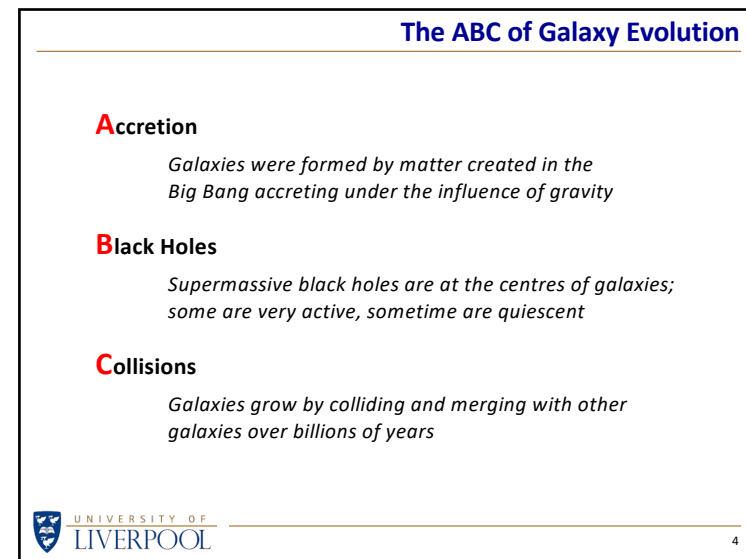
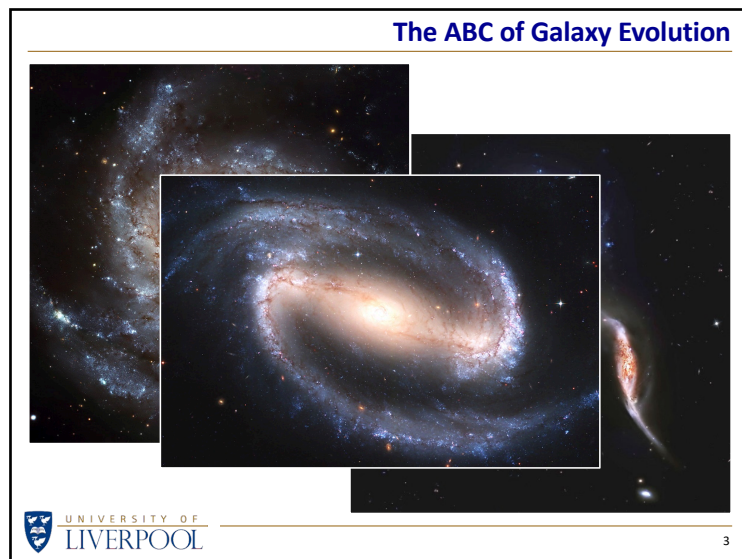
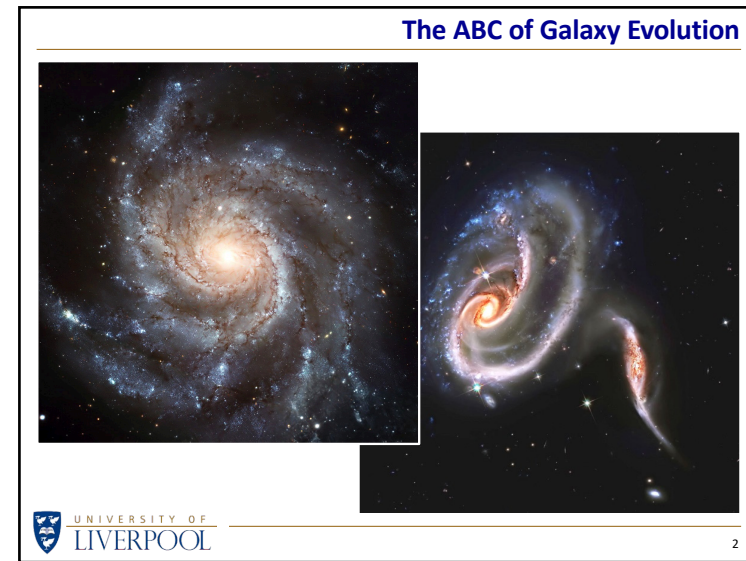


