

# The 4<sup>th</sup> KIAS workshop on cosmology and structure formation

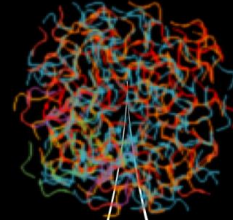
*Carlos S. Frenk*  
*Institute for Computational Cosmology,*  
*Durham*



# The initial conditions

## INFLATION

$t=10^{-35}$  sec



QUANTUM  
SPACE-TIME  
FOAM?



$$p = -\rho$$

# BLAP!

THE ENTIRE  
OBSERVABLE  
UNIVERSE!

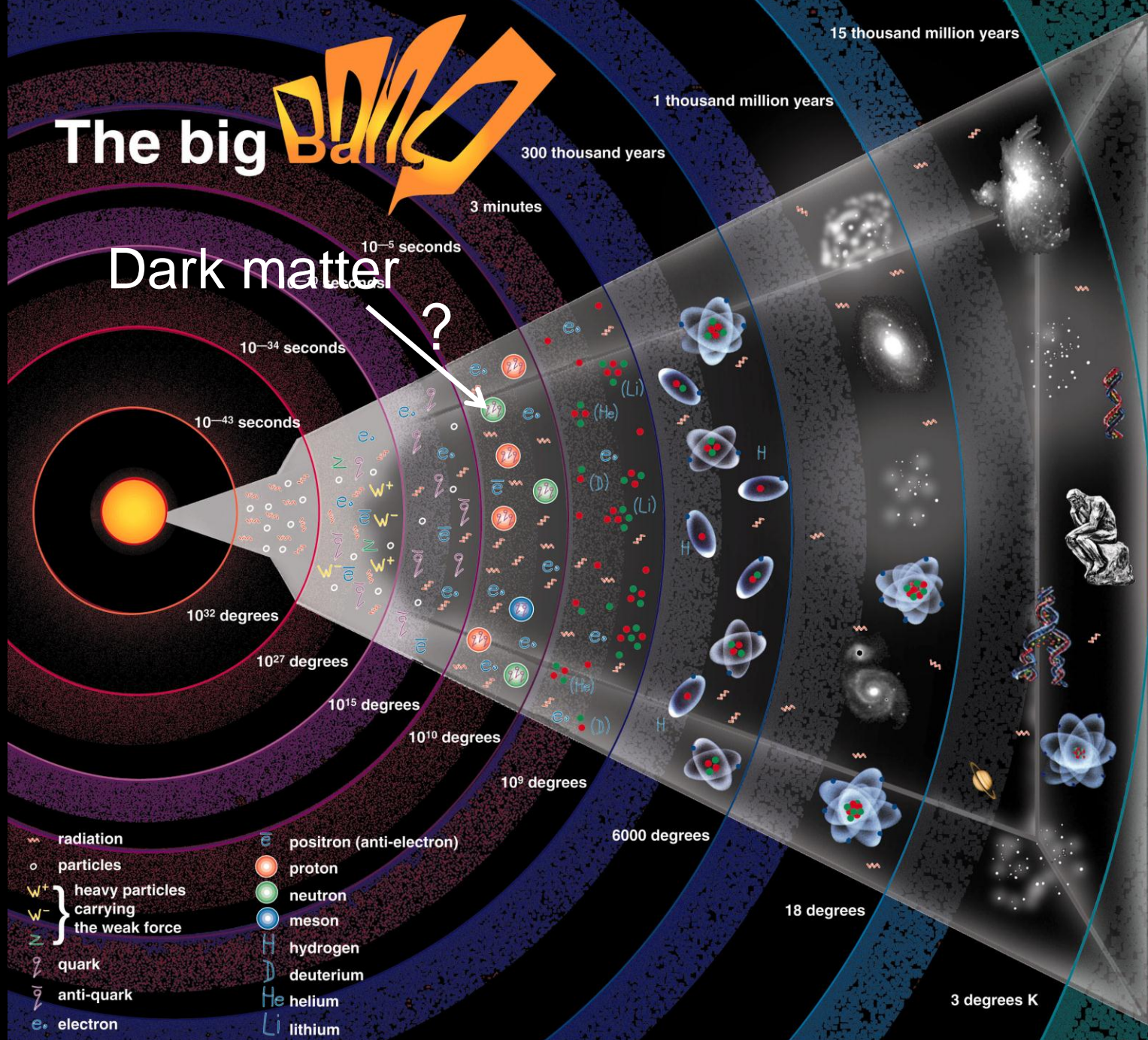
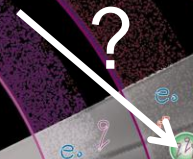
from G. Efstathiou



# The big Bang

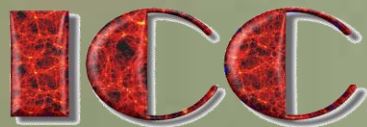
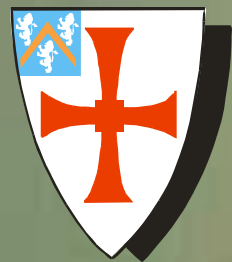


## Dark matter



- ~ radiation
- o particles
- W<sup>+</sup> heavy particles
- W<sup>-</sup> carrying the weak force
- Z
- q quark
- q̄ anti-quark
- e<sup>-</sup> electron

- e<sup>+</sup> positron (anti-electron)
- p proton
- n neutron
- m meson
- H hydrogen
- D deuterium
- He helium
- Li lithium



# The standard model of cosmogony: $\Lambda$ CDM

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# The standard model of cosmogony

⇒  $\Lambda$ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc



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⇒  $\Lambda$ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

... at the expense of:

- dark energy with negative pressure
- structure seeded by quantum (and so Gaussian) fluctuations during inflation
- dark matter in the form of as yet undiscovered (susy?) particles



# The standard model of cosmogony

What are the prospects for testing the 3  
fundamental assumptions of  $\Lambda$ CDM ?



# The standard model of cosmogony

## The formation of structure

- Interesting in its own right
- Broad test of CDM



# The cosmic dark energy

Constraining  $w=p/\rho$ ; modified gravity

current constraints (Guzzo):  $w=-1 \pm 0.1$

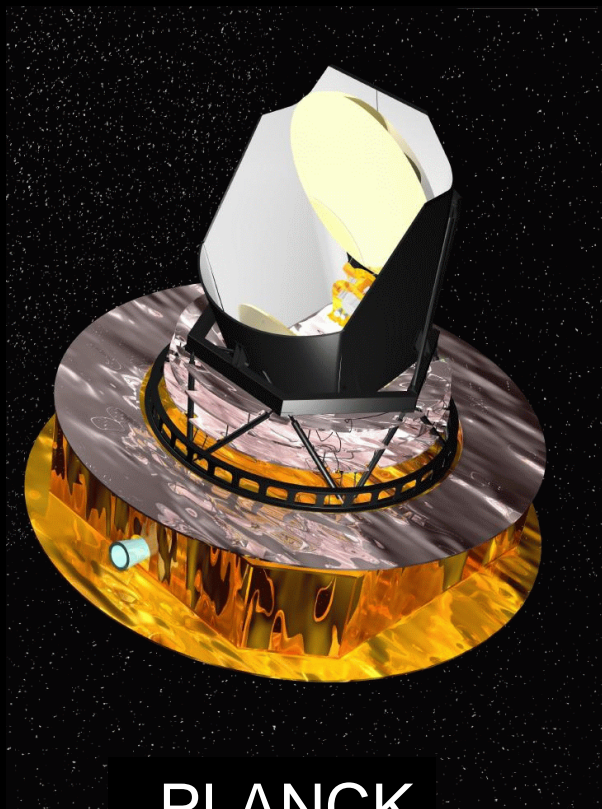
- Growth rate of structure:
  - Cluster  $F(M,z)$  (Takada)
  - Coherent motions (z-space distortions) Guzzo (VIPERS)
  - Song: constraints from SDSS – agree with  $\Lambda$ CDM
  - non-linear corrections and other systematics;
- Geometry: BAOs: want 1% accuracy
  - Galaxy/QSO surveys
  - 21 cm (Chen)
  - Systematic effects? (Taruya, Shafieloo)

