# 4 Galaxy Clusters

**C & O, Sec. 27.3**

- The **Local Group** of galaxies is a collection of about 35 galaxies in the neighborhood of the Milky Way [see Figure 27.11 for a schematic depiction]. Andromeda (M31), M33 and the Milky Way are its most massive members.

$*$ The radius of the Local Group is around 400 kpc, and Andromeda and the Milky Way are on opposite sides; they currently approach each other at around 119 km/sec.

- Kepler's Third Law can be used to estimate the total mass $M$ of these two members of the Local Group. Assume that they are in a highly-eccentric elliptical orbit of semi-major axis $a$ and current separation $r$. Conservation of energy and Kepler III establish that

$$v^2 \;=\; GM\left(\frac{2}{r}-\frac{1}{a}\right)\quad , \quad P^2 \;=\; \frac{4\pi^2}{GM}\,a^3 \quad . \tag{4}$$

Eliminating $a$, these combine to give

$$v^2-\frac{2GM}{r}+\left(\frac{2\pi GM}{P}\right)^{2/3} \;=\; 0 \quad . \tag{5}$$

We have $r = 770\,\text{kpc}$ and $v = 119\,\text{km/sec}$, and only need the period $P$ of the orbit. This must be of the order of the Hubble time (13.7Gyr) plus the approximate time $r/v$ until they collide (an overestimate). The total mass is then found to be

$$M \;\sim 7.9\times 10^{45}\text{g} \;=\; 4.0\times 10^{12}M_\odot \quad . \tag{6}$$

This yields a mass-to-light ratio of $\sim\, 60M_\odot/L_\odot$, and provides further dynamical evidence for **dark matter** using this binary mass determination.

[*Reading Assignment: C. & O. p. 1061: Other Groups within 10 Mpc*]

- On larger scales, galaxies congregate in **clusters** of different varieties. **Poor clusters** of galaxies typically have few constituent members ($\lesssim 50$), but **rich clusters** such as *Virgo* or *Coma* can possess thousands of galaxies.

$\boxed{\textbf{Plot:}}$ HST Image of Abell 2218 Cluster

# HST Image of Abell 2218 Cluster

- From Hubble Image Gallery

- The **Virgo cluster** is a nearby (16 Mpc) rich, irregular cluster with over 2000 constituent galaxies. It contains four giant ellipticals (including M87 with its relativistic jet), but is mostly made up of spiral galaxies.

- The **Coma cluster** is about 90 Mpc from Earth and is a rich, regular cluster with about 10,000 galaxies! The vast majority of its constituent galaxies are ellipticals and S0s, the more common scenario for rich clusters.

$\ast$ Clusters can be categorized according to their galaxy content, dividing into (i) cD-rich clusters with a predominance of cD galaxies and fewer spirals, (ii) spiral-poor clusters with mostly ellipticals but few cD ones, and (iii) spiral rich clusters with about 50% of their members being spirals.

**Longair Sec. 4.2.1**

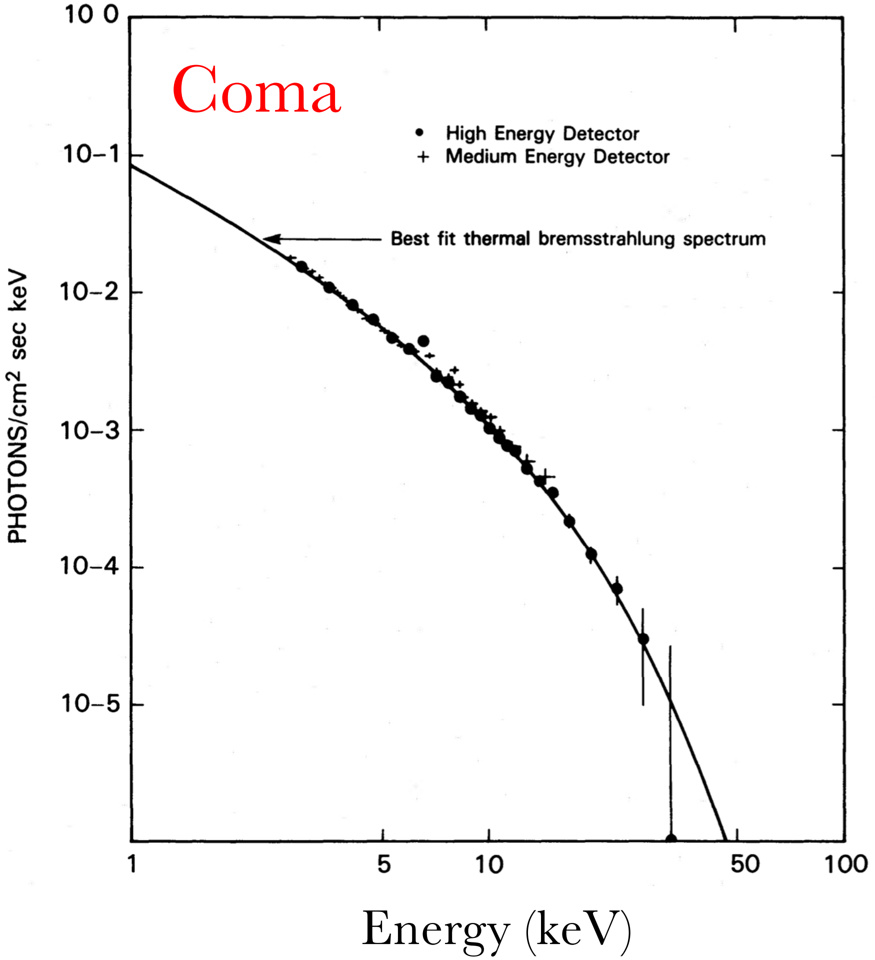
- Clusters have communal matter, including central pools of hot, tenuous gas that constitutes much of the **intracluster medium**. Tidal effects can become strong and hot gas leaves individual galaxies to reside in a collective cloud belonging to the entire cluster. This gas can emit **thermal bremsstrahlung** at temperatures in the range of $10^7 - 10^8\,\mathrm{K}$ (e.g. Allen & Fabian 1998) $\Rightarrow$ the domain of X-ray astronomy.

