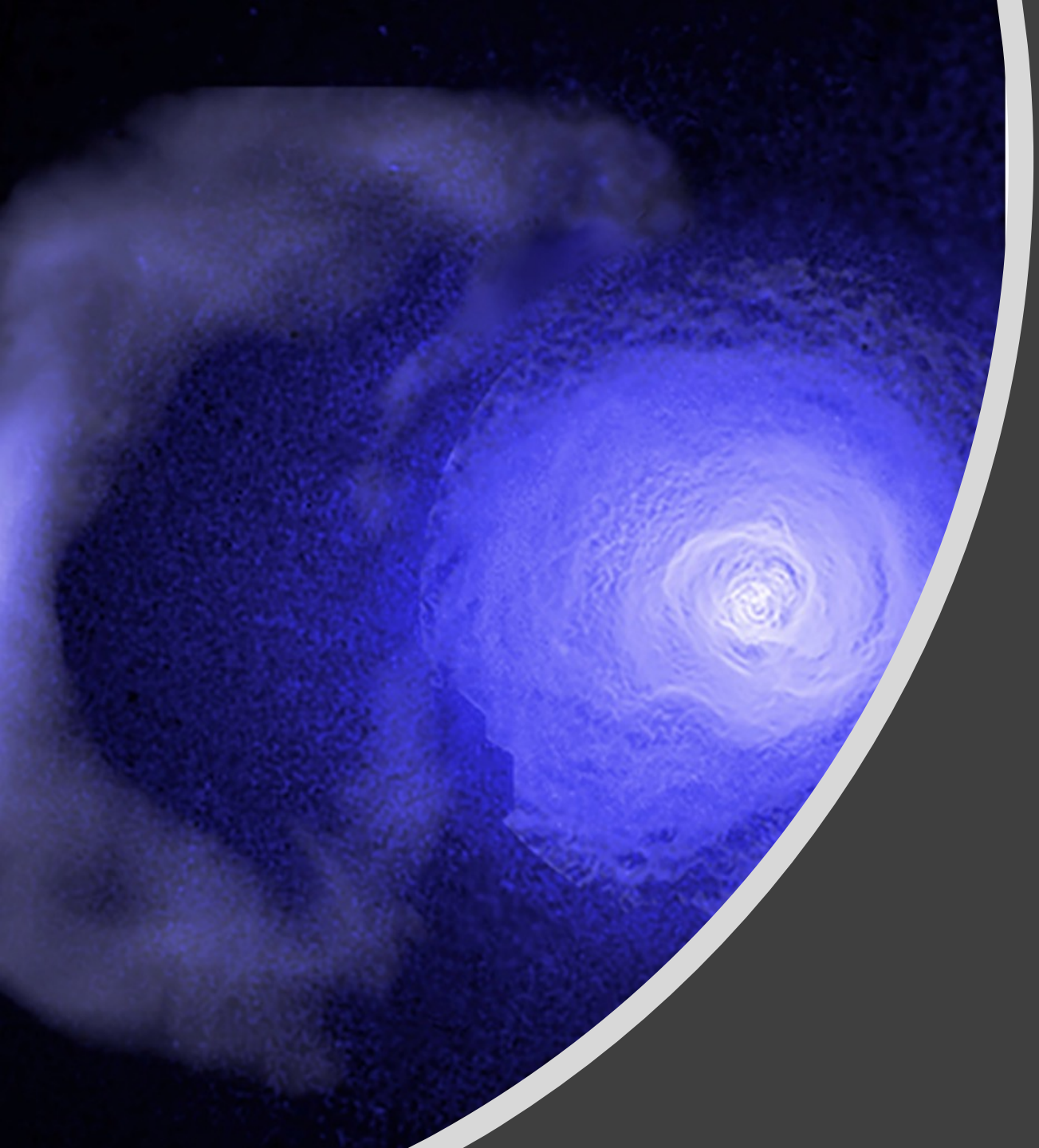


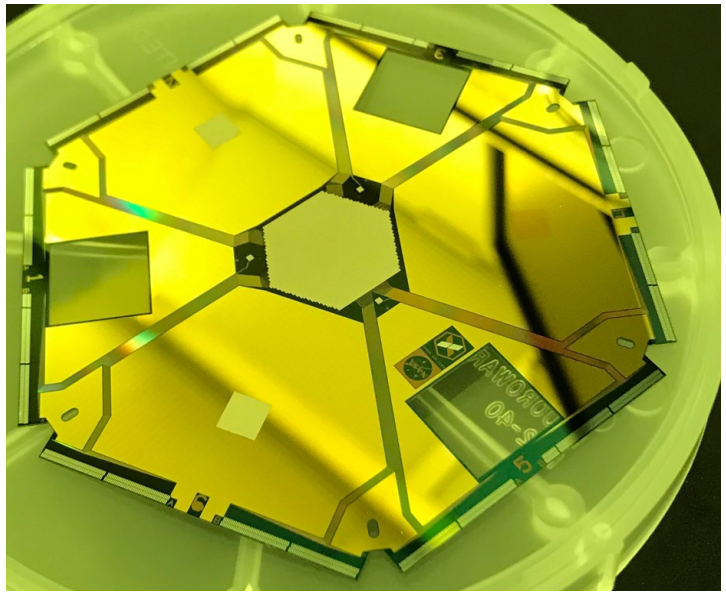
Simulating galaxy clusters

Sophie Beaumont, N. Clerc, E. Pointecouteau

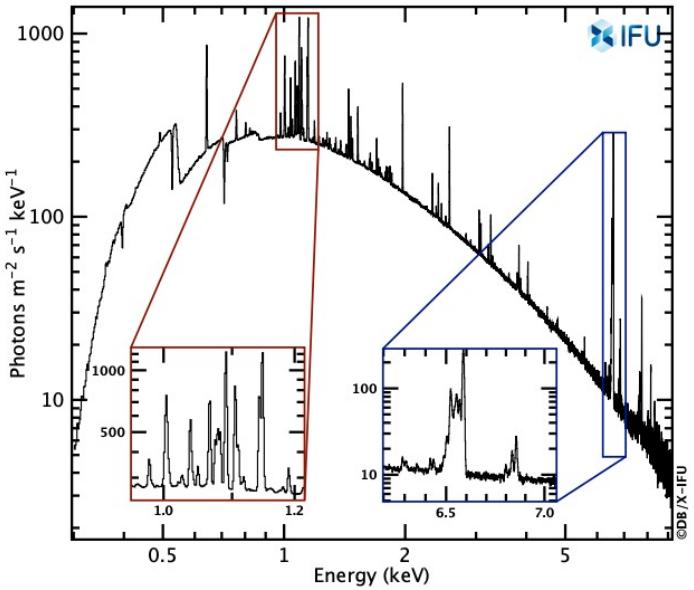
SIXTE Workshop 2022

The Athena/X-IFU

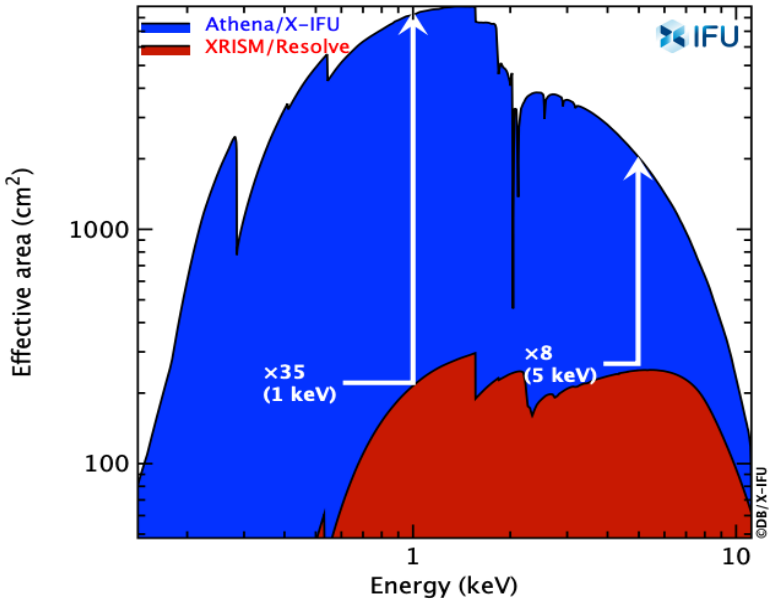
- Athena is the next X-ray observatory, to be launched in the mid 2030's
- The X-IFU is its cryogenic imaging spectrometer based on a **TES microcalorimeter array** of ~3k pixels



Prototype TES microcalorimeter array and its supporting wafer (Credit : NASA GSFC)



