Dark sector of cosmology

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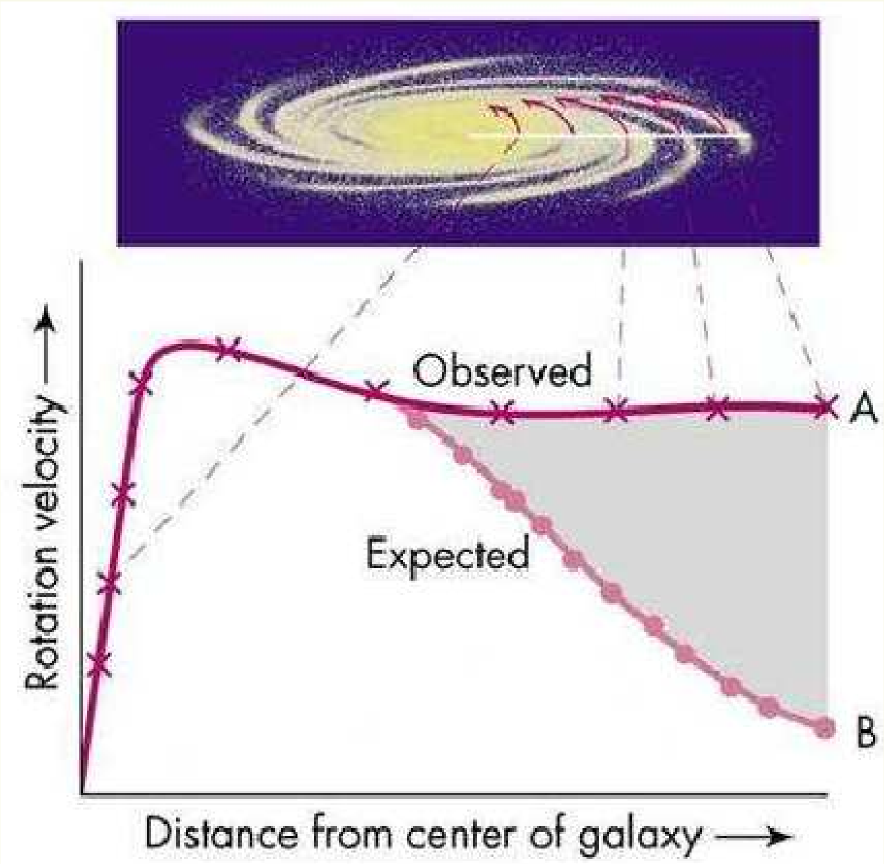
The outline of lecture

1. Dark matter:
    - a shot history and definition,
    - observational evidences for existence,
    - properties and candidates,
    - experiments and observations;
2. Dark energy:
    - a shot history and definition,
    - observational evidences for existence,
    - models,
    - observational constraints;
3. Dark Ages
    - time interval,
    - physical parameters of matter-energy components,
    - formation of first halos,
    - possibility of observations.

Galactic Rotation Curves

Kapteyn J. C. First Attempt at a Theory of the Arrangement and Motion of the Sidereal System, *The Astrophysical Journal* **55**, 302 (1922),
Jeans J. H. The Motions of Stars in a Kapteyn Universe, *Monthly Notices of the Royal Astronomical Society* **82**, 122 (1922),
Oort J. H. Observational evidence confirming Lindblad's hypothesis of a rotation of the galactic system, *Bulletin of the Astronomical Institutes of the Netherlands* **3**, (1927)



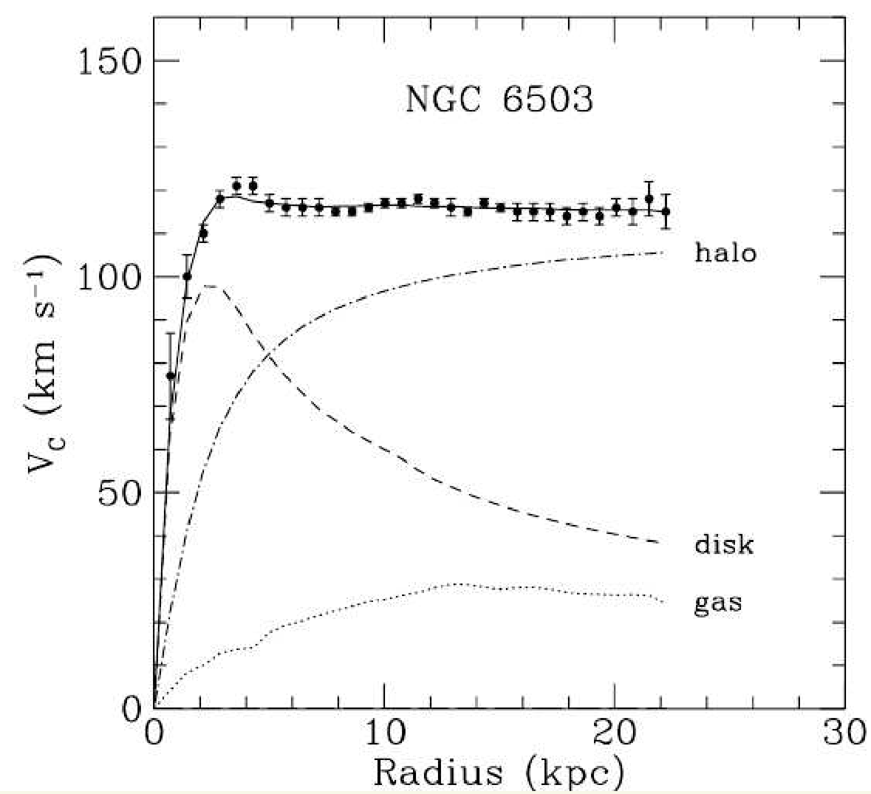
$$M_{tot}(r) = v_{obs}^2(r)r/G$$

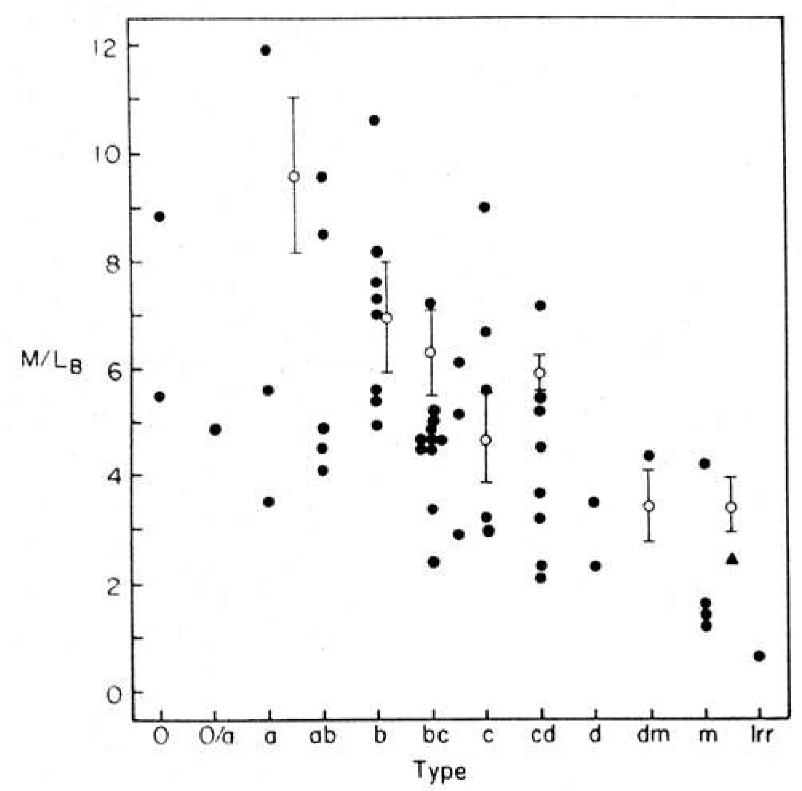
$$v_{pr}(r) = \sqrt{G\frac{M_{st+g}(r)}{r}}$$

$$v_{pr} < v_{obs}$$

Galactic Rotation Curves

Muller C. A. & Oort J. H. *Nature* **168**, 357 (1951),
Pawsey J. L. *Nature* **168**, 358 (1951),
Freeman K. C. *The Astrophysical Journal* **160**, 811 (1970),
Rubin V. C. & Ford J. W. Kent. *The Astrophysical Journal* **159**, 379 (1970),
Roberts M. S. & Rots A. H. *Astronomy and Astrophysics* **26**, 483 (1973).





Other prediction followed from the virial theorem:

In a stationary system of N particles bounded by a potential force, the time averaged complete kinetic energy $\langle T\rangle$ is related to the time-averaged complete potential energy $\langle U\rangle$ with the relation:

$$2\langle T\rangle = -\sum_{k=1}^{N}\langle \mathbf{F}_k \mathbf{r}_k\rangle,$$

where $\mathbf{F}_k$ is the force which acts on the particle k with coordinate $\mathbf{r}_k$. If potential force is such, that $U_k \sim r^n$, then

$$2\langle T\rangle = n\langle U\rangle.$$

In the case of gravitational interaction $n = -1$ and

$$2\langle T\rangle + \langle U\rangle = 0.$$

The sum of complete potential energy and double of complete kinetic one of stationary gravitational bounded system is zero.

$$M_{tot} = \langle v^2\rangle R/kG$$

Mass-to-light of groups and clusters of galaxies

Zwicky F. *Helvetica Physica Acta* **6**, 110 (1933),
Smith S. *Carnegie Institution of Washington* **532** (1936),
Holmberg E.A. *Annals of the Observatory of Lund* **6** (1937)

Class of objects	M/L_B in units of $(M/L_B)_\odot$
Pairs of galaxies	35-50
Small groups of galaxies	60-180
Local Group of galaxies	25-60
Coma Cluster	500
Rich clusters of galaxies	170-330

Padmanabhan T. *Theoretical Astrophysics. Volume III: Galaxies and Cosmology*, Cambridge University Press (2002).

de Swart J. G., Bertone G., van Dongen J. **How dark matter came to matter**, *Nature Astronomy*, **1**, id. 0059 (2017)

Definition of dark matter

Dark matter is a hidden or invisible mass in galaxies and clusters of galaxies which is necessary to explain their properties.

It can be:

- Dwarf stars, jupiters or other low- or non-luminous objects;
- Unknown type of matter which does not emit the electromagnetic radiation;
- At cosmological scales the gravity or Newtonian dynamics must be corrected.

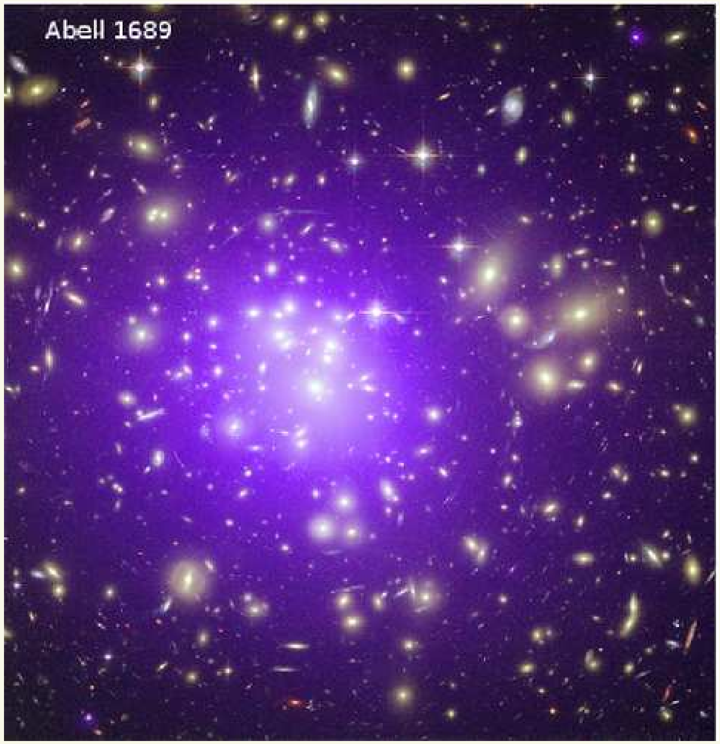
X-ray clusters of galaxies

$$G\frac{M_{tot}(r)\rho(r)}{r^2} = -\frac{d}{dr}\left(n(r)kT_X(r)\right);$$

$$M_{tot} = \frac{kT_X R_{cl}}{\mu m_p G} f(r_c/R_{cl}),$$

$$M_{tot} > \sum M_{gal} + M_{gas}$$

(Allen et al. (2001)).

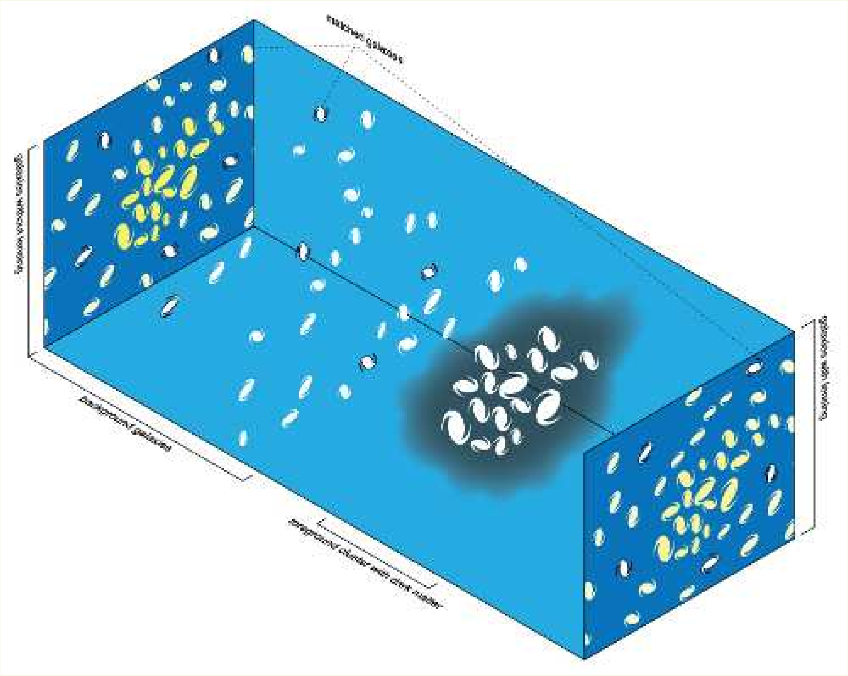


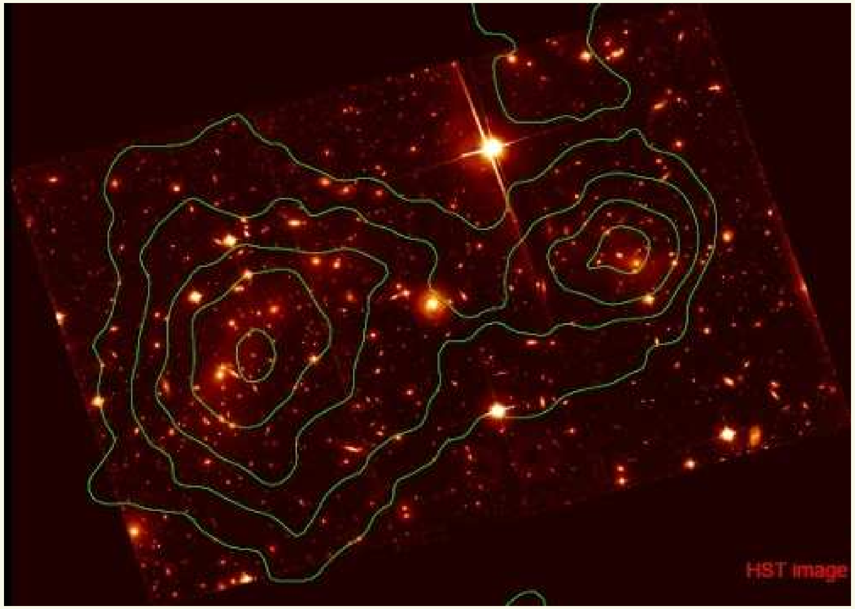
Gravitational lensing (weak)

Weak gravitational lensing leads to distortions in the distribution of background objects under the action of the field of gravitation of foreground objects, which are detected by statistical methods. The content of the dark matter of many clusters of galaxies is analysed using gravitational lensing. With the advent of large observations of the sky, the cosmological application of weak gravitational lensing was possible to obtain a statistical estimate of the average density of matter.

$$M_{tot} > \sum M_{gal} + M_{gas}$$

The theory was developed in 1990s by Blandford R., 1992, ARA&A 30 311; Kaiser N. & Squires G., 1993, ApJ 404 441

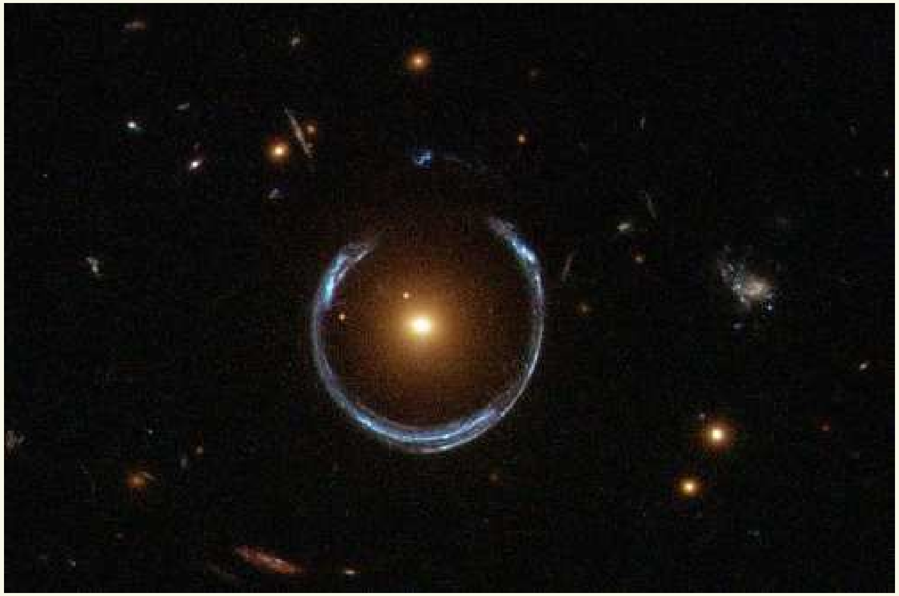


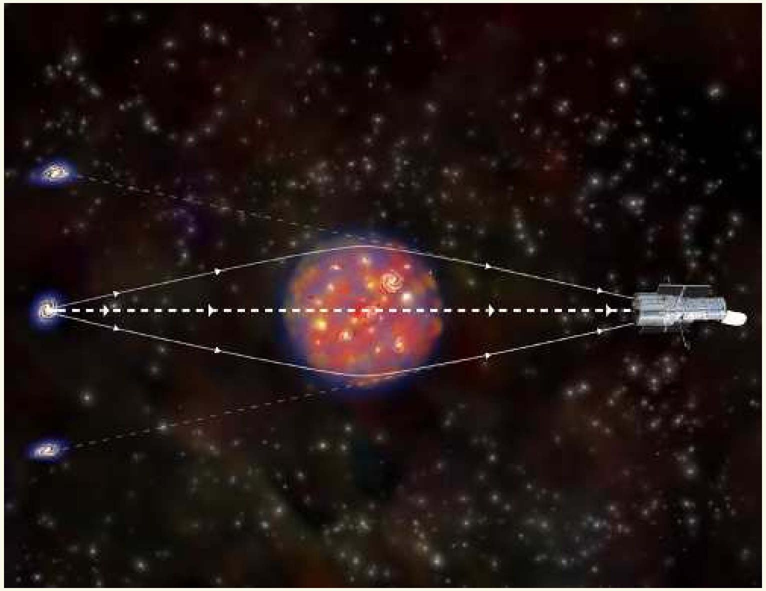


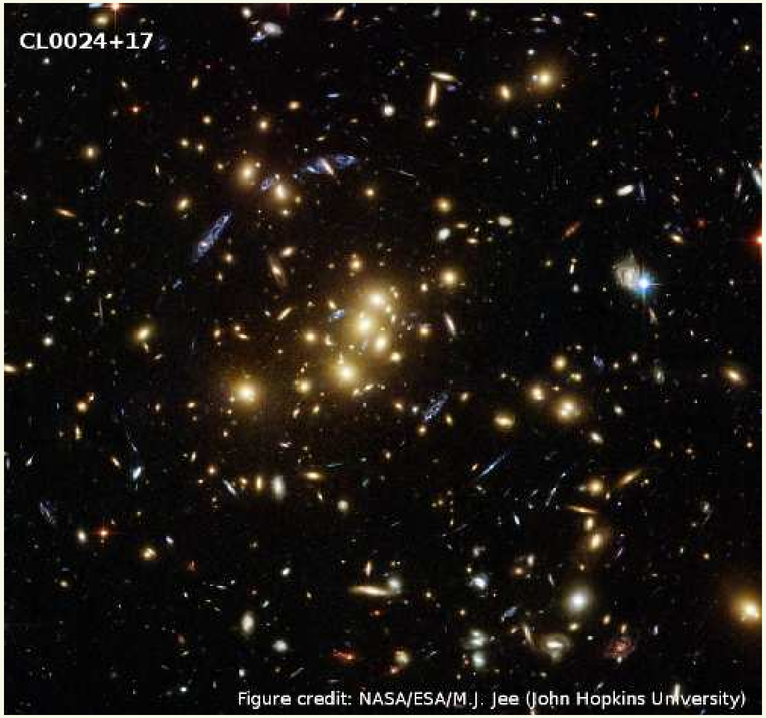
Gravitational lensing (strong)

By measuring the shape of distortions in the form of rings or arcs, it is possible to estimate the mass of the cluster-lens, and modern methods allow to determine the density profile and even map the distribution of mass in the cluster.

