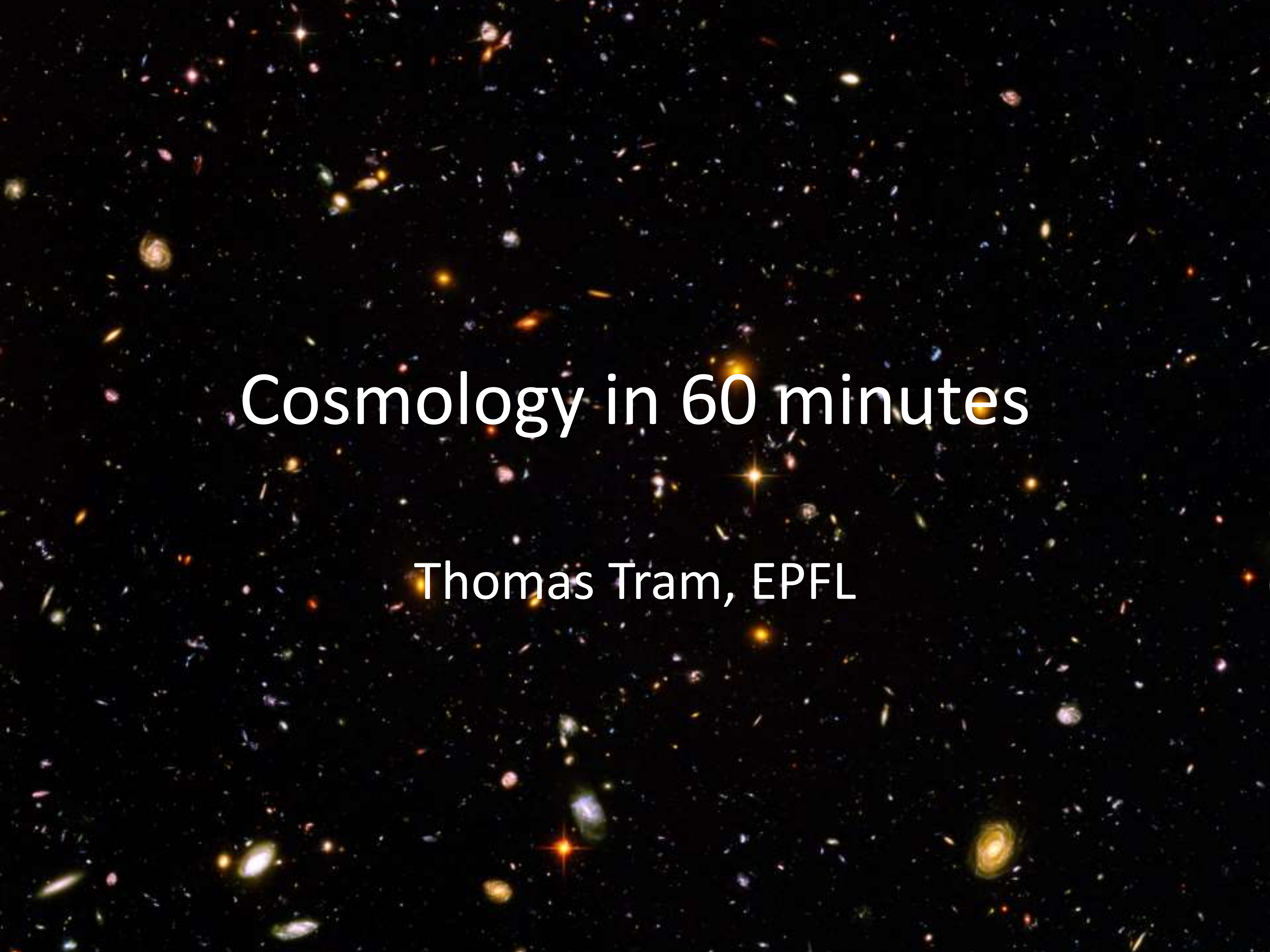
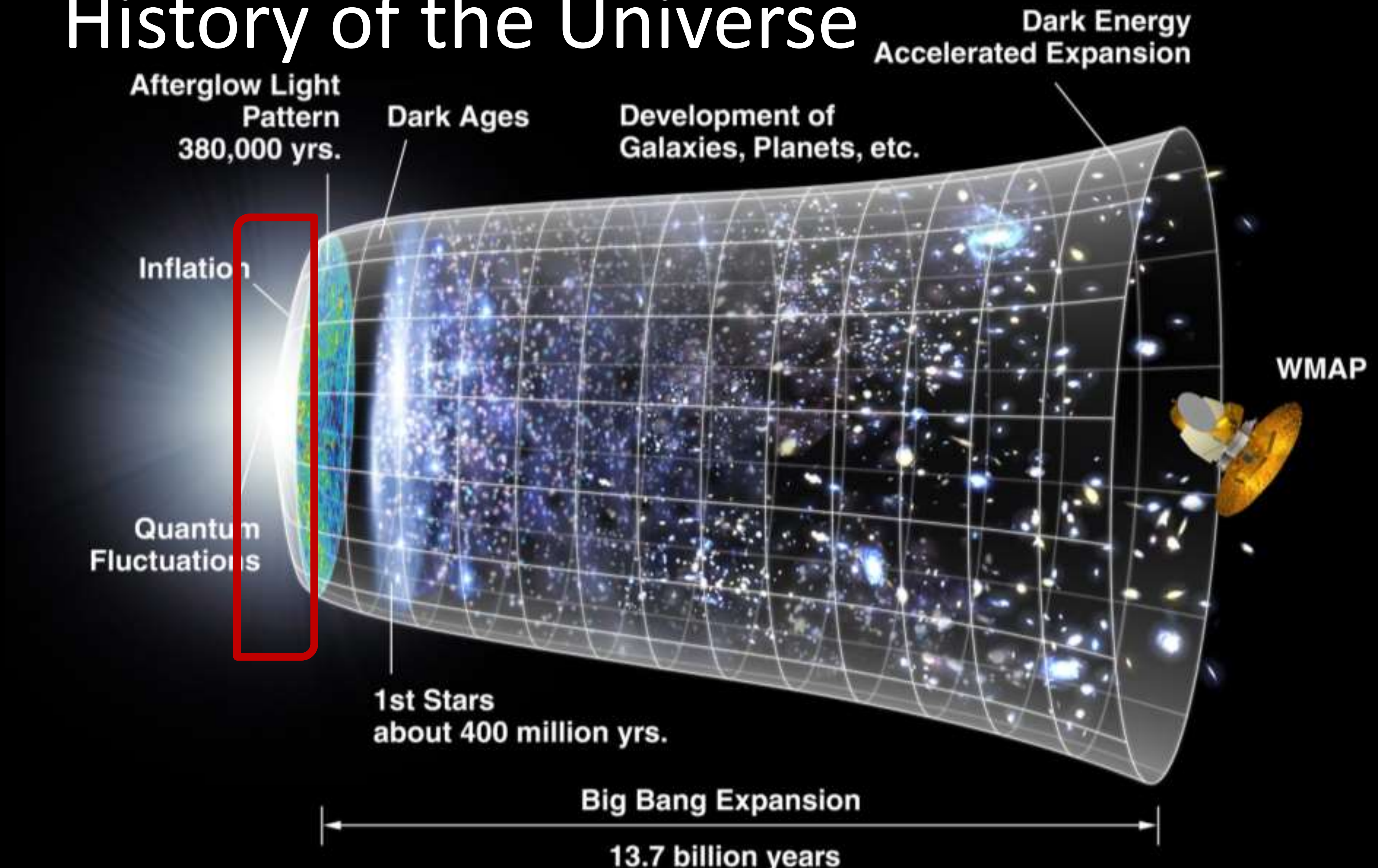


