Specificities of X-ray analysis

Atelier CTA - Meudon 2 octobre 2017

Specificities of X-ray analysis

Well. It's is very similar to VHE, but not quite the same.
Next talk?

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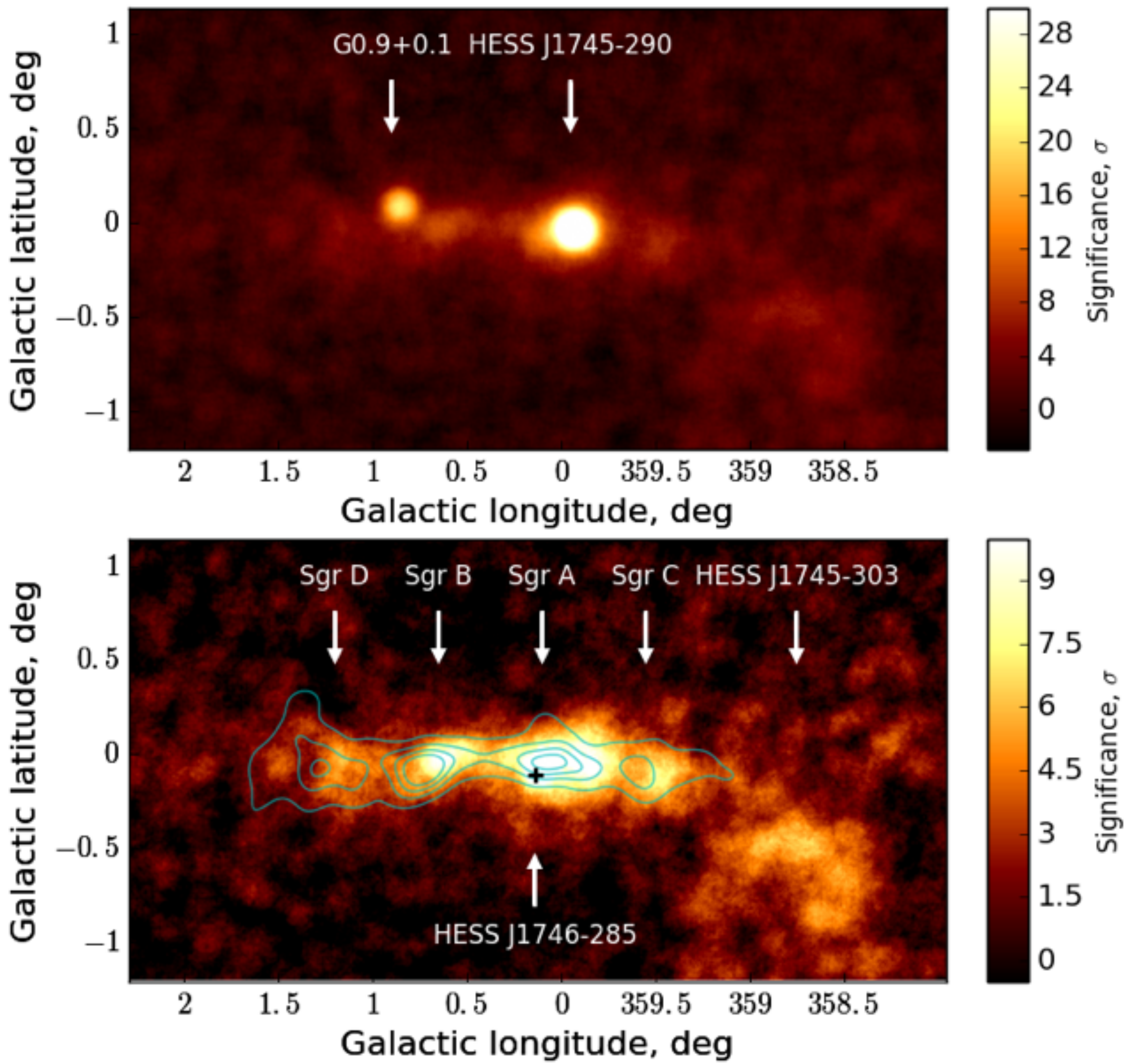
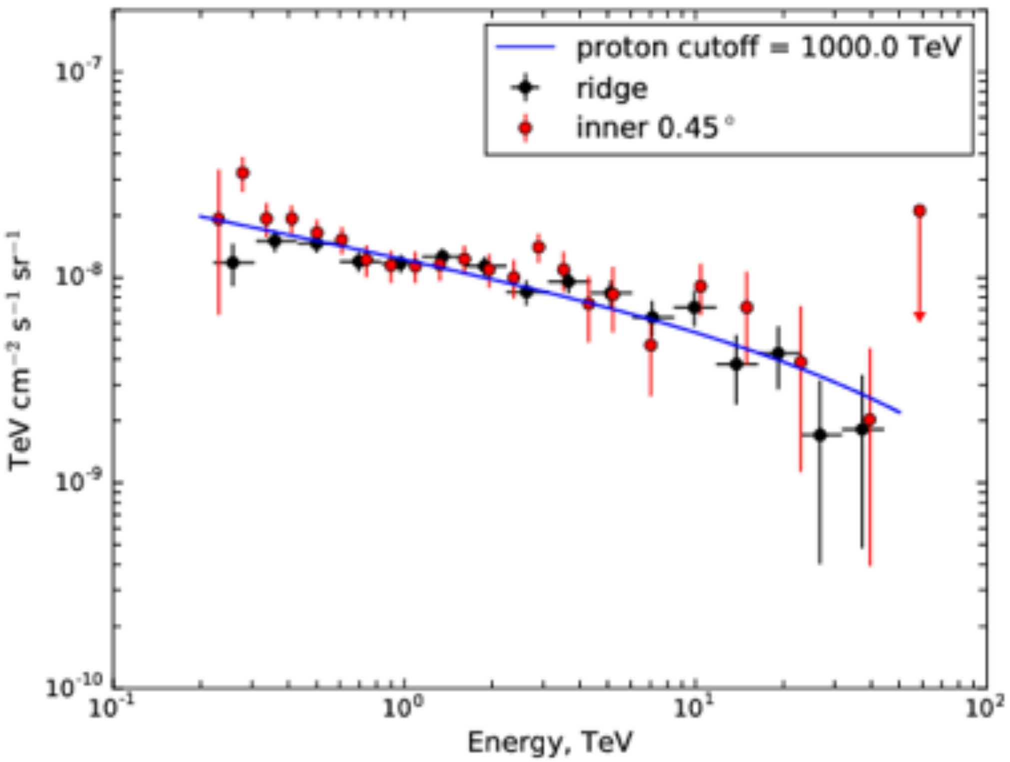
A case study: The Galactic Centre