X-IFU simulated spectrum of a Perseus like galaxy cluster. Hundreds of lines per spectrum (Credit : X-IFU team (data courtesy of C. Pinto and A.C. Fabian)



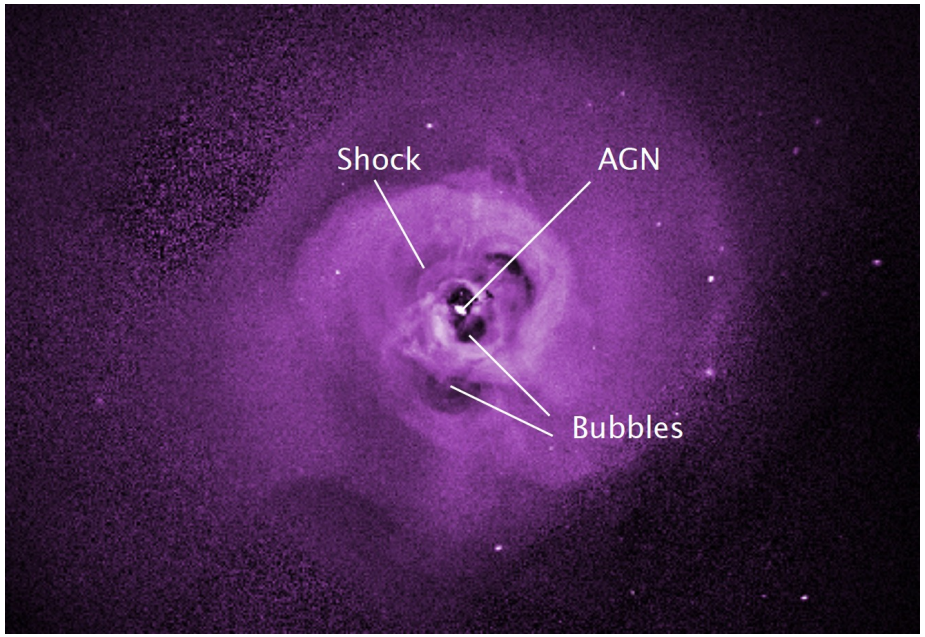
Effective area comparison between Athena X-IFU and XRISM resolve (Credit : IRAP and X-IFU team)

Science goal ~ Turbulence/Bulk motion in galaxy clusters

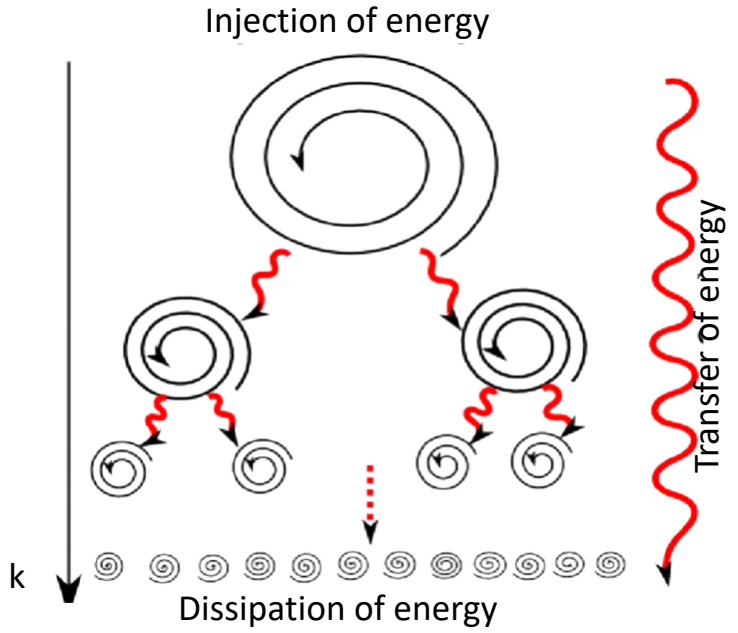
- Galaxy clusters = most massive gravitationally-bound objects in the Universe

