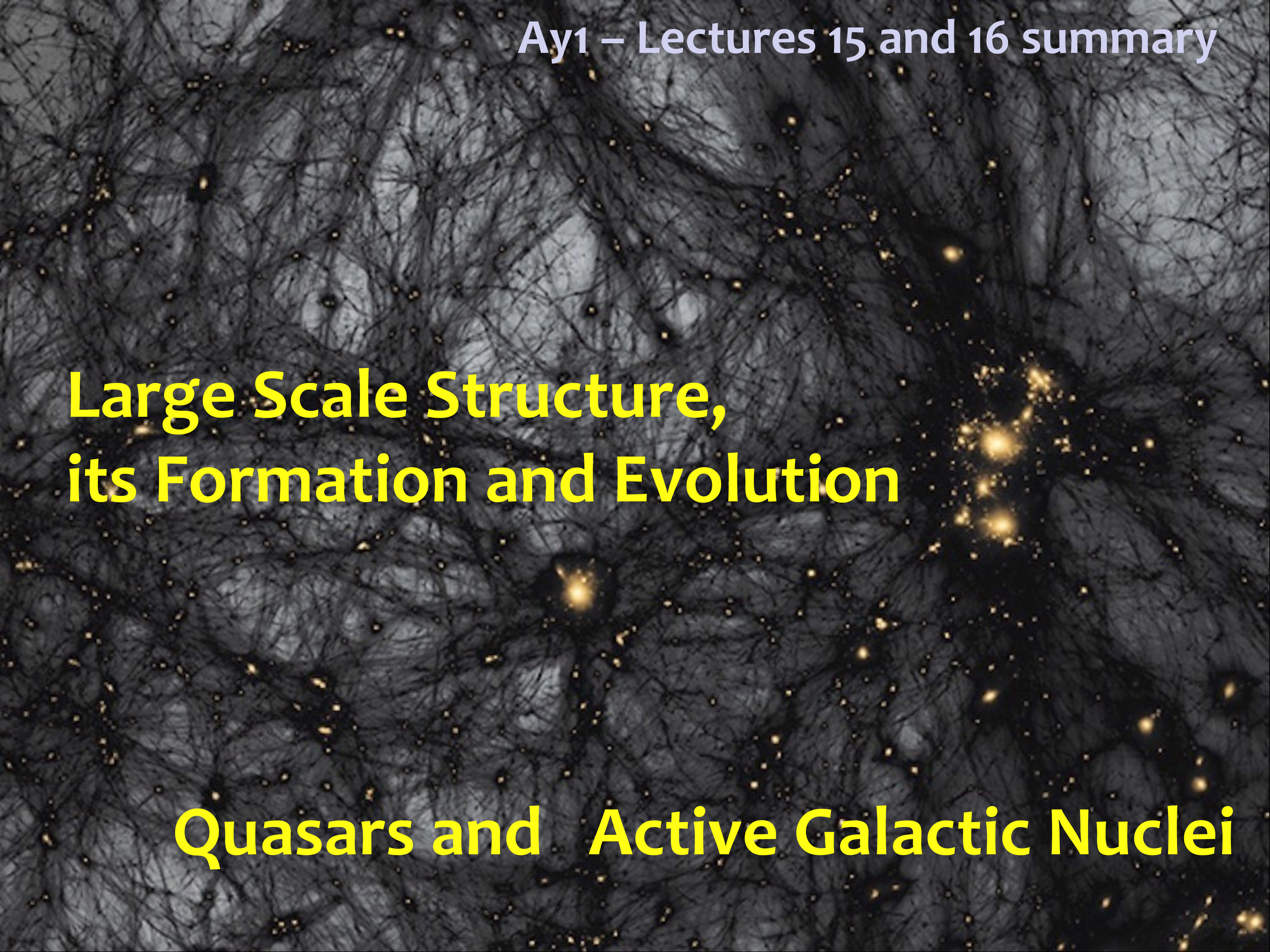
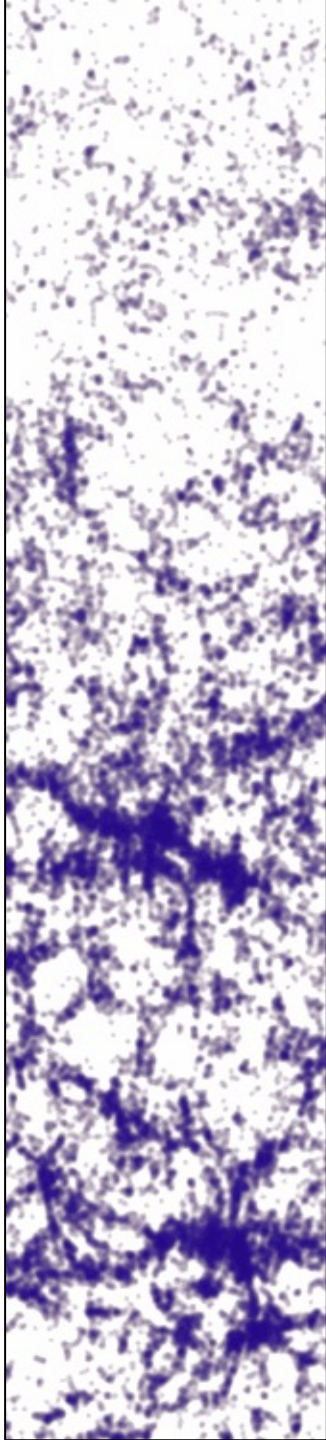


Ay1 – Lectures 15 and 16 summary

Large Scale Structure, its Formation and Evolution

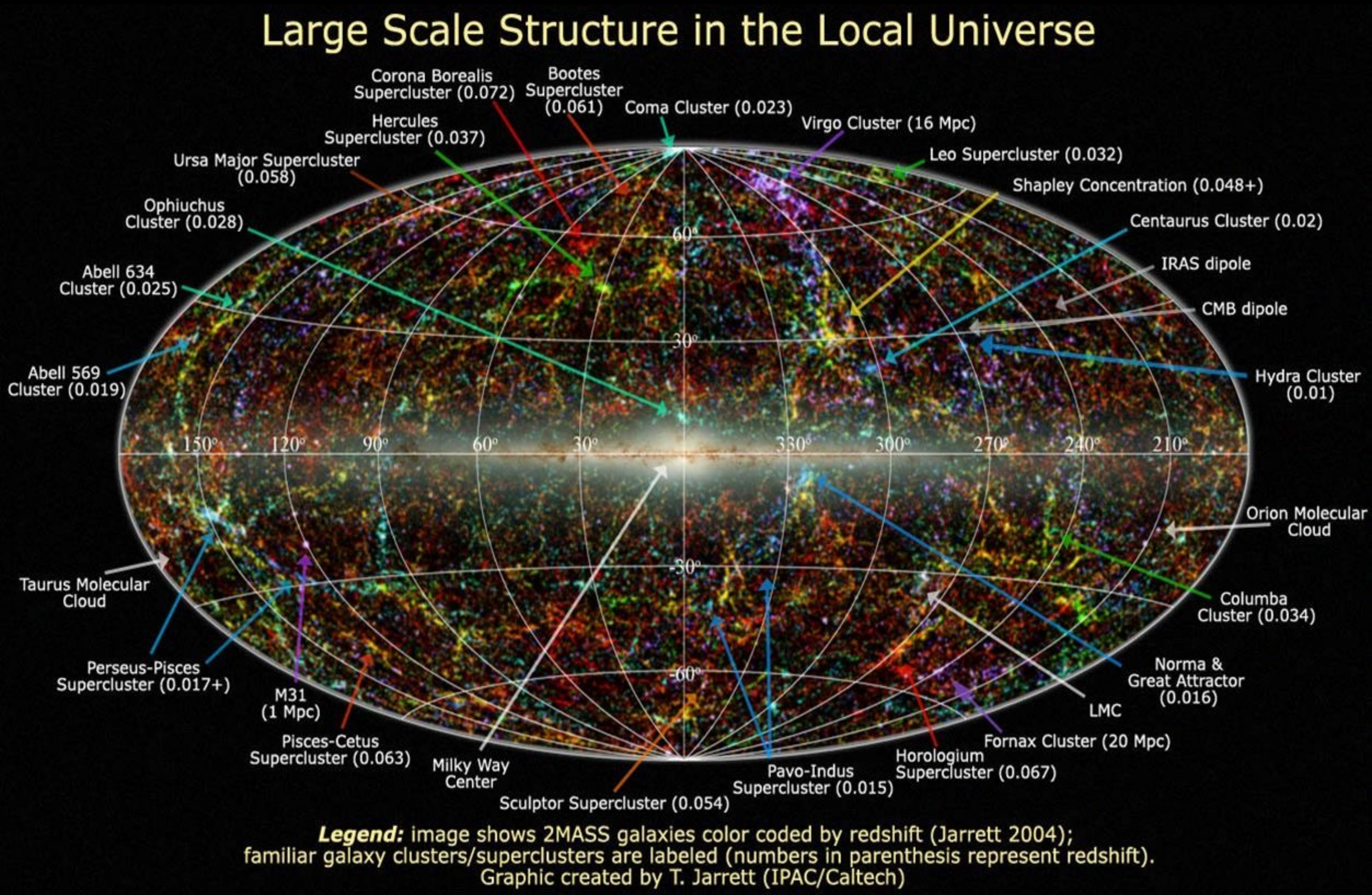
Quasars and Active Galactic Nuclei

Large-Scale Structure



- Density fluctuations in the early universe evolve into structures we observe: galaxies, clusters, etc.
- On scales > galaxies, we talk about the **Large Scale Structure (LSS);** groups, clusters, filaments, walls, voids, superclusters are the elements of it
- To map and quantify the LSS (and compare with the theoretical predictions), we need **redshift surveys**: mapping the 3-D distribution of galaxies in the space
  - Redshifts are a measure of distance in cosmology
  - We now have redshifts measured for ~ 2 million galaxies
- The existence of clusters was recognized early on, but it took a while to recognize that galaxies are not distributed in space uniformly randomly, but in coherent structures

A View From Our Galaxy in the Near-IR

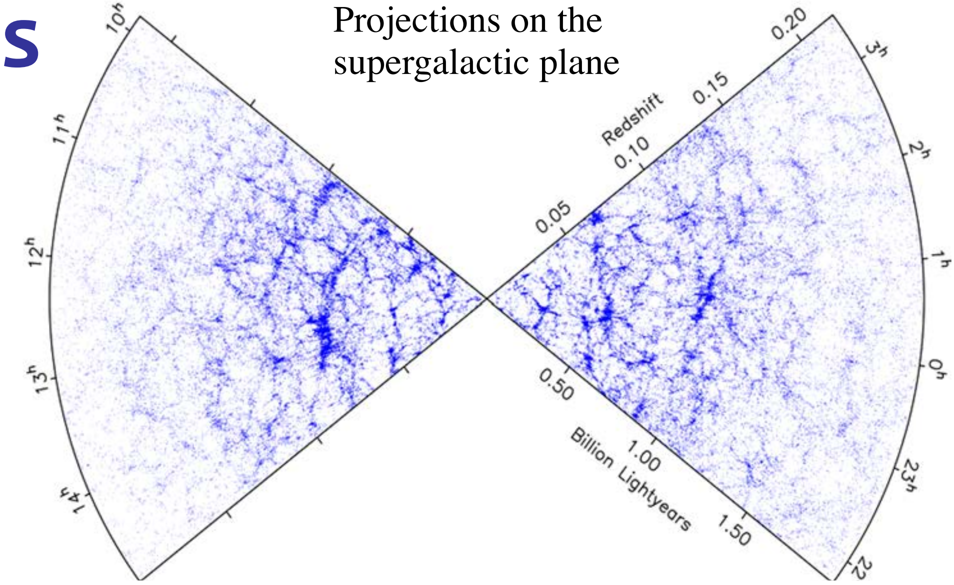


Large Scale Structure in the Local Universe

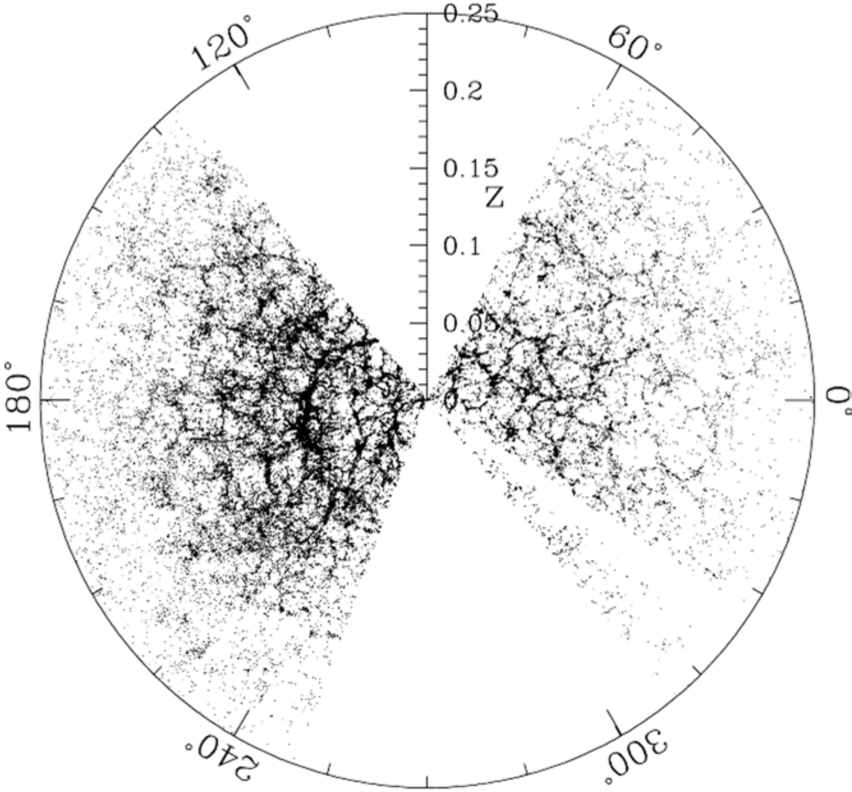
Legend: image shows 2MASS galaxies color coded by redshift (Jarrett 2004); familiar galaxy clusters/superclusters are labeled (numbers in parenthesis represent redshift). Graphic created by T. Jarrett (IPAC/Caltech)

Huge Redshift Surveys

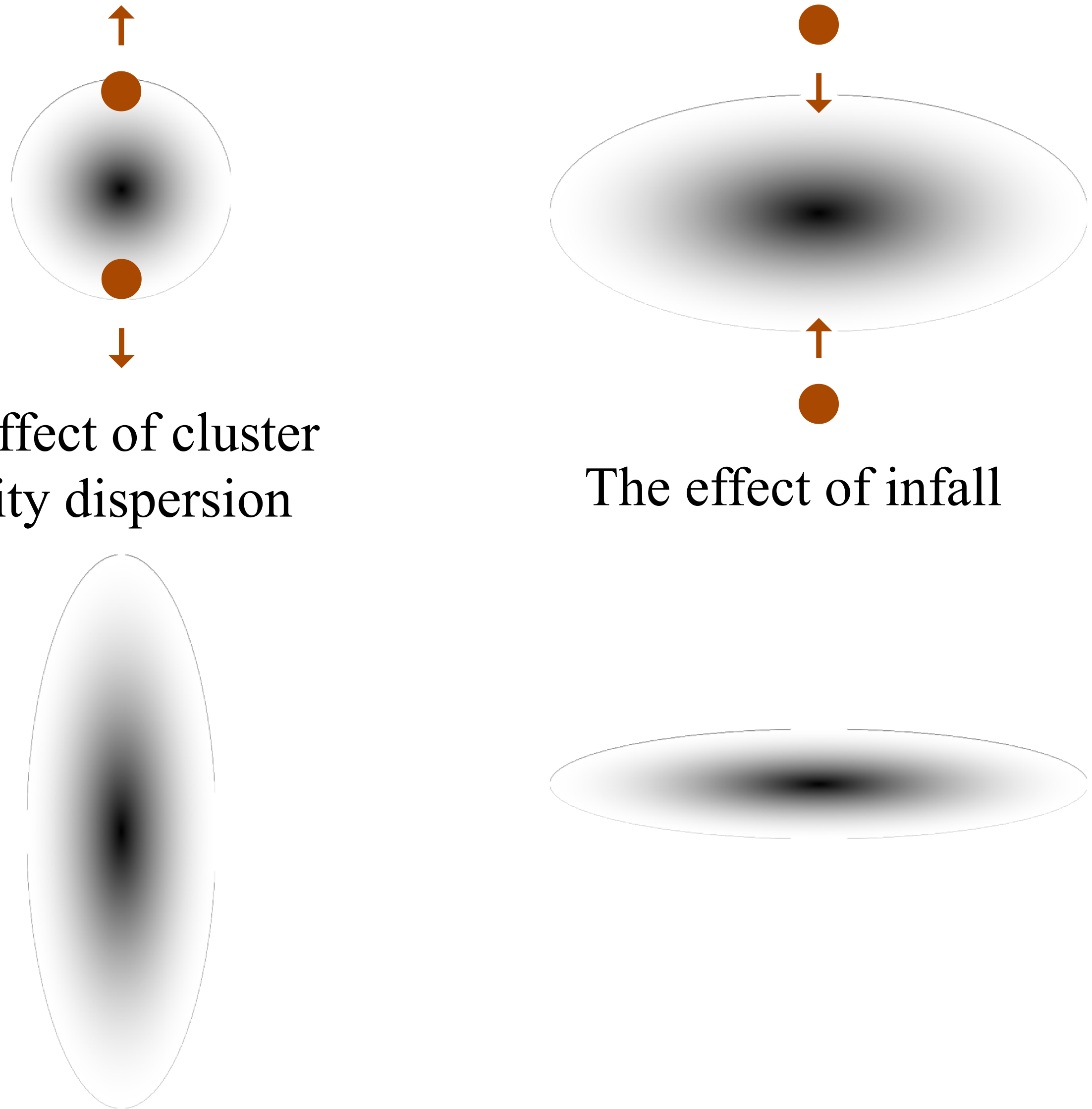
- **The 2dF (2 degree Field) redshift survey** with the 3.9-m Anglo-Australian telescope: ~250,000 galaxies to *z* ~ 0.3, and ~25,000 QSOs out to z ~ 2.3, covering 5% of the sky
- **The Sloan Digital Sky Survey (SDSS)** with a 2.5-m telescope at Apache Point Observatory in NM: multicolor imaging to *r* ~ 23 mag (~ 1 billion objects), spectra of ~1.5 million galaxies out to *z* ~ 1, ~0.5 million QSOs out to z ~ 6.5, and ~0.8 million stars, covering a third of the sky



Projections on the supergalactic plane



Redshift Space vs. Real Space



“Fingers of God”

Thin filaments

Real space
distribution

The effect of cluster
velocity dispersion

The effect of infall

Redshift space
apparent distrib.

