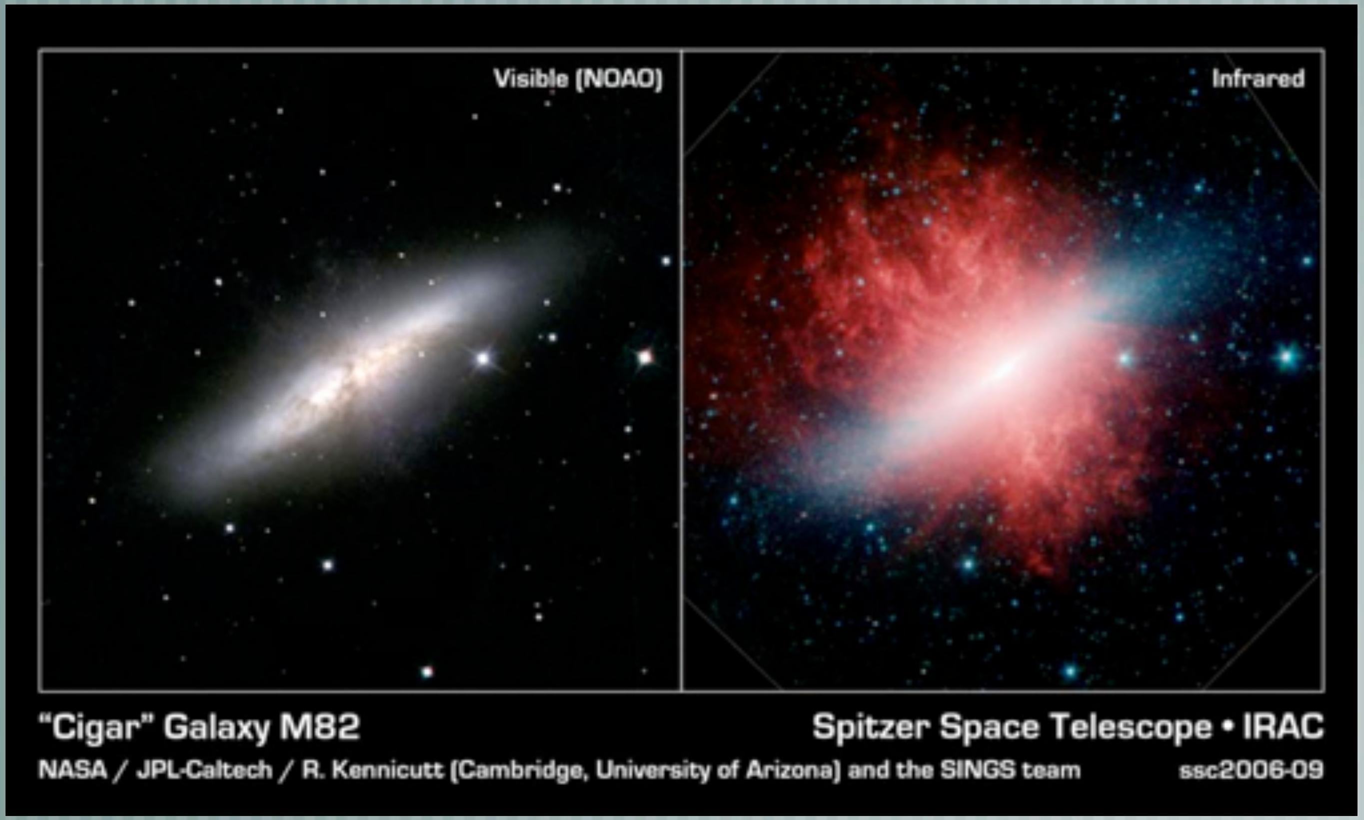
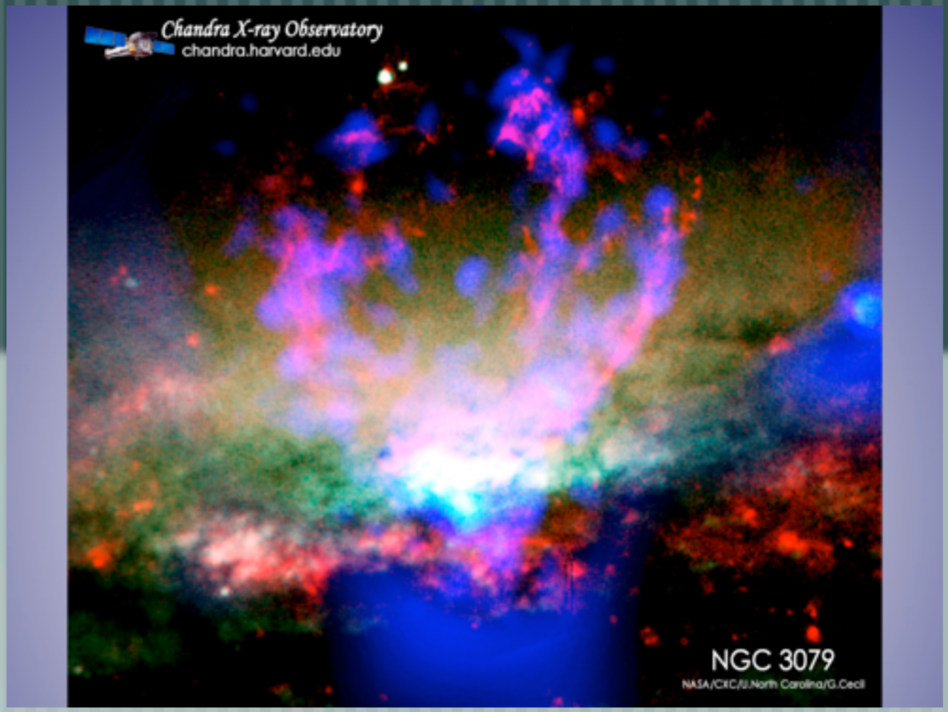
Gone with the wind

Black holes and their gusty influence on the birth of galaxies

Nadia Zakamska
Johns Hopkins University

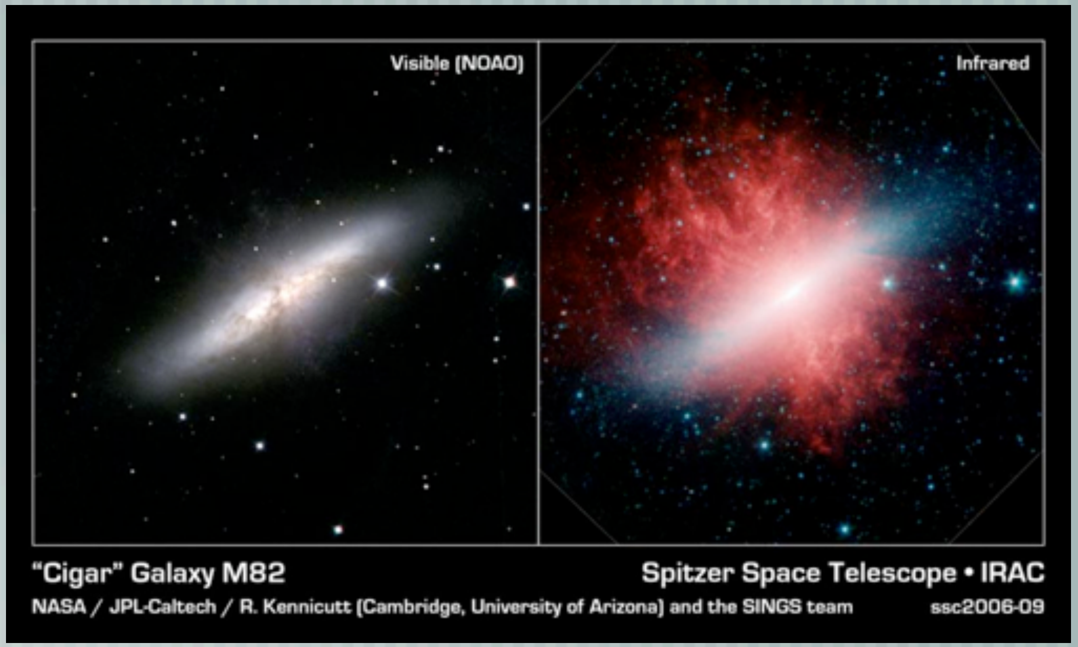


Overview



1. Galaxies from Big Bang to today

How do galaxies form?
Normal matter vs dark matter
What do we not know?



2. Supermassive black holes

How do we know they exist?
How can they do anything if they are black holes?

3. Interplay between galaxies and their black holes

How might the galaxy feed its black hole?
How might the black hole starve the galaxy?

1. Galaxies from Big Bang to today:
How do galaxies form?

Galaxies today (13.8 billion years after Big Bang)

Composed of billions to trillions of stars

Some have gas (from which new stars form)

Gas + stars = normal matter (hydrogen, helium)

Held together by gravity dominated by dark matter

M87; Sloan Digital Sky Survey

M51; Sloan Digital Sky Survey

1. Galaxies from Big Bang to today:

How do galaxies form?

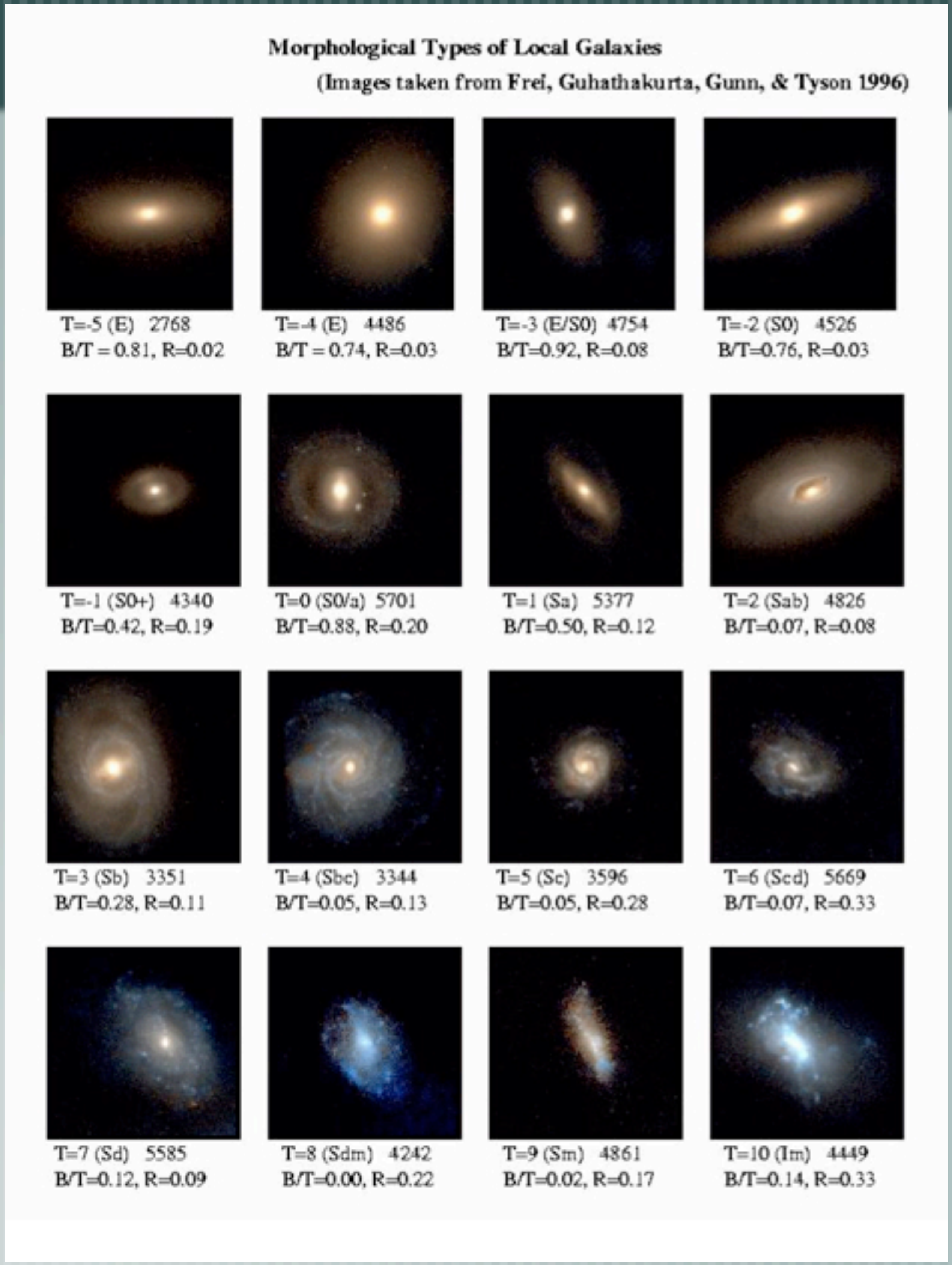
Galaxies today (13.8 billion years after Big Bang)

Composed of billions to trillions of stars

Some have gas (from which new stars form)

Gas + stars = normal matter (hydrogen, helium)

