Dark matter and physics beyond the standard model

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LAPTH- Annecy

18th-VSOP - QuyNonh

Plan

- Evidence for dark matter
- Relic density of dark matter
- Dark matter searches : overview
- Dark matter candidates and BSM
  - WIMPs and Supersymmetry
- Tutorial : micrOMEGAs and dark matter

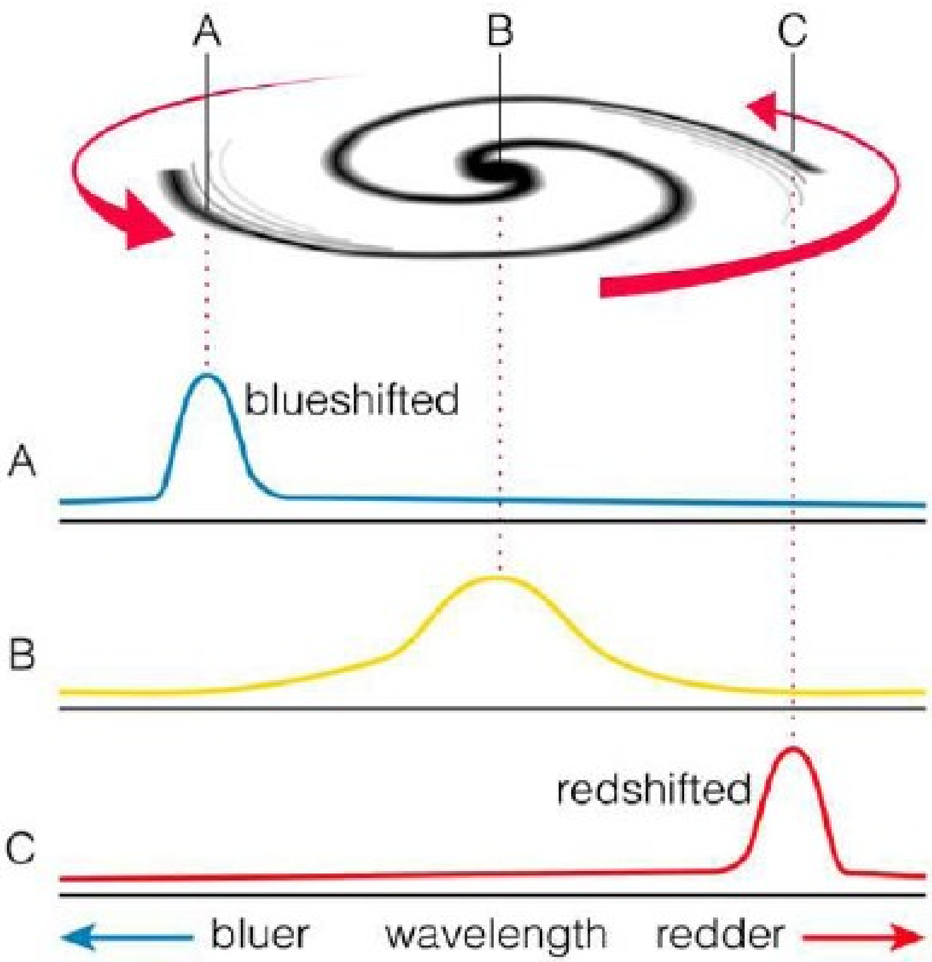
Dark matter

- In 1933: Fritz Wicky, a Swiss astronomer measured velocity dispersion in COMA cluster to estimate the cluster mass. He found mass was 400 times larger than the visible mass (deduced from luminosity estimation) He postulated the existence of a kind of matter that does not emit light → dark matter
- He was criticized (too much uncertainty) and forgotten BUT this result was confirmed later on many scales

Dark matter

- In 1970: Vera Rubin, US astronomer, measures the rotation velocity of spiral galaxies
- Velocities tend to a constant at large distances – presence of dark matter can explain this

Spiral galaxies



- Use the **21-cm emission line of hydrogen** gas clouds to trace orbital motions. *(Can also use stellar motions, but gas clouds are found to larger distances.)*

- Measure the galaxy's **rotation curve** to determine the total mass as a function of separation from the center.

