Astr 5465 April 22, 2020
Dark Matter in Galaxy Clusters

- **Velocity Dispersions in Galaxy Clusters**
  - Many Cluster Catalogs
    - Optically Selected (low z): Abell (1958), Hoessel Gunn & Thuan (1980)
    - Optical Morphology: e.g., Leir & van den Bergh (1977)
  - Application of the Virial Theorem
    - With the First Velocities within the Coma Cluster Zwicky (1933)
      Proposed Existence of Dark Matter
    - If $\sigma$ is Constant with Radius:
      \[ M(R) = \sqrt{\frac{\sigma^2 R}{G}} \]
    - $M(\text{Coma}) = 7 \times 10^{14} \text{ M}_\odot$, $M/L \sim 100$

- **First X-Ray Surveys**
  - Galaxy Clusters Are Luminous X-Ray Sources
    (Giaconni et al 1972)
    - Very Extended, $T \sim 10^8 \text{ K}$
      - Mass in Hot Gas Comparable to That in Stars
      - Strong Iron Line Implies Processed Gas
    - Gas Stripped from Galaxies
      - Ram Pressure and/or Interactions

- **Most Recent Surveys**
  - High $z$ Clusters in CDF-S: Giaconni et al (2001)
    - Cosmological Constraints ($\# vs z$, $\Omega_m$): White & Frenk 1991; Borgani et al. 2006; Mantz et al. 2007

- **Virial Models Still Imply Dark Matter**
  - Bullet Cluster Morphology Implies Non-Bayonic Dark Matter
    - Collision of Two Clusters
    - Hot X-Ray Gas Interacts and Dissipates Towards the Center
    - Dark Matter Morphology from Weak Lensing is Bi-Modal Implying No Dissipation
Gravitational Lensing

- Deep Imaging of Clusters of Galaxies Revealed
  Gravitational Lensing
  (Lynds & Petrosian 1986)
- HST Images of Clusters Reveals Huge Number of
  Arcs from Lensed Background Galaxies (e.g., Abell
  370, 1689 at right)
- Lensing Models Reveal Lots of Dark Matter
  (Grossman & Naryan 1989; Kneib 2012)
- Multiple Arcs Constrains Cosmological Models
  (Link & Pierce 1998)
  - Mass Profile Uncertainties Marginalized with Multiple Arcs at
    Different $z$
  - Can Constrain Angular Size vs $z$
- Large Cluster Lensing Surveys
  - MACS (Ebling et al. 2001): HST Imaging of ROSAT Clusters
  - Multi-cluster Treasury Program (MCT; Postman et al. 2011)
    • Many Papers on Modeling
- Weak Lensing (Kaiser 1985)
  - Distortions in Image Shapes (via shear) Constrains
    Projected Mass (Surface Density)
    • Requires Stable PSF Over Image
    • Requires Lots of Galaxies to Average Out Shapes
  - Results Constrain Dark Matter Distribution
    (Bardeau et al. 2007; Okabe et al. 2010)
Clusters as Nature’s High-z Telescope

- **Gravitational Lensing Provides Magnification of Background Sources**
  - Allows Detection of Extremely Distant Galaxies
  - Search for "Short", i.e., Visible Wavelength Dropouts
    - Bright in NIRCAM Images
  - Example: HCM-6A in A370, $z = 6.56$ (bottom, Egami et al. 2005)
  - Example: $z = 6.8$ Galaxy in A2218 (right, Kneib et al. 2004)

- **JWST Cluster Surveys Will Find Thousands!**
Catalogs of Field Galaxies

- **All Sky Galaxy Catalogs**
  - Optical Catalogs
    - Zwicky & ESO Catalogs
      - Magnitudes & Diameters
      - Surface Brightness Limits
      - Zone of Avoidance
  - Near Infrared Catalogs
    - 2MASS (near-IR)
    - IRAS (mid-IR)
      - Color Selections Yield Galaxies

- **Early Redshift Surveys**
  - CFA + 21cm Surveys
  - Blind 21 cm Surveys

- **Nearby Groups & Complexes (few Mpc)**
  - Local, M81, Sculptor, M101, etc
  - Dozens of Galaxies
    (Grav. Bound, ~ 1 – 2 Mpc Diameter)

