Galaxies Across Cosmic Time

I get wisdom day and night
Turning darkness into light.
St. Paul Irish Codex, translated by Robin Flowers

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Outline of this talk

+ boundary conditions
+ principal findings (4 questions + discovery area)
+ findings relevant to laboratory astrophysics

+ broader implications for laboratory astrophysics in support of NASA missions

Boundary conditions

Scope

+ statement of task: "formation, evolution, and global properties of galaxies and galaxy clusters, as well as active galactic nuclei and QSOs, mergers, star formation rate, gas accretion, and supermassive black holes"
+ negotiated redshift range: $0.1 \leq z \leq z_{reionization}$

Process

+ report was not to refer to specific new missions (approved missions like *JWST* were OK), but panel was asked to provide specific guidance about capabilities to PPPs
+ report sent out for review in September 2009

GCT approach

For each question:

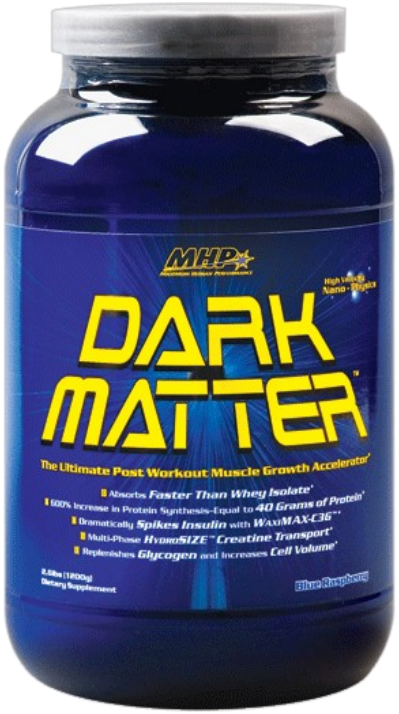
(1) formulate a set of sub-questions

(2) assess progress to date, and identify the critical observational steps for the next decade that could lead to the greatest additional progress (without regard for cost or current agency plans)

(3) rank these scientific programs as important, very important, and most important

Make separate endorsement of key connective tissue: theory and laboratory astrophysics.

