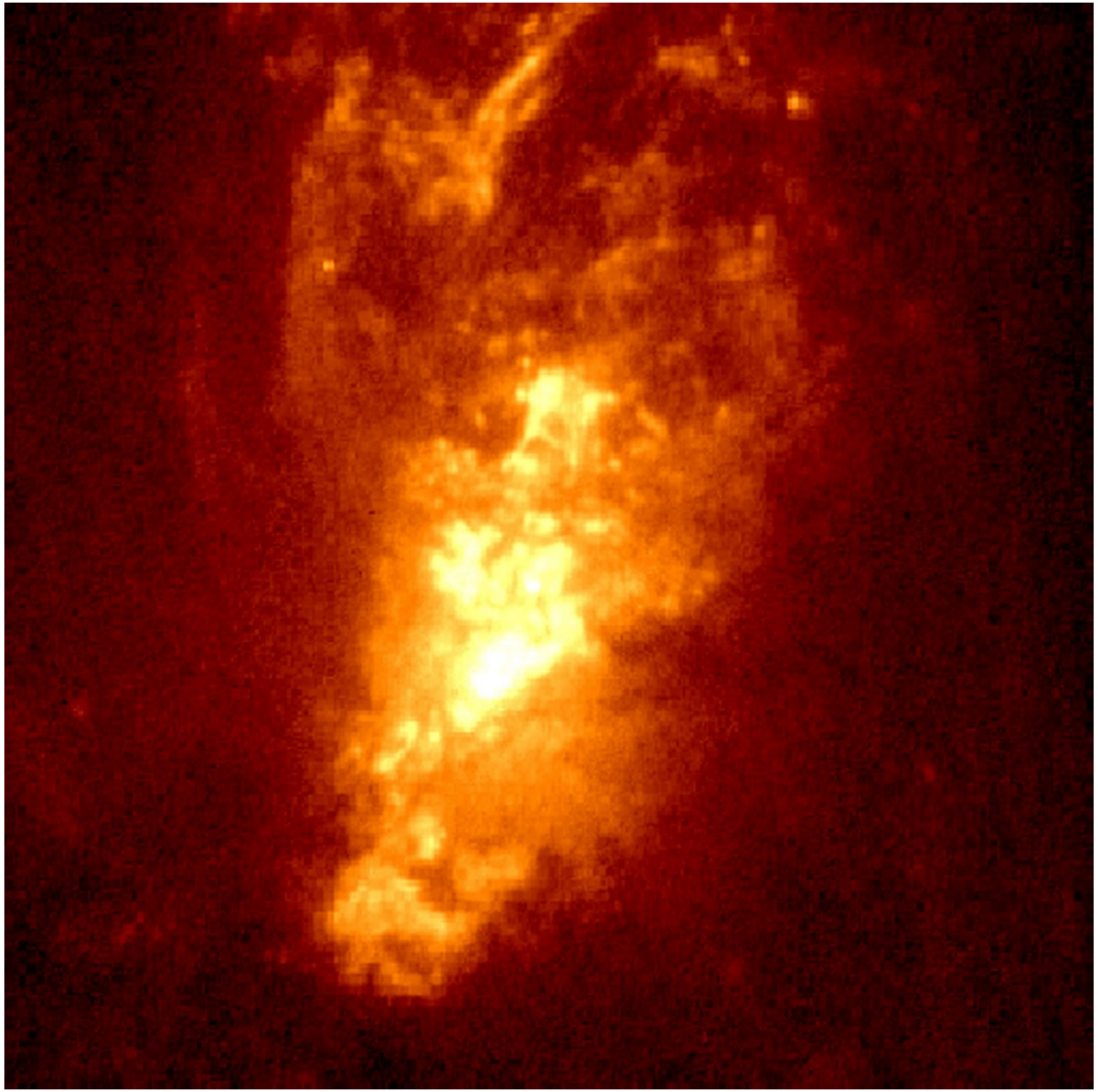
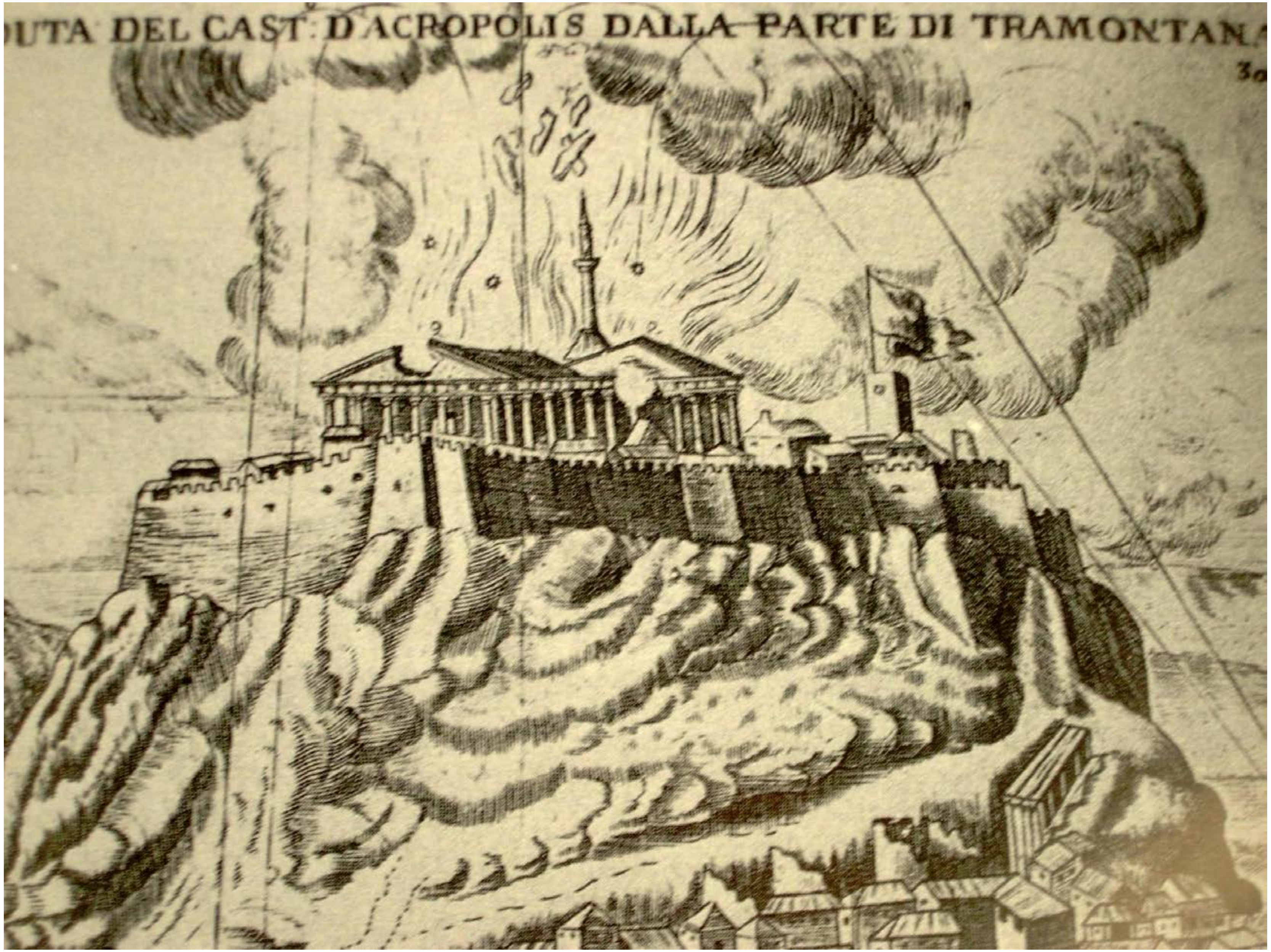
The Metagalactic Ionizing Background: Stars vs. Black Holes



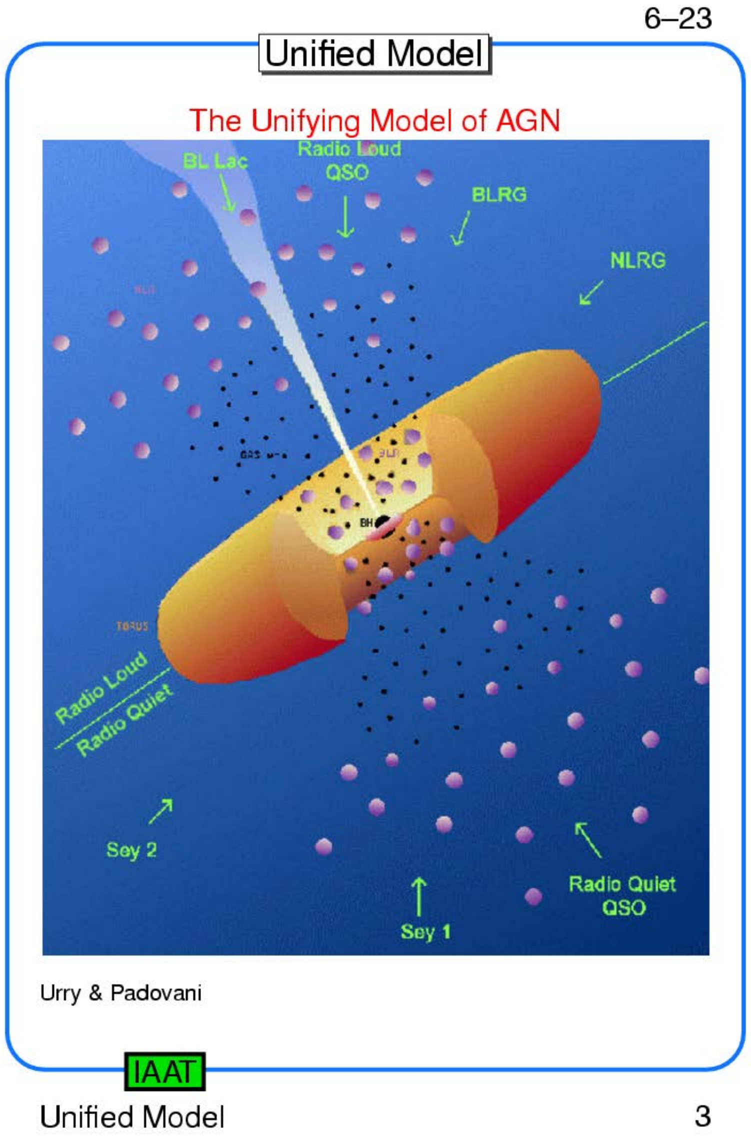
Key Questions

- What are the respective production rates of ionizing photons by hot stars and accreting supermassive black holes (AGN)?
- What fractions of these ionizing photons escape to the IGM?
- What processes set these escape fractions?
- How do these sources/processes vary as a function of redshift?
- In this talk I will try to give a global overview of these issues

