Cosmology: the era of new observables

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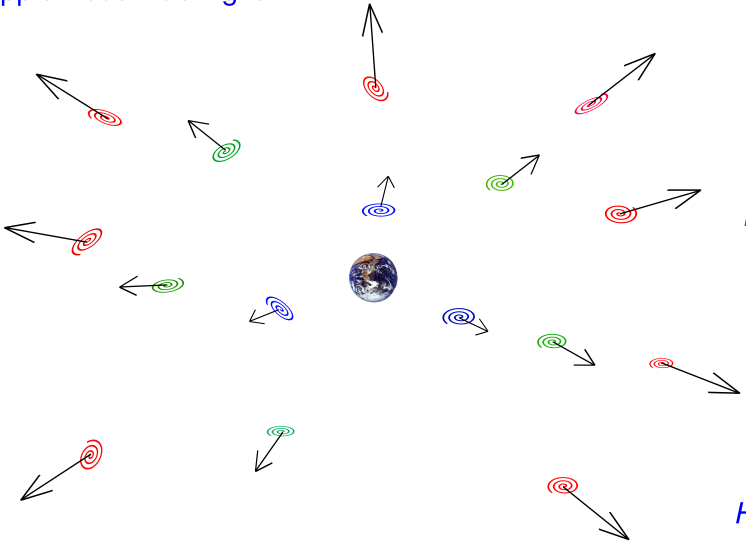
Universe is expanding

Doppler redshift of light

$L \propto a(t)$



$n \propto a^{-3}(t)$

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

Hubble parameter

Hubble Law

$H(t_0)\, r = v_r$

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

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

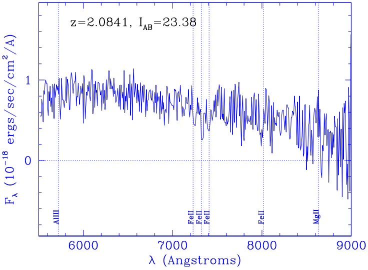
$$H_0 = h \cdot 100 \frac{\text{km}}{\text{s} \cdot \text{Mpc}} \quad h = 0.705 \pm 0.015$$

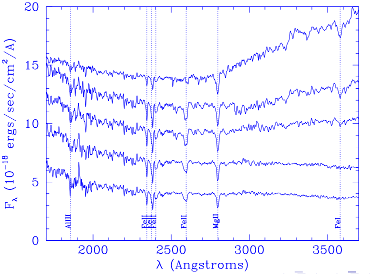
Age of the Universe

$$\tau_U \sim 1/H_0 \approx 14\,\text{by}$$

Size of the visible part of the Universe

$$l_{H_0} \sim 1/H_0 \sim 5\,\text{Gpc}$$





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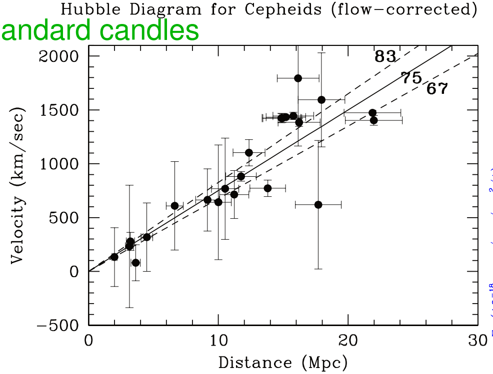
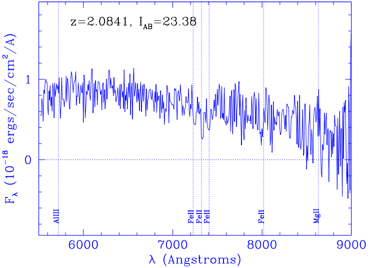
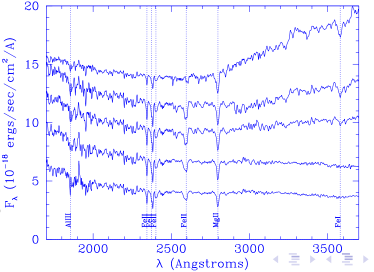
standard candles



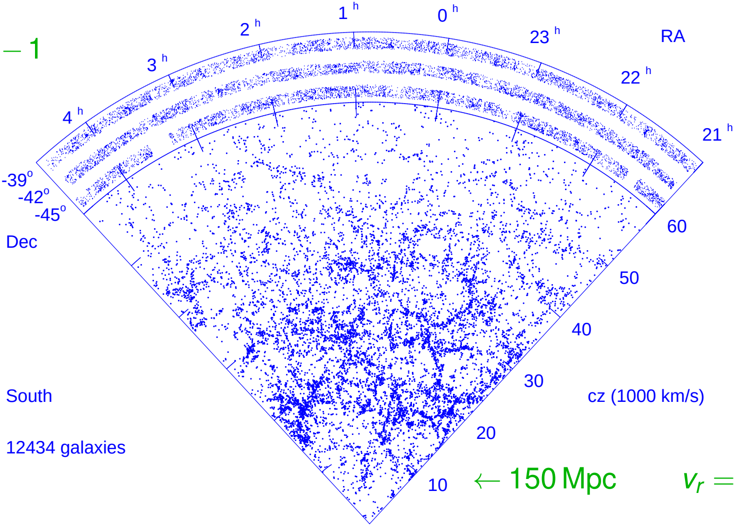




Universe is homogeneous and isotropic

redshift

$$z \equiv \frac{\lambda_{\text{detector}}}{\lambda_{\text{source}}} - 1$$

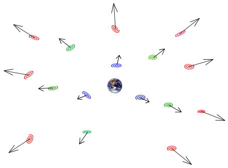


$\leftarrow$ 150 Mpc

$$v_r = c\,z$$

Conclusions from observations

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



Conclusions

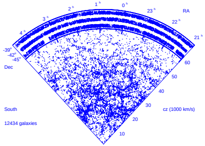
- interval between events gets modified

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

in GR expansion is described by the Friedmann equation

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

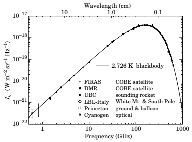
$$\rho_{\substack{\text{energy}\\ \text{density}}} = \rho_{\text{radiation}} + \rho_{\text{matter}} + \dots$$



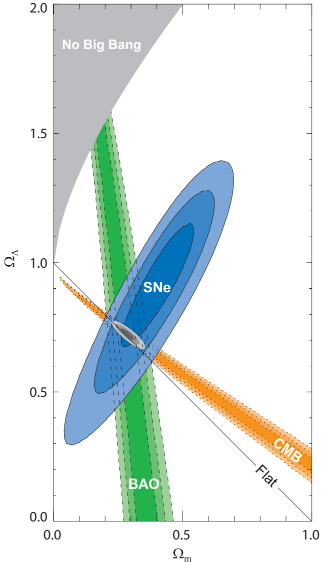
- in the past the matter density was higher, our Universe was “hotter” filled with electromagnetic plasma

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

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



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

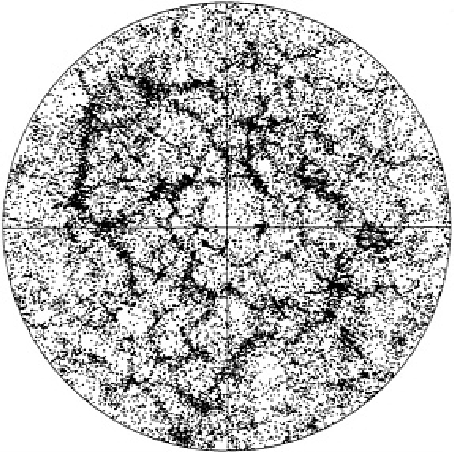
Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.046$

