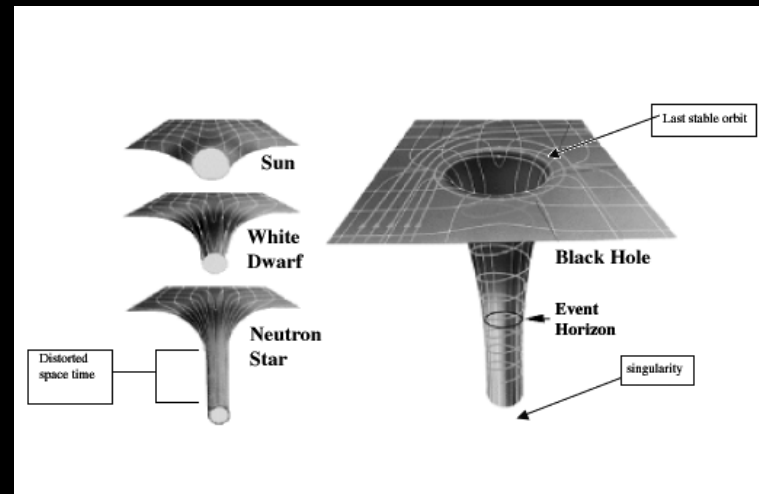
Measuring the Masses of Monster Black Holes

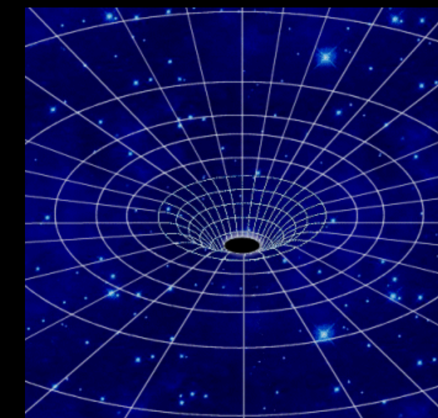
Prof. Misty C. Bentz
Dept. of Physics & Astronomy

Georgia State University

NSF

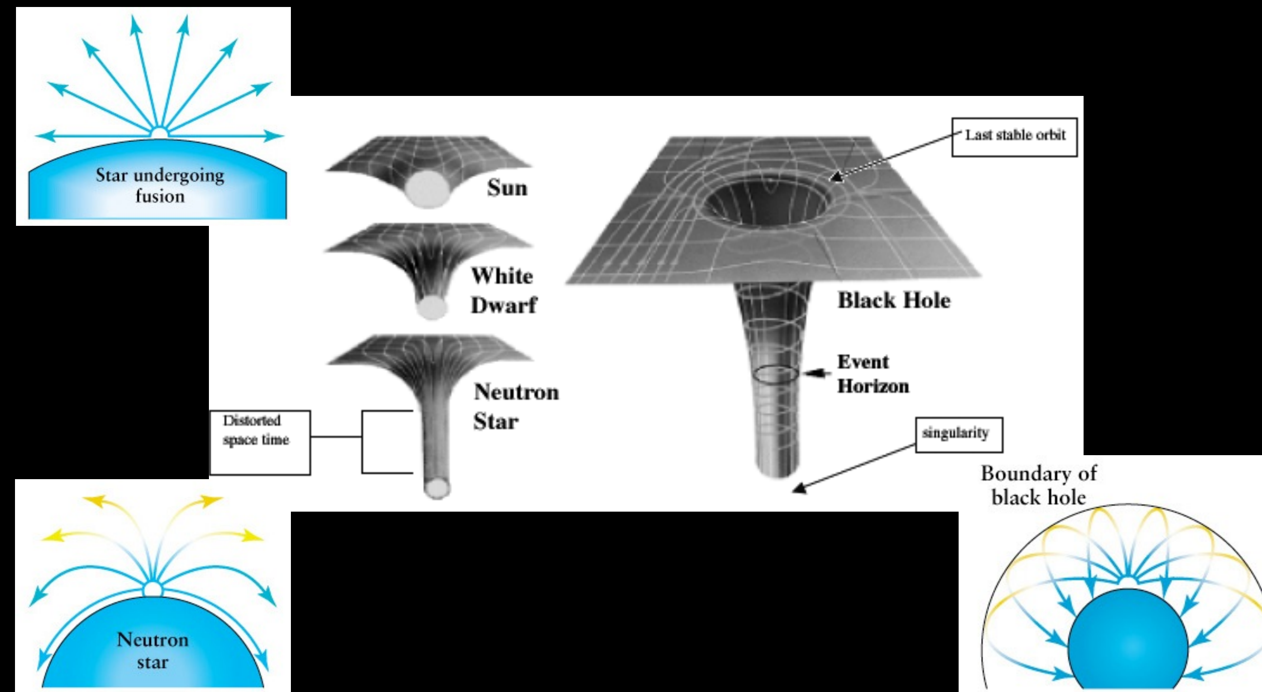
What is a black hole?



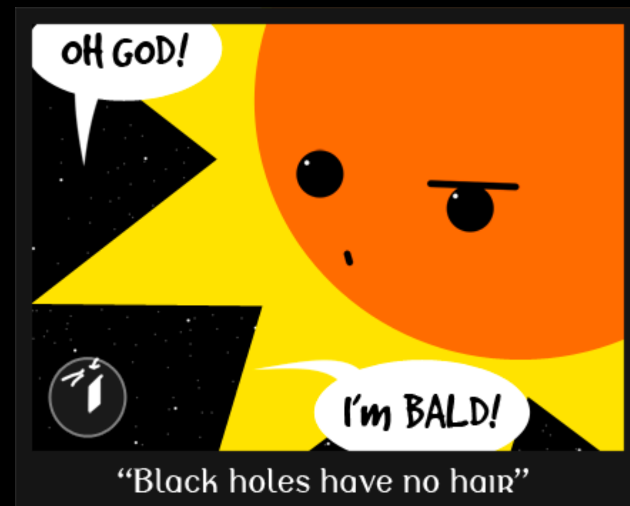


An object so dense that its gravity creates a "rip" in the fabric of the Universe

Black holes are “black” because no light can be emitted from them



What is there to know about a black hole?

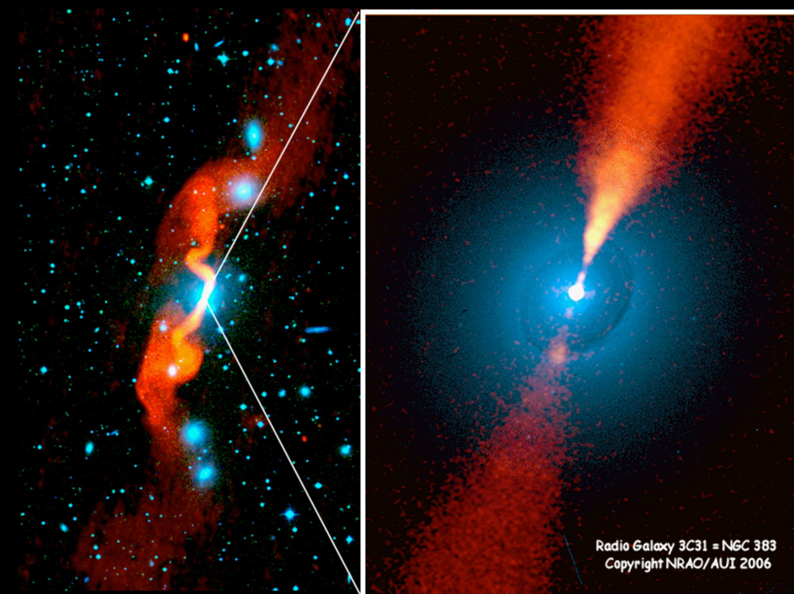


"Black holes have no hair"

1. mass
2. spin
3. ~~electric charge~~

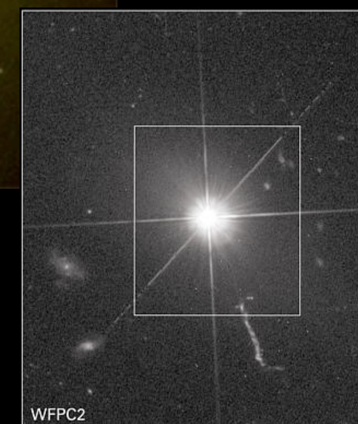
evaporation timescale is 10^67 years for 1 solar mass

