Physics 343 Lecture # 5:
Interstellar medium & active galactic nuclei

Schedule for the next week

Office hours: Mon 3:30-4:30pm = Baker; Thu 5:00-6:00 = Wu + "on call" Sections A, B, C = Baker; Sections D, E, F, G = Wu (note: you can come to any of these office hours!)

Next Monday:

Lab # 2 due. One correction: you should plot HI intensity vs. Galactic longitude rather than Galactic latitude.

Next week: Lab # 3 will be at regular section times (mandatory!).

The interstellar medium and its variants

ISM = interstellar medium = whatever gas and dust exists in the space between a galaxy's stars.

ICM = intracluster medium = hot gas filling the volume between galaxies in a group or cluster

IGM = intergalactic medium = material that has been ejected from galaxies or never made it into a galaxy in the first place

Why should we care about the ISM?

Tongue in cheek answer: every astronomy talk can be followed by one of three (ISM-related) questions:

(1) What about dust?

(2) What about magnetic fields?

(3) What about the initial mass function (i.e., relative numbers of newborn stars of different masses that result when a large gas cloud turns into stars all at once)?

Why should we care about the ISM?

Serious answer: the ISM serves as the raw material for star formation and the dumping ground for the products of stellar nucleosynthesis (notably, all elements heavier than helium).

Moreover, the ISM affects nearly all observations we make by absorbing, scattering, or swamping the radiation from other sources of interest.

(for dust, absorption + scattering = extinction)

Key property of the ISM: composition

Gas mass fractions X (hydrogen) + Y (helium) + Z ("metals") = 1:

Shortly after the Big Bang: no stars yet

$X = 0.75$

$Y = 0.25$

$Z = 0.00$

In the Sun (and surrounding ISM):

$X = 0.739$

$Y = 0.248$

$Z = 0.012$ **(of which oxygen contributes 0.005)**

Key property of the ISM: phase

Two parcels of gas with the same composition can have very different physical states. We characterize the phase of interstellar gas with our answers to two questions:

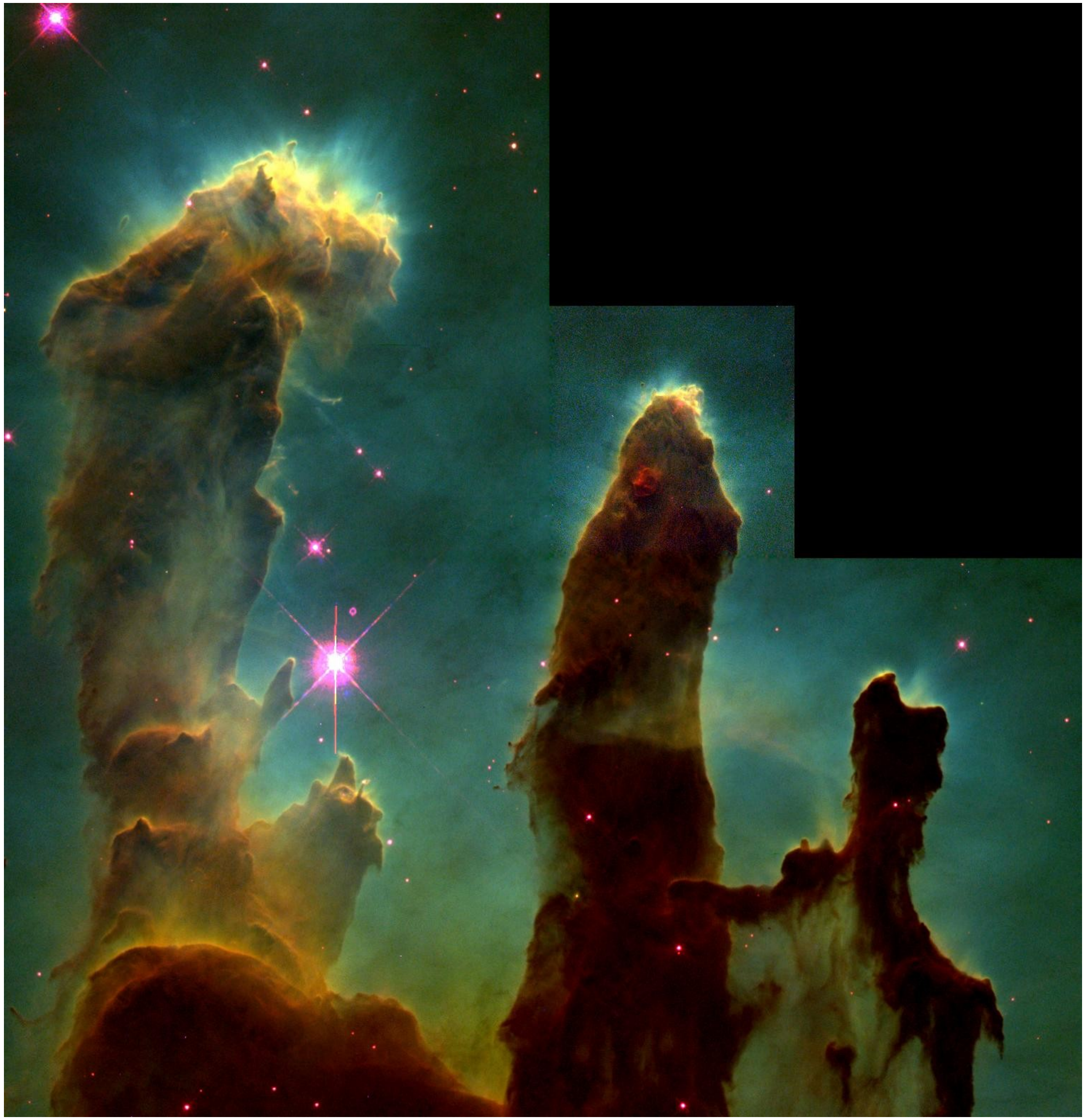
(1) In what form is the hydrogen predominantly found (ionized HII, neutral HI, and/or molecular H_2)?

(2) What are the temperature and density of the gas?

Observed phases of the ISM

Phase	n (cm^{-3})	T (K)	nT (K cm^{-3})	% V	% M
hot ionized	0.003	10^6	3000	50	4
warm ionized	0.1	8000	800	25	14
warm neutral	0.5	8000	4000	30	38
cold neutral	50	80	4000	1	30
molecular clouds	> 2000	10	> 20000	0.5	13

Molecular gas: birthplace of stars



Eagle Nebula, imaged with the *Hubble Space Telescope*:

young stars that have emerged from their dusty birth clouds
+ still younger stars that are still enshrouded

Star-forming regions

Carina Nebula imaged with the *Hubble Space Telescope*:

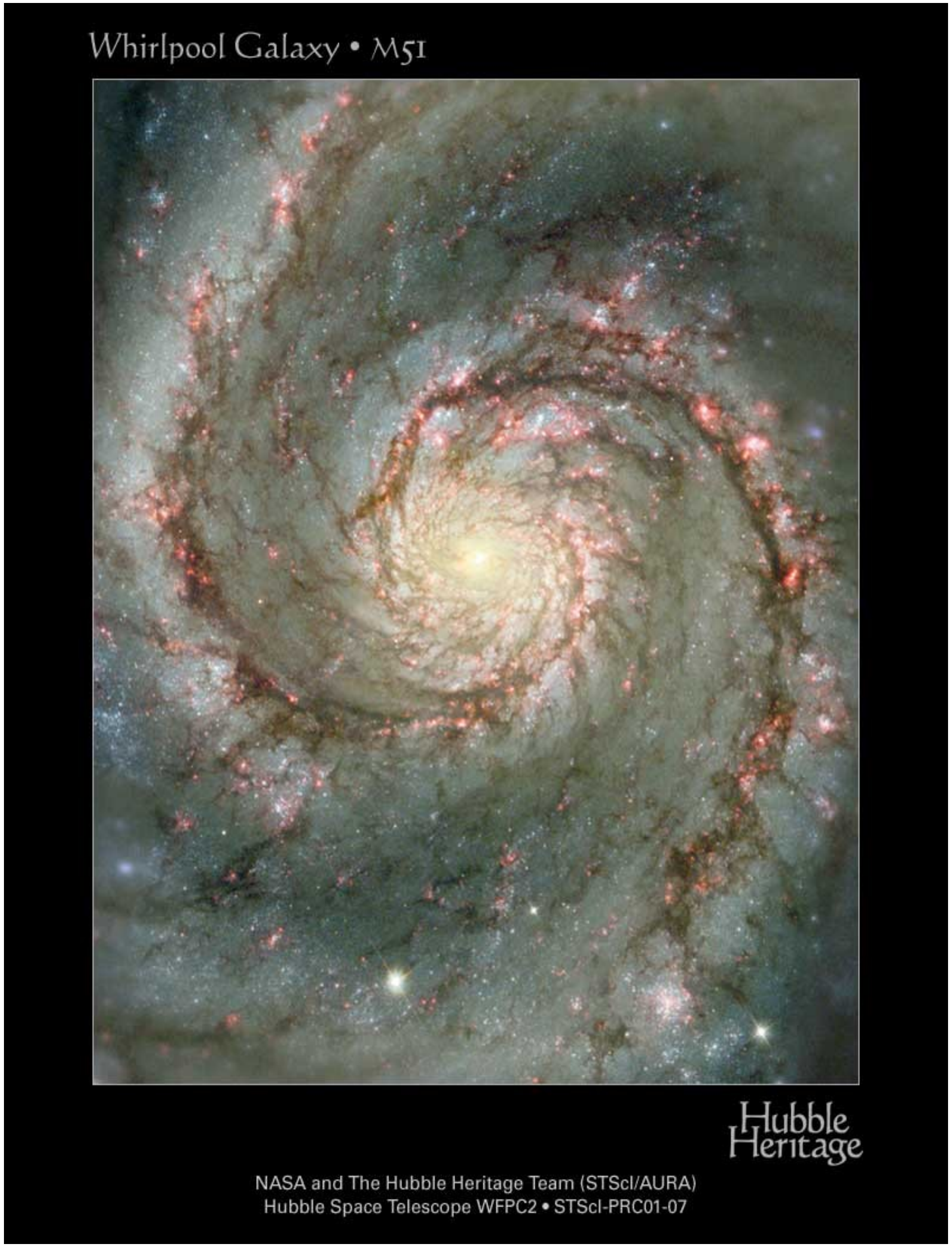
A

that they are on the verge of exploding (e.g., η Car).

