

# ASTRONOMÍA EXTRAGALÁCTICA

Marc HUERTAS-COMPANY

[mhuertas@iac.es](mailto:mhuertas@iac.es)

TUTORIAS: LUNES Y VIERNES DE 11h a 13h  
*[CON PREVIO AVISO]*

# EVALUACIÓN

## DOS PARTES:

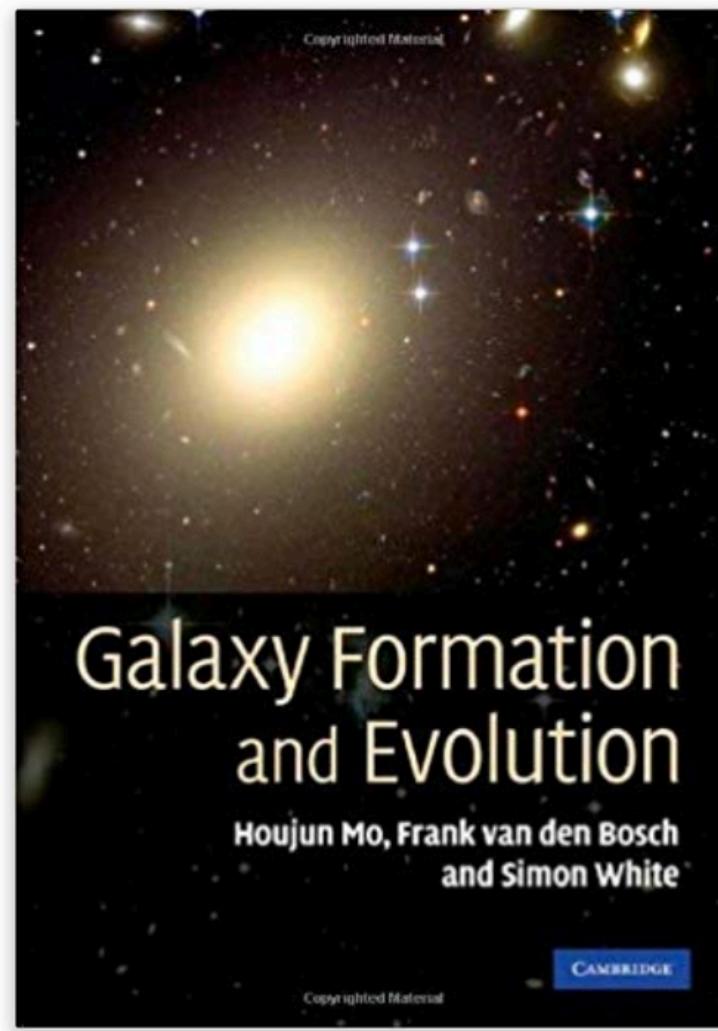
1. EVALUACIÓN CONTINUA: DOS PRÁCTICAS

2. EXAMEN ORAL: PRESENTACIÓN DE UN ARTÍCULO CIENTÍFICO

ONLINE  
RESSOURCES:

<https://github.com/mhuertascompany/UllM1extragal>

# BIBLIOGRAPHY



# OBJECTIVES

**THIS INTRODUCTORY COURSE IS THOUGHT TO PROVIDE A GLOBAL  
OVERVIEW OF THE FIELD OF GALAXY FORMATION IN A COSMOLOGICAL  
CONTEXT**

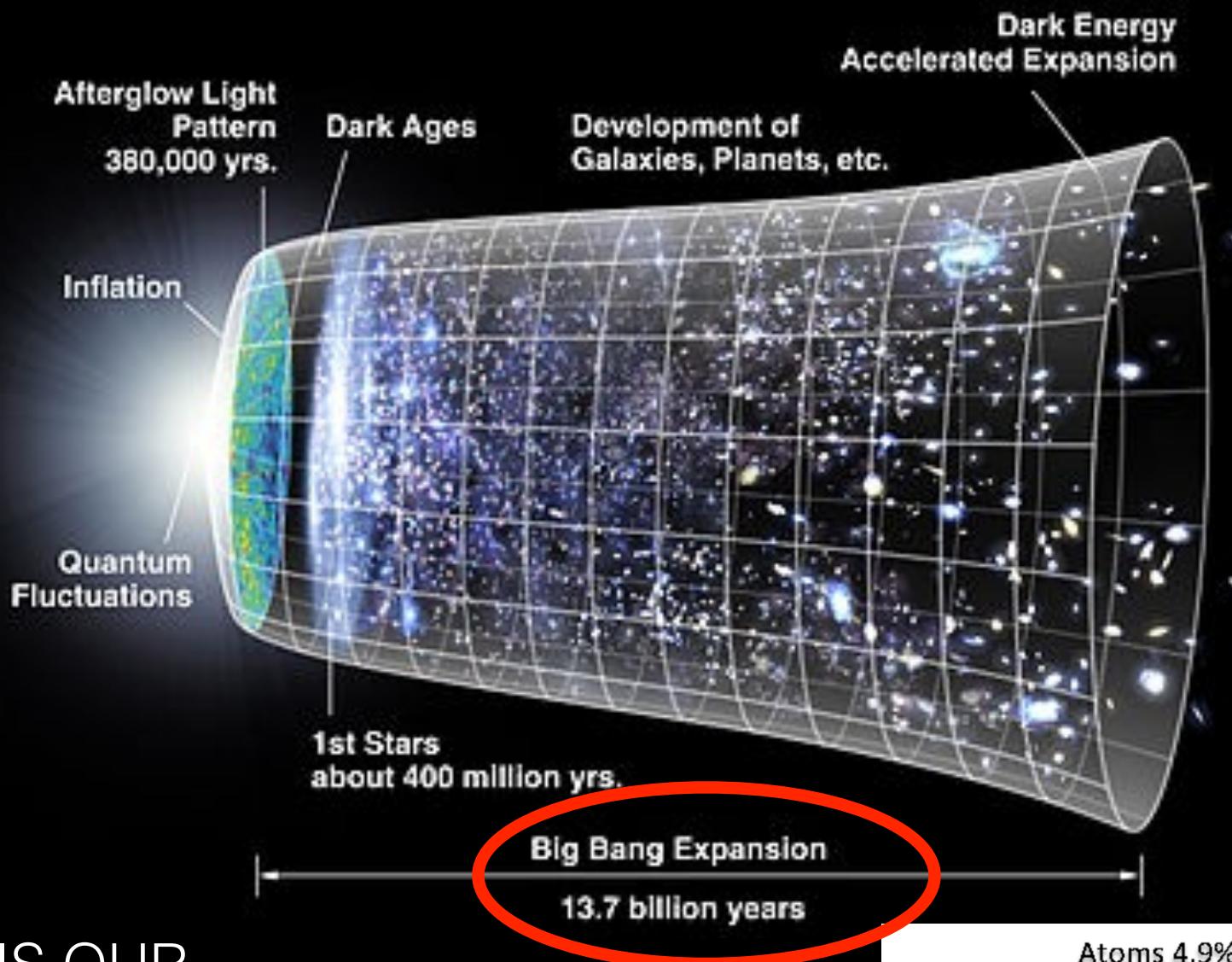
**WE WILL OVERVIEW THE MAIN CURRENT UNDERSTANDING AND  
INGREDIENTS IN GALAXY FORMATION**

**MOST OF THE ELEMENTS WILL BE PRESENTED QUALITATIVELY WITHOUT  
ENTERING IN THE EXACT DETAILS OF THE PHYSICAL PROCESSES**

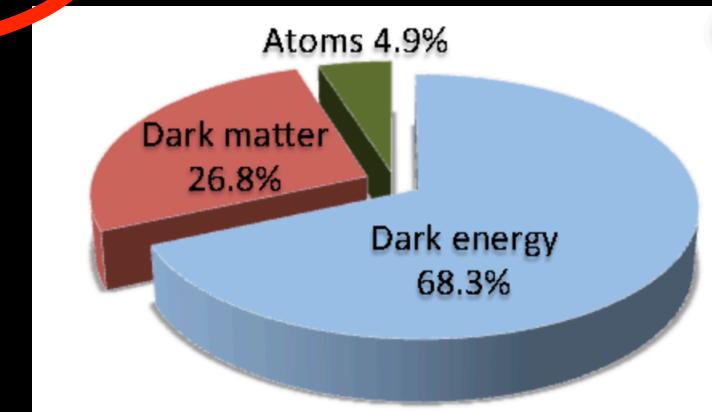
# PROGRAM

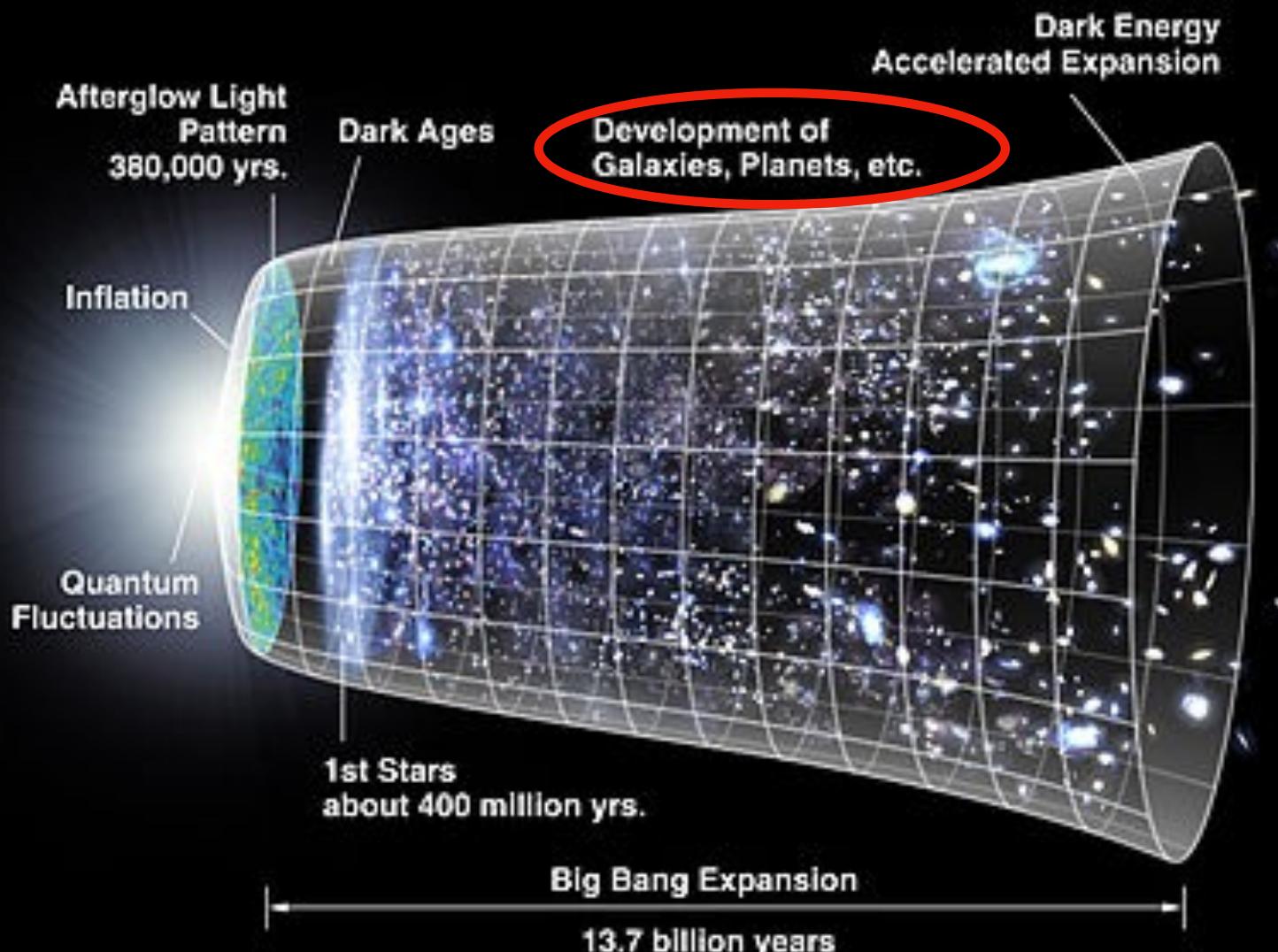
## [Preliminary]

- A GLOBAL UPDATED OVERVIEW OF GALAXY FORMATION
- STAR FORMATION AND FEEDBACK
- GALAXY MERGERS
- GALAXY EVOLUTION IN THE LAST 8Gyrs - MAIN MILESTONES
- ***METHODS:*** MACHINE LEARNING FOR GALAXY MORPHOLOGY ESTIMATION

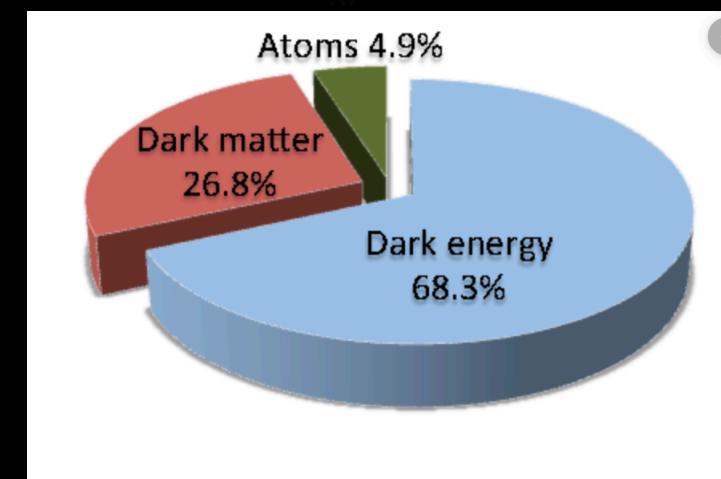


THIS IS OUR  
CURRENT  
UNDERSTANDING OF  
THE HISTORY  
OF THE UNIVERSE





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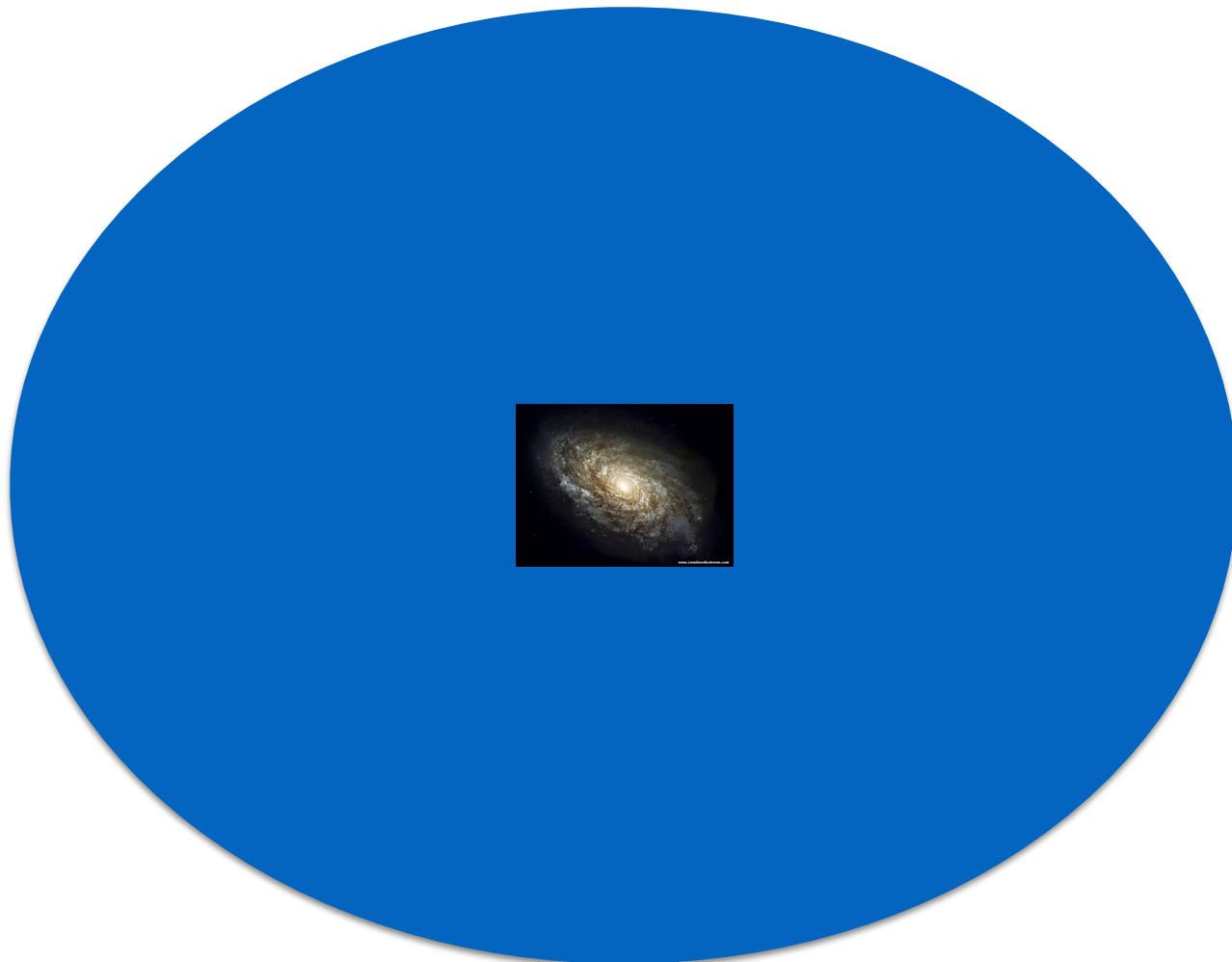


