Science horizons & technology challenges beyond the *Chandra* X-ray Observatory

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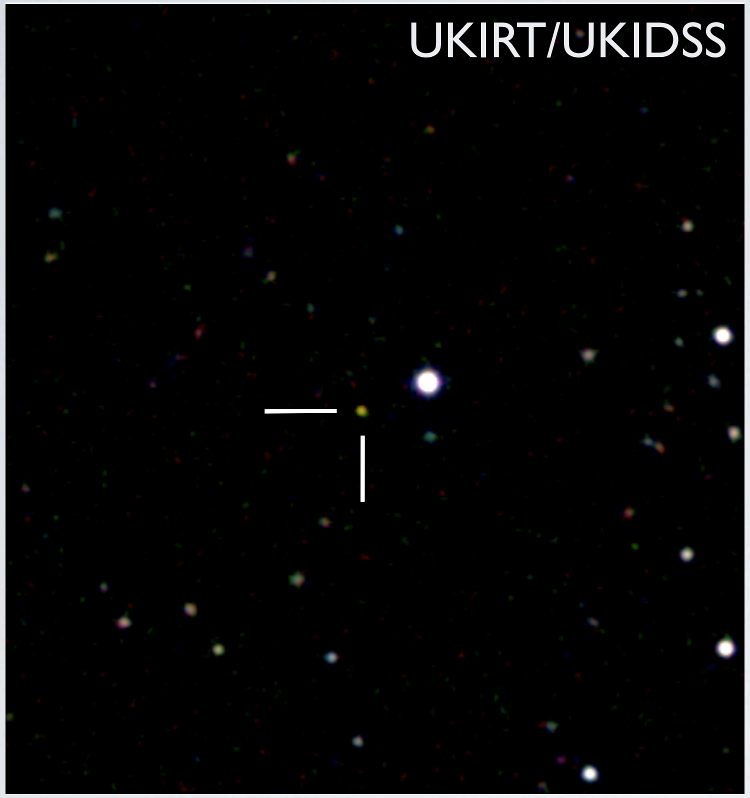
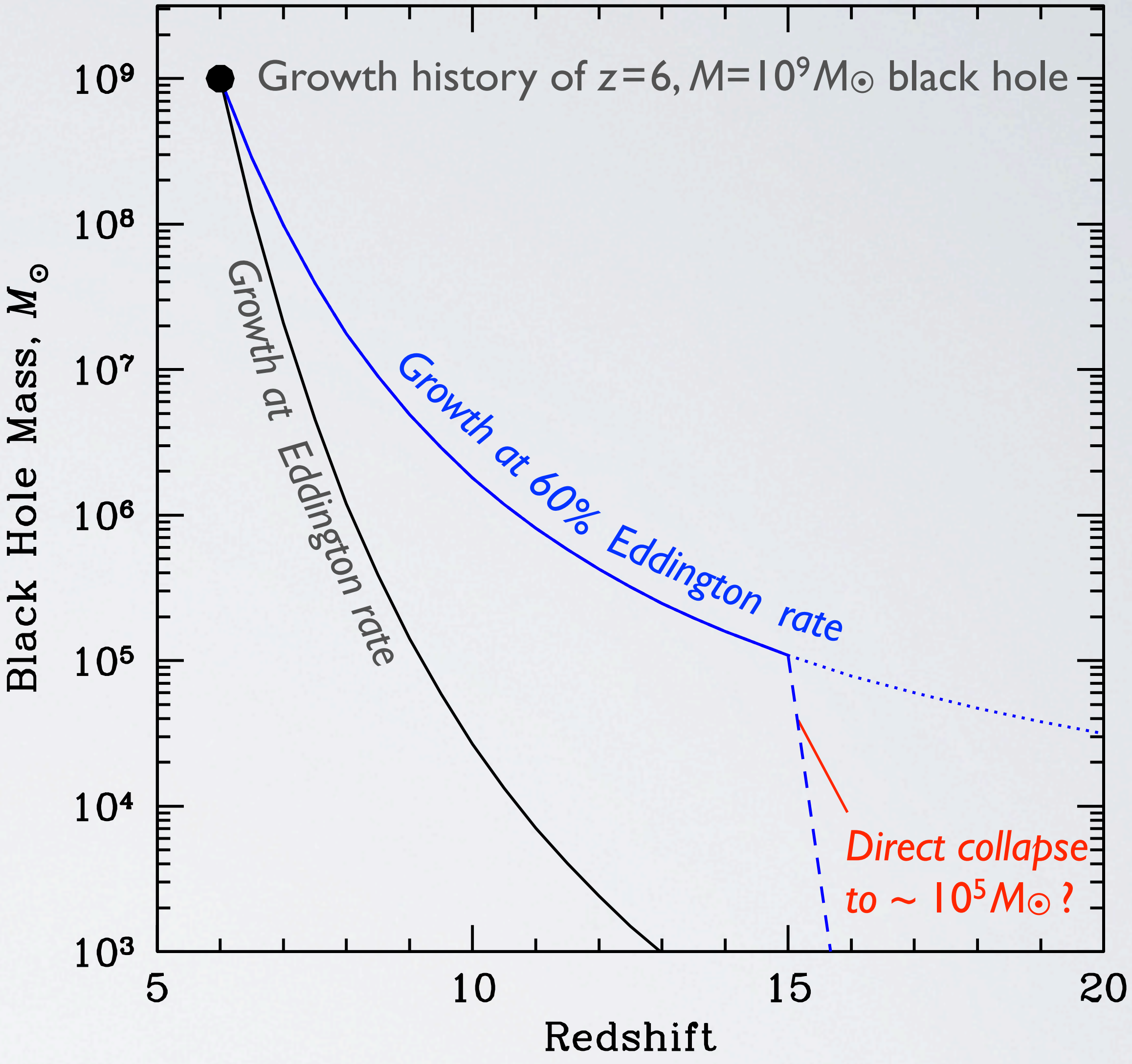
Future high-throughput X-ray observatory with sub-arcsec angular resolution and next-generation science instruments will address science questions such as:

- Early stages of the super-massive black holes growth.
- Co-evolution of galaxy clusters and billion-$M_\odot$ black holes since z ~ 6.
- Low-density diffuse baryons in the galaxy halos, cluster infall regions, and Cosmic Web.

Super-Massive Black Holes at infancy

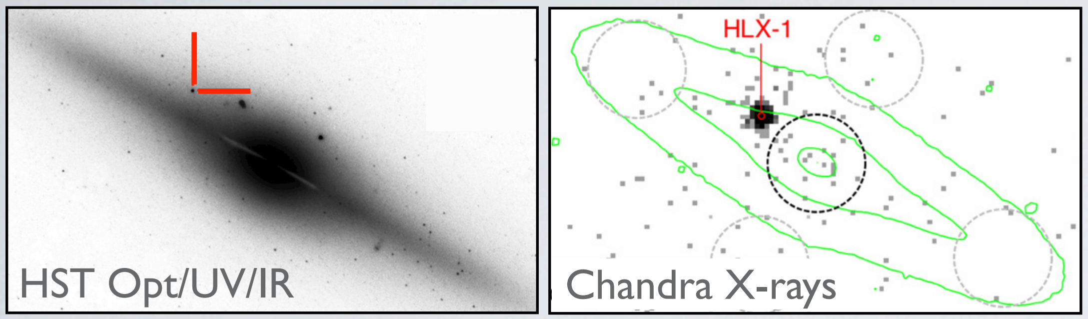


An extreme high-z quasar at z=7.1 with $M_{BH}=2\times10^9 M_\odot$ *(Mortlock et al.'11)*