Question 1

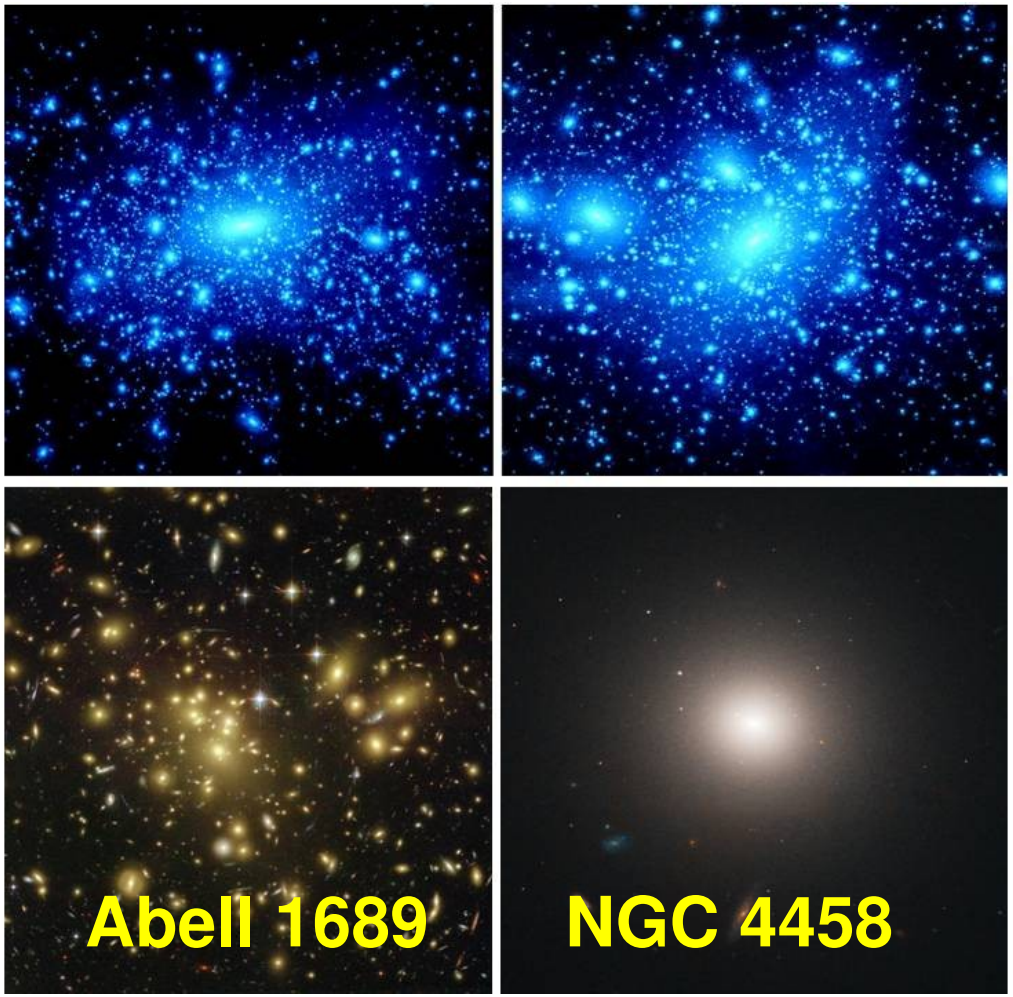


How do cosmic structures form and evolve?

+ **What is the structure of dark matter haloes on galaxy, group, and cluster scales?**
+ **What is the origin of the observed correlations among the fundamental properties of galaxies and of clusters, and how do they evolve with time?**

Question 1: Motivation

cluster galaxy



dark matter simulation

Hubble observation

credits: A. Kravtsov;
NASA/STScI, R. Ellis, E. Peng

Question 1: Next steps from space

Most important

(1) *HST*-resolution lensing studies of very large samples

→ dark matter halo profiles and mass functions

credit: NASA/STScI, N. Benitez + ACS science team

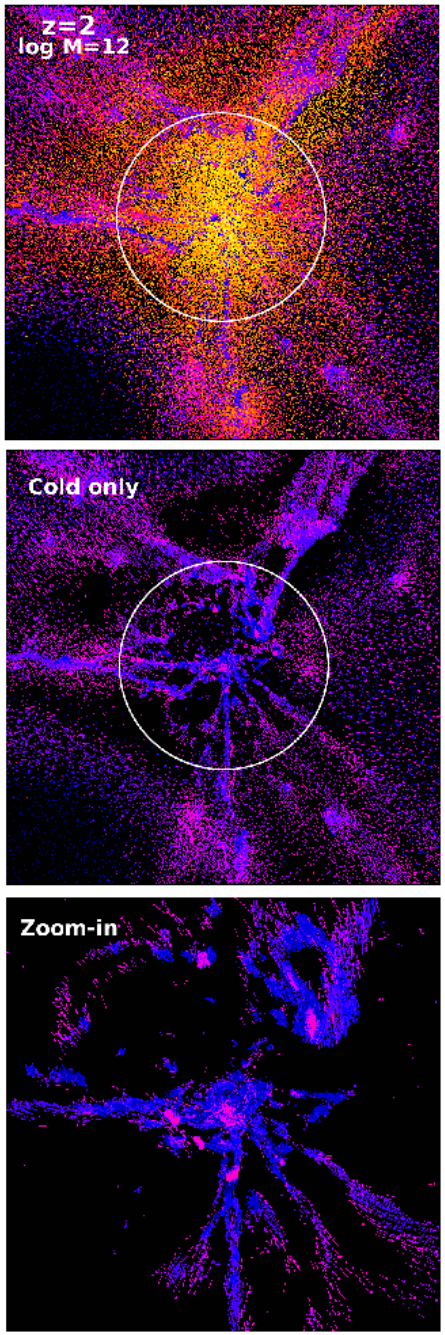
(2) X-ray spectroscopy of groups and clusters to $z \sim 2$

→ dynamics, ionization, temperature structure, metallicity of ICM + development of cluster scaling relations

Question 2

How do baryons cycle in and out of galaxies, and what do they do while they are there?