# WHAT ARE GALAXIES?

**HUGE COLLECTION  
OF GAS, STARS AND  
DUST**

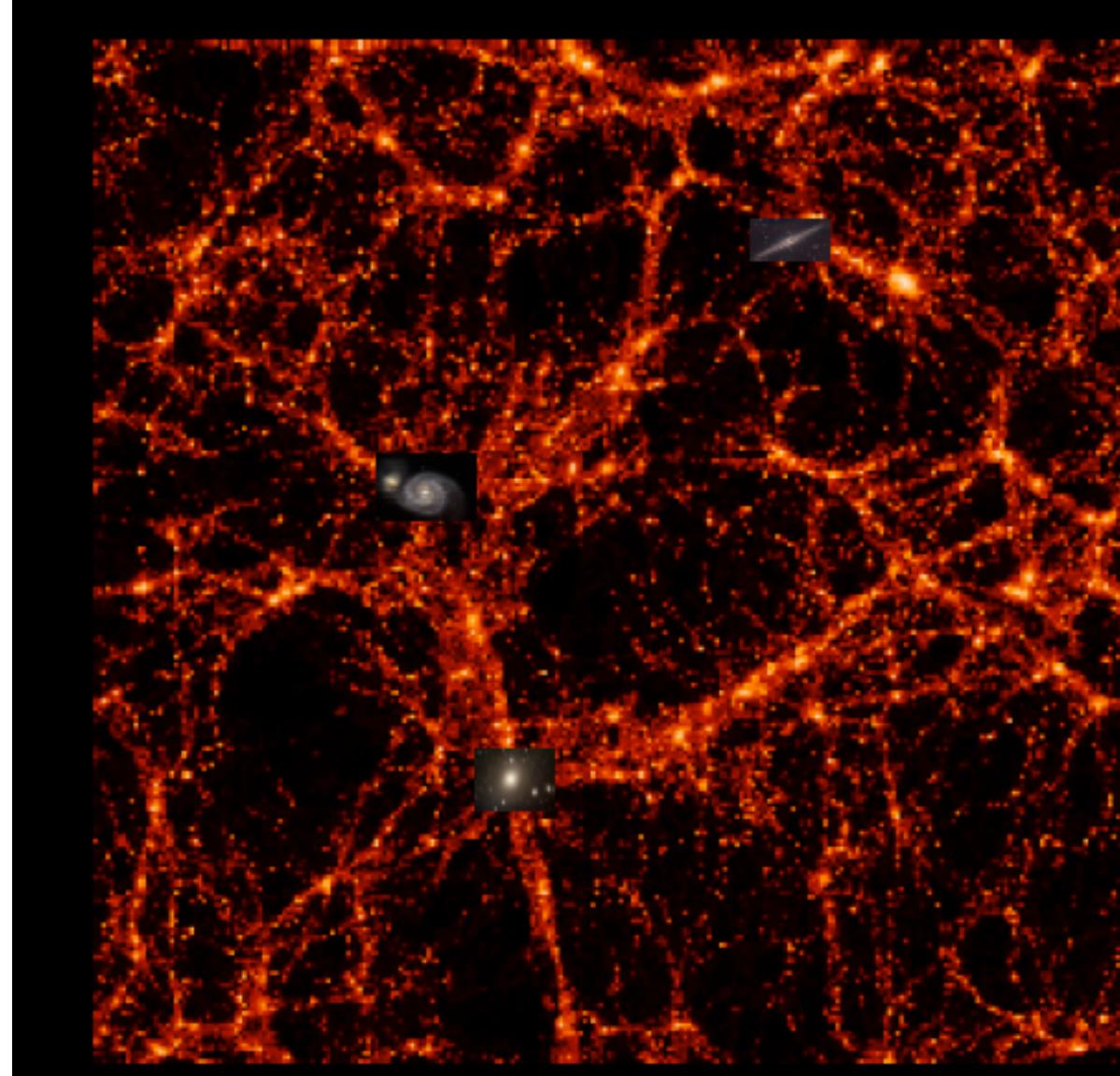


# GALAXY

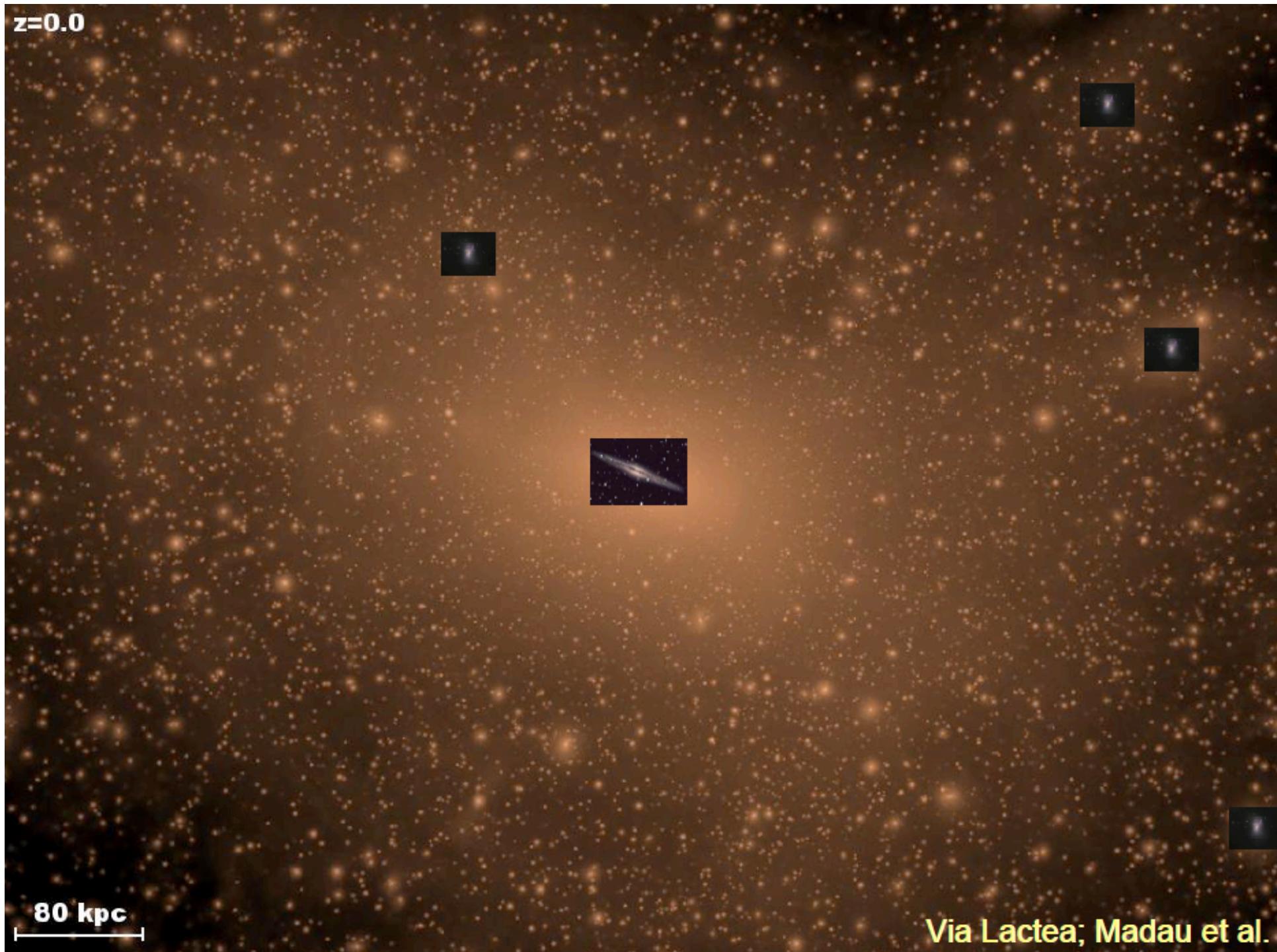


“A dark matter potential well with a small fraction of baryonic matter in the central regions”

**SMALL “BLOBS” OF  
NORMAL  
MATTER IN A  
HUGE DARK  
MATTER HALO**

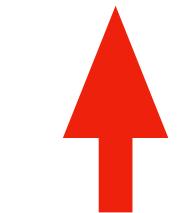


**z=0.0**

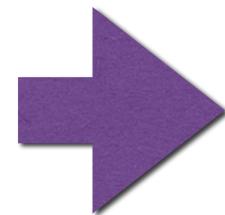


Via Lactea; Madau et al.

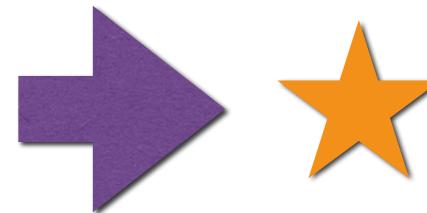
GAS IN  
ASTRONOMY  
MEANS  
HYDROGEN...



**GAS**



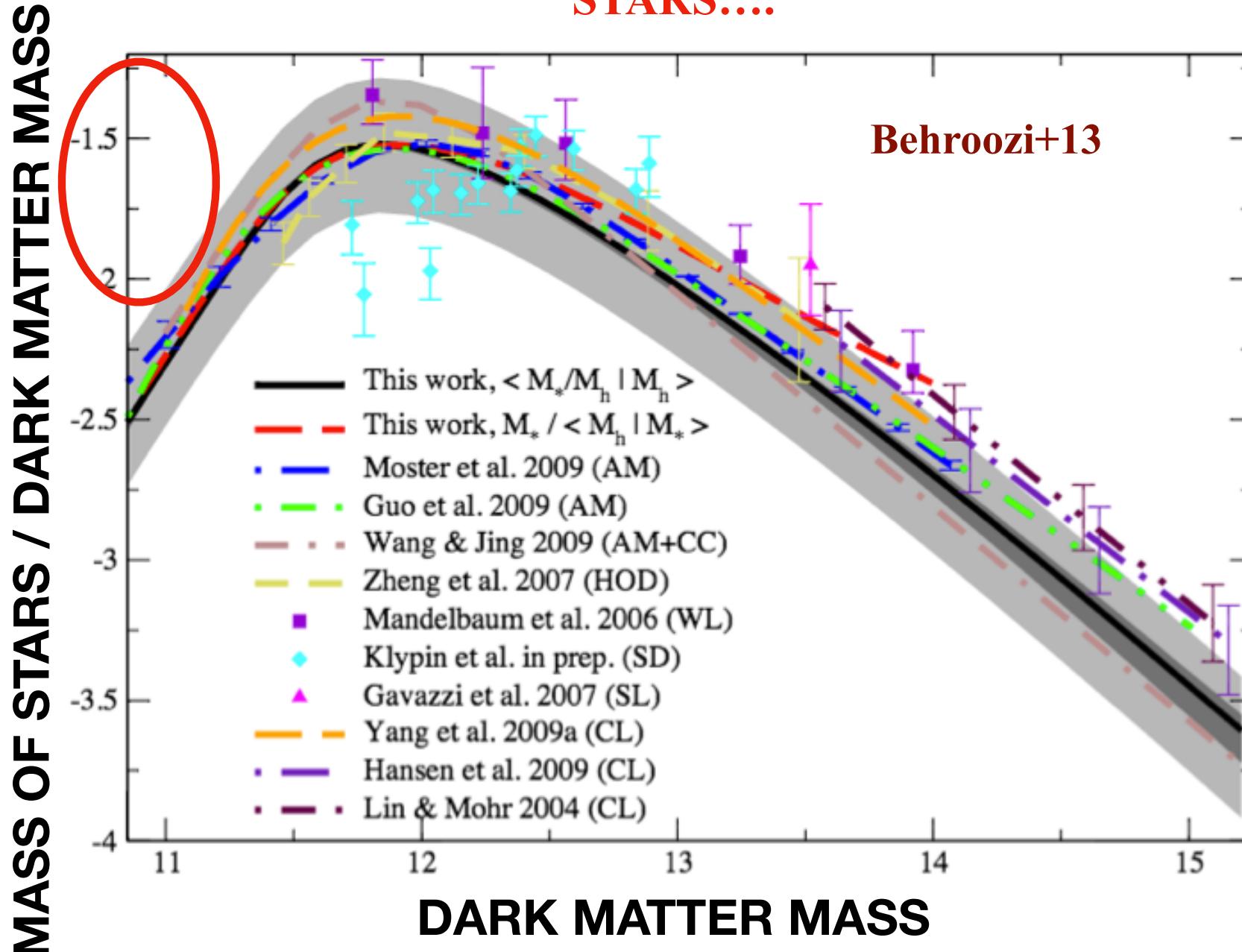
**STAR-FORMATION RATE (SFR)**  
A KEY OBSERVABLE...  
TYPICALLY MEASURED IN  
“SOLAR MASSES / YEAR”



**STARS**

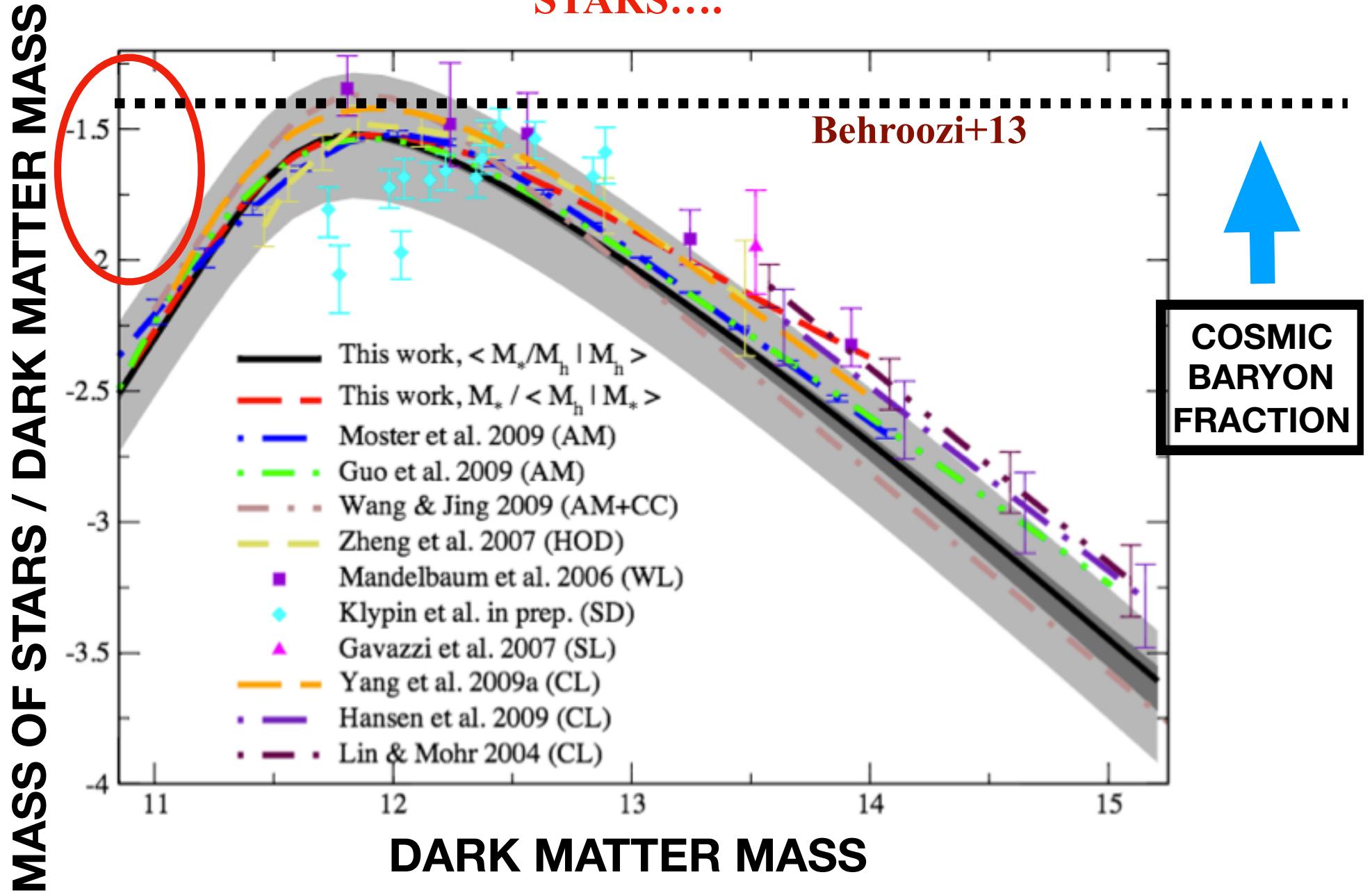
**GALAXIES ARE “MACHINES” THAT FORM STARS**

# ONLY A SMALL FRACTION OF THE GAS IS CONVERTED INTO STARS....



... WE WILL COME BACK LATER TO THIS KEY PLOT...

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# **UNDERSTANDING GALAXIES...**

**MEANS UNDERSTANDING THE  
PROCESSES THAT TRANSFORM  
GAS INTO STARS**

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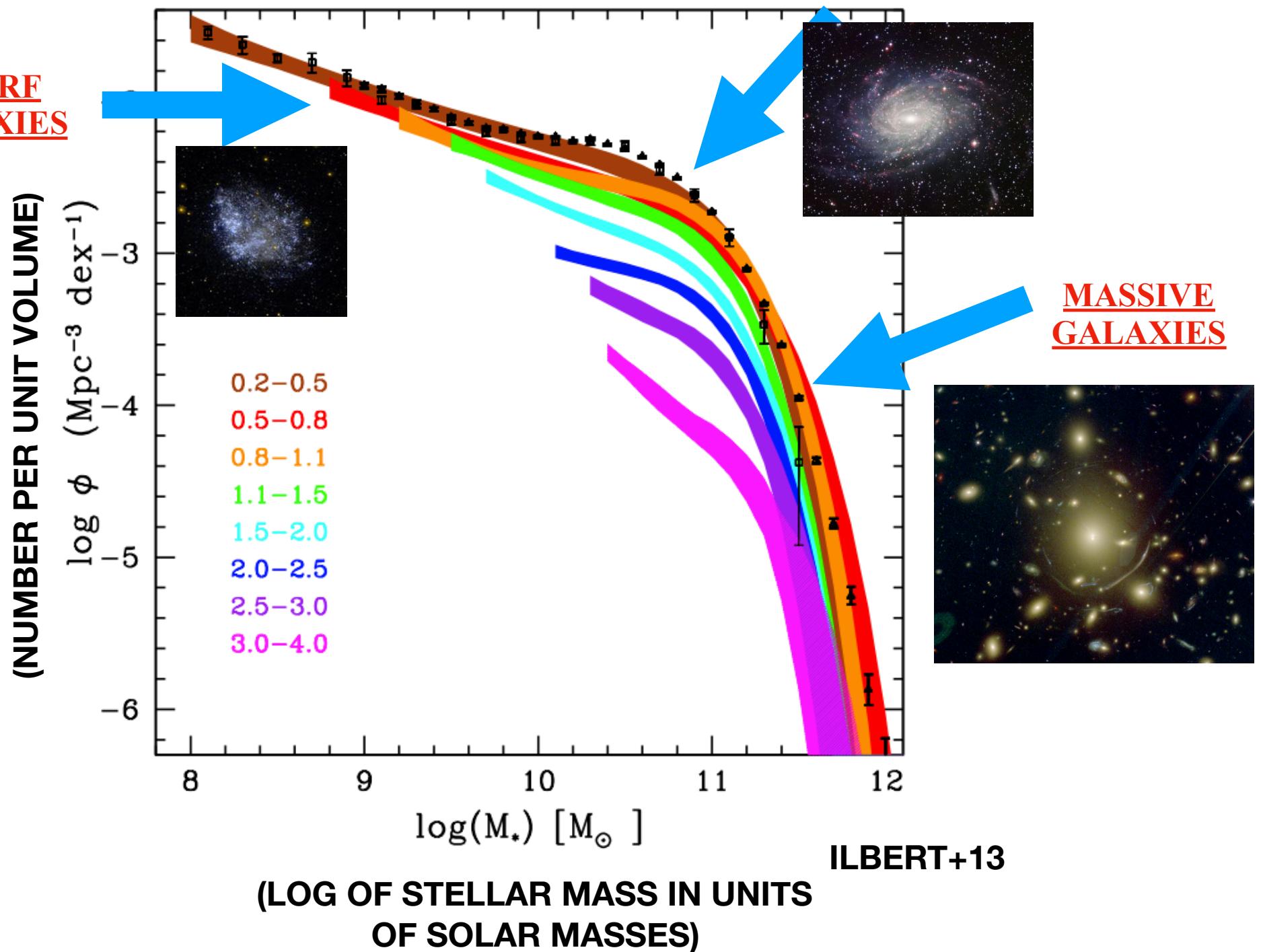


