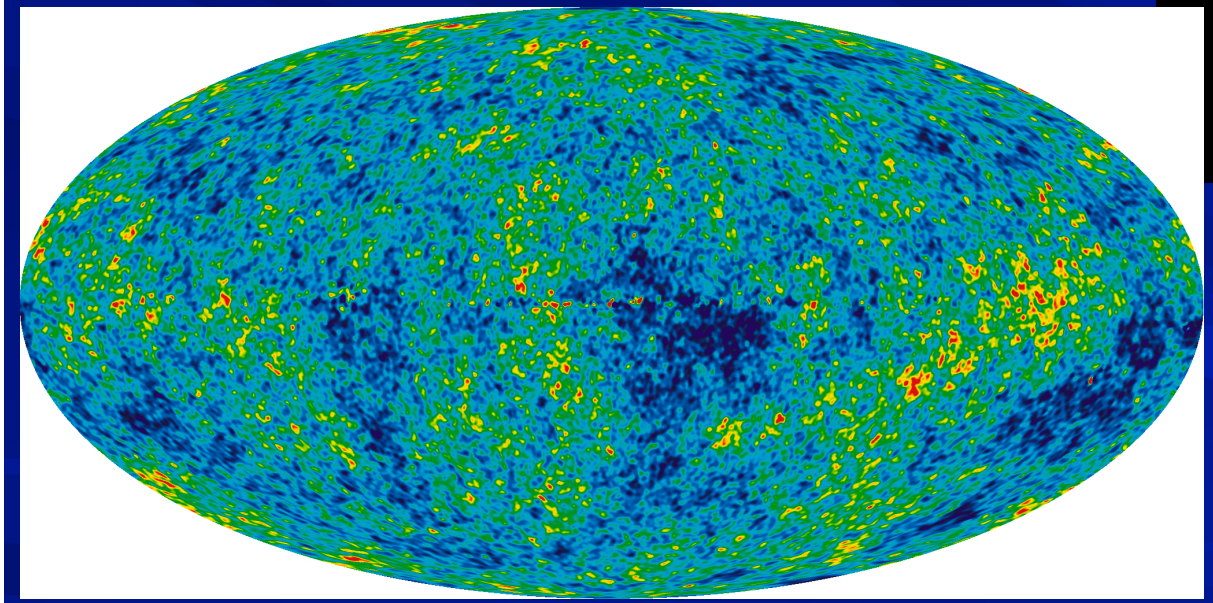
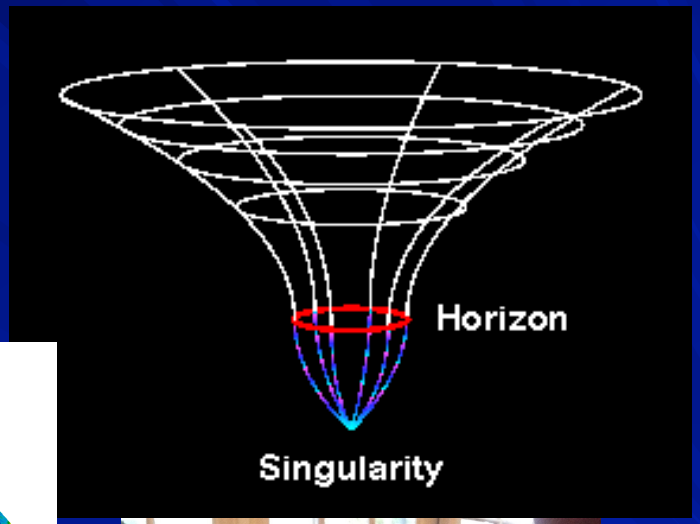
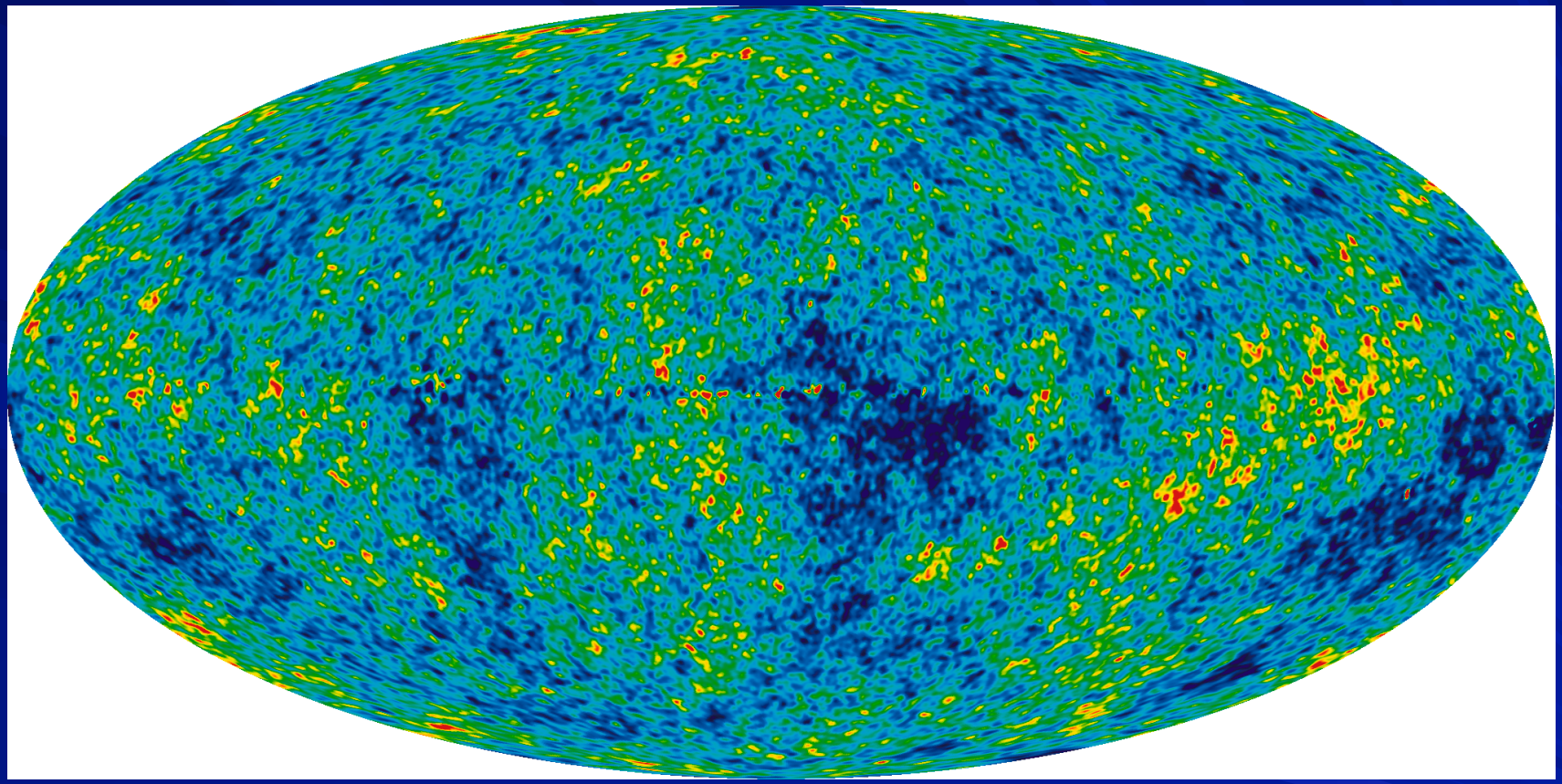
How the Universe Evolved from Smooth to Lumpy: The Formation of Galaxies & Massive Black Holes

Eliot Quataert (UC Berkeley)



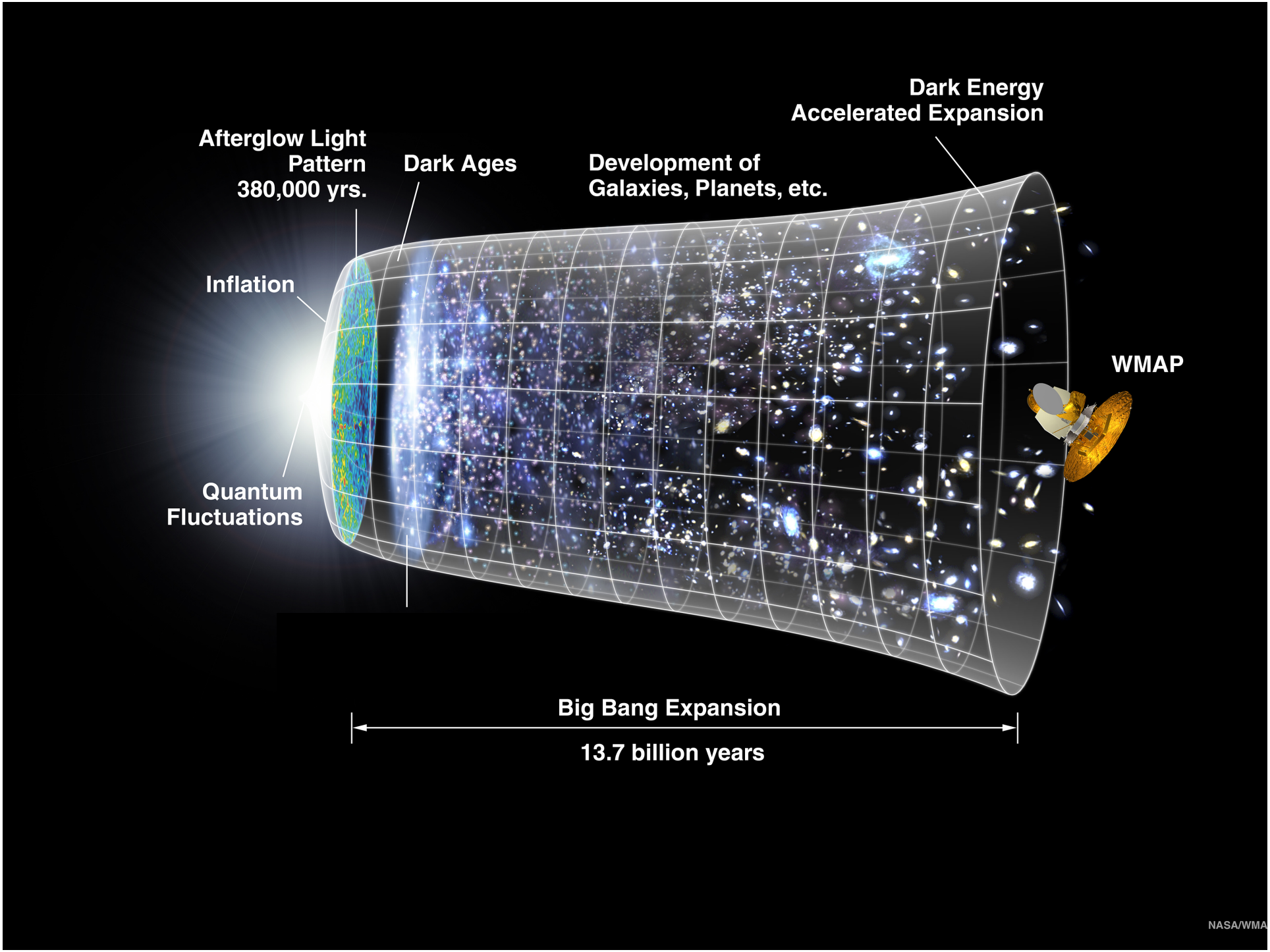


The Distant Past, Observed Today



Smooth Early Universe Observed in Cosmic Microwave Background

Tiny ~ 0.001% differences in temperature/density
from one part of the universe to another