# The cosmic dark energy

- Systematic effects? (Taruya, Shafieloo, Jing)
  - Lensing: intrinsic alignments (detected in SDSS) – can model
  - z-space distortion - ?

# Quantum fluctuations from inflation?

- Non-gaussianity:
  - Methods to search for it : Szapudi (ISW), Rossi (CMB), Hellwing (galaxy distr.), Iliev (halo bias at high-z, reionization)
  - Current results (Szapudi): interesting discrepancies
- Gravity waves from inflation (Ganga)



PLANCK

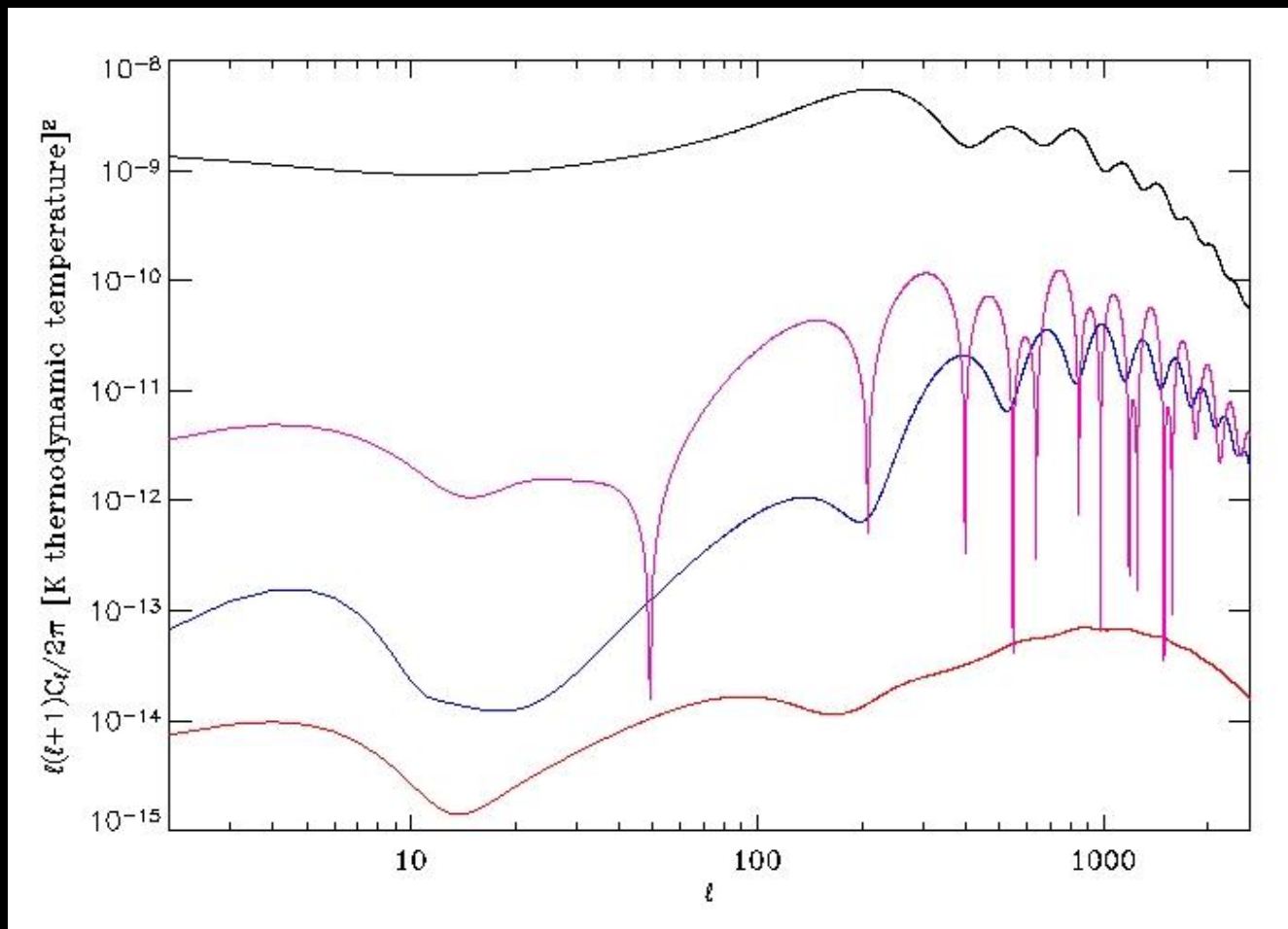
Inflation uniquely predicts tensor mode fluctuations (gravity waves)

could be discovered by Planck  
(polarization power spectrum)

(if we are very lucky)