+ How do galaxies acquire gas across cosmic time?
+ What processes regulate the conversion of gas to stars as galaxies evolve?
+ How are the chemical elements created and distributed?
+ Where are the baryons as a function of redshift?



Question 2: Motivation

Credits: NASA/CXC/STScI/JPL, D. Strickland, C. Engelbracht; Kereš et al. (2009)

Question 2: Next steps from space

Very important

(1) spectral mapping and high-resolution spectroscopy in UV, with sensitivity of a ~4m space telescope

→ physics of circumgalactic gas, warm IGM at $z < 1.5$

(2) far-IR spectroscopy of luminous dusty galaxies

→ accurate star-formation/accretion diagnostics

Important

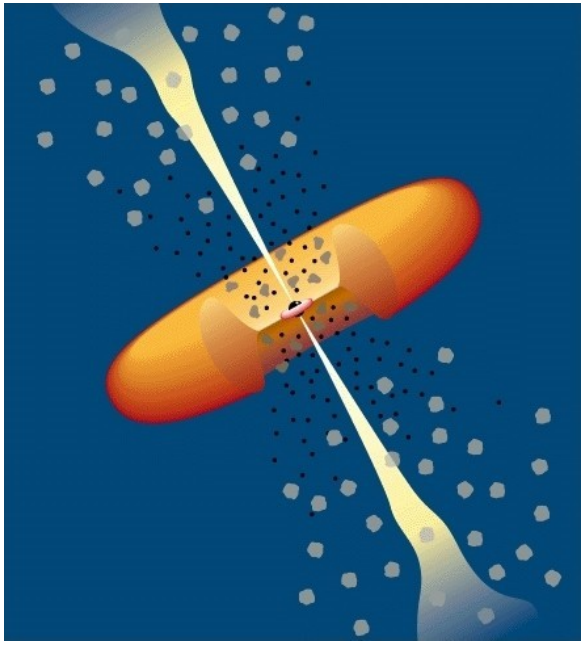
(1) integral field spectroscopy of $z \sim 2$ galaxies with *JWST*

