Jack Singal
University of Richmond

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Mechanics and Evolution of Supermassive Black Holes with AGN Population Studies

Outline

1. The Case for multiwavelength AGN population studies
   I. The case for AGN
   II. The case for multiwavelength population studies

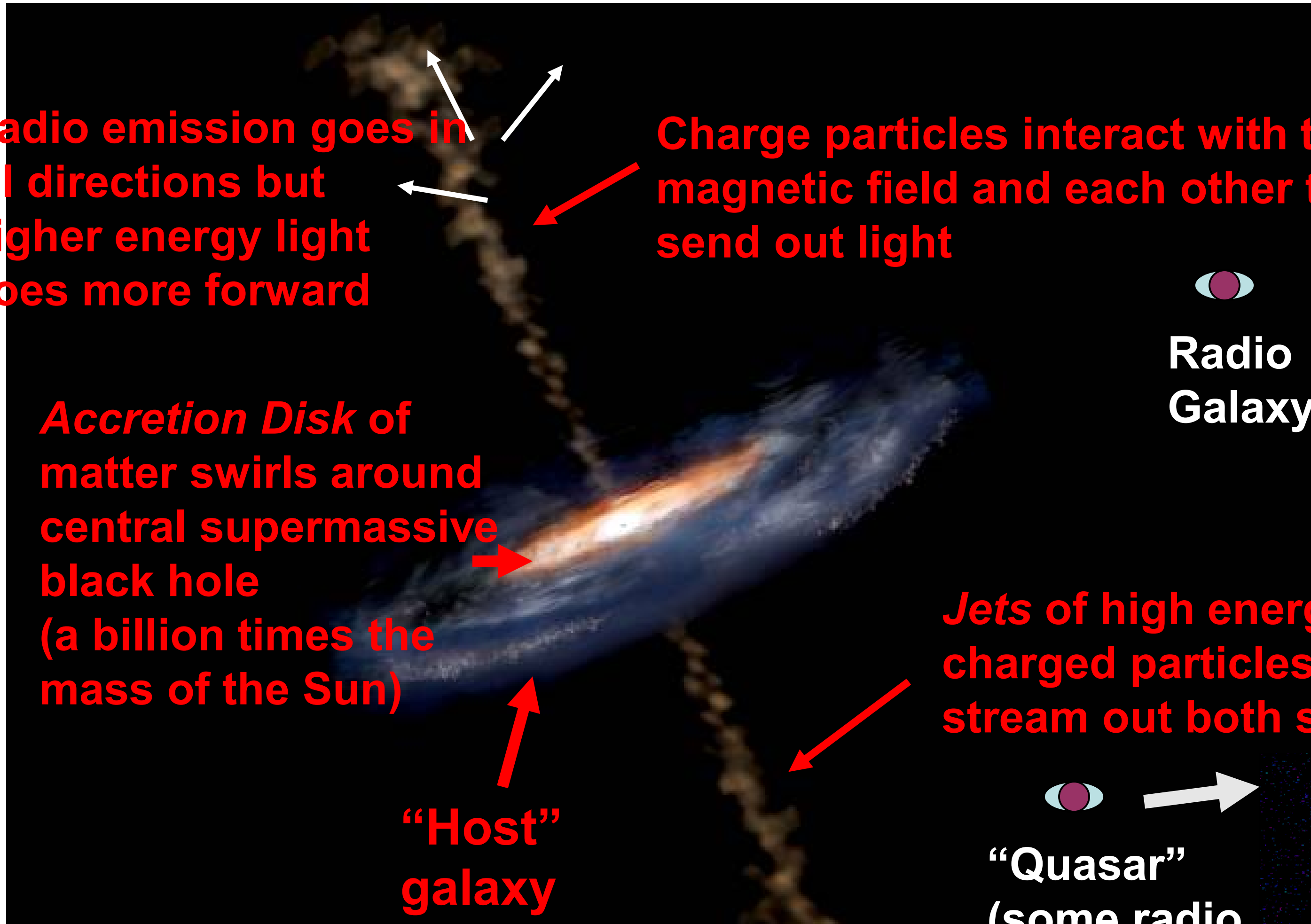
2. Statistical challenges because of truncated data

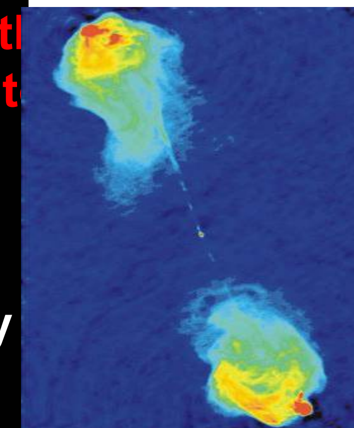
3. Luminosity Evolutions and implications for SMBHs
   1. Optical
   2. Radio
   3. Infrared

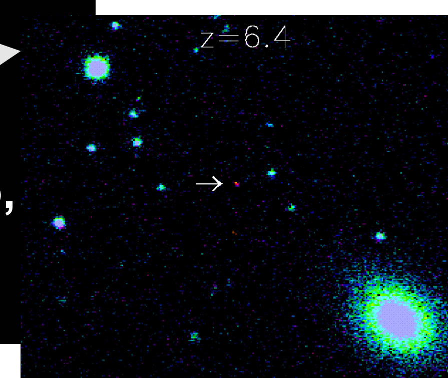
4. Luminosity Correlations and implications for SMBHs
   1. Optical-radio
   2. Optical-infrared

