Quasars and the Birth & Evolution of Galaxies

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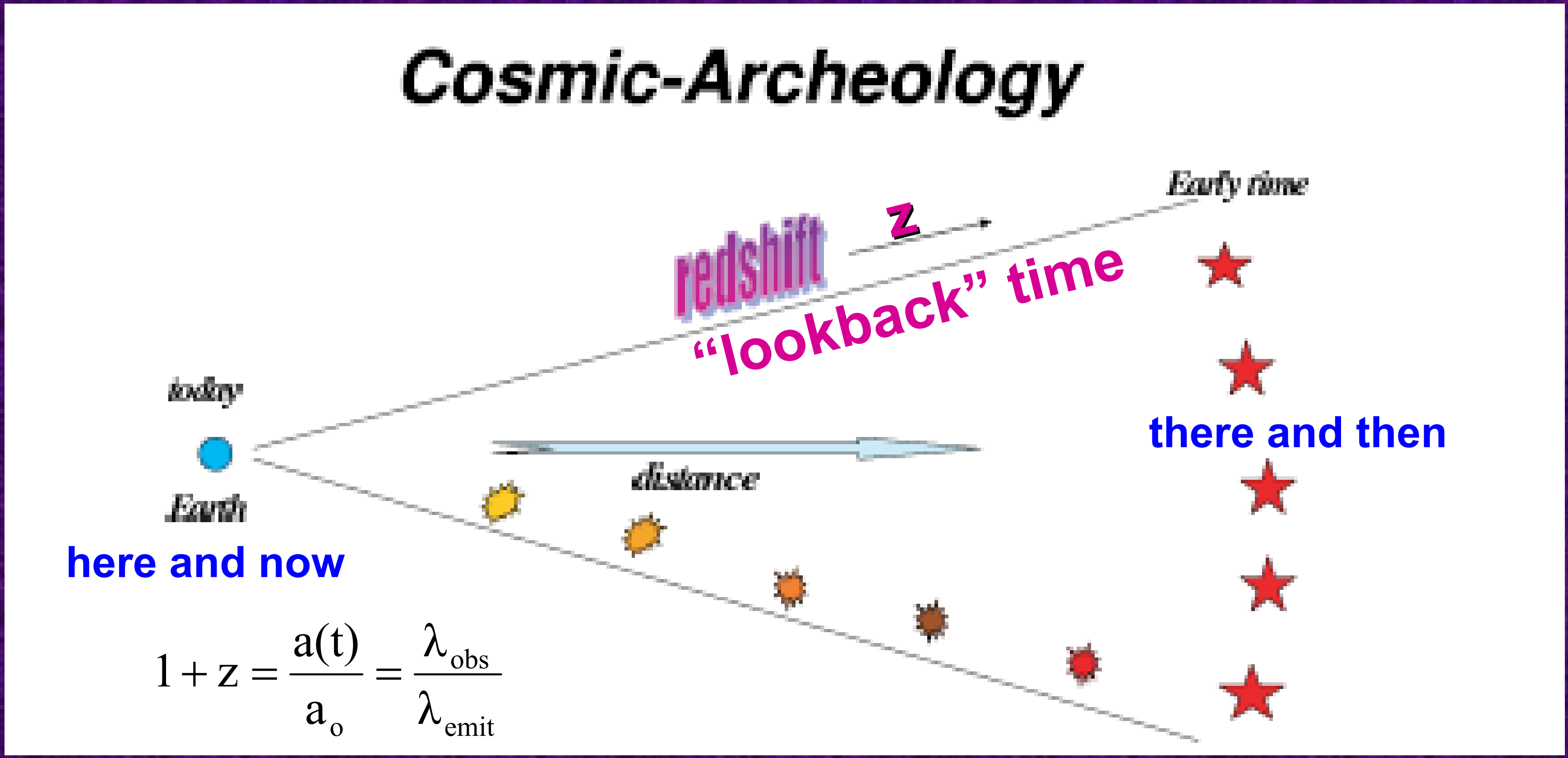
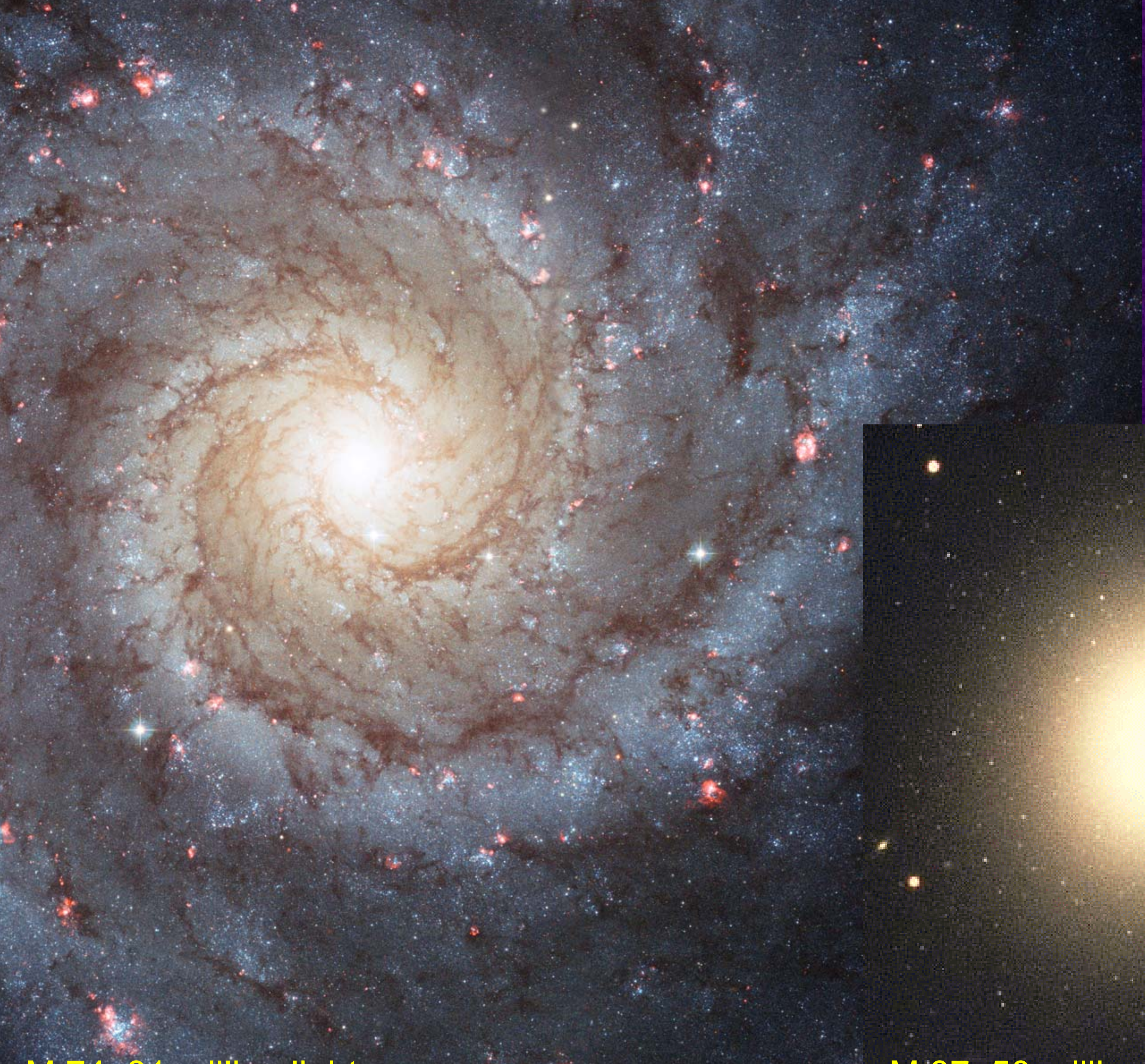
Astronomers are "cosmic archeologists"



$$1 + z = \frac{a(t)}{a_o} = \frac{\lambda_{obs}}{\lambda_{emit}}$$

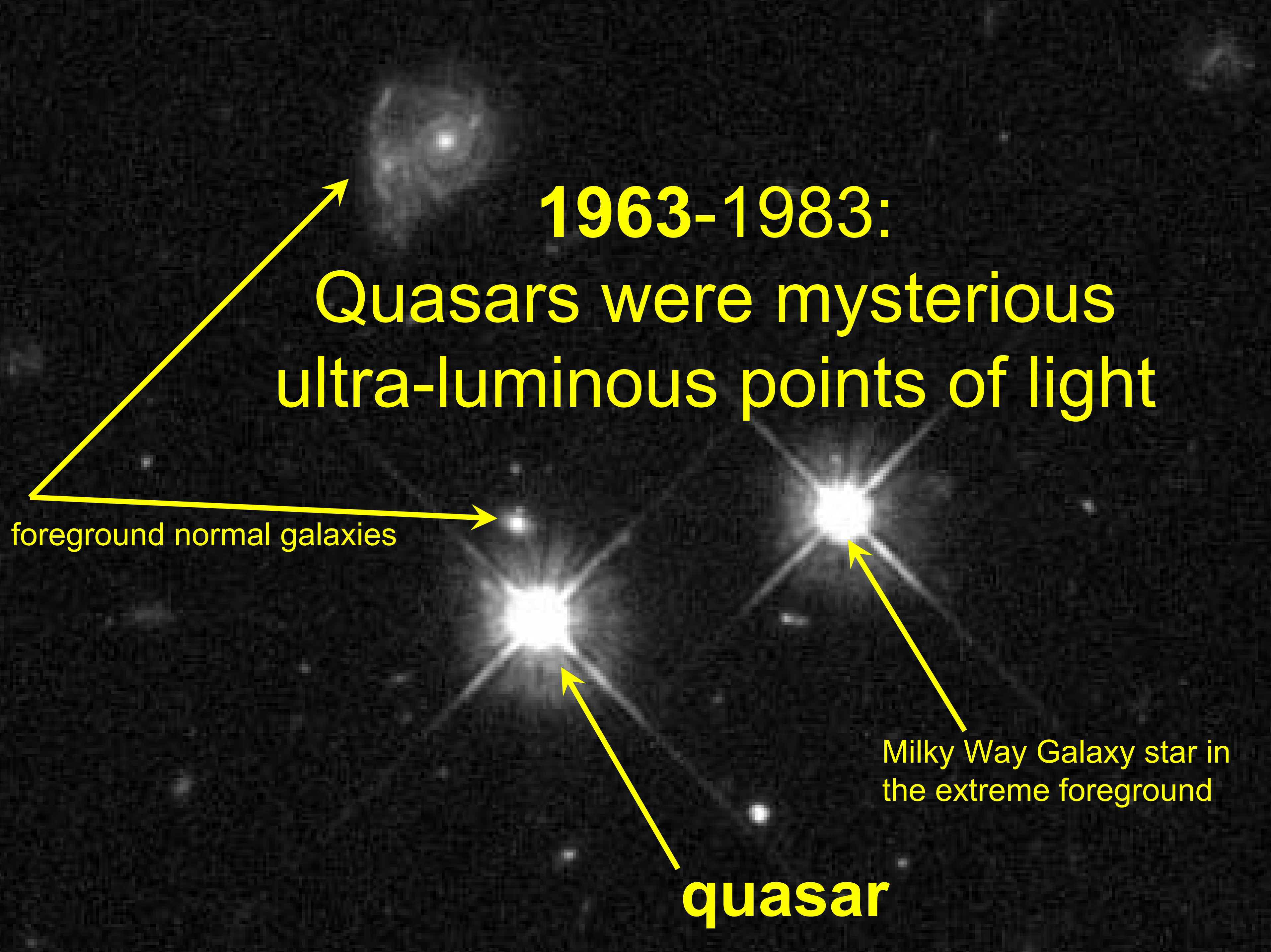
"Cosmology is like archeology. The deeper one looks the more ancient is the layer that is revealed, owing to the finite propagation speed of light." (Avi Loeb, 2006)

spiral, **elliptical** galaxies in the local universe: $10^{10} - 10^{12}$ **stars** bound by gravity