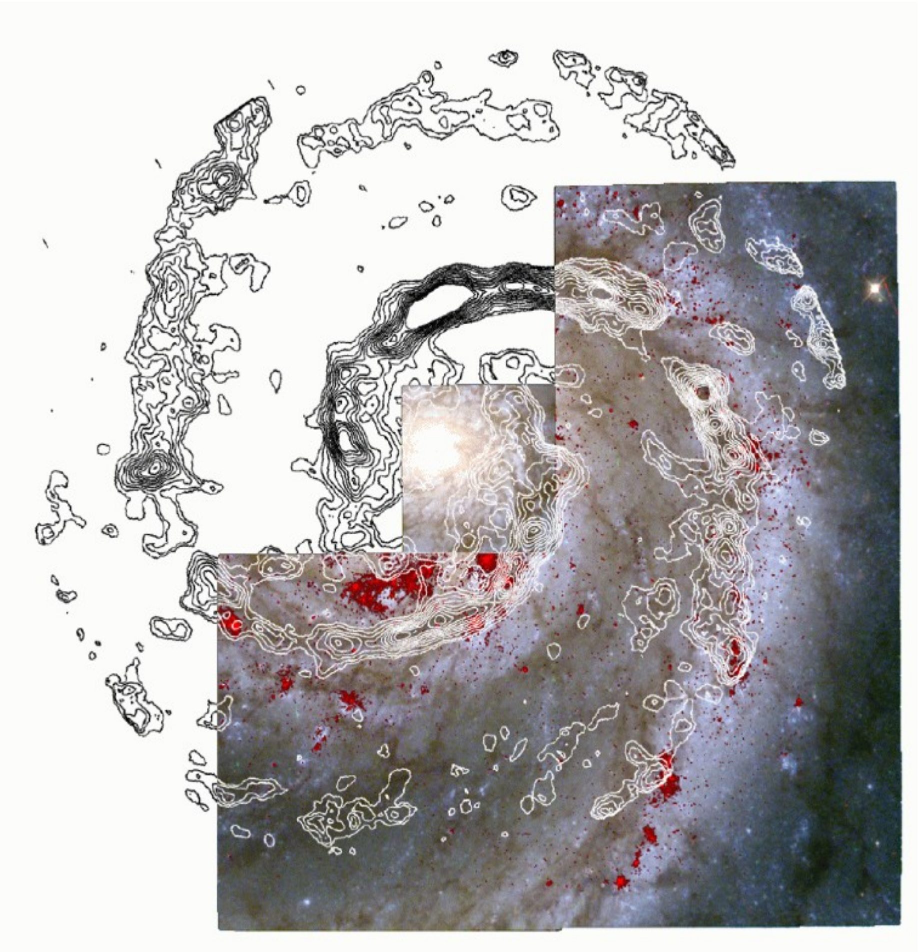
Don't mess with the interstellar medium!

The "defiant finger" in the Carina Nebula (NASA/*HST*).

Molecular gas: birthplace of stars

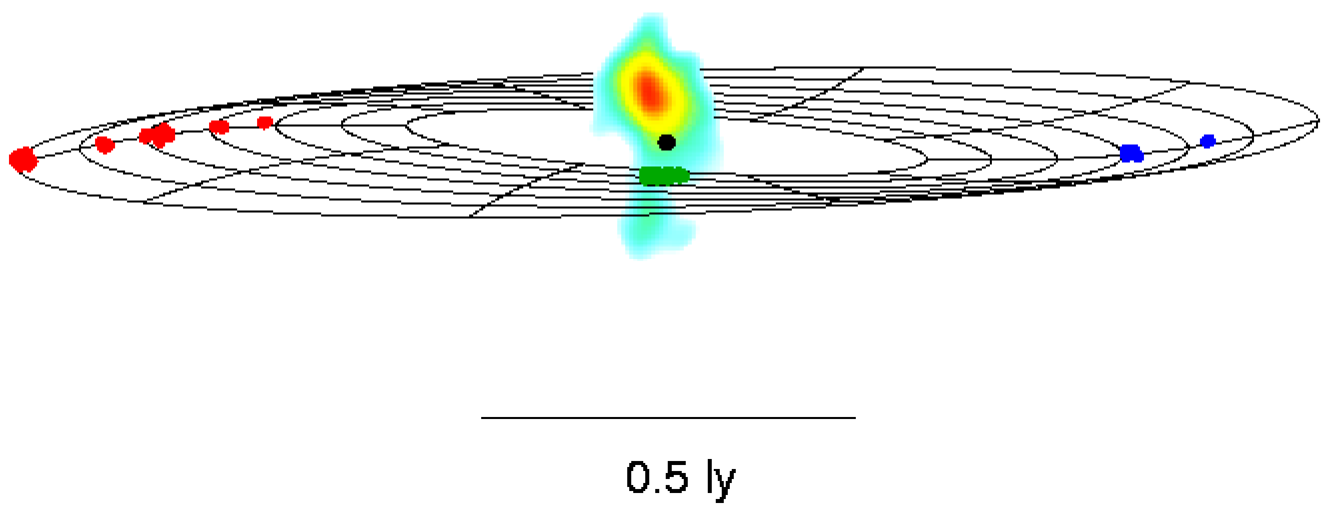


M51: CO contours overlaid on Pa α emission + optical light



Molecular gas: fuel for black holes

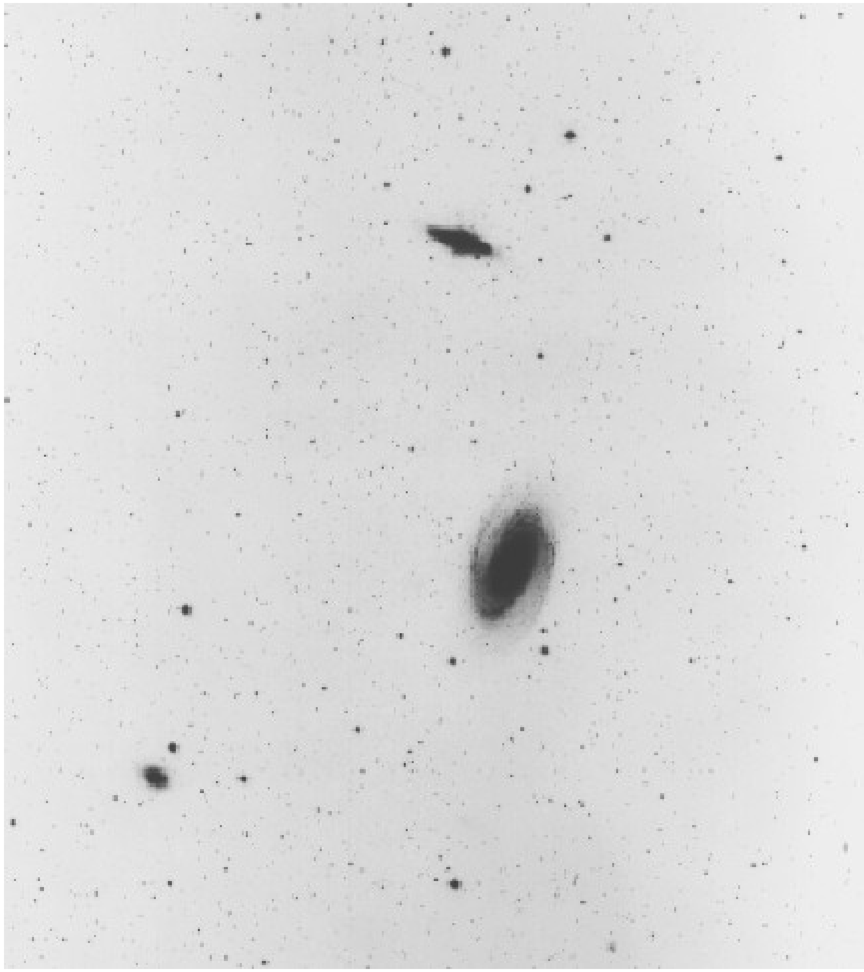
NGC4258: H_2O maser emission from dense, warm gas in clumps that are moving towards us, away from us, and in the plane of the sky (Herrnstein et al. 1997).

