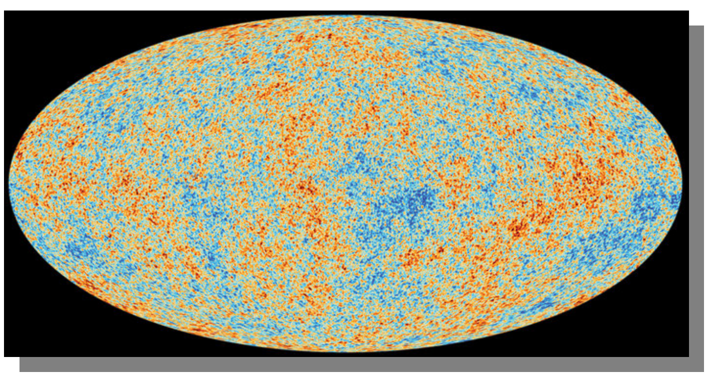
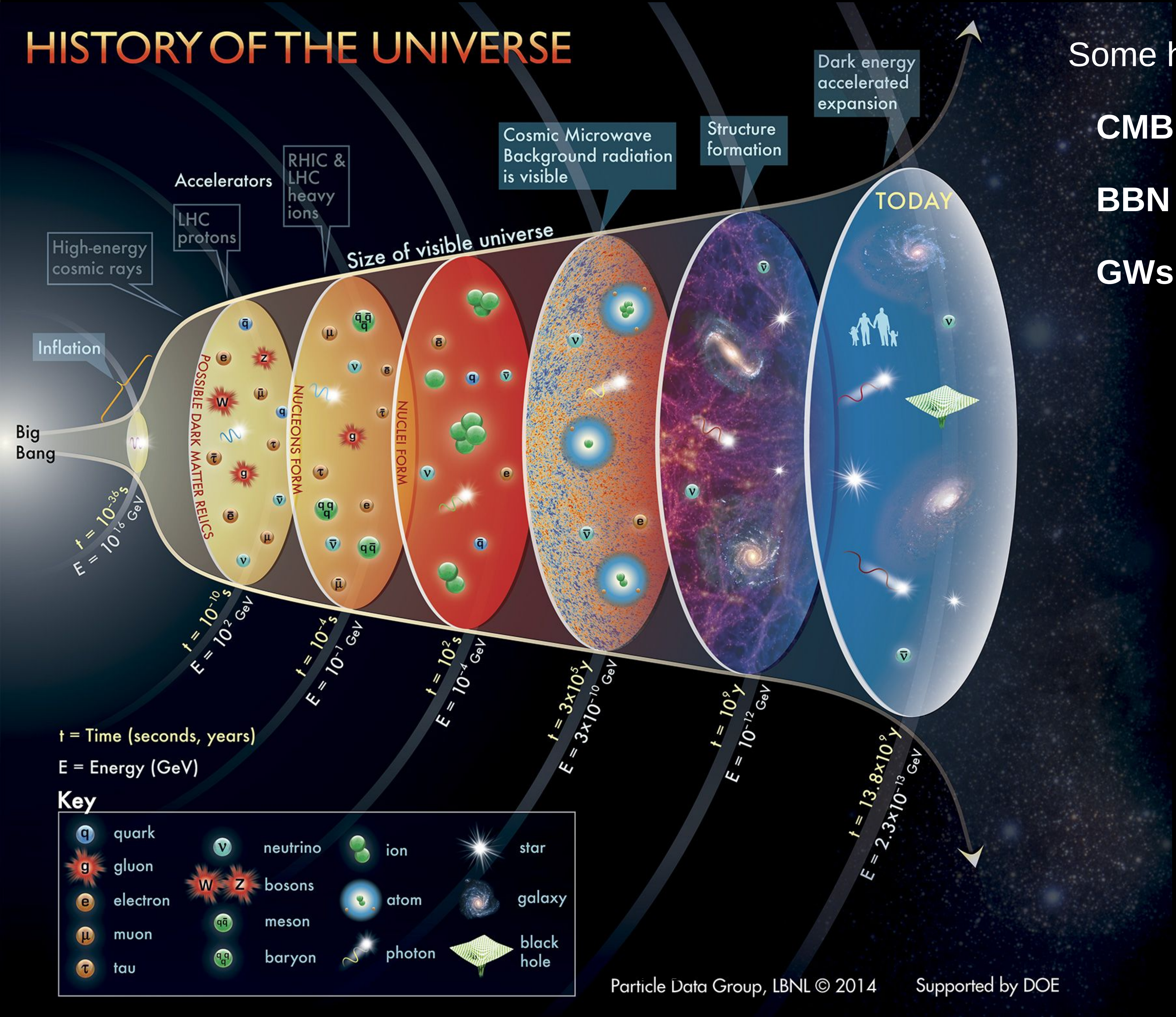
Particle Physics from Cosmology

CERN Fermilab School 2023 – Special lecture

Valerie Domcke (CERN)



$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \psi + h.c. + \bar{\Psi}_i y_{ij} \psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$



Some highlights:

CMB + LSS

BBN

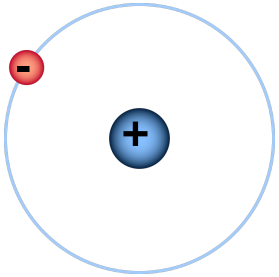
GWs

Cosmic microwave background

(and large scale structure)

The cosmic microwave background

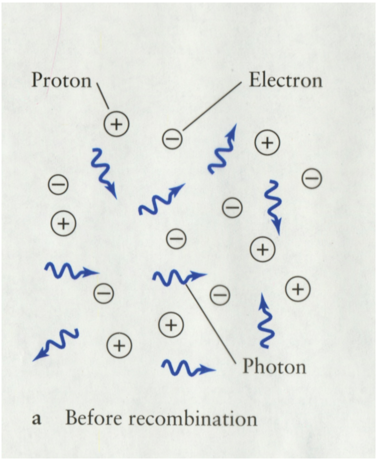
binding energy of hydrogen atom: $T \sim \mathrm{eV}$



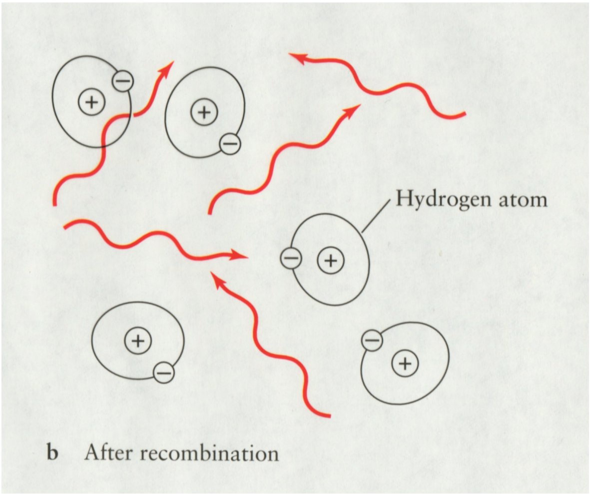
$T > \mathrm{eV}$ → time → $T < \mathrm{eV}$

- many free charged particles (electrons & protons)
- photons scatter multiple times, universe not transparent

- electrons and protons from electrically neutral hydrogen atoms
- universe becomes transparent



a Before recombination



b After recombination

The cosmic microwave background

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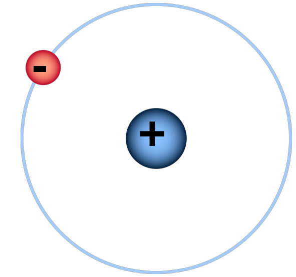

