

Some Examples of Virtual Observatory Enabled Science

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Lecture 2 - Part 1

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What Are the Some Distinguishing Characteristics of the VO-Style Science?

- Data-intensive: use of massive (TB-scale and beyond) data sets
 - Poissonian errors not important, systematics dominate
- Data complexity, e.g., multi-wavelength and/or multi-scale and/or multi-epoch data sets, 100's or 1000's parameters per source, combining imaging, spectroscopy, etc.
 - Heterogeneity and visualization are key issues
- Computationally intensive
- Traditional solutions do not scale to the scope of new problems
 - Need new tools and algorithms
- Data and computing resources are generally geographically distributed
- Inherently cross-cutting in many ways...

Virtual Observatory Science Examples

- Combine the data from multi-TB, billion-object surveys in the optical, IR, radio, X-ray, etc., for:
 - Precision large scale structure in the universe
 - Precision structure of our Galaxy
- Discover rare and unusual (one-in-a-million or one-in-a-billion) types of sources
 - E.g., extremely distant or unusual quasars, brown dwarfs, etc.
- Probe the evolution of quasars discovered using different techniques (e.g., optical, radio, X-ray, etc.) over the cosmic time
- Match Peta-scale numerical simulations of star or galaxy formation with equally large and complex observations

... etc., etc.

Illustrative Example #1: A Panchromatic Census of Active Galactic Nuclei (or: Supermassive Black Holes) in the Universe, and Their Evolution Over Cosmic Time

Why is this Important?

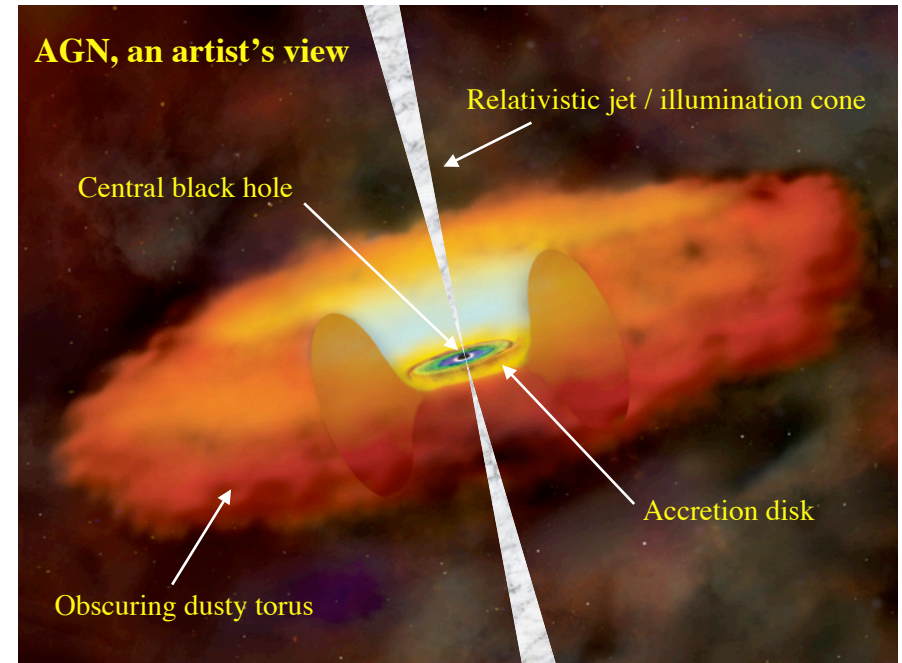
- AGN are one of the key constituents of the universe
- They are fundamentally related to galaxy formation and evolution
- They contain some very interesting relativistic physics

Why is it VO-Style?

- Each AGN discovery/study method has its own biases and selection effects; a panchromatic view would provide a more complete picture
- Large data sets are needed, as is their fusion

Quasars and AGN

- They are highly energetic manifestations in the nuclei of galaxies, believed to be powered by accretion onto massive black holes
- Empirical classification schemes and various types have been developed, on the basis of the spectra; but recently, various unification schemes have been developed to explain AGN as different appearances of the same underlying phenomenon
- Quasars/AGN are observed to evolve strongly in time, with the comoving densities of luminous ones increasing by $\sim 10^3$ from $z \sim 0$ to $z \sim 2$
- At $z \sim 0$, at least 30% of all galaxies show some sign of a nuclear activity (mostly low level); $\sim 1\%$ can be classified as Seyferts (moderately luminous), and $\sim 10^{-6}$ contain luminous quasars
- However, we think that most or all non-dwarf galaxies contain SMBHs, and thus probably underwent at least one AGN phase



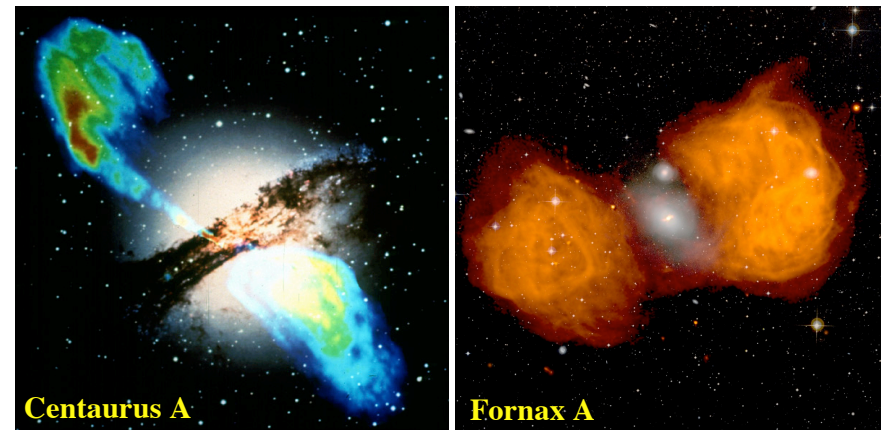
Observable Properties of AGN

- Energy emission over a broad range of frequencies, from radio to gamma 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, usually broad emission lines in their spectra
- Can reach large luminosities, up to $\sim 10^{15} L_{\odot}$
- Strong variability at all time scales
 - Implies small physical size of the emission region
- Central engines unresolved
- Zero 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