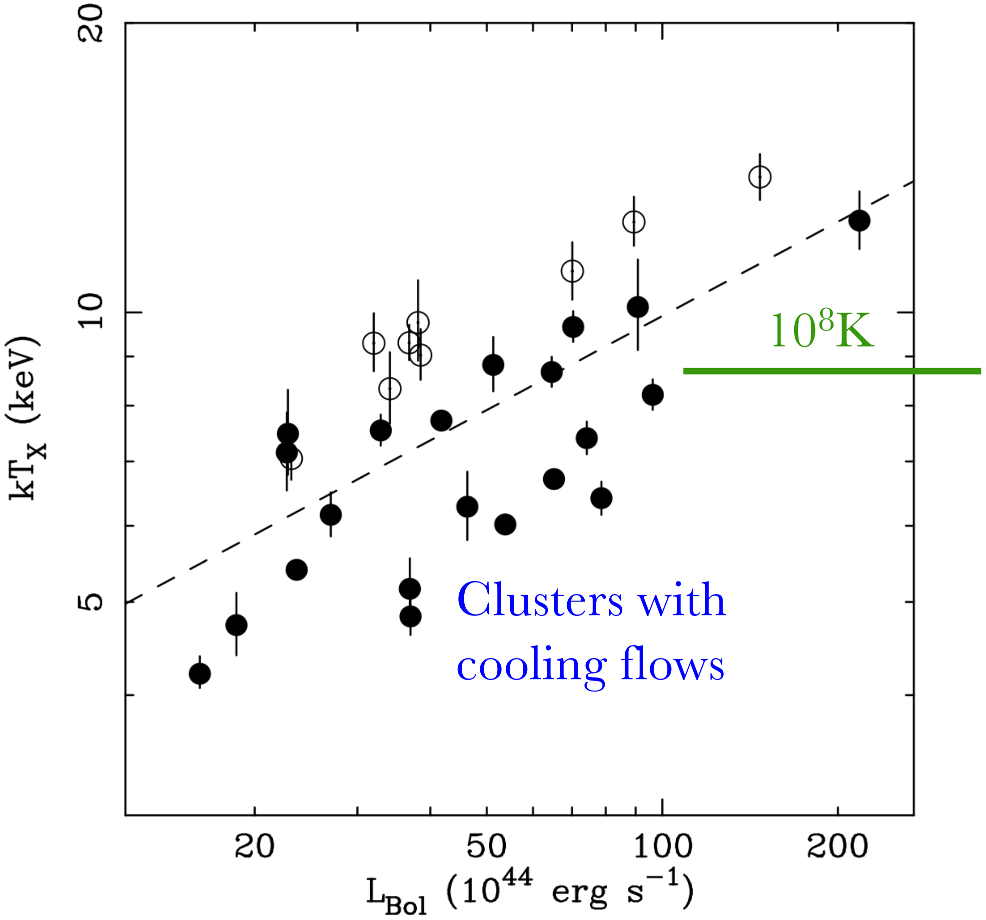
**Plot:** Thermal Bremsstrahlung from Clusters

- Assuming an isothermal sphere of gas, one can use the temperature to estimate virial speeds $\sigma \sim 10^3\,\mathrm{km/sec}$ for the gas. The bremsstrahlung emission rate then leads to an inferred gas density of $n_p \sim 0.01\,\mathrm{cm}^{-3}$ for a cluster core radius of 0.3 Mpc. While this is not high by Galactic standards, it is much larger than for the IGM (intergalactic medium). Gas collisions can thus be very influential. On Hubble times, radiative cooling of the hot gas by bremsstrahlung is significant. This then leads to **cooling flows** in denser central regions of the cluster gas.