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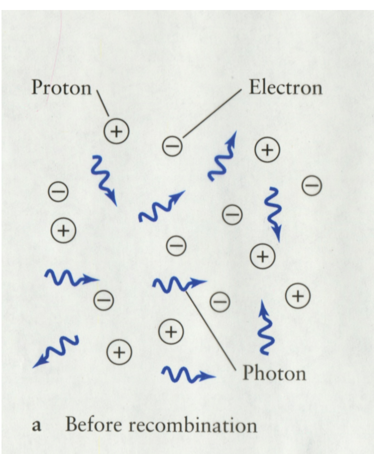
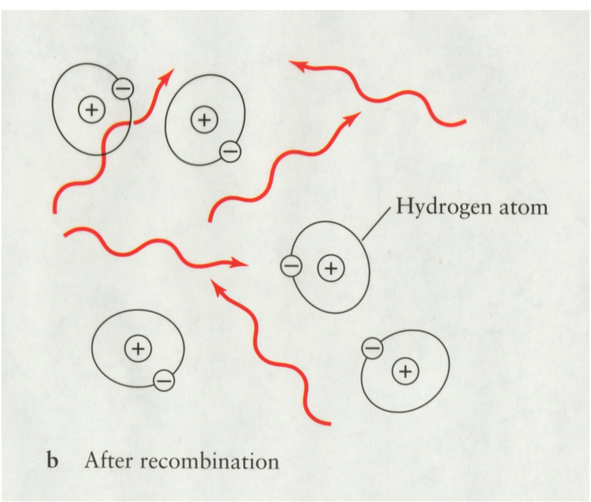
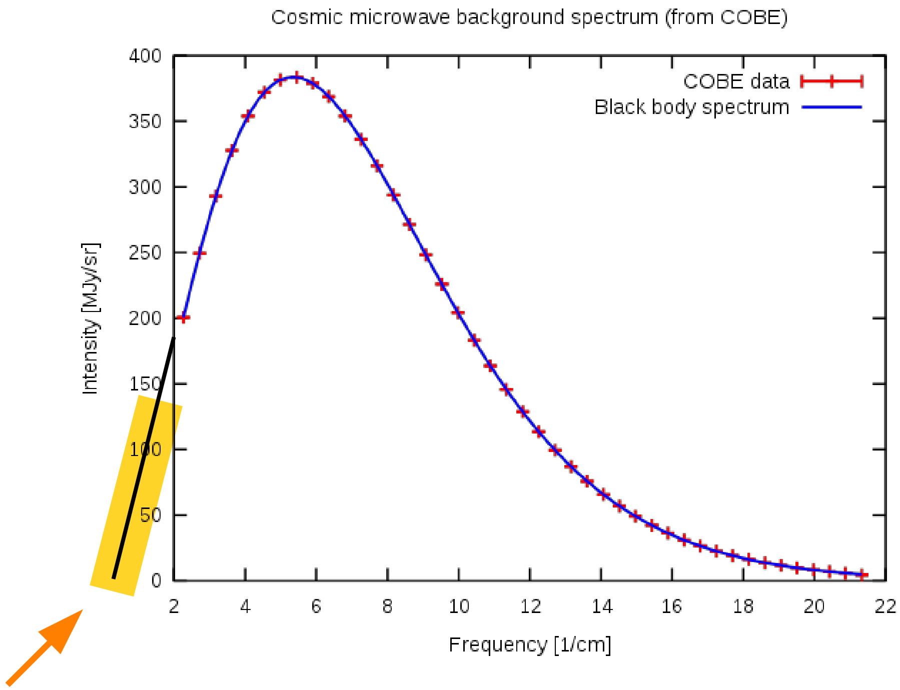


- thermal radiation with T ~ 3000 K as cosmic background radiation
- cools in expanding universe to T << 3000 K



CMB black body radiation

COBE satellite,
1989-93



Penzias, Wilson (nobel prize 1978)

- cosmic microwave background well measured today
- black body radiation with T = 2.7 K (microwaves)
  → universe has expanded by factor 1000 since CMB decoupling

confirms key prediction of `big bang‘ theory

2019 nobel prize Peebles for his contributions to theoretical cosmology

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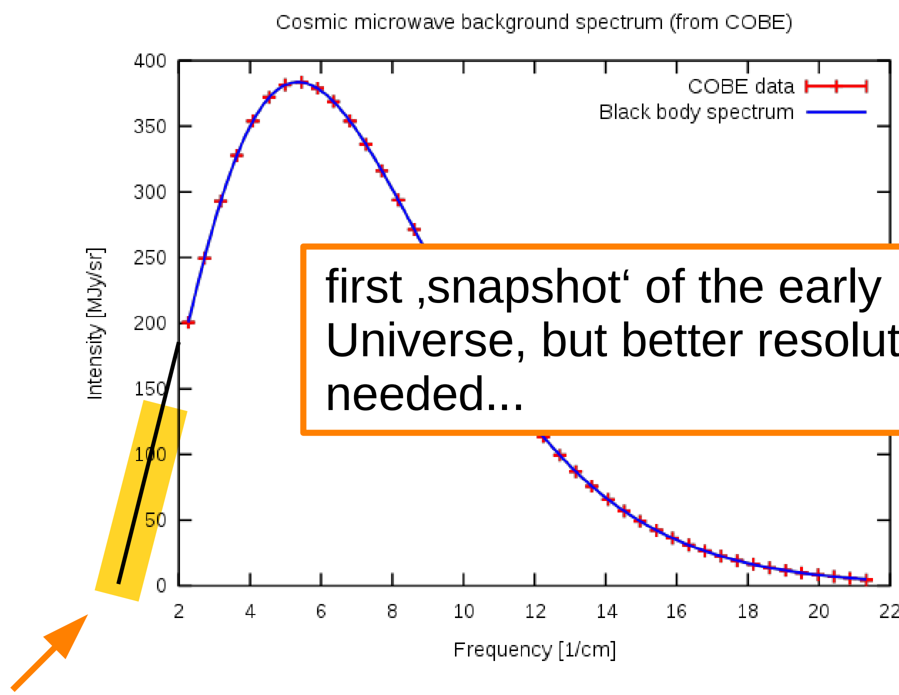

first ‚snapshot‘ of the early Universe, but better resolution needed...

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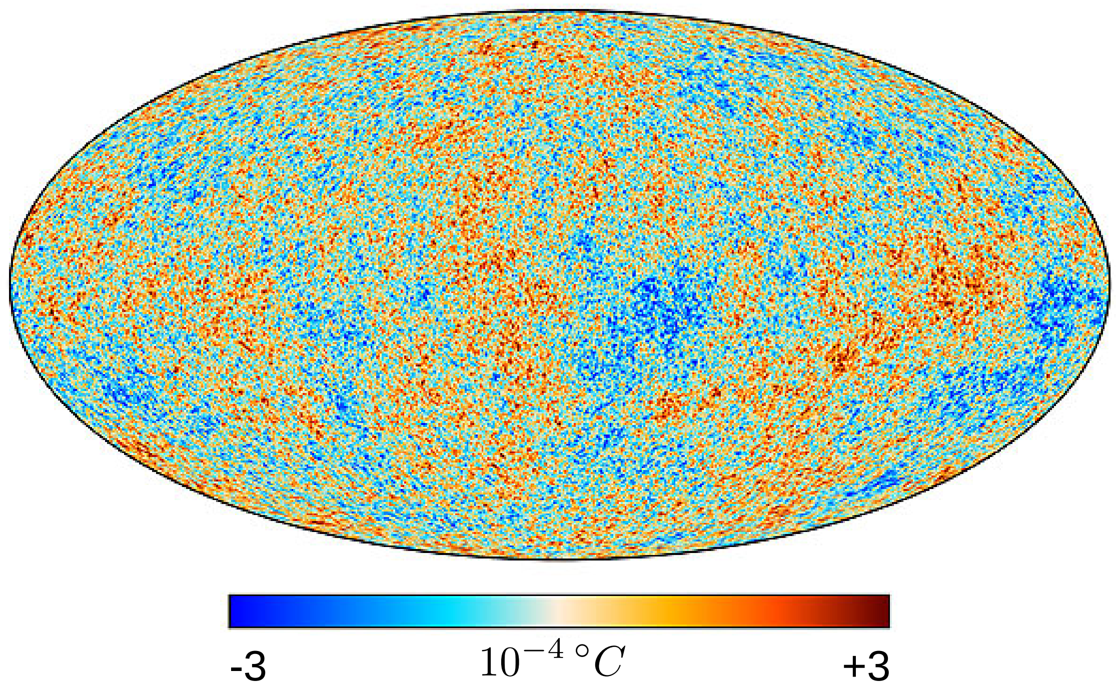
anisotropies in the CMB

completely homogeneous plasma → homogeneous universe after cooling

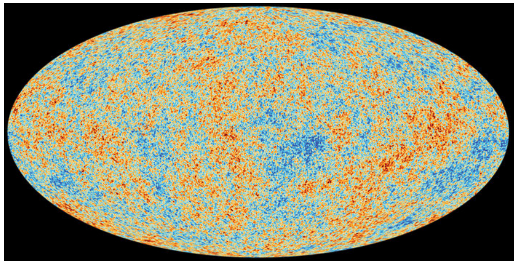
- small perturbations needed as seeds for galaxies to form through gravitational collapse
- anisotropies in the CMB, deviation from black body radiation 1:10^4

