Anomalies and discrepancies in cosmology: How long till it starts feeling good?

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Experimenal data in Particle Physics

- We know the initial states of particles before interaction,
  use photons, electrons, positrons, protons, neutrons, ions, neutrinos...
- Then they collide and we measure the particles in the final state
- Thus we learn about interaction
- Each experiment may be repeated:
  – with the same facility
  – building a copy in the same or other place
  – constructing similar devise
  ...
  And results must be the same
  ...on average within QM need many collisions

  theory predicts distributions

Experimenal data in Cosmology and Astrophysics

- Each experiment may be unique (unrepeatable):
  – observe only one Universe
  – (so far) registered only one SN explosion
  – might observe only one magnetic monopole (?)
  – can study only one star
  – (so far) can study only one planet
  ...
- we register photons, neutrinos, gravitational waves, electrons, positrons, protons, nuclei,
  but only photons, neutrinos and gravitational waves can point at the source
- Can not directly check the model of sources
- Can not directly check the media in between

Outline

1. General facts, key observables and ΛCDM model
2. Anomalies
   - BBN: Lithium, mostly
   - CDM problems at small scales
   - CMB anisotropy
3. Discrepancies: Hubble, clusters, lensing…
   - Cosmological data
   - What can be behind…

"Natural" units in particle physics

$$\hbar = c = k_B = 1$$

measured in GeV: energy E, mass M, temperature T

$m_p = 0.938$ GeV, $1\ \text{K} = 8.6 \times 10^{-14}$ GeV

measured in GeV^{-1}: time t, length L

$1\ \text{s} = 1.5 \times 10^{24}\ \text{GeV}^{-1}$, $1\ \text{cm} = 5.1 \times 10^{13}\ \text{GeV}^{-1}$

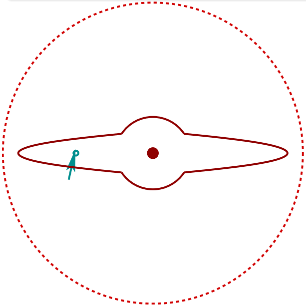
Gravity (General Relativity): $V(r) = -G\frac{m_1 m_2}{r}$ $[G] = M^{-2}$

$$M_{\text{Pl}} = 1.2 \times 10^{19}\ \text{GeV} = 22\ \mu\text{g} \qquad G \equiv \frac{1}{M_{\text{Pl}}^2}$$

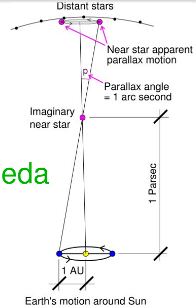
"Natural" units in cosmology

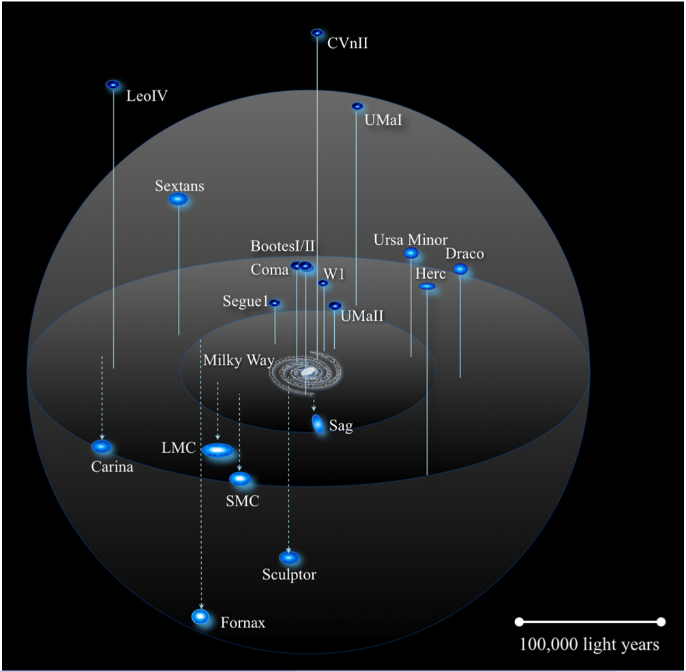
$$1\ \mathrm{Mpc} = 3.1 \times 10^{24}\ \mathrm{cm}$$

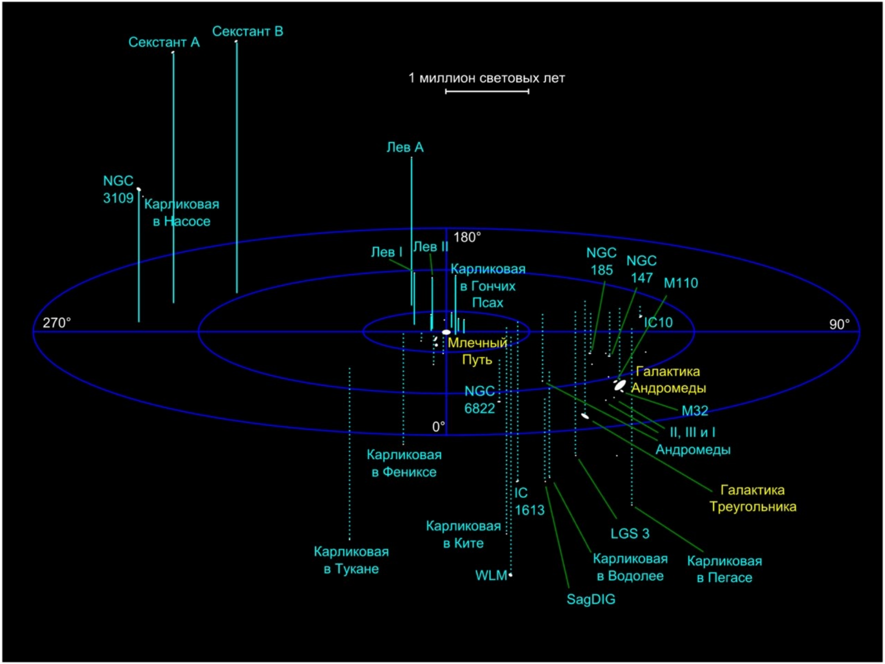
$1\ \mathrm{AU} = 1.5 \times 10^{13}$ cm	mean Earth-to-Sun distance
$1\ \mathrm{ly} = 0.95 \times 10^{18}$ cm	distance light travels in one year
	$1\ \mathrm{yr} = 3.16 \times 10^{7}$ s
$1\ \mathrm{pc} = 3.3\ \mathrm{ly} = 3.1 \times 10^{18}$ cm	distance to object which has a parallax angle of one arcsec

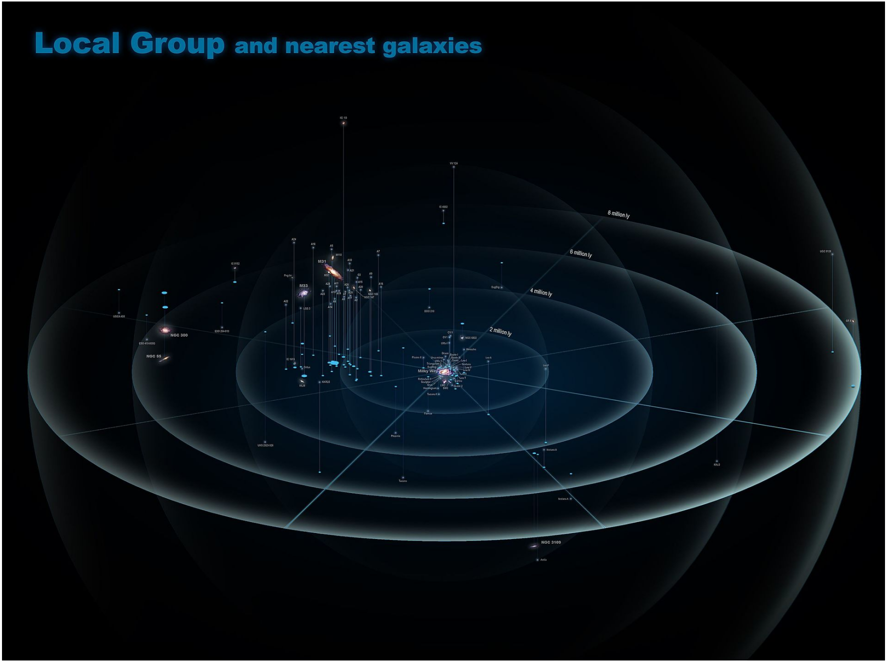


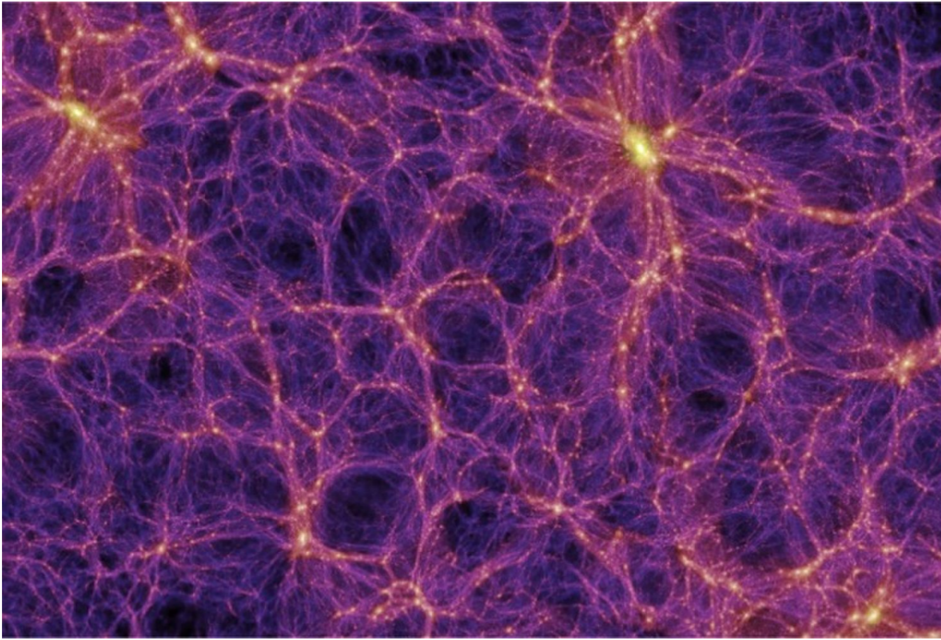
100 AU — Solar system size
1.3 pc — nearest-to-Sun stars
1 kpc — size of dwarf galaxies
50 kpc — distance to dwarves
0.8 Mpc — distance to Andromeda
1-3 Mpc — size of clusters
15 Mpc — distance to Virgo




CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years


Секстант A
Секстант B
1 миллион световых лет
Лев A
NGC 3109
Карликовая в Насосе
180°
Лев I
Лев II
Карликовая в Гончих Псах
NGC 185
NGC 147
M110
270°
IC10
90°
Млечный Путь
Галактика Андромеды
NGC 6822
M32
II, III и I Андромеды
0°
Карликовая в Фениксе
Галактика Треугольника
IC 1613
LGS 3
Карликовая в Ките
Карликовая в Тукане
Карликовая в Водолее
Карликовая в Пегасе
WLM
SagDIG


Local Group and nearest galaxies
8 million ly
6 million ly
4 million ly
2 million ly
M31
M33
NGC 300
NGC 55
Milky Way
NGC 3109



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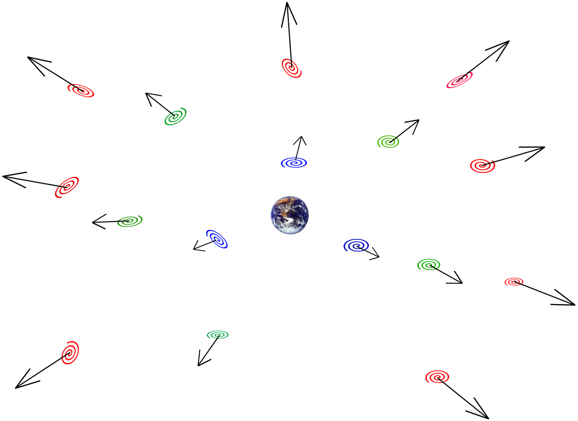
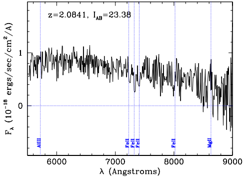
Universe is expanding $\lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1 + z$