$\ast$ The X-ray flux can be used to measure the mass of the radiating gas, and its radial gradient can be used to infer (via hydrostatic support) the total mass of the cluster ($\Rightarrow$ dark matter yet again!). For the Perseus cluster, Böhringer (1995) determined that the inferred *galaxy:gas:dark matter* mass ratio is 1:3:10.

# Thermal Bremsstrahlung from Clusters





- *Left panel*; isothermal **bremsstrahlung** fit to HEAO-1 X-ray spectrum of the Coma cluster, with T~8.8 x $10^7$K (i.e. 7.6 keV). Henriksen & Mushotsky (1986, ApJ **302**, 287).
- *Right panel:* Bremsstrahlung temperature versus bolometric luminosity for a variety of clusters; those with central **gas cooling flows** are denoted by filled circles. From Allen & Fabian (1998, MNRAS **297**, L57).

• The cluster gas temperatures $T \sim 10\,\mathrm{keV}$ approach that of the cosmic X-ray background (XRB) emission. This suggests that clusters could be significant contributors to the XRB. Yet AGN are generally dominant above 10 keV, since they are generally quite hot due to their Comptonized continua.

**Plot:** Swift + INTEGRAL Cosmic X-ray Background

• The spatial decoupling of cluster gas from constituent galaxies is most stunningly displayed in the **Bullet cluster** observations by Chandra in X rays. This system at $z = 0.296$ is believed to be formed from the collision of two clusters. The ensemble cluster exhibits significant **gravitational lensing**, from which inferences of dark matter density profiles are made.

**Plot:** Bullet Cluster (1E0657-558): a Lens for Dark Matter

These profiles are bi-polar in geometry (Clowe et al. 2006; ApJL **648**, L109), with the dark matter poles being separated more widely than the gas profile measured with the X ray data. The conclusion is that the dark matter retains its ballistic character in the collision of clusters due to its weakly-interacting nature, predominantly only under the influence of gravity.

• There is some evidence for evolution of clusters, in that clusters in the early universe were necessarily smaller and therefore more likely to exhibit interacting galaxies (e.g. spirals) that would eventually virialize into a predominance of ellipticals that is evinced in rich clusters today.

