# AGN feedback with XRISM and *Athena*

Matteo Guainazzi, *Athena* Study Scientist and XRISM ESA Project Scientist

Main collaborators:
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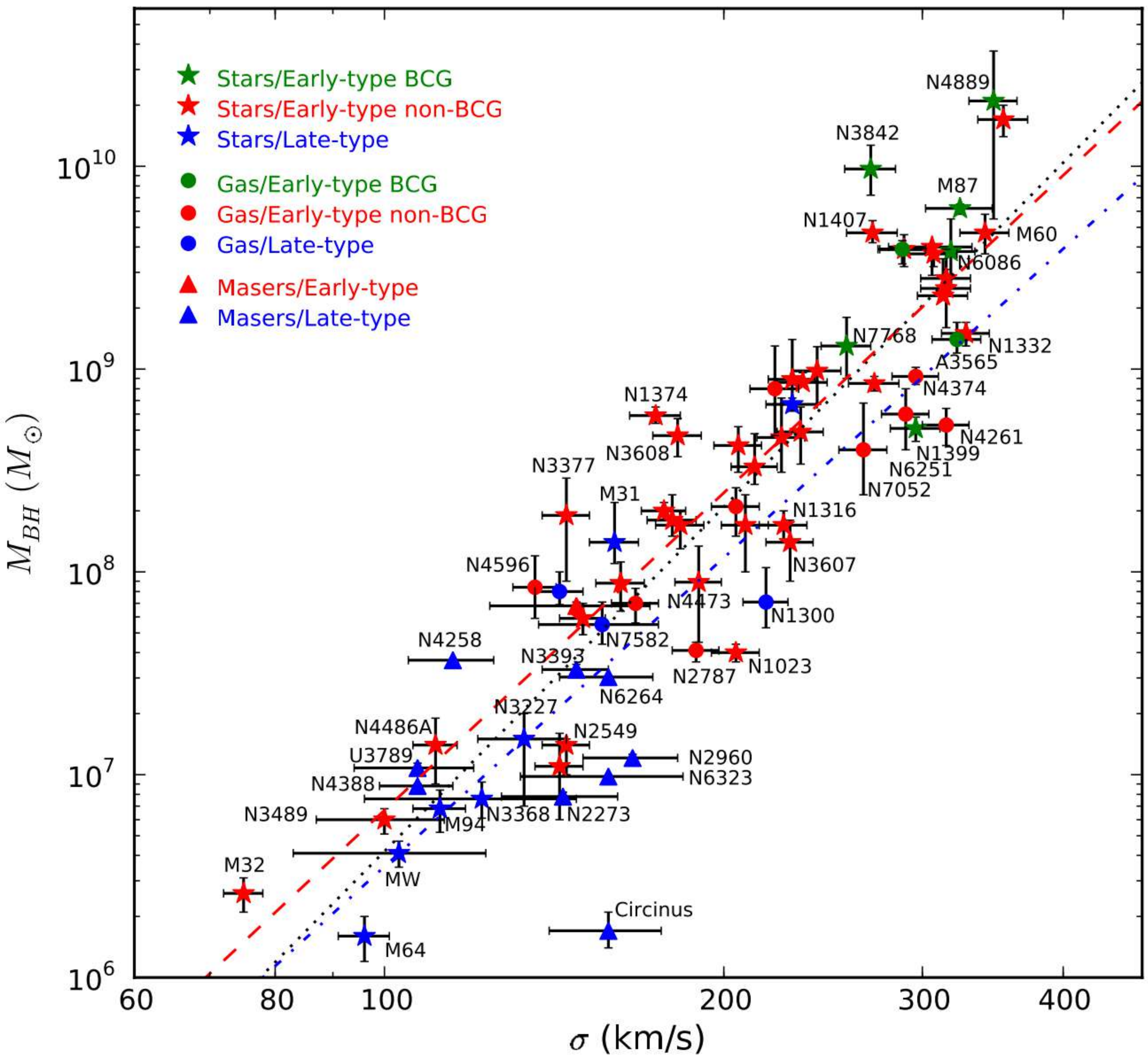
and the whole *Athena* Science Study Team (ASST)

References:
Dadina, Guainazzi, Cappi, Vignali, Malaguti, Comastri, 2010, A&A, 516, 9
Laha, Guainazzi, Chakravorti, Dewangan, & Kembhavi, 2014, MNRAS, 441, 2613
Longinotti, Krongold, Guainazzi, Giroletti, Panessa, Constantini, Santos-LLeo, Rodriguez-Pascual, 2015, ApJ, 813, L39
Laha, Guainazzi, Chakravorti, Dewangan, & Kembhavi, 2016, MNRAS, 457, 3896
Laha, Guainazzi, Ghosh, Piconcelli, Gandhi, Markowitz, Bagchi, 2018, ApJ, 868, 10
Barret, Decourchelle, Fabian, Guainazzi, Nandra, Smith, den Herder, 2019, arXiv:1912.04615

# AGN feedback

McConnell & Ma, 2013, ApJ, 764, 184




- Relations between black hole mass and host galaxy bulge mass/size estimators
- Strongest correlation vs. stellar velocity dispersion ($M_{BH} \propto \sigma^{4-5}$)
- Black hole size/bulge size ~ $10^{-8}$-$10^{-9}$
- Black hole "sphere of influence" ~pc:

$$R_{\rm BH,sph} = \frac{GM_{\rm BH}}{\sigma_*^2} \simeq 10.7 \frac{M_{\rm BH}}{10^8 {\rm M}_\odot} \left[\frac{\sigma_*}{200 {\rm km\,s^{-1}}}\right]^{-2} {\rm pc}$$

- Messenger → AGN feedback

# $M_{BH}$ and $M_{gal}$ scaling laws

derivation of these formulae in the review by Fabian, 2012, ARA&A, 50, 455

radiation force outwards — gravity force inwards

$$\frac{4\pi G M_{\rm BH} m_{\rm p}}{\sigma_{\rm T}} = \frac{G M_{\rm gal} M_{\rm gas}}{r^2} \Rightarrow M_{\rm BH} = \frac{f \boxed{\sigma^4} \sigma_{\rm T}}{\pi G^2 m_{\rm p}}$$

[In reality the relevant Eddington limit is that on dust, leading to the observed $M_{BH}/M_{gal}$ normalisation: $\sim\sigma_T/\sigma_d \sim 10^{-3}$]

**Black holes have sufficient energy to unbind galaxies:**

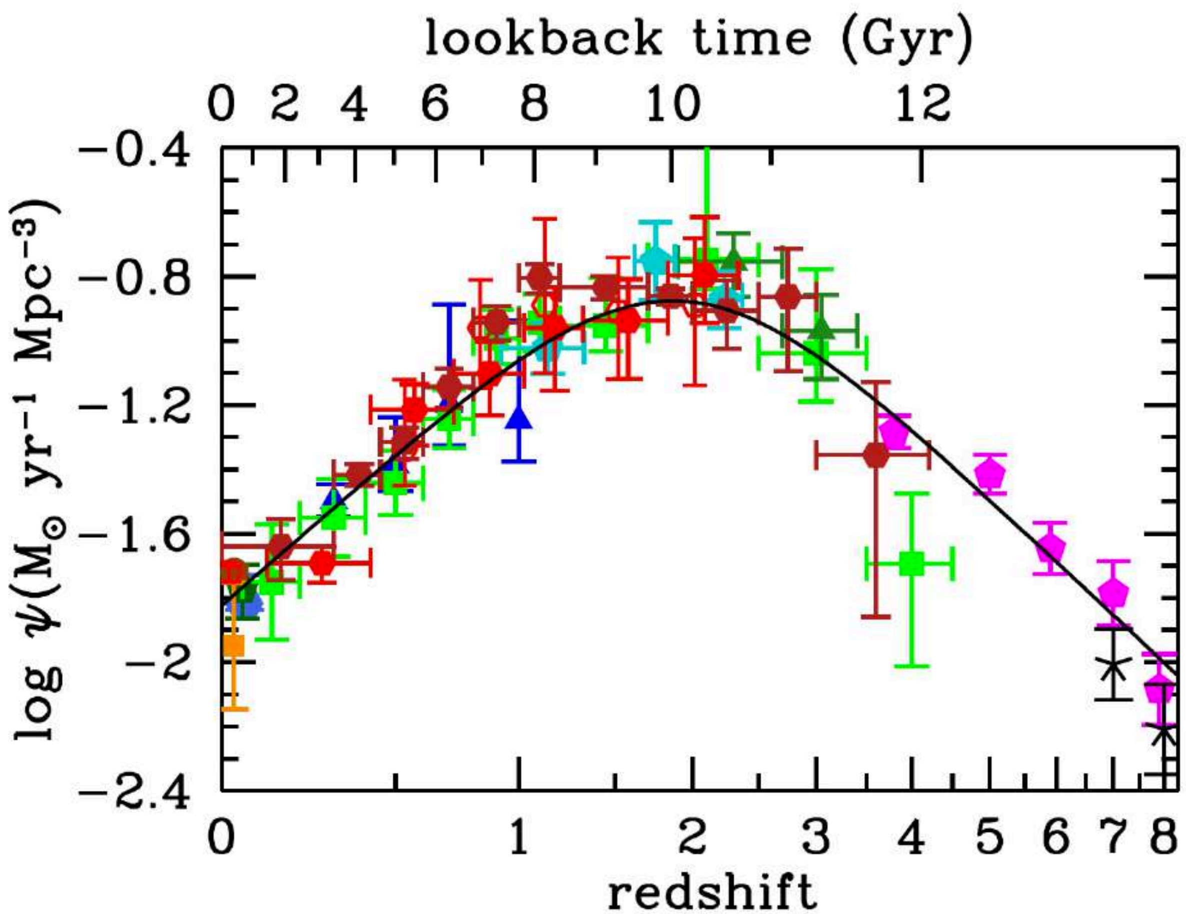
$$E_{\rm BH} = 0.1 M_{\rm BH} c^2 \quad E_{\rm gal} \approx M_{\rm gal}\sigma^2 \quad M_{\rm BH} \approx 1.4 \times 10^{-3} M_{\rm gal}$$

$$E_{\rm BH}/E_{\rm gal} \approx 1.4 \times 10^{-4} (c/\sigma)^2$$

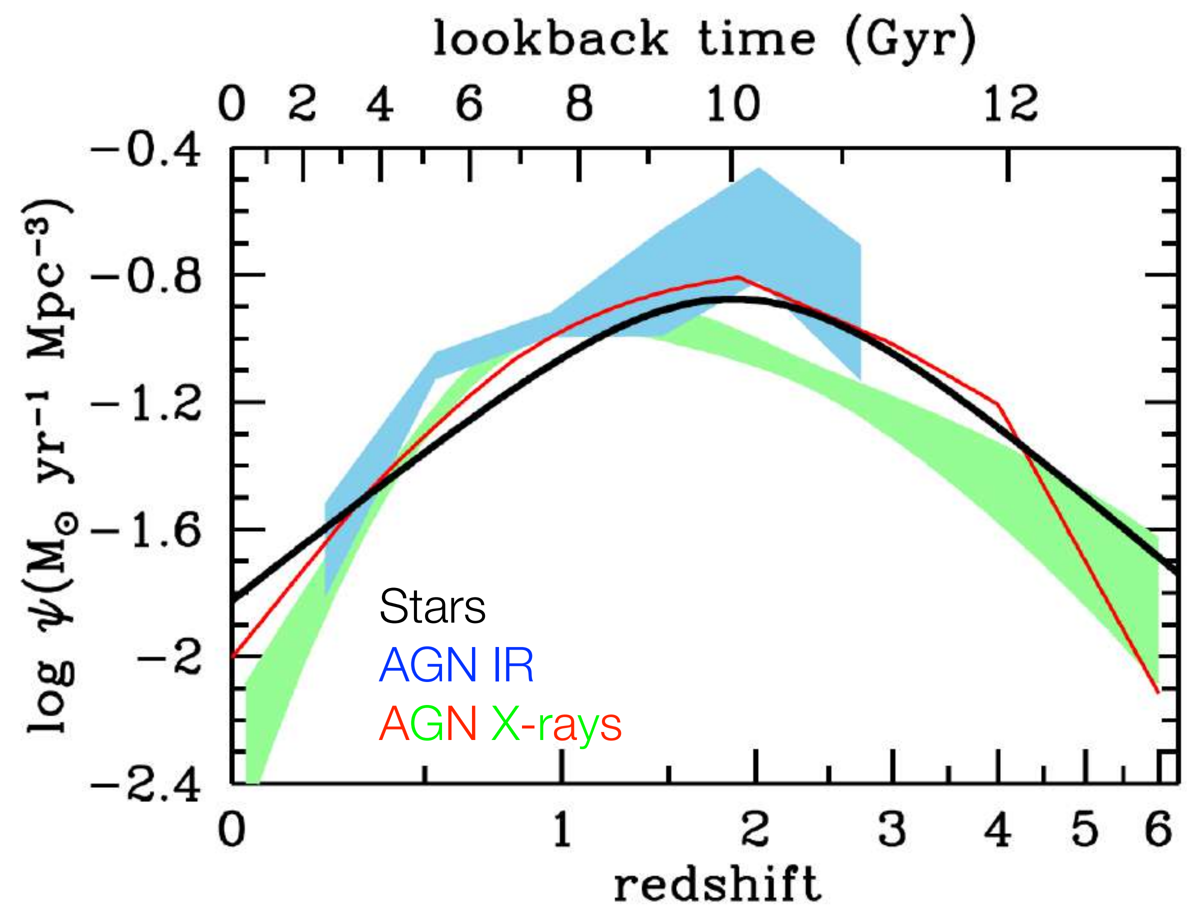
$$\sigma < 400 \text{ km s}^{-1}, \text{ so } E_{\rm BH}/E_{\rm gal} > 80$$

# Co-evolution of accreting BH and star formation

Madau & Dickinson, ARAA, 52, 415




Star formation history:
known down to z~8



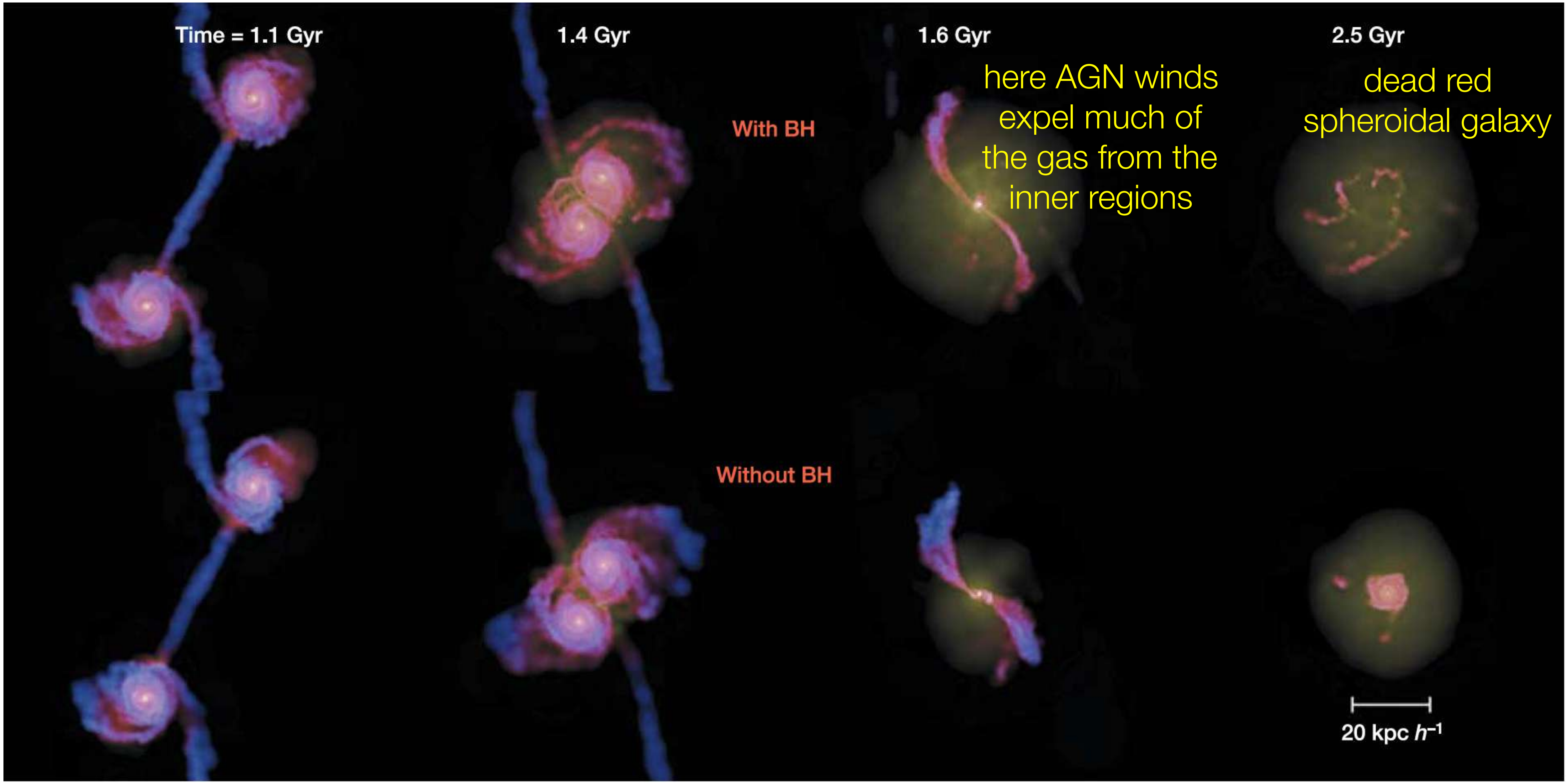

BH accretion history:
uncertain for z≥2

**Morphological resemblance between the two curves**
**Further evidence for AGN/galaxy co-evolution**

# Feedback and cosmological evolution of galaxies

di Matteo et al., 2005, Nature, 433, 604

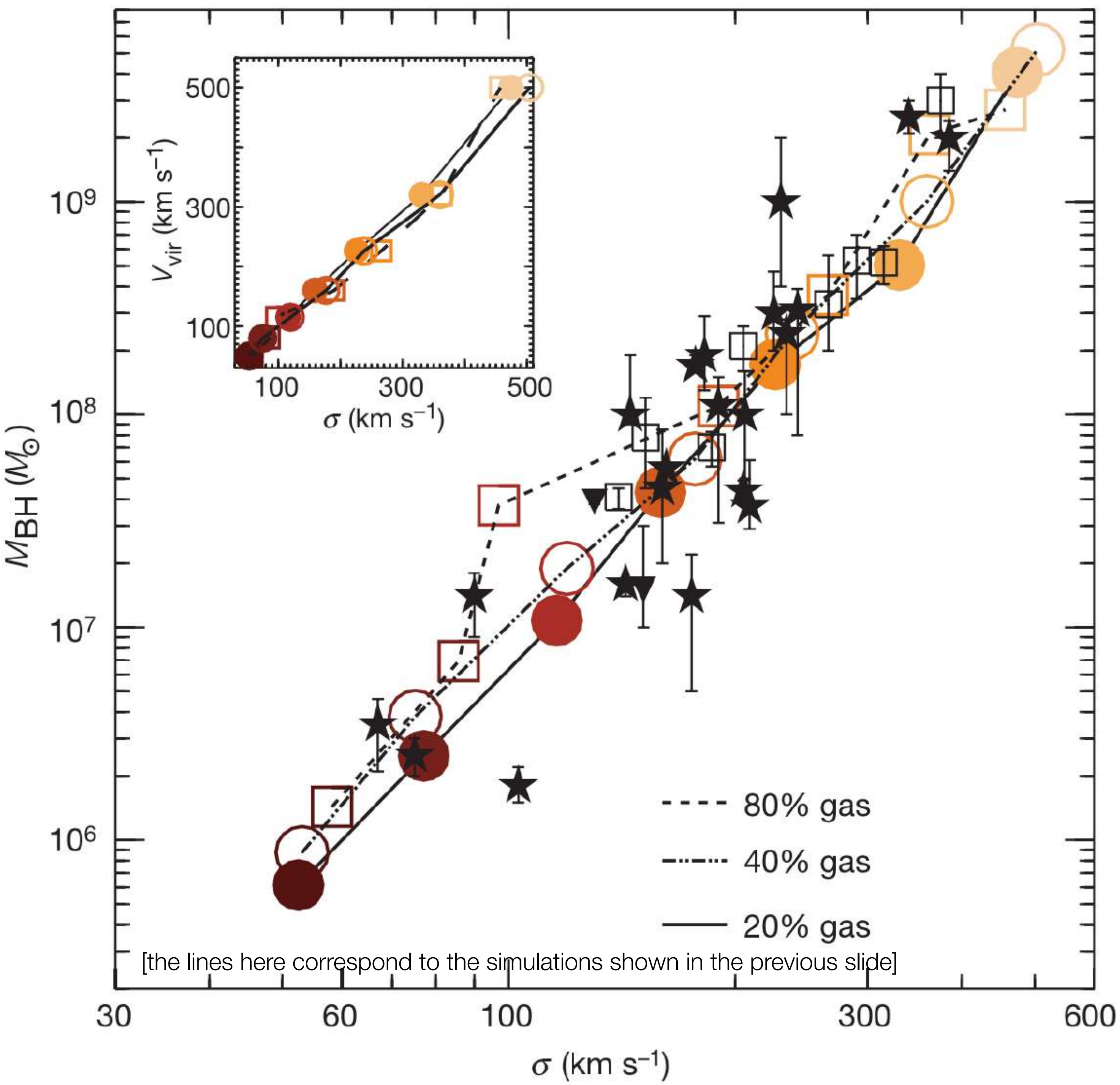
Example of a simulation of BH accretion and star formation after the merging between two Milky Way-like galaxies



# When is feedback important?

di Matteo et al., 2005, Nature, 433, 604

$L_{KE} \equiv (dE_{feeback}/dt) \sim 5\%\ L_{accretion}$




[the lines here correspond to the simulations shown in the previous slide]

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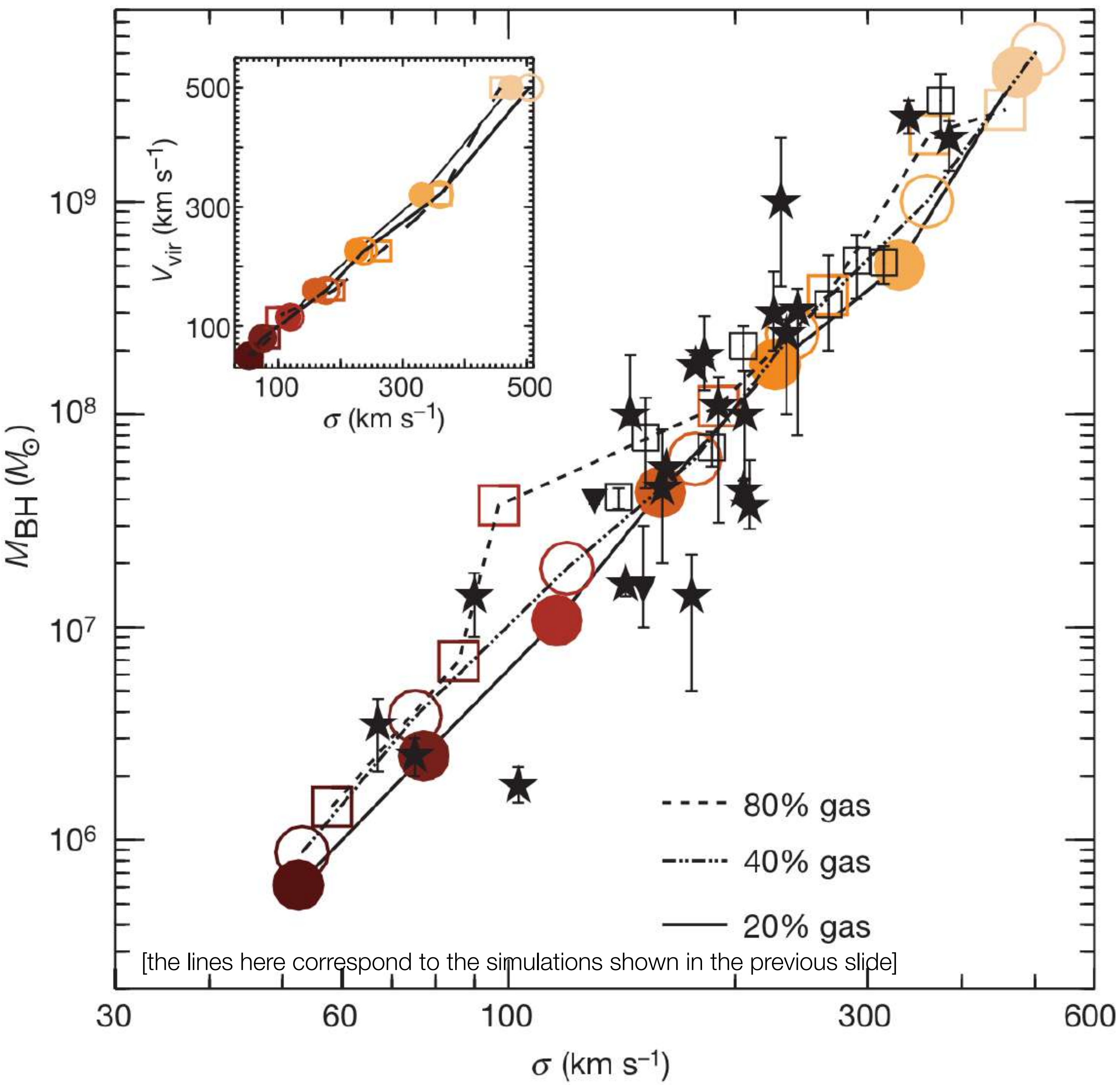
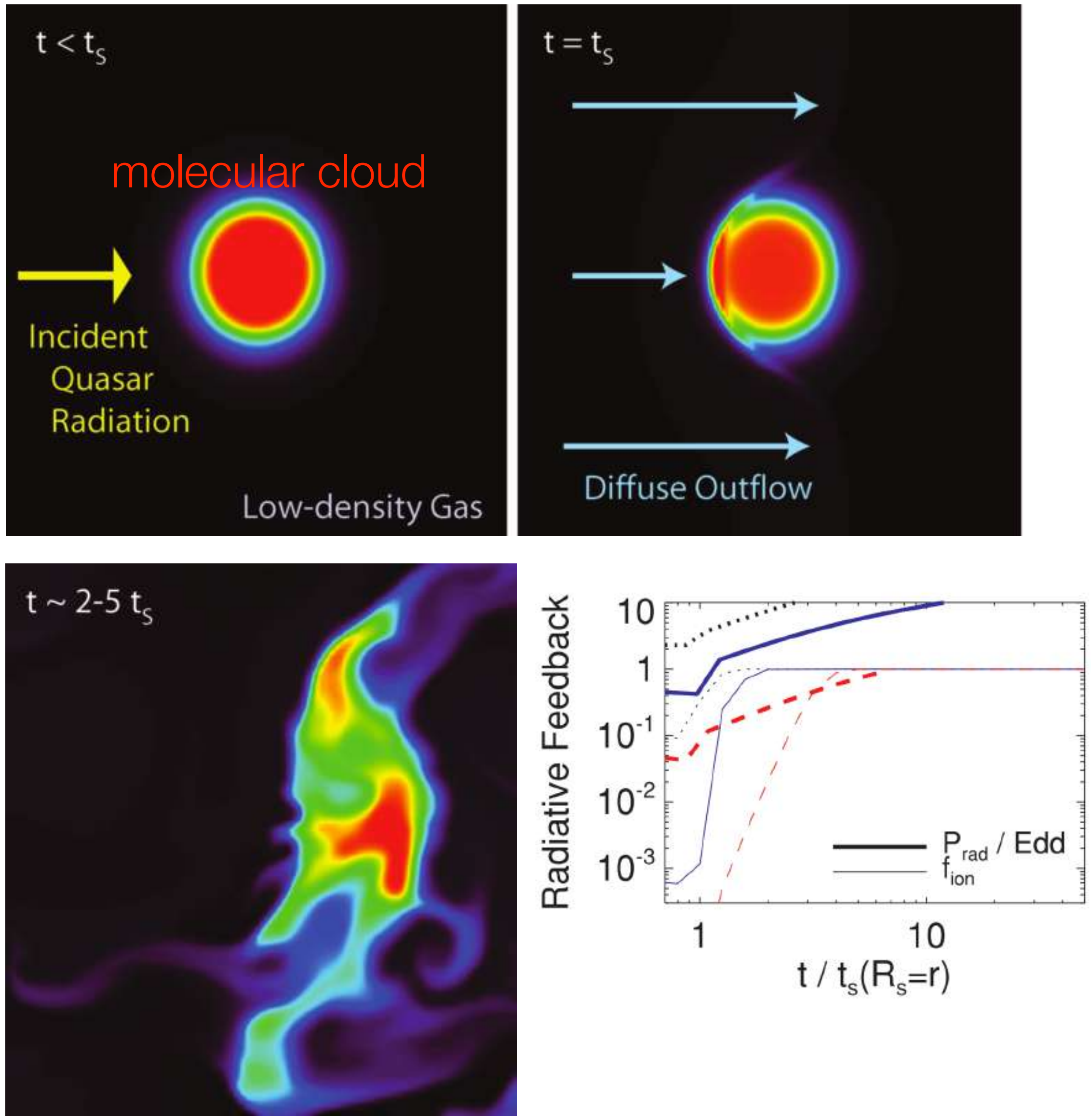
di Matteo et al., 2005, Nature, 433, 604

Hopkins & Elvis, 2010, MNRAS, 401, 7

$L_{KE} \equiv (dE_{feeback}/dt) \sim 5\% \; L_{accretion}$

$\mathbf{L_{KE} \equiv (dE_{feeback}/dt) \sim 0.5\% \; L_{accretion}}$



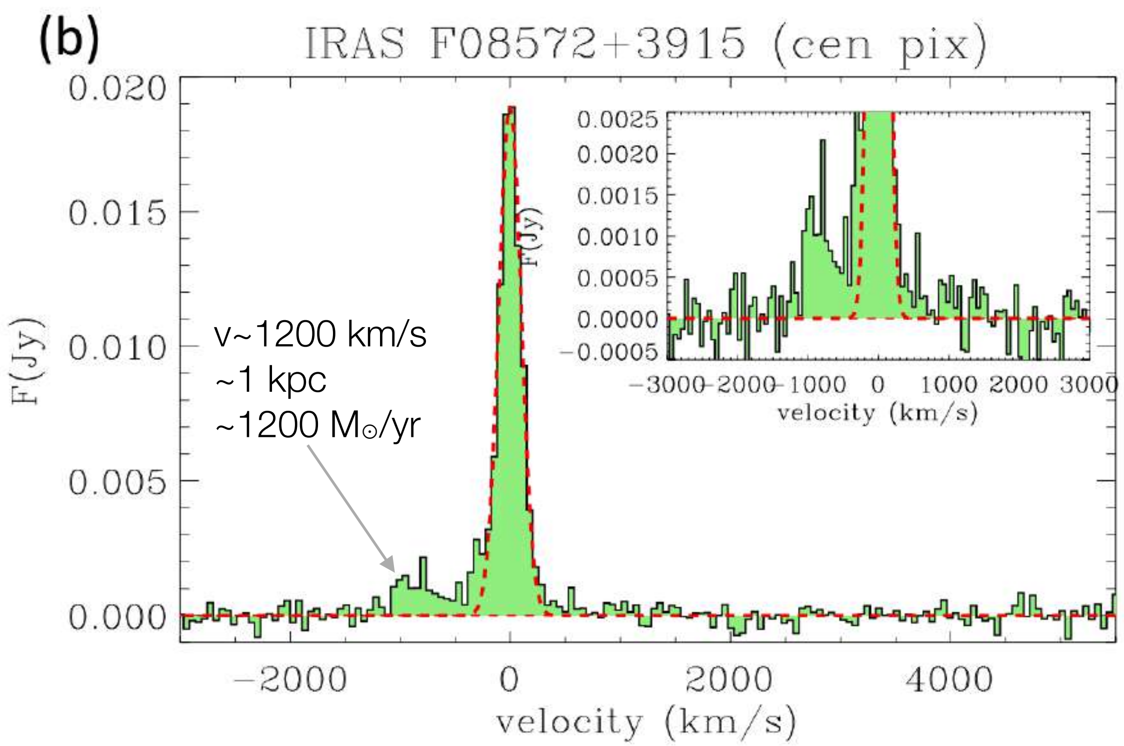



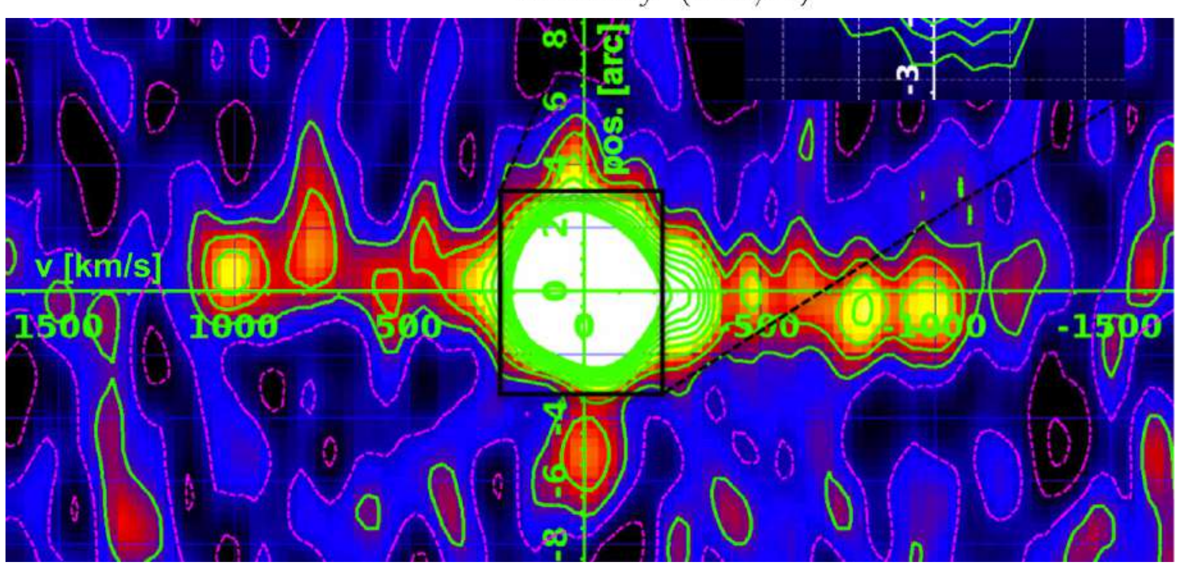
# Galaxy molecular outflows

Cicone et al., 2014, A&A, 562, 21

Feruglio et al., 2010, A&A, 518, L155

Recent discovery of molecular outflows in CO(1-0) observations of AGN-powered Ultra-luminous IR Galaxies (ULIRG)



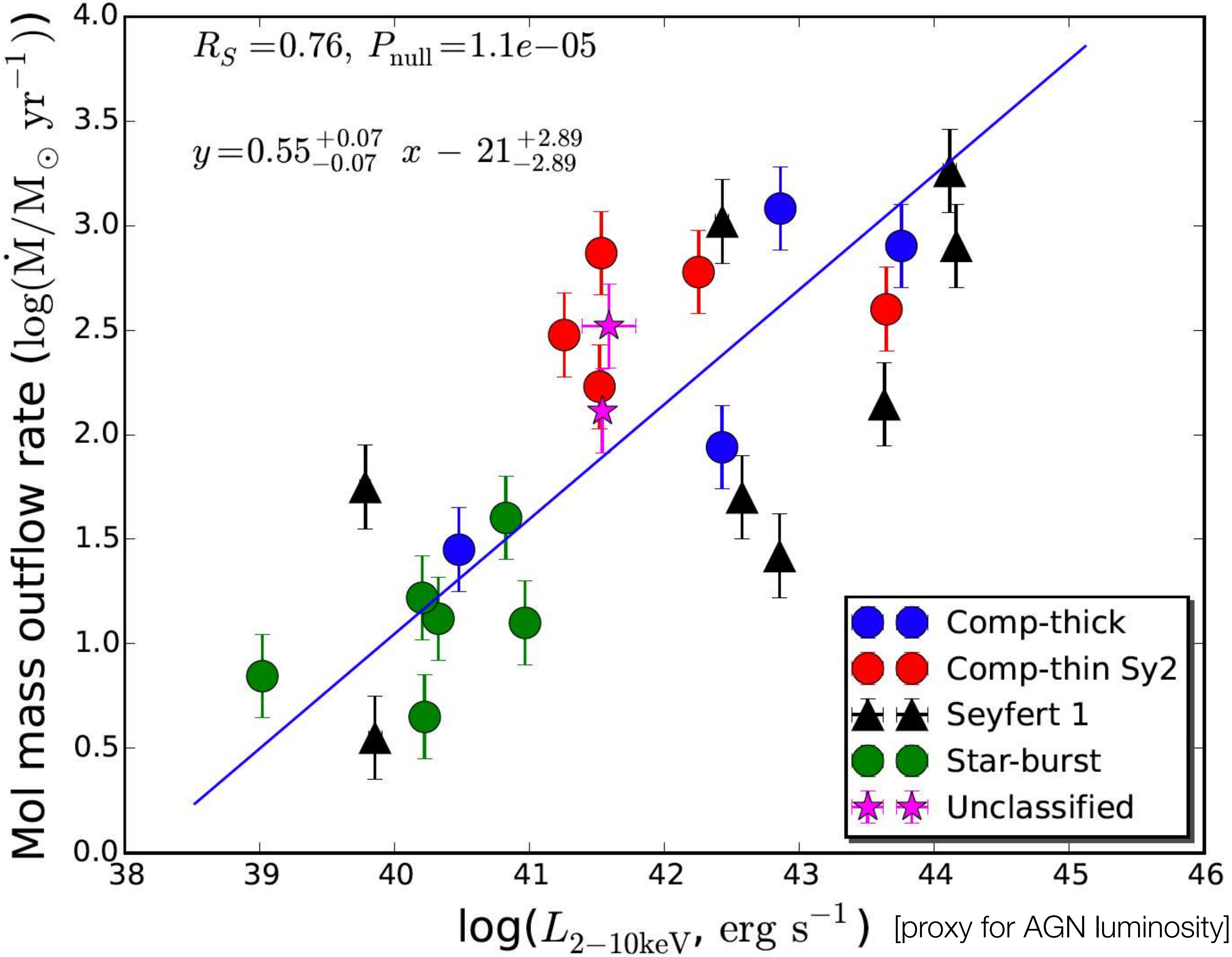




*E.g.*: Markarian 231:

- Outflow rate ~700 M⊙
- Spatial scale ~0.6 kpc
- Gas fully blown out the galaxy in ~1.5x10$^{7}$ years
- [Salpeter time ~5x10$^{7}$ years]
- Energy deposited into the galaxy ~6x10$^{57}$ erg
- [Binding energy of the galaxy ~8x10$^{57}$ erg]

# Molecular outflows are AGN driven

Laha, et al., 2018, ApJ, 868, 10

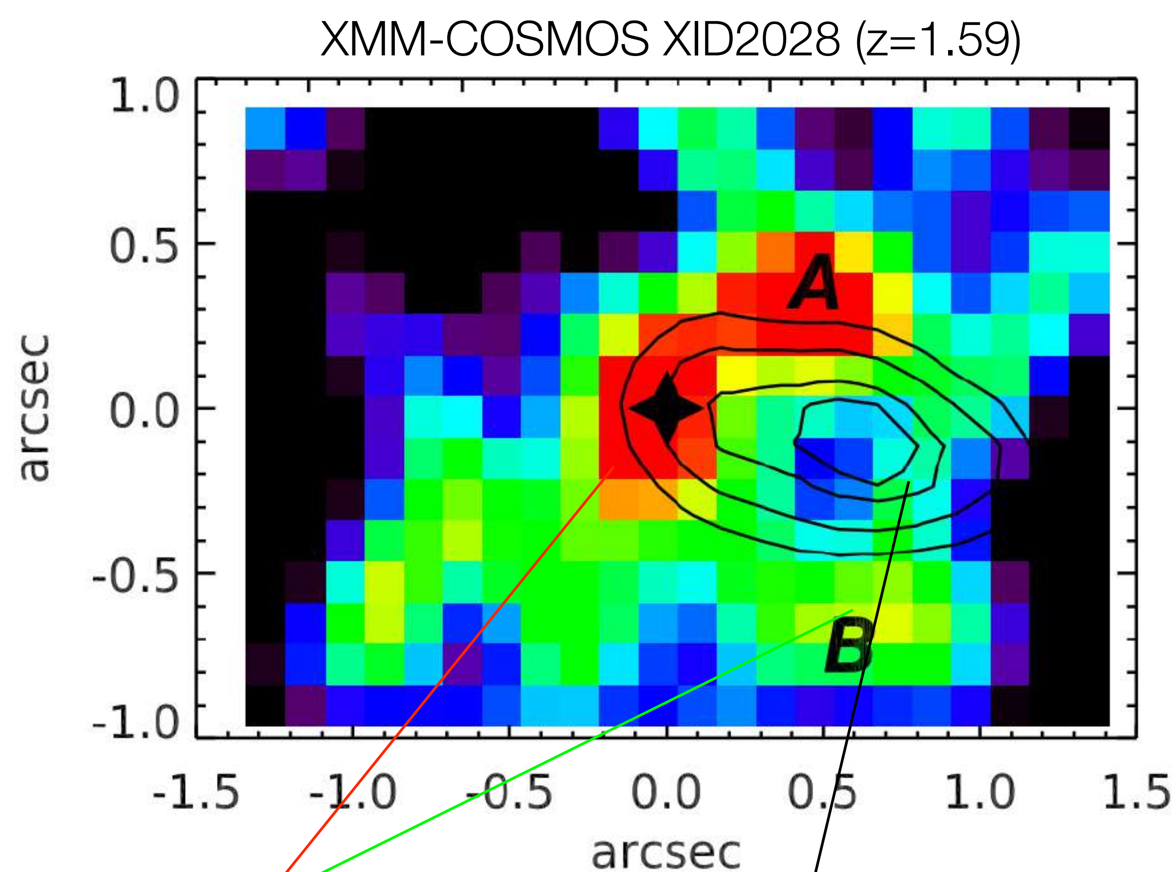


# Evidence of outflow-driven feedback

Cresci et al., 2015, ApJ, 799, 82

Page et al., 2012, Nature, 485, 213

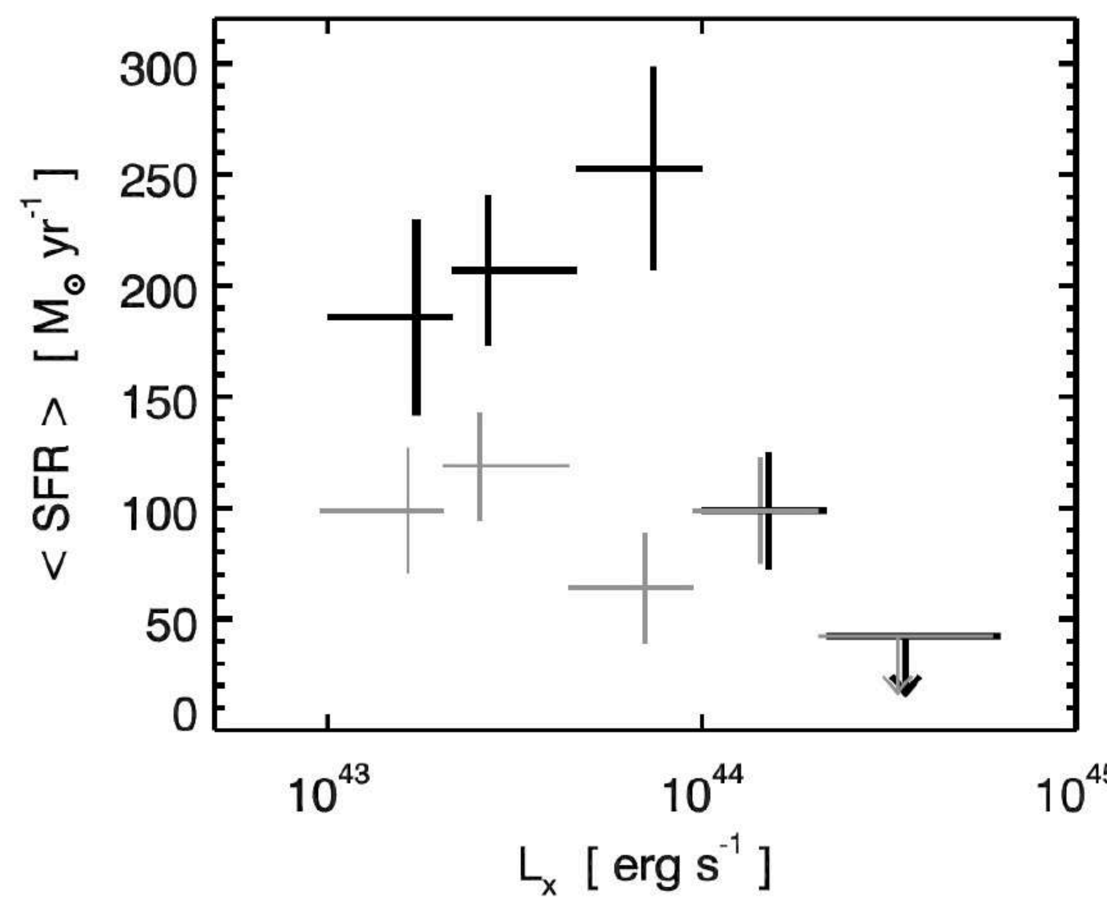
## Ionised gas ([OIII]) in powerful QSOs produce +ve and -ve feed-back




$H_\alpha$ (SFR~230 M⊙ $yr^{-1}$)
"positive" and
"negative" feedback!