A QSO exploding the galactic labyrinth…

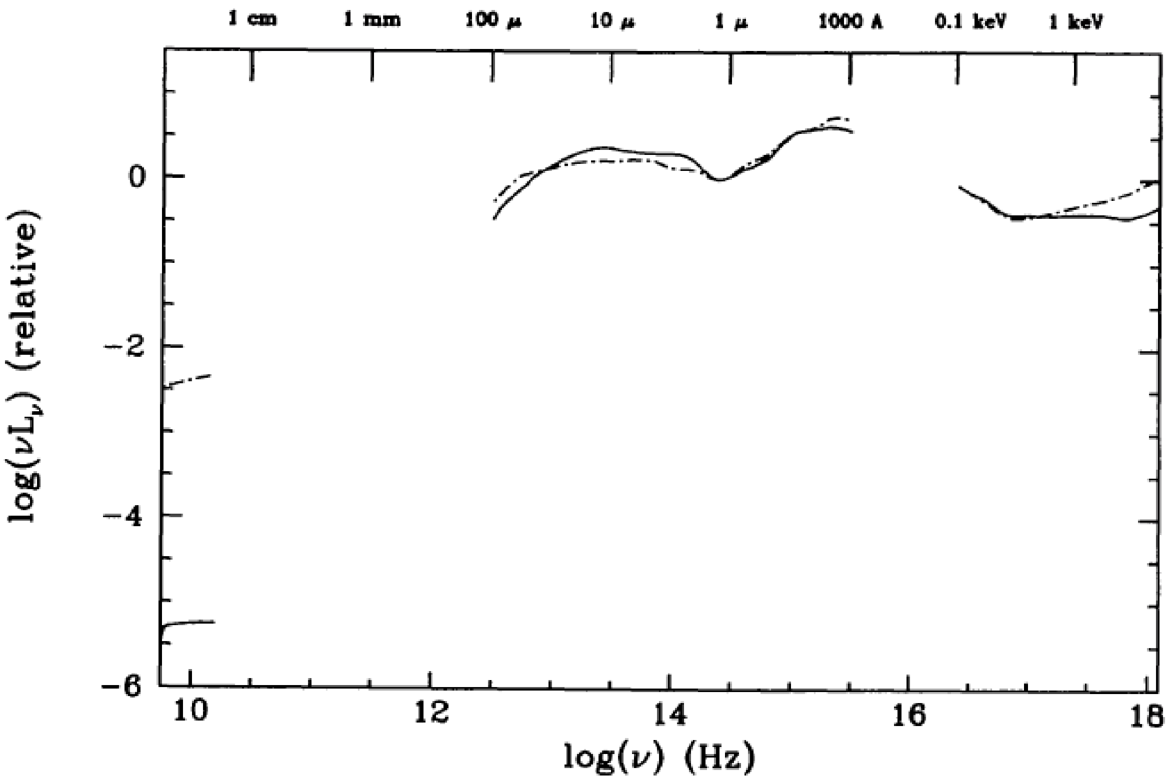


First, a brief “AGN Primer”



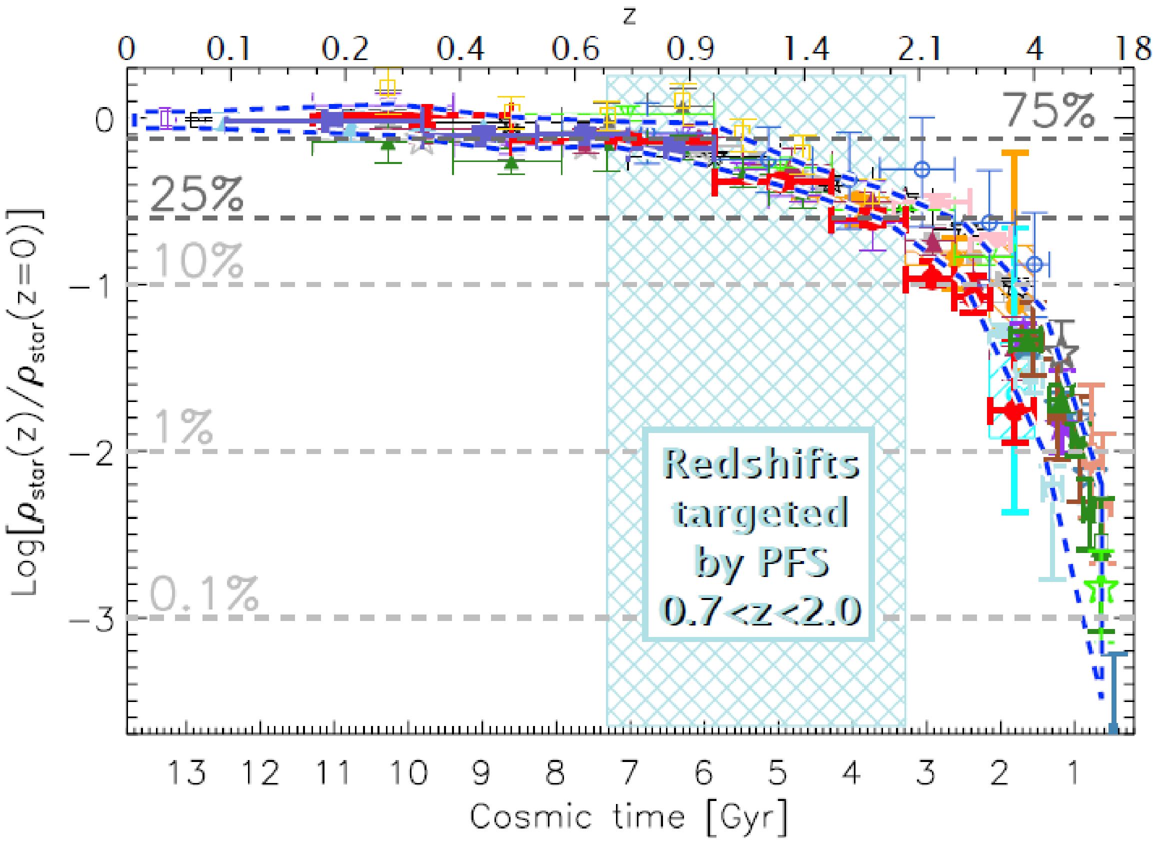
- Central engine: SMBH + accretion disk produces X-rays and ionizing and non-ionizing UV + visible photons
- Dust in the obscuring torus absorbs UV and visible photons and radiates in NIR/MIR
- View “central engine” directly in Type 1 AGN
- Central engine occulted in Type 2 AGN