Galaxy Distribution and Correlations

- If galaxies are clustered, they are "correlated"
- This is usually quantified using the ***2-point correlation function***, ***$\xi(r)$***, defined as an "excess probability" of finding another galaxy at a distance ***r*** from some galaxy, relative to a uniform random distribution; averaged over the entire set:

$$dN(r) = \rho_0 \left(1 + \xi(r)\right) dV_1 dV_2$$

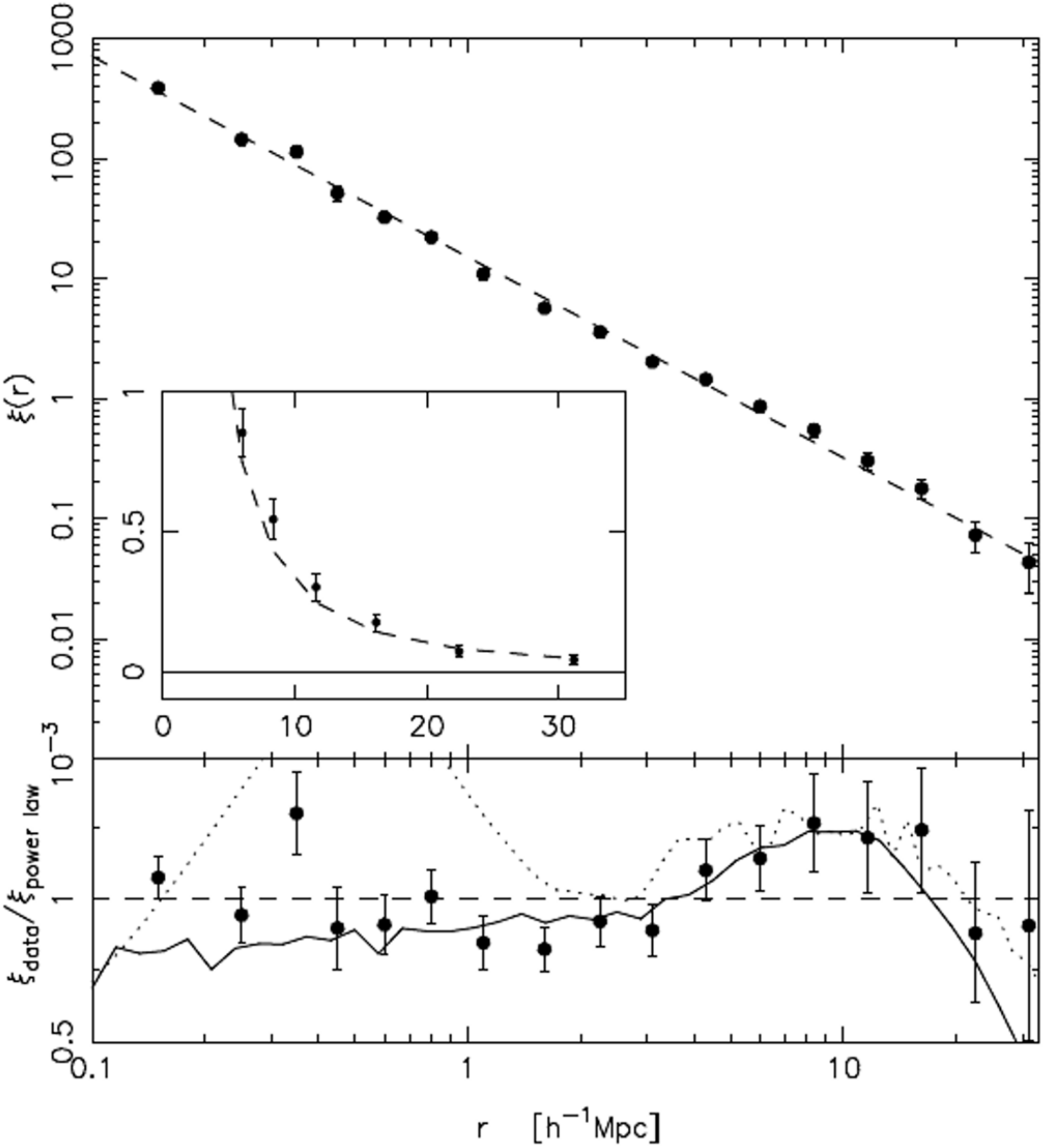
- Usually represented as a power-law:

$$\xi(r) = \left(r / r_0\right)^{-\gamma}$$

- For galaxies, typical *correlation or clustering length* is $\boldsymbol{r_0} \sim 5$ h^{-1} Mpc, and typical slope is $\gamma \approx 1.8$, but these are functions of various galaxy properties; clustering of clusters is stronger

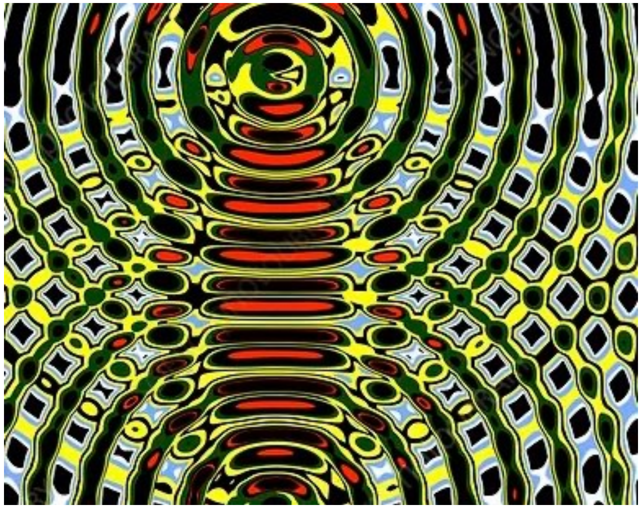
Galaxy Correlation Function

As measured by the 2dF redshift survey

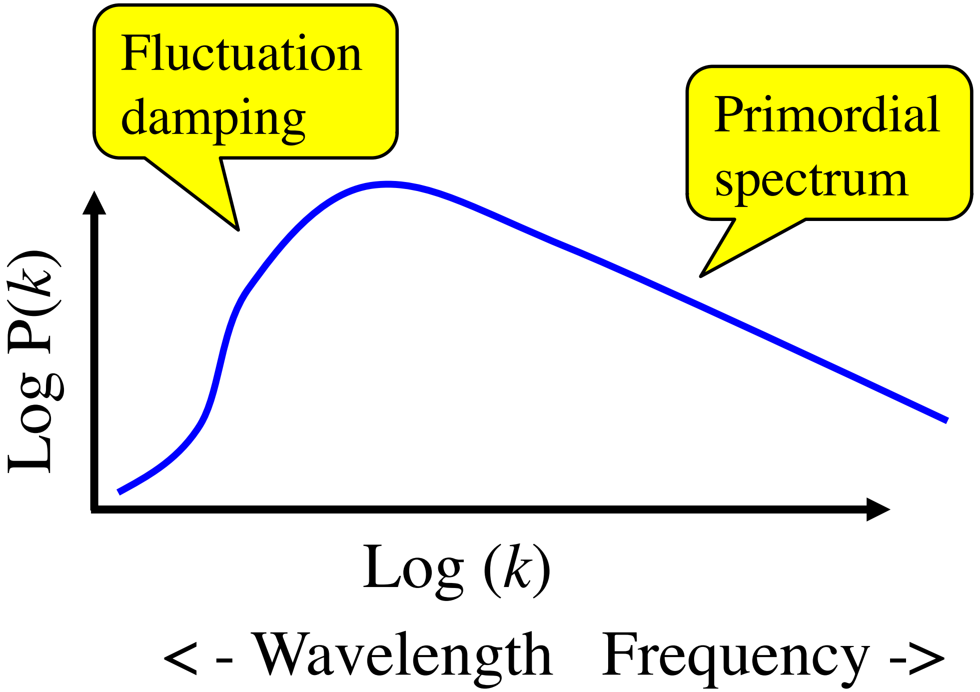


Deviations from the power law:

Power Spectrum of Galaxy Clustering

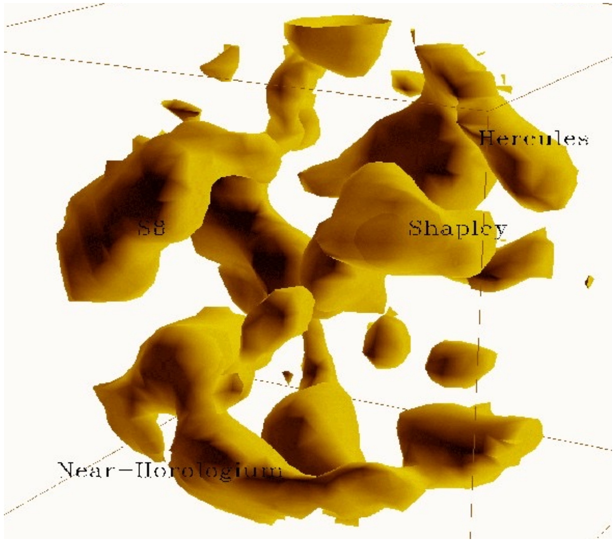


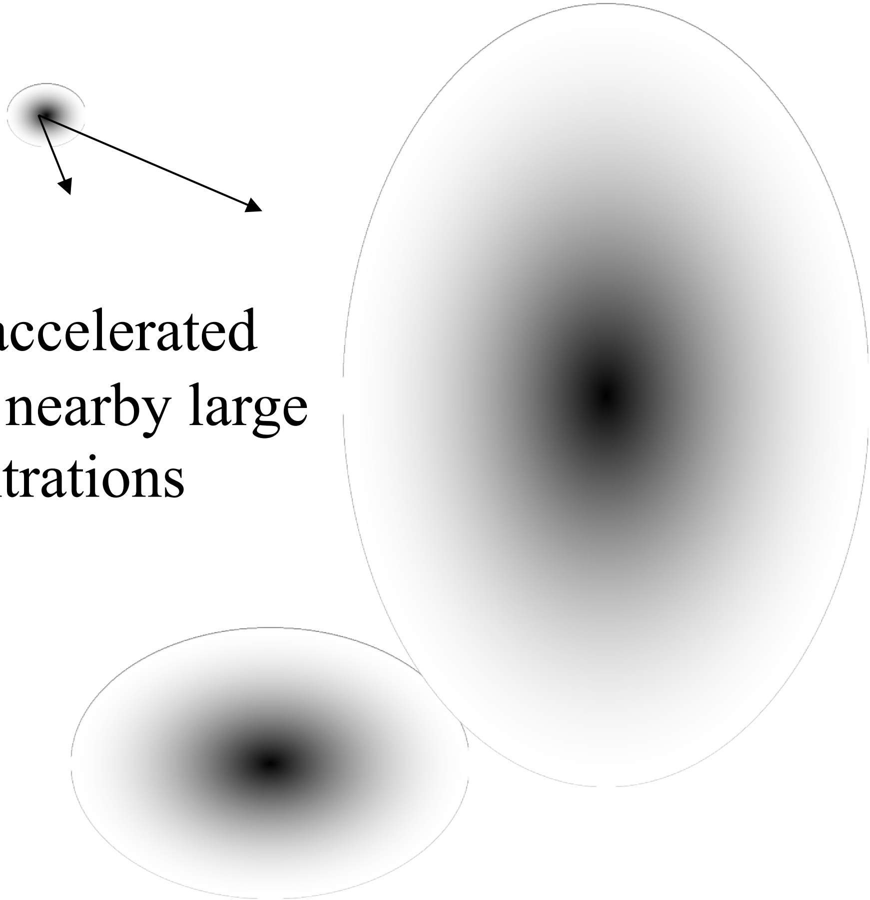
- A more modern alternative to the 2-point correlation function is the Fourier Power Spectrum of the galaxy density field
- The overall density is expressed as a sum of density waves with varying spatial frequencies and amplitudes
- The power spectrum tells us how much mass is clumped on what spatial scale
- It can be directly connected to theoretical predictions
- Power spectrum and the correlation function are a Fourier pair



Large-Scale Density Field Inevitably Generates a Peculiar Velocity Field

The PSCz survey
local 3-D density field





A galaxy is accelerated towards the nearby large mass concentrations

Integrated over the Hubble time, this results in a peculiar velocity

The pattern of peculiar velocities should thus reflect the underlying mass density field

How to Measure Peculiar Velocities?

1. Using distances and residuals from the Hubble flow:

$$V_{total} = V_{Hubble} + V_{pec} = H_0 D + V_{pec}$$

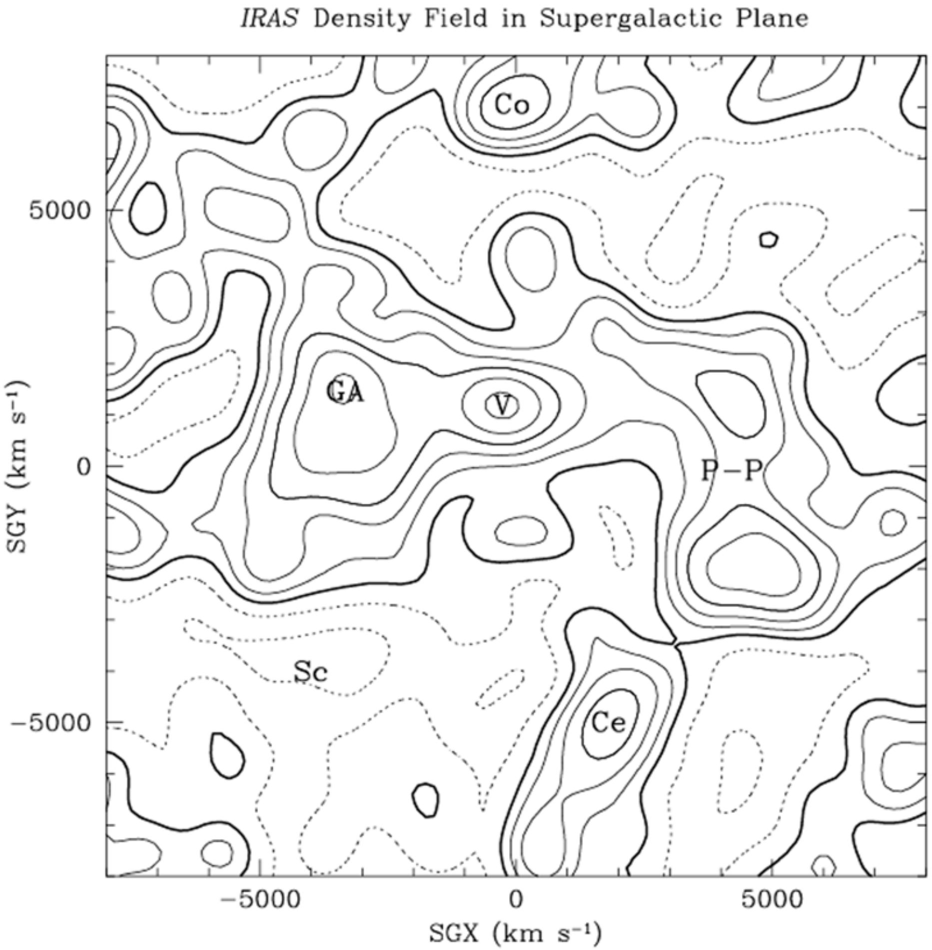
- So, if you know relative distances, e.g., from Tully-Fisher, or D_n-σ relation, SBF, SNe, …you could derive peculiar velocities
- A problem: distances are seldom known to better than ~10% (or even 20%), multiply that by V_{Hubble} to get the error of V_{pec}
- Often done for clusters, to average out the errors, but there could be systematic errors - distance indicators may vary in different environments

2. Statistically from a redshift survey

- Model-dependent

Measuring Peculiar Velocity Field Using a Redshift Survey

- Assume that galaxies are where their redshifts imply; this gives you a density field
- You need a model on how the light traces the mass
- Evaluate the accelerations for all galaxies, and their esimated peculiar velocities
- Update the positions according to new Hubble velocities
- Iterate until the convergence
- You get a consistent density and velocity field



Peculiar Velocities: Summary

- Measurements of peculiar velocities are very, very tricky
  - Use (relative) distances to galaxies + Hubble flow
  - Use a redshift survey + numerical modeling
- **Several general results**:
  - We are falling towards Virgo with ~ 300 km/s, and will get there in about 10 - 15 Gyr
  - Our peculiar velocity dipole relative to CMB originates from within ~ 50 Mpc
  - The LSC is falling towards the Hydra-Centaurus Supercluster, with a speed of up to 500 km/s
  - The whole local ~ 100 Mpc volume may be falling towards a larger, more distant Shappley Concentration (of clusters)
- The mass and the light seem to be distributed in the same way on large scales (here and now)

Galaxy Biasing

Suppose that the density fluctuations in mass and in light are not the same, but

$$(\Delta\rho/\rho)_{light} = b\,(\Delta\rho/\rho)_{mass}$$

Or:

$$\xi(r)_{light} = b^2\,\xi(r)_{mass}$$

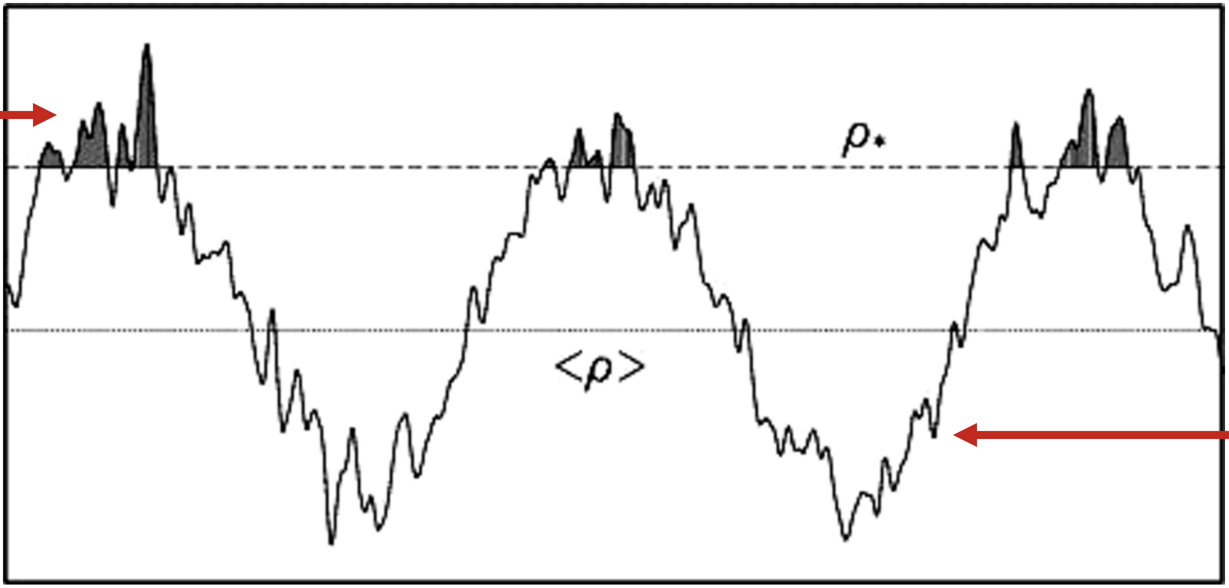
Here ***b*** is the *bias factor*.

If $b = 1$, light traces mass exactly (this is indeed the case at $z \sim 0$, at scales larger than the individual galaxy halos). If $b > 1$, light is a *biased tracer* of mass.

One possible mechanism for this is if the galaxies form at the densest spots, i.e., the highest peaks of the density field. Then, density fluctuations containing galaxies would not be typical, but rather a biased representation of the underlying mass density field; if 1-σ fluctuations are typical, 5-σ ones certainly are not.

