The ICM velocity structure in simulated galaxy cluster mergers

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in collaboration with: J. ZuHone

CENTER FOR
ASTROPHYSICS
HARVARD & SMITHSONIAN

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Outline

- ICM motions: *synergy between obs. and sims.*
- Velocity structure: simulations
- Velocity structure: X-ray mocks
- Current & future plans

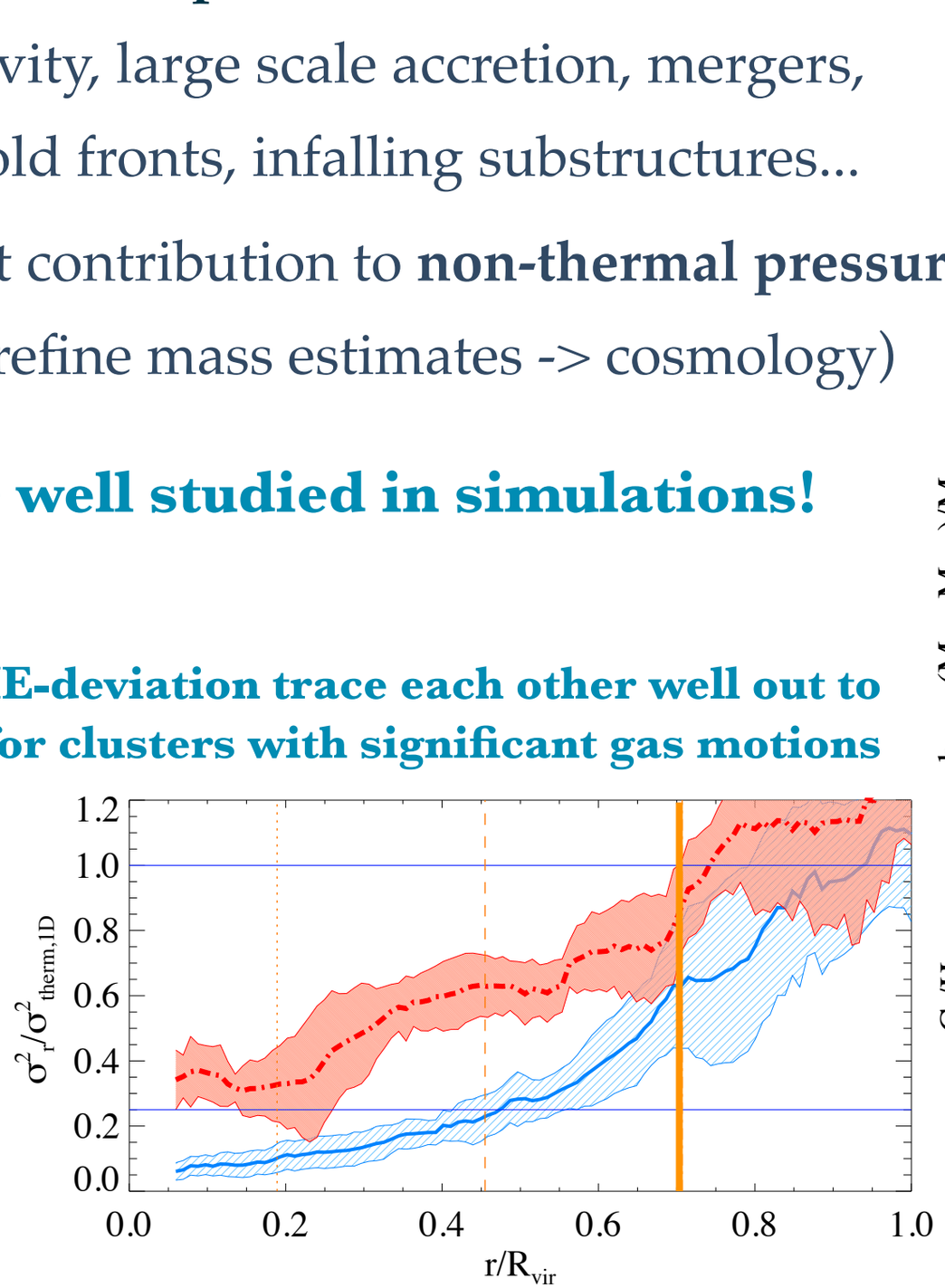
Motivation

- **Gas motions are present in the ICM**: turbulence, AGN activity, large scale accretion, mergers, shocks, cold fronts, infalling substructures...
- Dominant contribution to **non-thermal pressure** support (refine mass estimates -> cosmology)

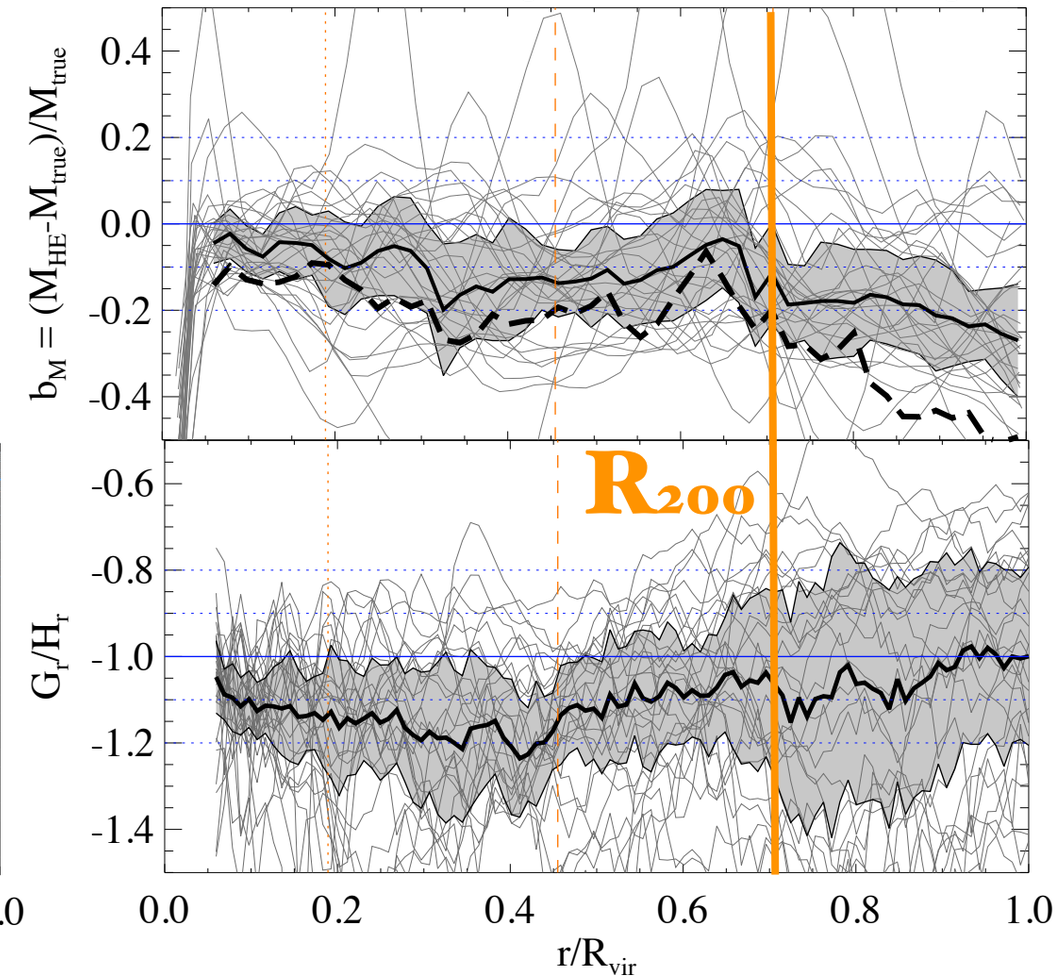
Rasia+06; Nagai+07; Piffaretti+08; Fang+09; Lau+09,13; Vazza+09; **VB**+2011; Suto+13; Zhuravleva+13; Nelson+14; **VB**+2016; Shi+15,16; Vazza+18; Pratt+19

This can be well studied in simulations!

M-bias and HE-deviation trace each other well out to R_{200}, except for clusters with significant gas motions



VB et al. (2016); Dianoga simulated clusters (S. Borgani)



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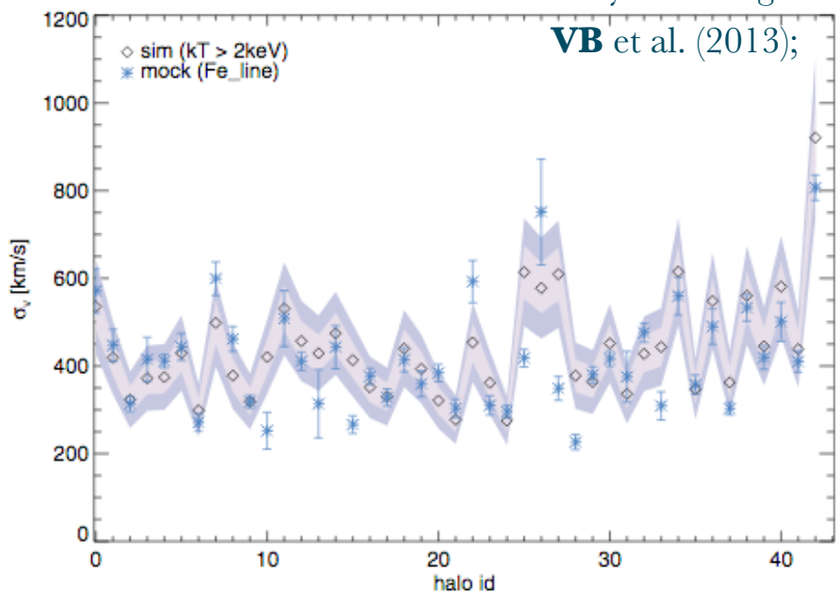
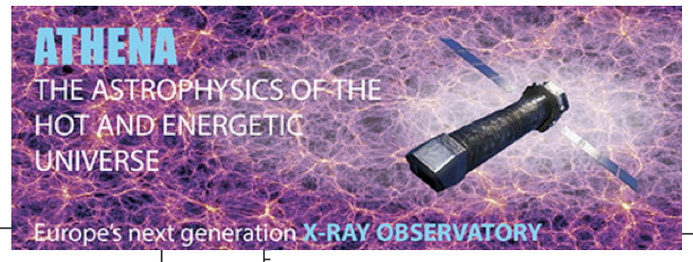
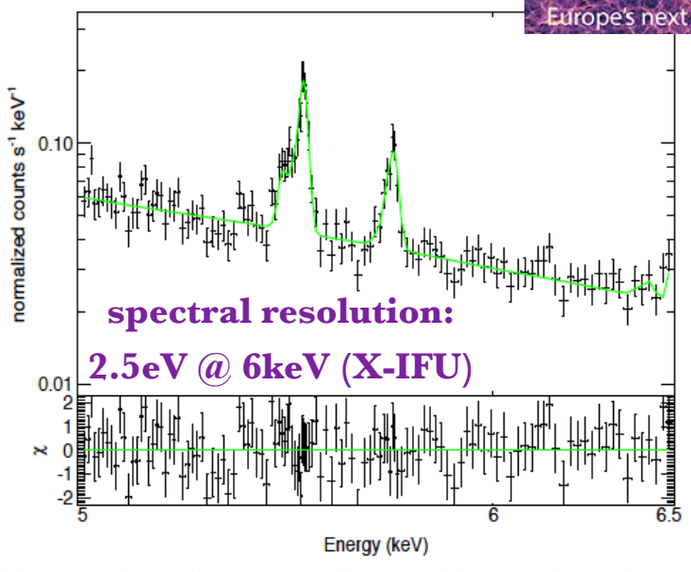
MAGNETICUM simulations by K. Dolag

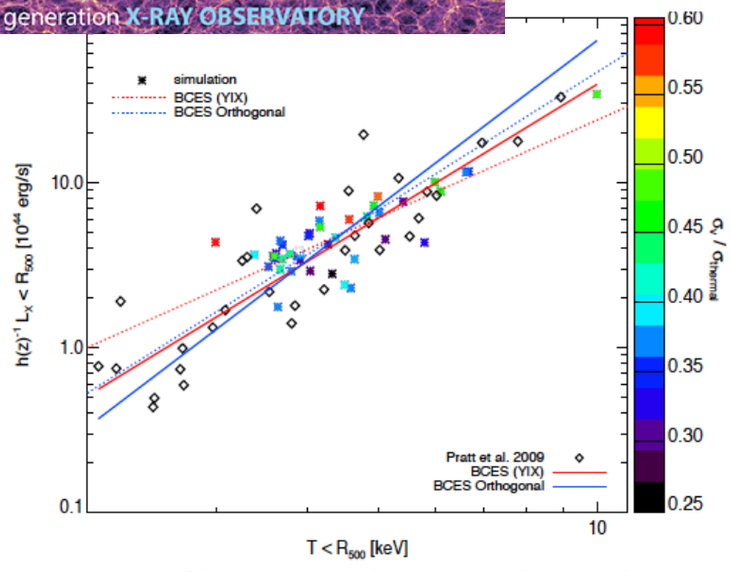




See review by Simionescu+19

VB+13;
ZuHone+16a,16b,18;
Roncarelli+18





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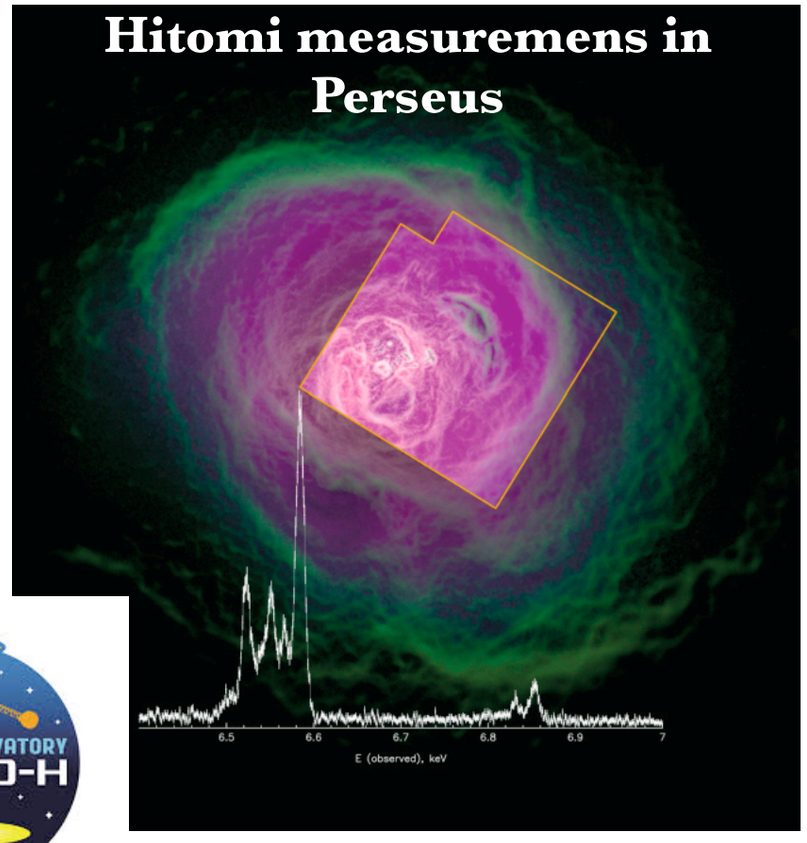
- First direct measurements by Hitomi, future X-ray missions needed (`XRISM`, `Athena`, `Lynx`...) -> *simulations & mocks!*



