What could we learn about high energy particle physics from cosmological observations at largest spatial scales ?

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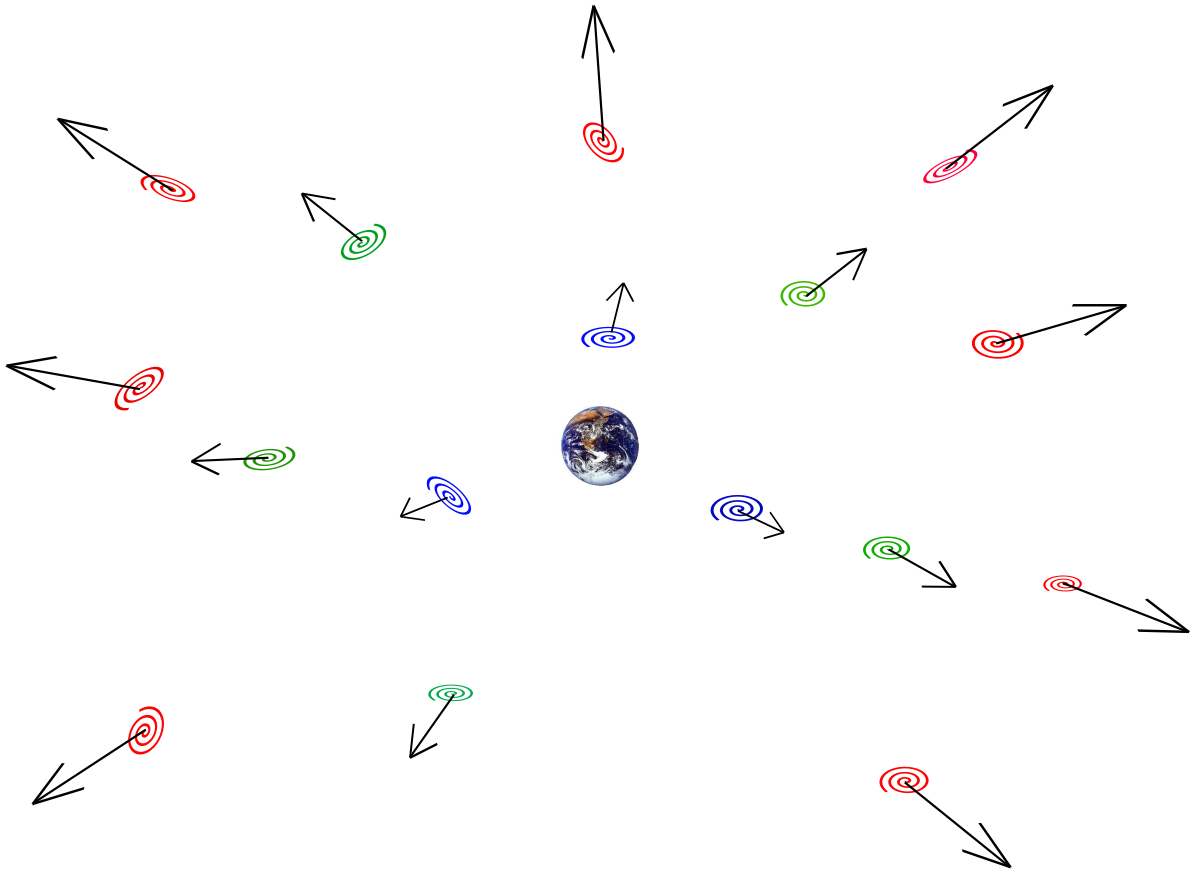
The main message

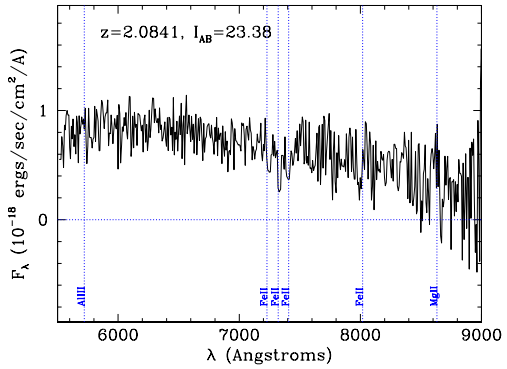
- Physics at the highest energy scales may be probed with observations at the largest spatial scales (just somewhat smaller than the size of the visible Univserse)
- However, we are not (yet) ready to make the tests realistic (theory)

