The (co-)evolution of galaxies and Active Galactic Nuclei

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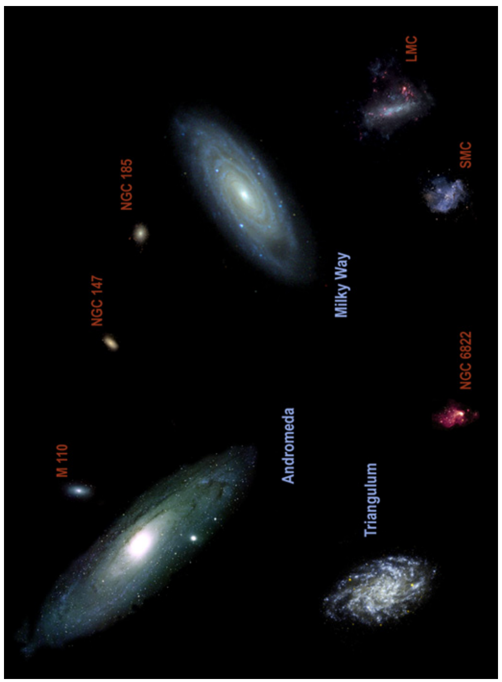
Outline

- Historical review of studies on the star-formation history of the Universe: from the 90s to the 21st century
- Paradigm shift in our understanding of galaxy formation: the role of AGN
- AGN/galaxy co-evolution studies: observations and models

How do galaxies form and evolve?

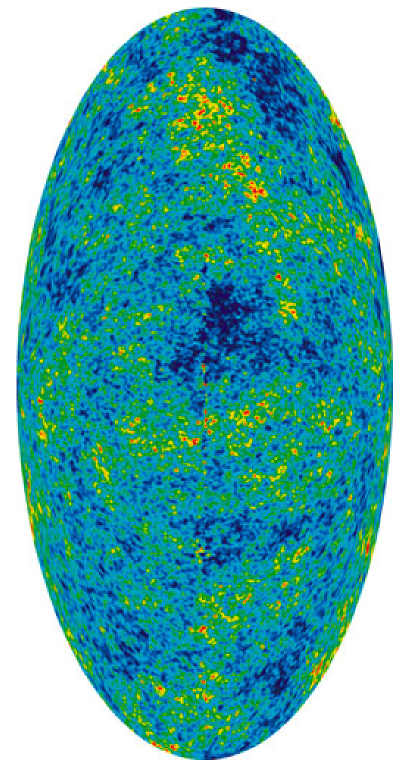
$z=0$



$t=13.7x10^9y$

How?

$z=1000$



$t=0$

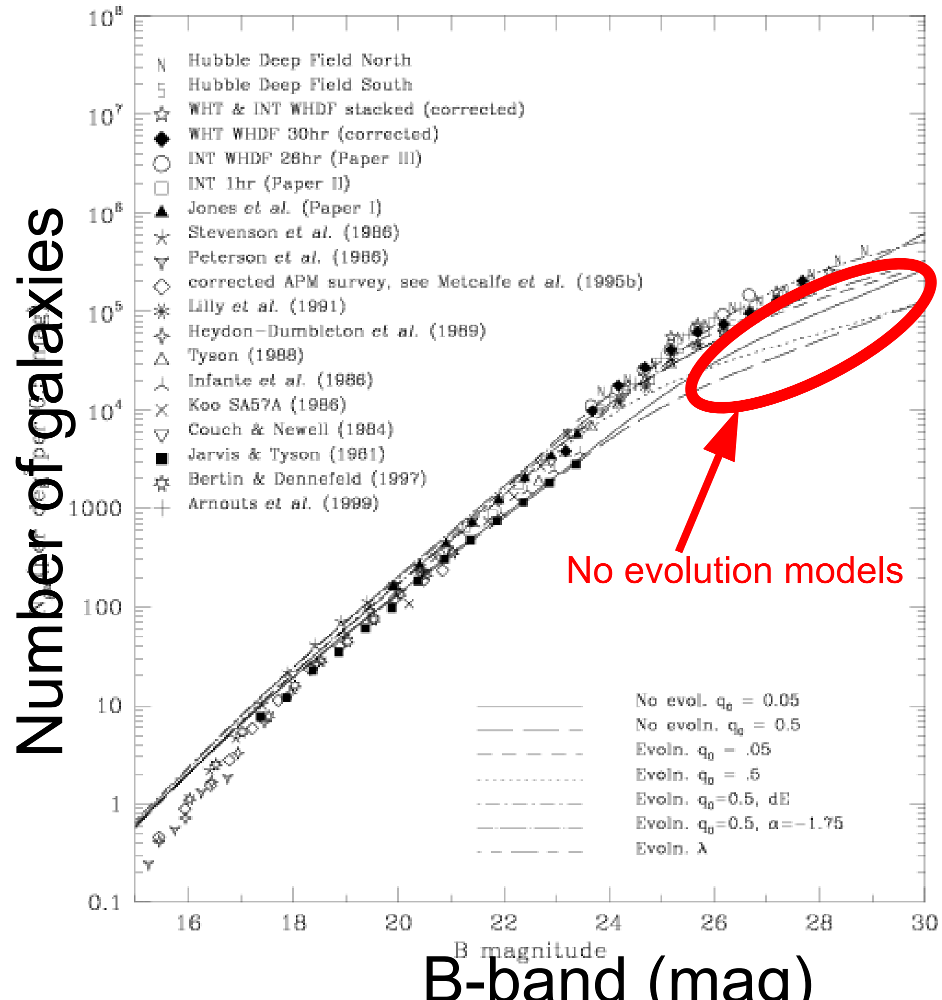
How do galaxies form and evolve?

- Only 5-10% of galaxies host powerful Active Galactic Nuclei at their centres
- Until recently AGN were though as exotic objects with no relevance to galaxy formation/evolution
- Early efforts to understand galaxies focused on their stars, i.e. when and how they were formed.

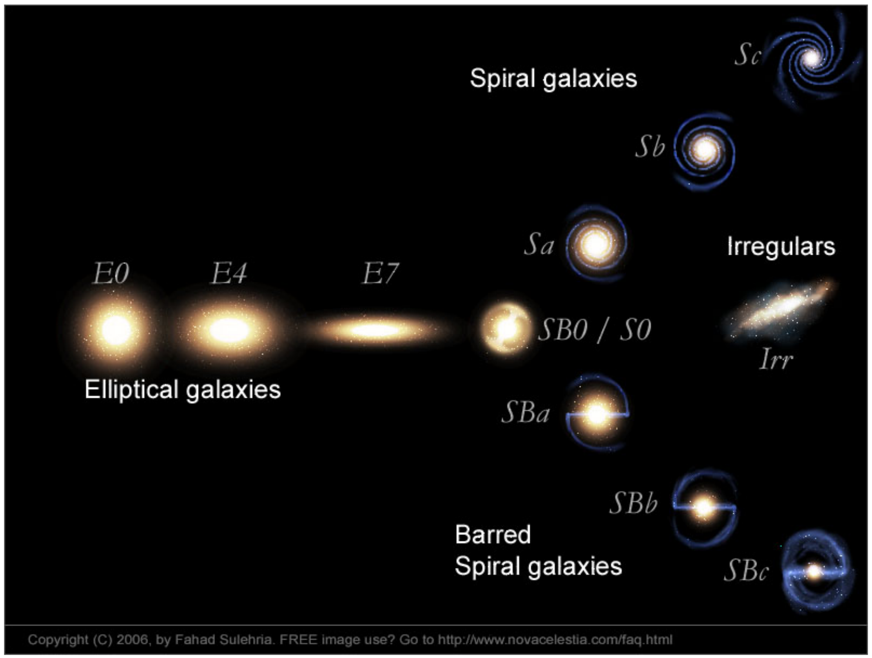
Evolution of the Universe in the 90s

Galaxy number counts:

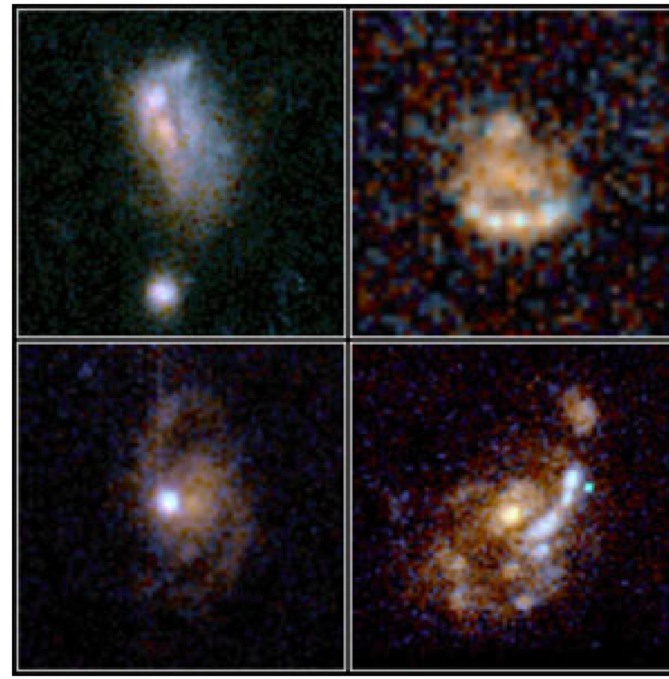
More galaxies at high redshift than at z=0



Evolution of the Universe in the 90s

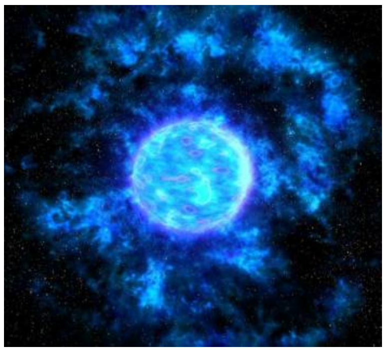


Hubble sequence well defined at z=0. Most galaxies fall into spiral/elliptical classes.



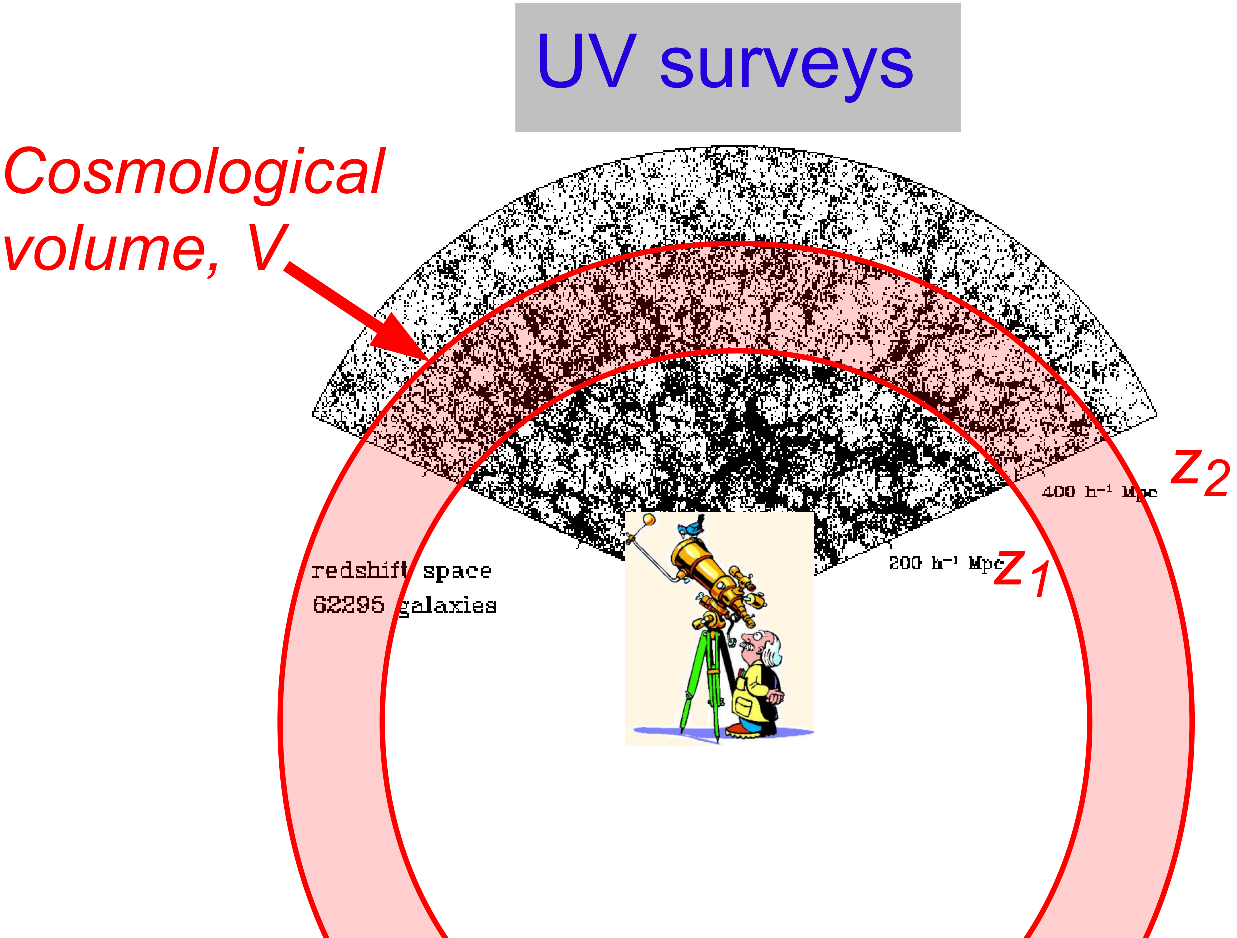
HST showed that the Hubble sequence breaks down at high redshift: Irregulars become the dominant population.

