The far frontier and outstanding challenges

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The far frontier and outstanding challenges

1. The importance of AGN outflows and how they are driven
2. The epoch of reionization
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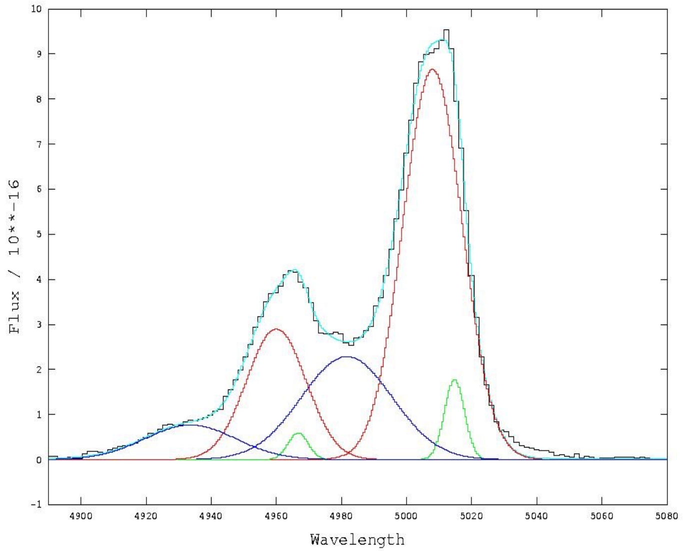
The impact of the AGN activity on the host galaxy evolution

The observational evidence for AGN feedback: summary

- Jet mode feedback (associated with the expanding relativistic jets and lobes of radio sources). There is now convincing evidence that the feedback effect associated with the jets and lobes of radio galaxies and quasars has a substantial effect on the cooling of the gas in the hot X-ray haloes.
- Quasar mode feedback (associated with broad winds driven by the AGN close to the nucleus). Although there is now plenty of evidence from absorption and emission line studies that AGN drive near-nuclear outflows, it is not clear that these outflows are as powerful as required by the evolutionary models.

Quantifying quasar mode feedback



For a spherical outflow, mass outflow rates and kinetic powers in the outflows given by:

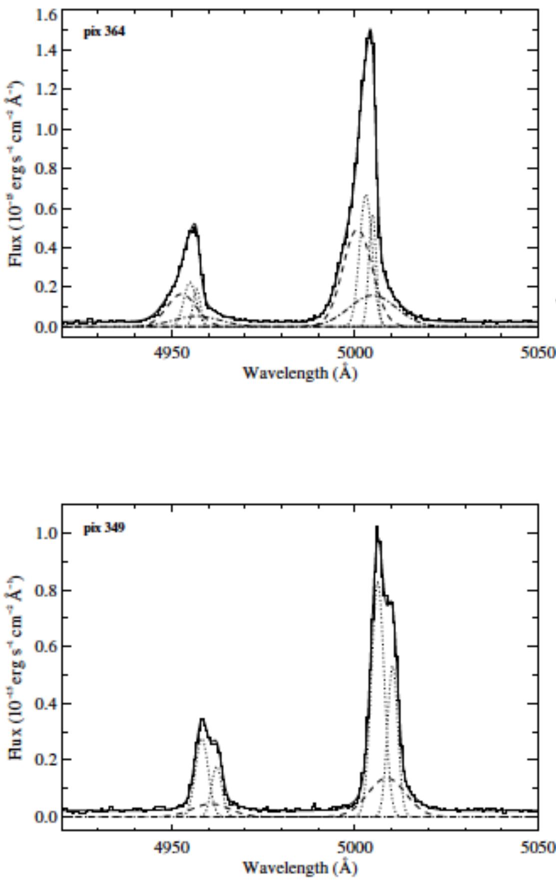
$$\dot{M} = \frac{3L(H\beta)m_p v_{out}}{N\alpha^{eff}_{H\beta} h\nu_{H\beta} r} \propto \frac{L(H\beta)v_{out}}{Nr}$$

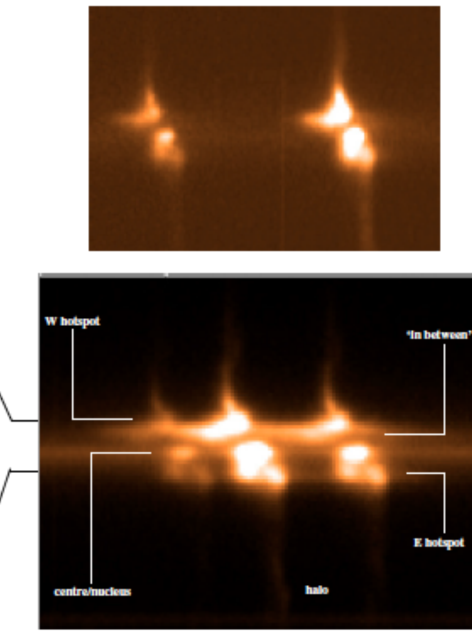
$$\dot{E} \propto \frac{\dot{M}}{2}(v^2_{out} + (FWHM)^2/2)$$

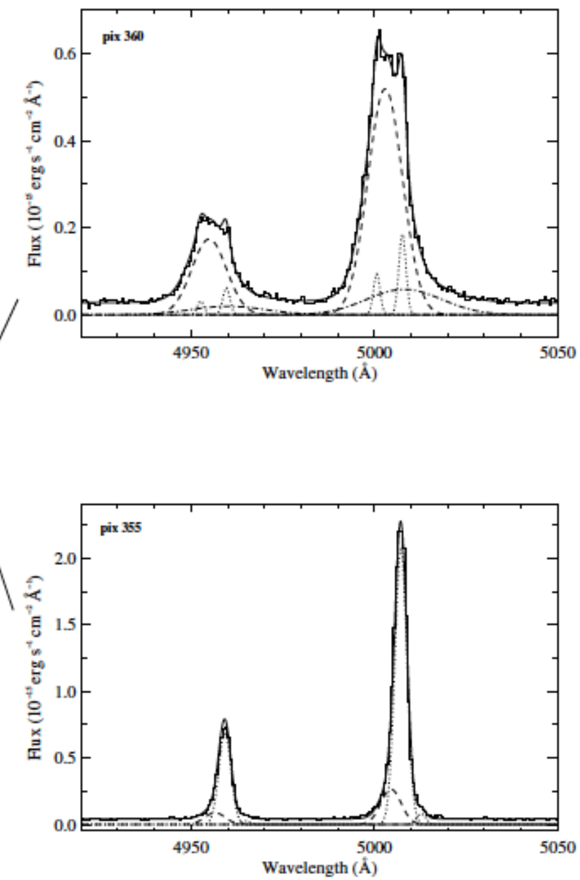
But the Hβ luminosities (*L(H*β*)*) can be difficult to measure accurately because of reddening effects, the radii of the outflows (*r*) are highly uncertain because the outfows are unresolved or poorly resolved, and the gas densities (*N*) are also uncertain because the key diagnostic emission lines (e.g. [SII]6717,6731) are badly blended due to the large line widths.

➔ *The energetic significance of the outflows is often not well quantified.*

Spatially resolved ionized gas ([OIII]) outflow in IC5063 (z=0.011)







Warm gas outflow:

$$\dot{M} \sim 0.08 \ M_{sun} yr^{-1}$$

$$\dot{E} \sim 2 \times 10^{40} \ erg\, s^{-1}$$

$$\dot{E} / L_{bol} \sim 3 \times 10^{-4}$$

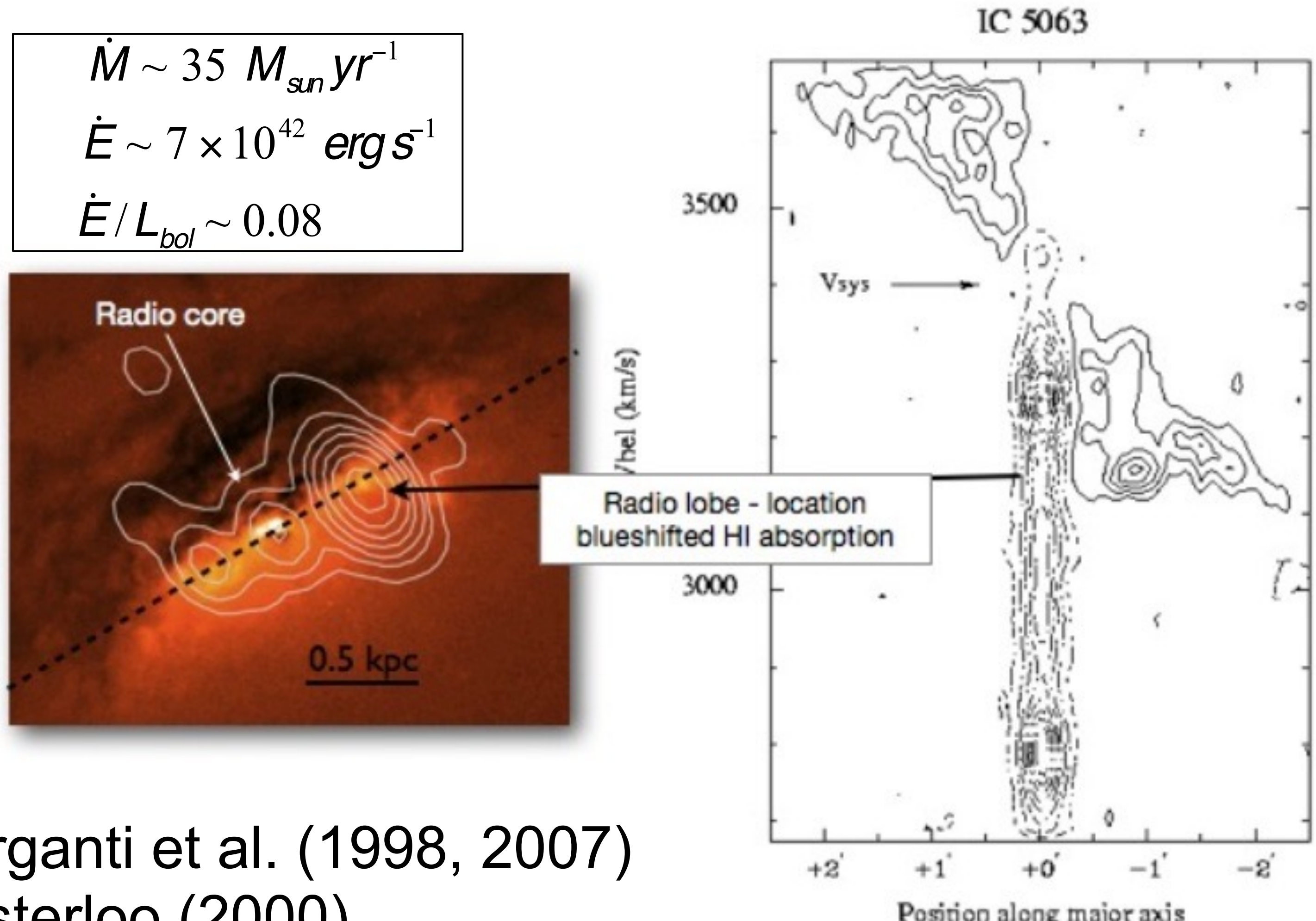
Morganti et al. (2007)

HI 21cm outflow in IC5063

(z=0.011, P_{5GHz} = 3x10^{23} W Hz^{-1})

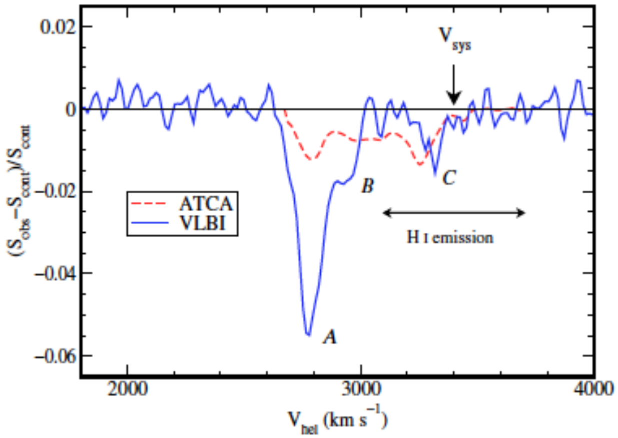
HI Outflow:

$$\dot{M} \sim 35 \ M_{sun} \, yr^{-1}$$
$$\dot{E} \sim 7 \times 10^{42} \ erg \, s^{-1}$$
$$\dot{E} / L_{bol} \sim 0.08$$

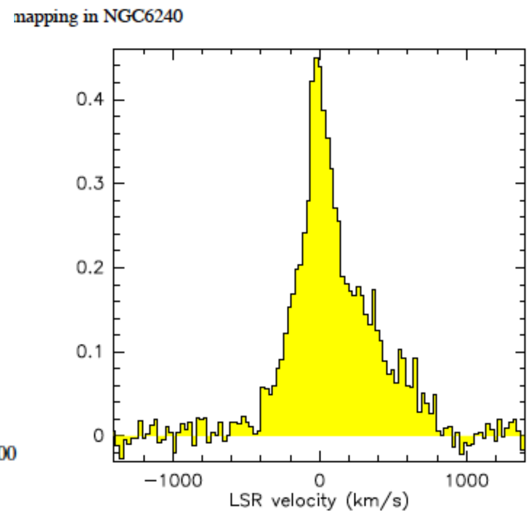


Morganti et al. (1998, 2007)
Oosterloo (2000)

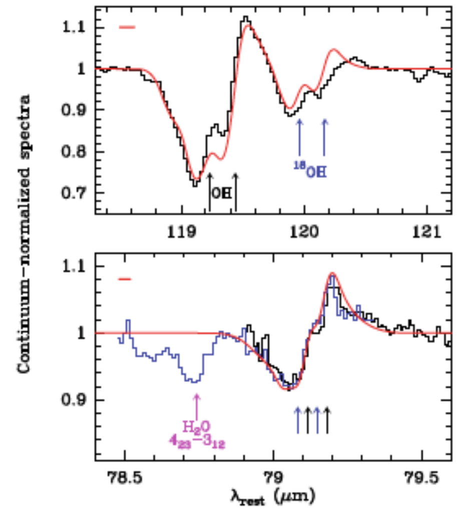
Neutral and molecular outflows in AGN



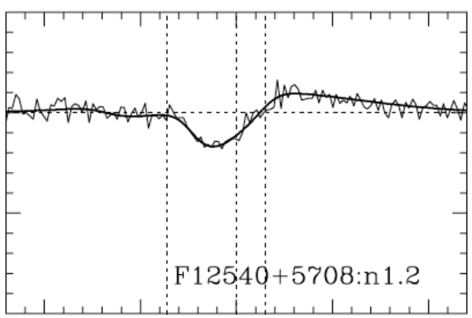
Neutral: HI 21cm
Morganti et al. (1998, 2005)



Molecular: CO
e.g. Feruglio et al. (2010 2013), Cicone et al. (2013)



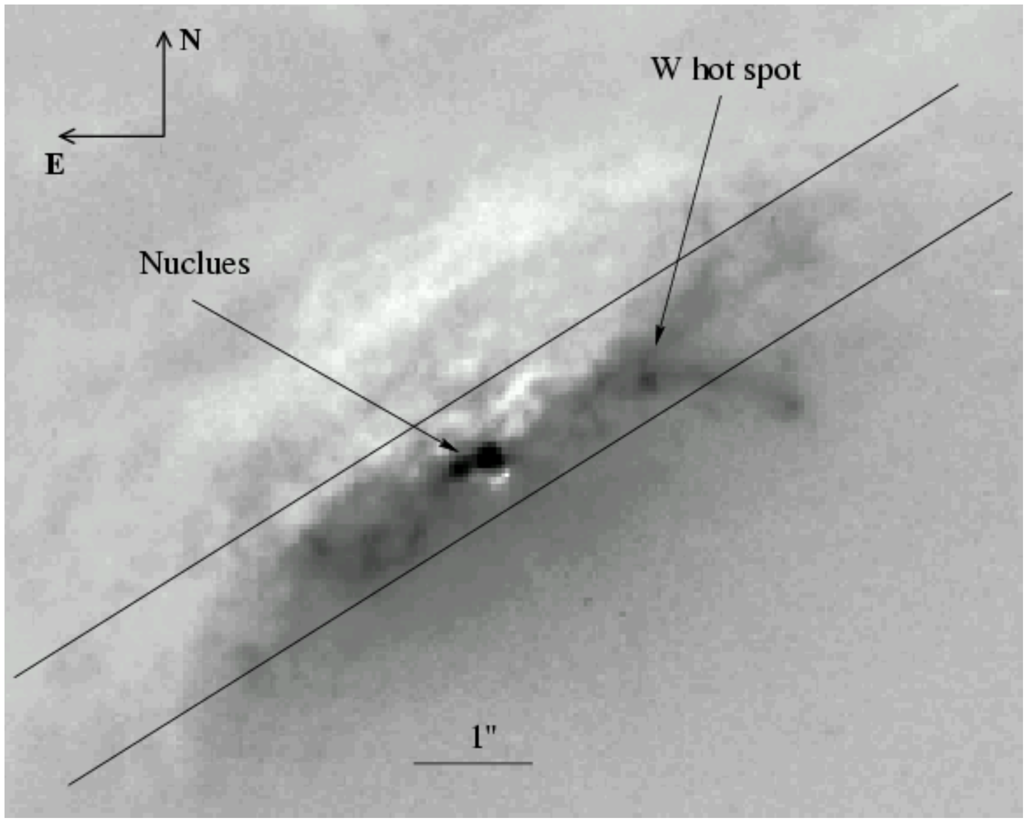
Molecular: OH
Fisher et al. (2010), Veilleux et al. (2013)



Neutral: NaID
Rupke et al. (2005)

Broad wings detected up to 1,000s km/s in neutral and molecular gas in some AGN; the associated outflows are often more massive and energetic than the ionized gas outflows