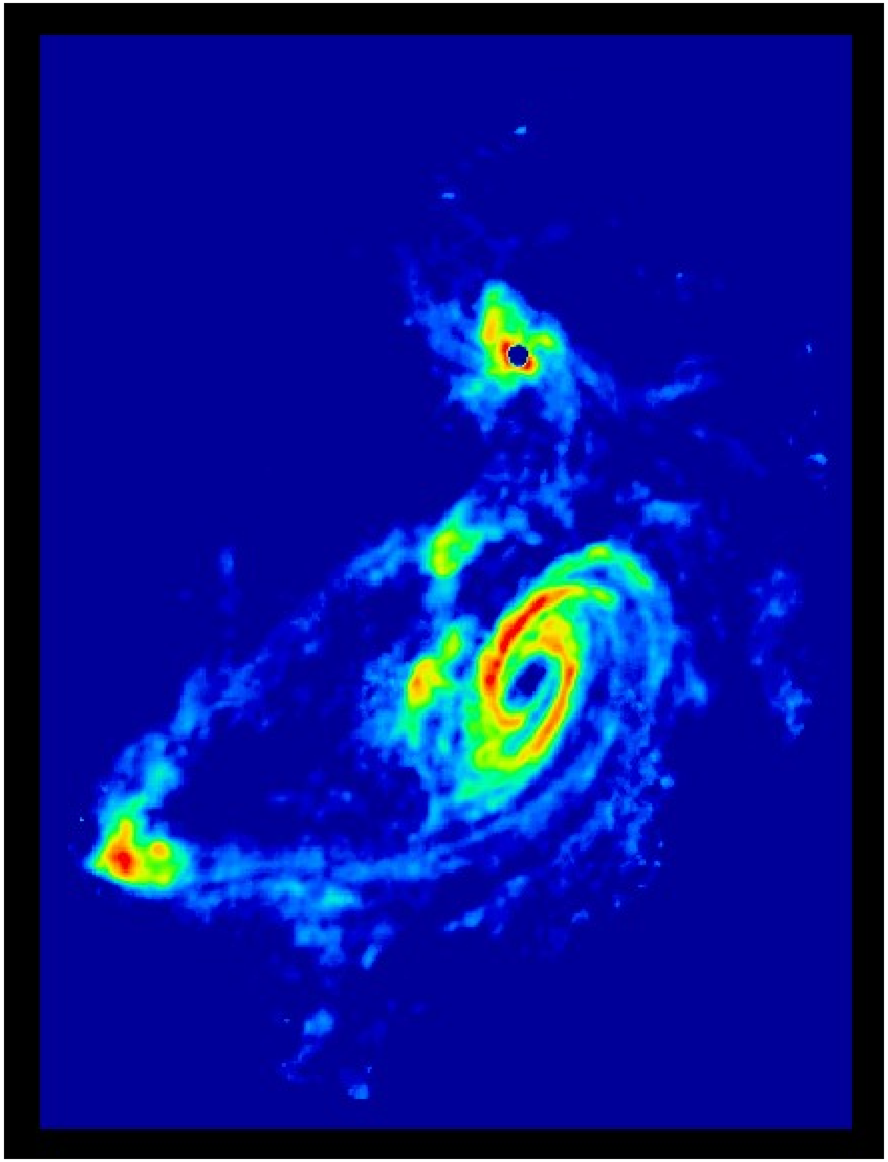


This gas fuels the black hole, which drives a jet perpendicular to the disk.

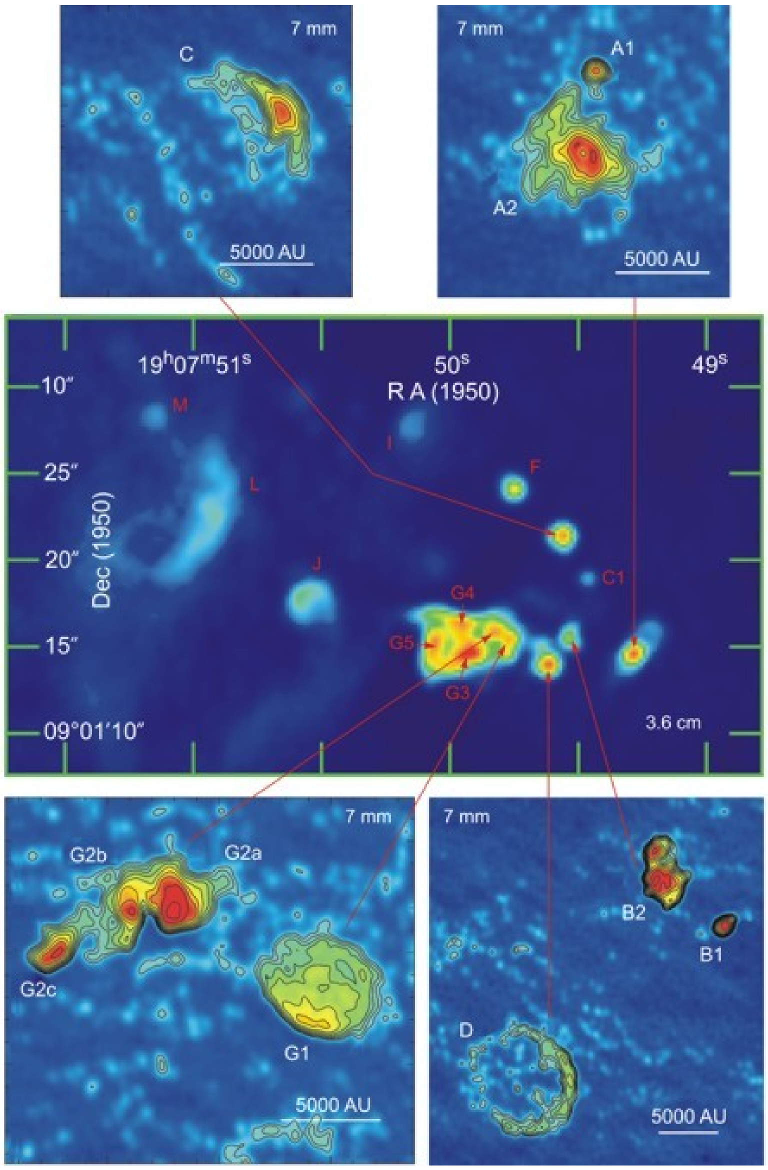
Atomic gas: a major gas reservoir

M81 group: optical starlight (left) + VLA HI (right)





Ionized gas: HII regions...



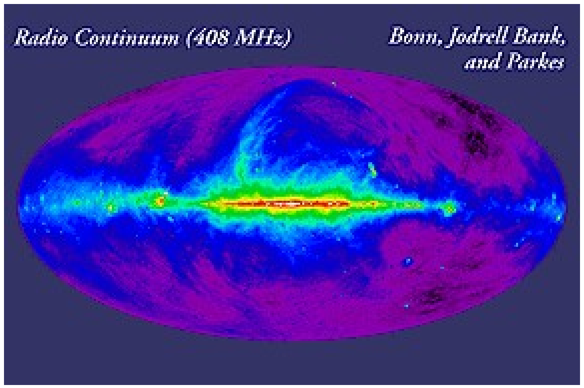
Free-free emission from young, "ultracompact" (high-n_e) HII regions in Milky Way: middle = 3.6cm, insets = 7mm

C. DePree, M. Goss, J. Welch, & D. Wilner

...and superwinds

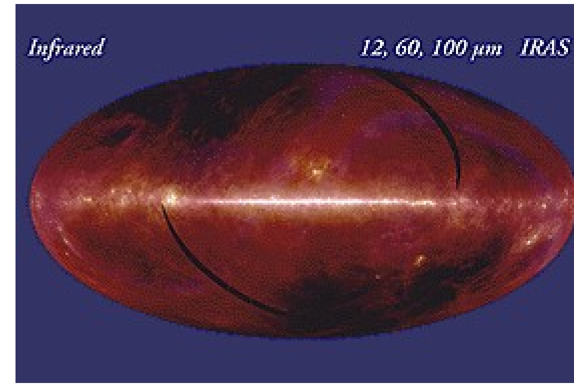
Starburst galaxy M82: X-ray emitting hot gas and Hα emission from ionized gas trace ejection of material along minor axis