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

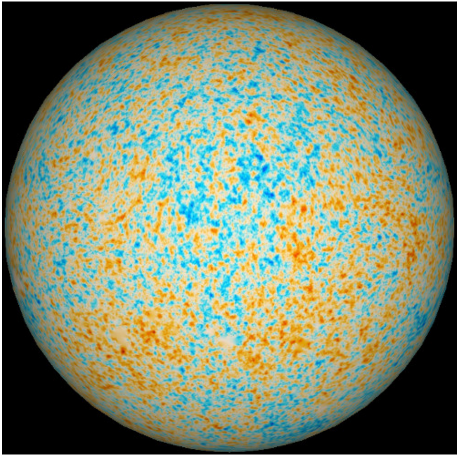
Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.28$

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

Recombination: $p+e \to H+\gamma$, $T_{rec} \approx 0.25\,\text{eV}$



Large Scale Structure



CMB anisotropy

These inhomogeneities (matter perturbations)

originate from the initial matter density (scalar) perturbations

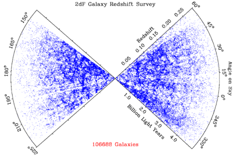
$\delta\rho/\rho \sim \delta T/T \sim 10^{-4}$, which are

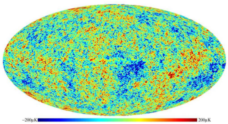
adiabatic $$\delta\left(\frac{n_B}{s}\right) = \delta\left(\frac{n_{DM}}{s}\right) = \delta\left(\frac{n_L}{s}\right)$$

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

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

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





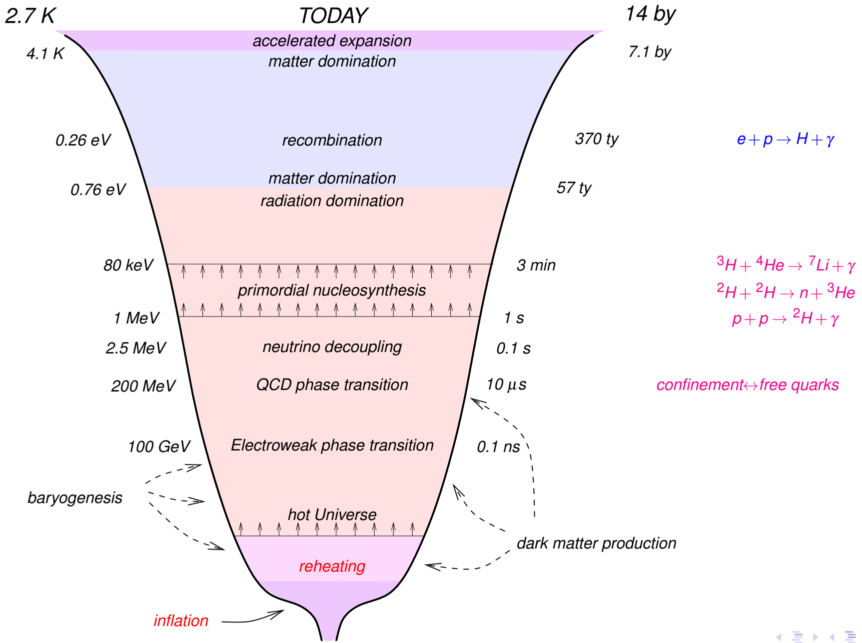
Standard cosmological model $ds^2 = dt^2 - a^2(t)dx^2$

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

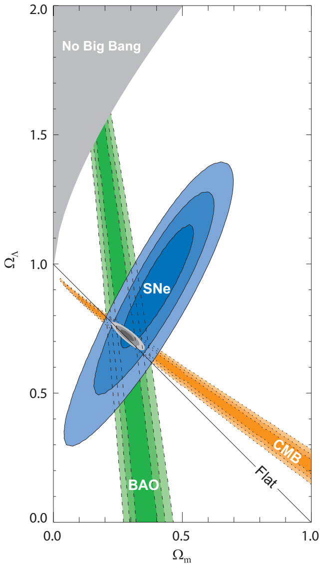
- $T_\gamma = 2.735\,\mathrm{K}, \quad \Longrightarrow \quad \Omega_\gamma \sim 10^{-5}$
- $N_\nu \approx 3, \quad \sum m_\nu < 0.2\,\mathrm{eV} \quad \Longrightarrow \quad \Omega_{\nu,\neq 0},\, \Omega_{\nu,0} \sim 10^{-5}$?
- $\Omega_B = 4.5\% \quad \Longrightarrow \quad \eta_B \equiv n_B/n_\gamma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


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e+p \to H+\gamma$
0.76 eV
matter domination
57 ty
radiation domination
80 keV
3 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 phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Dark Energy: nonclumping matter?

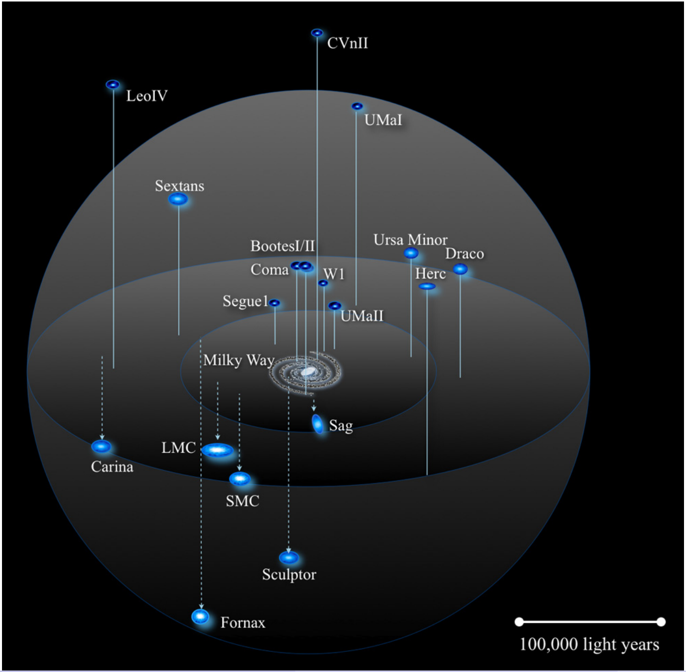


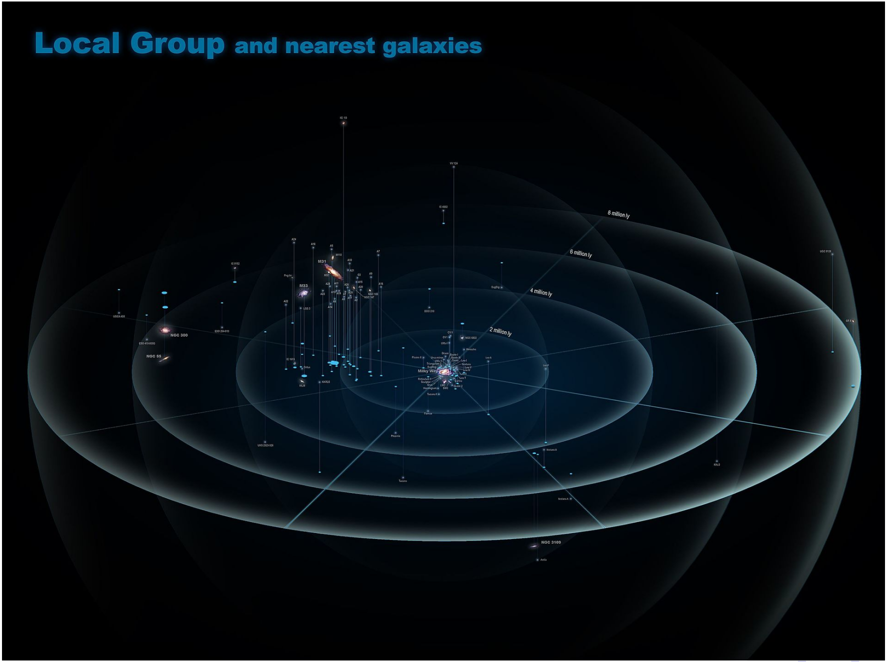
- estimates of Matter contribution confined in galaxies and clusters $\rho_c - \rho_M \neq 0$ but the Universe is flat, so $\rho_{curv} \simeq 0$
- corrections to the Hubble law : red shift – brightness curves for standard candles (SN Ia)
- The age of the Universe
- CMB anisotropy, large scale structures (galaxy clusters formation), etc

