AGN in X-rays

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My target

What is an Active Galactic Nucleus?

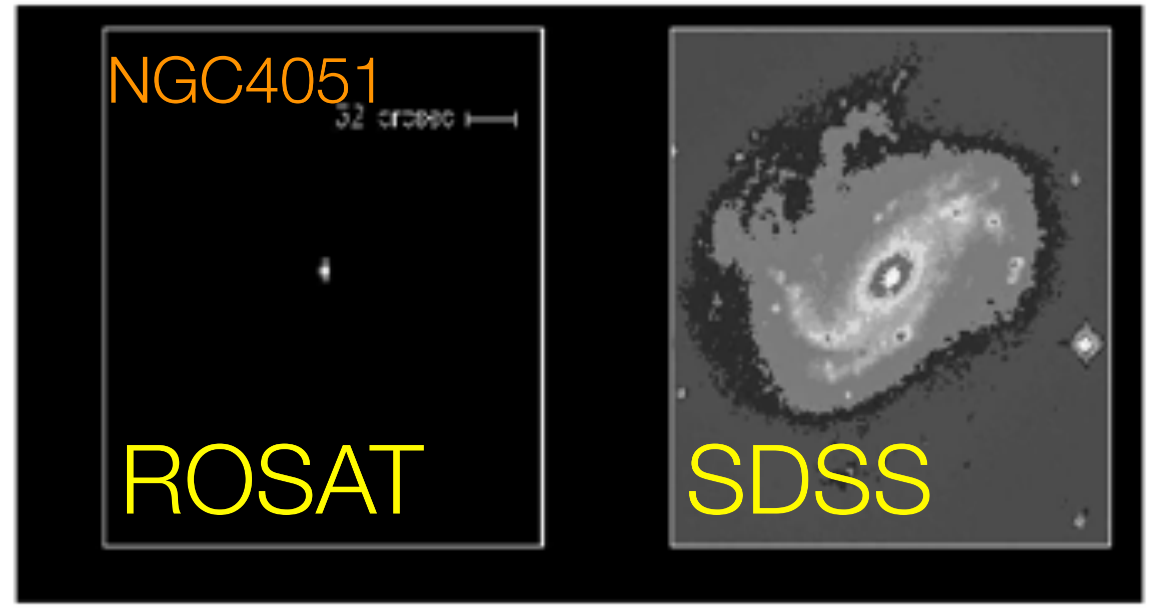
Galactic: it's a galaxy
Active: it hosts a light source brighter than its stars
Nucleus: this source is close to the center

Basic facts:

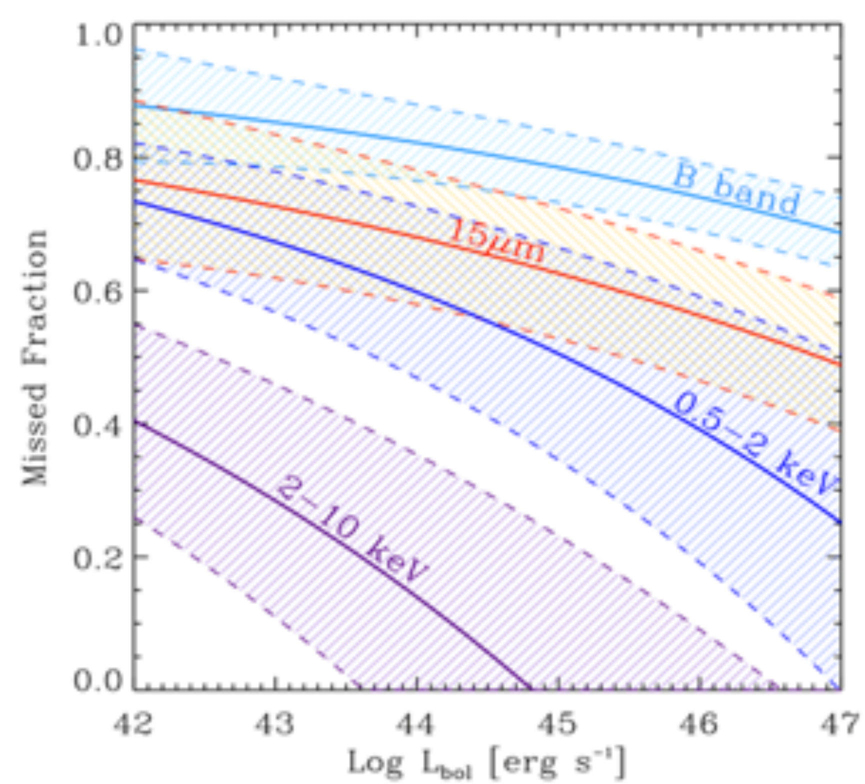
- They are amongst the most luminous objects in the Universe ($L=10^{8}-10^{15}$ times the Sun)
- Their luminosity is believed to be due to radiation emitted by matter accreting on a Black Hole (BH)
- Eddington limit for gravitation exceeding radiation pressure requires $M>10^{4}\ M_{\odot}$
- They sometimes host highly collimated jets
- They host plenty of gas and dust in their innermost ~100 pc (for reference, the diameter of the Milky Way is ~20 kpc)

Why observing them in X-rays?

(Mushothzky, 2004, in “Supermassive black holes in the distant Universe”, A.J.Barger ed., Kluwer Academical Publisher)

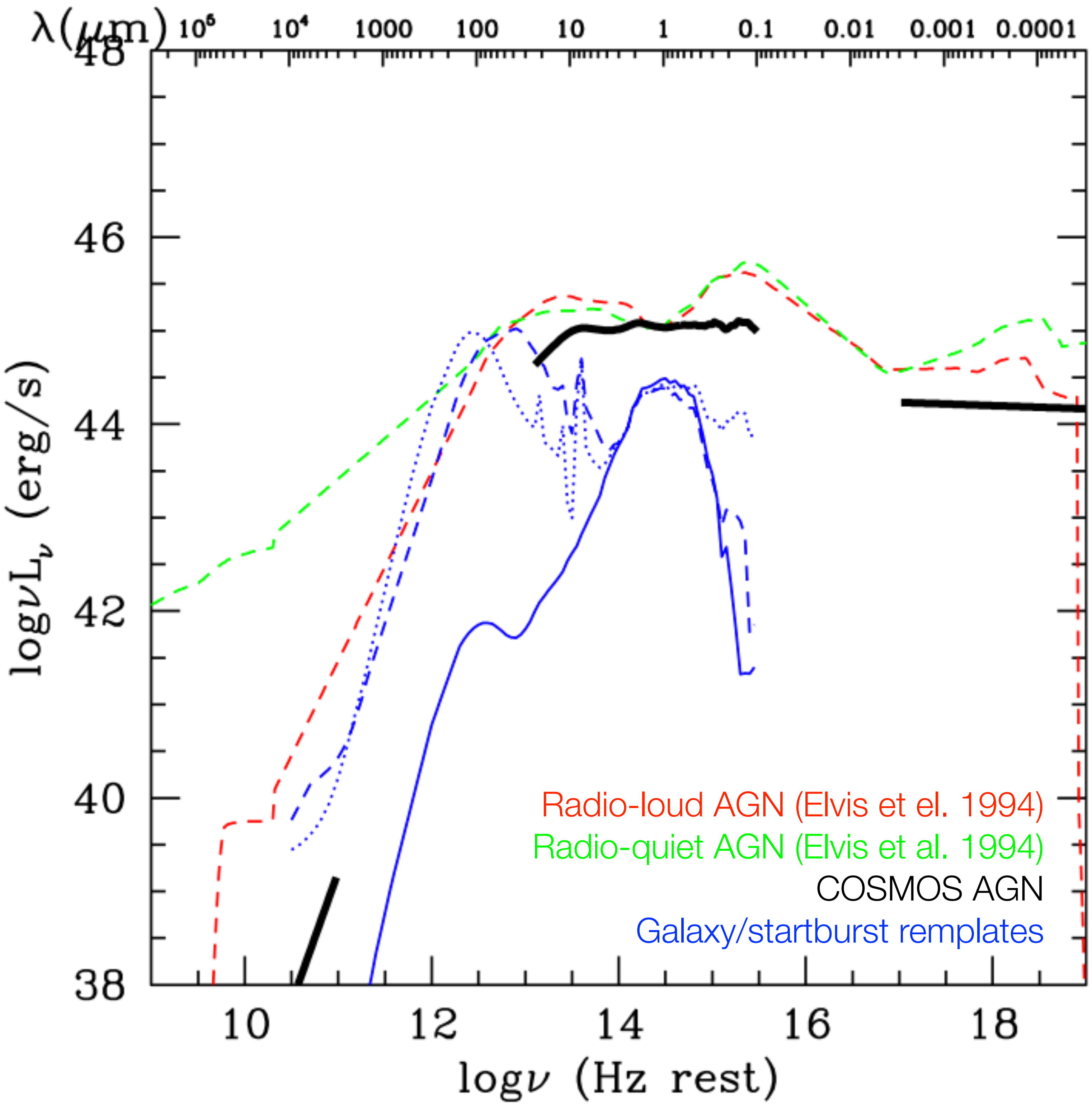


- High contrast between AGN and stars
- Penetrating power of X-rays
  - Sources with $L \leq 10^{42}$ erg s^{-1} can be detected up to z~3
  - $L_X \sim 0.03\text{-}1\ L_{bol}$
- Large area density:
  - 400 sources deg^{-2} in the 2-8 keV band [at $F_X \sim 10^{-15}$ cgs]
  - <150 sources deg^{-2} in optical surveys
- Large X-rays variability amplitude



Spectral Energy Distribution (AGN)

Elvis et al., 2012, ApJ, 759. 6



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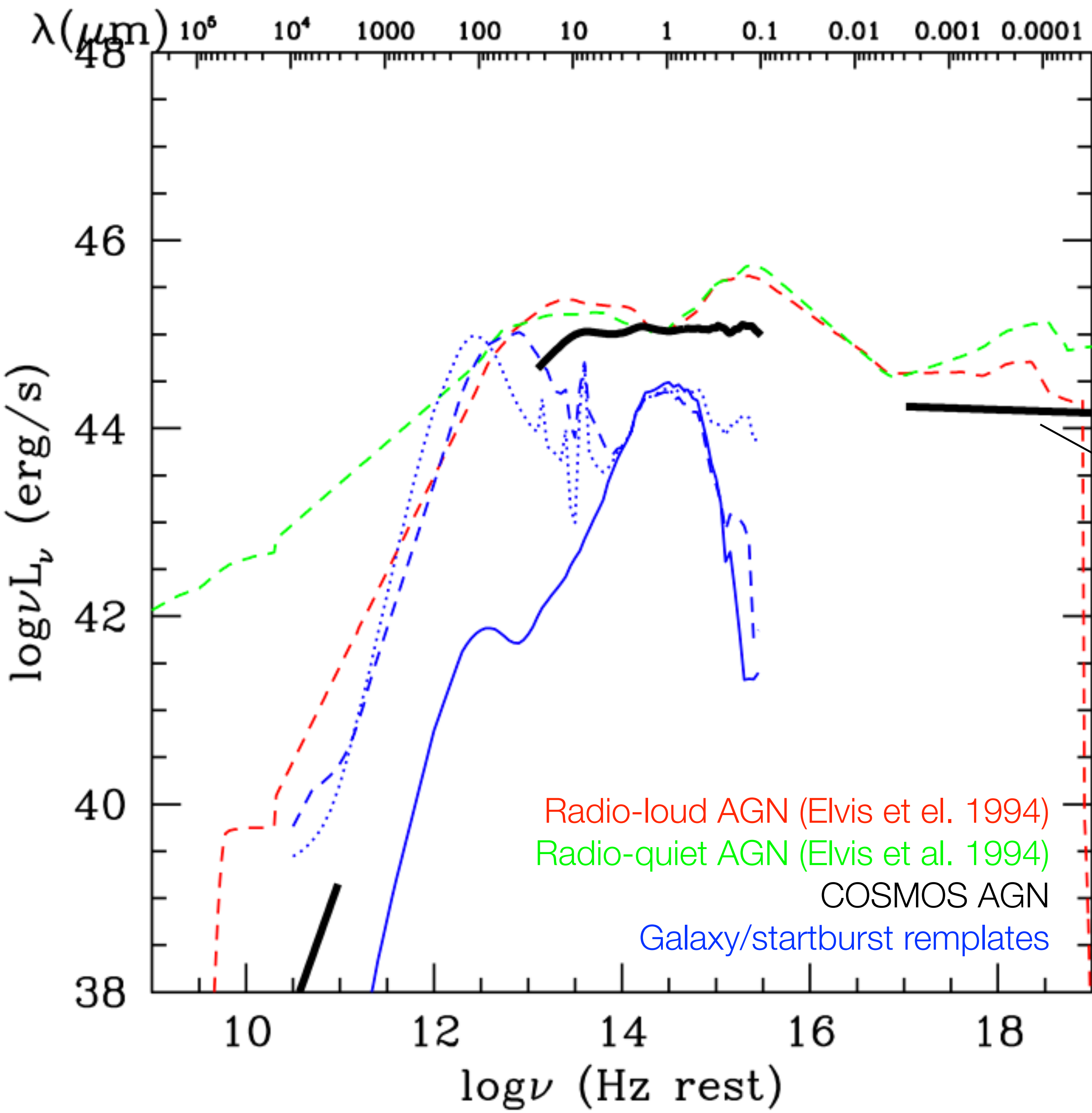

X-rays: **corona**
Comptonizing disk photons

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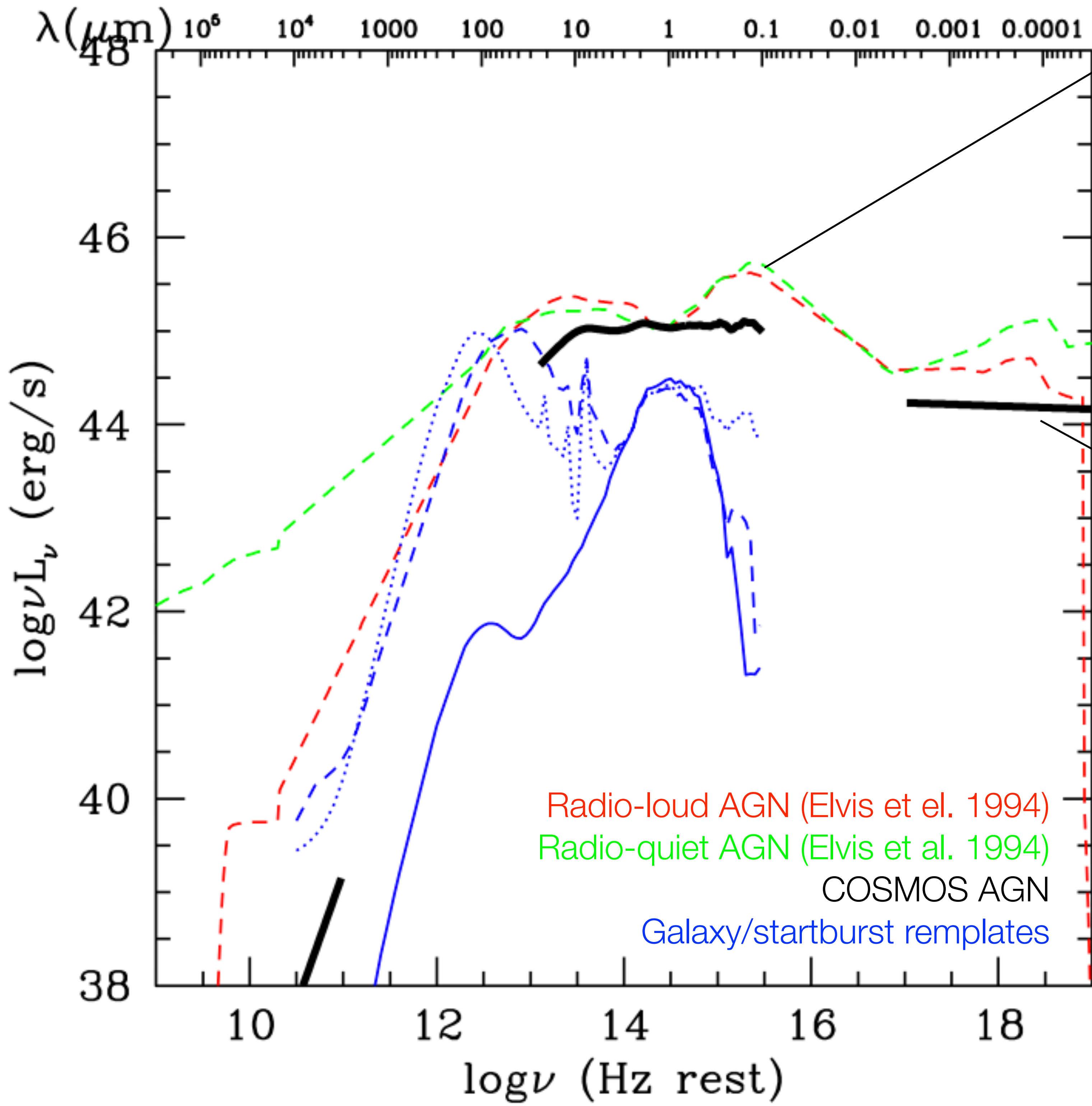
Elvis et al., 2012, ApJ, 759. 6