Ultra-violet as star-formation indicator



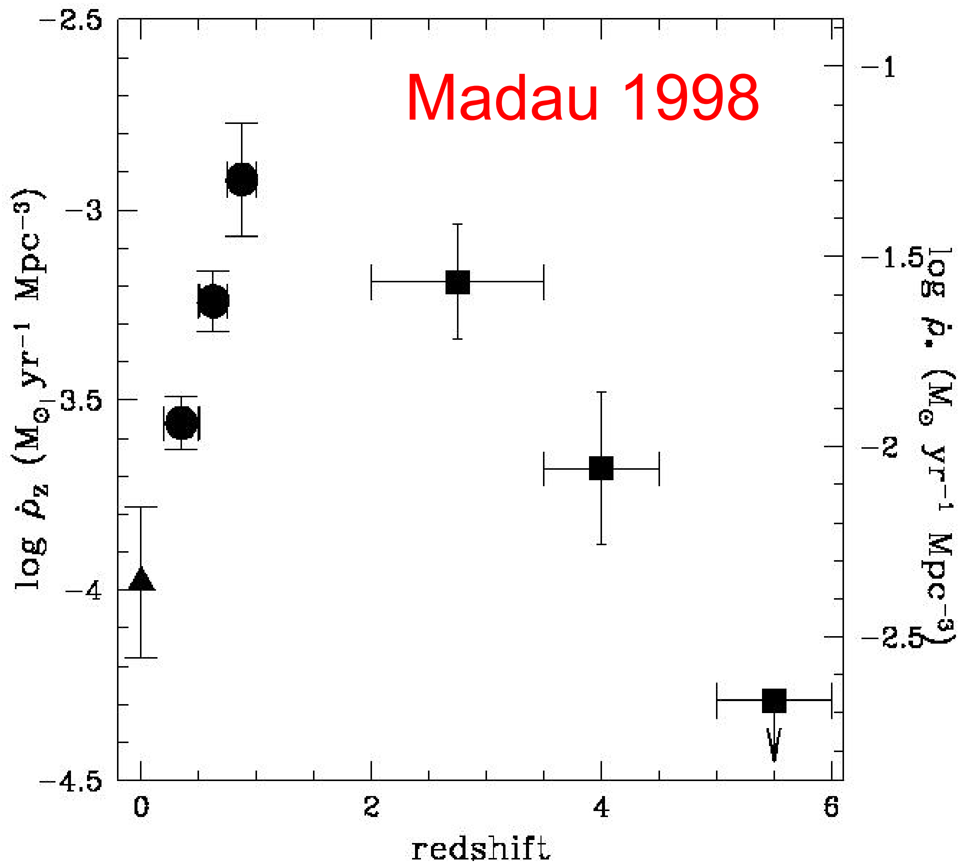
- Young massive stars
  - $T \sim 10^4$-5×10^4K
  - Spectrum peaks at UV (<3000Å)
- UV luminosity scales with star-formation rate

Rest-frame UV galaxy surveys



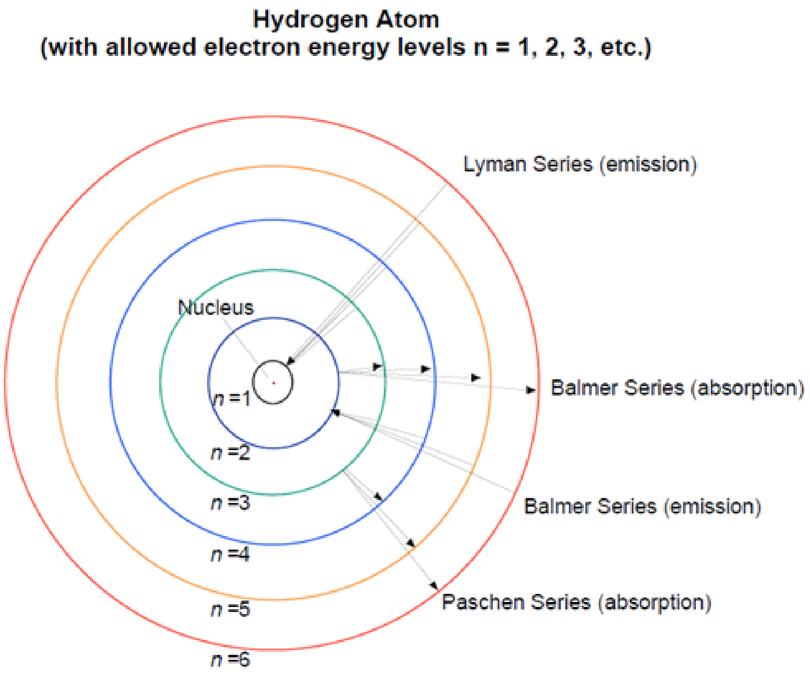
Star-formation history of the Universe in the '90s

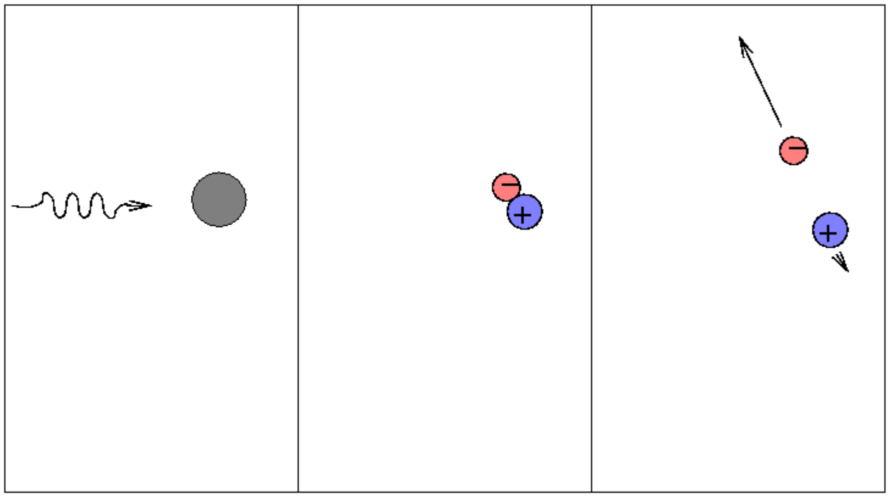
- UV luminosity as SF indicator: $L_{UV} \sim$ SFR
- Majority of stars formed at z=1-2
- Drawbacks:
  - dust extinction
  - Incomplete samples at z>2



Bound-free transitions of Hydrogen

Lyman Limit (912Å) corresponds to the energy required to ionise neutral hydrogen, i.e. excite the electron from n=1 to the continuum.

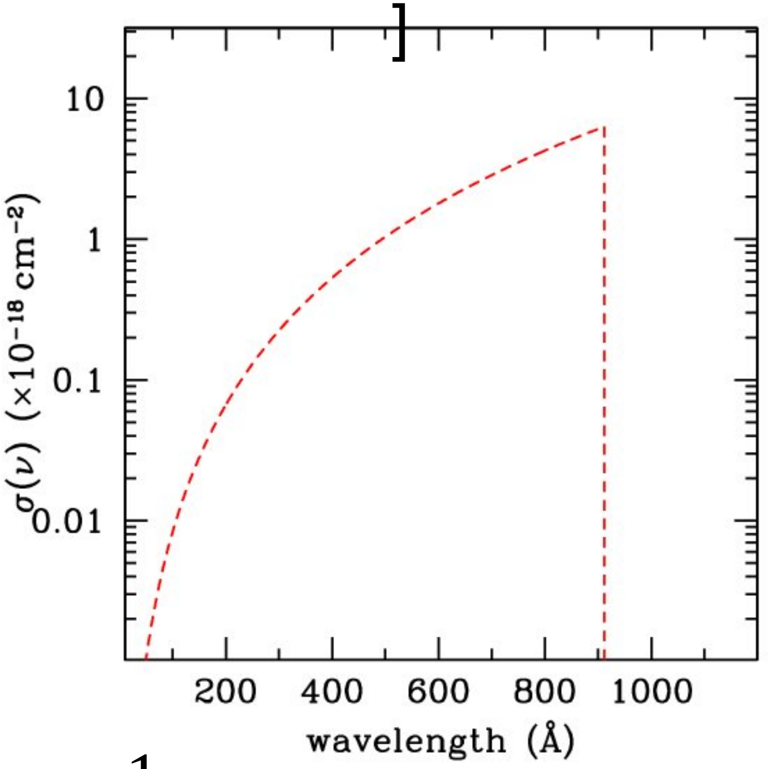




Bound-free cross section for H-like atoms

$$\sigma_n = \frac{64\pi^4}{3\text{sqrt}\,3}\frac{m_e e^{10}}{ch^6}\frac{Z^4}{\nu^3 n^5} g_n(\nu), g_n(\nu) \approx 1$$

$$\sigma_n(\nu) = 2.8\text{x}10^{29}\frac{Z^4}{\nu^3 n^5}$$



Cross section at Lyman limit:

$$\sigma_1 = 6.3\text{x}10^{-18}\, cm^{-2}$$

Free path

$$\tau_1 = \int_0^L N_{ISM}\sigma_1 ds \rightarrow \tau_1 \approx N_{ISM}\sigma_1 L \rightarrow L = \frac{1}{N_{ISM}\sigma_1}$$

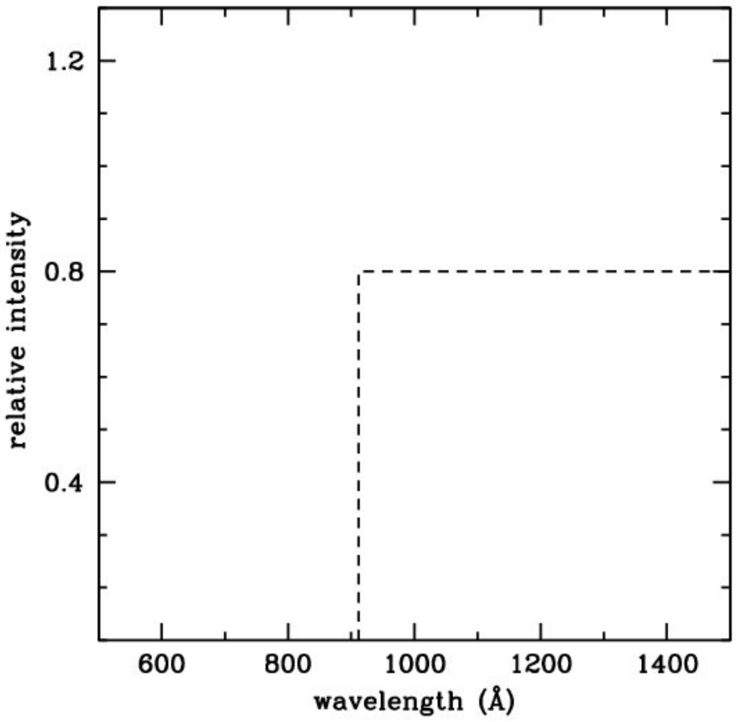
$$for\ N_{ISM} = 1\text{cm}^{-3}, L = 1.6\text{x}10^{17}\, cm = 0.05\text{pc}$$

Lyman break in galaxies

Hydrogen is the most abundant atom in galaxies.

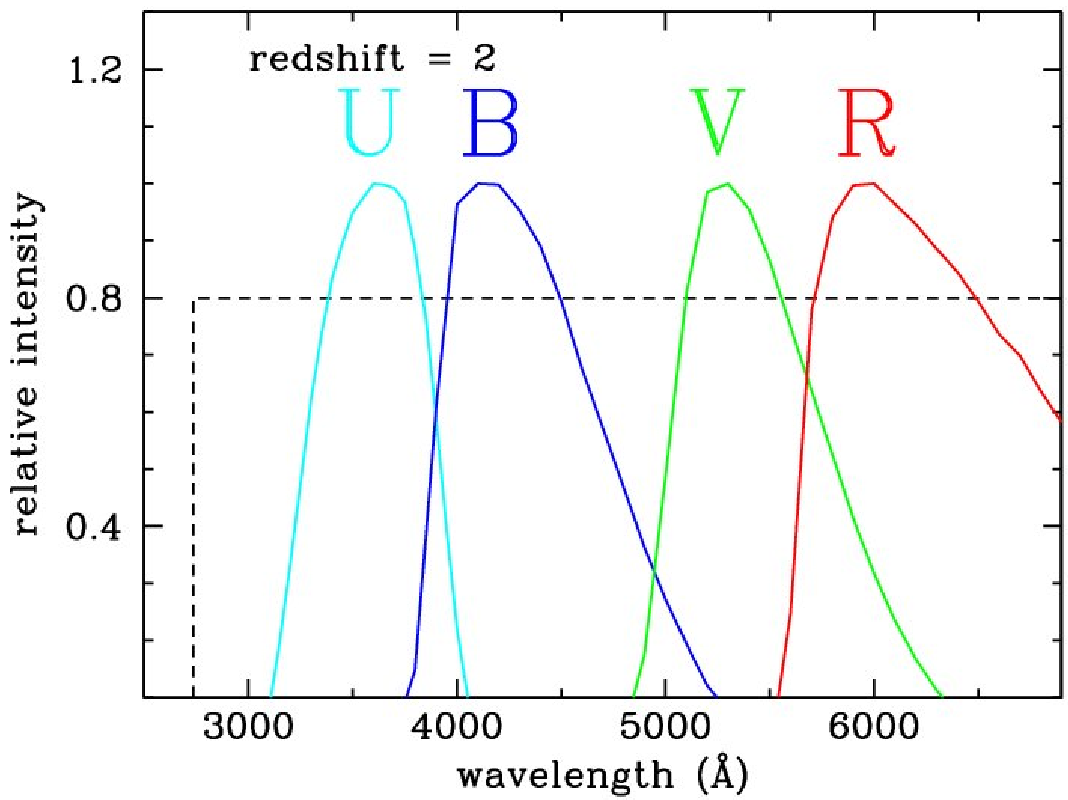
Therefore almost ALL photons more energetic than 912Å are absorbed by hydrogen and excite it.

