12 January 2026, *LUMIERE workshop, Orsay (France)*

Challenges of extended source analysis with XRISM

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omp
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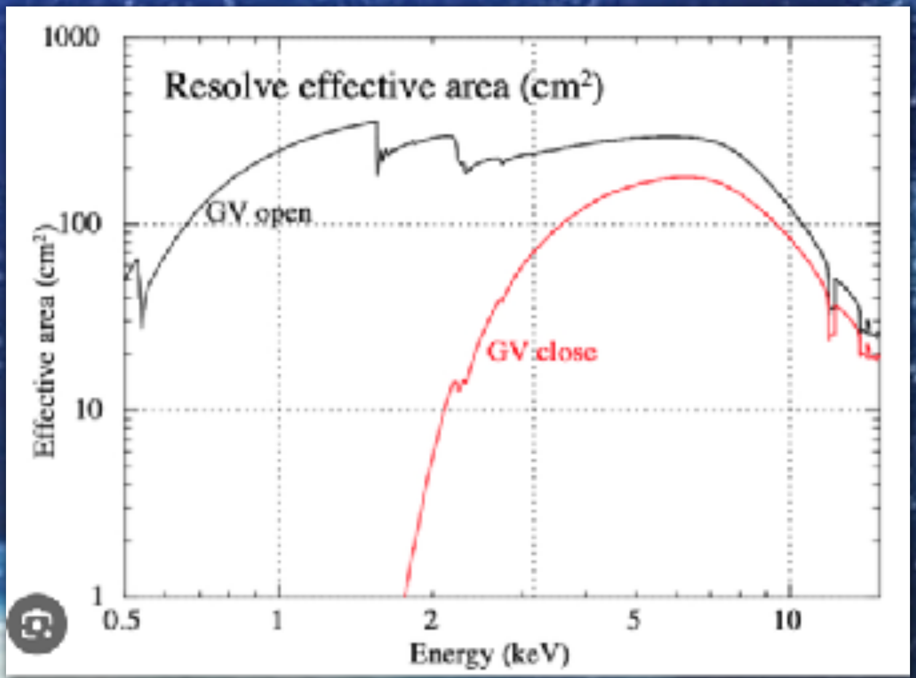
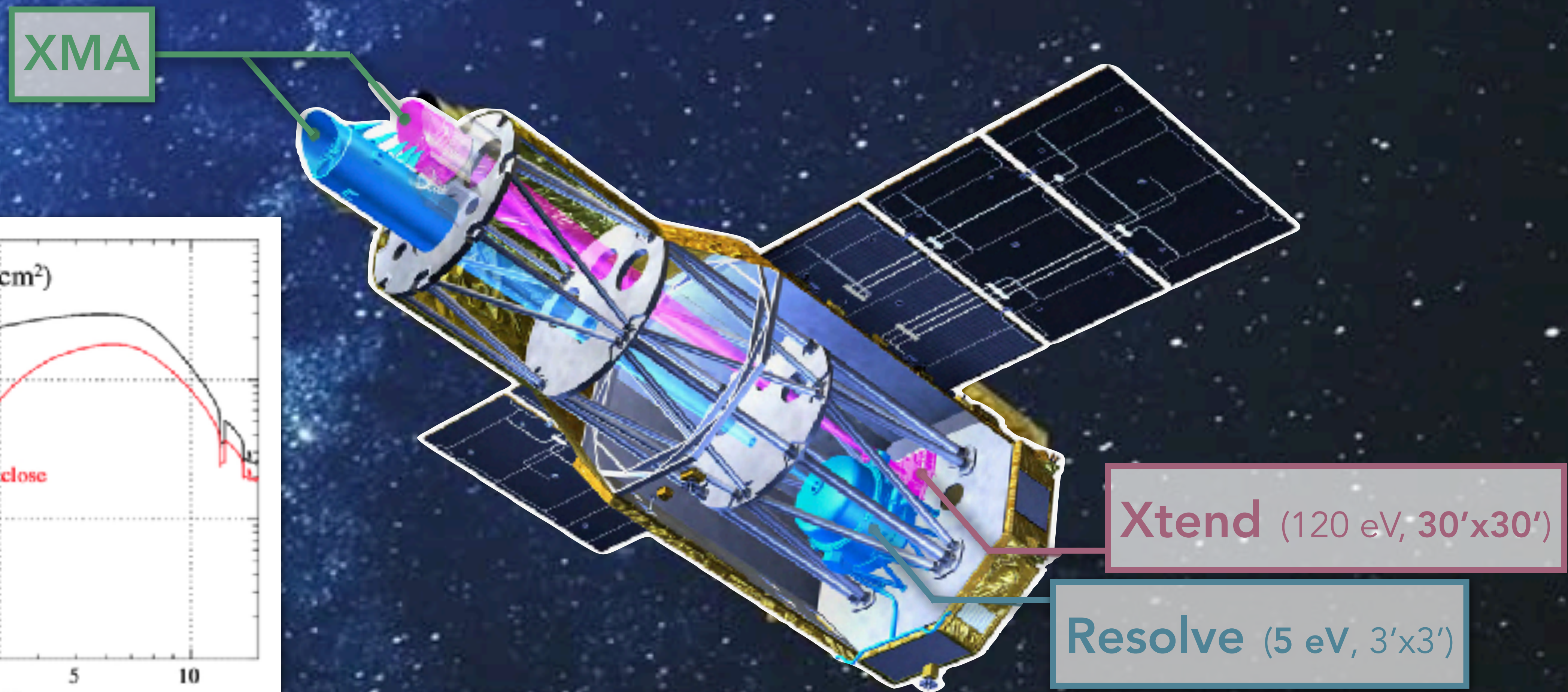
XRISM

✓ Launched on 7 September, 2023
(from Tanegashima Space Center, Japan)

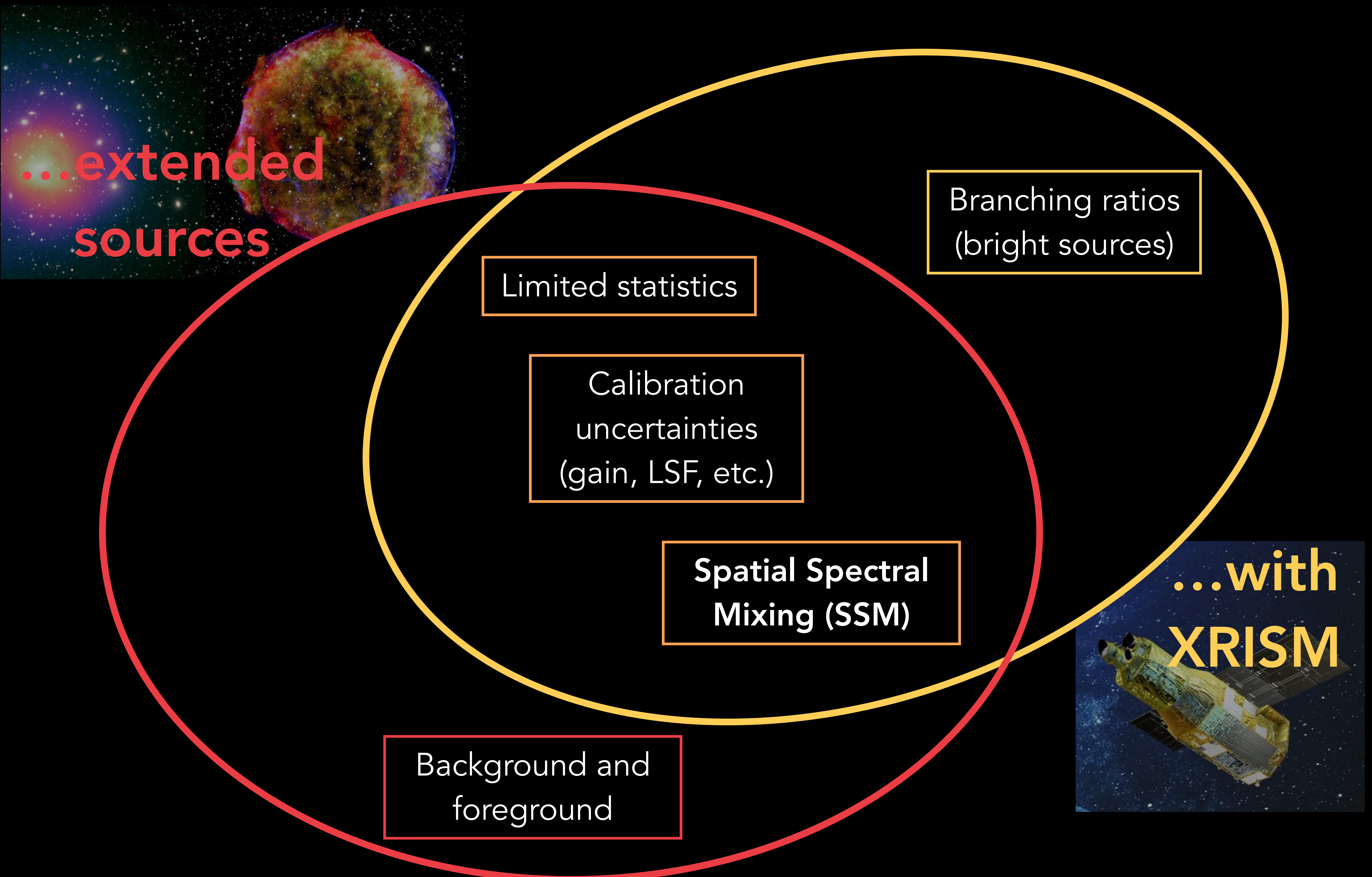




✓ General Observer (GO) cycle #1 completed
✓ General Observer (GO) cycle #2 underway
✓ General Observer (GO) cycle #3 proposal deadline on Feb 27, 2026

✓ Mission is nominal, **excellent performances**…
✓ …**however**, gate valve (Be window) has not opened

Challenges of analysing…



Limited statistics

Limited statistics

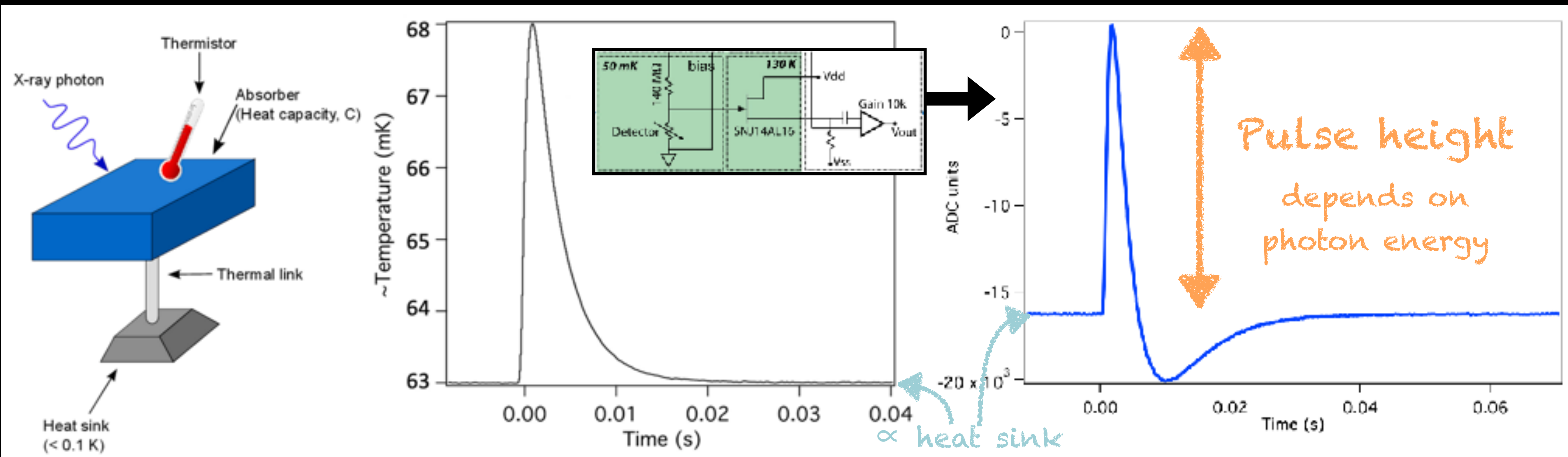
✓ **Optimise your analysis methods** (see talks by Liyi Gu, Peter Boorman, Johannes Buchner, Simon Dupourqué, etc.)

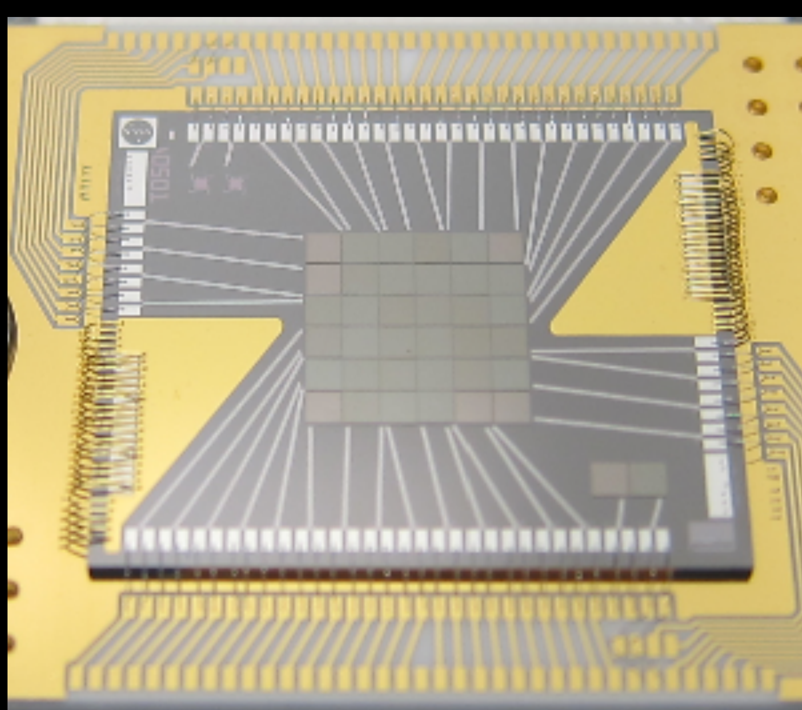
✓ **Ask for more exposure** 😉

✓ **Ask for a more sensitive telescope** (see talk by Didier Barret)…

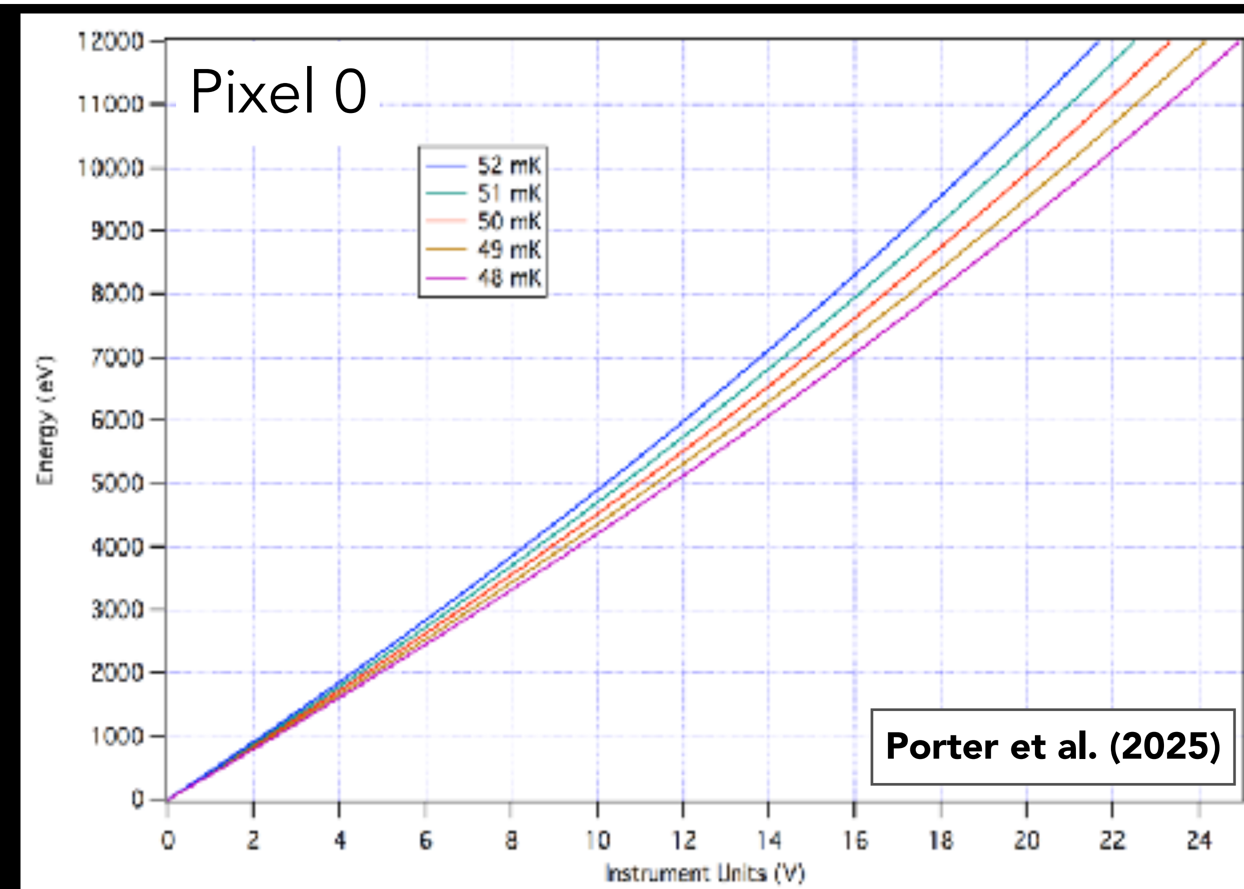
Calibration uncertainties

Energy gain calibration

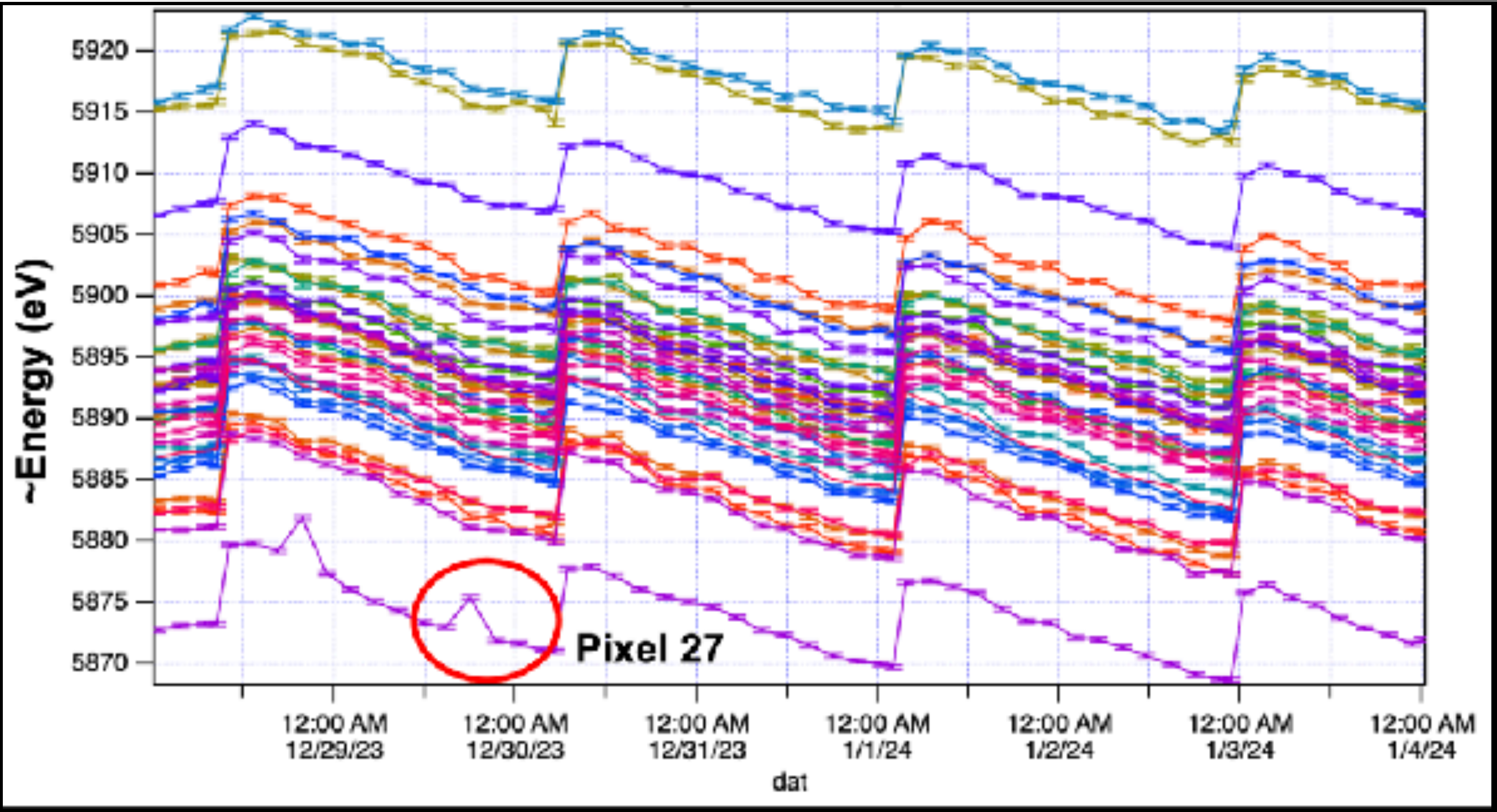




… x36 pixels!



Energy gain calibration



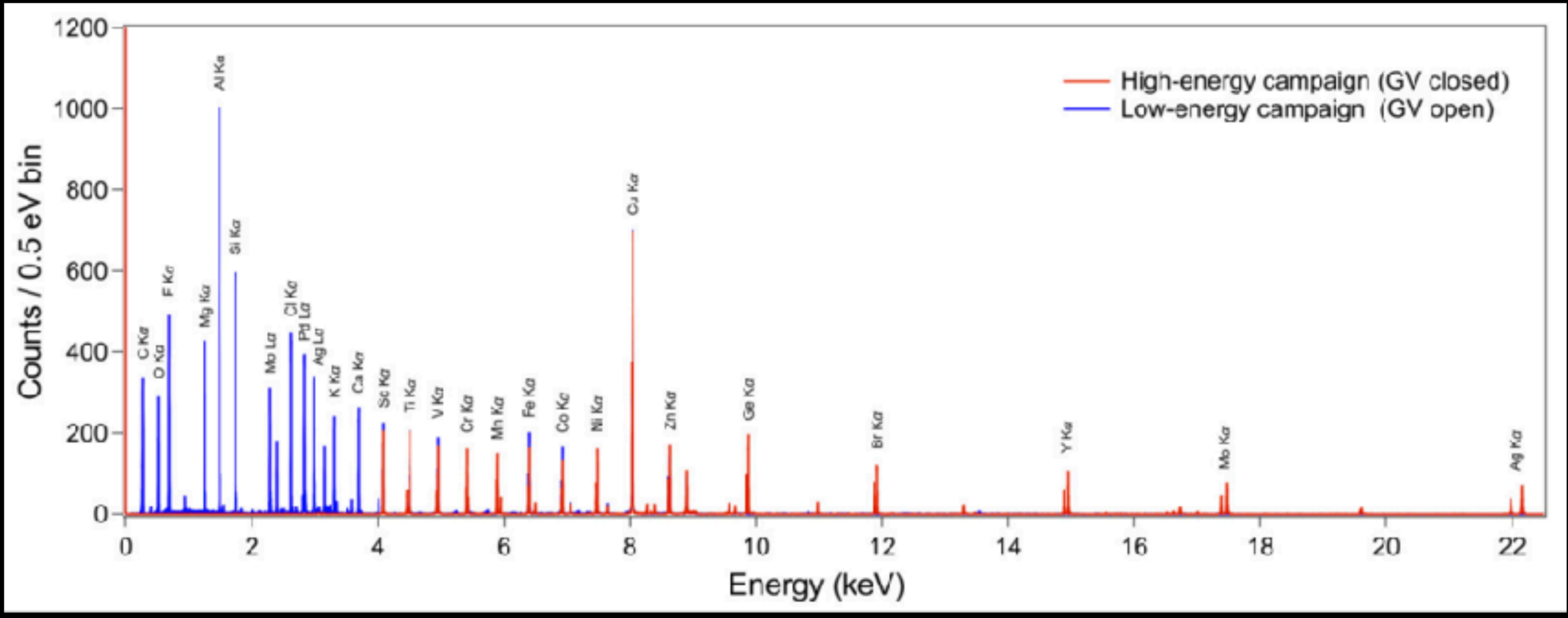
Flight calibration

Fiducials: Gain tracking using the Filter Wheel ^{55}Fe source during Earth eclipse (Centaurus cluster for ~7 days)

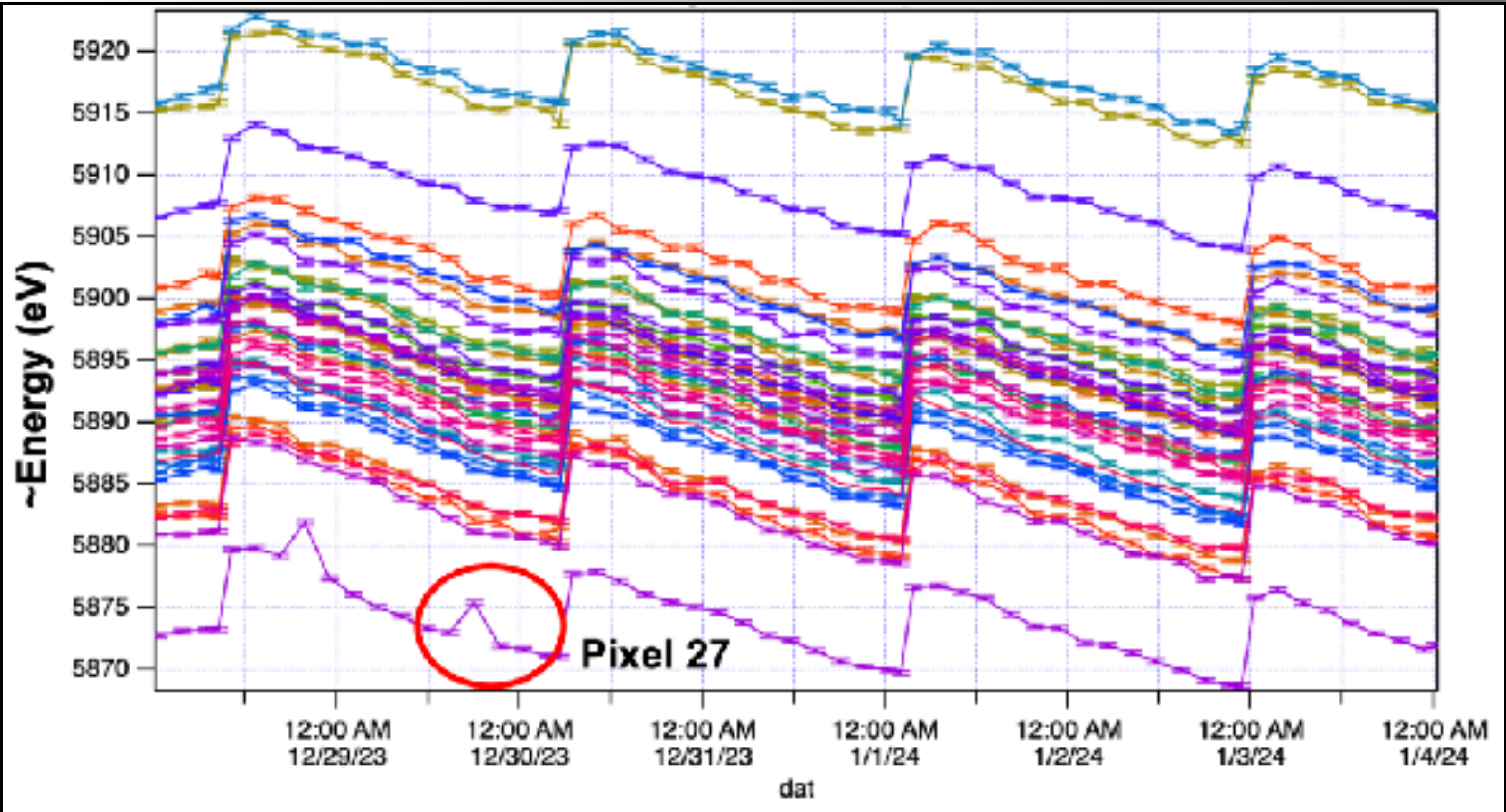
Credit: F. S. Porter

Eckart et al. (2025)

Ground calibration



Energy gain calibration



Flight calibration

Fiducials: Gain tracking using the Filter Wheel ^{55}Fe source during Earth eclipse
(Centaurus cluster for ~7 days)

Credit: F. S. Porter

Schipman et al. (2024)

GVC: no line access between 2 – 5.4 keV in flight calibration!