Dark Energy
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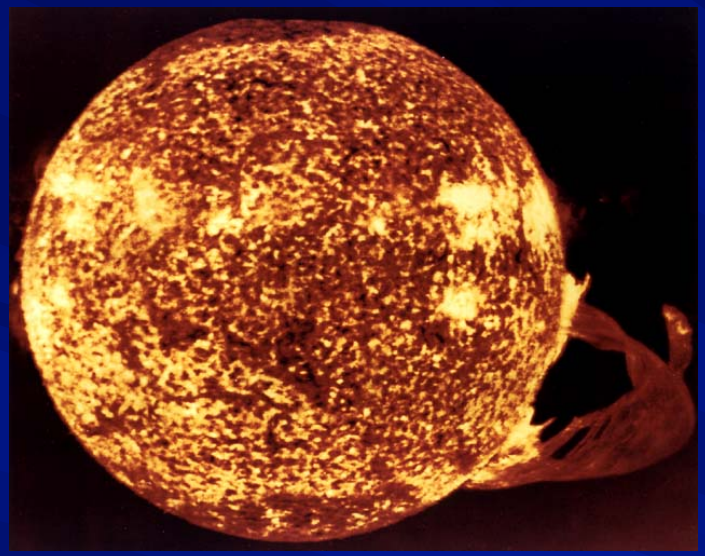
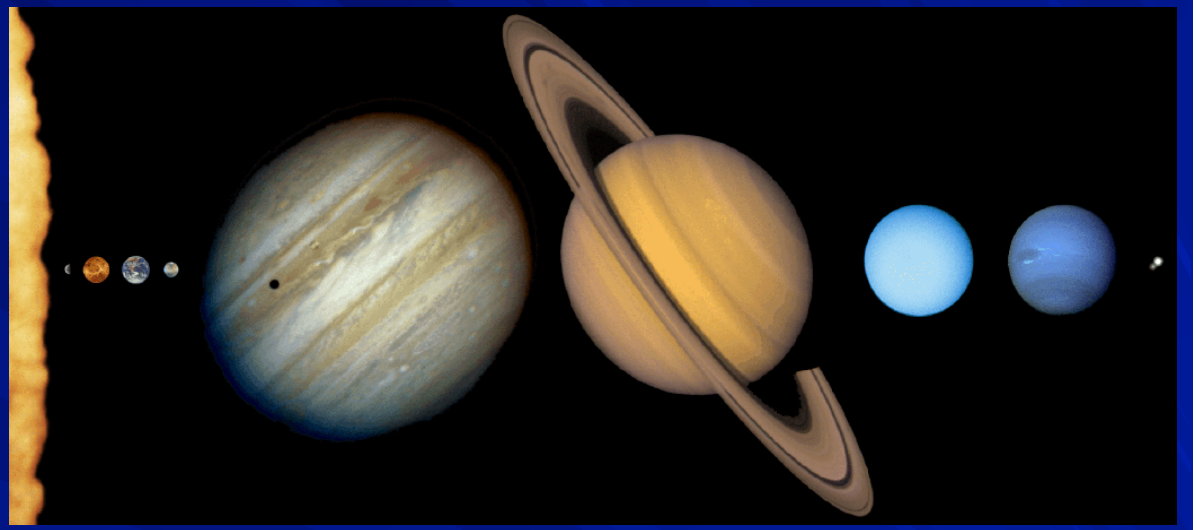
The Lumpy Universe





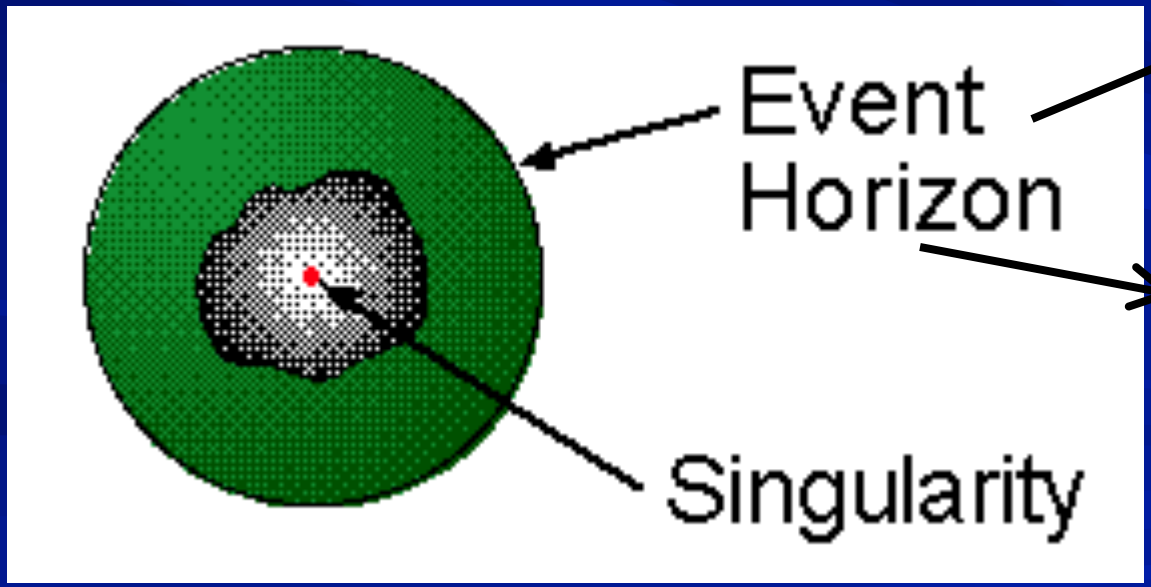
The Milky Way Galaxy

The Hubble Deep Field

Black Holes

the Densest Objects in the Universe

If an object is small enough, gravity overwhelms all other forces & the object collapses. Gravity is so strong that nothing, not even light, can escape.



"Radius" of a BH

≈ 2 miles for a solar mass

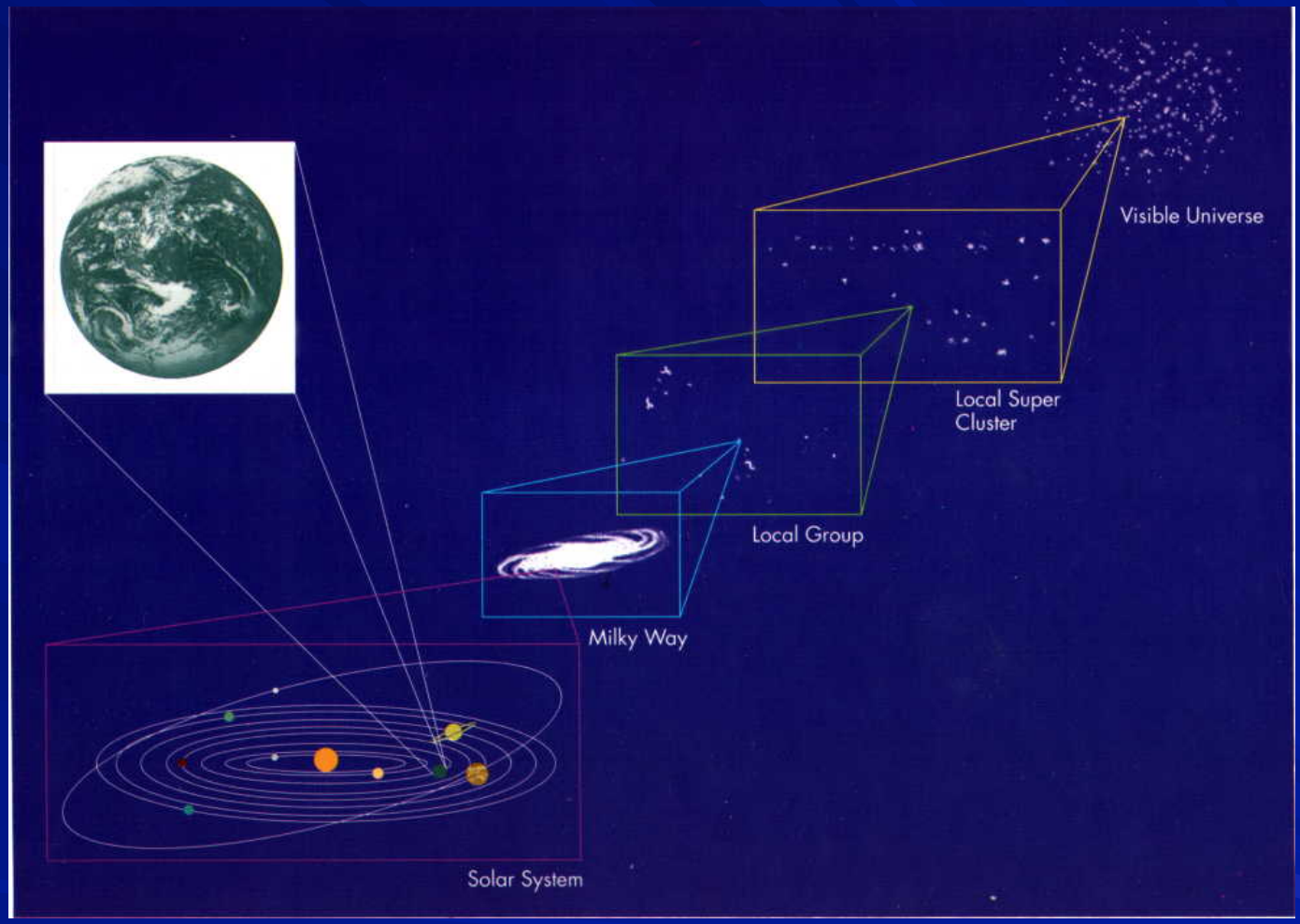
≈ 1 inch for an Earth mass

NOT a solid surface

All Mass at the Center

(GR not valid there)

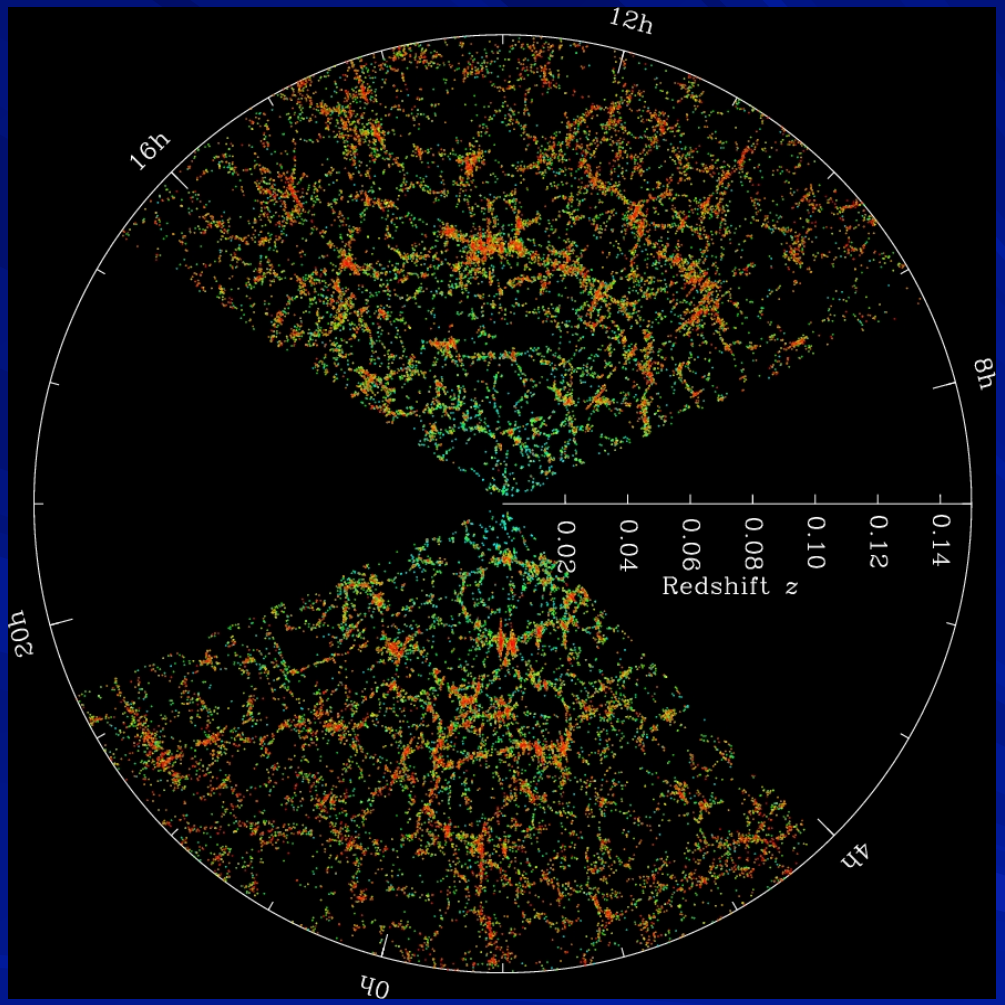
A Cosmic Census



For all our conceits about being the center of the universe, we live on a routine planet of a humdrum star stuck away in an obscure corner on an unexceptional galaxy which is one of about 100 billion galaxies. That is the fundamental fact of the universe we inhabit, and it is very good for us to understand that. *Carl Sagan*