Cosmology in 60 minutes

Thomas Tram, EPFL

History of the Universe

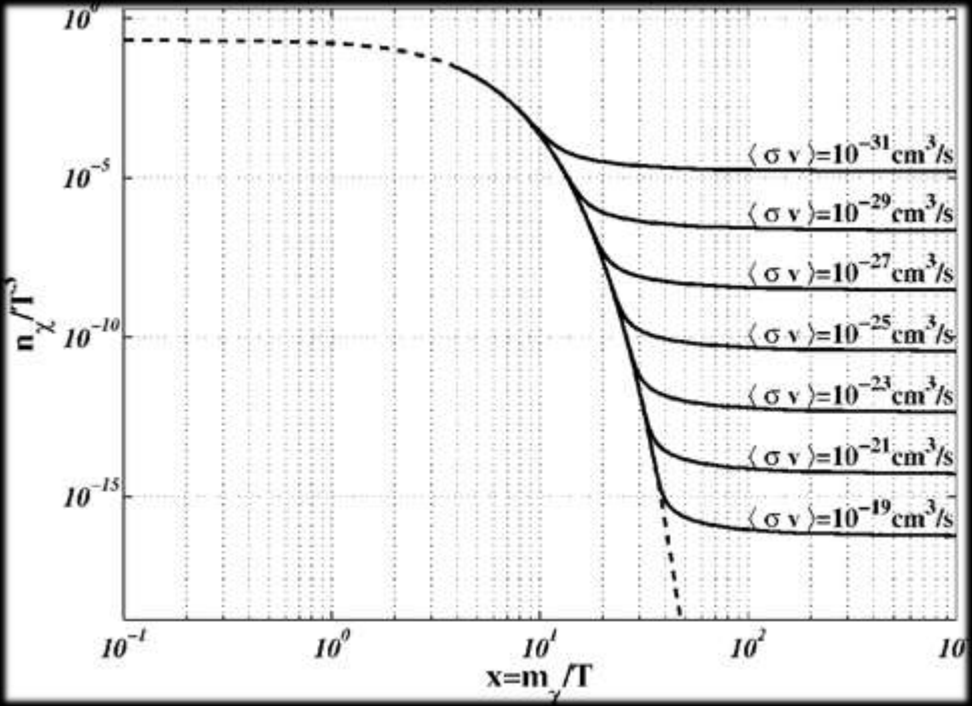


Time	Temp.	Epoch
10^{-39} s?	**10^{16} GeV?**	Inflation
10^{-39} s	**10^{16} GeV**	Grand Unification Scale
10^{-11} s	**100 GeV**	Electroweak Scale
10^{-9} s	**20 GeV**	Freeze-out of 400 GeV WIMP
10^{-5} s	**150 MeV**	QCD Scale (Quarks condense)
0.7 s	**1 MeV**	Neutrinos decouple
3 s	**0.5 MeV**	Positrons annihilate
80 s	**0.1 MeV**	Big Bang Nucleosynthesis
380000 years	**0.25 eV 3000K**	CMB: The Universe becomes transparent

The origin of species I

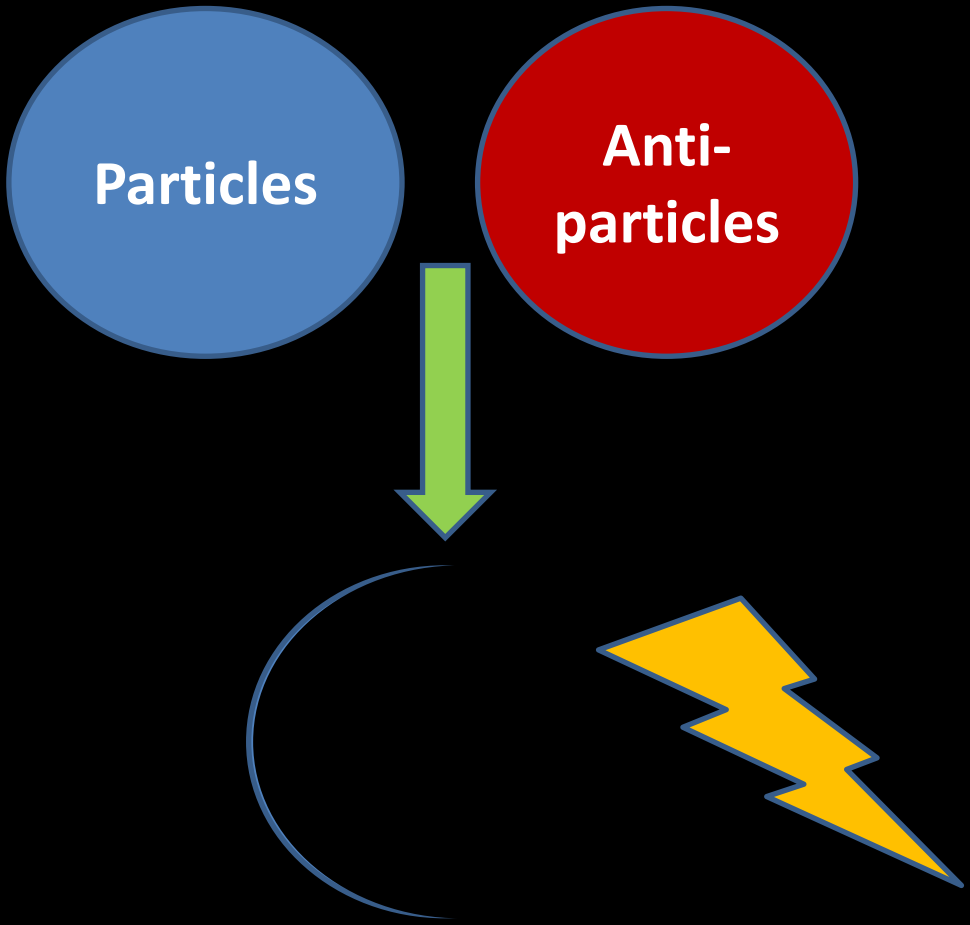
- Thermal production
  - Standard mechanism for WIMP dark matter
  - Weaker interaction -> more abundant today

$$\frac{dY}{dt} = T_\gamma^3 \langle \sigma v \rangle \left\{ Y_{\mathrm{Eq}}^2 - Y^2 \right\}$$



The origin of species II

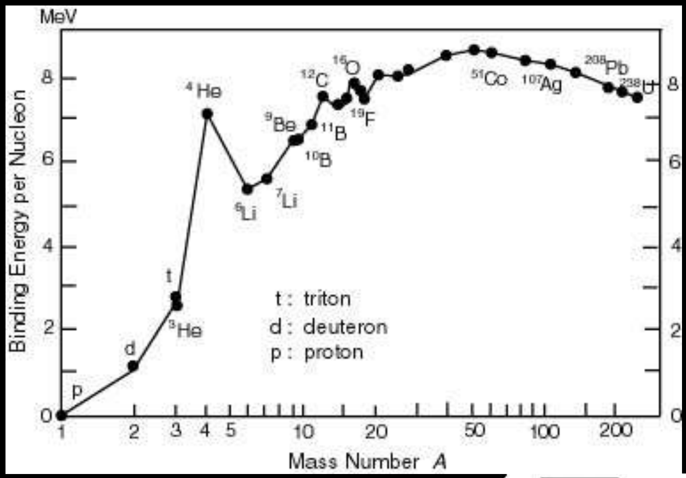
- Asymmetric production
  - Baryons and electrons
  - Asymmetric DM
- Sakharov conditions:
  - Baryon number violation
  - C and CP symmetry violation
  - Interactions out of thermal equilibrium

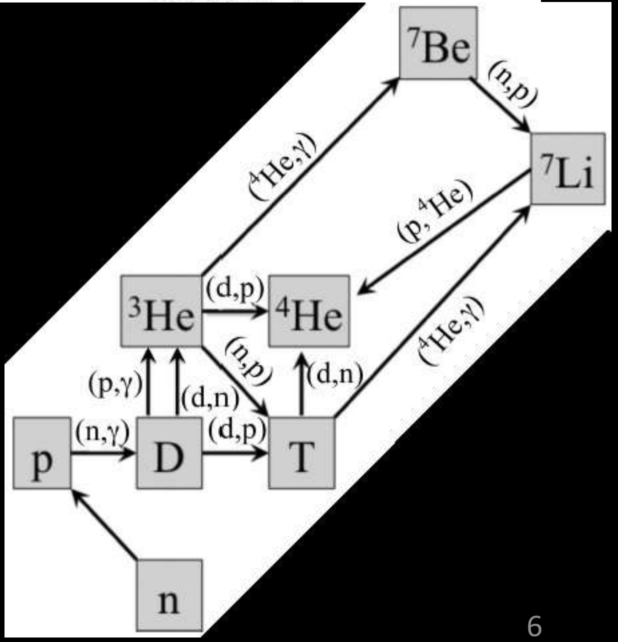


Big Bang Nucleosynthesis

- Plasma at $T \simeq 1\text{MeV}$:
  - Rel. particles in equilibrium: $\gamma, e^{\pm}$
  - Decoupled rel. particles: ν_e, ν_μ, ν_τ
  - Non-rel. particles: baryons (p, n)
  - $p + e^{-} \leftrightarrow n + \nu_e$

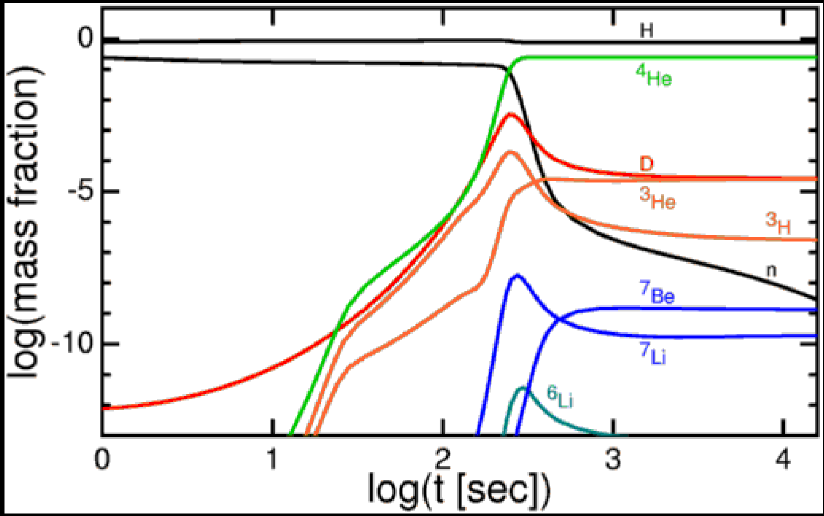
The first observables!