High Density Peaks as Biased Tracers

Take a cut through a density field. Smaller fluctuations ride atop of the larger density waves, which lift them up in bunches; thus the highest peaks (densest fluctuations) are a priori clustered more strongly than the average ones:

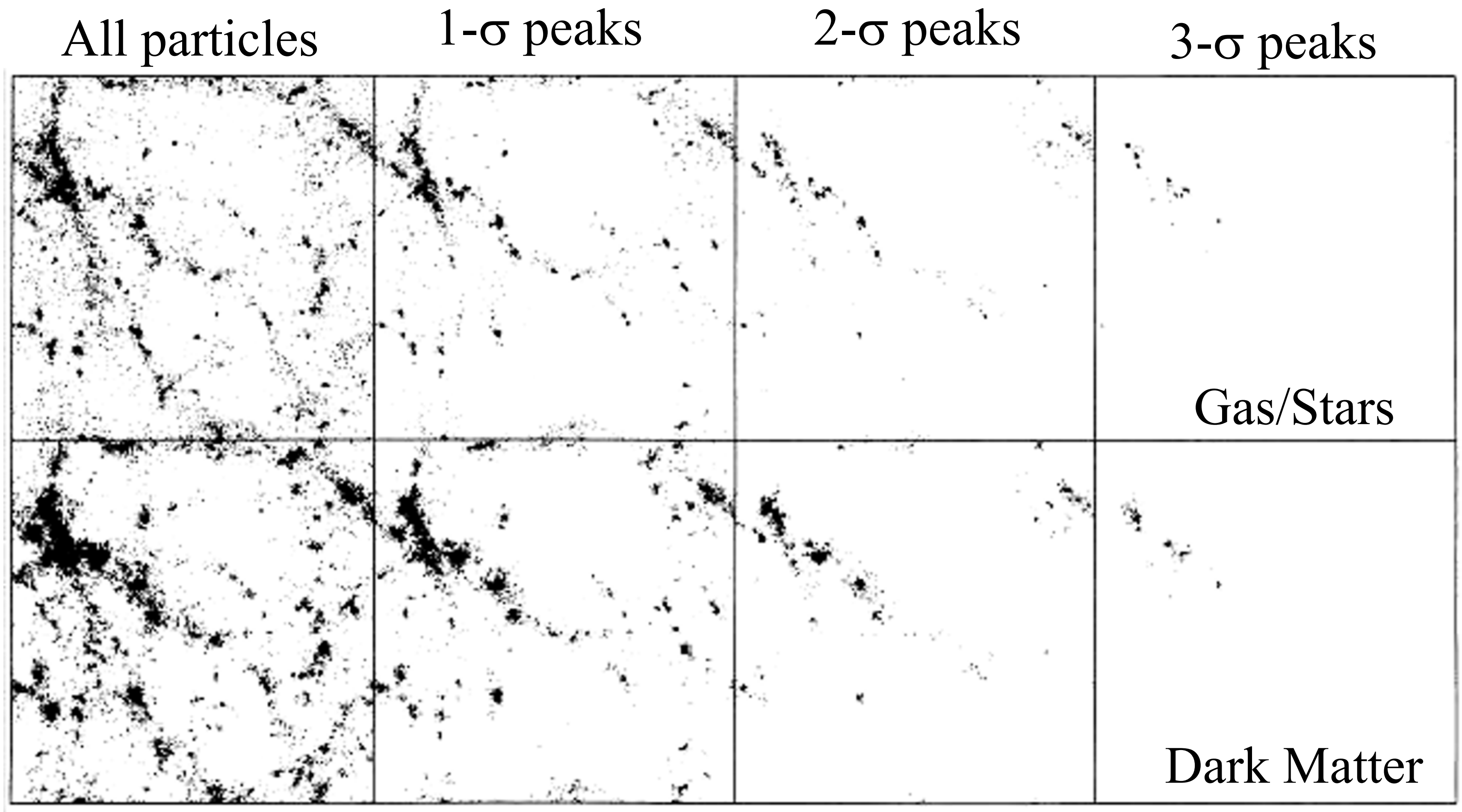


Proto-cluster

Proto-void

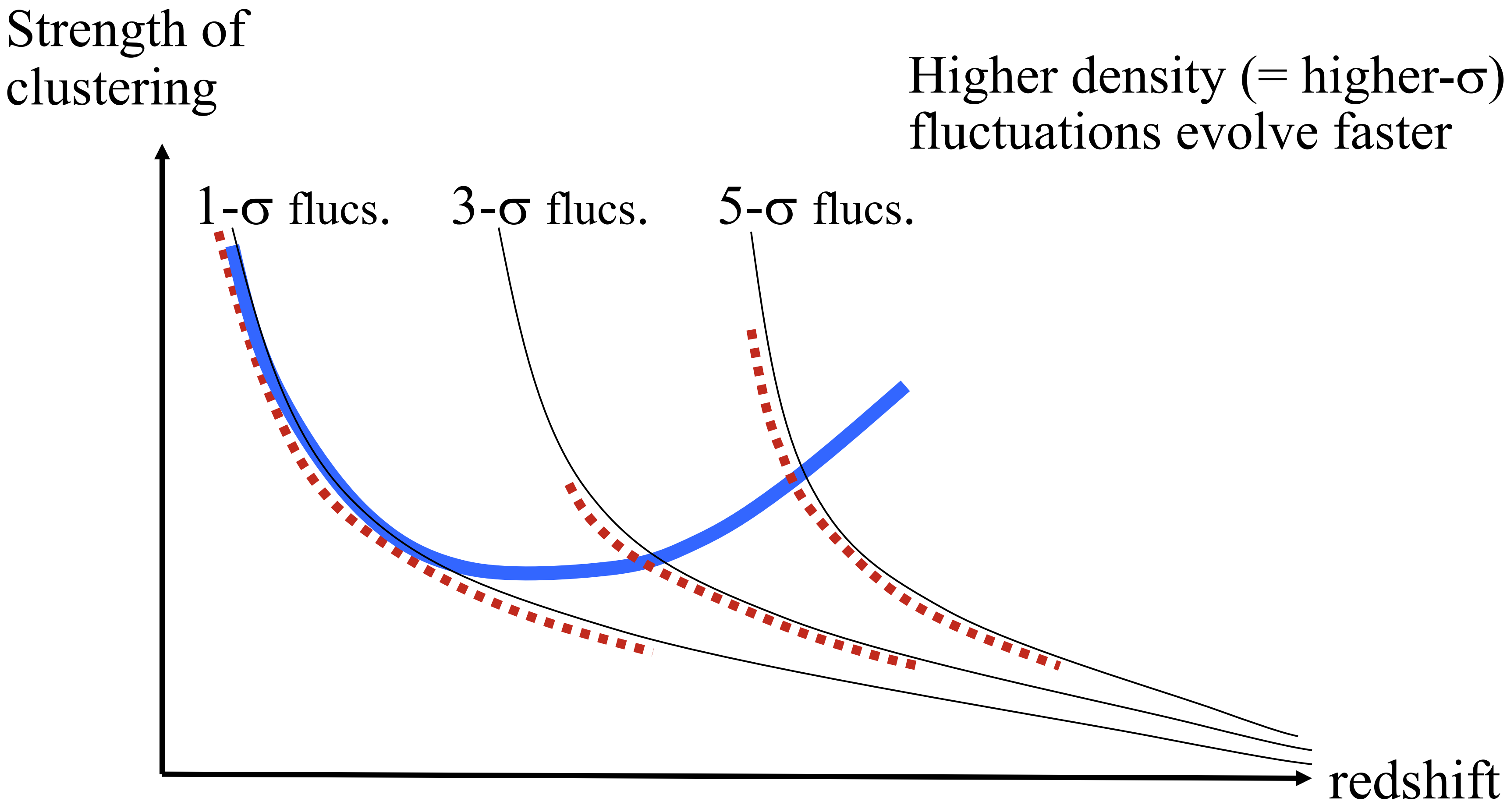
Thus, if the first galaxies form in the densest spots, they will be strongly clustered, but these will be very special regions.

An Example From a Numerical Simulation



(From an N-body simulation by R. Carlberg)

Biasing and Clustering Evolution



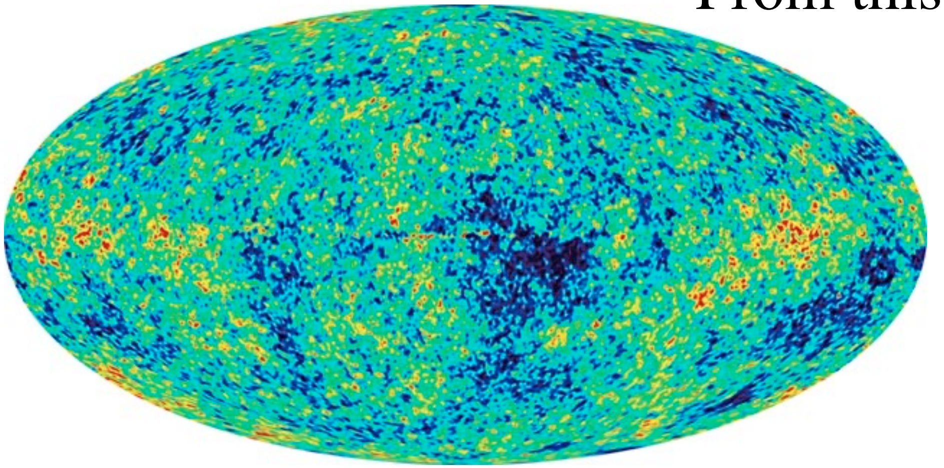
Higher density (= higher-σ) fluctuations evolve faster

At progressively higher redshifts, we see higher density fluctuations, which are intrinsically clustered more strongly …

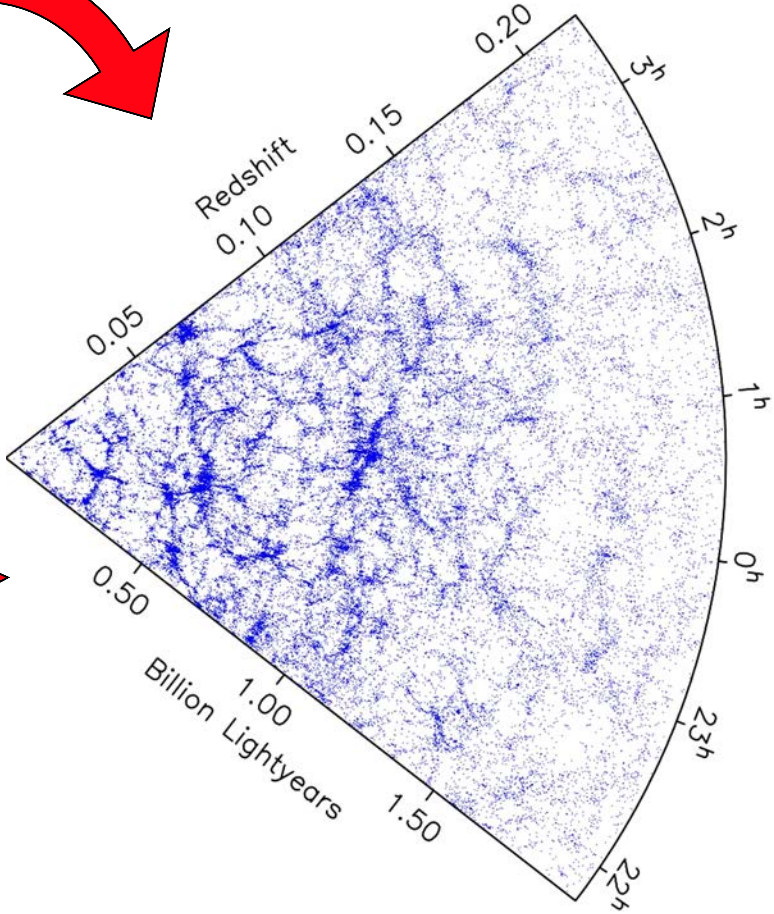
Thus the net strength of clustering seems to increase at higher z's

Structure Formation and Evolution

From this $(\Delta\rho/\rho \sim 10^{-6})$



to this
$(\Delta\rho/\rho \sim 10^{+2})$



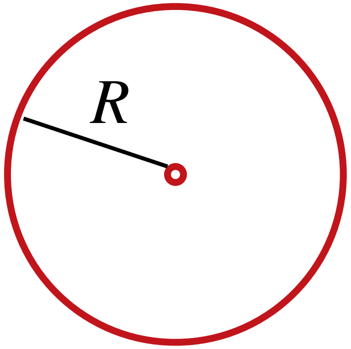
to this
$(\Delta\rho/\rho \sim 10^{+6})$

Origin of Structure in the Universe

- Origin and evolution of the structure in the universe (galaxies, large-scale structures) is a central problem in cosmology
- Structure is generally thought to arise through a growth of density perturbations which originate in the early universe
  - We think they came from quantum fluctuations in the scalar field that caused inflation, and were then amplified by the exponential inflation of the universe
- What do we know about the early structure formation?
  - We see CMB fluctuations with $\delta T/T \sim 10^{-6} \sim \Delta\rho/\rho$, since radiation and baryons are coupled before recombination
  - High-z objects: We observe galaxies and quasars at $z > 6$. A galaxy requires an overdensity of $\sim 10^{6}$ relative to the mean

How Long Does It Take?

The (dissipationless) gravitational collapse timescale is on the order of the free-fall time, t_{ff}:



The outermost shell has acceleration $g = GM/R^2$
It falls to the center in:

$$t_{ff} = (2R/g)^{1/2} = (2R^3/GM)^{1/2} \approx (2/G\rho)^{1/2}$$

Thus, low density lumps collapse more slowly than high density ones. More massive structures are generally less dense, take longer to collapse. For example:

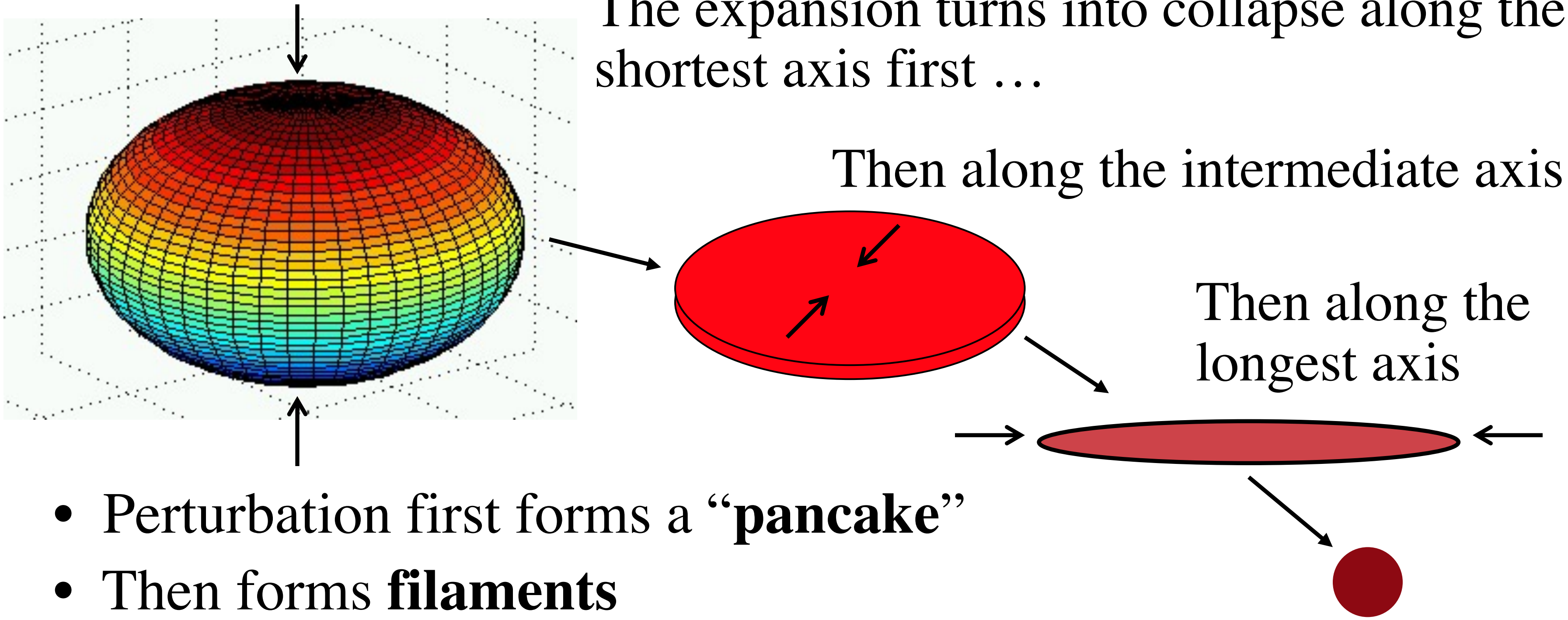
For a galaxy: $t_{ff} \sim 600\ \mathrm{Myr}\ (R/50\mathrm{kpc})^{3/2}\ (M/10^{12}M_\odot)^{-1/2}$

For a cluster: $t_{ff} \sim 9\ \mathrm{Gyr}\ (R/3\mathrm{Mpc})^{3/2}\ (M/10^{15}M_\odot)^{-1/2}$

So, we expect that galaxies collapsed early (at high redshifts), and that clusters are still forming now. This is as observed!

Non-Spherical Collapse

Real perturbations will not be spherical. Consider a collapse of an ellipsoidal overdensity:



The expansion turns into collapse along the shortest axis first …

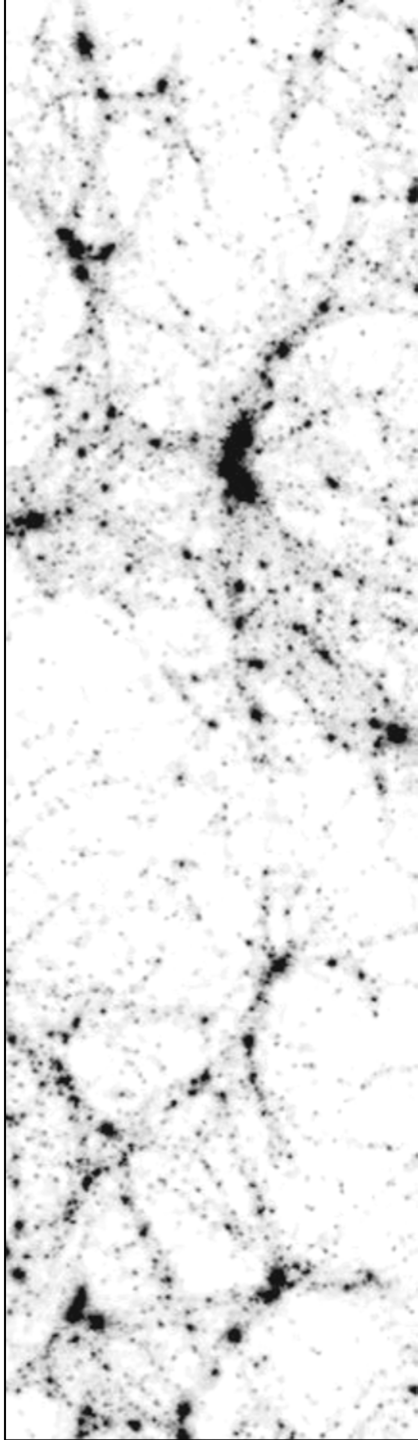
Then along the intermediate axis

Then along the longest axis

- Perturbation first forms a “**pancake**”
- Then forms **filaments**
- Then forms **clusters**

This kinds of structures are seen both in numerical simulations of structure formation and in galaxy redshift surveys

Structure Formation in the Cold Dark Matter Scenario



- CDM particles don't diffuse out of small lumps. So lumps exist on all scales, both large and small
- Small lumps collapse first, big things collapse later. The larger overdensities will incorporate smaller things as they collapse, via merging
- Structure forms early, and it forms **"bottom-up"** Galaxies form early, before clusters, and clusters are still forming now
- This picture is known as **"hierarchical structure formation"**
- This closely matches what we observe, and also produces the right kind of CMB fluctuations

Cooling and Dissipative Galaxy Formation

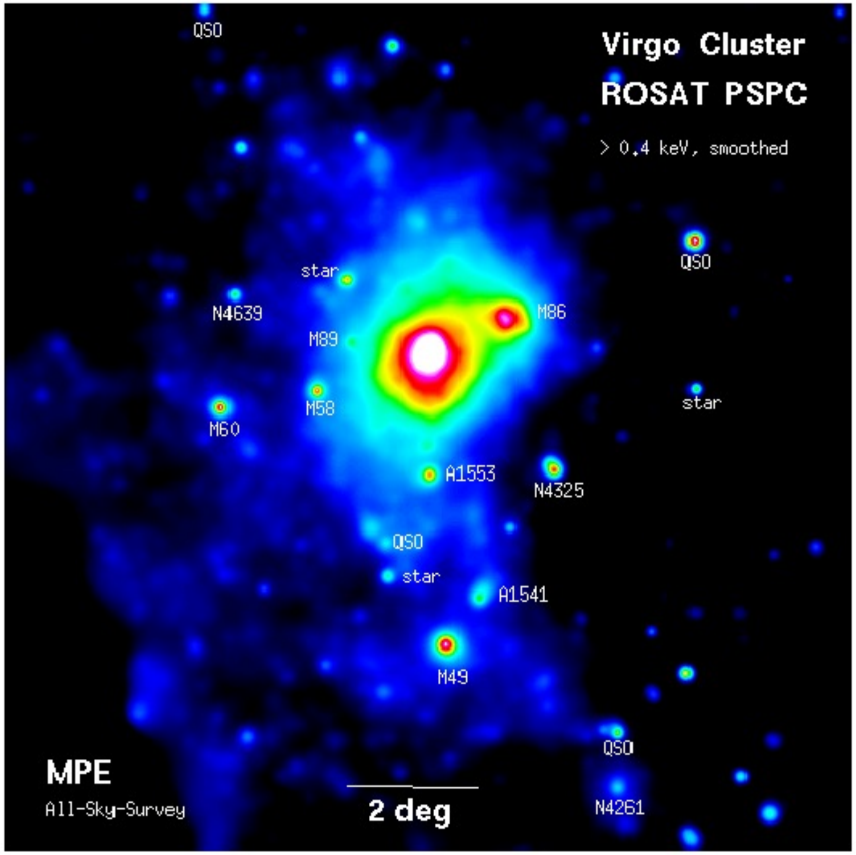
- Pure gravitational infall leads to overdensities of ~ 200 when the virialization is complete
- That is about right for the clusters of galaxies
- But galaxies are ~ 10^6 times denser than the mean; that means that they had to collapse by an additional factor of 10+
- Therefore, they had to release (dissipate) this excess binding energy. This process is called cooling, and it is what separates galaxies from the large scale structure

