Measurement of Galactic ^{26}Al with the Compton Spectrometer and Imager

https://arxiv.org/pdf/2202.11713.pdf

What is ^{26}Al?

A good spectral resolution in the MeV band is needed

A γ ray emission line at 1809 keV (in the laboratory frame) from the decay of ^{26}Al nuclei into ^{26}Mg (τ = 0.715 Myr)

May help in tracking the Star Forming regions in the MW, since it's plausibly powered both by CCSN and Wolf Rayet wind bringing heavy elements to ISM.

Where is it observable?

It’s observable from the whole sky, with peaks of emission in the regions of the Inner Galaxy

↓

COMPTEL and SPI

How may a new Compton instrument help this kind of survey?

COSI had an experimental flight in 2016 and its data may provide some hints

COSI(2016): a 46 days long balloon flight at an altitude between 33 and 22 kms

The direction of photons is inferred by the crossing of Compton scattering cones, since there's no electron tracking by the detectors

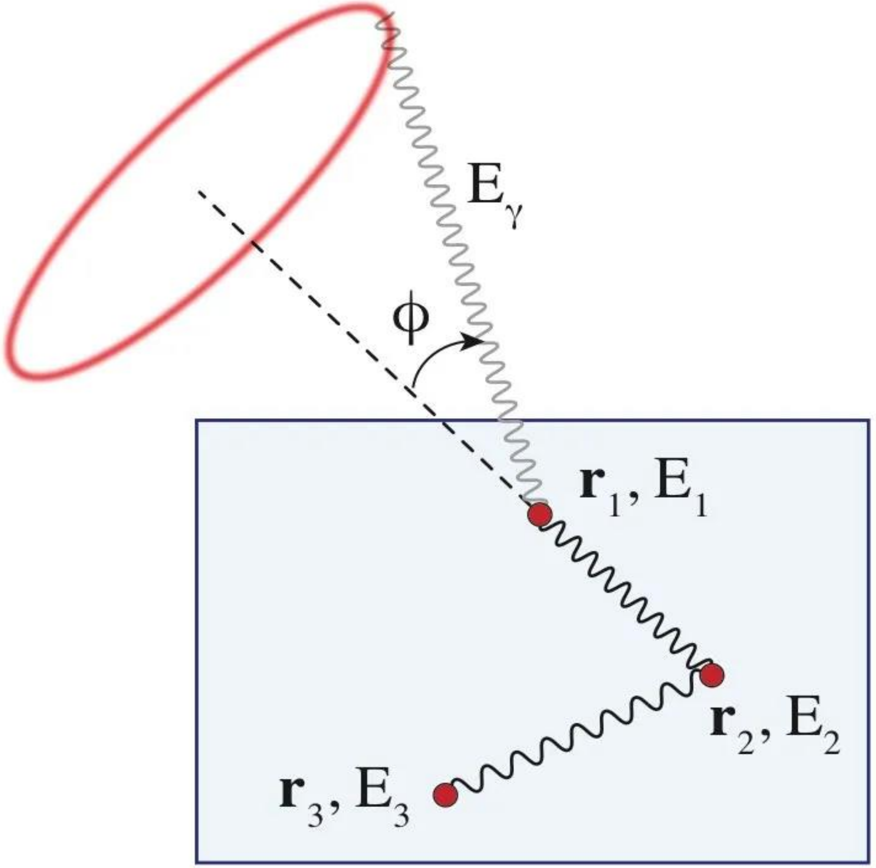
Twelve compact cross-strip Germanium Compton detectors always pointed at zenith shielded by CsI (BGO for COSI-SMEX) in order to tackle atmospheric albedo radiation (overall)

Introduces an instrumental activation background which should be empirically accounted for while performing data analysis (*as we shall see...*)

Direction of the incoming photons and energy if the scattering products are completely confined inside the detectors.

Only events with n_interactions ≥ 2 shall be considered

It is possible to study COSI's capabilities for imaging and spectral analysis in the ^{26}Al band and understand how useful COSI-SMEX will be in this kind of survey



https://cosi.ssl.berkeley.edu/instrument/design/

Deepening about the compact Compton detector

The time lapse between 2 interactions in a compact Compton detector is shorter than the timing accuracy of the detector: the ordering and discrimination processes are not as easy as in the double-layer case.

A special method based on Compton scattering kinematics is used : https://arxiv.org/abs/astro-ph/0005250

1

ϕ angle < 90, altitude of 33 kms (weaker influence by the Earth albedo background)

2

Only events with total initial energy in the 1750-1850 keV range are selected

3

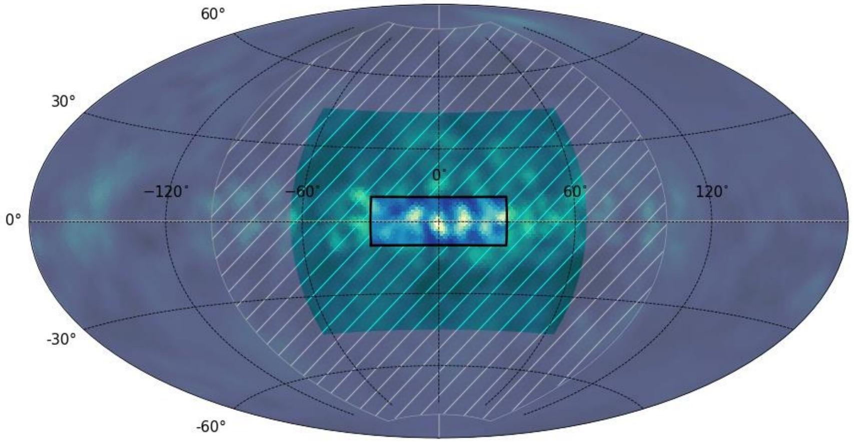
Events with more than 7 interactions are more likely to be pair production events rather than Compton scatters.