- **Nearest Clusters (within 20 Mpc)**
  - Ursa Major, Virgo, Fornax, Eridanus
  - Hundreds of Galaxies
    (Grav. Bound, ~ 10 Mpc Diameter)

- **Primary Features in Large-scale Structure (~ 100 Mpc)**
  - Filaments with Embedded Clusters
  - Supercluster Complexes
  - Voids
Very Large-scale Structures

- **Local Superclusters**
  - On Larger Scales Other Rich clusters & Superclusters (~ 150 Mpc)
    - Coma Cluster + Supercluster
    - Hercules Cluster + Supercluster
    - Shapley Supercluster (several Abell Clusters)
    - Pisces-Cetus Supercluster Complex
    - Virgo Cluster Looks a Bit Small
  - **Rich Clusters**
    - Thousands of Galaxies
      (Grav. Bound, 10s of Mpc in Diameter)
  - **Large Filaments with Embedded Clusters**
    - Not Grav. Bound, Only the Clusters
    - Nearly Empty Voids

- **Redshift-Independent Distances**
  - Tully-Fisher Distances
  - $D_n - \sigma$ Distances
  - Surface Brightness Flutuations
  - Tip of the Red Giant Branch
  - Use Distance Indicator to Predict Hubble Velocity
  - Subtract to Obtain Line-of-Sisght Peculiar Motion
**Peculiar Velocity Field & $\Omega_m$**

- **Gravitational Acceleration & Density**
  - **Local Peculiar Velocity Field**
    - Lots of Peculiar Motions of Small Scales (e.g., Tully et al 1991), Including Virgo-centric Flow (~ 250 km/sec)
    - Early Results on Larger Scales Indicated Larger Streaming (~ 600 km/sec) of Local Volume Towards a “Great Attractor” (Dressler et al. 1987)
    - Was this a “Bulk Flow” Towards a Nearby Structure?
      - Hydra Centaurus Seemed Too Small
      - Velocities Too Large Over Too Small a Scale for LCDM with CMB Normalization
    - Reanalysis + New Data Sets Reduced Flow Amplitude to ~ 300 km/sec Over $cz < 5000$ km/sec
      (e.g., Mathewson & Ford 1994)
  - **Peculiar Velocities on the Largest Scales**
    - Errors in Distance Are Logarithmic
    - Errors in Peculiar Velocities Rise with Distance
      - Requires Large Samples of Unbiased Distance Indicators
    - Signal Comparable to That in CMB (~ 600 km/sec) Within 100 Mpc
      - Culprit Likely the Shapley Supercluster
  - **POTENT Reconstructions (Dekel 1994)**
    - Reconstruction of Density Field from Peculiar Motions
    - Only Line of Sight Peculiar Velocities Available
    - Requires Smoothing ( $cz \sim 1200$ km/sec, approx. the distance to Virgo)
  - **Redshift Space Distortions**
- **$\Omega_m$ from Peculiar Velocities**
  - $\Omega_m = 0.25 \pm 0.05$
Redshift Space Distortions

• Density Fluctuations Result in Systematic Peculiar Velocities

• Statistical Approach via Correlation Function
  – Combining Spatial Correlations & Velocity Correlation Reveals ”Redshift Space Distortions” (see figure)
    • Systematic Errors in Distance (V/H₀) Along Line-of-Sight
  – “Finger of God” Due to Line-of-Sight Velocity Dispersion Within Bound Groups
    • Foreground Galaxies Inferred too Far Away
    • Background Galaxies Inferred too Close
  – Squashing From Peculiar Motions
    • Similar Effect But in Projection

• \( \Omega_m \) from Peculiar Velocities
  – Assuming LCDM for Dark Matter
    • CMB Normalization
    • No Larger-scale DM Distribution
  – \( \Omega_m = 0.3 \pm 0.05 \)
References

• Evolution of X-ray Clusters of Galaxies, Rosati, Borgani & Norman, ARAA, 40, 539
• Cluster Lenses, Kneib & Natarajan 2012, arXiv: 1202.0185v2