Local group members will survive

$\rho_\Lambda = 0.68\rho_c$ $a(t) \propto e^{H_\Lambda t}$

$$\rho_\Lambda \sim 10^{-5}\ \mathrm{GeV/cm^3} \sim \left(10^{-11.5}\ \mathrm{GeV}\right)^4$$


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


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
IC 10

Dark Energy: all evidences are from cosmology

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

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

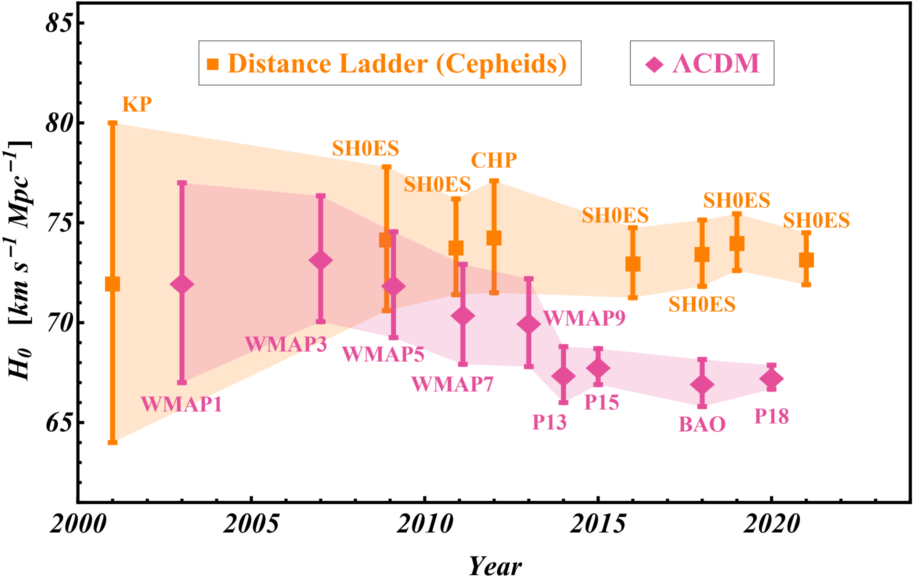
both parts contribute

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

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?


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

2105.05208

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

$$H^2(z) = H_0^2\left(\Omega_\Lambda + \Omega_M(1+z)^3 + \Omega_{cur}(1+z)^2 + \Omega_{rad}(1+z)^4 + \dots\right), \quad 1+z \equiv \frac{a_0}{a(t)}$$

$$ds^2 = dt^2 - a^2(t)\left(d\rho^2 + r^2(\rho)\, d\Sigma^2_{(2)}\right)$$

Light propagation changes...

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

$$L(z) = a_0 \times r(\rho(z)), \quad \rho(z) = \int d\rho = \int_t^{t_0} \frac{dt'}{a(t')} = \int_0^z \frac{dz'}{H(z')} \to \frac{z}{H_0}, \quad \text{at} \quad z \to 0$$

- Measuring brightness J of an object of known luminosity F "standard candles"

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

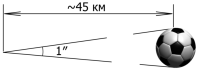
- New observables:
  – time delays between images of SN explosion
  – standard sirens: Gravitational Waves from observed astrophysical source
  – ...

Sound waves in photon-electron plasma

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

single-type galaxies, and sound horizon !!

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



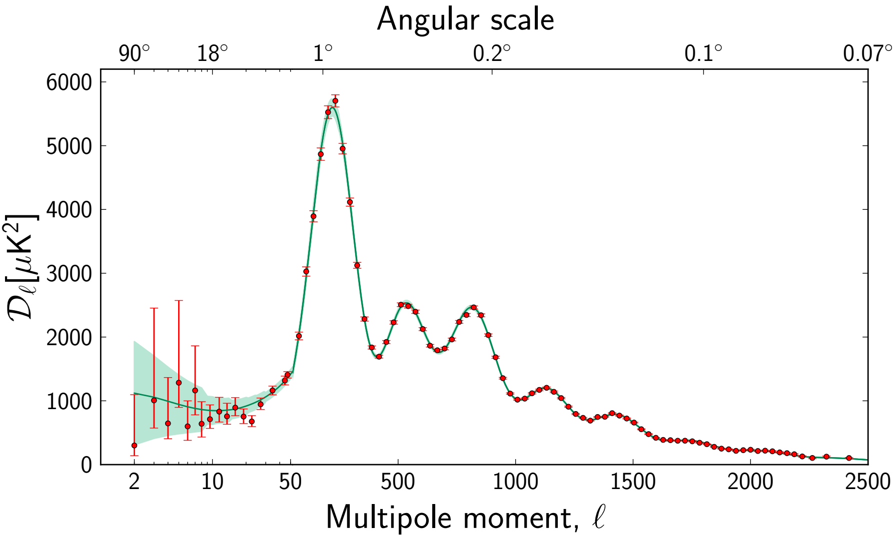
- Subhorizon Inhomogeneities of photons $\delta\rho_\gamma/\rho_\gamma$ oscillate with constant amplitude at RD and with decreasing amplitude at MD, thus we can measure $T_{RD/MD}/T_{rec}$
- Phase of oscillations decoupled after recombination depends on the wave-length, recombination time and sound speed

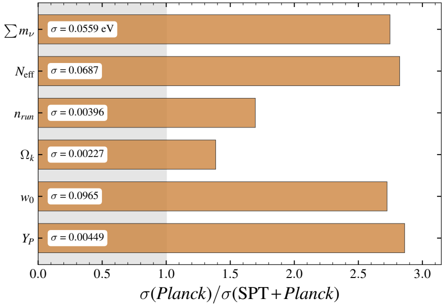
$$\delta\rho_\gamma/\rho_\gamma \propto \cos\left(k\int_0^{t_{rec}} \frac{v_s\,dt}{a(t)}\right) = \cos(k\,l_{sound})\,, \quad l_{sound} \sim \frac{1/\sqrt{3}}{H_{rec}}$$

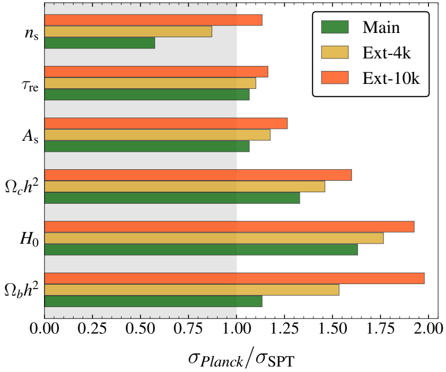
-

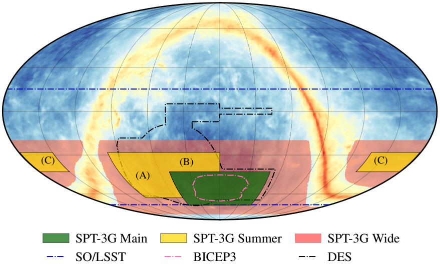
$$\delta T(\theta,\varphi) = \sum a_{lm} Y_{lm}(\theta,\varphi)\,, \qquad \langle a^*_{lm} a_{lm}\rangle = C_l \equiv 2\pi\mathscr{D}_l/(l(l+1))$$

CMB measurements $l_{rec}, \Omega_{DM}, \Omega_B, \Omega_\Lambda, \Delta_{\mathscr{R}}, n_s, z_{rei}$