Copyright: Background: NASA/CXO; Spectrum: Hitomi Collaboration/JAXA, NASA, ESA, SRON, CSA

X-ray energy resolution of few eV

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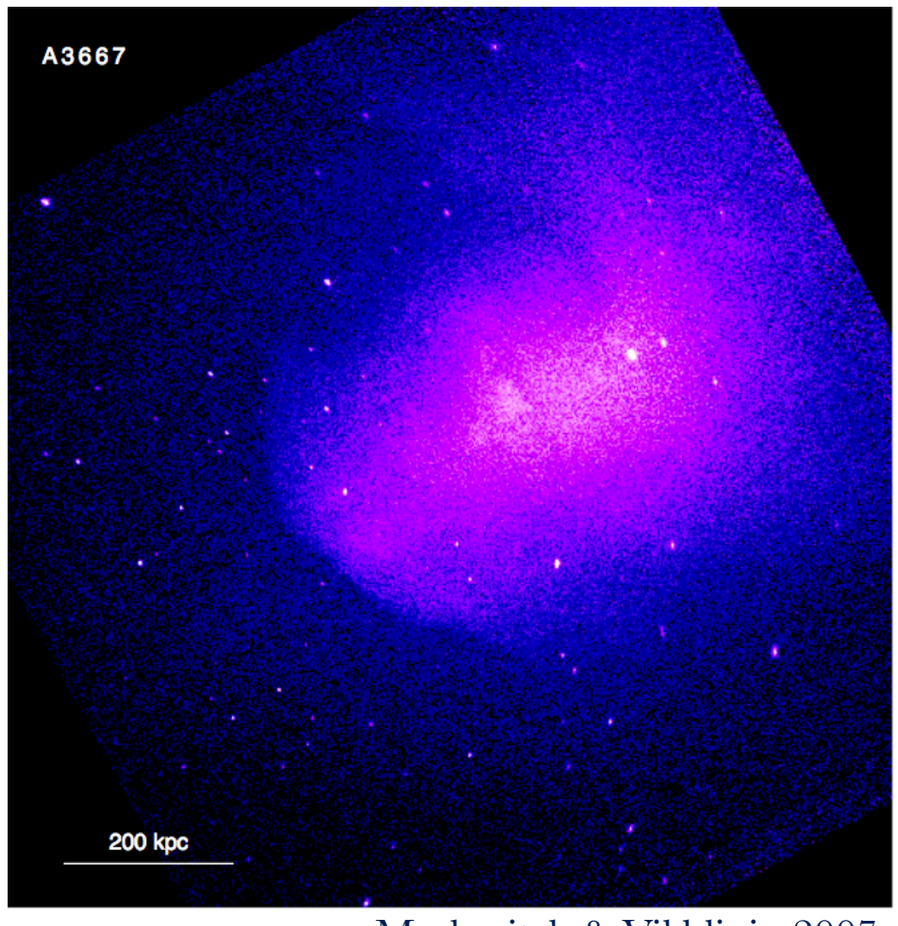
- Galaxy Cluster mergers optimal targets for significant bulk & turbulent motions: possibility to map turbulence in ICM

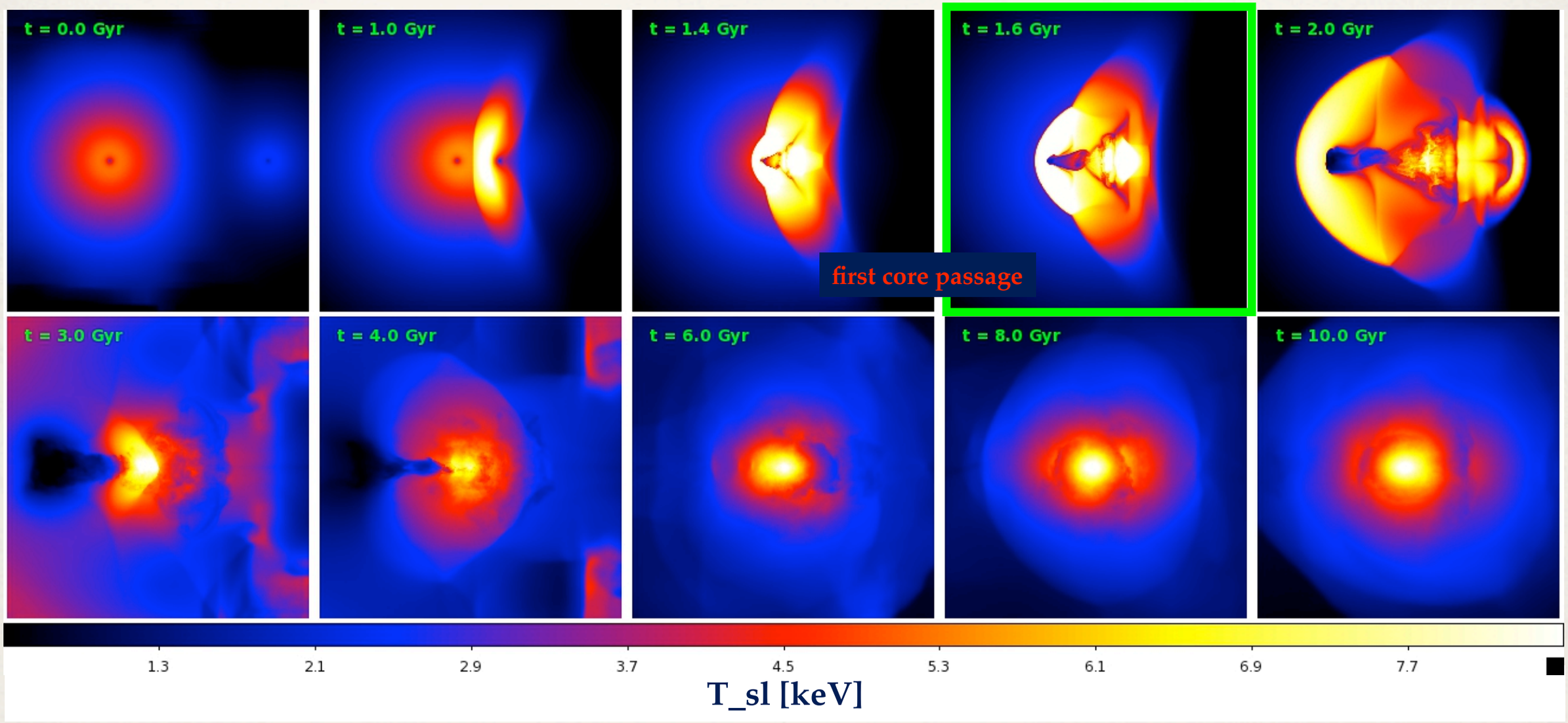


Markevitch & Vikhlinin 2007

Simulations

- Controlled galaxy cluster mergers (see also ZuHone+2011)
- Several configurations (impact parameter/mass ratio)
- Non-radiative runs: DM+gas(+stars)
- Arepo code

Study case:
impact parameter b=0
mass ratio 1:3



Relaxed `cool-core'-like systems:

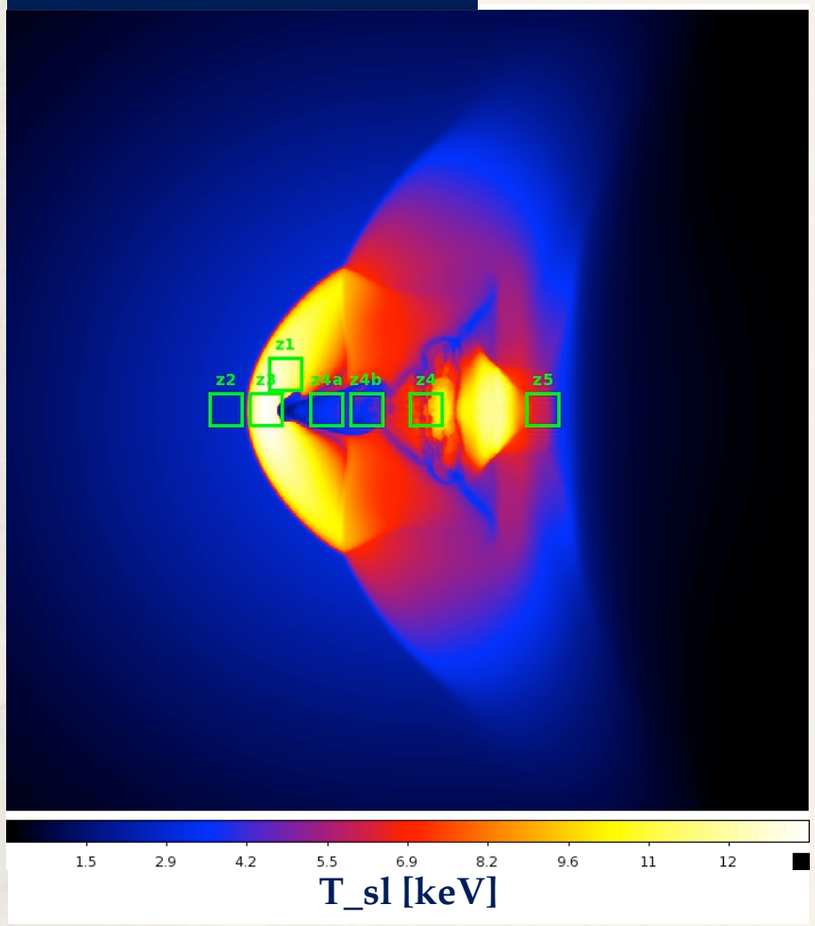
primary: M200 = 6e14 M_sun; R200~1.5Mpc; T_X=4.97 keV

secondary: M200 = 2e14 M_sun; R200~1Mpc; T_X=2.42 keV

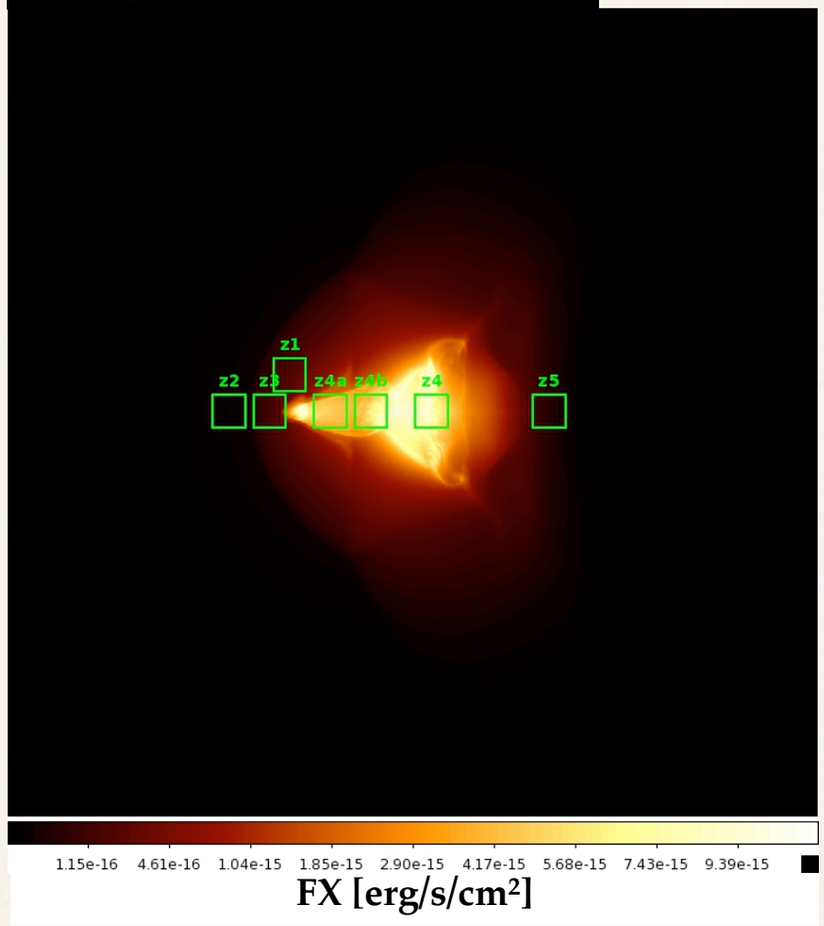
z-projection: l.o.s. perpendicular to the merger plane

~1.6 Gyr, immediately after the first core passage

Temperature (T_{sl})

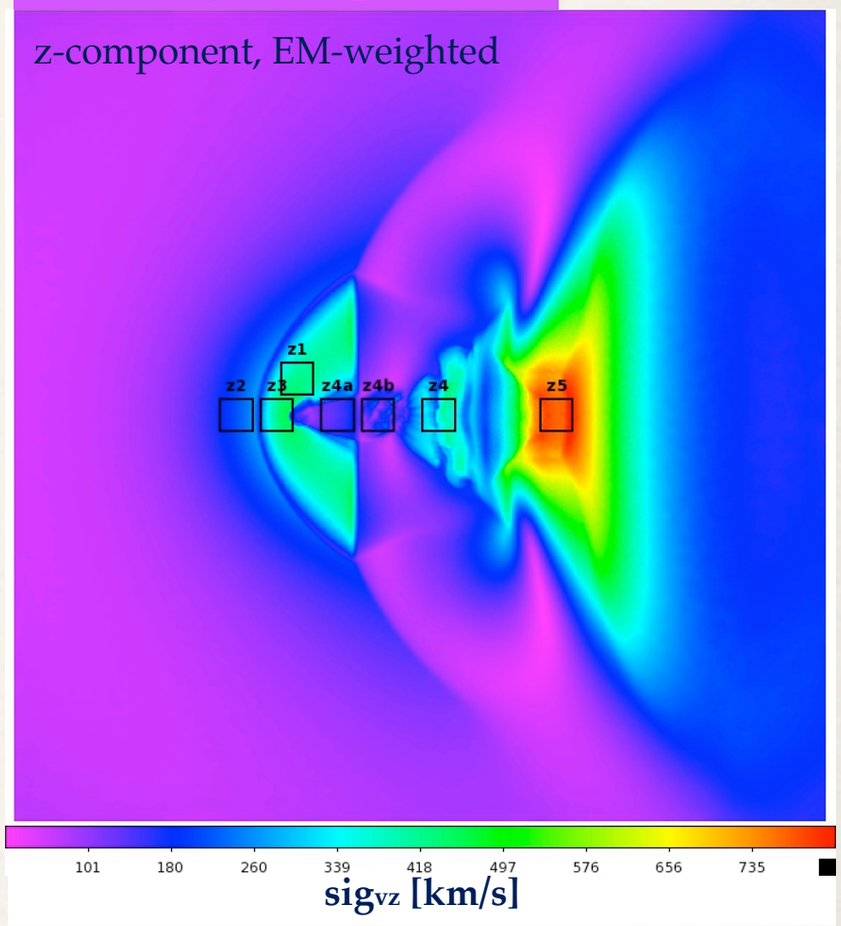


X-ray Flux [0.5-7 keV]

