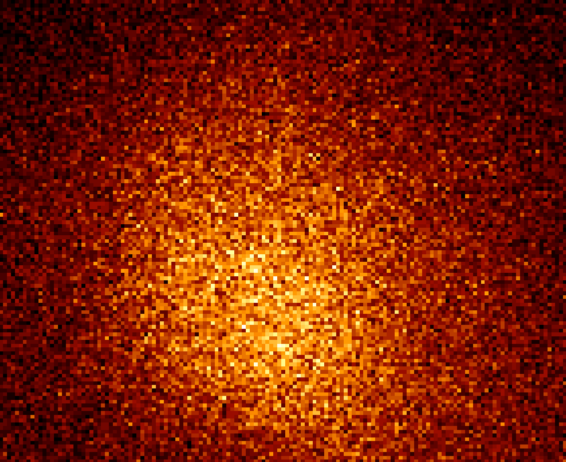
Millennium Gas Simulation: An X-ray Observer's View



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A Few things you should know

How structures form

-Large scale structures are those larger than individual galaxies
-Basic formation mechanism: gravitation instability
-Inhomogeneities existed in universe's density (CMB)
-Dense regions expand slower than less-dense
-Highly dense regions collapse (stars, gas clouds, etc.)
-Collapse happens in a hierarchal fashion (clusters are last)
-Gravity is not all, pressure gradients push outwards

B. Ryden, *Introduction to Cosmology*

A few more things you should know

Halo: a self-bound, quasi-equilibrium structure comprised of multiple, interacting fluids (dark matter, multi-phase baryons, and radiation) formed via gravitational collapse within a cosmic web of random noise.

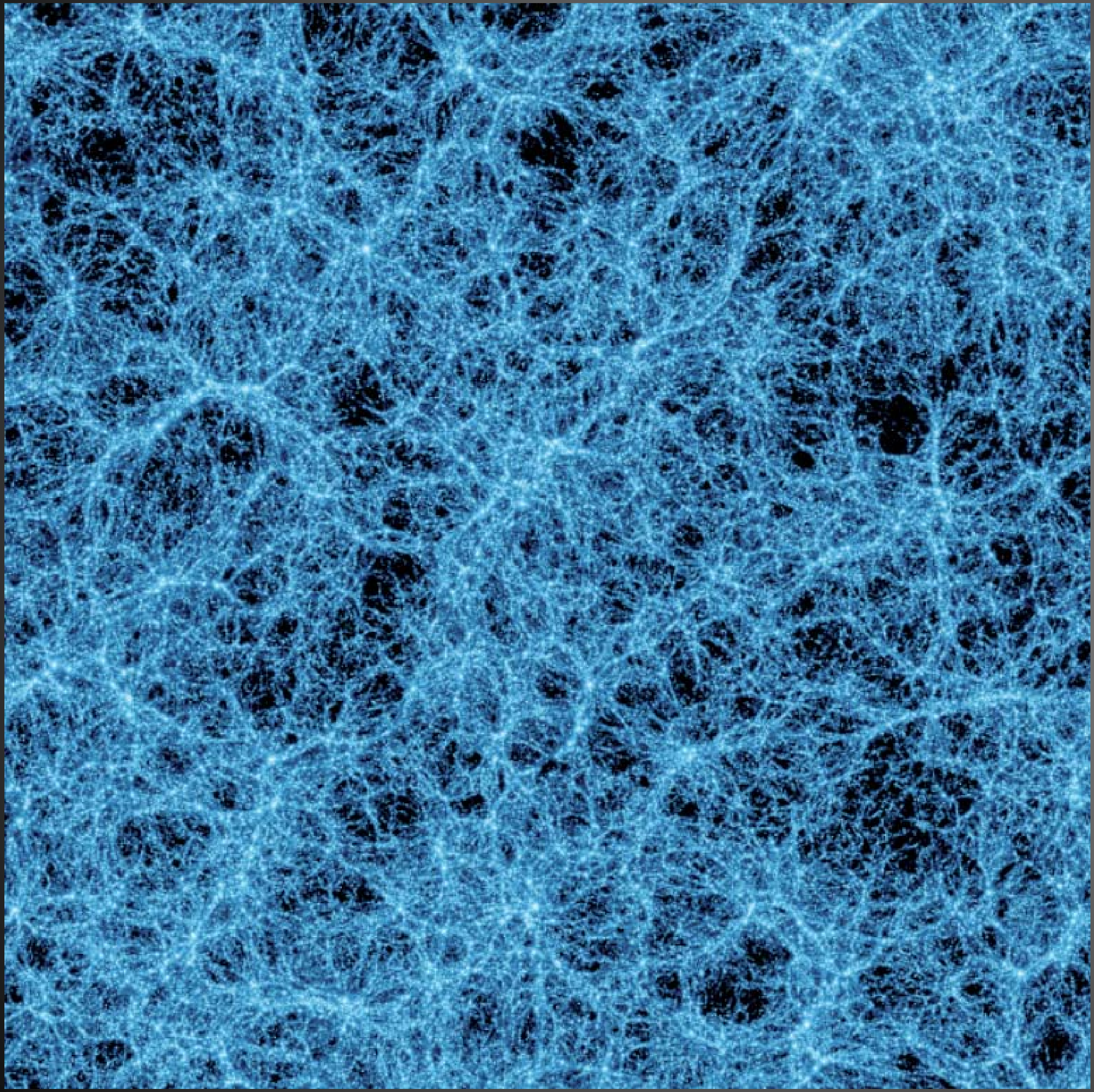
Cluster: a redshift-space projection of a massive halo, *and its line-of-sight neighbors, with the resultant system containing multiple, bright galaxies and other visible components (multi-phase baryons, non-thermal matter, etc.).*