Universe is expanding

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

Doppler redshift Z of light

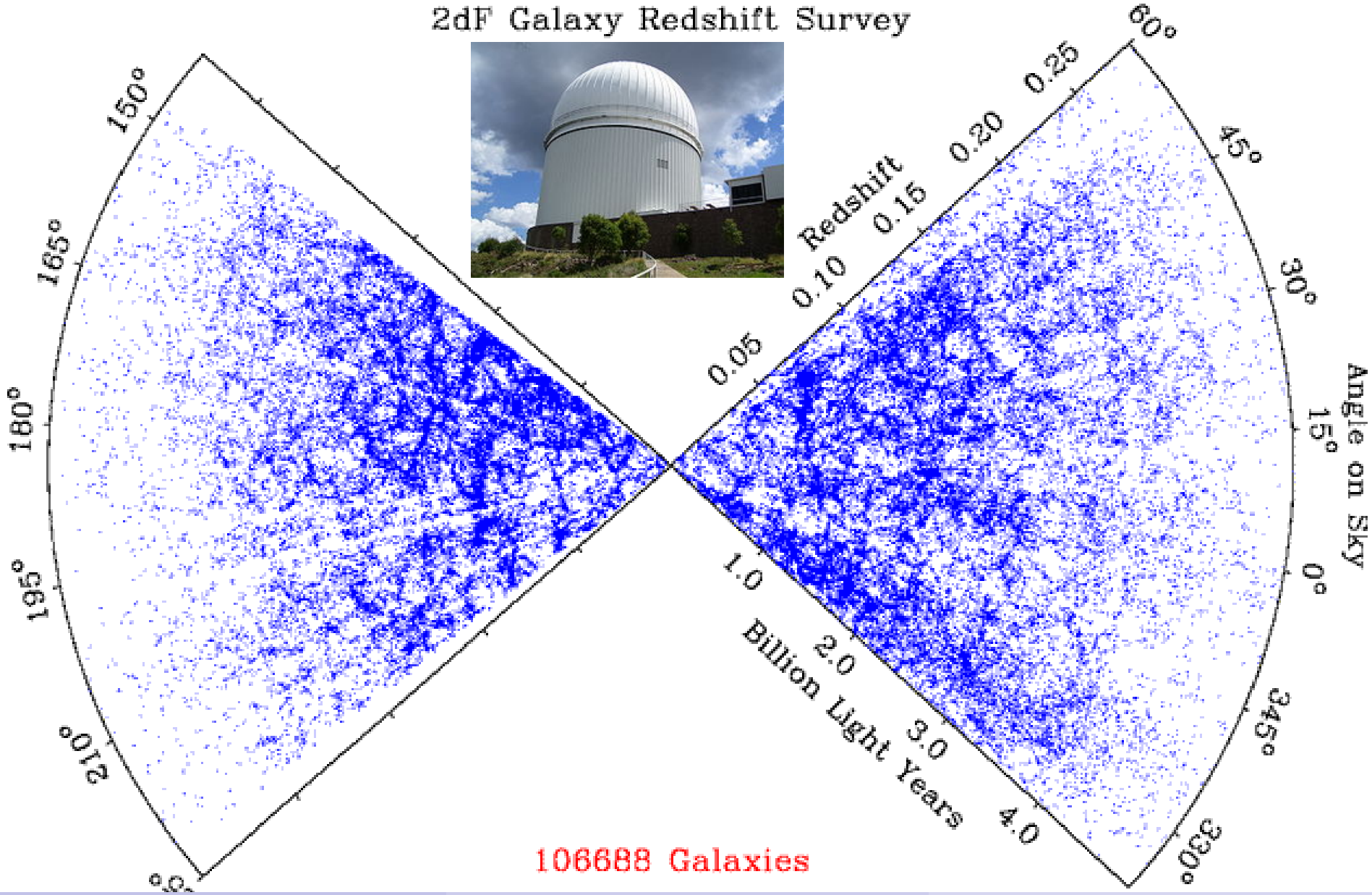




$L \propto a(t)$

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

Universe is homogeneous and isotropic

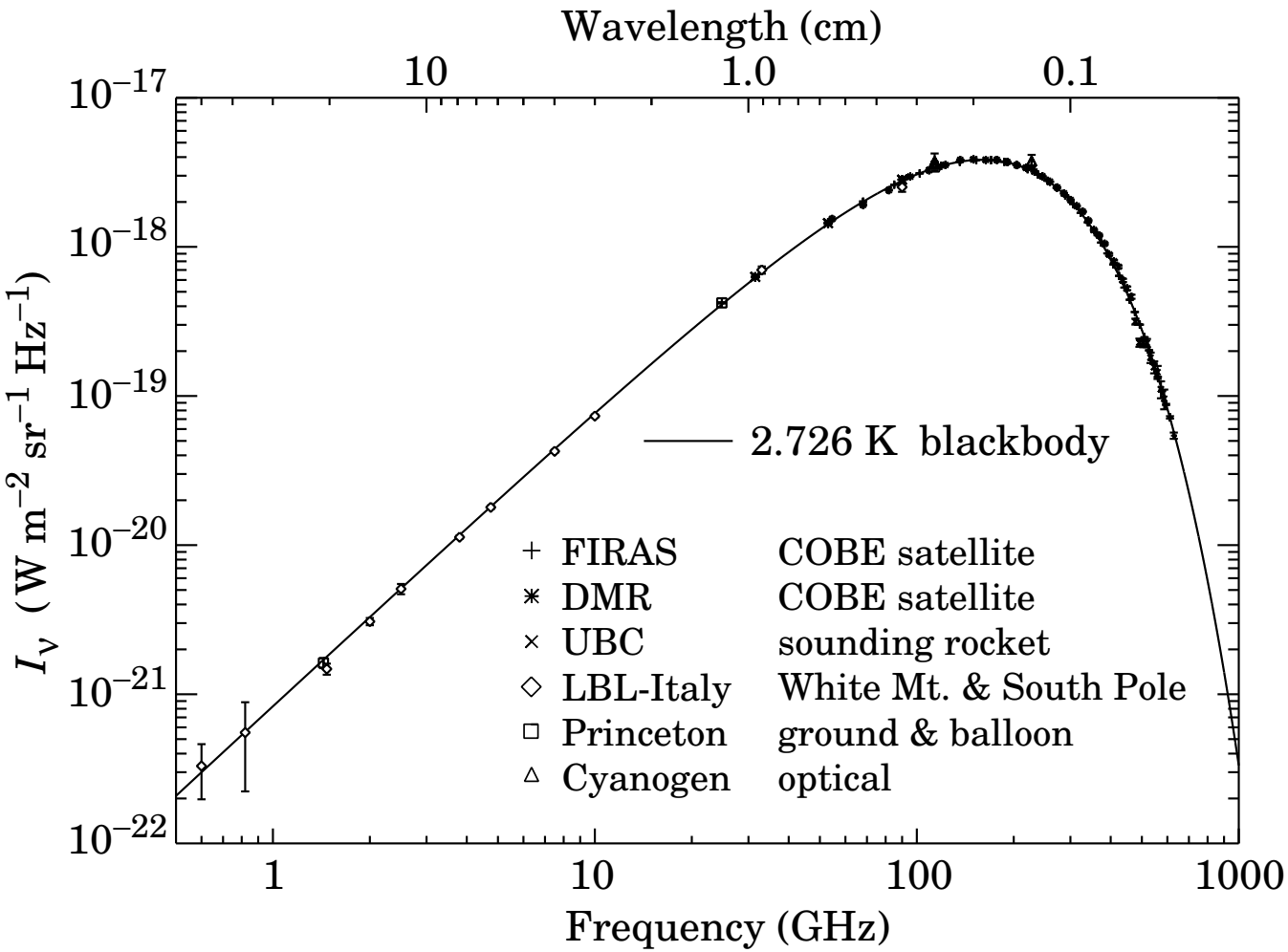


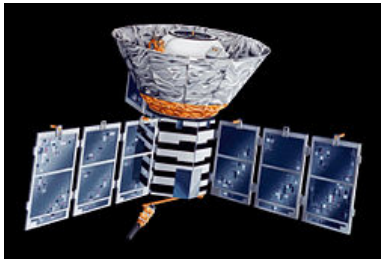
Universe is occupied by “thermal” photons

the spectrum (shape and normalization!) is thermal

$T_0 = 2.726$ K

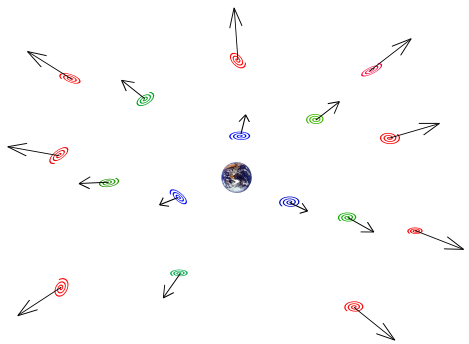
$n_\gamma = 411$ cm^{-3}





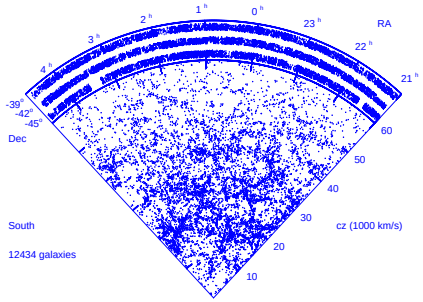
Conclusions from observations

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



- interval between events gets modified

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

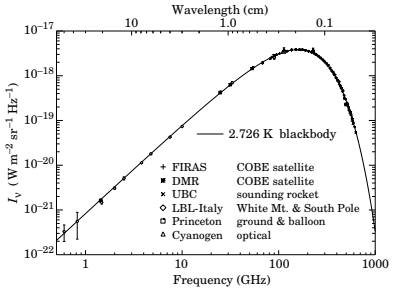


- in GR expansion is described by the Friedmann equation

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

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

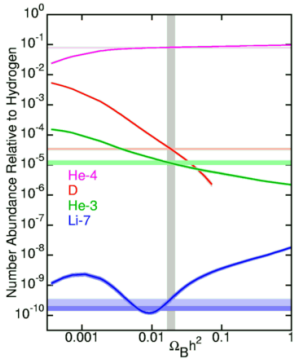
$$\rho_{\text{matter}} \propto 1/a^3(t), \quad \rho_{\text{radiation}} \propto 1/a^4(t), \quad \rho_{\text{curvature}} \propto 1/a^2(t)$$



