Cosmology & Black Holes: an Astronomical perspective

Xavier Barcons

Instituto de Física de Cantabria (CSIC-UC)

Contents

Cosmology, the expanding Universe

(with significant input from Francisco J. Carrera)

Observational grounds of modern Cosmology

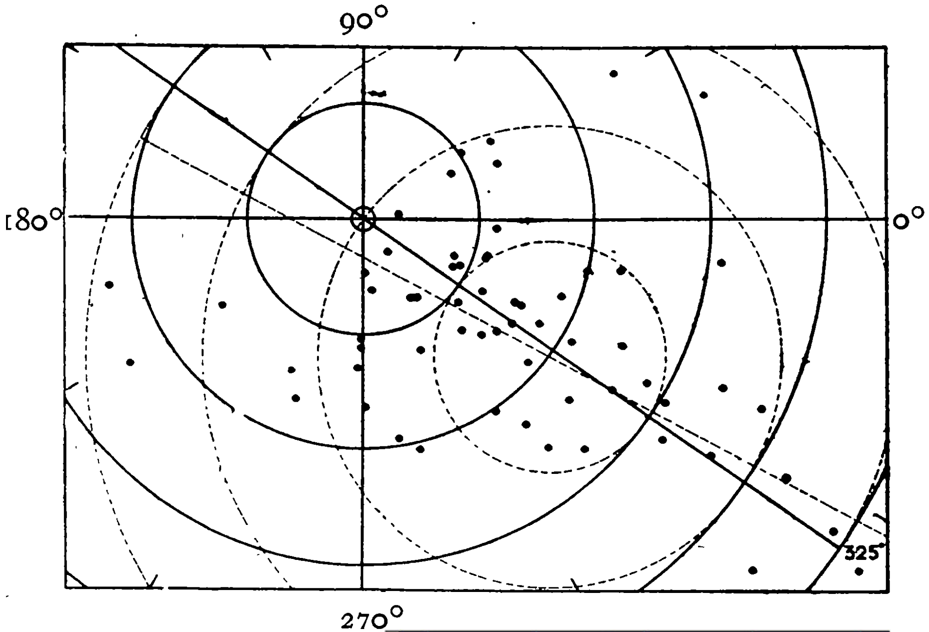
- "Island" universes: galaxies beyond the Milky Way
- The Sun and our Galaxy
- The expanding Universe
- Chemistry and the Cosmos
- The changing Universe
- The Cosmic Microwave Background

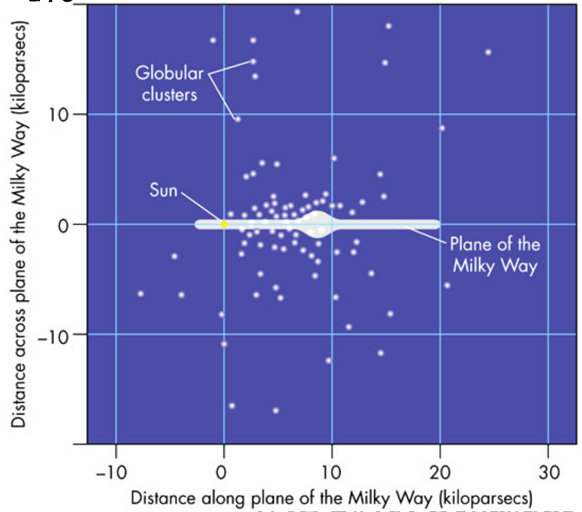
Other "Universes"

- Until the beginning of the XXth century, it was accepted that the Universe was just our own Galaxy.
- In 1924, E. Hubble successfully measured the distance to the Andromeda nebula, concluding that it was beyond our own Galaxy.
- Many (but not all) nebulae turned out to be other galaxies similar to our own, i.e., other "Universes".

The role of the Sun in our Galaxy

- H. Shapley (1918) successfully measured the positions of ~30 globular clusters in our Galaxy.
- This showed that the Galaxy is larger than it was expected
- It also showed that our Sun occupies a "very peripheral and eccentric place" in the Galaxy, far from its centre.

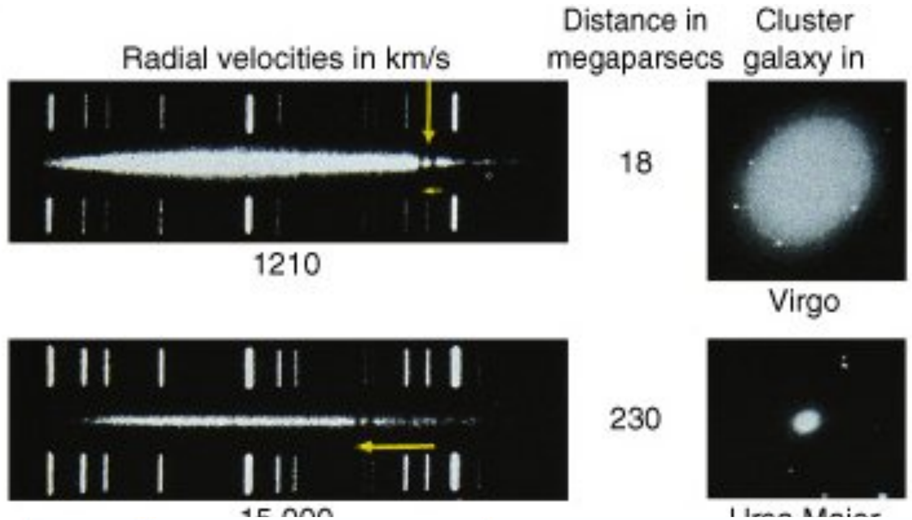


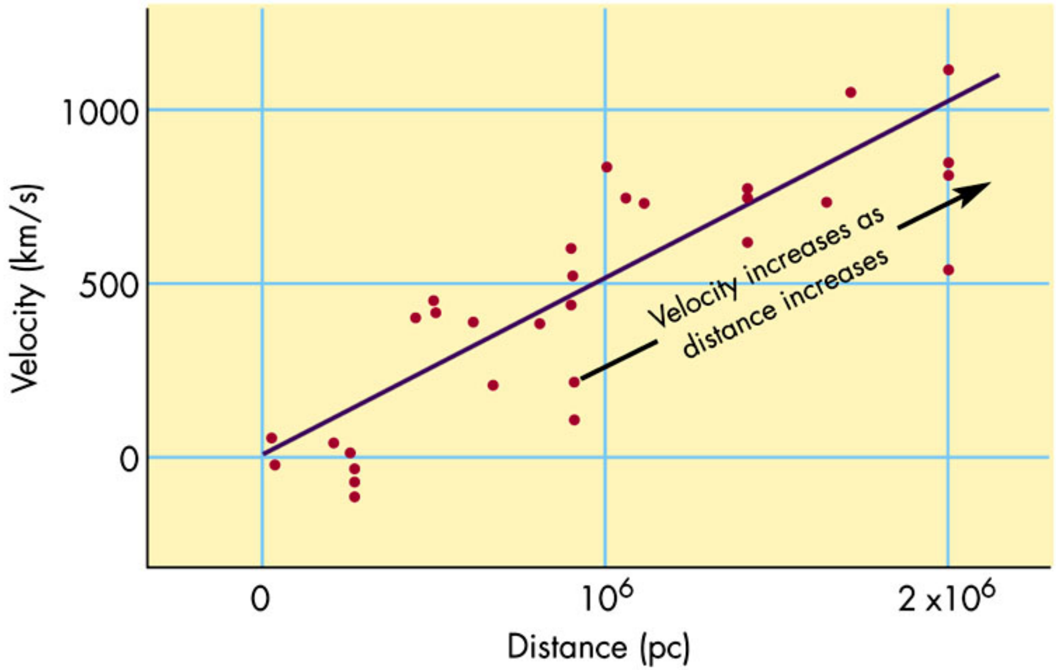


The expansion of the Universe

- Slipher (1913) measured the velocity of the Andromeda galaxy: -300 km/s
- E. Hubble (1929) measured velocities of 17 galaxies. The smaller and fainter, the larger their recession velocity: **Hubble's law**

$$v = H\,d$$

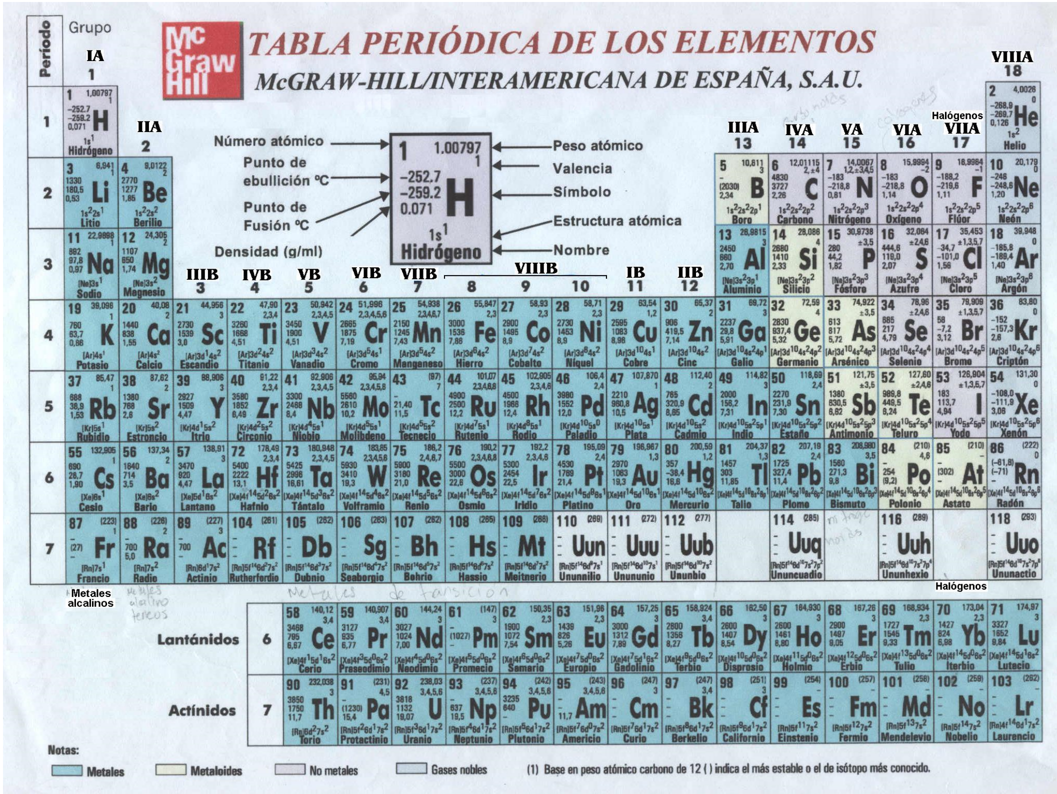




Elements and the cosmos

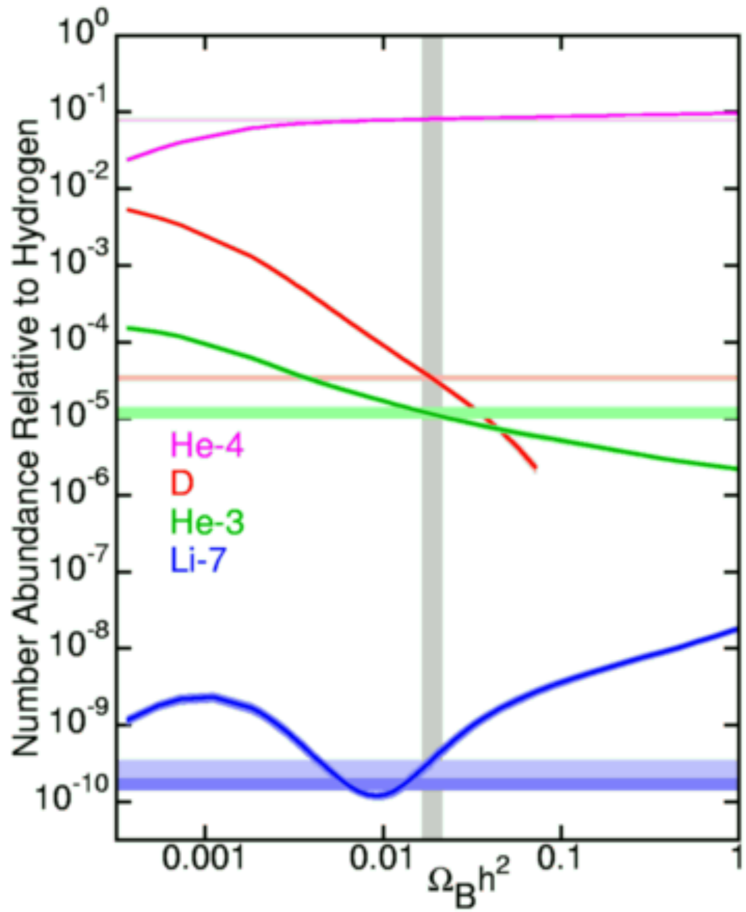
- A.S. Eddington (1920) proposed that stars contain fusion nuclear reactors, which produce He out of H.
- Burbidge et al (1957) concluded that stars have not been able to produce all He seen, nor other chemical elements.
- Primeval origin: the Universe went through a phase where all of it was a "soup" where chemical elements were created.

When and where did the chemical elements form?



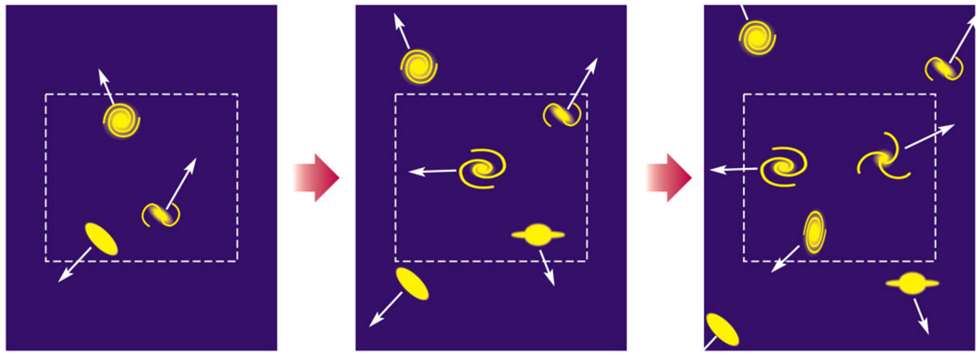
Big-bang nucleosynthesis

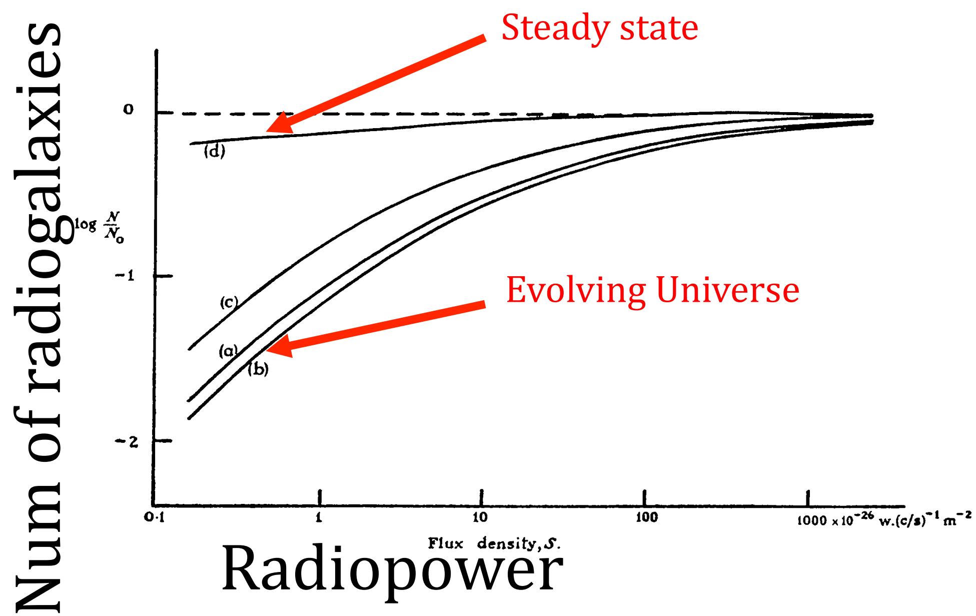
- First proposed by Alpher, Bethe and Gammow - α β γ (and Hermann), predicting a reclit radiation of 10 K.
- A Universe made out of a homogeneous hot soup would produce 75% of H, 25% of He plus minor abundances of Li and Deuterium.
- Amazingly good agreement with observations.