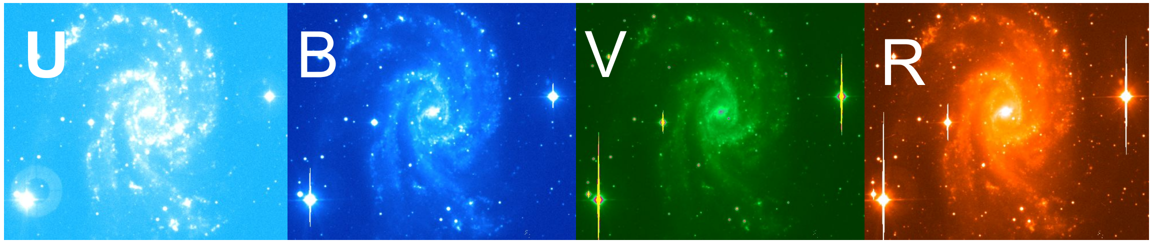
Galaxy spectra look like step function around 912Å: Lyman break



Lyman Break Galaxy selection

- Lyman break: 912Å
- galaxy light below 912Å is absorbed by the ISM: sharp cutof in galaxies' SEDs.
- High-z galaxy selection method using broad-band photometry





Steidel et al.

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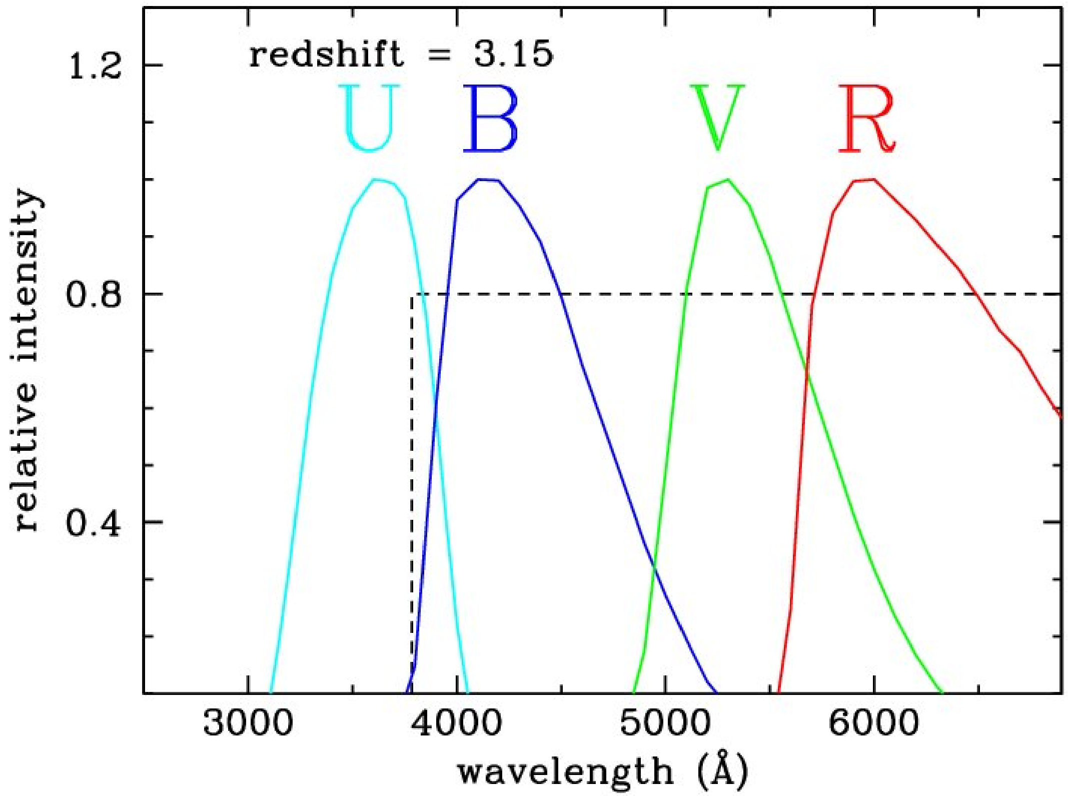

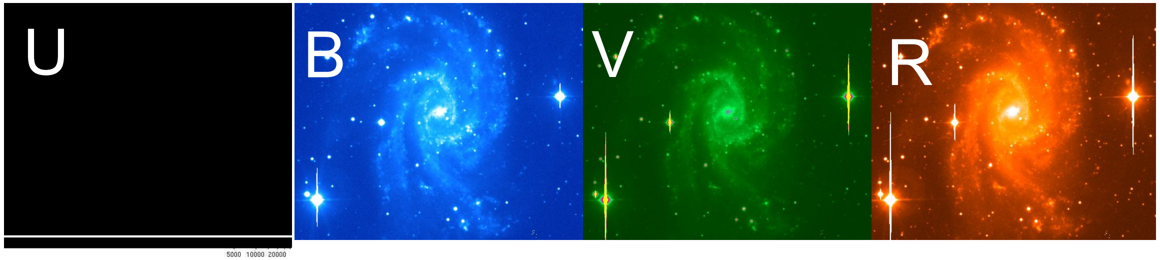

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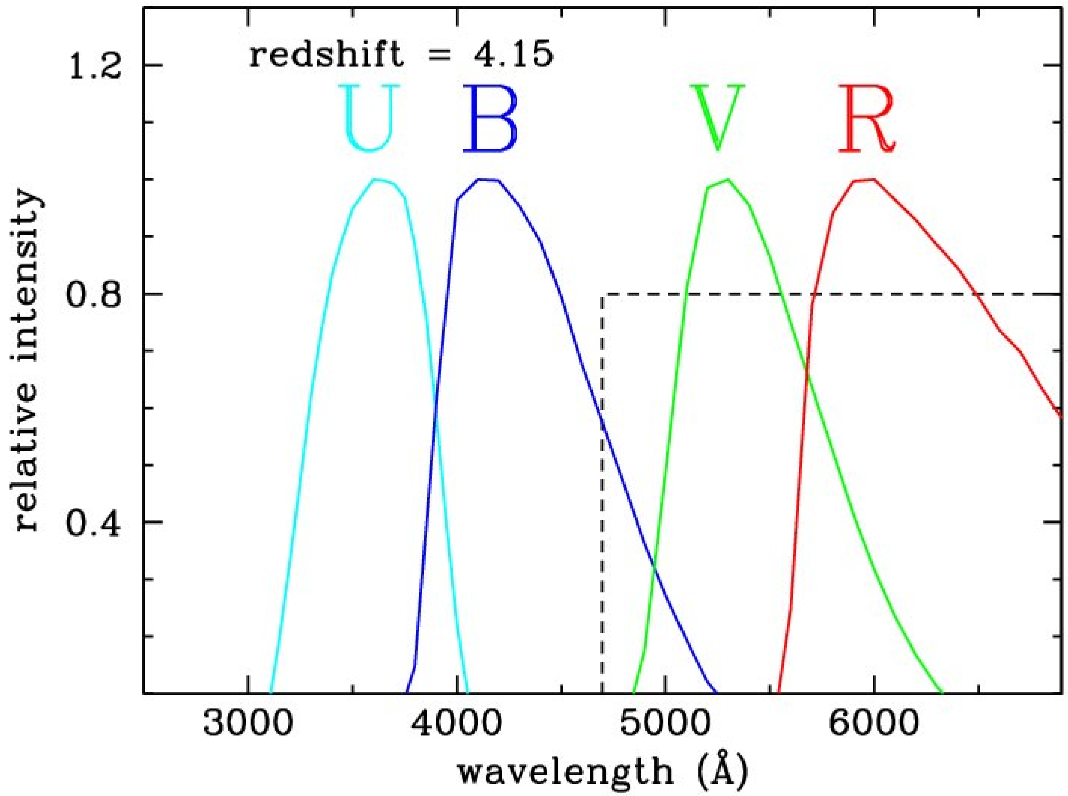

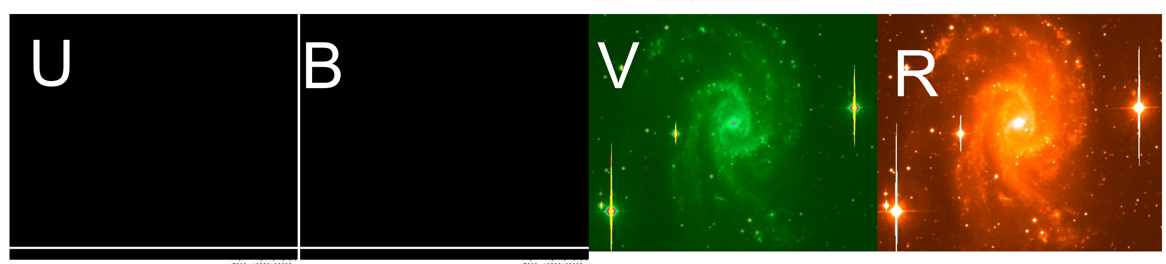

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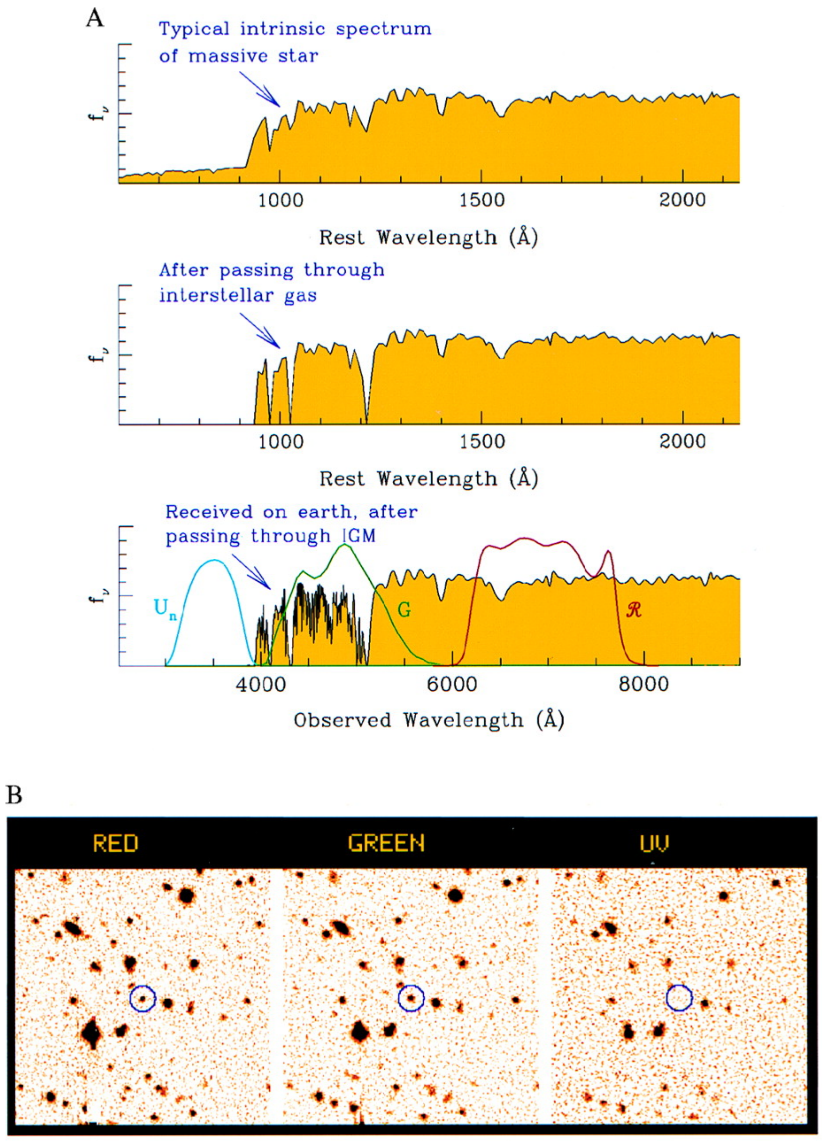
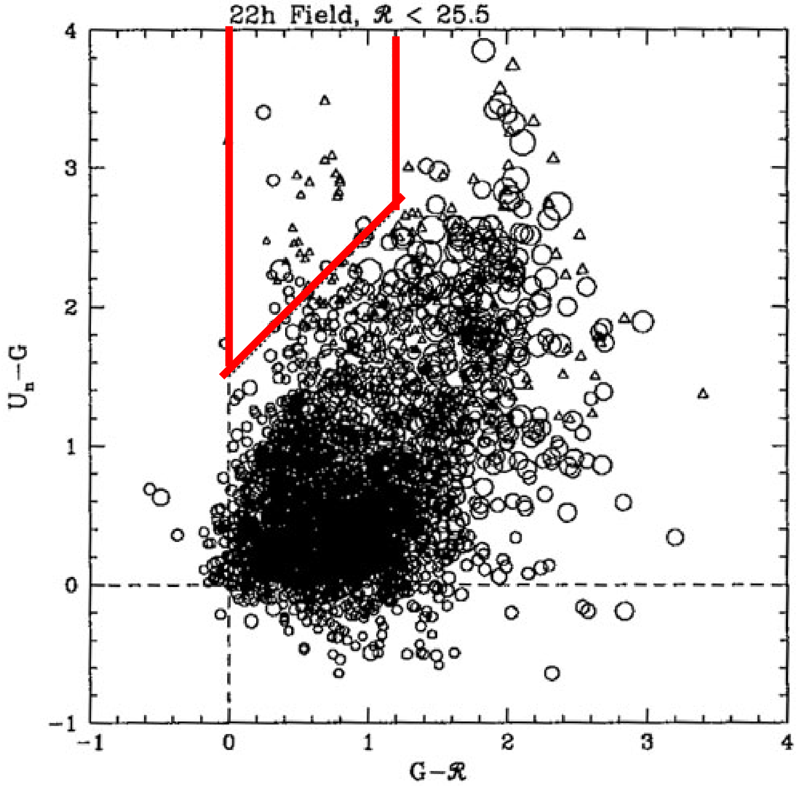