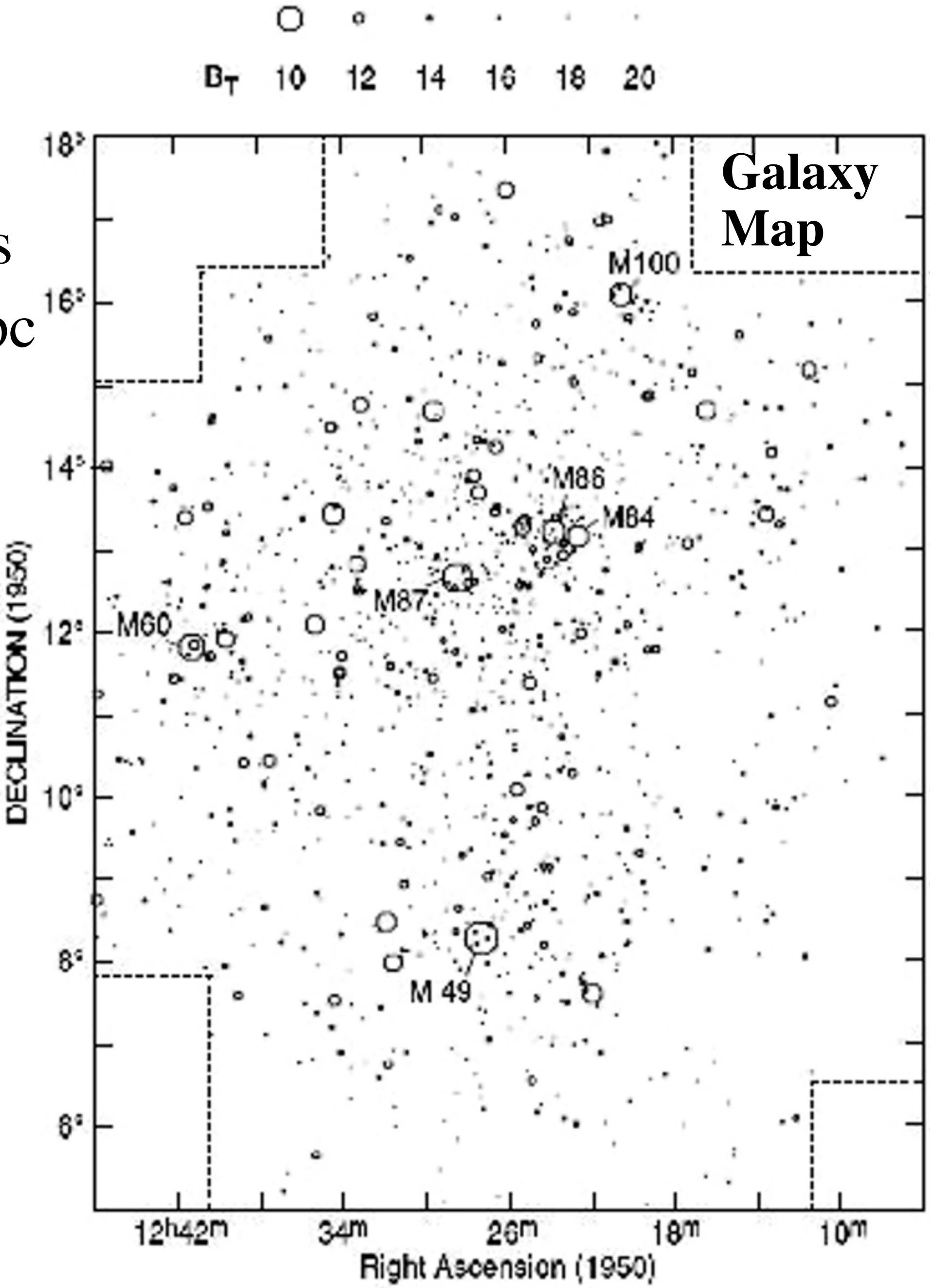
Clusters of Galaxies:

- Clusters are perhaps the most striking elements of the LSS
- Typically a few Mpc across, contain ~ 100 - 1000 luminous galaxies and many more dwarfs, masses ~ 10^{14} - 10^{15} $M_\odot$
- Gravitationally bound, but may not be fully virialized
- Filled with hot X-ray gas, mass of the gas may exceed the mass of stars in cluster galaxies
- Dark matter is the dominant mass component (~ 80 - 85%)
- Only ~ 10 - 20% of galaxies live in clusters, but it is hard to draw the line between groups and clusters, and at least ~50% of all galaxies are in clusters or groups
- Clusters have higher densities than groups, contain a majority of E's and S0's while groups are dominated by spirals
- Interesting galaxy evolution processes happen in clusters

The Virgo Cluster:

- Irregular, relatively poor cluster
- Distance ~ 16 Mpc, closest to us
- Diameter ~ 10° on the sky, 3 Mpc
- ~ 2000 galaxies, mostly dwarfs

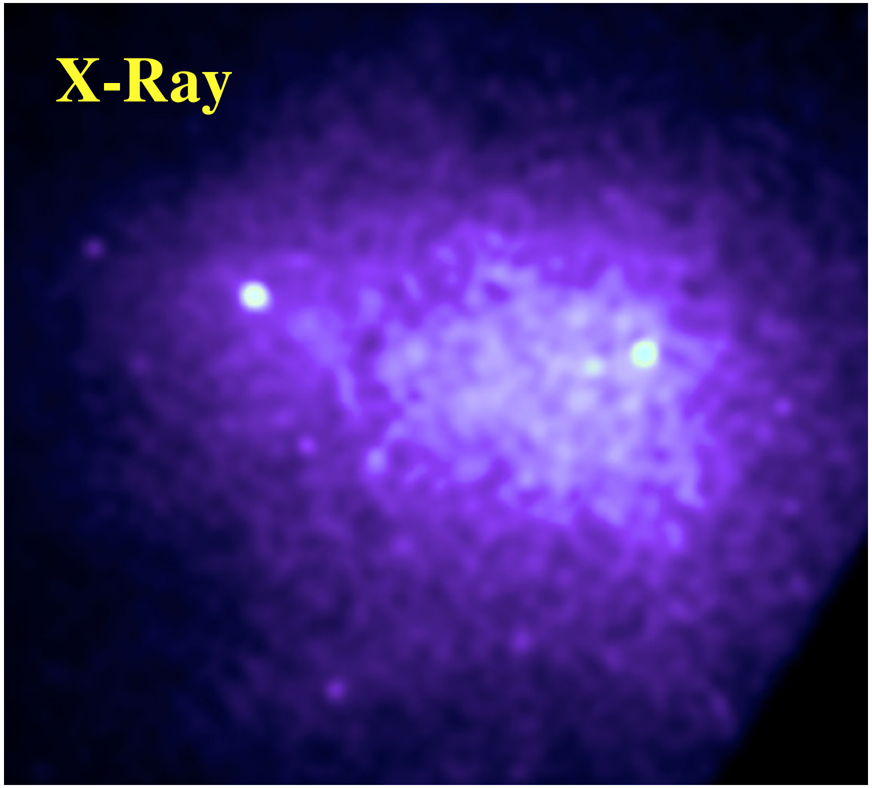


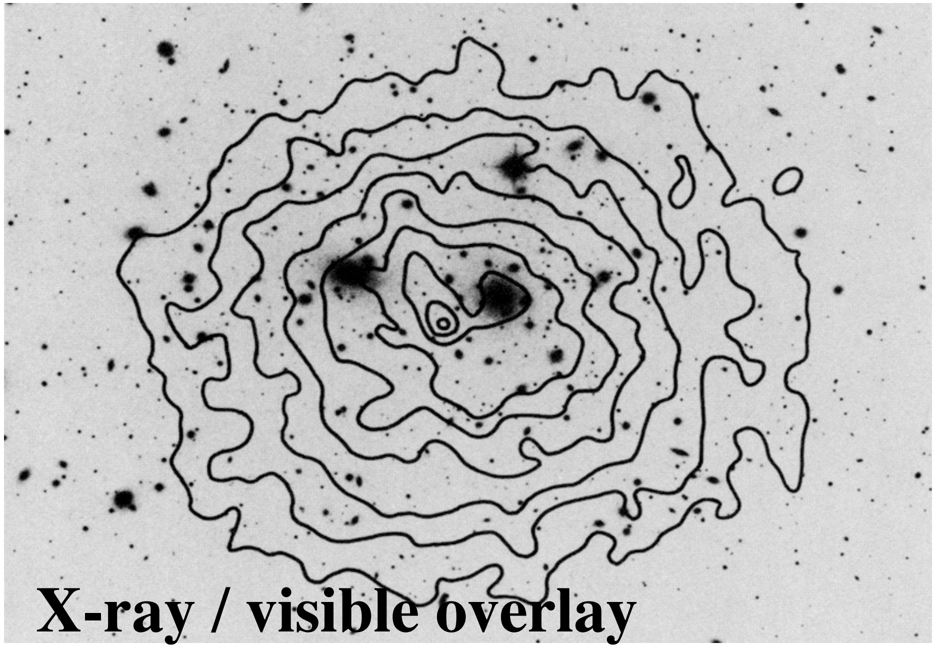


Galaxy Map

The Coma Cluster

- Nearest rich cluster, with >10,000 galaxies
- Distance ~ 90 Mpc
- Diameter ~ 4-5° on the sky, 6-8 Mpc





Surveys for Galaxy Clusters

Galaxy clusters contain galaxies, hot gas, and dark matter, and we can search for them through each of these components

1. **Optical:** Look for overdensities of galaxies on the sky
    - Could use colors for an additional selection
    - **Disadvantage:** vulnerable to projection effects

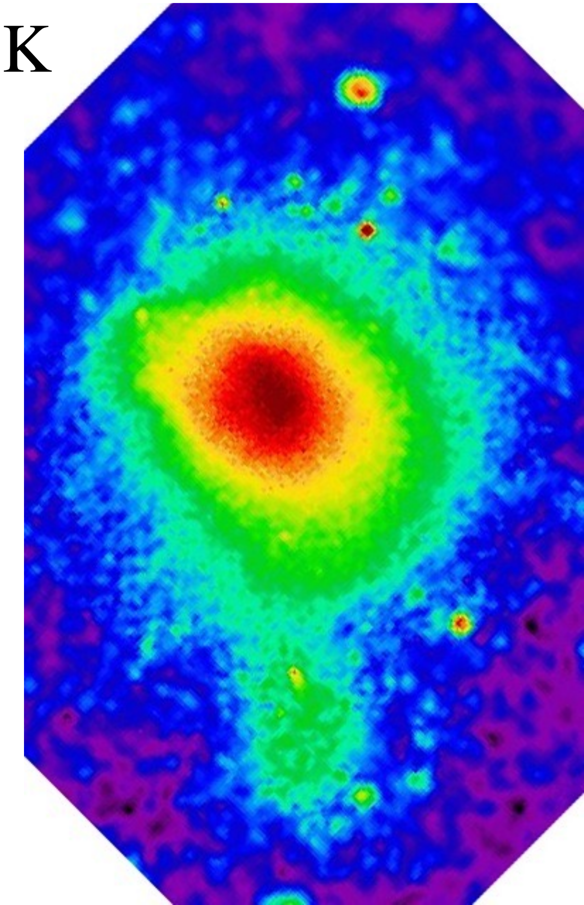
2. **X-Ray**: Clusters contain hot gas, and are prominent X-ray sources
    - ***Much less*** vulnerable to accidental projection effects

3. **Sunyaev-Zeldovich effect**: Distortion of the CMB due to photons scattering off electrons in the cluster
    - **Advantage:** redshift independent, can see clusters far away

4. **Weak Gravitational Lensing**: look for systematic distortions in background galaxy images
    - Selection based on mass. Difficult observationally

Hot X-ray Gas in Clusters

- Some of the gas is primordial, never condensed into galaxies, and heated via shocks as the gas falls into the cluster potential
- But some must have come from galaxies, expelled by galactic winds, since metallicity is ~ 1/3 Solar
- Virial equilibrium temperature T ~ 10^7 – 10^8 K
- Excellent probe of the cluster gravitational potential, used to measure cluster masses
- Temperatures are not uniform: "hot spots" may be due to mergers as clumps of galaxies fell into the cluster, or to energy input by active galactic nuclei
- There are good correlations between the cluster mass, X-ray luminosity, and temperature



Virial Masses of Clusters:

Virial Theorem for a test particle (a galaxy, or a proton), moving in a cluster potential well:

$$E_k = E_p / 2 \quad \rightarrow \quad m_g\, \sigma^2 / 2 = G\, m_g\, M_{cl} / (2\, R_{cl})$$

where σ is the velocity dispersion

Thus the cluster mass is: $M_{cl} = \sigma^2 R_{cl} / G$

Typical values for clusters:

$\sigma \sim 500 - 1500$ km/s

$R_{cl} \sim 3 - 5$ Mpc

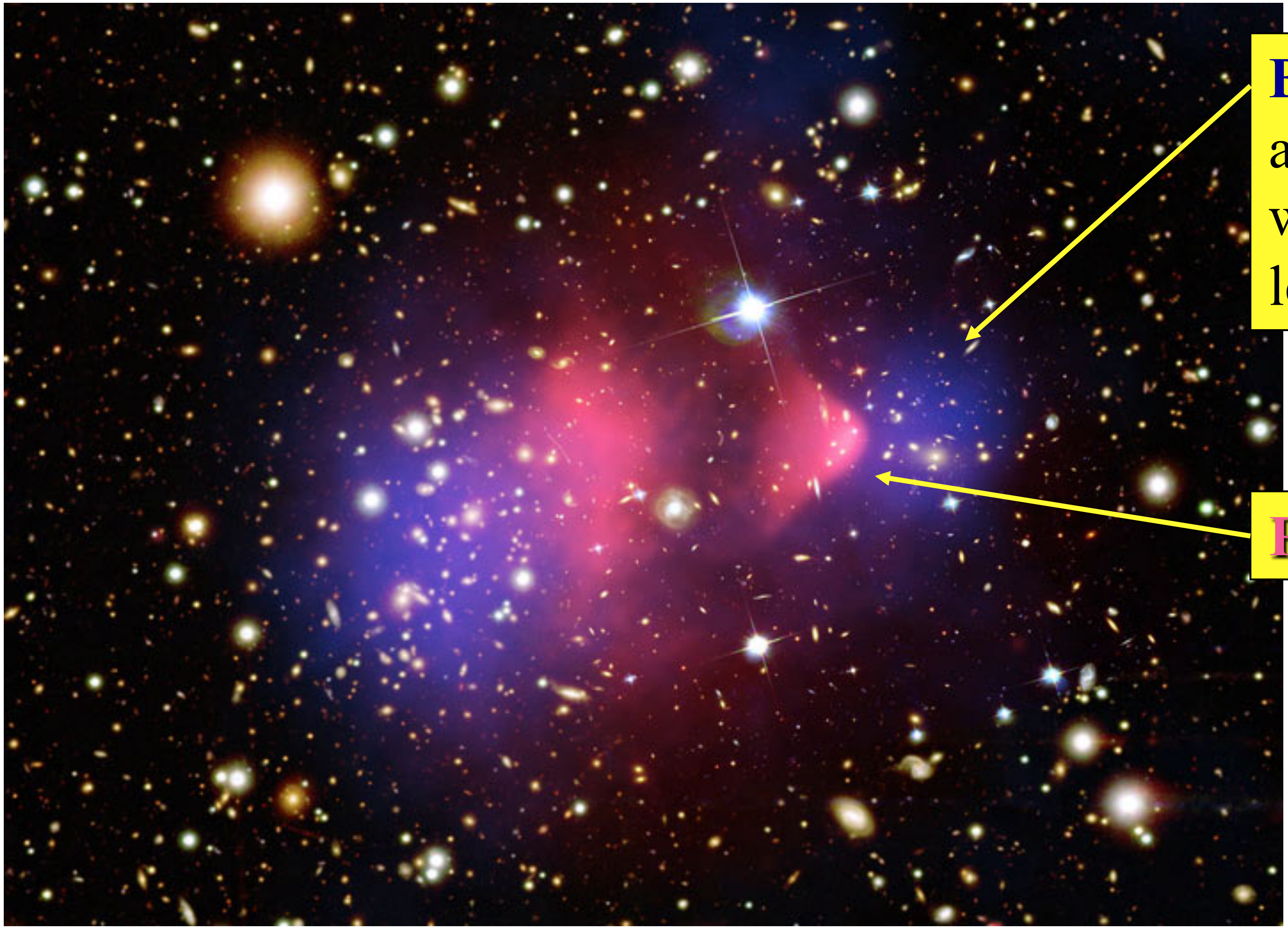
Thus, typical cluster masses are $\boldsymbol{M_{cl} \sim 10^{14} - 10^{15}\, M_\odot}$

The typical cluster luminosities (~ 100 - 1000 galaxies) are $L_{cl} \sim 10^{12}\, L_\odot$, and thus $(M/L) \sim 200 - 500$ in solar units

→ ***Lots of dark matter!***

Dark Matter and X-Ray Gas in Cluster Mergers: The "Bullet Cluster" (1E 0657-56)

The dark matter clouds largely pass through each other, whereas the gas clouds collide and get shocked, and lag behind



Blue: dark matter, as inferred from weak gravitational lensing

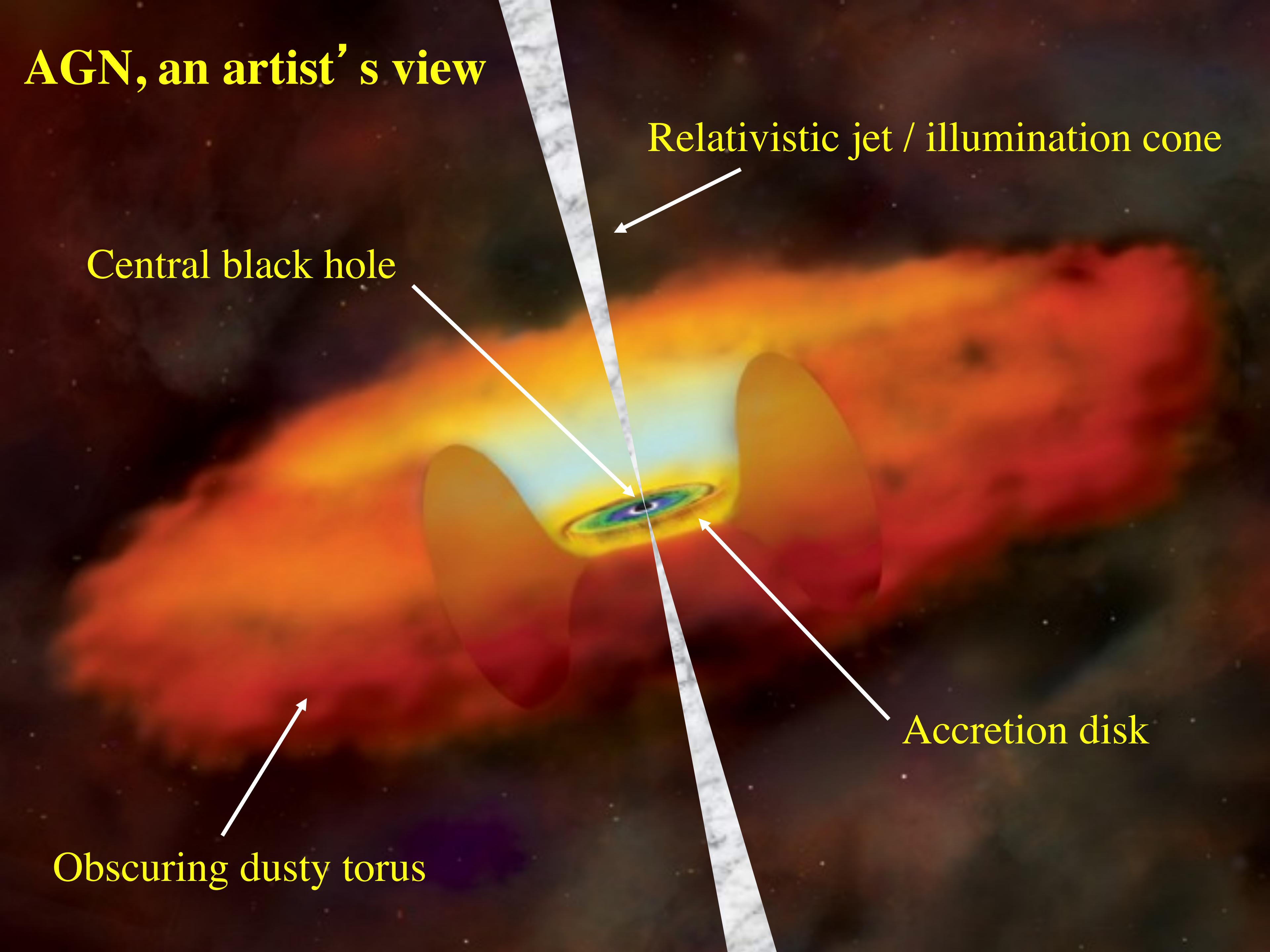
Pink: X-ray gas

(Bradac et al.)