# CMB angular power spectrum

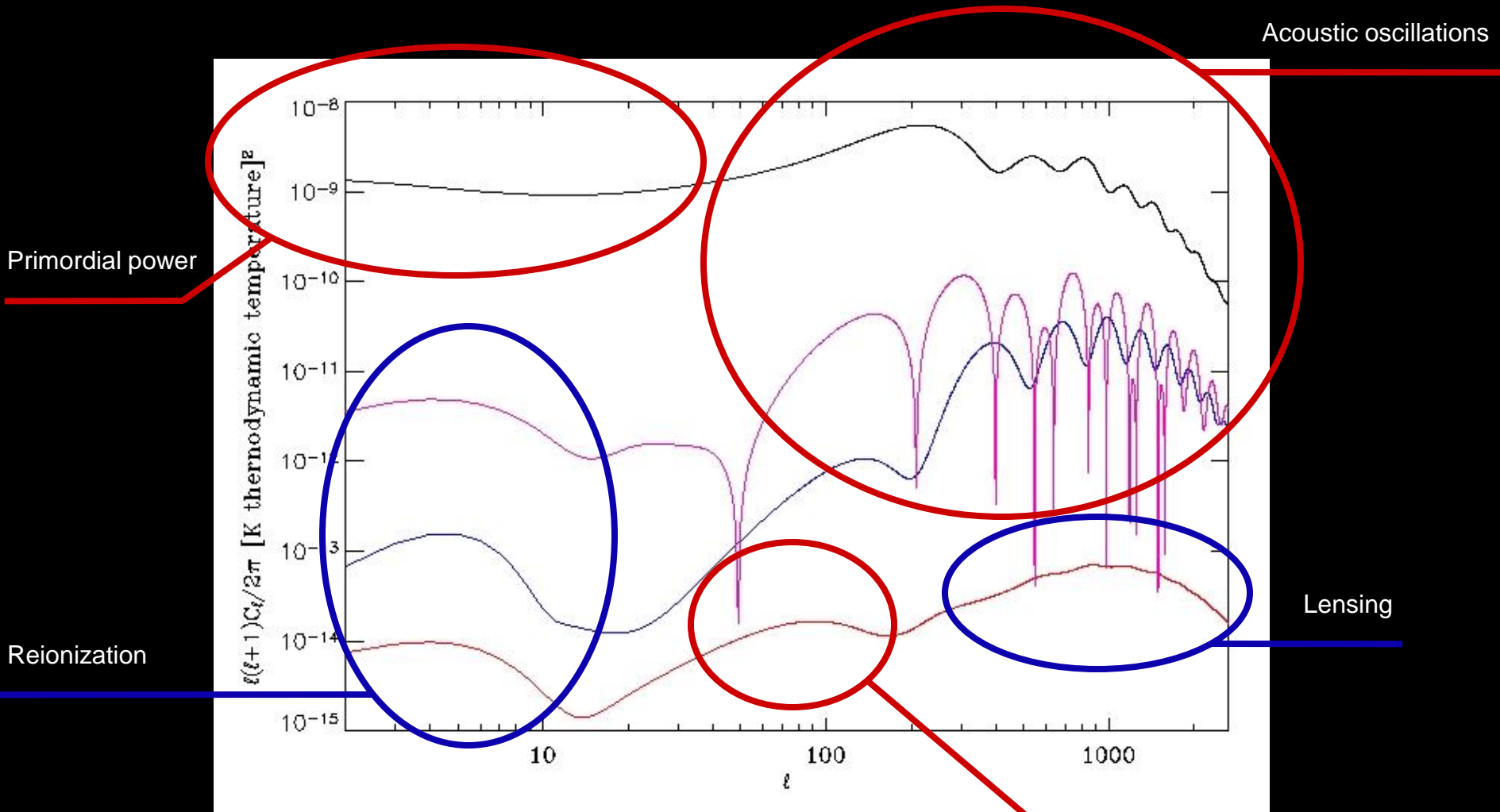


Angle  $\approx 200/\ell$  degrees





# CMB angular power spectrum



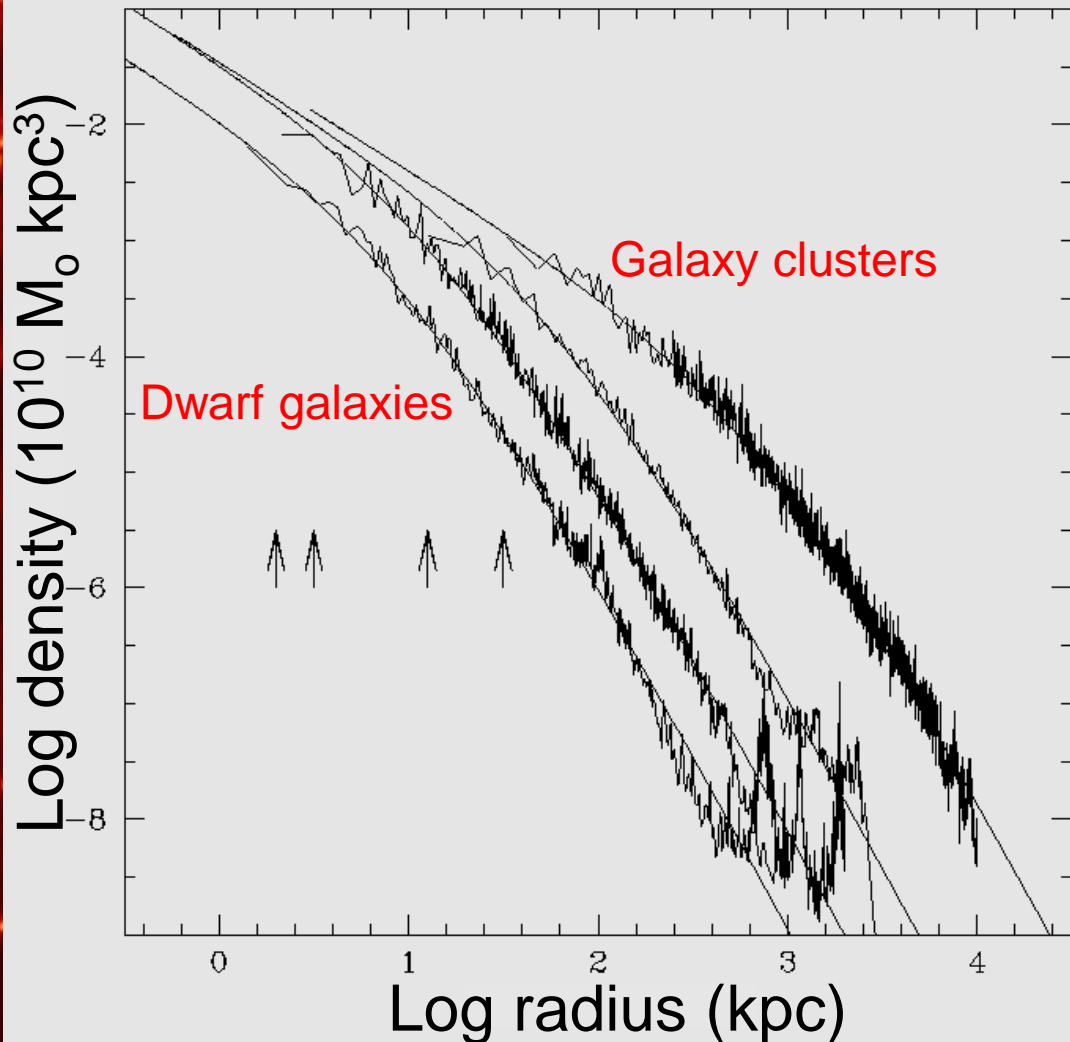
from Carlo Baccigalupi

Angle  $\approx 200/l$  degrees

Gravity waves

Institute for Computational Cosmology

# Cold dark matter?



Halo density profiles are independent of halo mass & cosmological parameters

There is no obvious density plateau or 'core' near the centre.