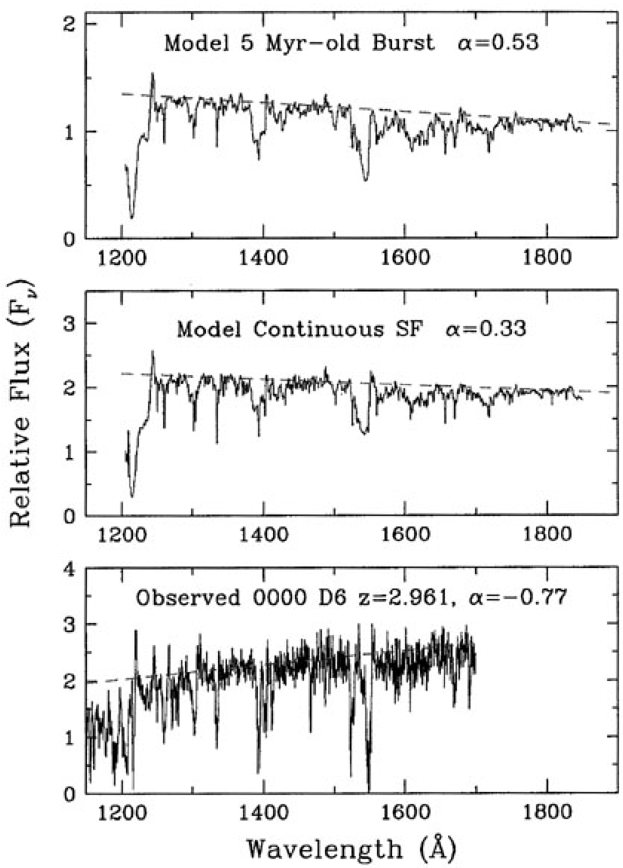
Lyman Break Galaxy selection

- Selection of high redshift galaxies using simple colour cuts
- Extremely efficient
  - High success rate
  - Low contamination
- Well defined selection function
- Large numbers of *z*~3 and *z*~4 starbursts



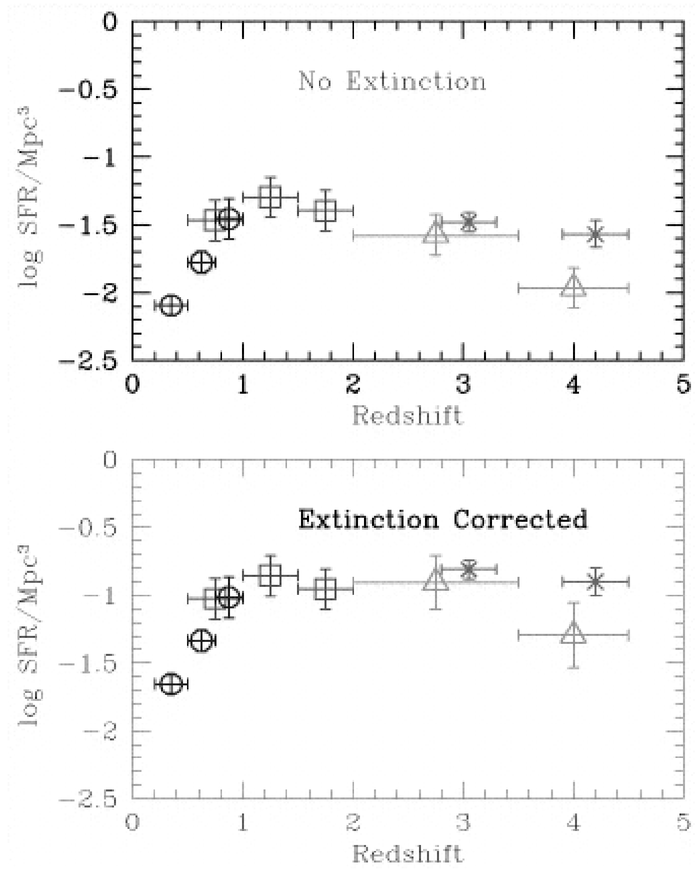
Dust in LBGs

- UV continuum slope indicator of dust extinction
- LBGs show steeper UV slopes than expected: dust reddening
- SFRs inferred from L_{UV} should be revised upward by factor 3-7.



Star-formation history of the Universe in the '90s

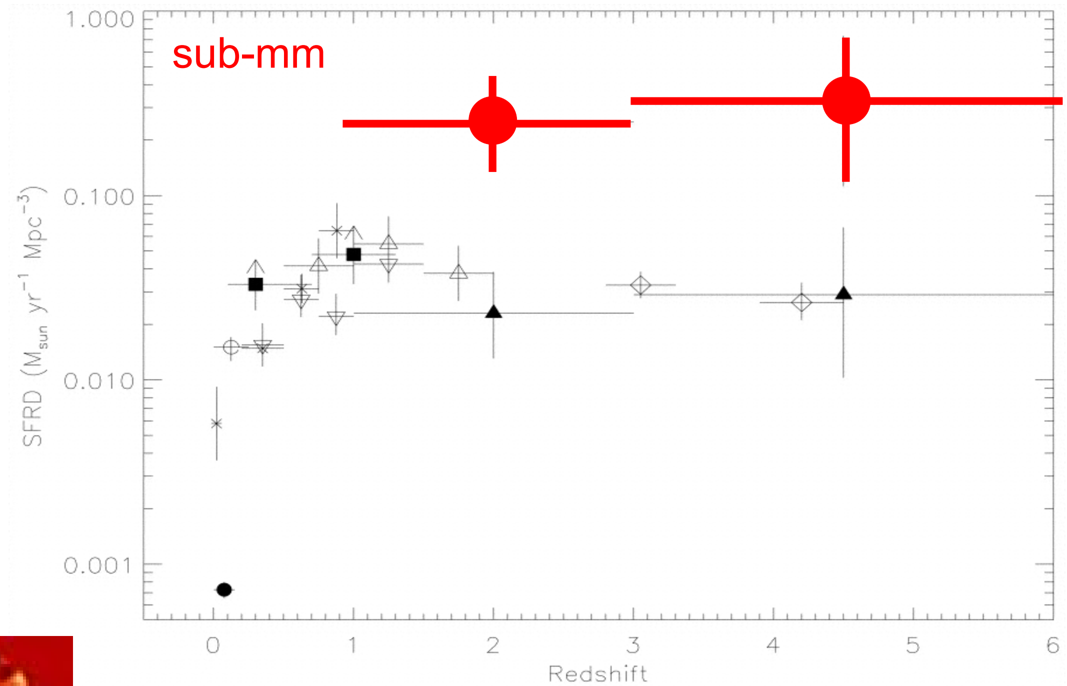
- Selection of large samples of z~3 and z~4 galaxies
- Selection function well defined
- Extinction corrections



Steidel et al. 1998

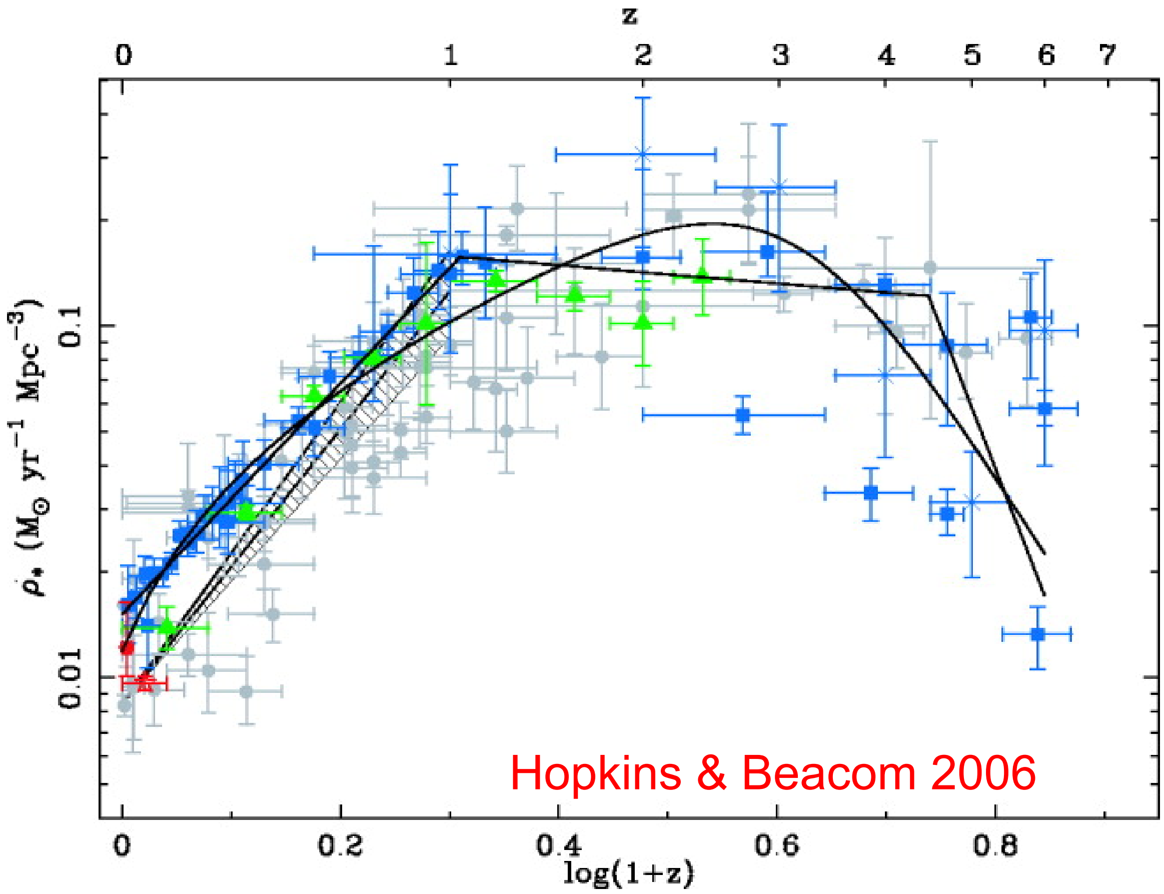
Star-formation history of the Universe in the '90s

- sub-mm observations: dust independent SF estimator
- UV underestimates the SF by 1dex
- contamination of sub-mm samples by AGN?