HESS
E > 200 GeV
250h



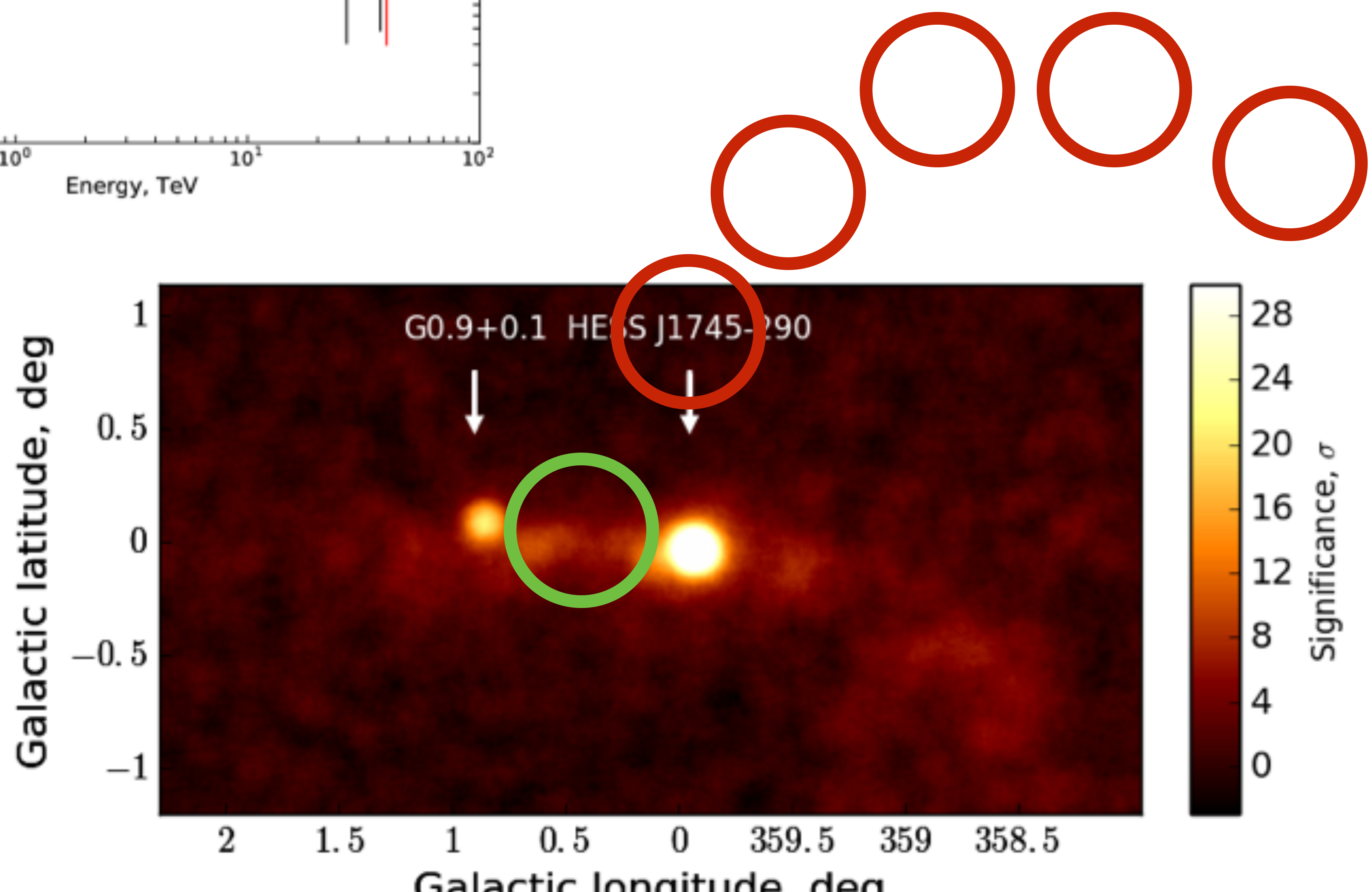
HESS, 2017

A case study: The Galactic Centre



Spectrum extraction and bkg estimation with multiple OFF

HESS
E > 200 GeV
250h

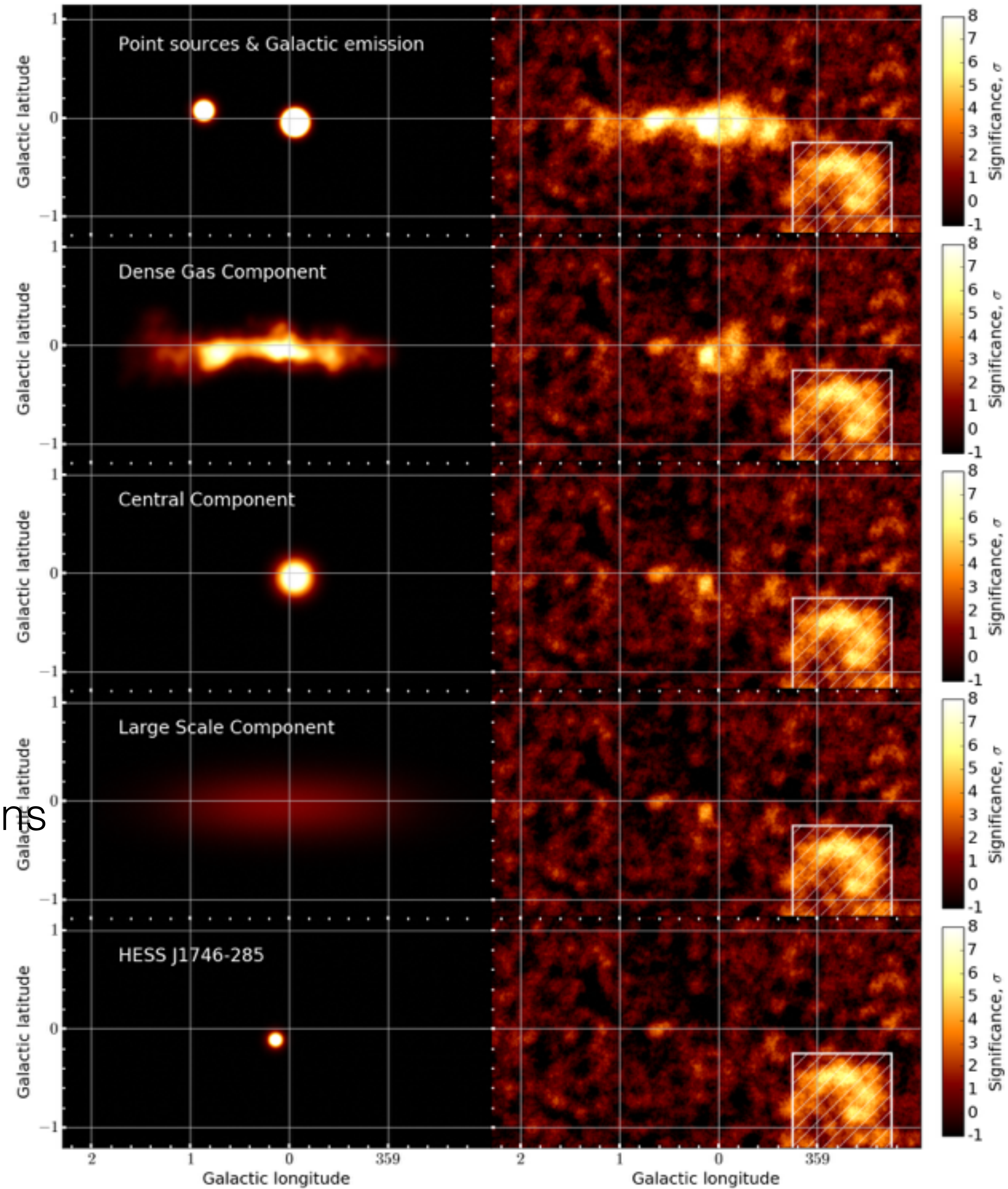


HESS, 2017

2D maximum likelihood

Requires:

- counts maps
- background maps
  - locally estimated
  - empty field observations