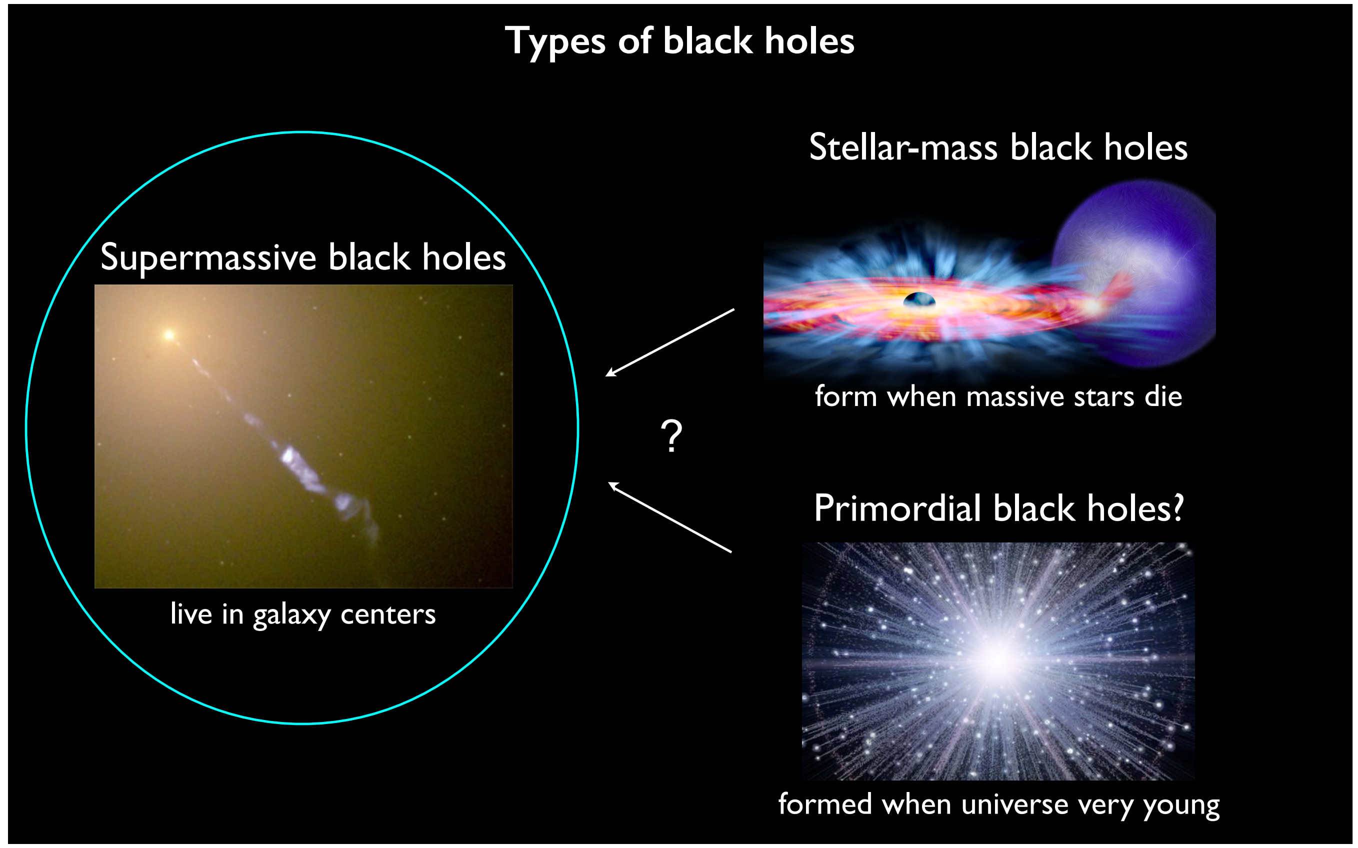
Evidence of monster black holes



blue-green = visible
red-orange = radio

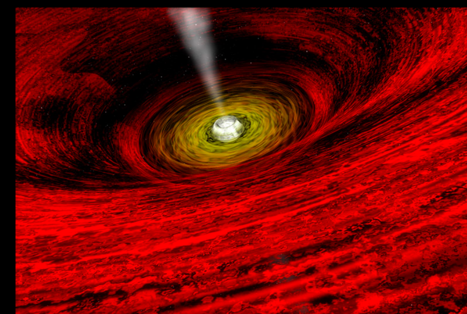
More evidence of monster black holes



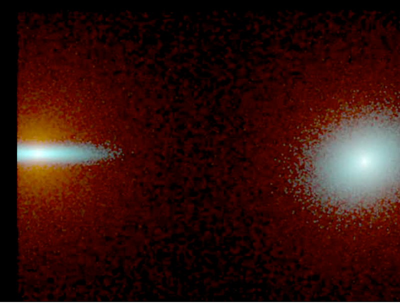


Types of black holes
Supermassive black holes
live in galaxy centers
Stellar-mass black holes
form when massive stars die
?
Primordial black holes?
formed when universe very young

Growing supermassive black holes



Active black holes are currently feeding (growing)



When galaxies merge, their black holes will eventually merge too

Some Big Questions

Which came first ---
the galaxy or the black hole?

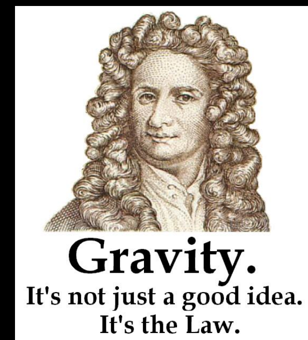
How did the black holes form?

How do the black holes grow?

How do the black holes affect the galaxies
in which they live (and vice versa)?

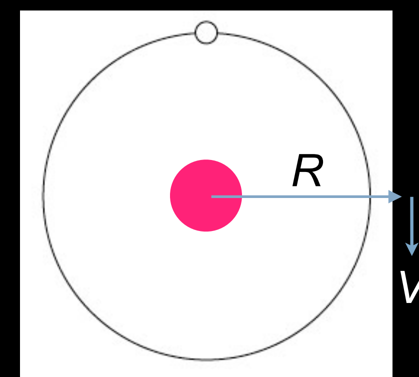
Black hole mass measurements are one key to
answering these questions and others

Measuring Masses

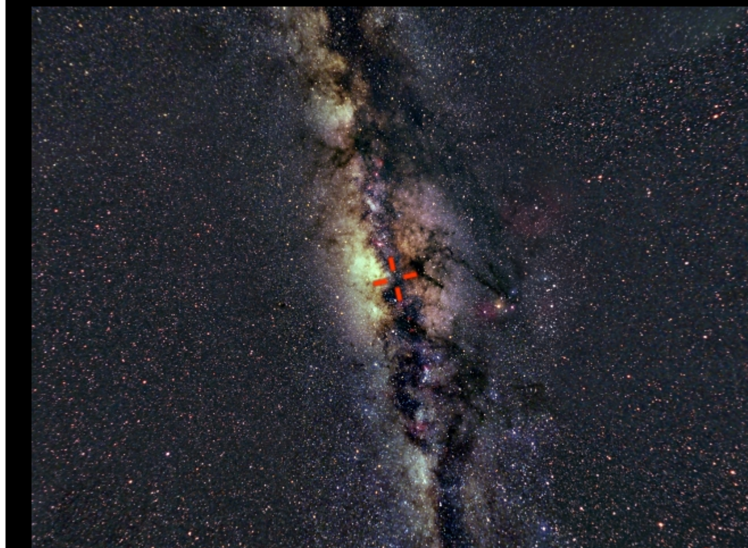


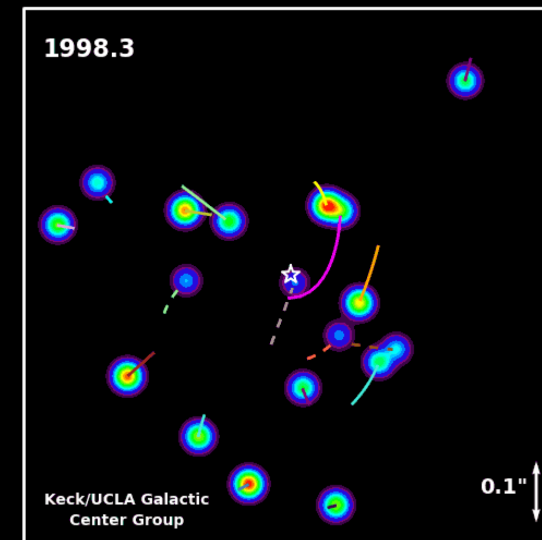
We can measure the mass of an object if something is orbiting around it, and we know