Mean Type 1 AGN SED



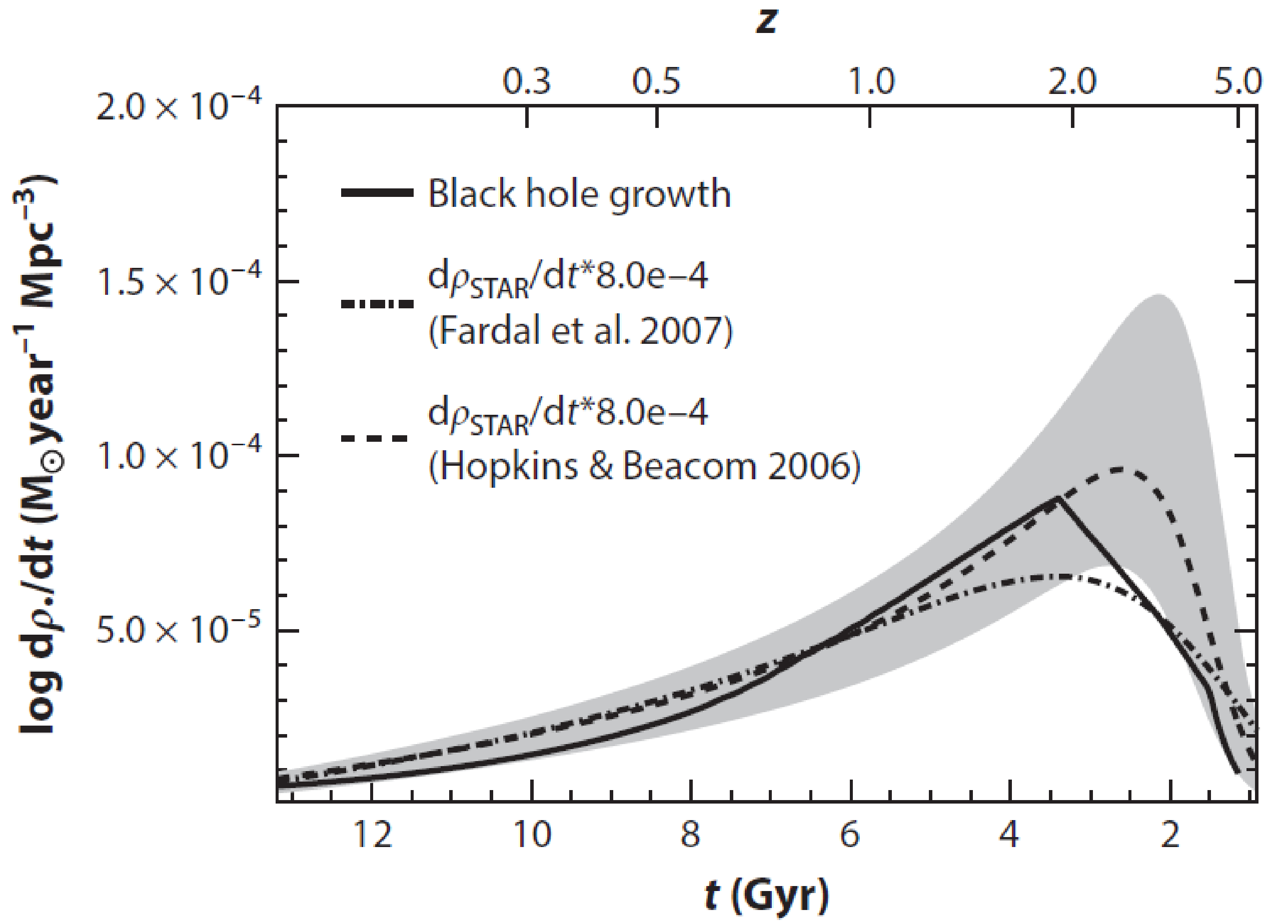
- Wavelengths below ≈ 1 μm from the central engine
- Wavelengths from ≈ 1 to 100 μm from the obscuring torus
- Roughly equal luminosities imply torus absorbs at least ½ of the emission from the central engine
- Elvis+1994

The Post-EOR Era Dominates Cosmic Construction



- Roughly 99% of star formation and >99% of SMBH growth happened after EOR
- My talk will mostly focus of this post-EOR time-frame

Post-EOR Cosmic Production Rates of Stars & SMBH



- Over the post-EOR era, SFR ≈ 10^3 dM_{BH}/dt
- Shankar +09

Production Efficiency of LyC Photons by Stars & AGN

Stars

Assume a standard Kroupa/Chabrier IMF. The fiducial number of Lyman continuum photons produced per stellar baryon is $ʒ_* \approx 4000$

In round numbers $L_{ion} \approx 10\% \ L_{bol}$

This can vary by factors of a few depending of the properties of the hot massive stars (metallicity, binarity, rotation, etc.)

AGN

Take the mean QSO SED, and assume a $L_{bol} = 10\% \ c^2 \ dM/dt$. Then the corresponding LyC production rate is $ʒ_{QSO} \approx 10^6$ photons/baryon

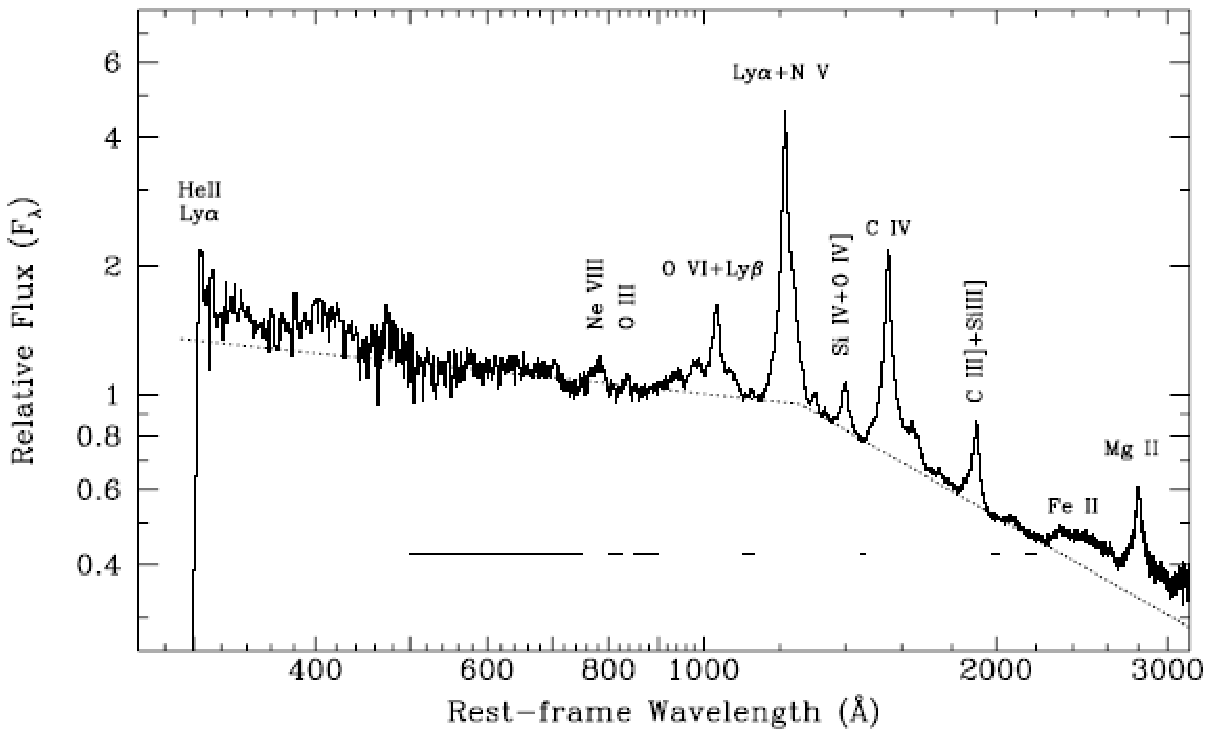
In round numbers $L_{ion} \approx 30\% \ L_{bol}$

So $ʒ_{QSO} \approx 250 \ ʒ_*$

Relative Production Rates of LyC photons

- $\varepsilon_{*,AGN}$: The emission-rate of ionizing photons per co-moving volume element
- This is just the product of rate of SFR (or dM_{BH}/dt) per unit volume times the production rate of photons per baryon by stars (or AGN)
- $\varepsilon_{AGN}/\varepsilon^* = 10^{-3} \times 250 = 0.25$
- For ionizing the IGM, we also need to know the escape fractions f_{QSO} and f_*
- During post-EOR era, we know that f* is small (of-order 1 to 10%)
- What about AGN?

The escape of ionizing radiation from AGN



- Type 1 QSOs show no feature at the Lyman limit: they are transparent (Telfer+)
- Presence strong of NIR/MIR emission from UV-heated dust + emission-lines from photo-ionized gas and relative numbers of Type 1 and 2 QSOs means that f_{QSO} is really more like 30-50% over 4π ster

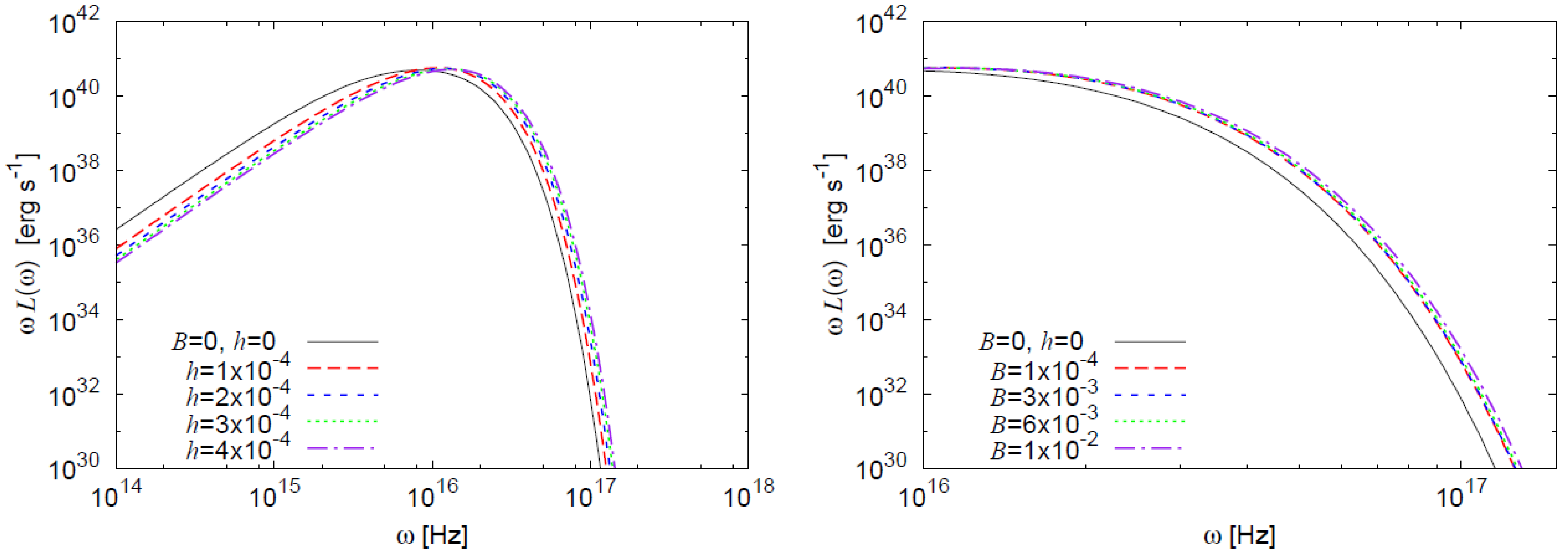
AGN likely more important for the post-EOR LyC

