Where are the missing baryons?

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Reasons to care

- Concordance of many measures of baryon number (BBN, CMB, ….)
- Evolution of our personal baryons (galaxies, stars, planets, "metals")
- Baryons are significant fraction of mass (~1/6 to 1/5), modeling needed for precision cosmology
- General effects on light propagation
- For this talk, electrons are baryons too

History of baryons

- z~4000: helium recombination
- z~1000: recombination
- z~20: first stars, ionization, feedback
- z~7: percolation of ionized regions
- z~3: percolation of helium ionization
- z~1 to 2: bulk of star, AGN formation
- z~0: ~90% still in ionized gas

cosmic baryon budget today

Stars	0.003
Neutral gas	0.0006
Molecular gas	0.00016
cluster gas	0.002
coronal gas	0.037
Total (WMAP)	0.044 +/- 10%

For error budget and details: Fukugita, Hogan, Peebles 1998; update, Fukugita astro-ph/0312517, Fukugita & Peebles 2004

Ways to count baryons

Stars, remnants: population synthesis

Molecular gas: CO line emission

Neutral gas: 21cm line emission

Hot cluster gas: thermal X-ray emission, Sunyaev-Zeldovich effect

Warm ionized plasma: QSO absorption lines, electron scattering, soft X ray emission

Stars (~7% of baryons)

- Add up light in galaxies of various types
- Estimate mass per light
  - Population models
  - Central dynamics
  - Local observations of faint stars
- Much of mass is in remnants, dwarfs
- Invisible populations constrained by microlensing experiments

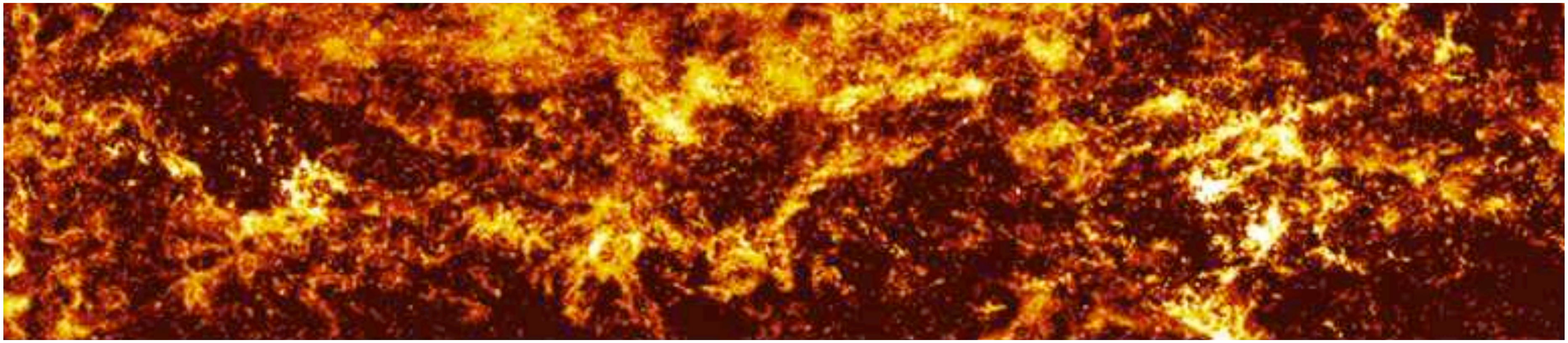
Stars in more detail

- Luminosity Function (SDSS, Blanton et al 2001, 2003, Yasuda et al 2003)
- Mass to Light (Kauffmann et al 2003)
- Extrapolation to small M (Kroupa 2001, Reid 1999, Burgasser et al 2003)
- Metals, NS remnants ~10% of stars

Molecular gas (~0.3%)

- Transient/dynamic state of star formation cycle
- Survey CO emission in nearby galaxies
- Extrapolate to dominant molecular state

Molecular gas in the Milky Way



Extragalactic CO survey: Keres, Yun and Young (2003)

Extrapolation to H using Young & Scoville (1991)

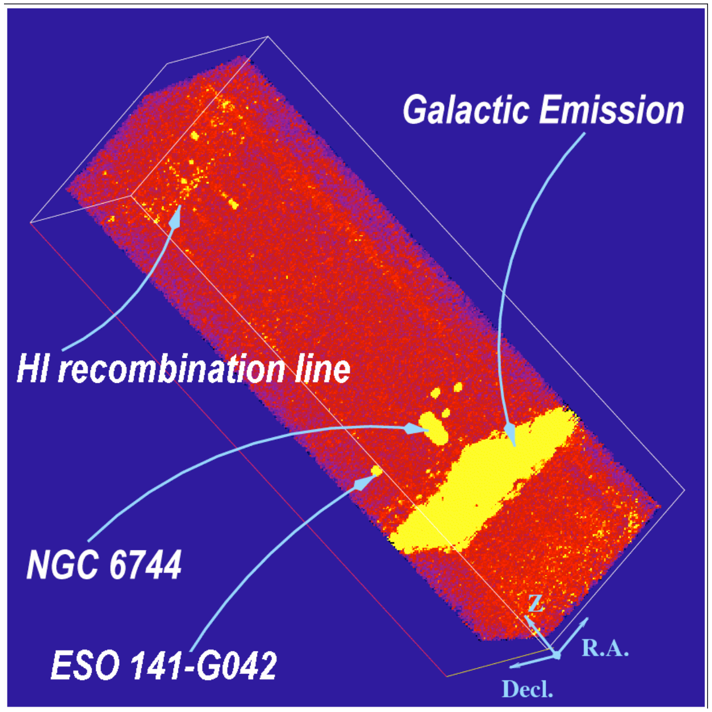
Future: ALMA etc

Neutral gas (~1.5%)