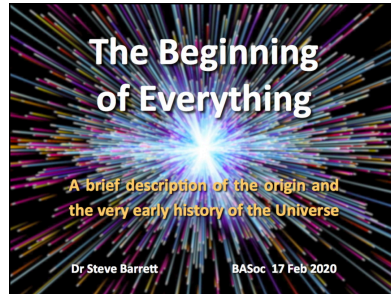
# The ABC of Galaxy Evolution



# The ABC of Galaxy Evolution

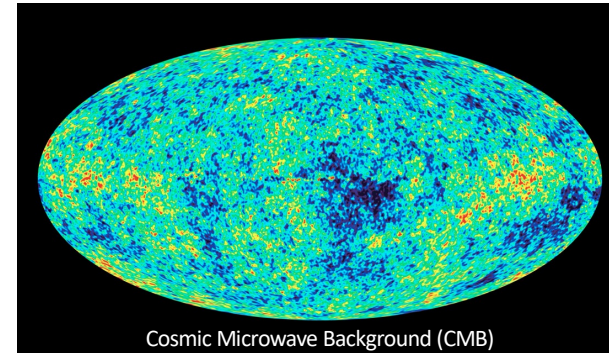
## Where Does the Story Start?

At the Beginning ...



## Where Does the Story Start?

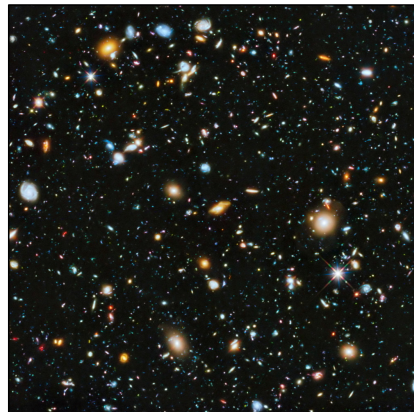
At the Beginning ... of Everything ...



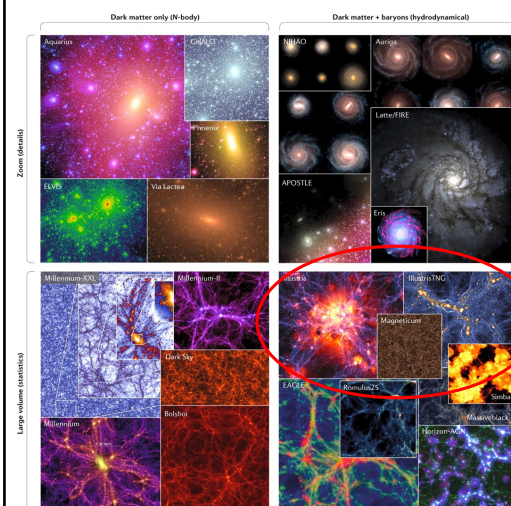
Cosmic Microwave Background (CMB)

## Cosmic Structure

How did the Universe evolve from the CMB to being a structure full of galaxies?



## Simulations



Everything we understand about the evolution of cosmic-scale structures is the result of computer simulations.

This talk uses images and videos from the 'Illustris' simulations.

# The ABC of Galaxy Evolution

## Cosmic Structure

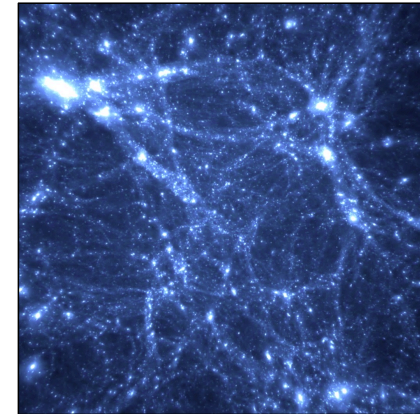
The 'dimples' in the cosmic golf ball gave rise to the variations in the CMB...



