Crises, Tensions and Mysteries in Modern Cosmology

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Outline

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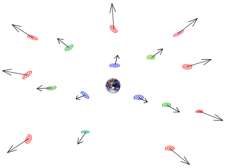
Conclusions from observations

The Universe is homogeneous, isotropic, hot and expanding...



Conclusions

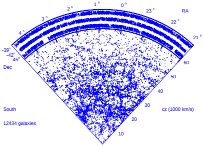
- interval between events gets modified

$$ds^2 = c^2\, dt^2 - a^2(t)\, d\mathbf{x}^2$$

in GR expansion is described by the Friedmann equation

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

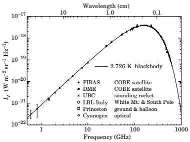
$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$



- in the past the matter density was higher, our Universe was “hotter” filled with electromagnetic plasma

$$\rho_{\text{matter}} \propto 1/a^3(t)\,, \quad \rho_{\text{radiation}} \propto 1/a^4(t)\,, \quad \rho_{\text{curvature}} \propto 1/a^2(t)$$

certainly known back to $T \sim 1\,\text{MeV} \sim 10^{10}\,\text{K}$



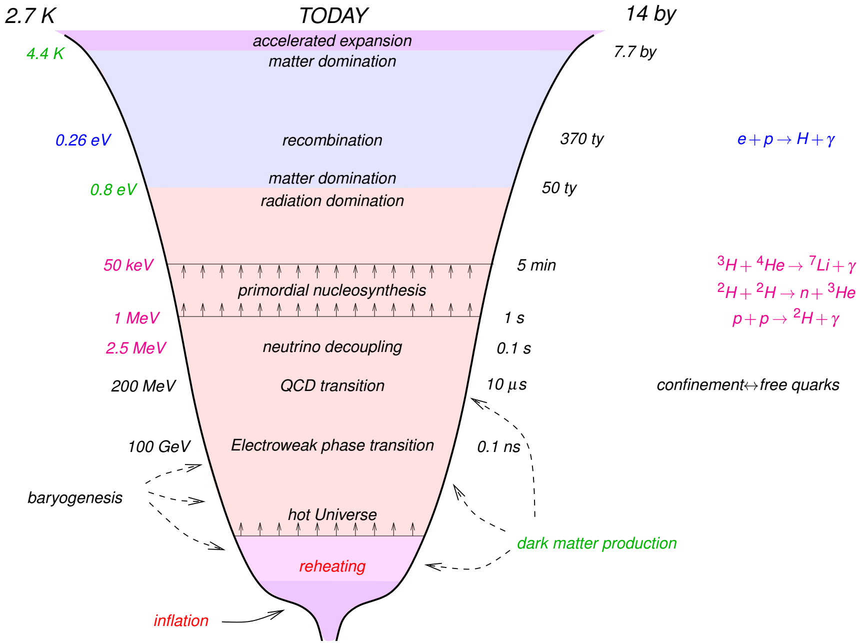
Standard cosmological model $ds^2 = dt^2 - a^2(t)dx^2$

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = H_0^2\left[\Omega_\Lambda + (\Omega_{DM} + \Omega_B + \Omega_{\nu,m\neq 0})\left(\frac{a_0}{a}\right)^3 + (\Omega_\gamma + \Omega_{\nu,m=0})\left(\frac{a_0}{a}\right)^4\right]$$

- $l_{s,rec} \sim l_{H,rec}/\sqrt{3} \rightarrow \quad H_0 = h \cdot 100\,\text{km/s/Mpc} \quad h = 0.67, \quad \Longrightarrow \quad \rho_0 = 5\,\text{GeV/m}^3$
- $T_\gamma = 2.735\,\text{K}, \quad \Longrightarrow \quad \Omega_\gamma \sim 10^{-5}$
- $N_\nu = 3.03.., \quad \Omega_\nu h^2 = \frac{\sum m_\nu}{93.12\,\text{eV}}, \quad \sum m_\nu < 0.2\,\text{eV} \quad \Longrightarrow \quad \Omega_{\nu,\neq 0}, \Omega_{\nu,0} \sim 10^{-5}$?
- $\Omega_B = 4.5\% \quad \Longrightarrow \quad \eta_B \equiv n_B/n_\gamma = 6 \times 10^{-10}$
- $\Omega_{DM} = 27.5\%$
- $\Omega_\Lambda = 68\% \quad \Longrightarrow$ flat space
- adiabatic, gaussian, almost flat matter perturbations

$$\langle\left(\frac{\delta\rho}{\rho}\right)^2\rangle \sim A_S \int \frac{dk}{k}\left(\frac{k}{k_*}\right)^{n_S - 1}$$

  with $A_S = 3 \times 10^{-9}$ and $n_S = 0.97$
- no tensor perturbations, $r \equiv A_T/A_S < 0.05$
- reionization at $z_{rei} \equiv a_0/a = 8$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TODAY
14 by
accelerated expansion
4.4 K
7.7 by
matter domination
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.8 eV
50 ty
radiation domination
50 keV
5 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

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List of long-standing problems

- What is Dark Energy?
- What is Dark Matter?
- BAU ?
- Why the Universe is flat, homogeneous and isotropic?
- What is the source of perturbations?
- Li^7 in BBN...
- Cores vs Cusps in the galaxy centers...
- Lack of dwarf galaxies...

Dark Energy: all evidences are from cosmology

Working hypothesis is cosmological constant $\Lambda \approx \left(2.5\times 10^{-3}\,\text{eV}\right)^4$:
$p = w(t)\rho$, $w = \text{const} = -1$, $\rho = \Lambda$

$$S_\Lambda = -\Lambda \int d^4x \sqrt{-\det g_{\mu\nu}}$$

both parts contribute

$$S_{\text{grav}} = -\frac{1}{16\pi G}\int d^4x \sqrt{-\det g_{\mu\nu}}\, R\,,$$
$$S_{\text{matter}} = \int d^4x \sqrt{-\det g_{\mu\nu}} \left(\frac{1}{2}g^{\lambda\rho}\partial_\lambda\phi\partial_\rho\phi - V(\phi)\right)$$

natural values

$$\Lambda_{\text{grav}} \sim 1/G^2 \sim \left(10^{19}\,\text{GeV}\right)^4, \quad \Lambda_{\text{matter}} \sim V(\phi_{vac}) \sim (100\,\text{GeV})^4, (100\,\text{MeV})^4, \ldots$$

Why Λ is small? Why $\Lambda \sim \rho_{\text{matter}}$? Why $\rho_B \sim \rho_{DM} \sim \rho_\Lambda$ today?