- HI phase: high column, self shielded from ionizing UV radiation
- Dominates baryon mass in small fraction of galaxies
- Dominates ISM in disks
- Accurate census from 21cm surveys (low redshift)
- From QSO damped absorbers (high z)

21 cm at low z

- Extragalactic surveys: Rao & Briggs (1993), HIPASS [Zwaan et al. 2003], ALFALFA (Arecibo, underway)
- Well controlled above threshold of HI column, angular resolution



Cluster gas (~5%)

- Arbitrary definition: gas in rich clusters
- Accurate census from X ray emission
- Dominates baryons in clusters (~90%)
- ~universal fraction of ionized gas
- ~universal ratio of baryon to dark matter

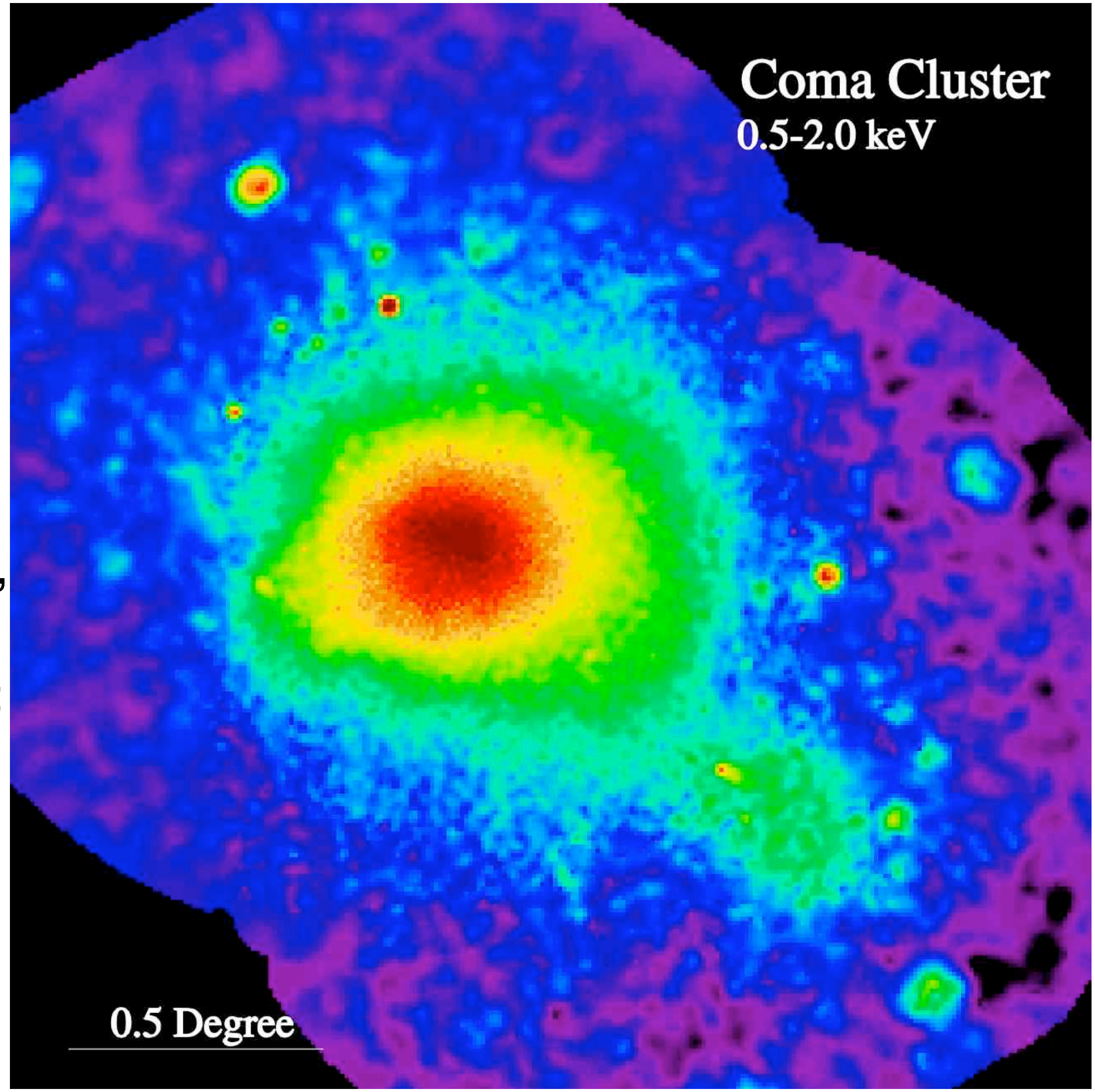
The Coma Cluster

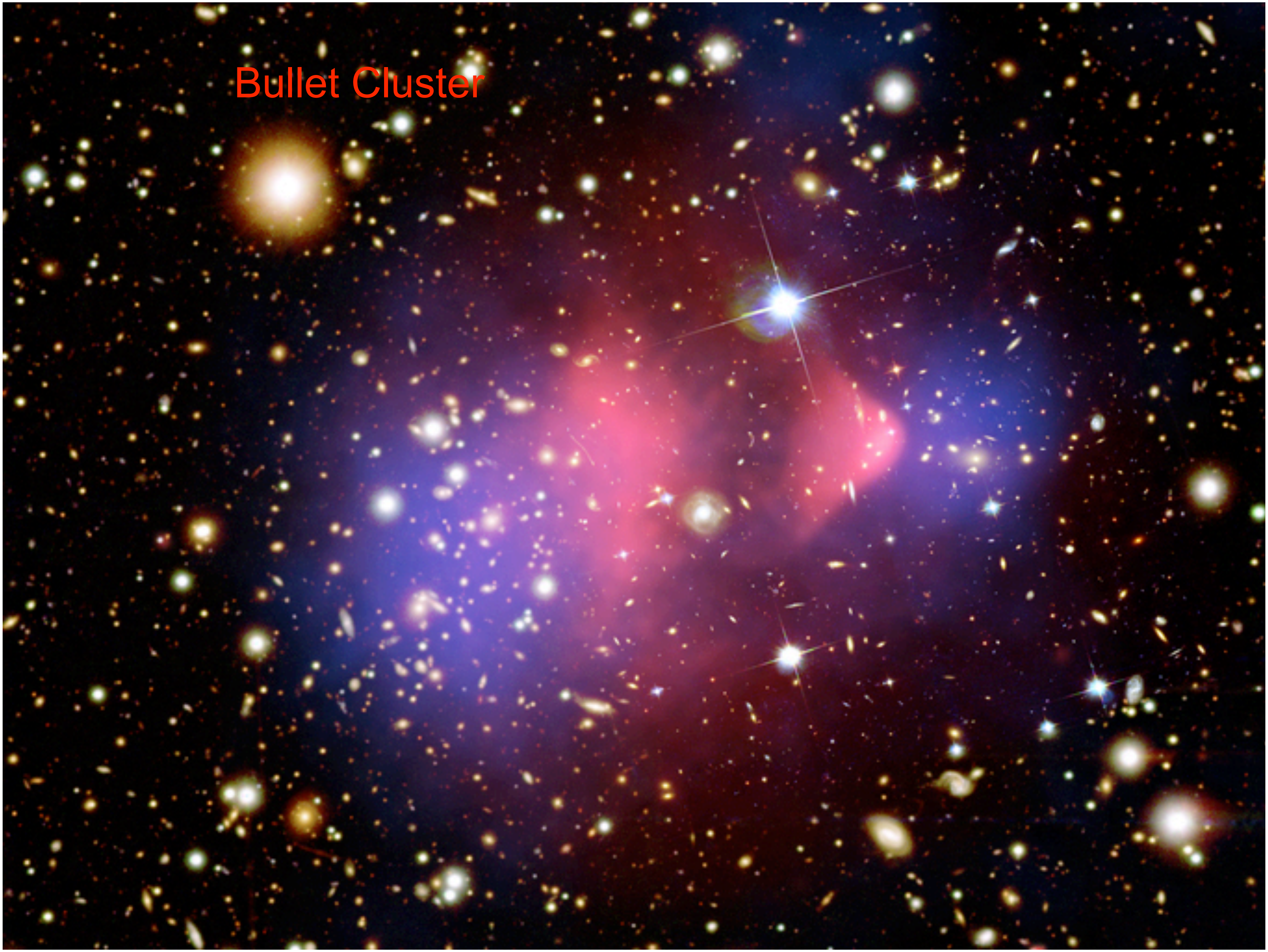
1000’s of galaxies within 1 Mpc

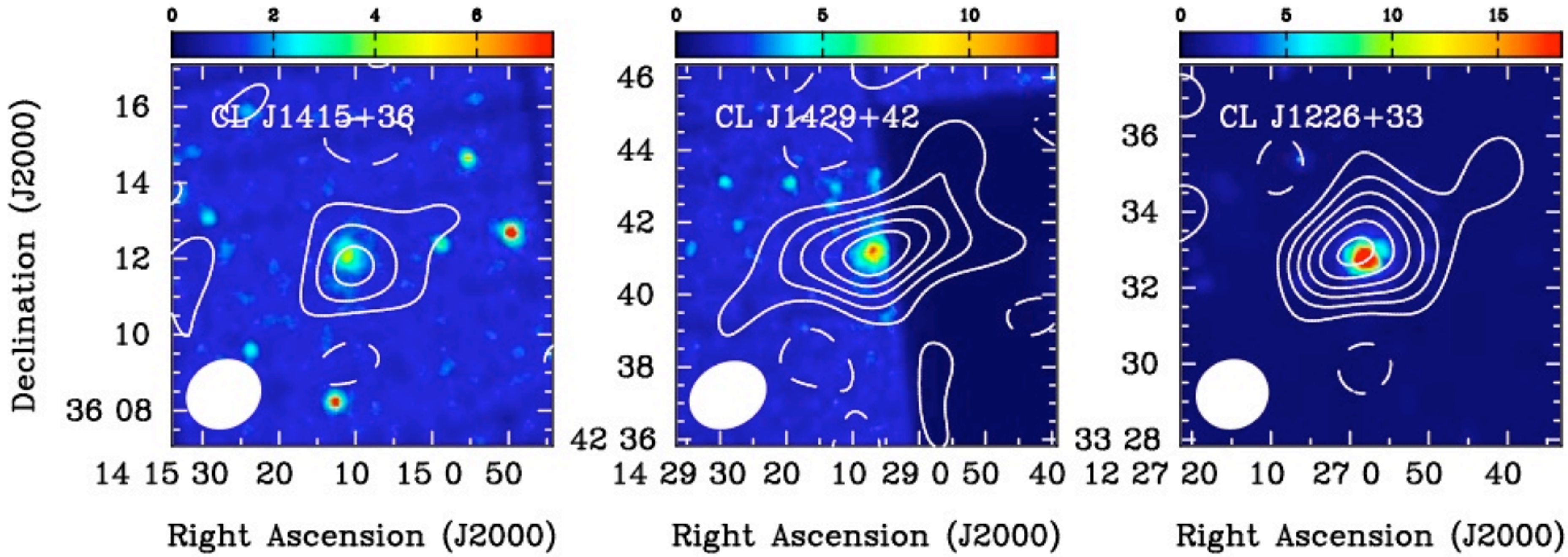
- Nearest example of a “rich” cluster.
- Very massive! $>10^{14}M_{\odot}$
- Typical galaxy velocities of 1000 km/s