Supermassive Black Holes

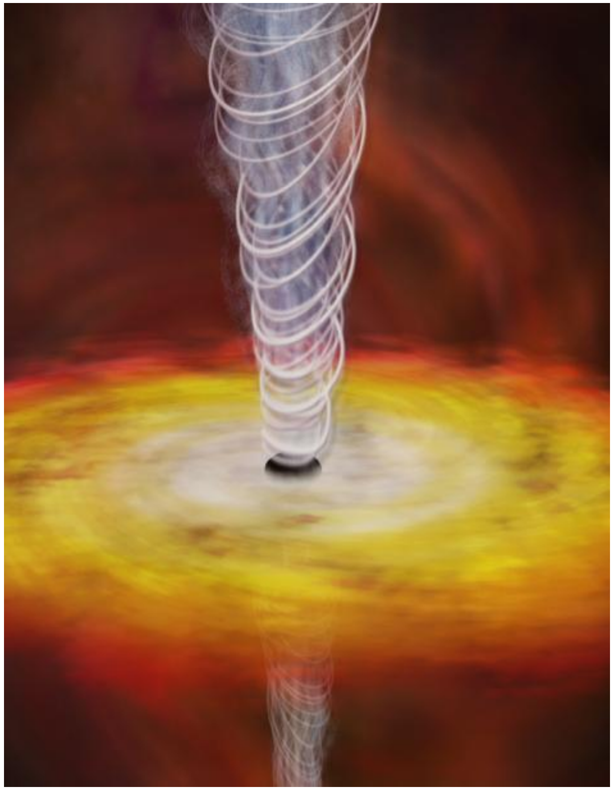
The phenomenon of *Active Galaxies*







Active Galaxies (AGN)



What's going on at the center?

This is (very) incompletely understood

In the Blandford-Znajek mechanism (1977, *MNRAS*, 179, 433) the rotational energy of the spinning supermassive black hole is extracted to accelerate matter into jets

Faster BH rotation → brighter jets

The amount of matter that gets near the black hole is determined by the black hole mass and the amount of material available

More massive BH → more matter → brighter jets

More massive BH → more matter → brighter accretion disk

If we could discover how active galaxies change over the history of the Universe, we could learn about the evolution over time of supermassive black hole systems

AGN in Multiwavelength

Faster BH rotation → brighter jets

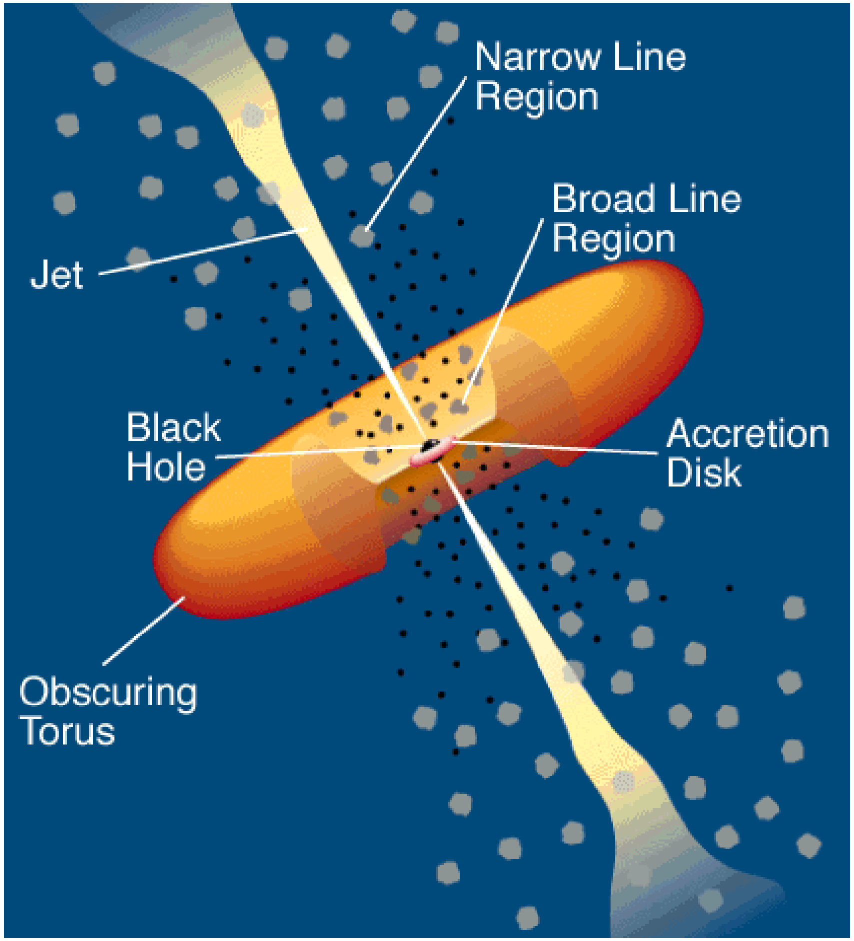
More massive BH → more matter → bigger jets → brighter jets

More massive BH → more matter → brighter accretion disk

Accretion disk is hot gas
→ *glows primarily in optical, UV, X-rays*

Jets are high energy charged particles interacting with magnetic field and each other
→ *glow primarily in radio, X-rays, and higher energy X- and gamma-rays if aligned with observer*

Possible torus of dust
→ *Glows in infrared, obscures accretion disk at certain angles*



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To learn about the nature and evolution of supermassive black hole systems:

One possibility: Study a few resolved, nearby objects in great detail… or…

We could do population studies of tens of thousands of unresolved objects to find out how the radio, infrared, optical, X-ray, and gamma-ray emission have changed over the history of the universe, and how they are correlated with each other.