“Blue bump”: thermal emission from the **accretion disk**

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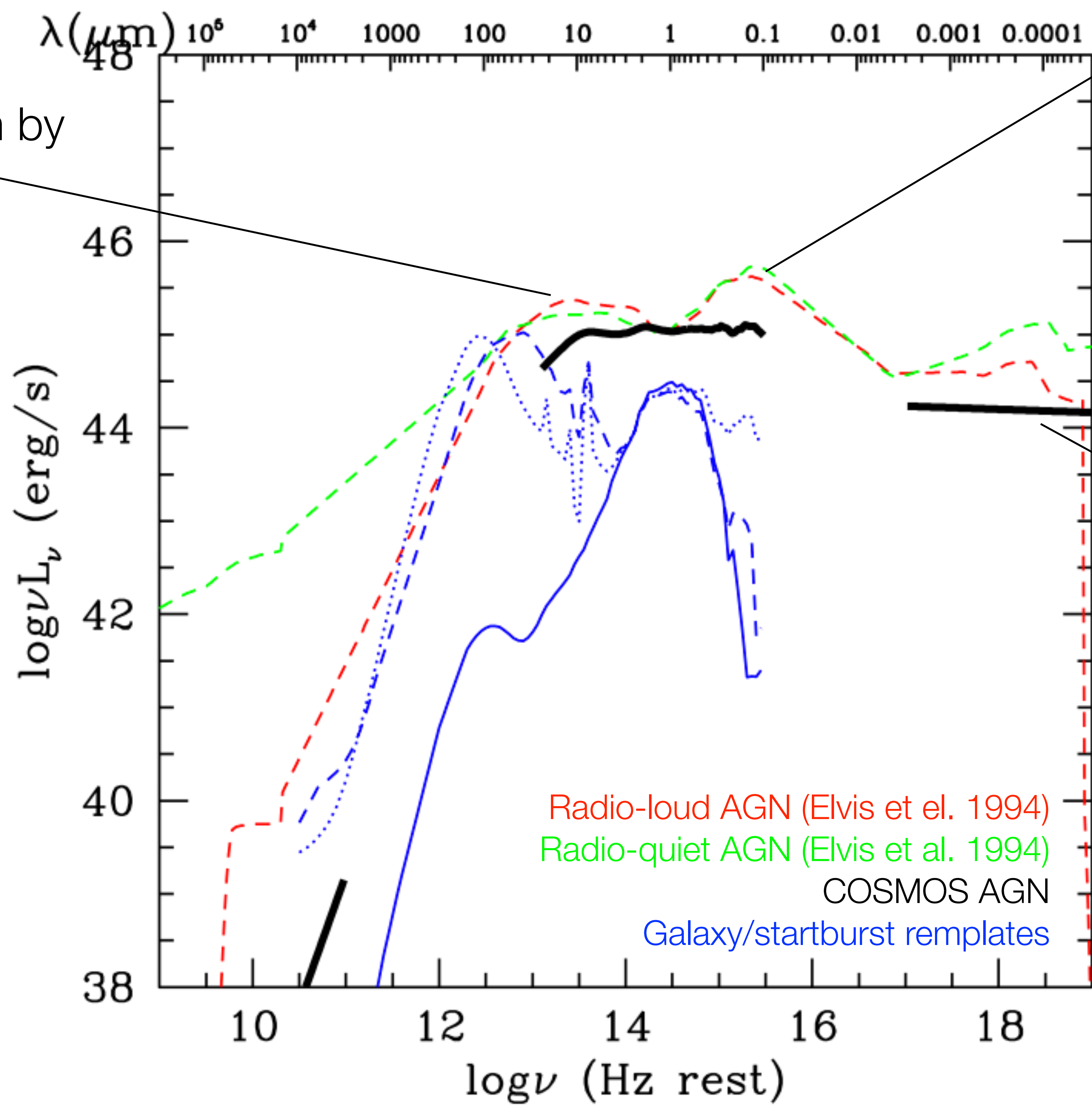
“IR peak”: reprocessing of nuclear emission by **nuclear dust**



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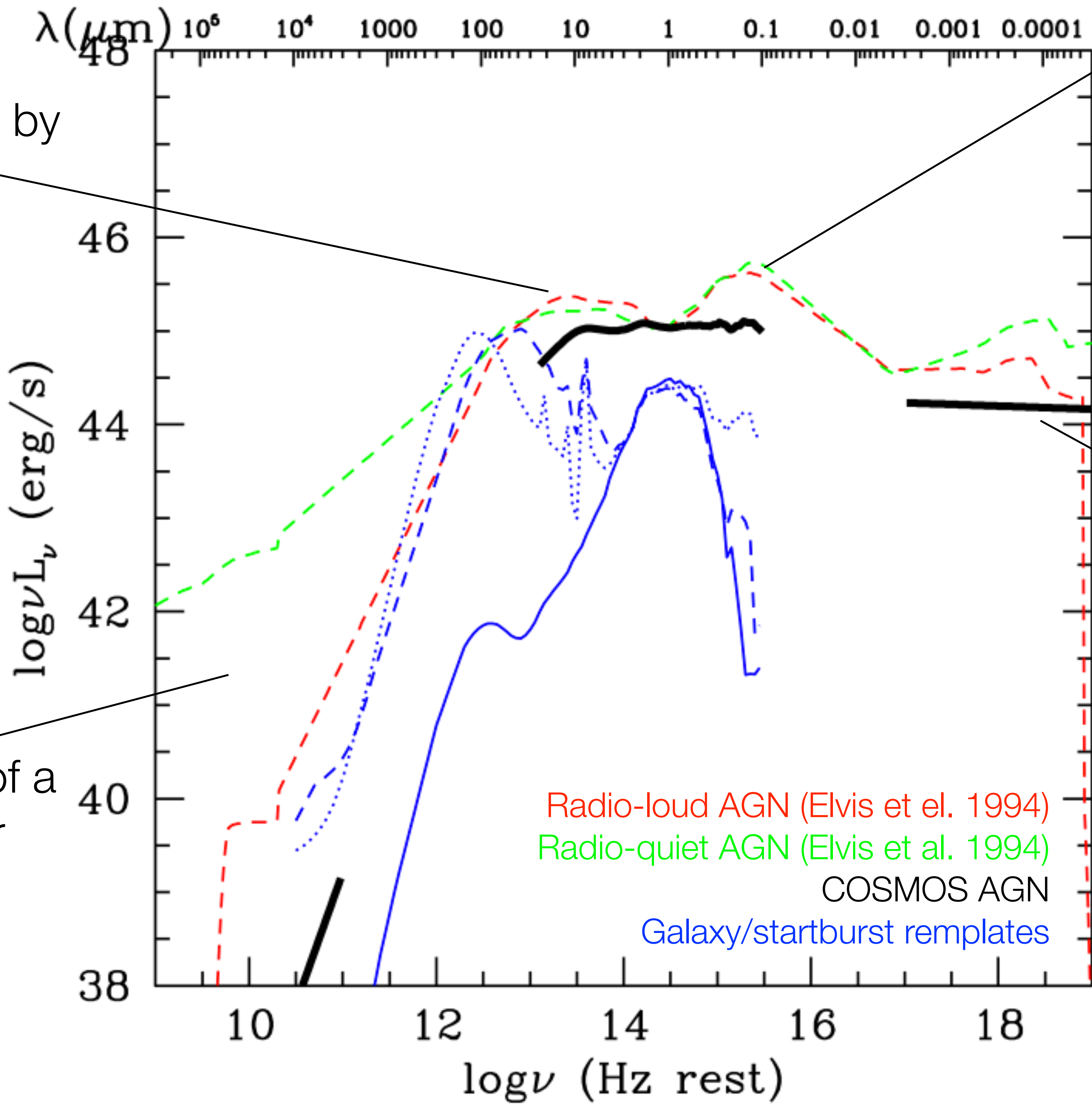

X-rays: **corona** Comptonizing disk photons

Radio: signature of a **relativistic jet** (or lack thereof)

Why studying AGN?

- Because the cosmological evolution of X-rays is strictly linked to that of their host galaxy
- Because they allow us to determine the most elusive property of astrophysical black hole (spin)
- Because they offer us the opportunity of studying the behaviour of matter under Strong Gravity
- Because they explain the Cosmic X-ray Background (CXB)

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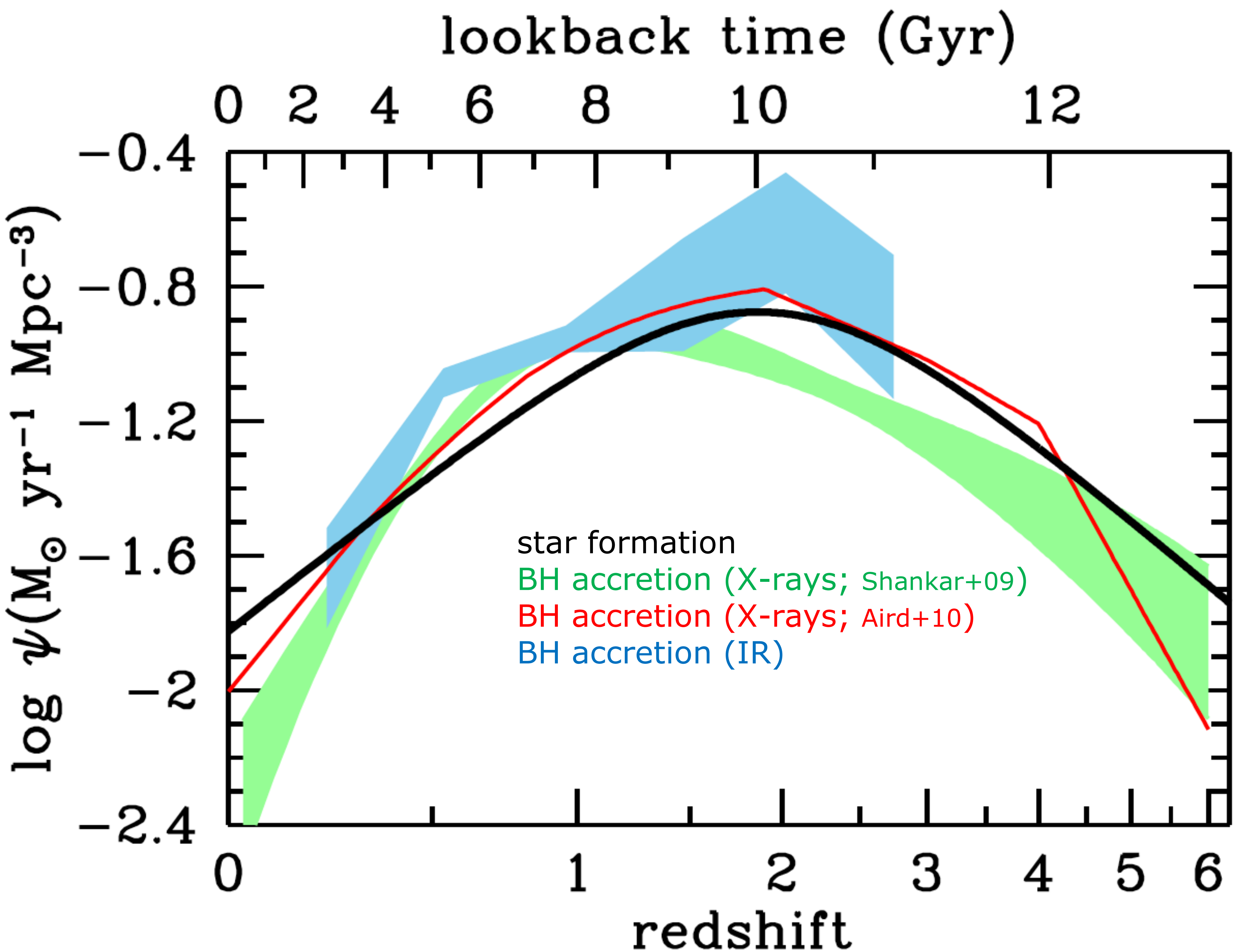
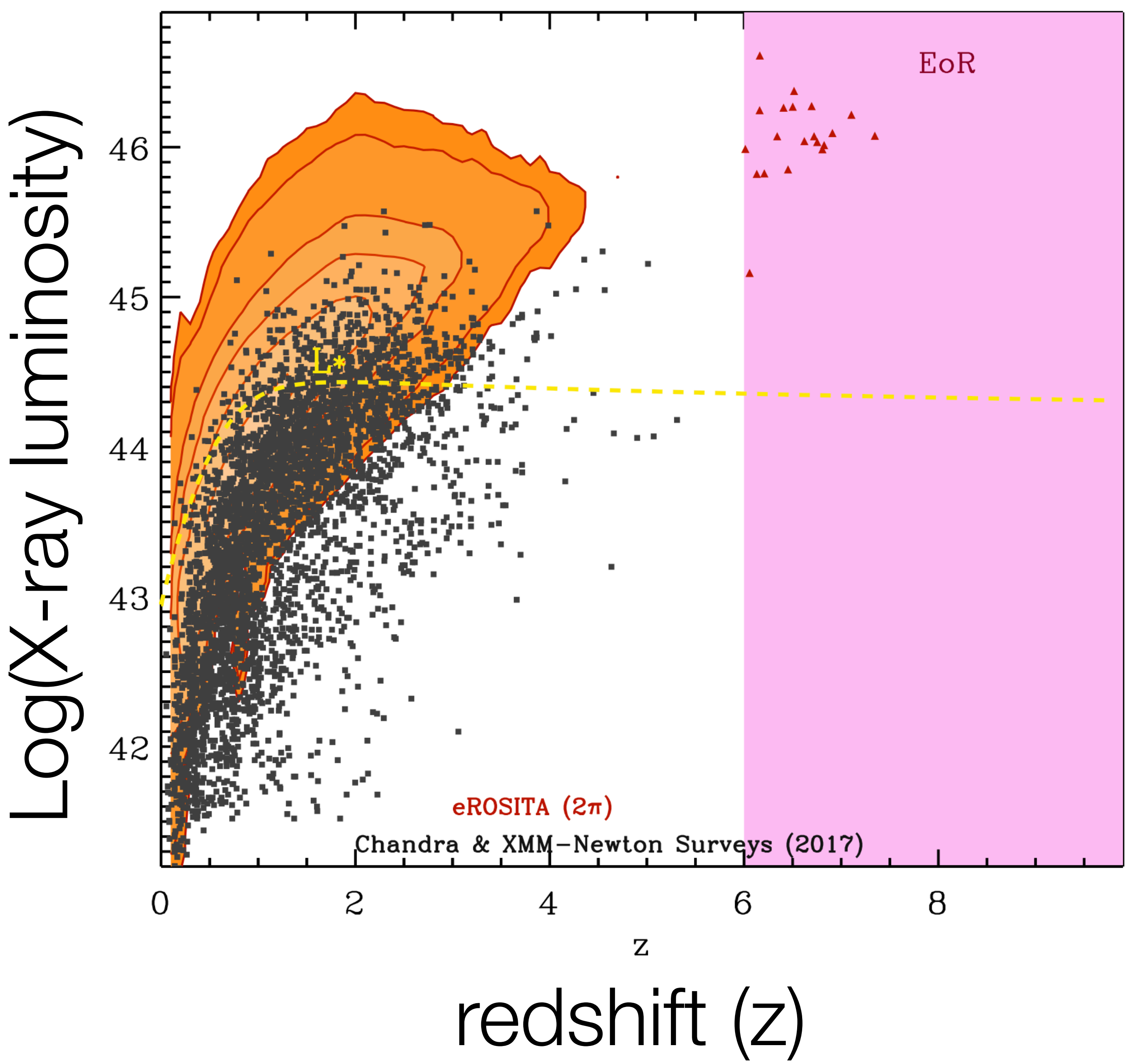
Concurrent evolution of BHs and star formation

Madau & Dickinson, ARA&A, 52, 415



How to address it?

Courtesy J.Aird (Ioa) & A.Rau (MPE)



- Most of the X-ray sources in an ACIS/EPIC field-of-view are AGN
- Chandra and XMM-Newton *surveys* detected ~105 AGN
- We understand how AGN evolve for z≤3
- The space density of luminous AGN peaks at higher redshift than faint AGN ("downsizing")

How to address it?

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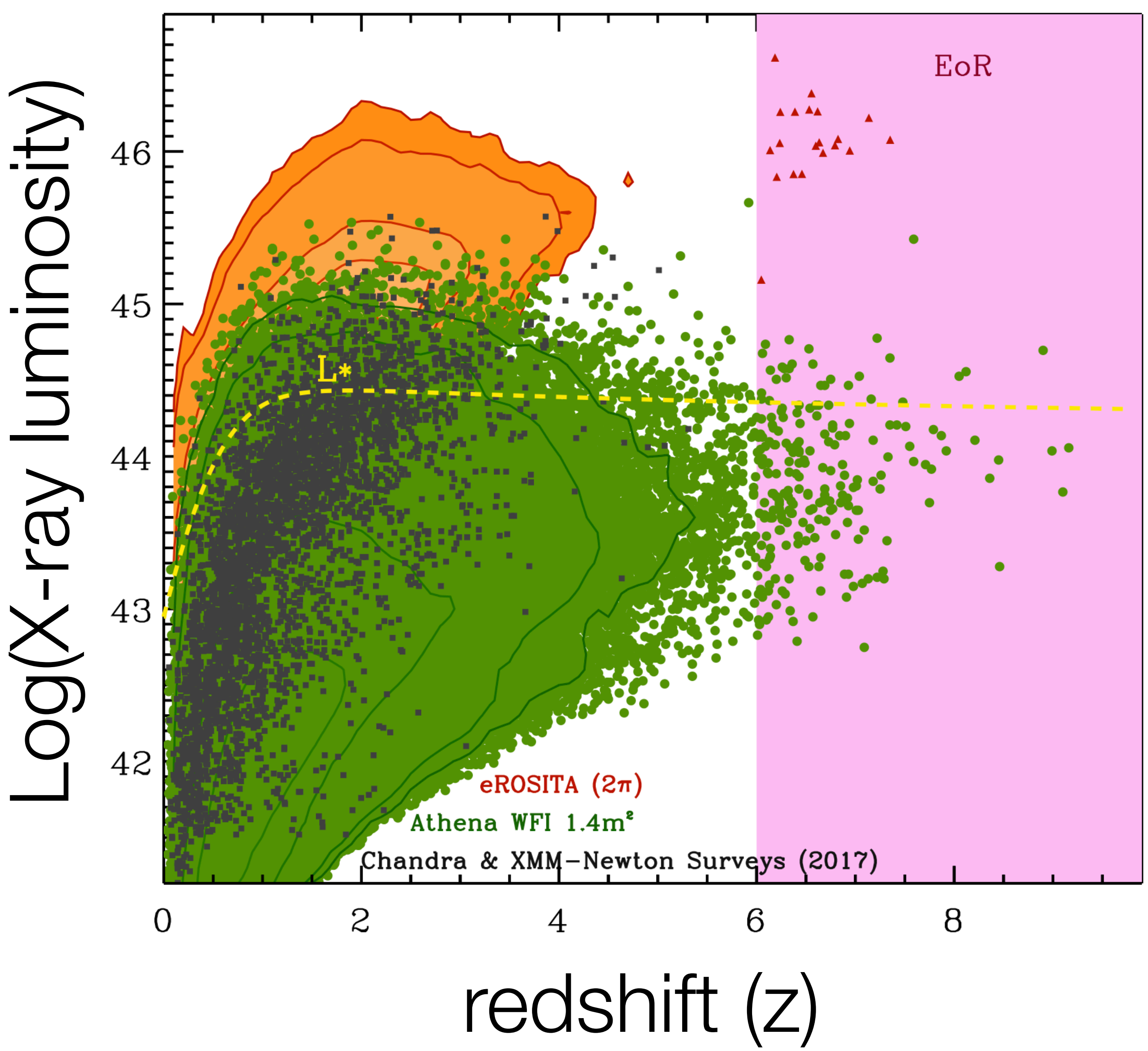
Important area of research for *Athena*
(see Keith's talk later)