  ⟹ Key to further understanding our universe

- Often assumed in hydrostatic equilibrium, *but* strong hints part of gas pressure provided by bulk and turbulent motions



Perseus clusters in X-ray (Credit: Simionescu et al, 2019)



Energy transfer through turbulences (Credit: derived from Humbert, 2014)

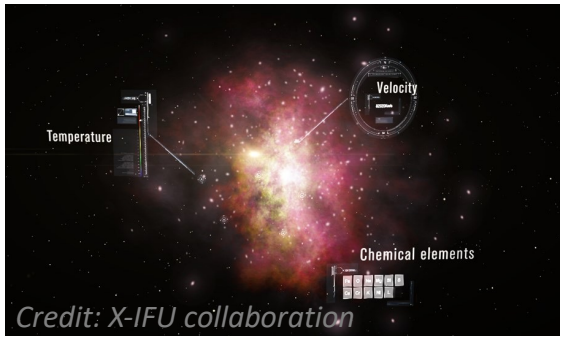
End-to-End simulation

- In order to assess the capability of measuring turbulence in galaxy clusters with X-IFU, we perform E2E simulations

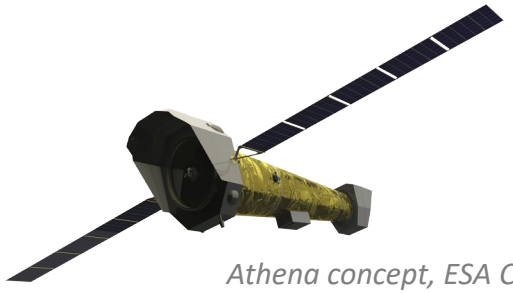
  Aim : 1. Recover the turbulence parameters (i.e. injection & dissipation scales, slope and normalization)
  2. Find optimum observation strategy to recover those parameters

- Work in continuity with previous work from P. Peille and E. Cucchetti

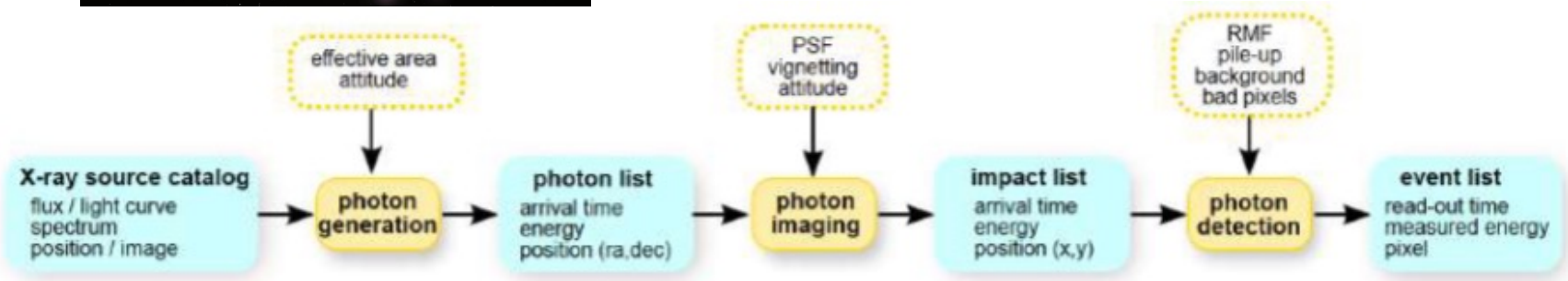
- Simulation using the SIXTE (Simulation of X-ray Telescopes) simulator



Credit: X-IFU collaboration



Athena concept, ESA CDF
Credit: IRAP, CNES, ESA & ACO



Overview of SIXTE E2E simulation process (Credit : Wilms et al. 2014)

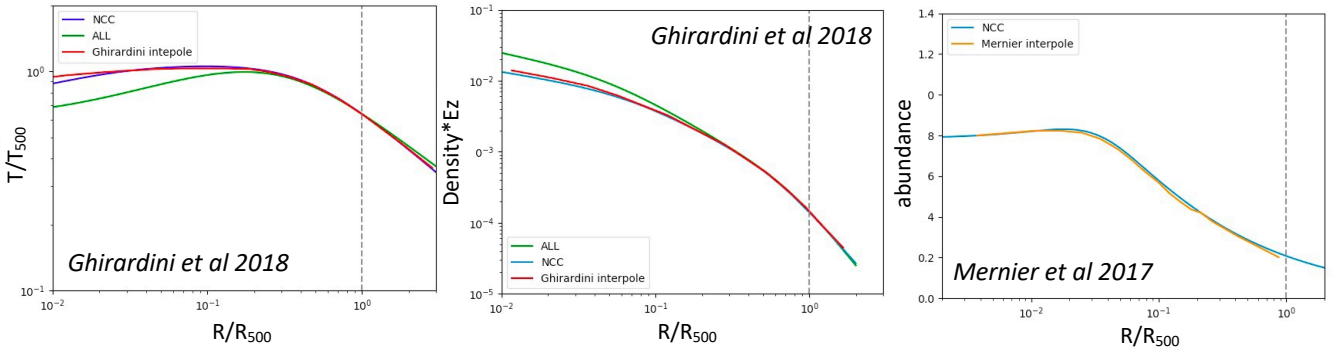
Photon list generation

- Chose not to use SIXTE for the photon generation
  ↳ generated independently, to allow parallelization and reduce computational time