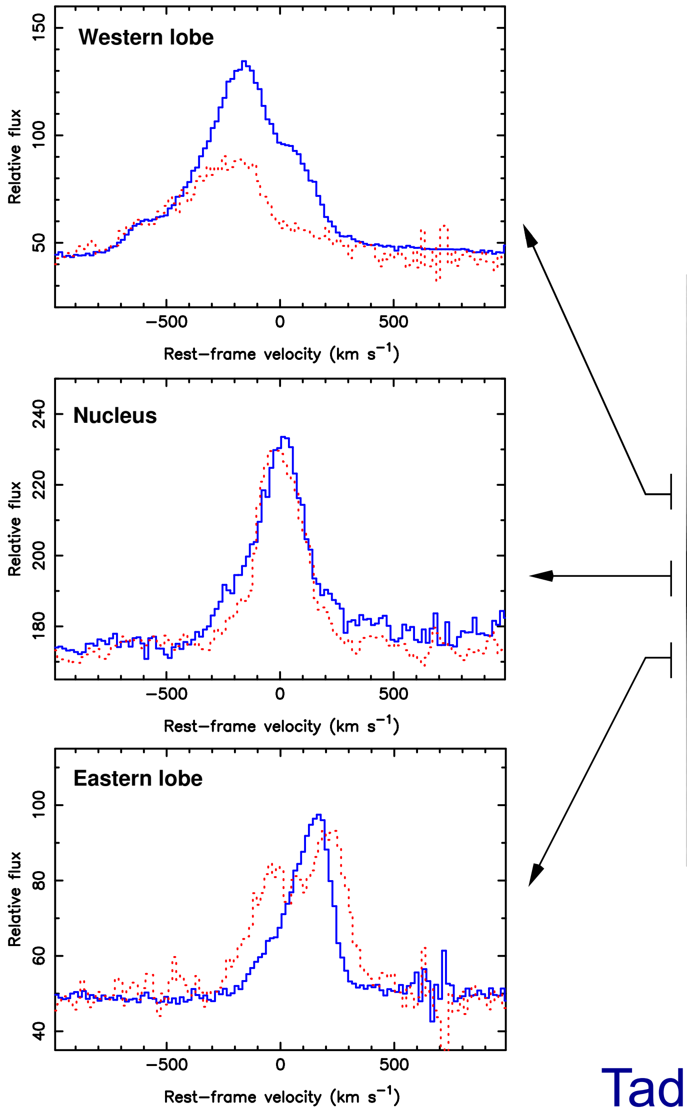
ESO VLT/ISAAC observations of IC5063



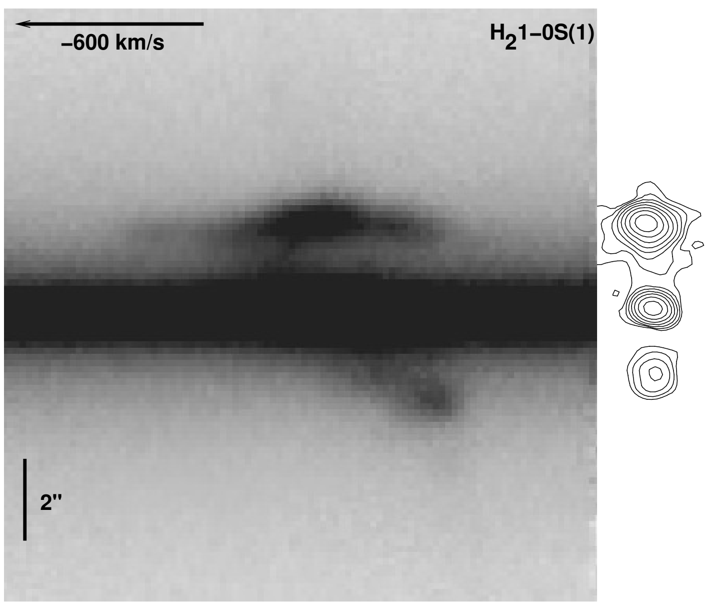
Slit aligned with radio axis

Near-IR (K-band) long-slit spectroscopy of IC5063 covering the H_2 1-0S(1) molecular hydrogen line

Warm molecular outflows in IC5063 I line profiles



VLT/ISAAC long-slit spectrum



Tadhunter et al. , 2014, Nature, 511, 440

AGN feedback summary

- Clear evidence from X-ray cavities that jet-mode AGN feedback plays a key role in preventing hot gas from cooling, affecting the shape of the galaxy LF
- Most AGN also show evidence for near-nuclear outflows (quasar mode feedback) in the form of broad, blueshifted emission and absorption features
- Surprisingly, much of the mass of the outflows is carried by molecular and neutral phases of the ISM, rather than highly ionized gas
- But the energetic significance of the quasar mode feedback associated with the near-nuclear outflows is highly uncertain
- More work needs to be done on spatially resolved AGN-driven outflows in the local Universe…

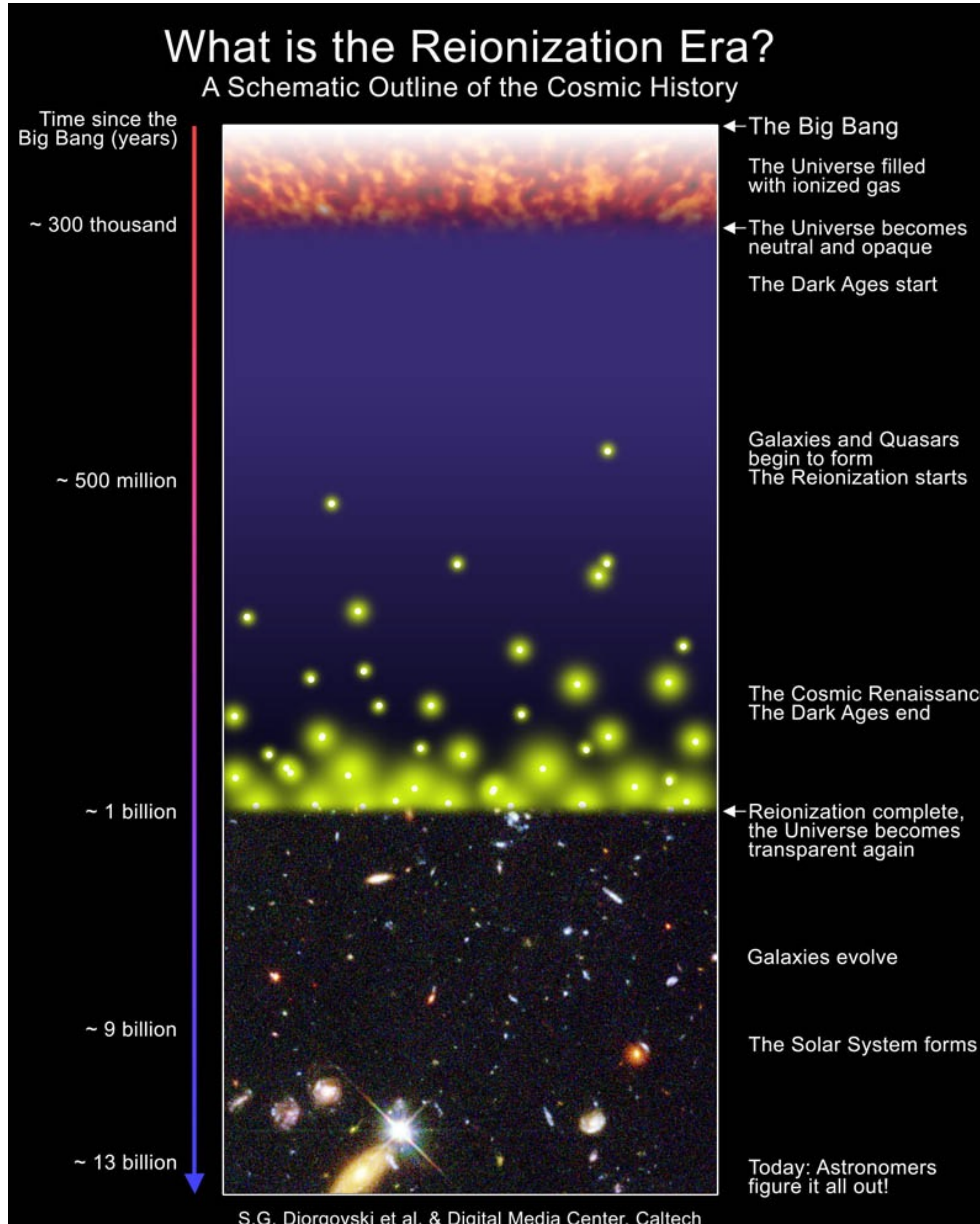
The epoch of reionization: a probe of galaxy evolution in the early Universe (<1 Gyr)

Reionization

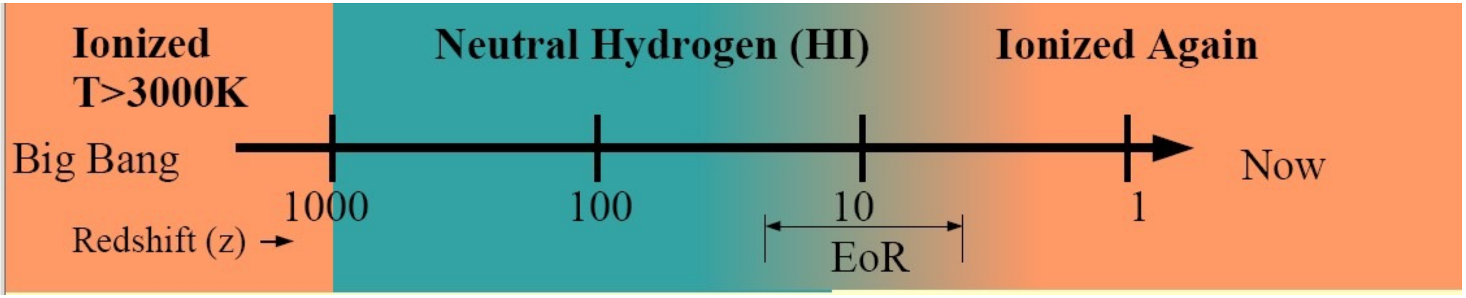
300,000 years after the big bang the gas had cooled sufficiently for it to become neutral (*epoch of recombination*).