1. the orbital distance (*R*), and
2. the orbital speed (*V*)



Center of the Milky Way





4,000,000x the Sun's mass
packed in a space smaller than the Solar System!

closest approach for SO-2 is 125 AU (about the distance of Voyager spacecrafts from the Sun)
animation is 0.8" x 0.8" = 0.1 ly x 0.1 ly

HUDF – about 3' across
smaller than the tip of mechanical pencil lead held in front by outstretched arm
~ 1 million seconds = 11.5 days

Astronomer's Toolbox

=

All our work relies on understanding the
properties of light

Doppler Effect

wavelength is affected by motion

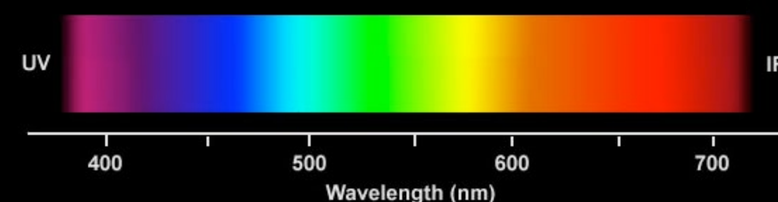
Example: the sound of a moving car

Waves traveling in <u>same</u> direction are bunched up
→ wavelength is shorter

Waves traveling in <u>opposite</u> direction are spread out
→ wavelength is longer

