Galaxy clusters and cosmology

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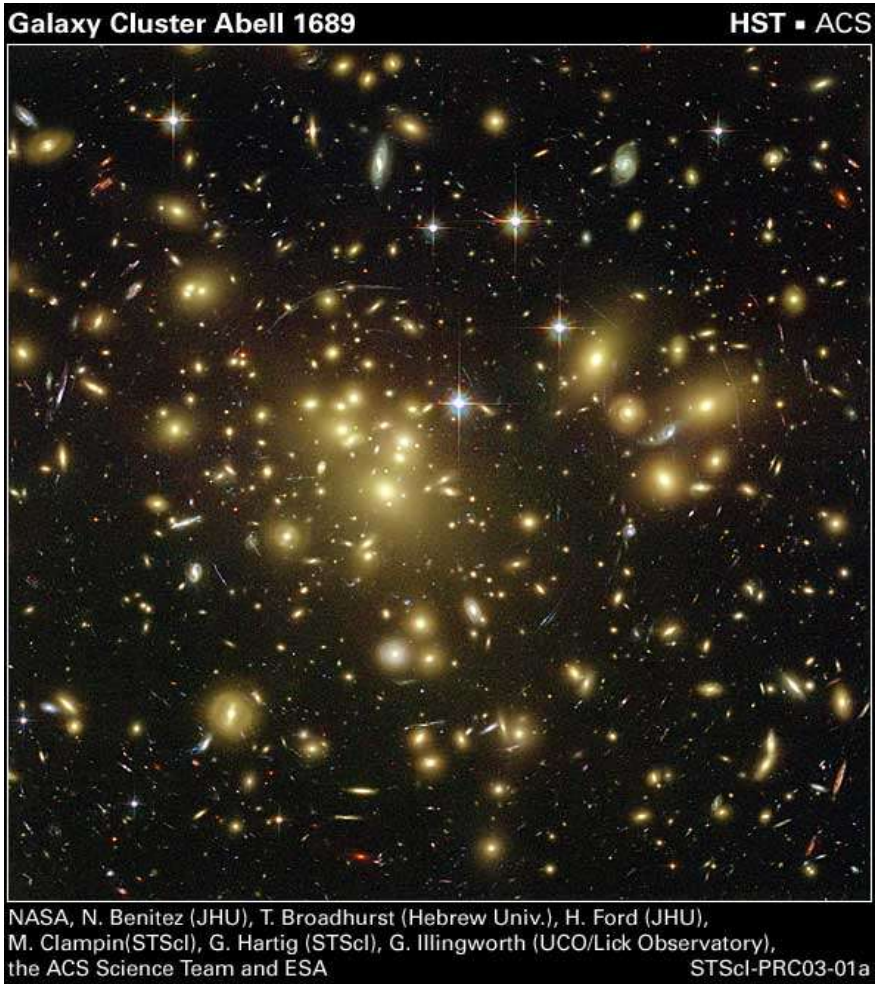
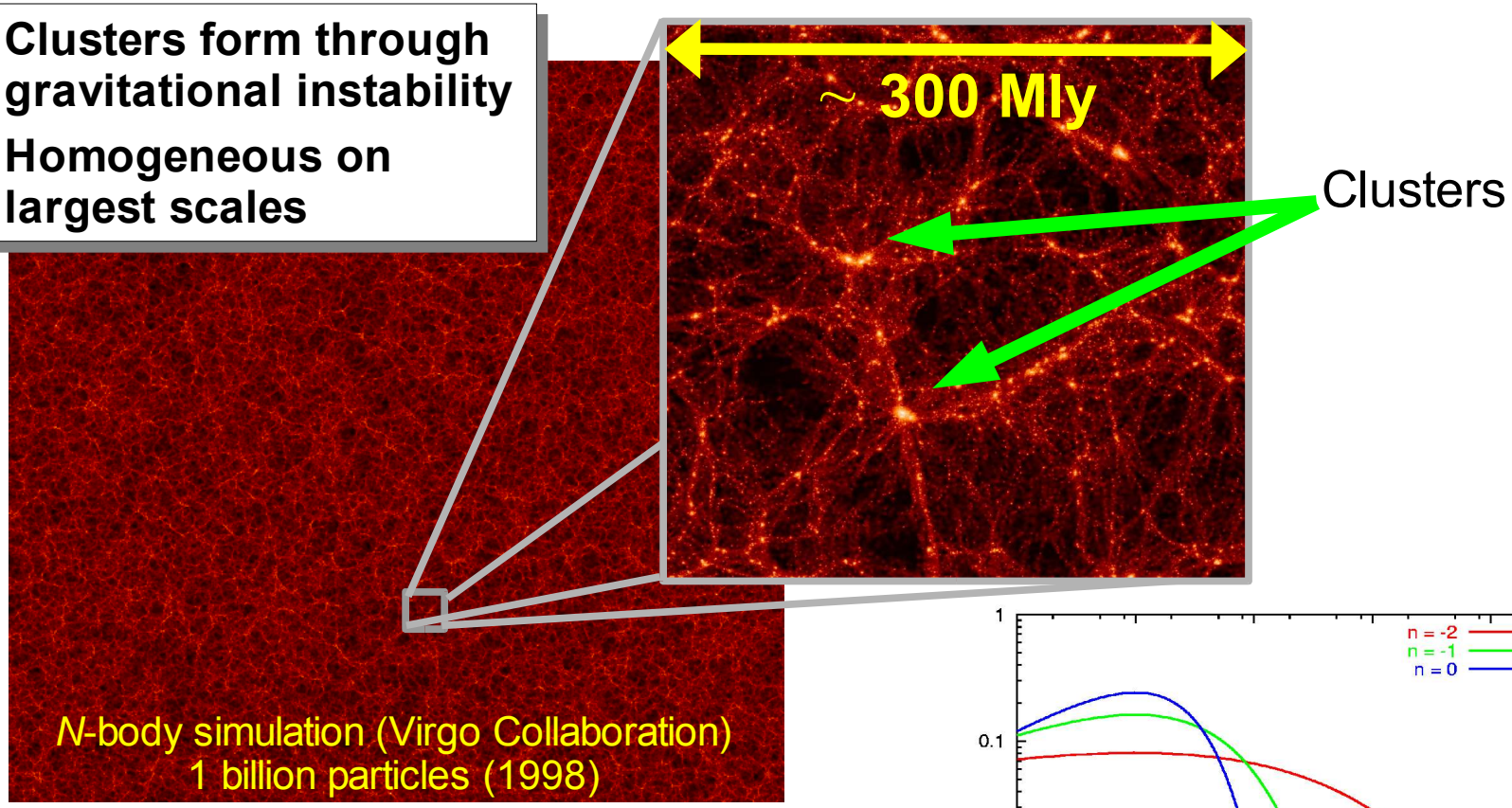
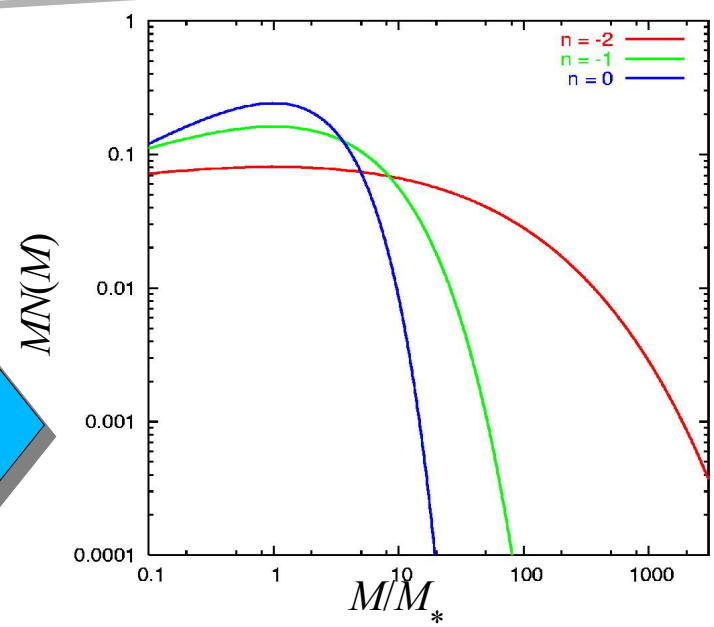
- **Most massive gravitationally bound objects in the Universe**
  - Masses ~ 10^{13} – 10^{15} M_{sun}
  - Sizes ~ 1 – 5 million ly
- **Composition (by mass)**
  - ~ 80 – 85% dark matter
    - Gravitational effects only
  - ~ 15 – 20% diffuse hot gas
    - X-rays, Sunyaev-Zel'dovich effect
  - ~ 1% galaxies
    - Optical, infrared, radio