How to select data?

Partition of data

1- COMPTEL and SPI: the Inner Galaxy (|*b*|<*10 deg*, |*l*|<*30 deg*) is a strong signal region: anyway within a range of 35 degrees from the boarders of this signal region a significant portion of signal photons is expected, even if the instrument is pointed out of it.

Sky and data are partitioned in broadened signal and background regions.

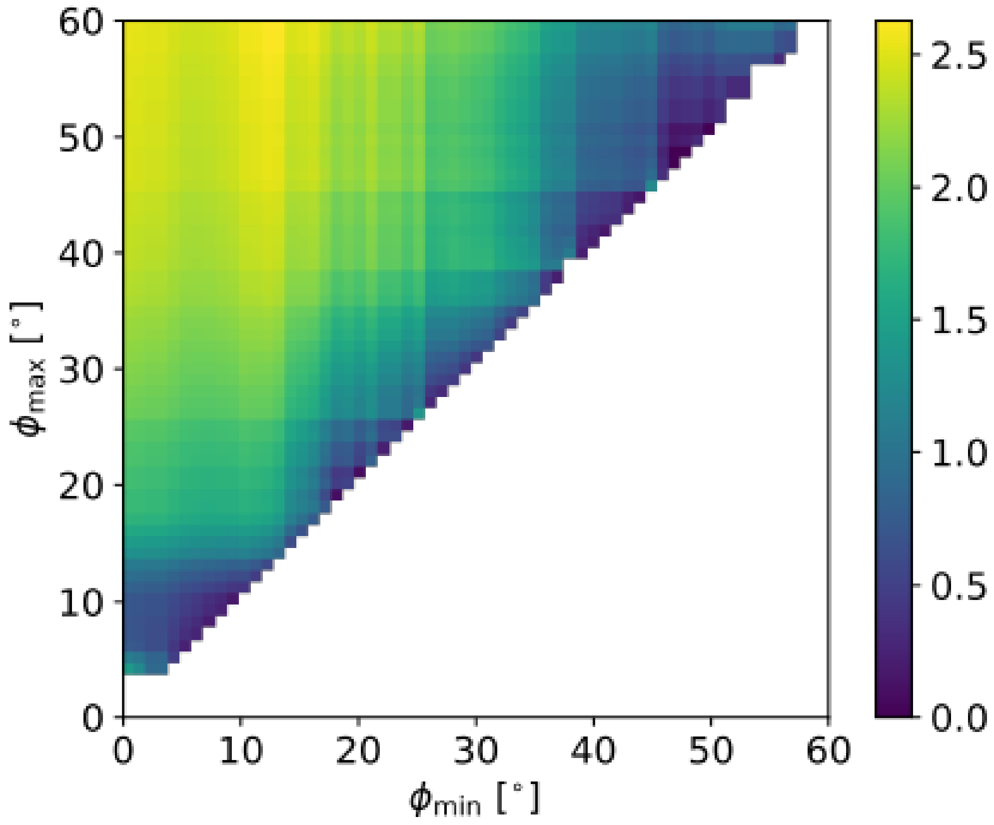


Why 35 degrees?

Beechert et al. 2022

Partition of data

A 35 degrees range gives a high signal-to-background ratio and provides sufficient statistics on the background (which is dominated by a peculiar spectral behaviour)



Beechert et al. 2022

Partition of data

2-Electronics' issues brought to the de-activation of 2 detectors within 2 days from the launch. A third detector was de-activated 20 days after the launch

Two data subsets are used

10 detectors

9 detectors

Data analysis

Signal data are binned in initial energy and each bin is compared with the superimposition of a sky model (inferred from a template map of the sky) and of a background model (inferred from data).

The sum of the two models gives an overall model:

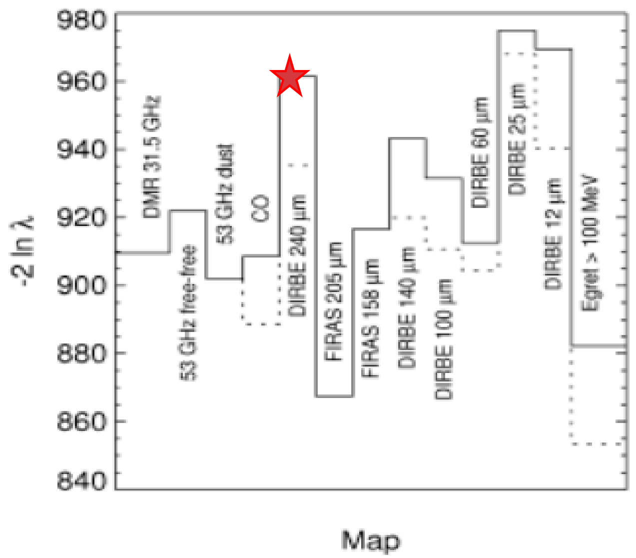
$$m_i = \alpha s_i + \beta b_i$$

Where α and β will be obtained with a best-fit parameters esteem based on the Maximum Likelihood technique.