Held together by gravity dominated by dark matter



1. Galaxies from Big Bang to today: How do galaxies form?

- Galaxies are luminous specks in otherwise dark Universe

  High density of matter at these locations

- But the Universe started very smooth

  400,000 years after the Big Bang – temperature the same to 7 parts per million

- Small fluctuations grew due to gravitational attraction

The fly-by through the Hubble Ultra Deep Field:

http://hubblesite.org/newscenter/archive/releases/2004/28/video/b/

STScI; Hubble Ultra Deep Field team

1. Galaxies from Big Bang to today:
How do galaxies form?

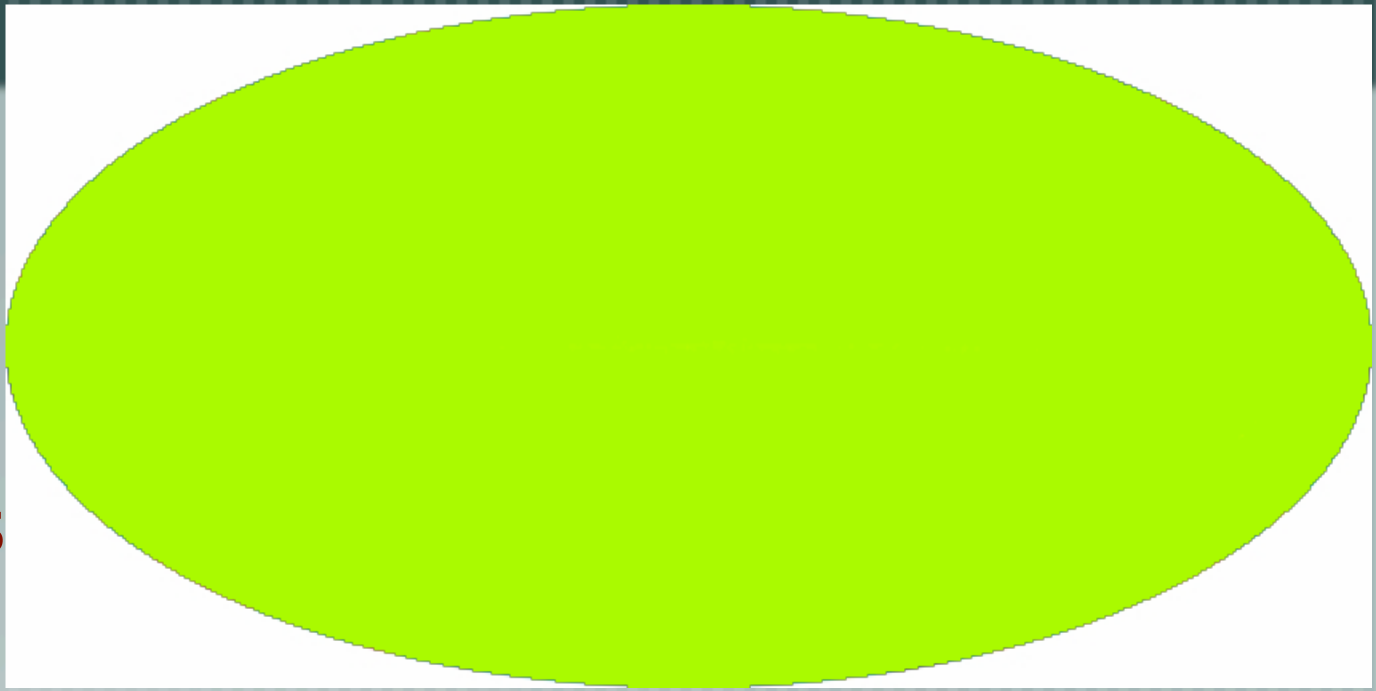
- Galaxies are luminous specks in otherwise dark Universe

High density of matter at these locations

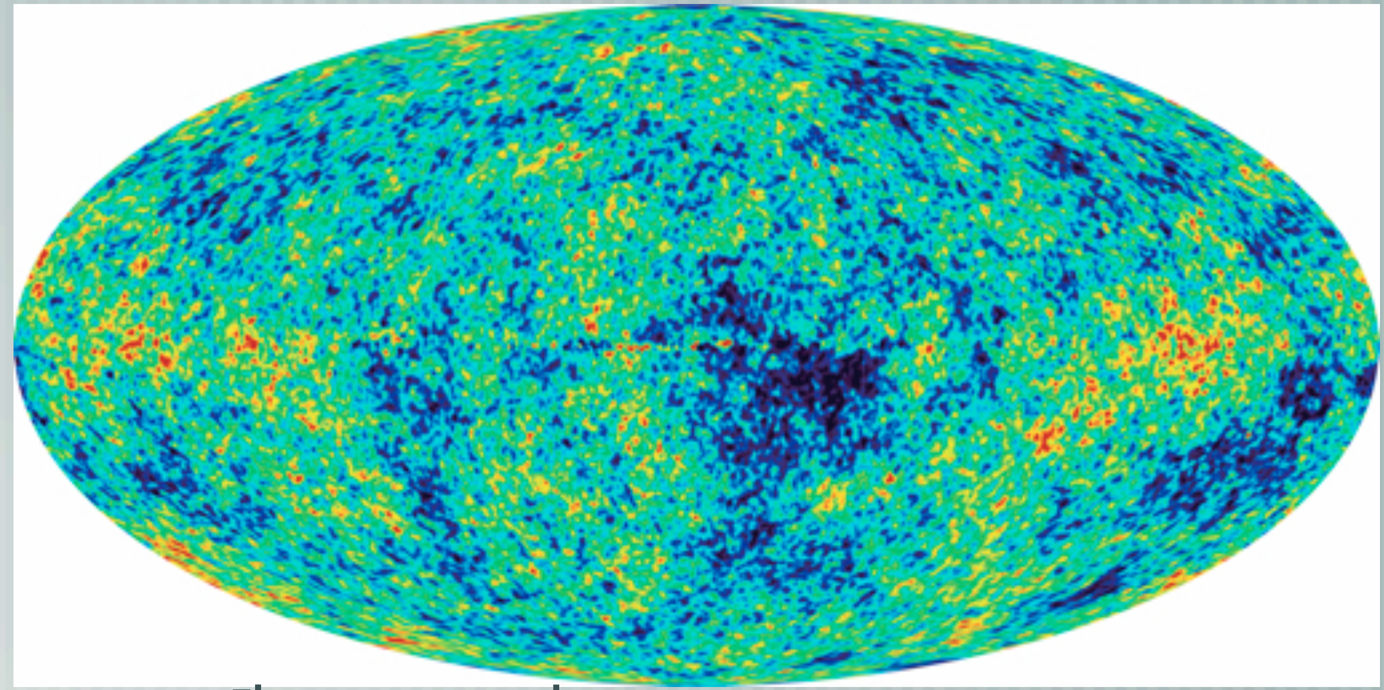
- But the Universe started very smooth

400,000 years after the Big Bang – temperature the same to 7 parts per million

- Small fluctuations grew due to gravitational attraction



Cosmic microwave emission



Fluctuations in the cosmic microwave emission (WMAP team)

1. Galaxies from Big Bang to today:
How do galaxies form?

Basic galaxy formation theory:

Start with small fluctuations

Dark matter dominated

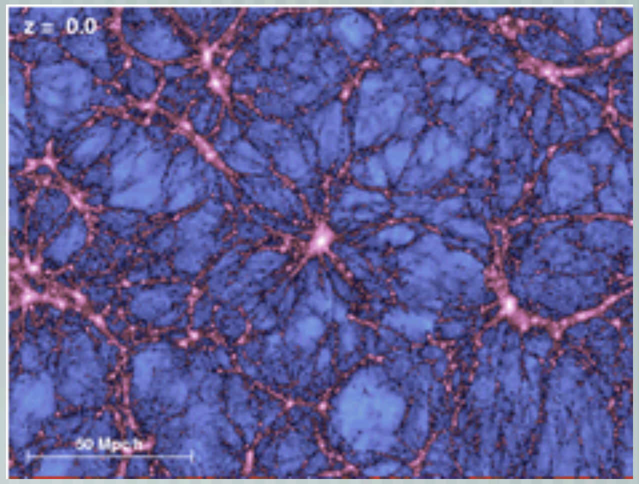
Expansion of the universe wants to smooth them over

Gravity wants to bring matter together... and wins

Small structures assemble into bigger structures

http://www.mpa-garching.mpg.de/galform/data_vis/

The time evolution of dark matter are next to this picture:



Millenium simulation project
V. Springel
The universe is also expanding, but we are watching the development of perturbations over this expansion

1. Galaxies from Big Bang to today:
How do galaxies form?

Basic galaxy formation theory:

Start with small fluctuations

Dark matter dominated

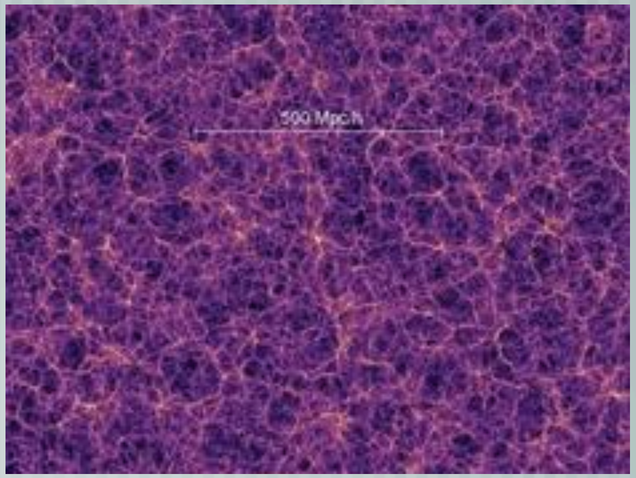
Expansion of the universe wants to smooth them over

Gravity wants to bring matter together… and wins

Small structures assemble into bigger structures

http://www.mpa-garching.mpg.de/galform/data_vis/

The fly-by movie of the modern-day structure on different scales are next to this picture:



Millenium simulation project
V. Springel
Snapshot at present time: zoom in and zoom out

1. Galaxies from Big Bang to today:
How do galaxies form?

- Normal matter flows into knots of the web along dark matter filaments
- Cools, becomes denser, forms stars
- Big galaxies swallow small galaxies
- Sometimes big galaxies merge

The movie illustrating accumulation of normal gas in galaxies along the dark matter filaments:

http://www.youtube.com/watch?v=-ZcEDqyMbFw

And this is the webpage of the group who conducted these simulations, with more movies available:

http://www.cfa.harvard.edu/itc/research/movingmeshcosmology/

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

Big successes: large scales

Overall geometry of the Universe – "precision cosmology"

Propagation of light through space

Galaxies are the luminous knots in the filamentary structure

Distribution of galaxies in space

Clustering of galaxies: big galaxies like big galaxies

http://hipacc.ucsc.edu/Bolshoi/Movies.html

In the presentation I showed part of the movie "Galaxies in Observed and Simulated Universes"

Bolshoi simulation
dark matter vs galaxies

1. Galaxies from Big Bang to today:
What do we know? What don’t we know?

Big successes: large scales

Overall geometry of the Universe – “precision cosmology”

Propagation of light through space

Galaxies are the luminous knots in the filamentary structure

Distribution of galaxies in space

Clustering of galaxies: big galaxies like big galaxies

In the presentation I showed the fly-by movie of Sloan Galaxies:

http://astro.uchicago.edu/cosmus/projects/sloangalaxies/movies/sdssrotate.mpeg

Many other beautiful movies available here:

http://astro.uchicago.edu/cosmus/downloads.html

COSMUS project (UChicago)
visualization of galaxies from Sloan Digital Sky Survey

1. Galaxies from Big Bang to today: What do we know? What don't we know?

Big successes: large scales

Overall geometry of the Universe – "precision cosmology"

Propagation of light through space

Galaxies are the luminous knots in the filamentary structure

Distribution of galaxies in space

Clustering of galaxies: big galaxies like big galaxies

Galaxy cluster Abell 2218
Image credit: A. Fruchter (STScI), HST, NASA

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

Things that aren't so great:

What is this dark matter business made of??

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

Things that aren't so great:

What is this dark matter business made of??

Amazing fact #1:
Dark-matter-only cosmology is much easier than dealing with normal matter
("dirty baryonic physics")

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

Things that aren't so great:

What is this dark matter business made of??

Why?
Dark matter: gravitational interactions only.
Normal matter: gravitational interactions plus cooling and heating.

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

Things that aren't so great:

Distribution of matter within galaxies: cores of small galaxies may be under-dense

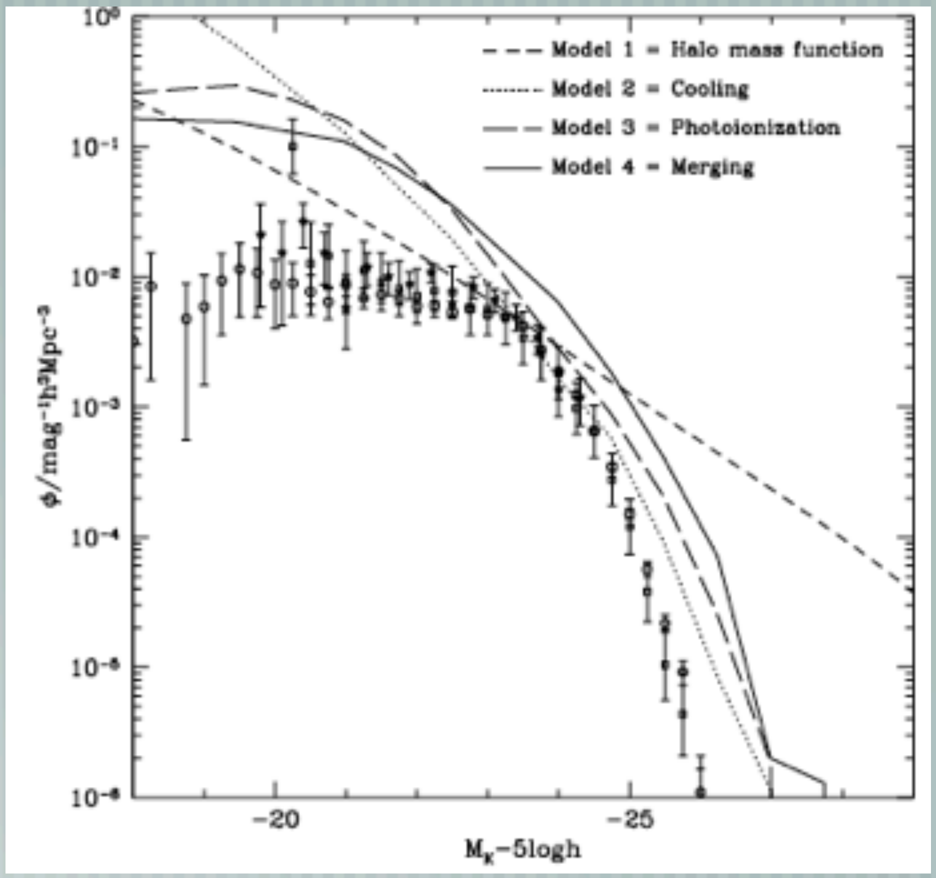
Number of galaxies: theory predicts too big, too many

Colors of galaxies: theory predicts too blue

Need to improve theory on galaxy scales

But then have to include normal matter!