→ dynamics, inflow, feedback, chemical enrichment

(2) moderate-*R* soft X-ray spectroscopy for ~100 sightlines

→ accurate inventory of warm-hot intergalactic medium

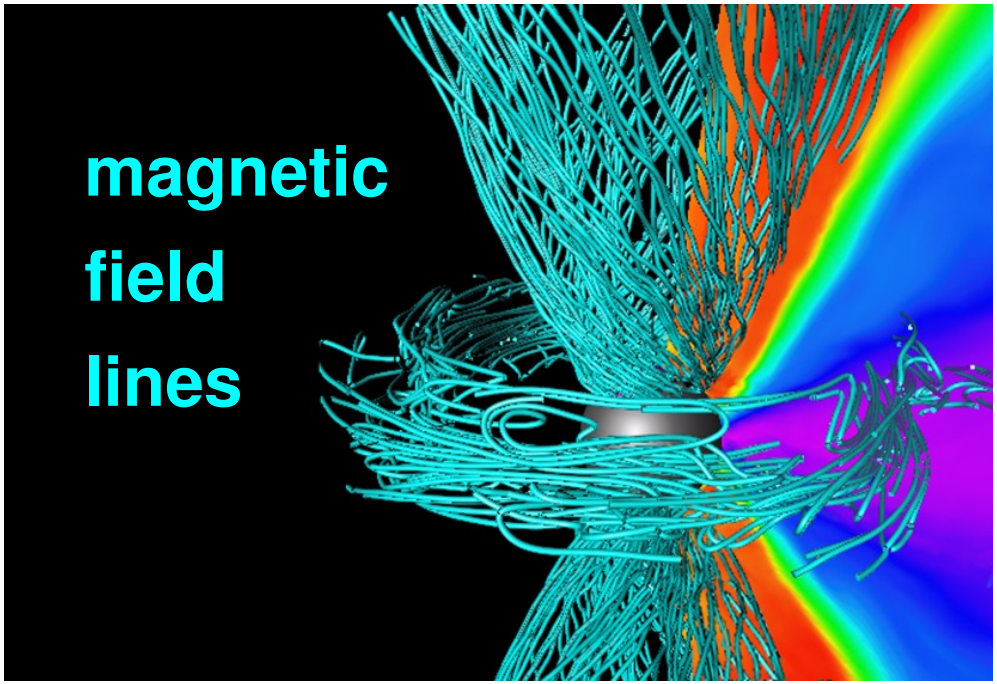
Question 3



How do black holes grow, radiate, and influence their surroundings?

+ How do black holes grow over cosmic time?
+ How do the quantity and form of energy production in accreting systems depend on black hole mass, accretion rate, and spin?
+ How does black hole feedback shape the evolution of cosmic structures?

Question 3: Motivation



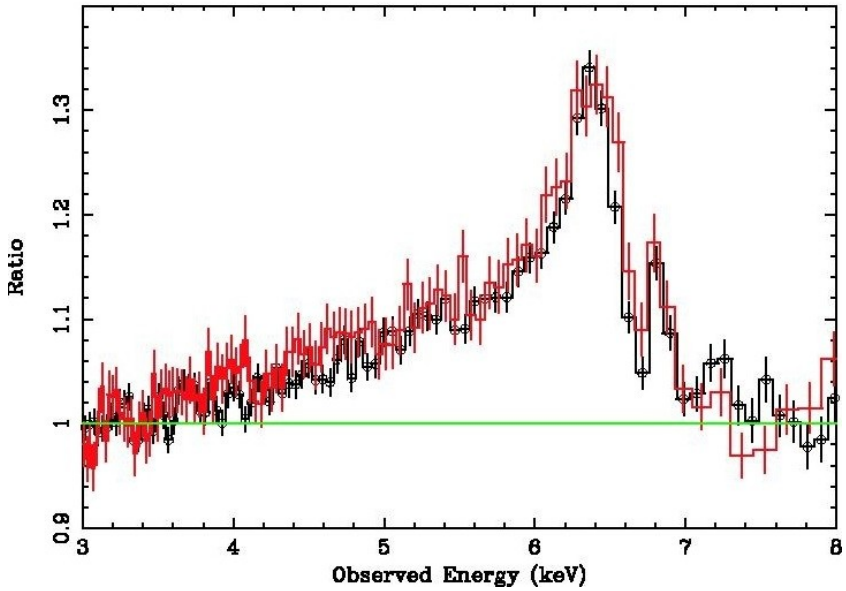
Credit: Hirose et al. (2004); NASA/CXC, A. Fabian

Question 3: Next steps from space

Most important

(1) high-S/N X-ray spectroscopy of ~100 nearby AGN

→ BH spin distribution; accretion/jet physics for brightest



MCG-6-30-15

XMM-Newton* + *Suzaku

Credit: Miniutti et al. (2007)