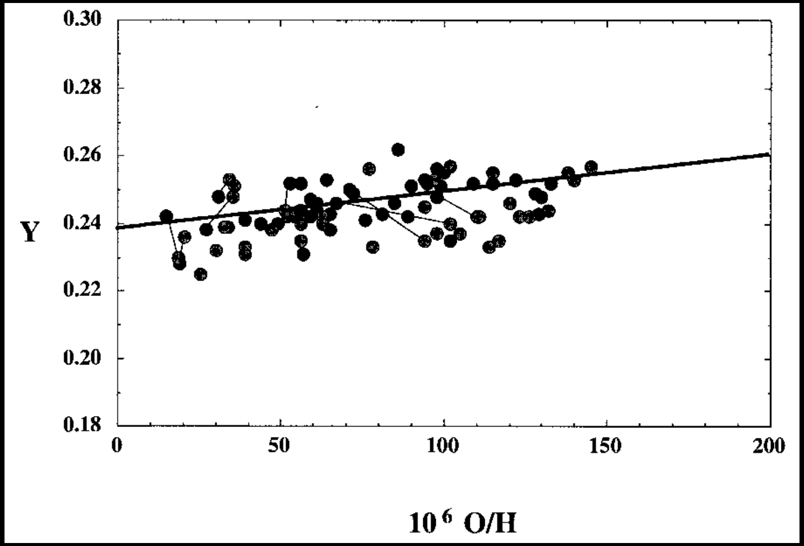




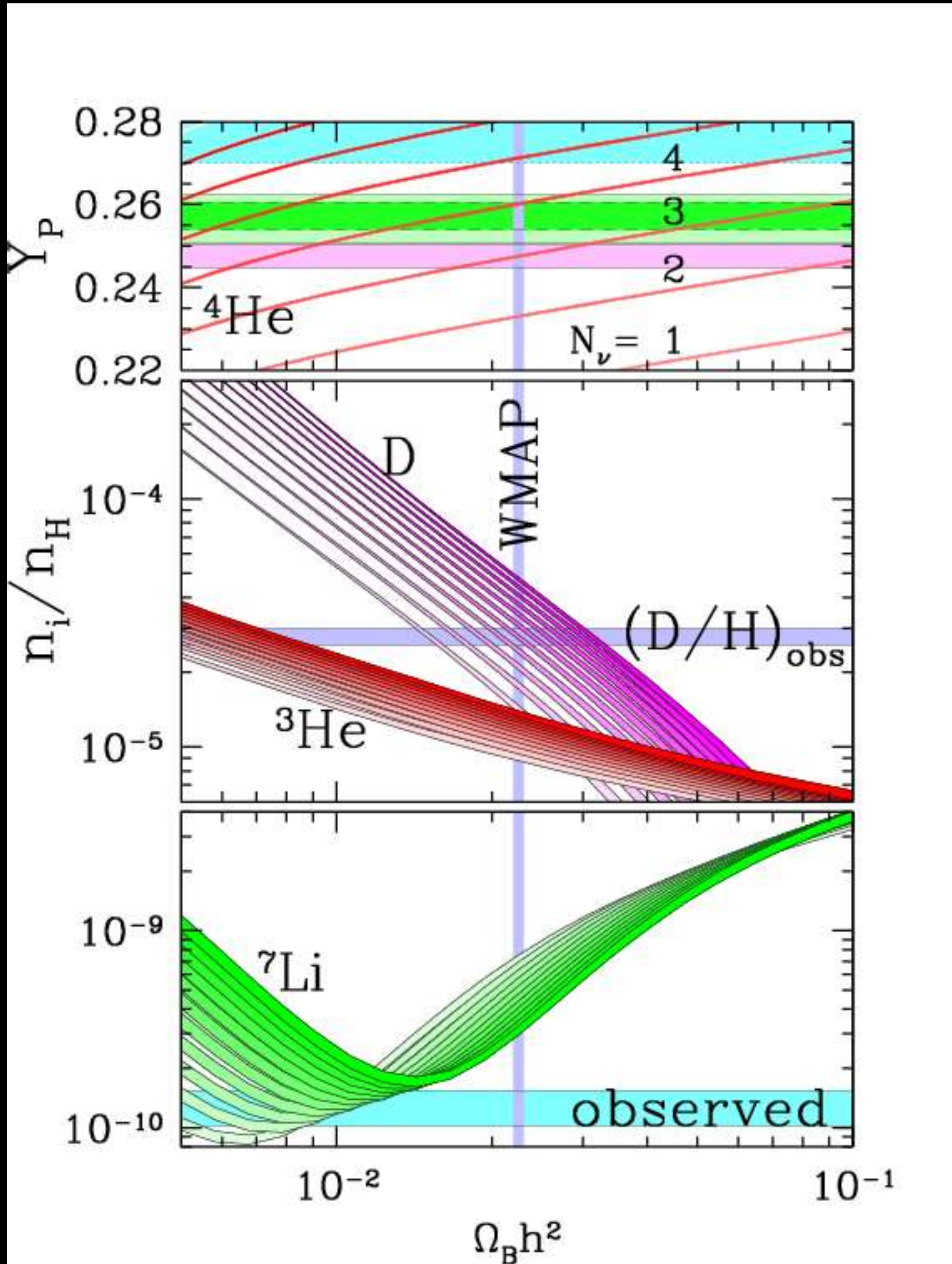
Primordial abundances

- We can compute the primordial abundances…
- and we can (almost!) measure/observe them!





Cosmology with BBN:

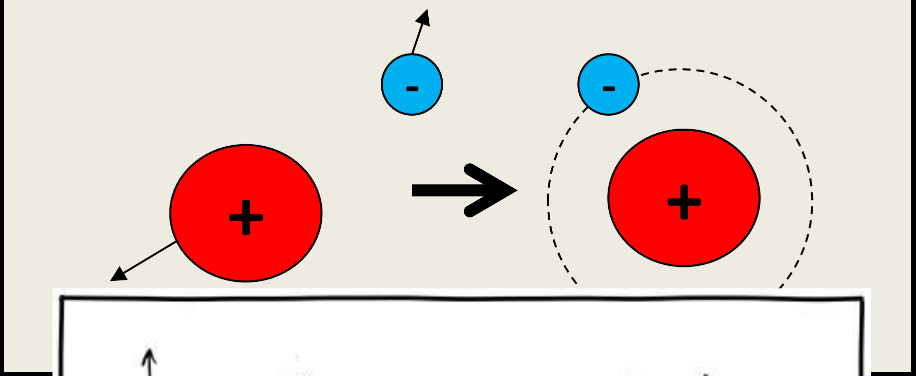


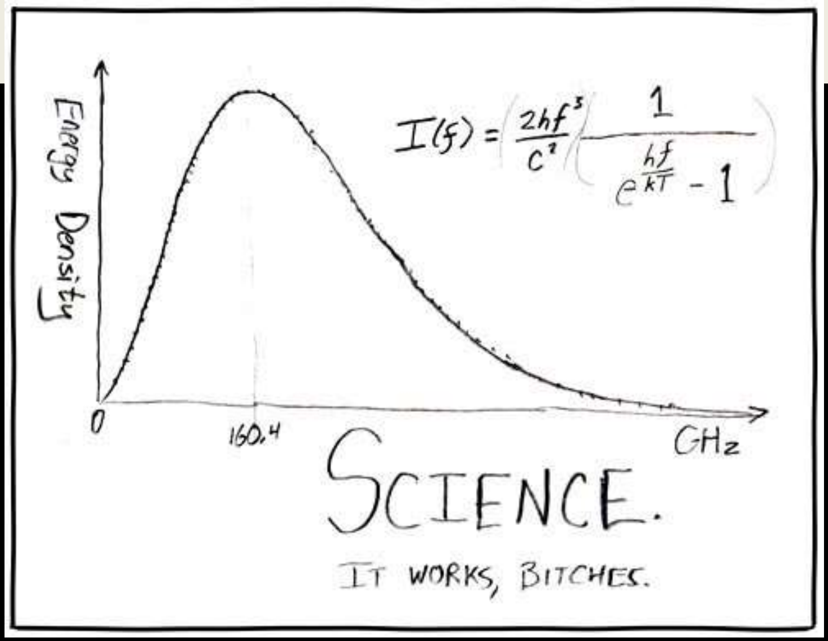
- Extra relativistic species?
  N_ν
- What is the fraction of baryons?
  $\Omega_b h^2$
- Where is the lithium?