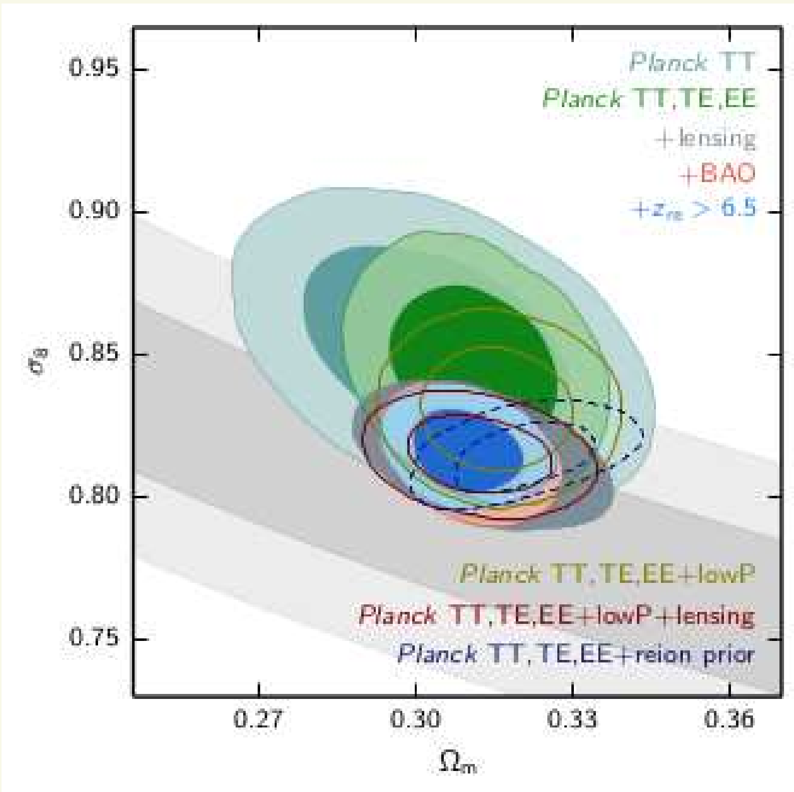
$$M_{tot} > \sum M_{gal} + M_{gas}$$

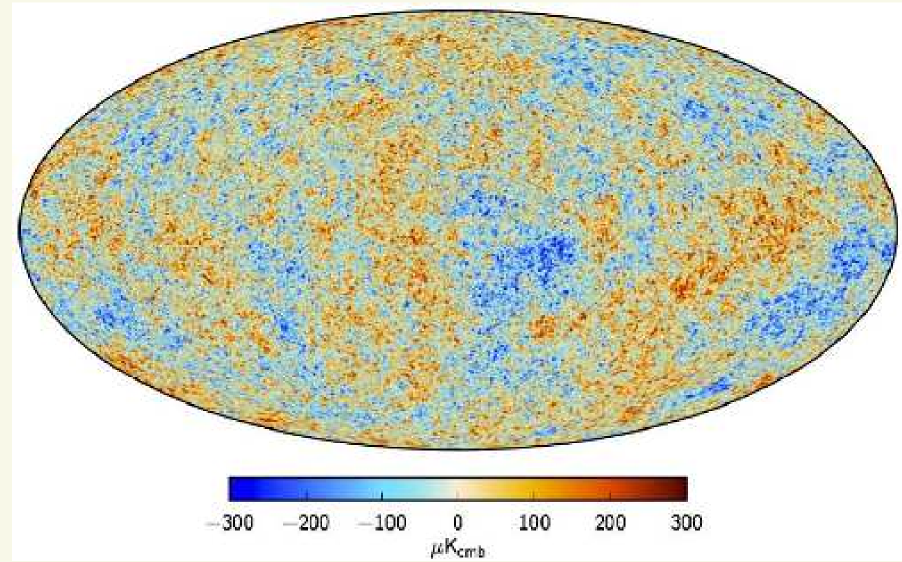


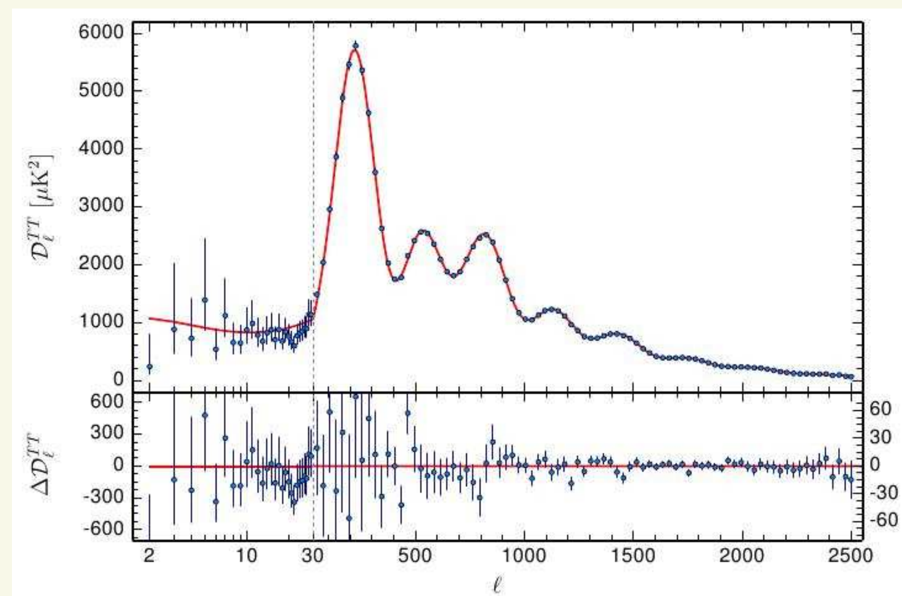




Temperature fluctuations of CMB







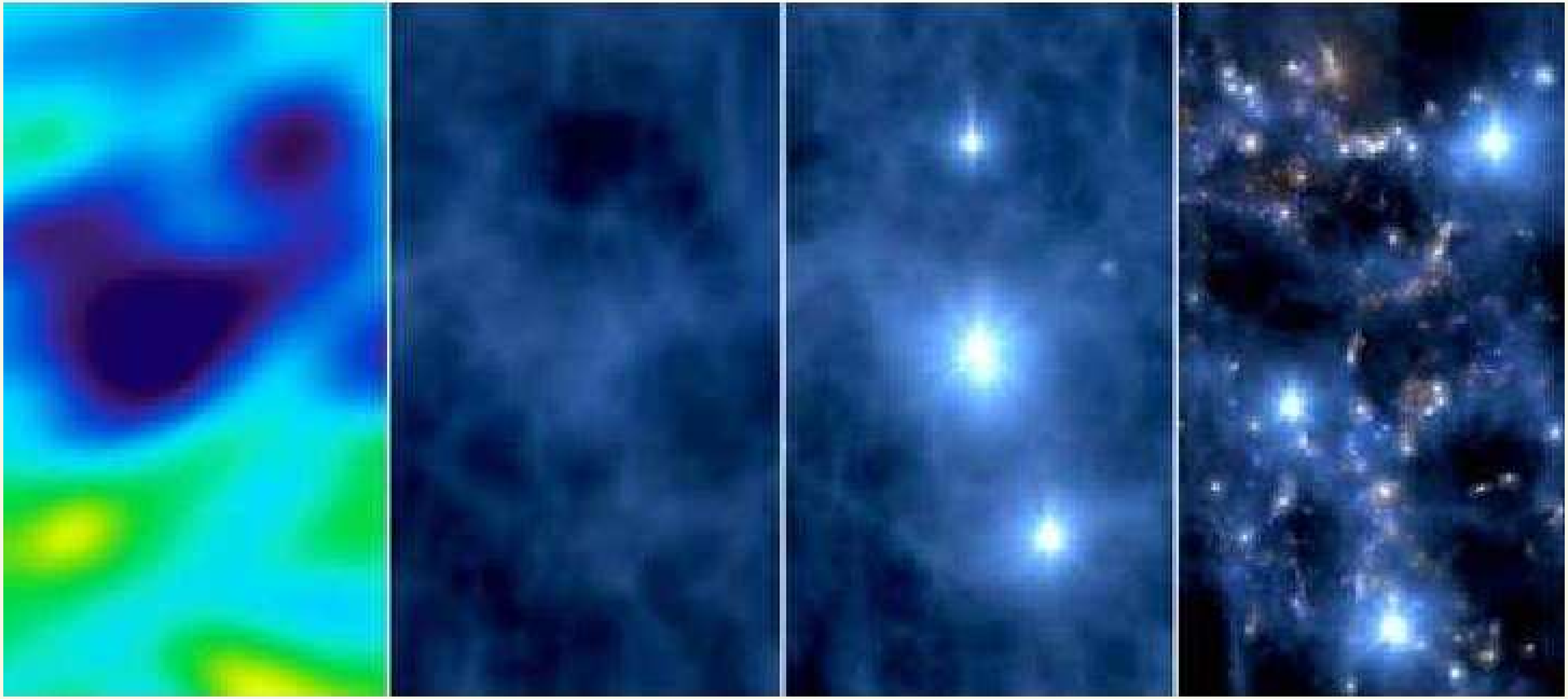
The density parameter of dark matter determined from the Plank2015 data is as follows ($H_0 = 68.7$ km/s/Mpc):

$$\Omega_{dm} = 0.251 \pm 0.004, \quad \Omega_b = 0.0484 \pm 0.001$$

Planck Collaboration, Planck 2015 results.I., A&A 594, A1 (2016)

Large-scale structure formation

$\frac{\Delta T}{T} \approx \frac{\Delta \rho_b}{\rho_b} \sim 10^{-5}$ $\frac{\Delta \rho_m}{\rho_m} \ll 1$

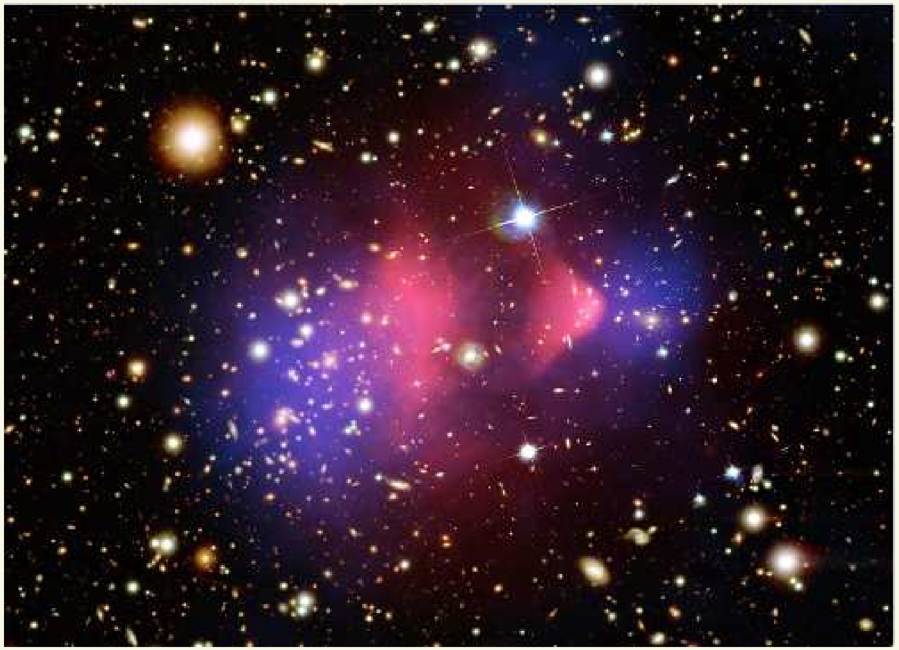


$\frac{\Delta \rho_{dm}}{\rho_{dm}} \sim 10^{-3}$ $\frac{\Delta \rho_m}{\rho_m} \gg 1$

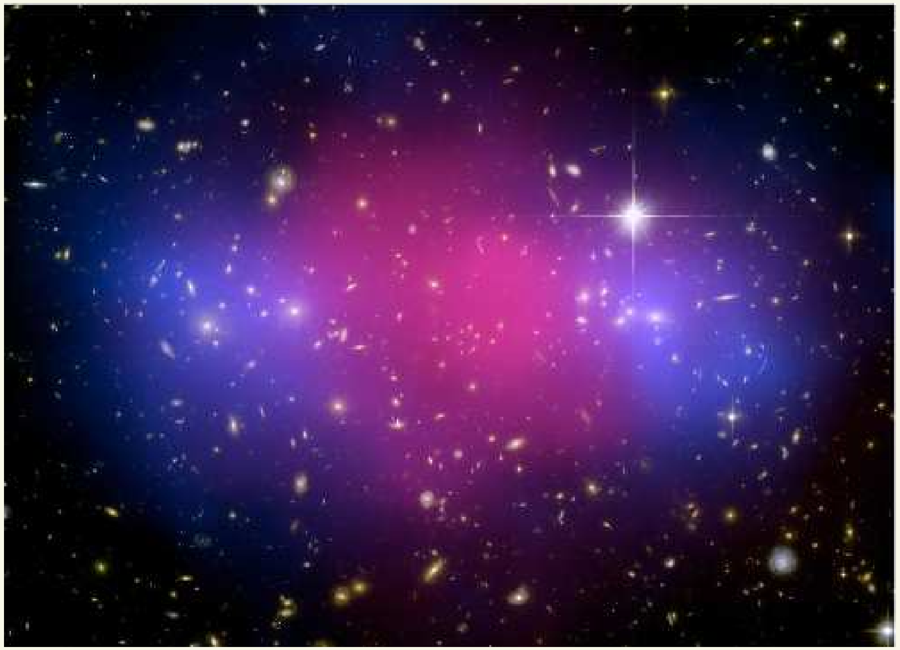
Galaxies, clusters of galaxies, and the observable structure of the universe were formed from the perturbations of density of dark matter generated in the early Universe. *Dark matter is massive non-baryonic electrically neutral particles*.

Gravitational lensing by merging clusters

“Bullet cluster” 1E0657-56



“Baby bullet” MACSJ0025.4-1222



The overlaid pink features show X-ray emission from hot, intra-cluster gas.
The overlaid blue features show a reconstruction of the total mass from measurements of gravitational lensing.

Dark matter consist from collisionless particles!

(Figure credit: Left: X-ray: NASA/CXC/CfA/ M.Markevitch et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/ D.Clowe et al. Optical image: NASA/STScI; Magellan/U.Arizona/D.Clowe et al.; Right: NASA/ESA/M.Bradac et al.; From Massey et al. Rep. Progr. Phys. 73, 086901 (2010)).

Properties of dark matter following from the observations:

1. The Universe contains about five times more dark matter than baryonic matter;
2. Dark matter interacts approximately normally via gravity;
3. Dark matter has a very small electroweak and self-interaction cross section;
4. Dark matter is not in the form of dense, planet-sized bodies;
5. Dark matter is dynamically cold or warm, but not hot.

Definition 2:

- Dark matter is fundamental component of the Universe, consist from collisionless massive particles which are clustered at galactical and large scales.

Dark matter candidates

The candidates to the DM particles roughly can be divided into 3 types:

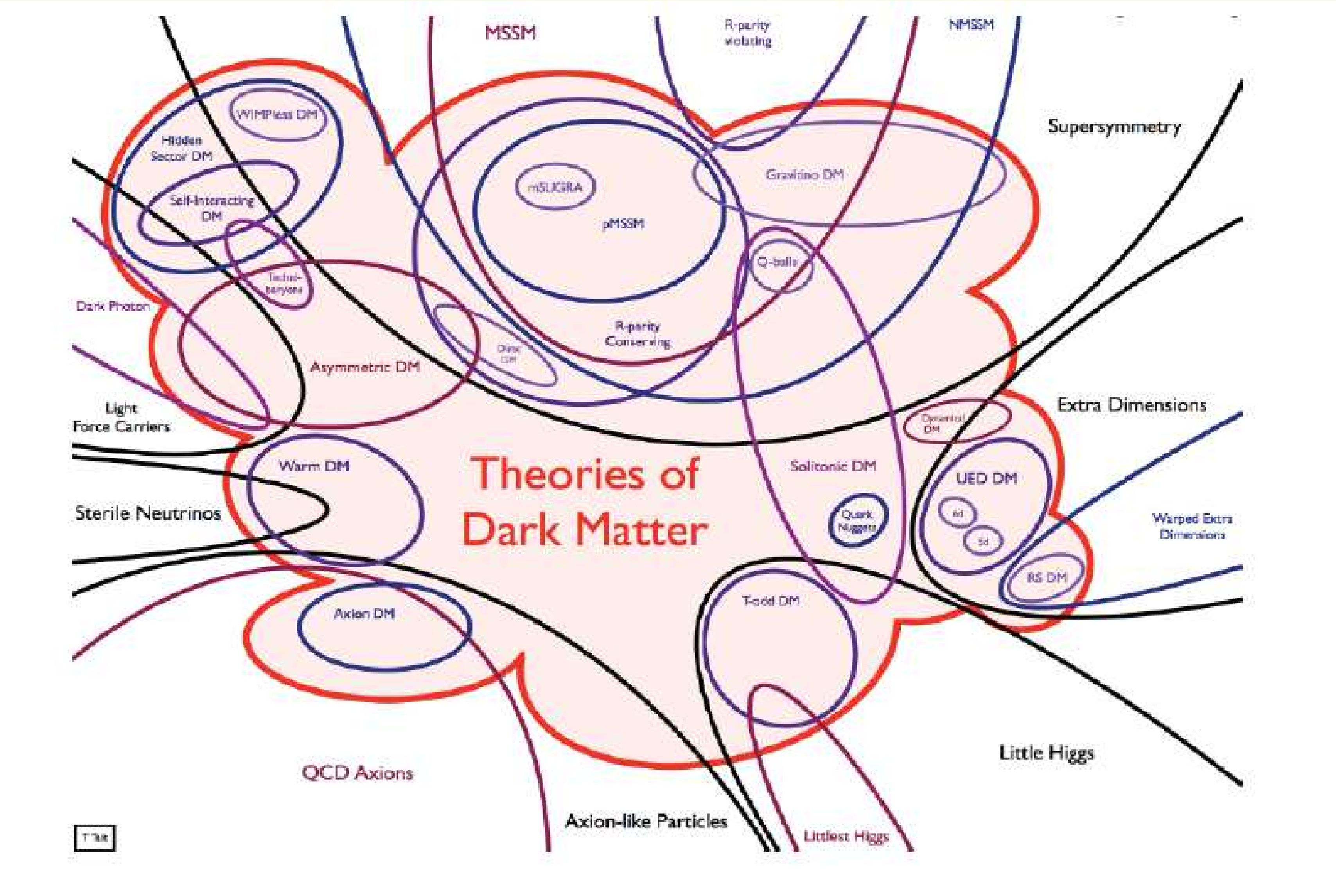
- axions;
- Lightest Supersymmetric Particles;
- others.

Axions are a natural solution of so-called strong CP problem. They are good candidates for CDM. The limitation (window) of the axiom mass following from the general considerations and standard assumptions of $m_a \leq 10^{-2}$ eV is rather narrow. Axions can lead to large amplitudes of iso-curvature perturbations that is why they can not be whole mass of dark matter, but only part of it.

Lightest Supersymmetric Particles (LSP) is the natural consequence of practically all supersymmetric particle theories (SUSY). If PR-parity is preserved then these particles are stable ($PR = (-1)^{3B+L+2C}$). To this class of particles belong the neutralino ($\sim 300 - 400$ GeV), gravitino, axino or s-neutrino. The most likely candidate for WIMP (GeV-TeV) is the **neutralino** with mass of $m_x \approx 100$ GeV.

Dark matter “zoo”

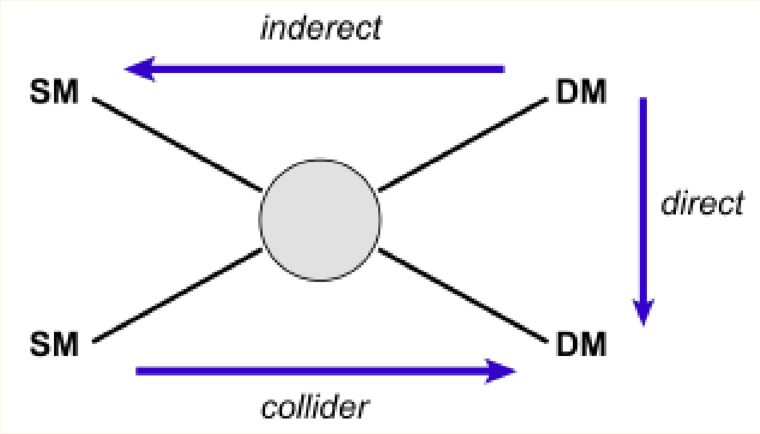
Others are in Dark Matter Zoo:



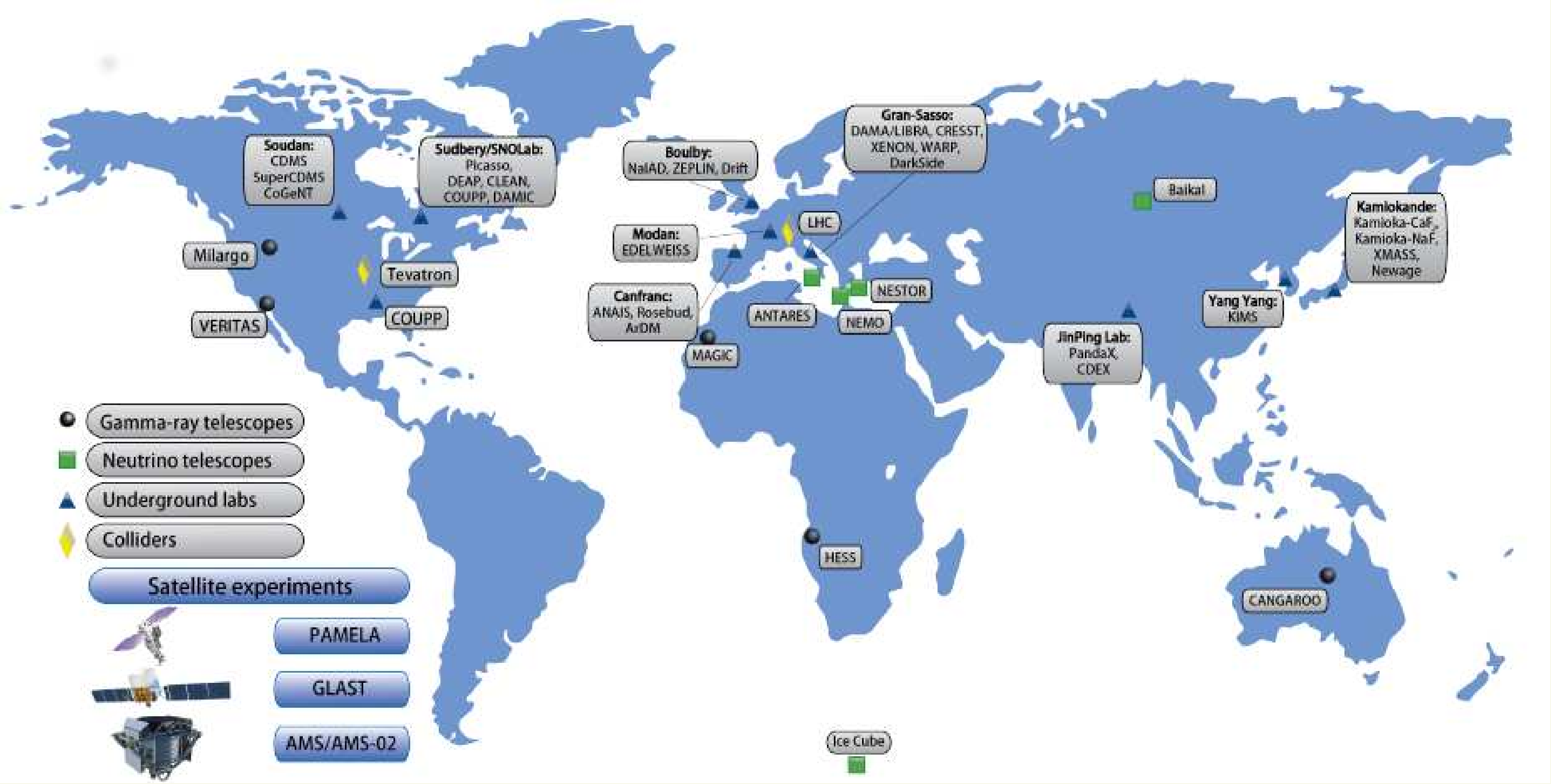
Strategies for search of dark matter particles

The search for dark matter particles takes place in two directions: **direct** detection of the energy of the nucleus recoil during the elastic scattering of the DM particle on the nucleon and **indirect** searches for traces or the effects of annihilation or interaction of DM particles in excess of the background of electromagnetic radiation, neutrinos, or antimatter.

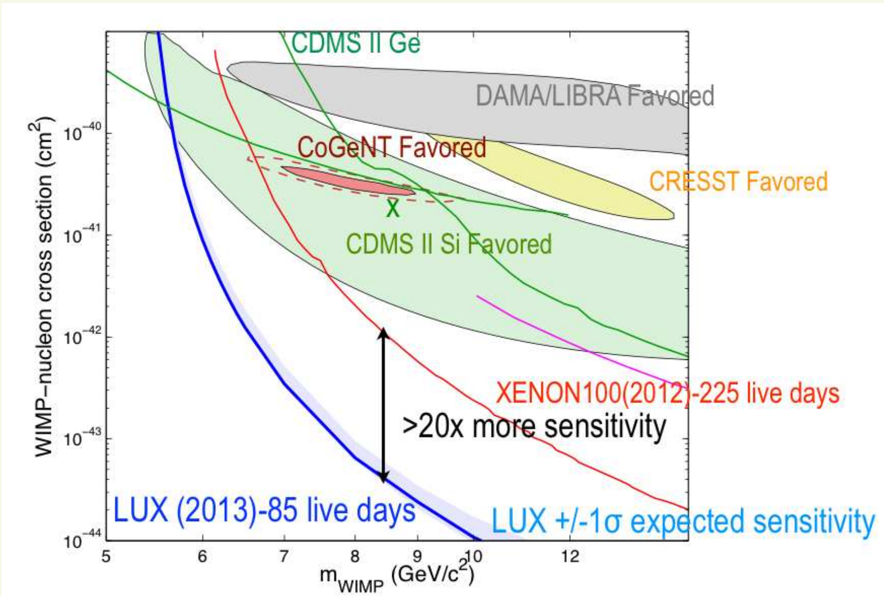
The detection of DM particles in one of the directions will not be sufficient to obtain conclusions about their nature — the astrophysical data will lack information to substantiate fundamental physics (for example, the validity of supersymmetry), and experiments on accelerators can not distinguish stable particles from particles from long time of life or to determine their relic concentration. Only an integrated and complementary approach will help ensure success.

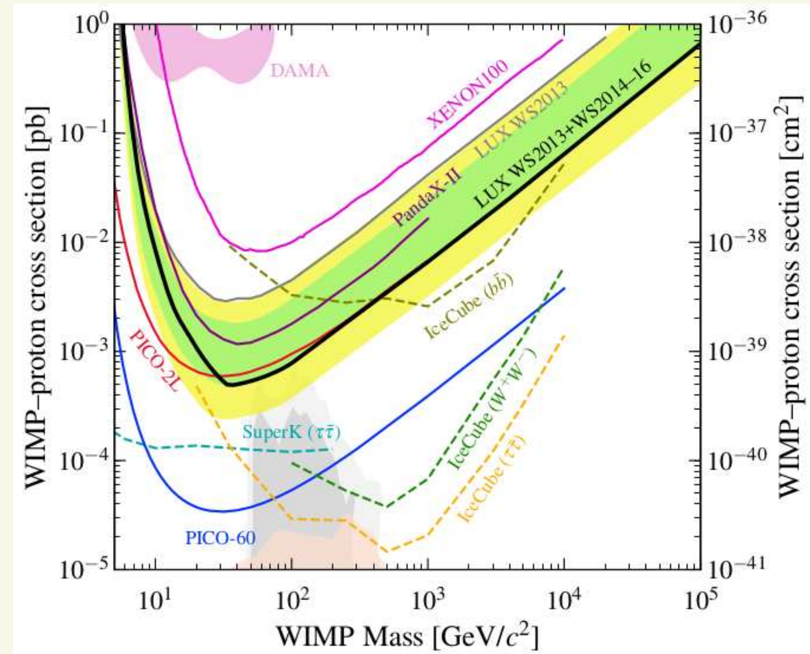


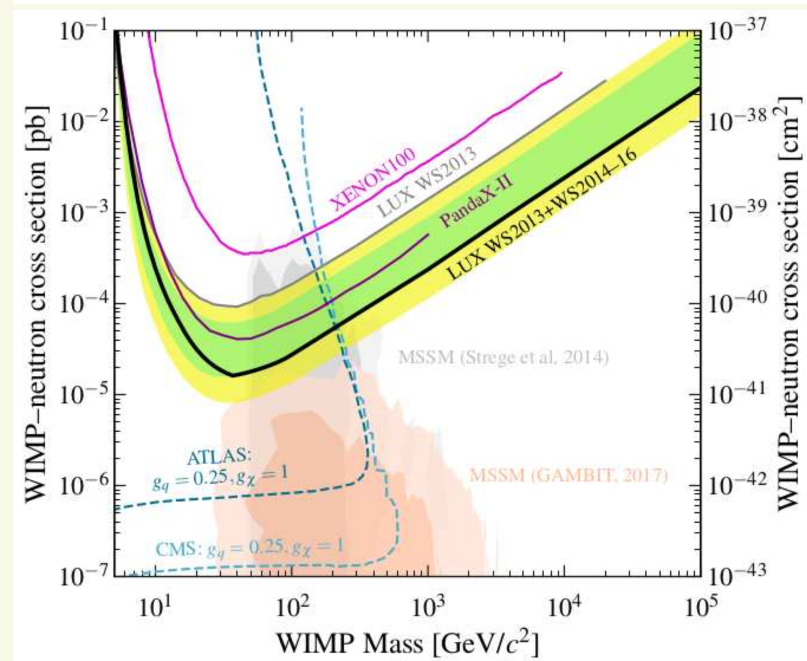
Experiments for search of dark matter particles



Results of experiments for search of dark matter particles







Lux Collaboration, Phys. Rev. Lett. 118, 251302 (2017)

Astrophysical messengers of dark matter

Indirect search signals	Active and planed experiments
Antinuclei	PAMELA, AMS-02, GAPS
Electrons and positrons	PAMELA, AMS-02, Fermi/LAT
Neutrino	Antares, IceCube, Km3NET, HyperK, PINGU
Gamma-rays	Fermi/LAT, MAGIC, HESS, HAWC, CTA, DAMPE, HERD, PANGU
Radio and microwave	

PAMELA: Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (2006); AMS: Alpha Magnetic Spectrometer 2011); GAPS: General AntiParticle Spectrometer (2017-2018); Fermi/LAT: Fermi Gamma-ray Space Large Area Telescope (2008); Antares: Astronomy with a Neutrino Telescope and Abyss environmental RESearch (2008); IceCube: IceCube Neutrino Observatory (2010); Km3NET: Cubic Kilometre Neutrino Telescope (2008); HyperK: Hyper-Kamiokande (2025); PINGU: Precision IceCube Next Generation Upgrade (proposed); MAGIC: Major Atmospheric Gamma Imaging Cherenkov Telescopes (2004); HESS: High Energy Stereoscopic System (2004); HAWC: High Altitude Water Cherenkov Experiment (2014); CTA: Cherenkov Telescope Array(2022); DAMPE: Dark Matter Particle Explorer (2015); HERD: High Energy cosmic Radiation Detection facility (2020); PANGU: PAir-productioN Gamma-ray Unit (proposed)

Fornego N., arXiv:1701.00119

Conclusions I

- Astrophysical and cosmological observations reliably indicate the existence of dark matter with averaged density parameters: $\Omega_{dm} = 0.251 \pm 0.004$. The cosmological model without DM ($\Omega_{dm} = 0$) is excluded at $> 50\sigma$ C.L. !
- The dark matter is massive non-baryonic electrically neutral particles;
- Dark matter has a very small electroweak and self-interaction cross section;
- Dark matter is not in the form of dense, planet-sized bodies;
- Dark matter is dynamically cold or warm, but not hot.
- The DM particles are not detected yet in any experiments, no direct, no indirect.