Clusters in X-Rays

- Filled with very hot (10^7K) gas
- Much more mass in the gas than in all the stars in the galaxies
- Baryon to dark matter ratio ~agrees with CMB, BBN
- ROSAT X ray clusters: Reiprich & Bohringer (2002)



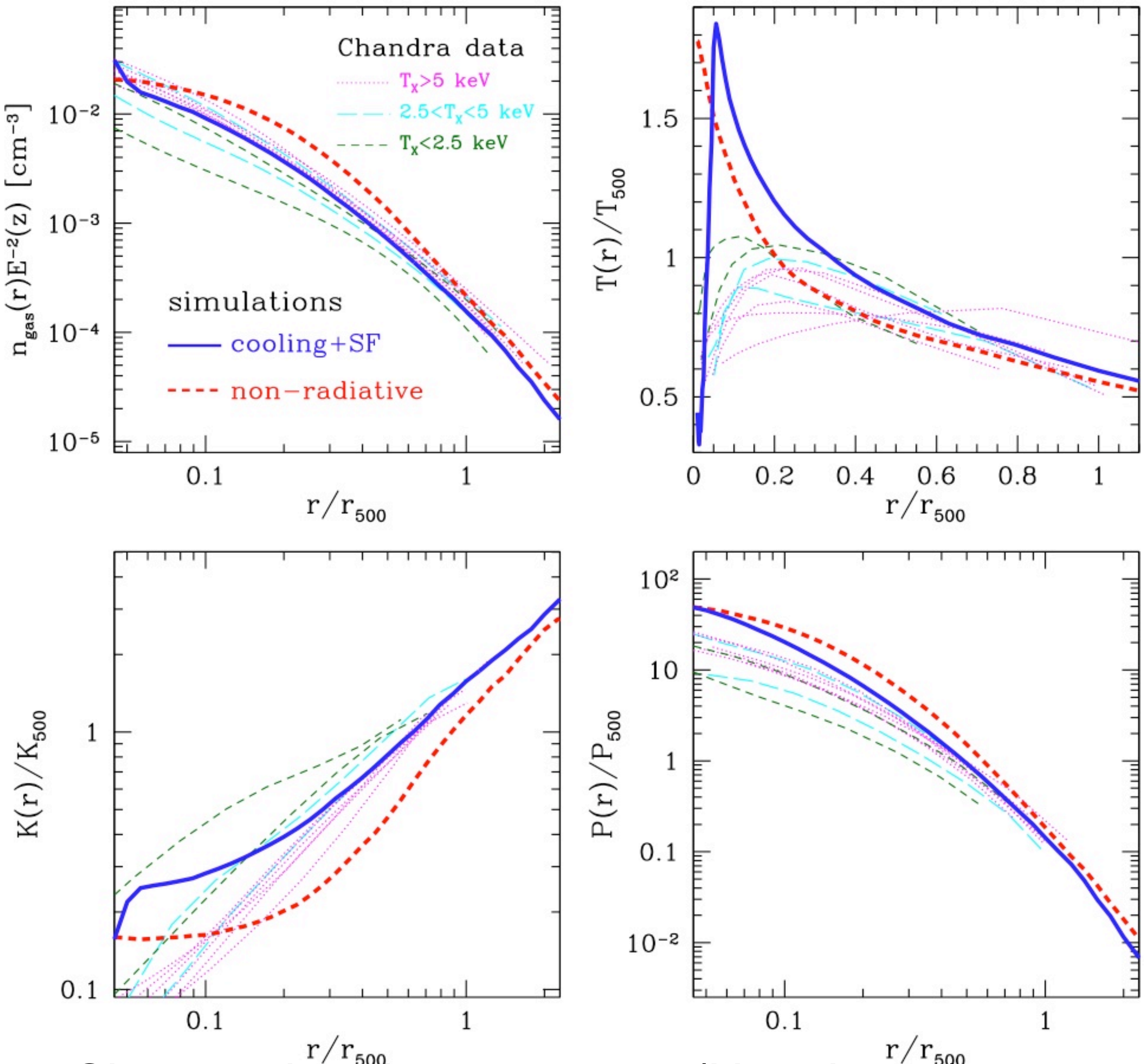

Bullet Cluster



Sunyaev-Zeldovich and X-ray images of clusters (SZ array, Muchovej et al.)

Clusters

- Simulations of Chandra, XMM-Newton data (Vikhilin et al 2005, Nagai et al 2006): profiles, abundances agree with LCDM
- Within factor 2 of universal baryon/DM ratio is directly observed (as predicted)
- Overall model consistency with multiple datasets (SZ, X ray, lensing)



Simulated and real clusters (Nagai et al)

Ionized plasma (~90%)

$z=1000$: scattering, acoustic waves (CMB large l, galaxy BAO)

