Astro-Cosmo-Particles

lecture in IEEE NPSS PEISS, Prague 2025

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Standard model of elementary particles

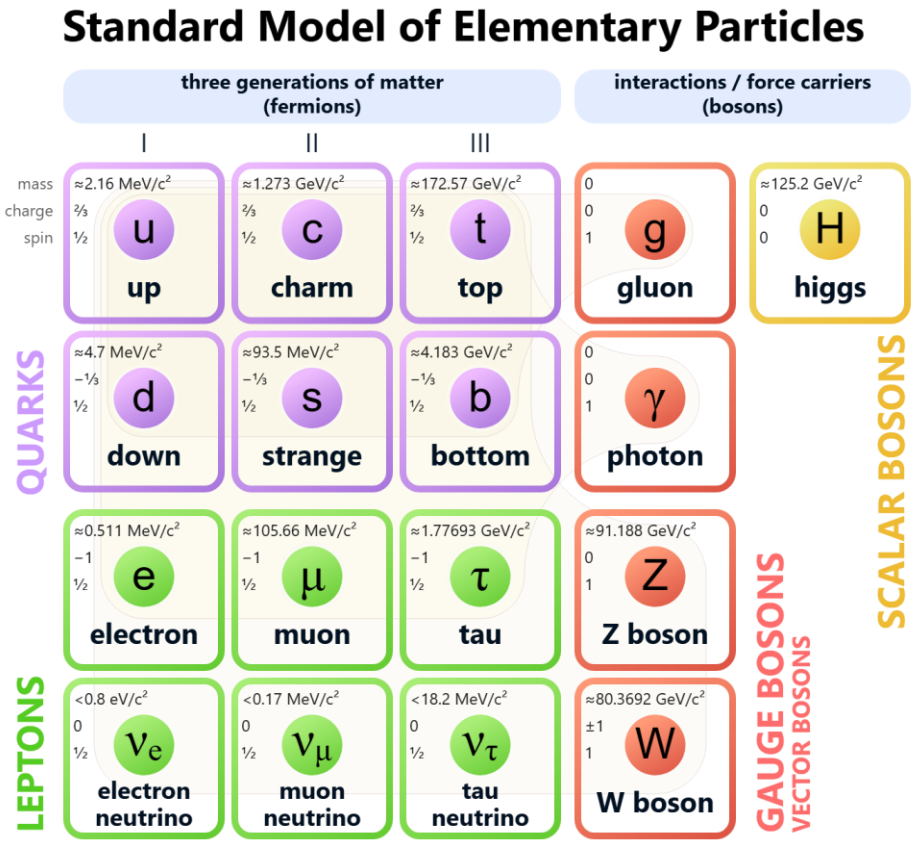
- **QFT** that describes **paticle types** and **their interactions** based on
  - **symmetry principle**

$$\underbrace{\mathrm{R}^{1,3} \rtimes \mathrm{O}(1,3)}_{\text{Poincaré group}} \times \underbrace{\mathrm{SU}(3)_c}_{\text{QCD}} \times \underbrace{\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}_{\text{\& electroweak}} \quad \text{gauge groups}$$

  spontaneous symmetry breaking (Higgs mechanism)

$$\underbrace{\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y}_{\text{electroweak}} \longrightarrow \underbrace{\mathrm{U}(1)_{\mathrm{em}}}_{\text{electromagnetism}}$$

- **Inputs:**
  - invariance alias symmetry pattern – 3 gauge coupling parameters
  - 3 generations of fermions
  - 9 (masses) + 4 (CKM mixing) + 3 (ν masses) + 6 (PMNS mixing)
  - 2 parameters of *minimal* Higgs mechanism
- **Outputs:**
  - gauge symmetries free of anomalies → 4 fermion electric charges
  - strongly coupled confining QCD → hadron spectrum
  - baryon and lepton number conservation (only approximate at quantum level)
  - effects of large fields → instantons (η', baryo(lepto)genesis), magnetic monopoles, cosmological topological defects



Standard model of elementary particles - exercises

1. **Minimize the Higgs potential** $V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$

   Substitute polar coordinates $\phi = h e^{i\varphi}$

   Solve the equation $\dfrac{\partial V}{\partial h} = 0$

2. **Quantize the electric charge in SM**

   gauge invariance requires equations of continuity

   $$\partial_\mu j_c^\mu \stackrel{!}{=} 0\,, \qquad \partial_\mu j_L^\mu \stackrel{!}{=} 0\,, \qquad \partial_\mu j_Y^\mu \stackrel{!}{=} 0\,.$$

   quantum one-loop effect (triangle diagram)

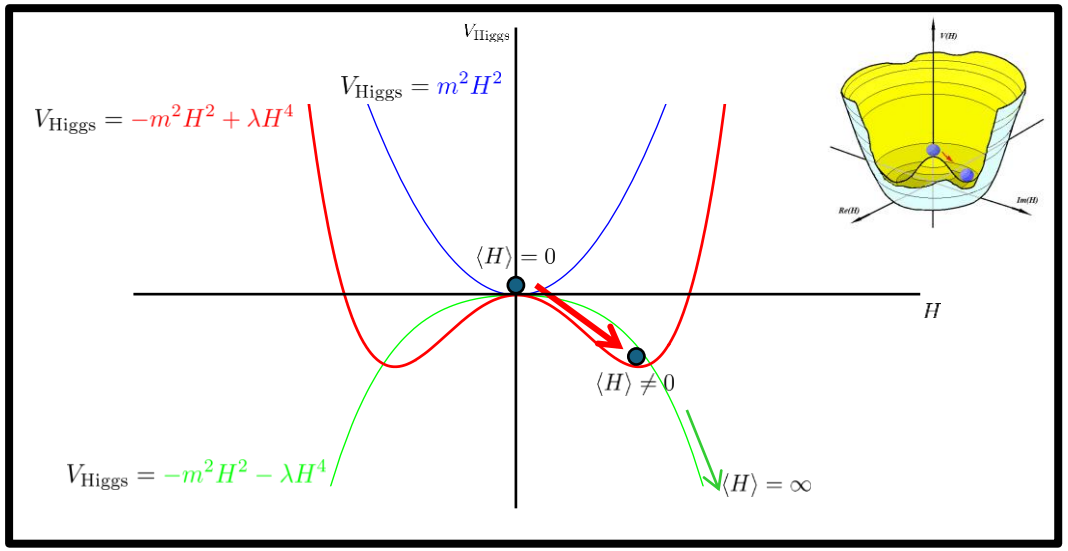
   $$\partial_\mu j^\mu \propto \sum_{\text{all chiral fermion fields}} \operatorname{Tr} T_a T_b T_c \stackrel{!}{=} 0$$

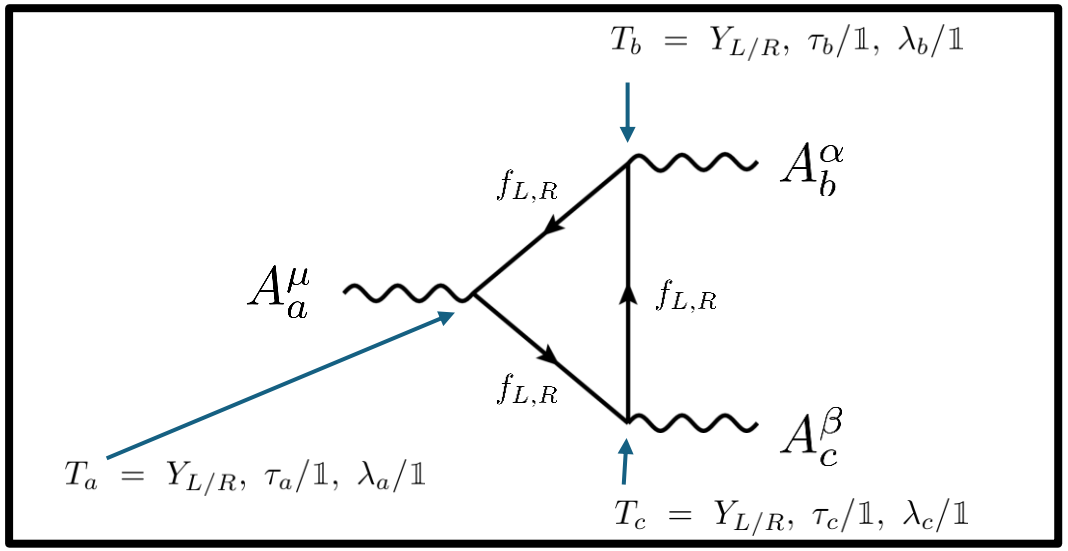
   that leads to conditions

   $$\sum Y_L - \sum Y_R \stackrel{!}{=} 0$$
   $$\sum Y_L^3 - \sum Y_R^3 \stackrel{!}{=} 0$$

   Solve them!
   What does it mean for electric charges?
   $Q = T_3 + Y$

   Convention taken from https://en.wikipedia.org/wiki/Mathematical_formulation_of_the_Standard_Model



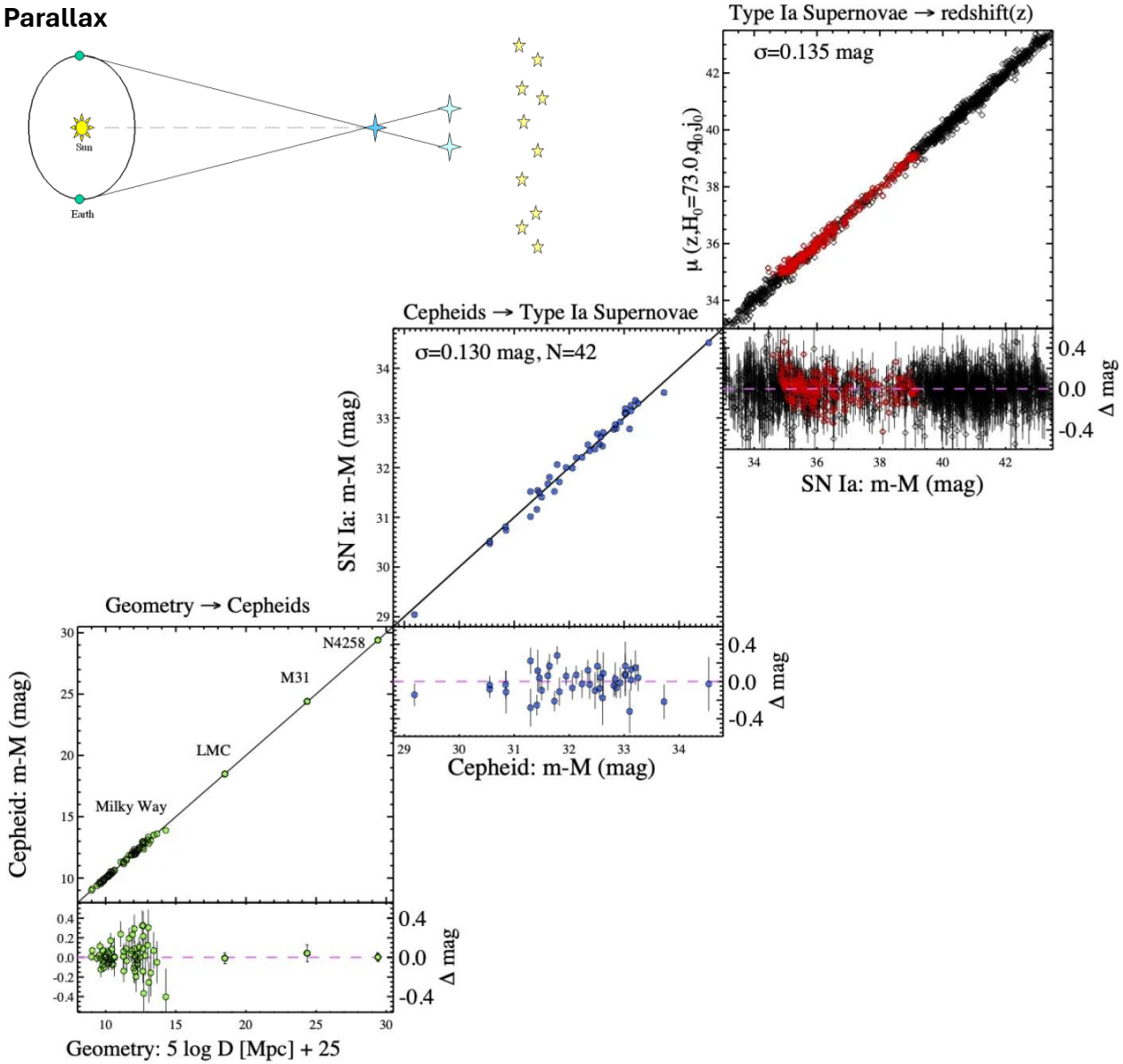


Distances

Cosmic Distance Ladder

#	Method	Typical Distance Range	Purpose / Application
1	**Radar Ranging**	Up to ~10 AU	Direct measurements within the Solar System
2	**Parallax**	Up to a few thousand parsecs	Distances to nearby stars (e.g., via Gaia mission)
3	**Spectroscopic Parallax**	Up to ~10 kpc	Stellar distances using spectral classification
4	**Cepheid Variables**	~1–40 Mpc	Distance to nearby galaxies using variable stars
5	**Type Ia Supernovae**	Up to ~1,000 Mpc or more	Standard candles for distant galaxies; cosmic acceleration
6	**Tully-Fisher Relation**	~10–100 Mpc	Spiral galaxies' distance via rotation-luminosity relation
7	**Surface Brightness / Lensing**	~100–500 Mpc	Intermediate-distance techniques; lensing time delays
8	**BAO / CMB (Model-Dependent)**	Up to ~13,000 Mpc (CMB at z∼1100z \sim 1100)	Anchoring distances in the early universe