STELLAR MASS:  
HOW MANY STARS HAVE BEEN  
PRODUCED

GAS FRACTION:  
AVAILABLE AMOUNT  
OF FUEL TO *FEED* STAR FORMATION

## MILKY-WAY TYPE GALAXIES

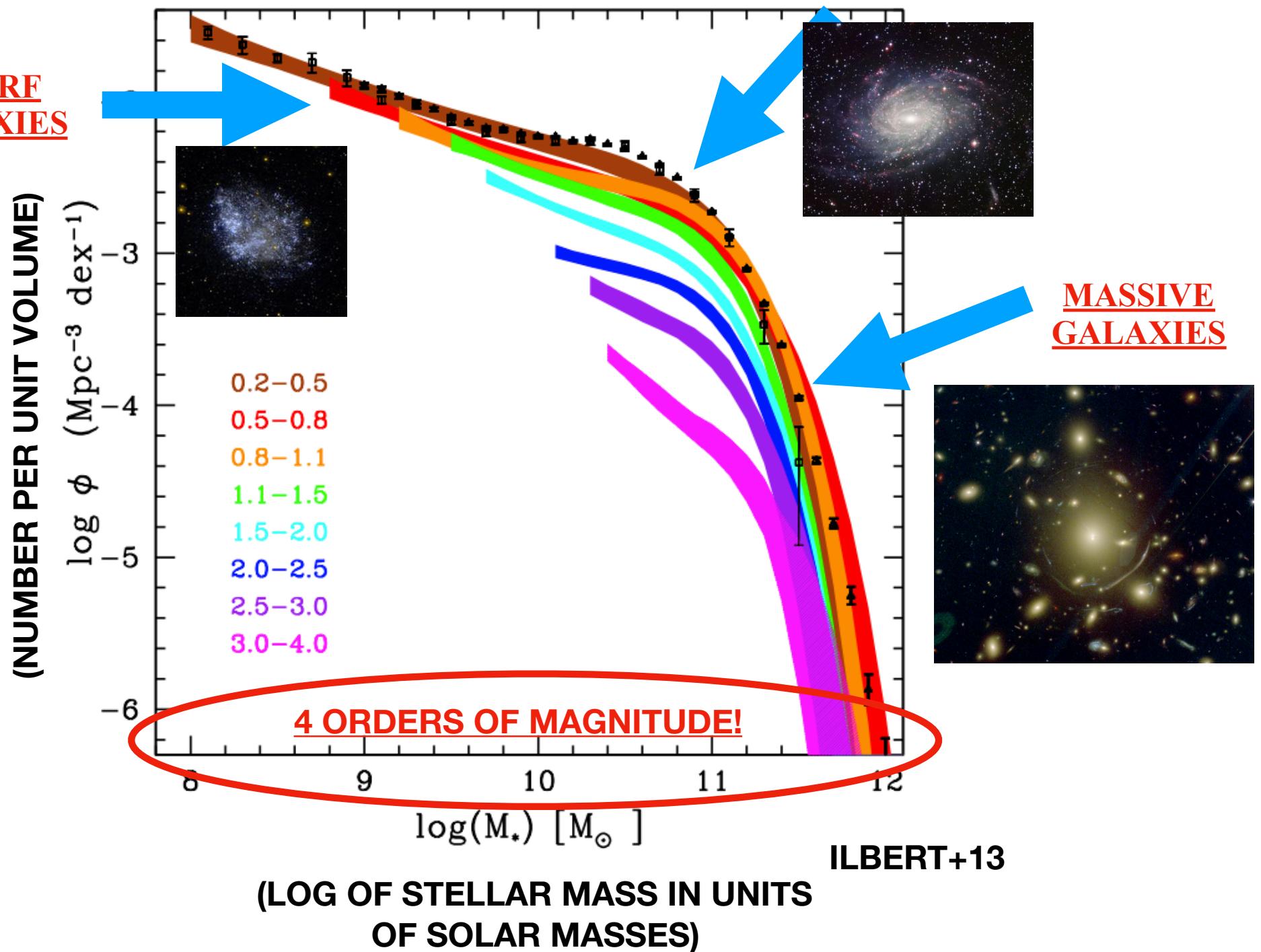
DWARF  
GALAXIES



MASSIVE  
GALAXIES

## MILKY-WAY TYPE GALAXIES

DWARF  
GALAXIES

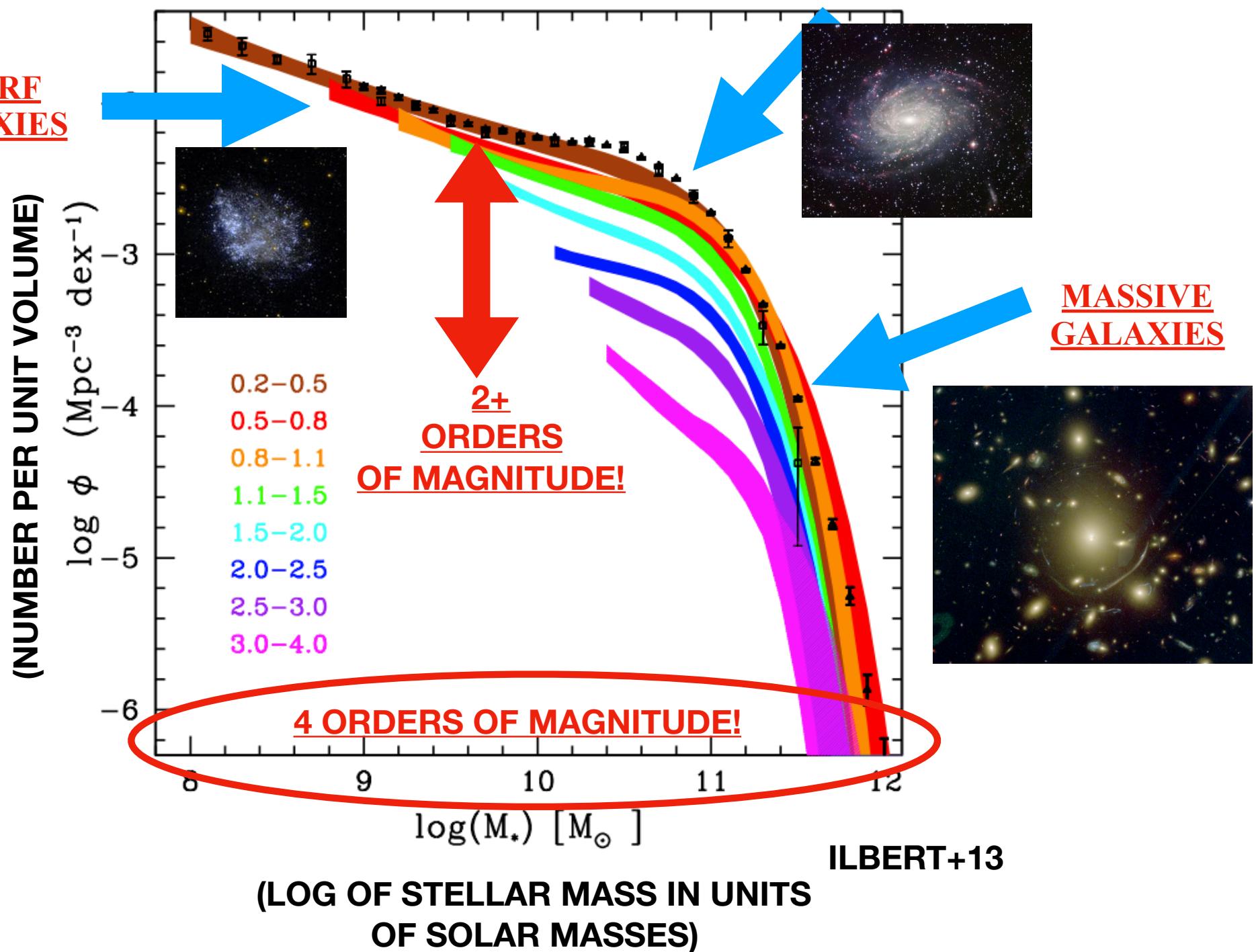


MASSIVE  
GALAXIES

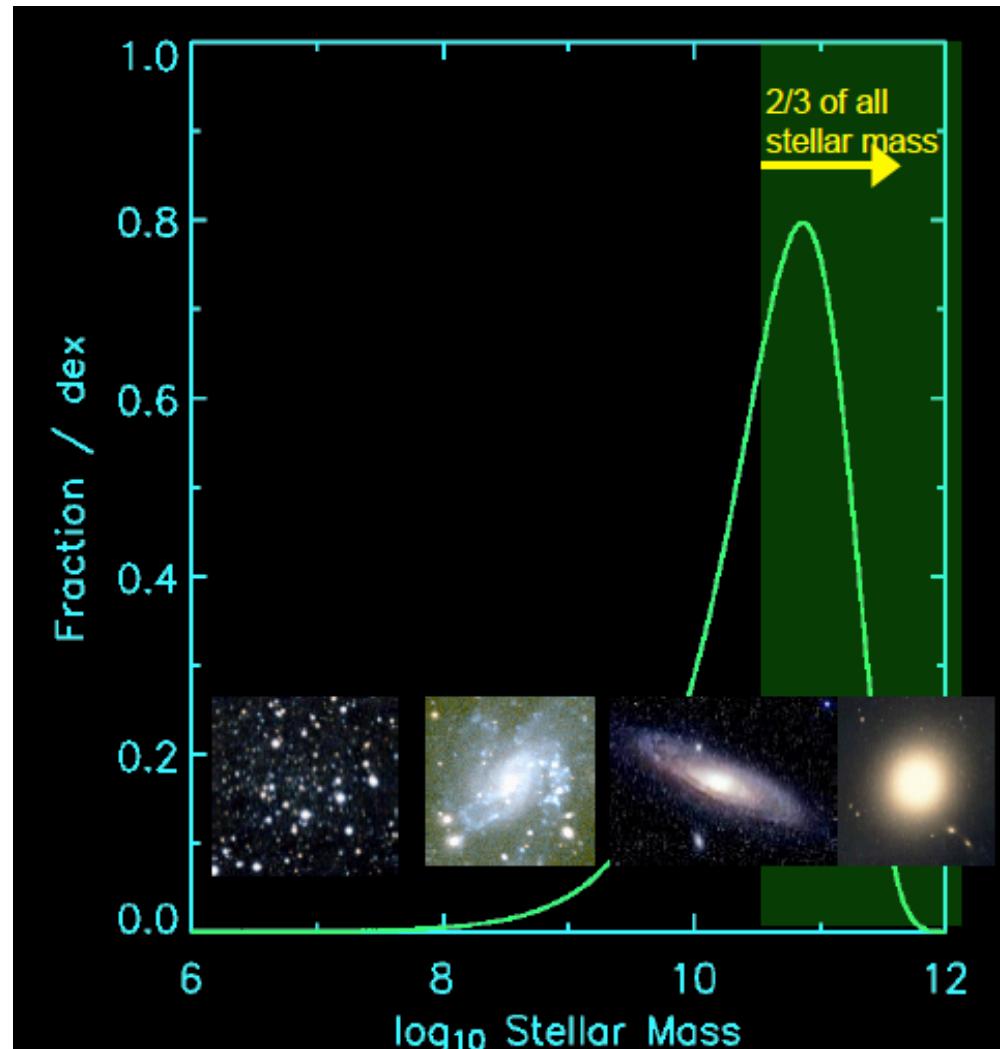
## MILKY-WAY TYPE GALAXIES

DWARF  
GALAXIES

MASSIVE  
GALAXIES

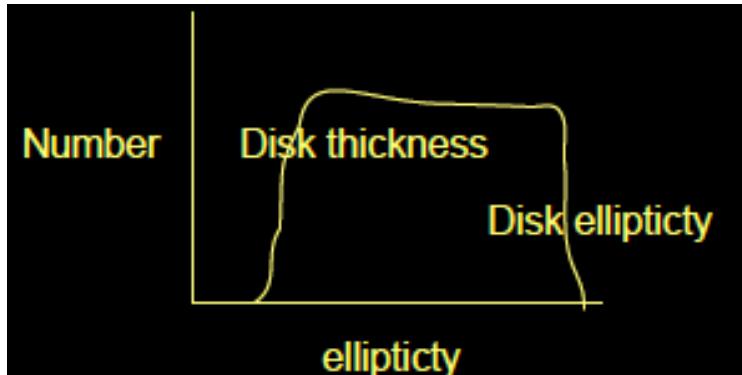


# MASSIVE GALAXIES DOMINATE STELLAR MASS OF THE UNIVERSE [EVEN IF LESS ABUNDANT IN NUMBERS]

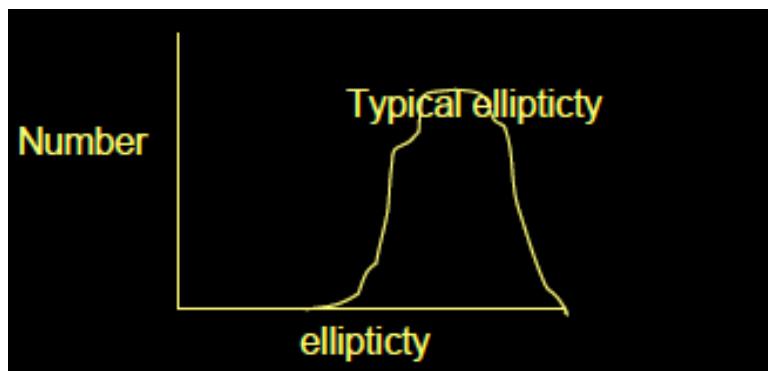


BELL+03

# GALAXY STRUCTURE



***DISKS -  
CONSERVED SOME ANGULAR MOMENTUM***

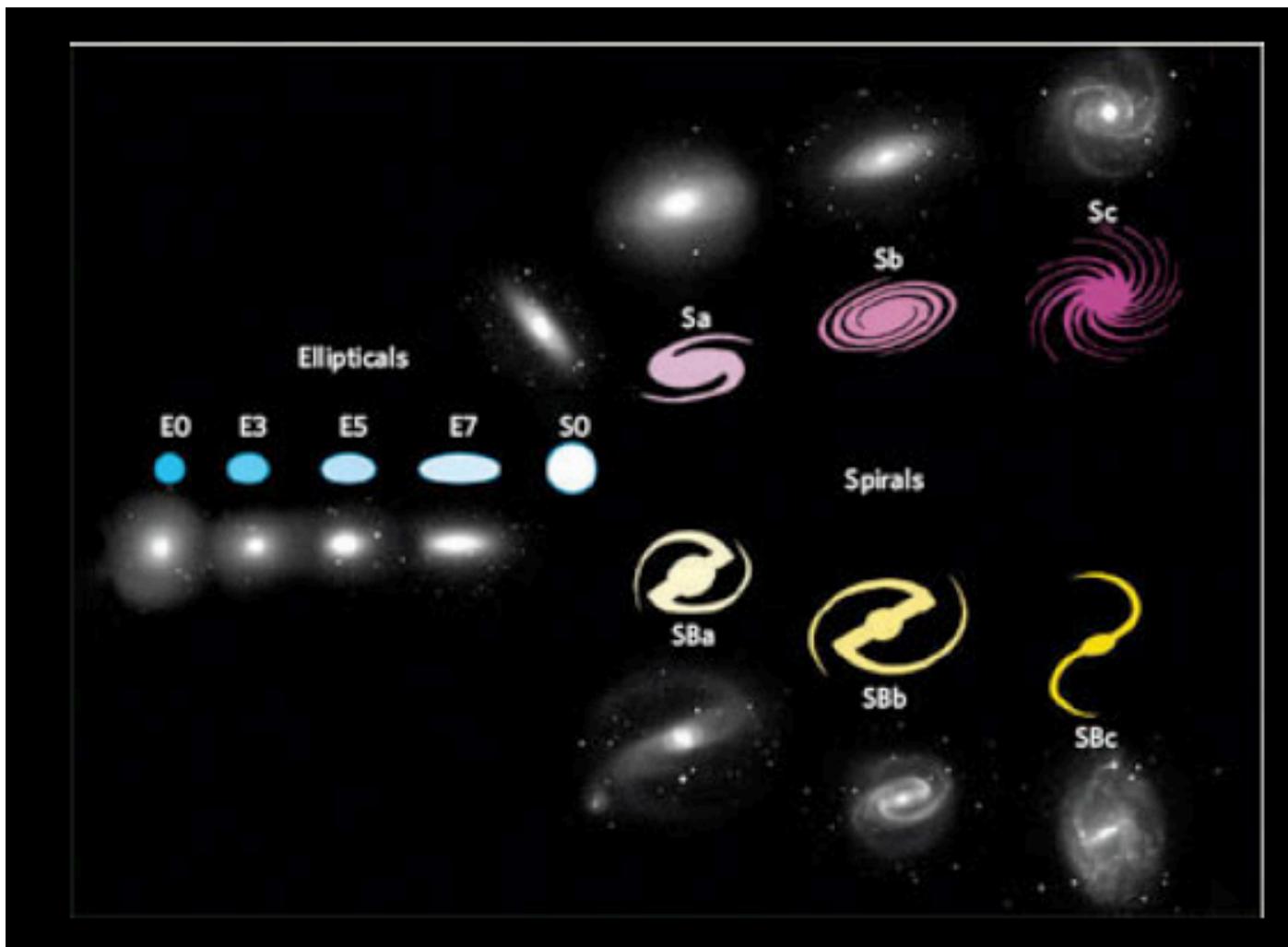


***SPHEROIDS -  
LOST ALL ANGULAR MOMENTUM***



# GALAXY STRUCTURE

## THE HUBBLE SEQUENCE



# WHAT ABOUT GAS?

**MAIN BODY OF GALAXIES (<30 Kpc) PRESENTS A WIDE RANGE  
OF GAS CONTENTS...**