AGN Population Studies

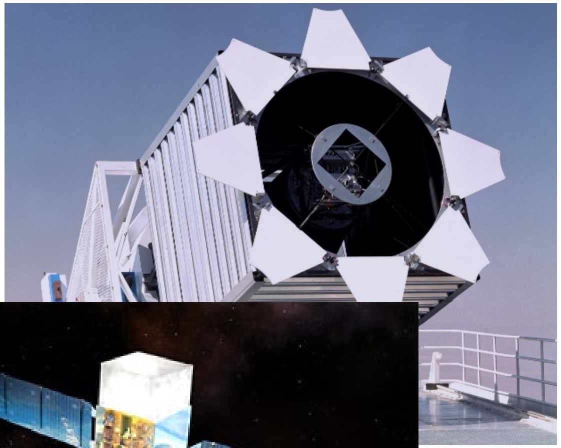
To learn about the nature and evolution of supermassive black hole systems:

We will do population studies of tens of thousands of unresolved AGN to find out how the radio, infrared, optical, X-ray, and gamma-ray emission have changed over the history of the universe, and how they are correlated with each other.

“Population Distributions and Correlations”

→ Utilize the publically available data from large scale surveys

Optical: Sloan Digital Sky Survey (SDSS)
Radio: FIRST
Infrared: Wide-Field Infrared Explorer (WISE), Spitzer Space Telescope
X-Ray: Chandra X-Ray observatory, XMM- Newton
Gamma-ray: Fermi Gamma-ray Space Telescope



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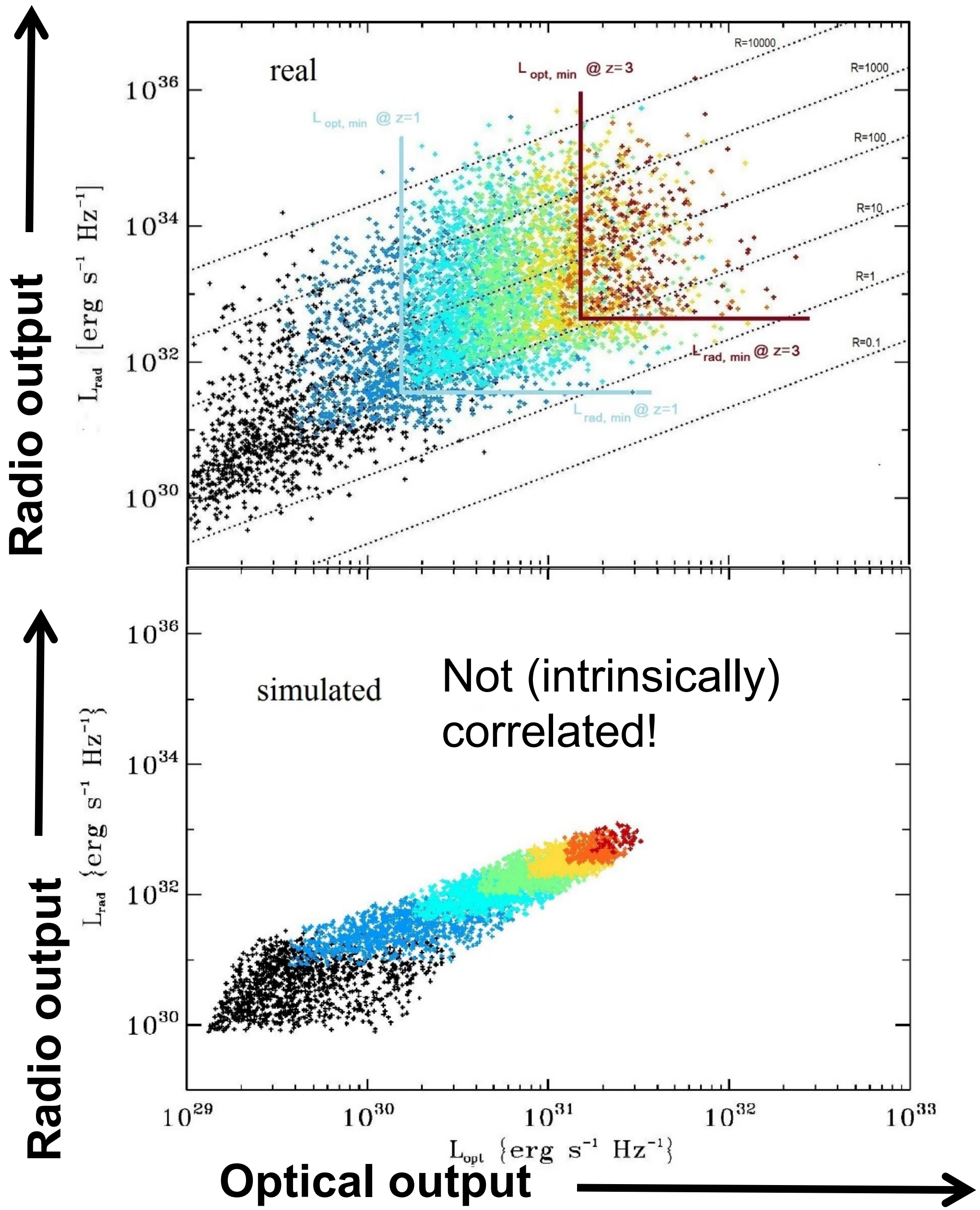
Consider – radio vs. optical output:



Are these “luminosities” correlated?