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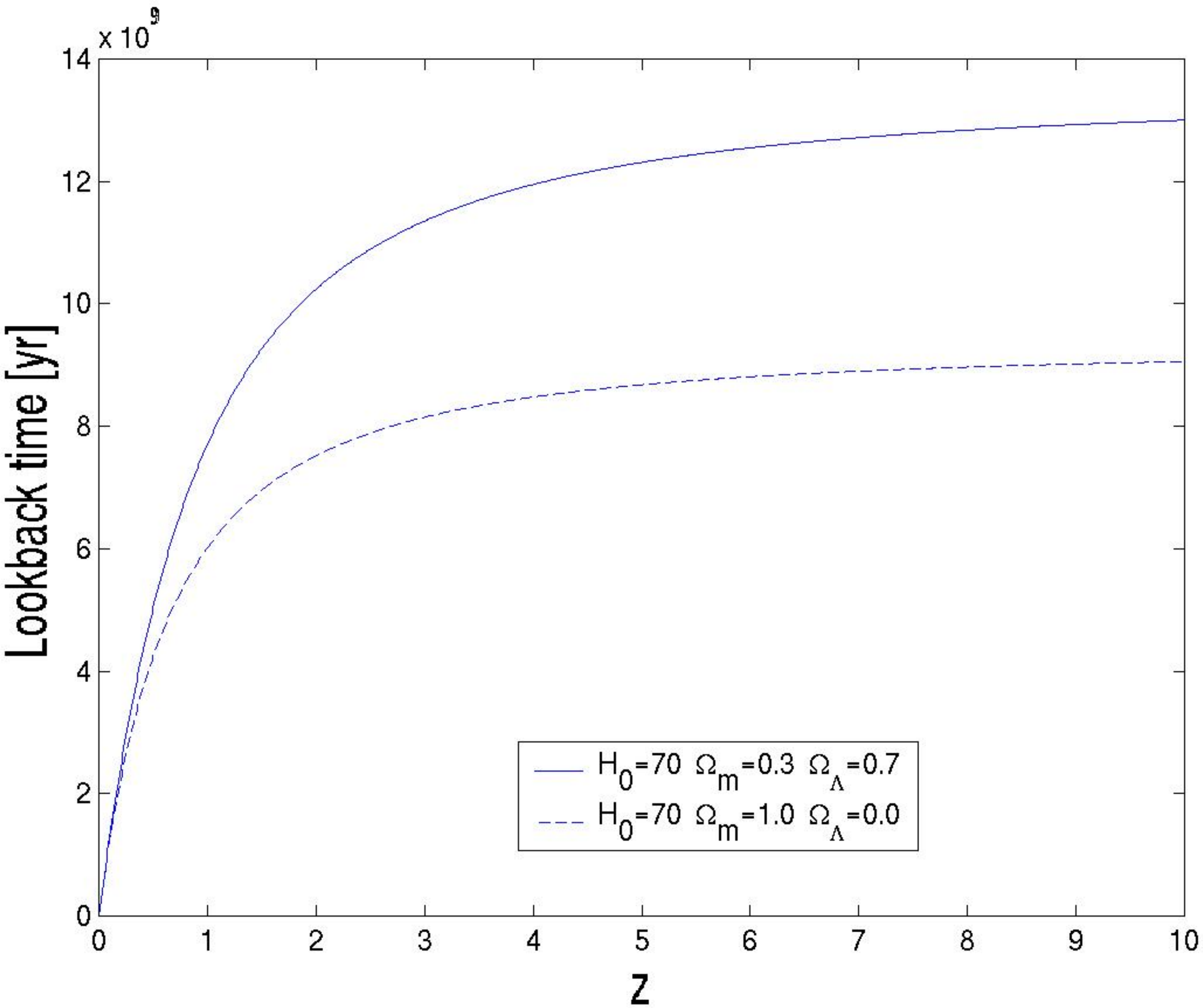
Redshift = z

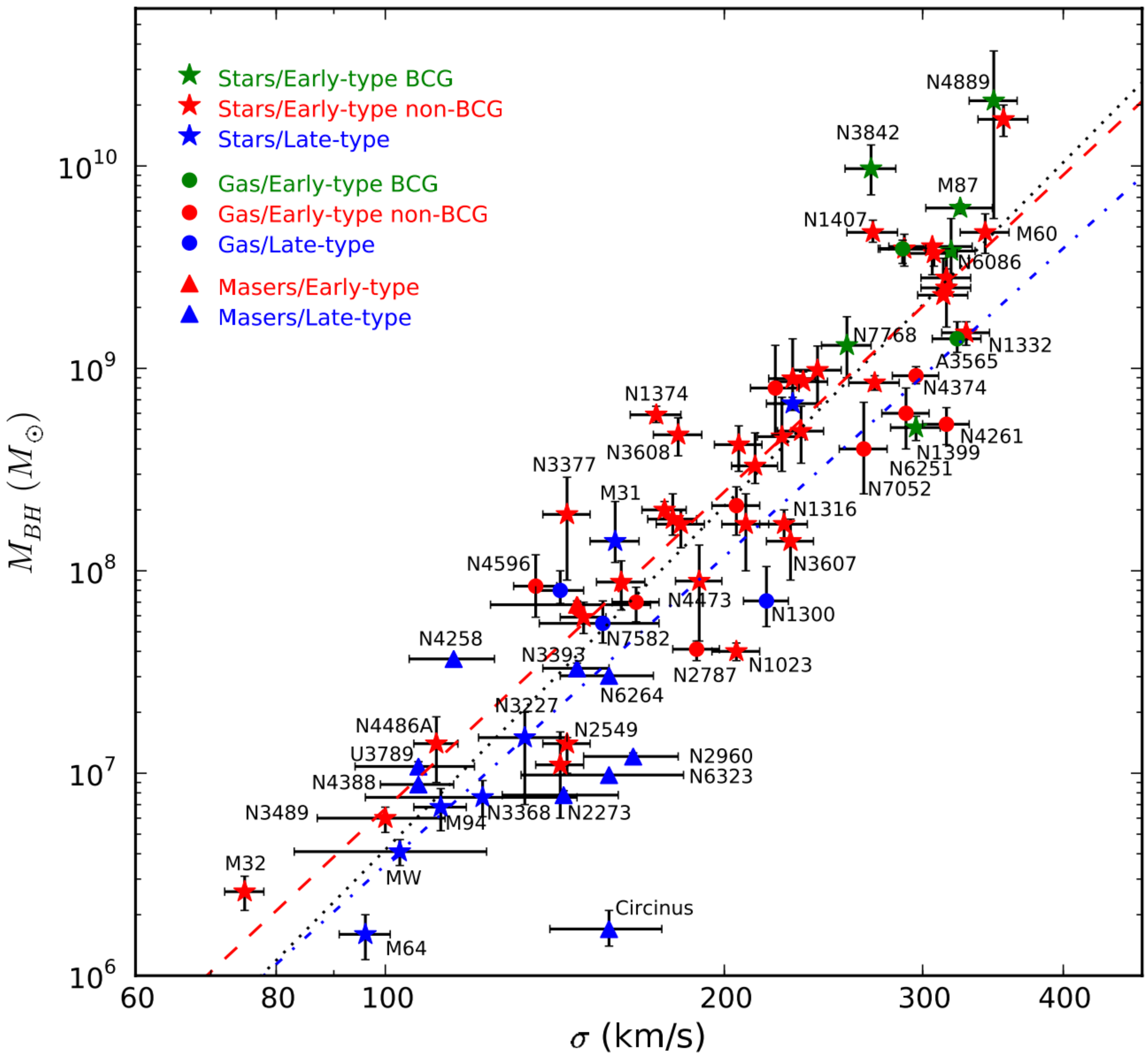
Credit: R. Jeffries (Keel University)



- Distant galaxies apparently move away from us
- The farther, the more their light is (apparently!) less energetic (red-shifted)
- The relation depends on models ("cosmology")
- z=3 is ~20% of the age of the Universe

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:

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

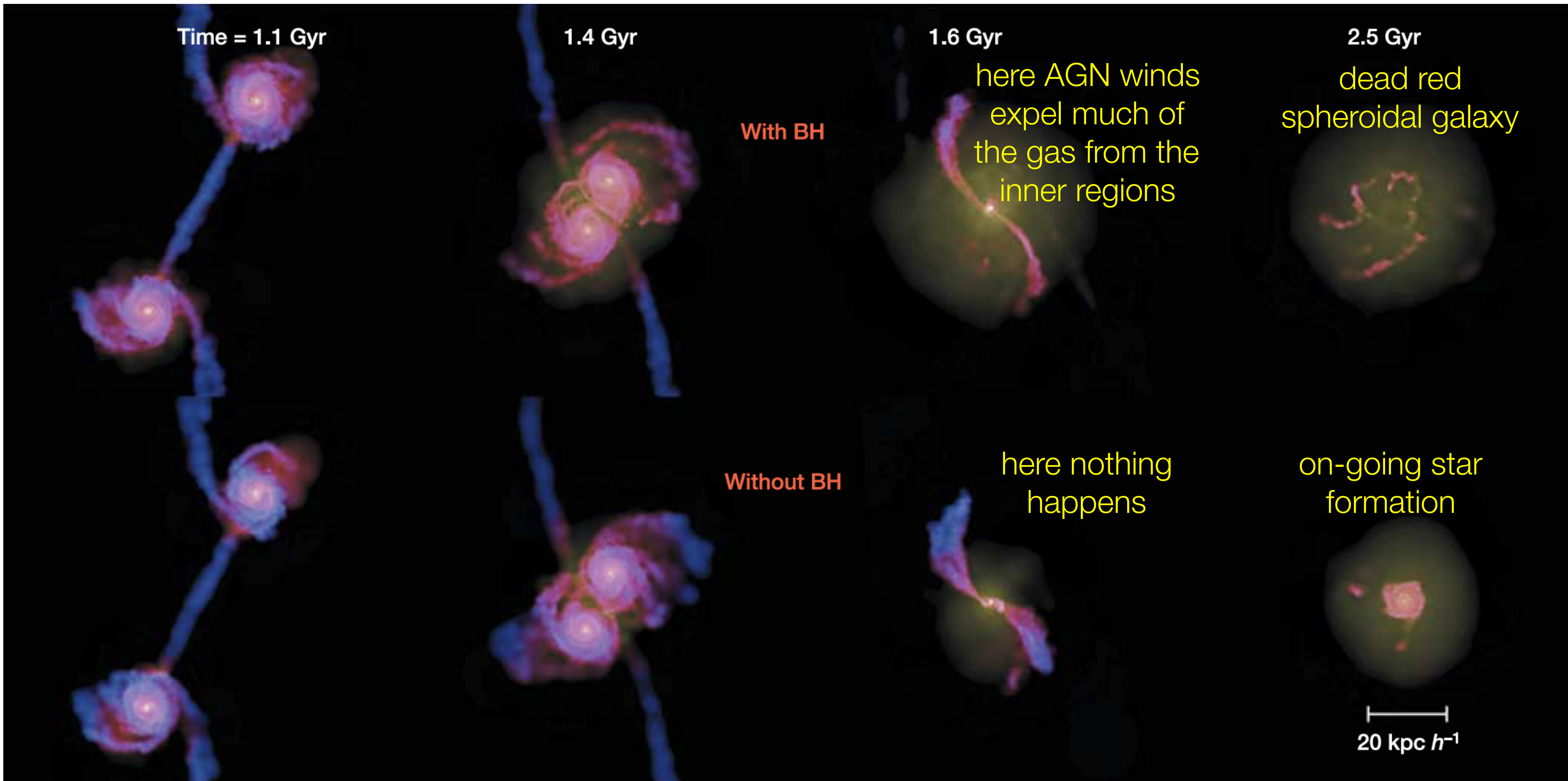
- Messanger → AGN feedback

(Courtesy ESO)

Feedback and cosmological evolution of galaxies

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

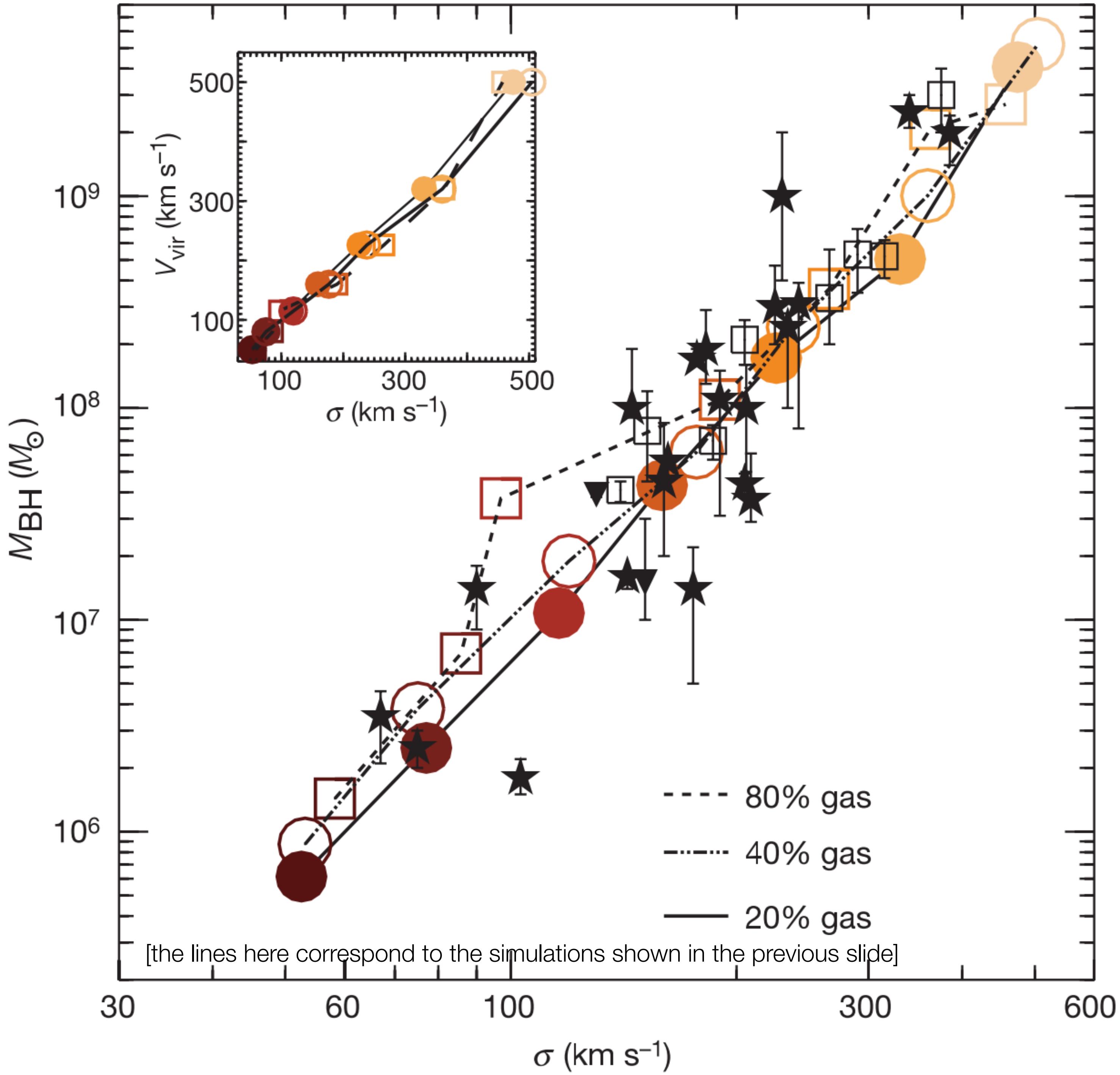
Example of a simulation of BH accretion and star formation after the merging between two Milky Way-like galaxies



When is feedback important?