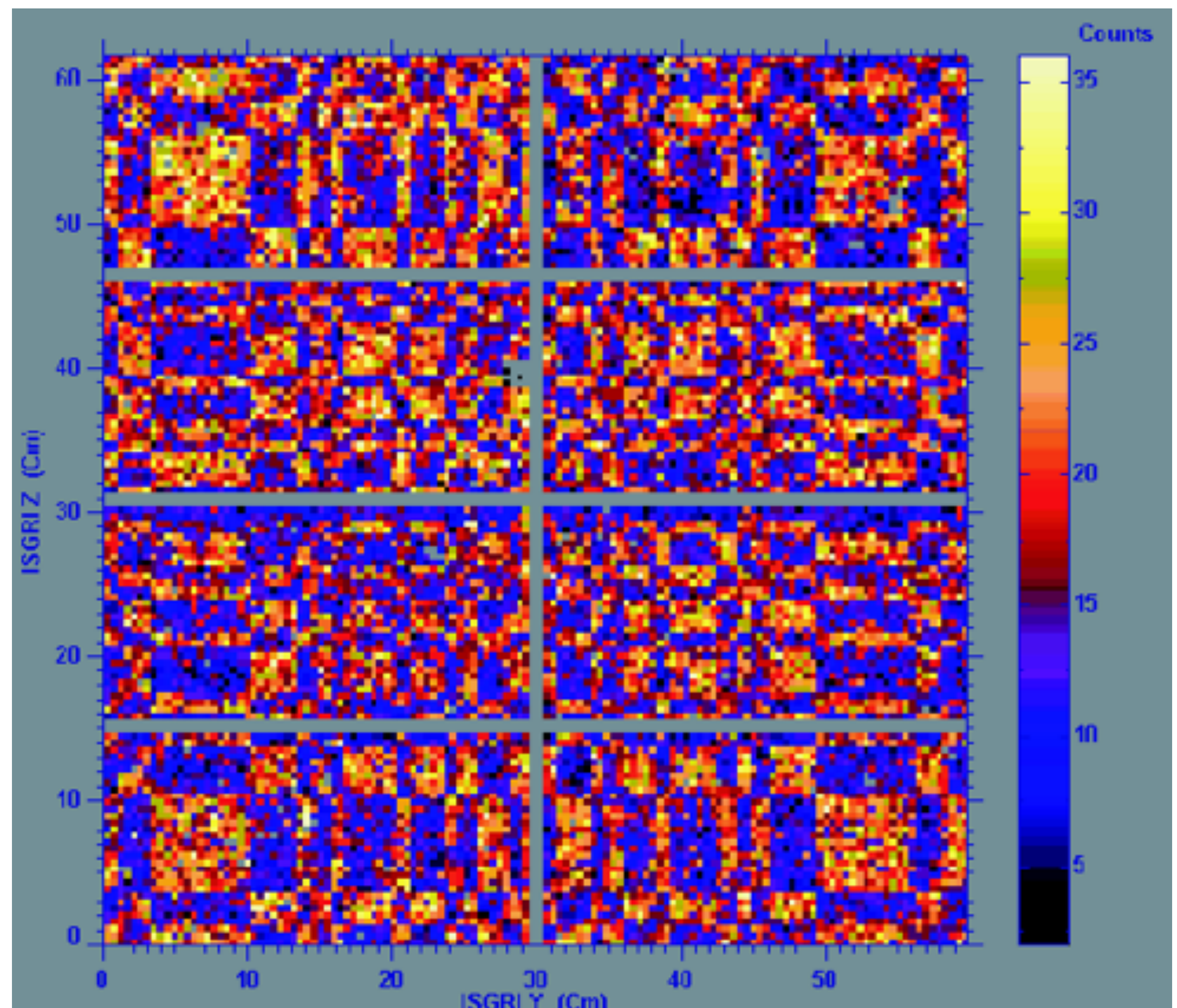


Principles of X-ray astronomy

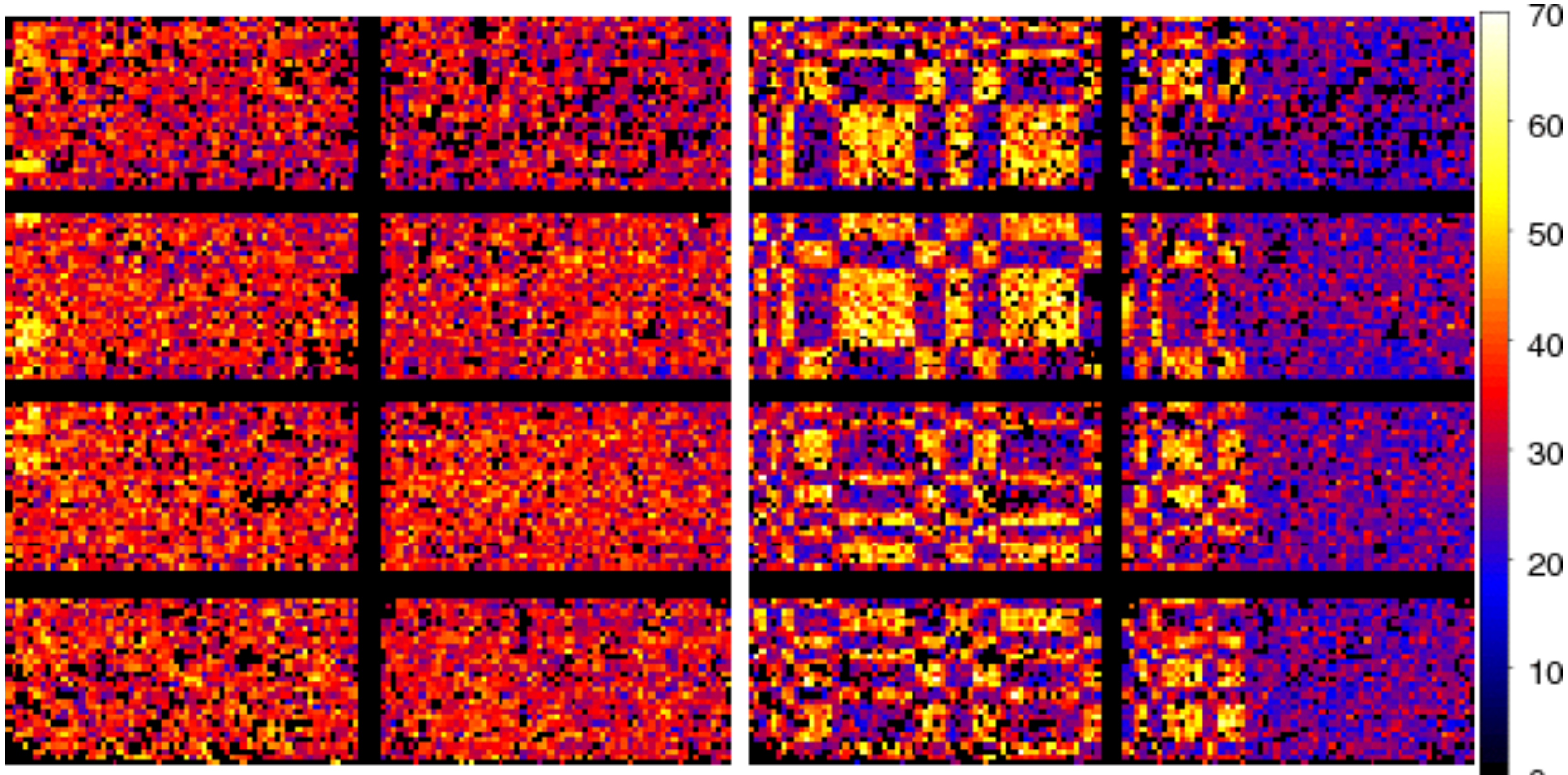
Photon counting experiments as VHE ones

- **Collimators**
- **Coded mask imaging**
  - Low signal to noise (e.g. Integral/IBIS/Isgri: 0.1 - 100 cps for a bkg of ~ 600 cps)
  - Wide FoV (e.g. Integral/IBIS ~ 9° fully coded, ~35° partially coded)
- **X-ray mirrors**
  - High signal to noise (e.g. XMM/EPIC/PN: ~1 cps for mCrab source for a bkg of 10^{-3} cps/arcmin^2)
  - Small FoV (e.g. XMM/EPIC : 30')