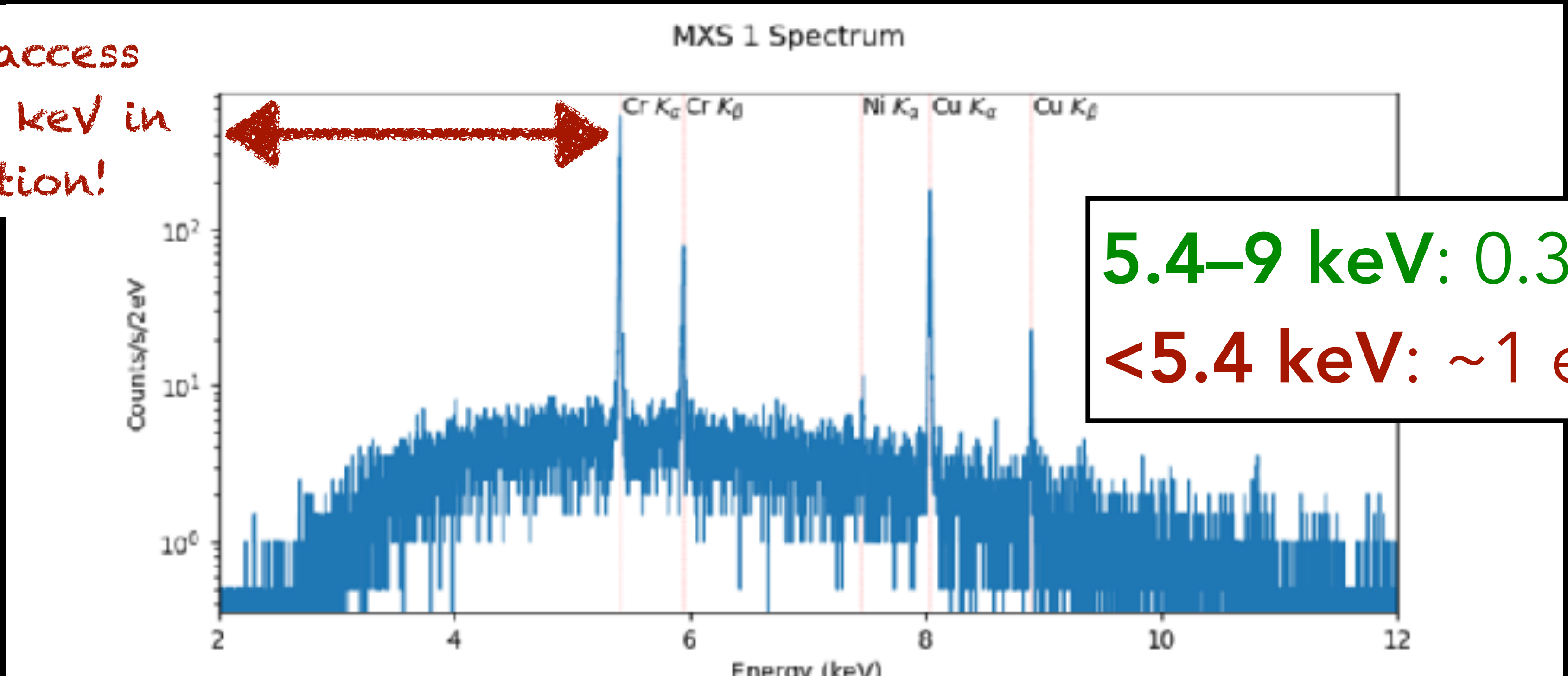


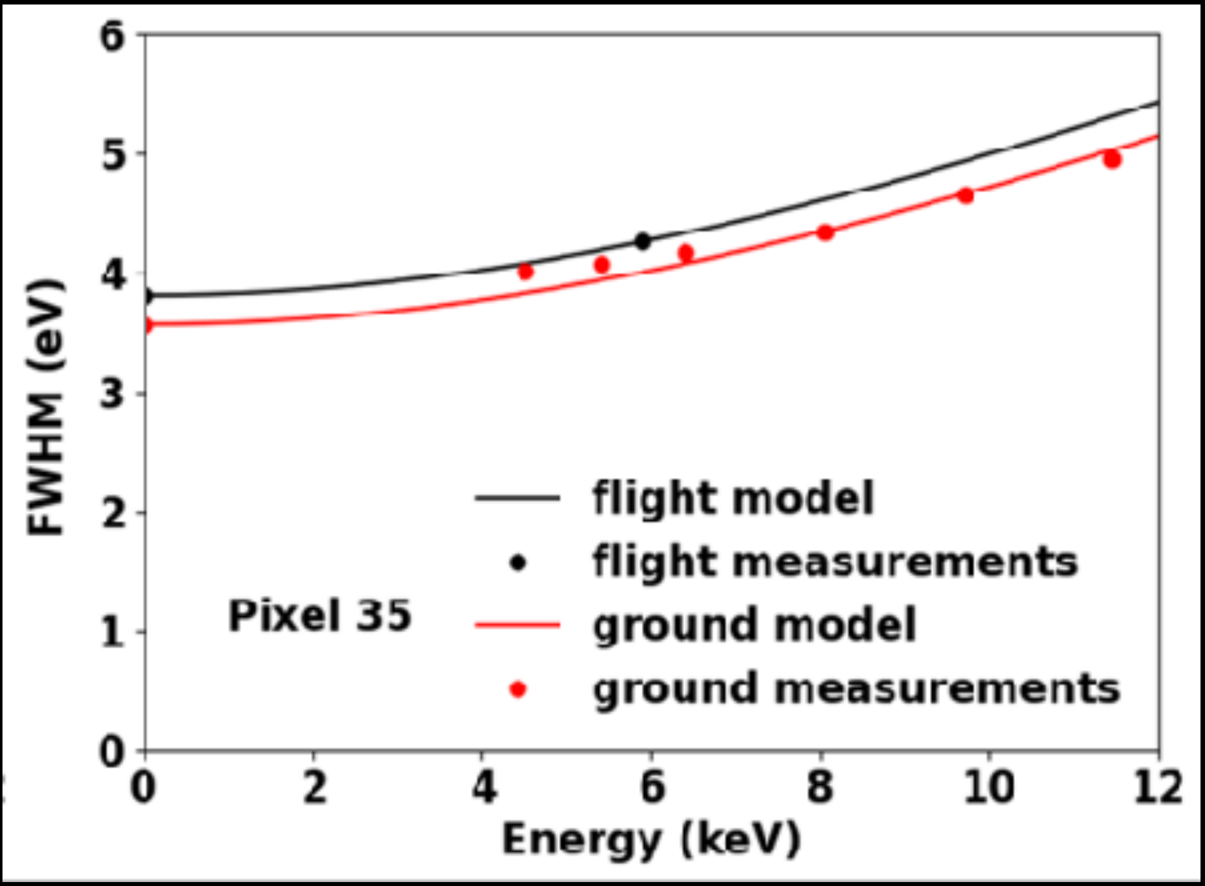
Fig 6: MXS1 (prime) in commissioning. This figure shows a standard spectrum of MXS1. The pulse parameters are described in the text. The characteristic lines of Cr K_α, Cr K_β, Cu K_α and Cu K_β as well as Ni K_α are labeled. The continuum is due to bremsstrahlung within the MXS device.

5.4–9 keV: 0.3 eV uncertainty
<5.4 keV: ~1 eV uncertainty

Flight calibration

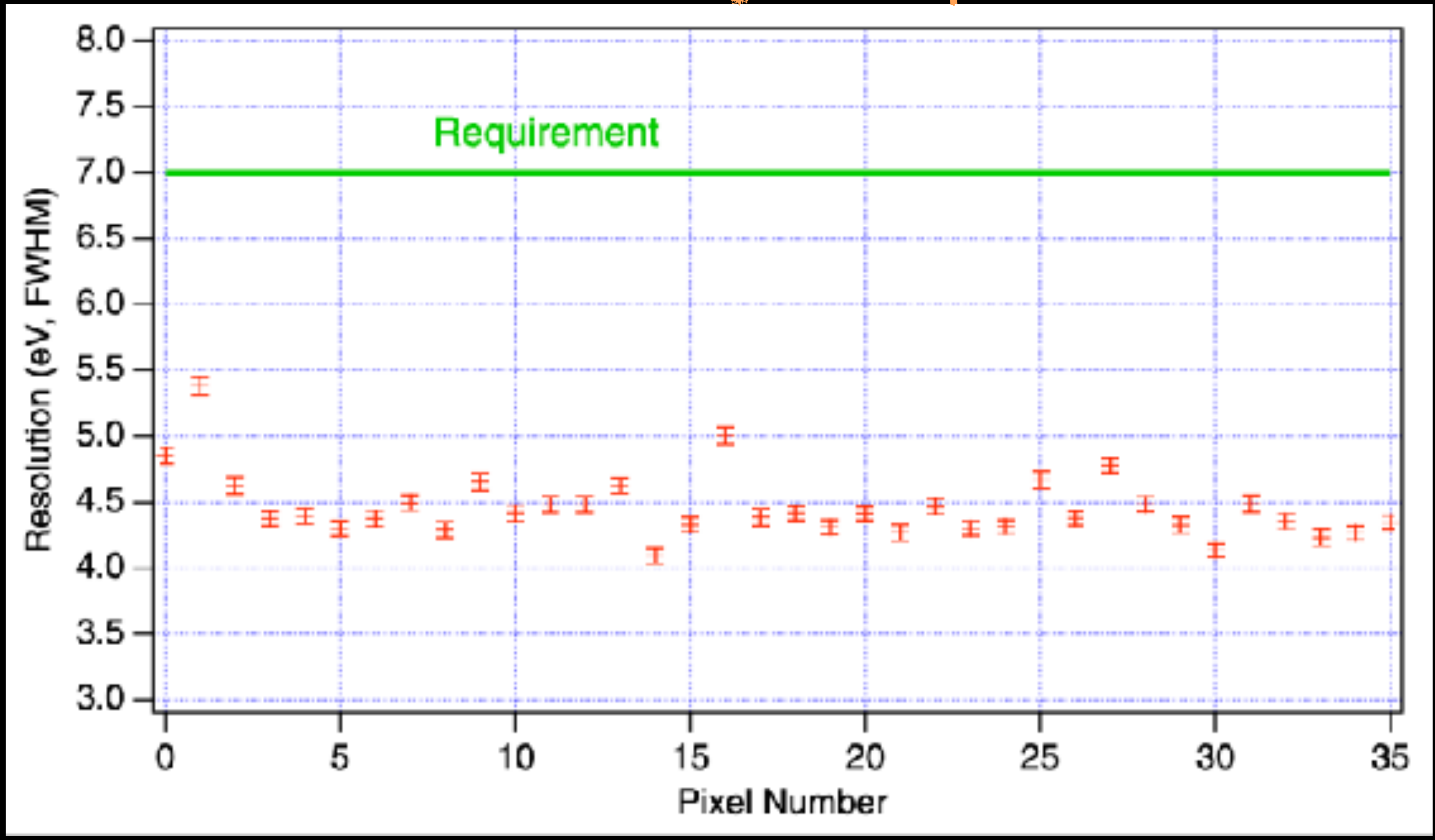
Line spread function (LSF) and energy resolution

Fixed pixel, all energies

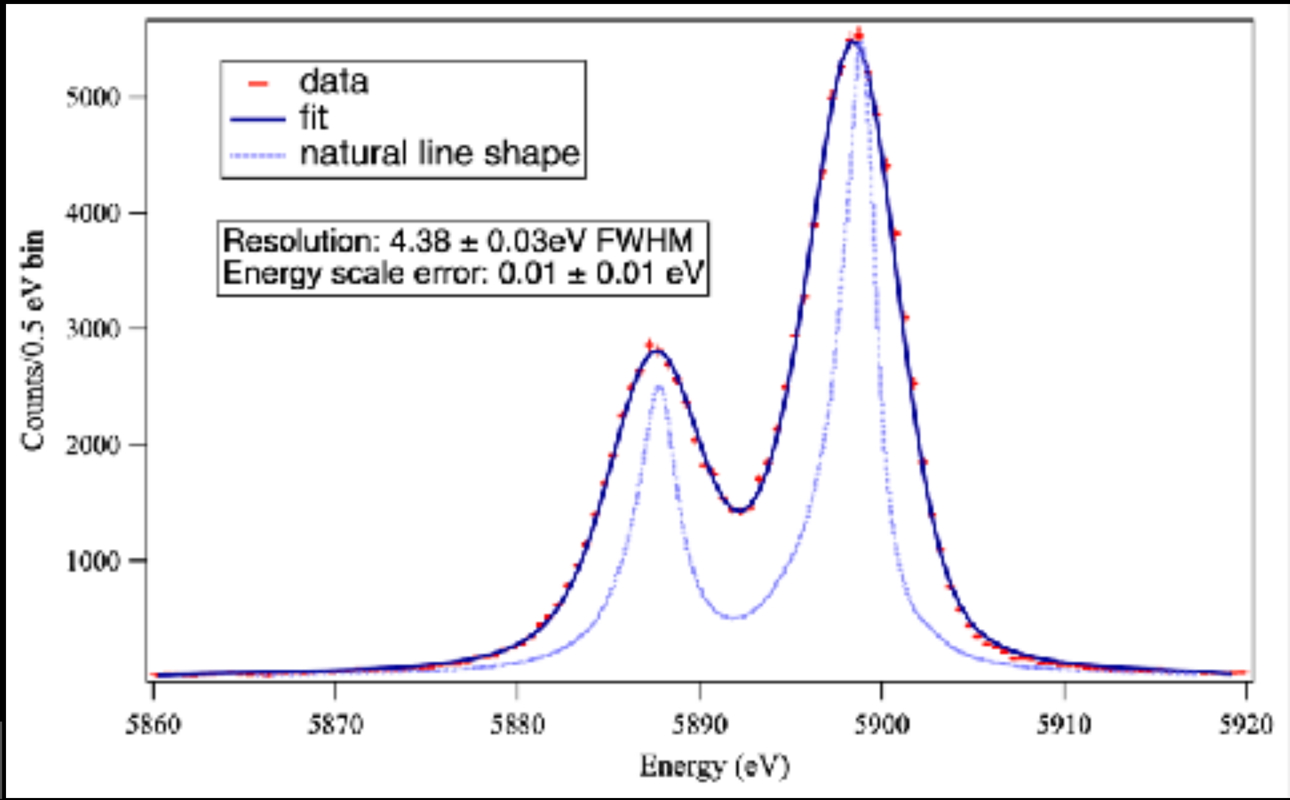


Leutenegger et al. (2025)

Fixed energy, all pixels



Porter et al. (2025)

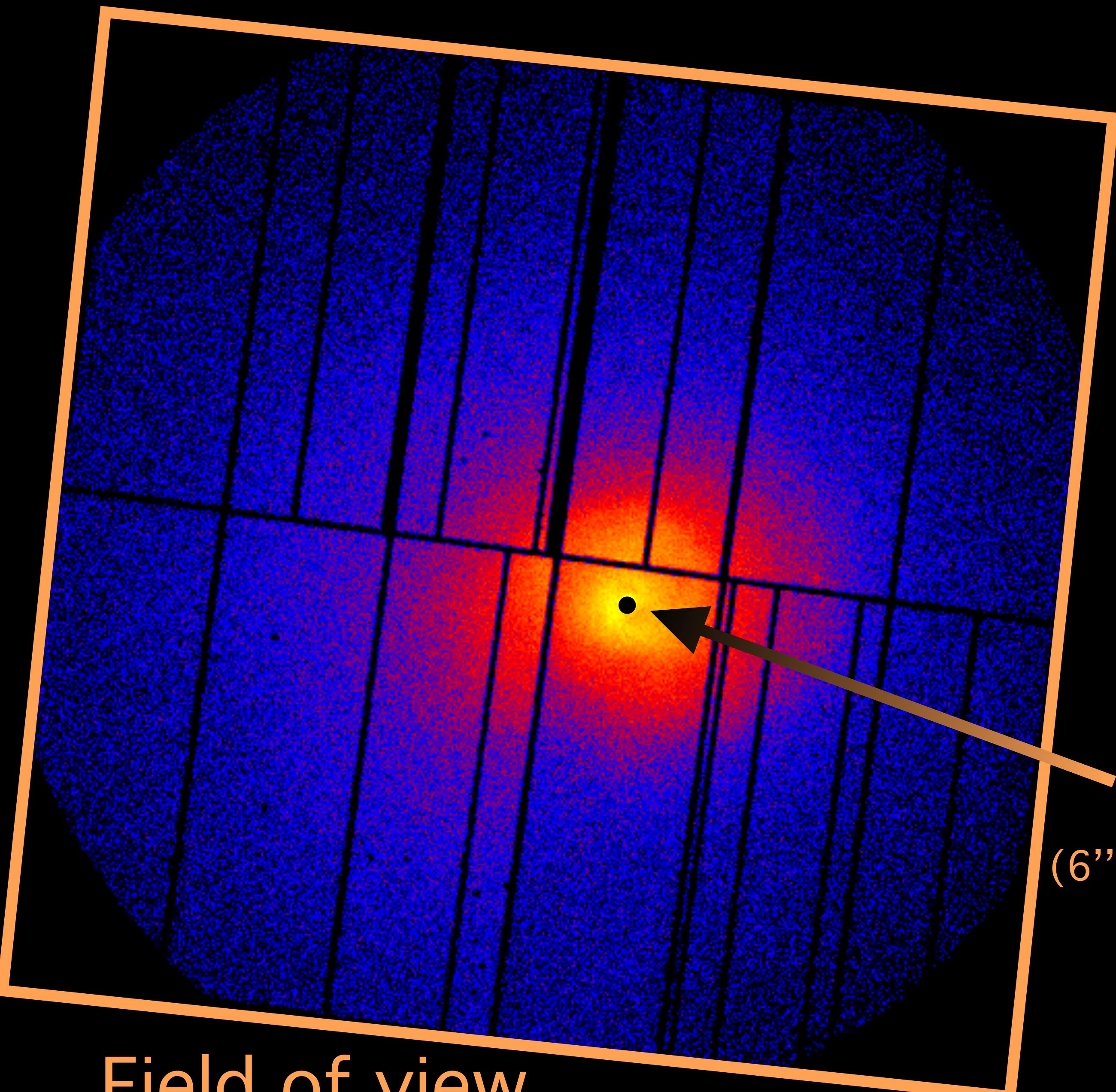


Porter et al. (2025)

Note: The LSF is not entirely Gaussian! (accounted for in the RMF)

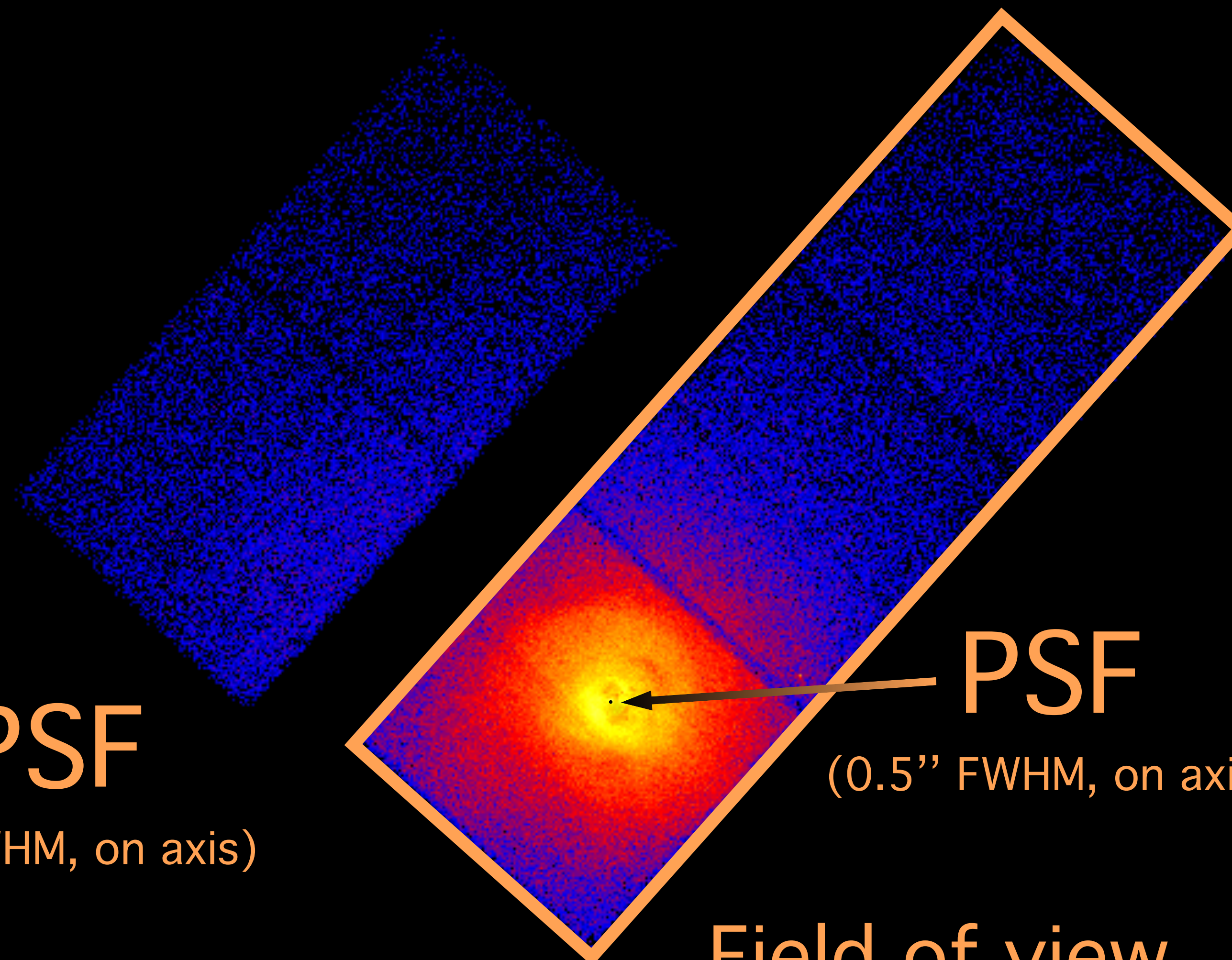
Spatial Spectral Mixing (SSM)