Doppler redshift Z of light





$L \propto a(t)$

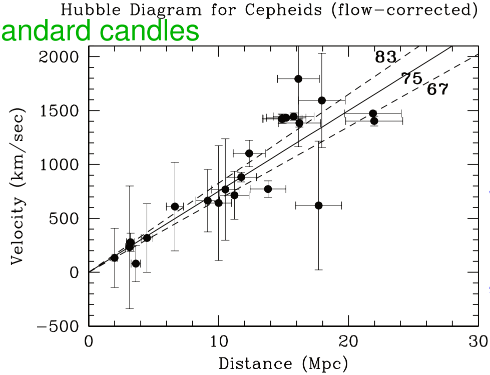
Hubble parameter $H(t) = \frac{\dot{a}(t)}{a(t)}$

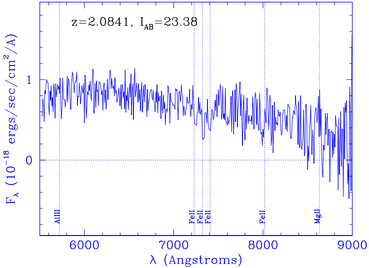
Expansion: redshift z $\qquad \lambda_{\text{abs.}}/\lambda_{\text{em.}} \equiv 1+z$

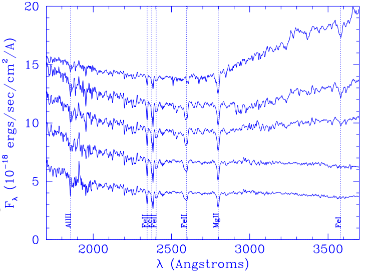
$z \ll 1$ Hubble law : $z = H_0 r$

$$H_0 = h \cdot 100\,\frac{\text{km}}{\text{s}\cdot\text{Mpc}}\,, \qquad h \approx 0.68$$

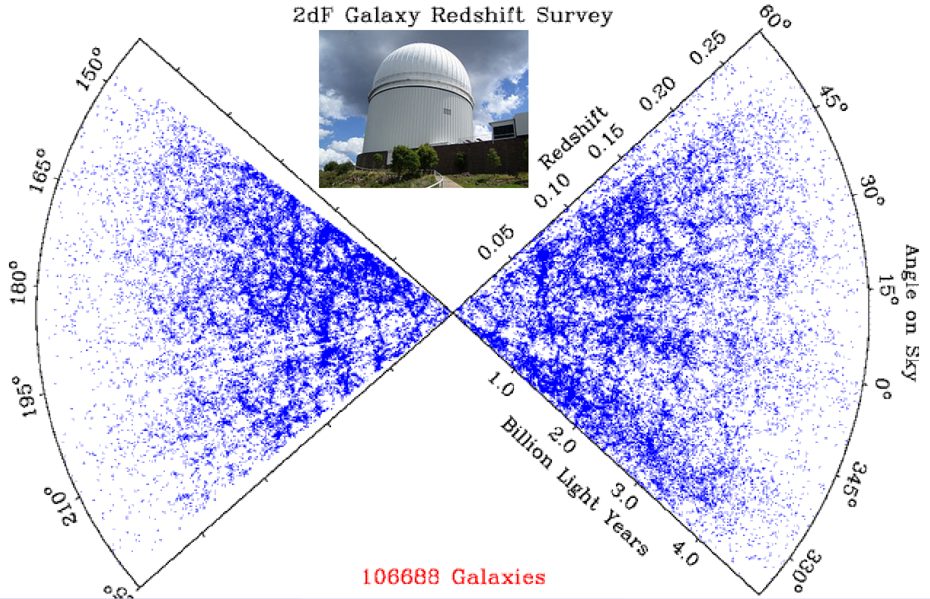
standard candles







Universe is homogeneous and isotropic



The Universe: age & geometry & energy density

$$[H_0] = L^{-1} = t^{-1}$$

time scale: $t_{H_0} = H_0^{-1} \approx 14 \times 10^9$ yr — age of our Universe

spatial scale: $l_{H_0} = H_0^{-1} \approx 4.3 \times 10^3$ Mpc — size of the visible Universe

t_{H_0} is in agreement with various observations

homogeneity and isotropy in 3d: — if exact

flat, spherical or hyperbolic — R^3, S^3 or H^3

Observations: "very" flat $R_{curv} > 10 \times l_{H_0}$

order-of-magnitude estimate: — $GM_U/l_U \sim G\rho_0 l_{H_0}^3/l_{H_0} \sim 1$

flat Universe

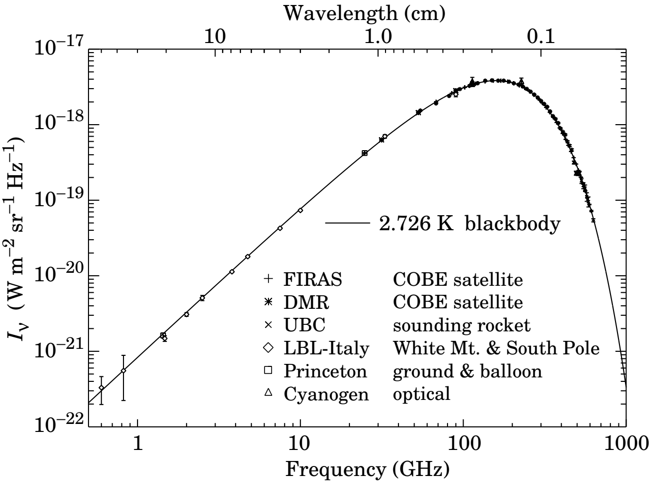
$$\rho_c = \frac{3}{8\pi} H_0^2 M_{Pl}^2 \approx 0.53 \times 10^{-5} \frac{\text{GeV}}{\text{cm}^3} \longrightarrow$$ 5 protons in each 1 m^3

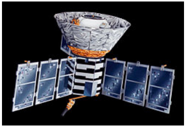
Universe is occupied by “thermal” photons

the spectrum (shape and normalization!) is thermal

$T_0 = 2.726$ K

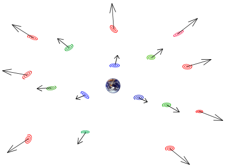
$n_\gamma = 411$ cm^{-3}





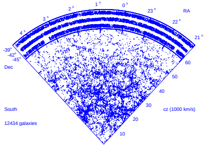
Conclusions from observations

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



- interval between events gets modified

$$\Delta s^2 = c^2\,\Delta t^2 - a^2(t)\,\Delta \mathbf{x}^2$$

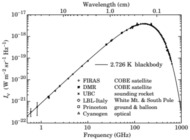


- in GR expansion is described by the Friedmann equation

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

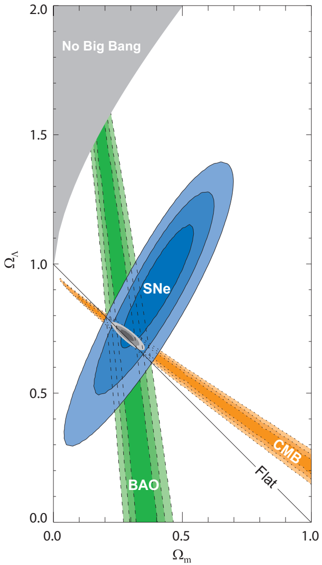
$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{matter}} + \rho_{\text{radiation}} + \dots$$

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



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

Astrophysical and cosmological data are in agreement



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

$$\rho^{\text{energy}}_{\text{density}} = \rho_{\text{radiation}} + \rho^{\text{ordinary}}_{\text{matter}} + \rho^{\text{dark}}_{\text{matter}} + \rho_\Lambda$$

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

$$\rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho^{\text{energy}}_{\text{density}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

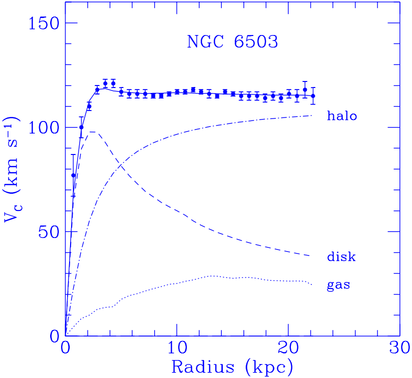
Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68$

Galactic dark halos: flat rotation curves

$$v(R) = \sqrt{G\frac{M(R)}{R}}$$

$$M(R) = 4\pi \int_0^R \rho(r) r^2 dr$$



observations: $v(R) \simeq$ const

visible matter:

internal regions $v(R) \propto \sqrt{R}$

external ("empty") regions $v(R) \propto 1/\sqrt{R}$

Matter distribution in the Milky Way

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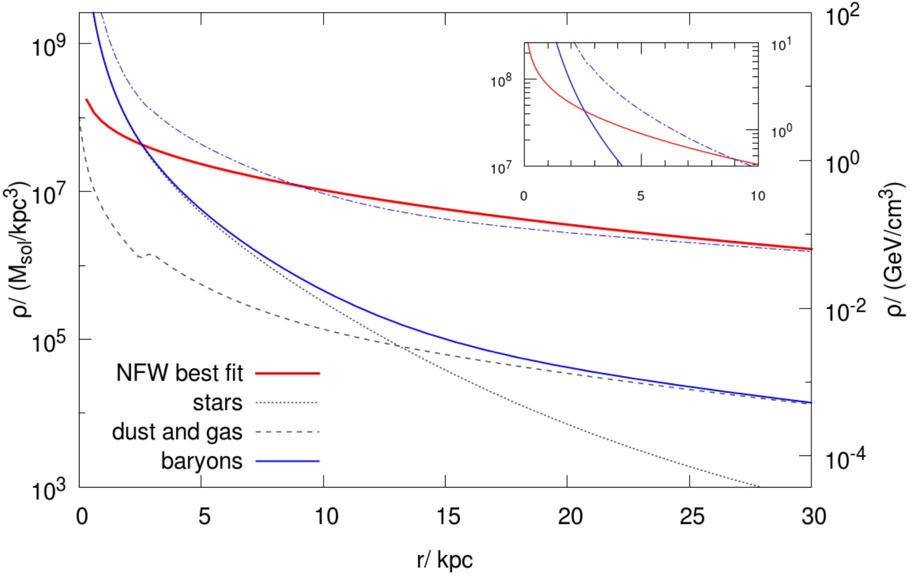


Dark Matter in clusters

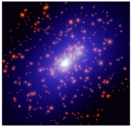
X-rays from hot gas in clusters

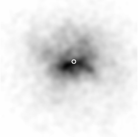
$$\frac{dP}{dR} = -\mu n_e(R) m_p \frac{GM(R)}{R^2}\,, \quad M(R) = 4\pi \int_0^R \rho(r) r^2 dr\,, \quad P(R) = n_e(R) T_e(R)$$

galaxies in clusters — virial theorem

$$U + 2E_k = 0$$

$$3M\langle v_r^2\rangle = G\frac{M^2}{R}$$

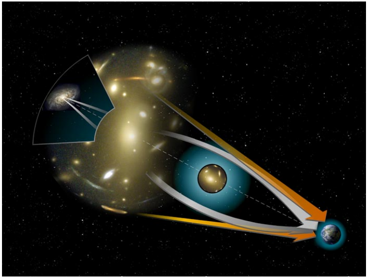


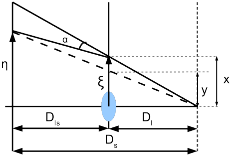


Milky Way: Virgo infall

Gravitational lensing in GR: $\alpha = 4GM/(c^2 b)$

Einstein Cross

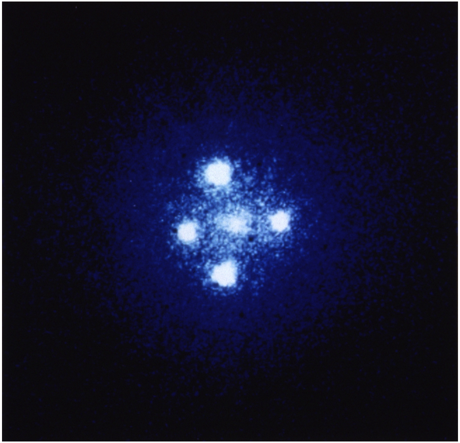




$$\vec{\eta} = \frac{D_s}{D_l}\,\vec{\xi} - D_{ls}\,\vec{\alpha}\left(\vec{\xi}\right)$$

common lens with specific refraction coefficient

$$\vec{\alpha}\left(\vec{\xi}\right) = \frac{4G}{c}\int \frac{\vec{\xi}-\vec{\xi}'}{\left|\vec{\xi}-\vec{\xi}'\right|^2}\, d^2\xi' \int \rho\left(\vec{\xi}',z\right) dz$$