Radio Galaxies: Typical Examples

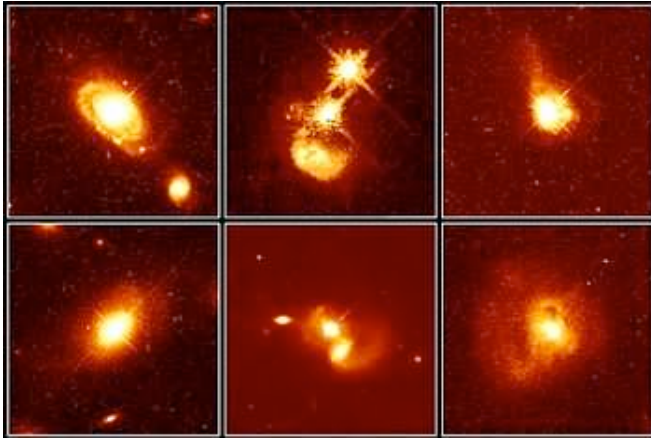
Radio overlayed on optical images



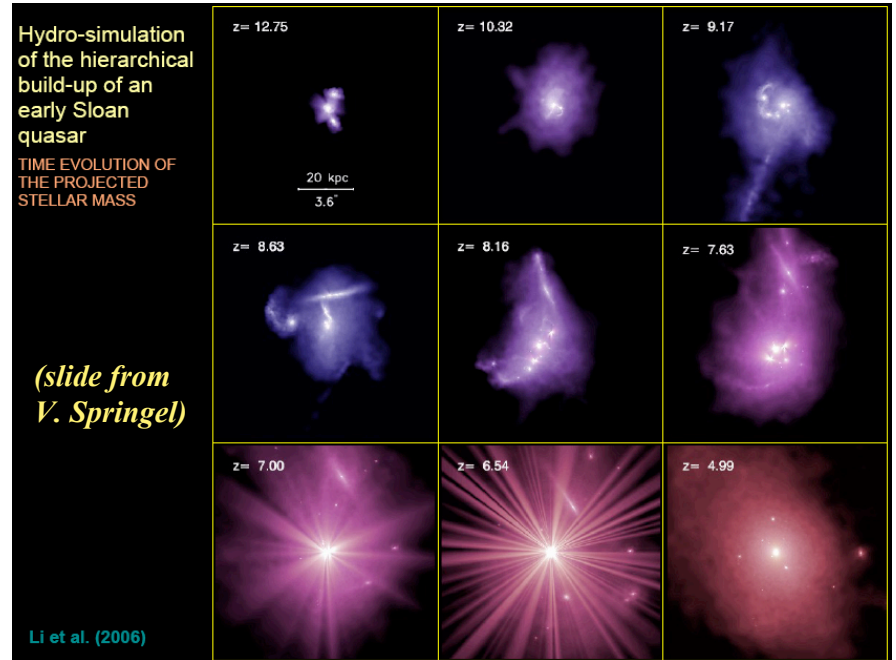
Energy stored in radio lobes can reach $\sim 10^{60} - 10^{61}$ erg. If jet lifetime is $\sim 10^8$ yrs, the implied mechanical luminosities are $\sim 10^{12} - 10^{13} L_{\odot}$

What Makes Quasars “Quase” ?

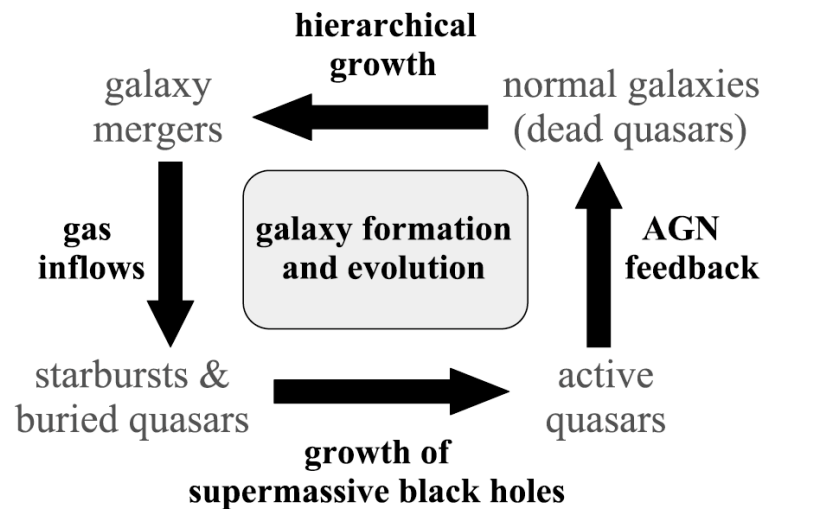
Dissipative galaxy interactions and mergers are believed to be fueling QSO activity - thus a QSO/galaxy evolutionary link



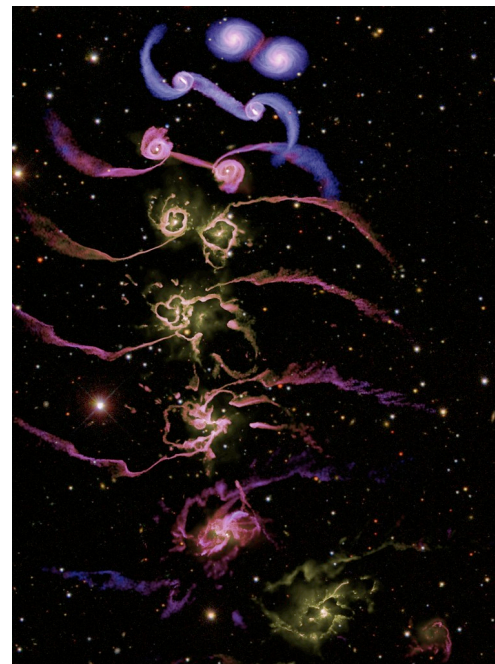
HST Images of QSO hosts



The Synergy of Galaxies and SMBHs



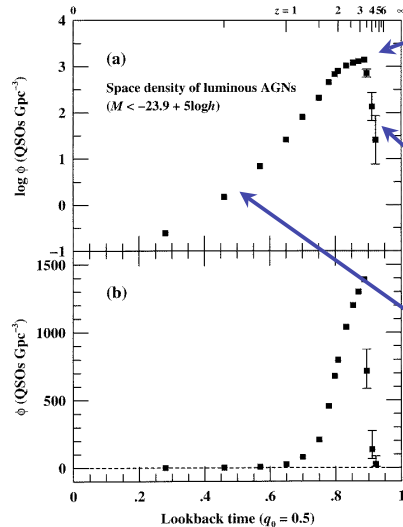
(from P. Hopkins)



Newly (re)ignited AGN can then regulate the growth and star formation in their hosts, through radiative and mechanical energy input feedback, and determine some of the fundamental properties of the host galaxies (and drive the observed correlations)

(Di Mateo, Springel, Hopkins, et al., and many others...)