An observed correlation can be induced by observational selection effects or similar redshift evolutions of the luminosities

Observed correlations do not accurately reflect ***intrinsic*** correlations!

(in flux-limited data)

“Flux” and “Luminosity”

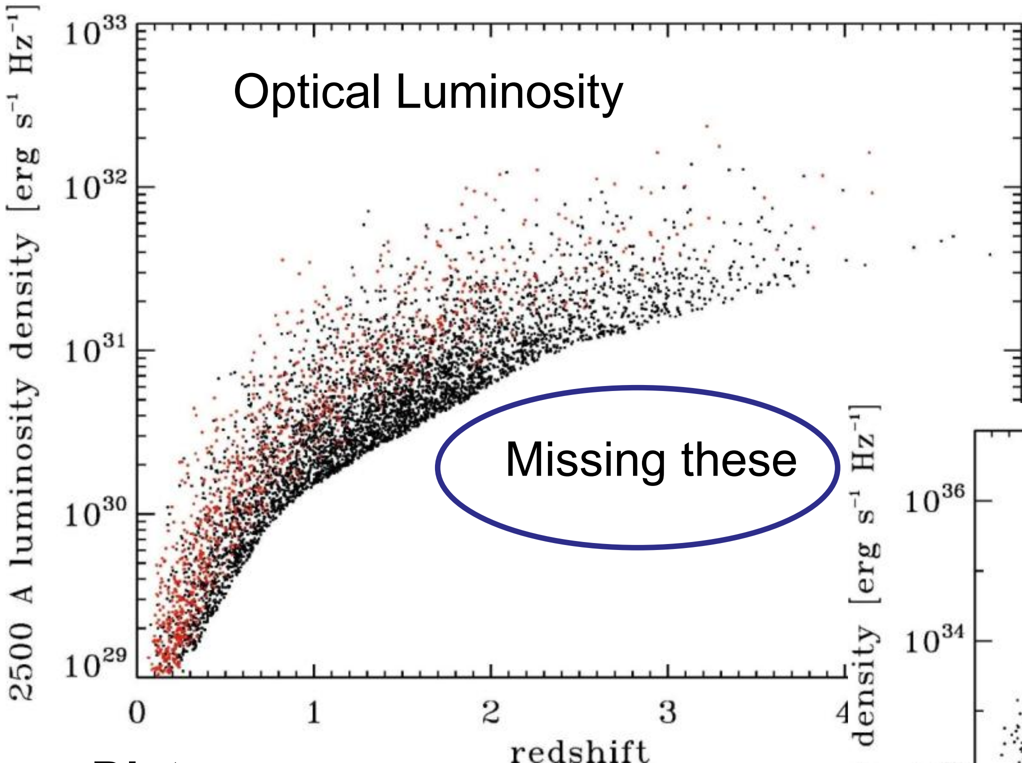
Luminosity –
how bright an
object actually is

$$F_{\nu} = \frac{L_{\nu} K(z)}{4\pi D_L^2(z)}$$

Flux – how bright an
object appears to us –
what we measure

Luminosity
Distance

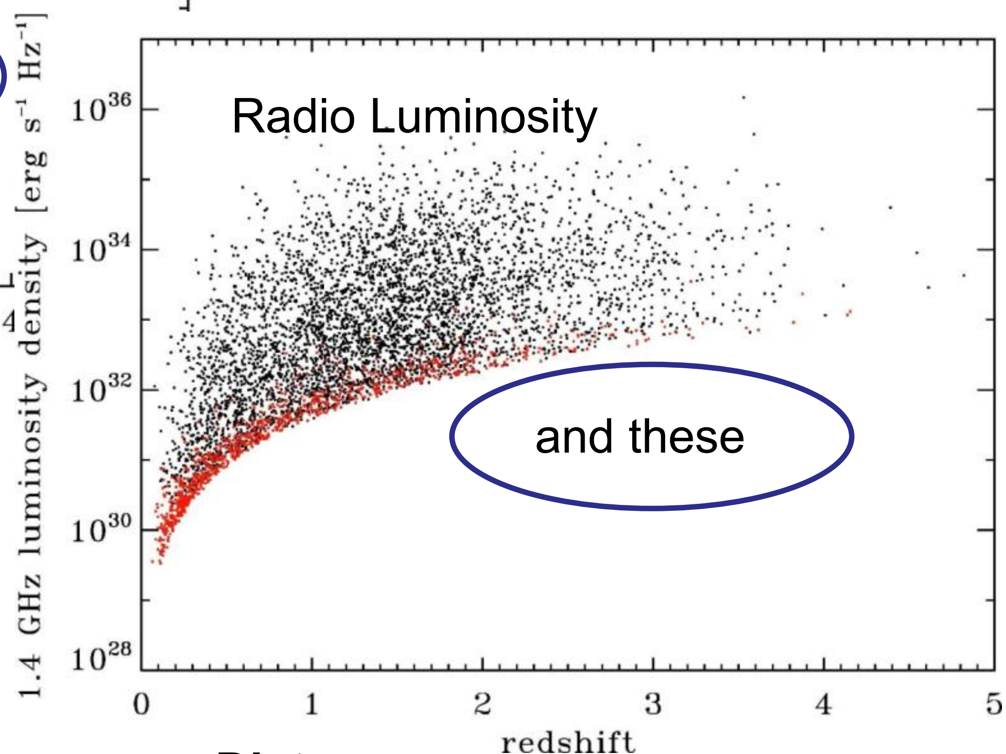
Example: SDSS optical x FIRST radio



5445 quasars seen in optical *and* radio

Distance →

Back in time →



We are 'missing' most of the data because of the flux limits!