- Rate of *escaping* LyC from AGN vs. Hot Stars
- Product of $(dM_{BH}/dt/SFR) \times (\zeta_{QSO}/\zeta_{*}) \times (f_{QSO}/f_{*})$
- This is ≈ 10 (1) for $\langle f_{*} \rangle = 1\%$ (10%)
- AGN win even though they have 1000 times less mass because:

  1) They are more efficient in generating ionizing radiation

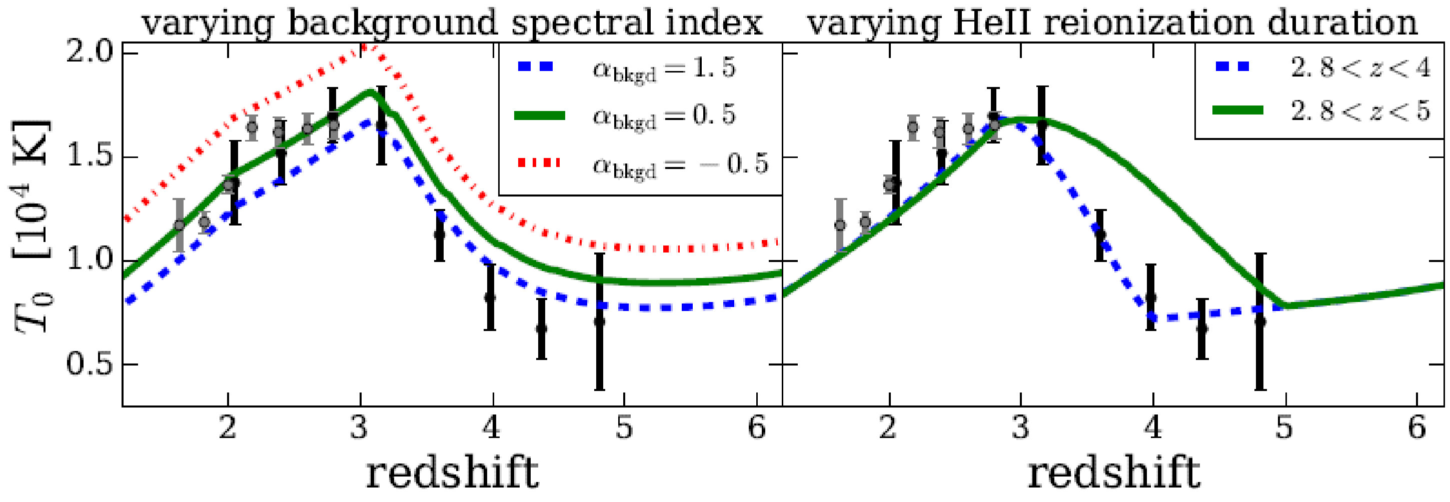
  2) They enable a higher fraction to escape to the IGM

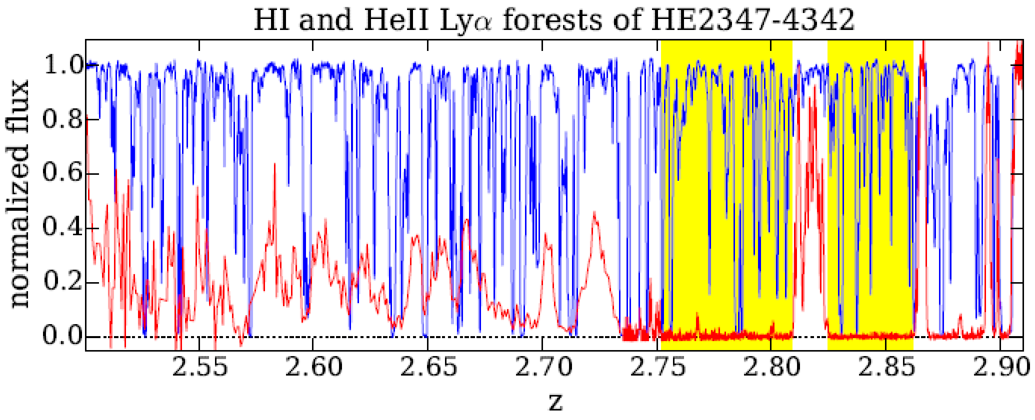
Production of He II Ionizing Photons



- AGN even more dominant – emission from accretion disk continues on smoothly to energies above 4 Ryd (χ_{HeII})
- Very different from hot star SEDs (cf. Hamann & Stanway talks)

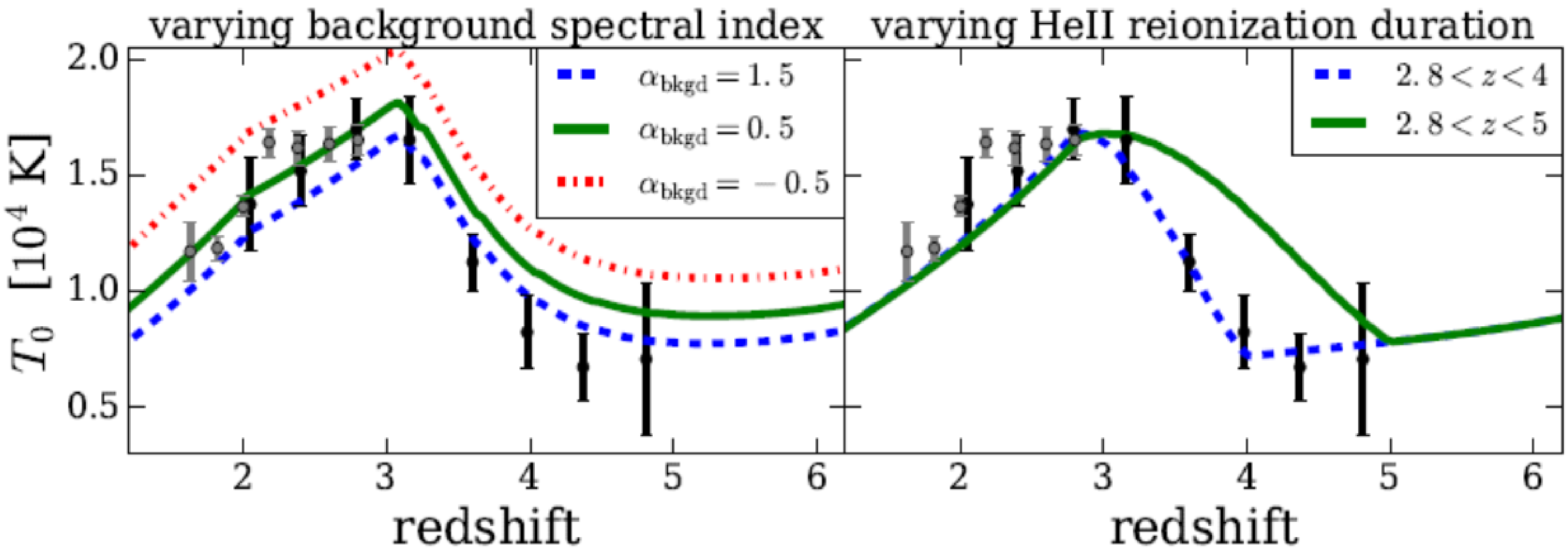
He II Reionization by QSOs (z ≈ 4.5 to 2.8)





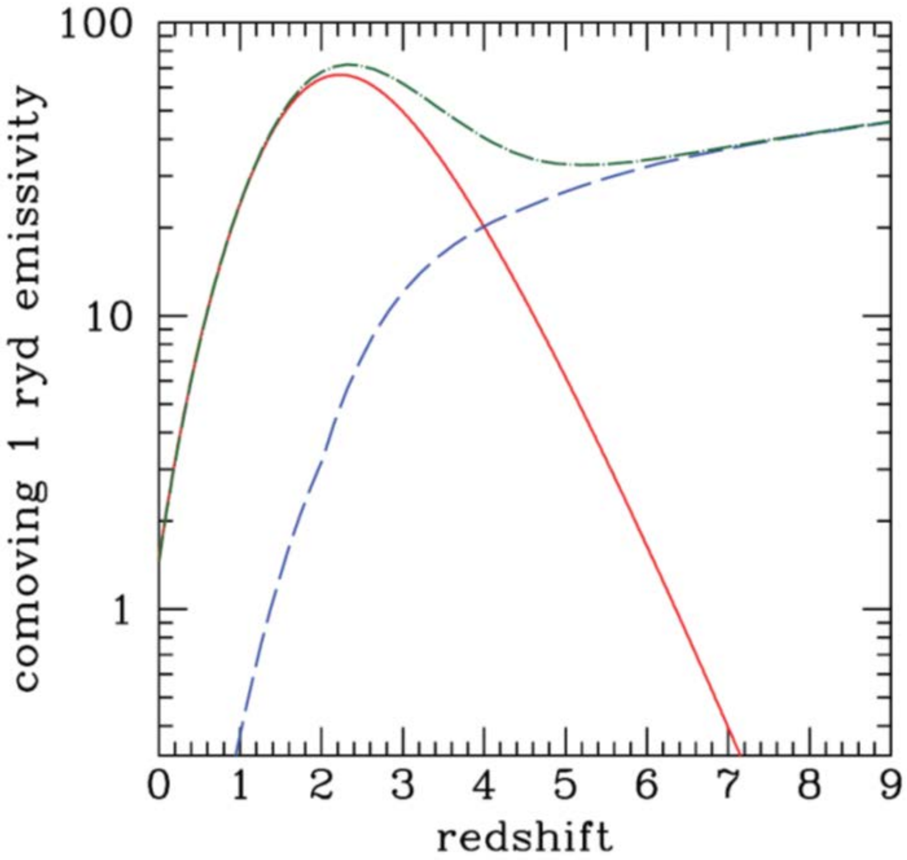
- Rise in T_{IGM} from z ≈ 4.5 from AGN HeII photoionization. Upton Sanderbeck+2015
- He II Lyα forest in QSO at z = 2.9 (near end of He II EOR). Worseck+2011