**FROM ALMOST GAS FREE TO ~80% OF COLD GAS (HI/HII)**  
**(ALSO CHANGES WITH TIME...)**

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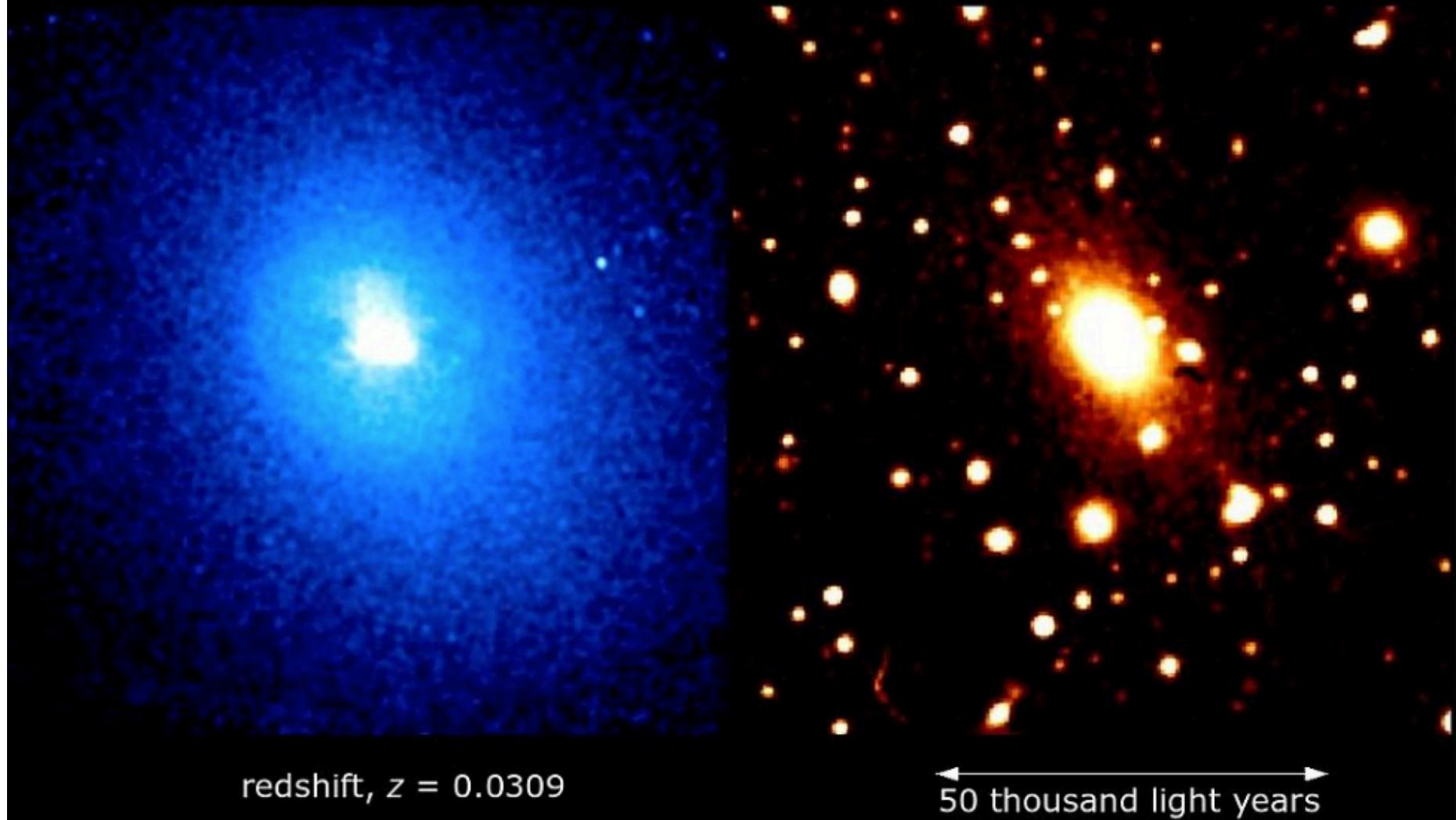
**BUT, MOST OF THE GAS IS IN WARM/HOT STATE:**

**80/90% OF THE BARYONS DO NOT FORM STARS!  
FILAMENTS, EXTENDED GAS HALOS —> CLEARLY SEEN IN  
CLUSTERS**

Abell 2199

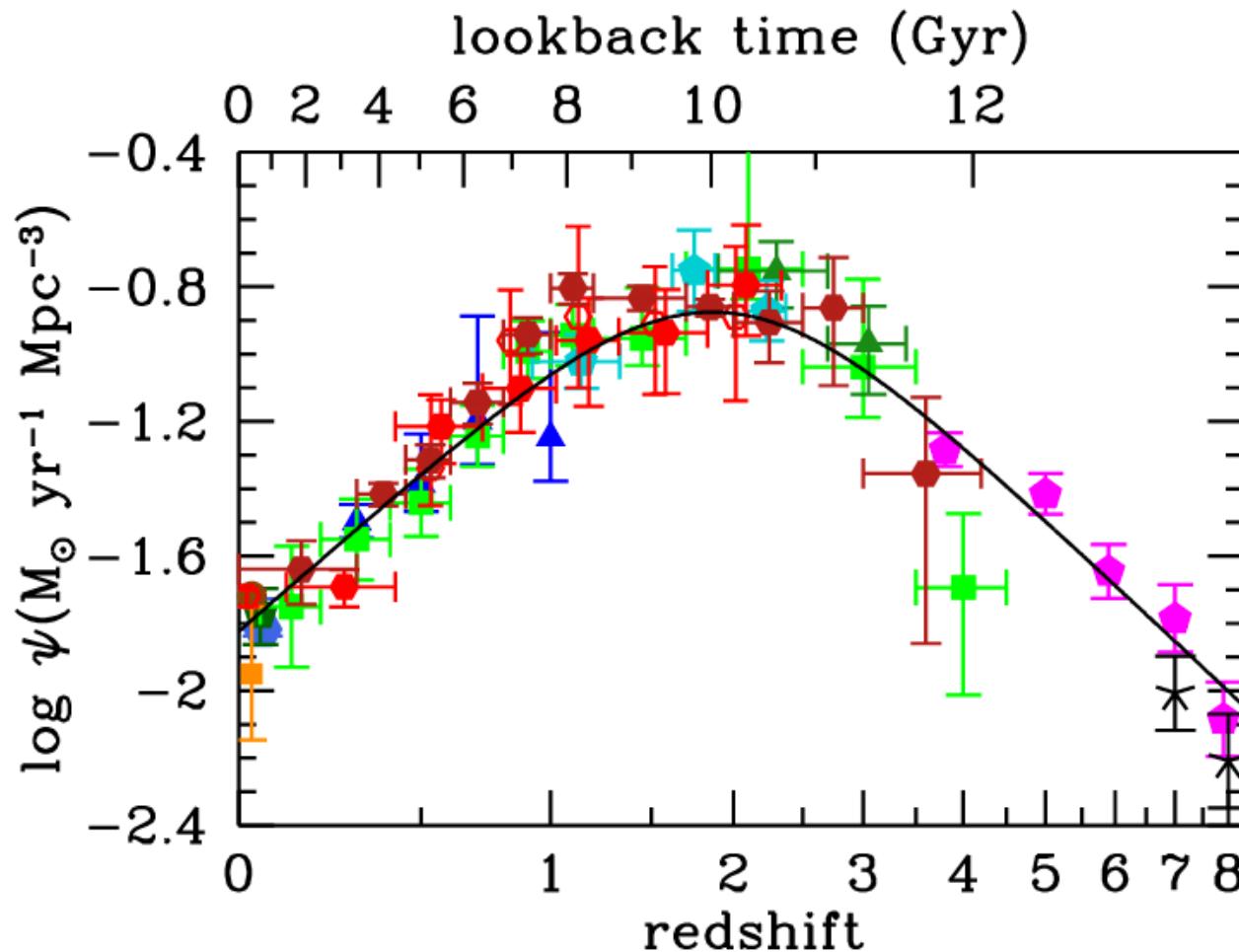
Chandra (X-ray)

DSS (Optical)



**HOT GAS IS CLEARLY VISIBLE IN CLUSTERS OF GALAXIES**

# DON'T FORGET GALAXIES EVOLVE...

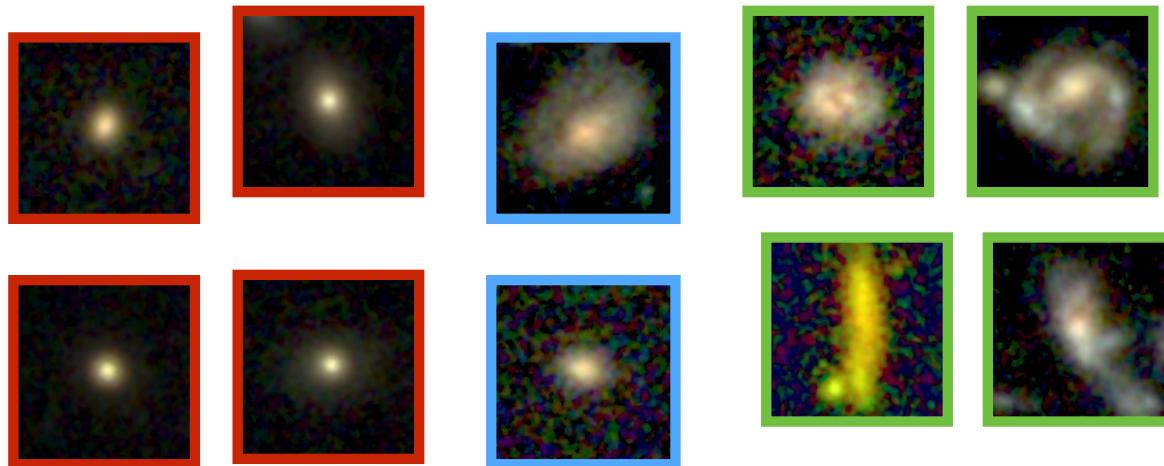
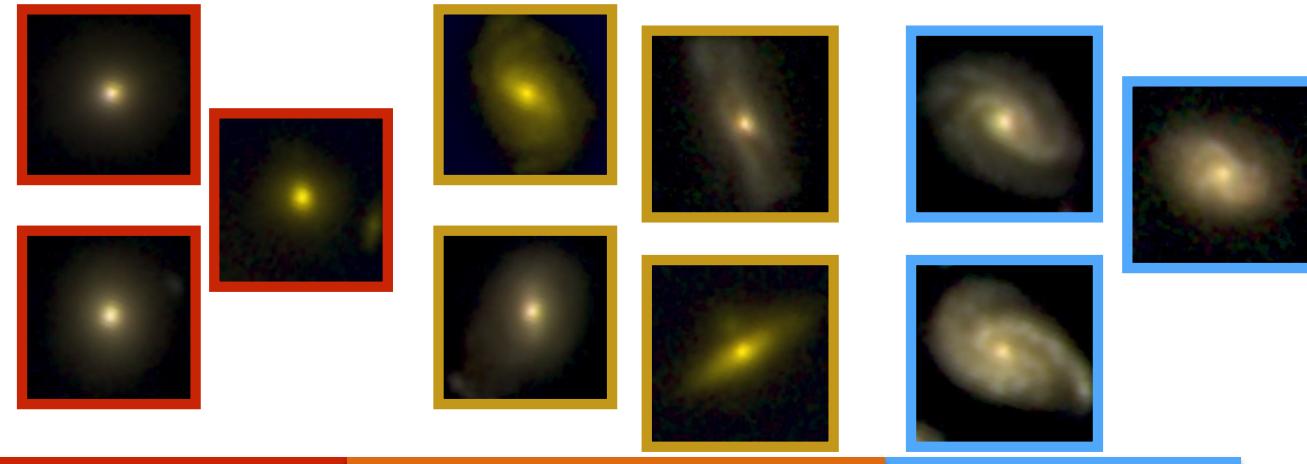


Madau&Dickinson+14

**~Milky Way+  
progenitors**

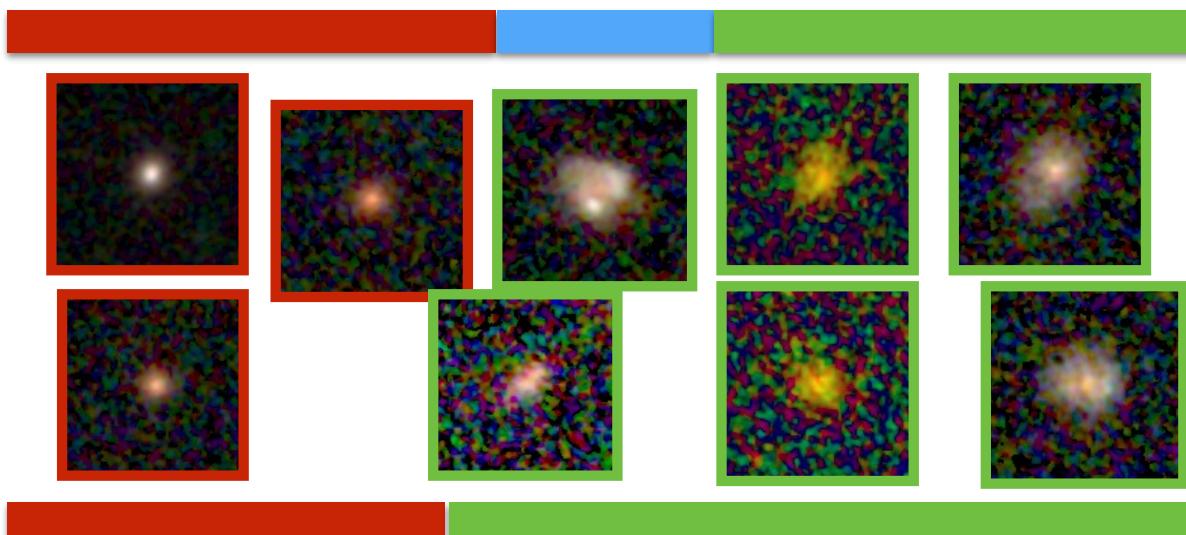
**$z < 1$**

**(7 Gyrs ago)**



**(~9 Gyrs ago)**

**$1 < z < 2$**



**(~11 Gyrs ago)**

**$z > 2$**

**MHC+16**

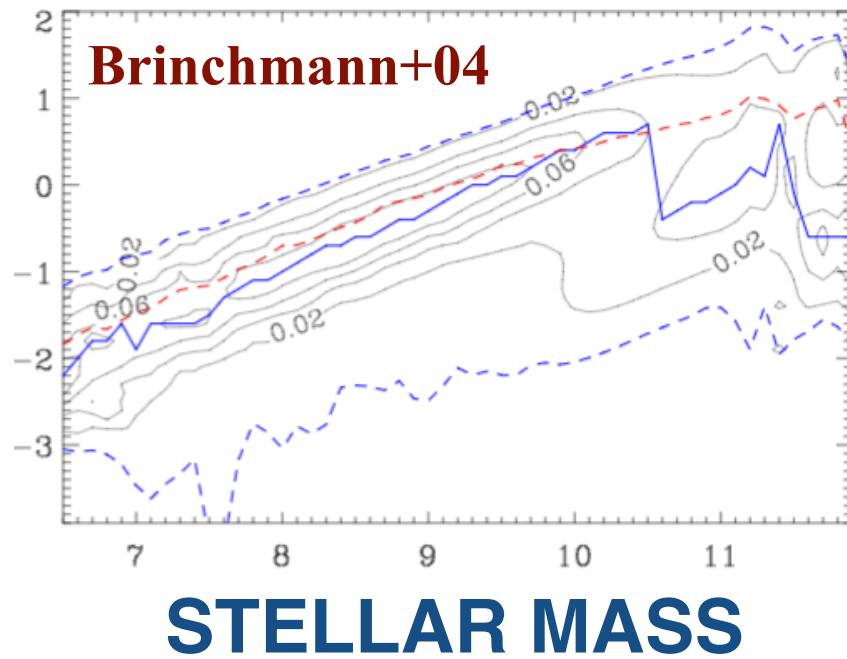
# DESPITE BEING COMPLEX SYSTEMS ... ASTONISHING REGULARITY

GIVEN, e.g STELLAR MASS ONE CAN PREDICT:

- ROTATION, VELOCITY DISPERSION TO 30%
- STAR-FORMATION RATE TO 30%
- SIZE TO A FACTOR OF 2
- HALO MASS IN WHICH GALAXY LIVES
- CAN PREDICT BLACK HOLE MASS TO A FACTOR OF 3