$5<z<10$: CMB large angle scattering

$3<z<4$: Helium absorption in QSOs

$2<z<5$: HI,CIV absorption in QSOs

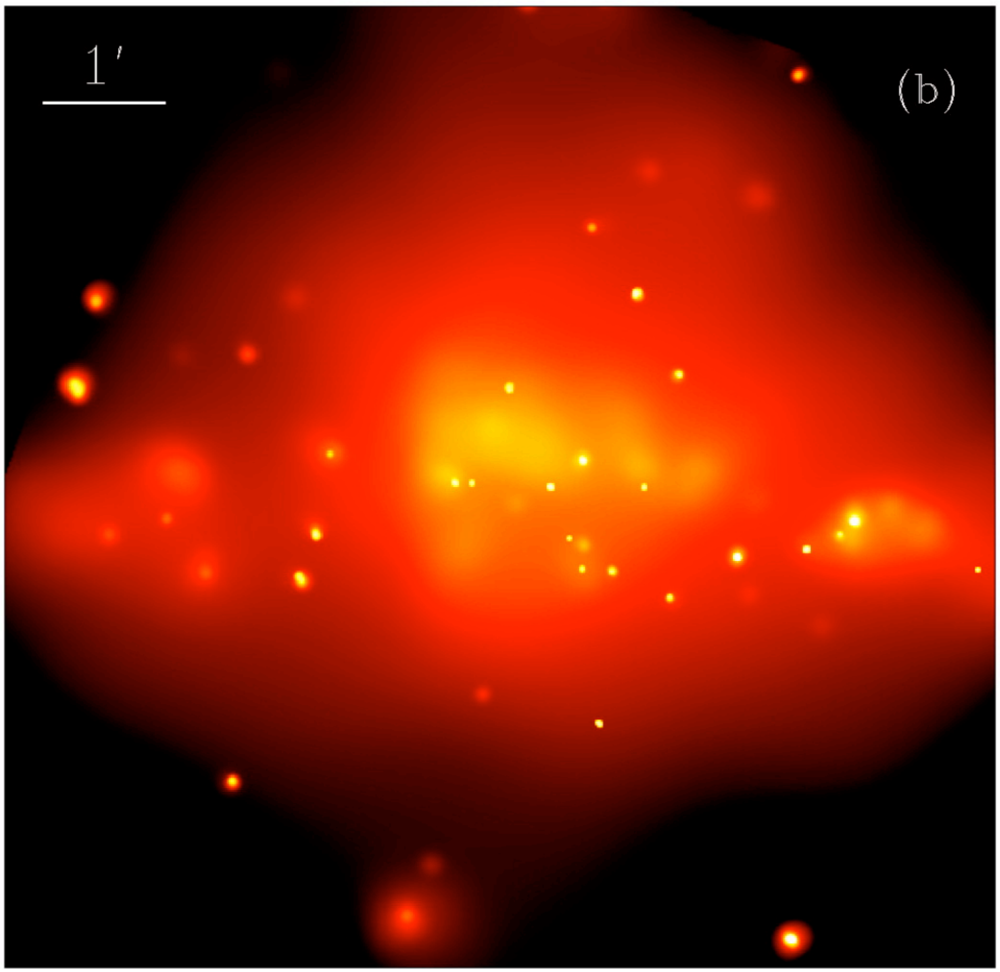
Low z: OVI absorption in QSOs

Nearby: emission from dense central parts of coronae, hot cluster halos

Dominant $T \sim 10^{6.3}$ K plasma

- Partly observable in central parts of nearby galaxies
- Most baryons are in extended diffuse coronae of galaxies and groups
- Precursor gas measured at higher z by e^- scattering and QSO absorption
- Some nongravitational heating, redistribution needed
- ~90% of baryons have always been gas