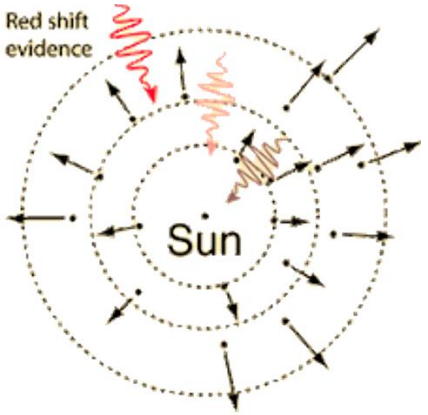
Parallax

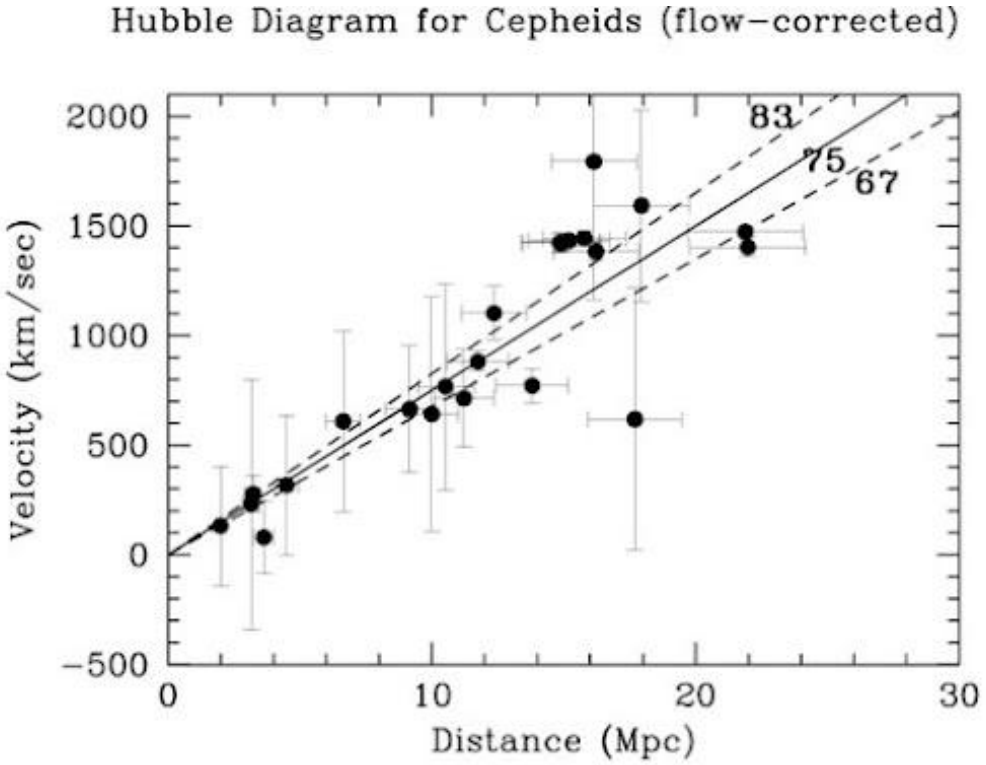


Expansion of the universe

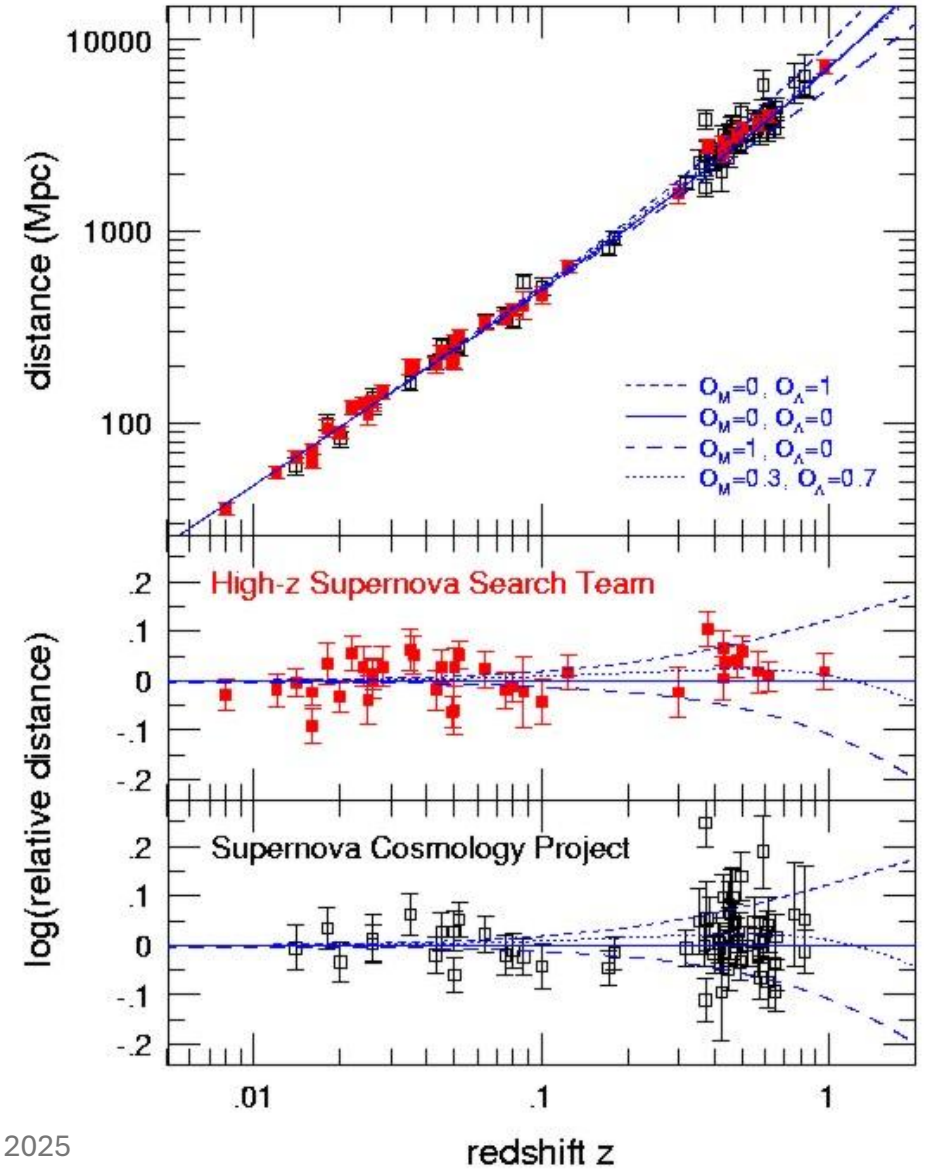
- **Hubble`s law**

$$v = H_0 d$$





Accelerated expansion of the Universe
2011 Nobel Prize – Perlmutter, Schmidt, Riess



Standard model of cosmology

- **General Relativity** (GR), describing a **homogeneous and isotropic Universe** (on large scales)

$$R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4}T_{\mu\nu}$$

differential equation for **FLRW metric** tensor field $g_{\mu\nu}(x)$

$$\mathrm{d}s^2 \equiv g_{\mu\nu}(x)\,\mathrm{d}x^\mu \mathrm{d}x^\nu = -c^2\mathrm{d}t^2 + a(t)^2 \mathrm{d}\boldsymbol{\Sigma}^2_{k=-1,0,+1}$$

$$T^\mu{}_\nu = \begin{pmatrix} \rho & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}$$

- **The matter-energy content (ΛCDM model)** includes:
  - Cold Dark Matter (**CDM**)
  - Baryons (all massive (relatively to actual conditions) non-relativistic stable particles)
  - Radiation (photons, neutrinos)
  - Dark energy (usually a cosmological constant **Λ**)

- The evolution of the Universe is governed by the **Friedmann equations**:

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

equation of continuity:

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + \frac{p}{c^2}\right) = 0$$

ΛCDM evolution of the universe

Equation of state:

$$p = w\rho$$

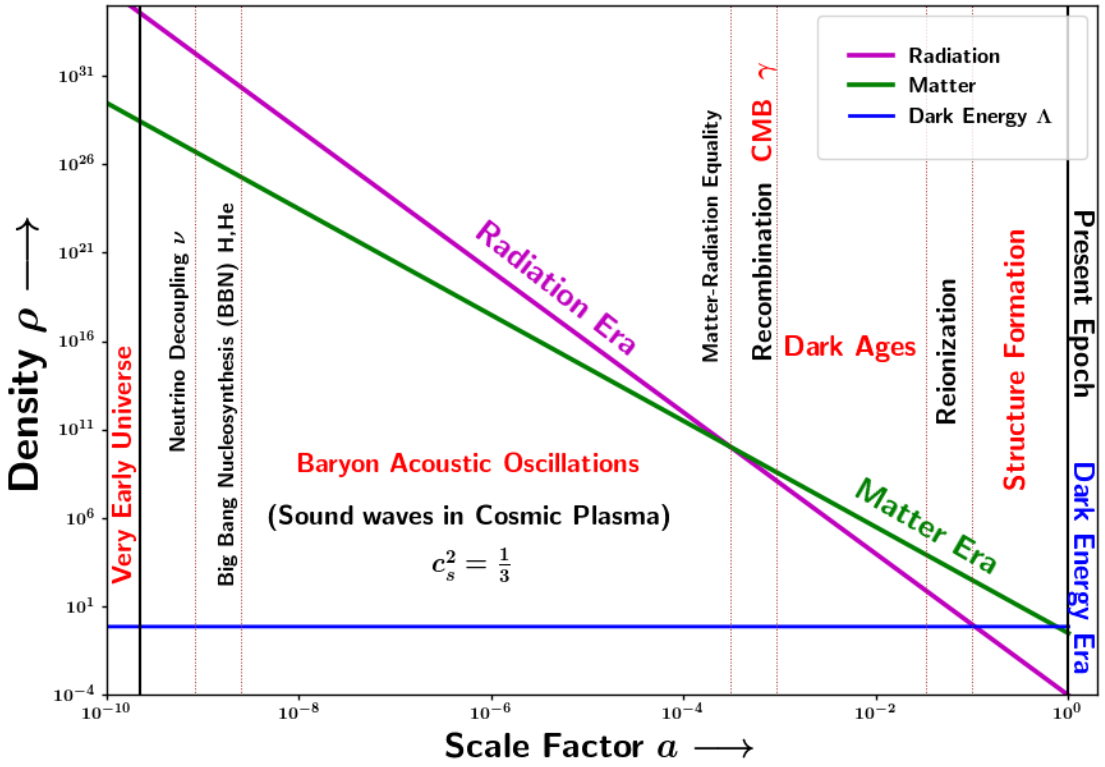
- $w = \frac{1}{3}$ for radiation (relativistic particles),
- $w = 0$ for pressureless matter (dust, dark matter),
- $w = -1$ for the cosmological constant (dark energy).

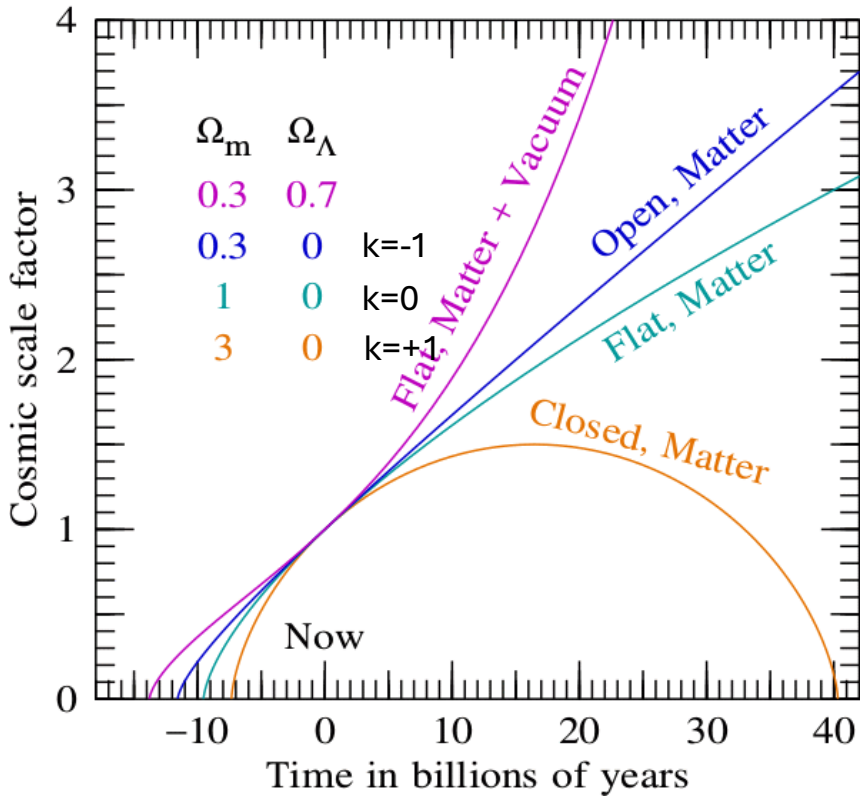
Continuity equation:

- Radiation: $\rho_r \propto a^{-4}$
- Matter: $\rho_m \propto a^{-3}$
- Curvature: $\rho_k \propto a^{-2}$
- Dark Energy: $\rho_\Lambda = \text{constant}$

Friedmann equation:

- Radiation-dominated era: $a(t) \propto t^{1/2}$
- Matter-dominated era: $a(t) \propto t^{2/3}$
- Dark energy-dominated era: $a(t) \propto e^{Ht}$





Relics

photons (CMB), neutrinos (CνB), dark matter (DM), matter density fluctuations (LSS), nuclear isotopes (BBN), gravitational waves....