Definition of dark energy

The physical essence which is causing the accelerated expansion of the Universe which is described in the framework of the general relativity (GR):

$$g(r) = -\frac{4\pi}{3} G(\rho + 3p/c^2) r > 0,$$

$$\rho + 3p/c^2 = \rho_m + 3p_m/c^2 + \rho_X + 3p_X/c^2 < 0,$$

$$p_X < -\frac{1}{3} c^2 (\rho_m + \rho_X) - p_m$$

Component X have been called the dark energy (Huterer D. & Turner M. 1998).

Source of gravitational field: $c^2\rho + 3p = c^2\rho(1 + 3w)$

Inertial mass: $c^2\rho + p = c^2\rho(1 + w)$

Observational evidence for existence of dark energy

- apparent magnitude - redshift for SNe Ia,
- apparent magnitude - redshift for GRBs,
- acoustic peaks in the angular power spectrum of the CMB,
- baryon acoustic oscillations in the spatial distribution of galaxies,
- angular size - redshift for X-ray galaxy clusters,
- formation of the large scale structure of the Universe,
- cross-correlation of ISW effect for CMB and the spatial distribution of galaxies,
- weak gravitational lensing of CMB,
- age of oldest stars in the Galaxy.

Candidates for dark energy

- cosmological constant Λ,
- scalar field (quintessence, phantom, quintom, K-essence, tachyon field, Chaplygin gas, barotropic fluid ...) which almost homogeneously fills the Universe,
- more general theory than GR or another gravitation theory (Brans-Dicke theory, f(R)-gravity, dilaton gravity, MOND...) .

Century of the cosmological constant

Albert Einstein in 1917 has added the cosmological constant into equations of General Relativity in order to obtain the model of eternal static world:

$$G_{\mu\nu} - \lambda g_{\mu\nu} = -\kappa \left(T_{\mu\nu} - \frac{1}{2} g_{\mu\nu} T \right),$$

$$G_{\mu\nu} = -\frac{\partial}{\partial x_\alpha} \left\{ \begin{matrix} \mu & \nu \\ & \alpha \end{matrix} \right\} + \left\{ \begin{matrix} \mu & \alpha \\ & \beta \end{matrix} \right\} \left\{ \begin{matrix} \nu & \beta \\ & \alpha \end{matrix} \right\} + \frac{\partial^2 \log \sqrt{-g}}{\partial x_\mu \partial x_\nu} - \left\{ \begin{matrix} \mu & \nu \\ & \alpha \end{matrix} \right\} \frac{\partial \log \sqrt{-g}}{\partial x_\alpha}$$

He assumed the energy-momentum tensor as for dust-like matter

$$T_{\mu\nu} = diag\{0,\, 0,\, 0, \rho\},$$

and metric of 3-sphere with radius R is in the imaginary Euclidean 4-space:

$$g_{\mu\nu} = -\left(\delta_{\mu\nu} + \frac{x_\mu x_\nu}{R^2 - (x_1^2 + x_2^2 + x_3^2)} \right).$$

GR+λ equations are satisfied if the following equalities holds:

$$\lambda = \frac{\kappa\rho}{2} = \frac{1}{R^2}.$$

Century of the cosmological constant

EPJH celebrated the Λ's anniversary by publications devoted to it

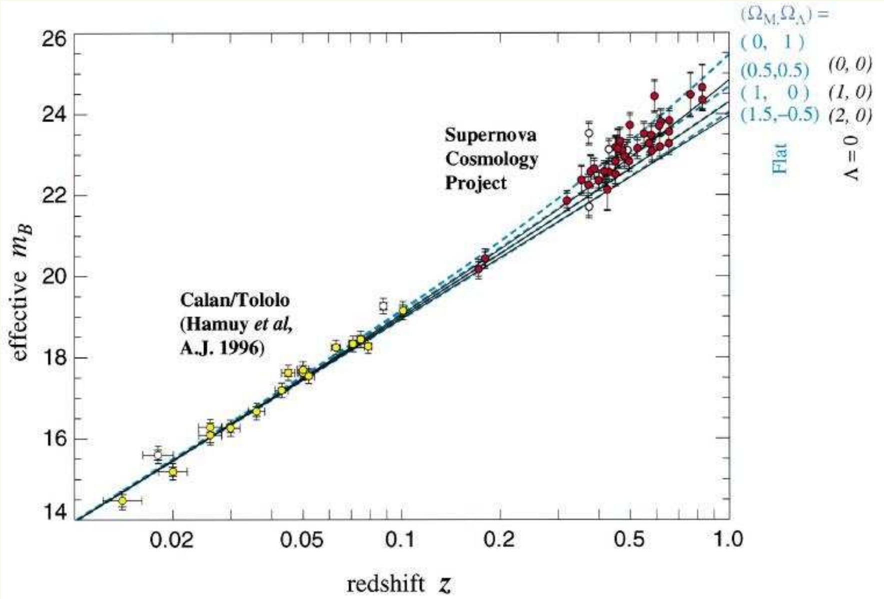
- O'Raifeartaigh, C., O'Keeffe, M., Nahm, W. and Mitton, S. Einstein's 1917 static model of the universe: a centennial review, *The European Physical Journal H* **42**, 431-474 (2017);
- O'Raifeartaigh, C., O'Keeffe, M., Nahm, W. and Mitton, S. One Hundred Years of the Cosmological Constant: from 'Superfluous Stunt' to Dark Energy, *The European Physical Journal H* **43**, 1-45, (2018);
- Novosyadlyj B. Century of Λ, *The European Physical Journal H*, (2018), DOI 10.1140/epjh/e2018-90007-y

They contain the description of

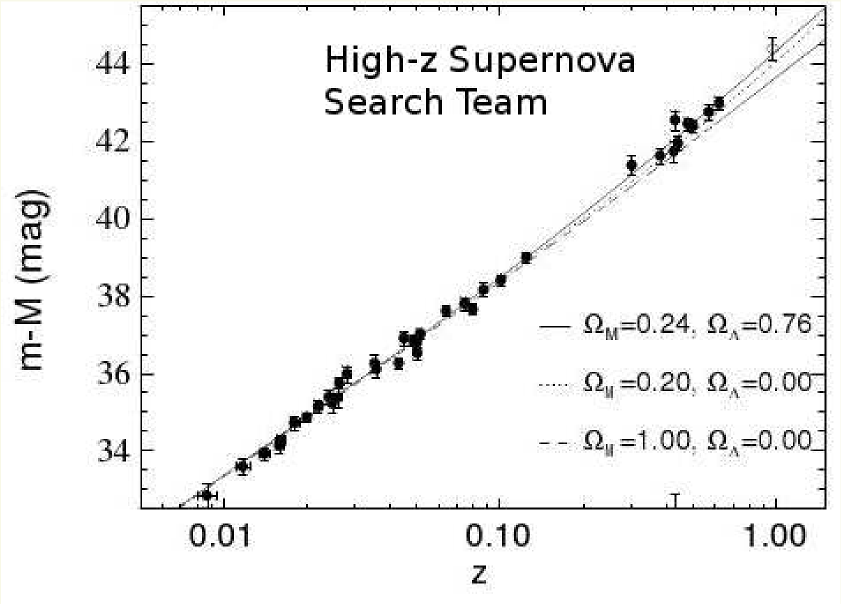
- motivation of its including in general relativity,
- Einstein's denial of it,
- discussions about its necessity, value and physical essence,
- problems of its physical interpretation,
- observational evidences for its existence,
- dark energy as generalisation of λ.

Discovery of the accelerated expansion of the Universe (1998)

SuperNova Cosmology Project



High-z SuperNova Search



$$d_L \equiv \sqrt{\frac{L}{4\pi F}} = \frac{c(1+z)}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m (1+z')^3 + \Omega_\Lambda}}$$

$$(m - M) = 5 \log d_L + 25 + \alpha(s-1) - \beta \mathcal{C},$$

$$z \equiv \Delta\lambda/\lambda = 1/a(t) - 1, \quad a(t) \text{ is scale factor}$$

Discovery of the accelerated expansion of the Universe (1998)

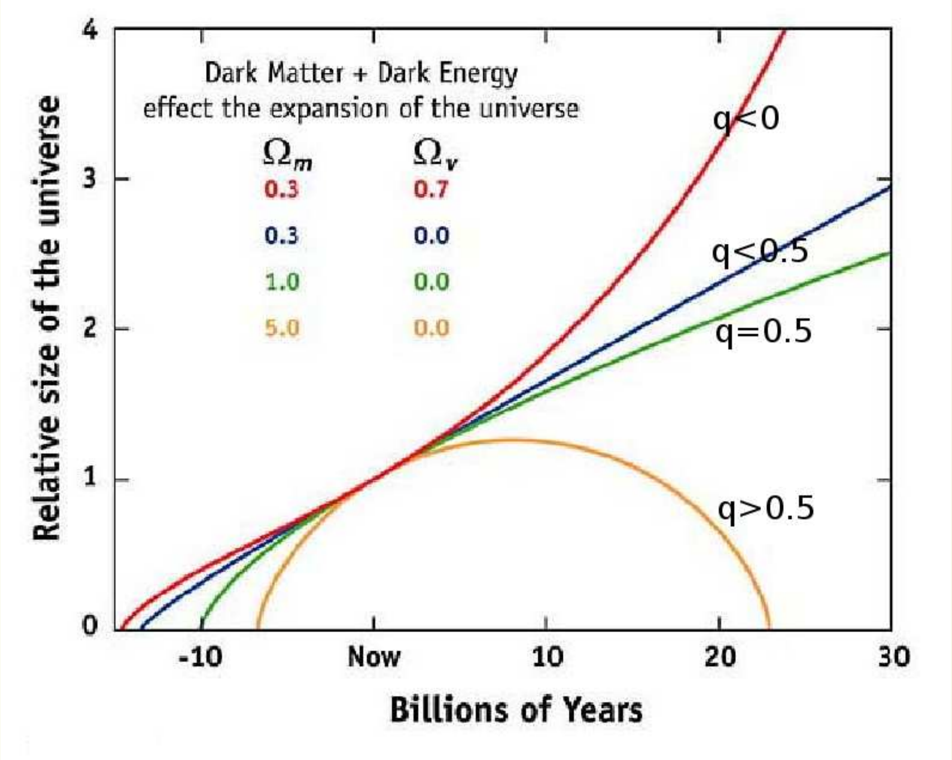
From the measurements of $d_L(z)$ for $\sim$50 SNe Ia by SNCP and HzSNS teams

$$q_0 \equiv -\frac{\ddot{a}}{aH^2} = -0.54 \pm 0.2 \quad (\ddot{a} > 0) \quad \text{at} \quad 3\sigma \quad (\approx 99.7\%) \quad \text{C.L.!}$$

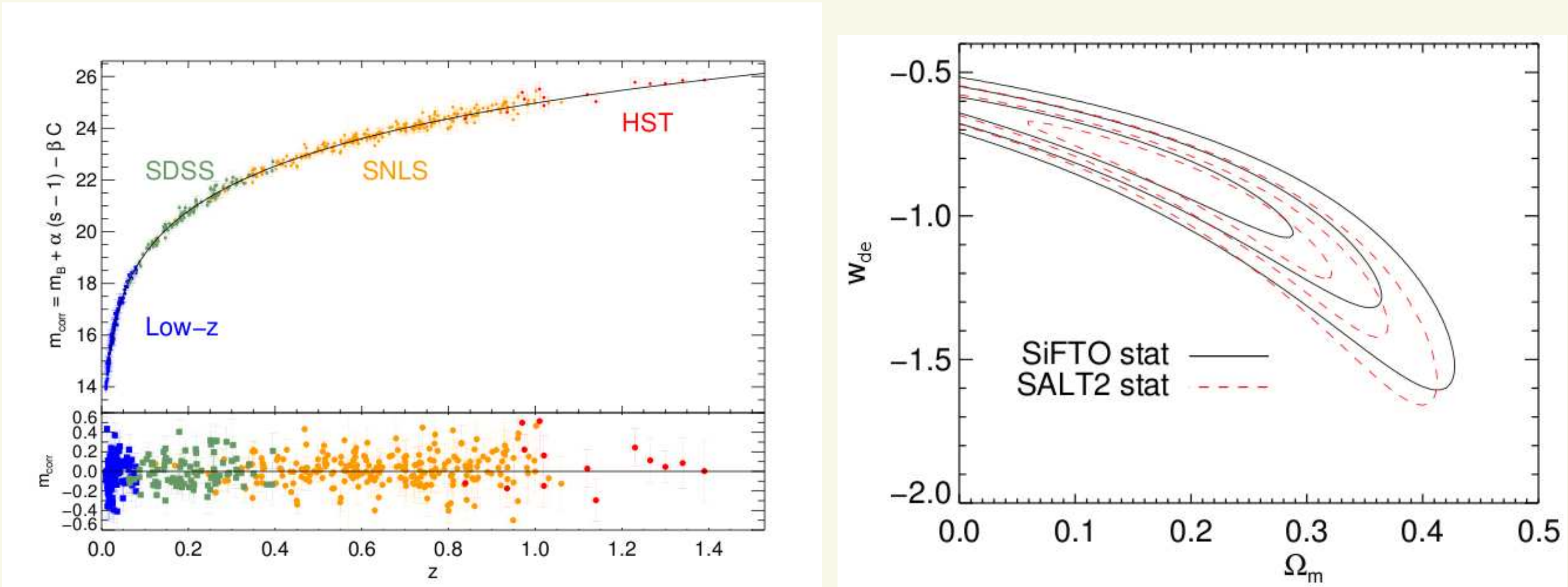
Perlmutter et al. (1999):

$$\Omega_m - 0.75\Omega_\Lambda = -0.25 \pm 0.125 \quad \rightarrow \quad \Omega_\Lambda = 0.71 \pm 0.07$$

Riess et al. (2004): $\Omega_\Lambda = 0.71^{+0.03}_{-0.05}$ (1σ C.L.)



The luminosity distance redshift relation and SNe Ia evidence

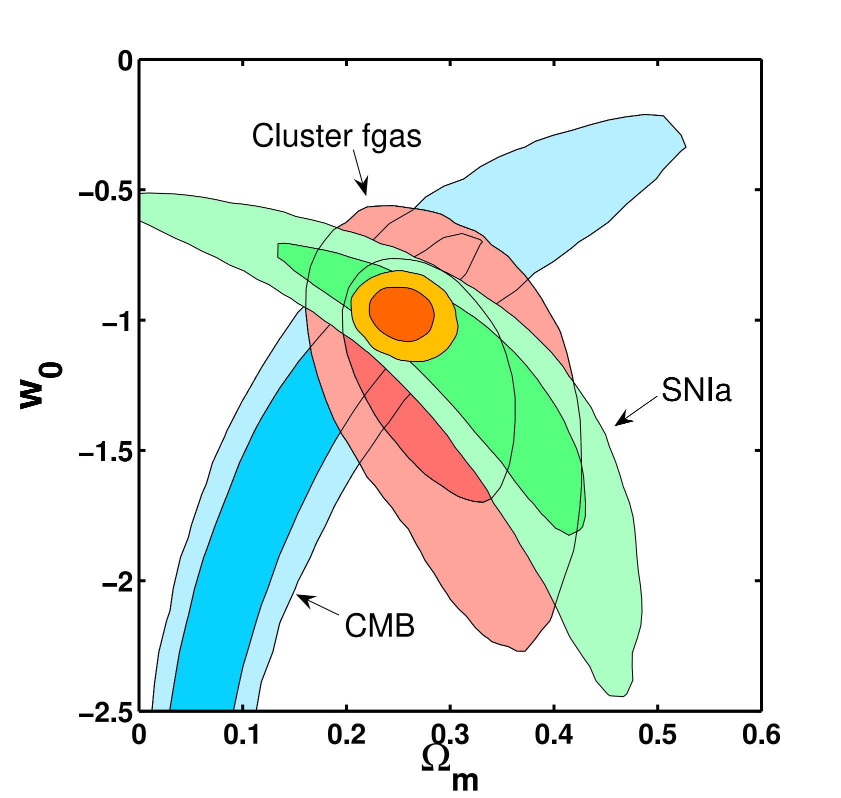


Left panel: the distance moduli $(m - M)(z)$ for 472 selected SNe Ia and residuals from best-fit curve (bottom).

Right panel: 68.3%, 95.4% and 99.7% confidence regions of the $\Omega_m - w_{de}$ plane from SNe Ia alone (SNLS3 compilation with SALT2 and SiFTO fitters) assuming a flat universe and constant dark energy equation of state.

(From Conley et al. (2011)).

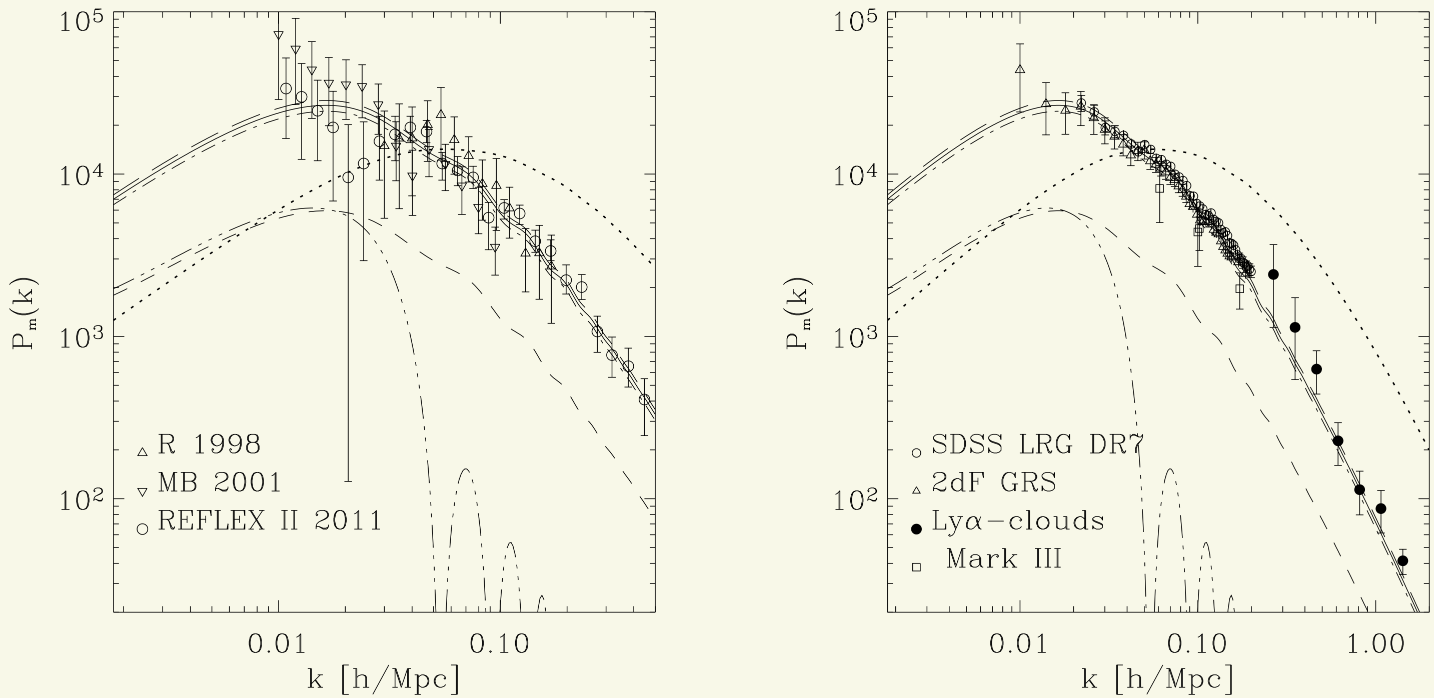
X-ray gas fraction in clusters



The 68.3% and 95.4% confidence constraints in the Ω_m-w_{de} plane obtained from the analysis of the Chandra f_{gas} data (red contours). Also the independent results obtained from CMB data (blue contours) and SNIa data (green contours) are shown. The inner, orange contours show the constraint obtained from all three data sets without any external priors.

(From Allen et al. (2008)).

Large-scale structure of the Universe



The linear power spectra in FMD, OMD, OMDb and ΛCDM models, which have been normalized at decoupling epoch to the amplitude of the angular power spectrum of CMB temperature fluctuations obtained in the COBE experiment, versus measured ones from the Abell/ACO and X-ray galaxy cluster catalogs (left panel), galaxy ones, peculiar velocity field catalogs and Lyα-clouds (right panel).

(From Dark energy: observational evidences and theoretical models (2013)).

Key experiments of 1998-2011 years

1998 – HzSNST (SN Ia, *Riess et al.*)

1998 – SNCP (SN Ia, *Perlmutter et al.*)

1999 – Toco (CMB, *Miller et al.*)

2000 – Boomerang (CMB, *Bernardis et al.*)

2000 – MAXIMA (CMB, *Hanany et al.*)

2001 – DASI (CMB, *Halverson et al.*)

2002 – ACBAR (CMB, *Kuo et al.*)

2003 – WMAP-1 (CMB, *Spergel et al.*)

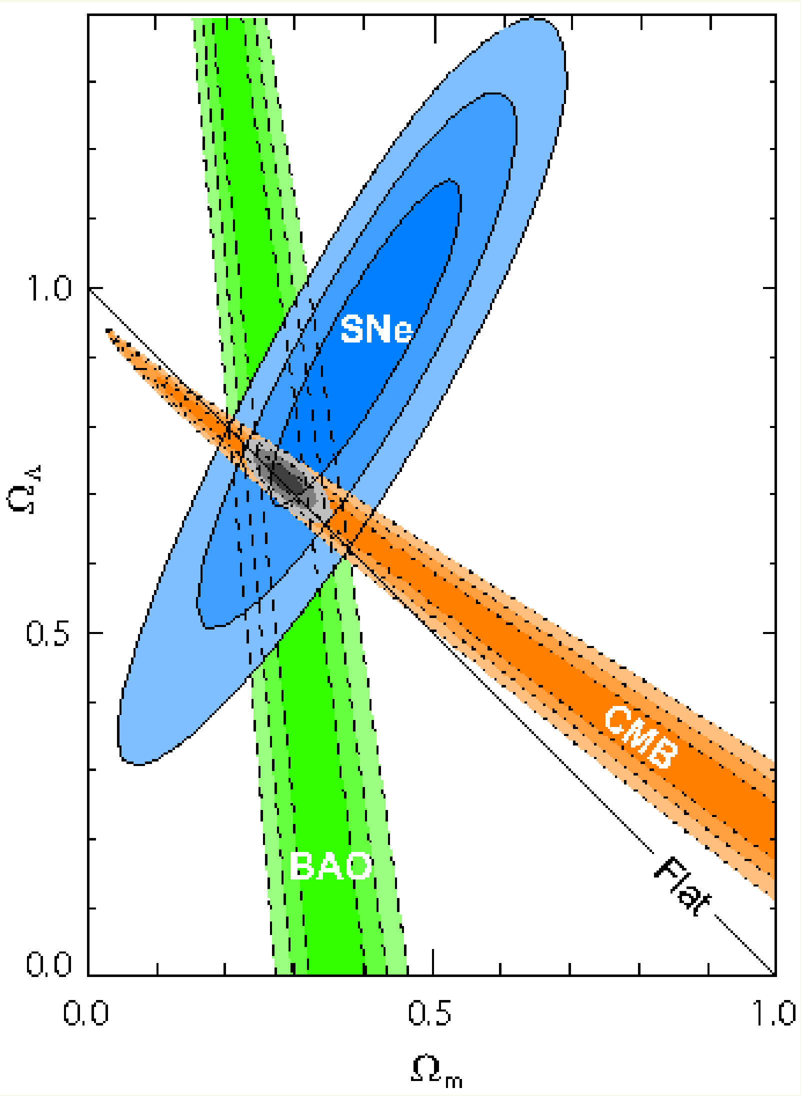
2005 – BAO (SDSS, *Eisenstein et al.*)

2006 – WMAP-3 (CMB, *Spergel et al.*)

2008 – WMAP-5 (CMB, *Komatsu et al.*)

2011 – WMAP-7 (CMB, *Komatsu et al.*)

2011 – ACT (CMB, *Dunkley et al.*)



Nobel Prize in Physics 2011

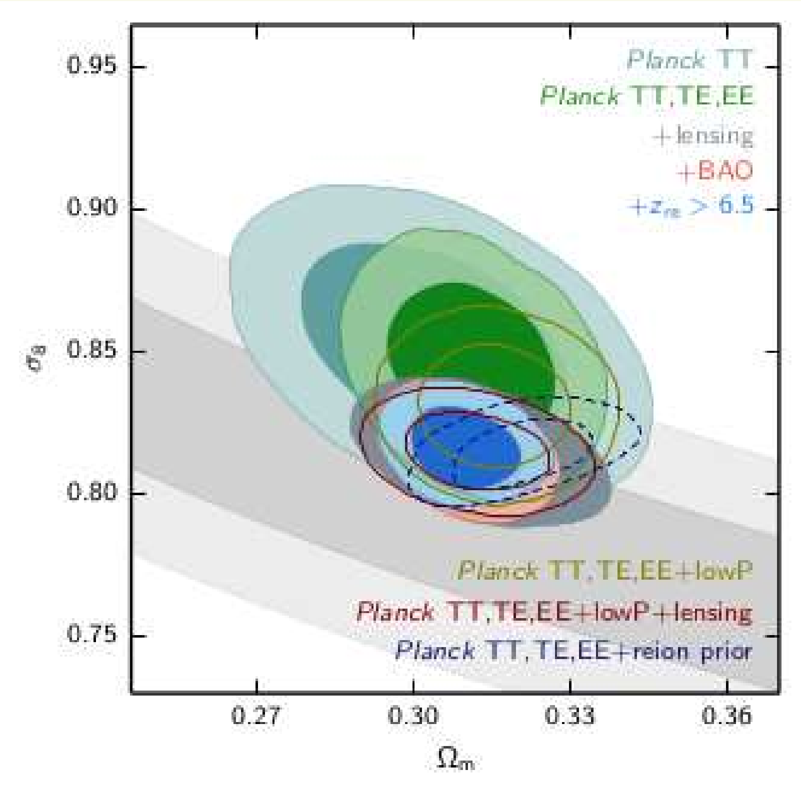
"For the discovery of the accelerating expansion of the Universe through observations of distant supernovae".