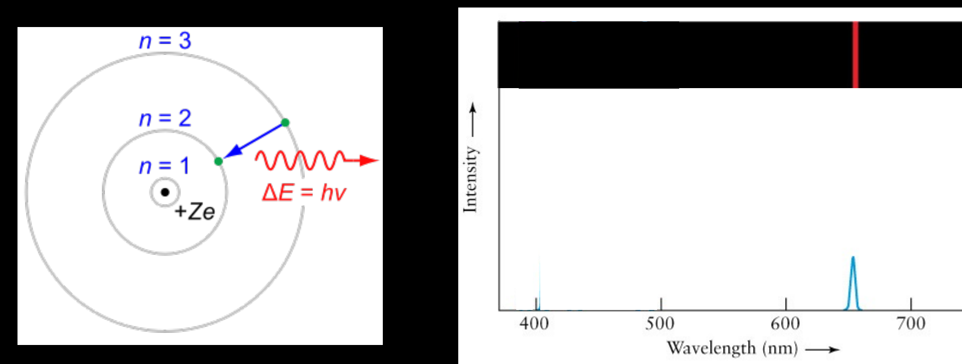
blue shift

red shift

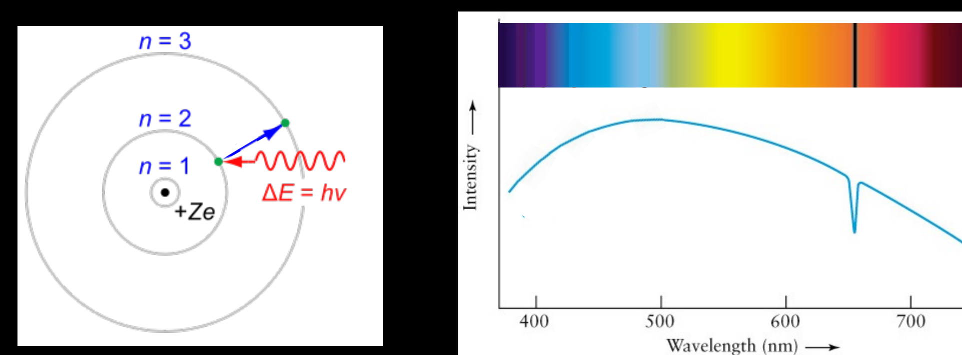


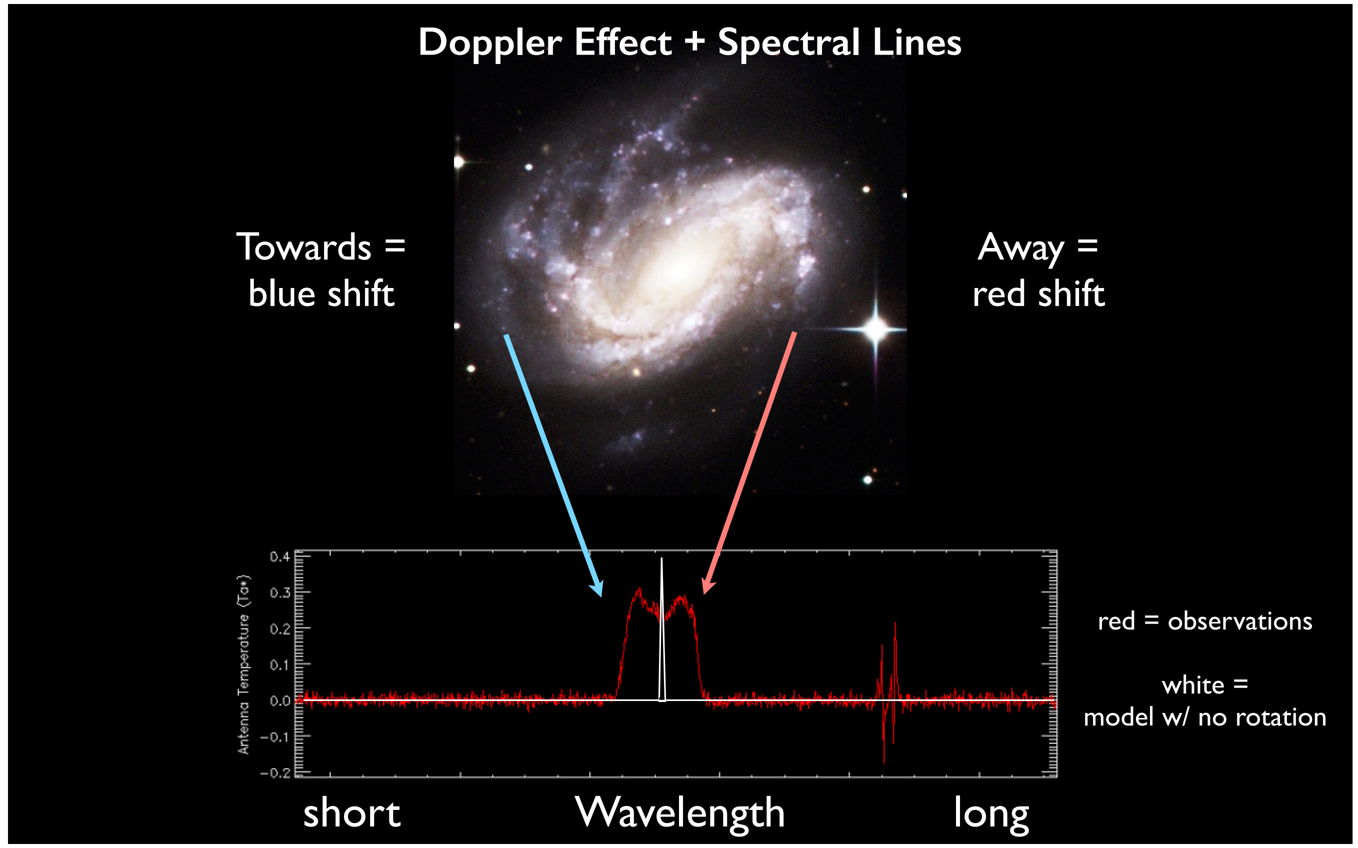
Spectral Lines

Emission



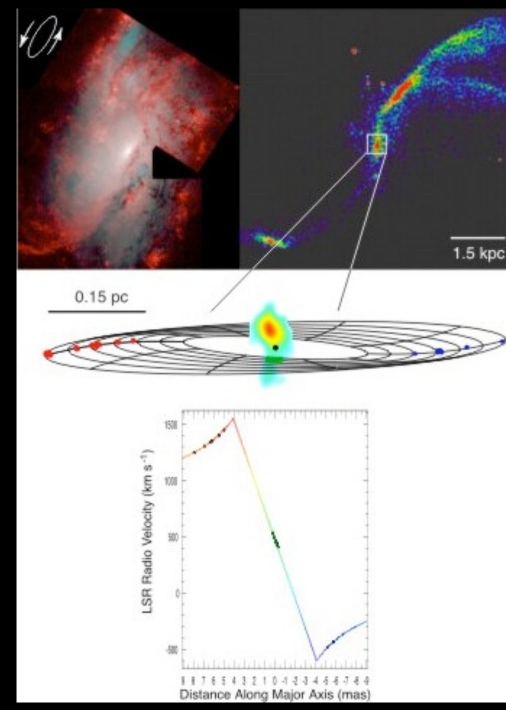
Absorption

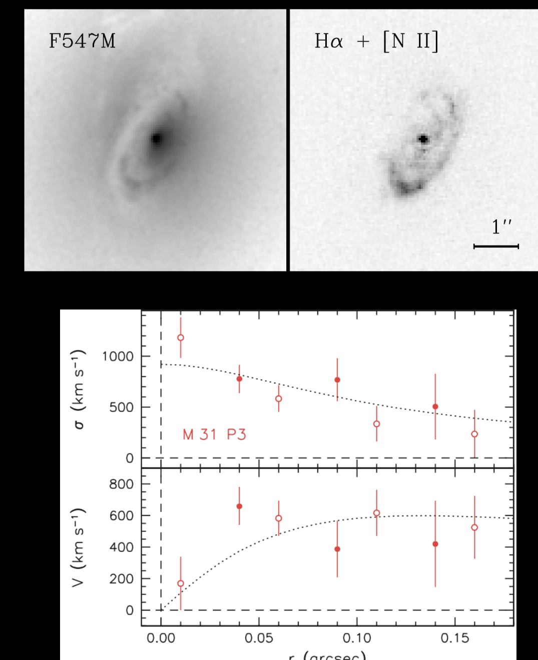




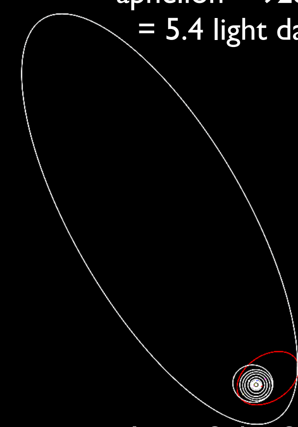
Doppler Effect + Spectral Lines
Towards = blue shift
Away = red shift
Antenna Temperature (Ta*)
0.4
0.3
0.2
0.1
0.0
−0.1
−0.2
red = observations
white = model w/ no rotation
short
Wavelength
long

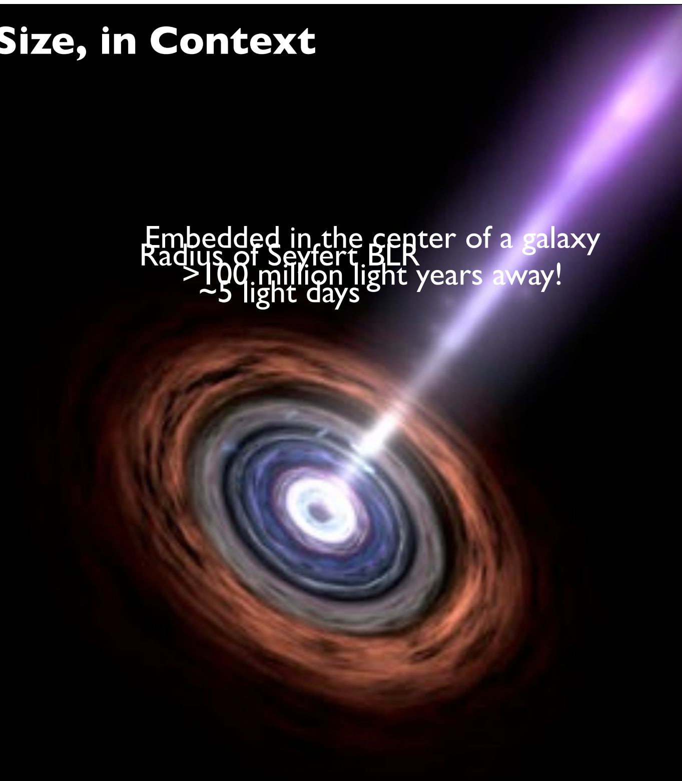
Gravity + Doppler Effect + Spectral Lines = Black Hole Mass

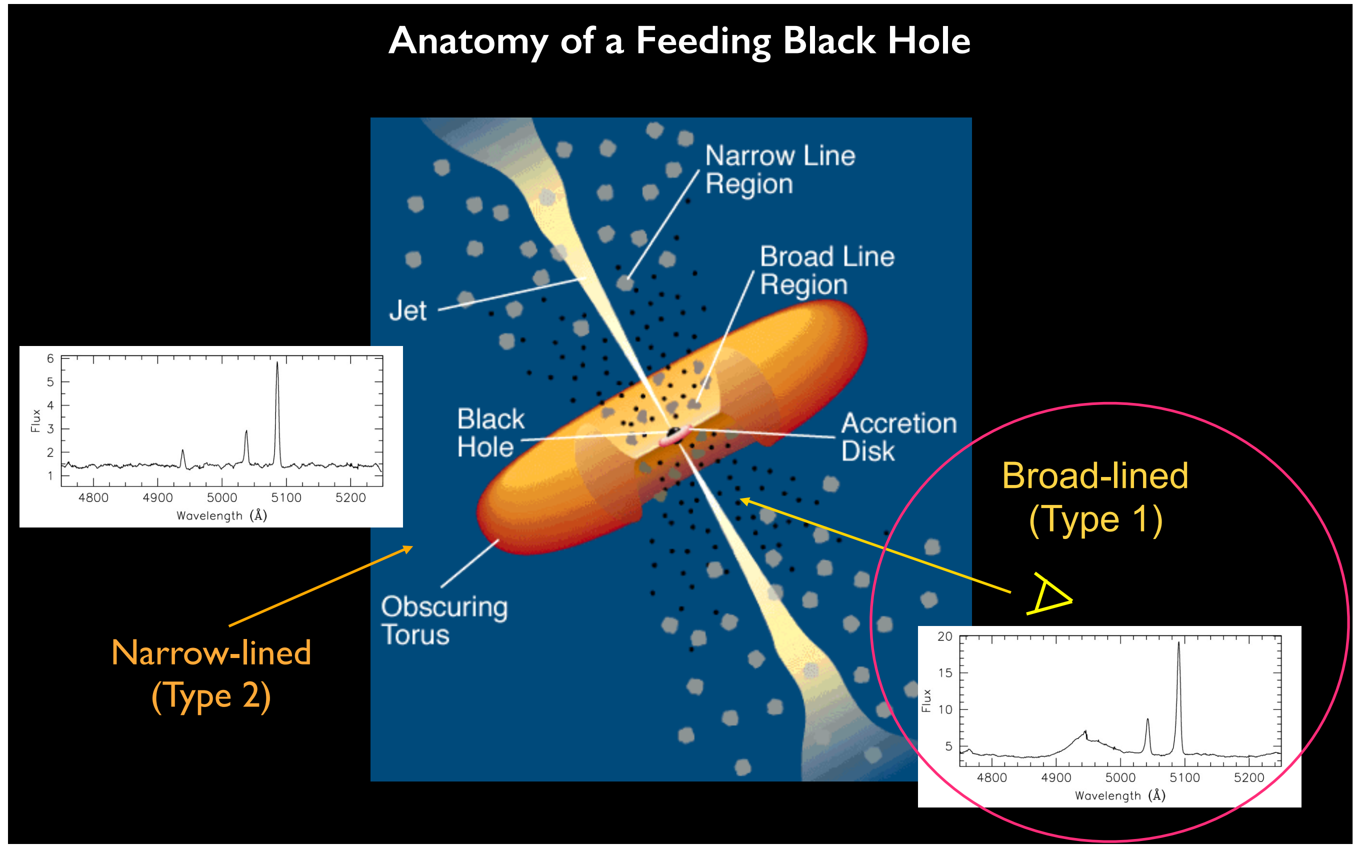




Physical Size, in Context



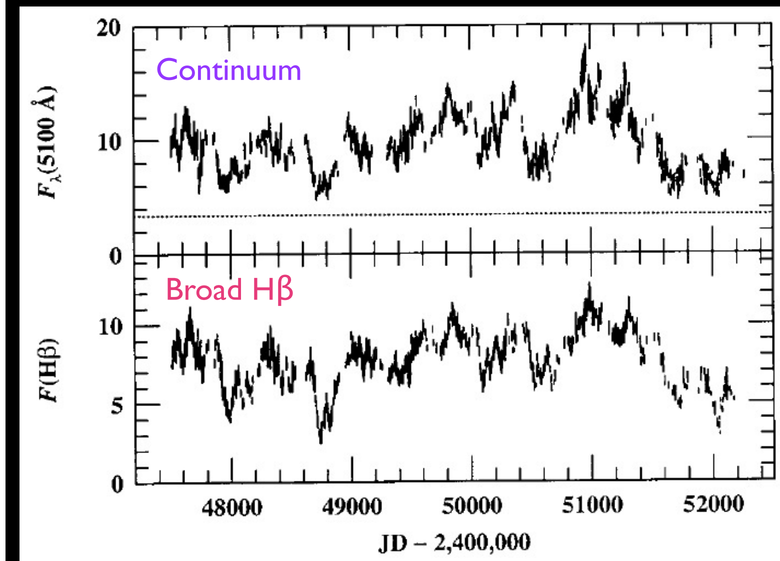




Anatomy of a Feeding Black Hole
Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus
Narrow-lined (Type 2)
Broad-lined (Type 1)
Flux
Wavelength (Å)
4800
4900
5000
5100
5200

