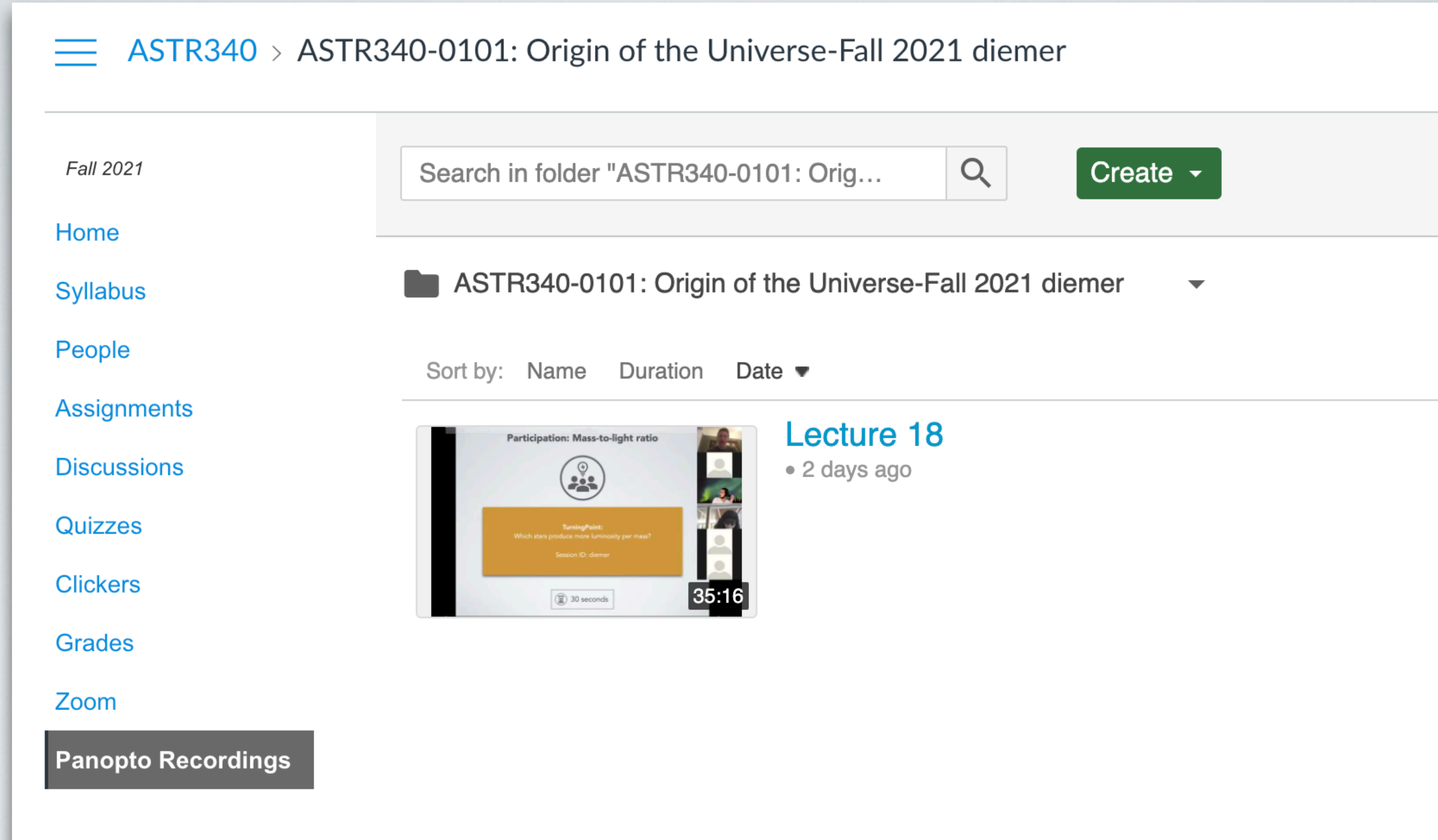
ASTR 340: Origin of the Universe

Prof. Benedikt Diemer