A Cosmic Census

Large-scale structure with SDSS



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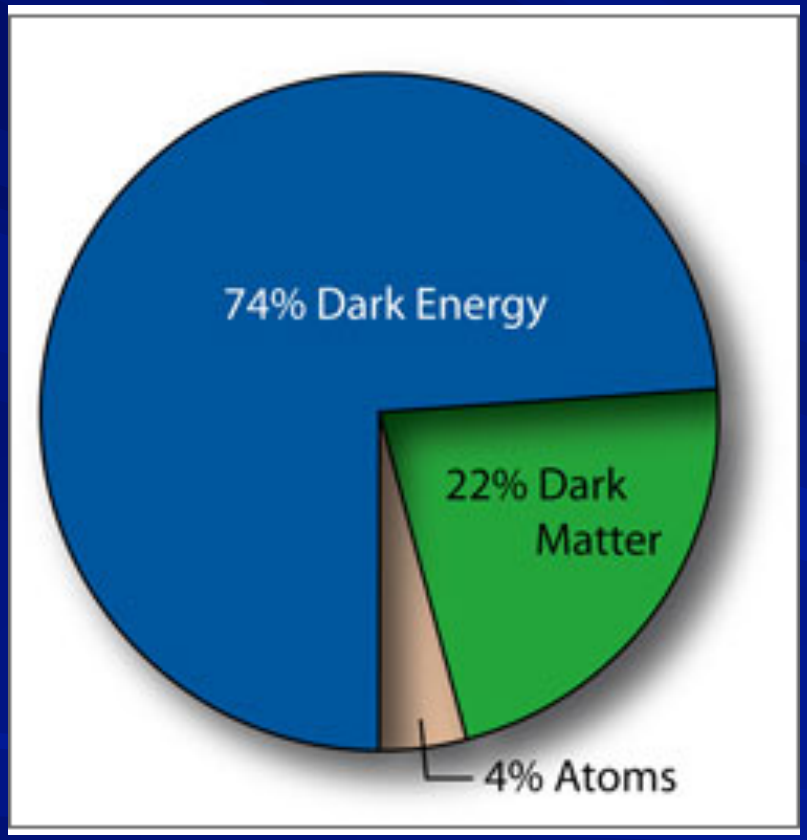
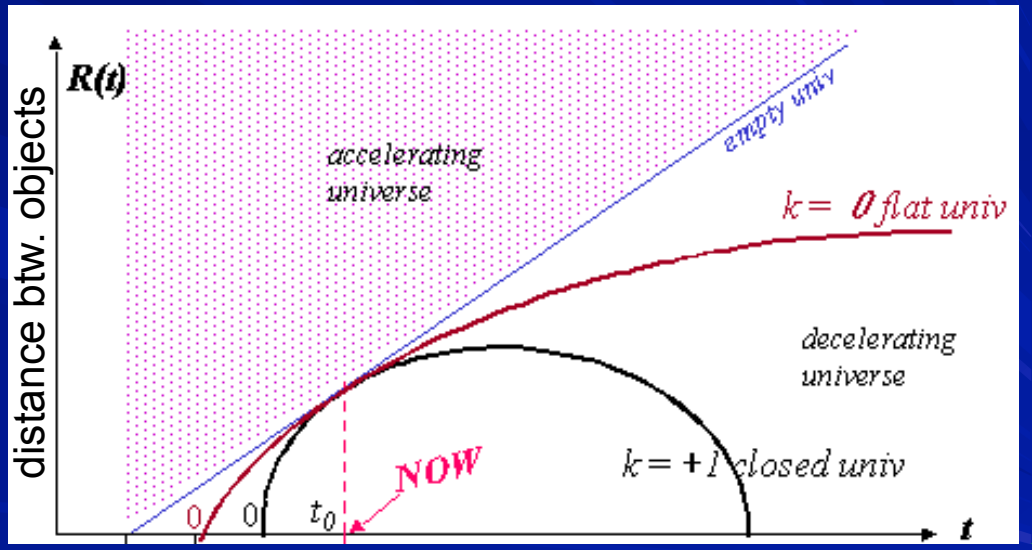
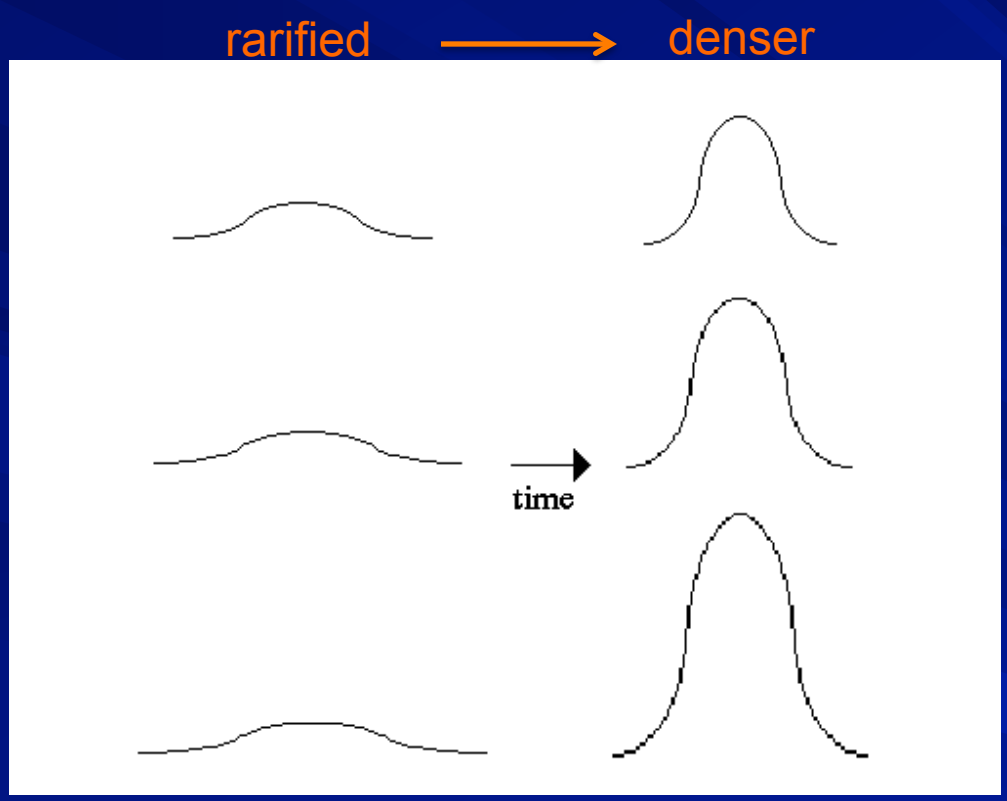
Dark Energy, Dark Matter Set the Stage

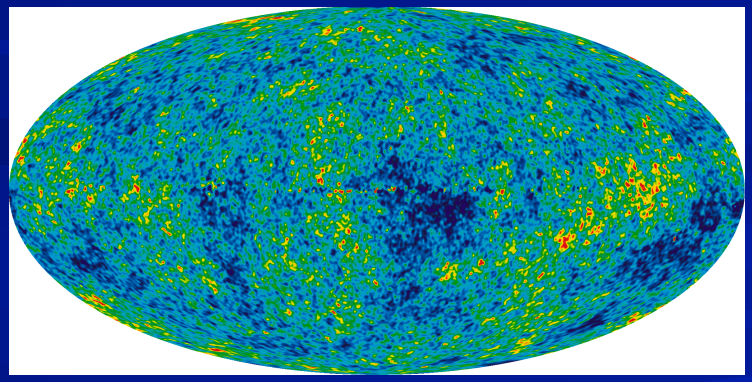


On the Largest Scales, Dark Energy & Dark Matter Determine the History of the Universe



Structure Grows Via Gravity



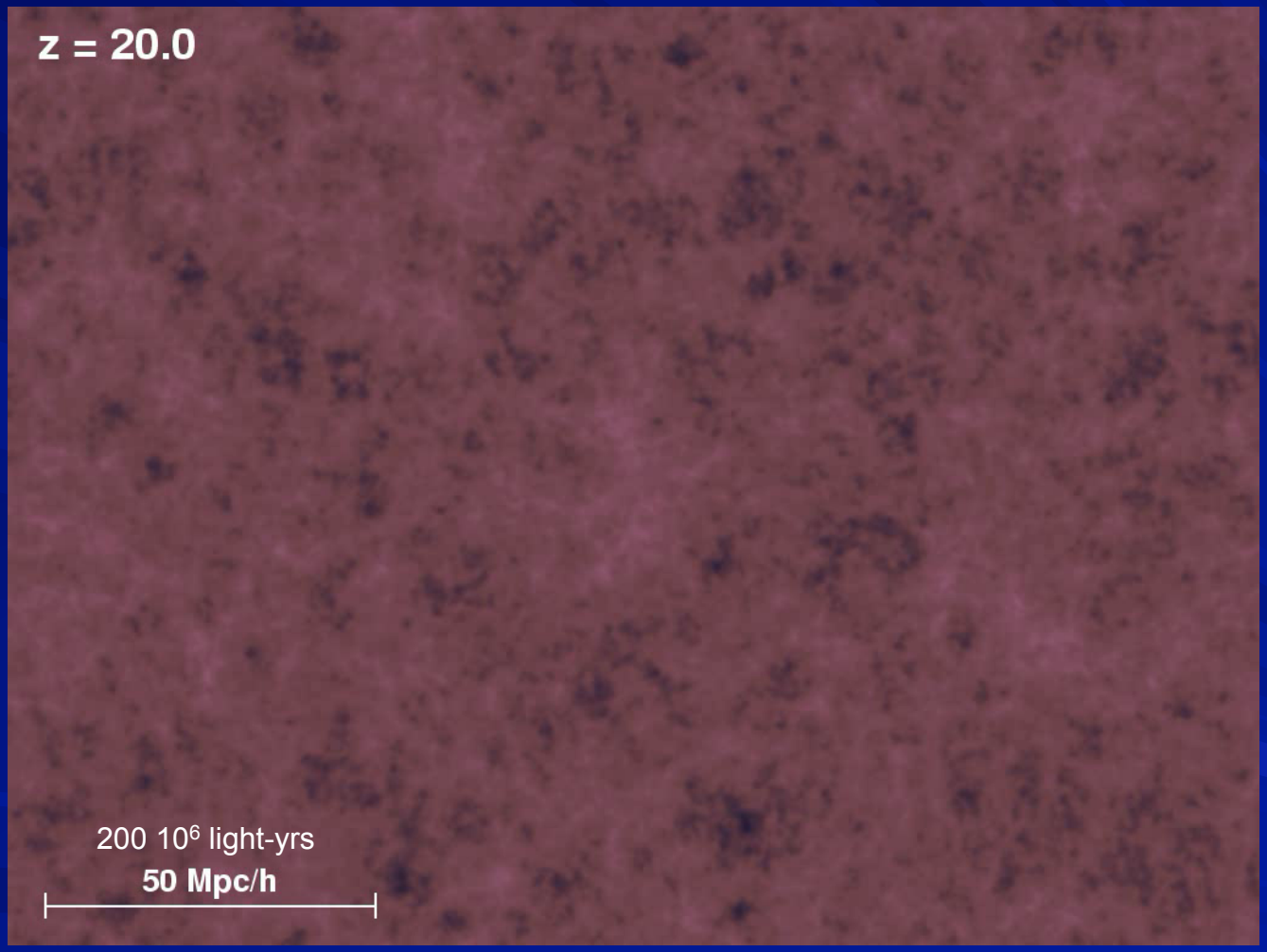


Regions denser than avg get denser & more massive due to relentless attractive force of gravity
(even though universe is expanding)

Dark Matter, ***NOT*** Dark Energy, Dominates this Growth

(dark energy smooth, not lumpy)

Structure Grows Via Gravity



(Credit: Volker Springel)