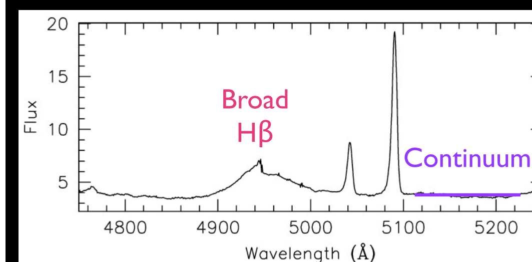
Brightness Variations

13 years of variability for NGC 5548



Peterson et al. 2002, ApJ, 581, 197

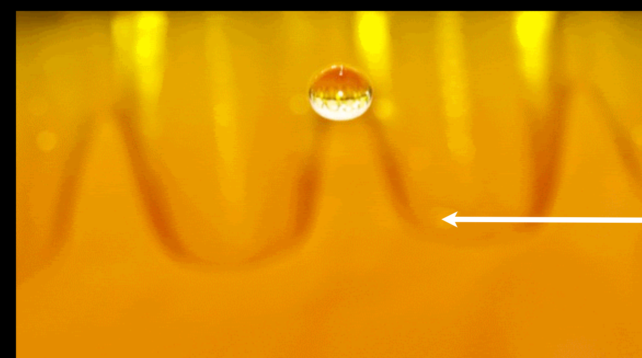
Correlated variability in the continuum and the broad emission lines



Time Delays

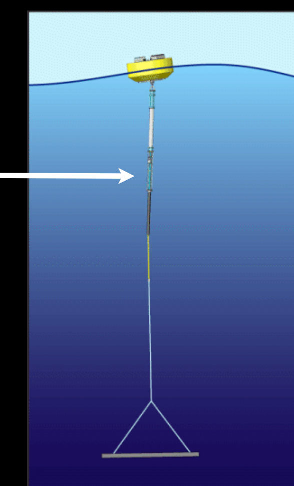
Light waves take time to travel
Speed of light is c, not ∞

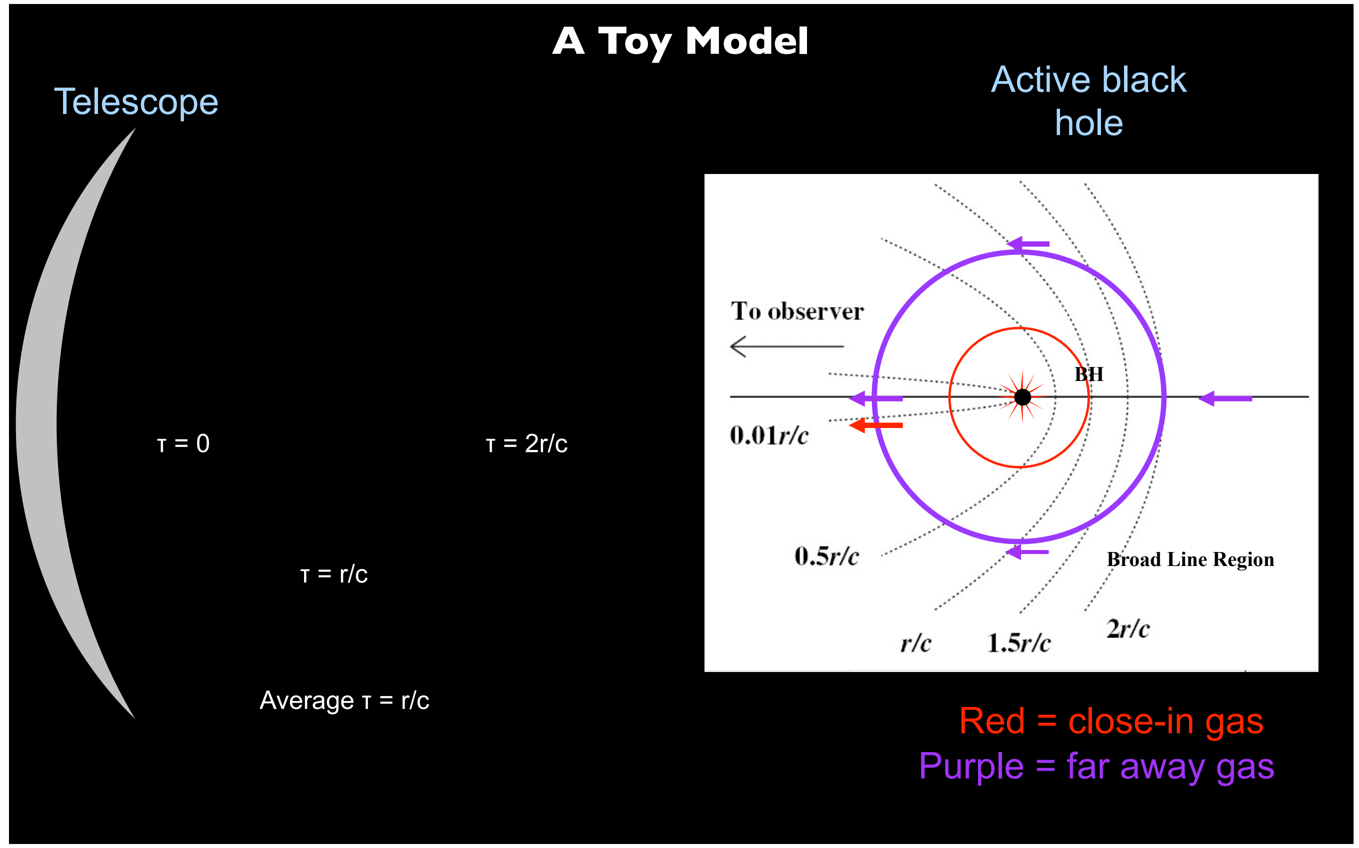
Event at $t = 0$



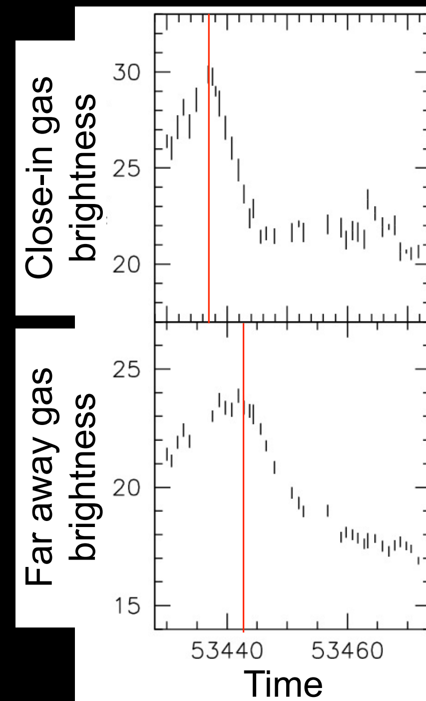
D

Response at $t = v/D$



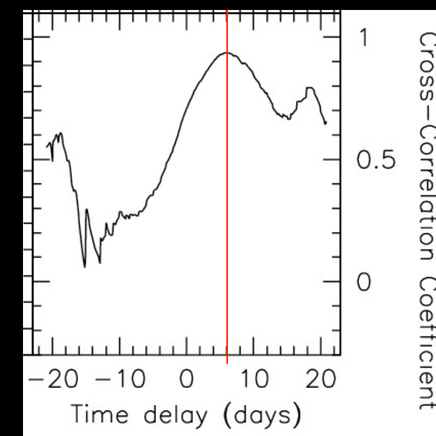

A Toy Model
Telescope
Active black hole
τ = 0
τ = 2r/c
τ = r/c
Average τ = r/c
To observer
BH
0.01r/c
0.5r/c
Broad Line Region
r/c
1.5r/c
2r/c
Red = close-in gas
Purple = far away gas

