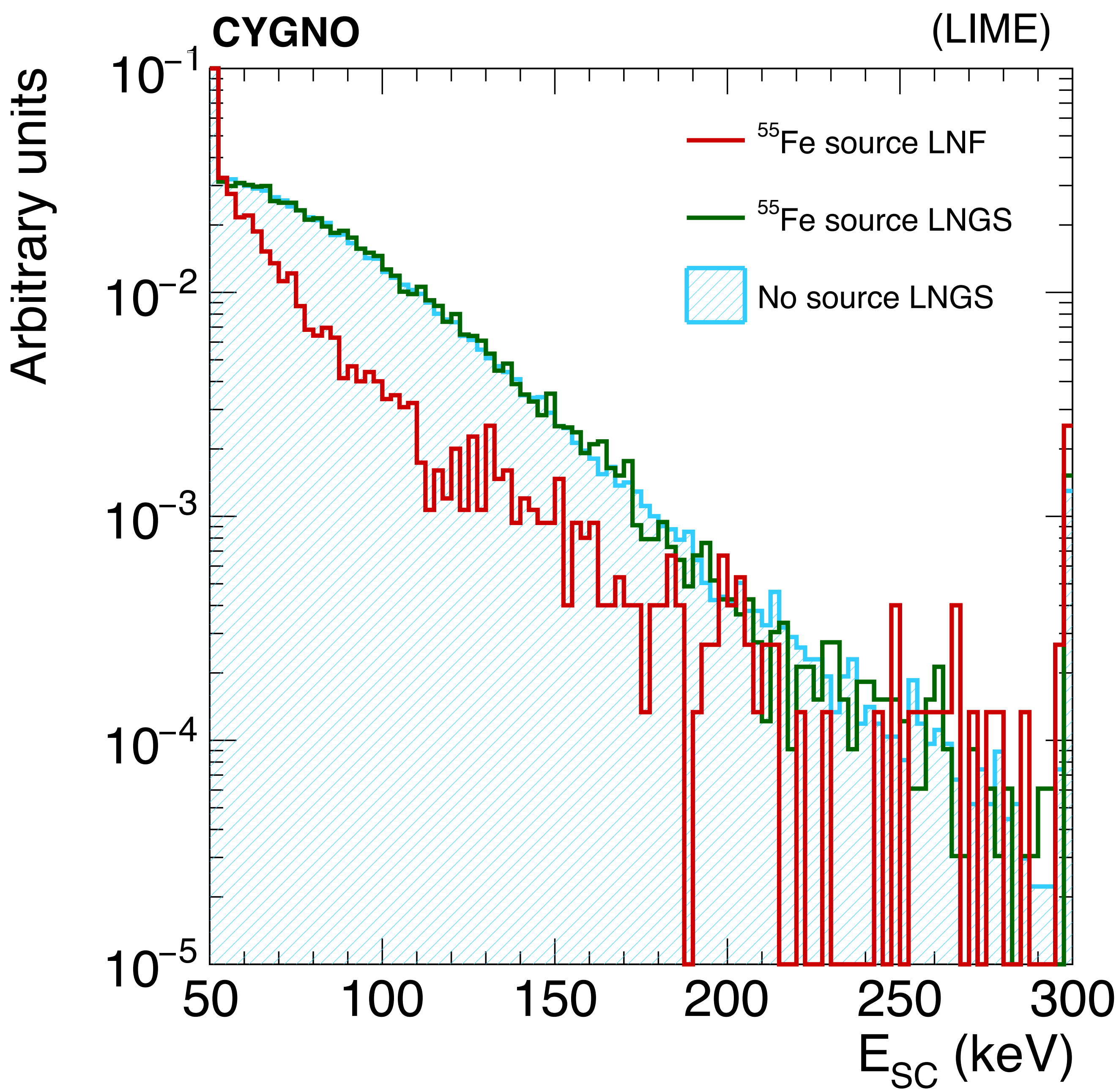
Doing a rate estimate difficult,
Especially for LNF, due to cluster splitting in high occupancy