White = dense
Blue = underdense

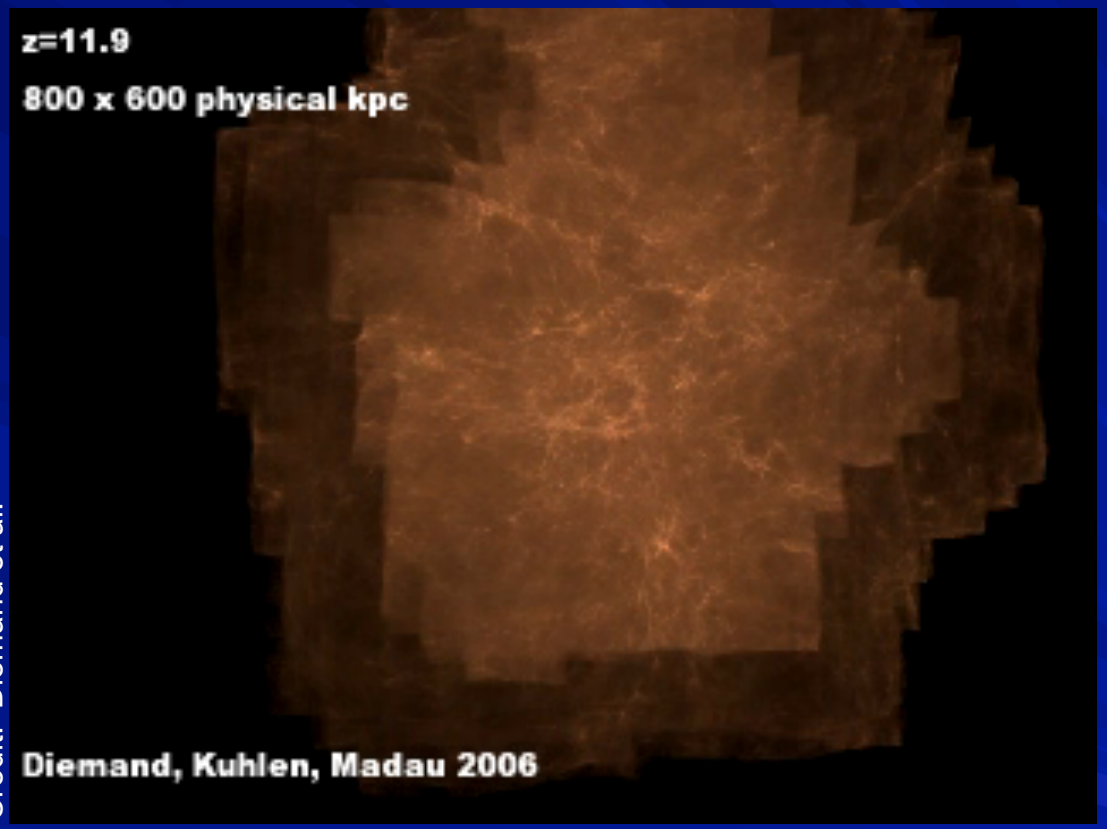
z=redshift

distance btw objects
~ 1/(1+z)

today: z = 0
CMB: z ~ 1100

Simulation of Dark Matter Distribution from z ~ 20 to present (F=ma!)
Regions grow until held together by their own gravity ("bound")
(object then no longer ***internally*** expands as universe does)

Structure Grows Via Gravity



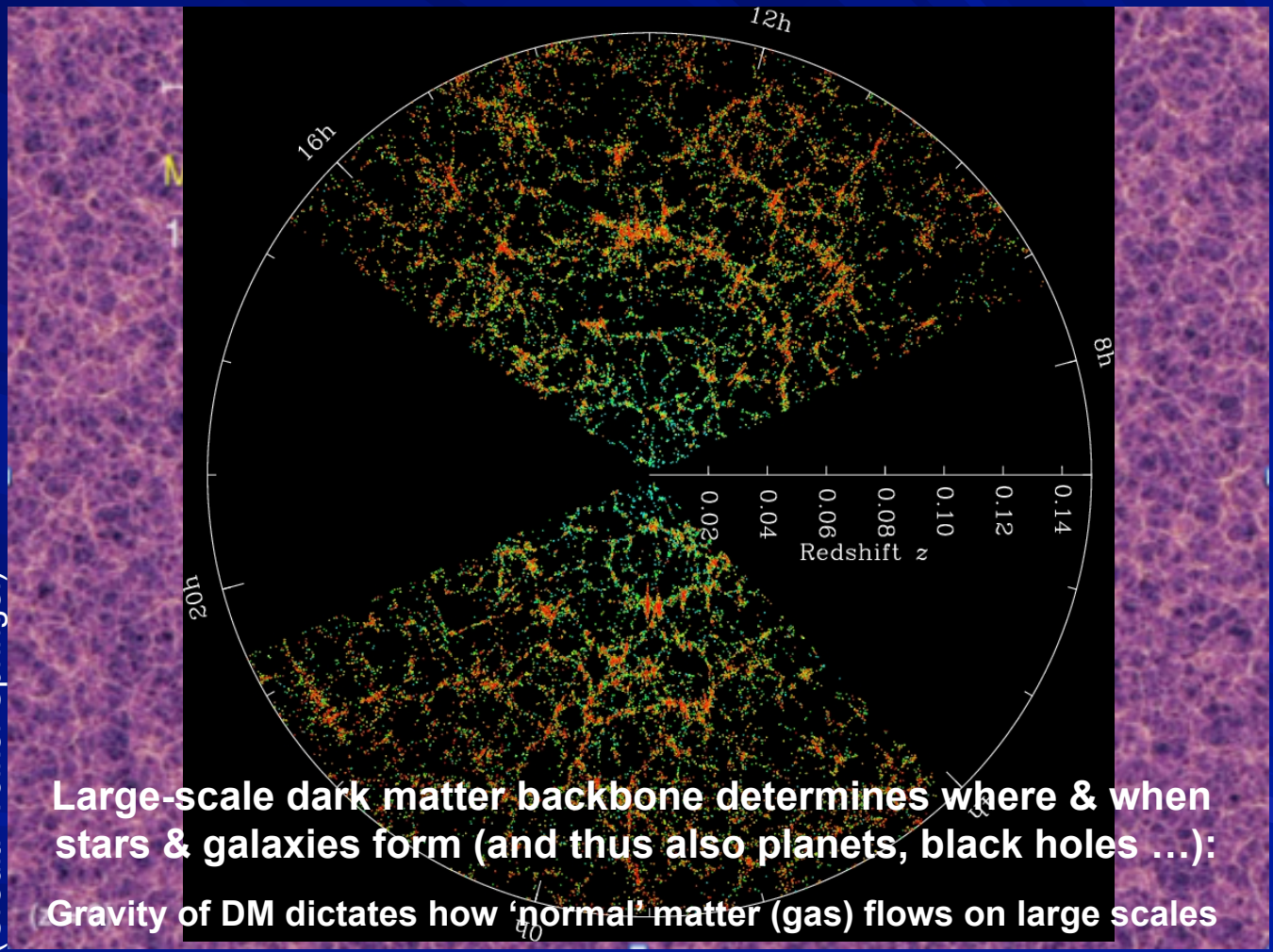
few million light-yrs

Credit: Diemand et al.

Simulation of Growth of Dark Matter
"Halo" in Milky-Way-like Galaxy:

First bound structures small – larger objects grow via collisions/mergers with other objects

‘Cosmic Web’ of Dark Matter today (z = 0)

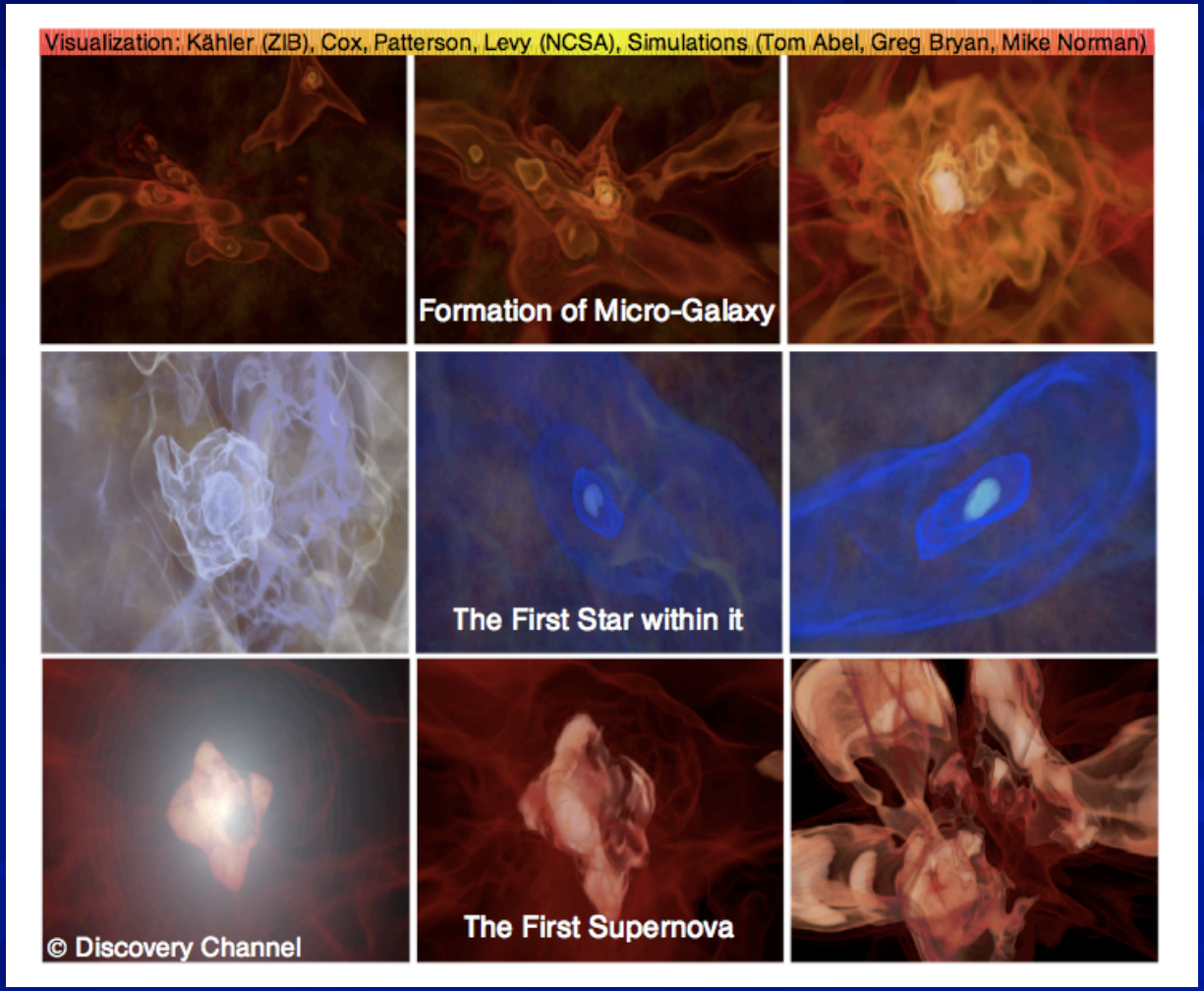


(Credit: Volker Springel)

Large-scale dark matter backbone determines where & when stars & galaxies form (and thus also planets, black holes …):

Gravity of DM dictates how ‘normal’ matter (gas) flows on large scales

The First Stars & Galaxies



First Galaxies:

~ $10^{4\text{-}5}$ M_{sun} DM
handful of stars

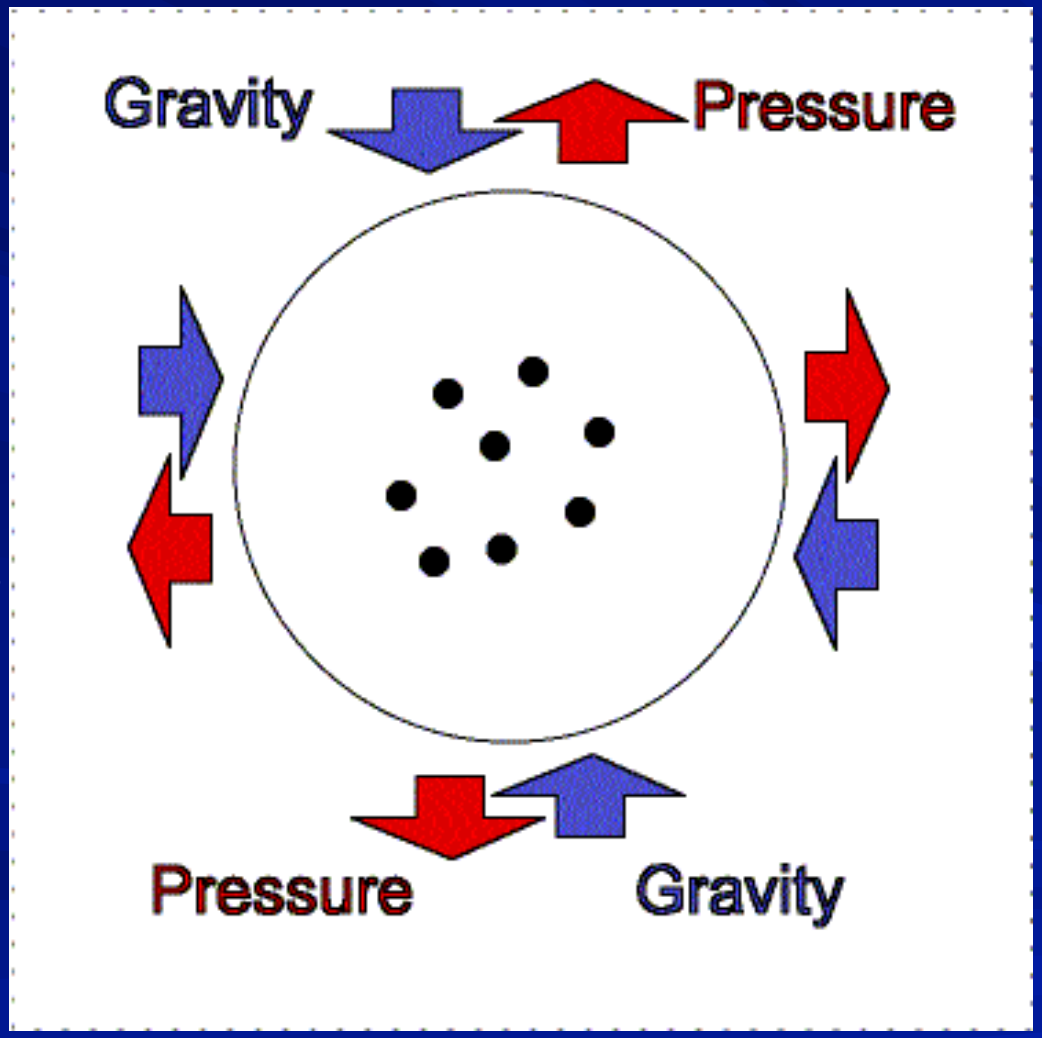
Milky Way:

~ trillion M_{sun} DM
~ trillion stars

Bound Dark Matter Objects First Form at z ~ 20
(few 100 million yrs after big bang):

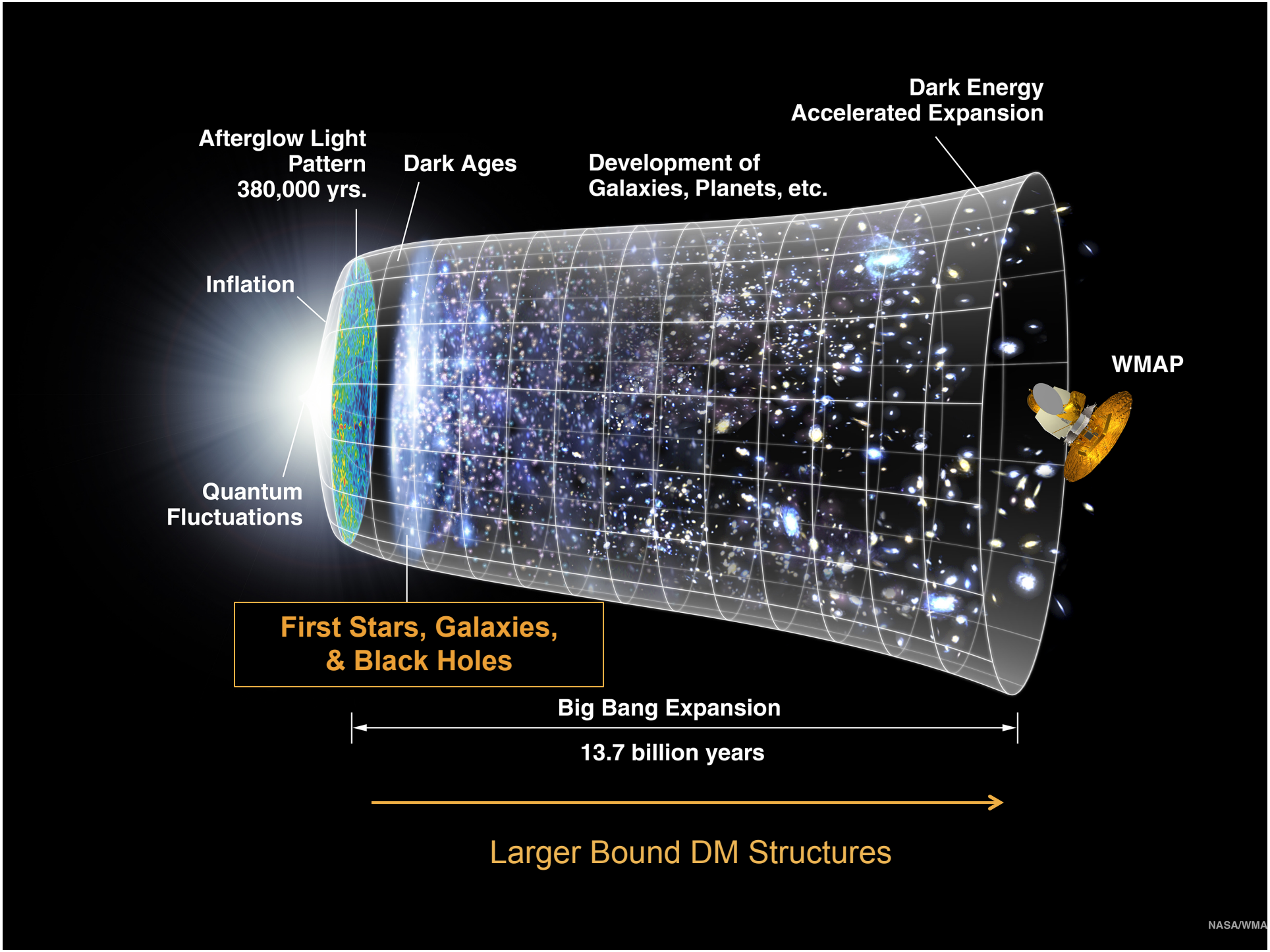
The First Black Holes

What Keeps Gravity at Bay in Stars?



From www.astronomynotes.com

- Stars: Pressure of hot interior balances gravity
- Fusion of H → He → C →… Fe keeps stars hot
- Fusion ceases after ~ million yrs for massive stars (≥ 30 M_{sun}) → collapse to black holes
- **First BHs (~ 10 M_{sun}) appear just after the first stars**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Larger Bound DM Structures
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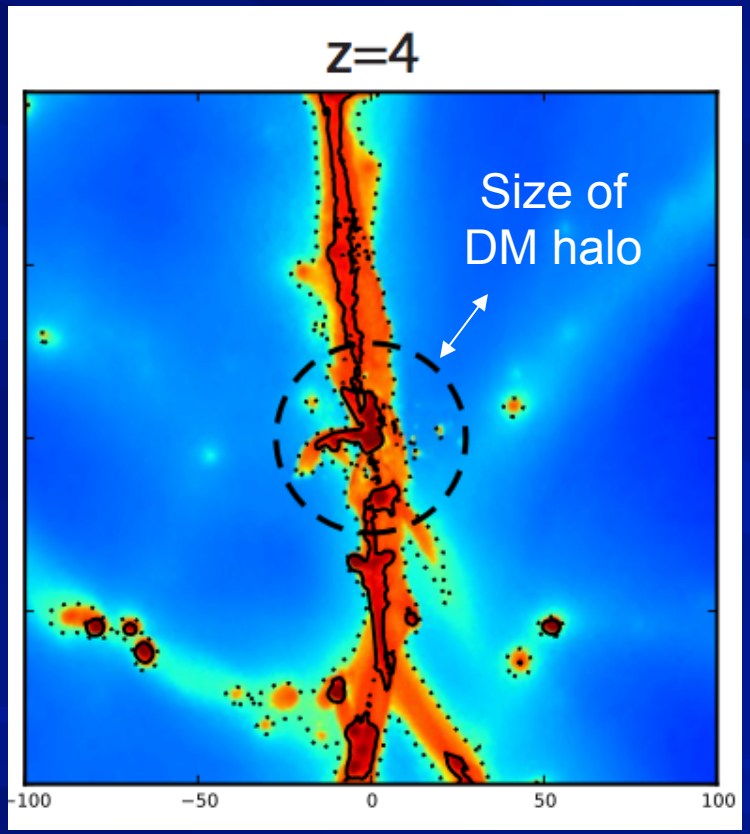
How Galaxies Grow

(i.e., the stuff we see, gas/stars, not DM)

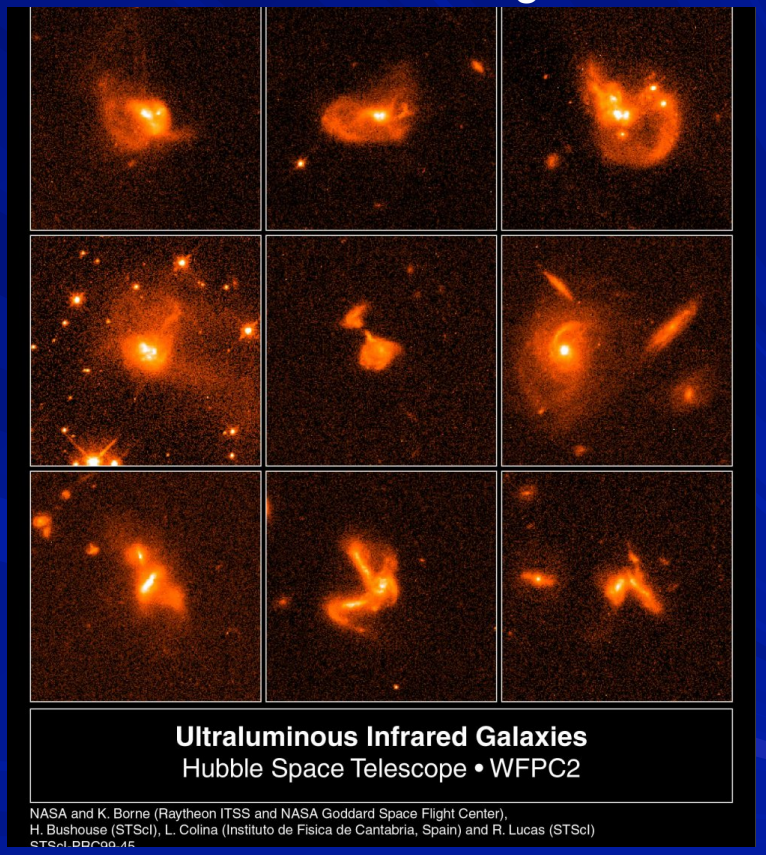
Continued inflow of gas into galaxies



Keres & Faucher-Giguere

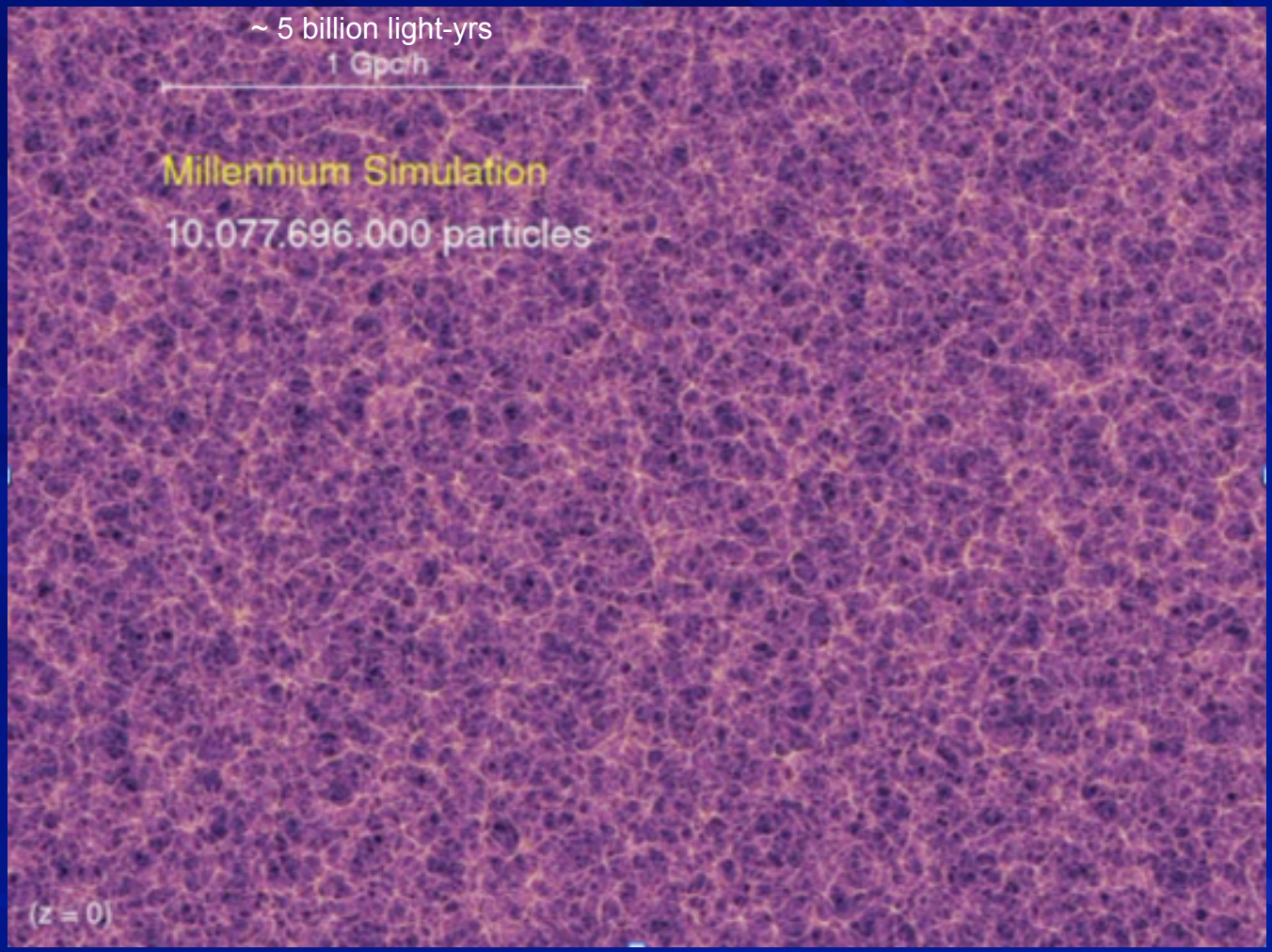
Red = cold, dense stream of gas flowing into galaxy in simulation

Collisions with other galaxies



Hubble Images of Merging Galaxies

Why Isn't Galaxy Formation a Solved Problem?



