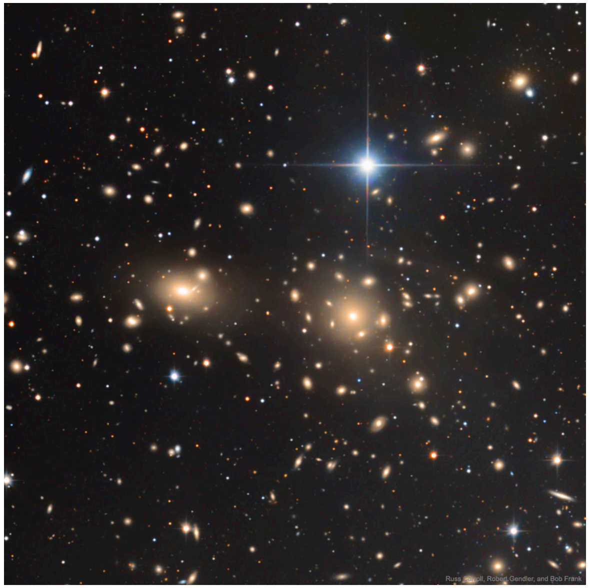
Astr 5465 April 22, 2020
Dark Matter in Galaxy Clusters

- **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)
    - X-Rays: Kellogg et al (1973), Jones & Forman (1984)
  - Application of the Virial Theorm
    - With the First Velocities within the Coma Cluster Zwicky (1933) Proposed Existence of Dark Matter
    - If σ is Constant with Radius:

$$M(R) = \sqrt{\frac{\sigma^2 R}{G}}$$

    - M(Coma) = 7 x 10^{14} M_o, M/L ~ 100
- **First X-Ray Surveys**
  - Galaxy Clusters Are Luminous X-Ray Sources (Giaconni et al 1972)
    - Very Extended, T ~ 10^8 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, Ω_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



APOD NASA: 2018 March 26

Bullet Cluster

Gravitational Lensing

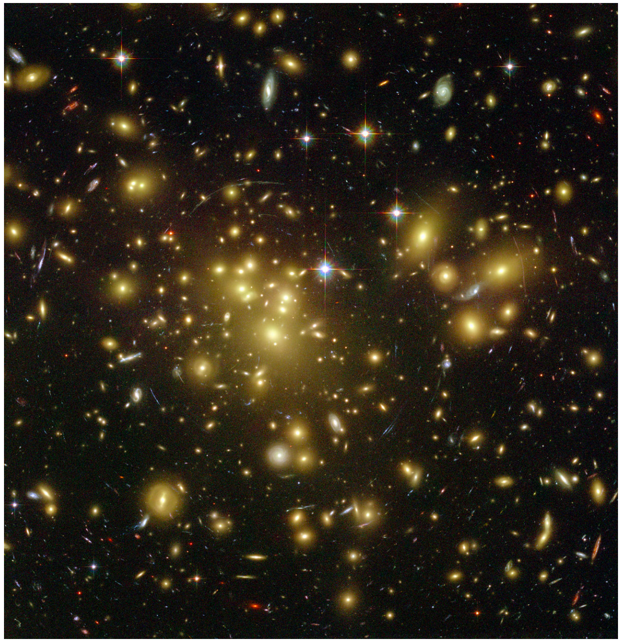
- Deep Imaging of Clusters of Galaxies Revealed Gravitational Lensing

  (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 Contrains 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)