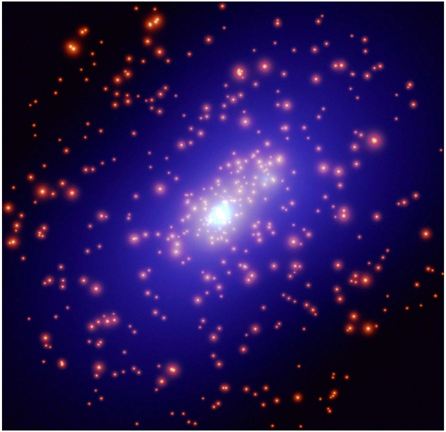


source: quasar $D_s = 2.4$ Gpc

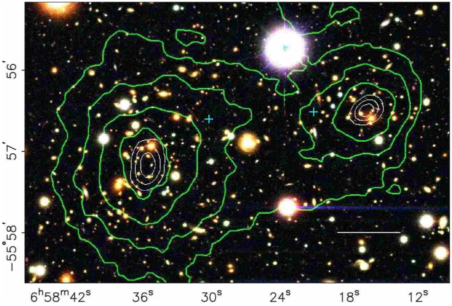
lens: galaxy $D_l = 120$ Mpc

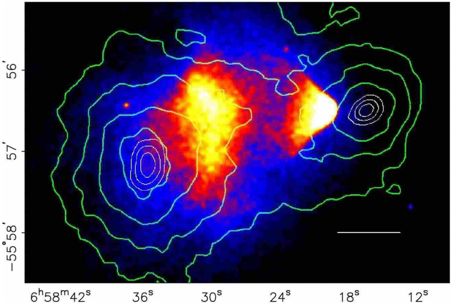
Dark Matter in clusters

gravitational lensing $\rho_{\rm B} \approx 0.25\rho_{DM}$



Colliding clusters (Bullet clusters 1E0657-558)





gravitational lensing

Observations in X-rays

$M \simeq 10 \times m$

scale is 200 kpc

clusters are at 1.5 Gpc

Dark Matter Properties $p = 0$

(If) particles:

1. stable on cosmological time-scale
2. nonrelativistic long before RD/MD-transition (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
3. (almost) collisionless
4. (almost) electrically neutral

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

If not: for bosons

$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

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

Determination of $a(t)$ reveals the composition of the present Universe

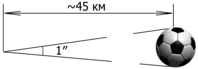
$\Delta s^2 = c^2\,\Delta t^2 - a^2(t)\,\Delta\vec{x}^2 \;\to\; ds^2 = g_{\mu\nu}\,dx^\mu\,dx^\nu$ Light propagation changes. . .

How do we check it? by measuring distance L to an object!

- Measuring angular size θ of an object of known size d

single-type galaxies

$$\theta = \frac{d}{L}$$



- Measuring angular size $\theta(t)$ corresponding to physical size $d(t)$ with known evolution

– BAO in galaxy distribution
– lensing of CMB anisotropy

$$\theta(t) = \frac{d(t)}{L}$$

- Measuring brightness J of an object of known luminosity F

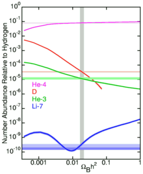
"standard candles"

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

In the expanding Universe all these laws get modified

Present knowledge about the past: back to 2-3 MeV

past stages		observables
deceleration/acceleration	$\ddot{a} = 0$	SN Ia, CMB, clusters
reionization	$\gamma + H \to p + e$	CMB, quasars, stars
recombination	$p + e \to \gamma + H^*$	CMB, BAO
RD/MD equality	$\rho_{\text{matter}} = \rho_{\text{radiation}}$	CMB, BAO
nucleosynthesis	$p + n \to D + \gamma,\ etc$	cold gas clouds
neutrino decoupling	$\nu_e + n \to p + e$	cold gas clouds



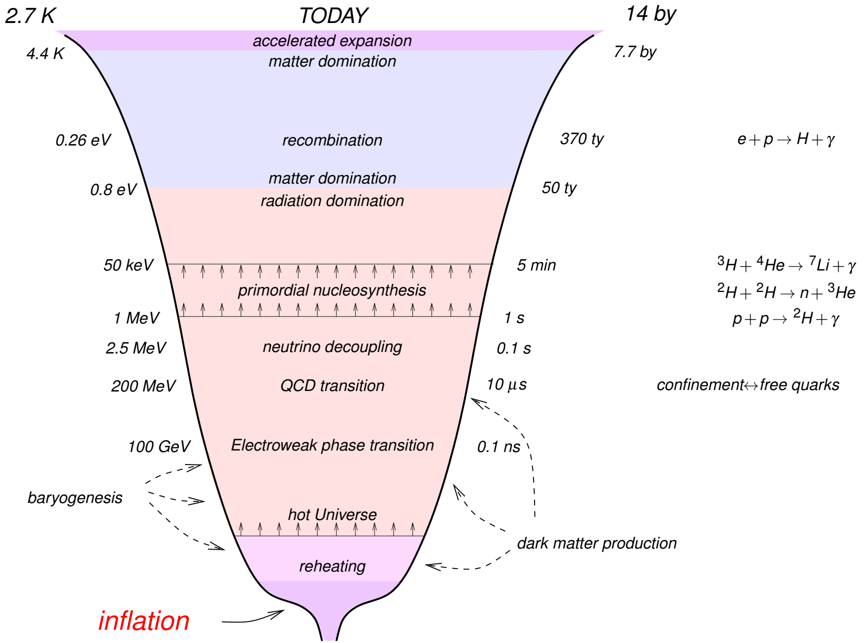
$$H^2 \propto \rho_\gamma + \rho_\nu$$

New Physics in Cosmology: any energy scales. . .

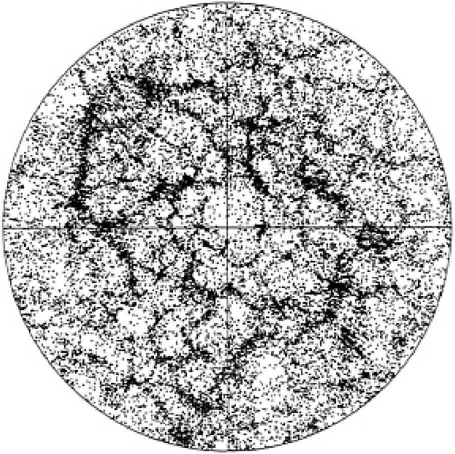
Cosmology constrains the time-scale, rather than energy-scale

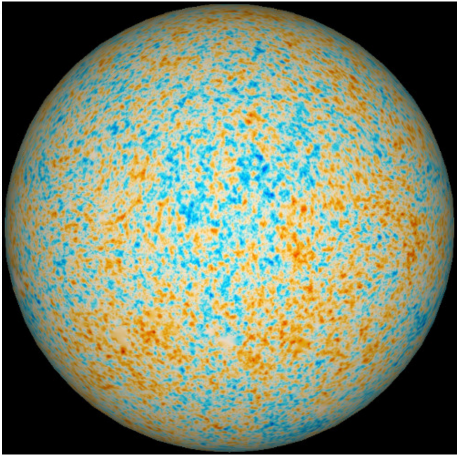
$$\Gamma \sim H \propto T^2/M_{Pl}$$

- Dark matter (if particles) — be produced by $T \gg 1\,\text{eV}$
- Dark energy — be present by $T \gg 5\,\text{K}$
- Baryon asymmetry — be generated by $T \gg 1\,\text{MeV}$


2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.8 eV
radiation domination
50 ty
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

Inhomogeneous Universe





Large Scale Structure

CMB anisotropy

These inhomogeneities (matter perturbations)

originate from the initial matter density (scalar) perturbations

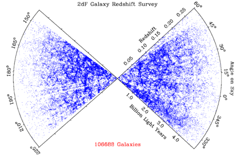
$\delta\rho/\rho \sim \delta T/T \sim 10^{-4}$, which are

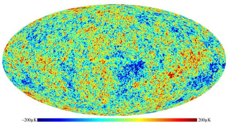
adiabatic $\quad \delta\left(\frac{n_B}{s}\right) = \delta\left(\frac{n_{DM}}{s}\right) = \delta\left(\frac{n_L}{s}\right)$

Gaussian $\quad \langle \frac{\delta\rho}{\rho}(\mathbf{k}) \frac{\delta\rho}{\rho}(\mathbf{k}') \rangle \propto \left(\frac{\delta\rho}{\rho}(\mathbf{k})\right)^2 \times \delta(\mathbf{k}+\mathbf{k}')$

flat spectrum $\quad \langle \left(\frac{\delta\rho}{\rho}(\mathbf{x})\right)^2 \rangle = \int_0^\infty \frac{\mathbf{dk}}{\mathbf{k}} \mathscr{P}_S(\mathbf{k}) \qquad \mathscr{P}_S(\mathbf{k}) \approx \mathrm{const}$

LSS and CMB $\quad \mathscr{P}_S \equiv A_S \times \left(\frac{k}{k_*}\right)^{n_s-1} \qquad A_S \approx 2.5\times 10^{-9}\,, \quad n_S \approx 0.97$





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

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

- $T_\gamma = 2.735\,\mathrm{K}, \quad \Longrightarrow \quad \Omega_\gamma \sim 10^{-5}$
- $N_\nu \approx 3, \quad \sum m_\nu < 0.2\,\mathrm{eV} \quad \Longrightarrow \quad \Omega_{\nu,\neq 0},\, \Omega_{\nu,0} \sim 10^{-5}$?
- $\Omega_B = 4.5\% \quad \Longrightarrow \quad \eta_B \equiv n_B/n_\gamma = 6\times 10^{-10}$
- $\Omega_{DM} = 27.5\%$
- $H_0 = 67\,\mathrm{km/s/Mpc} \quad \Longrightarrow \quad \rho_0 = 5\,\mathrm{GeV/m^3}$
- $\Omega_\Lambda = 68\% \quad \Longrightarrow$ flat space
- adiabatic, gaussian 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 $z \equiv a_0/a = 10$

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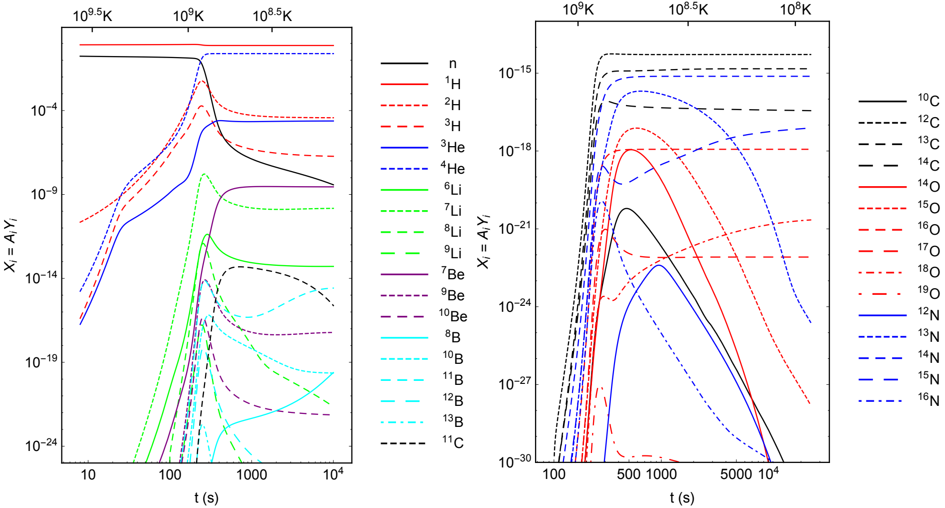
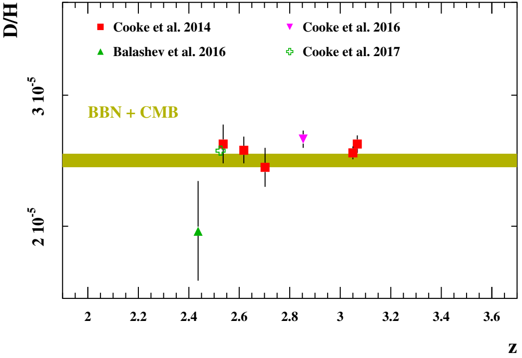
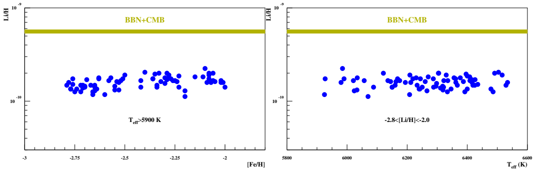
Nucleosynthesis