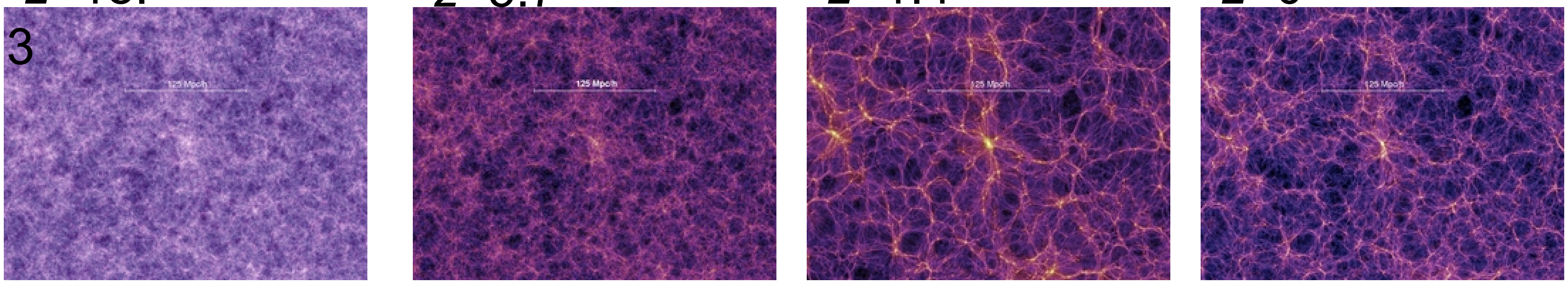
Barger et al. 2000

Star-formation history of the Universe in the 21 century



Cosmological simulations of galaxy formation

z=18.3 z=5.7 z=1.4 z=0

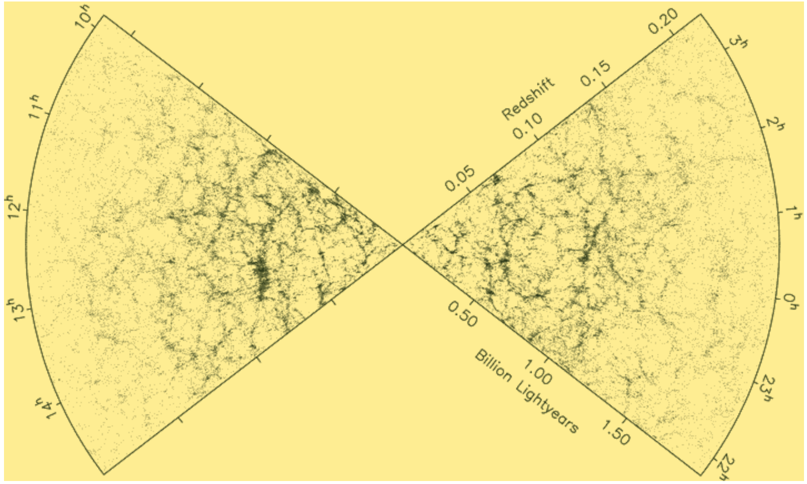


Millennium Simulation, Springel et al. 2005

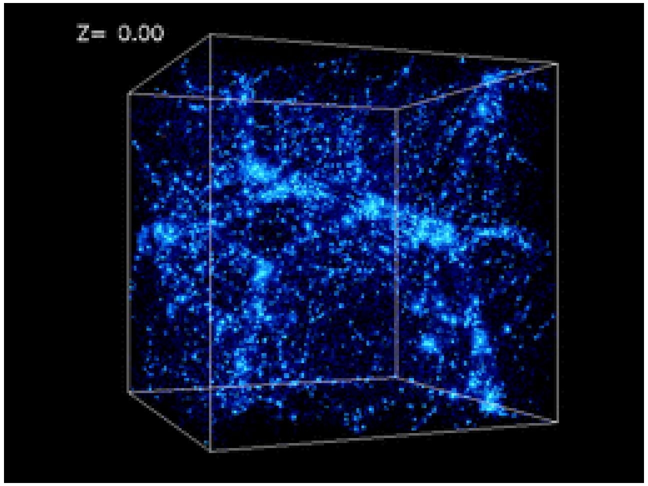
- Cold Dark Matter simulations
- Evolution of dark matter haloes
- Gravity only

Hierarchical evolution of the Universe

Observation: 2dFGRS



Simulation



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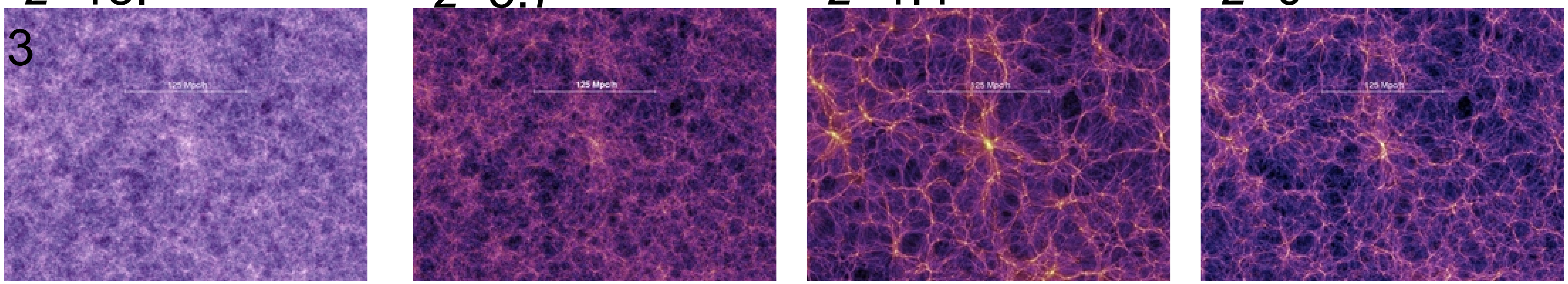
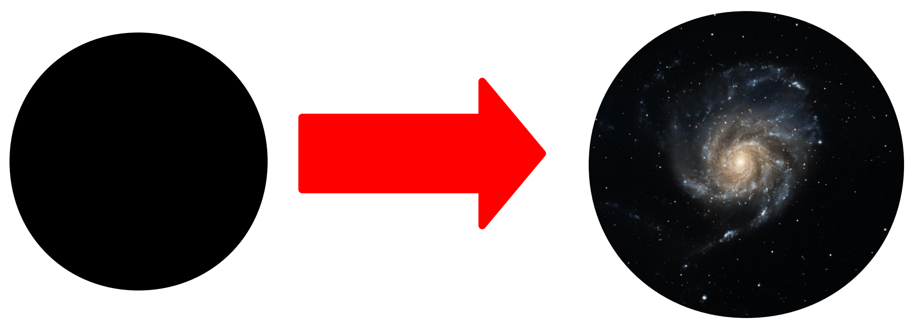


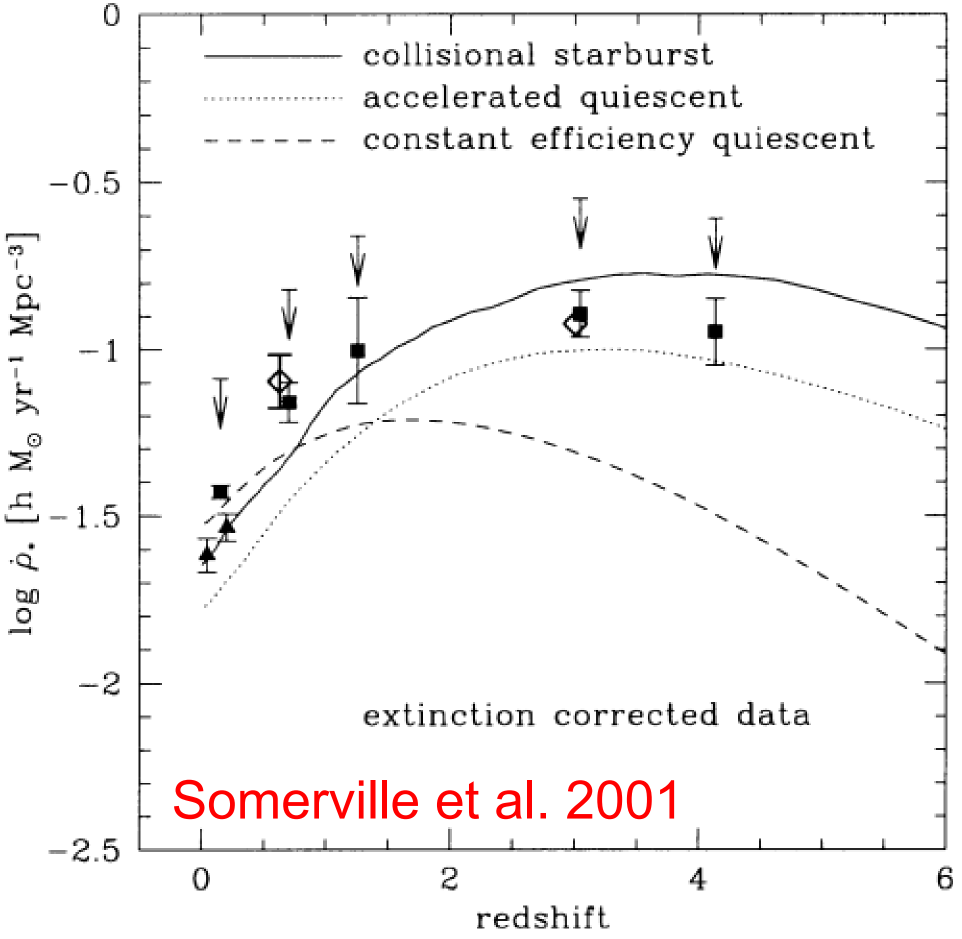
Millennium Simulation, Springel et al. 2005

- Cold Dark Matter simulations
- Evolution of dark matter haloes
- Gravity only
- Physically motivated prescriptions to describe galaxy formation



Cosmological simulations of galaxy formation

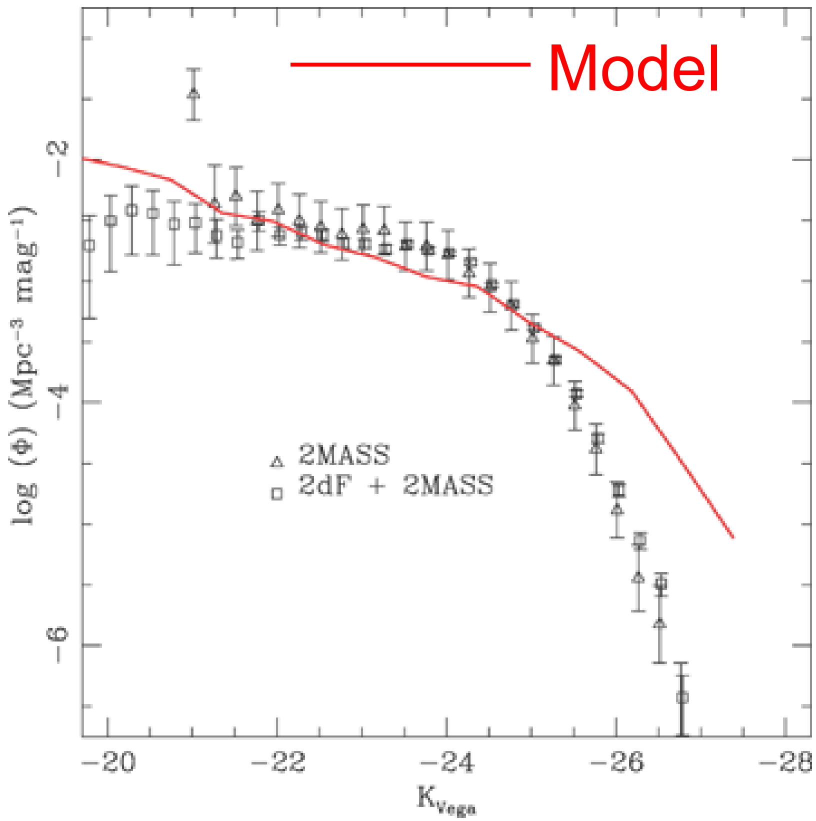
Cosmological simulations can reproduce star-formation history of the Universe



Cosmological simulations of galaxy formation

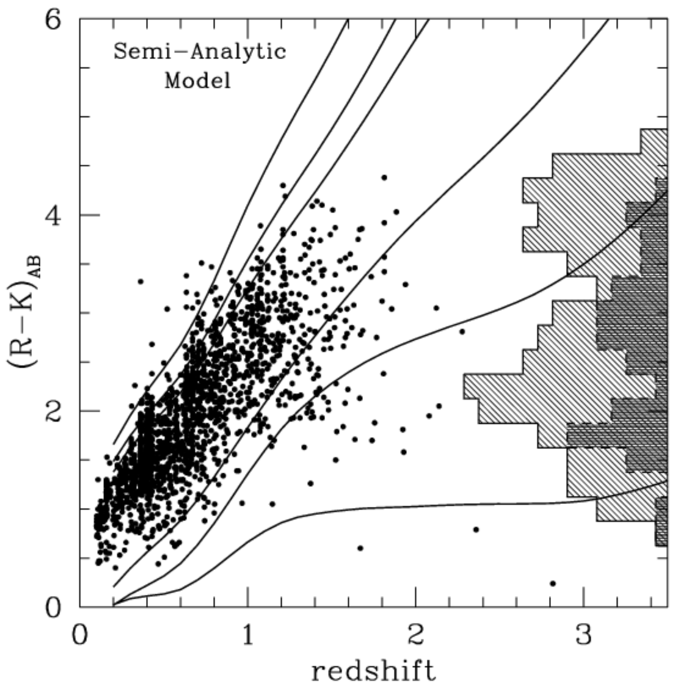
Cosmological sims: too many <u>massive</u> galaxies at z=0 than those observed

Gas cools too efficiently in simulations leading to high levels of star-formation.