- First : choosing the parameterization of the galaxy cluster

>> Toy model ~ non-cool core galaxy clusters at z=0.1, R_{500} = 1.3 Mpc

>> Temperature, abundance and electron density following :

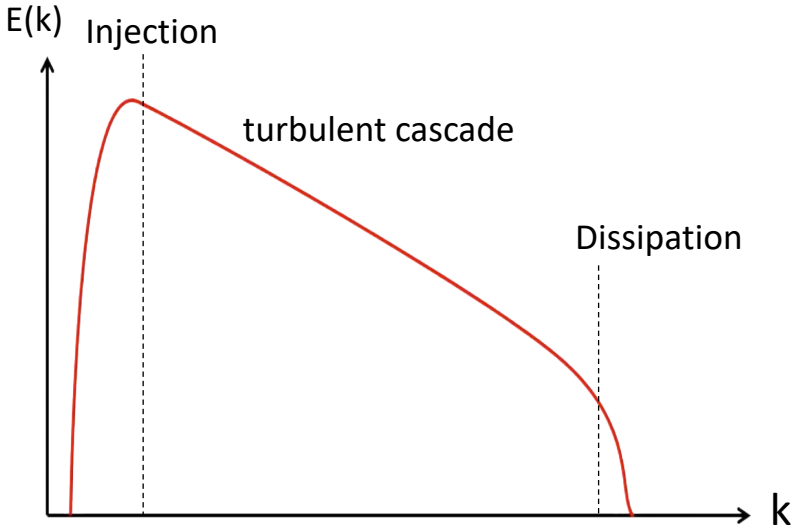


>> Redshift adjusted with a component from the speed along line-of-sight

>> X-ray emission spectra described by phabs*bapec model

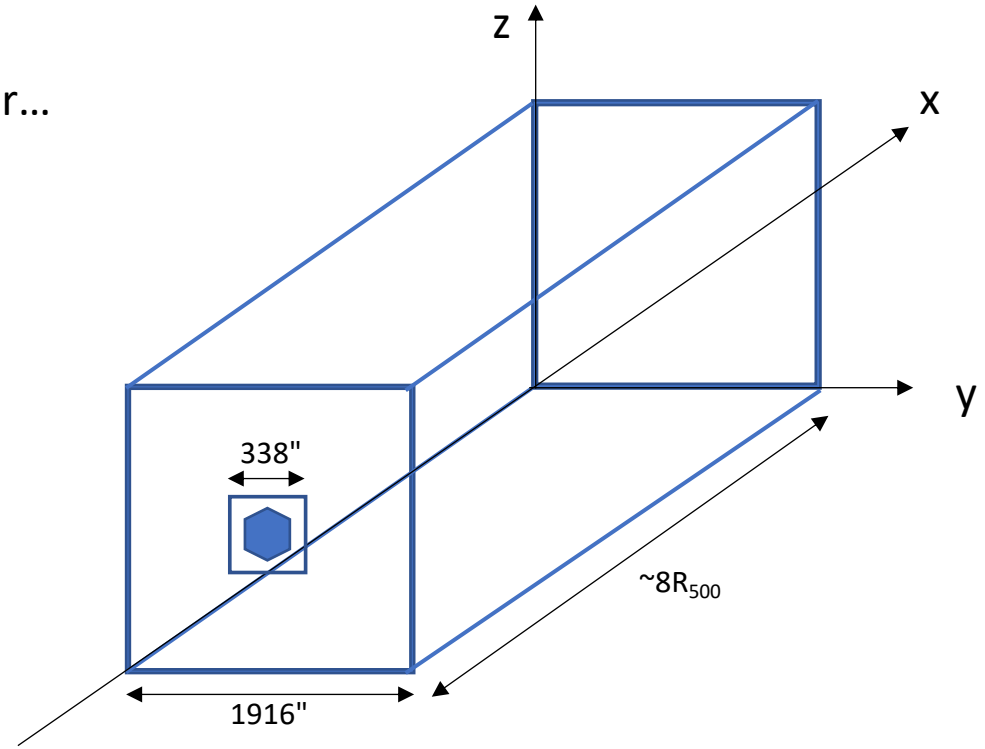
>> simplest model for turbulence (Kolmogorov)

$$P_{3D}(\underline{\boldsymbol{k}}) = C_n e^{-(k/k_{diss})^2} k^{\alpha} e^{-(k_{inj}/k)^2}$$



Photon list generation

- Then, defining a 3D cube to represent the cluster…

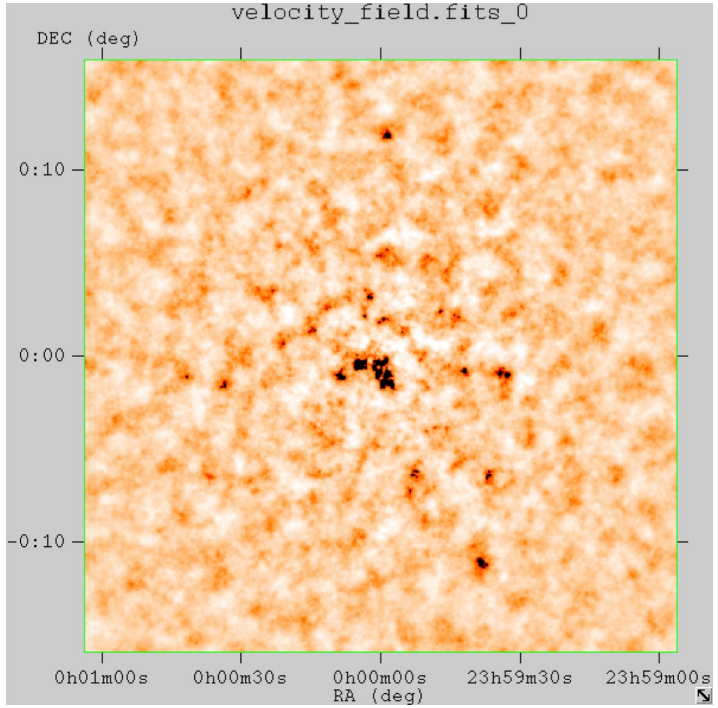


- Cube split into cells (or particles) of ½ X-IFU pixel size (i.e 2.365 ”)
- Simulated velocity grid -> 6480 x 810 x 810
  Input tables (1 pointing at a time) -> 6480 x 142 x 142

