

Cosmology in a nutshell

Vivian Poulin

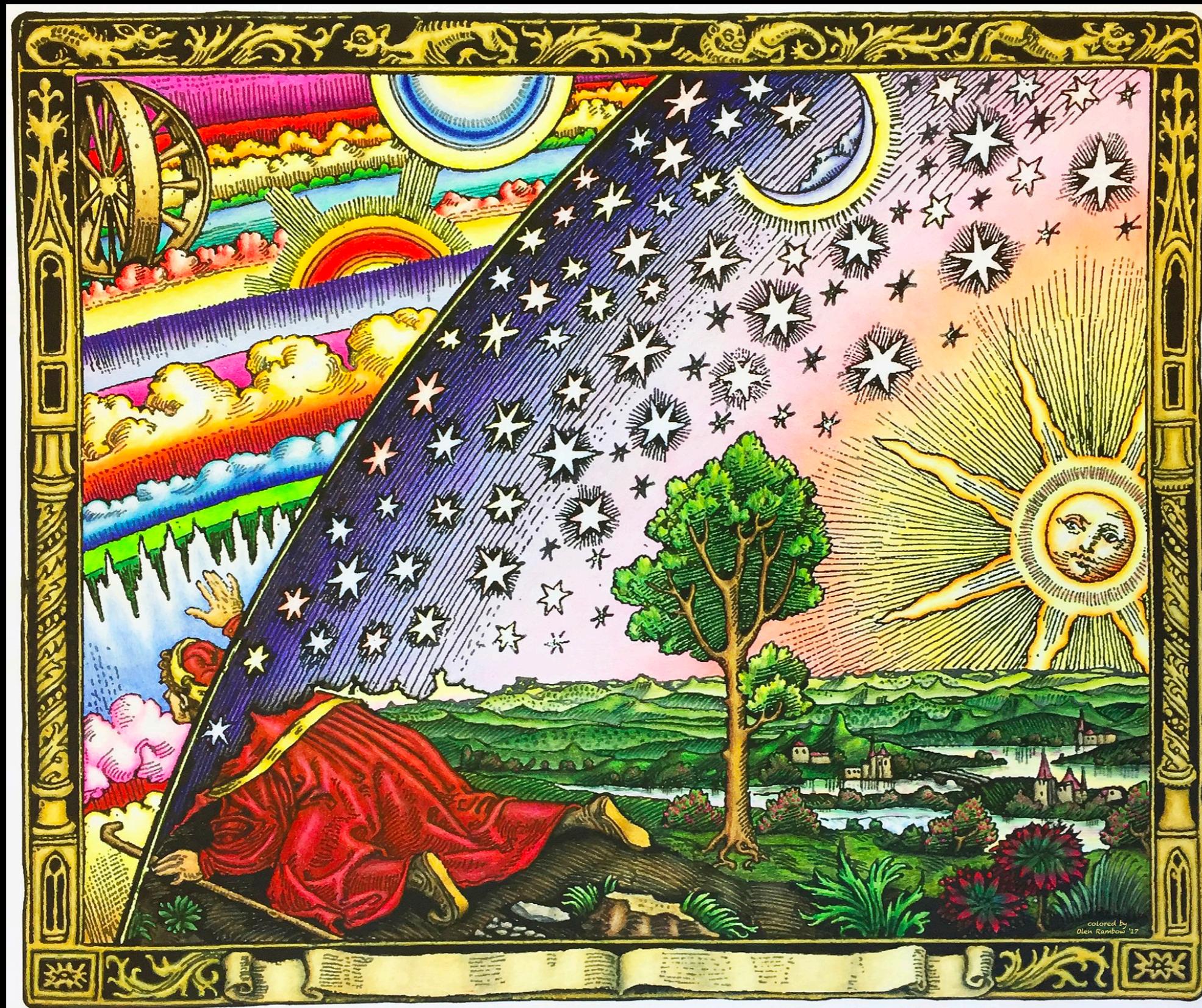
Laboratoire Univers et Particules de Montpellier
CNRS & Université de Montpellier

"Light Anti-Nuclei as a Probe for New Physics"

Leiden, Netherlands, October 2019

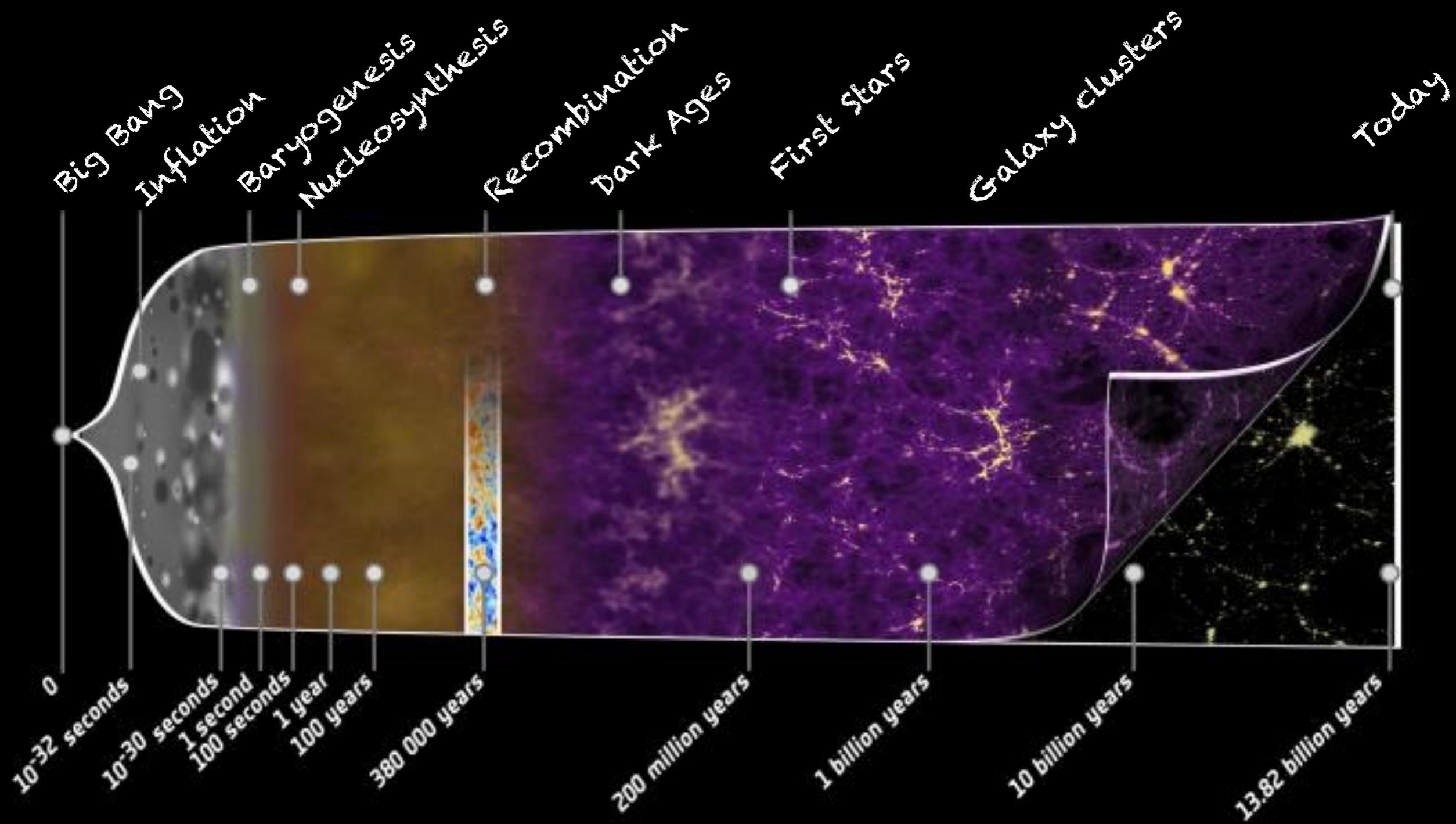


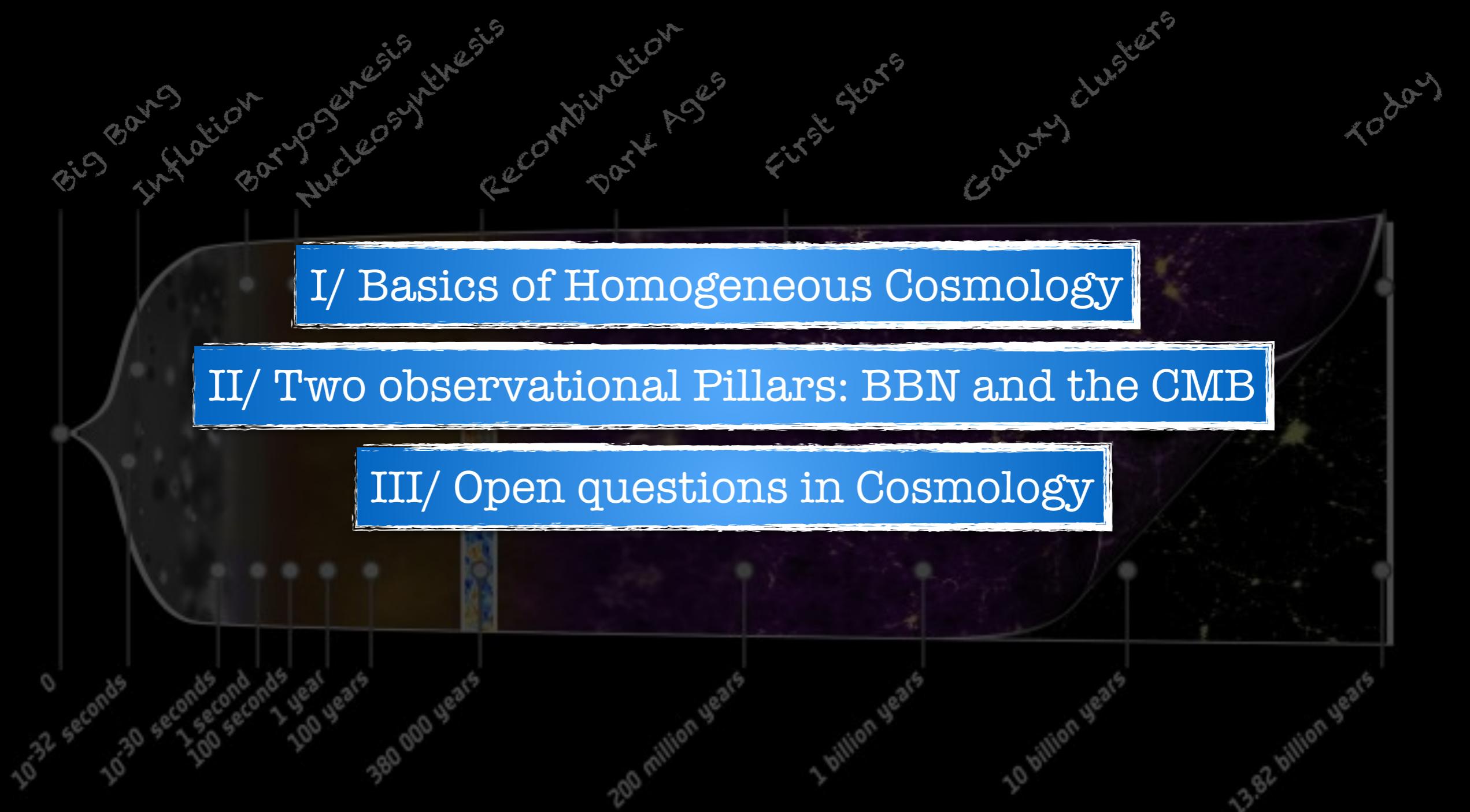
Cosmology describes the dynamics and structuration of our Universe



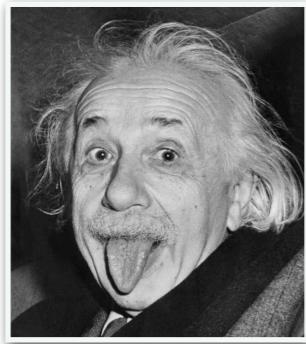
Camille Flammarion "L'atmosphère : météorologie populaire"

Cosmology describes the dynamics and structuration of our Universe





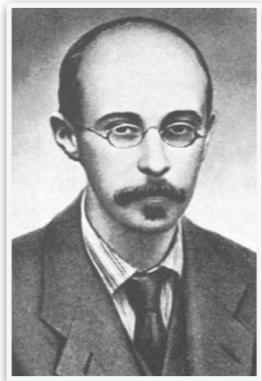
The Universe is expanding!