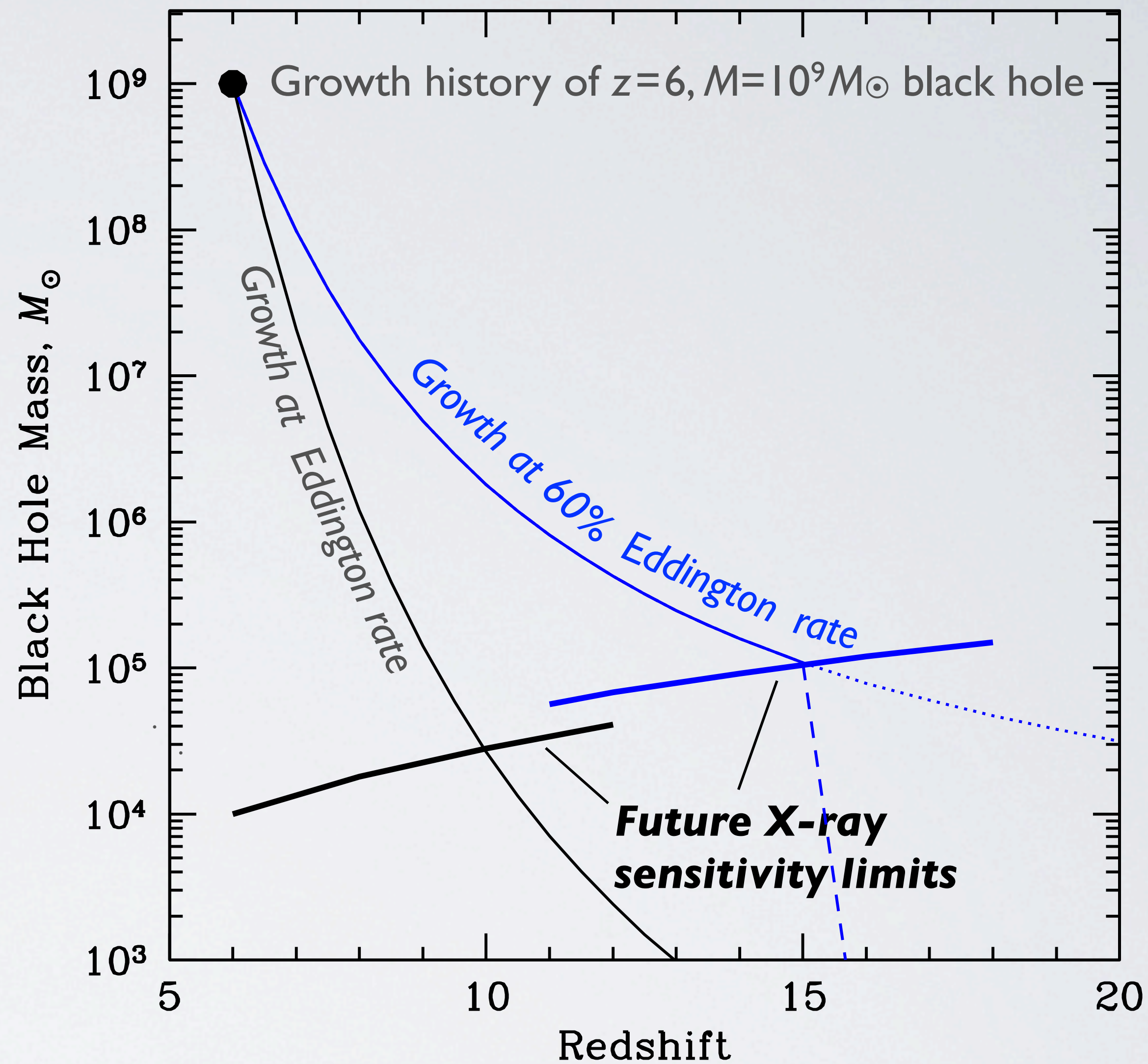


- Discovery of z>6 quasars with $M_{BH}>10^9 M_\odot$ poses a challenge — not quite enough time to grow.
- Likely, super-interesting physics at the progenitor stage (e.g., direct collapse of gas clouds to $\sim10^5 M_\odot$ black holes).
- *Need to observe progenitors with mass $10^4 M_\odot - 10^5 M_\odot$ at the highest z possible*

Super-Massive Black Holes at infancy



"HLX-1", best candidate for an intermediate-mass black hole, M_{BH}~$10^4 M_{\odot}$, in a galaxy 95Mpc away Farrell et al. 2009, Servillat et al. 2011, Davis et al. 2011). Require future X-ray mission capable of detecting comparable black holes to z ~ 10.