The evolving Universe

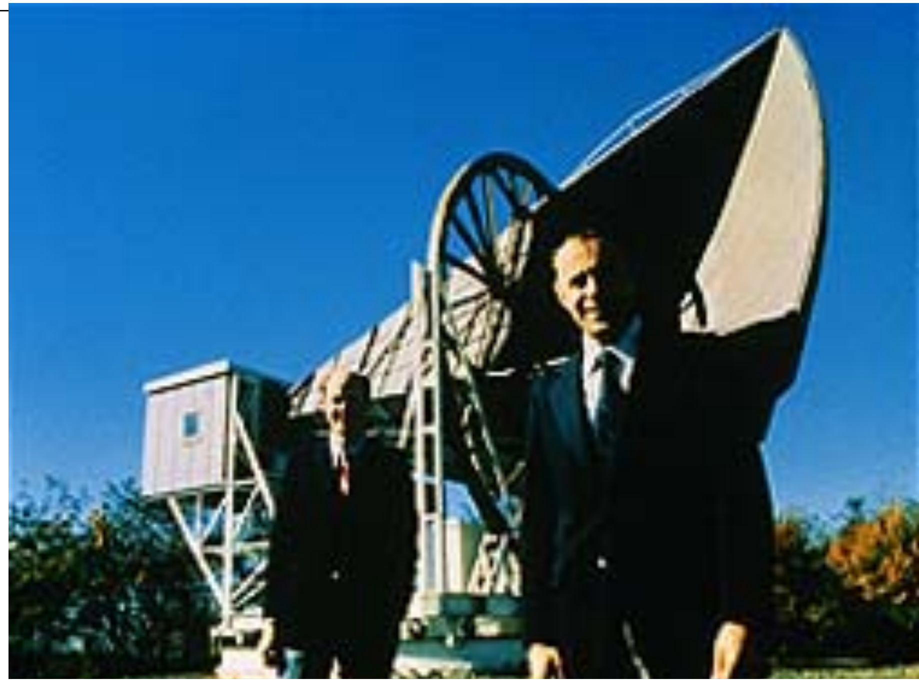
- The Steady State Theory (Bondi, Gold & Hoyle) proposed an unchanging Universe, where expansion would be compensated by continuous creation of matter.
- M. Ryle y R.W. Clarke studied radiogalaxy number counts and showed in 1961 that radiogalaxies change along cosmic history, providing further evidence against the steady state theory.

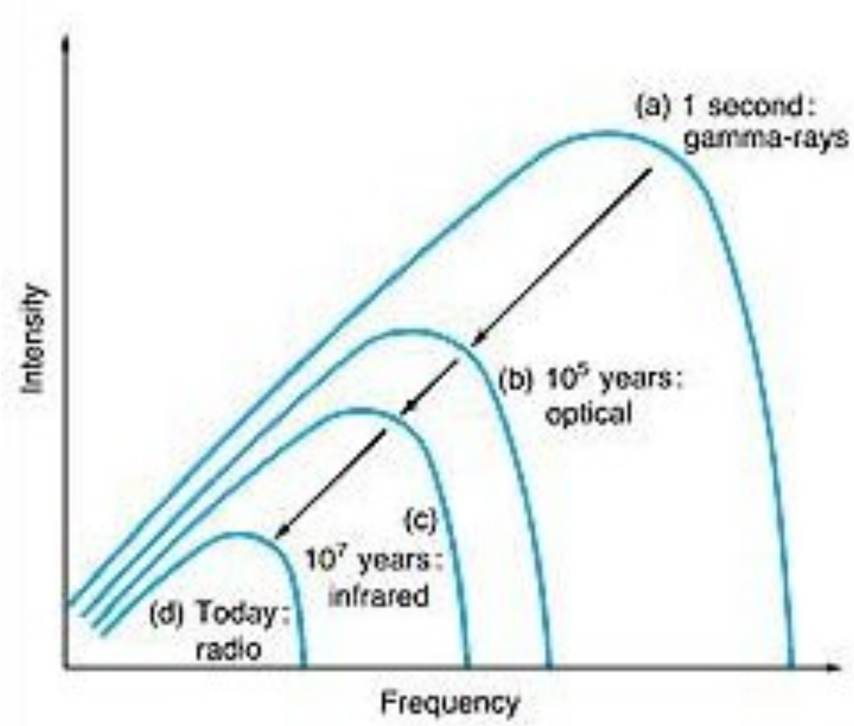




Cosmic Microwave Background

- Penzias & Wilson (1964): accidental discovery of an all-sky radiation at a temperature of 3 K.
- Dicke et al (1964): It's the fossil of a hot state of the early Universe:
  - The CMB must have been in thermal <u>equilibrium</u> with matter (the <u>Universe had once exceeded 4000 K</u>)
  - Radiation has cooled down due to the expansion of the Universe

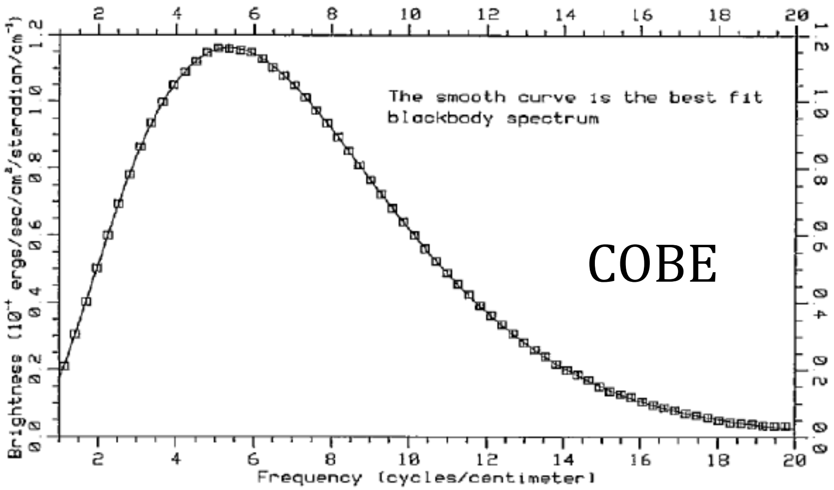


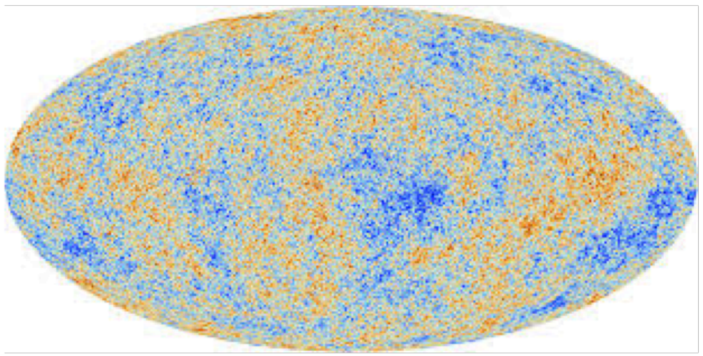


CMB: spectrum and fluctuations

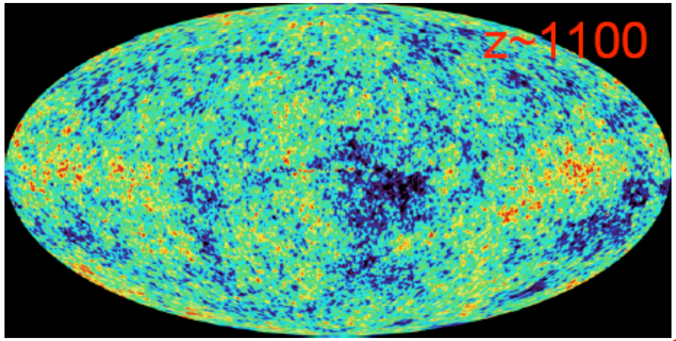
- Nobel Price in Physics 2006 awarded to **John C. Mather** and **George F. Smoot**

  "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation".
- Spectrum: Perfect blackbody at 2.735 K
- Fluctuations: at the level of $\sim 10^{-5}$, once the Galaxy and the dipole due to our motion are subtracted
- NASA's WMAP and ESA's Planck missions have determined the angular structure of the CMB to exquisite level





From a uniform to a highly structured Universe



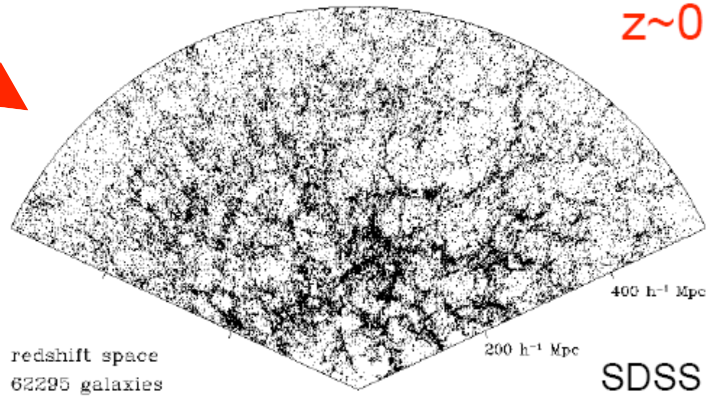
Initial conditions (density fluctuations):

- Given by the Cosmological model (Dark Matter, Dark Energy)
- Measured by CMB experiments

Gravity & much more

Highly structured
"baryonic" Universe:

Groups and clusters of galaxies
Filaments
Voids



The grounds of modern cosmology

- Cosmological principle: The Universe is **homogeneous** and **isotropic** on the large scale.
- The Universe is **expanding**
- The Universe **began some 13,750 million years ago with a Big Bang**.
- The structure and components of the Universe have changed along its history (**evolution**).
- **Theoretical framework**: General Relativity (A. Einstein 1915), with the Friedmann-Lemaître-Robertson-Walker model.

FRW cosmological model

- The metric

$$ds^2 = -c^2 dt^2 + a(t)^2\left[dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2\right]$$

- Friedmann's equations

$$\dot{a}^2 = -kc^2 + \frac{8\pi G\rho a^2}{3} + \frac{\Lambda a^2 c^2}{3}$$

$$\frac{d\left[\rho a^3\right]}{da} = -3\frac{p}{c^2}a^2$$

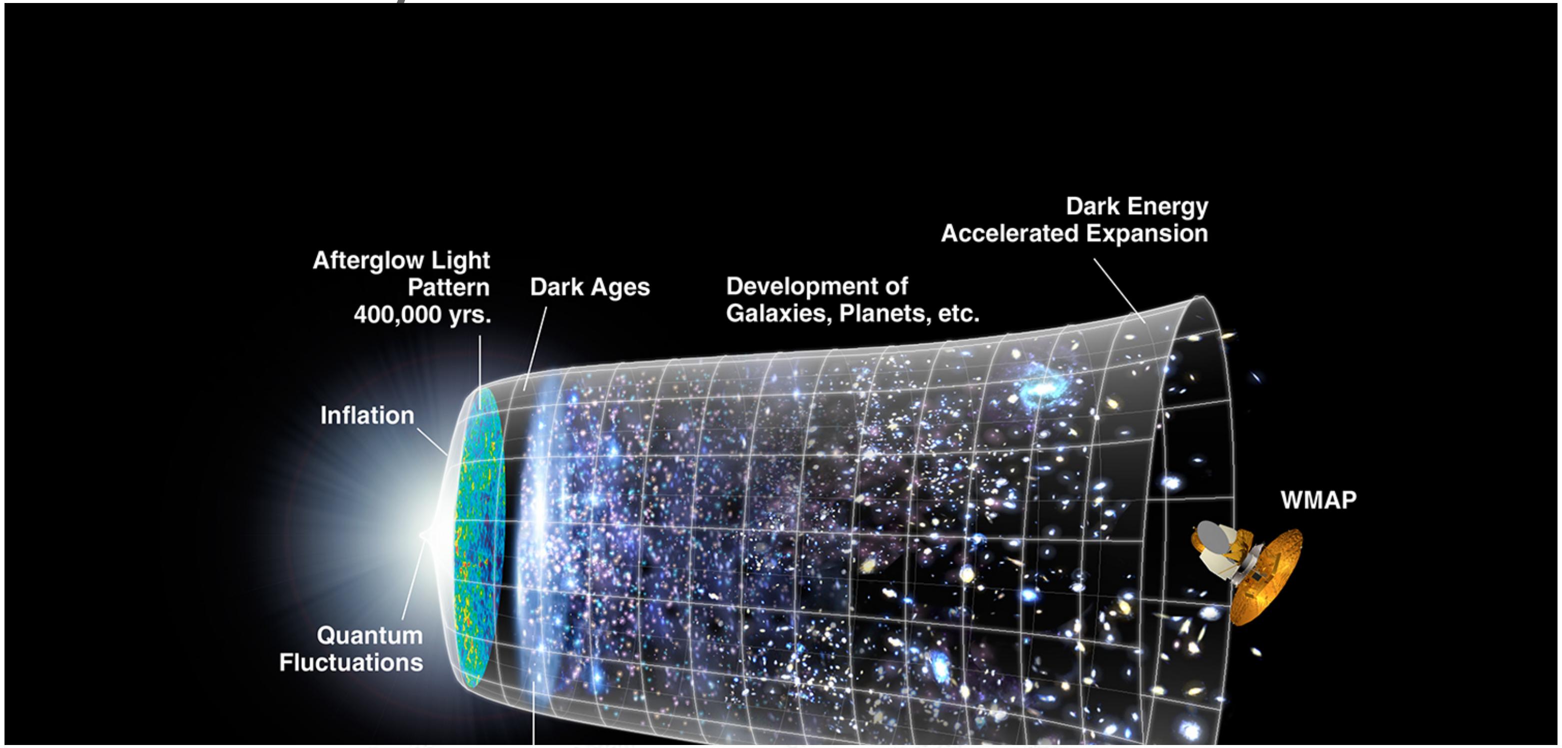
Cosmological parameters

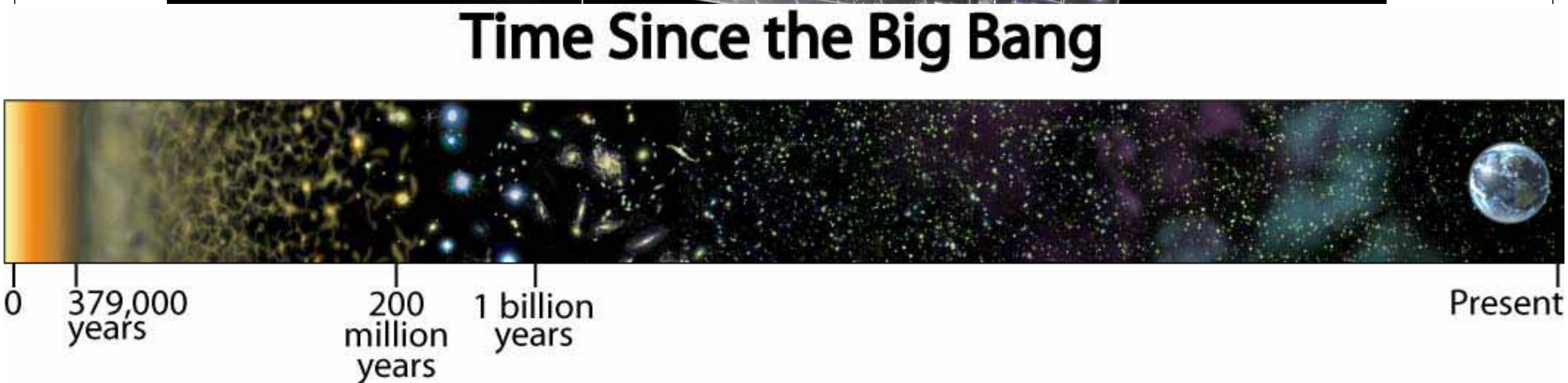
- Hubble constant $H_0 \sim 70$ km s^{-1} Mpc^{-1}
- Density appears to be within a factor of a few that of the critical density (~1 atom m^{-3})
- Universe appears to be spatially flat (k=0), but with a variety of components