A. Einstein



G. Lemaître



A. Friedmann



E. Hubble



V. Slipher

- Start from **Einstein's equations**

$$G_{\mu\nu} \equiv R_{\mu\nu} - \frac{1}{2}\mathcal{R}g_{\mu\nu} - \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Under **homogeneity** and **isotropy** hypothesis,
i.e. for a FLRW metric

$$ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right]$$

- Leads to the **FL equations**

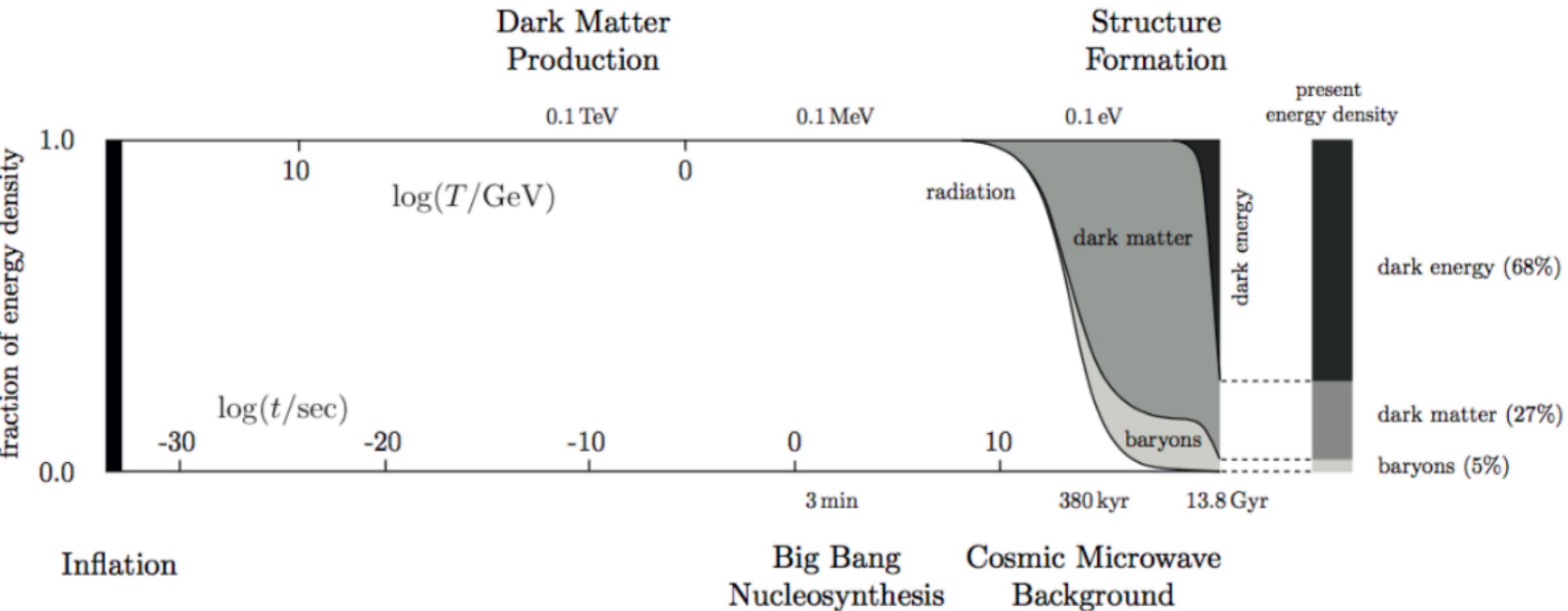
$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2(a) = H_0^2[\Omega_r a^{-4} + \Omega_m a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda]$$

$$\Omega_I \equiv \frac{\rho_{I,0}}{\rho_{\text{crit},0}}$$

- With a Hubble expansion rate nowadays

$$H_0 \simeq 70 \text{ km/s/Mpc}$$

A sketch of our Universe history



- At high temperature, kinetic equilibrium will be achieved through processes such as

$$e^\pm \gamma \leftrightarrow e^\pm \gamma \quad \nu_e e \leftrightarrow \nu_e e \quad p e^\pm \leftrightarrow p e^\pm \quad \text{Thermal equilibrium}$$

$$e^- p \leftrightarrow e^- p \gamma \quad \Rightarrow \mu_\gamma = 0 \quad e^+ e^- \rightarrow \gamma \gamma \quad \Rightarrow \mu_{e^-} = -\mu_{e^+}. \quad \text{Chemical equilibrium}$$

The Primordial Plasma at $z \gg 1000$

- These processes ensure that a Boltzmann distribution will be reached for each species:

$$f_{\pm} = \frac{1}{e^{(E-\mu)/T} \pm 1}$$

$$\begin{aligned} n(t) &= \frac{g}{(2\pi)^3} \int d^3 p f_s(t, p) \quad , \\ \rho(t) &= \frac{g}{(2\pi)^3} \int d^3 p E_s f_s(t, p) \quad , \\ -\mathcal{P}(t) \delta_j^i &= -\delta_j^i \frac{g}{(2\pi)^3} \int d^3 p \frac{p^2}{3E_s} f_s(t, p) \quad . \end{aligned}$$

- Number density, energy density and pressure depends on the ratio M/T :

$$n = \frac{g\zeta(3)}{\pi^2} T^3 \times \begin{cases} 1 & \text{bosons} \\ 3/4 & \text{fermions} \end{cases}$$

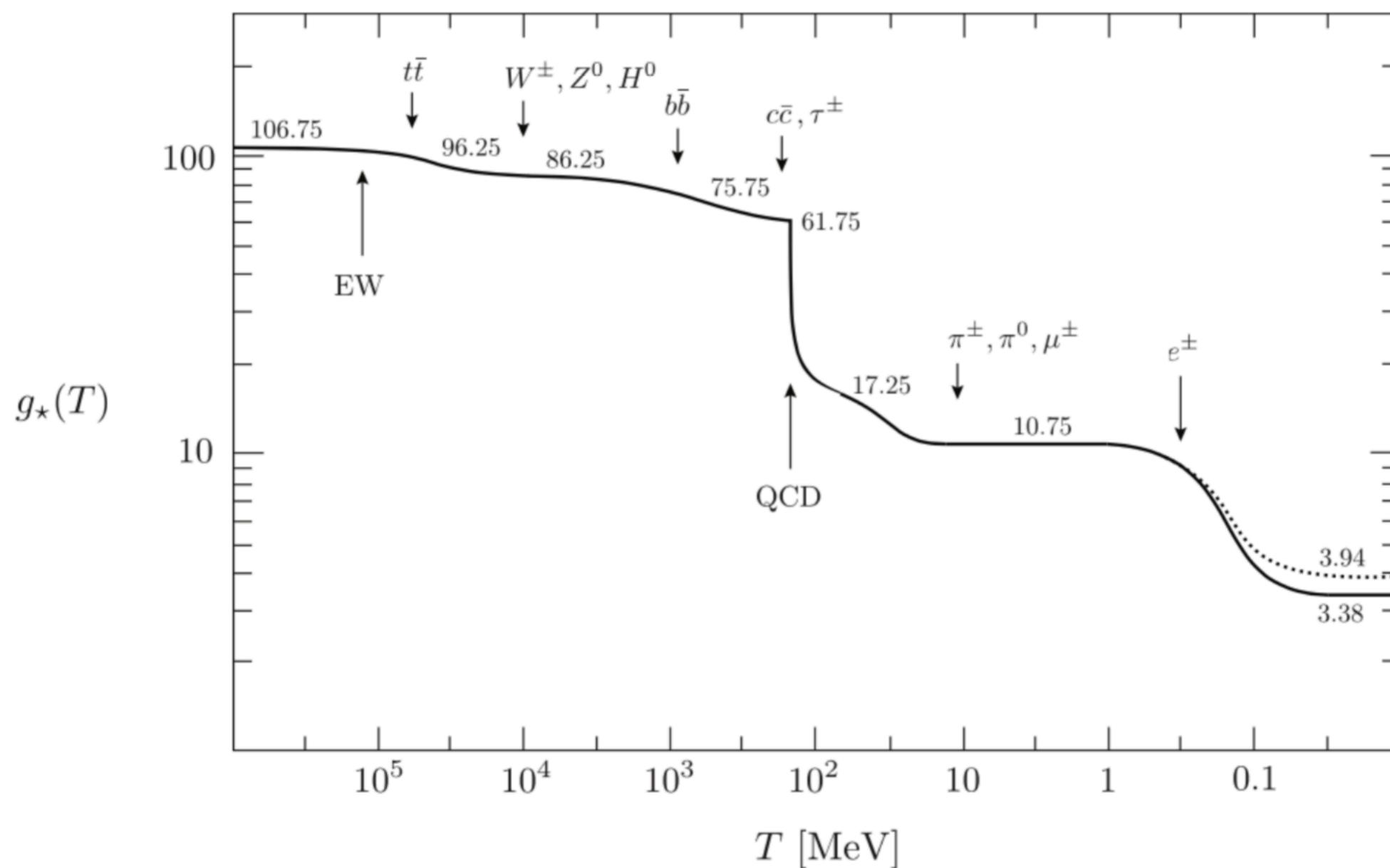
$$\rho = \frac{\pi^2}{15} g T^4 \times \begin{cases} 1 & \text{bosons} \\ \frac{7}{8} & \text{fermions} \end{cases}$$

$$\mathcal{P} = \frac{1}{3}\rho$$

$$\begin{aligned} n &= g \left(\frac{mT}{2\pi} \right)^{\frac{3}{2}} e^{-m/T} \\ \rho &= mn + \frac{3}{2}nT \underset{T \ll m}{\simeq} mn \\ \mathcal{P} &= nT \ll \rho \end{aligned}$$

- At early times, the universe is dominated by radiation:

$$\rho_r = \sum_i \rho_i = \frac{\pi^2}{30} g_{\text{eff}}(T) T^4 . \quad g_{\text{eff}}(T) \simeq \sum_{\text{bosons}} g_i \left(\frac{T_i}{T} \right)^4 \Theta(T - m_i) + (7/8) \sum_{\text{fermions}} g_i \left(\frac{T_i}{T} \right)^4 \Theta(T - m_i) .$$



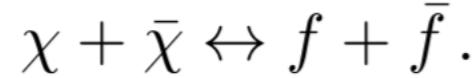
- From the 2nd law of thermodynamics:

$$s \equiv S/V \quad s_i(T, \mu) = \frac{\rho_i + \mathcal{P}_i - \mu n_i}{T} . \quad s = \sum_i s_i = h_{\text{eff}}(T) \frac{2\pi^2}{45} T^3 .$$

$$d(sa^3) = 0 \quad s(T)a^3 \propto h_{\text{eff}}(T)T^3a^3 = \text{const}$$

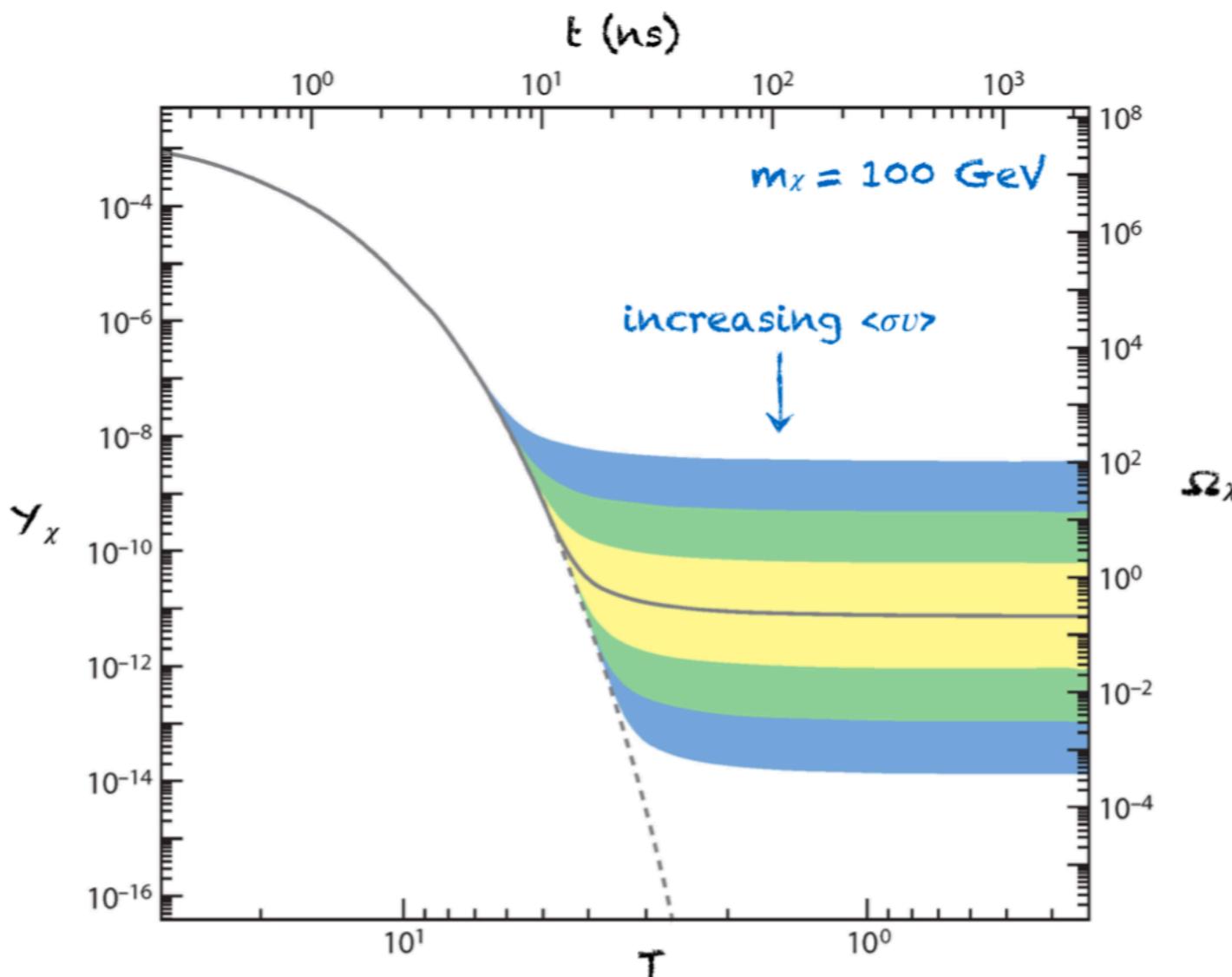
$$\Rightarrow T \propto h_{\text{eff}}^{-1/3}a^{-1} .$$

Freeze-out and the production of matter



$$\frac{dn_\chi}{dt} = \underbrace{-3Hn_\chi}_{\text{dilution}} + \underbrace{n_f^2 \langle \sigma_{f\bar{f} \rightarrow \chi\bar{\chi}} v \rangle}_{\text{production}} - \underbrace{n_\chi^2 \langle \sigma_{\chi\bar{\chi} \rightarrow f\bar{f}} v \rangle}_{\text{destruction}},$$

$$Y_\chi = n_\chi/s \quad \frac{dY_\chi}{dx} = -\frac{\lambda}{x^2} [\chi^2 - (Y_\chi^{(eq)})^2], \quad \lambda \equiv \frac{2\pi^2}{45} h_{\text{eff}}(M_\chi) \frac{M_\chi^3 \langle \sigma v \rangle}{H(M_\chi)}.$$



- Applied to CDM:

$$\Omega_{\text{cdm}} h^2 \simeq 0.12 \times \frac{3 \times 10^{-26} \text{cm}^3 \text{s}^{-1}}{\langle \sigma v \rangle}.$$

- Assuming homogeneous, baryon-symmetric universe and no B-violation processes:

$$\frac{n_B}{n_\gamma} = \frac{n_{\bar{B}}}{n_\gamma} \sim 10^{-17}$$



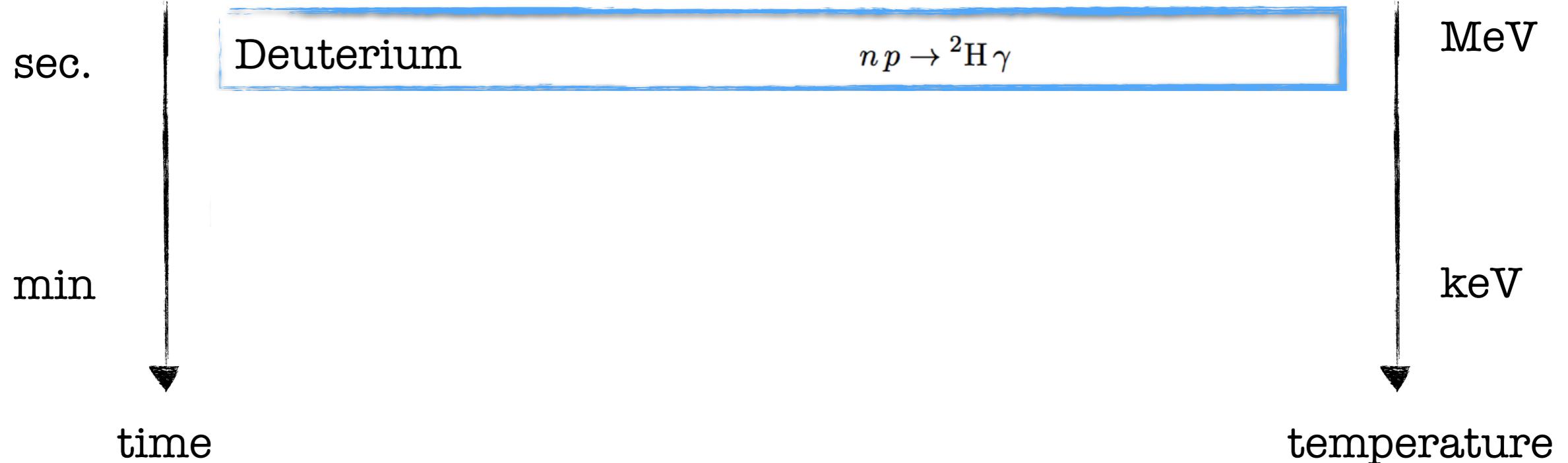
G. Gamow



R. Alpher

Big Bang Nucleosynthesis: The first « observational » pillar

- A few secs after BB ($T \approx \text{MeV}$): The creation of **all light elements (< Li)**.