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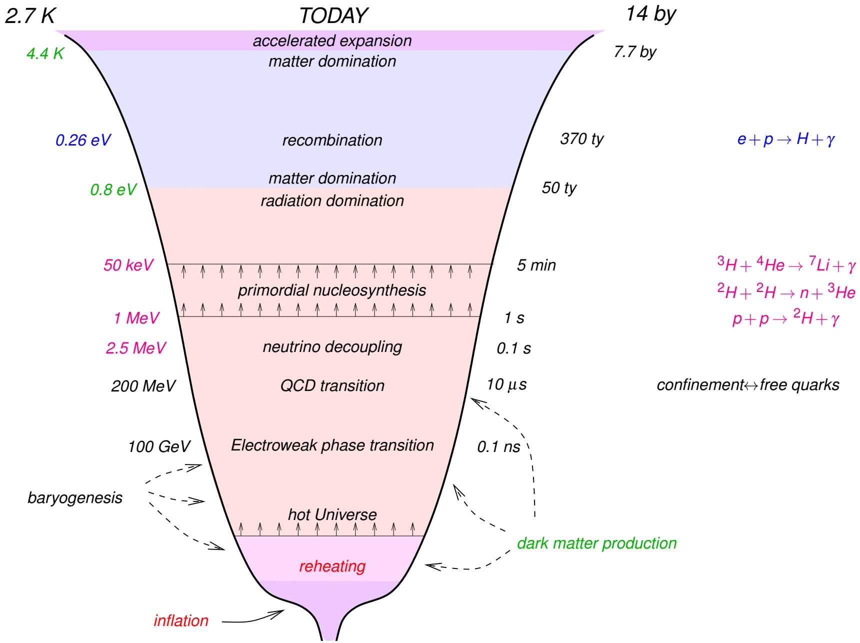
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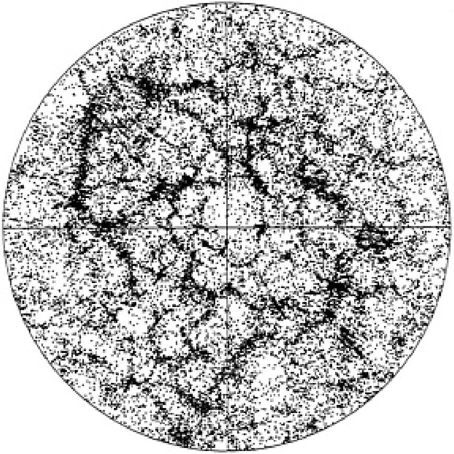
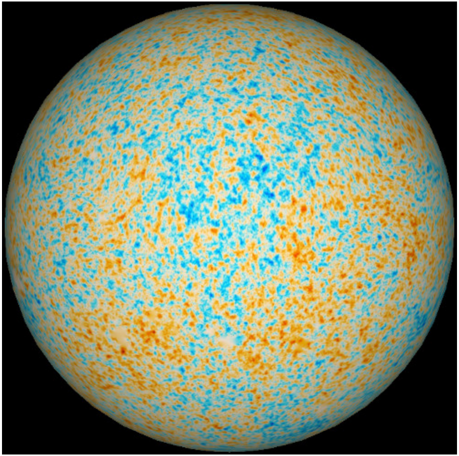
Inhomogeneous Universe

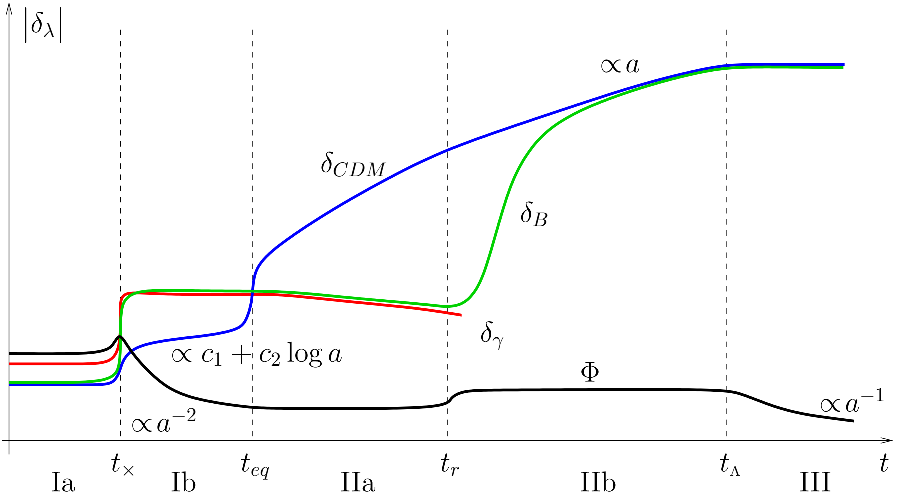


Large Scale Structure

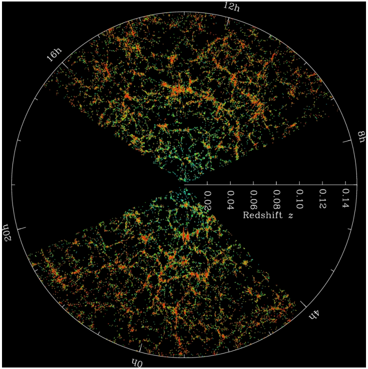


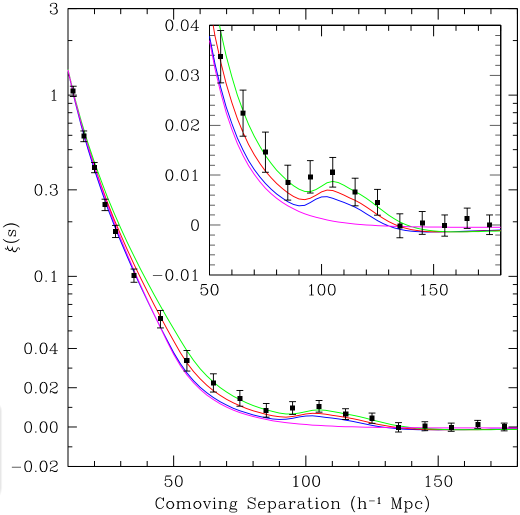
CMB anisotropy

Subhorizon modes ($k/a > H$) at various stages



Baryon Acoustic Oscillations (BAO), Sakharov





peak at $r_s \approx 147\,\mathrm{Mpc}$

$$\xi_z(s) \propto \frac{\langle n_z(\vec{x})\, n_z(\vec{x}+\vec{z})\rangle_{\vec{x}}}{n_z\, n_z}$$

Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. stable on cosmological time-scale

   requires new (almost) conserved quantum number

2. produced in the early Universe

   some time before RD/MD-transition ($T = 0.8\,\text{eV}$)

3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies: $l_{fs} = a\int v(t)dt/a(t)$
   smoothed out by free streaming

   If were in thermal equilibrium: $M_X \gtrsim 1$ keV

4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$
5. (almost) electrically neutral CMB distortion
6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Dark Matter properties from astrophysics

1. stable on cosmological time-scale
2. (almost) collisionless — to form ellipsoidal halos
3. (almost) electrically neutral — to be Dark
4. stability of globular stellar clusters — $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV
   otherwise too strong tidal forces
5. confinement in a galaxy: — quantum physics!

   de Broglie wavelength: $\lambda = 2\pi/(M_X v_X) < l_{\text{galaxy}}$, — for bosons

   in a galaxy
   $v_X \sim 0.5 \cdot 10^{-3}$ $\longrightarrow$ $M_X \gtrsim 3 \cdot 10^{-22} \to 10^{-20}$ eV

   for fermions

   Pauli blocking: $M_X \gtrsim 0.75 \to 1.5$ keV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_X(\mathbf{x})}{M_X} \cdot \frac{1}{\left(\sqrt{2\pi} M_X v_X\right)^3} \cdot e^{-\frac{\mathbf{p}^2}{2M_X^2 v_X^2}}\Bigg|_{\mathbf{p}=0} \leq \frac{g_X}{(2\pi)^3}$$