Number of galaxies per decade in mass



←Small, faint galaxies   Large, massive galaxies→

Luminosity function of galaxies
Benson et al. 2003

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

Things that aren't so great:

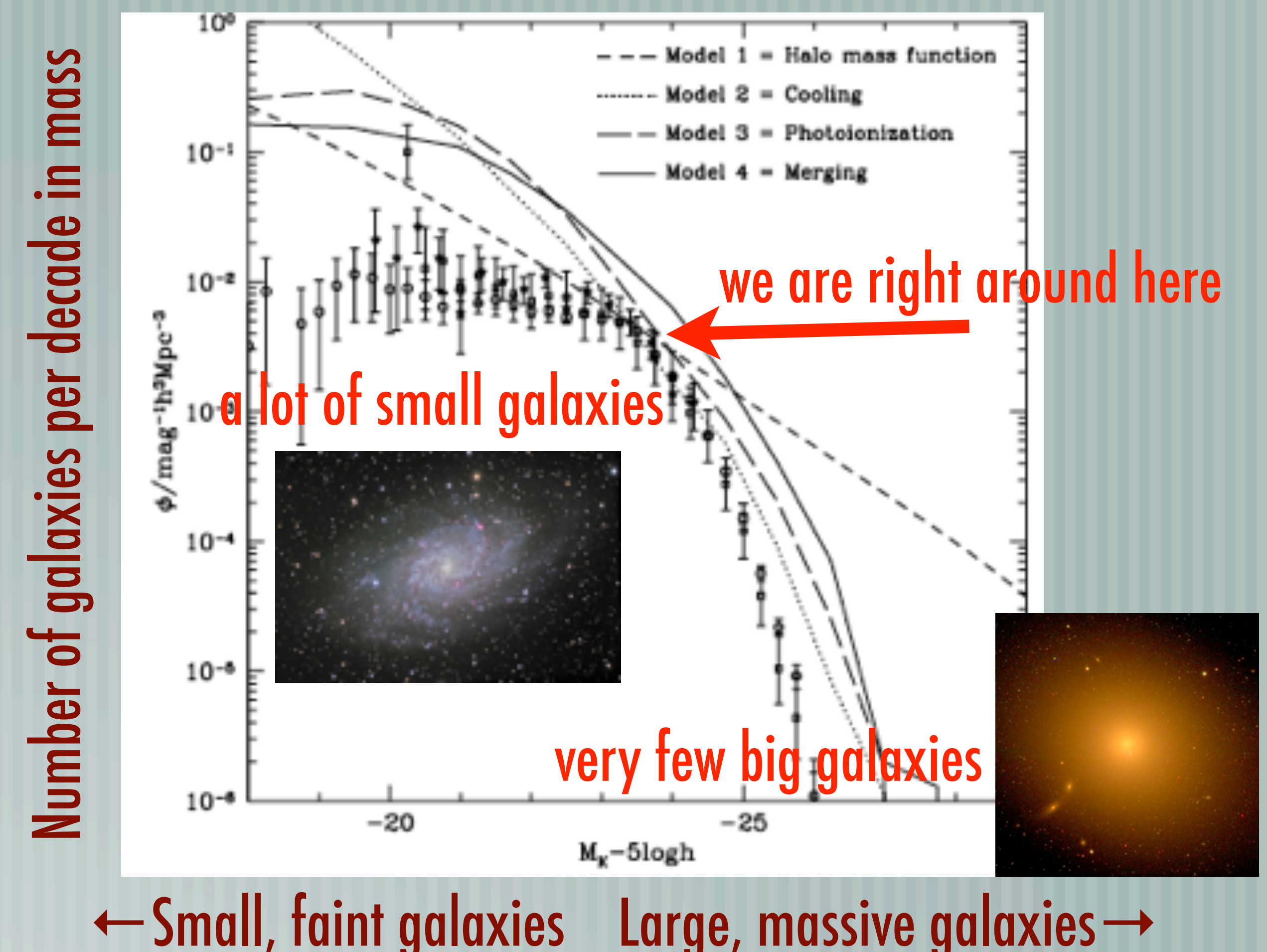
Distribution of matter within galaxies: cores of small galaxies may be under-dense

Number of galaxies: theory predicts too big, too many

Colors of galaxies: theory predicts too blue

Need to improve theory on galaxy scales

But then have to include normal matter!



Luminosity function of galaxies
Benson et al. 2003

1. Galaxies from Big Bang to today: What do we know? What don't we know?

Things that aren't so great:

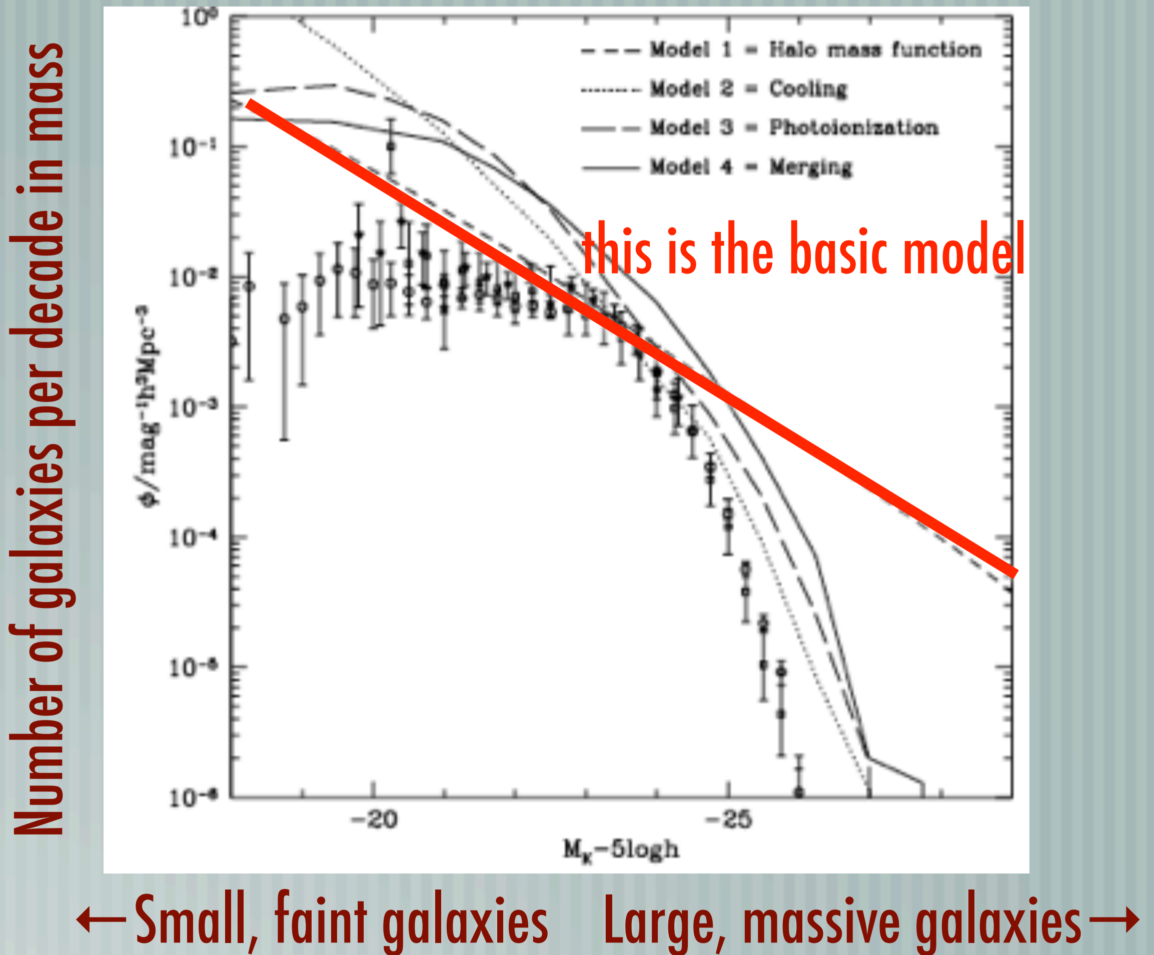
Distribution of matter within galaxies: cores of small galaxies may be under-dense

Number of galaxies: theory predicts too big, too many

Colors of galaxies: theory predicts too blue

Need to improve theory on galaxy scales

But then have to include normal matter!



Luminosity function of galaxies
Benson et al. 2003

1. Galaxies from Big Bang to today:
What do we know? What don't we know?

The trick:

Need to reheat gas / blow it away to prevent stars from forming

Things that explode help!

Supernovae not enough...

Black holes to the rescue

Many beautiful movies from Abel / Kaehler / Wise group:

http://www.slac.stanford.edu/~kaehler/homepage/visualizations/visualizations.html

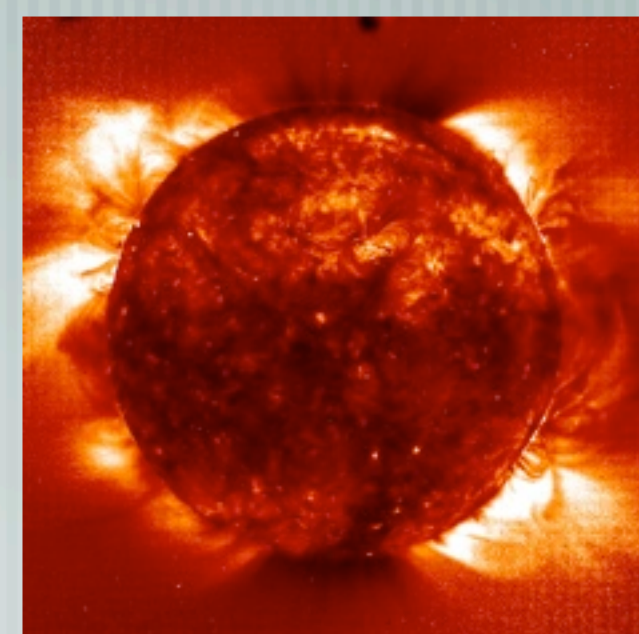
The one I showed in the talk is the last movie on this page:

http://www.slac.stanford.edu/~kaehler/homepage/visualizations//first-stars.html

First supernova in dwarf galaxy
J. Wise, R. Kahler, T. Abel (Stanford)

2. Black holes: Introduction

- Squeeze Earth into a size of a grape
- Squeeze Sun into the size of Manhattan
- Gravity so strong that nothing (even light) can escape
- In astronomy, two types of black holes:
  - Stellar remnants (a few Suns = a few Manhattans)
  - Supermassive black holes (more than a million Suns)



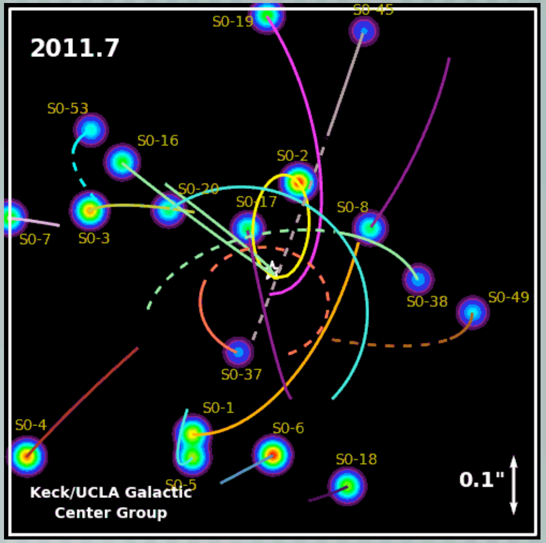
2. Supermassive black holes:
How do we know they exist?

- It appears that every (massive) galaxy has one in the center
- A million to a billion masses of the Sun stuffed into the size of the Solar System
- Exert gravity on surrounding stars

In our Galaxy: individual stars

In other galaxies: sum of all stellar motions

Tend to be bigger in bigger galaxies

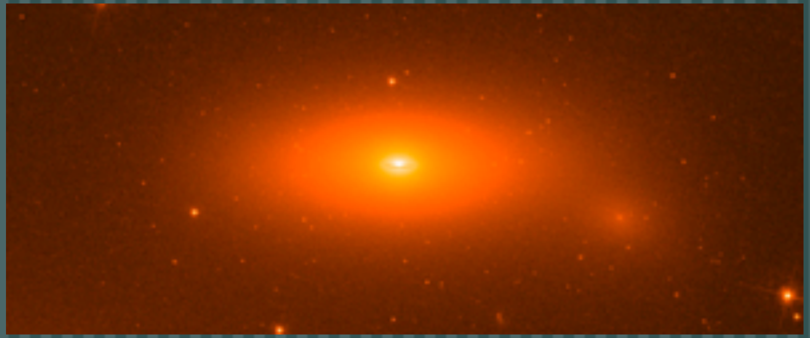


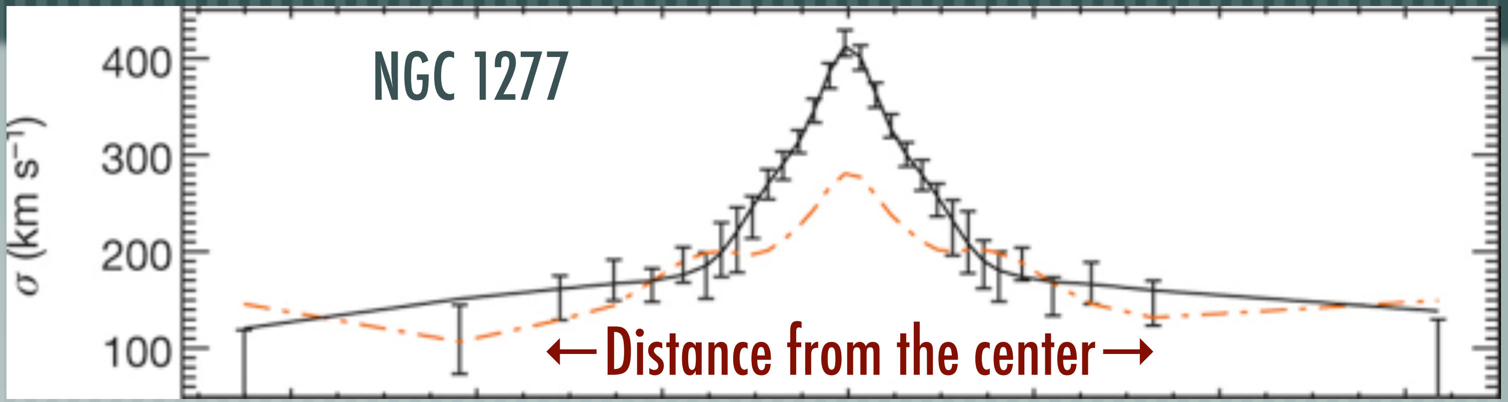
Movie of stellar orbits around the black hole in our Galaxy:

http://www.astro.ucla.edu/~ghezgroup/gc/pictures/orbitsMovie.shtml

Led by R.Genzel (Germany), A.Ghez (UCLA)