Countours: [OIII]
v~600-800 km $s^{-1}$
$dM_{out}/dt \gtrsim 1000$ M⊙ $yr^{-1}$

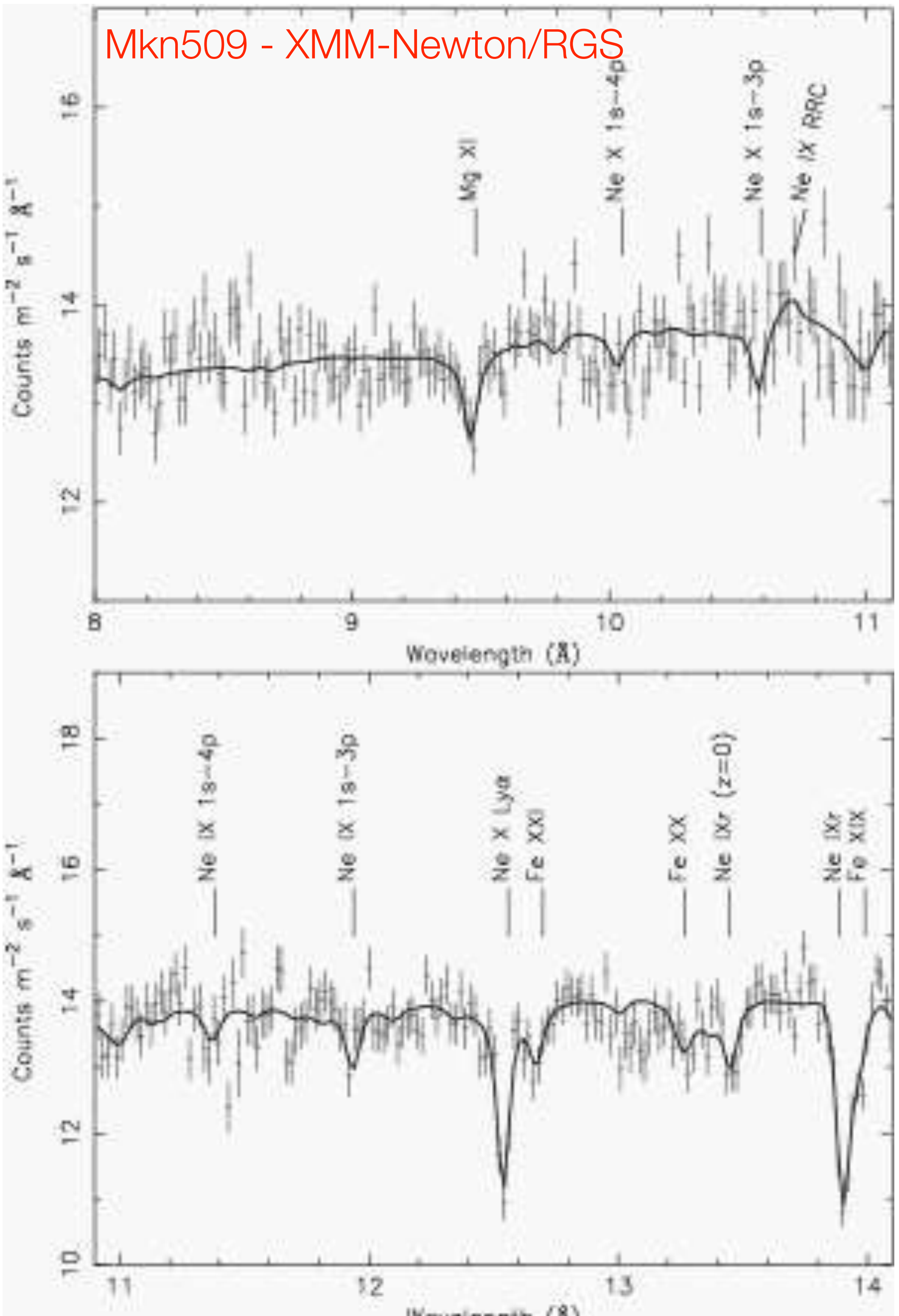
## Star formation is inhibited in $L_X > 10^{44}$ erg/s AGN (1<z<3)



# AGN X-ray winds: Warm absorbers

Detmers et al., 2011, A&A, 534, A37

estimate of incidence fraction in Laha et al., 2014, MNRAS, 441, 2613




- Resonant absorption lines: He-/H-like ions of C, O, Ne, Mg, N, Si, Fe ...
- Present in $77\pm9\pm^{3}_{14}$% of nearby AGN
- Large range of physical properties ($N_H$, $v_{out}$, $n$ …)
- Mostly observed at grating resolution [$E/\Delta E \sim 10^{3-4}$]

Physics driven by the ionisation parameter:

ionising luminosity

$$\xi = \frac{L}{nr^2}$$

density distance

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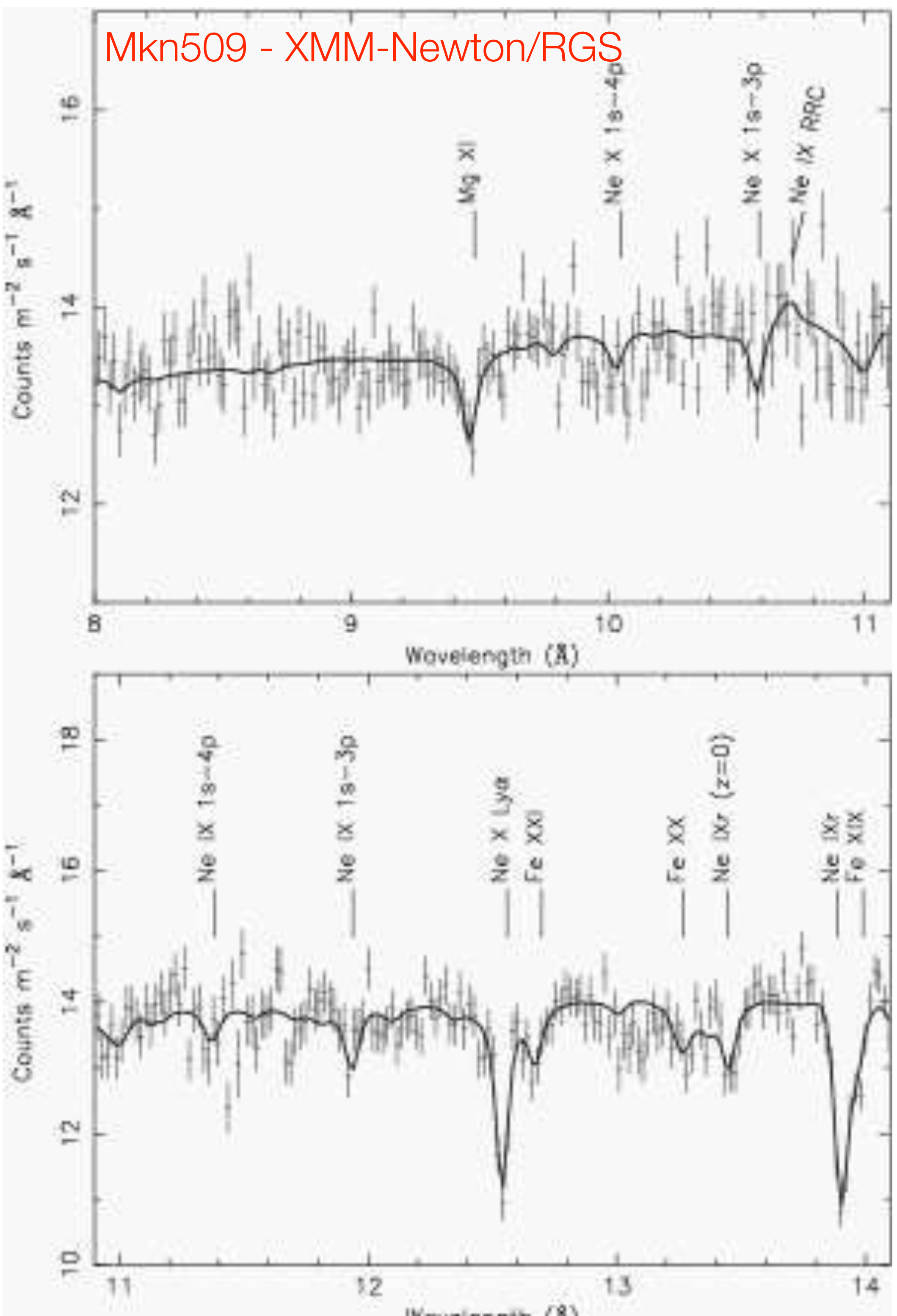


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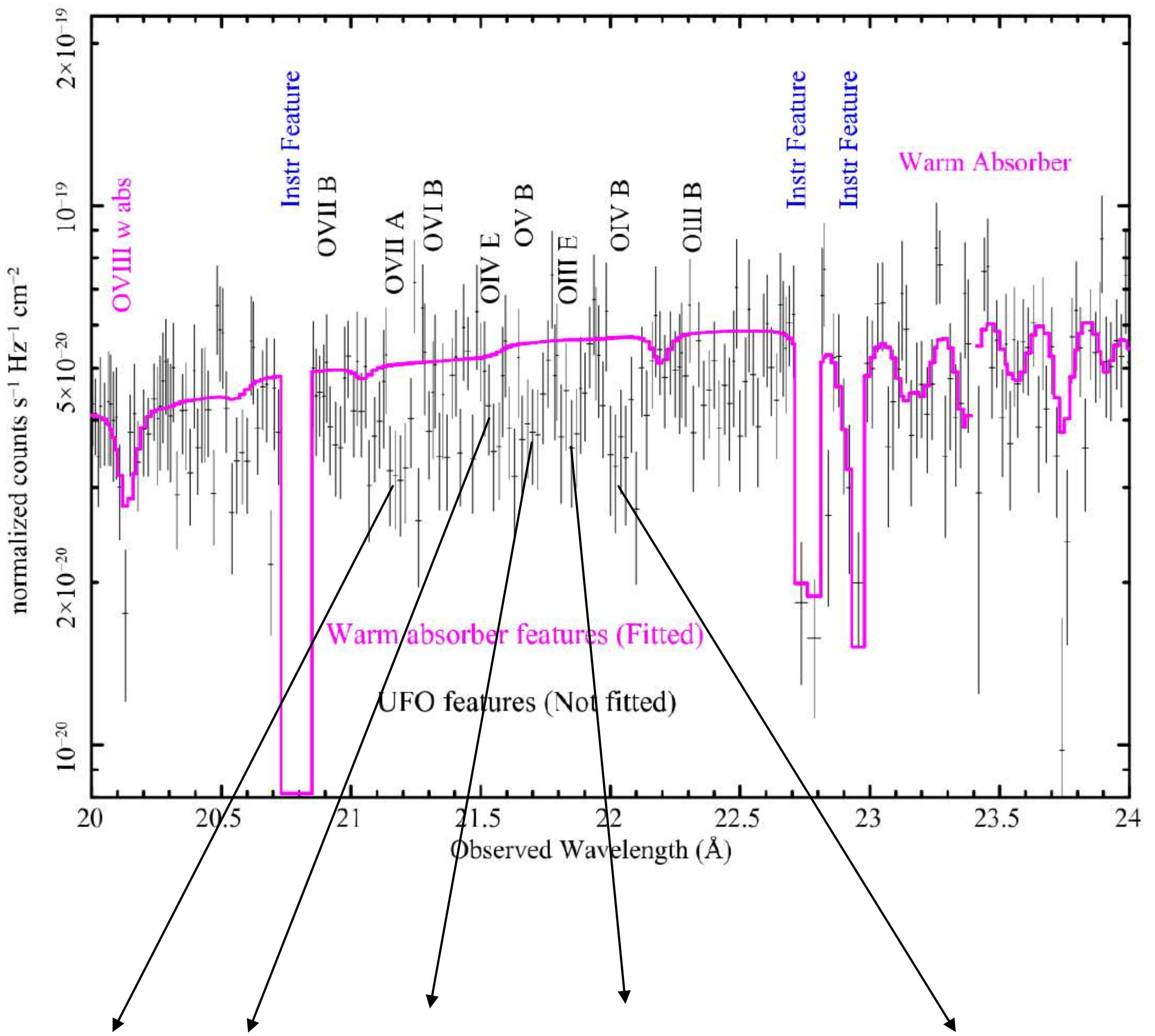
# AGN X-ray winds: Ultra-Fast Outflows (UFOs)

Longinotti et al., 2015, ApJ, 813, L39

discovery by Tombesi et al., 2010, A&A, 521, 57; Gofford et al., 2013, MNRAS, 430, 60

IRAS17020+4544 - XMM-Newton/RGS




These components correspond to $0.08<v_{out}<0.11c$

- Sub-relativistic speeds ($v_{out}$>0.1 *c*)
- Resonant He/H-like Fe absorption lines (≥7 keV)
- Present in ~30% of nearby AGN and radio-galaxies
- High-column density (≥$10^{23}$ $cm^{-2}$), highly-ionised
- Mostly (but not all) observed at CCD resolution [$E/\Delta E$~$10^{1-2}$]
- Transient (exception: PDS456)

# How to calculate wind feedback?

Crenshaw et al. 2003, ApJ, 594, 116

Assuming mass conservation through a spherical shell:

$$\dot{M}_{\rm out} = 4\pi r N_{\rm H} \mu m_p C_g v_r$$

Once this is know, the kinetic luminosity is: $\dot{E}_{\rm K} = L_{\rm KE} = \frac{1}{2}\dot{M}_{\rm out}\, v_{\rm out}^2$

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column density (measured)

Mass outflow rate

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covering factor

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Mass outflow rate

location of the outflowing clouds

column density (measured)

Once this is know, the kinetic luminosity is: $\dot{E}_{\rm K} = L_{\rm KE} = \frac{1}{2}\dot{M}_{\rm out}\, v_{\rm out}^2$

# How to calculate wind feedback?

Crenshaw et al. 2003, ApJ, 594, 116

Assuming mass conservation through a spherical shell:

covering factor

outflow velocity (measured)

$$\dot{M}_{\mathrm{out}} = 4\pi r N_{\mathrm{H}} \mu m_{p} C_{g} v_{r}$$

column density (measured)

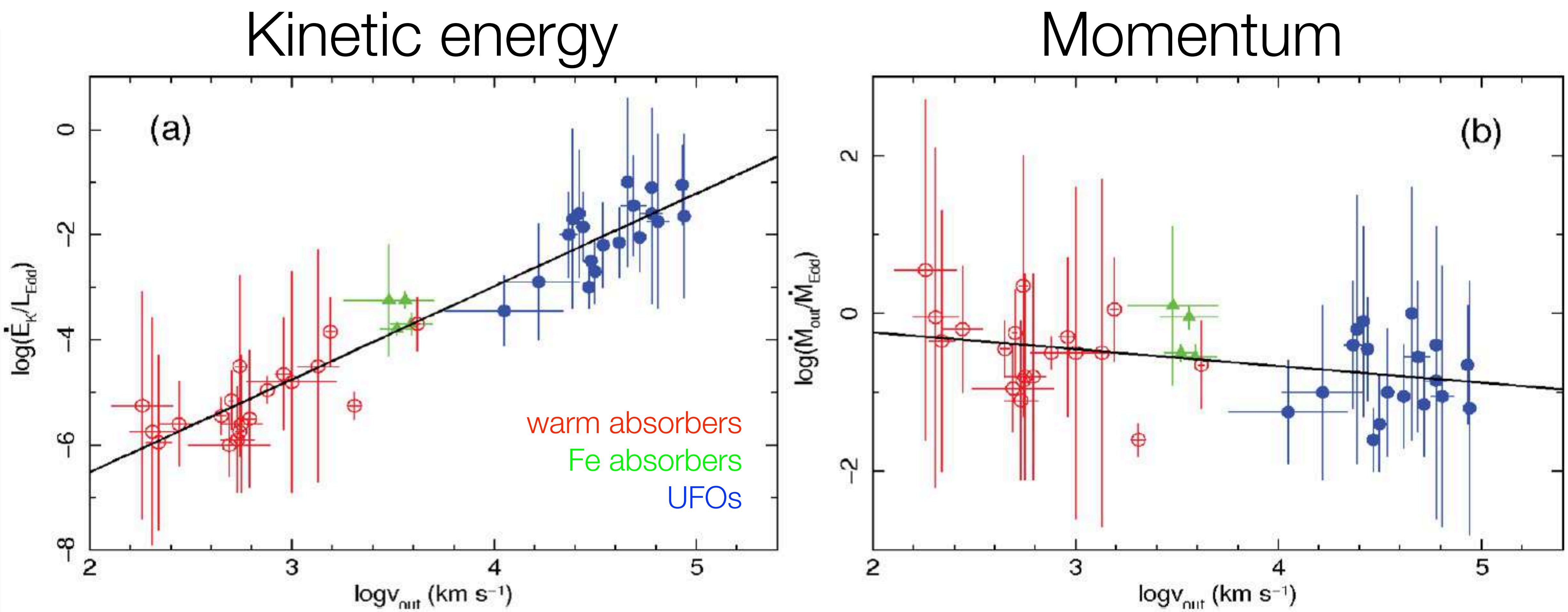
Mass outflow rate

location of the outflowing clouds

Once this is know, the kinetic luminosity is: $\dot{E}_{\mathrm{K}} = L_{\mathrm{KE}} = \frac{1}{2}\dot{M}_{\mathrm{out}}\, v_{\mathrm{out}}^{2}$

# Energetics of AGN outflows

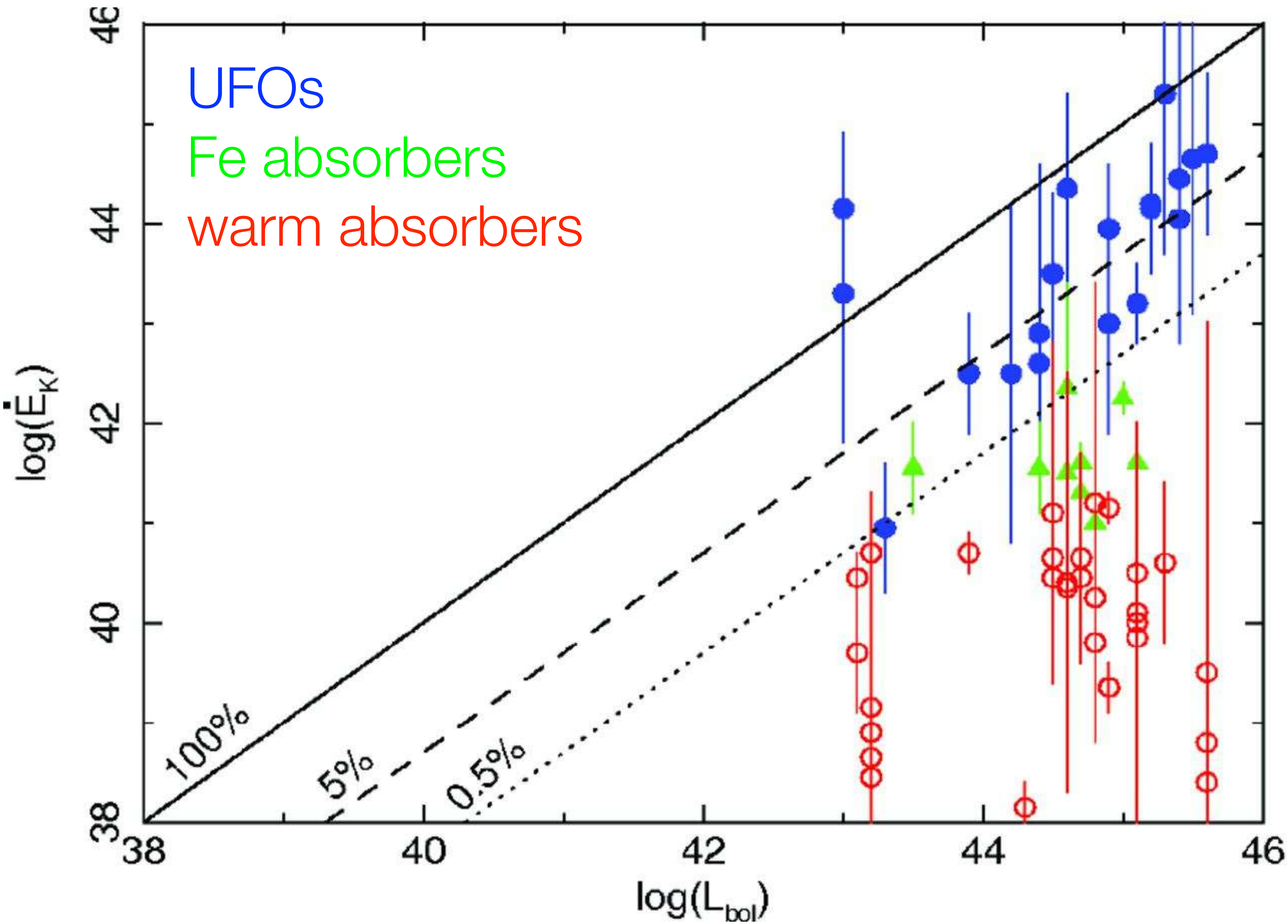
Tombesi et al., 2013, MNRAS, 430, 1102




Due to the $v_{out}^3$ dependency, UFOs carry more energy

# AGN feed-back ("quasar mode")

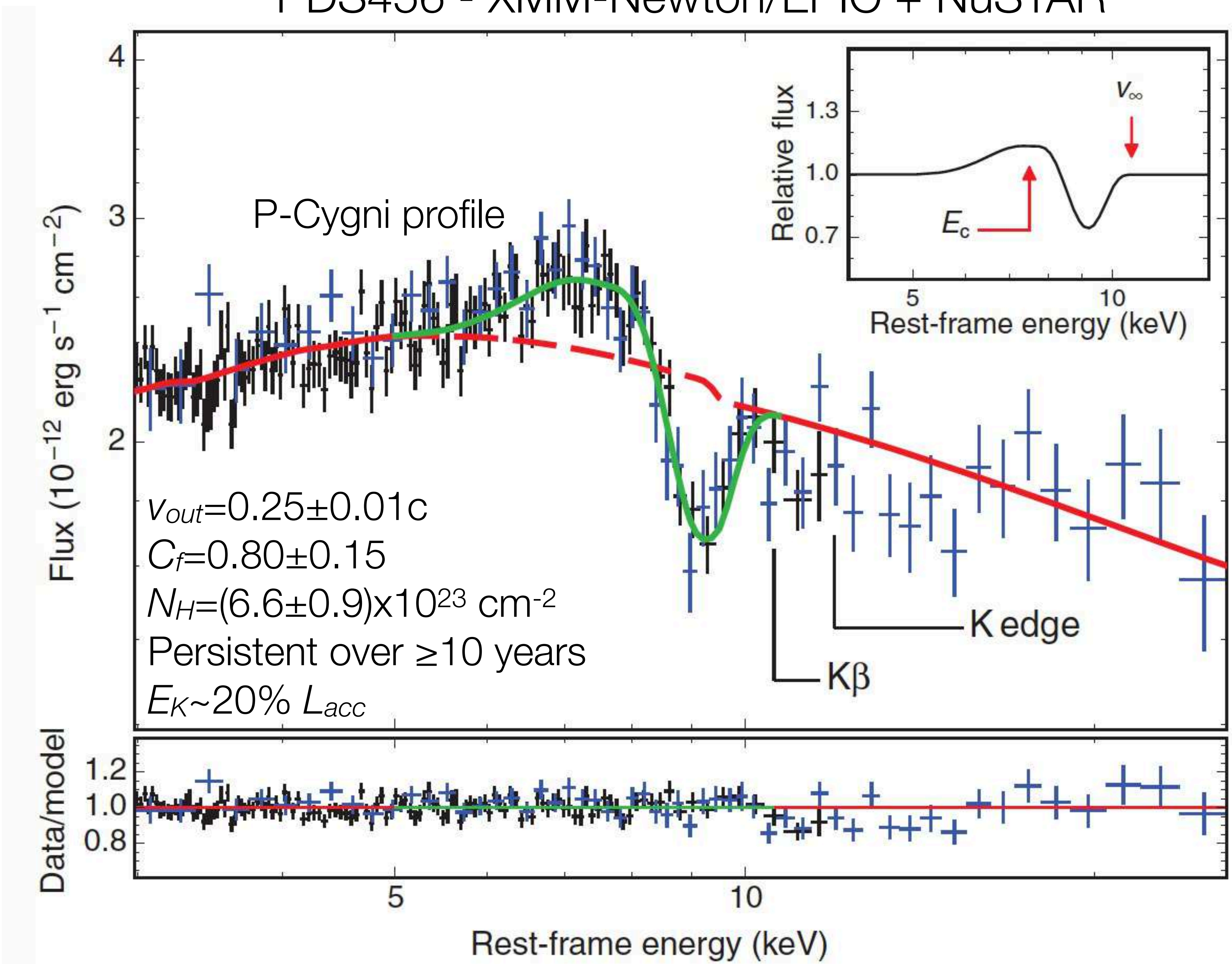
Tombesi et al., 2013, MNRAS, 430, 1102



# $C_f$ - only one determination in an individual source

Nardini et al., 2015, Science, 347. 860

PDS456 - XMM-Newton/EPIC + NuSTAR



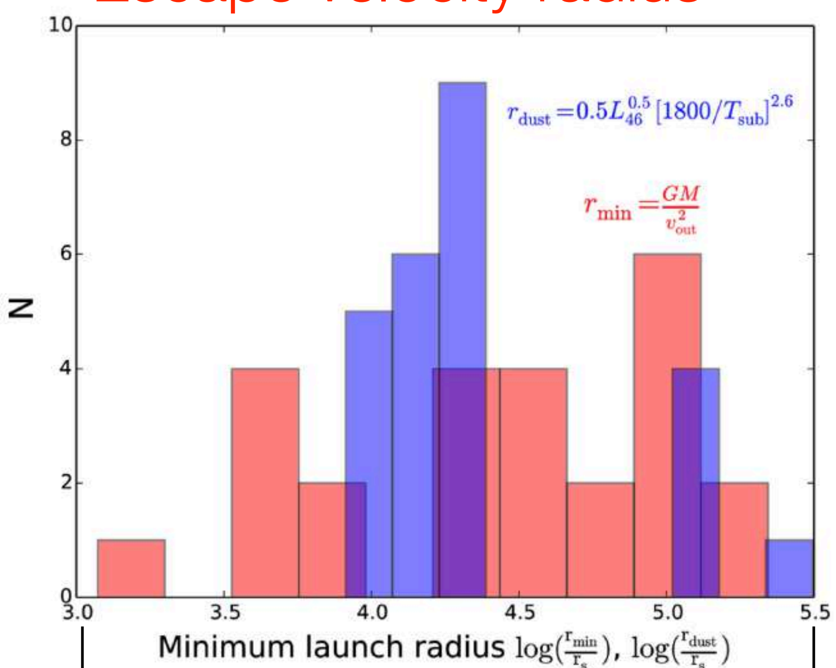
# Launch radius (*r*) of AGN winds

Laha et al., 2016, MNRAS, 457, 3896

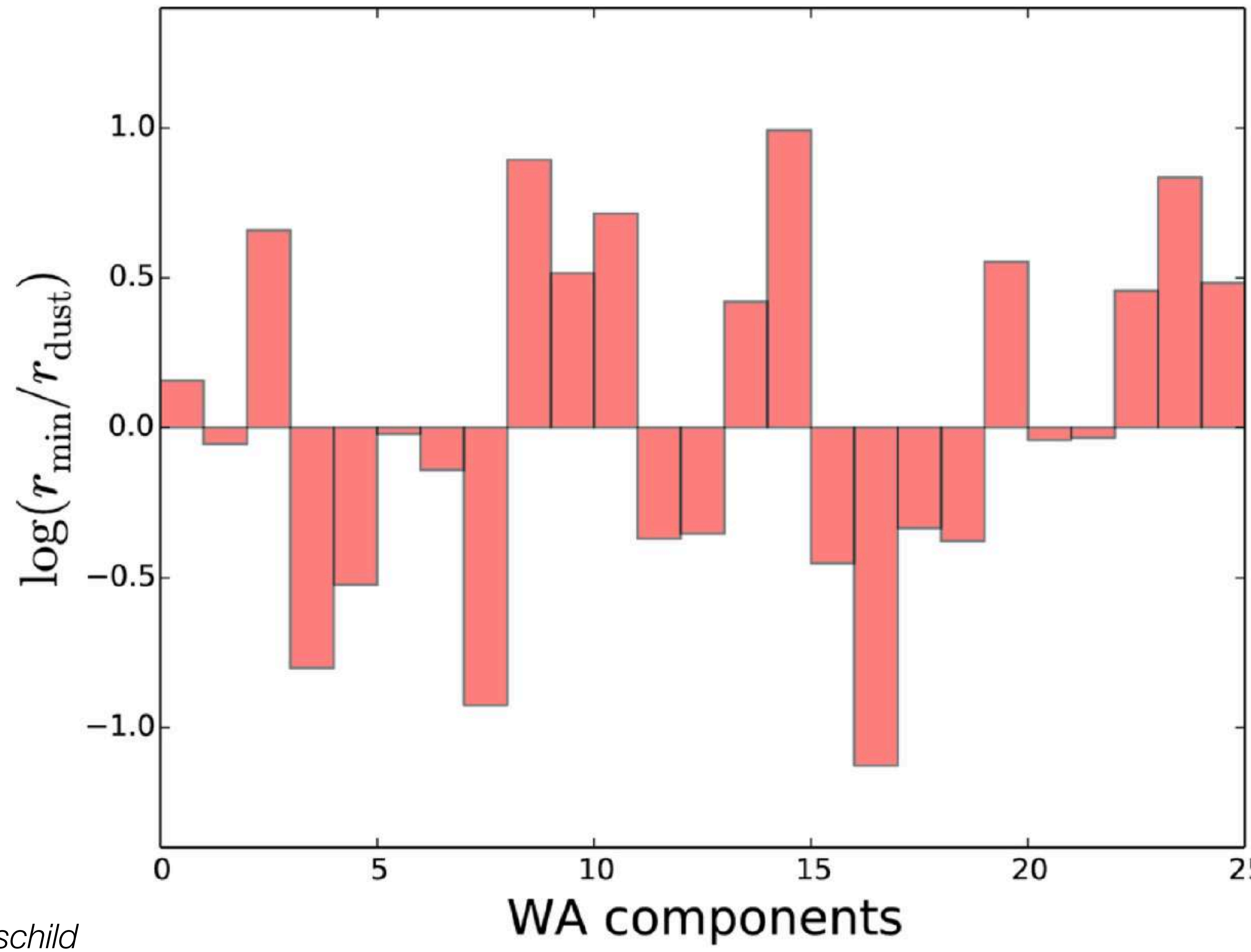
The launch radius can be estimated only *indirectly* in most cases …