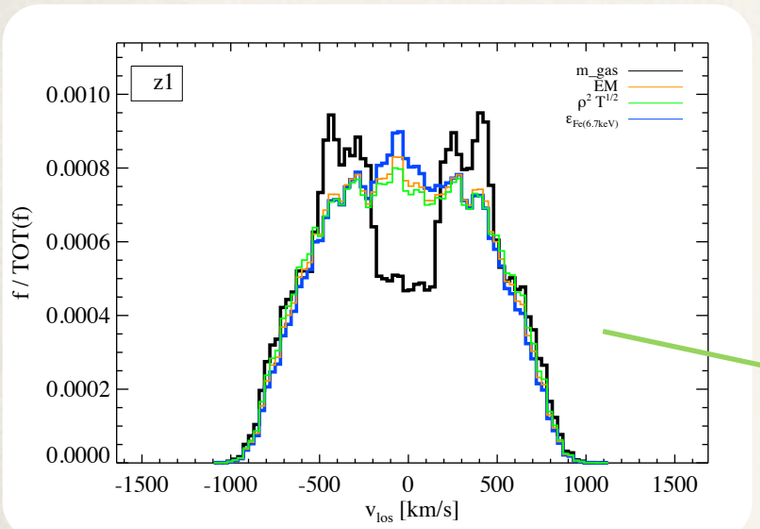


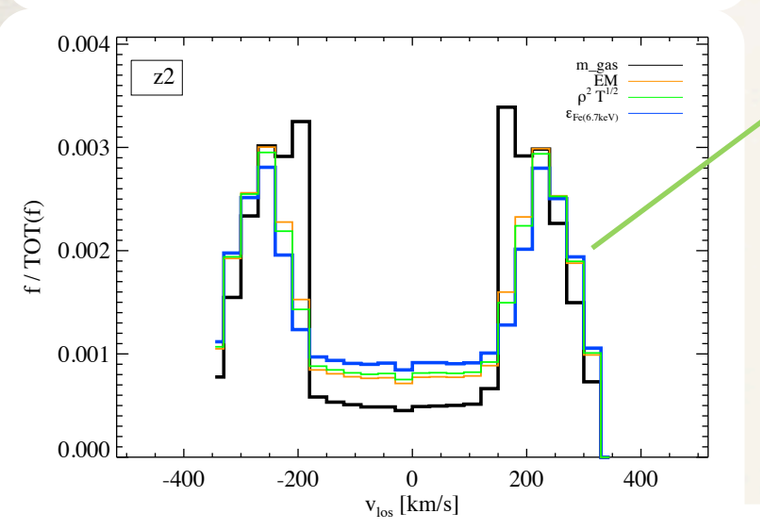
Velocity Dispersion

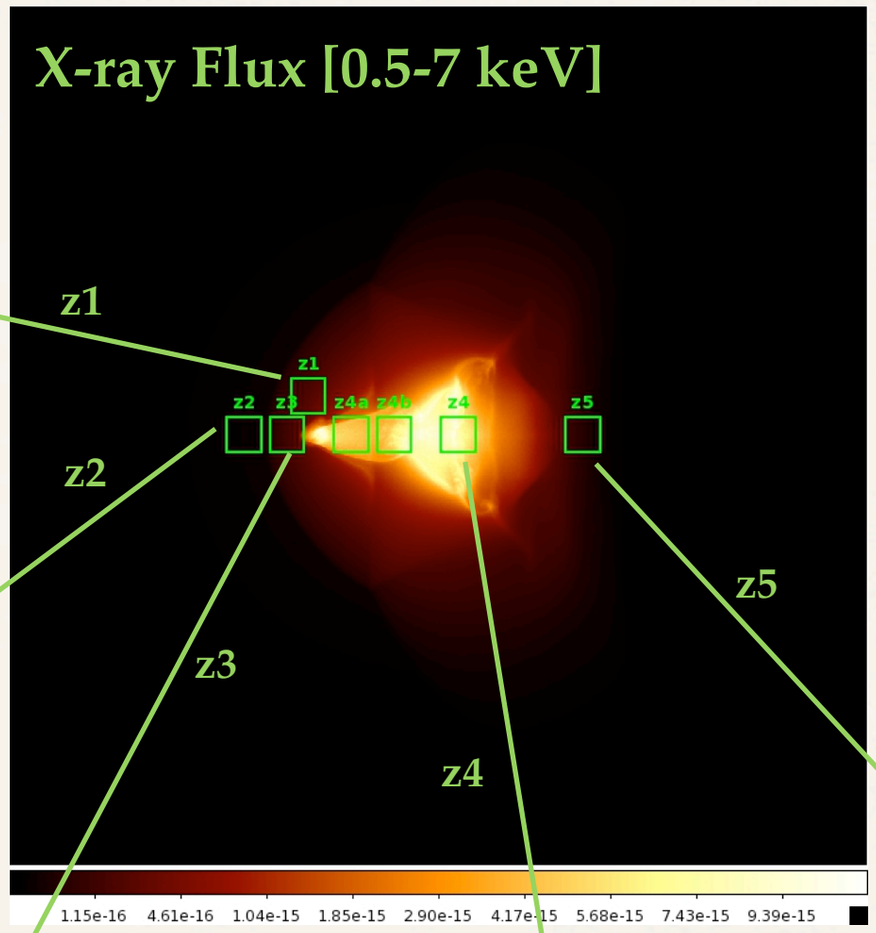
z-component, EM-weighted

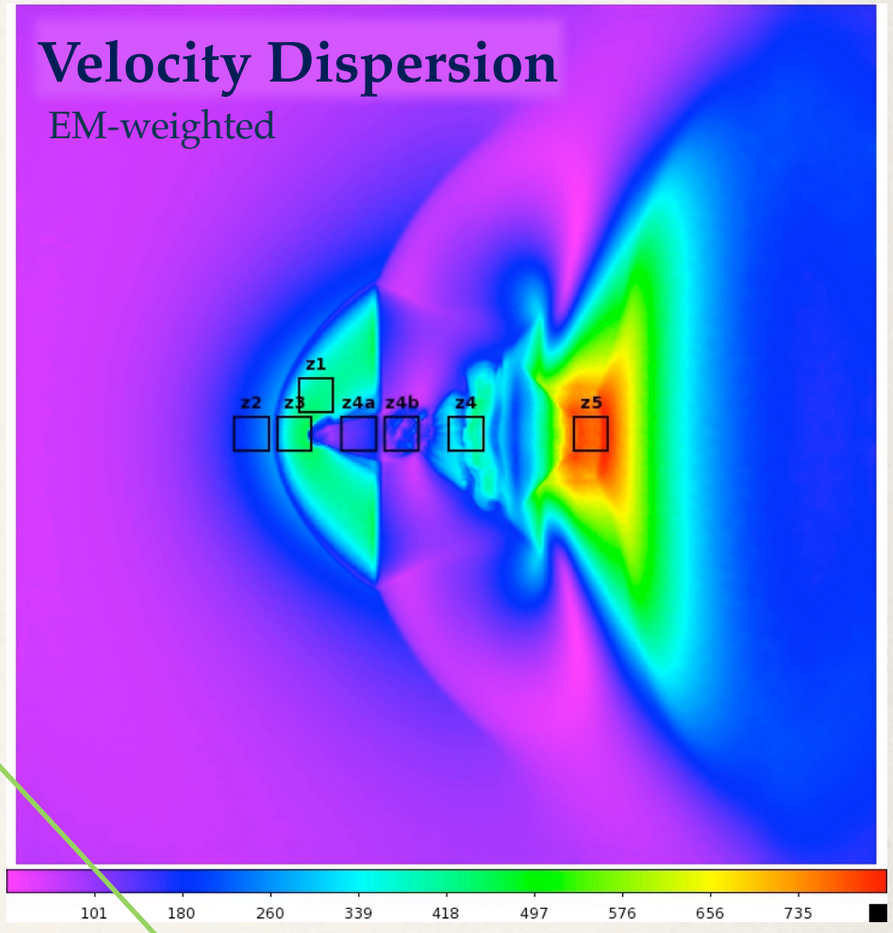


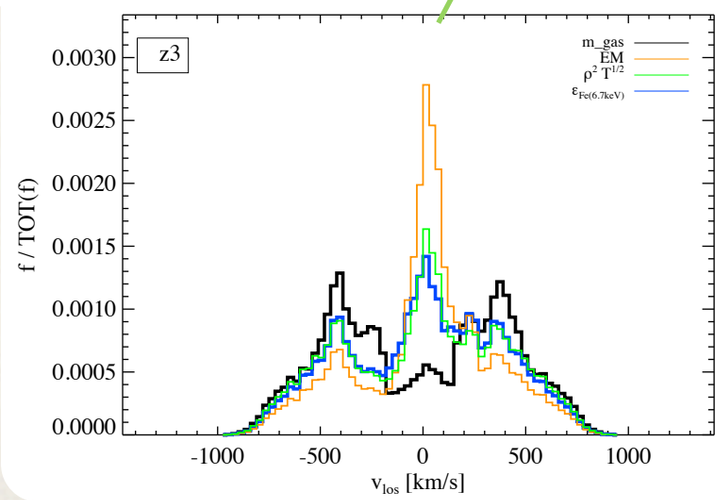
ICM velocity distributions from selected regions of interest