A multiwavelength view of the Milky Way

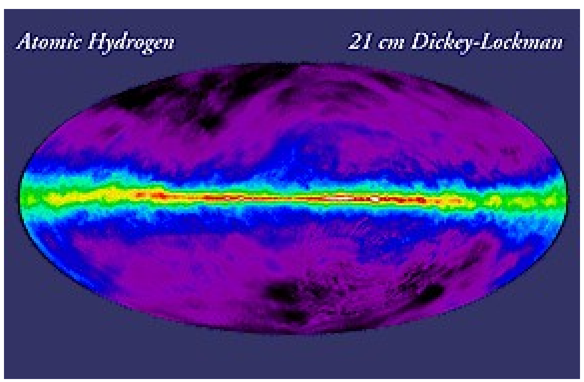


radio continuum

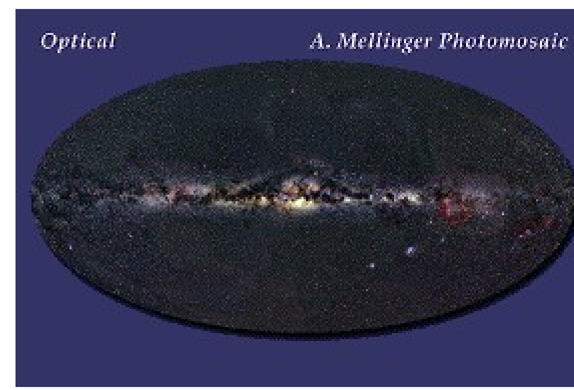
infrared (dust)



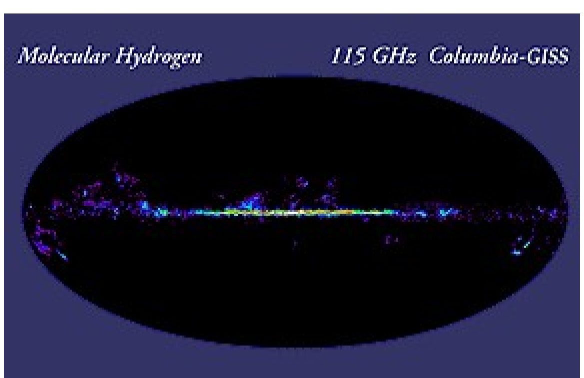
HI



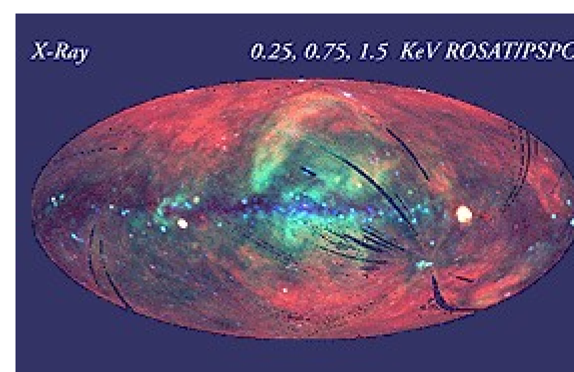
optical



CO (H_2)



X-ray



Pressure equilibrium

Phase	nT (K cm^{-3})
hot ionized	3000
warm ionized	800
warm neutral	4000
cold neutral	4000
molecular clouds	> 20000

Several phases of the ISM have the same thermal pressure as each other (*nkT*). This makes sense: a hot, dense bubble of gas will tend to expand until it reaches pressure equilibrium with its surroundings.

Molecular clouds do not follow this pattern: they are bound by self-gravity!

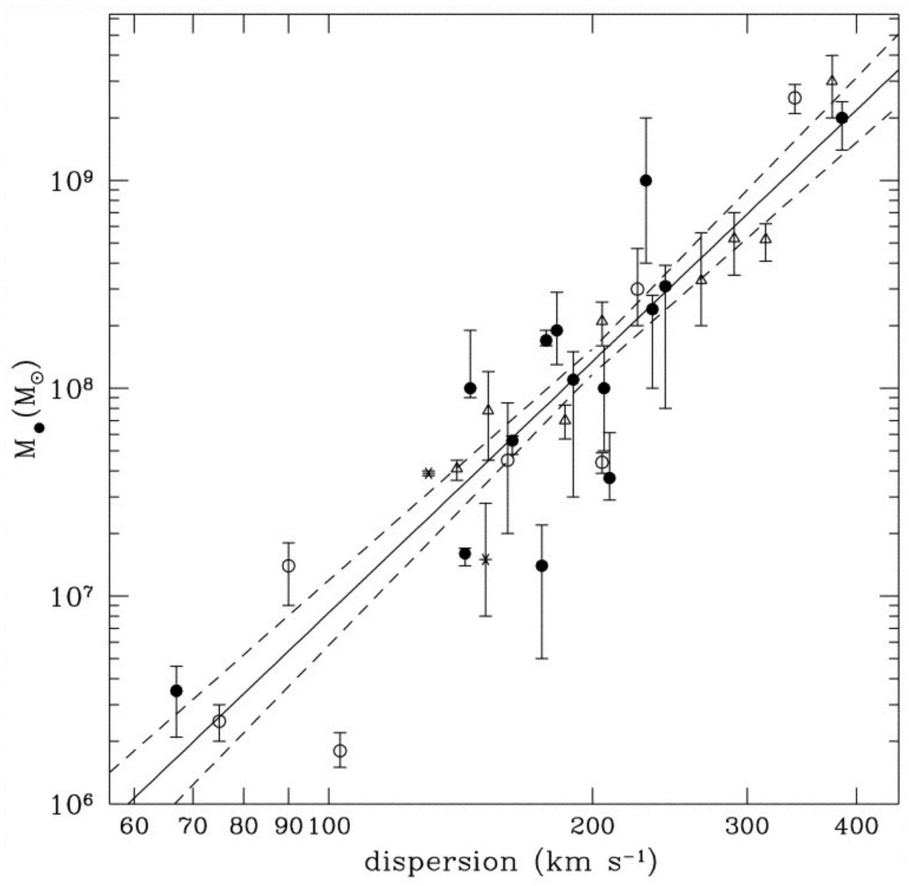
Quiz

Today: black holes are (nearly) ubiquitous

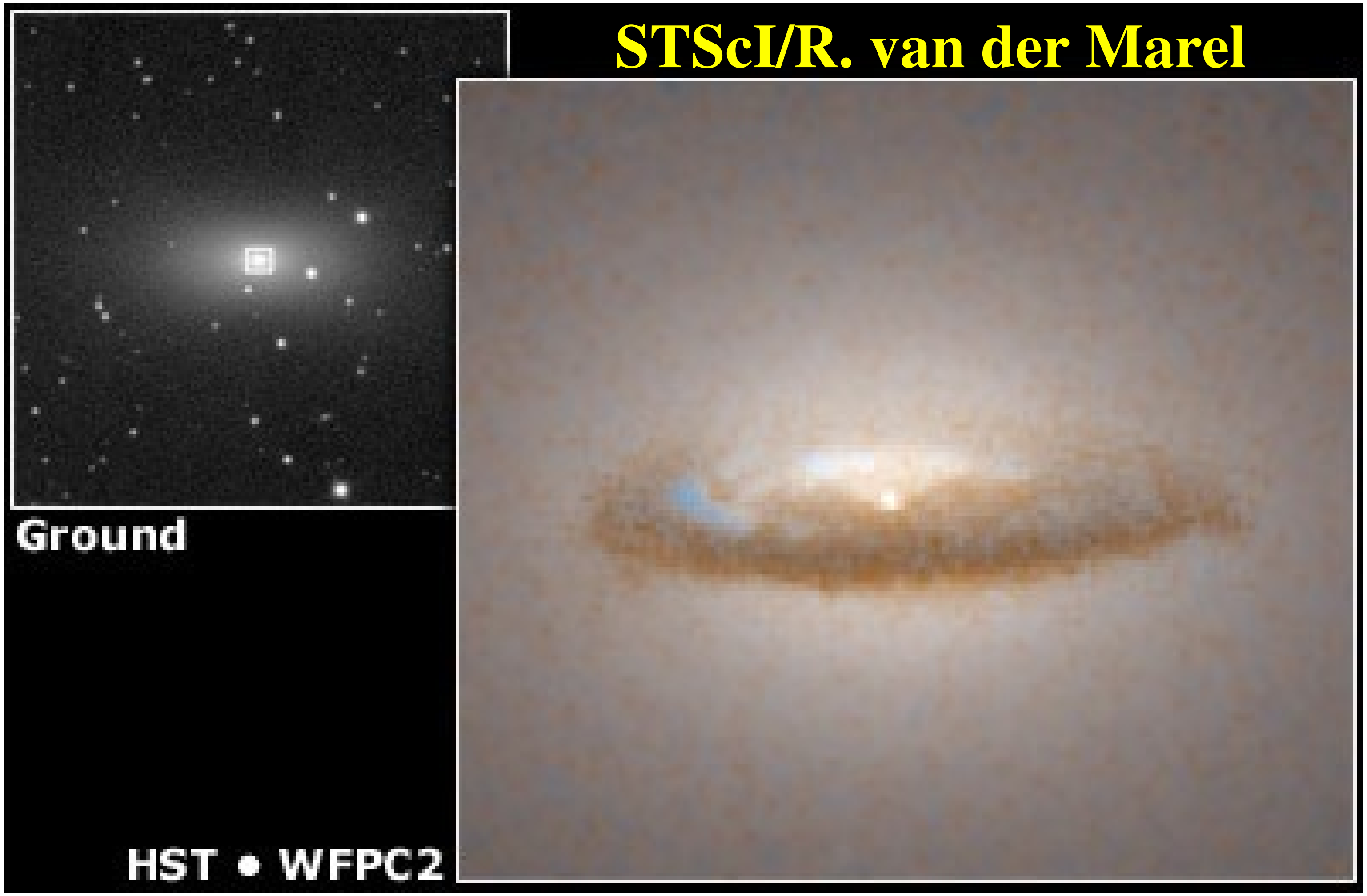
Elliptical galaxies and spiral galaxies with massive bulges all seem to have massive central black holes, whose masses follow a tight proportionality with velocity dispersion.