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

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



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

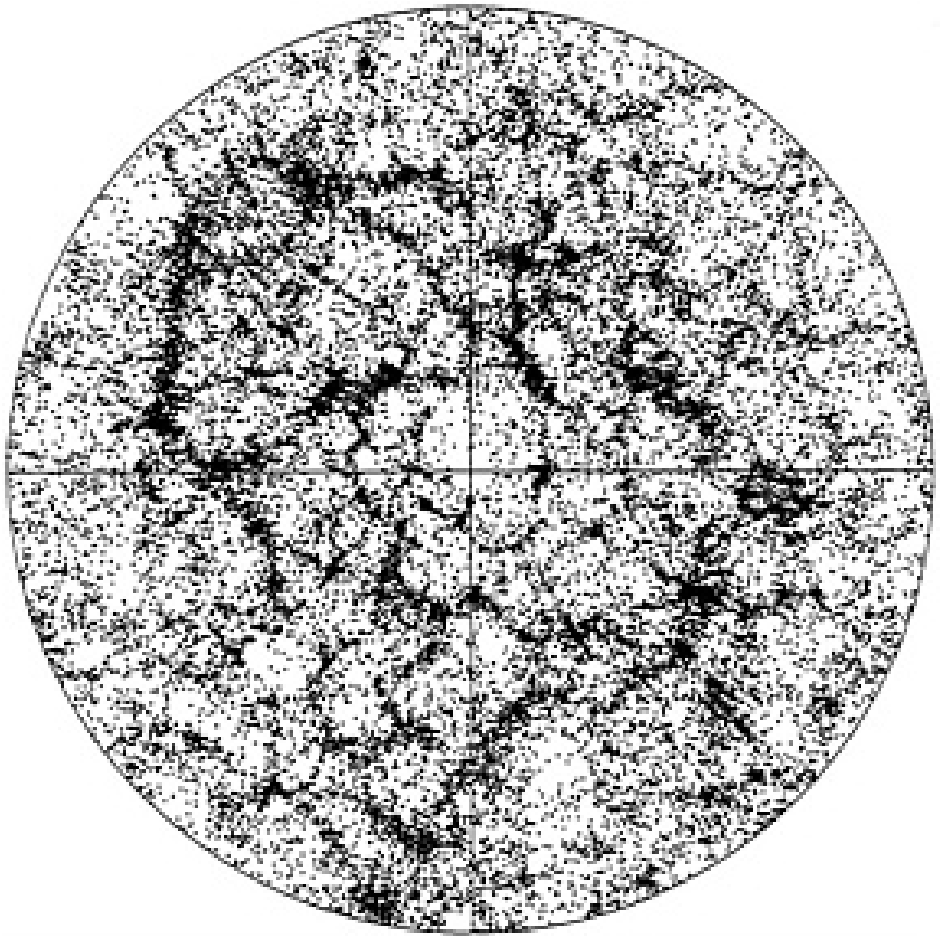
New Physics in Cosmology: any energy scales...

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

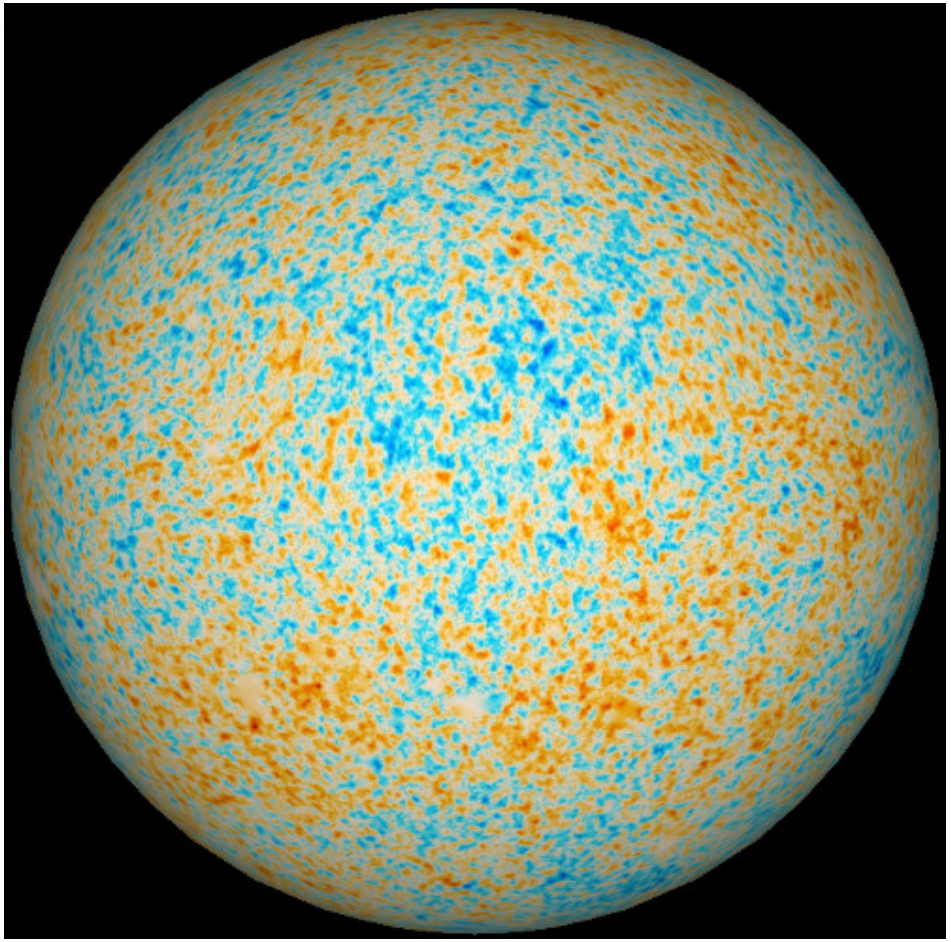
$$\Gamma \sim H \propto T^2/M_{\rm Pl}$$

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

Inhomogeneous Universe



Large Scale Structure



CMB anisotropy

These inhomogeneities (matter perturbations)

originate from the initial matter density (scalar) perturbations

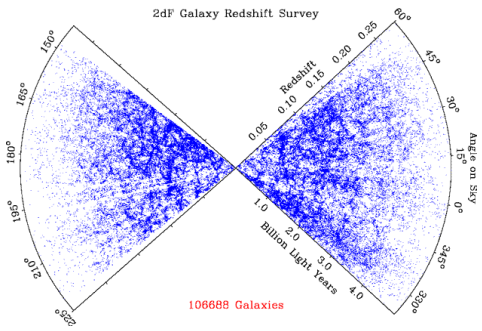
$\delta\rho/\rho \sim \delta T/T \sim 10^{-4}$, which are

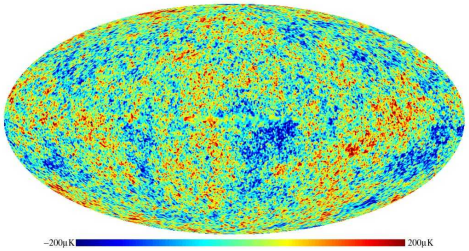
adiabatic $$\delta\left(\frac{n_B}{s}\right) = \delta\left(\frac{n_{DM}}{s}\right) = \delta\left(\frac{n_L}{s}\right)$$