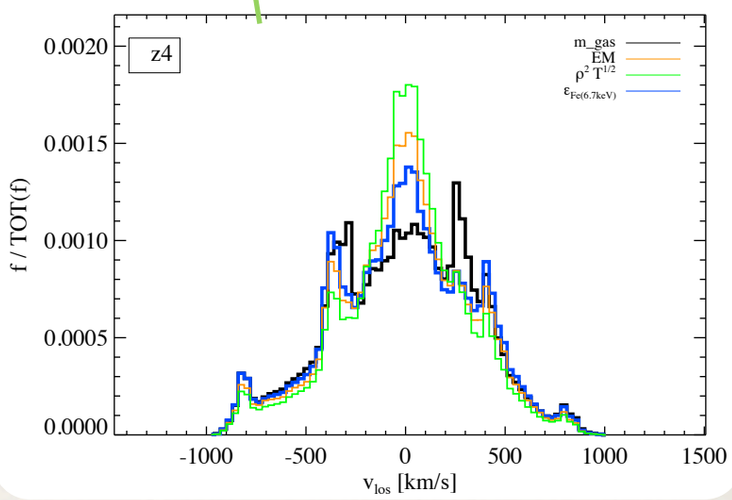


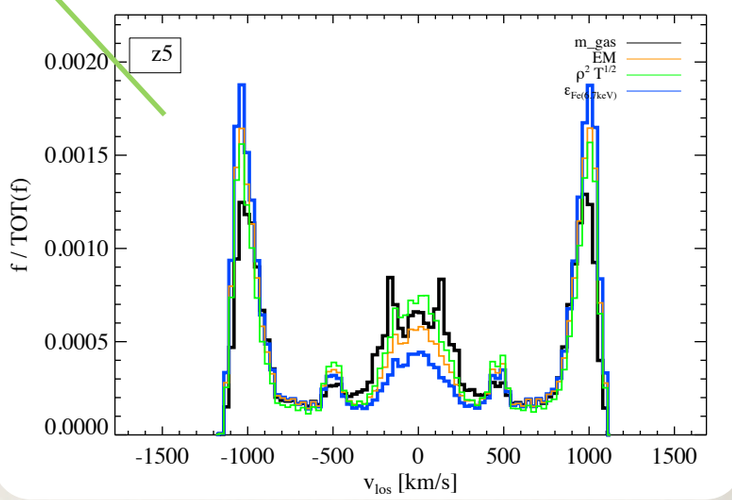




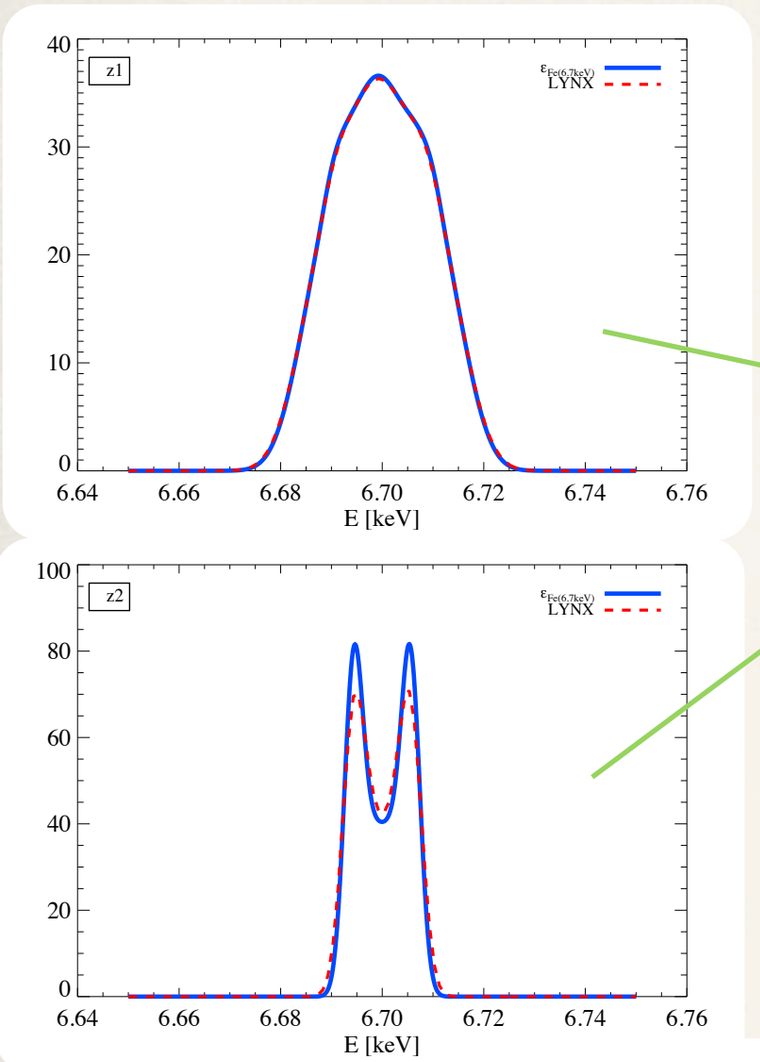


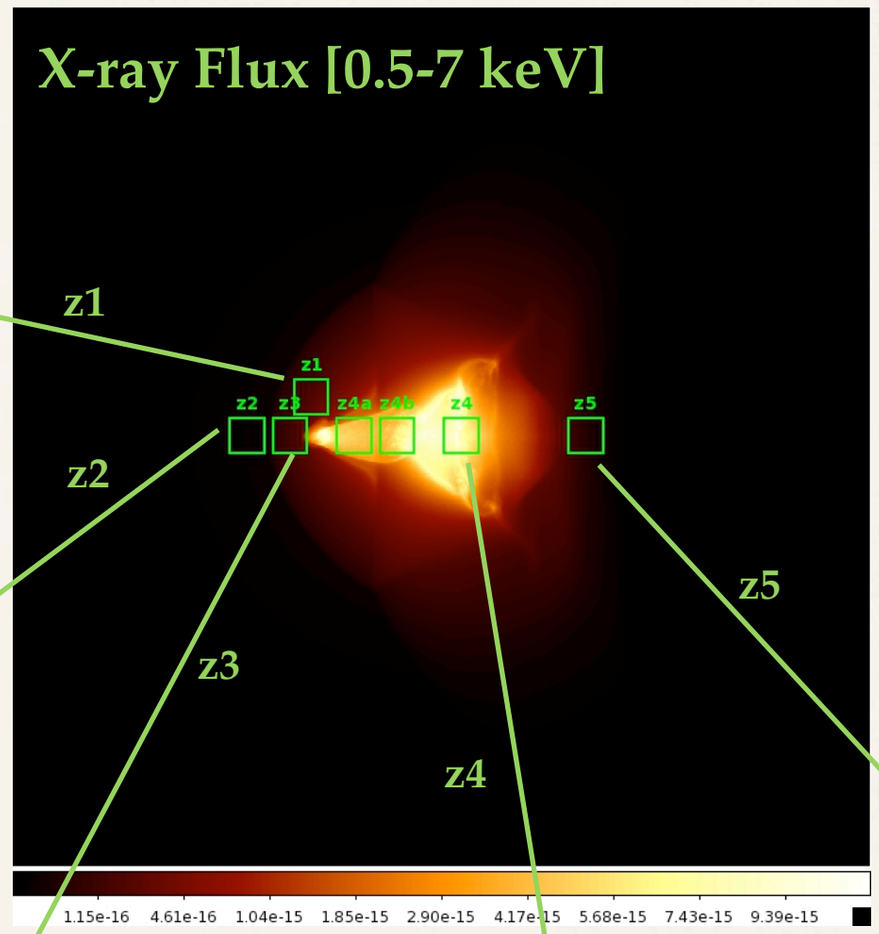


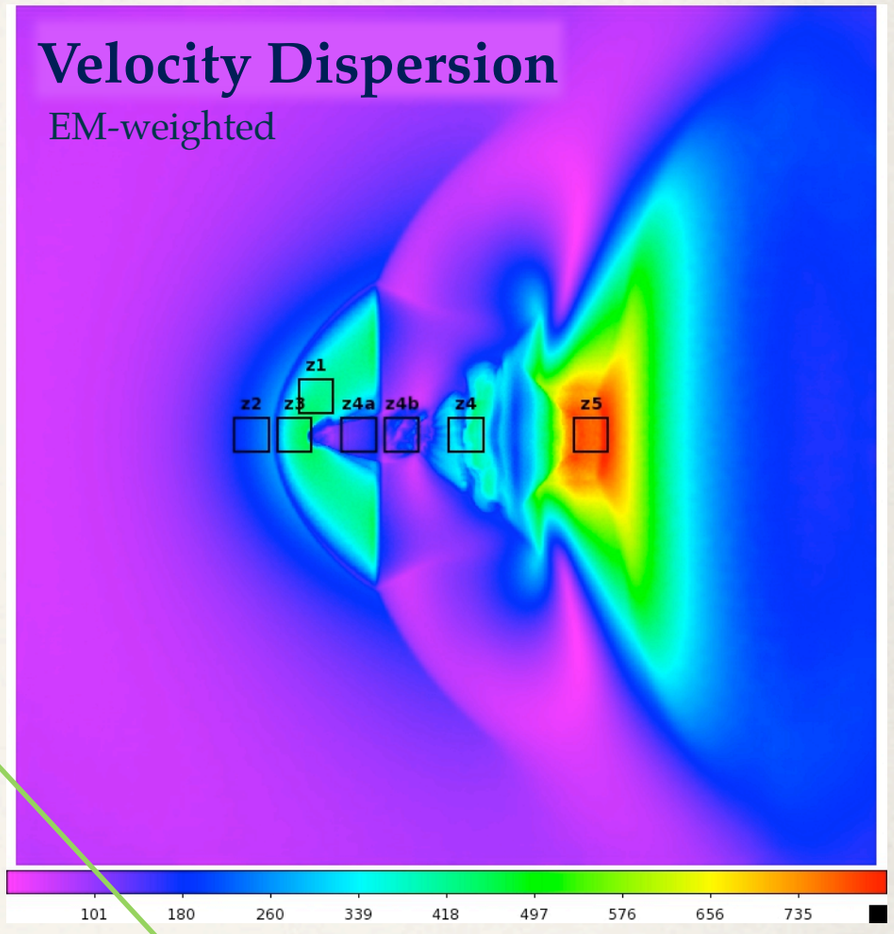


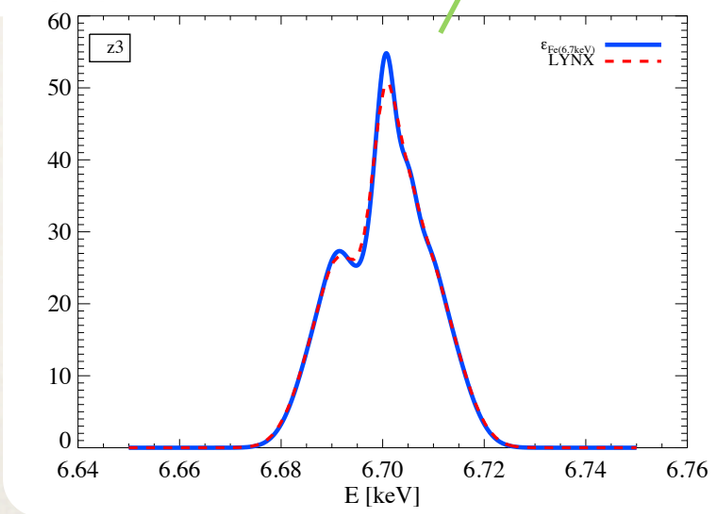


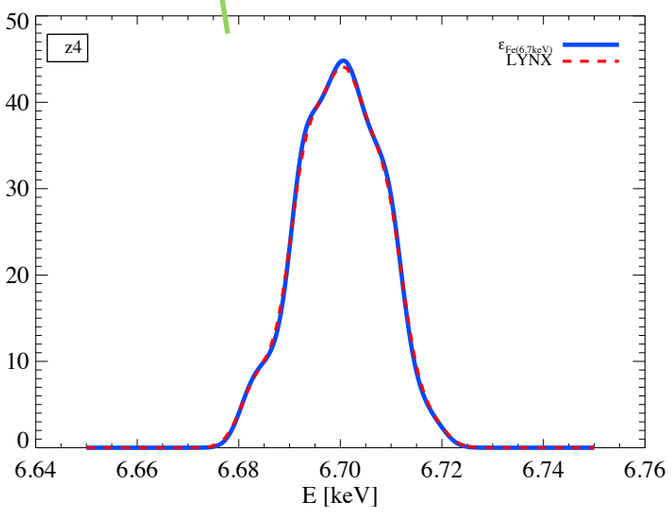
Theoretical shapes of Fe emission line

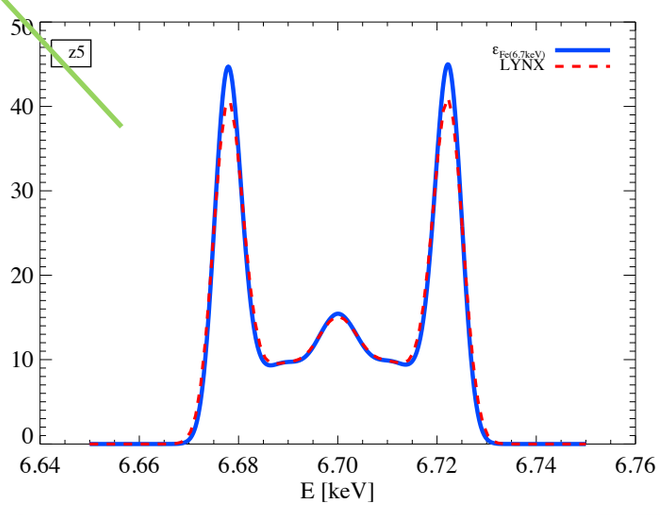












X-ray mock observations

- `APEC` model with fixed metallicity (Z=0.3 solar, Anders&Grevesse89)
- Assume Galactic absorption (`tbabs` model, nH = 4×10^{20} cm^{-2})
- pyXSIM/PHOX algorithm + SOXS
- Simulate 100ks XRISM observations (images/spectra) for the theoretical (3'x3' @z=0.057) pointings
- No background is included... *yet*

Spectral fit of Fe (6.7keV) line:

- use `tbabs(bapec)` model
- freeze nH & metallicity, fit the other params
- consider the [6-7]keV energy band including the Fe line

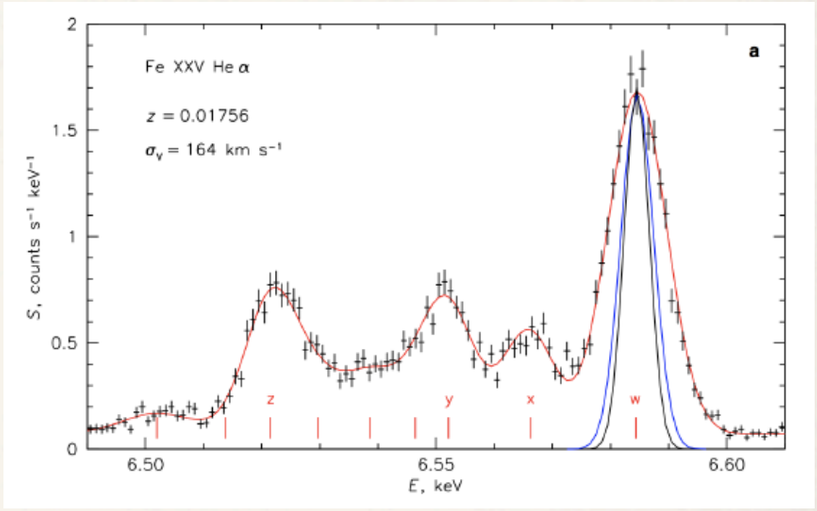
➡ estimate line *shift* & *broadening*

X-ray mock observations: XRISM

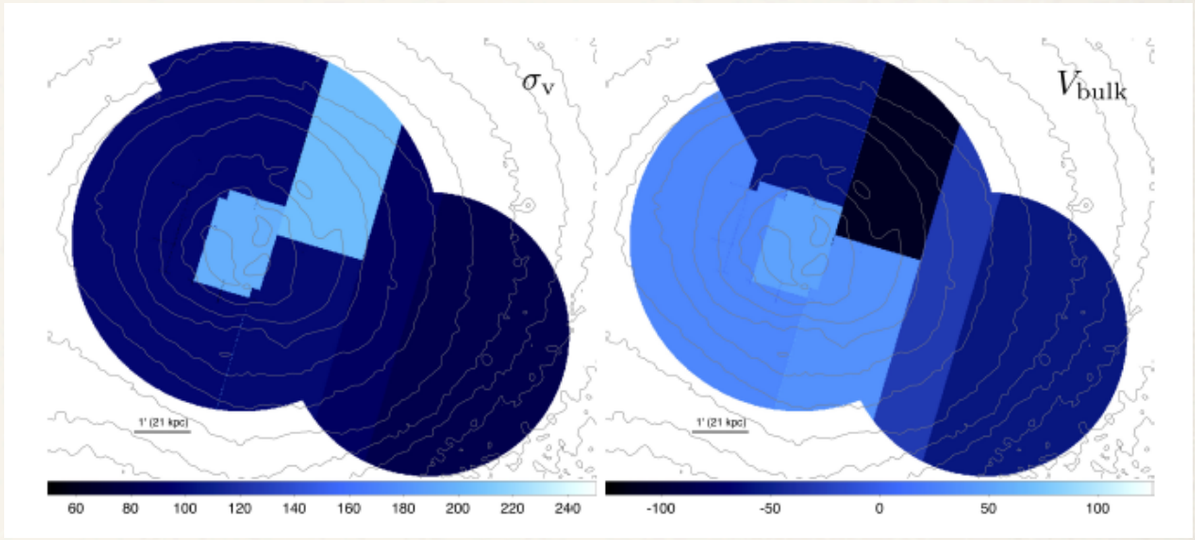
- XRISM as successor of Hitomi, with ***Resolve*** high spectral resolution X-ray microcalorimeter (`5-7eV energy resolution in the 0.3-12keV band, 3'x3' FoV`)

- map ICM velocities especially in sample of relaxed cluster cores as Hitomi did for Perseus