...and over billions of years collapsed into a cosmic web of filaments and voids.

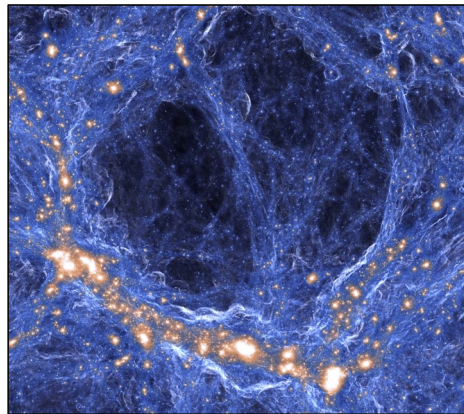
## Cosmic Web

The 'dimples' in the cosmic golf ball gave rise to the variations in the CMB...



...and over billions of years collapsed into a cosmic web of filaments and voids.

## Cosmic Web

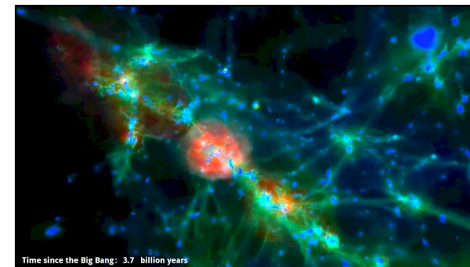


Simulations of the cosmic web show how the densest parts of the filaments are the nucleation sites for clusters of galaxies.

Matter flows through the filaments and accumulates to make the proto-galaxies.

## Galaxies and Stars

If a simulation of galaxy formation is to give realistic results then it must also take account of *star* formation and evolution.

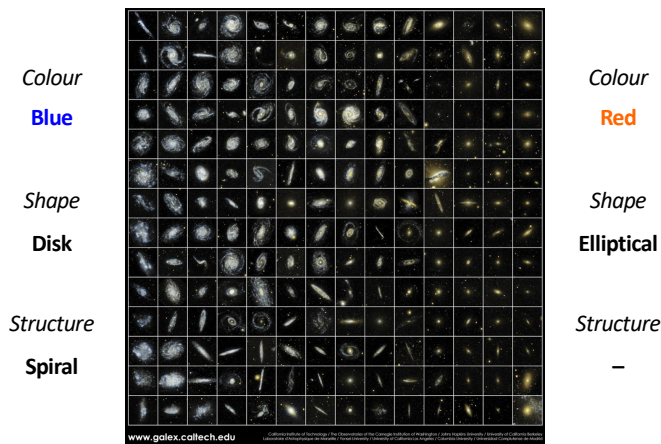


Gas blasted out (red bubbles) by black holes or massive stars ending their lives as supernovae can slow matter falling in from the filaments.



# The ABC of Galaxy Evolution

## Can Simulations Explain Galaxy Diversity?



## The ABC of Galaxy Evolution

### Accretion

*Galaxies were formed by matter created in the Big Bang accreting under the influence of gravity*

### Black Holes

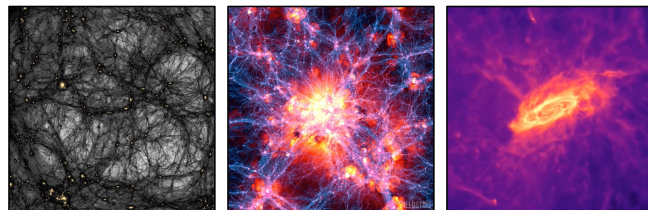
*Supermassive black holes are at the centres of galaxies; some are very active, sometime are quiescent*

### Collisions

*Galaxies grow by colliding and merging with other galaxies over billions of years*

## Illustris

The Illustris project is a set of simulations of galaxy formation and evolution that run from just after the Big Bang to the present day.