Those who interact are
in thermal equilibrium → T

The system (interacting, multi-species,
on expanding background)
obey Boltzmann equations.

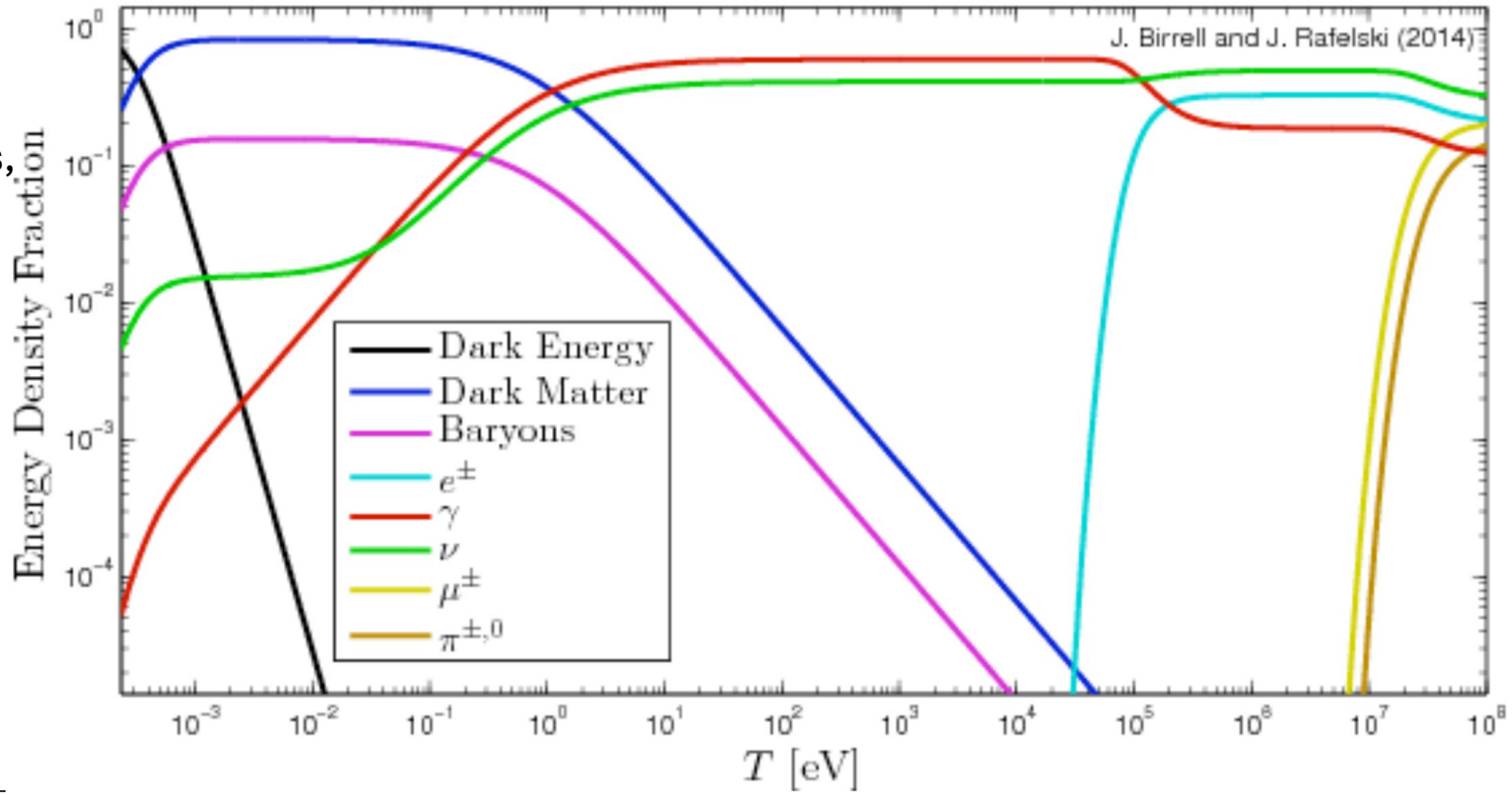
Decoupling $\Gamma(T) = H(T)$

interaction rate

- **fotons** $\Gamma(T) = n_e \sigma_T c$
- **massive particles** $\Gamma(T) = n\langle\sigma v\rangle$

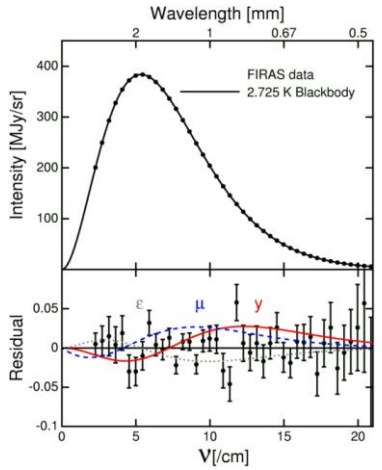
expansion rate

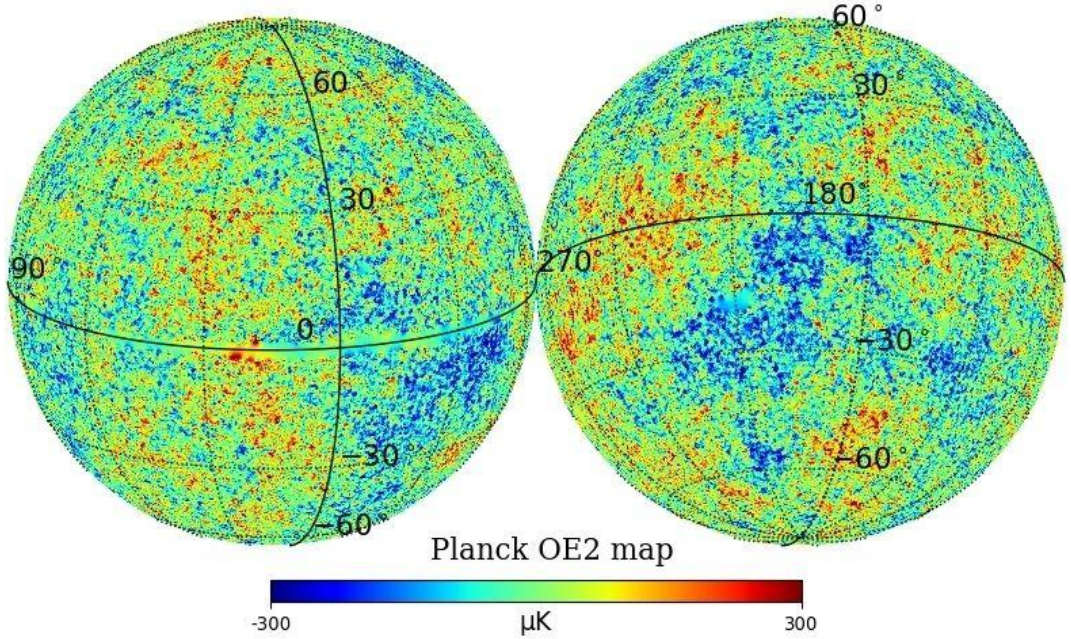
- **Hubble parameter** $H(T) = \sqrt{\frac{8\pi G}{3}\rho(T)}$

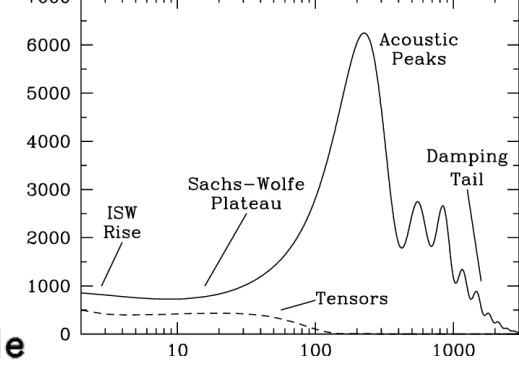


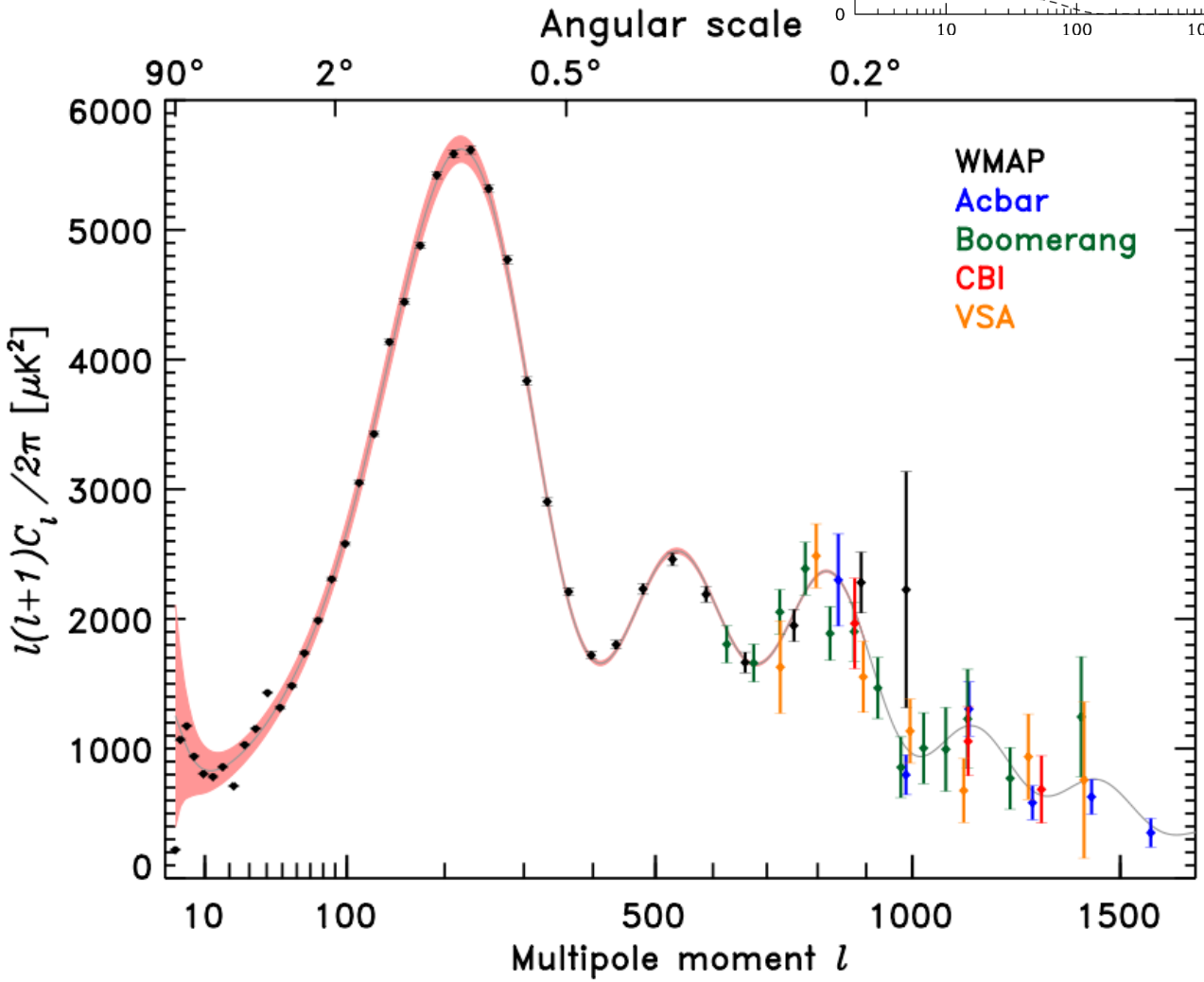
Cosmic Microwave Background

- **black body spectrum T = 2.73 K**
- **temperature anisotropies ~ 4.10^{-5}**
- **Decoupling: 380.000 yr**