Point spread function (PSF) and field of view



$$\frac{6''}{25'} = 0.4\%$$

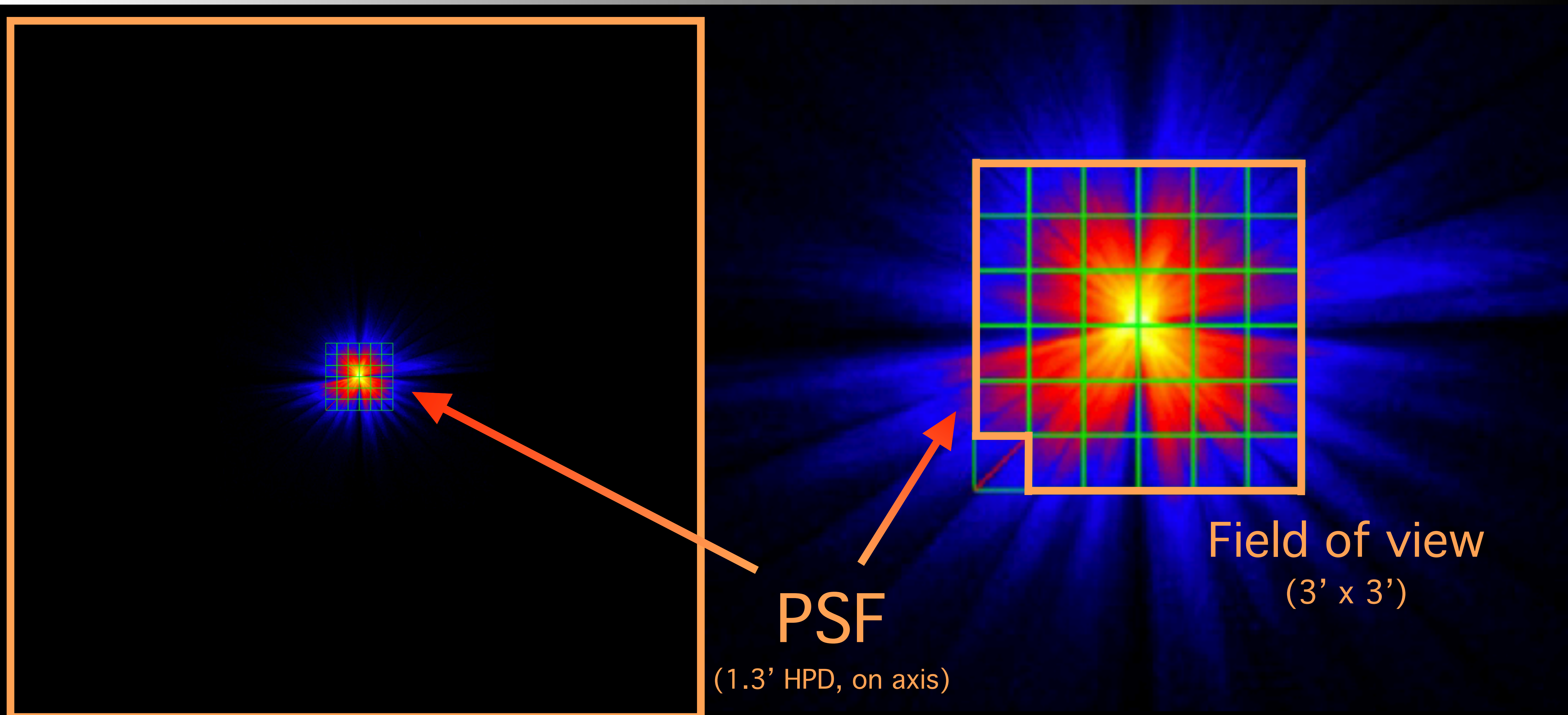
XMM-Newton EPIC



$$\frac{0.5''}{8.5'} = 0.1\%$$

Chandra ACIS

Point spread function (PSF) and field of view



Field of view
(38’ x 38’)

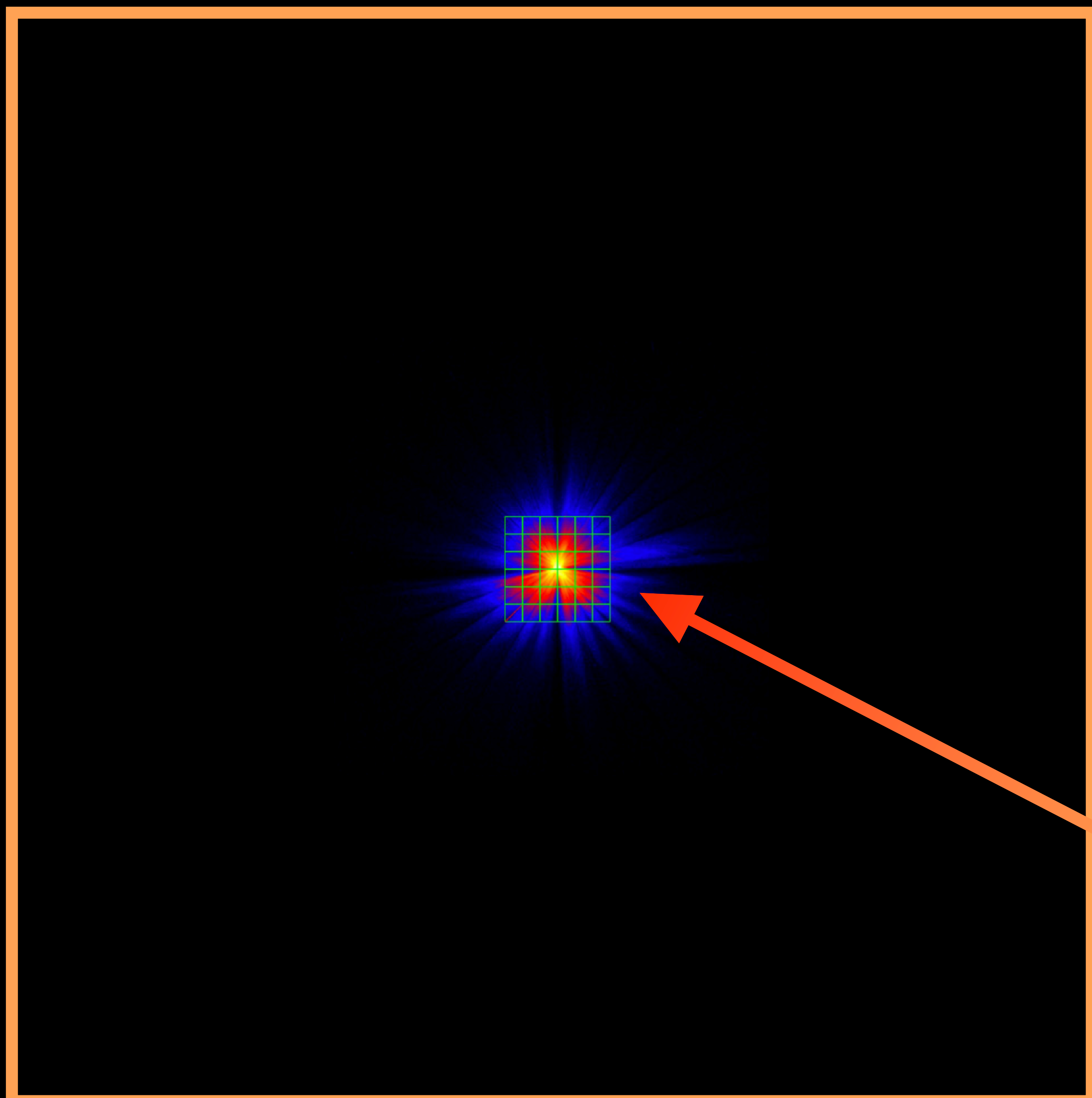
$$\frac{1.3'}{38'} = 2\%$$

$$\frac{1.3'}{3'} = 43\% \ (!)$$

XRISM Xtend

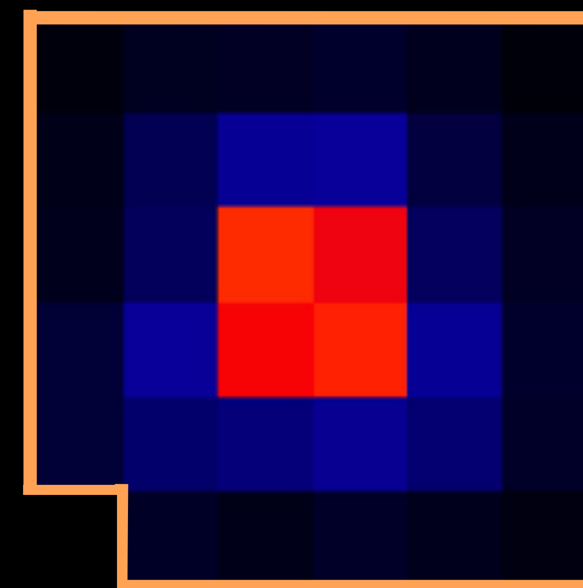
XRISM Resolve

Point spread function (PSF) and field of view



Field of view
(30' x 30')

PSF
(1.3' HPD, on axis)



Field of view
(3' x 3')

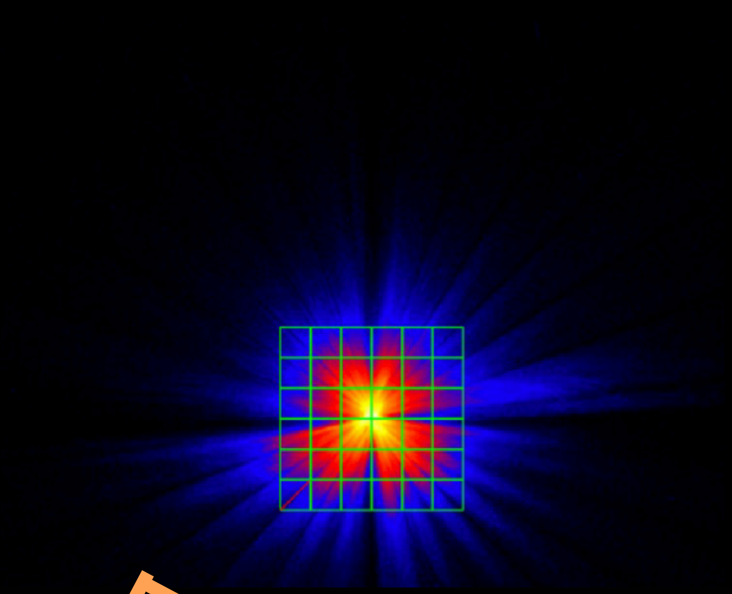
$$\frac{1.3'}{38'} = 2\%$$

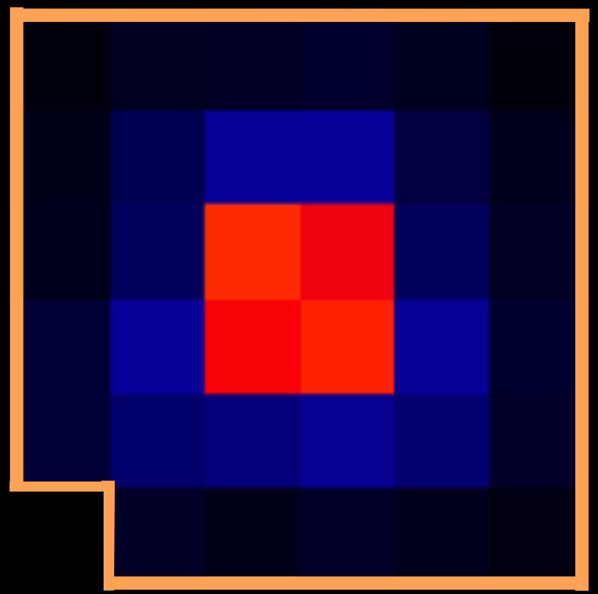
$$\frac{1.3'}{3'} = 43\% \; (!)$$

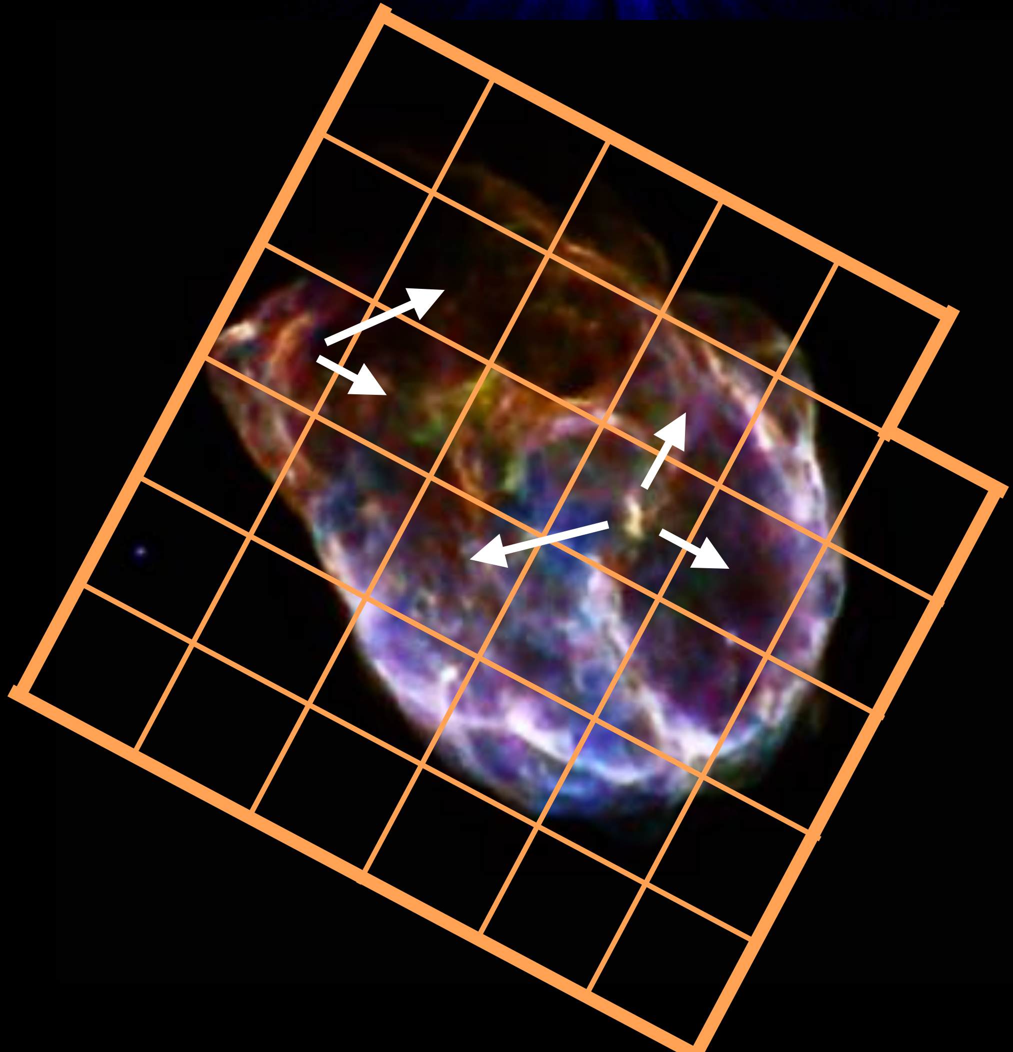
XRISM Xtend

XRISM Resolve

Spatial-Spectral Mixing: internal vs. external





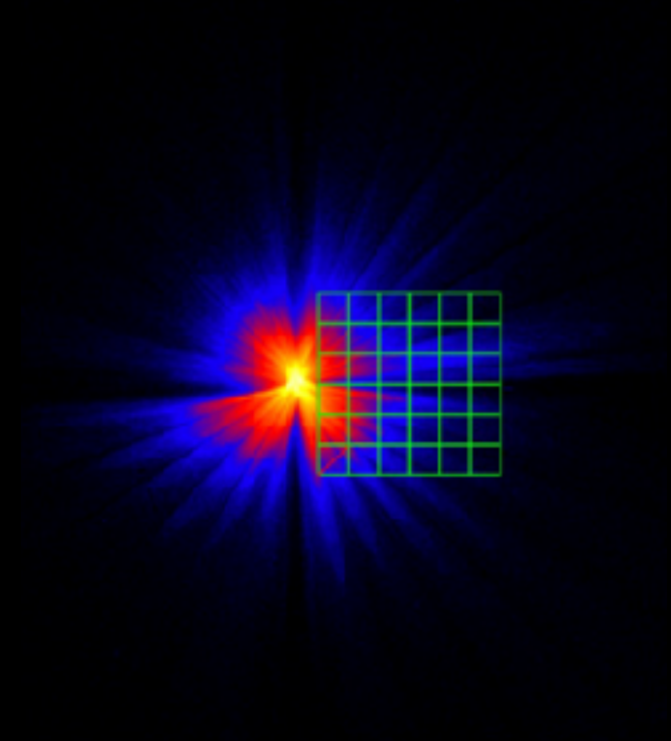


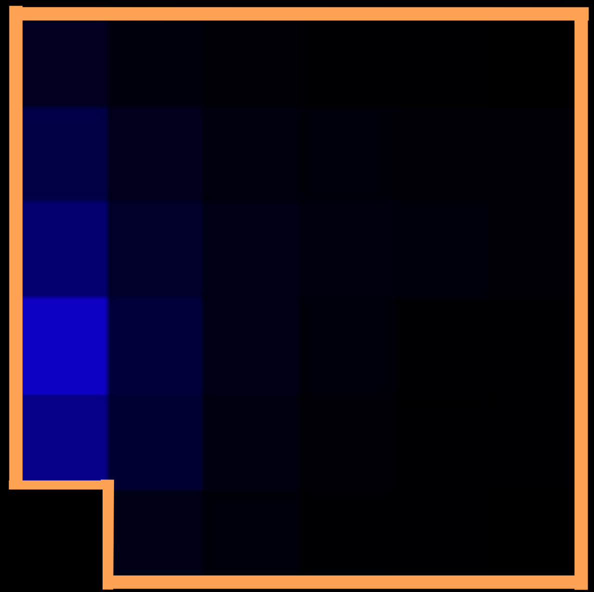
Internal SSM:

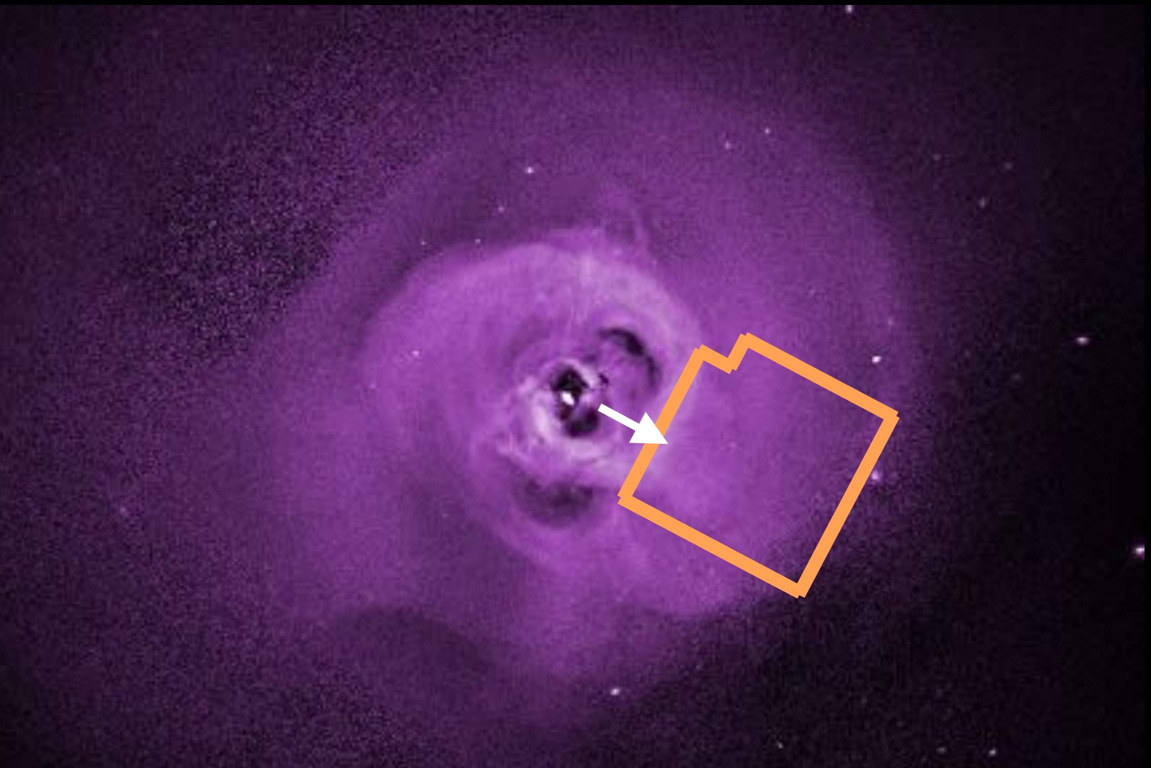
✓ **When the emission within the same field of view mixes across pixels and "contaminate" other regions within the same field of view**

✓ Examples: supernova remnants, complex star-forming regions, clusters with cavities, etc.

Spatial-Spectral Mixing: internal vs. external



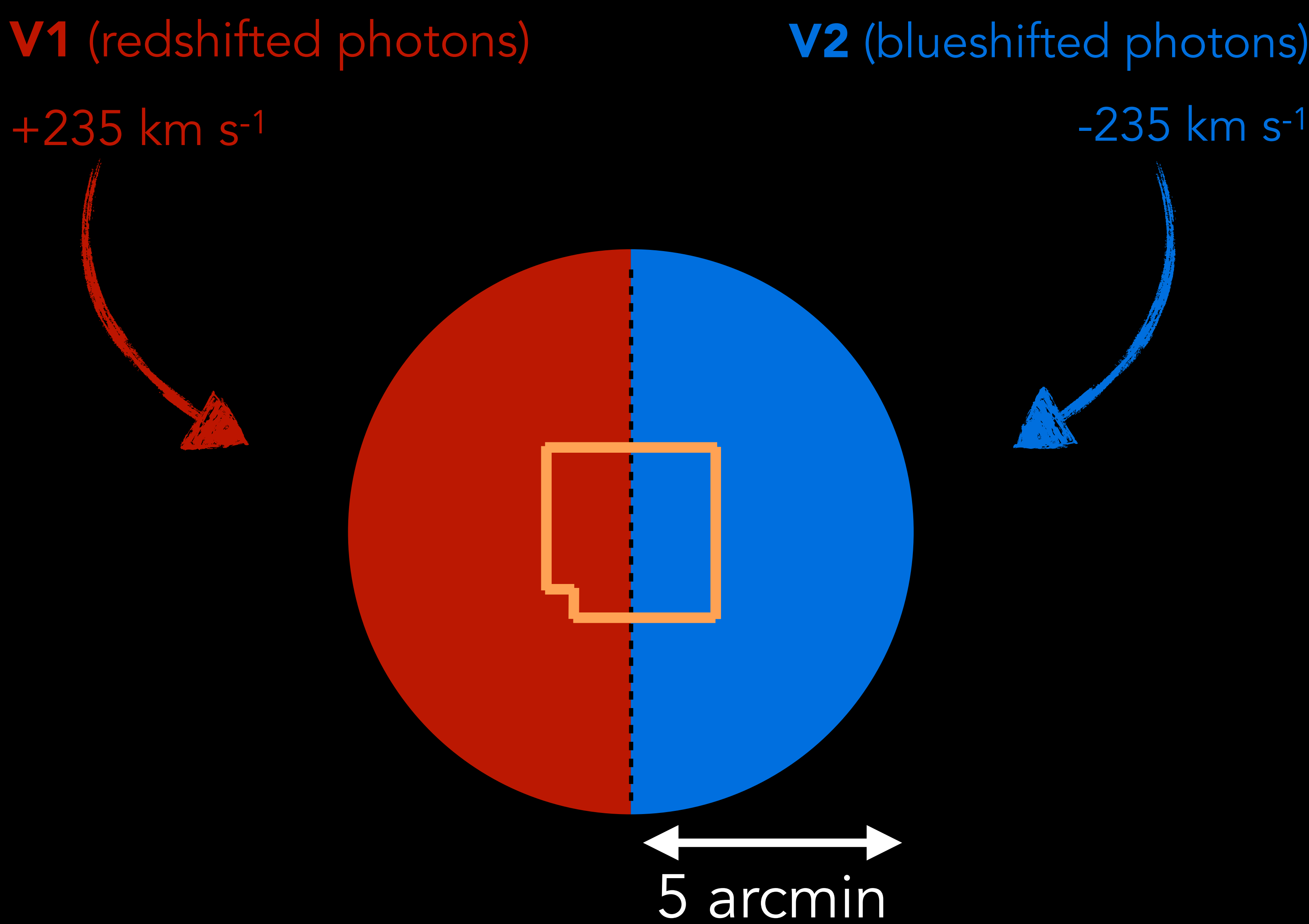


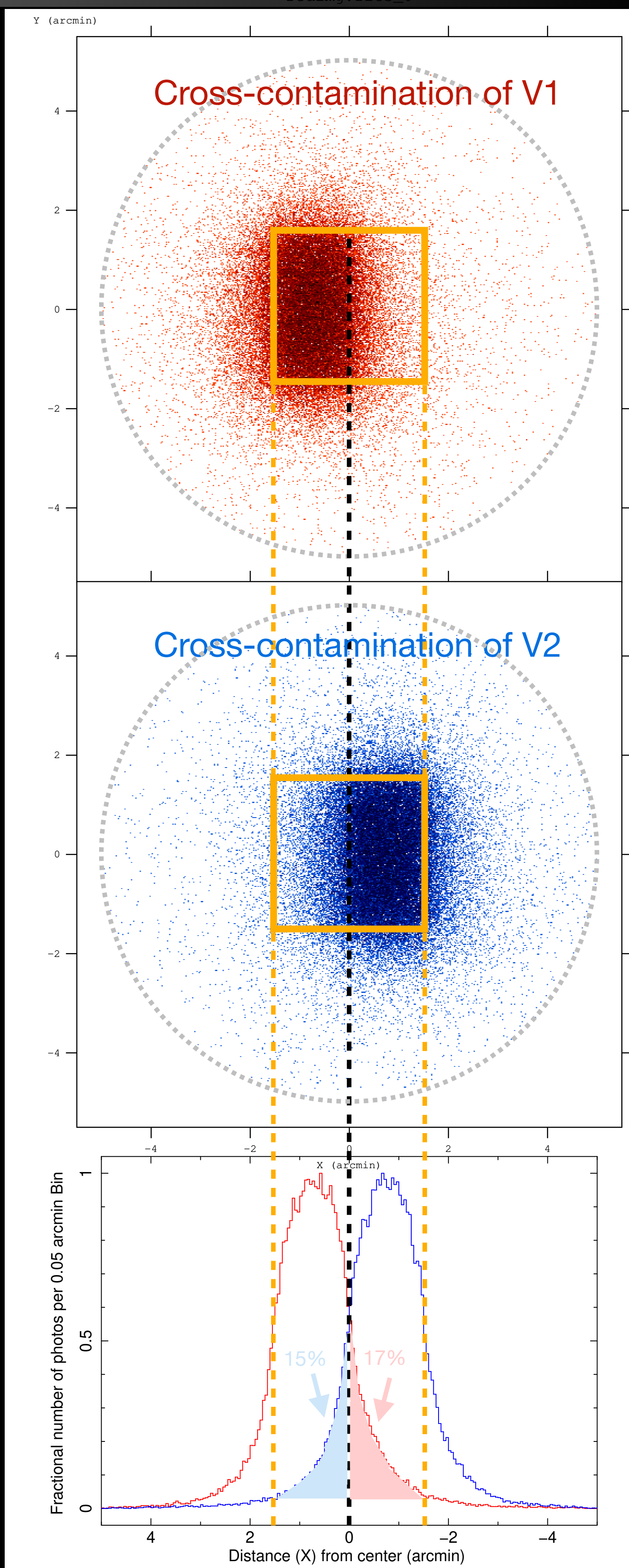


External SSM:

- ✓ **When sources outside the detector contaminate the detector region istelf**
- ✓ Examples: outskirts of a cool-core cluster, bright AGN nearby an extended source, etc.