$$H_0 = \left(\frac{\dot{a}}{a}\right)_0$$

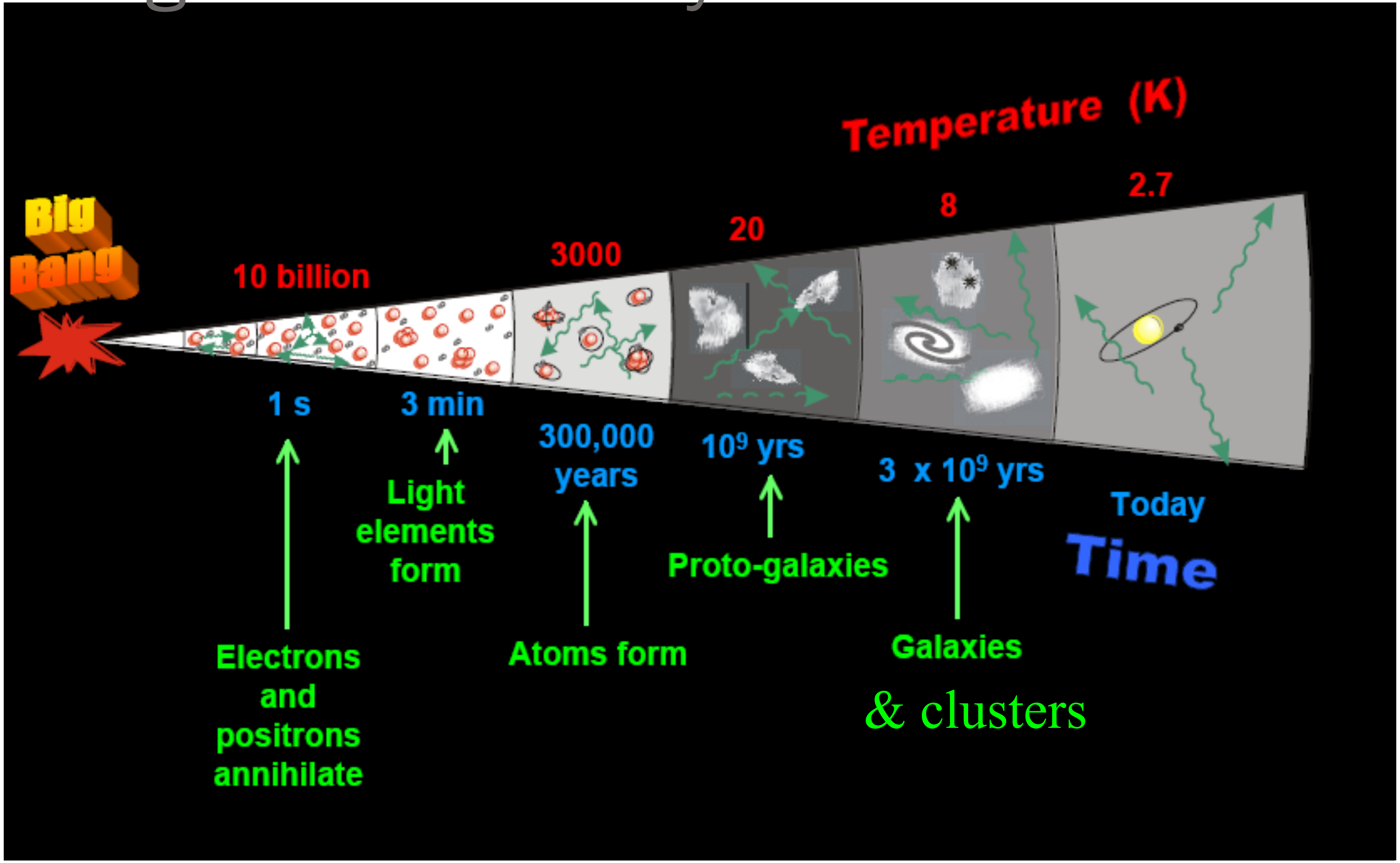
$$\Omega_0 = \frac{\rho_0}{\rho_{cr}} \qquad \rho_{cr} = \frac{3\pi G\rho_0}{3H_0^2}$$

The history of the Universe





Logarithmic history of the Universe



Dark Matter & Dark Energy

(significant input from A. Fernández-Soto)

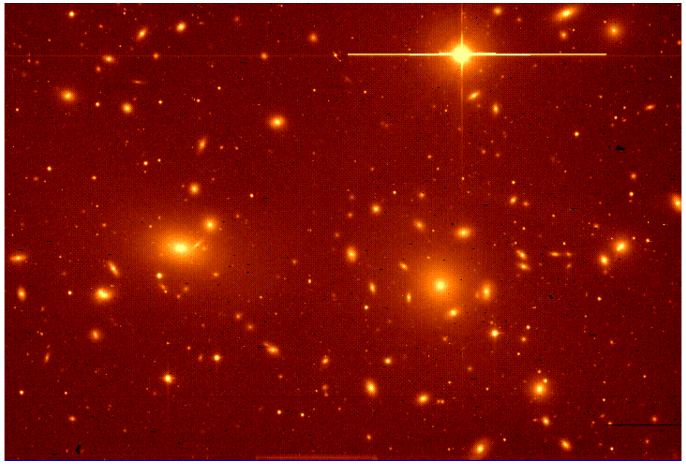
Zwicky and the “invisible matter”

- Measured the velocities of the galaxies in the Coma cluster
- Using Virial’s theorem:

$$M/L \sim 500\ M_{Sun}/L_{Sun}$$

- **Where is all that invisible matter?**
- First to mention DM in cosmology
  - We can’t see > 90% of what the Universe is made of
  - Can only “see” its gravitational effects

Fritz Zwicky (1898-1974)



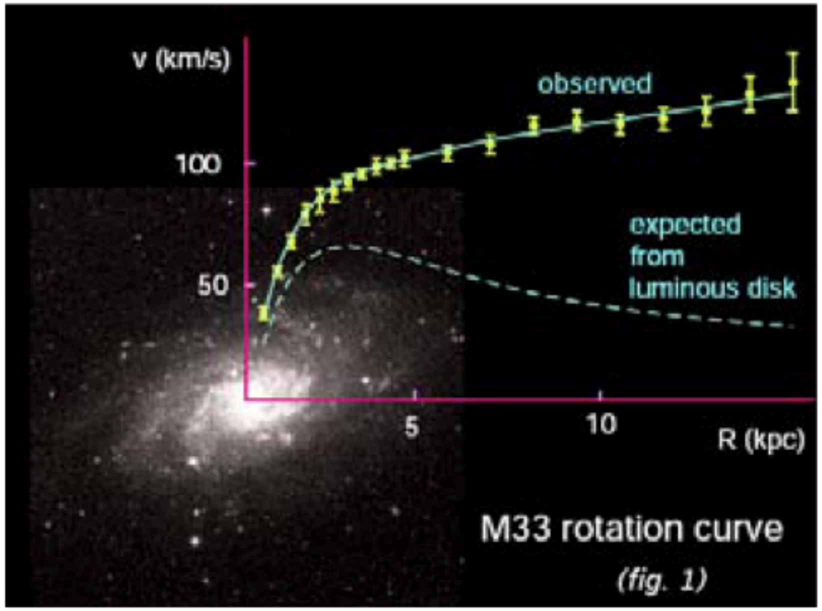
Coma cluster

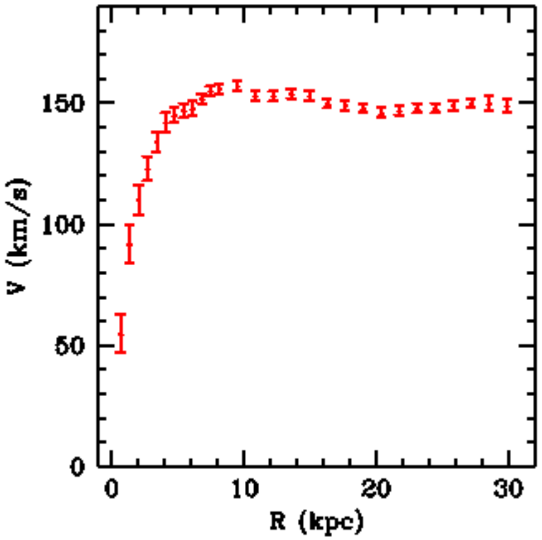
Some (early) theoretical support to Dark Matter

- Spiral galaxies (bulge + disk) are dynamically unstable systems.
  - Need to be stabilized by a spherical halo
- Without any DM, the growth of cosmological structures would be too slow:
  - Late decoupling epoch
  - No time to form structures that we see today

Observational support to DM: Galaxy rotation curves

- HI (21 cm) rotation curves in nearby galaxies appear flat, while a decline is expected if matter follows the distribution of light





Dark Matter in Galaxies

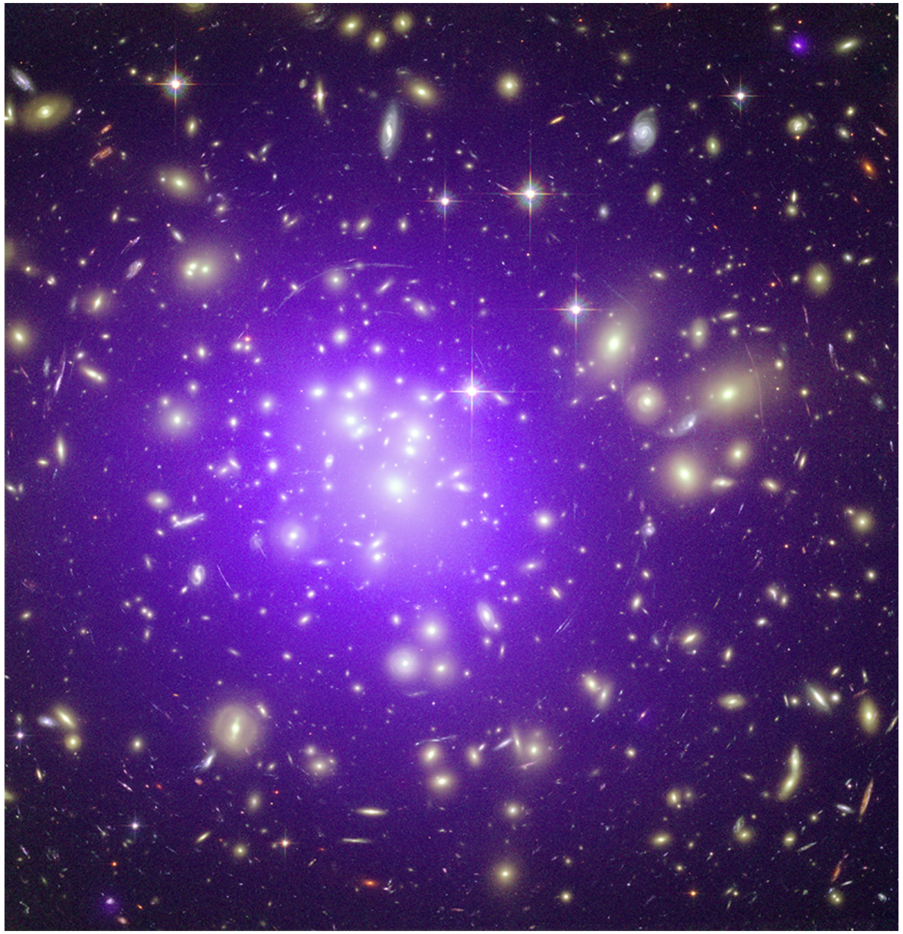
- Luminous matter (stars)

  $\Omega_{lum}h=0.002–0.006$
- Dark matter

  $\Omega_{gal}>0.02–0.05$
- Only a lower limit, as we do not know the extent of the Dark matter halo
- Could be baryonic DM, still consistent with Big Bang Nucleosynthesis
- If DM is baryonic, microlesing events could be seen.

DM evidence from clusters

- Clusters of galaxies are strong X-ray emitters:
  - Diffuse radiation, not tracing the individual galaxies
  - Thermal bremsstrahlung at temperatures of several keV ($>10^8$ K)
  - Fe Kα emission line at 6.7 keV: reveals highly ionized gas.
- Origin of the X-ray emission: ionized ICM
  - Enriched gas (0.3 Solar metallicity)



Properties of the Intra-cluster Medium

- Gas trapped in the cluster potential well
- Density up to $n \sim 10^{-3}$ cm^{-3}
- Gas in local thermal equilibrium:

  $t_{ep} \sim 2\ 10^5\ T_8^{\ 3/2}\ n_{-3}^{\ -1}$ yr

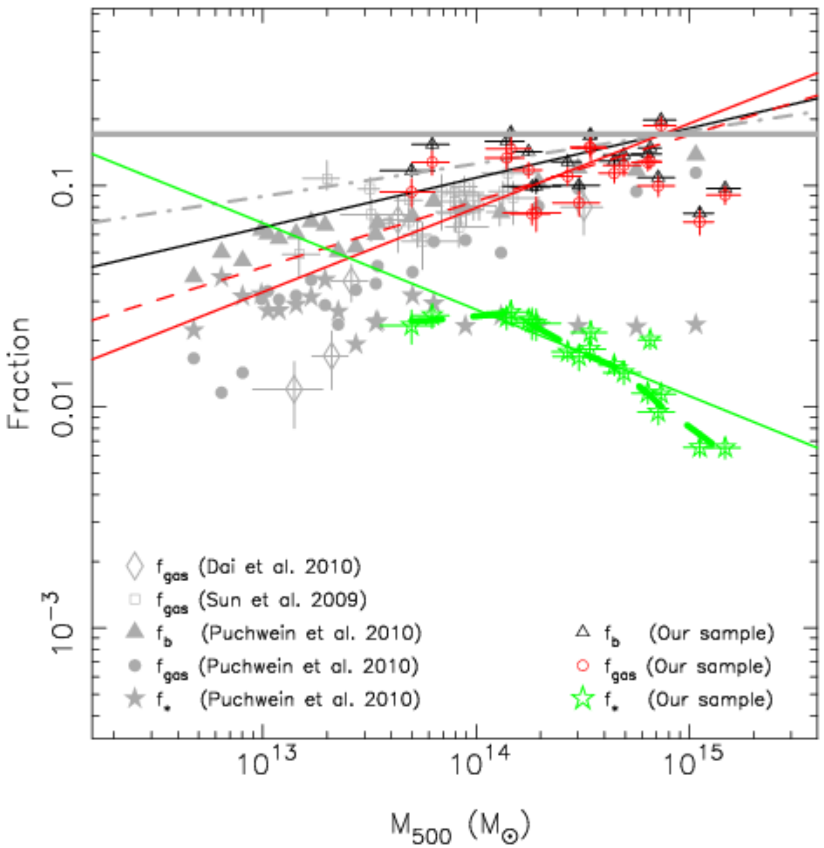
  $t_{cross} \sim 10^9\ R_{Mpc}\ v_8^{\ -1}$ yr