- To each cell (~40 million per pointing) will be associated a value of turbulent velocity => turbulent velocity cube and redshift, T, abundance, and emissivity => input table

Photon list generation

- Turbulent velocity field



- Input table

fv: Binary Table of input_table_0.fits[1] in /data/xifu/home/sbeaumont/Turbu_300kpc_500ks_repeat01/Y+0_Z+0/simputfiles/part0/

File Edit Tools Help

	RA	DEC	T	FE_ABUND	REDSHIFT	NORM
Select	1D	1D	1D	1D	1D	1D
All	degrees	degrees	keV			
Invert	Modify	Modify	Modify	Modify	Modify	Modify
1	-3.041032837626E-02	-5.681050070655E-03	1.474014768974E+00	9.707655183447E-02	9.933215379715E-02	9.339954051396E-15
2	-3.041032837626E-02	-5.012691242452E-03	1.474017928557E+00	9.707671898813E-02	9.922410547733E-02	9.340120100947E-15
3	-3.041032837626E-02	-4.344332412883E-03	1.474020693216E+00	9.707686524881E-02	9.903363883495E-02	9.340265397706E-15
4	-3.041032837626E-02	-3.675973582133E-03	1.474023062942E+00	9.707699061601E-02	9.894151985645E-02	9.340389940311E-15
5	-3.041032837626E-02	-3.007614750382E-03	1.474025037726E+00	9.707709508932E-02	9.945443272591E-02	9.340493727598E-15
6	-3.041032837626E-02	-2.339255917813E-03	1.474026617561E+00	9.707717866838E-02	9.963335841894E-02	9.340576758593E-15
7	-3.041032837626E-02	-1.670897084607E-03	1.474027802443E+00	9.707724135292E-02	9.914942830801E-02	9.340639032521E-15
8	-3.041032837626E-02	-1.002538250946E-03	1.474028592366E+00	9.707728314273E-02	9.893646836281E-02	9.340680548796E-15
9	-3.041032837626E-02	-3.341794170123E-04	1.474028987328E+00	9.707730403768E-02	9.916778653860E-02	9.340701307031E-15
10	-3.041032837626E-02	3.341794170123E-04	1.474028987328E+00	9.707730403768E-02	9.900964051485E-02	9.340701307031E-15
11	-3.041032837626E-02	1.002538250946E-03	1.474028592366E+00	9.707728314273E-02	9.876482188702E-02	9.340680548796E-15
12	-3.041032837626E-02	1.670897084607E-03	1.474027802443E+00	9.707724135292E-02	9.918778389692E-02	9.340639032521E-15
13	-3.041032837626E-02	2.339255917813E-03	1.474026617561E+00	9.707717866838E-02	9.949777275324E-02	9.340576758593E-15
14	-3.041032837626E-02	3.007614750382E-03	1.474025037726E+00	9.707709508932E-02	9.956596046686E-02	9.340493727598E-15
15	-3.041032837626E-02	3.675973582133E-03	1.474023062942E+00	9.707699061601E-02	1.000841856003E-01	9.340389940311E-15
16	-3.041032837626E-02	4.344332412883E-03	1.474020693216E+00	9.707686524881E-02	1.007845550776E-01	9.340265397706E-15
17	-3.041032837626E-02	5.012691242452E-03	1.474017928557E+00	9.707671898813E-02	1.004668250680E-01	9.340120100947E-15
18	-3.041032837626E-02	5.681050070655E-03	1.474014768974E+00	9.707655183447E-02	1.000520586967E-01	9.339954051396E-15
19	-2.974196963226E-02	-8.354485417349E-03	1.474015953814E+00	9.707661451692E-02	1.005271449685E-01	9.340016319492E-15
20	-2.974196963226E-02	-7.686126592328E-03	1.474020693216E+00	9.707686524881E-02	1.002178117633E-01	9.340265397706E-15

Go to: Edit cell:

- Spectra (and flux) needed for each cell
  ↳ using precomputed tables of spectra for range of T and Z, @ z = 0.1 (fix)
  ↳ correct T, Z interpolated, then z adjusted by shifting the spectra

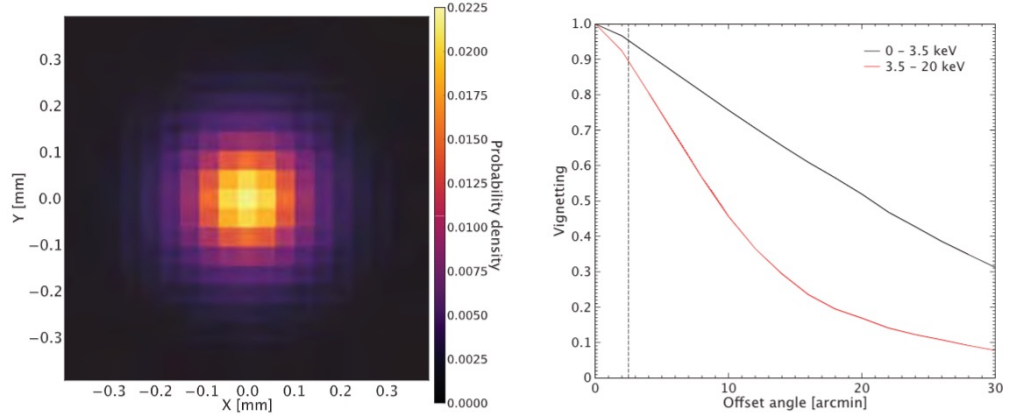
- From input table cut in parts, generation of the **photon list** for each cells