2. Supermassive black holes: How do we know they exist?





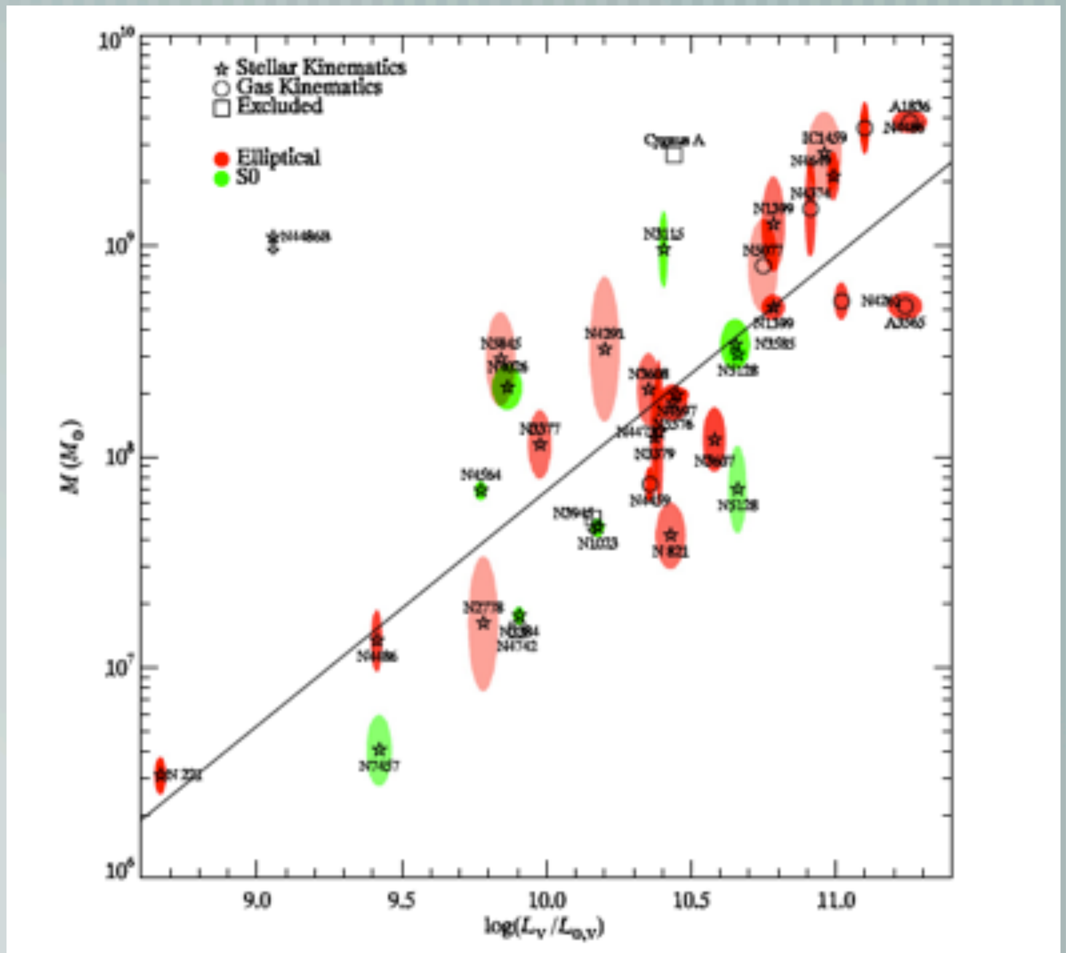
van den Bosch et al. 2012

- It appears that every (massive) galaxy has one in the center
- A million to a billion masses of the Sun stuffed into the size of the Solar System
- Exert gravity on surrounding stars

In our Galaxy: individual stars

In other galaxies: sum of all stellar motions

Tend to be bigger in bigger galaxies



Gultekin et al. 2009
(Nuker team, inc. S. Tremaine, IAS)

2. Supermassive black holes:
How do we know they exist?

- It appears that every (massive) galaxy has one in the center
- A million to a billion masses of the Sun stuffed into the size of the Solar System
- Exert gravity on surrounding stars
  - In our Galaxy: individual stars
  - In other galaxies: sum of all stellar motions
  - Tend to be bigger in bigger galaxies

Amazing fact #2:
Supermassive black holes are much more mundane than the mysterious title would suggest

2. Supermassive black holes:
What can they do?

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can't get out – including light.
- However, matter just outside black hole can be very vocal

Black hole eats surrounding gas

Gas produces radiation (lots of it!)

The movie of a black hole forming out of a cluster of stars is the first one on this page:

http://research.physics.illinois.edu/cta/movies/se/index.html

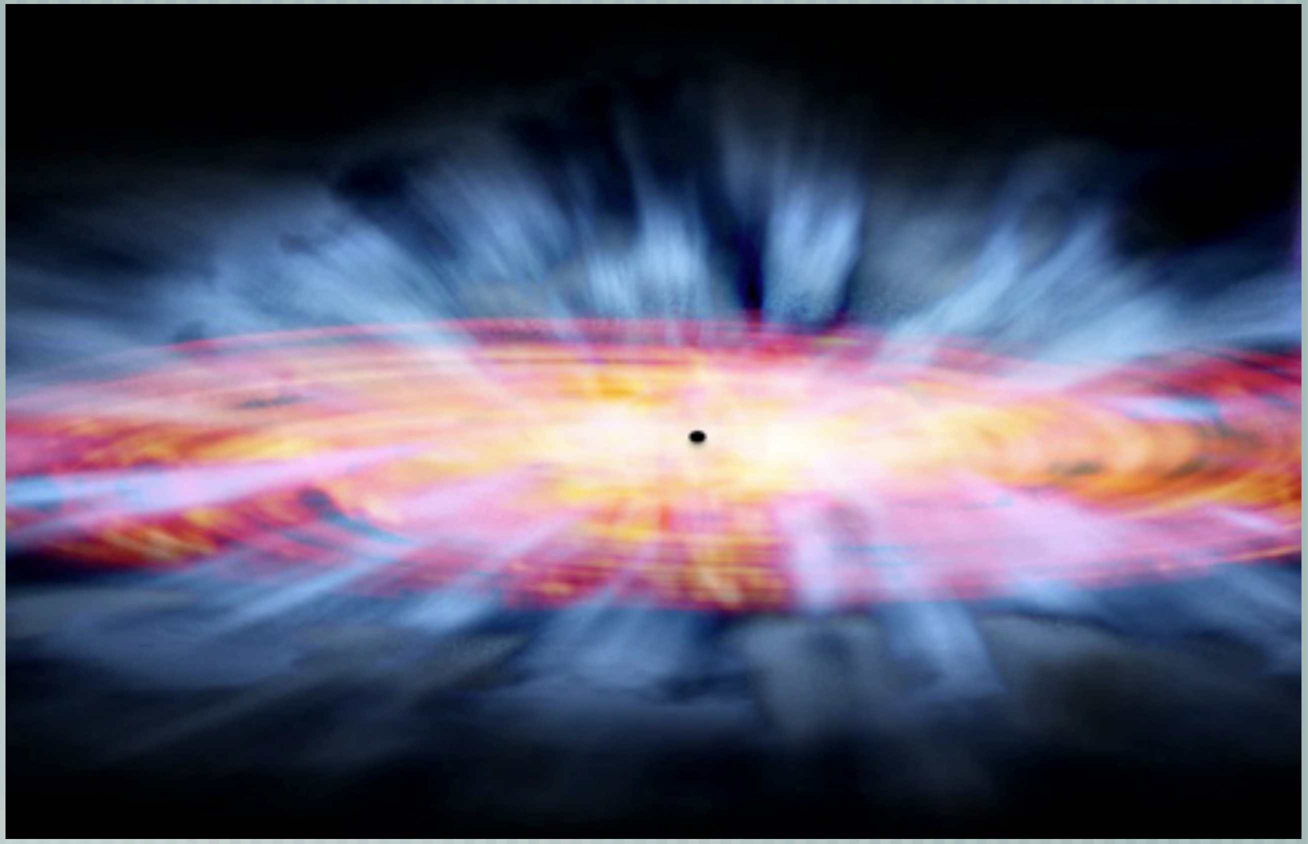
Shapiro & Teukolsky

2. Supermassive black holes: What can they do?

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can't get out – including light.
- However, matter just outside black hole can be very vocal

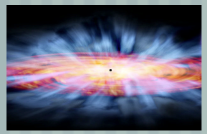
Black hole eats surrounding gas

Gas produces radiation (lots of it!)



Artist: Weiss (NASA), Ak (Penn State)

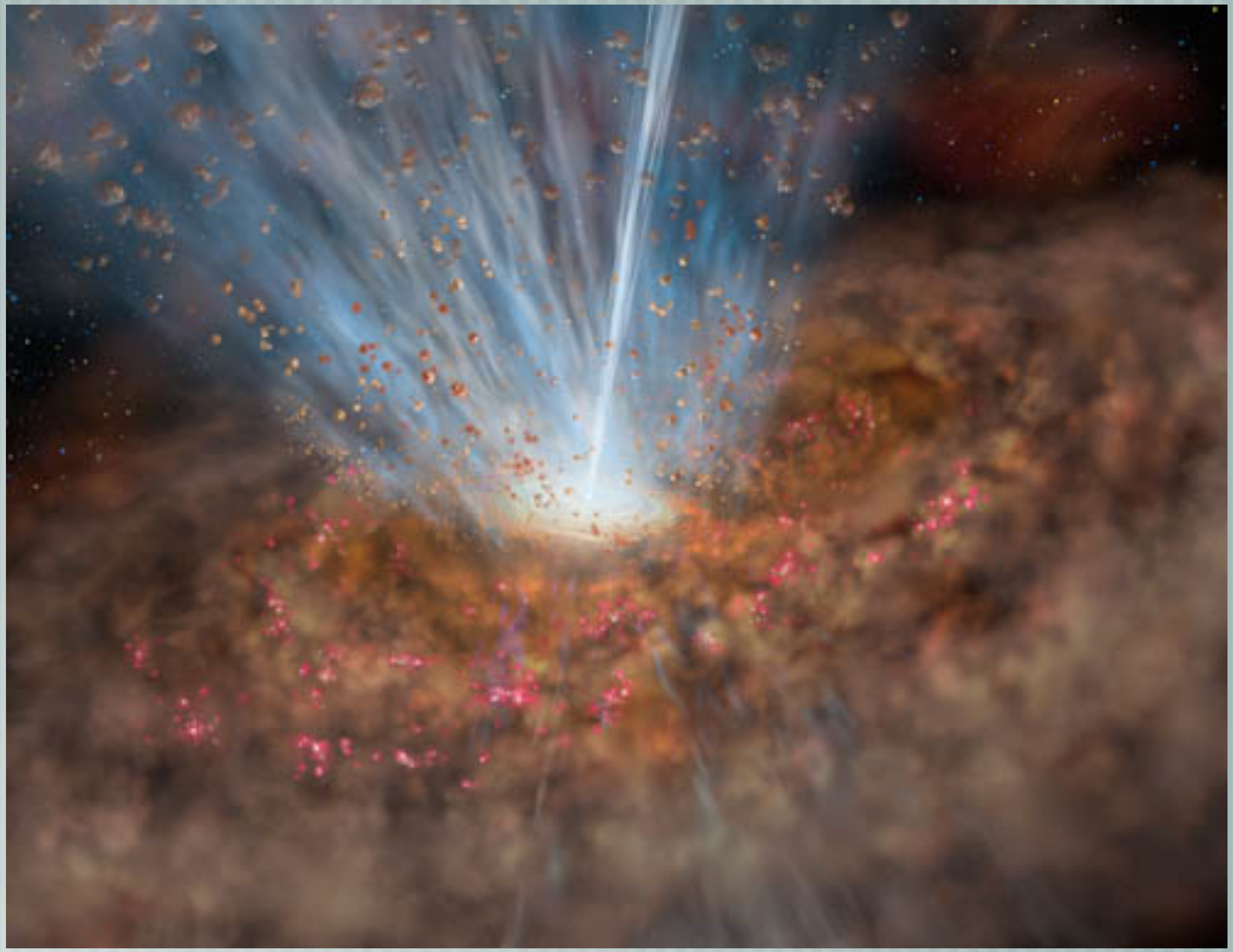
2. Supermassive black holes:
What can they do?



- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can't get out – including light.
- However, matter just outside black hole can be very vocal

Black hole eats surrounding gas

Gas produces radiation (lots of it!)



Artist: L. Cook / Gemini Observatory

2. Supermassive black holes:
What can they do?

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can’t get out – including light.
- However, matter just outside black hole can be very vocal

Black hole eats surrounding gas

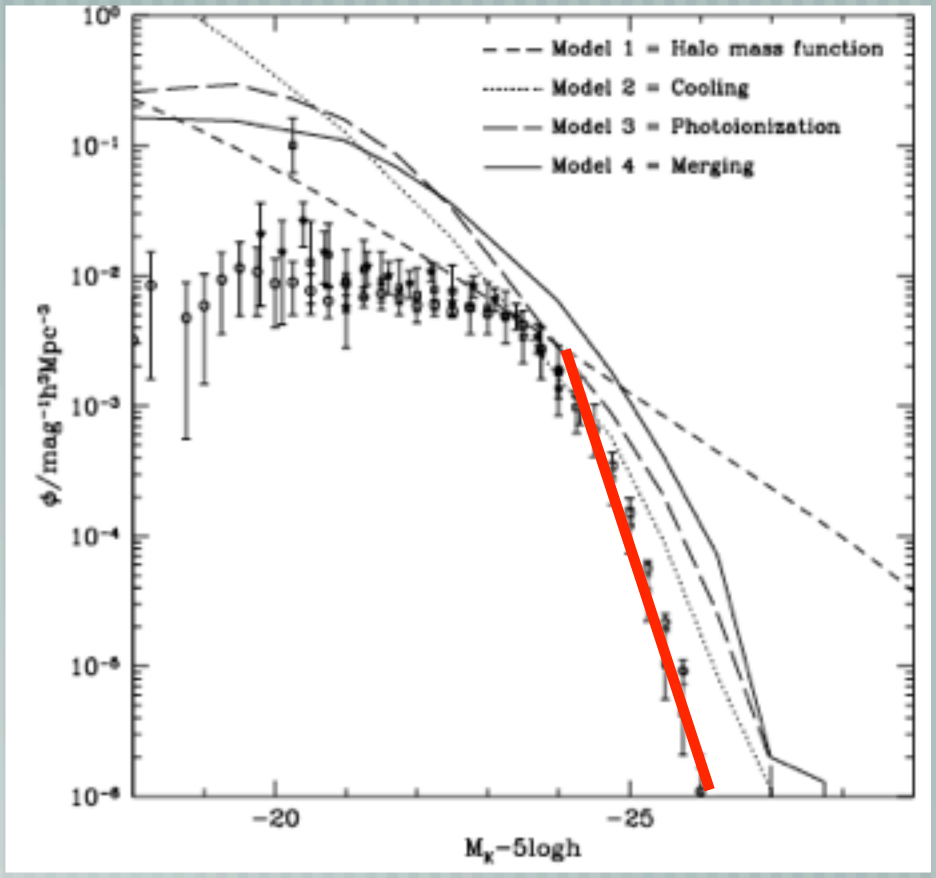
Gas produces radiation (lots of it!)