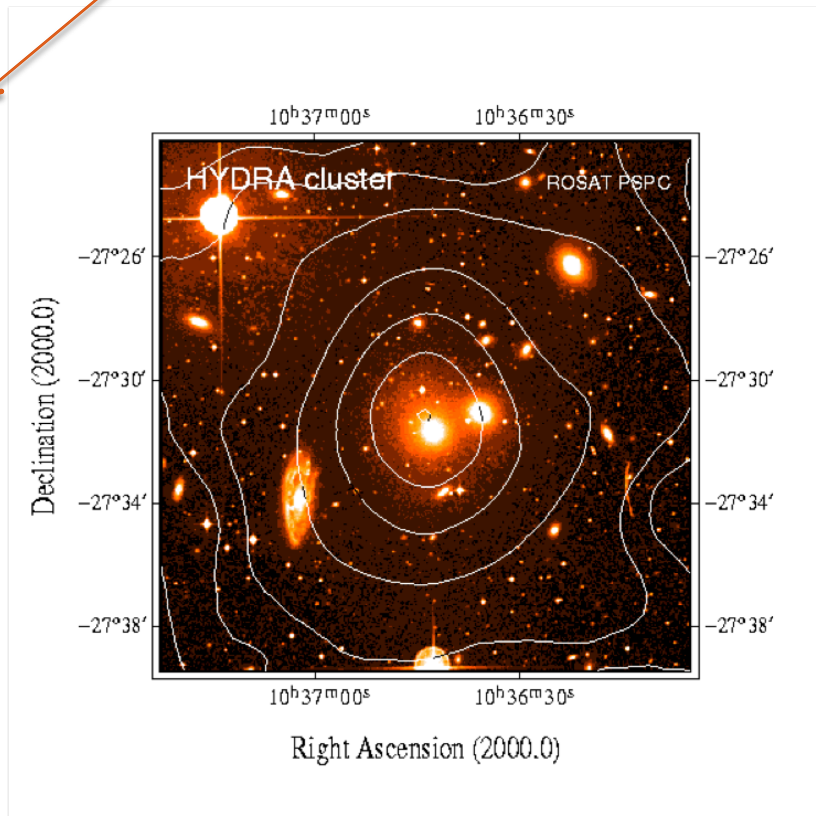
- Gas must be in hydrostatic equilibrium, as otherwise large flows > $10^4\ M_{Sol}\ yr^{-1}$

$$\frac{dP_{gas}(r)}{dr} = -\rho_{gas}(r)\frac{d\Phi(r)}{dr}$$

Cluster masses from ICM hydrostatic equilibrium

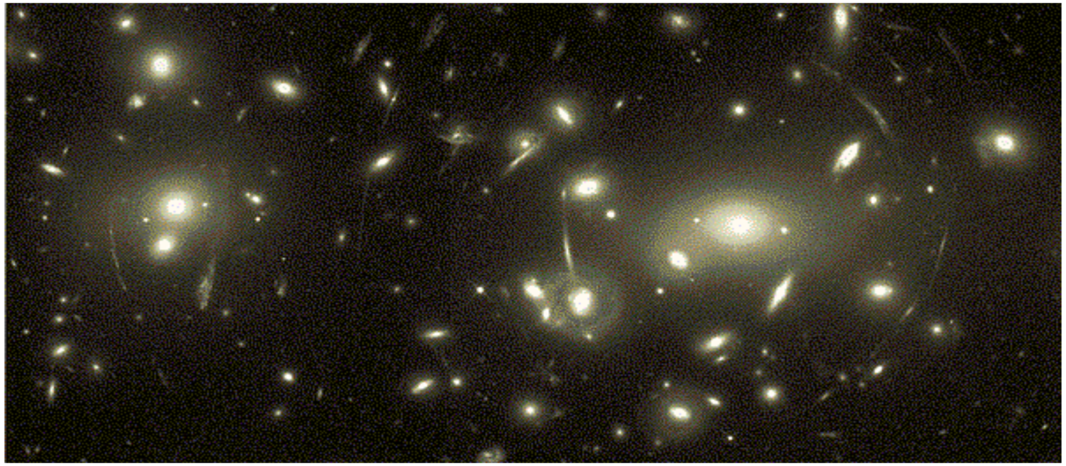
Cosmic baryon fraction

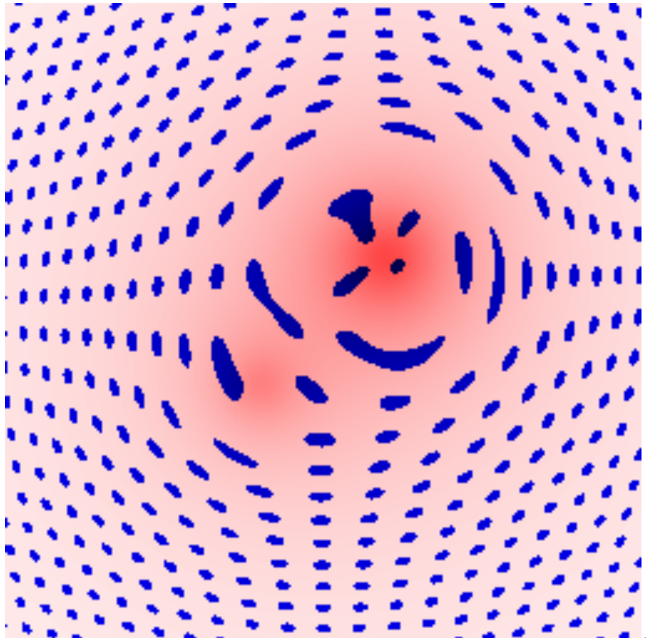




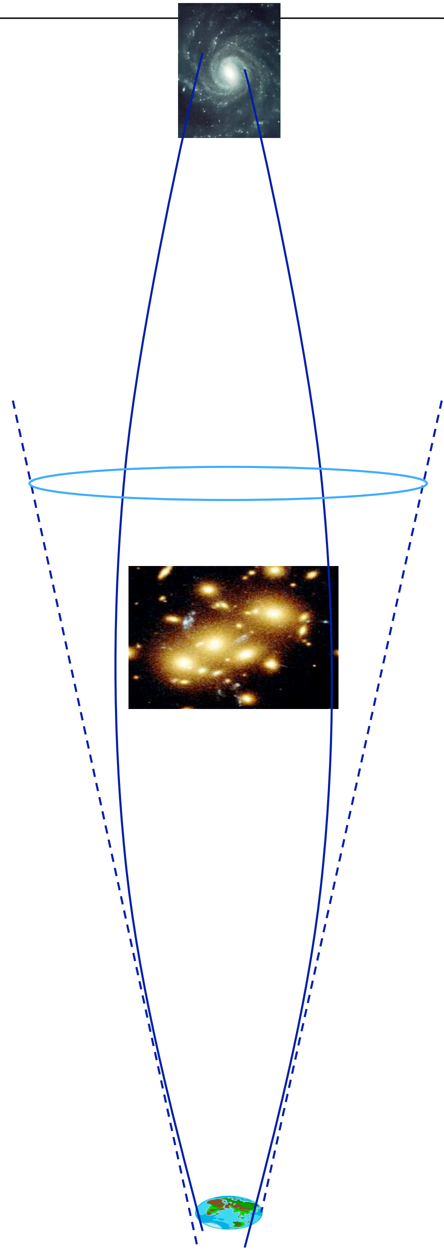
Gravitational lenses

- Matter in clusters (both dark or visible) acts as a lens, deforming space-time
- Observational traces
  - Multiple images
  - Magnification
  - Banana shaped galaxies
  - Arcs and arclets





From Ned Wright's Cosmology Page



Good evidence for non-baryonic DM

Dark Energy prelude:
The cosmological constant

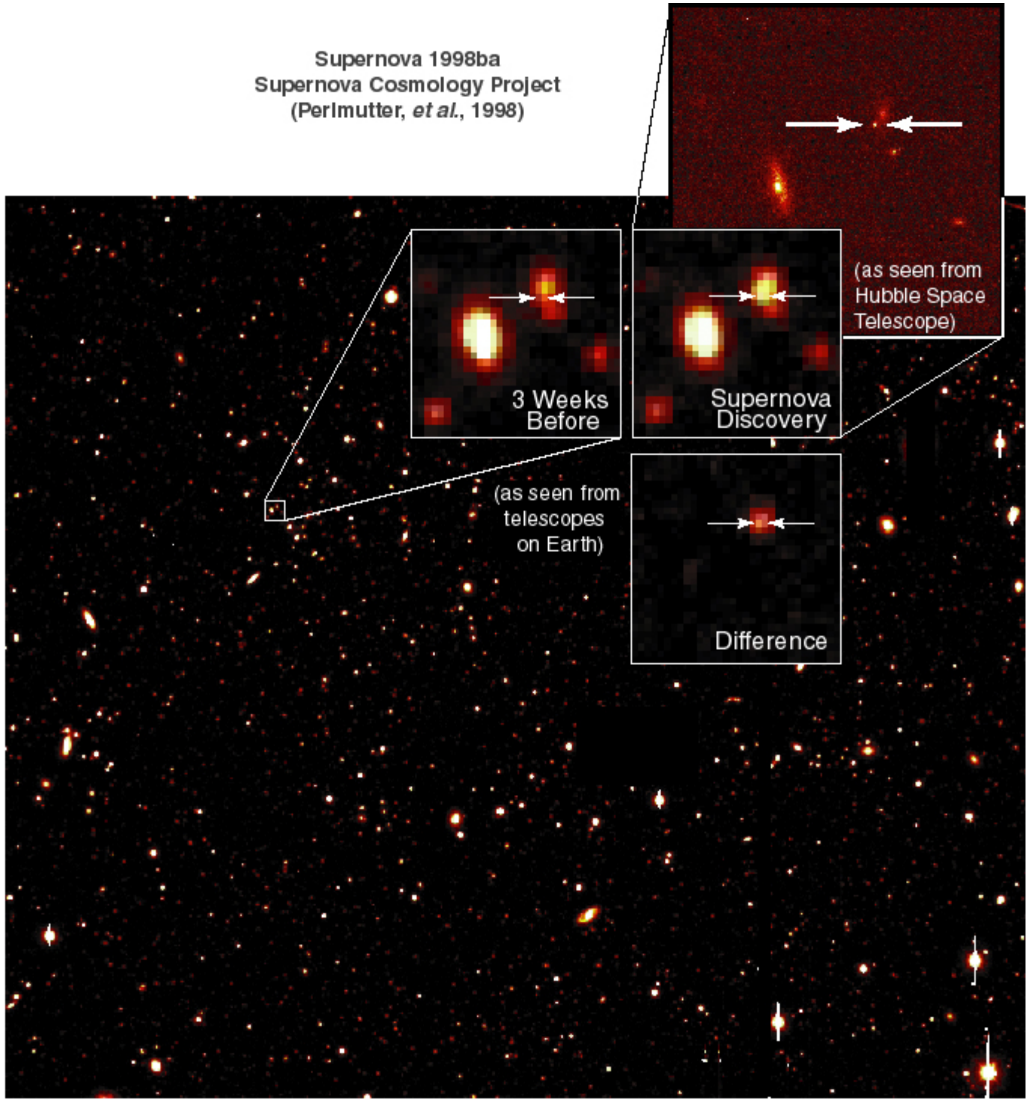
- General Relativity, Einstein and the Cosmological constant

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} + \Lambda\, g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Curvature

Stress-Energy

Supernovae Ia, as standard candles

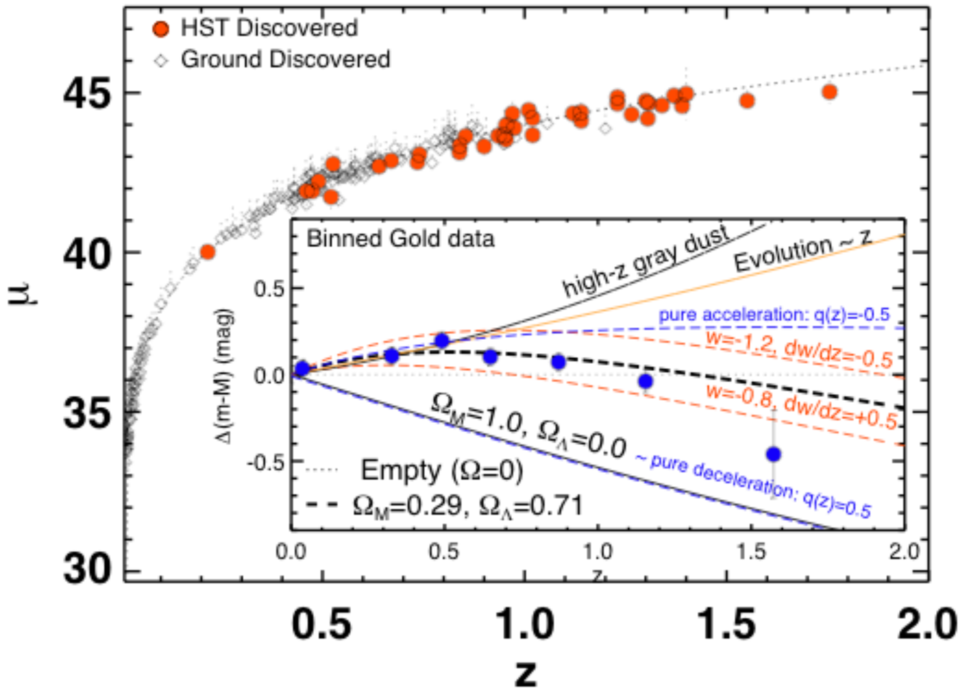


SNe can be detected out to very large distances: their brightness is as large as that of the whole galaxy

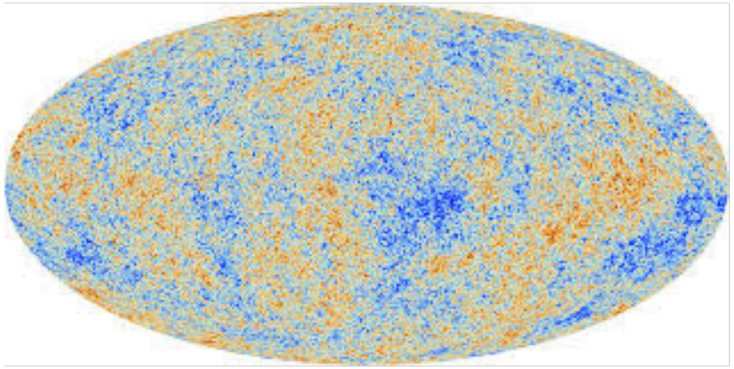
SNe Ia result from the collapse of a white dwarf that has grown unstable beyond the Chandrasekhar limit due to the transfer from a companion evolved star: likely universal

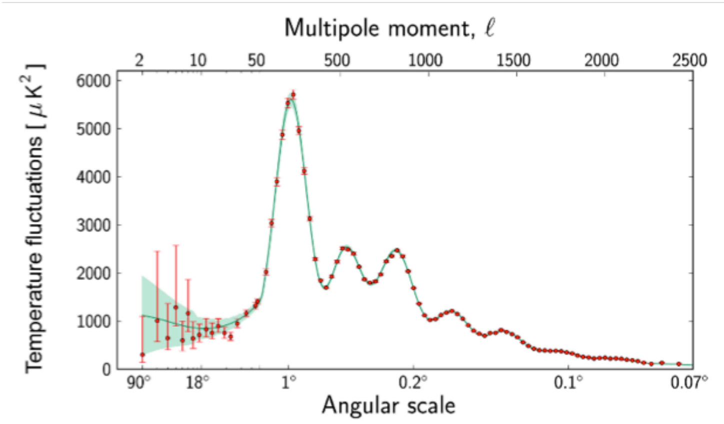
Cosmology with SNe Ia

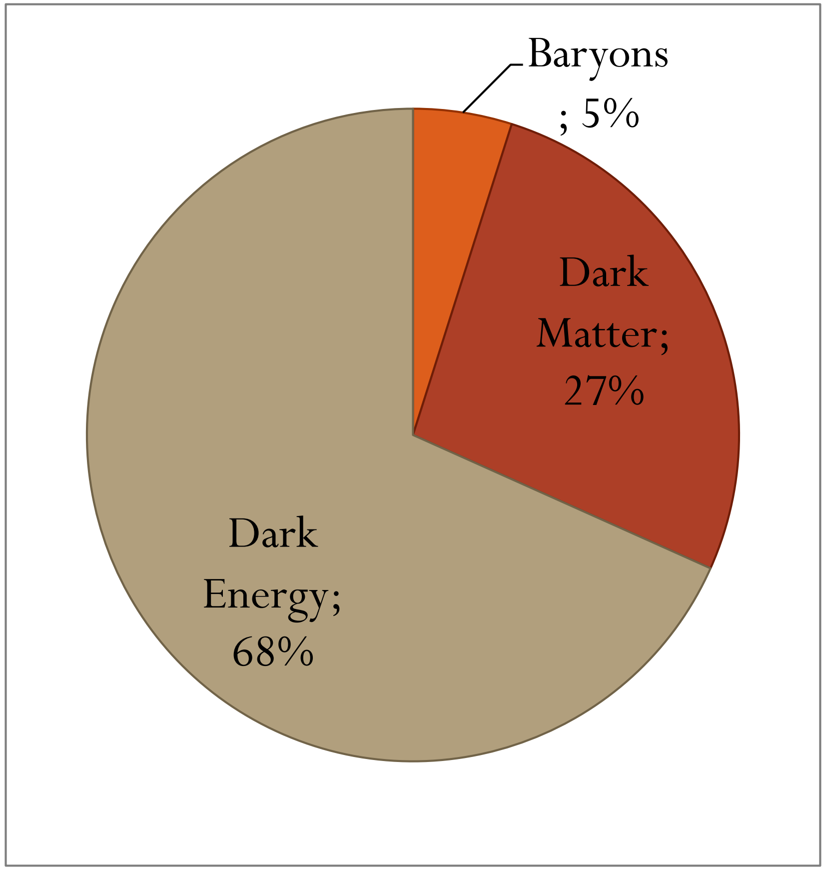
- Assumed to be "standard candles" but
  - Need to apply corrections for brightness, dust and duration
  - Physics of SNe Ia explosions simple only to first order
- Can use the measured magnitude to infer the distance to the host galaxy
- Measuring the redshift of the host galaxy closes the loop between distance and velocity expansion
- Direct probe of Cosmological parameters out to very high redshift