Coded mask imaging principle



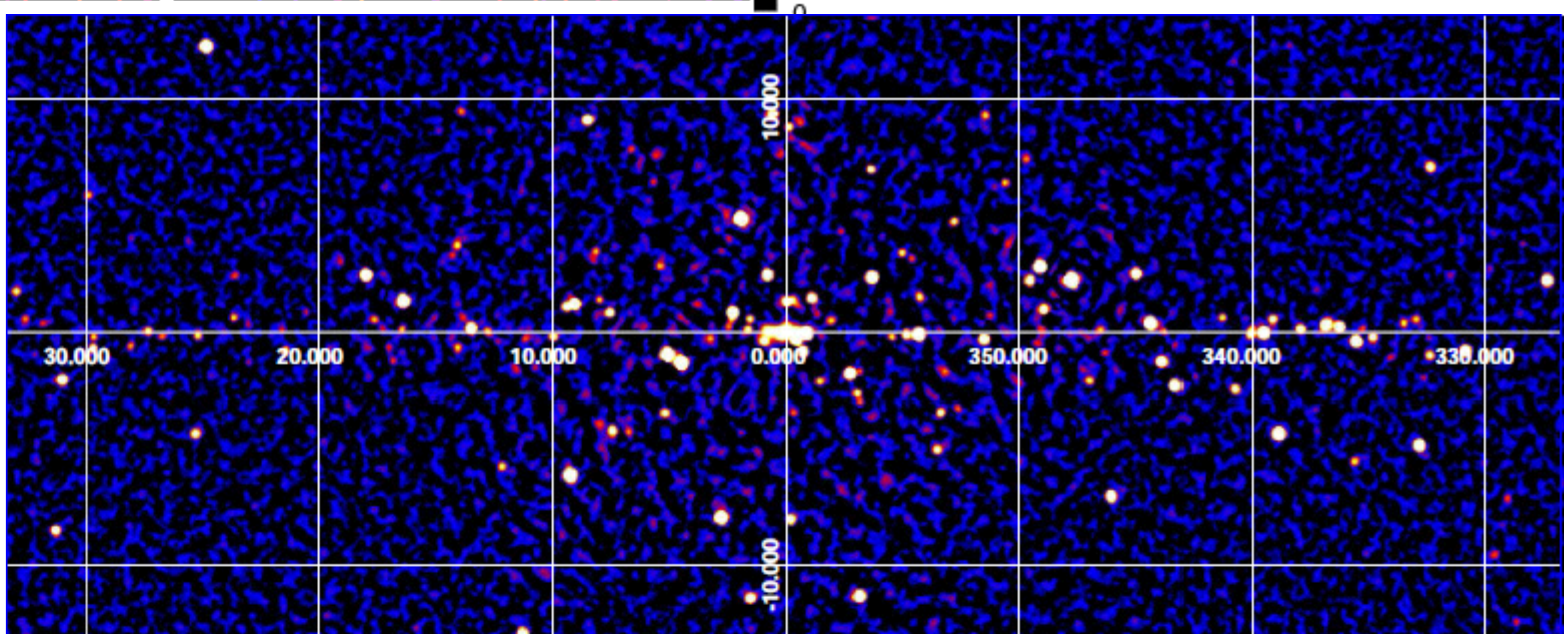
Coded mask imaging principle



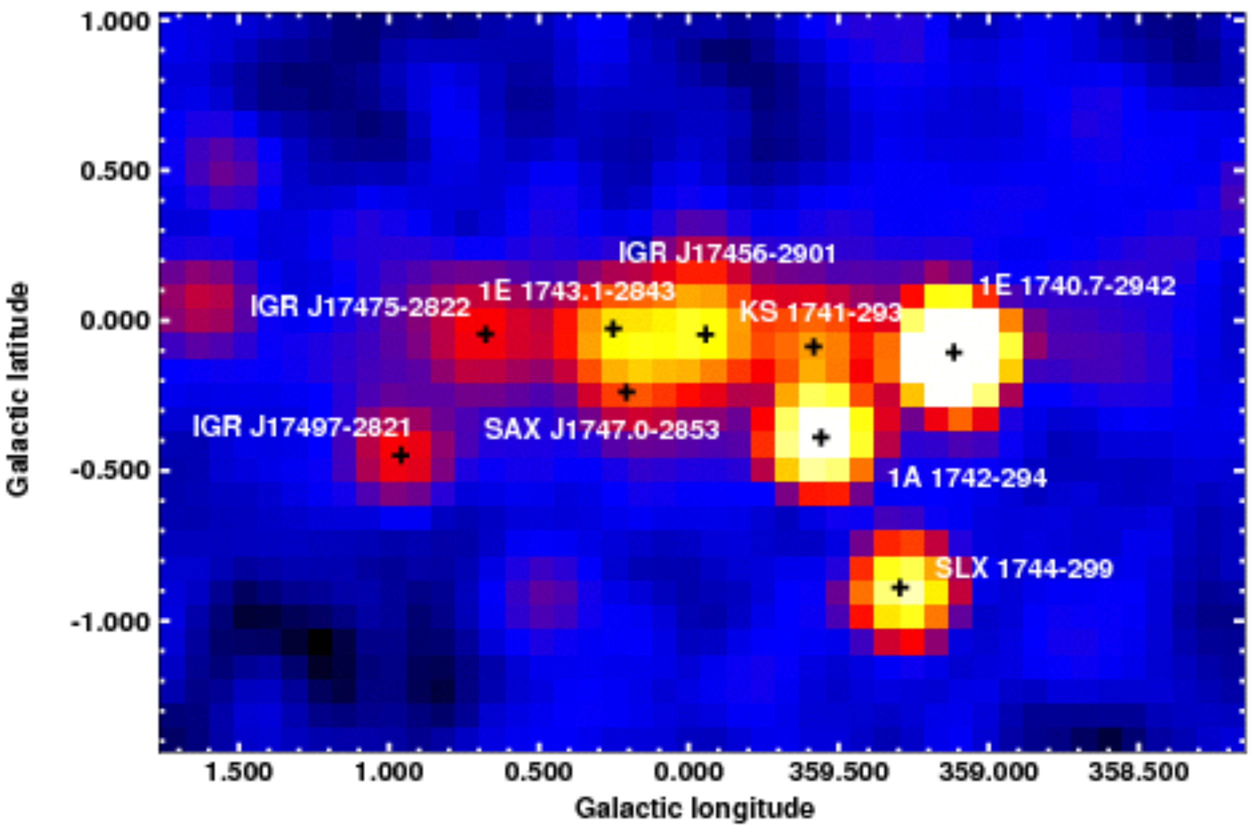
Shadowgrams

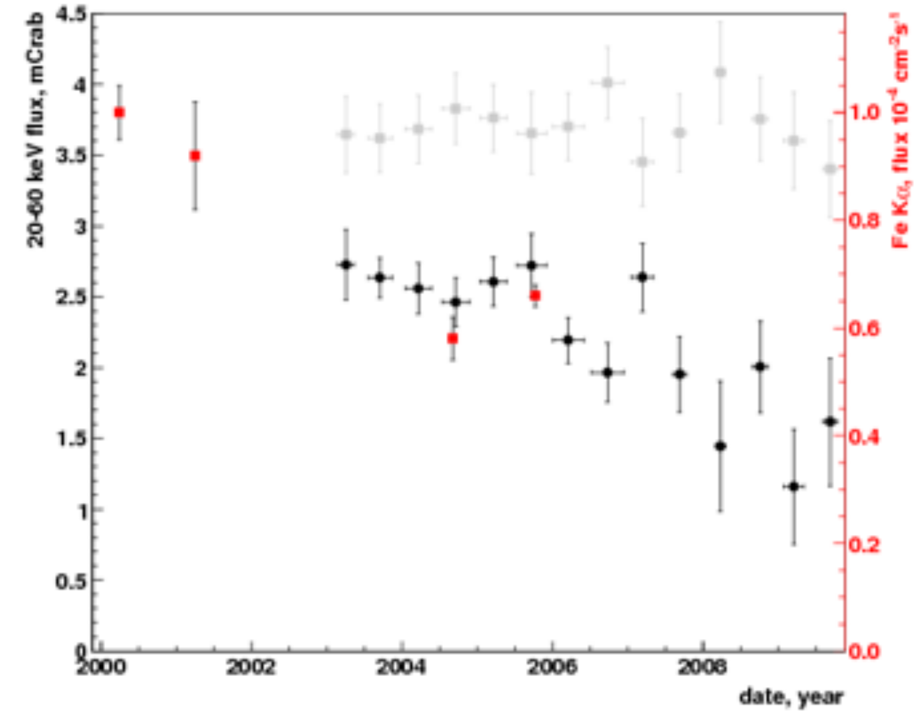
reconstructed sky map

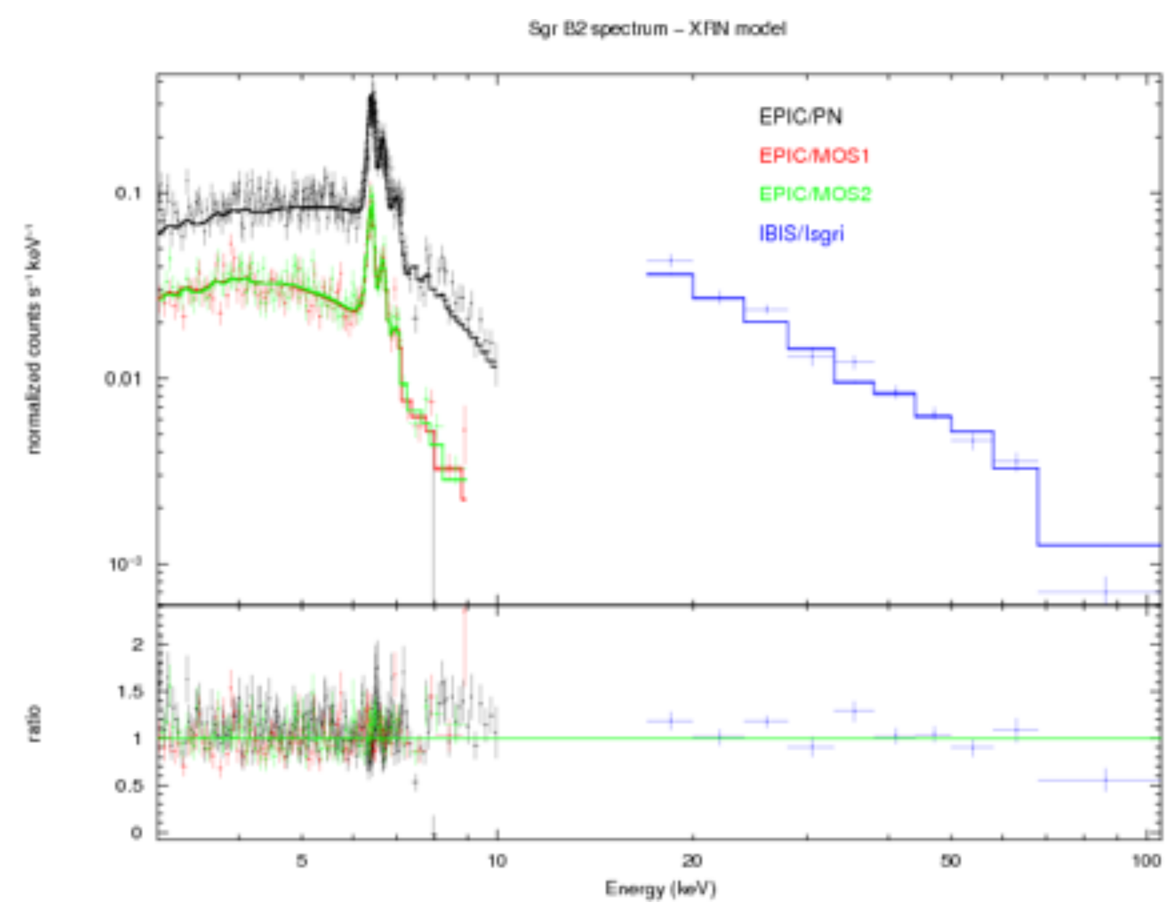
from Krivonos+07



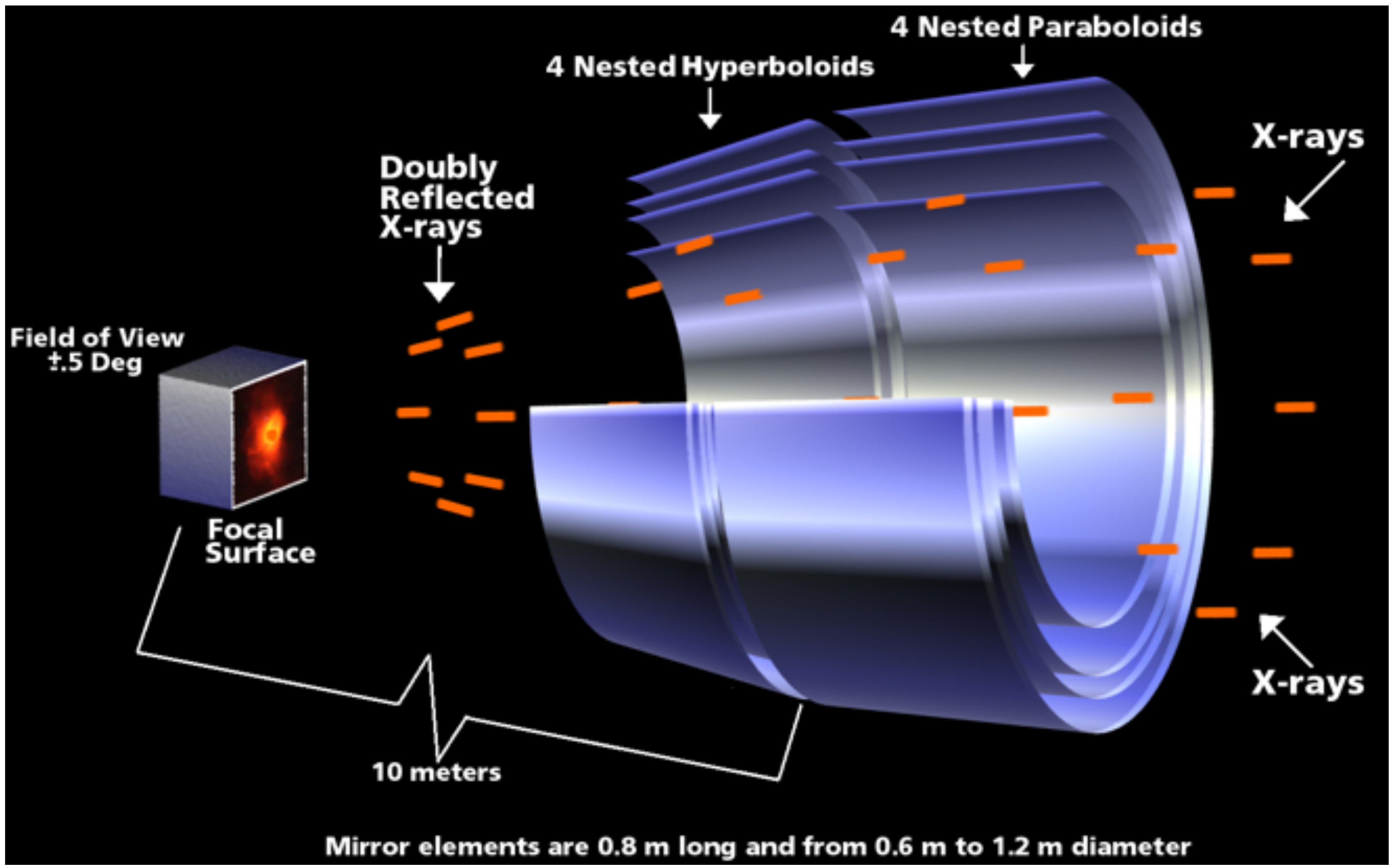
A case study: the Galactic Centre







X-ray optics



4 Nested Paraboloids
4 Nested Hyperboloids
X-rays
Doubly Reflected X-rays
Field of View ±.5 Deg
Focal Surface
X-rays
10 meters
Mirror elements are 0.8 m long and from 0.6 m to 1.2 m diameter