The Cosmic Microwave Background

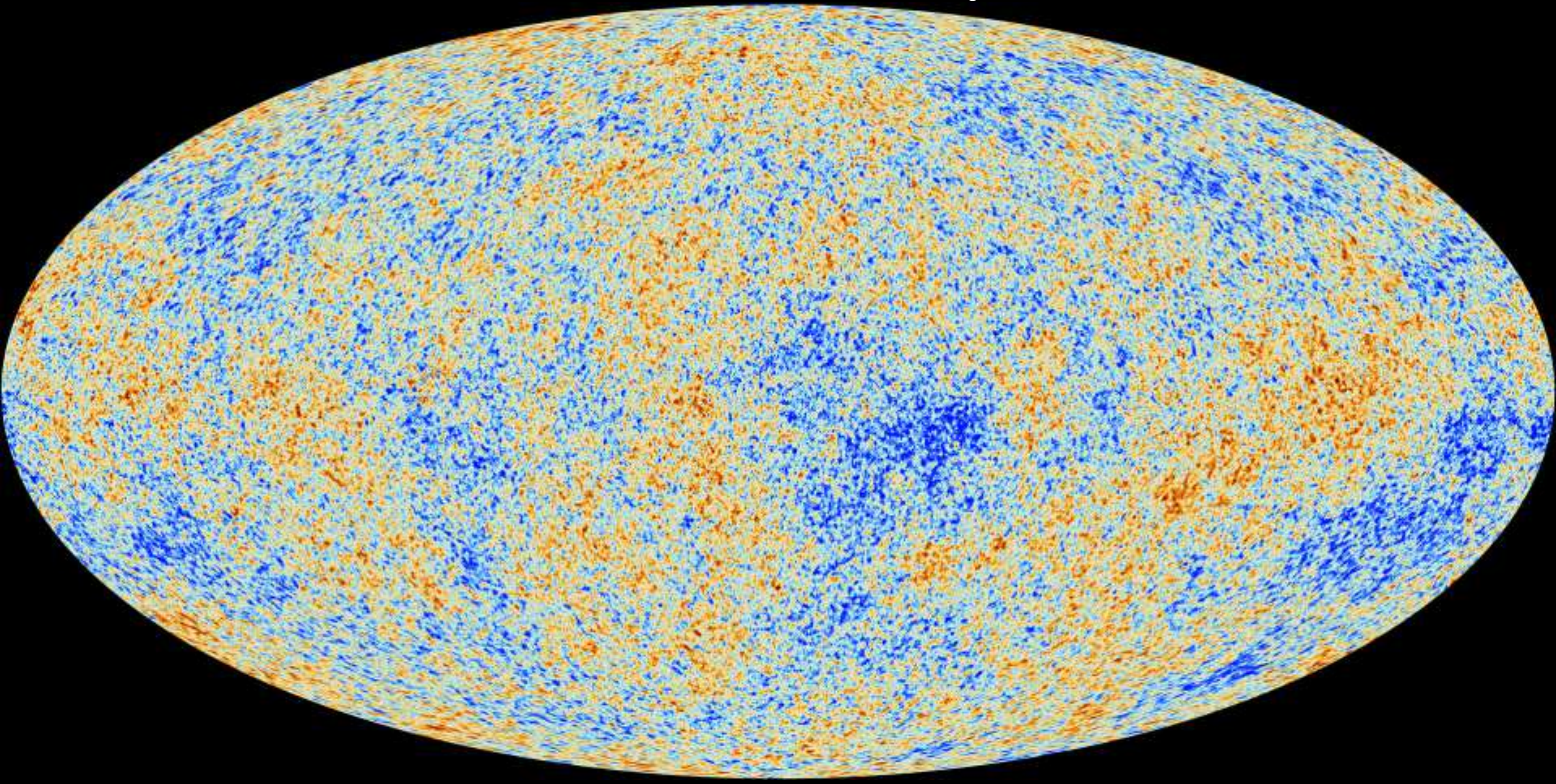
- (Re-)combination
  - 380,000 years after Big Bang
  - $T \simeq 0.25\text{eV}$
  - The Universe becomes transparent to photons
- Blackbody radiation
  - $T_{\gamma 0} = 2.725\text{K}$
  - Uniform at the level 10^{-5}

