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

Where Does the Story Start?

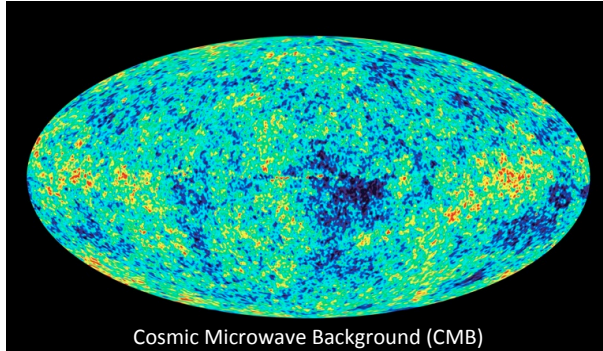At the Beginning … of Everything …

The ABC of Galaxy Evolution

Where Does the Story Start?

At the Beginning … of Everything …

Cosmic Microwave Background (CMB)

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5

Cosmic Structure

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

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6
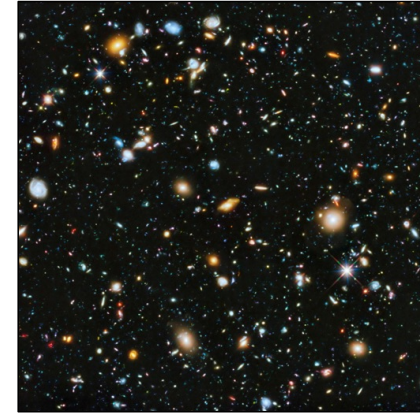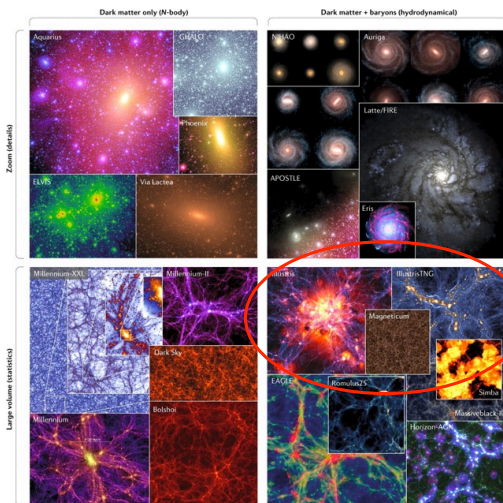
Simulations

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.

7

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.

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8

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Cosmic Web

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

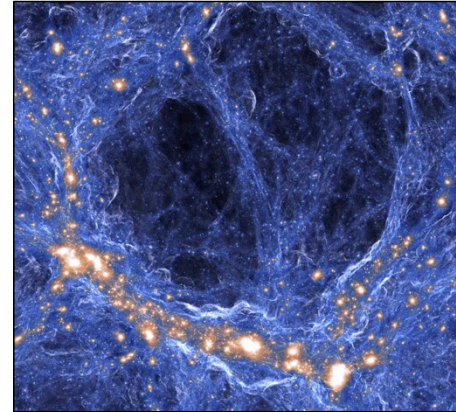… and over billions of years collapsed into a cosmic web of filaments and voids.


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9
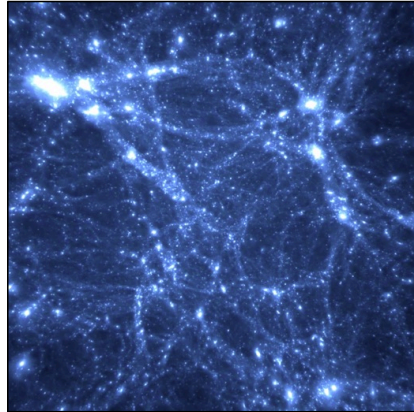
Cosmic Web

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.

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10

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.

Time since the Big Bang: 3.7 billion years
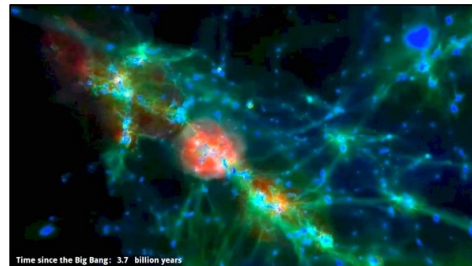
Gas blasted out (red bubbles) by black holes or massive stars ending their lives as supernovae can slow matter falling in from the filaments.

