High-resolution spectroscopy of Active Galactic Nuclei (AGN)

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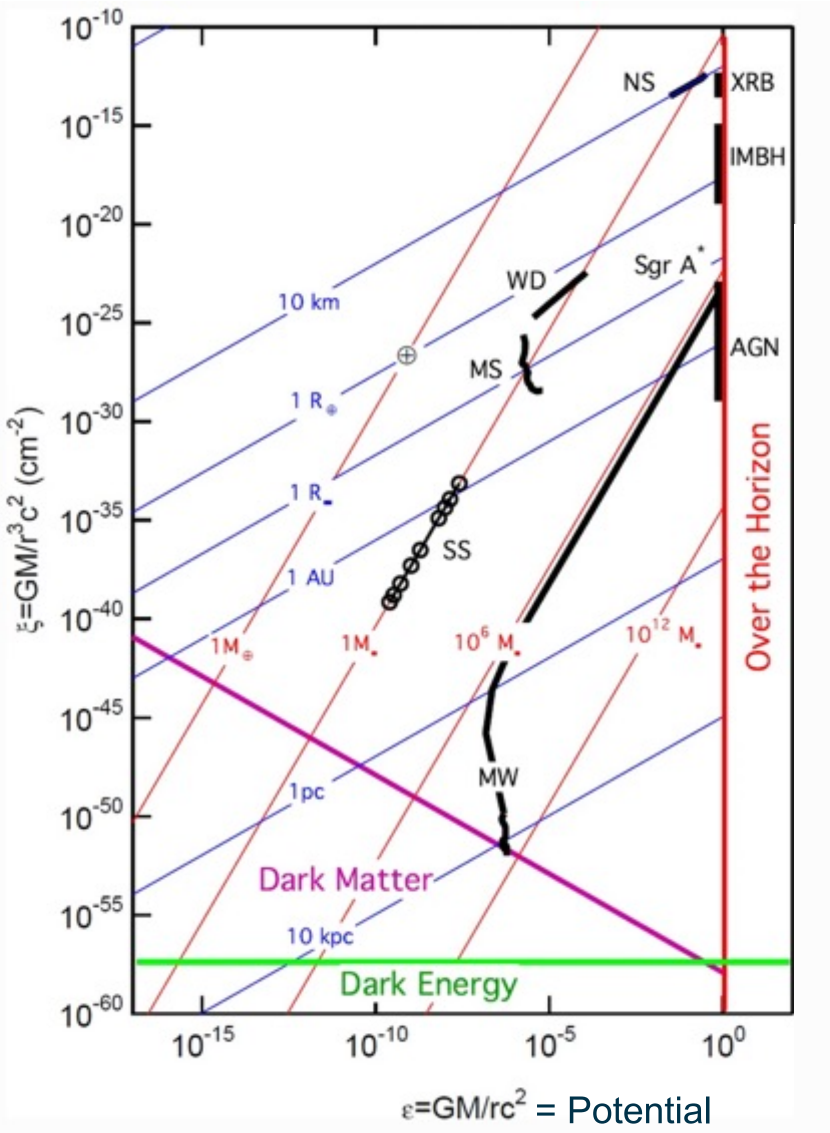
Credit NASA/CXC/A.Hobart

AGN probe General Relativity in the "strong field" regime

Psaltis, 2008, LRR, 11, 9

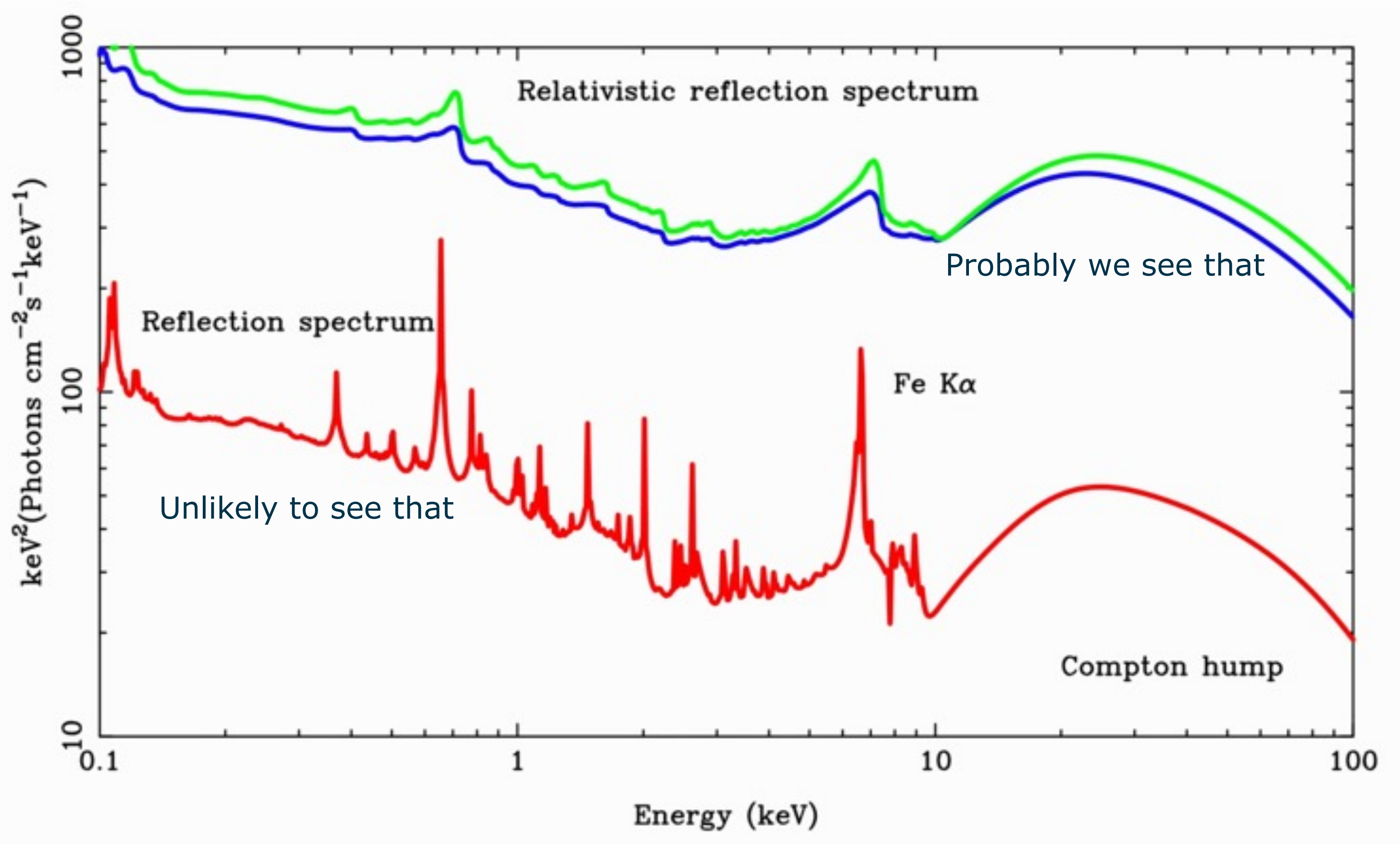
Bambi et al., 2021, SSR, 217, 65

= Space-time curvature



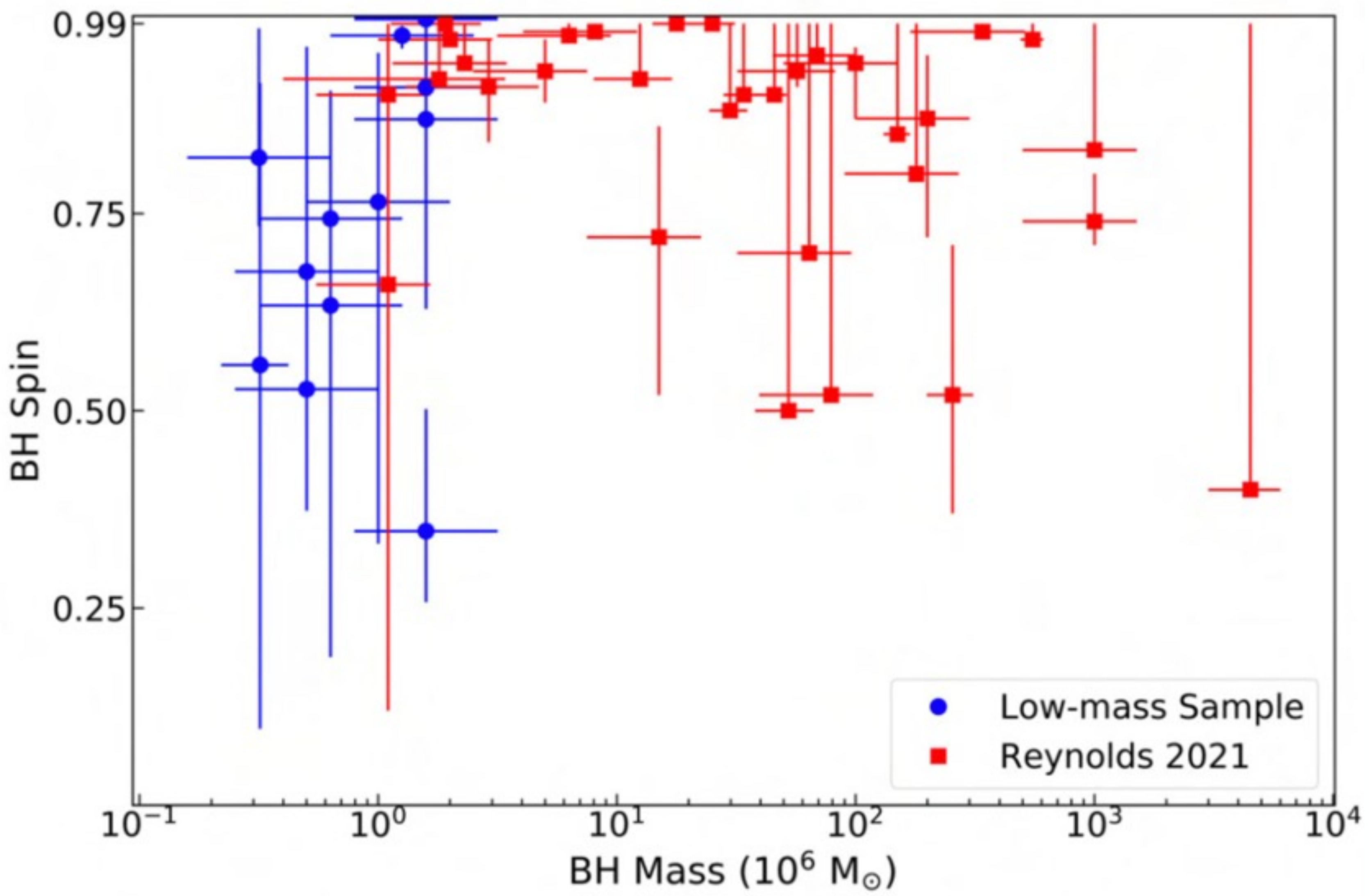
Spectrum of an X-ray illuminated AGN accretion disk

Rest frame vs. GR kernel for a Schwarzschild or Kerr BH



Distribution of AGN BH spin in the local Universe

Mallick et al., 2022, MNRAS, 513, 4361

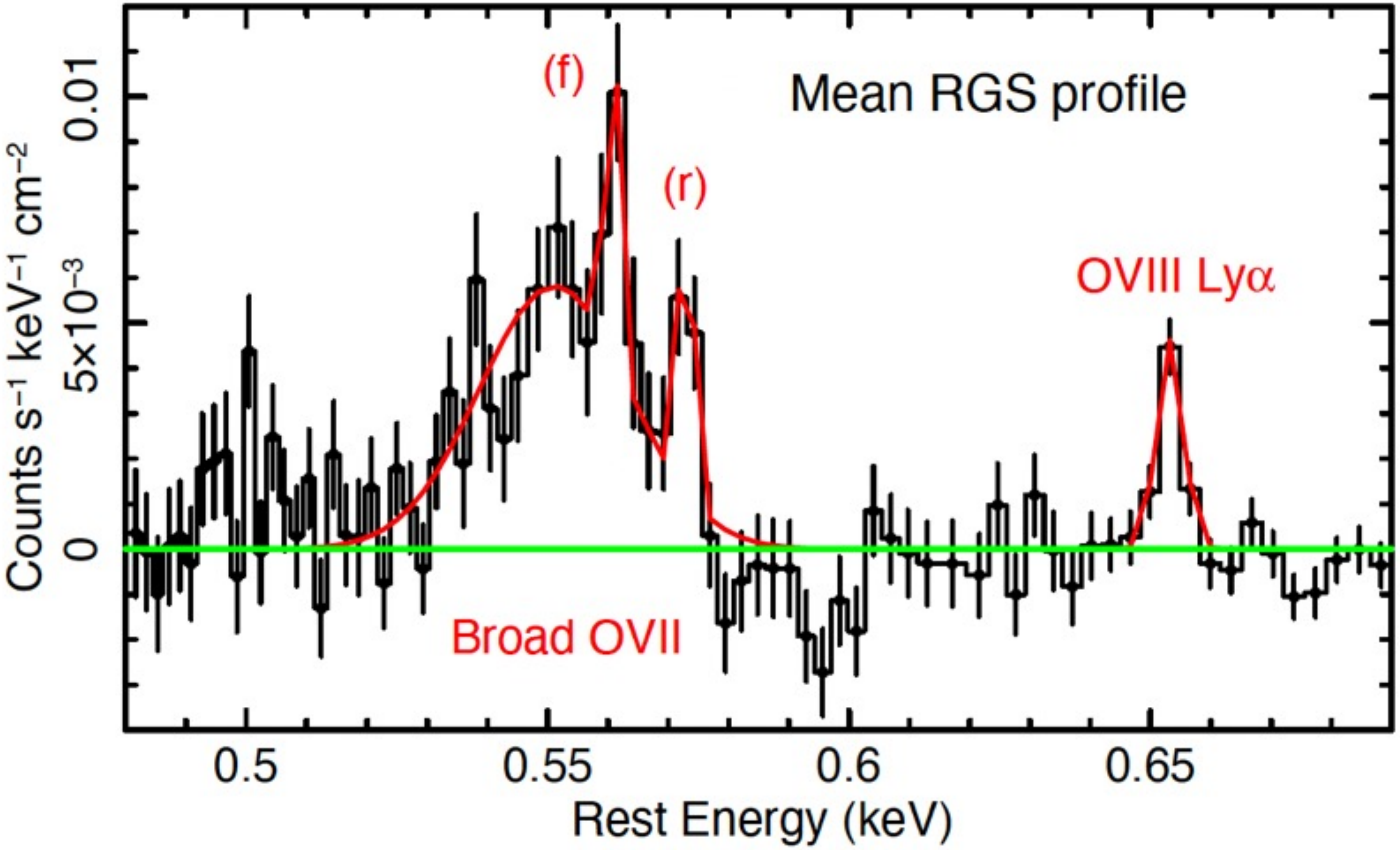


- The distribution of black hole spins in AGN is a fossil remnant of galaxy evolution
- High-spin: coherent accretion
- Low-spin: frequent episodes of [spin-mixing] galaxy mergers