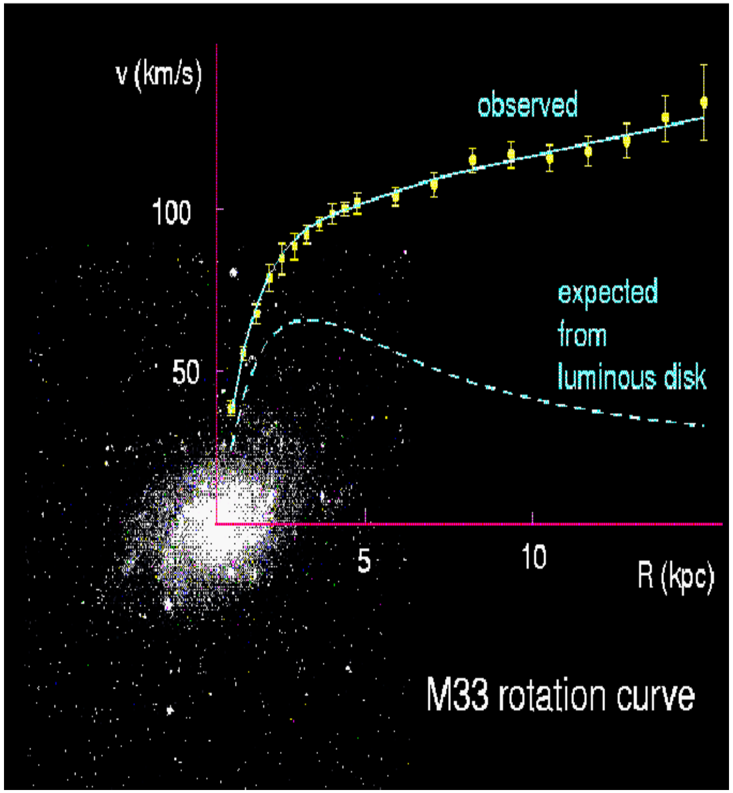
Rotation curves of galaxies

- Negligible luminosity in galaxy halos, occasional orbiting gas clouds allow measurement of rotation velocities and distances

- Newton

$$v(r) = \sqrt{\frac{GM(r)}{r}},$$

- r> $r_{luminous}$,
  M(r) =constant
  →v should decrease
- Observations of many galaxies: rotation velocity does not decrease
- Dark matter halo would provide with M(r)~r v-> constant



Evidence for dark matter: overview

- Most of the matter in the universe cannot be detected from the light emitted (dark matter)
- Presence of dark matter is inferred from motion of astronomical objects
  - If we measure velocities in some region there has to be enough mass for gravity to hold objects together
  - The amount of mass needed is more than luminous mass
    - The galactic scale
    - Scale of galaxy clusters
- Dark matter is required to amplify the small fluctuations in Cosmic Microwave background to form the large scale structure in the universe today
  - Cosmological scales

Mass-to-Light ratios

- Ratio of the mass of an object to its total luminosity – measured in terms of solar mass and solar luminosity
- Mean luminosity can be computed given a distribution of galaxies with total luminosity L

$$\mathcal{L} = \int L\phi(L)dL$$

- Measured to be $\mathcal{L} \approx 2 \pm 0.3 \times 10^8 h_0 L_\odot Mpc^{-3}$
- Defining critical energy density $\rho_c = \frac{8H^2}{8\pi G_N} = 1.88 \times 10^{-29} h_0^2 gcm^{-3}$
- Critical mass to light ratio

- Cosmological matter density

$$\Omega_m = \frac{\rho}{\rho_c} = \frac{M/L}{(M/L)_c}$$

Taking ratio of mass of all stars to luminosity emitted in volume hundred parsec around the Sun find that there is no need for DM around the Sun however on larger scales(small groups of galaxies) or on scales of clusters considerable amounts of dark matter

-→ $\Omega_m \sim 0.1 - 0.3$

Any non-luminous component of the Universe can only be detected indirectly by its gravitational effect on luminous matter

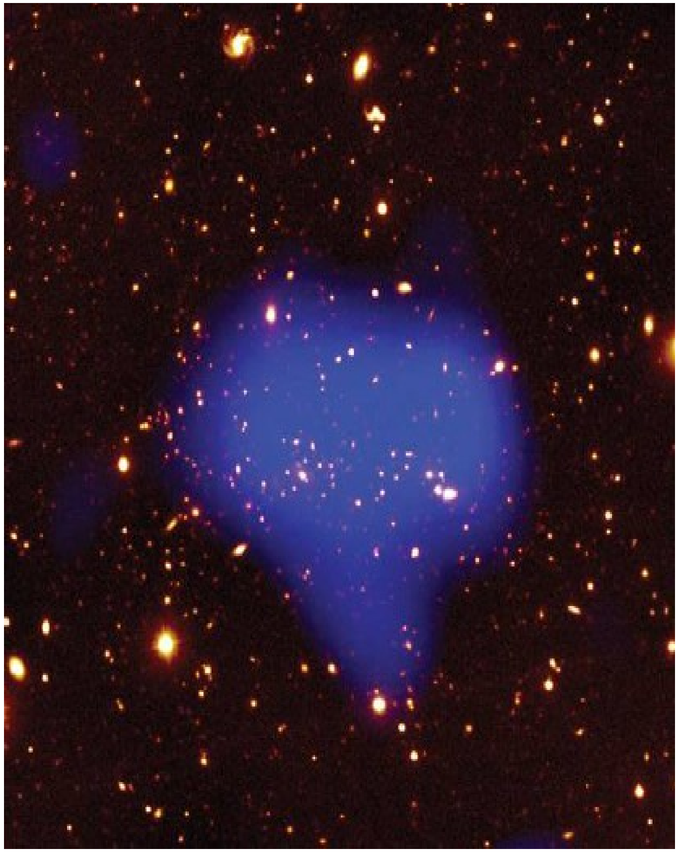
Mass of galaxies

- The luminous mass in galaxies can be in:
  - Dust : emits in the infra red part of the spectrum. Dust-particles are heated by stars and radiate thermal energy.
  - Cool gas : mostly neutral hydrogen, which has an emission line at 21 cm. (in radio frequency).
  - Hot gas
  Hot gas is mostly in accretion discs of heavy stars result is X-ray radiation.
  - Stars : mostly detected in visible range.
- Luminous mass is mostly in form of stars and cool gas.