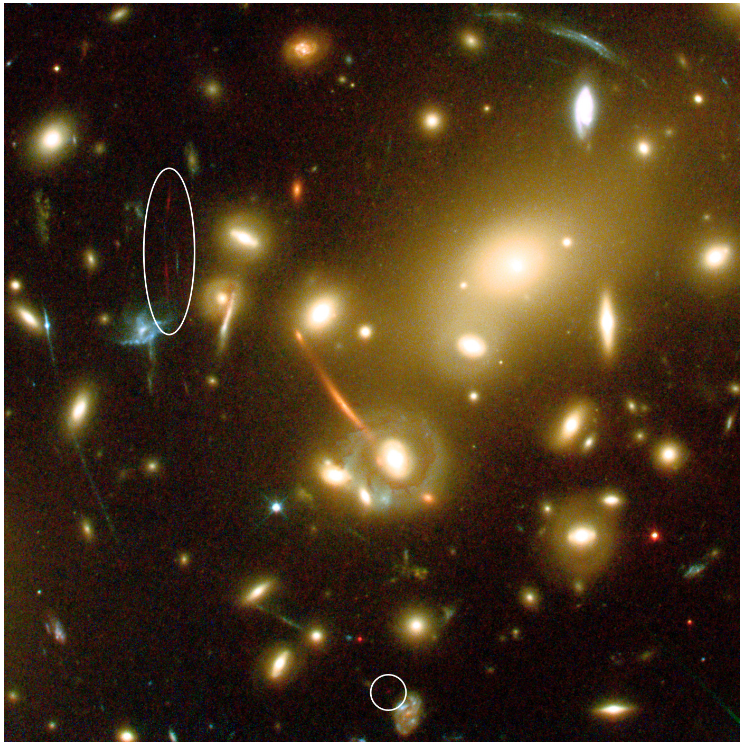
Abell 370



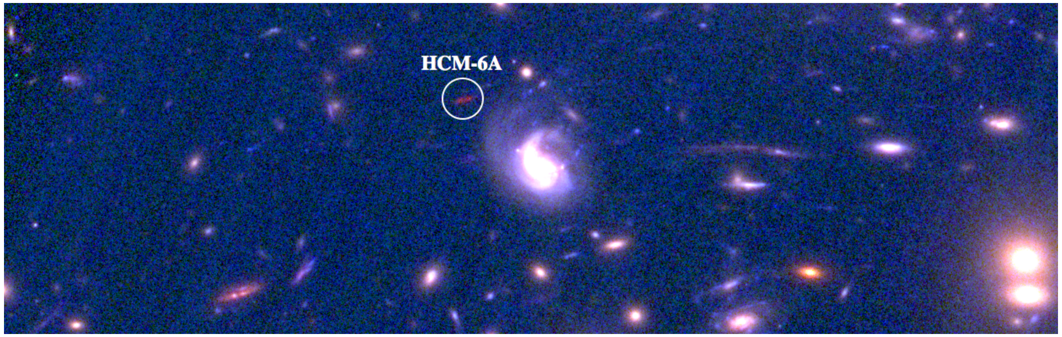
Abell 1689

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!**



Abell 2218

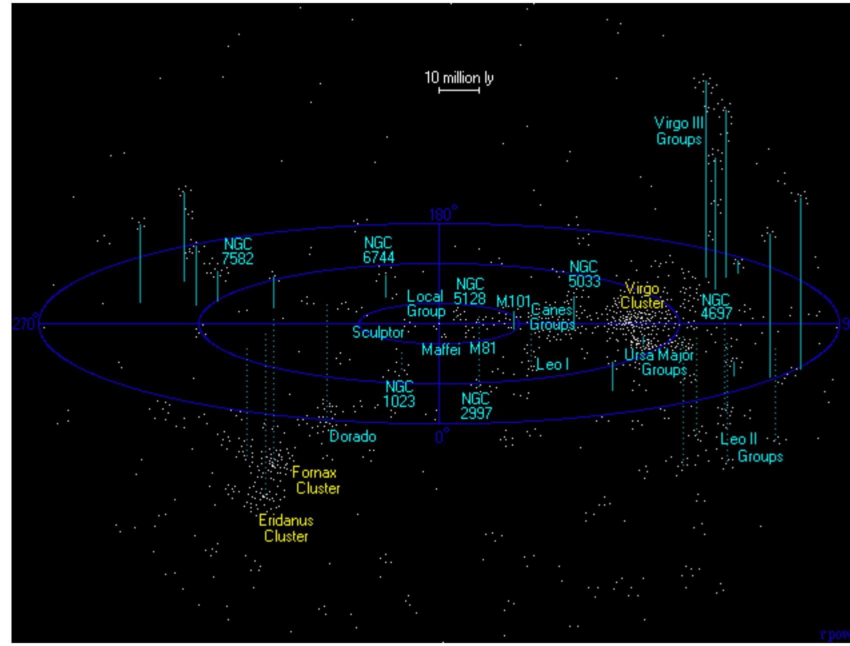


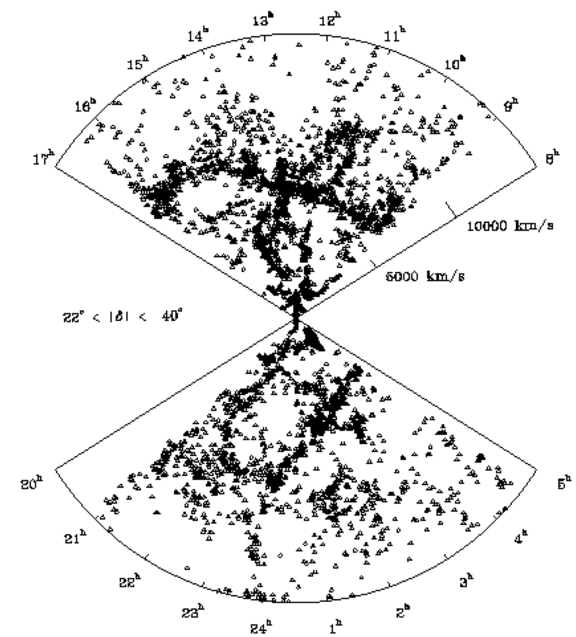
Catalogs of Field Galaxies

- 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

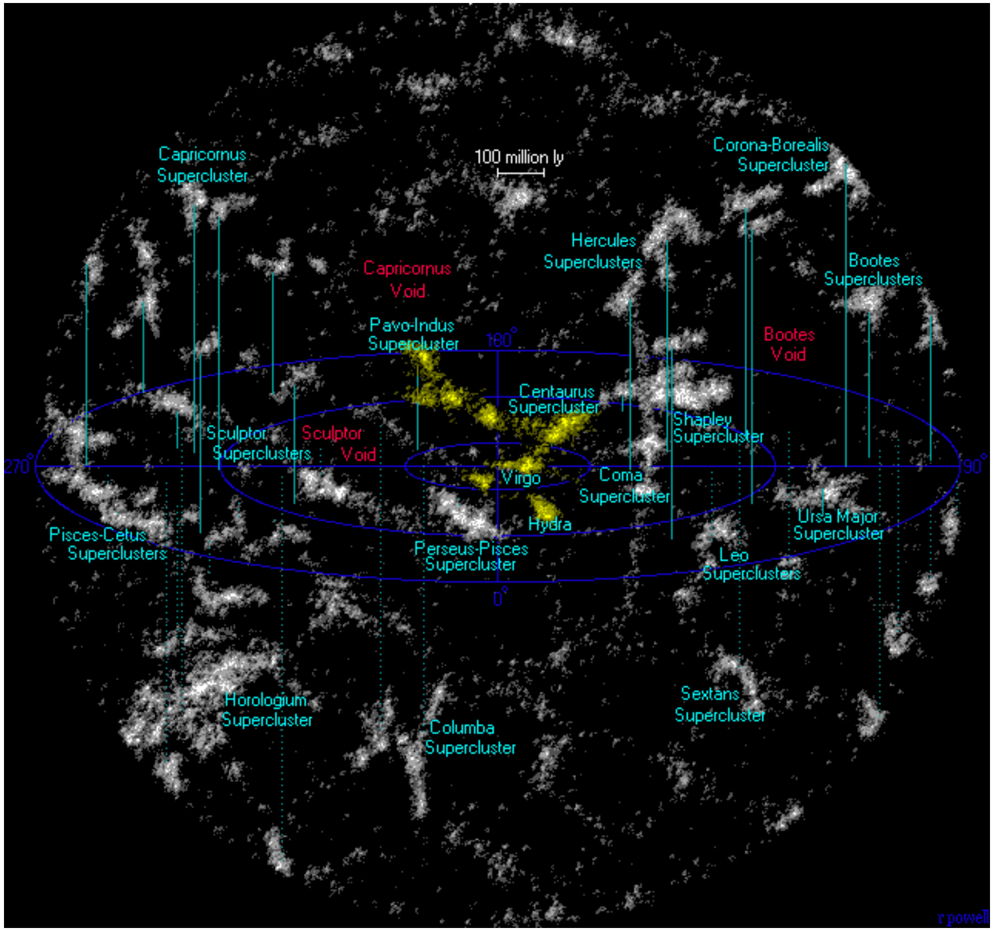




Very Large-scale Structures

- **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**