Quasars and Active Galactic Nuclei

- Highly energetic manifestations in the nuclei of galaxies, powered by accretion onto supermassive massive black holes
- Empirical classification schemes have been developed, on the basis of the spectra; but recently, various unification schemes have been developed (~ the same underlying phenomenon)
- Evolve strongly in time, with the comoving densities of luminous ones increasing by ~ 10^3 from $z \sim 0$ to $z \sim 2$
- At z ~ 0, at least 30% of all galaxies show some sign of a nuclear activity; ~ 1% can be classified as Seyferts, and ~ 10^{-6} contain luminous quasars
- We think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase

AGN, an artist’s view

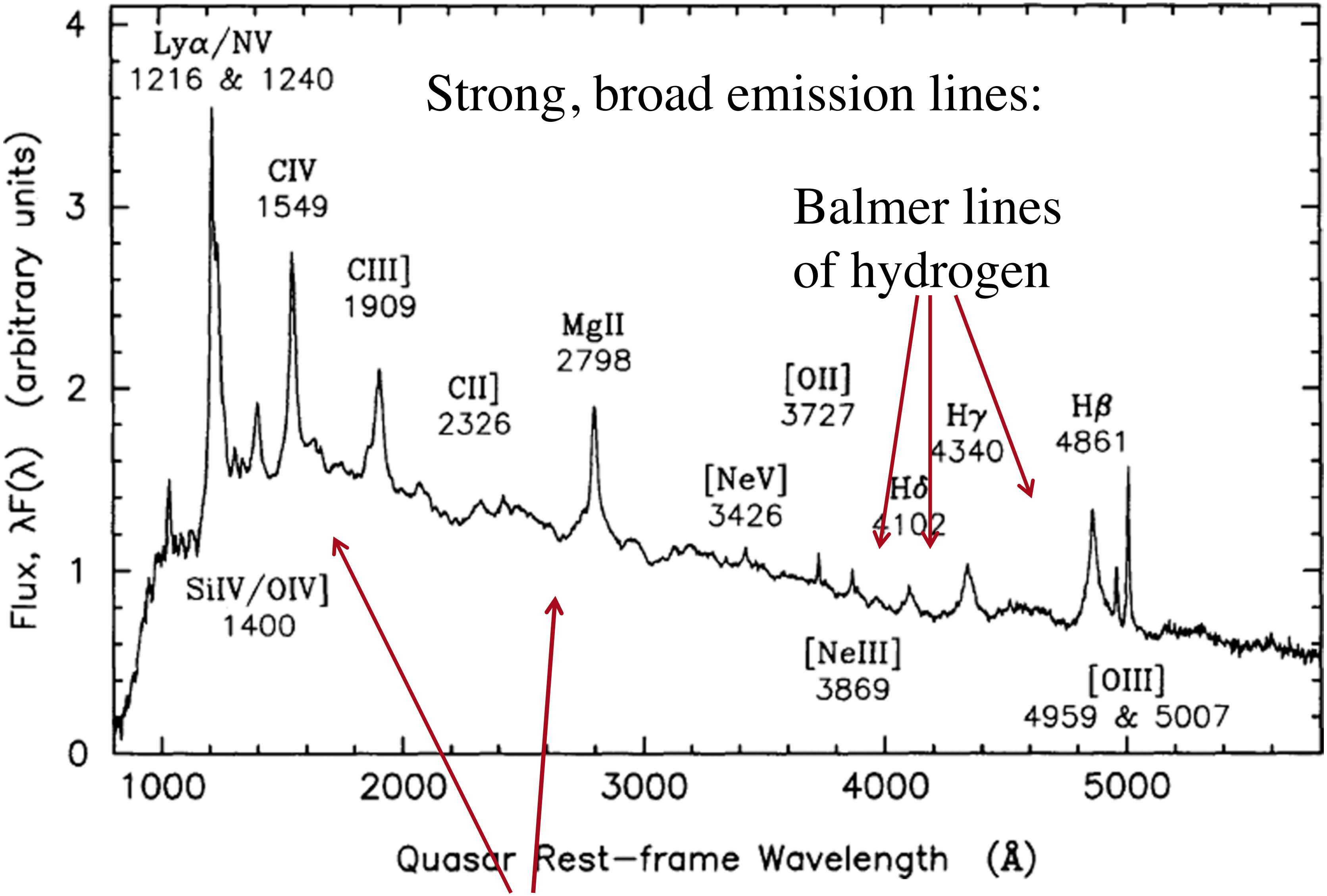


Observable Properties of AGN

- Emission over a broad range of frequencies, radio to γ-rays
  - Nonthermal radio or X-ray emission is a good way to find AGN
  - Generally bluer spectra than stars: "UV excess"
  - Colors unlike those of stars, especially when modified by the intergalactic absorption
- Presence of strong, broad emission lines in their spectra
- Can reach large luminosities, up to ~ $10^{15}\ L_\odot$
- Strong variability at all time scales
  - Implies small physical size of the emission region
- Central engines unresolved
- Undetectable proper motions due to a large distances

All of these have been used to devise methods to discover AGN, and each method has its own limitations and selection effects

UV-Optical Spectra of Quasars



Strong, broad emission lines:

Balmer lines of hydrogen

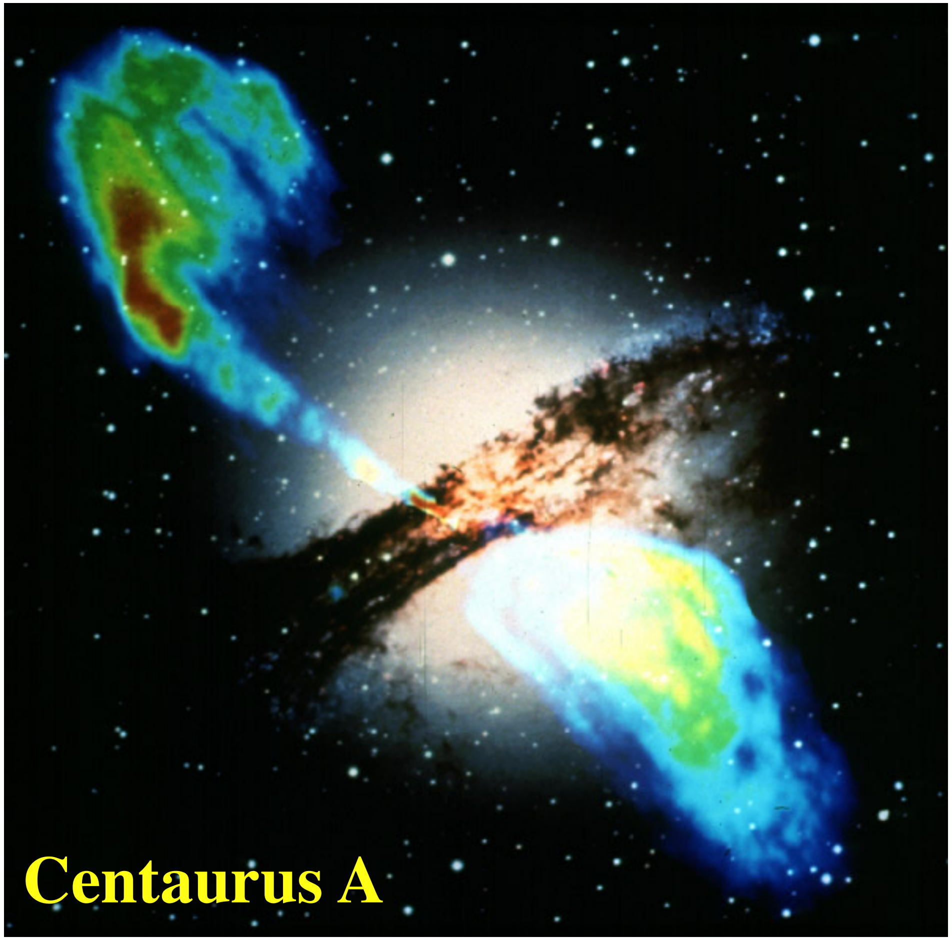
Prominent lines of abundant ions

AGN Classification

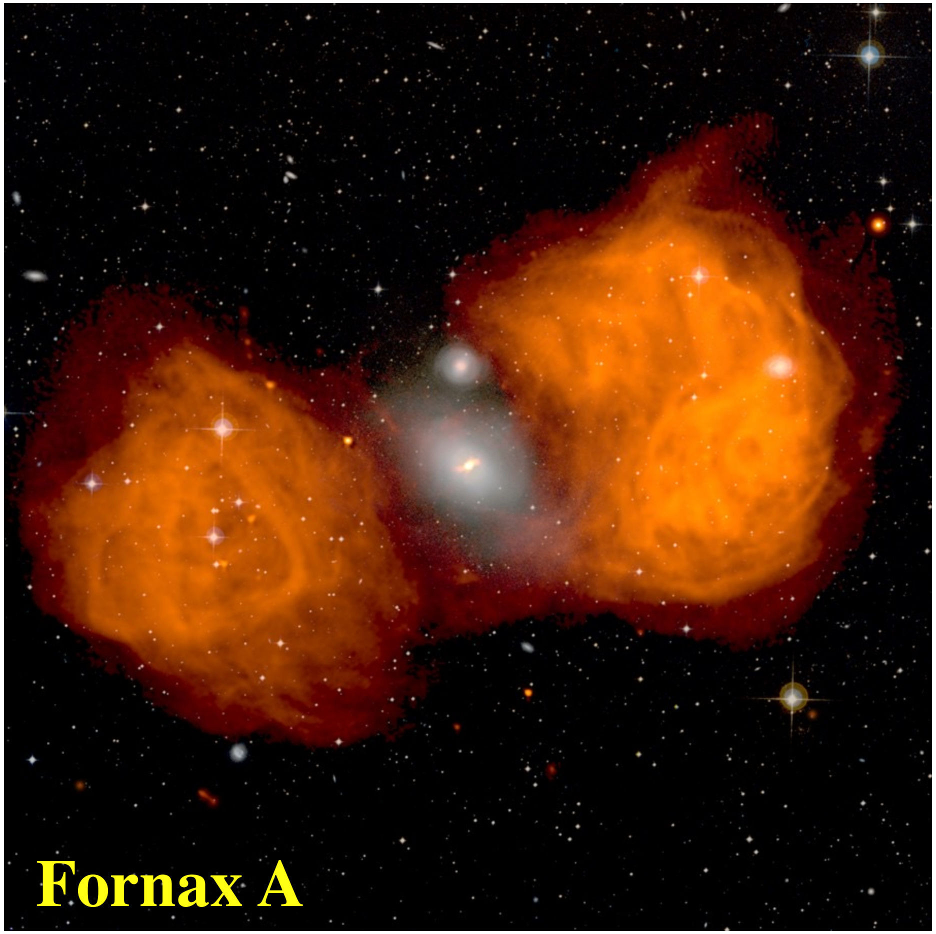
- According to radio emission:
  - Radio loud: radio galaxies (RGs) and quasars; F-R types I and II
  - Radio quiet (but perhaps not entirely radio silent)
- According to optical spectrum:
  - Narrow-line RGs, Seyfert 2's; Liners
  - Broad line RGs, Seyfert 1's, quasars
- According to optical luminosity:
  - Seyfert to quasar sequence, range of radio powers, etc.
- Special types:
  - Blazars (aka BL Lac's) and optically violently variable (OVV) objects
- These classifications are largely parallel
- Some distinction may reflect real, internal physical differences, and some may be simply orientation effects
  - This is the central thesis of the AGN unification models

Radio Galaxies: Typical Examples

Radio overlayed on optical images



Centaurus A

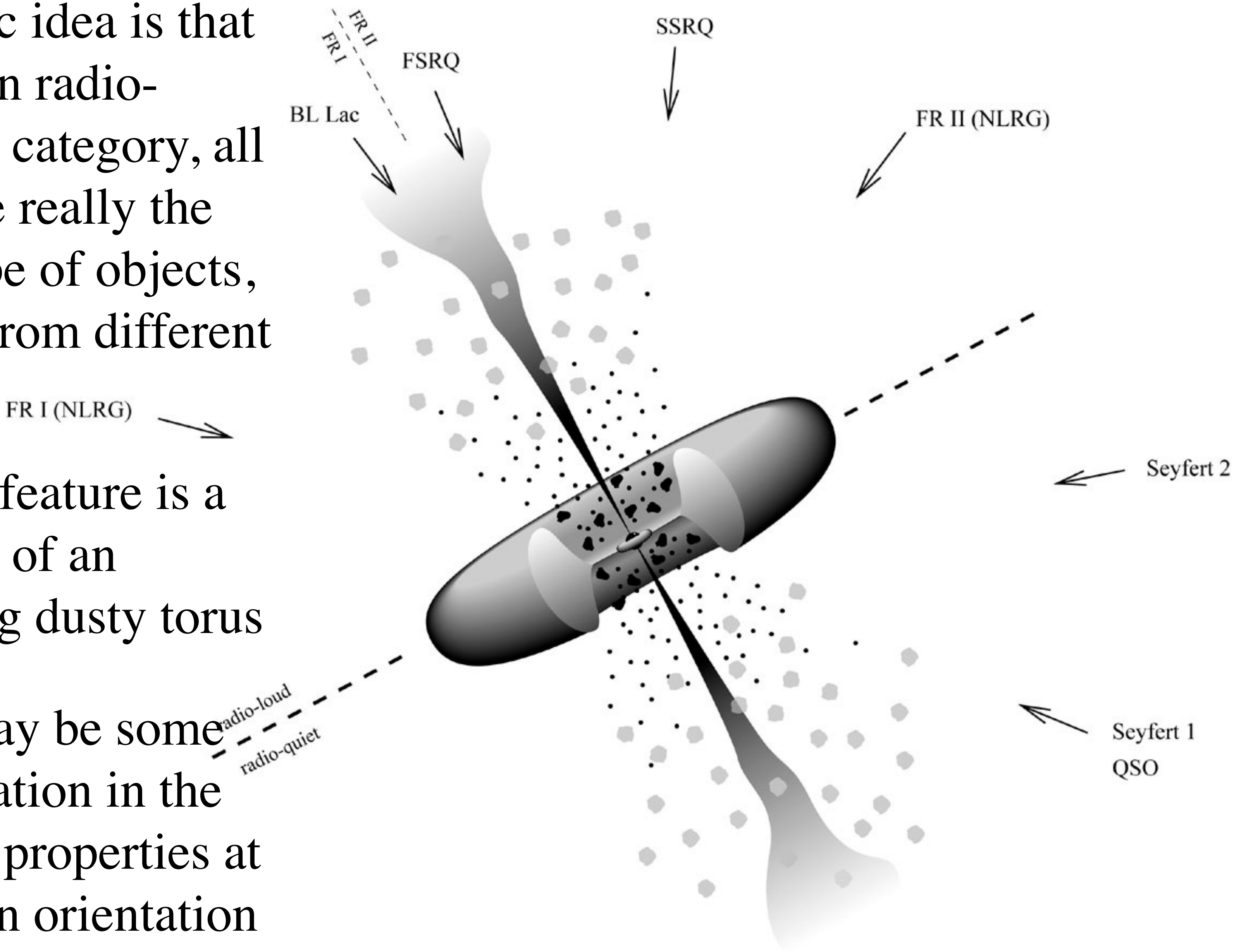


Fornax A

Energy stored in radio lobes can reach $\sim 10^{60}$ - 10^{61} erg. If jet lifetime is $\sim 10^{8}$ yrs, the implied mechanical luminosities are $\sim 10^{12}$ - 10^{13} $L_{\odot}$

Unification Models for AGN

- The basic idea is that in a given radio-loudness category, all AGN are really the same type of objects, viewed from different angles
- The key feature is a presence of an obscuring dusty torus
- There may be some real variation in the physical properties at any given orientation



AGN Unification

It is now reasonably secure to also fit quasars and blazars, and the radio loud equivalents, into this unified scheme:

Obscured	**Seyfert 2**	**Type 2 QSO or radio galaxy**
Unobscured	**Seyfert 1**	**Type 1 QSO or radio quasar**
Viewed directly down the jet	**Blazars**	

Accretion rate

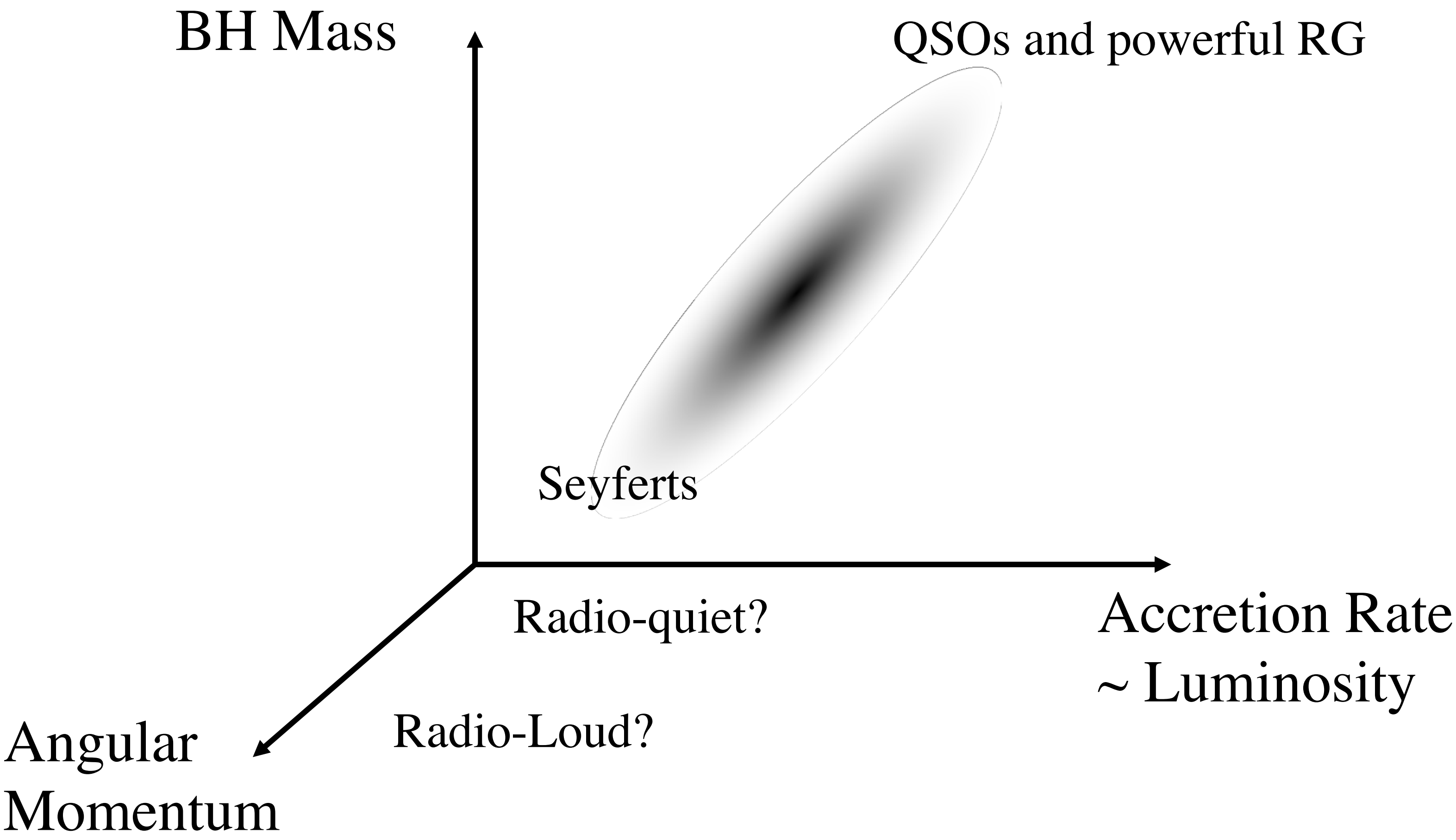
Type 2 or highly obscured luminous AGN are also needed to make up the hard X-ray background. Populations of such objects have been found recently both in the optical and X-ray surveys