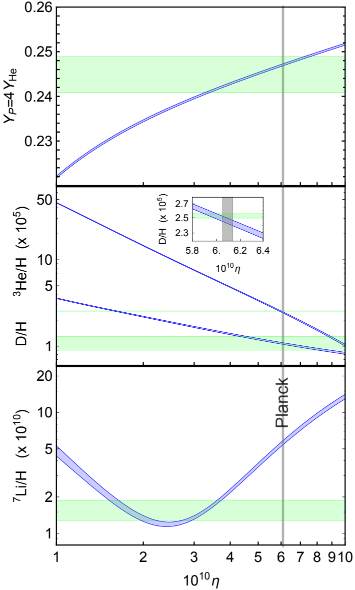


1801.08023

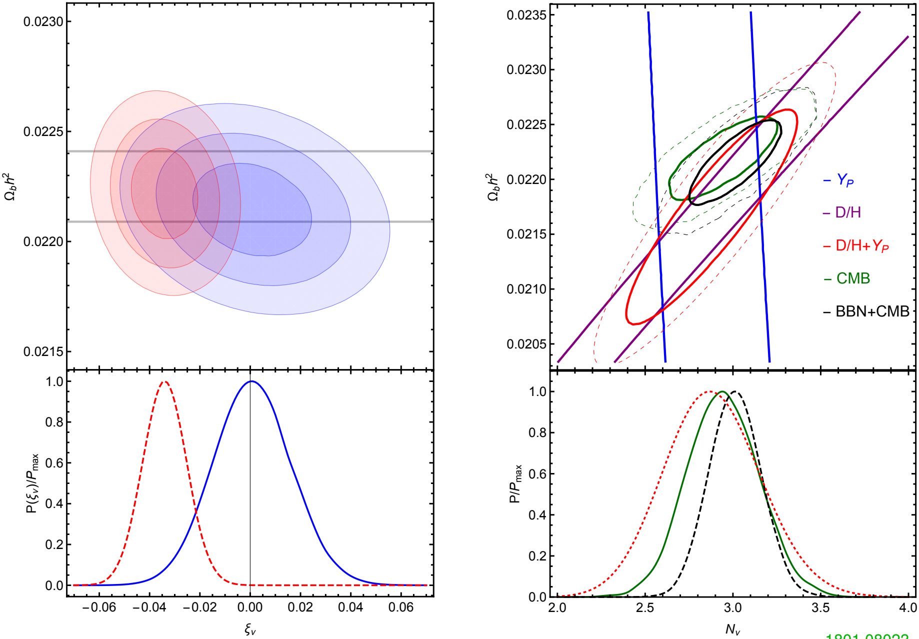
Nucleosynthesis $\eta = n_B/n_\gamma$







1801.08023


0.0230
0.0225
0.0220
0.0215
$\Omega_b h^2$
1.0
0.8
0.6
0.4
0.2
0.0
$P(\xi_\nu)/P_{max}$
−0.06
−0.04
−0.02
0.00
0.02
0.04
0.06
ξ_ν
0.0235
0.0230
0.0225
0.0220
0.0215
0.0210
0.0205
$\Omega_b h^2$
– Y_P
– D/H
– D/H+Y_P
– CMB
– BBN+CMB
1.0
0.8
0.6
0.4
0.2
0.0
P/P_{max}
2.0
2.5
3.0
3.5
4.0
N_ν

1801.08023

Three are commonly recognized

- Core-cusp problem

  Dark Matter density profiles in the centers of simulated halos are cusped
  while in observed dwarf galaxies are cored

- Lack of dwarf galaxies

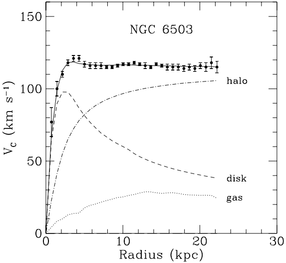
  Matter perturbations of almost flat spectrum produce flat halo mass spectrum
  low abundance of small galaxies

- Too-big-To-fail problem

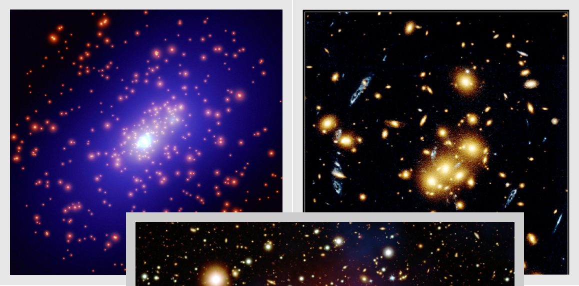
  There must be galaxies heavy enough to keep baryons inside
  Milky Way hosts only two such galaxies

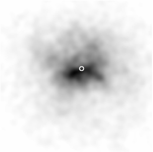
Dark Matter in astrophysics

Rotational curves



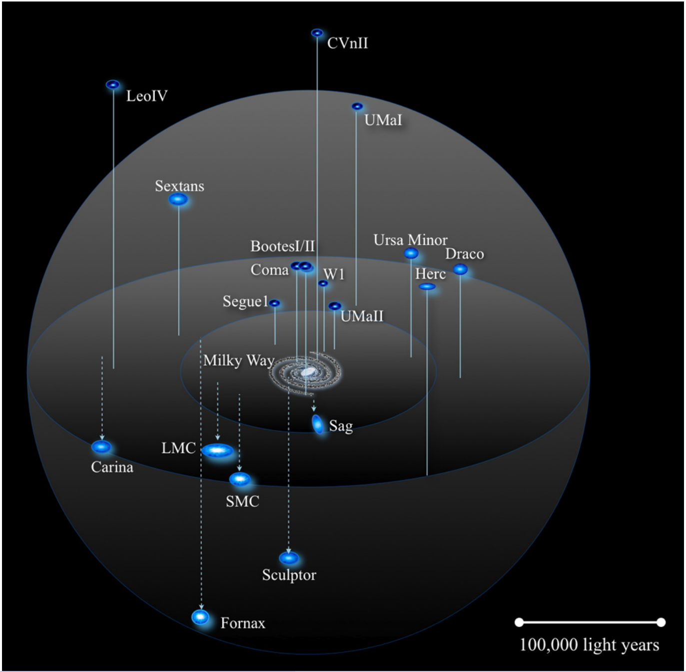
Gravitational lensing





X-rays from centers of galaxy clusters

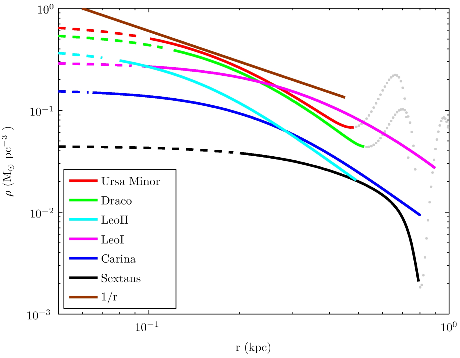
“Bullet” cluster


CVnII
LeoIV
UMaI
Sextans
BootesI/II
Ursa Minor
Draco
Coma
W1
Herc
Segue1
UMaII
Milky Way
Sag
LMC
Carina
SMC
Sculptor
Fornax
100,000 light years

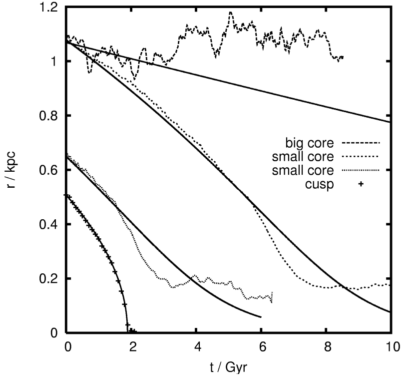
Cores in dwarf galaxies

- NFW profile fits nicely DM in galaxy clusters $\rho \propto r^{-1}(r+r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
  most DM-dominated objects

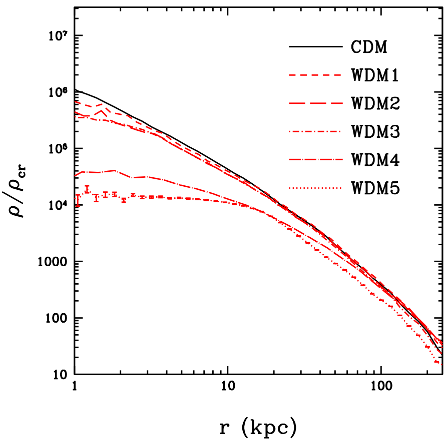
Cores observed

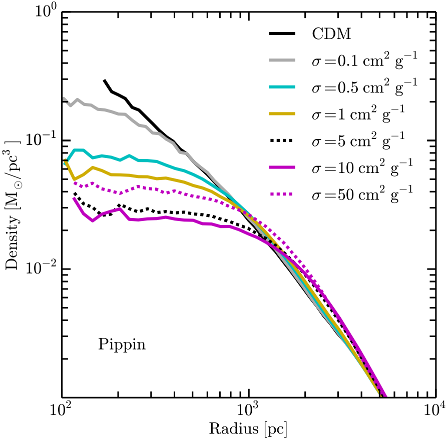


5 Clusters in the Fornax dSph



Central parts: free streaming or selfinteraction?





$m = 2$ keV ... 50 eV

1202.1282

1412.1477

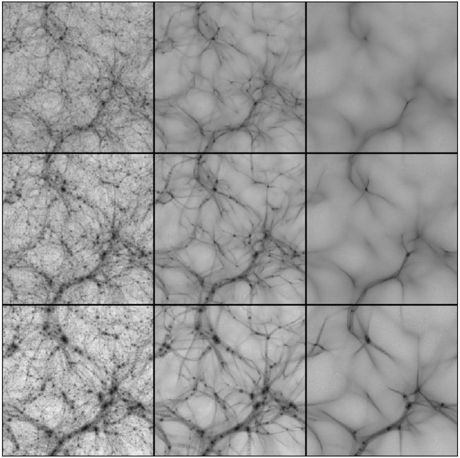
Missing satellites: free streaming or selfinteraction?