The sky model

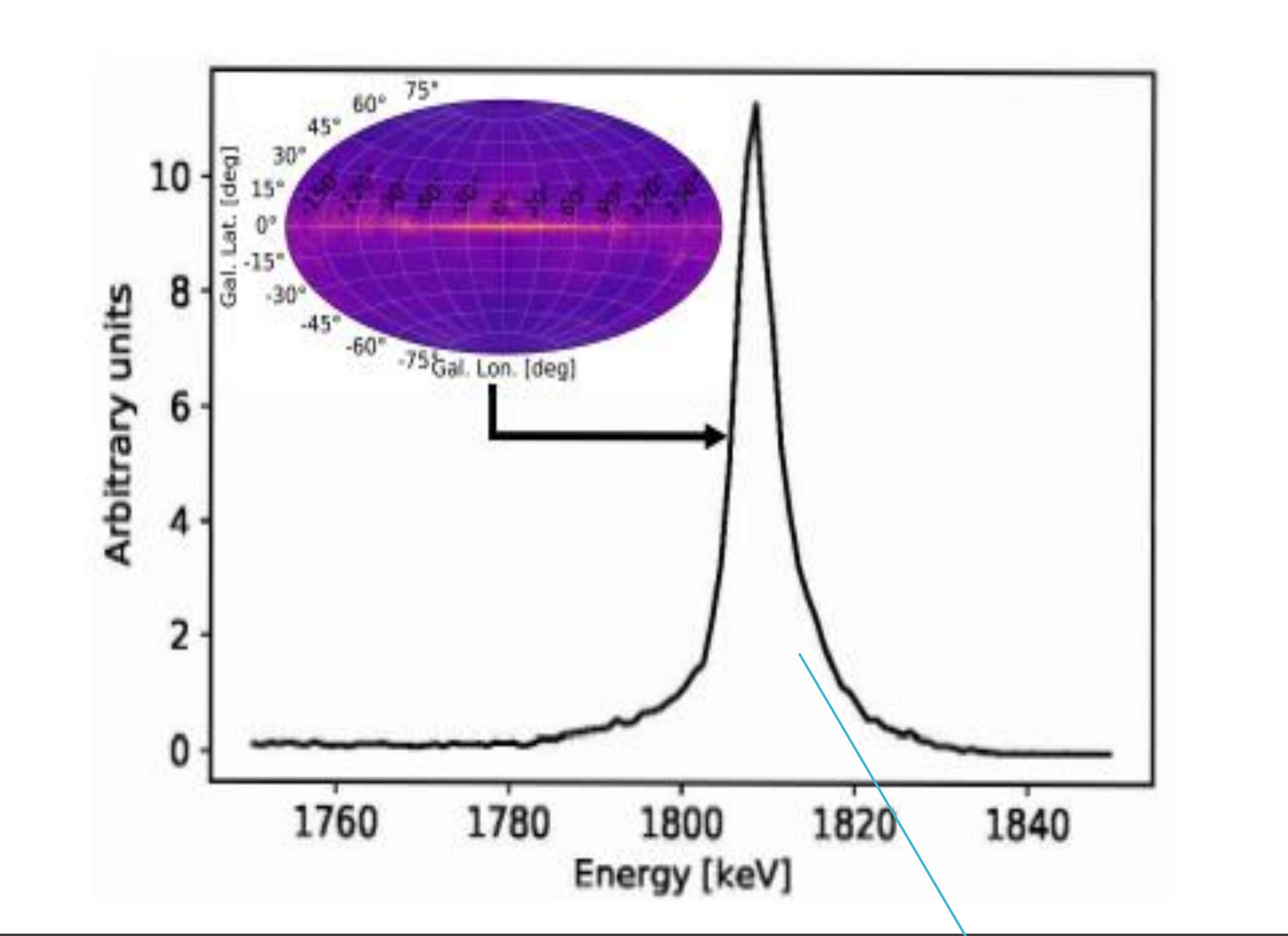
Both COMPTEL and SPI provide maps of the sky in the MeV band, and in the ^{26}Al line, but they are affected by artifacts due to the strong statistical noise dependence of the algorithms used for the data interpretation and imaging (*https://arxiv.org/abs/astro-ph/9903172* , *Bloemen et al. 1999*).

But few DIRBE's (IR) maps provide a good tracking of the 1.8 MeV line without artifacts (*https://articles.adsabs.harvard.edu/pdf/1999A%26A...344...68K*, *Knodlseder et al. 1999*)