$$p^+ + e^- \rightarrow H$$

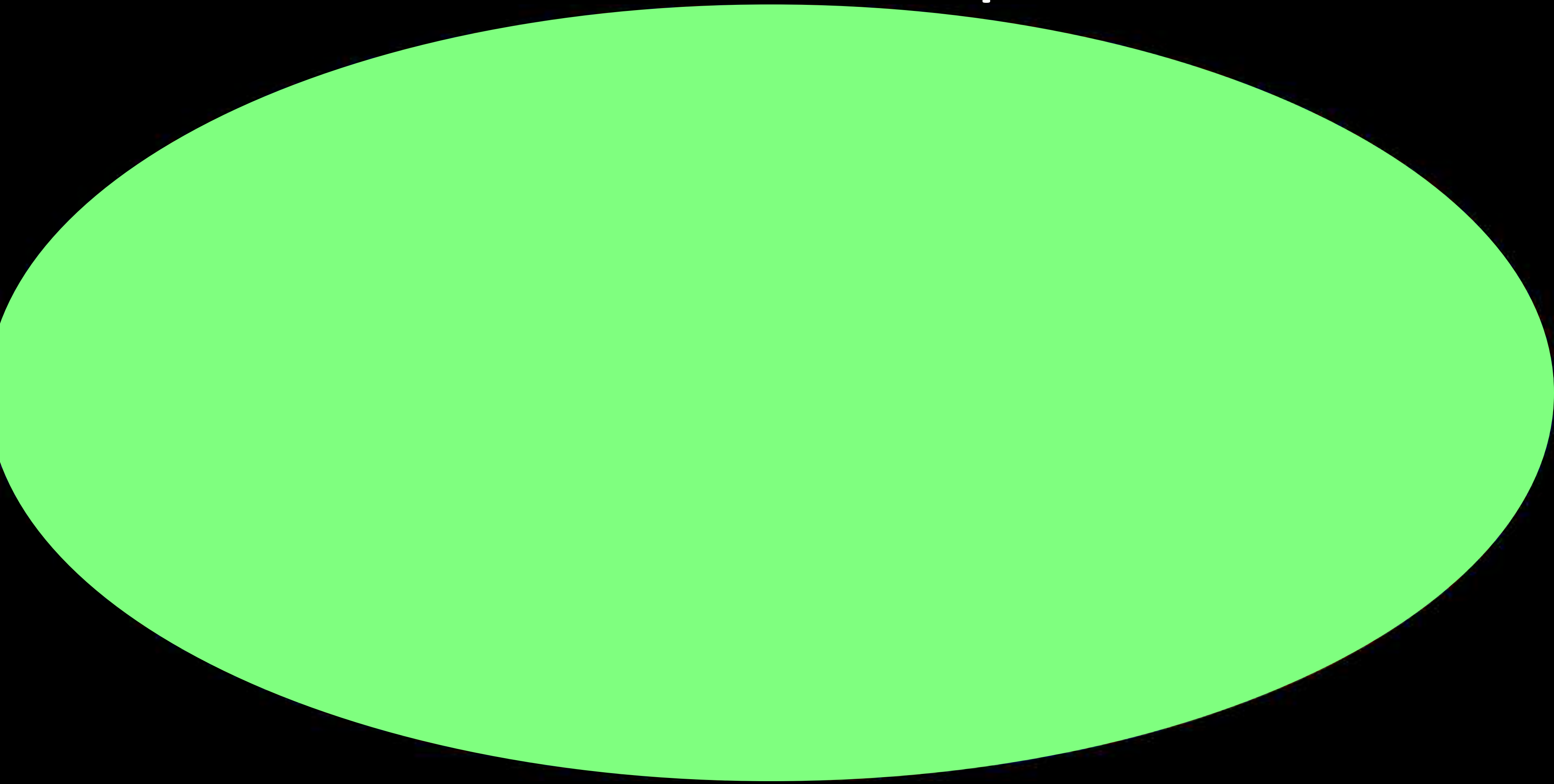




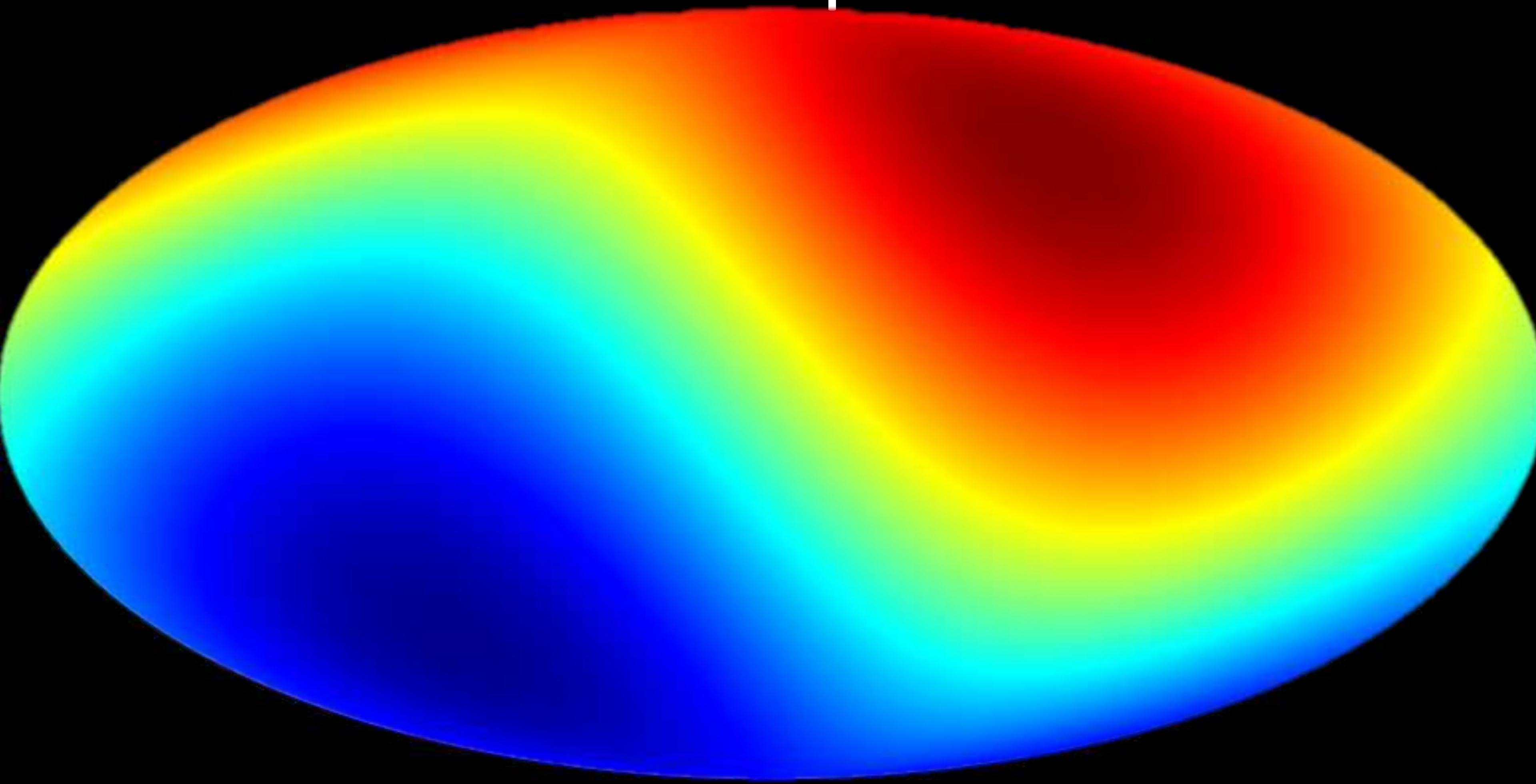
CMB anisotropies



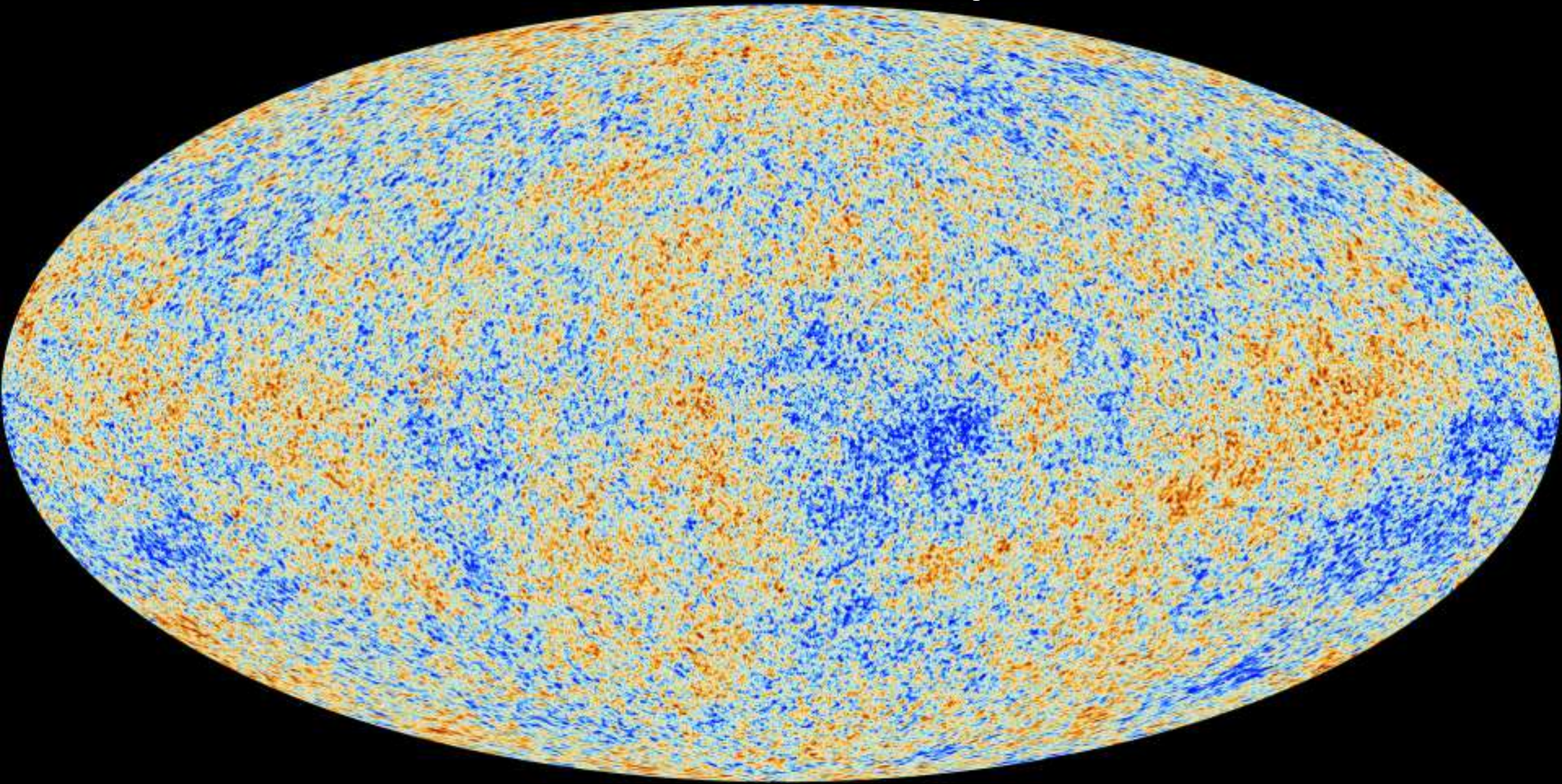
CMB is isotropic



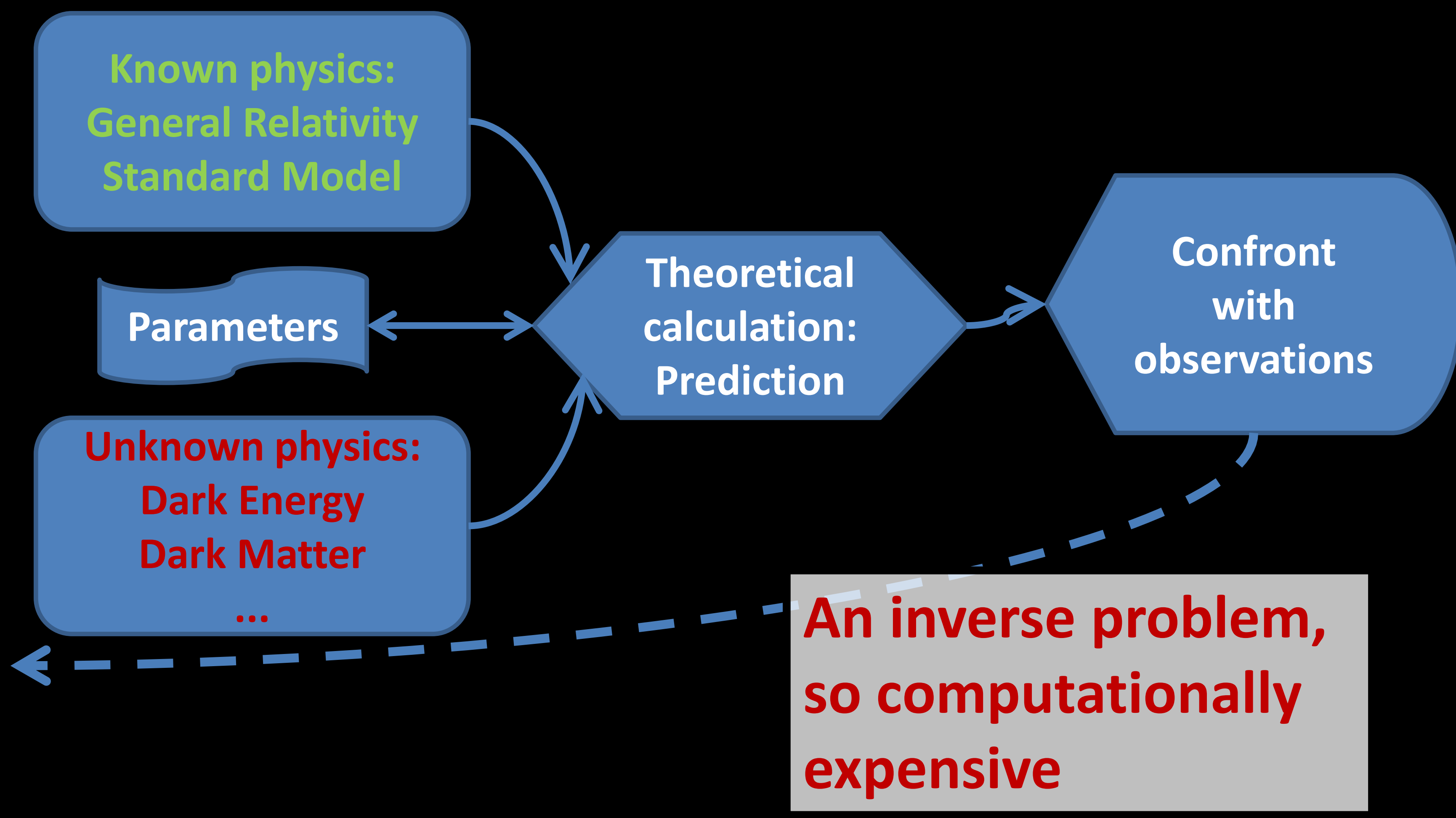
CMB dipole



CMB anisotropies

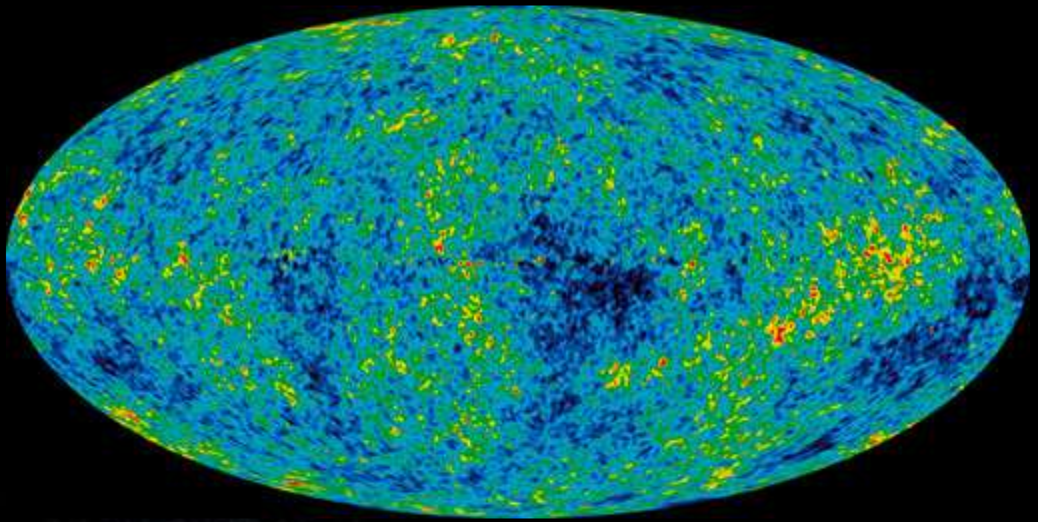