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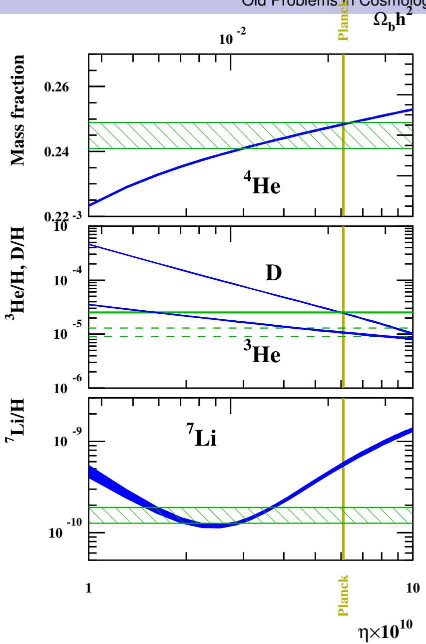
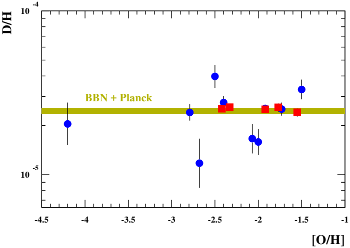
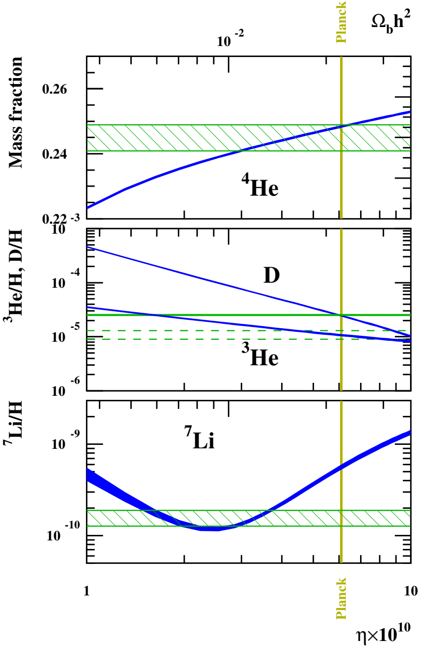


1707.01004 Measurement of $\eta_B = n_B/n_\gamma$ at $T \sim 1$ MeV



Sakharov conditions for successful baryogenesis:

1) $\Delta B \neq 0$
2) $\Delta C \neq 0$, $\Delta CP \neq 0$
3) out-of-equlibrium



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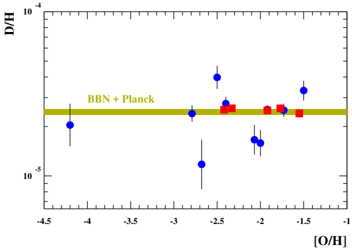
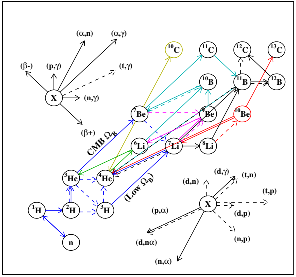


Lack of Lithium. . .

Exotics needed?



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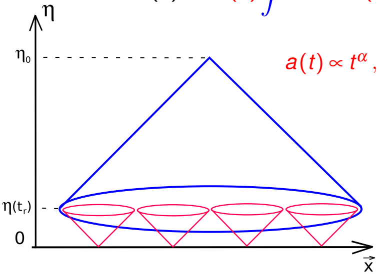
Horizon problem $l_H(t)$

a distance covered by photon emitted at $t = 0$

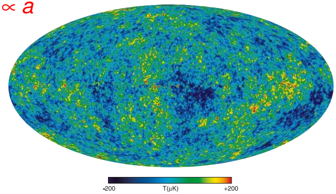
size of the causally connected part, that is the visible part of the Universe (“inside horison”)

$$ds^2 = dt^2 - a^2(t)\,dx^2 = a^2(\eta)\left(d\eta^2 - dx^2\right) \qquad ds^2 = 0$$

$$l_H(t) = a(t)\int dx = a(t)\int d\eta = a(t)\int_0^t \frac{c\,dt'}{a(t')} \propto t \quad \propto 1/H(t)$$



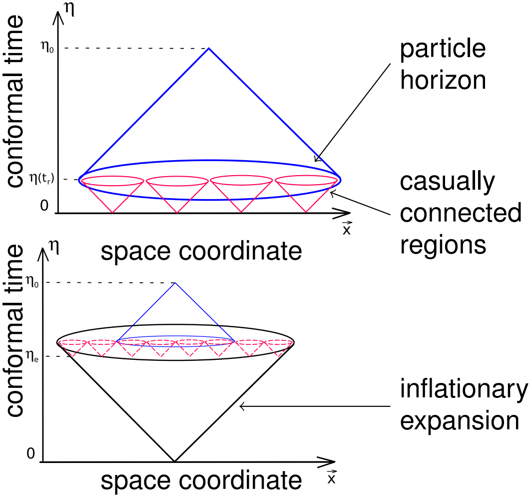
$a(t) \propto t^{\alpha}\,,\ 0 < \alpha < 1\,,\ L_{phys} \propto a$

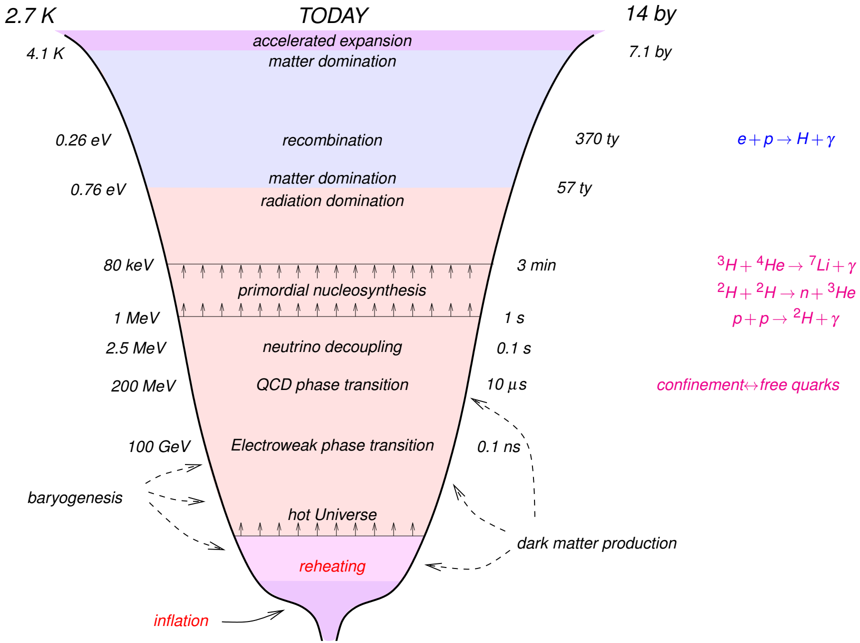


$$l_{H_0}/l_{H,r}(t_0) \sim l_{H_0}/l_{H,r}(t_r)\,a(t_r)/a_0 \sim H_r/H_0\,a(t_r)/a_0 \sim \sqrt{1+z_r} \simeq 30$$

Inflationary solution of Hot Big Bang problems

- no initial singularity in dS space
- all scales grow exponentially, including the radius of the 3-sphere
  the Universe becomes exponentially flat
- any two particles are at exponentially large distances
  no heavy relics
  no traces of previous epochs!
- no particles in post-inflationary Universe
  to solve entropy problem we need post-inflationary reheating





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Chaotic inflation at large fields: graceful exit

If $V(\phi)$ dominates by chance

Chaotic inflation, A.Linde (1983), A.Linde (1984)

$$\ddot{\phi} - \Delta\phi/a^2 + 3H\dot{\phi} + V'(\phi) = 0$$

for power-law potential at $\phi > M_{Pl}$

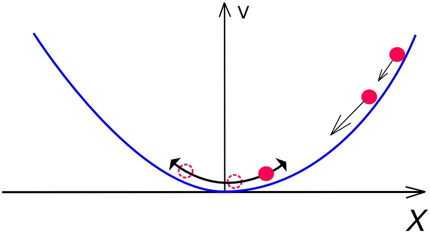
$$V \simeq \text{const}$$

"slow roll" solution

$$H^2 = \frac{8\pi}{3M_P^2} V(\phi)\,, \quad a(t) \propto e^{Ht}$$

valid while slow roll conditions

$$M_P^2 \frac{V''}{V} \ll 1\,, \quad M_P^2 \frac{V'^2}{V^2} \ll 1$$



Inflaton must couple to Standard Model fields to reheat the Universe after inflation