PLANCK satellite,
2009 - 2013

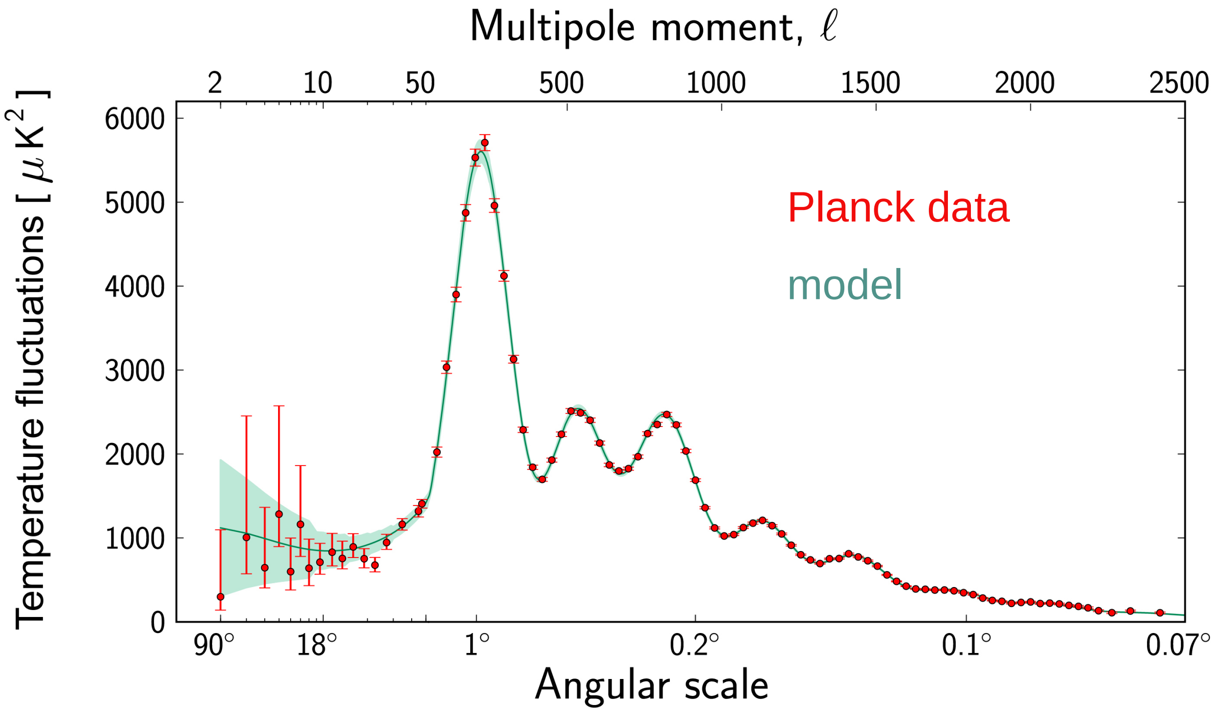


PLANCK 2018 data release

anisotropies in the CMB



statistical analysis



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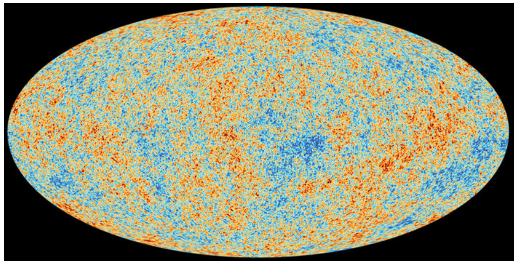

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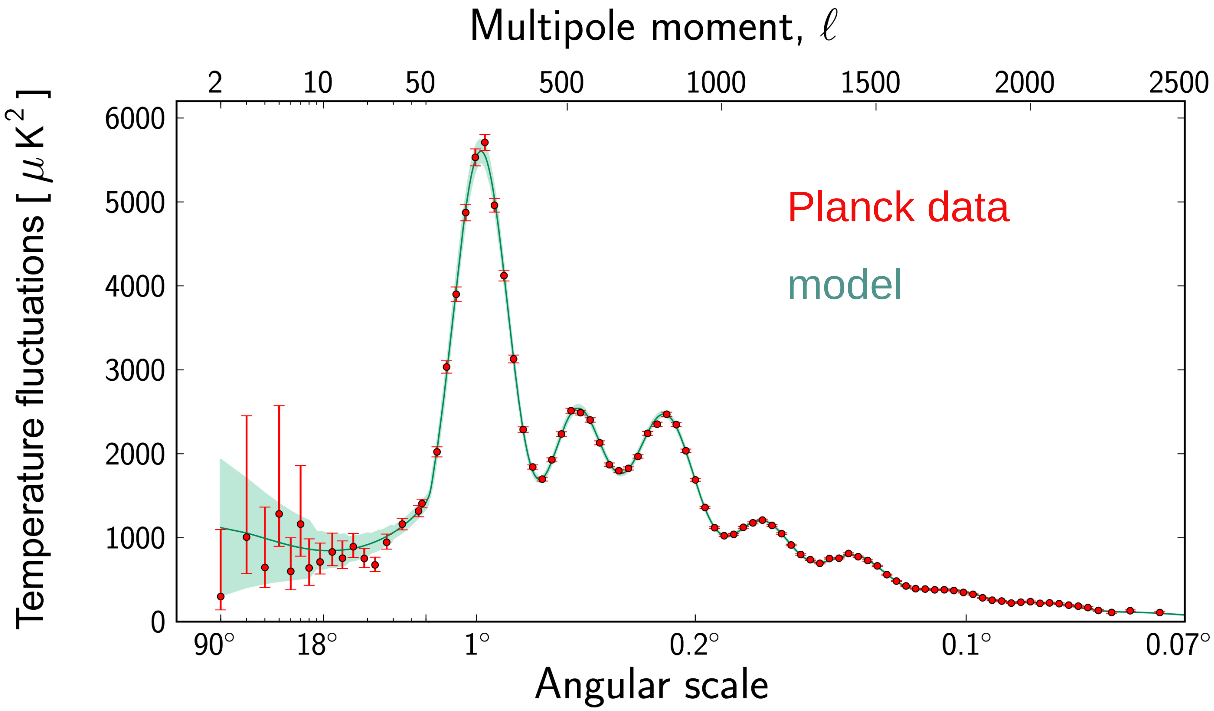
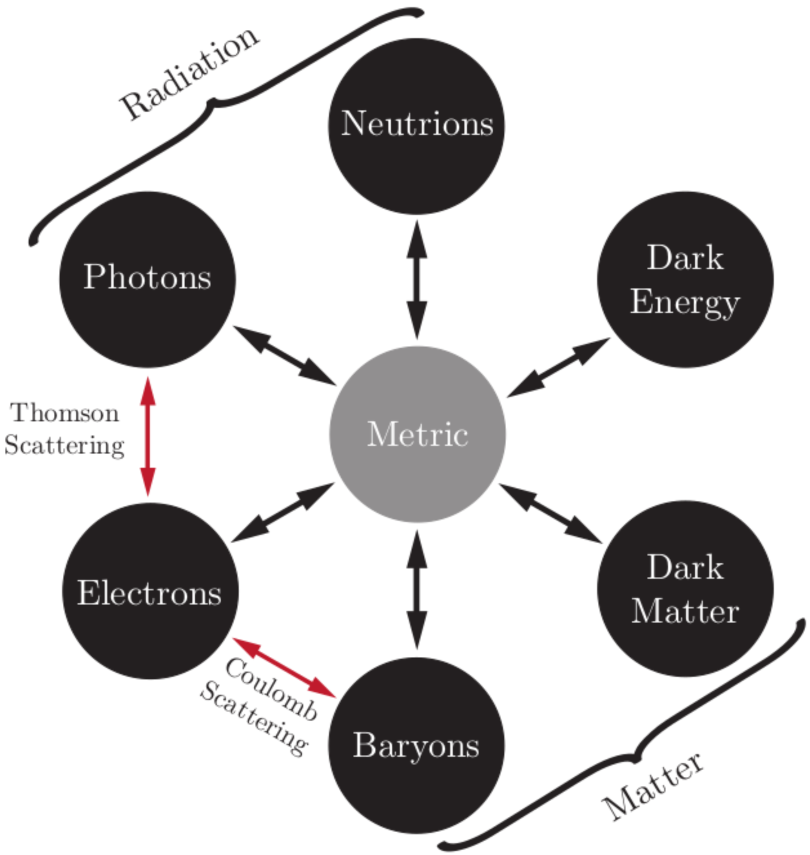


model prediction depens on

properties of the plasma	→	proton and photon density
initial conditions for fluctuations	→	cosmic inflation
expansion since CMB decoupling	→	total energy density of the universe
photon scattering since CMB decoupling	→	re-ionisation of H by star formation