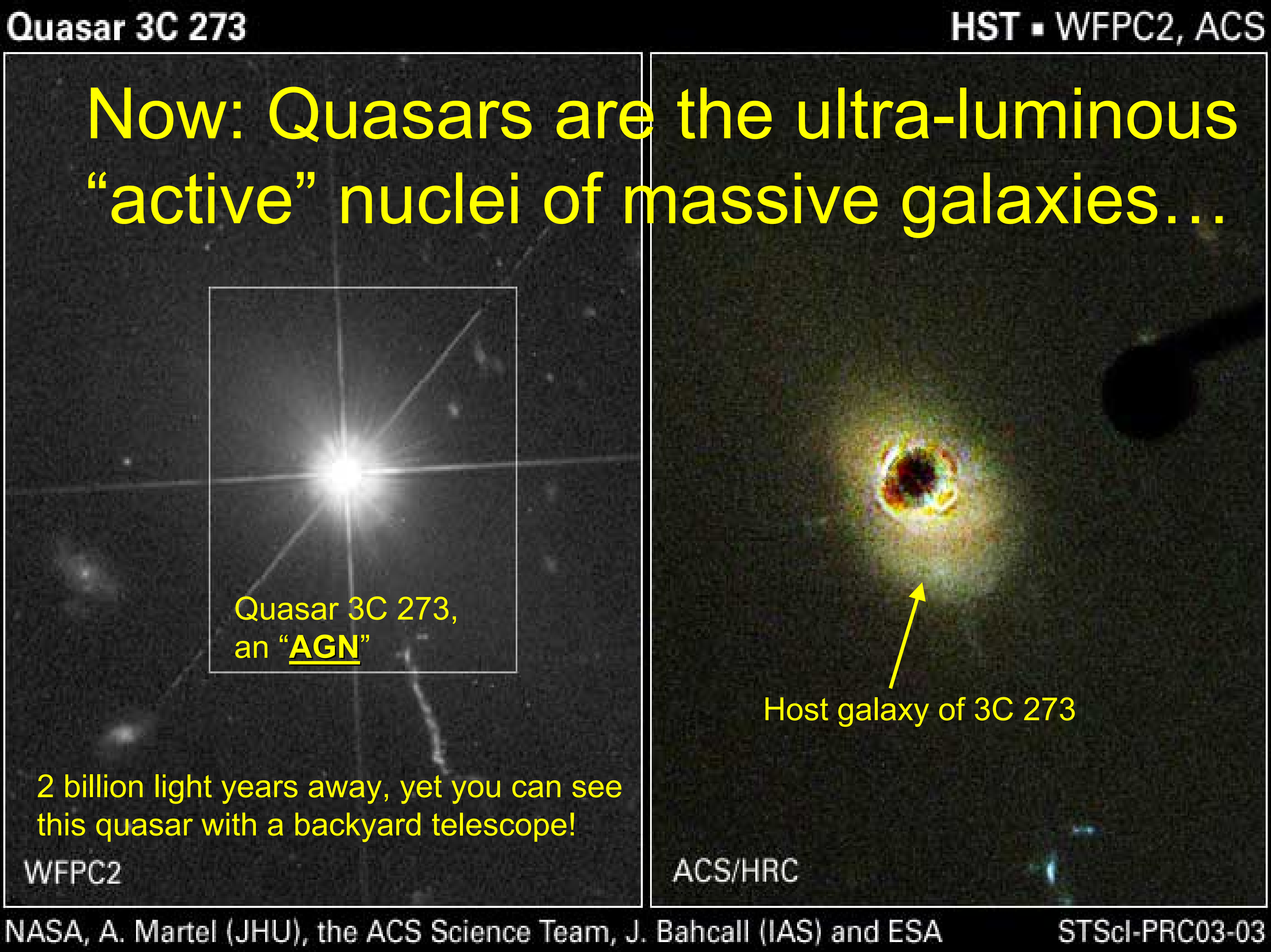


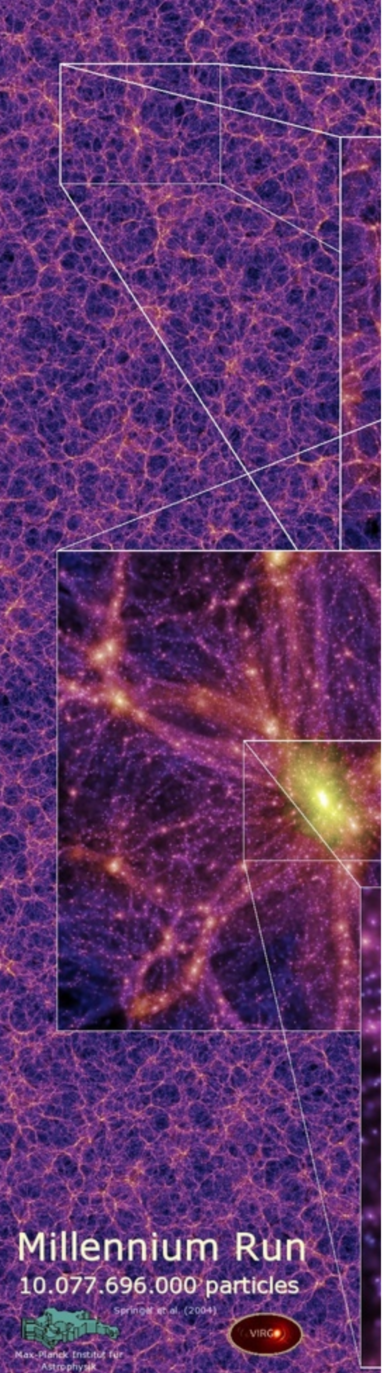
M 74, 31 million light years away

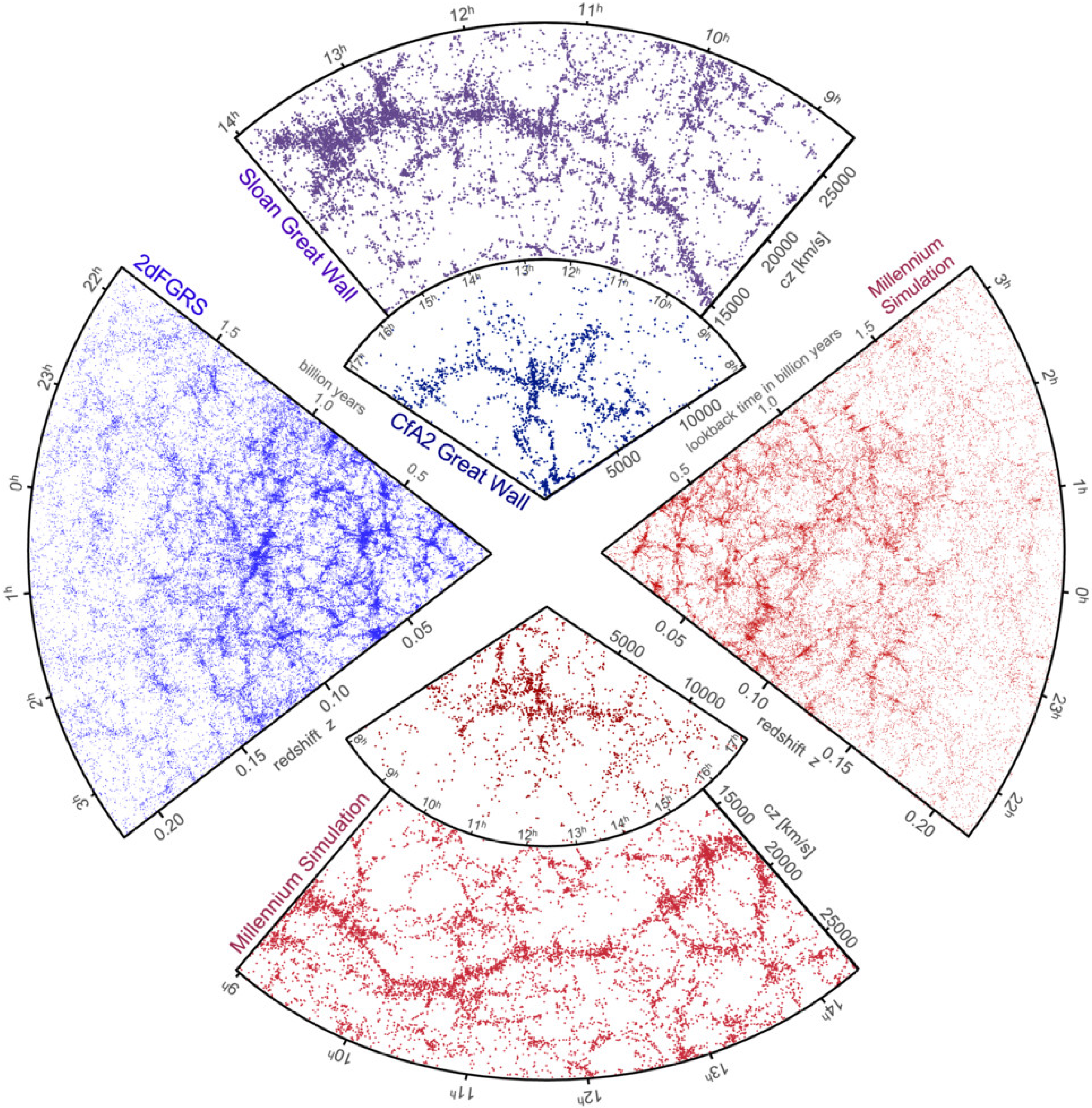
M 87, 50 million light years away


1963-1983:
Quasars were mysterious
ultra-luminous points of light
foreground normal galaxies
Milky Way Galaxy star in
the extreme foreground
quasar

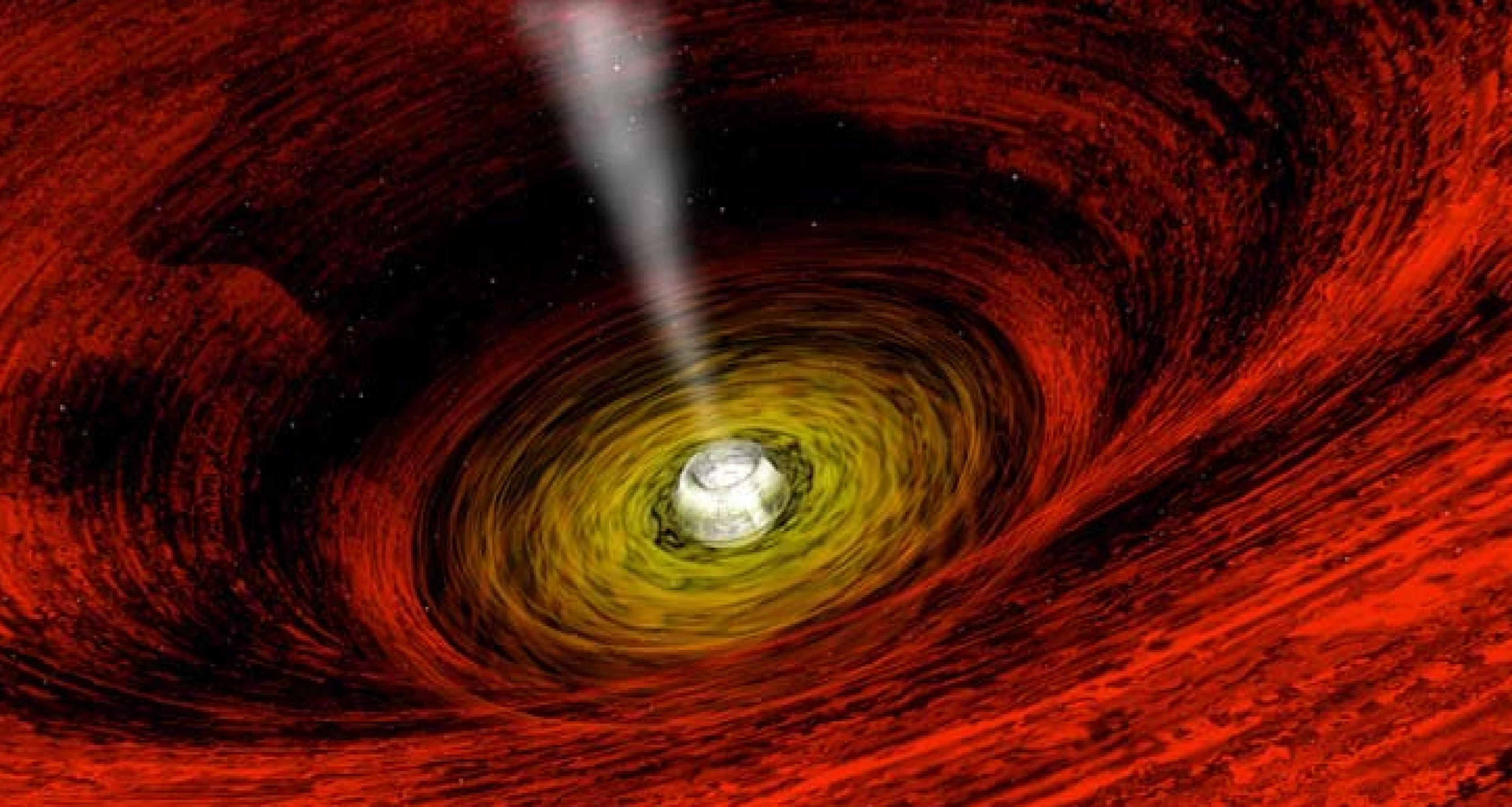
Now: Quasars are the ultra-luminous "active" nuclei of massive galaxies…







Springel et al. 2006

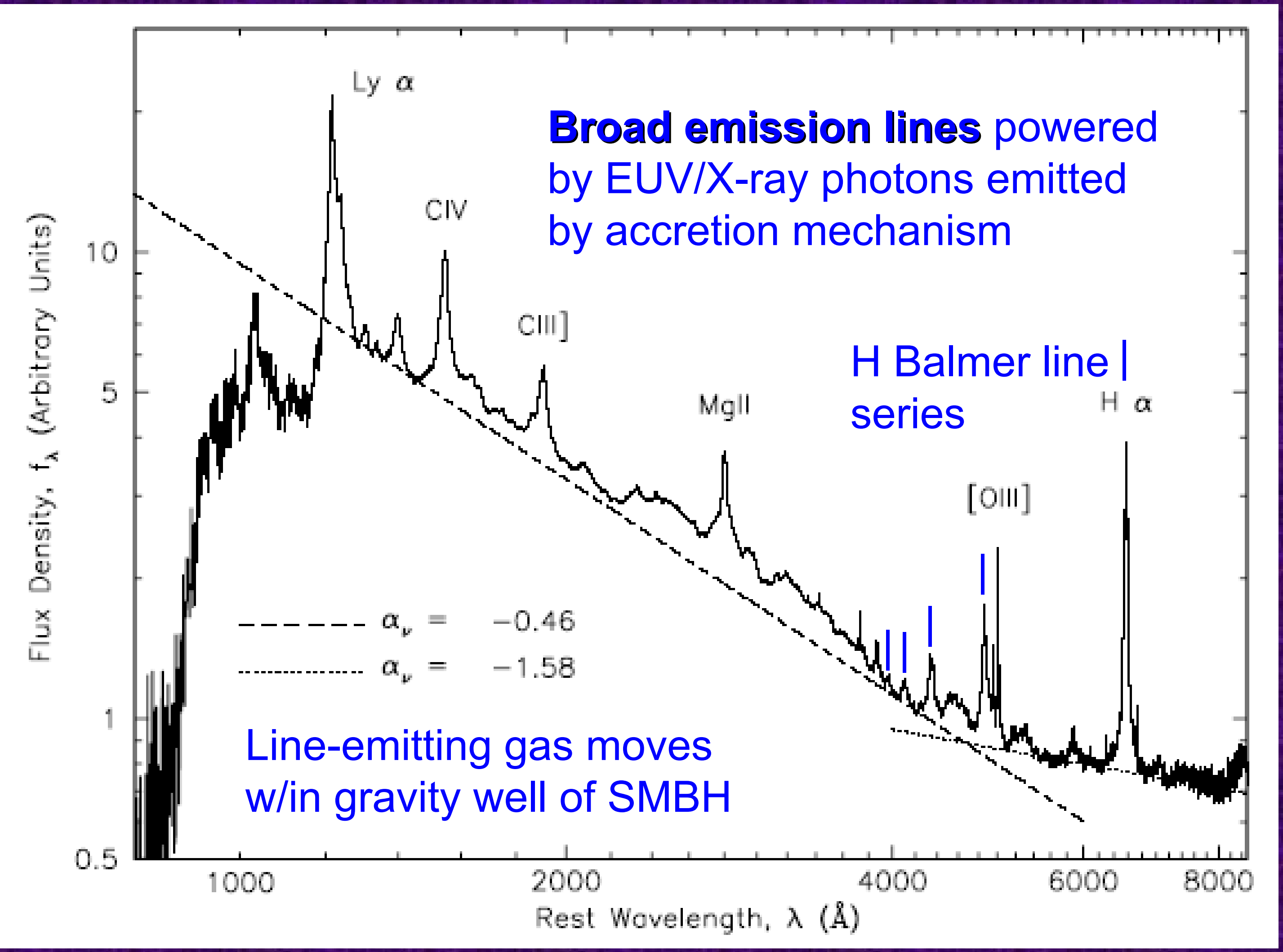


…and are powered by gravitational **accretion of gas** onto super-massive black holes (**SMBH**) lying at the centers of galaxies

(paradigm first suggested by Zel’dovich & Novikov 1964; E.E. Salpeter 1964)

A “generic” UV-optical spectrum of a Quasar

(a composite spectrum of ~2000 individual quasar spectra)



Heavy element emission lines observed to highest redshift quasars with **z ~ 6.5**:

universe then just ~900 Myr old, so significant star formation episode must have occurred before!