A (very) simple example…



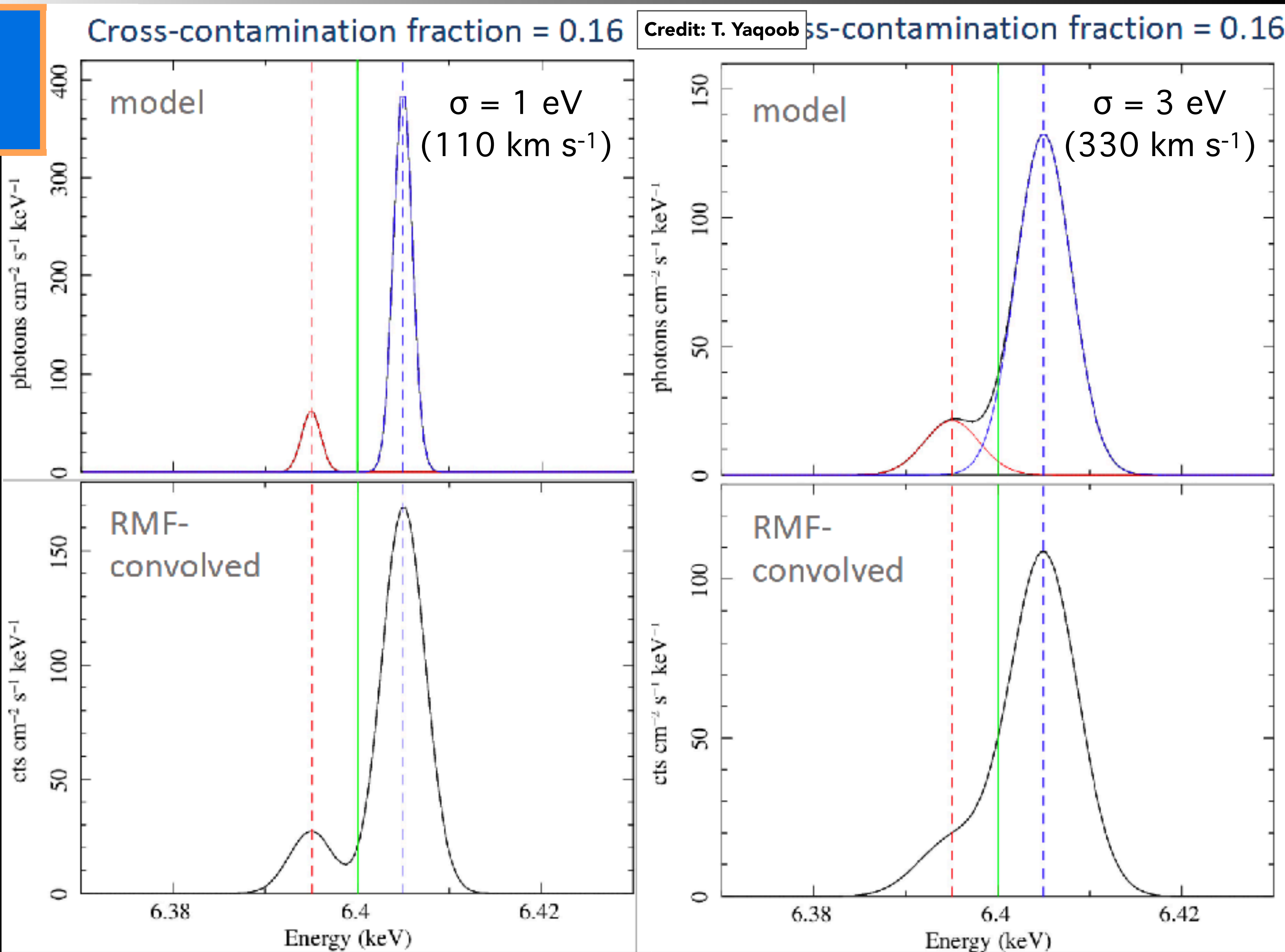


Spatial mixing…

- Fraction of V2 photons mixing into the **V1** region: 17%
- Fraction of V1 photons mixing into the **V2** region: 15%

Credit: T. Yaqoob

A (very) simple example…



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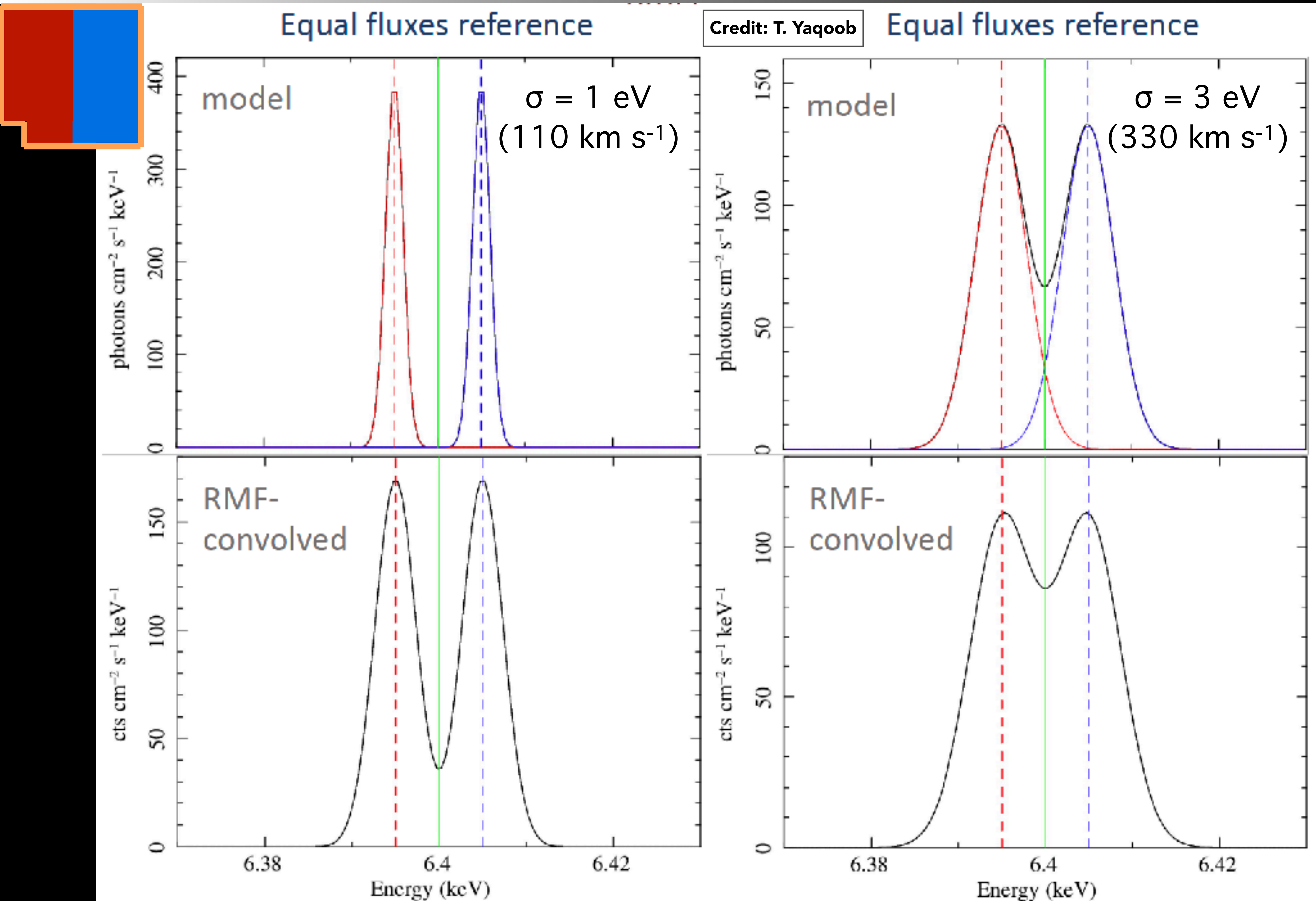
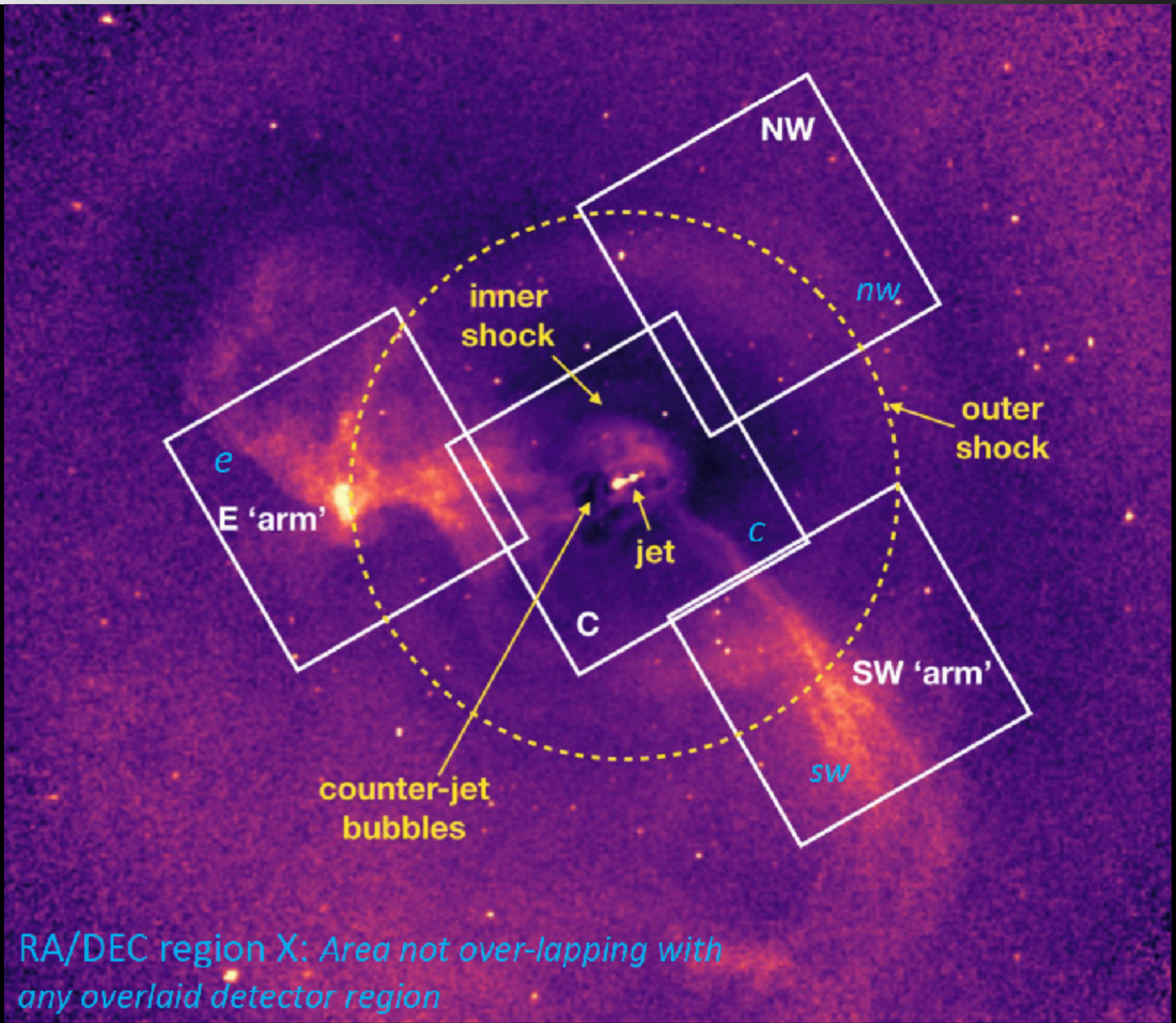


Addressing the problem

Ready to fall into the rabbit hole…?

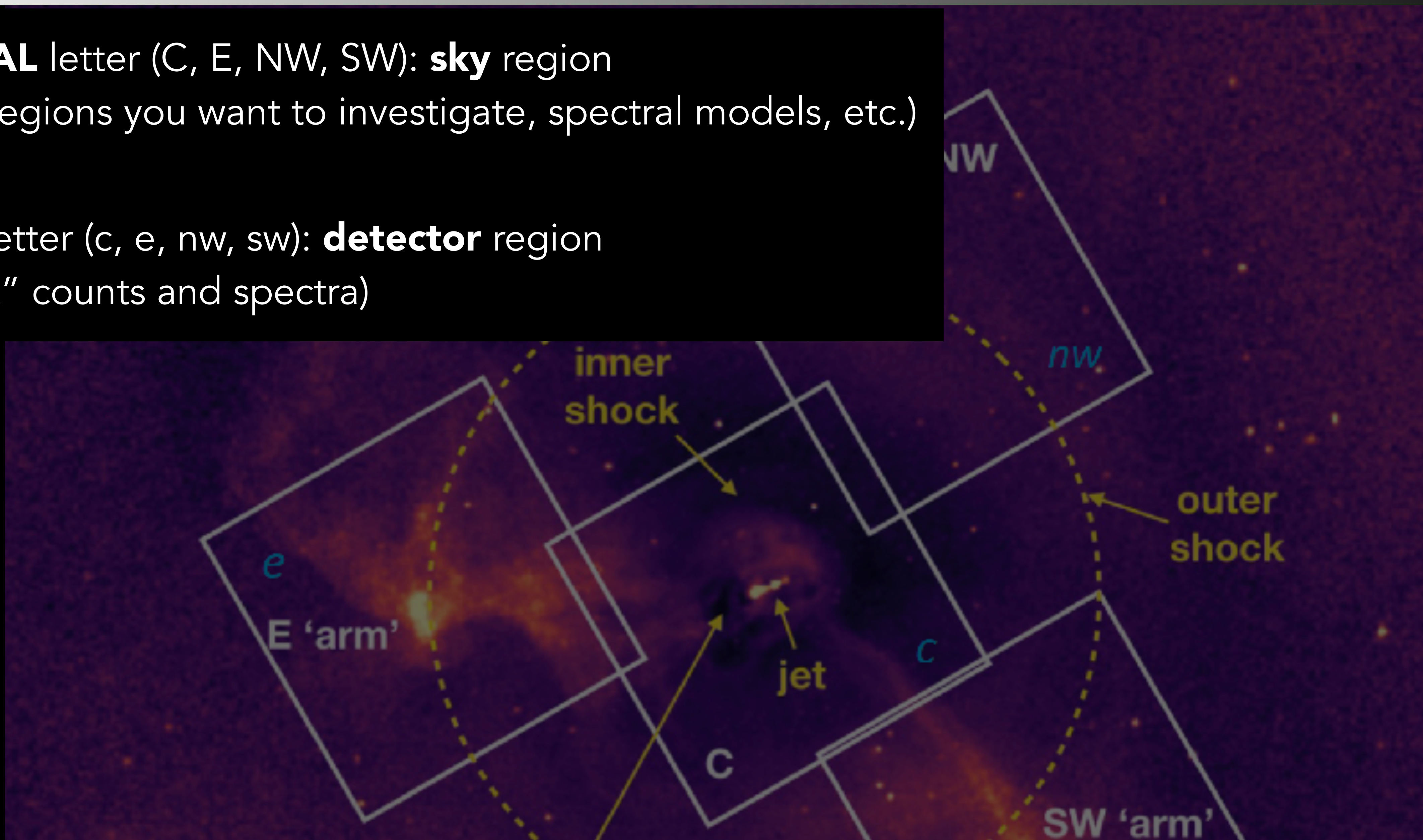
A concrete case (Virgo cluster)



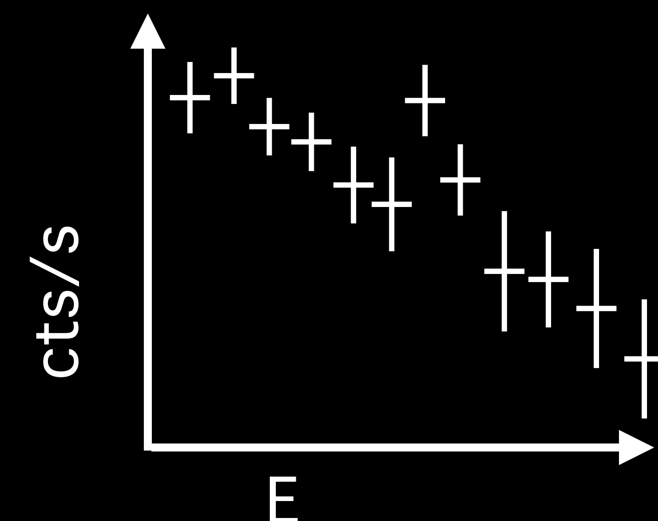
A concrete case (Virgo cluster)

- ✓ **CAPITAL** letter (C, E, NW, SW): **sky** region
  (“true” regions you want to investigate, spectral models, etc.)

- ✓ **small** letter (c, e, nw, sw): **detector** region
  (“output” counts and spectra)



- ✓ **S_i** = observed ***spectrum*** of detector region i
- ✓ **M_J** = ***spectral model*** of sky region J
- ✓ **R_i** = ***response matrix*** (RMF) of detector region i
- ✓ **A_i** = ***effective area*** (ARF) of detector region i



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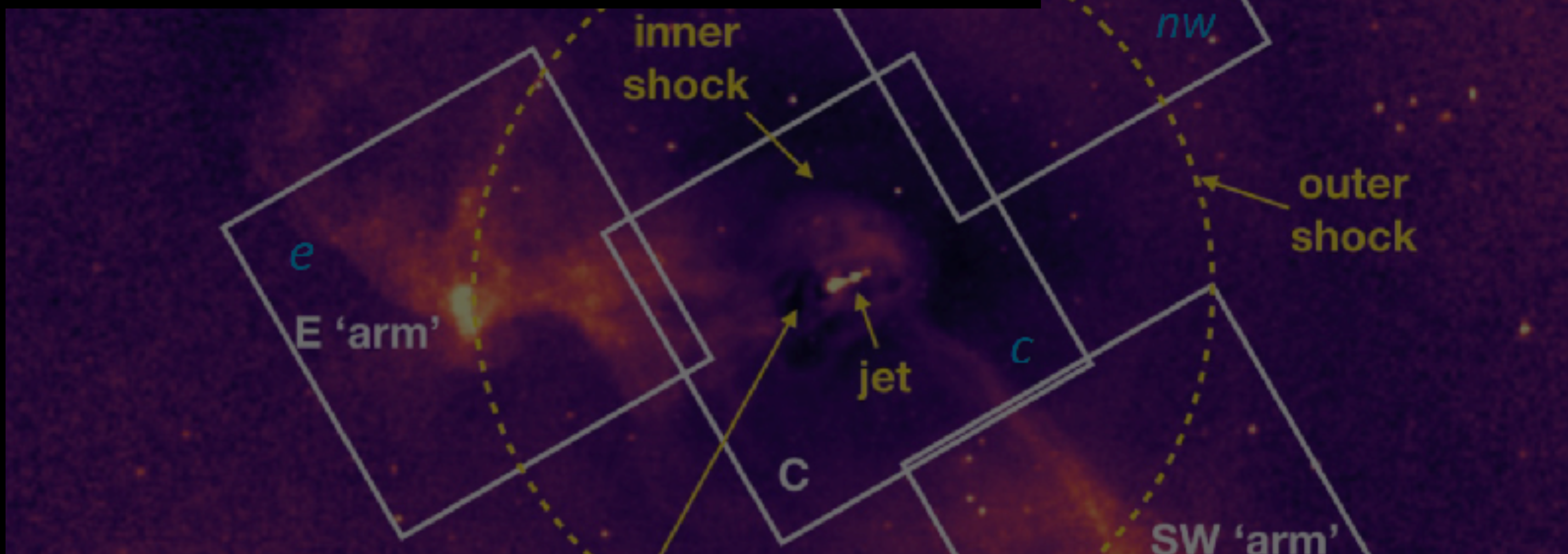

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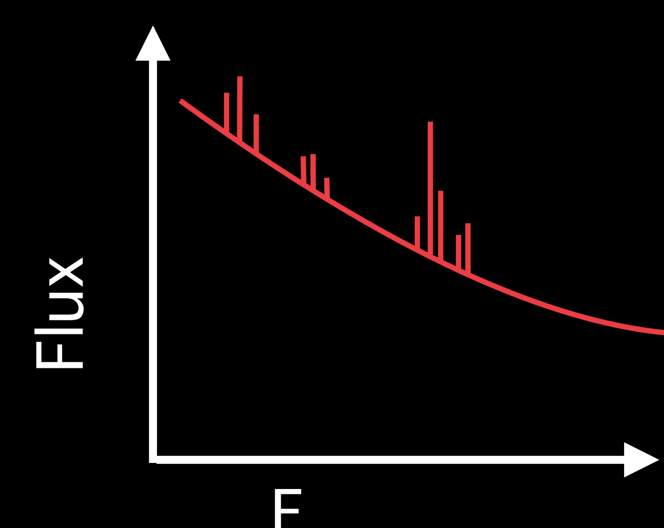

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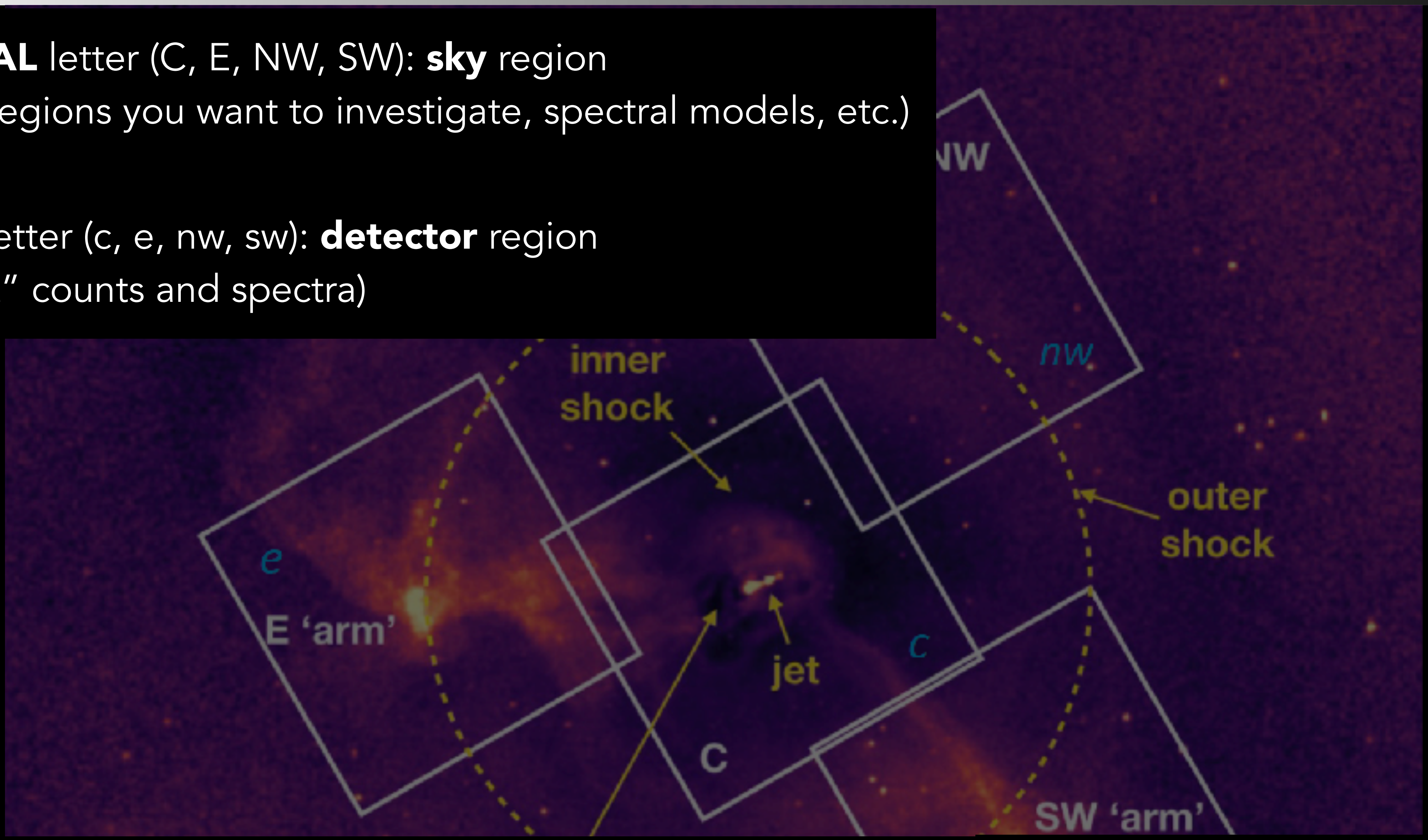