Dust sublimation radius

Escape velocity radius




$10^3$ $R_{Schwarzschild}$ $10^{5.5}$ $R_{Schwarzschild}$



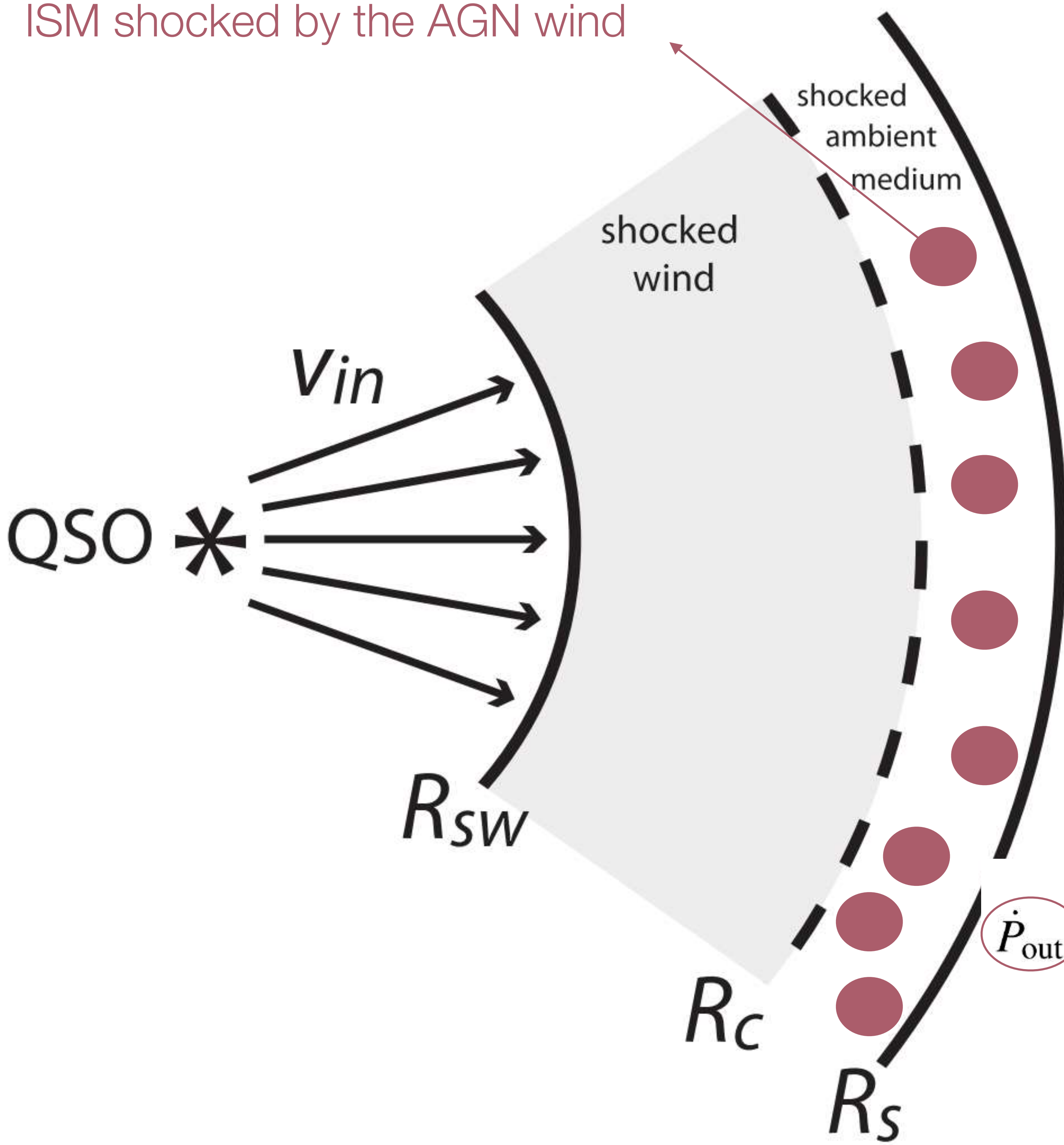

… leading to uncertainties up to 1 order-of-magnitude

# The physics of energy-conserving outflows

Faucher-Giguère & Quataert, 2012, MNRAS, 423, 605

Zubovas & King, 2012, ApJ, 745, L34

Cold molecular clouds are entrained in the ISM shocked by the AGN wind




AGN wind

molecular outflow

$$\frac{1}{2}\dot{M}_{\rm w} v_{\rm w}^2 \simeq \frac{1}{2}\dot{M}_{\rm out} v_{\rm out}^2$$

$$\downarrow$$

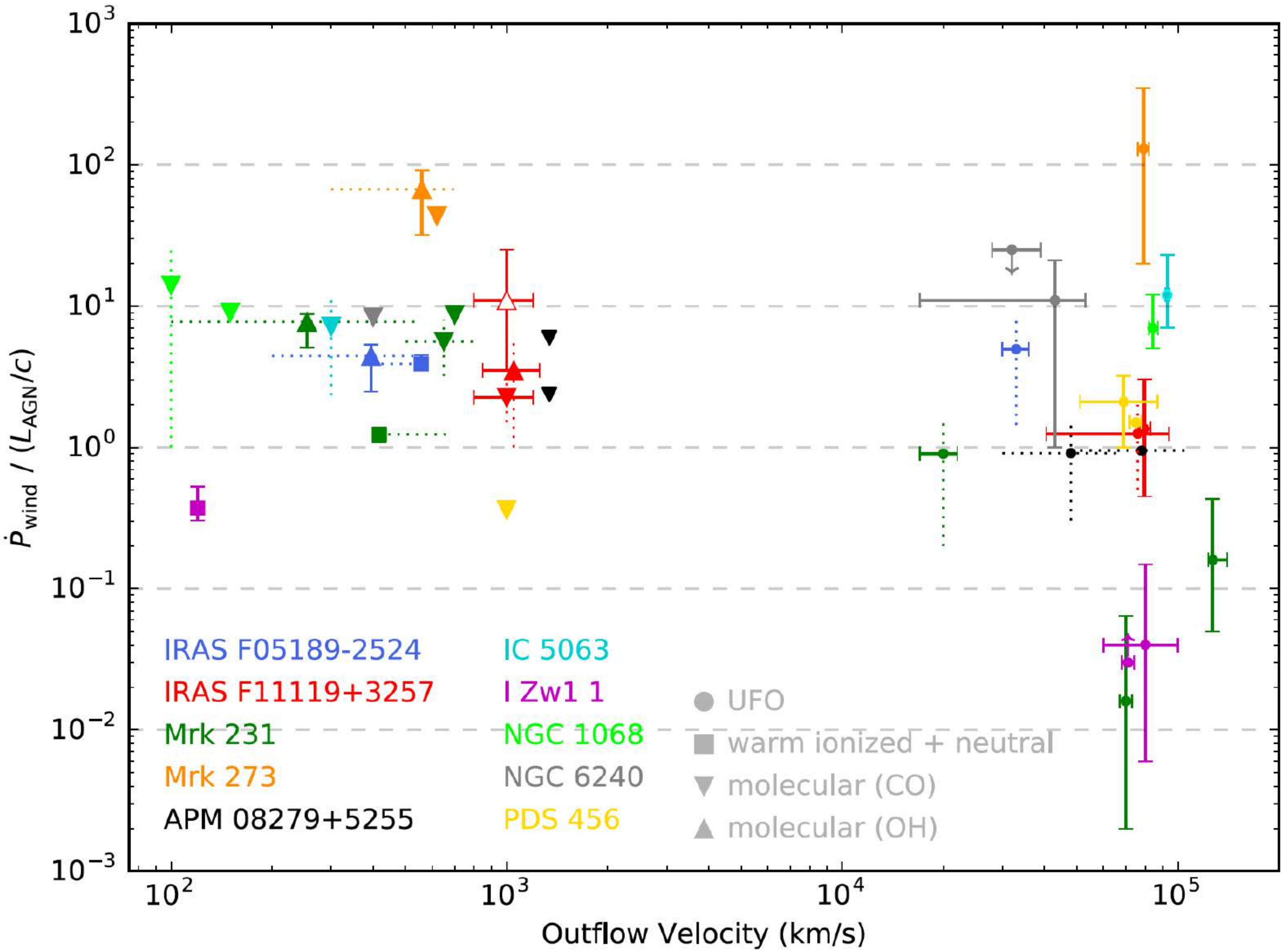
$$\frac{\dot{P}_{\rm w}^2}{2\dot{M}_{\rm w}} \simeq \frac{\dot{P}_{\rm out}^2}{2\dot{M}_{\rm out}}$$

$$\downarrow$$

$$\dot{P}_{\rm out} = \dot{P}_{\rm w}\left(\frac{\dot{M}_{\rm out}}{\dot{M}_{\rm w}}\right)^{1/2} = \frac{L_{\rm Edd}}{c} f_{\rm L}^{1/2} \sim 20\sigma_{200}^{-2/3} l^{1/6} \frac{L_{\rm Edd}}{c}$$

# Energy-driven (at least at galactic scale)

Smith et al., 2019, ApJ, 887, 69



# Summary of outflow pending issues

cf. Gaspari et al., 2020, Nature Astronomy, 4, 10

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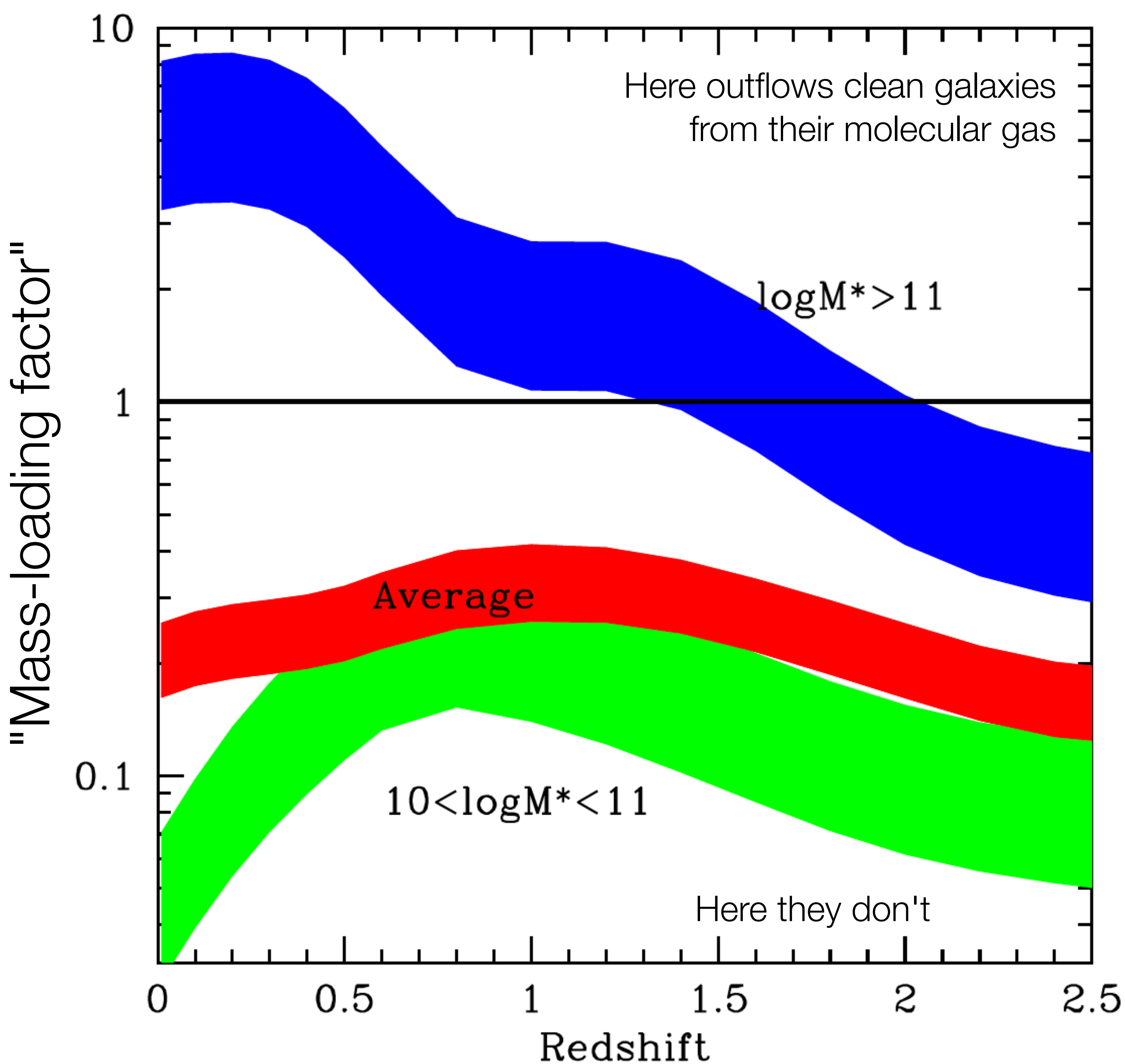
- How much energy/momentum rate are needed for feedback?
- Connection between ionised, neutral and molecular phases
- Distribution function of basic observables in complete samples?
- How does the molecular outflows form in hot outflows?

# The cosmological impact of AGN outflows

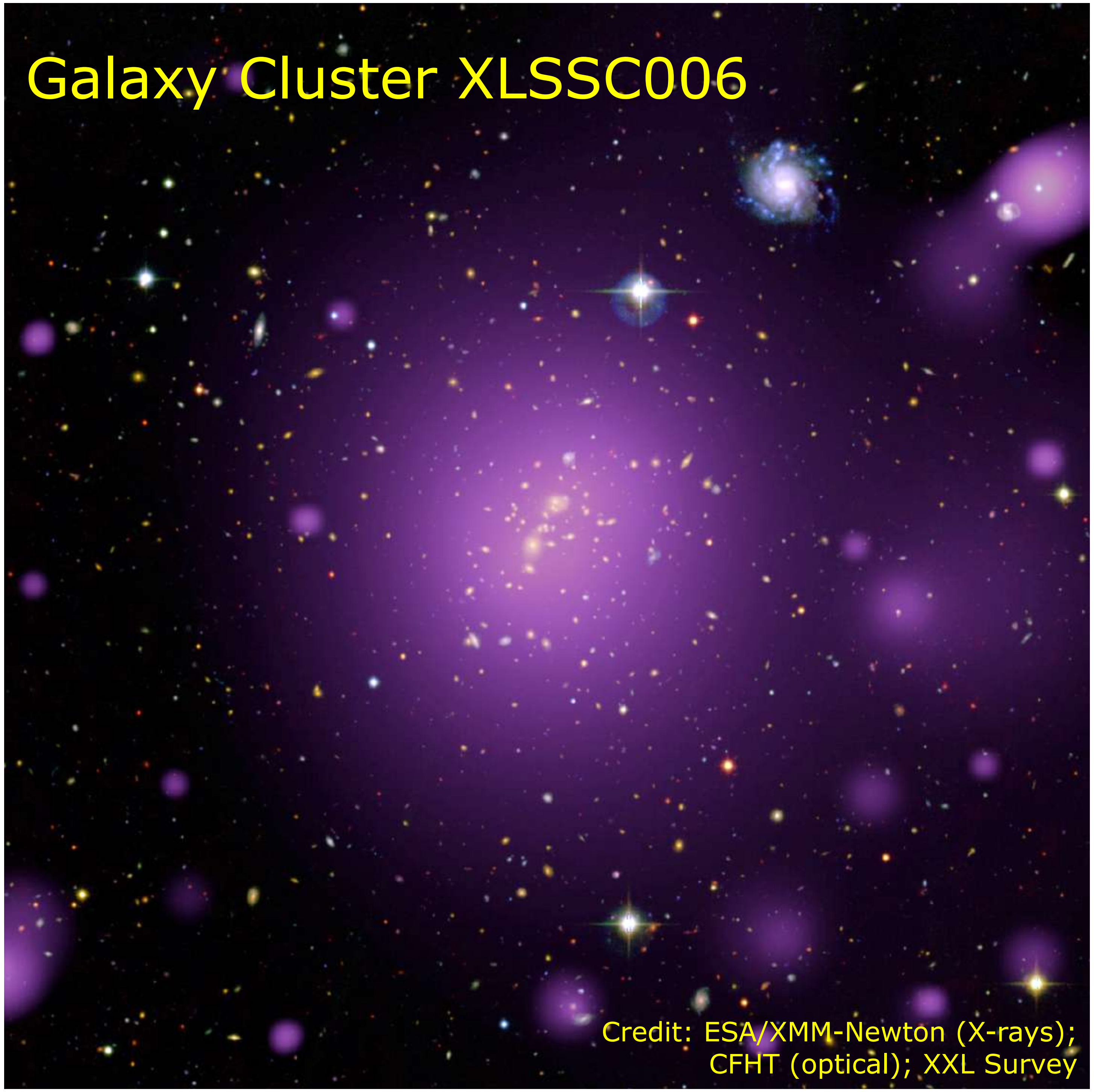
Fiore et al., 2017, A&A, 601, 143




[Shown here: the ratio of the average mass outflow ratio density versus the average star formation density]

- AGN outflows are on average powerful enough to clean galaxies in massive galaxies at z<2
- <u>Tentative conclusion, though</u>: "At higher redshift, uncertainties in both wind mass outflow […] and SRFD are today too big."

# Galaxy clusters




- The largest gravitationally-bound structures in the Universe
- 100-1000s galaxies in a volume comparable to that between the Milky Way and Andromeda
- Formed at the nodes of the cosmic web at z~2-3
- Optical (white/yellow): galaxies
- X-rays (purple glow): $T \geq 10^6$ K plasma
- Invisible: dark matter (85% of the total mass in the cluster)

# Gas cooling time

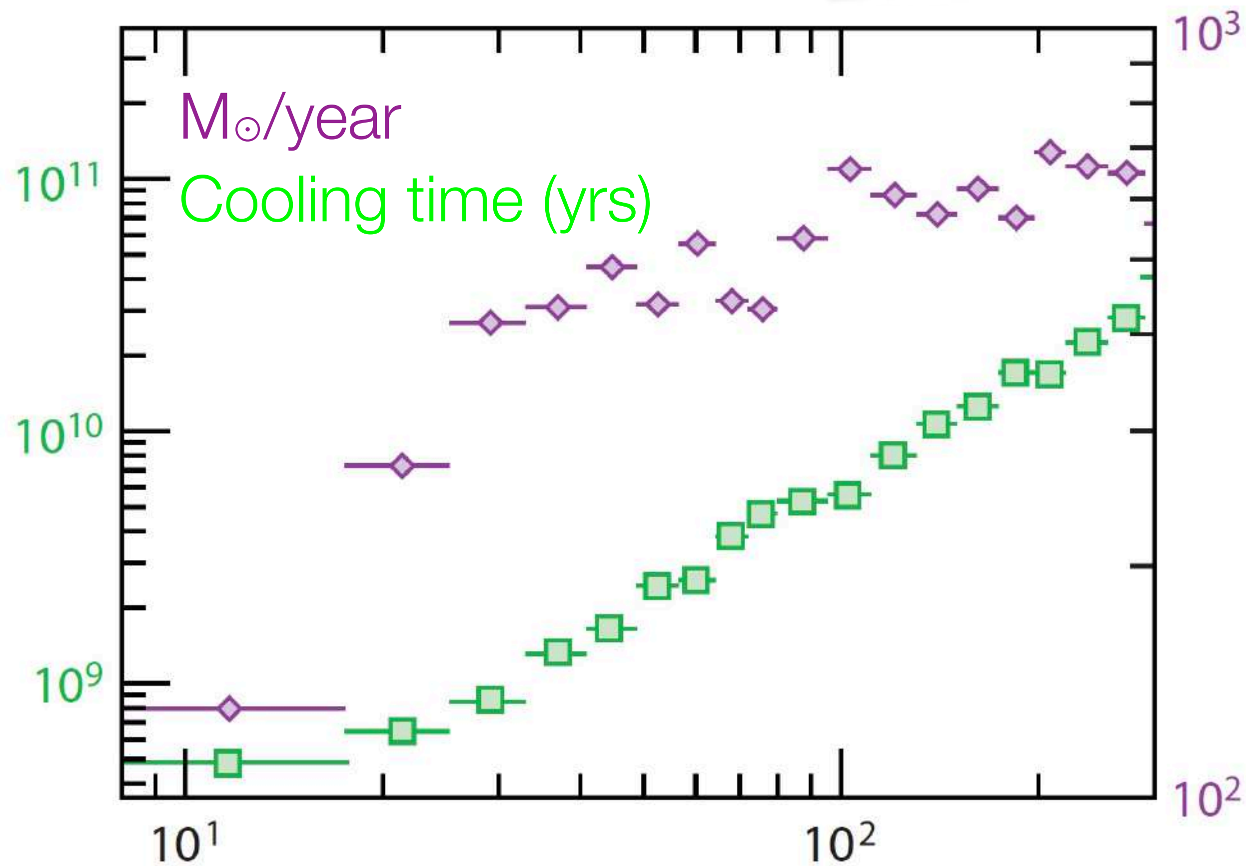
Fabian, 2012, ARA&A, 50, 455

Mittal et al., 2010, A&A, 501, 835

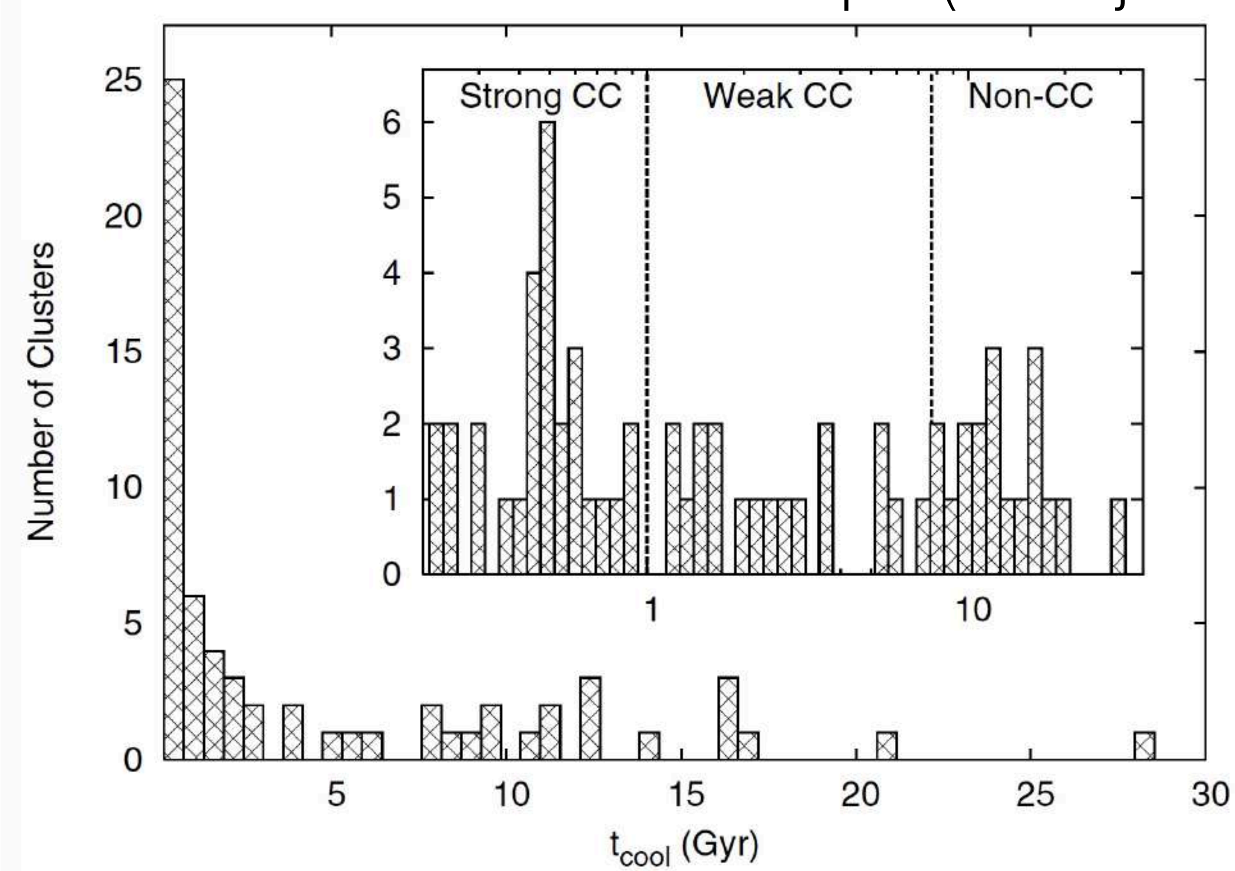
The X-ray emitting gas implies short cooling times, and very high levels of star formation ($10^{2-3}$ $M_\odot$/year)— not seen!

$$\dot{M} = \frac{2}{5}\frac{L\mu m}{kT}$$

Abell 1835



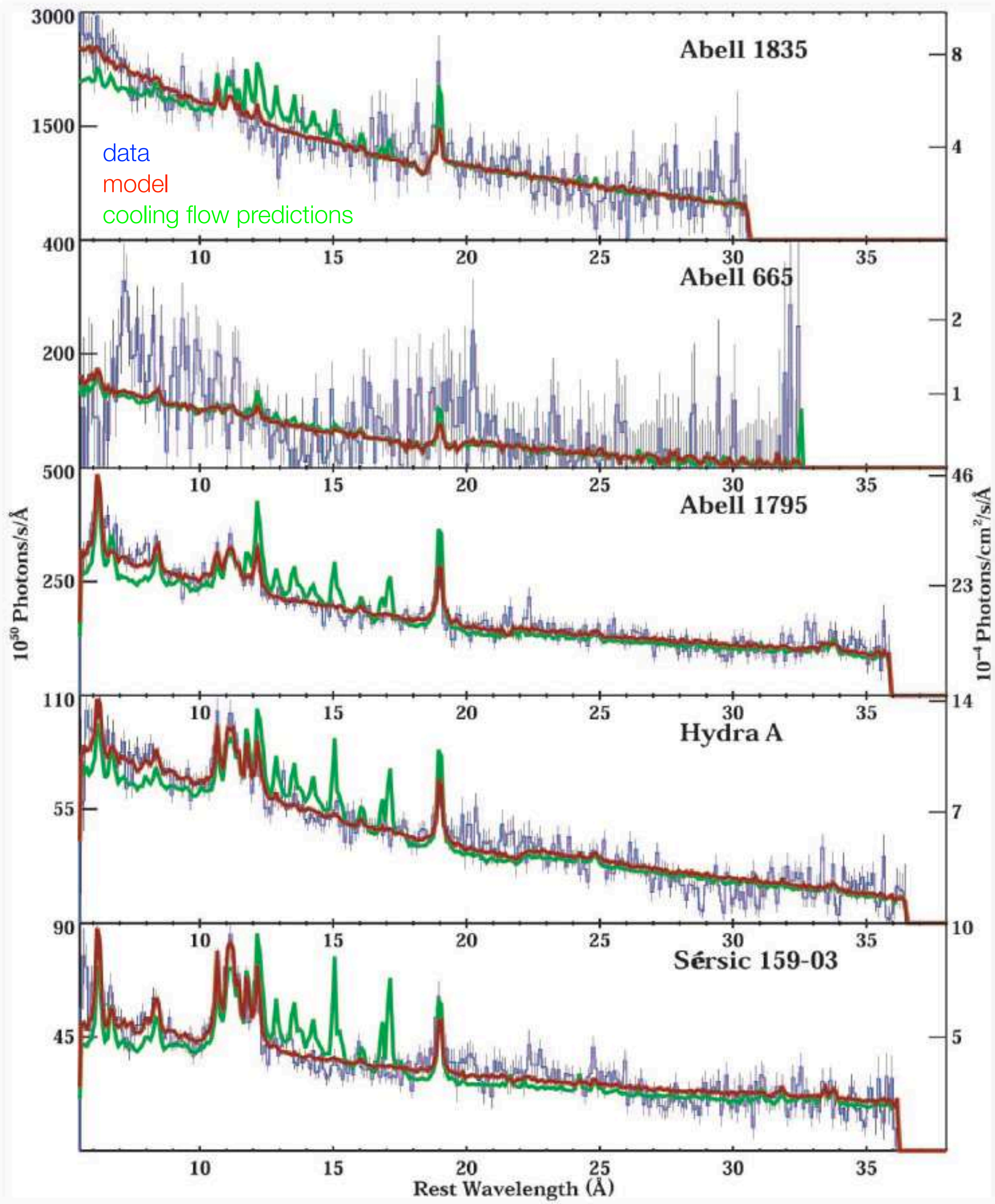

HIFLUGCS sample (64 objects)



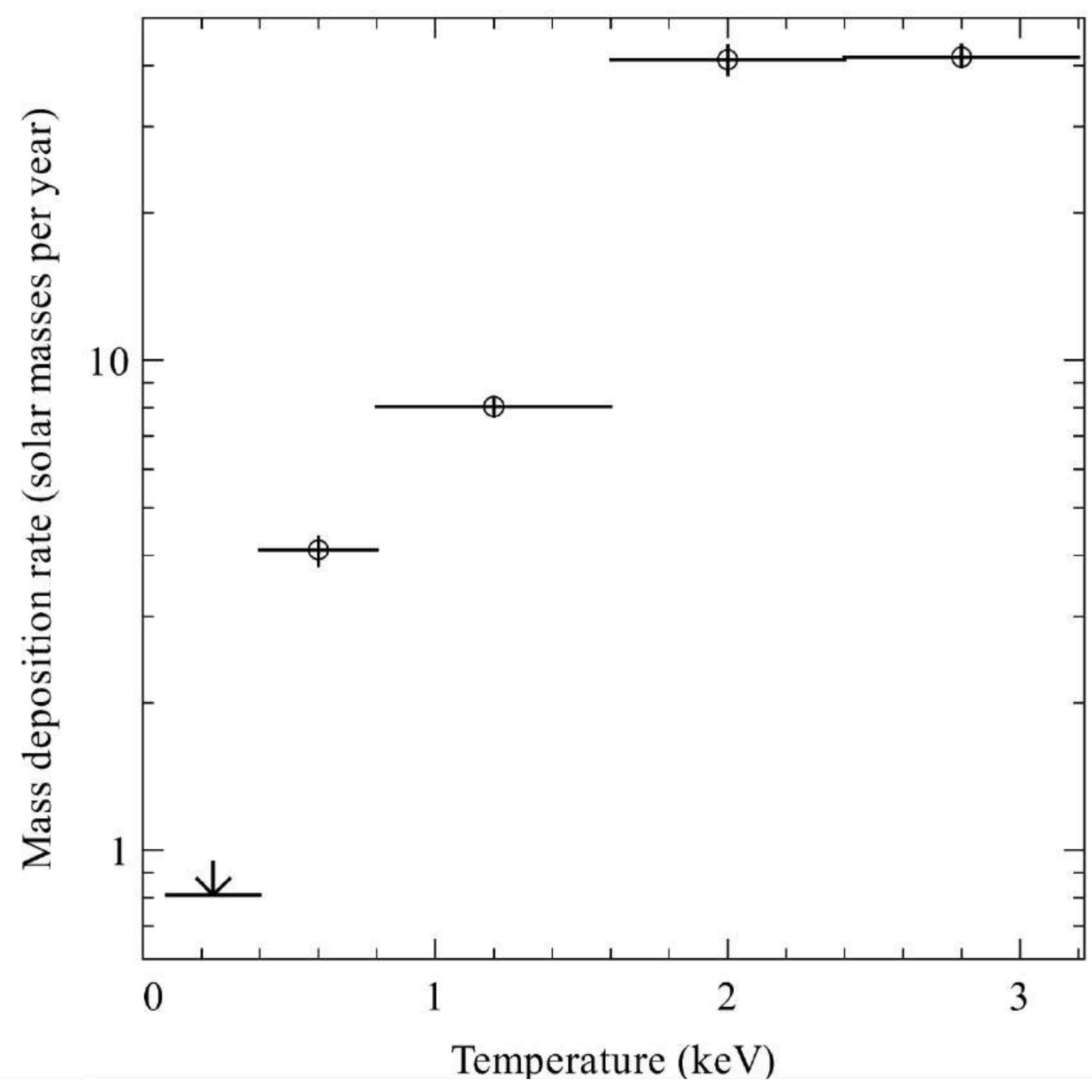
# Lack of cool gas from X-ray spectroscopy

Peterson et al., 2003, ApJ, 590, 207

Sanders et al., 2008, MNRAS, 385, 1186




High-resolution RGS spectra unveiled missing cool gas

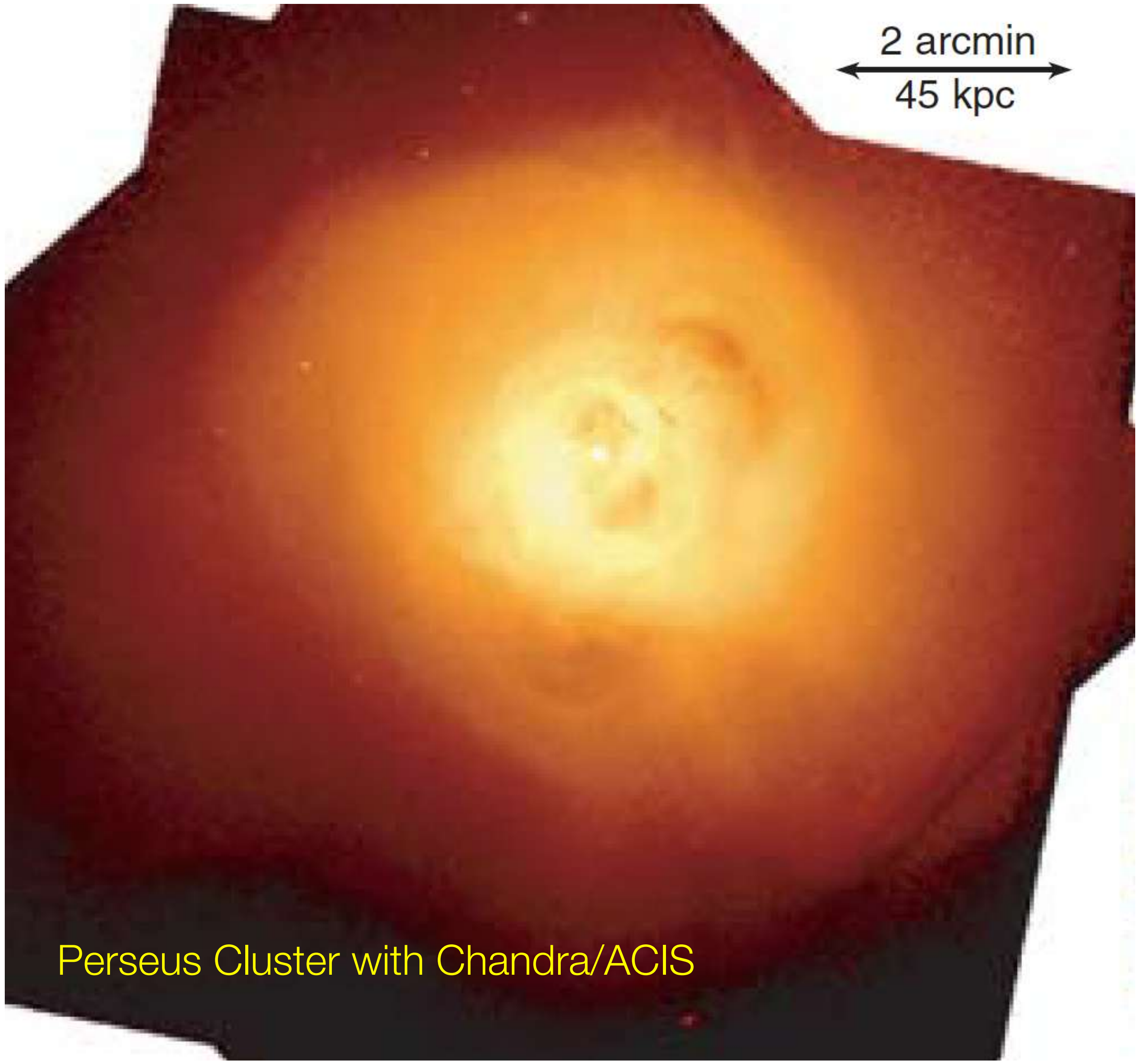


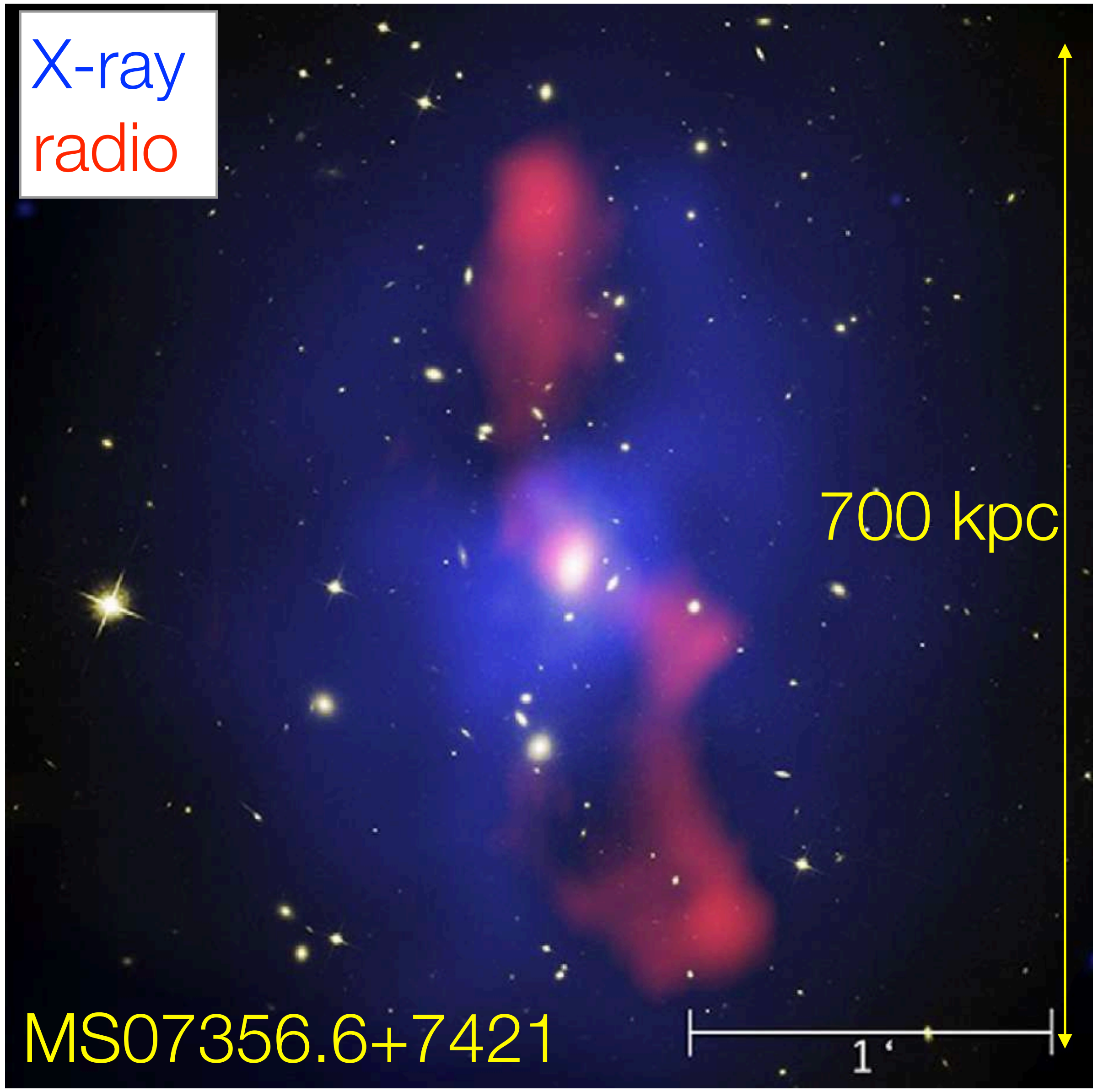
# "Radio mode" AGN feedback

Sanders & Fabian, 2007, MNRAS, 381, 1381

McNamara et al., 2009, ApJ, 698, 594

X-ray images of galaxy clusters show structures (putatively) due to the interaction between the AGN radio jet and the intra-cluster medium



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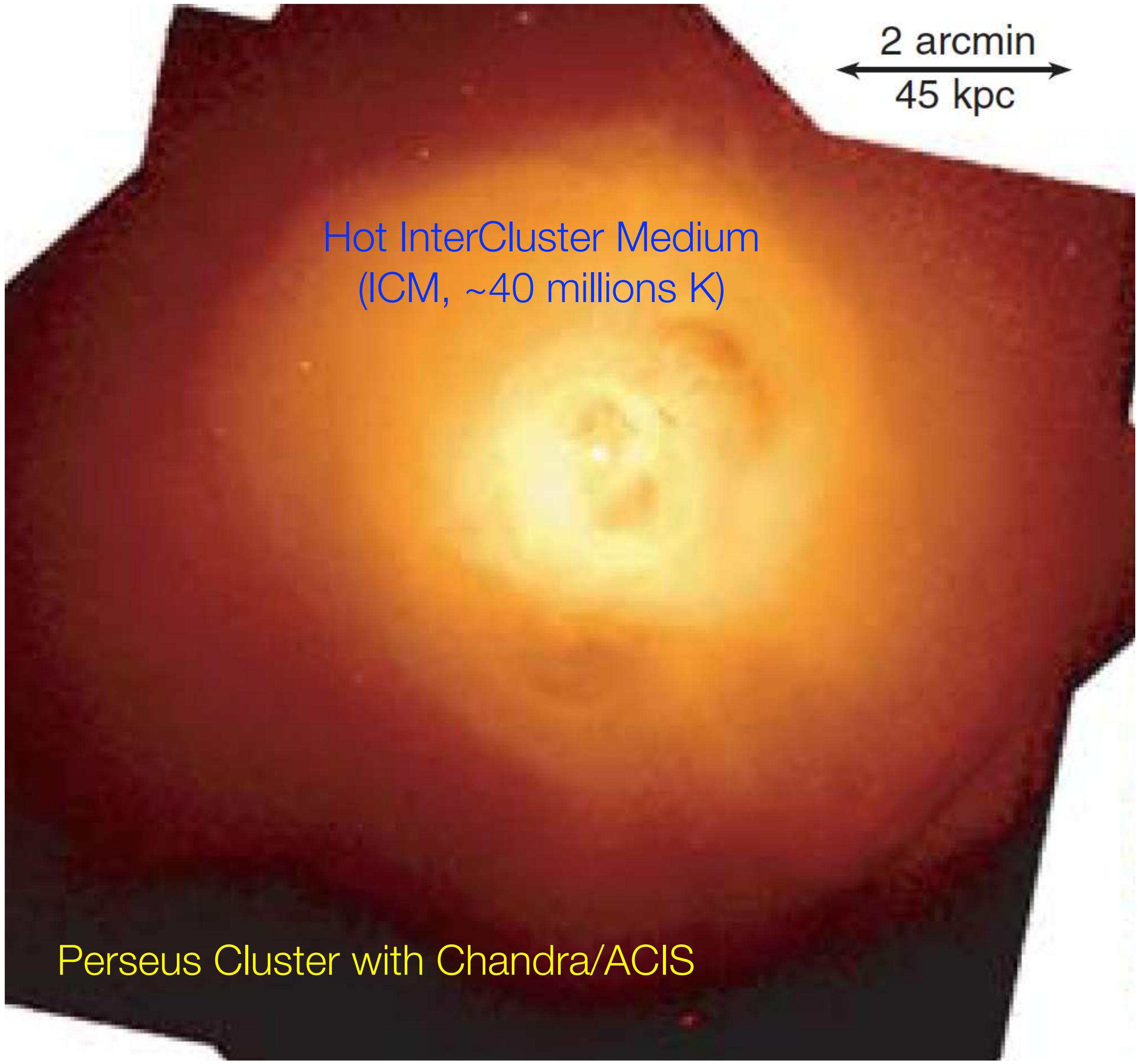