SDSS Quasar Composite Spectrum
Vanden Berk et al. 2001

“Monster” Black Holes in Galactic Nuclei

- With masses **M** = 10^8 – several × 10^9 M_{sun}, they’re called *super-massive black holes (aka “monsters”)*
- Accretion process releases ~10% of the rest mass of the accreted gas within region only a bit larger than solar system!

→ $L_{quasar} \approx 10^{12} - 10^{15}$ L_{sun}, limited by max rate of accretion that scales with **M**

(a lá Eddington’s radiation pressure limit):

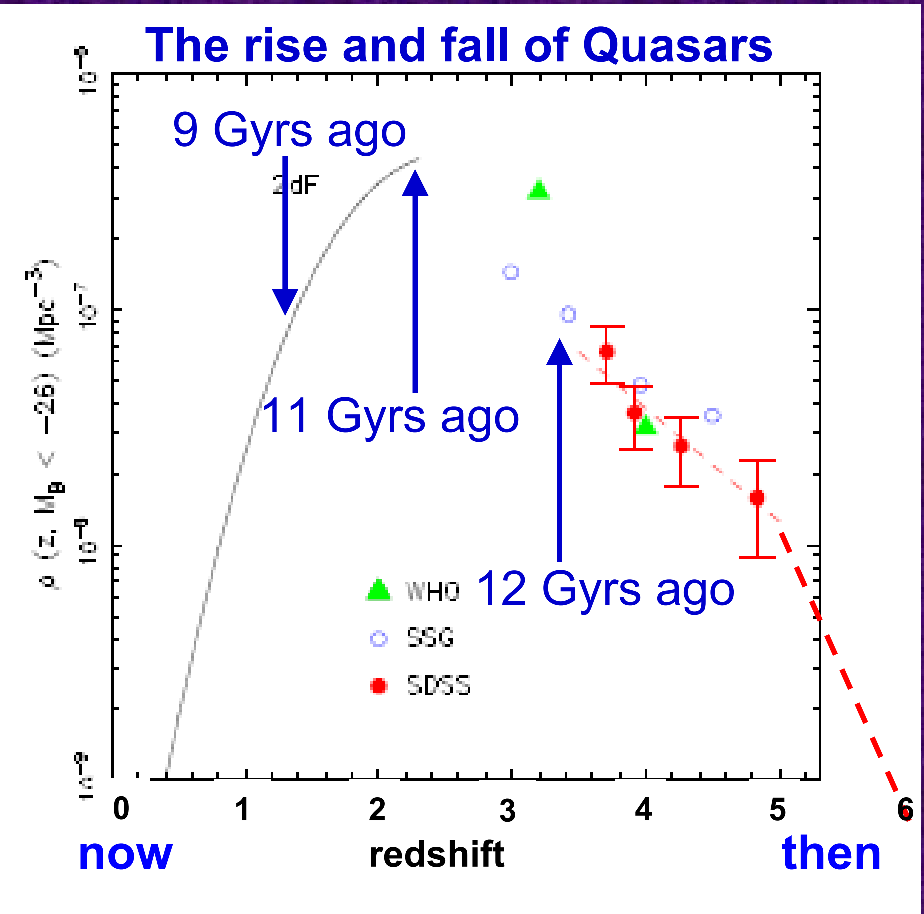
$$\mathbf{L_{crit} \sim L_{Edd} \approx 1.5 \times 10^{39}\ Watts \cdot (M / 10^8\ M_{sun})}$$

- Luminous quasars are *now* extinct
  - nearest is 2 billion light years distant
  - low-power (10^9 – 10^{12} L_{sun}) **Active Galactic Nuclei** (“AGN”) sparsely populate *local universe*

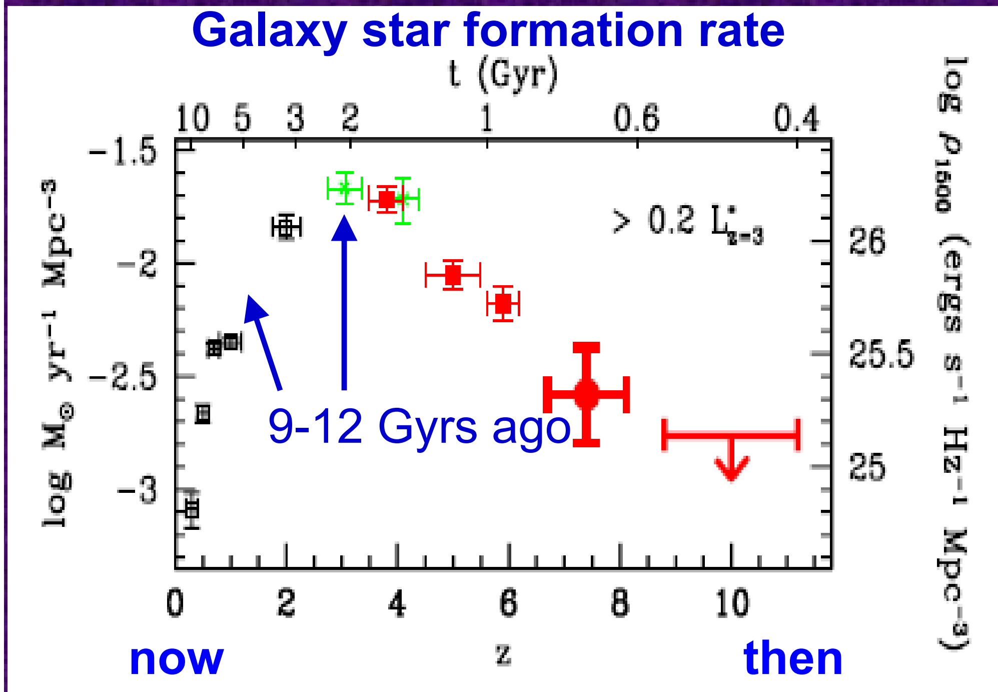
Quasars are interesting brutes of the cosmos, but so what??

Three interesting recent findings…

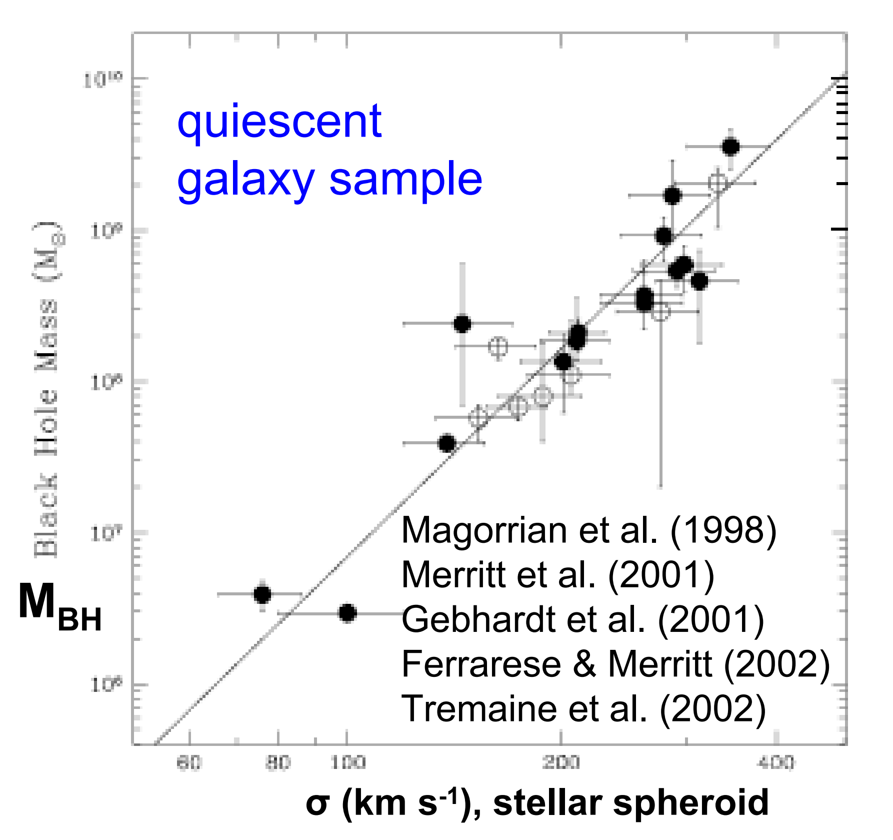
Rise and Fall of Quasar population mimics galaxy star formation rate through cosmic time

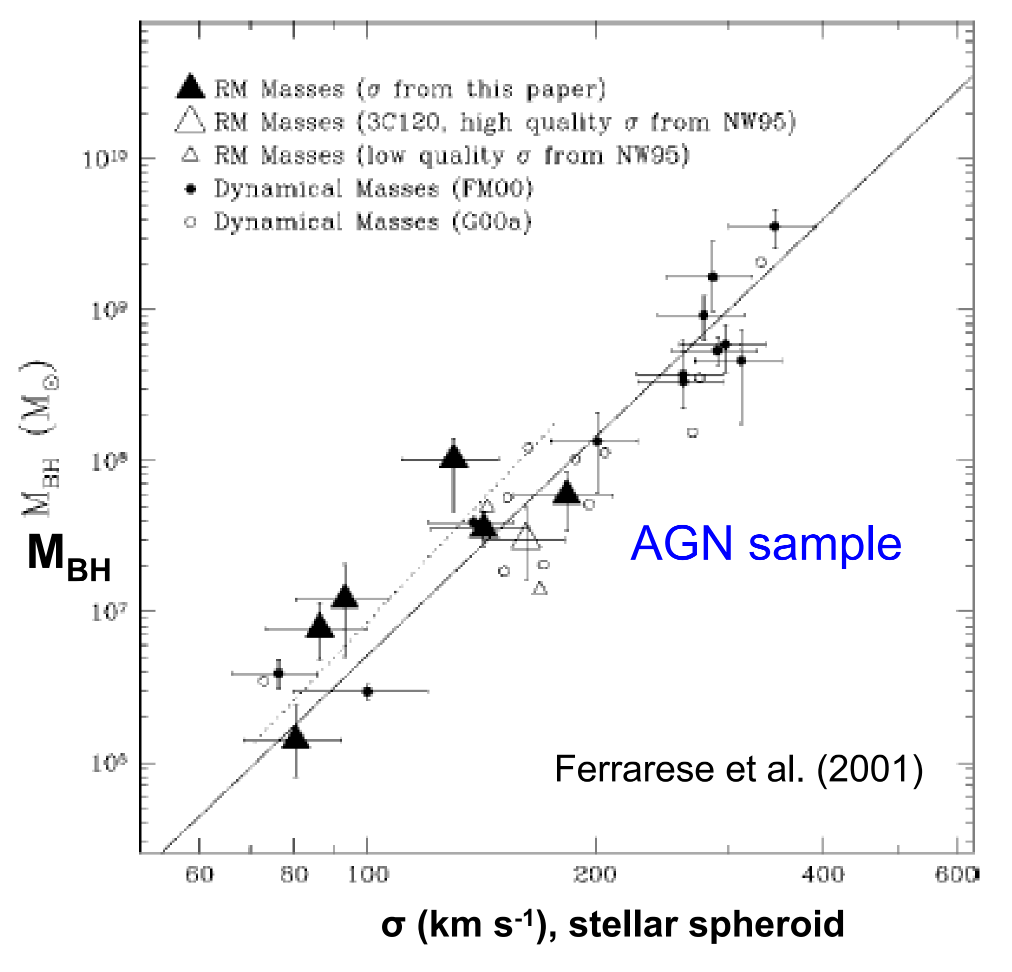


Bouwens et al. (2008)



And another curiosity…





All big galaxies (> 10^{10} M_{sun}) have super-massive black holes in their nuclei, AND $\langle M_{BH} / M_{stellar\ spheroid} \rangle \approx 0.0015$ (!)