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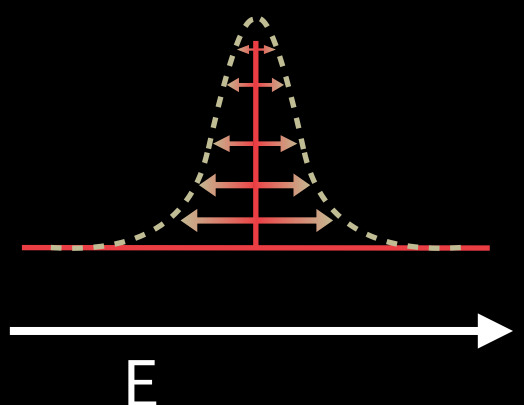

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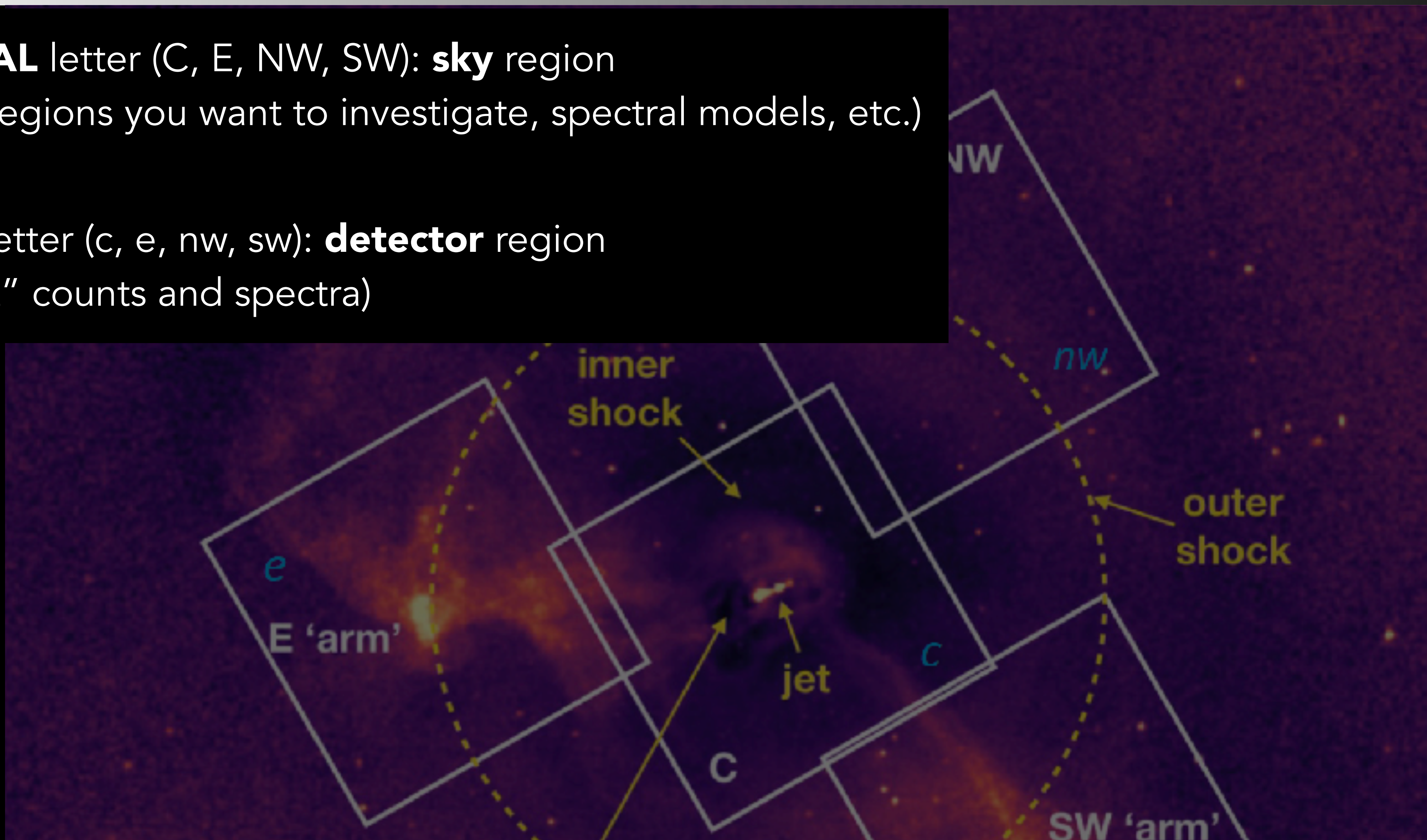

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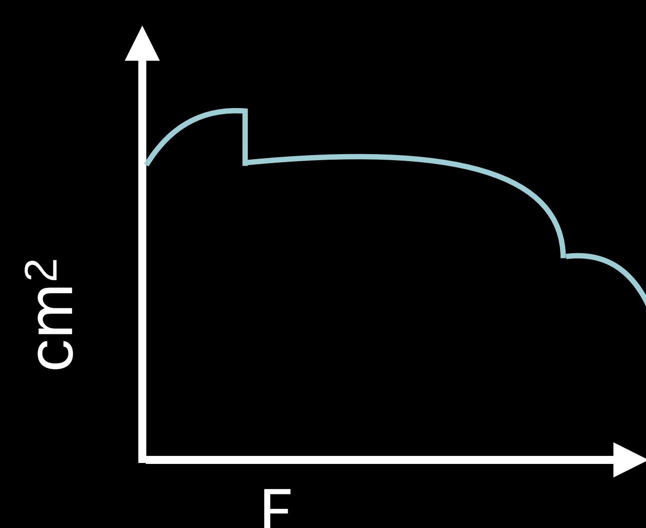
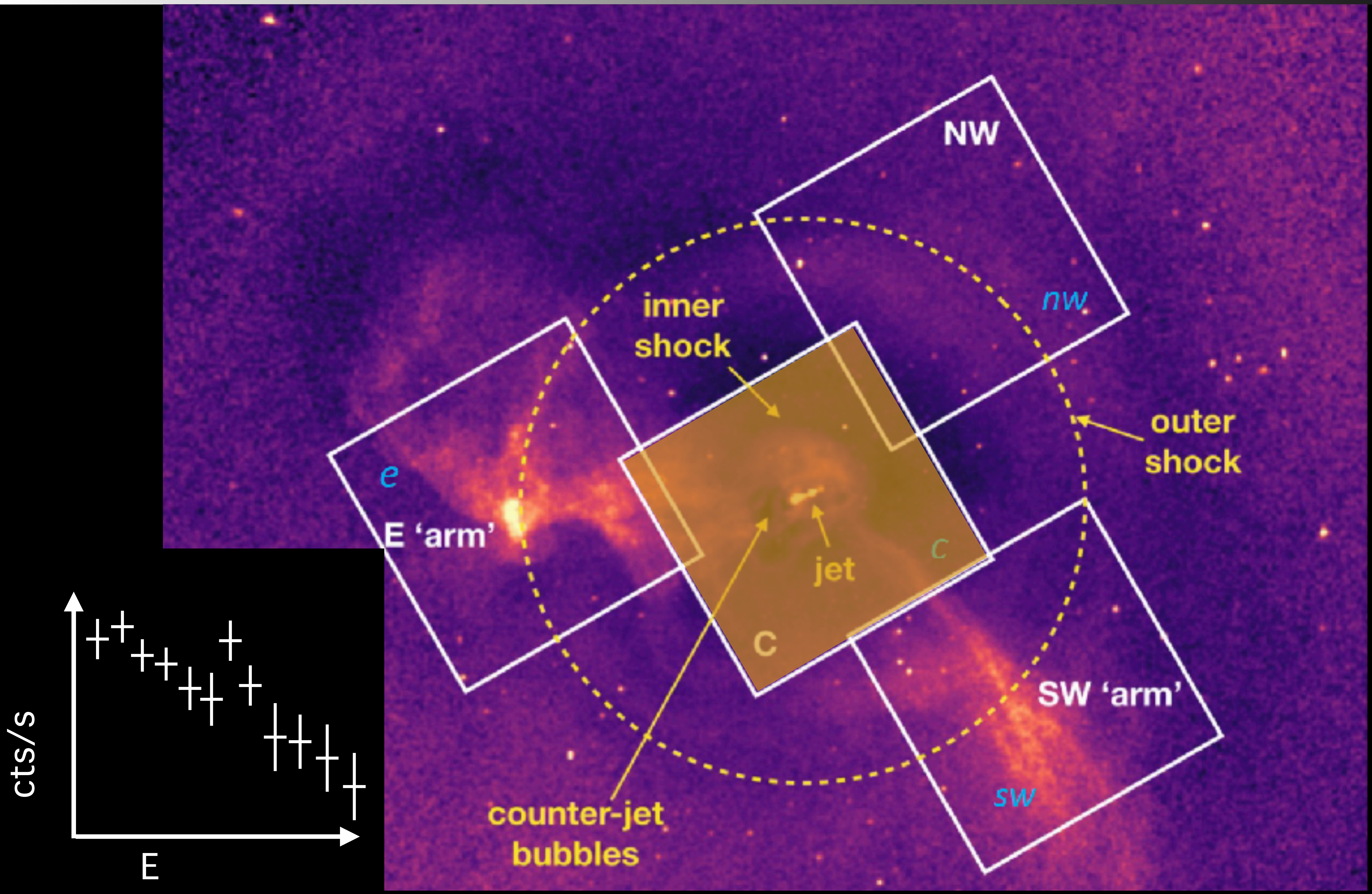
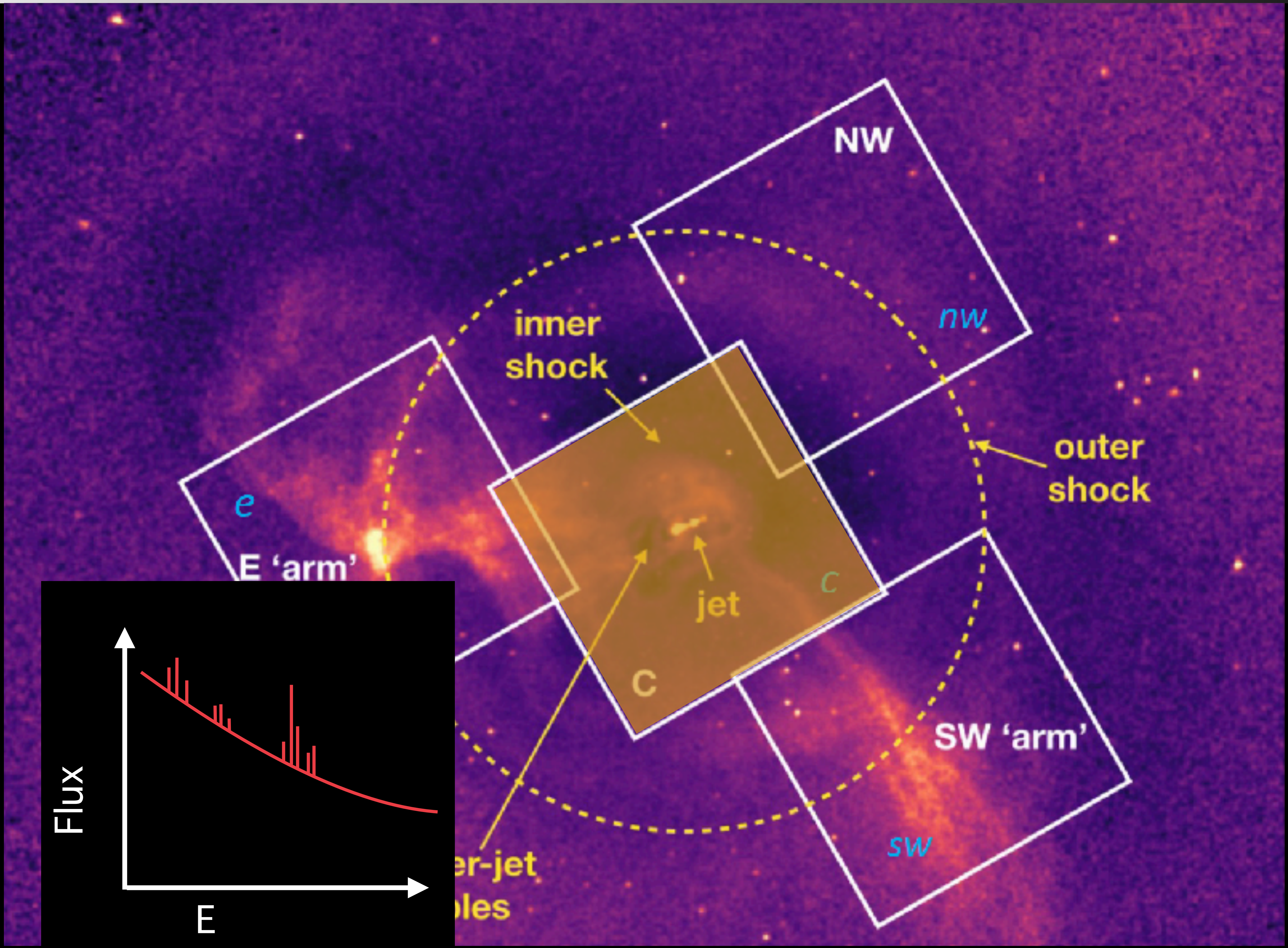


A concrete case (Virgo cluster)



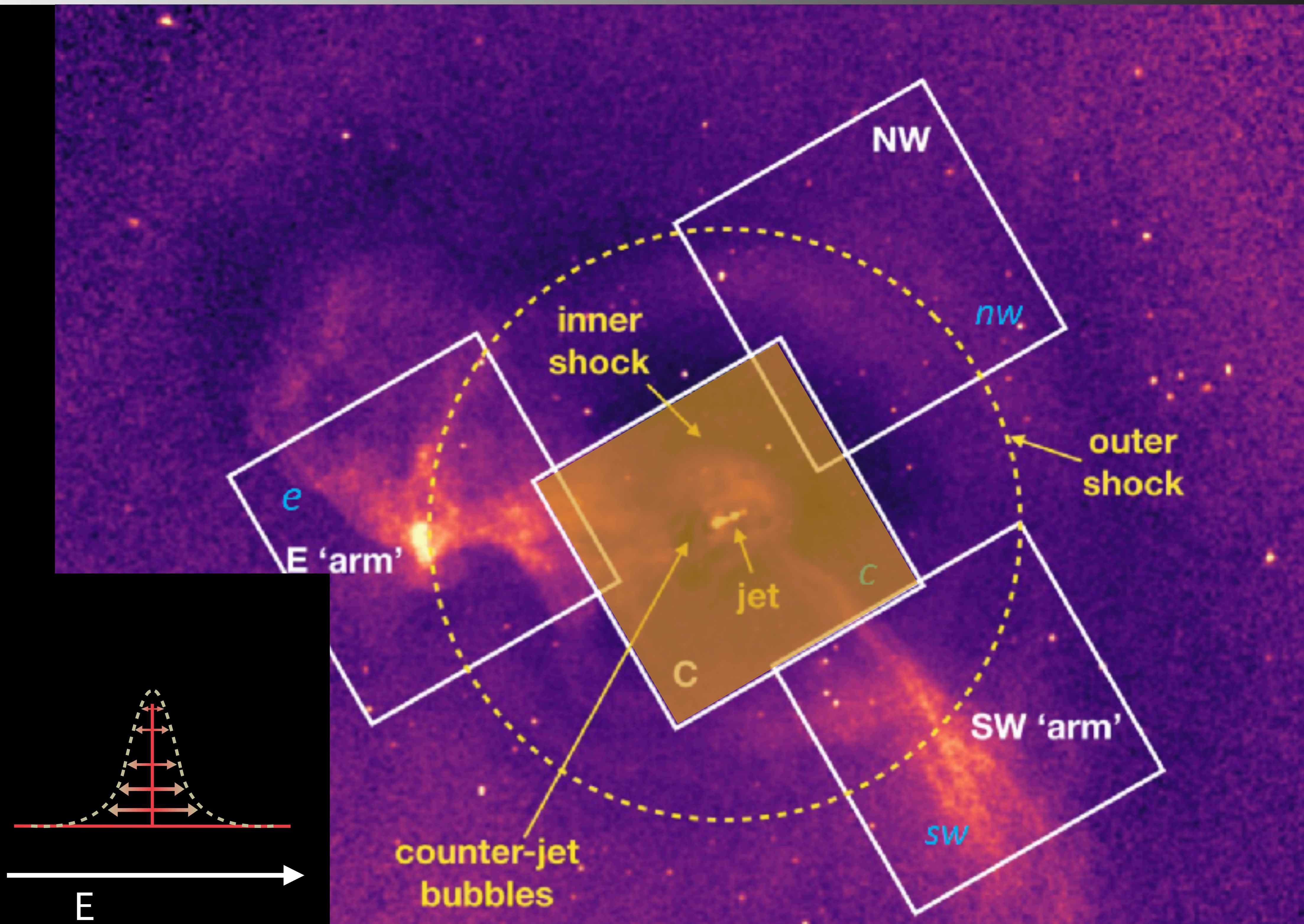
S_c =

A concrete case (Virgo cluster)



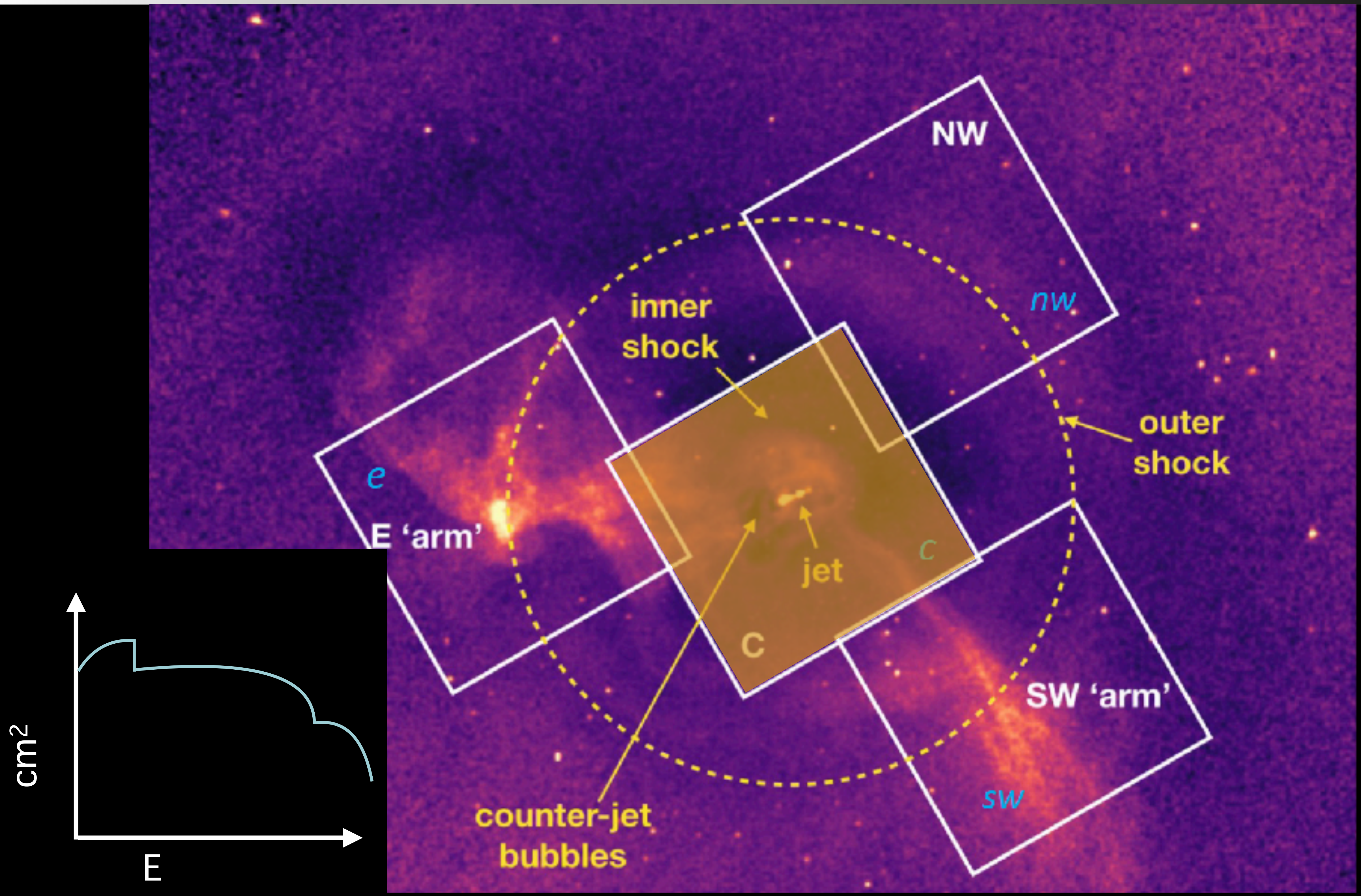
$S_c = A_c R_c$ **M_c**

A concrete case (Virgo cluster)



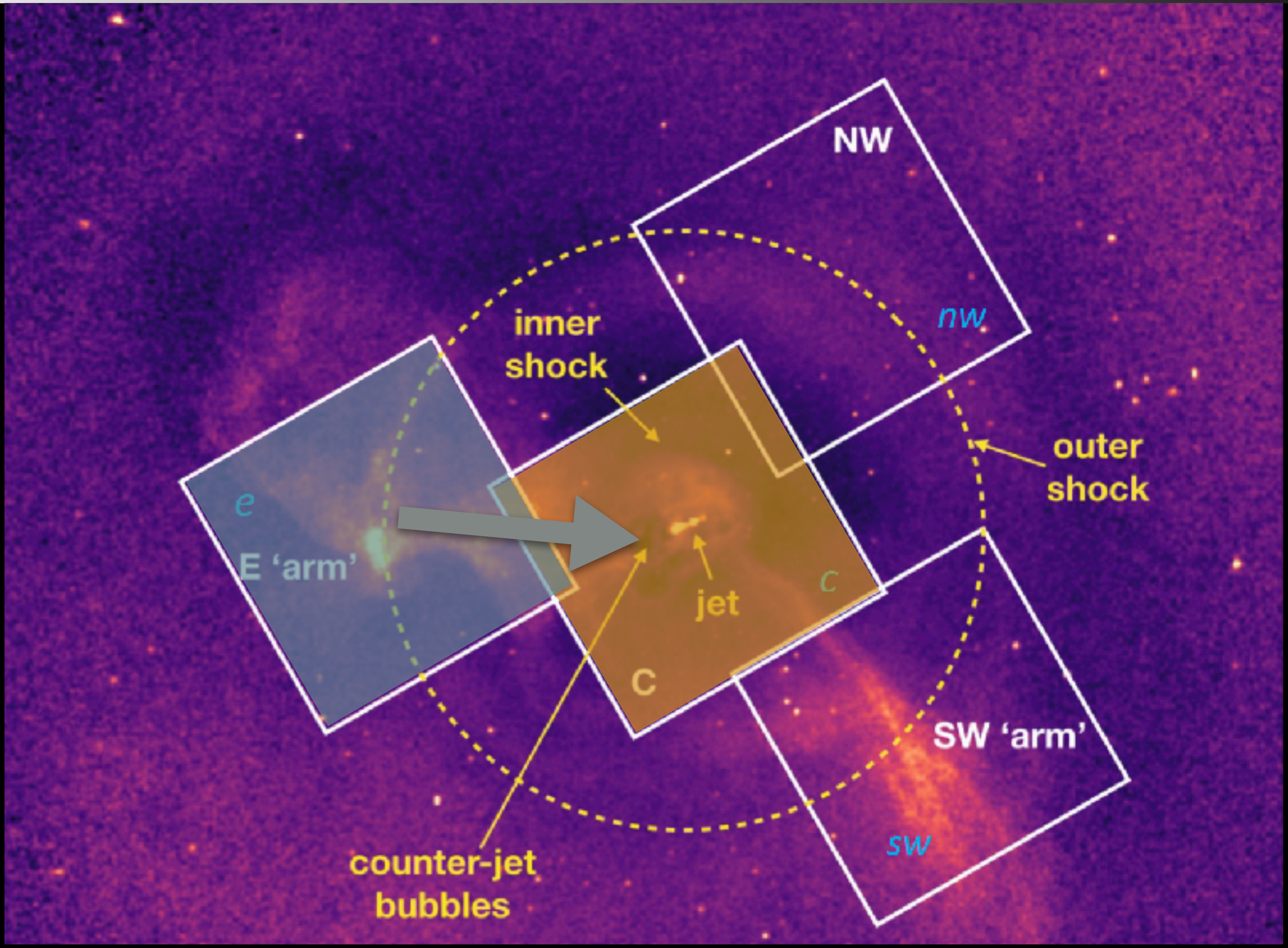
$S_c = A_c \mathbf{R_c}$ M_C

A concrete case (Virgo cluster)