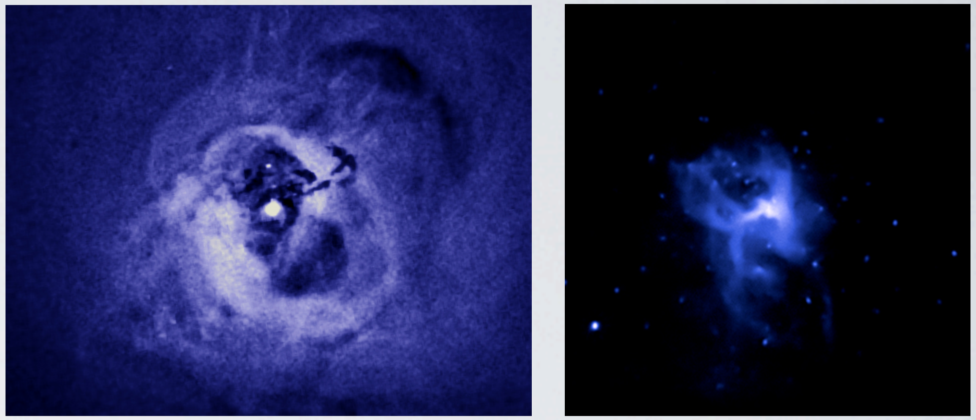
- Lower-mass black holes, $M_{BH}<10^6 M_{\odot}$, are essentially X-ray objects:
  - Spectral peak (λ_{max} ~ $M_{BH}^{1/4}$) shifts below 100 Å, reducing optical/UV output;
  - Obscuration impacts optical/UV flux (2/3 of low-L population at low z). IR selection of obscured AGNs relies on λ=3–20 μm bands, redshifted to λ>30 μm at z=10.

- *Future X-ray Observatory envisioned to detect unobscured hard X-rays, E>2 keV, from hot accretion disk corona (~10% of L_{bol}) at z=10 for Eddington accretion on $M_{BH}=3\times10^4 M_{\odot}$*

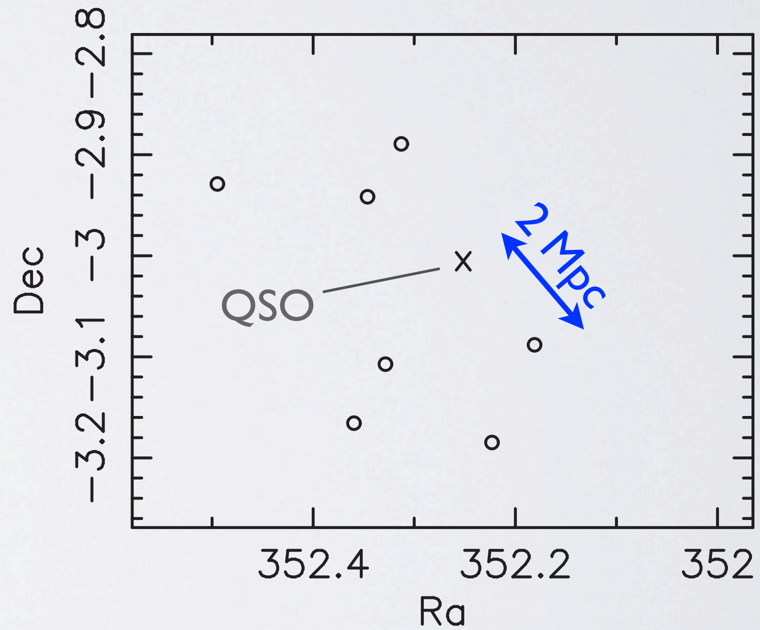
Interaction of 10^9 $M_\odot$ Black Holes and their environment from z=6 to z=0

Interaction of Super-Massive Black Holes and environment is a fundamental astrophysical process at all z.

- $10^9 M_\odot$ black holes of the luminous z=6 quasars should "live" in the proto-cluster environment.
- However, Lyman-break galaxy surveys do not show obvious clusters around high-z quasars (Kim et al. 2009 and others).
- Does the quasar emission quench galaxy formation around it at z>6?
- Need to search for the host proto-clusters independent of galaxy counts.
- *Proto-clusters at z=6 are X-ray objects so future X-ray Observatory should be scoped to measure their properties.*