Distance →

Back in time →

Methods

Determining the correlations between the luminosities, and the changes in the luminosities over time, is a nuanced statistical challenge

Can’t go into it here but:

Techniques explored in :
- Singal et al., 2019, *ApJ,* 877, 63
- Singal, George, & Gerber, 2016, *ApJ*, 831, 60
- Petrosian & Singal, 2015, *Proc IAU S313*
- Singal, 2015, *MNRAS*, 115, 122
- Singal et al., 2011, *ApJ*, 743, 104
- Singal et al., 2012, *ApJ*, 753, 45
- Singal et al., 2013, *ApJ*, 764, 43
- Singal, Petrosian, & Ko, 2014, *ApJ*, 786, 109

Let’s look at some results:

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Evolving Luminosity Functions

If a class of object changes in average luminosity over time, that is called "**Luminosity Evolution**"

Let's parameterize the luminosity evolution in waveband *a* - as a function of redshift (z) - like this:

$$\langle L_a \rangle (z) = \langle L_a \rangle_{z=0} \cdot g_a(z)$$

with $g_a(z) = (1+z)^{k_a}$ or $g_a(z) = \dfrac{(1+z)^{k_a}}{1 + \left(\dfrac{1+z}{z_{cr}}\right)^{k_a}}$

$g_a(z)$ is the best-fit correlation function between band *a* luminosity and redshift

If k_a is positive, the objects get brighter (on average) in waveband a with increasing redshift (back in time).

Optical & Radio: Luminosity Evolutions

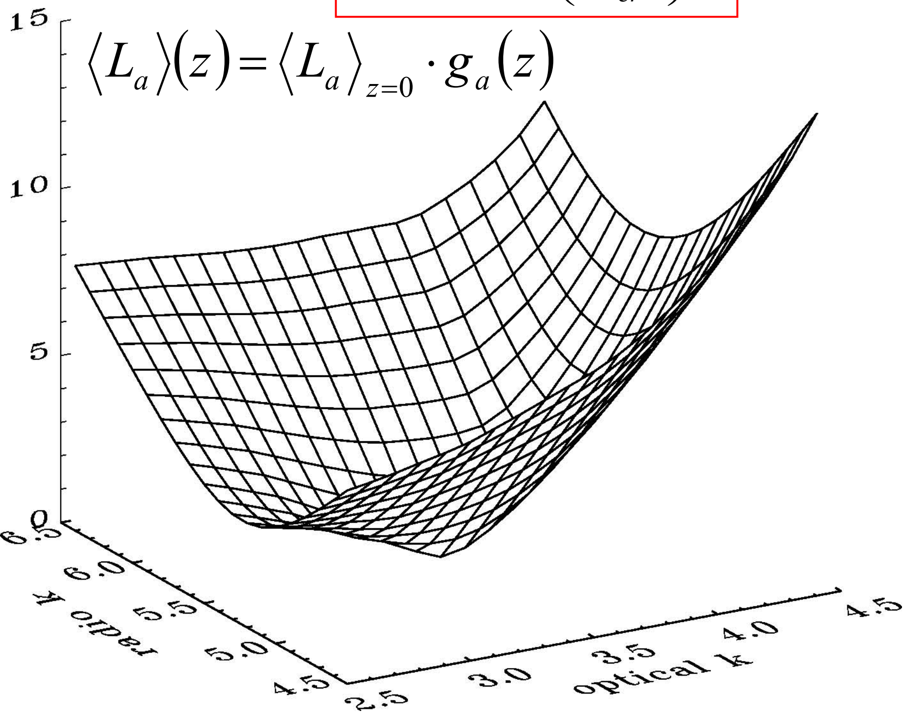
$$L'_a \to \frac{L_a}{g_a(z)}$$

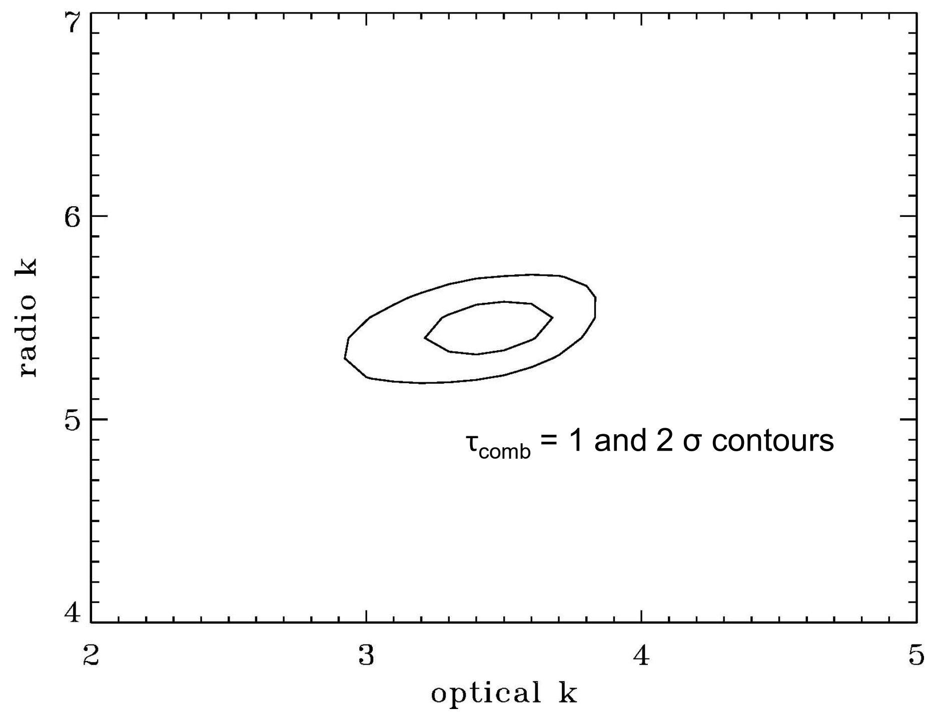
$$\boxed{g_a(z) = \frac{(1+z)^{k_a}}{1+\left(\frac{1+z}{z_{cr}}\right)^{k_a}}}$$