Quantum perturbations at inflation

$$\ddot{\varphi}_k + 3H\dot{\varphi}_k + \frac{k^2}{a^2}\varphi_k = 0$$

conformal time, rescaled field: $dt \equiv a(\eta)d\eta, \quad \phi \equiv \chi/a(\eta)$:

$$a = -\frac{1}{H\eta}, \quad \frac{k}{a} = H \quad \longrightarrow \quad k\eta = 1$$

$$\chi_k'' + \left(k^2 - \frac{2}{\eta^2}\right)\chi_k = 0$$

classical solutions

$$\chi_k = C_1 \times e^{ik\eta}\left(1 + \frac{i}{k\eta}\right) + C_2 \times e^{-ik\eta}\left(1 - \frac{i}{k\eta}\right)$$

Unexpected bonus: generation of perturbations

- Quantum fluctuations of wavelength λ of a free massless field φ have an amplitude of $\delta\varphi_\lambda \simeq 1/\lambda$
- In the expanding Universe: $\lambda \propto a$

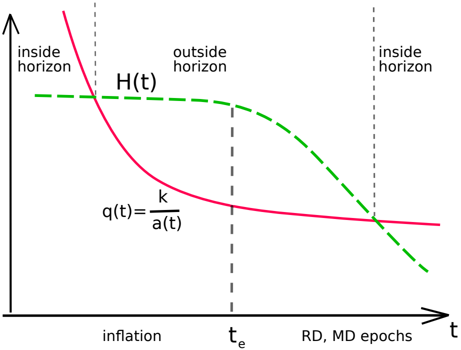
inflation: $l_H \sim 1/H = \text{const}$, so modes “exit horizon”
Ordinary stage: $l_H \sim 1/H \propto t$, $l_H/\lambda \nearrow$, modes “enter horizon”

Evolution at inflation

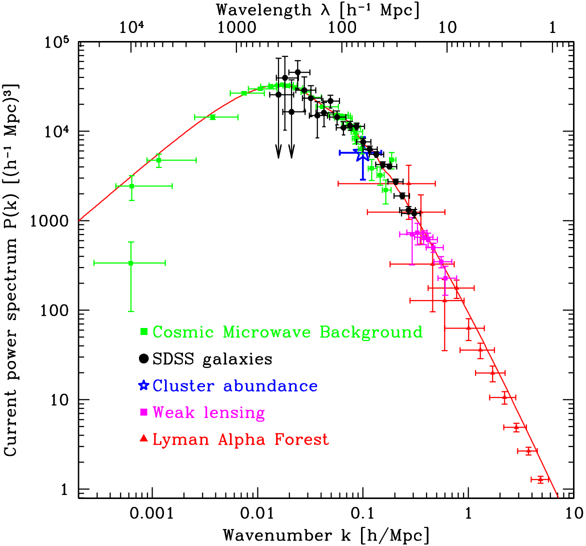
- inside horizon: $\lambda < l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda \propto 1/\lambda \propto 1/a$

- outside horison: $\lambda > l_H$
  $\lambda \propto a \Rightarrow$ $\delta\varphi_\lambda = \text{const} = H_{infl}$!!!

- got “classical” fluctuations:
  $\delta\varphi_\lambda = \delta\varphi_\lambda^{quantum} \times e^{N_e}$



Actually we observe rather narrow range



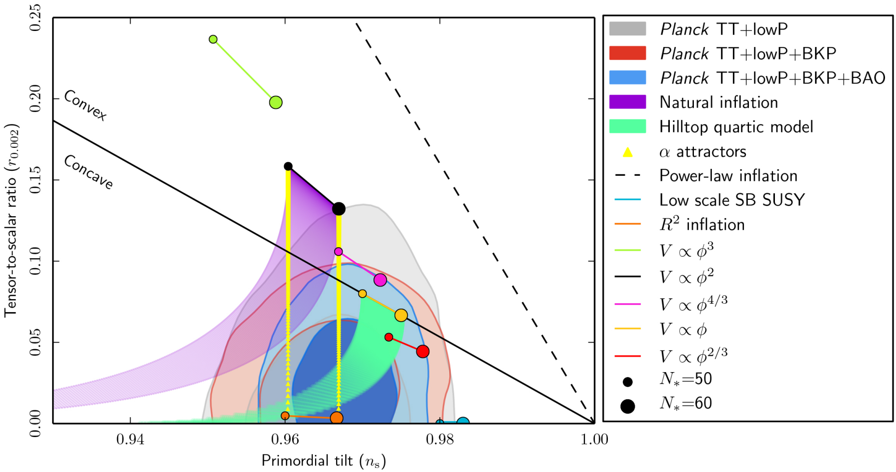
Observable range:

$$\frac{k_{max}}{k_{min}} \sim 10^5$$

$$\Delta N_e \simeq 10$$

Small scales cannot describe:
for a long time in nonlinear regime

Planck 2015 bounds on tensor perturbations



$$r = \frac{A_T}{A_S} \propto \frac{\dot{\phi}^2}{H^2 M_{Pl}^2} \propto \left(\frac{V'}{V}\right)^2 \ll 1$$

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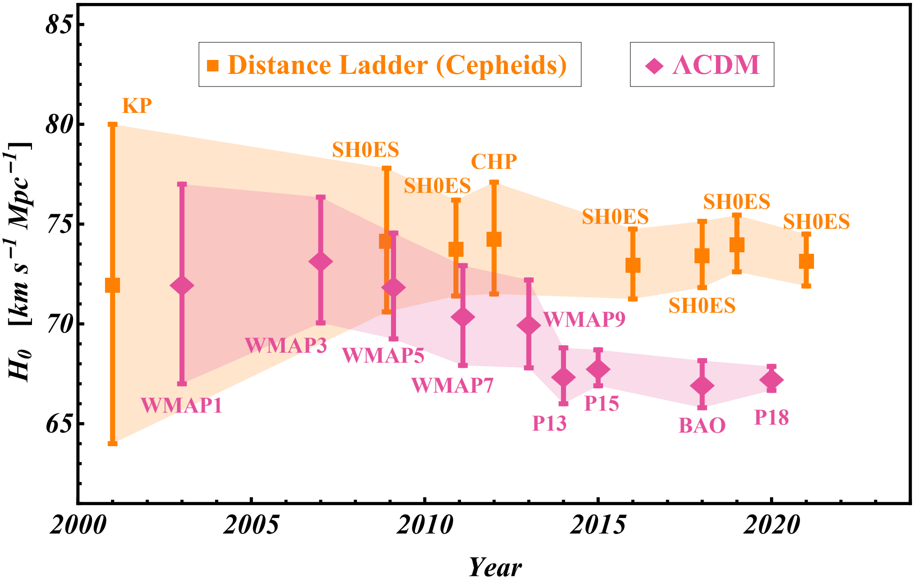
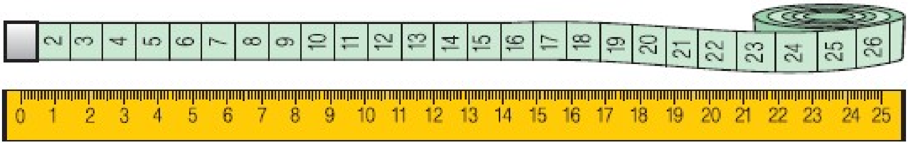
- σ_8 tension... 3-2-1 σ
- Various tensions between different sets of data...