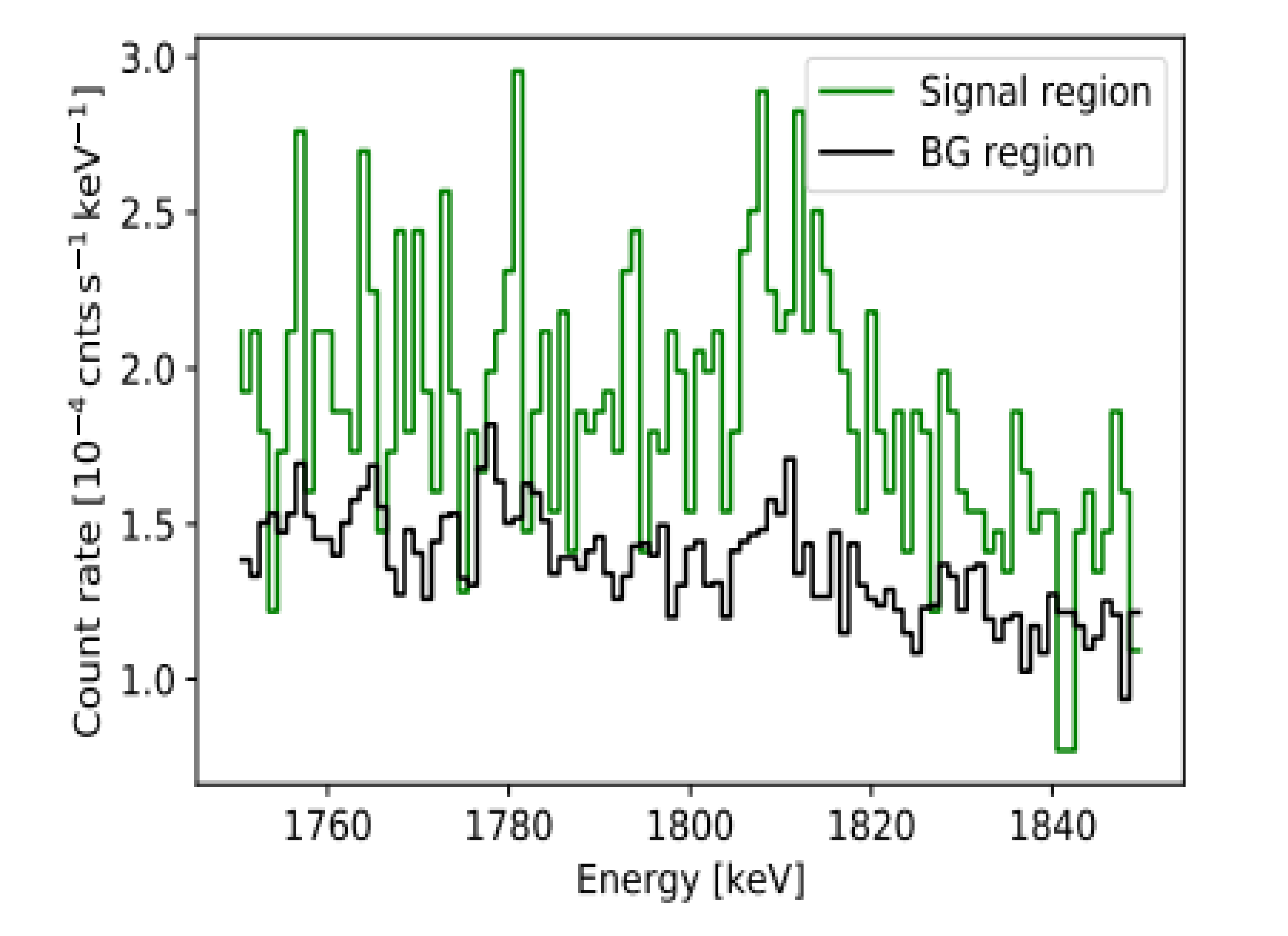
The spectral sky model defined by COSI's response to the DIRBE 240 μm map (inset image) over 50 2016 flights. (*Beechert et al. 2022*)

Constant flight altitude of 33 kms and constant atmospheric transmission (assumption)



Weak asimmetry imputed to increasing cross-talking in the electronics at higher energies

Counts vs. Energy in the real 2016 data collected by COSI *(Beechert et al., 2022)*



The background model

It's inferred from the expected background-dominated region of the sky, i.e. the background region

↓

It's assumed to be based on a power-law continuum and lines of decaying elements (with Gaussian profile)