Amazing fact #3:
1 gram of matter releases enough energy (radiation) as it falls into a black hole to throw 5 kilograms of matter out of the galaxy

3. Putting it all together:
Interplay between galaxies and their black holes

- There is enough energy in infalling matter to reheat / clear up the entire galaxy of gas
- Black hole winds can suppress formation of overly massive galaxies

Number of galaxies per decade in mass



←Small, faint galaxies Large, massive galaxies→

Luminosity function of galaxies
Benson et al. 2003

3. Putting it all together:
Interplay between galaxies and their black holes

Theory:

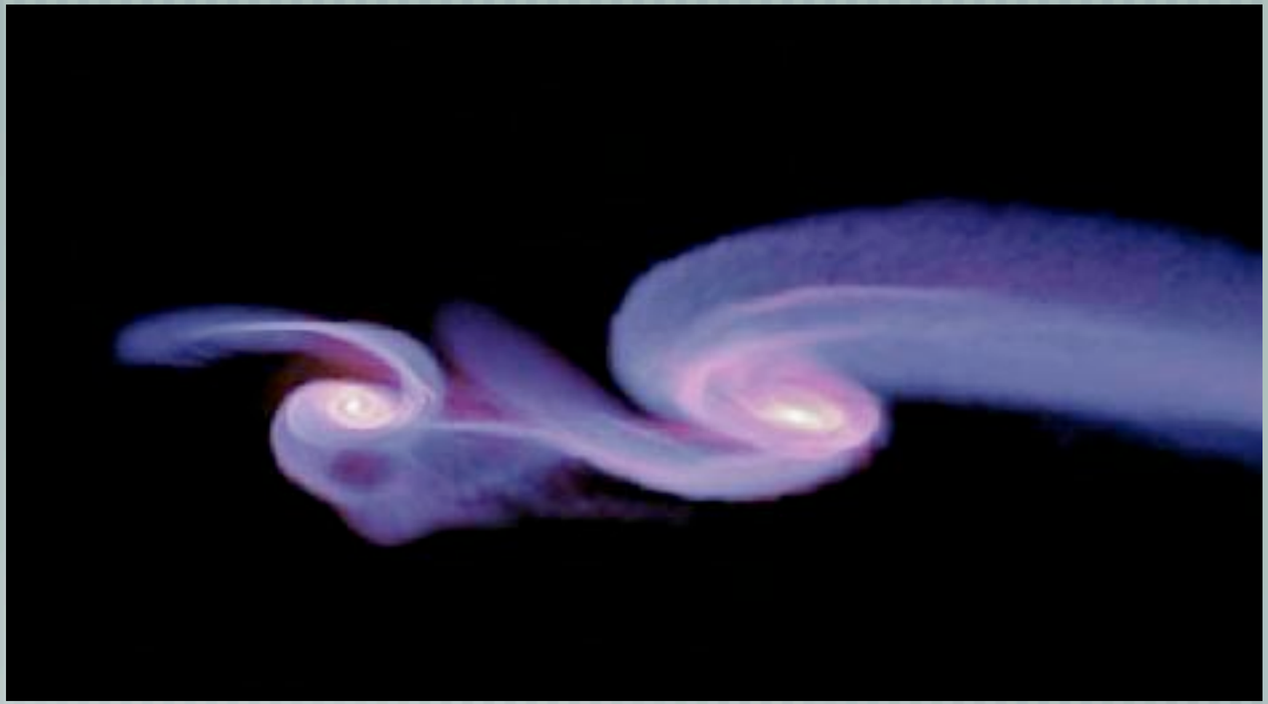
New gas is fuel for both the stars in the galaxy and the black hole

Galaxy grows, black hole grows

Black hole becomes too powerful, blows away remaining gas

Bomb that keeps going for a million to ten million years

Left with massive galaxy, massive black hole, no gas



Many beautiful simulations of merging galaxies:

http://users.obs.carnegiescience.edu/tcox/movies/movies.html

The one I showed in the talk is the third category
"Major Mergers with BH"

V. Springel (also T.J.Cox, P.Hopkins)

3. Putting it all together:
Interplay between galaxies and their black holes

Theory:

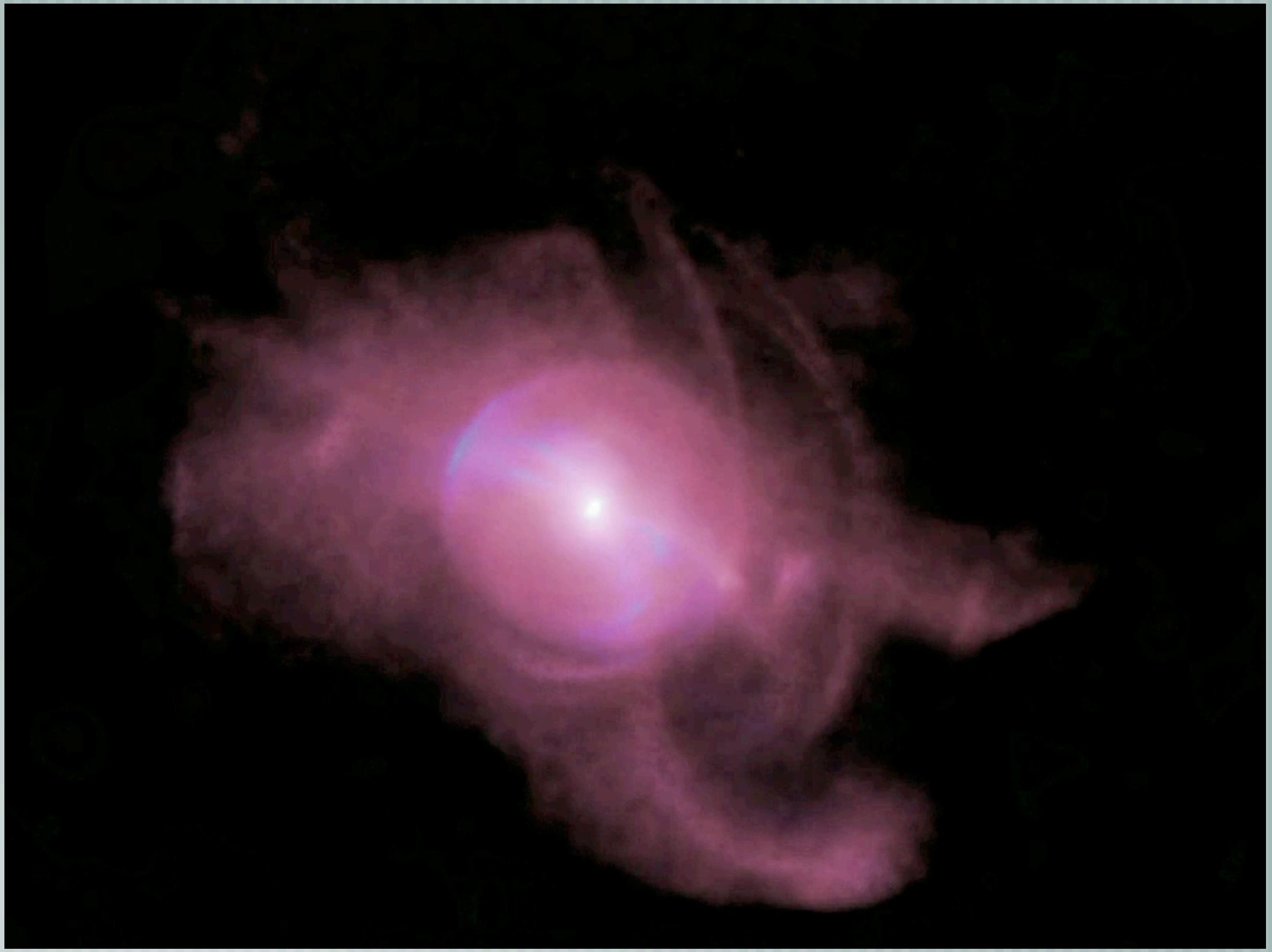
New gas is fuel for both the stars in the galaxy and the black hole

Galaxy grows, black hole grows

Black hole becomes too powerful, blows away remaining gas

Bomb that keeps going for a million to ten million years

Left with massive galaxy, massive black hole, no gas



V. Springel (also T.J.Cox, P.Hopkins)

3. Putting it all together: Interplay between galaxies and their black holes

Observations:

Several groups looking for black-hole-driven winds

Modern observational astronomy: many wavelengths probing different aspects / physical conditions in this problem

“Queue” automated observing

For this project: classical observing on Gemini, Magellan

3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

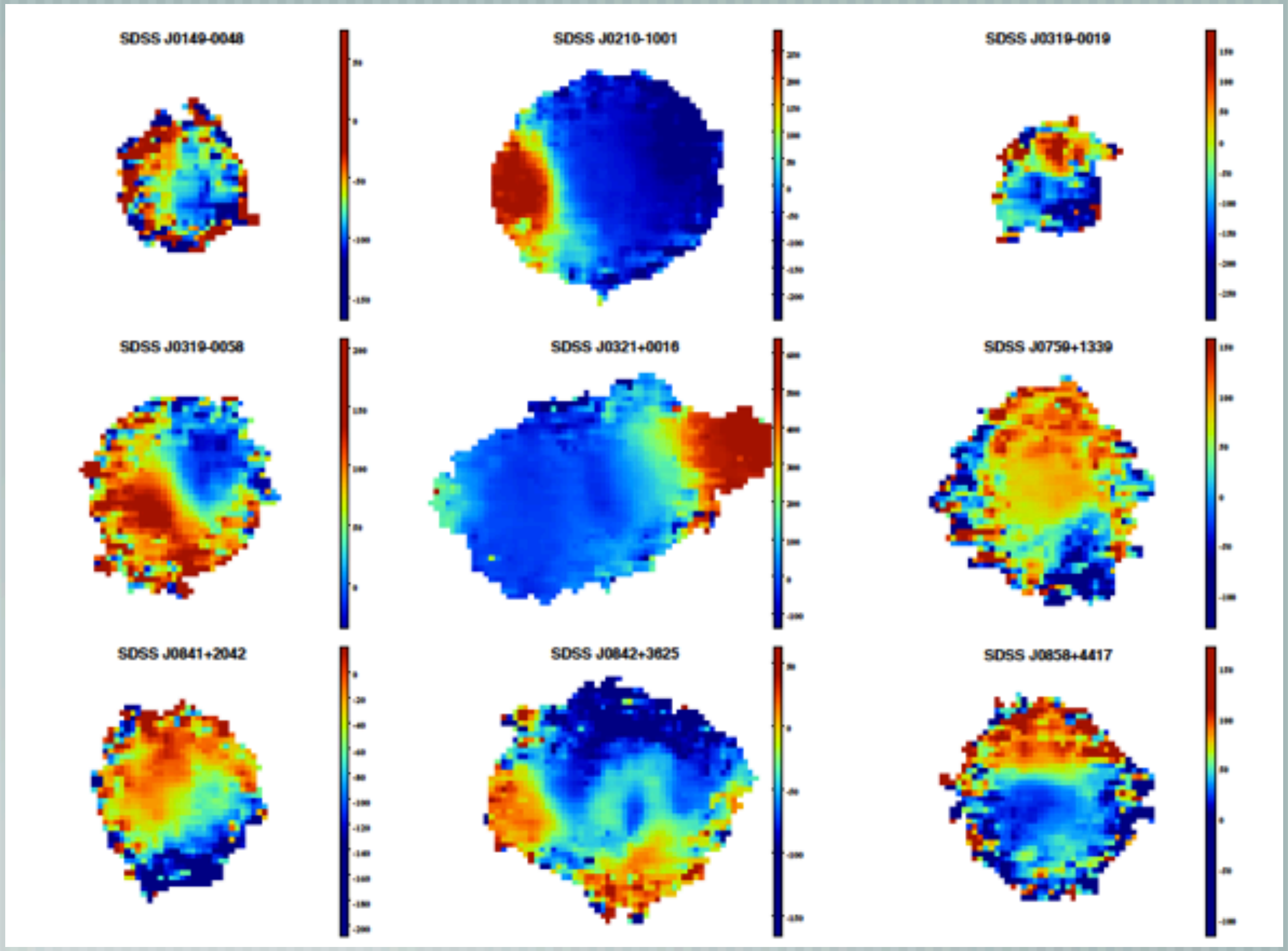
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