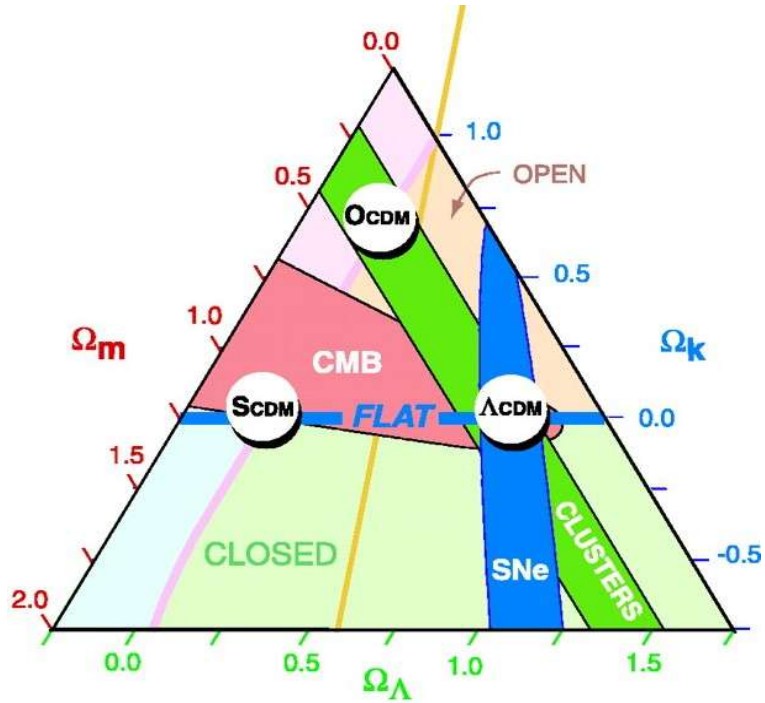


- **Clusters form through gravitational instability**
- **Homogeneous on largest scales**



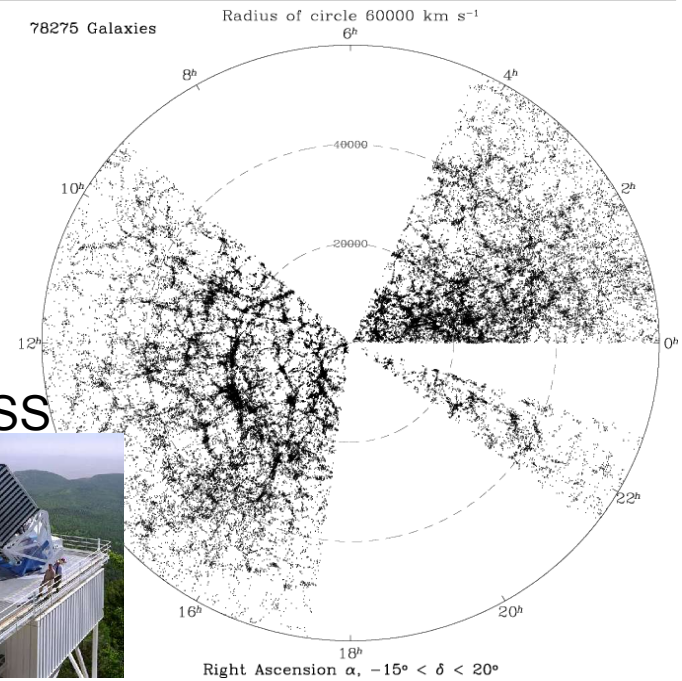
- **Mass distribution**
  - Exponential falloff at high masses
  - Sensitive to
    - Energy density of Universe
    - Magnitude of density fluctuations
    - Primordial spectrum shape