(Navarro, Frenk & White '97)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

More massive halos and halos that form earlier have higher densities (bigger  $\delta$ )

# Cold dark matter?

- NFW density profile?
  - Clusters: lensing (Takada) → agree with NFW
  - Dwarf spheroidals (CSF) → consistent with NFW
- Satellite problem?
  - CSF, SILK → Galaxy formation: feedback



# The standard model of cosmogony

⇒  $\Lambda$ CDM provides an excellent description of mass power spectrum from 10-1000 Mpc

... at the expense of:

- dark energy with negative pressure ← future surveys?
- structure seeded by quantum fluctuations during inflation ← Testable w. Planck & surveys
- dark matter in the form of as yet undiscovered (susy?) particles ← indirectly (cusps, satellites)



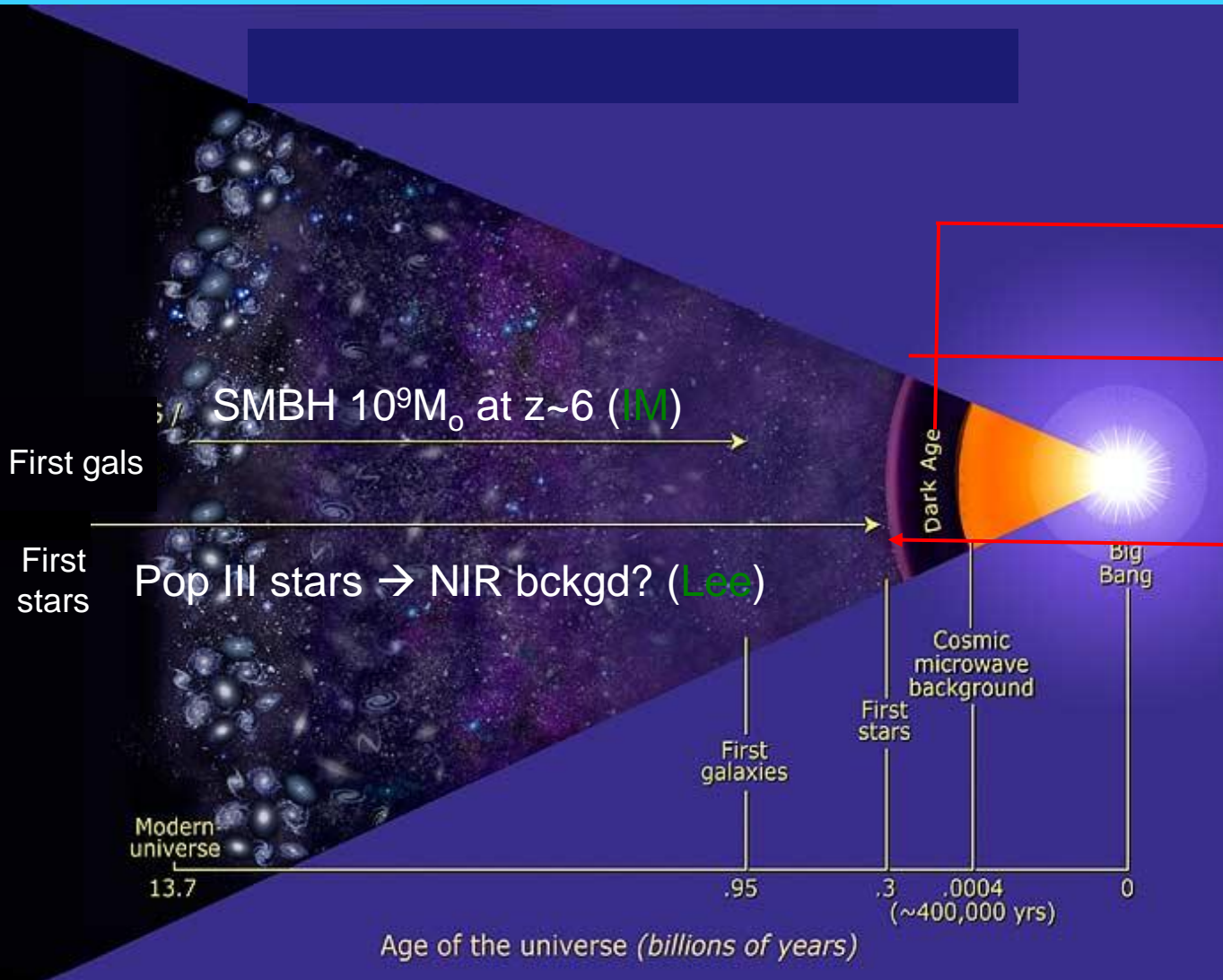
# The standard model of cosmogony

## The formation of structure

- Interesting in its own right
- Broad test of CDM



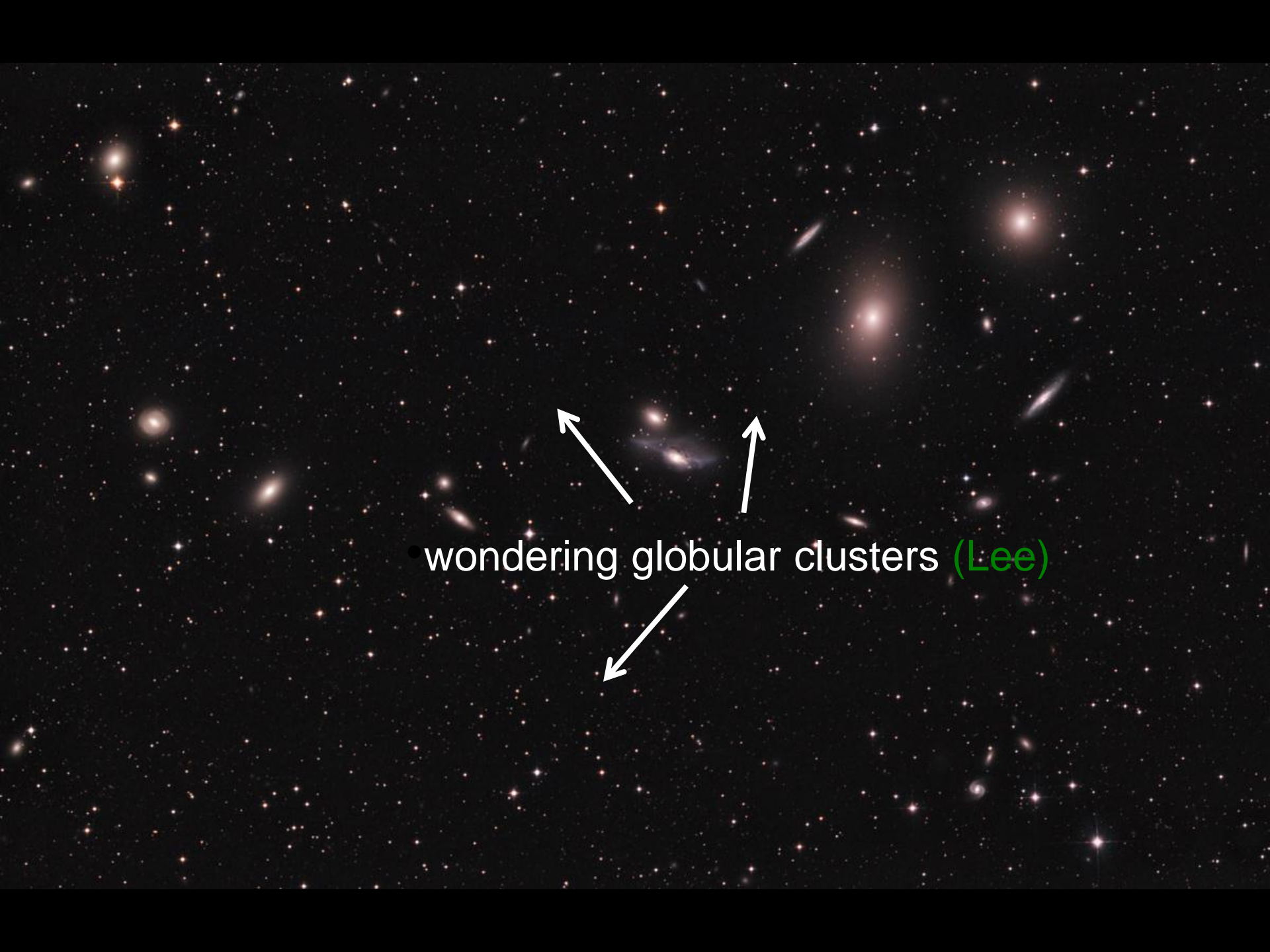
# Formation of structure: early times



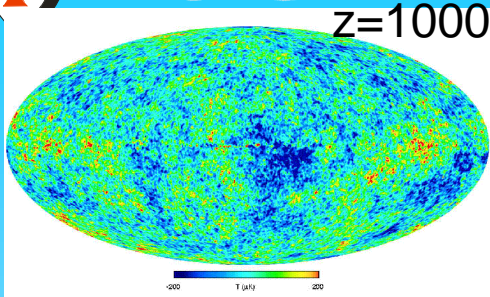
Gas is neutral

observable: LOFAR,  