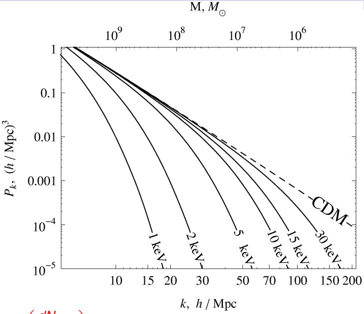
Missing satellites:

$$\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$$

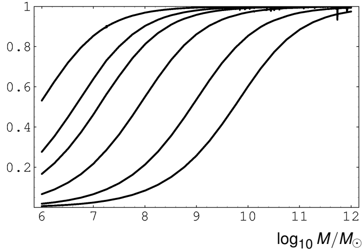
no-scale

100 instead of 1000

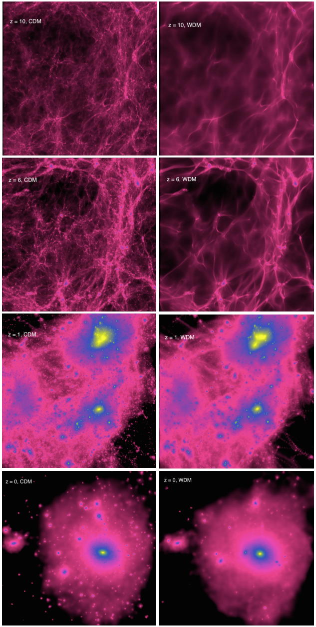


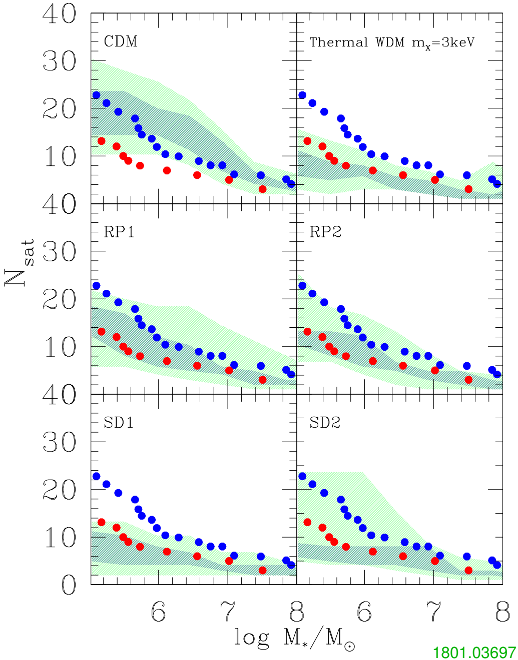


$$\left(\frac{dN_{obj}}{d\ln M}\right)_{WDM} \Big/ \left(\frac{dN_{obj}}{d\ln M}\right)_{CDM}$$



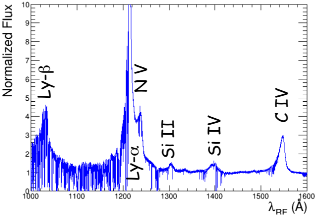
1801.03697 WDM $m = 3.3\,\mathrm{keV}$



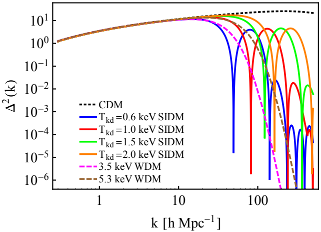


1801.03697

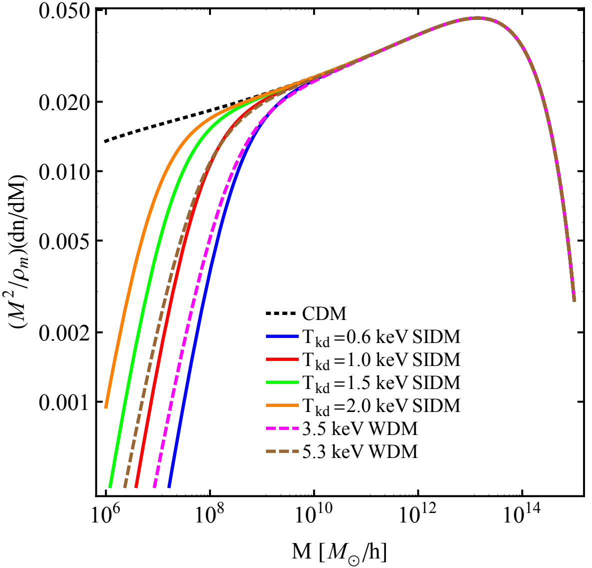
Missing satellites: dwarfs vs Ly-α



1702.03314

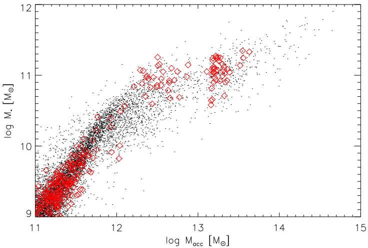


1709.09717



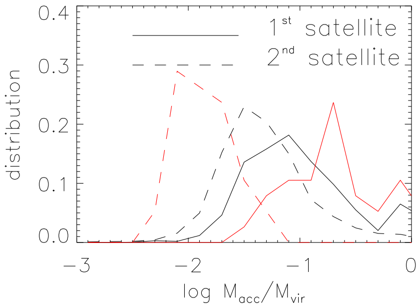
Too-big-to-fail: selection bias? at 1%

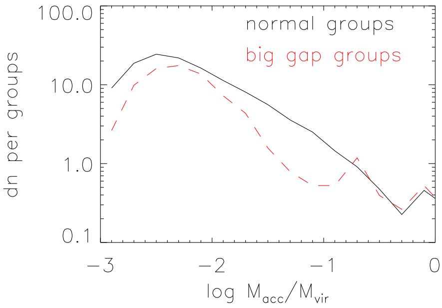
1605.03964



MW: two heavy satellites (LMC and SMC) with $v > 55$km/s
and nothing within $25 < v/(km/s) < 55$
while 10 subhalos are expected

$M_{LMC}/M_{SMC} = 10...$





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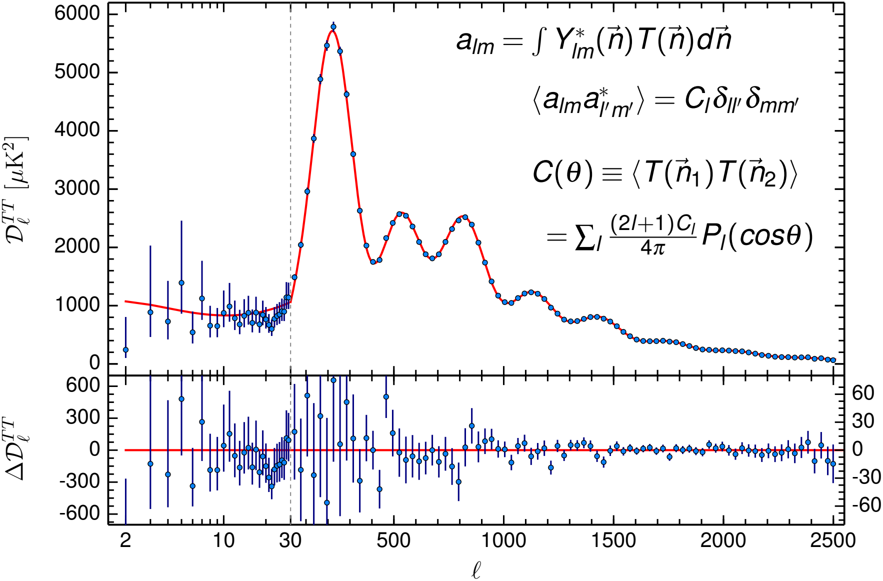
CMB anisotropy spectrum by Planck

1502.01582



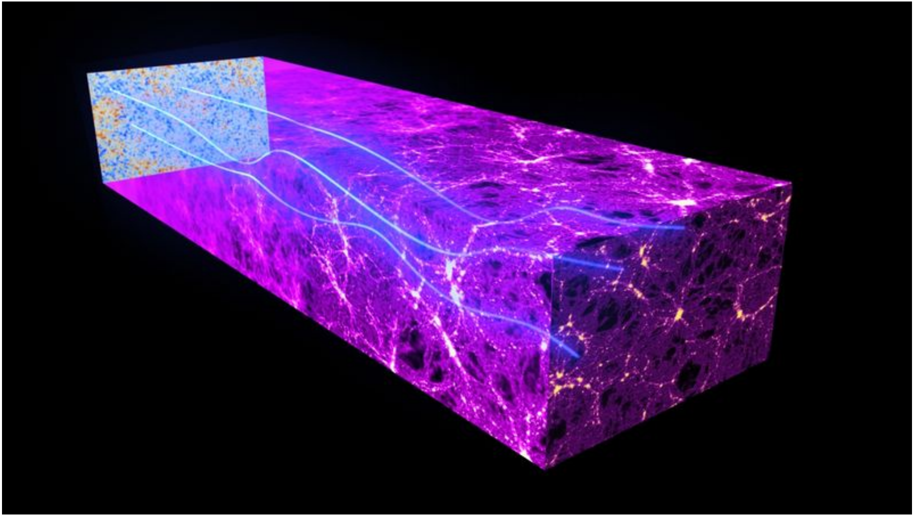
$$a_{lm} = \int Y^*_{lm}(\vec{n})T(\vec{n})d\vec{n}$$

$$\langle a_{lm}a^*_{l'm'}\rangle = C_l\delta_{ll'}\delta_{mm'}$$

$$C(\theta) \equiv \langle T(\vec{n}_1)T(\vec{n}_2)\rangle$$

$$= \sum_l \frac{(2l+1)C_l}{4\pi} P_l(cos\theta)$$

Initial or Induced: propagation in expanding Universe



CMB anomalies

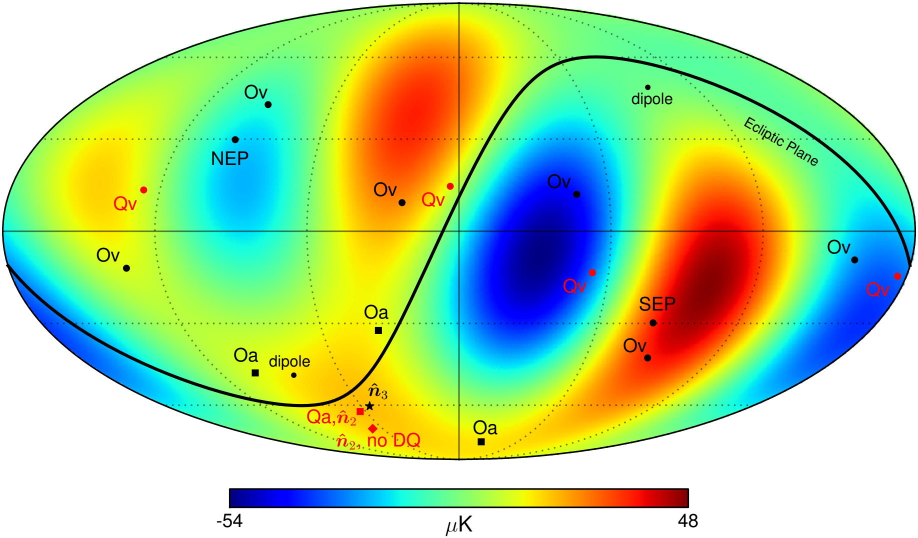
- quadrupole-octopole alignment, $p < 0.5\%$
- $l = 1, 2, 3$ alignment, $p < 0.2\%$
- odd parity preference $l_{max} = 28$, $p < 0.3\%$; $l_{max} < 50$, $p < 2\%$ (lee)
- dipolar modulation for $l = 2 - 67$, $p < 1\%$
- cold spot, $p < 1\%$
- low variance ($N_{side} = 16$), $p < 0.5\%$
- 2-correlation $\chi^2(\theta > 60^\circ)$, $p < 3.2\%$
- 2-correlation $S_{1/2}$, $p < 0.3\%$; (larger masks) $p < 0.1\%$
- hemispherical variance asymmetry, $p < 0.1\%$

$$S_{1/2} \equiv \int_{-1}^{1/2} C^2(\theta) d(\cos\theta)$$

topology? primordial spectrum with broken scale invariance or isotropy?
ISW from local LSS? ... Foregrounds?