In practice, one solves numerically (e.g. PArthENoPE)

- The Friedmann-Lemaître and continuity equations
- A set of integrated coupled Boltzmann equations (one per nuclei)
- A Boltzmann equation for the neutrinos phase-space distribution.

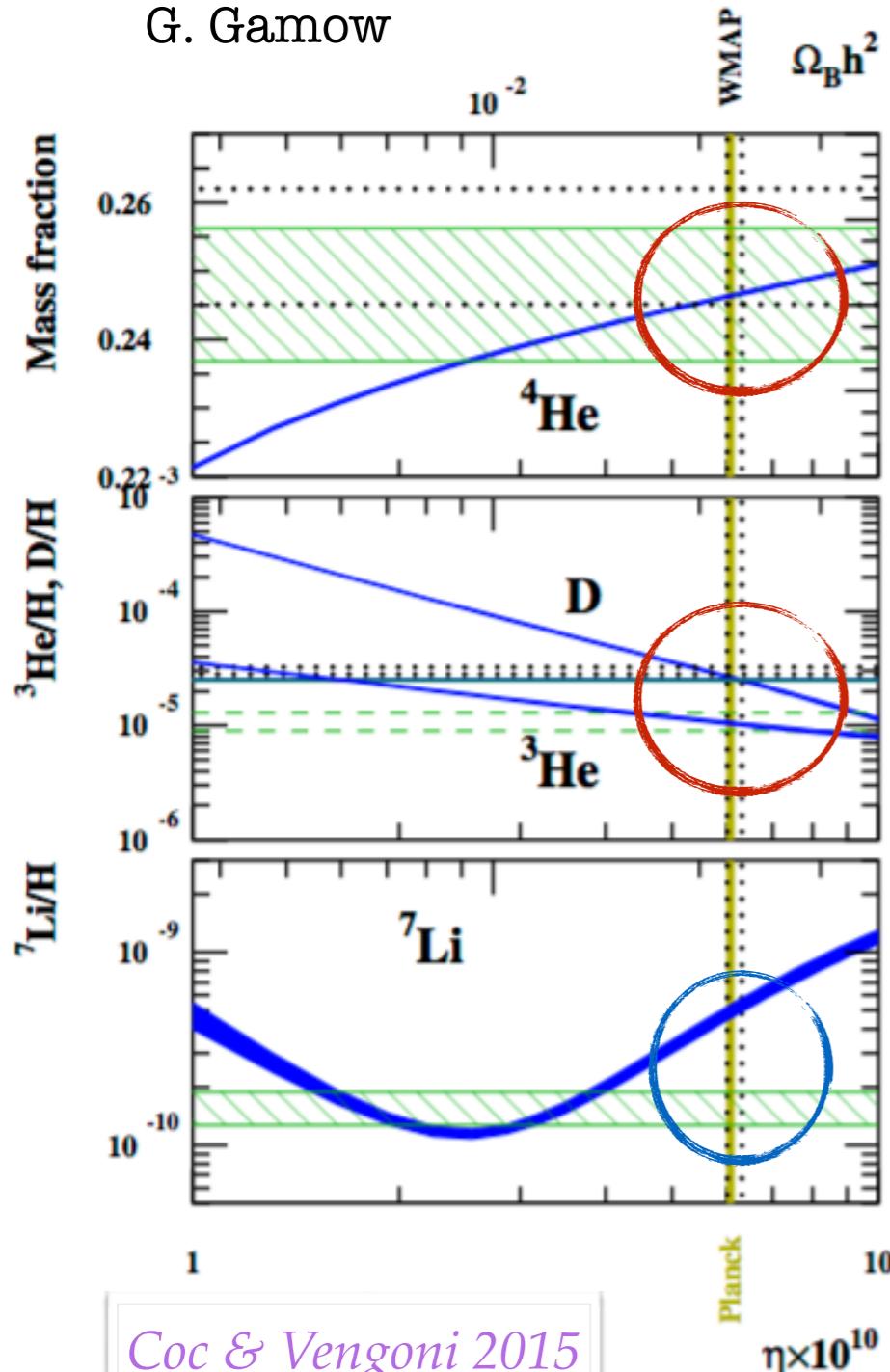


G. Gamow

Big Bang Nucleosynthesis: The first « observational » pillar



R. Alpher



Coc & Vengoni 2015

One free parameter:
the baryon-to-photon ratio

$$\eta = n_b/n_\gamma \approx 6 \times 10^{-10}$$

For 3 nuclei, great success!

$$\begin{aligned} {}^4\text{He}/\text{H} &= Y_p > 0.2368 \\ 2.56 \times 10^{-5} < {}^2\text{H}/\text{H} &< 3.48 \times 10^{-5} \\ {}^3\text{He}/\text{H} &< 1.5 \times 10^{-5} \end{aligned}$$

The « Lithium problem »

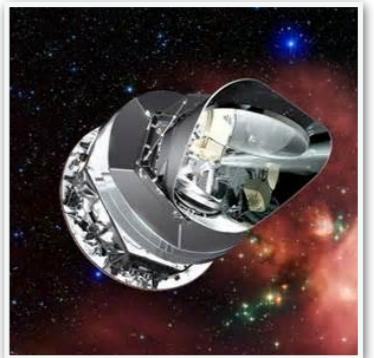
Over-prediction of the ${}^7\text{Li}$ abundance

$$Y_{\text{Li}}^{\text{theo}} = 3 \times Y_{\text{Li}}^{\text{obs}}$$



Penzias & Wilson

Cosmic Microwave Background: The second « observational » pillar

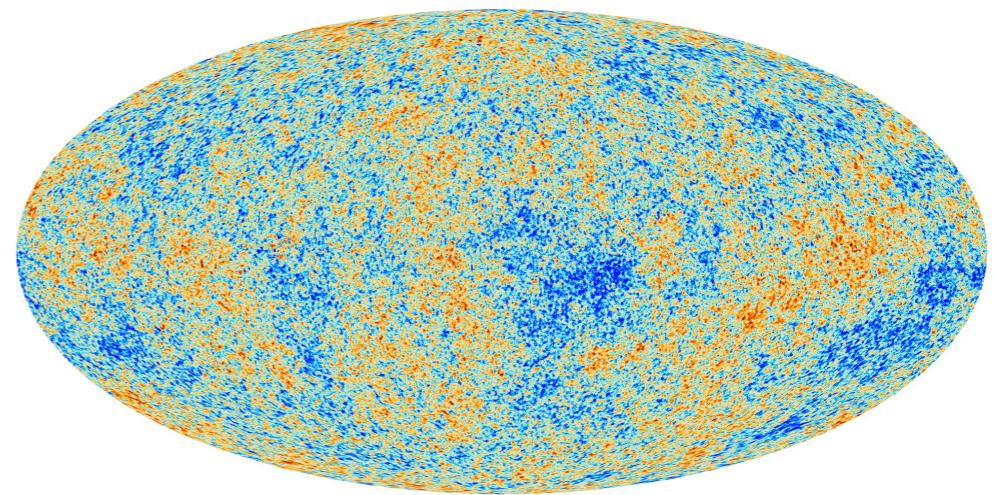
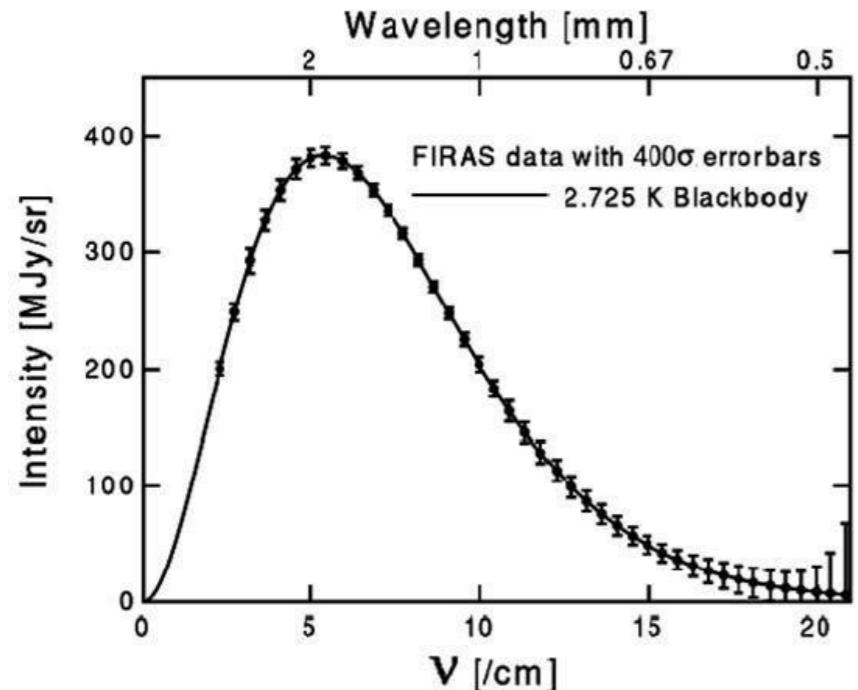


Planck

- Thermal radiation: a relic from the « hot » primordial era.
- Predicted by Gamow, observed (accidentally!) by Penzias & Wilson.

The most perfect blackbody ever observed ...

... carrying tiny anisotropies.



$$T = 2.72548 \pm 0.00057 \text{ K}$$

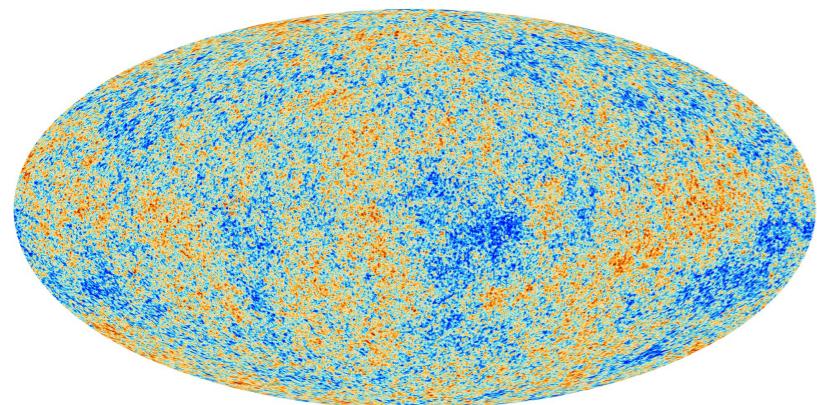
Firas [[astro-ph/9605054](#)]

Planck 2015 (ESA website)

Homogeneity and fluctuations come from inflation!

CMB power spectrum

- Temperature and polarization anisotropies carries a wealth of information: how to exploit it?



$$\Theta(\vec{n}) \equiv \frac{\delta T}{T}(\theta, \phi) = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

CMB temperature fluctuations are random: Quantum fluctuations of the inflaton.

Our theory **does not** predict temperature fluctuations, only statistical properties.
 => We need **moments of the distribution !**
 the so called « n-points correlation functions ».

Paradigm : $\Theta(\vec{n})$ follows a **Gaussian distribution**.
 Linear perturbation theory ensures that this will always be the case.