# 5 Large Scale Structure

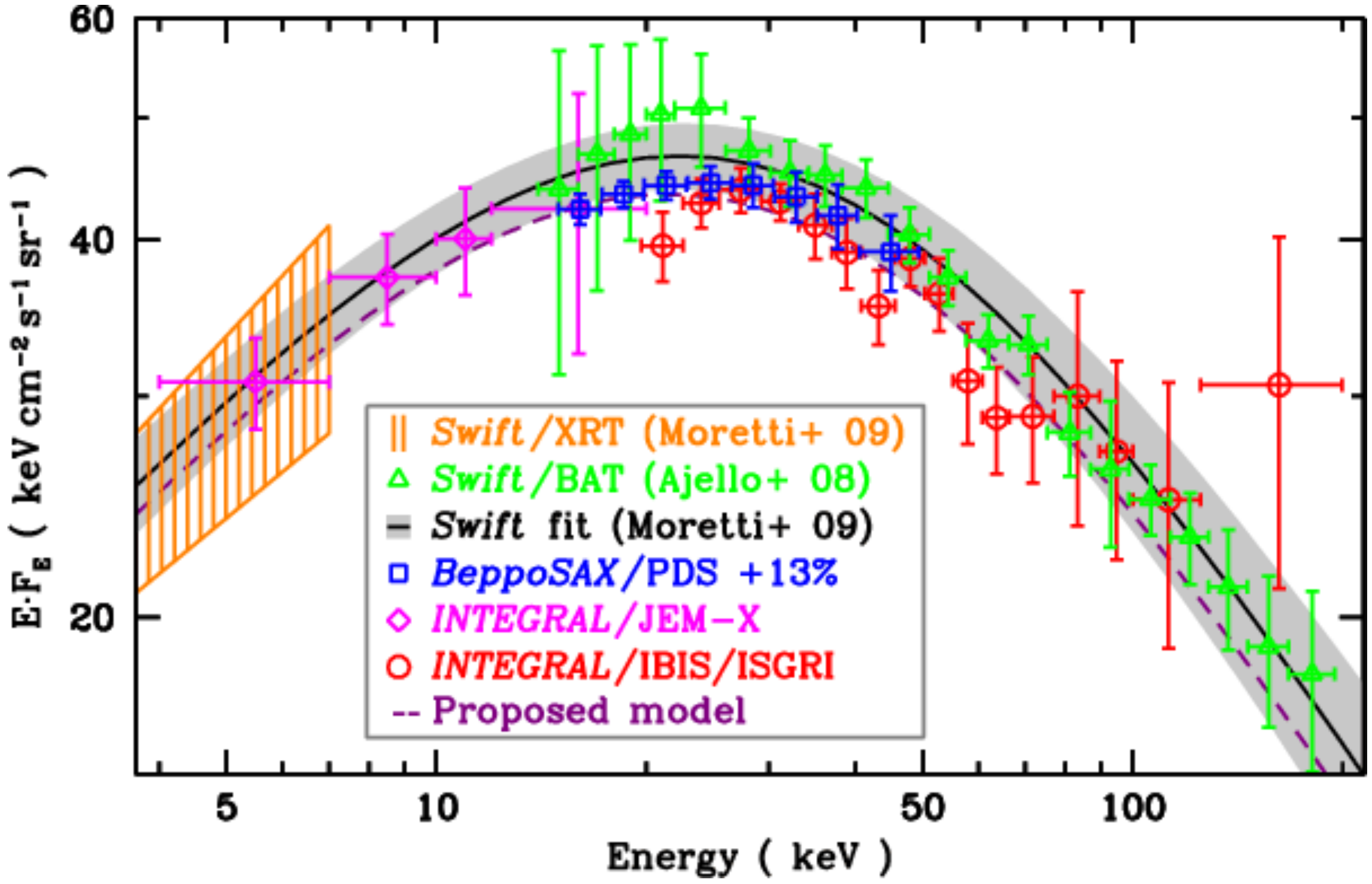
**C & O, pp. 1070-9**

• The apparently chaotic/random nature of our local peculiar environment gives way to ordered structures on the scales of $z \sim 0.01 - 0.03$. Such structures includes clusters, filaments, sheets and voids.

**Longair, Sec. 2.2**

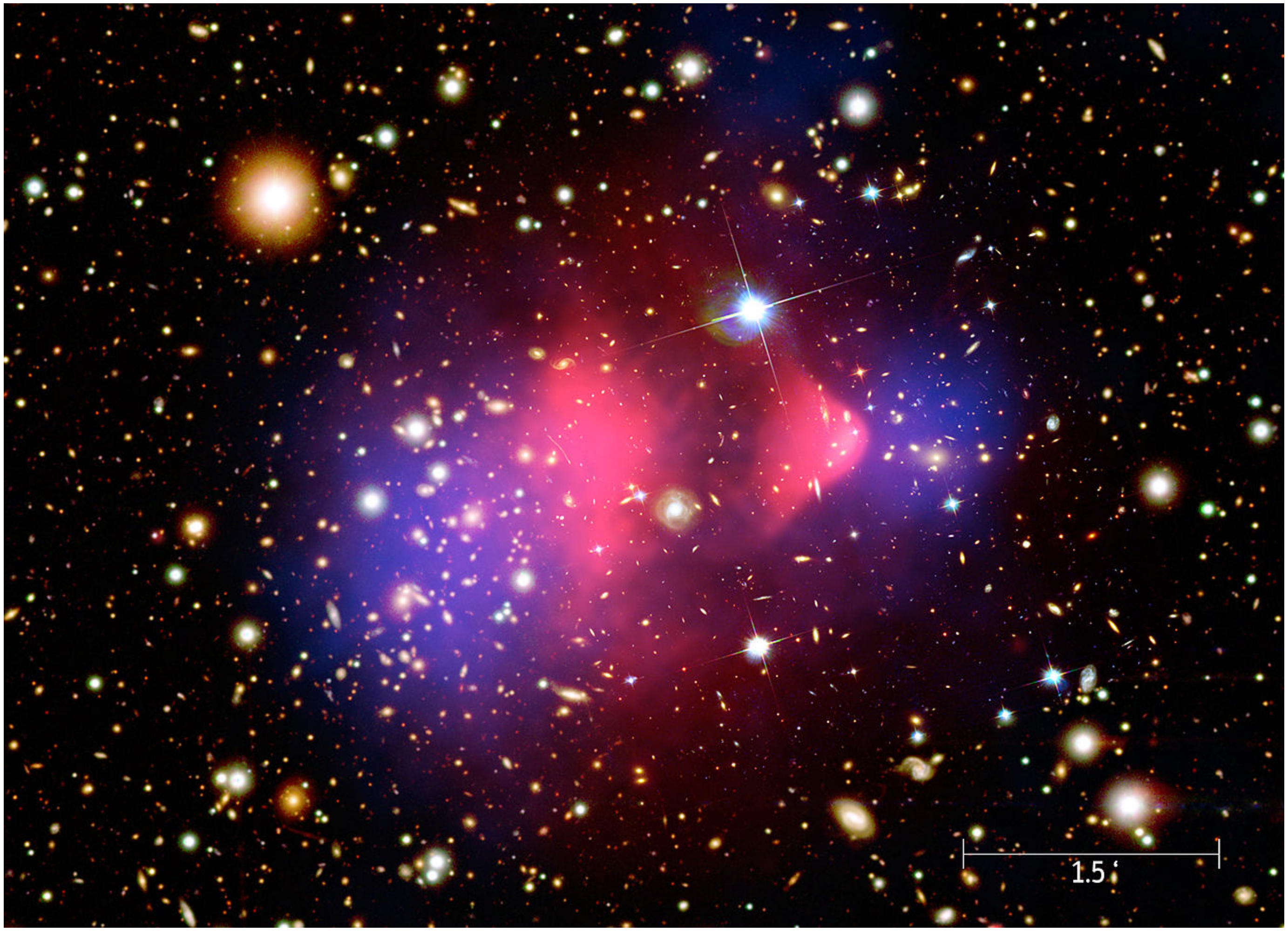
• The CfA Redshift Survey in the optical provided first evidence for sheet-like rather than filamentary structure, evidence that is important for struc-