CMB fluctuations (after Planck)

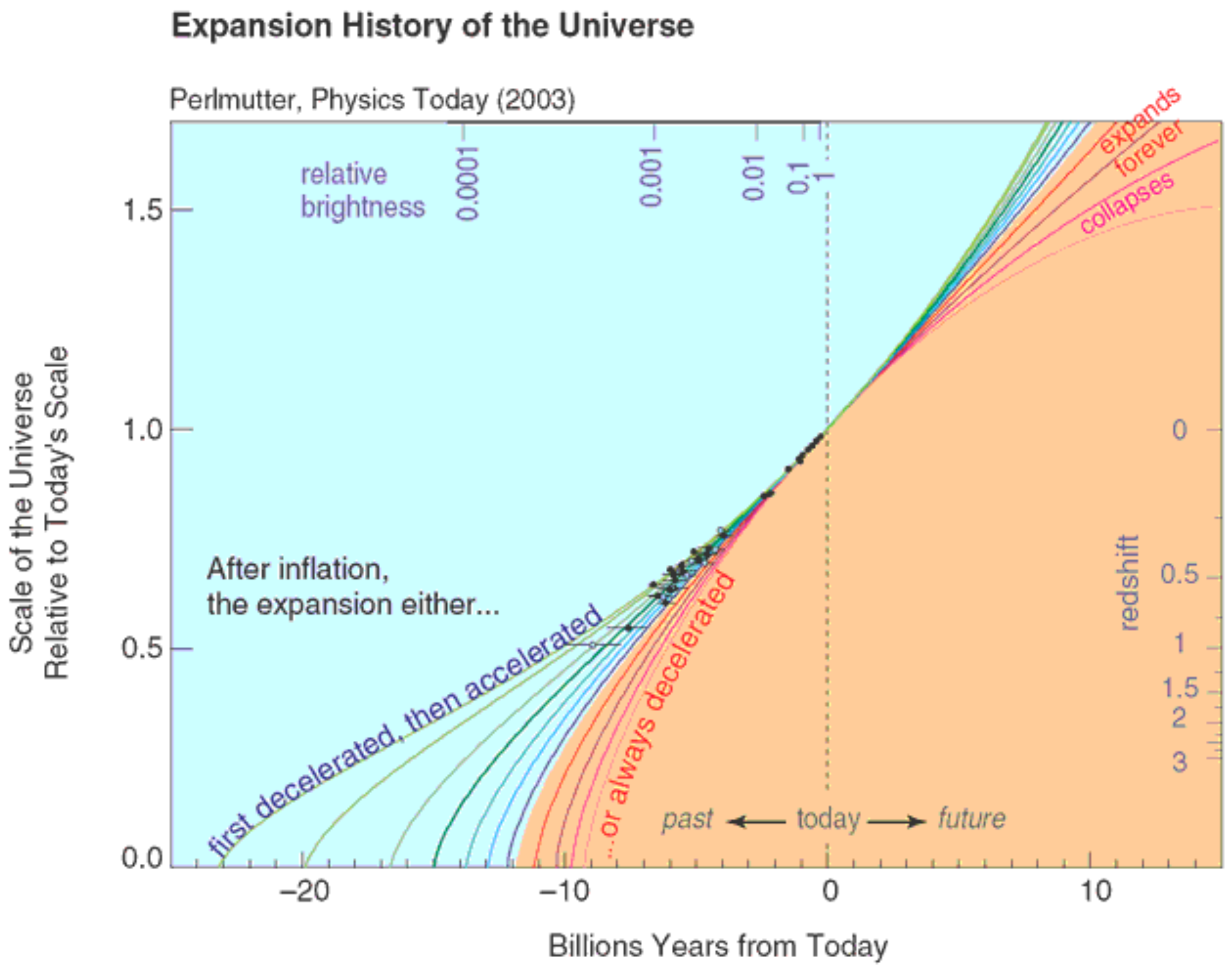




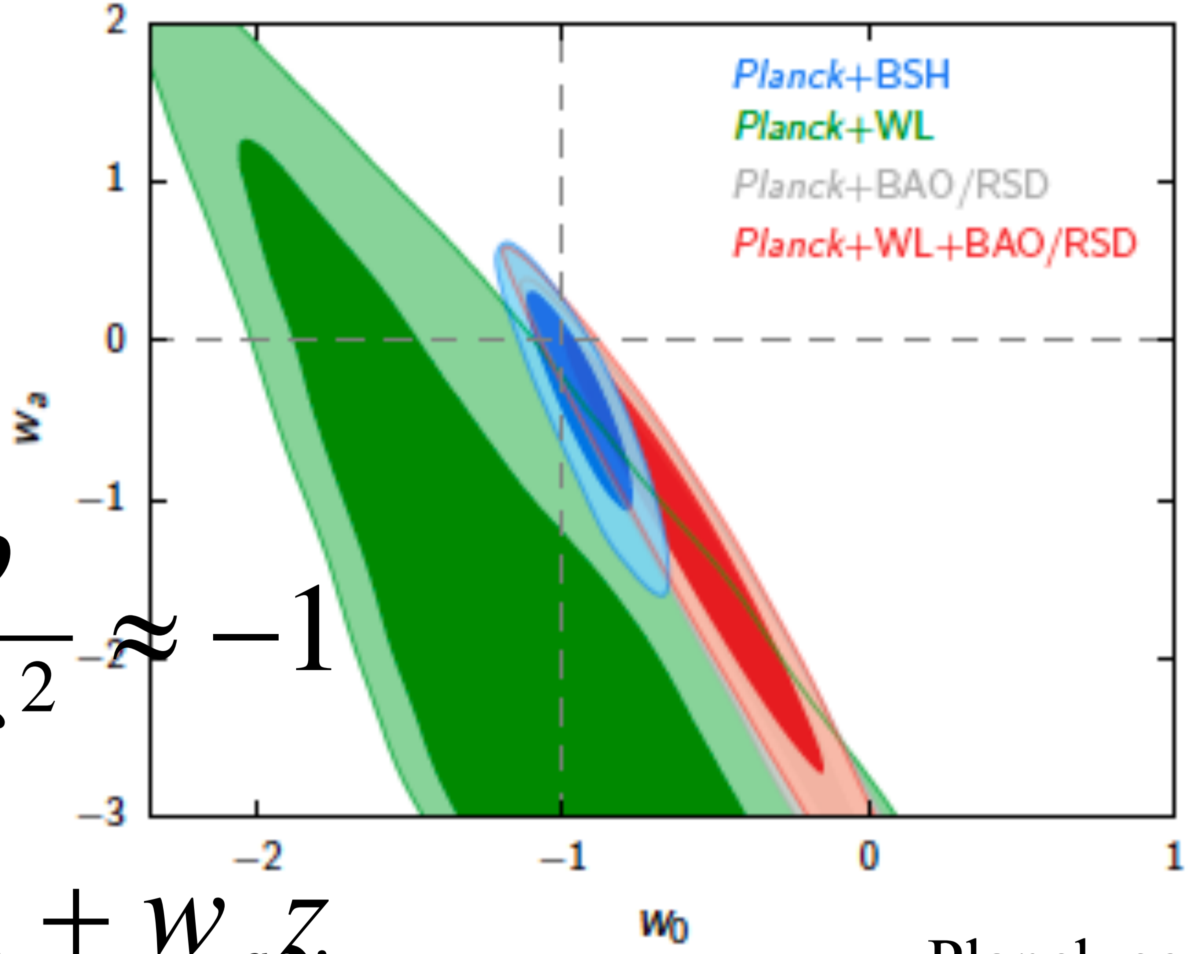


The angular power spectrum of CMB fluctuations is sensitive to all Cosmological parameters, in particular to Ω_{matter} and Ω_{Λ}

The Universe is accelerating. Dark Energy is its main constituent.



The equation of state of the Universe



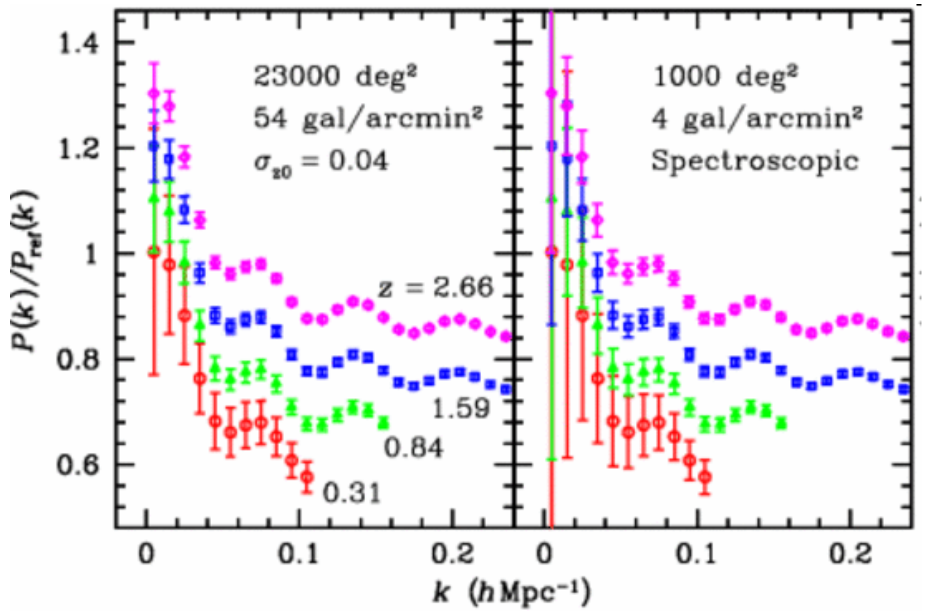
$$w = \frac{p}{\rho c^2} \approx -1$$

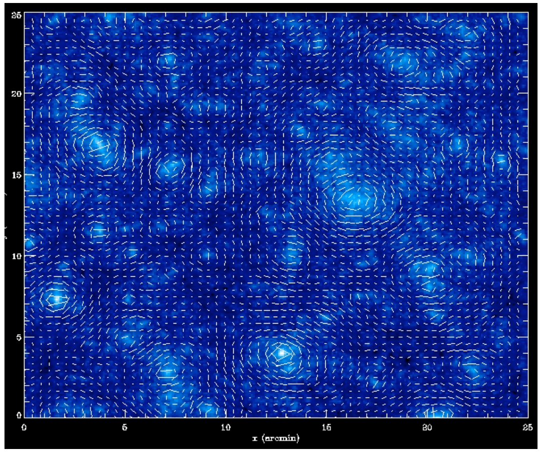
$$w = w_0 + w_a z$$

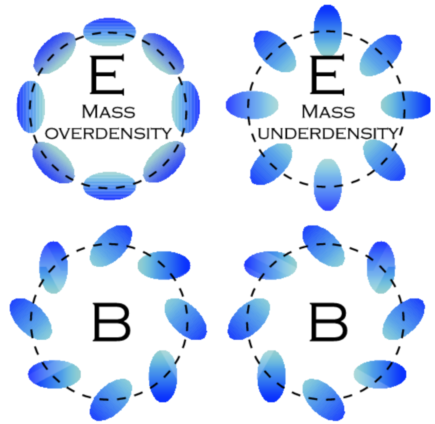
Planck coll 2015

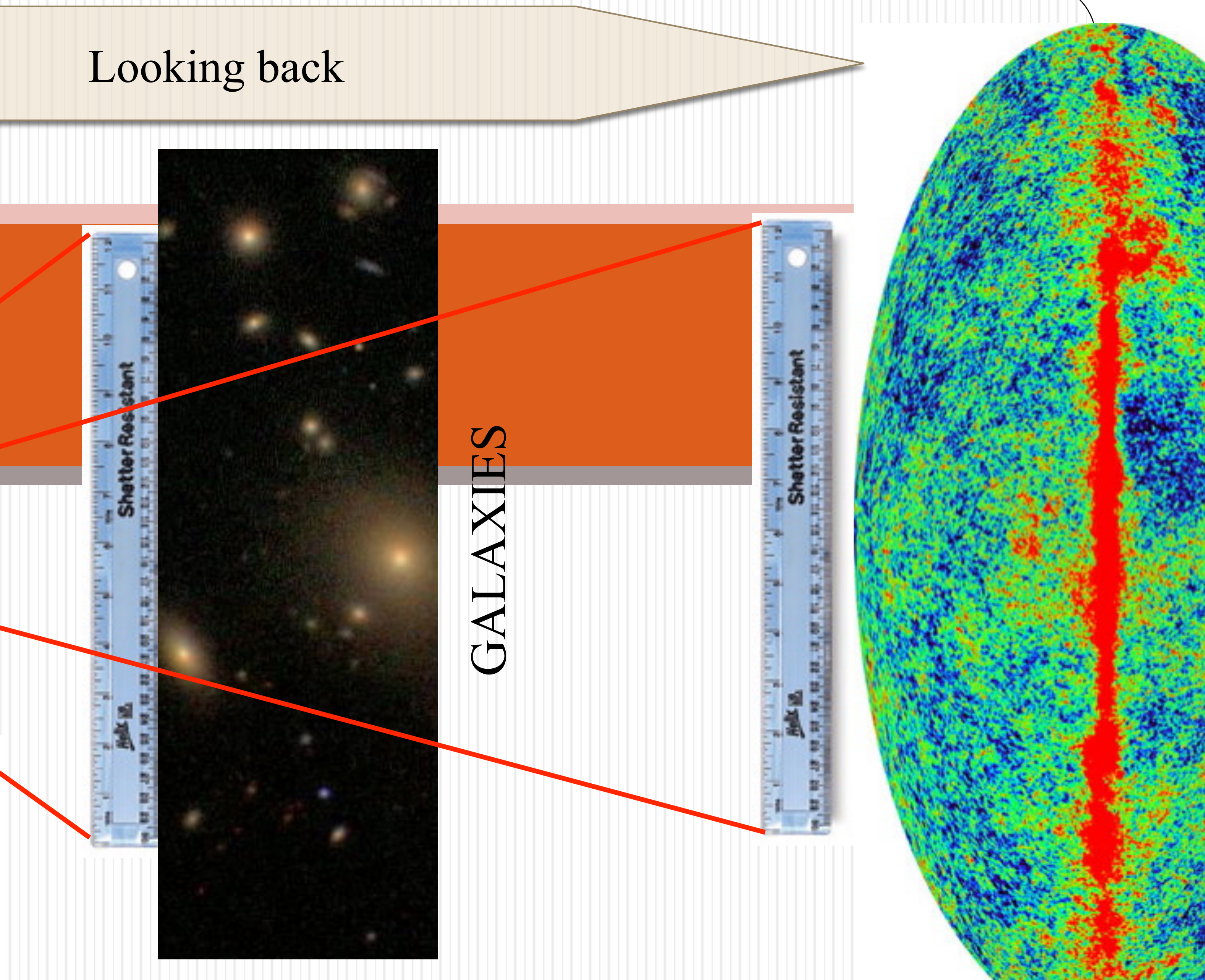
Other ways to measure Dark Energy

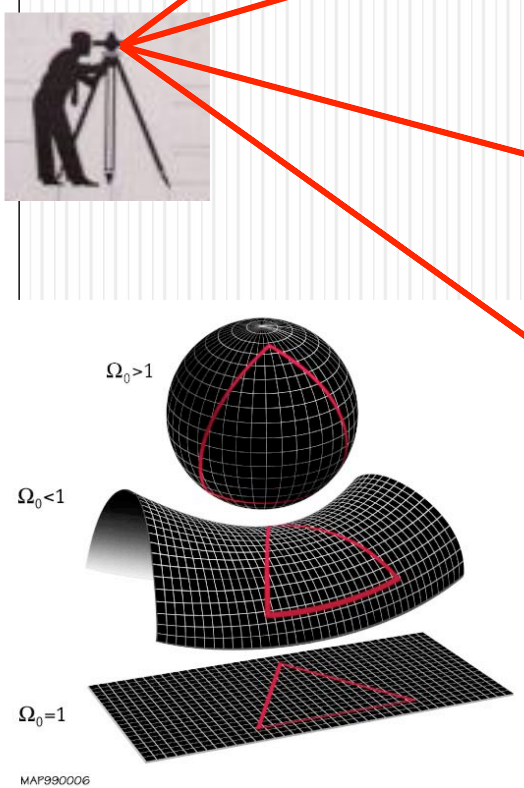
- The following to be achieved by ESA's Euclid mission
  - Evolution in the **acoustic peaks** in the spatial distribution of galaxies (BAO)
  - **Weak lensing** on large scales
- **Counting clusters** of galaxies back to early epochs
- Baryon **gas fraction** in clusters