Not a X-ray high-resolution science, but …

Reeves et al., 2021, A&A, 649, L3

RGS spectrum of Mkn110

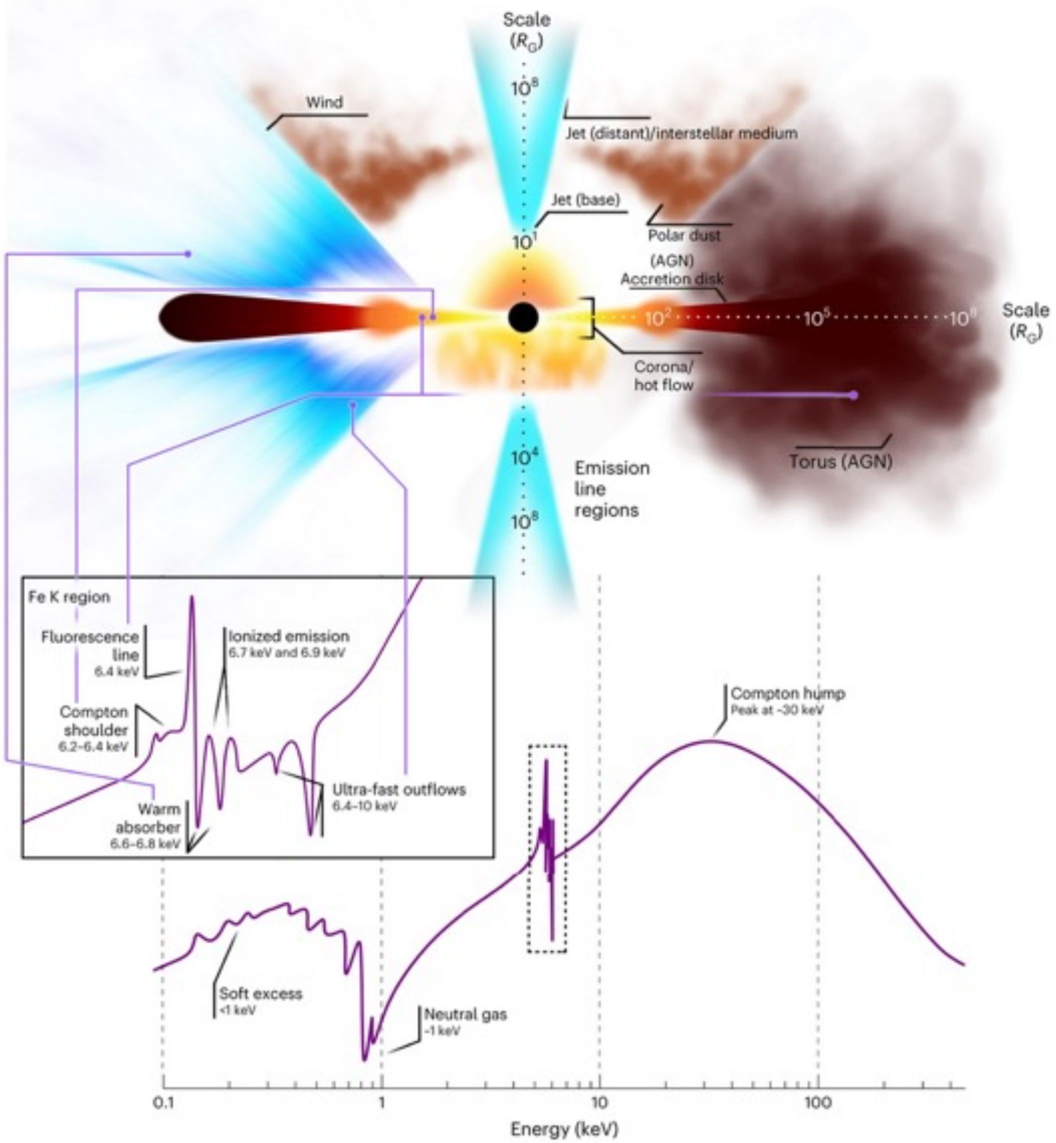


- v_{FWHM} ~ 15,900 km s^{-1}
- Produced at ≤30 R_g
- Density (n_e~3x10^{14} cm^{-3}) consistent with accretion disk theory
- Only two other RGS detections known
- CCD-dominated science prior to the advent of XRISM and NewAthena
[Barret & Cappi, 2019, A&A, 628, 1.
For an iconoclastic view: Parker at el. 2022, MNRAS, 513, 551]

[R_g is the "gravitational radius"]

X-ray spectroscopy uniquely probe the AGN structure

Gandhi et al., 2022, Nature Astronomy, 6, 1364



- AGN are *unresolved* and *unresolvable*
- Important nuclear spatial scales:
  - R_{ISCO}: innermost stable disk orbit
  - $R_{X\text{-}ray}$: X-ray source
  - R_{BLR}: gas in virial motion*
  - R_{dust}: sublimation radius
- Spectroscopy allows us to perform milli-arcseconds (indirect) imaging

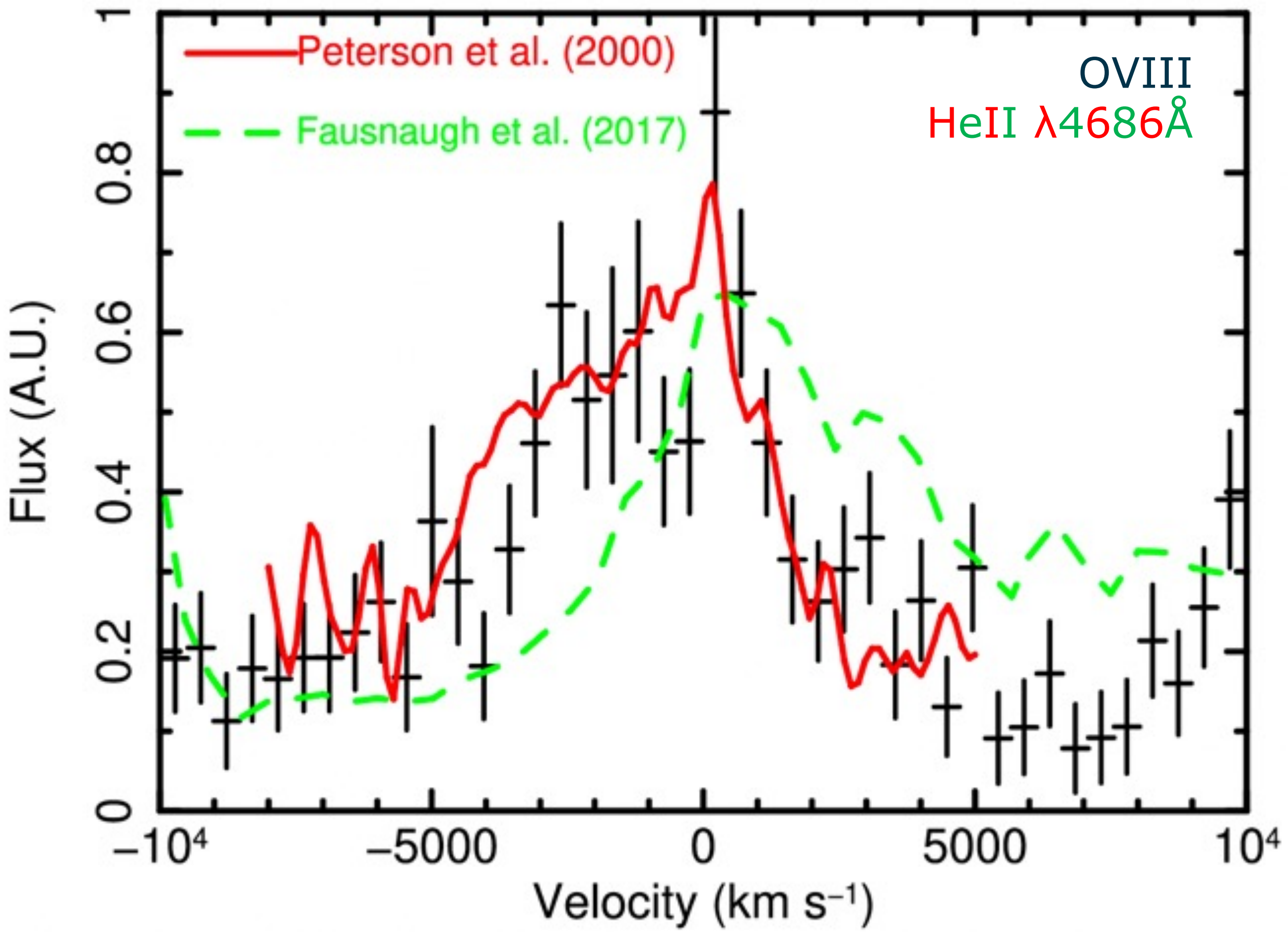
*BLR=*Broad Line Regions*. Emit broad (~10^3 km s^{-1}) emission lines, originally used to identiy AGN in galaxies