# Cosmic Diffuse X-ray Background



- From Türler et al. (2019, A&A **512**, A49), indicating T~20 keV. Original work in Marshall et al. (ApJ 1980) indicated a thermal bremsstrahlung fit of T~40 keV. These are a bit higher than gas temperatures in galaxy clusters.

# Bullet Cluster: Collisions in Action



**1E 0657-56**

- Bullet cluster (z=0.3) melange. Combined Hubble, Chandra (red) and dark matter distribution (blue) inferred from gravitational lensing. This illustrates the power of lensing as a diagnostic tool.
- From Chandra CXC Image Gallery [Credit: Markevitch, Clowe]

ture formation models. Geller and Huchra led the Survey efforts over a period from the late 1970s to the early 1990s, delivering sky locales and redshifts for several thousand galaxies.

$*$ Infra-red surveys can often see deeper at high latitudes, probing to higher $z$ and therefore sampling homogeneity and isotropy more.

- The modern day upgrade has been the Sloan Digital Sky Survey (SDSS), in the optical/IR, that has delivered 3D positions for over a million galaxies in the 21st century.

$\boxed{\textbf{Plot:}}$ Sloan Digital Sky Survey Map

Departures from isotropy and homogeneity are probed by a galaxy-separation two-point correlation function, $w(\theta)$, such that number $N(\theta) = n_g[1+w(\theta)]$ depends on the angular separations $\theta$ between pairs of galaxies.

$\boxed{\textbf{Plot:}}$ SDSS Galaxy Two-point Correlation Function

- The observed correlation has a scale-independent form for 20 kpc $\lesssim$ 10 Mpc of $dw/d\theta \propto \theta^{-1.7} \propto (\delta r)^{-1.7}$, i.e. $w(\theta) \propto \theta^{-0.7}$. Generating this form serves as a diagnostic goal for structure formation models that include both dark matter and dark energy in gravitational interactions.