Data reduction in X-ray astronomy

- X-ray data analysis philosophy is similar to that of VHE astronomy, in particular spectral analysis, but:
  - Limited dependance of event list on event reconstruction algorithms
  - Higher signal to noise, shorter integration times.
  - Less combination of different observations required on average.
  - More steady observation conditions during an exposure

Data reduction in X-ray astronomy

- **Not always fully dedicated pipelines or analysis packages, especially for high level analysis**
  - Often partly rely on heasarc's ftools
  - High level analysis most of the time done with heasarc Xanadu
    - Timing (XRONOS), Spectral (XSPEC) and image analysis
  - Chandra provides high level analysis tools (but not specific to Chandra analysis)
    - sherpa (1D + 2D fitting), ISIS (for high resolution grating spectra)
- **IRF usually stored according to CalDB standard**
  - https://heasarc.gsfc.nasa.gov/docs/heasarc/caldb/caldb_doc.html
- **Most tools developed for single exposure**
  - multiple exposure analysis often require significant work from the user

Spectral Extraction and Fitting in X-rays

- **Very similar philosophy as currently used in Cherenkov astronomy**
  - 1D spectra (histogram of counts vs spectral channel) fitted with physical models using forward folding methods
  - But spectra extracted in region in detector or physical coordinate system (i.e. not in a region defined on the sphere). *Complex in case of multiple observations.*
- **Relies on OGIP data & IRF format**
  - PHA file
  - `arf`
  - `rmf`
  - Both possibly weighted to account for response variation in extended sources
  - Assumes IRF constant for all events in a given spectrum.

arf & rmf

$$m_i = m\,(E_i < E_{rec} < E_{i+1}) = \int_{E_i}^{E_{i+1}} dE_{rec} \int dE_0 \; t \; \Phi(E_0) \times A_{eff}(E_0) \times ED(E_{rec}|E_0)$$

- we rewrite the expected number of signal counts in bin i :

$$m\,(E_i < E_{rec} < E_{i+1}) = \int dE_0 \; t_{obs} \; \Phi(E_0) \times A_{eff}(E_0) \times \int_{E_i}^{E_{i+1}} ED(E_{rec}|E_0)$$
$$= \int dE_0 \; t_{obs} \; \Phi(E_0) \times \texttt{arf}(E_0) \times \texttt{rmf}(E_0, i)$$

- `arf` ancillary response function
  - 3 columns fits table (ENER_LO, ENER_HI, SPECRESP)
- `rmf` redistribution matrix function
  - MATRIX extension with 6 columns
  - for each true energy (ENER_LO, ENER_HI), redistribution matrix in contiguous groups (N_GRP, F_CHAN, N_CHAN, MATRIX)
  - EBOUNDS extension : 3 col table (CHANNEL, E_MIN, E_MAX) : bin number and rec. energy

Background estimation

- For X-ray mirrors, background often measured in the FoV of the same exposure, but empty field or closed lid observations can be used (e.g. ESAS for XMM-Newton).

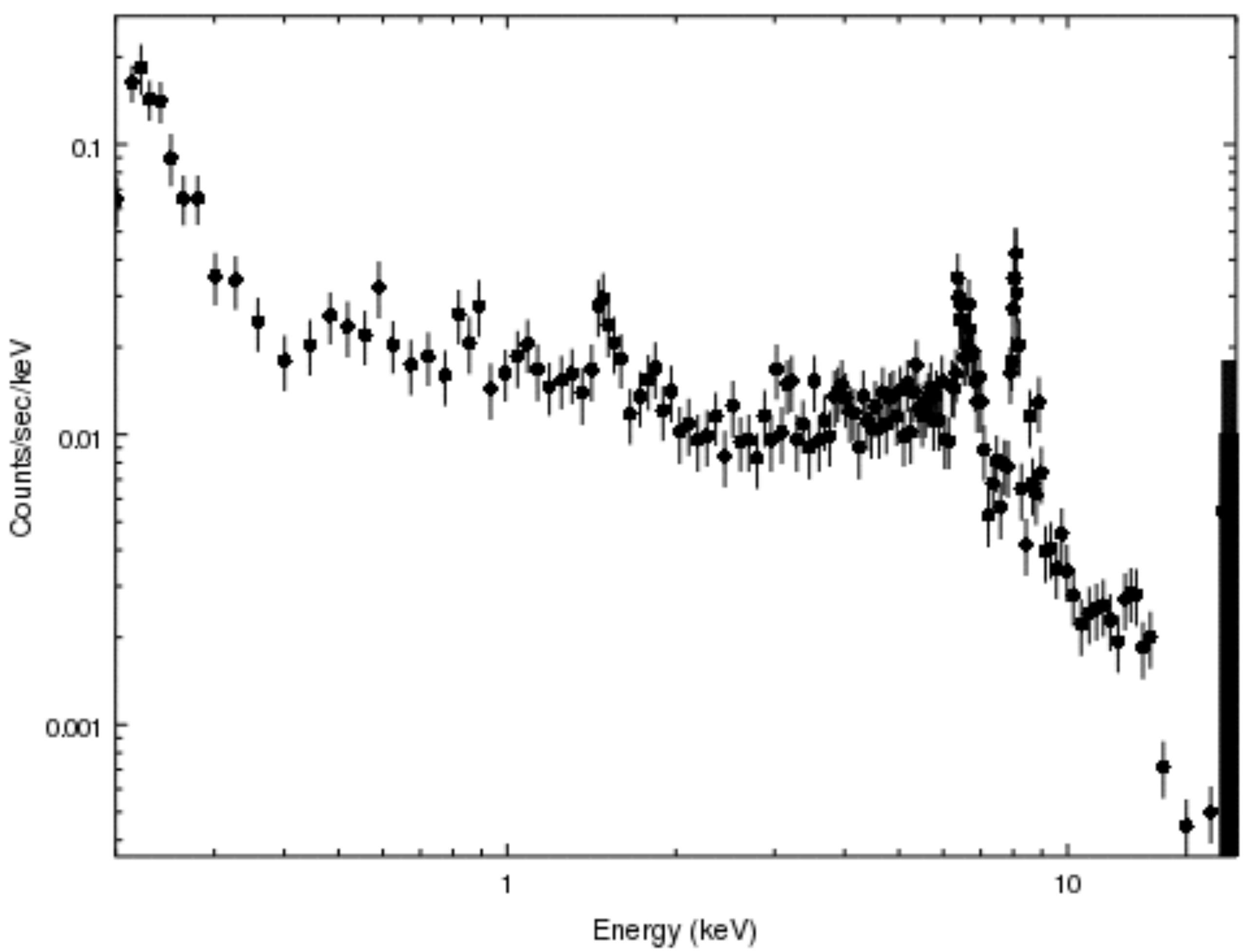
    - But all background components do not vary in a similar manner in the FoV

- Background modeling can be used to properly remove each bkg component

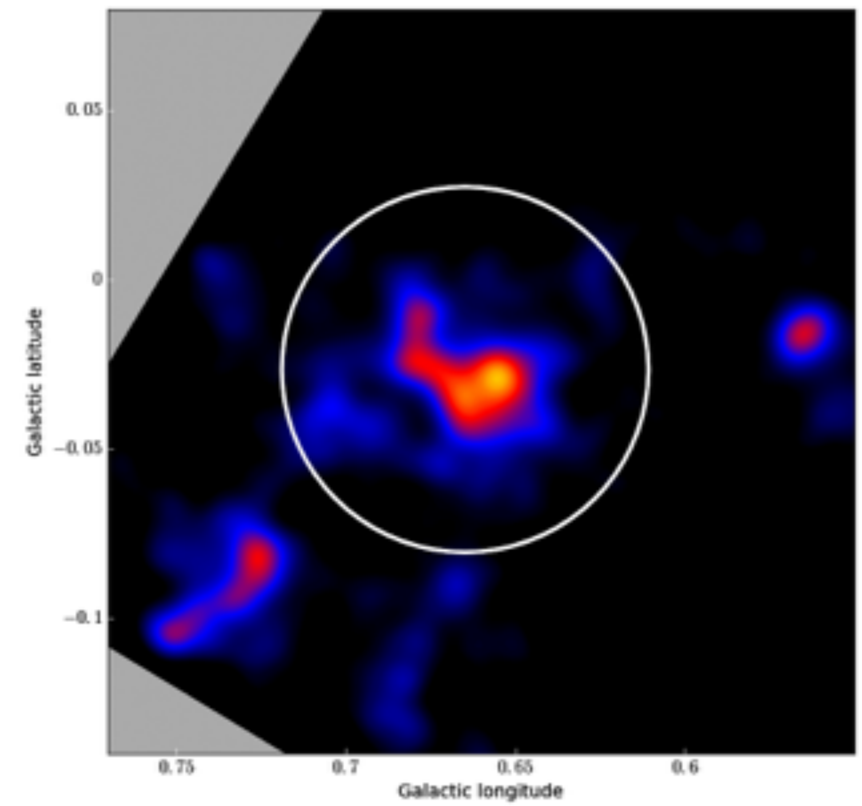
Backgrounds in an X-ray imager

- **Typical background consists of:**
  - **Quiescent Particles Bkg (QPB)**
    - Not modulated by mirrors or instrument responses
    - Steady during an observation but vary over time
  - **Solar Flare Particles** (large contamination removed during filtering process)
  - **Cosmic X-ray Bkg (CXB)**
    - Astrophysical background modulated by mirrors and IRF. Modified by foreground absorption
  - **Local astrophysical backgrounds**
    - Can vary in the FoV