(Häring & Rix 2004; Ferrarese et al. 2006)

(→ physical size scale ratio is at least ~600, and so are dynamically disconnected)

And yet another…

…*also* scale with M_{BH} →

Broad emission line intensity ratios that scale with gas **metallicity** $Z \equiv$ Ab(heavy elements) / Ab(H)…

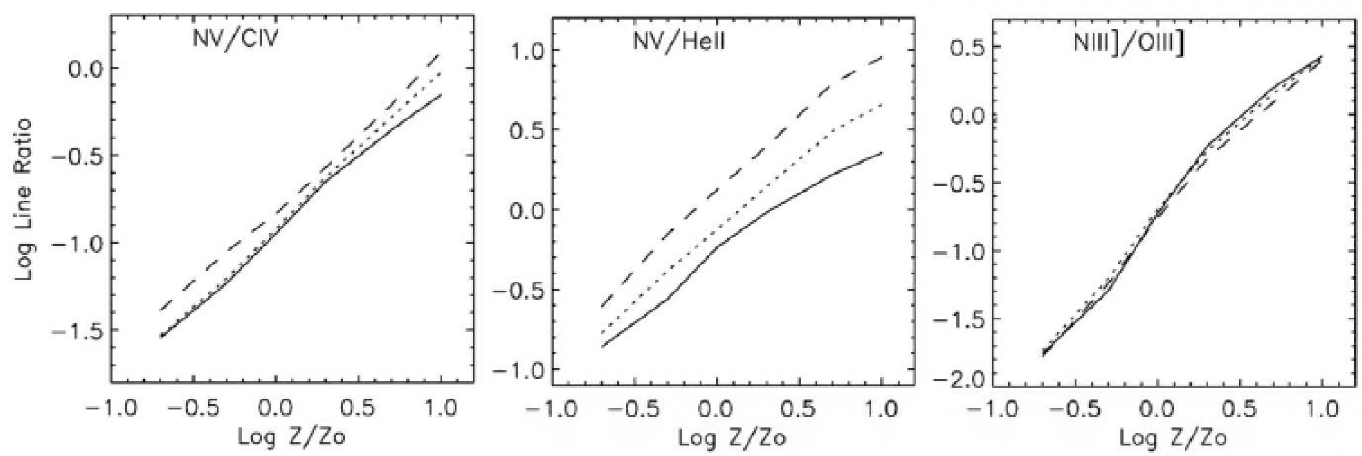
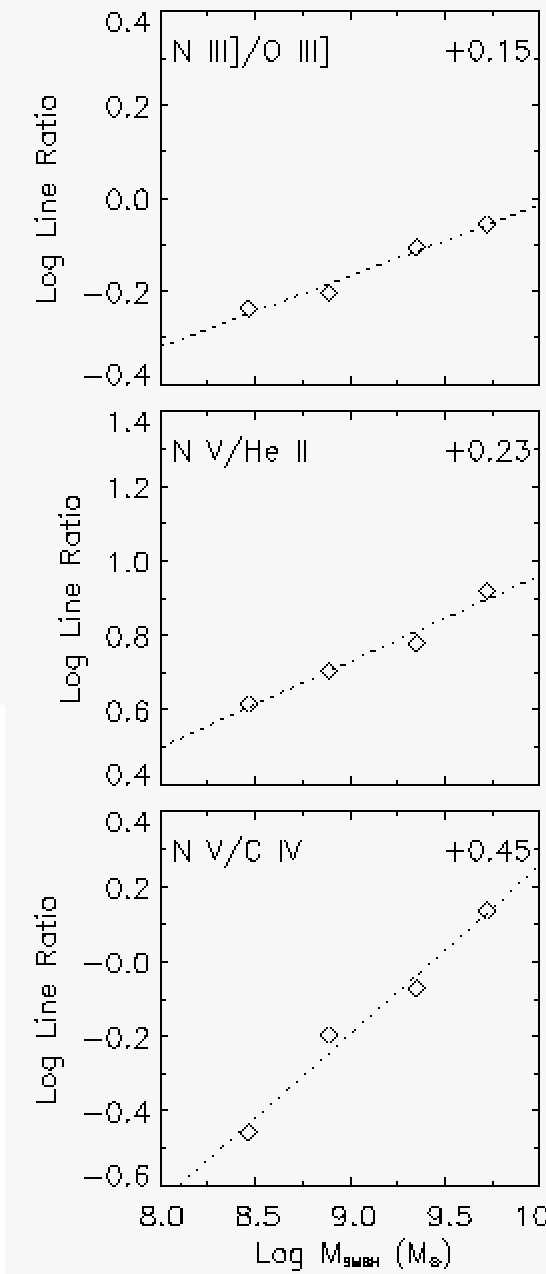
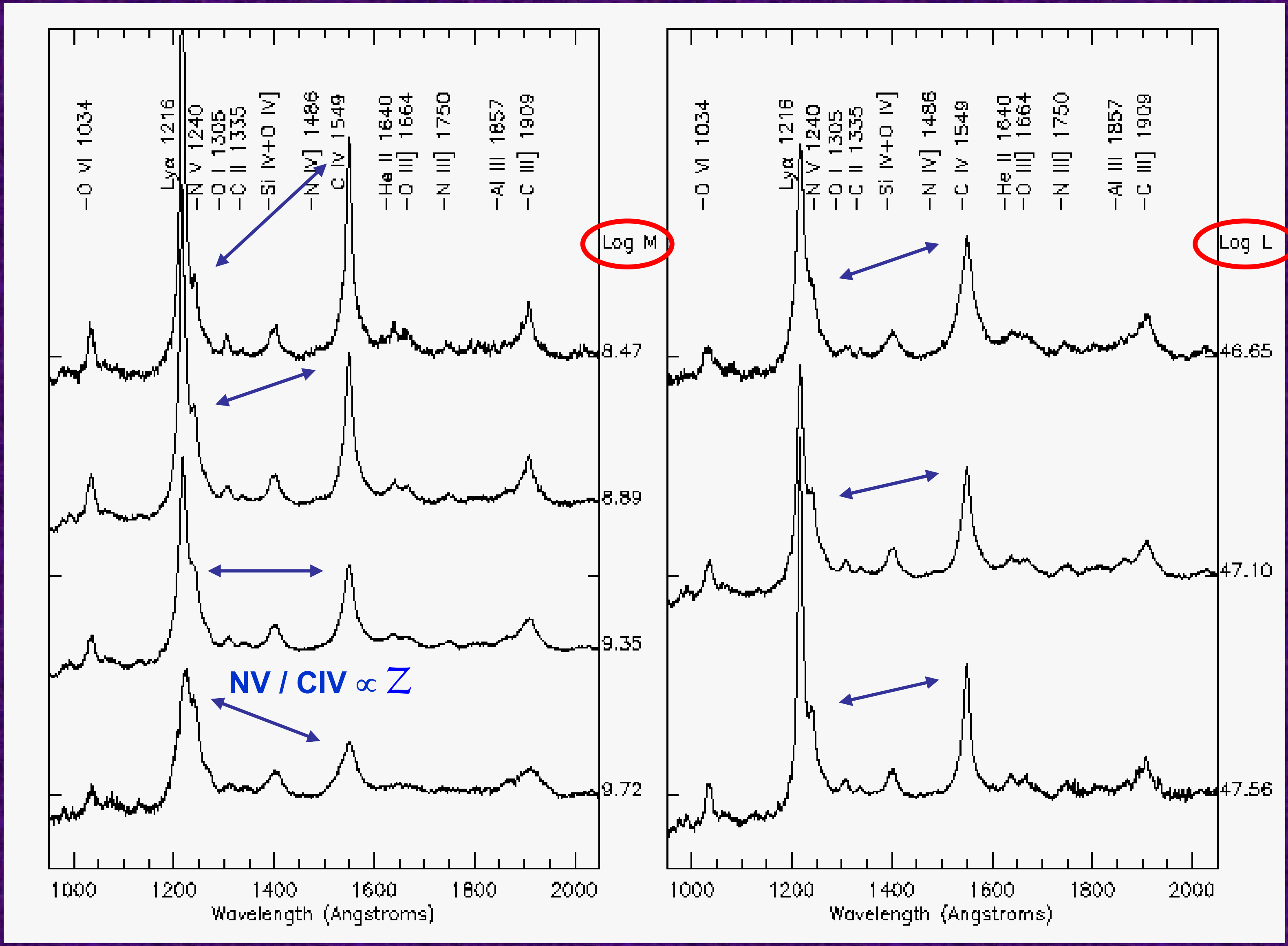


Figure 1. Theoretical BEL ratios vs. metallicity for three different ionizing spectral shapes (solid, dashed, dotted lines) in the LOC model (Hamann et al. 2002).

Warner et al. 2003



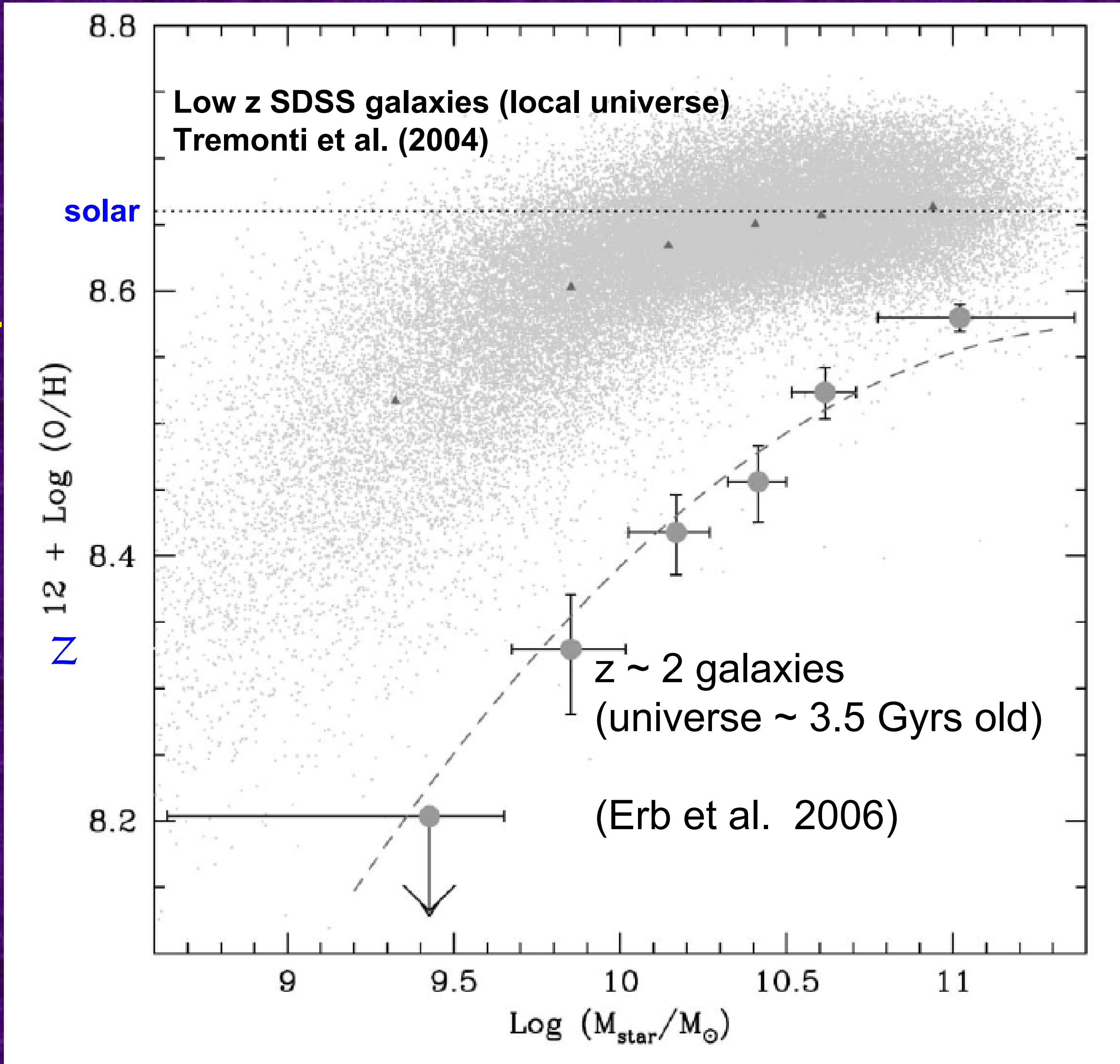
$L \approx 10^{40}$ Watts $\qquad M_{BH} \approx 10^{9} M_{sun}$



Composite quasar spectra for fixed L and $\mathbf{M_{BH}} \rightarrow$
an underlying trend is found between BH mass and Z (Warner et al. 2006)

that mirrors the well-known **galaxy** mass – metallicity relationship

(measured on *galactic* size scales)



Summary of findings so far…

- Quasars found in galactic nuclei, powered by accretion of matter onto super-massive black holes
- rise/fall of Quasar population mimics galaxy star formation rate through cosmic time
- $\langle M_{BH} / M_{stellar\ spheroid} \rangle \approx 0.0015$
- M_{smbh}, $M_{stellar\ bulge}$ found independently to scale with gas metallicity Z on enormously different size scales

What's the connecting thread?

The quasar – galaxy formation connection

Silk & Rees 1998, Kauffman & Haehnelt 2000; Volonteri, Haardt, & Madau 2003; Granato et al. 2004; Di Matteo, Springel, & Hernquist 2005; Hopkins et al. 2006.