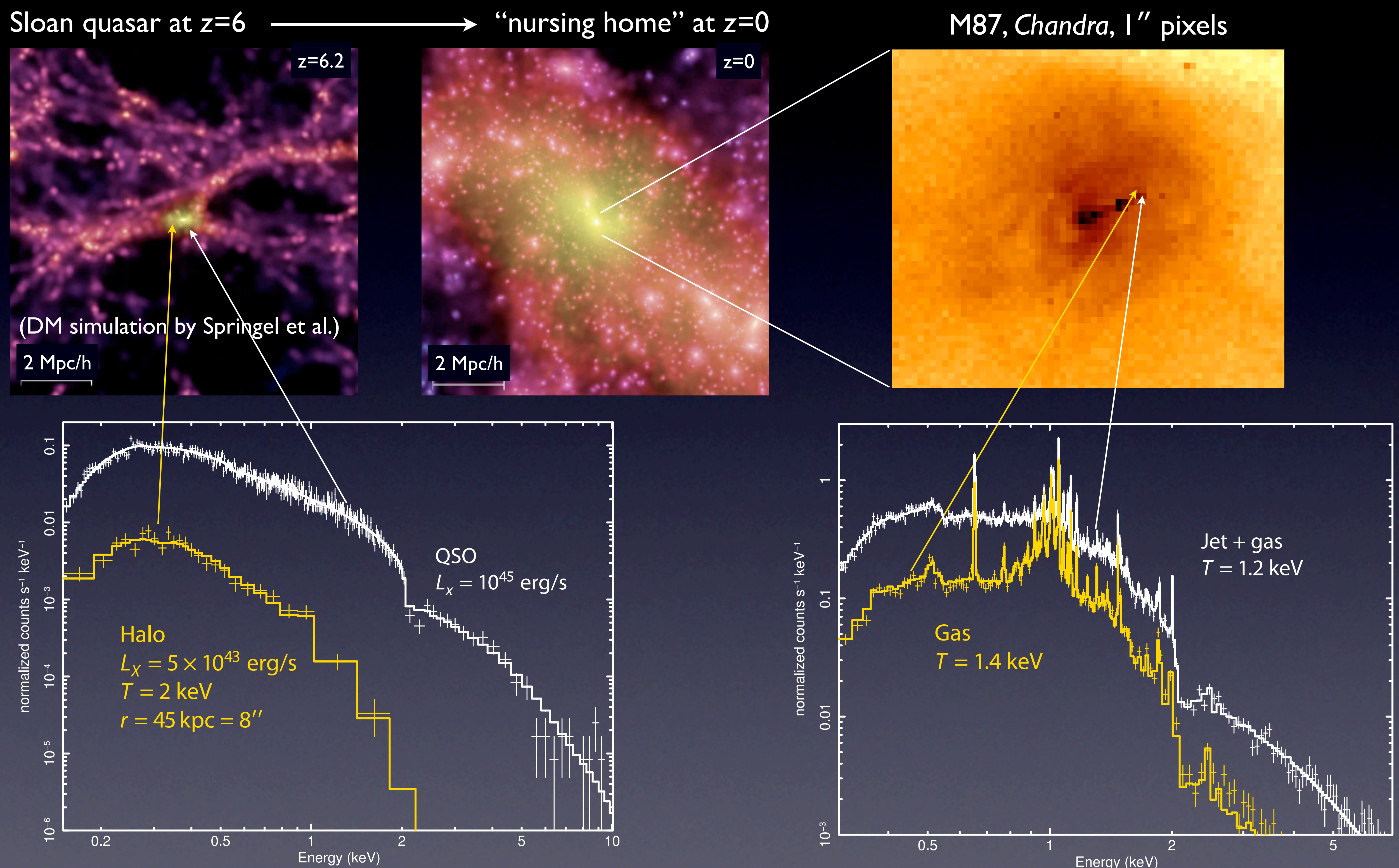


Energy feedback from super-massive black holes into hot gas in galaxy clusters and individual galaxies: Chandra X-ray images of Perseus Cluster (left) and M84 (right)