Radio Loud vs. Radio Quiet

Possible physical reason why some AGN are radio loud, and others are radio quiet is the ***spin*** of the SMBH:

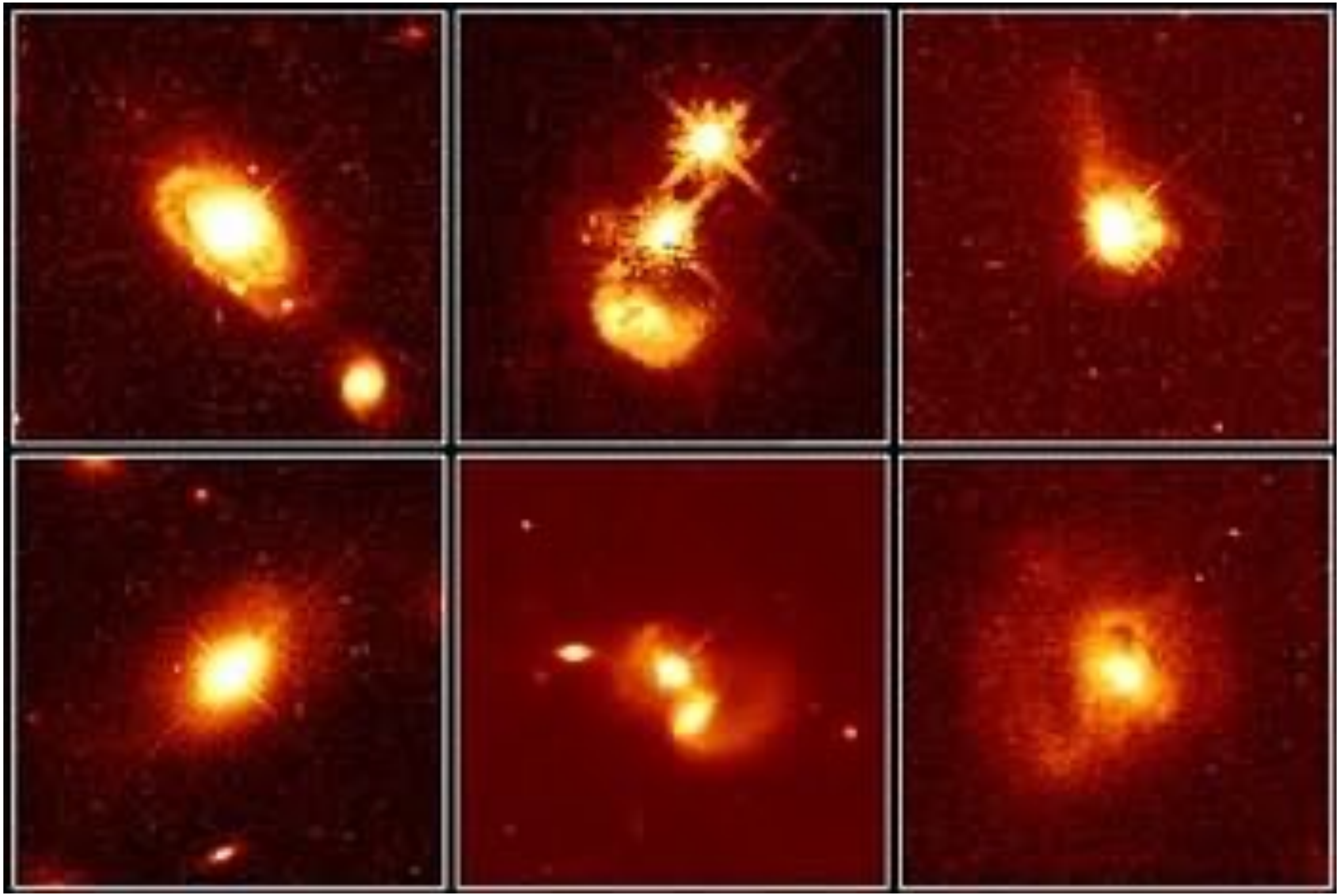
Radio loud	**Radio quiet**
High spin black holes	Low spin black holes
Produce jets, which are the origin of radio emission (note: blazars are radio loud)	No jets
Jets powered by spin energy extracted from black hole	Spectrum produced by the accretion disk (blackbody + nonthermal emission)
Also have accretion disks	

AGN: A Physical Classification



… but in addition, there will be some dependence on the viewing orientation

What Makes Quasars “Quase” ?



HST Images of QSO hosts, indicative of interacting systems

Where Does the Energy Come From?

- Accretion onto the central supermassive black holes provides the only known viable answer
- The fuel comes from ~ kpc scales (or larger) and ends near the ***Schwarzschild radius***,

$$R_s = \frac{2GM}{c^2}$$

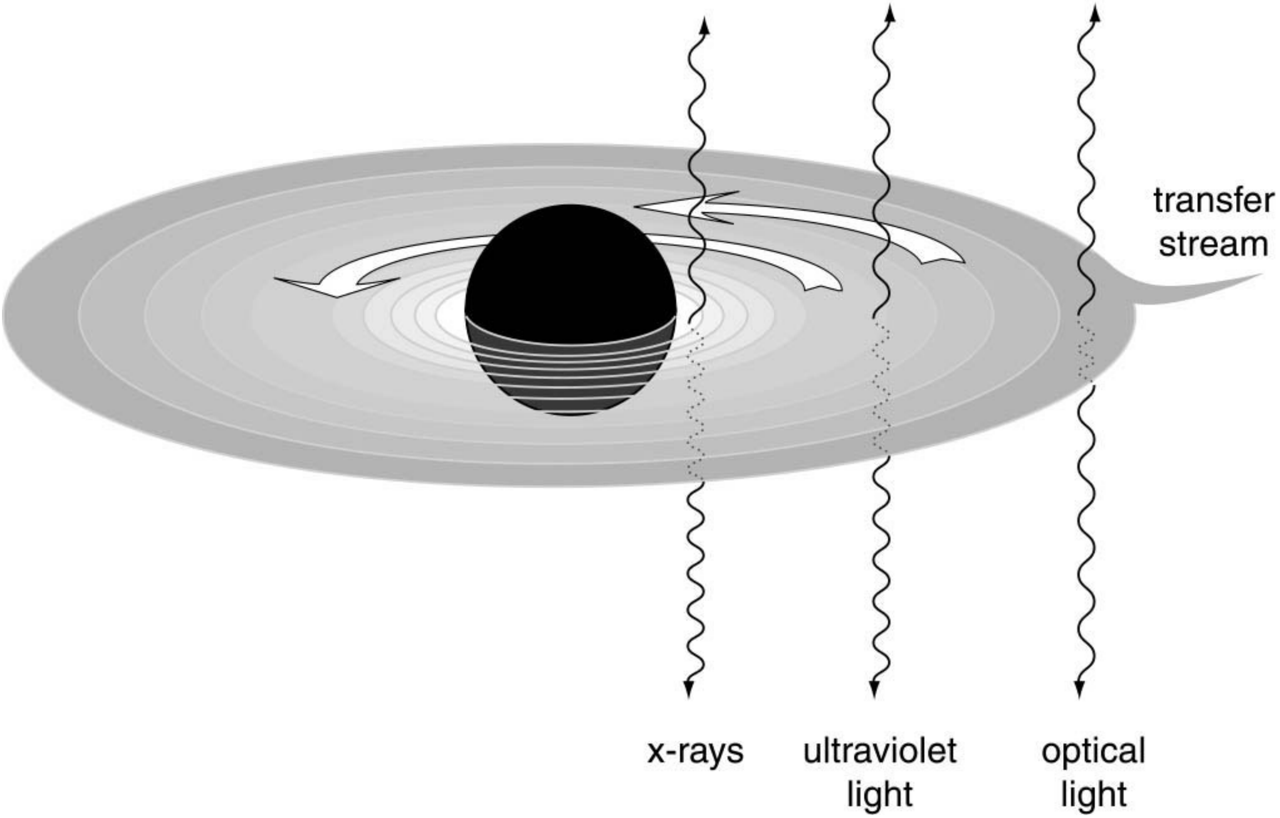
(actually, the relevant radius is the smallest stable orbit, at a few R_s). For a $M_\bullet \sim 10^8 M_\odot$, $R_s \sim 3 \times 10^8$ km ~ 10^{-5} pc

- The binding energy for a mass element m is: $E_b(R) = G\, m\, M_\bullet / R$
- In order for it to be accreted over many orders of magnitude in radius, it has to release the amount of energy comparable to E_b namely $G\, m\, M_\bullet / R_{min} = m\, c^2 / 2$, where $R_{min} \sim$ a few R_s

➡ ***Accretion to black holes can result in the energy release comparable to the rest mass energy!*** Usually a ~ 10% net efficiency is assumed, still much larger than the 0.1% energy conversion efficiency of thermonuclear reactions.

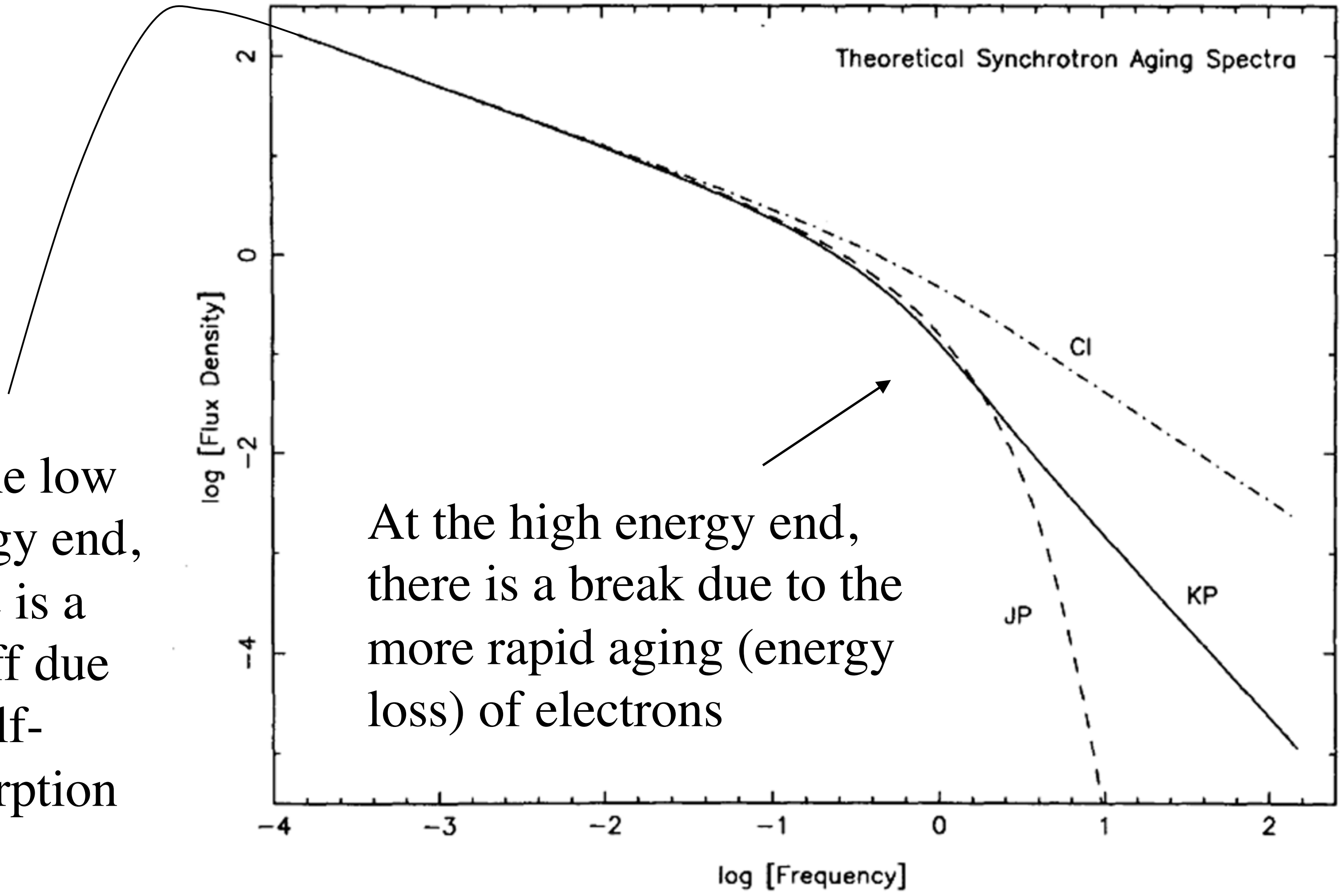
Energy Release From Central Engines

Some of it will emerge as a mix of ***thermal emission*** from various parts of the accretion disk; some emerges as a ***non-thermal synchrotron emission*** from particles accelerated by the magnetic fields embedded in the accretion disk or the BH itself



Synchrotron Radiation

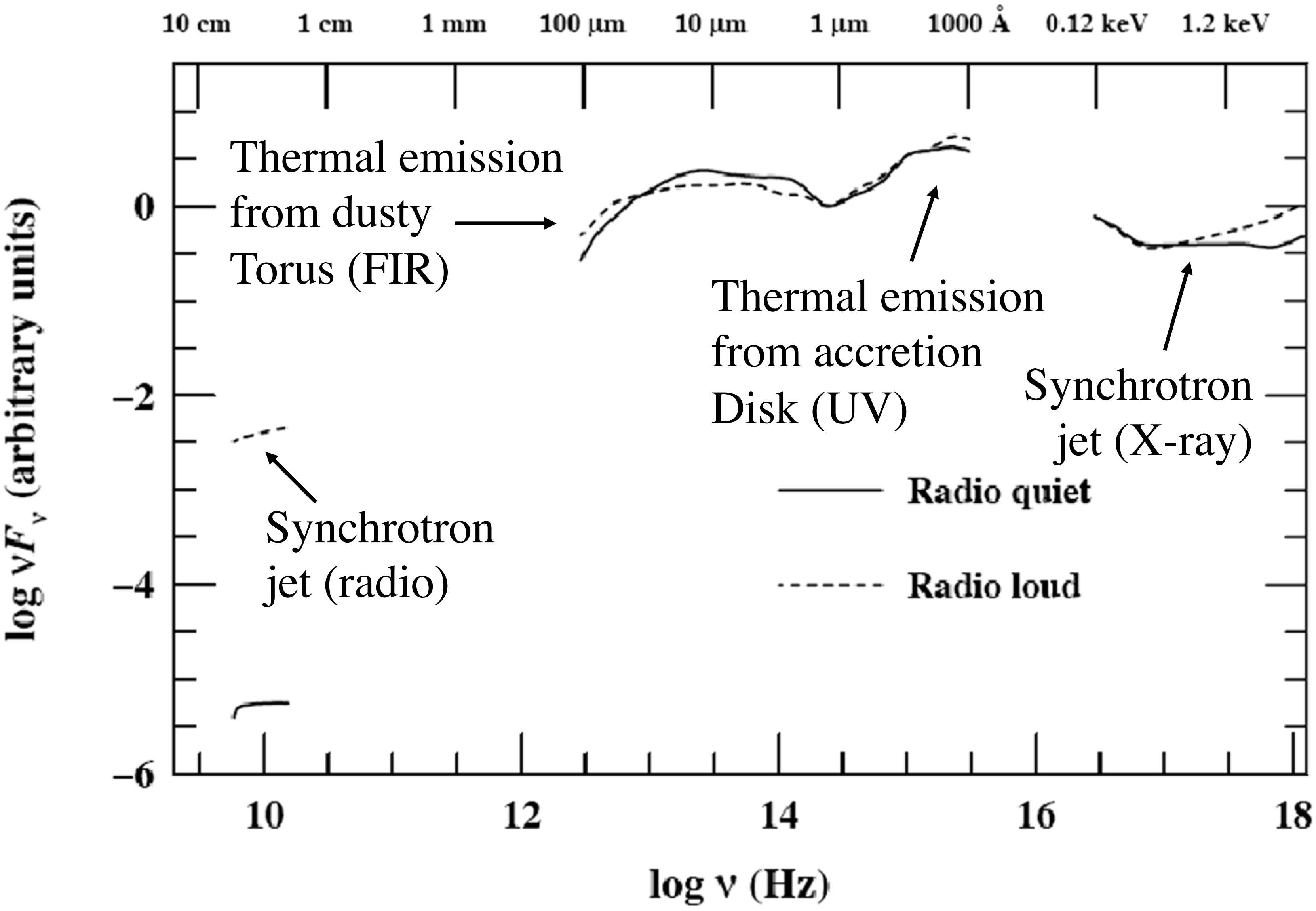
If the distribution of electron energies is a power-law (a common case), so will be the emergent spectrum, $P(\nu) \sim \nu^{\alpha}$, but with cutoffs



At the low energy end, there is a cutoff due to self-absorption

At the high energy end, there is a break due to the more rapid aging (energy loss) of electrons

Explaining the Broad-Band Spectral Energy Distribution in AGN



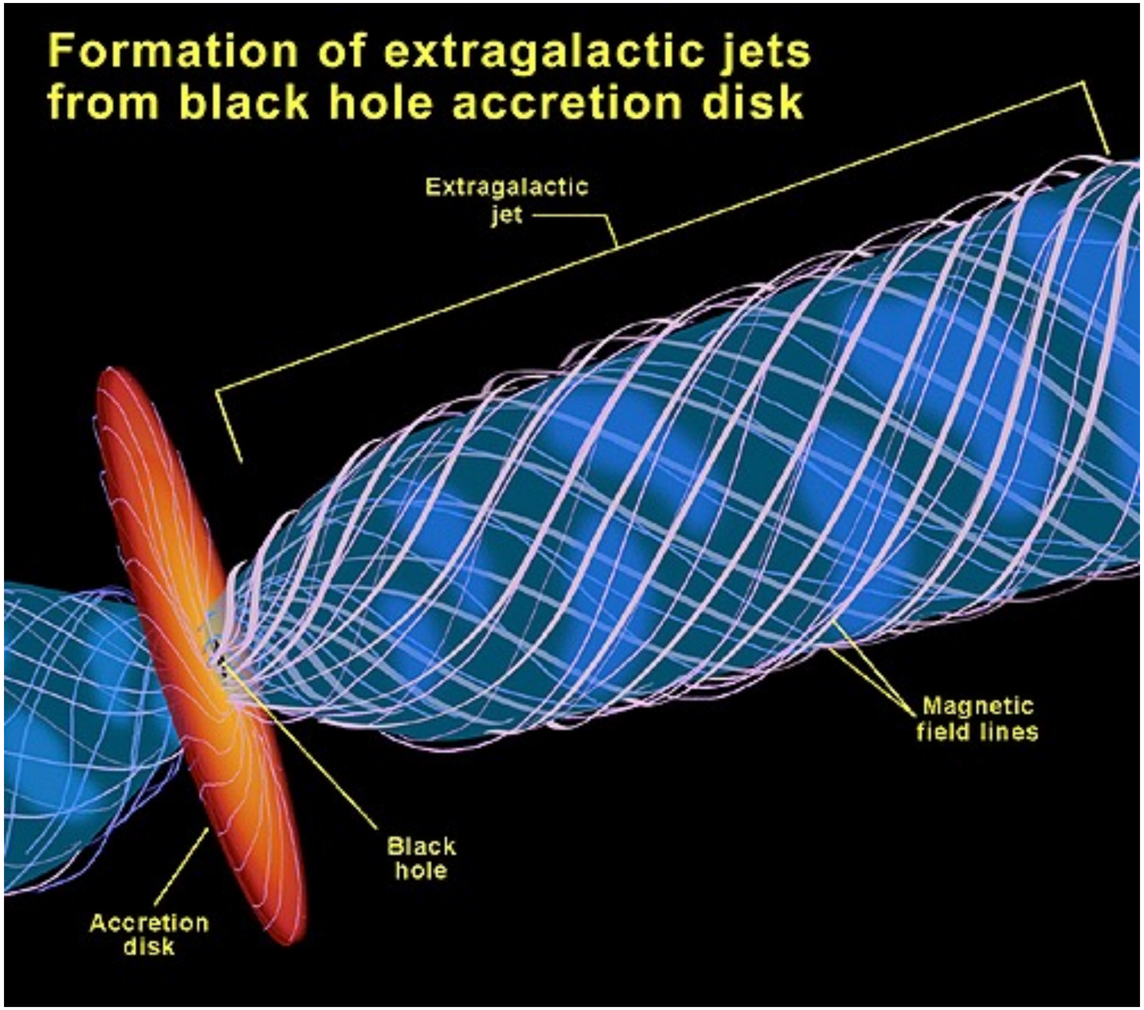
Thermal emission from dusty Torus (FIR)