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

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



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Hopkins & Elvis, 2010, MNRAS, 401, 7

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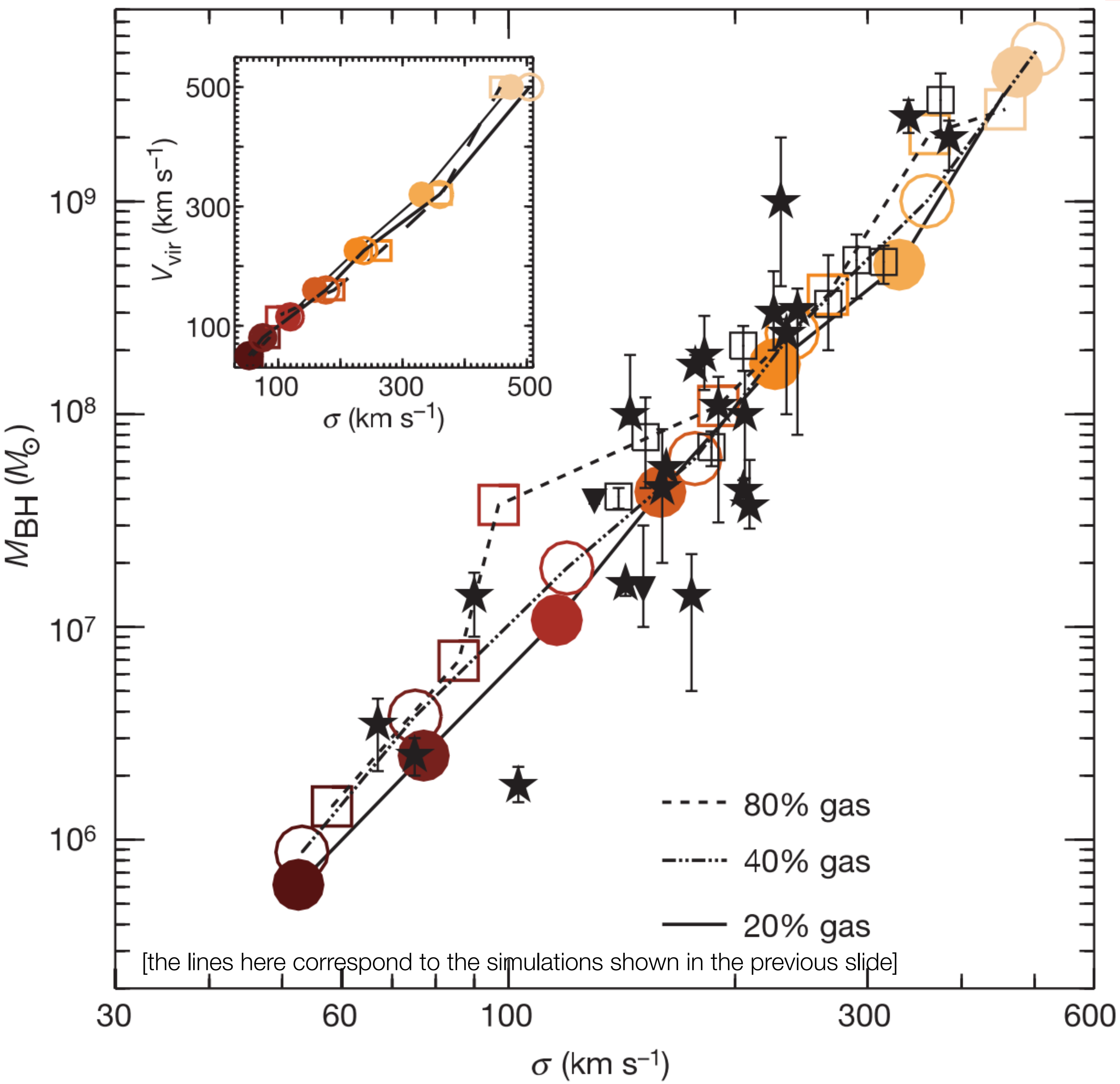
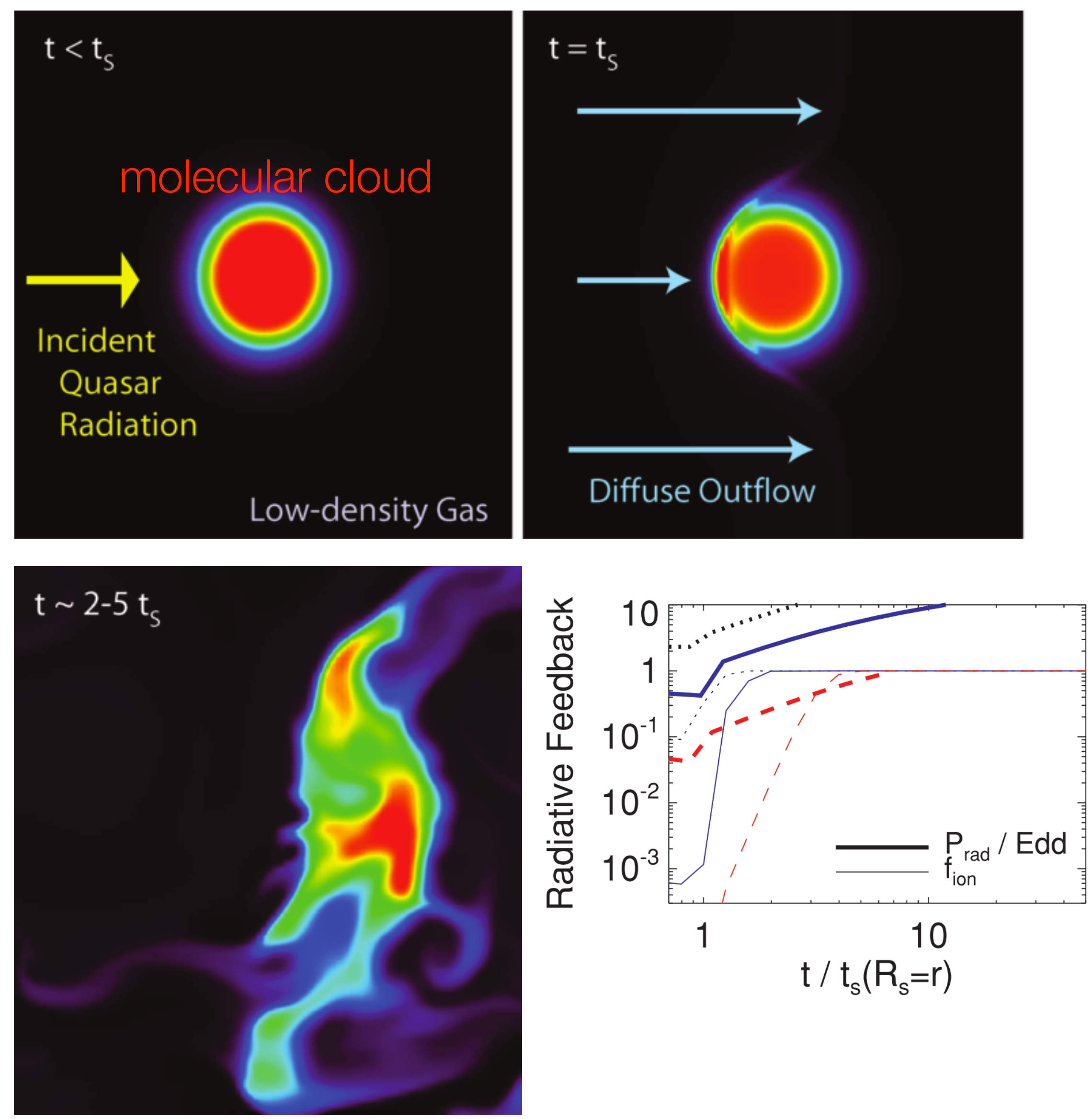
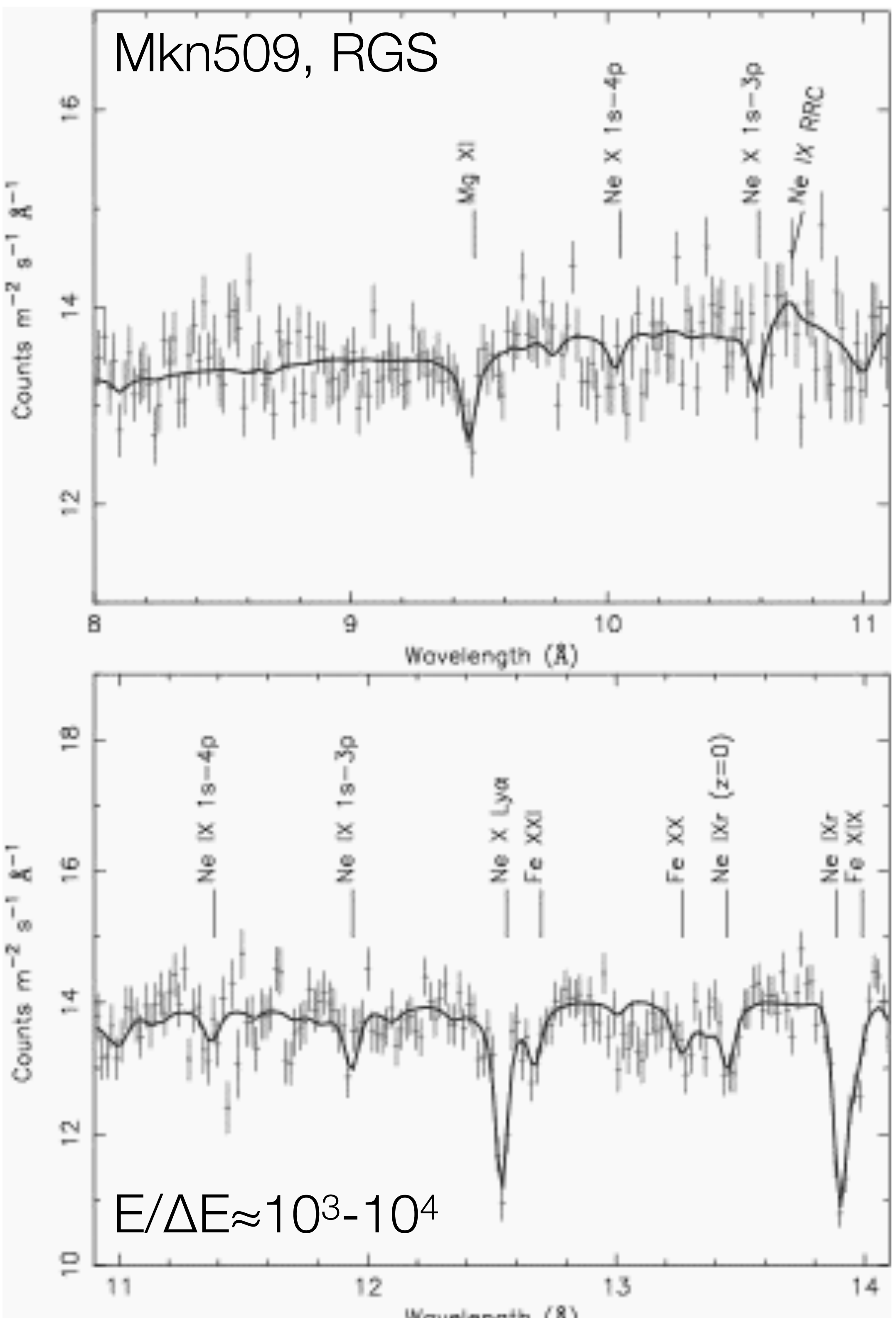




High-resolution view: warm absorbers

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



- Known since 30 years (Halpern et al. 1984), physics possible only with high-resolution spectra with *Chandra*/HETG and XMM-Newton/RGS
- Resonant absorption lines: He- and H-like ions of C, O, Ne, Mg, N, Si, Fe ...
- Present in $77 \pm 9 \pm^{3}_{14}$% of nearby AGN (Laha et al., 2014) → covering fraction, C_g
- v~10^3 km/s to ~0.3 c
- log(ξ)≲10^4 cgs
- N_H~10^{20-24} cm^{-2}
- Photoionised by AGN radiation field

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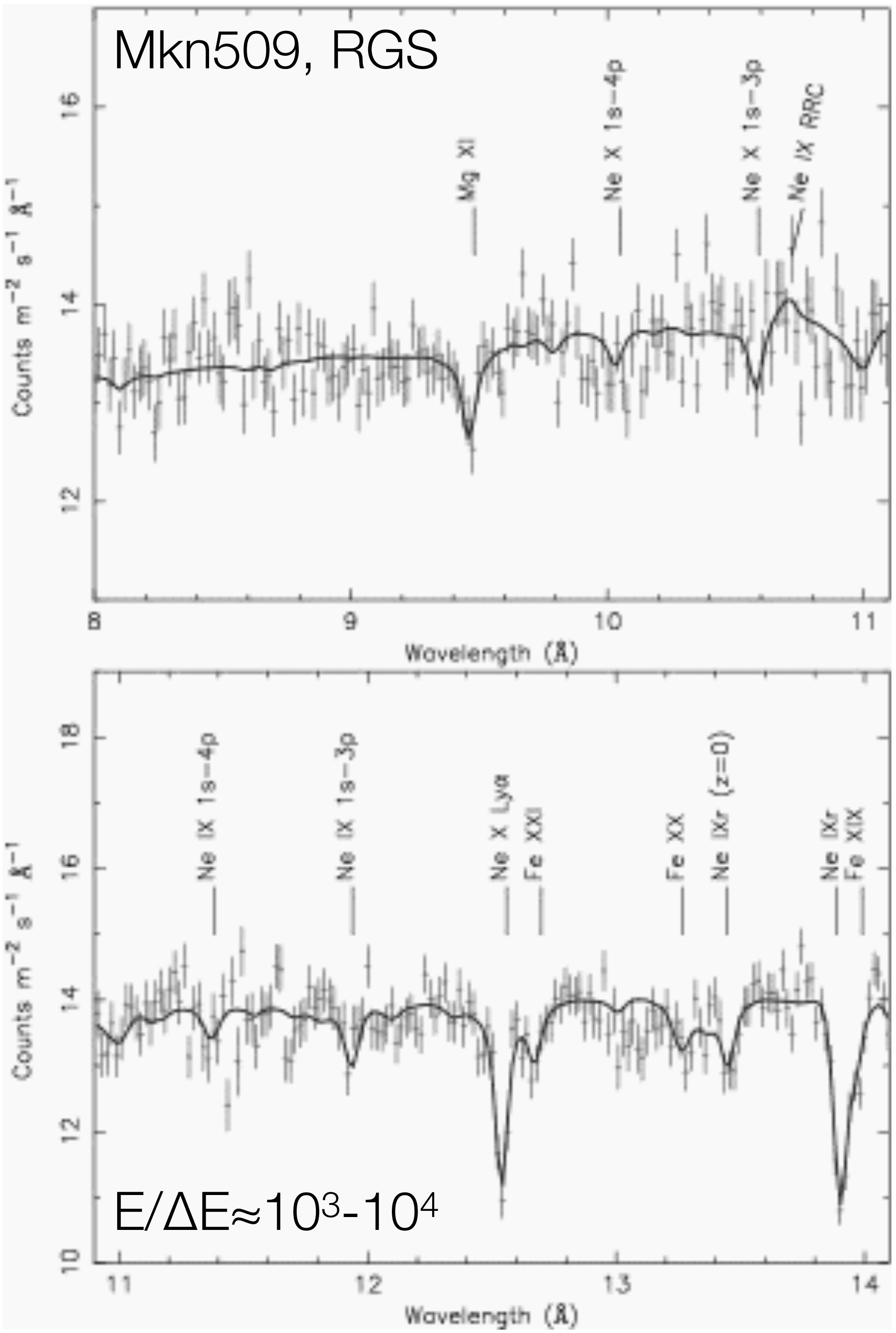

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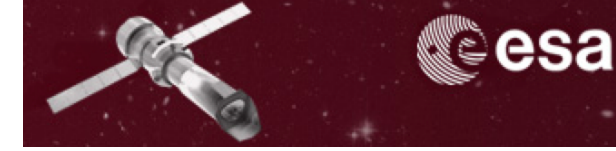
What do we measure?

- We measure directly (by identifying lines): ionisation state, multi-ion components, $\log(N_H,i)$ for each ionic species, outflow velocity
- From photoionisation codes (CLOUDY, ION, PHASE, TITAN, XSTAR) we can derive N_H, T, ξ, once energy and ionisation balance, and a Spectral Energy Distribution (SED) is assumed
- We get the covering fraction from the ratio of AGN showing warm absorbers in a well defined (complete, unbiased …) sample
- There is an *intrinsic degeneracy* between the volume density of the outflow and the distance between the absorber and the ionising source:



Time-dependent photo-ionisation

Nicastro et al., 1999, ApJ, 511, 109

ionisation parameter (measured)

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

ionising luminosity (observable)