Only two moments of interest :

$$\langle \Theta(\vec{n}) \rangle = 0 \quad \langle \Theta(\vec{n}_1) \Theta(\vec{n}_2) \rangle \neq 0$$

Power spectra = Harmonic Transform of the 2-points correlation functions

$$\Theta(\vec{n}) \equiv \frac{\delta T}{T}(\theta, \phi) = \sum_{\ell, m} a_{\ell m} Y_{\ell m}(\theta, \phi)$$

$$\langle \Theta(\vec{n}_1) \Theta(\vec{n}_2) \rangle = \sum_{\ell, m, \ell', m'} \langle a_{\ell m} a_{\ell' m'}^* \rangle Y_{\ell m}(\vec{n}_1) Y_{\ell' m'}^*(\vec{n}_2)$$

$$\langle a_{\ell m} \rangle = 0 \quad \langle a_{\ell m} a_{\ell m}^* \rangle = \delta_{\ell \ell'} \delta_{mm'} C_{\ell}^{\text{SHI}}$$

It represents the **variance of the distribution** for a given scale $\ell = \pi/\theta$
 (in real space, you can relate it to the **amplitude of fluctuations** in a given box size)

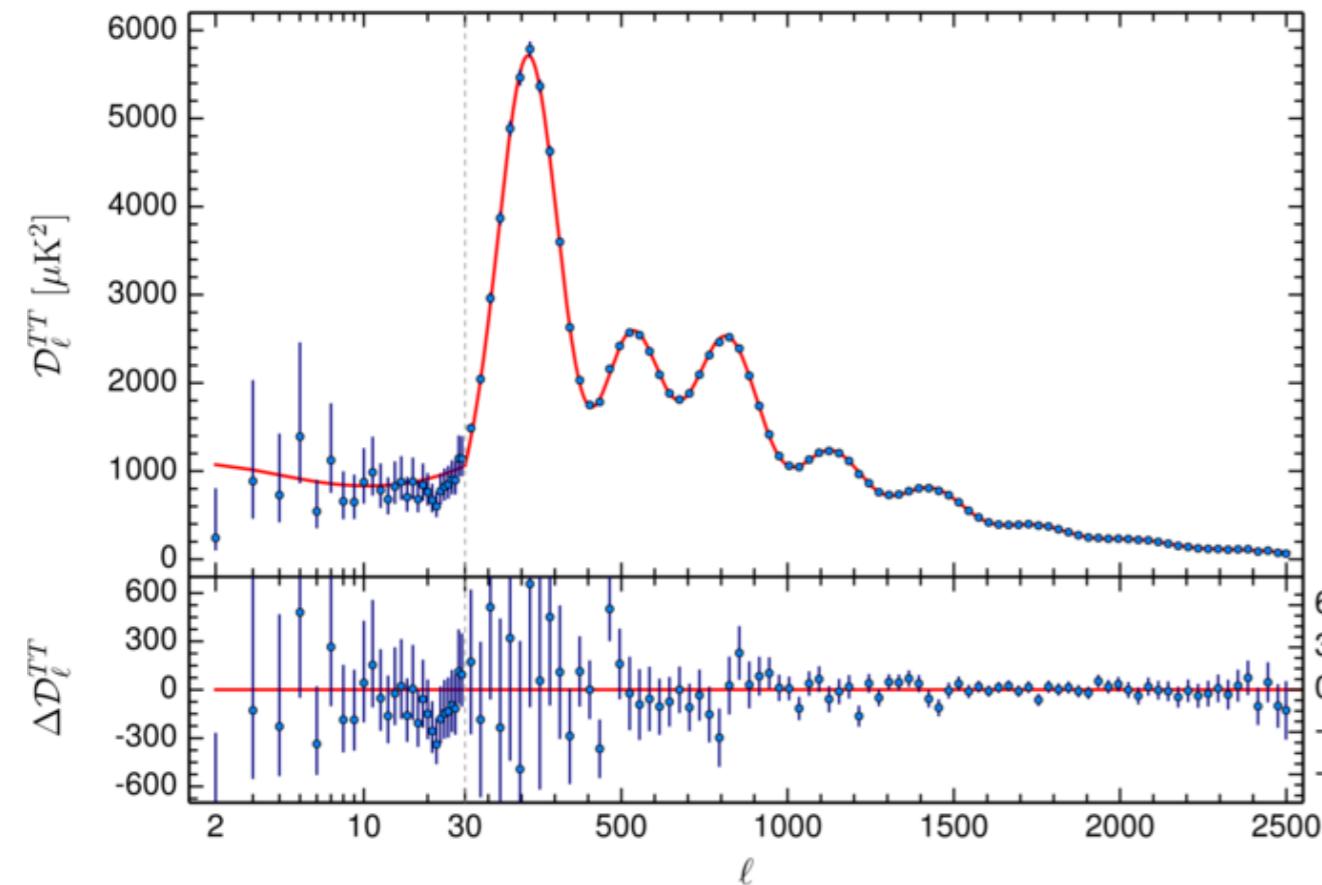
We can determine this power spectra **both experimentally and theoretically** !

Minimal LCDM = 6 free parameters to fit : $\{\omega_b, \omega_{cdm}, h, A_s, n_s, z_{reio}\}$

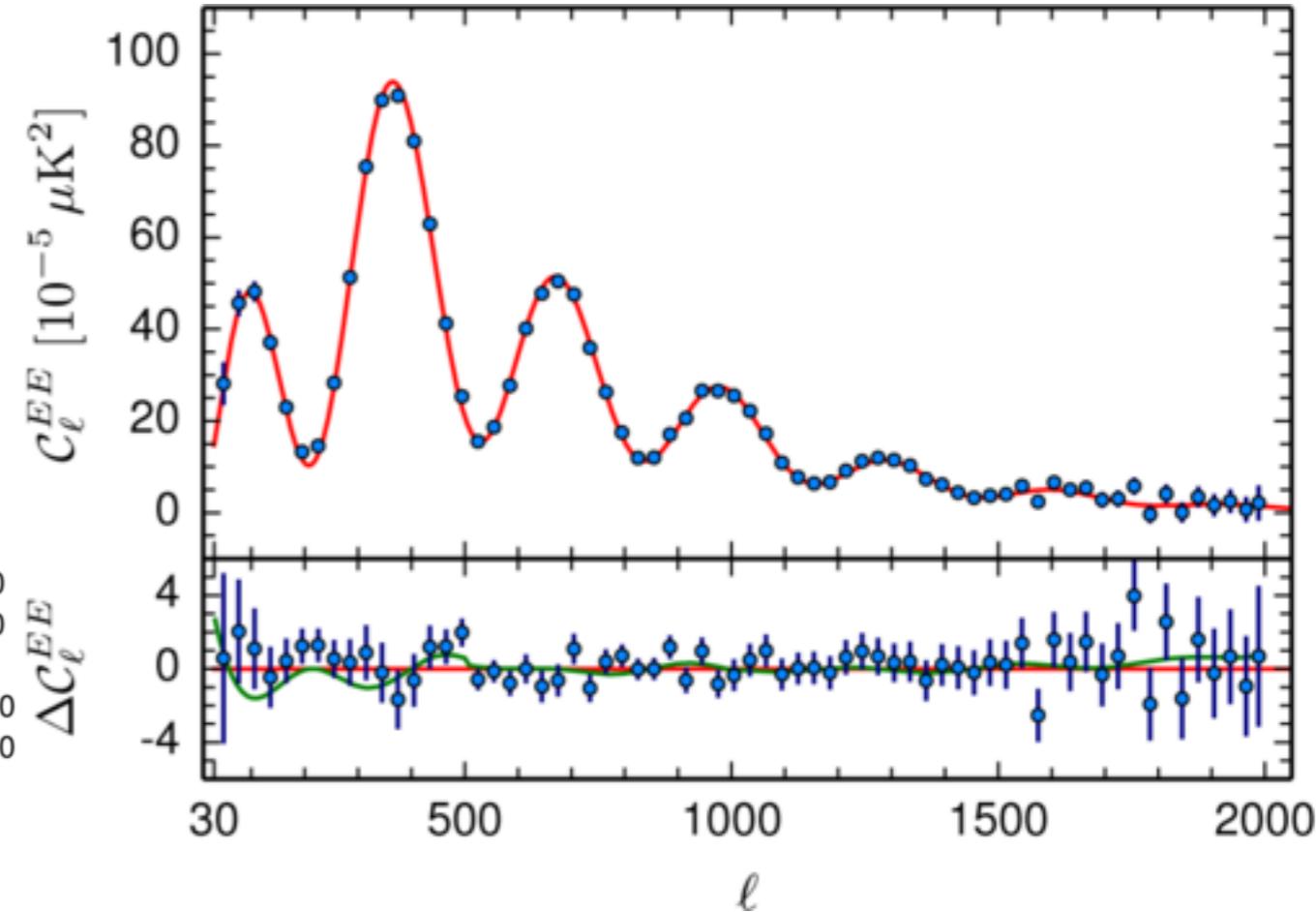
One can extend this minimal model and search for new physics !

CMB power spectrum

Temperature



E-mode polarization



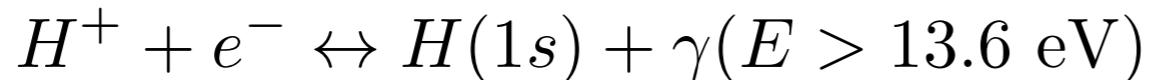
Planck 2015 [arXiv:1502.01589]

A characteristic scale and a series of acoustic peaks

What information is hidden in these spectra?

A fundamental time: the time of recombination

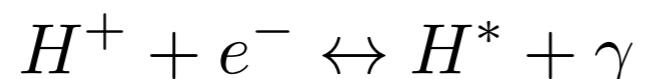
- Era of the universe at which p and e- recombine.
- About 380 000 y after the Big Bang at $T \approx 0.2 \text{ eV}$.



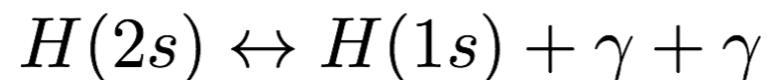
Leads to the « saha » equation at equilibrium
 => Wrong in Cosmology!

Toy model: The « three-levels atom »

by J. Peebles



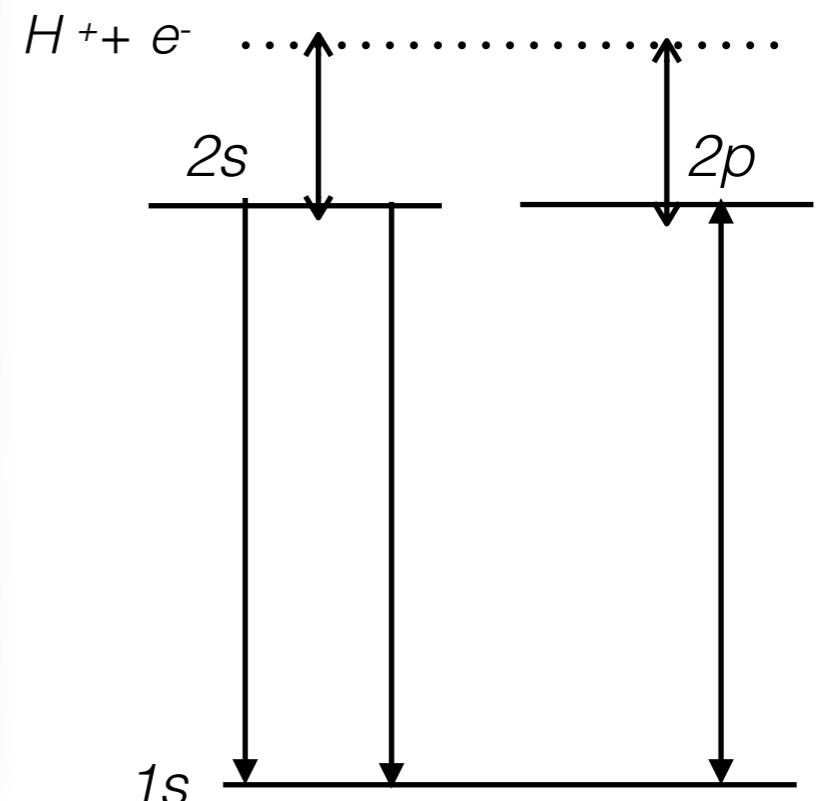
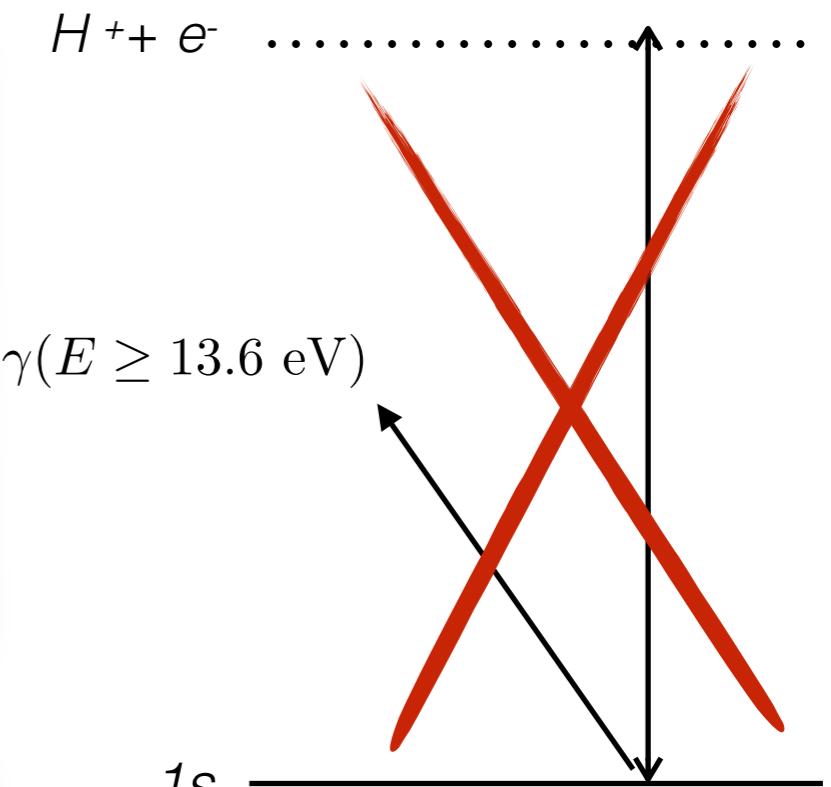
followed by