21cm, WMA

H is reionized at  
 $z \sim (10-6)$  (Iliev:  
simulations;  
Chen:physics)

A deep-field astronomical image showing a vast field of galaxies and stars against a black background. In the center, there is a cluster of galaxies. Three white arrows point from a central text label to three specific objects within this cluster: one pointing up and to the left, one pointing up and to the right, and one pointing down and to the left. The objects appear to be globular clusters or small galaxies.

•wondering globular clusters (Lee)



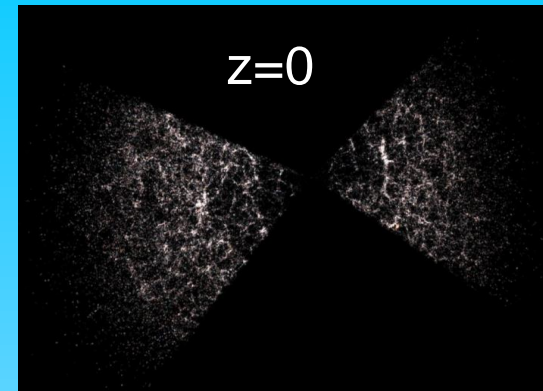
## Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$ ; dark matter

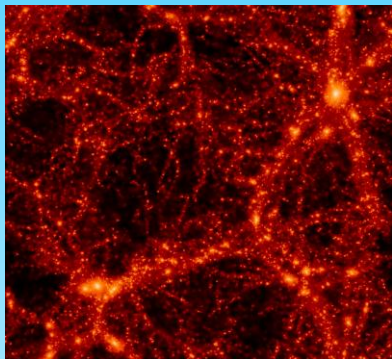
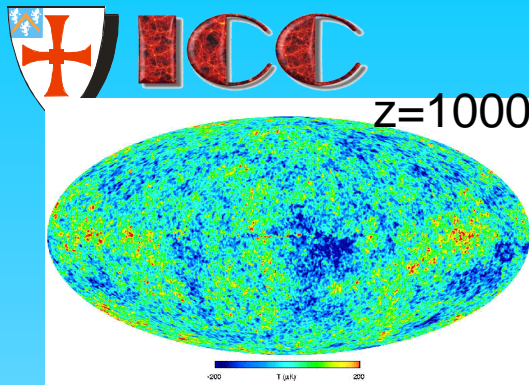


## Primordial fluctuations

$$\delta\rho/\rho(M, t)$$



Formation and evolution of galaxies



## Cosmological model

$(\Omega_m, \Omega_\Lambda, h)$ ; dark matter

## Primordial fluctuations

$$\delta\rho/\rho(M, t)$$

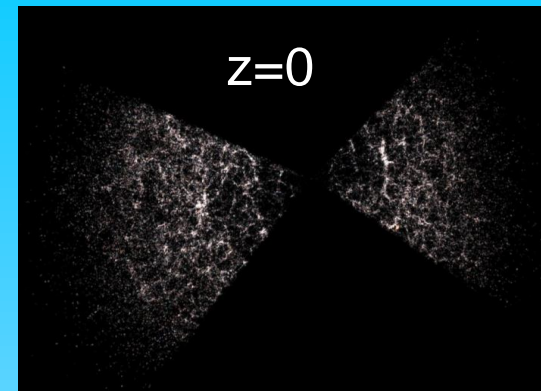
Dark matter halos  
(N-body simulations)

Gas processes  
(cooling, star formation, feedback)