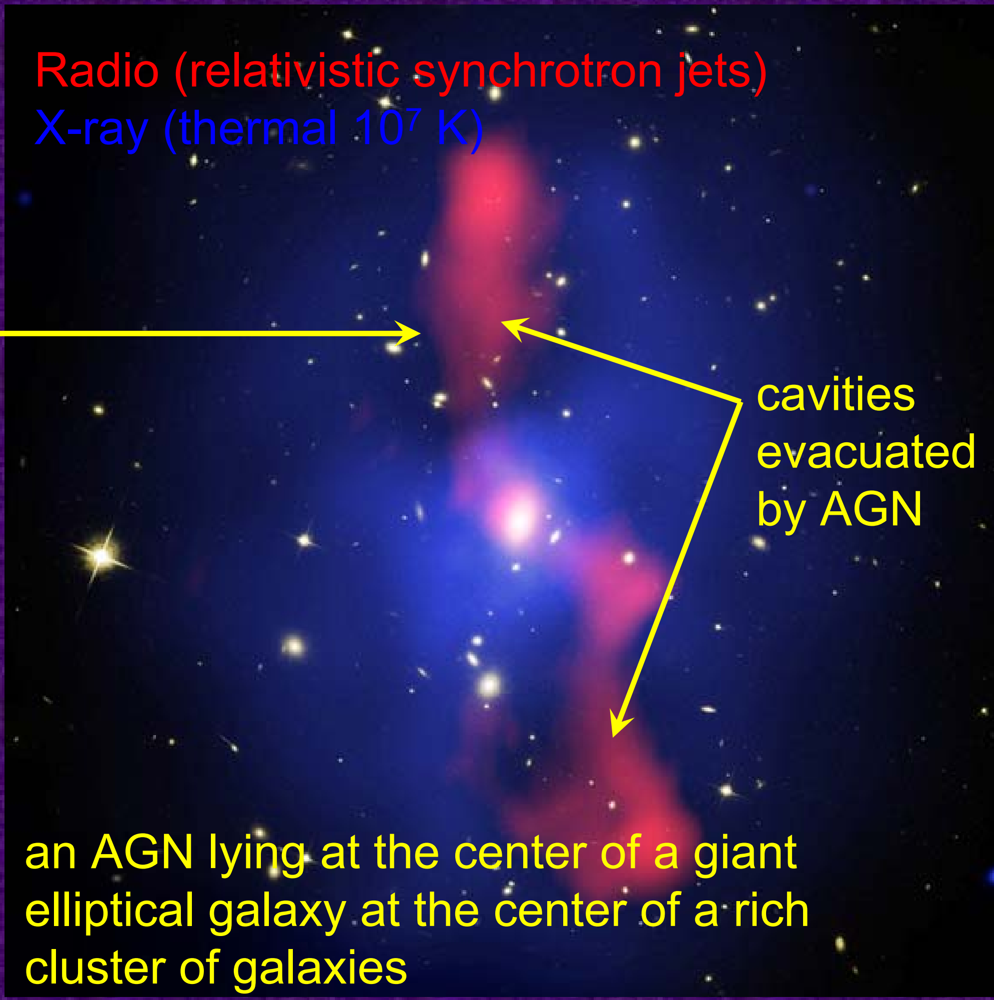
- Collisions between gas rich proto-galaxies drive gas toward and into the galactic nuclei, sparking prodigious star formation and feeding the monster(s)…
- …until the monster becomes massive enough thus radiatively powerful enough to
  - heat and/or blow remaining gas out of the galactic well,
  - → throttling star formation and ultimately starving itself to death.
- Denser, more massive regions evolve more rapidly…
  - give birth to more stars (→ more massive galaxies)
  - are able to reach higher gas & star metallicities
  - have more gas available to feed SMBH
  - require that SMBH grows to greater mass before becoming powerful enough to blow out remaining gas from galaxy's deeper gravity well

Self-regulated growth via “AGN Feedback”

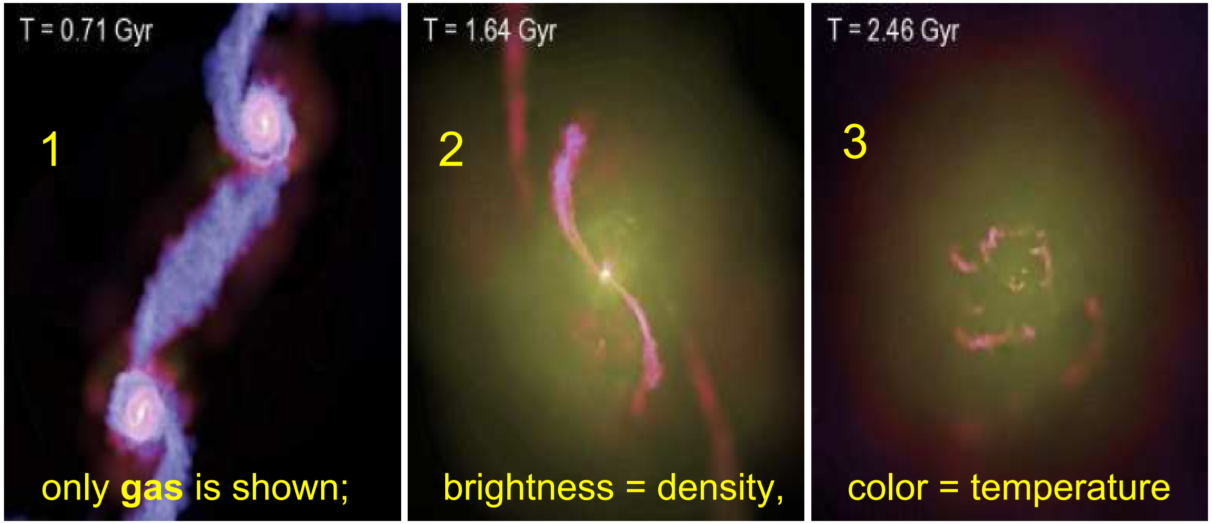
- radiatively powered winds
- photo-ionization heating of galactic environment
  → over-pressurization
- relativistic matter jets
- various shock/pressure waves

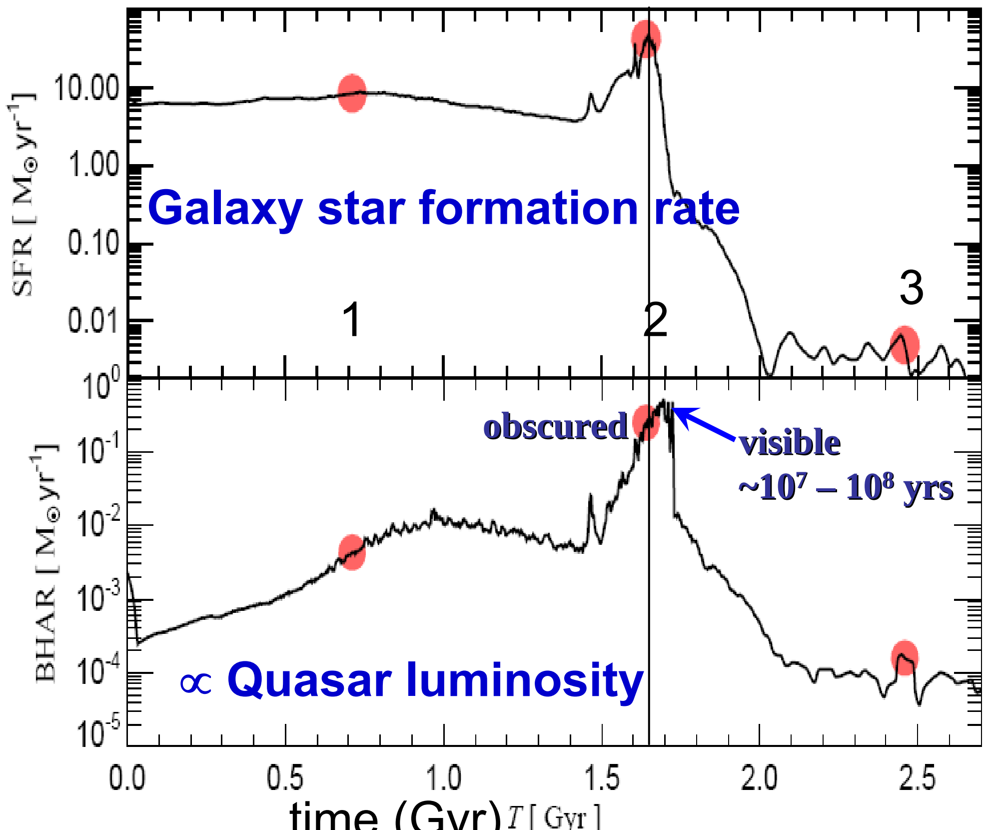
- plus nuclear starbursts (supernovae, super winds)
  – but stars can’t do it alone!

- The cosmic equivalent of a “2-liter *Coke*™ Chug”



Galaxy cluster MS0735 (McNamara et al. 2006)

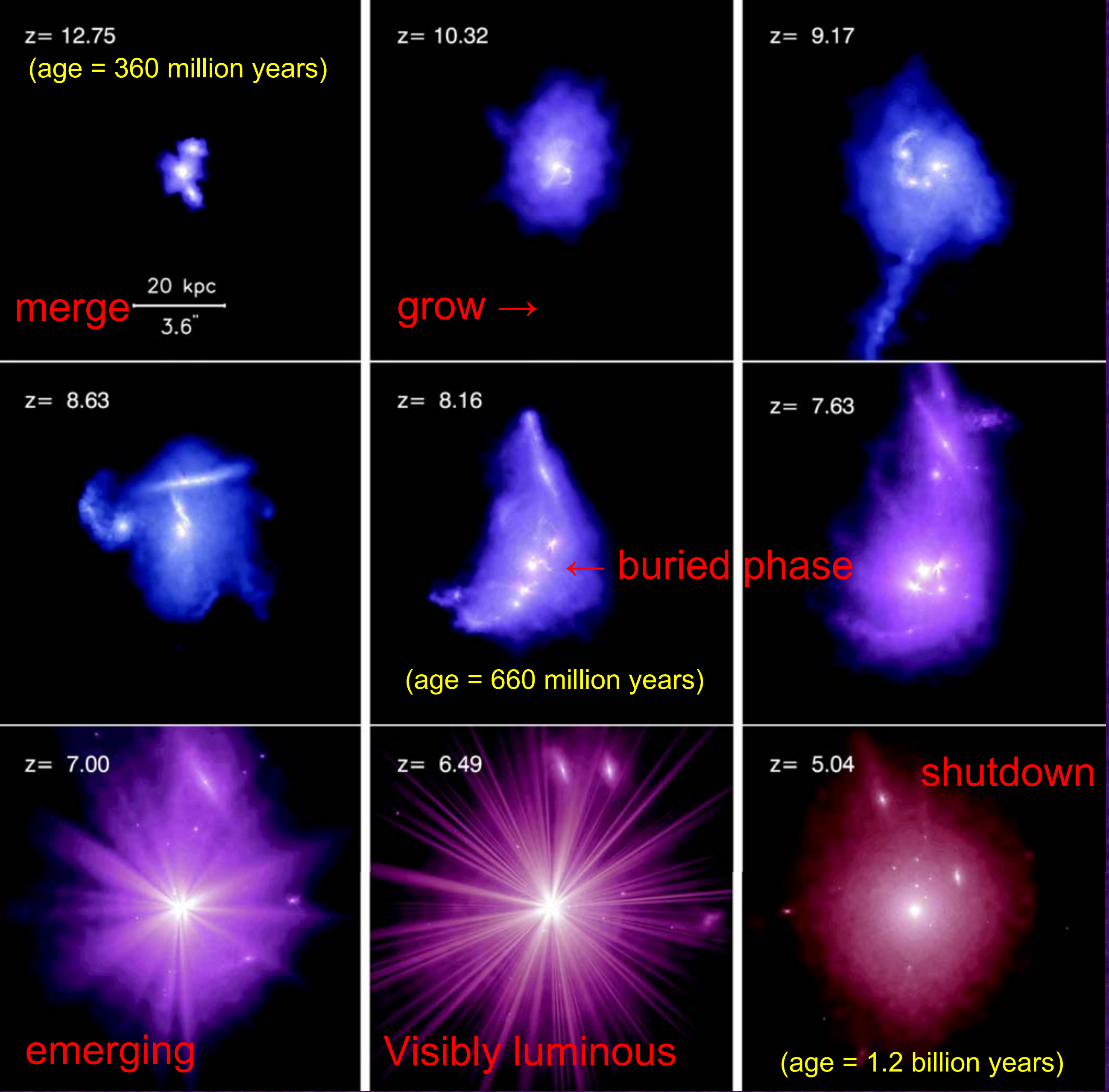




gas rich disk 'proto-galaxies' merge in early universe…

1. After first pass: gas driven into nuclei, monsters grow; star formation rate high; gas metallicity grows…
2. Major merger completes with enormous amounts of gas driven into center, star form. rate zooms, luminous quasar turns on
3. Quasar "blowout" throttles star formation, *then* starves itself

Di Matteo et al. 2004;
Hopkins et al. 2005;
Springel et al. 2006

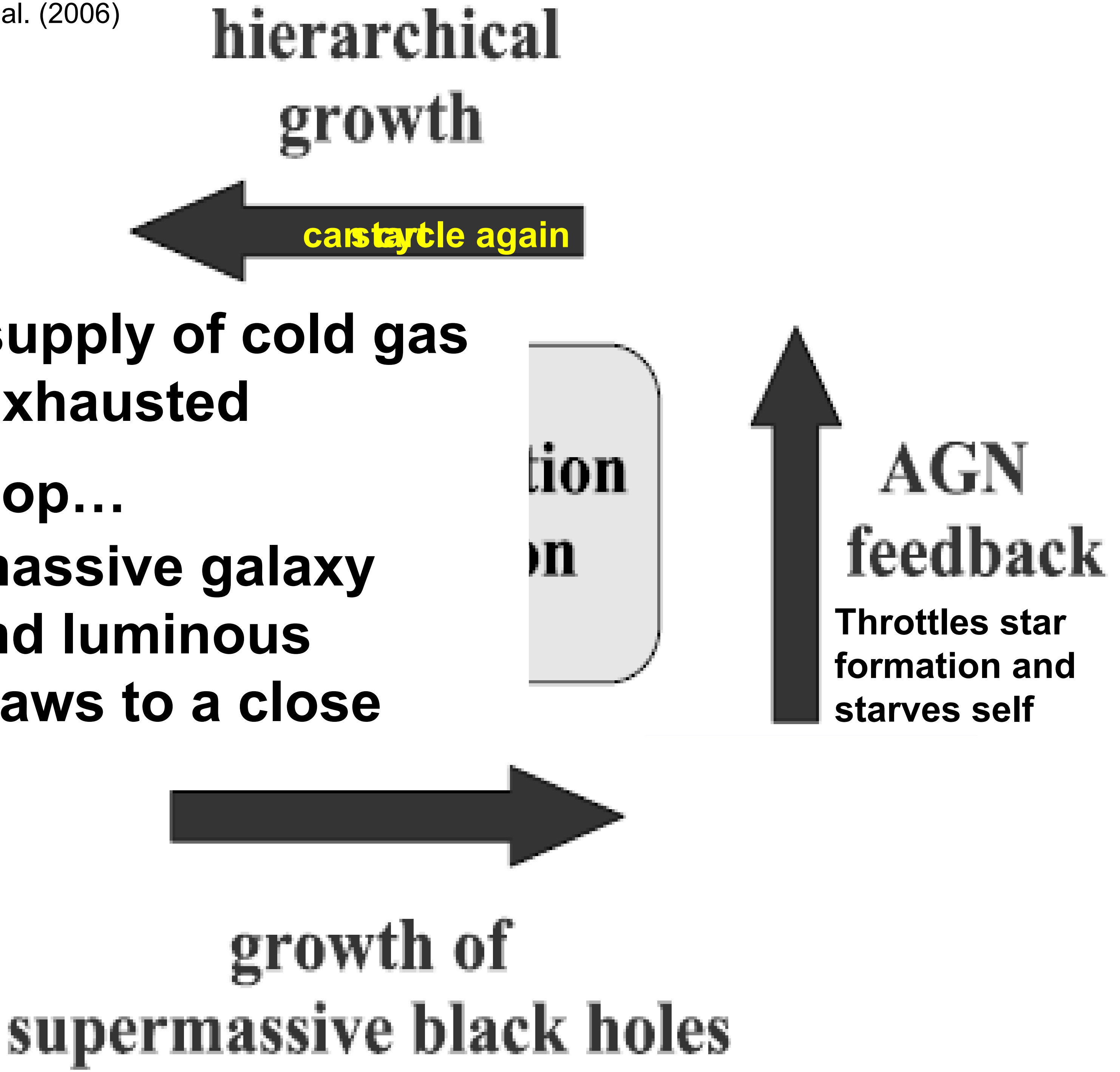


In this simulation (Li et al. 2007), 8 BHs merge w/in a massive dark matter halo, resulting in an enormous starburst, and then luminous quasar at z = 6.54, with final $M_{BH} \approx 2 \times 10^9 M_{sun}$

Quasar driven blowout shuts down star formation (stellar population then passively ages), and then the quasar itself.