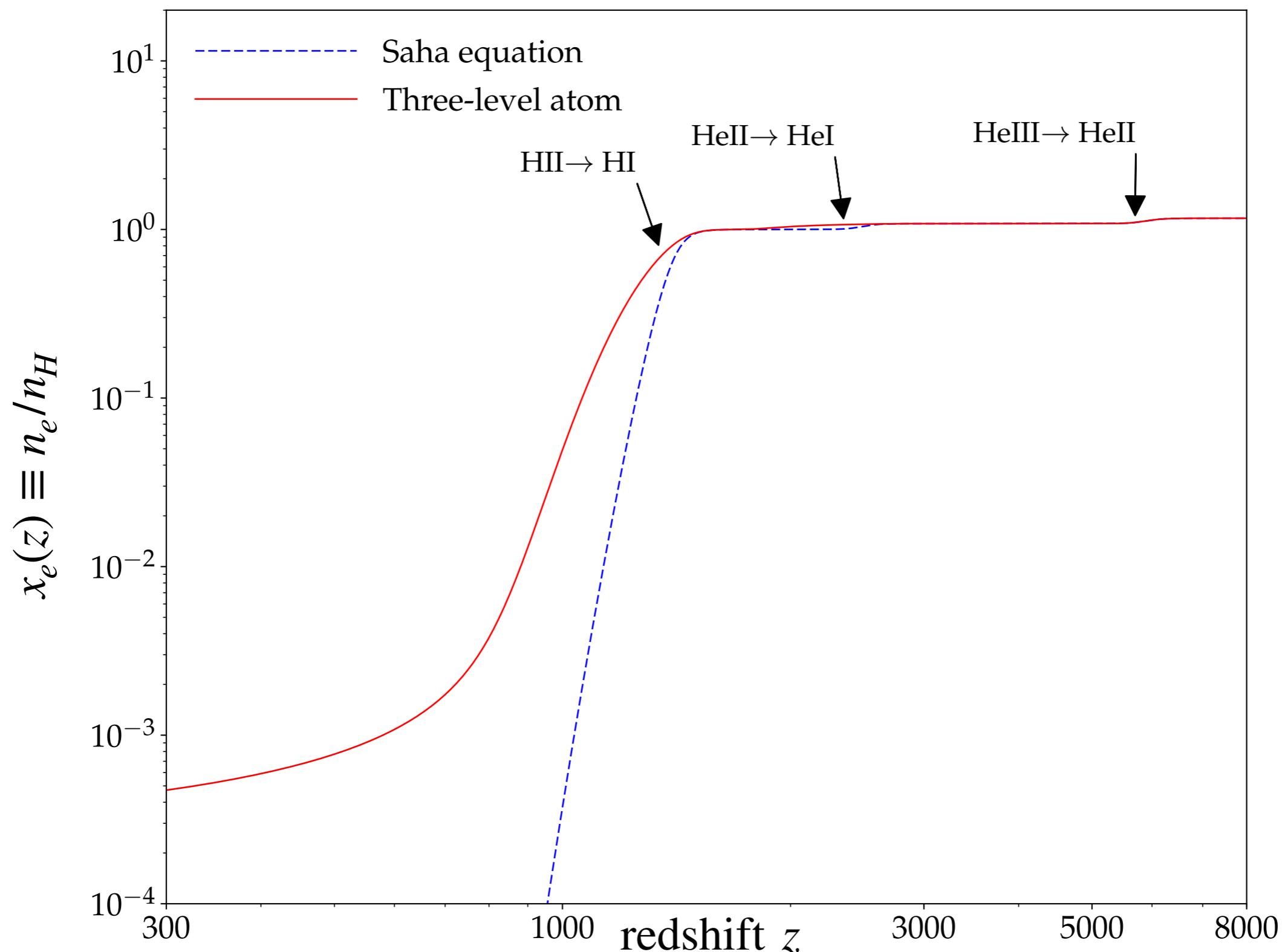
For cosmology, sub % precision is needed !

Thus, numerical codes have been developed:

e.g. **Hyrec, CosmoRec and a fudged Recfast**

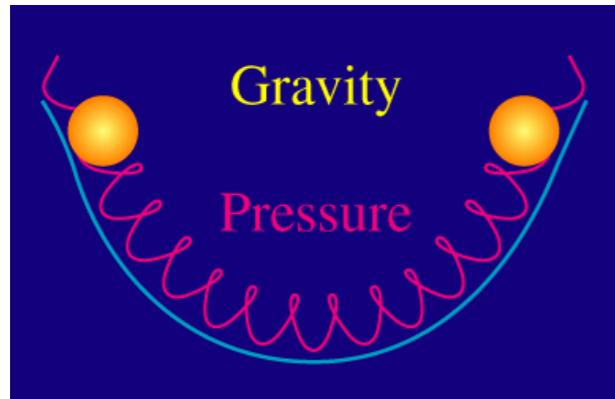


Era of recombination at $T \simeq 0.2 \text{ eV} \Leftrightarrow z \simeq 1100$



A fundamental scale: the sound horizon at decoupling

- Start from $\delta G_\nu^\mu = 8\pi G \delta T_\nu^\mu$ and $\mathcal{L}(\delta f) = \pm a\Gamma \delta f$: leads to Boltzmann hierarchy!
- In the tightly-coupled photon-baryons fluid, we can combine equations to get:



$$\Theta''_{T0} + \frac{R'}{1+R} \Theta'_{T0} + k^2 c_s^2 \Theta_{T0} = -\frac{k^2}{3} \phi + \frac{R'}{1+R} \psi' + \psi''$$

Friction Pressure Gravity

A damped, forced acoustic oscillator in k -space!

credit: Hu & White

- Characterised by a sound speed:

$$c_s^2 = \frac{\delta p_\gamma + \delta p_b}{\delta \rho_\gamma + \delta \rho_b} = \frac{1}{3(1+R)}$$

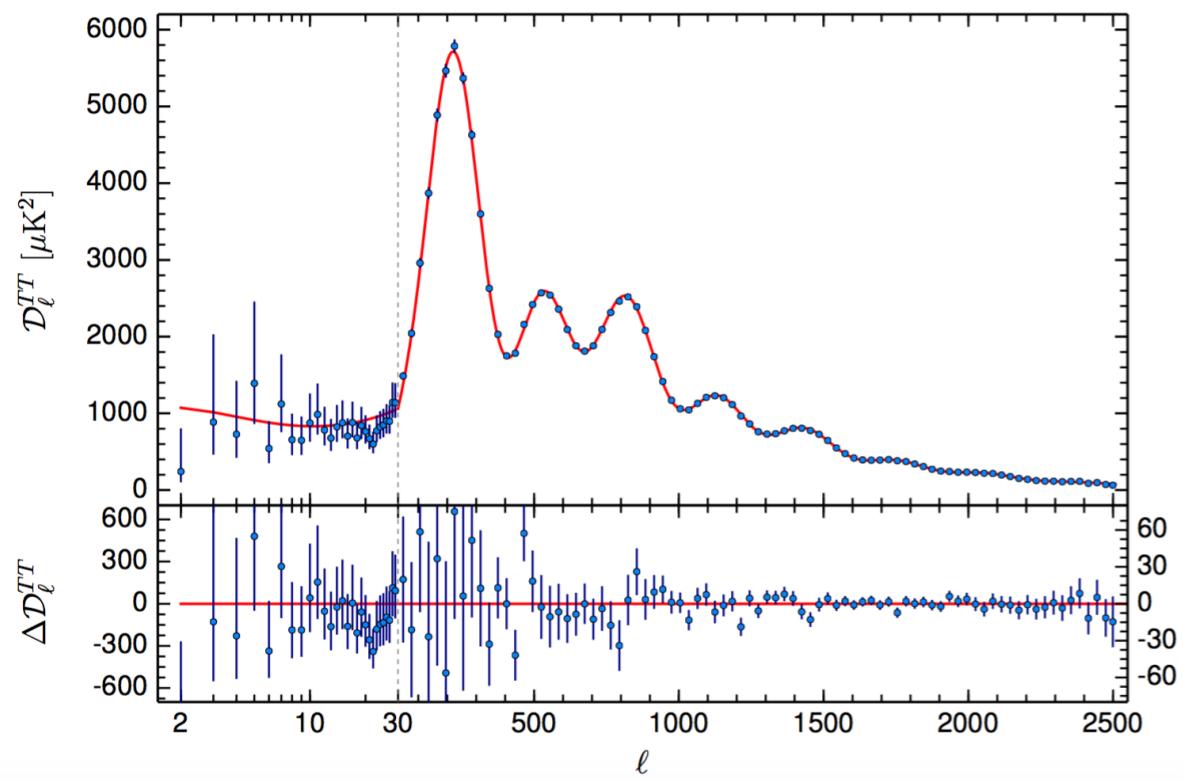
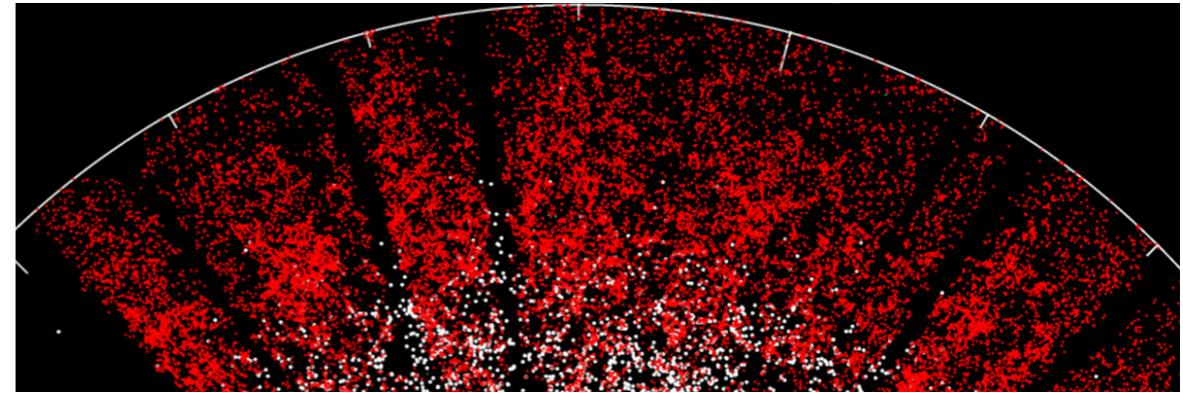
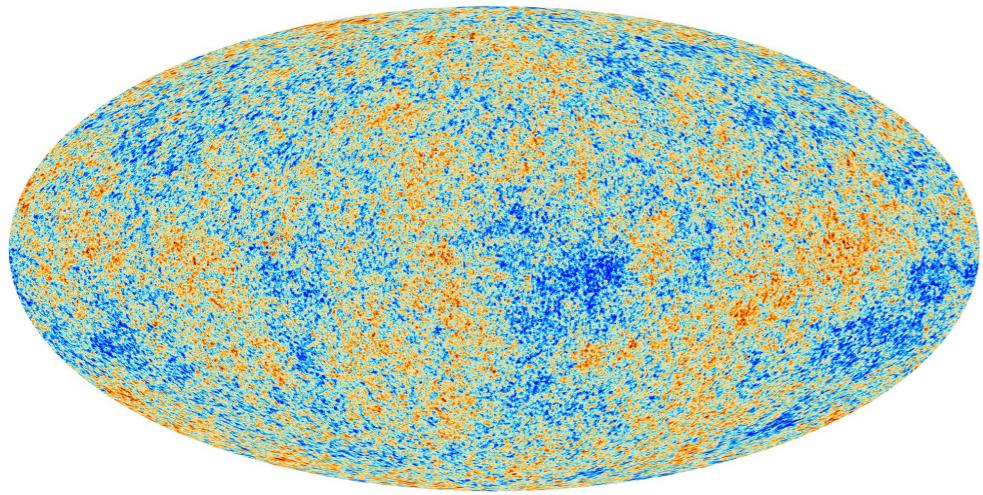
- Friction of photons with baryons:

$$R \equiv \frac{3}{4} \frac{\bar{\rho}_b}{\bar{\rho}_\gamma}$$

- Key quantity: the sound horizon

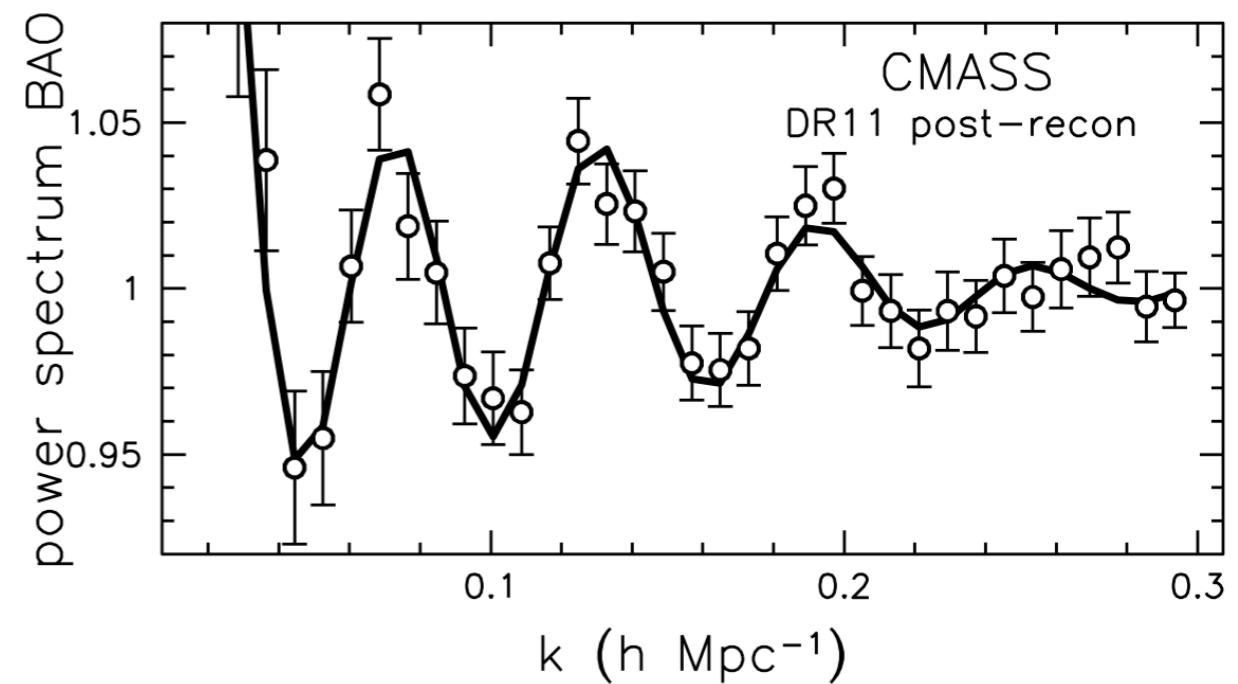
$$r_s \equiv \int_{\tau_{\text{ini}}}^{\tau} c_s d\tau \underset{\tau_{\text{ini}} \ll \tau}{\simeq} c_s \tau .$$

The sound horizon is a standard ruler!