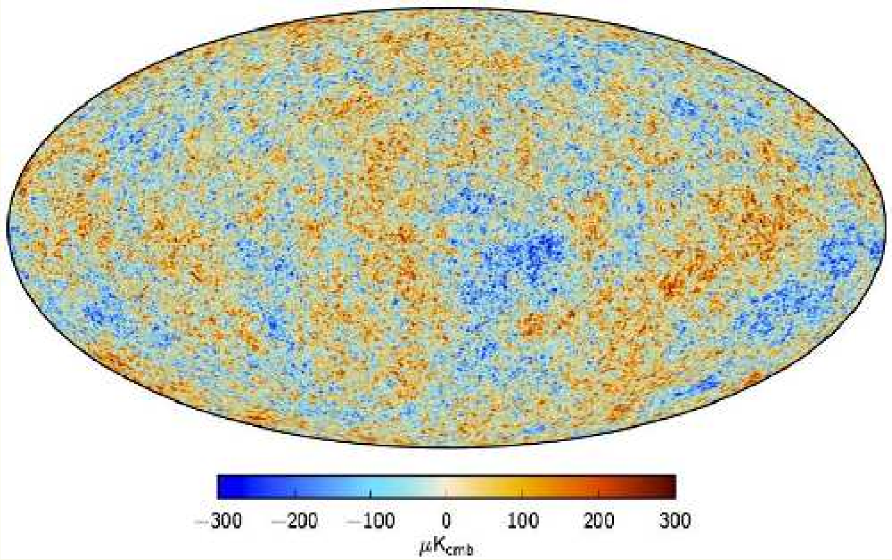
Perlmutter S. (team SNCP), Nature, **391**, 51 (1998)
Perlmutter S. (team SNCP), ApJ. **517**, 565 (1999)

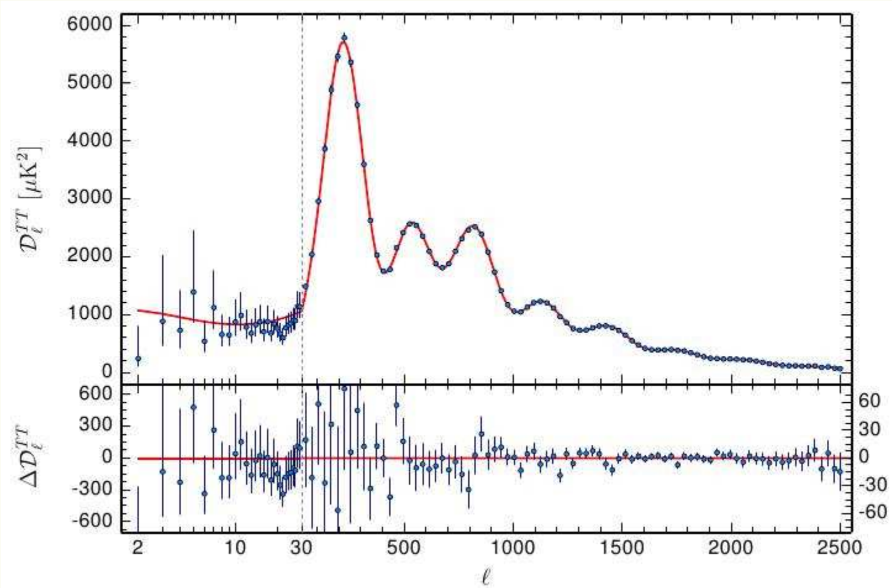
Riess A. G. (HzSNS), AJ. 1**16**, 1009 (1998)

Schmidt B. P. (HzSNS), ApJ. **507**, 46 (1998)

Temperature fluctuations of CMB







The density parameter of dark matter determined from the Plank2015 data is as follows ($H_0 = 68.7$ km/s/Mpc):

$$\Omega_{dm} = 0.251 \pm 0.004, \quad \Omega_b = 0.0484 \pm 0.001$$

Planck Collaboration, Planck 2015 results.I., A&A 594, A1 (2016)

The Planck legacy release 2018

Set of papers (18.07.2018):

I. Overview, and cosmological legacy of Planck.

II. LFI data processing.

III. HFI data processing.

IV. CMB and foreground extraction.

V. Power spectra and likelihoods.

VI. Cosmological parameters.

VII. Isotropy and statistics.

VIII. Gravitational lensing.

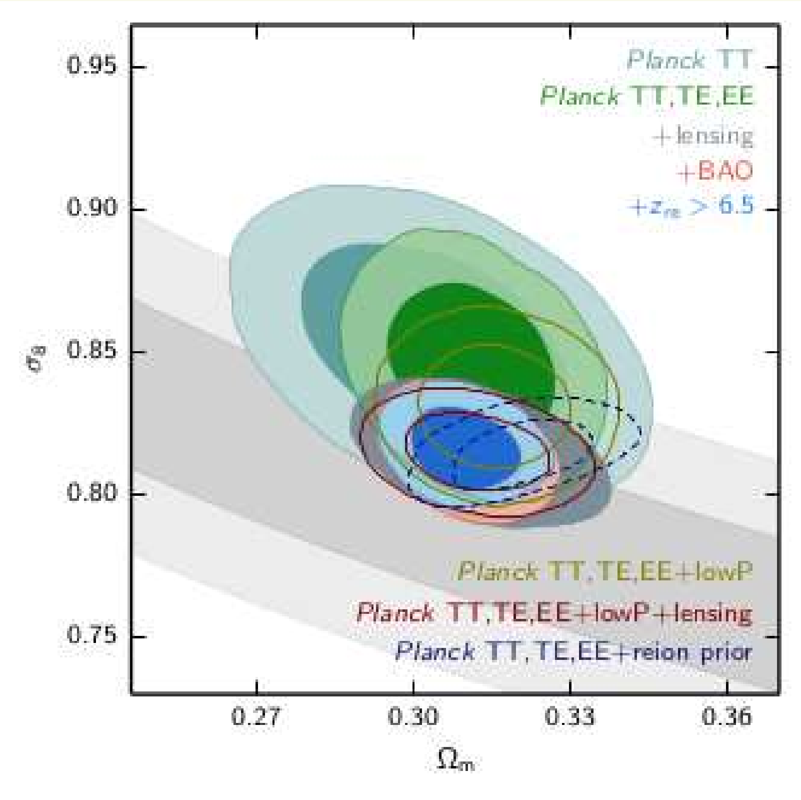
IX. Constraints on primordial non-Gaussianity.

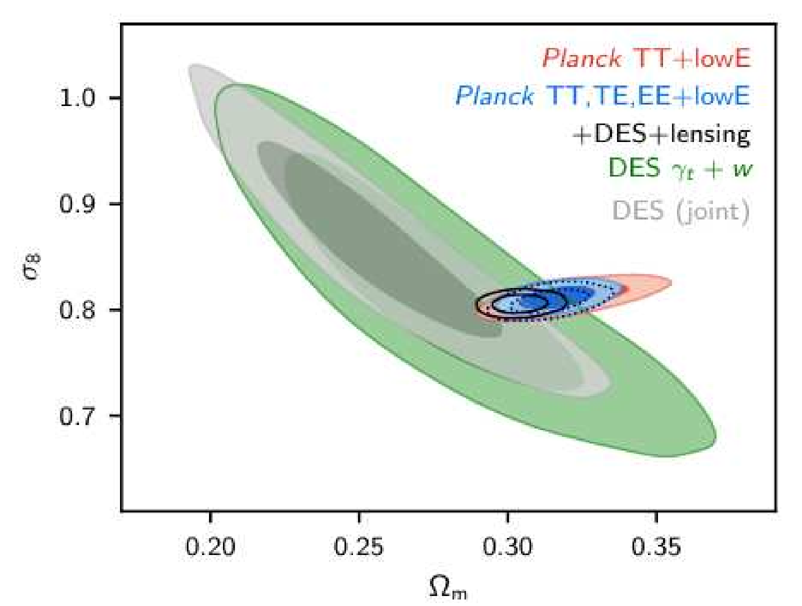
X. Constraints on inflation.

XI. Polarized dust foregrounds.

XII. Galactic astrophysics from polarization.

The Planck legacy release 2018





$$\Omega_{dm} = 0.251 \pm 0.004,$$

$$\Omega_b = 0.0484 \pm 0.001$$

Planck 2015 results.I., A&A 594, A1 (2016)

$$\Omega_{dm} = 0.261 \pm 0.002,$$

$$\Omega_b = 0.0489 \pm 0.0003$$

Planck 2018 results.VI., arXiv:1807.06209 (2018)

Cosmological parameters from Planck 2018 (18.07.2018)

Parameters	Planck alone	Planck +BAO
$\Omega_{\rm b}h^2$	0.02237$\pm$ 0.00015	0.02242$\pm$ 0.00014
$\Omega_{\rm dm}h^2$	0.1200$\pm$ 0.0012	0.11933$\pm$ 0.00091
$100\theta_{\rm MC}$	1.04092$\pm$ 0.00031	1.04101$\pm$ 0.00029
τ	0.0544$\pm$ 0.0073	0.0561$\pm$ 0.0071
$\ln(10^{10}A_{\rm s})$	3.044$\pm$ 0.014	3.047$\pm$ 0.014
$n_{\rm s}$	0.9649$\pm$ 0.0042	0.9665$\pm$ 0.0038
H_0	67.36$\pm$ 0.54	67.66$\pm$ 0.42
Ω_Λ	0.6847$\pm$ 0.0073	0.6889$\pm$ 0.0056
$\Omega_{\rm m}$	0.3153$\pm$ 0.0073	0.3111$\pm$ 0.0056
σ_8	0.8111$\pm$ 0.0060	0.8102$\pm$ 0.0060
$z_{\rm re}$	7.67$\pm$0.73	7.82$\pm$0.71
Age[Gyr]	13.797$\pm$ 0.023	13.787$\pm$ 0.020

Planck Collaboration, Planck 2018 results.I., arXiv:1807.06205 (2018)

Problems of Λ

- Is Λ the second gravitational constant?
  If "yes", then what means that value of $\Lambda = 3H_0^2\Omega_\Lambda \propto 10^{-56}\,\mathrm{cm}^{-2}$ (or $\propto 10^{-122}$ against $G = 1$ in the Planck units)?

- Is Λ a measure of vacuum energy (Zeldovich, 1968)?

  If "yes", then why $\rho_\Lambda = 3H_0^2\Omega_\Lambda/8\pi G \propto 10^{-29}\,\mathrm{g/cm^3}$ is 10^{-54} orders of magnitude smaller than the modern prediction considering the vacuum energy of all known scalar and vector fields (Martin, 2012)?

- Fine-tunning problem: at the end of inflations (reheating) $\rho_\Lambda/\rho_{m+\gamma} \sim 10^{-96}$. Why? Current physics does not explain...

- Coincidence problem: at the current epoch $\rho_\Lambda \approx \rho_m$, at the epoch of reionization $\rho_\Lambda \approx \rho_\gamma$ (arXiv:1707.03388). Why? Current physics does not explain...

Anthropic principle (Weinberg, 1987) as solution: if the cosmological constant were only one order of magnitude larger than its observed value, the universe would suffer catastrophic inflation, which would preclude the formation of stars, and hence life.

Models of dark energy

Dynamical DE

$\delta\rho_{de} \neq 0, \quad V_{de} \neq 0$

quintessence

phantom

scalar fields

tachyon fields

quintom

Chaplygin gas

K-essence

.

.

non-minimally coupled

Non-dynamical DE

$\delta\rho_{de} = 0, \quad V_{de} = 0$

Λ-model

vacuum fields

f(R)-gravity

MOND

holographic dark energy

.

.

.

Scalar field $\Longleftrightarrow$ dynamical fluid

$$\mathcal{L}(X, U(\phi)), \qquad X \equiv \frac{1}{2}\phi_{;i}\phi^{;i}$$

$$T_{ij} = \mathcal{L}_{,X}\phi_{,i}\phi_{,j} - g_{ij}\mathcal{L}$$

$$T_{ij} = (\rho_{de} + p_{de})u_i u_j - p_{de} g_{ij}$$

$$p_{de} = \mathcal{L} \qquad \rho_{de} = 2X\mathcal{L}_{,X} - \mathcal{L}$$

$$w_{de} \equiv \frac{p_{de}}{\rho_{de}} = \frac{\mathcal{L}}{2X\mathcal{L}_{,X} - \mathcal{L}} < -\frac{1}{3} \qquad c_s^2 \equiv \frac{\delta p_{de}}{\delta \rho_{de}} = \frac{\mathcal{L}_{,X}}{\mathcal{L}_{,X} + 2X\mathcal{L}_{,XX}} \geq 0$$

$$\Omega_{de} \equiv \frac{\rho_{de}}{\rho_{cr}} = \frac{8\pi G}{3H_0^2}\rho_{de} \qquad c_a^2 \equiv \frac{\dot{p}_{de}}{\dot{\rho}_{de}}$$

Scalar field as dark energy: a few examples of Lagrangians

Lagrangian	EoS	Effect. sound speed	References
$\mathcal{L} = \frac{1}{2}\phi_{;i}\phi^{;i} - V(\phi)$	$w_{de} = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)}$	$c_s^2 = 1$	[1-6]
$\mathcal{L} = -\frac{1}{2}\phi_{;i}\phi^{;i} - V(\phi)$	$w_{de} = \frac{-\dot{\phi}^2 - 2V(\phi)}{-\dot{\phi}^2 + 2V(\phi)}$	$c_s^2 = 1$	[7-13]
$\mathcal{L} = -V(\phi)\sqrt{1 - \phi_{;i}\phi^{;i}}$	$w_{de} = \dot{\phi}^2 - 1$	$c_s^2 = -w_{de}$	[14-21]
$\mathcal{L} = -V(\phi)\sqrt{1 + \phi_{;i}\phi^{;i}}$	$w_{de} = -\dot{\phi}^2 - 1$	$c_s^2 = -w_{de}$	[22]
$\mathcal{L} = F(X) - V(\phi)$	$w_{de} = \frac{F - V}{2XF' - F + V}$	$c_s^2 = \frac{F'}{F' + 2XF''}$	[23]
$\mathcal{L}(\phi, X, U(\phi))$	$w_{de} = \frac{\mathcal{L}}{2X\mathcal{L}_{,X} - \mathcal{L}}$	$c_s^2 = \frac{\mathcal{L}_{,X}}{\mathcal{L}_{,X} + 2X\mathcal{L}_{,XX}}$	[24-30]

[1] Ratra & Pebbles (1988); [2] Wetterich (1988); [3] Peebles & Ratra (1988); [4] Turner & White (1997); [5] Caldwell et al. (1998); [6] Zlatev et al. (1999); [7] Caldwell (2002); [8] Caldwell et al. (2003); [9] Fabris & Concalves (2006); [10] Kujat et al. (2006); [11] Lima & Pereira (2008); [12] Schrerrer & Sen (2008); [13] Creminalli et al. (2009); [14] Padmanabhan (2002); [15] Gibbons (2002); [16] Frolov et al. (2002); [17] Bagla et al. (2003); [18] Abramo & Finelli (2003); [19] Gorini et al. (2004); [20] Sen (2005); [21] Calcagni & Liddle (2006); [22] Babichev et al. (2006, 2008); [23] Haq Ansari & Unnikrishnan (2011); [24] Armendariz-Picon et al. (2001); [25] Malquarti et al. (2003); [26] Malquarti et al. (2003); [27] de Putter & Linder (2007); [28] Aguirregabiria et al. (2005); [29] Bilic (2008); [30] Bilic et al. (2009).

Complete references are in the book at arXiv:1502.04177

Scalar field as dark energy: a few examples of potentials

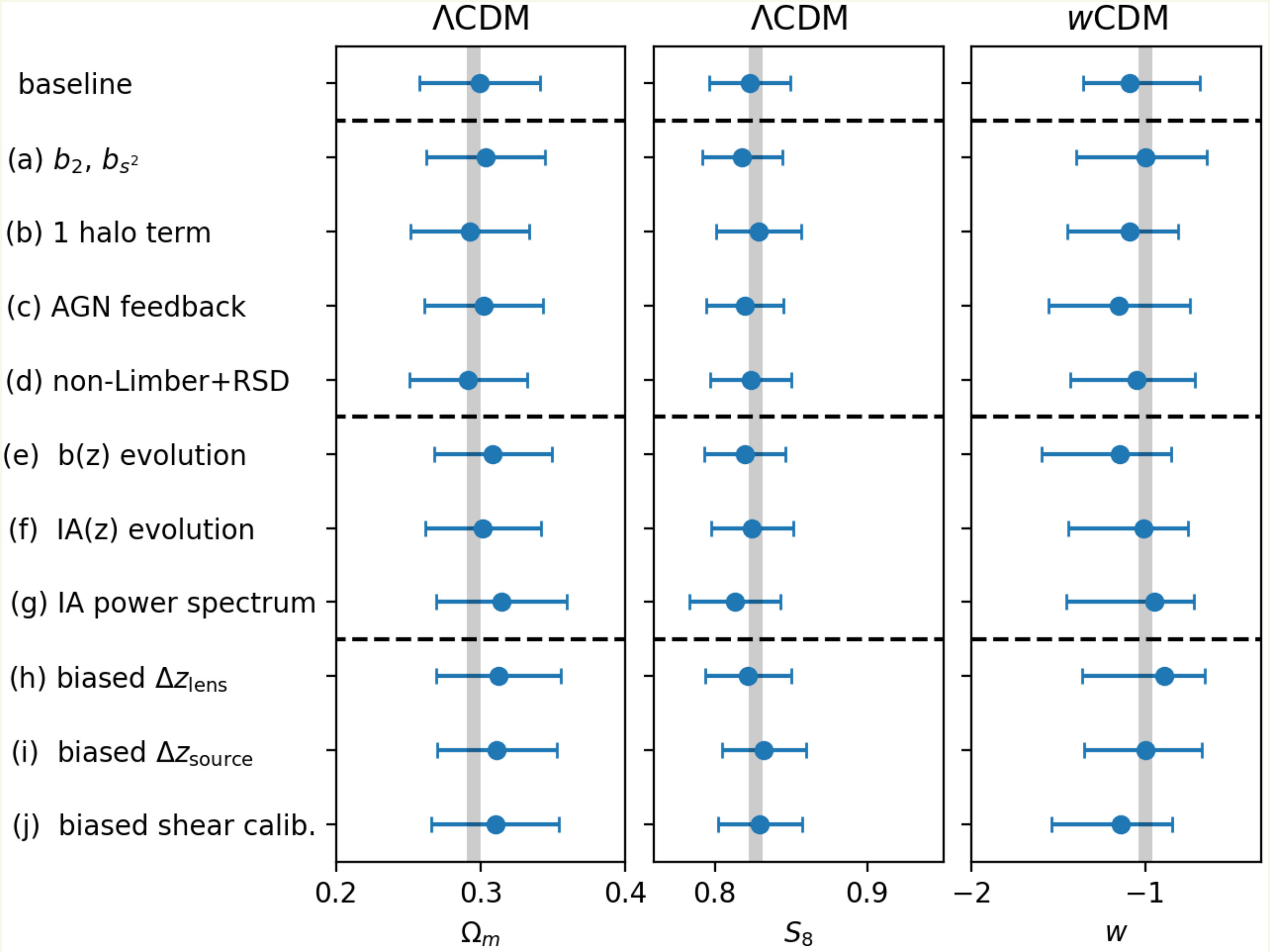
Potential	Where did it come from; References
$V = M^{4-n}\phi^n$, $n > 0$	particle physics; Linde (1990)
$V = M^{4+n}\phi^{-n}$, $n > 0$	SUSY; Binetruy (1998); Masiero et al. (1999); SG; Brax & Martin (1999); Copeland et al. (2000);
$V = \Sigma_n a_n \phi^n$	polynomial potential
$V = M^4 \exp\left(-\beta\phi/M_p\right)$	moduli; Ferreira & Joyce (1998); dilaton field; Barreiro et al. (2000);
$V = M^4 \exp\left(M_p/\phi\right)$	exponential tracker fied
$V = M^{4+n}\phi^{-n}\exp\left(\alpha\phi^2/M_p^2\right)$	SUSY; Binetruy (1998); Masiero et al. (1999); SG; Brax & Martin (1999); Copeland et al. (2000);
$V = M^4\cos^2\left(\phi/2f\right)$	pseudo-Nambu-Goldstone boson; Frieman et al. (1995)

Scalar field as dark energy: examples of EoS parametrization

EoS parametrization	
$w_{de} = const$	1-parametric
$w_{de} = w_0 + w_a \frac{z}{z+1} = w_0 + w_a(1-a)$	2-parametric CPL; Chevallier & Polarski (2001); Linder (2003);
$w_{de} = w_0 + w_a \frac{z}{(z+1)^2}$	2-parametric; Bagla et al. (2003);
$w_{de} = w_0 + w_a \frac{z(z+1)}{z^2+1}$	2-parametric; Barboza & Alcaniz (2008);
$w_{de} = \frac{w_0}{w_0+(1+w_0)(z+1)^{3(1+w_a)}}$	2-parametric GCG; Thakur et al. (2012);
$w_{de} = w_0 + w_a \left(\frac{z}{z+1}\right)^7$	2-parametric; Pantazis et al. (2016);
$w_{de} = \frac{z_{tr}+1}{z+z_{tr}+2}\left[w_0 + w_a \frac{z}{z+1}\right] - \frac{z+1}{z+z_{tr}+2}$	3-parametric; Komatsu et al. (2009);
$w_{de} = w_0 + \frac{(w_f - w_0)}{1+\exp(\frac{z-z_{tr}}{\Delta})}$	4-parametric; Bassett et al. (2002);