→ in total only 6 parameters

Boltzmann equations



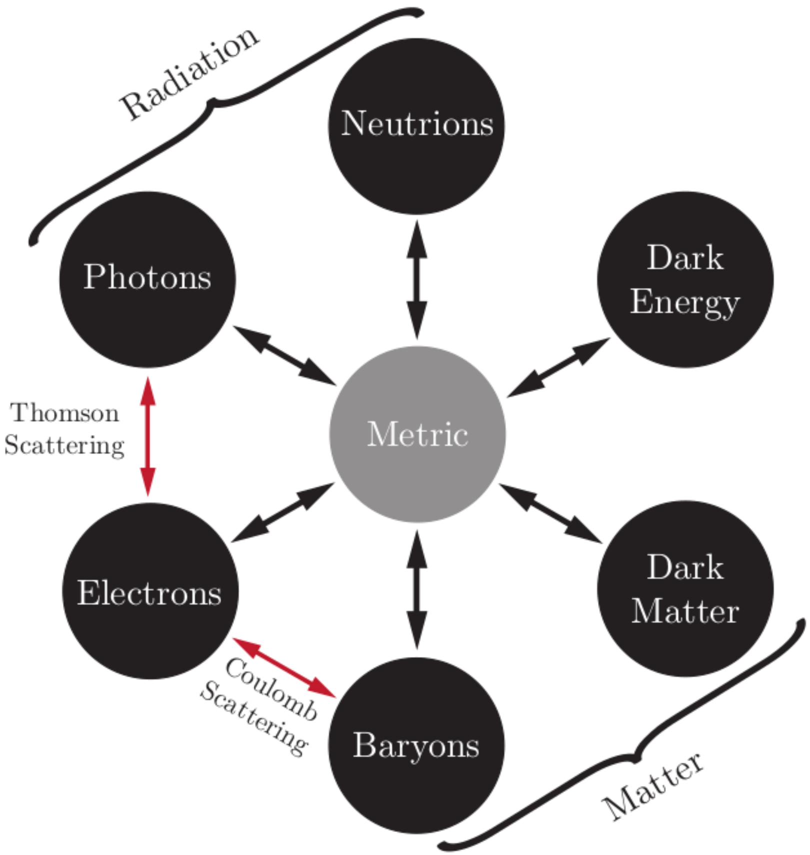
see e.g. lecture notes Daniel Baumann, Advanced Cosmology

photon distribution:

$$f(\eta, \vec{x}, \vec{p}) = \left[\exp\left(\frac{p}{\bar{T}(\eta)(1 + \Theta(\eta, \vec{x}, \hat{p}))}\right) - 1\right]^{-1}$$

$\delta T / \bar{T}$

Boltzmann equations



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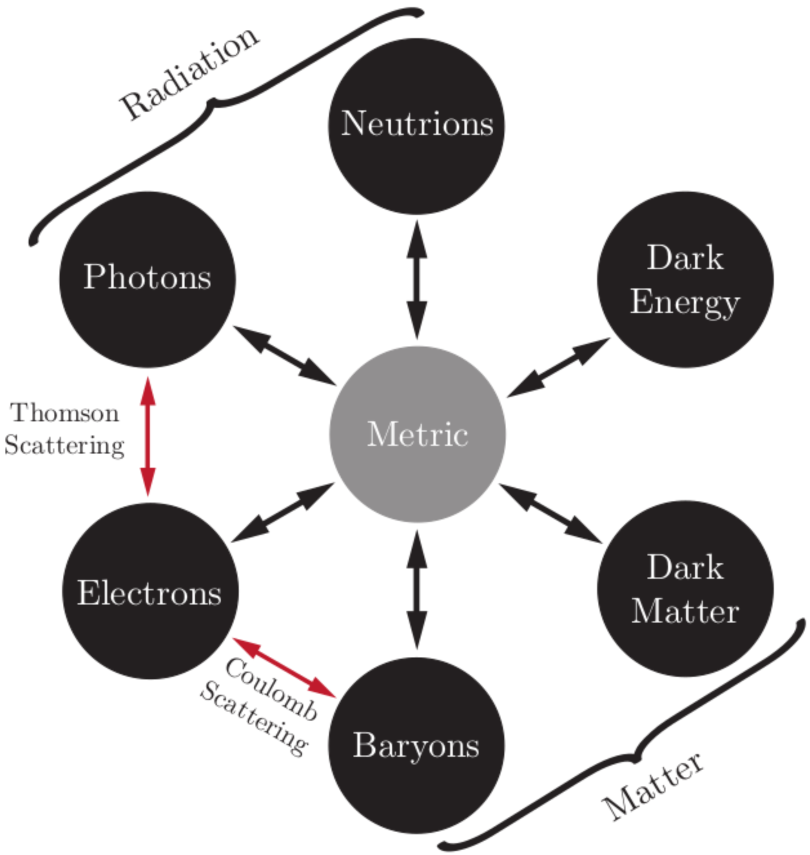
Θ: $\delta T/\bar{T}$

$$\Theta' + \hat{p}\vec{\nabla}\Theta - \Phi' + \hat{p}\vec{\nabla}\psi = -\Gamma$$

$d\Theta/d\eta$ — dilation — potential wells / gravity — Thomson scattering

Boltzmann equations



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$\delta T/\bar{T}$

$$\Theta' + \hat{p}\vec{\nabla}\Theta - \Phi' + \hat{p}\vec{\nabla}\psi = -\Gamma$$

$d\Theta/d\eta$ dilation gravity potential wells Thomson scattering

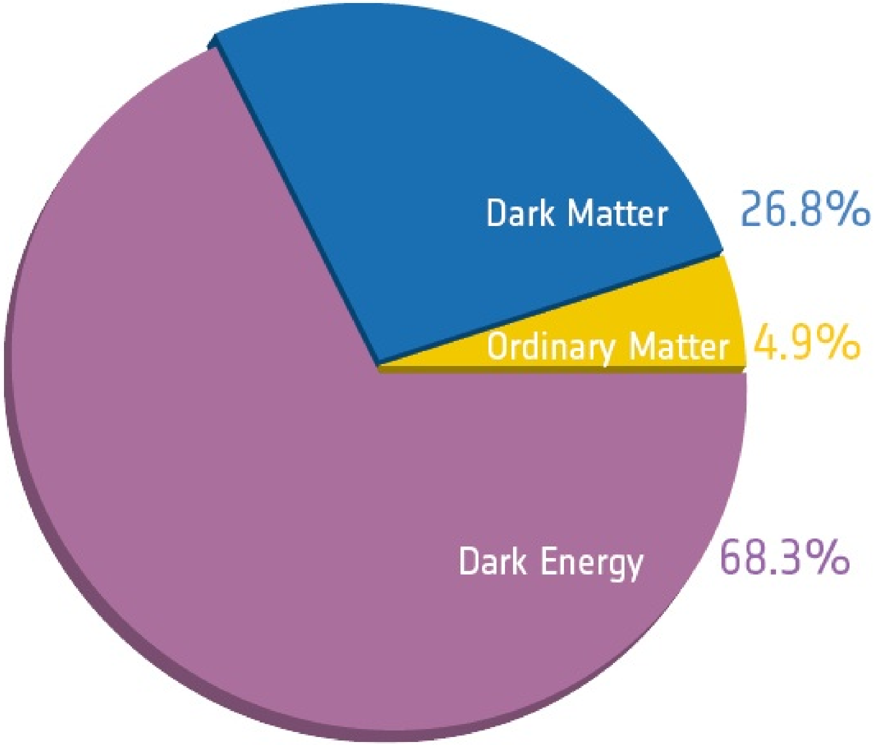
$$\frac{\delta T}{\bar{T}}(\hat{n},\eta_0) = \Theta(\eta_0,\vec{x}_0,-\hat{p})$$

$$= (\Theta+\Psi)_{\rm dec} + \hat{n}\vec{v}_{b,\rm dec} + \int_{\eta_{\rm dec}}^{\eta_0} d\eta\,(\Phi'+\Psi')$$