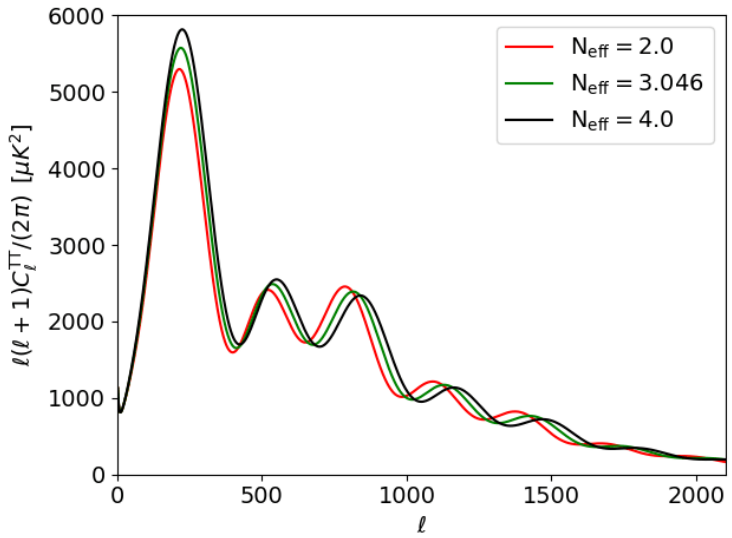


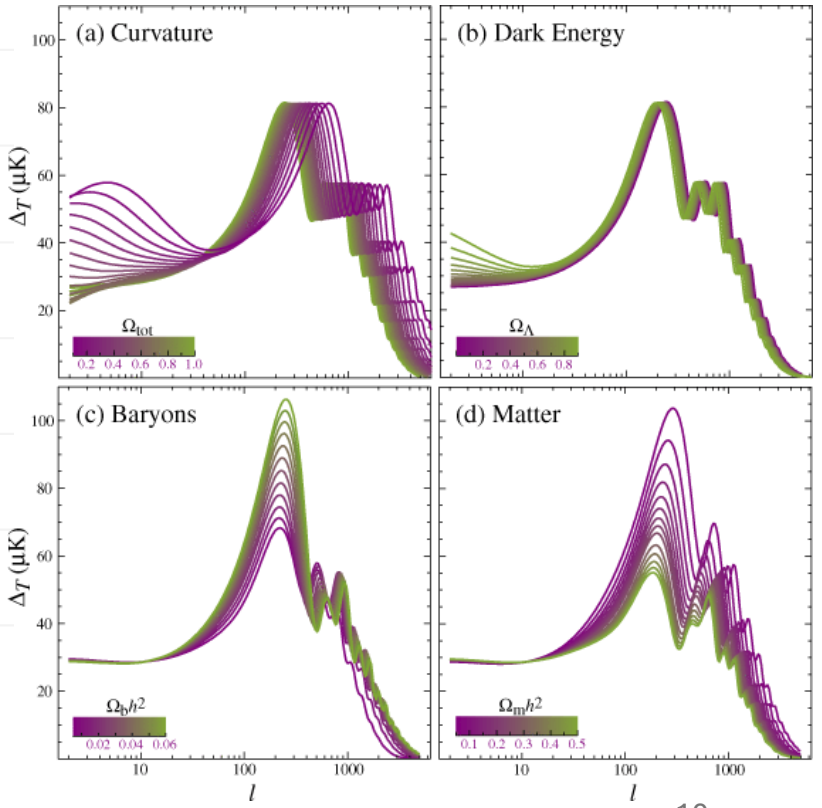




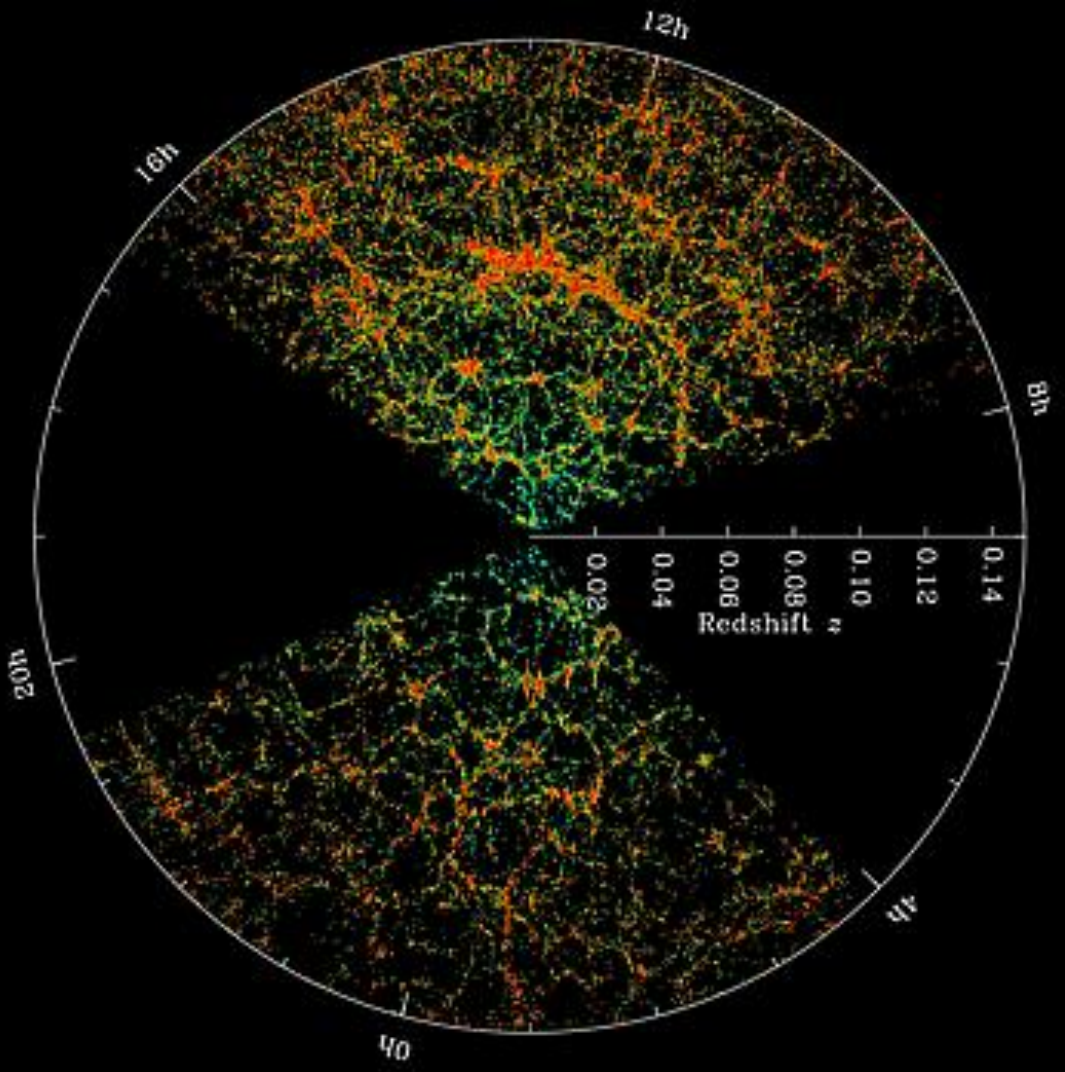
CMB power spectrum

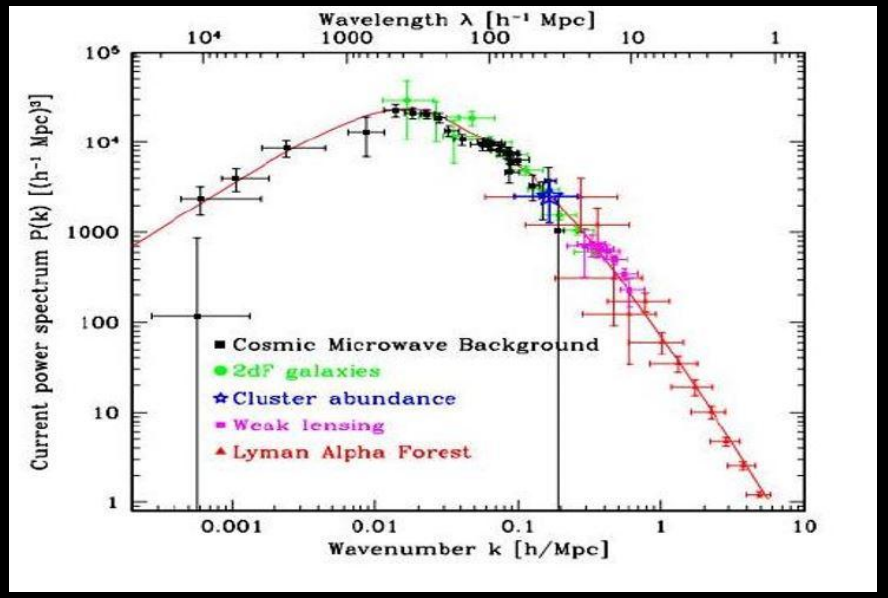
Parameter	Deduced From	Physical Meaning
$\Omega_b h^2$	Peak heights (odd vs even)	Baryon content
$\Omega_c h^2$	Peak spacing and height	Cold dark matter density
Ω_k	1st peak position	Geometry (curvature of the universe)
H_0	Angular scale of peaks	Hubble expansion rate
τ	Low-ℓ polarization	Reionization epoch
n_s	Tilt of spectrum	Shape of primordial fluctuations
A_s	Amplitude	Initial fluctuation strength
r	Large-scale B-mode polarization	Inflationary gravitational waves
N_{eff}	Damping tail, early expansion	Number of light relativistic species
$\sum m_\nu$	Lensing, peak smoothing	Total neutrino mass

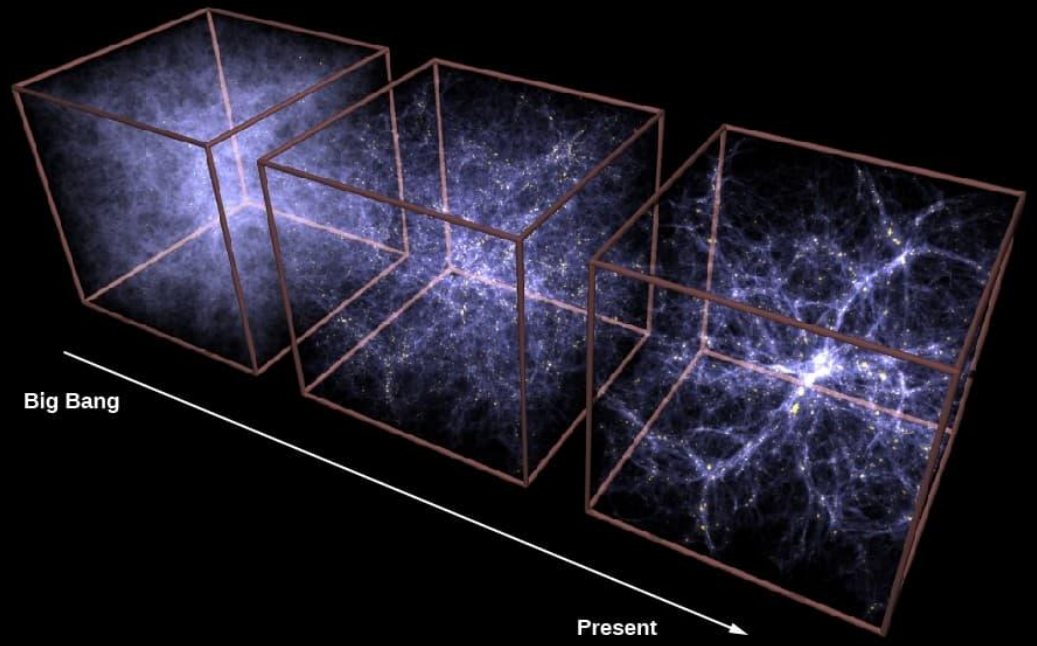




Large scale structures





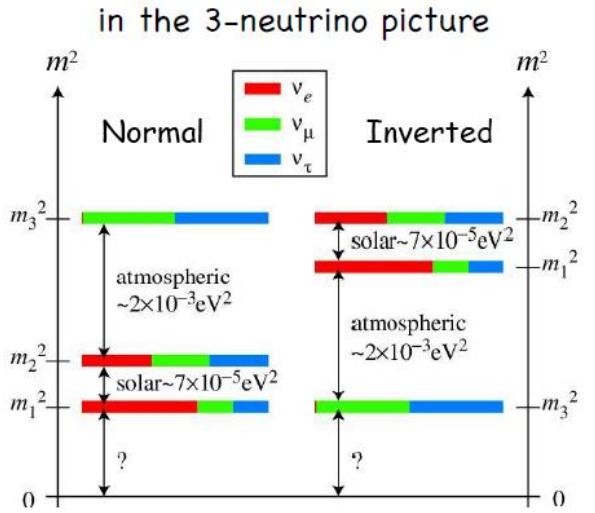


Matter power spectrum

Parameter	Deduced From in $P(k)$	What It Tells Us
$\Omega_m h^2$	Overall shape, turnover scale	Matter content
Ω_b	BAO amplitude and position	Baryon-to-matter ratio
$\sum m_\nu$	Suppression at small scales	Neutrino mass
A_s	Overall amplitude	Primordial fluctuation strength
n_s	Tilt of spectrum	Initial fluctuation scale dependence
$f\sigma_8$	Redshift-space distortions	Growth rate of structure
Dark Energy	Redshift evolution of $P(k)$	Expansion history
Galaxy Bias	Ratio $P_g(k)/P_m(k)$	Galaxy–matter relation
Dark Matter Nature	Small-scale cutoff	Cold vs warm dark matter