What is cosmology?

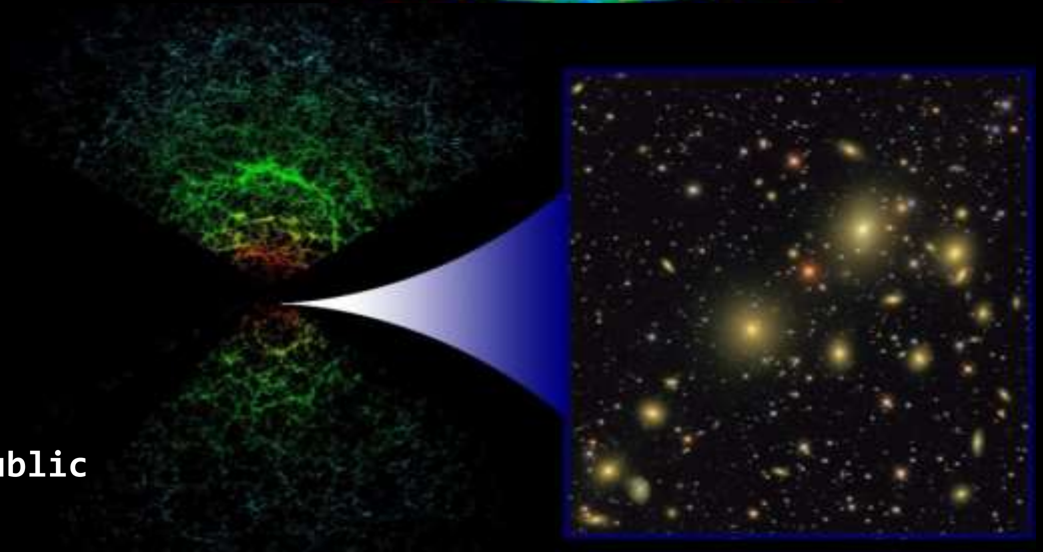


Two sets of data

- Cosmic Microwave Background (CMB)
- Large Scale Structure (LSS)

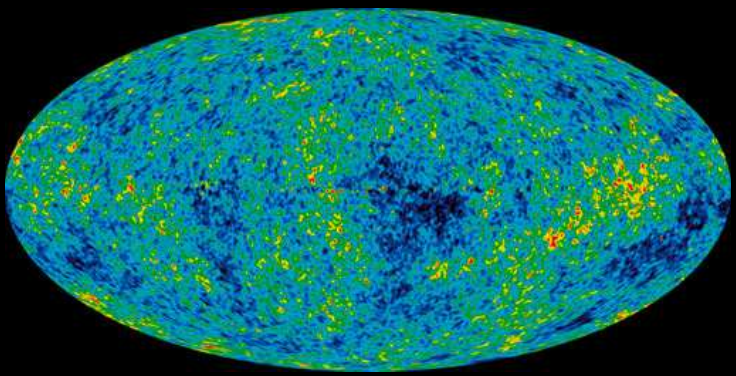


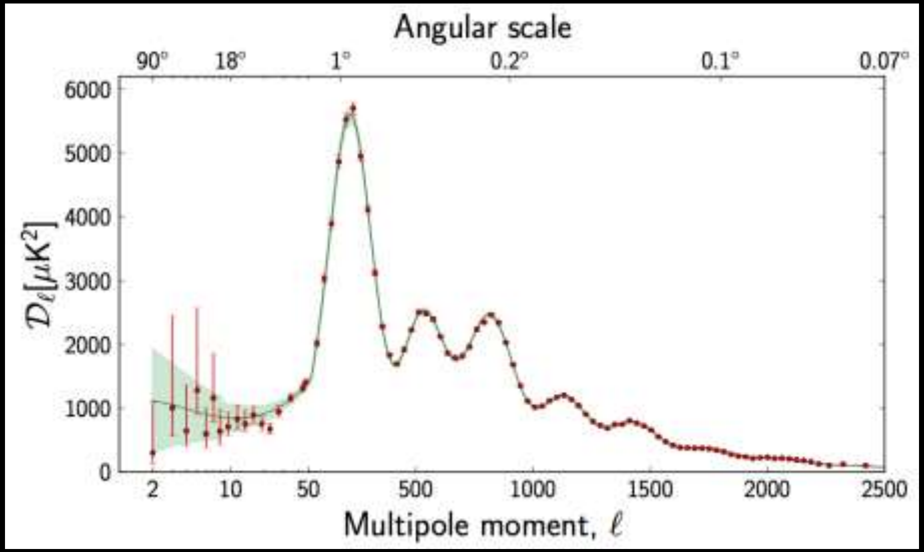
Solve the Boltzmann equations for perturbations.