Sachs-Wolfe (SW) Doppler integrated SW

+ Einstein's equations for metric perturbations

standard model of cosmology (ΛCDM)

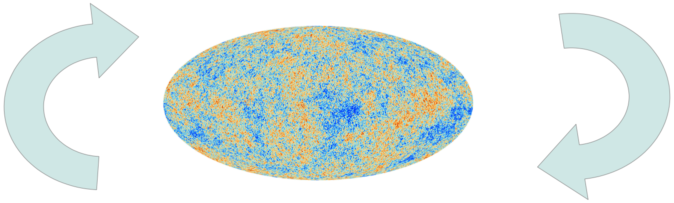


no direct detection yet,
many properties unknown

we kind of understand

we really don‘t understand

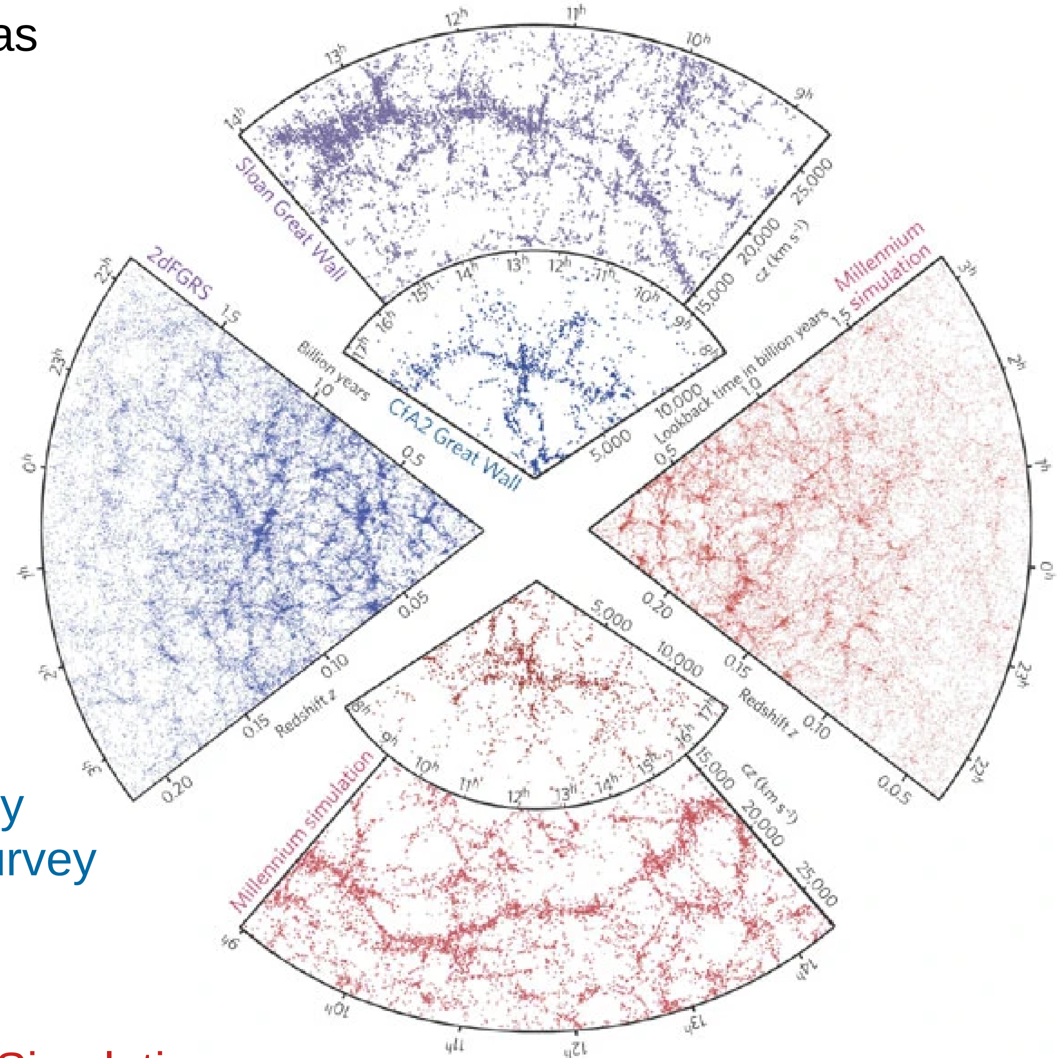
particle physics



cosmology

Large Scale Structure

- anisotropies in primordial plasma act as seeds for gravitational collapse
- formations of stars, galaxies and filaments
- statistical properties of CMB anisotropies → galaxy distribution



Sloan Digital Sky Survey
2dF Galaxy Redshift Survey

Millenium Simulation

Big Bang Nucleosynthesis (BBN)

(formation of light elements)

BBN – deuterium formation

a) neutron freeze-out

b) deuterium formation

BBN – deuterium formation

a) neutron freeze-out

$T \gg \mathrm{MeV}: \; n \nu_e \leftrightarrow p e^-, \; \ldots \quad$ w. rate $\lambda_{p\to n} = \lambda_{n\to p}\, e^{-\Delta m/T}$

$\uparrow \; m_n - m_p = 1.293\,\mathrm{MeV}$

$X_n \equiv \frac{n_n}{n_n + n_p}, \quad \dot{X}_n = \lambda_{p\to n}(1 - X_n) - \lambda_{n\to p} X_n$

$\dot{X}_n = 0 \rightarrow X_n^{eq} = \left(1 + e^{\Delta m/T}\right)^{-1}$

b) deuterium formation

BBN – deuterium formation

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luckily O(1)!

$\left.\begin{array}{l}\lambda_{n\to p}, \lambda_{p\to n} \sim H \\ \text{at } T_{dec} \sim \mathrm{MeV}\end{array}\right\} \to n$ decoupling $\to X_n(t_{dec}) = X_n^{eq}(t_{dec}) = \frac{1}{1 + e^{\Delta m/T_{dec}}}$

(weak force vs. gravity)

$(\simeq 0.15)$

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$\lambda_{n\to p}, \lambda_{p\to n} \sim H$ at $T_{dec} \sim$ MeV (weak force vs. gravity) $\Big\} \rightarrow$ n decoupling $\rightarrow$ $X_n(t_{dec}) = X_n^{eq}(t_{dec}) = \dfrac{1}{1 + e^{\Delta m/T_{dec}}}$

$(\simeq 0.15)$

b) deuterium formation $\quad n p \leftrightarrow D \gamma$ (in eq. until 10^{-3} eV)

$$\text{in eq:} \quad X_D = X_n X_p \frac{24\, \zeta(3)}{\sqrt{\pi}} \left(\frac{T}{m_p}\right)^{3/2} \eta \, e^{\Delta_D/T}$$

$\Delta_D = m_p + m_n - m_D = 2.23$ MeV

$\uparrow$

$$\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$$

deuterium bottle-neck

BBN – deuterium formation

a) neutron freeze-out

$T \gg \text{MeV}$: $n \nu_e \leftrightarrow p e^-$, ... w. rate $\lambda_{p\to n} = \lambda_{n\to p}\, e^{-\Delta m/T}$

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$X_n \equiv \frac{n_n}{n_n + n_p}$, $\dot{X}_n = \lambda_{p\to n}(1 - X_n) - \lambda_{n\to p} X_n$

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$\lambda_{n\to p}, \lambda_{p\to n} \sim H$ at $T_{dec} \sim \text{MeV}$ (weak force vs. gravity) $\Big\} \to$ n decoupling $\to X_n(t_{dec}) = X_n^{eq}(t_{dec}) = \frac{1}{1 + e^{\Delta m/T_{dec}}}$ $(\simeq 0.15)$