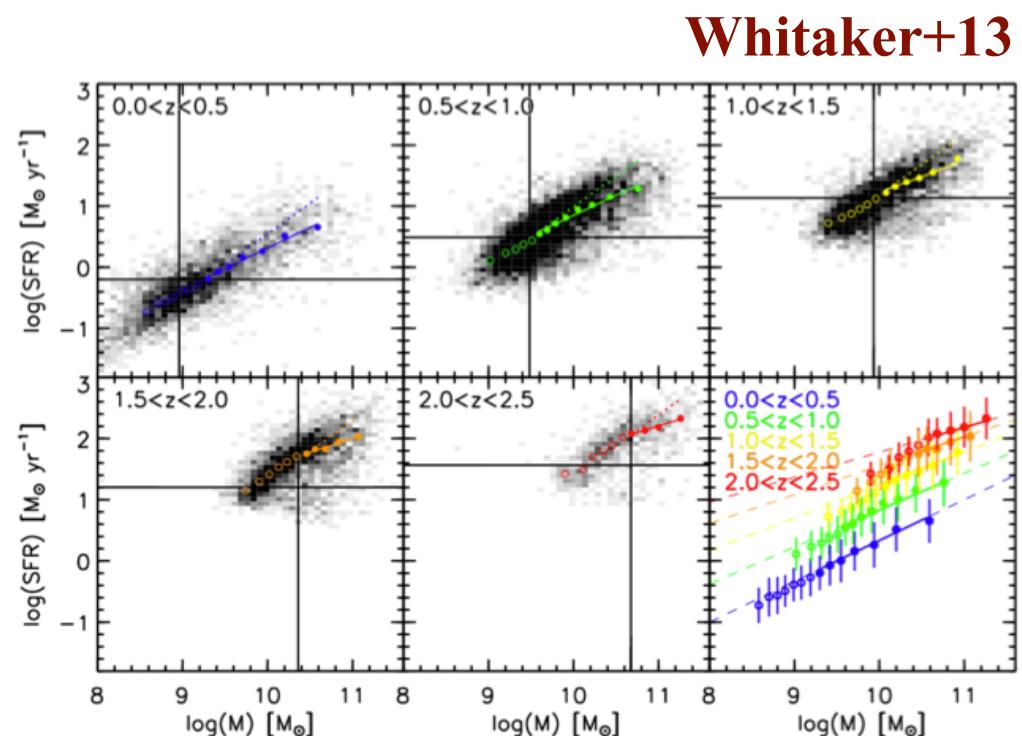
# STAR FORMATION MAIN SEQUENCE

STAR FORMATION RATE

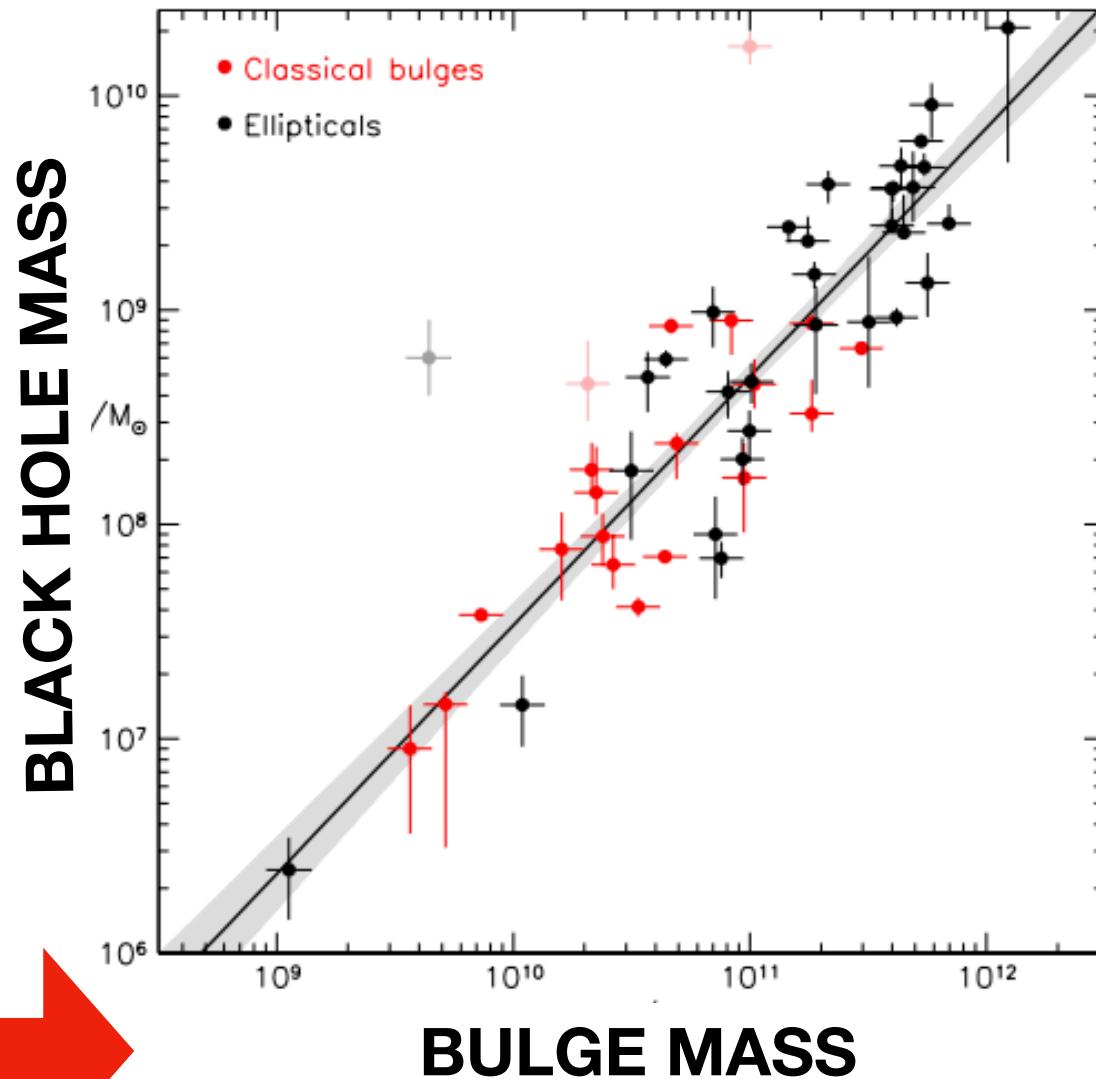


And also at higher  
redshift  
[HST legacy]

In the local Universe  
[SDSS legacy]

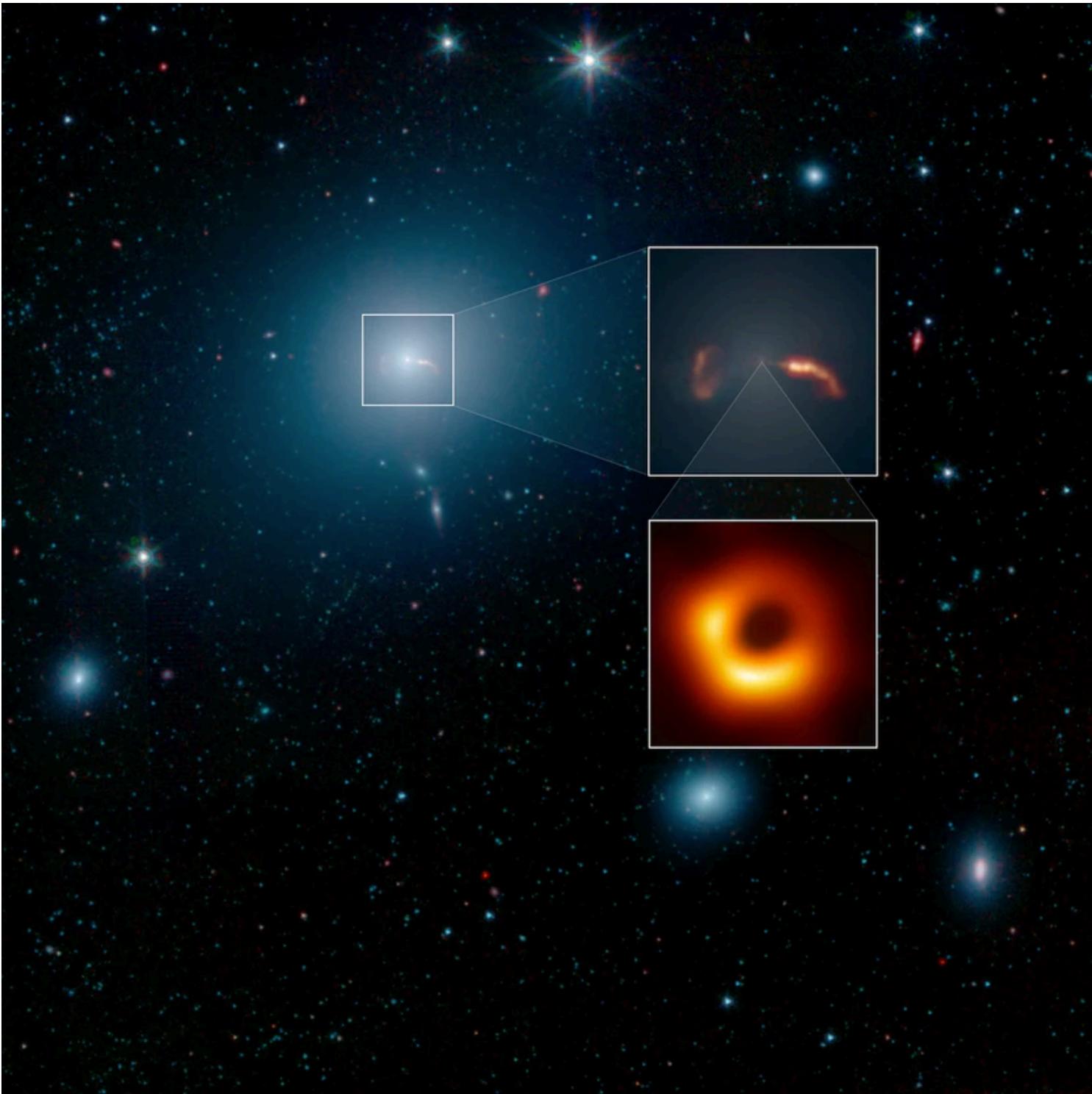


# MBH-MBULGE RELATION



THREE  
ORDERS OF  
MAGNITUDE  
DIFFERENCE!

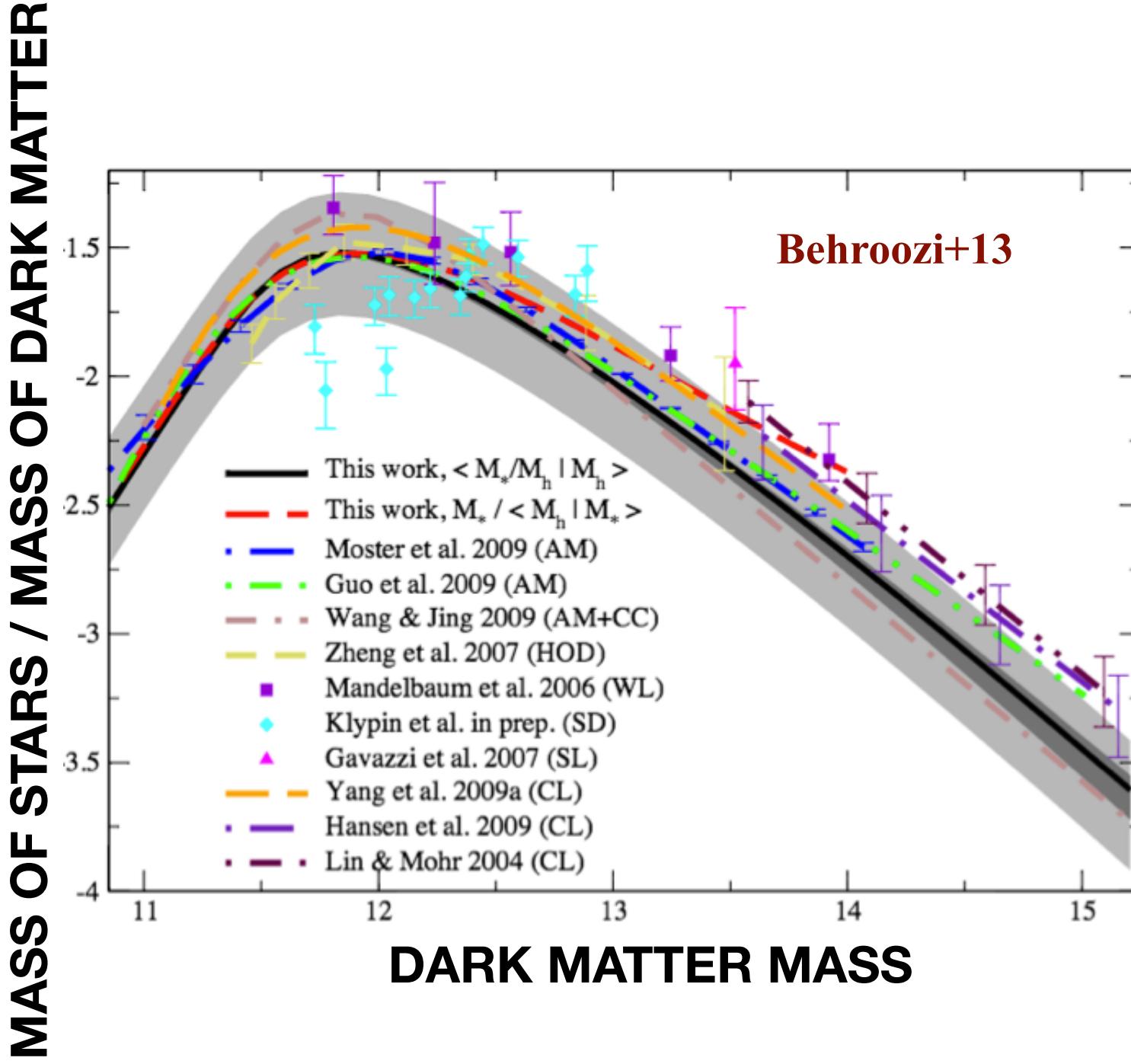
Kormendy&Ho+13



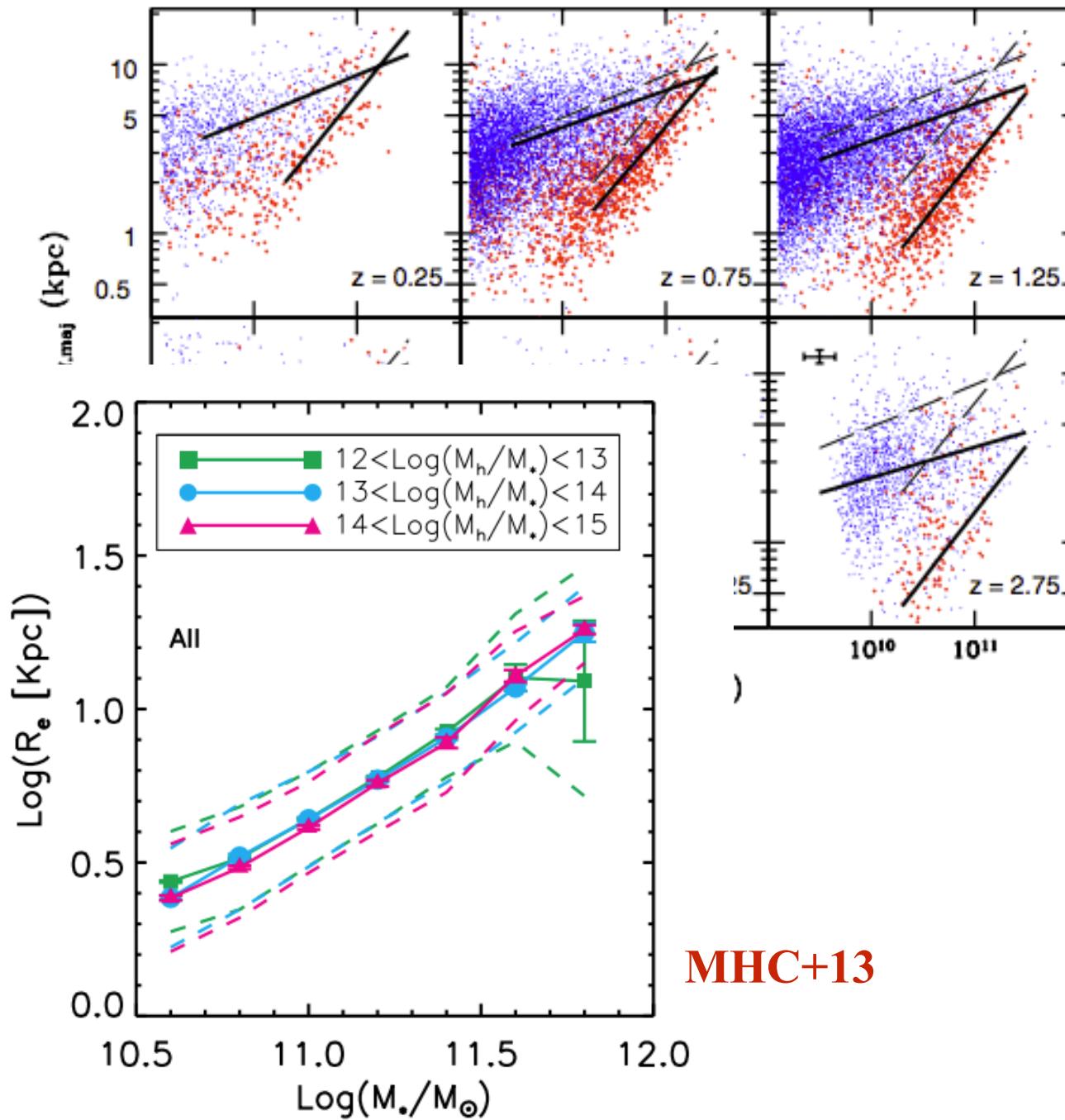
# Black Hole at the center of the Milky Way

<https://www.youtube.com/watch?v=TF8THY5spmo>

# MASS-HALO RELATION



# MASS-SIZE RELATION



van der Wel+13

# CURRENT PICTURE OF GALAXY FORMATION (IN 5 BULLET POINTS)

- 1. FORMATION OF THE DARK MATTER HALO
- 2. GAS ACCRETION / COOLING
- 3. GROWTH THROUGH ACCRETION OF GAS  
(SMOOTH, STUFF THAT CANNOT COOL INTO HALOS)  
+ MERGING (WHERE STARS COLD / GAS ALREADY  
FORMED)
- 4. STAR FORMATION IN THE COOLED GAS
- 5. FEEDBACK

- 1. FORMATION OF THE DARK MATTER HALO

**GAS PRESSURE AT EARLY TIMES STOPS BARYONS FROM CLUMPING**

**DARK MATTER → NO PRESSURE → ACTS AS SEED FOR GALAXY FORMATION**

<https://www.youtube.com/watch?v=jHoHz9fSGVI#action=share>

**DEUS N-BODY SIMULATION**

- 1. FORMATION OF THE DARK MATTER HALO

**Gravitational instability scenario assumes the early universe to be almost perfectly smooth, with the exception of tiny density deviations with respect to the background density.**

**These small perturbations are accompanying by small velocity perturbation to the general Hubble expansion.**

**From the CMB observations:**

$$\Delta T \sim 10^{-5} K$$

- 1. FORMATION OF THE DARK MATTER HALO

If the fluctuations are  $\delta\rho/\rho \ll 1 \rightarrow$

they grow via gravity and can be described by linear perturbation theory.

When they grow so that  $\delta\rho/\rho \sim 1 \rightarrow$

They are able to separate from the global expansion and collapse to form a bounded system.