Looks smooth but probably is not

Such observations provide measurements for comparing with theory



Liu / Zakamska / Greene 2013

3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

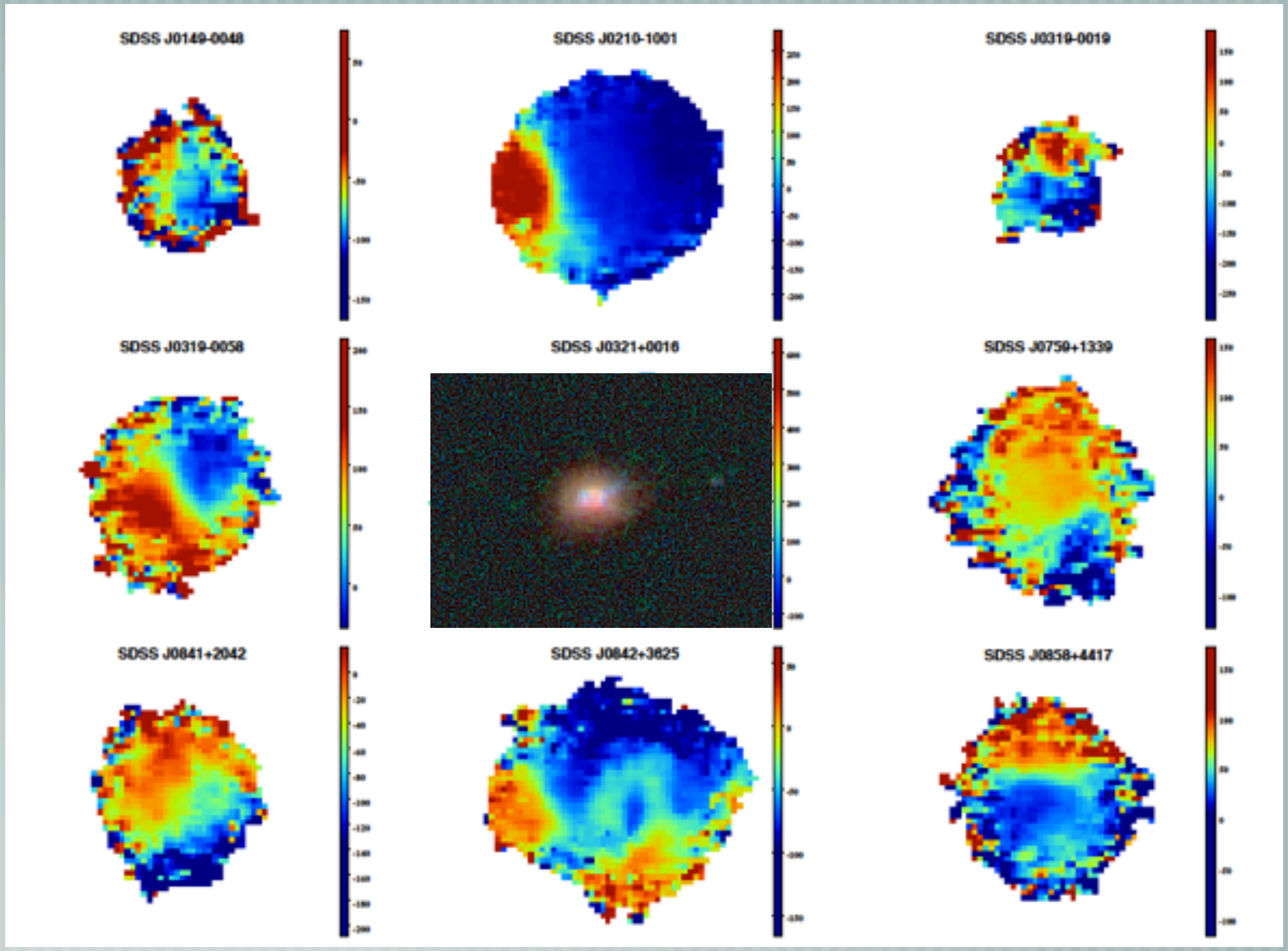
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

Looks smooth but probably is not

Such observations provide measurements for comparing with theory



Liu / Zakamska / Greene 2013

3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

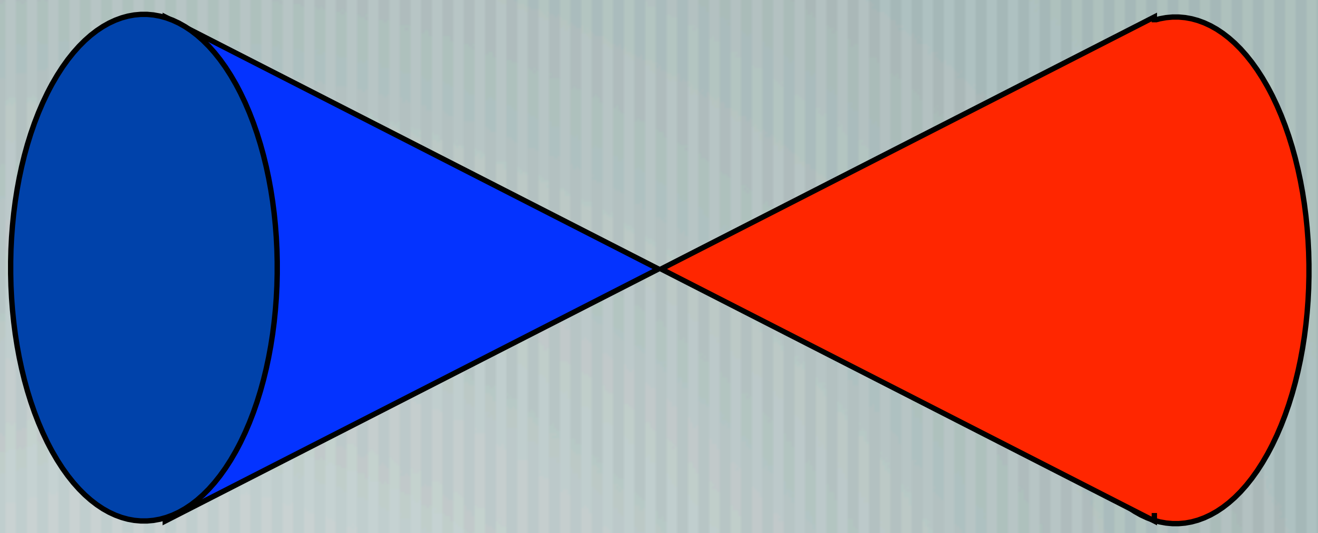
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

Looks smooth but probably is not

Such observations provide measurements for comparing with theory



3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

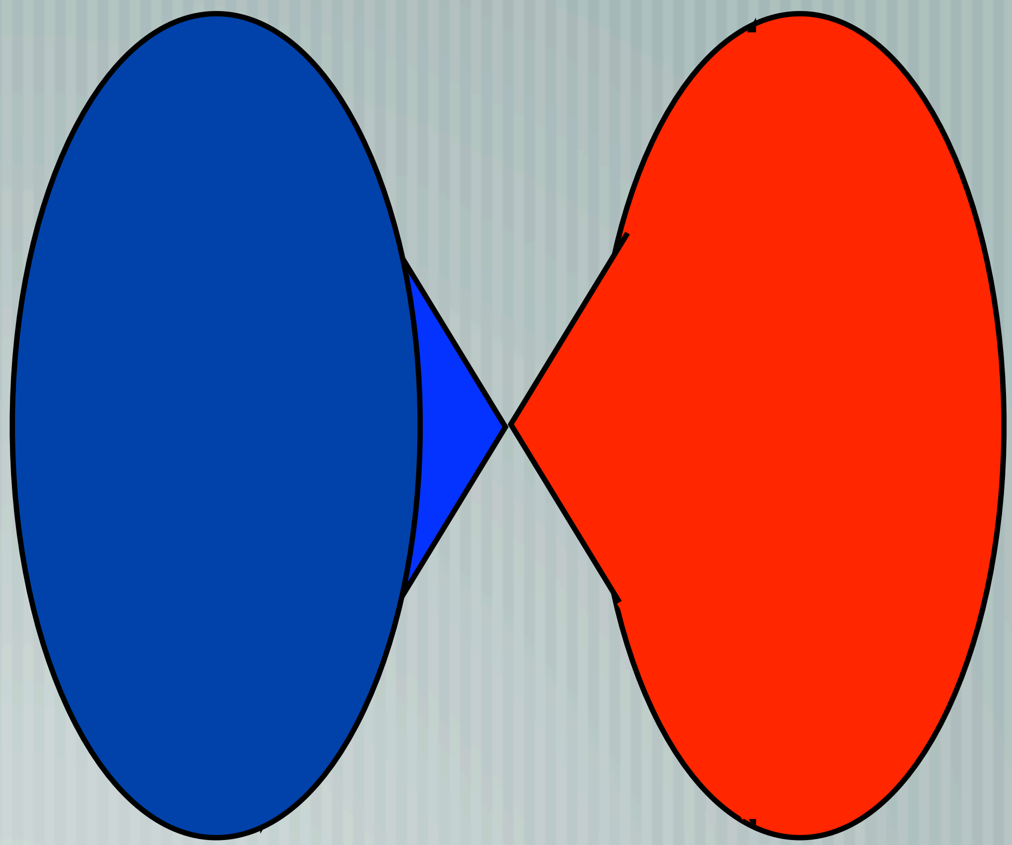
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

Looks smooth but probably is not

Such observations provide measurements for comparing with theory



3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

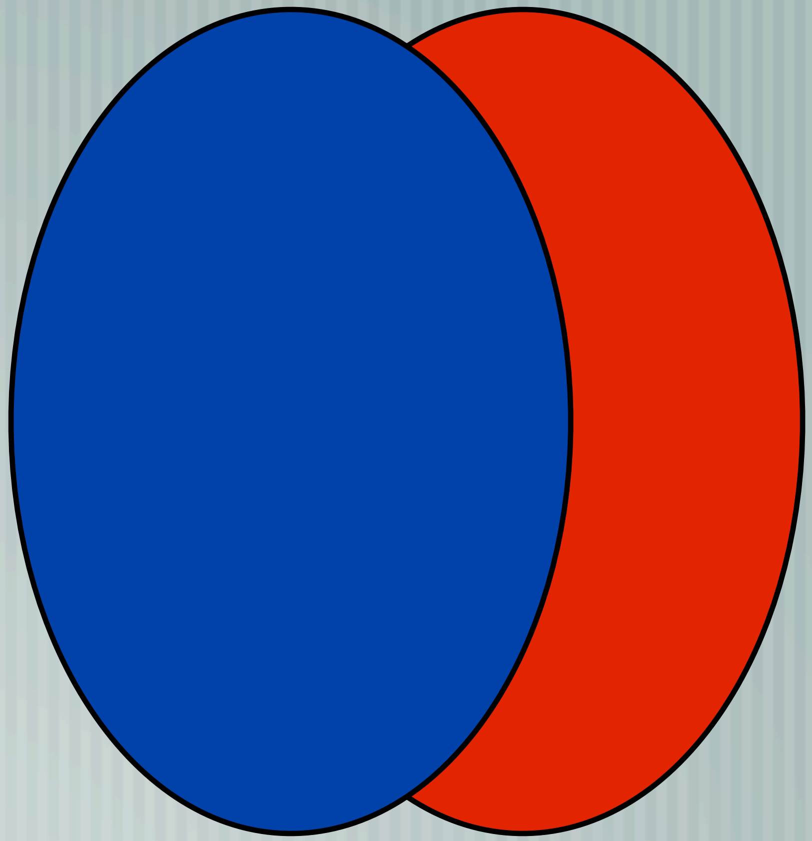
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

Looks smooth but probably is not

Such observations provide measurements for comparing with theory



3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

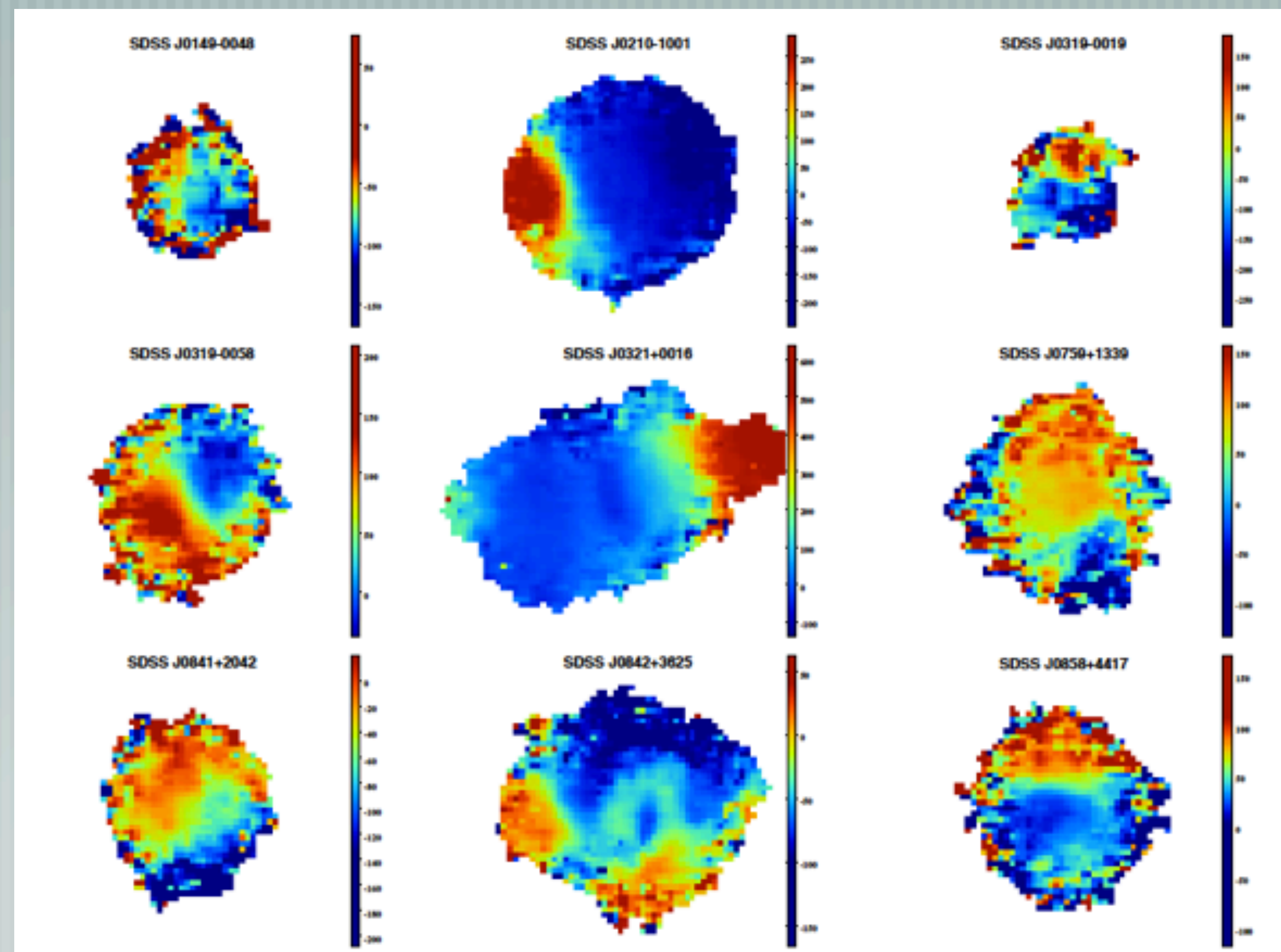
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

Looks smooth but probably is not

Such observations provide measurements for comparing with theory



Liu / Zakamska / Greene 2013

3. Putting it all together:
Interplay between galaxies and their black holes

What do we actually observe?