"Cosmic triangle" (Bahcall et al. 1999)

- **Leverage over dark energy equation of state ($p = w\rho$)**
  - Clusters form late ($z < 2$)
  - Dark energy dominates expansion rate at late times
- **Opportunity to overconstrain concordance cosmological model**



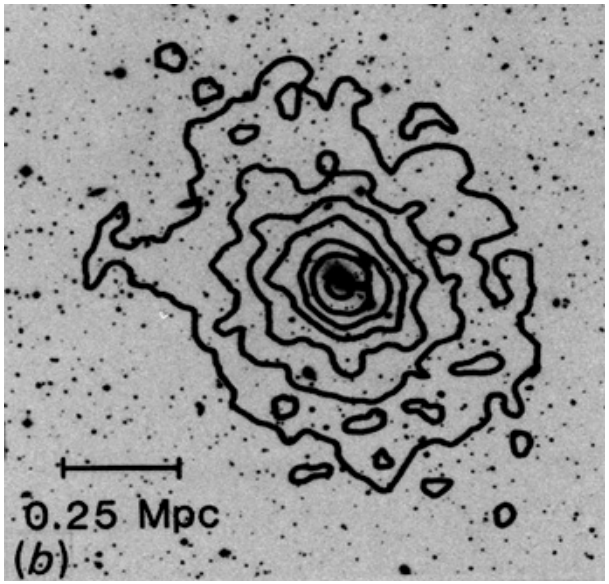
SDSS

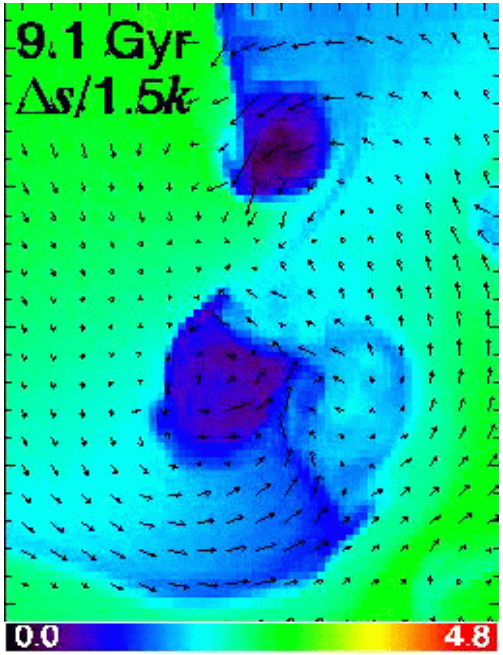
Ongoing/planned surveys will produce samples of > 10^4 clusters during next 5-10 years

- **Optical** (SDSS, LSST, etc.)
- **Sunyaev-Zel'dovich** (SZA, SPT, etc.)
- **X-ray** (XCS, DUO)

Measuring cluster masses

- **Velocity dispersion of galaxies**
  - Virial equilibrium assumption
- **X-ray temperature of gas**
  - Hydrostatic equilibrium assumption
- **Gravitational lensing**
  - Most direct method
  - Contamination by surrounding structure