Planck 2018+BAO+RSD (2023)

$$\sum m_\nu < 0.09\,\text{eV} \quad 95\,\%\ \text{C.L.}$$



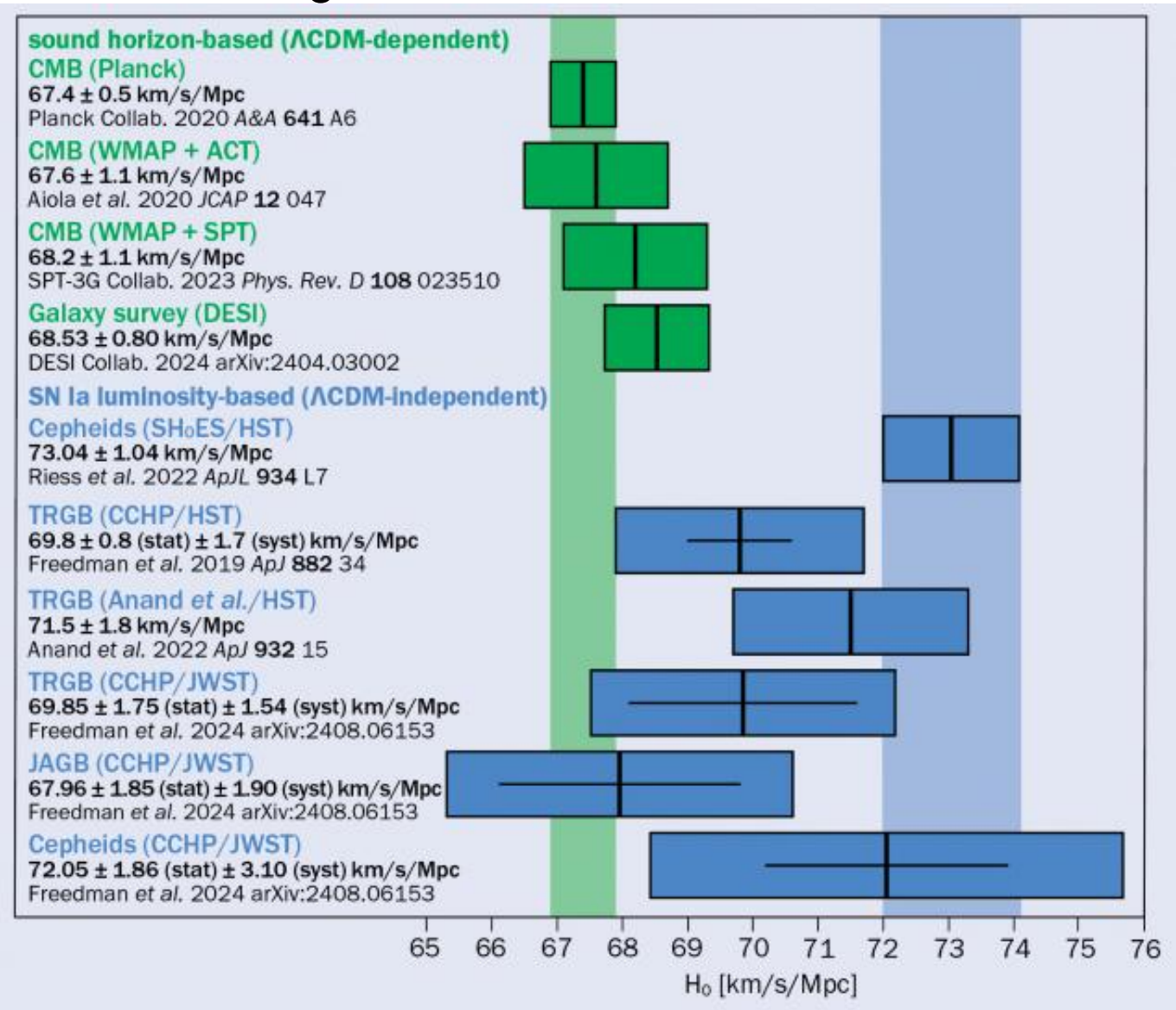
$$\sum m_\nu > 0.054\ \text{eV} \quad \text{(Normal Hierarchy)}$$

$$\sum m_\nu > 0.090\ \text{eV} \quad \text{(Inverted Hierarchy)}$$

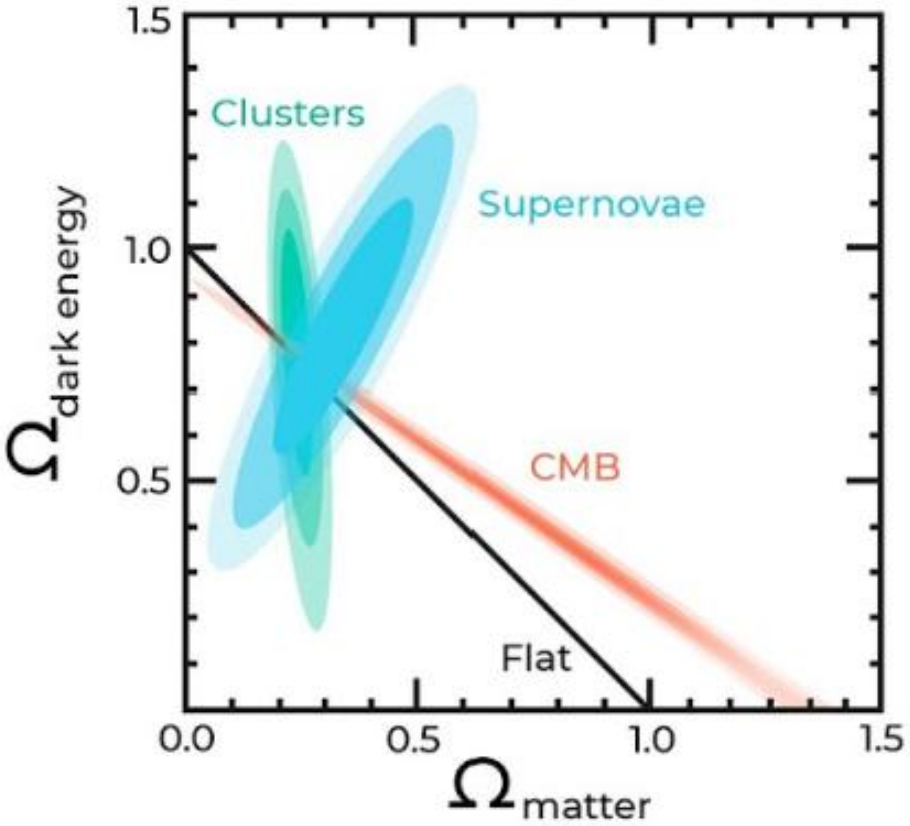
Hubble tension - H_0 value discrepancy

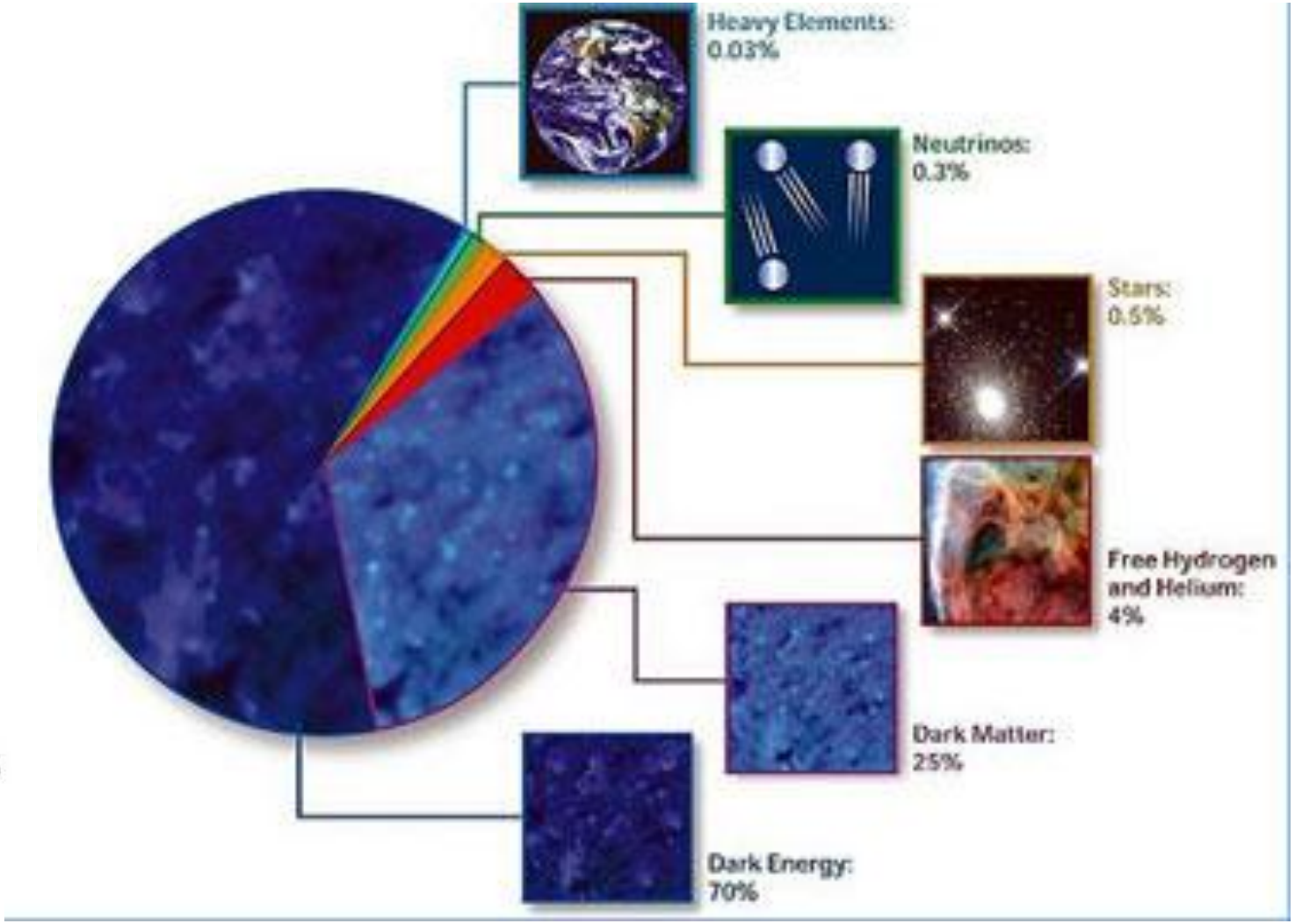
ΛCDM model fit to CMB and LSS data

Cosmological distance ladder

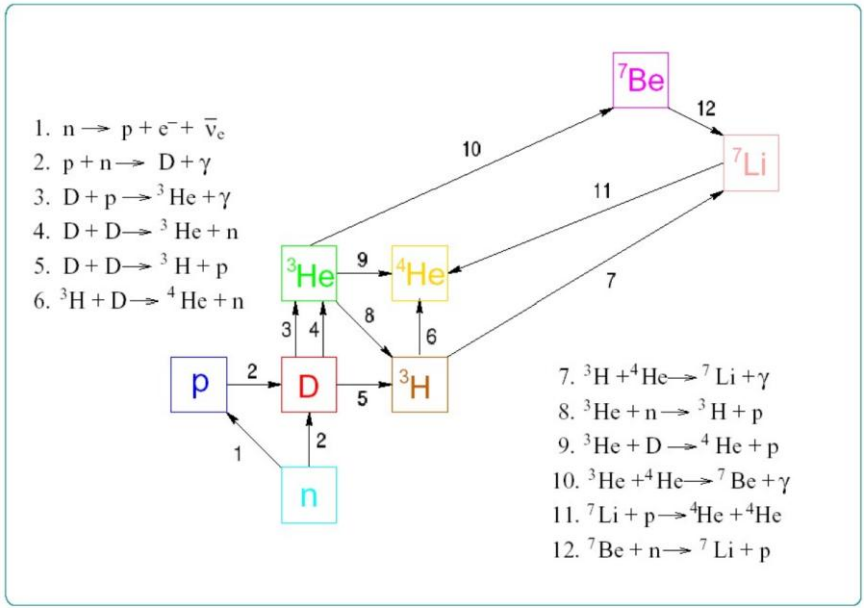


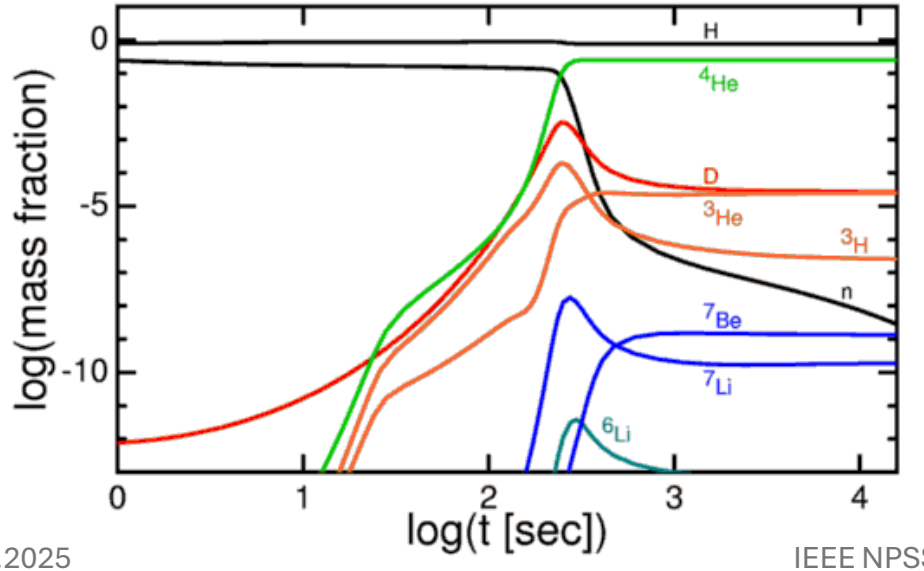
Energy density budget of the universe by ΛCDM model