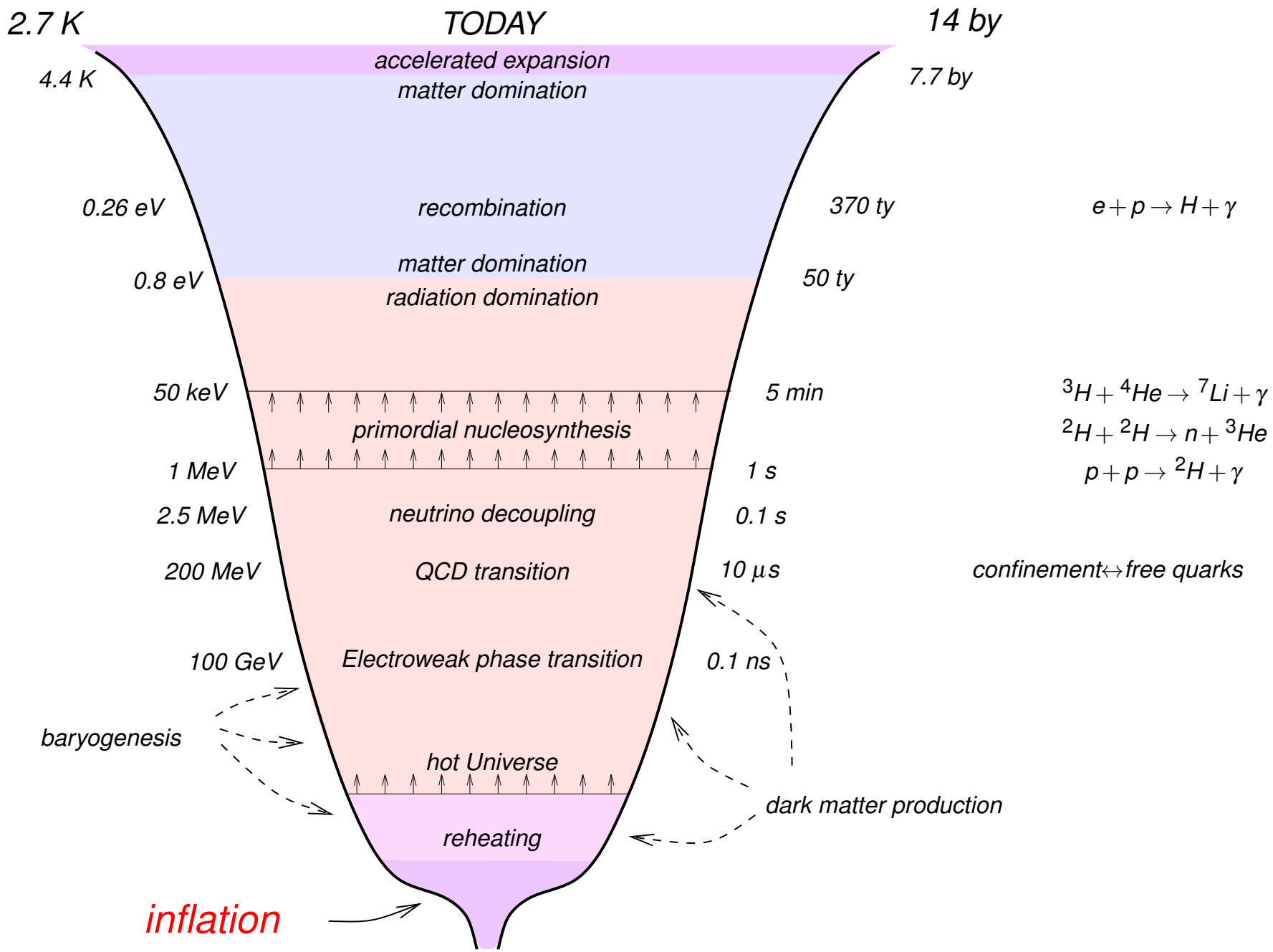
Gaussian $$\langle \frac{\delta\rho}{\rho}(\mathbf{k})\frac{\delta\rho}{\rho}(\mathbf{k}')\rangle \propto \left(\frac{\delta\rho}{\rho}(\mathbf{k})\right)^2 \times \delta(\mathbf{k}+\mathbf{k}')$$

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

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






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
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

Generation of perturbations at inflation

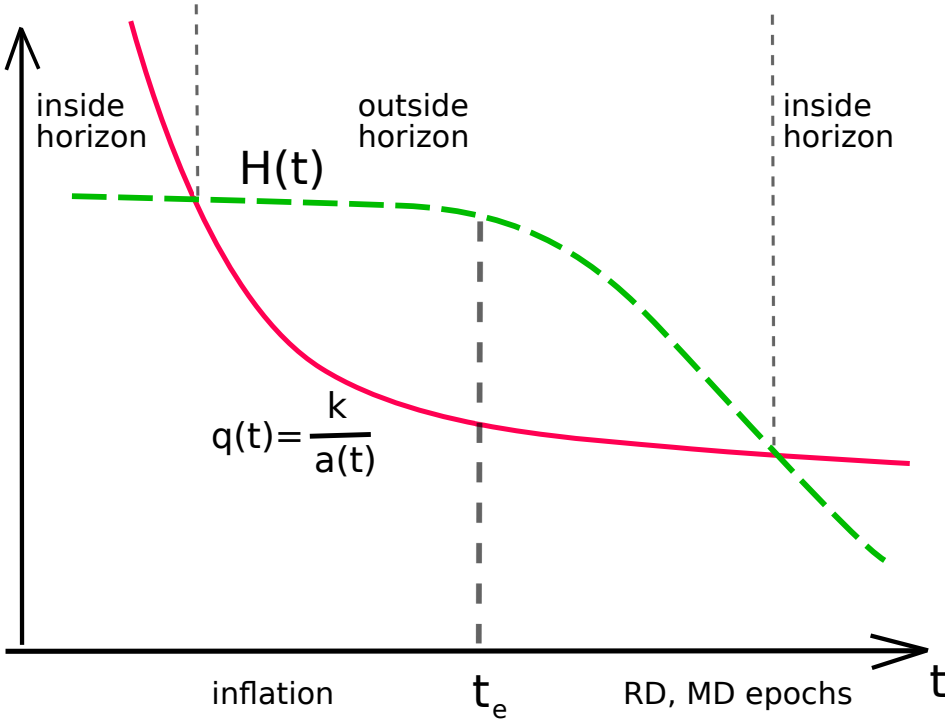
Quantum fluctuations of wavelength λ of a free massless field φ (inflaton and gravitons !!)
have 3-momenta $q \simeq 1/\lambda$ and an amplitudes of $\delta\varphi_\lambda \simeq q$

Evolution at inflation

- inside horizon: $q > H$
  $q \propto 1/a \Rightarrow$ $\delta\varphi_\lambda \propto q \propto 1/a$

- outside horison: $q < H$
  $q \propto a \Rightarrow$ $\delta\varphi_\lambda = \text{const} = H_{infl}/2\pi$!!!