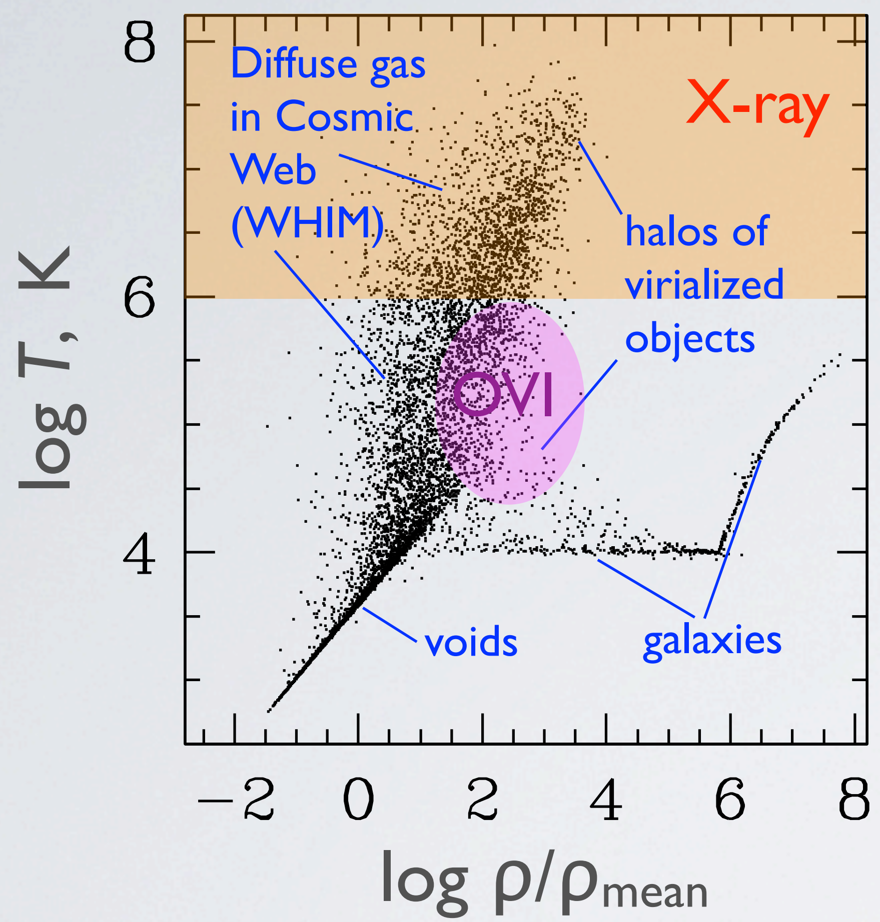
Distribution of Lyman-break galaxies around z=6.4 quasar observed with Subaru (Utsumi et al. 2010). While there is an overall excess of galaxies in the field, there is no concentration within 2Mpc of the quasar itself.

Interaction of $10^9\ M_\odot$ Black Holes and their environment from z=6 to z=0

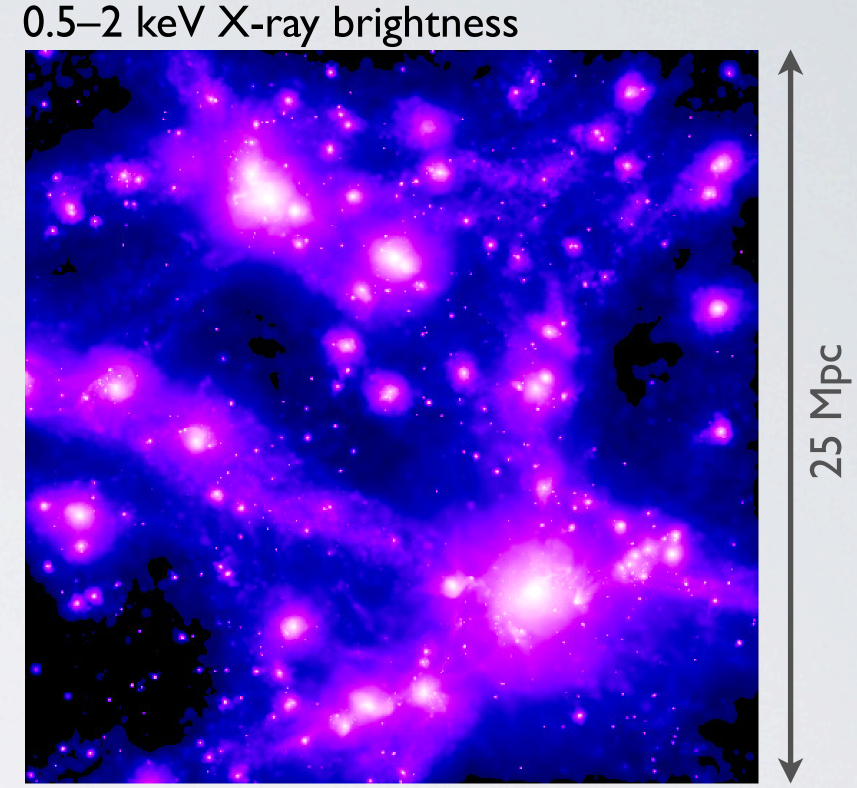


Future X-ray observatory will measure hot gas in dark matter halos around z=6 quasars, and provide a detailed picture of energy feedback into galaxy clusters at z<0.5

Mapping diffuse baryons in the Cosmic Web.