(Bulgeless disk galaxies do not follow the same relation.)

Tremaine et al. (2002)

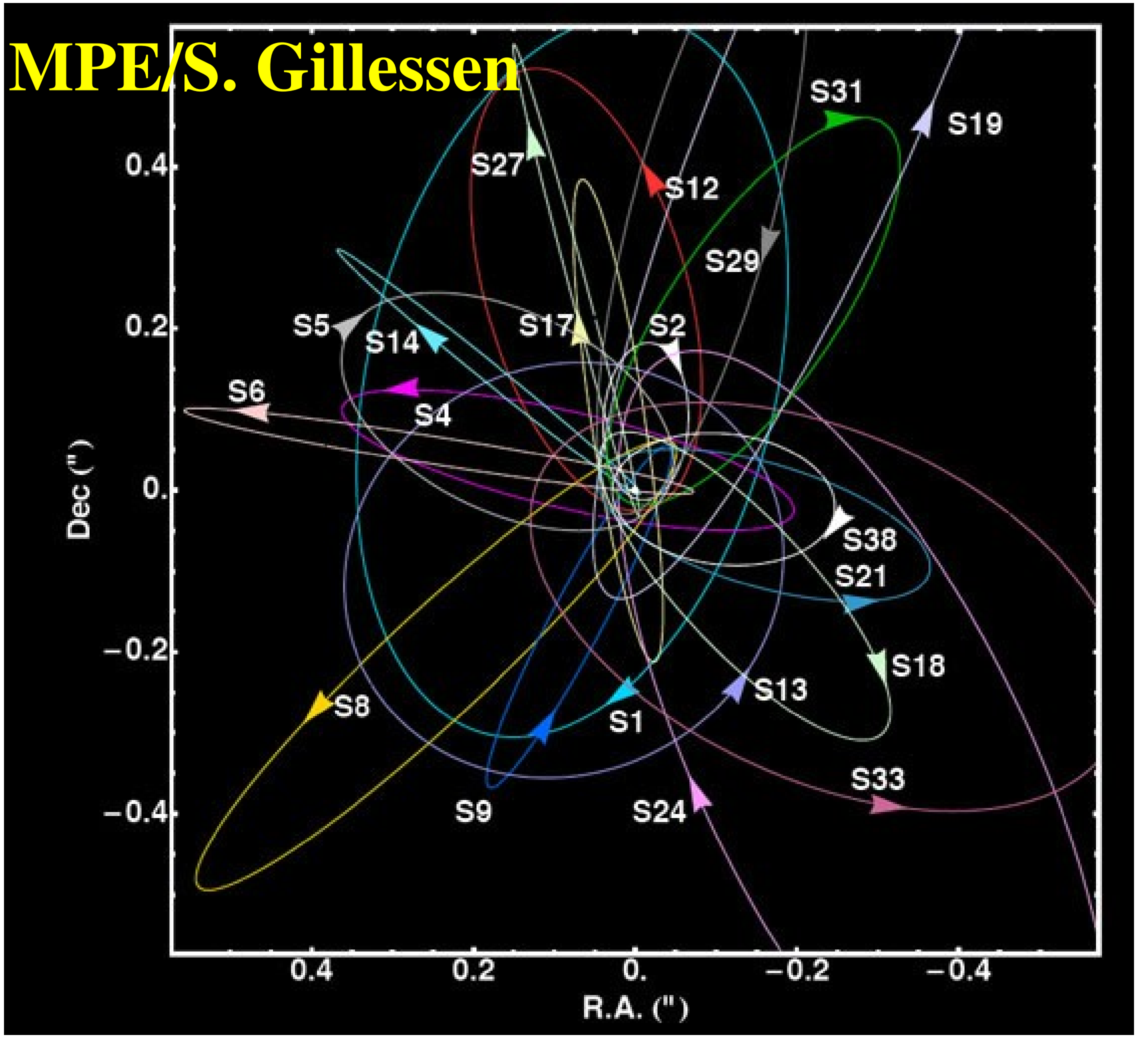


Measuring black hole masses



Some black hole masses are measured via gas dynamics, using the same equations you are using in lab # 2.

Measuring black hole masses



Milky Way's black hole mass has been measured by the proper motions of individual stars.

The Schwarzschild radius

As a reminder: a black hole is an object so massive that there is a Schwarzschild radius R_S from within with not even light can escape. (This is an example of an "event horizon", although not the only example.)

R_S can be derived by setting the escape velocity equal to c:

$$R_S = 2GM/c^2$$

(This is not a valid relativistic derivation, but it happens to yield the right answer!)

What happens to gas near a black hole?

Conservation of angular momentum means gas doesn't fall straight into the Schwarzschild radius.

Instead, potential energy (-*GMm/r* for a particle with mass *m* and distance *r* from the black hole) is slowly converted into thermal energy (i.e., heat) due to particle collisions. This is a process known as accretion.

What happens next?

Broadly speaking, there are two options...

Option # 1: radiatively inefficient accretion

The thermal energy can remain in the form of thermal energy (i.e., the accreting gas remains hot), or be converted into kinetic energy (i.e., turbulence/outflow).

In either case, little radiation emerges; astronomers refer to these situations as RIAFs (radiatively inefficient accretion flows).

The black hole at the center of the Milky Way drives a RIAF!

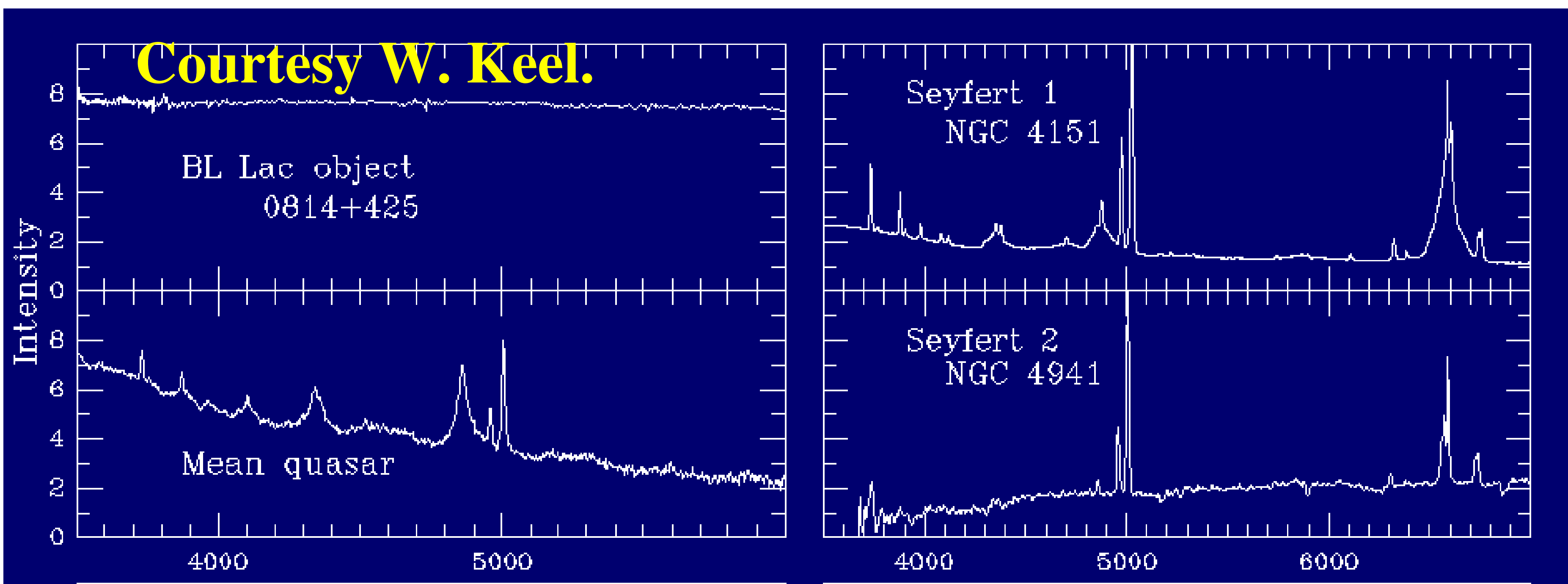
Option # 2: radiatively efficient accretion

The alternative scenario is that a large fraction of the thermal energy is converted to radiation. In this case, we have a radiatively efficient accretion flow, and can observe one or more consequences that mark the center of a galaxy as an active galactic nucleus (AGN; plural = "AGN" or [ugh...] "AGNs").