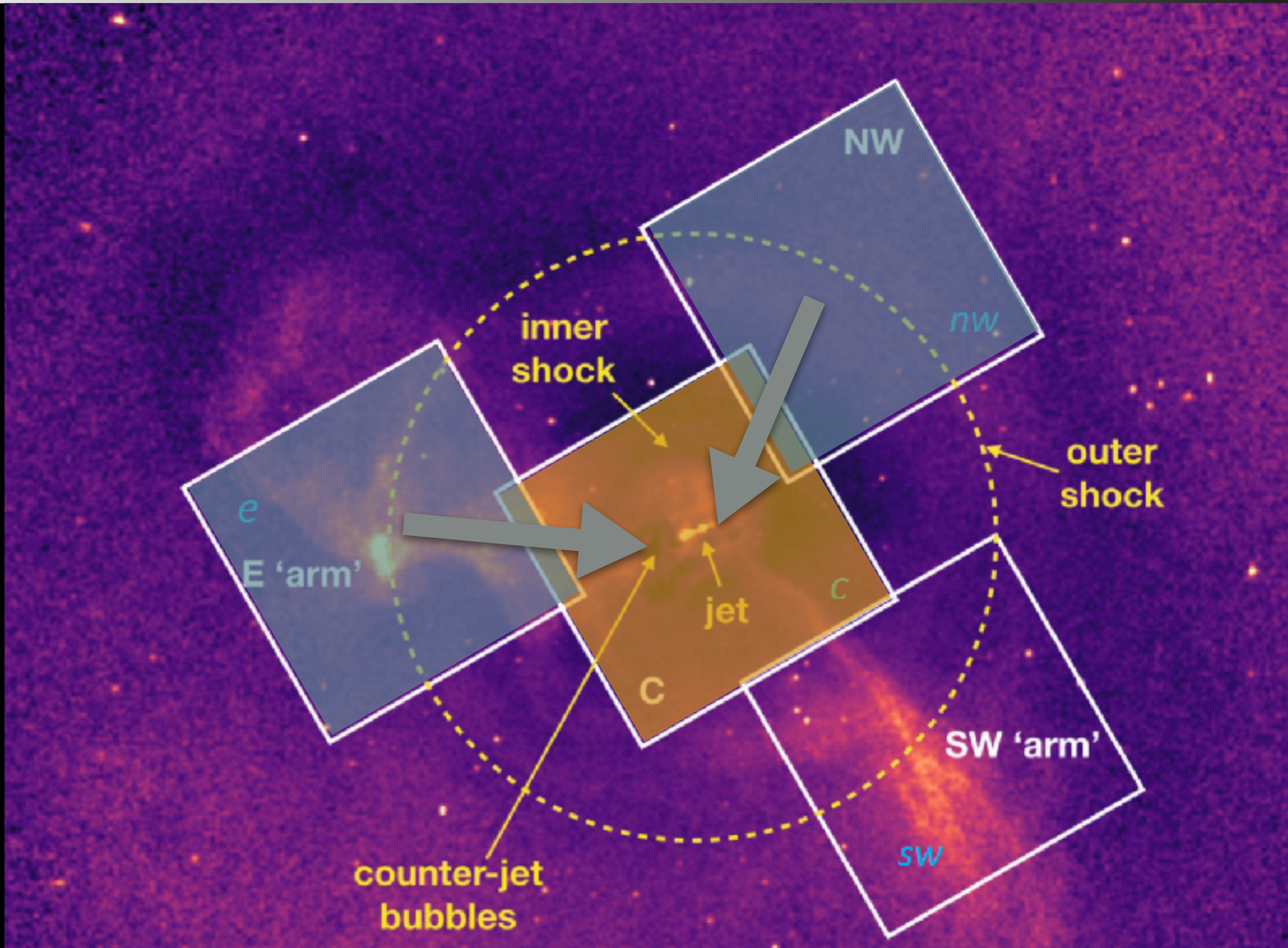
$S_c = \mathbf{A_c} R_c$ M_C

A concrete case (Virgo cluster)



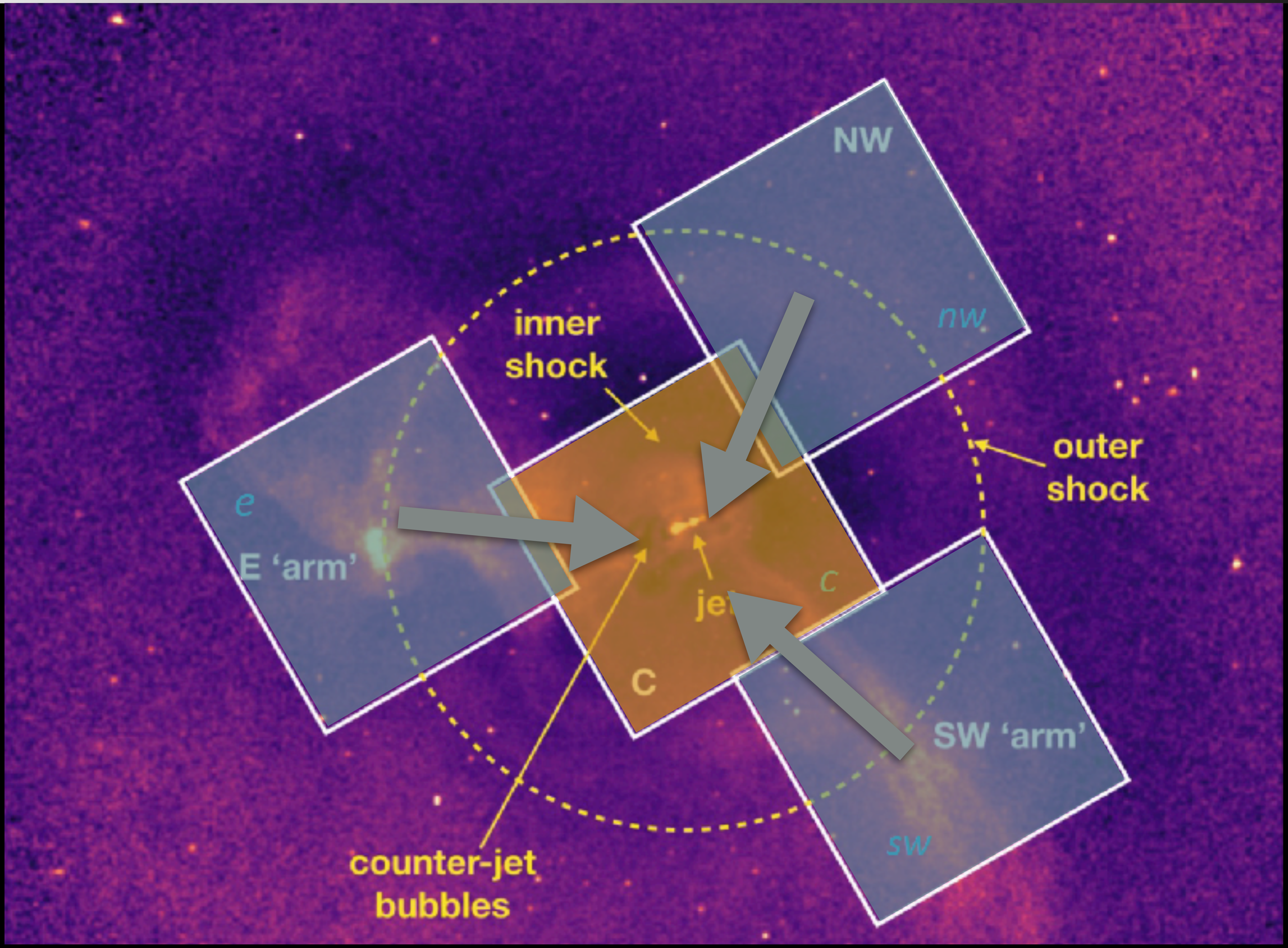
$S_c = A_c R_c [\mathbf{P_{C \to c}} M_C + \mathbf{P_{E \to c}} \mathbf{M_E}$]

A concrete case (Virgo cluster)



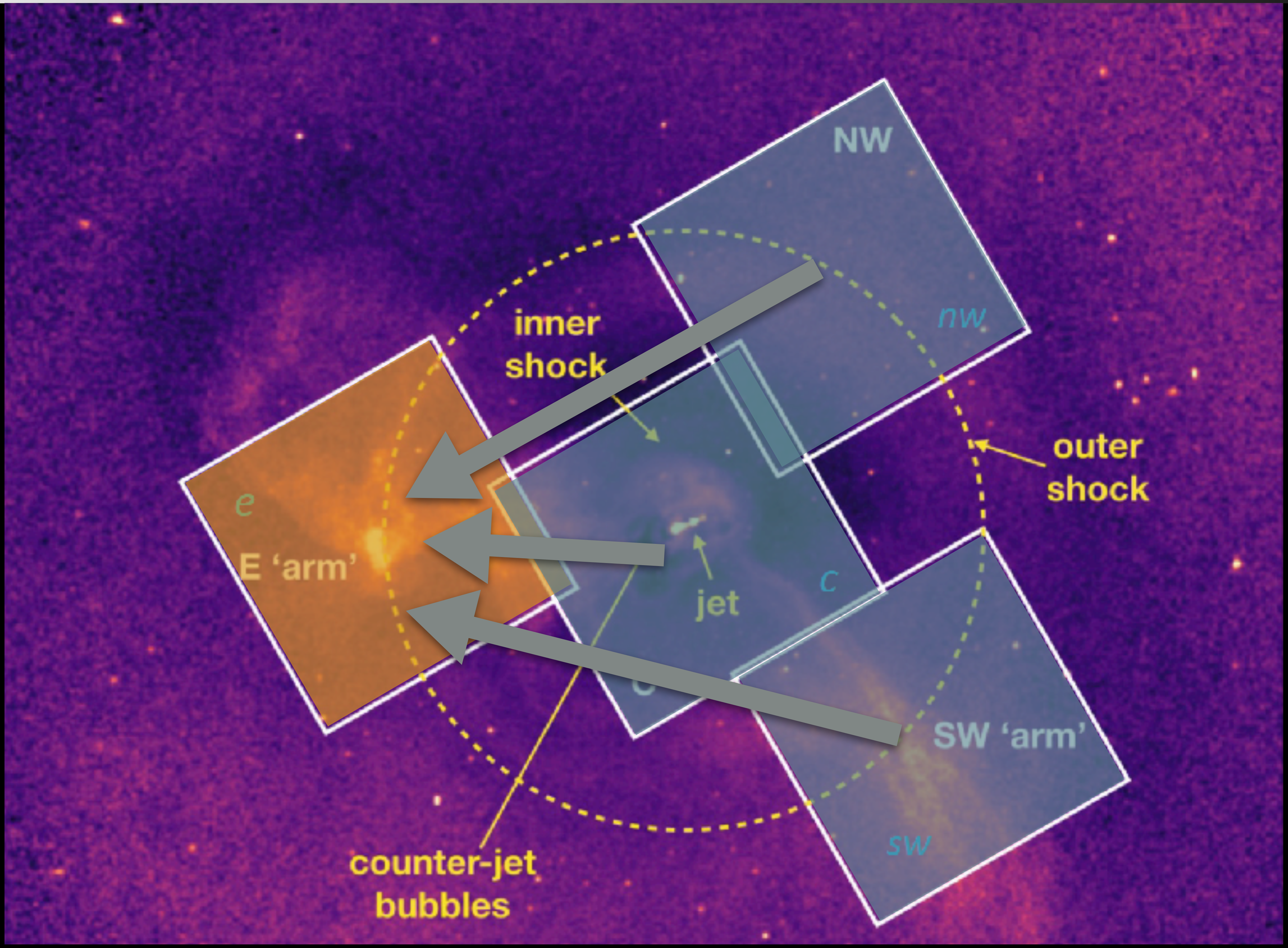
$$S_c = A_c\, R_c\, [P_{C\to c}\, M_C + P_{E\to c}\, M_E + \mathbf{P_{NW\to c}\, M_{NW}} \qquad]$$

A concrete case (Virgo cluster)



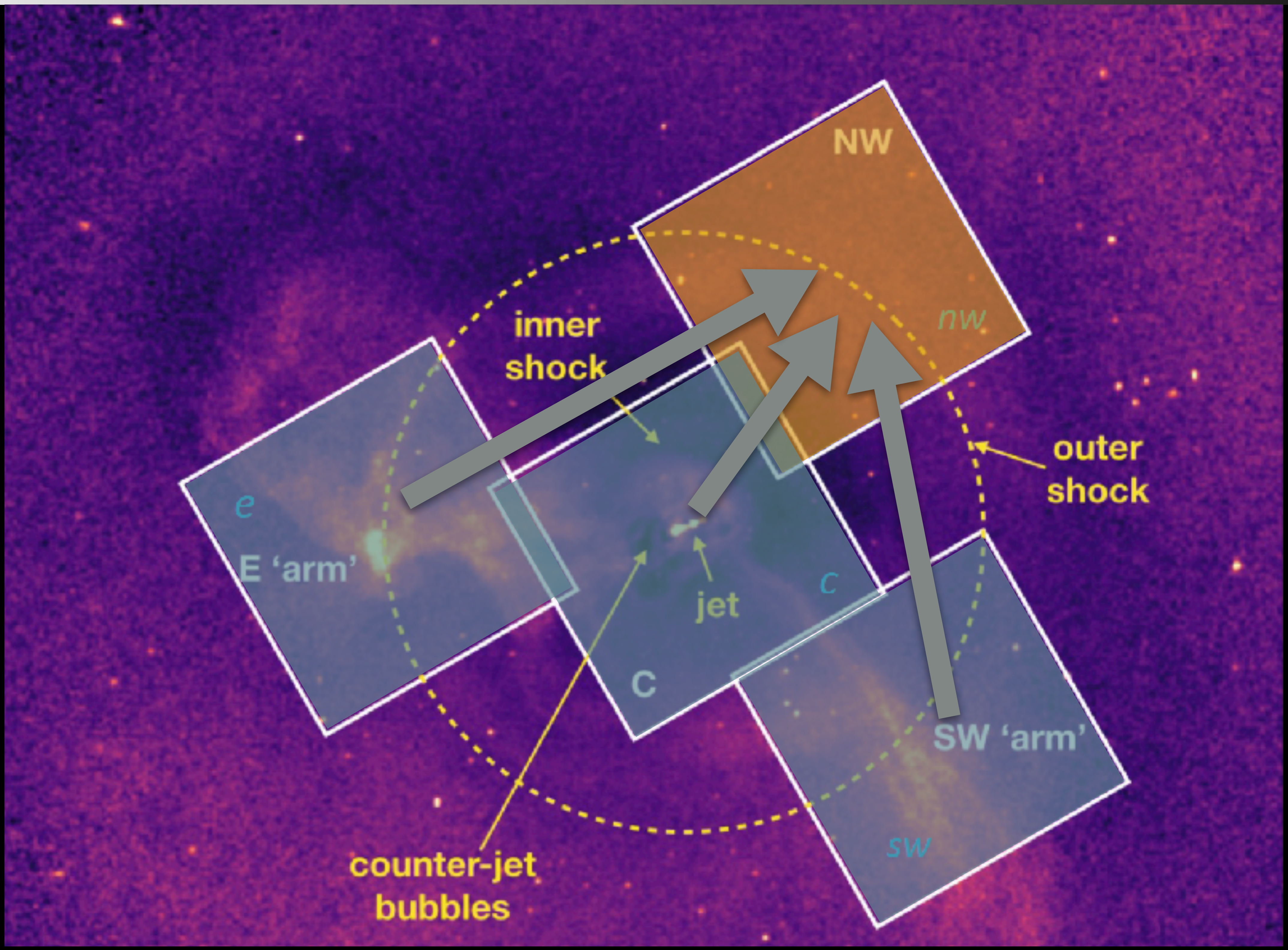
$S_c = A_c R_c [P_{C\to c} M_C + P_{E\to c} M_E + P_{NW\to c} M_{NW} + \mathbf{P_{SW\to c} M_{SW}}]$

A concrete case (Virgo cluster)



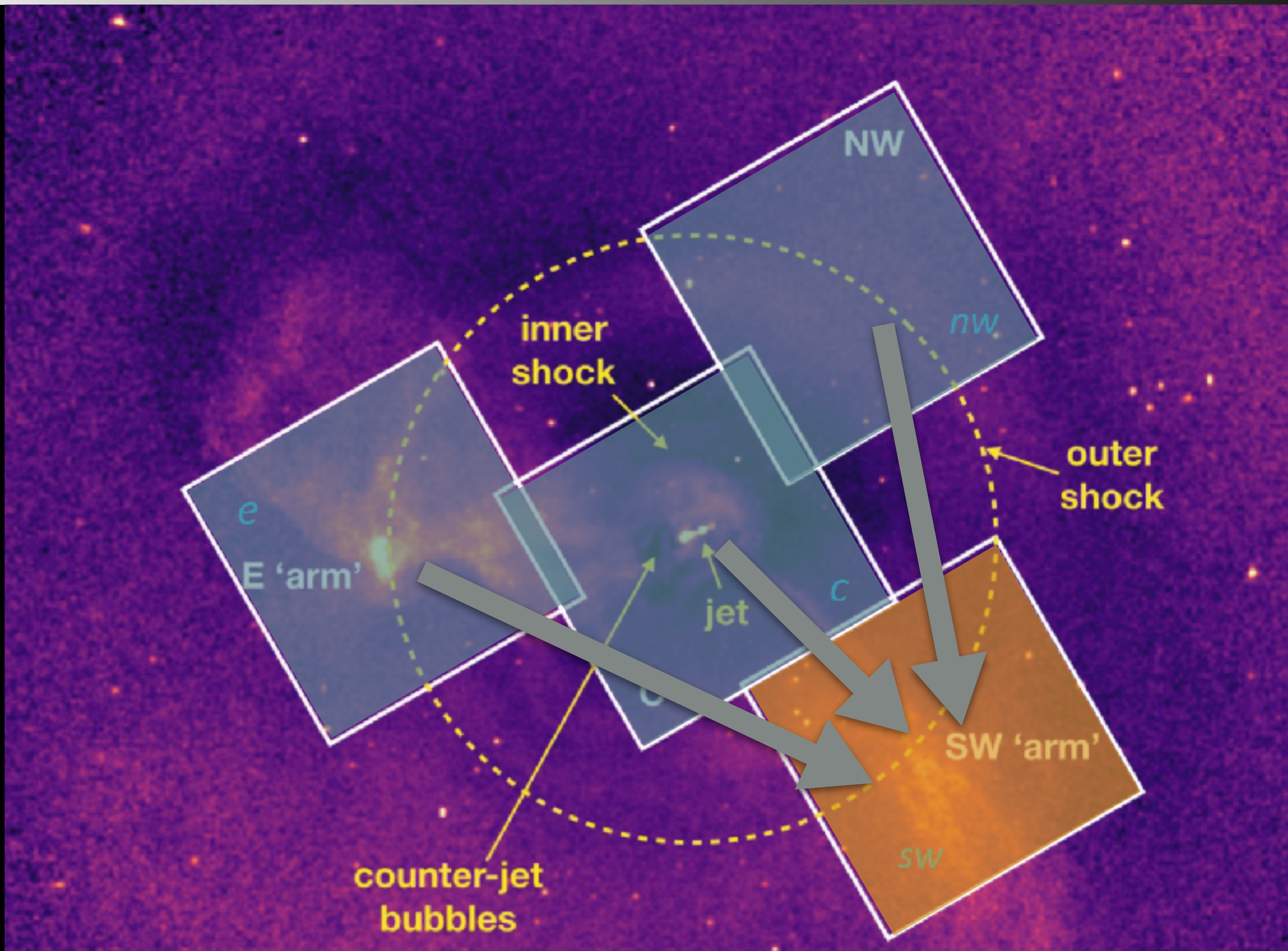
$$S_e = A_e\, R_e\, [P_{C\rightarrow e}\, M_C + P_{E\rightarrow e}\, M_E + P_{NW\rightarrow e}\, M_{NW} + P_{SW\rightarrow e}\, M_{SW}]$$

A concrete case (Virgo cluster)



$$S_{nw} = A_{nw}\, R_{nw}\, [P_{C\to nw}\, M_C + P_{E\to nw}\, M_E + P_{NW\to nw}\, M_{NW} + P_{SW\to nw}\, M_{SW}]$$

A concrete case (Virgo cluster)



$$S_{sw} = A_{sw} R_{sw} [P_{C \to sw} M_C + P_{E \to sw} M_E + P_{NW \to sw} M_{NW} + P_{SW \to sw} M_{SW}]$$

A concrete case (Virgo cluster)

$$\begin{bmatrix} S_c = A_c\, R_c\, [P_{C\to c}\, M_C + P_{E\to c}\, M_E + P_{NW\to c}\, M_{NW} + P_{SW\to c}\, M_{SW}] \\ S_e = A_e\, R_e\, [P_{C\to e}\, M_C + P_{E\to e}\, M_E + P_{NW\to e}\, M_{NW} + P_{SW\to e}\, M_{SW}] \\ S_{nw} = A_{nw}\, R_{nw}\, [P_{C\to nw}\, M_C + P_{E\to nw}\, M_E + P_{NW\to nw}\, M_{NW} + P_{SW\to nw}\, M_{SW}] \\ S_{sw} = A_{sw}\, R_{sw}\, [P_{C\to sw}\, M_C + P_{E\to sw}\, M_E + P_{NW\to sw}\, M_{NW} + P_{SW\to sw}\, M_{SW}] \end{bmatrix}$$

Observed spectra of detector region i

Effective areas of detector region i

Response matrices of detector region i

Spectral models of sky region J

$$S_i = A_i\, R_i \sum_J P_{J\to i}\, M_J$$

A concrete case (Virgo cluster)

$$\begin{cases} S_c = A_c R_c [P_{C\to c} M_C + P_{E\to c} M_E + P_{NW\to c} M_{NW} + P_{SW\to c} M_{SW}] \\ S_e = A_e R_e [P_{C\to e} M_C + P_{E\to e} M_E + P_{NW\to e} M_{NW} + P_{SW\to e} M_{SW}] \\ S_{nw} = A_{nw} R_{nw} [P_{C\to nw} M_C + P_{E\to nw} M_E + P_{NW\to nw} M_{NW} + P_{SW\to nw} M_{SW}] \\ S_{sw} = A_{sw} R_{sw} [P_{C\to sw} M_C + P_{E\to sw} M_E + P_{NW\to sw} M_{NW} + P_{SW\to sw} M_{SW}] \end{cases}$$

Coefficients of photon mixing from sky region J into detector region i

$$S_i = A_i R_i \sum_J P_{J\to i} M_J$$

4 x 4 = 16 models fitted simultaneously to 4 observed spectra

A concrete case (Virgo cluster)

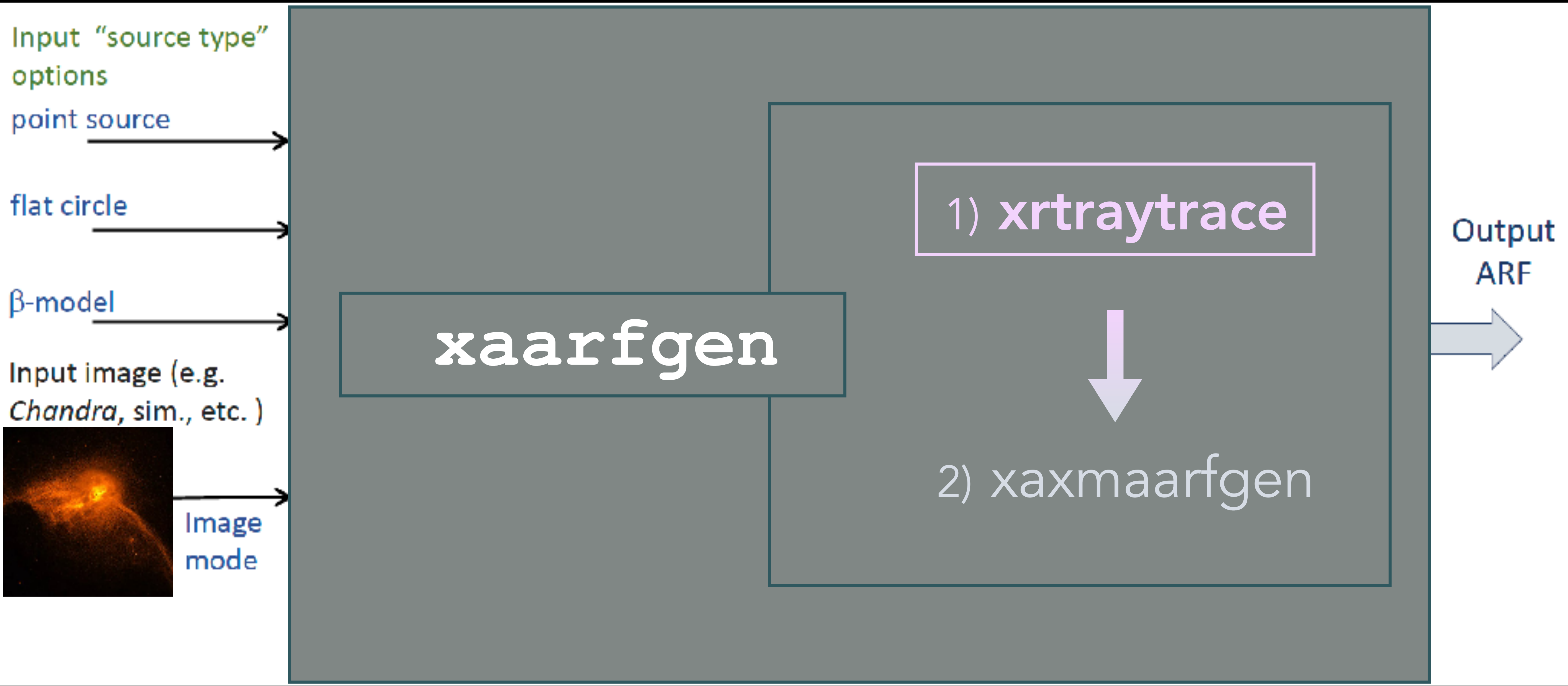
How to obtain the $P_{J \to i}$ coefficients?