But ~5% energy coupling currently *adjustable parameter* so that M_{BH} / $M_{\text{stellar bulge}}$ reaches ~0.002 by z ≈ 5.

intensity = stellar density; color = specific star formation rate; ‘artificial’ rays indicate quasar luminosity adapted from Hopkins et al. (2006)



Available supply of cold gas becomes exhausted

← exits loop…

epoch of massive galaxy building and luminous quasars draws to a close

Thank You!

Extra slides

Measuring M_{BH}:
(another talk)

$M = k_1 \times v^2 R_{BLR} / G$

where
v = line width
$R_{BLR} = k_2 \times L^{0.5}$

from 'simple' photoionization physics and measurements of broad emission line reverberation

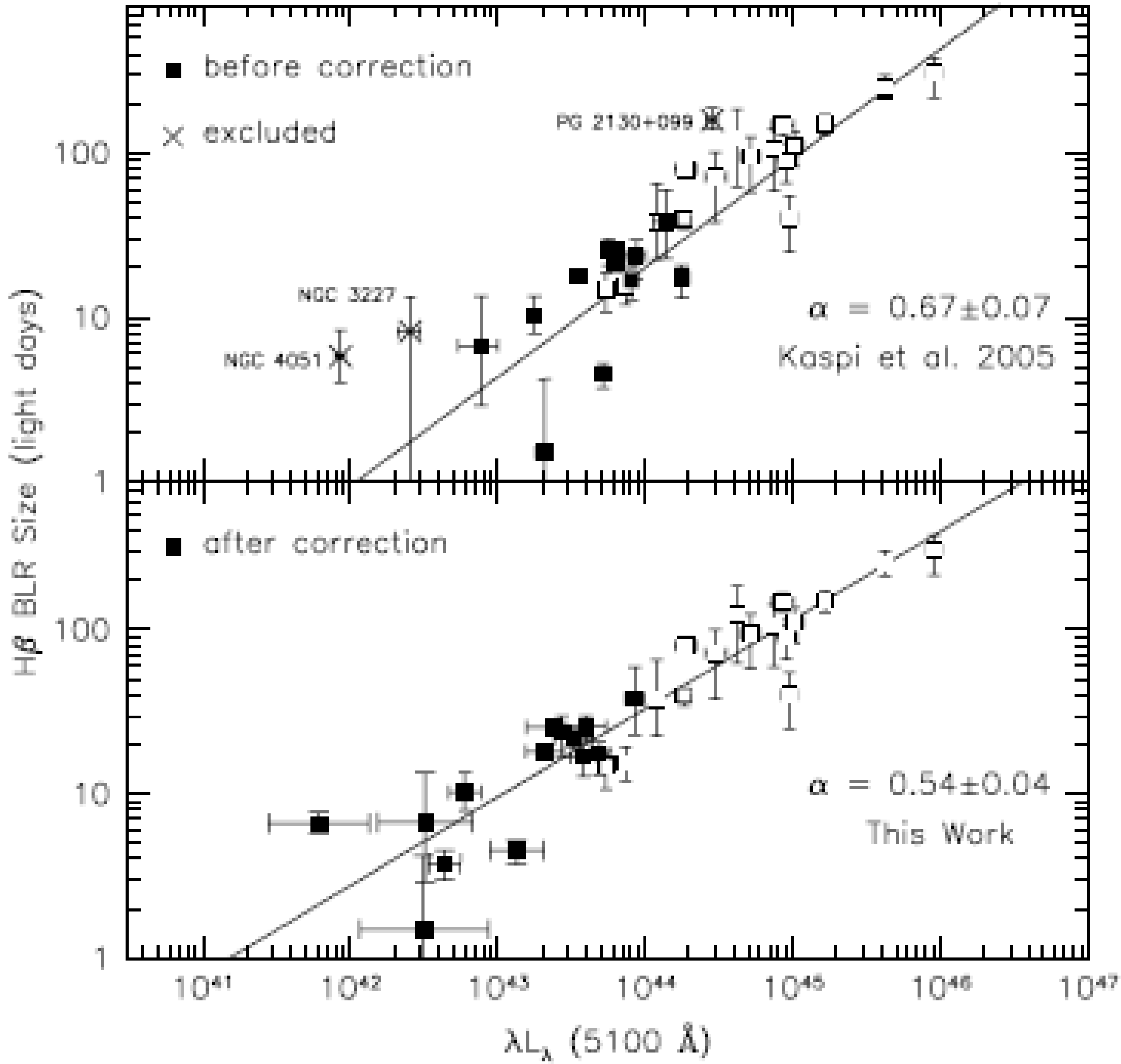
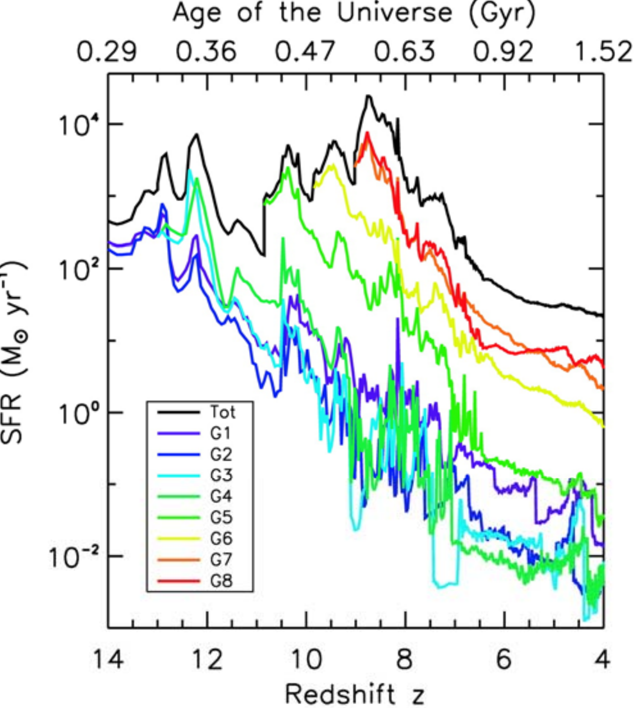
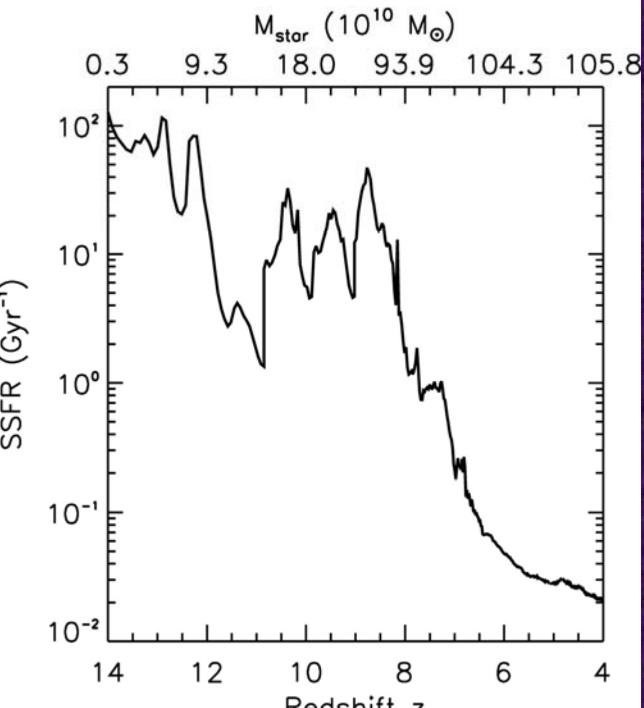
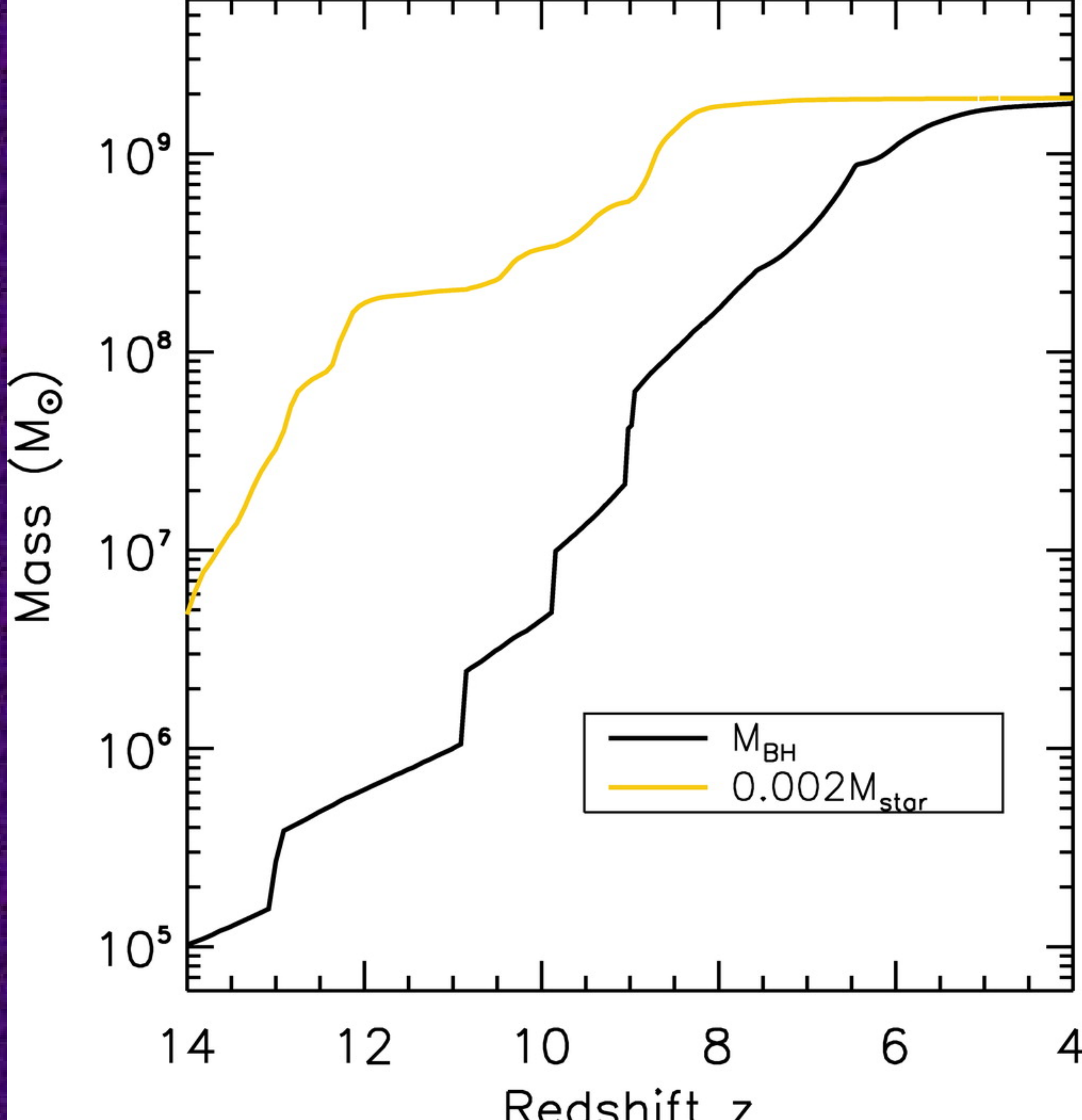
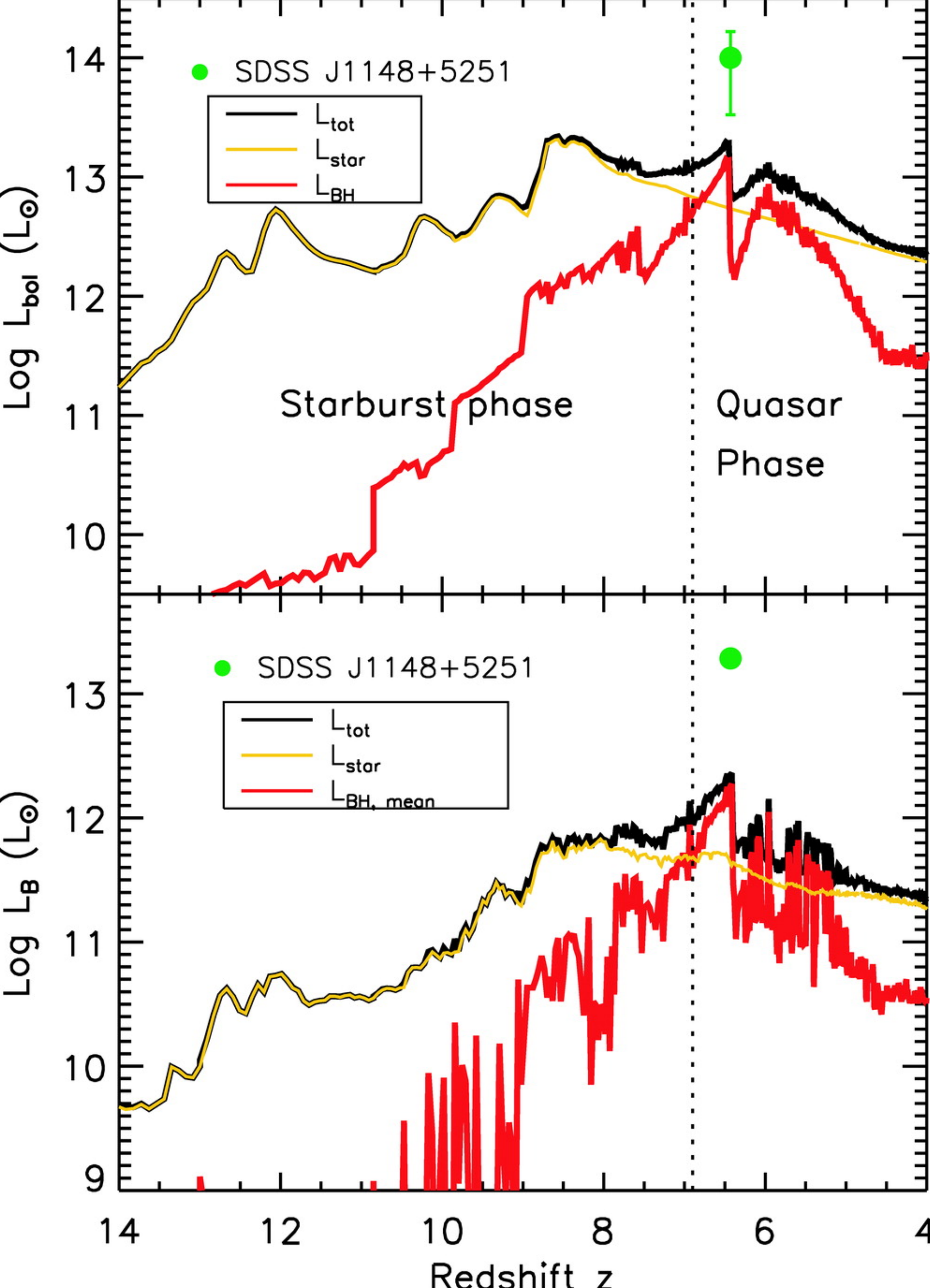