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



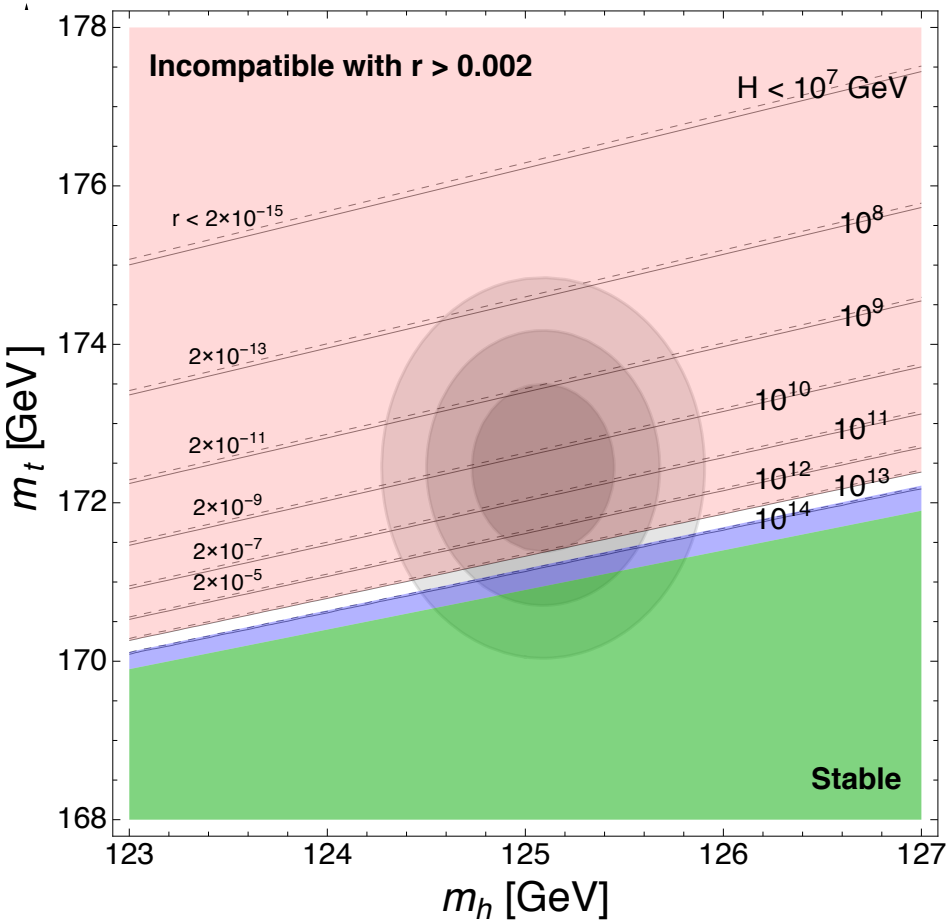
scalar modes $\delta\phi_\lambda \sim H_{infl}$

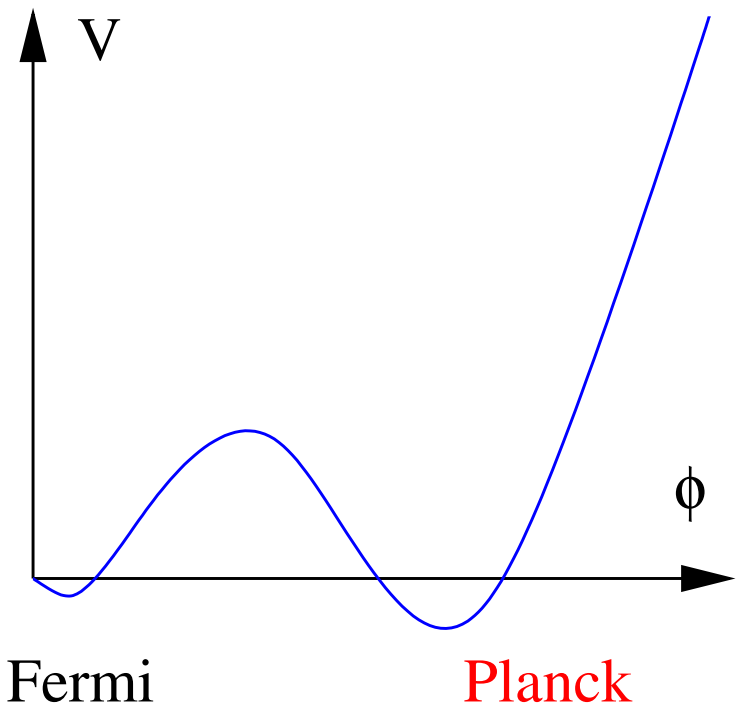
tensor modes $\delta g_{\mu\nu} \sim h \sim H_{infl}/M_{Pl}$

Later at normal stage

$H \propto 1/t$, $q/H \nearrow$, modes "enter horizon"

All bosons fluctuate including the SM Higgs $\phi \sim H/2\pi$





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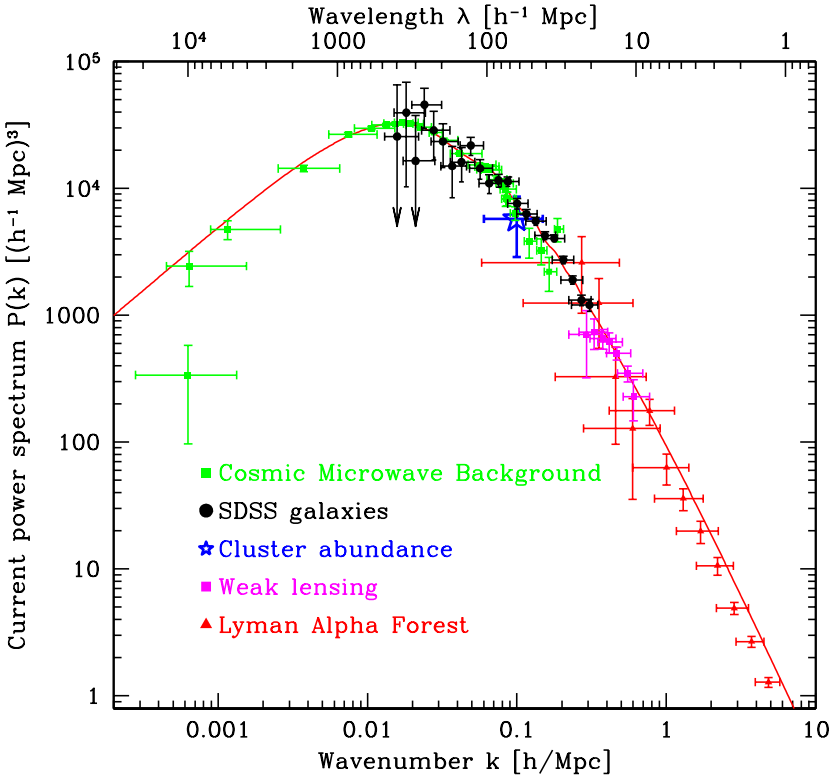
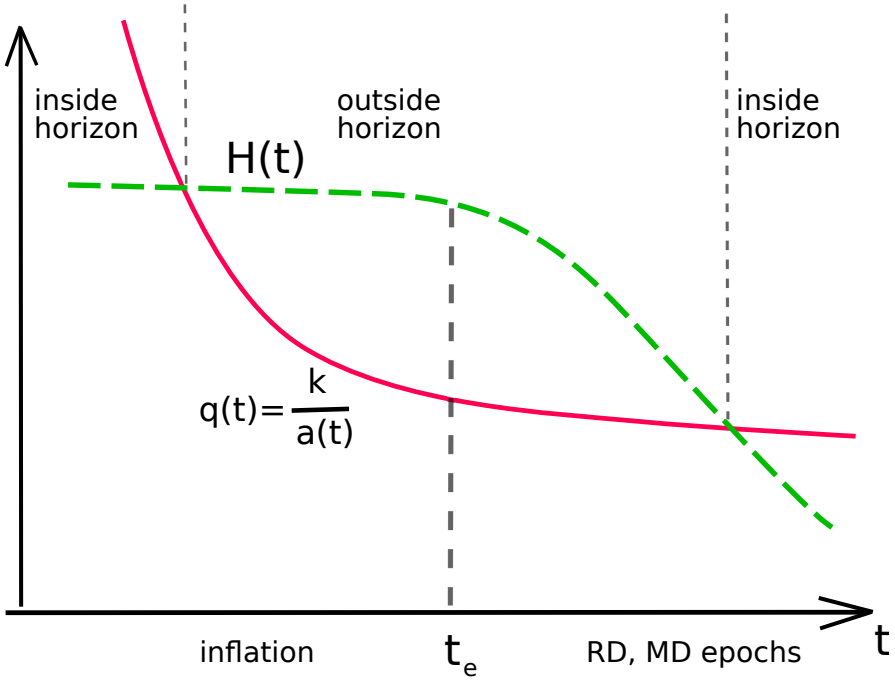
Thus we