Distance Ladder (Cepheids)
ΛCDM
KP
SH0ES
SH0ES
CHP
SH0ES
SH0ES
SH0ES
SH0ES
WMAP1
WMAP3
WMAP5
WMAP7
WMAP9
P13
P15
BAO
P18
H_0 [$km\ s^{-1}\ Mpc^{-1}$]
85
80
75
70
65
2000
2005
2010
2015
2020
Year

2105.05208

Distance ladder... from observer



MEASURE

- size of the Earth orbit

$$2\pi R = v \times 1\,\text{year}$$

- distance through angle (annual paralax)

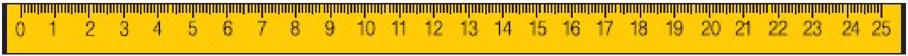
$$L = \theta \times 2R$$

- luminosity F via brightness J and distance

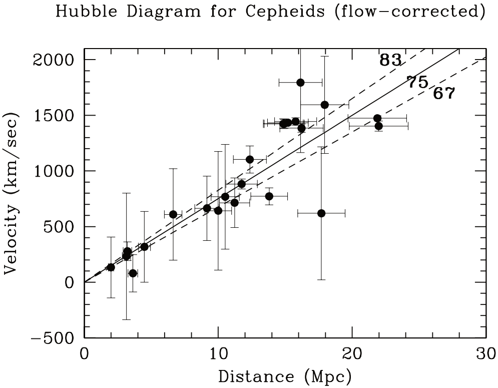
$$J = \frac{F}{4\pi L^2}$$

- find a relation between F and other observable (frequency of bursts, decay rate, ...) – the standard candle is defined !

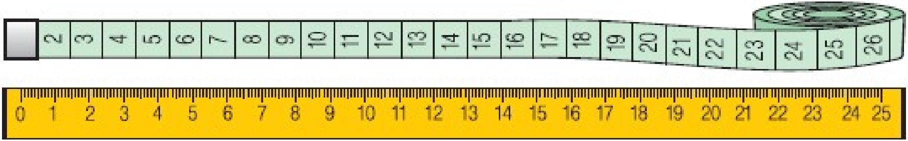
Distance ladder... from observer



Measure luminosity with brightness and distance



Distance ladder... from cefeids to supernovae

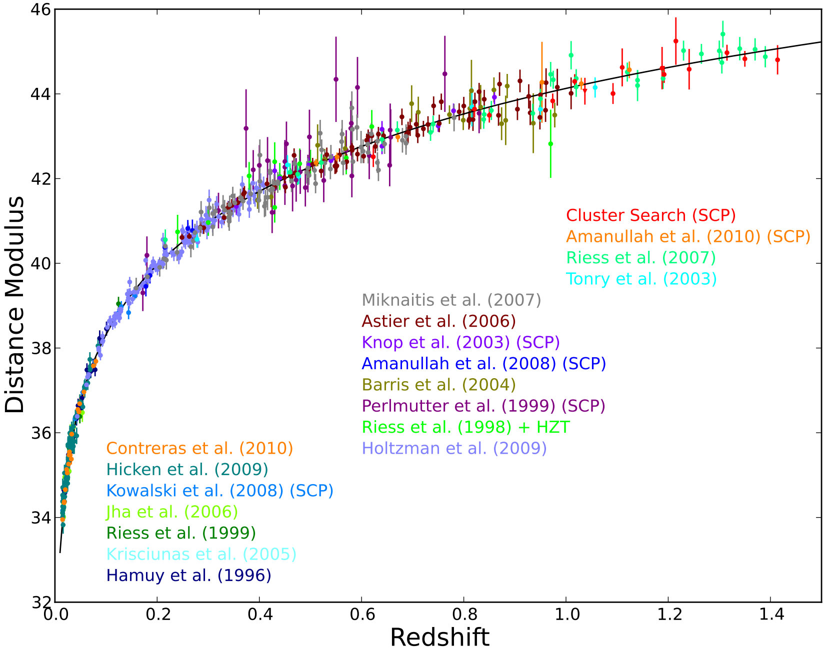


Measure the brightness J of the object of luminosity F – "standard candles"

$$J = \frac{F}{4\pi L^2} \longrightarrow J = \frac{F}{4\pi L^2 (1+z)(1+z)} \qquad \frac{\text{energy}}{\text{time} \times \text{area}}$$

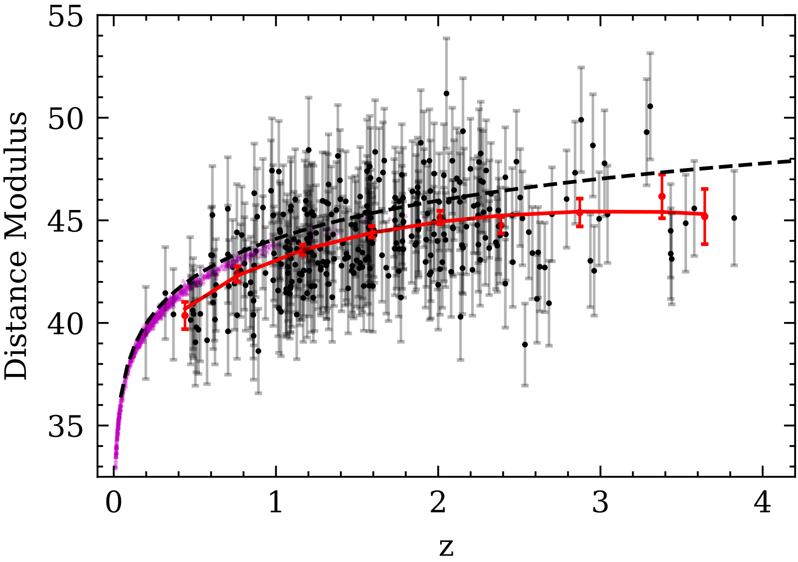
In the expanding Universe it gets modified

$$J = \frac{F}{4\pi {d_{ph}}^2}\,, \qquad \text{where} \qquad d_{ph} \equiv (1+z) \times L = (1+z)\int_0^z \frac{dz'}{H(z')}$$

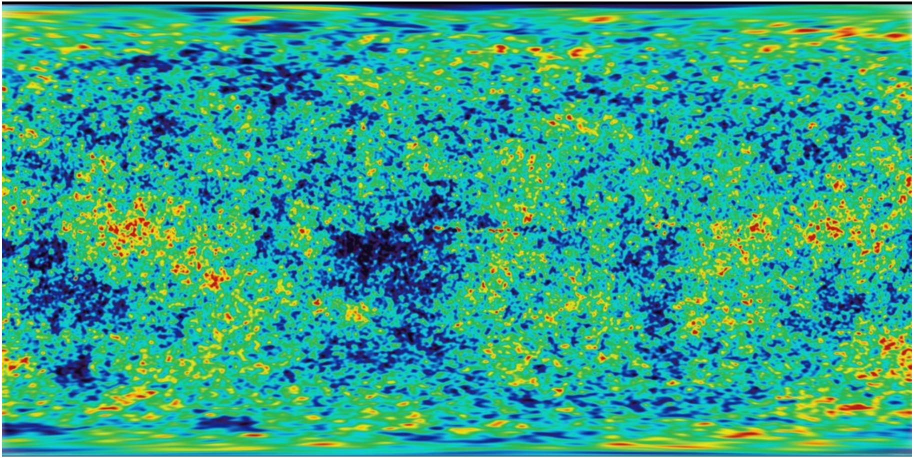

46
44
42
40
38
36
34
32
Distance Modulus
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Redshift
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter et al. (1999) (SCP)
Riess et al. (1998) + HZT
Holtzman et al. (2009)
Contreras et al. (2010)
Hicken et al. (2009)
Kowalski et al. (2008) (SCP)
Jha et al. (2006)
Riess et al. (1999)
Krisciunas et al. (2005)
Hamuy et al. (1996)