A case study: The Galactic Centre



XMM spectrum

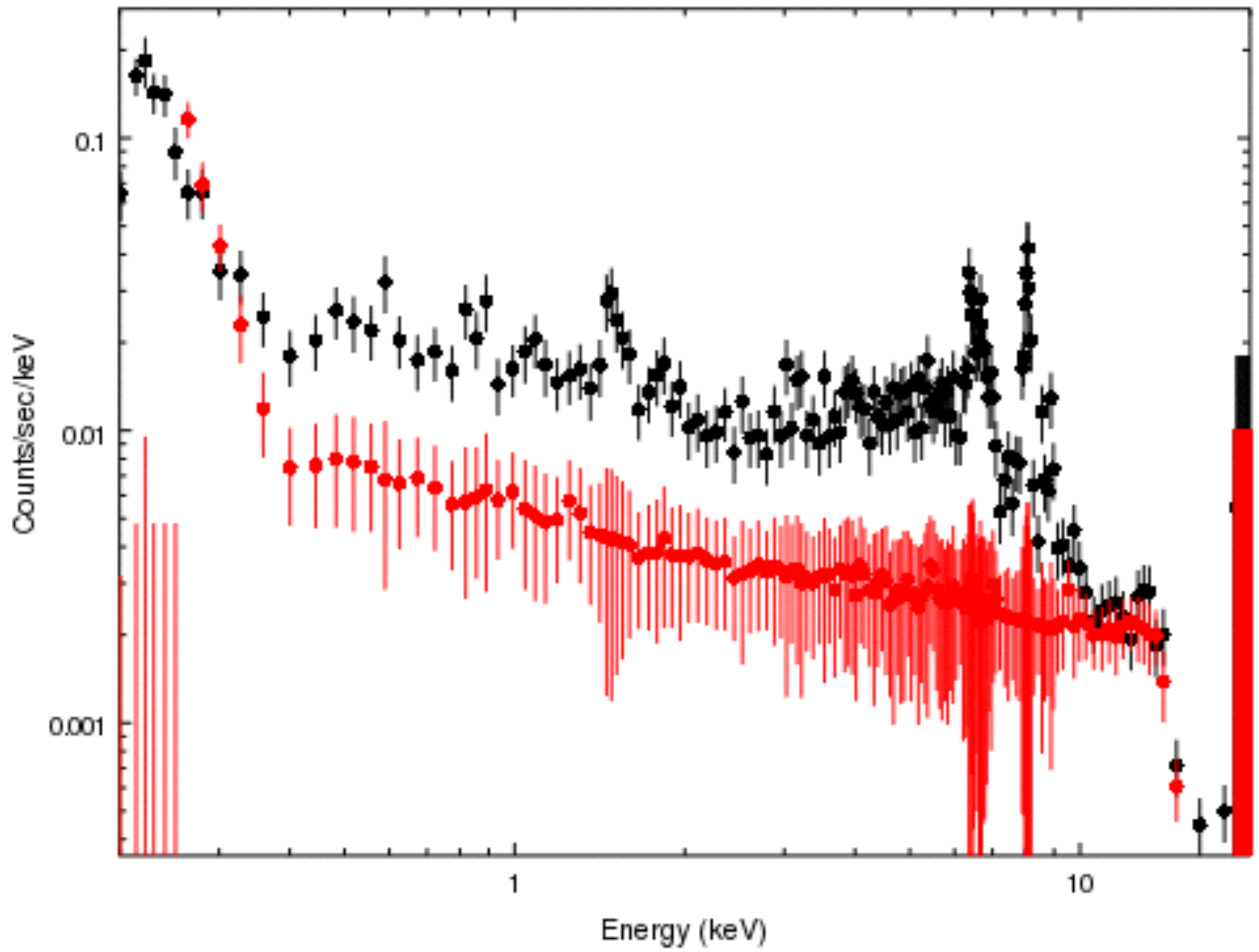


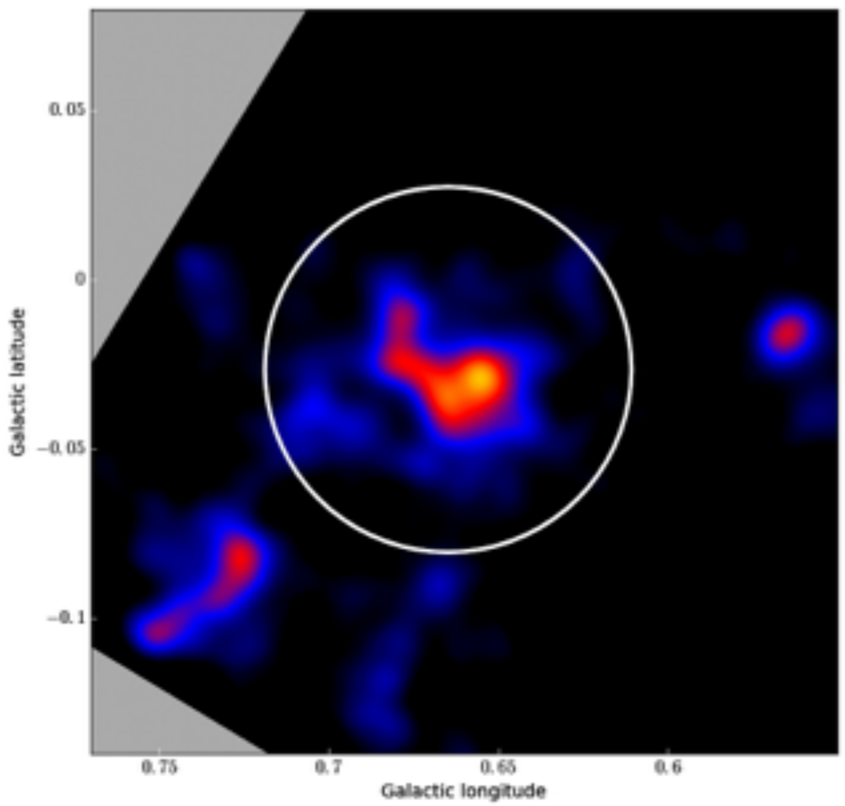
Chandra, 6.4 keV line

Sgr B2 mol. cloud

Data

A case study: The Galactic Centre

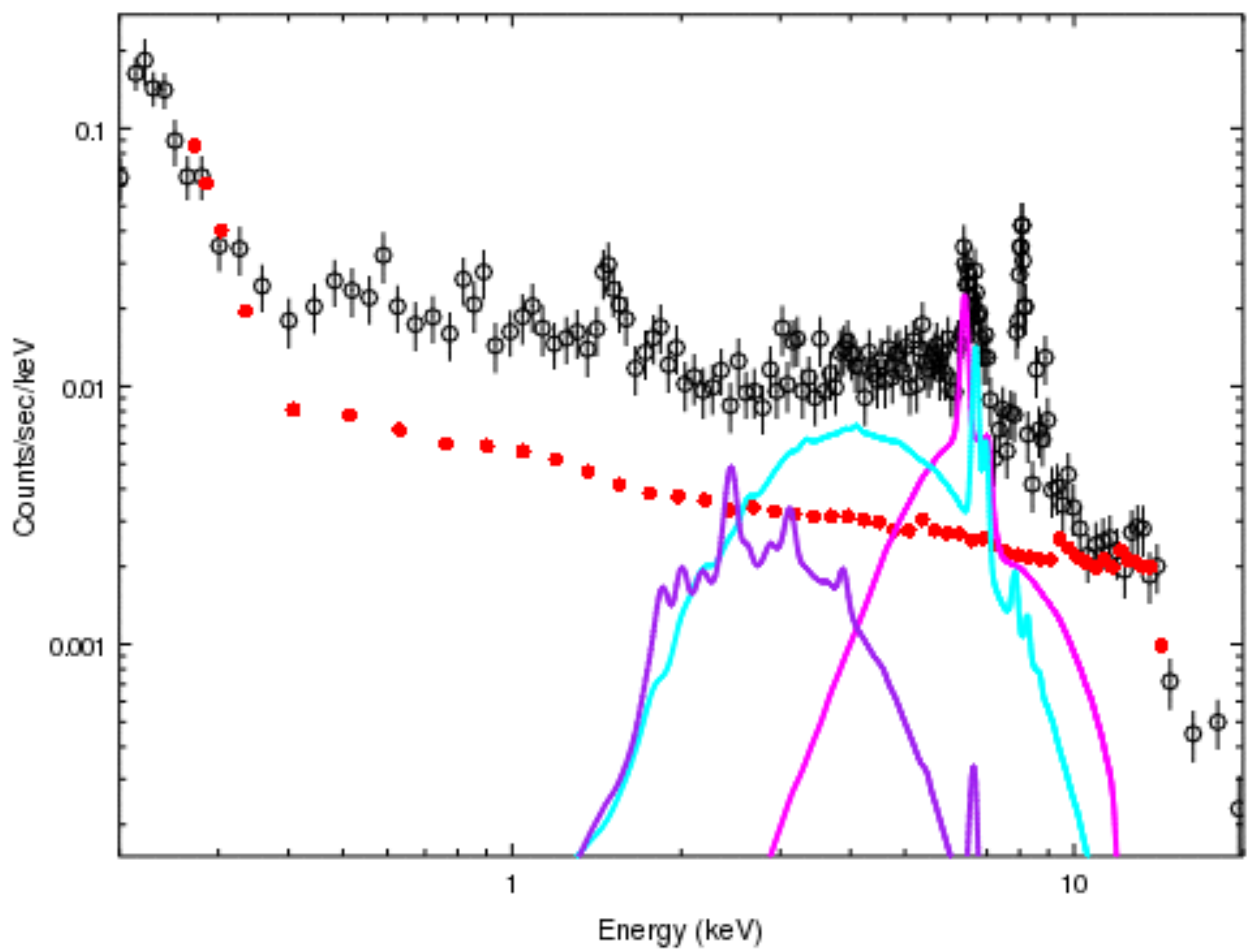


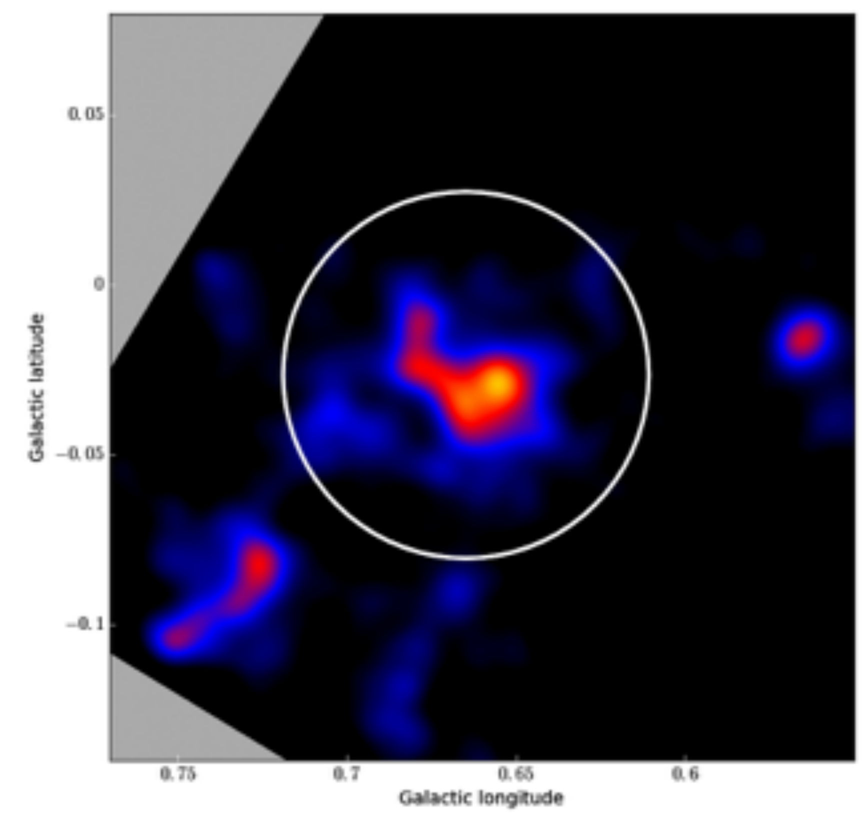


Data

QPB from closed lid observations (ESAS)

A case study: The Galactic Centre





Spectral fit performed on a single spectrum or a set of spectra

Spectral Fitting in X-rays

- Statistics used during spectral fitting often gaussian (chisquare) or modified Poisson (e.g. chi-square gehrels, default option in sherpa)
  - Result can be sensitive to energy binning. Grouping is an important element.
- ON-OFF likelihood implemented in all fitting tools but not so frequently used
  - CStat in XSPEC
  - WSTAT in sherpa and ISIS

Spectral Fitting in X-rays

- We have ON_i and OFF_i events per bin i. We have want to maximize :

$$\log \mathscr{L} = \sum_i ON_i \log(m_i + b_i) - (m_i + b_i) + OFF_i \log\left(\frac{b_i}{\alpha}\right) - \frac{b_i}{\alpha}$$