either constrain inflation, $H \lesssim \ldots 10^{10}\,\mathrm{GeV} \ldots$ and hence GW, that is r

or ask for NP at a lower scale

Probing the matter power spectrum



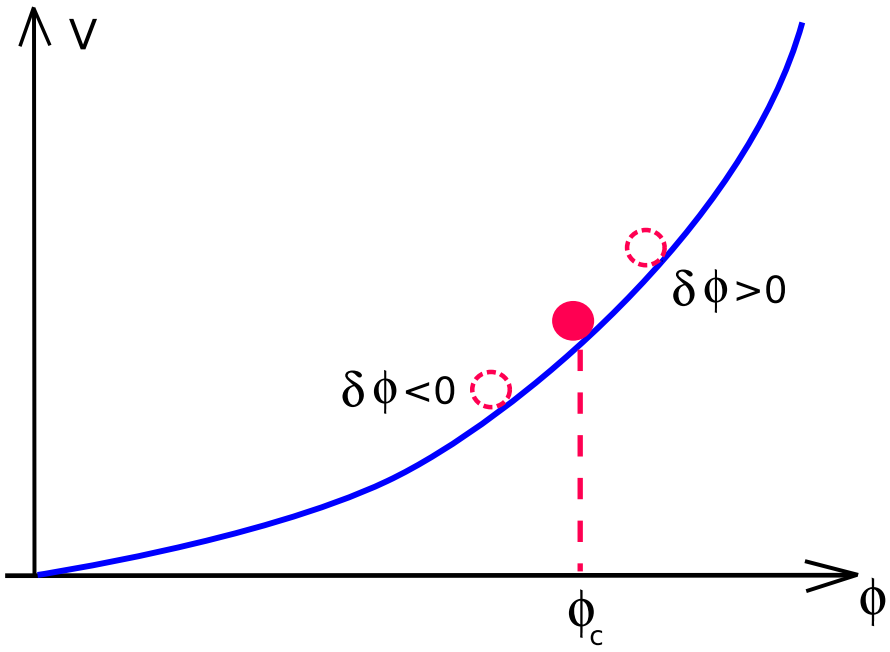


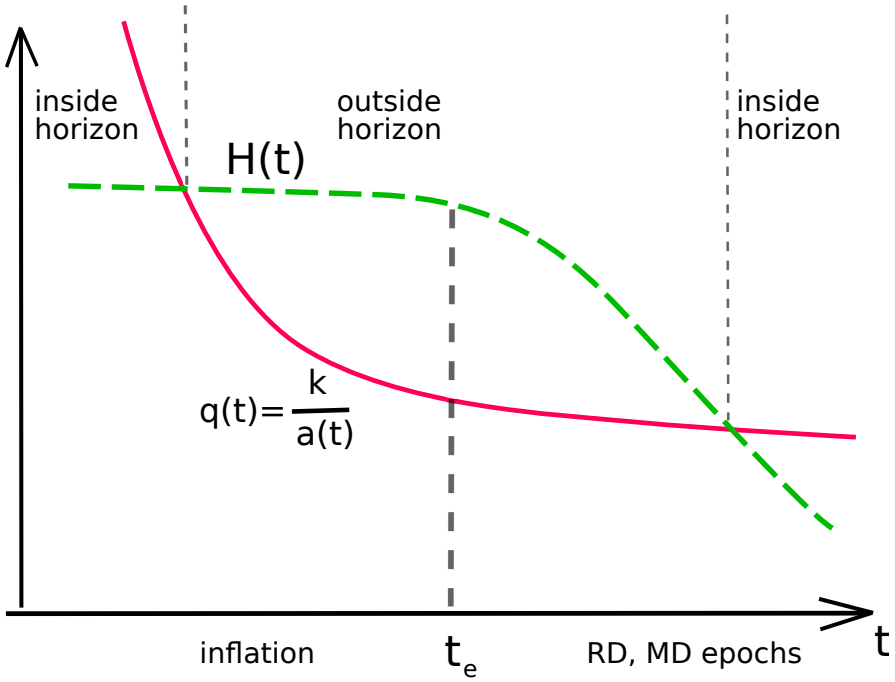
$$\delta\phi \to \frac{\delta\rho}{\rho} \sim \frac{H^2}{\dot{\phi}} \propto \frac{V^{3/2}}{V'}, \qquad h \sim \frac{H}{M_{Pl}} \propto V^{1/2}$$

upper limit on the inflation scale

from the absence of tensor modes (relic Gravity Waves) $V^{1/4} \lesssim 10^{16}\,\mathrm{GeV}$