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b) deuterium formation $np \leftrightarrow D\gamma$ (in eq. until 10^{-3} eV)

in eq: $X_D = X_n X_p \frac{24\,\zeta(3)}{\sqrt{\pi}} \left(\frac{T}{m_p}\right)^{3/2} \eta\, e^{\Delta_D/T}$

$\Delta_D = m_p + m_n - m_D = 2.23\ \text{MeV}$

$\hookrightarrow \frac{X_D}{X_n X_p} \sim 1$ at $T_{BBN} \sim \frac{\Delta_D}{33} = 0.068\ \text{MeV}$

$\uparrow$ $\eta = \frac{n_B}{n_\gamma} \sim 10^{-10}$

$(\hat{=}\ t = 3\ \text{min})$ deuterium bottle-neck

BBN – light element abundances

c) light element abundances

- $p\,D \to {}^3He\,\gamma, \ldots$; $D\,T \to {}^4He\,n, \ldots$
- no stable $A = 5$ nuclei
  - $\to$ all D converted to ${}^4He$
  - $\to Y_p({}^4He) = 2\,X_n(t_{BBN}) = X_n(t_{dec}) \cdot e^{-t_{BBN}/\tau_n} \simeq 0.24$

neutron decay

$\tau_n \sim 15\,\text{min}$

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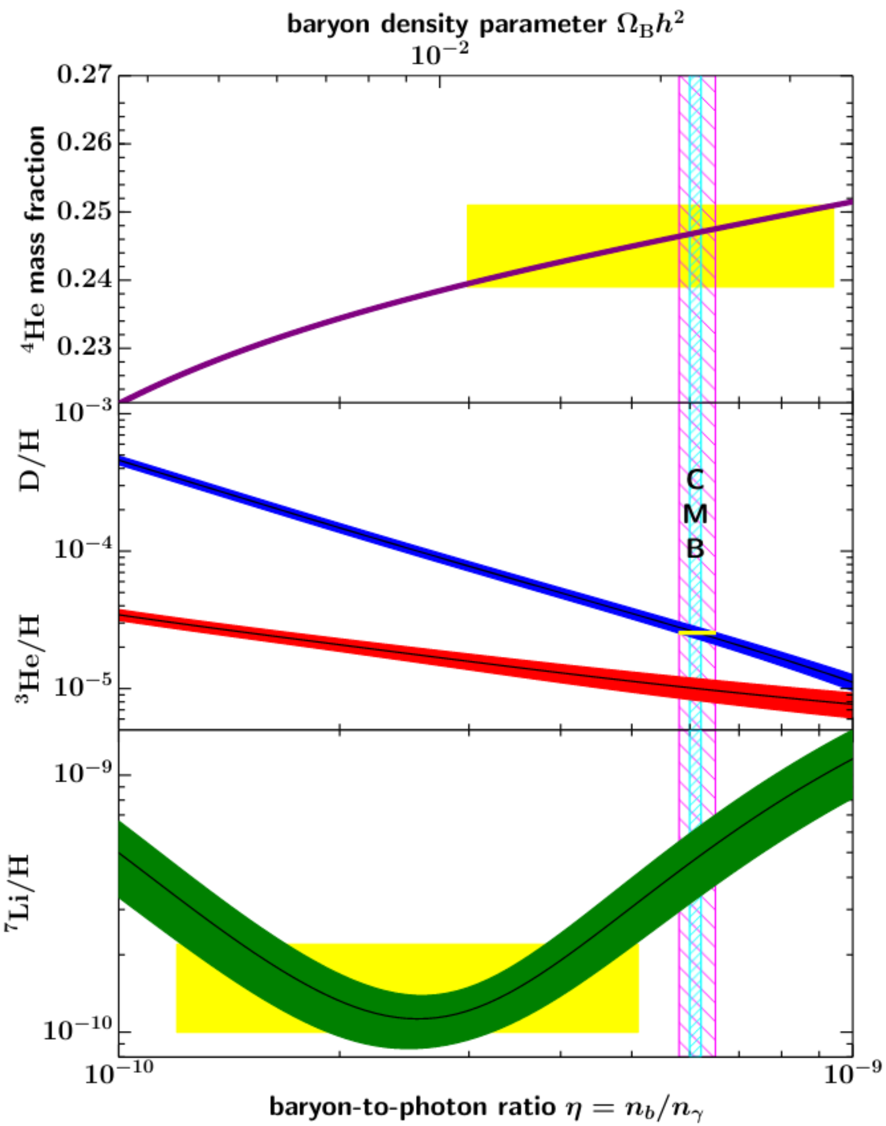
neutron decay

$\tau_n \sim 15\,min$

- small η delays ^{4}He formation (due to D photo dissociation)
- fraction of n is lost to n-decay
- ^{4}He abundance as measure of baryon-to-photon ratio η
  (similar for ^{3}He, D, ^{7}Li)