X-ray BLR: innermost region of the optical BLR

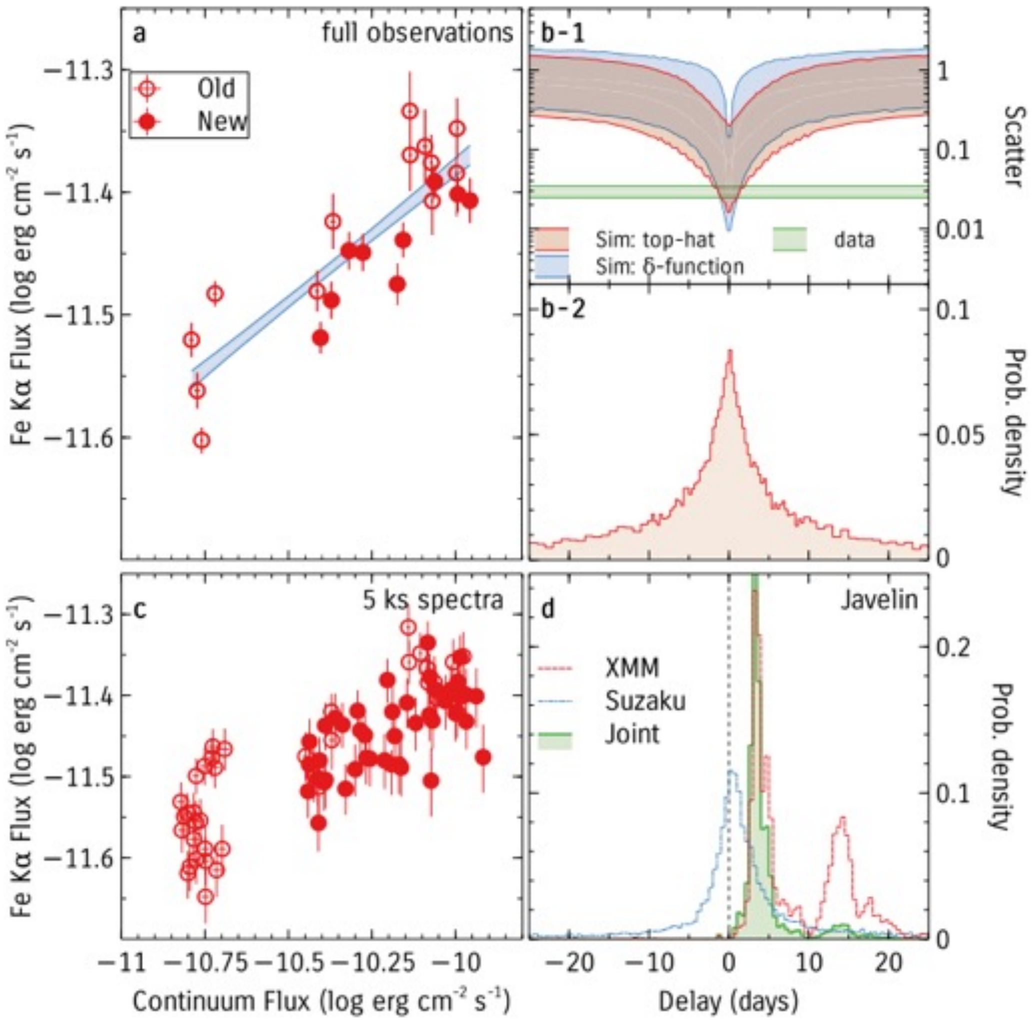
Peretz et al., 2019, ApJ, 879, 102

Zoghbi et al., 2019, 884, 26

X-ray BLR in NGC4051



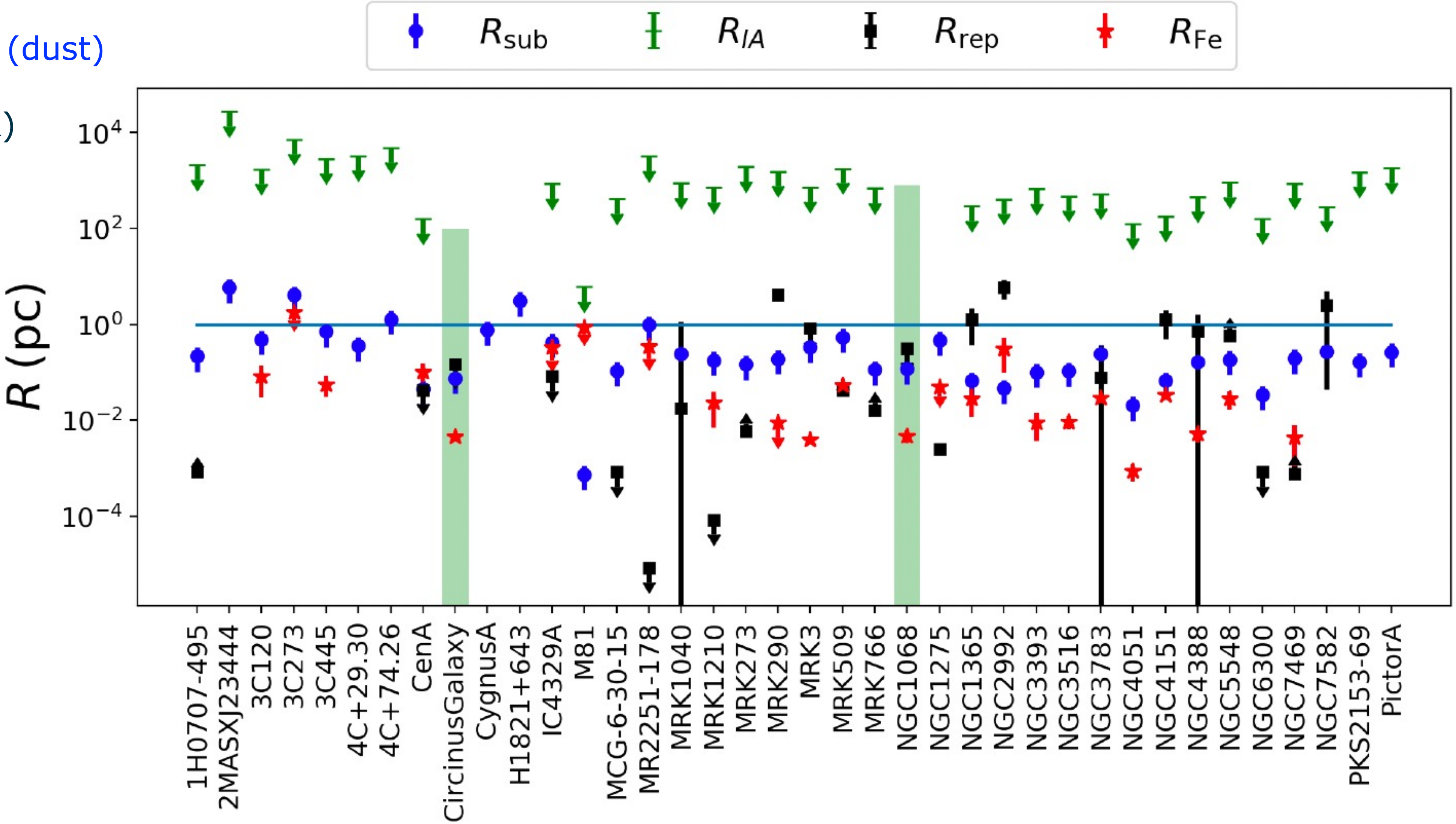
BLR reverberation in NGC4151



Emission region of the K_α fluorescent line

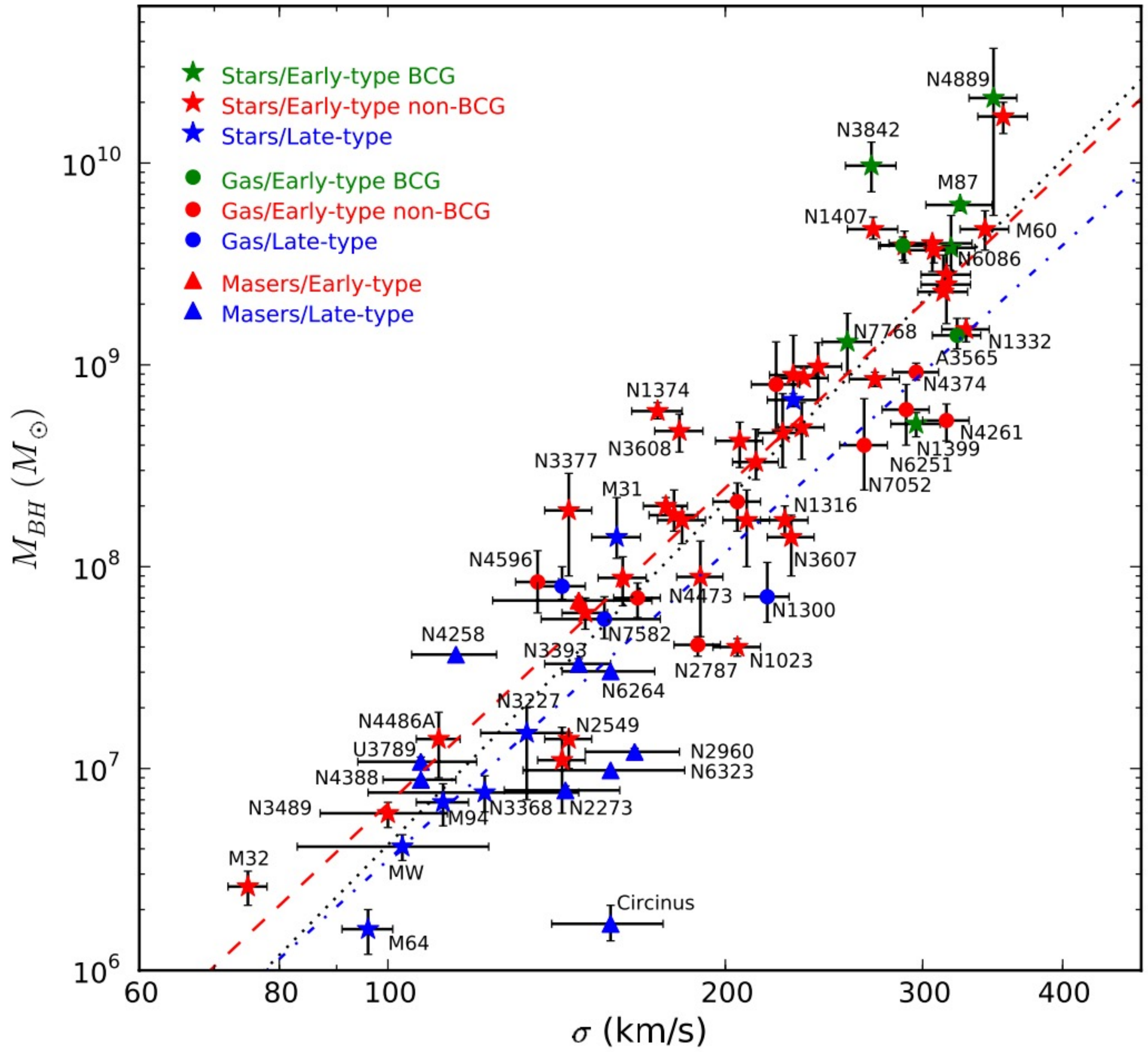
Andoine et al., 2022, A&A, 664, 46

Legenda:
R_{sub}=sublimation radius (dust)
R_{IA}=image radial profile
R_{rep}=reverberation (BLR)
R_{Fe}= Fe K_α line FWHM

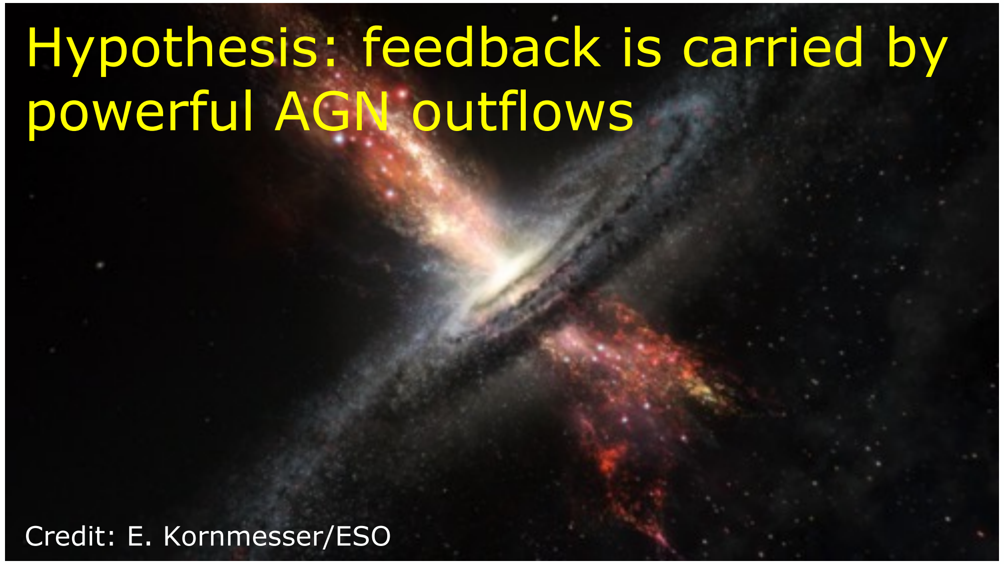


AGN “feedback”

McConnell & Ma, 2013, 764, 1841306.2319



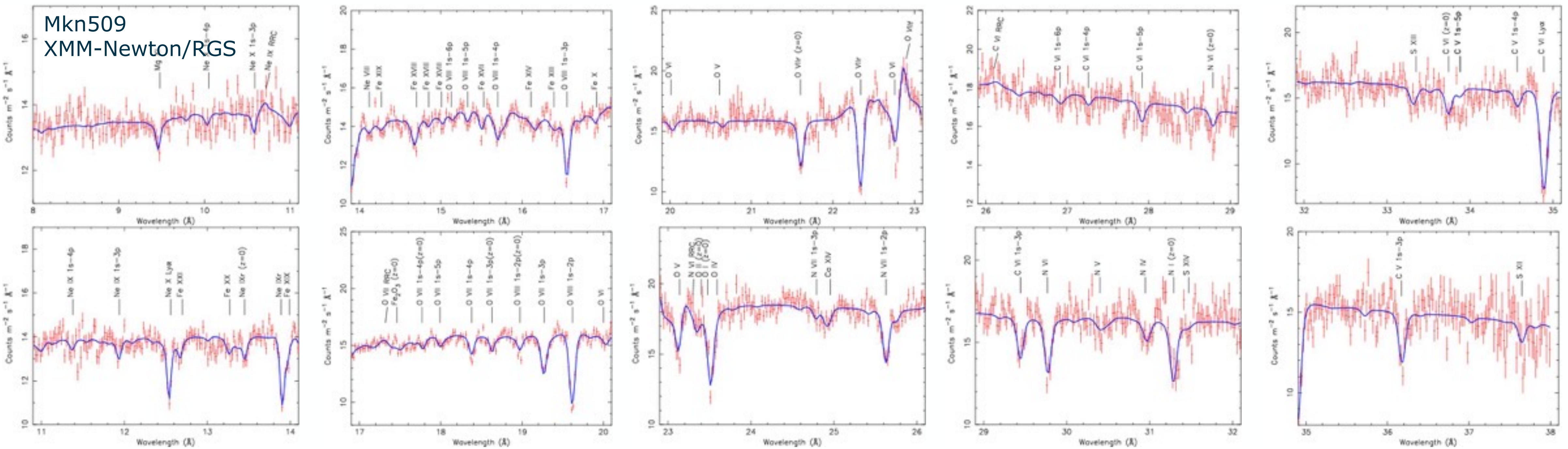
- Tight correlations between the BH mass and quantities related to the galaxy size (here is stellar velocity dispersion) in massive bulges
- Strong evidence for a causal relation between BH grow and star formation: “**AGN feedback**”



Credit: E. Kornmesser/ESO

Absoprtion-dominated AGN X-ray spectra

Detmers et al., 2011, A&A, 534, 38



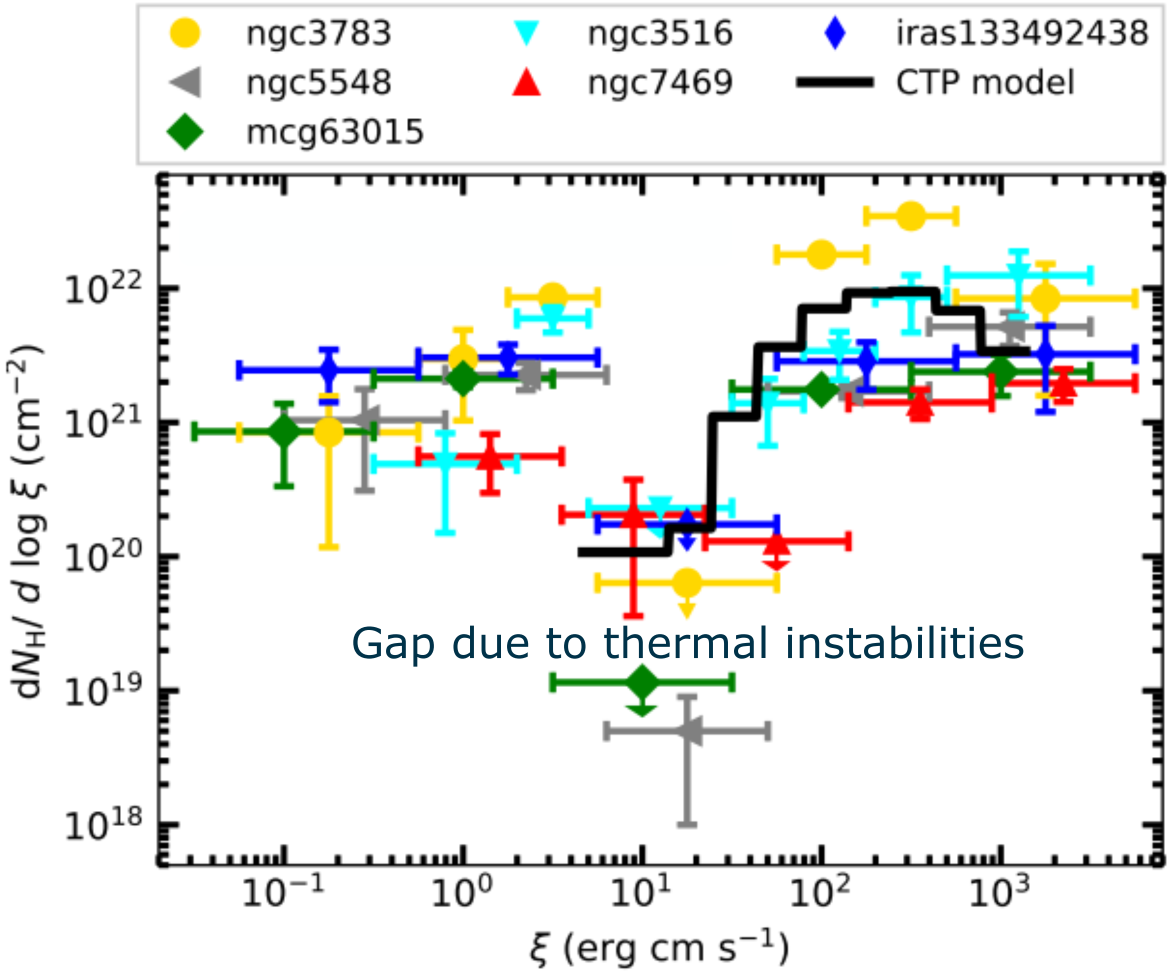
- Resonant absorption lines from He- and H-like ions from C (0.3 keV) to Fe (~7.0 keV)
- Detected in ~3/4th of nearby AGN [Laha, Guainazzi et al., 2014, MNRAS, 441, 2613]
  - Fundamental constituent of the accretion disk/BH coupling
- Wide range of velocities (10^{3-5} km/s), column densities (10^{20-24} cm^{-2}), ionization states

The physics of X-ray outflows is *mostly* known

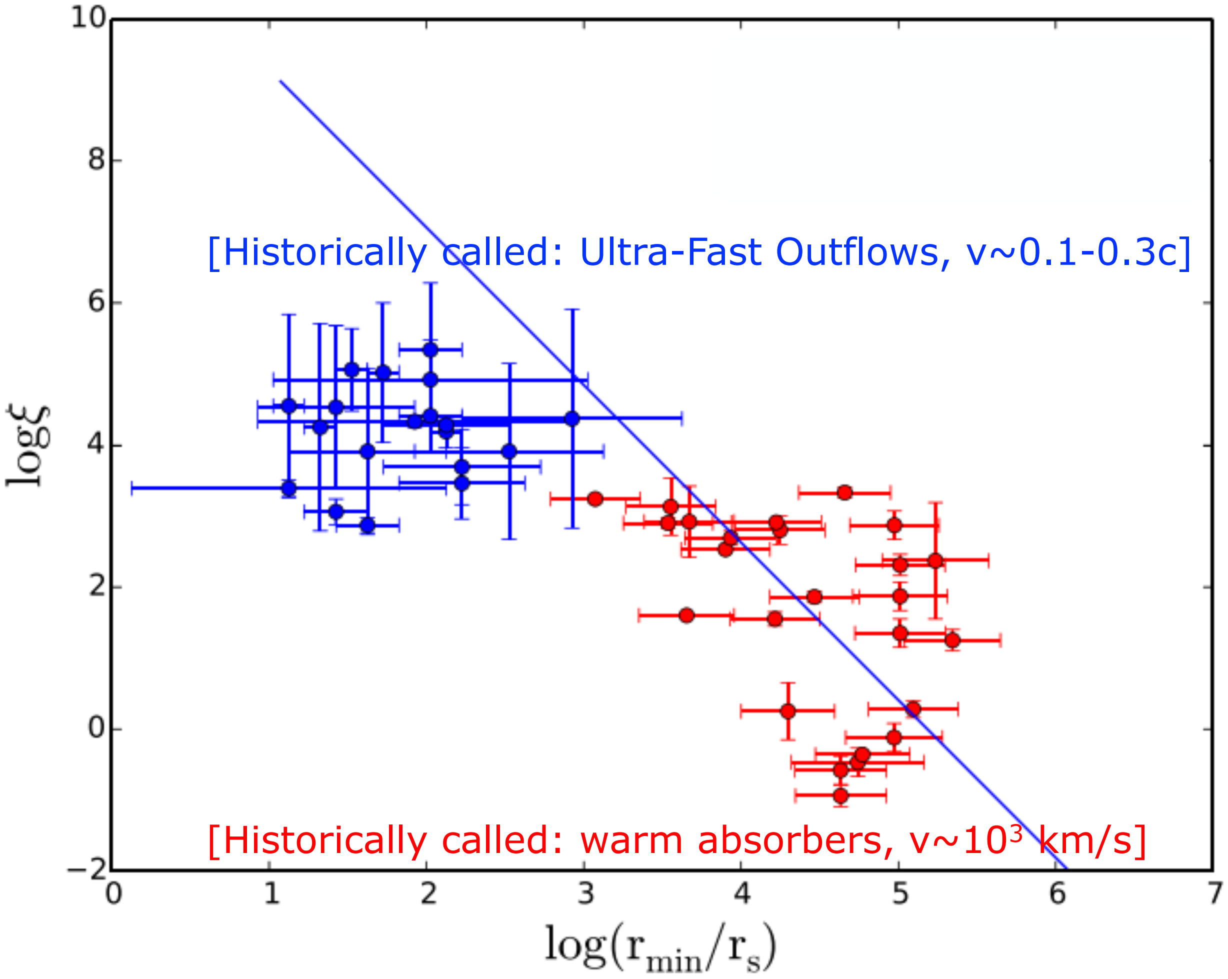
Adhikari et al., 2019, ApJ, 881, 78

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

Absorption Measure Distribution



Estimated launching radius



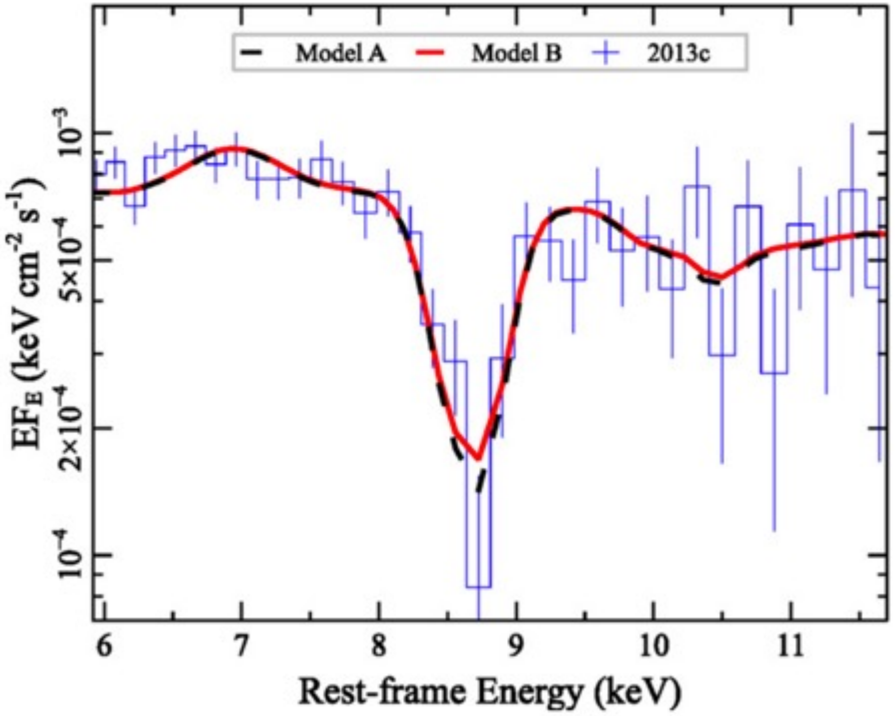
Most UFO measurements are at CCD resolution