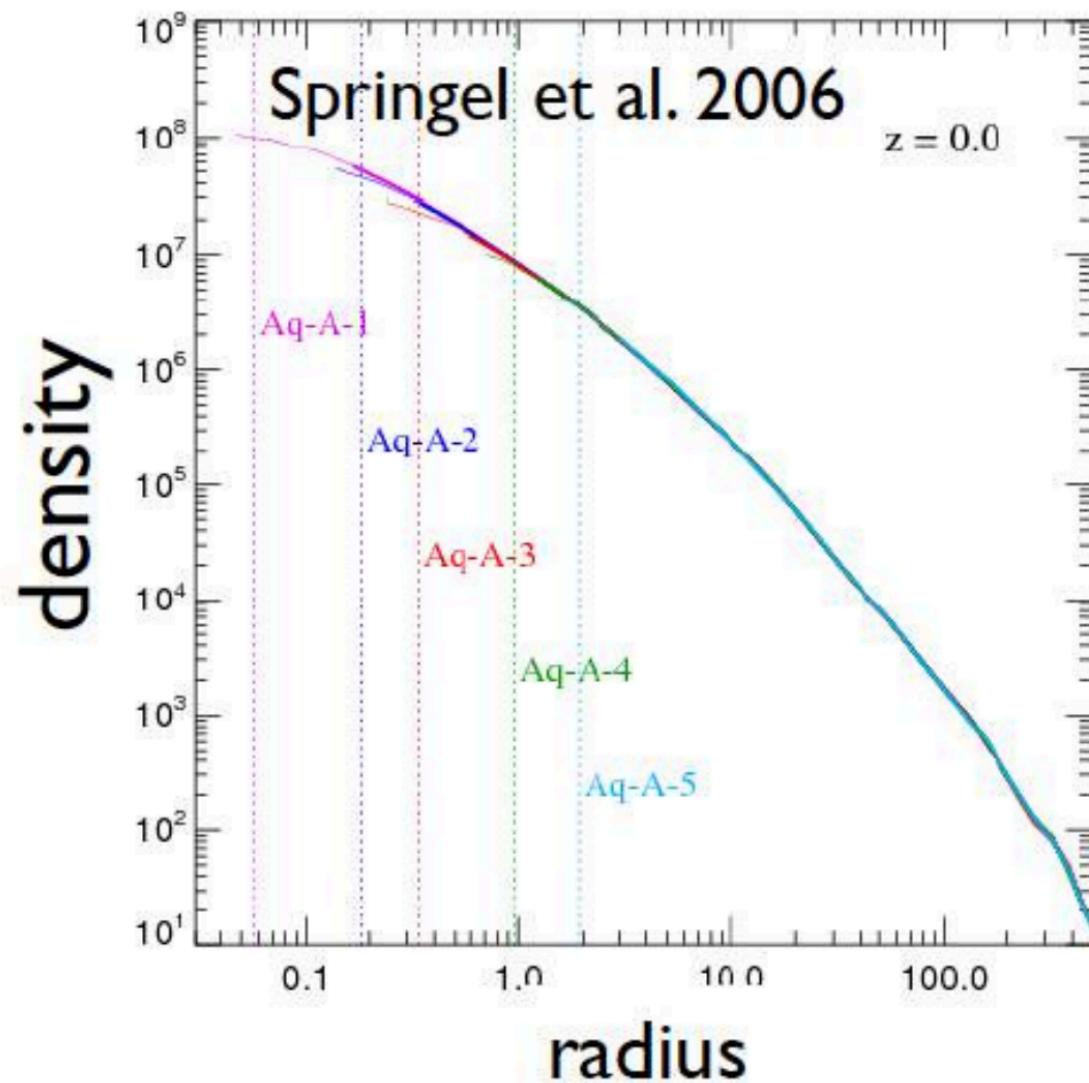


**DARK MATTER HALO**

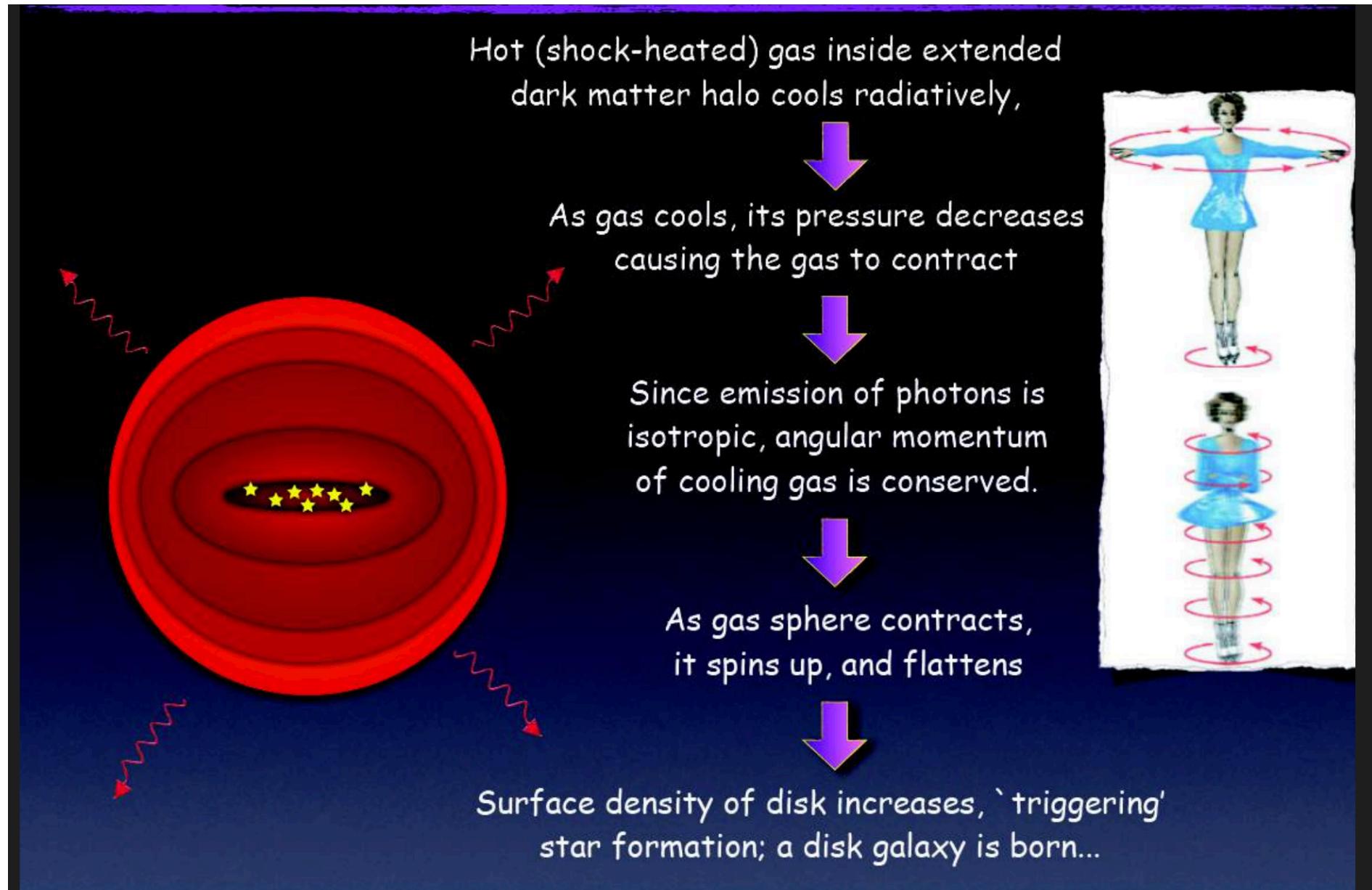
At the turnaround radius, fluctuations reach its maximum radius and collapse, entering the non-linear regime.

Finally, the system will reach virialization.

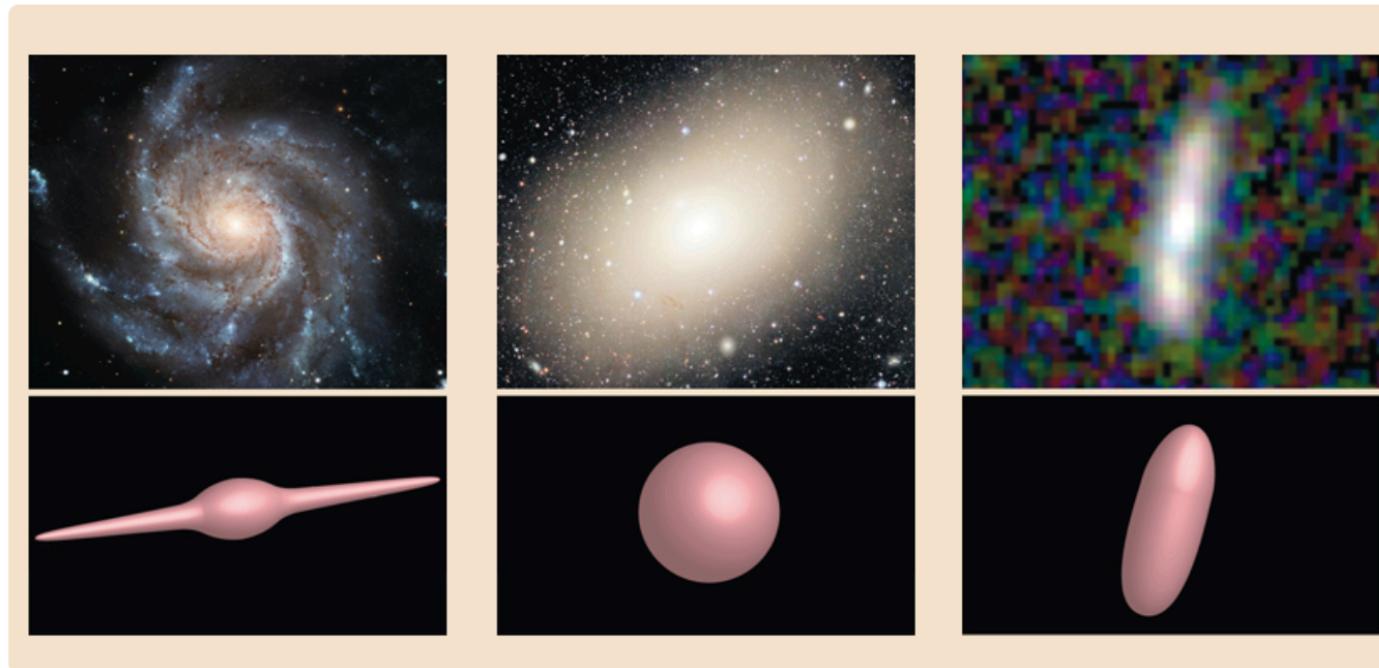
# DARK MATTER PROFILES ARE SELF SIMILAR



## • 2. GAS ACCRETION / COOLING



# HOWEVER: NUMERICAL SIMULATIONS + OBSERVATIONS SHOW SOME GALAXIES START AS “PICKLES”



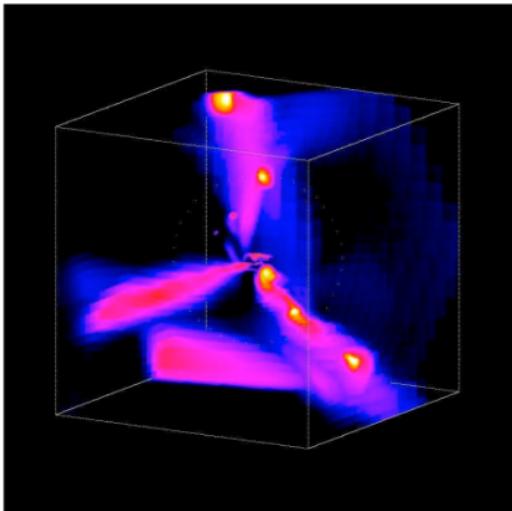
“Galaxies do not form in isolation; rather, they emerge along the long filaments of dark matter, called the *cosmic web*, that bind together the entire universe”

**PRIMACK+**

- 3. GROWTH THROUGH ACCRETION OF GAS (SMOOTH, STUFF THAT CANNOT COOL INTO HALOS) + MERGING (WHERE STARS COLD / GAS ALREADY FORMED)

**ACCRETION COULD CONSERVE SOME ANGULAR MOMENTUM - COMES FROM TORQUES AS GALAXIES TURN AROUND AND COLLAPSE, E.G COFFEE CUP [MAO, MO, WHITE 98]**

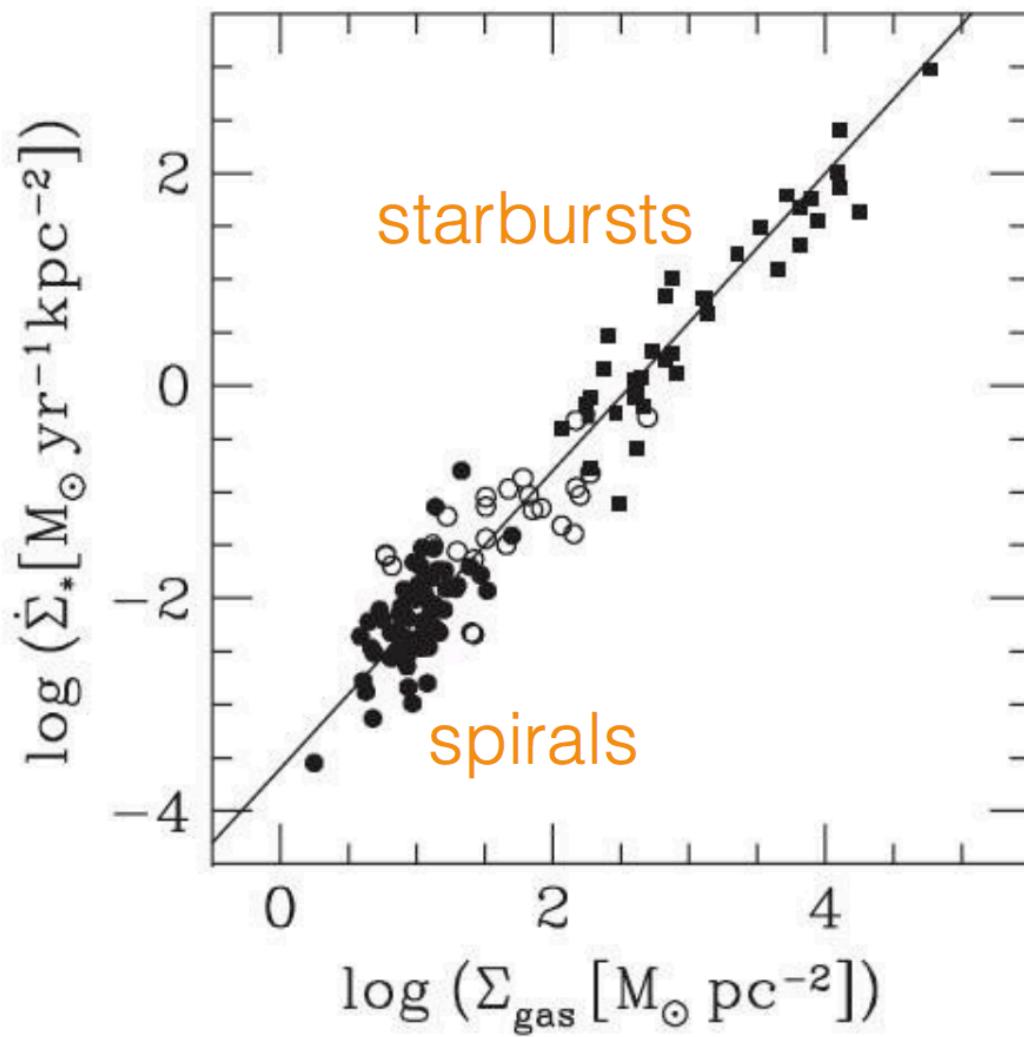
**MERGING RANDOMIZES ANGULAR MOMENTA  
[TOOMRE&TOOMRE 72]**



<https://www.youtube.com/watch?v=CcopGM8iUCY>

- 4. STAR FORMATION IN THE COOLED GAS

$$\dot{\Sigma}_* = (2.5 \pm 0.7) \times 10^{-4} \left( \frac{\Sigma_{\text{gas}}}{M_\odot \text{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot \text{yr}^{-1} \text{kpc}^{-2}$$