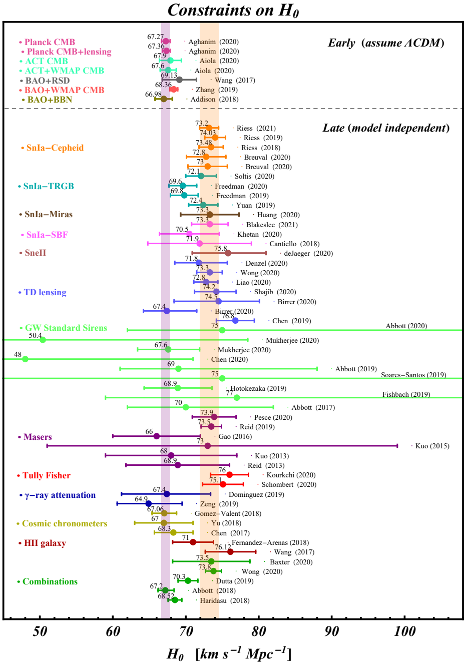






New data from CMB

2403.17925



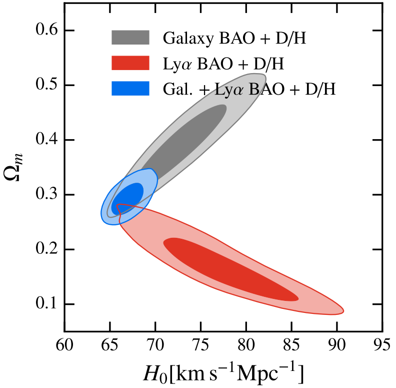
2105.05208 **Need new parameters?**

– dynamical DE: $p = -\omega(z)\rho$,..

– multicomponent DM:
decaying, talking to DE, talking to baryons, sterile neutrinnos, axions,..

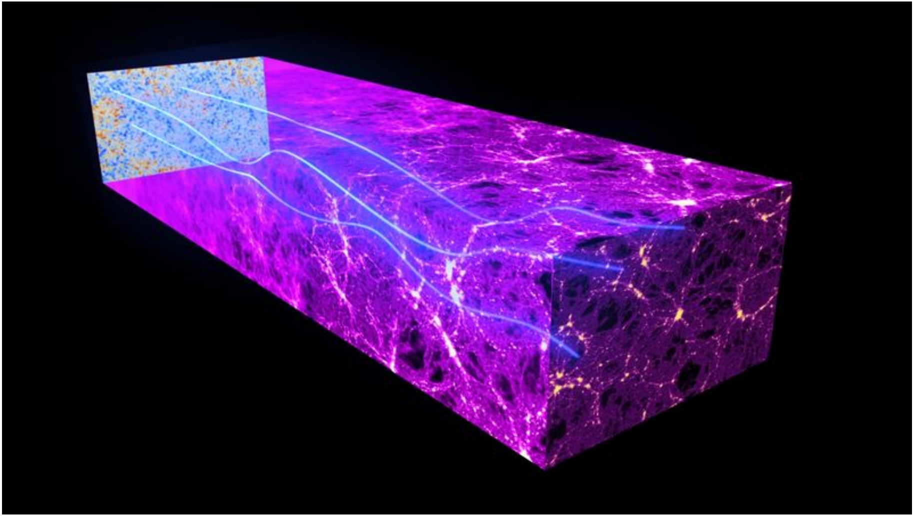
– massive neutrinos, non-zero curvature,..

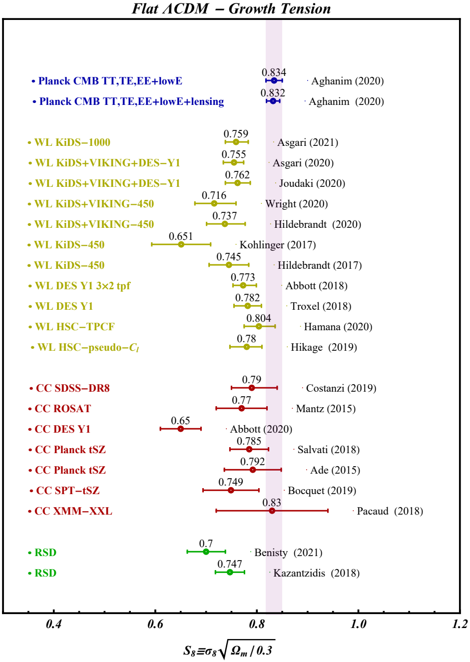
– nonstandard cosmology: early dark energy, late rapid transition,..



Tensions between data sets... 1707.06547

On top of that: propagation in expanding Universe





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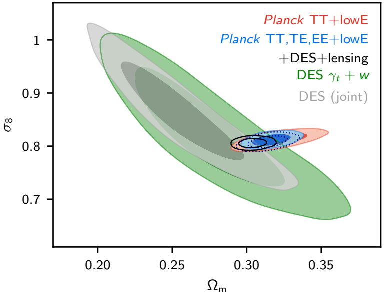
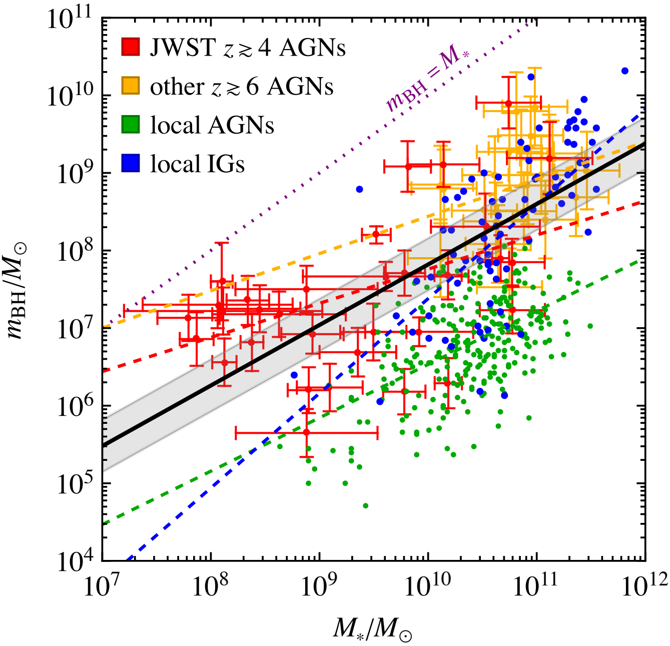
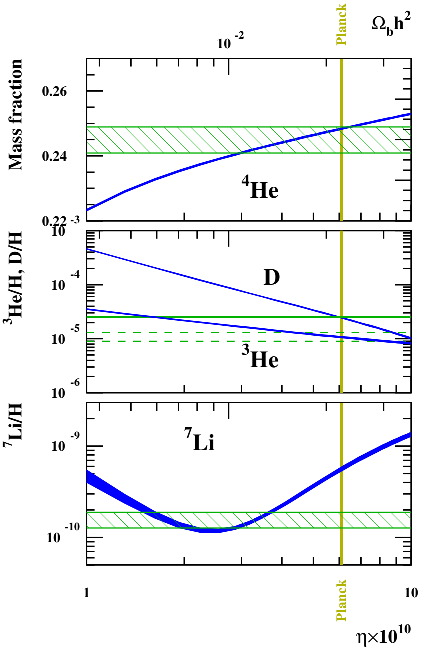


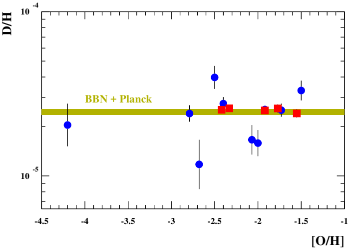
1807.06209


JWST $z \gtrsim 4$ AGNs
other $z \gtrsim 6$ AGNs
local AGNs
local IGs
$m_{BH} = M_*$
$m_{BH}/M_\odot$
$M_*/M_\odot$
10^4
10^5
10^6
10^7
10^8
10^9
10^{10}
10^{11}
10^7
10^8
10^9
10^{10}
10^{11}
10^{12}

2304.19650

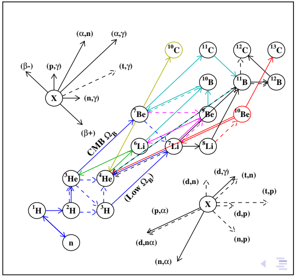


1707.01004 Measurement of $\eta_B = n_B/n_\gamma$ at $T \sim 1$ MeV

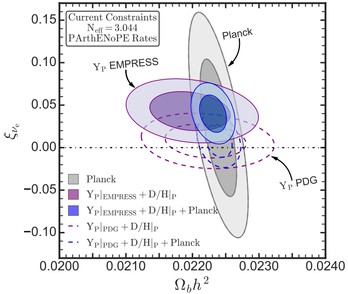


Lack of Lithium. . .