Gofford et al., 2013, MNRAS, 430, 60

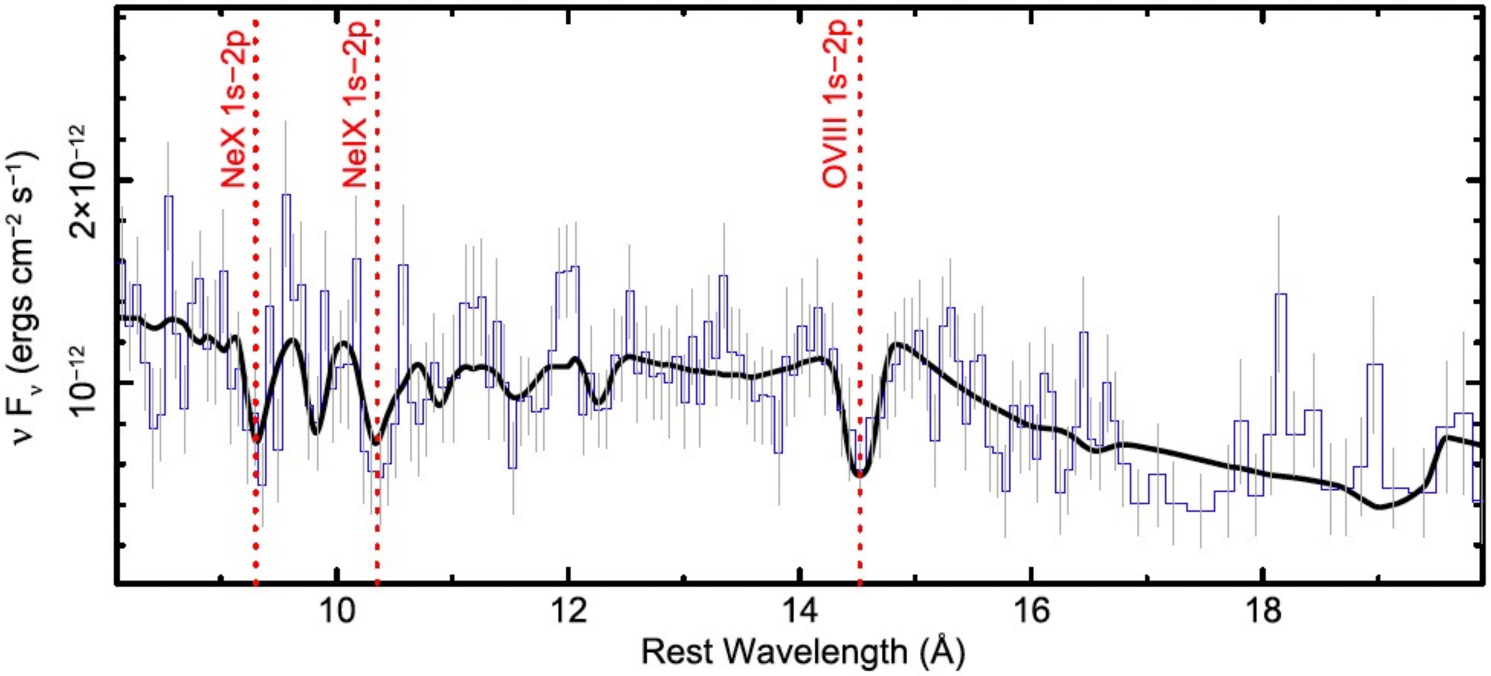
Reeves et al., 2020, ApJ, 895, 37

Spectra of the UFOs in **PDS456** (the brightest AGN in the local Universe)

Suzaku/XIS (v_{out}~0.261±0.007)



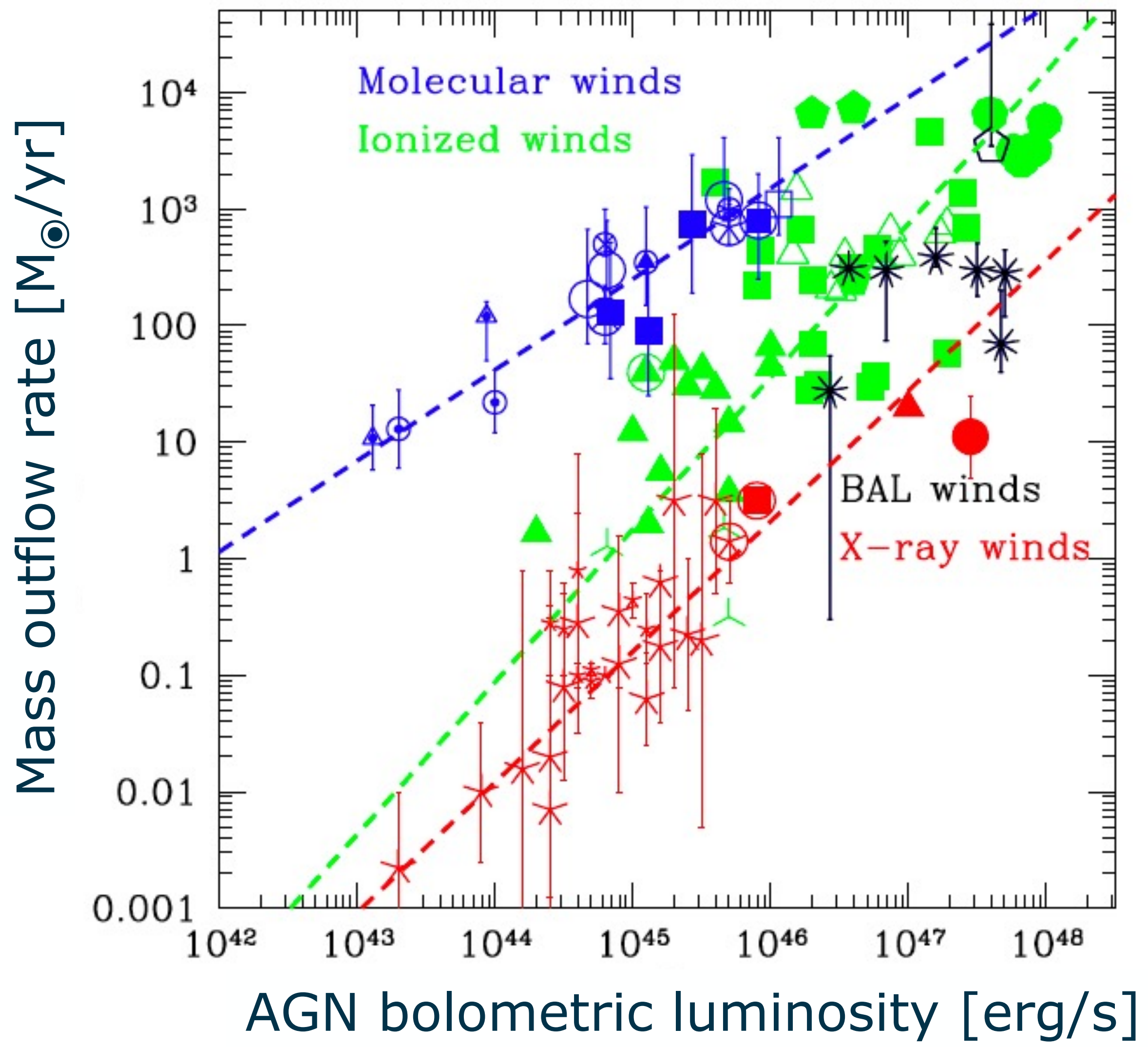
XMM-Newton/RGS (v_{out}~0.258±0.003)