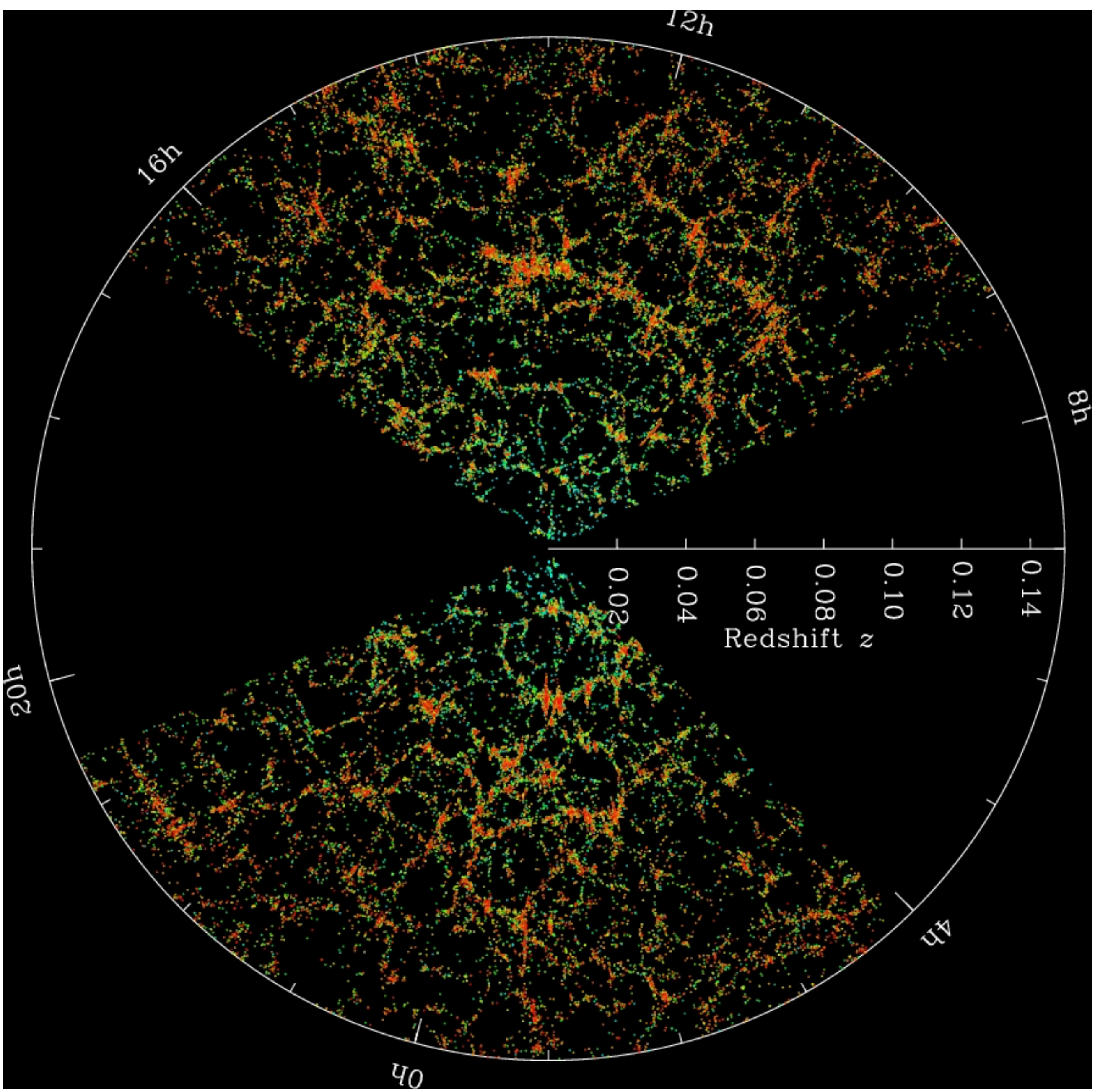
$*$ On separation scales $\delta r \gtrsim 10\,\text{Mpc}$, the correlation drops more rapidly with increasing $\theta$ $\Rightarrow$ quasi-homogeneity on large scales. This forms the foundation of the Cosmological Principle.

- Deeper probes of isotropy are possible in high energy astrophysics, such as X-ray background (XRB) sky maps that sample moderate redshifts, though not with the high $z$ of the CMB map.

$\boxed{\textbf{Plot:}}$ *eROSITA* X-ray map, 0.3–2.3 keV

Early measurements of the XRB indicated that it was very smooth on the sky. Yet these were of poor angular resolution. The much improved view with the new *eROSITA* soft X-ray telescope has in fact resolved many sources, many being Seyfert galaxies. Yet there is still a residual unresolved component that may or may not be true diffuse emission, likely associated with clusters.