The simulations account for the effects of dark matter, star formation, black holes and supernovae in calculating how matter accumulates over billions of years into galaxies.

## IllustrisTNG

The Illustris simulations ran for 20 million cpu hours (2013–2015)

These were followed by even more sophisticated simulations ...

### Illustris – The Next Generation !

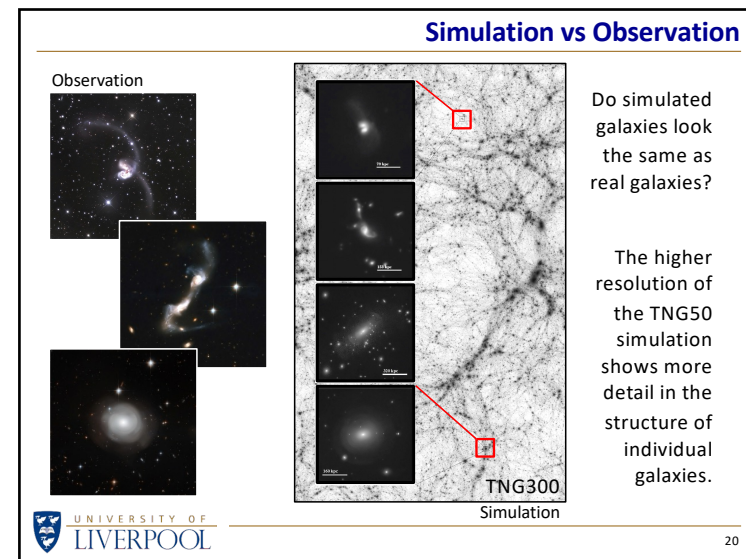
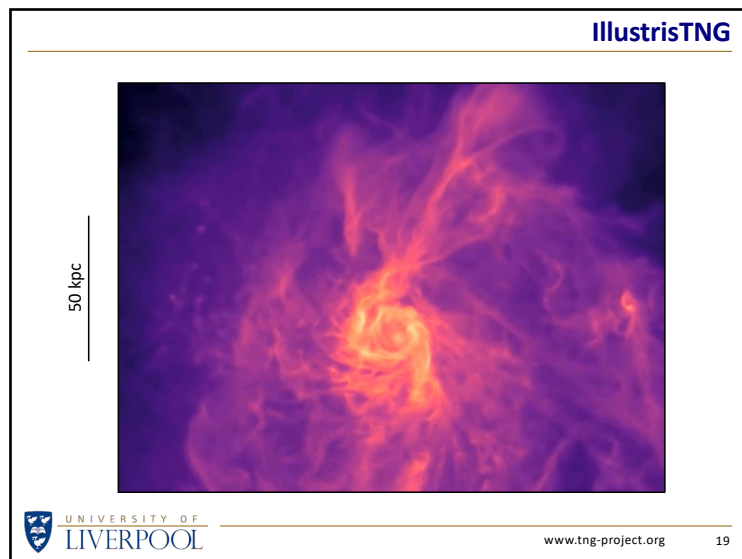
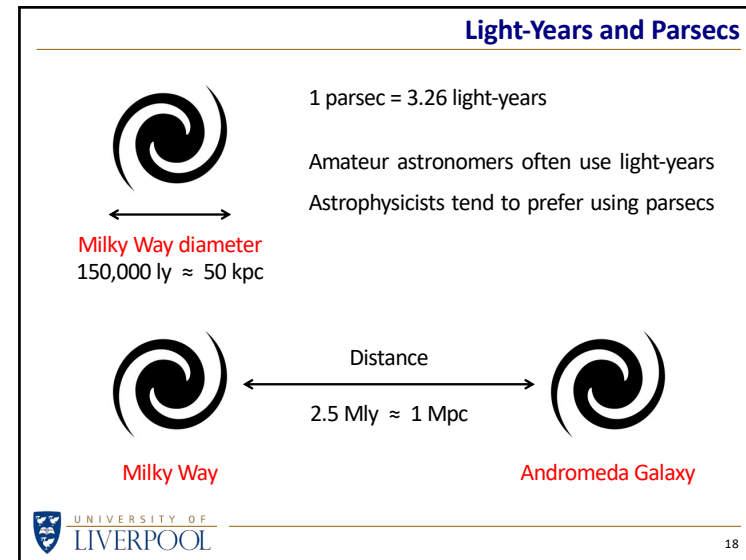
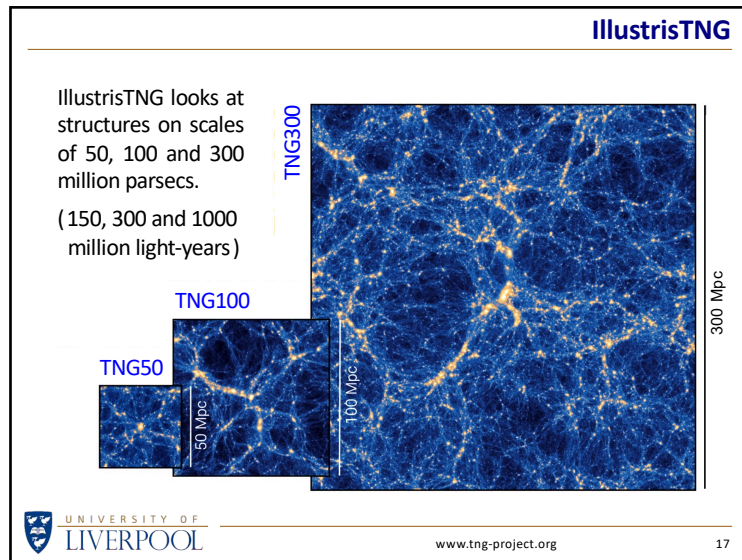
IllustrisTNG simulations ran for 200 million cpu hours (2017–2019)