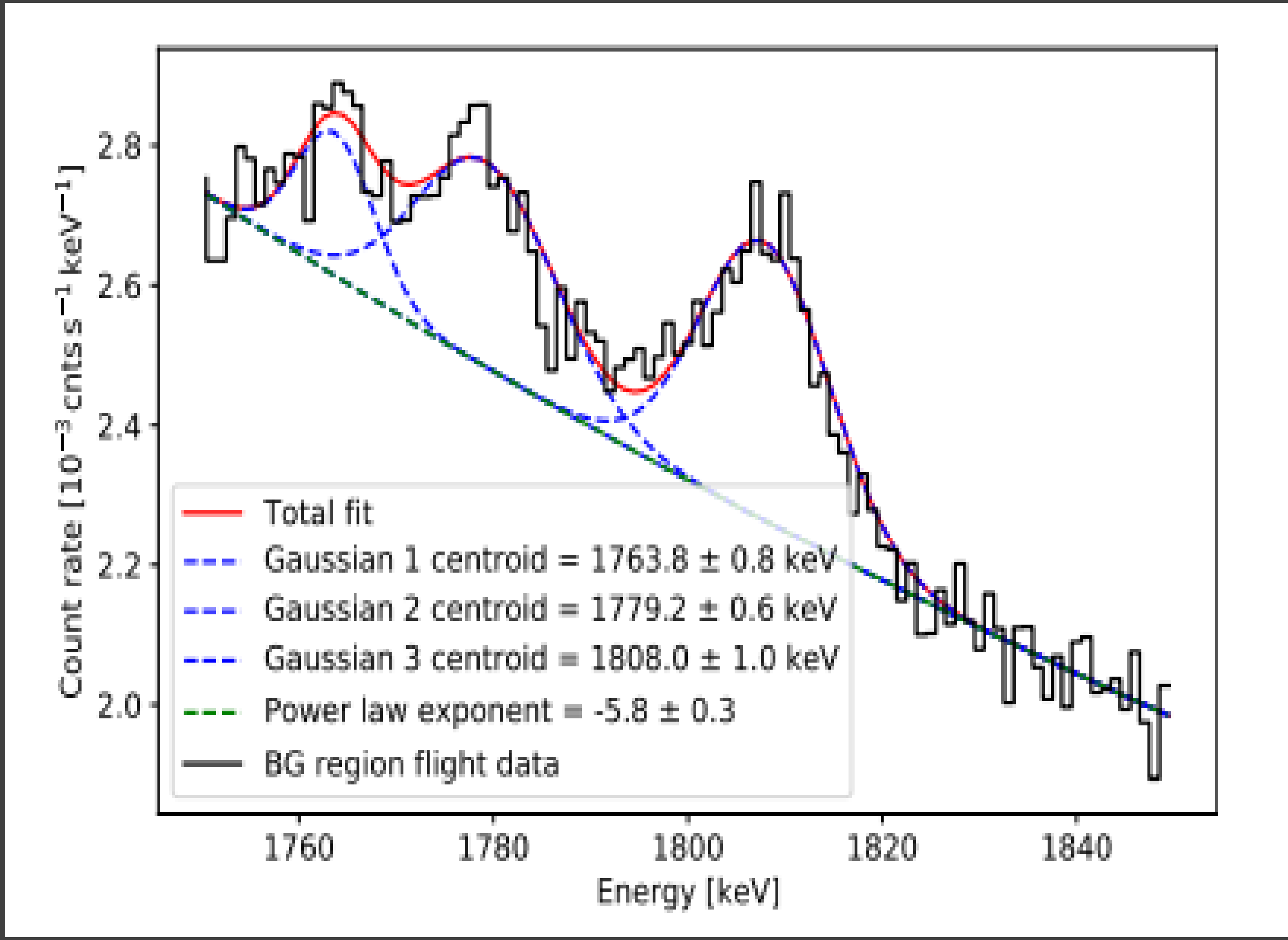
$$b(E) = C_0 \left(\frac{E}{E_c}\right)^{\gamma} + \sum_{l=1}^{3} \frac{A_l}{\sqrt{2\pi}\sigma_l} \exp\left(-\frac{1}{2}\left(\frac{E - E_l}{\sigma_l}\right)^2\right)$$

The background model: background lines

The background lines fitted with Gaussian functions come from the excitation of materials in the payload followed by radioactive decay.

- ^{238}U: 1764 keV
- $^{27}Al(n,\gamma)^{28}Al(\beta^-)^{28}Si$: 1779 keV
- $^{27}Al(n,d)^{26}Mg$ and $^{26}Na(\beta^-)^{26}Mg^*$: 1808 keV

Empirical fit to COSI flight data in the background region (*Beechert et al. 2022)*



Workflow from now on

1. Infer parameters with the Maximum Likelihood
2. Check their consistency with expectations
3. Bring ‘higher order’ corrections and constraints and express them as a function of some new parameters
4. Back to 1)

First Iteration

A computation of the 11 parameters already considered is performed with combined data from the inner Galaxy:

Important results:

- $\alpha = 1.1 \pm 0.3$ $\longrightarrow$ ^{26}Al line is effectively there, and it's not part of the background;
- Significance of the sky is 3.7σ, with σ provided by the computation of the Likelihood;
- No line other than ^{26}Al shows up in the *signal-background* spectrum.

Second Iteration

A second iteration for line shifting and broadening (which are expected to be consistent with the dynamics of the Milky Way as obtained in *https://doi.org/10.1051/0004-6361/201322563*):