The History of the Comoving Number Density of Quasars



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

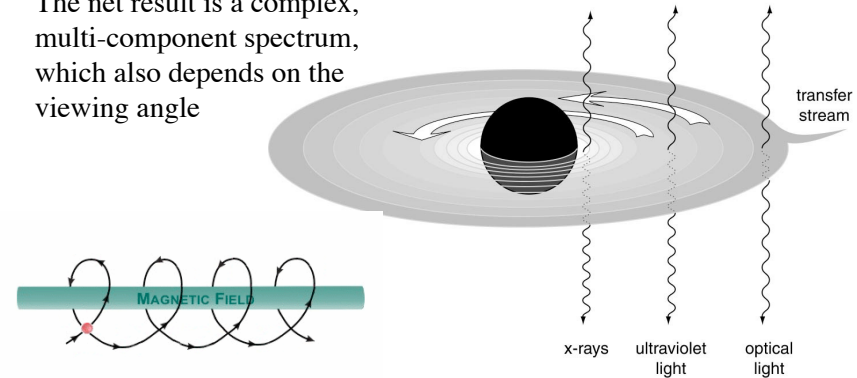
The Rise of Quasars: Initial Assembly of the Host Galaxies, Growth of the SMBHs

The Decline at Low z 's: Diminishing Fueling Events

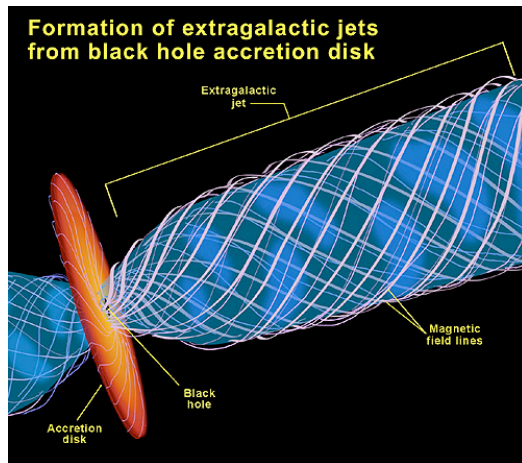
Energy Release From Central Engines

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

The net result is a complex, multi-component spectrum, which also depends on the viewing angle



AGN Jets: Accelerators in the Sky

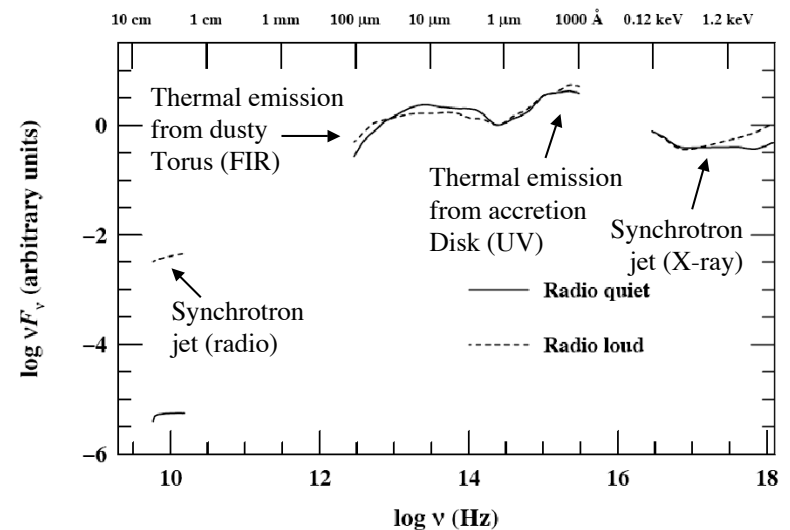


Magnetic fields are threaded through the accretion disk, and/or the spinning black hole itself

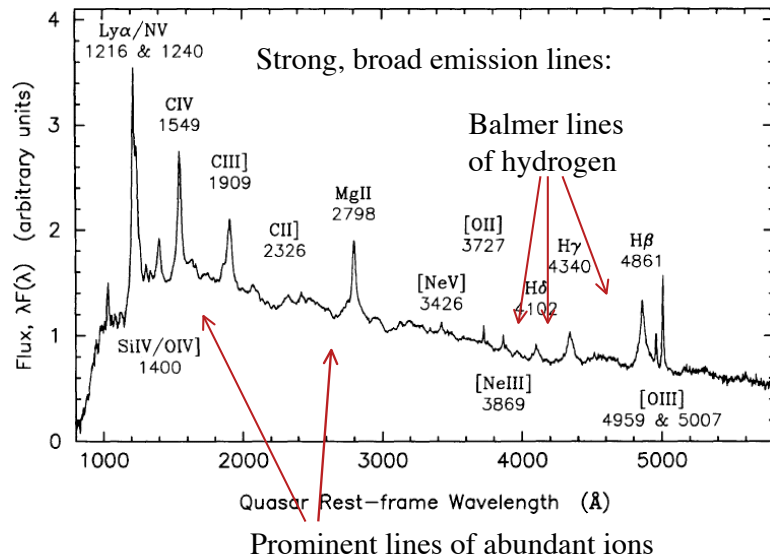
The spin turns the magnetic lines of force into well-defined and tightly wound funnels, along which charged particles are accelerated