Eventually, sufficient quasars and massive stars were formed to re-ionize the gas (*epoch of reionization*).

Information about the epoch of reionization (e.g. the exact redshift range over which it occurred) can be used to test models of galaxy evolution in the very early Universe.



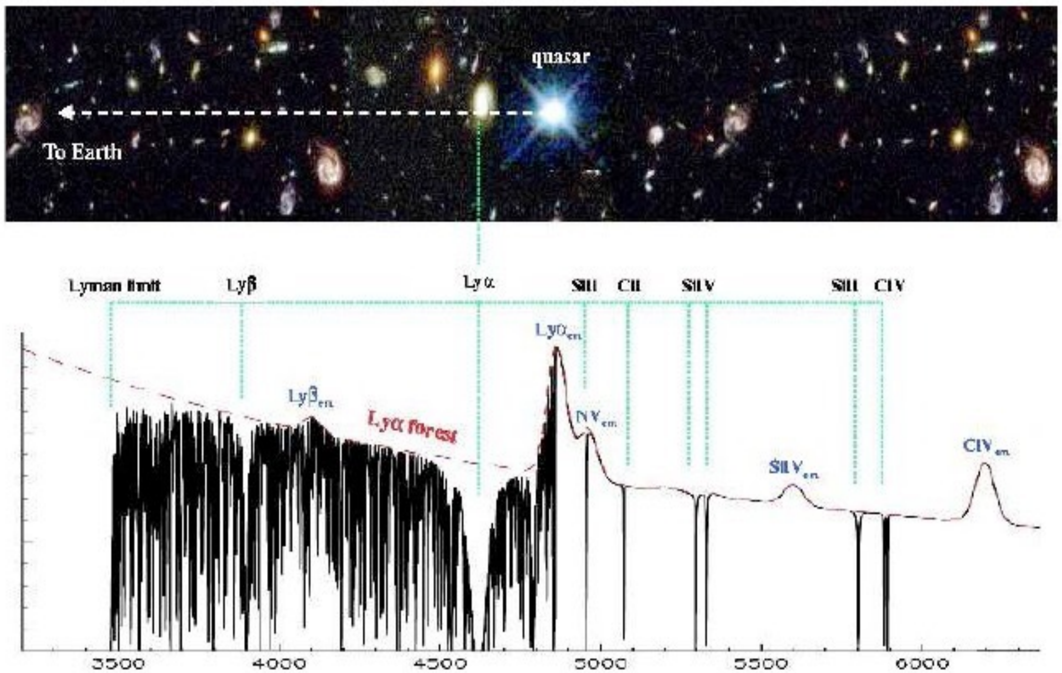
Investigating the epoch of reionization



Prior to the epoch of reionization, space was permeated by a continous, neutral medium consisting mainly of neutral hydrogen. This medium absorbed strongly in the Lya transition of hydrogen. Any bright background source (e.g. quasar) formed prior to the epoch of reionization would be expected to show a deep absorption trough covering the redshift range from redshift of the source to the redshift corresponding to full reionization. This is known as the *Gunn-Peterson effect*.

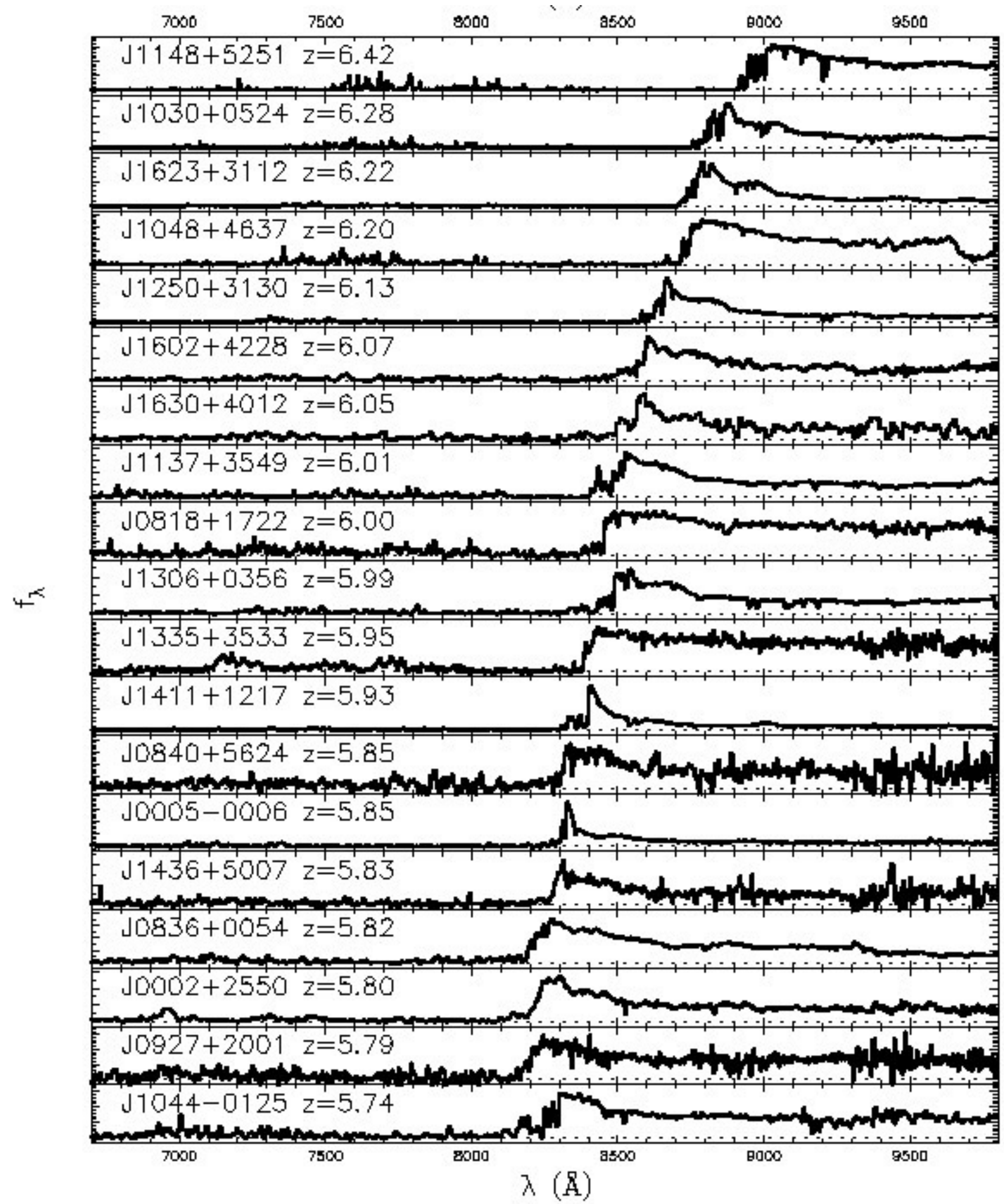
Detecting the epoch of reionization with quasar absorption lines

Spectrum of high-z quasar



We already see the absorbing effect of all the gas clouds between us and a distant quasar in the *Lyman Forest*. It is well-established that the absorbing effect of the Lyman forest increases towards high redshift, but the Gunn Peterson effect will cause a deeper, more continuous trough.