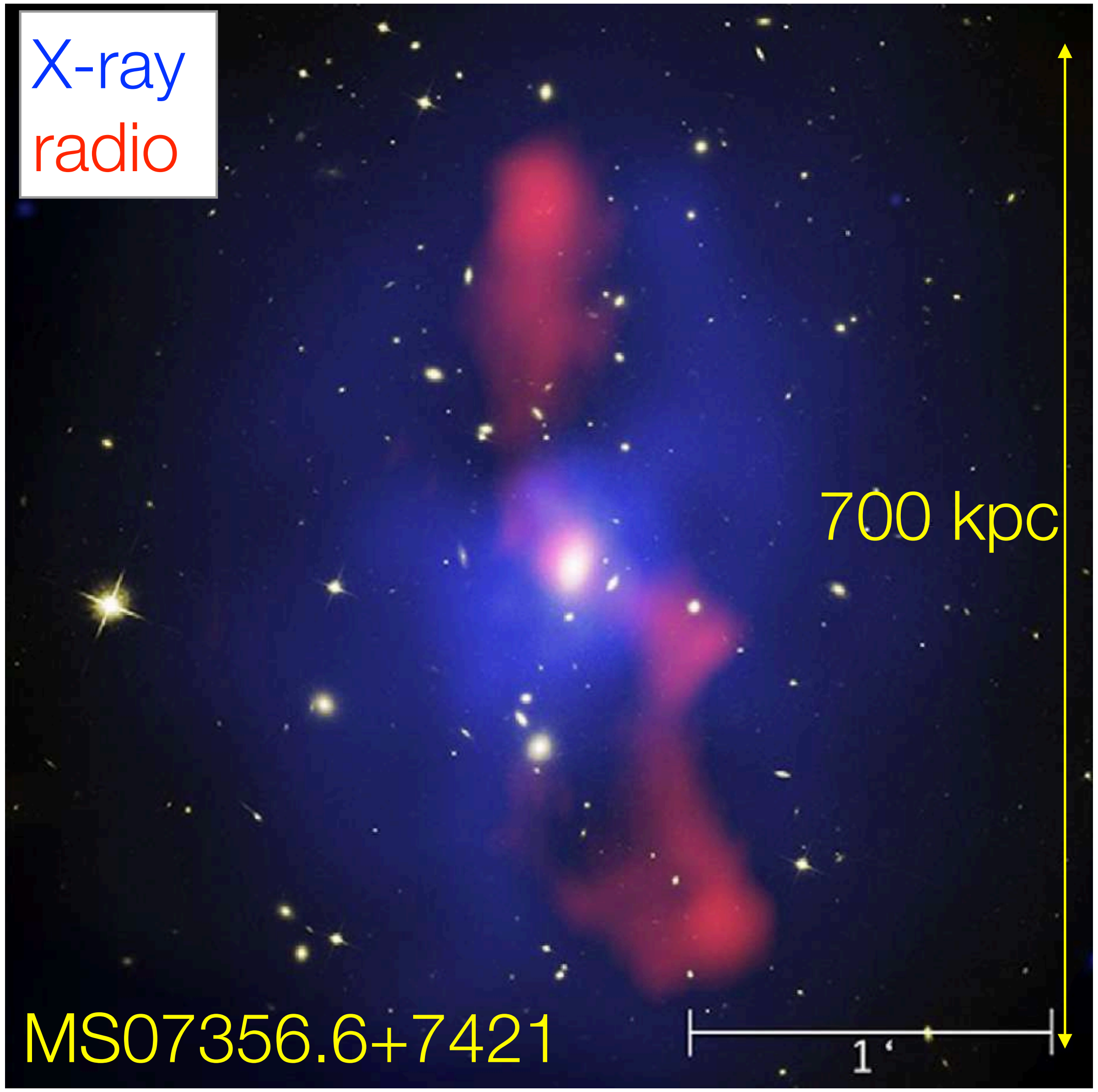

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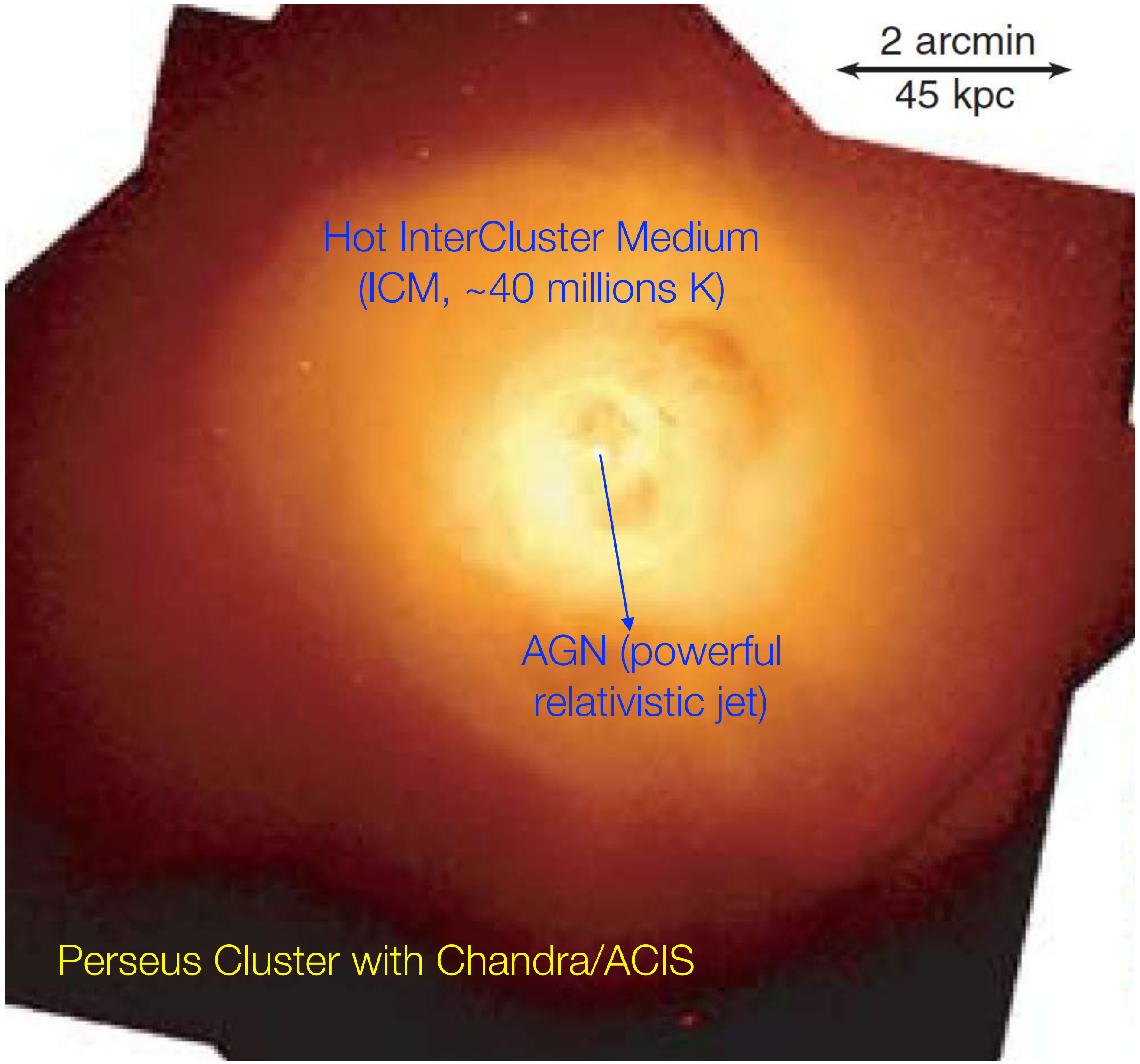


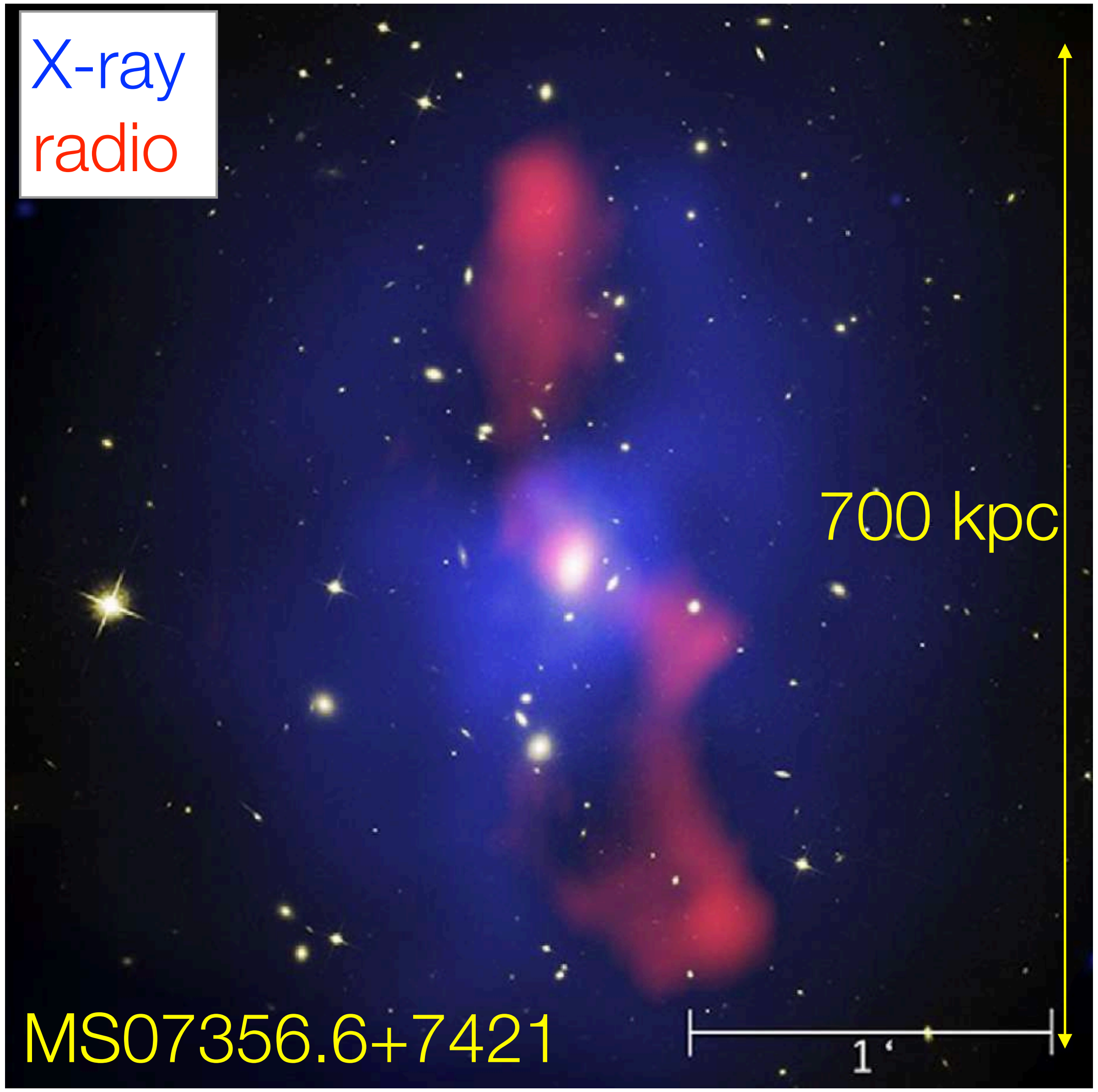

# "Radio mode" AGN feedback

Sanders & Fabian, 2007, MNRAS, 381, 1381

McNamara et al., 2009, ApJ, 698, 594

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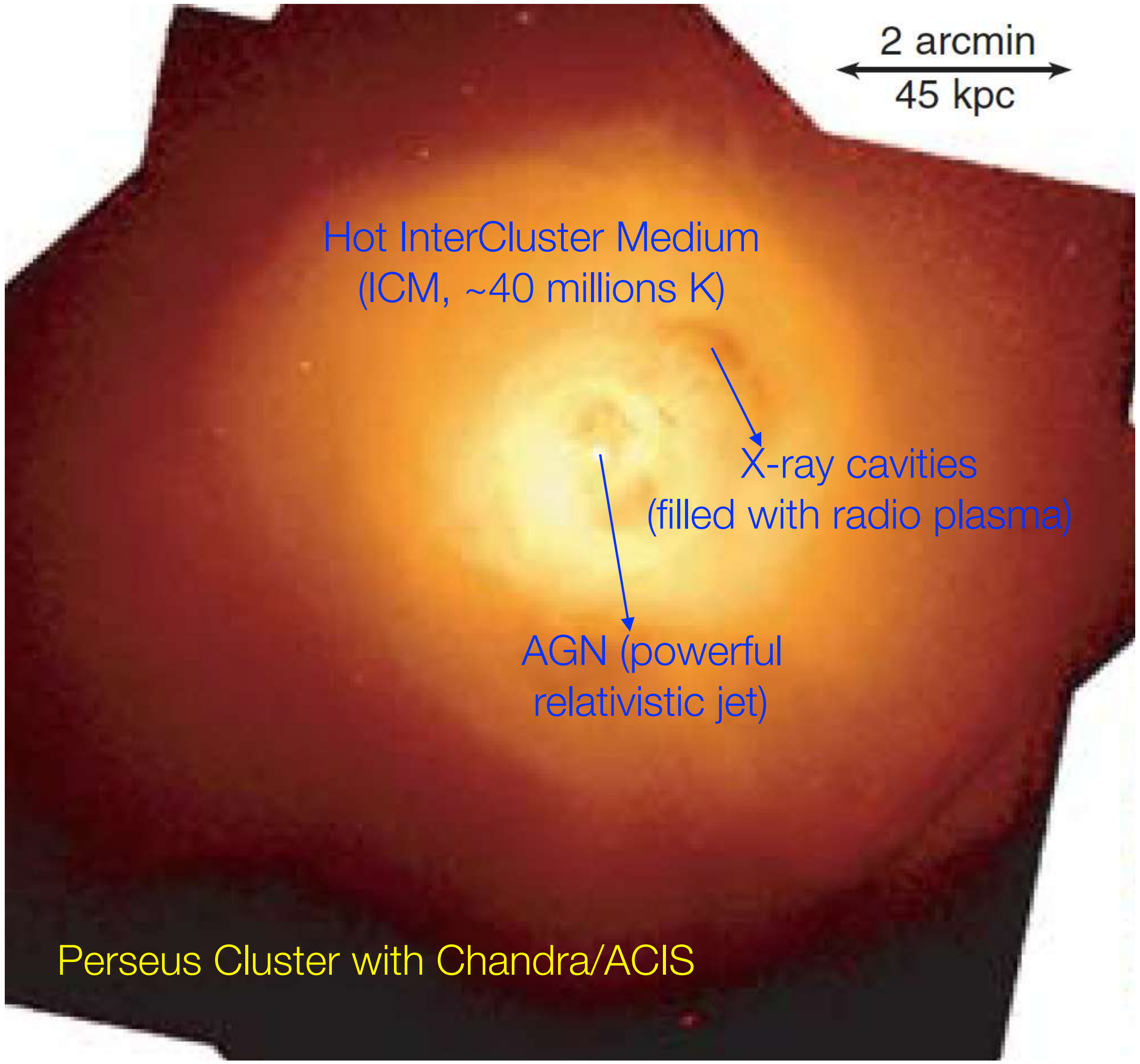


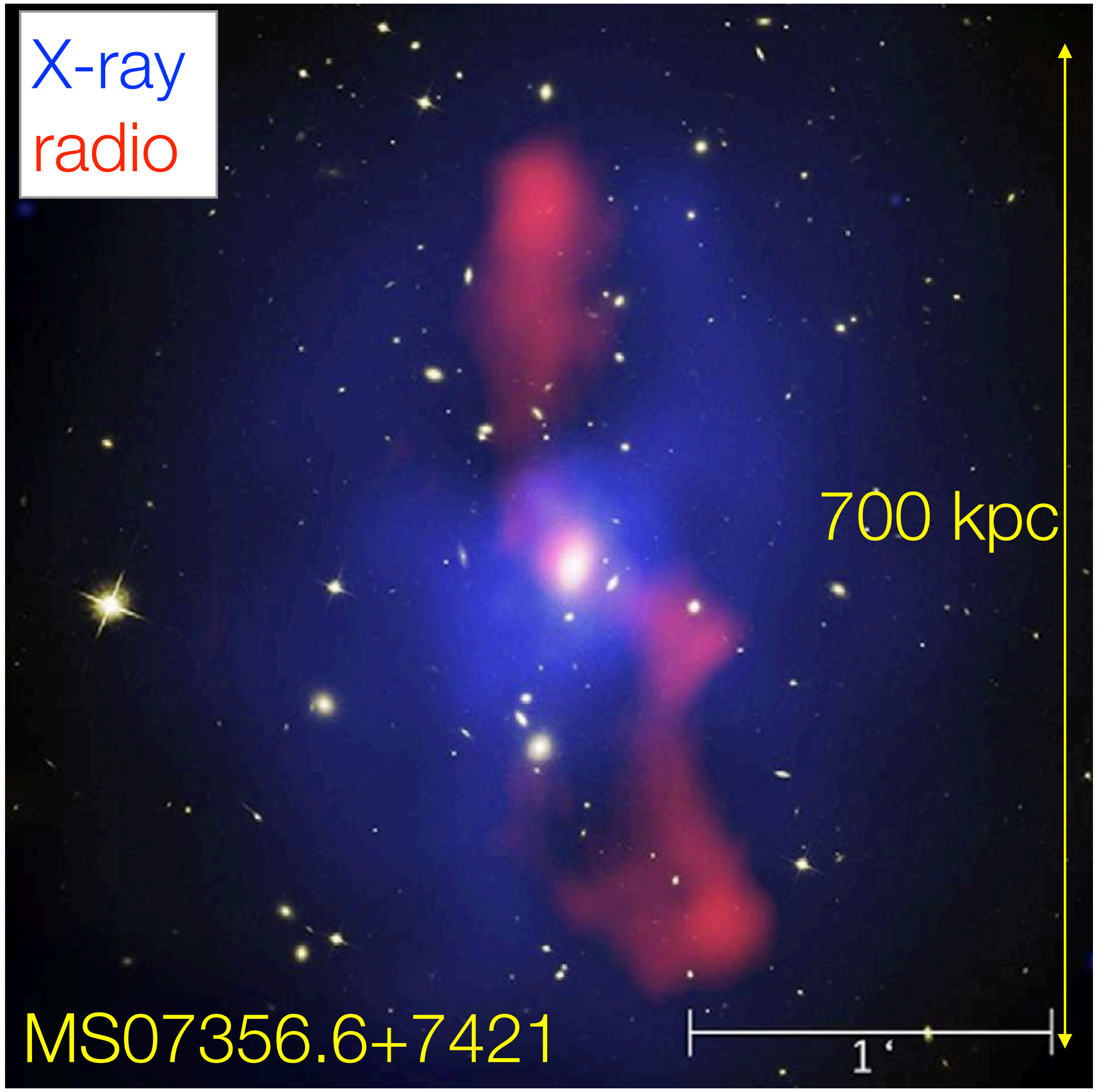

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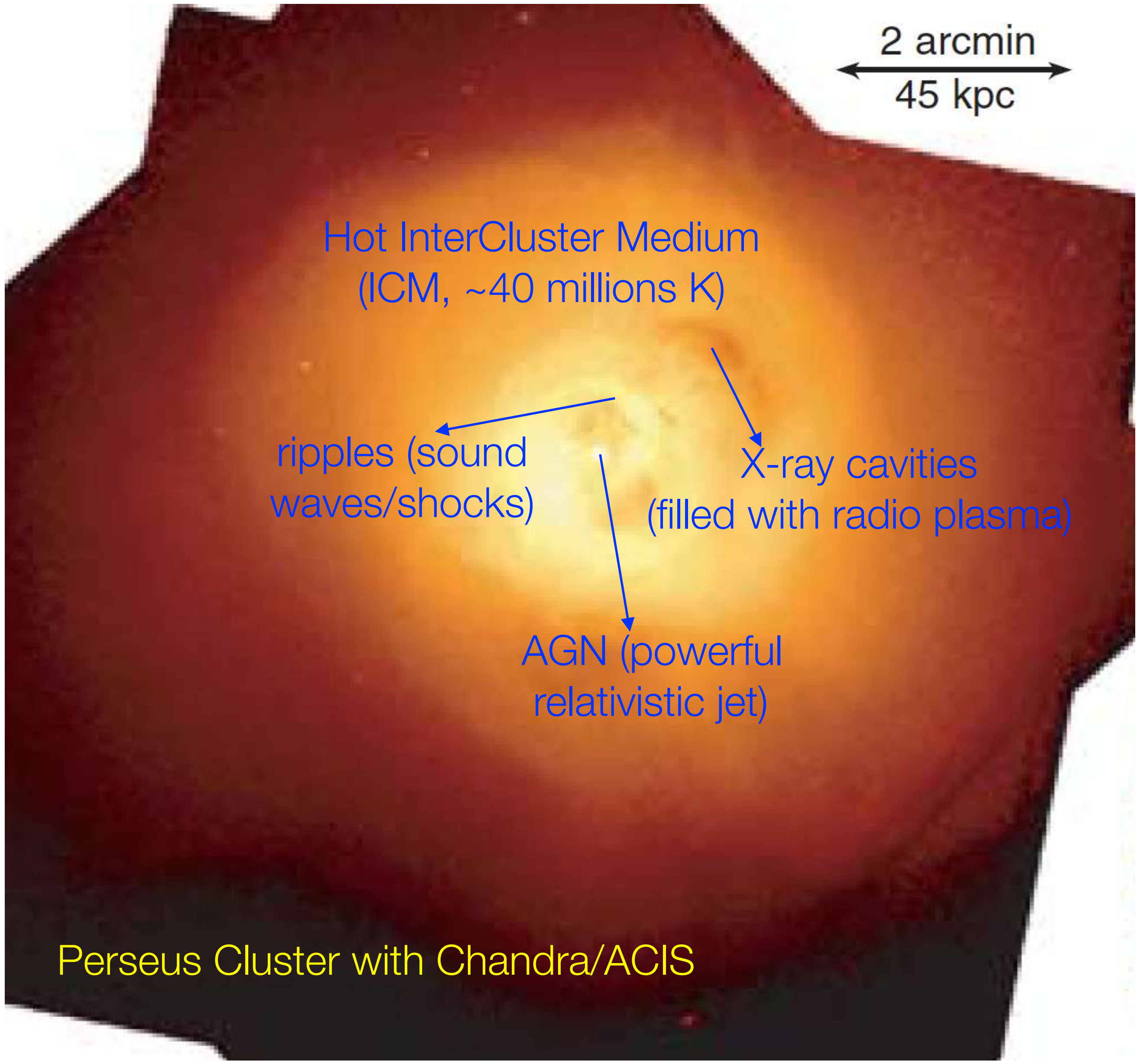
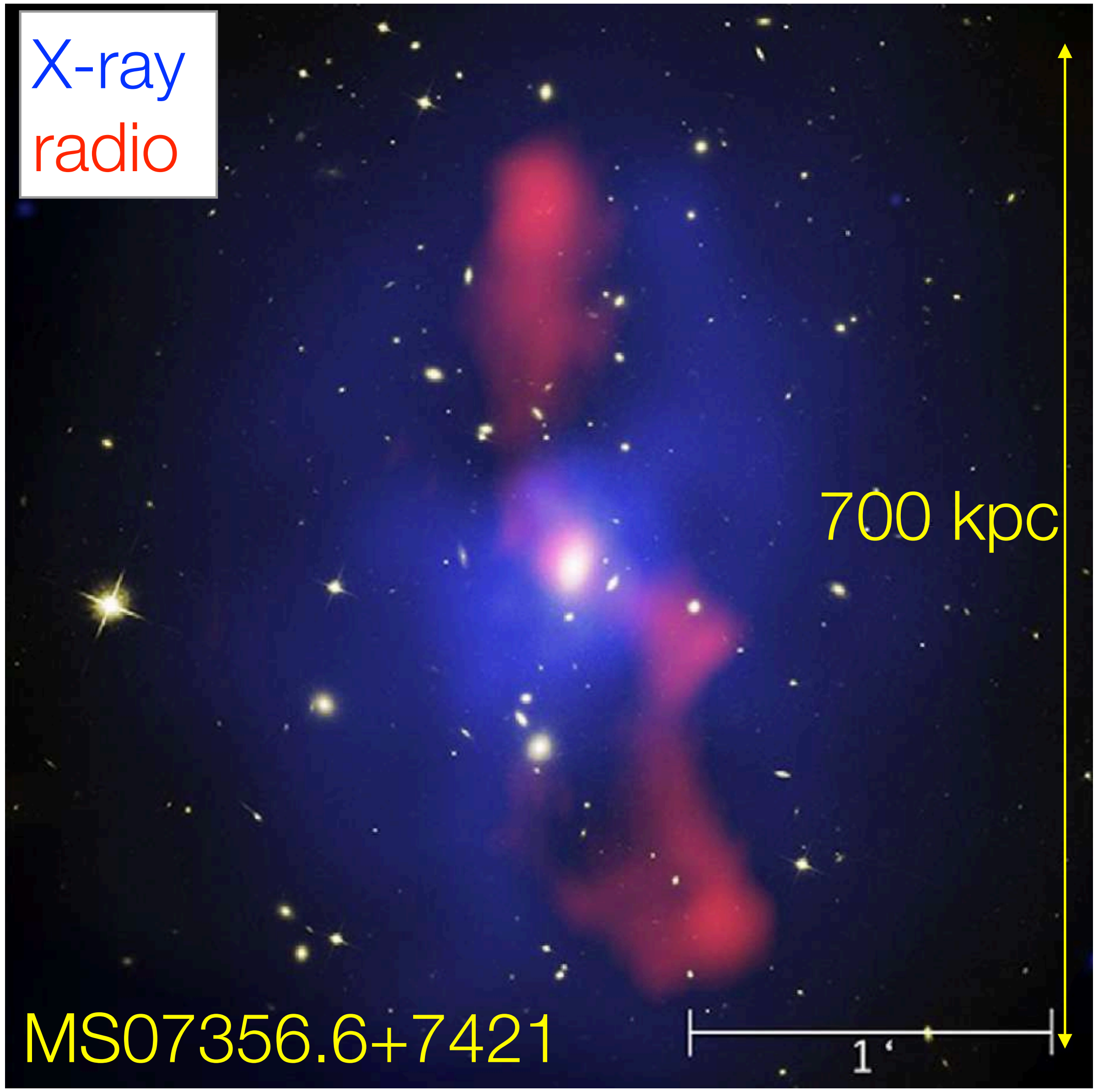
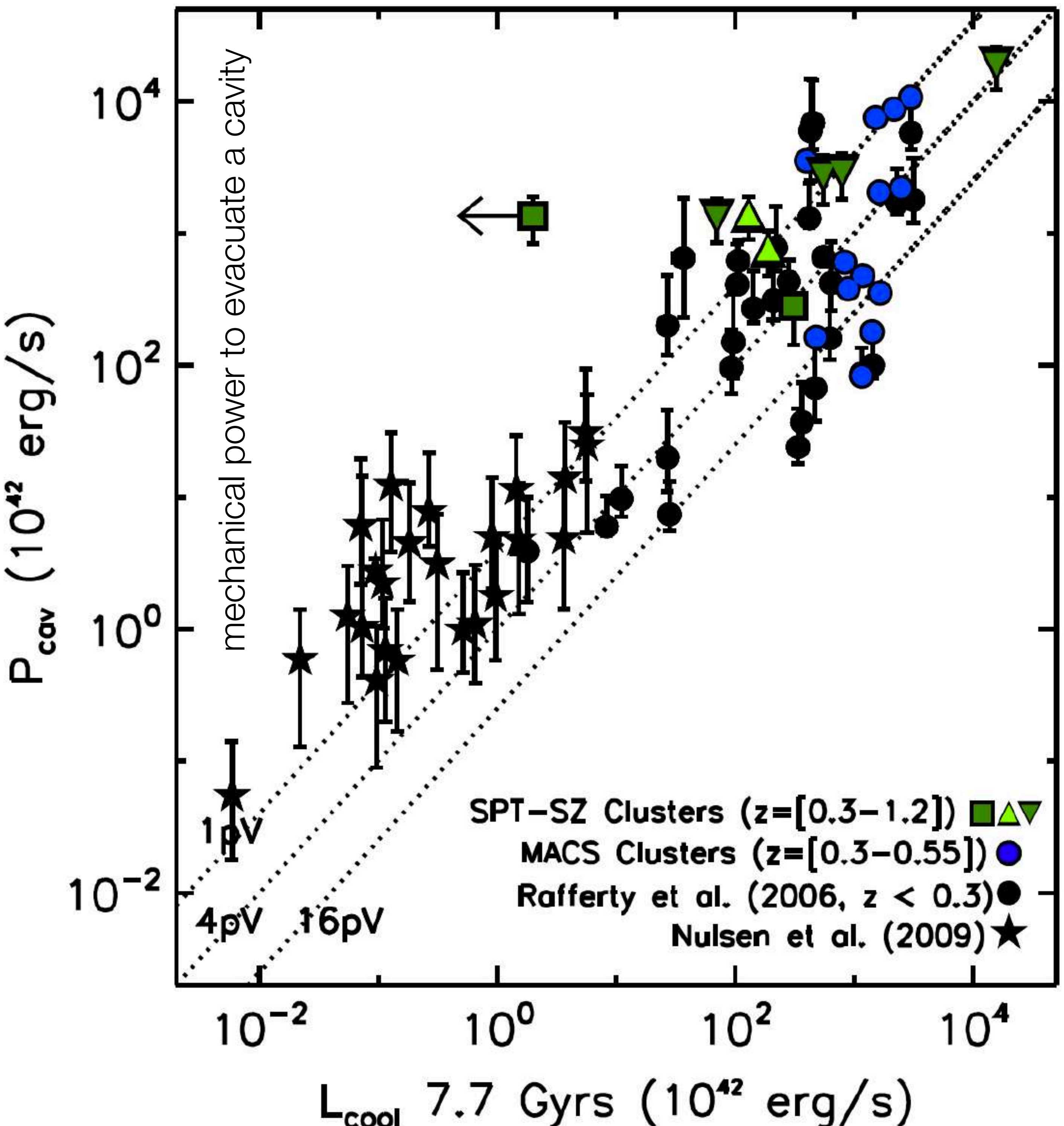


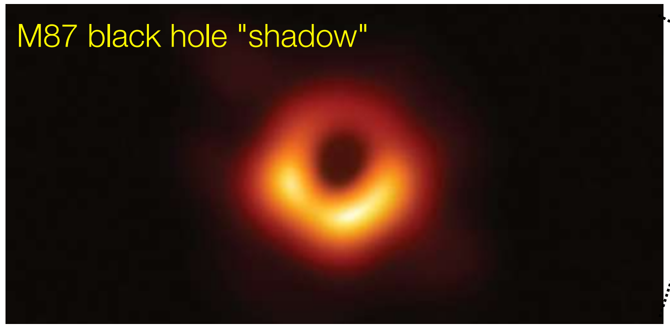



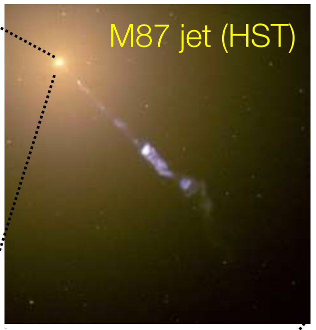
# Is this indeed feedback from the radio AGN?

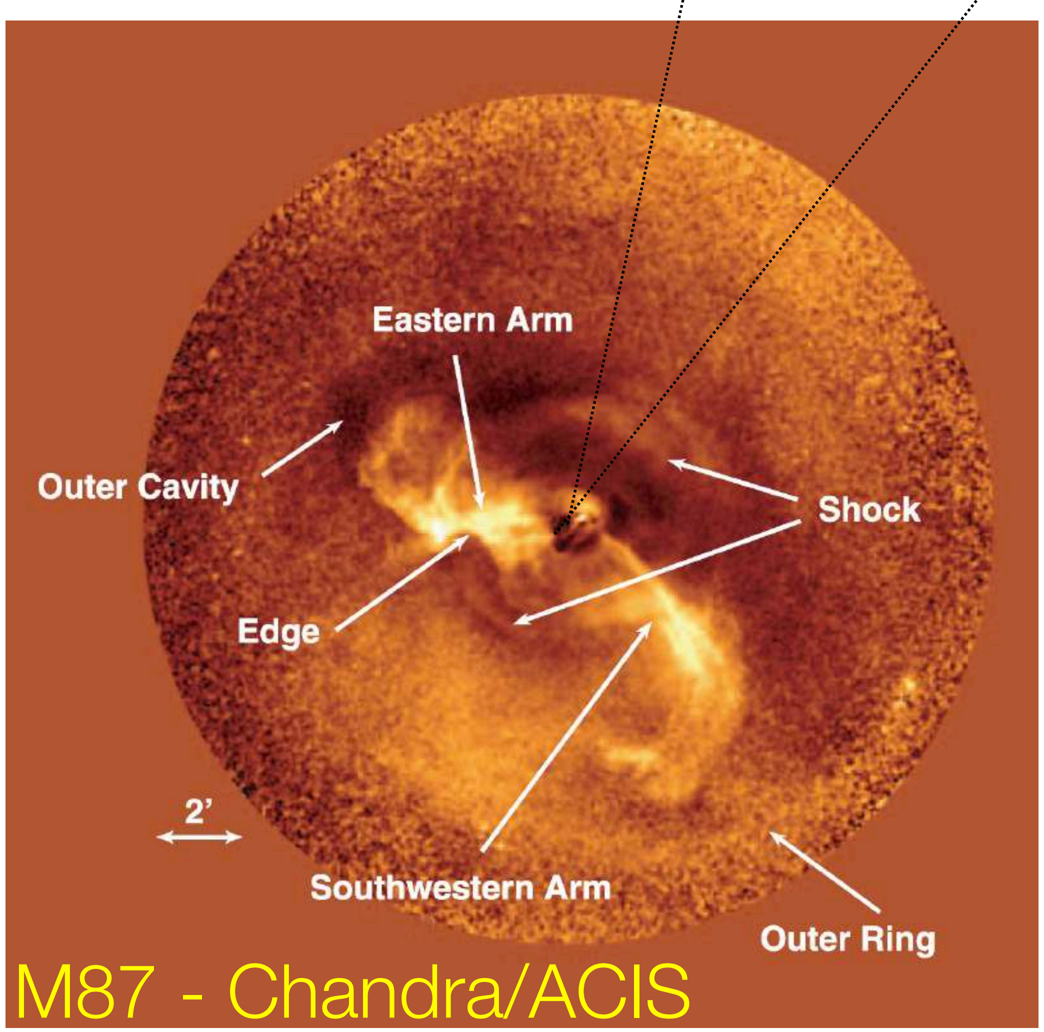
Hlaveck-Llarrondo et al., 2015

Forman et al. 2007, ApJ, 665, 1057



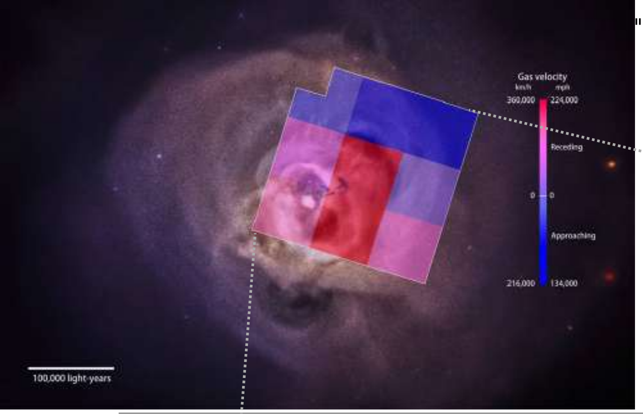




luminosity in the cooling region

", OAB, 18 February 2020

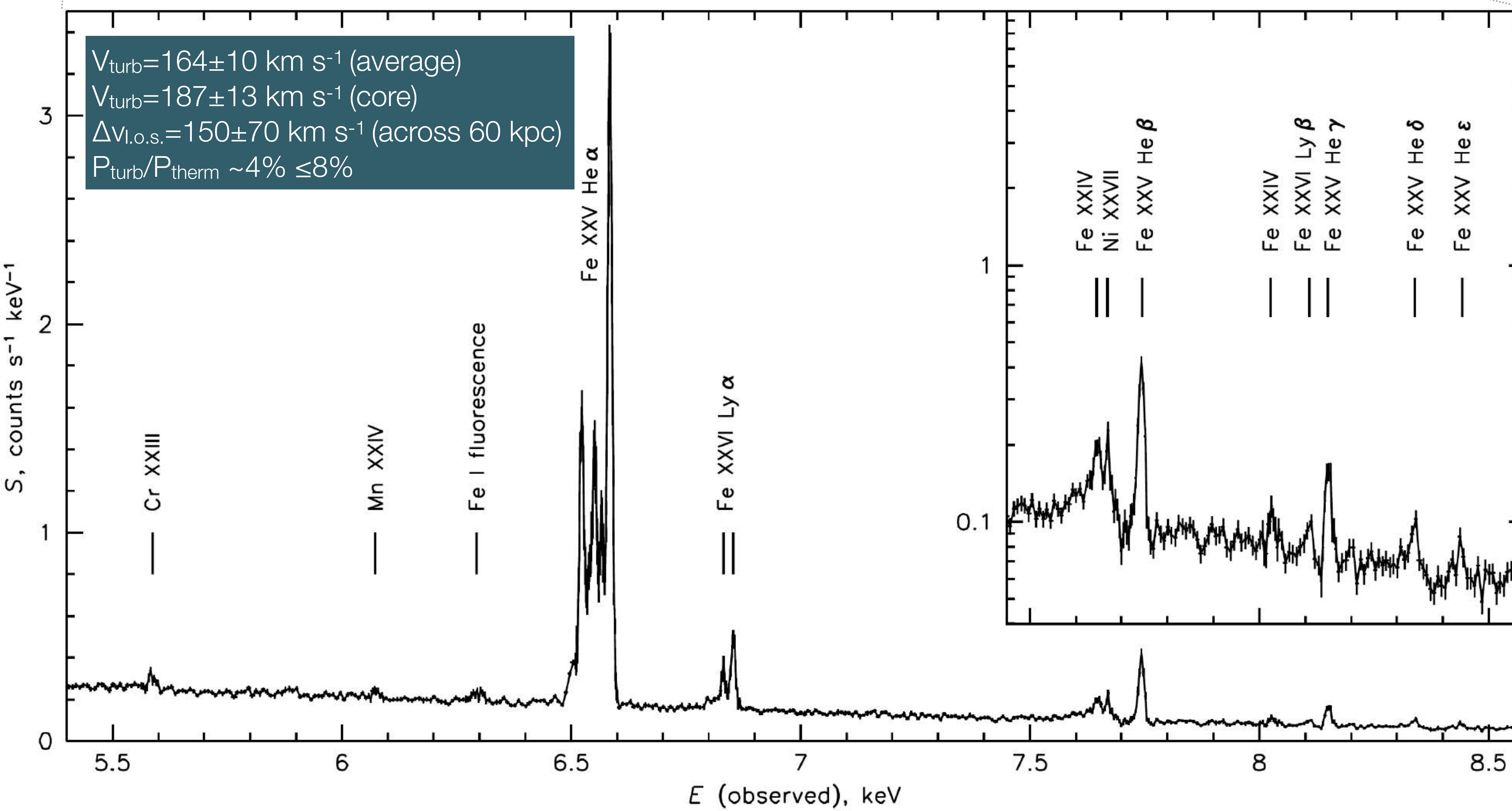



LETTER
doi:10.1038/nature18627

The quiescent intracluster medium in the core of the Perseus cluster

The Hitomi collaboration*

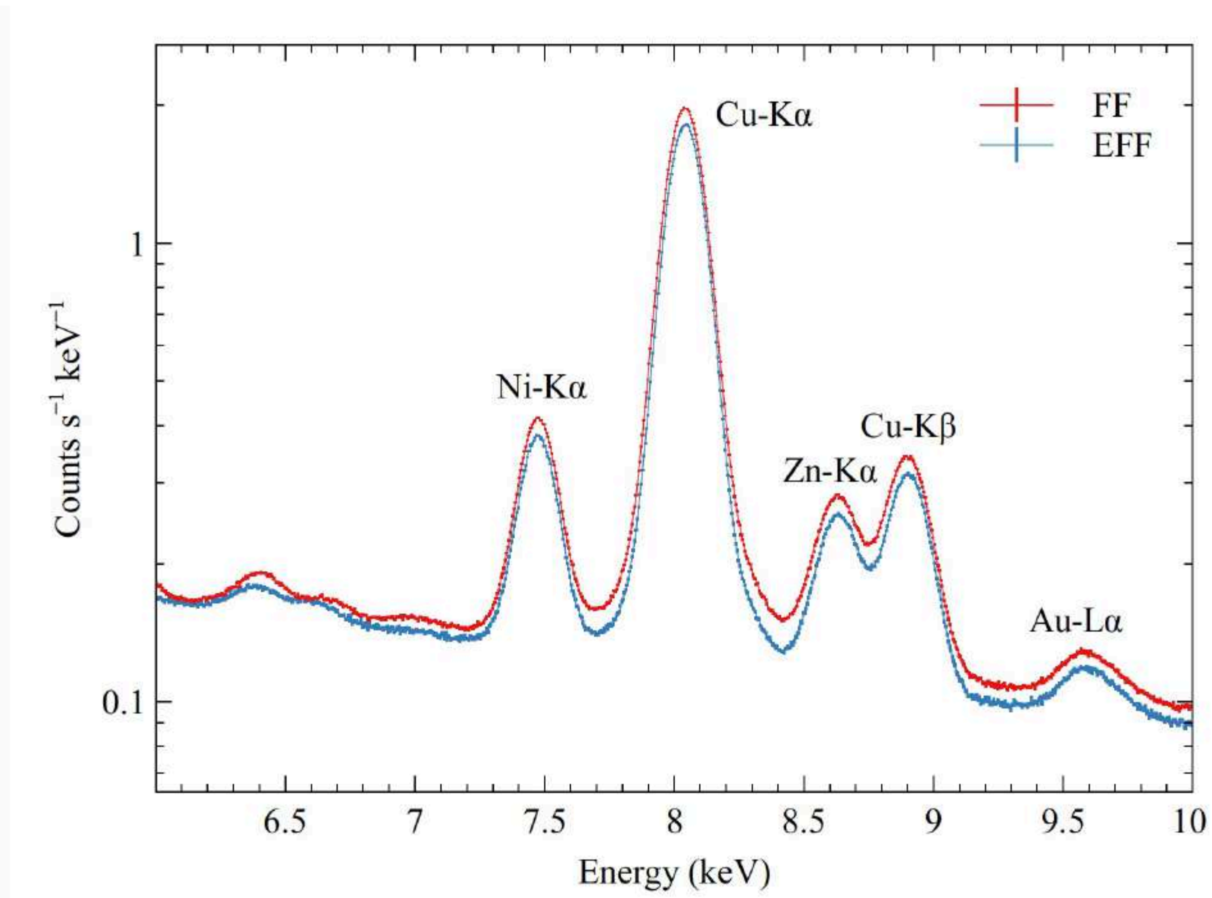
**Hitomi/SXS** spectrum in the innermost ~60 kpc of the Perseus Cluster