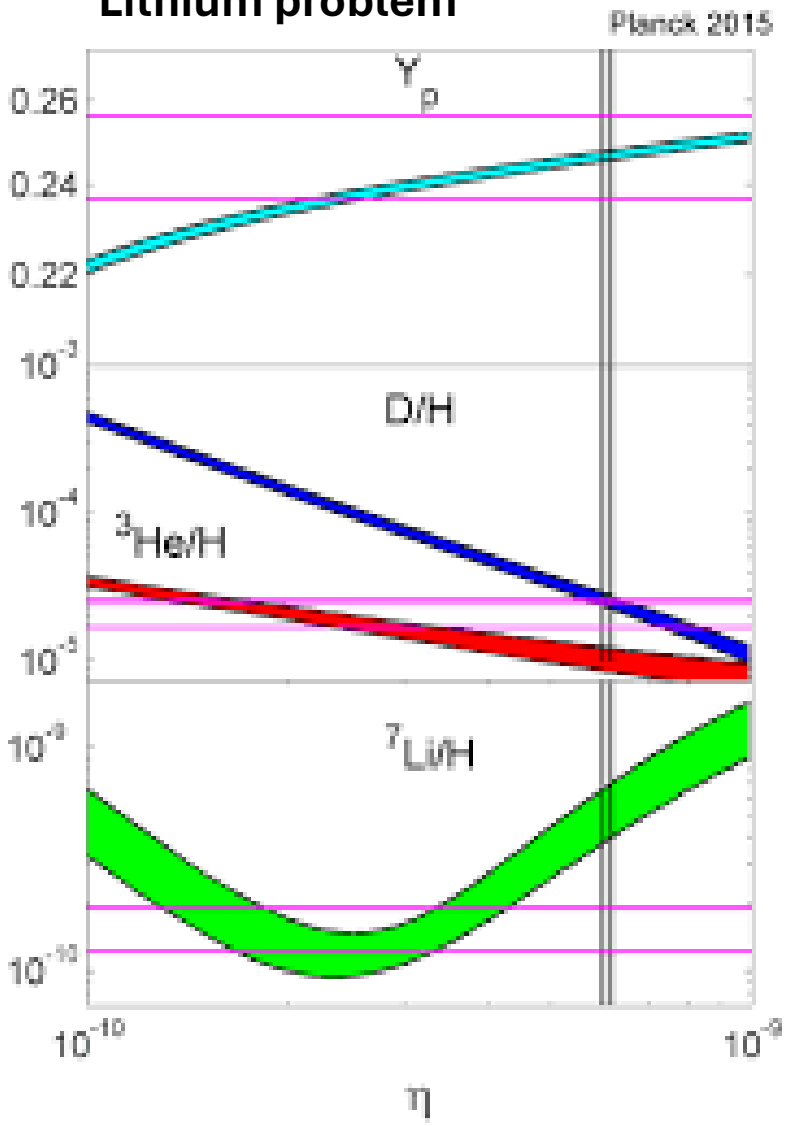


Big Bang Nucleosynthesis





Lithium problem

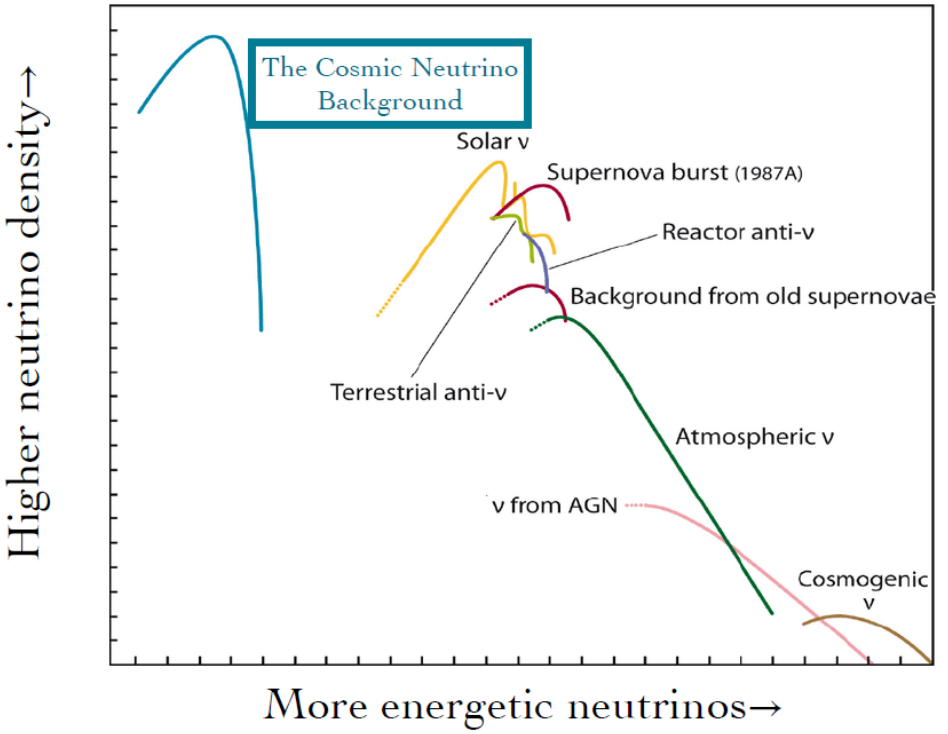


Cosmic neutrino background

Decoupling
- **1 second after the Big Bang,**
- red shift $z=10^{10}$

Temperature
- **~10^{-4} eV,**
- **~1.95 K,**
- hard to detect directly (PTOLEMY)

$$f_\nu(p,T) = \frac{1}{\exp(p/T)+1}$$



Density today ~ 336 cm^{-3}

Radiation density of the early universe

$$\rho_{\mathrm{R}} = \frac{\pi^2}{15} T_\gamma^4 (1+z)^4 \left[1 + \frac{7}{8} N_\nu \left(\frac{4}{11}\right)^{4/3}\right],$$

SM prediction	$N_\nu \simeq 3.046$
BBN	$N_\nu = 3.14\ ^{+0.70}_{-0.65}$ at 68% c.l.
Planck	$N_\nu = 3.15 \pm 0.23$

The existence of the CNB affects **large-scale structure formation**, **CMB anisotropies**, and is indirectly supported by **precision measurements** of cosmic parameters.

Baryon abundance of the universe

Sakharov Conditions (1967):
To generate baryon asymmetry, three conditions must be met:

1. **Baryon number violation**

$$\Gamma(X \to Y + B) \neq 0$$

2. **C-symmetry and CP-symmetry violation**

$$\Gamma(X \to Y + B) \neq \Gamma(\overline{X} \to \overline{Y} + \overline{B})$$

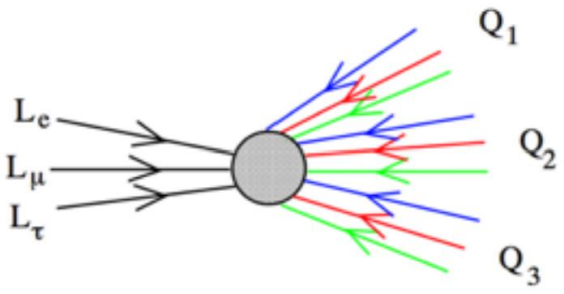
3. **Departure from thermal equilibrium**

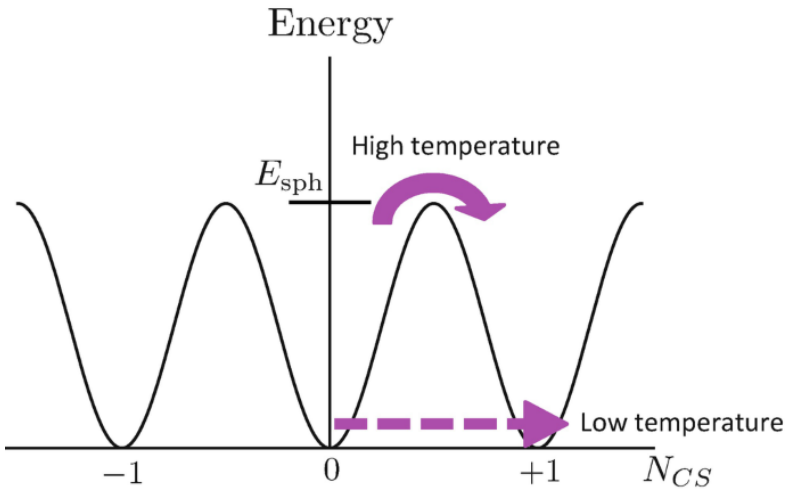
$$\Gamma(X \to Y + B) \neq \Gamma(Y + B \to X)$$

all in SM
but not enough – quark sector is too constrained

Leptogenesis
seesaw for neutrino masses
→ **heavy neutral Majorana leptons**
→ **C & CP & lepton number violation**

lepton abundance is converted to baryons by B-L conserving sphaleron at T ~ electroweak scale

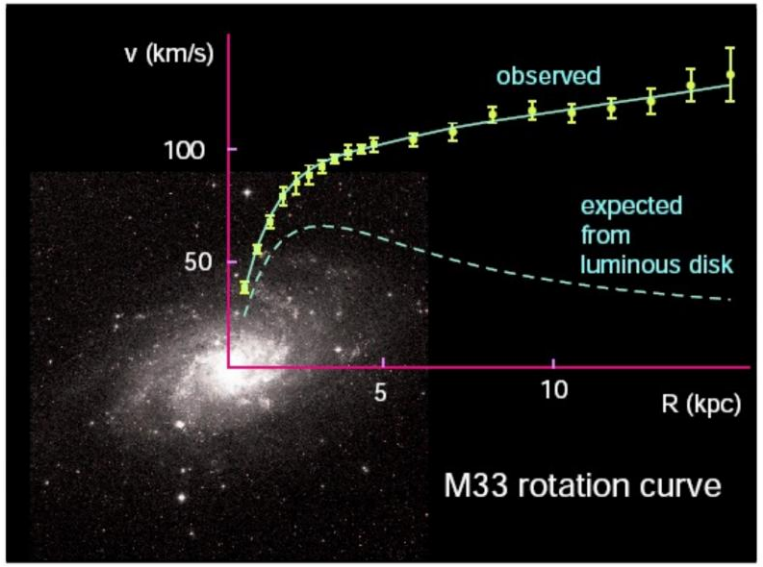




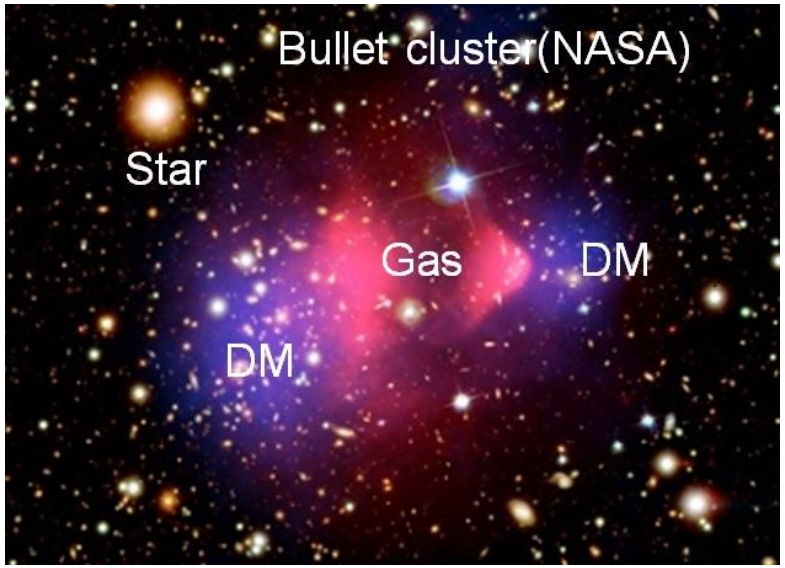
Dark matter

Cosmology models predict dark matter in accordance with astronomy:

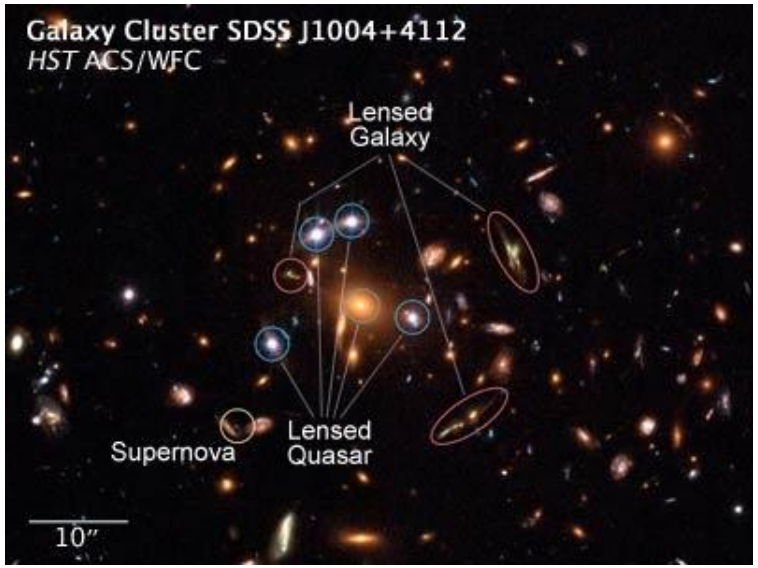
Galactic rotational curves



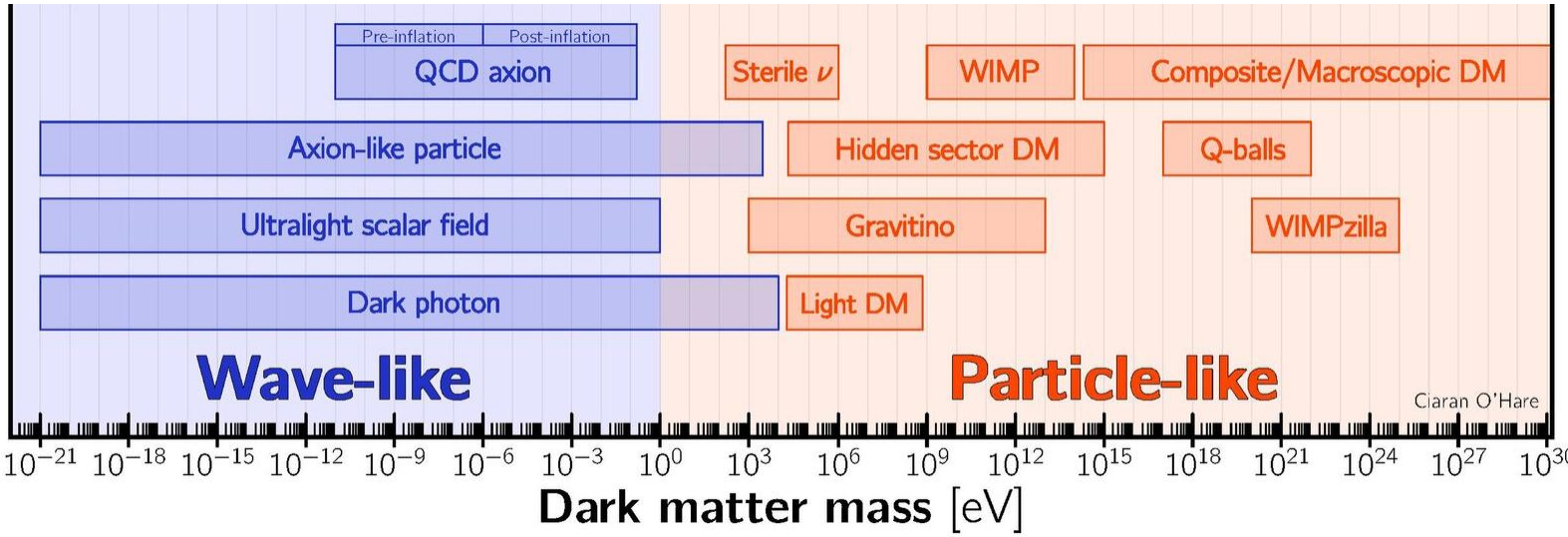
Collisions of galaxies and clusters



Gravitational lensing



DM candidates



Cosmic Inflation

What is Inflation?