Current determination of dark energy parameters

Observational data: cosmic shear, galaxy-galaxy lensing, galaxy clustering

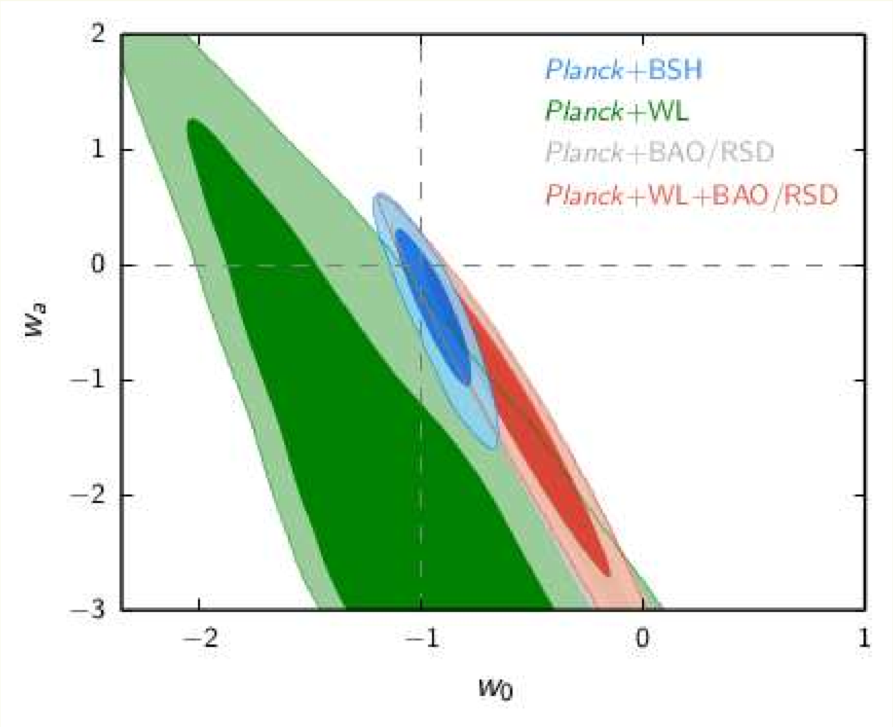


$$S_8 = \sigma_8 \sqrt{\Omega_m / 0.3}$$

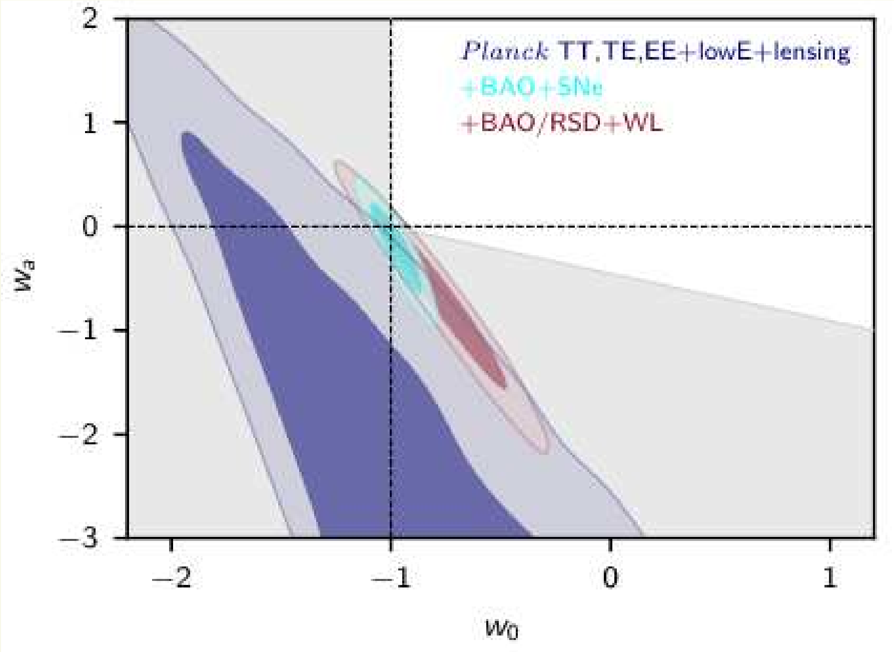
[Dark Energy Survey Collaboration, arXiv:1706.09359 (2017)]

Planck 2018 + other data

Planck 2016



Planck 2018



$$\Omega_{de} = 0.689 \pm 0.006, \quad w_0 = -0.961 \pm 0.077, \quad w_a = -0.28^{+0.31}_{-0.27};$$

$$w_0 = -1.028 \pm 0.032, \quad w_a = 0.$$

Planck Collaboration, Planck 2018 results.VI., arXiv:1807.06209 (2018)

Dark energy and expansion of the Universe

$$\text{Einstein equations :} \quad R_{ij} - \frac{1}{2} g_{ij} R = \kappa \left(T_{ij}^{(r)} + T_{ij}^{(m)} + T_{ij}^{(de)} \right)$$

$$\text{Friedmann metric :} \quad ds^2 = g_{ij} dx^i dx^j = c^2 dt^2 - a^2(t) \delta_{\alpha\beta} dx^\alpha dx^\beta$$

$$\text{EoS equation :} \quad p = w c^2 \rho \quad (w_r = \frac{1}{3}, \quad w_m = 0, \quad w_{de} < -\frac{1}{3})$$

$$T^{k\,(r)}_{i;k} = 0 \quad \rightarrow \quad \dot{\rho}_r = -4 \frac{\dot{a}}{a} \rho_r \quad \rightarrow \quad \rho_r(t) = \rho_r^0 a^{-4}$$

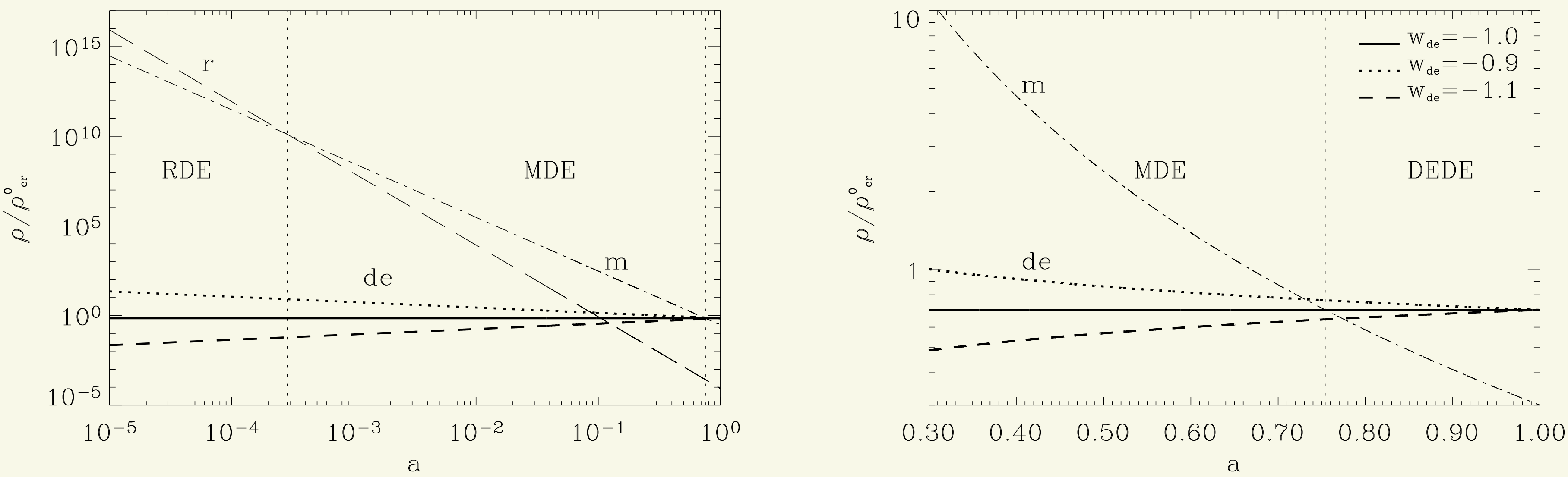
$$T^{k\,(m)}_{i;k} = 0 \quad \rightarrow \quad \dot{\rho}_m = -3 \frac{\dot{a}}{a} \rho_m \quad \rightarrow \quad \rho_m(t) = \rho_m^0 a^{-3}$$

$$T^{k\,(de)}_{i;k} = 0 \quad \rightarrow \quad \dot{\rho}_{de} = -3(1 + w_{de}) \frac{\dot{a}}{a} \rho_{de} \quad \rightarrow \quad \rho_{de}(t) = \rho_{de}^0 a^{-3(1+\tilde{w}_{de})},$$

where

$$\tilde{w}_{de}(a) = \frac{1}{\ln(a)} \int_1^a w_{de}(a') d \ln a' \quad \text{and} \quad \tilde{w}_{de} = w_{de} \quad \text{for} \quad w_{de} = const$$

Dark energy and expansion of the Universe



The evolution of energy density of relativistic (r), matter (m) and dark energy $w =$const (de) components. RDE - Radiation Dominated Epoch, MDE - Matter Dominated Epoch and DEDE - Dark Energy Dominated Epoch. All lines correspond to model with $\Omega_m = 0.3$ and $\Omega_{de} = 0.7$. The MDE-DEDE crossing line is shown for Λ-model ($w_{de} = -1$).

Dark energy and expansion of the Universe

$$H \equiv \frac{\dot{a}}{a}, \qquad q \equiv -\frac{\ddot{a}}{aH^2}$$

$$H = H_0 \sqrt{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_{de} f(a)},$$

$$q = \frac{1}{2} \frac{2\Omega_r a^{-4} + \Omega_m a^{-3} + (1+3w)\Omega_{de} f(a)}{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_{de} f_(a)},$$

where

$$\Omega_x \equiv \frac{\rho_x^{(0)}}{\rho_{cr}^{(0)}}, \quad \rho_{cr}^{(0)} \equiv \frac{3H_0^2}{8\pi G}, \quad f(a) \equiv \frac{\rho_{de}(a)}{\rho_{de}^0} = a^{-3(1+\tilde{w}_{de}(a))}$$

Why does dynamical dark energy evolve?

- because space-time evolves: $R = 6\left(\frac{\ddot{a}}{a} - \frac{\dot{a}^2}{a^2}\right) = -6\,(1+q)\,H^2$
- inherent property

Specifying of scalar field models of dark energy

$$\frac{\dot{p}_{de}}{\dot{\rho}_{de}} = c_a^2 = const \quad \rightarrow \quad p_{de} = c_a^2 \rho_{de} + C$$

[Babichev, Dokuchaev & Eroshenko (2005)]

$$\frac{dw_{de}}{da} = 3a^{-1}(1 + w_{de})(w_{de} - c_a^2)$$

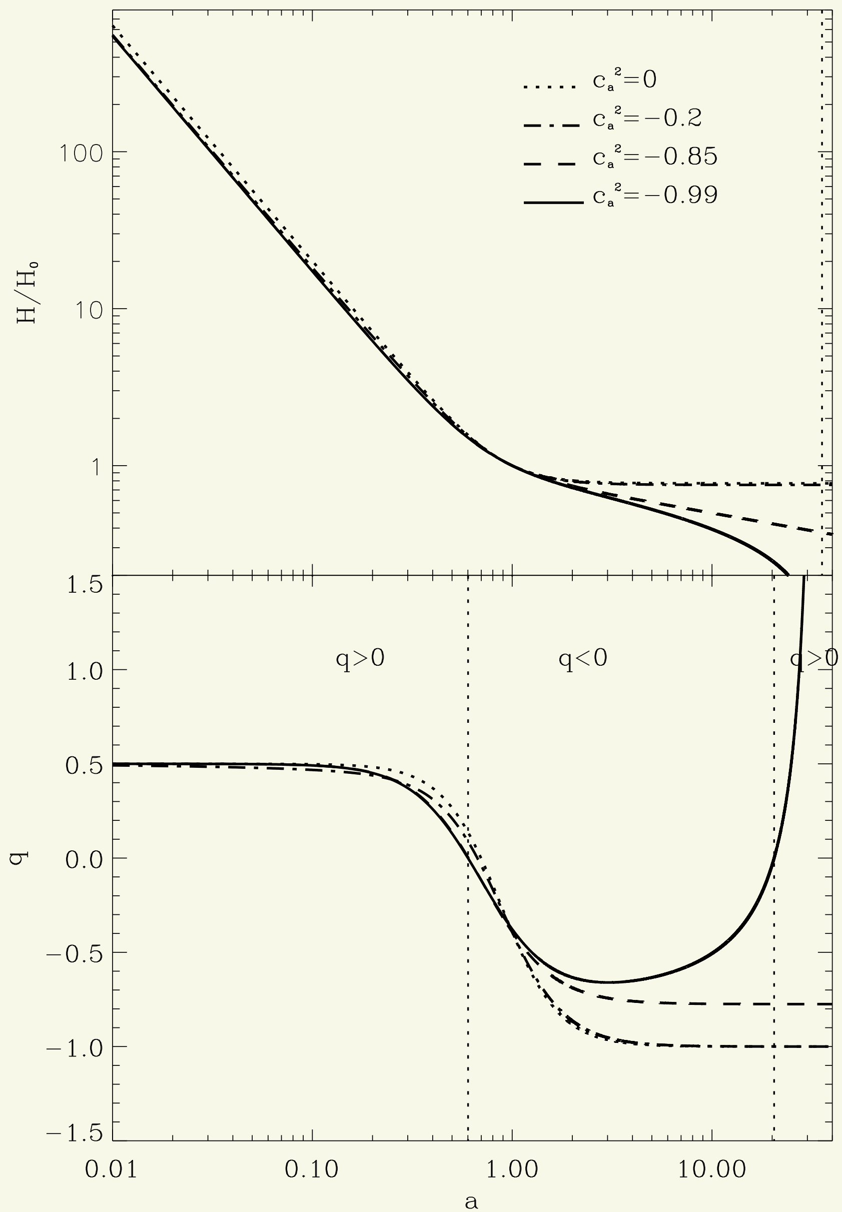
$$w_{de}(a) = \frac{(1 + c_a^2)(1 + w_0)}{1 + w_0 - (w_0 - c_a^2)a^{3(1+c_a^2)}} - 1$$

$$\rho_{de}(a) = \rho_{de}^{(0)} \frac{(1 + w_0)a^{-3(1+c_a^2)} + c_a^2 - w_0}{1 + c_a^2}$$

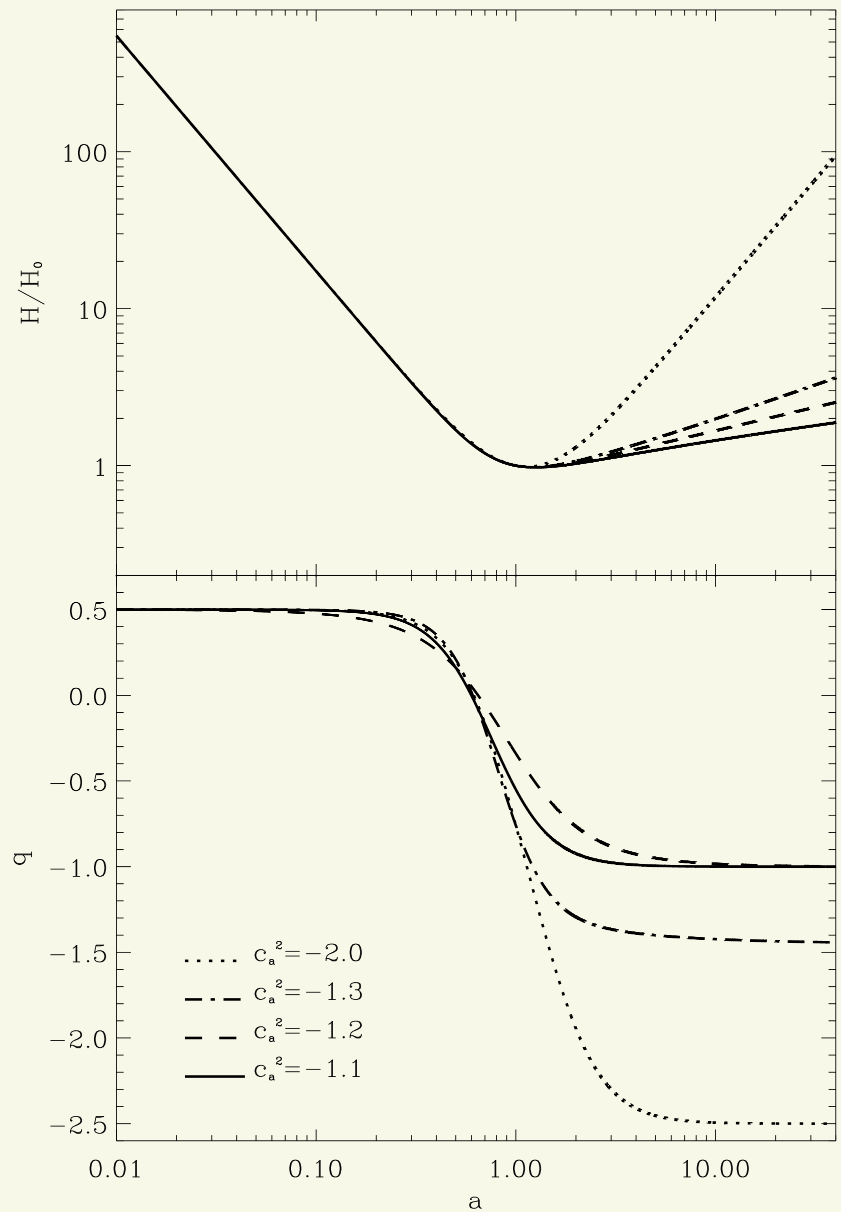
$$f(a) = \frac{(1 + w_0)a^{-3(1+c_a^2)} + c_a^2 - w_0}{1 + c_a^2}$$

Dynamics of expansion of the Universe with scalar field dark energy

Quintessence

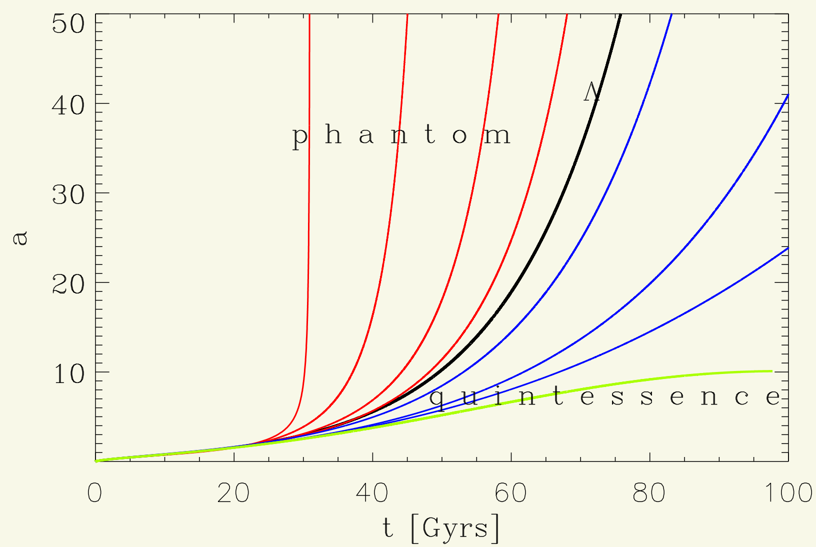


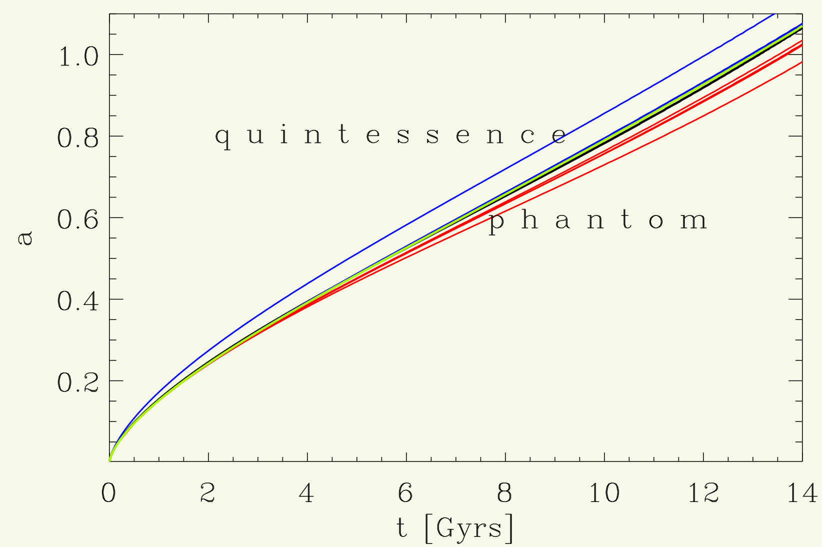
Phantom



Future of the Universe depends on the nature of dark energy

$$t(a) = \int_0^a \frac{da'}{a' H(a')} \quad \rightarrow \quad a(t)$$





Big Rip singularity: $t_{BR} - t_0 \approx \frac{2}{3}\frac{1}{H_0}\frac{1}{|1+c_a^2|}\sqrt{\frac{1+c_a^2}{(1+w_0)\Omega_{de}}}$

Reconstruction of Lagrangian of scalar field

For $c_s^2 = const$ we obtain $L = VX^{\frac{1+c_s^2}{2c_s^2}} - U$

$$U = \frac{\rho_{de}(c_s^2 - w_{de})}{1 + c_s^2},$$

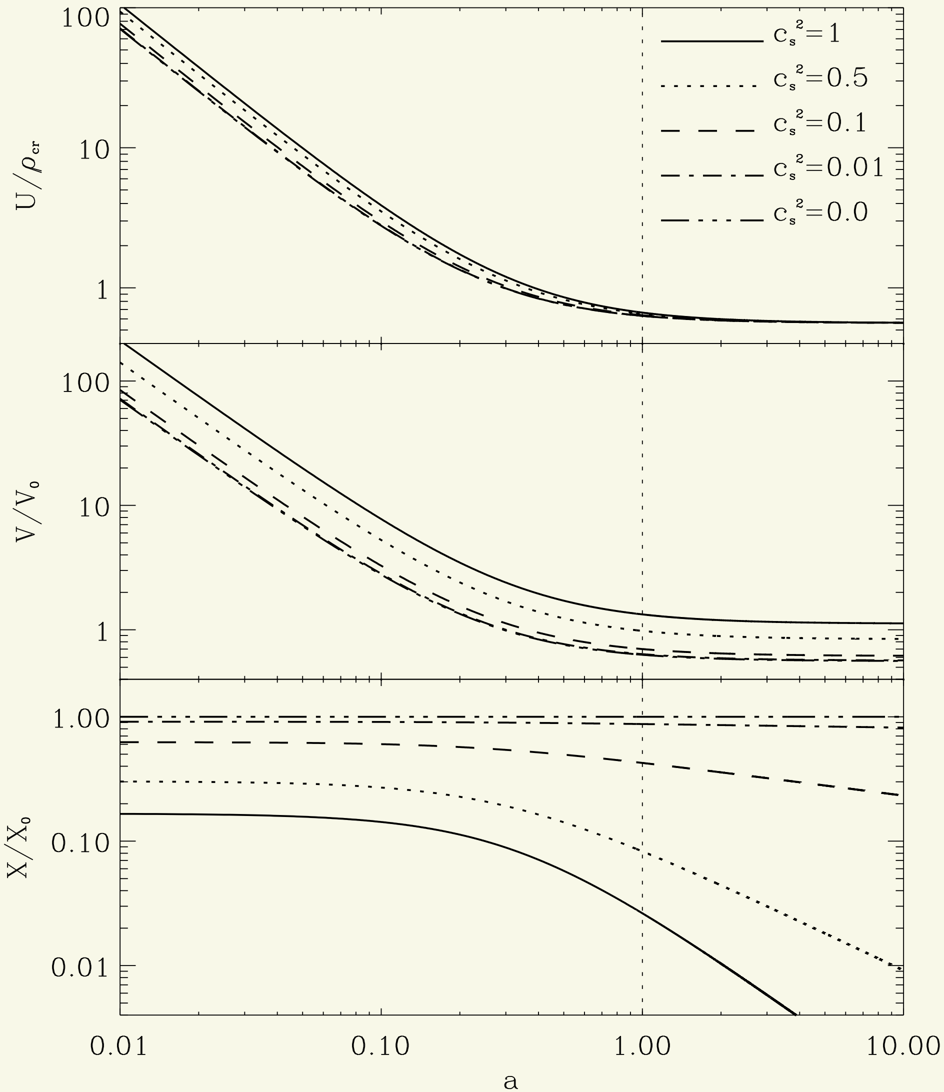
$$V = V_0(c_s^2 - w_{de})\rho_{de},$$

$$X = \left(\frac{c_s^2}{1 + c_s^2}\frac{|1 + w_{de}|}{c_s^2 - w_{de}}\right)^{\frac{2c_s^2}{1+c_s^2}}(\pm V_0)^{-\frac{2c_s^2}{1+c_s^2}}$$

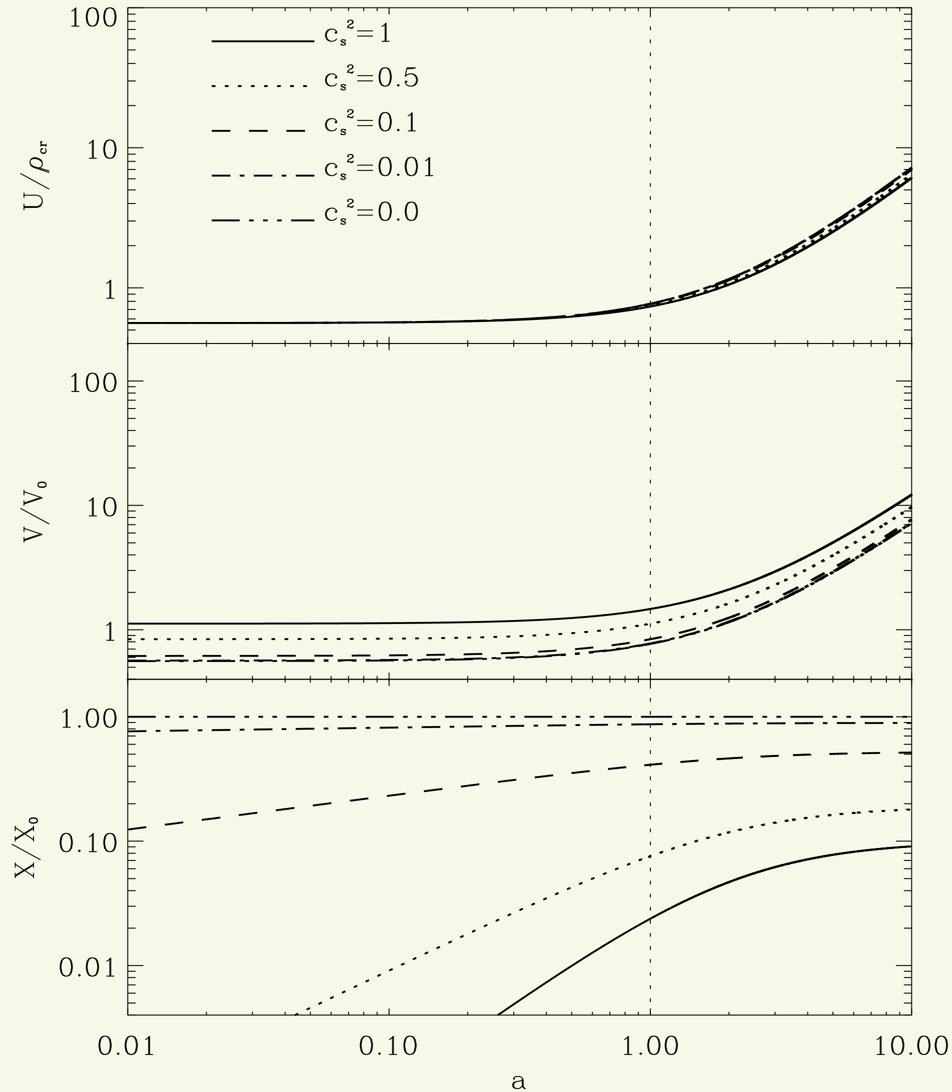
[Sergijenko & Novosyadlyj, Phys.Rev.D, 92 (2015); arXiv:1407.2230]