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www.illustris-project.org   11

Can Simulations Explain Galaxy Diversity?

Colour

Blue

Shape

Disk

Structure

Spiral

www.galex.caltech.edu

Colour

Red

Shape

Elliptical

Structure
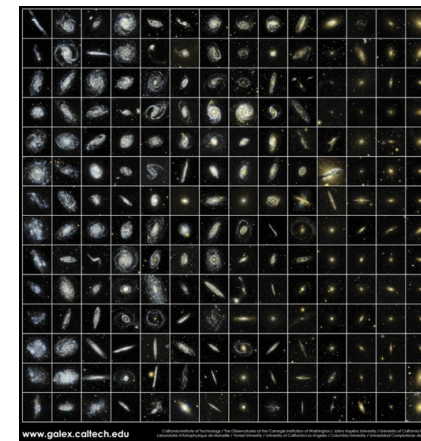
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12

The ABC of Galaxy Evolution

Slide 13

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

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13

Slide 14

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.
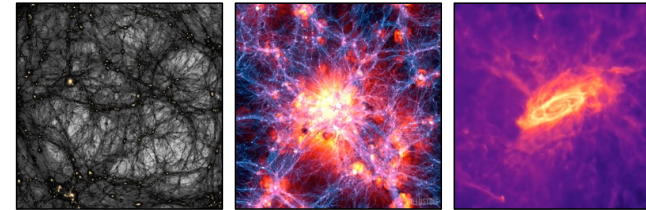
Dark matter web   Black holes + supernovae   Matter accretion

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.

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Slide 15

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.)
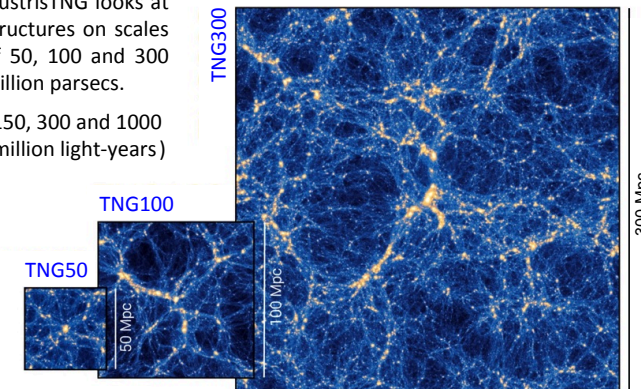
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Slide 16

IllustrisTNG

IllustrisTNG looks at structures on scales of 50, 100 and 300 million parsecs.

(150, 300 and 1000 million light-years)

TNG300

TNG100

TNG50

50 Mpc   100 Mpc   300 Mpc

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Light-Years and Parsecs

1 parsec = 3.26 light-years

Amateur astronomers often use light-years

Astrophysicists tend to prefer using parsecs

Milky Way diameter
150,000 ly ≈ 50 kpc

Distance
2.5 Mly ≈ 1 Mpc

Milky Way   **Andromeda Galaxy**

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17

IllustrisTNG

50 kpc

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Simulation vs Observation

Observation

Do simulated galaxies look the same as real galaxies?

The higher resolution of the TNG50 simulation shows more detail in the structure of individual galaxies.

TNG300
Simulation

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19

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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21

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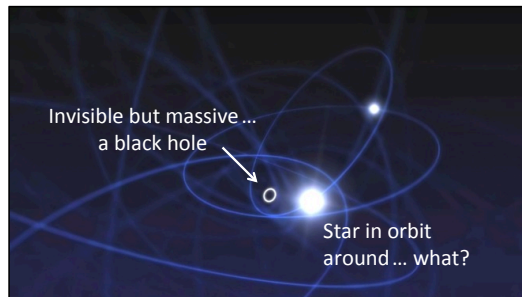
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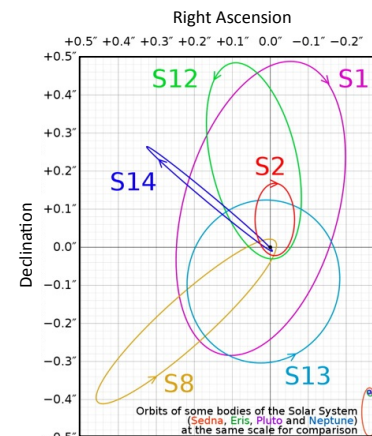
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22

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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23