Cosmics component at LNF expected to have **dE/dx MPV = 3.3 keV/cm**

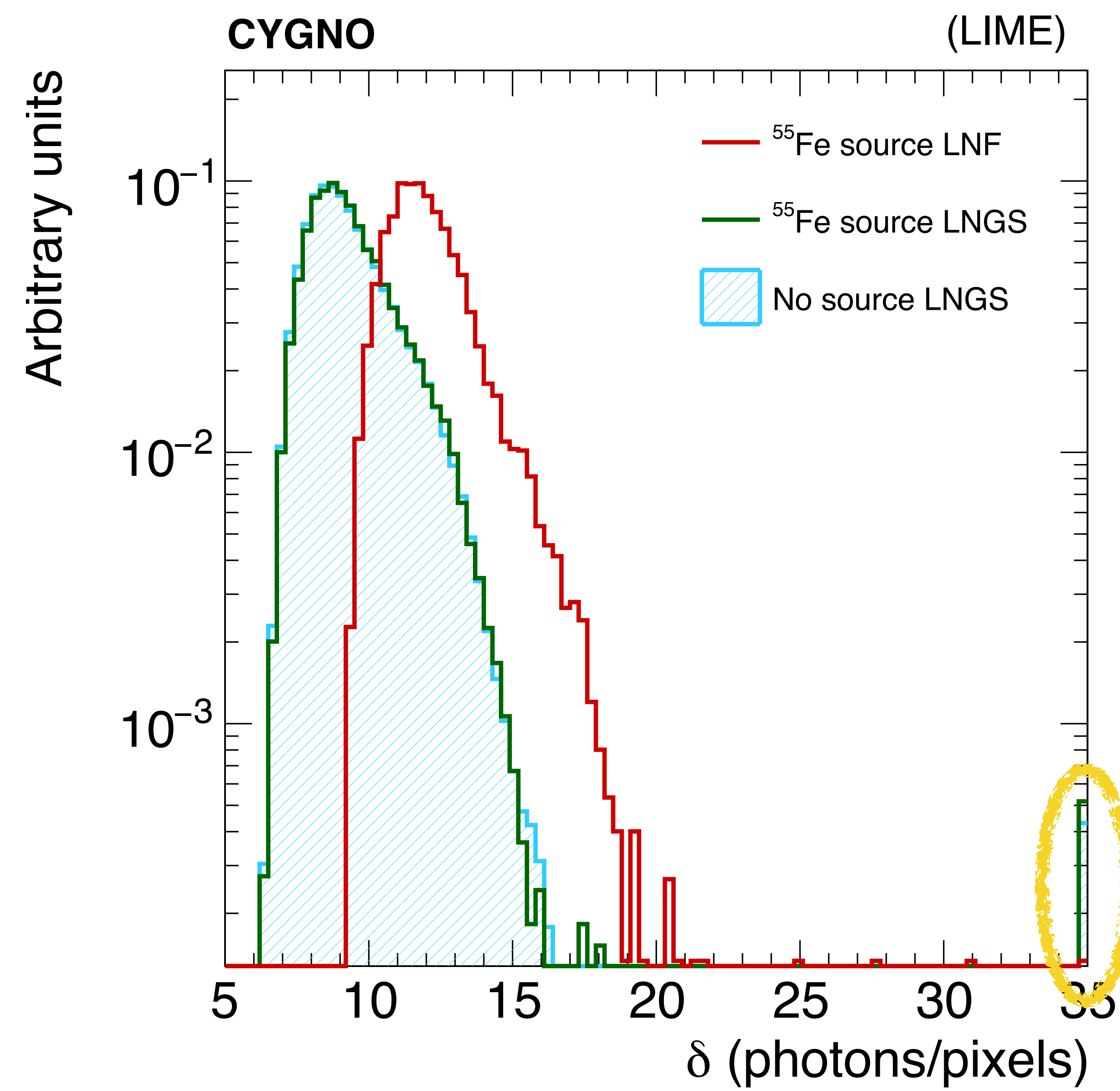
N.B. Energy scale is *90% lower* at LNGS

Long tracks spectrum comparison

- All clusters longer than 10 cm. No removal of the cosmics-dominated phase space (Marin's band)