Next step is quasars

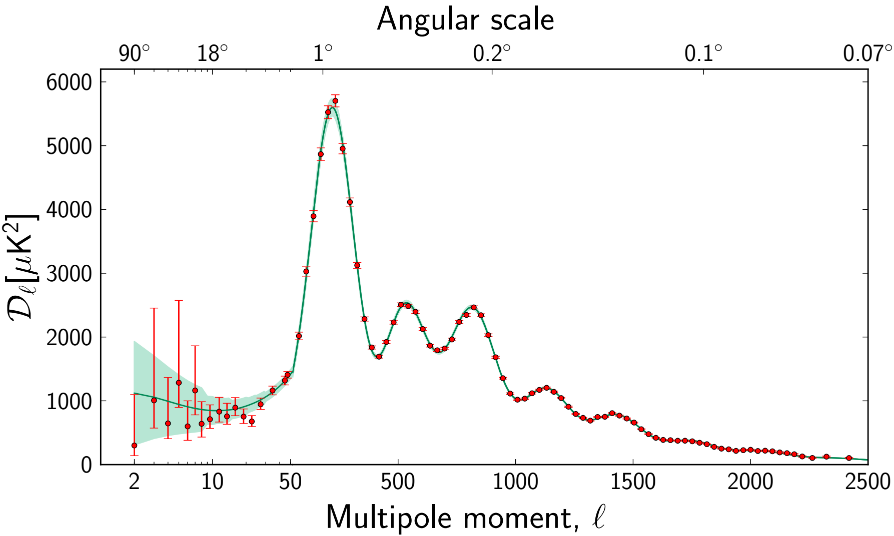
2110.03671



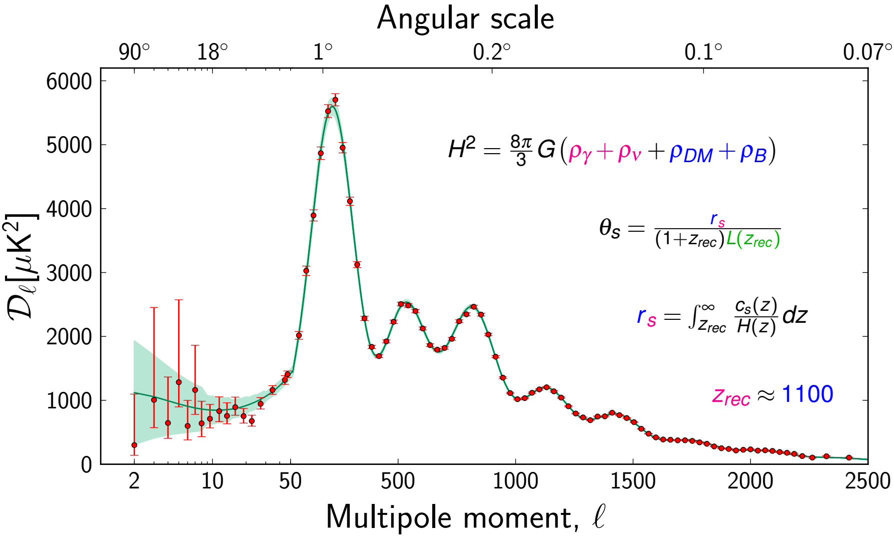
CMB map



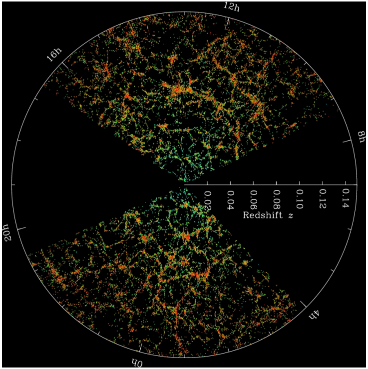
fit to ΛCDM model $\theta_{rec}, \Omega_{DM}h^2, \Omega_B h^2, z_{rei}, A_S, n_s$

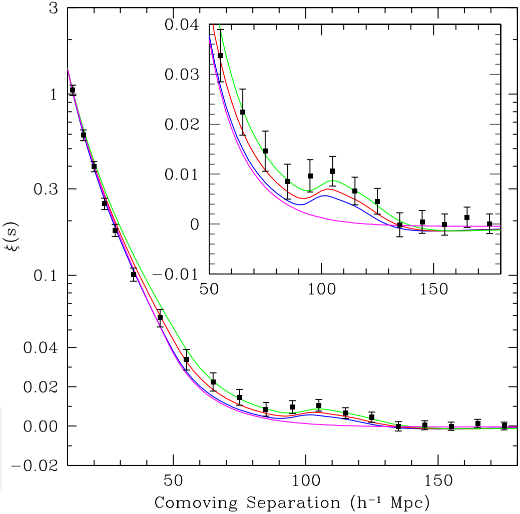


The way to infer the Hubble constant



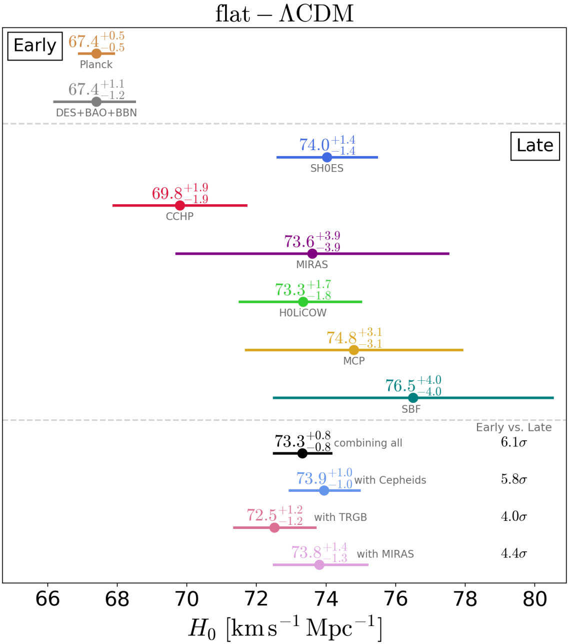
Baryon Acoustic Oscillations (BAO), Sakharov



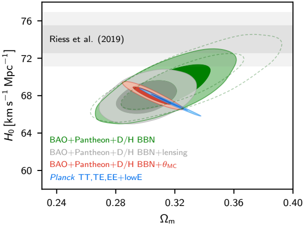


peak at $r_s \approx 147\,\mathrm{Mpc}$

$$\xi_z(s) \propto \frac{\langle n_z(\vec{x})\, n_z(\vec{x}+\vec{z})\rangle_{\vec{x}}}{n_z\, n_z}$$