Thermal emission from accretion Disk (UV)

Synchrotron jet (X-ray)

Synchrotron jet (radio)

The Origin of AGN Jets

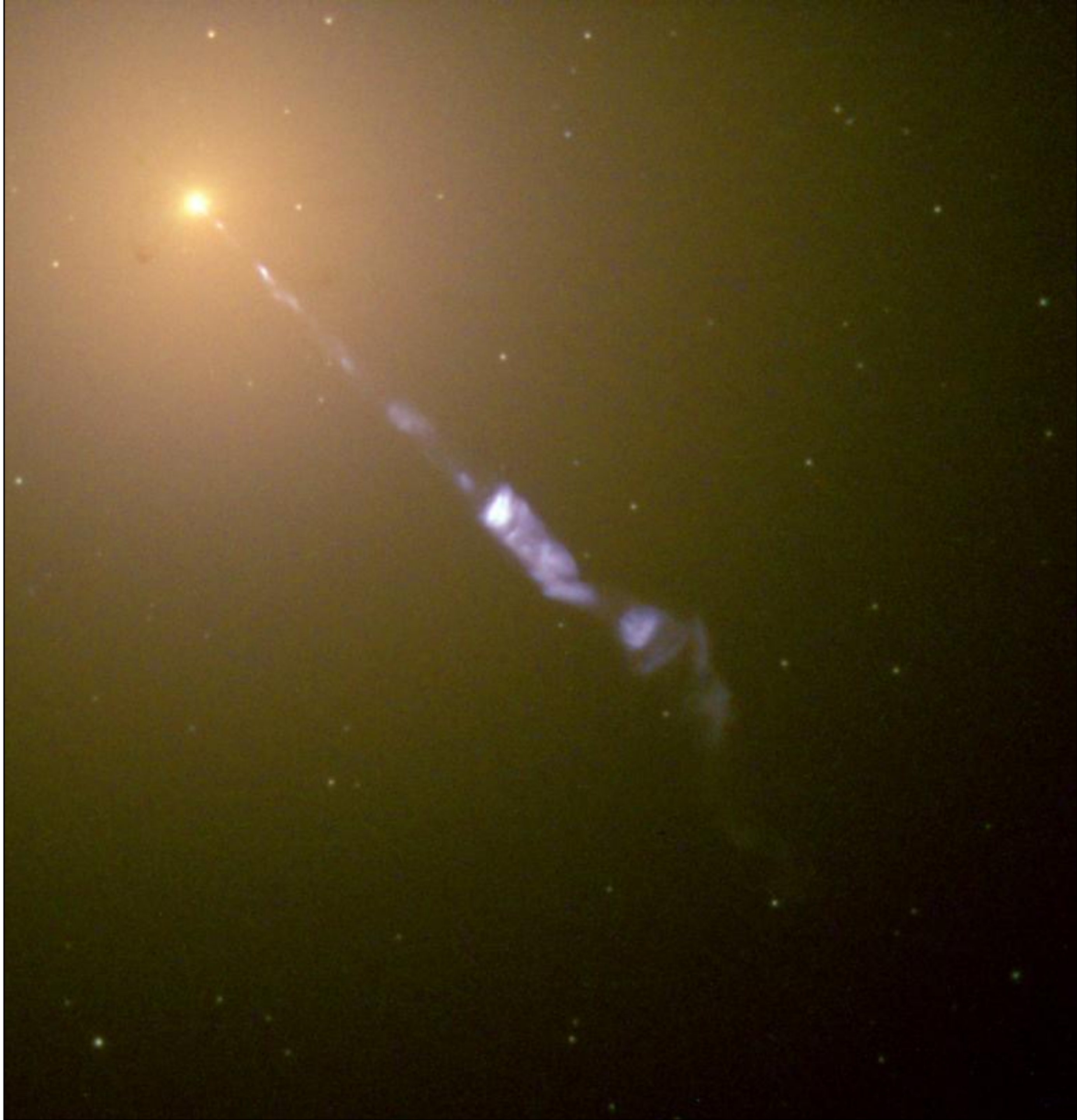


Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

The spin turns the magnetic lines of force into well-defined and tightly wound funnels, along which charged particles are accelerated

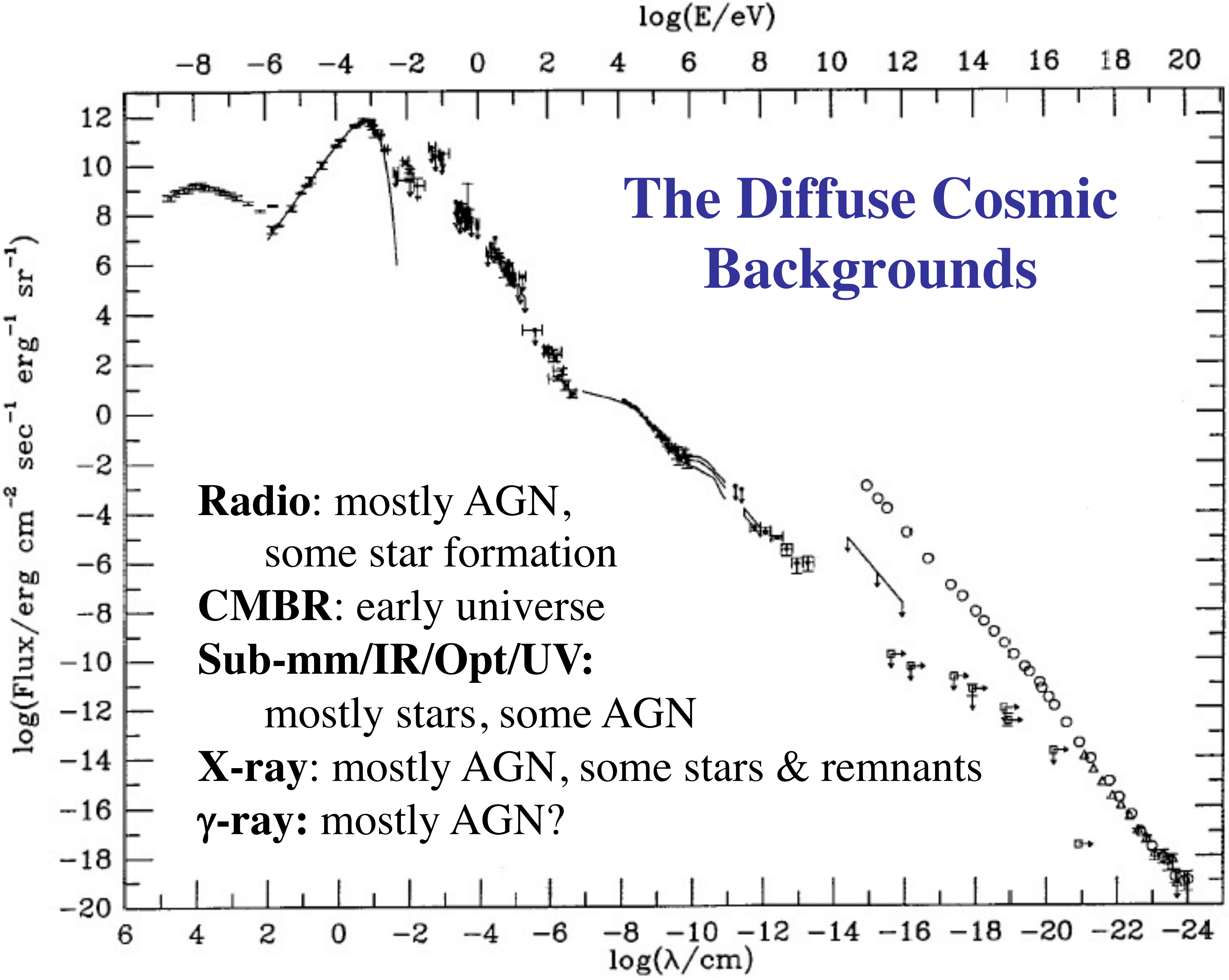
This saps the rotational energy of the disk and/or the BH itself; aside from radiation, mechanical energy is carried by the jets to lobes

… and in some cases in the visible light as well (M87 here)



The origin of the emission is the synchotron mechanism: accelerated particles moving in a magnetic field

The Diffuse Cosmic Backgrounds



Radio: mostly AGN,
some star formation

CMBR: early universe

Sub-mm/IR/Opt/UV:
mostly stars, some AGN

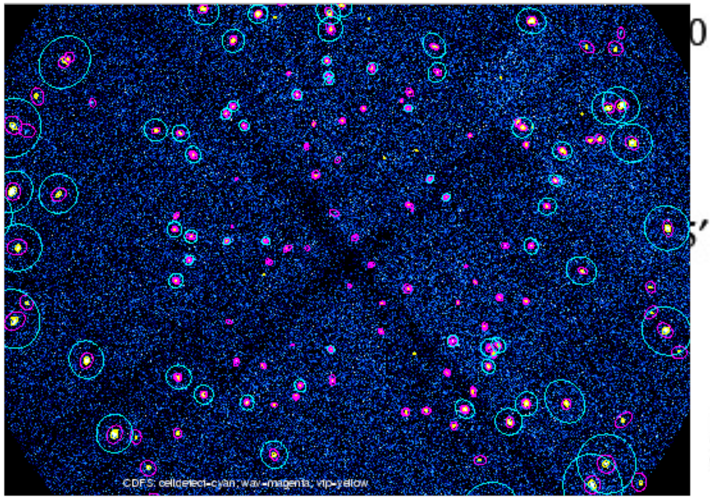
X-ray: mostly AGN, some stars & remnants

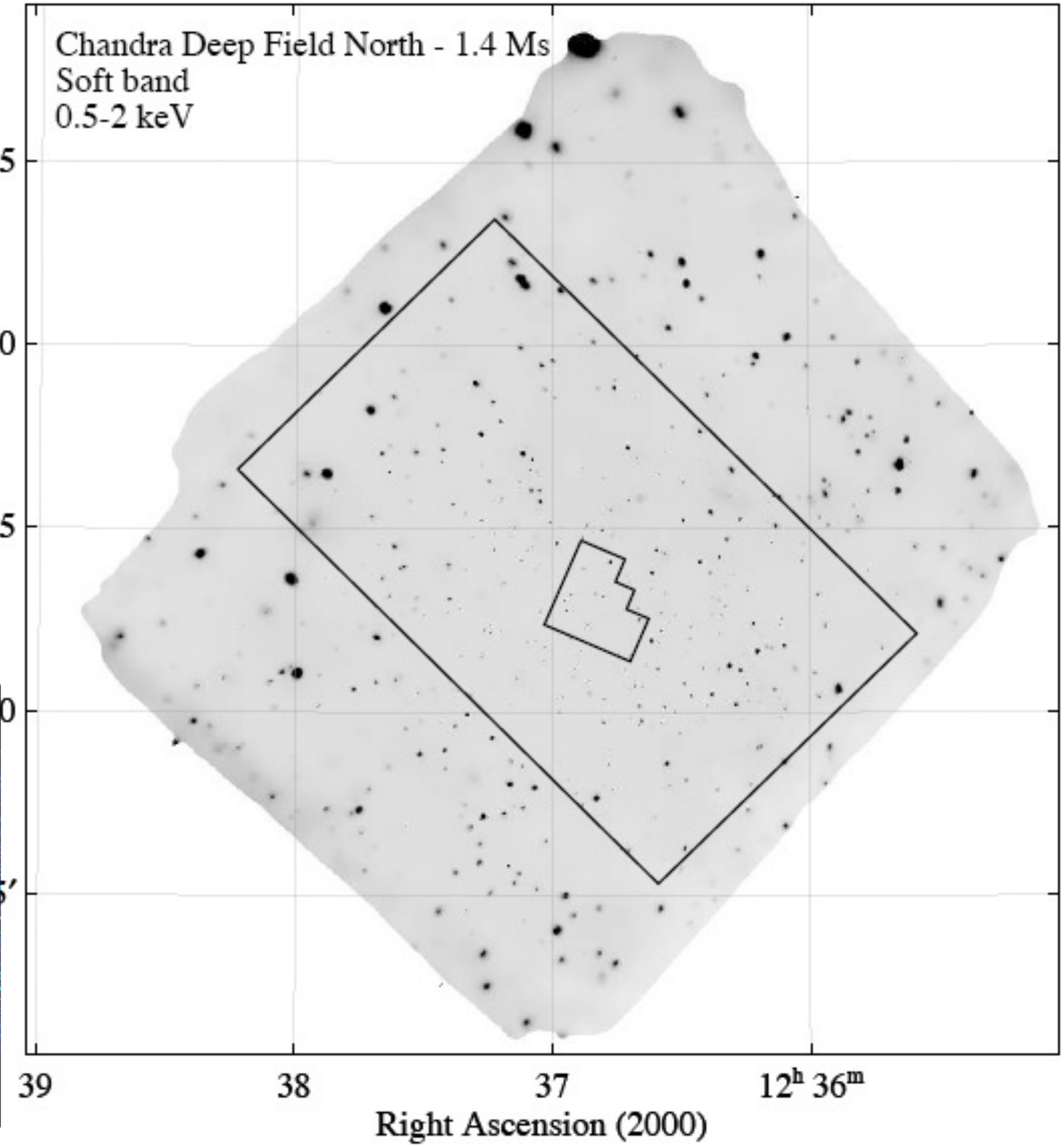
γ-ray: mostly AGN?

Resolving the CXRB

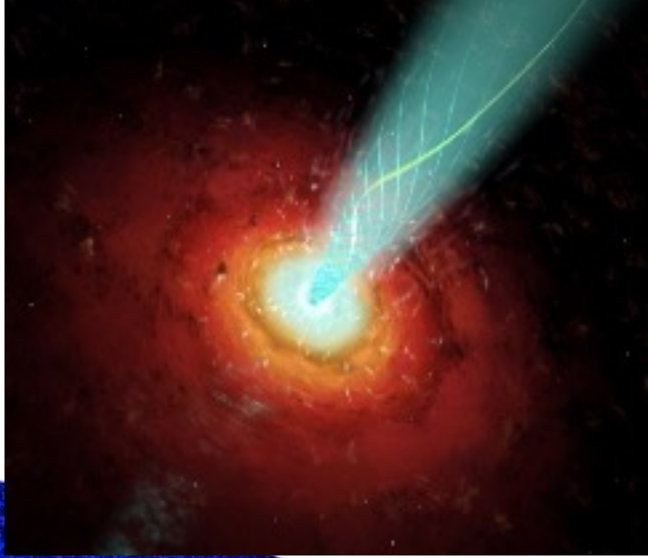
Deep X-ray imaging of fields where there is already deep HST imaging and ground based spectroscopy, also followed in radio, IR, etc.

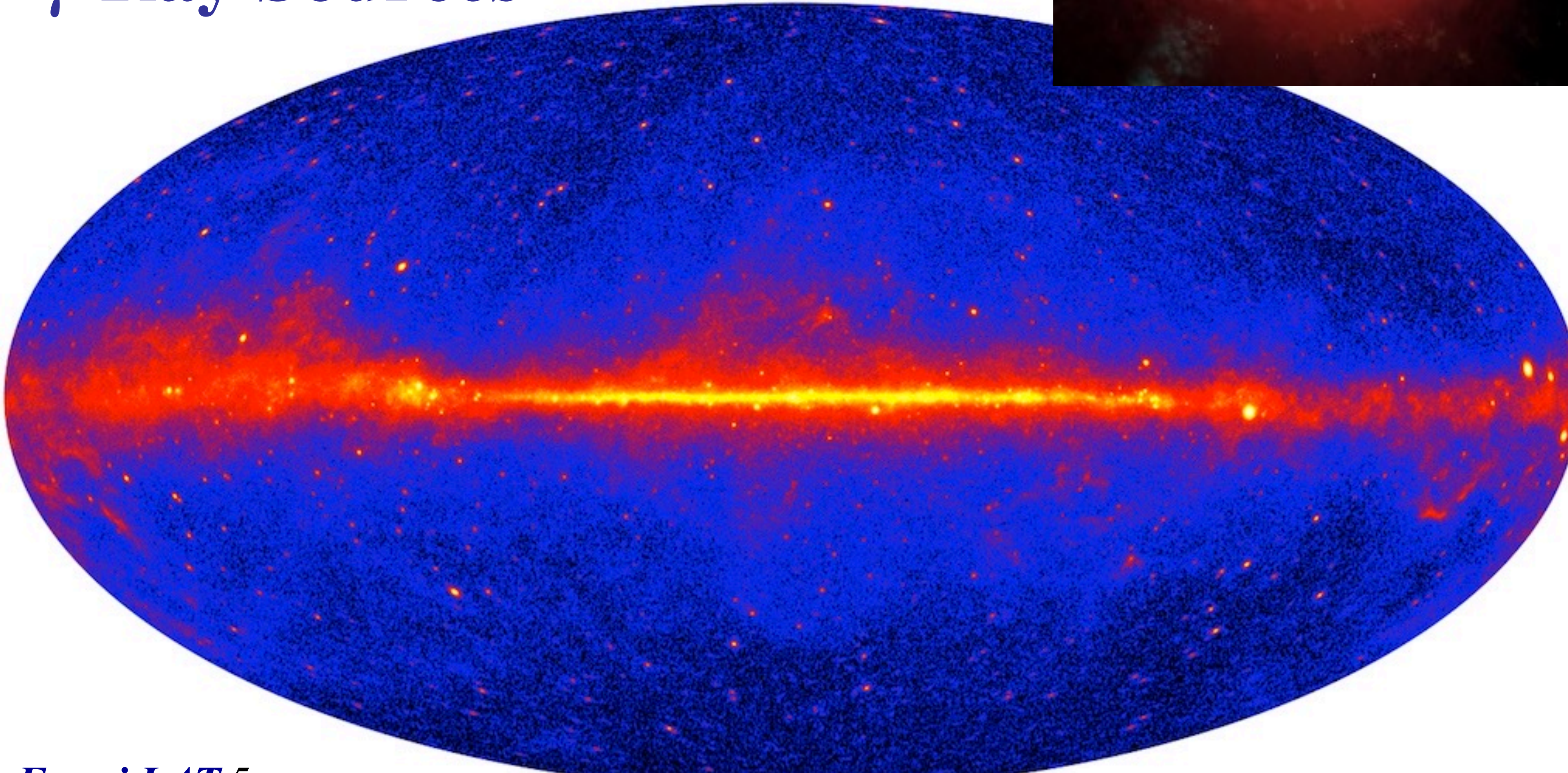
Chandra deep field





Beamed AGN (Blazars) are (probably) the Principal Extragalactic γ-Ray Sources

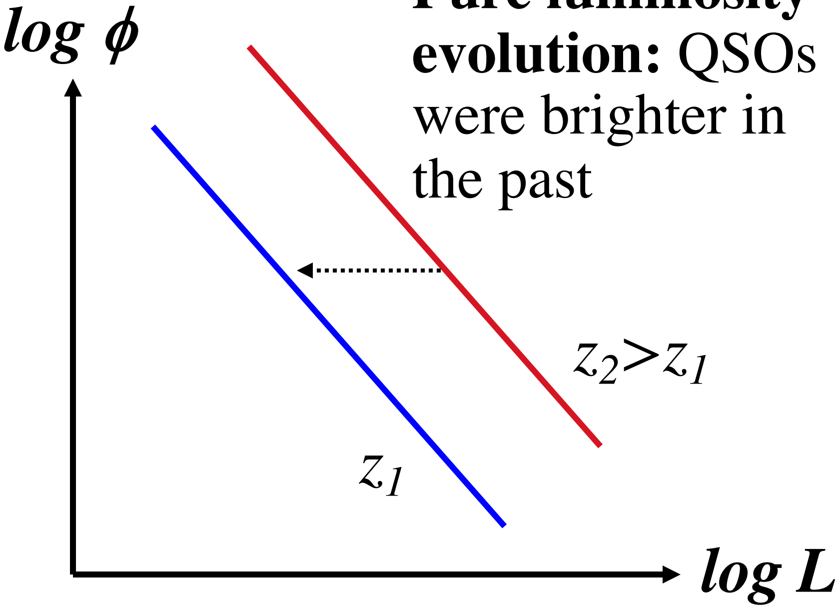




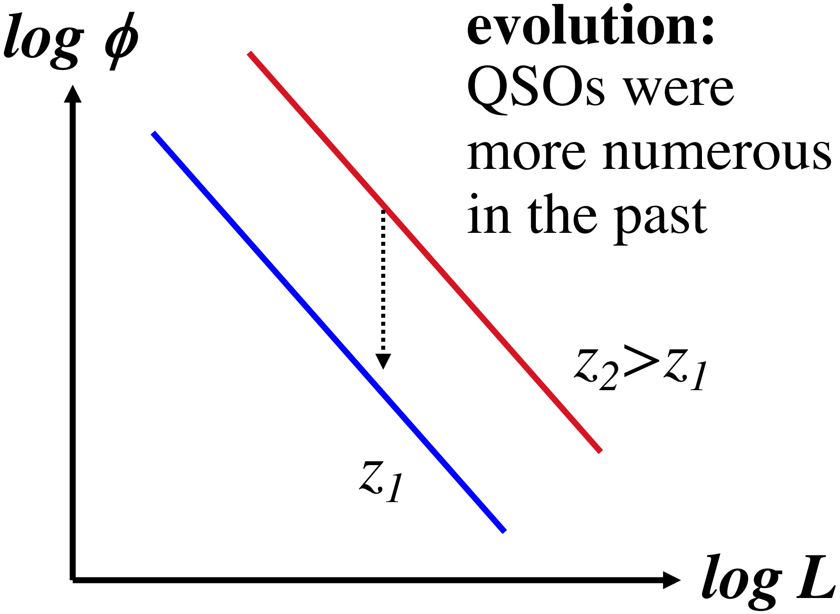
Fermi LAT 5 year map

Quasar Evolution

- How is the luminosity function of QSOs, and their total comoving density changing in redshift?
- This may help us understand better the origins of the AGN activity and their relation to galaxy evolution
- QSO numbers increase rapidly with redshift, but are luminosities or densities changing? For a pure power-law luminosity function, the answer is ambiguous:

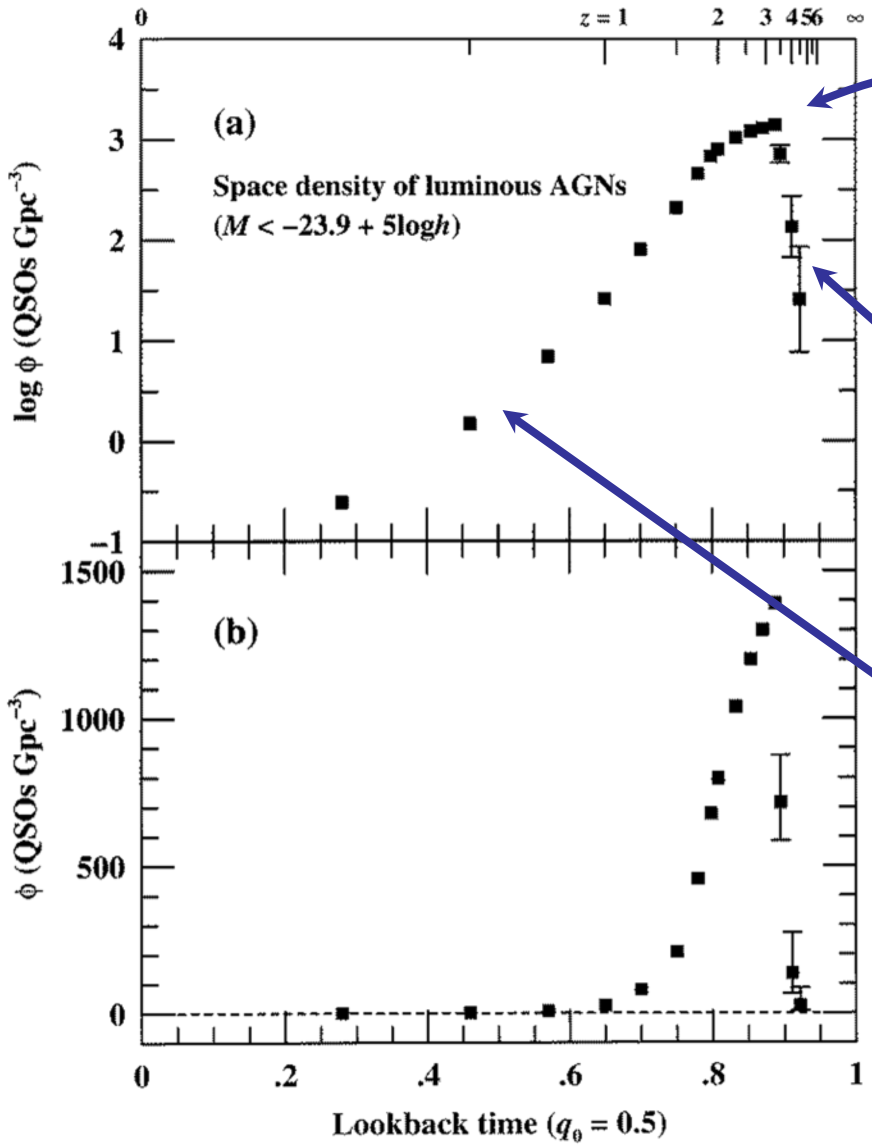


Pure luminosity evolution: QSOs were brighter in the past



Pure density evolution: QSOs were more numerous in the past

The History of the Comoving Number Density of Quasars



The Peak of the Quasar Era at z ~ 2 - 3: The Maximum Merging Epoch?

The Rise of Quasars: Initial Assembly of the Host Galaxies, Growth of the SMBHs

The Decline at Low *z*' s: Diminishing Fueling Events

AGN Feedback

Radiative energy input:

- Ionizes the host ISM and cluster IGM, curtailing star formation
- Drives a galactic wind due to coupling with the gas, expels the chemically processed material into the IGM
- Comparable mechanical energy input from the jets (mainly important in clusters?)

- Note:

$$E_{AGN} \sim L_{AGN}\, t_{AGN} \sim 10^{12}\, L_\odot\ 10^7\ \mathrm{yr} \sim 10^{60}\ \mathrm{erg}$$

$$E_{bind.gal.} \sim M_{gal}\, V_{gal}^2 \sim 10^{12}\, M_\odot\ (200\ \mathrm{km/s})^2 \sim 10^{60}\ \mathrm{erg}$$

The Nature of the BH "Seeds"

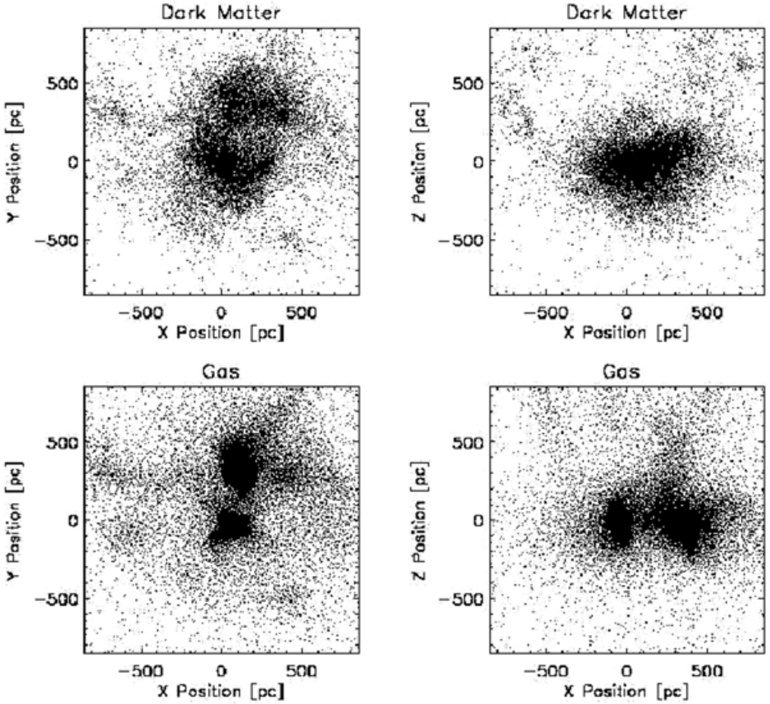
Some plausible choices include:

- Primordial, i.e., created by localized gravitational collapses in the early universe, e.g., during phase transitions
  - No evidence and no compelling reasons for them, but would be very interesting if they did exist; could have "any" mass…
- Remnants of Pop. III massive stars: $M_{seed} \sim 10 - 100\ M_\odot$
  - Could be detectable as high-*z* GRBs
- Gravitational collapse of dense star clusters, or runaway mergers of stars: $M_{seed} \sim 10^2 - 10^4\ M_\odot$
- Direct gravitational collapse of dense protogalactic cores

More than one of these processes may be operating …

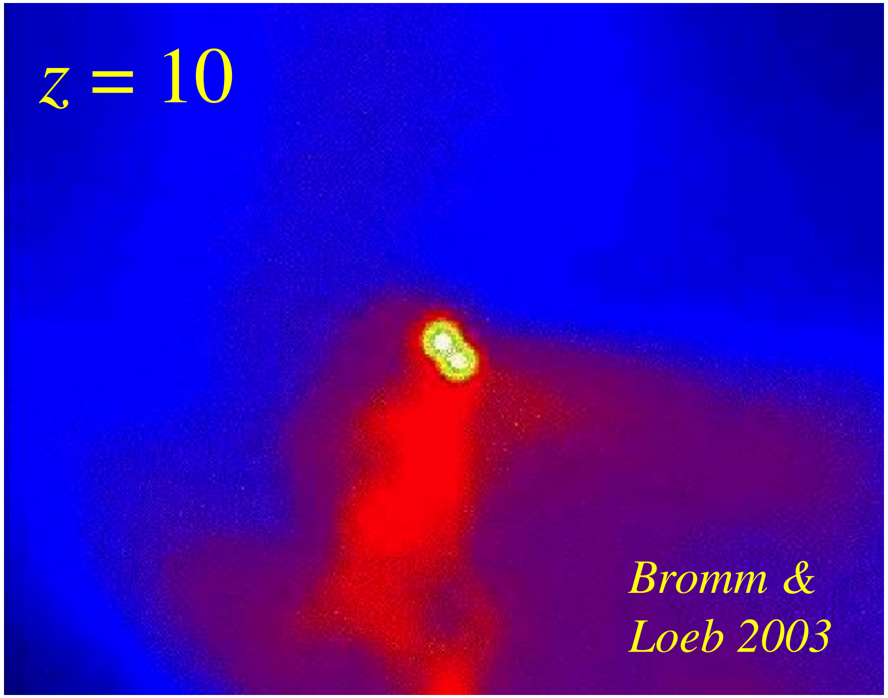
The process must be very rapid in order to produce observed luminous quasars at high redshifts, with $M_{bh} \sim 10^9\ M_\odot$

Pop III Black Holes and the Origin of AGN



- Explosions of massive Pop III stars can produce relict BHs with $M_\bullet \sim$ few - $10^2\ M_\odot$
- Direct collapse of zero-spin mini-halos may lead to BHs with $M_\bullet \sim 10^4 - 10^6\ M_\odot$

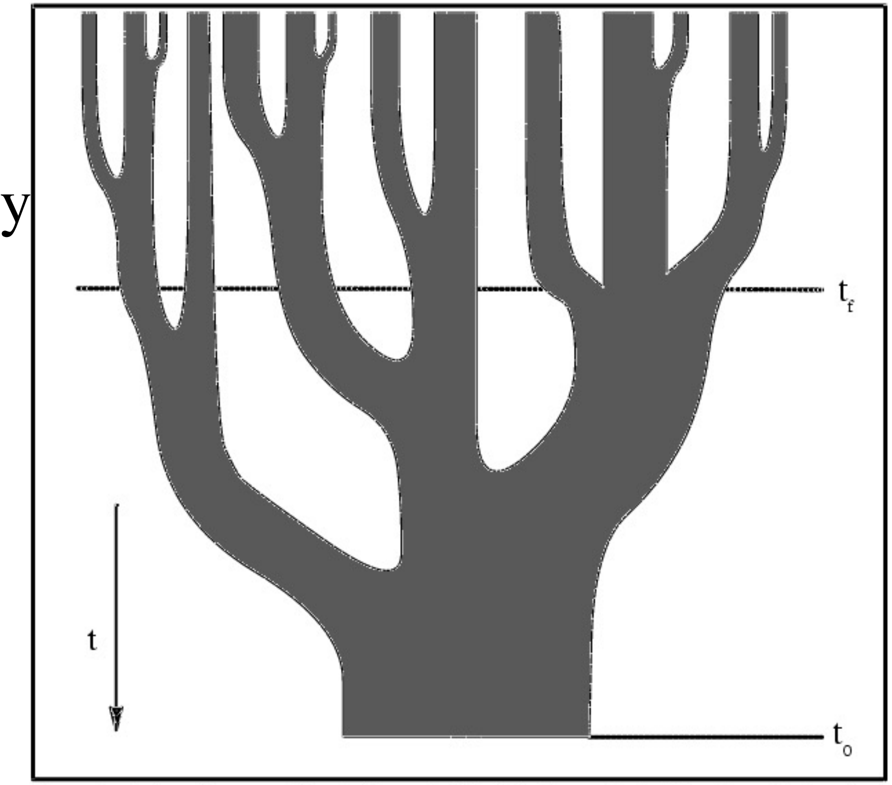
- They can grow through rapid accretion and merging to become central engines of AGN (SMBH)
- Mergers of these early BHs may generate gravitational waves detectable by LISA



Bromm & Loeb 2003

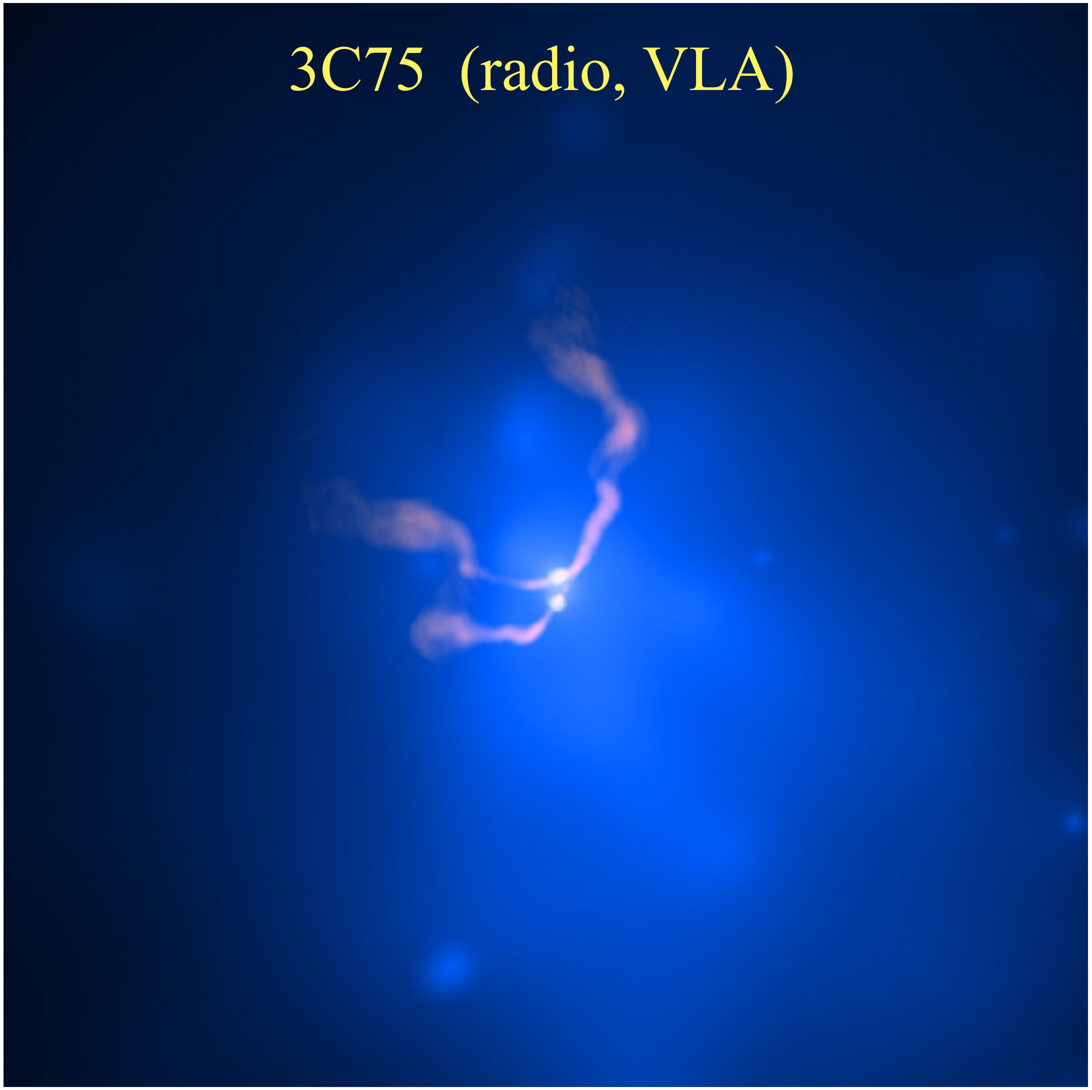
SMBH Growth Mechanisms

- In a hierarchical picture, as galaxies merge so will their BH's
  - Some may get ejected in 3-body interactions; their subsequent fate may be interesting
- This can naturally lead to the establishment of the SMBH - host galaxy correlations, which may be also sharpened by the AGN feedback

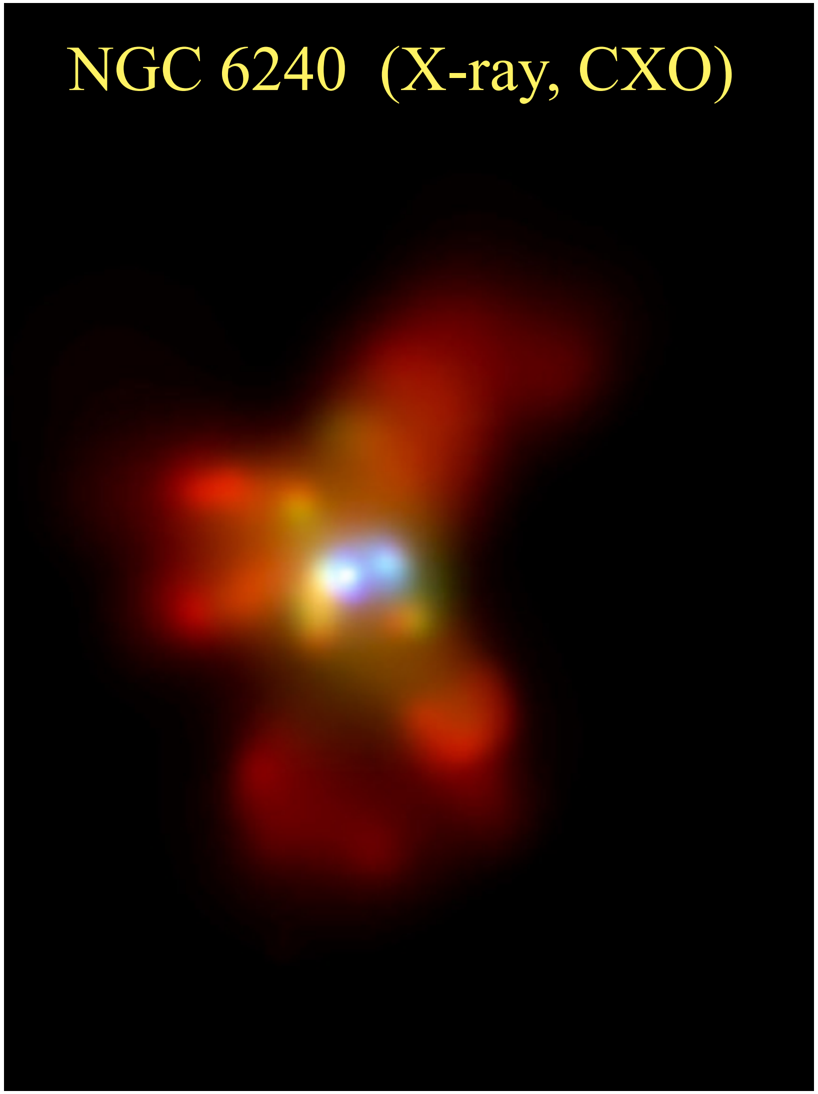


- Note that BH merging simply *re-arranges* the distribution of the collapsed mass; *collapsed mass grows by accretion*, following the BH seed collapse
- This fueling/build-up may be especially effective in mergers

Pre-Merger SMBH Binaries Are Observed at Low Redshifts



3C75 (radio, VLA)



NGC 6240 (X-ray, CXO)