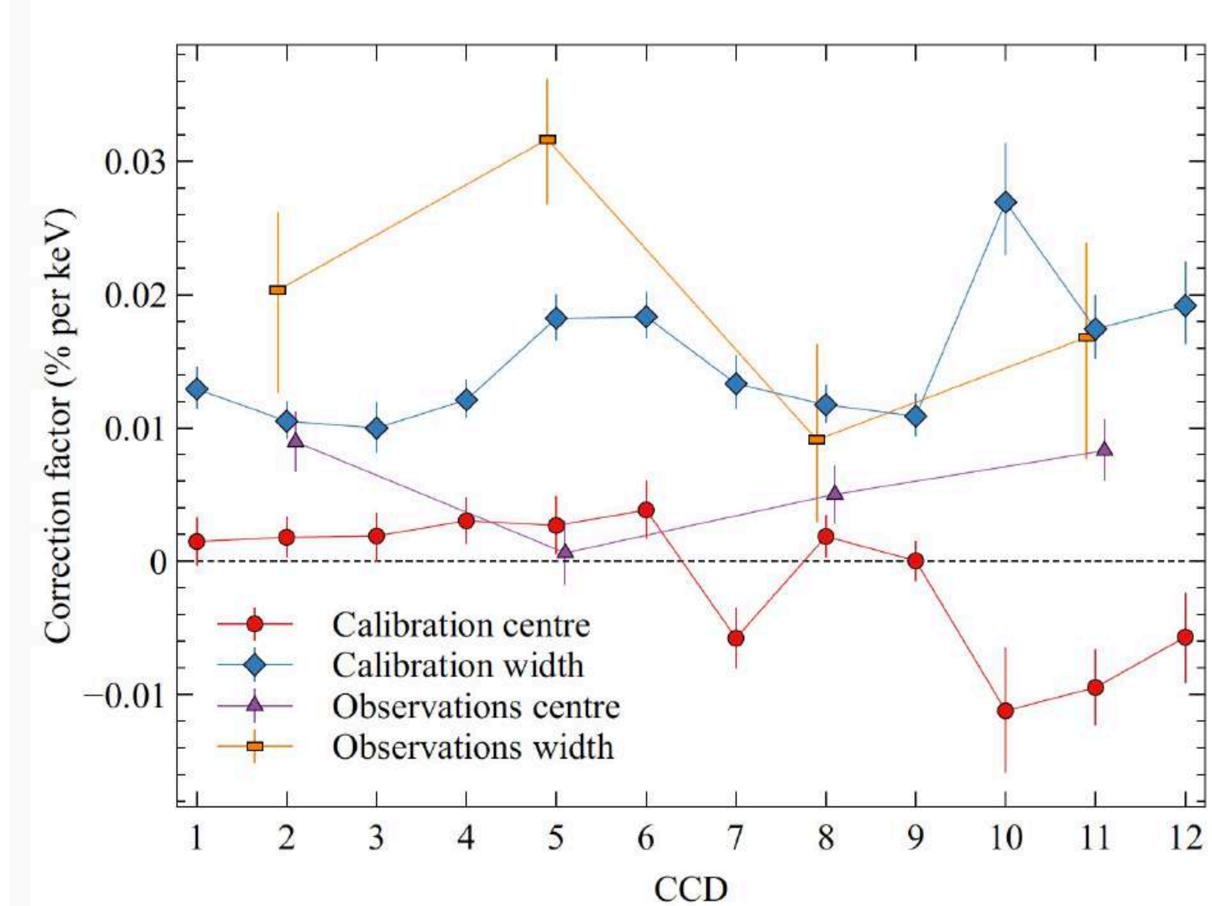


# Systematics effects kill CCD measurements

Sanders et al. 2020, A&A, 633, 42

32.6 Ms of Full Frame and 19.7 Ms of Extended FF calibration data in EPIC-pn (CCD) yields a systematic accuracy of ~150 km s$^{-1}$

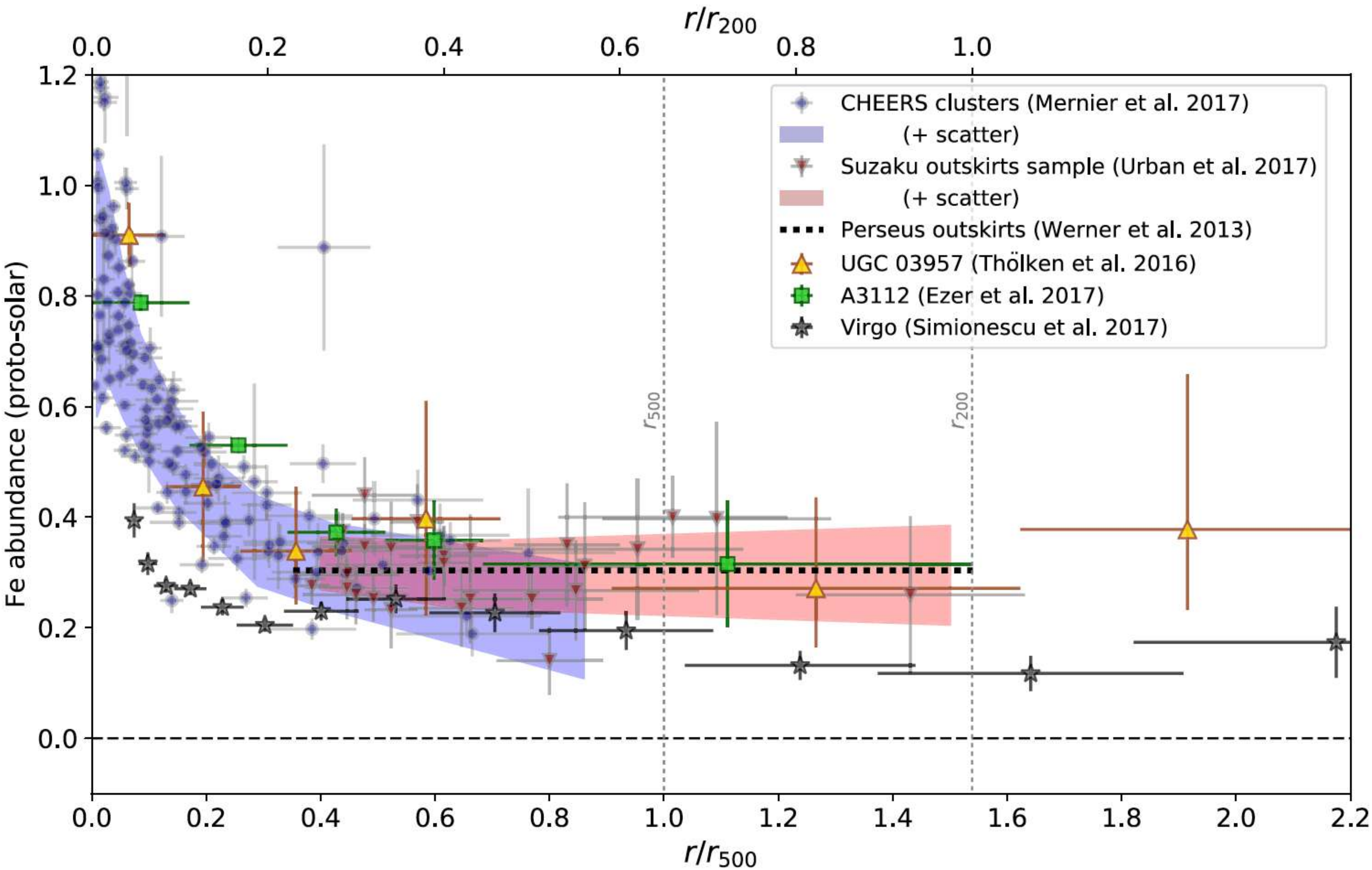



~200 ks of self-calibrated *Hitomi*/SXS data yield x10 better accuracy

# Moderate metal mixing from core to outskirts

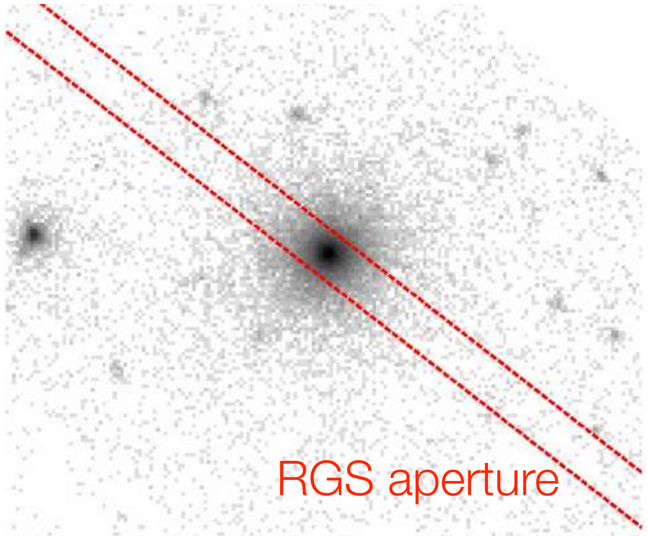
Merrier et al., 2018, SSRv, 214, 129

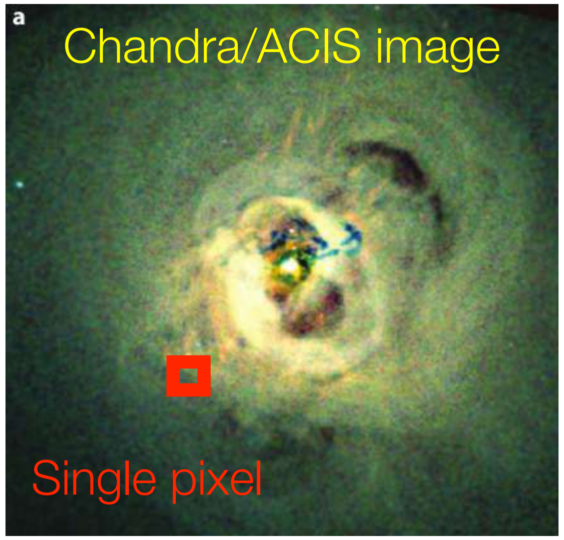


# X-ray spectroscopy, today

Pinto et al., 2018, MNRAS, 480, 4113

Guainazzi et al., 2015, JATIS, 1, 7001



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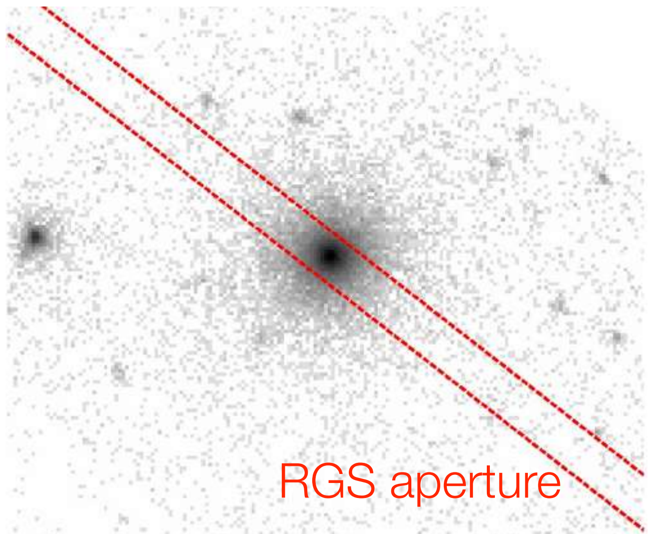


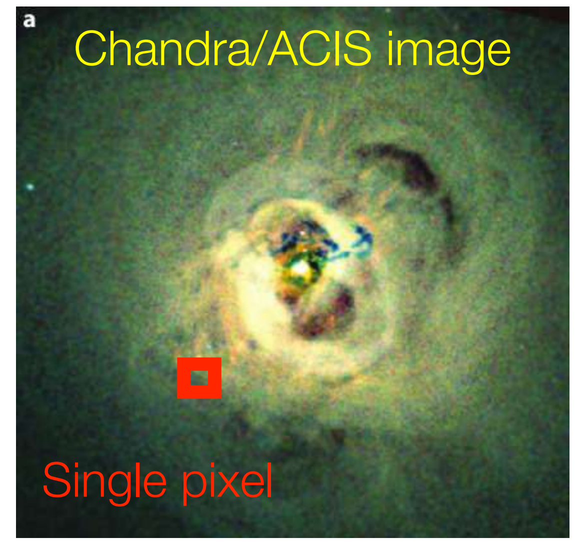


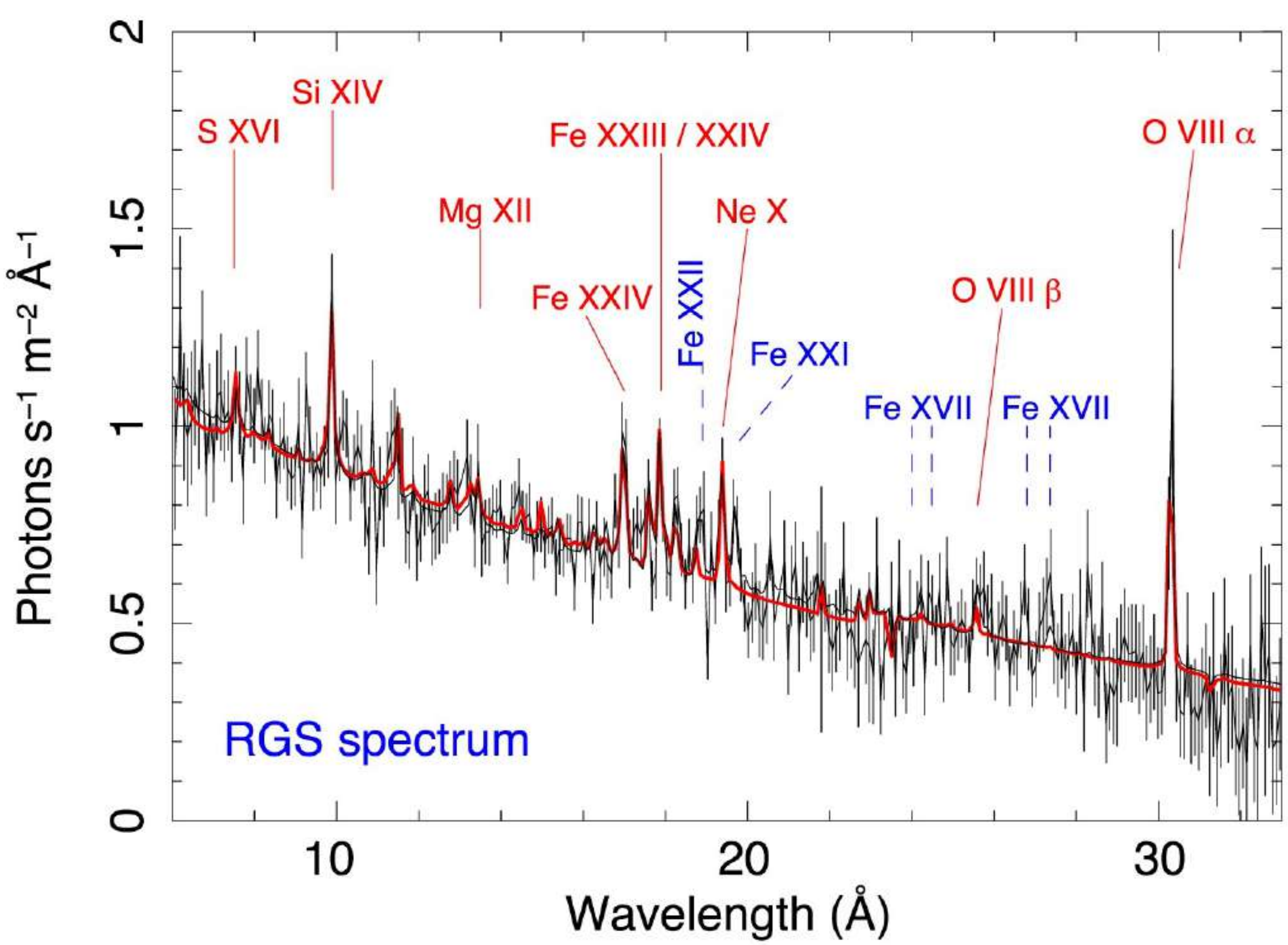

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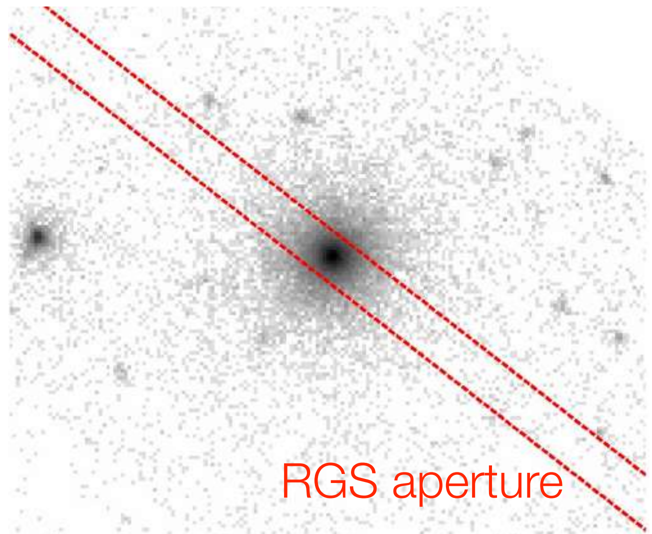
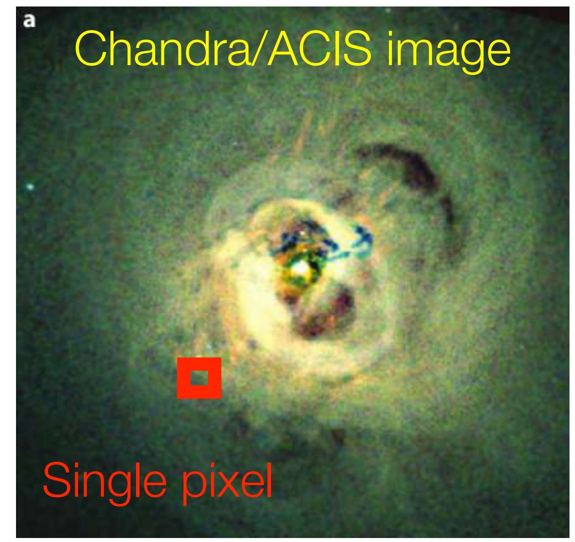
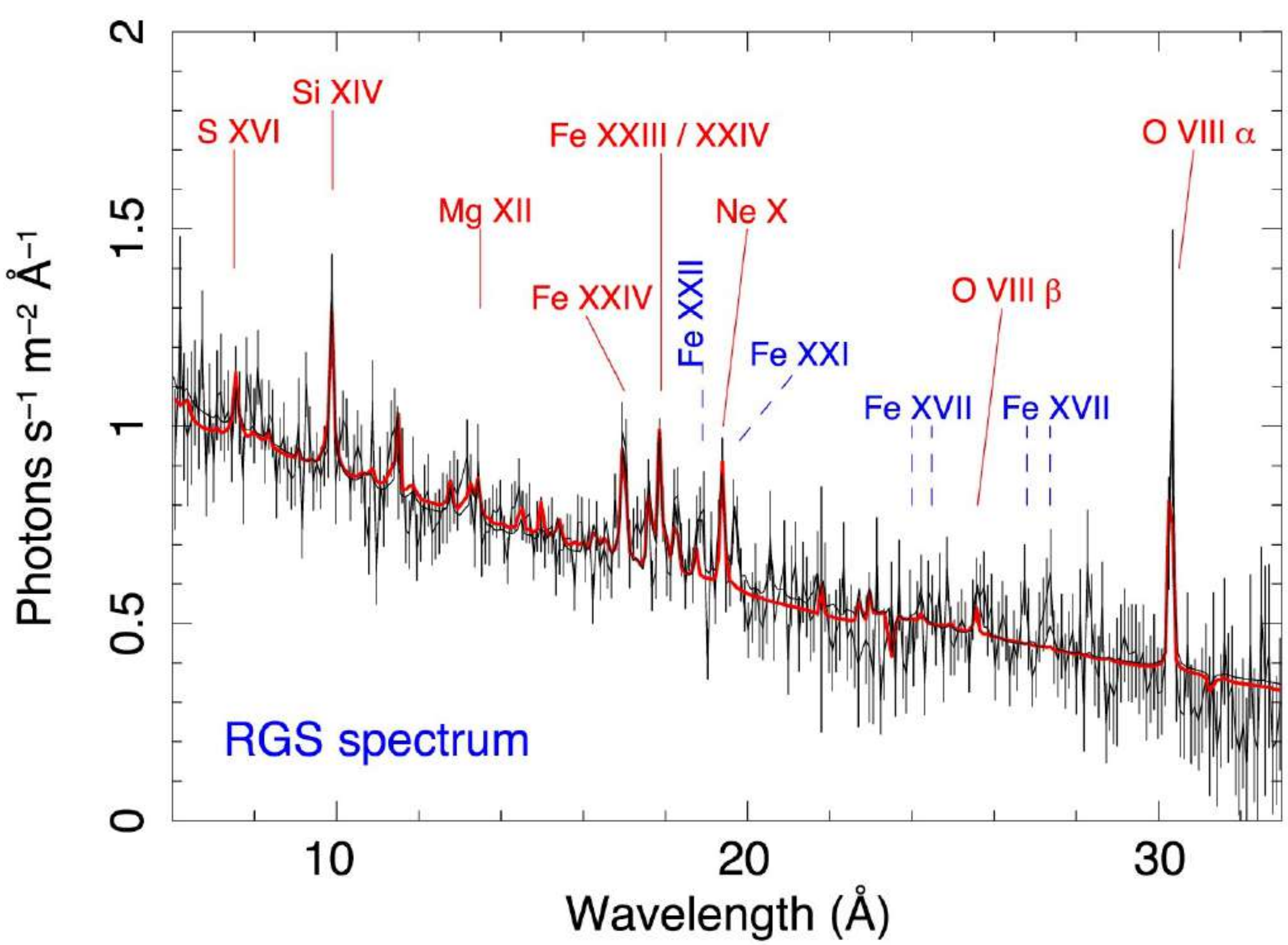
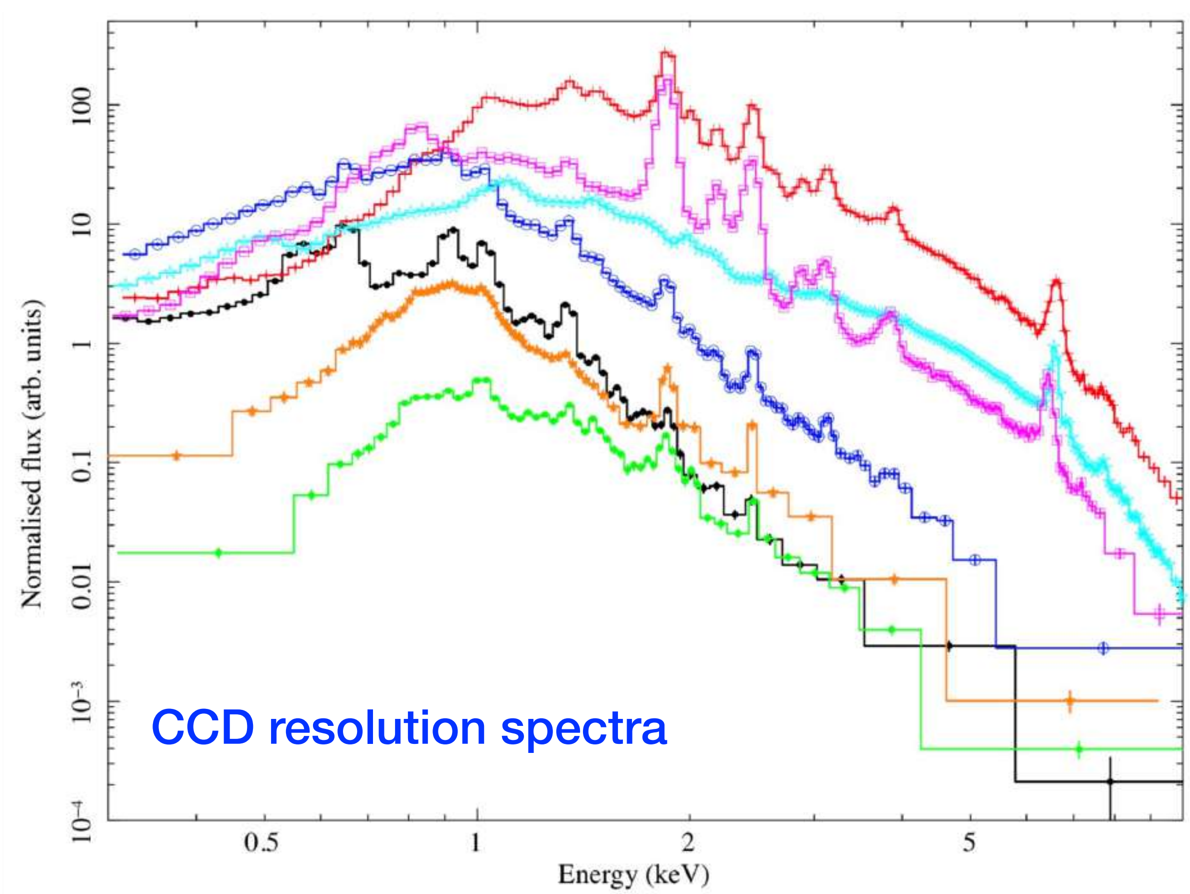


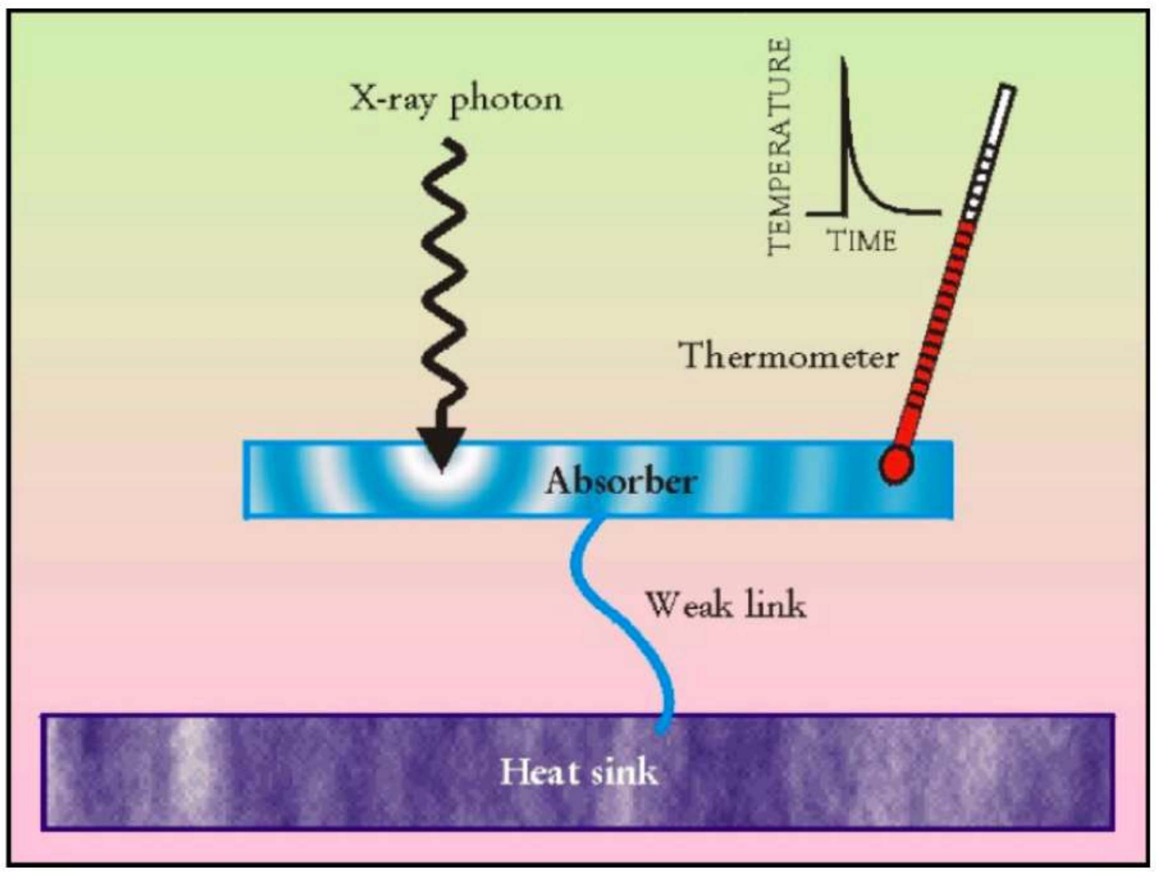



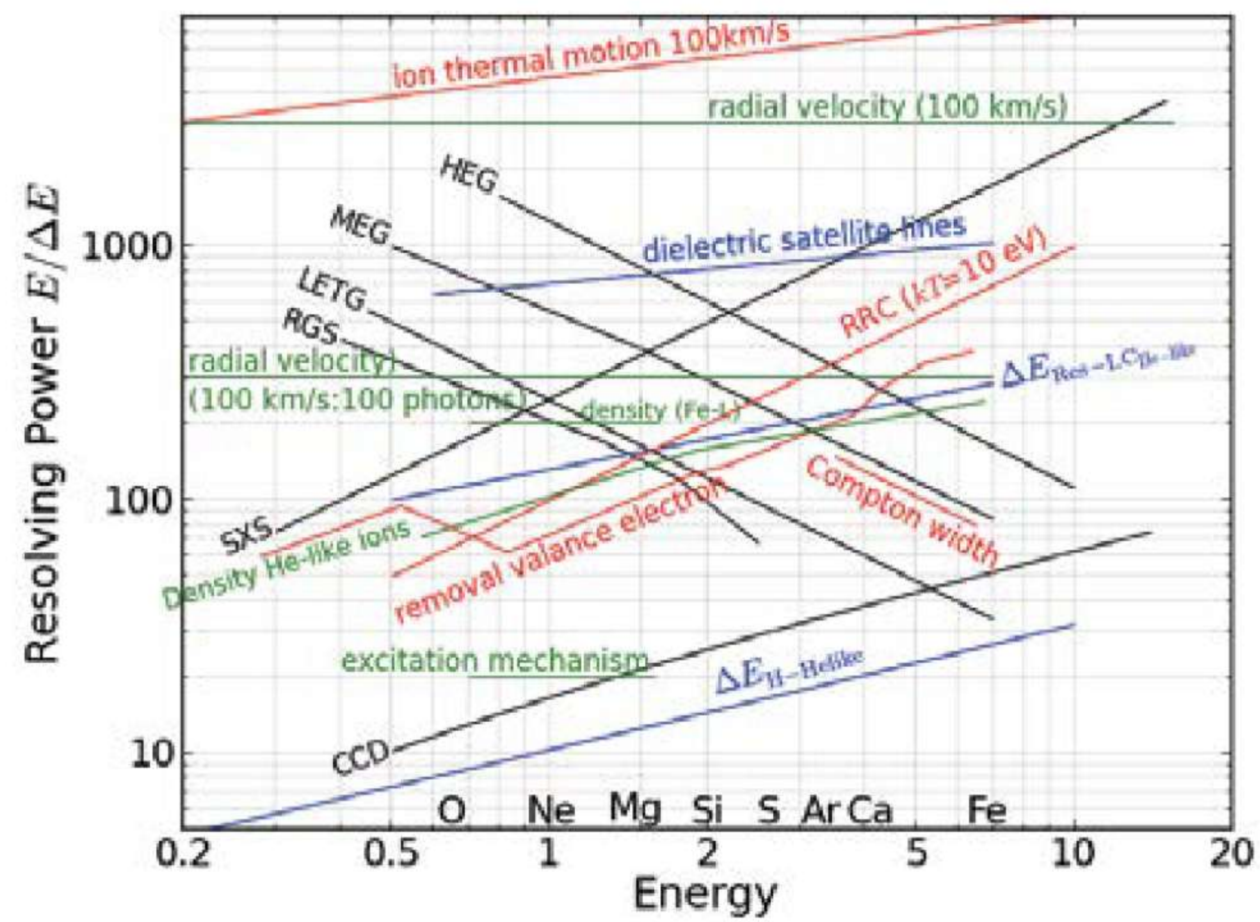



# X-ray spectroscopy, tomorrow: μ-calorimeters

Credit: F. Paerels (Columbia University)

The technology of micro-calorimeters will bring spectroscopy of "cold" plasma into a totally unexplored regime




Open the window of non-dispersive, imaging high-resolution spectroscopy

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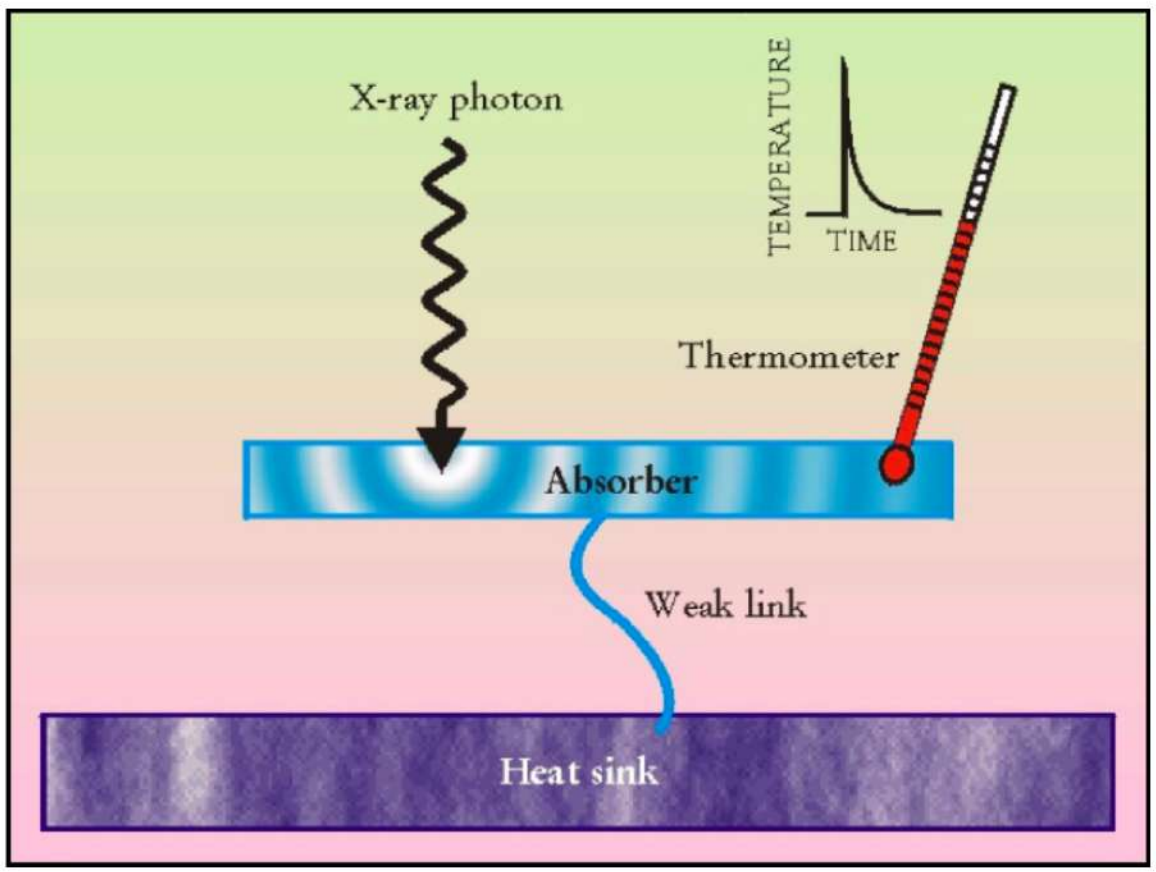