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

Explaining the Broad-Band Spectral Energy Distribution in AGN



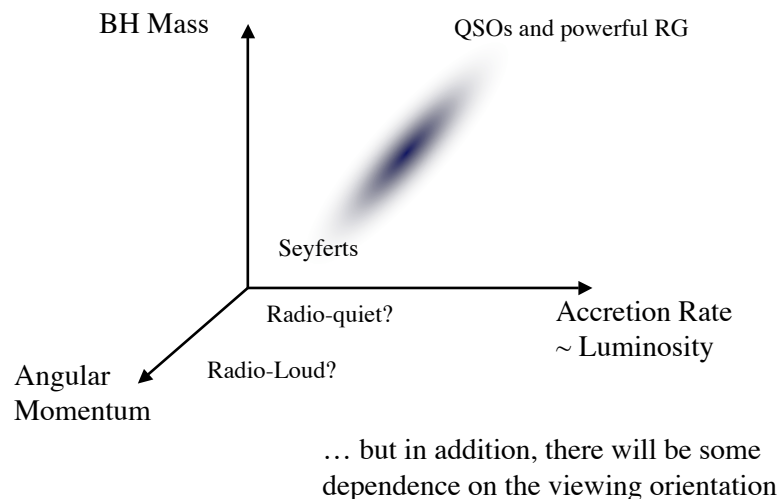
UV-Optical Spectra of Quasars



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

AGN: A Physical Classification



Quasar Surveys

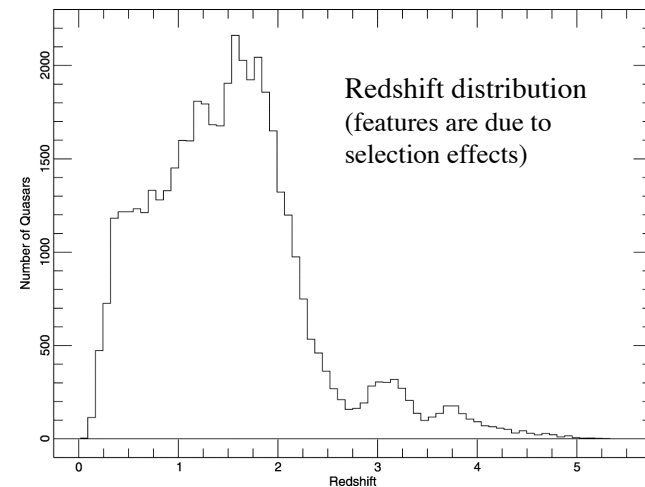
- In order to study QSOs (and other AGN), we first have to find them, in large numbers, and hopefully in a systematic fashion
 - This is especially important for studies of their evolution
- Recall that *each discovery method has its own biases*
- Nowadays the most popular technique is to use colors to separate QSOs from normal stars
 - In optical, one can also use slitless spectroscopy, variability, and zero proper motions
- Soft X-ray (up to few keV) and optical selection find the same types of relatively unobscured objects; hard X-ray selection and FIR/sub-mm detect more obscured populations; radio finds both
- Next: multi-wavelength, survey cross-matching in the Virtual Observatory framework - will help with the selection effects

Quasar Surveys and Catalogs

- To date (~ 2007), there are $\sim 100,000$ QSOs catalogued, plus maybe $\sim 500,000$ color-selected QSO candidates
 - Most come from large systematic surveys, e.g., SDSS and 2QZ
 - Many smaller surveys in the past were done at Palomar, e.g., Palomar Green (PG), Palomar CCD (PC), Palomar Sky Survey (PSS), and now Palomar-Quest (PQ)
 - There were also many searches for emission line objects (some are AGN, some starformers), e.g., Mrk, UM, CSO, KISS, etc.
 - Older heterogeneous catalogs include Hewitt & Burbidge, and Veron & Veron-Cetty compilations
- There are now also $> 10^5$ X-ray sources catalogued (most are probably powered by AGN)
- There is also probably close to $\sim 10^6$ radio sources in various catalogs, and many (most?) of them are powered by AGN
 - Major radio surveys include: Parkes (PKS), Green Bank (GB), NRAO VLA Sky Survey (NVSS), Faint Images of Radio Sky at Twenty cm (FIRST), etc.

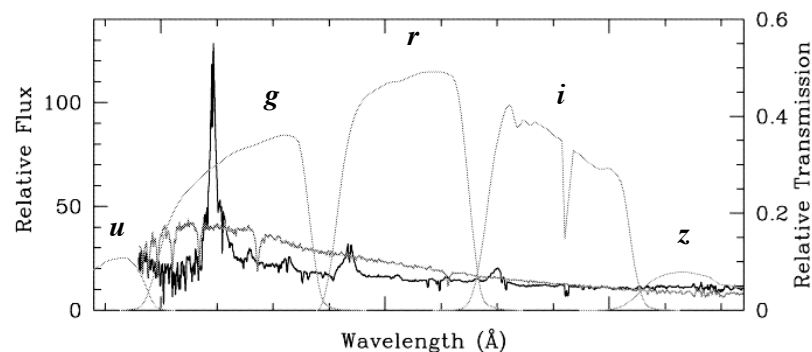
SDSS Quasar Survey

The largest QSO survey to date. Uses optical colors to select QSO candidates, reaching out to $z \sim 6.4$



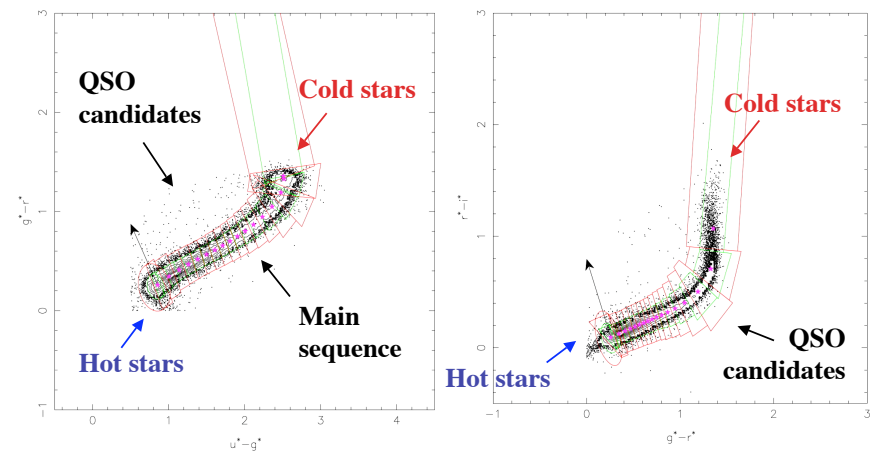
SDSS Quasar Survey

Ratios of fluxes in different survey filters (=colors) are in general different for QSOs and for stars - even though both look “stellar” on the images. The colors will change with redshift as different features (emission lines, continuum breaks) shift from one filter to another. For each redshift range, a different filter combination would be the optimal one for QSO selection