BBN – theory vs observation



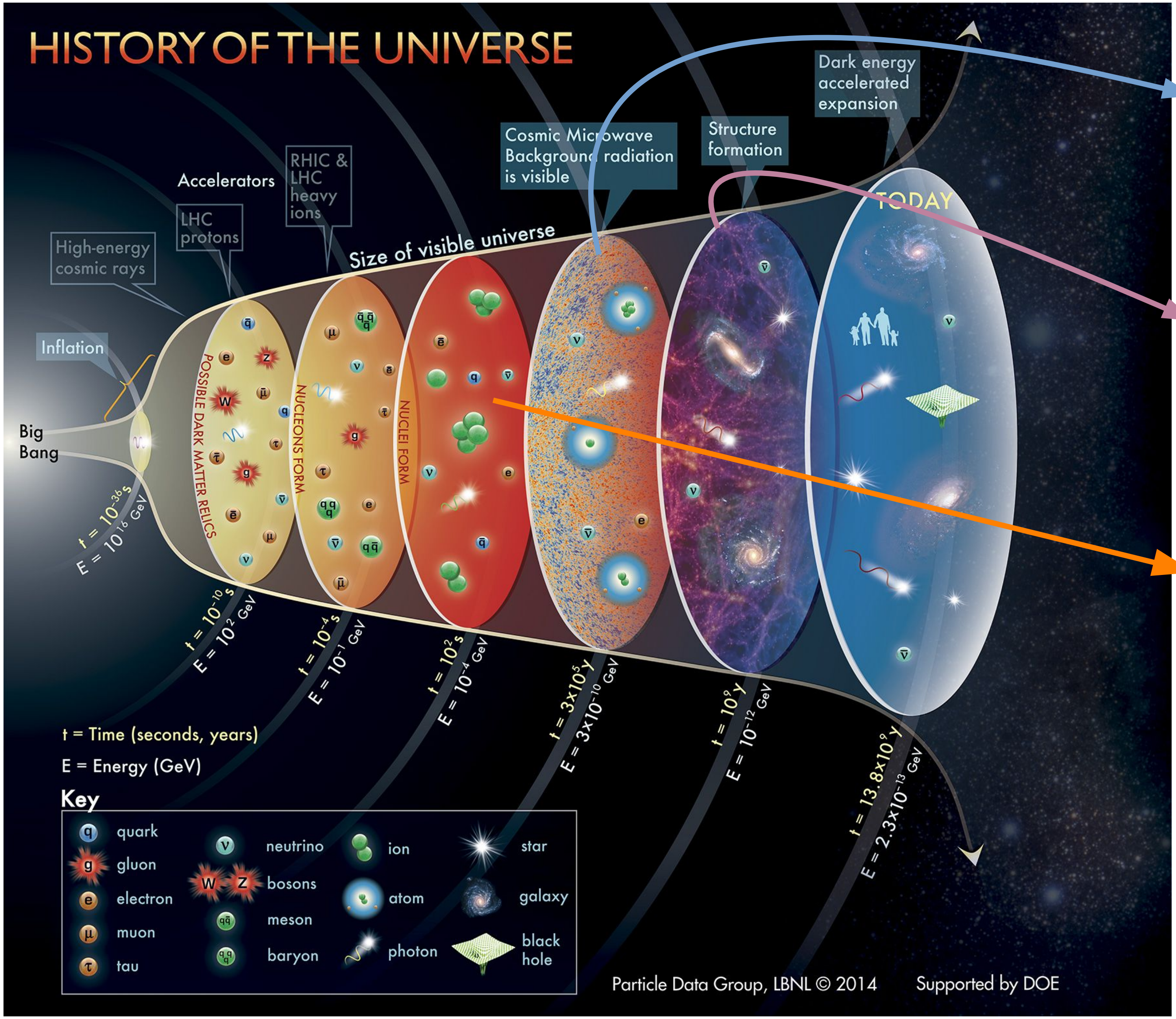
observed abundances

colored bands: BBN predictions

- **measurement of baryon asymmetry**
- **consistency check of ΛCDM**

Fig. from PDG

snapshots of our universe

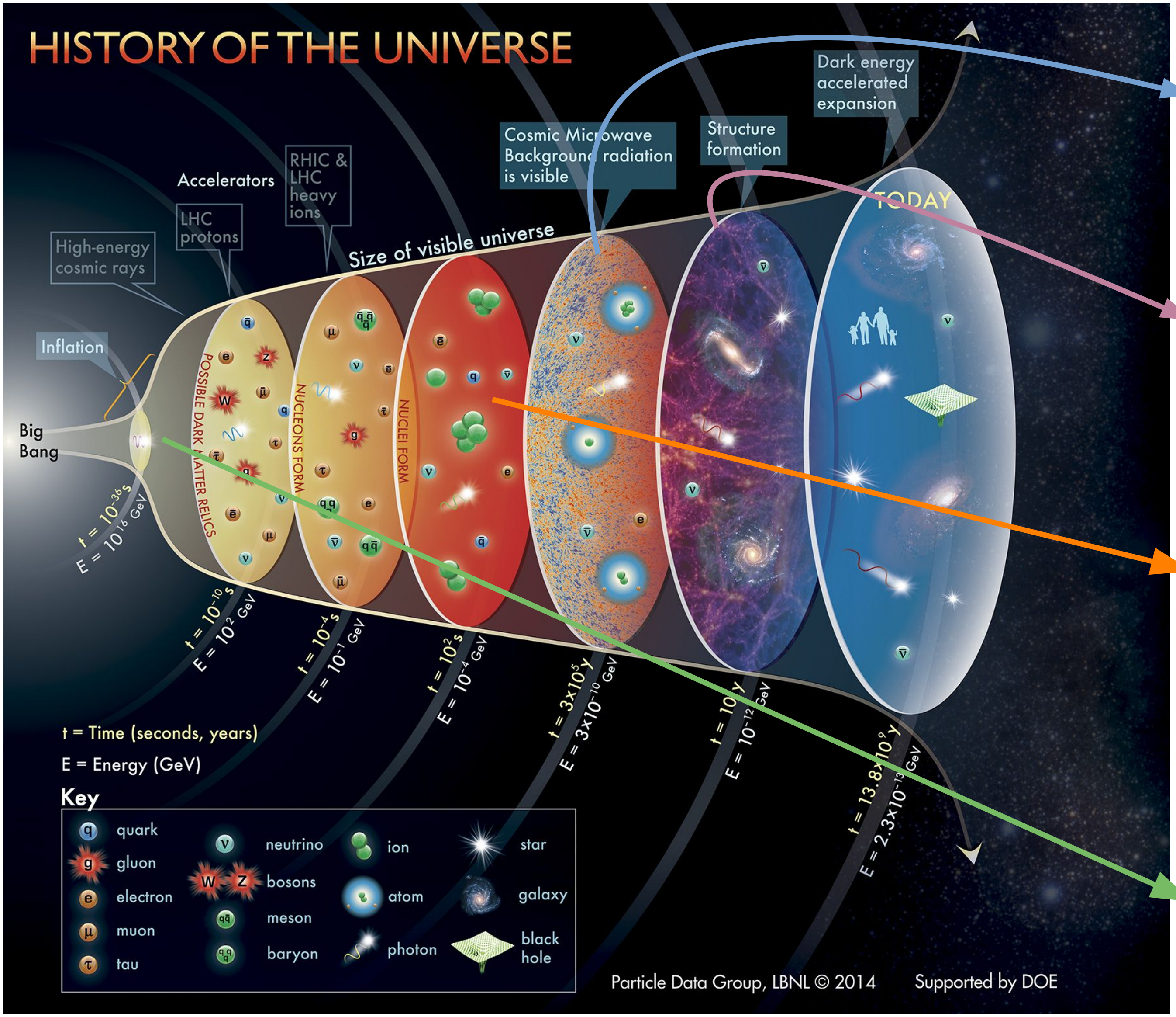


CMB as a probe of thermal plasma constituents at eV and subsequent expansion history

CMB anisotropies vs galaxy counts as probe of structure formation (eg DM properties)

BBN as probe of thermal plasma constituents at MeV

snapshots of our universe



CMB as a probe of thermal plasma constituents at eV and subsequent expansion history

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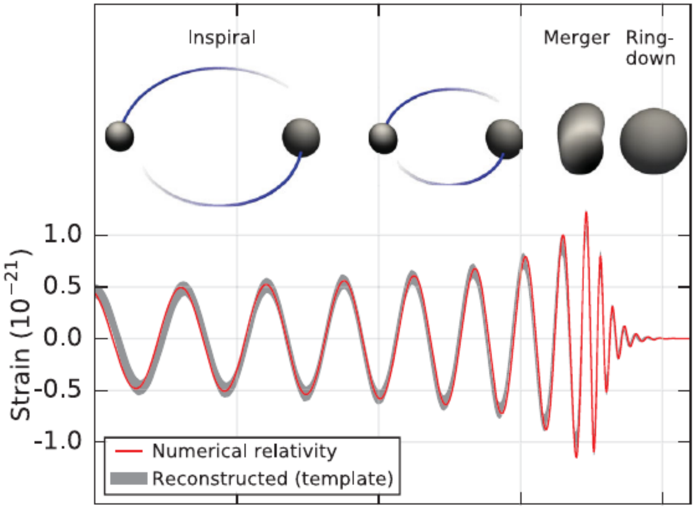
gravitational waves as new window to the very early universe

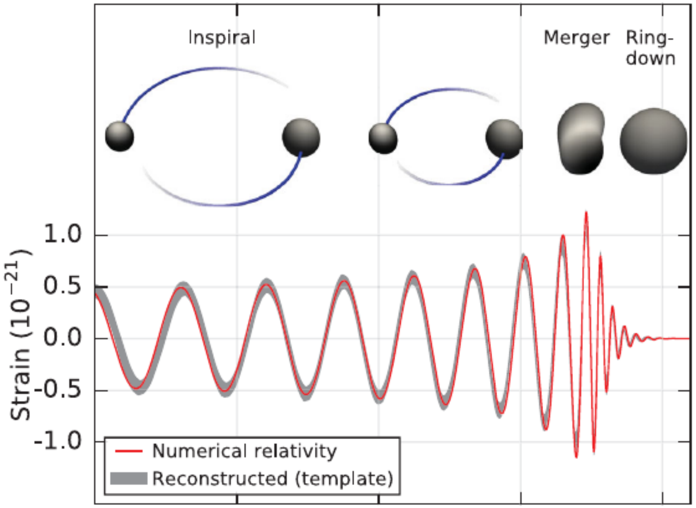
gravitational waves



LIGO Livingston, USA

2015: first direct observation of GWs, collision of two black holes a billion years ago

gravitational waves



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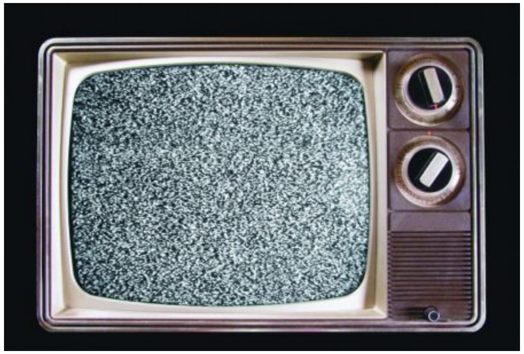
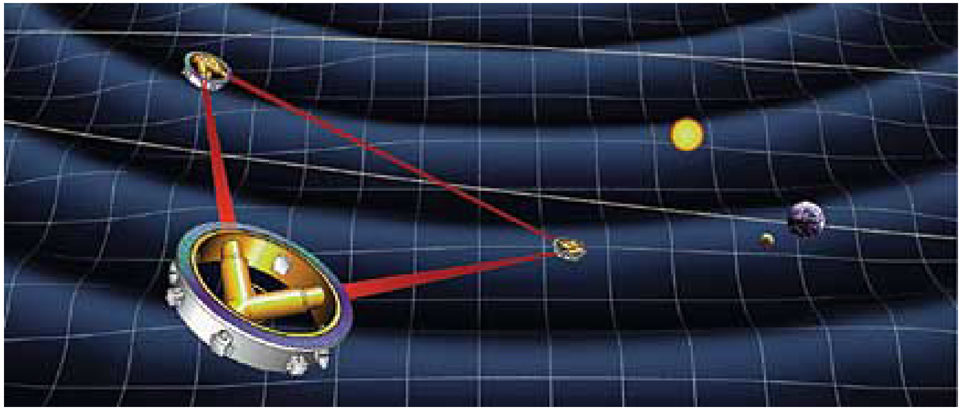