- We have no model for background, so we want to marginalize over b_i

$$\frac{\partial \log \mathscr{L}}{\partial b_i} = \frac{ON_i}{m_i + b_i} + \frac{OFF_i}{b_i} - \left(1 + \frac{1}{\alpha}\right) = 0$$

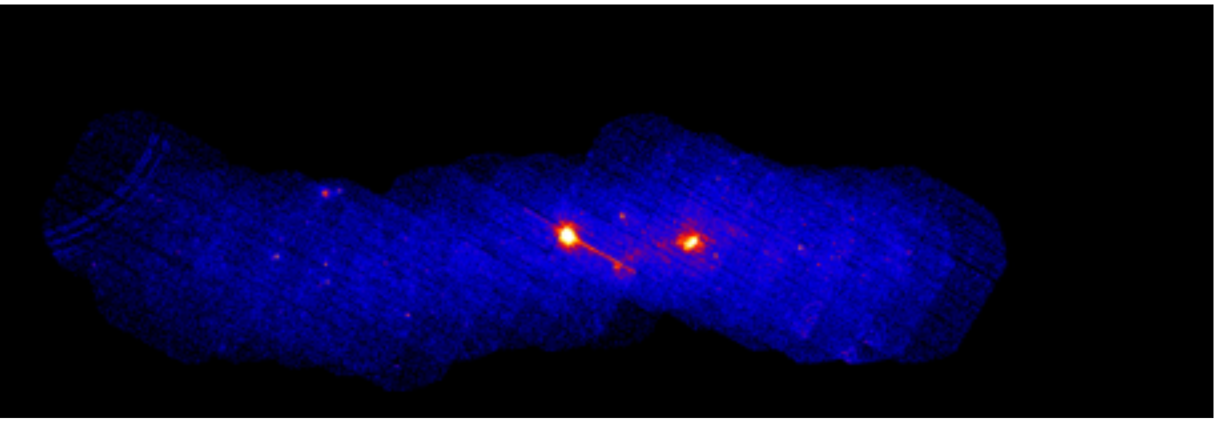
- Hence

$$b_i = f(m_i) = \frac{1}{2}\left[\frac{ON_i + OFF_i}{(1+\frac{1}{\alpha})} - m_i\right] + \frac{1}{2}\sqrt{\left[m_i - \frac{ON_i + OFF_i}{(1+\frac{1}{\alpha})}\right]^2 + 4\frac{m_i\, OFF_i}{(1+\frac{1}{\alpha})}}$$

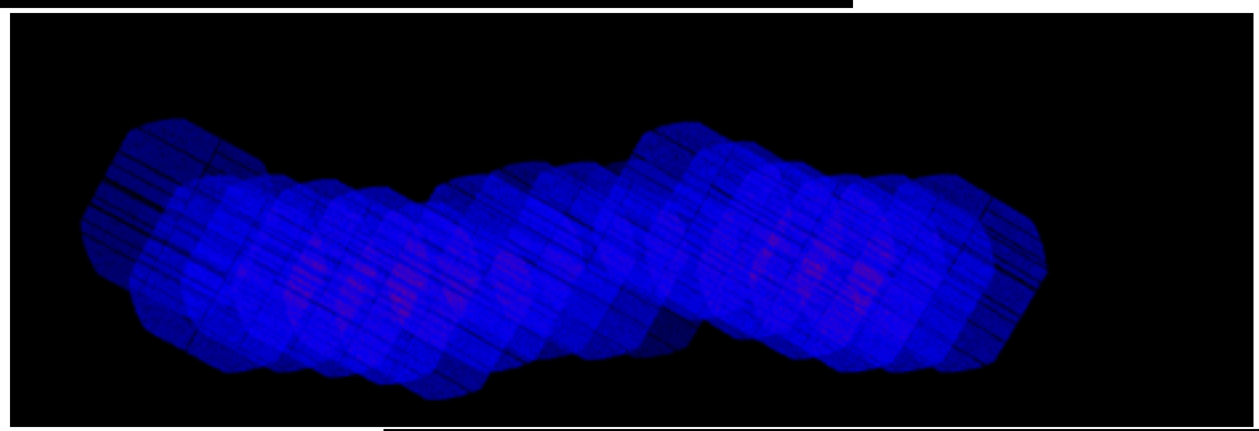
Image production and analysis

- Exposure maps taking into account vignetting (note that actual exposure depends on the assumed spectral shape)
- Background maps produced from blank sky or closed lid observations
  - Need to be reprojected on the correct astrometry
  - Normalization is complex (high energy range where QPB dominates or outside FoV)
  - Different contributions from bkg difficult to disentangle
- Out of Time events removal
- Note: source detection tools provided mostly for single exposures