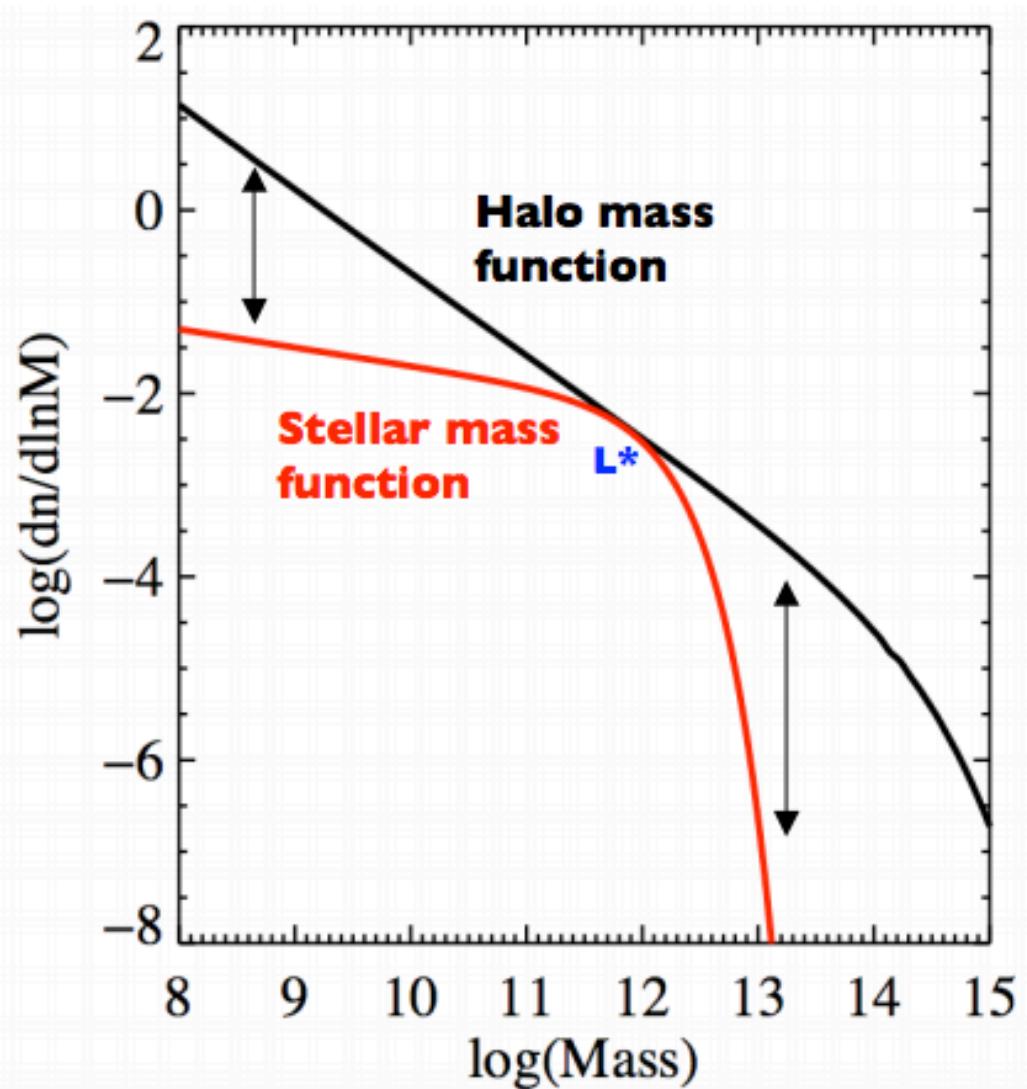
KENNICUT+98

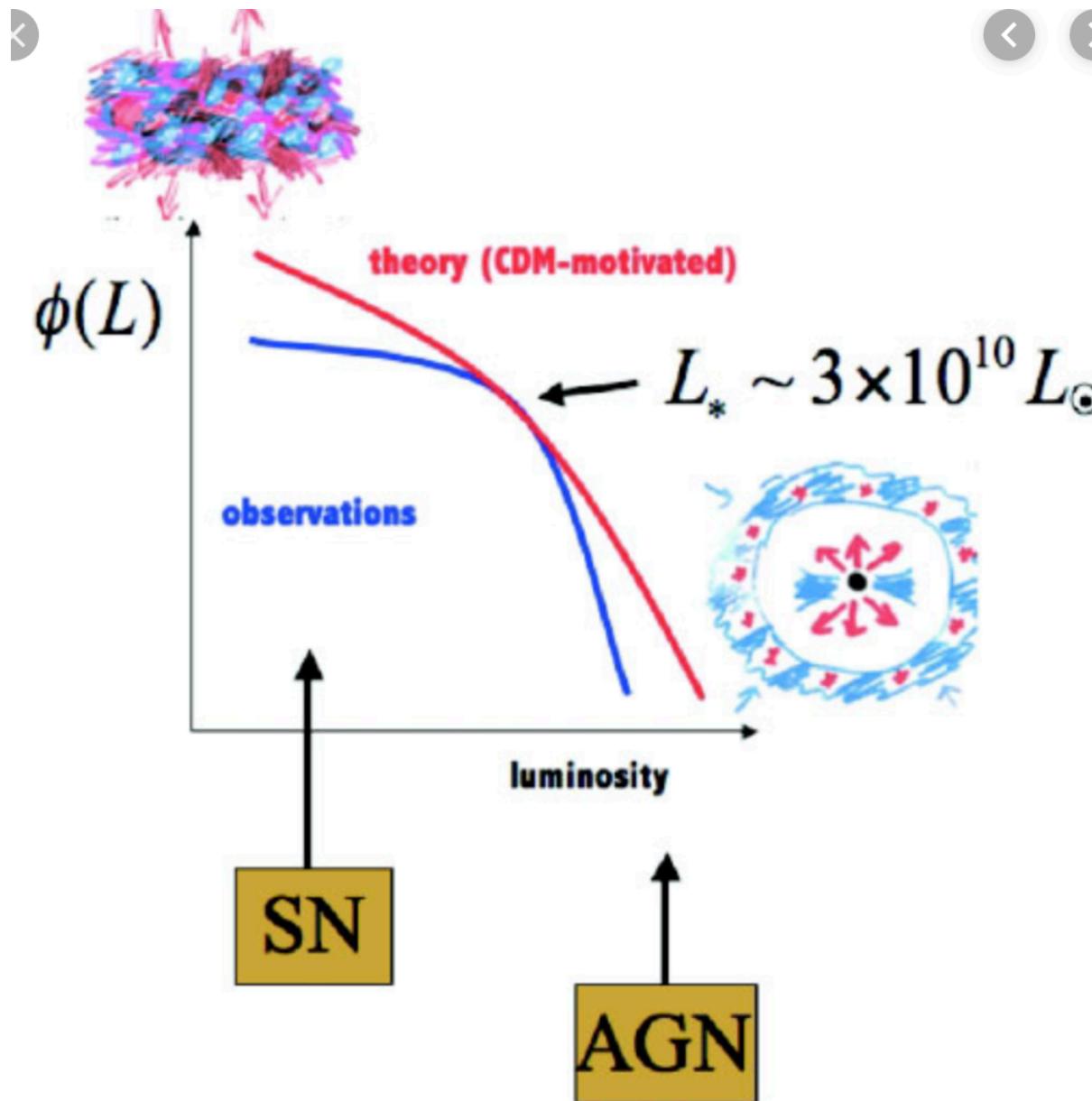
- 5. FEEDBACK

**SUPERNOVAE / STELLAR WINDS —> OUTFLOW OF HOT, METAL ENRICHED GAS  
[DEKEL&SILK]**

**WINDS CAUSED BY SUPER MASSIVE BLACK HOLES [AGNs]**

# WHY DO WE NEED FEEDBACK?

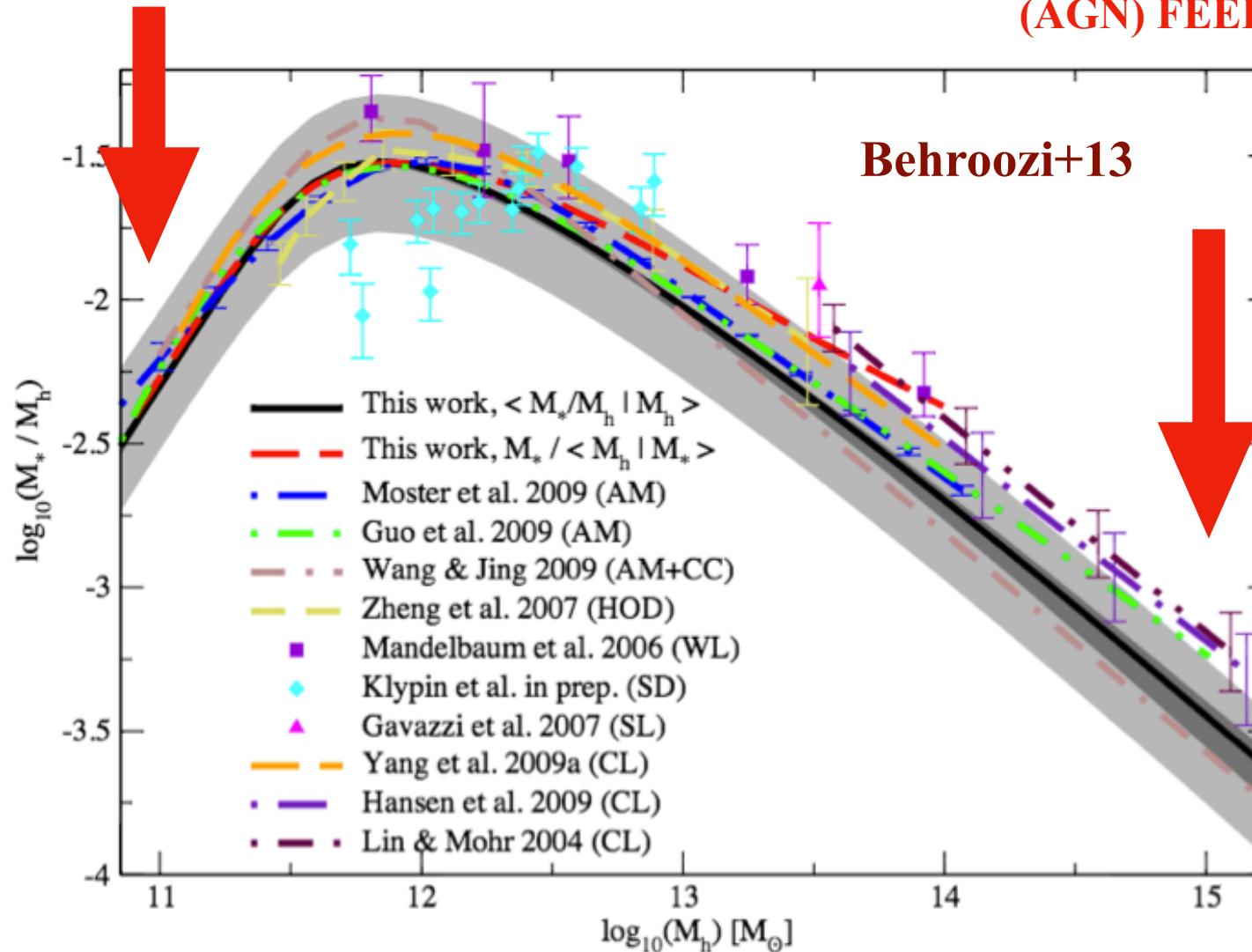




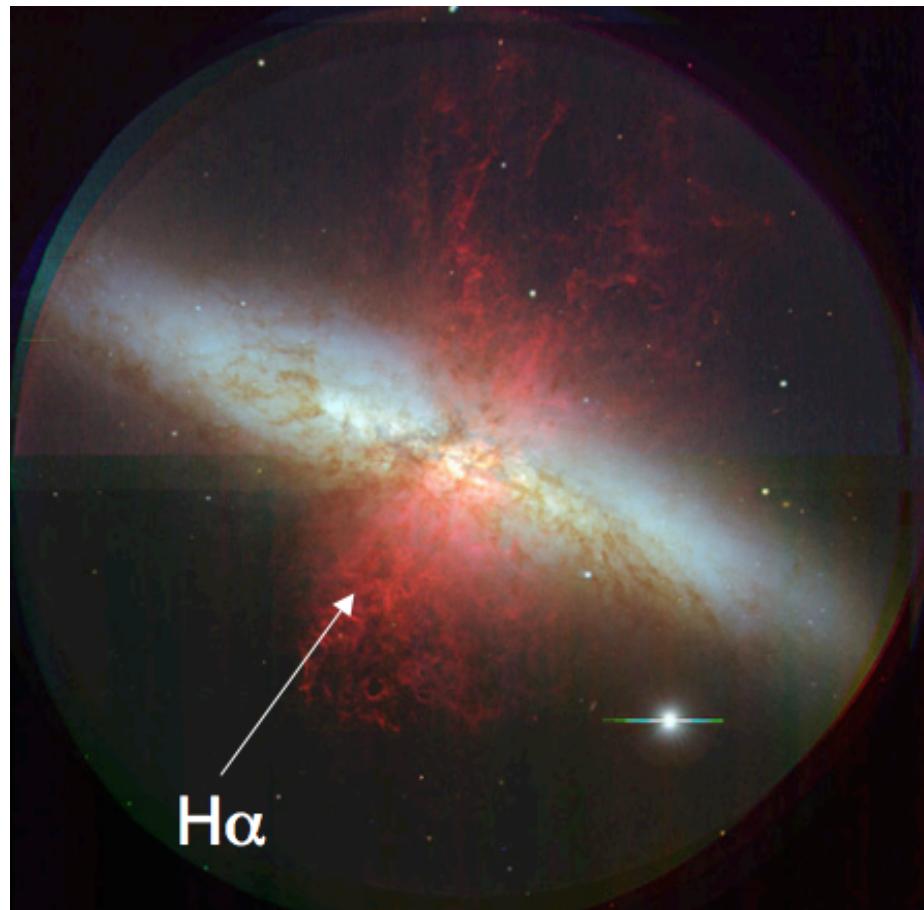
# WHY DO WE NEED FEEDBACK?

SUPERNOVA FEEDBACK  
(ENERGY INJECTED BY  
EXPLOSION  
OF MASSIVE STARS)

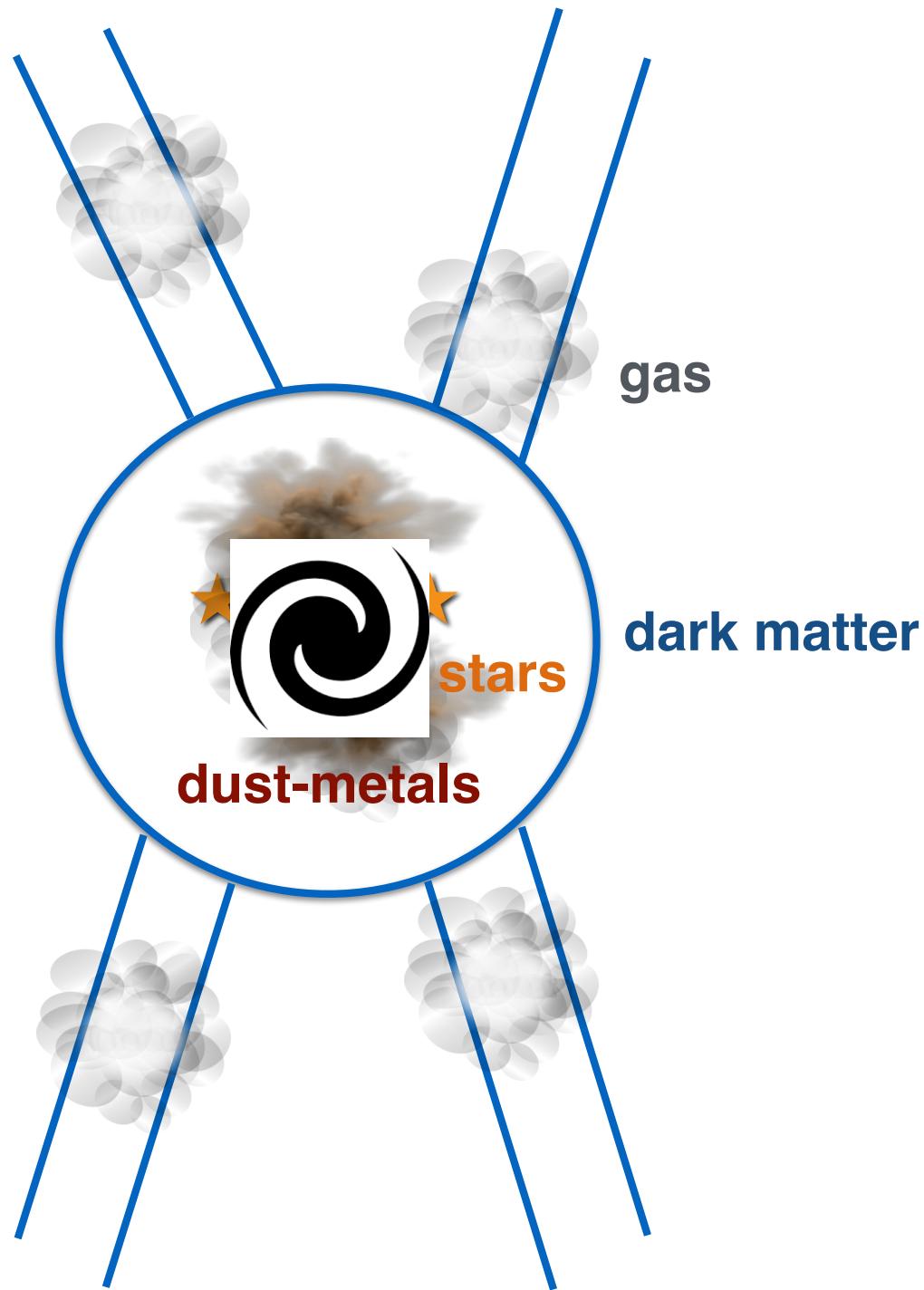
ACTIVE GALACTIC NUCLEI  
(AGN) FEEDBACK

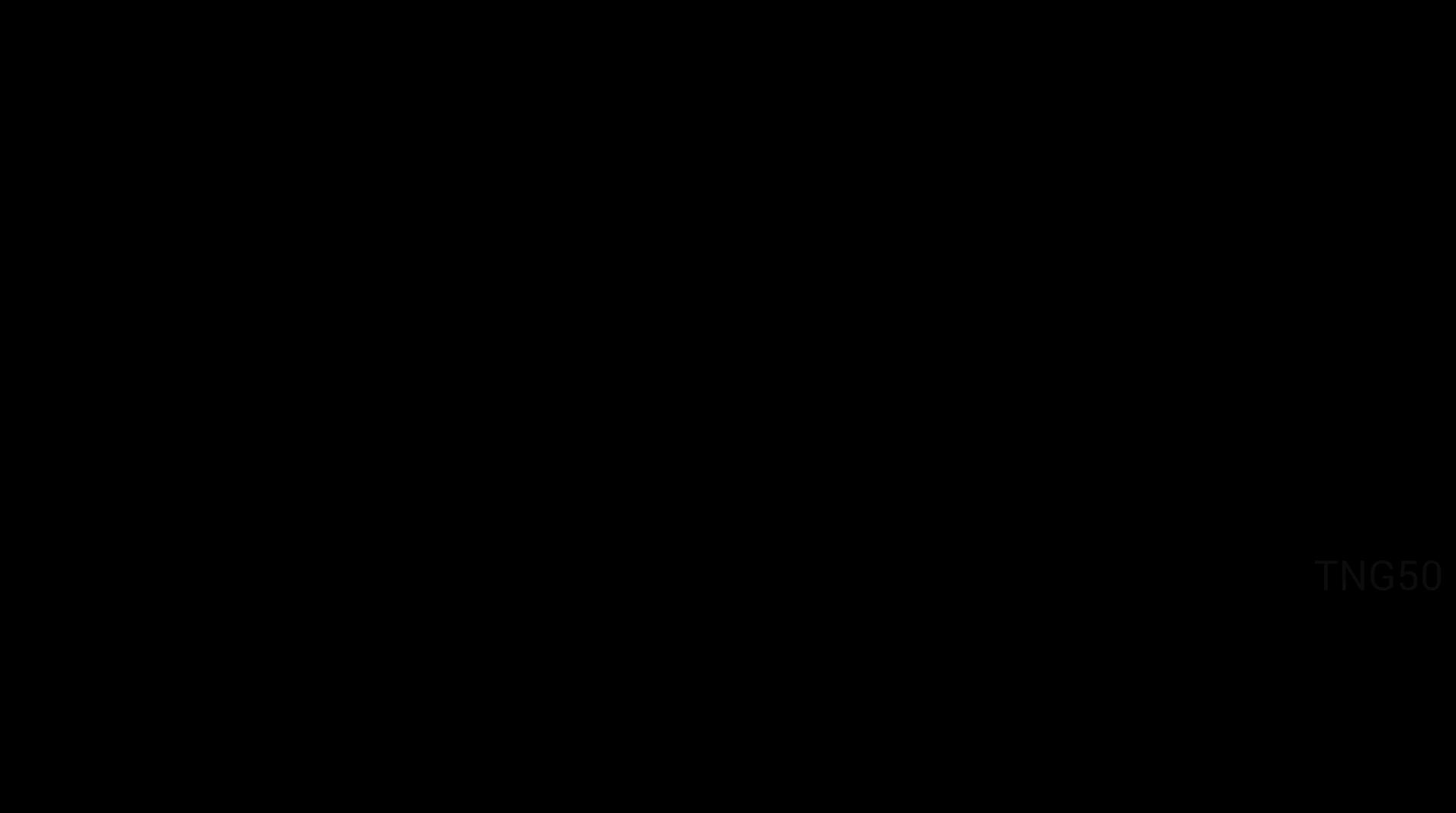


WE NEED MECHANISMS TO PREVENT THE GAS TO COOL....