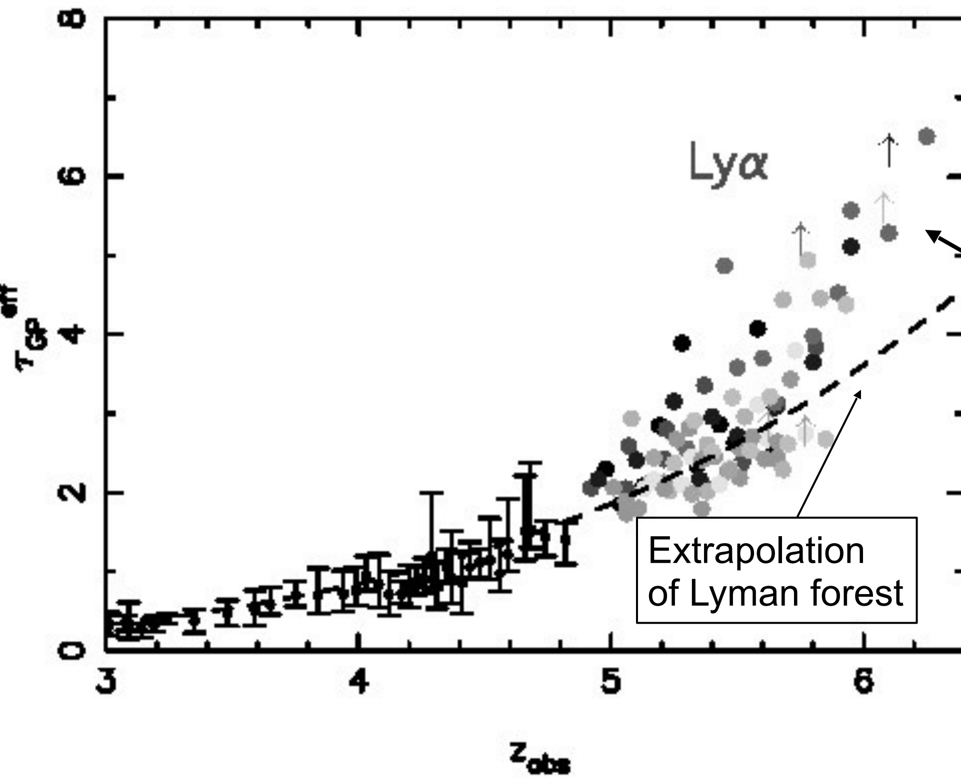
Detection of the Gunn Peterson effect in the most distant quasars? - I.



The depth of the absorption on short wavelength side of the Lyα emission line appears to increase rapidly at the highest redshifts -- faster than expected from the extrapolated evolution in the Lyman forest.

Detection of the Gunn Peterson effect in the most distant quasars? - II.

Absorption optical depth below the Lyα line.



Extrapolation of Lyman forest

Rapid increase in absorption depth below the Lyα line, at z > 6 may mark the end of the epoch of reionization, and the detection of the Gunn Peterson effect.

The absorption optical depth is determined using the ratio of the measured to the expected continuum flux below Lyα.

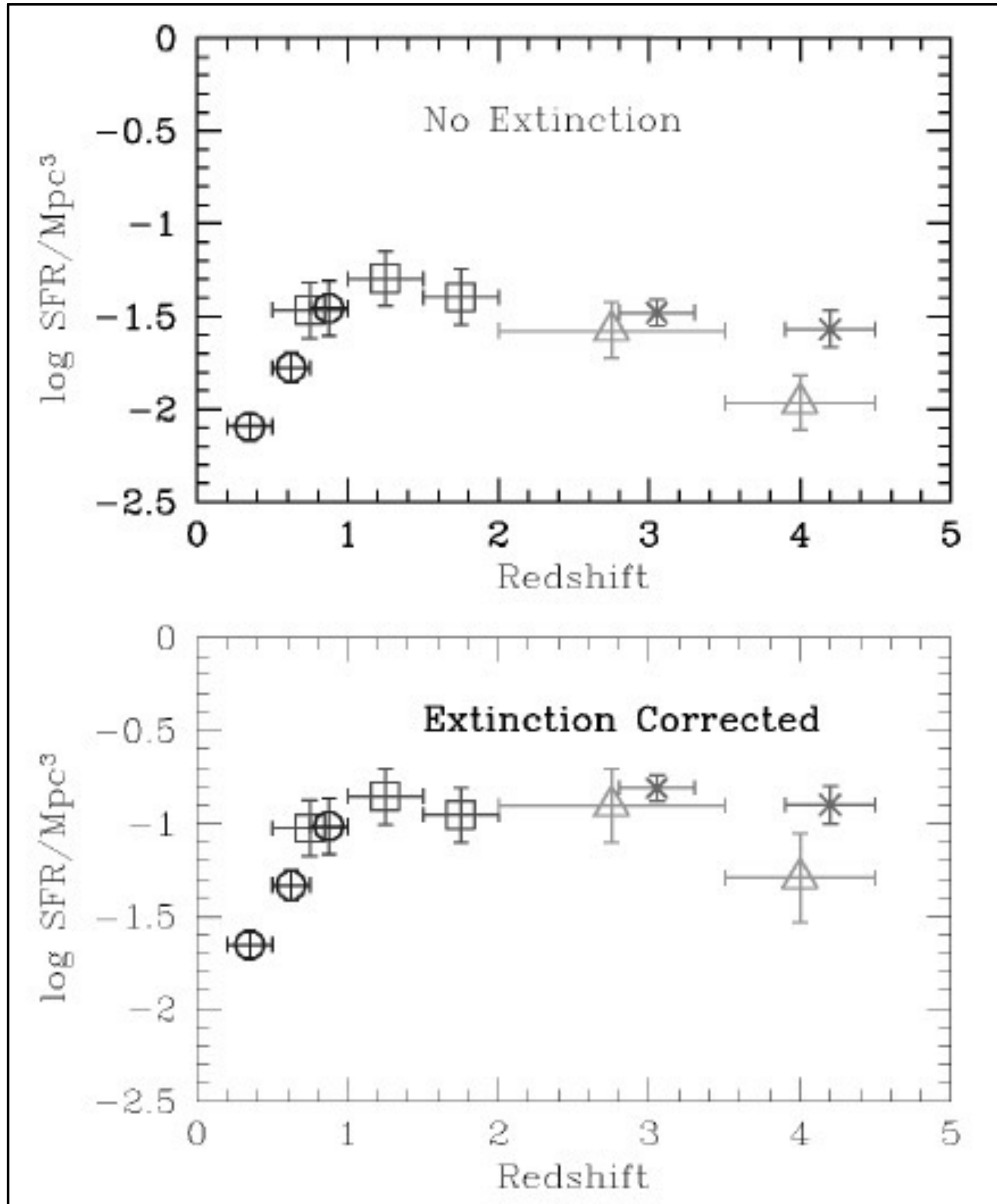
Summary of results on epoch of reionization

- Close examination of the spectra of distant quasars shows a rapid increase in absorption depth below Lyα at $z > 6$ that is much faster than expected on the basis of of the extrapolation of the Lyman forest absorption.
- This may mark the epoch of reionization (or the end of it), and the detection of the Gunn Peterson effect.
- But the statistics are relatively poor (few known quasars at $z>6$) and there is considerable scatter in the absorption optical depth at all redshifts $z>5$, suggesting patchy obscuration in the neutral obscuring medium.
- Clearly, more observations are required to confirm that the effect is real, and to measure the structure of the absorption.

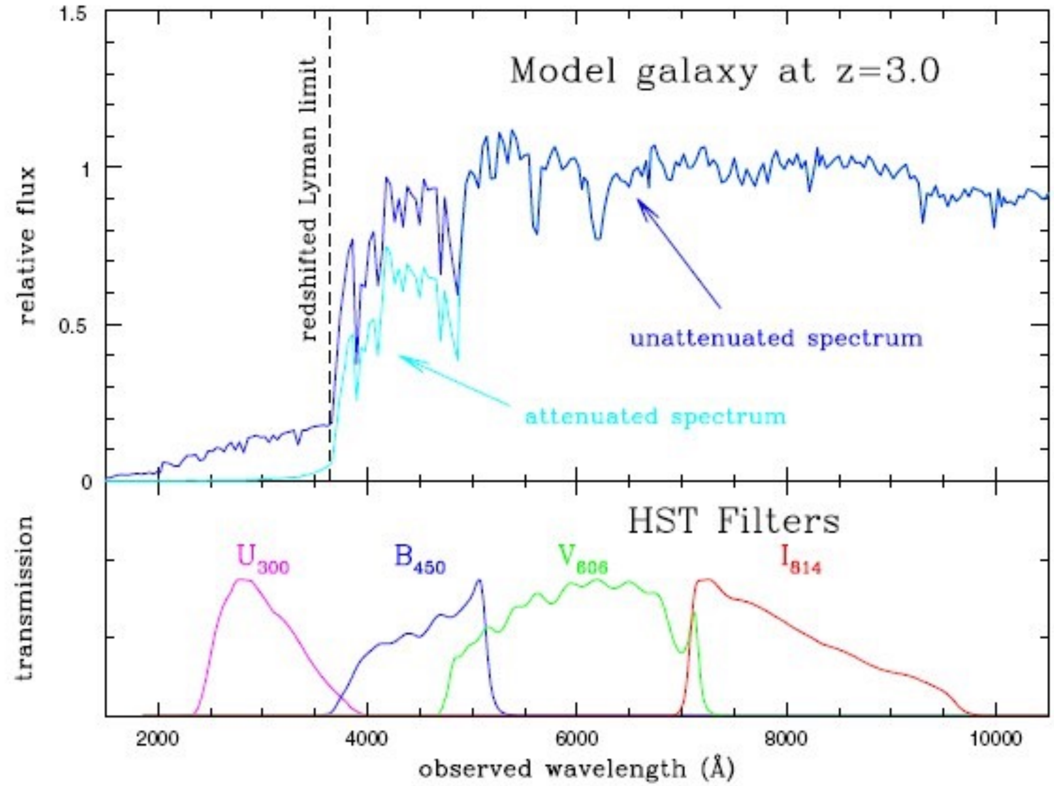
Pushing the redshift limit: star formation in the early Universe