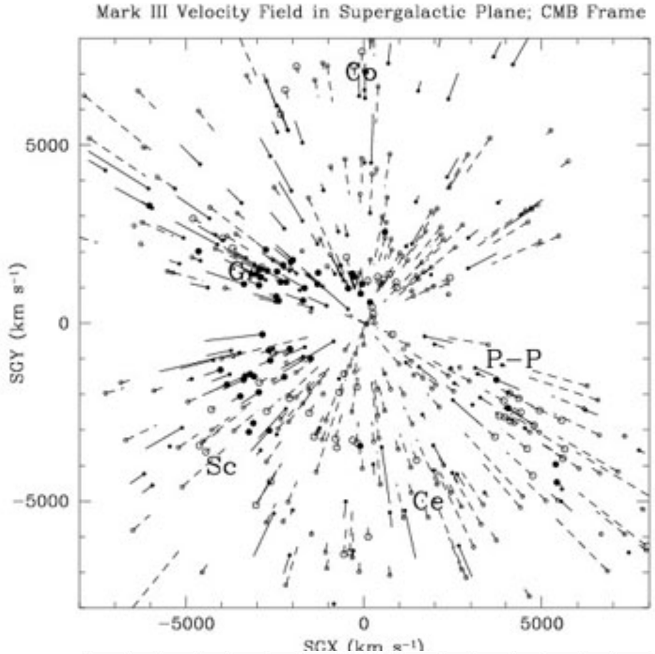
    (Grav. Bound, 10s of Mpc in Diameter)
  - **Large Filaments with Embedded Clusters**
    - **Not Grav. Bound, Only the Clusters**
    - **Nearly Empty Voids**
- **Redshift-Independent Distances**
  - **Tully-Fisher Distances**
  - **$D_n - \sigma$ Distances**
  - **Surface Brightness Flutuations**
  - **Tip of the Red Giant Branch**
  - **Use Distance Indicator to Predict Hubble Velocity**
  - **Subtract to Obtain Line-of-Sisght Peculiar Motion**