Large-scale dark matter backbone determines where & when stars & galaxies form (and thus also planets, black holes …):

Gravity of DM dictates how 'normal' matter (gas) flows on large scales

The Major Challenge In Galaxy Formation

It's not a 1-way Street ("Feedback"):
Gas Stops Following DM Inside Galaxies

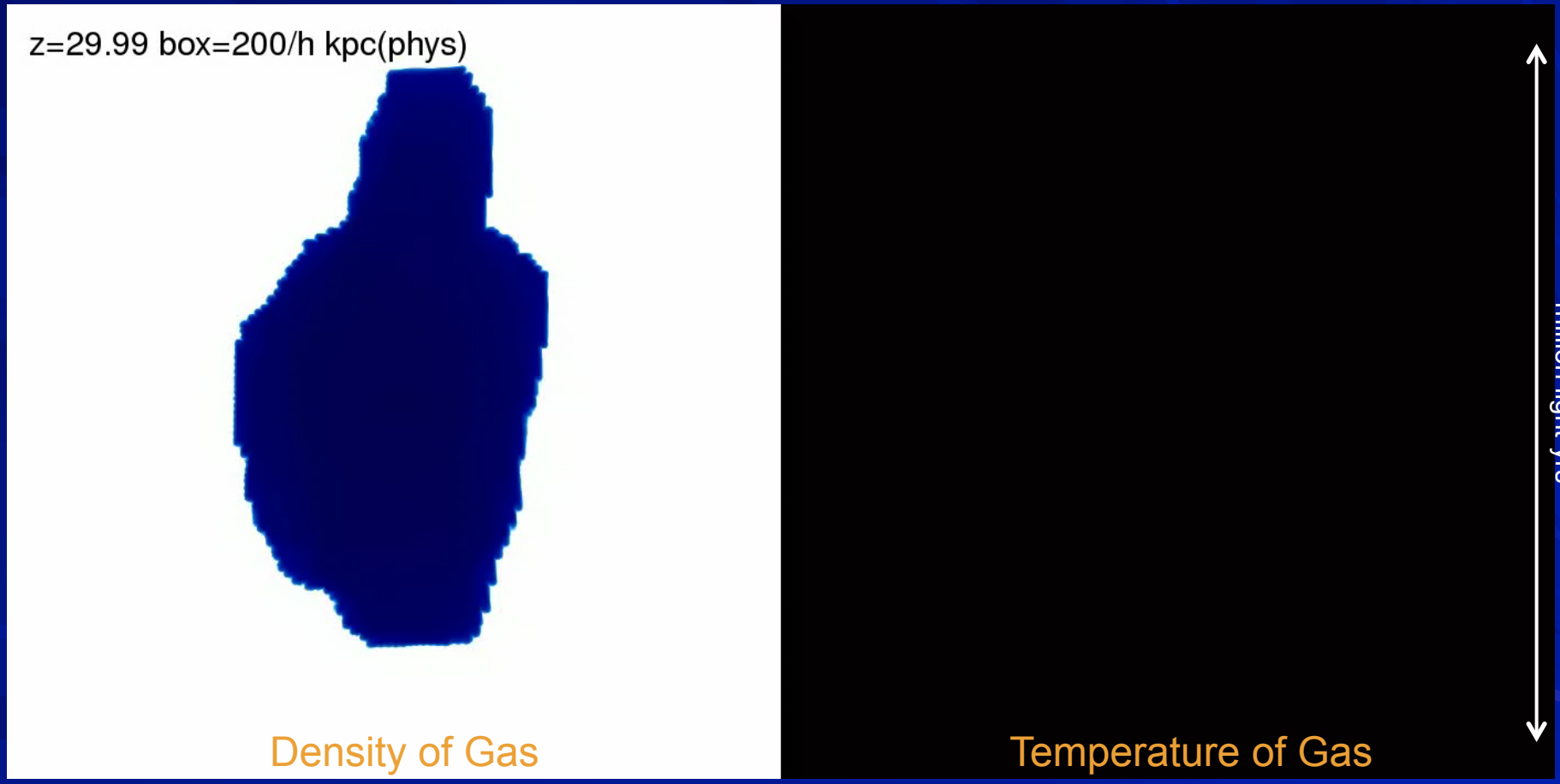
Supernovae (exploding stars), stellar winds,
& stellar radiation churn up their surroundings

Most gas that flows into galaxies flows back out!

Images of Galaxy-Scale Outflows
of Gas Driven by Star Formation

The Major Challenge In Galaxy Formation

It's not a 1-way Street: Gas Stops Following DM Inside Galaxies



Dusan Keres, Phil Hopkins, & EQ

Simulation of a Region that will become a MW-like Galaxy
with Models for how Star Formation Impacts Surrounding Gas

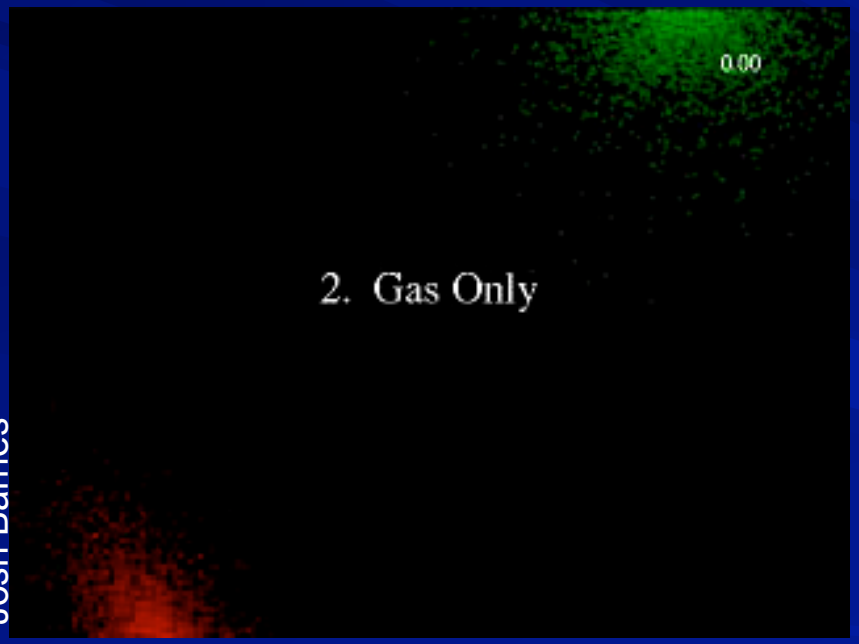
How Massive BHs at the Centers of Galaxies Grow

- Event Horizon ~Size of Solar System for ~Billion M_{sun} BH
- Size of Galaxy ~Million x Size of Solar System
- BHs are ***NOT*** cosmic vacuum cleaners: only inside the horizon is matter pulled inexorably inward

- Far away from a BH, gravity is **no different**
- If a BH were to replace the sun, the orbits of the planets would be **unchanged**
  (just like the Earth orbits happily around the sun)

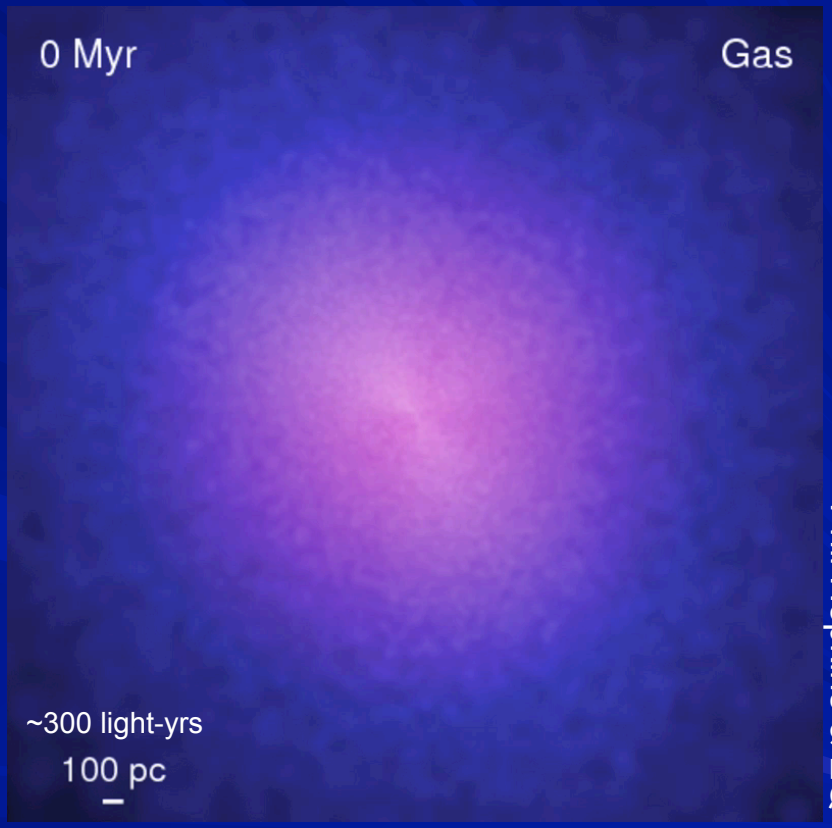
How Massive BHs at the Centers of Galaxies Grow

Simulations of Gas Inflow During Galaxy Collisions



Josh Barnes

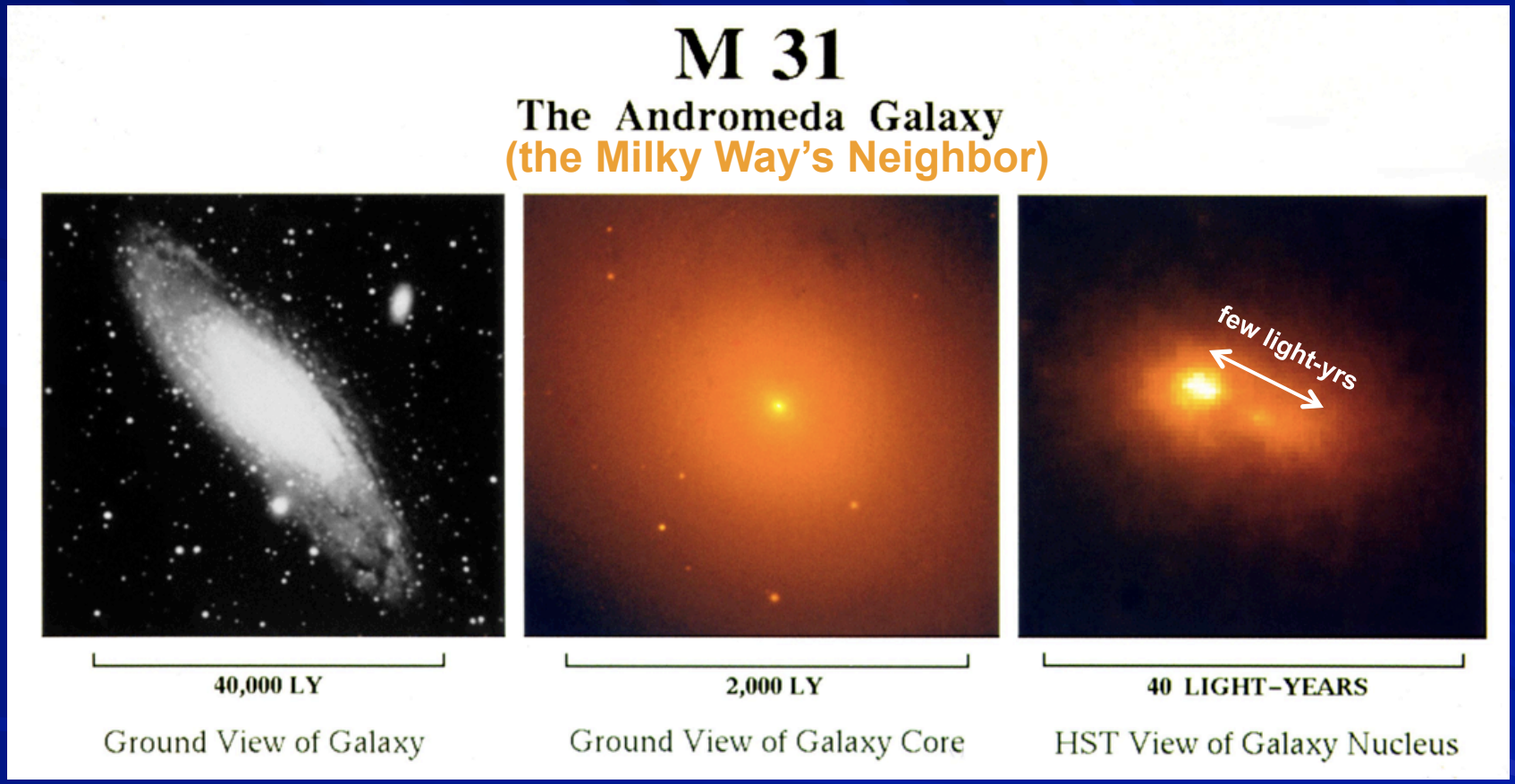
Large Asymmetries in Gravity
➔ Gas Flows to the Center