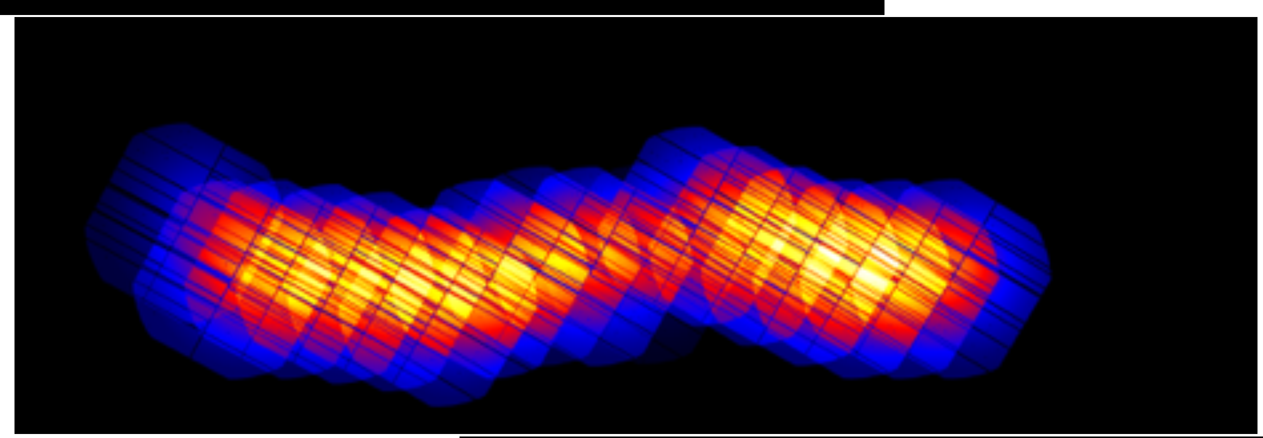
A case study: The Galactic Centre



counts

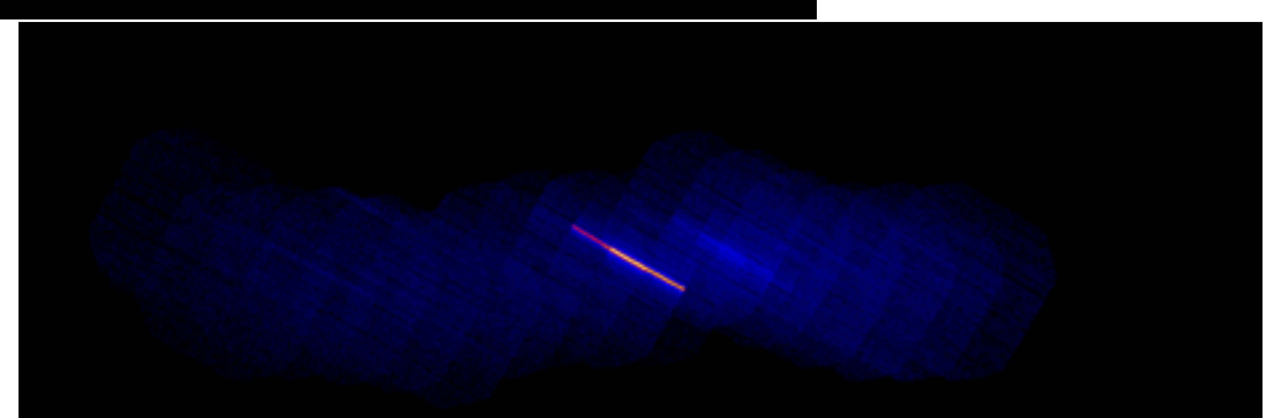


bkg



exposure

OoT



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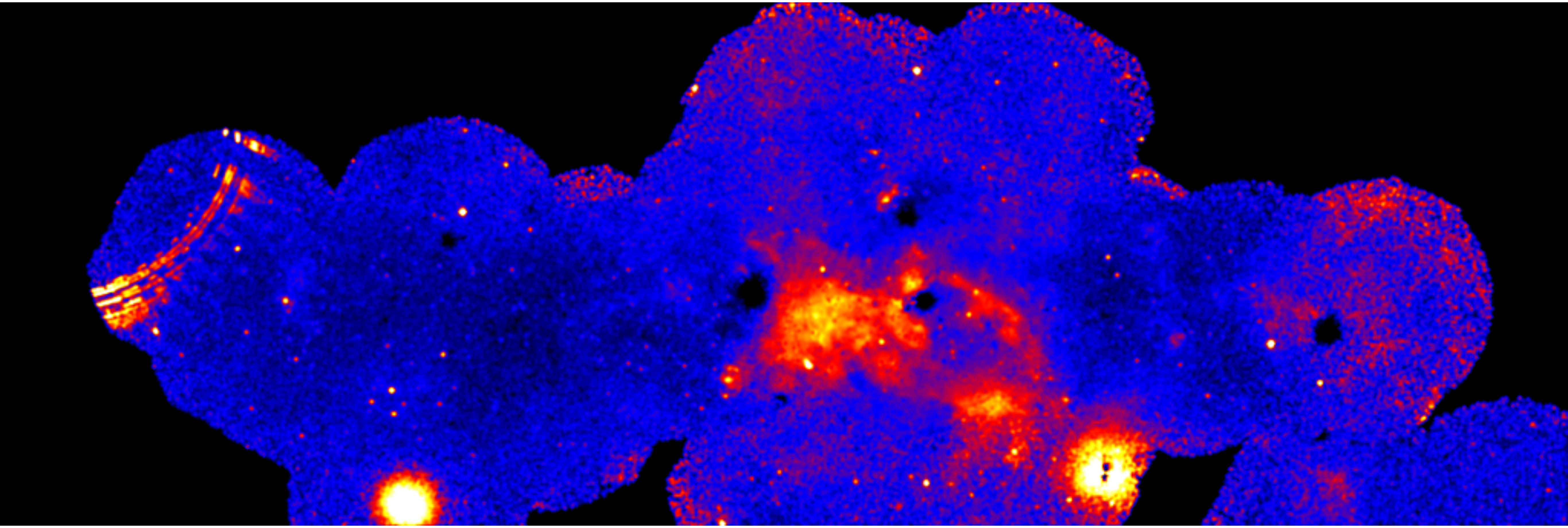
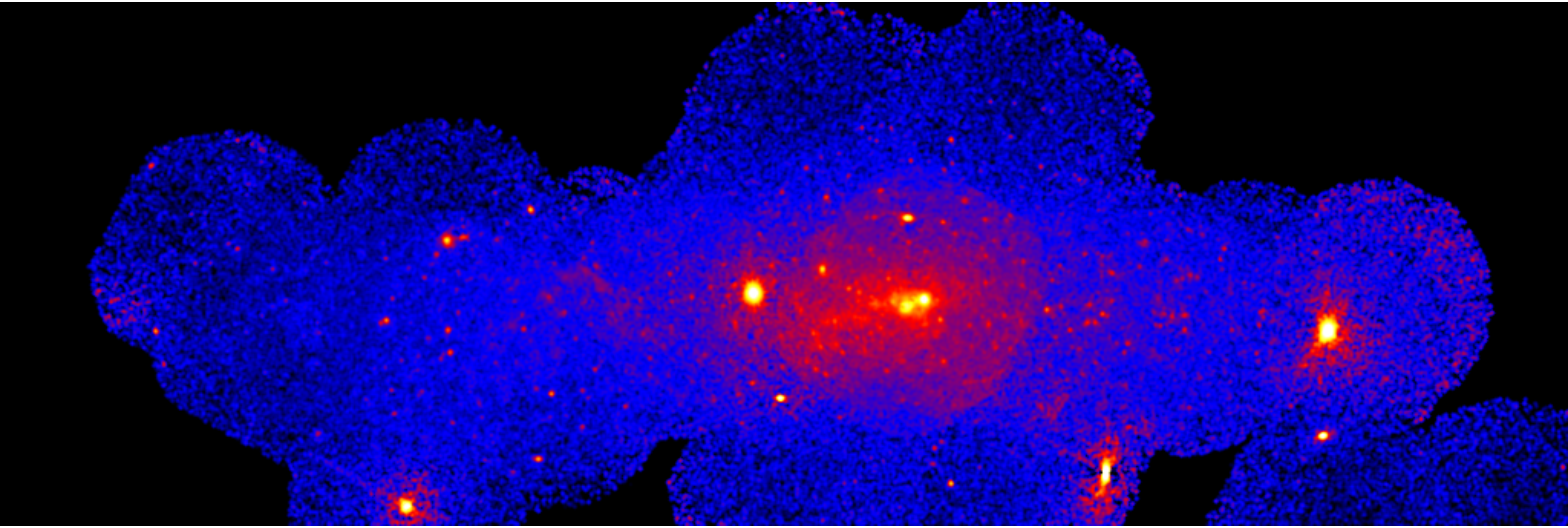


Component separation:

kT ~1 keV plasma (APEC)

A case study: The Galactic Centre



Component separation:

kT ~ 6 keV plasma (APEC)

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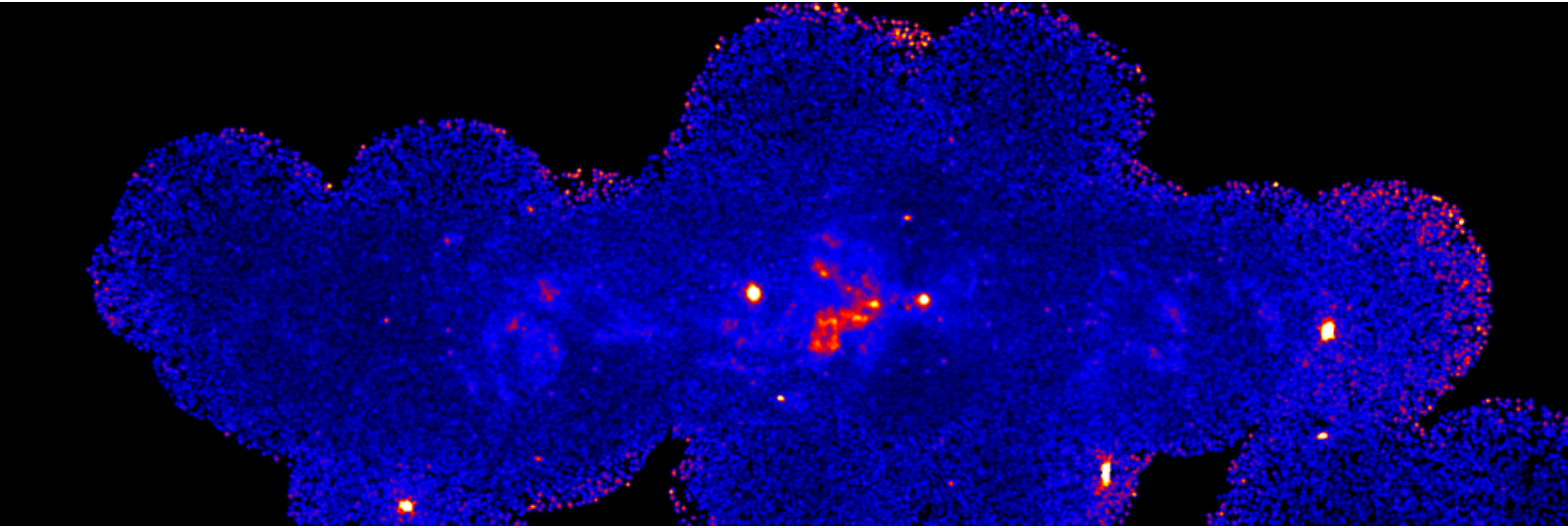

Component separation:

X-ray reflection nebulae

Summary

- X-ray data analysis philosophy is similar to that of VHE astronomy, but:
  - No dependance on event reconstruction algorithms
  - Higher signal to noise, shorter integration times.
  - Less combination of different observations required on average.
  - More steady observation conditions.
- Background extraction in data or empty field observations or closed lid data
  - Some components of astrophysical origin need to be modeled
- Detailed spectral modeling with forward folding. Less relevant in imaging analysis

A case study: The Galactic Centre