Lecture 19 • Concordance cosmology and the Hubble tension

11/09/2020

Recording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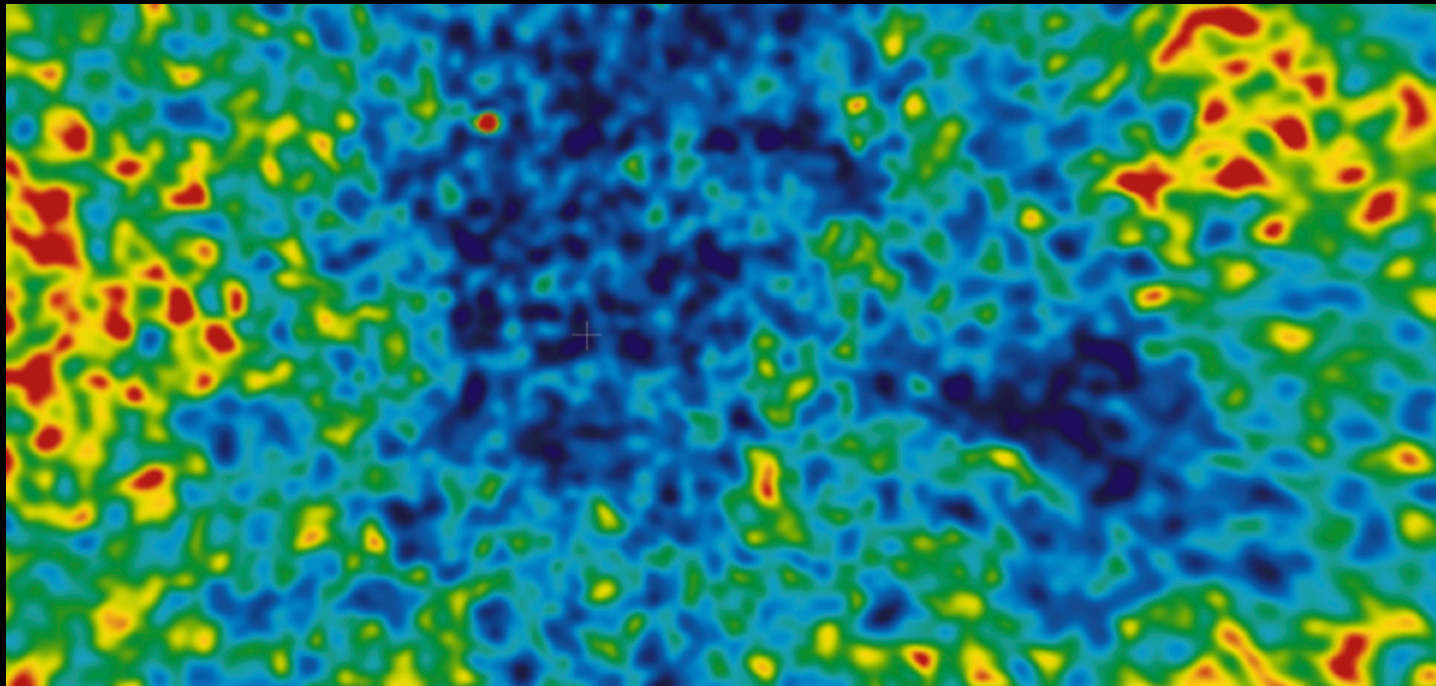