Hitomi obs. of Perseus Cluster



Hitomi Collaboration 2016

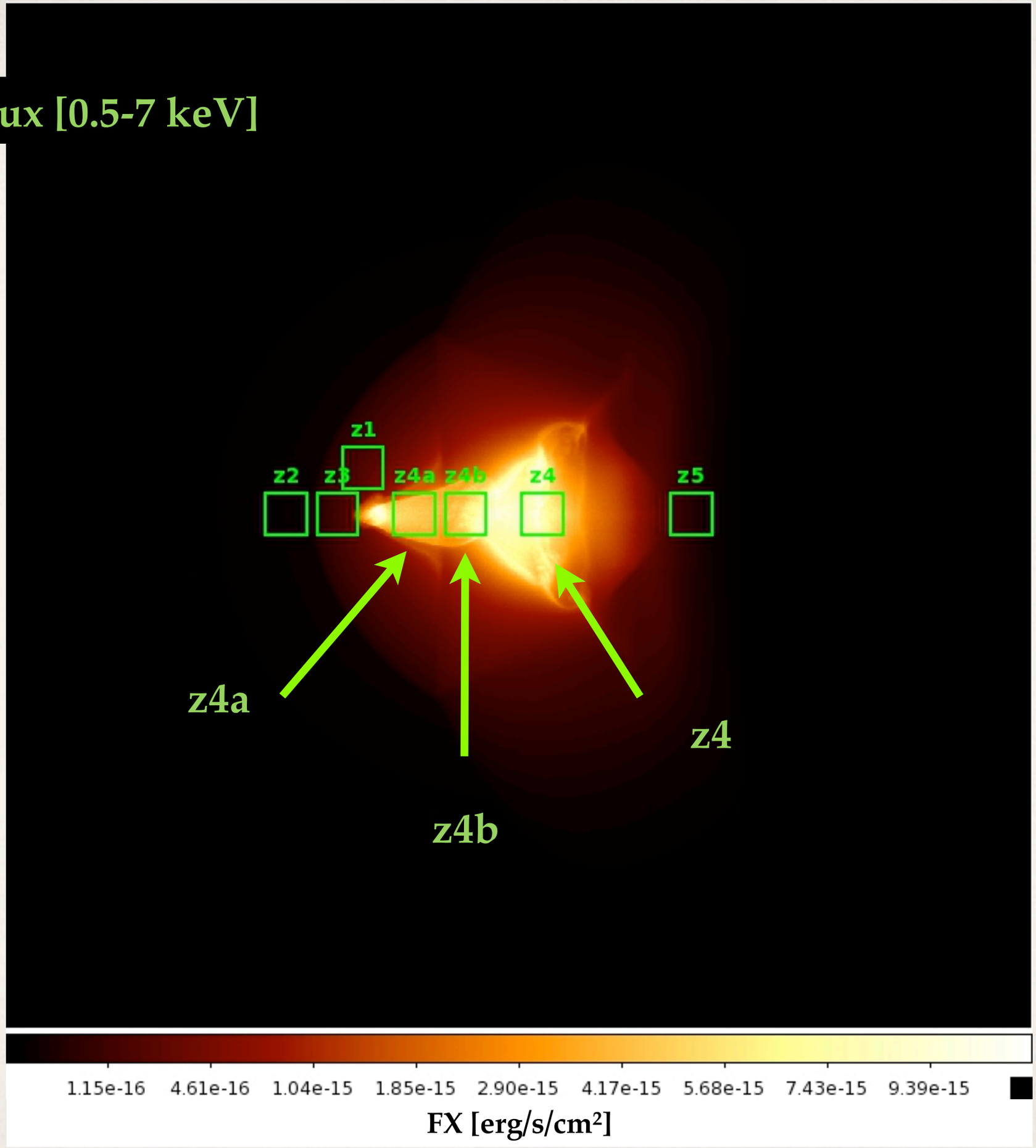


Hitomi Collaboration 2018a

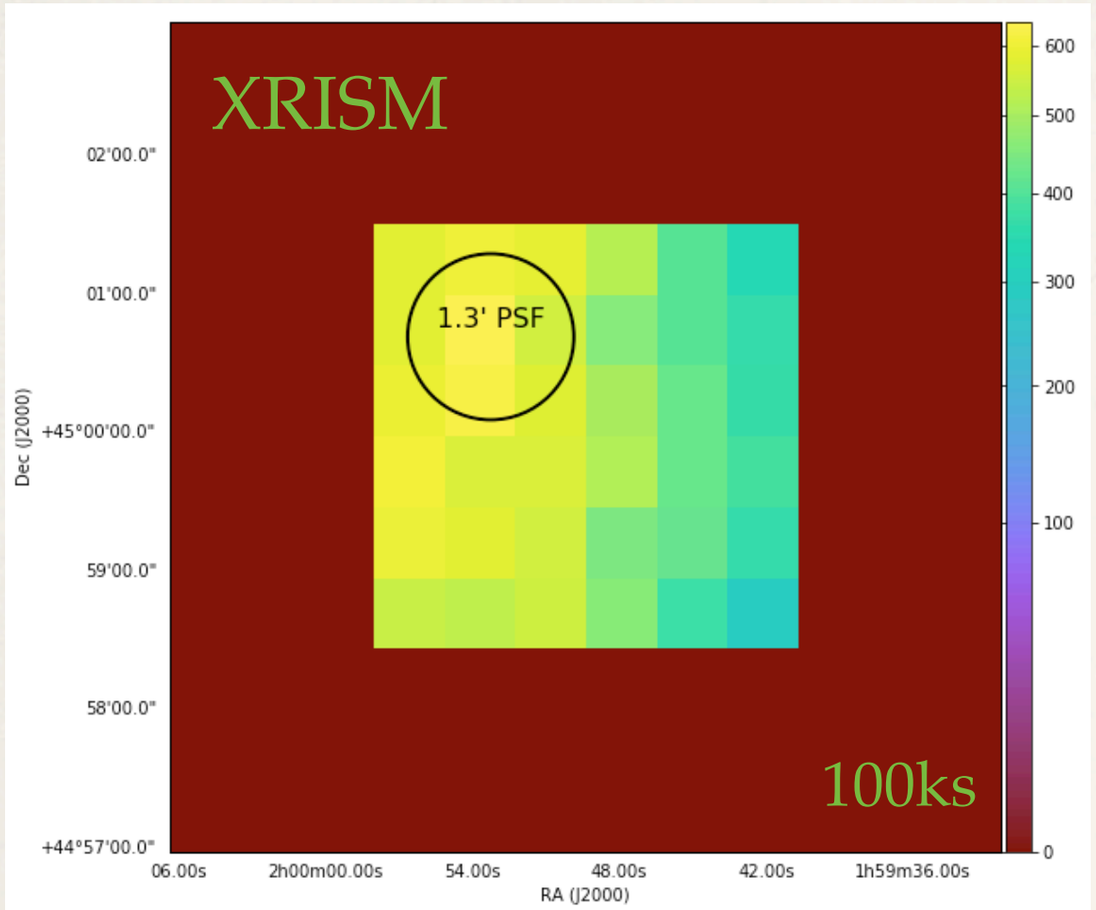
- evaluate impact of minor and major mergers:

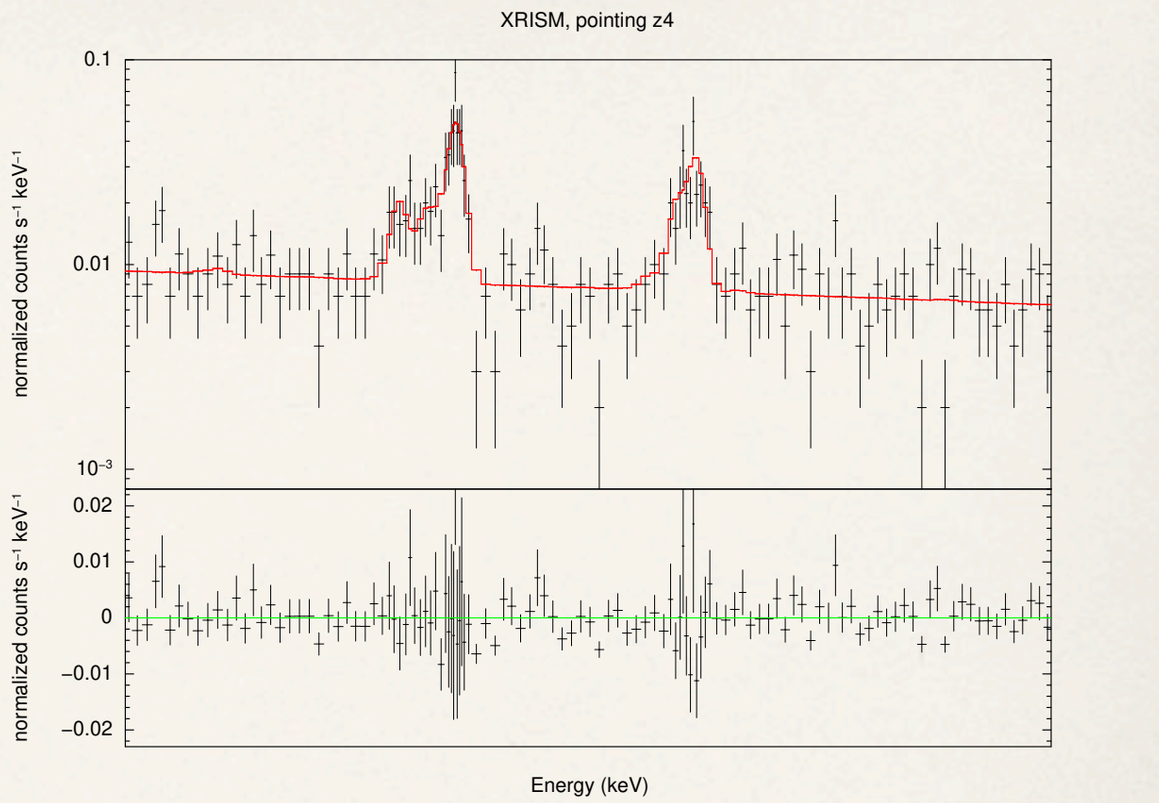
  - ✳ interesting targets: mergers along l.o.s. can produce bulk motions of several 1000 km/s and turbulent motions of ~1000 km/s
  - ✳ inspect role of gas state complexity & projection effects: synergy with sims
  - ✳ measure l.o.s. bulk velocities to understand the geometry and velocity of the occurring merger

X-ray Flux [0.5-7 keV]



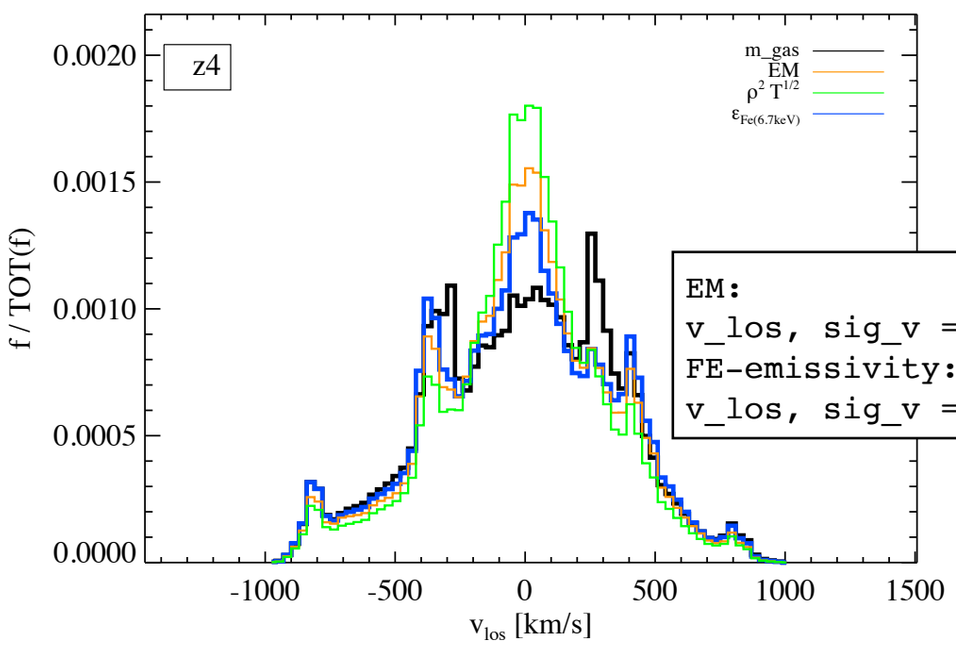
consider brightest regions among those selected



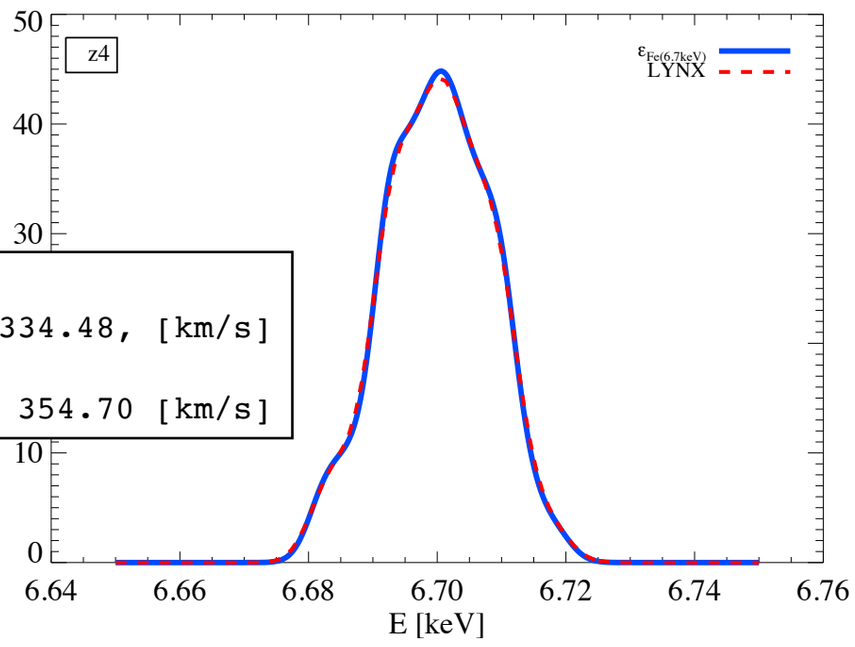


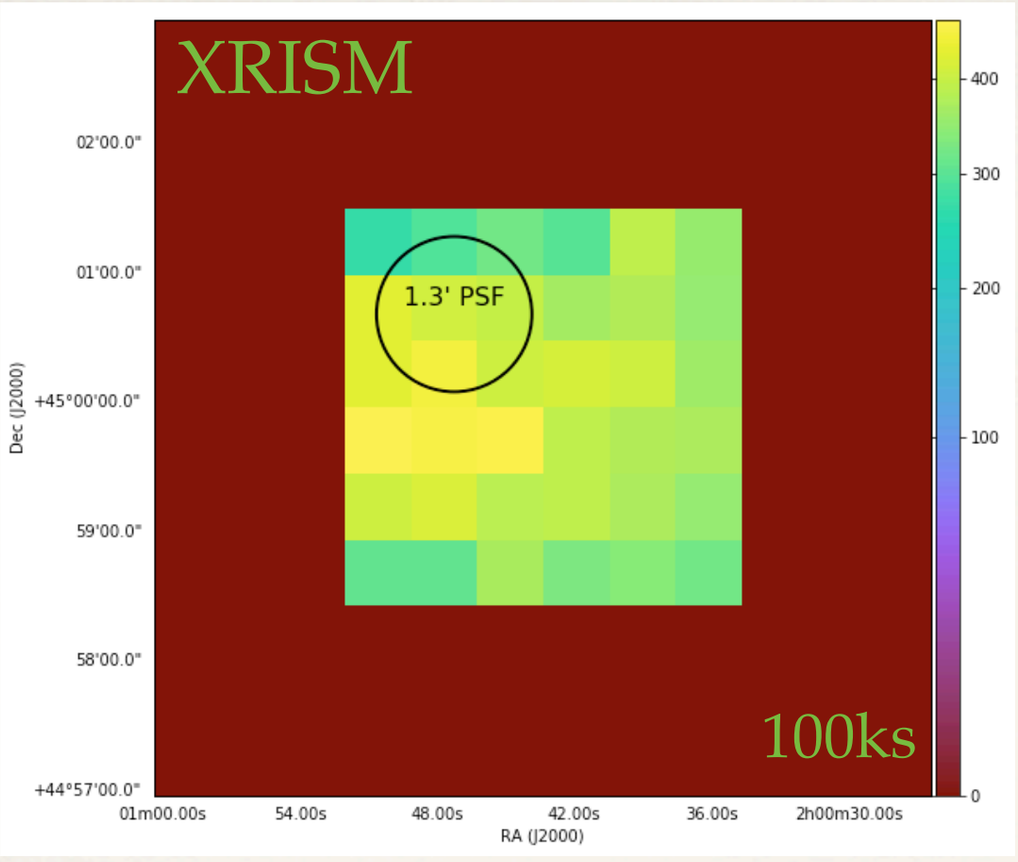
vbiffi 26–Feb–2019 15:39

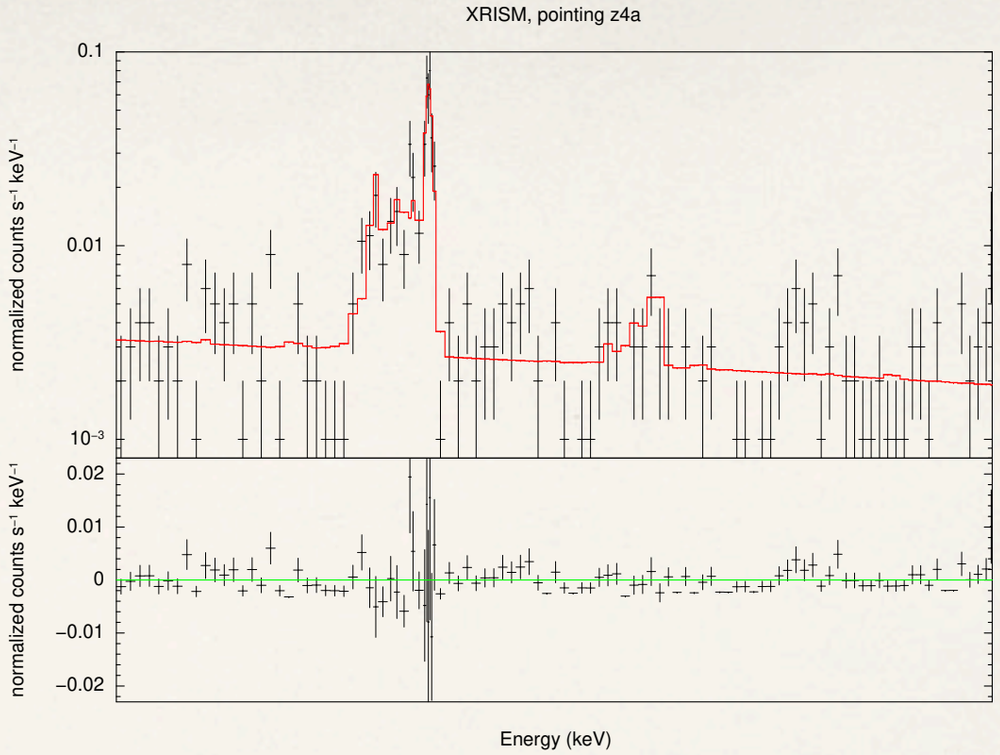
```
redshift = 0.0569 +- 0.0002
v_los = 27.21 +- 55.44 [km/s]
sig_v = 335.332 +- 48.26683142 [km/s]
```




```
EM:
v_los, sig_v = 2.93, 334.48, [km/s]
FE-emissivity:
v_los, sig_v = -0.53, 354.70 [km/s]
```