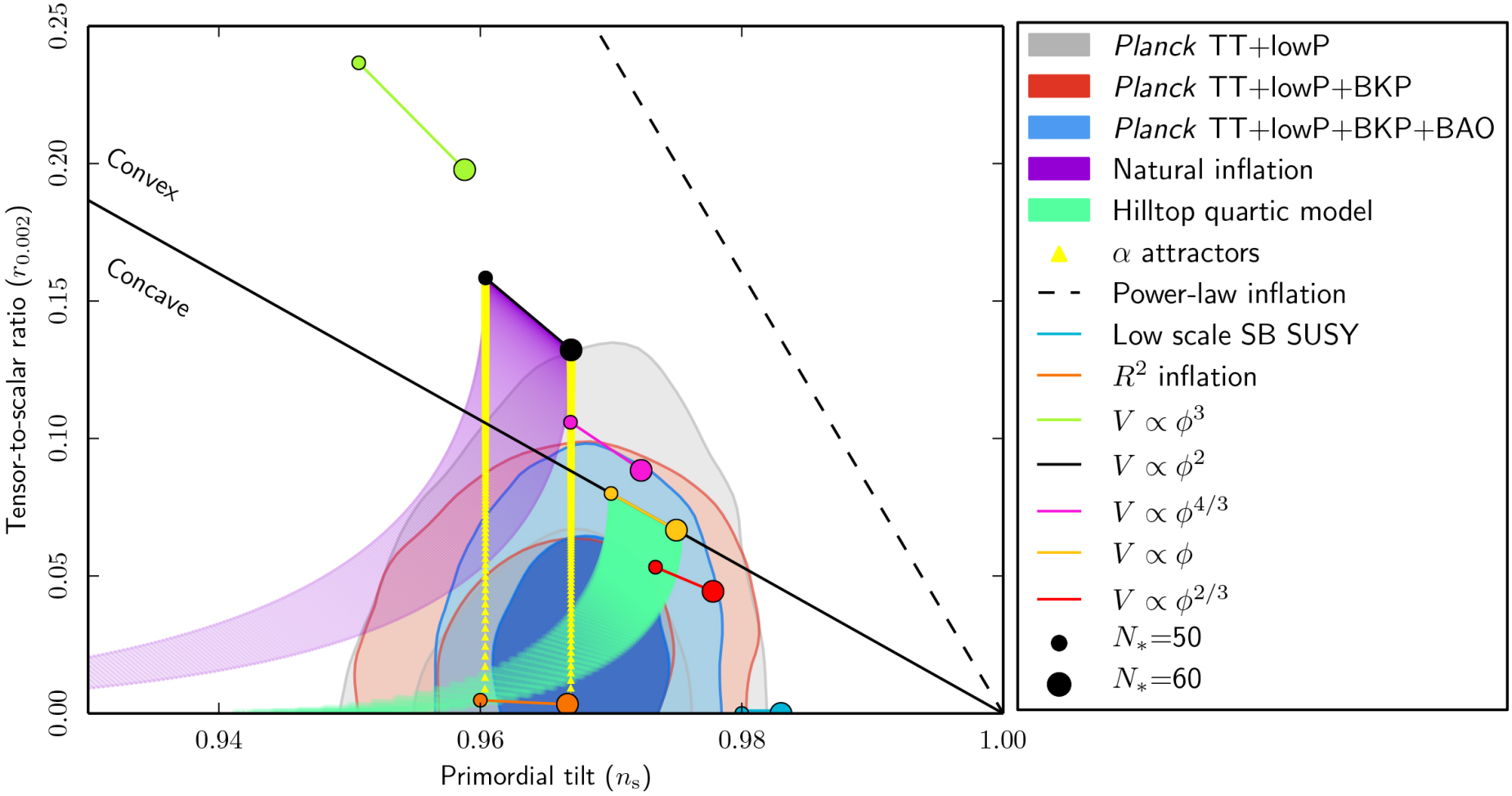
Probing the inflaton dynamics





$$A_S \to \frac{V^{3/2}}{V'}, \quad n_S \to \frac{V''}{V}, \left(\frac{V'}{V}\right)^2, \quad r \equiv \frac{A_T}{A_S} \to \left(\frac{V'}{V}\right)^2$$

Planck 2015 favors flat inflaton potentials



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

Inflationary models and quantum corrections

perturbations $\delta T/T \sim 10^{-4}$ fix $\mu \approx 10^{13}$ GeV

R^2-inflation by A.Starobinsky (1980)

$$V(\phi) = \frac{3\mu^2 M_P^2}{4}\left(1-\exp\left(-\sqrt{2/3}\,\phi/M_P\right)\right)^2 ,$$

- large fields:

  exponentially flat

  protected by

  the shift invariance

  $\phi \to \phi + \text{const}$

- small fields:

  polynomial potential

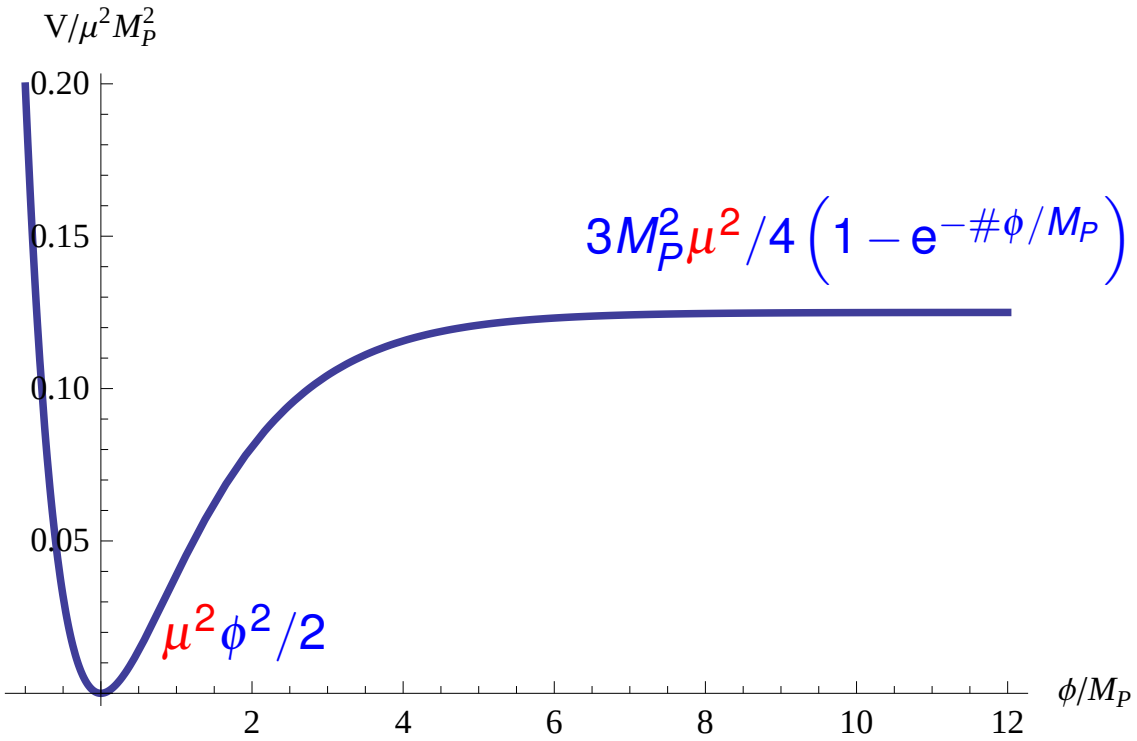
  protected by

  the renormalizability

  $\phi^2 + \phi^4$

- no way to match them at

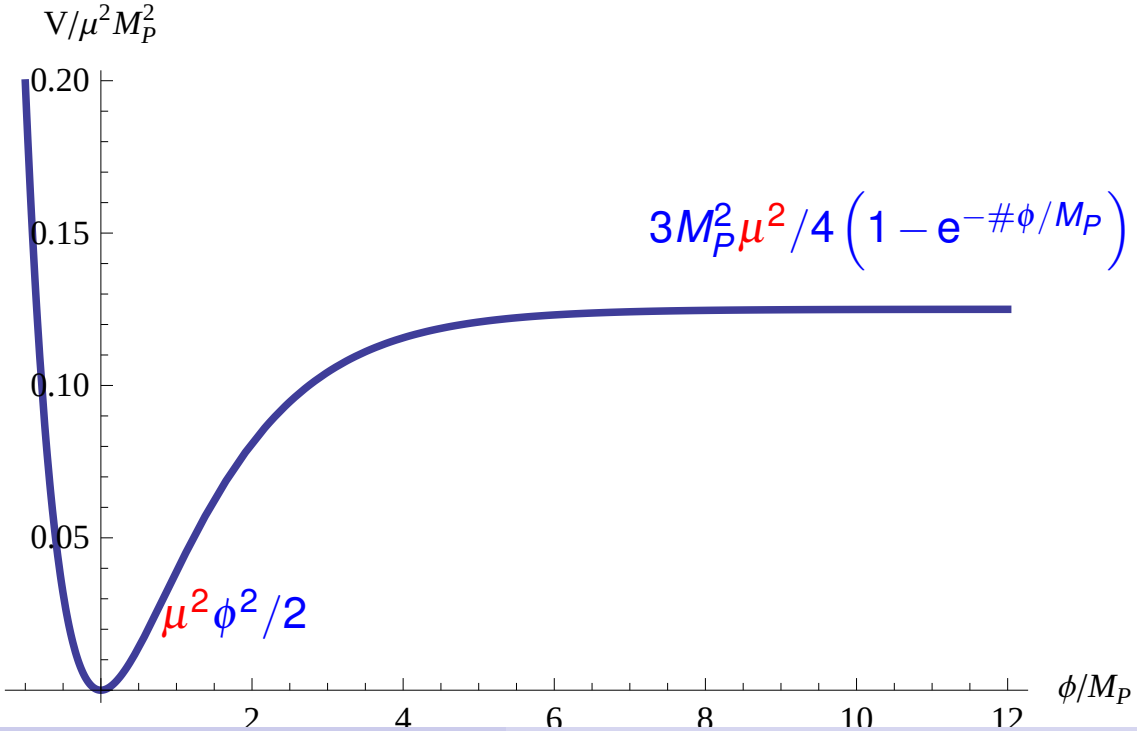
  $\phi \sim M_P$



Inflationary models and quantum corrections

- inflationary predictions are robust
- but we cannot test them with low energy particle physics experiment
- including physics at reheating
- similar observation for many other models: Higgs-iflation, α-attractor, etc