Mass of Clusters

- Clusters contain large amounts of very hot Xray emitting gas

- Temperature of this hot gas measures the cluster's mass because the gas has to be held in cluster by gravity (hydrostatic equilibrium)



Galaxy clusters

- 1933 : Zwicky got first evidence of dark matter in galaxy clusters (Coma)
- Virial Theorem relates kinetic energy with Potential energy
  - $Ek_{avg} = -1/2\ PE_{avg}$
  - Measure velocities of individual galaxies using Doppler shift
  - – calculate the radial velocity dispersion and estimate the total mass of the cluster

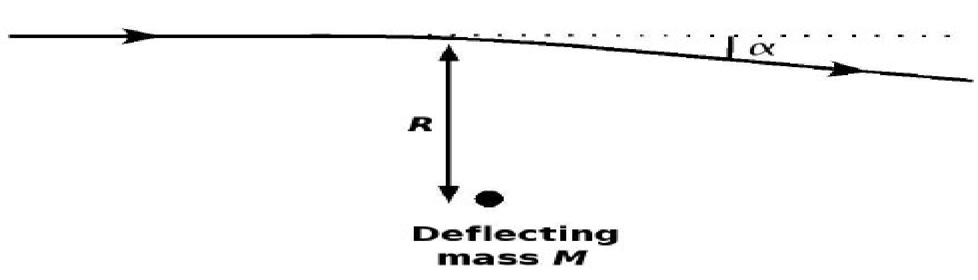
Recent estimates of mass of Coma Cluster using this method as well as Xray maps imply

$$\Omega=0.2\text{-}0.4$$

Confirmed by many observations on galaxy clusters

Gravitational lensing

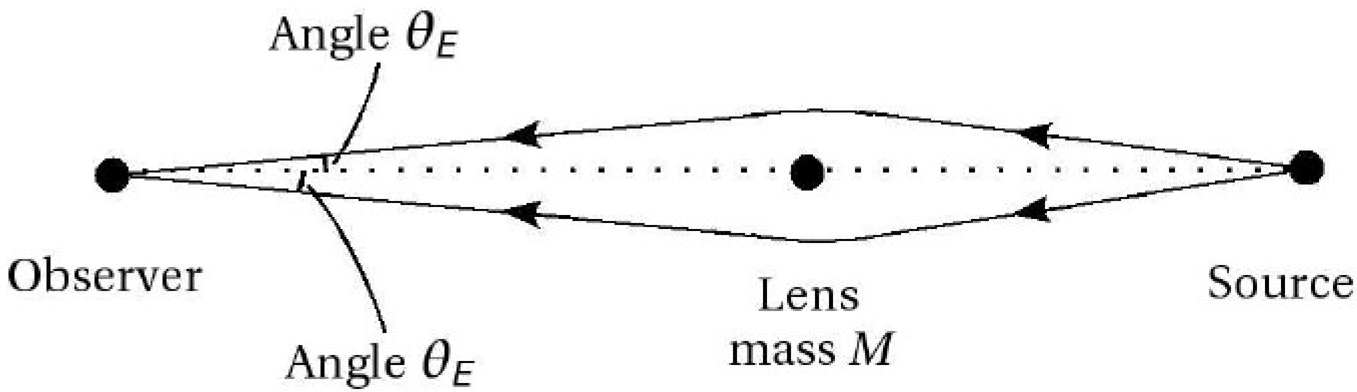
- Einstein's theory of relativity predicts that strong gravitational fields will bend the path of nearby light rays.
- A very large mass can bend light rays and become a lens (the lens is gravitational field)
- Requires a very large mass (e.g. mass of a galaxy or cluster) and a distant light source behind it