A less technical def. is a collection of galaxies bound by mutual gravitational attraction, intracluster medium (a hot gas, more massive than galaxy collection by ~2-10), and dark matter.

Redshift (z): $1 + z = a(t)^{-1}$

1 Mpc = 3.09×10^{22} m = 3.26×10^{6} light years

Structure of the Universe

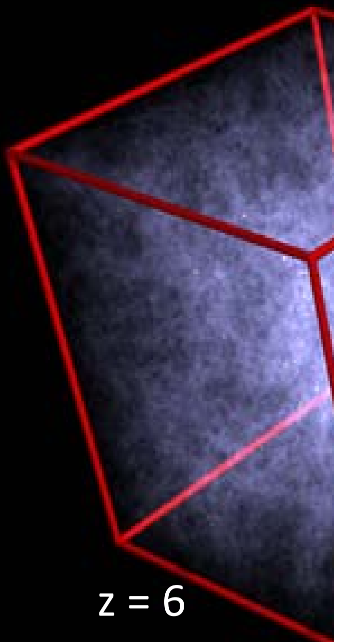


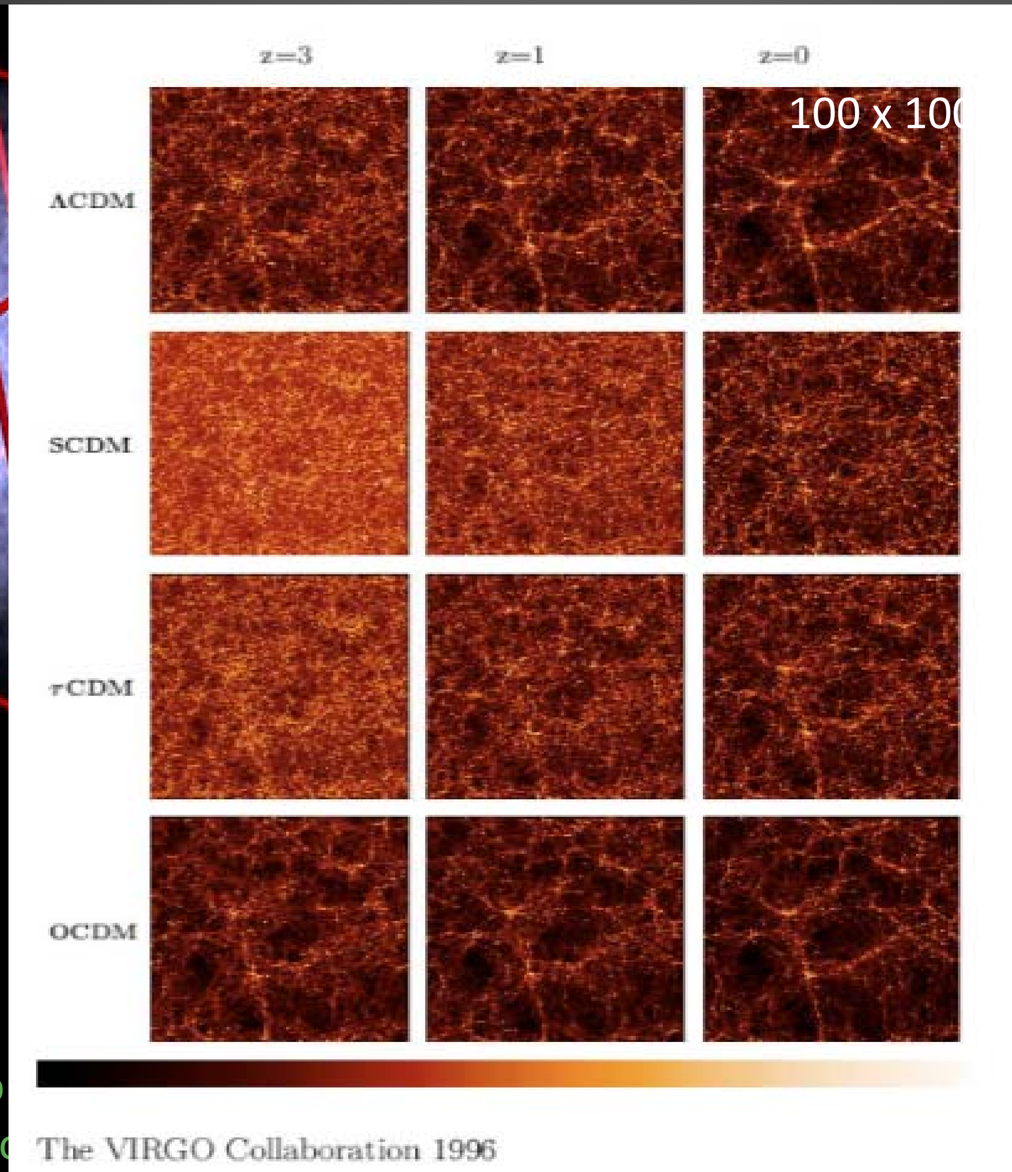
GADGET-2 resimulations of Millennium Sim volume @ Nottingham (F. Pearce)