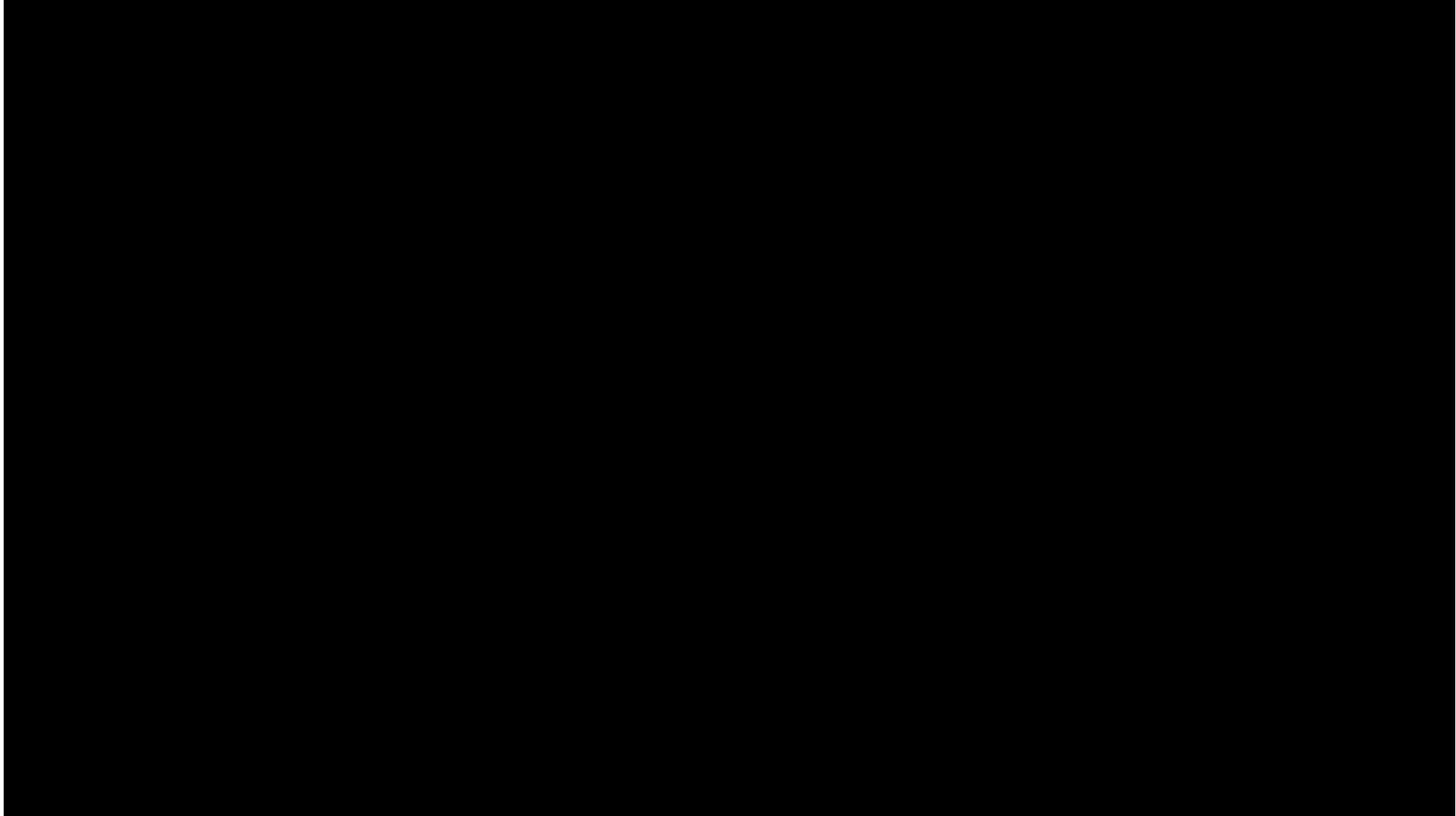
**M82**





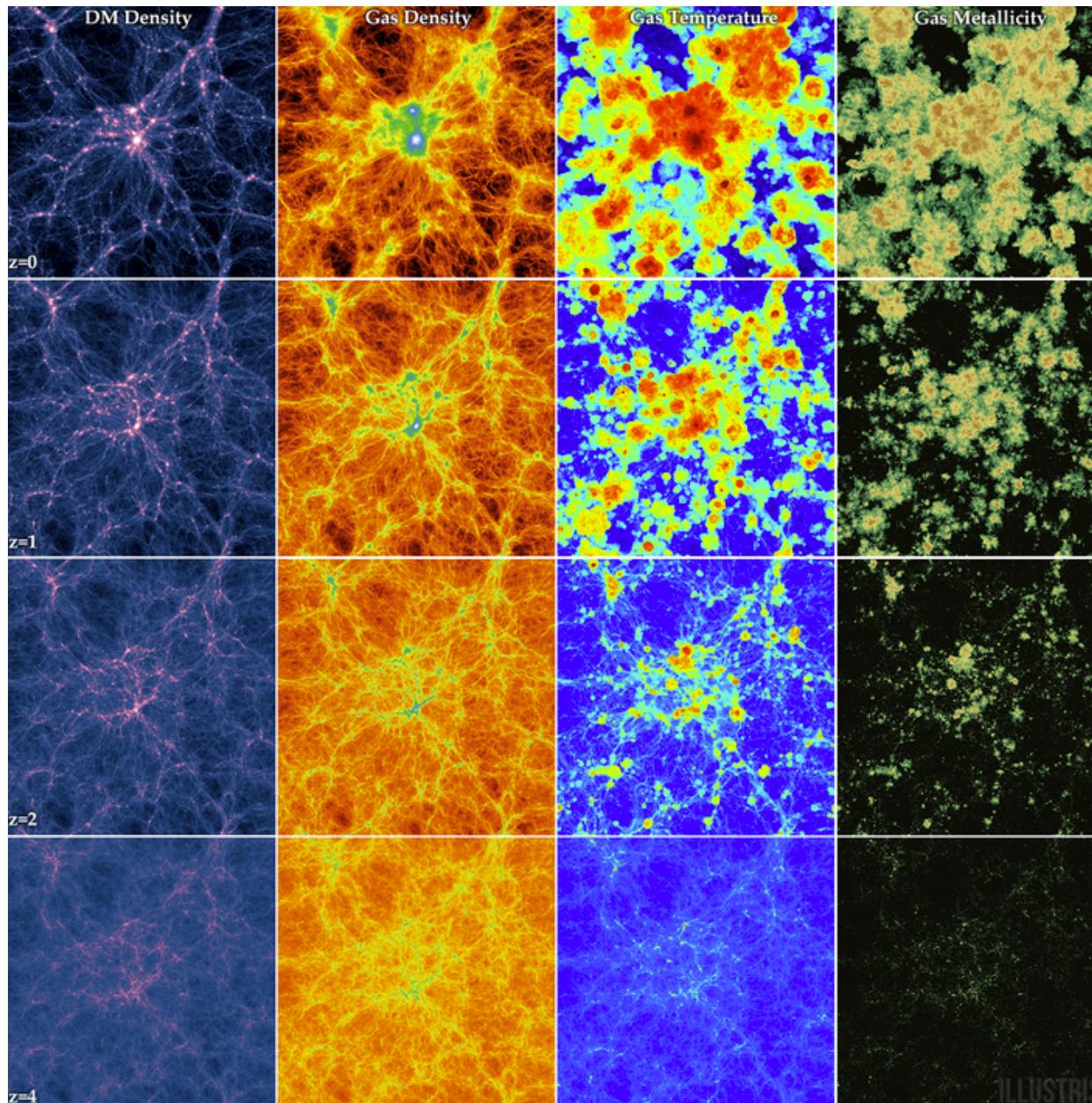
TNG50

[TNG50 simulation](#)



TNG100 simulation

# DARK MATTER → GAS → STARS → METALS

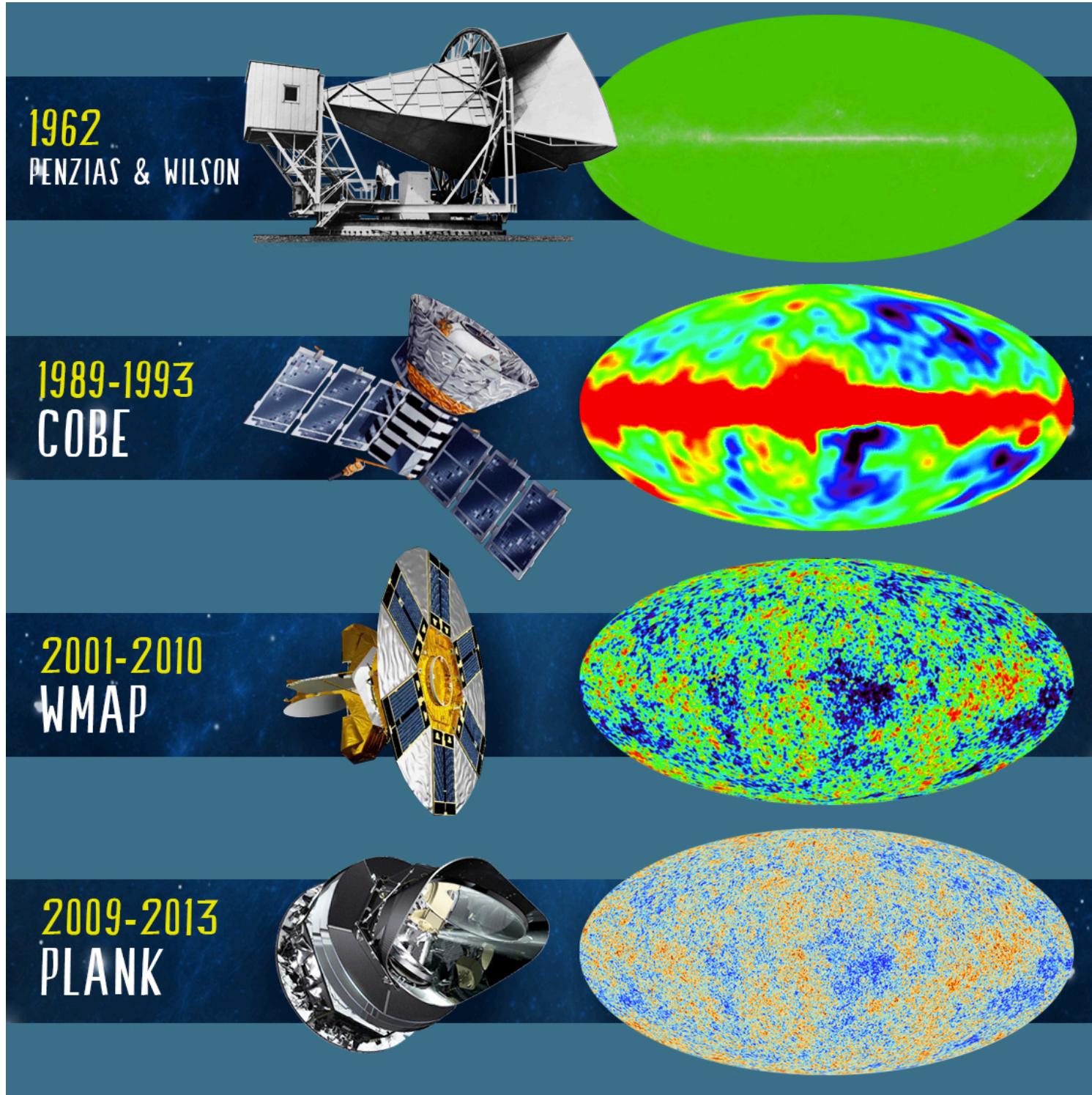


Illustris Simulation ([illustris-project.org](http://illustris-project.org))

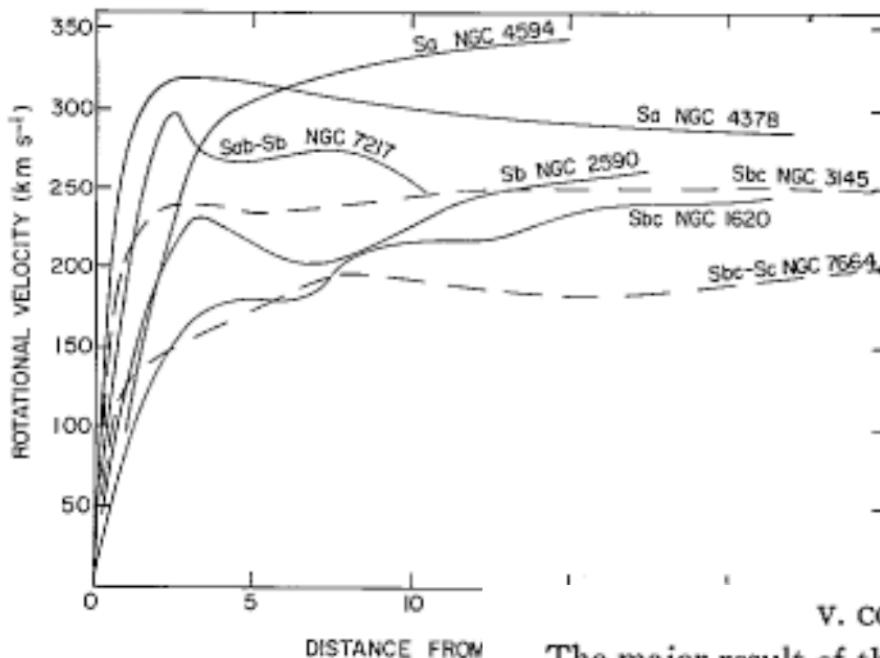
# KEY HISTORICAL LANDMARKS IN GALAXY EVOLUTION

- DISCOVERY OF GALAXIES (SEE JAIRO'S)
- COSMIC MICROWAVE BACKGROUND → BIG-BANG
- DISCOVERY OF DARK MATTER
- REALIZATION THAT GALAXIES EVOLVE
- DARK MATTER MASS FUNCTIONS  $\neq$  GALAXY MASS FUNCTION → FEEDBACK

- COSMIC MICROWAVE BACKGROUND



## • DISCOVERY OF DARK MATTER

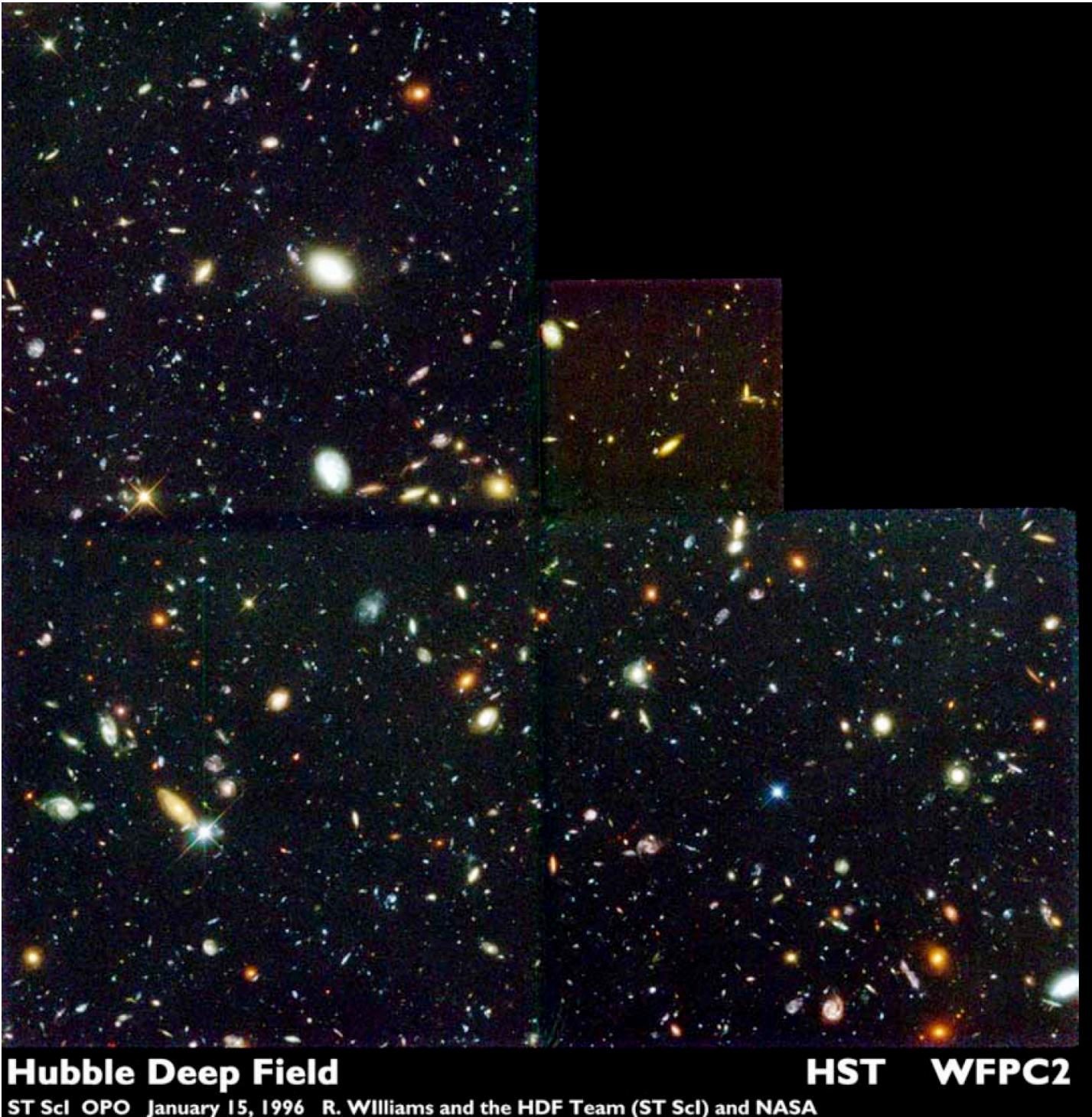


### V. CONCLUSIONS

The major result of this work is the observation that rotation curves of high-luminosity spiral galaxies are flat, at nuclear distances as great as  $r = 50$  kpc. Roberts and his collaborators (Roberts 1976) deserve credit for first calling attention to flat rotation curves. Recent 21 cm observations by Krumm and Salpeter (1976, 1977) have strengthened this conclusion. These results take on added importance in conjunction with the suggestion of Einasto, Kaasik, and Saar (1974), and Ostriker, Peebles, and Yahil (1974) that galaxies contain massive halos extending to large  $r$ . Such models imply that the galaxy mass increases significantly with increasing  $r$  which in turn requires that rotational velocities remain high for large  $r$ . The observations presented here are thus a necessary but not sufficient condition for massive halos. As shown above, mass distributions from disk models or spherical models

Rubin et al. 1978

• GALAXIES EVOLVE - THE HST LEGACY



**Hubble Deep Field**

ST Scl OPO January 15, 1996 R. Williams and the HDF Team (ST Scl) and NASA

**HST   WFPC2**

# TAKE AWAY...

- GALAXIES ARE BARYONIC RESIDUE IN CENTER OF DARK MATTER HALOS
- STARS + COLD GAS MASS FUNCTION DIFFERENT FROM DARK MATTER MASS FUNCTION
- MOST BARYONS ARE IN WARM MODE (NOT IN GALAXIES)
  - WHY? FEEDBACK...
- VIEWED FROM GLOBAL PROPERTIES...ASTONISHING REGULARITY BUT
- GALAXY FORMATION IS COMPLEX!