The Universe is spatially flat to < 10%

From WMAP & SDSS websites

(Supermassive) Astrophysical Black Holes

What is a black hole.

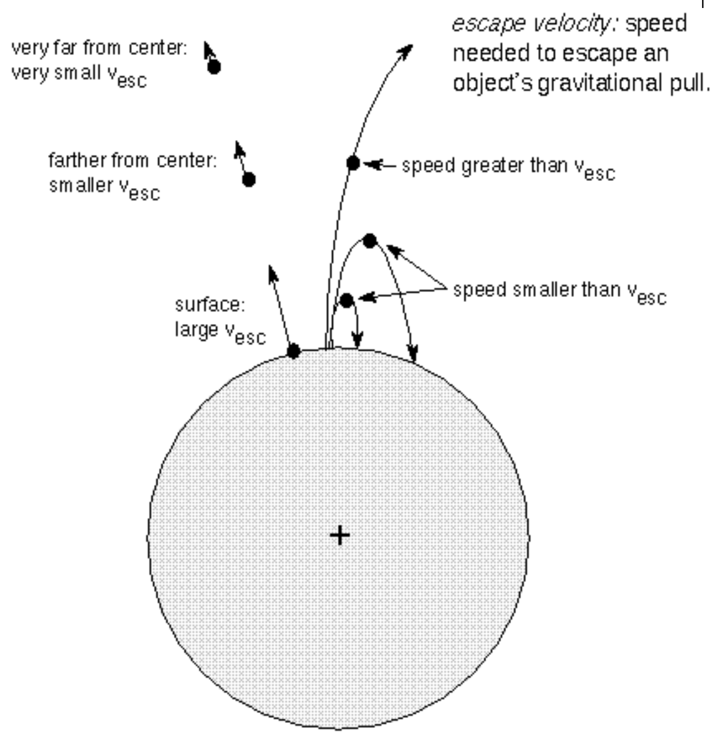
- **Wikipedia**: A Black Hole is a geometrically defined region of spacetime exhibiting such strong gravitational effects that nothing – including particles and electromagnetic radiation – can escape from inside it.
- Rev. John Michell explained in 1784 that a body 500 times denser than the Sun, would not allow light to escape
- Pierre Laplace established in 1796 that a celestial body with Earth's density, but 250 times larger than the Sun would not allow light to escape from inside it.
- Subramanyan Chandrasekhar, Ralph Fowler showed last century that there is nothing that can prevent gravitational collapse above a certain mass (of a few times the mass of the Sun).
- The term "Black Hole" was introduced by John A Wheeler in1967

Escape velocity

- Black Hole: Large mass concentration, on which surface

escape velocity= speed of light

$$escape\,velocity = \sqrt{\frac{2GM}{R}}$$



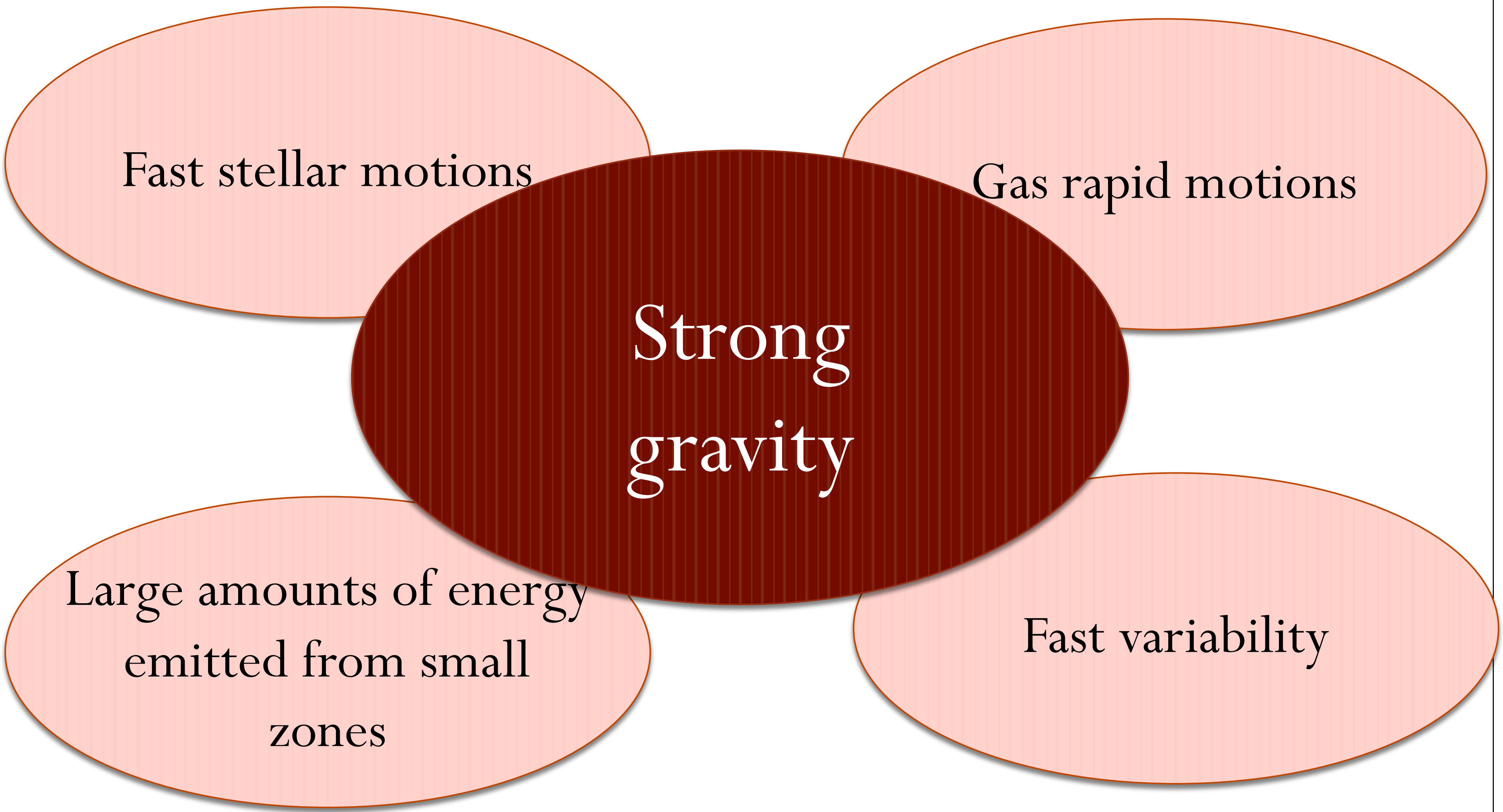
- **Schwarszchild** radius for a body of mass M is such that **escape velocity= speed of light.**

$$R_s = \frac{2GM}{c^2}$$

Truths and myths around Black Holes

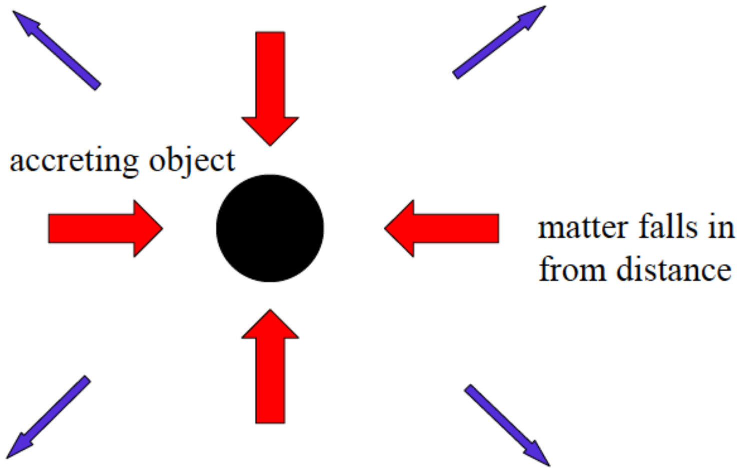
- Very intense gravitational force: a **trillion and a half** ($1.5\ 10^{12}$) times larger in a Solar mass BH than in the Earth's surface
- What falls "in" cannot come "out", most likely including information
- "Average density" of a Black Hole:
  - Solar-mass BH = larger than an atomic nucleus
  - Super-massive BH of 10^9 solar masses: density of water
- Black holes distort space-time in their vicinity, giving rise to spectacular General Relativistic effects: gravitational redshift, Lense-Thirring precession, time delays, etc.
- BH can (and are expected to) rotate, but there is a limit to their angular momentum per unit mass: a=0 (no rotation) up to a=0.998 (maximum)

How do we "see" astrophysical BHs?



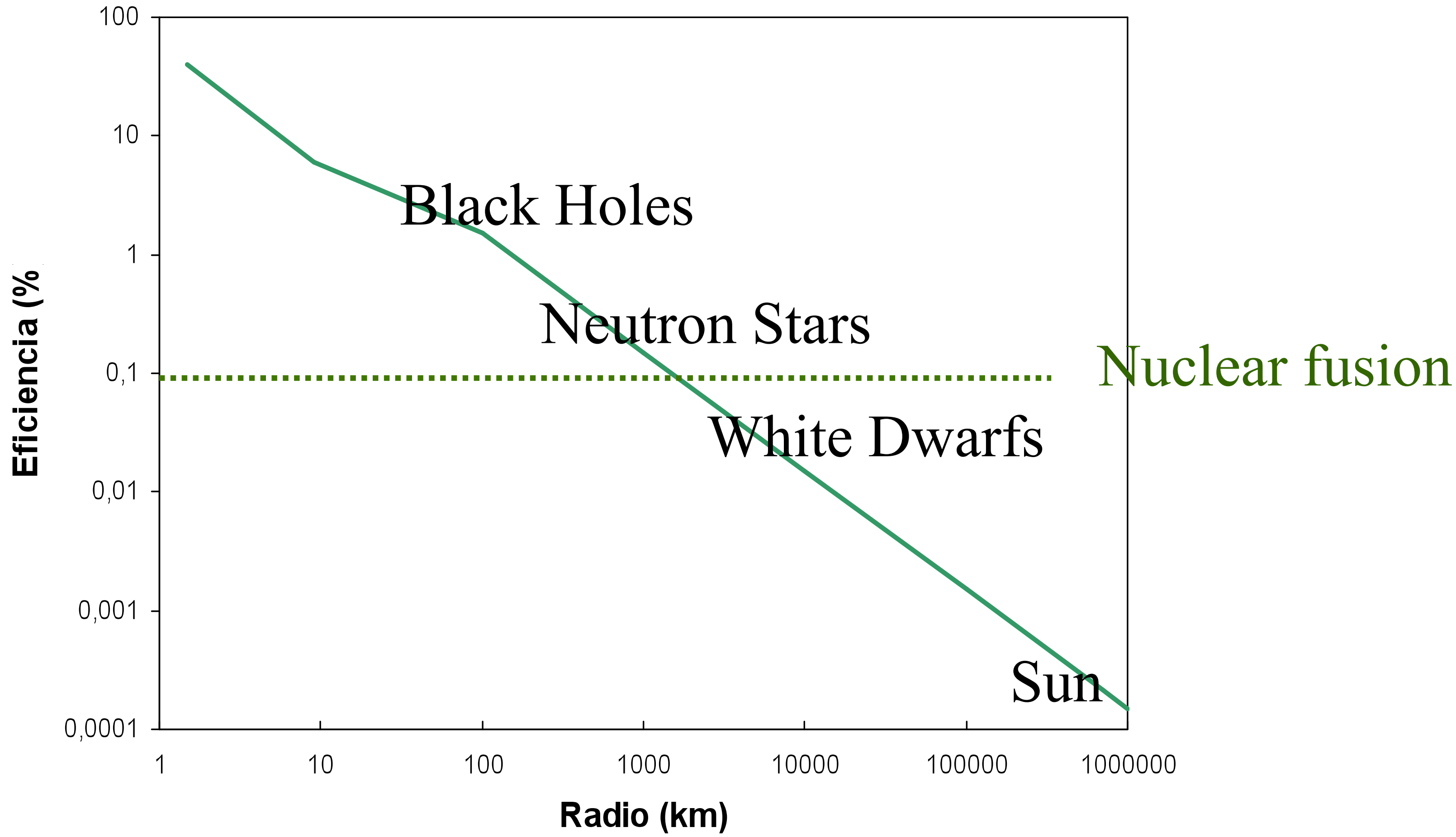
Accretion

- Matter falling towards a celestial body by gravitational attraction.
- The gravitational energy acquired by the falling matter is released in the form of:
  - Stellar heating or BH mass growth
  - Mechanical and radiative energy output
- Accretion converts mass into energy



$$Energy\,/\,Mass = \frac{GM}{R}$$

Is accretion an efficient process?