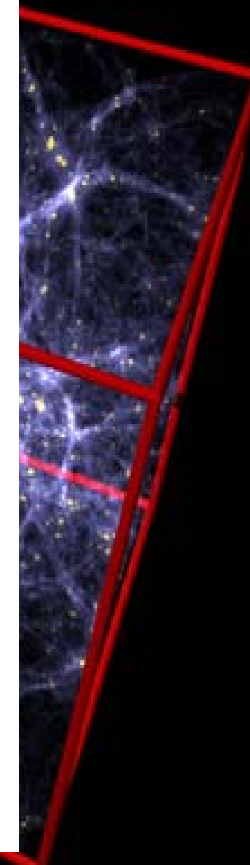
500 x 500 x 50 Mpc h^{-1}

Galaxy clusters are the bright dots

Evolution of Structure







100 x 10 100 Mpc h^{-1}

Jenkins et al, 1998
Astrophysical Journal,499, 20-40.

z = 6

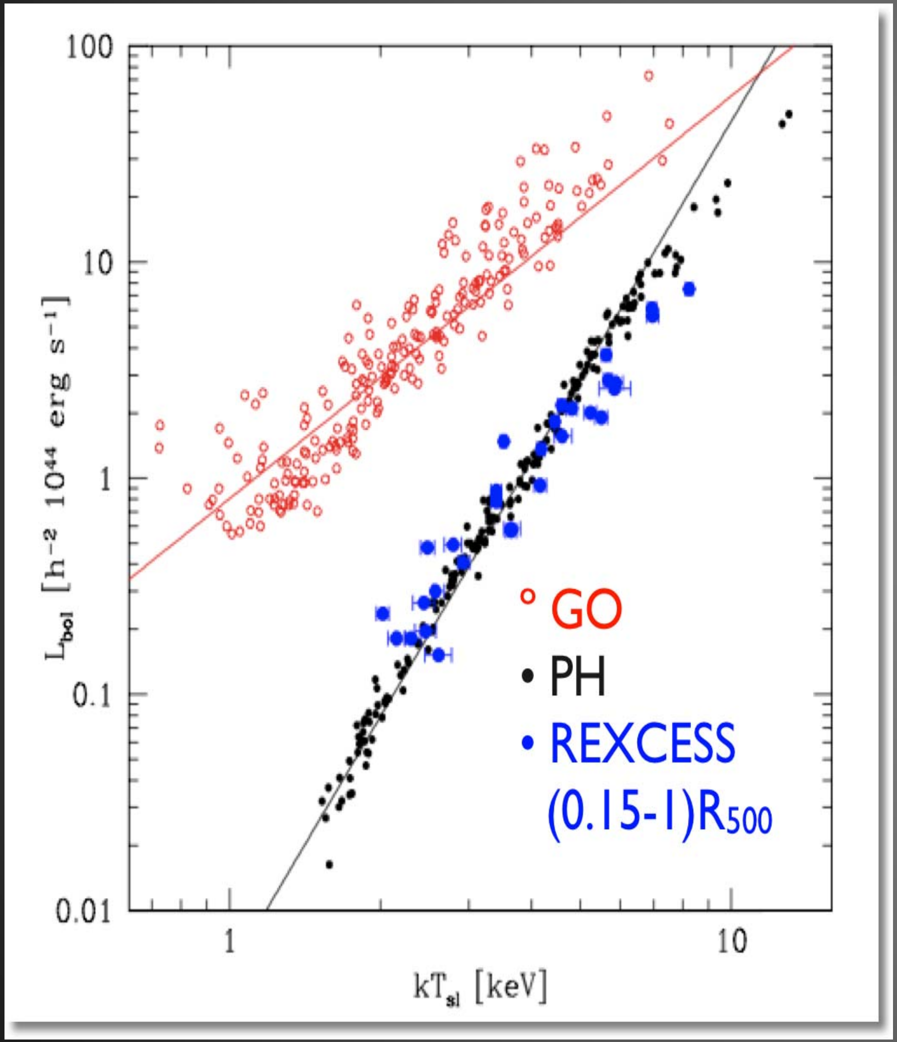
Credit: Volker Sp
The VIRGO Cons

Why galaxy clusters matter

- Clusters are the largest objects whose mass we can reliably measure
- As such we can determine the level of structure on scales up to 10^{15} M_{sun}
- Compare this for present-day to earlier times show rate of structure formation
- Constraining cosmological parameters
- “Closed boxes” that retain all gaseous matter
- The baryonic component of clusters contains a great deal of information about galaxy formation