Gasdynamic simulations

Semi-analytics

Formation and evolution of galaxies

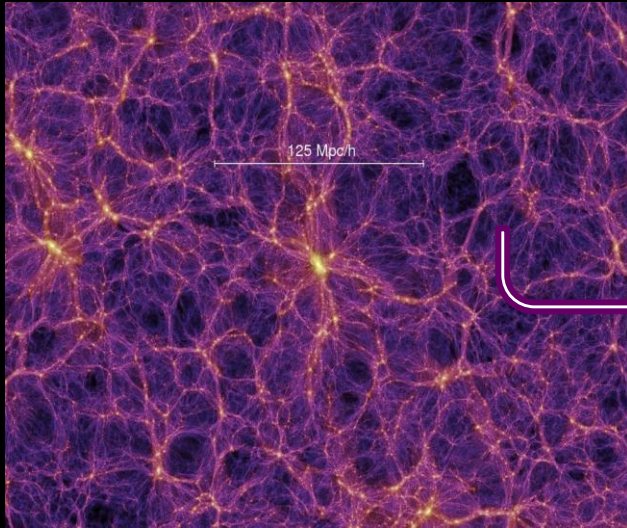




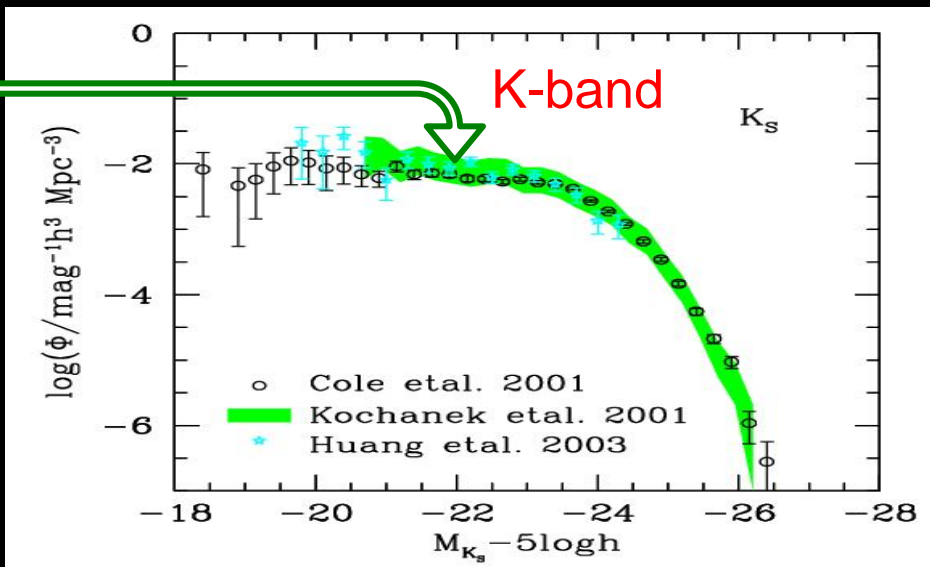
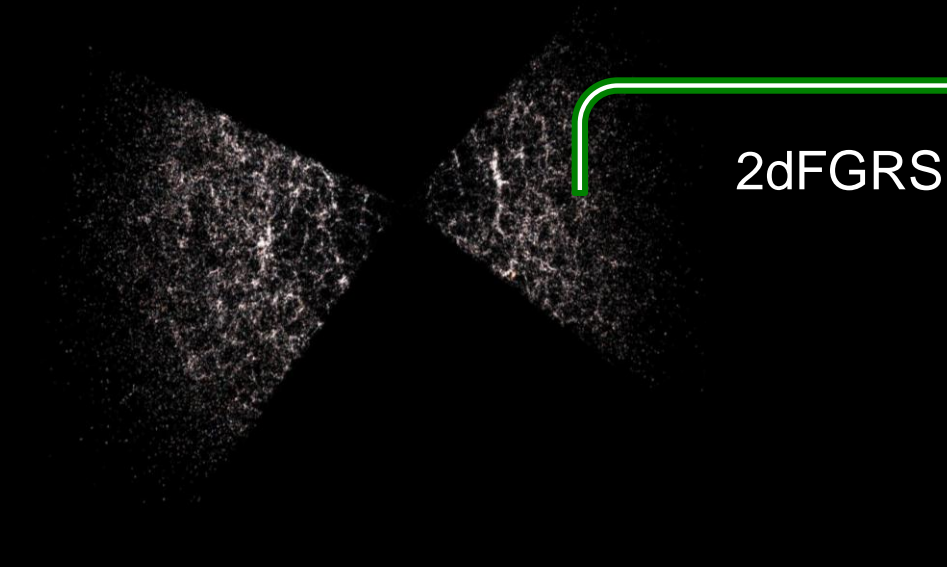
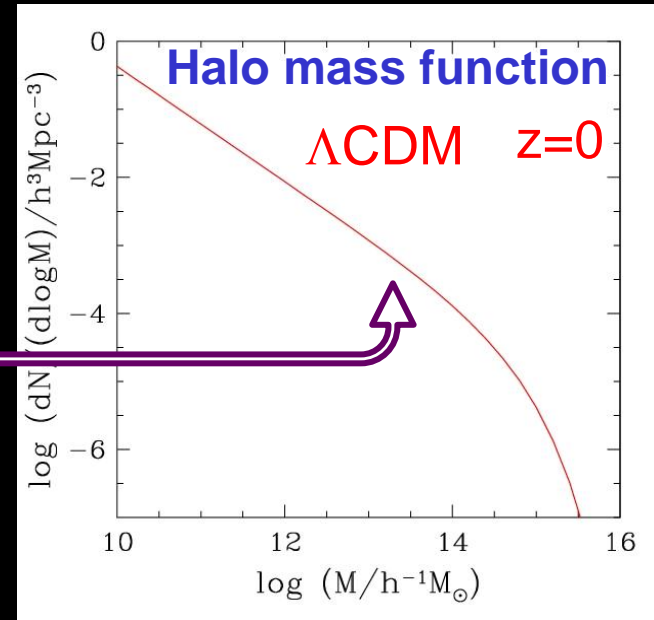