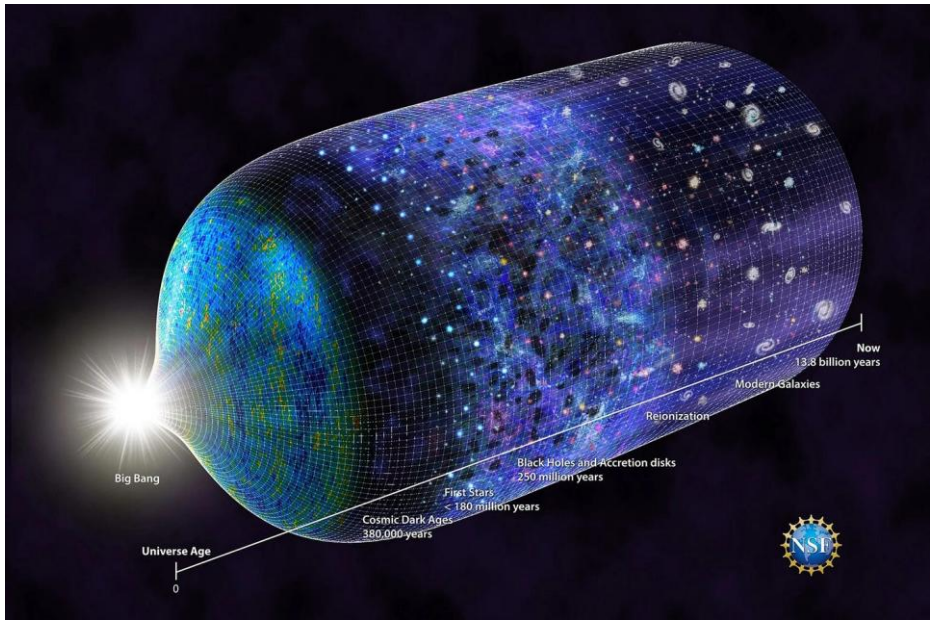
- A period of **extremely rapid expansion** of the universe, occurring about 10^{-36} to 10^{-32} seconds after the Big Bang.
- Proposed to solve key problems in classical Big Bang cosmology.

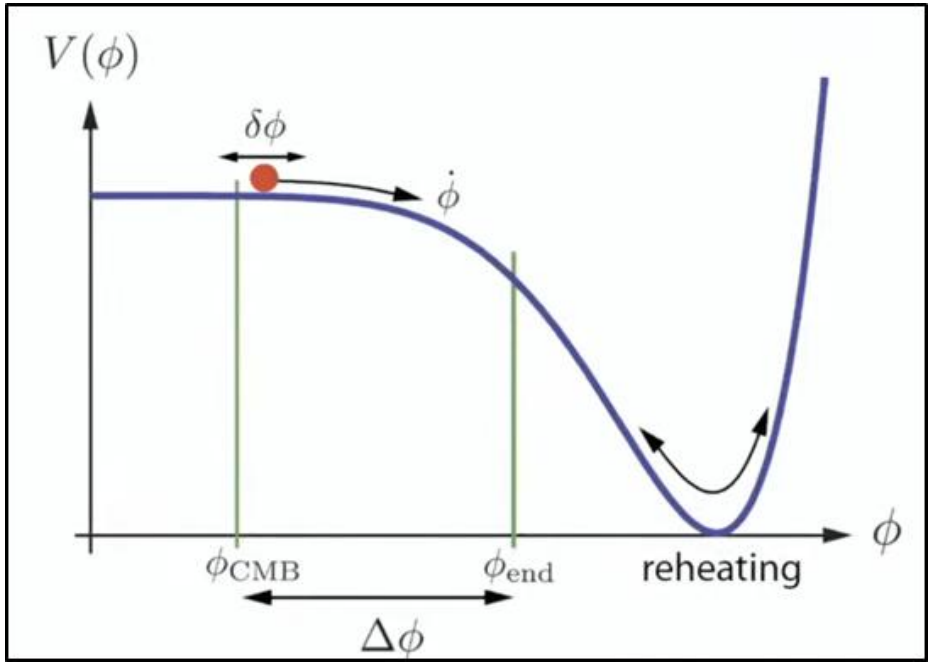
Why is Inflation Important?

- **Horizon Problem**: Explains why the universe looks uniform in all directions.
- **Flatness Problem**: Drives the universe toward spatial flatness.
- **Monopole Problem**: Dilutes exotic relics predicted by grand unified theories.

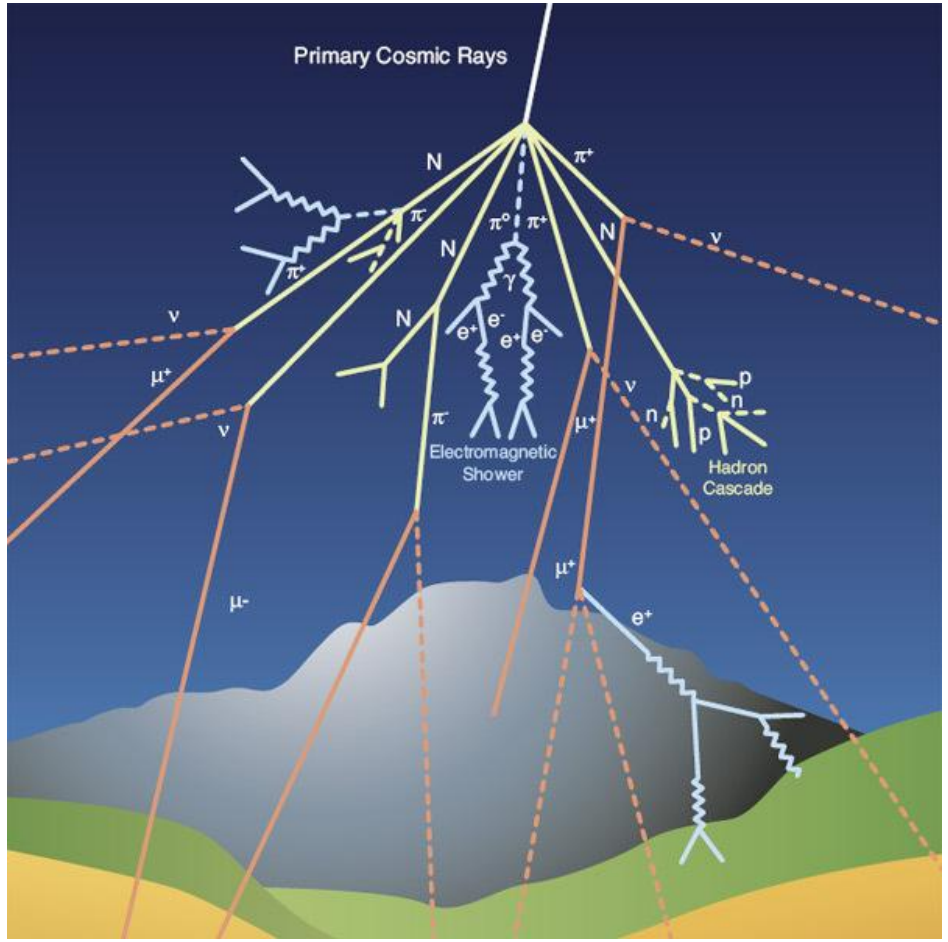
Mechanism:

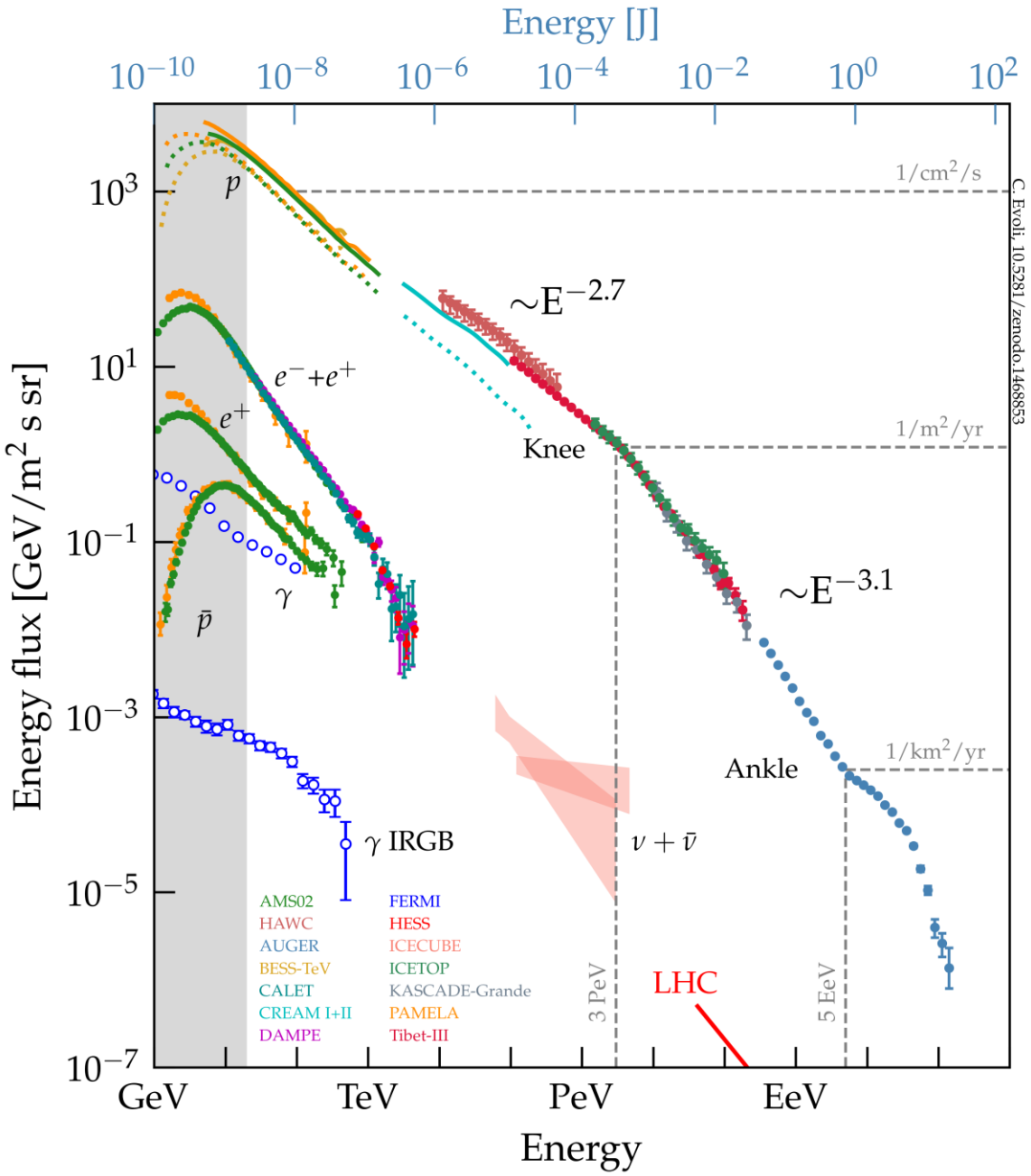
- Driven by a hypothetical **inflaton field** with a nearly constant potential energy.
- Causes exponential growth of the scale factor:
  $a(t) \propto e^{Ht}$