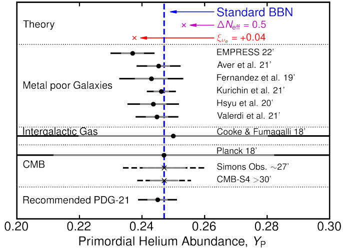
Exotics needed?

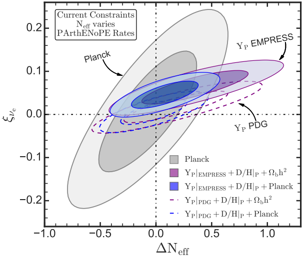


Present observations... probe ξ_{ν_e} and ΔN_ν

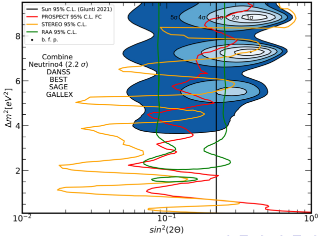


2208.03201 Helium abundance





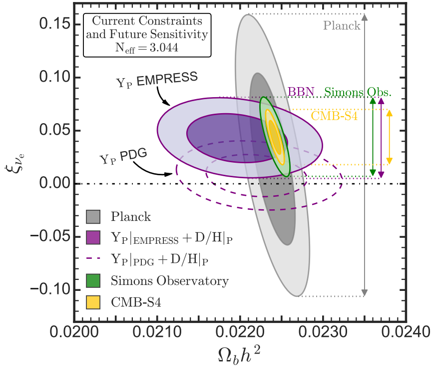
May be useful . . . to safe sterile neutrinos

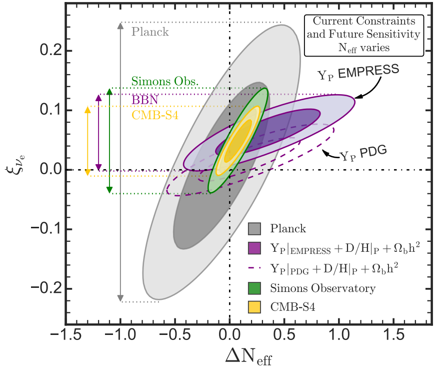


2109.14654

Future with Simons Observatory and CMB-S4

2208.03201





Observables in cosmology

- Astrophysical data
  - Observations in galaxies: stars and clouds 3d-map of Milky Way
  - Observations in galaxy clusters: galaxies, gas, distortions
- Cosmological data
  - Observation of sources at cosmological distances (far=early)
  - Baryonic Aciustic (Sakharov) Oscillations (BAO) in two-point galaxy correlation function Full shape function
  - Evolution of galaxy clusters in the Universe
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  -
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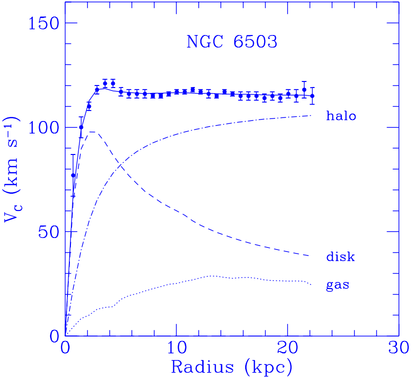
Galactic dark halos: flat rotation curves

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

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



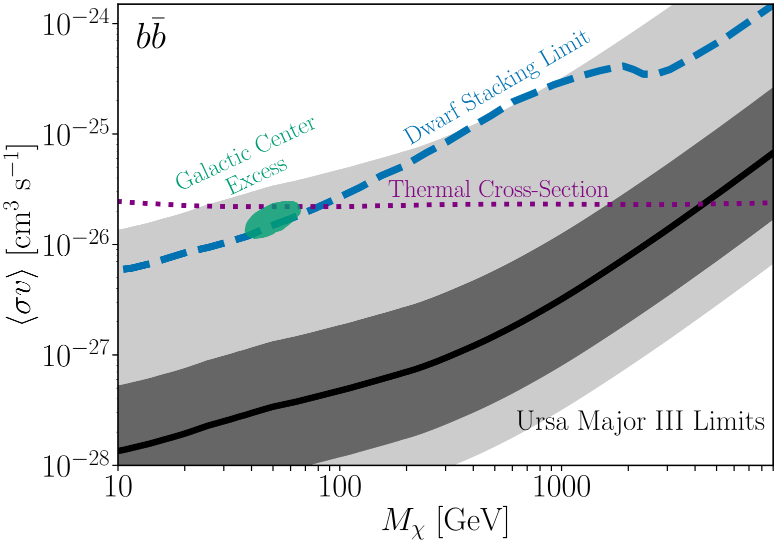
observations: $v(R) \simeq \text{const}$

visible matter:

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

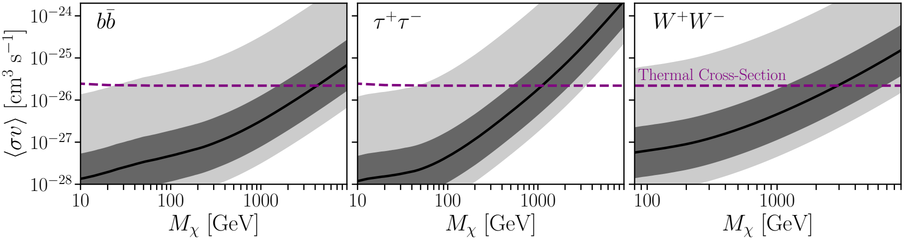
external ("empty") regions $v(R) \propto 1/\sqrt{R}$

Ursa Major III: $\Omega_{DM} \propto 1/\langle\sigma v\rangle$, $F \propto \langle\sigma v\rangle \times n(r)^2$ 2311.14611