Gas at 20,000 deg – unlike stars, gas does not produce a lot of emission

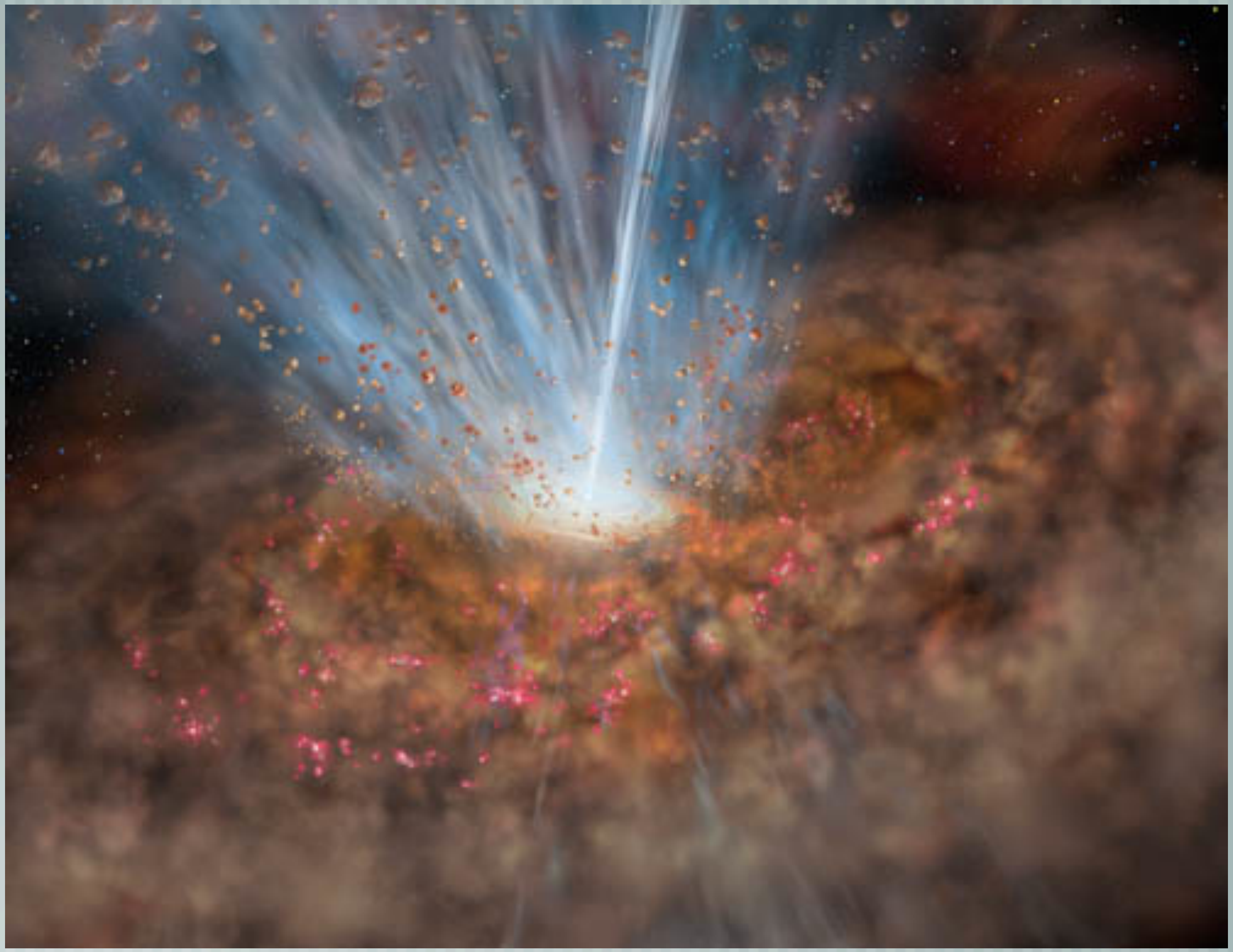
Measure: Extent over the galaxy

Measure: Amount of gas

Measure: Velocities

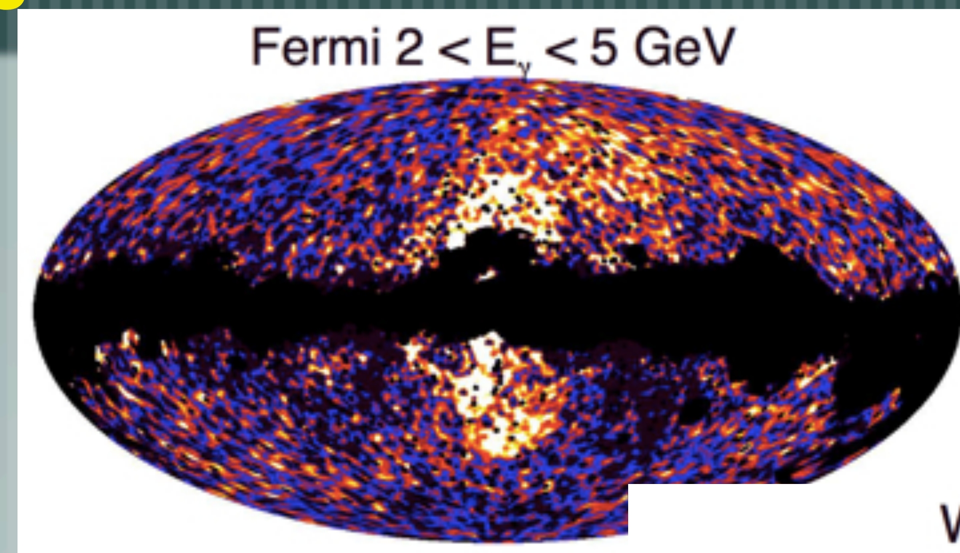
Looks smooth but probably is not

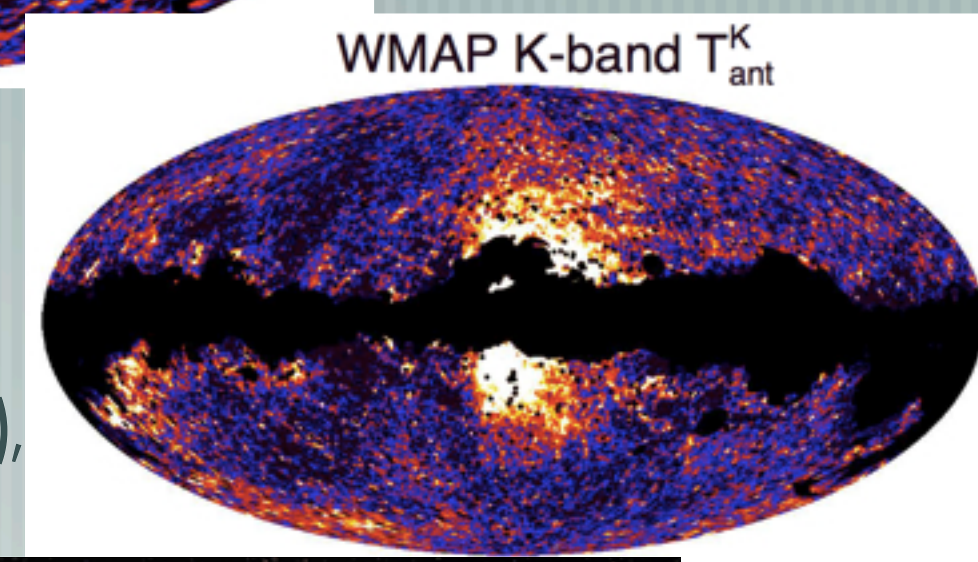
Such observations provide measurements for comparing with theory



Artist: L. Cook / Gemini Observatory

3. Putting it all together:
Interplay between galaxies and their black holes





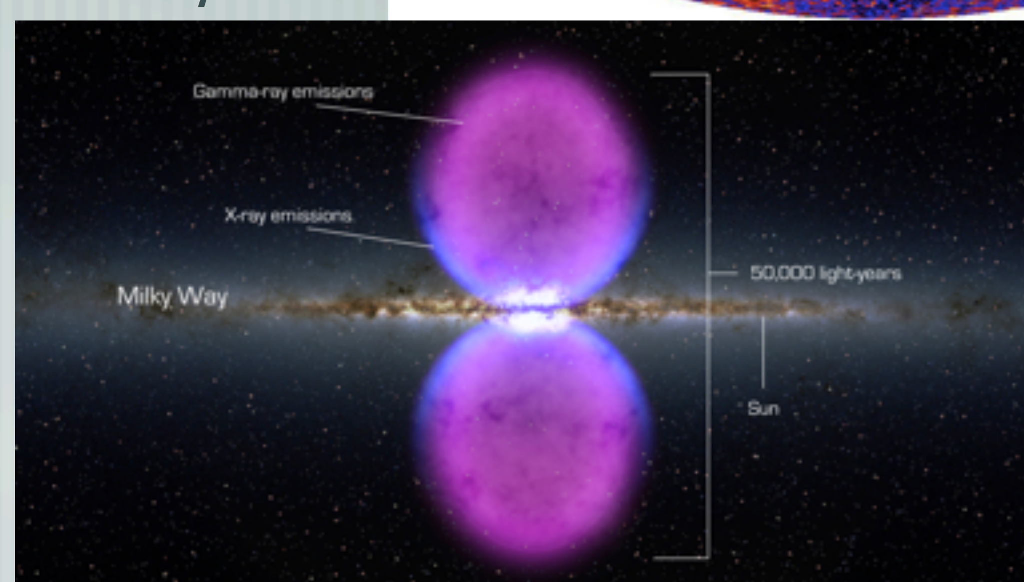
What do we actually observe?

In our Galaxy: see relic of ancient black-hole driven explosion?

“Gamma-ray bubbles” (Fermi Gamma Ray observatory)

“Microwave haze” (Wilkinson Microwave Anisotropy Probe)

D. Finkbeiner (Harvard), illustration by NASA



Summary

- Galaxies are luminous knots of the cosmic web (largely dark matter)
- Massive galaxies contain supermassive black holes in their centers
- Both galaxies and black holes formed from gas that cooled and condensed
- As matter falls into black hole, the released energy clears the gas from the galaxy

Amazing fact #4:
The pictures and movies aren’t just pictures and movies... They are solutions to equations

Summary

- Galaxies are luminous knots of the cosmic web (largely dark matter)
- Massive galaxies contain supermassive black holes in their centers
- Both galaxies and black holes formed from gas that cooled and condensed
- As matter falls into black hole, the released energy clears the gas from the galaxy

$$\frac{\partial \delta_b}{\partial t} + \frac{1}{a}\nabla \cdot (1+\delta_b)\boldsymbol{v} = 0\,, \tag{2}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \frac{1}{a}(\boldsymbol{v}\cdot\nabla)\boldsymbol{v} + H\boldsymbol{v} = -\frac{1}{\rho_b a}\nabla\,, \tag{3}$$

$$\frac{\partial E}{\partial t} + \frac{1}{a}\nabla \cdot [(E+p)\boldsymbol{v}] = -3H(E+p) - H\rho_b \boldsymbol{v}^2 - \frac{\rho_b \boldsymbol{v}}{a}\nabla\phi - \Lambda\,; \tag{4}$$

$$\begin{aligned} df &= \frac{\partial f}{\partial t}dt + \left(\frac{\partial f}{\partial x}dx + \frac{\partial f}{\partial y}dy + \frac{\partial f}{\partial z}dz\right) + \left(\frac{\partial f}{\partial p_x}dp_x + \frac{\partial f}{\partial p_y}dp_y + \frac{\partial f}{\partial p_z}dp_z\right) \\ &= \frac{\partial f}{\partial t}dt + \nabla f \cdot d\mathbf{r} + \frac{\partial f}{\partial \mathbf{p}}\cdot d\mathbf{p} \\ &= \frac{\partial f}{\partial t}dt + \nabla f \cdot \frac{\mathbf{p}dt}{m} + \frac{\partial f}{\partial \mathbf{p}}\cdot \mathbf{F}dt \end{aligned}$$

$$\frac{\partial \Sigma}{\partial t} + \nabla\cdot(\Sigma\boldsymbol{v}) = 0, \tag{1}$$

$$\frac{\partial \boldsymbol{v}}{\partial t} + \boldsymbol{v}\cdot\nabla\boldsymbol{v} + \frac{1}{\Sigma}\nabla p = \frac{2H}{4\pi\Sigma}(\nabla\times\boldsymbol{B})\times\boldsymbol{B} - \nabla(\Phi_{\rm ext}+\Phi), \tag{2}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{v}\times\boldsymbol{B}), \tag{3}$$

$$\nabla^2\Phi = 4\pi G\delta(z)\Sigma, \tag{4}$$

$$\Phi_{\rm ext}(R,\phi;t) = \Phi_{\rm ext,0}\cos\left[m\phi - \phi_0(R) - m\Omega_p t\right], \tag{5}$$

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho\boldsymbol{v}) = 0\,,$$

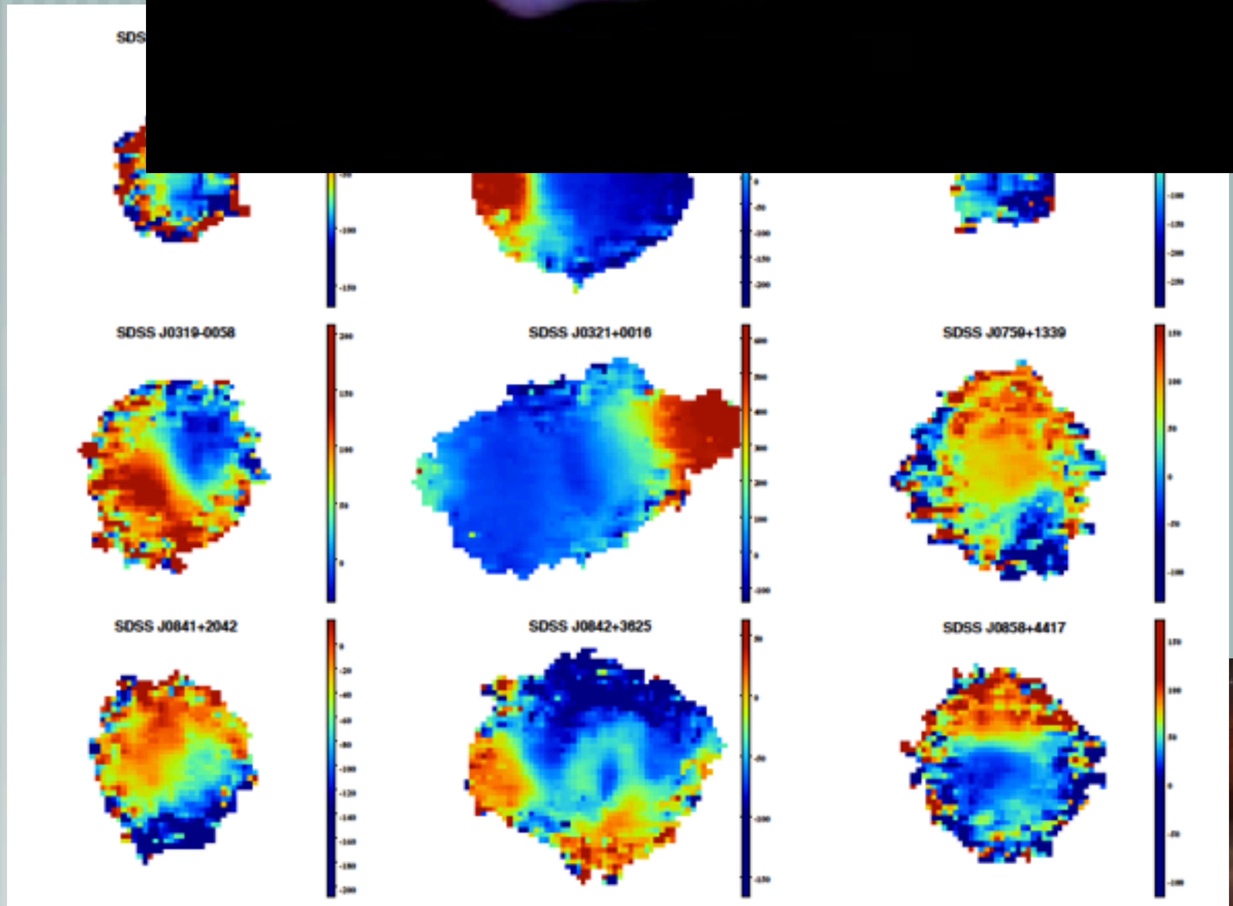
$$\frac{\partial}{\partial t}(\rho\boldsymbol{v}) + \nabla\cdot(\rho\boldsymbol{v}\boldsymbol{v}) = -\nabla P - \rho\nabla\phi\,,$$