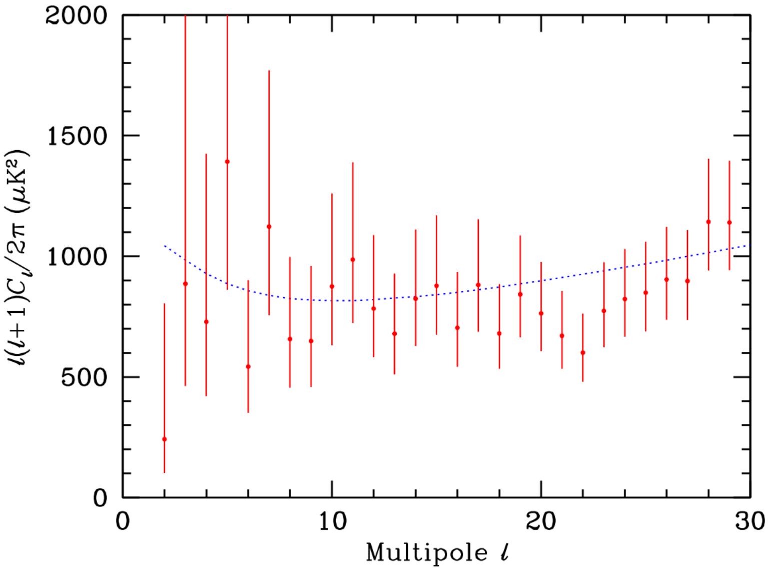
CMB anisotropy: alignment

1502.01582



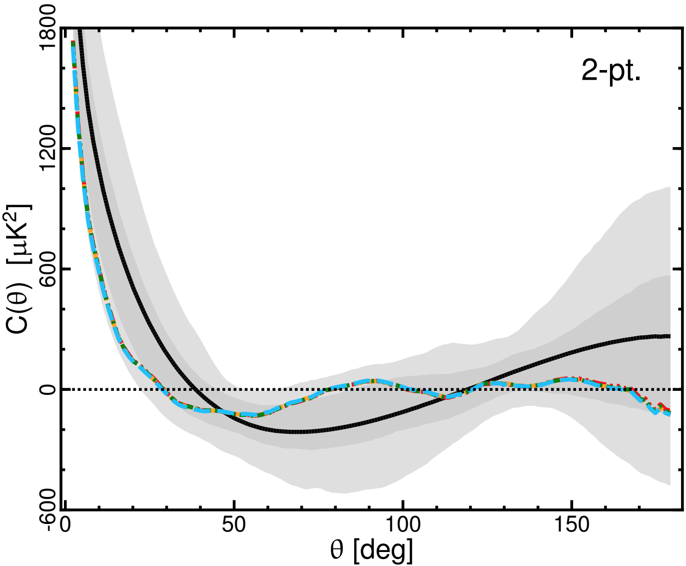
CMB anisotropy at large angles

1603.09703



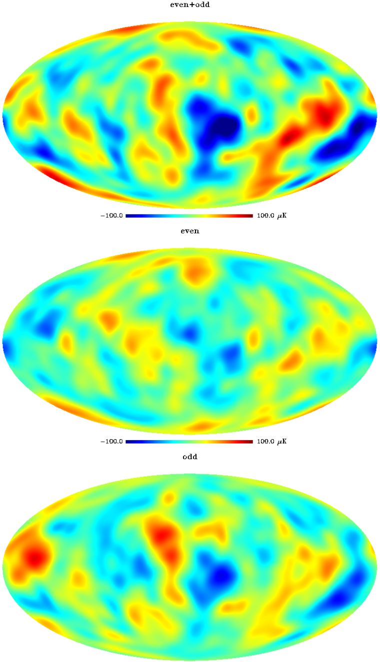
Low variance and correlation

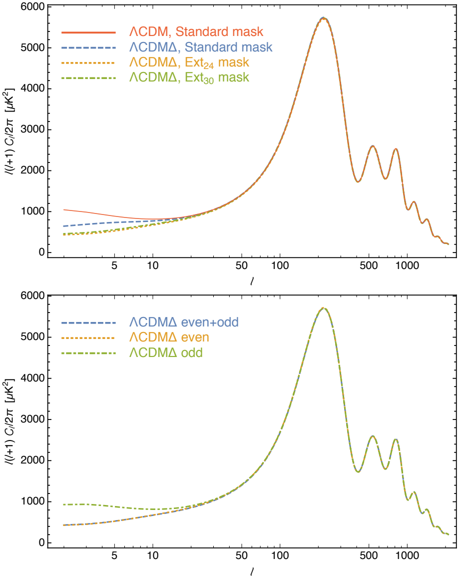
1506.07135



$C_l = \frac{1}{2l+1}\sum_{m=-1}^{m=1}|a_{lm}|^2$

$\text{Var}[C_l] = \frac{2}{2l+1}C_l^2$



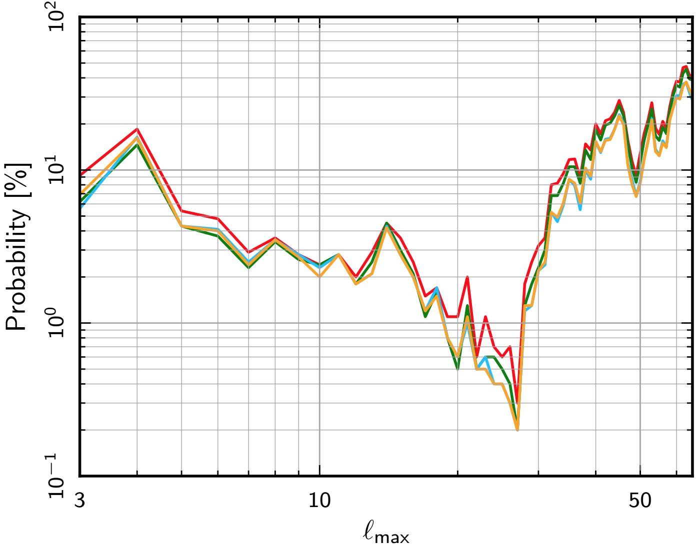


$$P(k) = k^3/(k^2+\Delta^2)^{2-n_s/2}$$

1712.03288

Odd parity

1506.07135

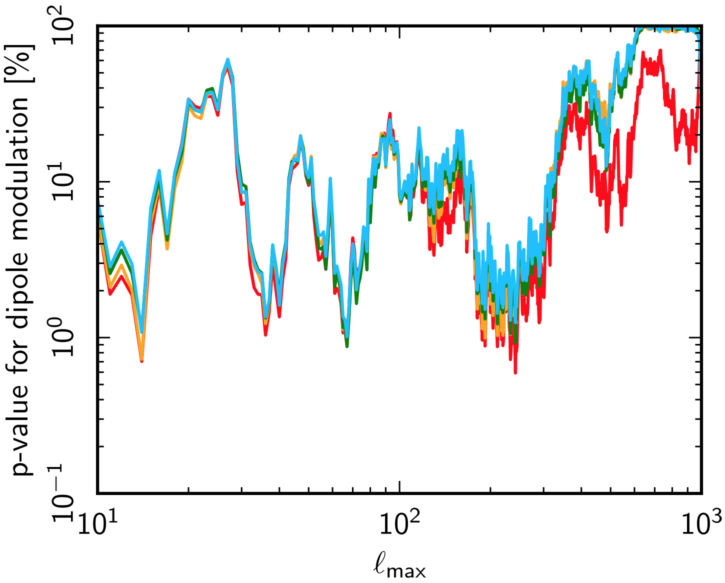


$$2\left(\frac{\delta T}{T}(\vec{n})\right)_{\pm} \equiv$$

$$\frac{\delta T}{T}(\vec{n}) \pm \frac{\delta T}{T}(-\vec{n})$$

Dipolar modulation

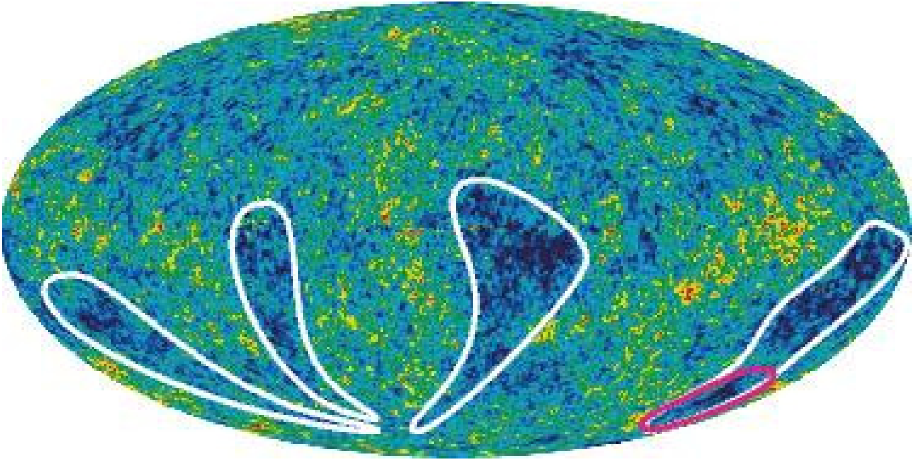
1506.07135



$T(\vec{n}) \to$
$(1 + \vec{w}\vec{n})\,T(\vec{n})$

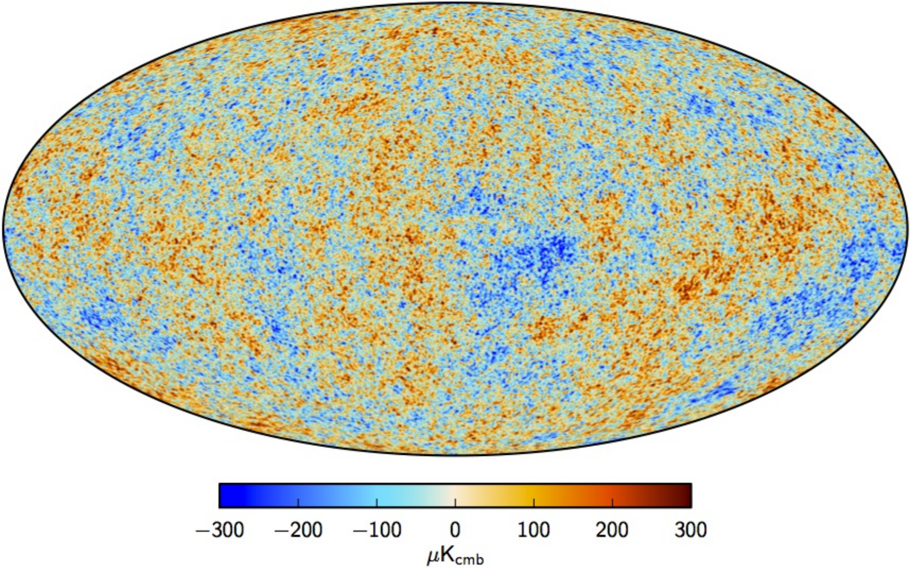
Cold spot (WMAP)

1001.4758



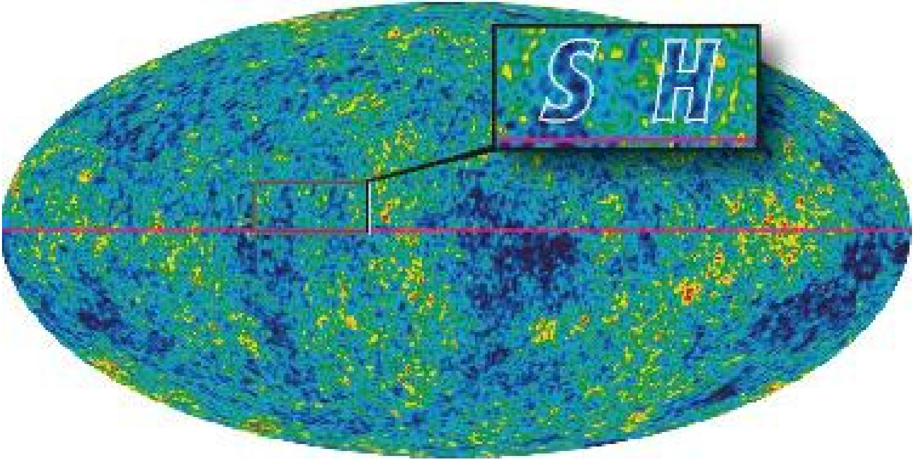
Cold spot (Planck)

1502.01582



Letters in the sky

1001.4758



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Discrepancies in cosmological parameters

- Hubble parameter measurements

  Hubble from local measurements and cosmic ladder vs CMB
  astrophysics vs cosmology

- Cluster counts

  matter clustering σ_8 from cluster number counts vs CM & BAO
  or X-ray telescopes & Planck vs Planck

- Cosmic shear

  galaxies vs CMB spots as sources for gravitational lensing
  or CFHTLens vs Planck