For combined radio and optical dataset

Have to do a simultaneous minimization of $\tau_{comb} = \sqrt{\tau_{opt}^2 + \tau_{rad}^2}$

$$\langle L_a \rangle(z) = \langle L_a \rangle_{z=0} \cdot g_a(z)$$





$\boxed{k_{opt}=3.4\pm0.2,\ k_{rad}=5.5\pm0.2}$

Quasars have undergone significant evolution with redshift in both radio and optical, with greater evolution in radio. Quasars were more "*radio loud*" in the past!

Implications of these quasar radio and optical results

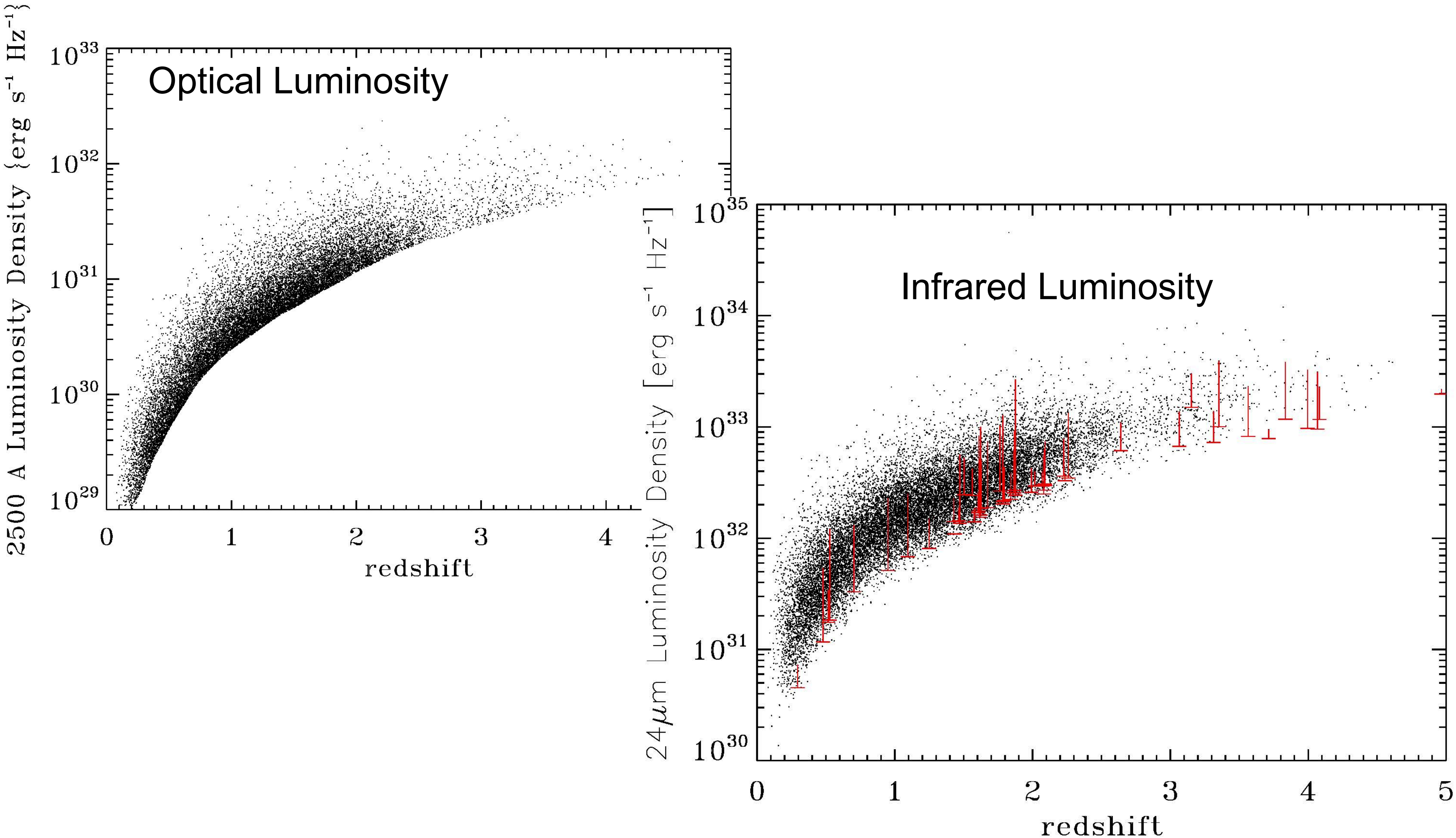
- Quasars were brighter in the past
- Quasars were more radio loud in the past (ratio of radio to optical emission was higher)

→ **Going back in the past, jets get bigger relative to disks**

Reminder: Radio emission comes primarily from jet and optical comes primarily from accretion disk. For a given size of accretion disk, faster spinning black holes will make bigger jets.