unknowns: density & distance

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recombination time

$$t_{\frac{X^i}{2}} = \frac{1}{\alpha_{\mathrm{rec}}(X^i, T_e)n_e}$$

How to calculate 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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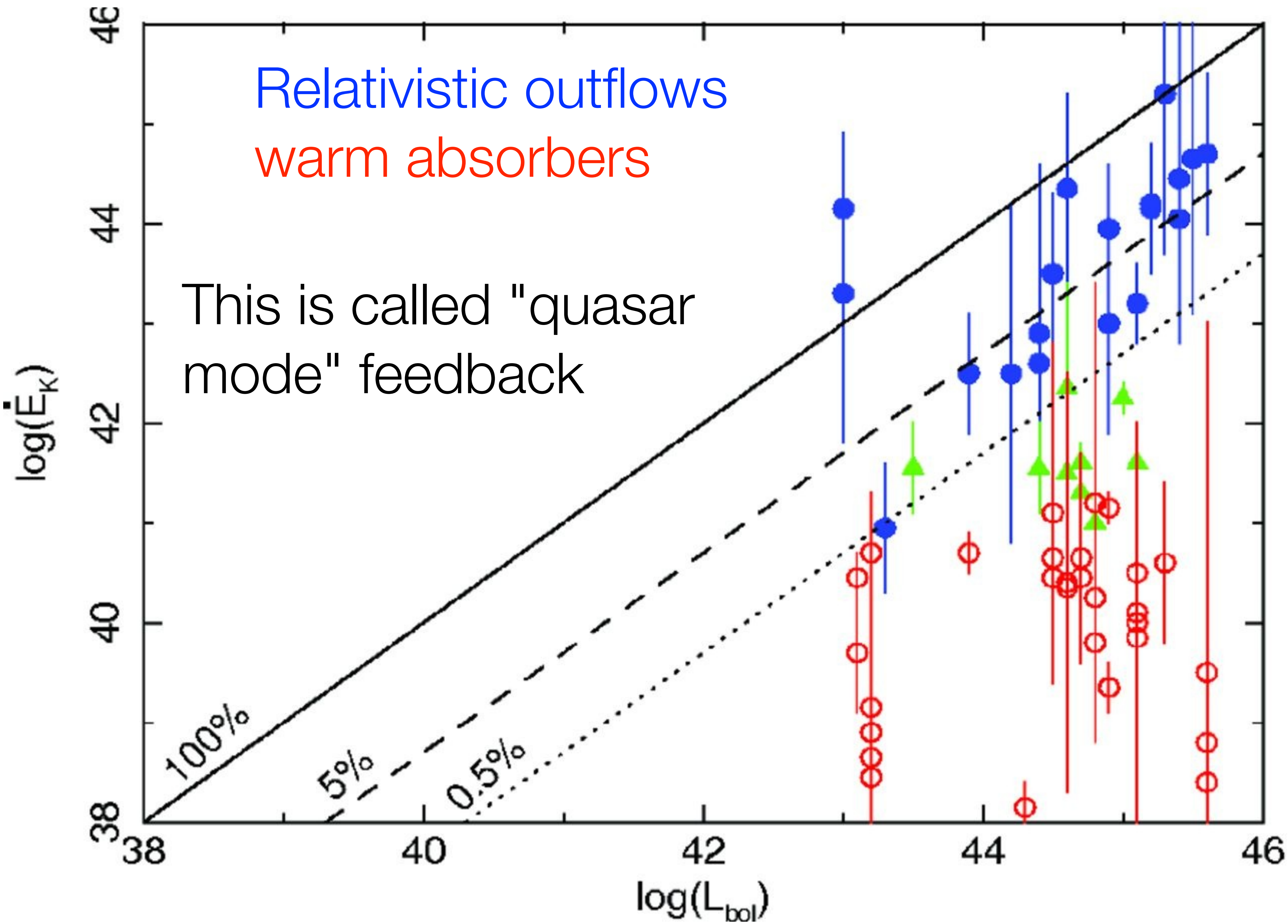
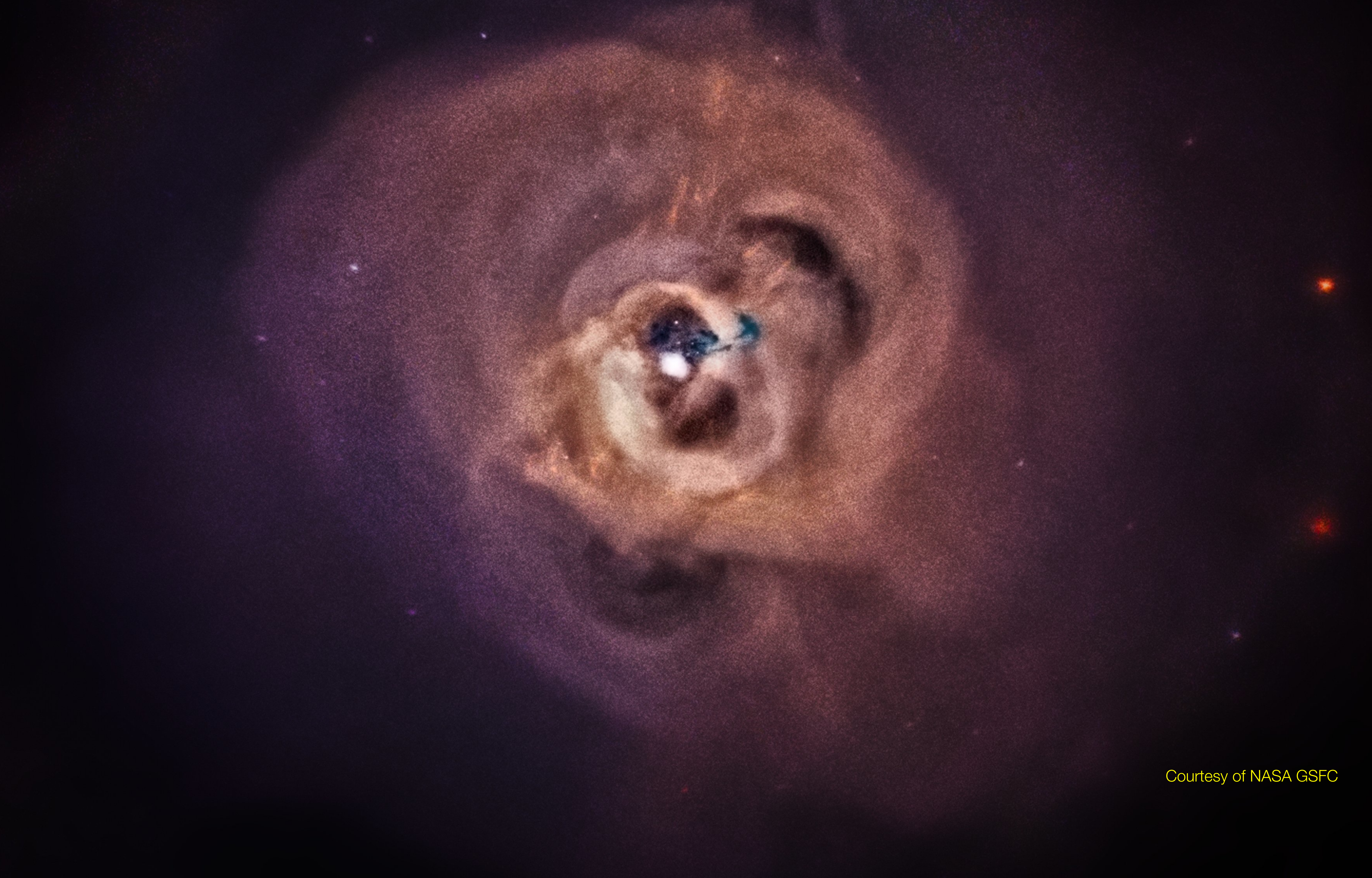
UFOs are good candidates for feed-back

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



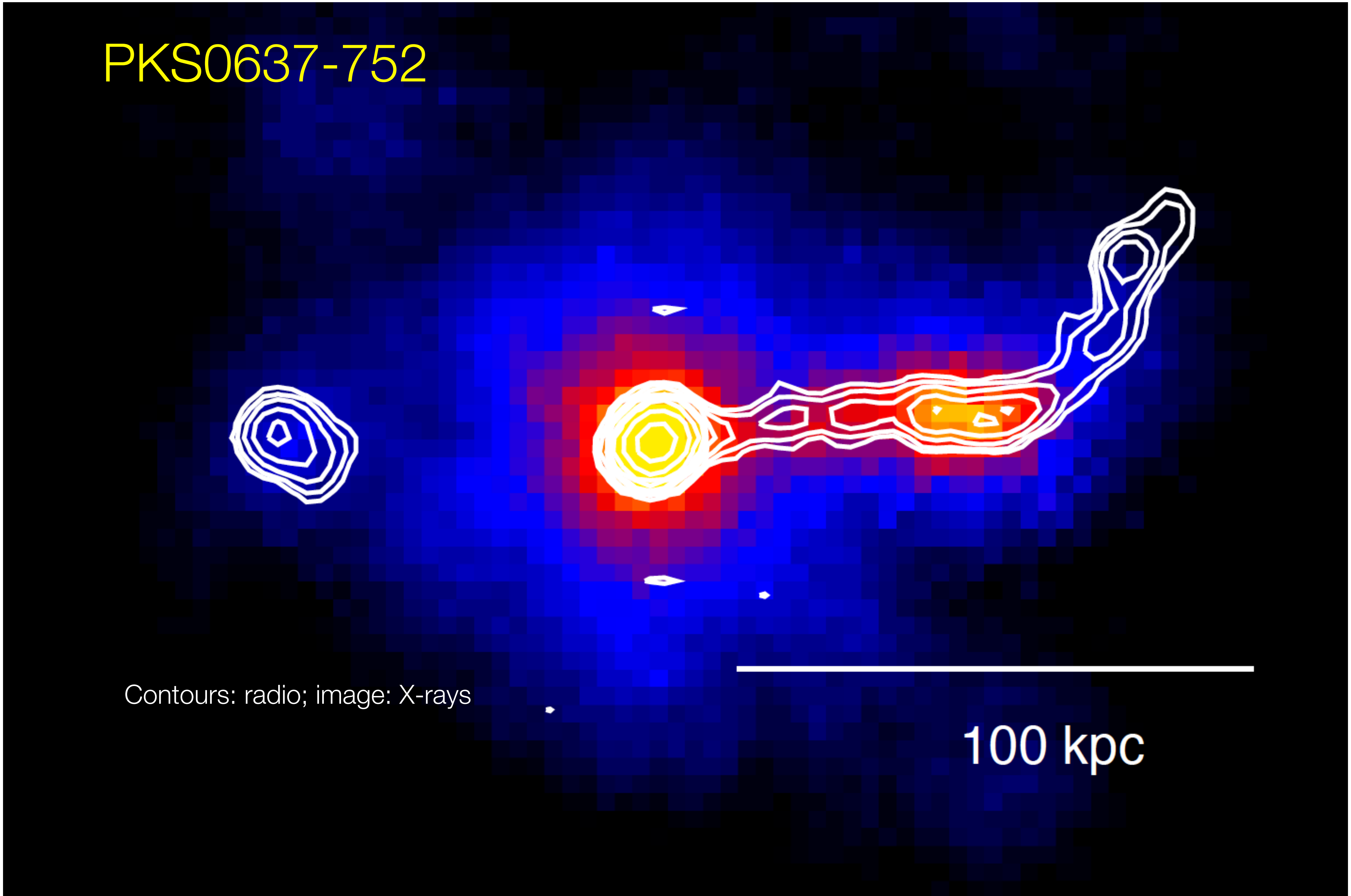
Chandra/ACIS image of the Perseus Cluster (see K.Arnaud's presentation)



Courtesy of NASA GSFC

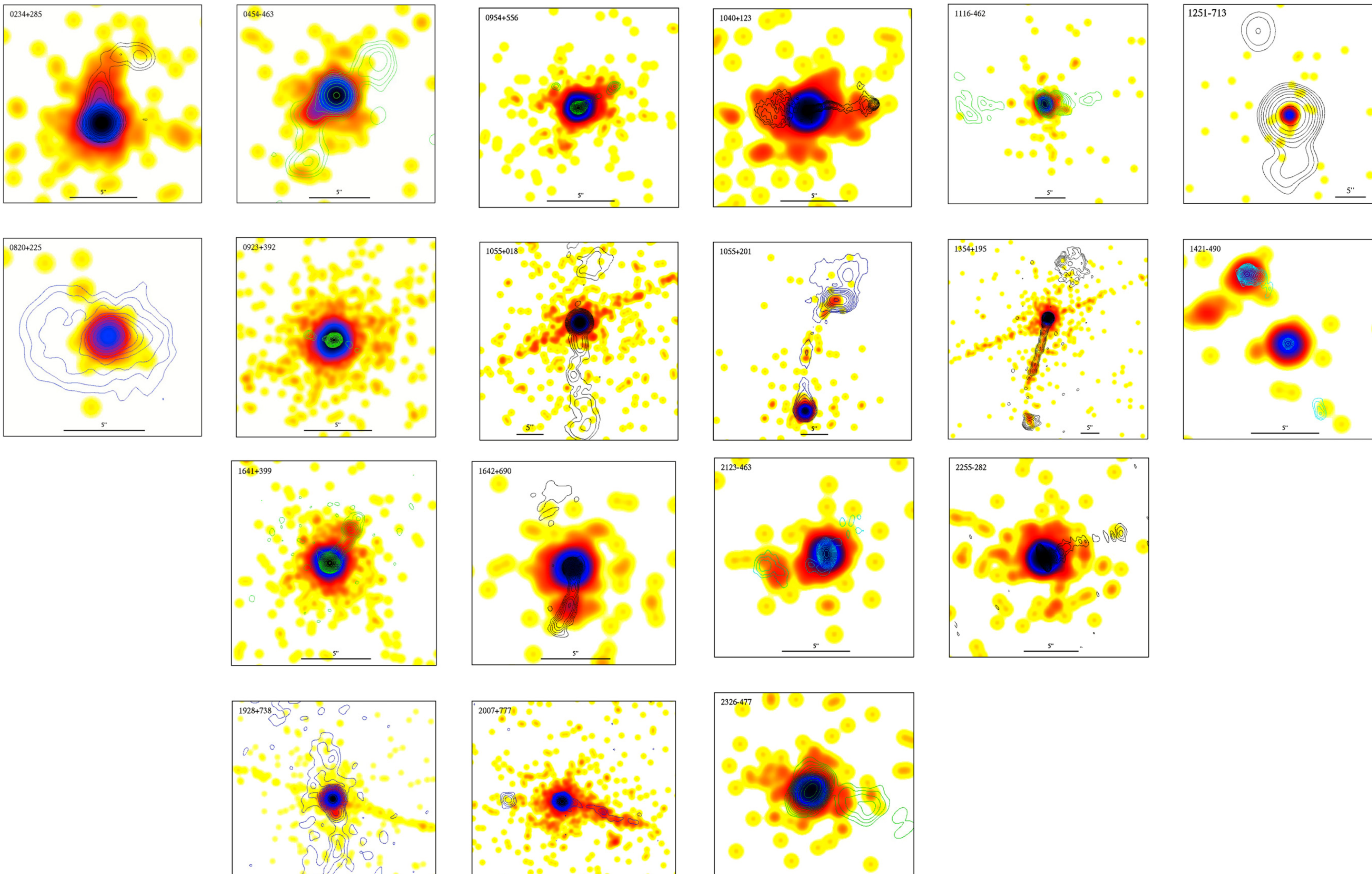
Chandra has revolutionised the field, by chance …

Schwartz et al., 2000, ApJ, 540, 69



Very high ratio of X-ray jet detections

Marshall et al., 2011, ApJ, 193, 15

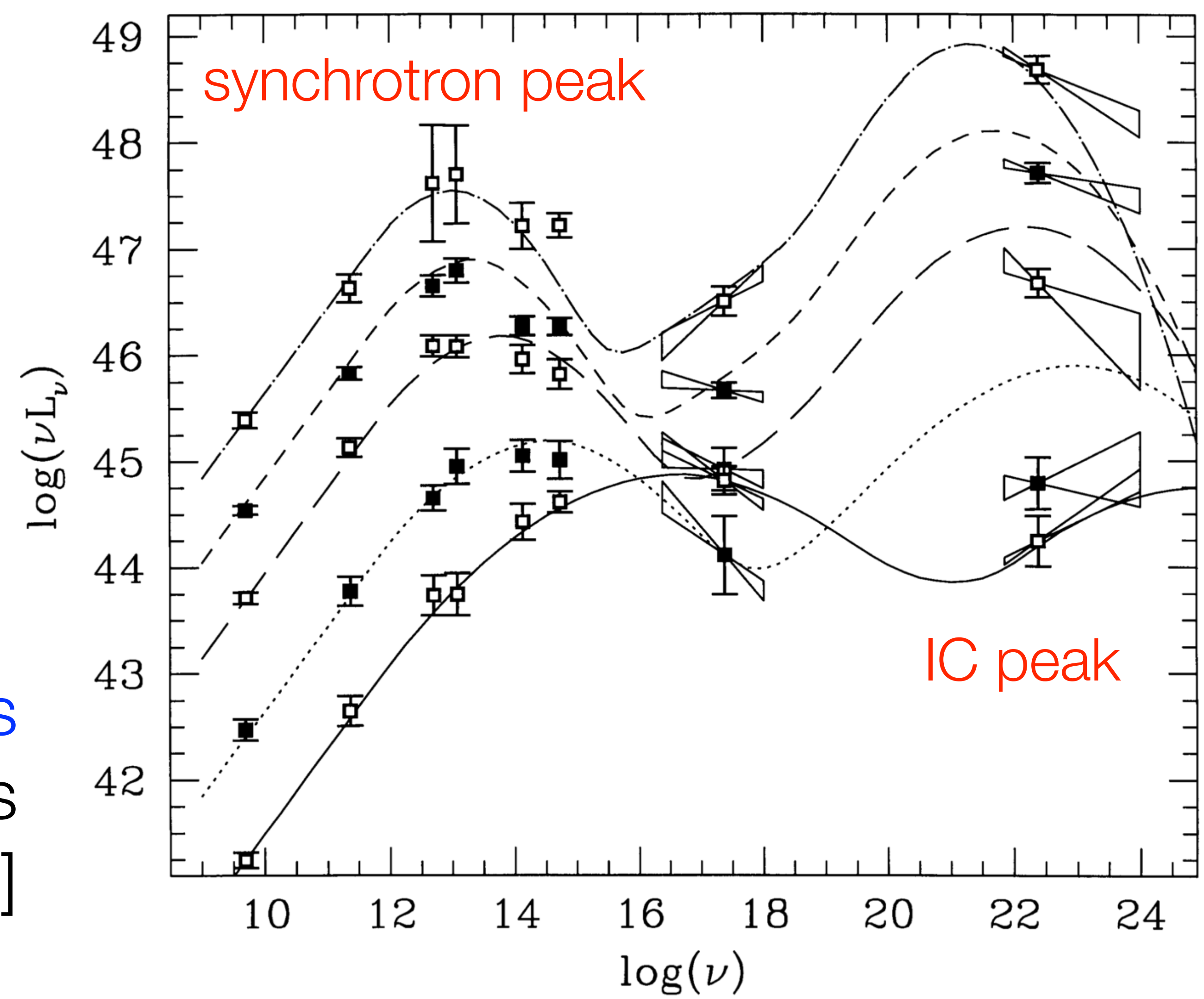


Important physical processes

for the whole treatment of the physics, see the lectures by G.Romero at this Workshop

Fossati et al. 1998, MNRAS, 299, 433

- Synchrotron
- Inverse-Compton (IC); seed photons: Cosmic Microwave Background (CMB)