Phil Hopkins & EQ

'Zoom-in' Simulations of Gas Inflow in the Center of a Galaxy

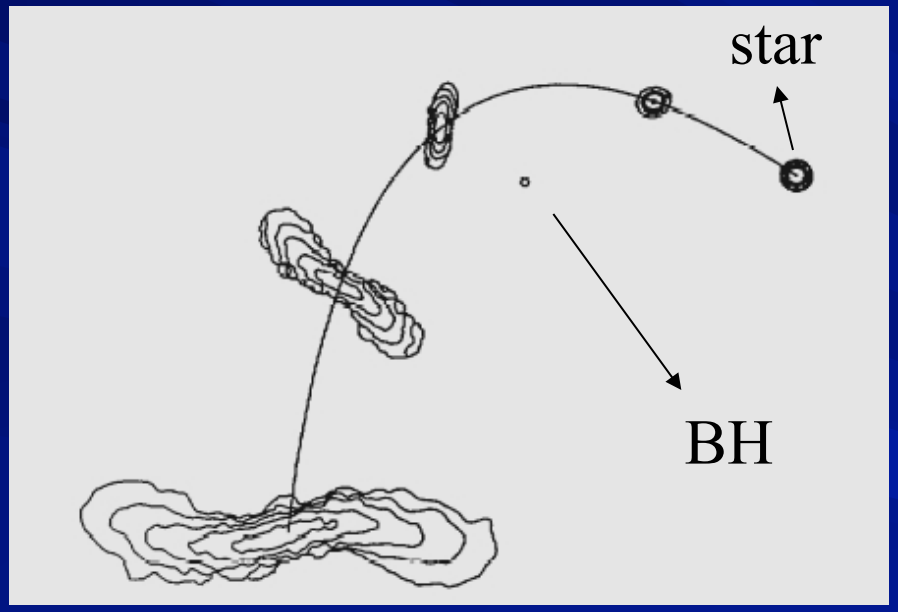
The ‘Double’ Stellar Nucleus of M31: A Fossil from the Era of BH Growth?



2 Nuclei an **Illusion**: Signature of Asymmetric Stars Like That Needed to Fuel BH Growth

Other (subdominant) Routes to BH Growth

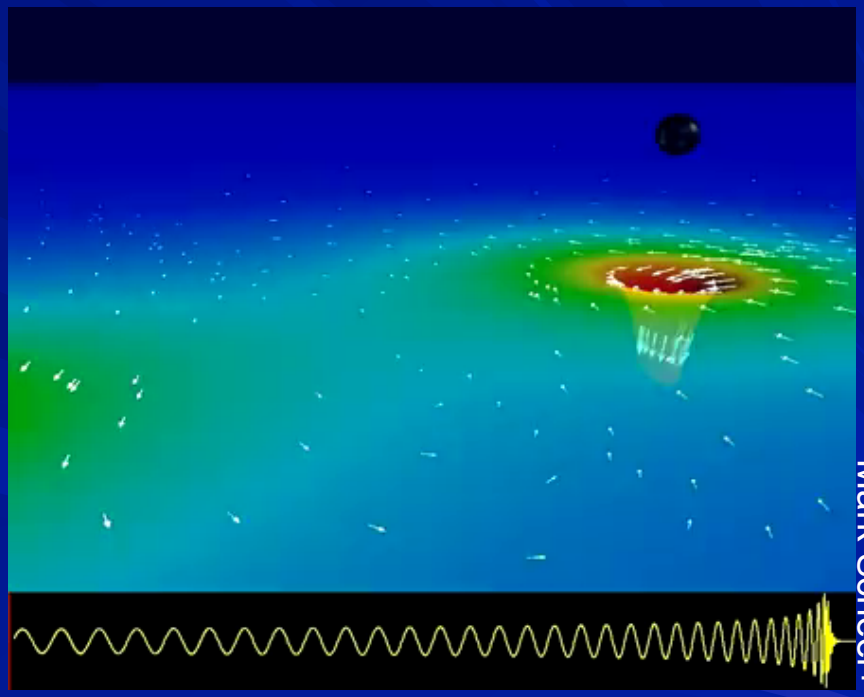
BHs shred & swallow nearby stars



Evans & Kochanek

- Every ~ $10^{4\text{-}5}$ yrs/galaxy
- Can build ~ 10^5 M_{sun}

BHs merge when host galaxies merge

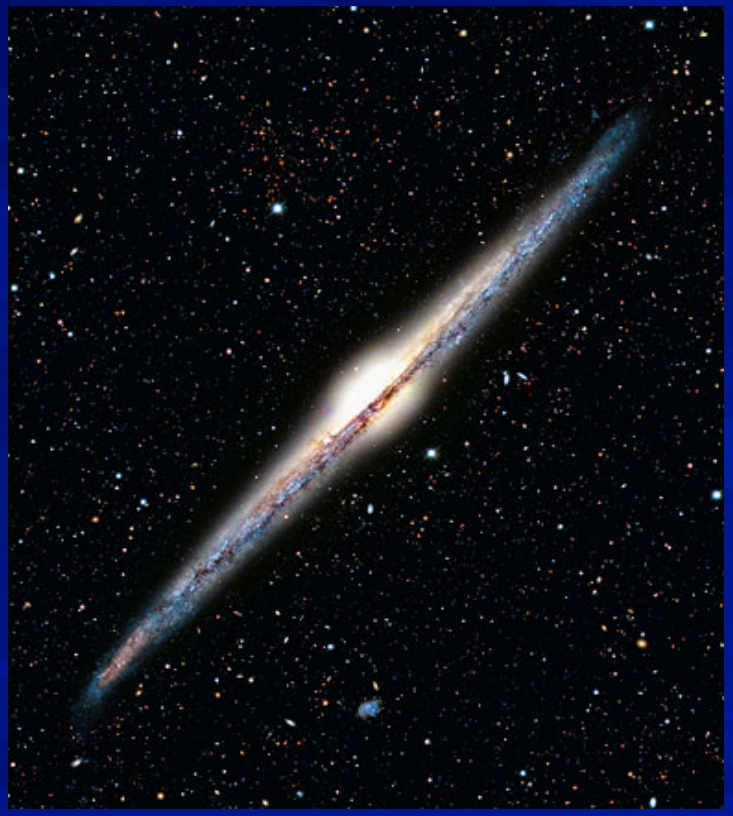


Mark Scheel+

General Relativity Simulation of Merging BHs

- More common earlier in universe's history (high z)

The BH-Galaxy Connection: The Key Observational Clue



Spiral Galaxy (disky/pancake)

Elliptical/Bulge Galaxy (spherical)

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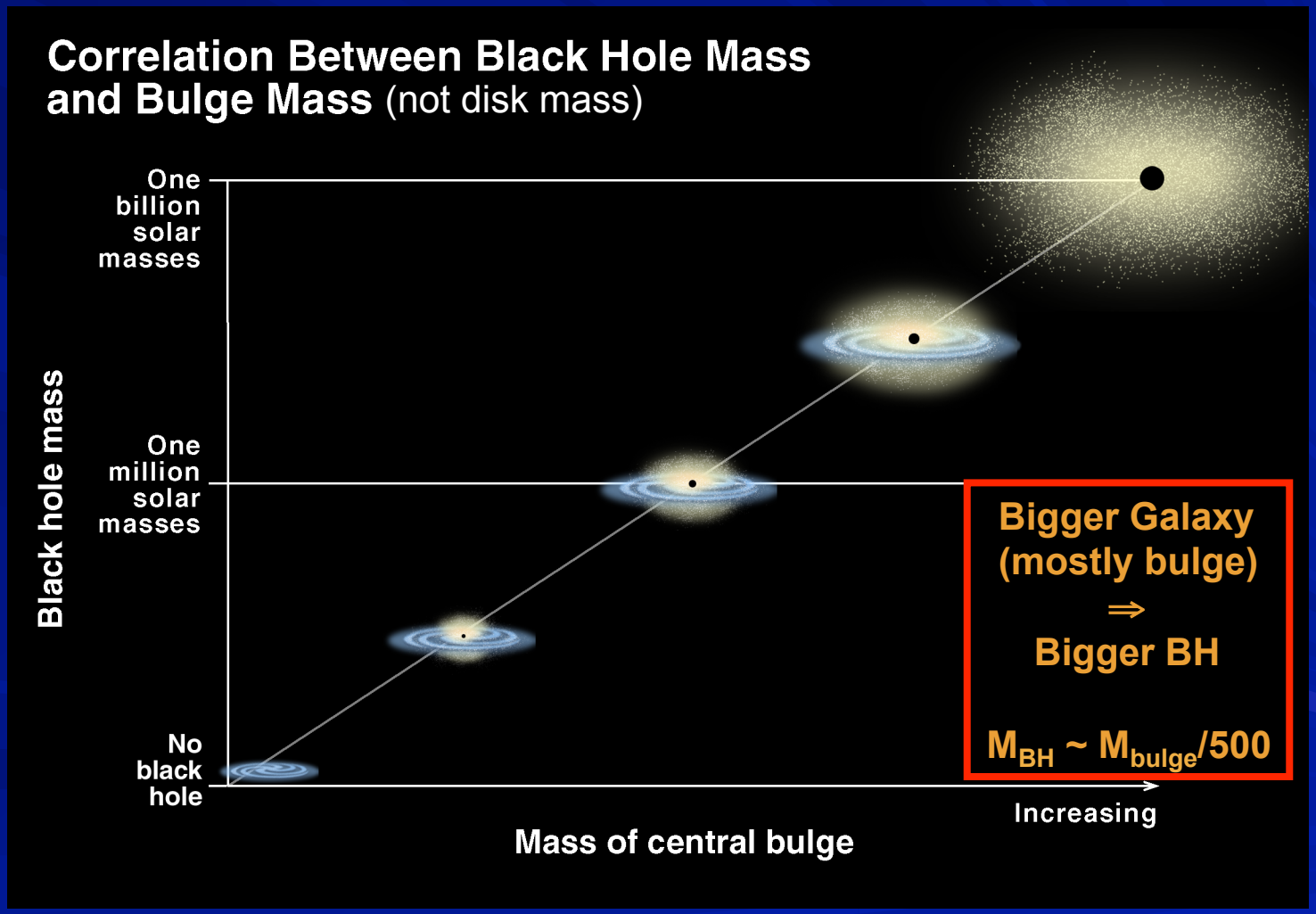
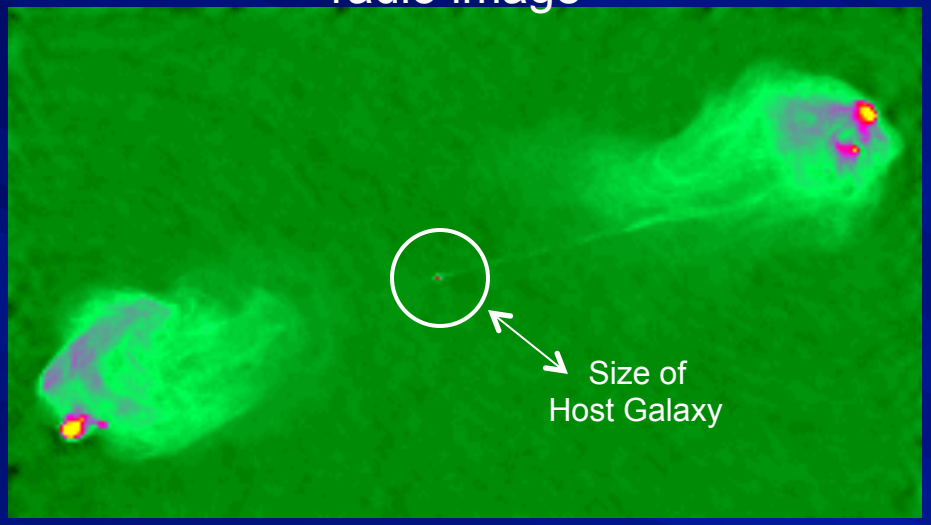