SDSS Quasar Survey

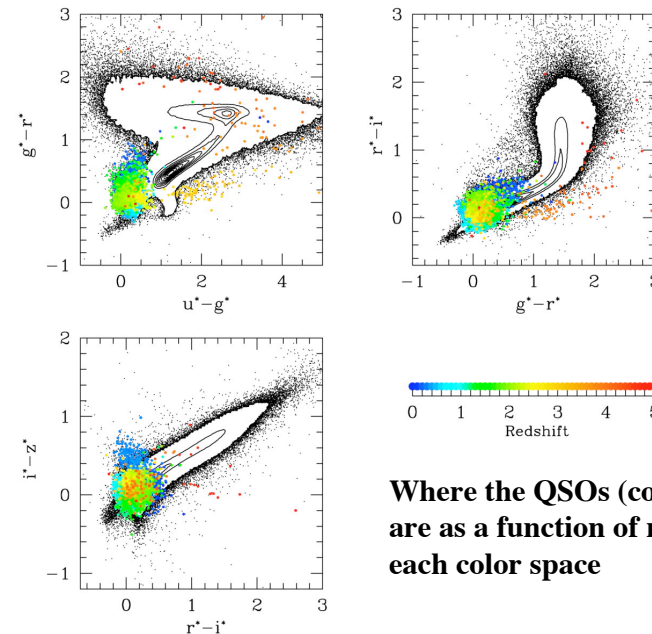
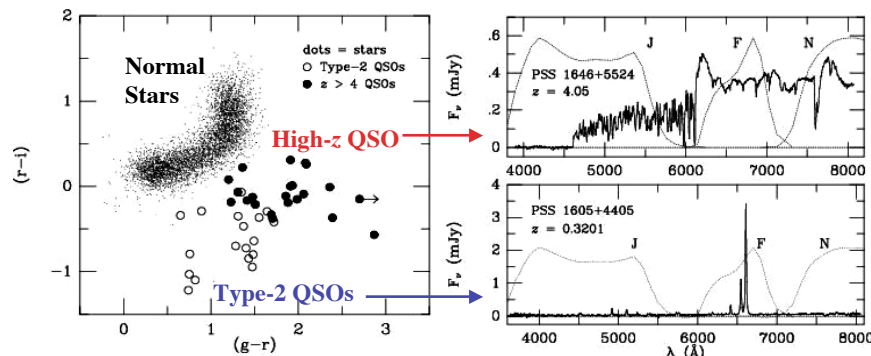
Examples of color selection of QSOs, as outliers away from the stellar locus



Using Colors to Find Quasars

At $z > 3.5 - 4$, absorption by the intergalactic hydrogen makes QSOs very red in the blue part of the spectrum, while they retain their intrinsic blue colors in the red part of the spectrum ...

However, presence of strong emission lines can also affect colors



Black dots:
stars and
galaxies

Where the QSOs (colored dots)
are as a function of redshift in
each color space

What Should VO Survey for AGN Do?

- Do a multicolor selection using federated surveys from UV (e.g., GALEX), optical (SDSS, PQ,...), to NIR (2MASS, UKIDSS...)
 - Calibrate selection using spectroscopically confirmed samples
- X-ray source IDs
- Radio source IDs, as a function of radio morphology and spectral index
- Mid-IR and FIR selected samples from Spitzer, sub-mm obs., etc.
- Federate all samples and evaluate various selection effects, as a function of redshift, luminosity, etc.
- Evaluate corrected comoving densities, luminosity functions, and obscured fractions as functions of redshift
- Correlate with large-scale environments using galaxy catalogs

Test for the extent
and relative
contribution of
optically obscured
QSO populations

Illustrative Example #2: Clusters of Galaxies, Their Evolution, and Cosmological Uses

Why is this Important?

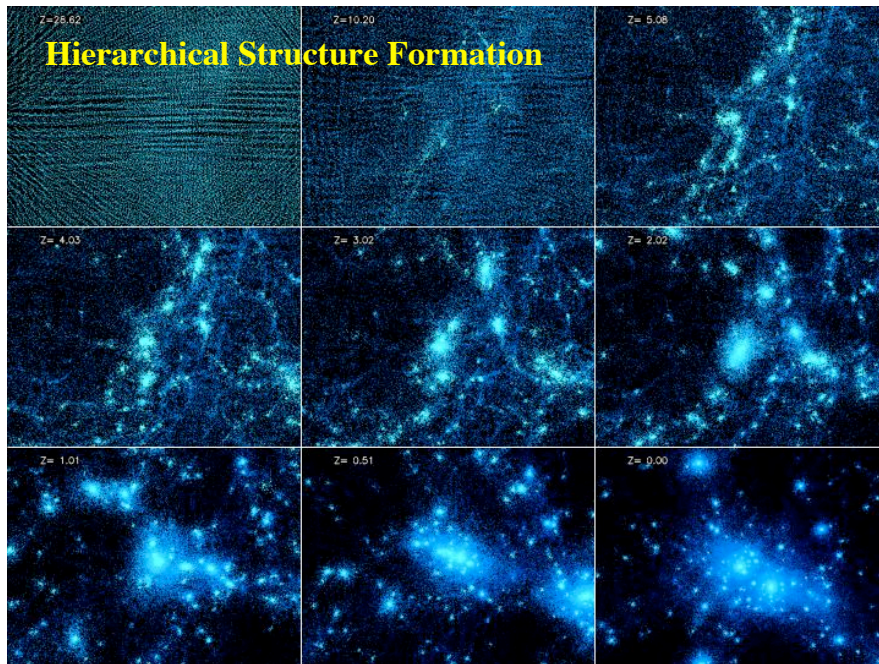
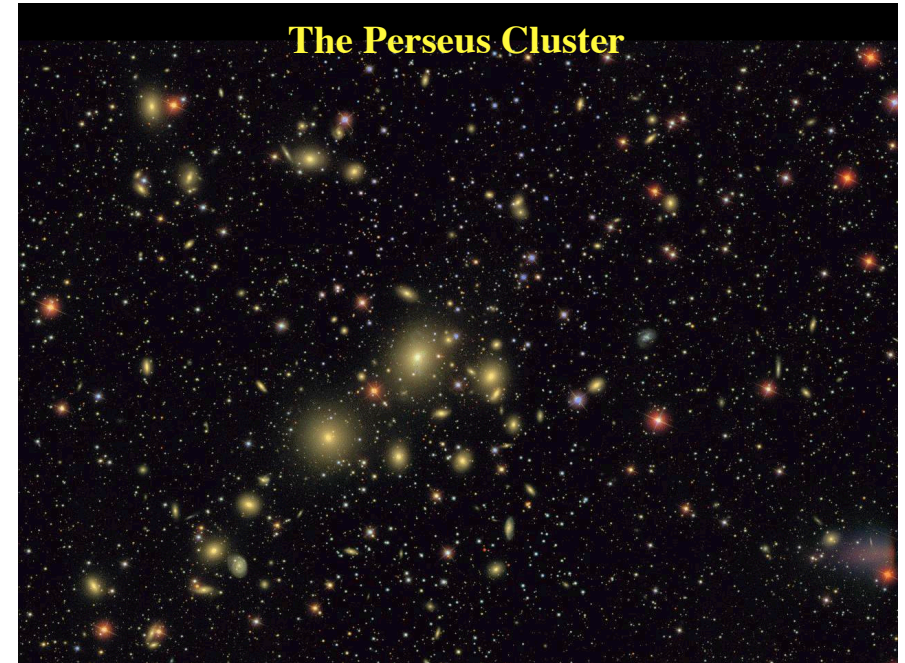
- Clusters are a major element of the large-scale structure of the universe, and the largest virialized structures
- They are fundamentally related to galaxy formation and evolution
- They can be used as cosmological probes