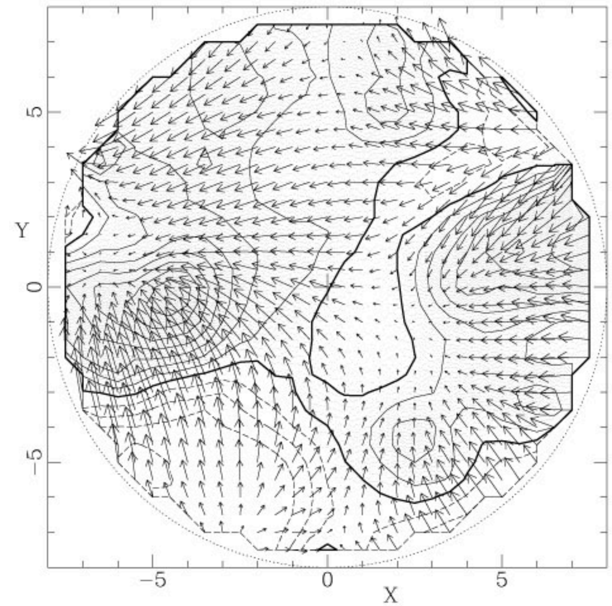


Peculiar Velocity Field & Ω_m

- **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 ΛCDM with CMB Normalization
    - Reanalysis + New Data Sets Reduced Flow Amplitude to ~ 300 km/sec Over cz < 5000 km/sec

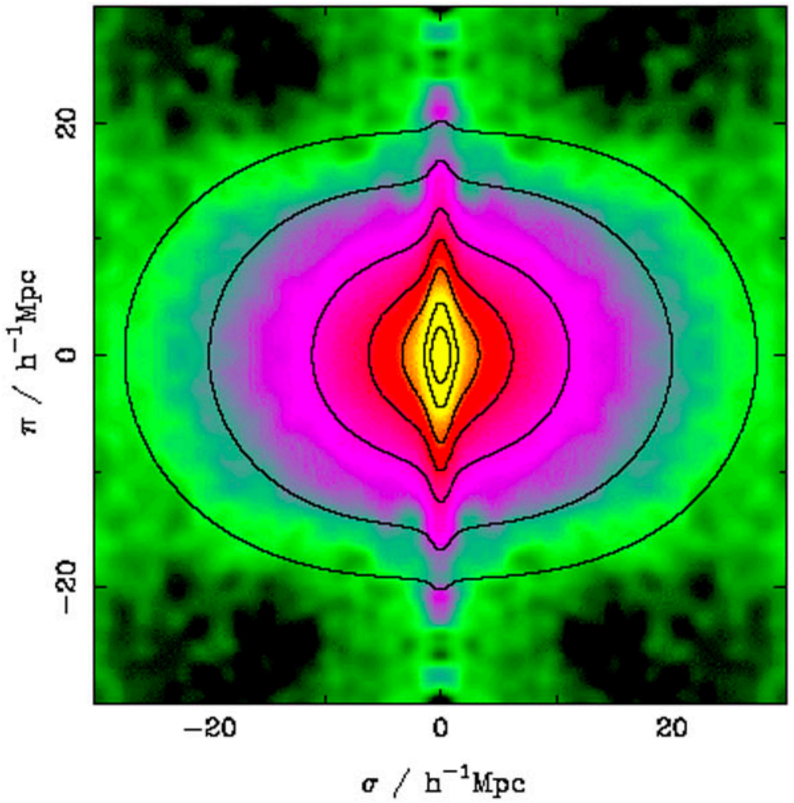
      (e.g., Mathewson & Ford 1994)
  - **Peculiar Velocities on the Largest Scales**
    - Errors in Distance Are Logarithmic
    - Errors in Peculiar Velocities Rise with Distance
      - Requires Large Samples of Unbiased Distance Indicators
    - Signal Comparable to That in CMB (~ 600 km/sec) Within 100 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 ~ 1200 km/sec, approx. the distance to Virgo)
  - **Redshift Space Distortions**
- **Ω_m from Peculiar Velocities**
  - Ω_m = 0.25 +- 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/H_0) 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
- Ω_m from Peculiar Velocities
  - Assuming LCDM for Dark Matter
    - CMB Normalization
    - No Larger-scale DM Distribution
  - Ω_m = 0.3 +- 0.05



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