Madau diagram revisited

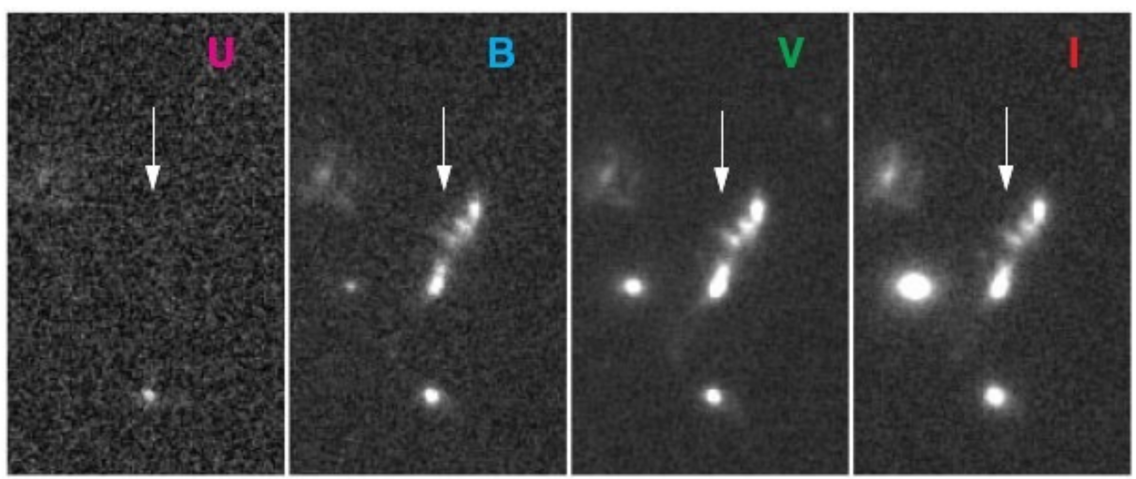
How far (in redshift) can we push the study of the star formation history of the Universe?



Redshifts of distant galaxies: example of U-band dropout

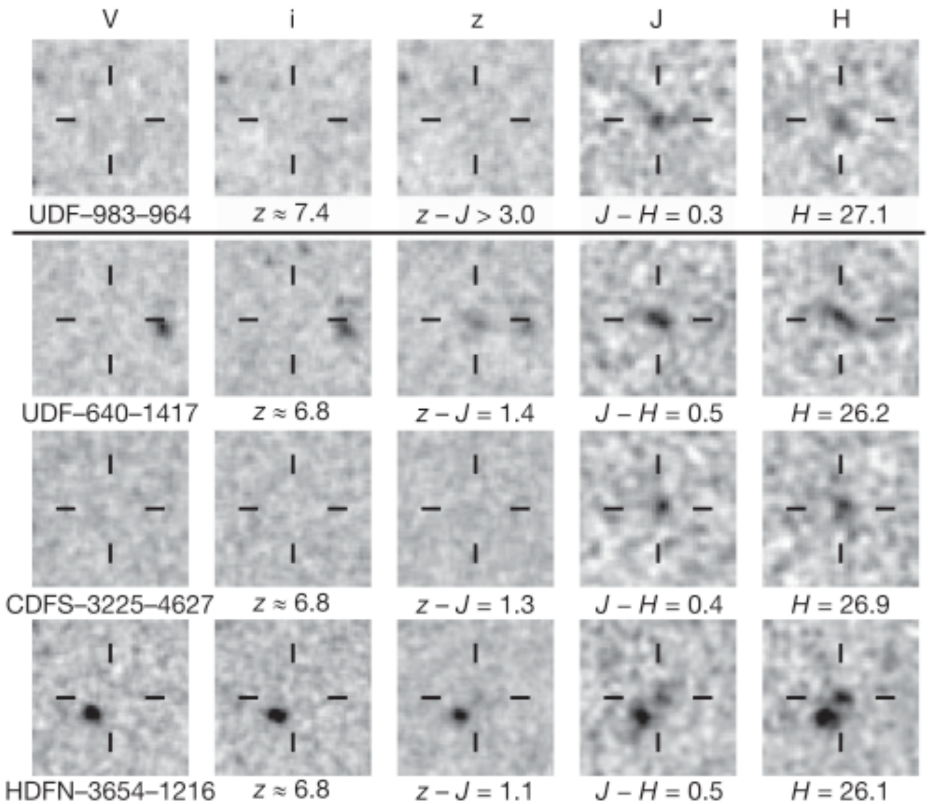


The Lyman dropout technique can be used to detect, and measure redshifts for galaxies that are too faint for conventional spectroscopy.

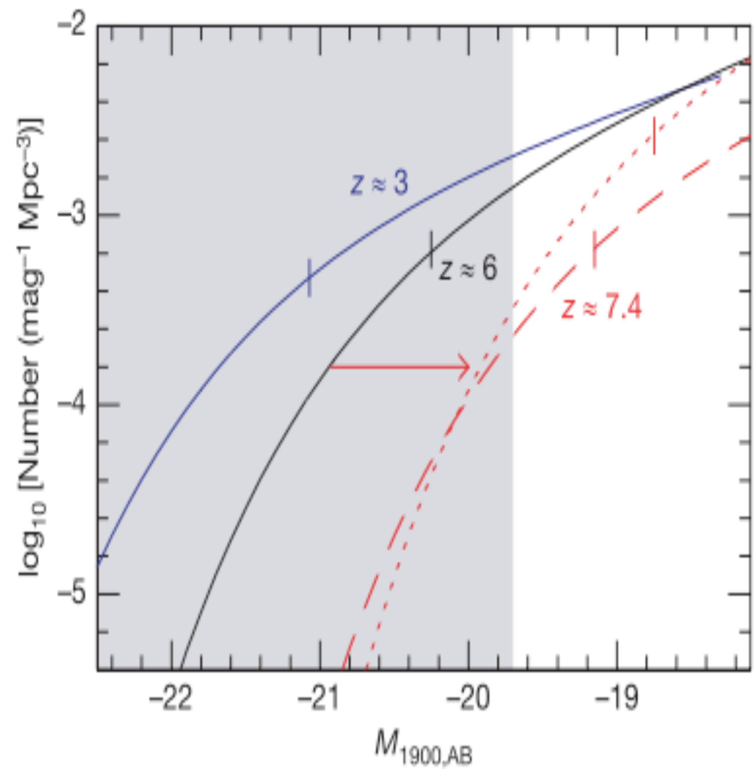


Pushing the redshift limit: galaxies at z~7 Bouwens et al. (2006) near-IR dropouts

z-band dropout candidates



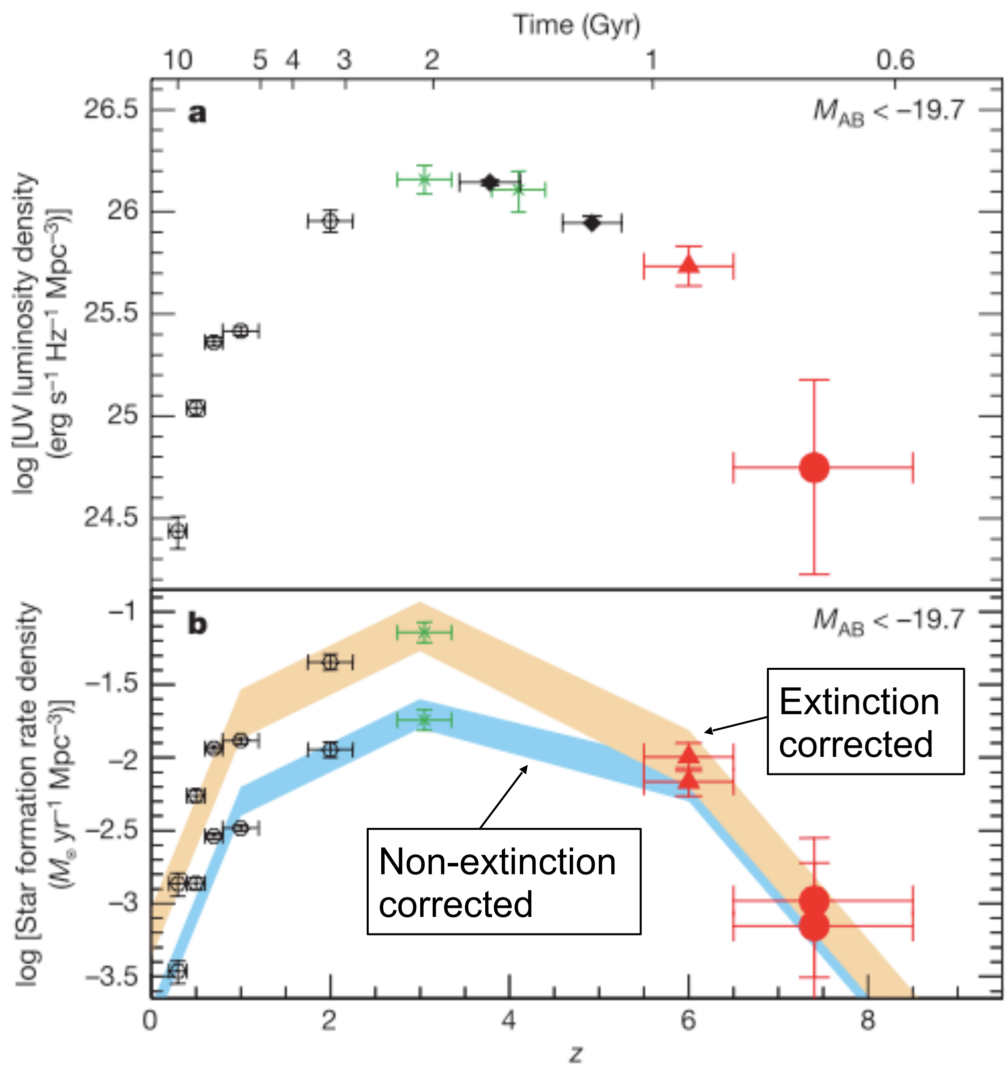
Luminosity functions



The detection of only four z-band dropouts in the wide field HST optical/IR imaging study of Bouwens et al. (2006), provides evidence for a substantial evolution in the luminosity function from z~6 to z~7.