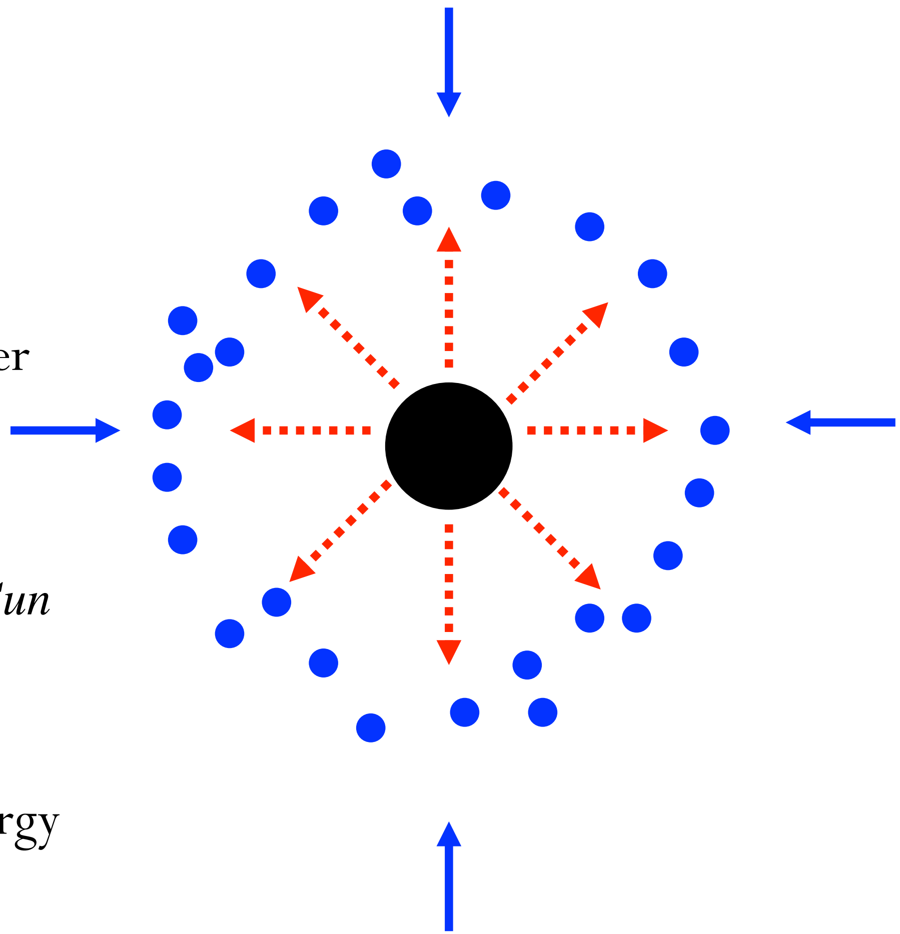


How much power can be extracted from an accreting BH?

- Can an unlimited amount of power be extracted from a Black Hole through accretion?
- **NO**: Radiation pressure by the energy released through accretion can stop matter falling onto a BH: **Eddington limit**.

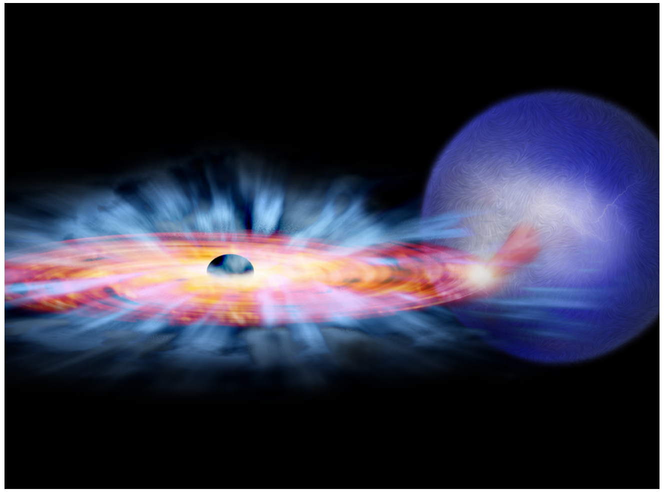
$$L_{Edd} = 100000 \left(\frac{M_{BH}}{M_{Sun}} \right) L_{Sun}$$

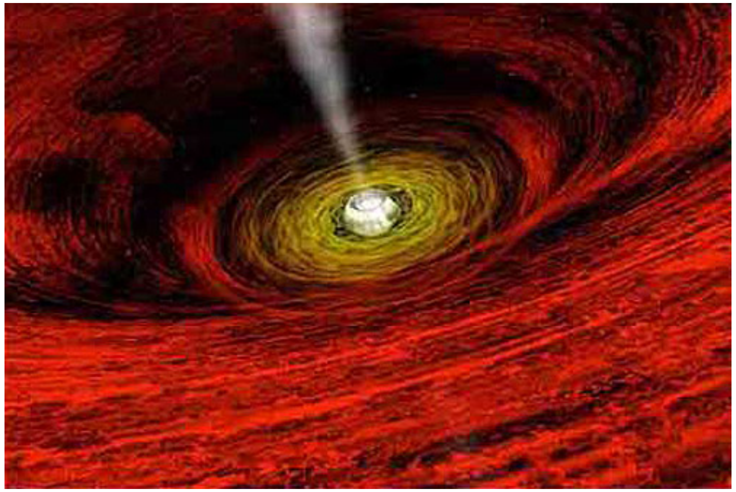
- The Eddington limit can be exceeded if accretion occurs through a plane and energy is released through the poles.



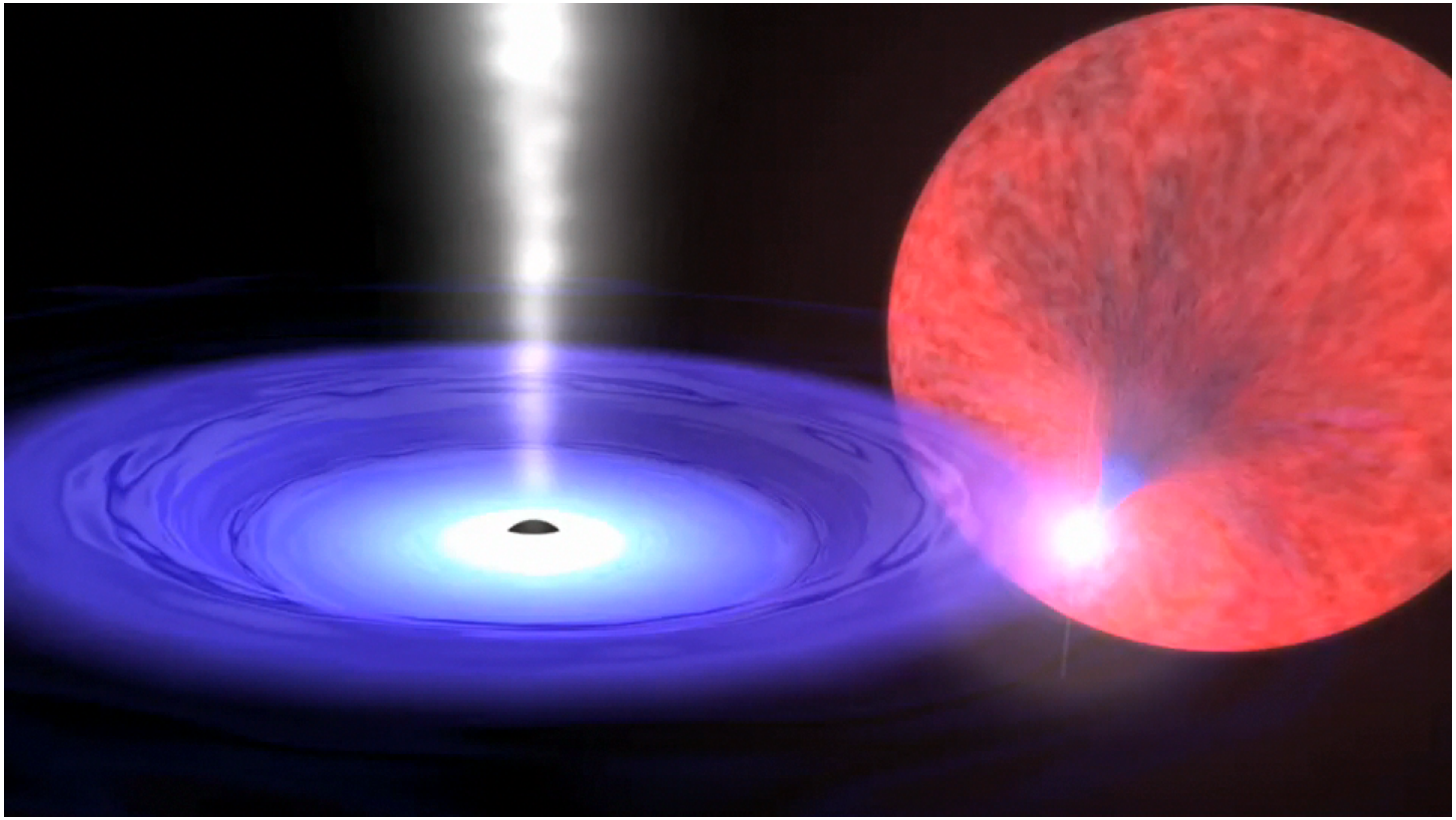
Black Hole demographics

- Stellar Black Holes
  - Mass up to ~10 M_{Sun}, formed by gravitational collapse of a massive star
- Intermediate Mass Black Holes?
  - Mass 100 - 10.000 M_{Sun}
  - Their exstence is still debated
- Super-massive black holes
  - Mass100.000 - 10.000.000.000 M_{Sun}





Stellar Black Holes

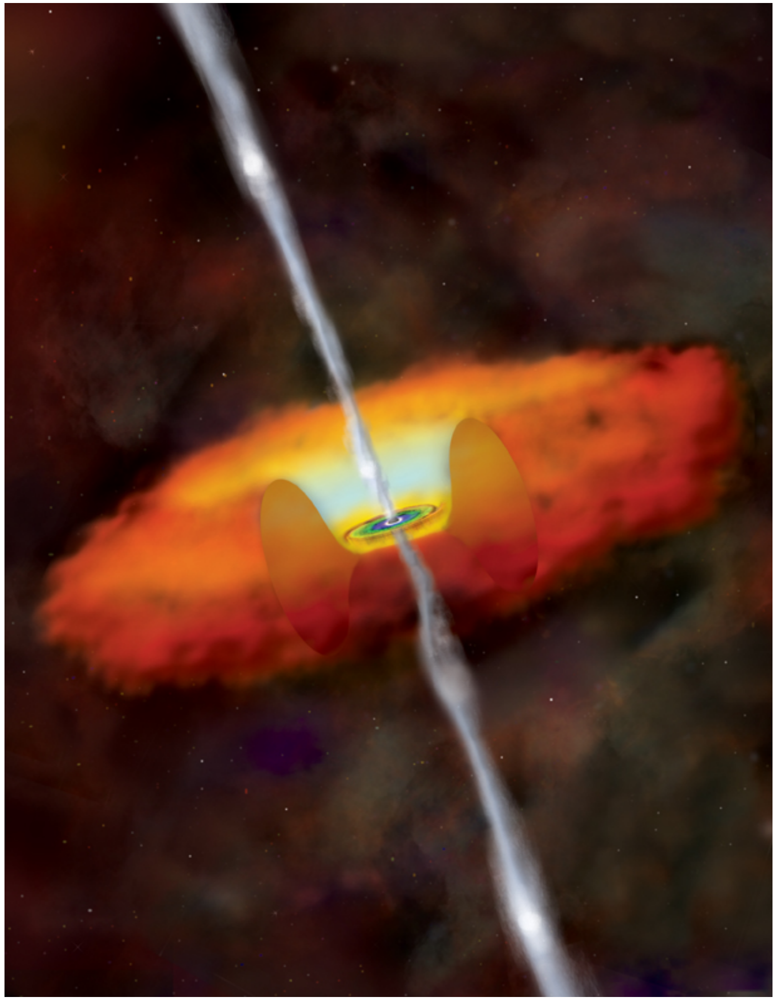


NASA/Chandra

Super-massive Black Holes

Nasa/Chandra

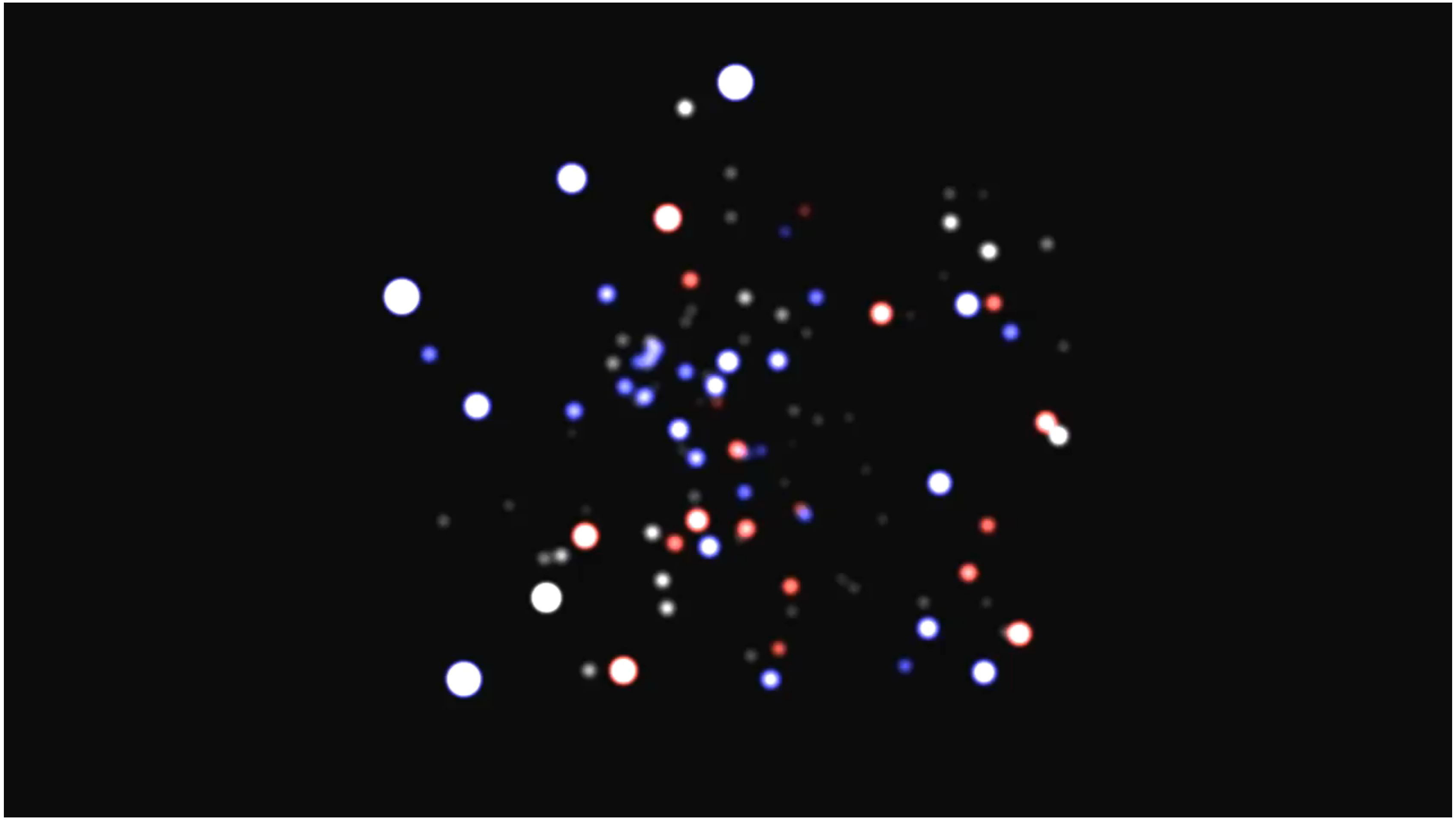
AGN –Active Galactic Nuclei



- Super-massive Black Holes (SMBH) accreting at high rate (L/L_{edd}> 0.01)
- QSOs are the high-luminosity part of the family
- They emit radiation across the electromagnetic spectrum
  - X-rays (corona in accretion disk)
  - Ultraviolet (inner accretion disk)
  - Visible (outer accretion disk)
  - Infrared heated molecular gas & dust)
  - Radio (jets of relativistic electrons)