N4631 at 0.3 to 1.5 keV

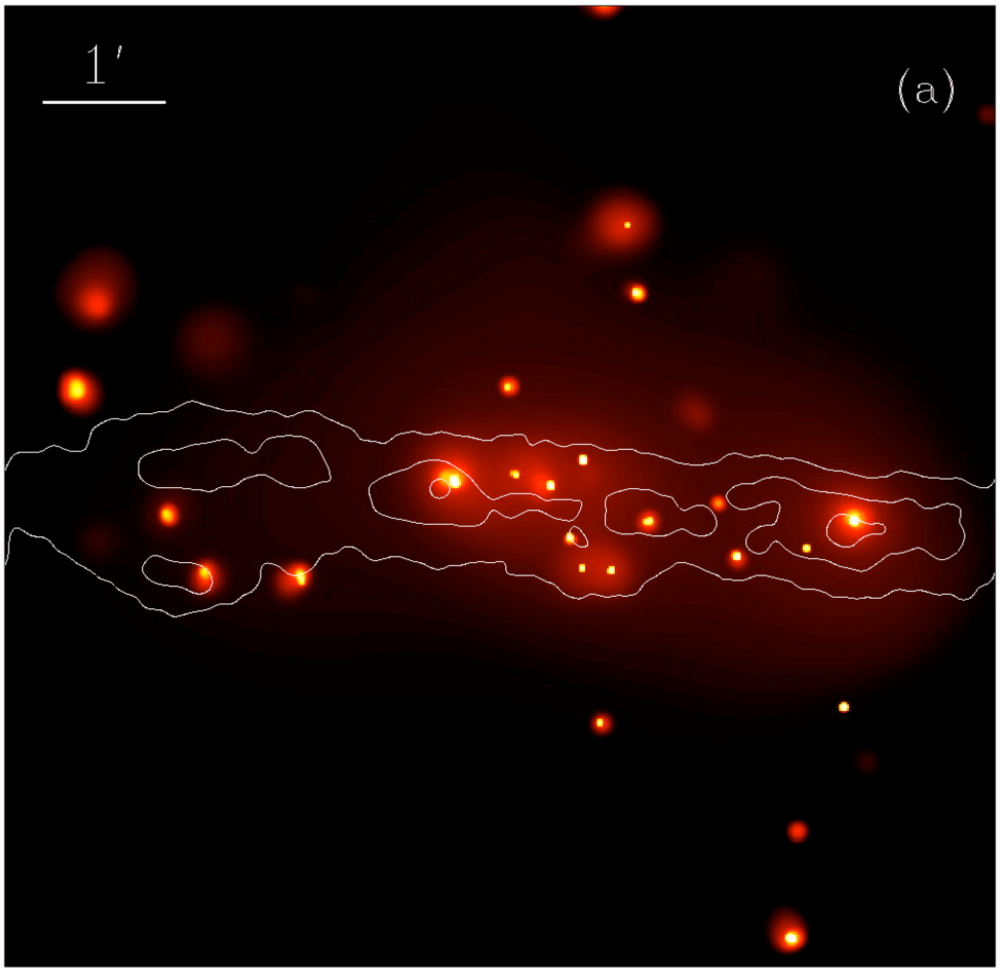


Shows $10^{6.5}$K gas in extended ~8kpc corona

Most baryons lie in similar coronae, farther out and more diffuse, on ~300 kpc scale