- **Method 1**: leave normalisations of the 16 models free
  - …Bad idea! (Empirical, black box, too many free params, degeneracies, etc.)
- **Method 2**: estimate coefficients from ray-tracing simulations
  - …Via ARF generator (part of the XRISM data reduction software)

A concrete case (Virgo cluster)

➡ **Method 2**: estimate coefficients from ray-tracing simulations

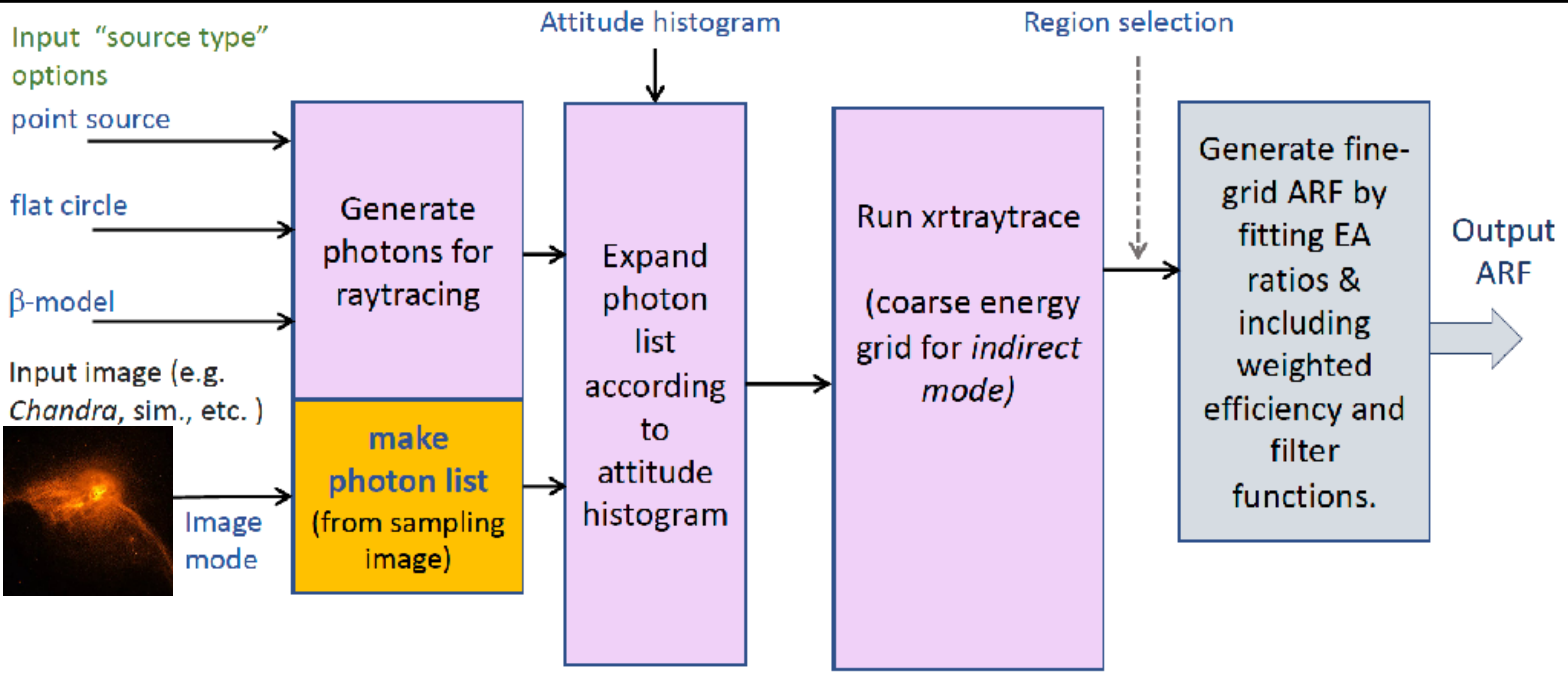
➡ …Via ARF generator (part of the XRISM data reduction software)



Credits: T. Yaqoob

A concrete case (Virgo cluster)

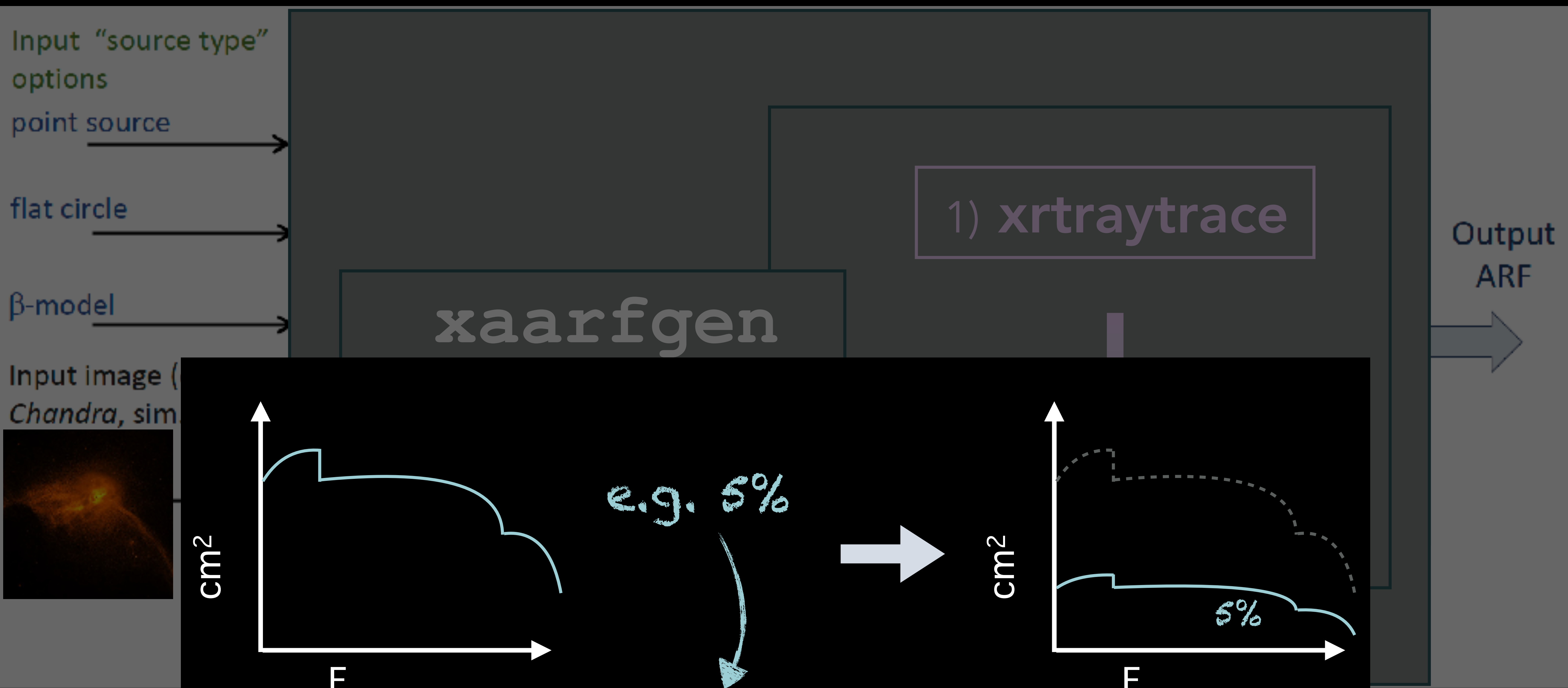
- **Method 2**: estimate coefficients from ray-tracing simulations
  - …Via ARF generator (part of the XRISM data reduction software)



Credits: T. Yaqoob

A concrete case (Virgo cluster)

- **Method 2**: estimate coefficients from ray-tracing simulations
  - …Via ARF generator (part of the future XRISM data reduction software)



$$(A_i \times P_{J\rightarrow i}) \Rightarrow A_{J\rightarrow i}$$

A concrete case (Virgo cluster)

$$
\begin{bmatrix}
S_c = A_c\, R_c\, [P_{C\rightarrow c}\, M_C + P_{E\rightarrow c}\, M_E + P_{NW\rightarrow c}\, M_{NW} + P_{SW\rightarrow c}\, M_{SW}] \\
S_e = A_e\, R_e\, [P_{C\rightarrow e}\, M_C + P_{E\rightarrow e}\, M_E + P_{NW\rightarrow e}\, M_{NW} + P_{SW\rightarrow e}\, M_{SW}] \\
S_{nw} = A_{nw}\, R_{nw}\, [P_{C\rightarrow nw}\, M_C + P_{E\rightarrow nw}\, M_E + P_{NW\rightarrow nw}\, M_{NW} + P_{SW\rightarrow nw}\, M_{SW}] \\
S_{sw} = A_{sw}\, R_{sw}\, [P_{C\rightarrow sw}\, M_C + P_{E\rightarrow sw}\, M_E + P_{NW\rightarrow sw}\, M_{NW} + P_{SW\rightarrow sw}\, M_{SW}]
\end{bmatrix}
$$

Observed spectra of detector region i

Effective areas of detector region i

Response matrices of detector region i

Spectral models of sky region J

$$S_i = A_i\, R_i \sum_J P_{J\rightarrow i}\, M_J$$

A concrete case (Virgo cluster)

$$
\begin{bmatrix}
S_c = R_c\,[A_{C\rightarrow c}\,M_C + A_{E\rightarrow c}\,M_E + A_{NW\rightarrow c}\,M_{NW} + A_{SW\rightarrow c}\,M_{SW}] \\
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Spectral models of sky region J

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4 x 4 = 16 models fitted simultaneously to 4 observed spectra

A concrete case (Virgo cluster)

$$\begin{cases} S_c = R_c\,[A_{C\rightarrow c}\,M_C + A_{E\rightarrow c}\,M_E + A_{NW\rightarrow c}\,M_{NW} + A_{SW\rightarrow c}\,M_{SW}] \\ S_e = R_e\,[A_{C\rightarrow e}\,M_C + A_{E\rightarrow e}\,M_E + A_{NW\rightarrow e}\,M_{NW} + A_{SW\rightarrow e}\,M_{SW}] \\ S_{nw} = R_{nw}\,[A_{C\rightarrow nw}\,M_C + A_{E\rightarrow nw}\,M_E + A_{NW\rightarrow nw}\,M_{NW} + A_{SW\rightarrow nw}\,M_{SW}] \\ S_{sw} = R_{sw}\,[A_{C\rightarrow sw}\,M_C + A_{E\rightarrow sw}\,M_E + A_{NW\rightarrow sw}\,M_{NW} + A_{SW\rightarrow sw}\,M_{SW}] \end{cases}$$

Effective areas of detector region i

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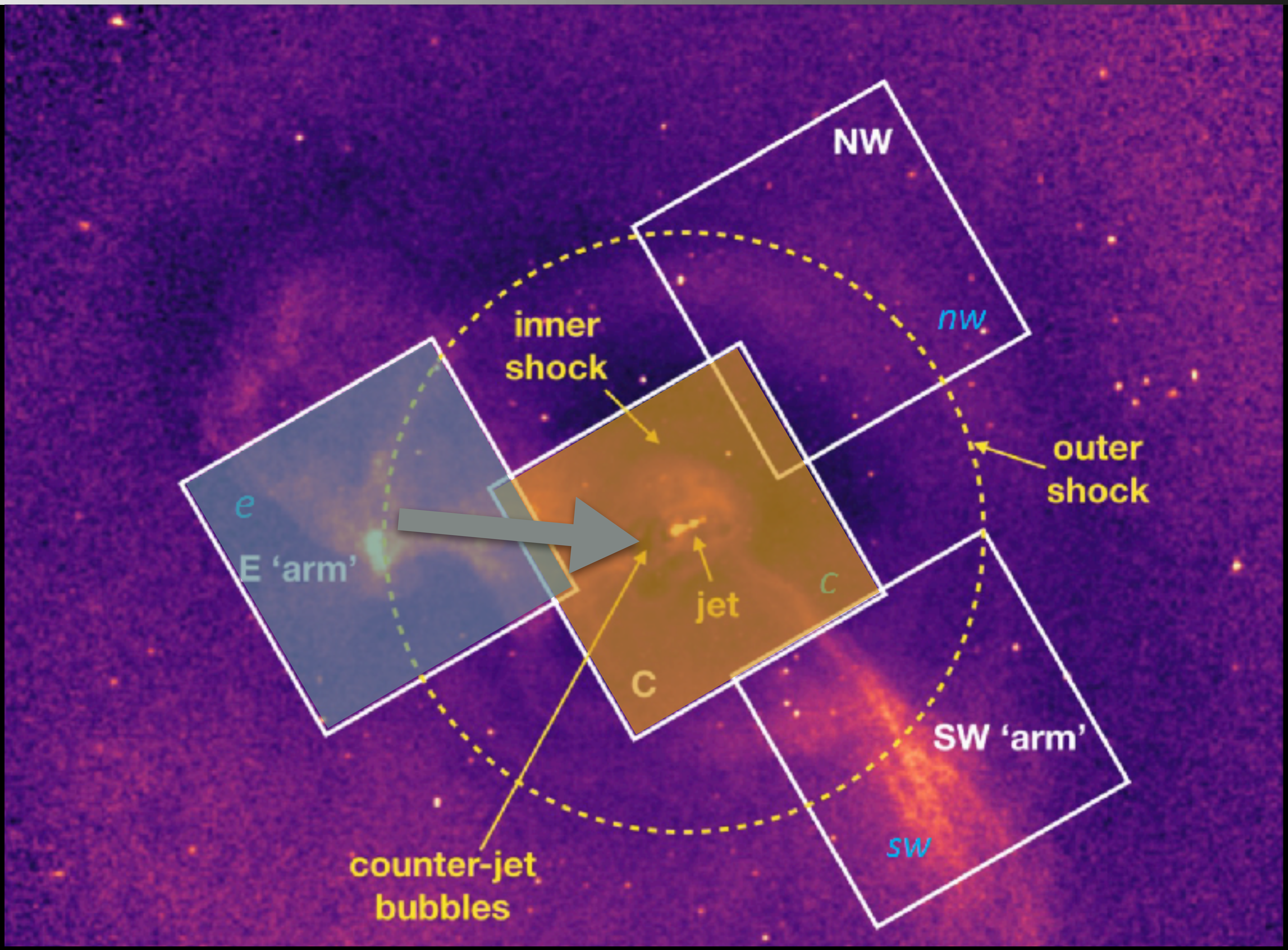
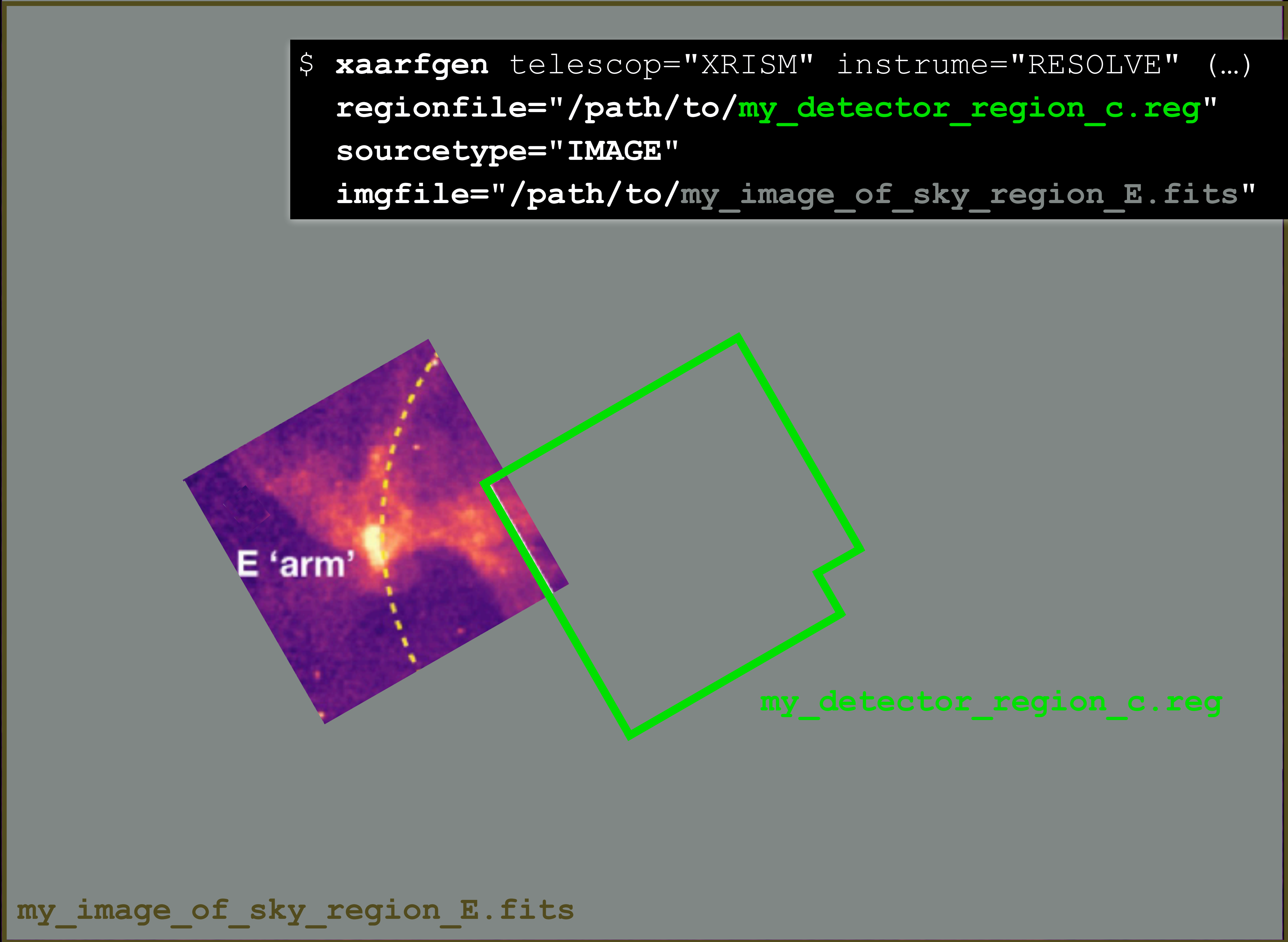
Even more concretely…



$S_c = R_c\,[(\ldots) + \mathbf{A}_{E\to c}\,\mathbf{M}_E + (\ldots)]$

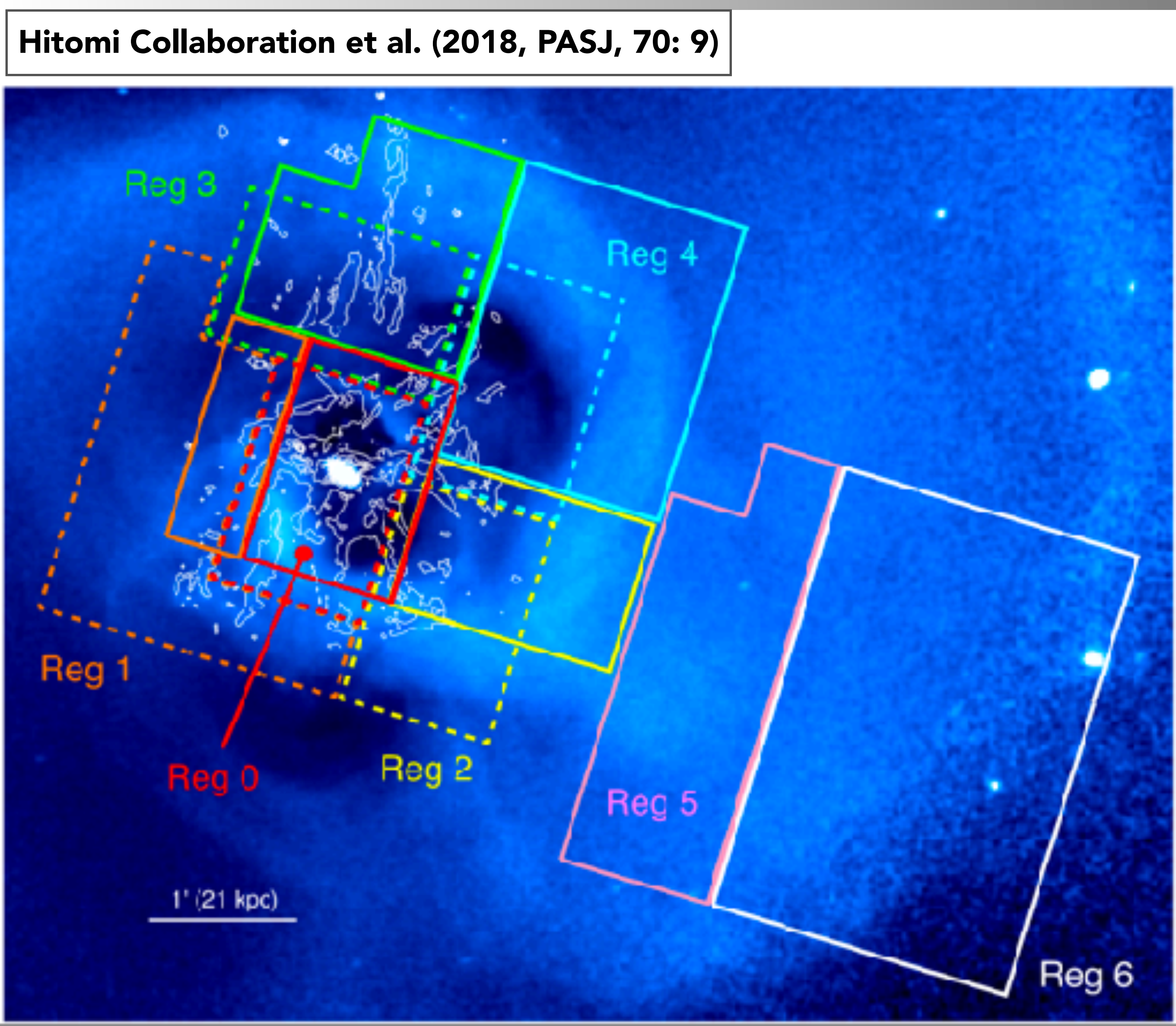
Even more concretely…

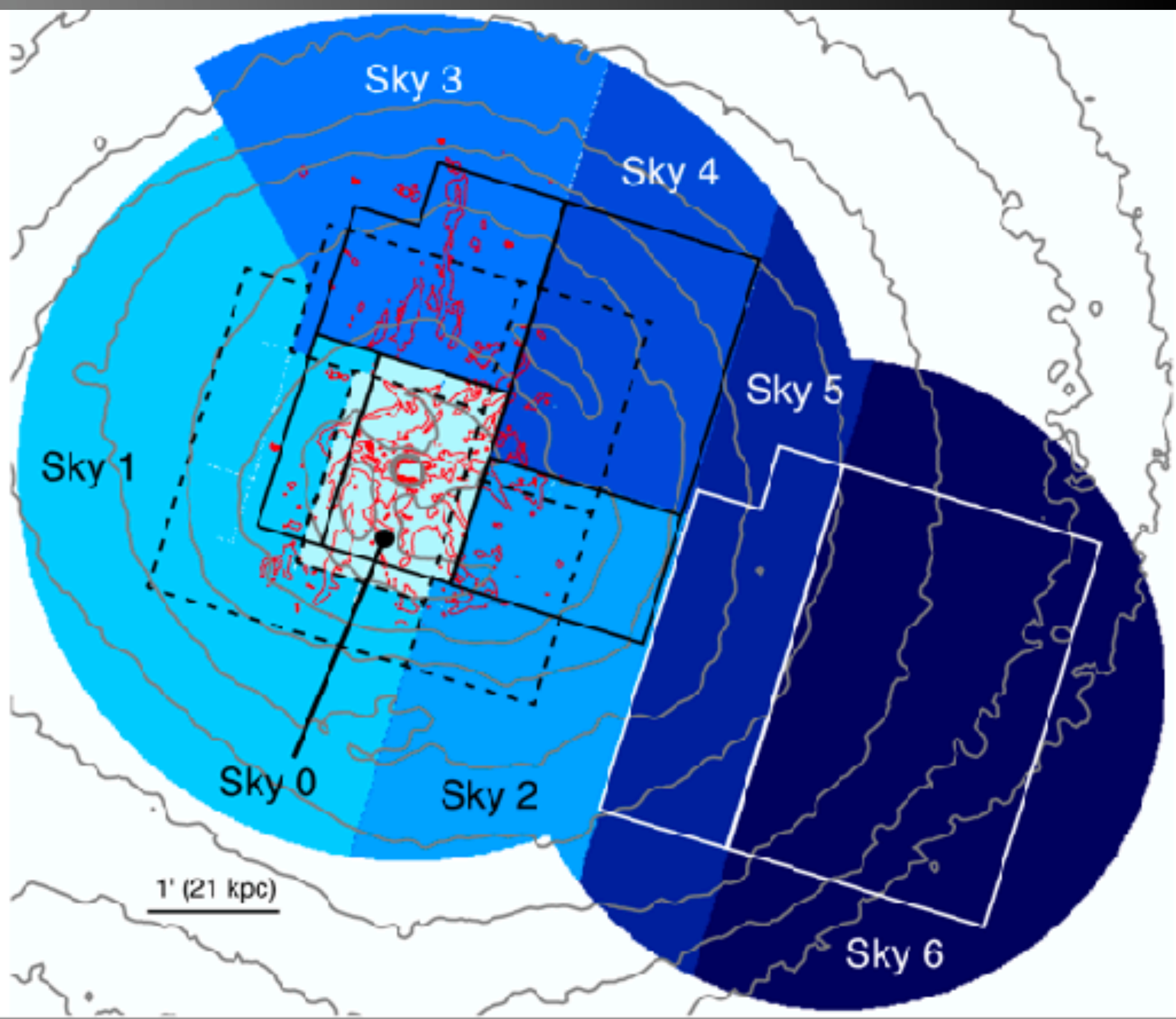
```
$ xaarfgen telescop="XRISM" instrume="RESOLVE" (…)
  regionfile="/path/to/my_detector_region_c.reg"
  sourcetype="IMAGE"
  imgfile="/path/to/my_image_of_sky_region_E.fits"
```



$$S_c = R_c\,[(\ldots) + \mathbf{A}_{E\to c}\,\mathbf{M}_E + (\ldots)]$$

Another concrete case (Perseus cluster)