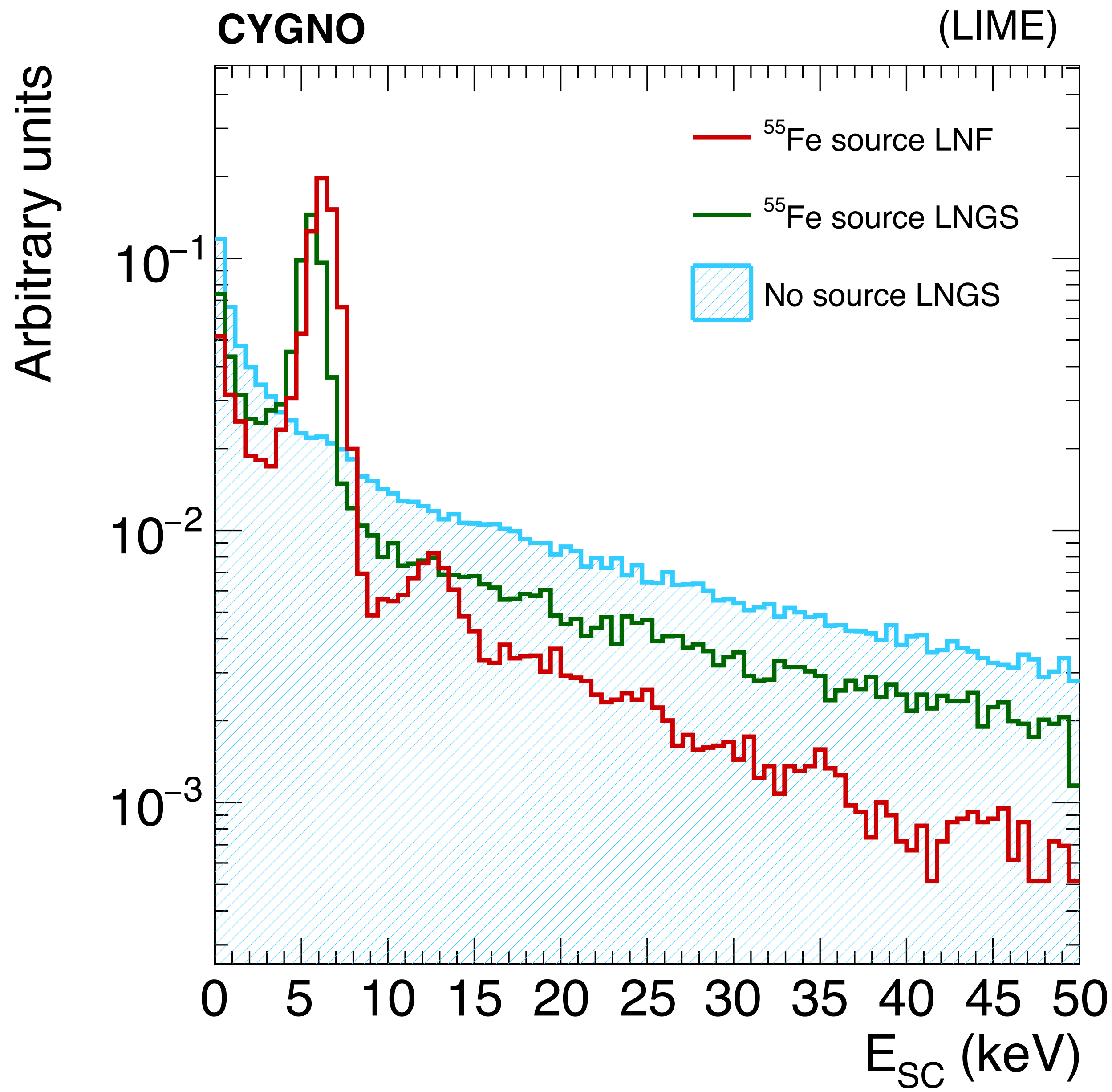


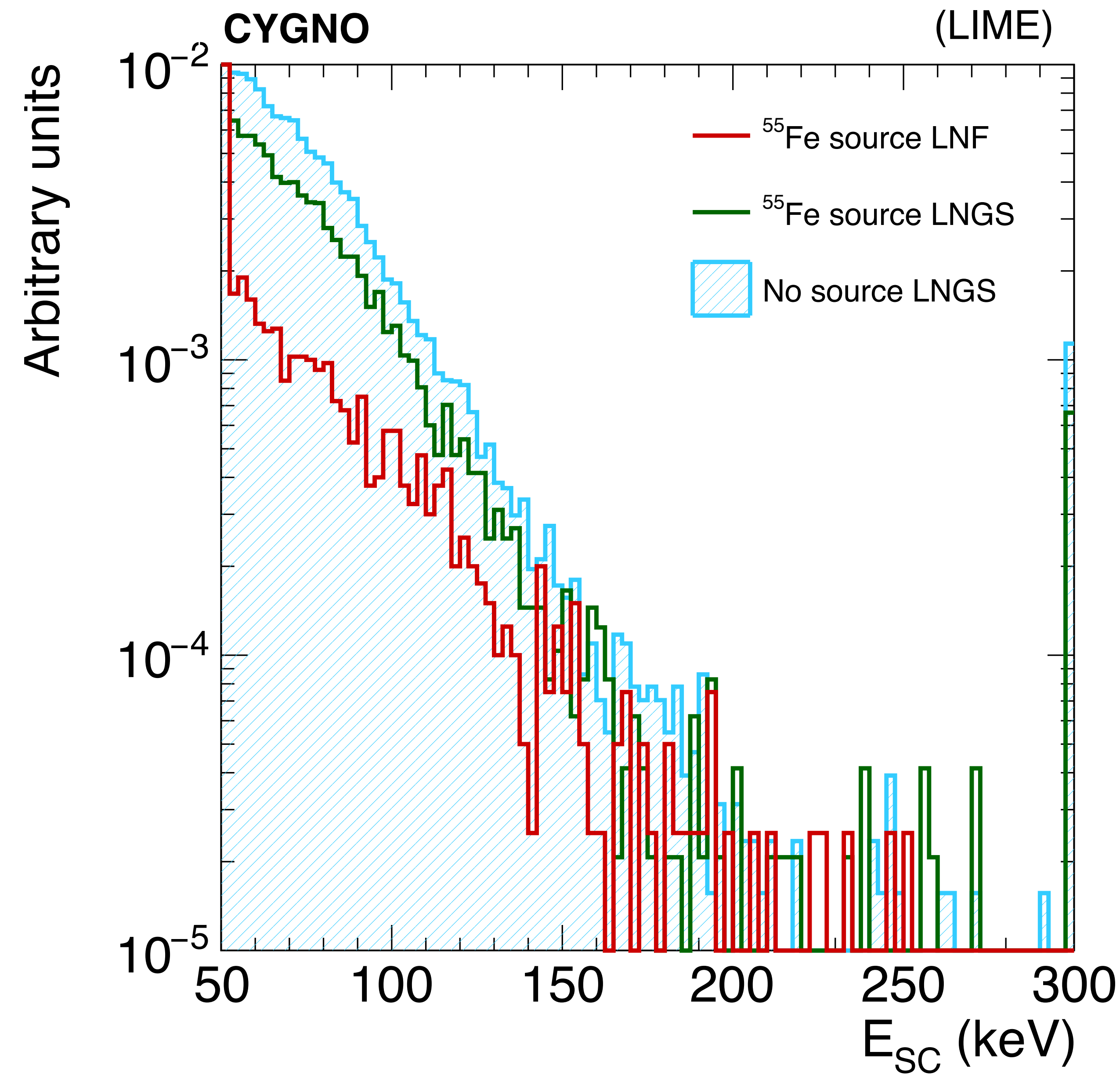
Harder spectrum at LNGS of the long tracks



Higher rate of α tracks?
(Overflow bin in this plot)

Short tracks (^{55}Fe - dominated)





Absolute energy calibration:
K(LNF) = 1400 counts / keV
K(LNGS) = 1260 counts / keV

Higher rate of hot spots?
(Overflow bin in this plot)

Conclusions

- *Performance understanding on LIME at LNF mature*
  - Paper in preparation should be available for internal review after Christmas
- *LNGS data analysis started*
  - A lot of data collected with and without Fe source to be analysed
  - First results seems roughly in line with what we expected (energy scale and background rates w/o shielding)
  - All the data collected so far are reconstructed and copied to the cloud
    - **Description of data-taking here, reconstructed data here.**
      - Documentation as usual in the wiki page here
    - *Autumn22* tag of the code robust, occupancy is small enough with 300 ms exposure, no problem of long tracks cut by global exposure time limit
    - ⇒ now it is time for a serious comparison with simulation
- *Many developments on the PMT side* (see F. Borra's presentation in next session)
  - Time to (re-)integrate it in the reconstruction code to put output in the RECO files
- ***Future:*** $^{241}\mathrm{Am}$ ***source data*** (with a shield to increase S/B, needed for low activity source)

A challenge for you

- What is the nuclear decay / fluorescence involving Ca (well, gypsum) that emits X-rays with E=190 keV ?