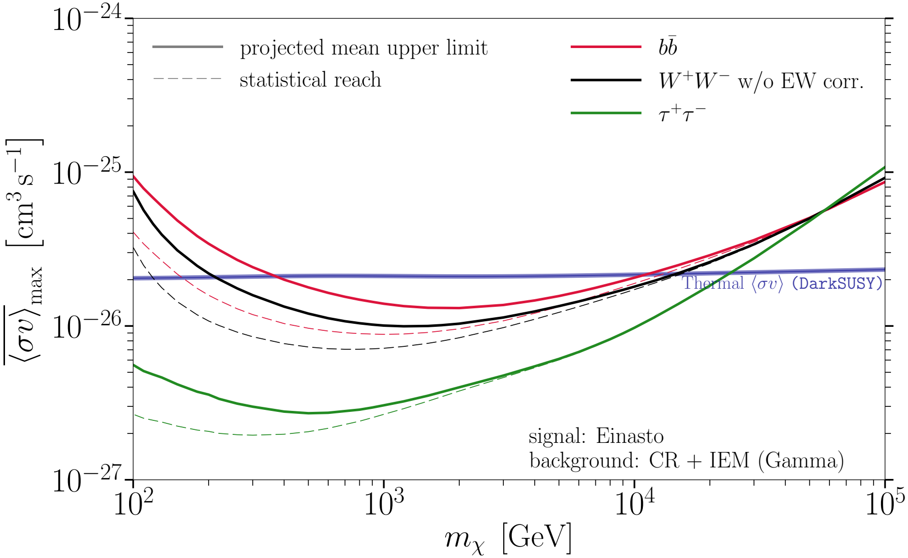
Ursa Major III

2311.14611



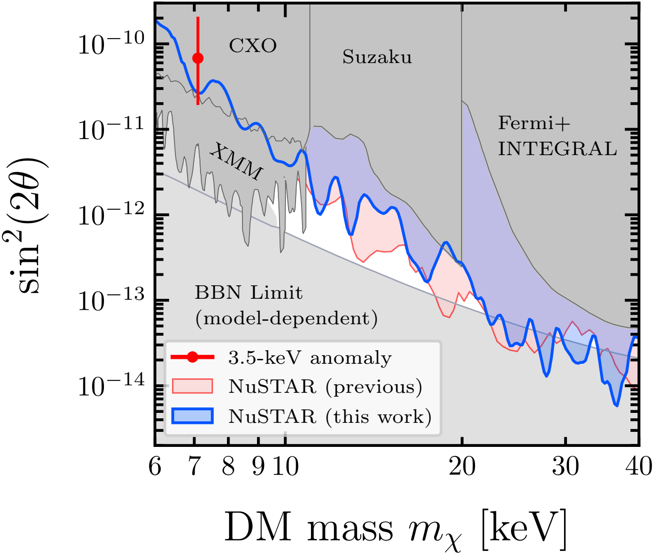
Next generation: CTA

2108.09078



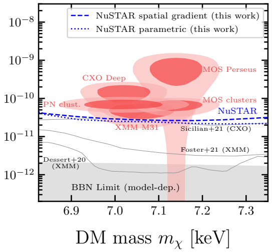
. . . present searches: NuSTAR

2207.04572



- upper limits on mixing: from *X*-ray searches
- lower limits on mass: from structure formation

  and BBN predictions



Observables in cosmology

- Astrophysical data
  - Observations in galaxies: stars and clouds — 3d-map of Milky Way
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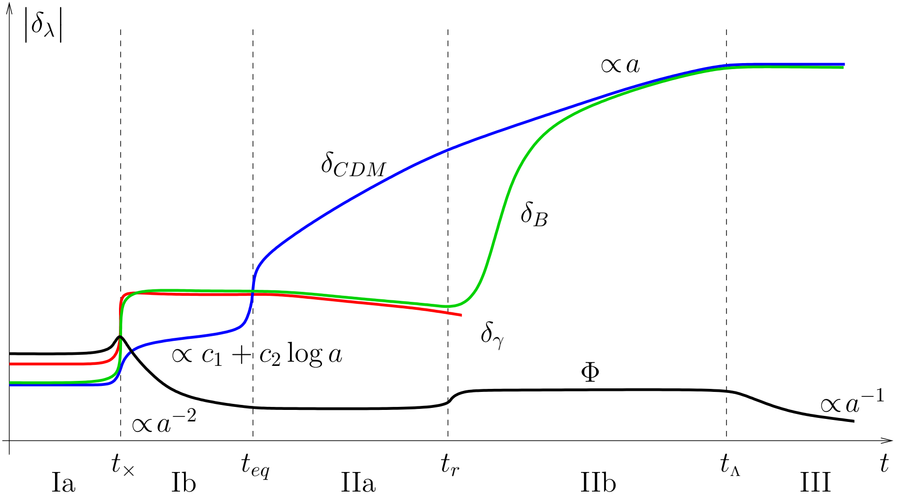
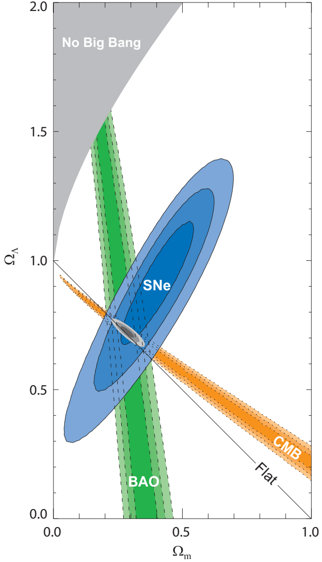
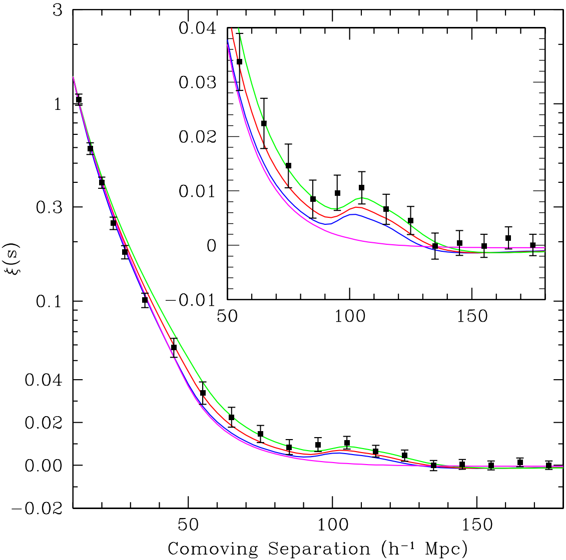
Subhorizon modes ($k/a > H$) at various stages



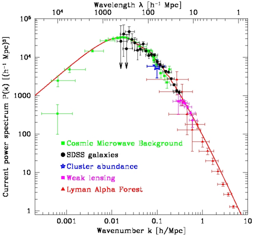




$$110/0.7\,\text{Mpc} \simeq l_{H,r}(t_0) \times \sqrt{v_s^2} \simeq l_{H_0}/\sqrt{3}/\sqrt{1+z_r}$$

Key observable: matter perturbations

- CMB is isotropic, but “up to corrections, of course...”
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy!
     $$\frac{\Delta T}{T} \sim 10^{-4} - 10^{-5}$$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination ($e + p \to \gamma + H^*$)
- Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ $\Longrightarrow$ galaxies (CDM halos)



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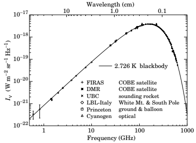
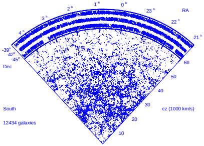
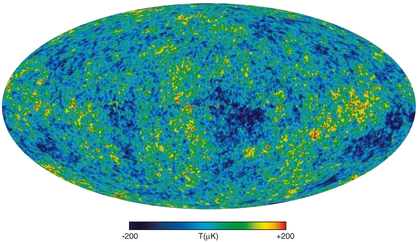
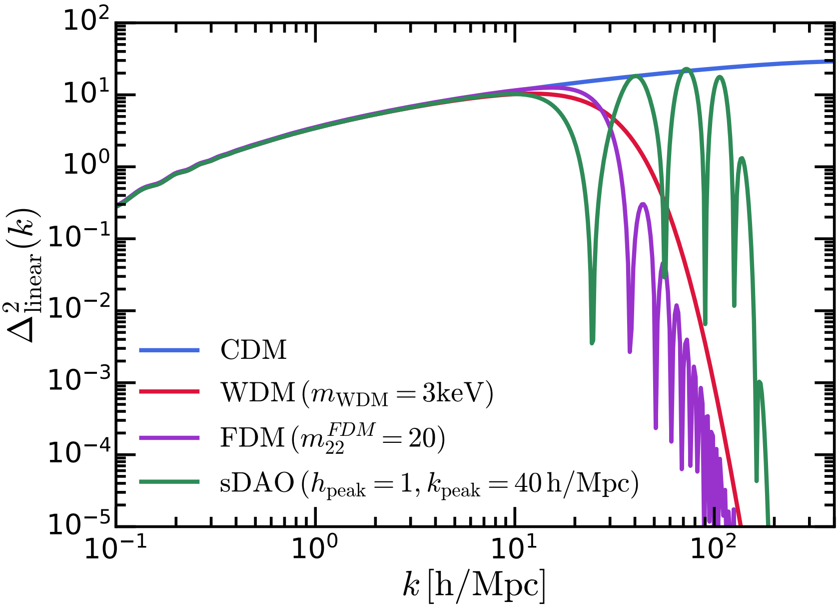
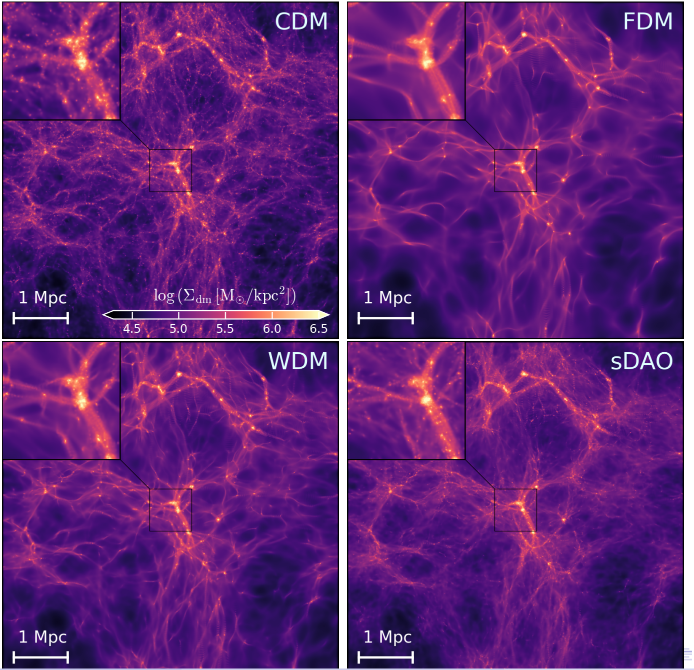