( If the simulations ran on an average desktop computer, they would have to run for over 20,000 years to give comparable results. )





# The ABC of Galaxy Evolution



# The ABC of Galaxy Evolution

## TNG50 Disk Galaxies

Where is the Hydrogen? Where are the Stars?

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## Milky Way Analogue

TNG50 generates galaxies with masses of about 200 billion stars that look a lot like the Milky Way.

The face-on view shows the spiral arms and the edge-on view shows the central 'bulge' and the thin disk.

face-on

5 kpc

edge-on

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## The ABC of Galaxy Evolution

**Accretion**

*Galaxies were formed by matter created in the Big Bang accreting under the influence of gravity*

**Black Holes**

*Supermassive black holes are at the centres of galaxies; some are very active, sometime are quiescent*

**Collisions**

*Galaxies grow by colliding and merging with other galaxies over billions of years*

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## At the Heart of a Galaxy

How do we know what lies at the centre of a galaxy?

A close look at stars orbiting near the centre of the Milky Way tells us that there is something invisible but **very** massive lurking there ...

Invisible but massive ...  
a black hole

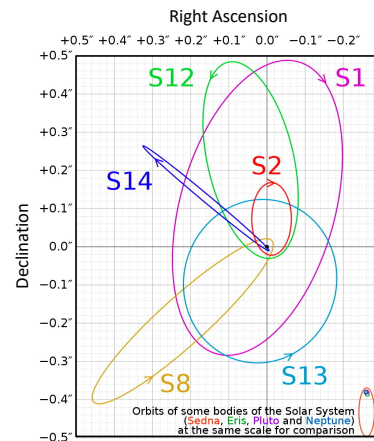
Star in orbit  
around ... what?