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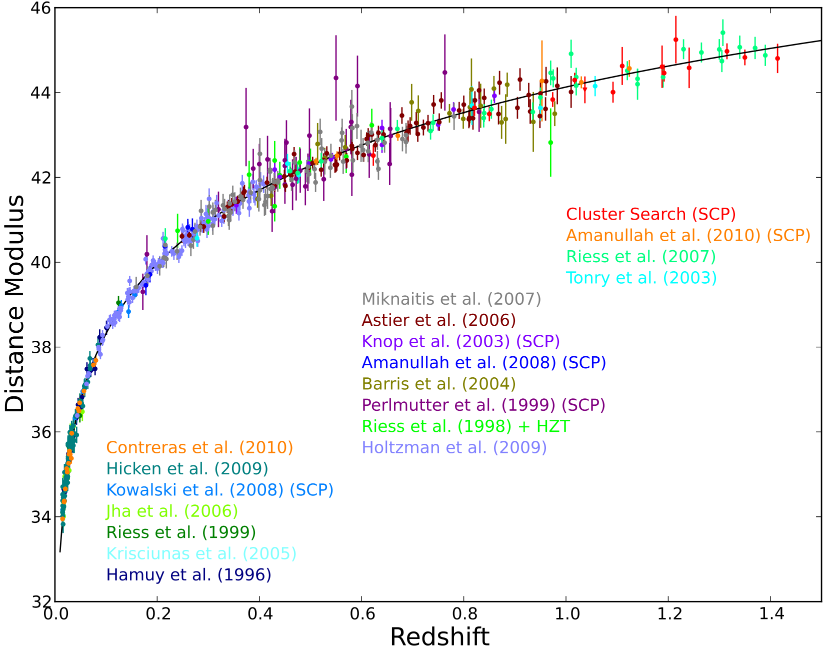
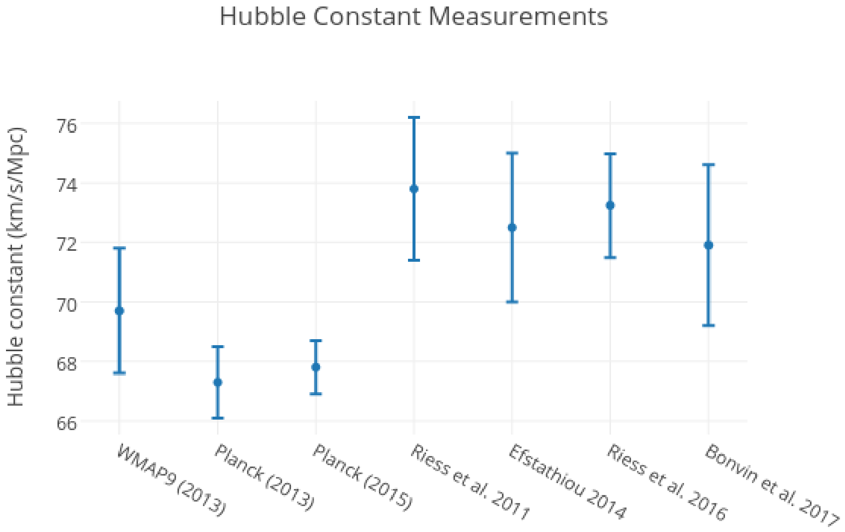
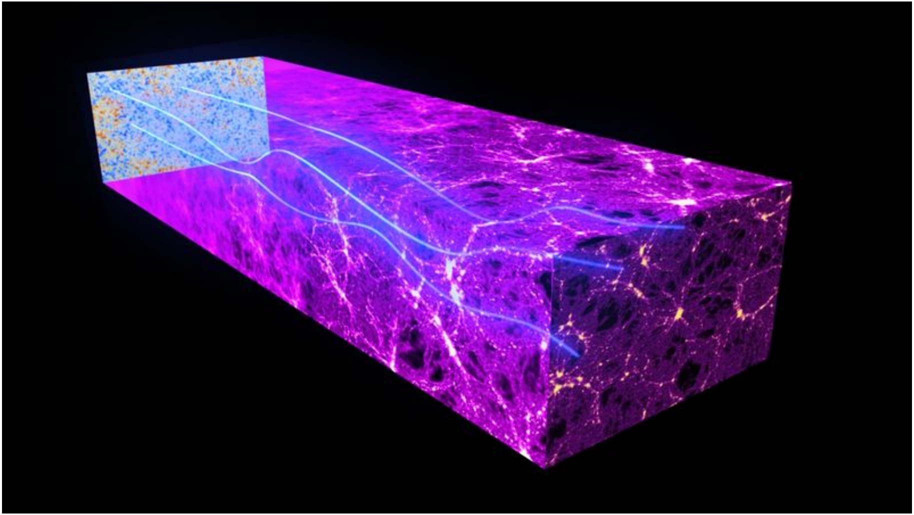

Distance Modulus
Redshift
46
44
42
40
38
36
34
32
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Cluster Search (SCP)
Amanullah et al. (2010) (SCP)
Riess et al. (2007)
Tonry et al. (2003)
Miknaitis et al. (2007)
Astier et al. (2006)
Knop et al. (2003) (SCP)
Amanullah et al. (2008) (SCP)
Barris et al. (2004)
Perlmutter 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)



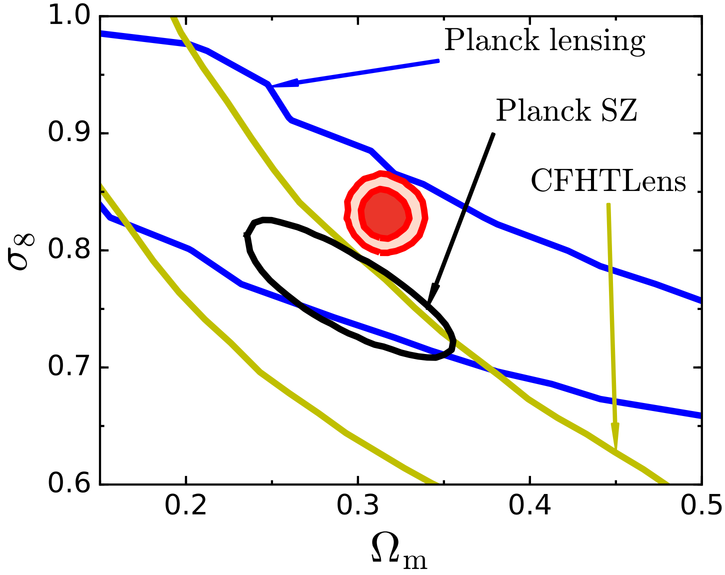
recently $H_0 = 67.06 \pm 1.68$ km/s/Mpc cosmic chronometers + SNIa (Pantheon + HST) 1802.01505

Inhomogeneities from CMB & LSS: propagation in expanding Universe



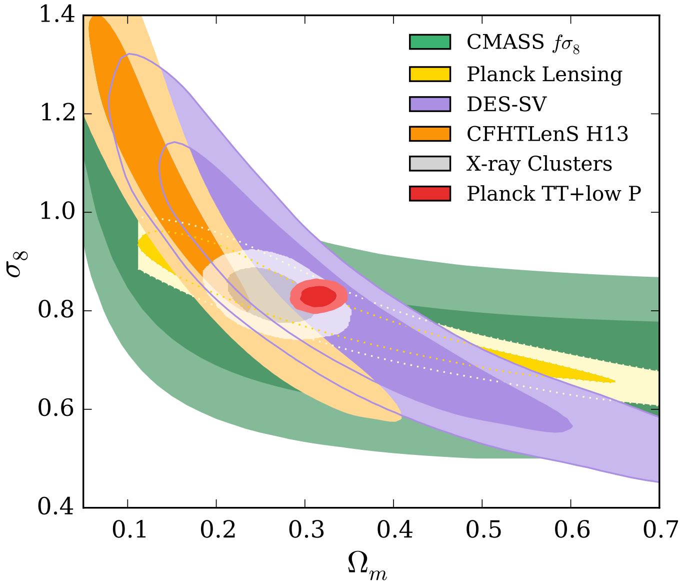
Lensing vs clusters

1801.07348



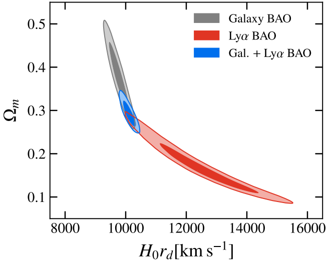
Cosmic shear and clusters

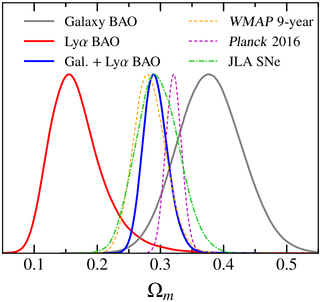
1507.05552

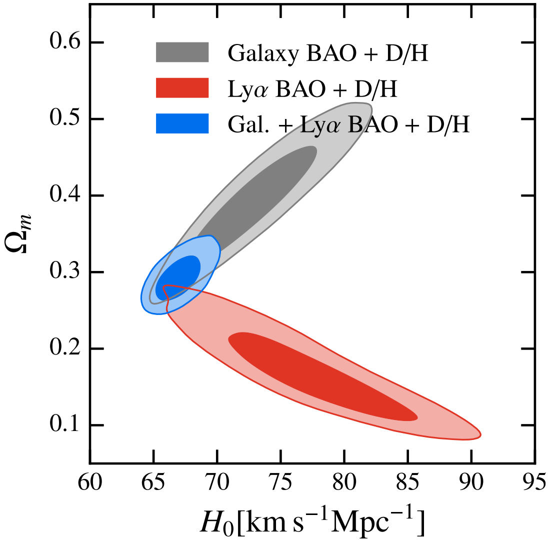


Impact of BAO: Galaxies vs Ly-α

1707.06547







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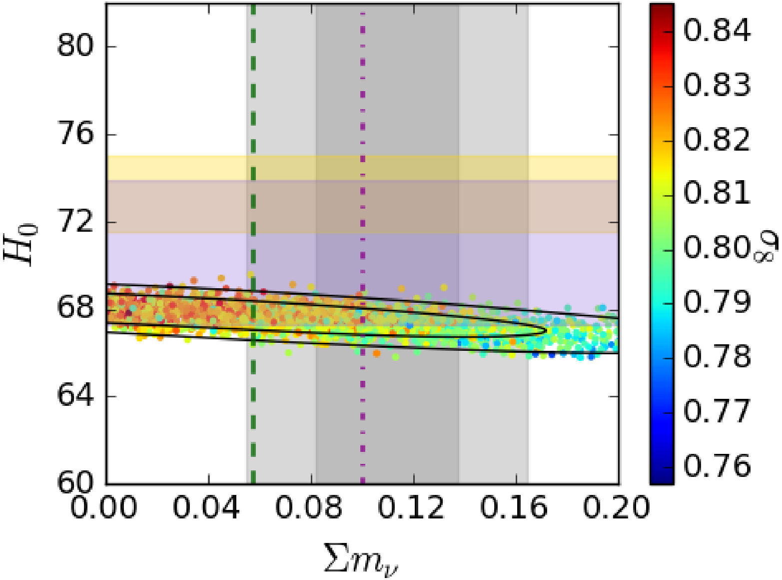
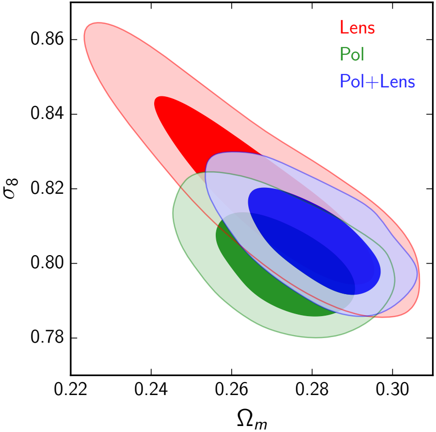
Cosmology grasping neutrino masses

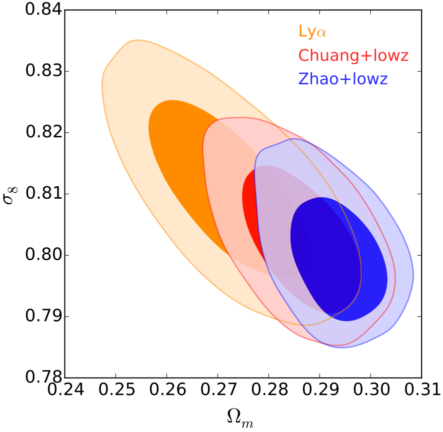
1711.05210



A fraction of decaying DM?