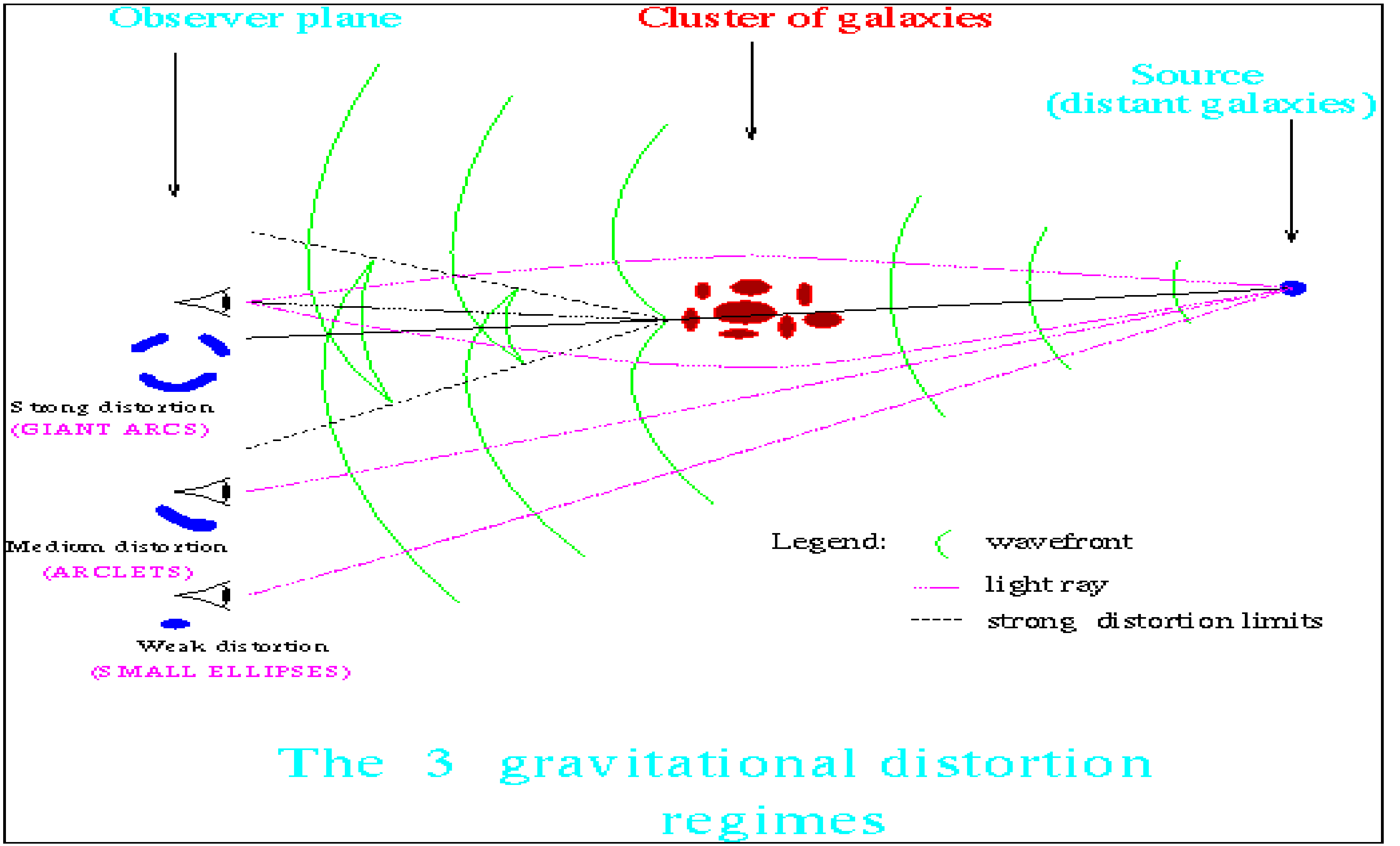
$$\alpha = \frac{4GM}{c^2 R} .$$

- Quasars are very distant objects in Universe and very common, find distant quasars perfectly aligned with a galaxy -> gravitational lens of quasar, image altered

- Effect of lensing: Lensing of a point object by a point Mass : Einstein's rings



Lensing by clusters



The lens produces two effects.

1) it deflects the light rays
2) it induces a pure gravitational time delay.

A deflected light ray which intersects the observer will arrive with a pure geometrical delay and a pure gravitational delay.

Depending on the lens configuration, the observer will see multiple and strongly distorted images (arcs), single distorted images with elliptical shape (arclets), or weakly distorted images (weak shear regime) with individual elongation almost invisible.

Strong lensing is rare but gives strong local constraints on the potential.