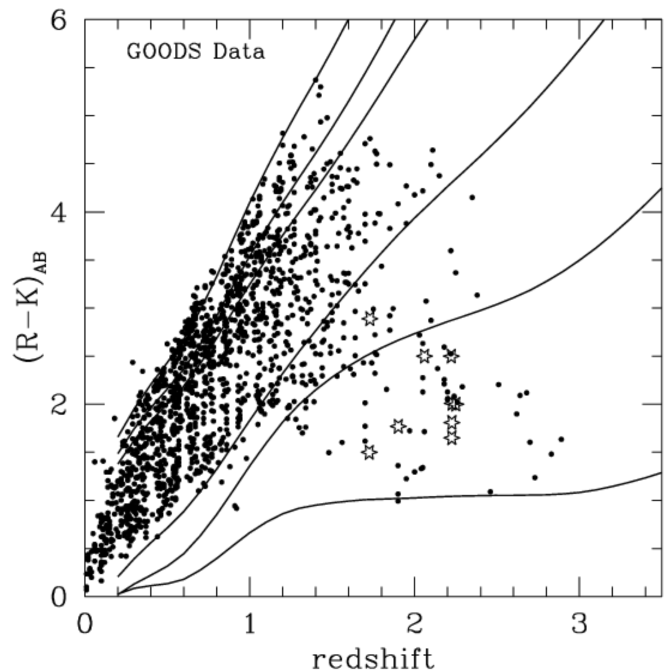


Fontanot et al. 2007

Cosmological simulations of galaxy formation

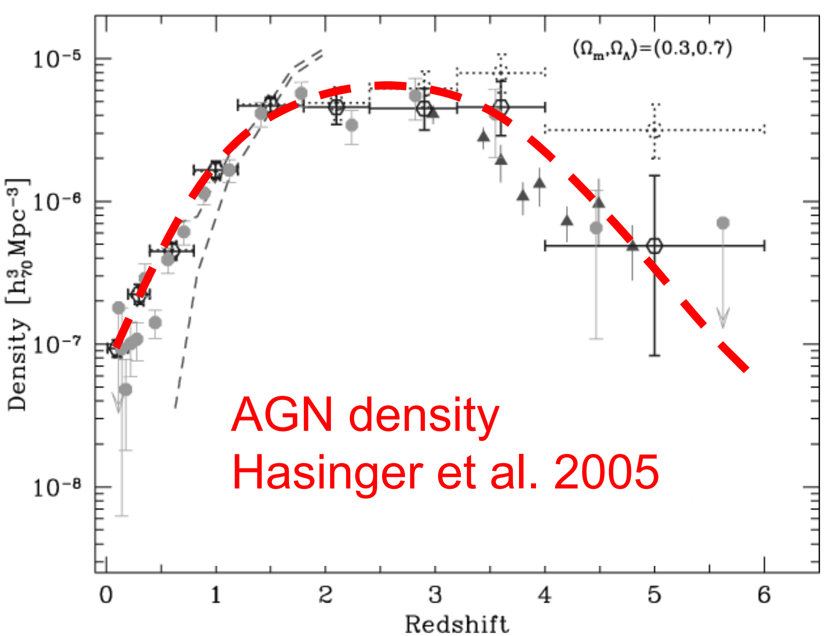


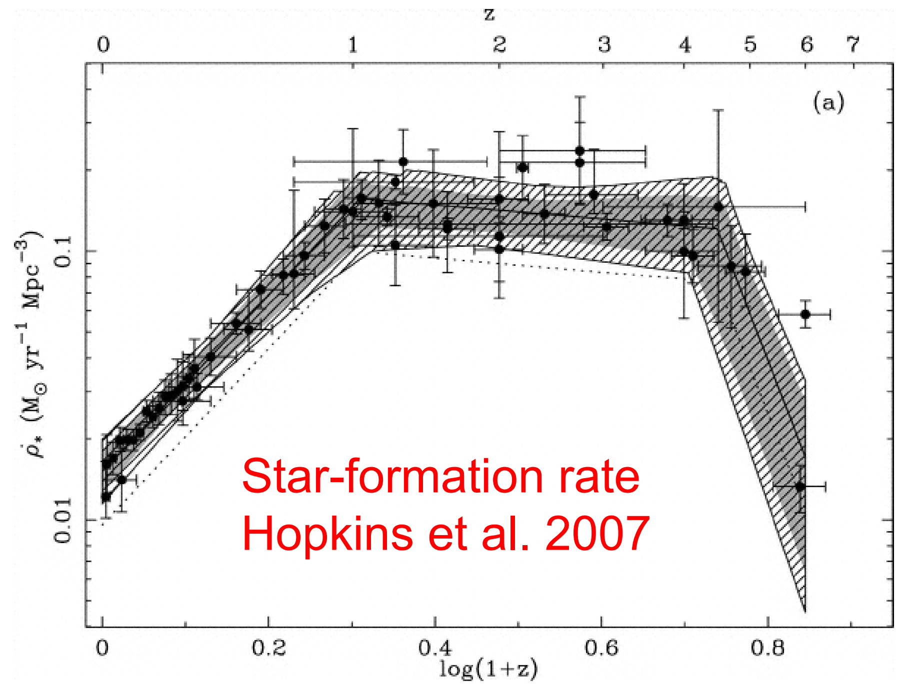
Cosmological simulations: too many massive blue (star-forming) galaxies at z~1



Need to suppress star-formation in massive galaxies at z~1.

Evolution of AGN & Star-formation

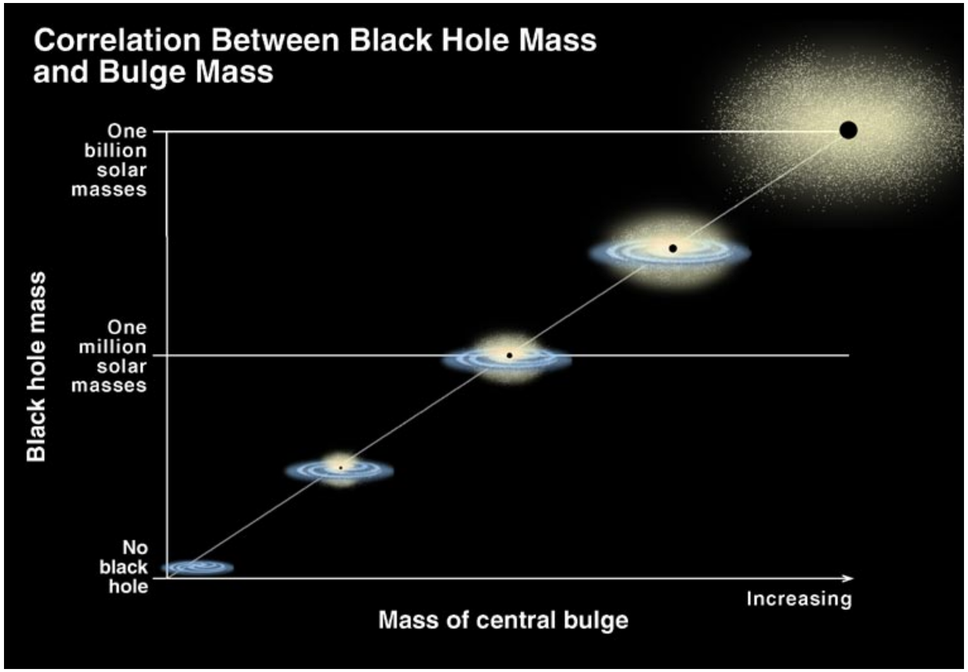




AGN and star-formation have similar evolution patterns }

- Rapid increase to *z*~1
- Flattening up to *z*~4
- Possible decrease at *z*>4

Massive black holes at the centres of galaxies



Black hole mass correlated to host galaxy bulge mass.

↓

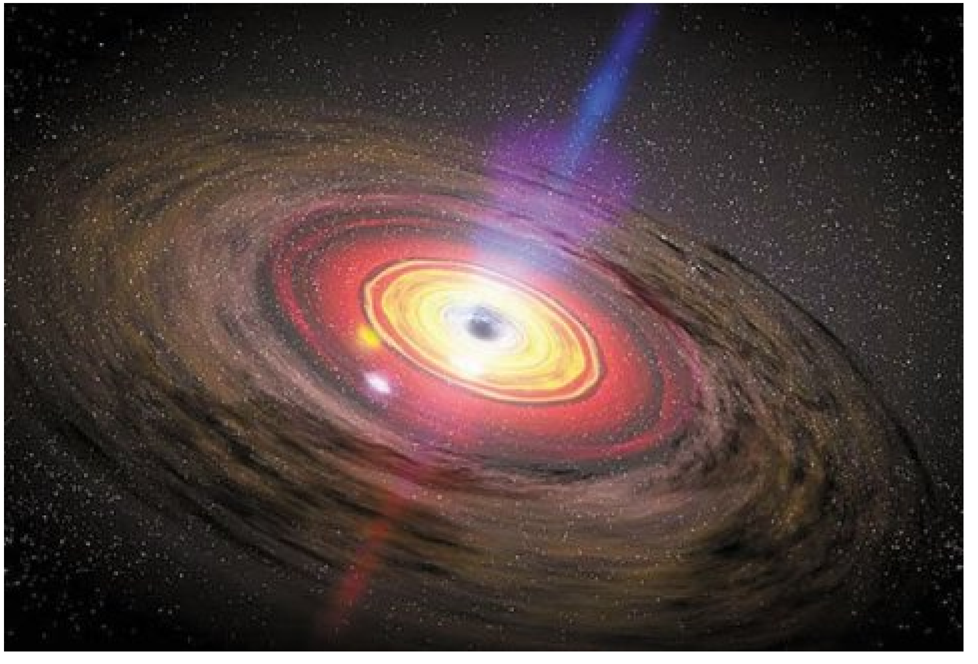
Formation of bulge and growth of black hole are related.

↓

AGN play a significant role in the evolution of galaxies

$M_{BH}=10^{-3}M_{bulge}$

AGN: active super-massive black holes

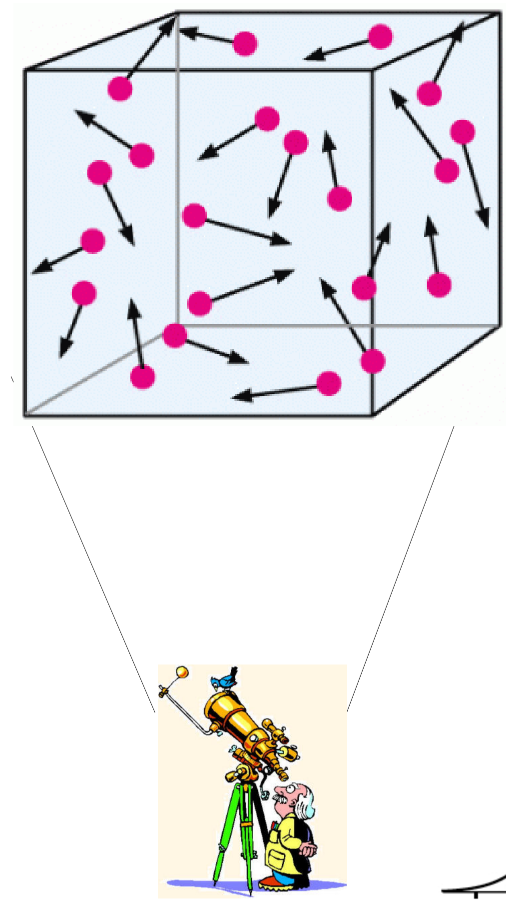


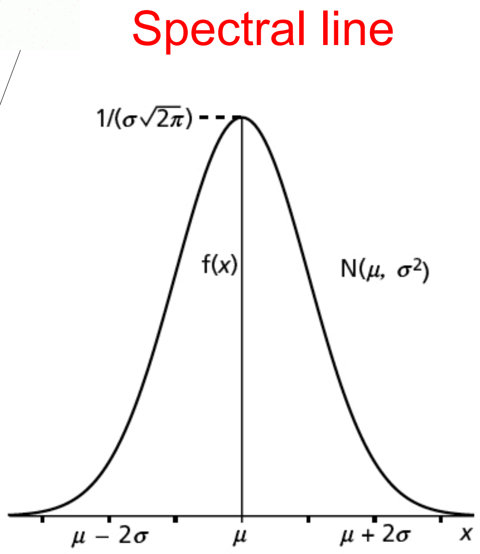
Binding energy of a galaxy bulge

- Galaxy bulges resemble ideal gas
  - Pressure from stellar motions
  - No collisions between stars
- Kinetic energy

  $T=0.5 \cdot M \cdot \sigma^2$
- Binding energy

  $U=2T=M \cdot \sigma^2$





Effect of AGN energy output on the host galaxy

Total energy radiated by AGN:

$E = \eta M_{BH} c^2$

$M_{BH} \sim 10^9\, M_\odot$

$E_{radiated} \sim 10^{60}$erg

Binding energy of a galaxy bulge:

$E_{bulge} = M_{bulge} \sigma^2$

$M_{Bulge} \sim 10^{11}\, M_\odot$

$\sigma = 200$km/s

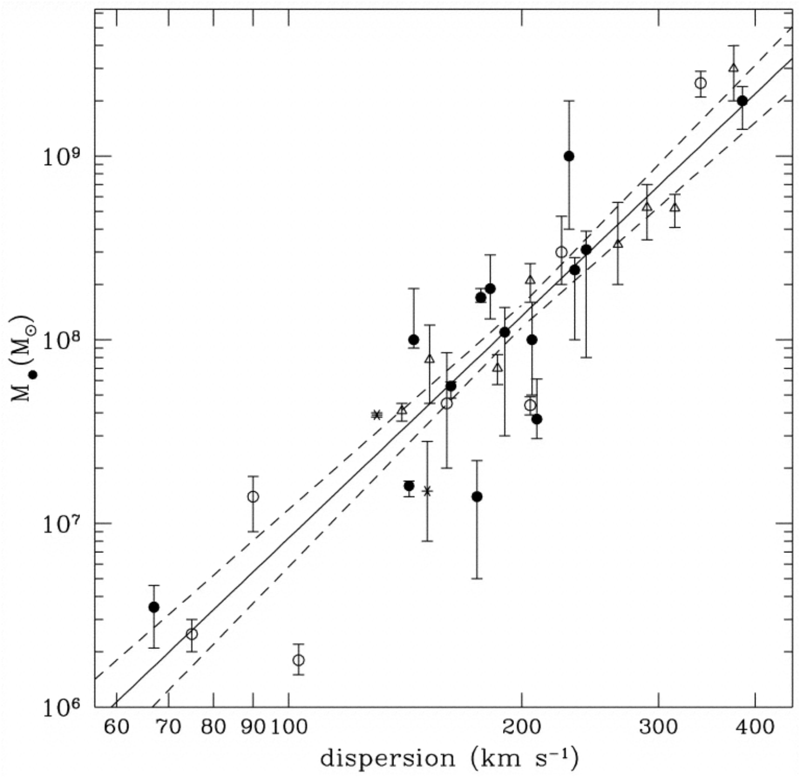
$E_{binding} \sim 10^{58}$erg

1% of the AGN output can blow the galaxy apart

M_{BH}-σ relation

Observation:

$$\log M_{BH} = (8.13 \pm 0.05) + (4.02 \pm 0.32)\ \log \sigma$$

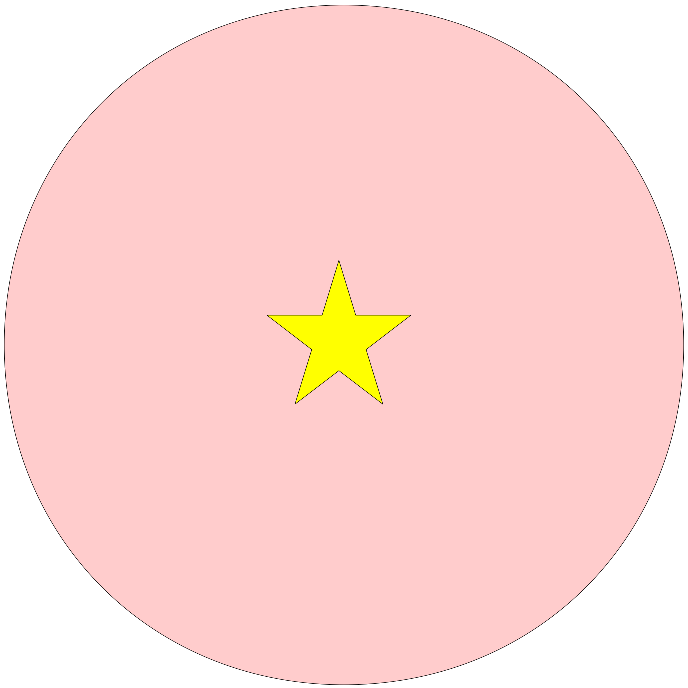


Tremaine et al. 2002

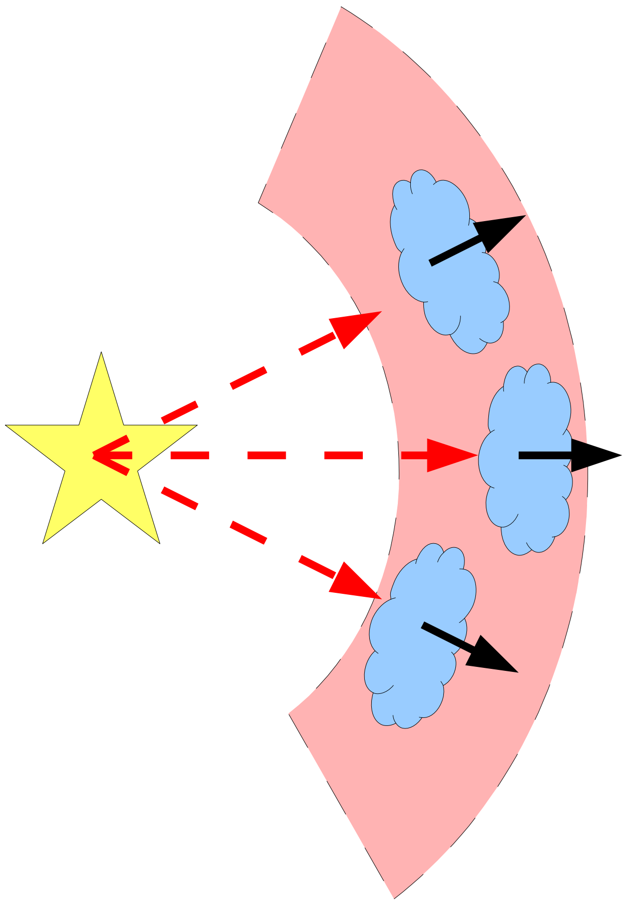
$$\rho = \frac{f_g \sigma^2}{2\pi G r^2},$$

f_g: gas fraction

$$M(R) = 4\pi \int_0^R \rho r^2 \, dr = \frac{2 f_g \sigma^2 R}{G}.$$



$$\dot{M}_{\rm out} v \simeq \frac{L_{\rm Edd}}{c},$$



King 2003

$$\dot{M}_{\rm out} v \simeq \frac{L_{\rm Edd}}{c},$$

$$\rho = \frac{f_g \sigma^2}{2\pi G r^2},$$

$$M(R) = 4\pi \int_0^R \rho r^2 \, dr = \frac{2 f_g \sigma^2 R}{G}.$$

Equation of motion:

$$\frac{d\vec{p}}{dt} = \vec{F} \Rightarrow \frac{d(M(R)\dot{R})}{dt} = \rho(R) * v^2 * 4\pi R^2$$

Force on shell is from ram pressure, $P_{\rm ram} = \rho \cdot v^2$

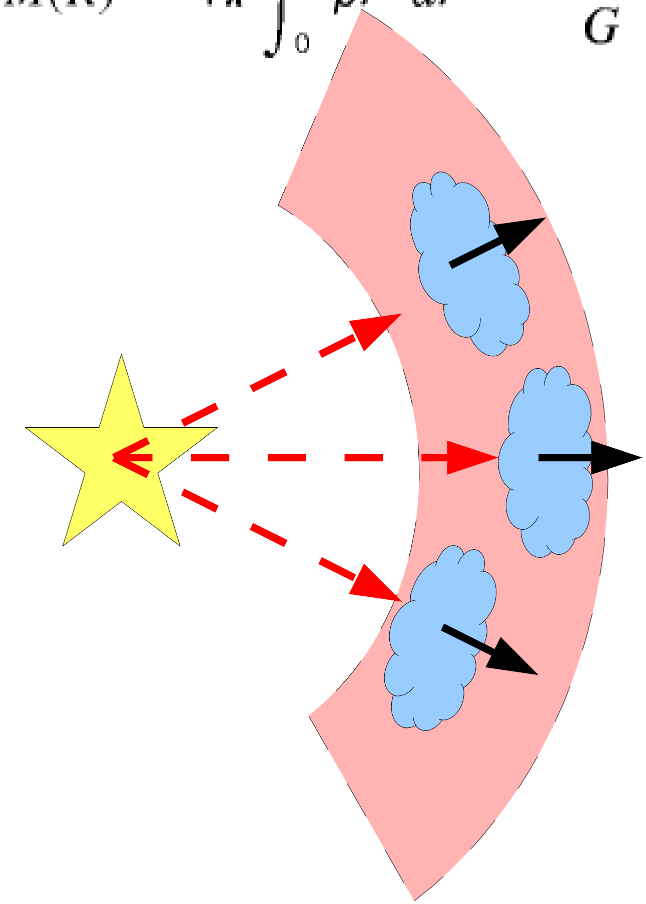
Applying mass continuity equation:

$$4\pi r^2 \rho v = \dot{M}_{out}$$

$$\frac{d(M(R)\dot{R})}{dt} = \rho(R) * v^2 * 4\pi R^2 \Rightarrow \dot{M}_{out} v = \frac{L_{edd}}{c}$$

$$M(R)\dot{R} = \frac{L_{edd}}{c} \cdot t \Rightarrow R^2 = \frac{G L_{edd}}{2 f_g \sigma^2 c} t^2 \Rightarrow u_m^2 = \frac{G L_{edd}}{2 f_g \sigma^2 c}$$

$$M_{BH} = \frac{f_g}{2\pi} \frac{\kappa}{G^2} \sigma^4 \Rightarrow \log M_{BH} = 8.06 + 4 \log \sigma$$



M_{BH}-σ relation

Observation:

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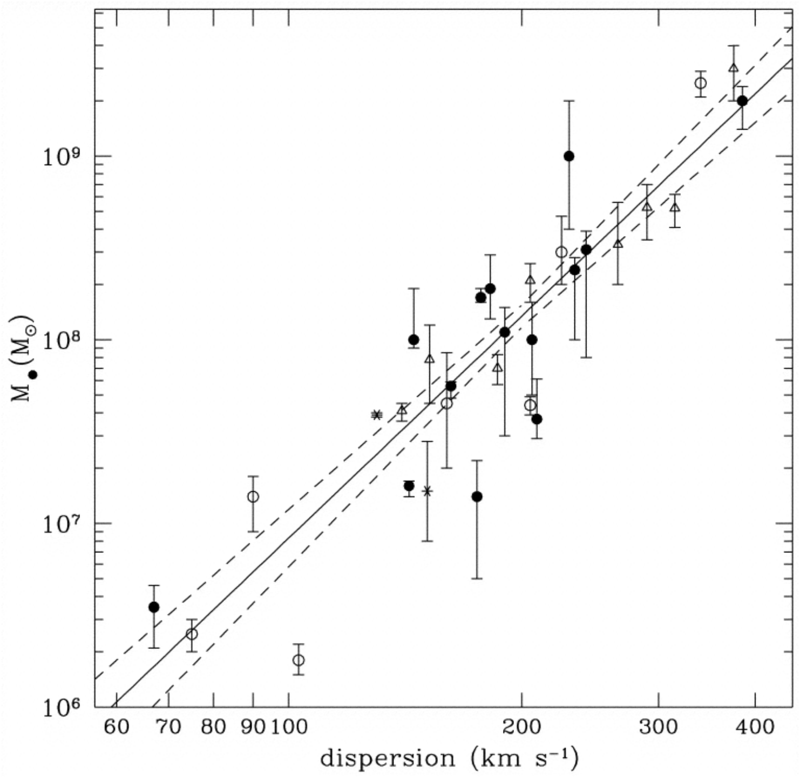
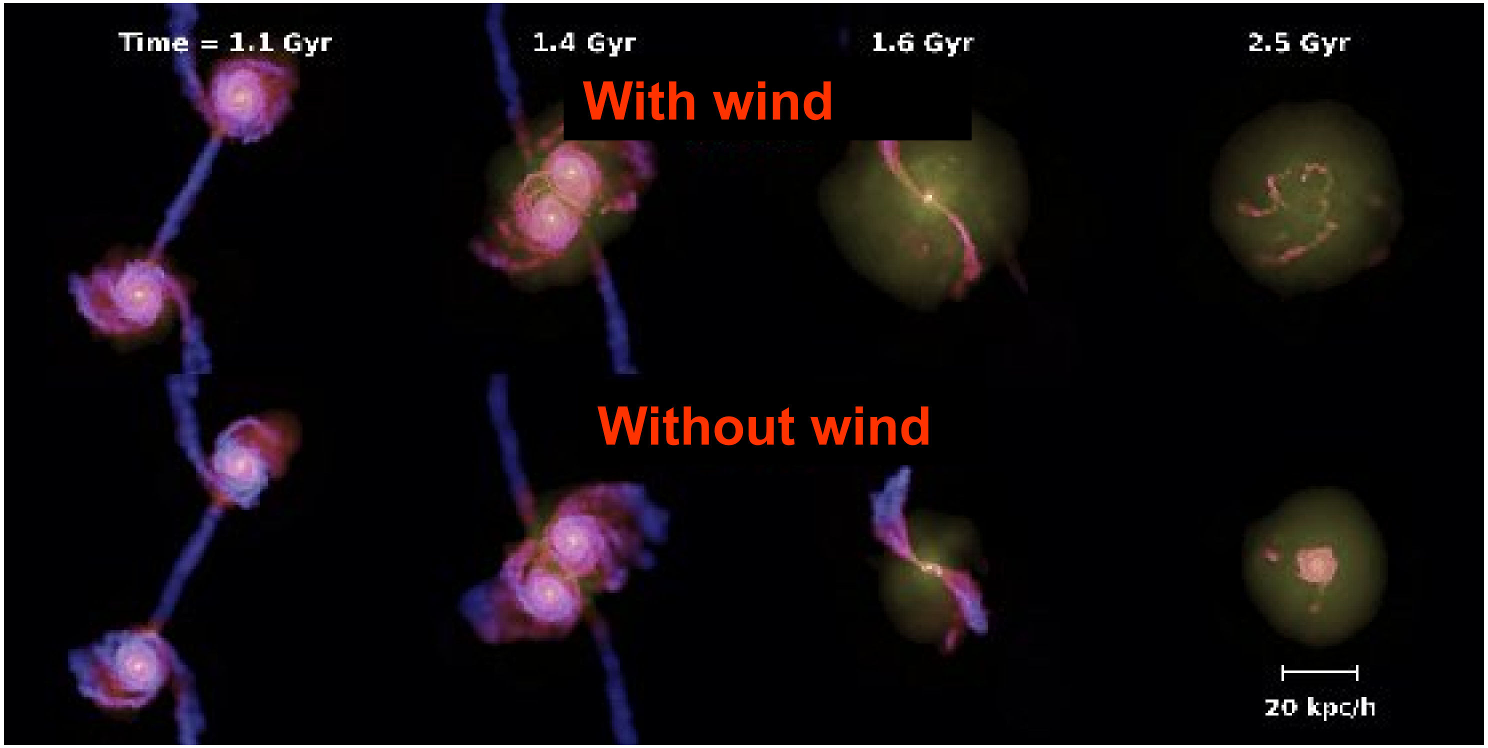
Theory (King 1999):