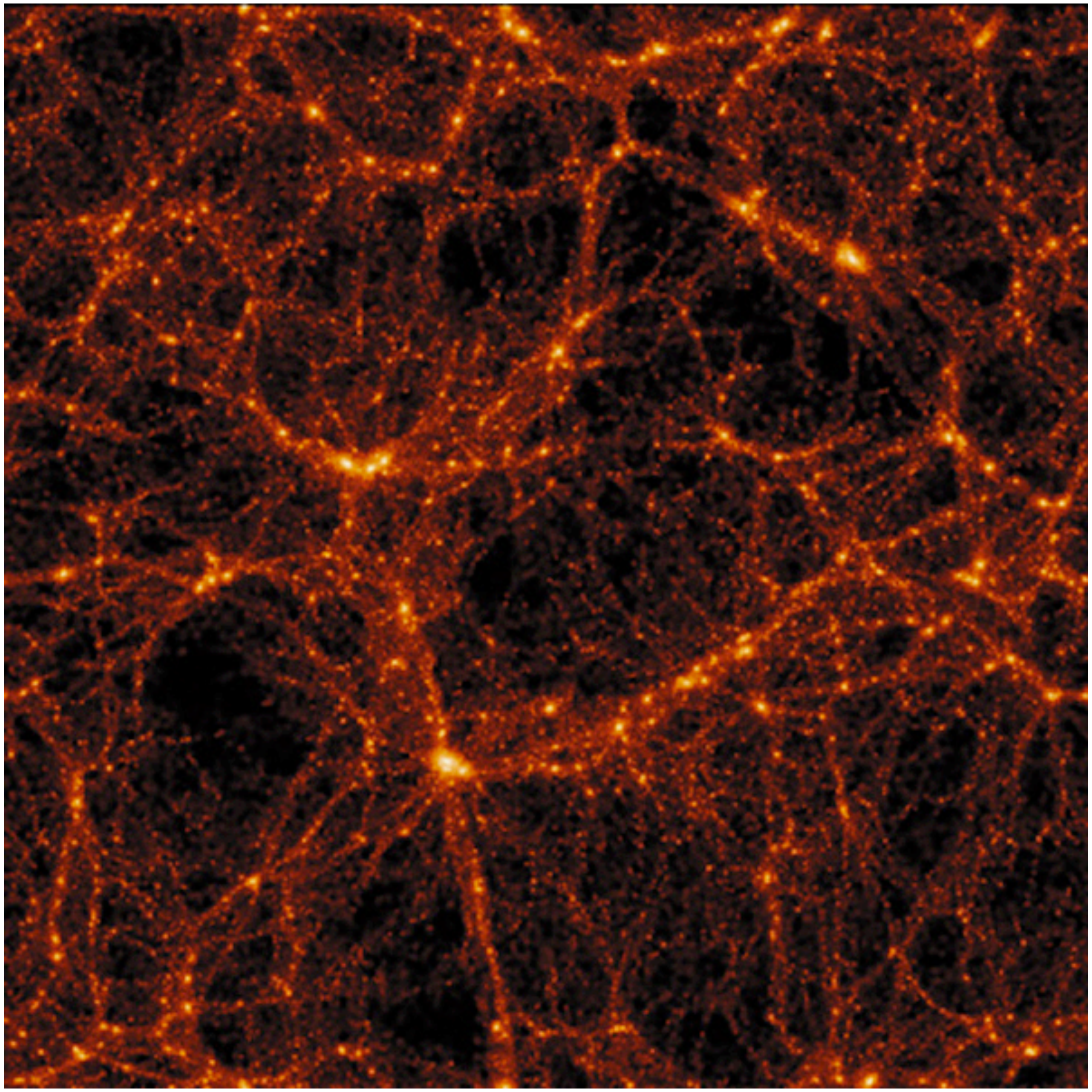
Mean separation of galaxies ~4 Mpc

N4631 at 1.5-7 keV

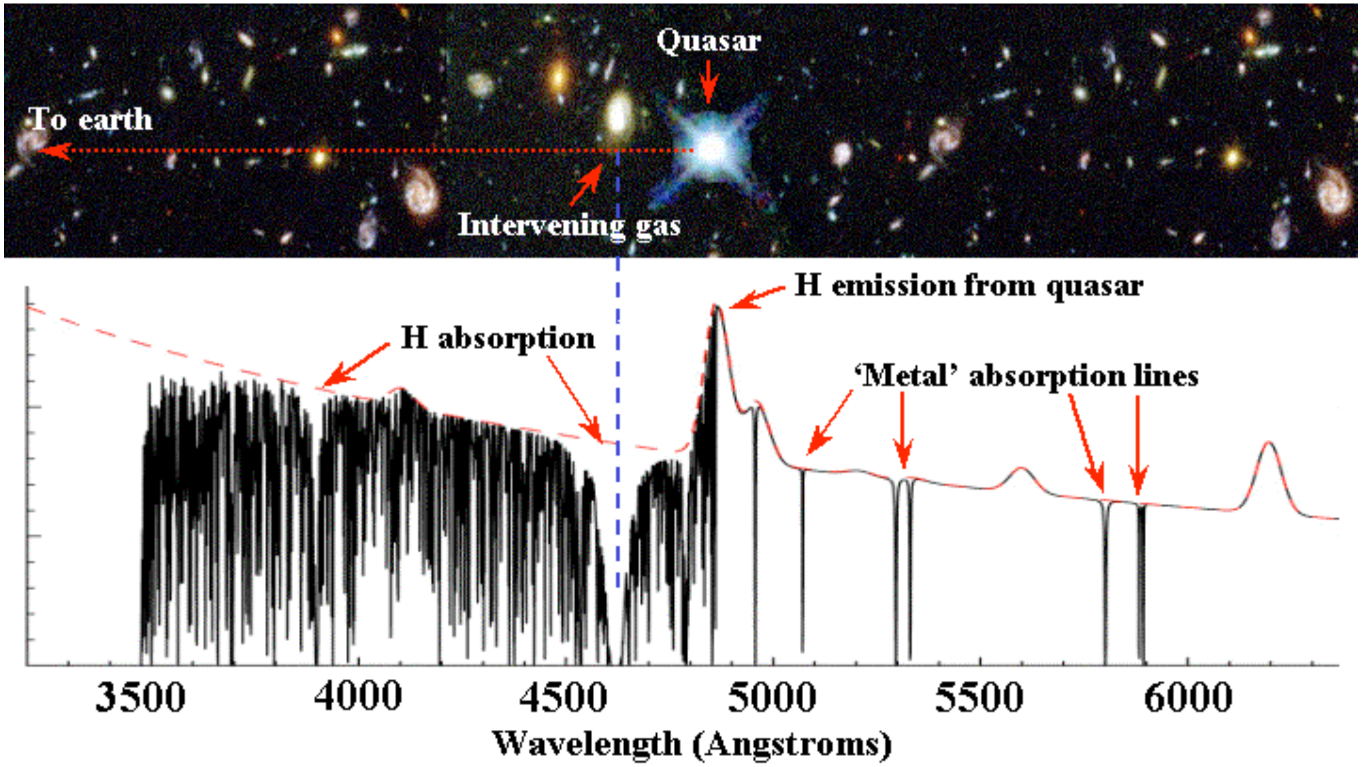


Wang et al 2001

Protogalactic gas: HI in cosmic web at z~3



•Simulations correctly predict the absorption from a small fraction of (dominant state) plasma in neutral HI (at z~ 2 to 5) and singly ionized He (at z~3)
•Requires significant ionization modeling
•For other species, also abundance uncertainties (eg OVI at low z)