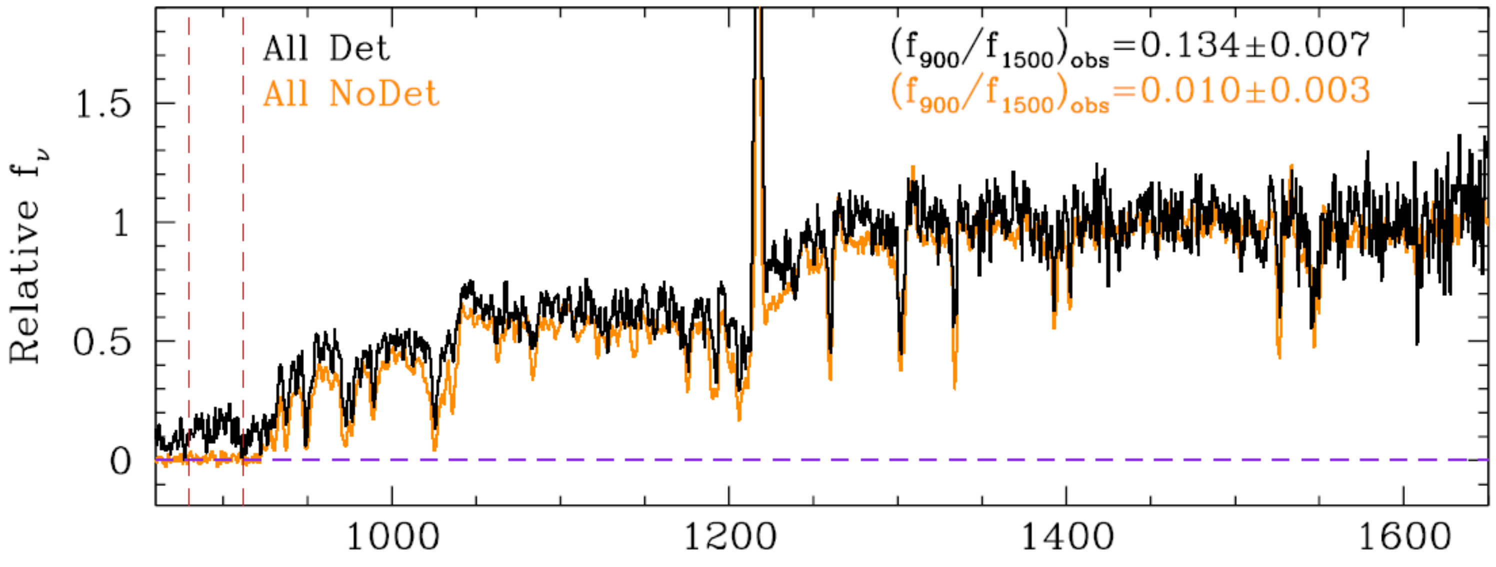
What about H I EOR?



- During EOR (z > 6) it appears that AGN can not dominate ionization:
- Too few AGN? (e.g. Haardt & Madau 12)
- Also, He II reionization (AGN dominated) does not begin until z ≈ 4 or 5 (too late)

When does the star/QSO change-over happen?





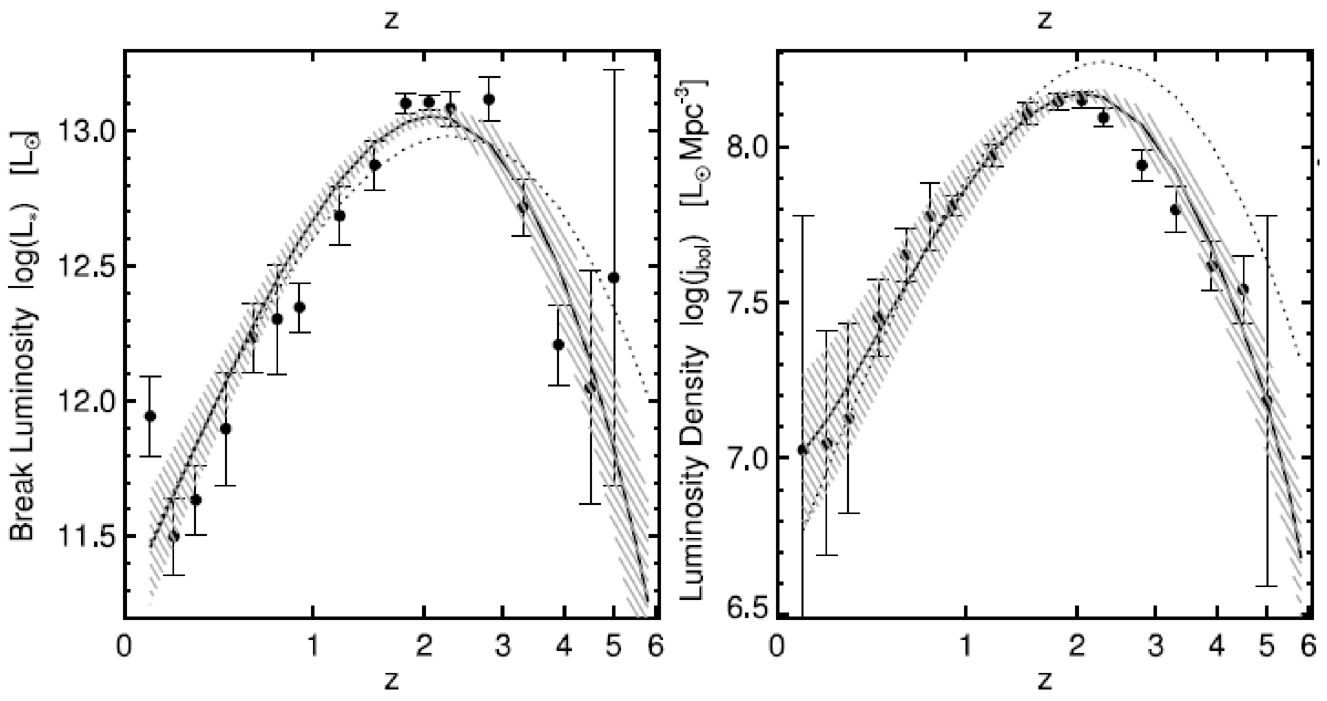
- Ratio (star formation/black hole growth) ≈ constant. The evolution of f_* is key
- Note: H&M12 assume $f_* \approx 0.02\% \, (1+z)^{3.4}$!! This yields change-over at z ≈ 4
- Steidel+18 data imply change-over at z ≈ 3 (4.5 x higher f_* than H&M12 model)

  See also Fletcher+18, Marchi+18, Jones+18

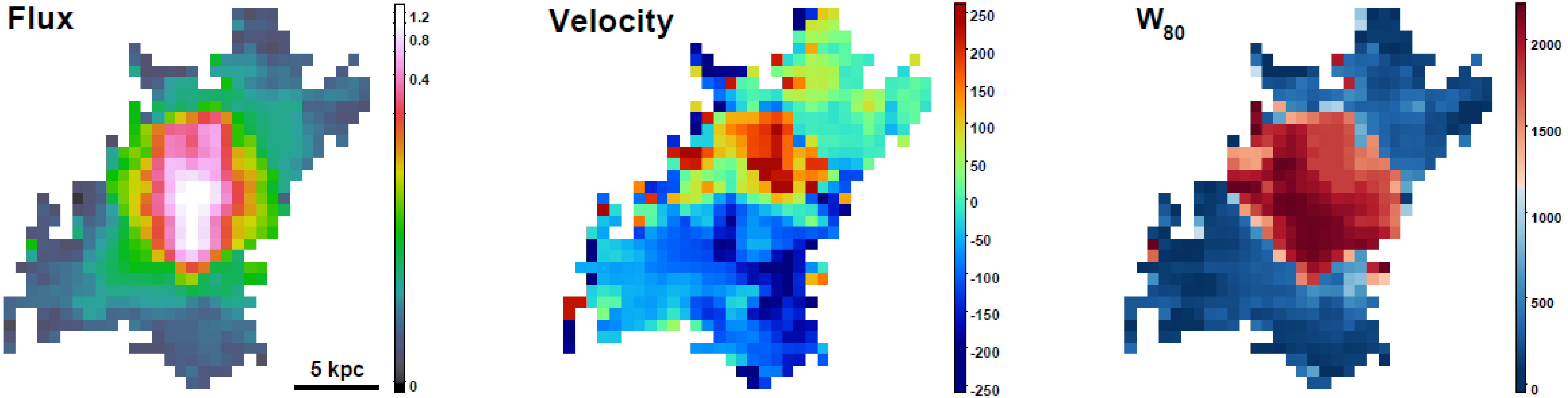
Why are AGN so leaky?