Potential and kinetic term for different values of c_s^2

$w_{de} = -0.9$



$w_{de} = -1.1$



Perturbations:

$$\rho = \overline{\rho}(1+\delta), \quad p = \overline{p}(1+\pi), \quad u^i = \overline{u}^i + \delta u^i,$$

$$T_{ij} = \overline{T}_{ij} + \delta T_{ij}$$

$$\phi = \overline{\phi} + \delta\phi,$$

$$\delta\rho_{de} = \left(\dot{\overline{\phi}}\dot{\delta\phi} - \Psi\dot{\overline{\phi}}^2\right)\left(\frac{\partial\mathcal{L}}{\partial X} + 2X\frac{\partial^2\mathcal{L}}{\partial X^2}\right) - \left(\frac{\partial\mathcal{L}}{\partial U}\frac{\partial U}{\partial\phi} - 2X\frac{\partial^2\mathcal{L}}{\partial X\partial U}\frac{dU}{d\phi}\right)\delta\phi,,$$

$$\delta p_{de} = \left(\dot{\overline{\phi}}\dot{\delta\phi} - \Psi\dot{\overline{\phi}}^2\right)\frac{\partial\mathcal{L}}{\partial X} + \frac{\partial\mathcal{L}}{\partial U}\frac{\partial U}{\partial\phi}\delta\phi,$$

$$V_{de} = \frac{k\delta\phi}{\dot{\overline{\phi}}}$$

$$ds^2 = c^2dt^2 + a^2(t)(\delta_{ij} + h_{ij})dx^i dx^j \quad (h \equiv h^i_i \ll 1),$$

$$R_{ij} = \overline{R}_{ij} + \delta R_{ij}, \quad R = \overline{R} + \delta R$$

Formation of large scale structure: some basic equations

$$\delta R^i_j - \frac{1}{2}\delta^i_j \delta R = \kappa \left(\delta T^{i\,(r)}_j + \delta T^{i\,(m)}_j + \delta T^{i\,(de)}_j\right)$$

Equations for Fourier modes of perturbations in the synchronous gauge comoving to matter component ($V_m = 0$):

$$\dot{\delta}_{de} + 3(c_s^2 - w_{de}) aH\delta_{de} + (1+w_{de})\frac{\dot{h}}{2} + (1+w_{de})\left[k + 9a^2H^2\frac{c_s^2 - c_a^2}{k}\right]V_{de} = 0,$$

$$\dot{V}_{de} + aH(1-3c_s^2)V_{de} - \frac{c_s^2 k}{1+w_{de}}\delta_{de} = 0,$$

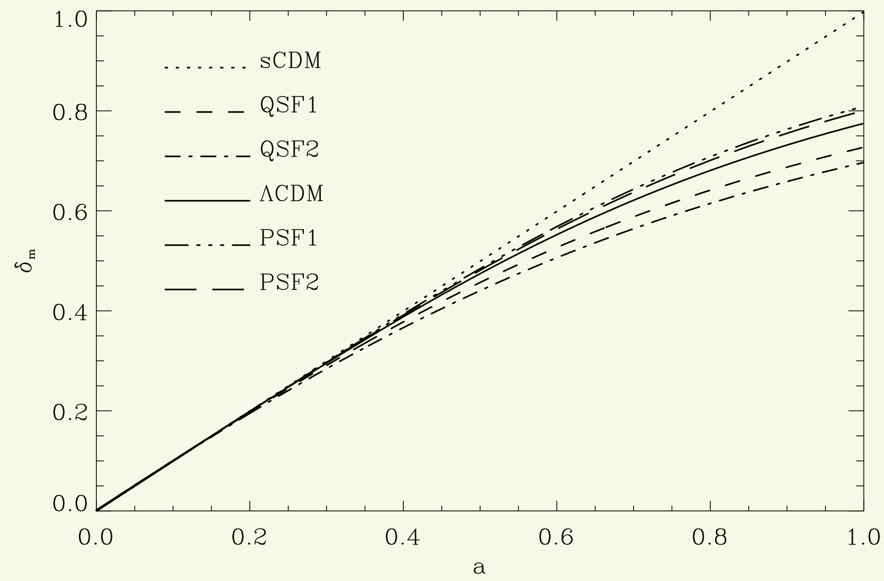
$$\dot{\delta}_m = -\frac{1}{2}\dot{h},$$

$$\ddot{h} + \frac{\dot{a}}{a}\dot{h} = -8\pi G a^2(\rho_m\delta_m + (1+3w_{de})\rho_{de}\delta_{de})$$

CAMB: http://camb.info.Lewis A., Challinor A, Lasenby A., Astrophys. J. 538, 473 (2000)

Evolution of matter density perturbations in the models with different types of DE

The evolution of matter density perturbations from the Dark Ages to the present epoch in sCDM, ΛCDM, QSF+CDM and PSF+CDM models (amplitudes are normalized to 0.1 at $a = 0.1$):



sCDM: $\Omega_m = 1$;

ΛCDM: $\Omega_m = 0.3$, $\Omega_{de} = 0.7$;

QSP1: $\Omega_m = 0.3$, $\Omega_{de} = 0.7$, $w_0 = -0.8$, $c_a^2 = -0.8$;

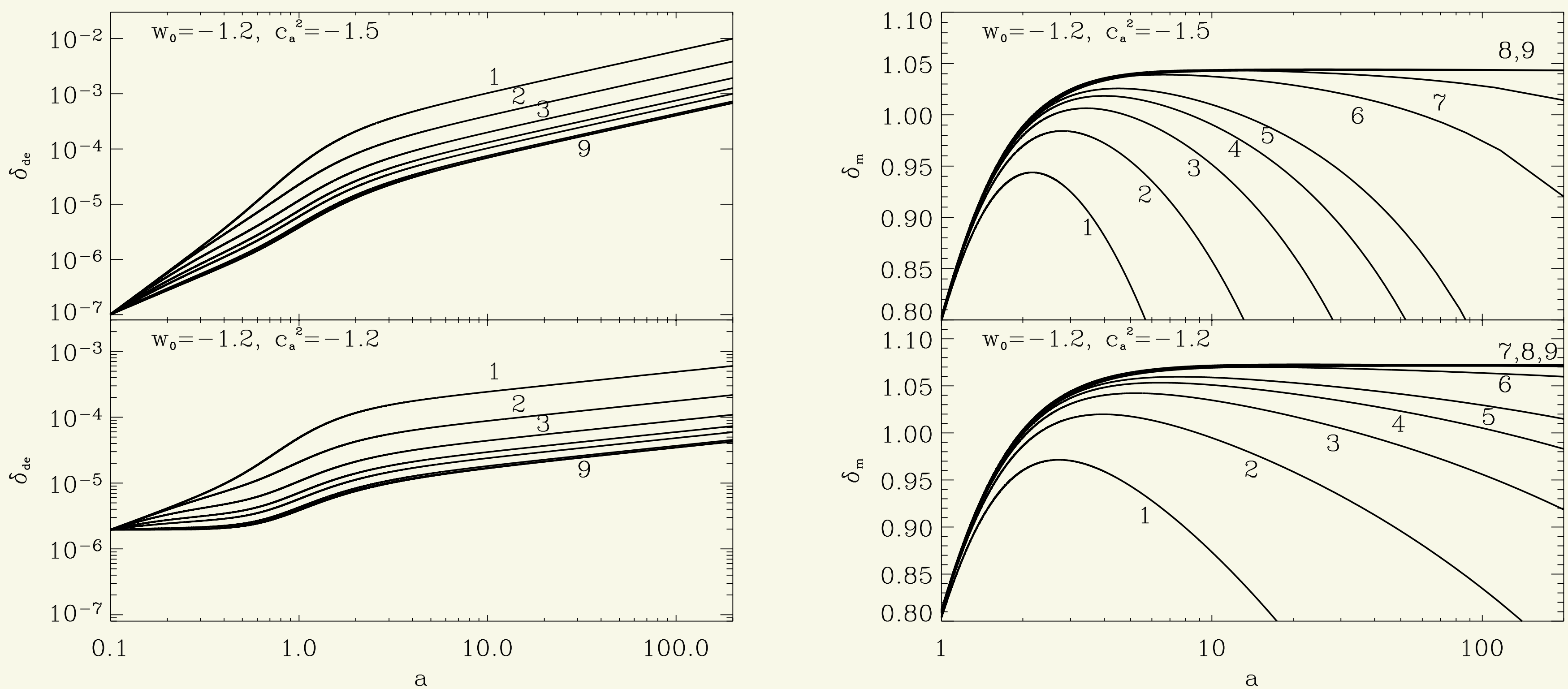
QSP2: $\Omega_m = 0.3$, $\Omega_{de} = 0.7$, $w_0 = -0.8$, $c_a^2 = -0.5$;

PSP1: $\Omega_m = 0.3$, $\Omega_{de} = 0.7$, $w_0 = -1.2$, $c_a^2 = -1.2$;

PSP2: $\Omega_m = 0.3$, $\Omega_{de} = 0.7$, $w_0 = -1.2$, $c_a^2 = -1.5$;

Evolution of density perturbations in the models with phantom dark energy

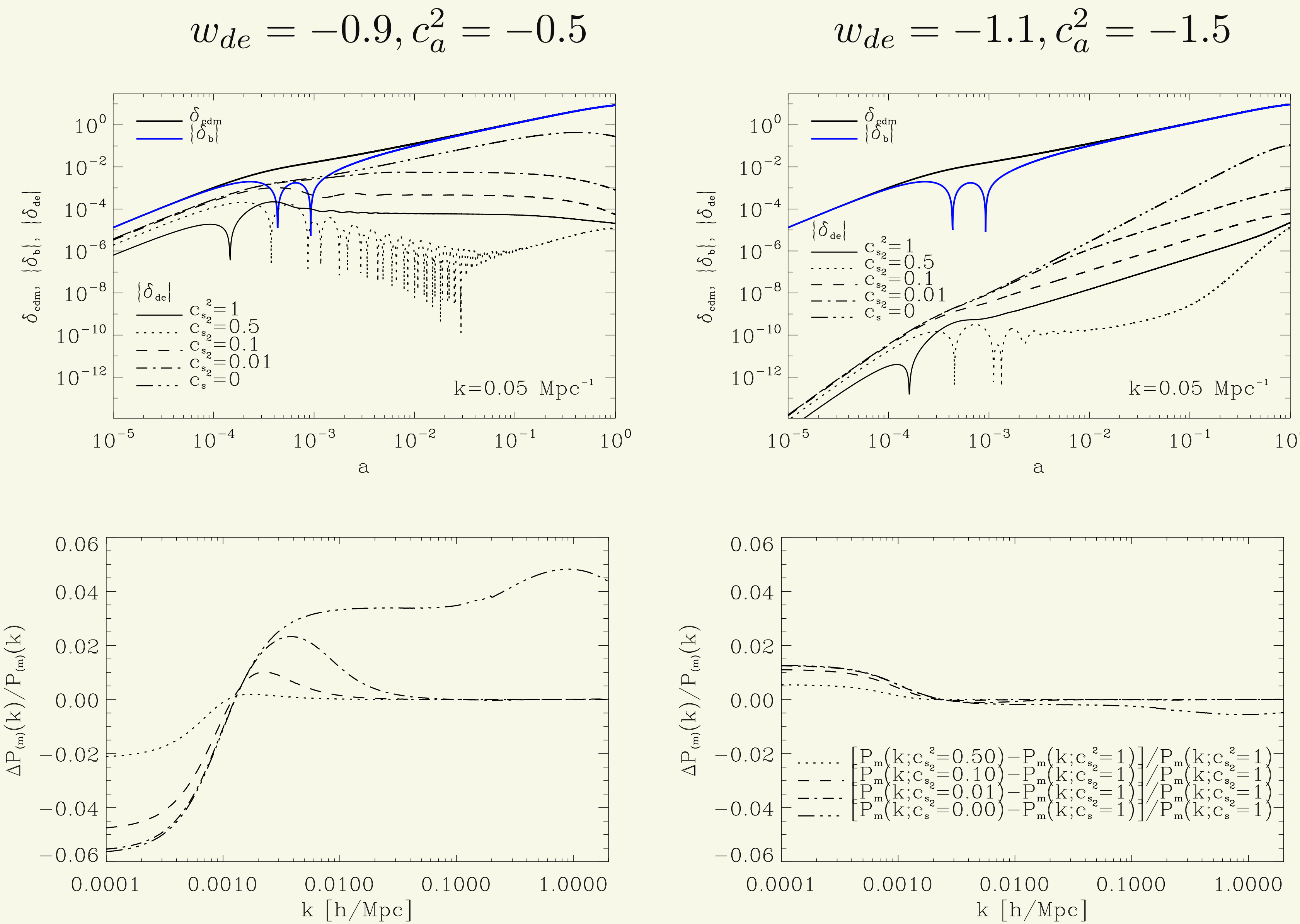
The evolution of different Fourier amplitudes of PSF and matter density perturbations from $a = 0.1$ to $a = 200$ for models with $w_0 = -1.2$, $c_a^2 = -1.5$ and $w_0 = -1.2$, $c_a^2 = -1.2$.



The different lines correspond to different wave numbers k (in Mpc^{-1}) as follows: 1 - 0.0005, 2 - 0.001, 3 - 0.0015, 4 - 0.002, 5 - 0.0025, 6 - 0.005, 7 - 0.01, 8 - 0.05, 9 - 0.1 Mpc^{-1}.

[Novosyadlyj, Sergijenko, Durrer & Pelykh, PhysRev D **86** (2012)]

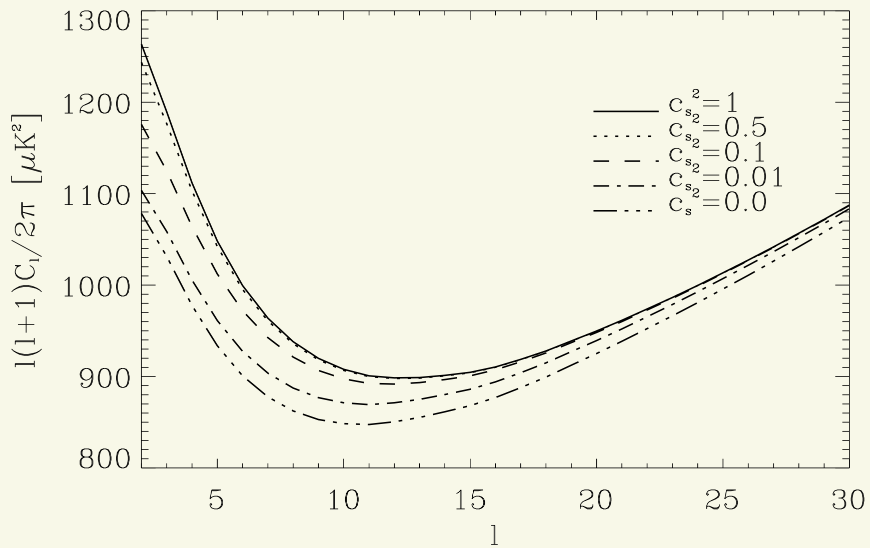
Density perturbations of dark matter, baryon matter and dark energy ($\mathrm{k} = 0.1\mathrm{Mpc}^{-1}$) (CAMB)

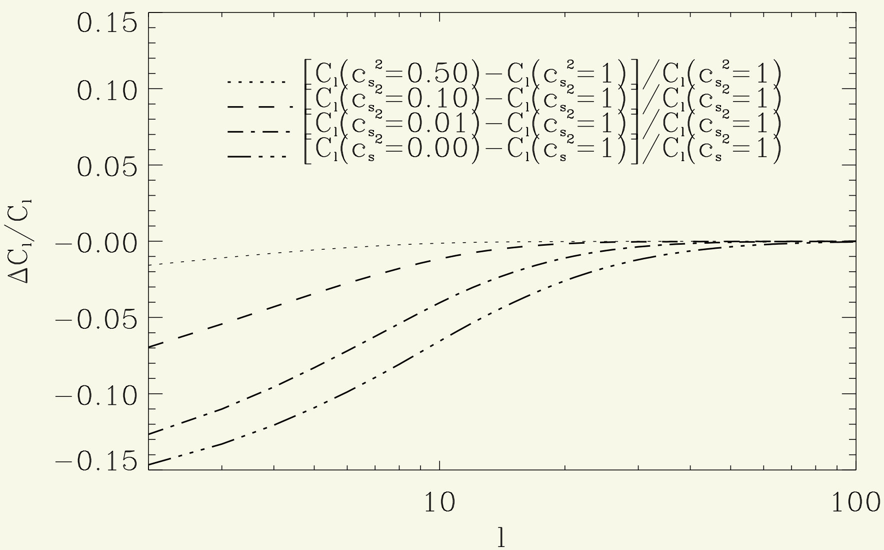


[Sergijenko & Novosyadlyj, Phys.Rev.D, 92 (2015)]

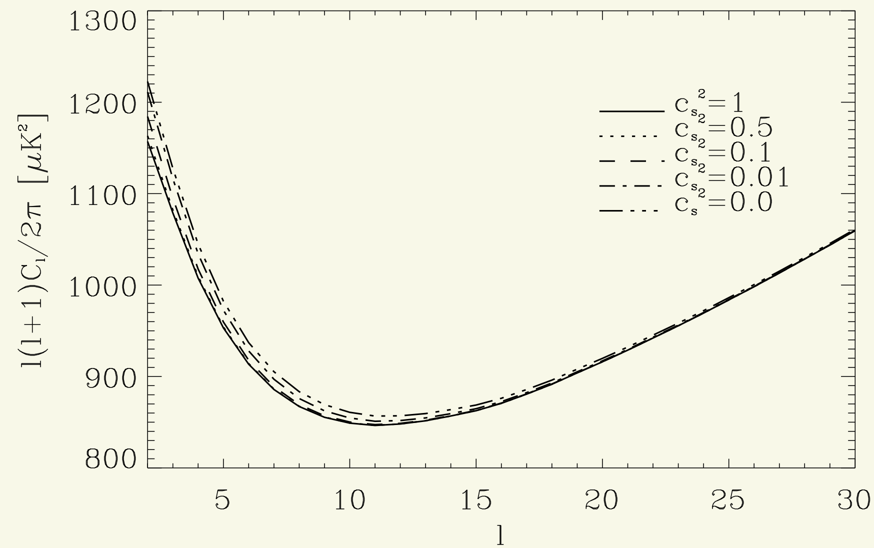
Influence of c_s^2 on CMB power spectrum of $\Delta T/T$ (CAMB)

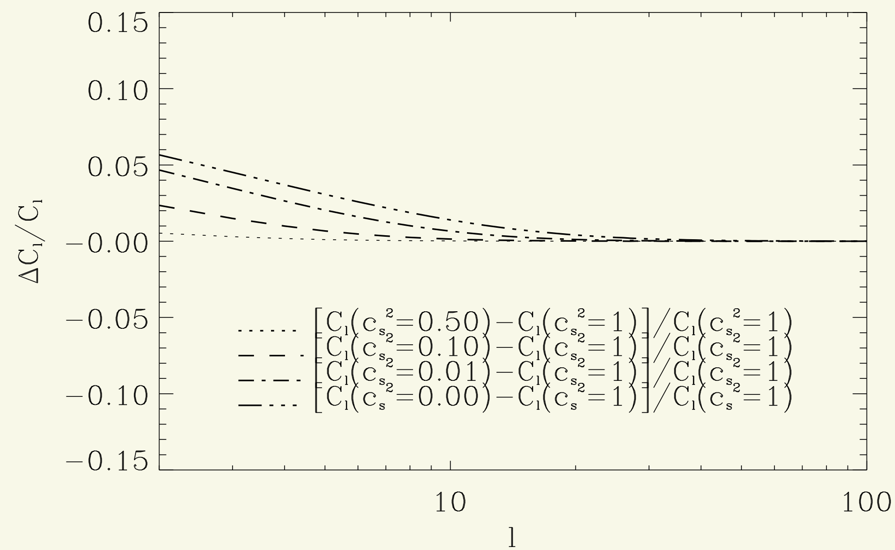
$$w_{de} = -0.9, c_a^2 = -0.5$$





$$w_{de} = -1.1, c_a^2 = -1.5$$





Observational data and method of determination of cosmological parameters

Observational data

CMB: Planck	Planck collaboration (2015)
CMB: WMAP9	Hinshaw et al. (2013)
BAO: SDSS DR7	Percival et al. (2010)
BAO: 6dF	Beutler F. et al. (2011)
BAO: SDSS DR9	Anderson et al. (2012)
SNe Ia: SNLS3	Sullivan et al. (2011)
SNe Ia: Union2.1	Suzuki et al. (2012)

Method

Markov Chain Monte Carlo CosmoMC [Lewis & Bridle (2002)]

Theoretical predictions vs observational data

CMB:

$$\frac{\ell(\ell+1)}{2\pi}C_\ell^{TT} = \langle(\Delta T)^2\rangle_{\theta\approx\pi/\ell}\,, \qquad \frac{(\ell+1)}{2\pi}C_\ell^{TE} = \langle\Delta T\cdot E\rangle_{\theta\approx\pi/\ell}$$

Power spectrum of matter density perturbation:

$$P(k) \equiv \langle\delta(k)\delta^*(k)\rangle = A_s k^{n_s} T^2(k;\Omega_i, w_0, c_a^2)$$

Its amplitude:

$$\sigma_8^2 = \frac{1}{2\pi^2}\int_0^\infty k^2 P(k) W^2(8\mathrm{Mpc}\cdot k/h)dk, \quad W(x) = 3\frac{\sin x - x\cos x}{x^3}$$

BAO:

$$R(z) \equiv \frac{r_s(z_{drag})}{D_V(z)}$$

SNe Ia:

$$(m-M) = 5\log d_L + 25 + \alpha(s-1) - \beta\mathcal{C},$$

$$d_L = \frac{c(1+z)}{H_0}\int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_{de} f(\frac{1}{1+z'})}}.$$

Theoretical predictions vs observational data

Likelihood function:

$$L(\mathbf{x};\theta_k) = exp\left(-\frac{1}{2}(x_i - x_i^{th})C_{ij}(x_j - x_j^{th})\right) \approx exp\left(-\frac{1}{2}\Sigma_i \frac{(x_i - x_i^{th})^2}{\sigma_i^2}\right)$$

Posterior function:

$$P(\theta_k;\mathbf{x}) = \frac{L(\mathbf{x};\theta_k)p(\theta_k)}{g(\mathbf{x})}$$

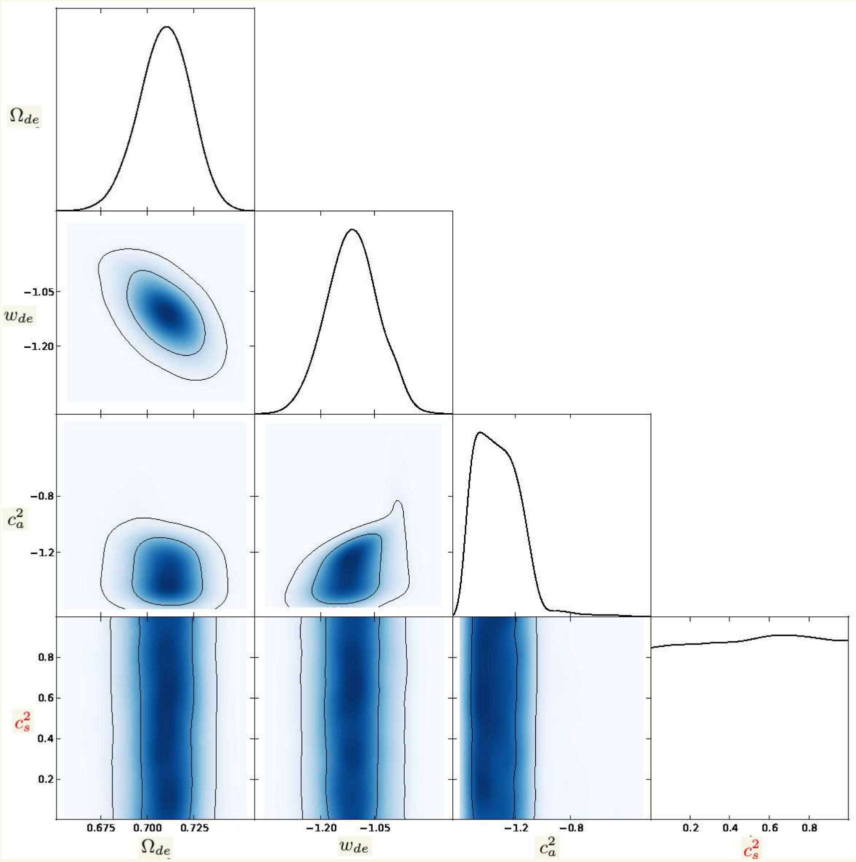
Parameters:

$$\theta_k : \ \Omega_{de},\ w_{de},\ c_a^2,\ c_s^2,\ \Omega_b,\ \Omega_{cdm},\ H_0,\ A_s,\ n_s,\ \tau_{rei}$$

Current determination of dark energy parameters

Observational data: Planck, WiggleZ, SN Union2.1, H_0

$$\Omega_{de} \quad 0.71^{+0.03}_{-0.03} \qquad w_{de} \quad -1.11^{+0.14}_{-0.14} \qquad c_a^2 \quad -1.32^{+0.25}_{-0.25} \qquad c_s^2$$



[Sergijenko & Novosyadlyj, Phys.Rev.D, 92 (2015)]

Conclusions II

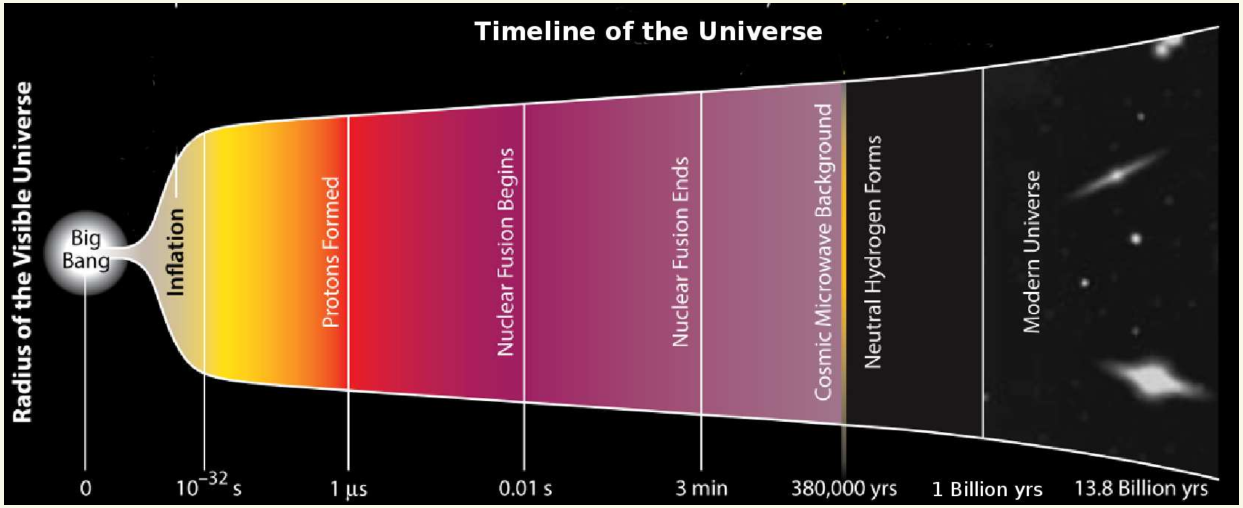
- Observational data prefer the cosmological model with DE density domination at current epoch: $\Omega_{de} = 0.7 \pm 0.02$.
  The model without DE ($\Omega_{de} = 0$) is excluded at $> 50\sigma$ C.L. !