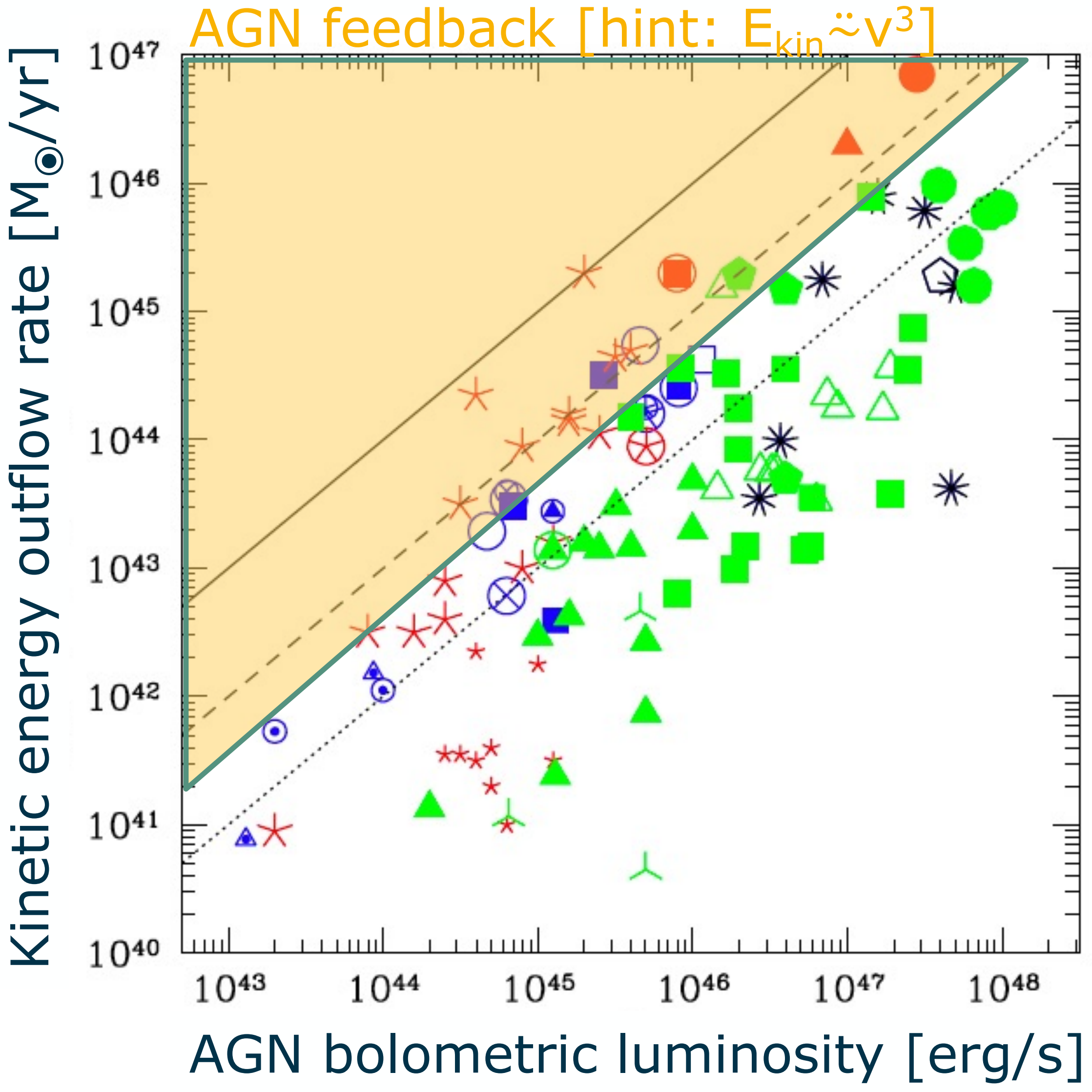


CCD-resolution dominated science before the advent of XRISM and NewAthena

Feedback effect of galactic outflows

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

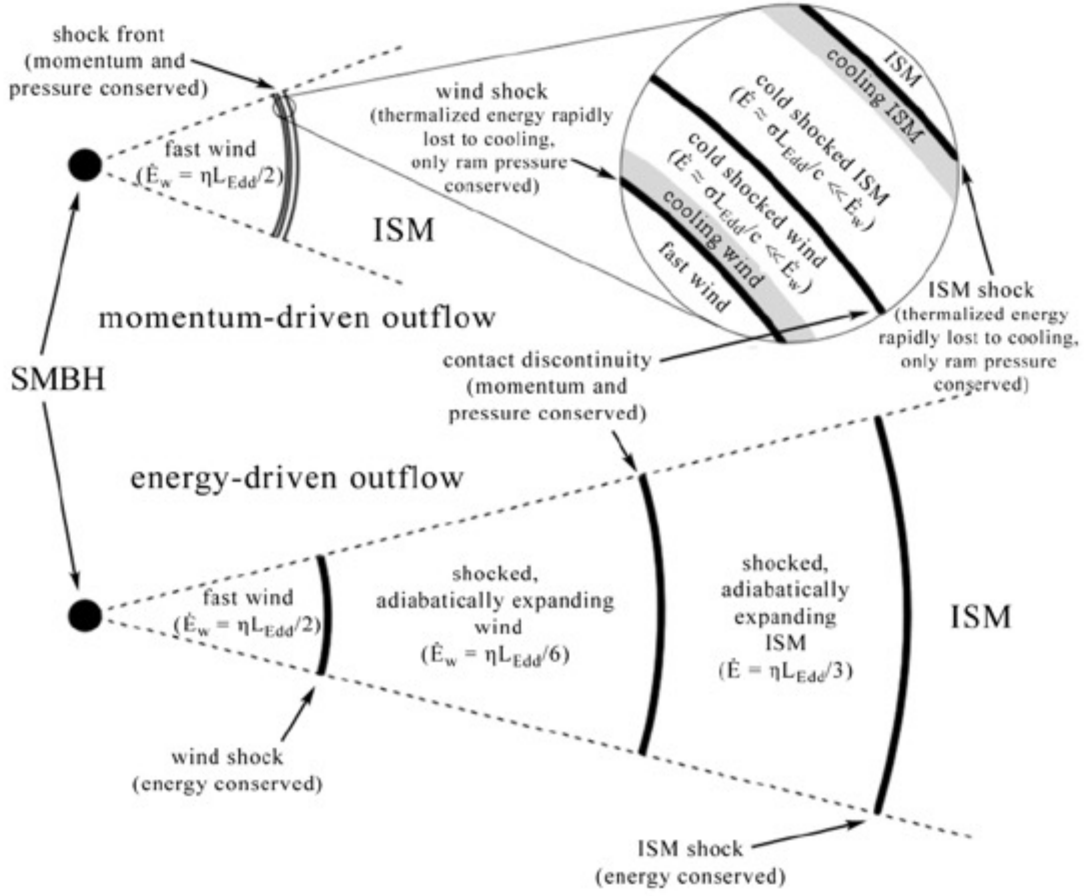




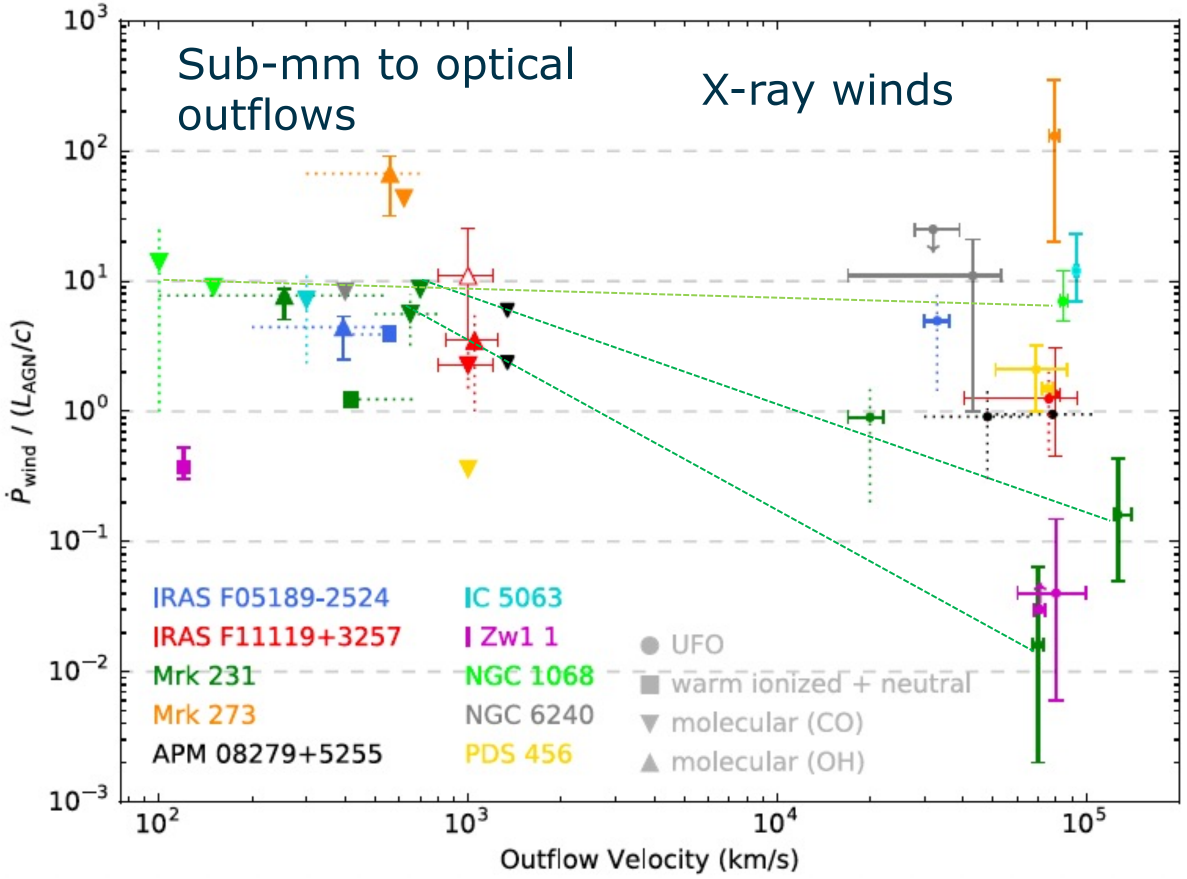
Connecting feedback at all scales

Zunovas & King, 2012, ApJL, 745, L34

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



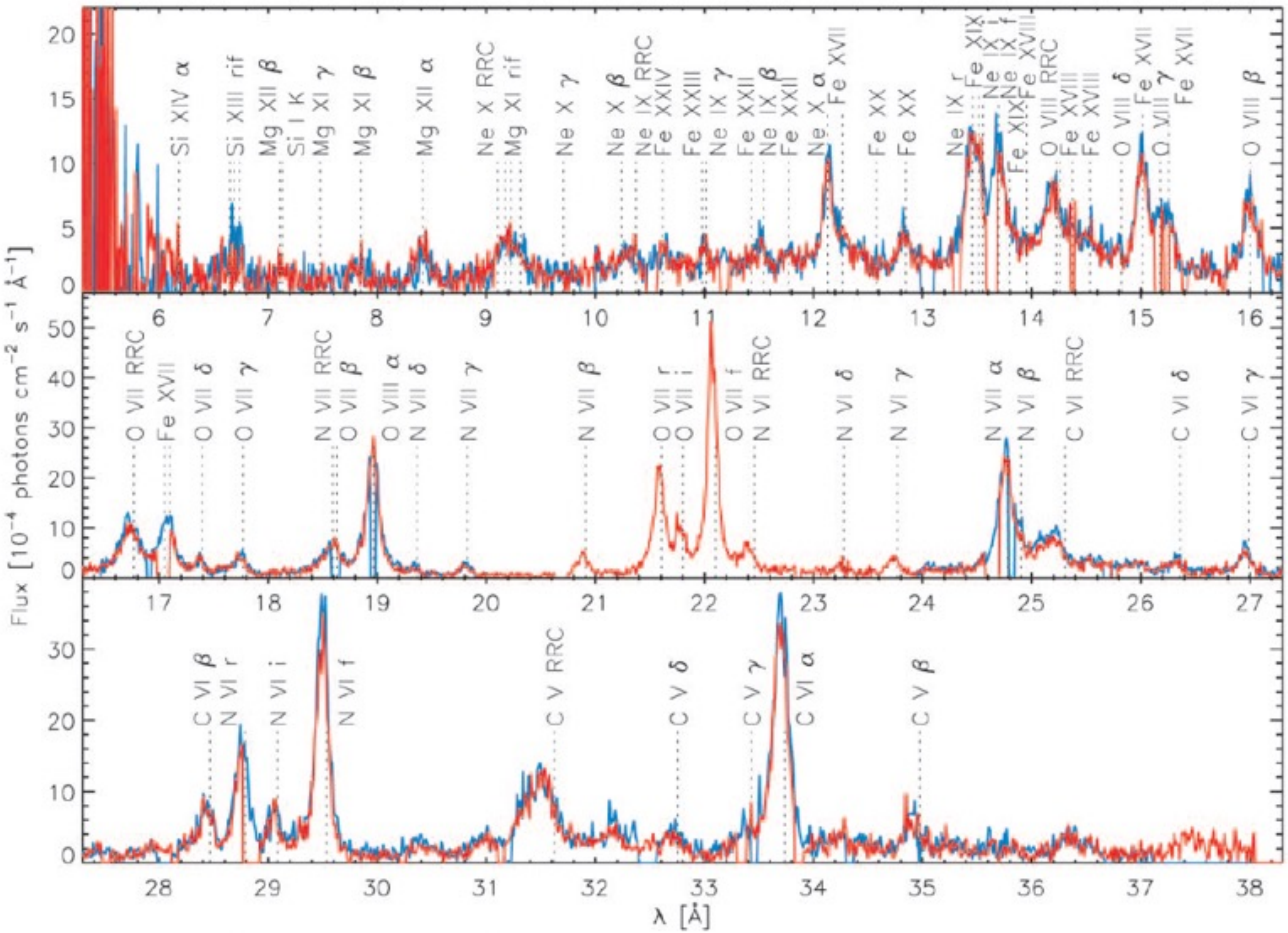
Outflow momentum rate vs. wind velocity



Do outflows conserve momentum or energy? Key unsolved question for feedback

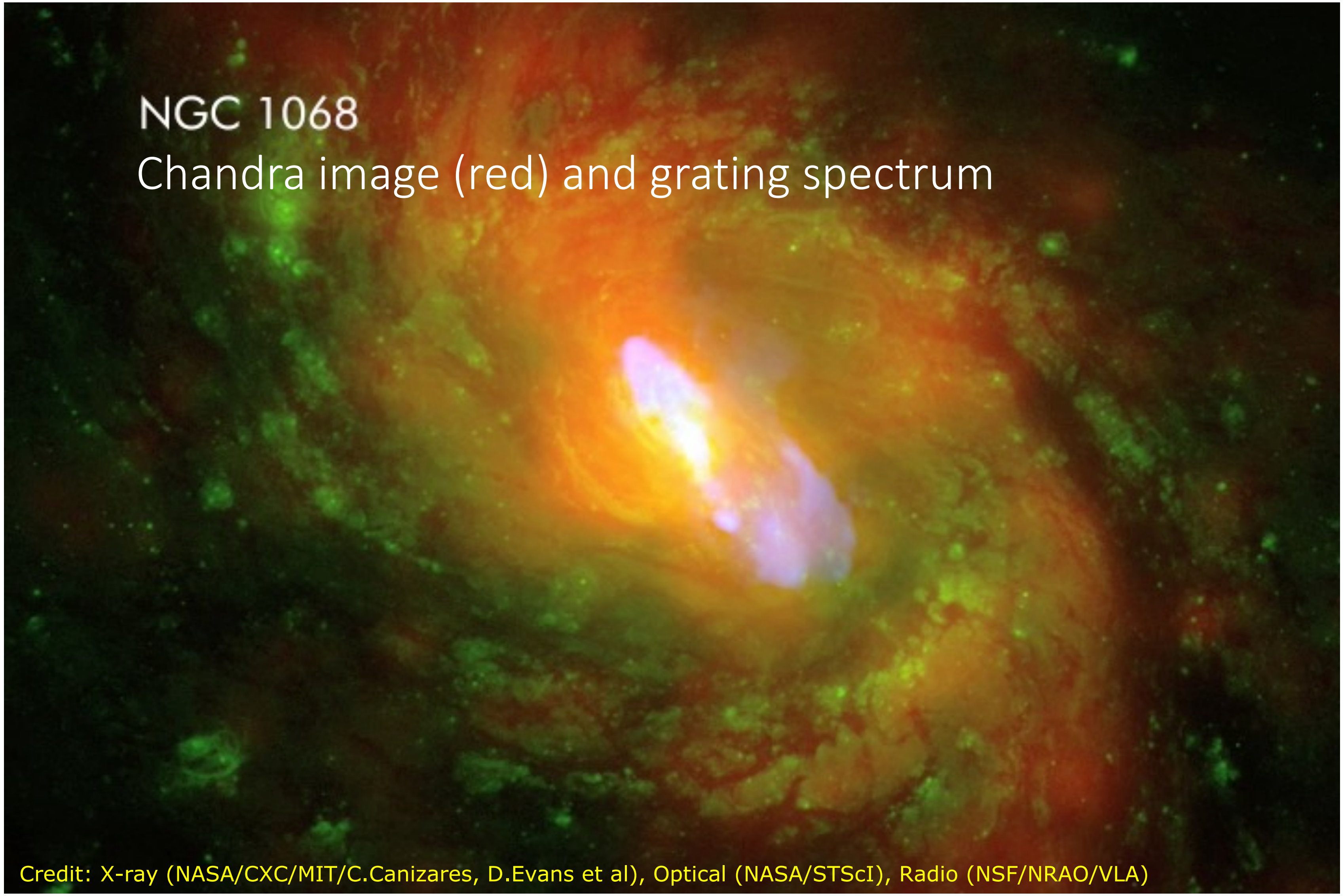
Emission-line dominated AGN spectra (RGS view)

Kinkhabwala et al., 2002, ApJ, 575, 732



- The deepest emission-line dominated X-ray spectrum of an AGN: NGC1068
- Unveiled when the direct AGN emission is obscured
- Photoionized plasma by the AGN radiation field
- Prototypes of all heavily absorbed AGN
  [Guainazzi & Bianchi, 2007, MNRAS, 374, 1290]
- Benchmark for atomic physics

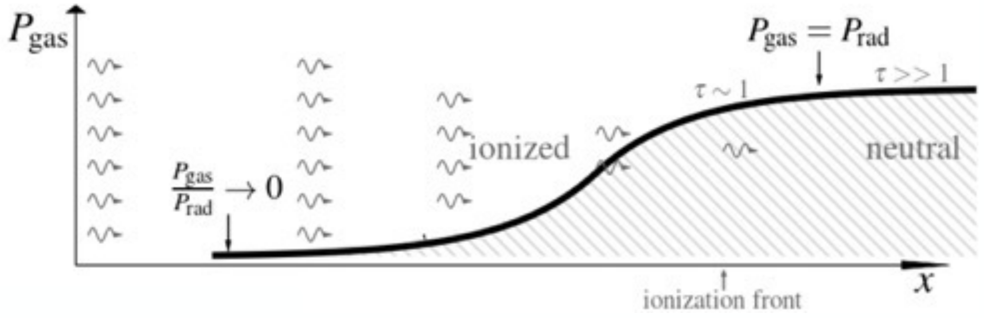
Emission-line dominated AGN spectra (*Chandra*)



- Spectra are produced by diffuse gas in the nuclear environment (≲1 kpc)
- Seen also in the optical "Narrow-Line Regions" and ionisation cones
- Moderately (~500 km s^{-1}) outflowing gas
  [Grafton-Waters et al., 2021, A&A, 649, 162]
- X-rays spatially coincident with [OIII] (optical) and jet (radio)
  [Bianchi, Guainazzi, Chiaberge, 2006, A&A, 448, 499]

Radiation Pressure Compression (RPC)

Stern et al., 2014, MNRAS, 445, 3025



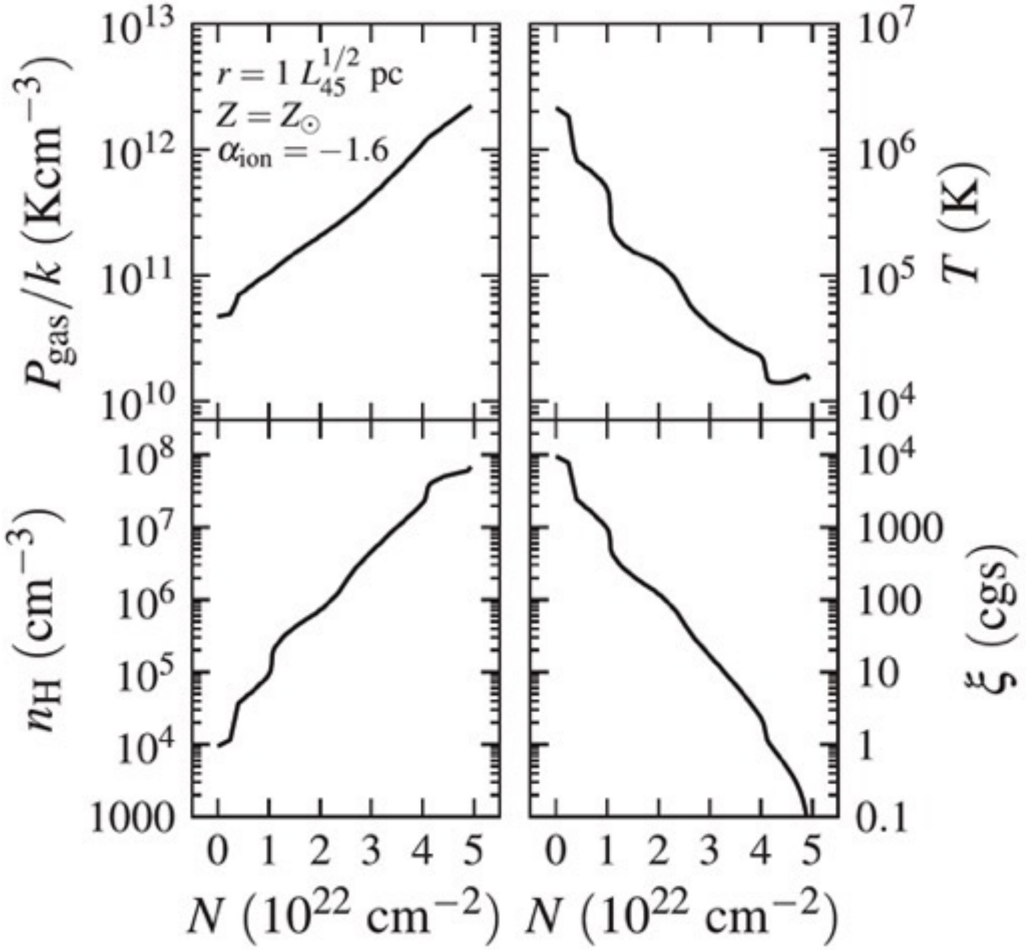
Let's take a gas cloud where:

1. radiation is the strongest force applied
2. *$P_{rad} \gg P_{gas,0}$*

It follows:

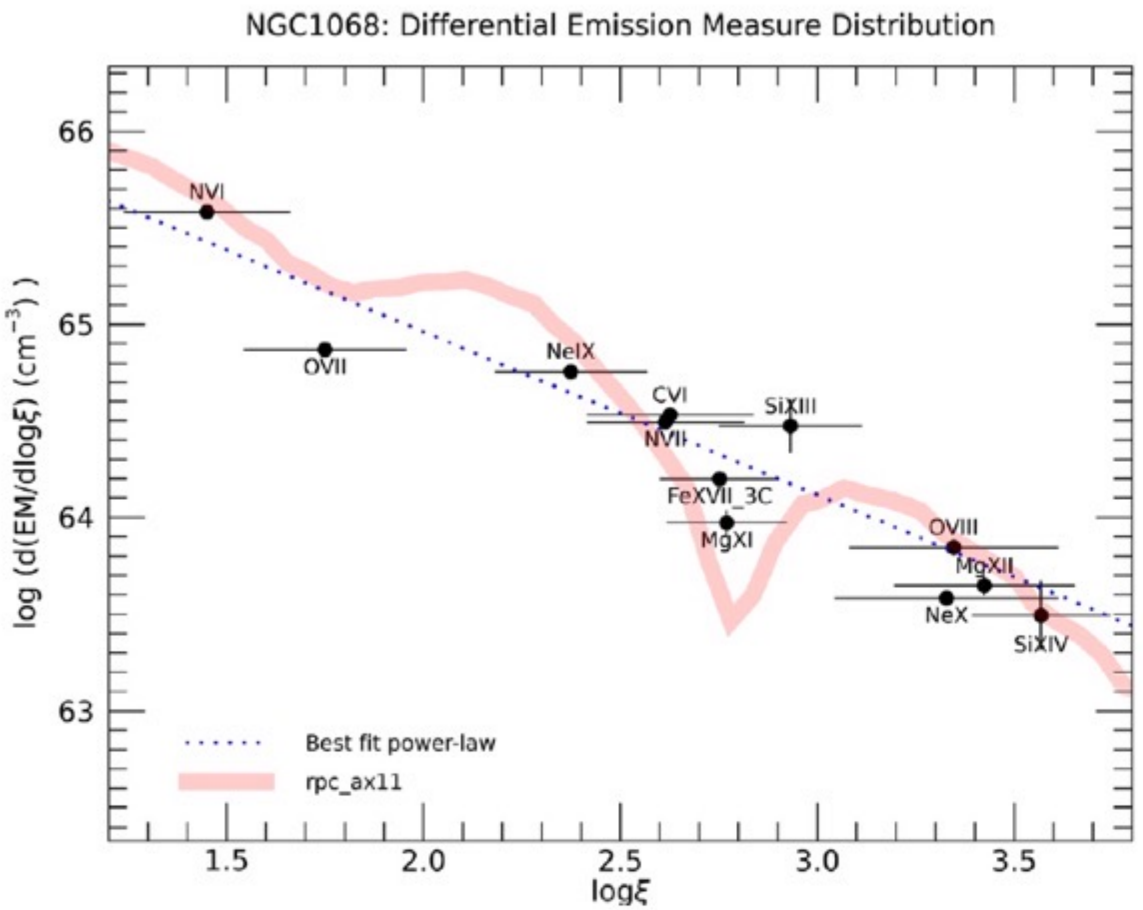
- At the ionisation front, $P_{gas}=P_{rad}$
- Wide range in N_H, kT, and ξ
    - co-spatial emission of a wide range of ions
- Differential Emission Measure determined by the hydrostatic equilibrium of the cloud
    - almost "free parameters-free"

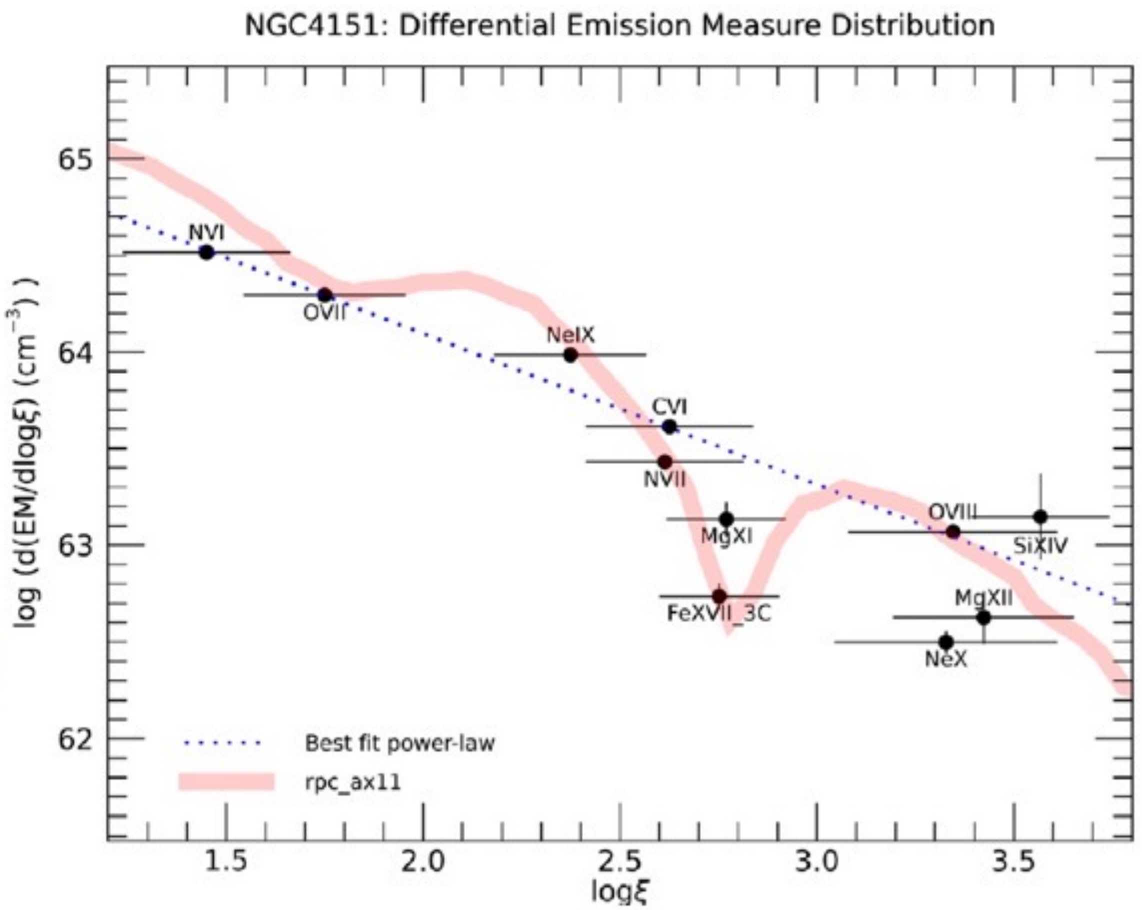
Structure of RPC cloud



Universal DEM describes well high-quality AGN spectra

Bianchi, Guainazzi, et al., 2019, MNRAS, 485, 416





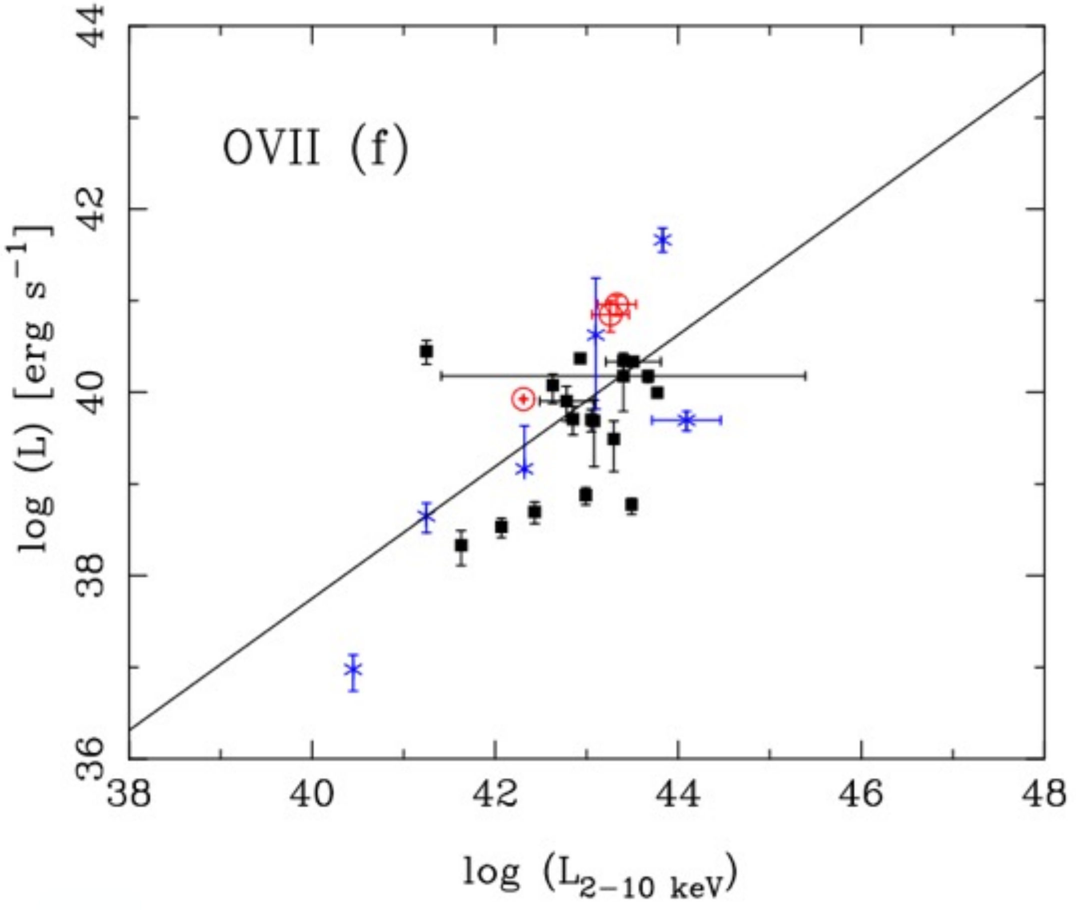
Similarly good fits on other 14 sources (these are just the highest-quality spectra)

Most likely, produced in the *innermost* NLR

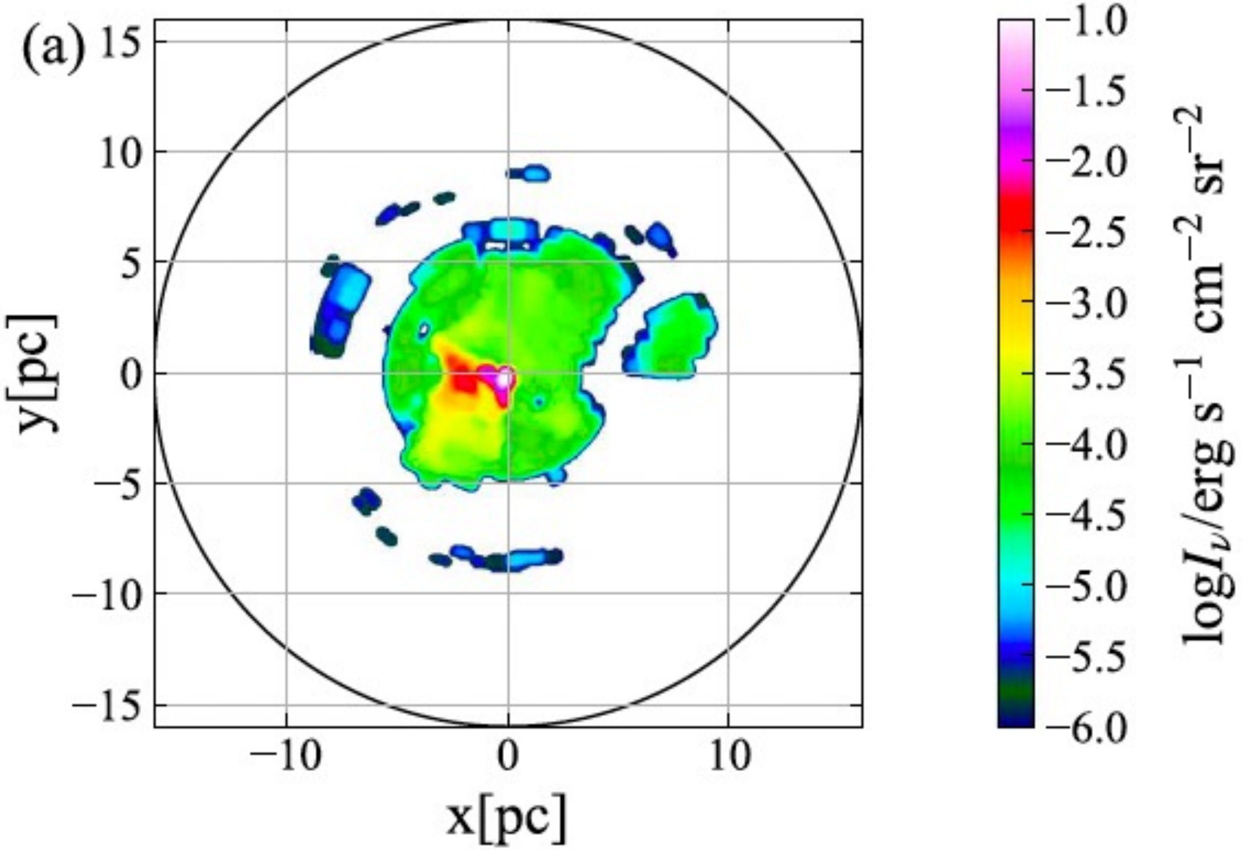
Reynaldi et al., 2020, MNRAS, 499, 5107

Ogawa et al., 2022, ApJ, 925, 55

X-ray lines correlate more strongly with AGN than with optical line luminosity



Radiation-driven torus "fountain models" predict a very concentrated OVIII emission

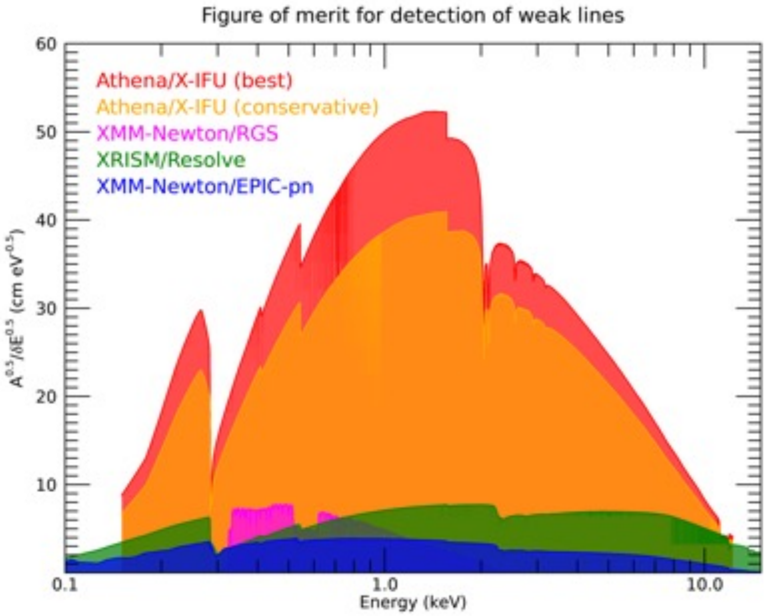


“Whereof what's past is prologue”

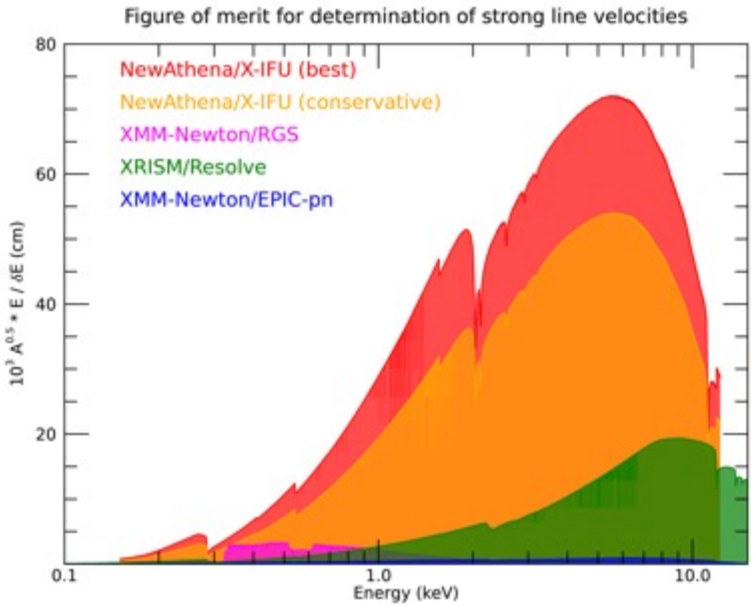
W. Shakespeare, “The tempest”