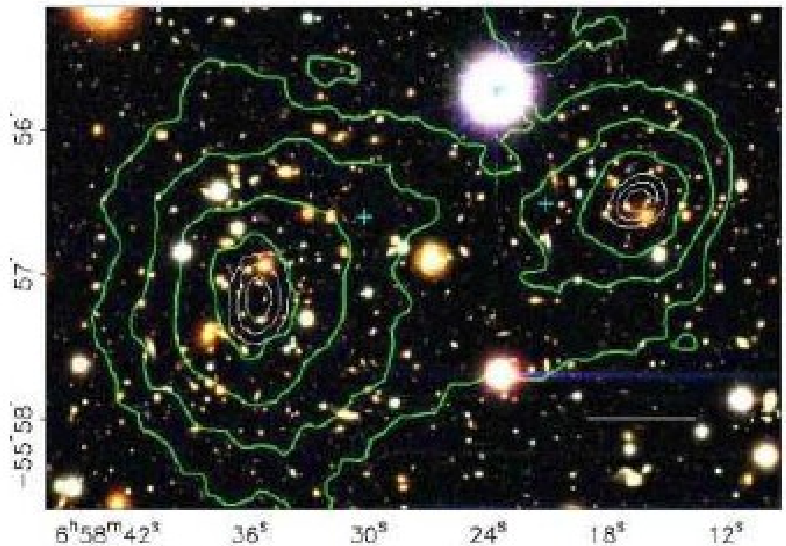
- Images of clusters of galaxies show many blue arcs which are gravitational lensed images of more distant background galaxies
- Detailed studies of arcs allows to measure the total mass of the cluster of galaxies
- Observations show that 10% of the total mass of the cluster is in the form of individual galaxies → the rest DM

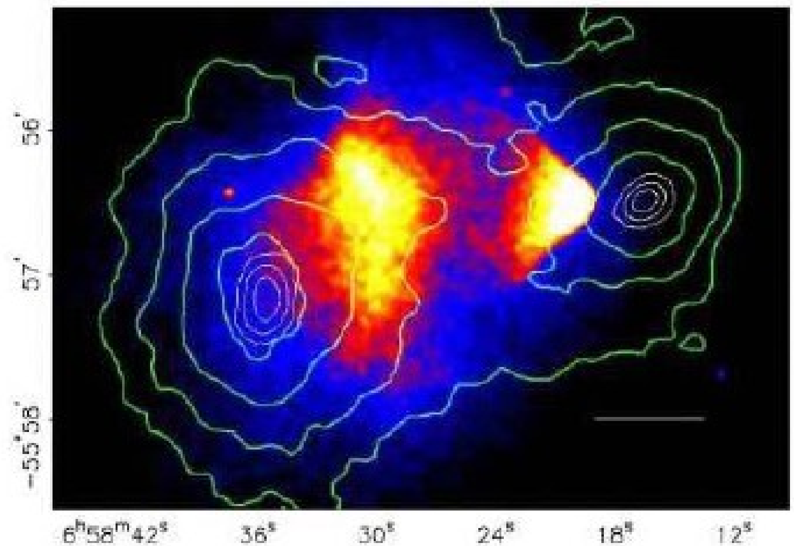
Bullet Cluster

- Collision of two clusters : direct evidence of dark matter
- Comparison of X-ray images of luminous matter with measurements of the cluster's total mass through gravitational lensing.
- Involves the observation of the distortion of light from background galaxies by the cluster's gravity -- the greater the distortion, the more massive the cluster.
- Two small clumps of luminous matter slowed down by the collision (interactions)
- Two large clumps of collisionless matter (not slowed down by the collision) – dark matter

Bullet cluster

- Total mass peak offset from X-ray peak (hot gas that forms most of baryonic mass) by 8 σ
- Most of mass in form of collisionless DM