Phase diagram for the baryons in the Local (z=0) Universe (theoretical prediction from Davé et al. 2010). Heated gas ($T>10^5$ K) in virialized halos and Cosmic Web accounts for >40% of all baryons by mass.

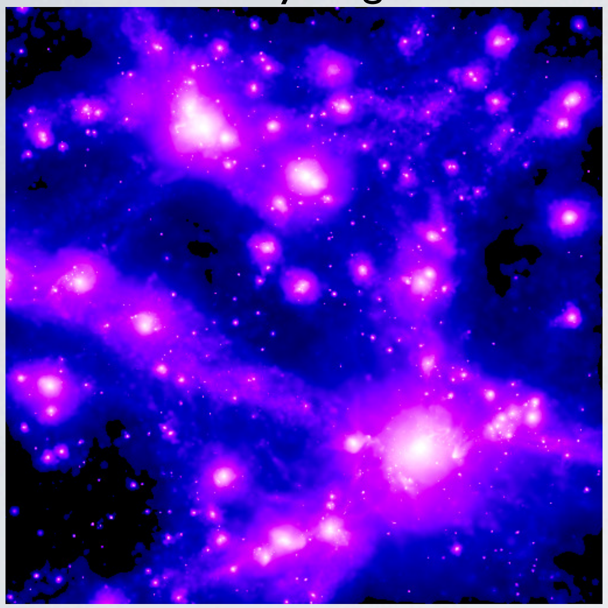


Simulated X-ray surface brightness (0.5–2 keV) in a 25 Mpc box around a massive (~10^{15} $M_\odot$) galaxy cluster (Rasia, Dolag et al.)

- Diffuse ionized intergalactic gas contains most of baryons in the local Universe.
- Current absorption line observations in UV (OVI) and X-rays (OVII) only scratch the full phase space.
- A large fraction of these baryons is heated to X-ray temperatures, $T>10^6$.
- For full understanding of the intergalactic gas, need ability to ***map*** it.

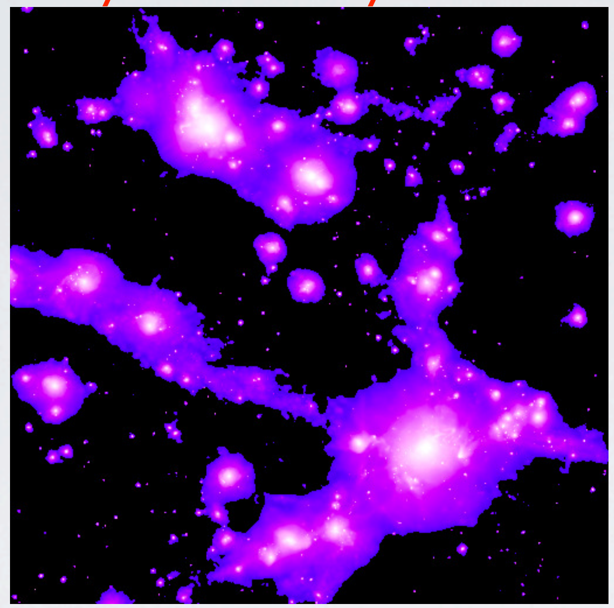
Mapping diffuse baryons in the Cosmic Web.