CMB map and TT power spectrum

Planck 2015 [arXiv:1502.01589]



P(k) and BAO measurements

Andersen et al. 2012 [arXiv:1203.6594]

The Line-of-sight formalism

$$C_\ell = \int \frac{dk}{k} \mathcal{P}_R(k) [\Theta_\ell(\tau_0, k)]^2 \quad \text{with} \quad \Theta_\ell(\tau_0, k) = \int_{\tau_0}^{\tau_0} d\tau S_T(\tau, k) j_\ell(k(\tau_0 - \tau))$$

$$S_T(k, \tau) \equiv \underbrace{g(\Theta_0 + \psi)}_{\text{SW}} + \underbrace{(gk^{-2}\theta_B)'}_{\text{Doppler}} + \underbrace{e^{-\kappa}(\phi' + \psi')}_{\text{ISW}} + \text{polarisation}$$

Inflation « Primordial » physics

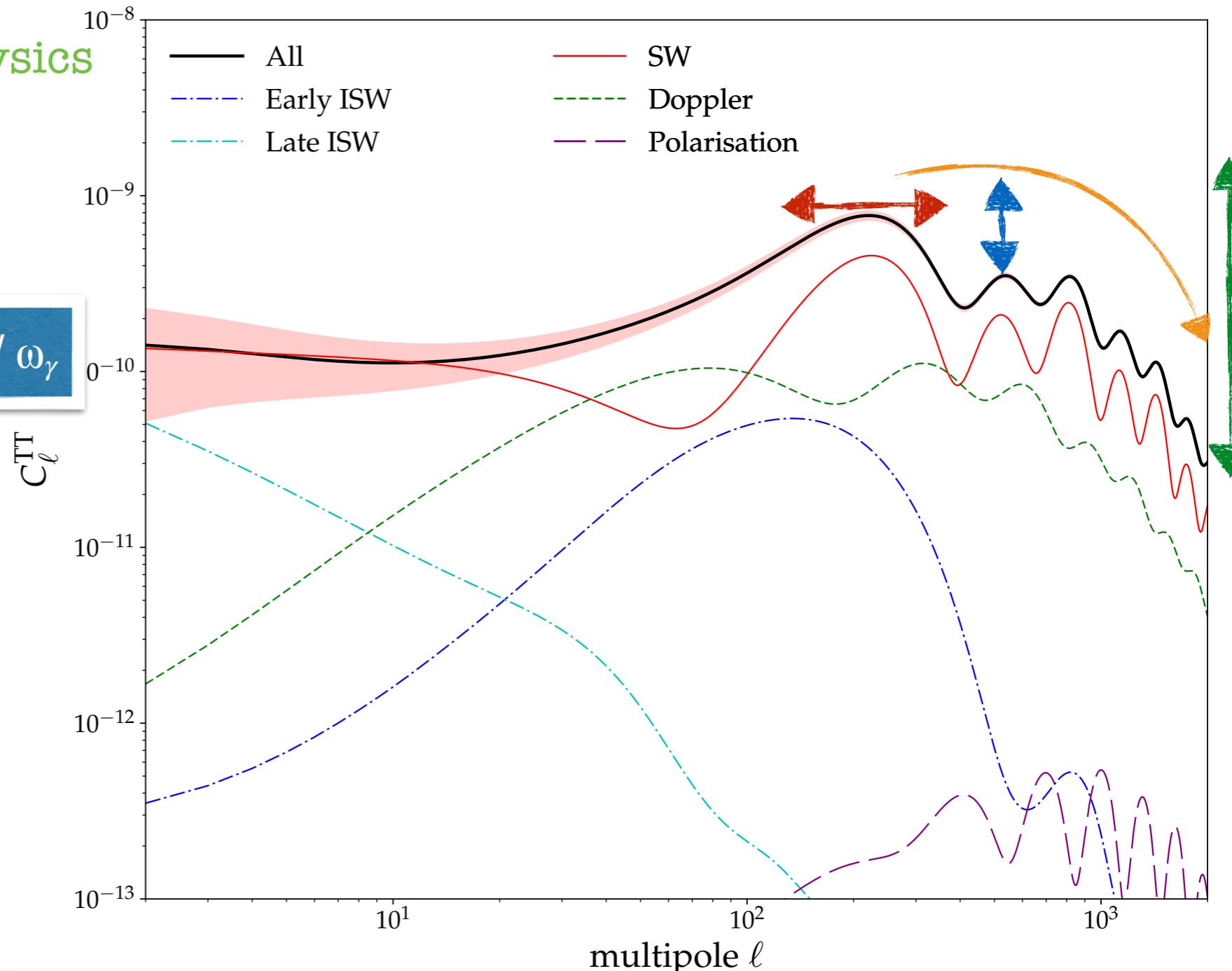
Peak position: $\omega_b, \omega_m, h, \Omega_\Lambda$