- **Supermassive Black Holes used to be spinning faster**

Next: SDSS (optical) x WISE (mid-infrared)



Singal, George, & Gerber, 2016, *ApJ*, 831, 60

SDSS x WISE: Luminosity Evolutions

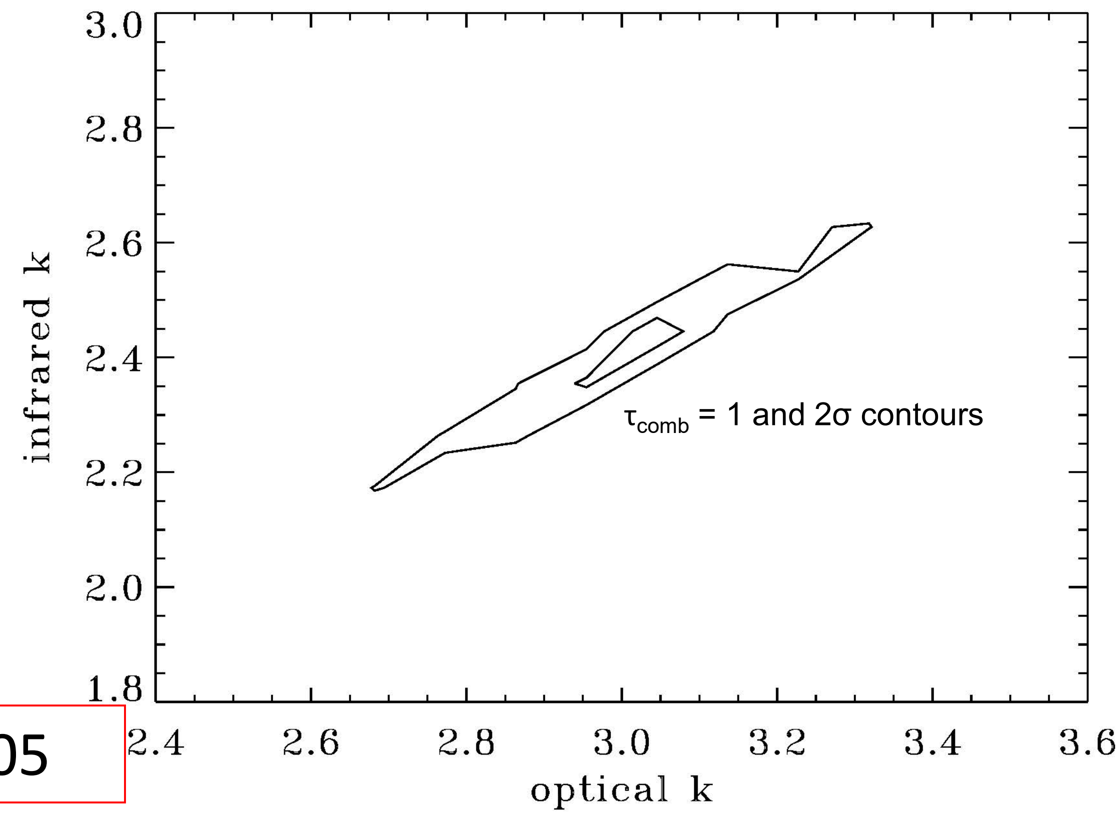
$$L'_a \rightarrow \frac{L_a}{g_a(z)}$$

$$\boxed{g_a(z) = \frac{(1+z)^{k_a}}{1+\left(\frac{1+z}{z_{cr}}\right)^{k_a}}}$$

For combined radio and optical dataset

Have to do a simultaneous minimization of $\tau_{comb} = \sqrt{\tau_{opt}^2 + \tau_{\inf}^2}$

$$\langle L_a \rangle(z) = \langle L_a \rangle_{z=0} \cdot g_a(z)$$



$\boxed{k_{opt}=3.35\pm0.1,\ k_{inf}=2.75\pm0.05}$

Quasars have undergone less evolution with redshift in 22 µm infrared than optical or radio

Singal, George, & Gerber, 2016, *ApJ*, 831, 60

Implications of these quasar mid-infrared and opical results

- Quasars were brighter in the past, and there were more of them
- Quasars were *less* “mid-infrared loud” loud in the past
- Quasars seem to have a minimum mid-infrared luminosity

- **The tori grow over time as more dust is available in the Universe (makes sense)**

- **Infrared emission dominated by something other than the jet. Probably even the lowest spin black holes (with the weakest jets) still have a torus to re-process accretion disk emission.**

Further discussion / info: J. Singal, George, & Gerber, 2016, *ApJ*, 831, 60

Honorable Mention: Gamma-Rays

FSRQ Blazars

Singal, Petrosian, & Ko, 2014, *ApJ*, 786, 109

$k_{L\gamma}=6.5\pm0.3$

FSRQ blazars have undergone significant gamma-ray luminosity evolution with redshift

Reminder: Gamma-ray emission comes from the jet. For a given size of accretion disk, faster spinning black holes will make bigger jets.