# The abundance of dark halos



Millennium run

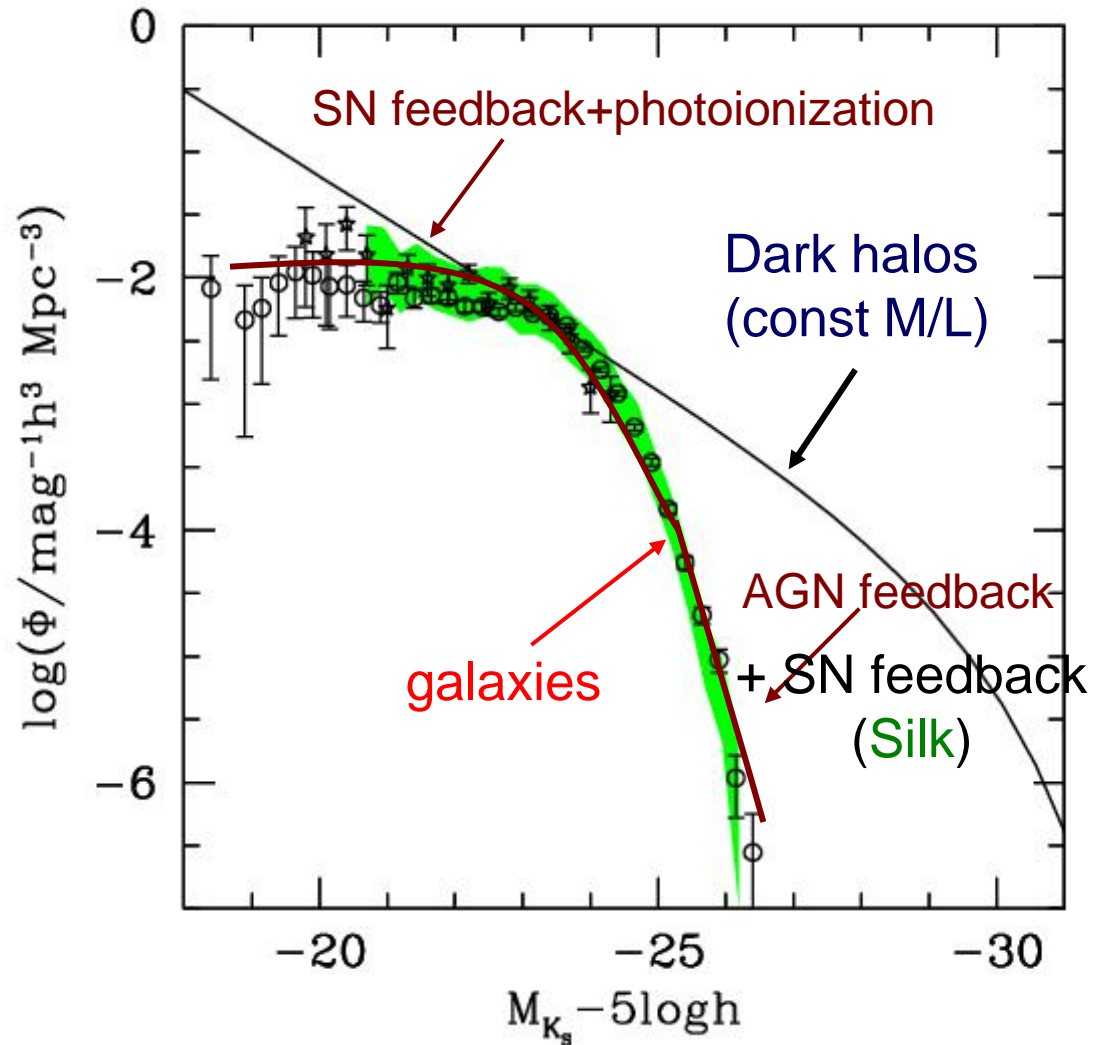


# The galaxy luminosity function

The halo mass function and the galaxy luminosity function have different shapes



Complicated variation of M/L with halo mass



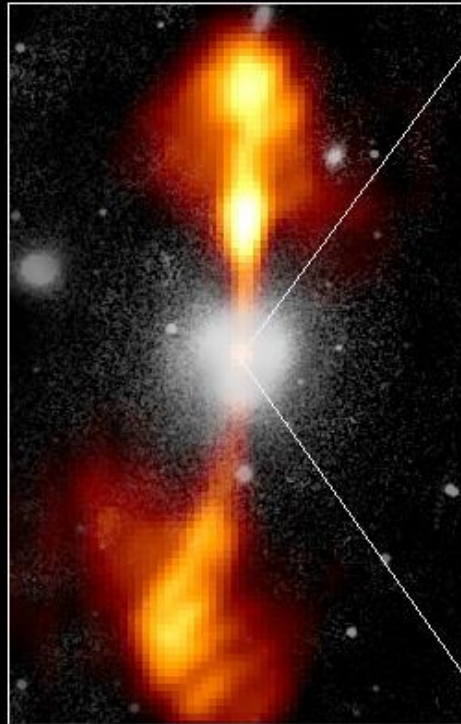


# Core of Galaxy NGC 4261

Hubble Space Telescope

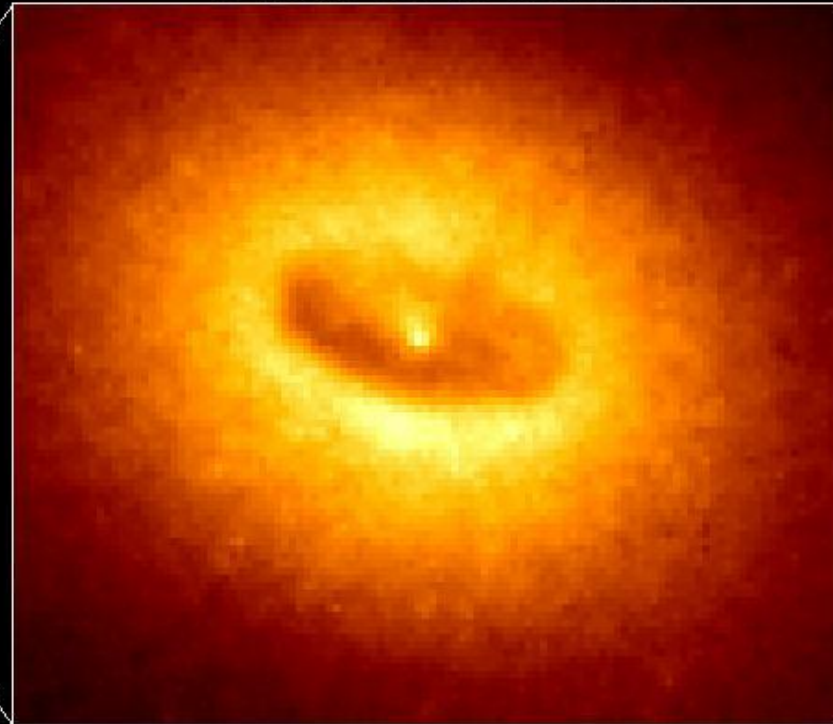
Wide Field / Planetary Camera

Ground-Based Optical/Radio Image



380 Arc Seconds  
88,000 LIGHT-YEARS

HST Image of a Gas and Dust Disk



17 Arc Seconds  
400 LIGHT-YEARS

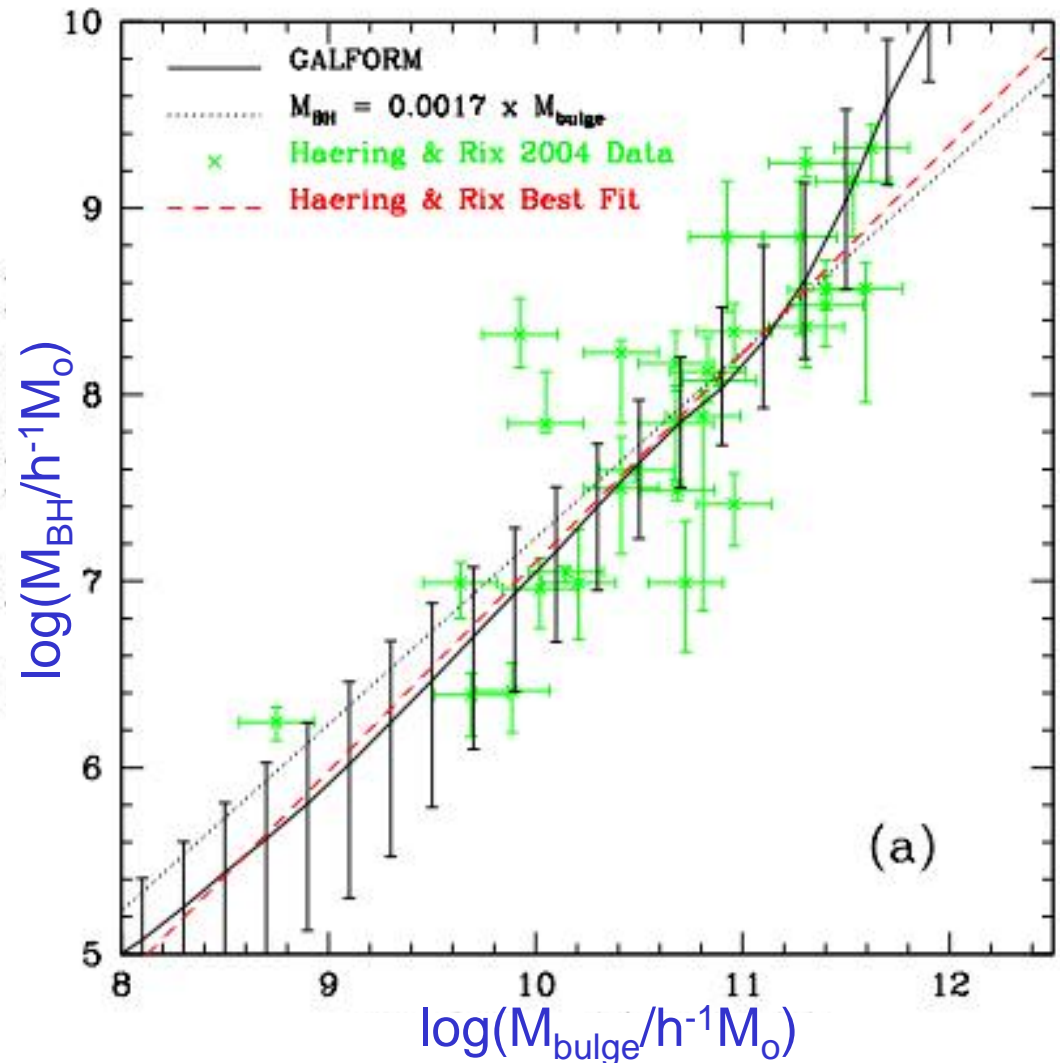
Radio jets → to bubbles that rise buoyantly and deposit energy into the ICM