Real Data



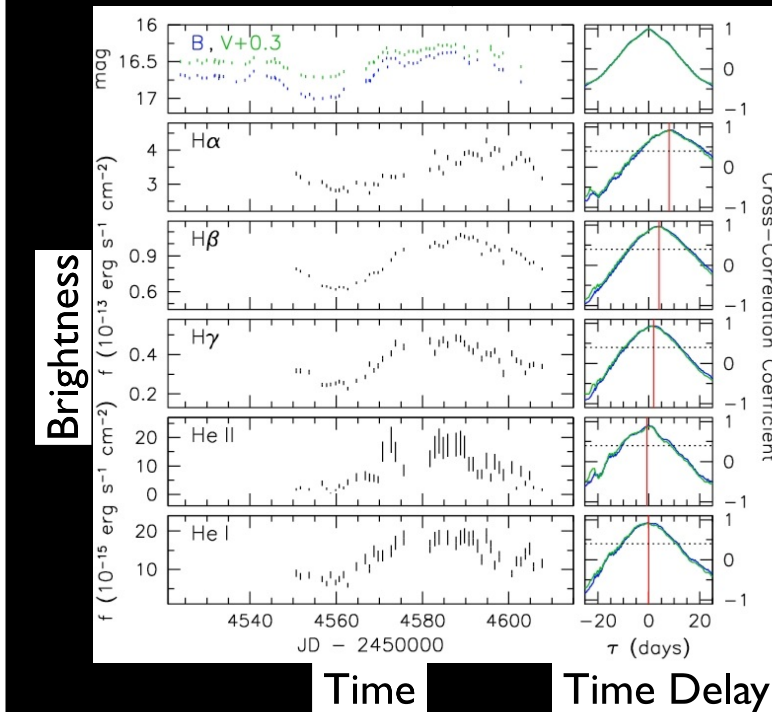
The shift between the two light curves tells us the time delay: 6 days in this case

(distance is 6 light-days)



Bentz et al. 2006, ApJ, 651, 775

Layers of the Onion



Cooler gas is *farther* from the black hole

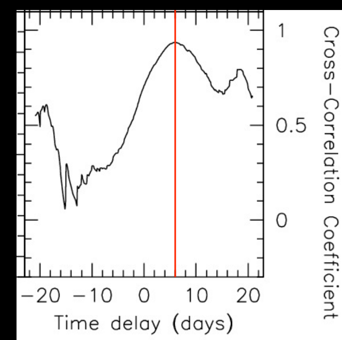
Hotter gas is *closer* to the black hole

Gas at different distances from the black hole will "echo" at different times

(Bentz et al 2010, ApJ, 716, 993)

Black Hole Masses

$$M_{BH} = f\,\frac{RV^2}{G}$$

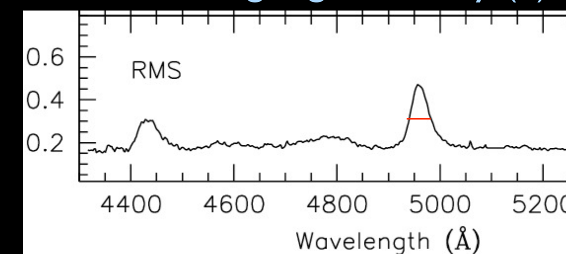


Time delay ($c\tau$) → average radius *R*

measured for ~50 black holes

width of broad emission line

→ line-of-sight gas velocity (*V*)



f includes all the messy physical details
(e.g., inclination, geometry, kinematics)

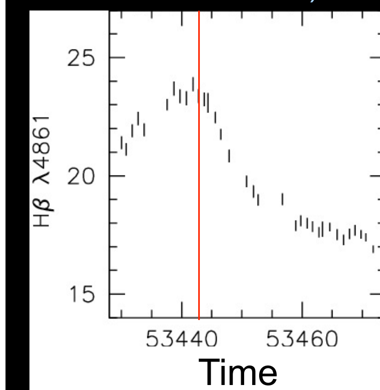
Unraveling the Messy Details

$$\Delta L(v,t) = \int_0^\infty \Psi(v,\tau)\,\Delta C(t-\tau)\,d\tau$$

Observed Echo
(emission line variations)

Response

Event
(continuum variations)

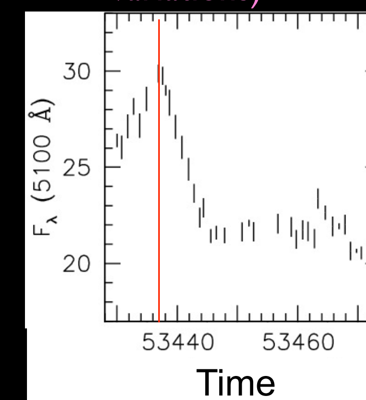


?

Deconvolution is needed!

Obstacles to overcome:

- Finite data length
- Irregular sampling
- Noisy data



Maximum Entropy Method (MEM) Solution

Find the <u>simplest possible solution</u> that <u>fits the data</u>

Entropy = S

$$S(\vec{p},\vec{q}) \equiv \sum_{j=1}^{M} p_j - q_j - p_j \ln\left(p_j/q_j\right)$$

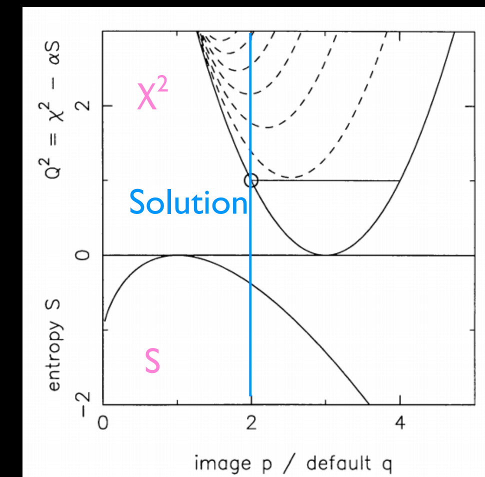
Measure of simplicity

Maximize the Entropy

$$0 = \frac{\partial S}{\partial p_i} = -\ln\left(p_i/q_i\right)$$

Minimize the information

Balanced by χ^2 to ensure realism



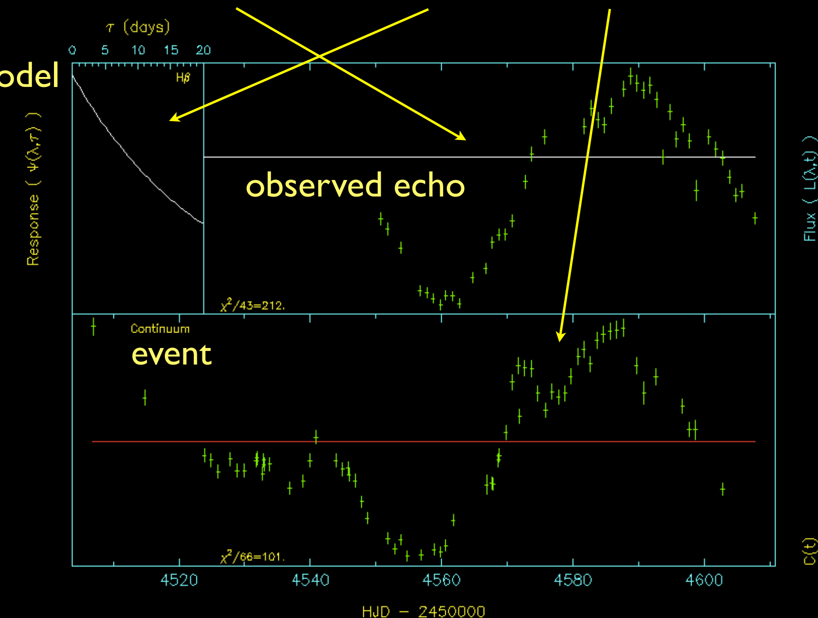
(Horne 1994, ASPC, 69, 23)