12 detector regions

(obs1: 2 regions - obs2: 5 regions - obs3: 5 regions)

J = 0,1,...,12

6 sky regions

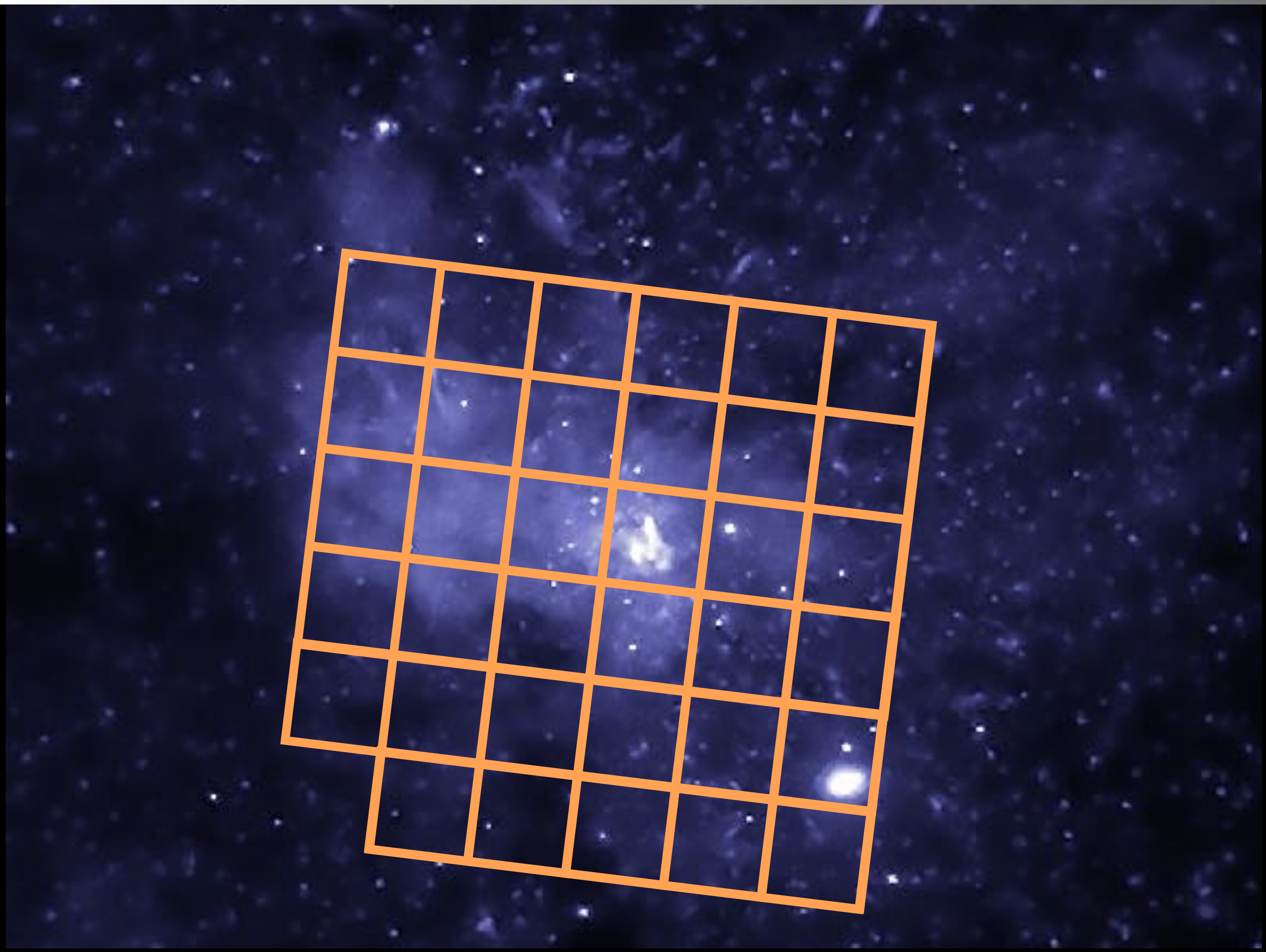
(Larger than detector regions to account for external SSM)

i = 0,1,...,6

$$S_i = R_i \sum_J A_{J\to i} M_J$$

12 x 6 = 72 models fitted simultaneously to 12 observed spectra (!)

Another concrete case (Sagittarius A*)



35 detector regions

J = 0,1,...,35

35 sky regions

i = 0,1,...,35

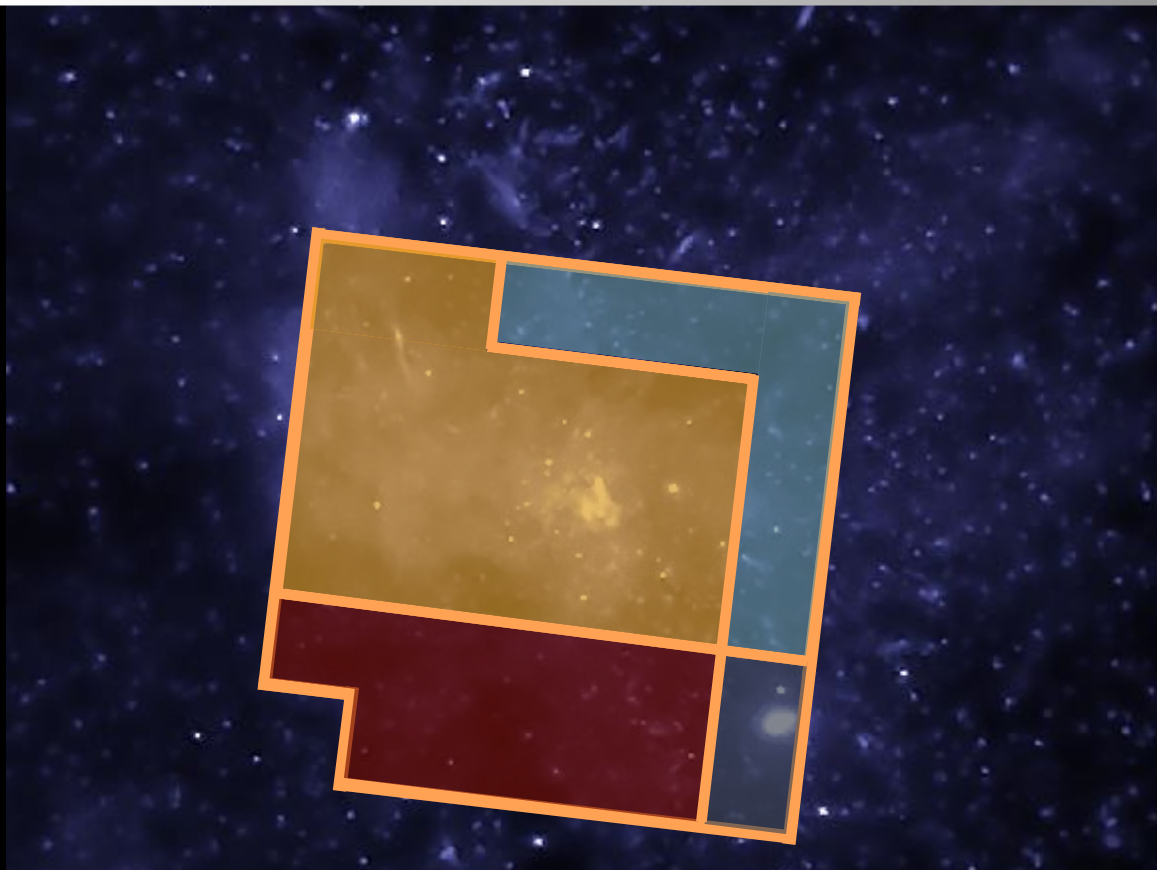
$$S_i = R_i \sum_J A_{J \rightarrow i} M_J$$

35 x 35 = 1225 models fitted simultaneously to 35 observed spectra !!

Problem: XRISM ARFs are **very** heavy to generate (>1-1.5 hour per ARF)!

➡ > 51 days on a single-core machine!

Mitigating the long ARF generation times



1. Divide a few regions of interest in a smart way (e.g. regions with similar special features, "optimise" the SSM, etc.)…

2. Treat each pixel separately vs "the rest" (modelled as a block)

3. Ignore regions with virtually inexistent SSM

4. A library of pre-computed PSFs may be made available some time soon (PSFlib)

5. ARFs can be computed over narrow energy ranges too…

6. …other options with your host institute? (Grid computing, computing clusters, etc.)

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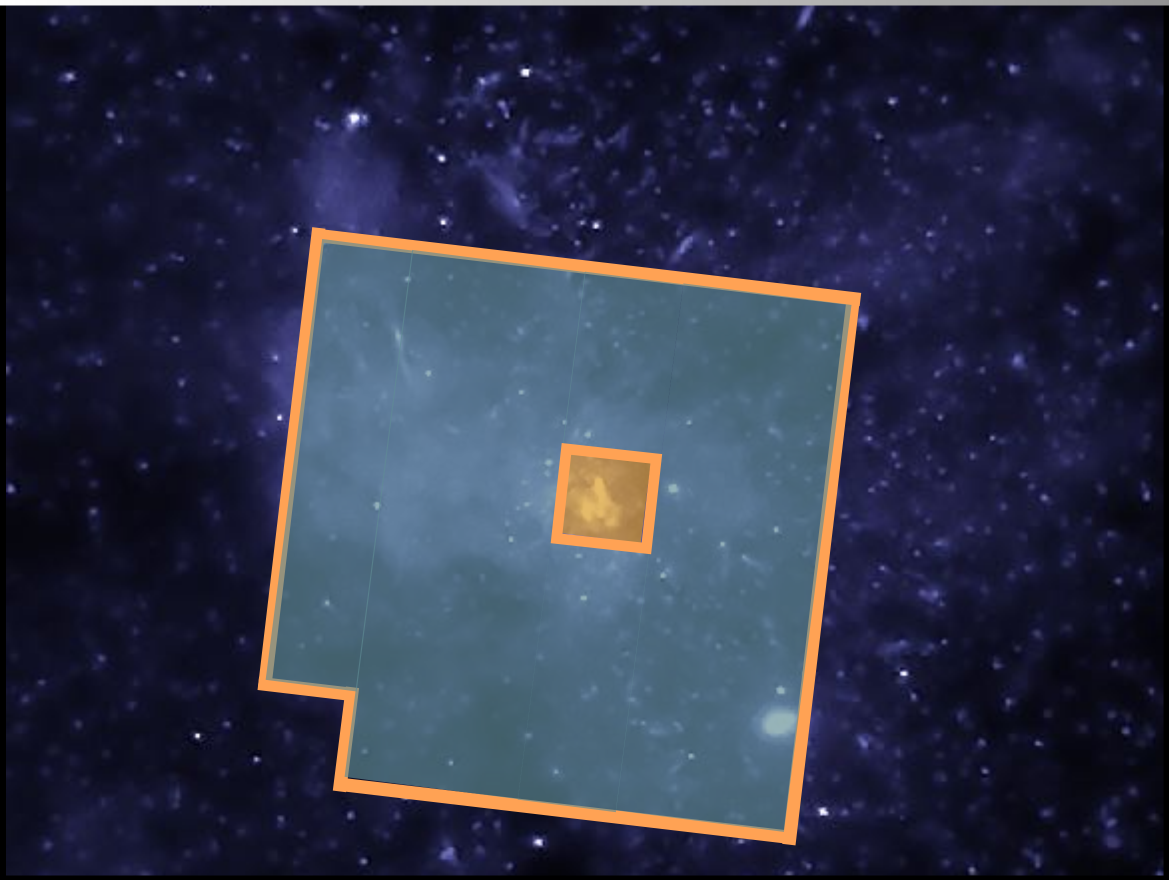

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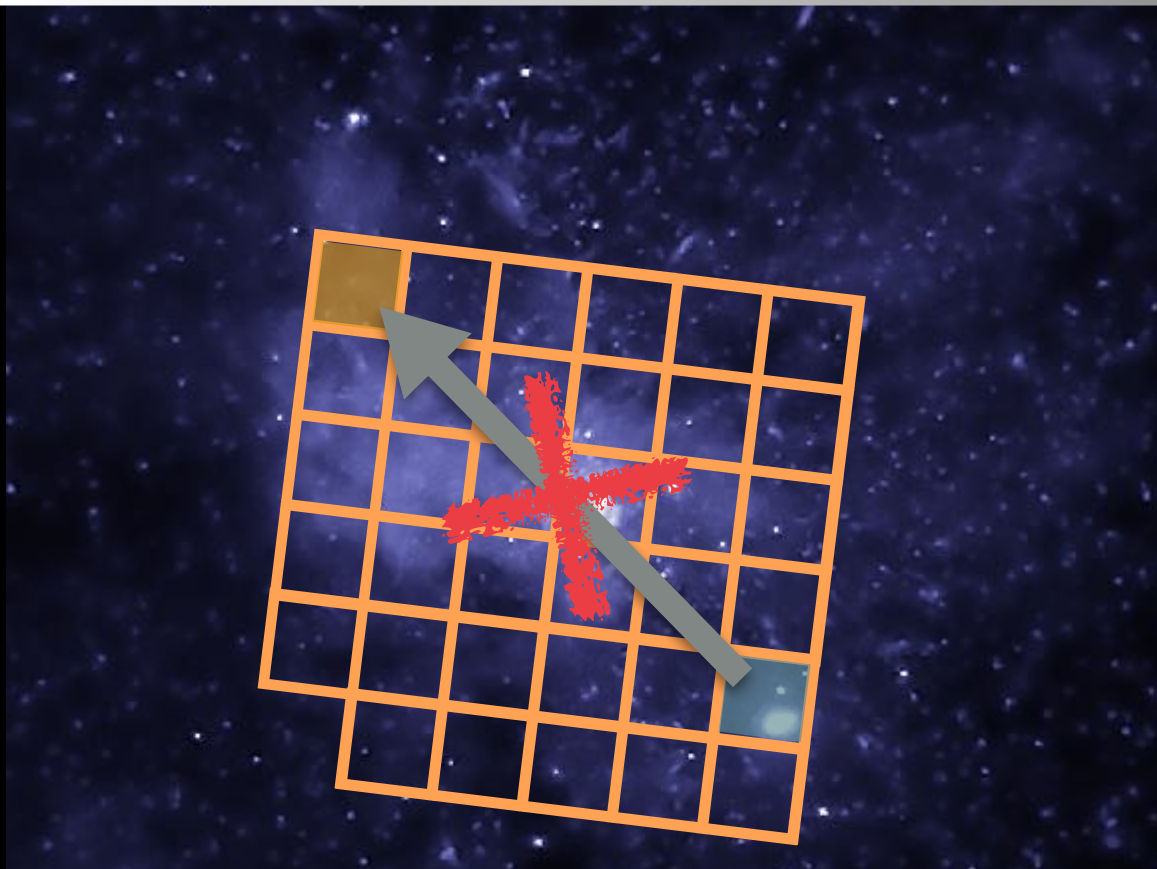

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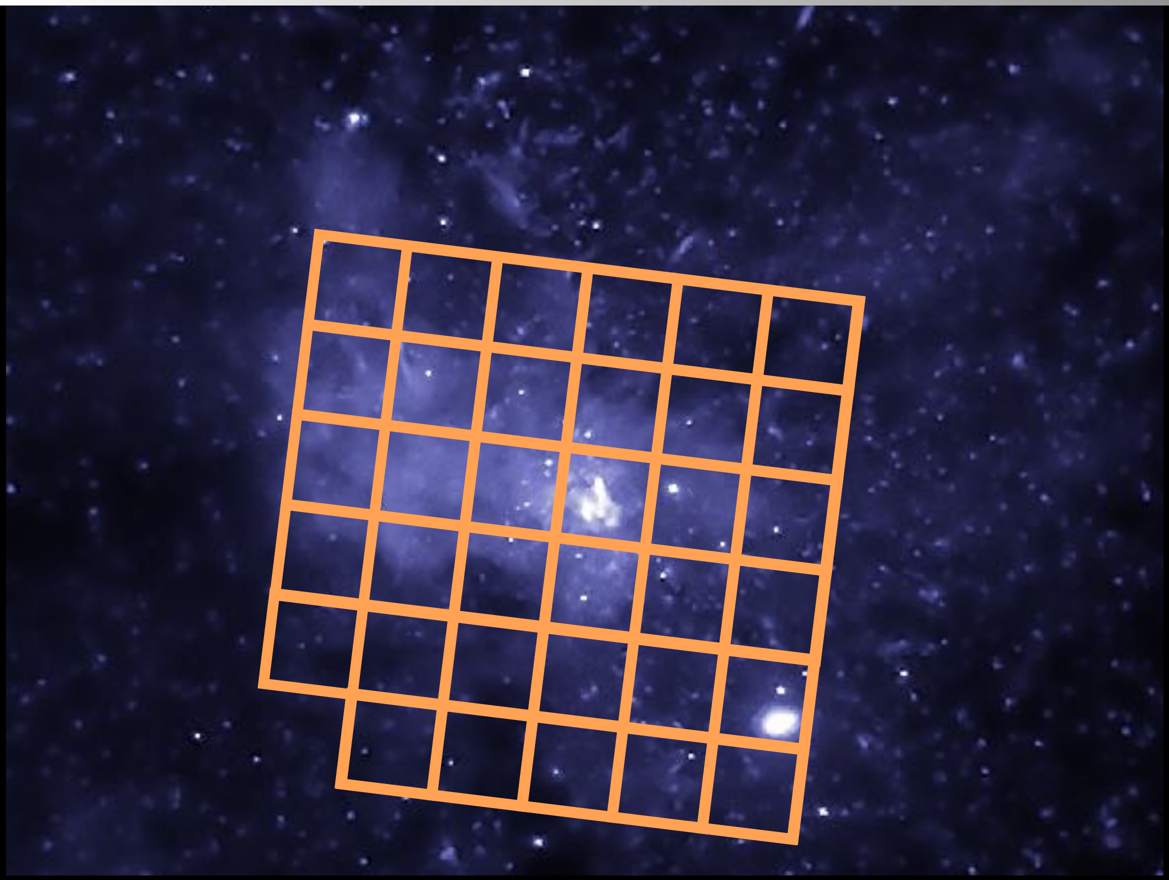

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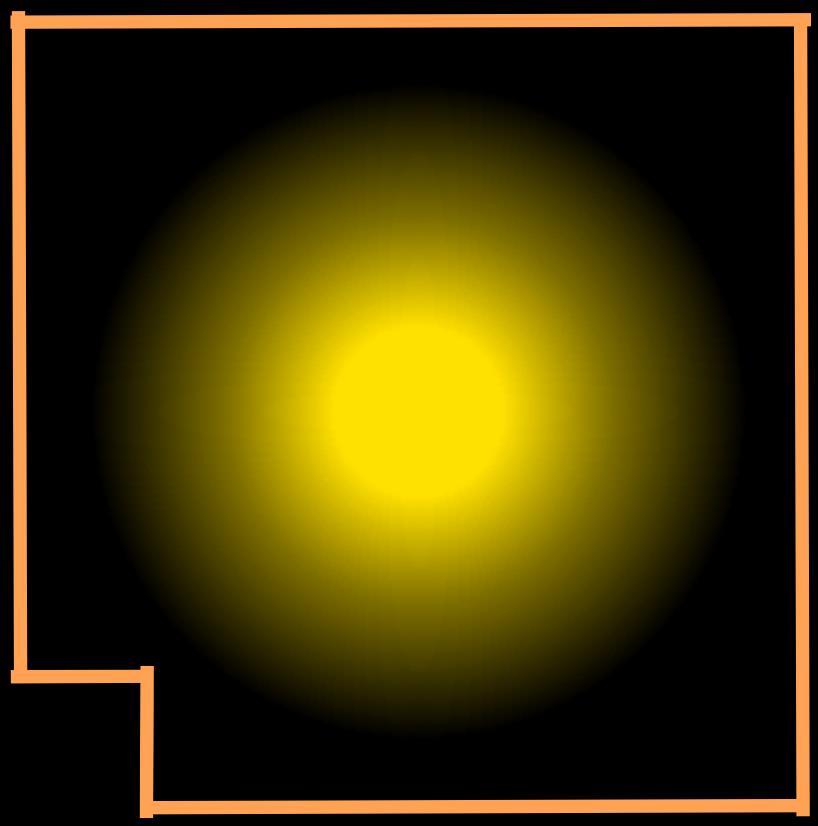
X-IFU: issue becomes opportunity



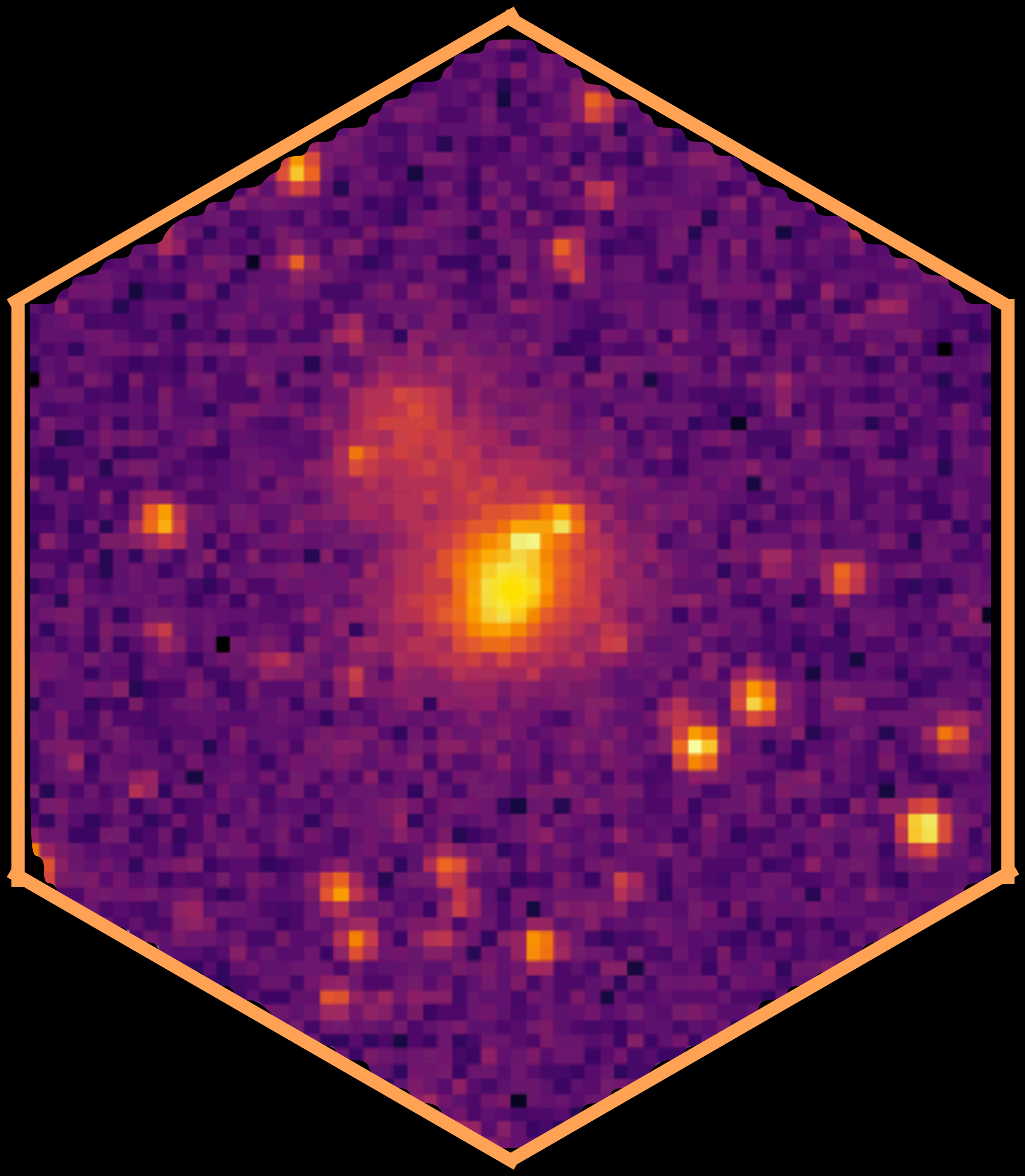
$$\frac{1.3'}{3'} = 43\% \; (!)$$

X-IFU: issue becomes opportunity

$$\frac{10''}{4'} = 4\%$$

No need for SSM modelling in X-IFU future observations…

X-IFU: issue becomes opportunity



$$\frac{10''}{4'} = 4\%$$

No need for SSM modelling in X-IFU future observations…

…but XRISM experience on SSM may help to use the best of the (X-) IFU capabilities!

(Pixel to pixel analysis in bright extended sources?)

Conclusion

✓ **Your favorite XRISM extended source will (very) likely be affected by SSM!**

✓ **Other systematic uncertainties** (energy gain & LSF calibration, background, etc.)

✓ Substantial SSM is **not necessarily "bad"** (see above example with ~50% purity)

✓ Data analysis will **NOT be a simple XSPEC fit**! (e.g. investigation of spectral signatures of SSM before fitting)

✓ Recommended to plan a coherent **tiling of regions** to investigate

✓ Lessons learned on XRISM may be (very) useful for future X-IFU pixel-to-pixel analyses