- ***One reason: radiative feedback***
- Change the ionization state of the foreground gas
- Strongren column:

  $N_{HII} = U\, c/\alpha_H \approx 10^{23}\, U\ cm^{-2}$
- $U = n_{Lyc}/n_e = Q_{ion}/[4\pi\, r^2\, n_e\, c]$
- Q_{ion} for L_* QSO is $\approx 10^3\ Q_{ion}$ for L_* galaxy ($z \approx 1 - 3$) – Hopkins+2006
- Correspondingly larger U and N_{HII}

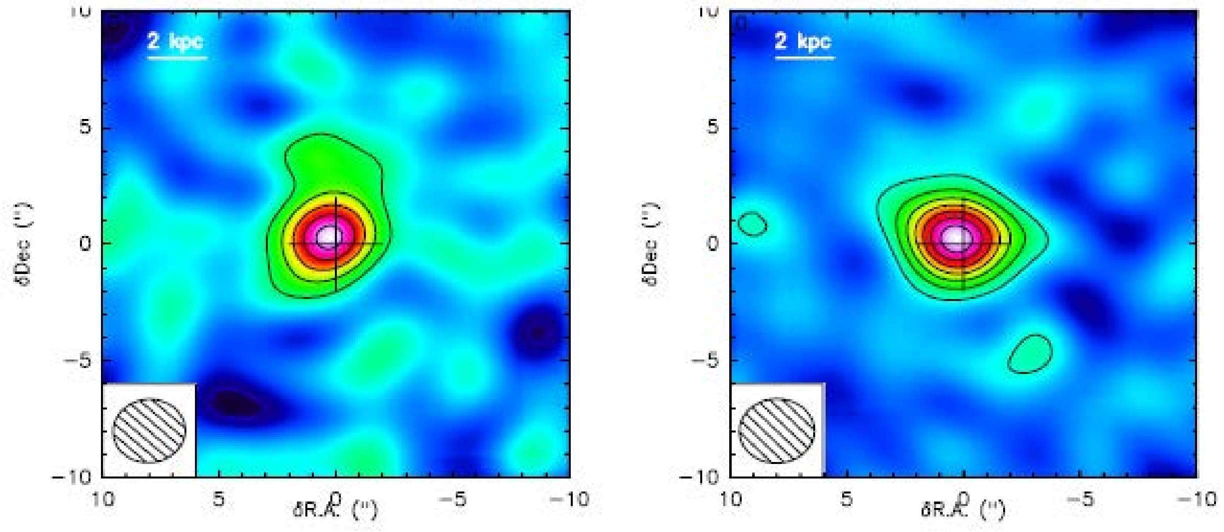


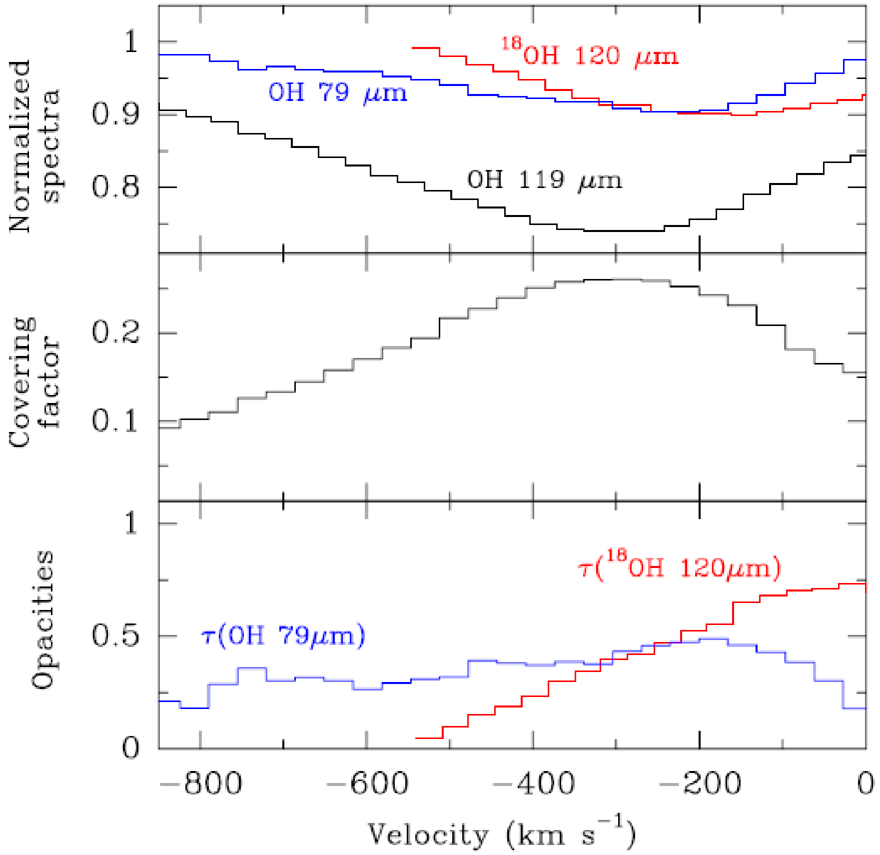
Another reason: mechanical feedback?



- Galaxy-scale outflow in Type 2 QSO seen in [OIII] – Zakamska+

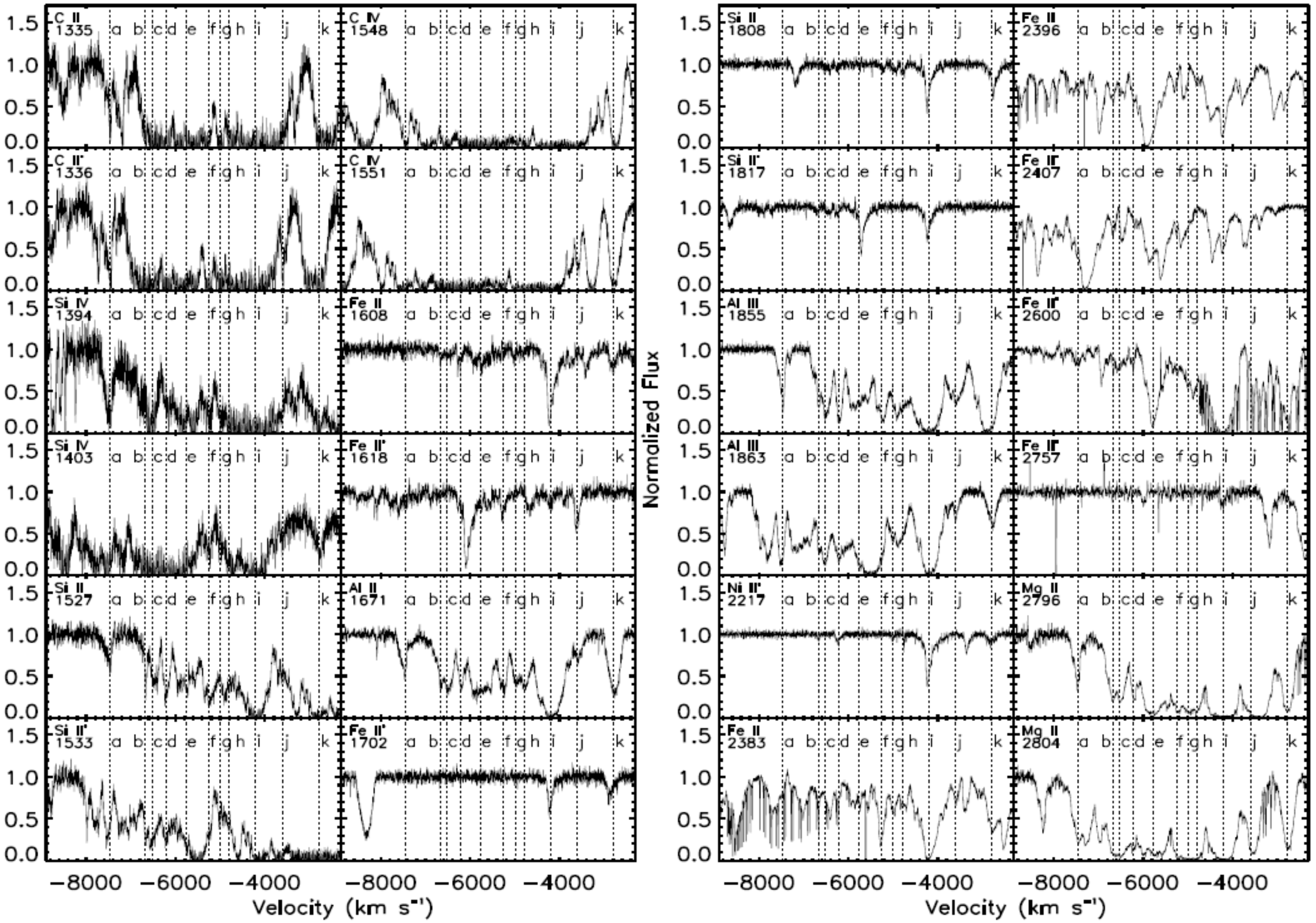
Molecular outflows in AGN-dominated ULIRGs