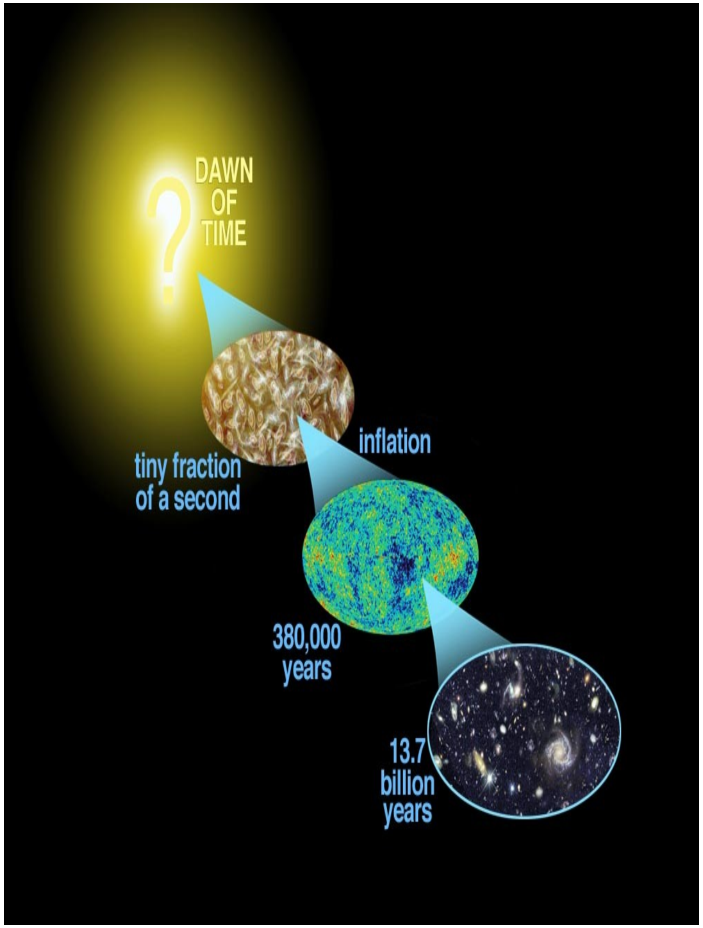




Cosmic microwave background

and total amount of dark matter in the universe

- Model of Gamow (1948) : Universe was once very hot and dense and has expanded and cooled to its present state
- Consequence : Background radiation originating from propagation of photons in early universe (once they decoupled from matter) with T a few K
- Discovered Penzias&Wilson 1965
- Universe is isotropic
- CMB is isotropic at 10^{-5} level and follows spectrum of a blackbody with T=2.726K
- Subsequent work on Big Bang Nucleosynthesis further confirmed the Big Bang model.
- Problem with initial conditions $\rightarrow$ the best solution is inflationary cosmology



Cosmological model

- Metric (geometry), Universe homogeneous and isotropic – only 2 parameters

$$ds^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

  - R: cosmological scale factor
  - k: 3-space curvature constant
  - k=0,1,-1 -> flat, closed, open Universe
- Einstein's eq. relate the geometry of the universe to its matter and energy content -> cosmological eq. motion

$$\mathcal{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathcal{R} = 8\pi G_N T_{\mu\nu} + \Lambda g_{\mu\nu}$$

- Assuming Universe is a perfect fluid

$$T_{\mu\nu} = -pg_{\mu\nu} + (p+\rho)u_\mu u_\nu$$

- Assuming perfect fluid -> Friedmann Robertson Walker

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{k}{R^2} + \frac{\Lambda}{3}$$

- Λ: cosmological constant
- H : Hubble parameter
  - relation between distance and recession velocity
  - best measured by Hubble Space Telescope at present

$$H_0 = 73 \pm 3 \mathrm{km s^{-1} Mpc^{-1}}$$

$$\rho_{crit} = \frac{3H^2}{8\pi G_N}$$

- Universe is flat when no cosmological constant and when energy density is critical density
- For specie i $\Omega_i = \rho_i/\rho_c$

Friedmann Eq.