0.5–2 keV X-ray brightness



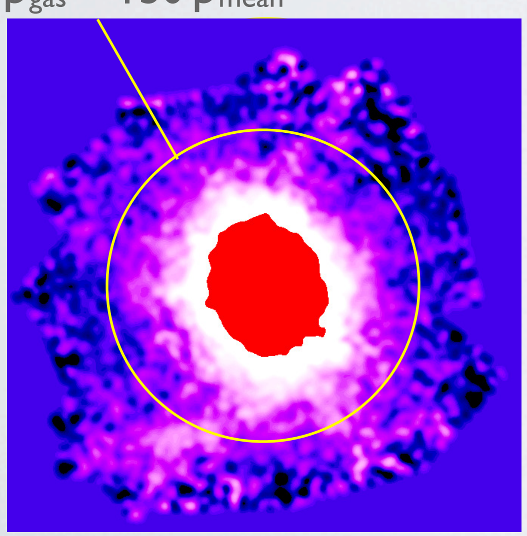
Simulated X-ray surface brightness (0.5–2 keV) in a 25 Mpc box around a massive (~10^{15} M$_\odot$) galaxy cluster (Rasia, Dolag et al.)

Accessible to future X-ray observatory

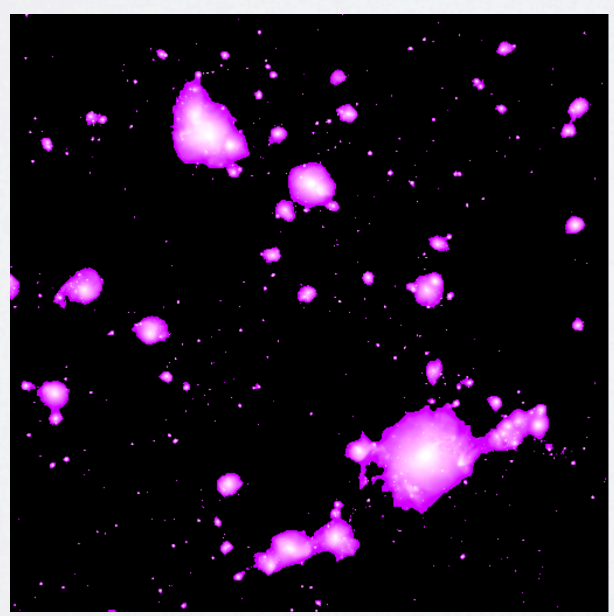


A factor of 30 sensitivity increase due to higher throughput and spectro-imaging capabilities, essential for foreground & background removal.

$\rho_{gas} \approx 150\ \rho_{mean}$



same sensitivity in the simulated map



Deep Chandra survey of A133 (300 ksec per location) detects hot gas at densities as low as ≈ 150 × cosmic mean. However, this still includes only isolated virialized structures in the simulated volume.

A future X-ray Observatory with higher throughput and spectro-imaging capability can reach brightness ~ 1/30 of current *Chandra* measurements:

- Map H and He in the Cosmic Web via bremsstrahlung, and heavy elements via emission and absorption lines.
- Regions with ρ/ρ_{mean} above ~30 and $T>1.5\times10^6$ K (containing ~50% of hot diffuse baryons by mass) will become observable.

Technology and Outline of the Future X-ray Observatory

- Long-term science needs (sensitivity and physical scales) require X-ray observatory with angular resolution of <1″ and high throughput coupled to next-generation detectors.

- Based on technological breakthrough for light-weight, high-resolution X-ray mirrors.
  - Several groups (e.g., SAO+Penn State, MSFC, GSFC) exploring different approaches.
  - Target TRL 4 by mid-decade and TRL 6 by 2020.

- With demonstrated optics technology, consider an X-ray observatory with
  - 10m focal length and maximally packed ~3m (diameter) aperture mirrors (~2.5 m^2 effective area)
  - advanced science instruments: X-ray microcalorimeter, active pixel sensor imager, and high-resolution gratings
  - no spacecraft requirements beyond those achieved for *Chandra*
  - size & mass consistent with Atlas V or Falcon 9 launch to L2

Such a mission will be 30–100× more powerful than Chandra

Technology and Outline of the Future X-ray Observatory

- Capabilities achieve science outlined in this talk and more:
  - early stages of the super-massive black holes growth at high z;
  - interaction of $10^9\ M_\odot$ black holes and their environment from z=6 to z=0;
  - mapping diffuse hot gas outside of virialized halos and into the Cosmic Web for local Universe;
  - observations of "hot-mode" accretion of the IGM onto massive galaxies;
  - active stars and studies of star formation regions;
  - physical processes in the supernovae remnants and hot gas in galaxy clusters.
- With technology support this decade and success-oriented schedule such an Observatory can be launched in 15–20 year time-frame.