Figure 1. The top panel shows the recalibration of the $R-L$ relationship from Kaspi et al. (2005) using the reanalyzed reverberation results of Peterson et al. (2004).

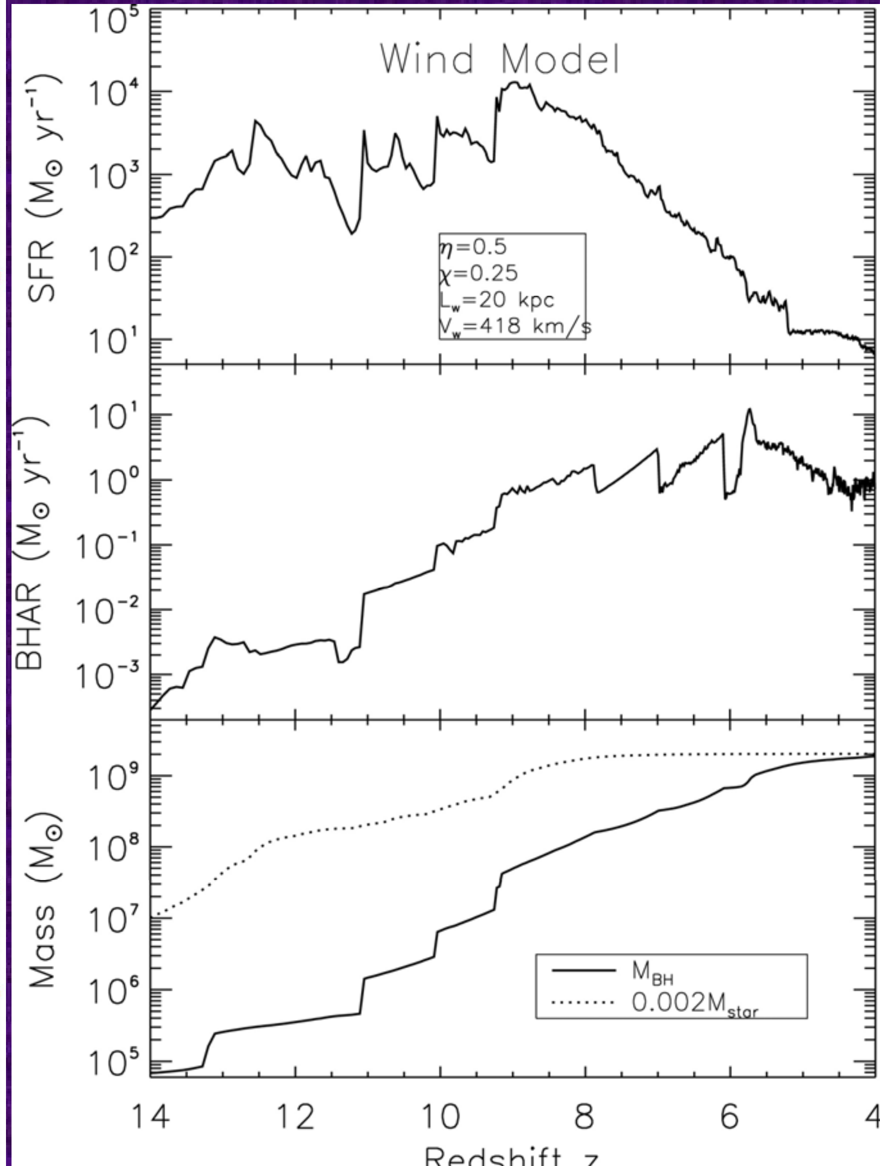

Age of the Universe (Gyr)
0.29 0.36 0.47 0.63 0.92 1.52
SFR (M⊙ yr⁻¹)
10⁴ 10² 10⁰ 10⁻²
Tot
G1
G2
G3
G4
G5
G6
G7
G8
14 12 10 8 6 4
Redshift z


M_star (10¹⁰ M⊙)
0.3 9.3 18.0 93.9 104.3 105.8
SSFR (Gyr⁻¹)
10² 10¹ 10⁰ 10⁻¹ 10⁻²
14 12 10 8 6 4
Redshift z

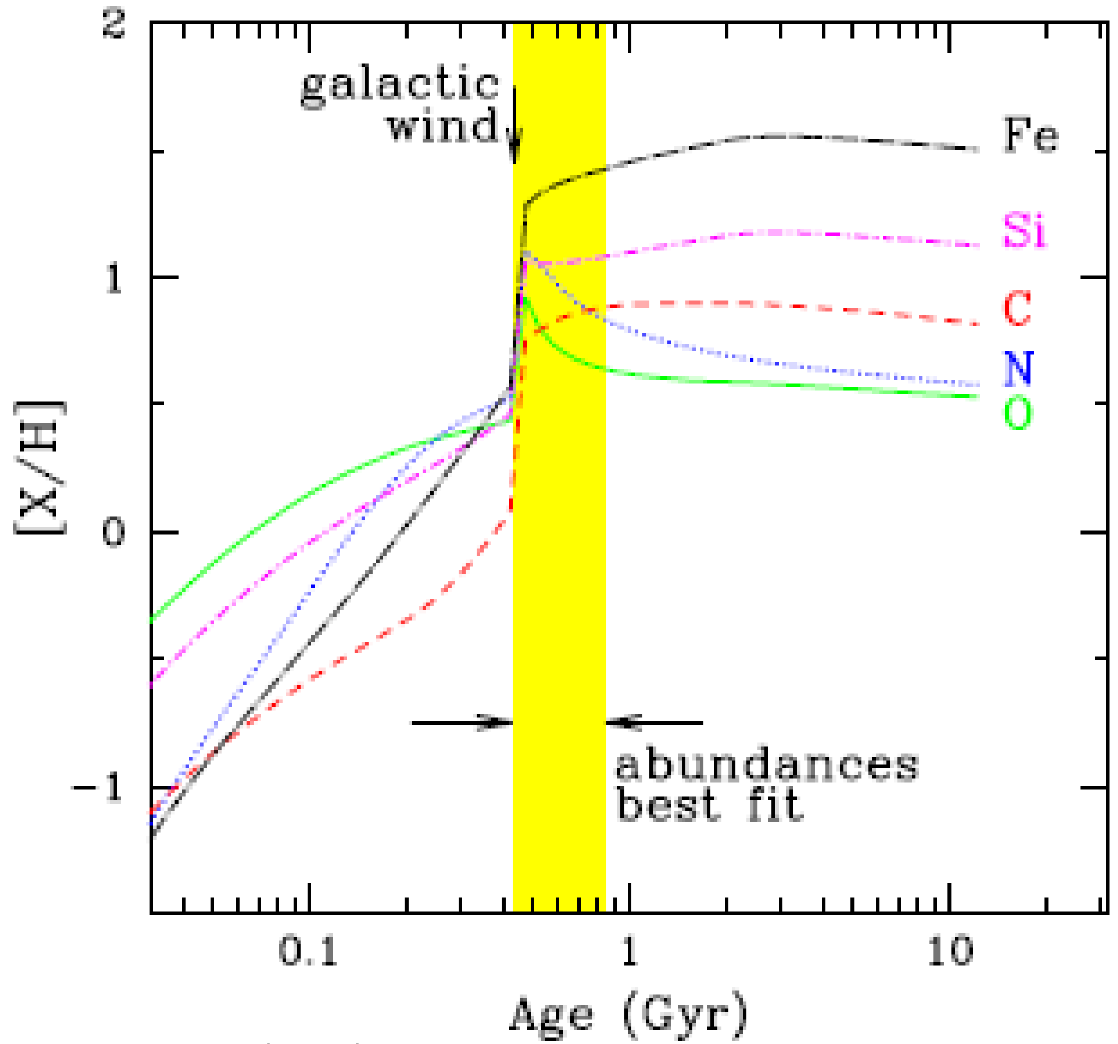

Mass (M⊙)
10⁹ 10⁸ 10⁷ 10⁶ 10⁵
M_BH
0.002M_star
14 12 10 8 6 4
Redshift z



SDSS J1148+5251
L_{tot}
L_{star}
L_{BH}
Log L_{bol} ($L_\odot$)
Starburst phase
Quasar
Phase
SDSS J1148+5251
L_{tot}
L_{star}
$L_{BH,\ mean}$
Log L_B ($L_\odot$)
Redshift z



Wind Model
SFR ($M_\odot$ yr^{-1})
η=0.5
χ=0.25
L_w=20 kpc
V_w=418 km/s
BHAR ($M_\odot$ yr^{-1})
Mass ($M_\odot$)
M_{BH}
$0.002M_{star}$
Redshift z



Maiolino et al. (2006)

Fig. 3. Abundances evolution for an elliptical galaxy including feedback effects. The downward arrow indicates the onset of the galactic wind. The shaded area indicates the abundance sets which best fit the line ratios observed in the QSO spectra.

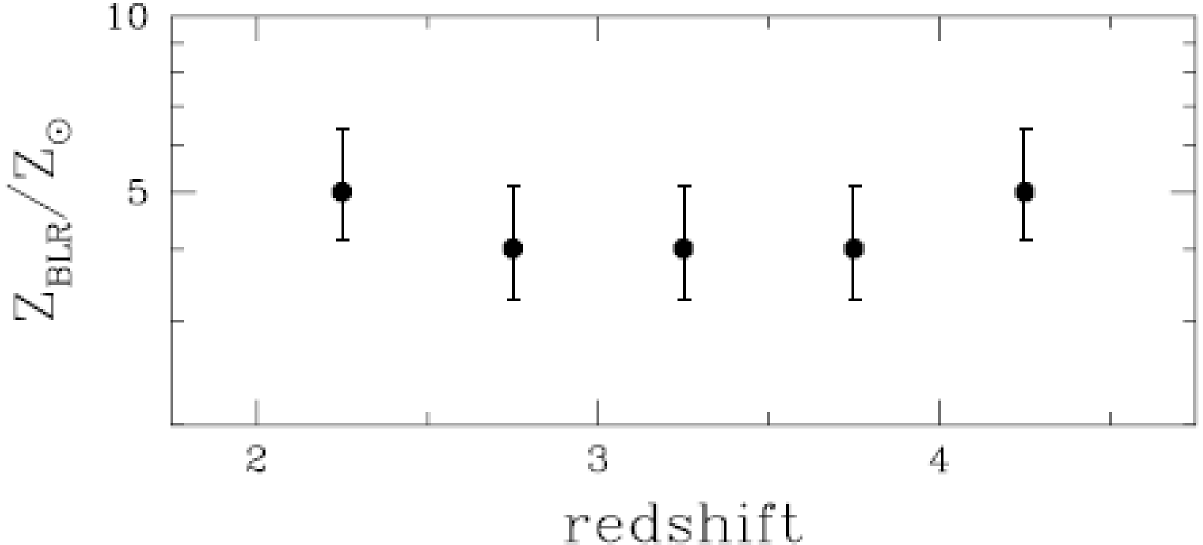


Fig. 38. Estimated metallicities from our composite spectra, averaged in the luminosity range $-25.5 > M_B > -28.5$, as a function of redshift. The estimation of the metallicity given in this figure is derived from the fit with the varying β and Γ, which are presented in Tables 12–16.