$$\log M_{BH} = 8.06 + 4\ \log \sigma$$

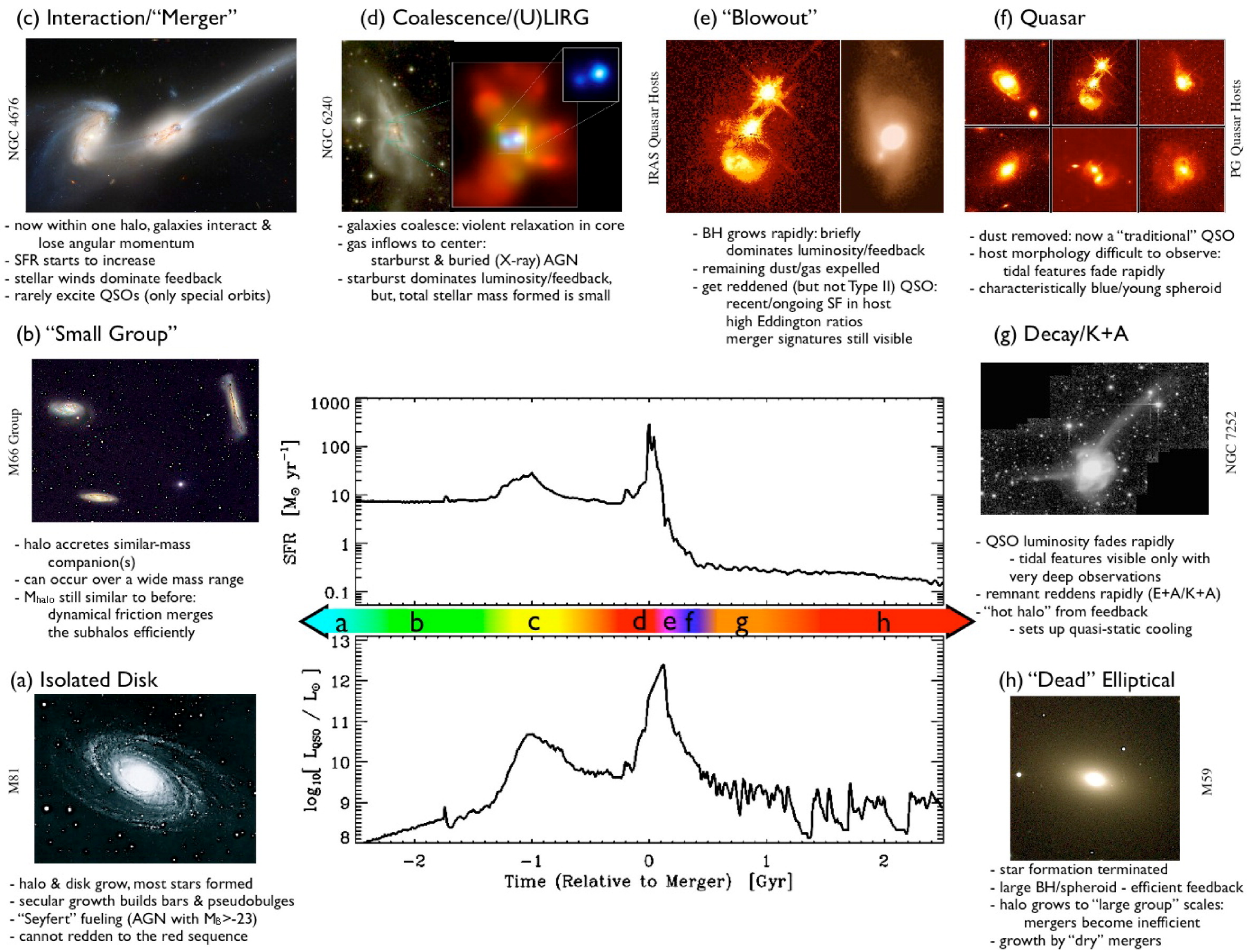


Tremaine et al. 2002

AGN feedback and galaxy evolution

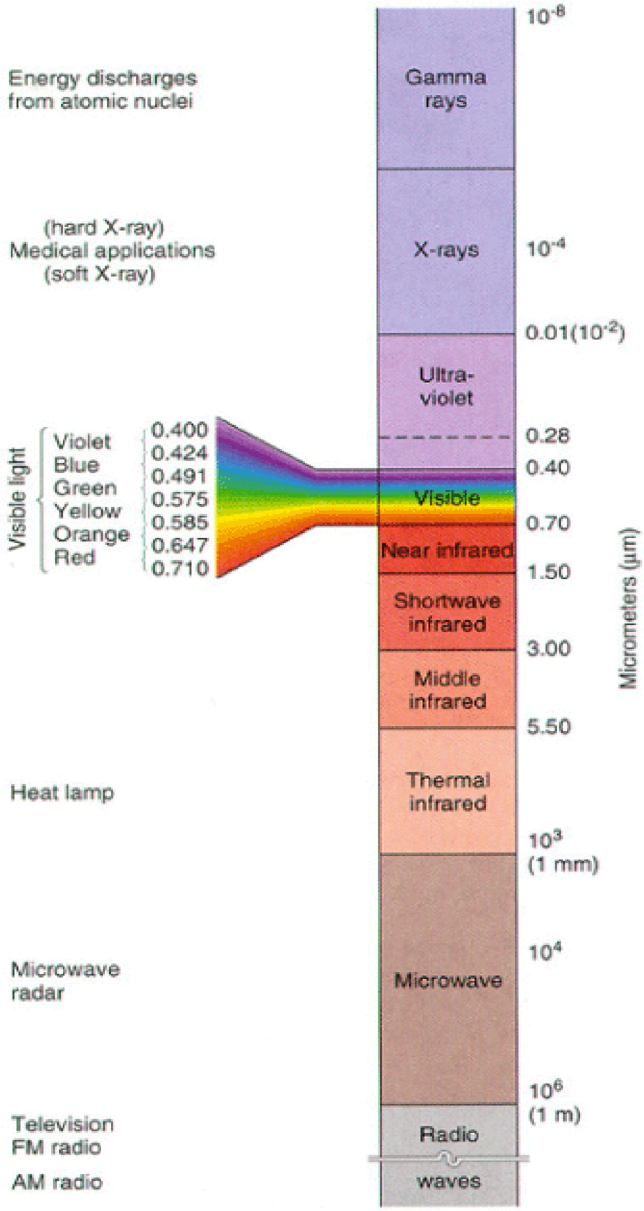


Simualtion of a galaxy merger with/without AGN winds (Di Matteo et al. 2005, Springel et al. 2005)



Hopkins et al. 2008

Multi-wavelength observations



source: Christopherson (2000) *Geosystems*

AGN activity

Stellar population,
Morphology, AGN

stellar mass

Hot dust (AGN/Star-formation)

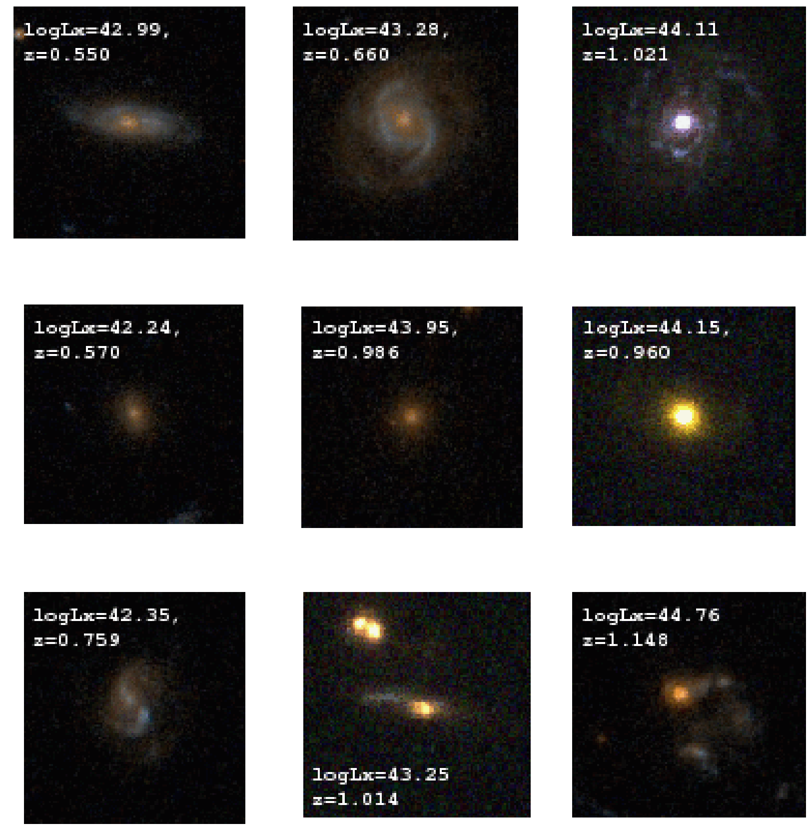
Cool dust (Star-formation)

Inter-Stellar Medium

Synchrotron, Bremsstrahlung
(AGN/Star-formation)

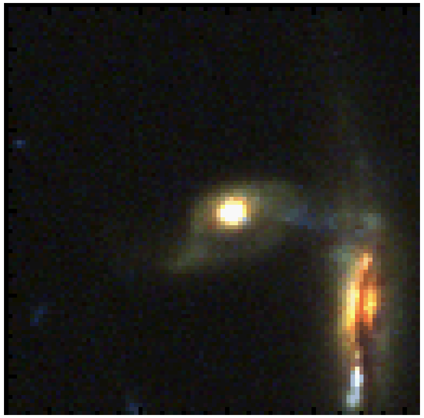
Observational constraints on AGN/galaxy co-evolution models

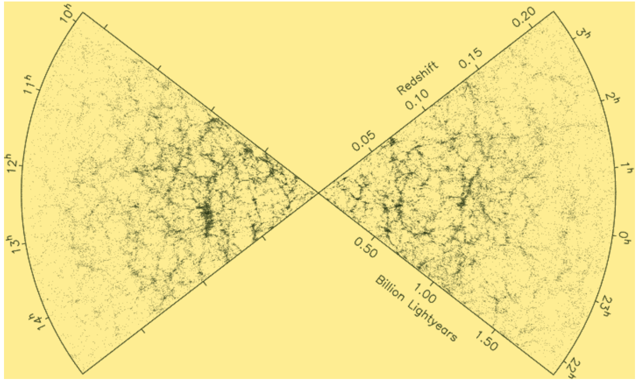
- Morphology of AGN hosts:
- Merger model predicts many irregulars
- NOT observed!



Observational constraints on AGN/galaxy co-evolution models

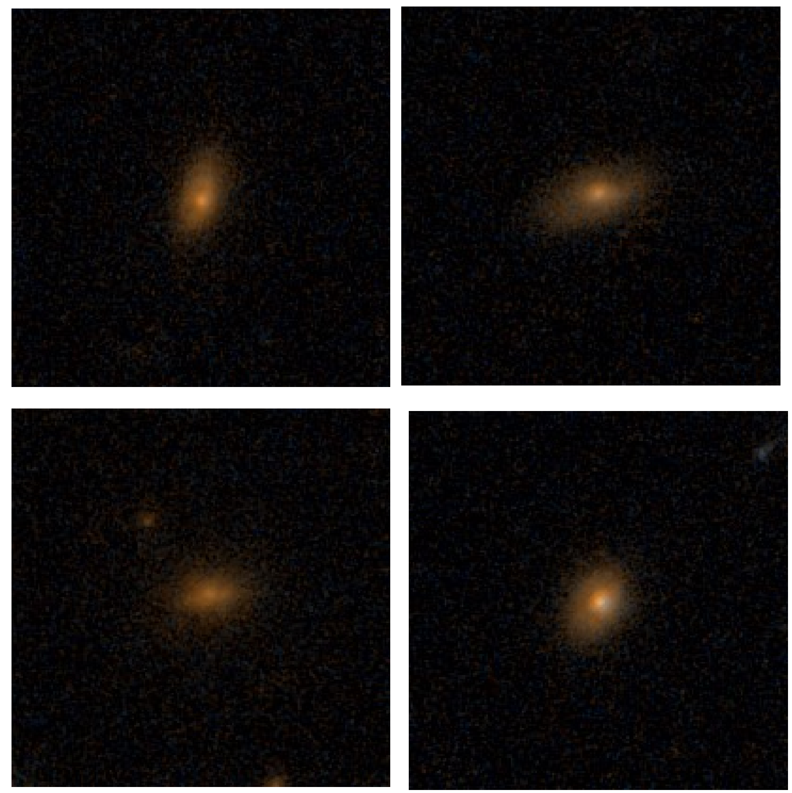
- Environment:
  - Small scale
  - Large scale
- Mergers predict pairs and low density environs
- Under debate





Observational constraints on AGN/galaxy co-evolution models

- Star-formation:
- Mergers predict high SFRs in AGN hosts
- Under debate
- Breakthrough is expected from Herschel data



Summary

- AGN play a fundamental role in the formation and evolution of galaxies.
- The details of the symbiotic relation of AGN and galaxies are a subject of intense observational studies

Διπλωματική/Διδακτορικό?

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Χρηματοδότηση από Ευρωπαική Ένωση

Bound-bound transitions of Hydrogen

Lyman series: transitions to n=1 shell.

Lyα (1216Å) transition from n=2 to n=1

Lyβ (1026Å) transition from n=3 to n=1

Lyγ (972Å) transition from n=4 to n=1

$$\lambda = \frac{hc}{E_i - E_f}.$$