Why is it VO-Style?

- Each cluster discovery/study method has its own biases and selection effects; a panchromatic view would provide a more complete picture
- Large data sets are needed
- Compare with numerical simulations to gain physical insights

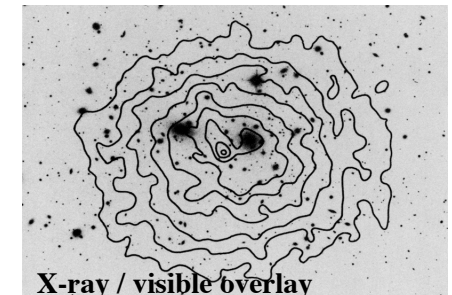
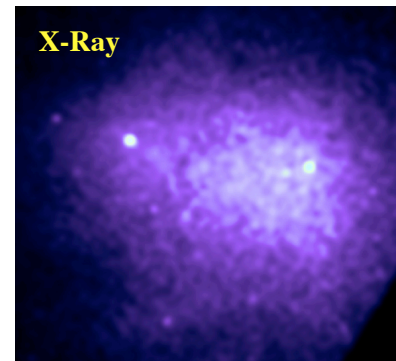
Clusters of Galaxies

- Clusters are perhaps the most striking elements of the LSS
- Typically a few Mpc across, contain $\sim 100 - 1000$ luminous galaxies and many more dwarfs, masses $\sim 10^{14} - 10^{15} M_{\odot}$
- 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 ($\sim 80 - 85\%$)
- Only $\sim 10 - 20\%$ of galaxies live in clusters, but it is hard to draw the line between groups and clusters, and at least $\sim 50\%$ 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 Coma Cluster

- Nearest rich cluster, with $>10,000$ galaxies
- Distance ~ 90 Mpc
- Diameter $\sim 4-5^\circ$ on the sky, 6-8 Mpc



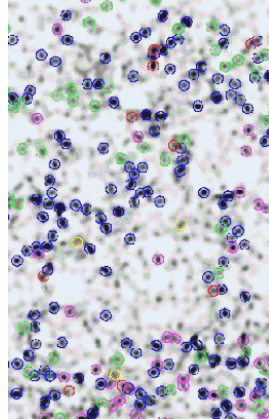
Surveys for Galaxy Clusters

Galaxy clusters contain galaxies, hot gas, and dark matter

Can survey for each of these components using observations in different wavebands:

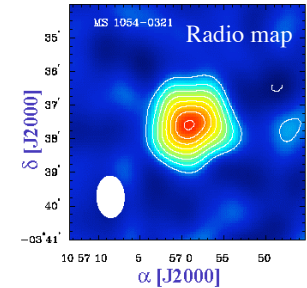
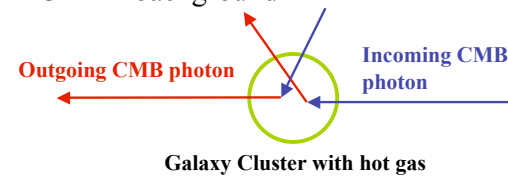
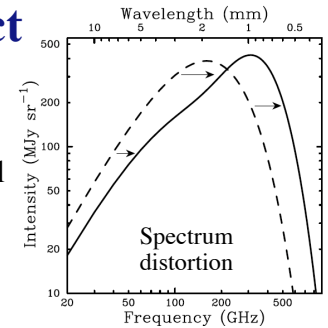
1. Optical

- Look for an overdensity of galaxies in patches on the sky
- Can use color information (clusters contain many red elliptical galaxies)
- At higher redshifts, use redder bands (IR)
- **Disadvantages:** vulnerable to projection effects, rich cluster in the optical may not have especially high mass



Sunyaev-Zeldovich Effect

- Clusters of galaxies are filled with hot X-ray gas
- The electrons in the intracluster gas will scatter the background photons from the CMBR to higher energies and distort the blackbody spectrum
- This is detectable as a slight temperature dip or bump in the radio map of the cluster, against the uniform CMBR background



Surveys for Galaxy Clusters

2. X-Ray

- Galaxy clusters contain hot gas, which radiates X-ray radiation due to bremsstrahlung
- Advantage: bremsstrahlung scales with density and temperature as $n^2 T^{1/2}$ - i.e. *quadratically* in the density. **Much less** vulnerable to accidental line-of-sight projection effects
- **Disadvantage:** still not detecting clusters based on mass

3. Sunyaev-Zeldovich effect

- Distortion of the CMB due to photons scattering off electrons in the cluster. Mass weighted measure, but really detects hot gas, not dark matter, and subject to messy hydrodynamics