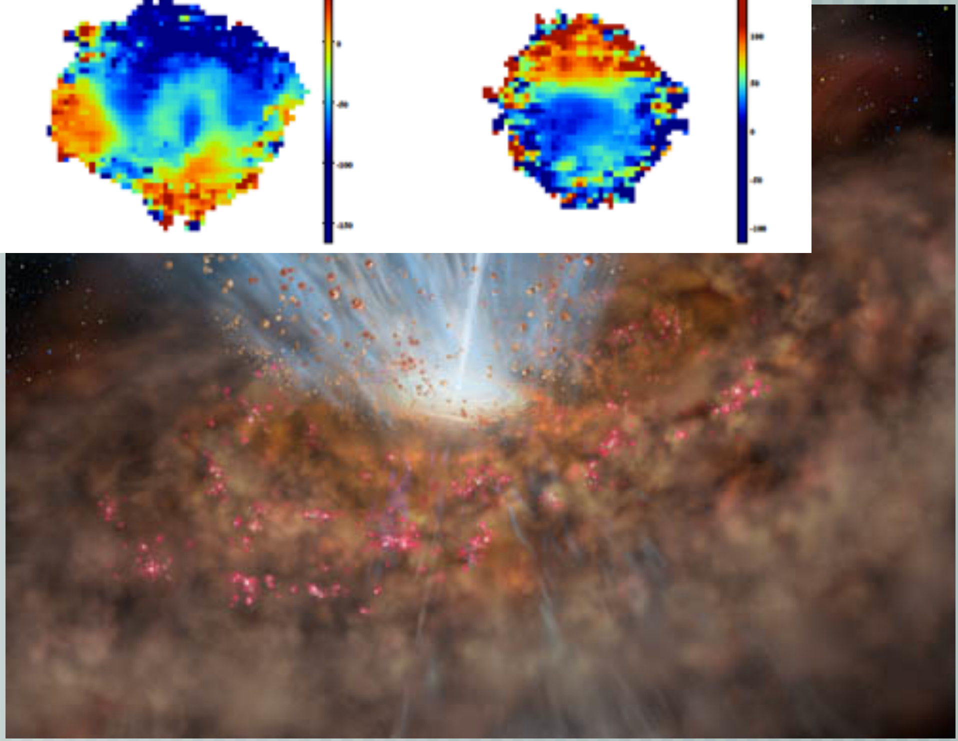
$$\frac{\partial}{\partial t}(\rho E) + \nabla\cdot[(\rho E + P)\boldsymbol{v}] = \rho\boldsymbol{v}\cdot\nabla\phi\,,$$

$$\nabla^2\phi = 4\pi G\rho\,.$$

Summary

- Galaxies are luminous knots of the cosmic web (largely dark matter)
- Massive galaxies contain supermassive black holes in their centers
- Both galaxies and black holes formed from gas that cooled and condensed
- As matter falls into black hole, the released energy clears the gas from the galaxy

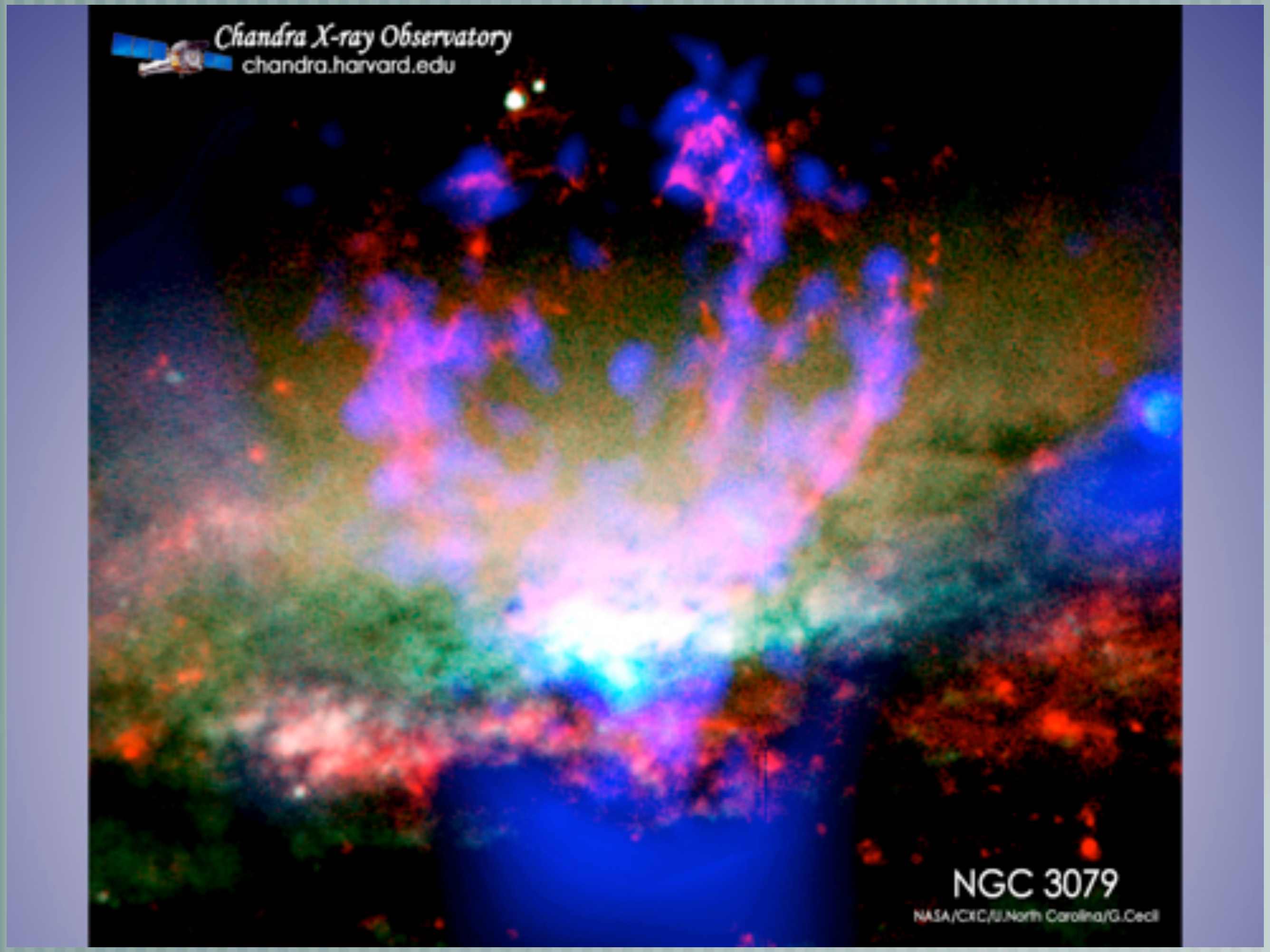




Gone with the wind

Black holes and their gusty influence on the birth of galaxies

Nadia Zakamska
Johns Hopkins University



2. Supermassive black holes: What can they do?

M87, SDSS

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can't get out – including light.
- However, matter just outside black hole can be very vocal

Relativistic outflows ("jets")

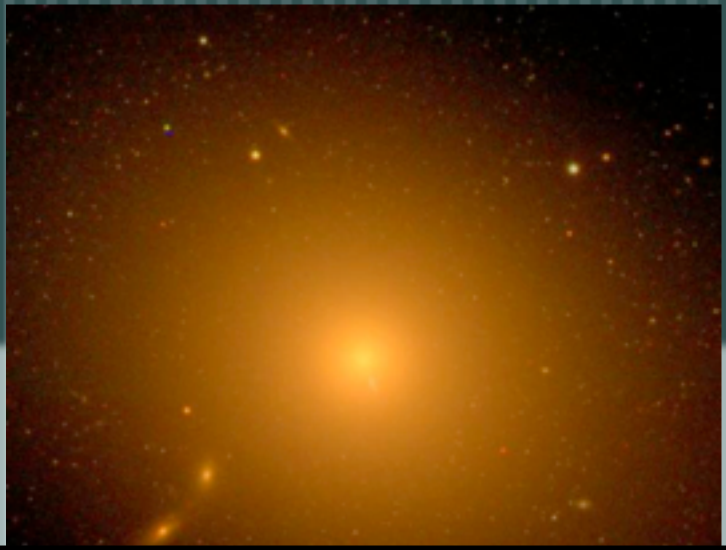
Radiation from the infalling matter: black holes need food to be active

2. Supermassive black holes:
What can they do?

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can’t get out – including light.
- However, matter just outside black hole can be very vocal

Relativistic outflows (“jets”)

Radiation from the infalling matter: black holes need food to be active



This is a pretty wimpy jet...

2. Supermassive black holes: What can they do?

Centaurus A,
Sterne & Welraum 2008

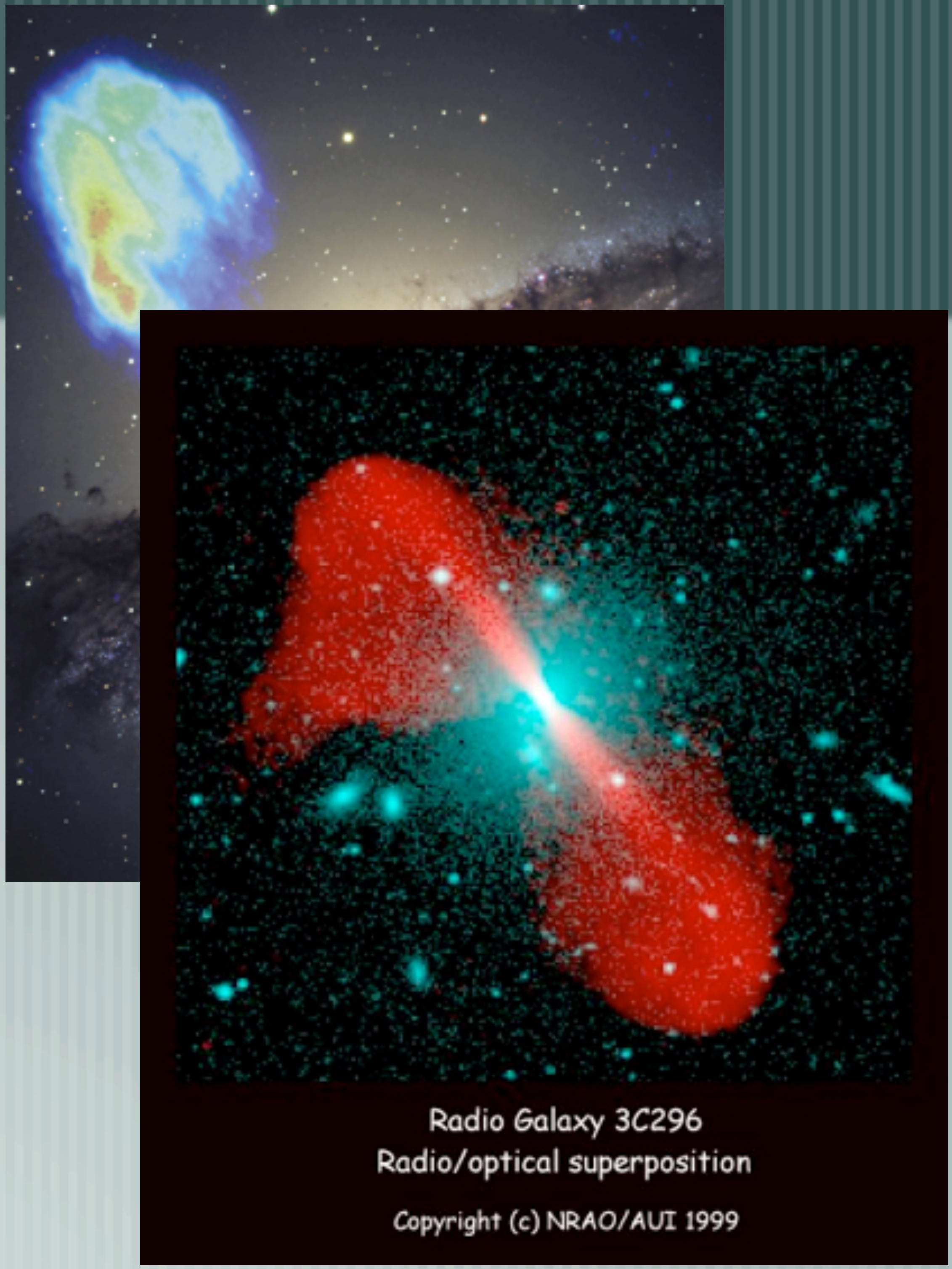
- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can't get out – including light.
- However, matter just outside black hole can be very vocal

Relativistic outflows ("jets")

Radiation from the infalling matter: black holes need food to be active

2. Supermassive black holes: What can they do?

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can’t get out – including light.
- However, matter just outside black hole can be very vocal
  - Relativistic outflows (“jets”)
  - Radiation from the infalling matter: black holes need food to be active



2. Supermassive black holes: What can they do?

- Most of the time sit passively in the center, exerting gravity
- Once something falls in, it can't get out – including light.
- However, matter just outside black hole can be very vocal
  - Relativistic outflows ("jets")
  - Radiation from the infalling matter: black holes need food to be active