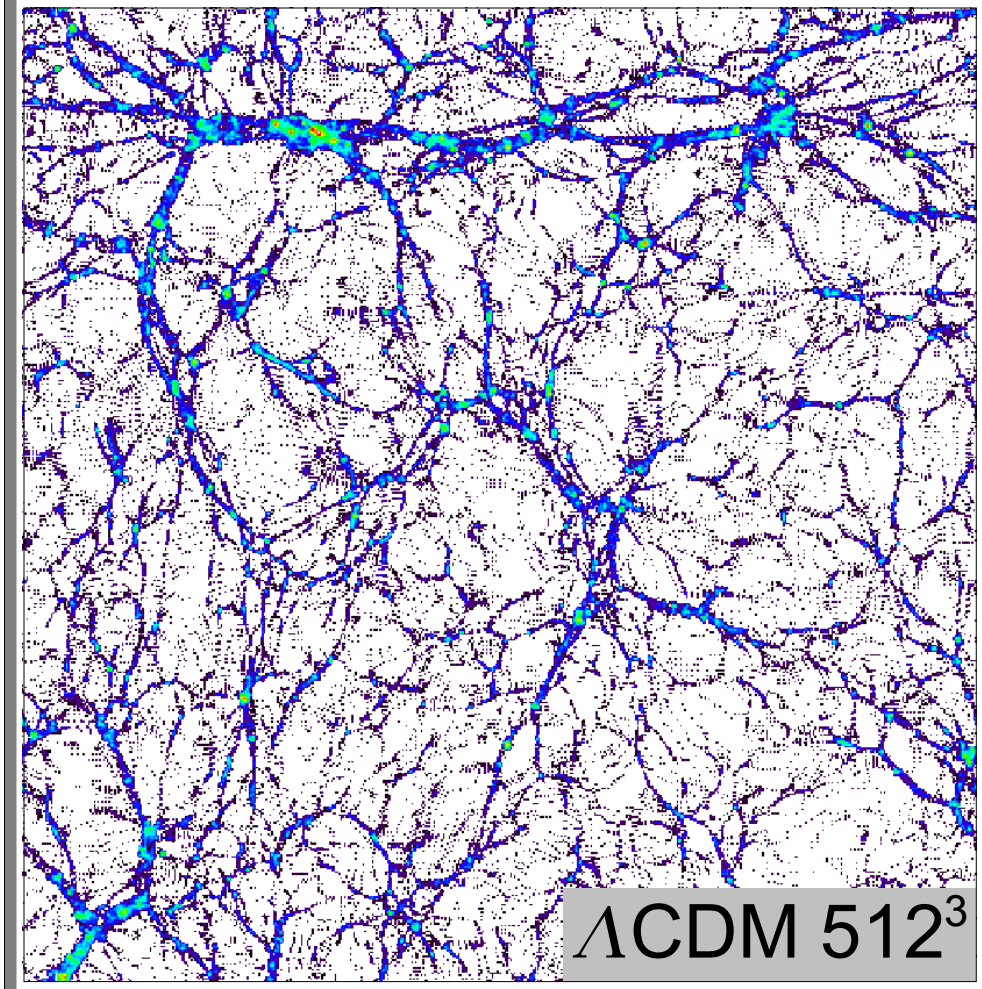
Ricker & Sarazin (2001)

Effects of nongravitational physics: ~10%

- **Merger shocks**
  - Temporarily boost X-ray luminosity and temperature
- **Entropy sources (e.g. supernovae)**
  - Break self-similar scaling relations
- **Other supports against gravity**
  - Turbulence and rotation
  - Cosmic ray pressure
  - Magnetic fields

Beyond Virgo (PMR, J. Mohr, S. Habib, K. Heitmann)

- **A new set of Hubble Volume-scale simulations**
  - Similar box size $\sim$ (3 Gly)^3 and number of clusters (> 10^4)
  - Include gasdynamics
  - Include subgrid models for similarity-breaking physics
- **Benefits**
  - Observables consistently included
  - Probe non-Gaussian scatter in mass-observable relations
  - Direct comparison with observations using survey analysis tools
  - Estimate completeness and systematic effects in surveys
- **"Issues"**
  - Uncertainties in similarity-breaking physics
  - Subtleties of cosmological adaptive mesh refinement
  - Massive data volume: $\sim$ 3 TByte per run

FLASH (Fryxell et al. 2000; Ricker et al. 2004)

- **Parallel adaptive mesh refinement hydro code developed at U. Chicago ASCI Center**
- **Cosmological modifications complete**
- **Work in progress**
  - Comparison with LANL tree (Warren) and particle-mesh (Heitmann) codes
  - Validation of cosmological AMR techniques
  - Subgrid model development
  - Simulated light-cone survey code
- **Eventual size of calculation**
  - 1024^3 particles ($m_p = 4\times10^{10}\ M_{Sun}$)
  - Up to $65{,}536^3$ effective mesh (Δx = 16 kpc)