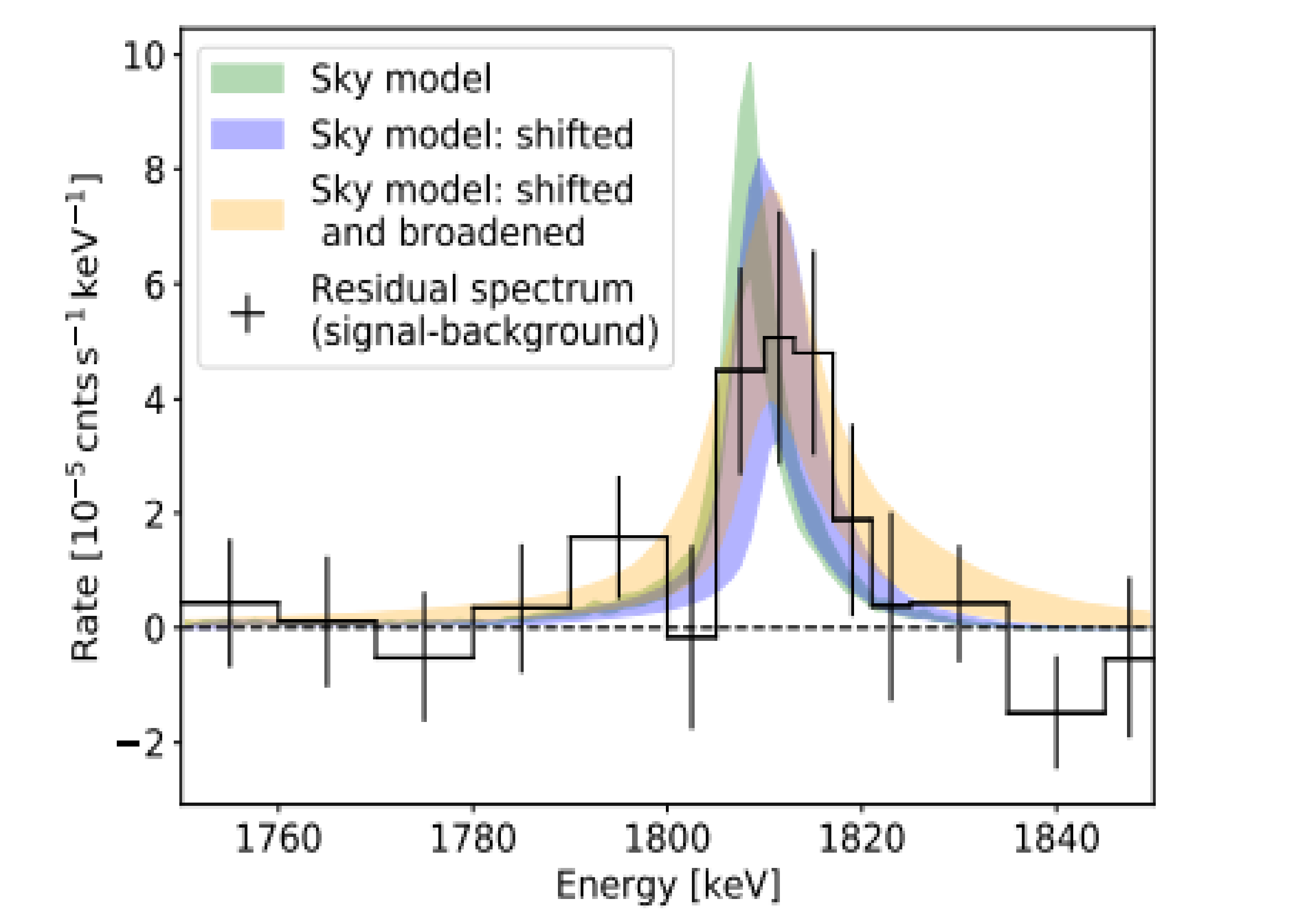
Line parameter	Value
Measurement significance	3.7σ
Inner Galaxy flux	$(8.6 \pm 2.5) \times 10^{-4}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$
Centroid	1811.2 ± 1.8 keV
Intrinsic sky broadening (2σ)	< 9.7 keV
Turbulent velocity (2σ)	$< 2800\,\mathrm{km\,s^{-1}}$

Beechert et al. 2022

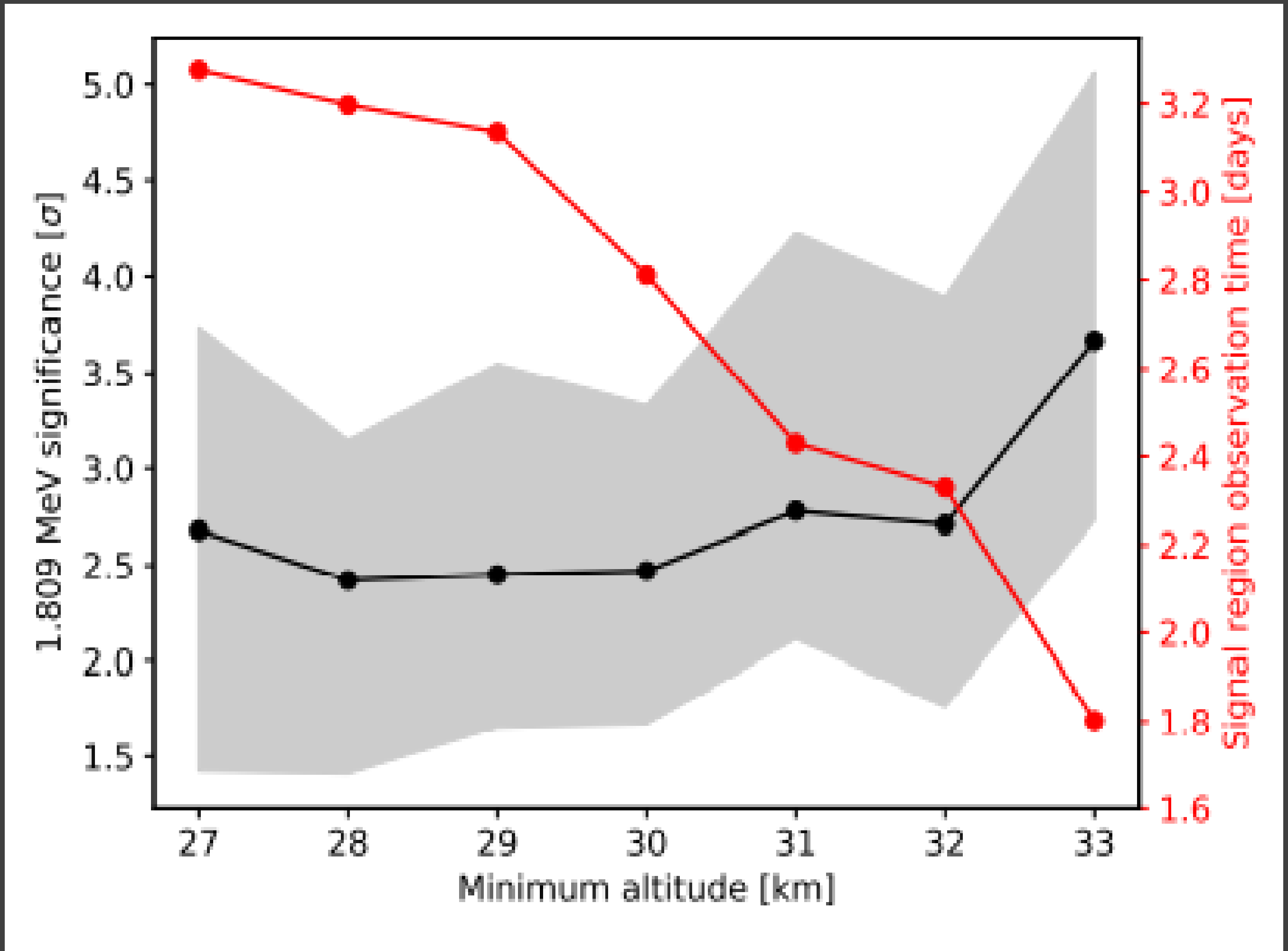
≈2x SPI and COMPTEL measured flux from the Inner Galaxy

Bias in the determination of the effective area?