$$(\Omega - 1)H^2 = \frac{k}{R^2}$$

K=0 Ω= 1

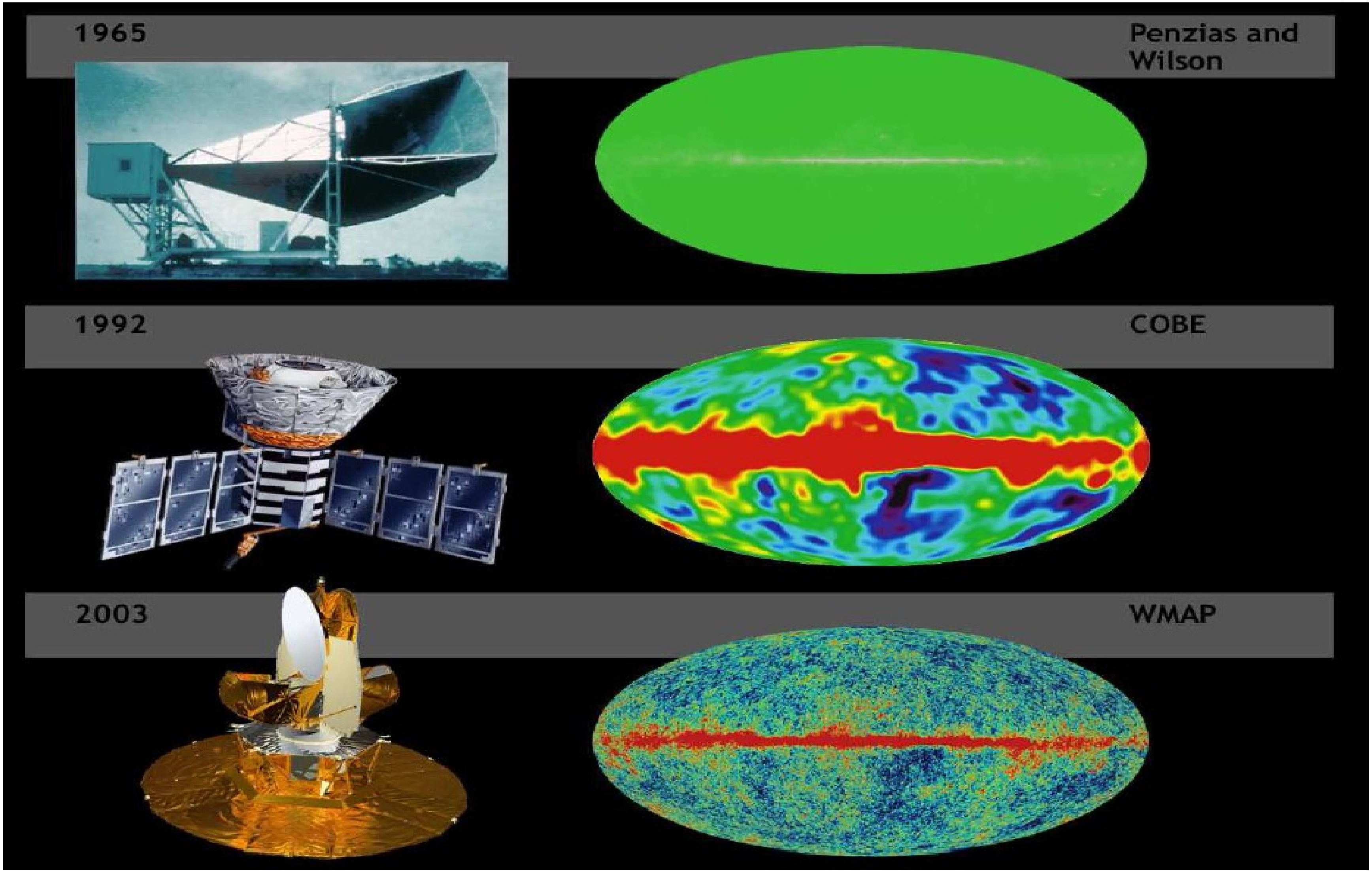
k=1, Ω>1

k=-1, $\Omega < 1$

Determination of cosmological parameters

- CMS is isotropic to 10^{-5} level and follows a black body with temperature T=2.726K
- Anisotropy to CMB tell the magnitude and distance scale of density fluctuation when universe was 1/1000 of present scale
- Study of CMB anisotropies provide accurate testing of cosmological models, puts stringent constraints on cosmological parameters
- In the last 10 years: huge progress in determination of cosmological parameters – in particular with WMAP and now Planck

Cosmic microwave background



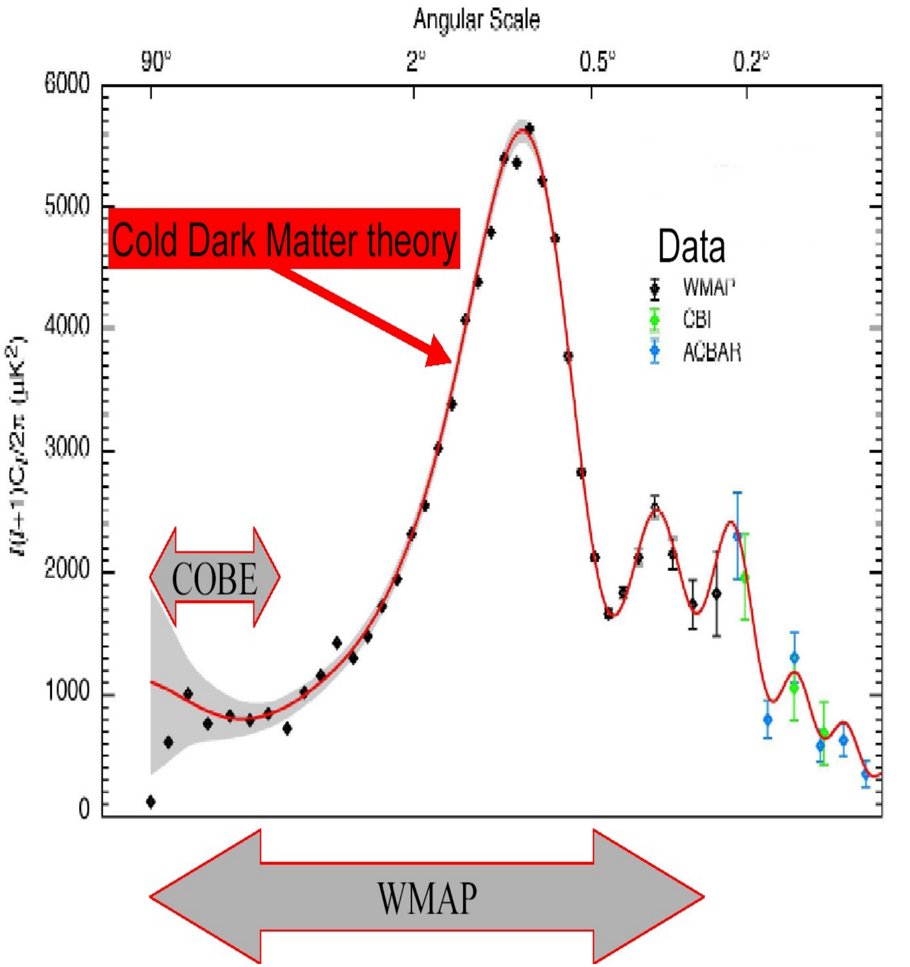
Density fluctuations

- Small anisotropy observed in sky
- All information contained in CMB maps can be compressed in power spectrum

$$\frac{\delta T}{T}(\theta,\phi)=\sum_{\ell=2}^{+\infty}\sum_{m=-\ell}^{+\ell}a_{\ell m}Y_{\ell m}(\theta,\phi)$$

$$C_\ell \equiv <|a_{\ell m}|^2> \equiv \frac{1}{2\ell+1}\sum_{m=-\ell}^{\ell}|a_{\ell m}|^2.$$