- **Supports conclusion that black holes used to be spinning faster**

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(Intrinsic) Luminosity Correlations

Two issues:

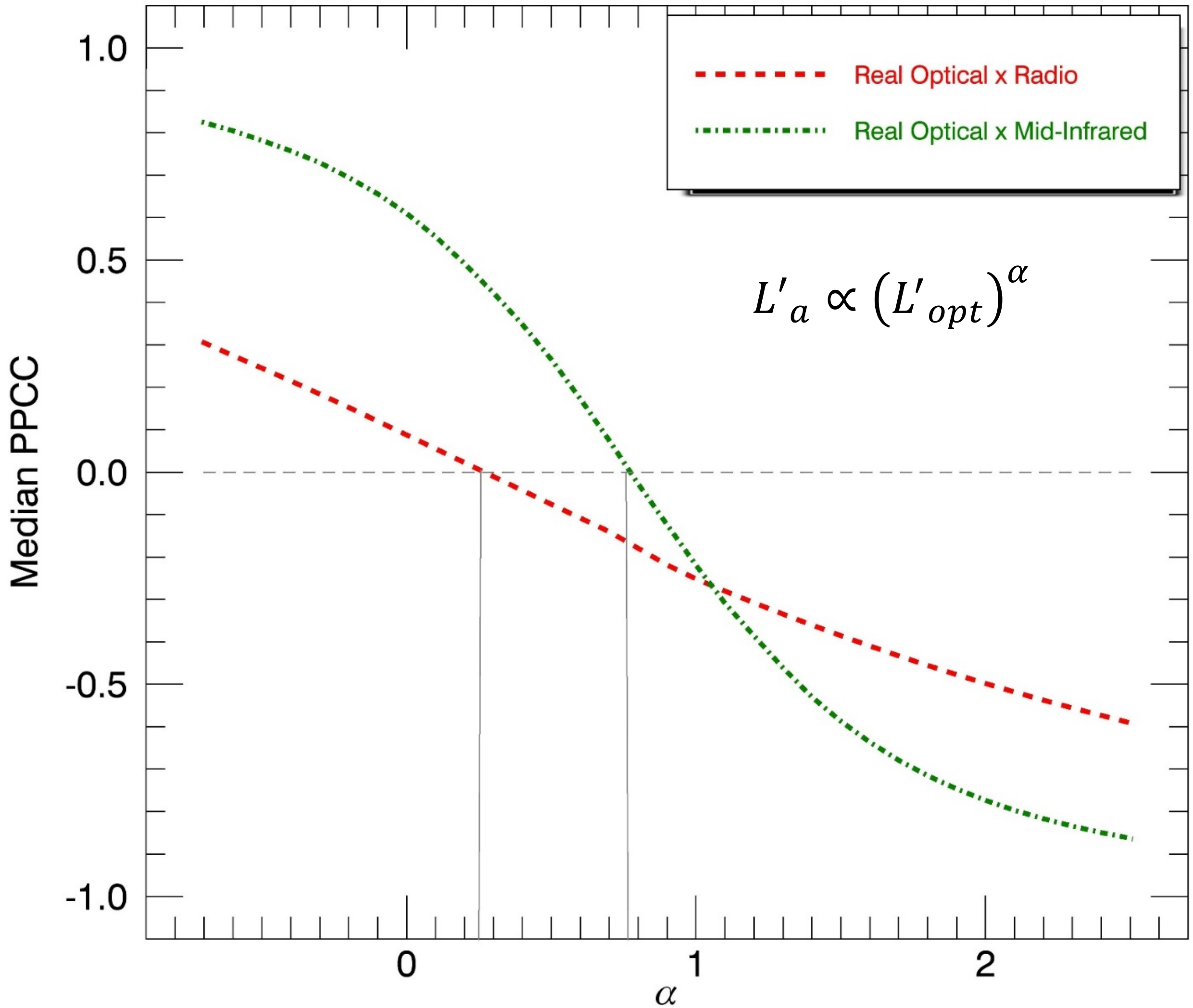
- How closely are the two luminosities (say radio and optical) *intrinsically* correlated?

- What is the form of the correlation?

$$L'_{rad} \propto \left(L'_{opt}\right)^{\alpha}$$

if $\alpha = 1$ then liner correlation, etc..

Form of Correlation: Real Radio-Optical & Mid-Infrared-Optical



Luminosity Correlations Conclusions

- We can access at least a good approximation of the degree of and form of intrinsic correlation between two luminosities by assessing the correlations and partial correlations in bins

- In quasars the optical and mid-infrared luminosities are very highly intrinsically correlated (both in degree of correlation and power-law form), while optical and radio luminosities are less intrinsically correlated

- This makes sense if accretion disk luminosity (related to SMBH size) is primarily responsible for the optical and mid-infrared emission while the radio emission depends on both SMBH size and spin

(Some) Overall Conclusions

• Large-scale AGN population studies are enabled by large extragalactic surveys and statistical techniques to access the true intrinsic distributions from flux-limited and truncated data

• We have employed one particular non-parametric technique to access the distributions

• We can estimate the intrinsic Luminosity-Luminosity correlations

A fairly consistent picture is emerging where:

• AGNs were brighter in all wavebands in the past relative to now

• AGN activity was more common in the past

• Considering optical (weaker) and radio (stronger) luminosity evolution we see that jet emission in the past was proportionally brighter when compared to accretion disk emission

• The weak correlation between radio and optical luminosities supports the Blandford-Znajek model of the black hole spin launching the jets

• Black holes were spinning more rapidly in the past relative to now

• The strong correlation between mid-infrared and optical luminosities supports the picture of infrared emission from a heated torus

• The weaker mid-Infrared luminosity evolution relative to the other bands indicates that torus emission is proportionally more important at later times than earlier, so tori have grown