(G. M. Voit *2005*)

Preceding Work



Stanek et al. 0910.1599

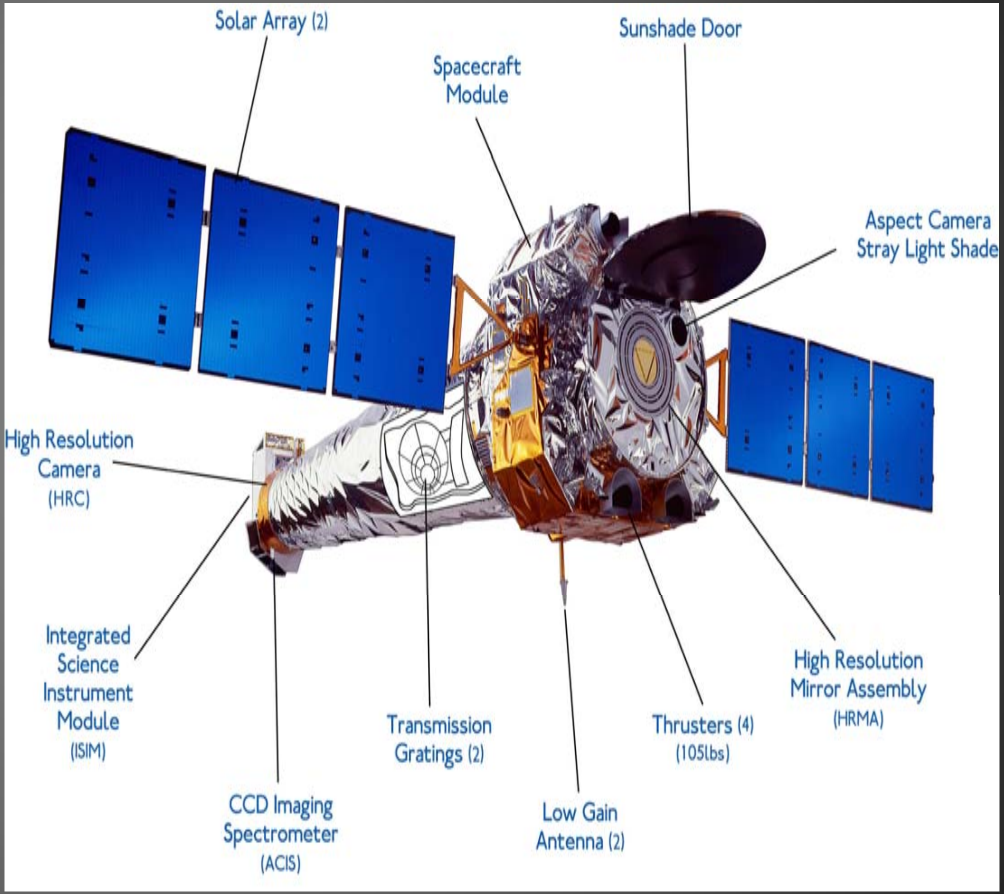
Millennium Gas Simulation (MGS)

- Re-simulation of Millennium Simulation (Largest project ever to simulate universe)
- MGS uses gas dynamics under 2 treatments.
  1) Shock heating using gravity only
  2) Cooling and preheating
- Examine structural properties and observable X-ray and Sunyaev-Zel'dovich (SZ) signals for halos
- Uses a God's-eye view for a volume of 500 Mpc h^{-1} side length