Photon imaging & detection with SIXTE / xifupipeline

Simulating effects of the telescope, including PSF and vignetting

Simulating parameters/effects related to the detection chain, including

- pixel geometry
- array geometry
- grading



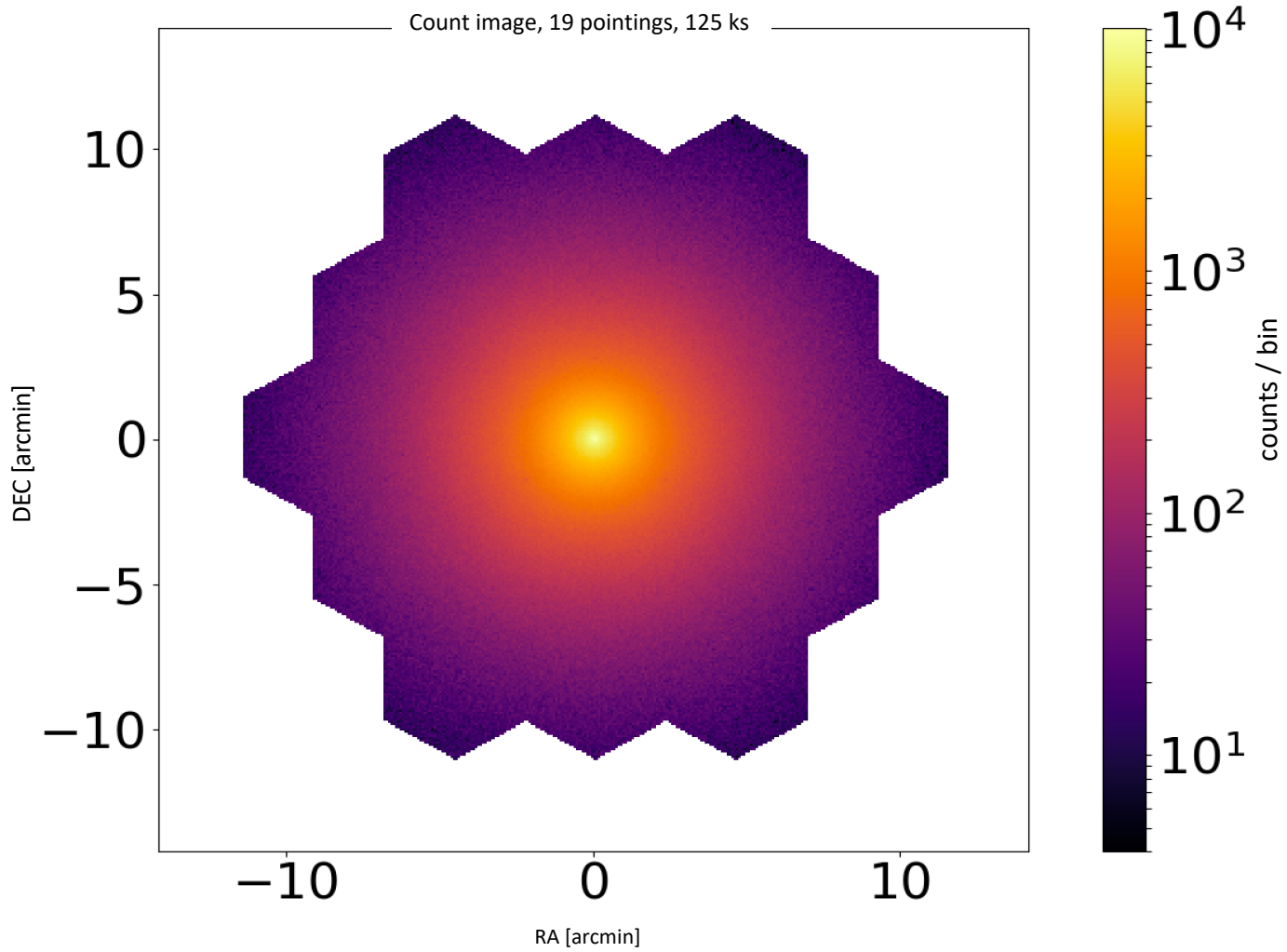
On-axis Athena PSF at 10 keV (left) and vignetting functions for different energies (right) (credit P. Peille)

Post-processing

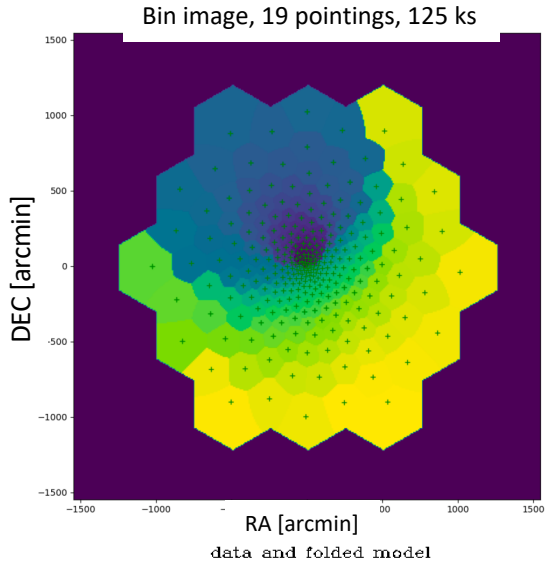
- Simulation ran 19 times, for different pointings

- For each pointing:
  - Parallelization ~ 40 CPUs
  - Runtime ~ 30 hours
  - Disk space ~ 5 to 25 Go