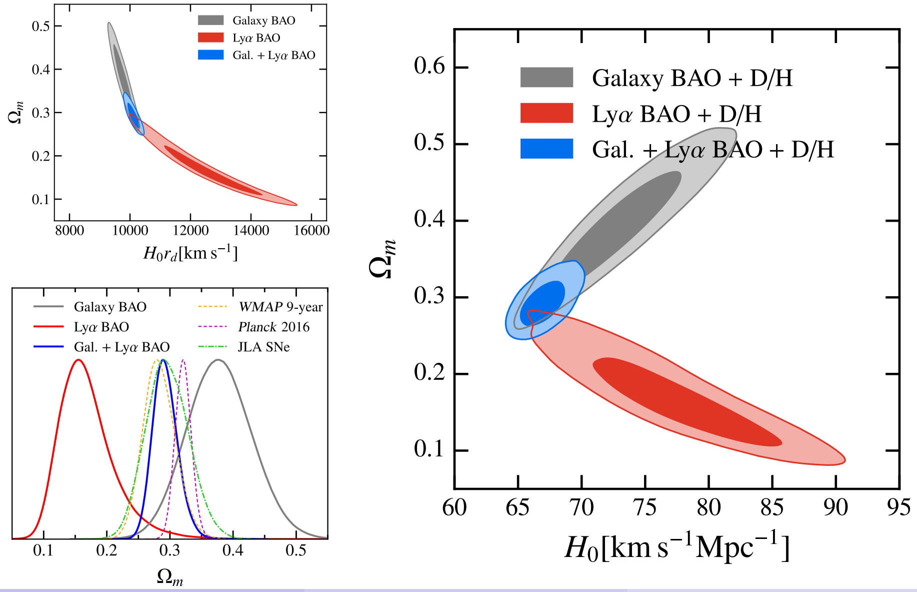
1807.06209



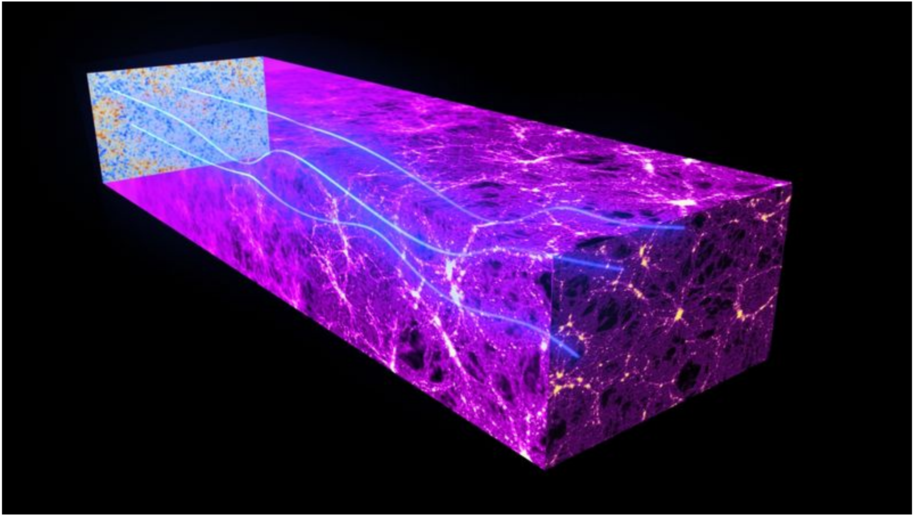
1907.10625

Impact of BAO: Galaxies vs Ly-α

1707.06547

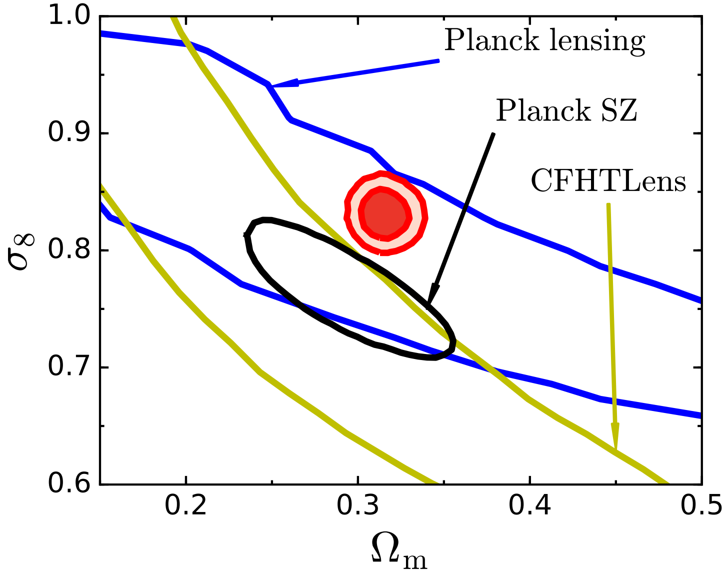


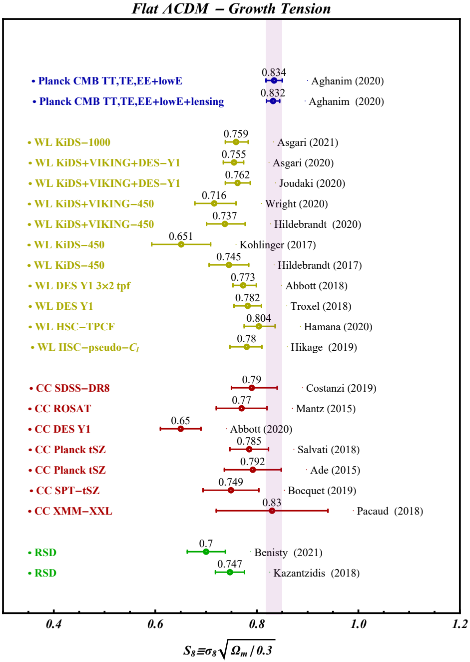
Matter in expanding Universe



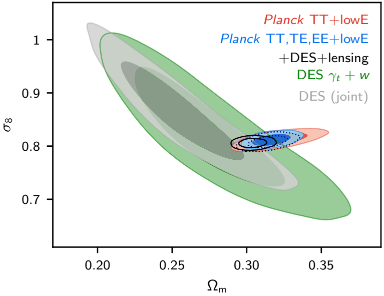
Lensing vs clusters

1801.07348





2105.05208



1807.06209

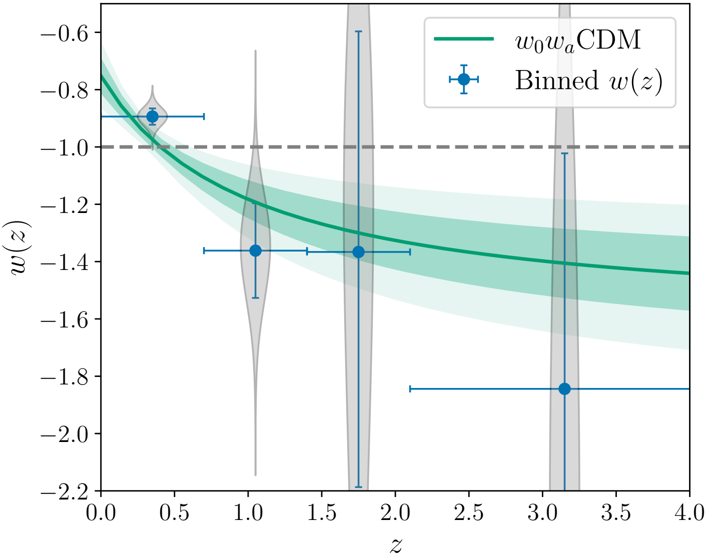
Outline

New Problems in Cosmology

- DESI (DR2 BAO) observes DE evolution: the phantom crossing in the past!!
- CMB anisotropy: ACT excludes (2σ) “simple” single models (including Starobinsky, Linde&Kalosh attractors etc)
- JWST&ALMA observes old galaxies in the young Universe ($z \simeq 10$)
- JWST observes Superheavy ($10^6\,M_\odot$) BH in the young Universe ($z \simeq 10$)
- LIGO&VIRGO observe GW from $10^2\,M_\odot$ mass scale binary BHs

Results of DESI: DE evolution $p = \omega(z)\rho$

2503.14738



$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3}\rho$

$\dot{\rho} + 3H(\rho + p) = 0$

$\omega = -1$: $p = -\rho$ gives $\rho = \text{const}$

$\omega > -1$ gives $\rho \searrow$

$\omega < -1$ gives $\rho \nearrow$

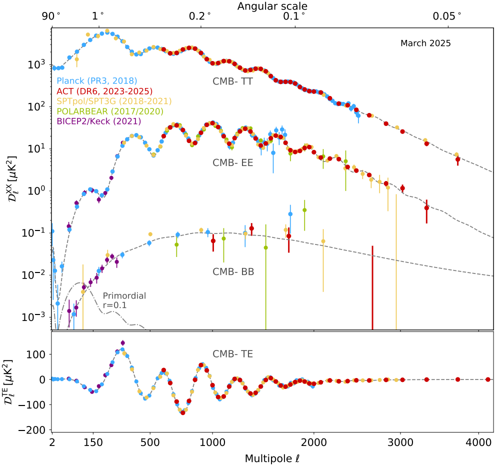
$\omega = 0$ is an oscillator: $\langle E_k \rangle = \langle E_p \rangle$ dark matter

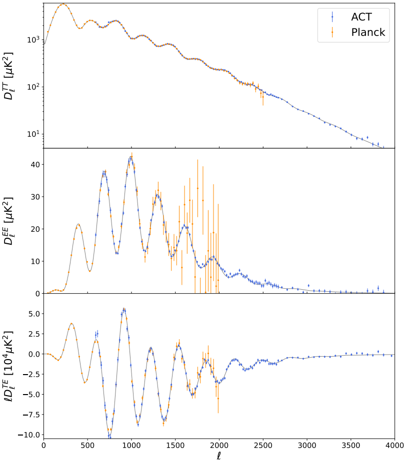
$\delta p = c_s^2 \delta\rho$

$\frac{\frac{1}{2}\dot{\phi}^2 + V(\phi)}{\frac{1}{2}\dot{\phi}^2 - V(\phi)} < -1$

All CMB data (ACT !!)