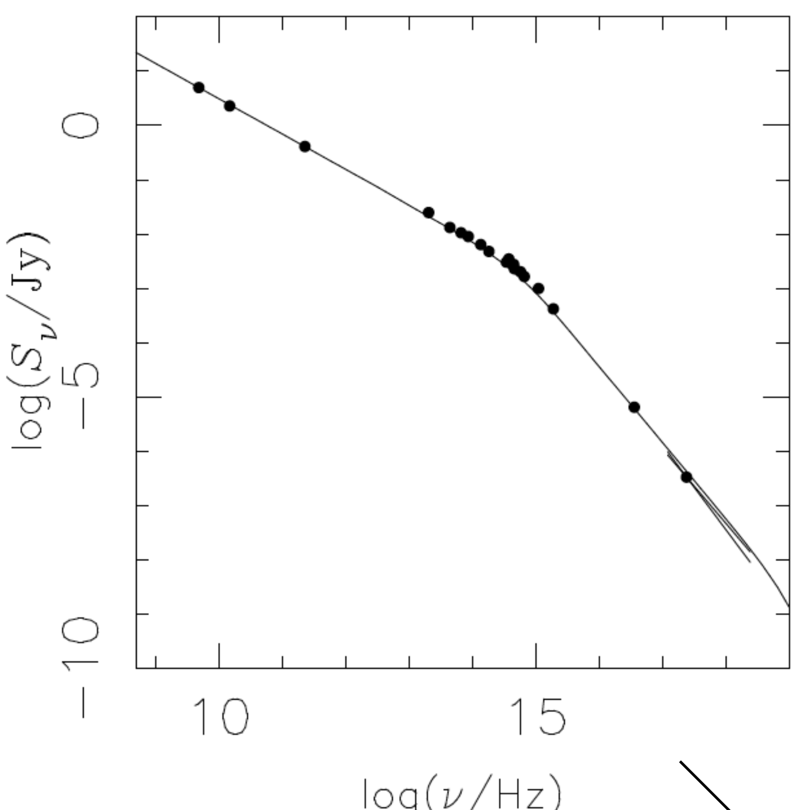


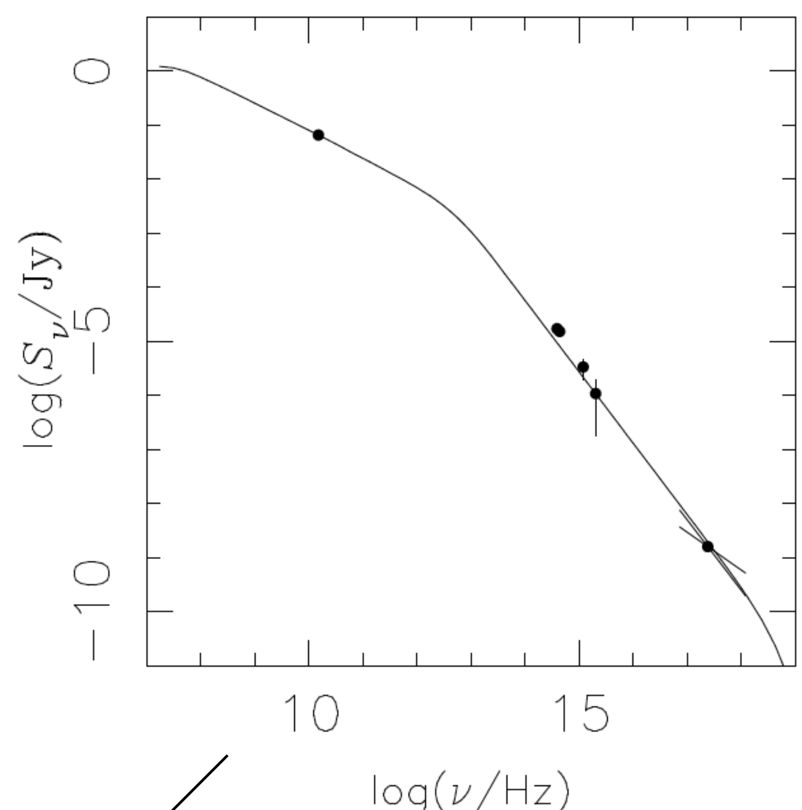
Example: blazars [AGN whose jet points towards us]

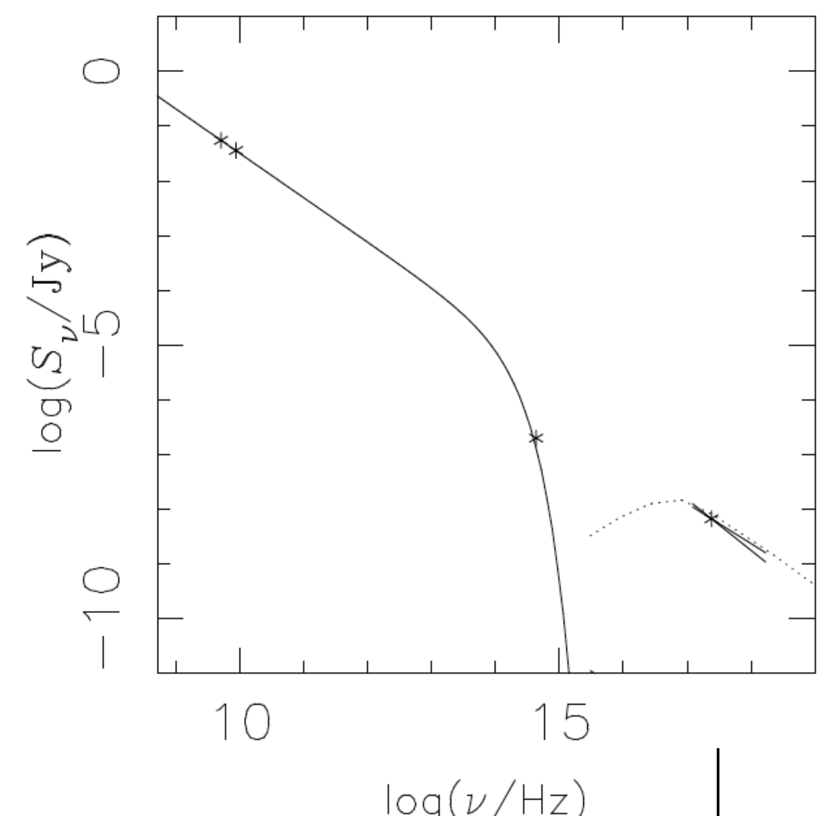
Physical process responsible for X-ray jets

Worrall, 2009, A&ARv, 17, 1

M87 FRI radio galaxy	3C346 FRII radio galaxy	PKS0637-752 QSO knot (WK7.8)







synchrotron

. in-situ acceleration

. knots trace variable AGN output

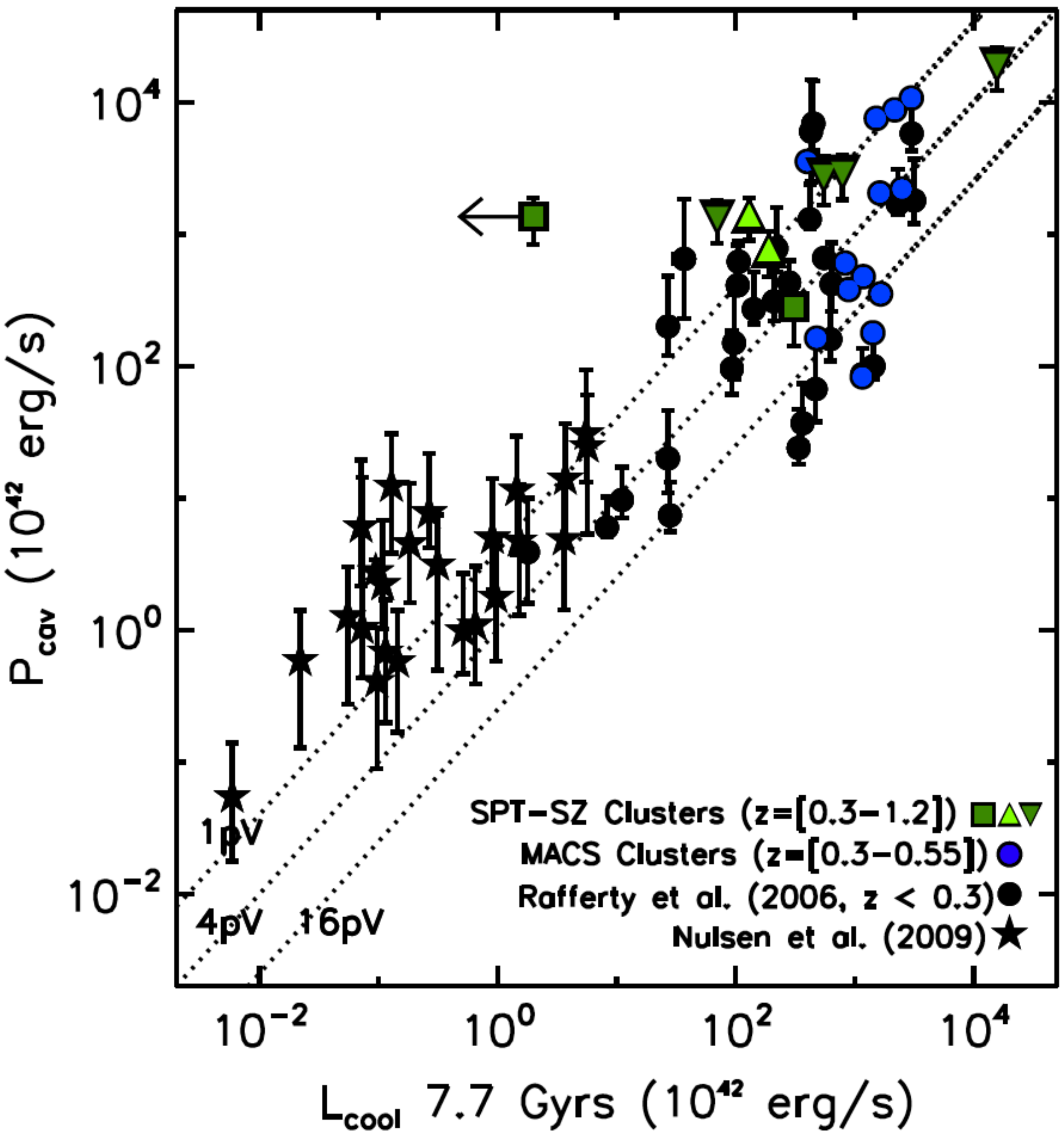
iC-CMB

. highly-relativistic bulk flow

. knots trace variation of particle acceleration

Jet power can inflate these cavities

Hlavackec-Larrondo et al. 2015, ApJ, 805, 35



- *Chandra* sample of galaxy clusters with cavities
- The work done to inflate the cavities (*y-axis*) is larger than the cluster cooling luminosity (*x-axis*)
- ⇒ Feedback (called "*radio-mode*")

Why studying AGN?

- Because the cosmological evolution of X-rays is strictly linked to that of their host galaxy

- Because they allow us to determine the most elusive property of astrophysical black hole (spins)

- Because they offer us the opportunity of studying the behaviour of matter under Strong Gravity

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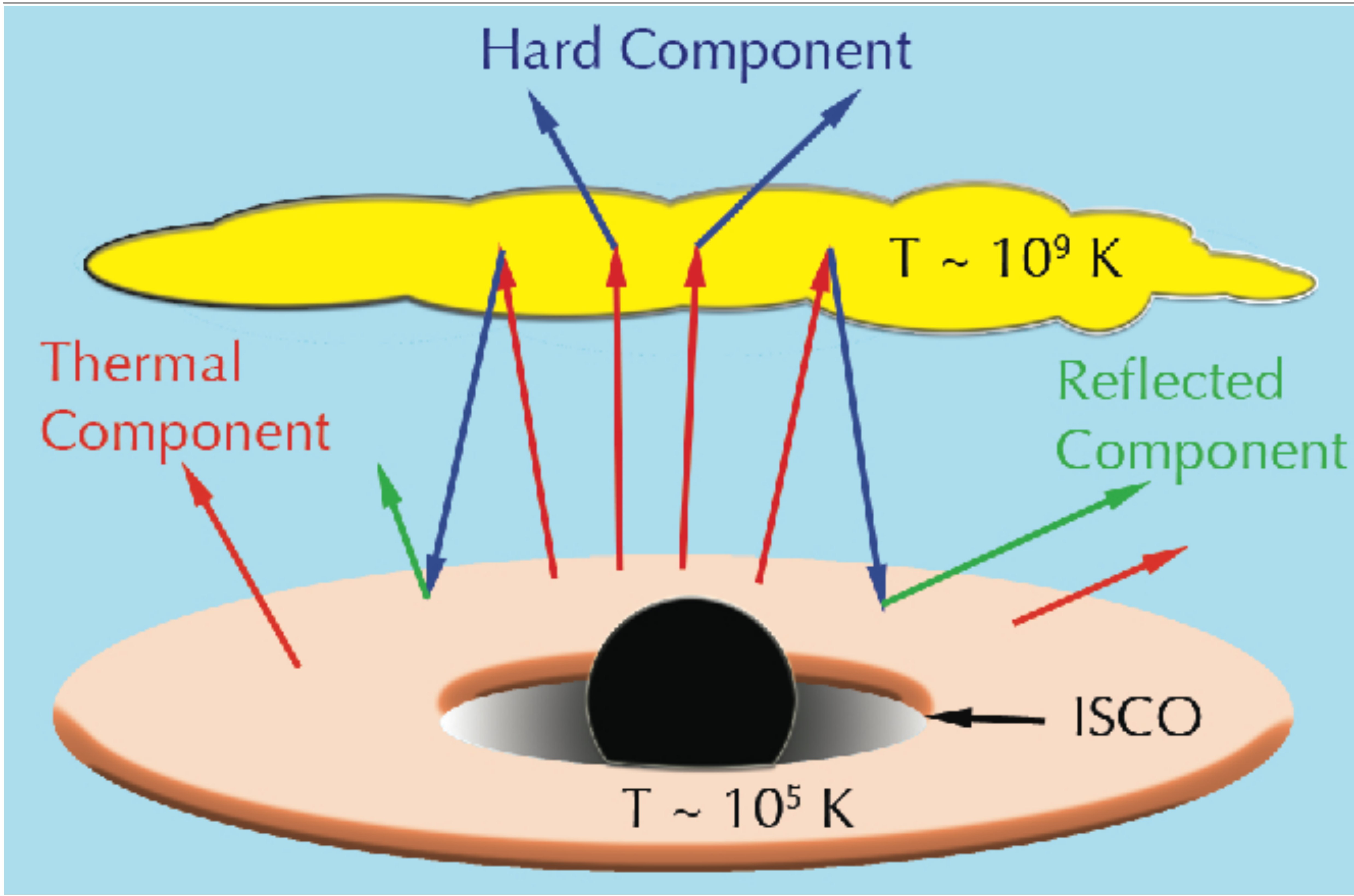
Artist's view of the innermost regions of an AGN

(Reynolds, 2013, astro-ph/1307.3246)

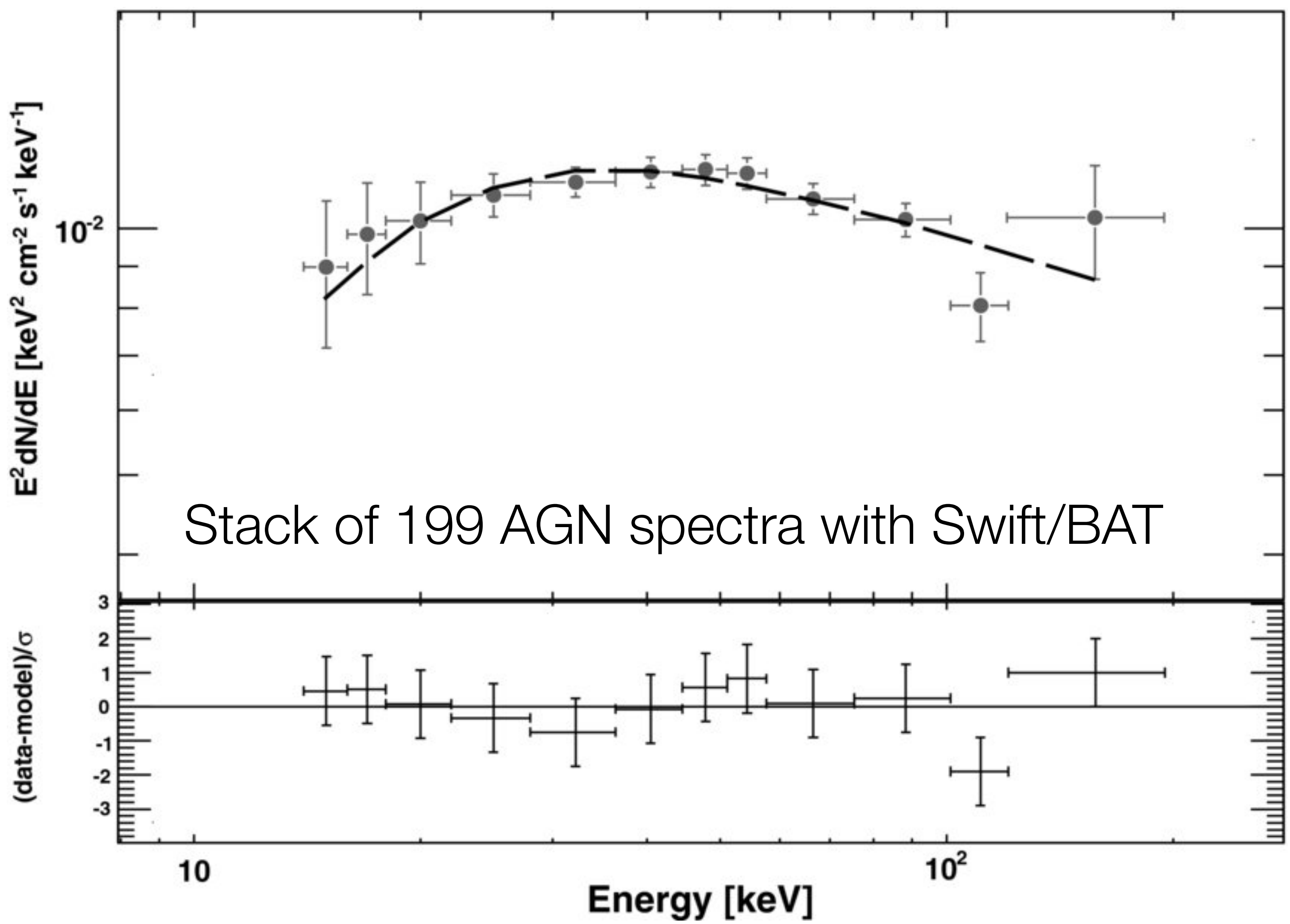


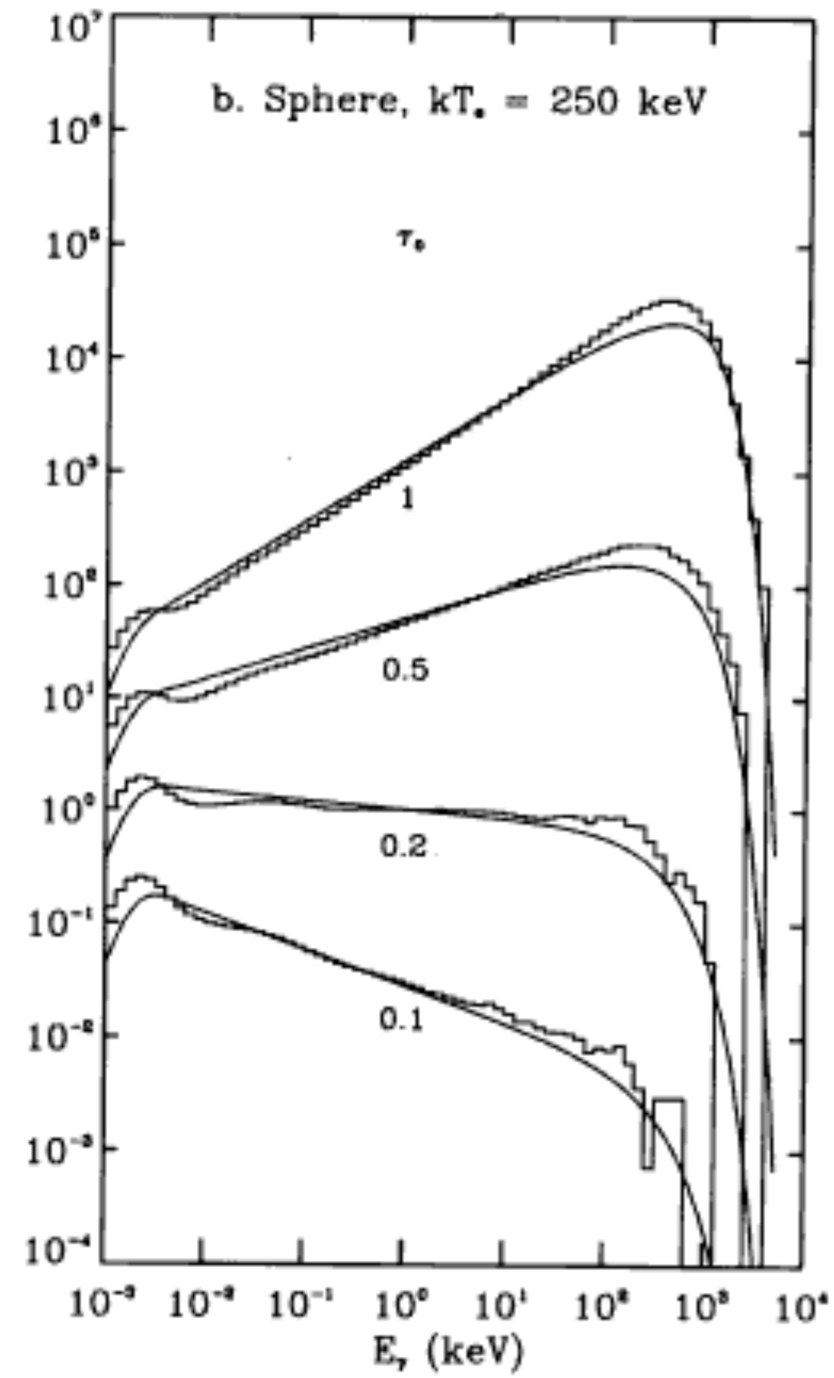
Primary continuum: coronal power-law plus cut-off