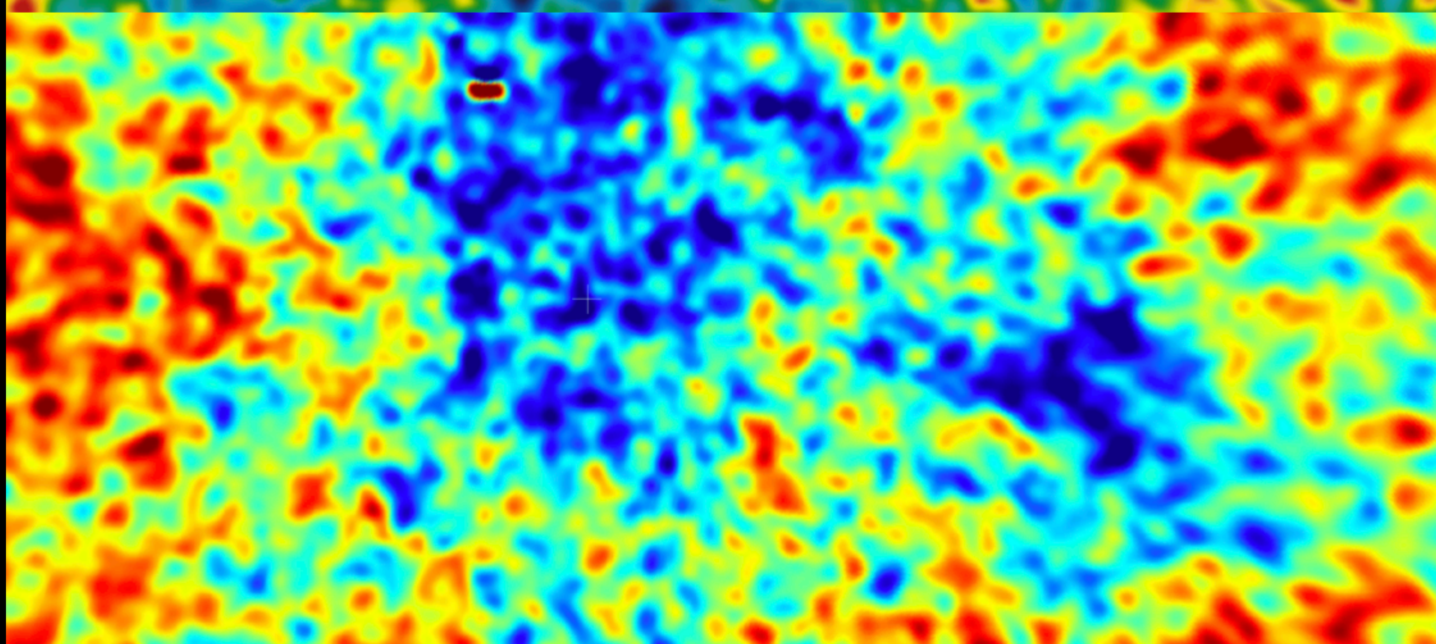
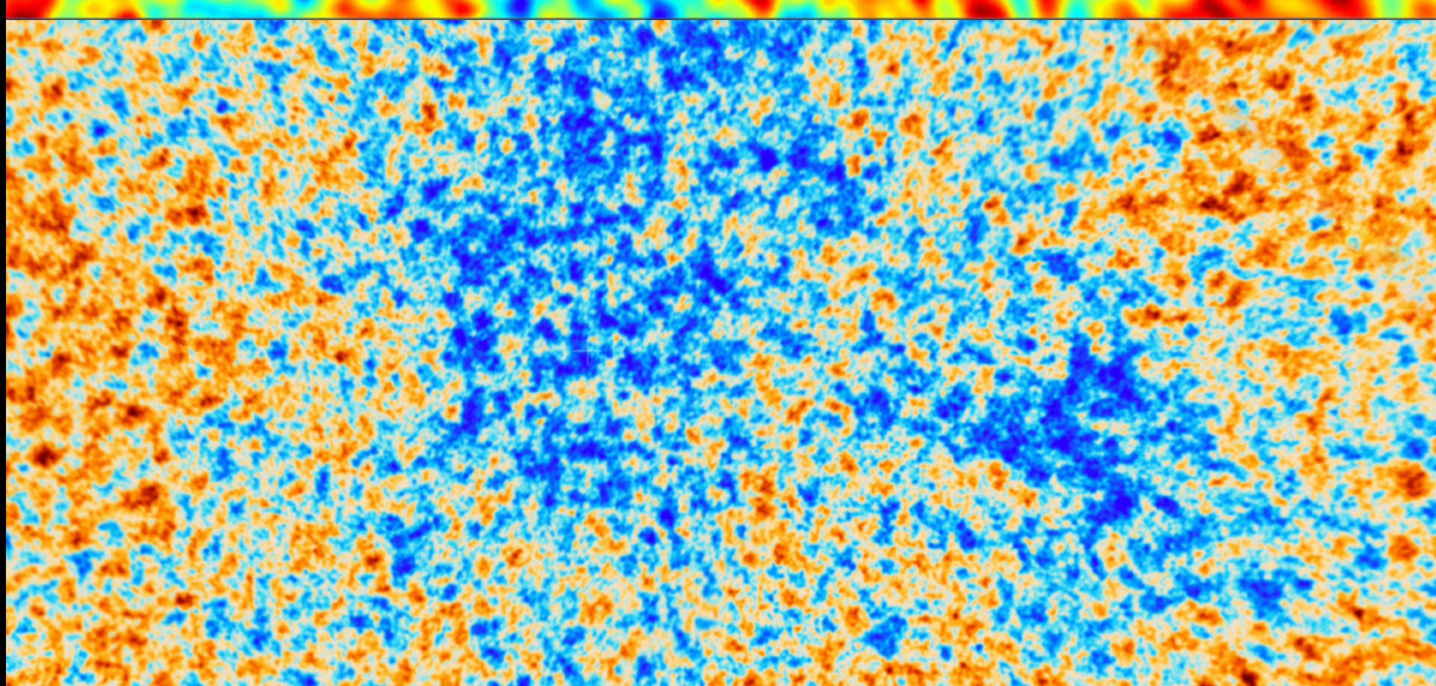