MEMEcho Example

Light curves and starting models

$$\Delta L(v,t) = \int_0^\infty \Psi(v,\tau)\Delta C(t-\tau)d\tau$$

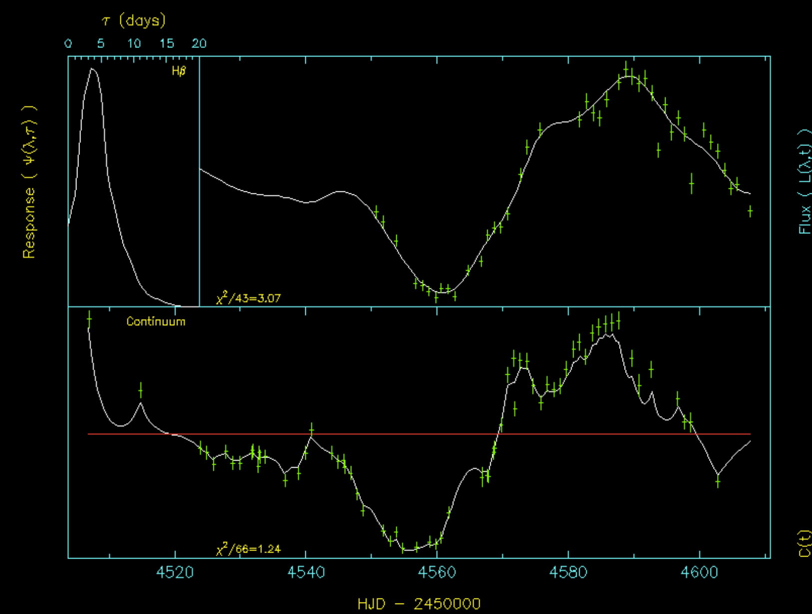
starting model



MEMEcho Example

After 100 iterations (not converged)

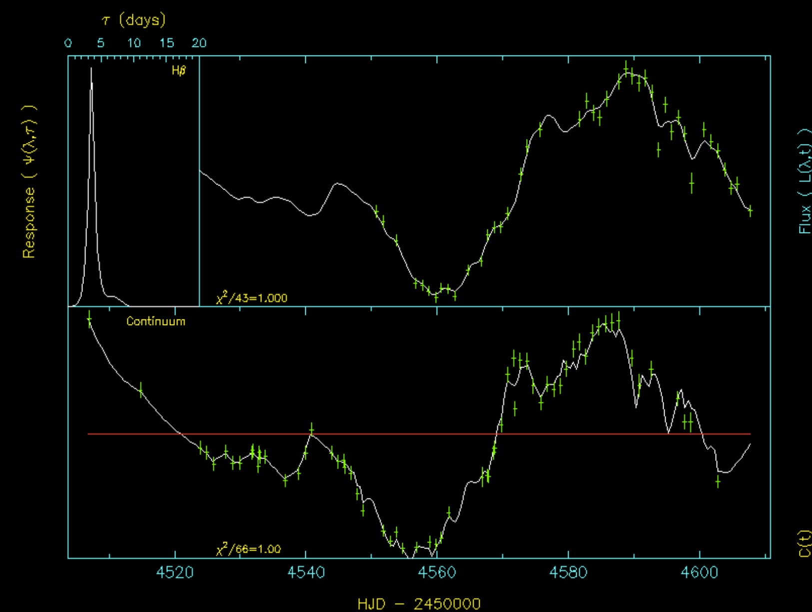
$$\Delta L(v,t) = \int_0^\infty \Psi(v,\tau)\,\Delta C(t-\tau)\,d\tau$$



MEMEcho Example

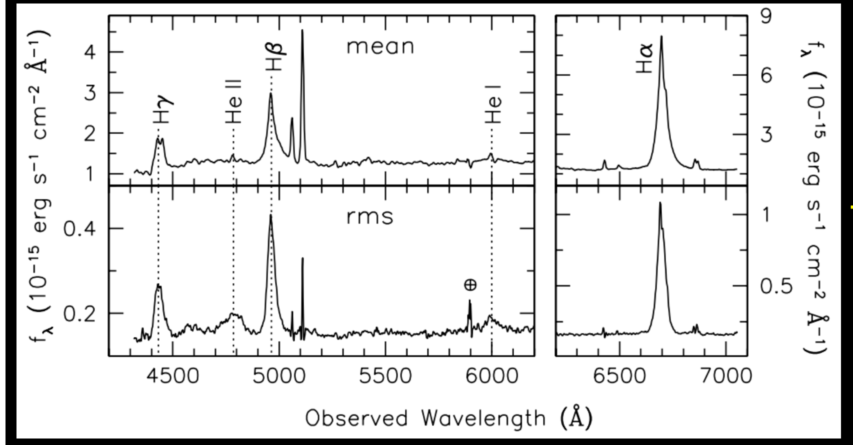
After ~1000 iterations (converged)

$$\Delta L(v,t) = \int_0^\infty \Psi(v,\tau)\,\Delta C(t-\tau)\,d\tau$$

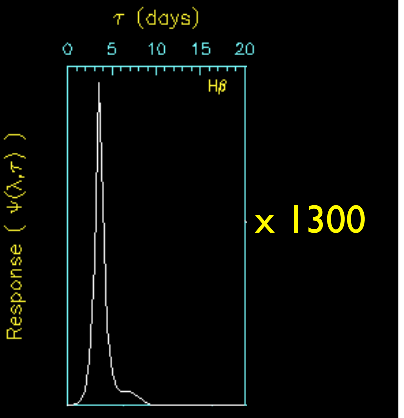


But wait, there's more!

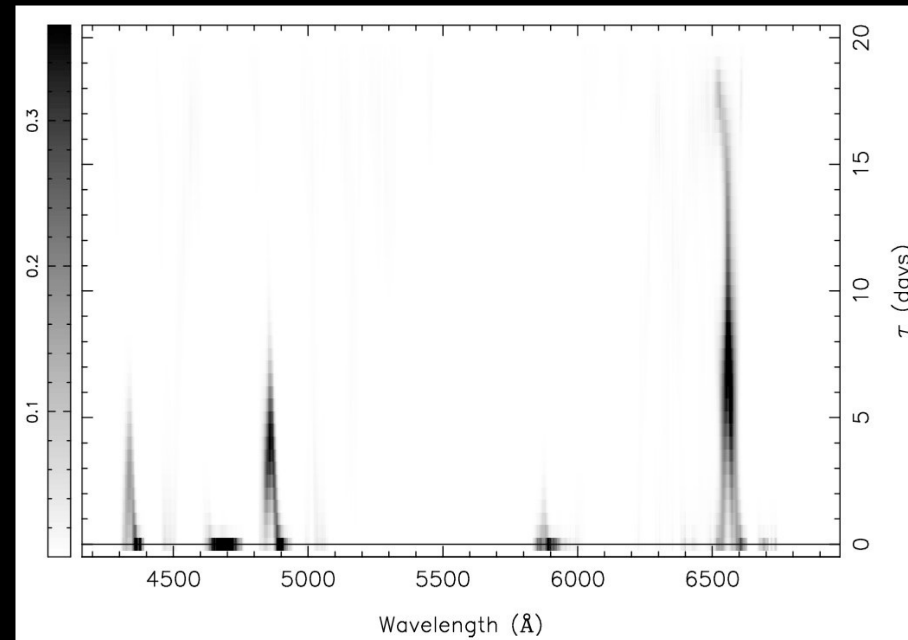
Every pixel across our spectrum has a corresponding response function!