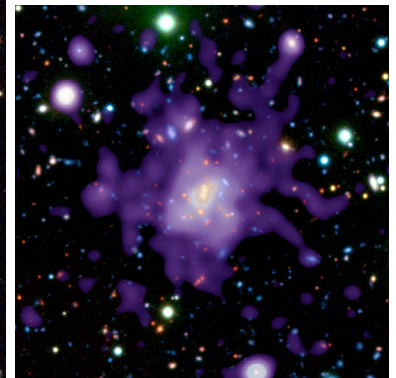
4. Weak Gravitational Lensing

- Selection based on mass. Difficult observationally



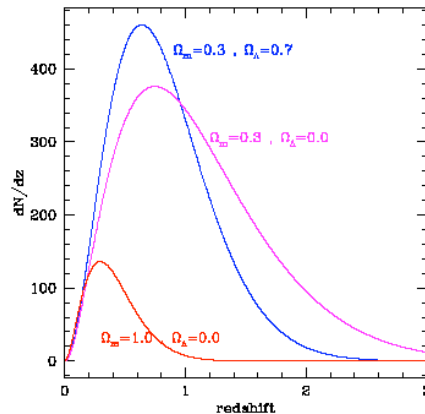
One of the most distant clusters now known, 1252-2927 ($z = 1.24$)

X-Ray

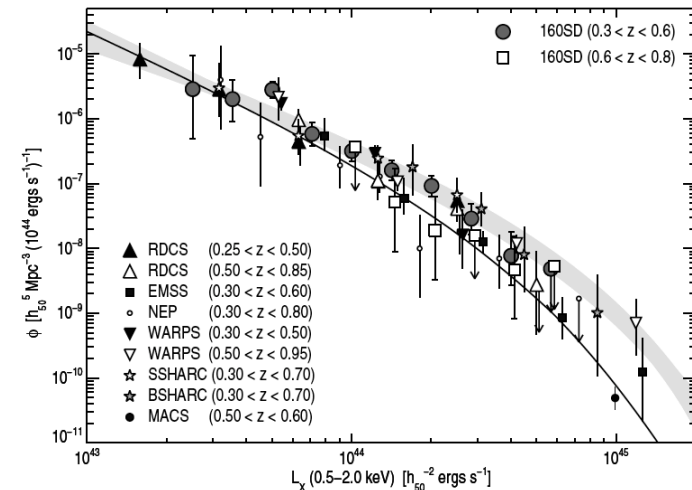


Clusters as Cosmological Probes

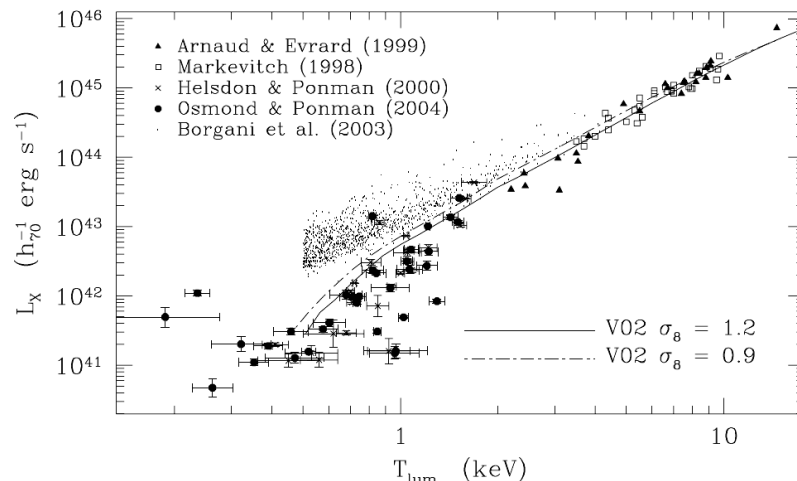
- Given the number density of nearby clusters, we can calculate how many distant clusters we expect to see
- In a high density universe, clusters are just forming now, and we don't expect to find any distant ones
- In a low density universe, clusters began forming long ago, and we expect to find many distant ones
- Evolution of cluster abundances:
 - Structures grow more slowly in a low density universe, so we expect to see less evolution when we probe to large distances



Evolution of the Cluster X-Ray Luminosity Function



In the process, one also discovers various interesting correlations, which can provide new insights into cluster physics and evolution (and selection effects?)



What Should VO Cluster Survey Do?

- Discover samples of clusters using the variety of approaches:
 - Projected overdensities, using different algorithms: adaptive kernel, matched filters, Voronoi tessellation, red sequence, cut & enhance ...
 - X-ray selection
 - S-Z effect (from CMBR obs.)
 - Bent radio sources
 - Weak lensing maps
- Federate overlapping samples and evaluate selection effects for each method, using a joint sample
- Interpret them as functions of cluster properties, e.g., richness, dynamical state, redshift, etc.
- Apply corrections and derive cluster luminosity and mass func's and their evolution is redshift
- Use for cosmological tests, and as a probe of cluster formation and evolution (compare with numerical simulations)

Illustrative Example #3: A Multi-Dimensional Portrait of Our Galaxy

Why is this Important?

- Understanding our large-scale cosmic home: its structure, dynamics, chemical composition, star formation, etc.
- Fossil evidence of our Galaxy's formation and evolutionary processes, presumably applicable to all galaxies

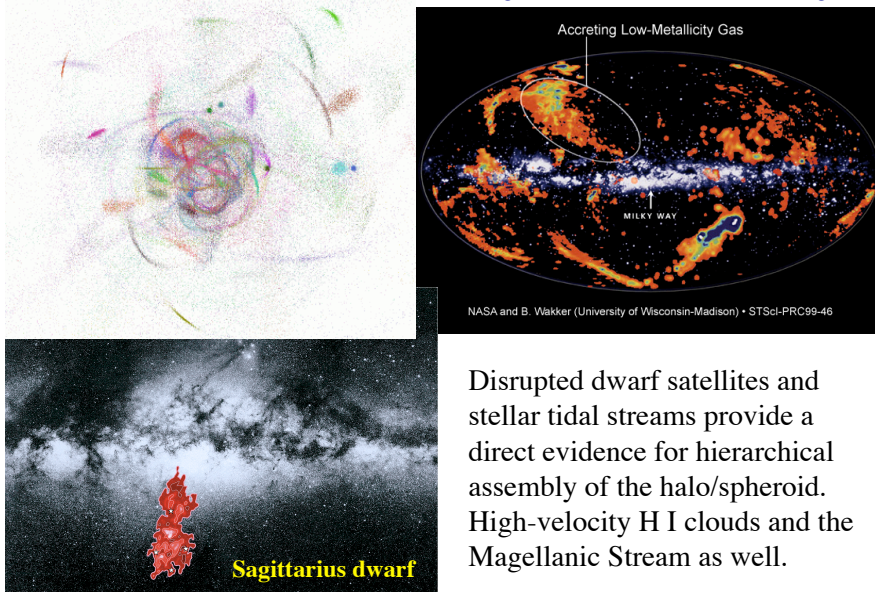
Why is it VO-Style?