# The black hole – galaxy connection

The  $M_{\text{BH}}$  -  $M_{\text{bulge}}$  relation



BH growth – gal formation

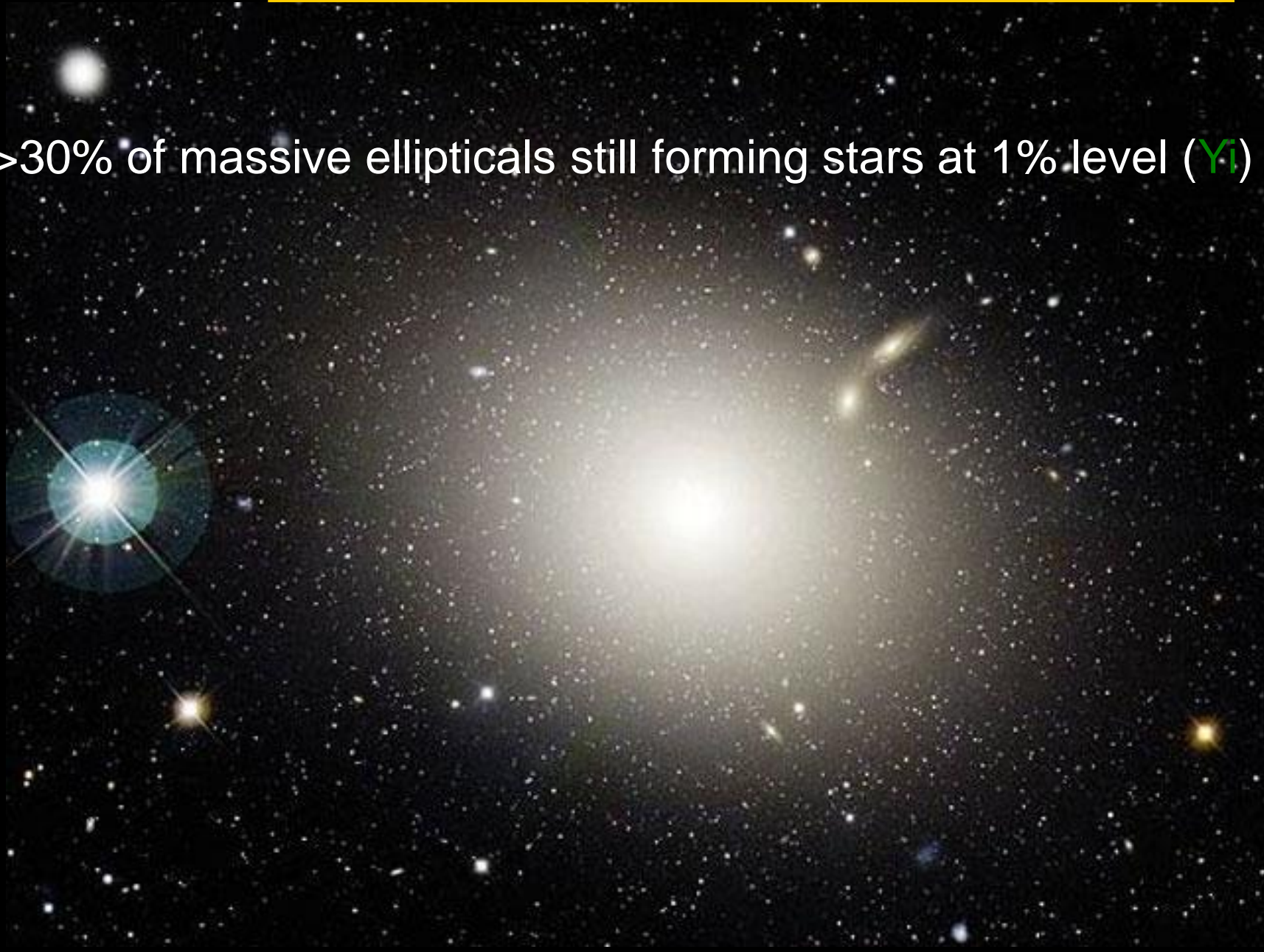






# The formation of cosmic structure

>30% of massive ellipticals still forming stars at 1% level (Yi)





31.25 Mpc/h



$z = 0.0$



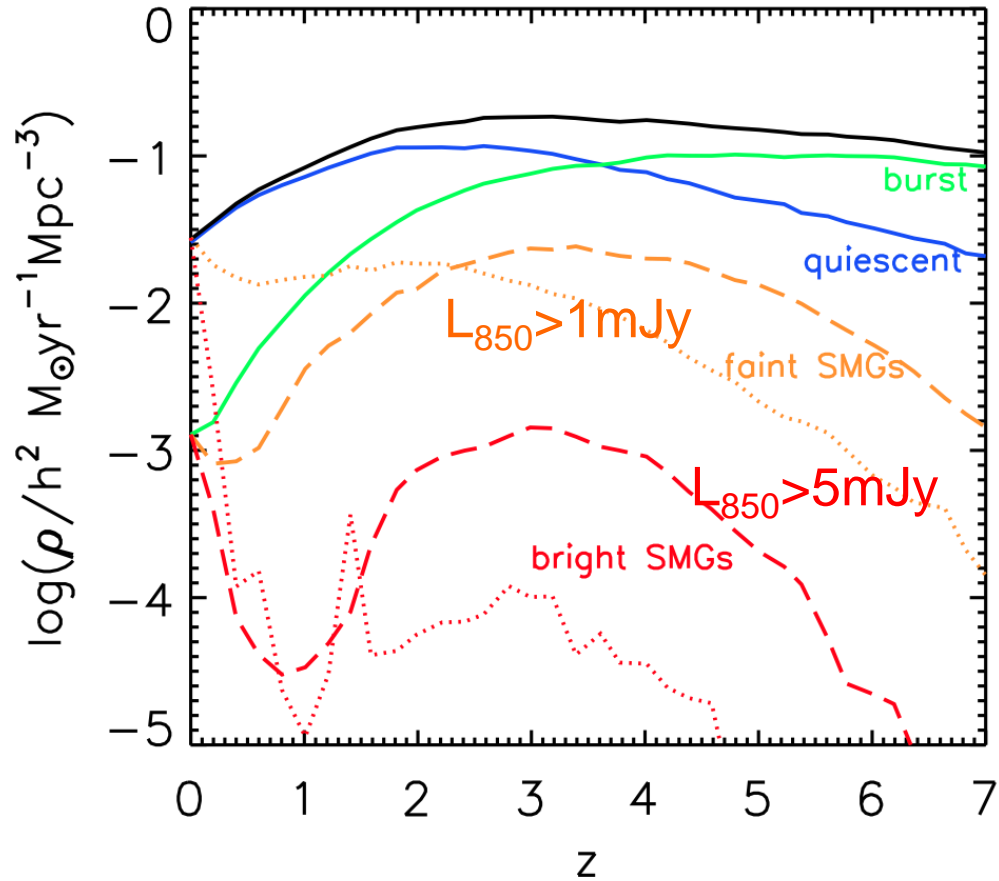
Suppression of star formation in voids is required to match  
CDM theory to obs

Voids have more neutral H and void gals  
have higher SFR



# The cosmic star formation

Kim



Hwang



The “golden” era in cosmology is not over

A night photograph of a city skyline reflected in water. The city is illuminated with warm lights, and the lights are reflected in the calm water in the foreground. The sky is dark, and the overall scene is peaceful and serene.

It has probably just begun!