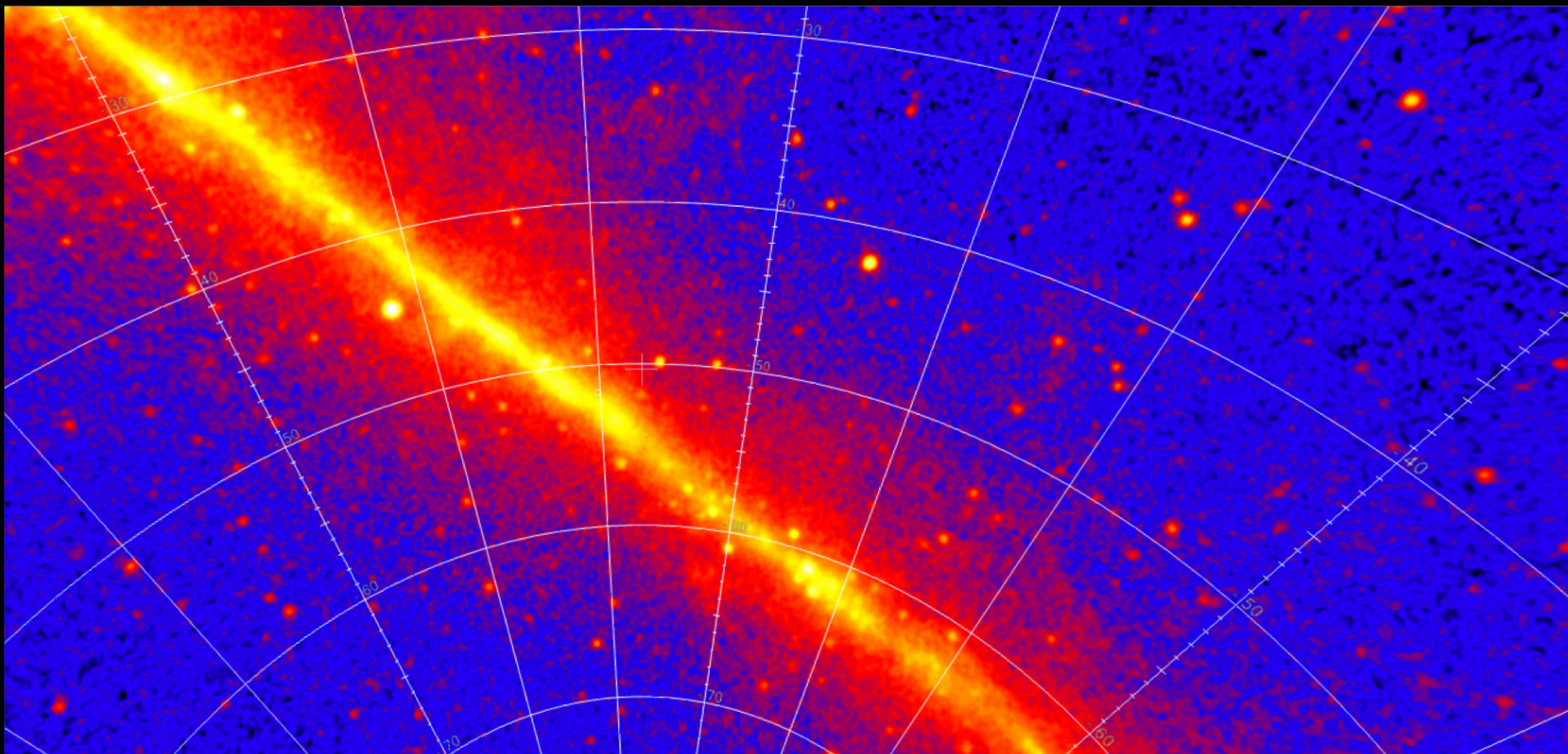
WMAP 3-year



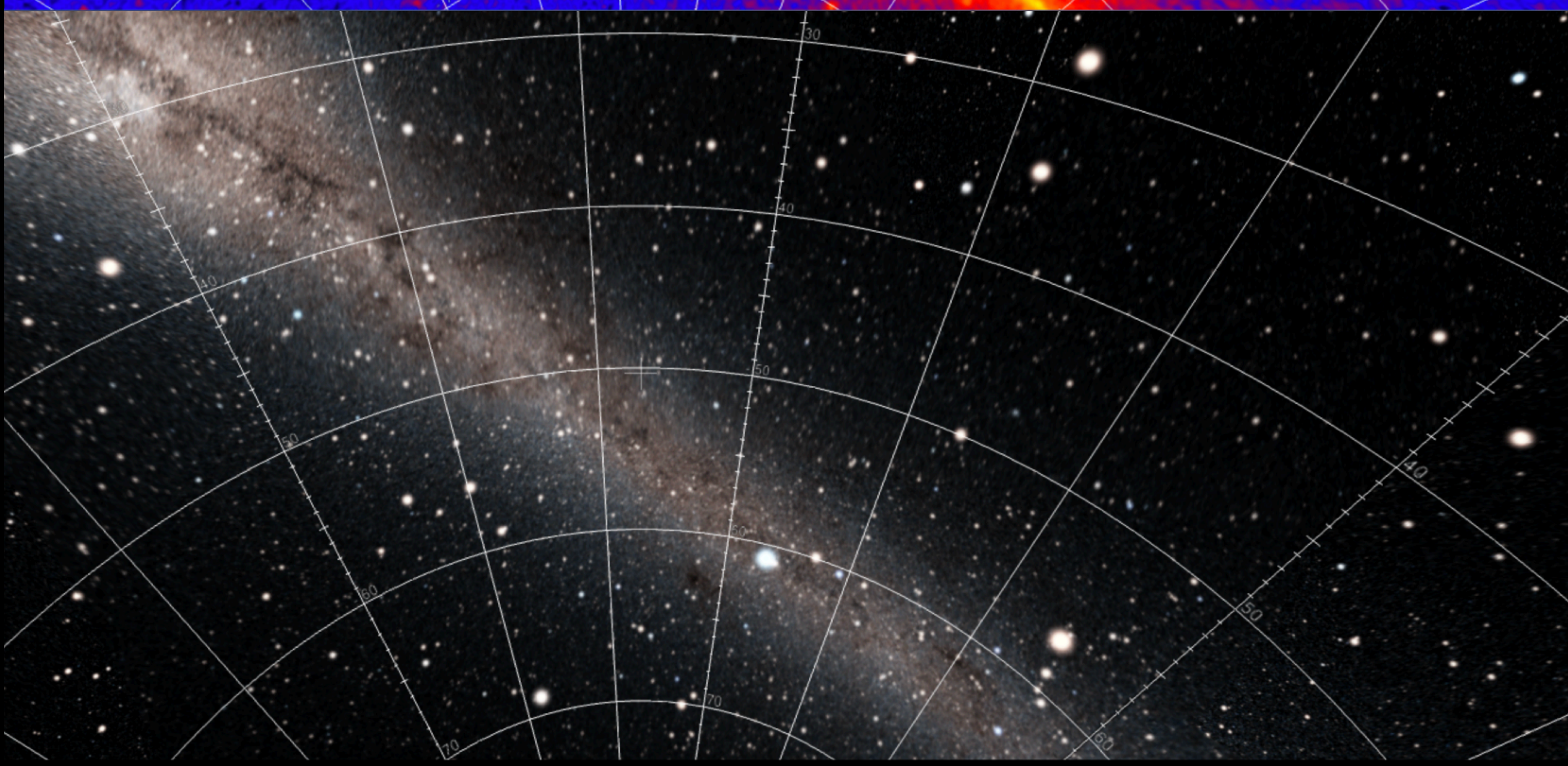
WMAP 5-year



Planck



Fermi (γ-ray)



2MASS (infrared)

Today

- Types of dark matter
- The numbers that describe cosmology
- Combining experiments: concordance
- Checks, consequences, extensions
- The Hubble tension

Part 1: Types of dark matter

Participation: Components

TurningPoint:
What are the major components of matter in the Universe, sorted from large to small?

Session ID: diemer

30 seconds

Participation: Rotation curves

TurningPoint:

Rising or constant rotation curves at large radii tell us that…

Session ID: diemer

30 seconds

Measuring the total mass of galaxies

- In the outermost parts of galaxies, v(r) is measured from hydrogen gas rather than stars
- While there is enough diffuse gas to measure v(r), it adds only a tiny amount of mass
- Orbital velocity stays **almost constant** as far out as we can track it
- Means that **enclosed mass increases linearly with distance**, even beyond the radius where starlight stops
- Meaning… there is a lot of non-luminous matter in galaxies: **dark matter!**