Beechert et al. 2022



Same analysis on lower altitudes data :
-observation time increases;
-signal to noise ratio falls off significantly.



Relaxing the same constraint on the background data brings almost no alteration to the SNR

Separating data subsets…

10 detectors 9 detectors

The same iteration procedure is performed on both and no substantial difference is observed with the combined data set.

Rigidity

Geomagnetic shielding provided by the magnetic dipole of the Earth

- Data from the signal and background region can be binned in Earth's latitude (of the balloon)
- Counts are weighted with rigidity and the time of observation in the range of latitude corresponding to their rigidity

$R=14.5\cos^4(\lambda)/r^2$

Once again no substantial change is observed (just a significance improvement up to 3.9σ).

Simulated Data

The depicted analysis is now performed on simulated data

-Constant altitude and atmospheric transmission

-no Doppler shifts/broadening are considered

Data are simulated on the basis of template maps:
-DIRBE 240μm;
-SPI 1.8MeV;
-COMPTEL 1.8MeV;
-ROSAT 0.25 keV.

Background data are simulated with the templates and with a special software accounting for cosmic rays, instrumental activation and Earth albedo.

Simulated Data: DIRBE 240μm

- Total sky flux is weaker than in the real flight data
- Features of the background change:

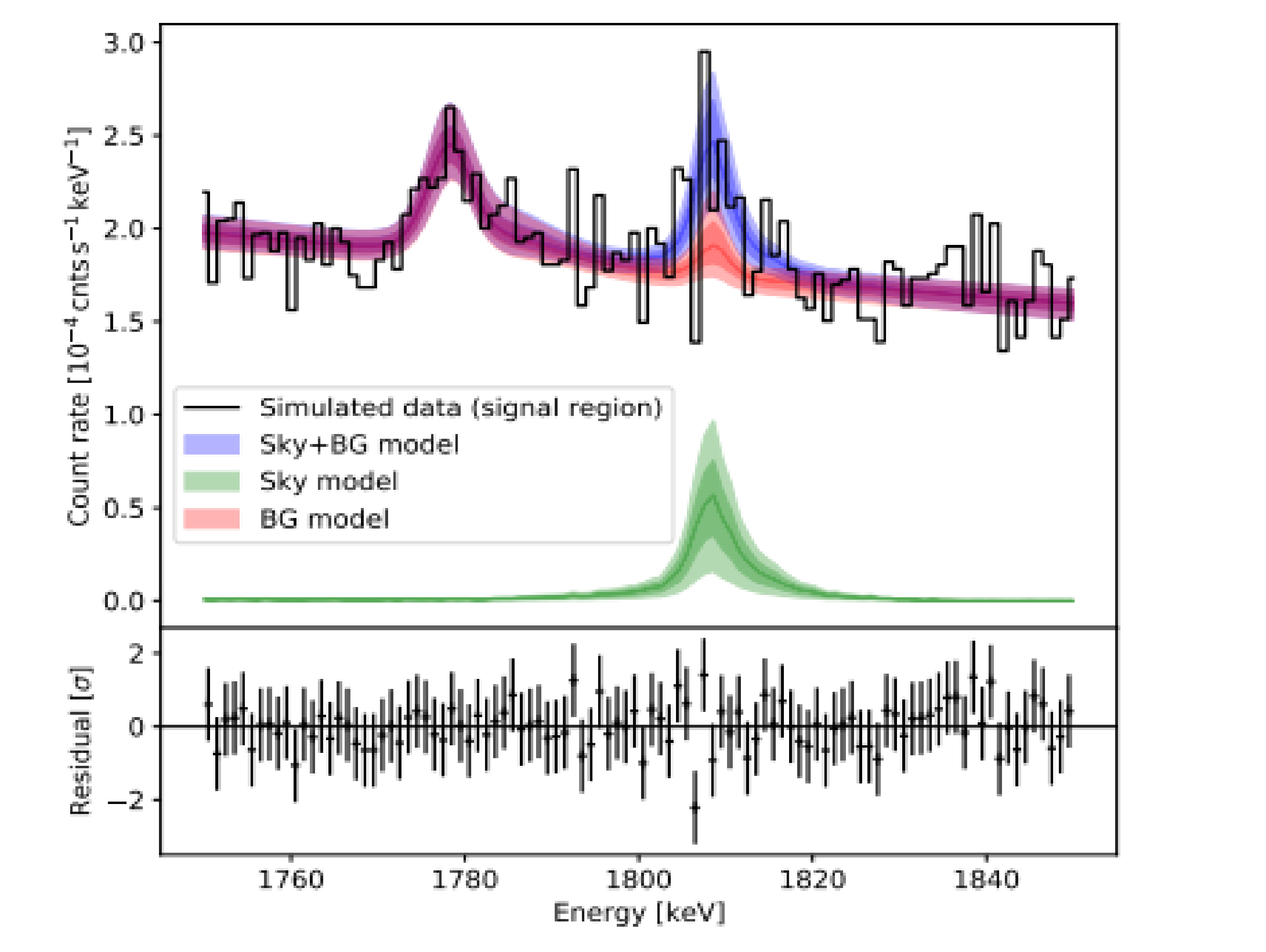
The ^{238}U line doesn't show: due to natural decay and not to cosmic ray activation on the payload?