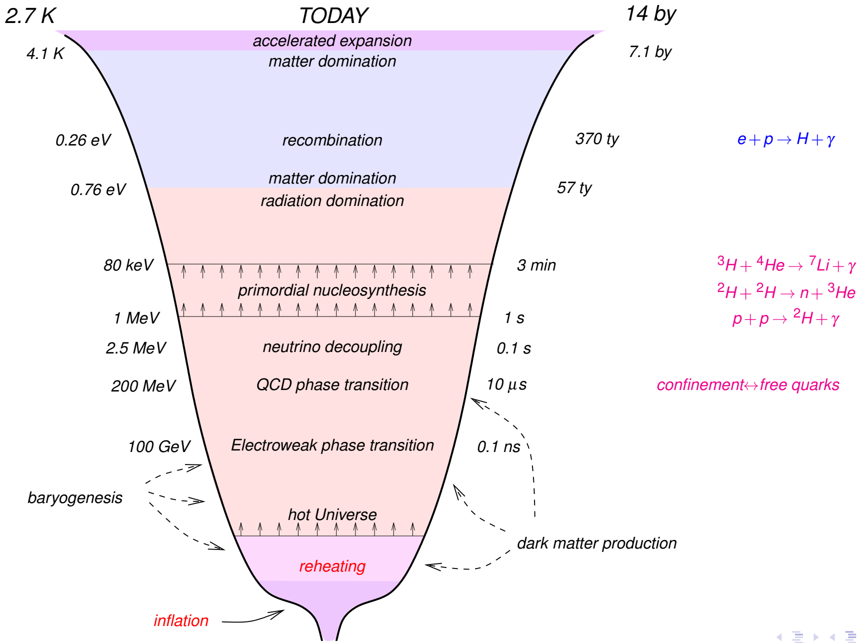




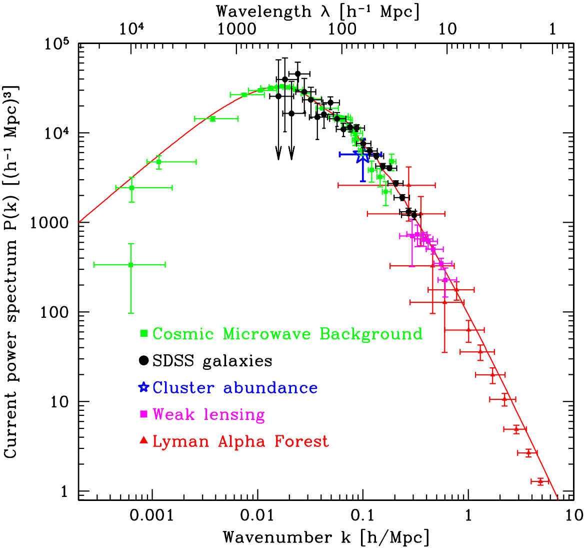
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$\Delta^2_{\rm linear}(k)$
10^{-1}
10^{0}
10^{1}
10^{2}
$k\,[\mathrm{h/Mpc}]$
CDM
WDM $(m_{\rm WDM} = 3\mathrm{keV})$
FDM $(m_{22}^{FDM} = 20)$
sDAO $(h_{\rm peak} = 1, k_{\rm peak} = 40\,\mathrm{h/Mpc})$



2304.06742


2.7 K
TODAY
14 by
accelerated expansion
4.1 K
matter domination
7.1 by
0.26 eV
recombination
370 ty
$e+p\to H+\gamma$
matter domination
0.76 eV
57 ty
radiation domination
80 keV
3 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 phase transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Actually we observe rather narrow range



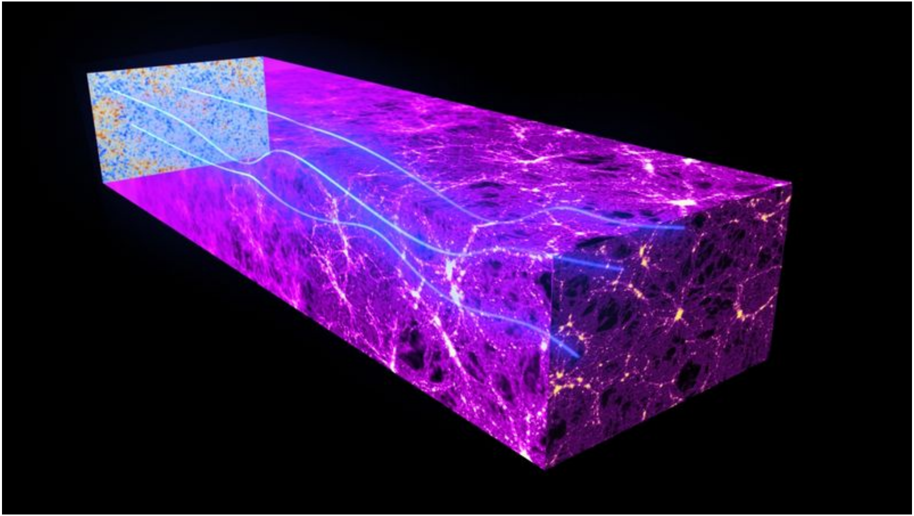
Observable range:

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

$$\Delta N_e \simeq 10$$

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

On top of that: propagation in expanding Universe



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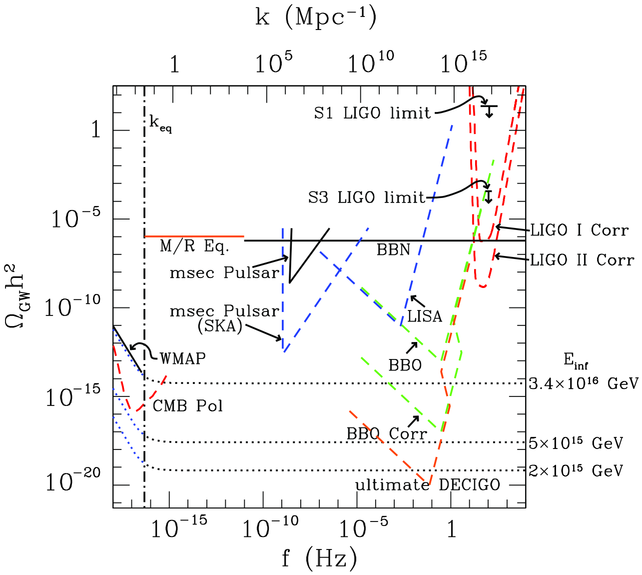
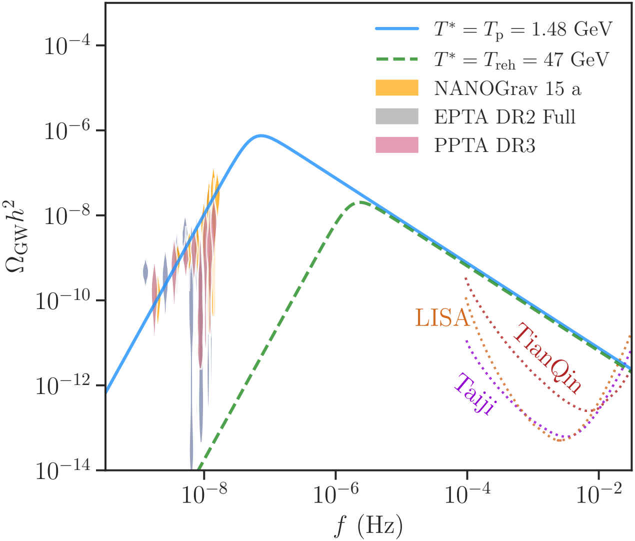
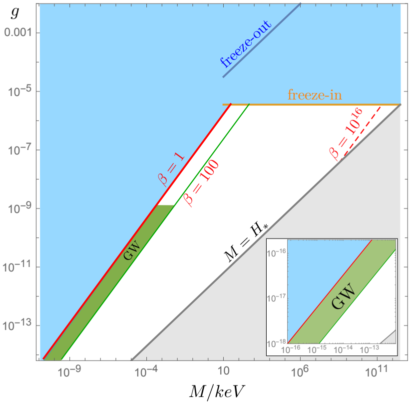
Prospects in 2014

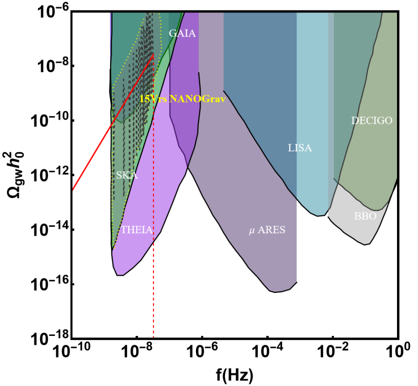


Example: EW Ist order Phase Transition

2307.01072





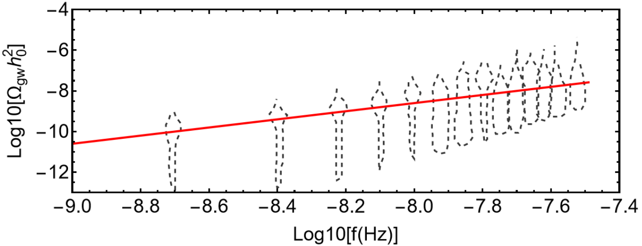


2105.05208

$$\beta \equiv \lambda/g^4$$

$$V = \frac{1}{2}M^2X^2 + \frac{\lambda}{4}X^4 - \frac{g^2T^2}{12}X^2$$

2307.04582



New data and New observables

- more Hubble tracers
- 21cm map
- 3-d map from Euclid
- improved CMB anisotropy
- CMB polarisation
- relic GW from inflation ?
- relic GW from Phase Transitions, etc?
- relic BH ?

New cosmological parameters

- nature of DE and DM
- neutrino masses
- reionisation schedule
- nongaussianity?
- isocurvature modes?
- scale of inflation
- reheating mechanism
- cosmological evolution

DM from oscillating scalar

$0 \neq g^2 < 10^{-11}$

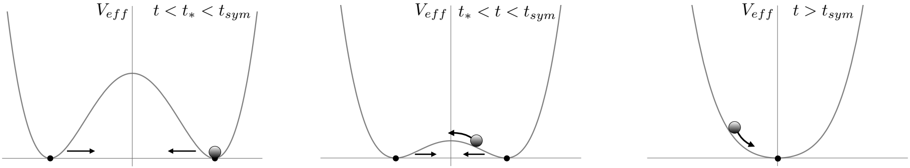
Z_2-invariant Higgs (Φ) portal

$$\Delta\mathscr{L} = \frac{1}{2} g^{\mu\nu}\partial_\mu X \partial_\nu X - \frac{1}{2} M^2 X^2 + g^2 X^2 \Phi^\dagger \Phi - \frac{\lambda}{4} X^4$$

Higgs particles in plasma change the potential:

$$g^2 X^2 \Phi^\dagger \Phi \;\rightarrow\; g^2 X^2 T^2/3$$

Z_2 symmerty is broken after reheating by the plasma contribution

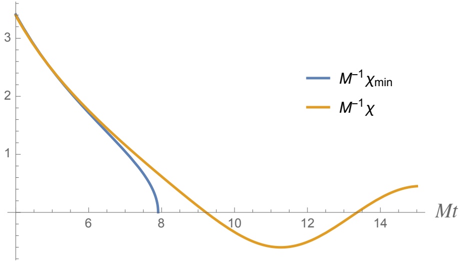


Temperature decrease restores Z_2

2004.03410

$$\Delta\mathscr{L} = \frac{1}{2}g^{\mu\nu}\partial_\mu X\partial_\nu X - \frac{1}{2}M^2X^2 + g^2X^2T^2/3 - \frac{\lambda}{4}X^4$$

X starts from the false vacuum



at $g^2T_*^2 \simeq M^2$ sign changes
and X starts to oscillate
gravitational misalignment

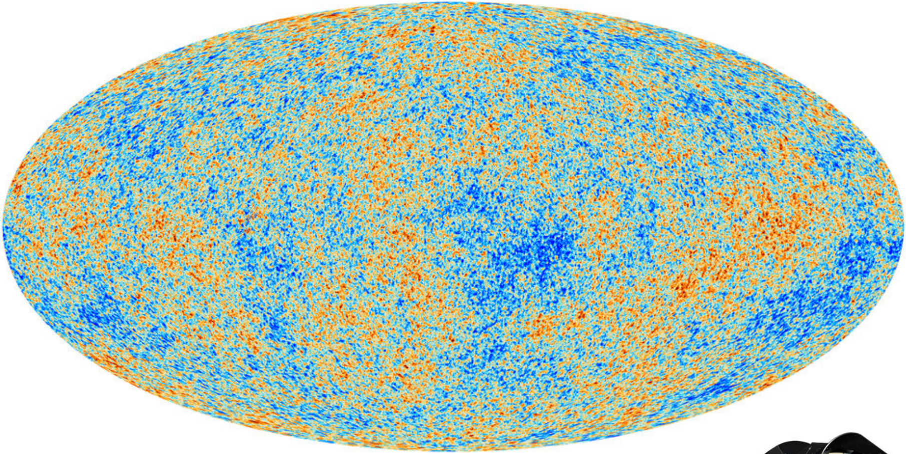
$$\rho_{DM}(t_*) = \frac{M^2\cdot S_*^2}{2} \simeq \frac{\left(M^5H_*\right)^{2/3}}{4\lambda}$$

And the correct amount of DM by classical oscillating field

$$p = \langle E_{kin}\rangle - \langle E_p\rangle = 0$$

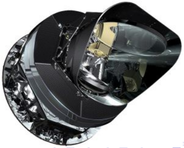
$$g^2 \simeq 10^{-12}\times\left(\frac{\lambda}{10^{-6}}\right)^{6/5}\times\left(\frac{10^6\,\text{GeV}}{M}\right)^2$$

First results of Planck (2013)



$$\frac{\Delta T}{T} \sim \frac{1}{1000}$$

Spectra are plankian!!



Cosmic Background Radiation is polarized