AGN in the optical

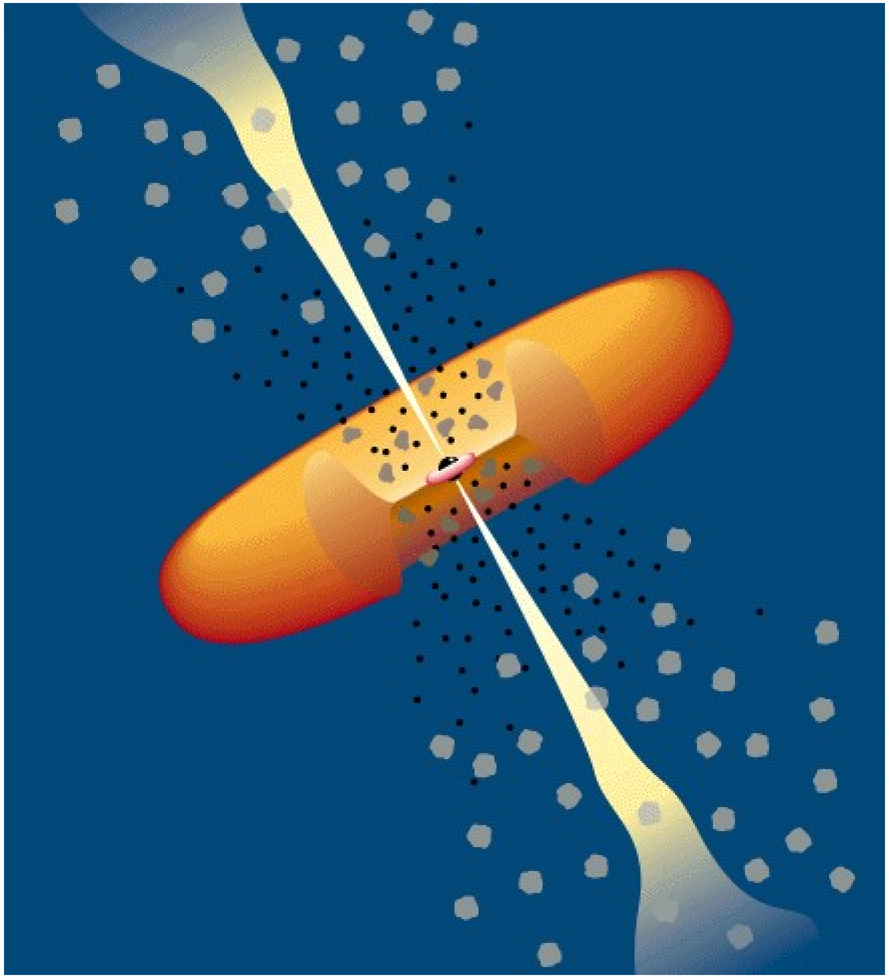
High-energy photons emerging from an AGN accretion flow (typically, an accretion disk) can ionize atoms in the surrounding gas.

Optically bright AGN are identified as Seyfert nuclei or quasars (quasi-stellar objects) depending on *L*.



AGN in the optical: type 1 vs. type 2

Some optically bright AGN show broad lines (> 1000 km/s in width) from ionized gas; others do not. Astronomers refer to these as "type 1" and "type 2" AGN.



Which we see depends on our viewing angle relative to a torus (i.e., doughnut) of cold, dusty molecular gas that can hide a broad-line region.

Courtesy M. Urry.

AGN in the X-ray

Sometimes the optical emission from ionized gas is so deeply enshrouded by dust (along all sightlines) that we can't detect an AGN in the optical at all!

In such cases, detecting high-energy photons directly in the X-ray may work better.

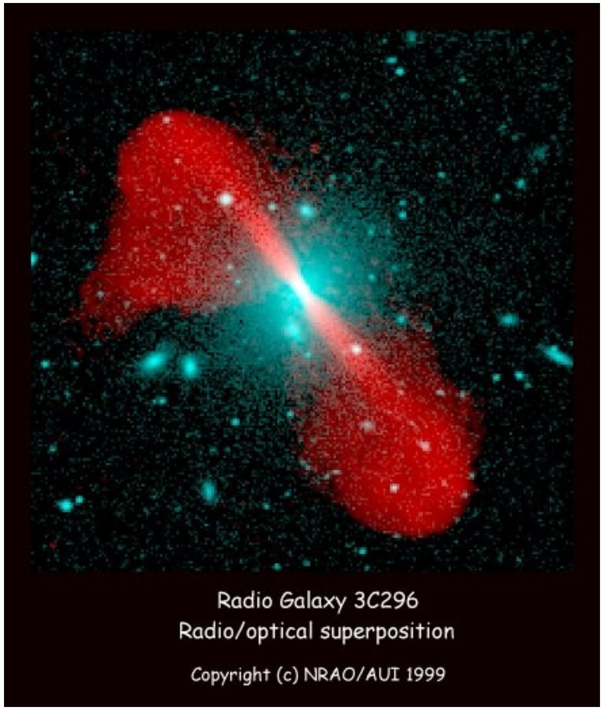
AGN in the radio

Independent of whether an AGN is type 1 or type 2 in the optical, or whether it shows X-ray emission or not, it may be either radio-loud or radio-quiet.

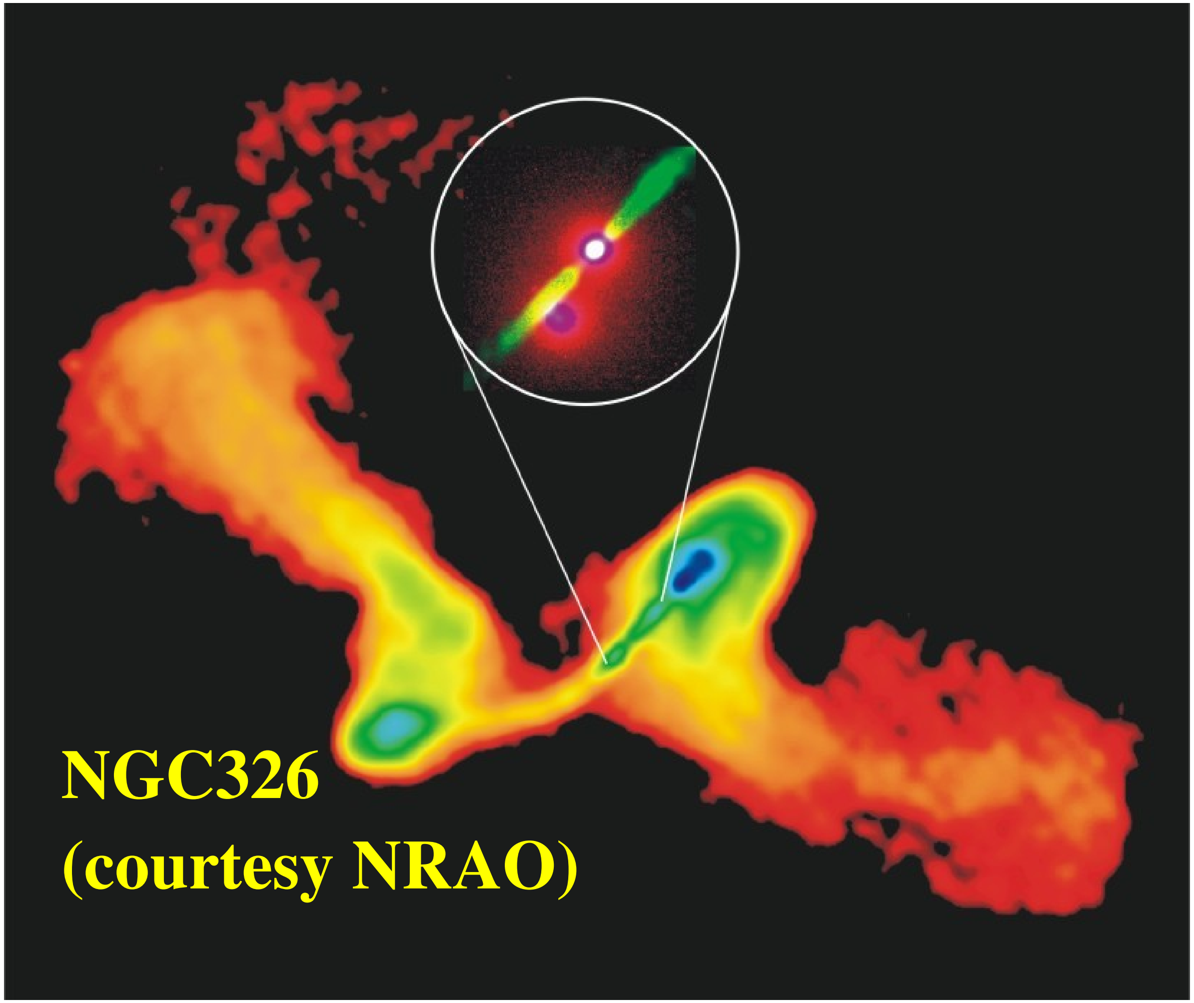
Radio emission is continuum emission due to synchrotron radiation (particles spiralling in a strong magnetic field... although precisely which particles is not always clear!).

Two categories of radio galaxies

Among radio-loud objects, we have
(1) Fanaroff-Riley type I ("FRI") objects that are core-dominated
(2) Fanaroff-Riley type II ("FRII") objects that are lobe-dominated



Some FRII sources are “X-shaped”



Main map = radio from Very Large Array; inset = optical from *Hubble Space Telescope*.