Pushing the redshift limit: galaxies at z~7
Bouwens et al. (2006) SFR

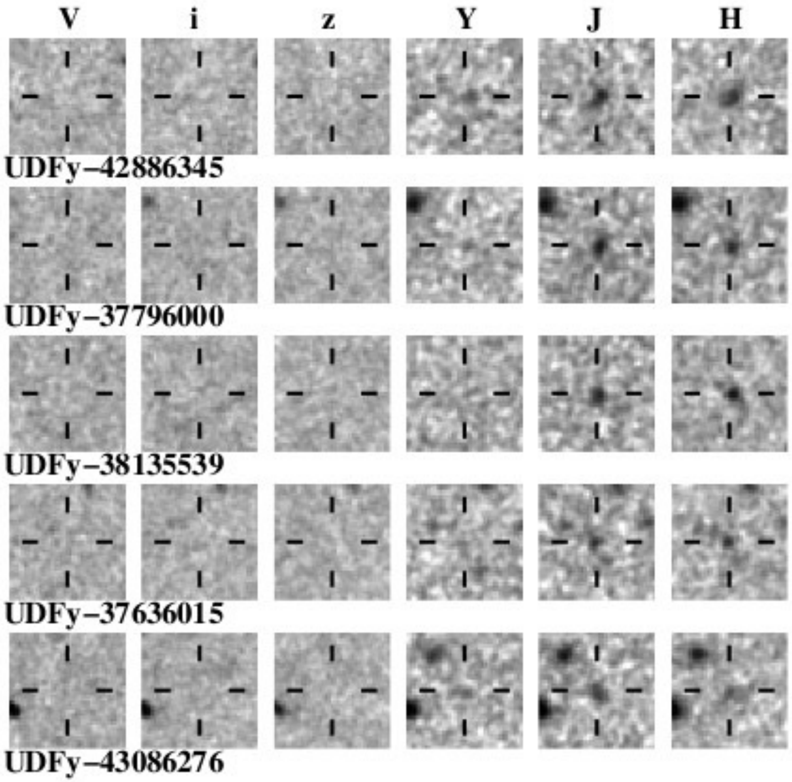
Based on the relatively small number of detections in the deep optical/IR survey of Bouwens et al. (2006), there appears to be a significant drop in both the UV luminosity density (top) and the star formation density (bottom) at z>6.5.

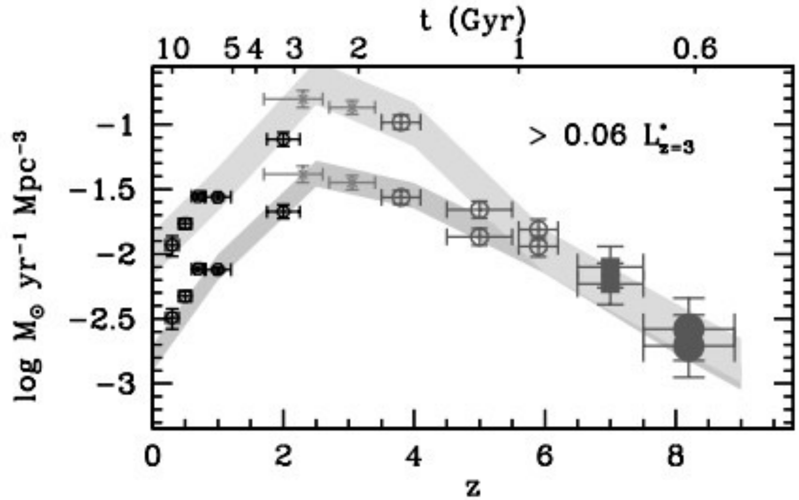


Summary of results for z~7 galaxies

- At z~7 we sample the Universe when it was only 0.75 Gyr old.
- Using the Lyman dropout technique at red optical/near-IR wavelengths a total of six z~7 candidates were detected by 2006 (with one spectroscopic confirmation).
- The relatively small number of z~7 candidates in deep, wide-field surveys provides evidence for a significant fall-off in the star formation density at z>6.5.
- But sample incompleteness may be a significant issue at such faint limits, and there remain the usual issues to do with the degree of reddening correction etc.
- The apparent fall off in star formation at may be due either to a decrease in the number of forming galaxies, or an increase in the absorption by the ISM at high redshifts.

Even further...z~8



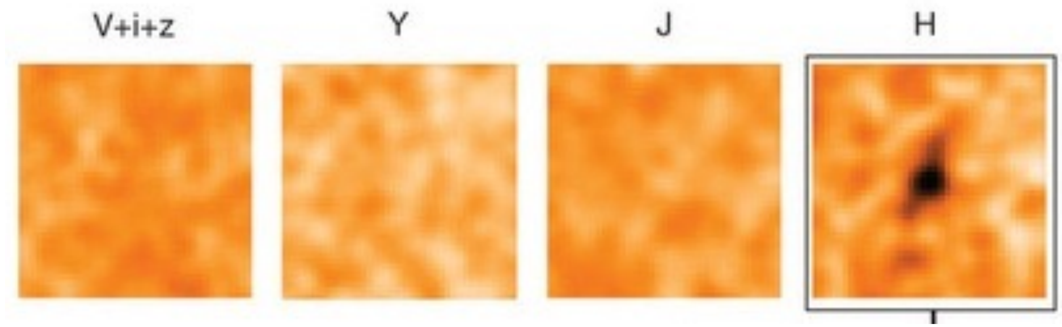


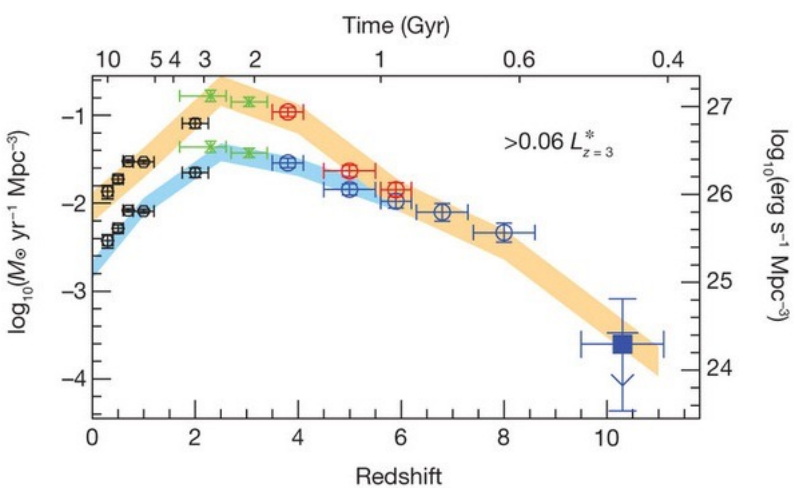
Bouwens et al. (2009)

Using the refurbished HST (with enhanced near-IR wide field capabilities) candidate galaxies were detected out to z~8, using Y-band dropouts (but none spectroscopically confirmed…).

Further still…z~10

J-band drop out: z~10



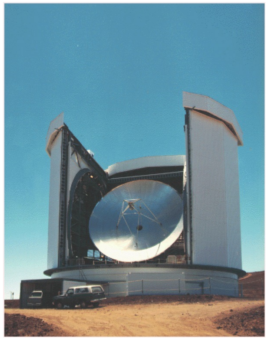


Bouwens et al. (2011)

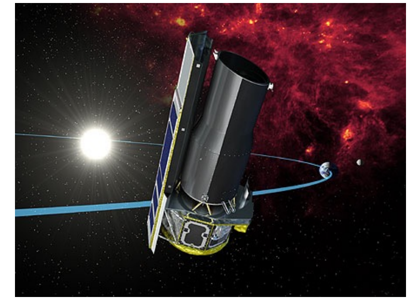
Far fewer galaxies detected at z~10 than predicted by extrapolation of z~7 - 8 results. The detected high-z galaxies can provide only ~12% of the UV flux required to reionize the Universe

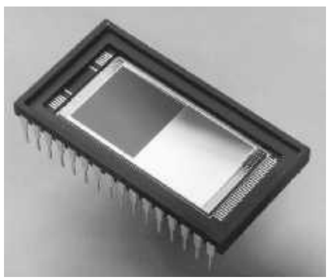
Course summary and outstanding challenges

We have the technology...