http://www.eso.org/~jliske/qsoal/

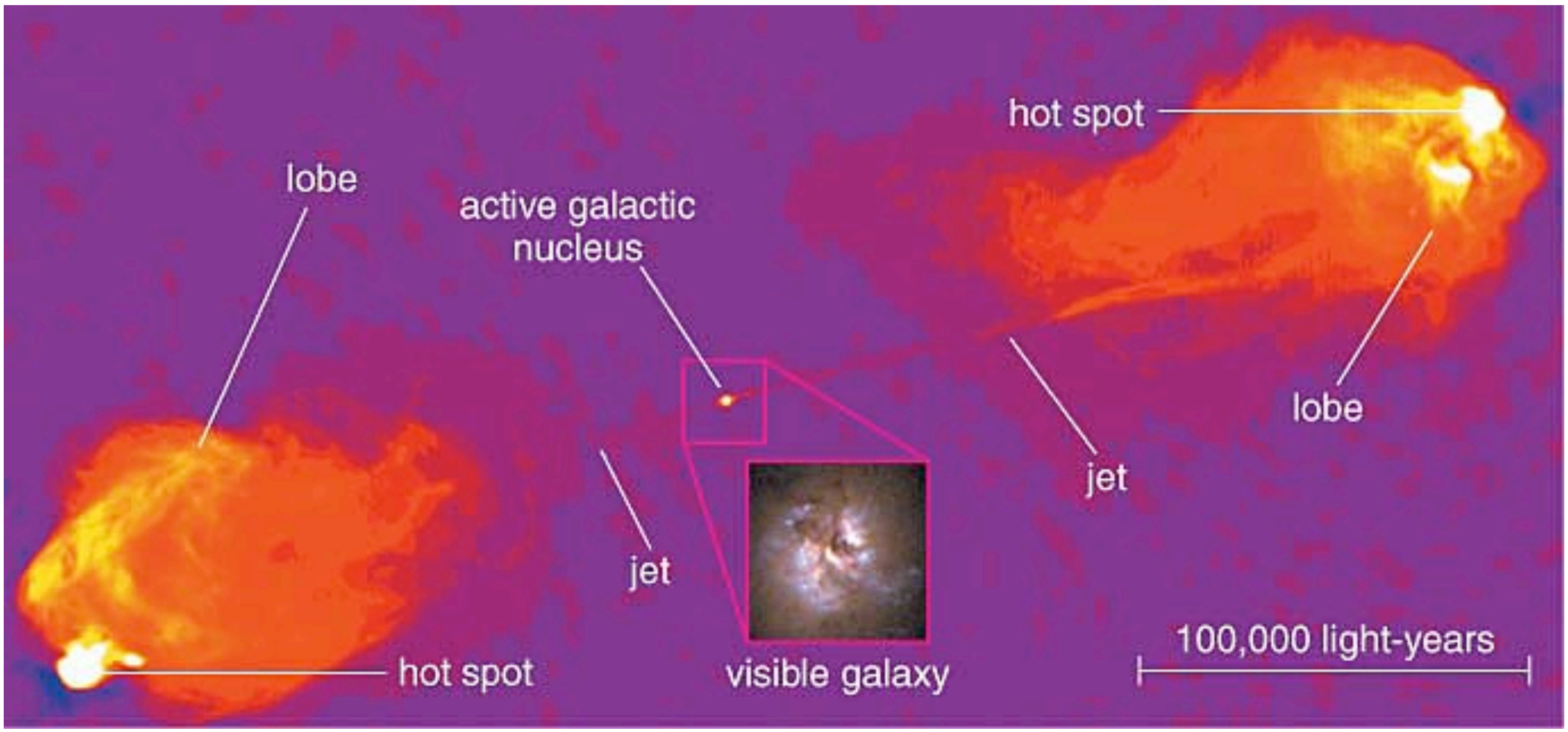
QSO absorption: limitations

- H Lyman alpha forest: tiny fraction in HI in bulk of gas; ionization corrections from simulations & UV background models (e.g. Gnedin et al); also used for power spectrum
- Saturation: most atoms are "invisible"
- Helium Lyman alpha: 304 A line, few quasars
- O VI: visible in low z plasma, abundance is unknown

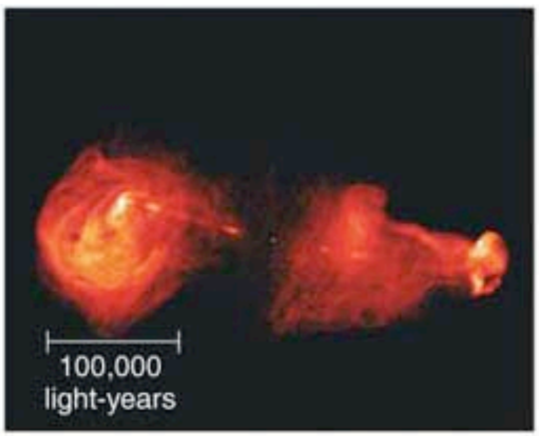
How much plasma?

- High z estimates agree: CMB, nucleosynthesis, BAO, QSO absorption in dominant species (H, He)
- Simulations predict too much gas in central parts of galaxies today, too much going into stars early on
- extra heating (nonlocal feedback) and hydrodynamic force required
- Stars, AGN, cosmic rays,….?

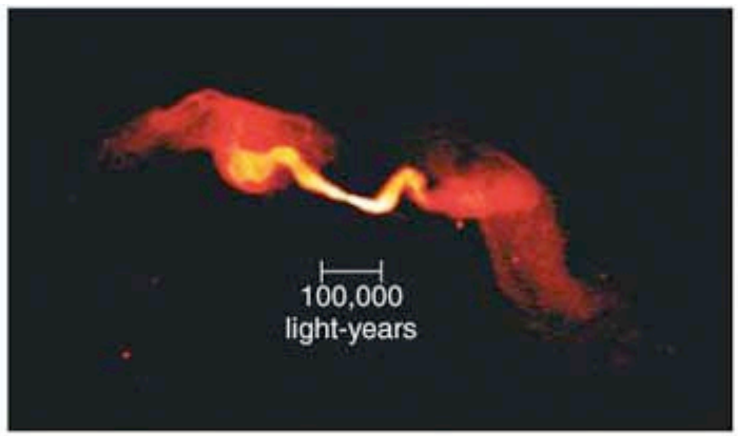
Radio Jets


hot spot
lobe
active galactic
nucleus
lobe
jet
jet
100,000 light-years
hot spot
visible galaxy

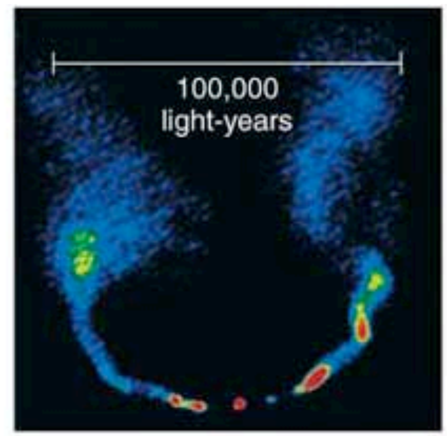
Jets in cluster gas



a Radio galaxy 3C 353.



b Radio galaxy 3C 31.



c Radio galaxy NGC 1265. The lobes are swept back because the galaxy is moving relative to the surrounding intergalactic gas.

no "missing" baryons!

- Multiple direct estimates agree
- Baryons are ``seen'' down to z~2
- >80% of baryons are invisible at z~0
- Connects with galaxy formation process: feedback from stars, AGN
- Better probes are possible at all redshifts:
  - CMB
  - QSO absorption
  - Soft X ray emission

Why worry?

- Bulk of baryons are affected by feedback, hydrodynamics
- Affects distribution of >10% of all mass, up to ~10 Mpc scales
- Limits on reliable simulation of mass distribution, precision cosmology, weak lensing (Rudd, Zentner, Kravtsov)
- galaxy formation regulation
- Why gravitational~stellar~AGN power?