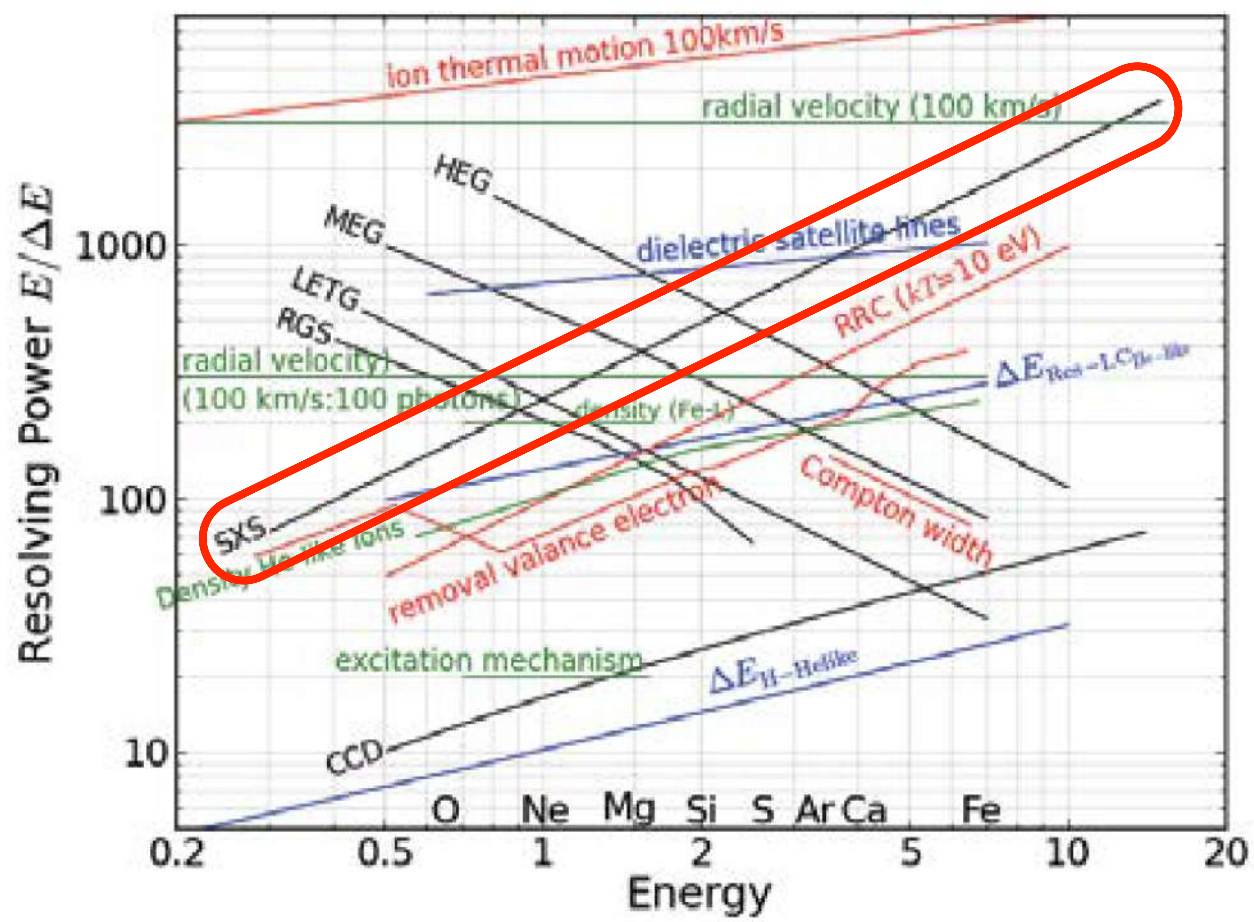


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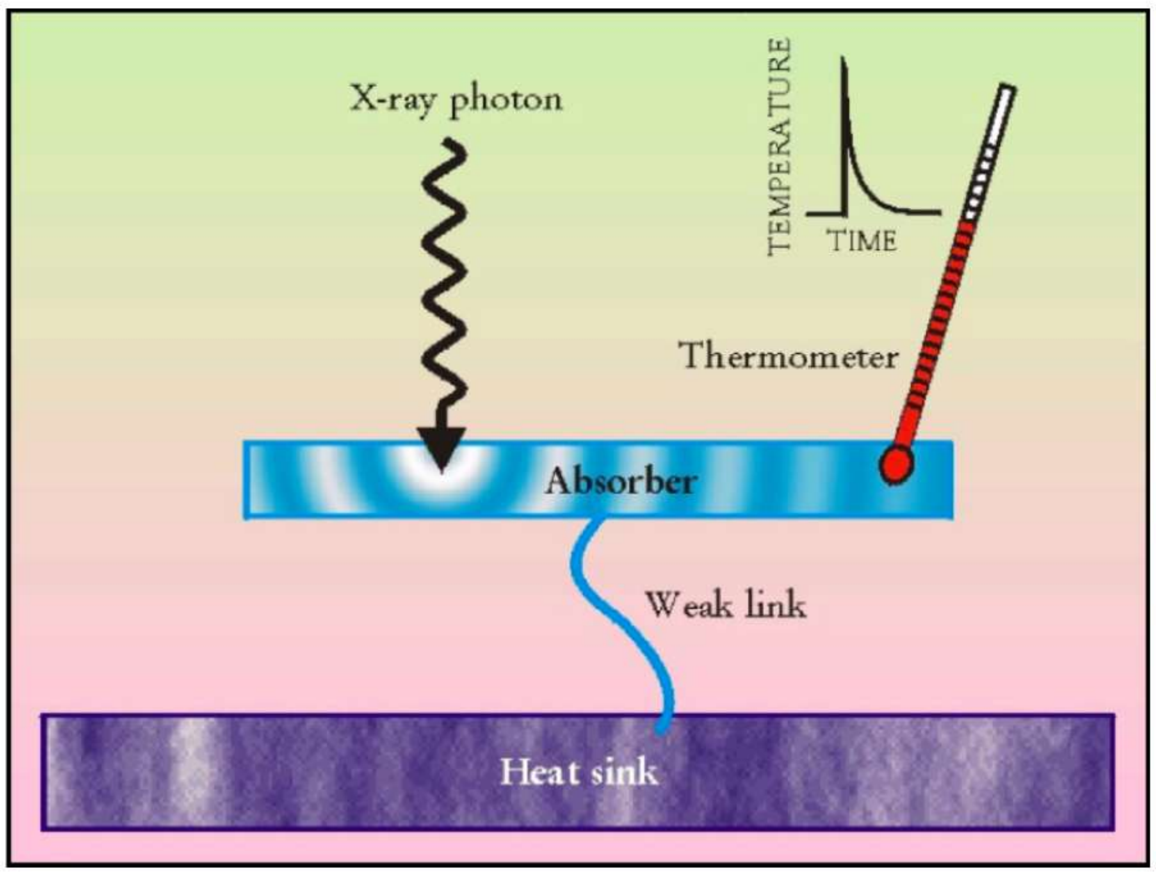
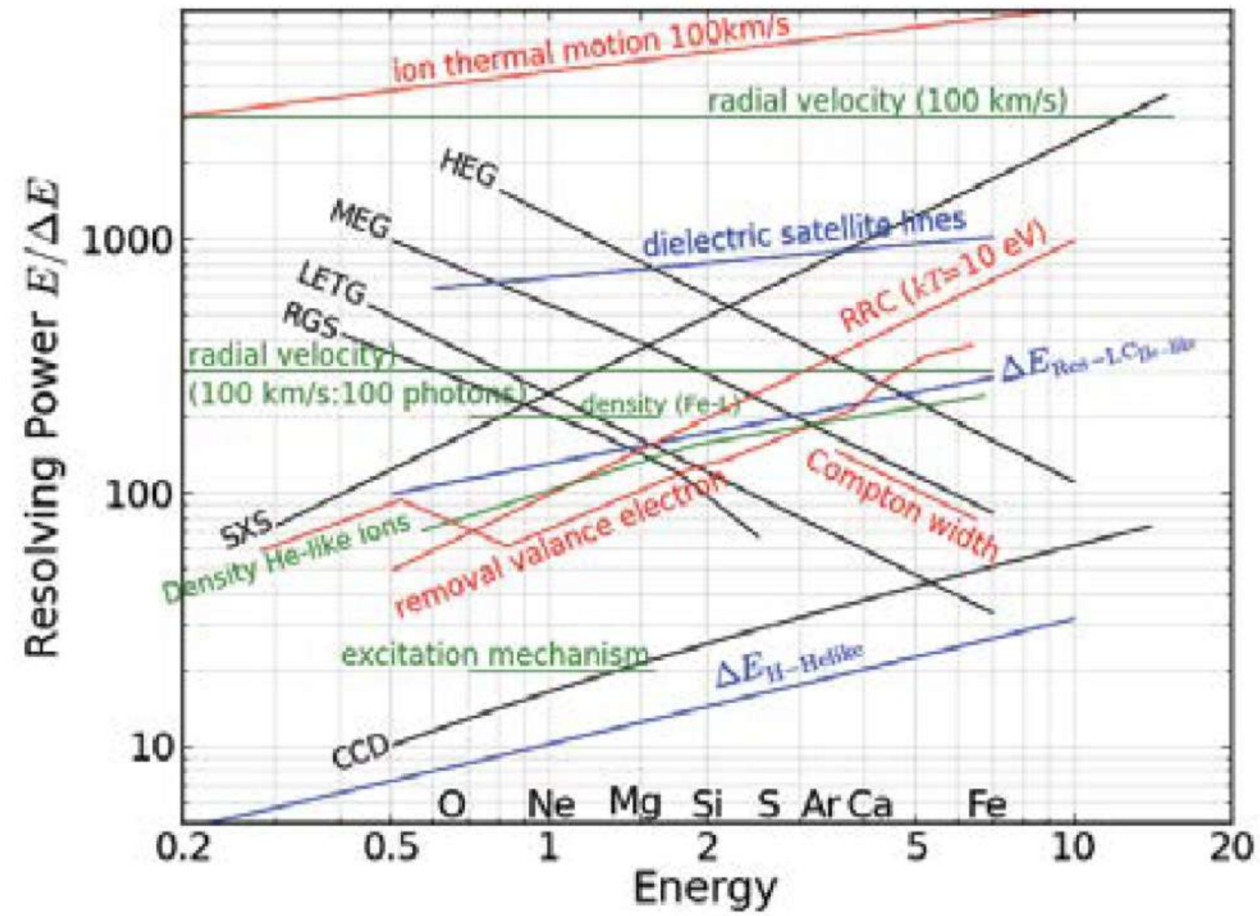
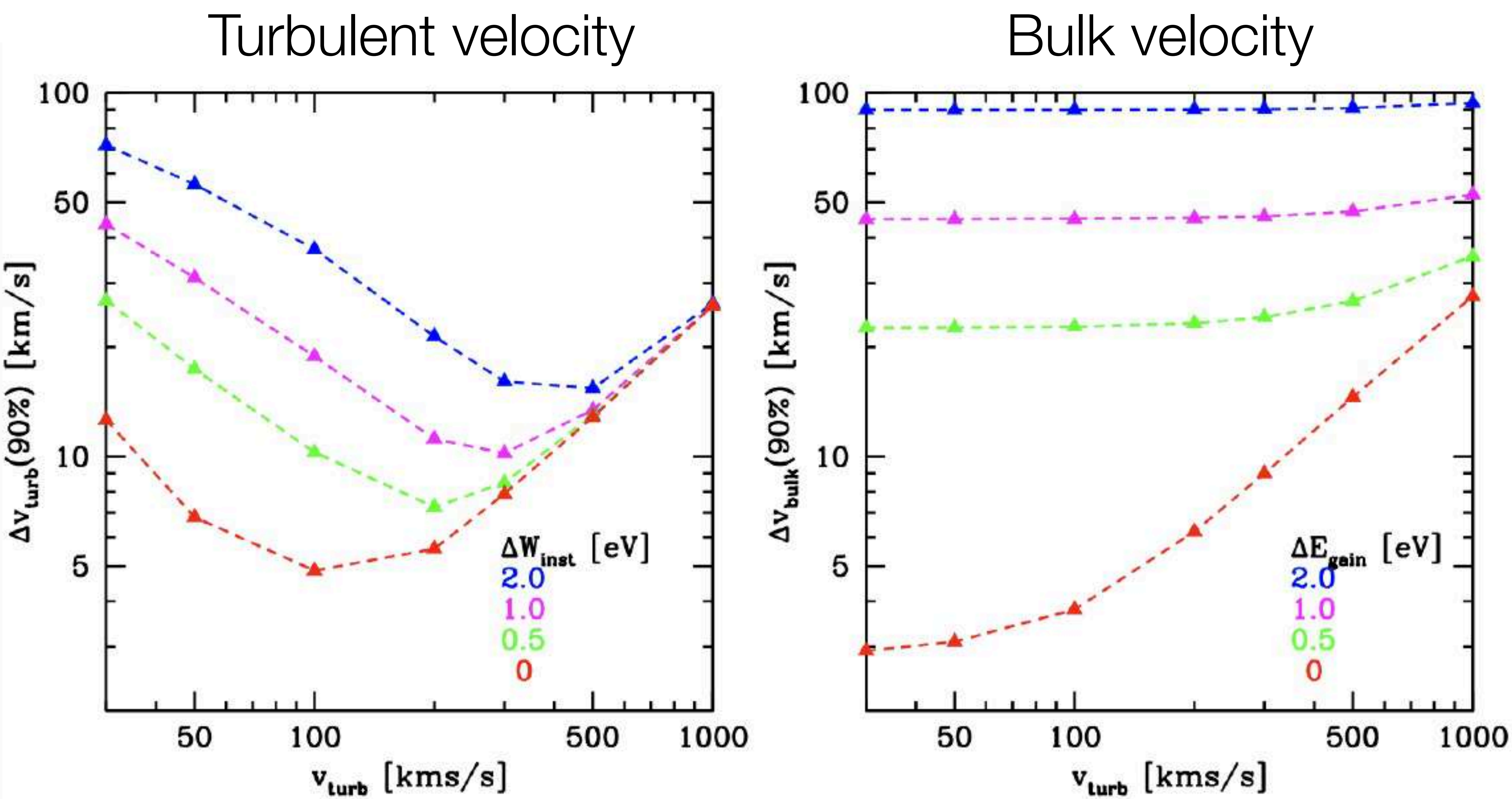



Open the window of non-dispersive, imaging high-resolution spectroscopy

# Dynamical measurement with a μ-calorimeter

XRISM Science Team, in preparation




A CCD imaging spectrometer can hardly do better than 1000 km s$^{-1}$

# X-Ray Imaging Spectroscopy Mission

- Following the demise of Hitomi operations, JAXA/NASA proposed a mission to recover the ”Resolving astrophysical problems by precise high-resolution X-ray spectroscopy” science theme: XRISM
  - European (ESA/SRON/UniGE) participation

- Payload requirements:
  - **Micro-calorimeter (Resolve): ≤7 eV energy resolution in the 0.3-12 keV energy range, 3’x3’ field-of-view**
  - CCD detectors (Xtend): Large-field (≥30’x30’) , ≤200/250 eV (B/EoL) energy resolution @6 keV
  - Soft X-ray telescope, ≤1.7’ Half Energy Width

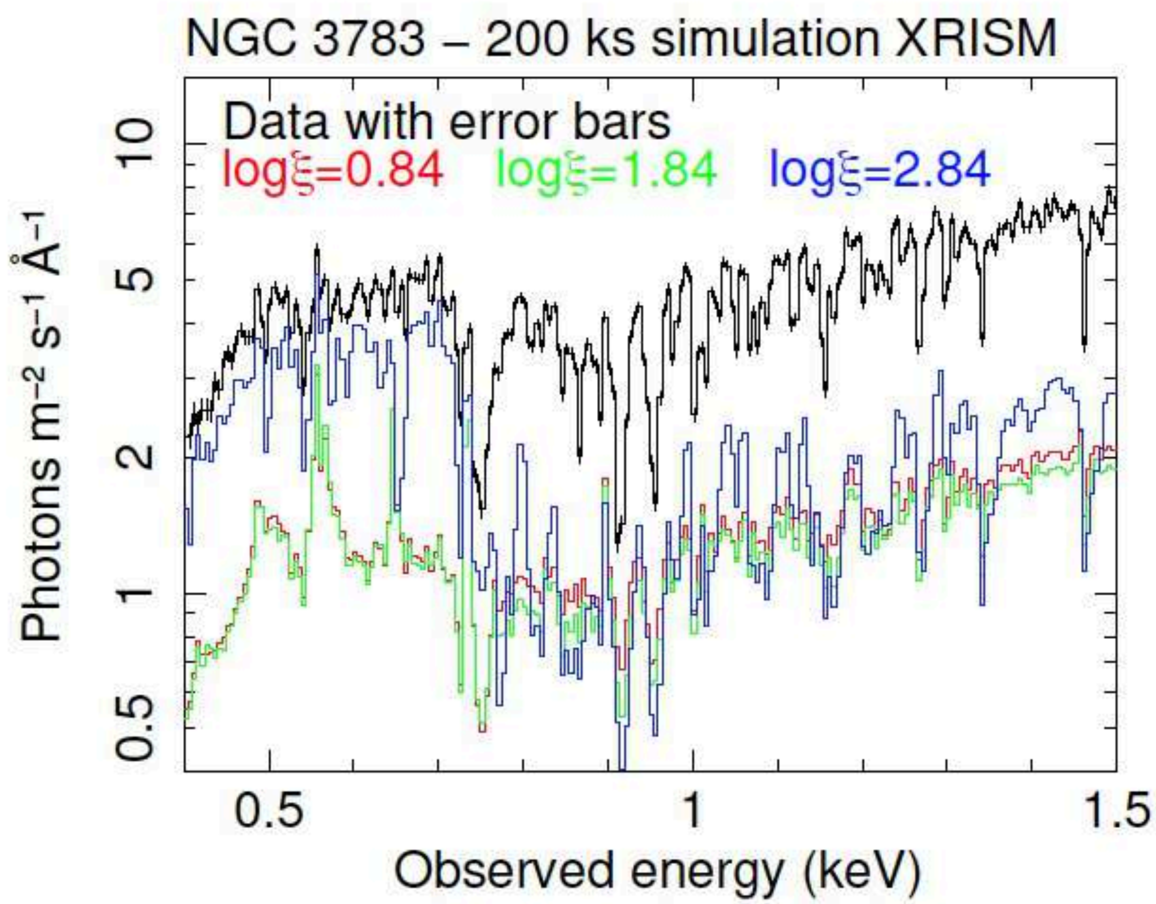
- Launch due ≤end of the Japanese Fiscal Year 2021

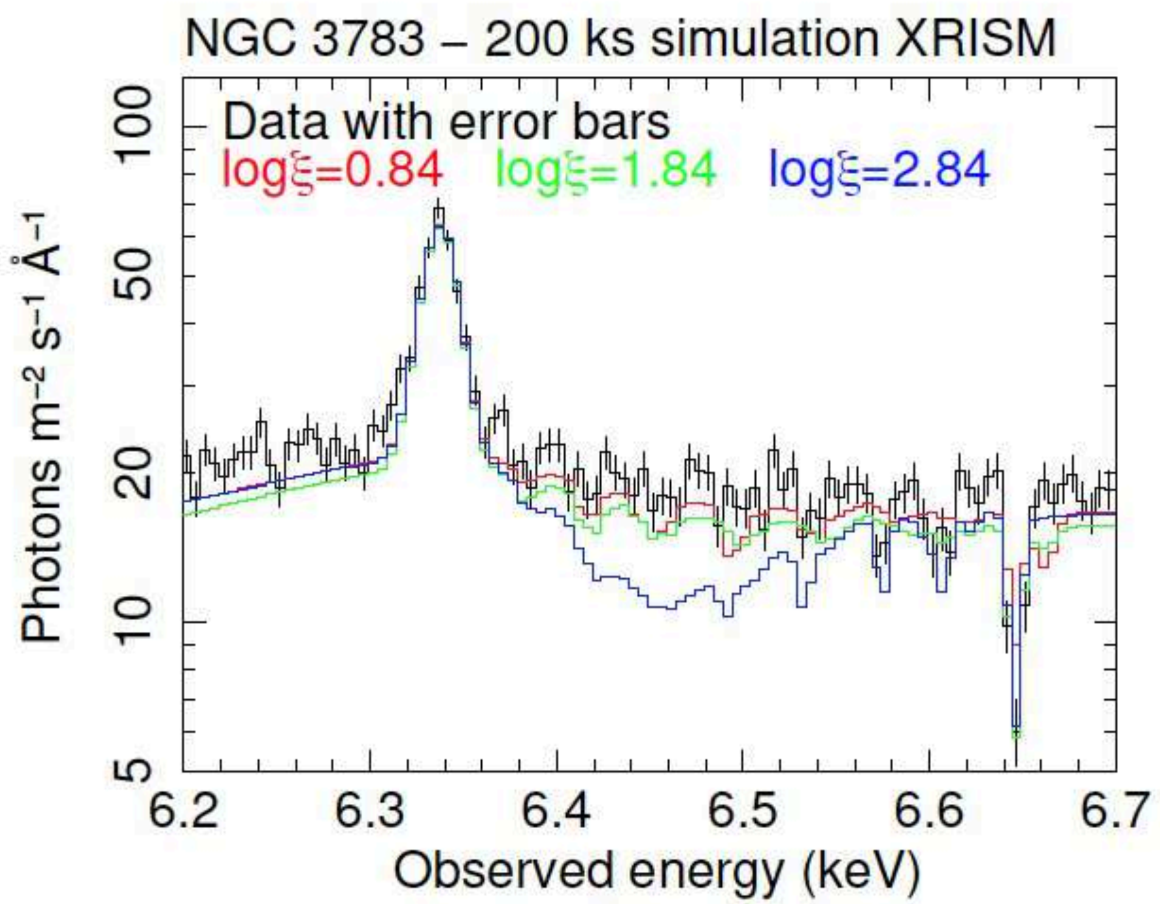
# Full Absorption Measure Distribution of AGN winds

Credit: J.Kaastra (SRON)

XRISM will detect a full series of Fe XXVI to XXVI transition, including higher Ly-α orders

| Ion | Transition | $E_{\rm rest}$ (keV) | S/N ($n\sigma$) |
|---|---|---|---|
| Fe XXV | 1s-2p | 6.70 | 20.4 |
| Fe XXV | 1s-3p | 7.88 | 5.3 |
| Fe XXVI | 1s-2p | 6.97 | 5.3 |
| Fe XXVI | 1s-2p | 6.95 | 2.8 |
| Fe XXIV | 1s-2p | 6.66 | 6.0 |
| Fe XXIV | 1s-2p | 1.17 | 8.0 |
| Ni XXVII | 1s-2p | 7.81 | 1.6 |

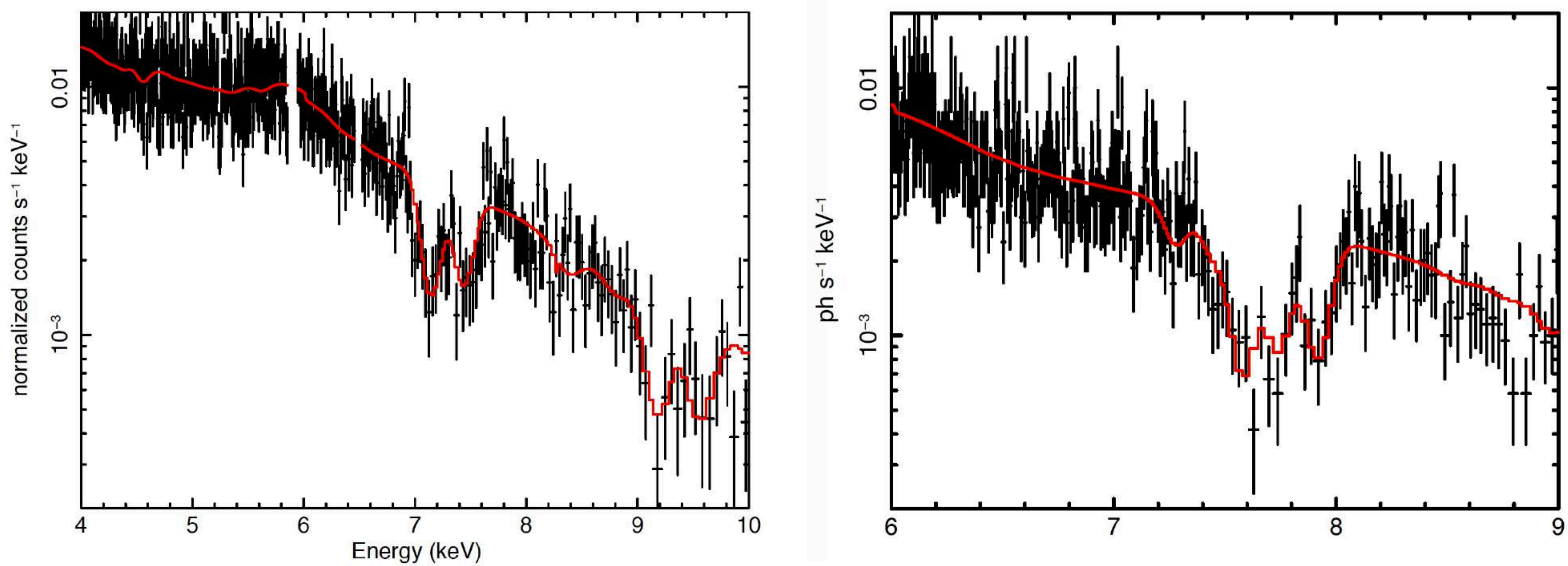


# Characterisation of the wind dynamics (PDS456)

Credit: K.Hagino (ISAS)

## XRISM/*Resolve* spectra of PDS456



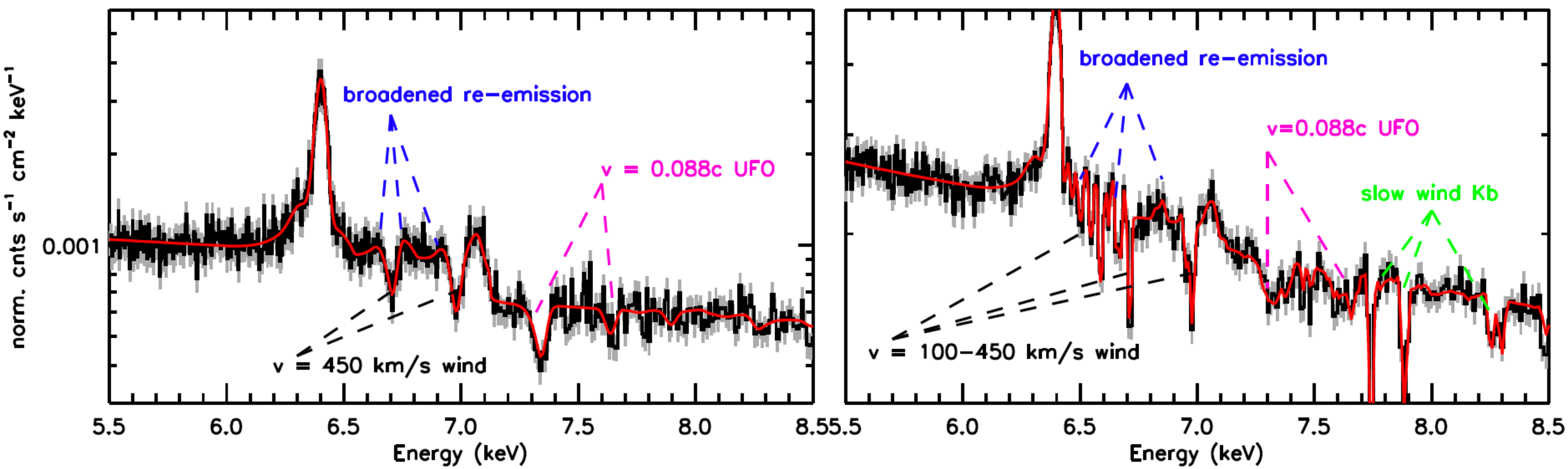

Turbulent velocity of 5000 km/s (*Suzaku*/CCD constraint)

3 dynamical components of 3000 km/s, separated by 0.02c each

# Wind launch radius via re-emission (NGC4151)

Credit: J.Miller (Un. Michigan)

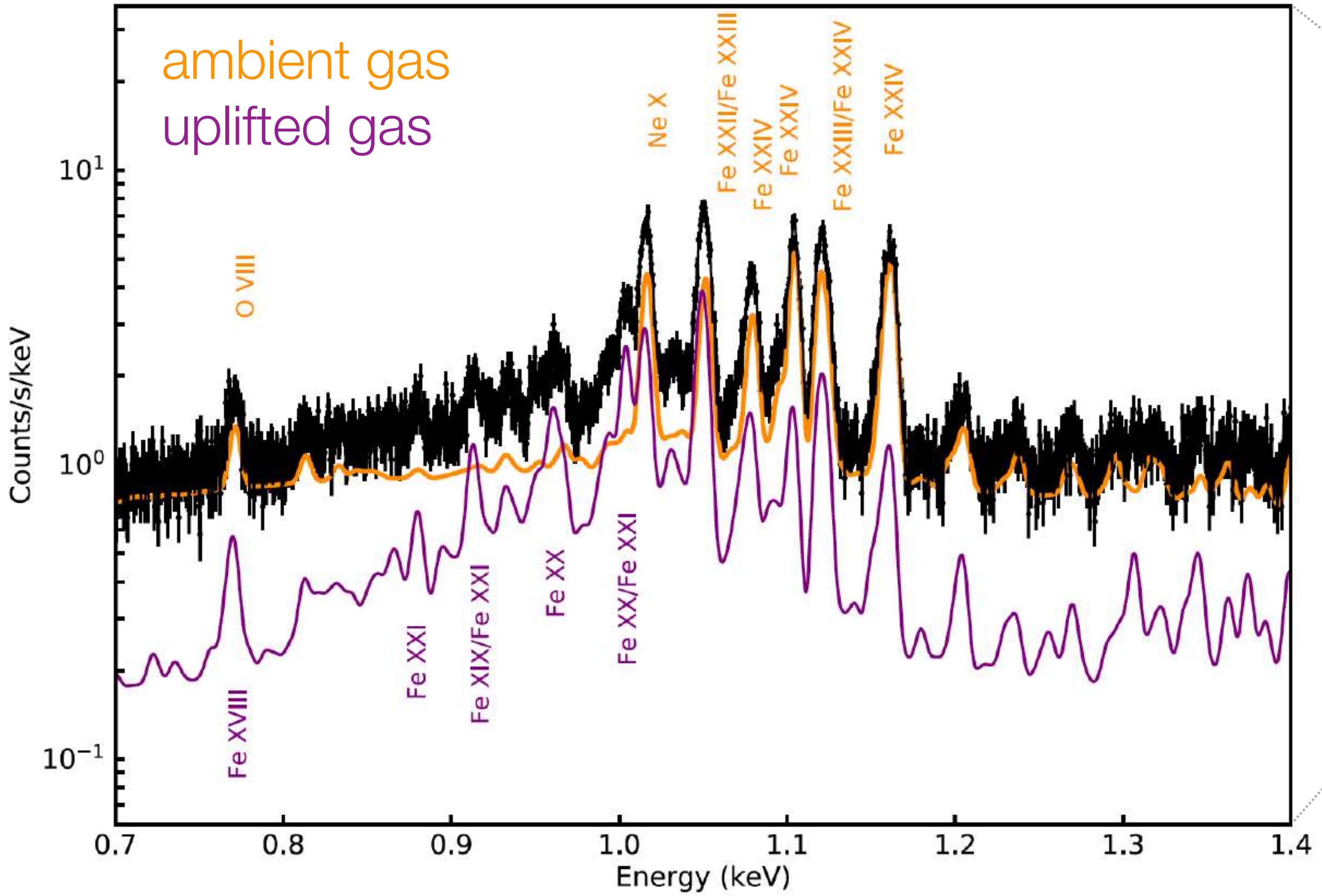
Determination of the wind launch radius through the width of the *emission* lines scattered by the outflow

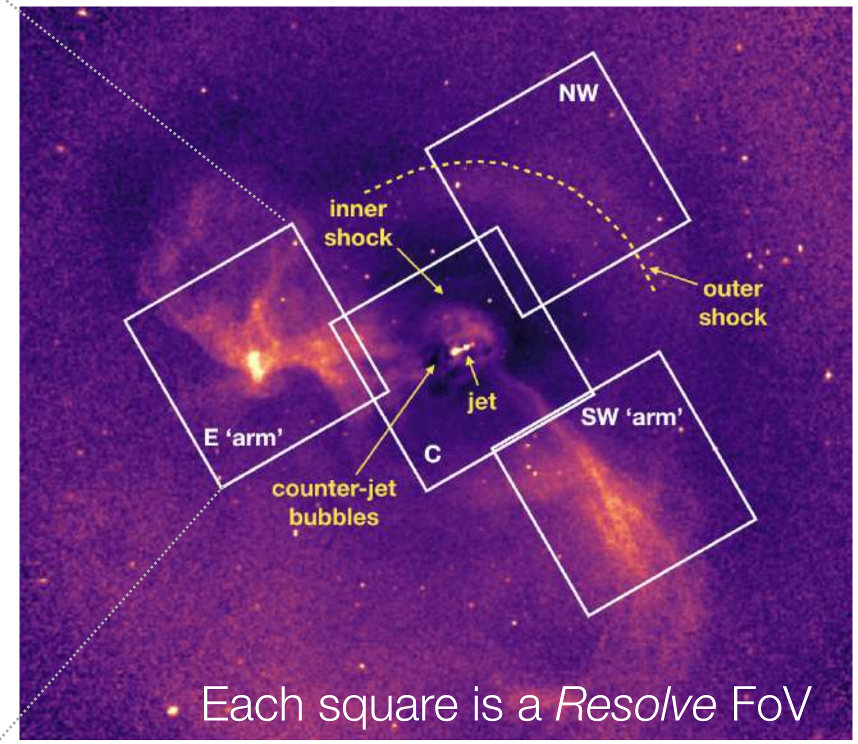



[*Resolve* simulations of NGC4151 in two different flux states]

# Calorimetry of AGN-uplifted hot gas in M87

Credit: A. Simionescu (SRON)




100 ks would allow Resolve to measure the velocity of the uplifted gas with $\Delta v = \pm 40$ km/s

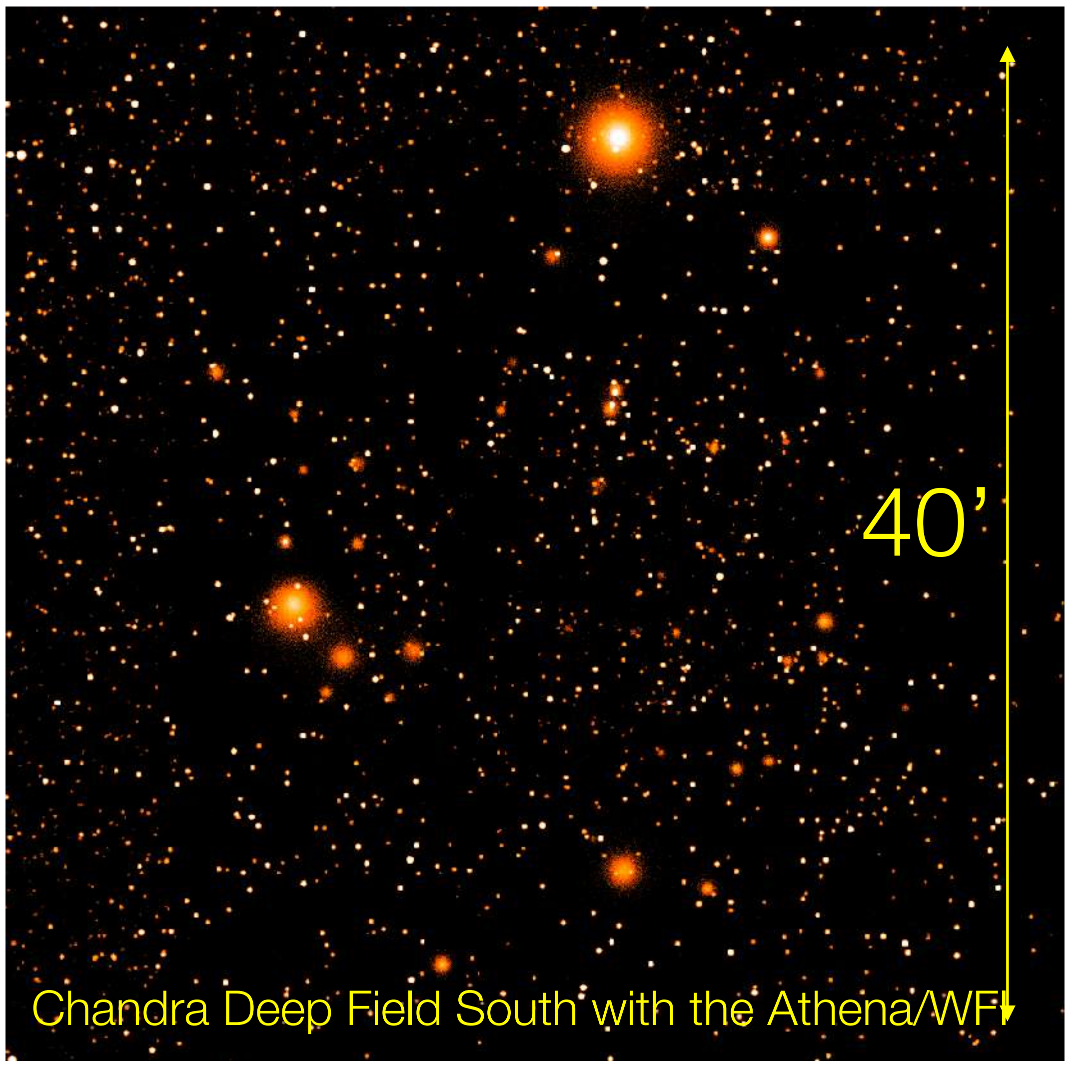
# Athena as an L-class ESA mission

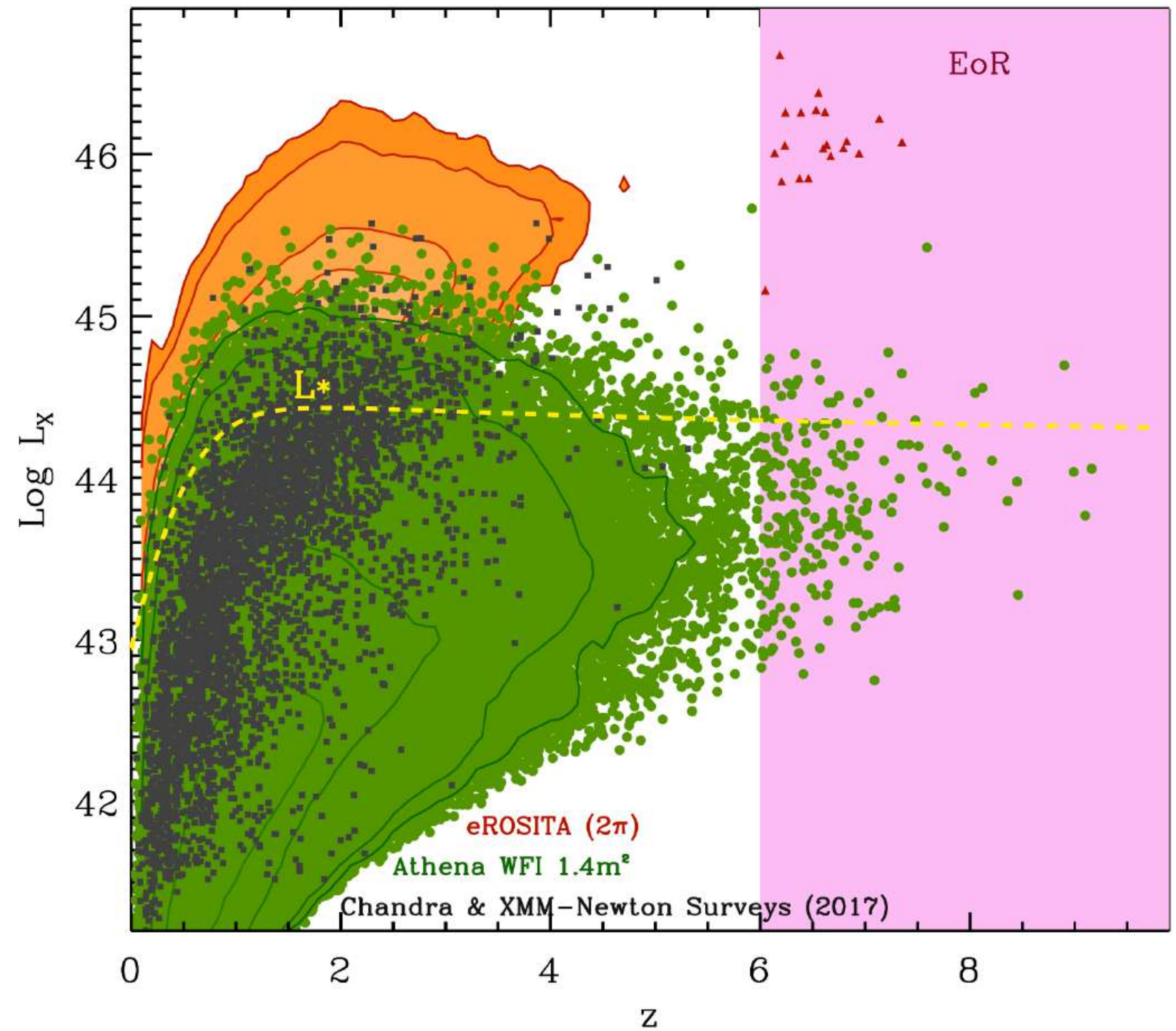
- Science theme: The Hot and Energetic Universe
- The Hot Universe: How does baryonic matter assemble in the large-scale structures? How do they evolve from the formation epoch to the present day?
- The Energetic Universe: How do black holes grow and shape galaxies?
- The Observatory and Discovery science:
  - Observatory science across all corners of astrophysics
  - Fast response (≤4 hours) capability to study transient source