Supermassive Black Hole

Right Ascension
+0.5″ +0.4″ +0.3″ +0.2″ +0.1″ 0.0″ −0.1″ −0.2″

S12   S1

S14   S2

S8   S13

Orbits of some bodies of the Solar System
(Sedna, Eris, Pluto and Neptune)
at the same scale for comparison

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
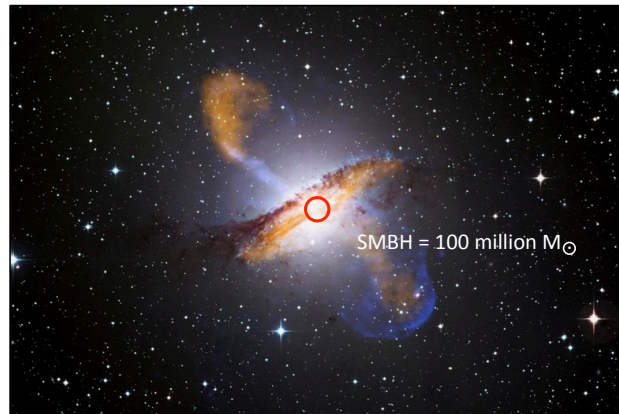
4 million $M_\odot$

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

$M_\odot$ = mass of our Sun

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24

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Centaurus A

SMBH = 100 million $M_\odot$

25

Black Holes Can Feed

Black holes can 'feed' on surrounding matter falling in

Accretion disks form because infalling matter cannot simply go straight 'down the plug hole'.

In the disk, some of the matter is converted to radiation.

26

M87 Jet

27

Image of SMBH in M87

SMBH = 6.5 billion $M_\odot$ M87*

Event Horizon Telescope Collaboration

28

Model of SMBH in M87

29

Hercules A

Visible (Hubble)

Size of Milky Way

Radio (Very Large Array)
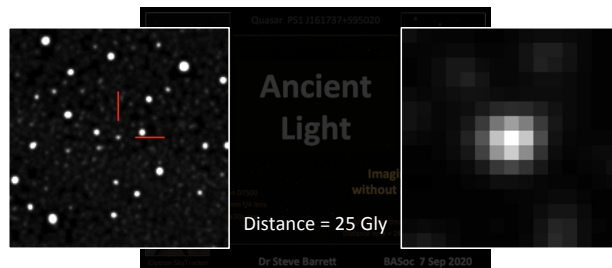
30
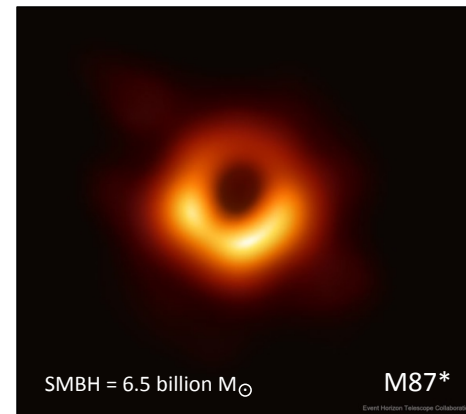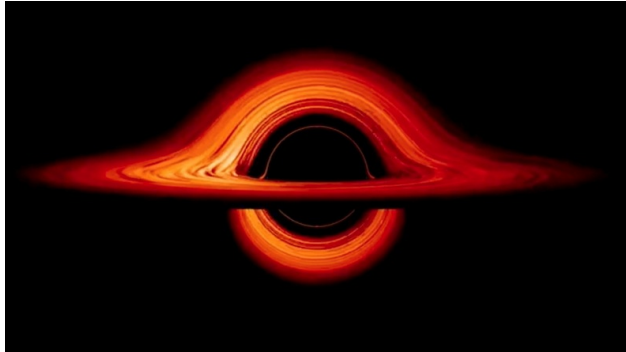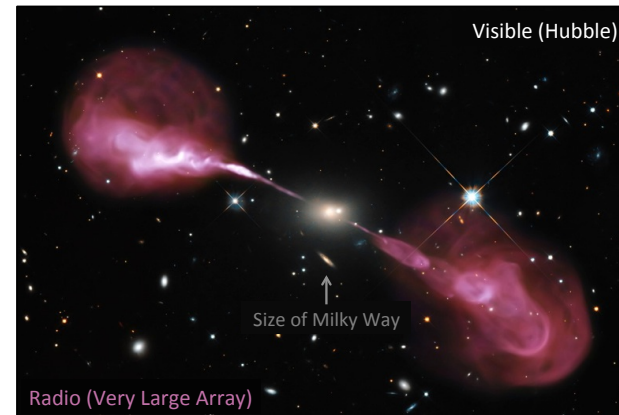
AGNs and Quasars