Are we seeing evidence of post-merger black hole spin flip?

VLBI mapping of radio galaxies

Very long baseline interferometry (VLBI) can be used to study the central parts of AGN: the emission is so strong on small scales that even intercontinental baselines can detect it!

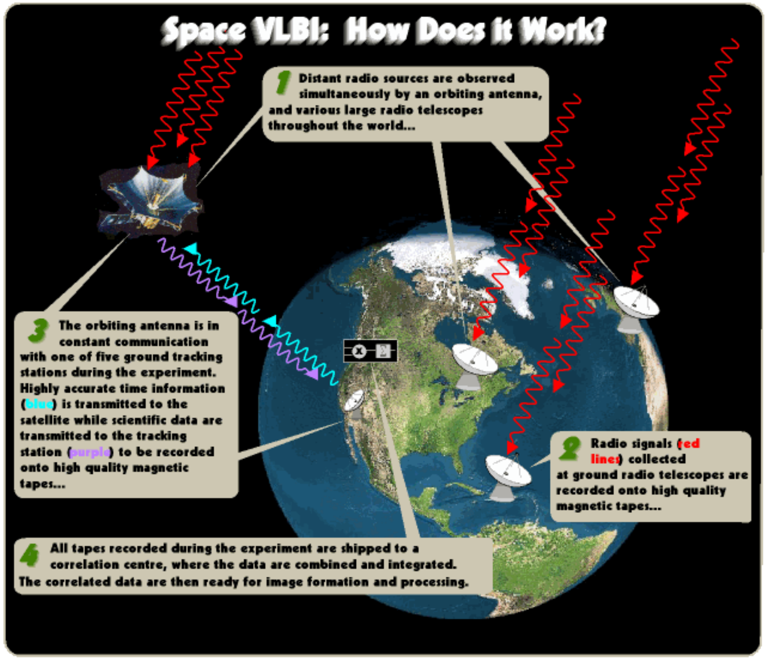
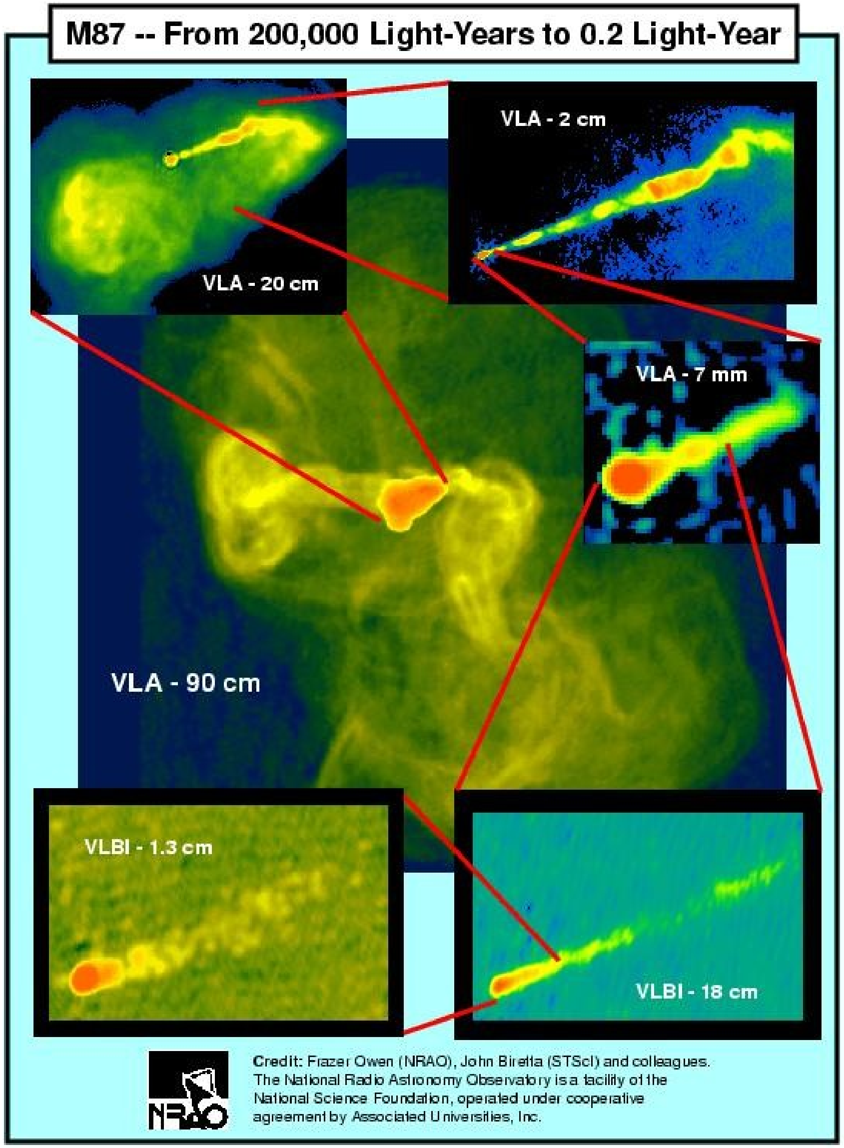


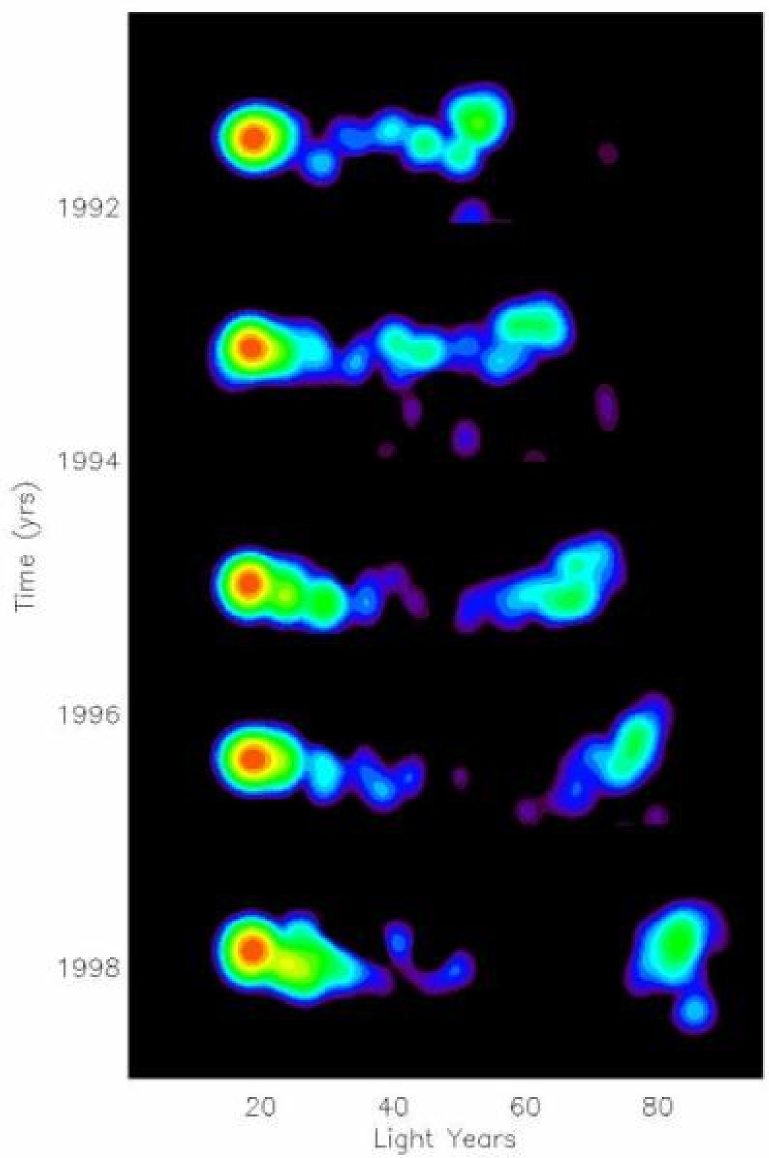
Exhibit A: M87 in the Virgo Cluster



Mapped with the VLA and the VLBA: note λ/B trends!