JCMT

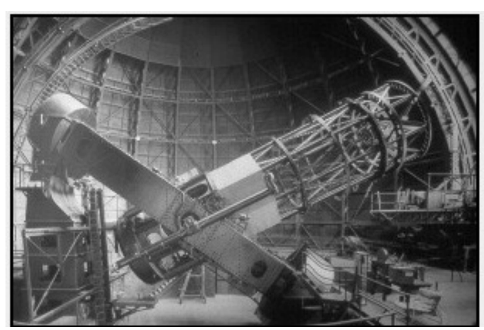

VLA

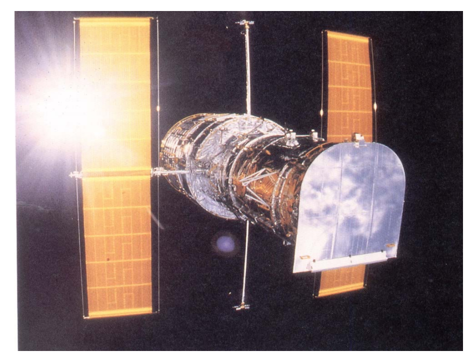

Spitzer


CCDs

Technology has played a key role in driving our improved understanding of galaxy evolution over the last 100 years.


Keck 10m


100” Mount Wilson


HST

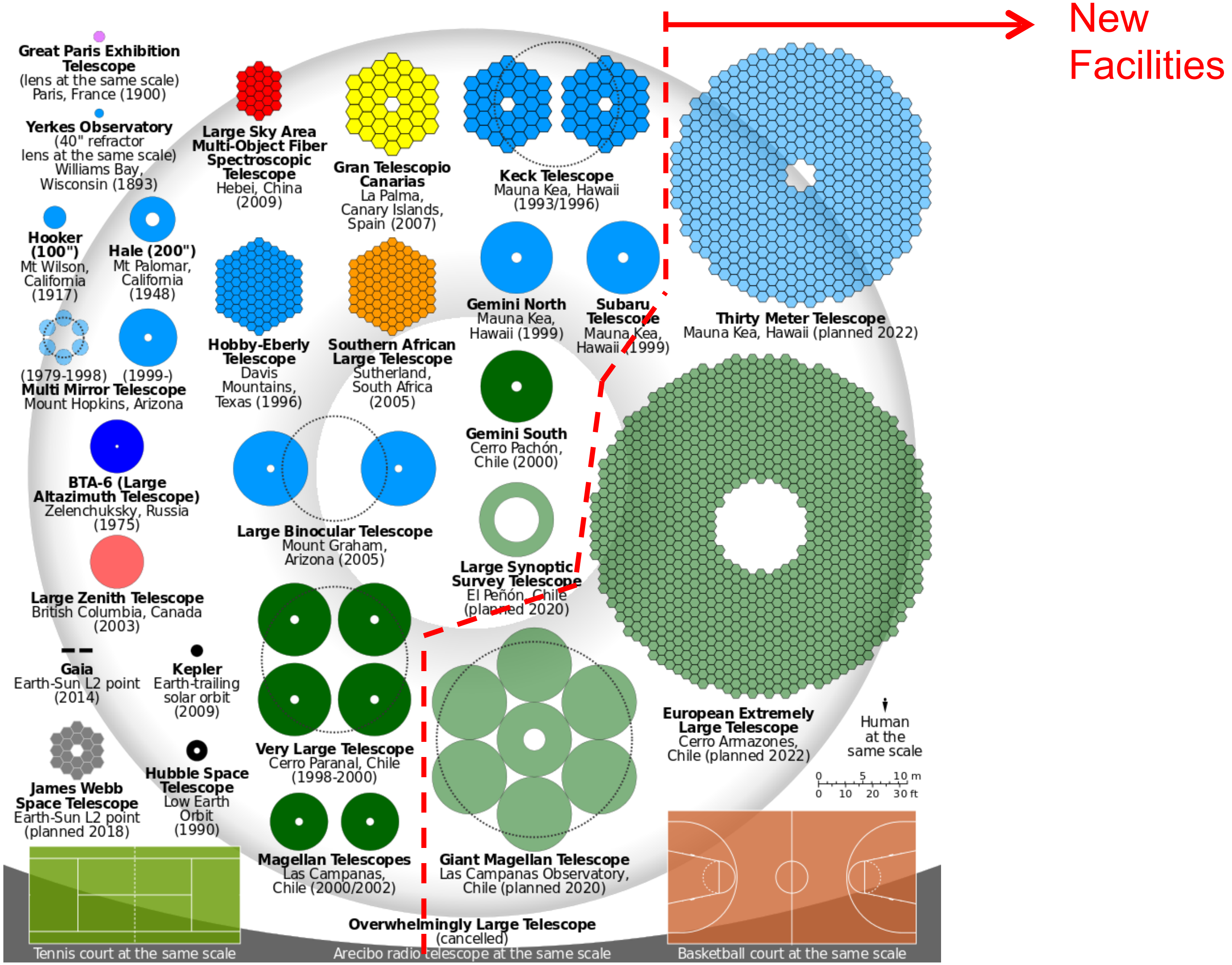
Galaxy evolution: what have we learnt?

- There is evidence for substantial evolution in galaxy morphologies and star formation density from z~0 to z~1; most of this evolution appears to have taken place in intermediate mass galaxies that are destined to form the Spiral galaxies observed in the local Universe.
- The most massive early-type galaxies were in place at z>3 and have shown little evolution since z~1; but early-type galaxies of intermediate/low mass have shown substantial evolution since z~1, perhaps forming via major gas-rich mergers (c.f. ULIRGs).
- The star formation density appears to show a slow decline between z~3 and z~8, with a steeper drop at z>8.
- Much of the star formation in the Universe is hidden by dust and, at high redshifts, more than 50% of the star formation density is associated with 24μm-selected and SMG galaxies.
- AGN are intimately linked to the evolution of their host galaxies: they are triggered as galaxies accrete gas as part of their evolution; they also drive massive outflows that directly affect the star formation histories of the hosts.

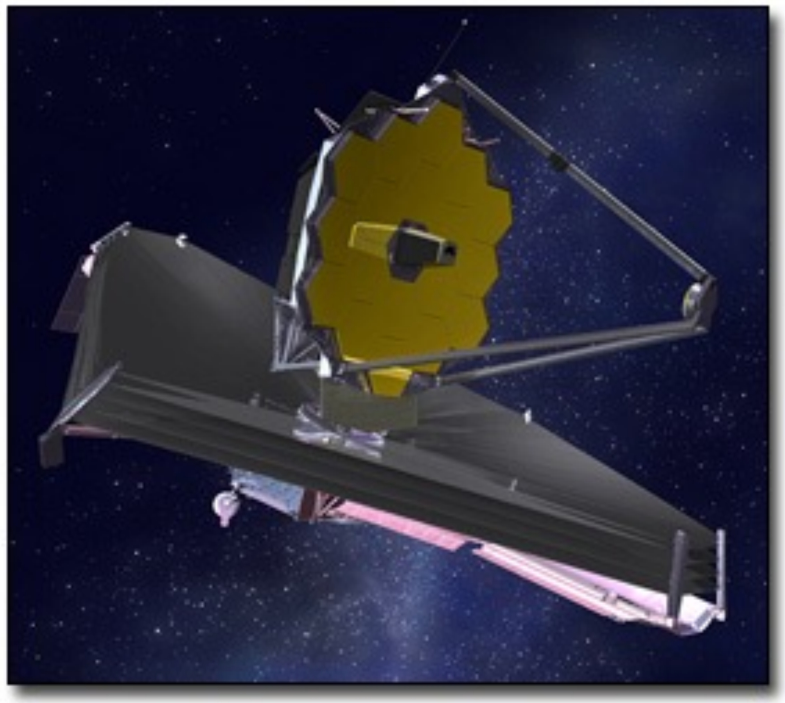
Outstanding challenges

- How are the various populations of high-z galaxies related (LBG, ERO, SMG, 24μm-selected etc.)?
- What do the LBG, SMG etc. become in the local Universe?
- Where are the high mass early-type galaxies forming in the distant Universe ($z > 3$)?
- How do we reconcile cosmic downsizing with hierarchical galaxy evolution models?
- Just how important are AGN outflows in affecting the evolution of galaxies?
- What is the redshift range of the epoch of reionization?

Upcoming facilities I
Large optical/IR telescopes



Upcoming facilities – II
James Web Space Telescope (JWST)



- 6m mirror
- Launch: 2018
- Optical to mid-IR

The JWST will be able to detect and image at high resolution the redshifted optical/near-IR light of the most distant galaxies.

Upcoming facilities III
The square kilometer array (SKA)

Consisting of 1000's of dishes and antennae, the SKA (total collecting area ~1 km^2) will be ~50x more sensitive that existing radio facilities and capable of detecting the radio emission of starburst galaxies at the highest redshifts.

Edwin Hubble

(1889 - 1953)

"At the last dim horizon, we search among the ghostly errors of observations for landmarks that are scarcely more substantial. The search will continue. The urge is older than history. It is not satisfied and it will not be oppressed"