(2) X-ray imaging spectroscopy of nearest groups/clusters

→ physics of turbulent/bulk flow feedback in ICM

Question 3: Next steps from space

Very important

(1) time-resolved UV (*HST*/COS) + X-ray spectroscopy of AGN

→ role of quasar winds in galaxy-scale feedback

(2) wide-field hard X-ray survey

→ complete AGN census as a function of redshift

(3) search for gravitational radiation at sub-LIGO frequencies

→ constraints on black hole merger history

Important

(1) X-ray polarization of blazars and radio-quiet AGN

→ jet magnetic field geometry; accretion disk structure

(2) gamma-ray (among other) observations of blazars

→ jet composition and formation mechanism

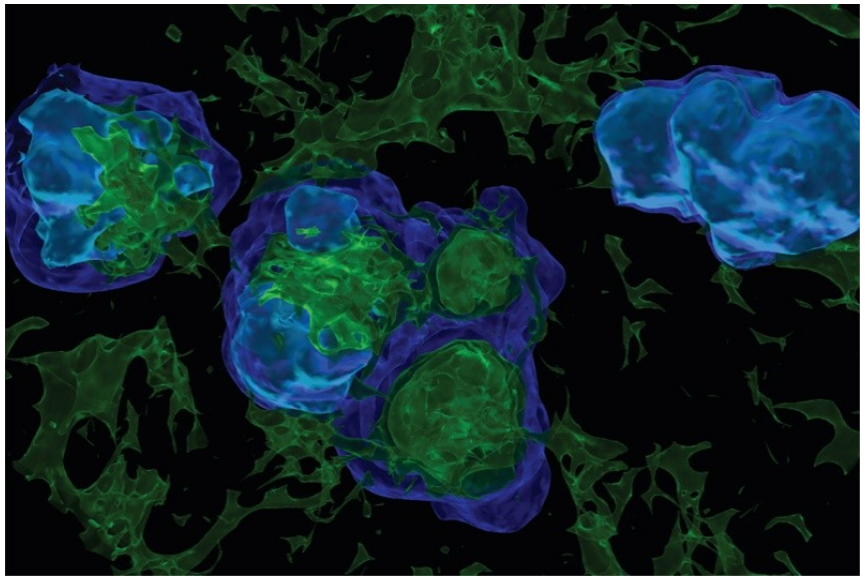
Question 4 + Discovery area

What were the first objects to light up the universe, and when did they do it?

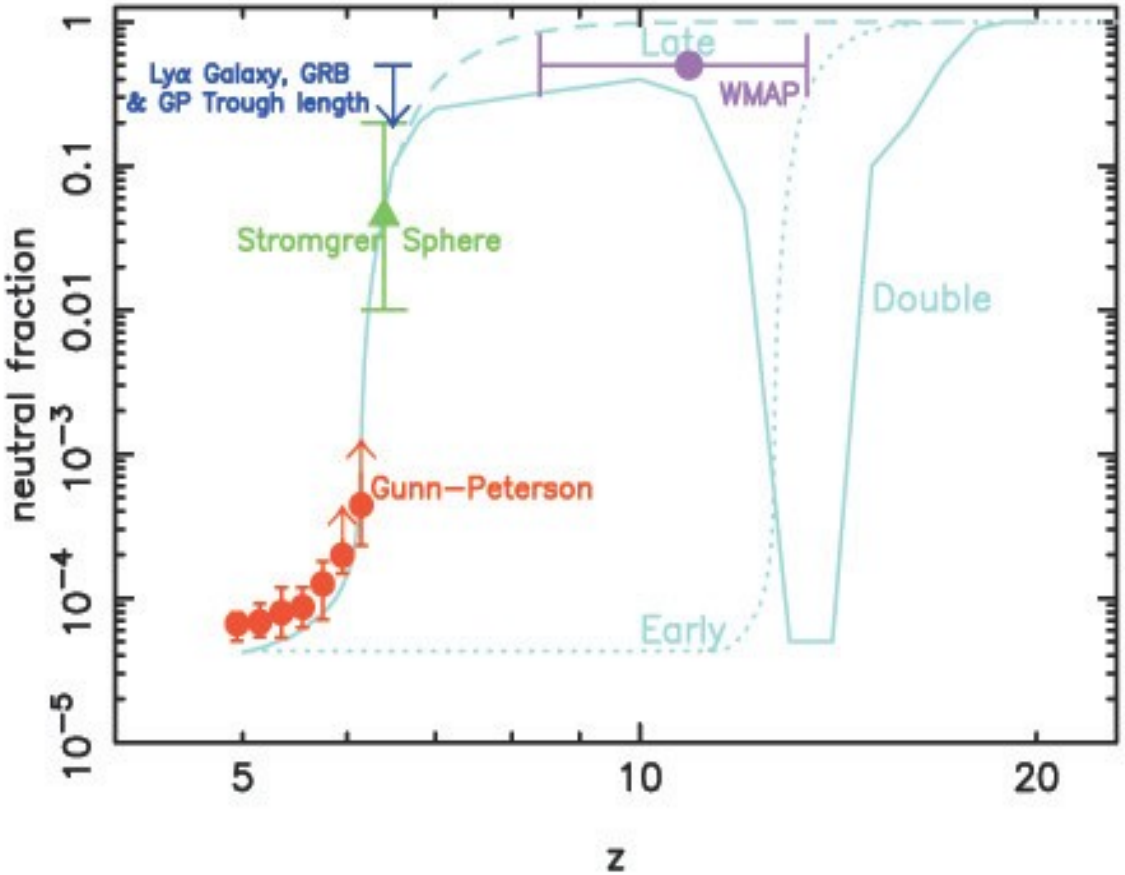
+ Where and when did the first objects form?
+ When did the first galaxies emerge, and what were they like?
+ How did these first objects reionize the universe?