- All files merged together

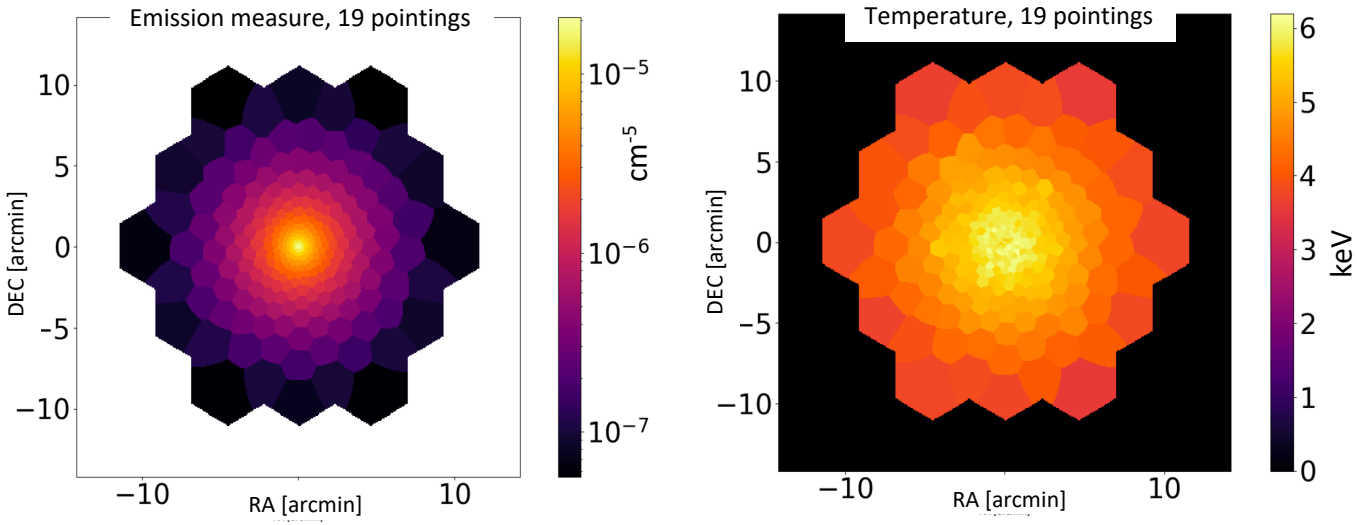


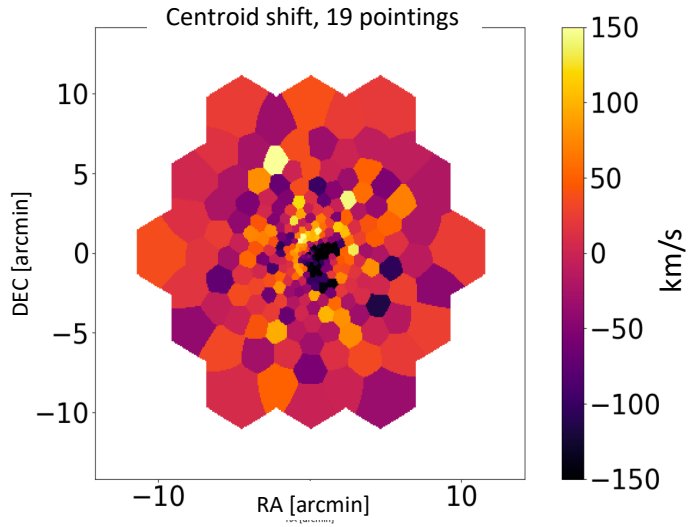
Post-processing



*Example simulated spectrum extracted from the central bin (model: phabs*bapec)*

⟹ Fit with xspec





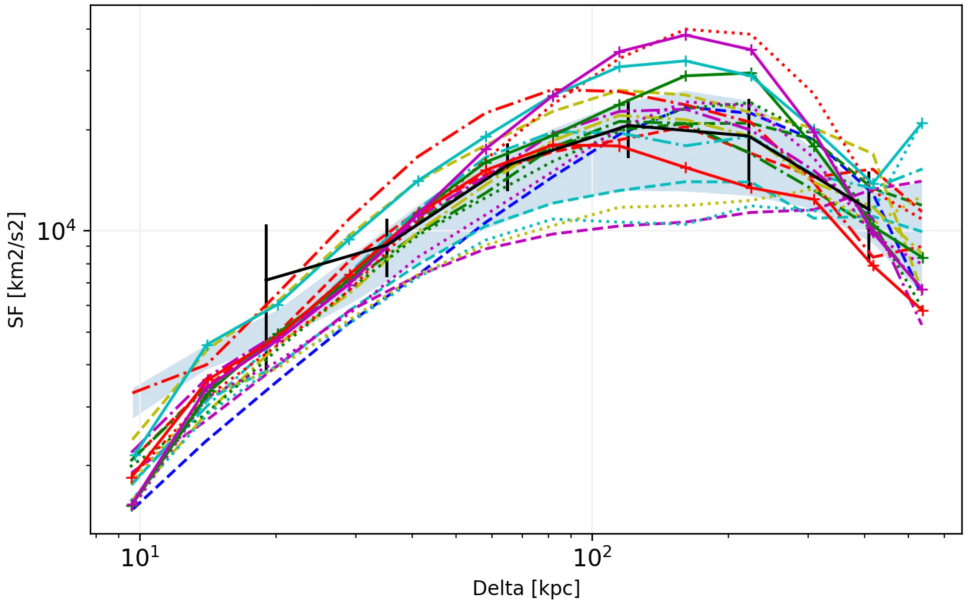
Output maps from the SIXTE simulation for our toy model, and an exposure time of 125 ks