- large fields:
  exponentially flat
  protected by
  the shift invariance
  $\phi \to \phi + const$
- small fields:
  polynomial potential
  protected by
  the renormalizability
  $\phi^2 + \phi^4$
- no way to match them at
  $\phi \sim M_P$



Summary

- The Universe was as hot as 2-3 MeV and most probably (much) hotter
- DM and BAU imply New Physics
  but cosmology does not point at a particular scale
- Inflation must save the EW vacuum,
  which can suggest New Physics
  (it is difficult to prove, because a new collider is needed to pin down m_t and m_h)
- Inhomogeneities of the largest sizes
  can allow us to probe physics at the highest energies.
  However, (most) models are nonrenormalizable,
  hence no direct connection between low- and high-energy model parameters

Quantum corrections to R^2...

$$S^{JF} = -\frac{M_P^2}{2}\int\sqrt{-g}\,d^4x\left(R-\frac{R^2}{6\,\mu^2}\right)+\ldots\xi R^2\log R\,,$$

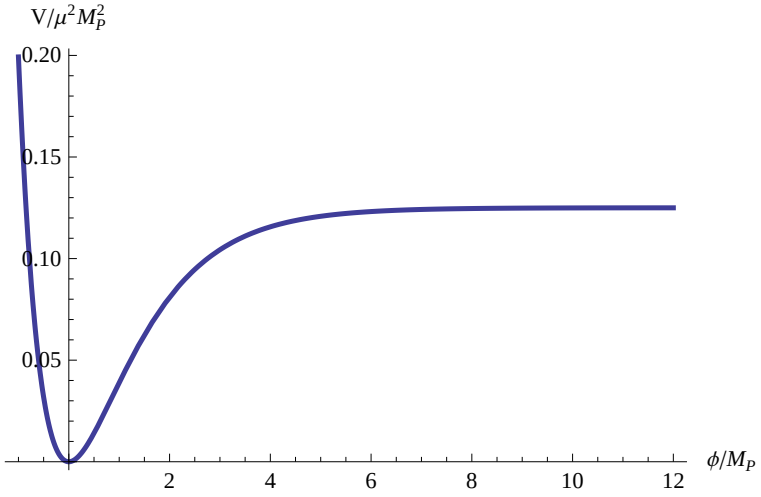
Jordan Frame $\to$ Einstein Frame [scale invariance $\to$ shift invariance] A.Starobinsky (1980)

$$g_{\mu\nu}\to\tilde{g}_{\mu\nu}=\chi\,g_{\mu\nu}\,,\qquad \chi=\exp\left(\sqrt{2/3}\,\phi/M_P\right)\,.$$

$$S^{EF}=\int\sqrt{-\tilde{g}}\,d^4x\left[-\frac{M_P^2}{2}\tilde{R}+\frac{1}{2}\tilde{g}^{\mu\nu}\partial_\mu\phi\partial_\nu\phi-\frac{3\,\mu^2 M_P^2}{4}\left(1-\frac{1}{\chi(\phi)}\right)^2\right]+S^{EF}_{matter}\,,$$

generation of perturbations $\sim 10^{-5}$

$$\frac{1}{2}\dot{\phi}^2\sim\frac{1}{2}(\partial_i\phi)^2\sim M_{\rm Pl}^4\gg V(\phi)$$



Quantum corrections to the Higgs-inflation

F.Bezrukov, M.Shaposhnikov (2007)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2}{2}R - \xi H^\dagger H R + \mathscr{L}_{SM}\right)$$

In a unitary gauge $H^T = \left(0, (h+v)/\sqrt{2}\right)$ (and neglecting $v = 246\,\text{GeV}$)

$$S = \int d^4x\sqrt{-g}\left(-\frac{M_P^2 + \xi h^2}{2}R + \frac{(\partial_\mu h)^2}{2} - \frac{\lambda h^4}{4}\right)$$

slow roll behavior due to modified kinetic term even for $\lambda \sim 1$

Go to the Einstein frame: $(M_P^2 + \xi h^2)R \to M_P^2 \tilde{R}$

$$g_{\mu\nu} = \Omega^{-2}\tilde{g}_{\mu\nu}\,, \qquad \Omega^2 = 1 + \frac{\xi h^2}{M_P^2}$$

with canonically normalized χ:

$$\frac{d\chi}{dh} = \frac{M_P\sqrt{M_P^2 + (6\xi+1)\xi h^2}}{M_P^2 + \xi h^2}\,, \quad U(\chi) = \frac{\lambda M_P^4 h^4(\chi)}{4(M_P^2 + \xi h^2(\chi))^2}\,.$$

we have a flat potential at large fields: $U(\chi) \to \text{const}$ @ $h \gg M_P/\sqrt{\xi}$

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

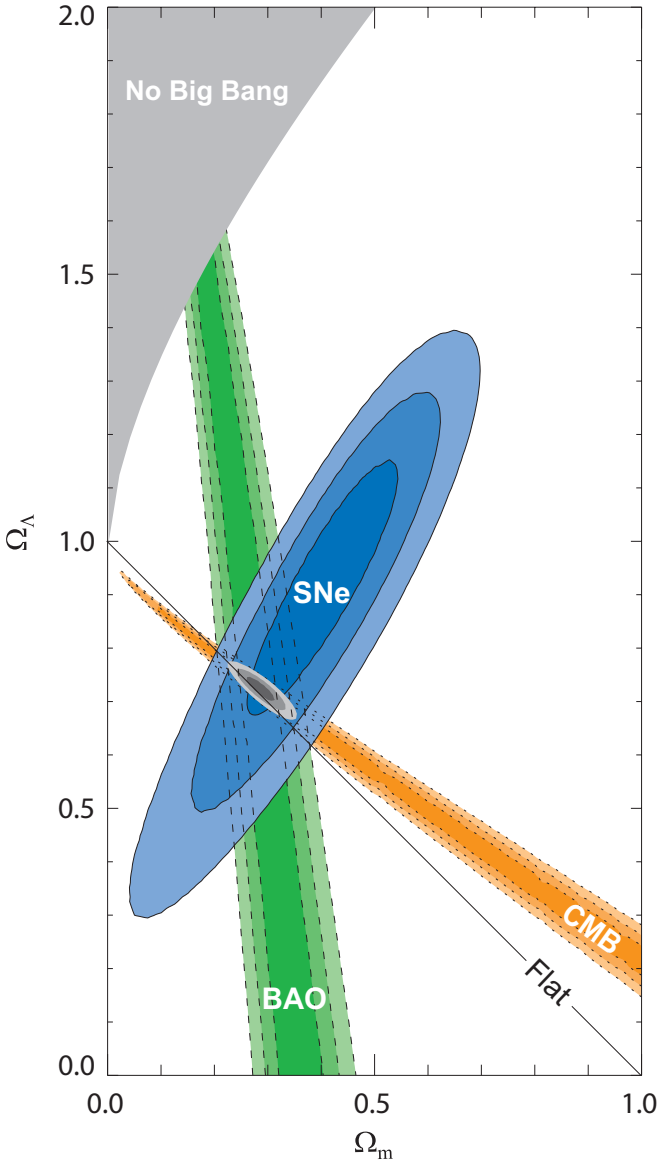
$\lambda = 2\pi/(M_X v_X)$, in a galaxy $v_X \sim 0.5 \cdot 10^{-3} \longrightarrow M_X \gtrsim 3 \cdot 10^{-22}$ eV

for fermions

Pauli blocking: $M_X \gtrsim 750$ eV

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

Astrophysical and cosmological data are in agreement



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

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

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

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

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

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

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

$z \ll 1$ 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