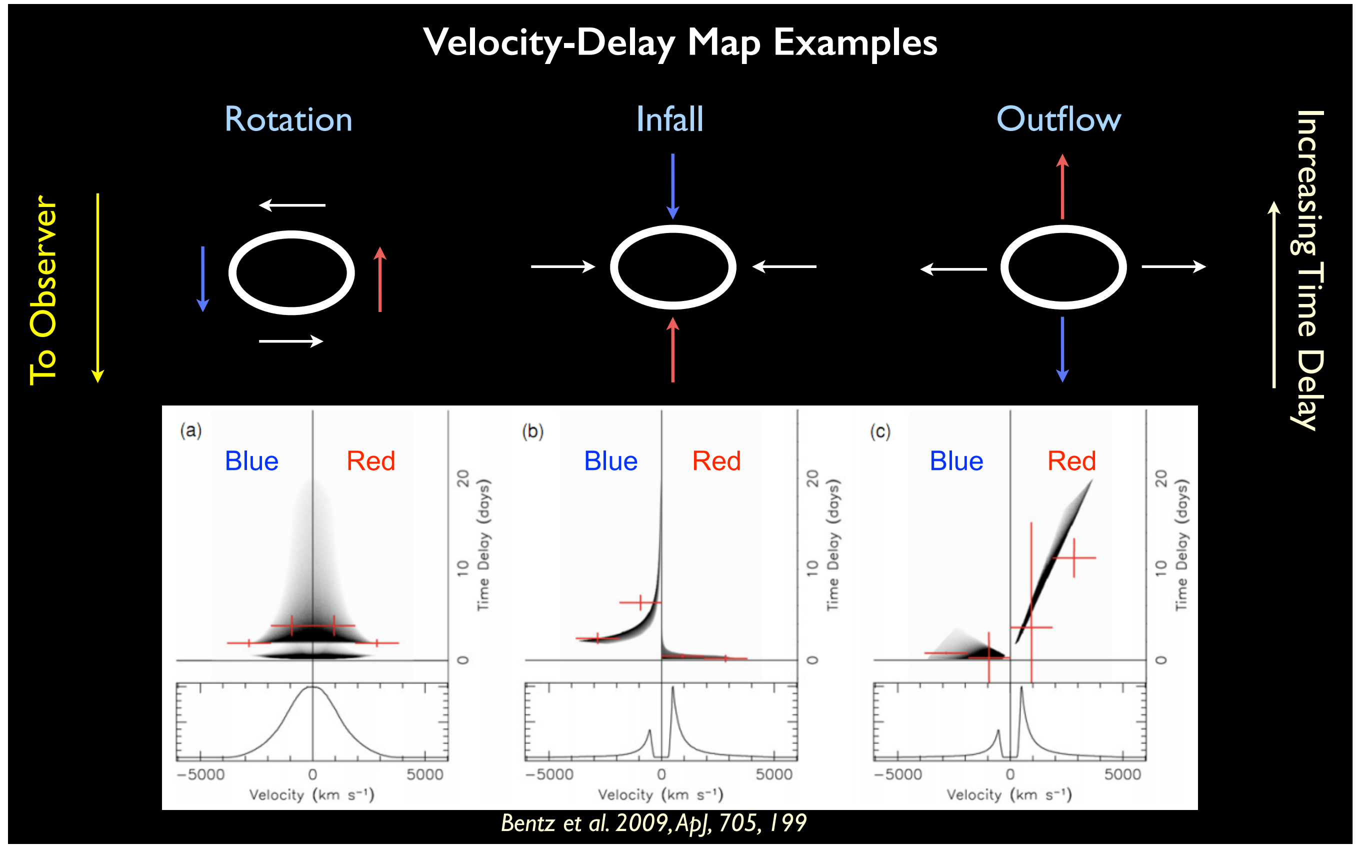


Bentz et al. 2009, ApJ, 705, 199

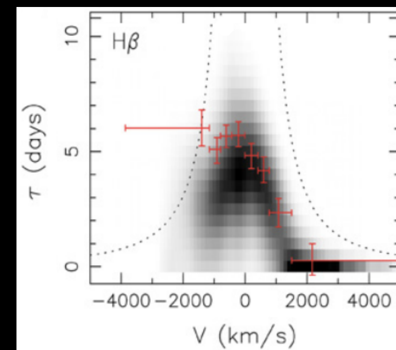


Velocity-Delay Map




Velocity-Delay Map Examples
Rotation
Infall
Outflow
To Observer
Increasing Time Delay
(a)
(b)
(c)
Blue
Red
Time Delay (days)
Velocity (km s⁻¹)
Bentz et al. 2009, ApJ, 705, 199

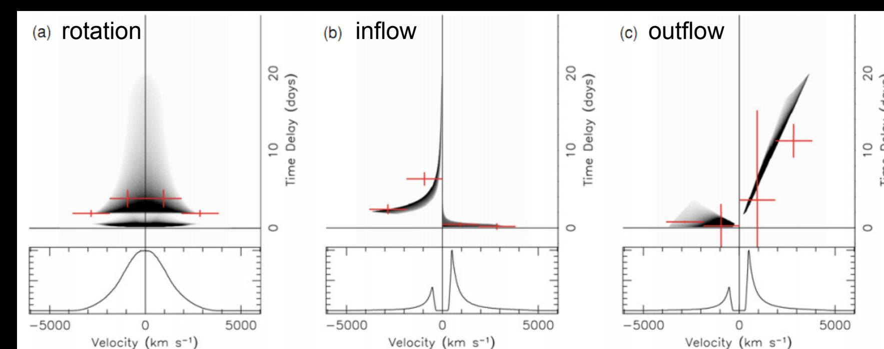
Velocity-Delay Map vs. Models



Bentz et al. 2010

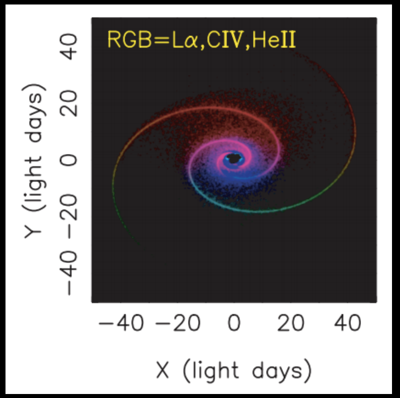
recovered velocity-delay map
rules out outflow

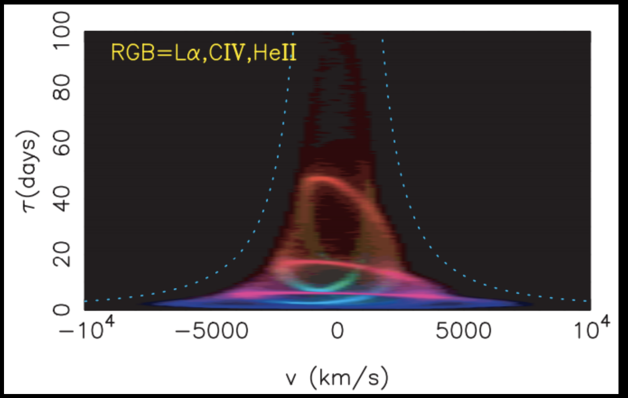
possible evidence for inflow



Hubble Space Telescope Mapping

Simulations





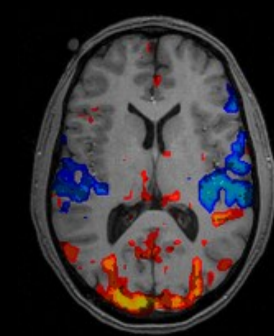
Horne et al. 2004, PASP, 116, 465

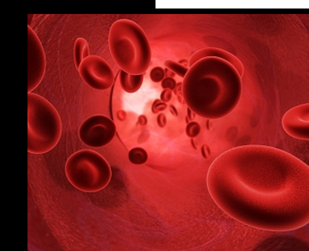
200 day monitoring campaign from space
Starts February 2014

Work for the Future

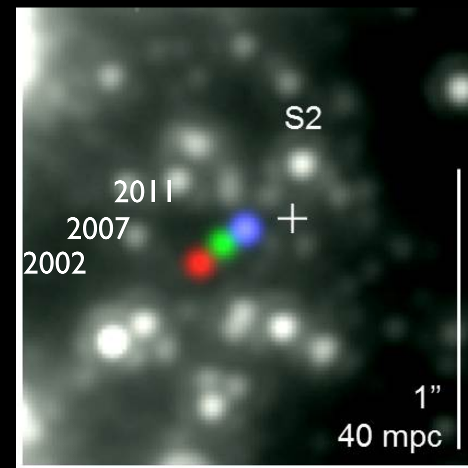
Lots of recent advances in signal processing and deconvolution techniques

Which ones can help push us forward?





2014 will be an interesting year for the Milky Way's black hole

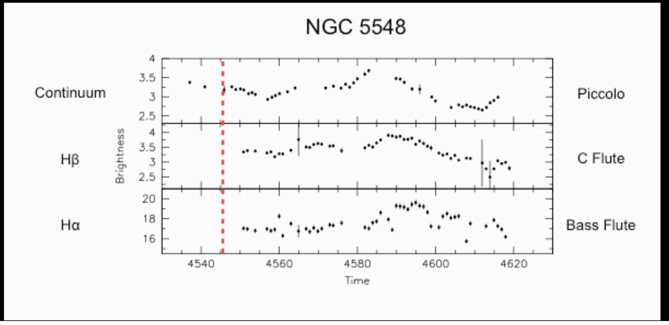


simulation of what we may see

Fantasy on Active Galaxies

A four movement piece for flute choir based on light curves of active black holes from my scientific research

Premiered by the Orange County Flute Ensemble at Visitor Night at the UCI Observatory on April 24, 2010



(Thank you!)

Galaxy alphabet from Galaxy Zoo and www.mygalaxies.co.uk

[redacted]