Analysis

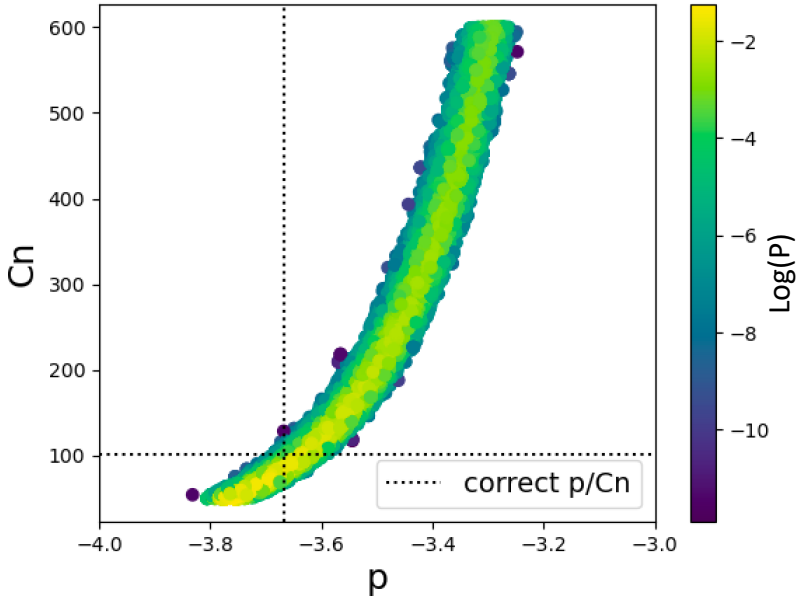
- Use of the structure function as diagnostic, calculated from the measurements of emission line centroid shifts
  ⇔ spatial correlation function

  SF can also be calculated from a theoretical model (Clerc et al 2019)

- Goal : assuming turbulence parameters (injection, dissipation, slope and normalization) not known, we try to recover them through MCMC fits, using modeled SF for prediction



Structure functions from 20 SIXTE simulations of the central pointing at 125 ks and modeled, for our toy model



Preliminary results from MCMC with the slope and normalization left free

Conclusions

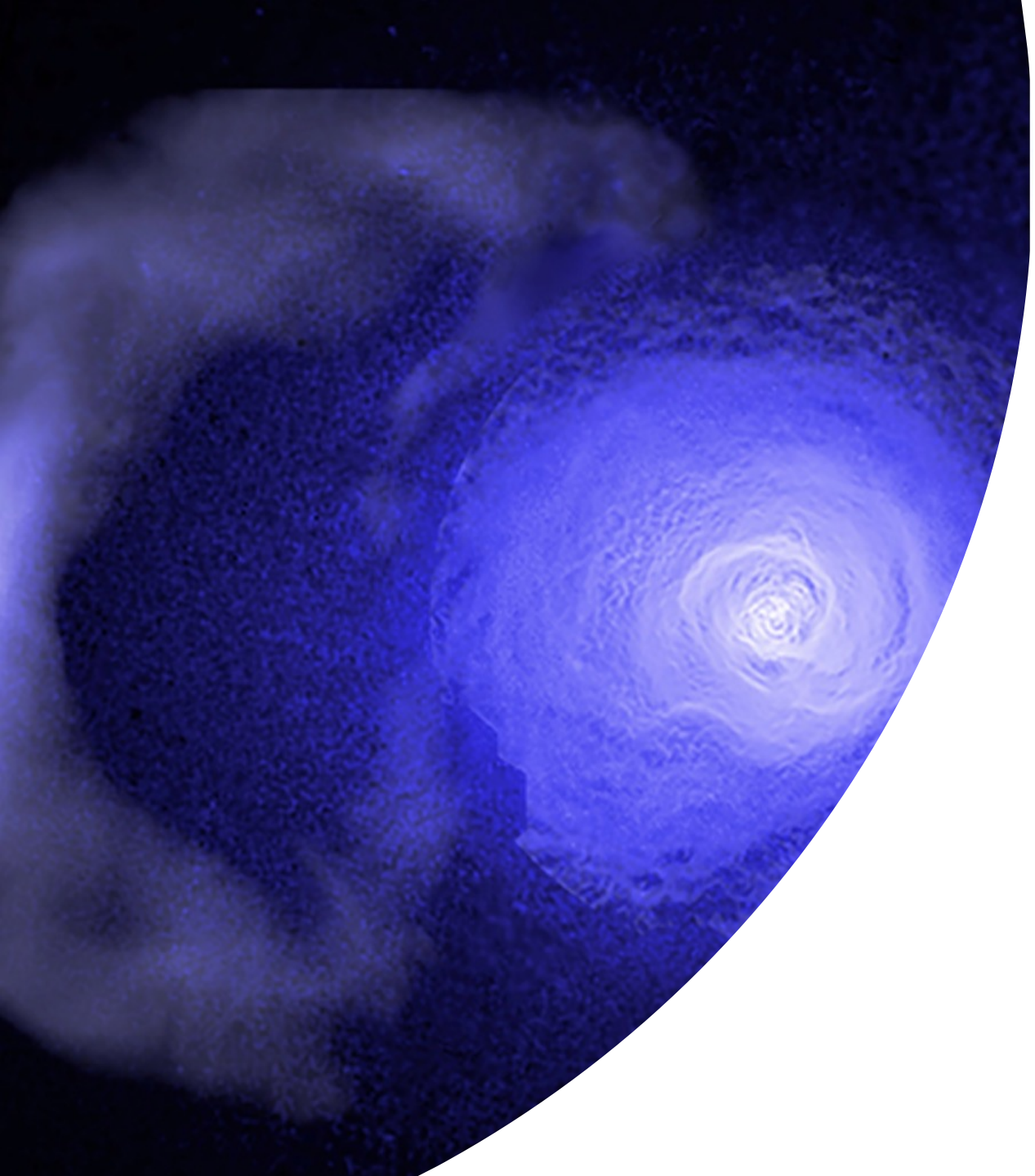
- SIXTE simulator allowed us to perform end-to-end simulations of galaxy cluster representative of what will be observed with Athena/X-IFU and investigate the bulk motion in those clusters

- So far, we performed:
  - multiple simulations of the central pointing
  - 2 full simulations with 19 pointings each, 500 ks exposure per pointing :

    ↳ each full simulation runs in ~10 days on 2*48 CPUs

- Full datasets taking ~1.5 Tb of disk space

- Follow up analysis on-going



Thank you for your attention.

Any questions ?