- It requires a very broad range of data sets and data types, and their fusion, including but not limited to:
 - Panoramic imaging: optical, NIR to study stars; multi-epoch to get the proper motions
 - Panoramic imaging: radio (continuum and 21 cm) and FIR (dust) to study the ISM and star formation
 - Spectroscopy: stars (radial velocities and chemical abundances) and gas (global kinematics, physical state)

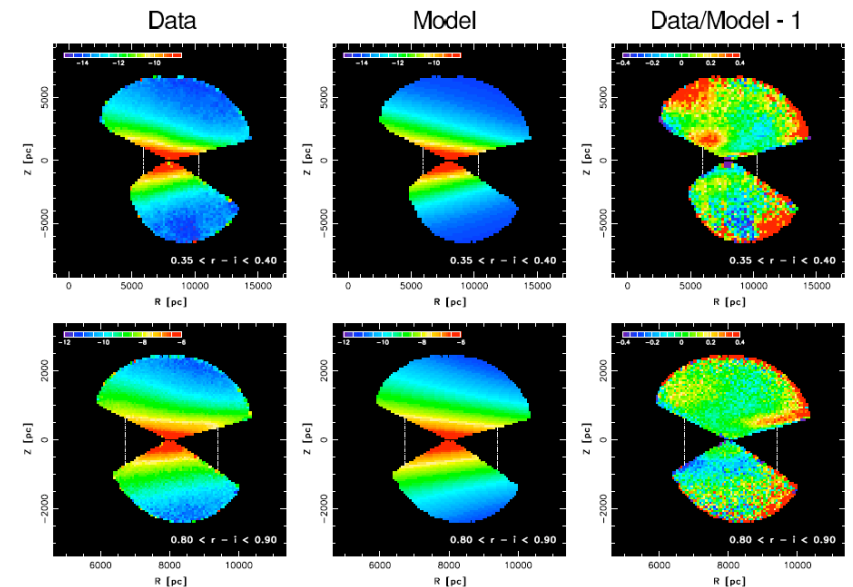
Constructing a Phase Space Portrait of the Milky Way

- Use stellar colors in the visible (e.g., SDSS) and IR (e.g., 2MASS) bands to simultaneously solve for stellar type and reddening, and thus absolute magnitude and distance → 3-D distribution of stars
 - Combine with FIR and molecular gas maps to derive the 3-D distribution of dust and cold gas
 - Kinematics of disk gas from H I 21-cm line and molecular lines
 - Stellar proper motions + radial velocities → stellar kinematics
 - Kinematics of the halo/infalling gas from absorption spectra
 - Distribution of the dark matter from stellar and gas motions
 - Separate different stellar population and kinematical components
 - Correlate with chemical abundances from spectroscopy
- ***Kinematical and density structure of our Galaxy, its formation***

Hierarchical Assembly of Our Galaxy



Evidence From SDSS Star Counts



Illustrative Example #4: Astrophysical Foregrounds to Cosmic Microwave Background

Why is this Important?

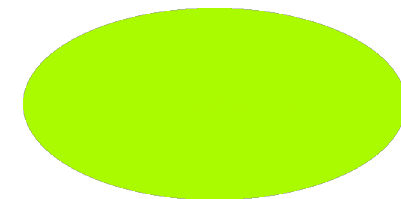
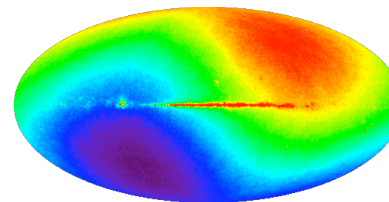
- One of the key cosmological and early-universe probes
- Foreground sources (compact and extended) distort the CMBR signal and inject energy to it
- Essential for interpretation of data from WMAP, Planck, etc.

Why is it VO-Style?

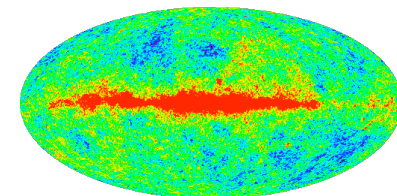
- It requires large, complete samples of galaxies, clusters, AGN, diffuse emission in our own Galaxy (radio to FIR to X-ray), their fusion and detailed modeling in order to separate the cosmological signal from the foreground effects

Cosmology With CMBR

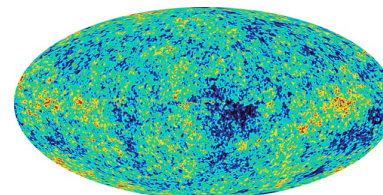
The CMBR sky from WMAP →



← Enhance the contrast by 10^3



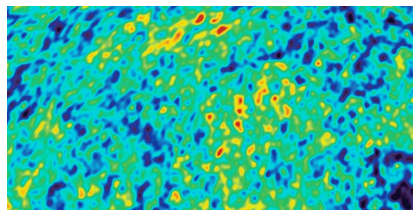
Remove the dipole and
enhance the contrast to 10^5 →



← Remove the Galaxy, the
contrast is 10^5 and see the
primordial density fluctuations

A characteristic fluctuation scale exists of ~ 1 degree

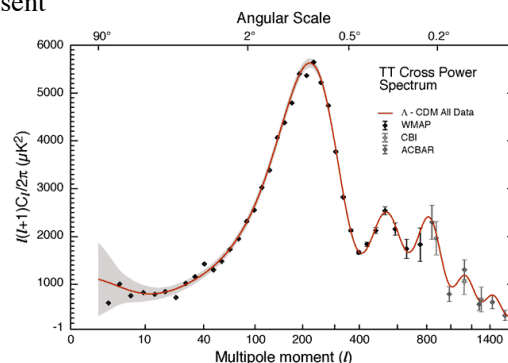
This corresponds to the size of the
particle horizon at the decoupling,
and thus to the longest sound
wavelength which can be present



This is quantified as an angular fluctuation power spectrum:

(WMAP, Bennett *et al.* 2003)

However, in order to get
to the pure cosmological
signal, one has to first
understand and remove
the various astrophysical
foregrounds



Precision now $\sim 10^{-6}$, going to $\sim 10^{-8}$

Understanding the CMBR Foregrounds