(Burlon et al., 2011, ApJ, 728, 58) (Hua & Titarchuk, 1995, ApJ, 449, 188)

The Hard Component *can be approximated* by a power-law with a high-energy exponential cut-off
⇒ Comptonization of a population of thermal electrons

Do not use `highecut*po`. Use `nthcomp` or `comptt`



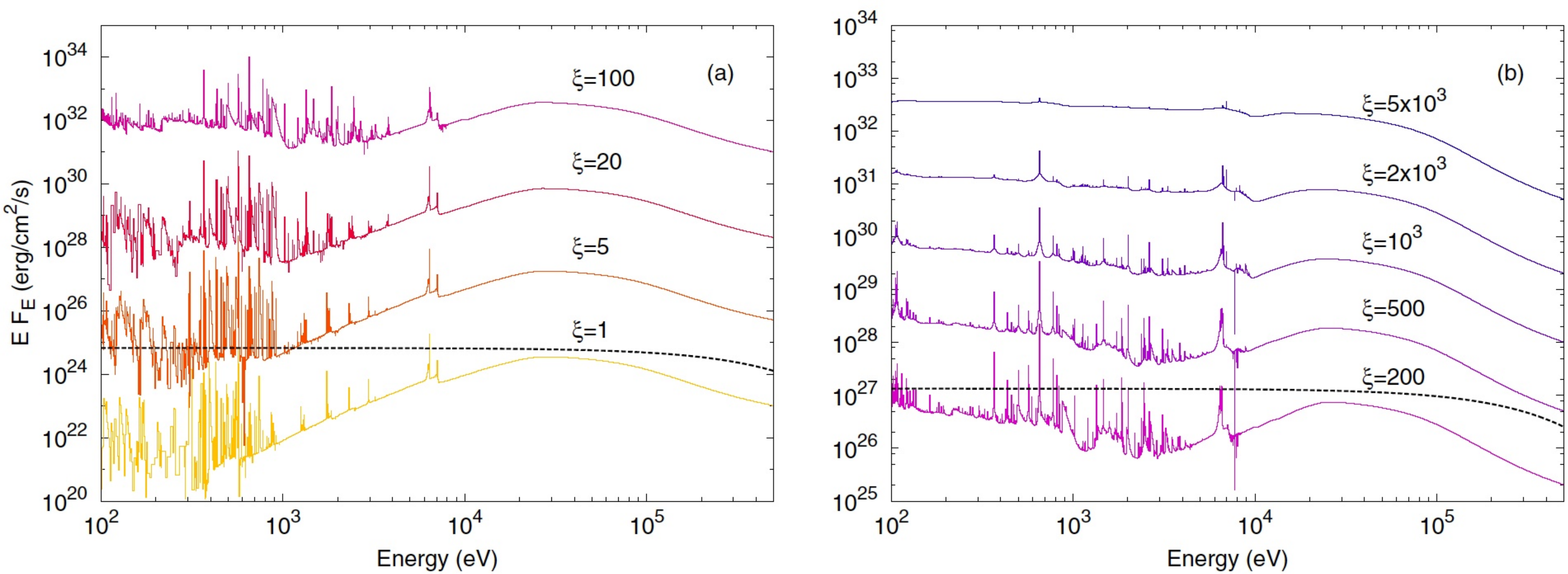


Reflection component: accretion disk

(Garcia et al., 2014, ApJ, 2013, 768, 146)

The disk reflection spectrum exhibit continuum and lines:

- the continuum is shaped by the interplay between photoelectric and Compton scattering cross-sections
  - "emission (Compton) hump" at ~20-30 keV
- fluorescence and recombination emission lines
- highly dependent on the ionisation state (*ξ*)
- use `xillver`



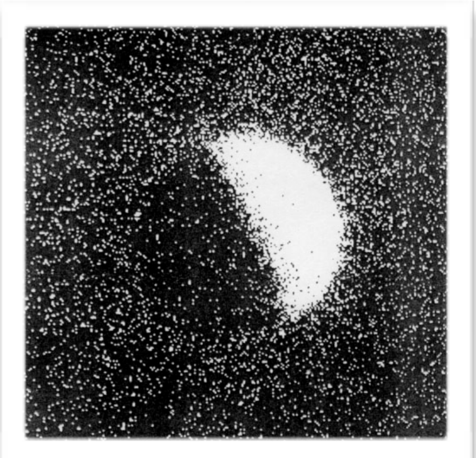
Cosmic X-ray Background (CXB)

(Revnivstev et al., 2014, Ast.Lett, 11, 667

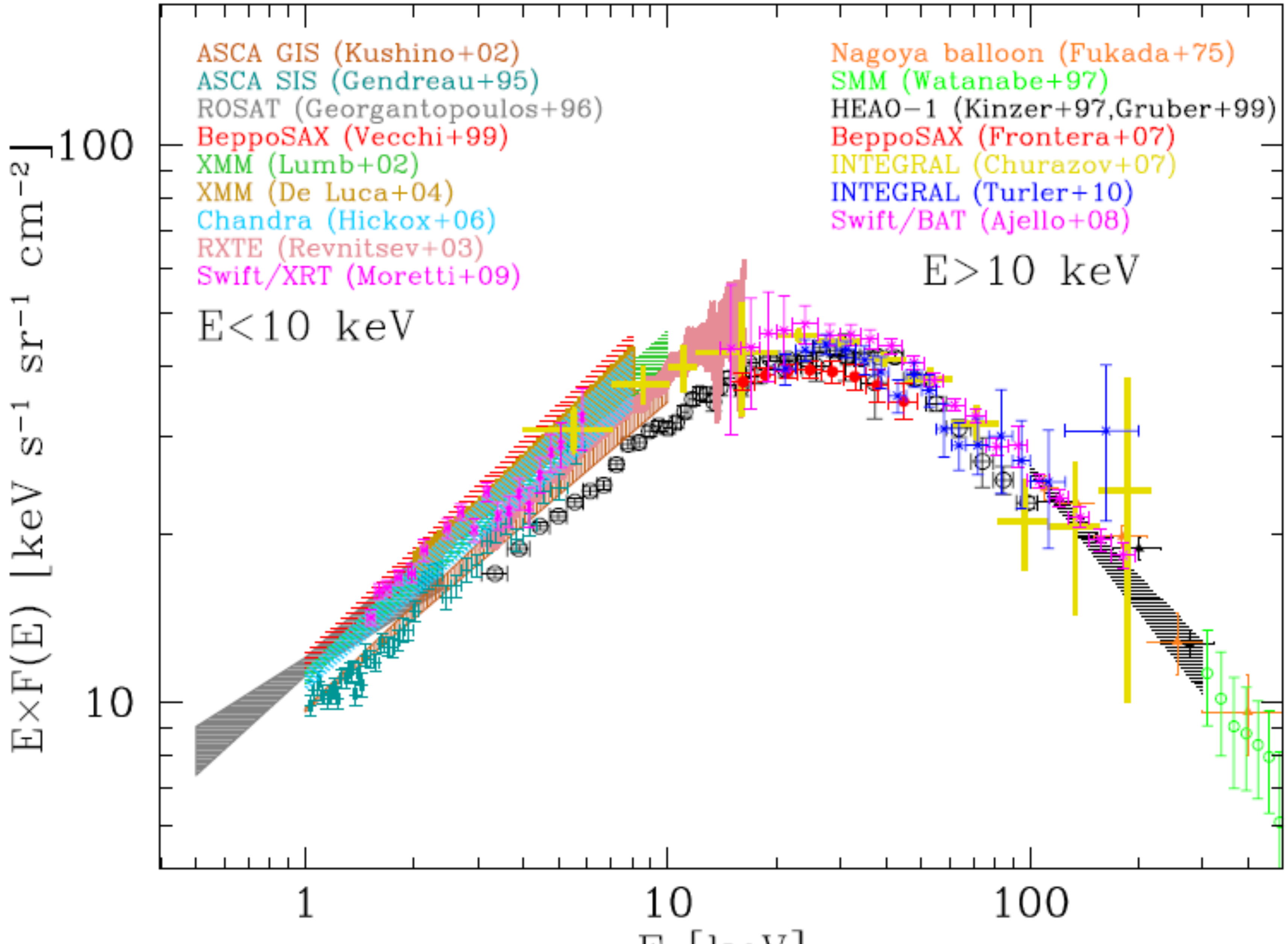
Spectral paradox: Γ_{CXB}~1.4, flatter than AGN (Γ_{AGN}~1.7-1.9)

Solution: X-ray obscuration + (minor contribution) Compton hump

- Uniform diffuse X-ray component (~10% of CMB)
- Extragalactic origin proved by ROSAT looking at the Moon



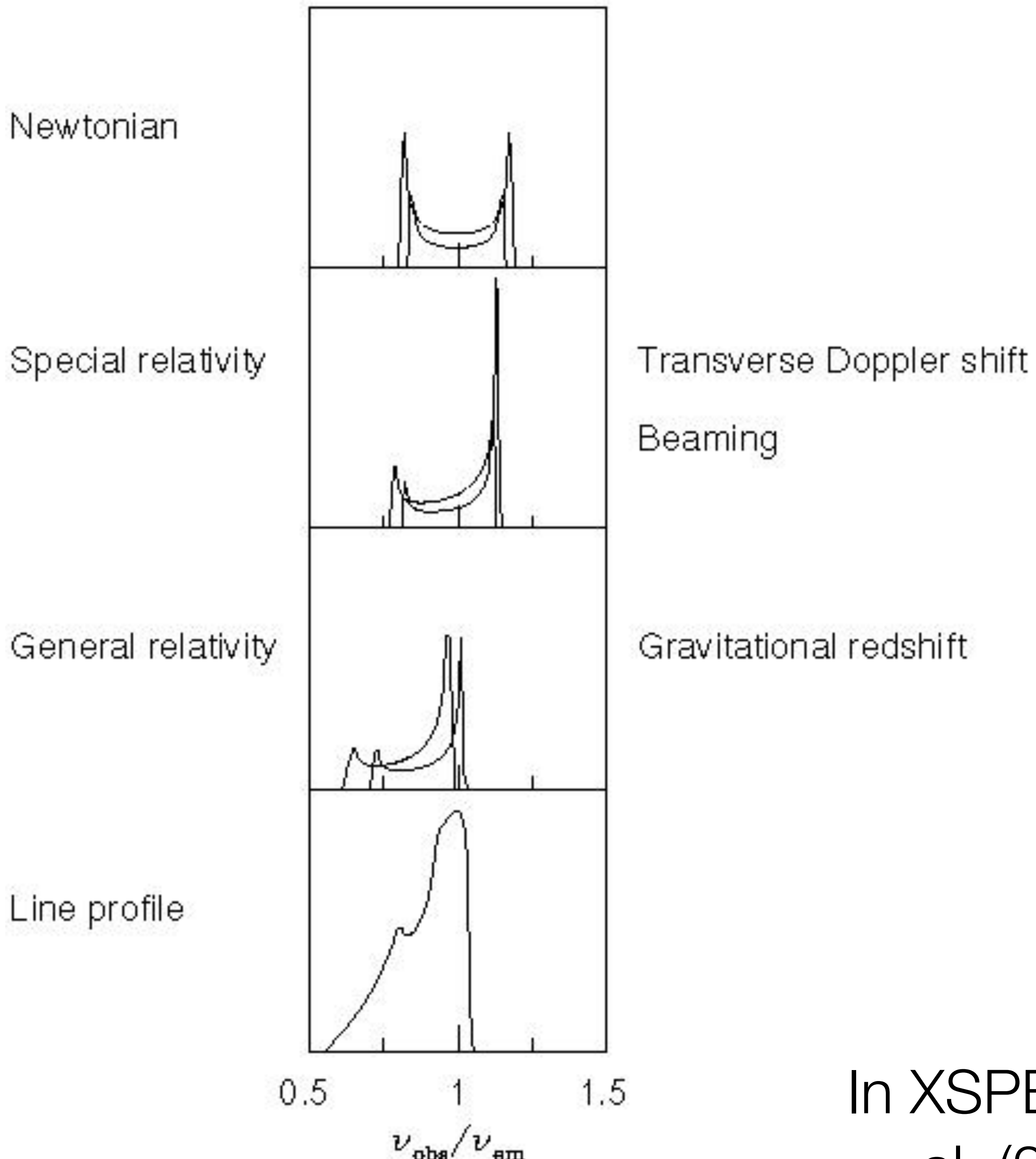
- ≥80-90% resolved in AGN



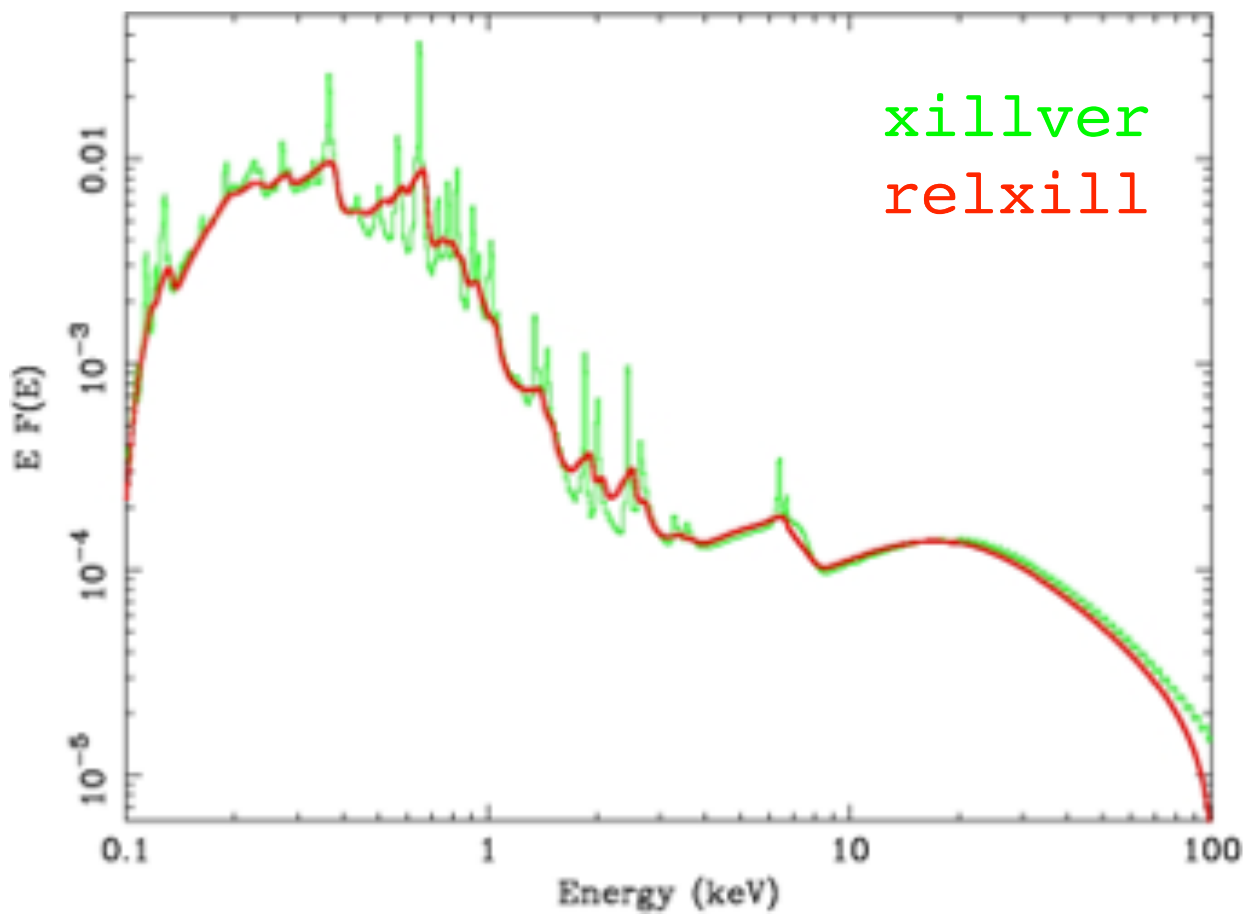
Relativistic broadening: physics

(from original calculations in Fabian et al.,1989, MNRAS, 238, 729)