`CLASS, available at:`
`https://github.com/lesgourg/class_public`

The Standard Model





- 6 base parameters:
  - Hubble rate today, H_0
  - Baryon density today
  - CDM density today
  - Redshift of reionisation
  - Amplitude and tilt of primordial perturbations

Dynamics of the Universe

- General relativity:

$$G_{\mu\nu}\left(g_{\mu\nu}\right) + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}$$

- Homogeneity and isotropy:

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu = -dt^2 + a(t)^2 \left(dx^i dx^i\right)$$

- Friedmann equations:

$$H^2 = \frac{8\pi G}{3}\rho(t), \qquad \dot{\rho} = -3H(\rho + p),$$

$$H \equiv \frac{\dot{a}}{a}.$$

Evolution of matter

- The conservation equation:

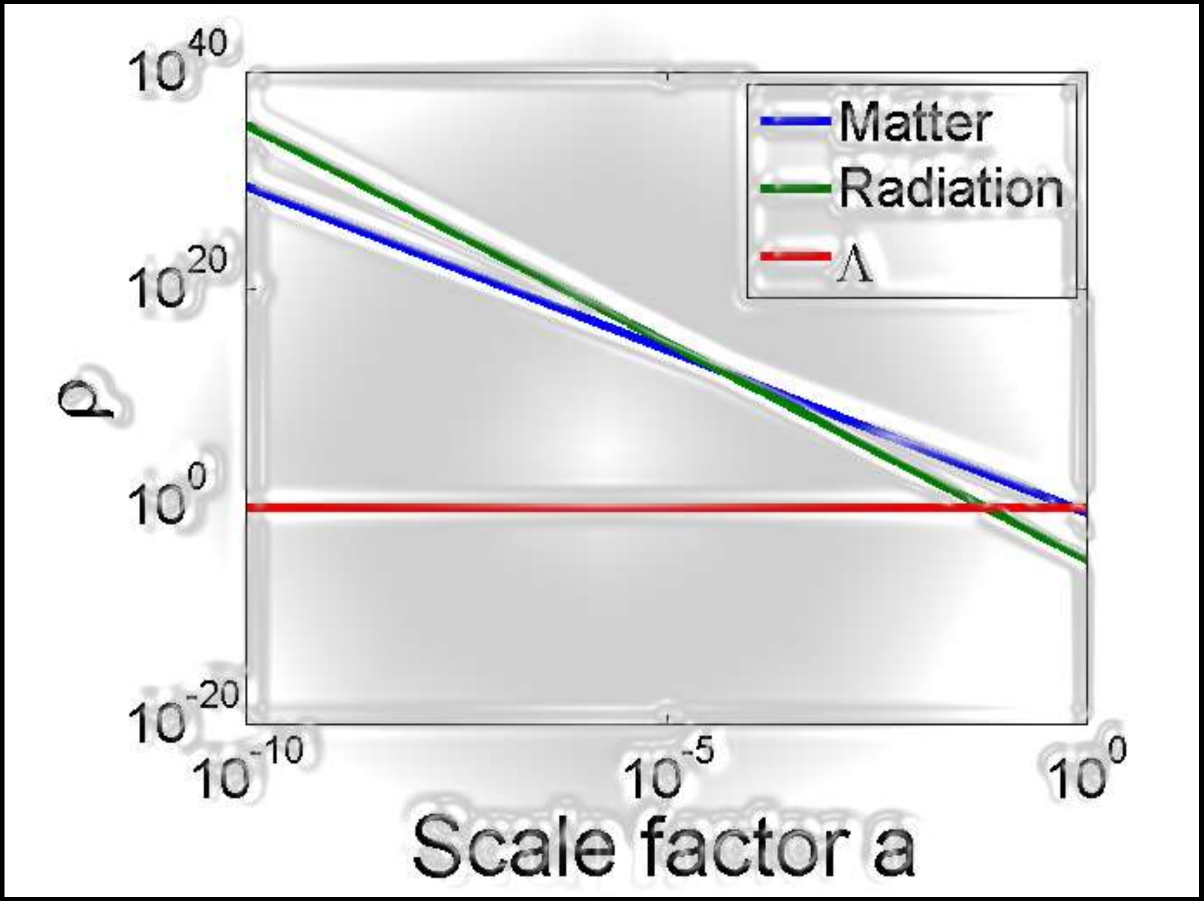
$$\dot{\rho} = \frac{d\rho}{da}\frac{da}{dt} = -3\frac{\dot{a}}{a}\rho(1+w),$$

$$\frac{d\rho}{da} = -3\frac{1}{a}\rho(1+w),$$

$$\rho = \rho_0 a^{-3(1+w)}.$$

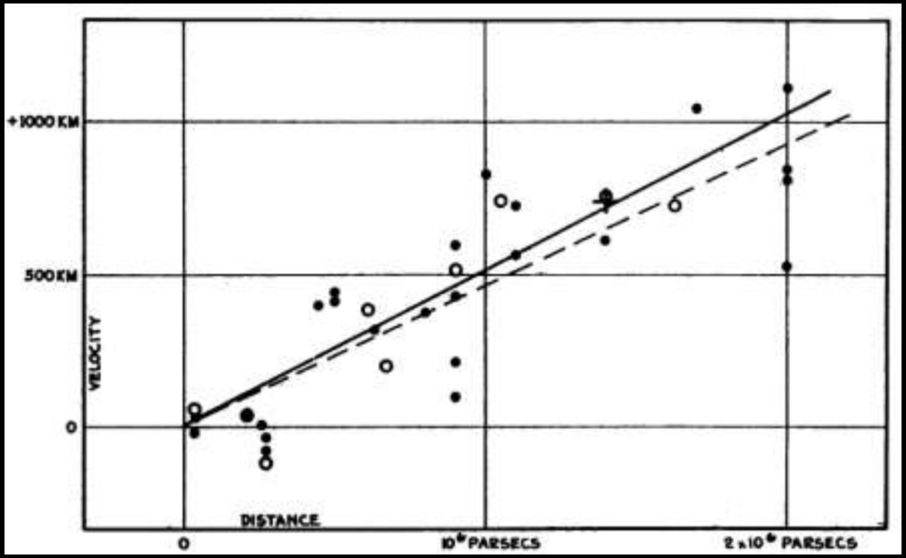
- Valid for non-interacting matter with constant equation of state w.

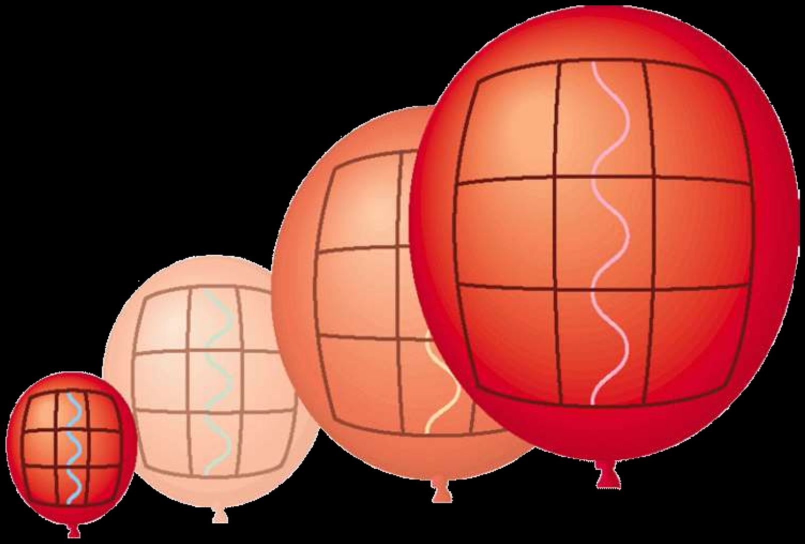
Epochs of domination



Hubble's law

- In 1929 Hubble famously observed spectral lines as a function of distance
- Wrong interpretation: expansion not velocity

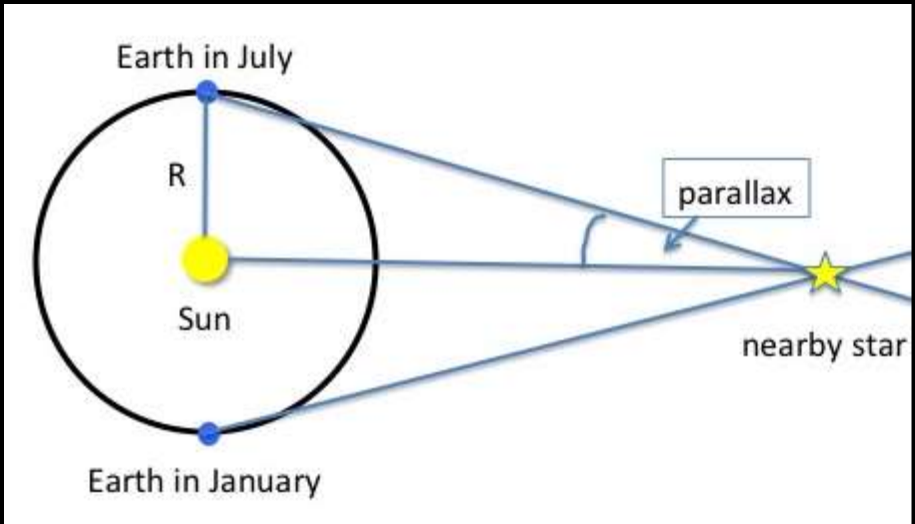




How to measure distances?