# Athena: the Hot Universe

Credit: A. Rau (MPE) and the WFI Team

Collect the largest X-ray spectroscopic sample of $L_X \leq L_*$ AGN up to z~8



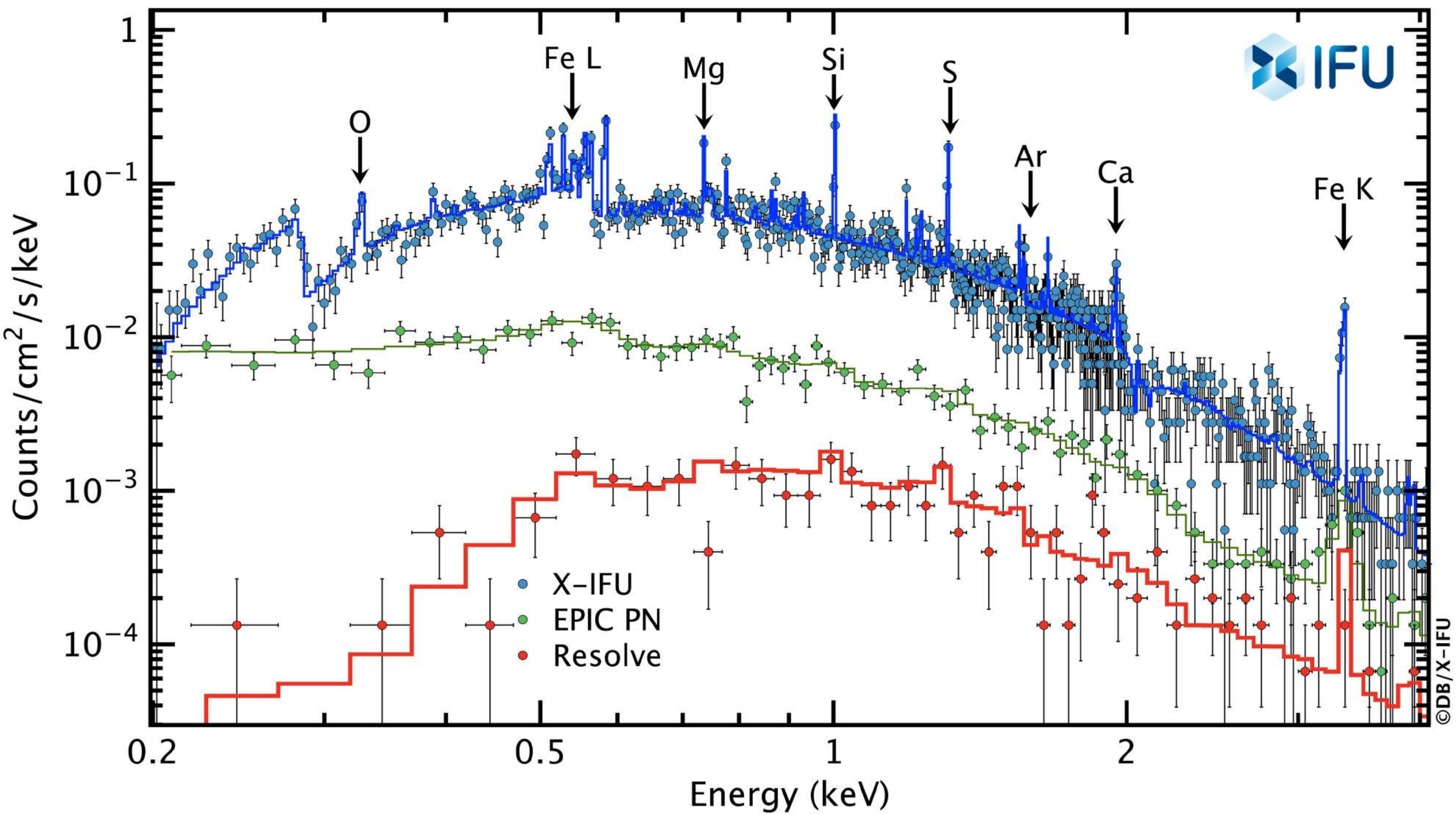

Wide Field Imager (WFI): Silicon Active Pixel Detector (DEPFET)

2.2" pixels - ΔE≤170 eV @6 keV - Fast Chip for ≥Crab science

# Athena: the Energetic Universe

Credit: D.Barret (IRAP) and the X-IFU Team

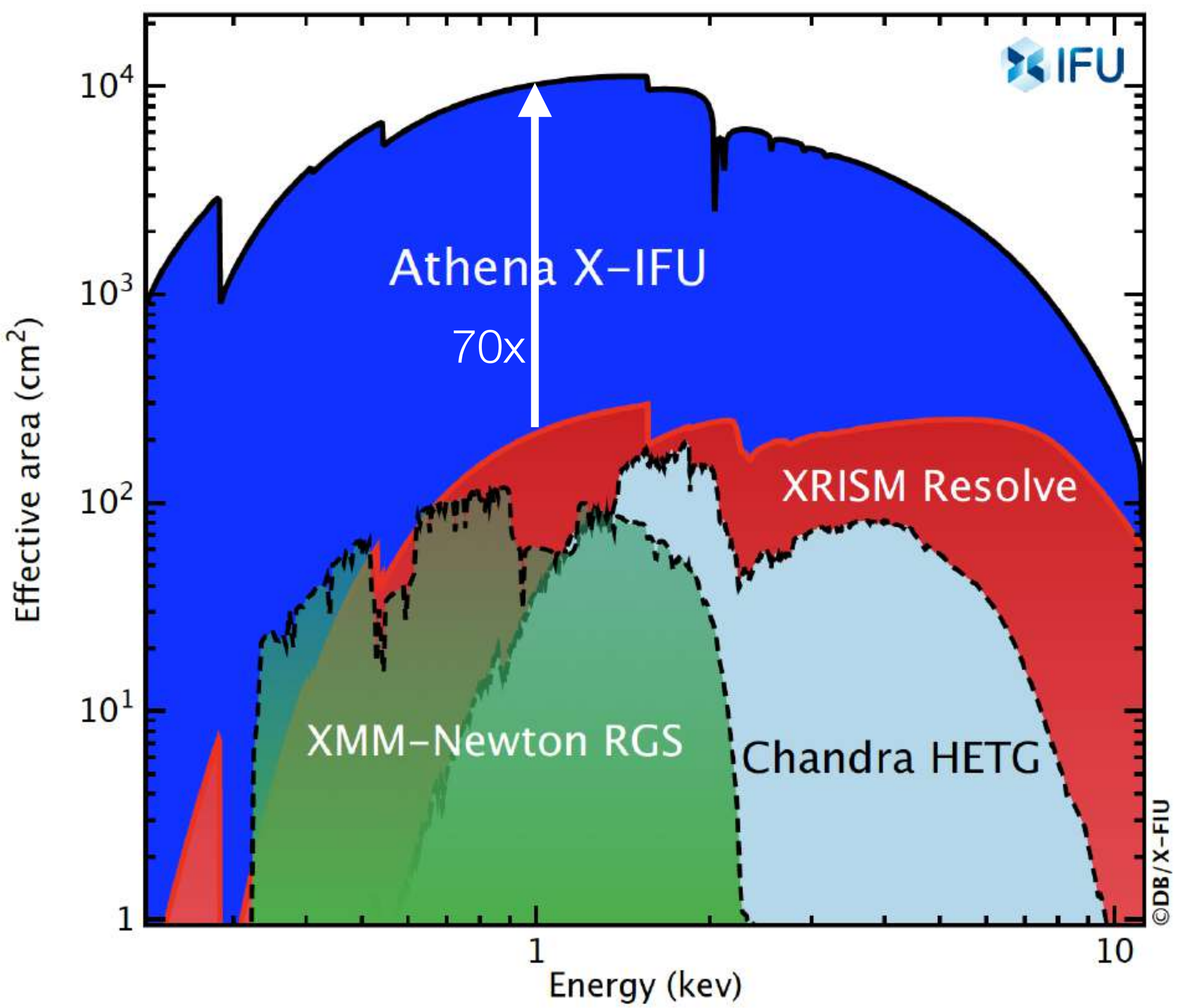
## X-IFU simulated spectrum of a galaxy cluster at z=1



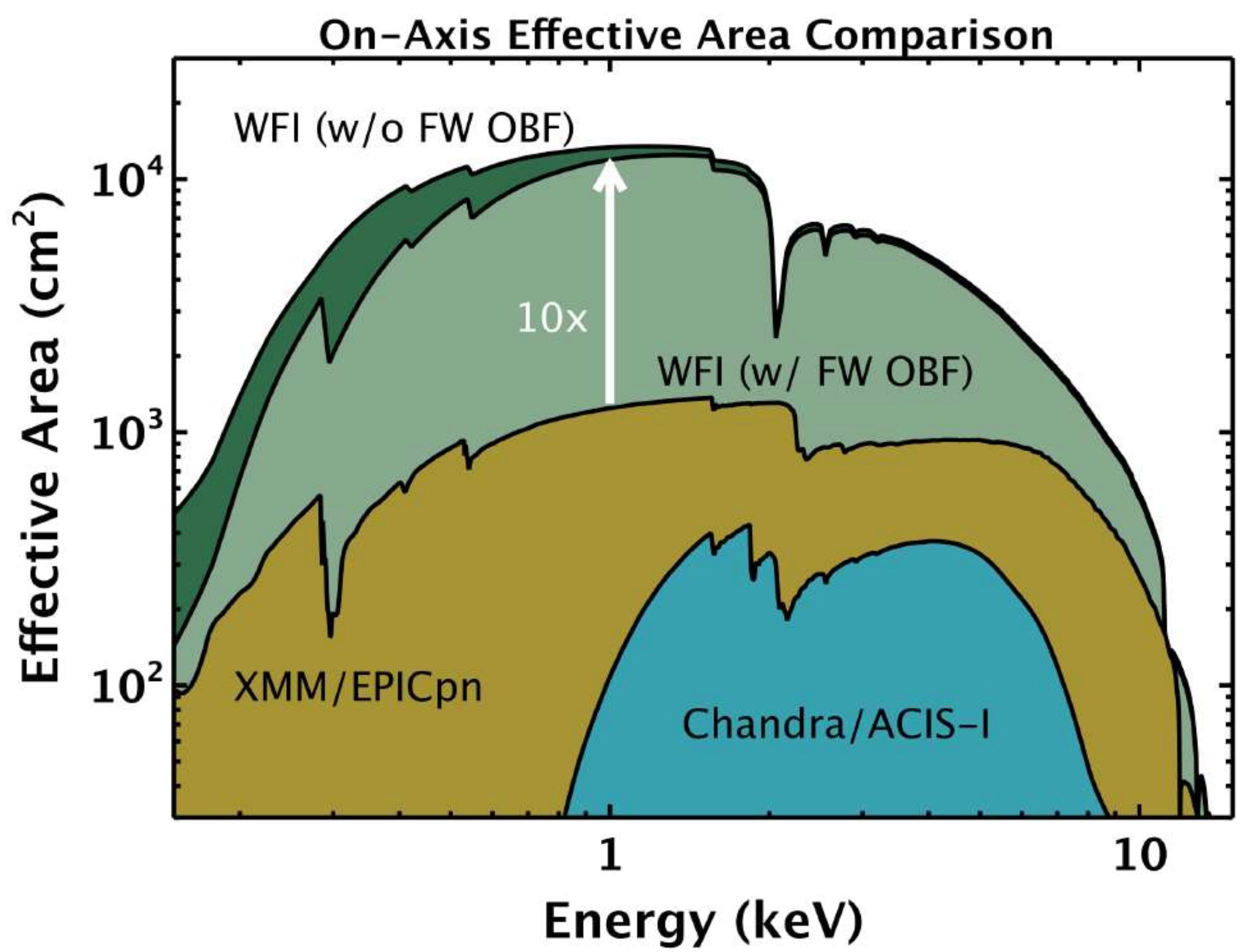
# Athena: large effective area

Barret et al., 2019, arXiv:1912.04615

## Athena mirror + X-IFU




## Athena mirror + WFI



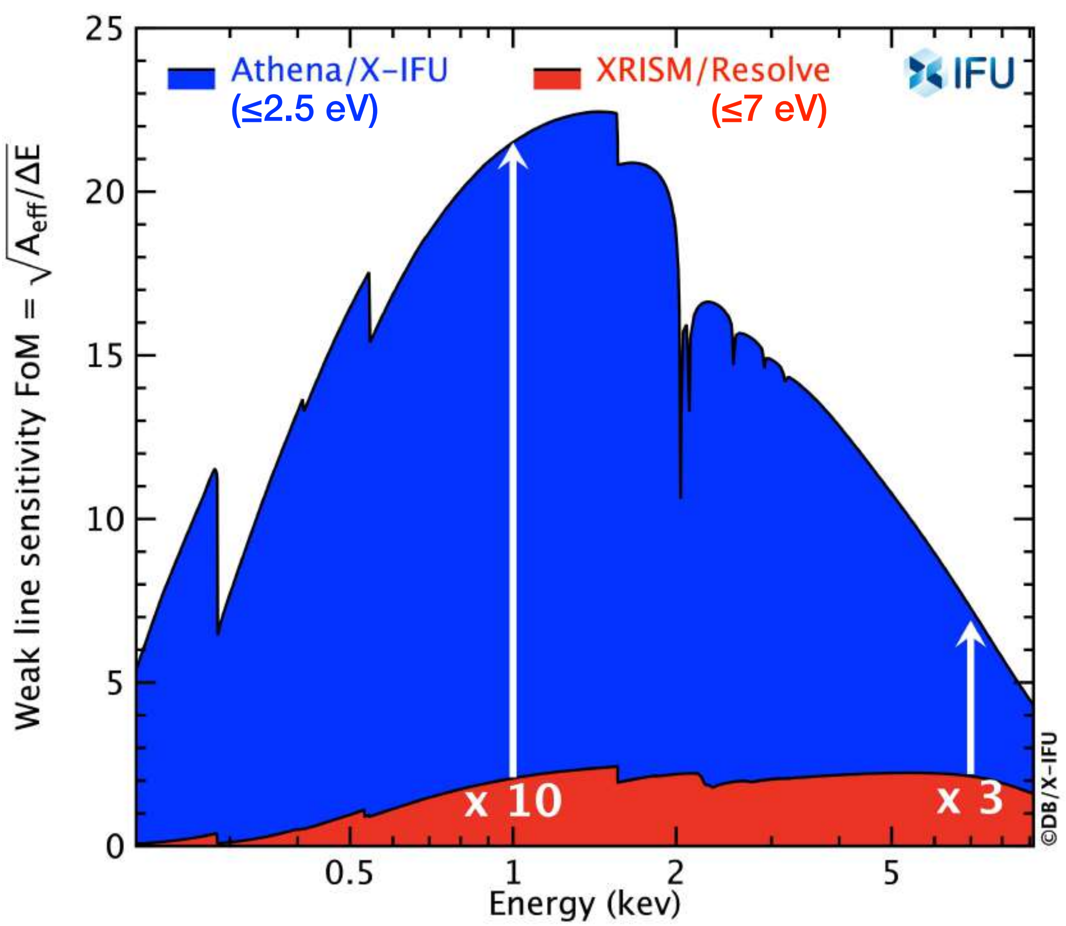


Silicon Pore Optics (ESA development)
Modular, high-throughput, light weight
HEW=5” (req.) on-axis
≤10” at 20” off-axis

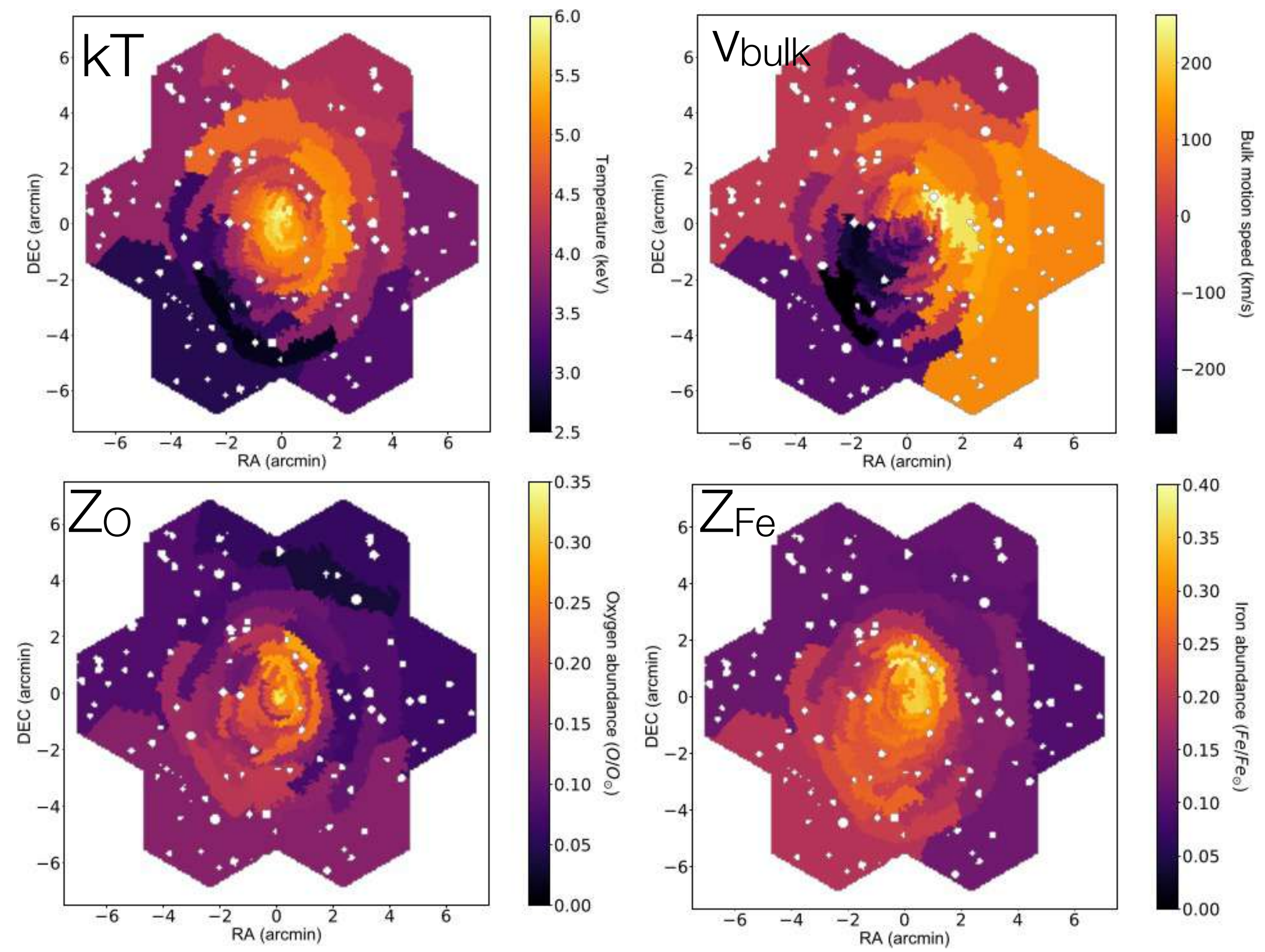
# *Resolve* vs. X-IFU: fight of Titans …

Credit: D.Barret (IRAP) and the X-IFU Team

Cucchetti et al, 2018. A&A, 6120, 173




z=0.1 galaxy cluster, $R_{500}$=1.1 Mpc, $T_{500}$=4.2 keV




Weak line sensitivity

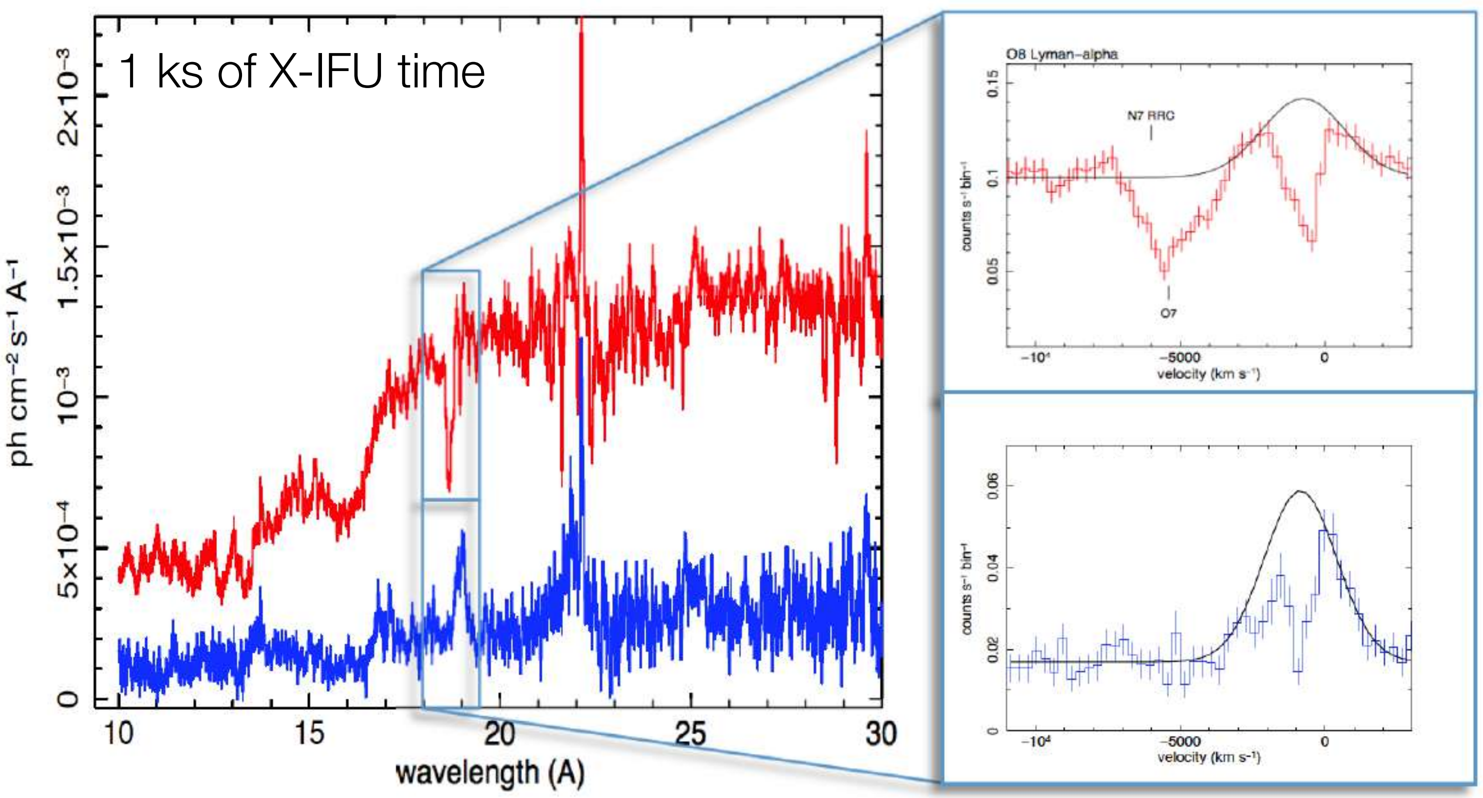
<u>*Resolve*</u>: 35 pixels, 30” size each, ⌀3’

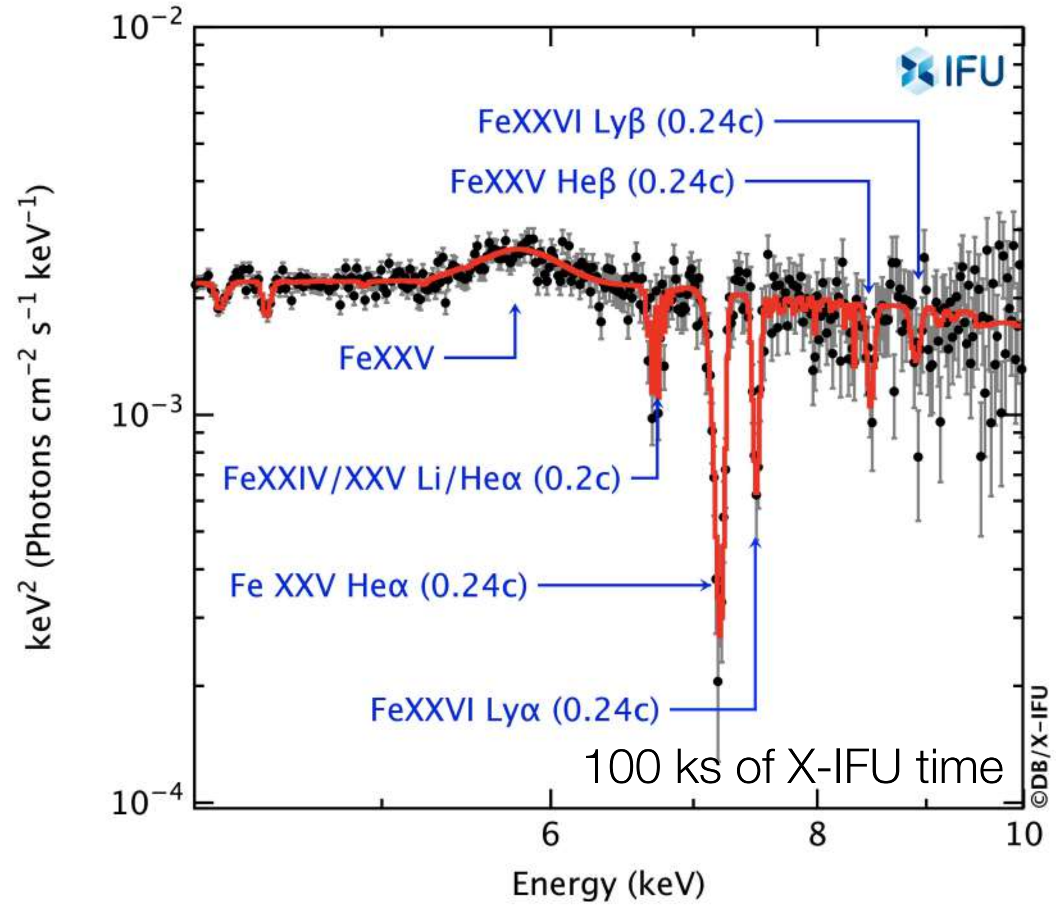
<u>X-IFU</u>: ~3180 pixels, 5” size each, ⌀5’

# Outflow spectroscopy on dynamical time-scales

Cappi et al., 2013, arXiv:1306.2330

Credit: D.Barret (IRAP) and the X-IFU Team



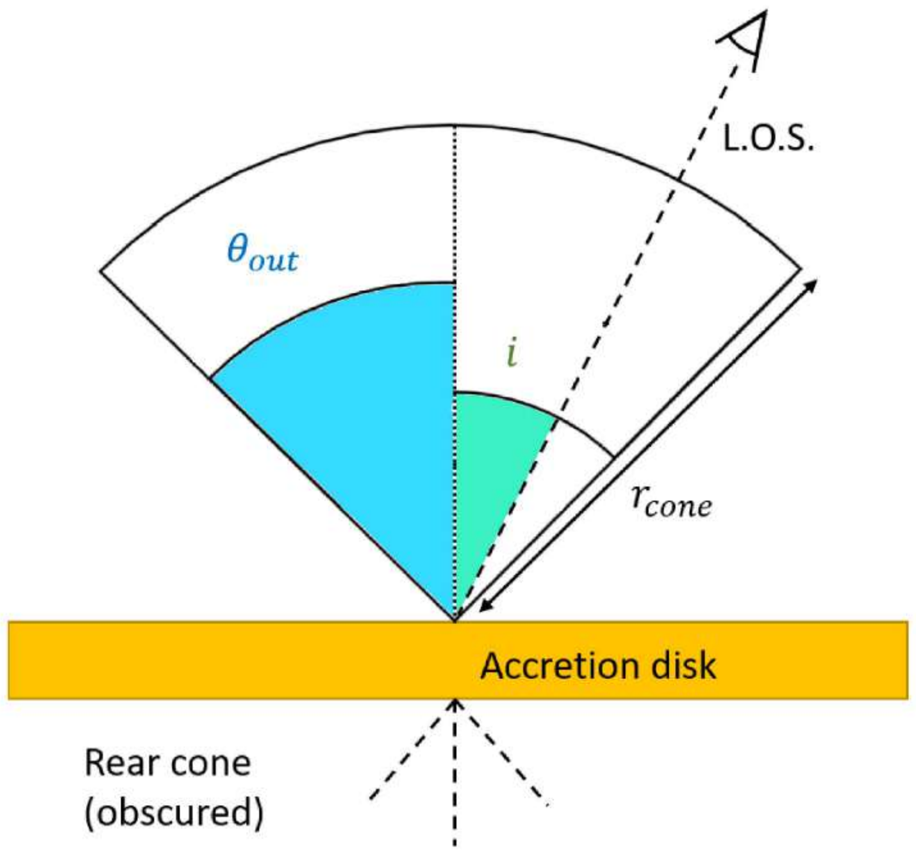

NGC4051 - $M_{BH}$~$1.6 \times 10^6\ M_\odot$

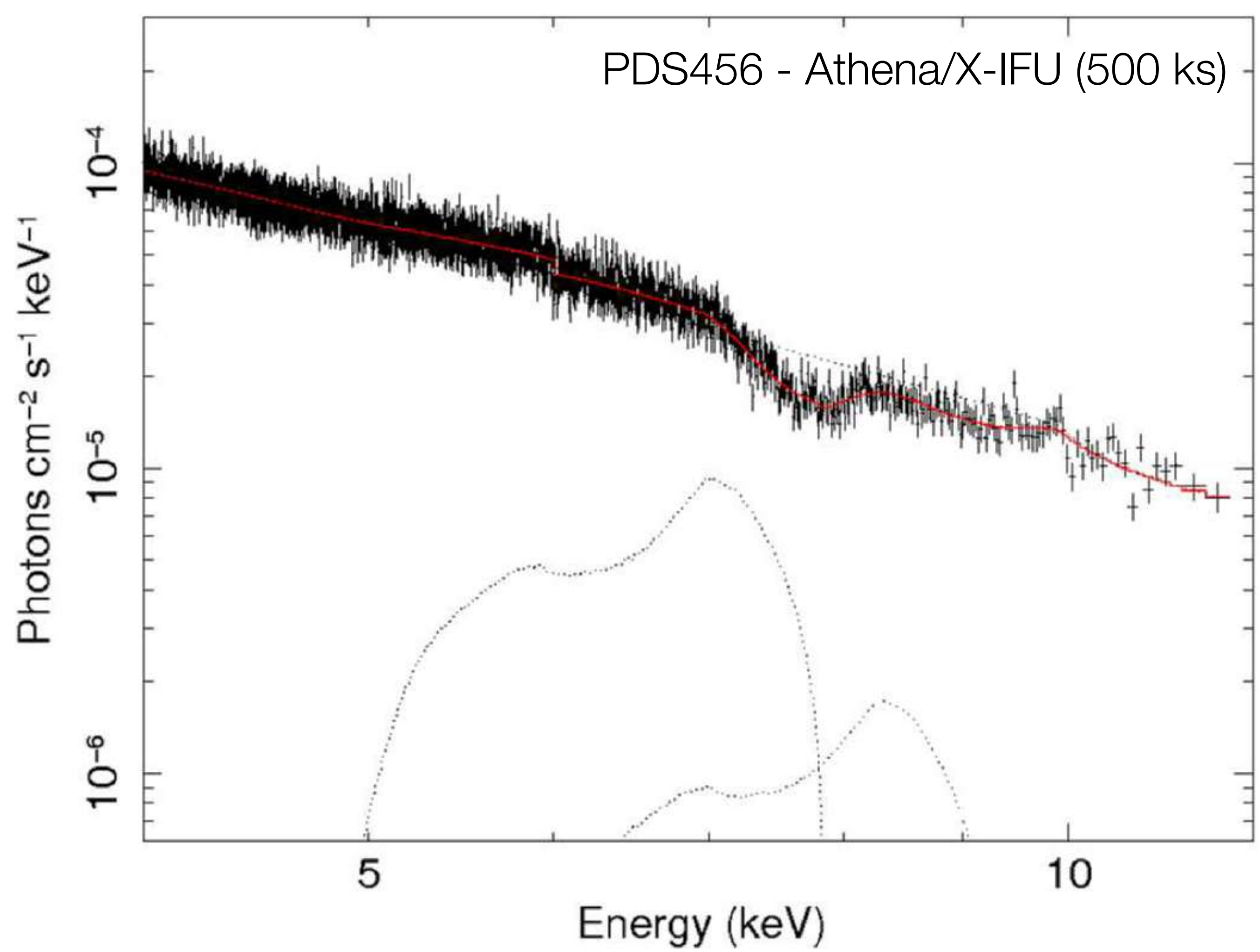
PDS456 - $M_{BH}$~$10^9\ M_\odot$

The exposure times are comparable to the time needed to cover/uncover the X-ray source

# Full structure of the AGN wind with X-IFU

Luminari et al., 2018, A&A, 619, 419



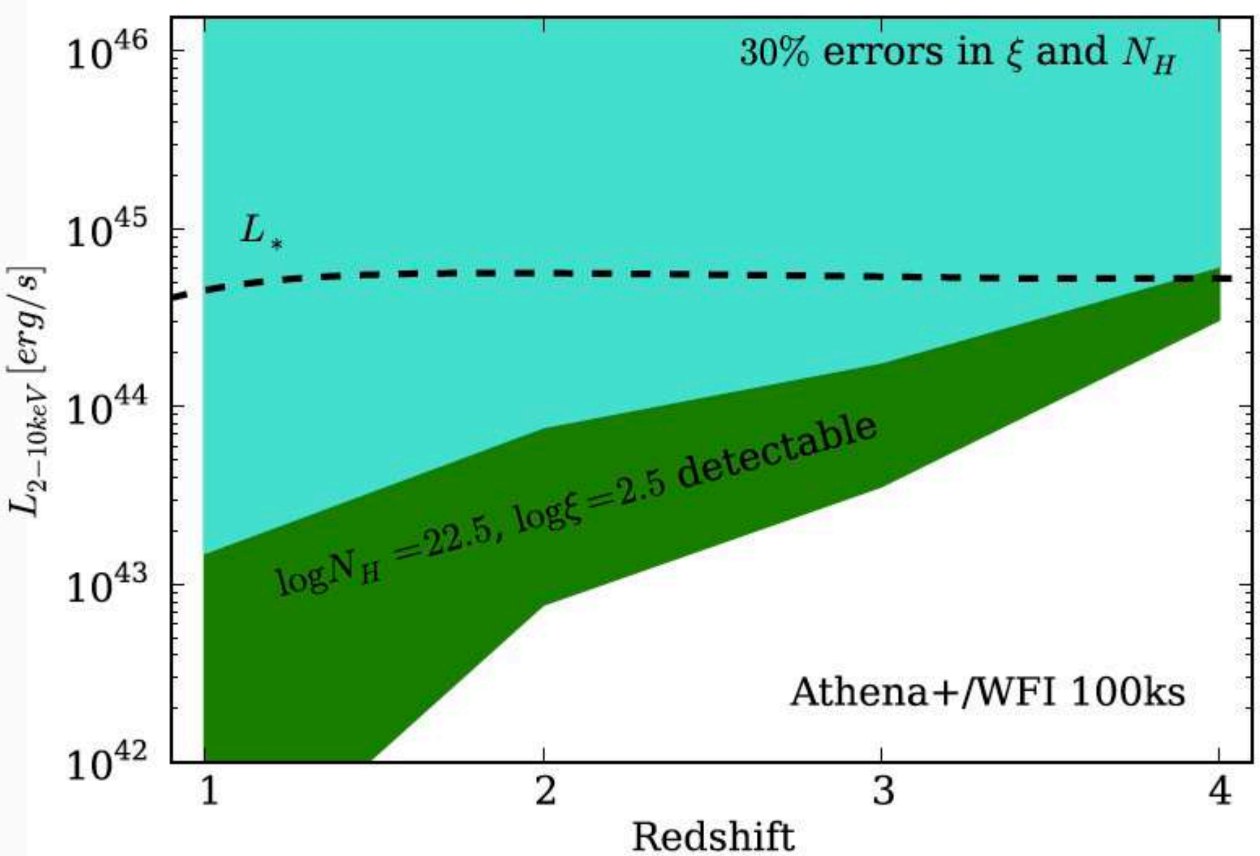

| Parameter | Input[(a)] | Results[(b)] |
|---|---|---|
| $v_{max}$ $(c)$ | 0.285 | $0.285 \pm 0.003$ |
| $s$ | 0.39 | $0.38 \pm 0.01$ |
| $\theta_{out}$ $(deg)$ | 71 | $66 \pm 4$ |
| $i$ $(deg)$ | 63 | $62 \pm 3$ |
| $\theta_{in}$ $(deg)$ | 21 | $22 \pm 4$ |
| Derived qts.[(c)] | | |
| $v_{min}$ $(c)$ | 0.174 | $0.176 \pm 0.005$ |
| $C_f$ | 0.60 | $0.53 \pm 0.06$ |