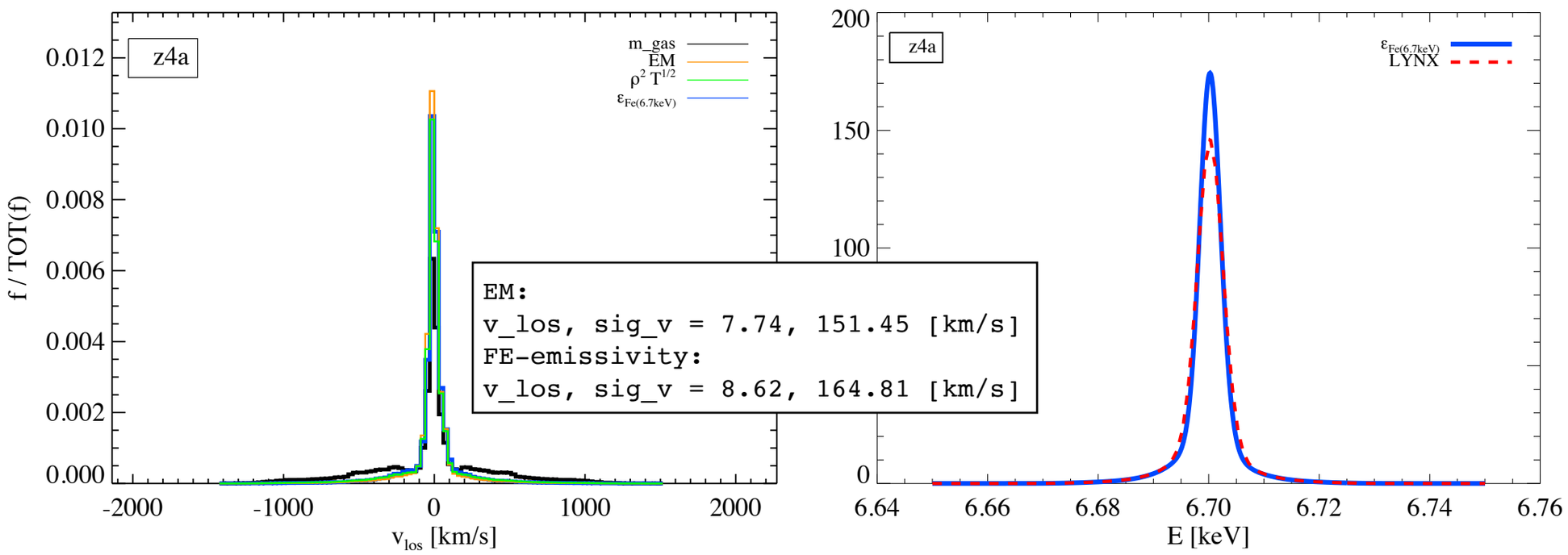


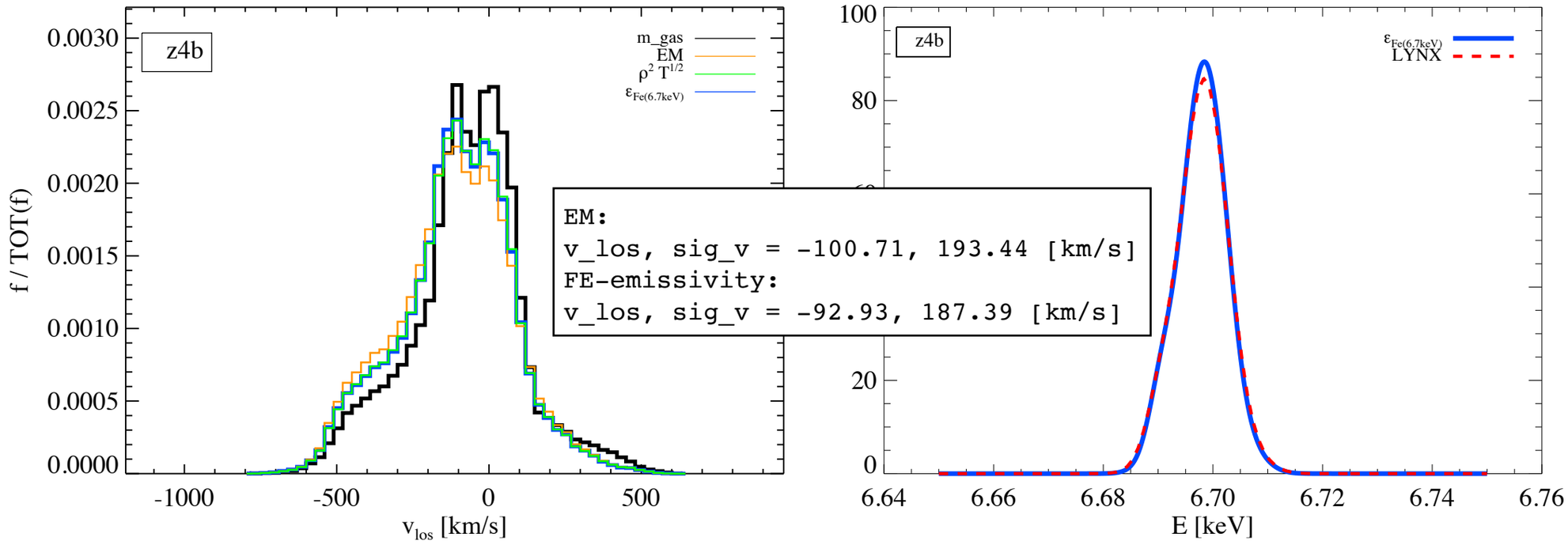


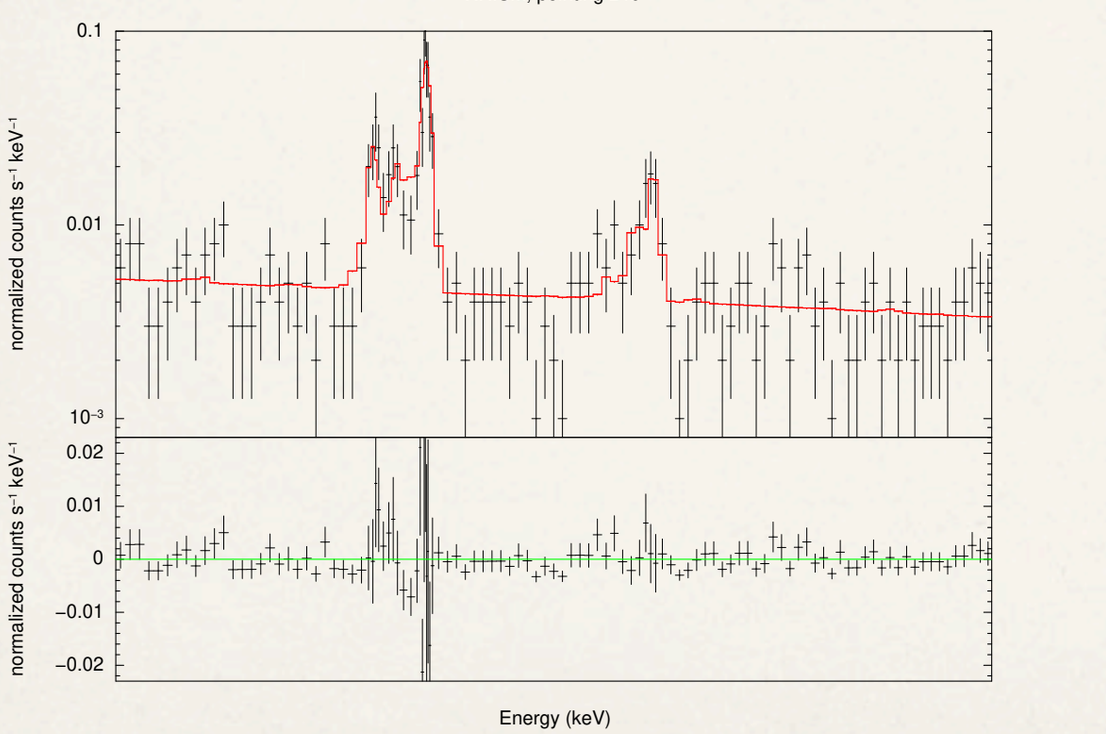


vbiffi 26–Feb–2019 15:39

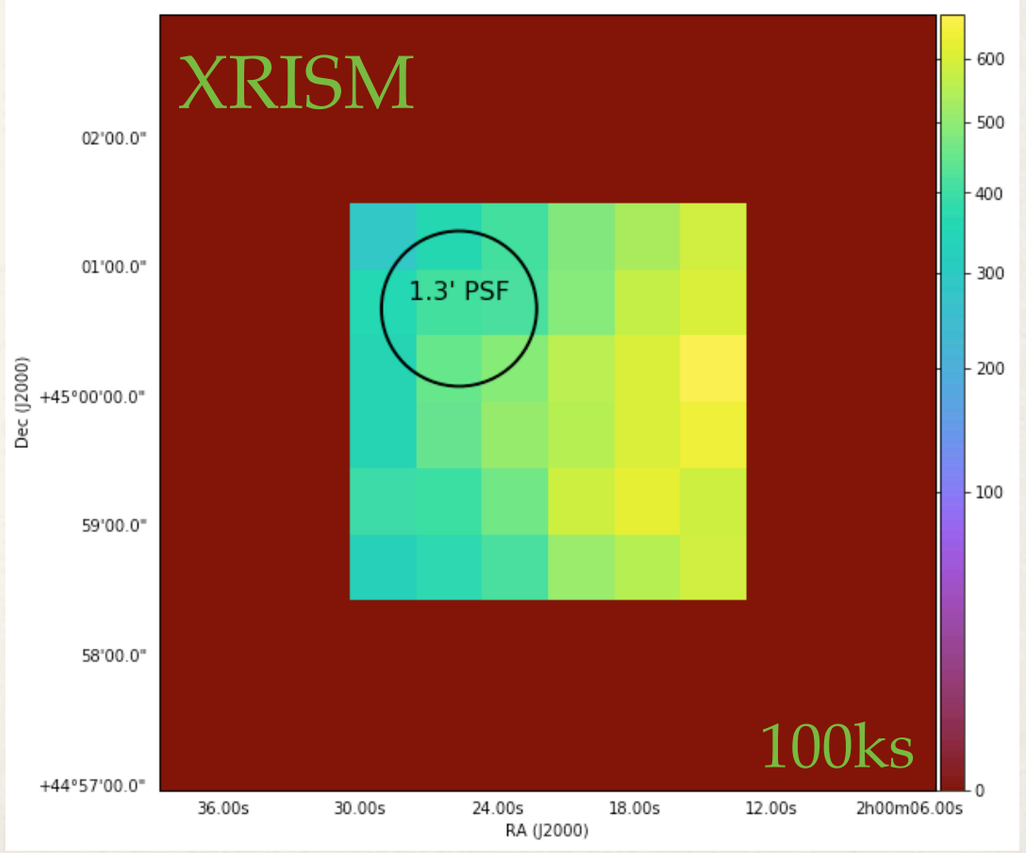
```
redshift = 0.05699 +- 9.498797615e-5
v_los = 1.56 +- 28.50 [km/s]
sig_v = 112.64 +- 29.99 [km/s]
```