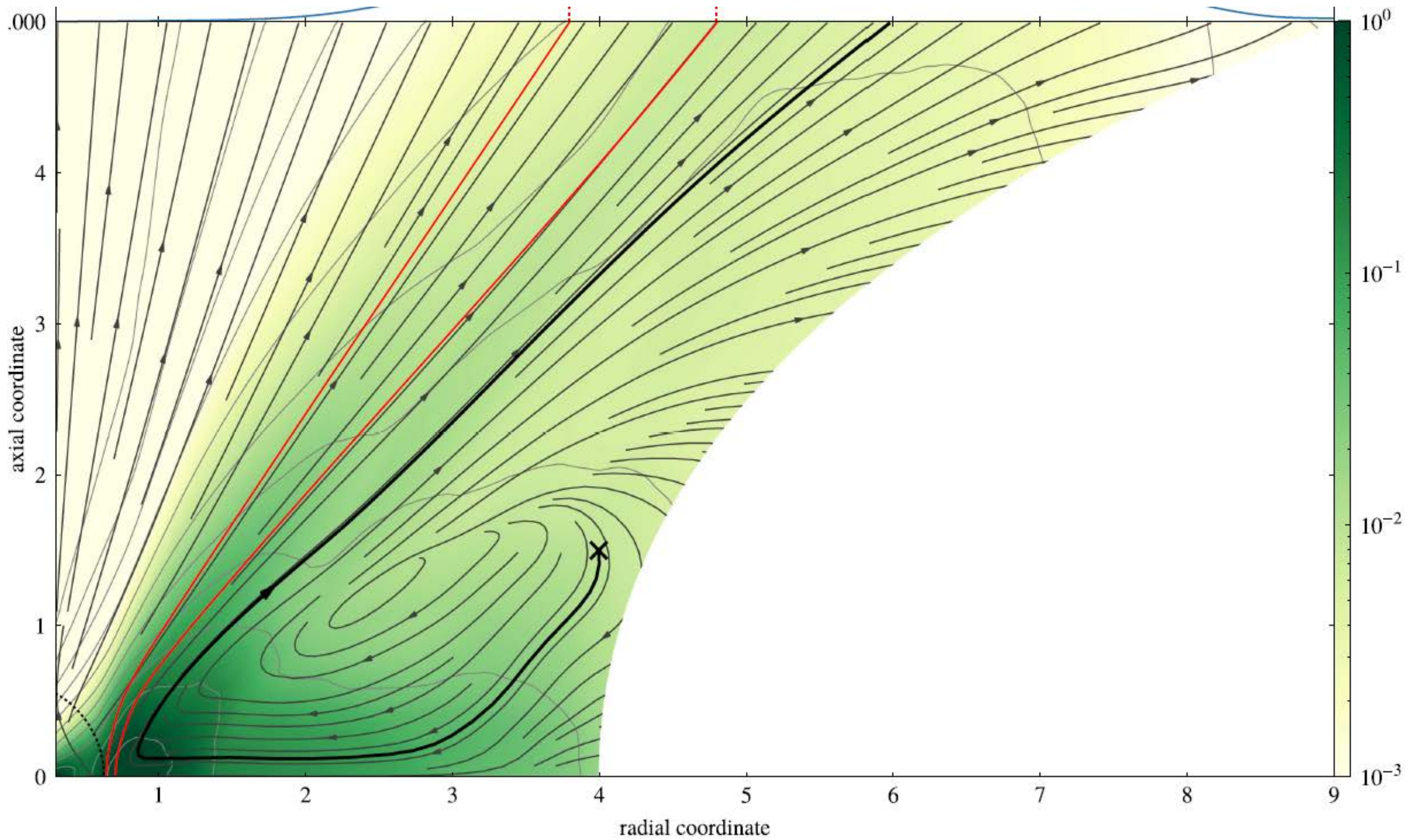
- Mrk 231 molecular outflow in CO emission and OH absorption
- Outflow velocity ≈800 km/s over few kpc-scale (Cicone+12;Fischer+10)

Broad-Absorption-Line QSOs



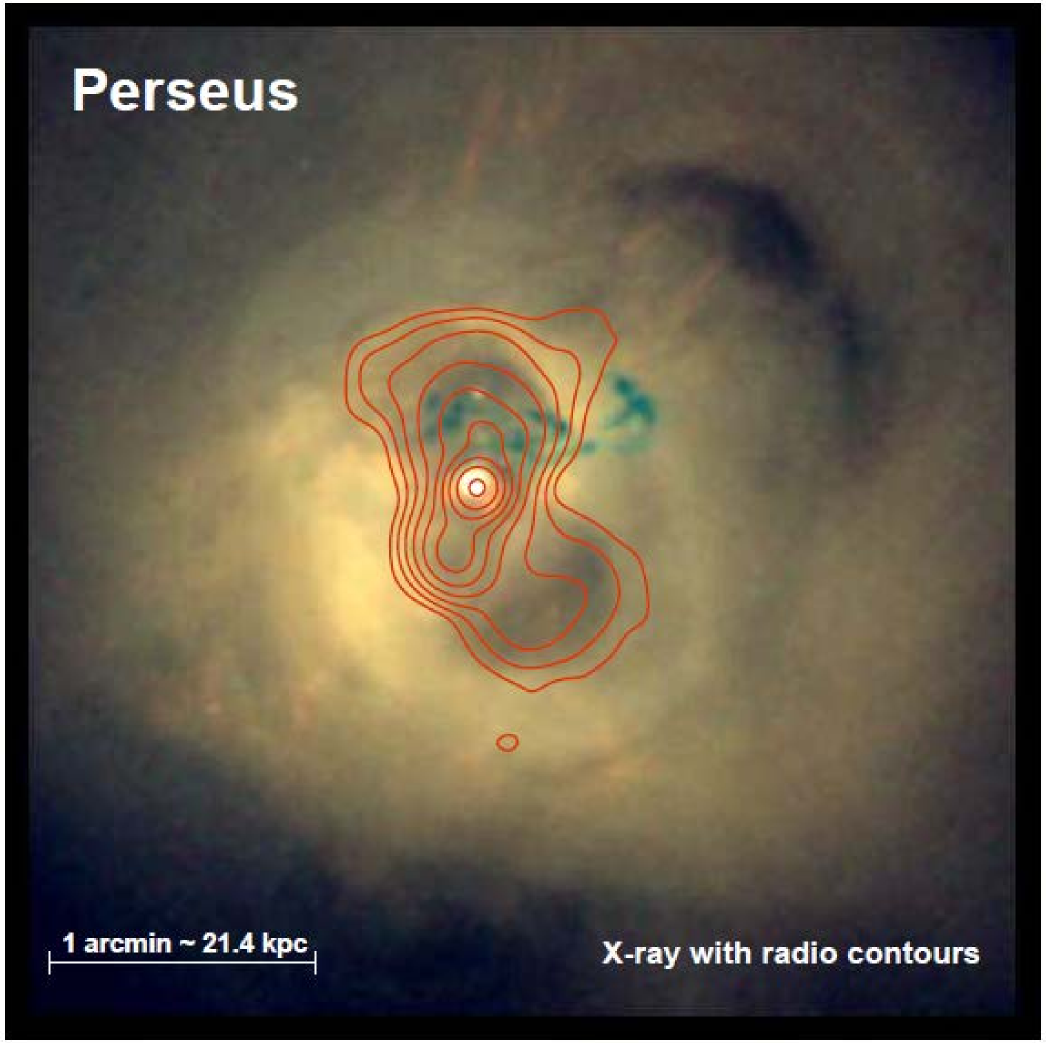
- Rare case where column density and size (6 kpc) of a BAL QSO is measurable
- Outflow at up to 8000 km/s with kinetic energy flux 10^{-3} L_{bol} (Dunn+2010)

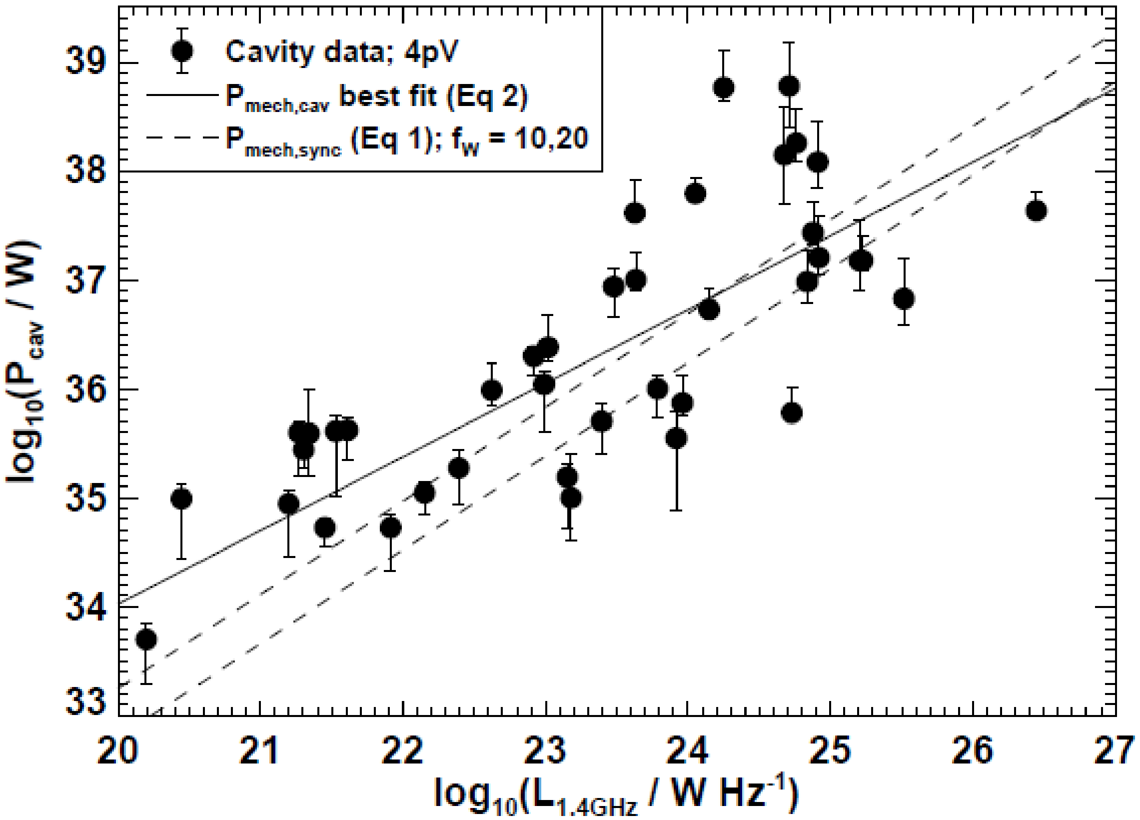
How are these QSO winds driven?