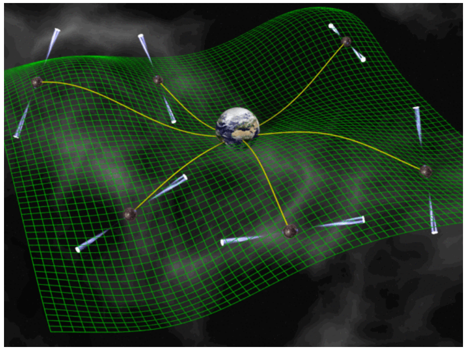
next challenge:
stochastic gravitational wave background

planned ESA Mission LISA



Hunting for gravitational waves

pulsar timing arrays



interferometers

LIGO

nHz mHz kHz

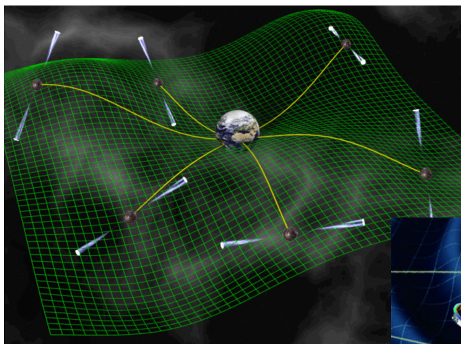
frequency

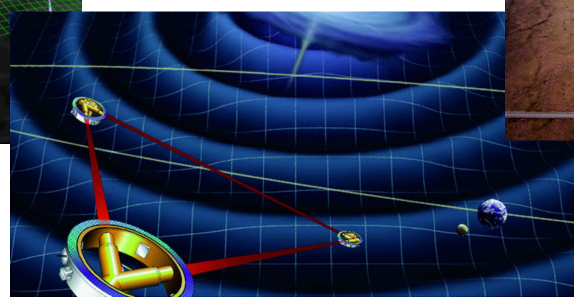
mass (merging compact objects)
time (cosmological events)

Hunting for gravitational waves

pulsar timing arrays

interferometers





LISA

LIGO

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Hunting for gravitational waves

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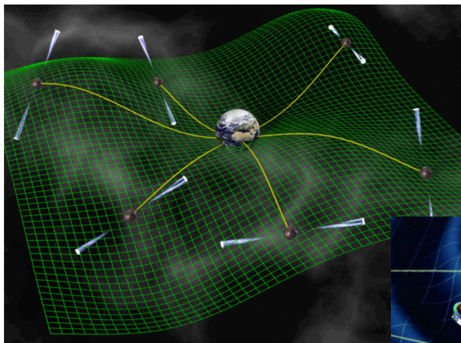

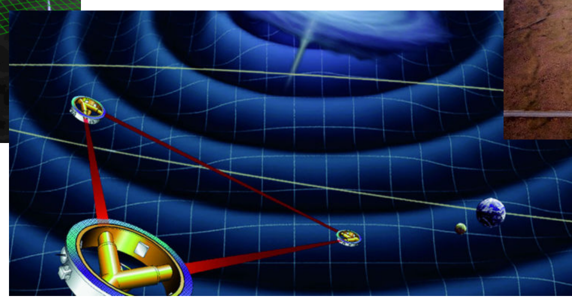

LISA

LIGO

?

nHz mHz kHz

frequency

mass (merging compact objects)
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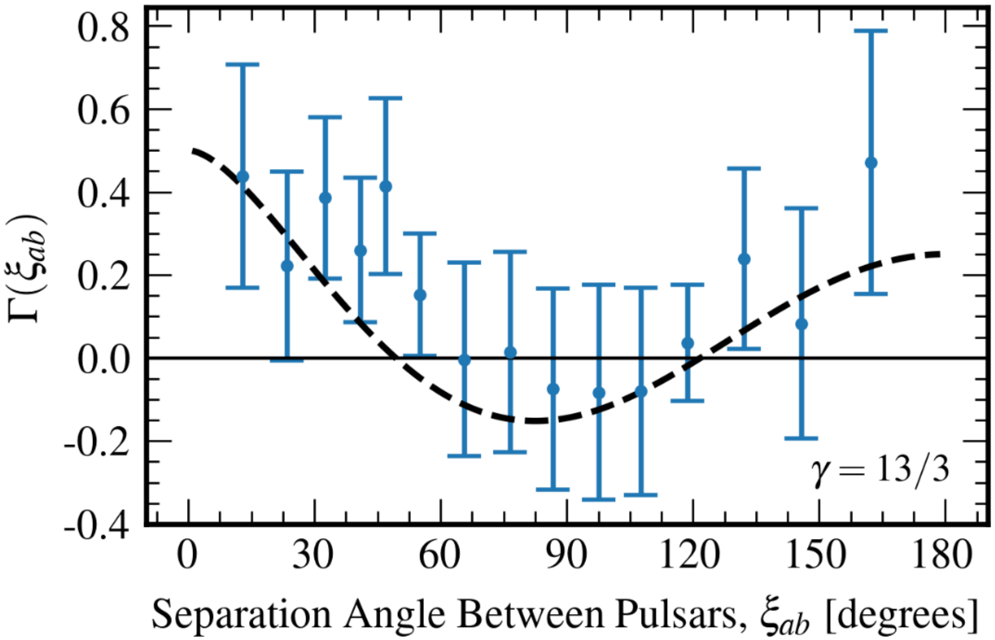
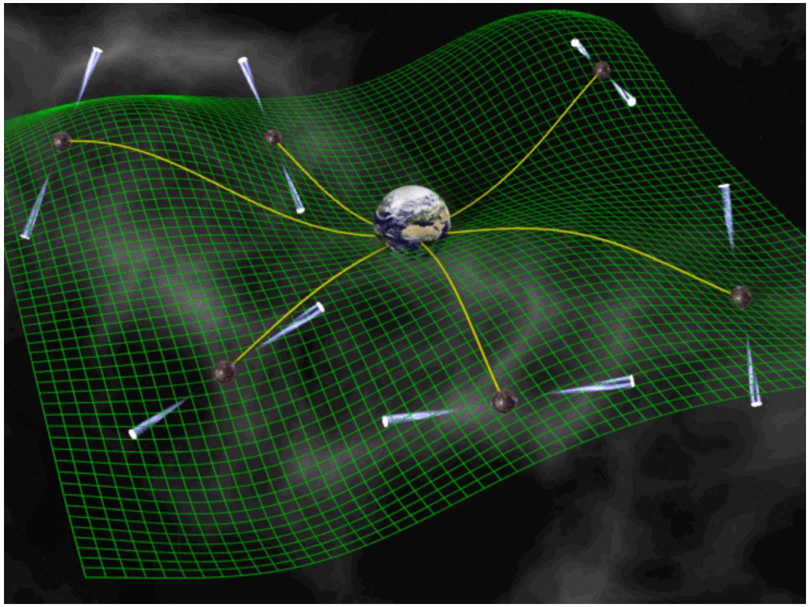
PTAs: A first glimpse of a SGWB?

Pulsar timing arrays, June 2023

Significant evidence for nHz GW signal,
consistent with SGWB



NANOGrav collaboration `23



SMBHBs or new physics?

more data & analyses coming!

conclusions and outlook

Early Universe = HEP lab

provides evidence for physics beyond the Standard Model:

dark matter ?

origin of the matter antimatter asymmetry ?

vacuum energy ?

cosmic inflation ?

→ laboratory experiments and astrophysical observations needed !