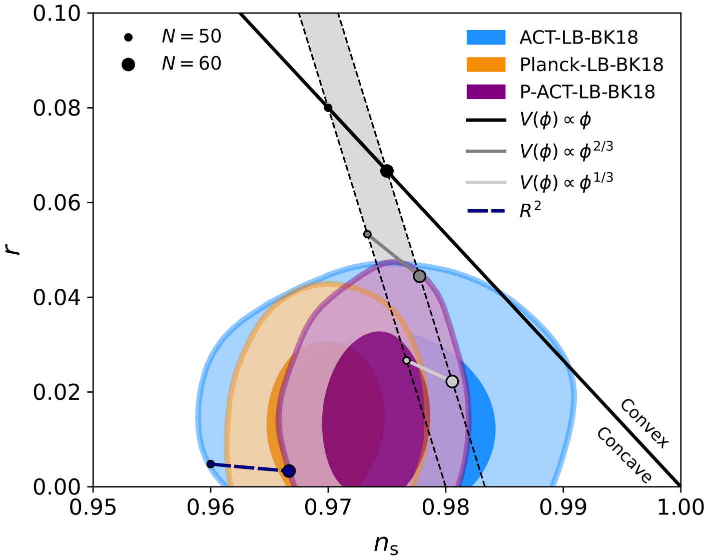
2503.14452





Simple models are excluded

2503.144454



Problems in Cosmology: Multicomponent solutions?

- Hubble crisis: 67.4 ± 0.5 (Planck) vs 73.0 ± 1.0 (SH0ES)
- σ_8 tension... 3-2-1 σ
- DESI (DR2 BAO) observes DE evolution: the phantom crossing in the past!!

- CMB anisotropy: ACT excludes (2σ) “simple” single models (including Starobinsky, Linde&Kalosh attractors etc)
- JWST&ALMA observes old galaxies in the young Universe ($z \simeq 10$)
- JWST observes Superheavy ($10^6\,M_\odot$) BH in the young Universe ($z \simeq 10$)
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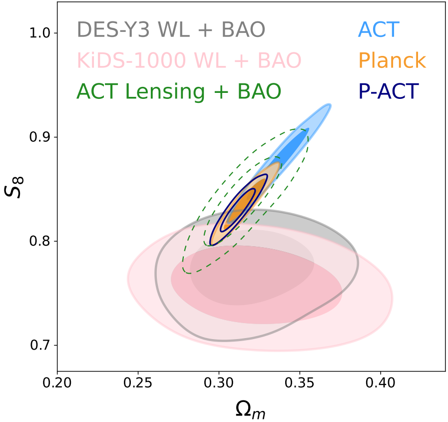
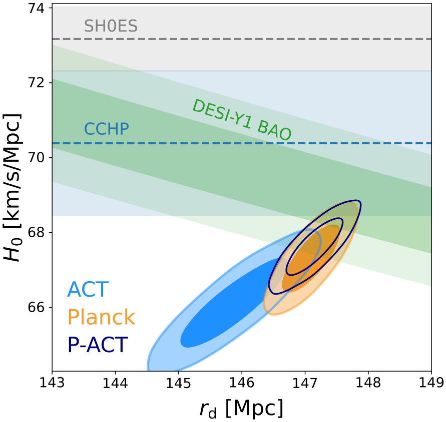
ACT and crisis and tensions

2503.14452





ACT and standard cosmology

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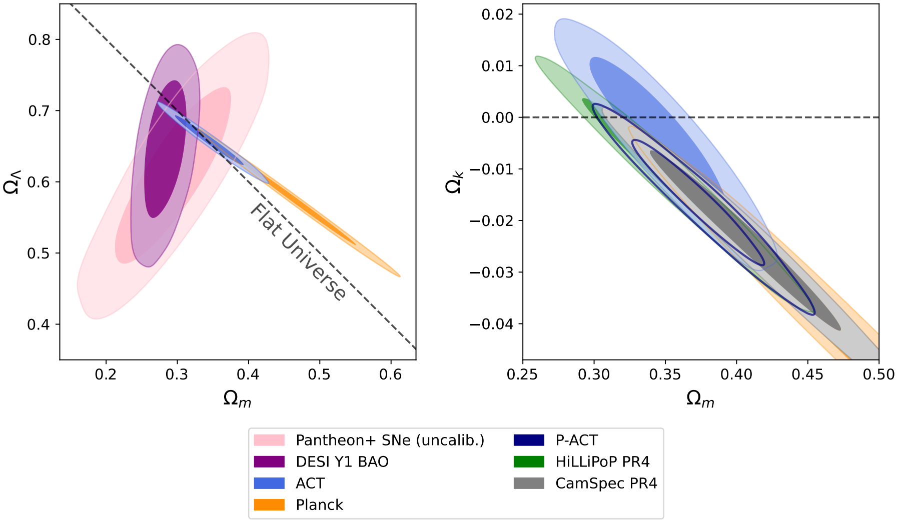

ACT and non-standard cosmology

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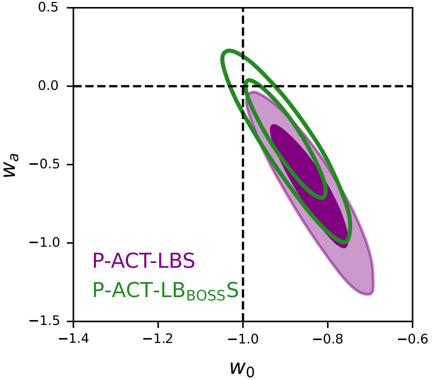

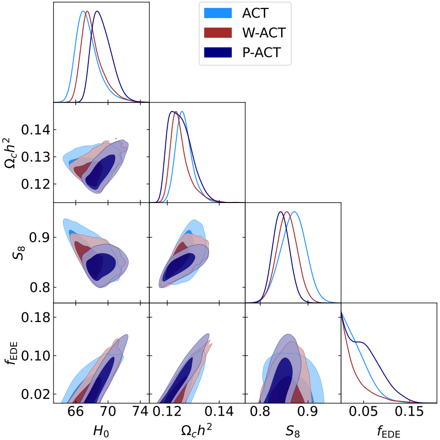

Cosmological data and neutrino masses

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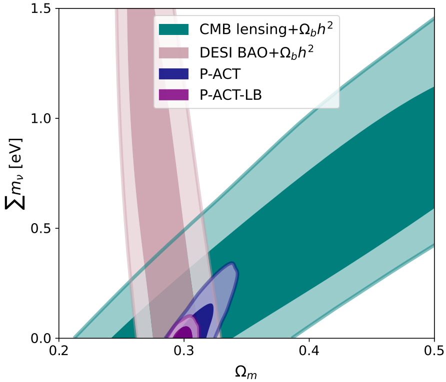

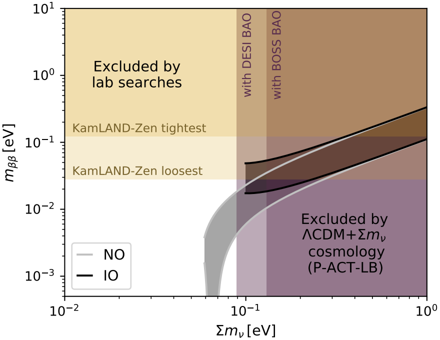

CMB, Lensing, BAO

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