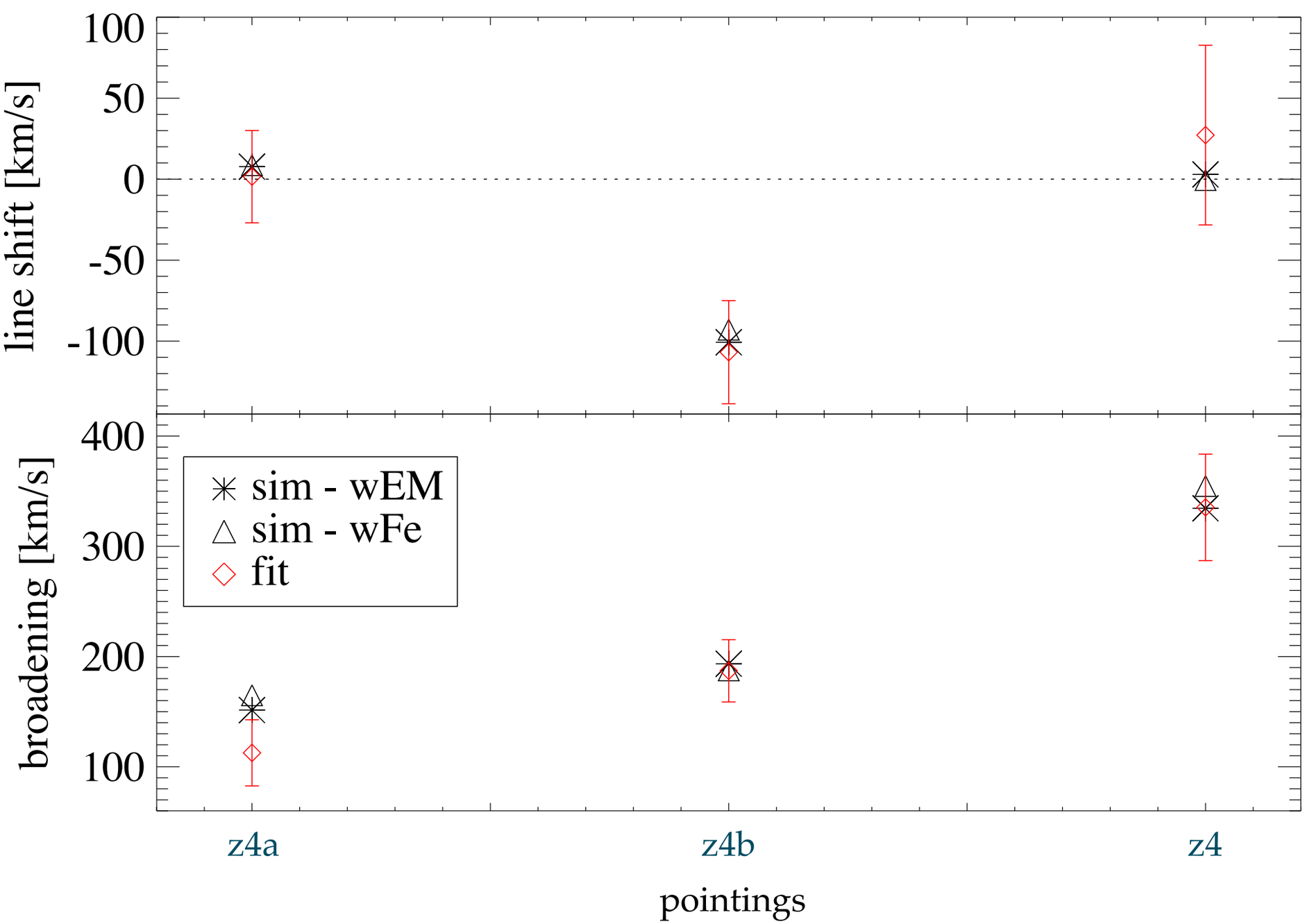




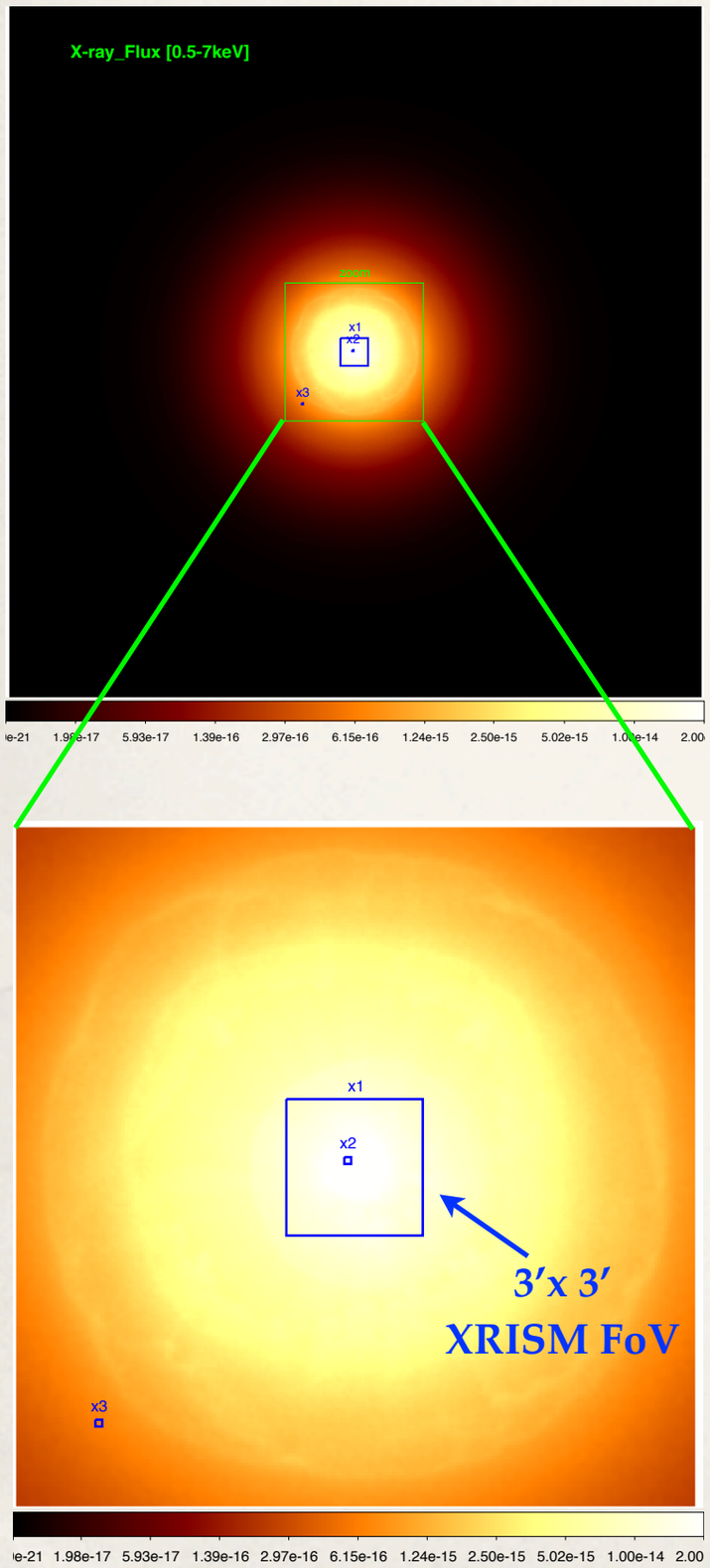

```
redshift = 0.0574 +- 0.0001
v_los = -106.83 +- 31.82  [km/s]
sig_v = 187.061 +- 28.231  [km/s]
```

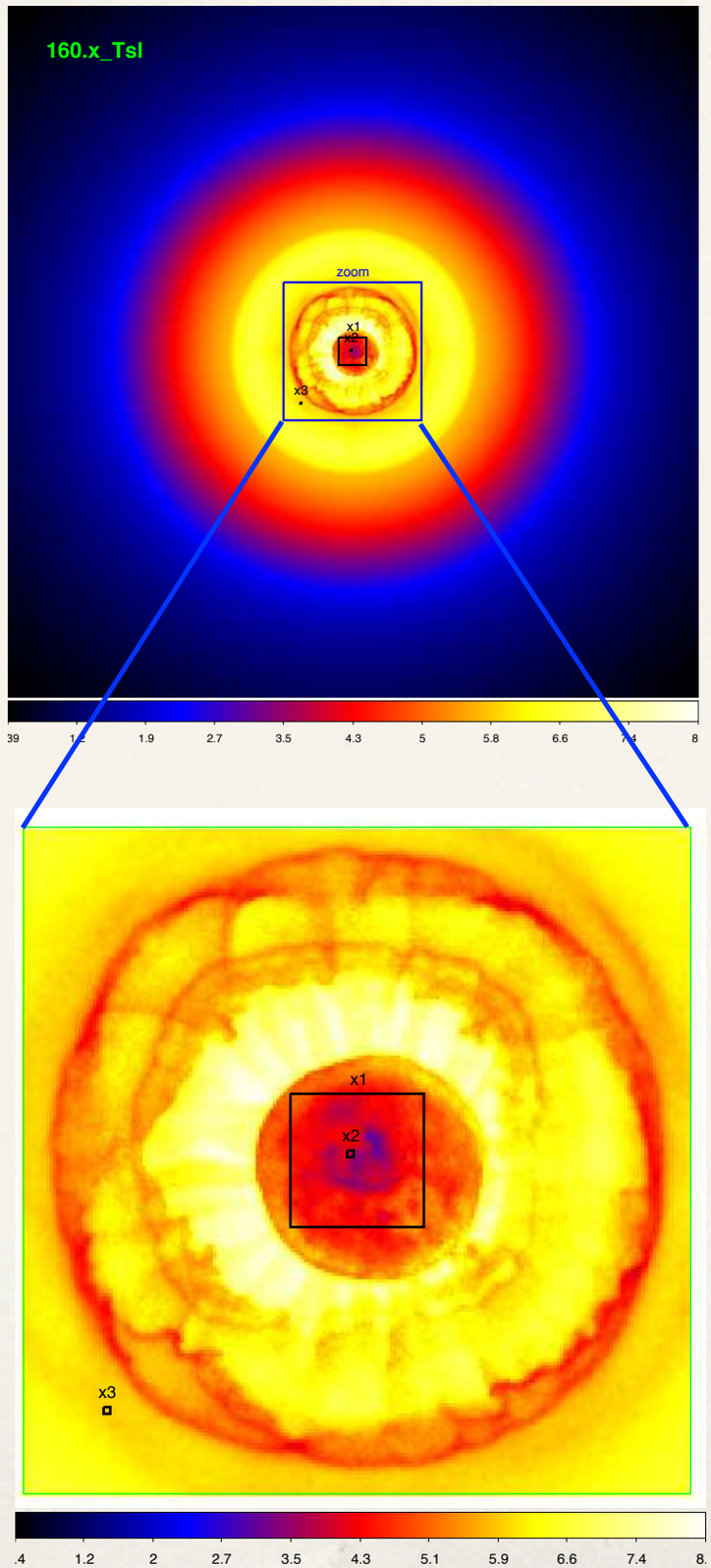


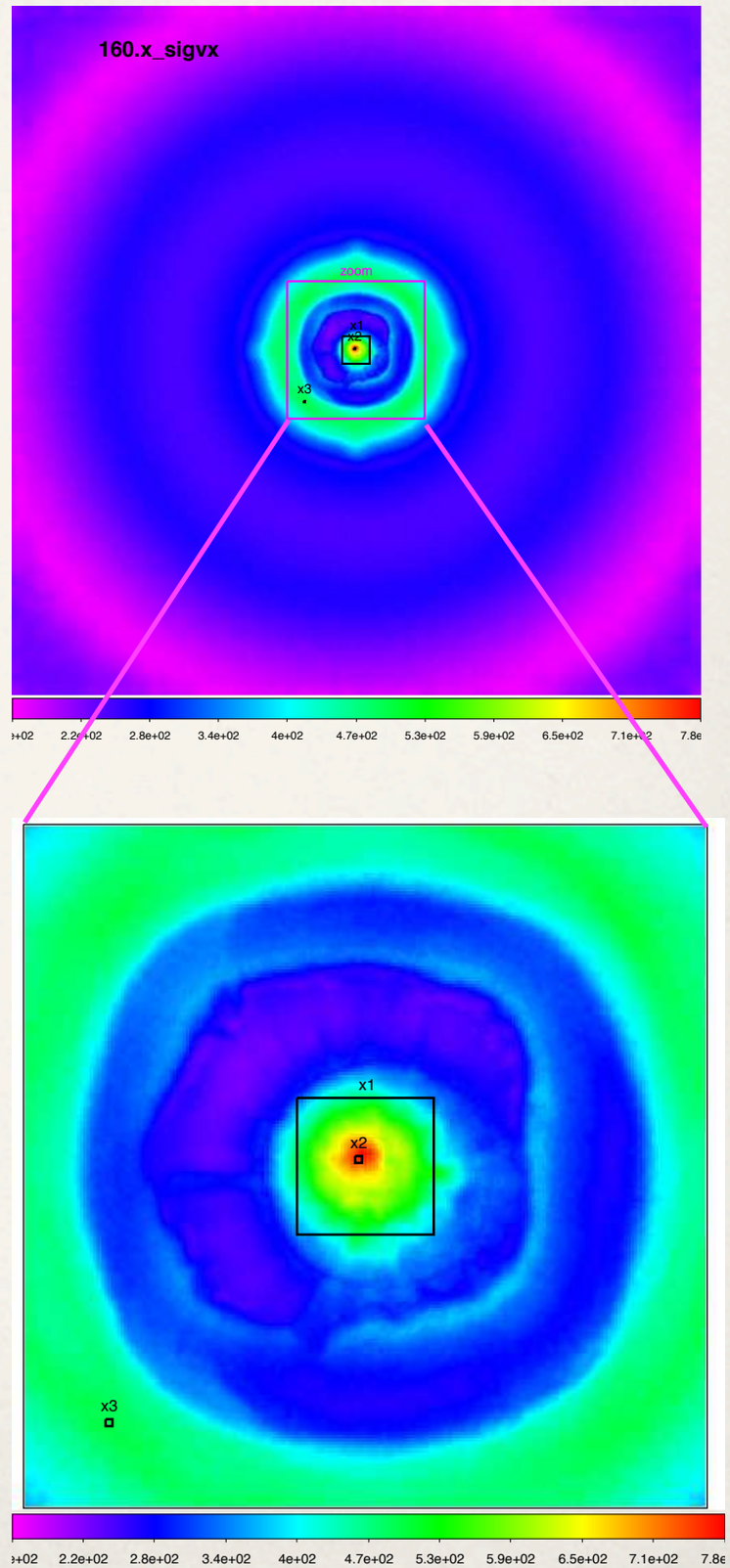
Direct comparison of XRISM estimates against simulations