Future spectroscopic performance Figures-of-merit

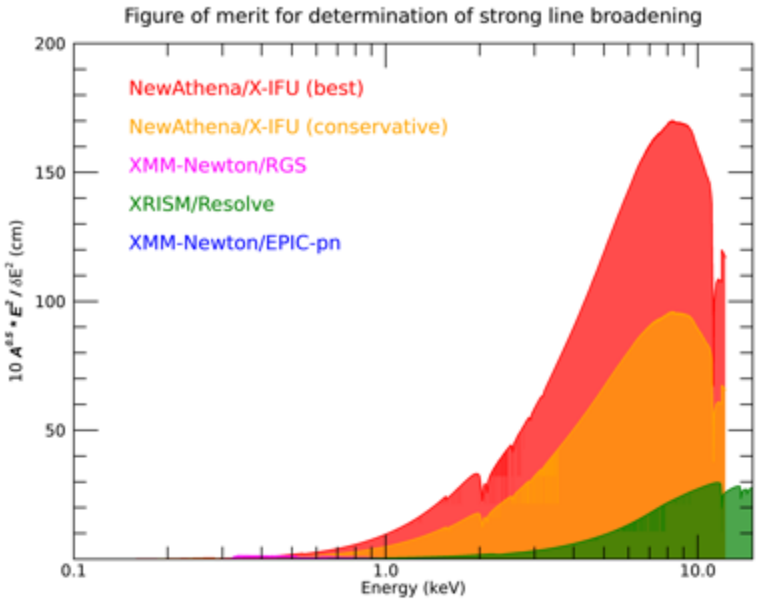
Weak line detection



Strong line velocity



Strong line broadening

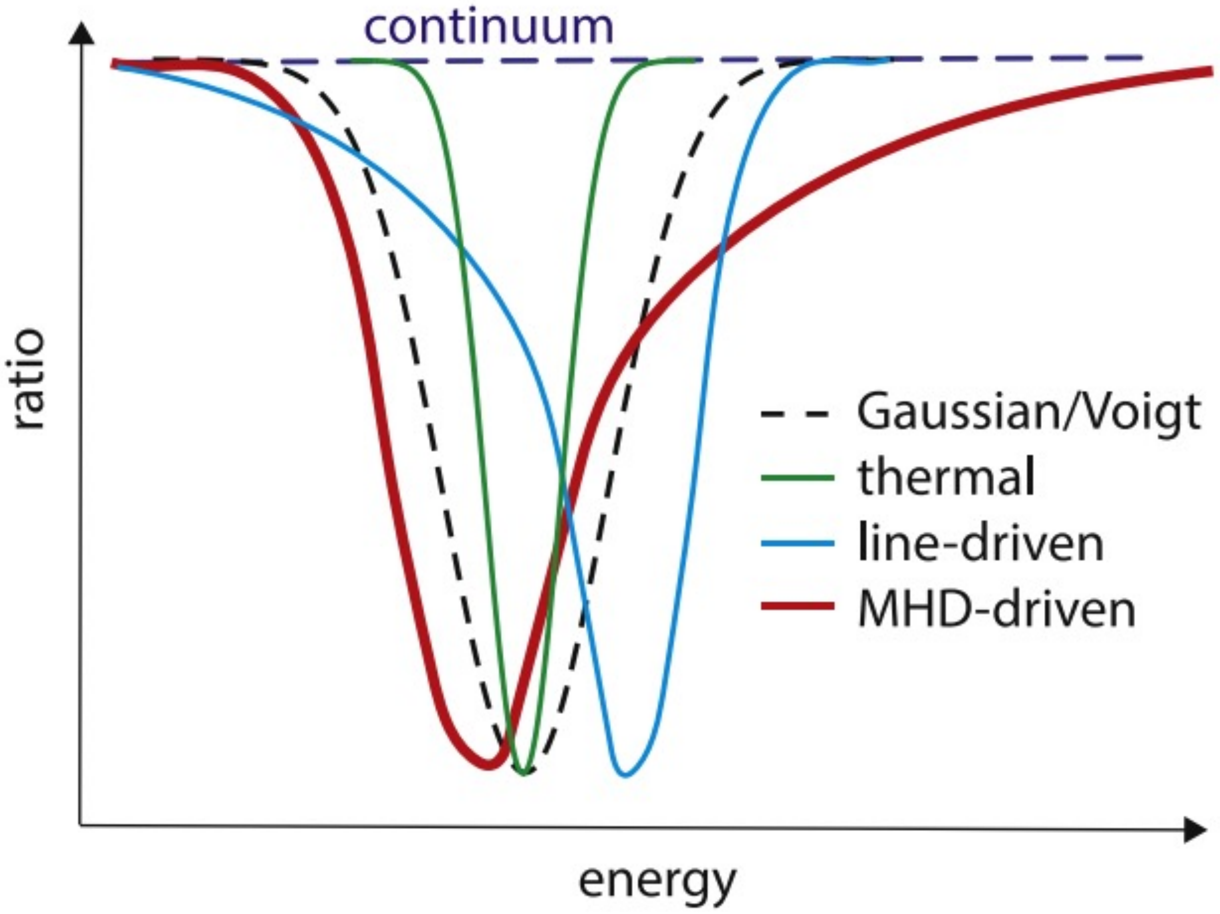


XRISM and NewAthena will cater for:

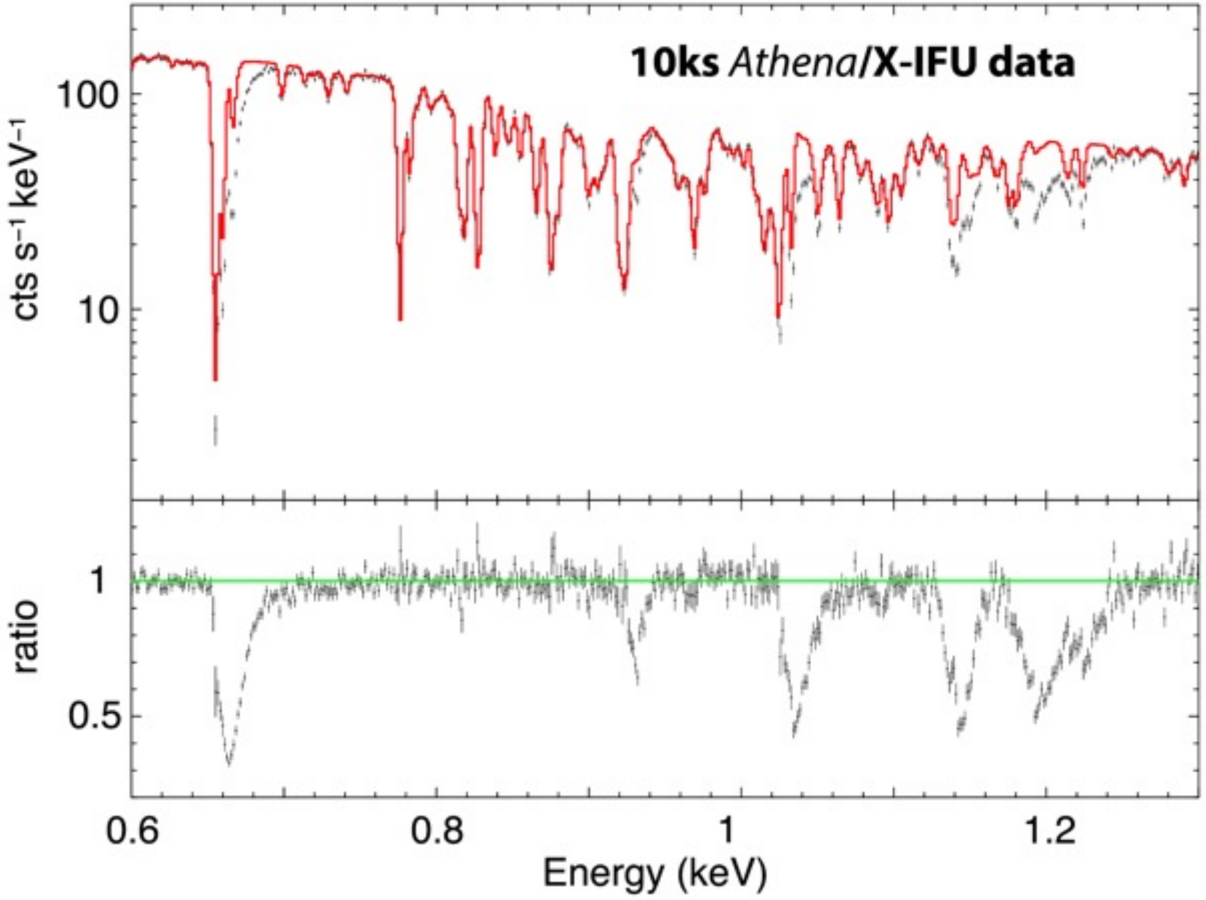
1. unprecedented energy resolution
2. large area
3. true integral-field unit capabilities

Outflow launching mechanism with *Athena*

Fukumura et al., 2022, ApJ, 940, 6



10 ks *Athena*/X-IFU simulation of an AGN with a MHD wind – removed in the residuals to show the "tell-tale" line profile



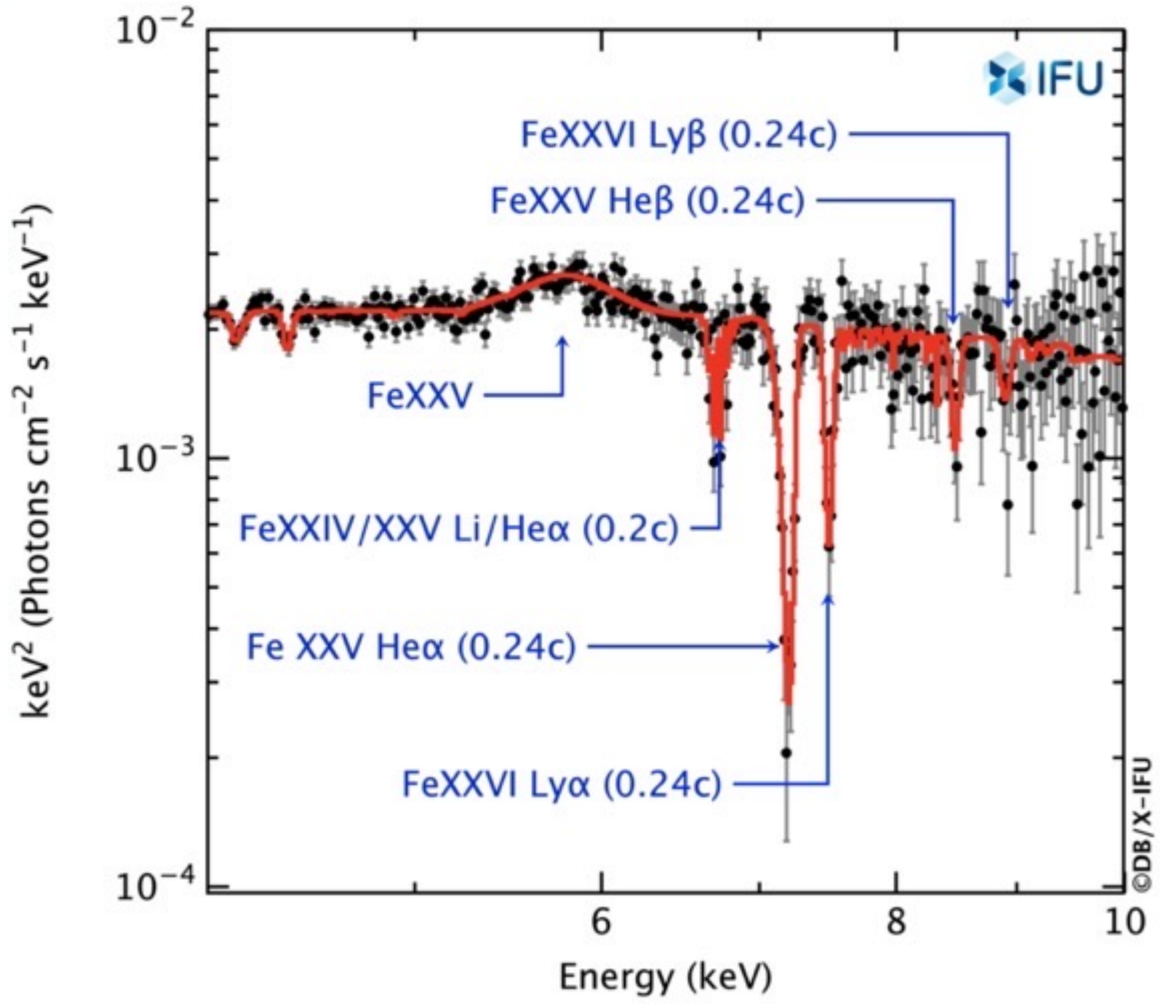
Similar measurements easy for XRISM on XRB
Longer exposures (~100 ks) needed for AGN