- To extract information from CMB anisotropy maps. Start from cosmological model with small number of parameters and find best fit



Cosmological model

- Cosmological model parameters ΛCDM

Hubble parameter

$$\Omega_m, \Omega_b, \Omega_\Lambda, \Omega_r, \Omega_\nu, \Delta_R^2, n \quad h, \tau$$

Density perturbations
(how the universe deviates
from homogeneity)

Ionization optical depth :
Related to probability that
a given photon scatters once

$$\Delta_R^2(k) = \Delta_R^2(k_*) \left(\frac{k}{k_*}\right)^{n-1}$$

	WMAP5	WMAP5+SDSS+SNe
$\Omega_b h^2$	0.0227 ± 0.0006	0.0227 ± 0.0006
$\Omega_{cdm} h^2$	0.110 ± 0.006	0.113 ± 0.003
$\Omega_\Lambda h^2$	0.74 ± 0.03	0.726 ± 0.015
n	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
τ	0.087 ± 0.017	0.084 ± 0.016
$\Delta^2_R \times 10^9$	2.41 ± 0.11	2.44 ± 0.10

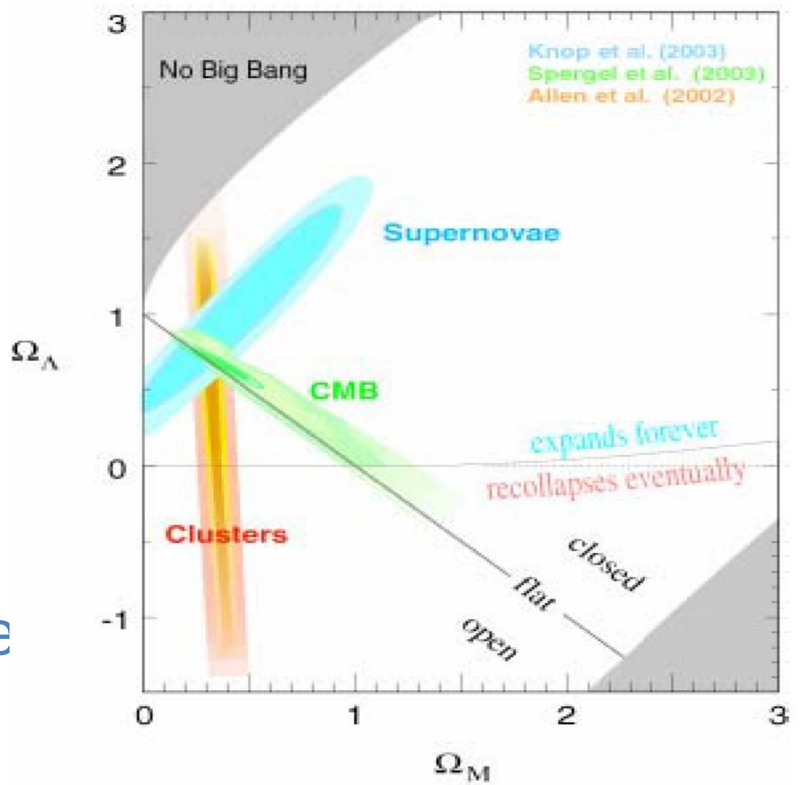
- Slight improvement with WMAP7
- Large dark energy component (assume to be cosmological constant)
- Precise evaluation of dark matter component
- Baryon density in agreement with BBN(.019-.024)

- In supernovae: relation between observed flux and intrinsic luminosity of an object which depends on the luminosity distance $$D_L = (1+z) r_e(z)$$

- z: redshift

$r_e(z)$ depend on the cosmological parameters Ω_m, Ω_Λ

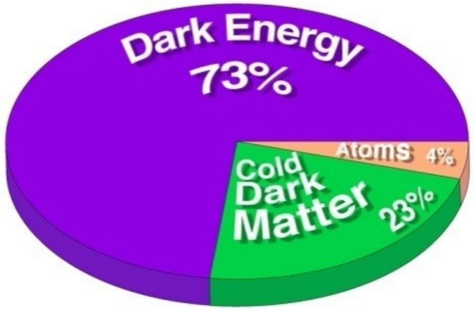
Observations of supernovae at large redshift constrain a combination of Ω_m, Ω_Λ nearly orthogonal to the one of WMAP



- Measurement of matter density is also obtained by measurements of clusters of galaxies e.g Sloan Digital Sky Survey (SDSS)

Conclusion

- At different scales evidence for dark matter
- Baryons form a small component of matter as shown from CMB and BBN
- CMB gives precise estimate of amount of dark matter
- Galaxy formation provide further evidence that dark matter exists



Universe is made of 23% cold dark matter. Can it be a new particle?