Chandra X-ray Observatory

Chandra Telescope

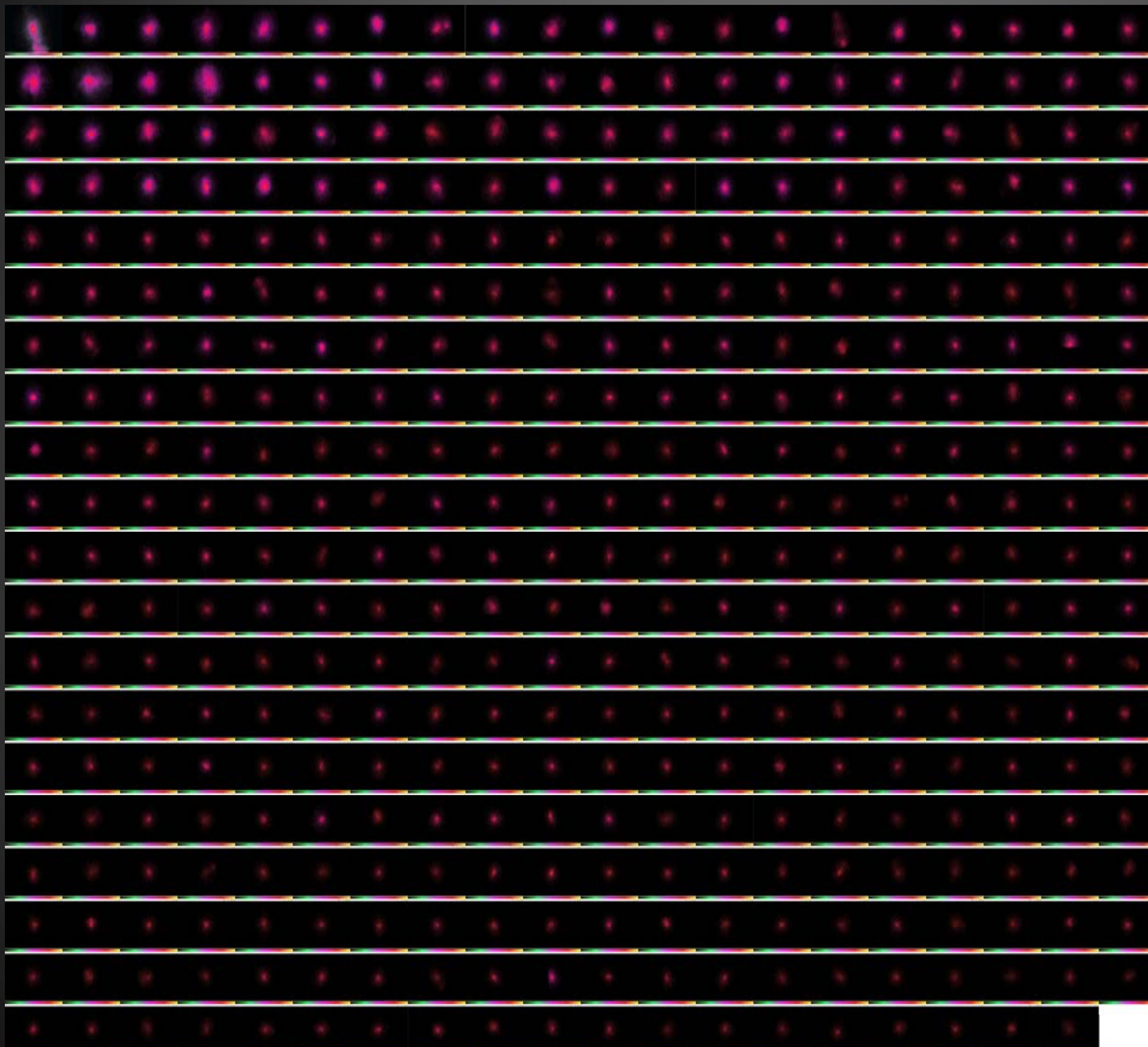
•X-ray telescope (0.1-10 keV)
• Satellite launched in 1999
• 3rd of NASA's "Great Observatories"
• Sensitive to X-rays at a much higher sensitivity than any other X-ray telescope
• Angular resolution of 0.5 arcsecond



Observer's view

• New set of simulations based on what we could observe
• Use same initial conditions under preheating