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# The ABC of Galaxy Evolution

## Supermassive Black Hole



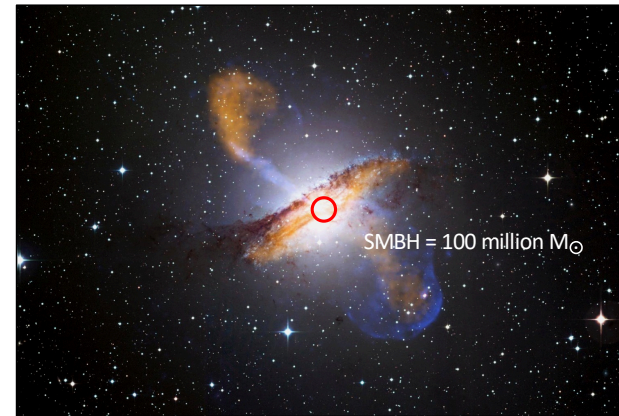
By recording star positions over more than a decade, it was calculated that the object keeping these stars in their orbits has a mass of

4 million  $M_{\odot}$

and a size of no more than a few light-hours ( $\approx$  orbit of Pluto).

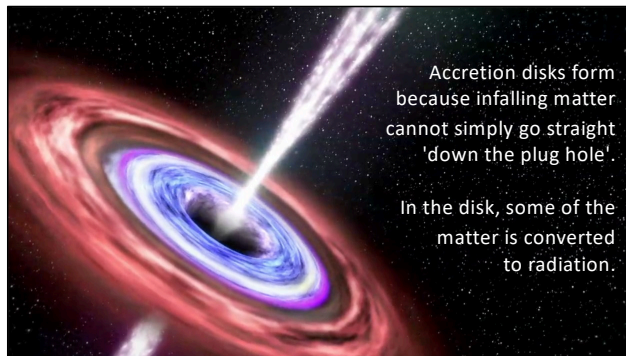
$M_{\odot}$  = mass of our Sun

## Centaurus A



## Black Holes Can Feed

Black holes can 'feed' on surrounding matter falling in



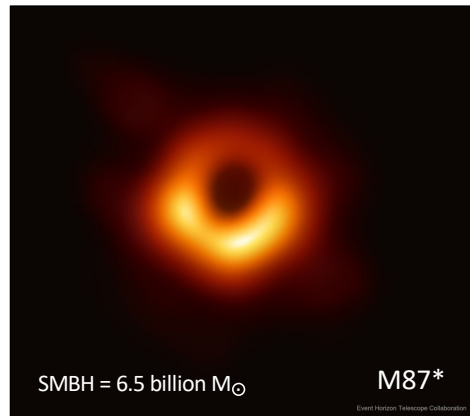
## M87 Jet





# The ABC of Galaxy Evolution

Image of SMBH in M87



Model of SMBH in M87

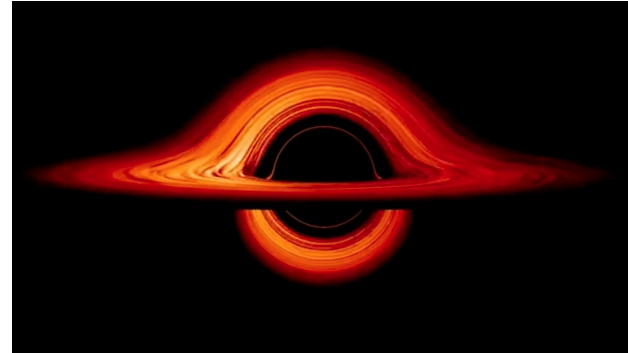
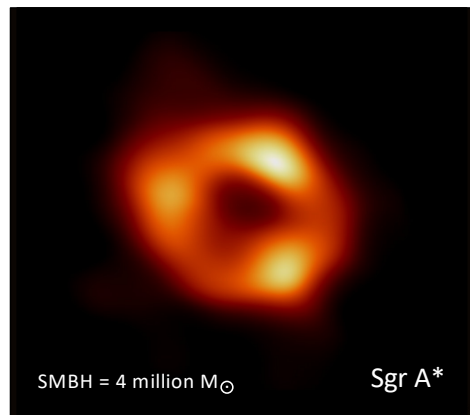
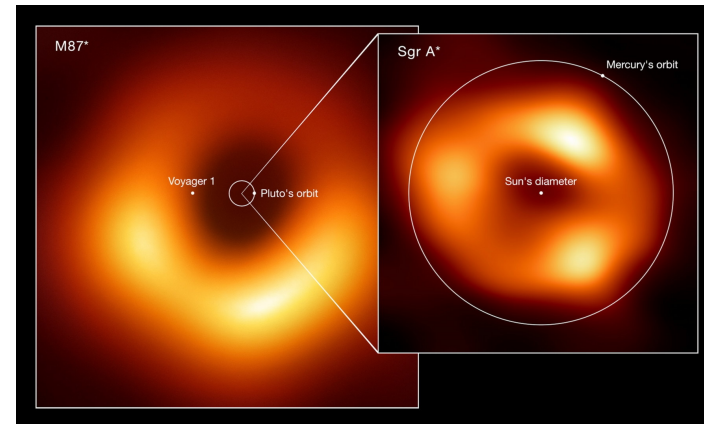