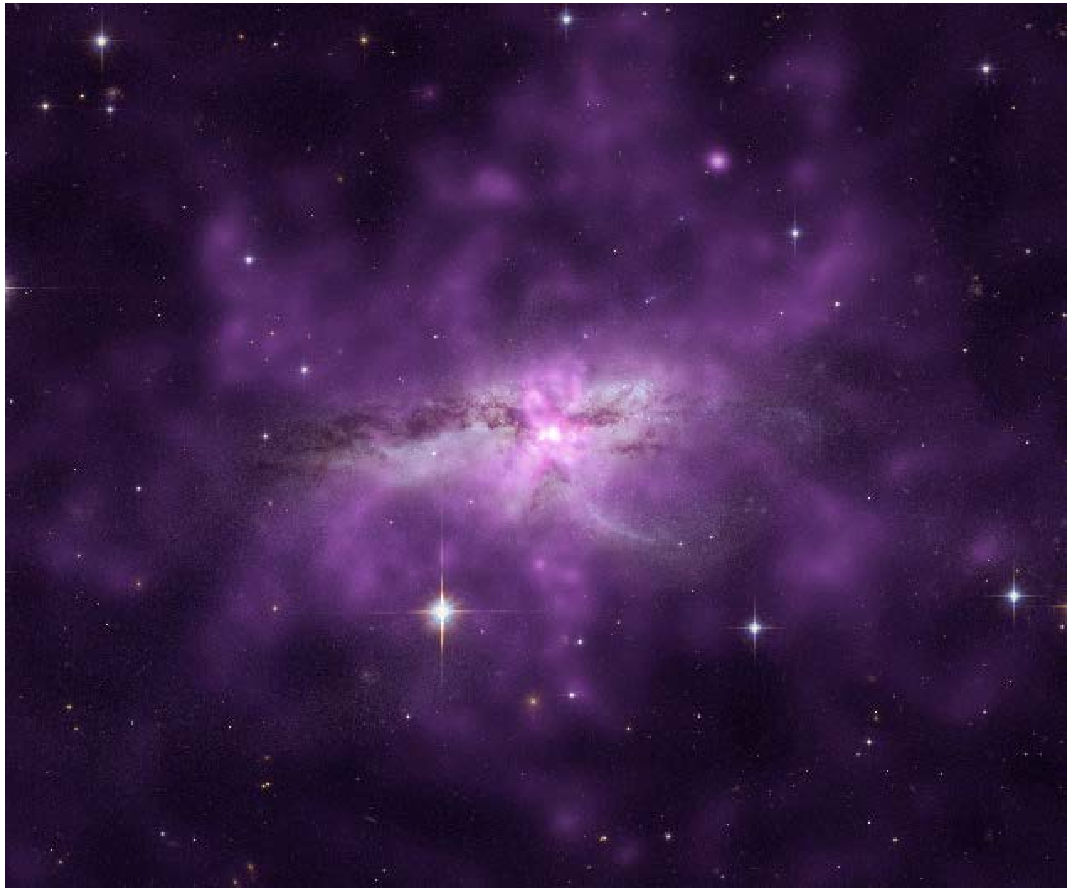
- Radiation pressure-driven "disk wind" (e.g. Proga et al.; ***Chan & Krolik 2017***)
- When optically-thick in IR, momentum flux in outflow can exceed L_{bol}/c
- MHD wind (e.g. Everett 2005; Elitzur & Shlosman 2006)

Radio-Mode Feedback (cf. Heckman & Best 2014)



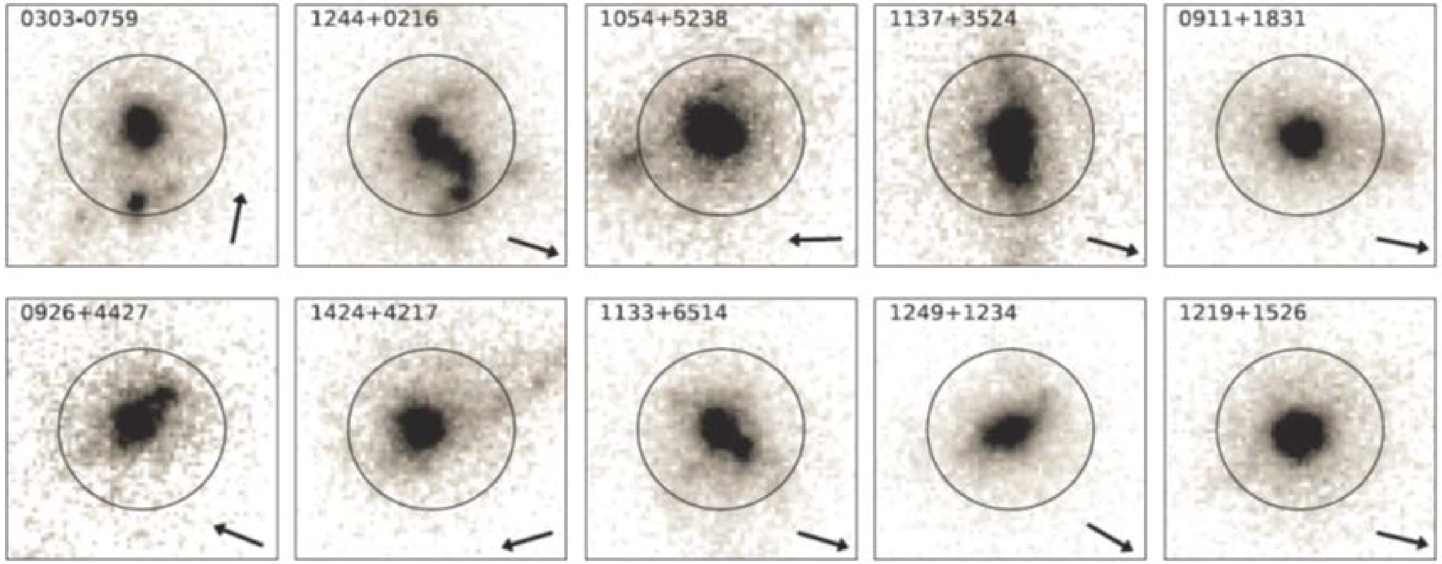


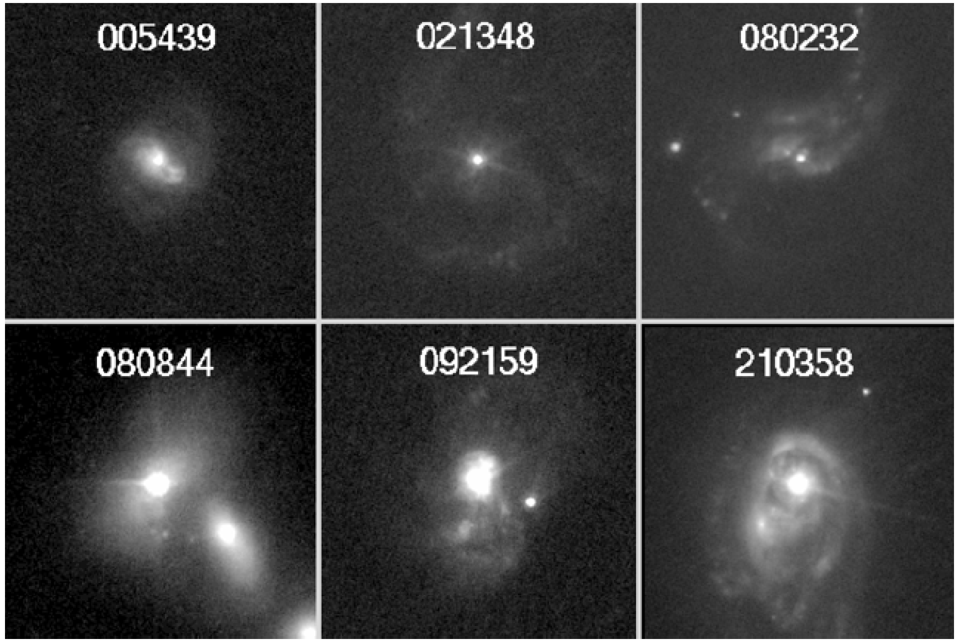
Qualitatively similar outflows driven by starbursts



- Starburst-driven outflows in M82 (10 kpc-scale) and NGC 6240 (100 kpc-scale)
- Mechanical feedback alone may not be enough for leakage of stellar LyC photons

Need “Extreme Feedback”?





- Leakers at low-z are very compact (extreme SFR/area). See also Marchi+18 ($z \approx 4$).
- Leads to extreme radiative (high J_ν, U, [OIII/OII]) and mechanical feedback (high P_{ram}).
- Compact starbursts are more “QSO-like” in their interaction with ISM.

Summary

- In the post-EOR universe, **QSOs likely produce the majority of H I *ionizing photons* that escape to the IGM**, and dominate for He II
- This is due to the much higher efficiency of the production of these photons (per baryon) and the much higher escape fraction
- QSOs are leaky because of intense radiative feedback (high U) and possibly mechanical feedback (winds/jets)
- QSOs likely not significant during EOR (too few)?
- IGM: **HI *ionization* mostly stars (early). HeII dominated by QSOs (later)**
- High escape fraction for stars during EOR associated with highly compact and intense star-formation? Leads to more intense “QSO-like” feedback