x-projection: l.o.s. along merger axis

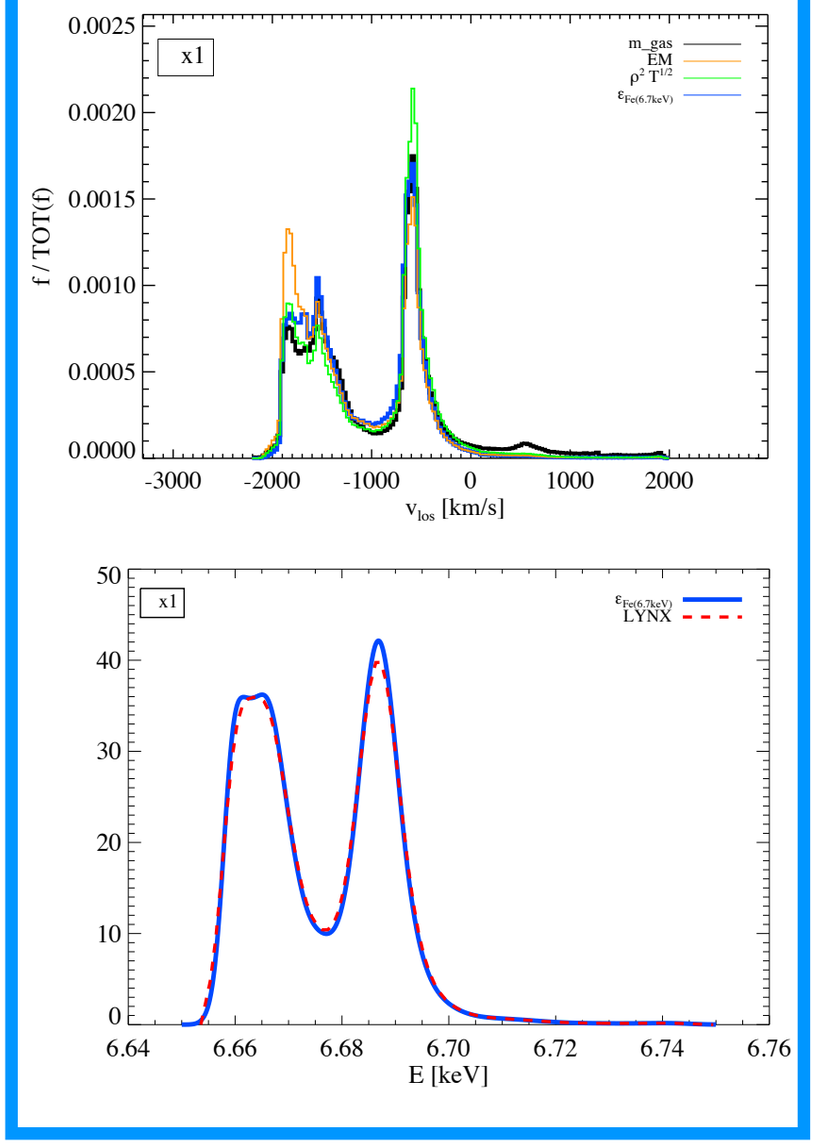


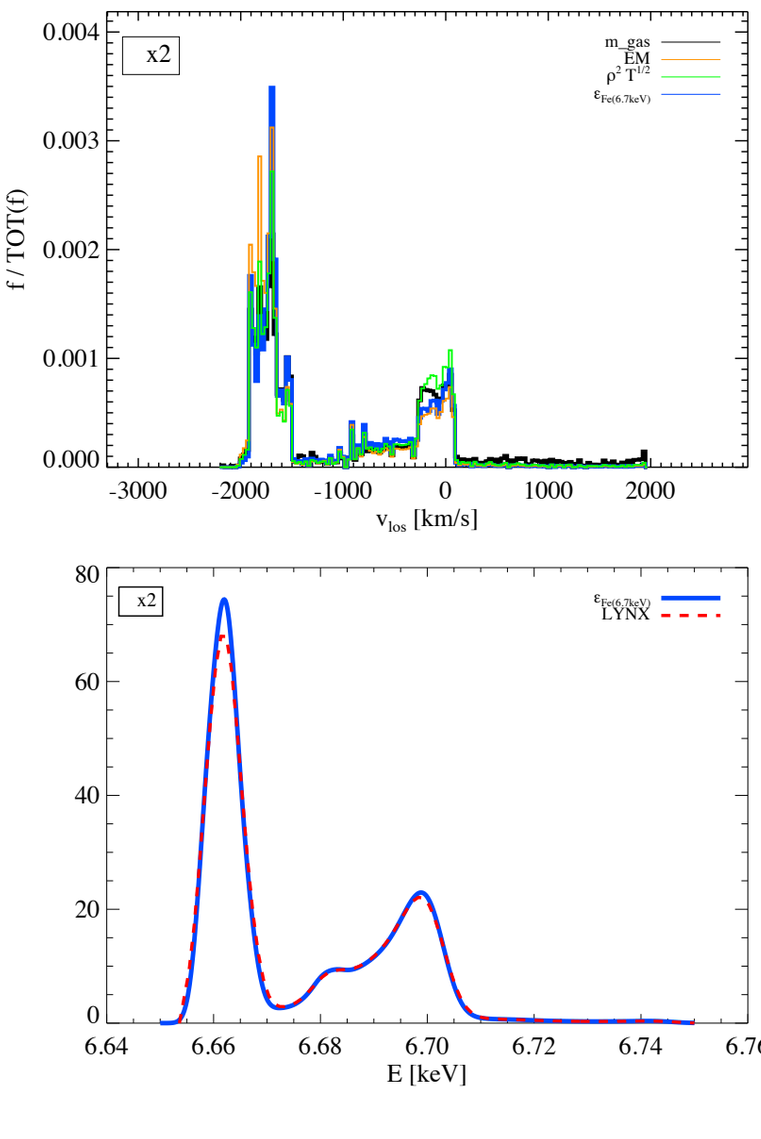


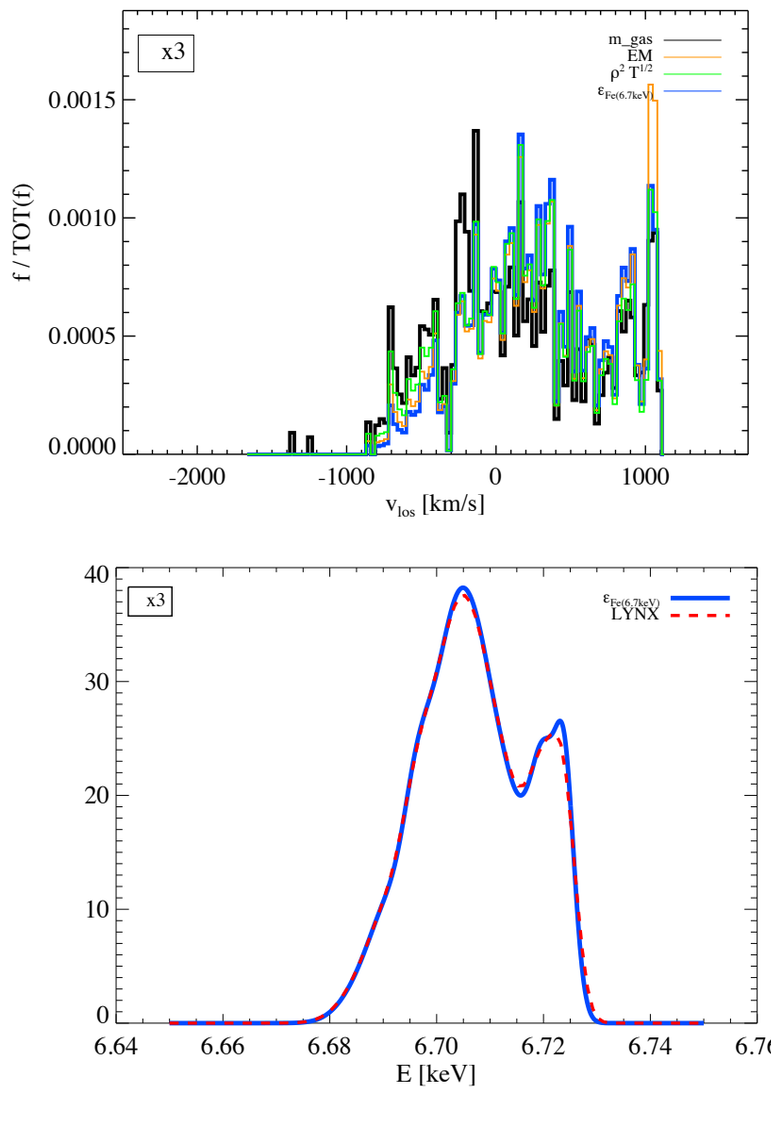


ICM velocity distributions & theoretical Fe-line shapes

3′x 3′ XRISM FoV



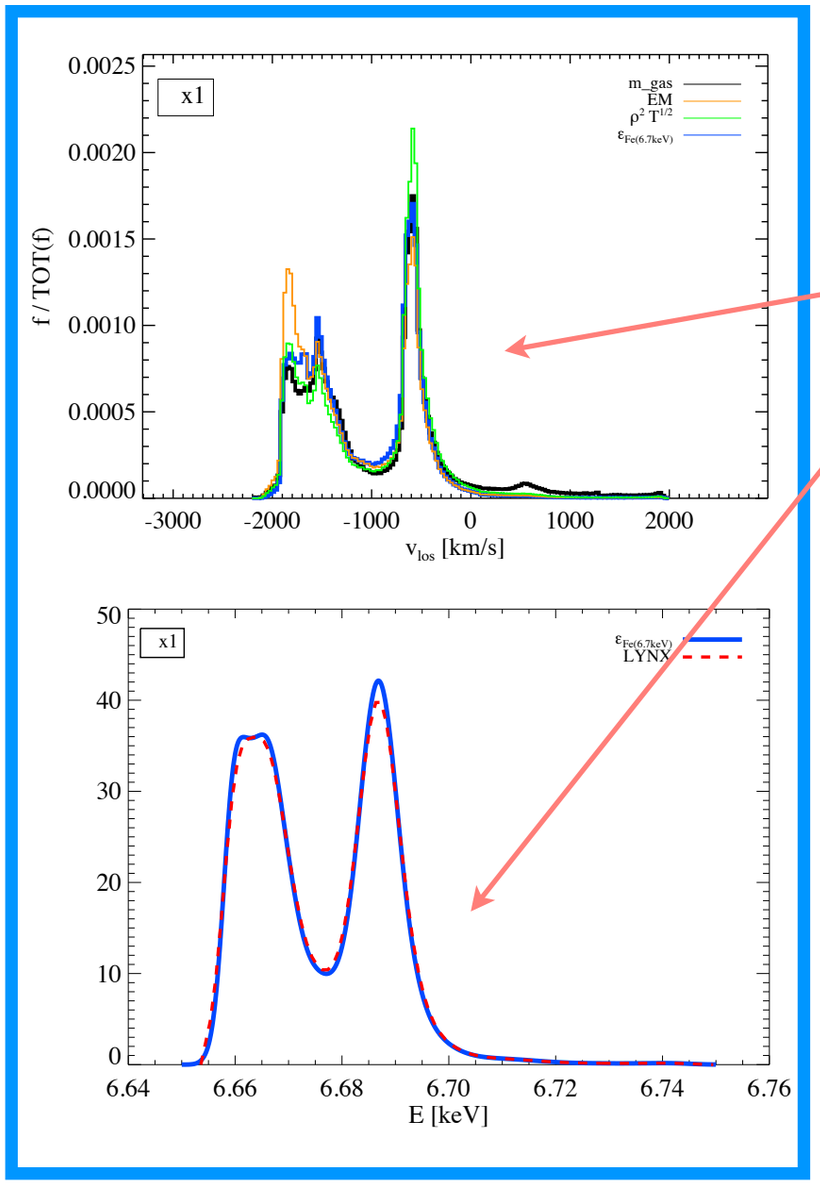




From the line (non-Gaussian) features
one can distinguish turbulence from
superposition of streaming motions

ICM velocity distributions & theoretical Fe-line shapes

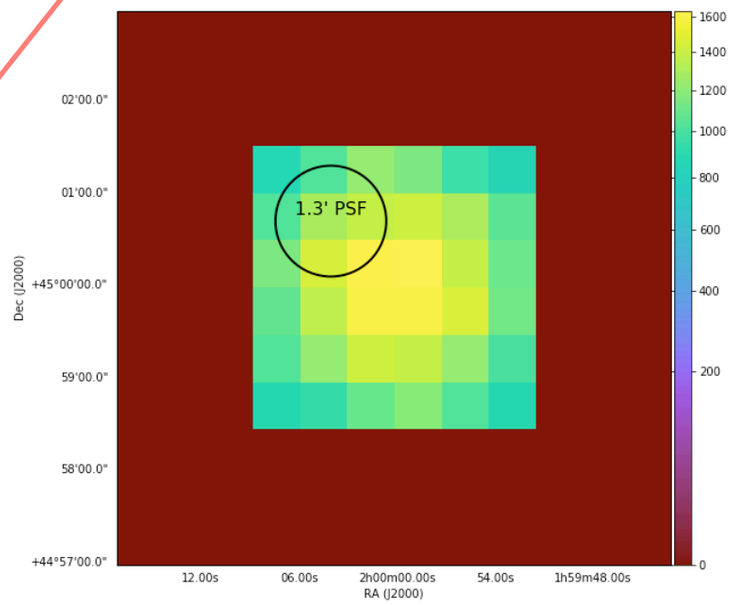
3′x 3′ XRISM FoV

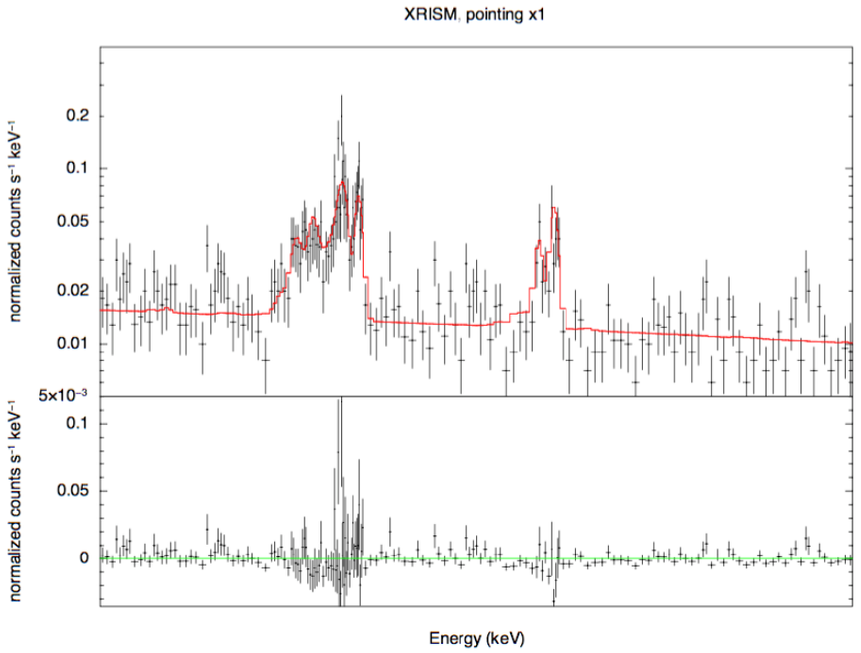



```
EM-weighted:          v_los=-1152.77   sig_vx=595.68
Fe-emiss-weighted: v_los=-1076.02   sig_vx=573.32
```

but

1-component Gaussian is ***not*** capturing the distribution!





2 bulk components clearly present: 2 merging systems

1) redshift~0.63 (v_los~-1700[km/s]), sig_v=342.27 +/- 52.54 [km/s]

2) redshift~0.59 (v_los~-660[km/s]), sig_v=160.13 +/- 29.97 [km/s]

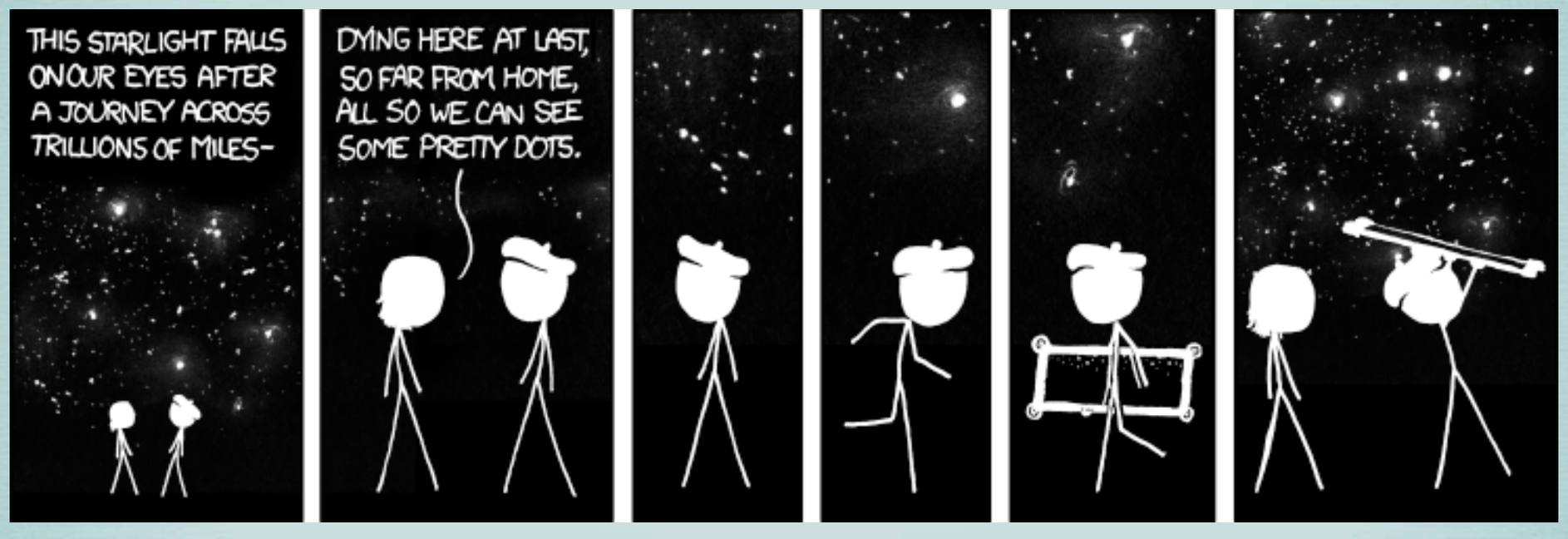
From the line (non-Gaussian) features
one can distinguish turbulence from
superposition of streaming motions

Conclusions

Astrophysics & Cosmology goal:
measurements of ICM motions are crucial for characterizing turbulence and for more precise cluster mass estimates

- Simulations, & mocks, can provide *predictions*, especially for upcoming missions like XRISM, LYNX & Athena
- Explore different weighting schemes for velocity distributions in comparison to the observable measurements: how to use safely simulations for predictions
- Constrain the expected capabilities (and challenges) in detecting different line shapes, and measuring line shifts and velocity broadening
- Constrain the limits due to projection and multi-velocity multi-phase ICM

THANKS!



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