Ratio of odd/even peaks: ω_b / ω_γ

Overall peaks size: ω_m / ω_γ

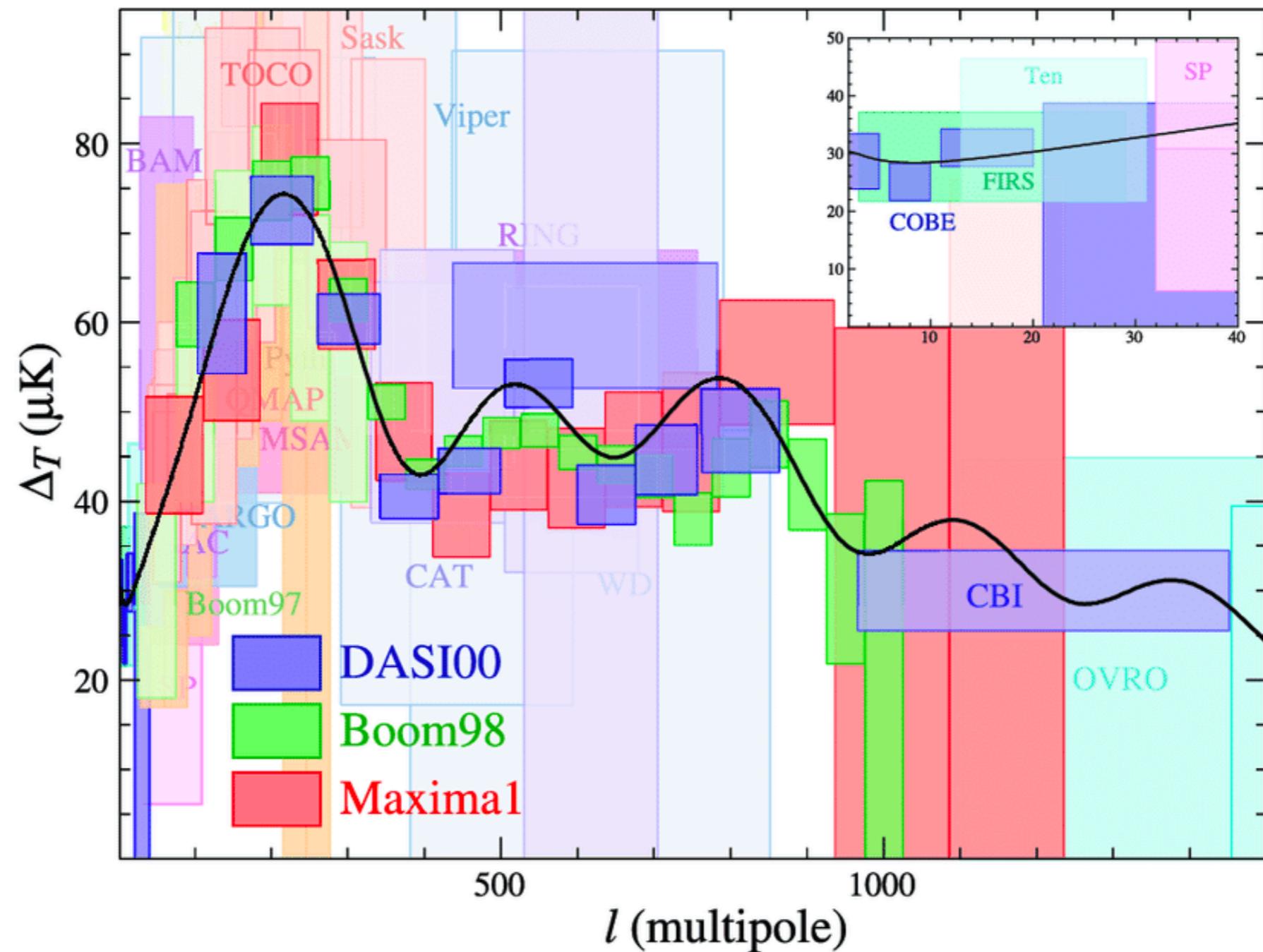
Silk damping: ω_b, ω_m

*Seljak & Zaldarriaga
APJ. 469 (1996) 437-444*



The Era of Precision Cosmology

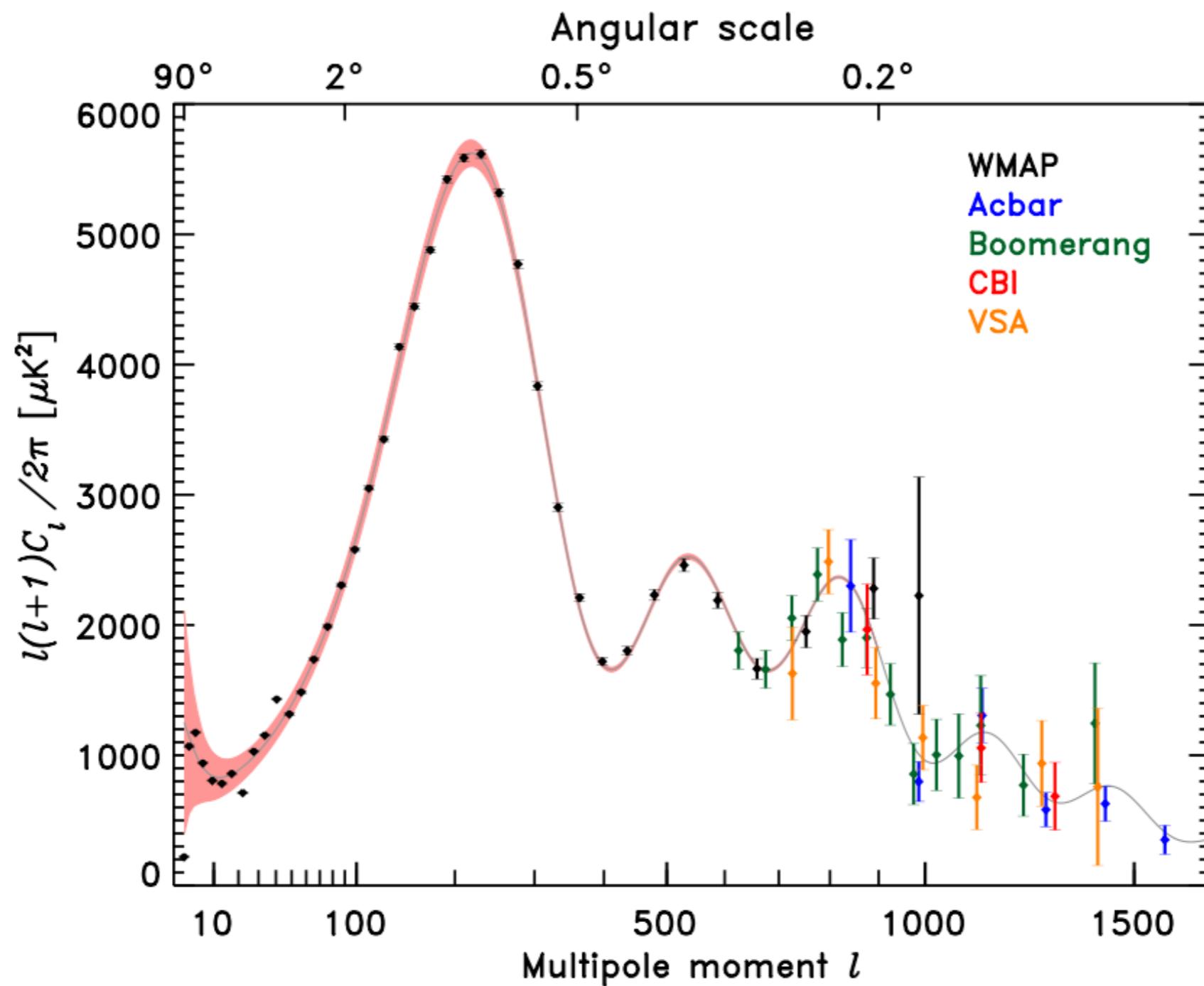
20 years ago



© Dodelson

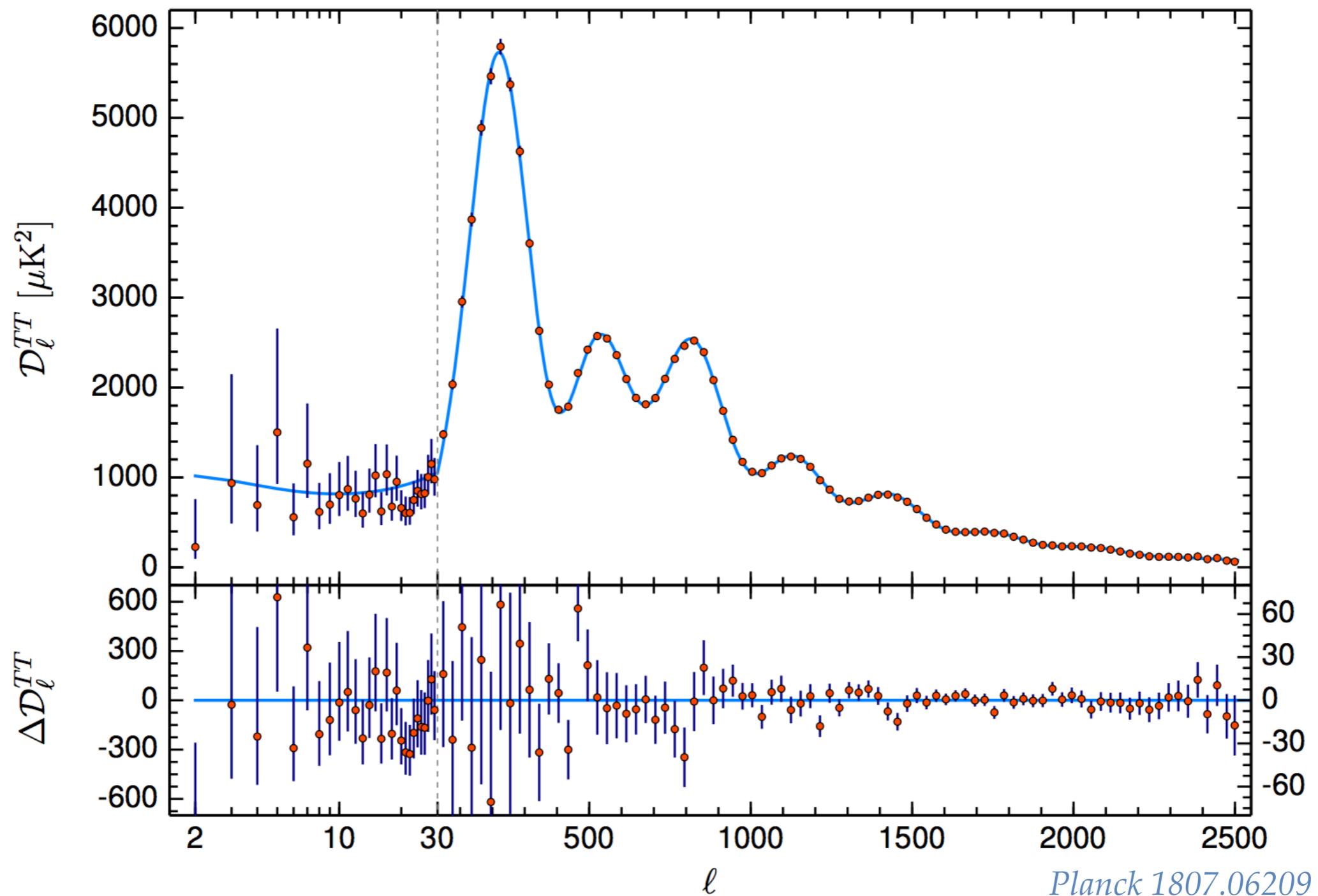
The Era of Precision Cosmology

10 years ago



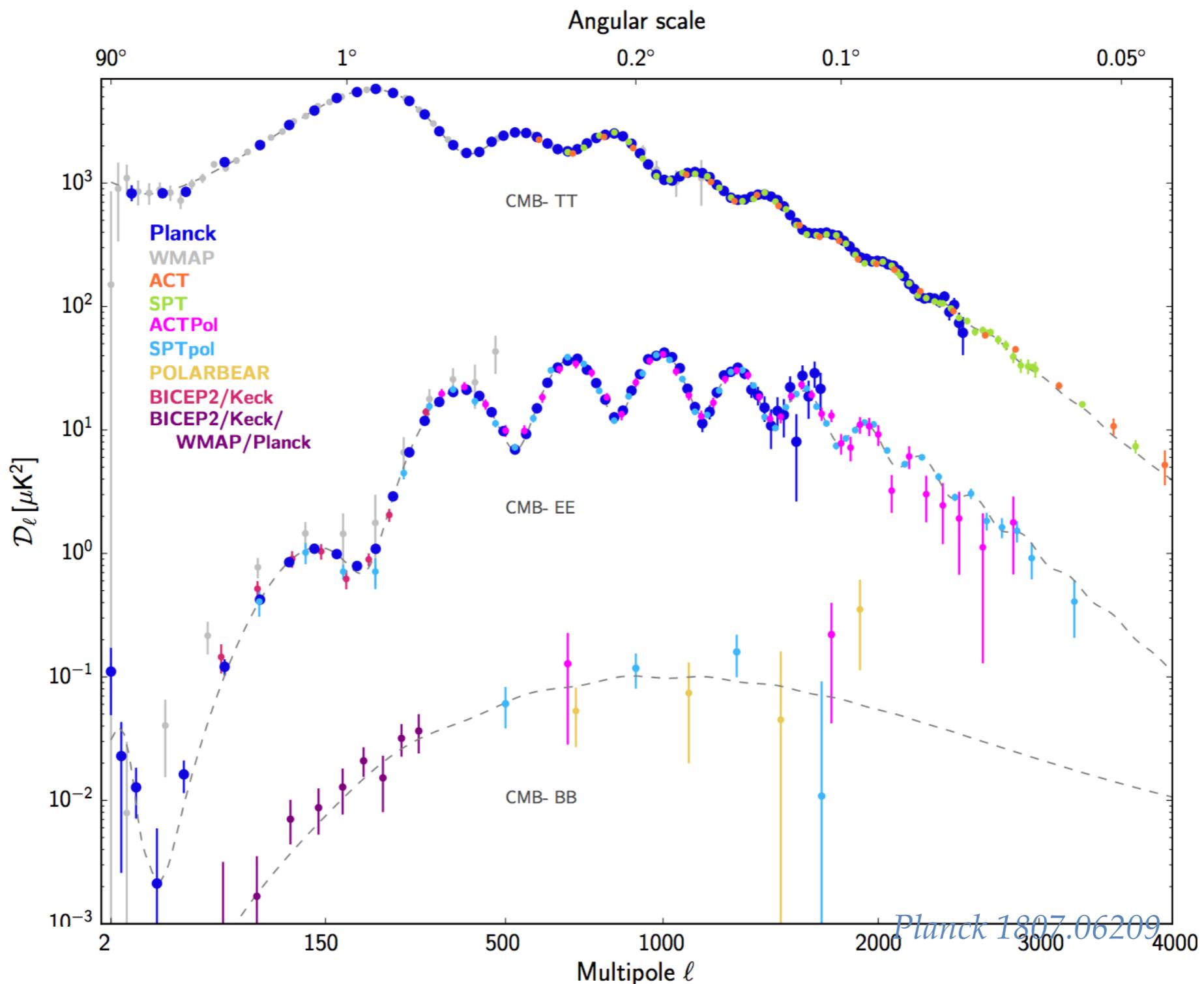
The Era of Precision Cosmology

Today



The Era of Precision Cosmology

Very good agreement between all CMB data!



The Era of Precision Cosmology

Astonishing success of Λ CDM Cosmology

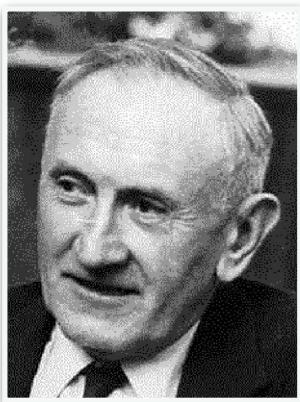
matter content
expansion rate (H_0, Λ)
star formation
Inflation

Parameter	<i>Planck alone</i>	<i>Planck + BAO</i>
$\Omega_b h^2$	0.02237 ± 0.00015	0.02242 ± 0.00014
$\Omega_c h^2$	0.1200 ± 0.0012	0.11933 ± 0.00091
$100\theta_{\text{MC}}$	1.04092 ± 0.00031	1.04101 ± 0.00029
τ	0.0544 ± 0.0073	0.0561 ± 0.0071
$\ln(10^{10} A_s)$	3.044 ± 0.014	3.047 ± 0.014
n_s	0.9649 ± 0.0042	0.9665 ± 0.0038
H_0	67.36 ± 0.54	67.66 ± 0.42

Planck alone
0.6% precision
1% precision
0.3% precision
13% precision
5% precision
0.5% precision
0.7% precision

e.g. 2015 data: TT +lowP reduced $\chi^2 = 1.004$

There are many open questions in Cosmology!



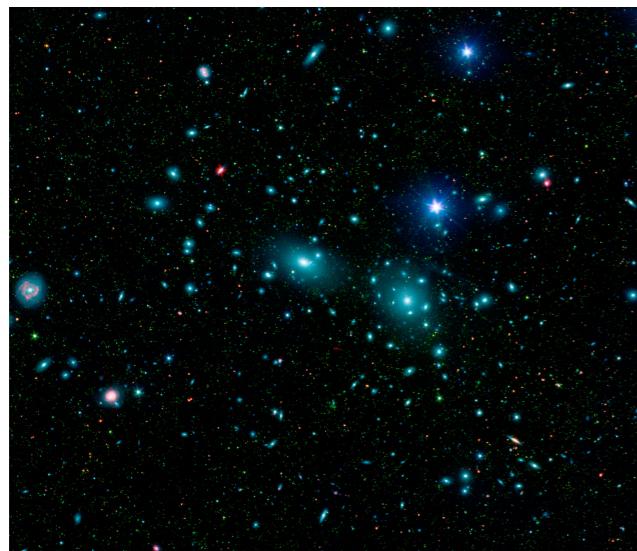
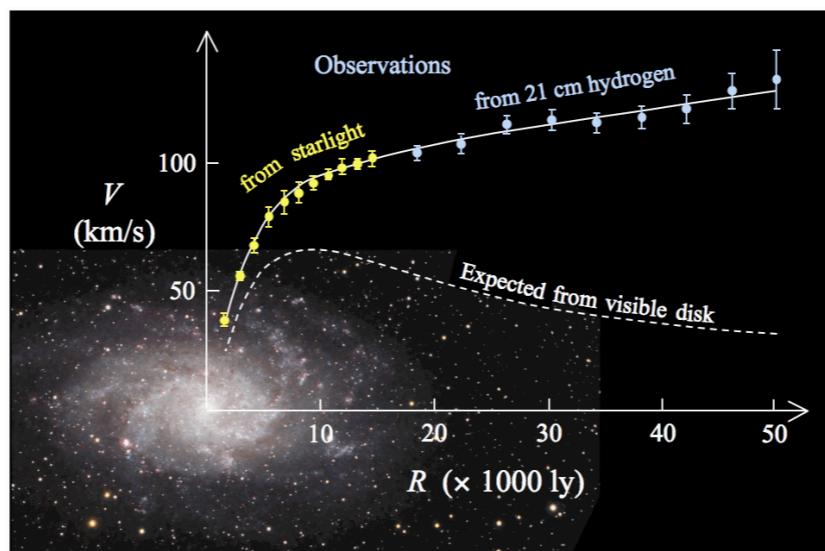
F. Zwicky

The Dark Matter problem

- « Discovered » first in galaxy clusters in the 1930's.
- A wealth of evidence on many scales.



V. Rubin

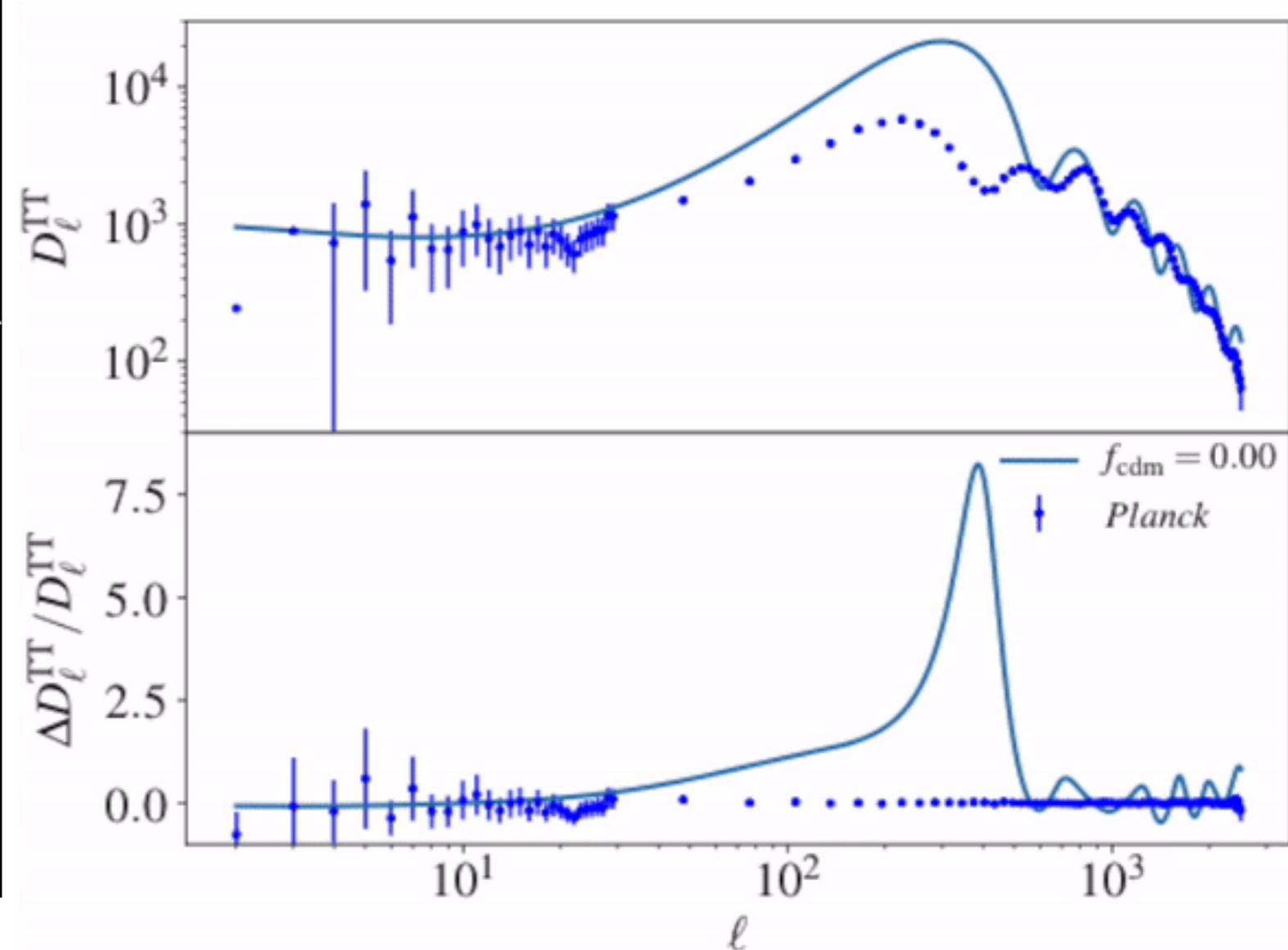
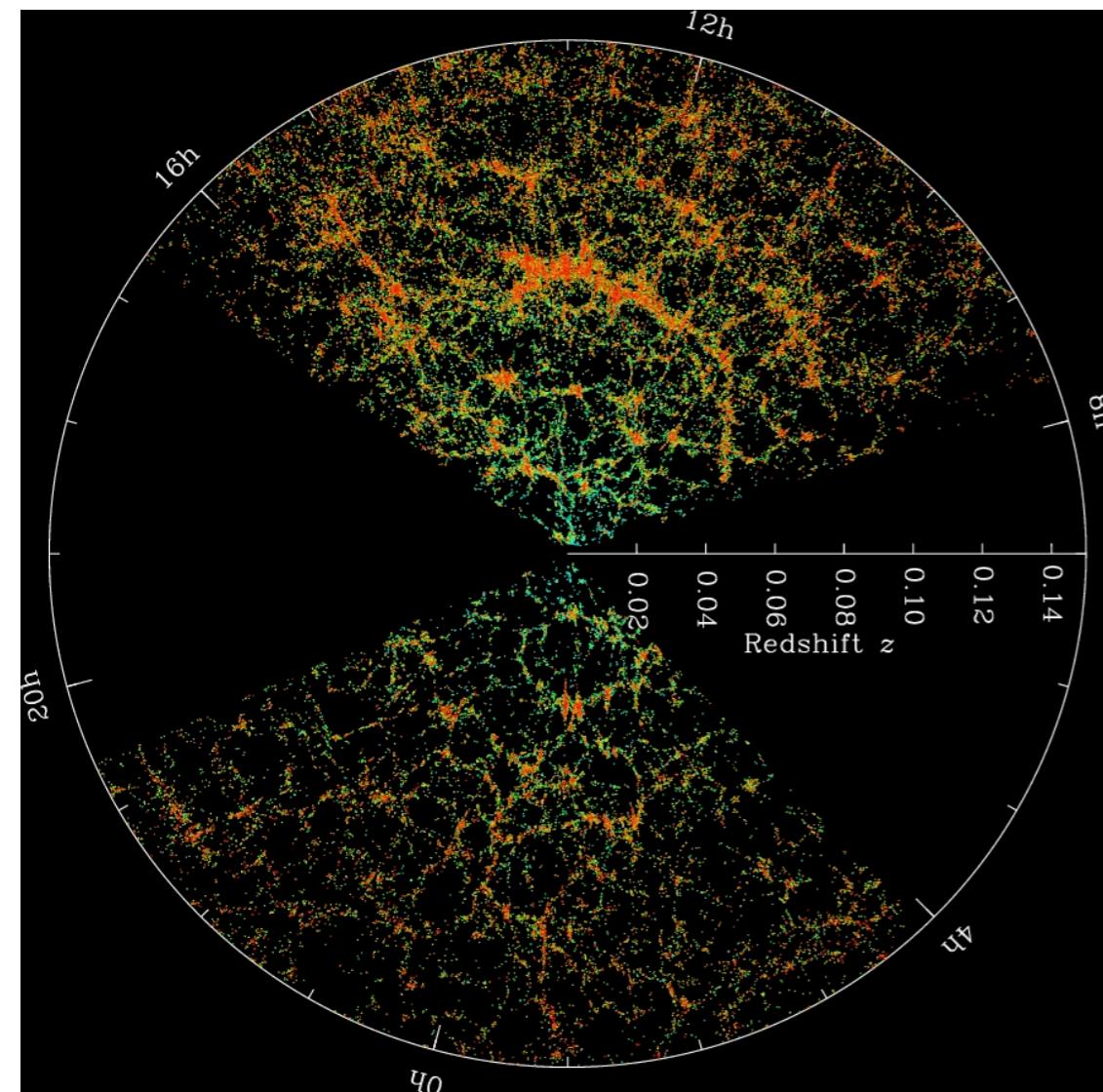
Virial theorem
in the Coma cluster