Image of SMBH in Milky Way

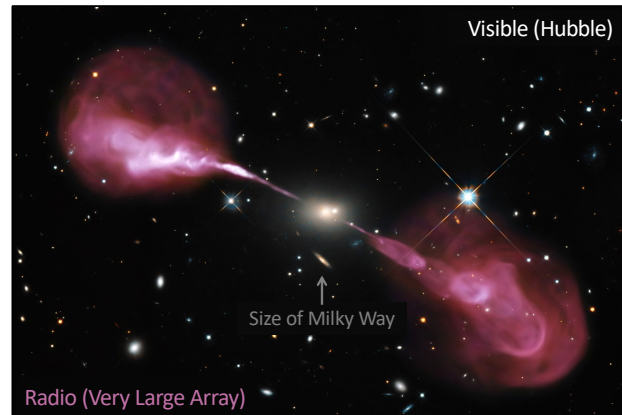


M87\* vs Sgr A\*



# The ABC of Galaxy Evolution

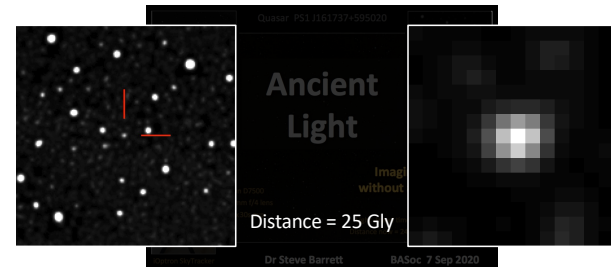
## Hercules A



## AGNs and Quasars

If a SMBH is feeding voraciously on its surrounding gas and stars then it is called an 'active galactic nucleus' (**AGN**).

The most energetic AGNs, called **quasars**, emit so much radiation that they can be observed from distances of billions of light-years.

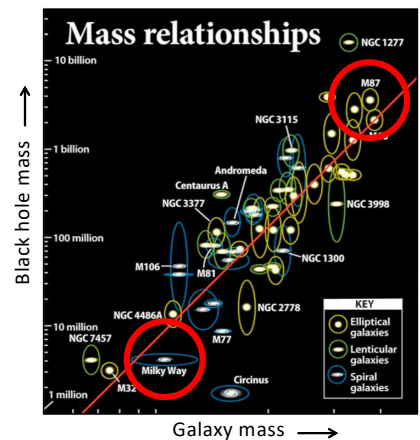


## Supermassive Black Holes

SMBHs have been found in a large number of galaxies.

Typically, SMBH mass is related to the mass of the host galaxy.

Which formed first: SMBH or galaxy?