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.
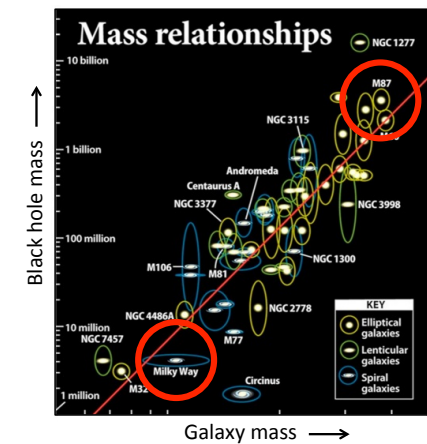

Distance = 25 Gly

31

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?

32

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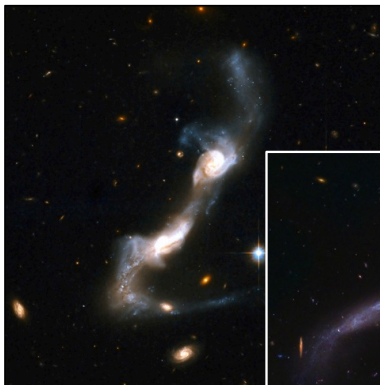
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33

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.

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34

Interacting Galaxies

Some images clearly show galaxies interacting with each other …

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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.

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36
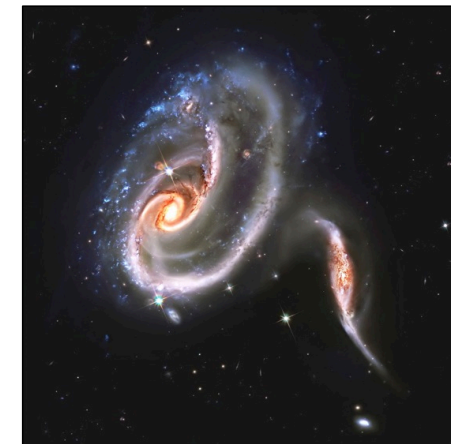
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Galaxy Soup

500 kpc

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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.

38

Milky Way−Andromeda Collision

M33

MW

M31

4.136 billion years

39

Milky Way−Andromeda Collision

1 Gyr

40
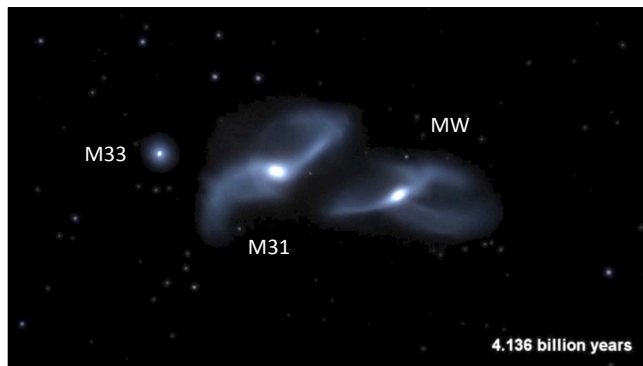
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Milky Way−Andromeda Collision

Milkdromeda?

Andrilky?

Androway?

5 Gyr

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45
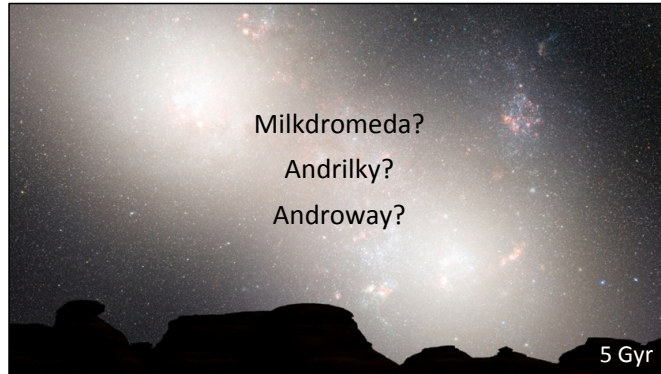
Milky Way−Andromeda Quasar?

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46

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47

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www.liverpool.ac.uk/~sdb/Talks

Dr Steve Barrett   SAS 21 Aug 2022