- Observational data related with cosmological scales (Planck results 2015) give strong constraints on the density of dark energy in the early Universe: $\Omega_{EDE} < 0.0071$.

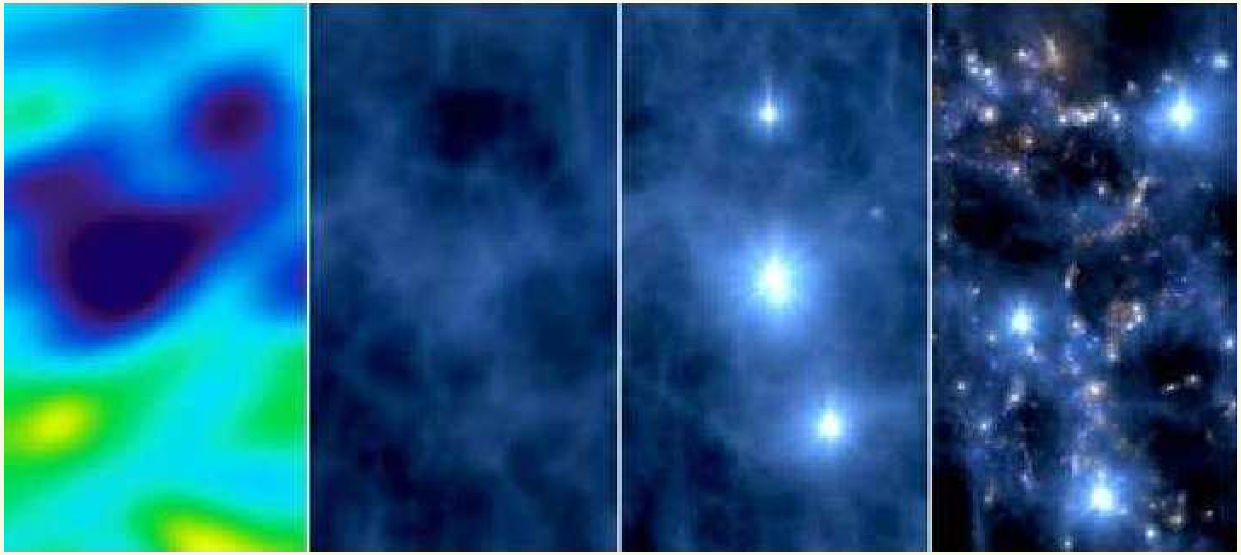
- Observational data related with cosmological scales do not distinguish the DE type: $w_0 = -1.0 \pm 0.15$.

- Currently available observational data related with cosmological scales give no possibility to constrain c_s^2 !

Cosmic Dark Ages and Cosmic Dawn

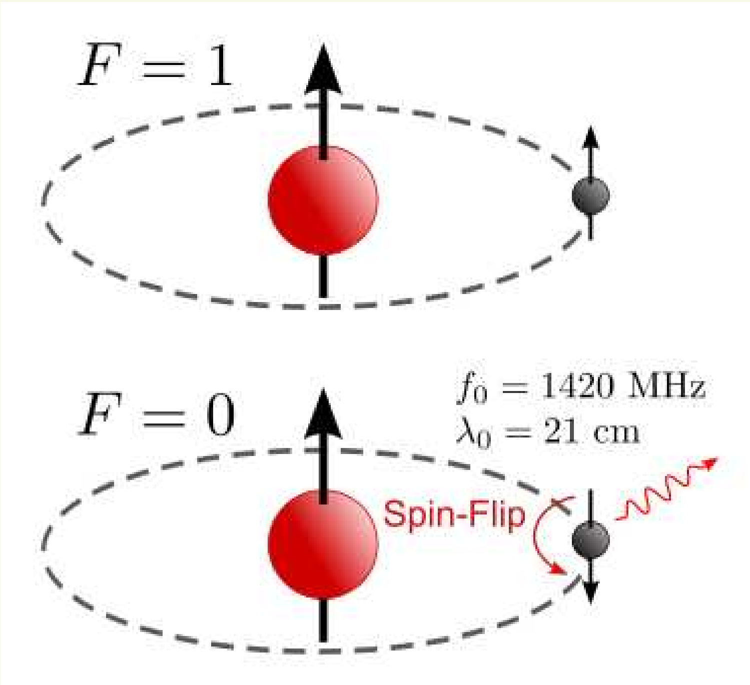


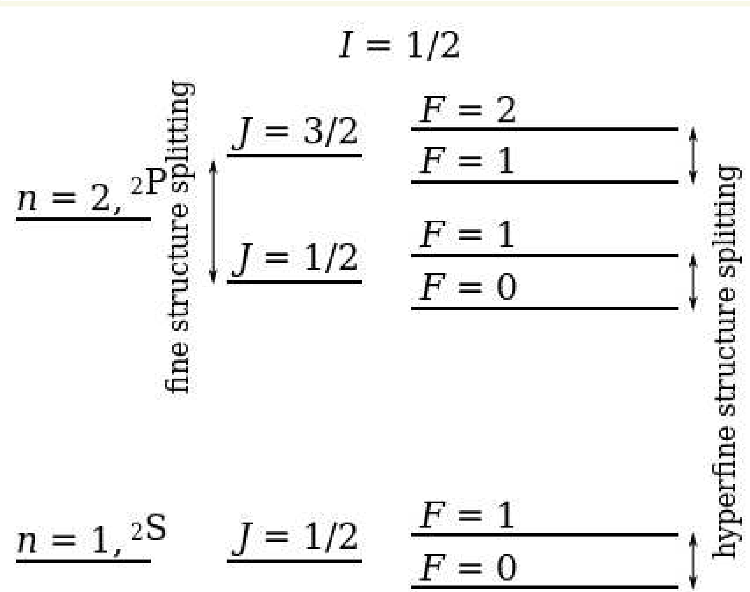
$z = 1000$ 30 10 5



Recombination epoch | Dark Ages | Cosmic Dawn | Reionization epoch

Hydrogen atom lines: hyperfine 21-cm





The possibility of 21-cm line emission or absorption by neutral H at high redshift has been considered by Hogan & Rees (1979), Scott & Rees (1990), Subramanian & Padmanabhan (1993), Kumar, Padmanabhan & Subramanian (1995), Bagla, Nath & Padmanabhan (1997), Madau, Meiksen & Rees (1997), Shaver et al. (1999), Tozzi et al. (2000), Zaldariaga et al. (2004):

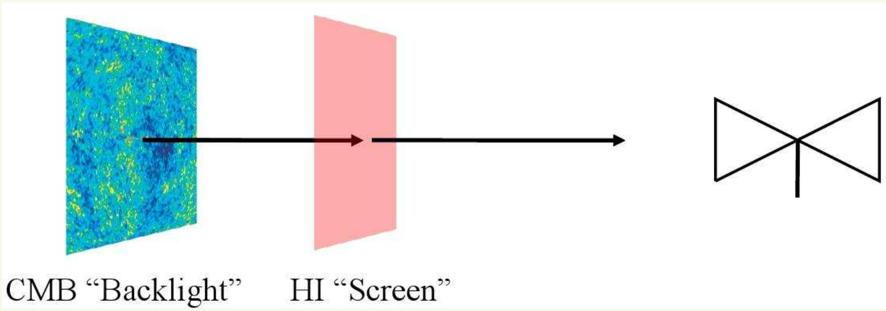
$$T_s(z) = T_m(z)\frac{A_{10}T_r(z) + 0.068C_{10}}{A_{10}T_m(z) + 0.068C_{10}}\ \mathrm{K}$$

$$z = [1000 - 10]\ :$$

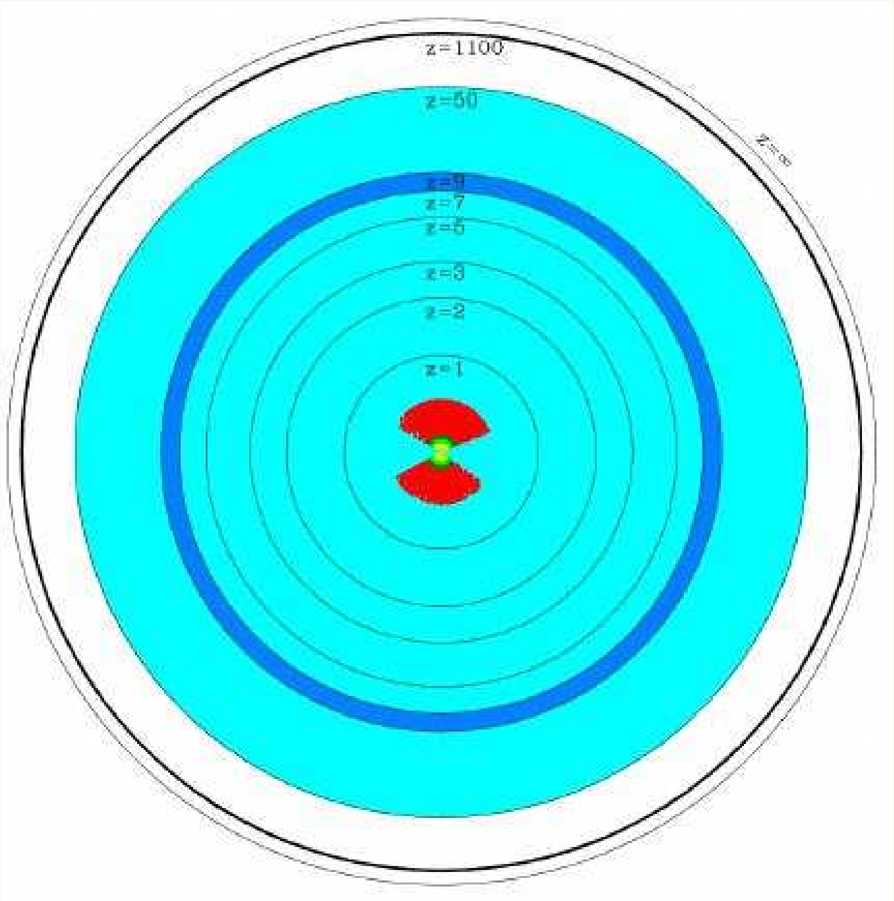
$$T_r = [2730{-}30]\ \mathrm{K}, \quad T_m = [2730{-}2.5]\ \mathrm{K},$$

$$n_H = [2{\cdot}10^8{-}276]\ \mathrm{m}^{-3}, \quad n_\gamma = 2{\cdot}10^9 n_b.$$

21 cm line from the Dark Ages



z=1100 z=300...30 z=0



Neutral Hydrogen line 21 cm:

$\lambda_0 = 21$ cm (rest frame),

$\nu_0 = 1420$ MHz

$\lambda_z = \lambda_0(1+z), \quad \nu_z = \nu_0/(1+z)$

$z = 10 : \lambda = 2.3$ m, $\quad \nu = 129$ MHz

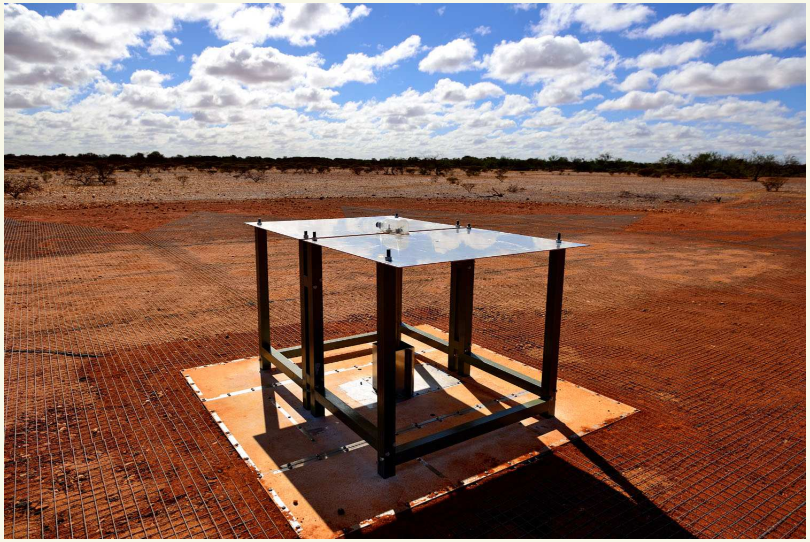
$z = 30 : \lambda = 6.5$ m, $\quad \nu = 45.8$ MHz

$z = 40 : \lambda = 8.6$ m, $\quad \nu = 34.6$ MHz

$z = 50 : \lambda = 10.7$ m, $\quad \nu = 27.8$ MHz

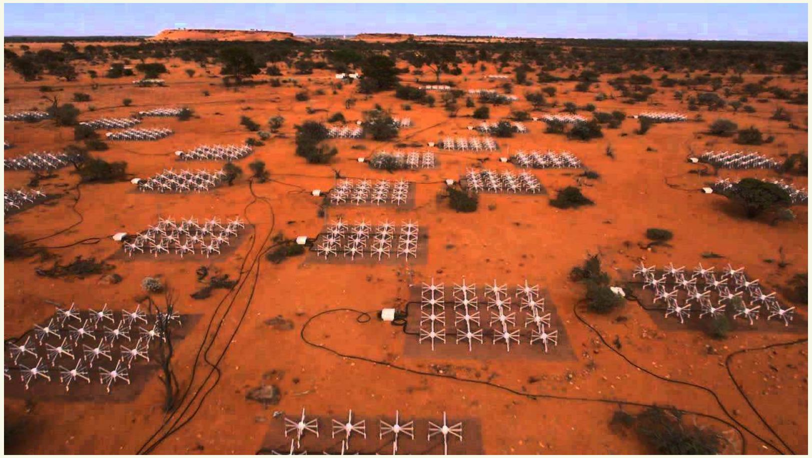
$z = 75 : \lambda = 16$ m, $\quad \nu = 18.7$ MHz

Observations of Dark Ages



Experiment to Detect Global Epoch of reionization Signature (EDGES), Western Australia

Precision Array for Probing the Epoch of Reionisation (PAPER), South Africa



Murchison Widefield Array (MWA), Western Australia

Hydrogen Epoch of Reionization Array (HERA), South Africa (under construction)

Observations of Dark Ages

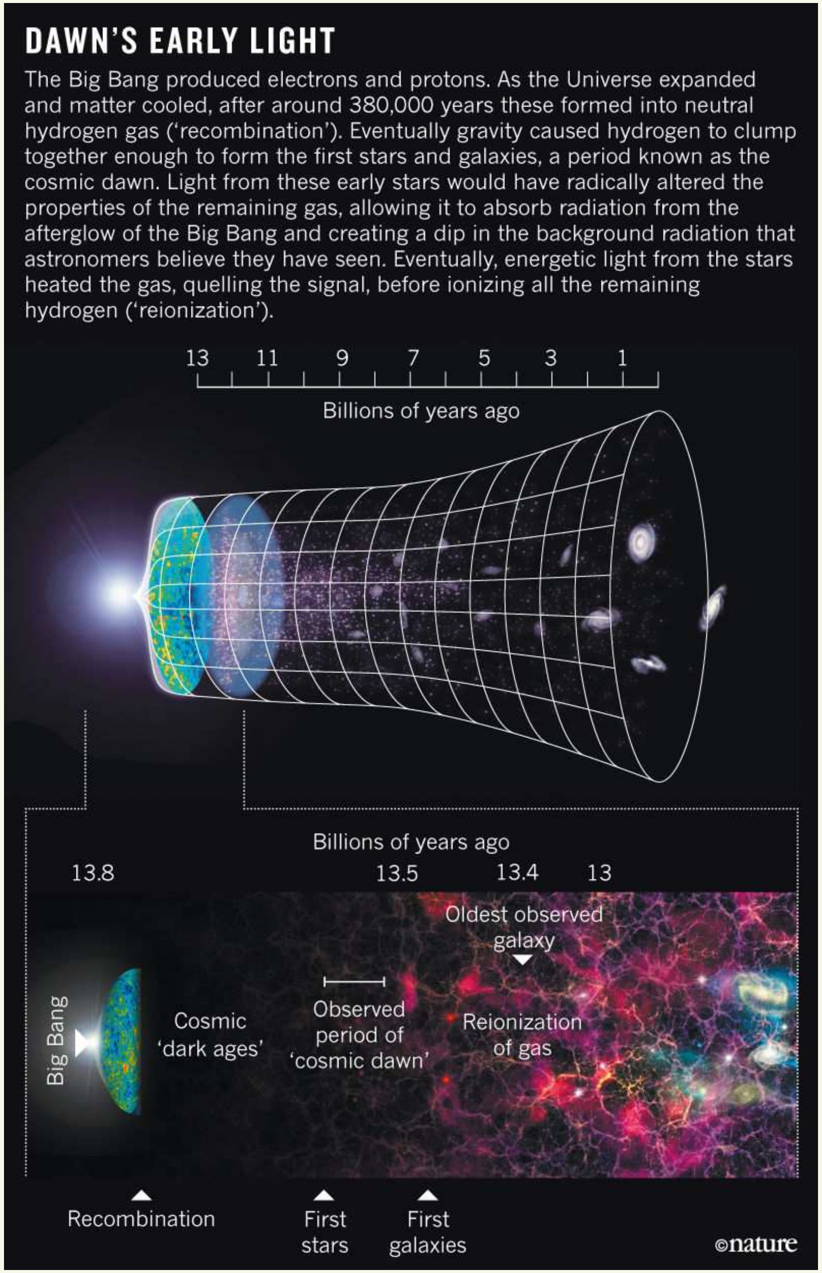

The 21 CentiMeter Array (21CMA), Tianshan Mountains, west China


LOFAR, Exloo, Netherlands


FAST (NAO of CAS), Guizhou province, China


SKA, project

Good news from EDGES



EDGES: Experiment to Detect Global Epoch of reionization Signature (Western Australia)

Nature, news: 28 Feb (doi: 10.1038/d41586-018-02616-8)]

doi:10.1038/nature25792

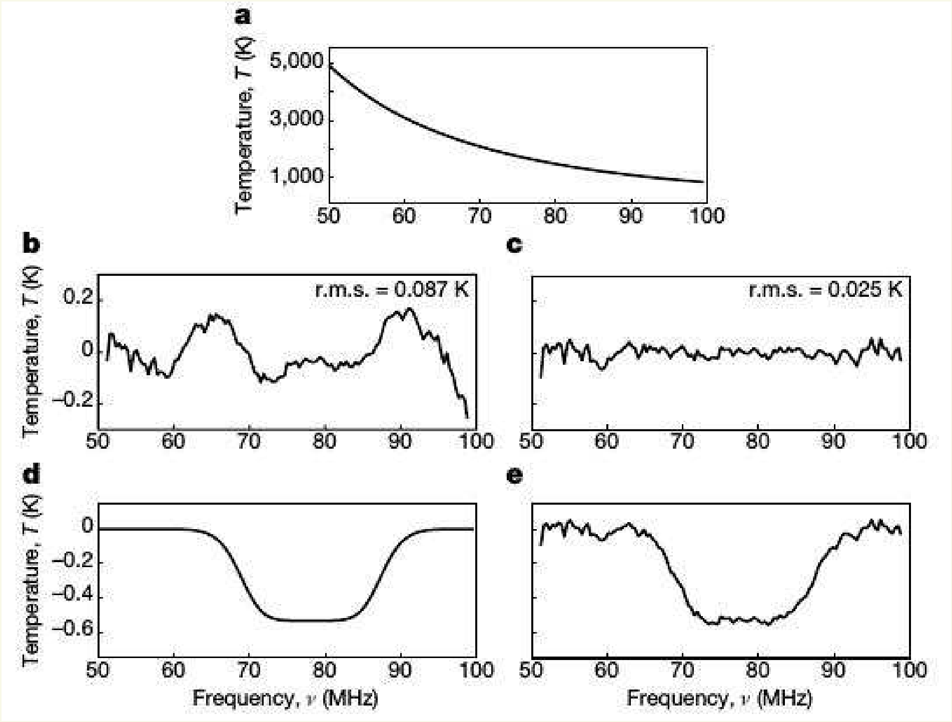
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]

After stars formed in the early Universe, their ultraviolet light is expected, eventually, to have penetrated the primordial hydrogen gas and altered the excitation state of its 21-centimetre hyperfine line. This alteration would cause the gas to absorb photons from the cosmic microwave background, producing a spectral distortion that should be observable today at radio frequencies of less than 200 megahertz[1]. Here we report the detection of a flattened absorption profile in the sky-averaged radio spectrum, which is centred at a frequency of 78 megahertz and has a best-fitting full-width at half-maximum of 19 megahertz and an amplitude of 0.5 kelvin. The profile is largely consistent with expectations for the 21-centimetre signal induced by early stars; however, the best-fitting amplitude of the profile is more than a factor of two greater than the largest predictions[2]. This discrepancy suggests that either the primordial gas was much colder than expected or the background radiation temperature was hotter than expected. Astrophysical phenomena (such as radiation from stars and stellar remnants) are unlikely to account for this discrepancy; of the proposed extensions to the standard model of cosmology and particle physics, only cooling of the gas as a result of interactions between dark matter and baryons seems to explain the observed amplitude[3]. The low-

The absorption profile is found by fitting the integrated spectrum with the foreground model and a model for the 21-cm signal simultaneously. The best-fitting 21-cm model yields a symmetric U-shaped absorption profile that is centred at a frequency of 78 ± 1 MHz and has a full-width at half-maximum of 19^{+4}_{-2} MHz, an amplitude of $0.5^{+0.5}_{-0.2}$ K and a flattening factor of $\tau = 7^{+5}_{-3}$ (where the bounds provide 99% confidence intervals including estimates of systematic uncertainties; see Methods for model definition). Uncertainties in the parameters of the fitted profile are estimated from statistical uncertainty in the model fits and from systematic differences between the various validation trials that were performed using observations from both instruments and several different data cuts. The 99% confidence intervals that we report are calculated as the outer bounds of (1) the marginalized statistical 99% confidence intervals from fits to the primary dataset and (2) the range of best-fitting values for each parameter across the validation trials. Fitting with both the foreground and 21-cm models lowers the residuals to an r.m.s. of 0.025 K. The fit shown in Fig. 1 has a signal-to-noise ratio of 37, calculated as the best-fitting amplitude of the profile divided by the statistical uncertainty of the amplitude fit, including the covariance between model parameters. Additional analyses of the

Detection of 21-cm line from end of Dark Ages by EDGES



Bowman et all., Nature, 555, 67 (2018)]

$$T_{21cm}(z) \approx 0.023 x_{HI}(z) \left[\left(\frac{0.15}{\Omega_m} \right) \left(\frac{1+z}{10} \right) \right]^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left[1 - \frac{T_r(z)}{T_s(z)} \right] \mathrm{K},$$

$$T_s(z) = T_m \frac{A_{10} T_r + (C_{10} + P_{10})\, T_*}{A_{10} T_m + (C_{10} + P_{10})\, T_*}, \qquad T_* = h\nu_0/k = 0.068\,\mathrm{K}$$

Zaldariaga et all., ApJ, 608, 622 (2004)]

Key problems for Dark Ages

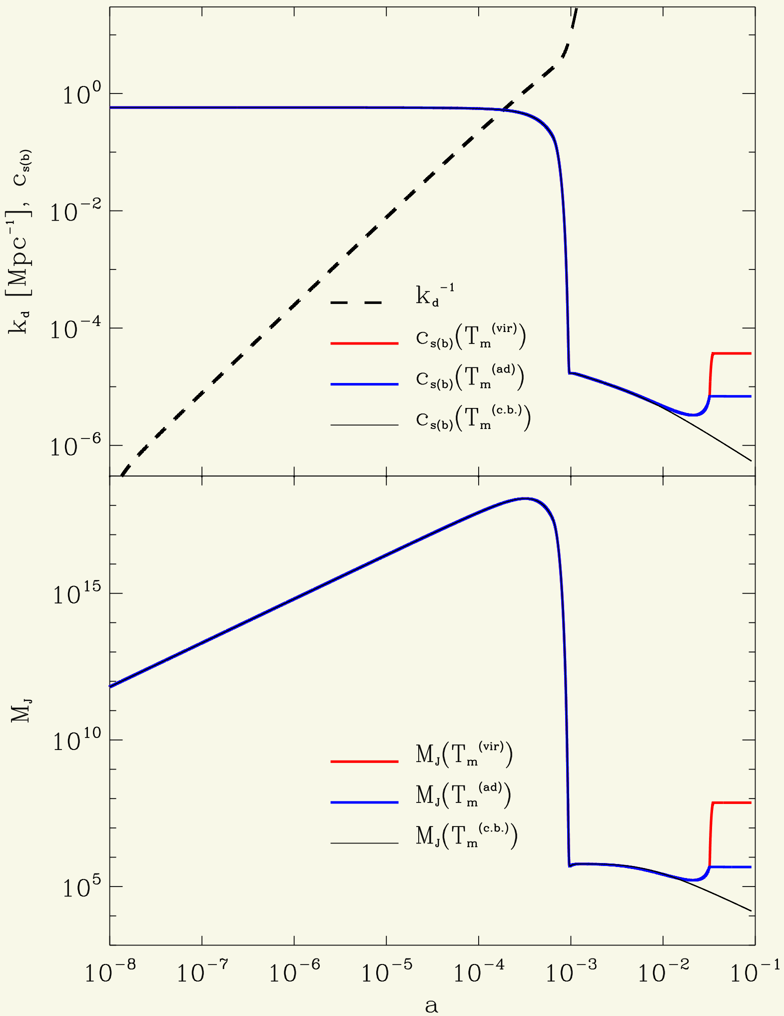
- When did the first sources of light have appeared? What was that?
- How the first stars have been formed?
- How SMBH in quasars have been formed?
- Complete reionization: what and how did it?
- How protogalaxy H-He clouds has fragmented to form first stars?
- Are there “fingerprints” of dark matter and dark energy?
- The first molecules in the dark ages: what, when and how much?