Discovery area: the Epoch of Reionization.

Question 4: Motivation



molecular/atomic/ionized



Credits: Bromm et al. (2009); Fan et al. (2006)

Question 4: Next steps from space

Most important

(1) deep (lensing-assisted?) surveys with *JWST*

→ detect He II and Lyα emission from first HII regions

Very important

(1) fast IR spectroscopic followup of large GRB samples

→ identify several dozen $z > 8$ GRBs

(2) near-IR absorption-line spectroscopy with *JWST*

→ physical conditions of IGM at end of reionization

Important

(1) measure CMB E-mode polarization (with *Planck* and ?)

→ independent probe of reionization epoch

Words on laboratory astrophysics

"Theory and Laboratory Astrophysics: the Next Decade"

"Underlying all of astronomy and astrophysics is critical work in theory and other intellectual infrastructure, such as laboratory astrophysics... Laboratory astrophysics is clearly important to understanding galaxies, black holes, and clusters across cosmic time... Although the lack of laboratory measurements may not today be a limiting factor in the studies outlined earlier in this report, it may well become the limiting factor as the data improve."

Called out as lab astro priorities

+ details of absorption by dust

+ cross sections for hot gas cooler than 4 million degrees

+ recombination rates that determine ionization equilibria

+ spectral features at millimeter to infrared wavelengths

Not characterized as an exclusive list.

Called out as "theory" priorities

Note WGLA white paper: "comprises both theoretical and experimental studies of the underlying physics..."

+ gas flows: physics of two-phase interfaces/instabilities due to gas moving through ambient media with very different temperatures and/or densities

+ feedback: simulations of MHD turbulence that accurately handle viscosity and conduction

+ plasma physics: magnetic reconnection, particle acceleration, cosmic ray transport

+ radiative processes: interaction with clumpy gas; jet/disk models with nonthermal, hydrodynamic elements

GCT report vs. AJB interpretation...

GCT programs without missions

Most important

(Q1) *HST*-resolution lensing studies of very large samples

Very important

(Q2) spectral mapping and high-resolution spectroscopy in UV, with sensitivity of a ~4m space telescope

(but: slated for technology development by main report!)

(Q3) wide-field hard X-ray survey

Missions with GCT programs

Stronger spectroscopic component

⇔ greater laboratory astrophysics relevance.

***JWST*: key spectroscopic science (Q4) driven by S/N of detection rather than precision, so relevance limited**

***SPICA:* possible US involvement through BLISS, but (as for *Herschel*) most GCT science (Q2) will be empirical**

***LISA*: no obvious lab astro relevance**

***IXO*: hugely relevant (Q1, Q2, Q3); in the next decade, we can "retire risk" on interpretation as well as technology**

Summary

GCT report identified four key questions – on cosmic structures, baryon cycling, black holes, and first light/ reionization – and prioritized observational programs to address them (not all of which were adopted).

Explicitly, laboratory astrophysics received a positive but general endorsement. Implicitly, extensive sub-grid physics "theory" priorities define a very strong case.

NASA spectroscopic missions (*IXO* and *UVST* more than *JWST* and *SPICA*) can retire risk to technology and interpretation over the next decade.

Thanks to GCT panelists

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