The 1779 keV line looks blended with another line at 1784 keV

The continuum is less steep (smaller γ) at the ^{26}Al line energies

Simulated Data: DIRBE 240μm

Beechert et al. 2022



Sky significance ~ 2.8σ, total Inner Galaxy counts in the ^{26}Al line are 1.8 times lower than for real flight data

Simulated Data: other template maps

Due to the different than zero ^{26}Al fluxes in the background region in every template

Always ≥1.5 times weaker fluxes for the ^{26}Al line with respect to 2016 flight data

- Both SPI and COMPTEL template maps yield Inner Galaxy fluxes consistent with DIRBE within 2σ
- ROSAT 0.25 keV is not a trakcer of ^{26} Al. The background subtracted line flux is consistent with zero

As expected

Beechert et al. 2022

Template map	Significance $[\sigma]$	Measured IG flux $[10^{-4}\,\mathrm{ph\,cm^{-2}\,s^{-1}}]$	Map IG flux $[10^{-4}\,\mathrm{ph\,cm^{-2}\,s^{-1}}]$	Sky amplitude α	BG amplitude β
DIRBE 240 μm	2.8 ± 0.5	2.5 ± 0.4	3.3	0.7 ± 0.1	28.7 ± 0.1
SPI 1.8 MeV	2.8 ± 0.4	1.9 ± 0.3	2.7	0.8 ± 0.1	28.8 ± 0.1
COMPTEL 1.8 MeV	3.2 ± 0.5	2.5 ± 0.4	3.3	0.9 ± 0.1	28.8 ± 0.1
ROSAT 0.25 keV	—	0.2 ± 0.1	0.3	0.3 ± 0.1	28.7 ± 0.1

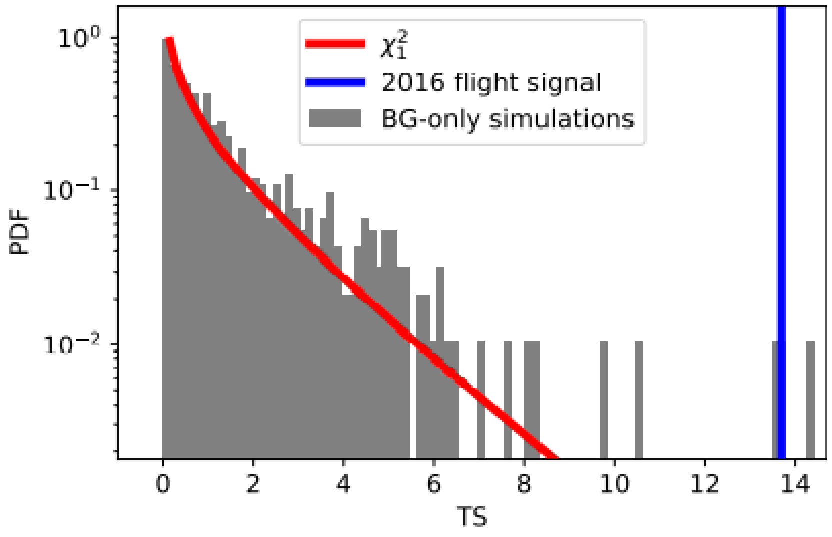
Summary of the results by simulating data with different template maps

Simulated data: background dominated map

By fitting 1000 times the real flight background region spectrum, and simulating a Poisson sample of background in the signal region a distribution for σ^2 is obtainable

It shows a χ^2_1 distribution

Real data from the signal region yield σ2 at a *p-value* < 10^{-3}



What about COSI-SMEX?

An example…

The spectral resolution of ≈ 4 keV (COSI): only raw esteem of the Doppler shift and broadening, therefore yielding very little insight into the dynamics of the ISM in the Inner Galaxy

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$$\Delta E = 2.9 \pm 1.4 \; keV$$
$$v_{turb} \leq 2800 \; km \; s^{-1}$$

↓

COSI-SMEX will improve both the spectral resolution (3 keV) and the minimum detectable flux at 1.8 MeV : more precise measures in shorter integration times.

COSI-SMEX will observe from a satellite platform: easier and less invasive background

Summary of inconsistencies

Systematic which affected also the 511 keV survey by COSI: it is attributed to a wrong determination of its effective area

- 1-The Inner Galaxy flux is twice the flux measured by SPI and COMPTEL
- 2-Origin of the ^{238}U line is still uncertain
- 3-The Inner Galaxy flux is 1.5÷2.0 times greater than the flux inferred from simulating data from template maps

Attributed to the raw assumption of no ^{26}Al emission in the background region

Corrections are very difficult to infer from high latitudes...

Finally…

The analysis pipeline for ^{26}Al from the Inner Galaxy is consistent with simulations from template maps

The two dominant inconsistencies have a (nearly) easy explanation

Inferring background from template-based simulations is the same as getting it from data (exception made for the ^{238}U line)

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Thank you for your attention!