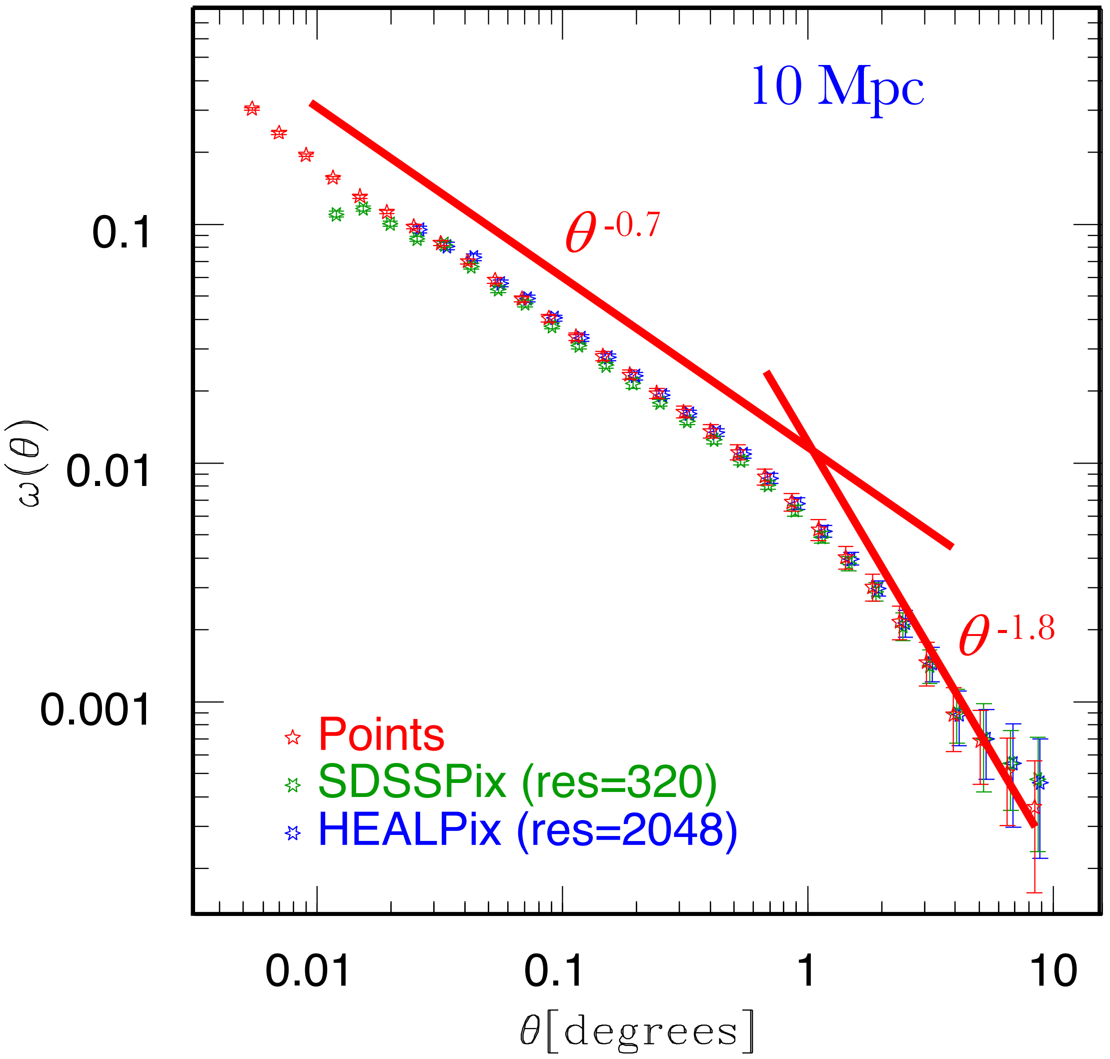
# SDSS 3D Galaxy Map



See https://classic.sdss.org/home.php

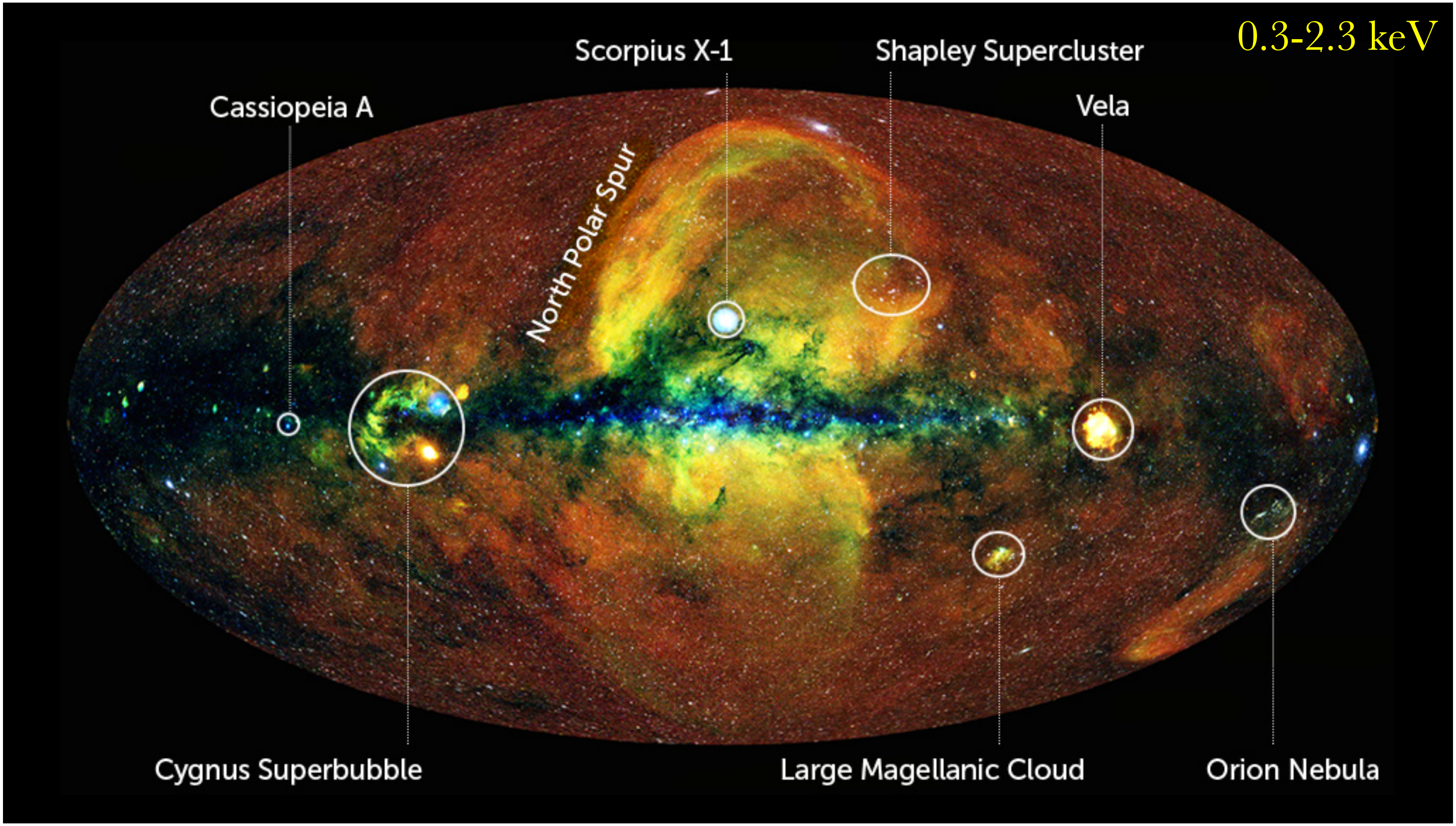
- 3D galaxy map from Sloan Digitial Sky Survey (SDSS). Redshift from the Milky Way defines the radial dimension. Redder galaxies have older stars. Galaxy clustering and filamentary/sheet-like structure is apparent.
- Over a million galaxies surveyed, 2000-2014.

# SDSS Galaxy 2-Point Correlation



Wang et al. MNRAS **432**, 1961 (2013)

# eROSITA X-ray Sky Map



- See https://www.mpe.mpg.de/7461761/news20200619 (June 2020)

# 5. ACTIVE GALAXIES

Matthew Baring – Lecture Notes for ASTR 360, Spring 2025

## 1 Global Energetics of Active Galaxies

• Active galaxies were discovered largely since WWII, both with developments in optical astronomy and the advent of radio astronomy. Key signatures of active galaxies include that they are typically much more luminous than normal galaxies, with $L \sim 10^{42} - 10^{47}\,$erg/sec. This is generally interpreted to imply that *their energy source is not nuclear.*

∗ In stellar nucleosynthesis, since main sequence stars are typically 5 orders of magnitude larger than their Schwarzschild radii, the efficiency of tapping their gravitational potential is of order $10^{-5}$ of their rest mass ⇒ **Kelvin-Helmholtz** $t_{\rm KH}$ timescales exceed the Hubble time $t_{\rm H}$ .

The efficiency nuclear energy production is at best 0.7% (for He production in the *pp* chain; talk about the nuclear binding energy curve). With an estimate $E_{\rm nucl} \sim 0.007 m_p c^2 N_p$ , one finds

$$10^{47}\,\hbox{erg/sec} \;\sim\; 10^{-7} M_{\odot}/sec \;\sim\; 3\times 10^{10} M_{\odot}/t_{\rm H} \quad . \qquad (1)$$

Hence core masses of $10^9 M_{\odot}$ are insufficient to sustain the luminosity over a Hubble time.

• In contrast, active galaxies possess compact cores that are designated **active galactic nuclei**, and these tap much stronger gravitational potentials.

∗ Gravity can, in principal, be 100 times more efficient, being sampled via **accretion** of matter onto a general relativistic **supermassive black hole** (SMBH) that serves as the **central engine** or powerhouse.