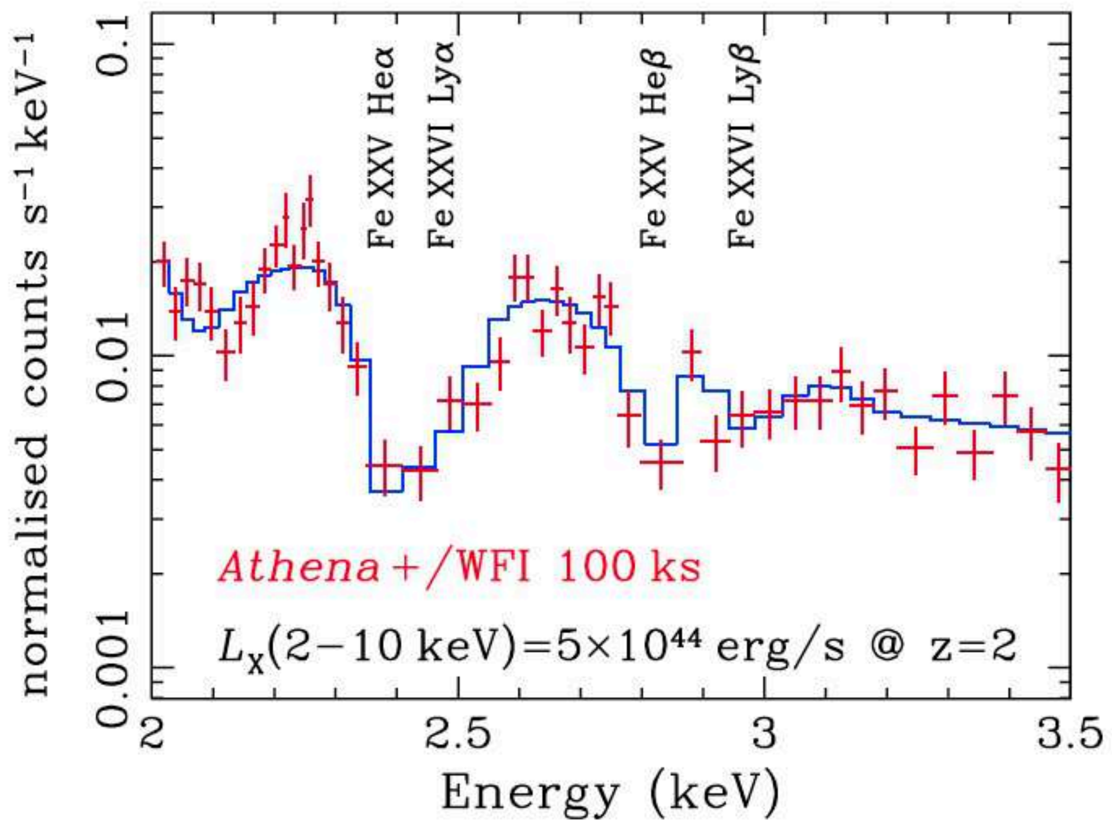
500 ks of X-IFU exposure time will constrain the presence of a cavity at the 90% confidence level

# Chasing AGN outflows at the peak of AGN activity

Georgakakis et al., 2013, arXiv:1306.2328

The WFI survey will discover 100s of AGN outflows at z=1-4



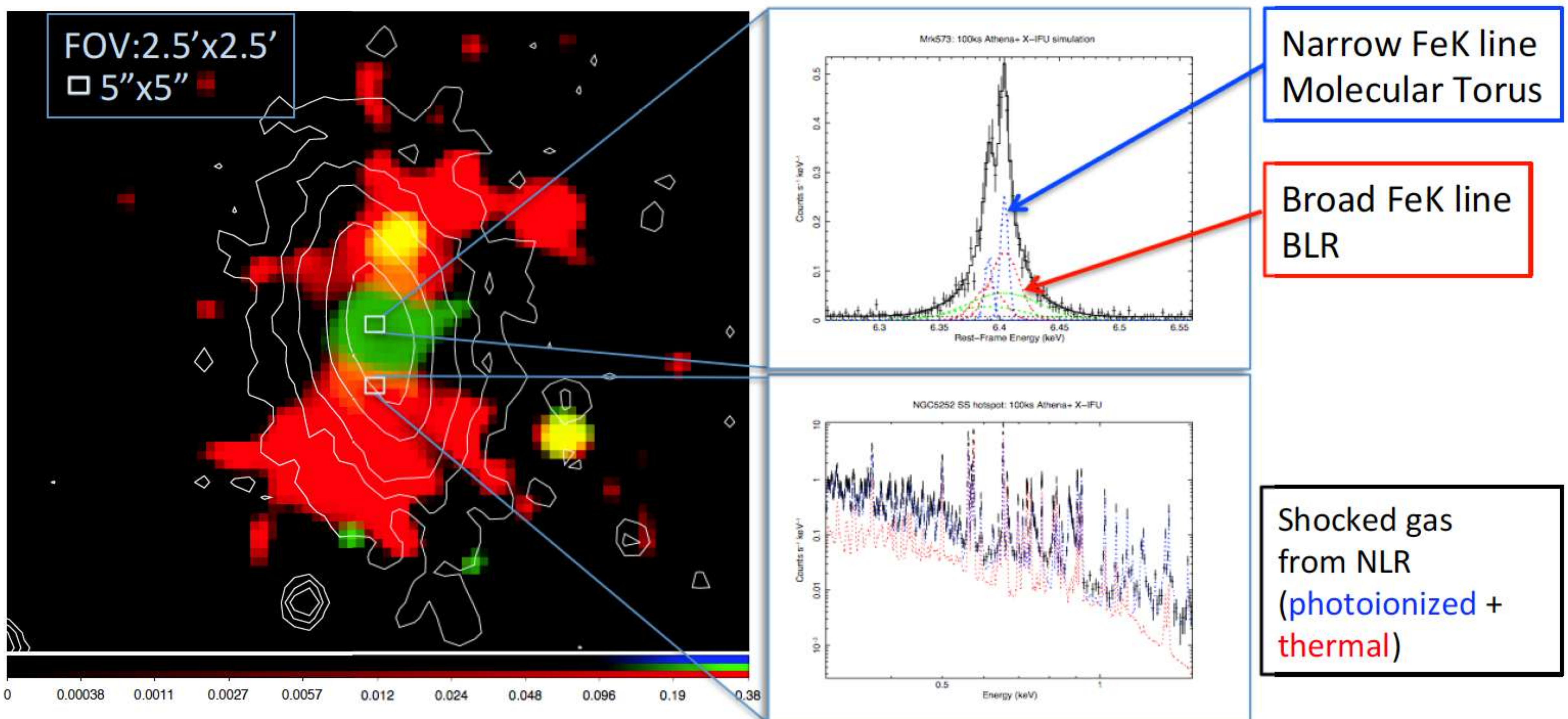

The brightest can be followed-up with dedicated X-IFU observations

# kpc-scale AGN-ISM interaction with *Athena*

Dadina et al., 2010, A&A, 516, 9

Cappi et al., 2013, arXiv:1306.2330

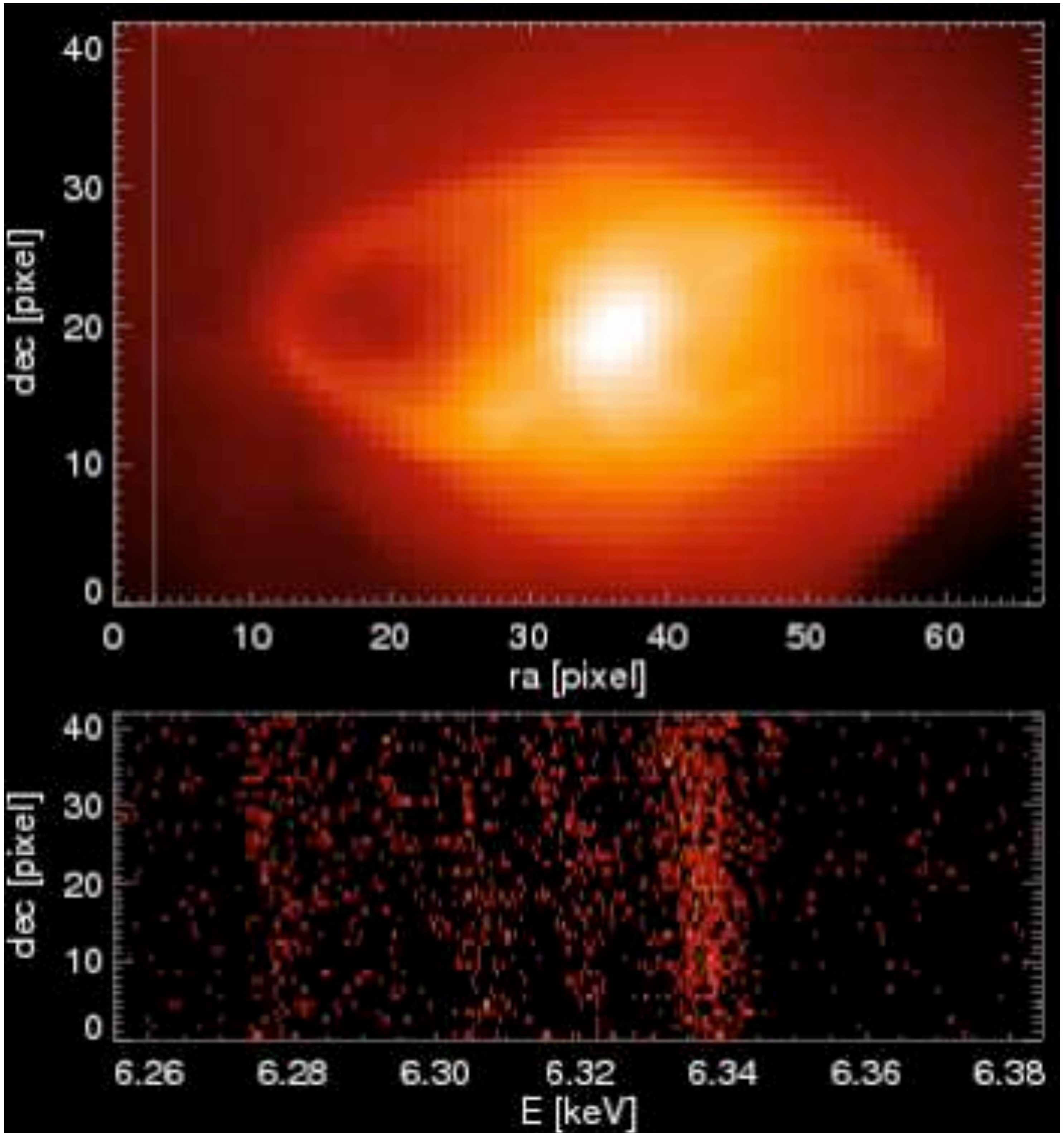
## X-IFU simulation of the nearby Seyfert Galaxy NGC5252



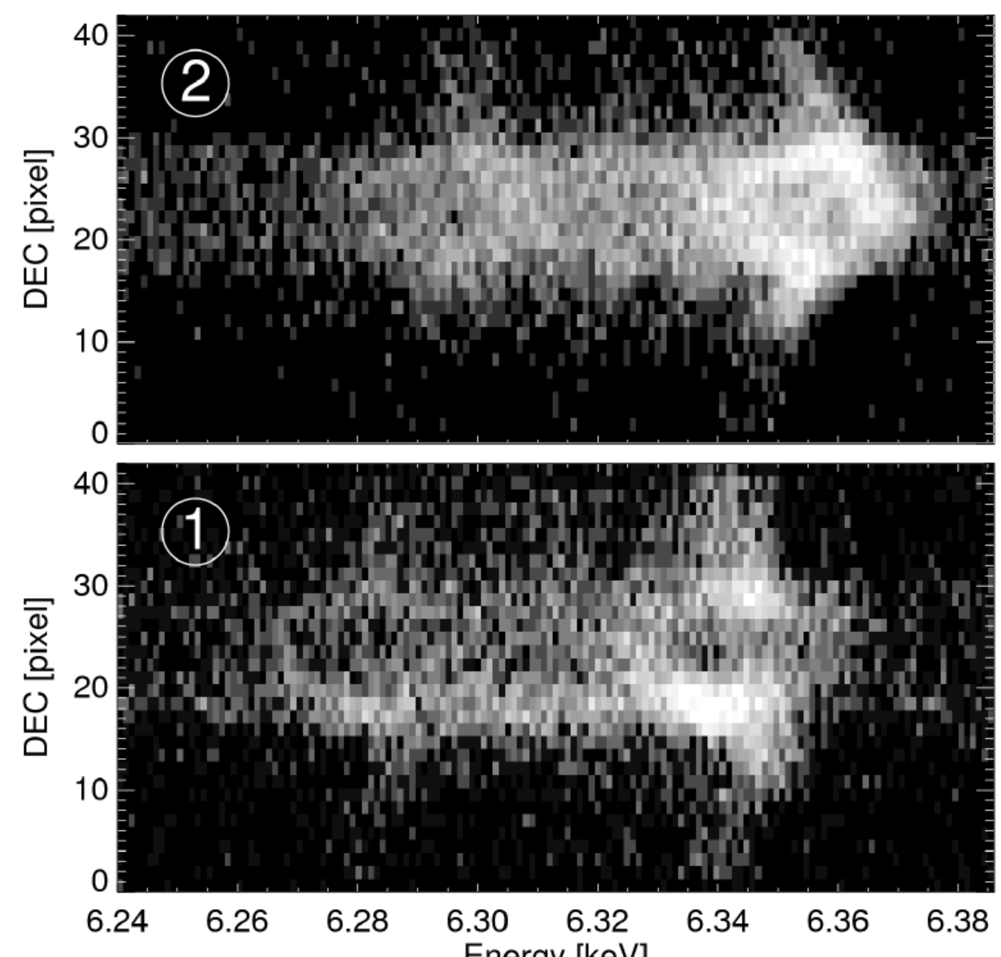
# Spatially-resolved spectroscopy of cavities

Credit for simulations: prof. S. Heinz (University of Wisconsin)

Croston et al., 2013, arXiv:1306.2323




Simulated X-IFU images and spatially-resolved spectra for shells and cavities in Cyg A



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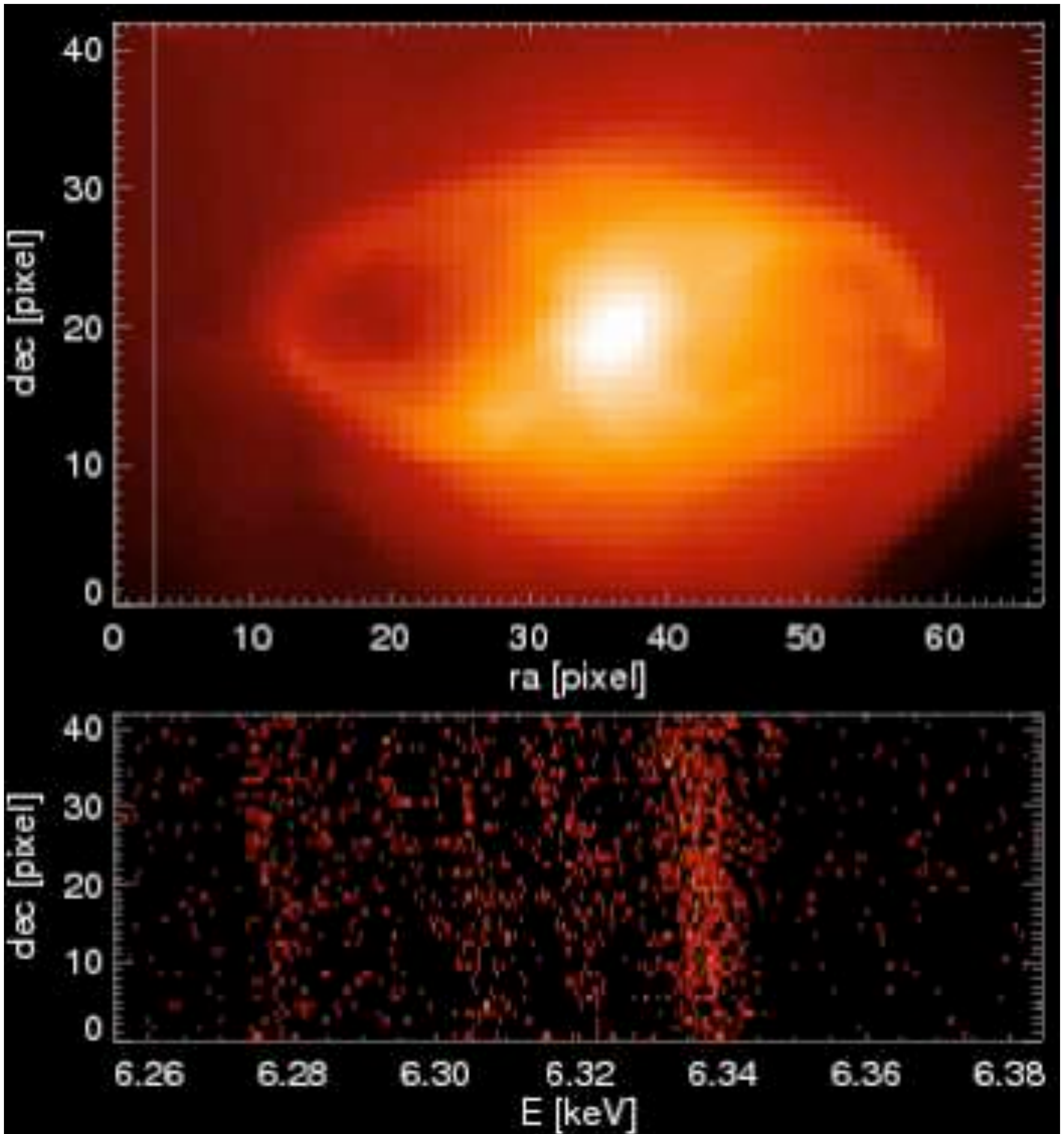
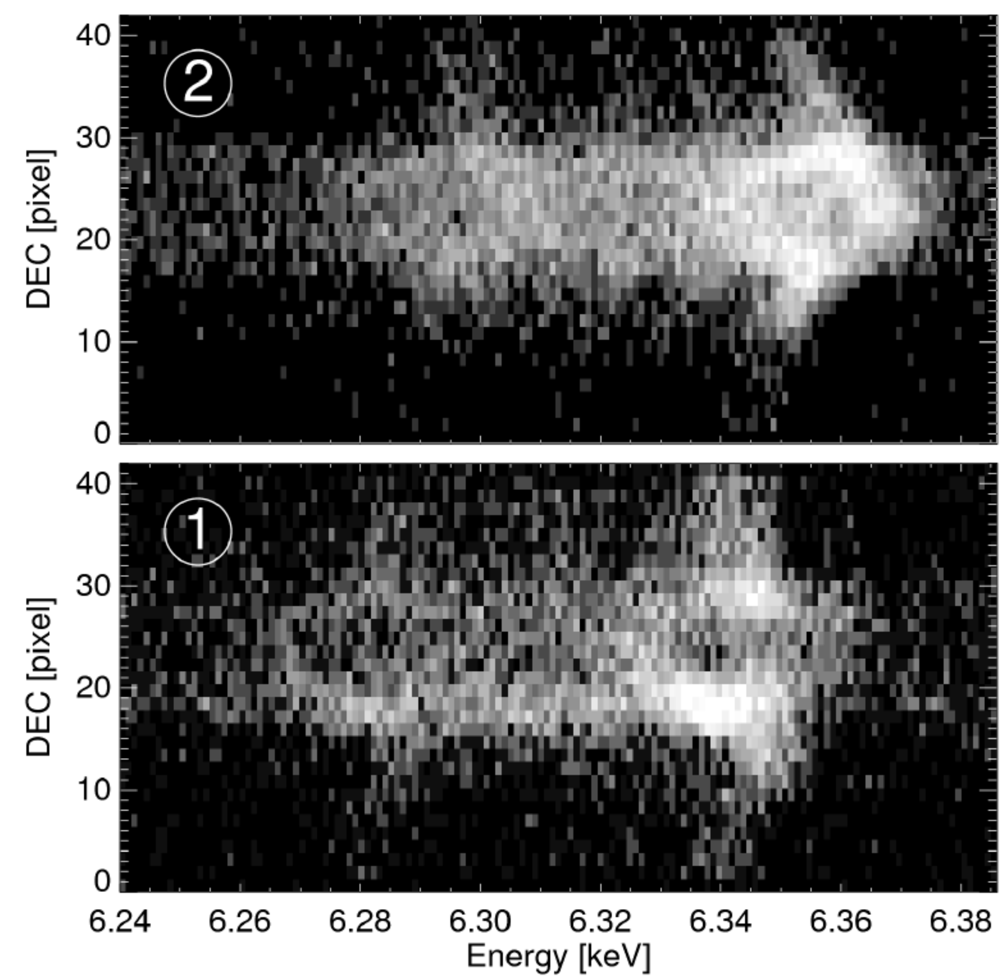


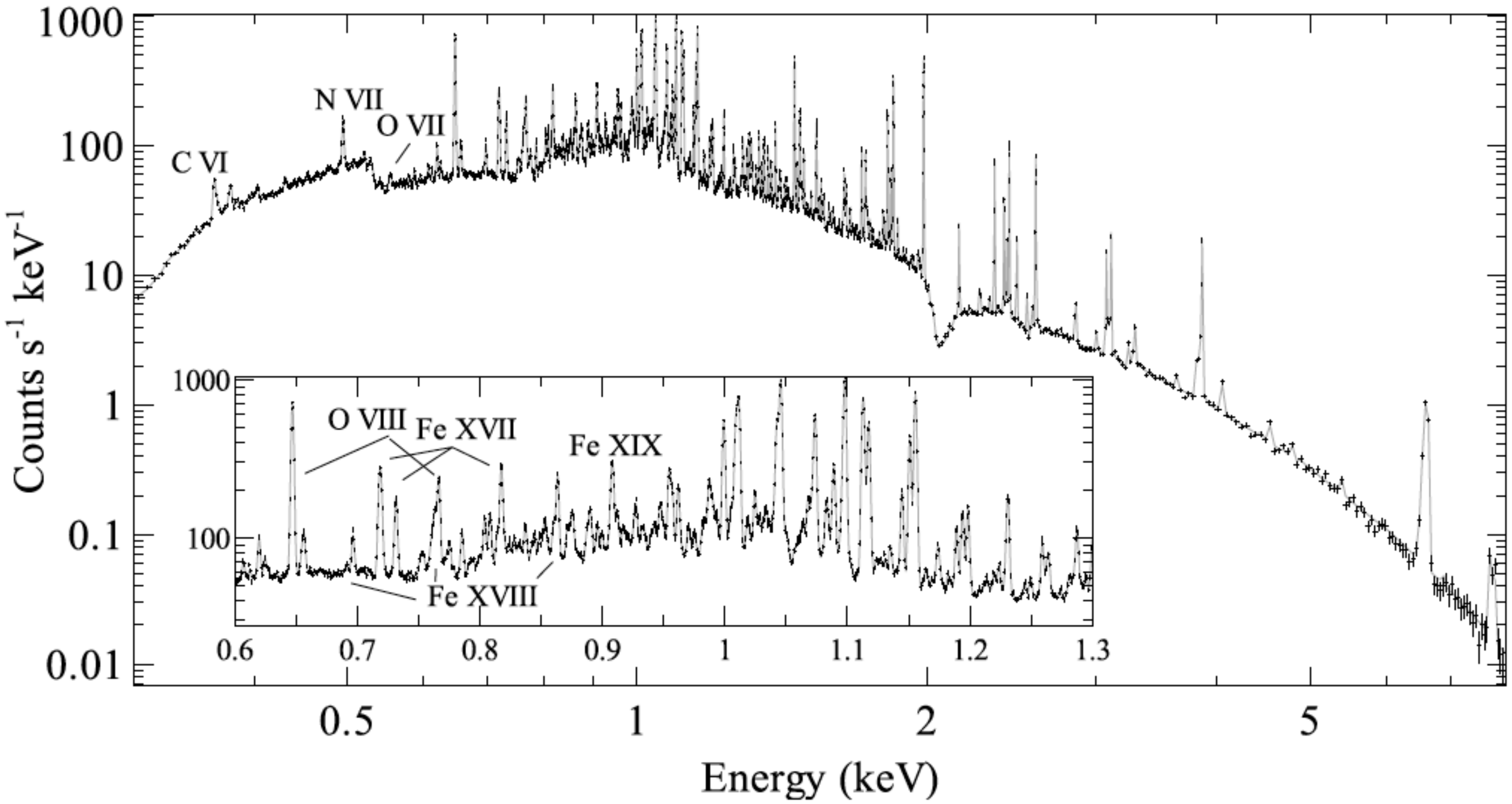

Simulated X-IFU images and spatially-resolved spectra for shells and cavities in Cyg A

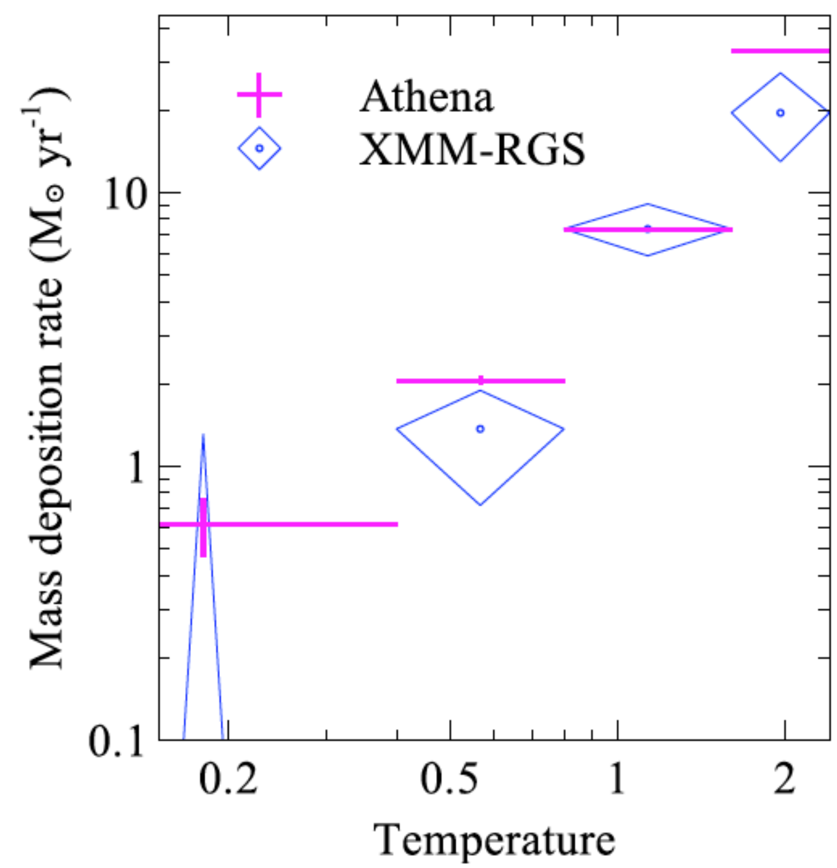


# Mass deposition rate: Athena vs. XMM-Newton

Croston et al., 2013, arXiv:1306.2323

20 ks of simulations of the Centaurus cluster
(with associated estimates of the mass deposition rate




Especially for the coolest lines (labelled) the mass
estimates improve by ~2 orders-of-magnitude

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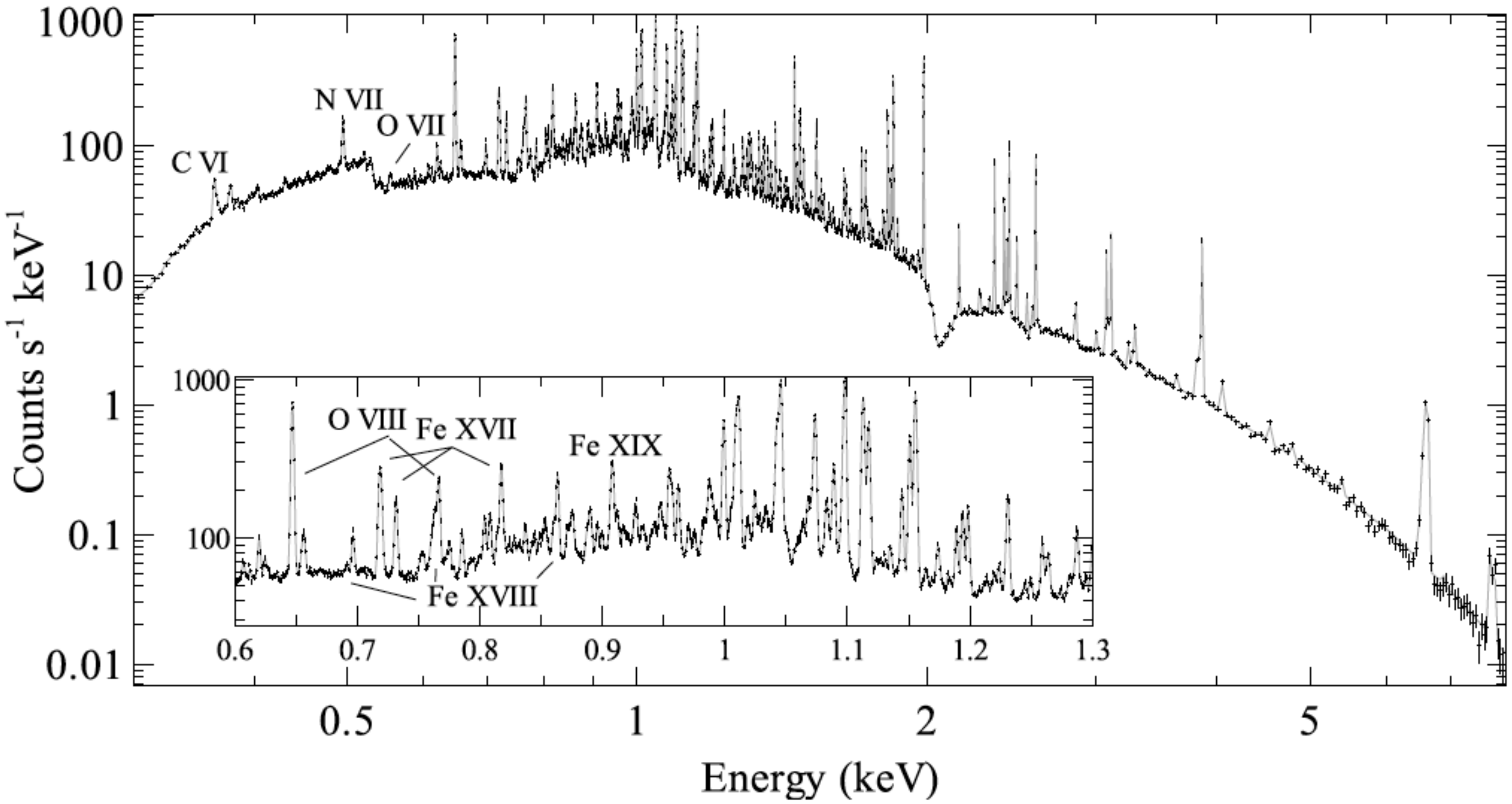


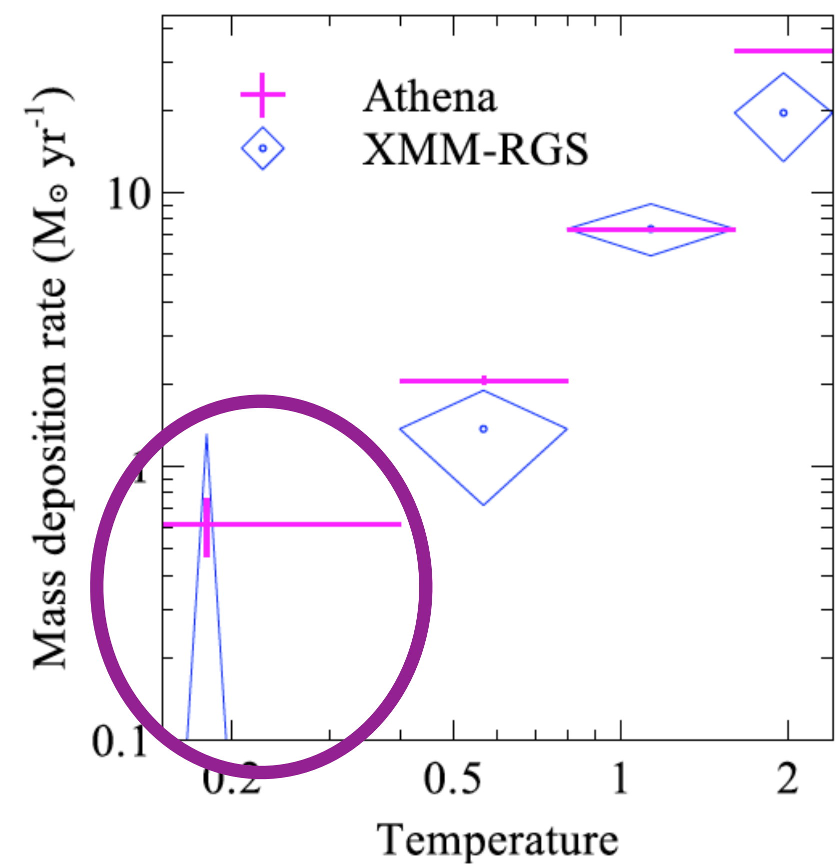


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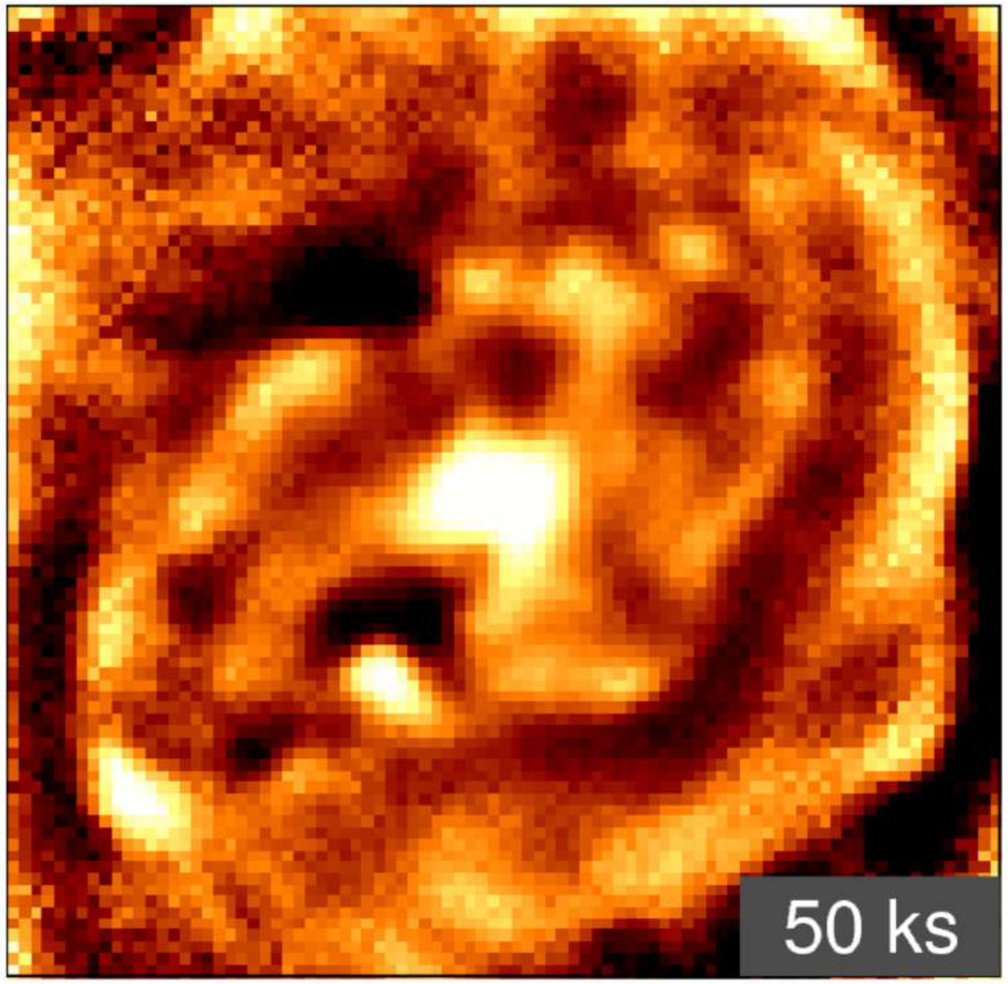
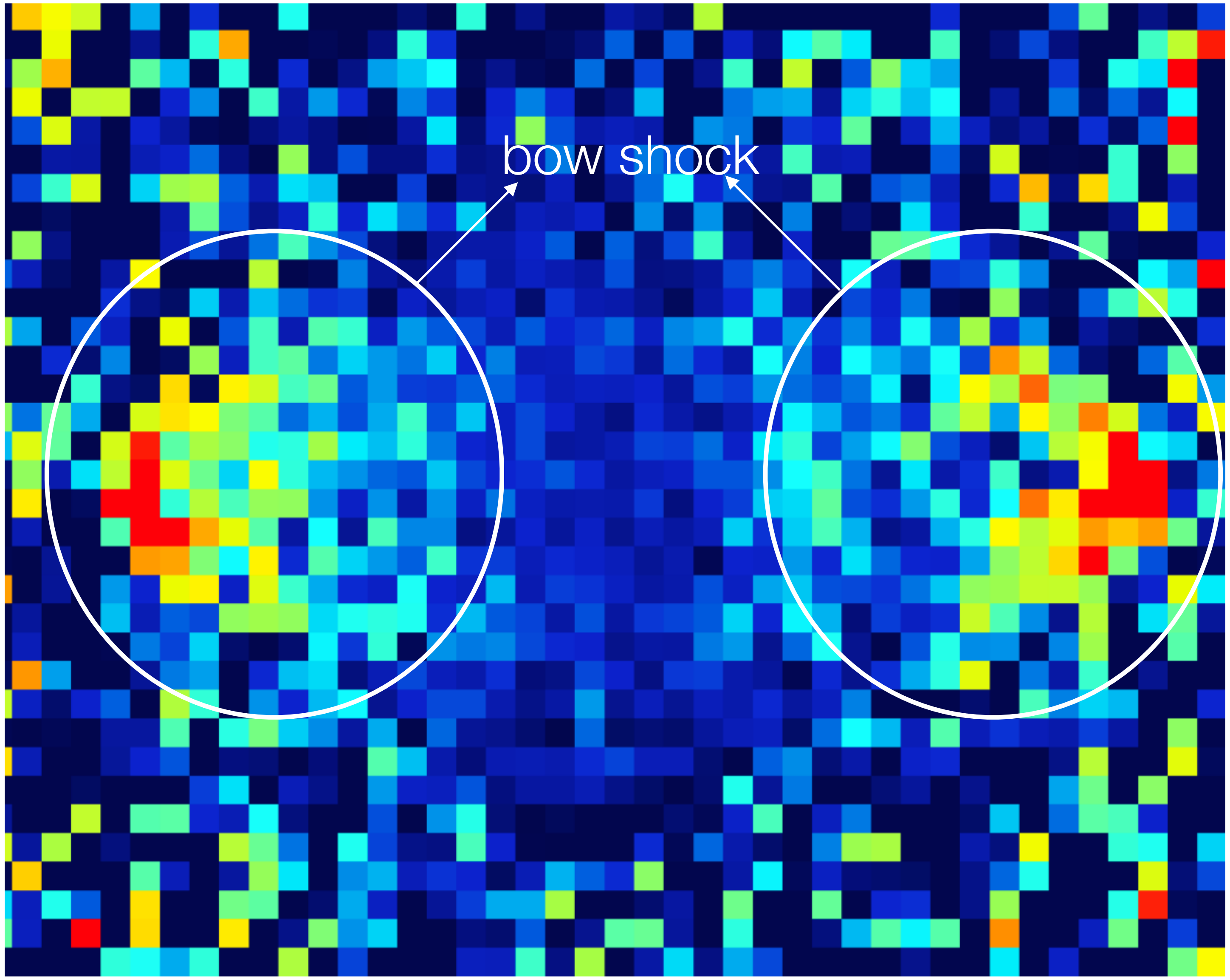
# From local to intermediate redshift Universe

Croston et al., 2013, arXiv:1306.2323

WFI map of ripples and shocks in a z=0.05 galaxy cluster




WFI (20 ks) temperature map of a z=0.1 radio galaxy in a group environment




kT=2 keV  kT=4.5 keV

# Athena programmatic

- As of November 2019 transition to **Phase B1**
  - *"From a community dream (Phase A) to a concrete reality in the ESA Science Program"*
- Adoption: Q4/2021, Launch early 2030s
- A community of over 800 scientists actively supports it
- Designed to address the Hot and Energetic Universe, will impact virtually *all corners of astrophysics*
- **Performance exceeding any existing or planned mission by more than one order-of-magnitude over several parameter spaces**