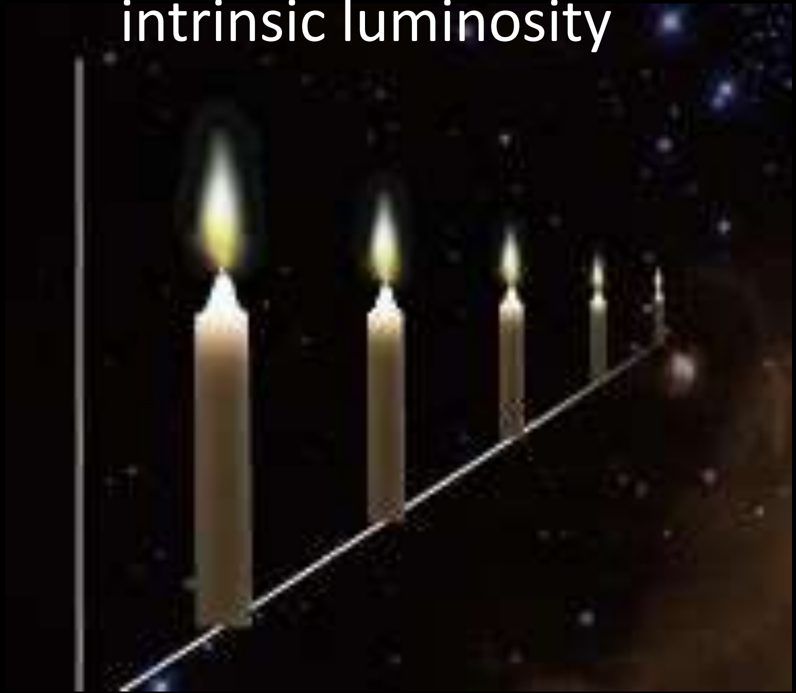
Parallax

- Measure the angle to an object now and in 6 months:



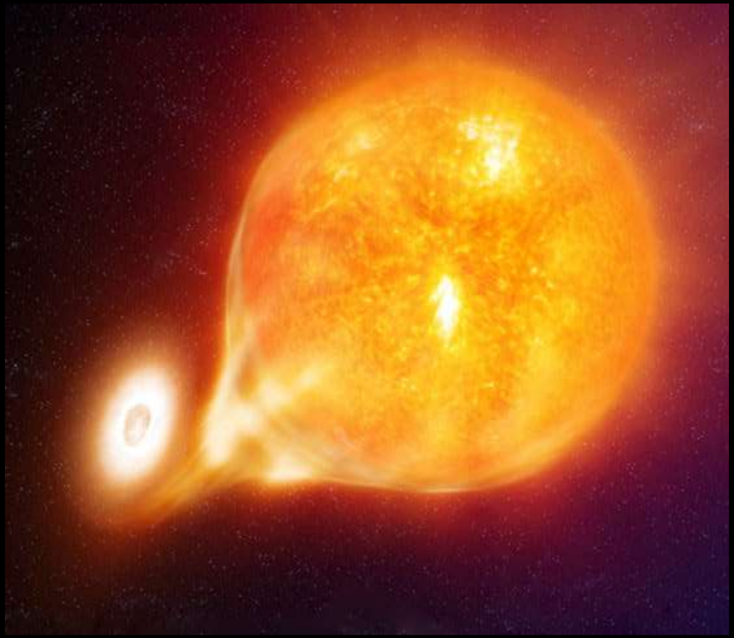
Standard candles

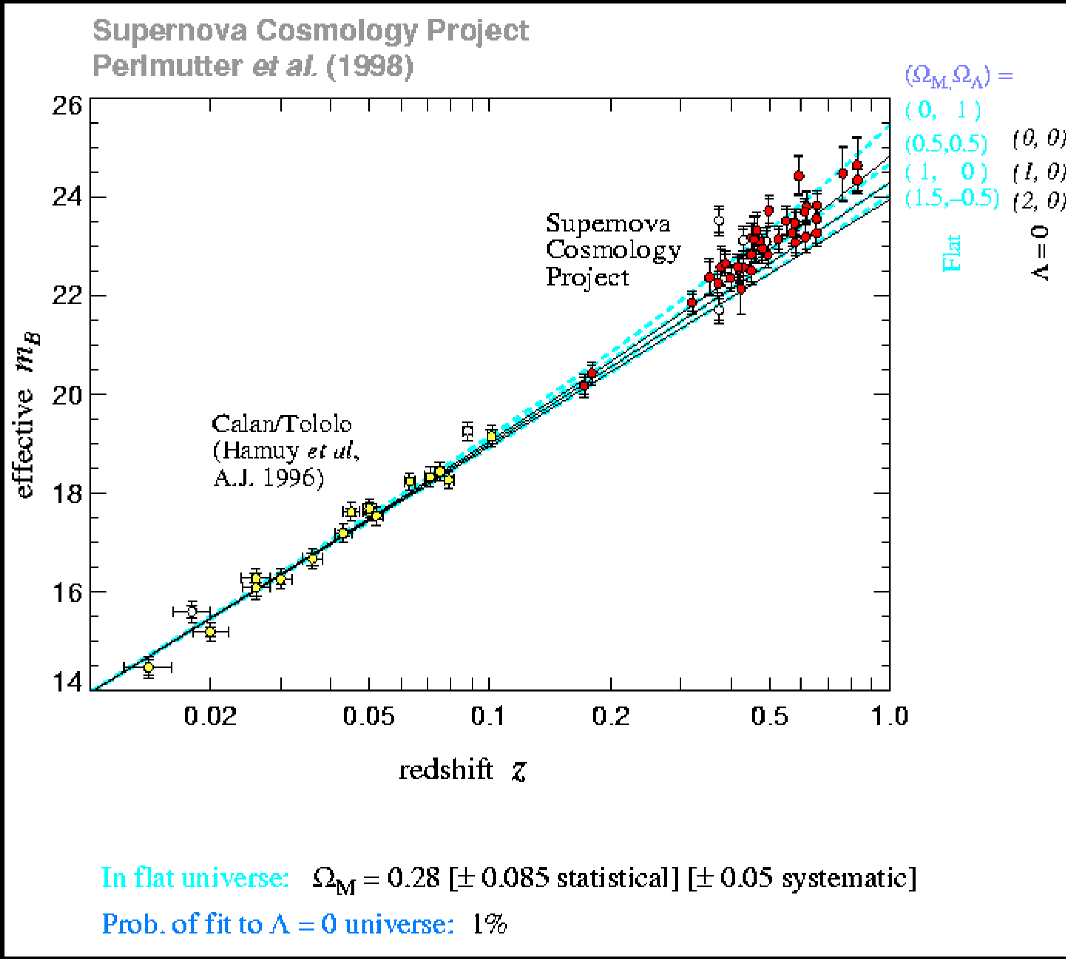
- Measure the luminosity of an object with known intrinsic luminosity



The accelerating Universe

- In 1998: Hubble diagram with type 1A supernovae





The accelerating Universe

The two Friedmann equations

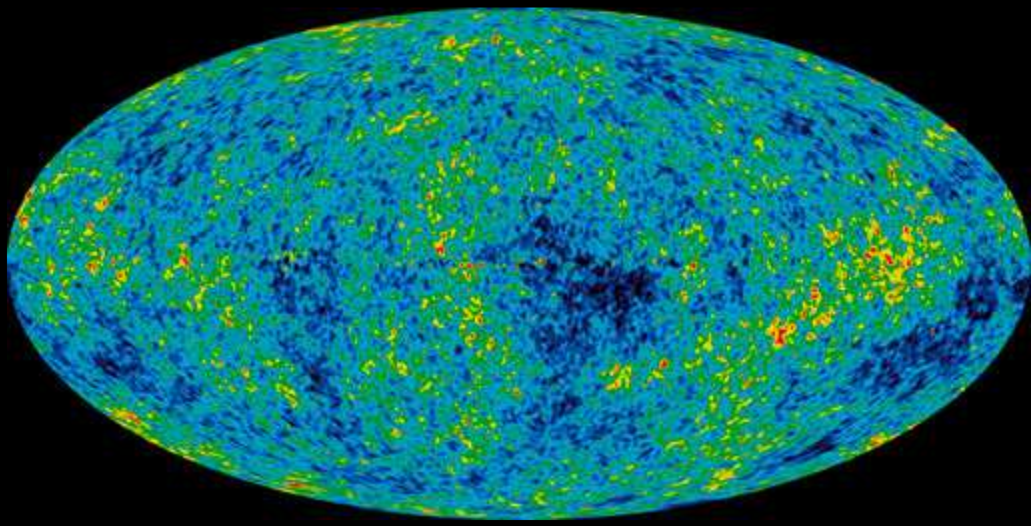
$$H^2 = \frac{8\pi G}{3}\rho(t), \qquad \dot{\rho} = -3H(\rho + p),$$

can be combined to

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho(1 + 3w).$$

So the expansion is accelerating if $w < -\frac{1}{3}$

Inflation



1. Horizon problem
2. Magnetic monopole problem
3. Flatness problem

$$H^2 = \frac{8\pi G}{3}\rho(t) - \frac{K}{a^2}, \qquad \rho = \rho_0 a^{-3(1+w)}$$

Bonus: Naturally predicts the *almost* scale invariant spectrum of initial perturbations.

Final words

- The Universe is a particle physics lab!
- Many different topics, lots of data!