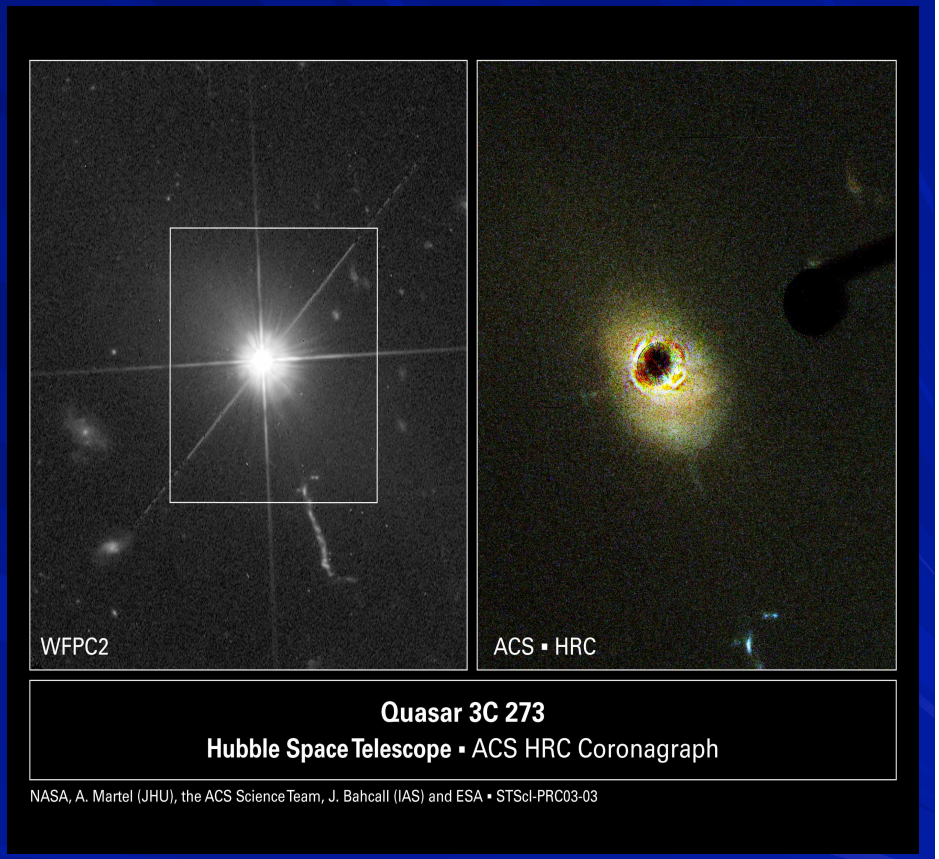
Karl Gebhardt+; Ferrarese & Merritt

Accretion: The Causal Connection btw Central Black Holes and their Host Galaxies

radio image



BH accretion ejects "jets" far outside its host galaxy into surrounding universe

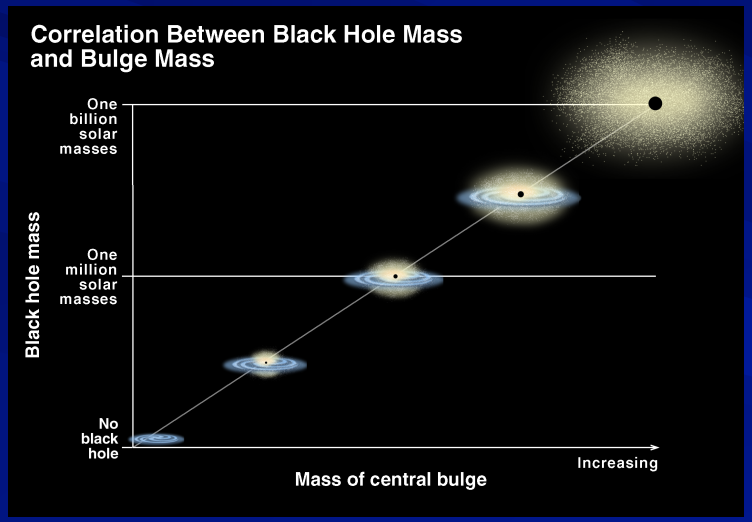


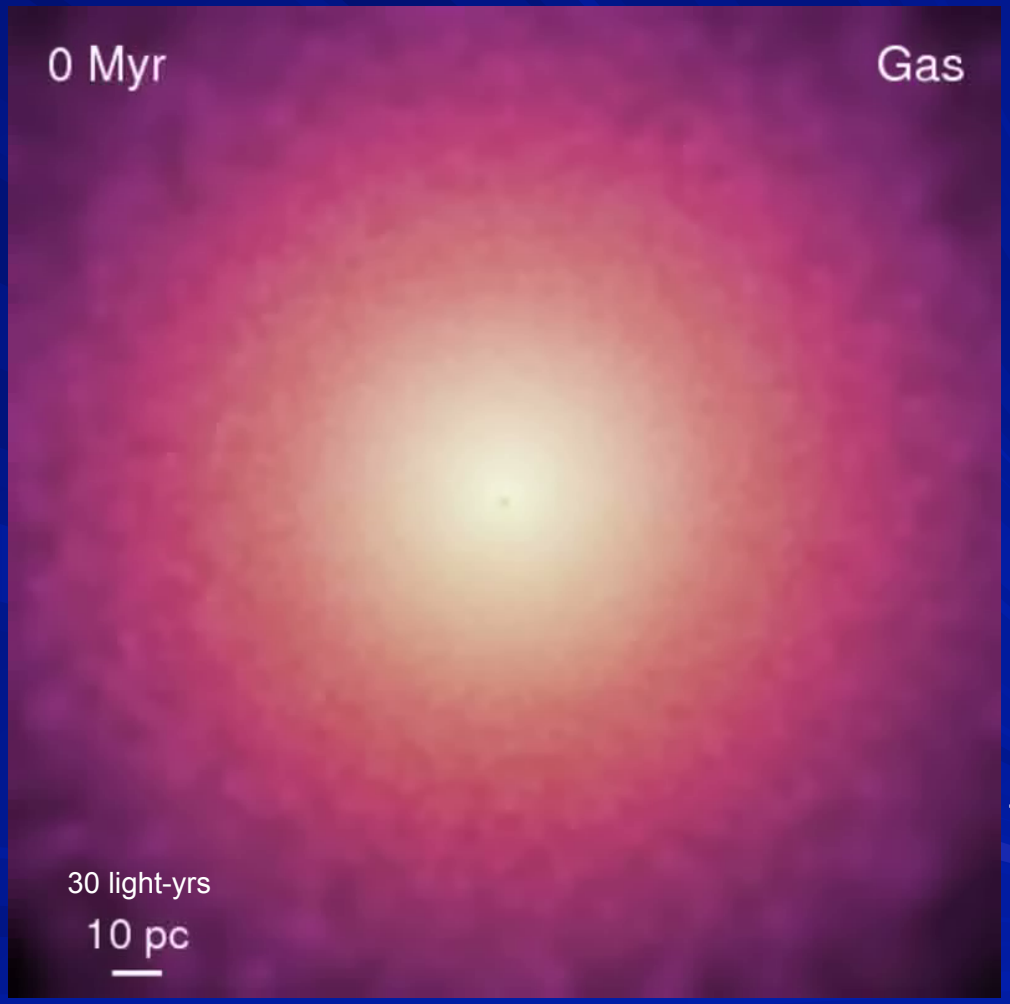
Gas spiraling into a BH gets very hot and emits *lots* of radiation & outflows

Accretion is how we "see" a black hole

BH accretion can outshine all the stars in its host galaxy!

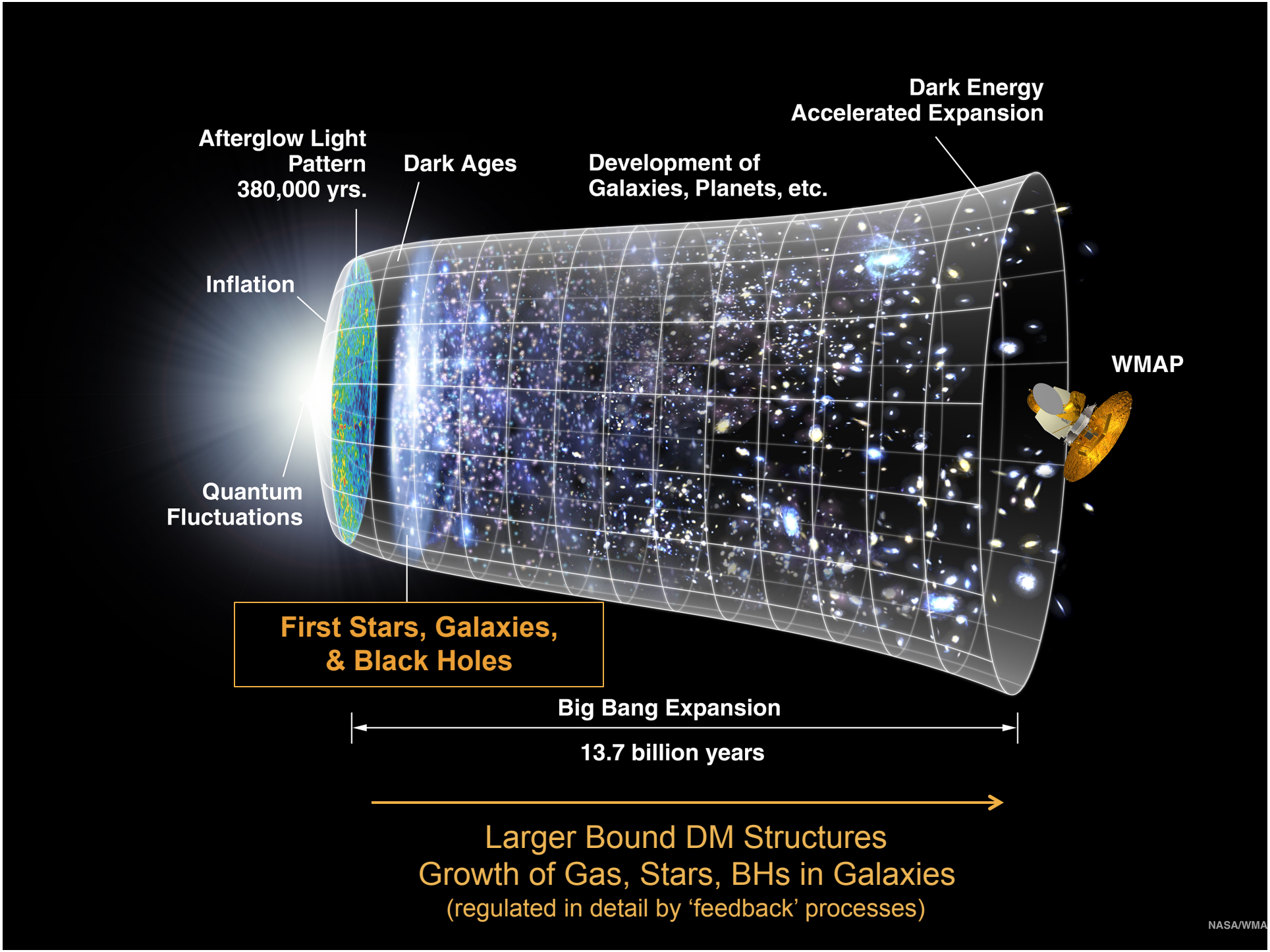
Accretion: The Causal Connection btw Central Black Holes and their Host Galaxies





Phil Hopkins & EQ

Simulation of Impact of BH Accretion & Outflows on Gas in Host Galaxy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