Credit: G.Miniutti (LAEX)



Imagine now this kernel convolved to the accretion disk reflection model



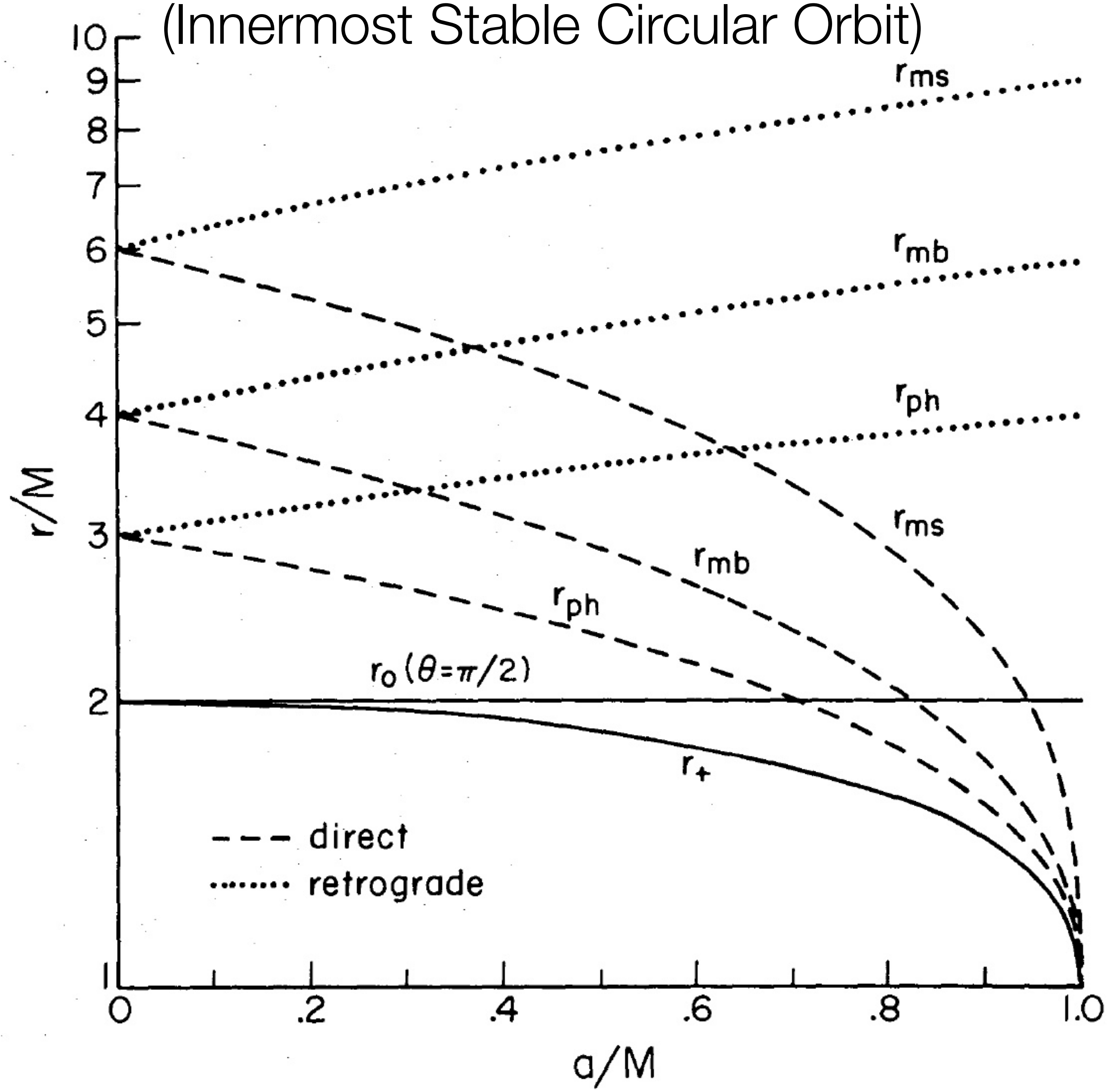
In XSPEC, use `relxill`, or Niedzwiecki et al. (2018, MNRAS, arXiv:1805.06065)

Dependency on the black hole spin

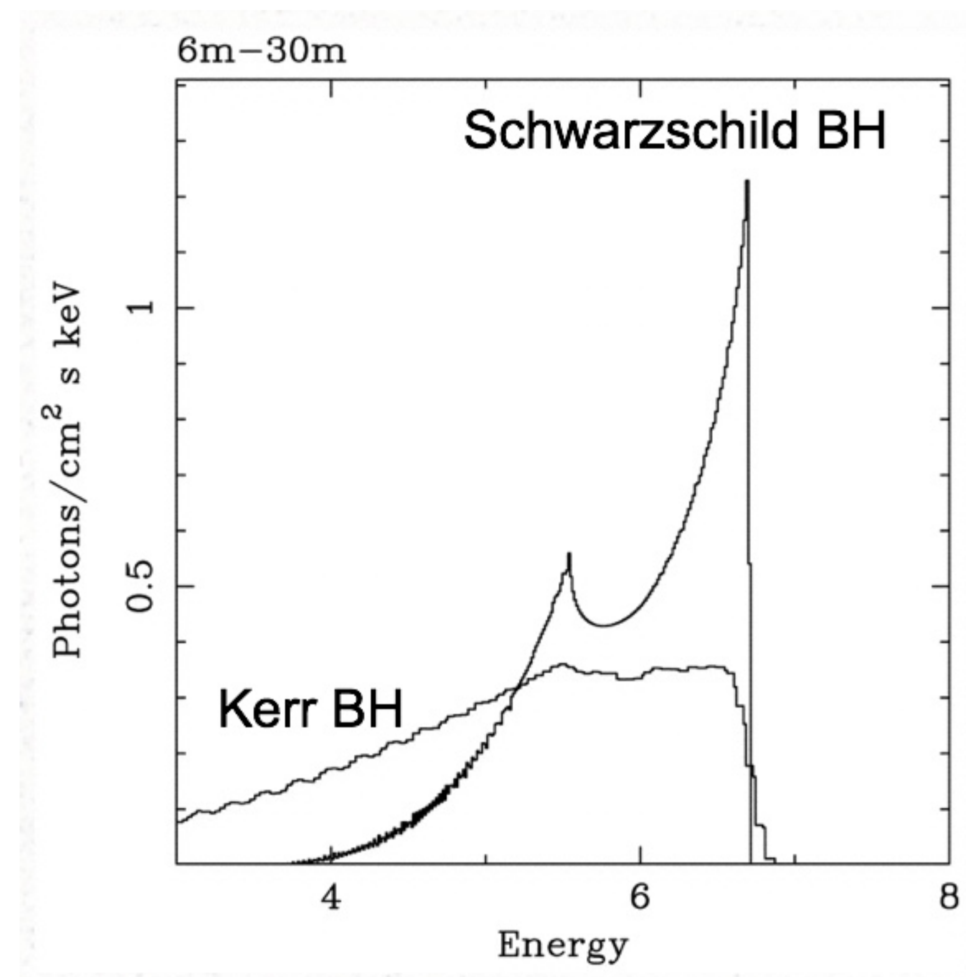
(Bardeen et al,, 1972, ApJ, 347, 369)

(Fabian et al., 2000, PASP, 112, 1145)

$r_{ms} \rightarrow r_{ISCO}$
(Innermost Stable Circular Orbit)



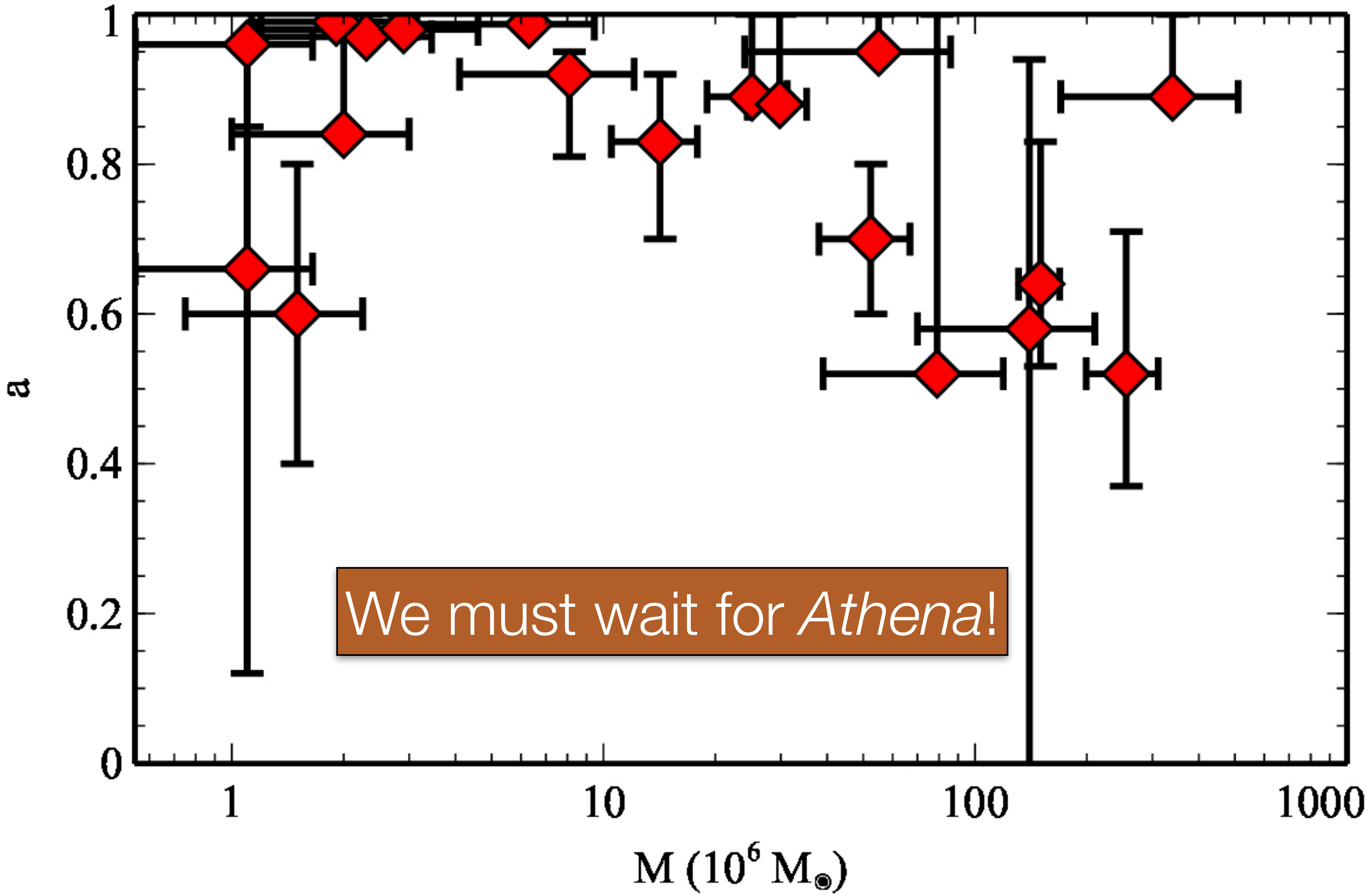
Assuming that the disk always reaches ISCO, we can use the line profile to derive the BH spin



Spin distribution

(Reynolds, 2013, astro-ph/1307.3246)

Bias! Higher spin AGN are radiatively more efficient, so easier to detect

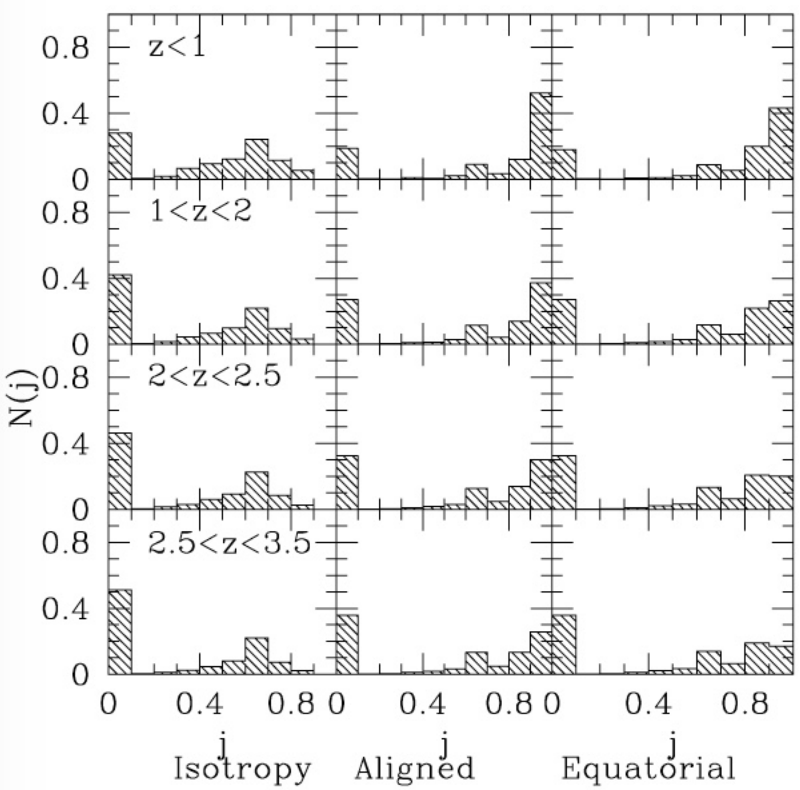


Implications

(Berti & Volonteri, 2008, ApJ, 684, 822)

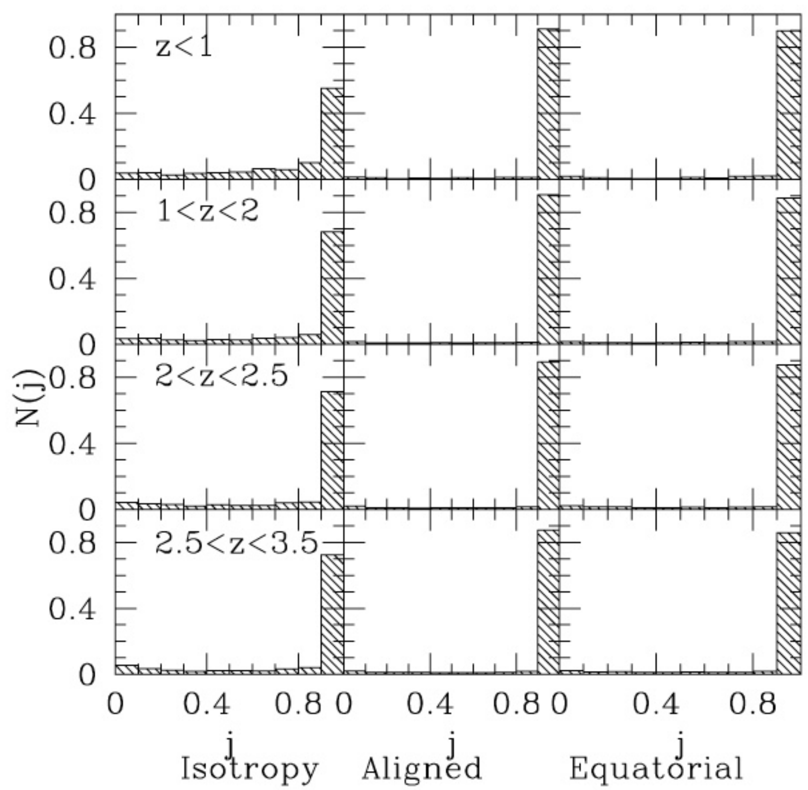
Measuring the distribution of BH spin in the local Universe tells us of the major driver of host galaxy evolution

Only mergers



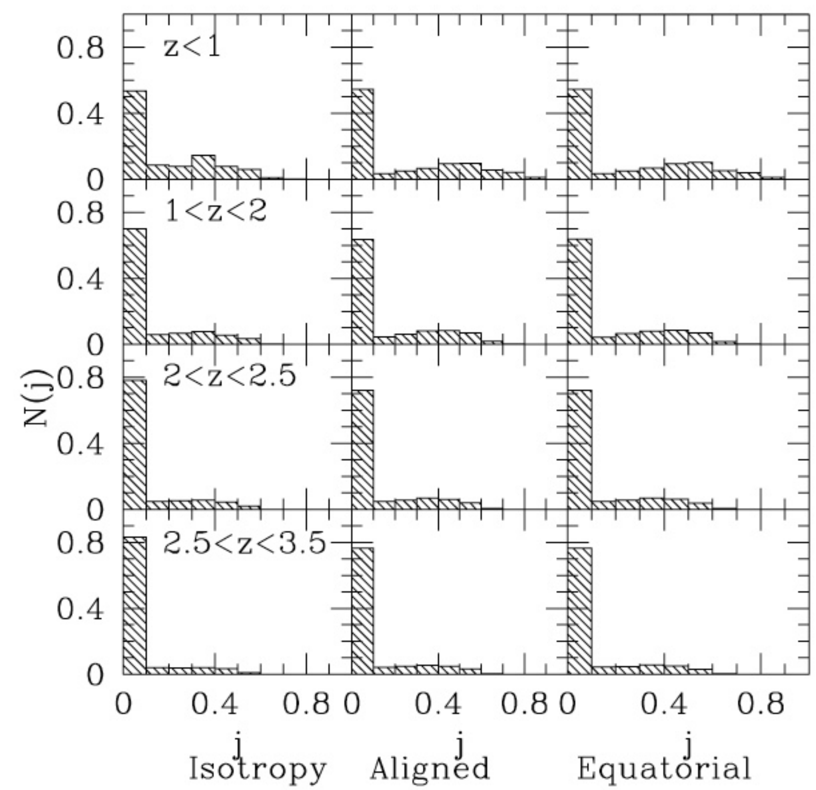
homogenous distribution

Mergers + coherent accretion



maximally spinning (Kerr)

Mergers + chaotic accretion



no spinning (Schwarzschild)

Not all Fe lines are broad

Kallman et al., 2014, ApJ, 780, 121