Outflow spectroscopy with micro-calorimeters

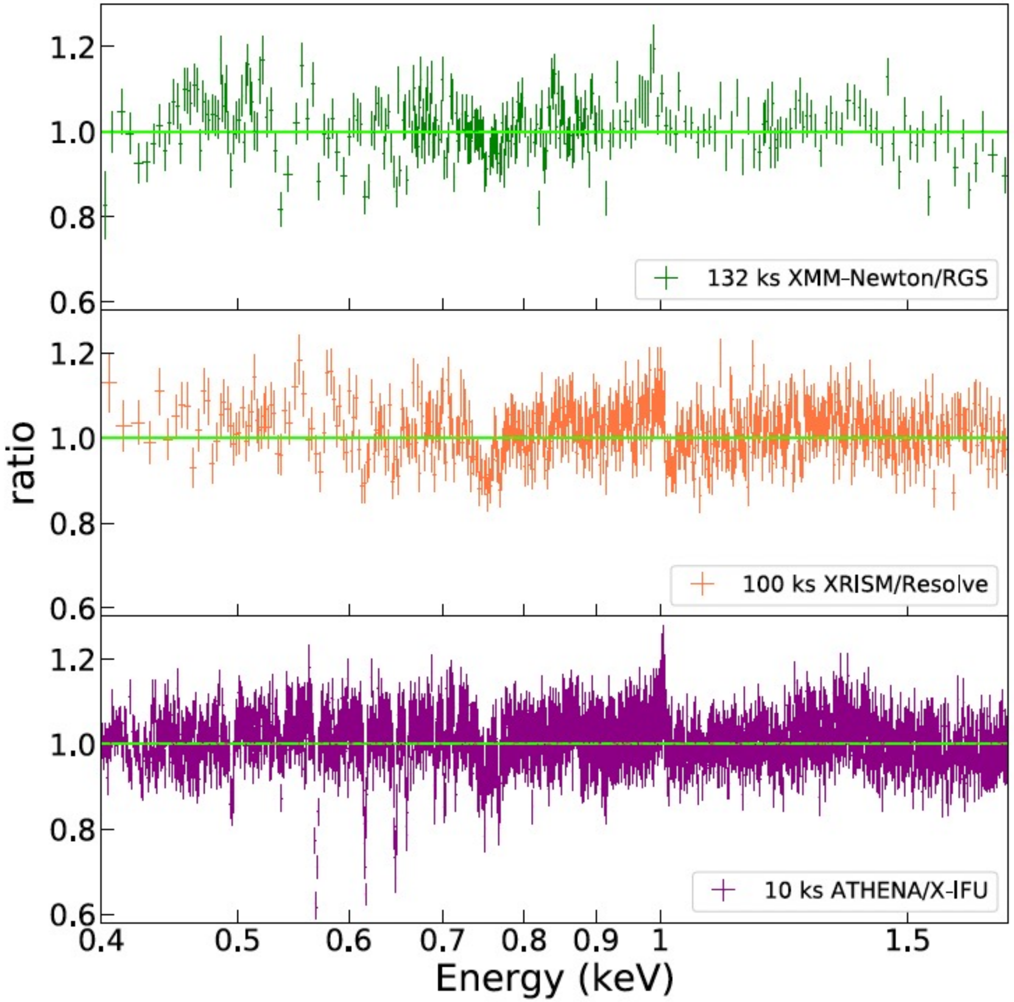
Credit: X-IFU Consortium

Xu et al., 2022, MNRAS, 513, 1910

PDS456 (L_{bol}~10^{46} erg s^{-1})
Athena/X-IFU – 100 ks



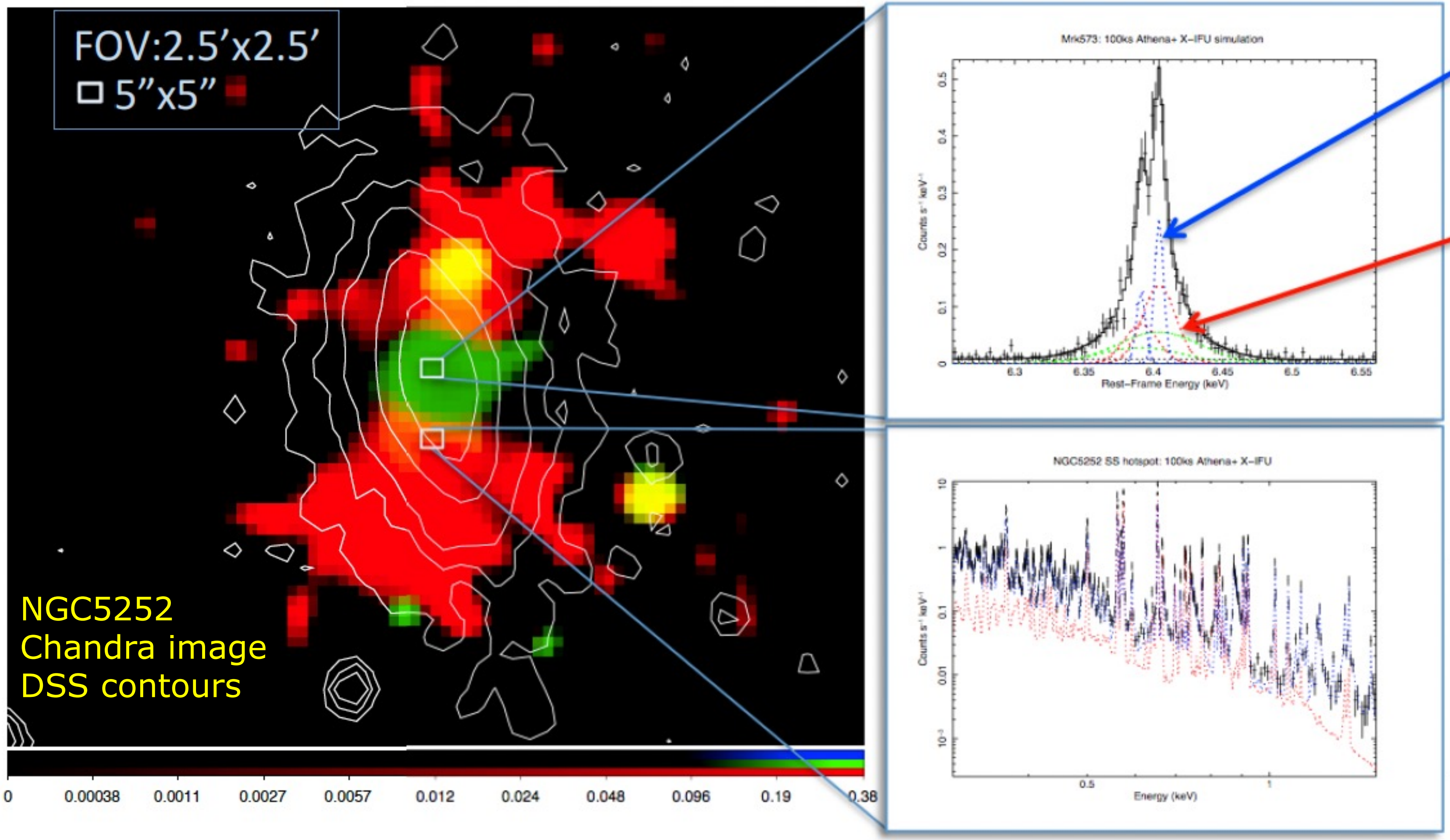
1H1934-063 (L_{bol}~10^{44} erg s^{-1})



Note the almost invisible absorption lines

Spatially-resolved NLR spectroscopy with *Athena*

Cappi et al., 2013, arXiv1306.2330



Narrow FeK line
Molecular Torus

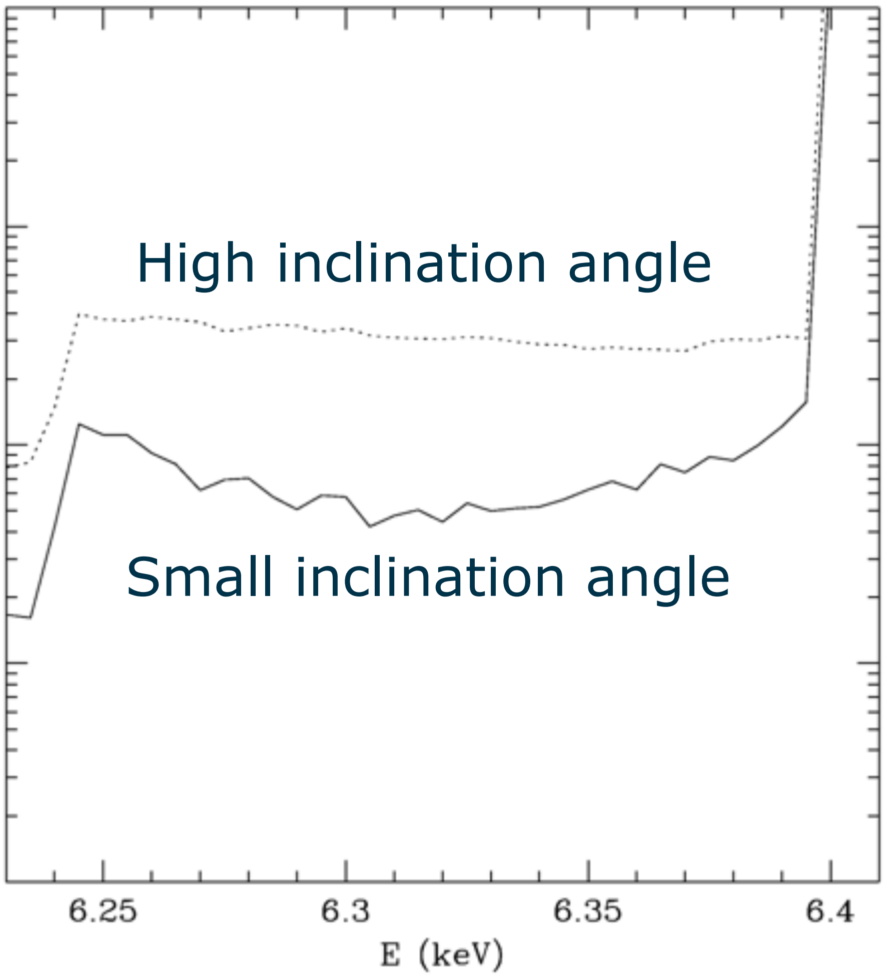
Broad FeK line
BLR

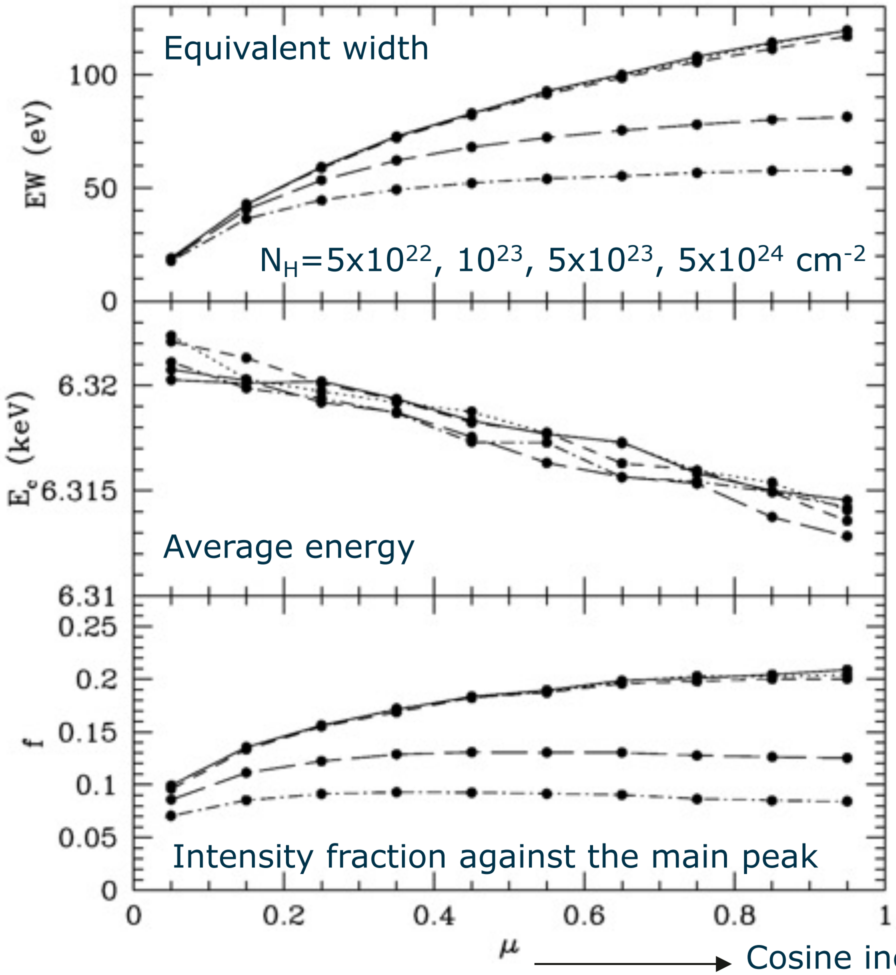
Shocked gas
from NLR
(photoionized +
thermal)

Theory of "Compton-shoulder"

Matt, 2002, MNRAS, 337, 147

Single electron scattering distorts the shape of an emission line on ≤0.2 eV scales





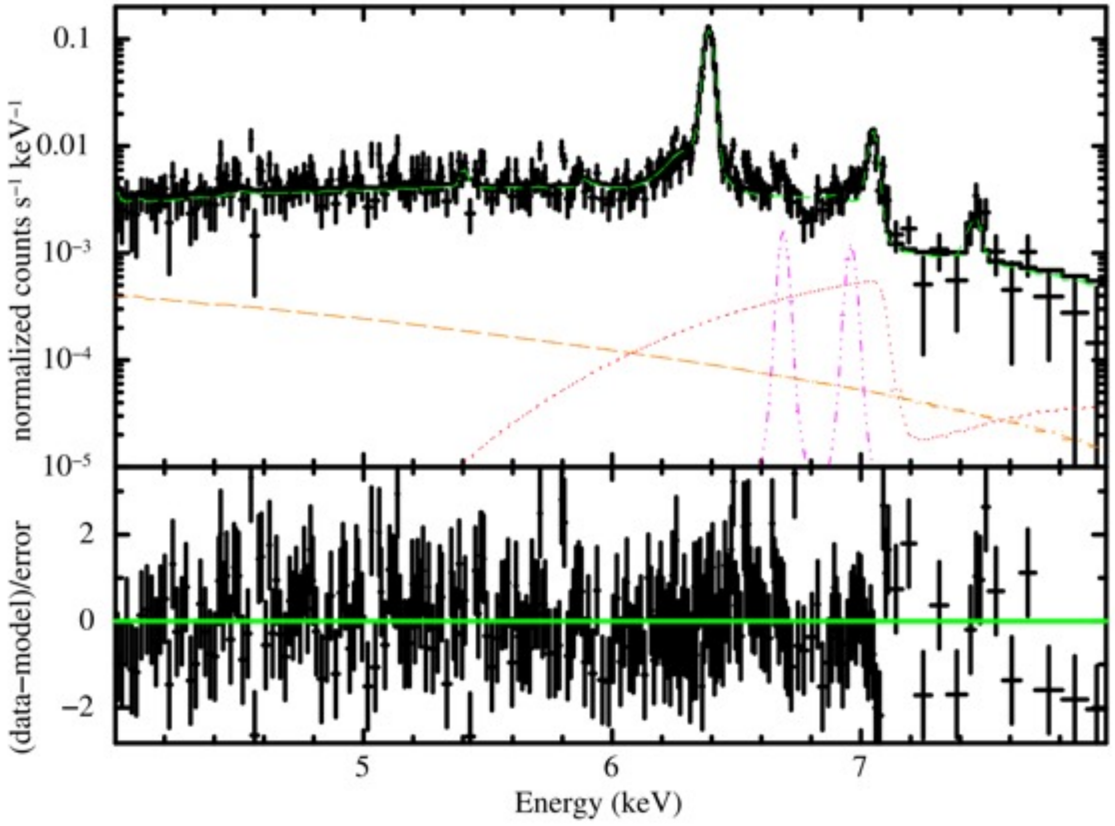
→ Cosine inclination angle

Compton shoulder in AGN torus with XRISM

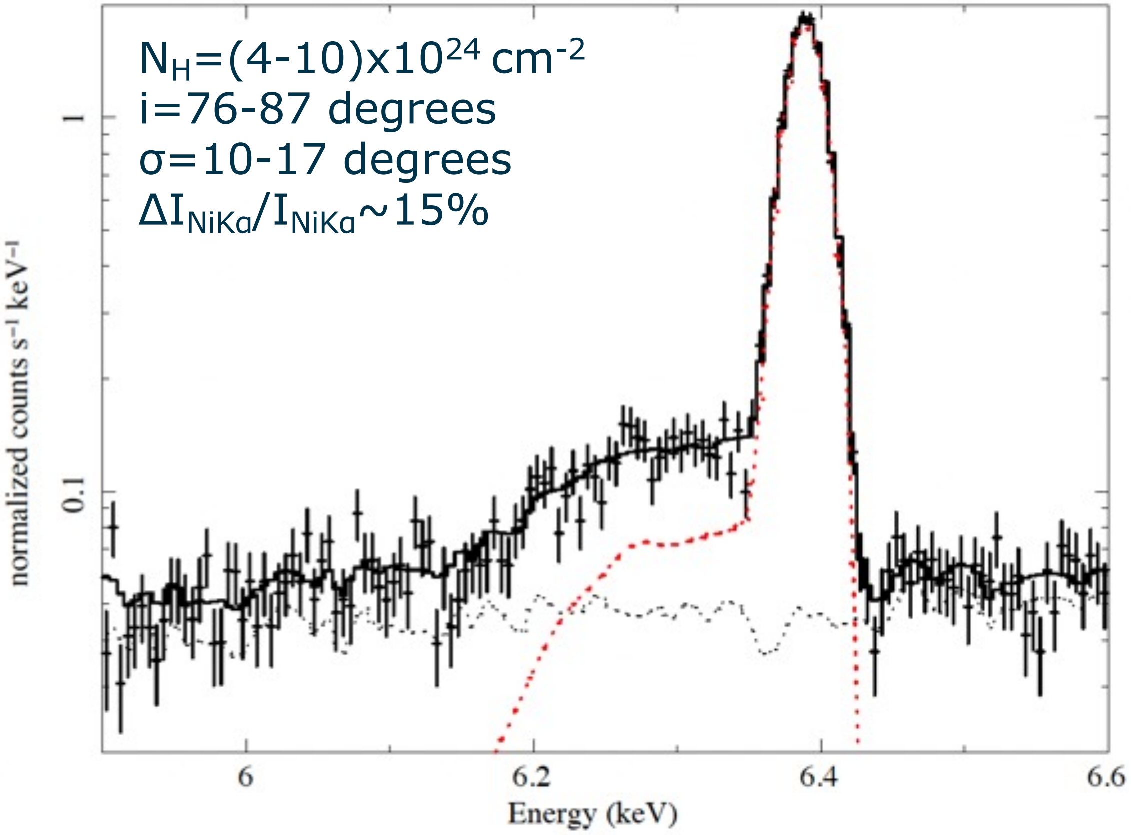
Hikitani et al., 2018, ApJ, 867, 80

Credit: Y. Ueda (Kyoto University)

Chandra/HETG (180 ks)



Circinus (Resolve 100 ks)



Constraining the geometry of the X-ray torus (*i*=inclination; *σ*=amplitude of the torus cloud distribution)

Credit: Nature Astronomy

Take-home messages

- Chandra and XMM-Newton high-resolution spectroscopy has revolutionized our view of super-massive accreting black holes
- Enabled a deep understanding of the physics of AGN outflows
- Unveiled a universal explanatory framework for hot photoionised gas in the nuclear environment: Radiation Pressure Confinement
- Probed the whole outflow chain eventually leading to "AGN feed-back" onto the host galaxy interstellar medium
- XRISM/NewAthena sorely needed to:
  - study the dynamics of all outflows phases
  - ascretain the outflow launching mechanism
  - constrain the X-ray reprocessor geomnetry
  - robustly determine the AGN BH spins distribution in the local Universe
- **Much more on AGN outflows in Missagh's talk after lunch!**