Visualization of 399 halo event files

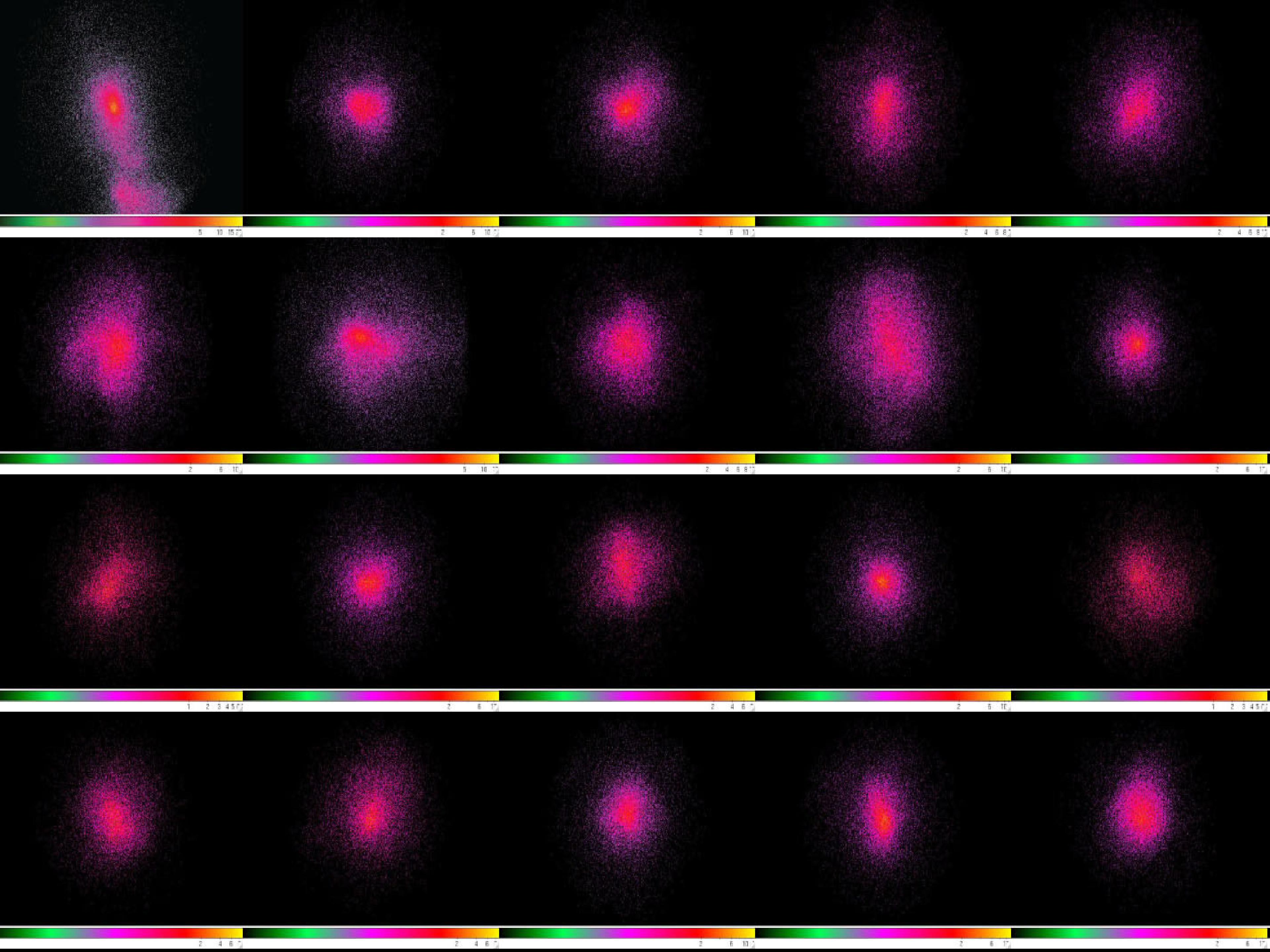


Snapshot 102

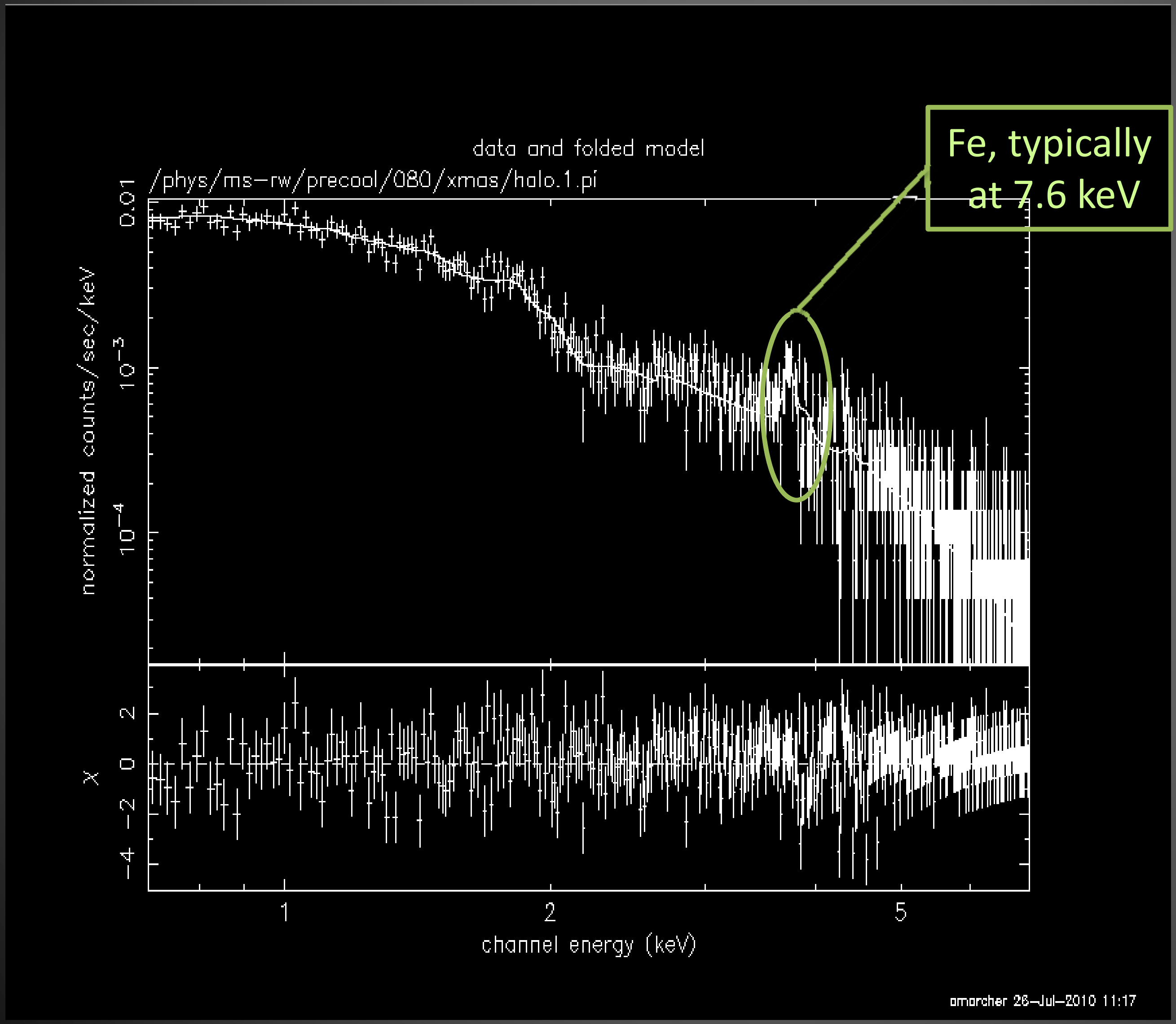
@z=0.4909

Ranked by mass (highest mass in top left, lowest in bottom right)

Generated by submitting initial conditions to Chandra (physical model, exposure time, redshift, mass etc.)



Extracted Spectrum



Snapshot 080

Halo 1 (most massive)

z = 0.8034

Good relation for lower energies

Lots of scattering at higher energies

A quick sanity check

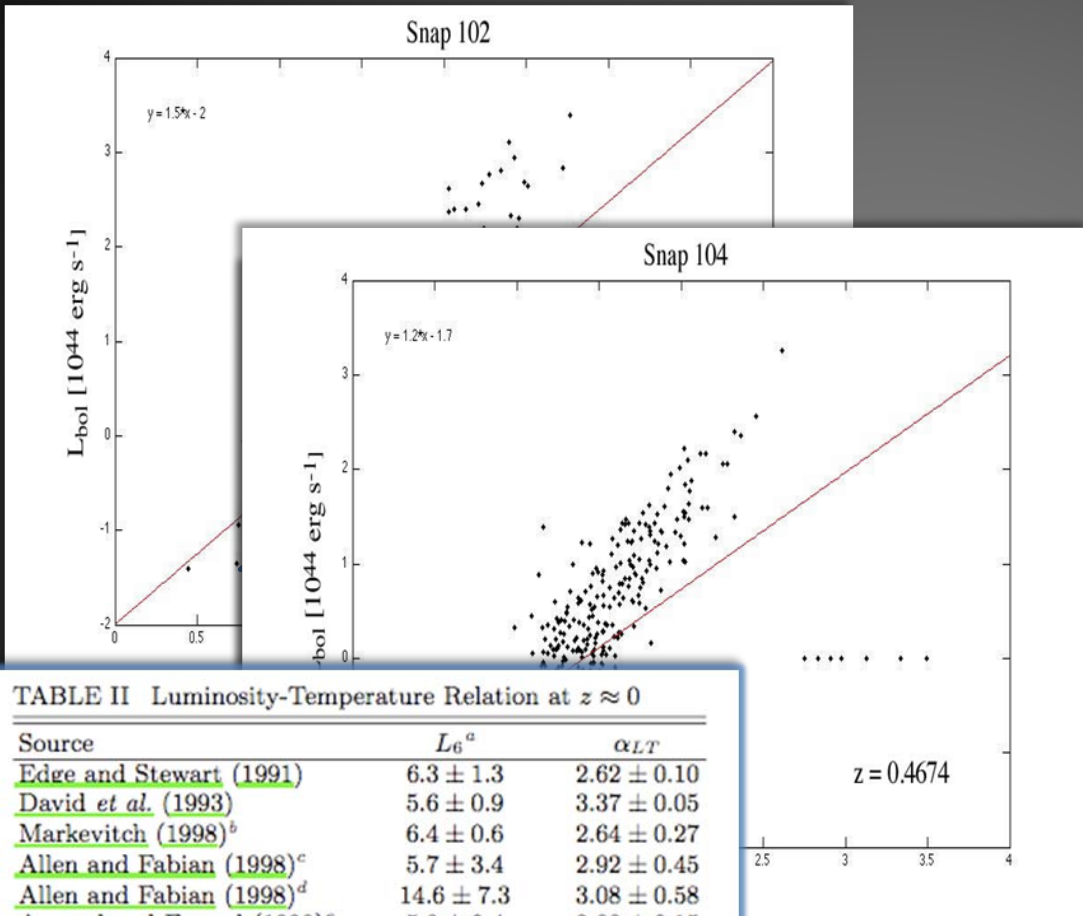


TABLE II Luminosity-Temperature Relation at $z \approx 0$

Source	L_6[a]	α_{LT}
Edge and Stewart (1991)	6.3 ± 1.3	2.62 ± 0.10
David *et al.* (1993)	5.6 ± 0.9	3.37 ± 0.05
Markevitch (1998)[b]	6.4 ± 0.6	2.64 ± 0.27
Allen and Fabian (1998)[c]	5.7 ± 3.4	2.92 ± 0.45
Allen and Fabian (1998)[d]	14.6 ± 7.3	3.08 ± 0.58
Arnaud and Evrard (1999)[e]	5.9 ± 0.4	2.88 ± 0.15
Xue and Wu (2000)	7.6 ± 1.2	2.79 ± 0.08
Novicki *et al.* (2002)	6.0 ± 4.2	2.82 ± 0.43
Ettori *et al.* (2002)	7.3 ± 1.8	2.54 ± 0.42

[a]Bolometric X-ray luminosity is $L_X = L_6(T_{\rm lum}/6\,{\rm keV})^{\alpha_{LT}}$ with L_6 in units of $10^{44}\,h_{70}^{-2}\,{\rm erg\,s^{-1}}$.
[b]Cores of clusters excised to avoid cool cores.
[c]Clusters without cool cores.
[d]Clusters with cool cores.
[e]Sample avoids clusters with cool cores.