Galaxy rotation curves

X-ray & Weak lensing in
the Bullet Cluster

Historically discovered at galactic (and galaxy cluster) scales

Non-baryonic origin is mainly required by cosmological observables!



In the baseline Λ CDM:
 Dark Matter is stable, cold, only gravitationally interacting,
 with cosmological density today $\rho_{\text{cdm}} \approx 2.25 * 10^{-30} \text{ g cm}^{-3}$.



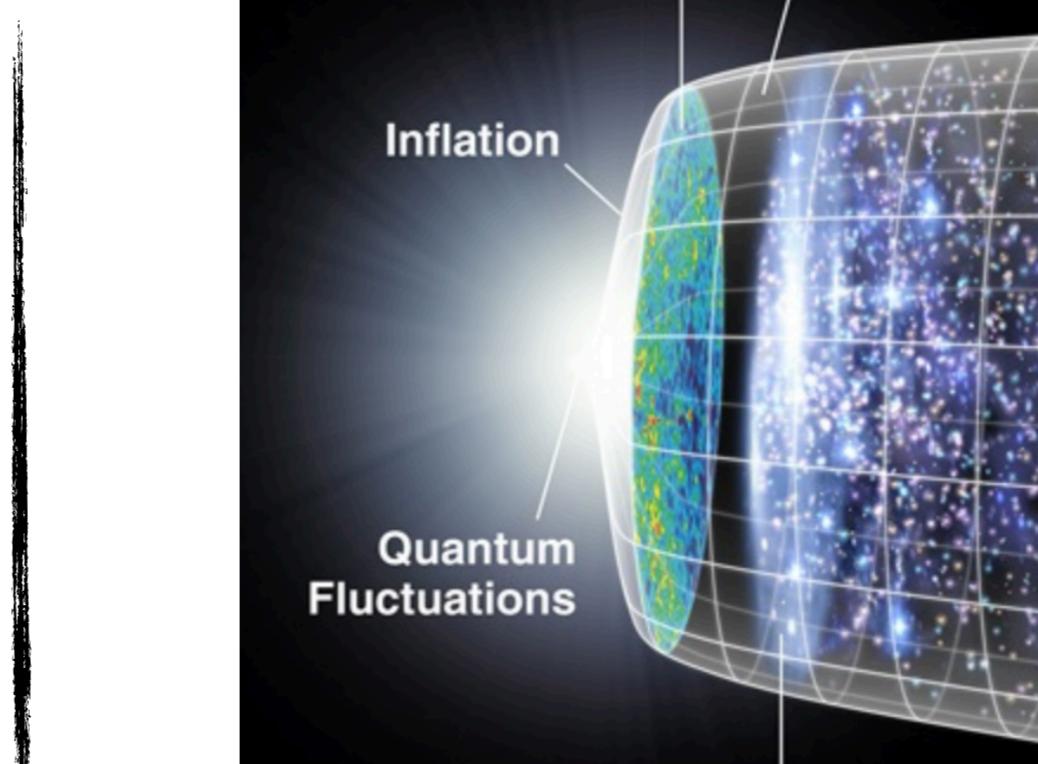
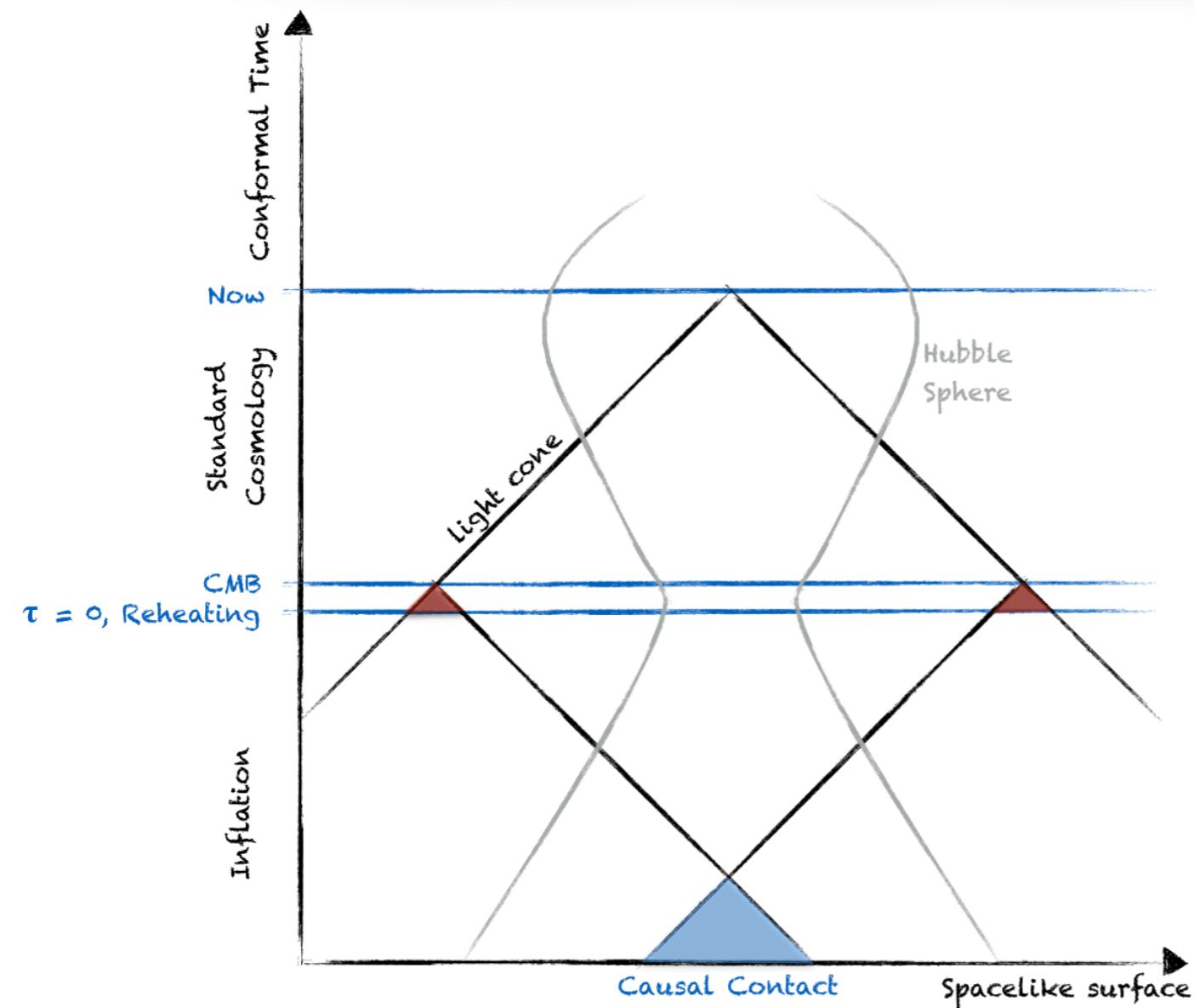
what is the nature of inflation?



A. Guth, P. Steinhardt, A. Linde

A. Starobinsky

- Postulated to solve horizon/flatness problems in 1978.
- Mechanism for origins of perturbations.



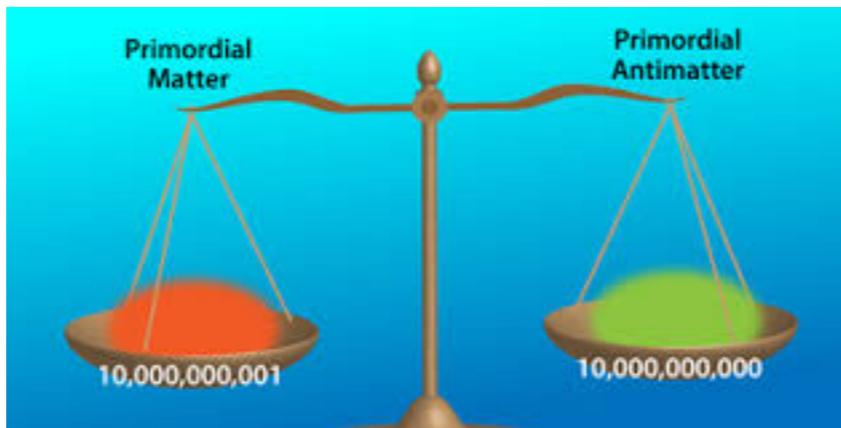
$$\langle 0 | |\delta\phi_k|^2 |0 \rangle \neq 0 \longrightarrow \langle \Theta(\vec{n}_1) \Theta(\vec{n}_2) \rangle \neq 0$$

$$\mathcal{P}_{\mathcal{R}}(k) = \frac{1}{8\pi^2} \frac{1}{\varepsilon} \frac{H}{M_{\text{pl}}^2} \Big|_{k=aH} \quad \mathcal{P}_t(k) = \frac{2}{\pi^2} \frac{H^2}{M_{\text{pl}}^2} \Big|_{k=aH}$$

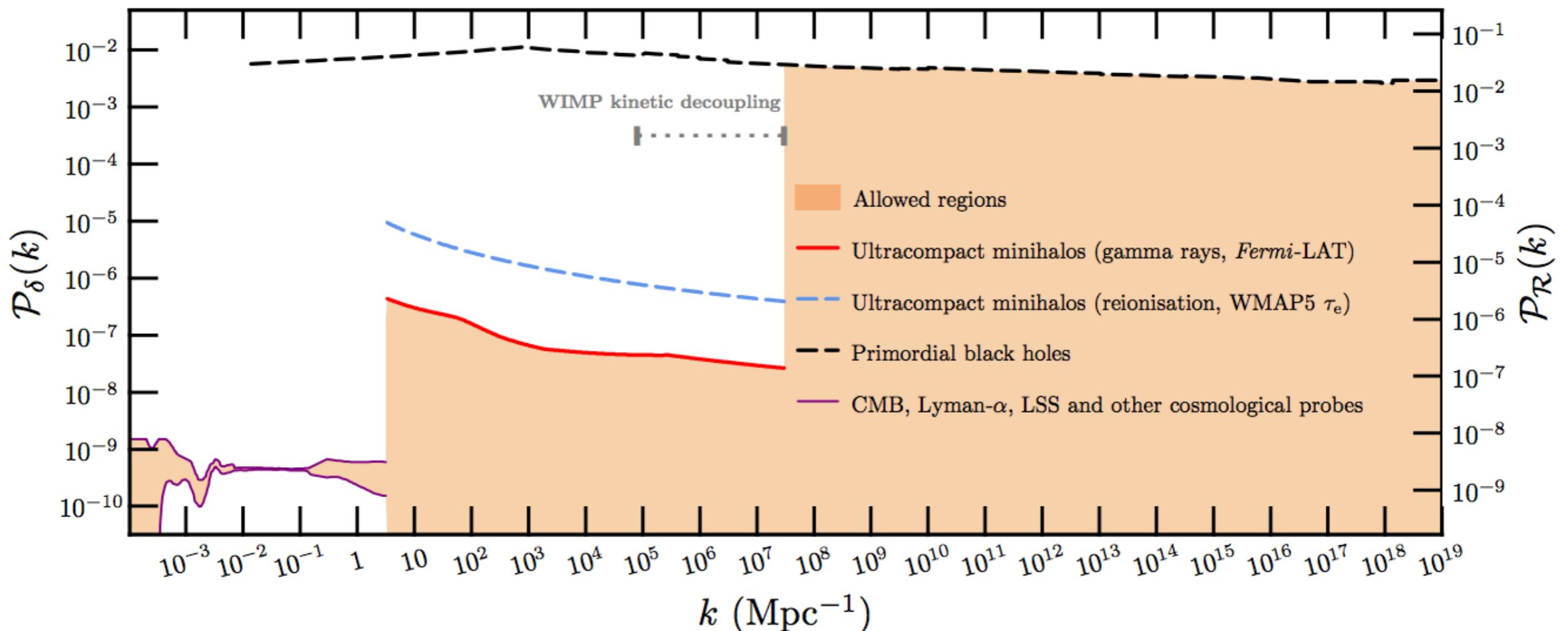
Matter/Antimatter asymmetry



A. Sakharov



- Why is there more matter than antimatter?
- Requires « Sakharov conditions » to be fulfilled.



- Could there be pocket of antimatter at small scales?