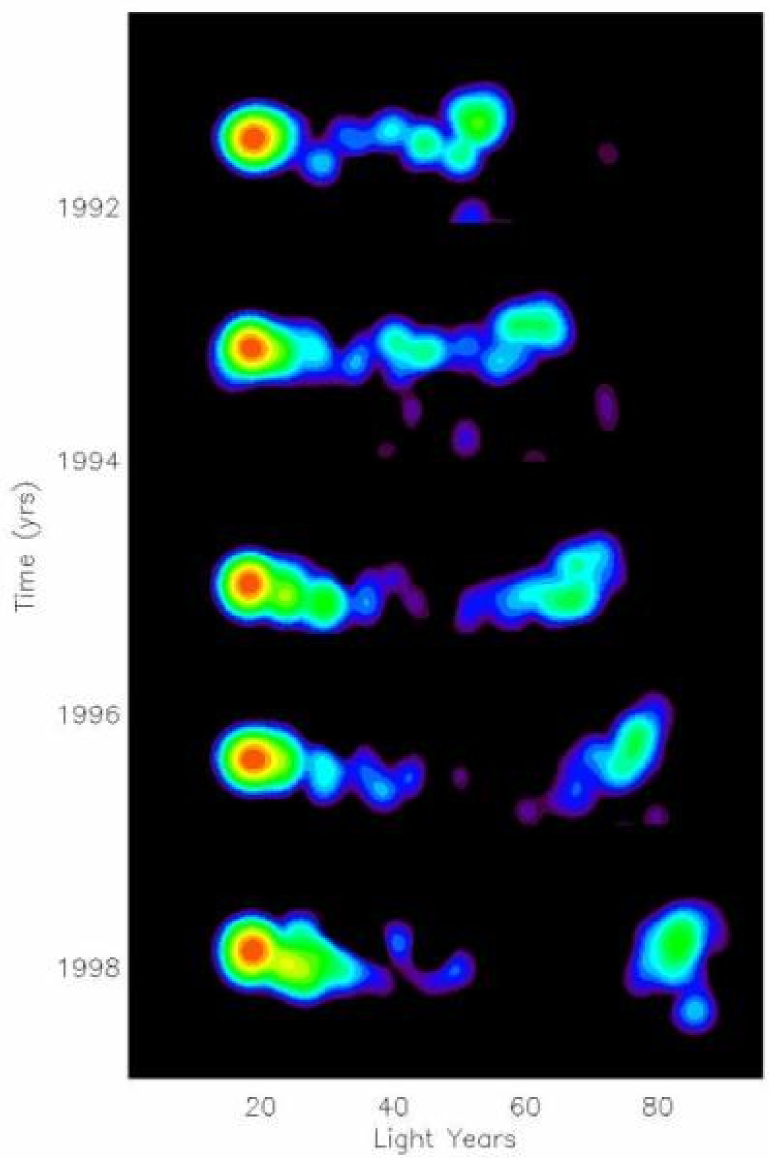
We can watch jets evolve in real time!

Example: VLBI observations of 3C279 reveal that blobs of radio-emitting plasma move 25 light-years in projection on the sky over the course of seven years of observations.

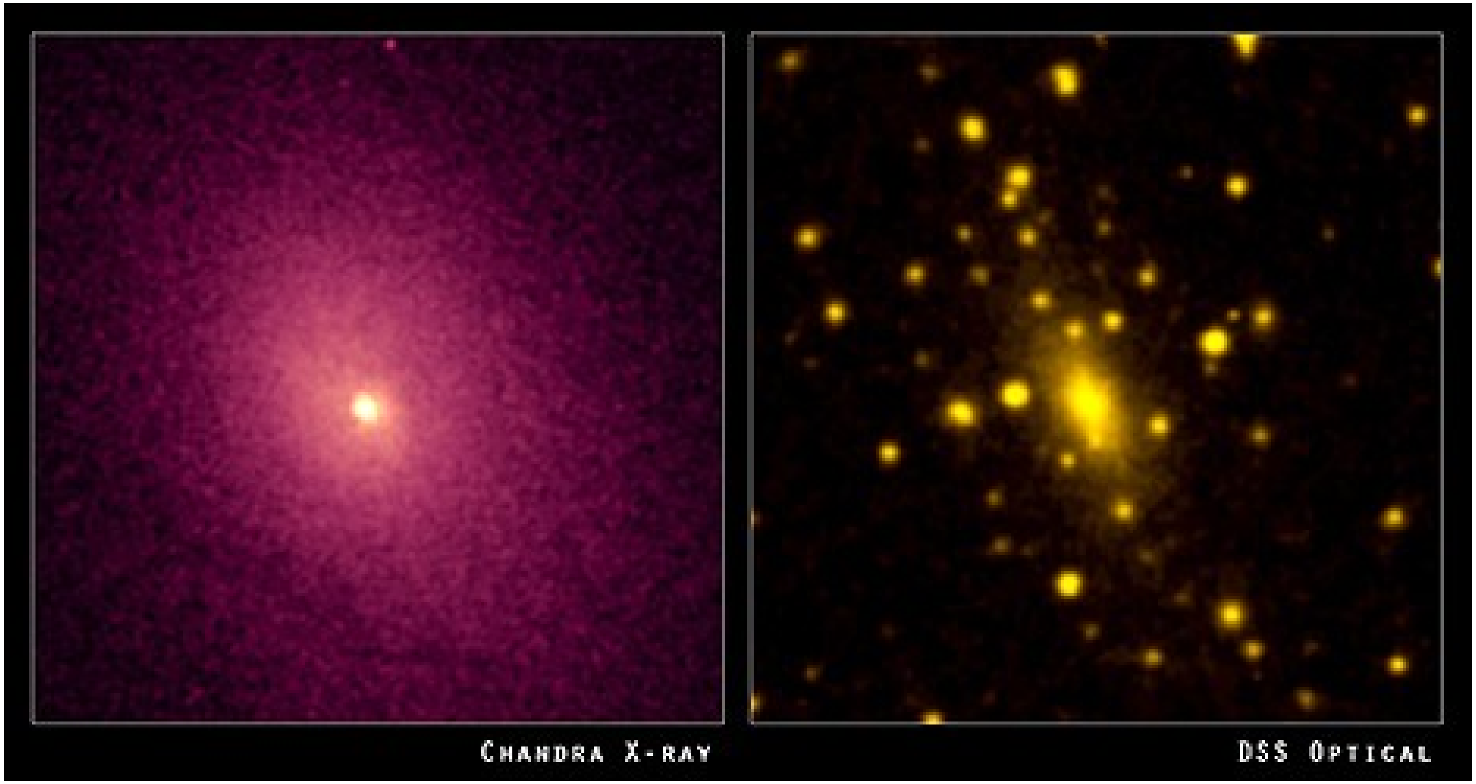


“Superluminal” motion: an optical illusion

Motion along the line of sight accounts for the apparent velocity > *c*.

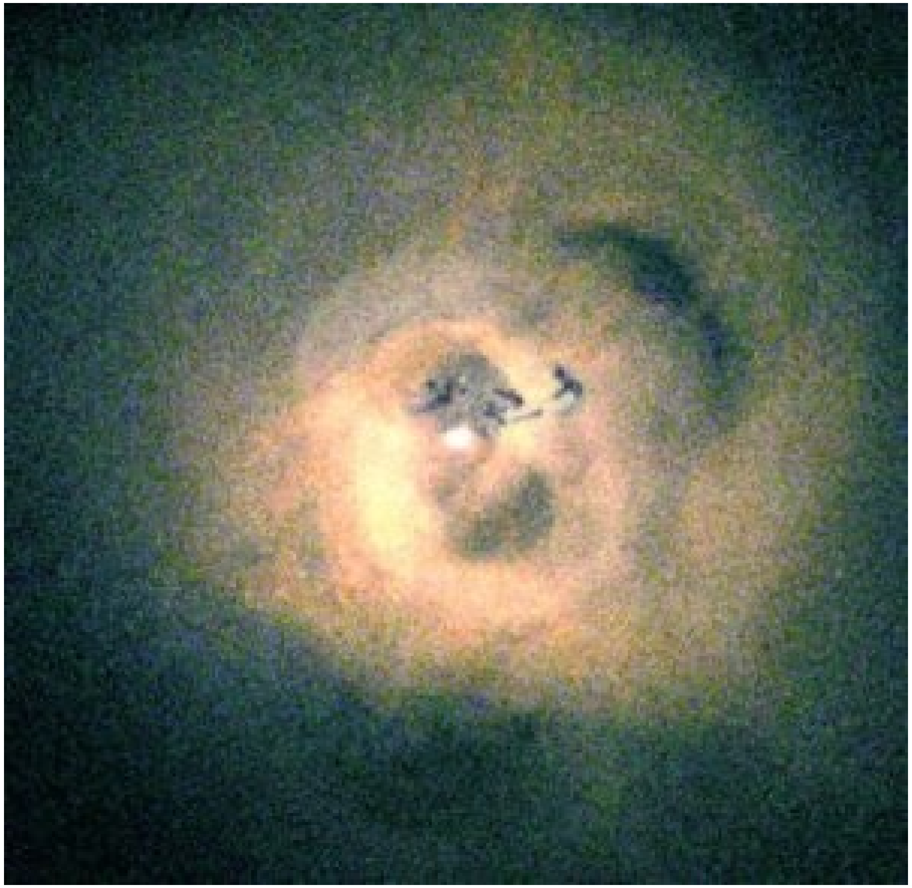


Galaxy clusters



Galaxy clusters have most of their (ordinary, baryonic) mass in the form of hot intracluster gas. Why doesn't this cool, flow to the center, and form stars in the central elliptical?

AGN feedback



Deep X-ray imaging of many clusters (here, the Perseus Cluster) shows shells and bubbles.

We think these were produced in past radio-loud events: a jet in the central elliptical turns on when the black hole is fed, driving away further fuel until it shuts itself off.

Use bent jets to find new clusters?

Radio jets + X-ray emission from hot intracluster gas: jets are bent as galaxies fall into clusters.

Horseshoe-shaped jets may mark the locations of undiscovered clusters!