The problem

The effective sound speed in the baryon matter varies with time through epochs:

$$c^2_{s\,(b)} = \frac{1}{3(1+R)}\left(\frac{n_{HII}}{n_H}\right)^2 + \frac{\gamma k T_m}{\mu_H m_H}\left(\frac{n_{HI}}{n_H}\right)^2,$$

$$R \equiv \frac{3}{4}\frac{\rho_b}{\rho_\gamma}.$$



The Jeans mass of baryon matter through epochs is as follows:

$$M_J = 7.2 \cdot 10^{10}\frac{c^3_{s\,(b)}}{\sqrt{\rho_b}}\,\mathrm{M}_\odot,$$

$$T_{vir} = 10^4\left(\frac{\mu_H}{0.6}\right)\left(\frac{M}{10^8 h^{-1}}\right)^{2/3}\left(\frac{\Delta_{vir}}{178}\right)^{1/3}\left(\frac{1+z}{10}\right)$$

Cosmological perturbations as seeds of halos

Perturbations of Friedmann-Lemaitre-Robertson-Walker metric:

$$ds^2 = g_{ij}dx^i dx^j = e^{\nu(t,r)}dt^2 - a^2(t)e^{\nu(t,r)}[dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)];$$

Perturbations of density and velocity of N-component:

$$\varepsilon_N(t,r) = \bar{\varepsilon}_N(t)(1+\delta_N(t,r)), \quad p_N(t,r) = w_N\varepsilon_N(t,r),$$
$$u^i_N(t,r) = \left\{\frac{e^{-\nu/2}}{\sqrt{1-v_N^2}},\ \frac{e^{-\nu/2}v_N}{a\sqrt{1-v_N^2}},\ 0,\ 0\right\}.$$

Components of energy-momentum tensor :

$$T^0_{0\,(N)} = \varepsilon_N + (\varepsilon_N + p_N)v_N^2, \quad T^1_{0\,(N)} = a^{-1}(\varepsilon_N + p_N)v_N,$$
$$T^1_{1\,(N)} = -p_N - (\varepsilon_N + p_N)v_N^2, \quad T^2_{2\,(N)} = T^3_{3\,(N)} = -p_N,$$

Cosmological background ($\nu = \delta_N = v_N = 0$):

$$H \equiv \frac{d\ln a}{dt} = H_0\sqrt{\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_{de}a^{-3(1+w_N)}}.$$

Equations for evolution of spherical perturbation to halo

Einstein equations and conservation equations

$$R^i_j - \frac{1}{2}\delta^i_j R = \frac{8\pi G}{c^4}\sum_N T^{i\,(N)}_j, \qquad T^{k\,(N)}_{i\,;k} = 0$$

give

$$\dot{\tilde{\nu}} + \left(1 + (1-\tilde{\nu})\frac{k^2}{3a^2H^2}\right)\frac{\tilde{\nu}}{a} = -\frac{\Omega_m\tilde{\delta}_m + \Omega_r a^{-1}\tilde{\delta}_r + \Omega_{de}a^{-3w_N}\tilde{\delta}_{de}}{\Omega_m a + \Omega_r + \Omega_{de}a^{1-3w_N}},$$

$$\dot{\tilde{\delta}}_N + \frac{3}{a}(c^2_{s(N)} - w_N)\tilde{\delta}_N - (1+w_N)\left[\frac{k^2\tilde{v}_N}{a^2H} + 9H(c^2_{s(N)} - w_N)\tilde{v}_N + \frac{3}{2}\dot{\tilde{\nu}}\right] - $$
$$-(1+c^2_{s(N)})\left[\frac{k^2\tilde{\delta}_N\tilde{v}_N}{a^2H} + \frac{3}{2}\tilde{\delta}_N\dot{\tilde{\nu}}\right] = 0,$$

$$\dot{\tilde{v}}_N + (1-3c^2_{s(N)})\frac{\tilde{v}_N}{a} + \frac{c^2_{s(N)}\tilde{\delta}_N}{a^2H(1+w_N)} + \frac{\tilde{\nu}}{2a^2H} - \frac{4k^2\tilde{v}^2_N}{3a^2H} + $$
$$+\frac{1+c^2_{s(N)}}{1+w_N}\left[\dot{\tilde{\delta}}_N\tilde{v}_N + \tilde{\delta}_N\dot{\tilde{v}}_N + (1-3w_N)\frac{\tilde{\delta}_N}{a}\tilde{v}_N + \frac{\tilde{\nu}\tilde{\delta}_N}{2a^2H}\right] = 0.$$

w_N and $c^2_{s(N)}$ of components

Component	w_N	$c^2_{s(N)}$
radiation	$\frac{1}{3}$	$\frac{1}{3}$
dark matter	0	0
dark energy	w_{de}	1
baryons	$\frac{\Omega_r}{3(\Omega_r+\Omega_b a)}\left(\frac{n_{HII}}{n_H}\right)^2 + \frac{9.18\cdot 10^{-14}}{\mu_H} T_m \left(\frac{n_{HI}}{n_H}\right)^2$	$c^2_{s(b)} = w_b$

$$n_H = n_{HI} + n_{HII}$$

Initial conditions:

Let's present

$$\nu(a_{init}, r) = \tilde{\nu} f(r), \quad \delta_N(a_{init}, r) = \tilde{\delta}_N f(r), \quad v_N(a_{init}, r) = \tilde{v}_N f'(r),$$

where $f(0) = 1$ and $f'(r) \propto r$ near the center $r = 0$.

Asymptotic relations when $a \to 0$:

$$\tilde{\nu}^{init} = -C, \quad \tilde{\delta}_N^{init} = \frac{3}{4}(1 + w_N)C, \quad \tilde{v}_N^{init} = \frac{C}{4a_{init}H(a_{init})}.$$

Power spectrum of curvature perturbations: $\mathcal{P}_R(k) = A_s(k/0.05)^{n_s - 1}$.

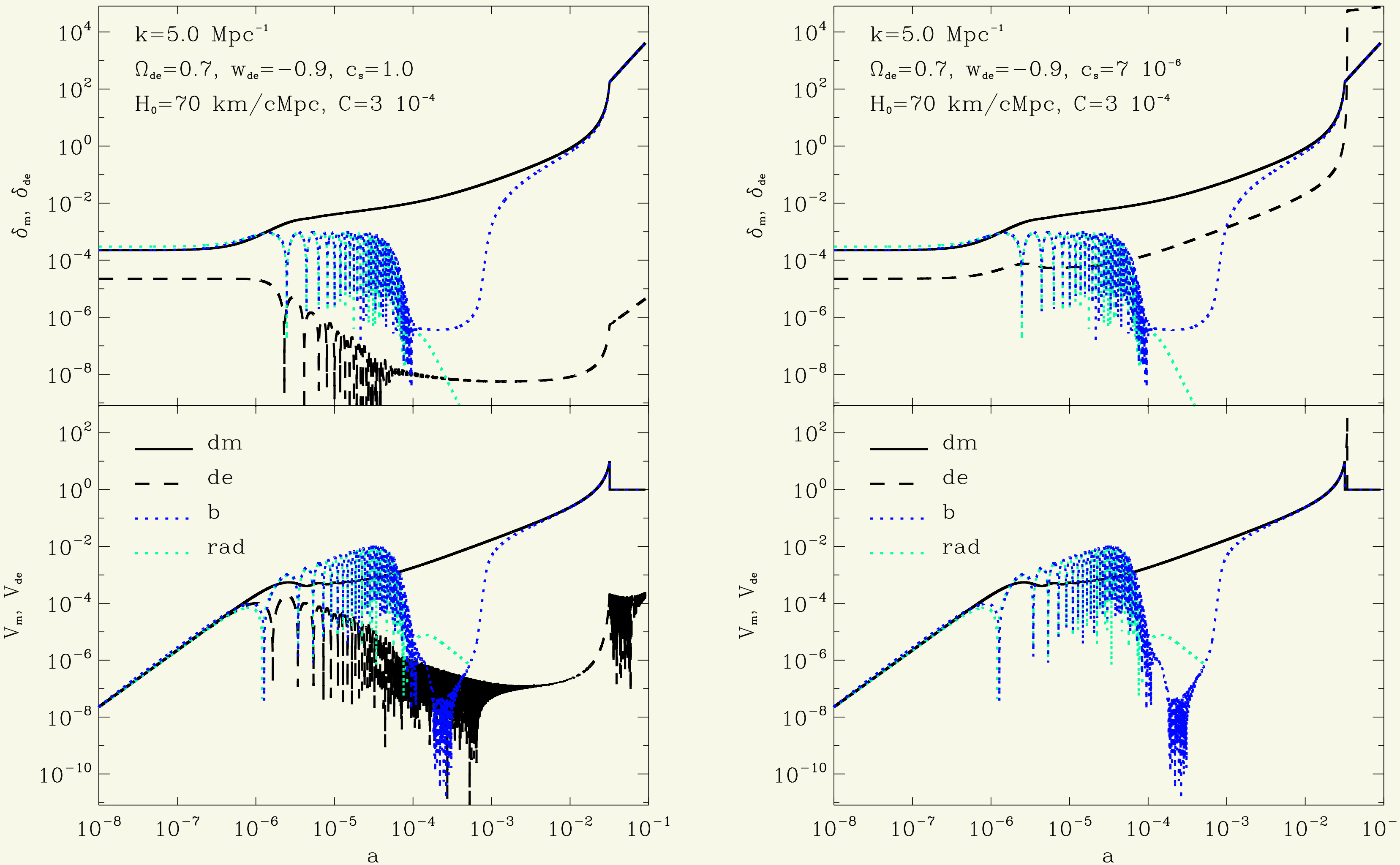
Planck2015 + HST + WiggleZ + SNLS3: $A_s = 2.19 \cdot 10^{-9}, \; n_s = 0.960$

For $ak^{-1} \gg ct \; \mathcal{P}_R \equiv \frac{9}{16} < \nu \cdot \nu >= const$

RMS amplitude: $\sigma \equiv < \nu \cdot \nu >^{1/2} \approx 5.7 \cdot 10^{-5} \left(\frac{5}{k}\right)^{\frac{n_s - 1}{2}}$.

We set $C \sim (1 - 3) \cdot 10^{-4} = (2 - 6)\sigma$ at $a_{init} = 10^{-8}$ for $k \sim (1 - 10)$ Mpc^{-1}.

Formation of dark matter halos in Dark Ages: results



Evolution of density and velocity perturbations of matter, dark energy, baryons and radiation which form halo with $M = 7 \cdot 10^8\,\mathrm{M}_{\odot}$. In the left panel the dark energy is scalar field with $c_s = 1$, in the right $c_s \ll 1$.

Density of dark matter and dark energy in halos

Density of baryonic matter:

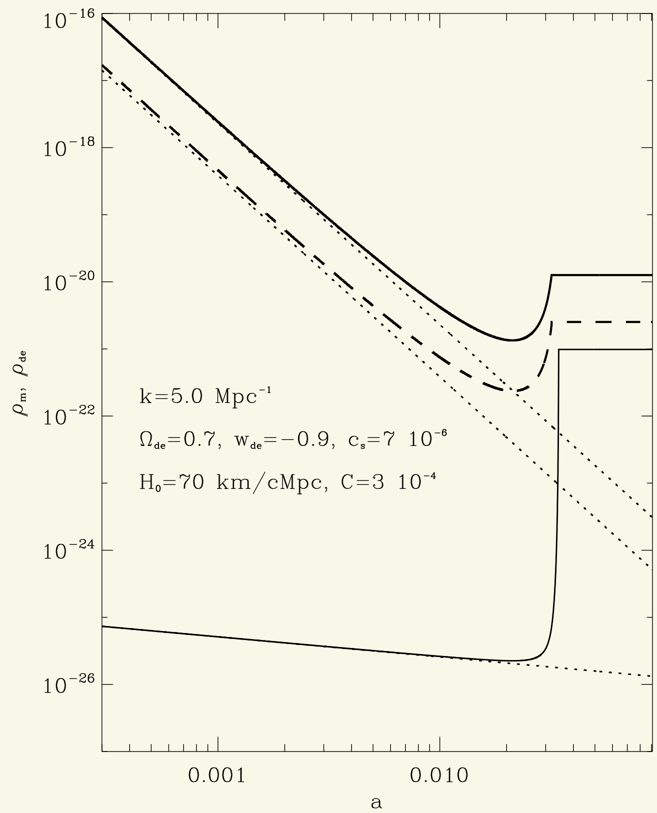
$$\rho_b = (1+\delta_b)\bar{\rho}_b, \quad \bar{\rho}_b = \frac{3H_0^2}{8\pi G}\Omega_b a^{-3};$$

Density of dark matter:

$$\rho_{dm} = (1+\delta_{dm})\bar{\rho}_{dm}, \quad \bar{\rho}_{dm} = \frac{3H_0^2}{8\pi G}\Omega_{dm} a^{-3};$$

Density of dark energy:

$$\rho_{de} = (1+\delta_{de})\bar{\rho}_{de}, \quad \bar{\rho}_{de} = \frac{3H_0^2}{8\pi G}\Omega_{de} a^{-3(1+w_{de})}.$$

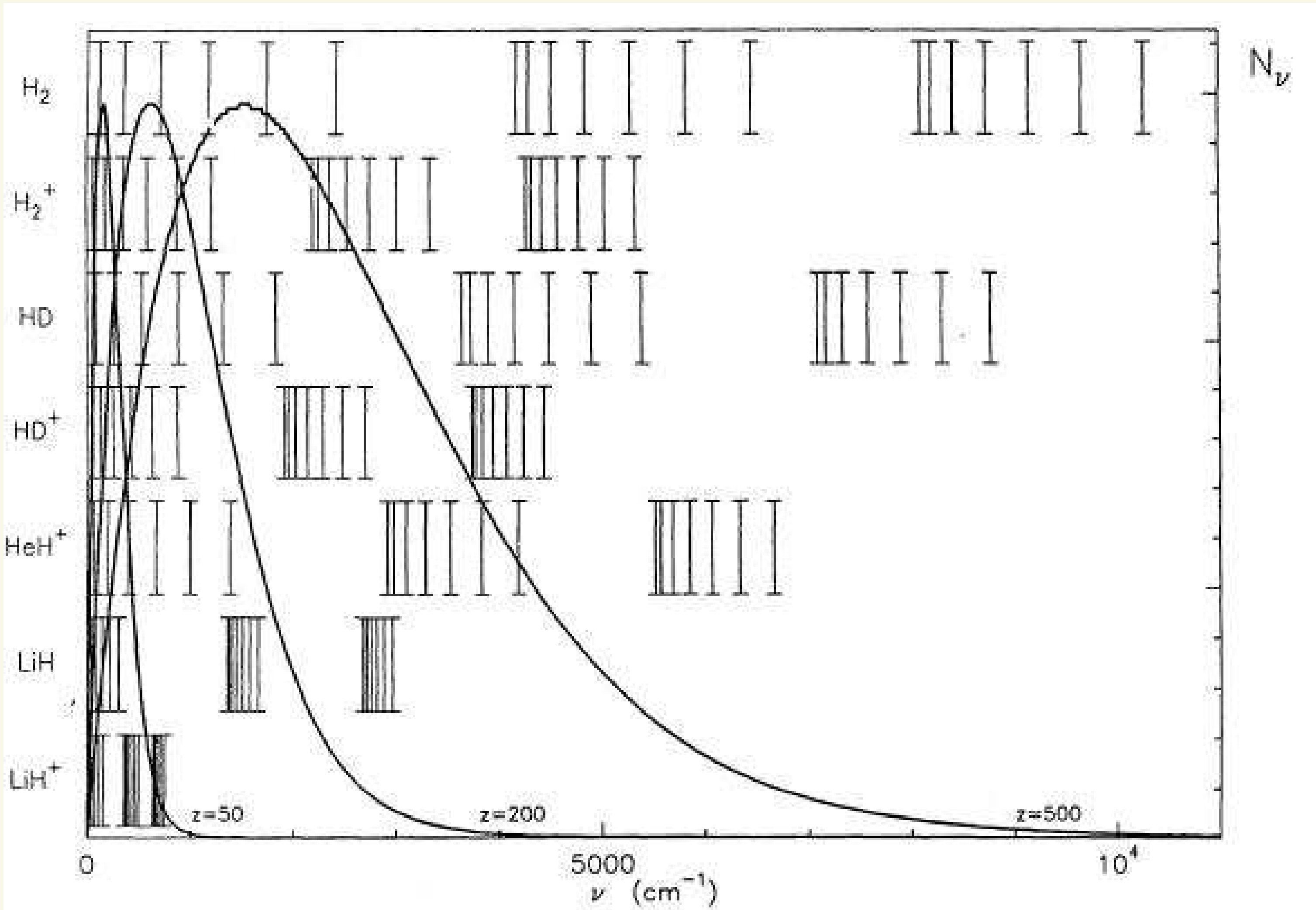


Dark energy density at the center of static halo has simple asymptotic for $\frac{r_g}{R_{halo}} \to 0$

$$\frac{\rho_{de}^{st}}{\bar{\rho}_{de}(z_v)} = 1 + 1.47 \cdot 10^{-4}\frac{1+w_{de}}{c_{s(de)}^2}(1+z_v)\Omega_m h^2\left(\frac{1\,Mpc}{k}\right)^2 \quad if \quad c_{s(de)} \neq 0. \qquad (1)$$

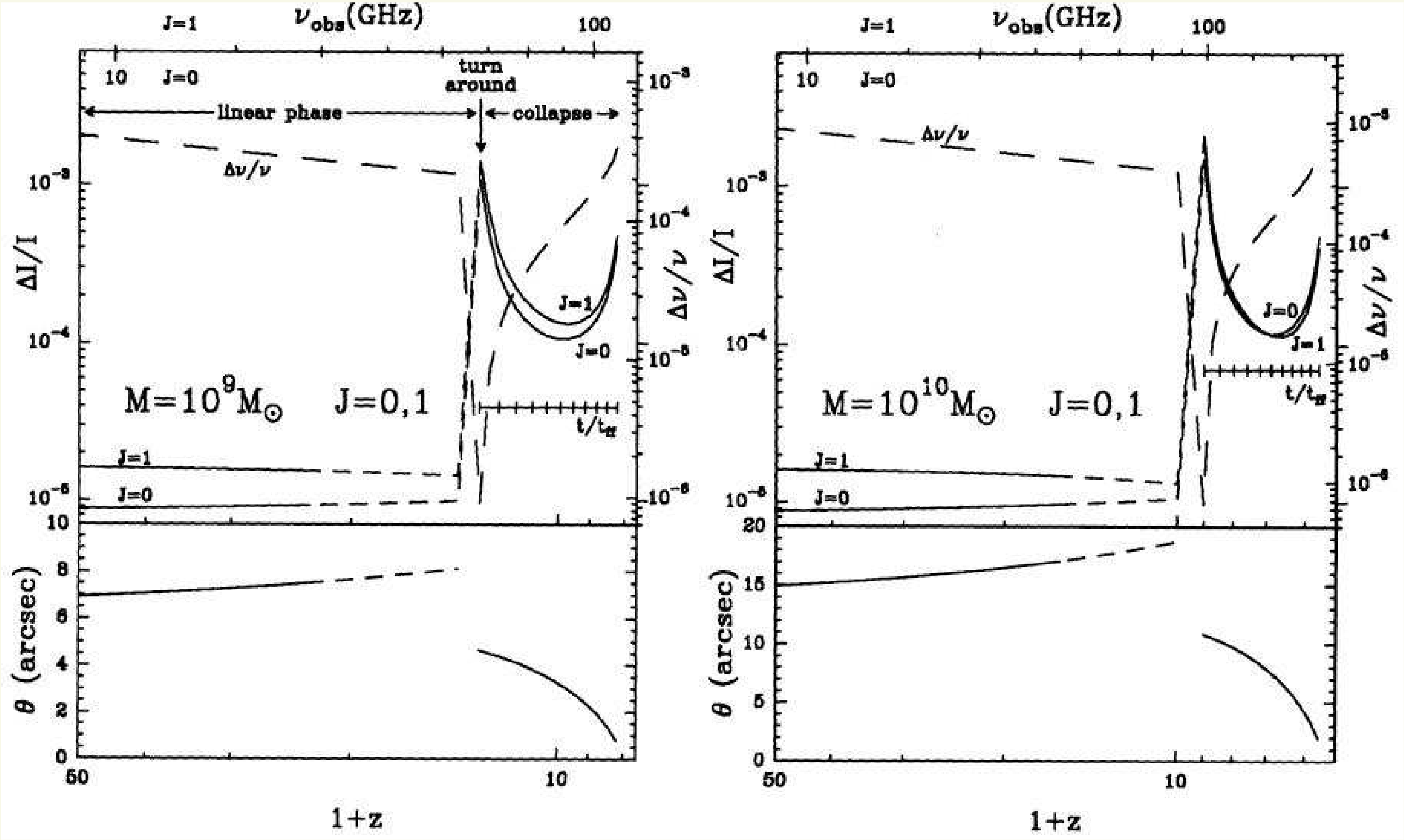
[Phys. Rev. D, 90, id.063004 (2014)]

Molecular signals from Dark Ages: expectation



[Maoli, Melchiorri, Tosti, ApJ, 425, 372 (1994)]

LiH lines J=0,1 from Dark Ages halos



[Maoli, Ferrucci, Melchiorri, Signore, Tosti, ApJ, 457, 1 (1996)]

Some review books:

Special issue on dark energy, *Eds. G. Ellis, H. Nicolai, R. Durrer, R. Maartens, Gen. Relat. Gravit.* ***40*** *(2008)*

Amendola L. and Tsujikawa S., *Dark Energy: Theory and Observations*, Cambridge University Press, 507 p. (2010)

Lectures on Cosmology: Accelerated expansion of the Universe. Lect. Notes in Physics **800**, Ed. G. Wolschin, Springer, 188 p. (2010)

Dark Energy: Observational and Theoretical Approaches, Ed. P. Ruiz-Lapuente, Cambridge University Press, 321 p. (2010)

Novosyadlyj B., Pelykh V., Shtanov Yu., Zhuk A., *Dark energy: observational evidence and theoretical models*, ed. V. Shulga, Akademperiodyka, Ukraine, 381 p. (2013)

Cosmology and Fundamental Physics with the Euclid Satellite, Amendola et al. (The Euclid Theory Working Group) (2016), arXiv:1606.00180

Conclusions III

- The dark matter halos can virialize at $z \approx 30$ if they are forming from high density peaks in the Gaussian field of initial density perturbations with $\delta_m^{init} \sim (5-6)\sigma_m$, where σ_m is rms density fluctuations computed for ΛCDM model with Planck2015 parameters.
- The dark matter halos which are forming from peaks with $\delta_m^{init} \sim (2-3)\sigma_m$ are virialized at $z \approx 10$, their number density are close to the number density of normal galaxies.
- The dark energy with low value of effective sound speed can be important for halo formation in Dark Ages.
- The key parameters of virialized halo - density and temperature, - depend on the moment of virialization a_v.

Thank you

for attention!