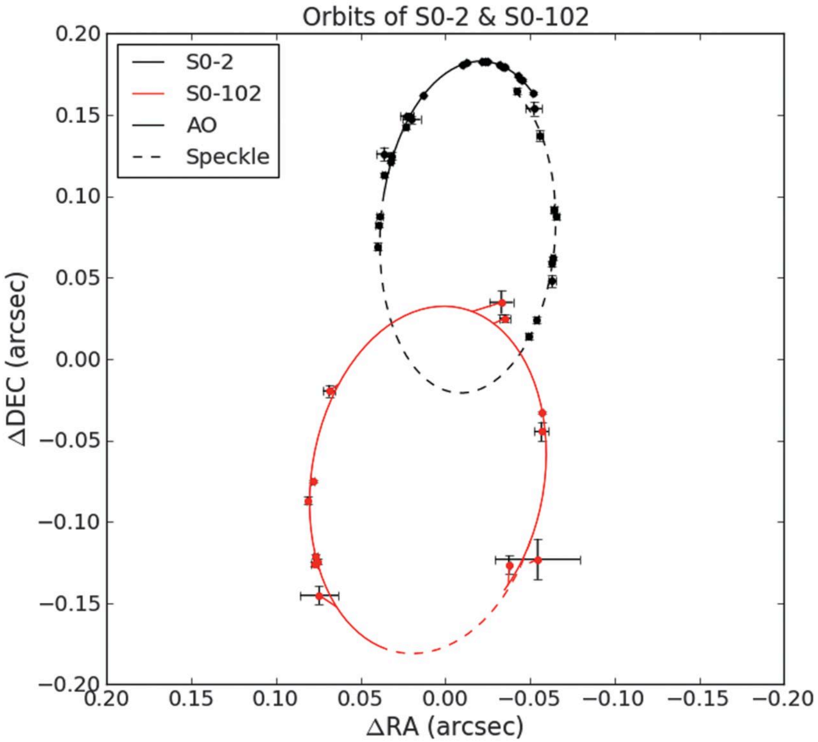
Super-Massive Black Holes in galaxy centres

Fast stellar motions around the centre of the Milky Way



ESO: Genzel et al

A 4 million solar mass BH at the center of the Milky Way

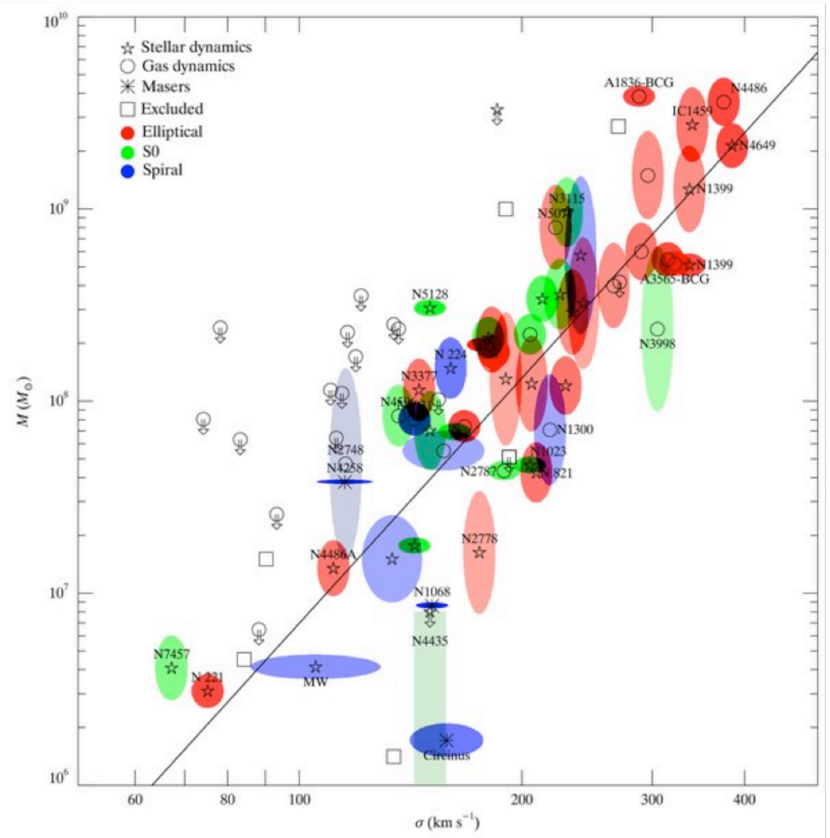


$$M_{BH} = (4 \pm 1) \times 10^6 M_{Sun}$$

$$\rho > 10^{17} M_{Sun} / pc^3$$

- There is no star or stellar cluster that can have such a high density.
- Alternatives are far more exotic than BHs

Rapid motions of gas and stars in the centres of most galaxies

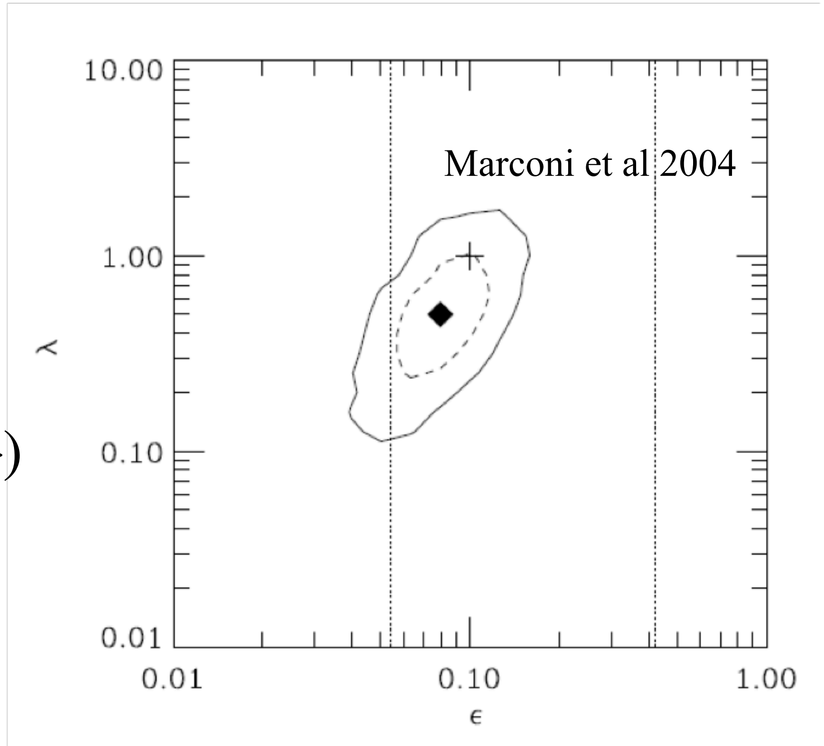


- A “Dark Mass” must exist at the centre of most galaxies, to keep these fast motions.
  - Unrelated to Dark Matter
- These SMBH have about **0.1%** of the total galaxy bulge mass

SMBH growth energetics

- Local SMBH distribution has to match growth and energy released in the cosmic X-ray background.

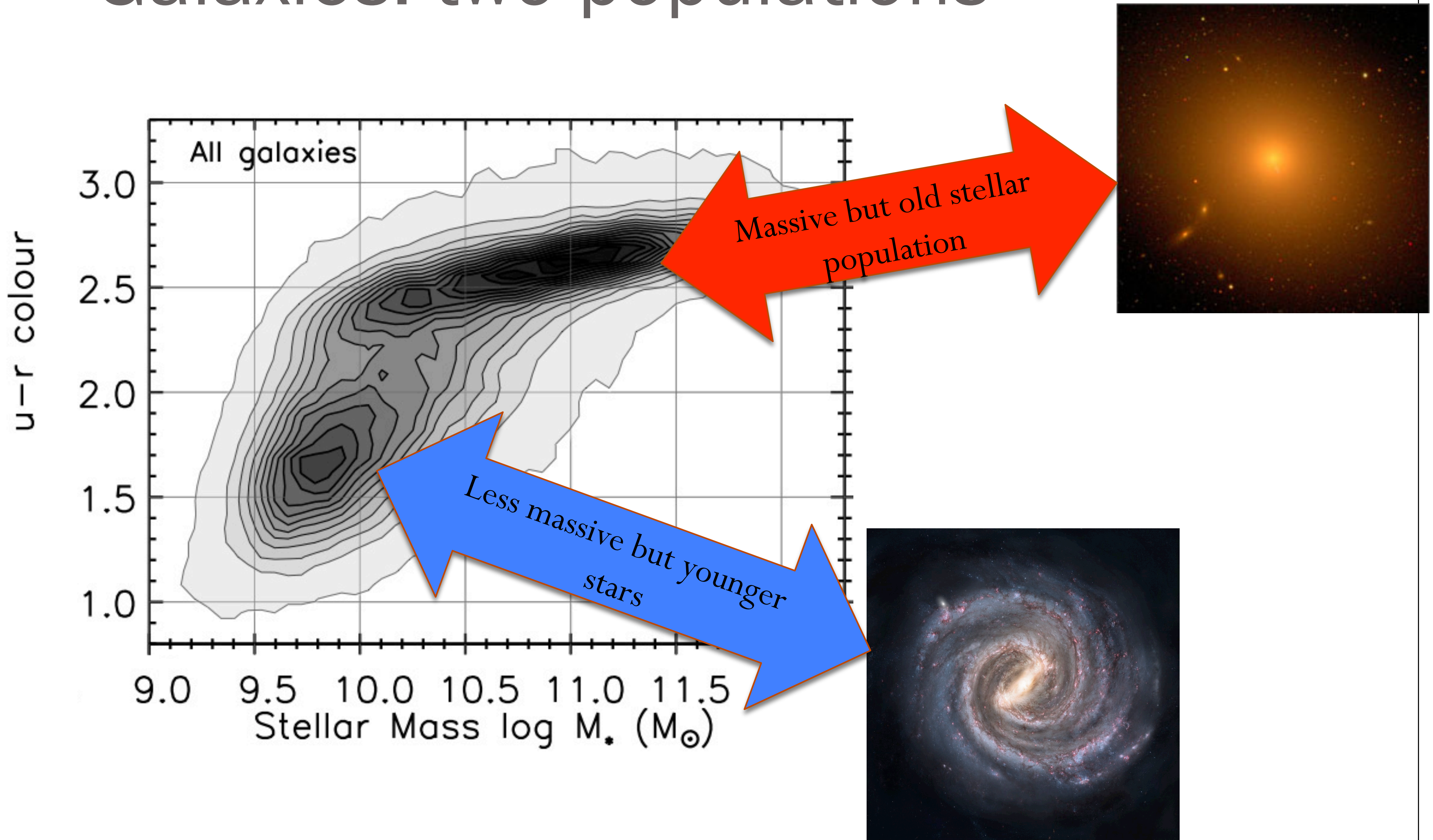
$$\rho_{BH} c^2 = \frac{1-\varepsilon}{\varepsilon} f_{obsc} K_{bol} 4\pi I_{XRB} (1+<z>)$$



- Key parameters:
  - Accretion efficiency ε
  - Eddington ratio λ
  - AGN obscured fraction

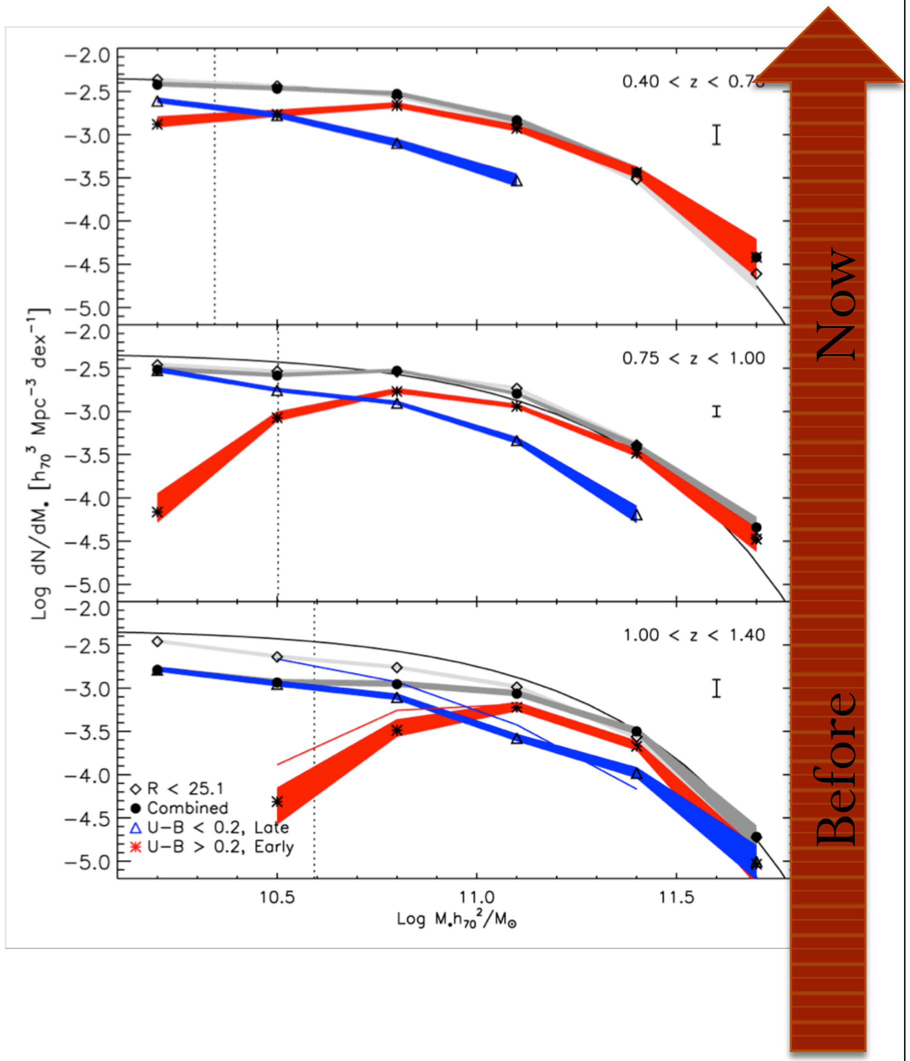
SMBH-galaxy co-evolution

Galaxies: two populations



Why do massive galaxies stop forming stars?

- Galaxies with larger stellar mass do not form stars: **red & dead.**
- Most of the massive galaxies were already formed at early epochs: **Downsizing**
- What quenches star formation in massive galaxies?



Reasons for downsizing

AGN Feedback

Starbursts/SNe

Mergers

Cluster environ.

Feedback: Why bother about SMBH?

Energy released to grow a SMBH (efficiency η~0.1)

$$E_{acc} = \varepsilon M_{BH} c^2$$

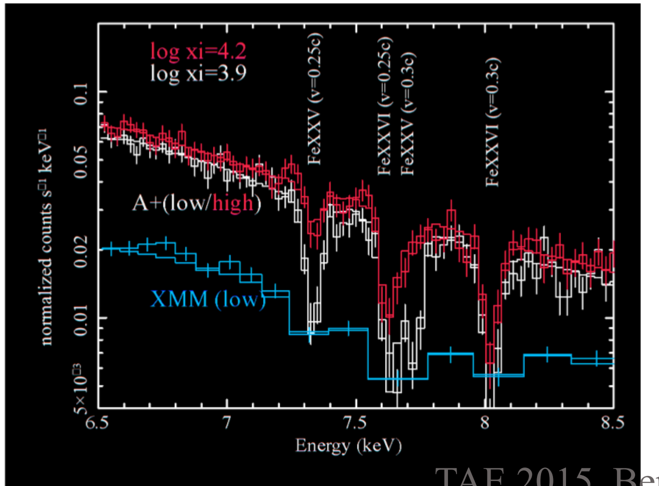
Gravitational binding energy of the host galaxy

$$E_{gal} \sim M_{gal} \sigma^2$$

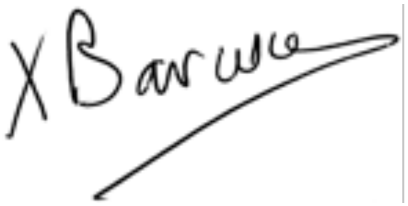
$$\frac{E_{acc}}{E_{gal}} \sim \varepsilon \left(\frac{M_{SMBH}}{M_{gal}} \right) \left(\frac{c}{\sigma} \right)^2 \sim 30 - 100$$

AGN energetics & feedback

- Radiative feedback
- Mechanical feedback:
  - QSO mode (winds & outflows): modest power (1% of the luminosity) but very efficient
  - Radio mode (jets): very powerful many times more energy than radiation, but possibly short duty cycle



Thank you!



- www.ifca.unican.es/barcons
- @xbarcons