Cosmic rays


Primary Cosmic Rays
Electromagnetic Shower
Hadron Cascade


Energy [J]
Energy flux [GeV/m² s sr]
Energy
GeV
TeV
PeV
EeV
1/cm²/s
1/m²/yr
1/km²/yr
Knee
Ankle
LHC
3 PeV
5 EeV
$\sim E^{-2.7}$
$\sim E^{-3.1}$
$e^- + e^+$
e^+
γ
$\bar{p}$
γ IRGB
$\nu + \bar{\nu}$
AMS02
HAWC
AUGER
BESS-TeV
CALET
CREAM I+II
DAMPE
FERMI
HESS
ICECUBE
ICETOP
KASCADE-Grande
PAMELA
Tibet-III
C. Evoli, 10.5281/zenodo.1468853

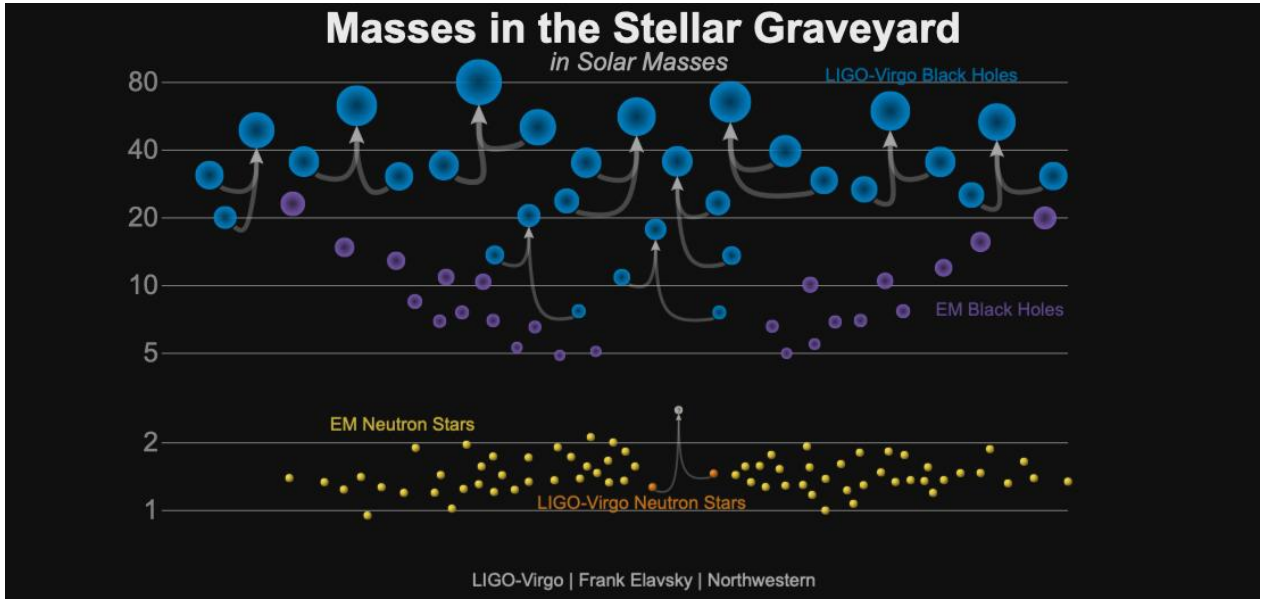
Gravitational waves

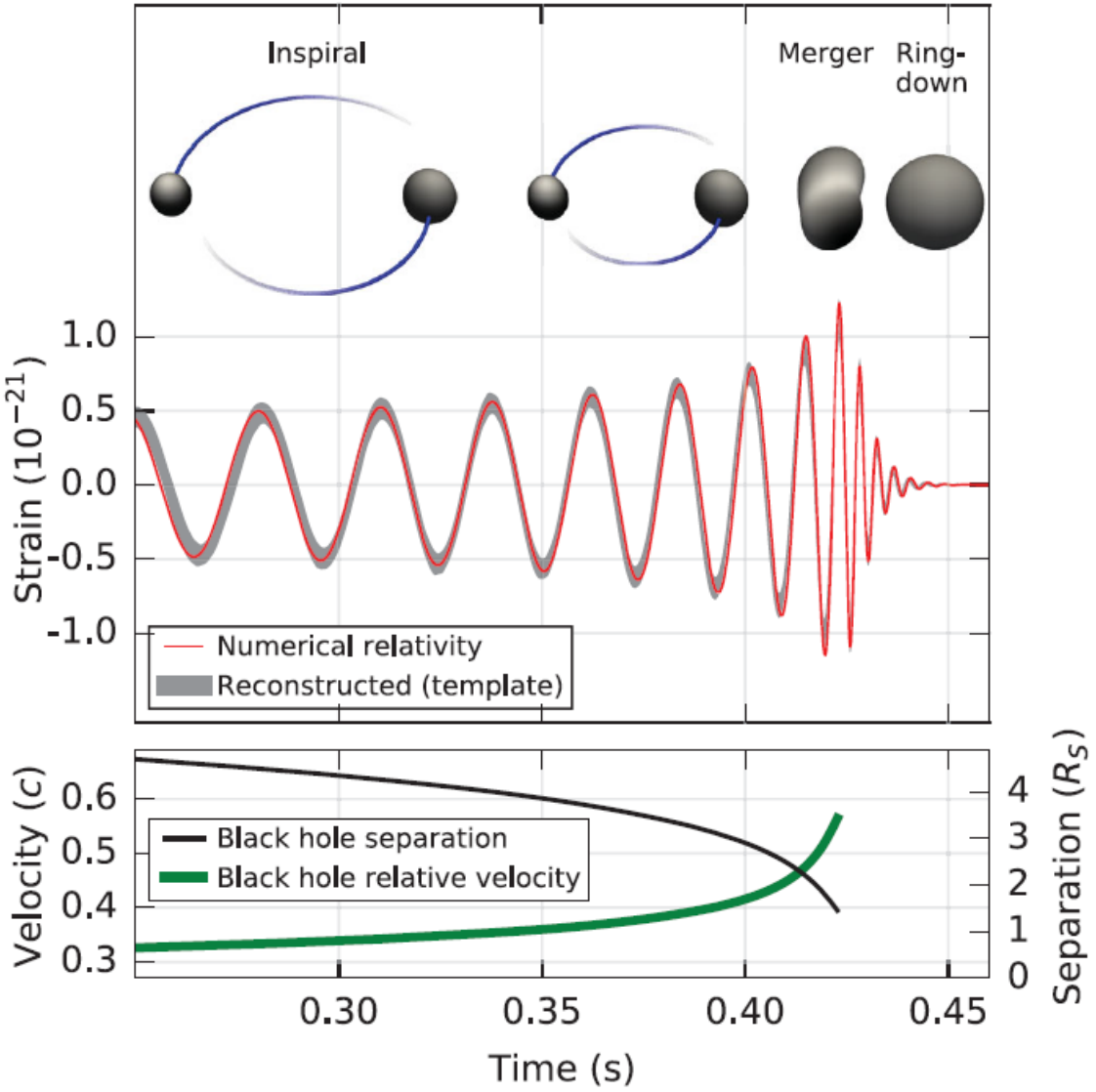
First observation 14. září 2015 (GW150914)

2017 Nobel prize - Rainer Weiss, Barry C. Barish, K. S. Thorne

Virgo (Italy)

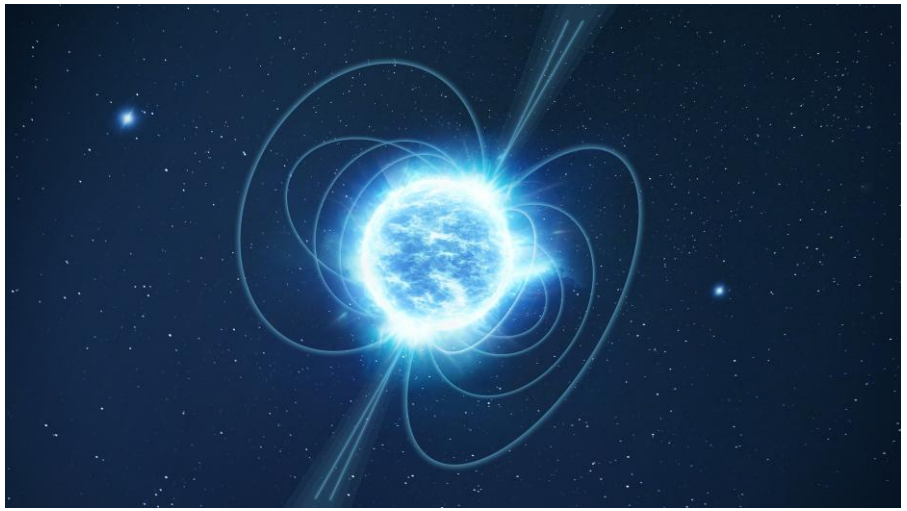
LIGO (USA)

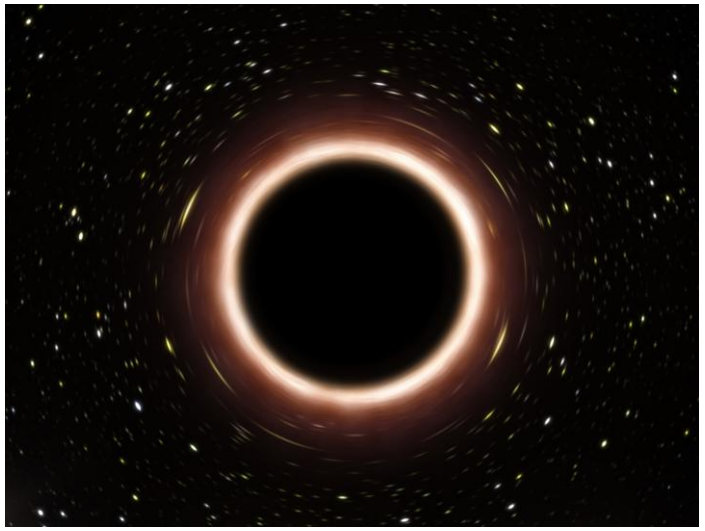


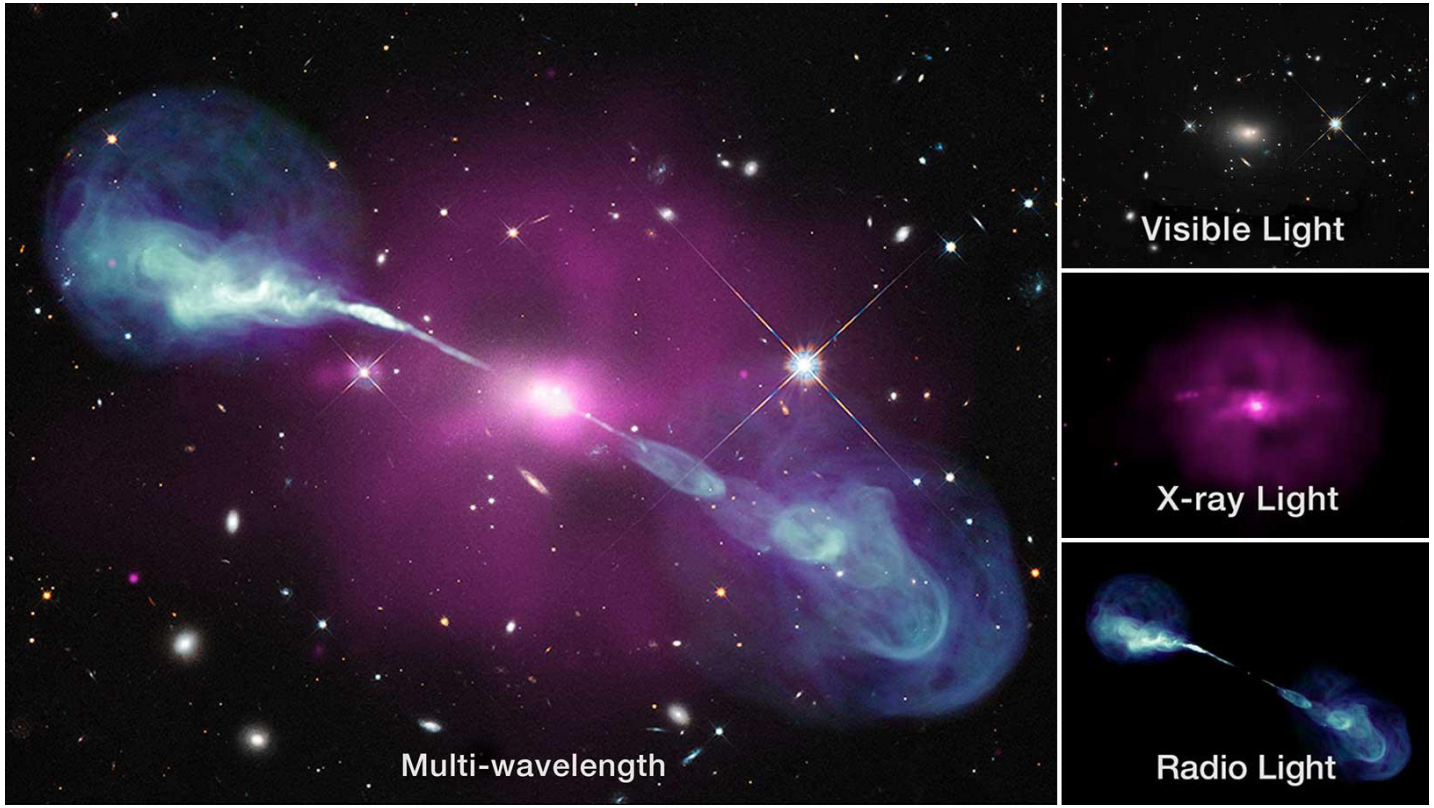


Neutron Stars, Black Holes, Active Galactic Nuclei, …

alias what I did not cover







Thank You for attention