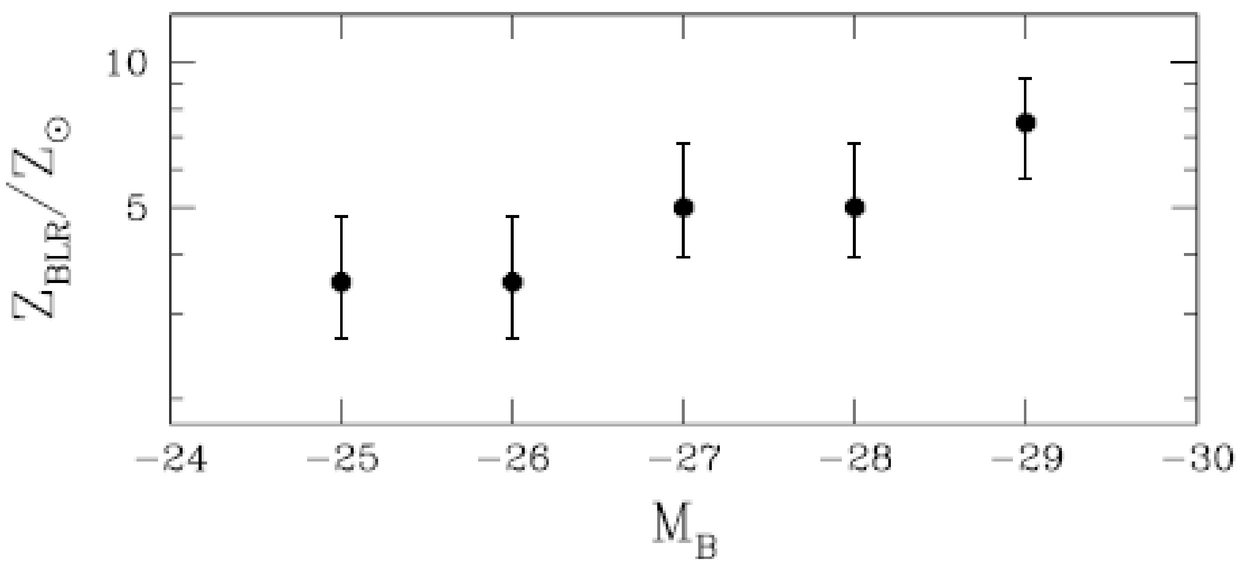
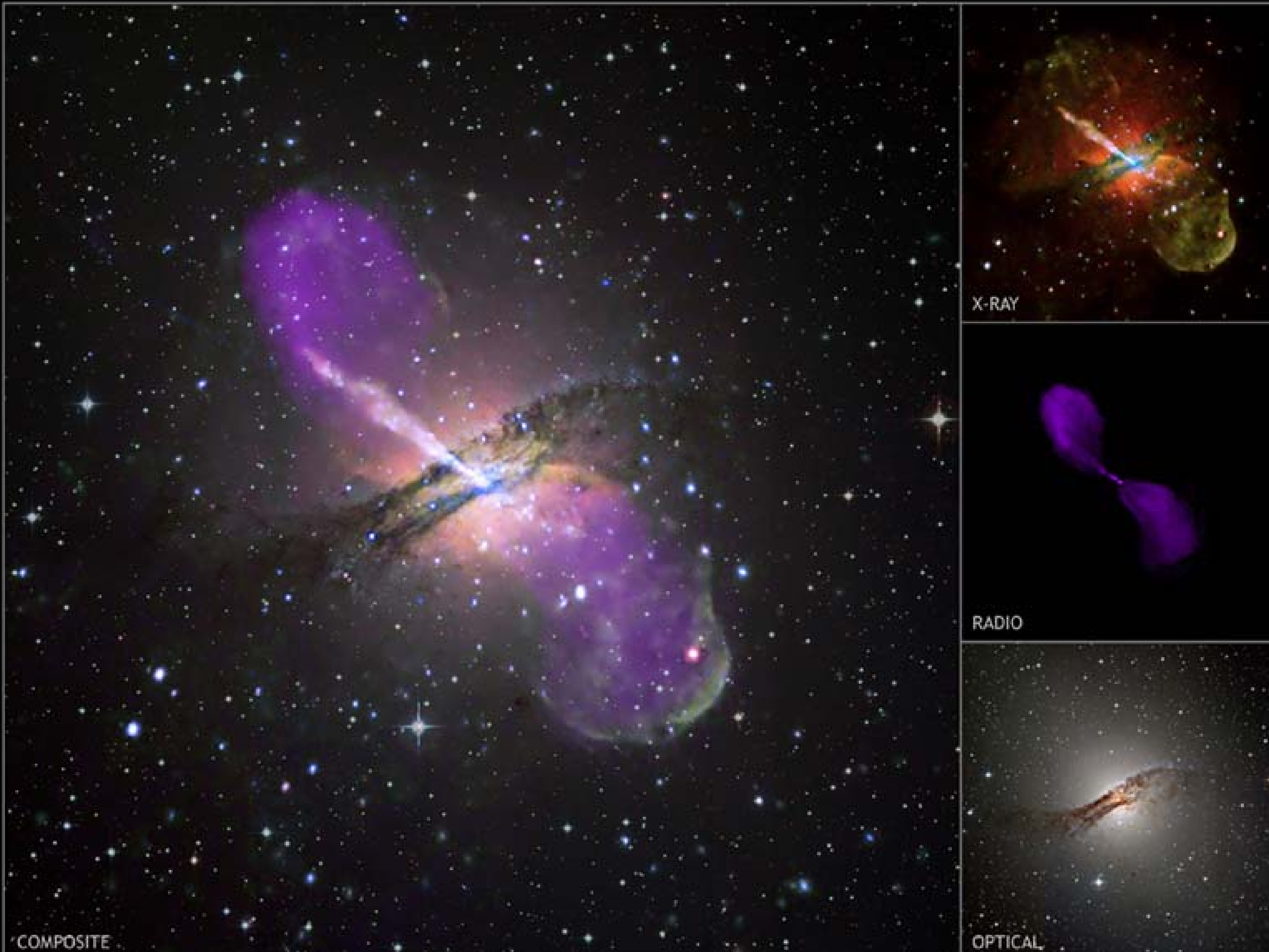


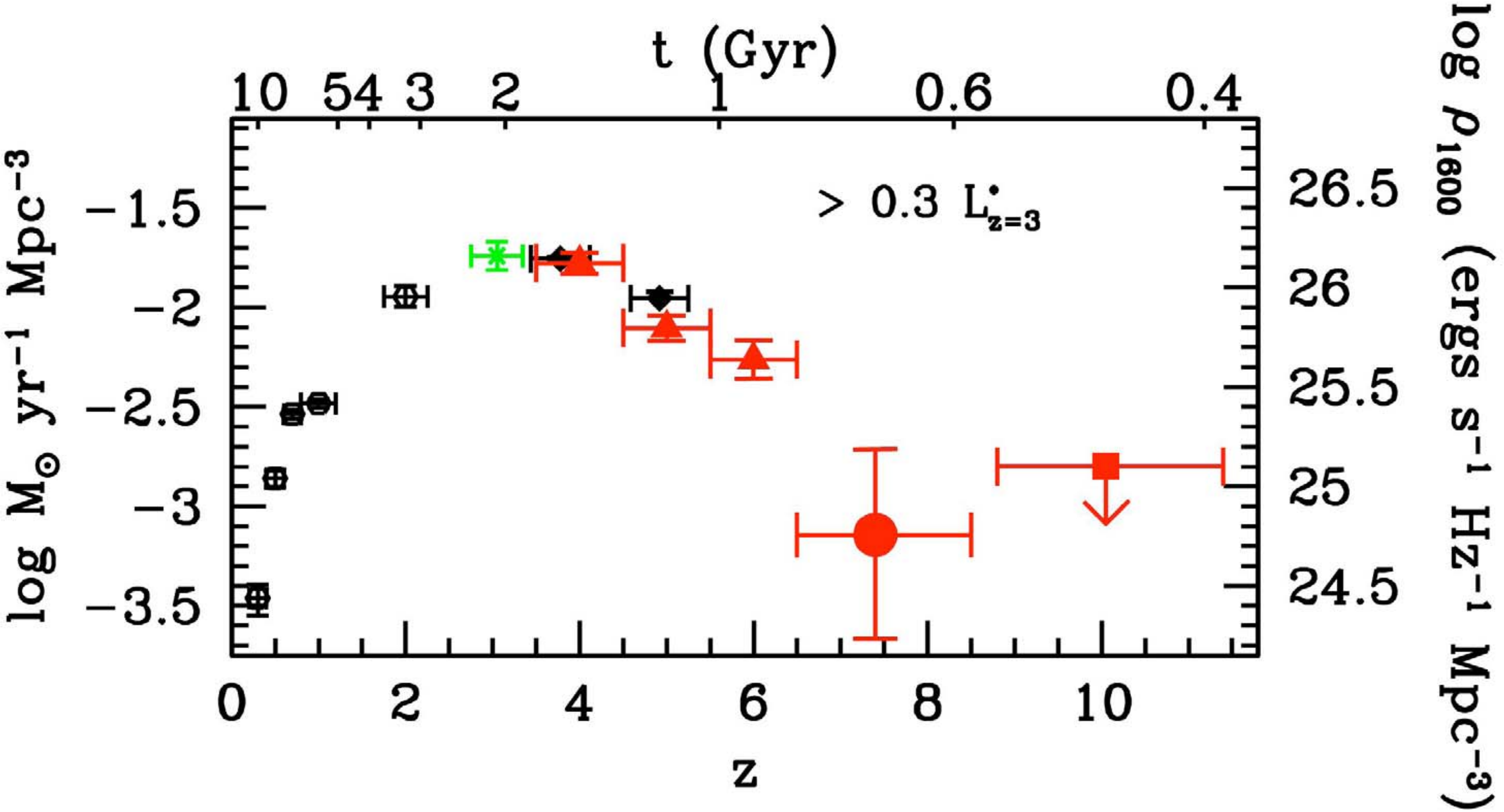
Fig. 39. Estimated metallicities from our composite spectra, averaged in the redshift range $2.0 \leq z < 3.0$, as a function of luminosity. The estimation of the metallicity given in this figure is derived from the fit with the varying β and Γ, which are presented in Tables 12 and 13.

Centaurus A, 11 million ly away

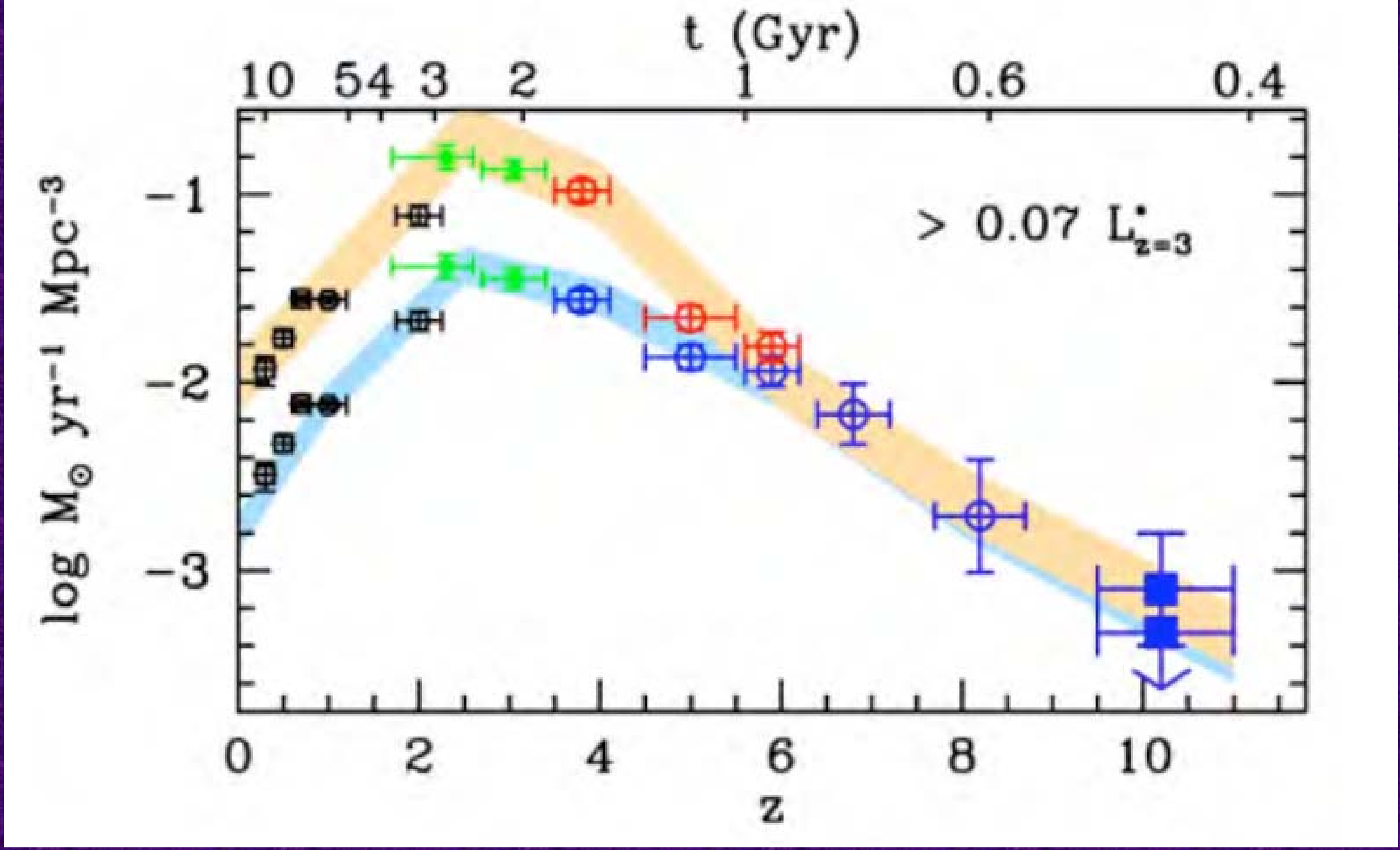
a disturbed **giant elliptical galaxy**.

Deep imaging reveals rings of stars.


X-RAY
RADIO
COMPOSITE
OPTICAL



t (Gyr)
10
54
3
2
1
0.6
0.4
> 0.3 $L^*_{z=3}$
log $M_\odot$ yr^{-1} Mpc^{-3}
−1.5
−2
−2.5
−3
−3.5
log ρ_{1600} (ergs s^{-1} Hz^{-1} Mpc^{-3})
26.5
26
25.5
25
24.5
0
2
4
6
8
10
z



http://arxiv.org/ftp/arxiv/papers/0912/0912.4263.pdf