## The ABC of Galaxy Evolution

### Accretion

*Galaxies were formed by matter created in the Big Bang accreting under the influence of gravity*

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*Supermassive black holes are at the centres of galaxies; some are very active, sometime are quiescent*

### Collisions

*Galaxies grow by colliding and merging with other galaxies over billions of years*

# The ABC of Galaxy Evolution

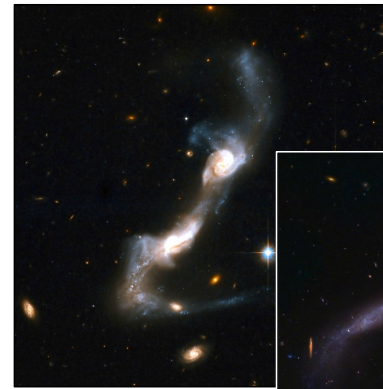
## Galaxy Snapshot



An image of a galaxy can give the false impression that the structure is essentially static, except for a slow rotation that can take hundreds of millions of years.

However, over its lifetime, it can evolve due to interactions with other galaxies.

## Interacting Galaxies



Some images clearly show galaxies interacting with each other ...



## Interacting Galaxies

Some images clearly show galaxies interacting with each other ...

... but the full influence of collisions and mergers in galaxy evolution can be appreciated only through simulations.



## Galaxy Soup



500 kpc



# The ABC of Galaxy Evolution

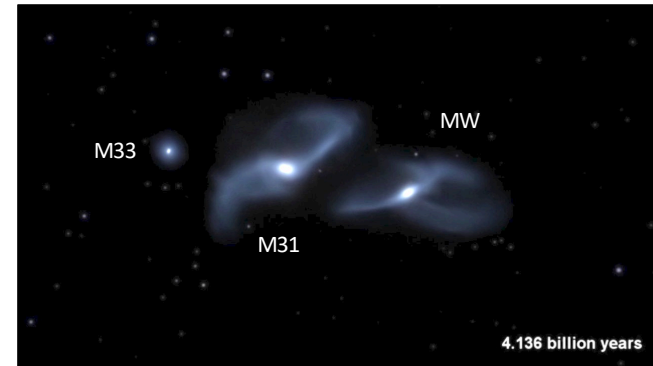
## Elliptical Galaxies



Crowded galaxy clusters often have a larger fraction of (redder) elliptical galaxies compared to (bluer) spirals.

More crowding means collisions are more likely, and colliding spiral galaxies result in elliptical galaxies.

## Milky Way–Andromeda Collision



## Milky Way–Andromeda Collision



## Milky Way–Andromeda Collision



# The ABC of Galaxy Evolution

Milky Way–Andromeda Collision



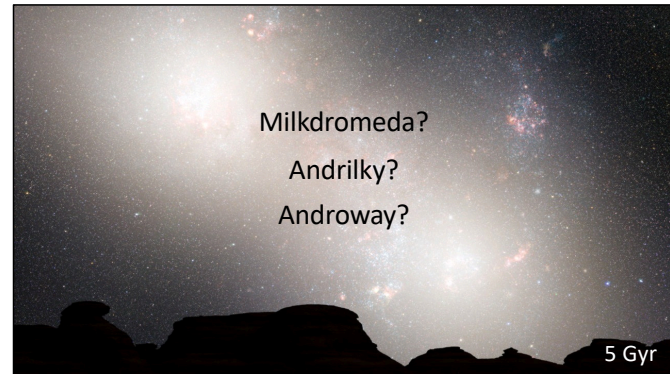
Milky Way–Andromeda Collision



Milky Way–Andromeda Collision



Milky Way–Andromeda Collision





# The ABC of Galaxy Evolution

## Milky Way–Andromeda Quasar?



## The ABC of Galaxy Evolution

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## The ABC of Galaxy Evolution



# The ABC of Galaxy Evolution

[www.liverpool.ac.uk/~sdb/Talks](http://www.liverpool.ac.uk/~sdb/Talks)

Dr Steve Barrett

BADAS 14 May 2025