- Log-log plot of L_{bol} v Temp
- Look for power law relation (Expected slope ~3)
- Linear relation can be seen
- More scattering than we anticipate
- Outlying data points

Simulation values

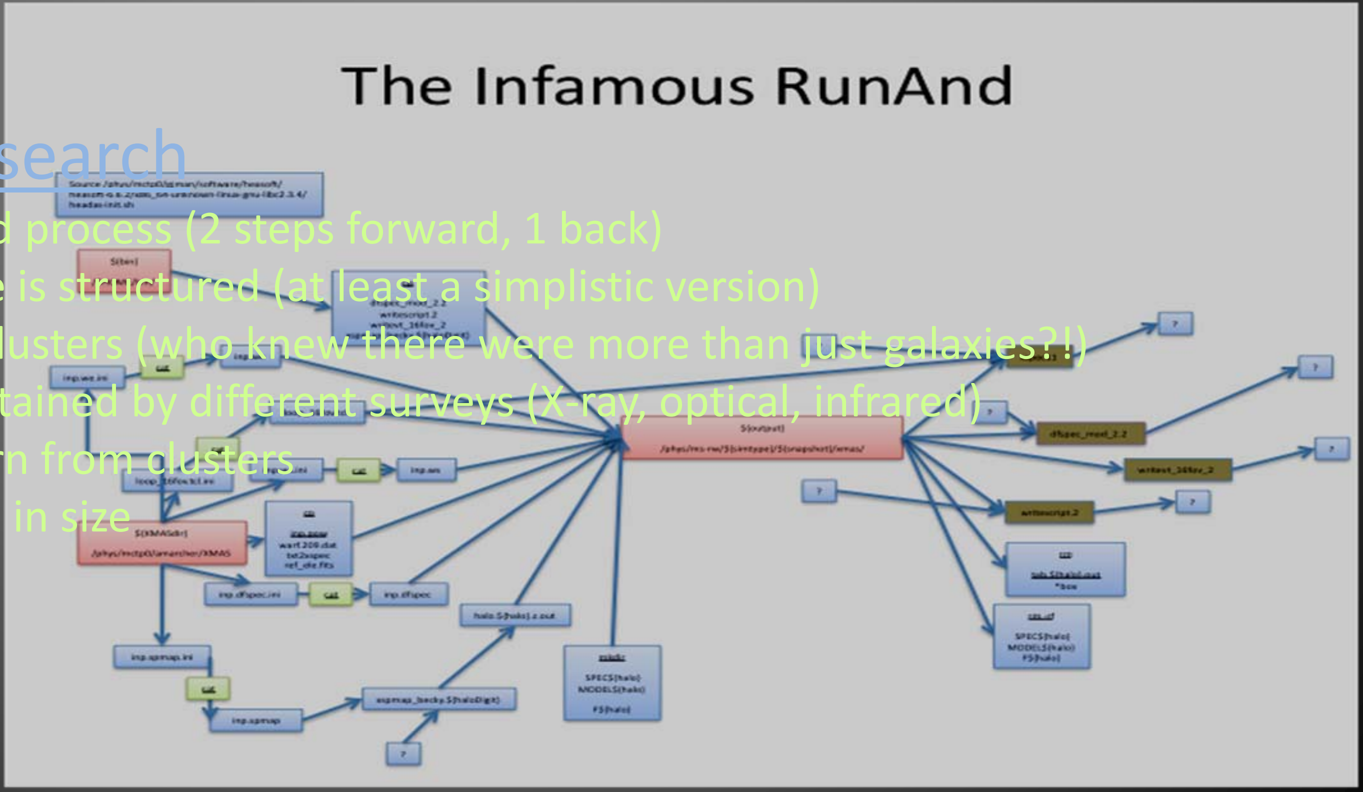
Snapshot 102: 1.5
Snapshot 104: 1.2

A few observed values summarized
(G. M. Voit *2005*)

What I learned…

The Computer Science

- Navigating a Unix environment
- C++ Programming (Hello World!)
- Small problems grow to big problems when working on large scales
- Positives and Negatives of batch computing on Legato



The Physics/Research

- Research is a fluid process (2 steps forward, 1 back)
- How the universe is structured (at least a simplistic version)
- Components of clusters (who knew there were more than just galaxies?!)
- Different data obtained by different surveys (X-ray, optical, infrared)
- What we can learn from clusters
- We are negligible in size