A.Chudaykin, D.G., I.Tkachev (2016,2017)





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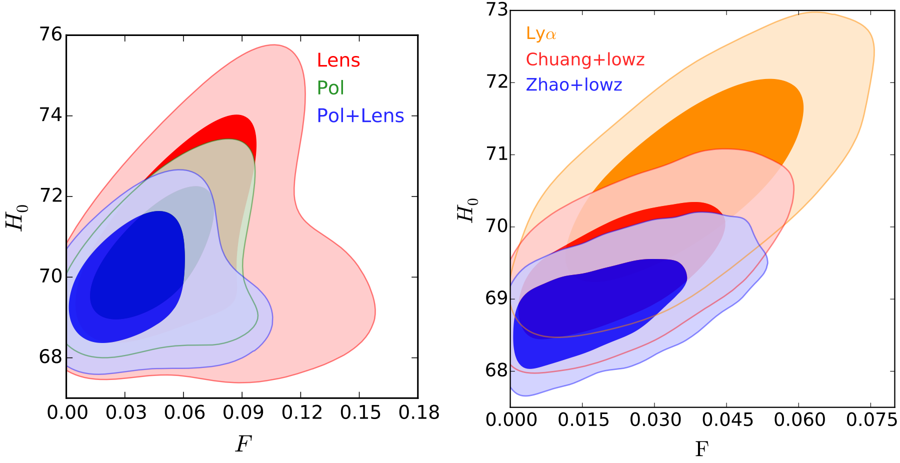
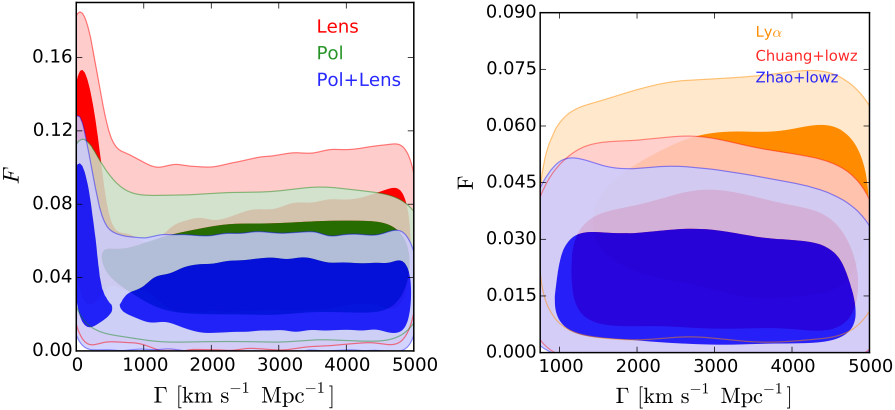
A.Chudaykin, D.G., I.Tkachev (2016,2017)



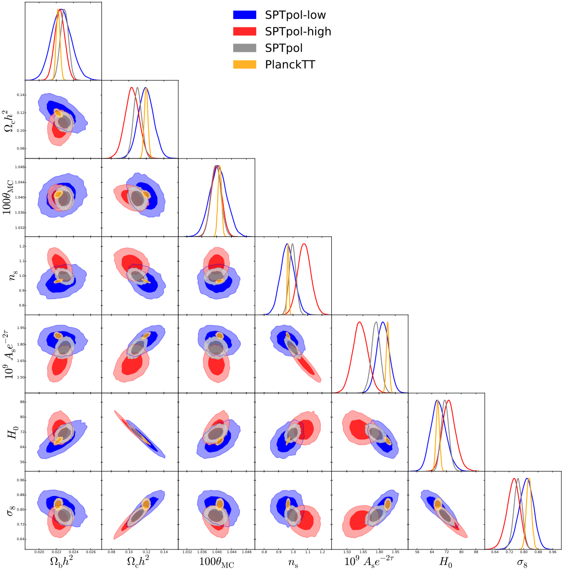
DDM can give better fit

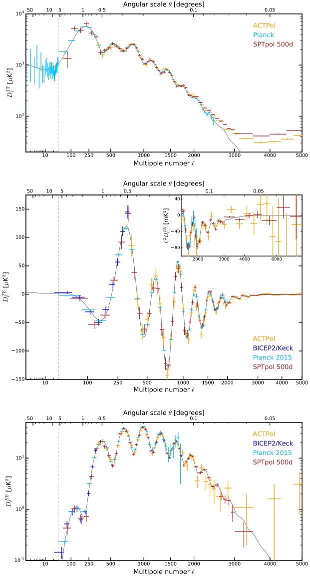
A.Chudaykin, D.G., I.Tkachev (2016,2017)



SPTPole with critical $l = 1000$

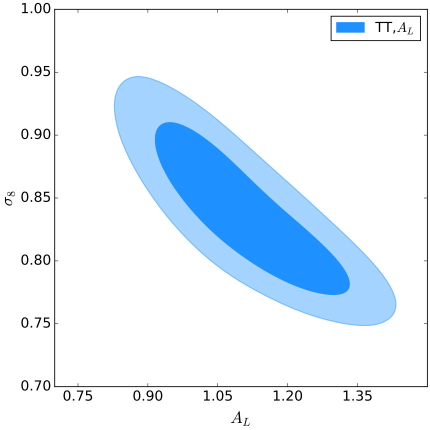
1707.09353

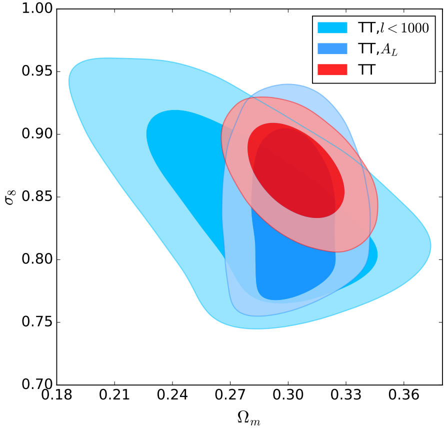




Neglecting Planck results with $l > 1000$

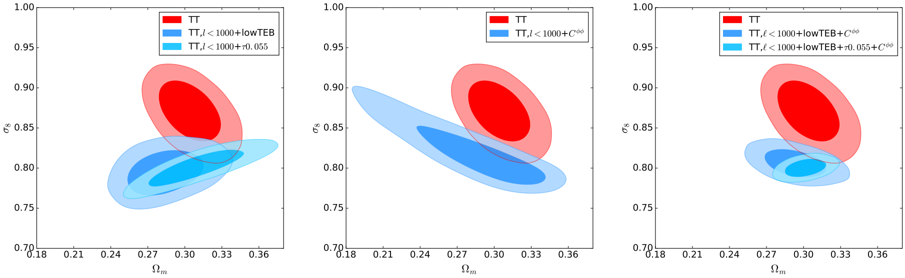
R. Burenin, 1806.03261





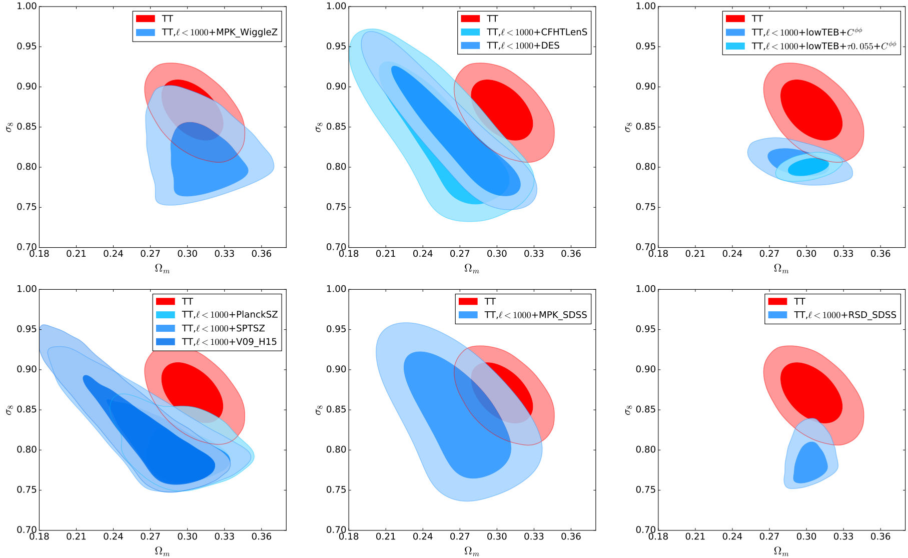
Neglecting Planck results with $l > 1000$

R. Burenin, 1806.03261



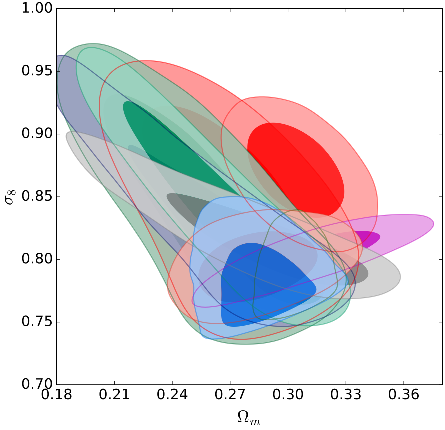
Neglecting Planck results with $l > 1000$

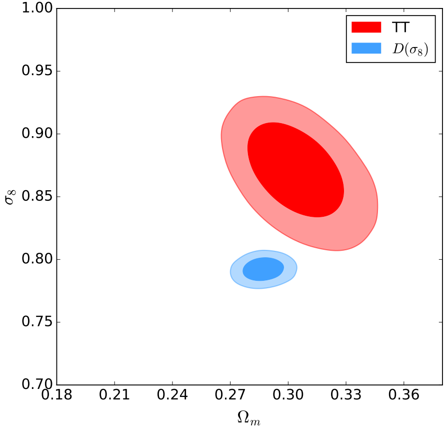
R. Burenin, 1806.03261



Neglecting Planck results with $l > 1000$

R. Burenin, 1806.03261





With BAO, H_0 and SNIIa

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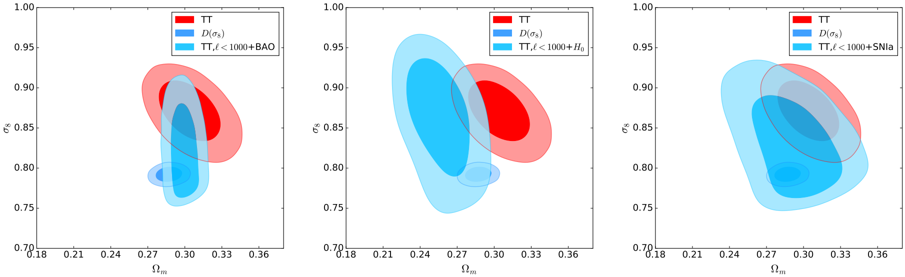

Neutrino mass??

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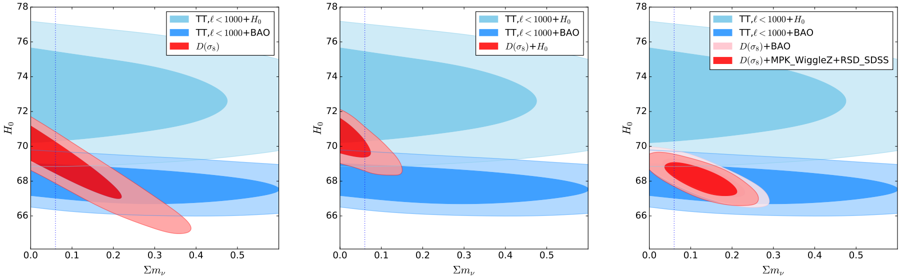


World-wide accepted problems...

Origins of...?

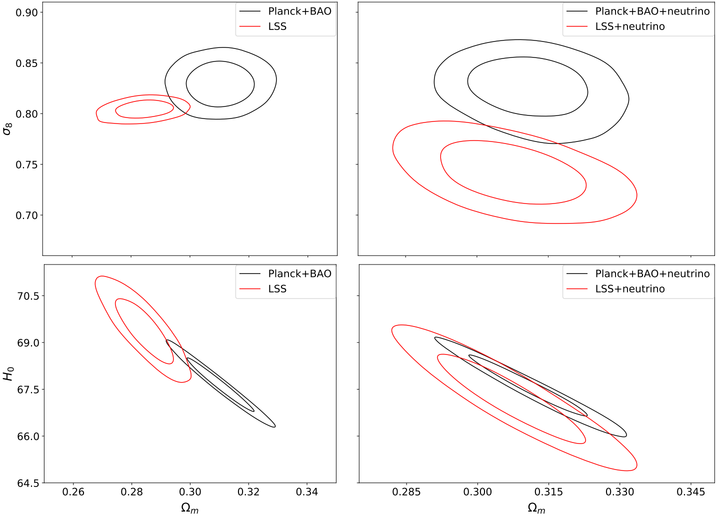
- Dark Matter
- Matter-antimatter asymmetry
- Dark Energy
- matter perturbations
- extragalactic magnetic field
- superheavy black holes in the galaxy centers
- ...

Coincidences

- $\Omega_{DM} \sim \Omega_B$
- $\Omega_M \sim \Omega_{DE}$
- $(\delta\rho/\rho)^2 \simeq n_B/n_\gamma$
- $T_d^n \sim (m_n - m_p)$
-

Backup slides

Do neutrino masses help ?



ΛCDM vs

ΛCDM + $\sum m_\nu$

1804.07154