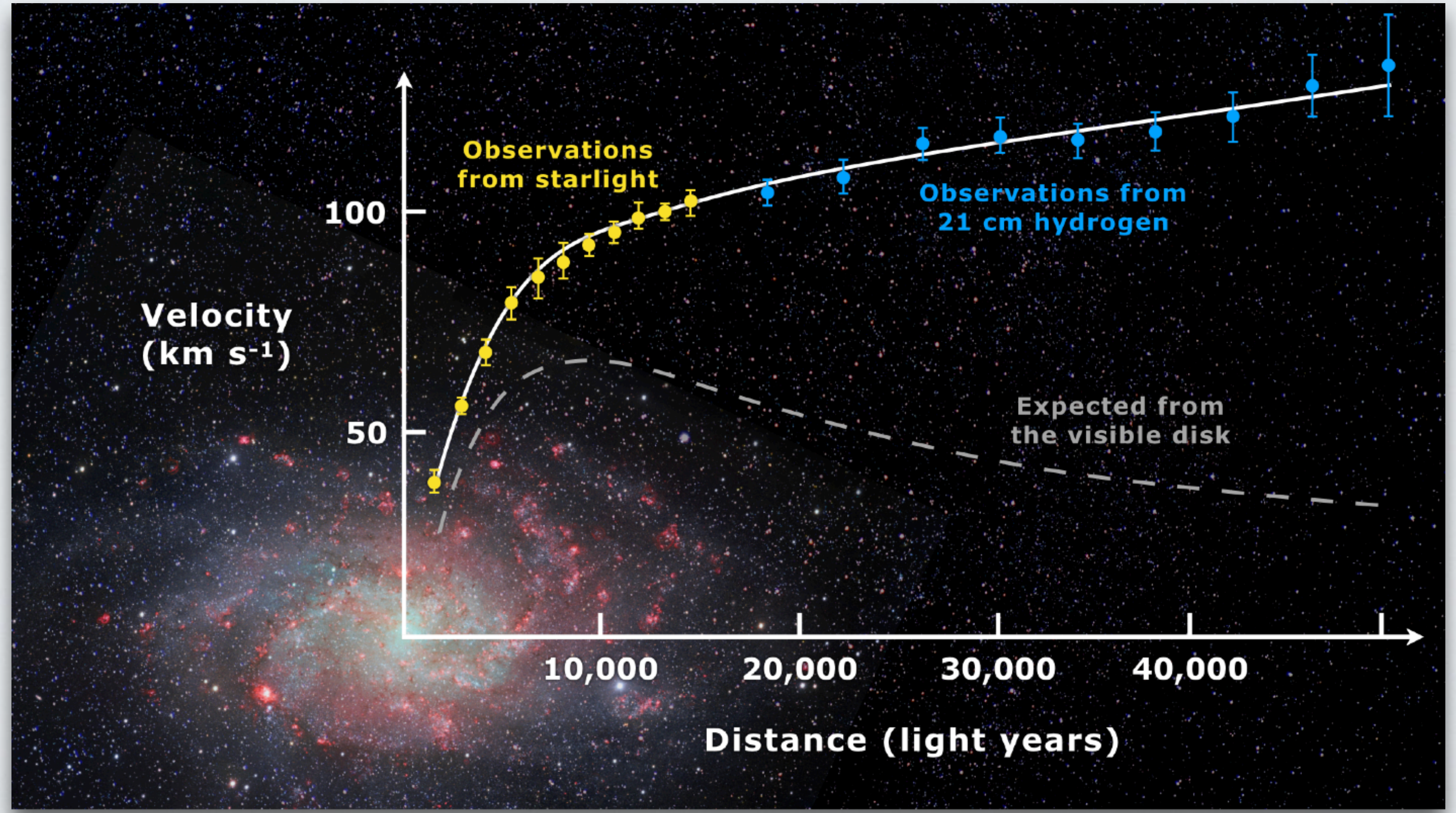


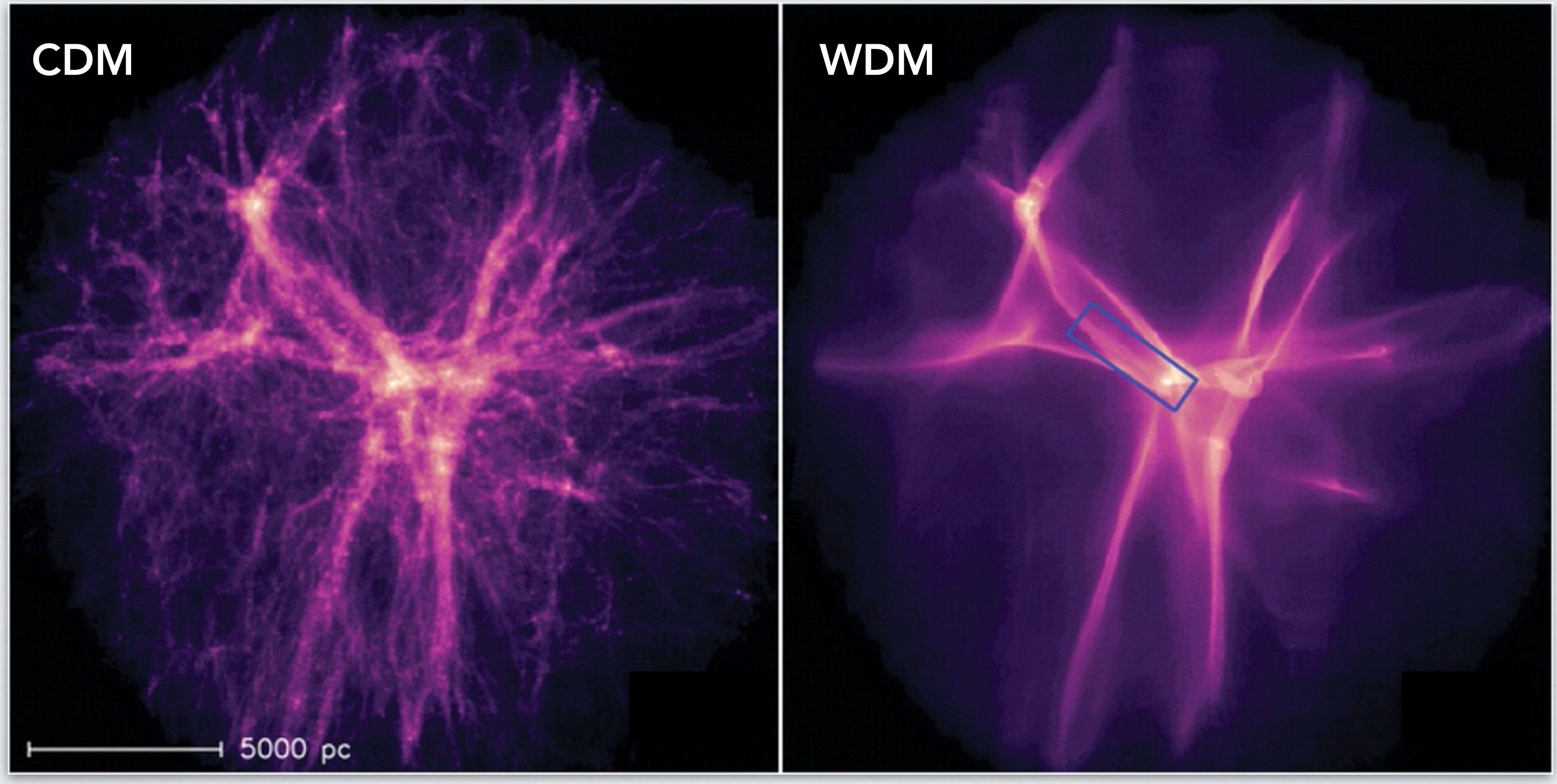
Image: Wikipedia

Dark matter halos

- Galaxies are surrounded by **dark matter halos**
- **Size of galaxies is 1-2%** the size of halos
- Halos are often very roughly spherical, but can have complex shapes
- Higher density of dark matter at the center

Dark matter

- Very likely one or multiple sub-atomic particle(s)
- Particles have a temperature:
  - **Cold Dark Matter (CDM)** = no or small initial velocities
  - **Warm Dark Matter (WDM)** = moderate initial velocities
  - **Hot Dark Matter (HDM)** = relativistic initial velocities near c
- Temperature determines the **structures** dark matter can form
- Warm/hot dark matter resists clumping by gravity more than cold DM
- Our Universe seems to contain **cold** dark matter



Gao & Theuns 2007

Dark matter

Poll at "Astrophysical Windows on Dark Matter" conference, 2021

Part 2: The numbers that describe cosmology

Participation: Free parameters

TurningPoint:
How many free parameters are we going to need to describe cosmology?

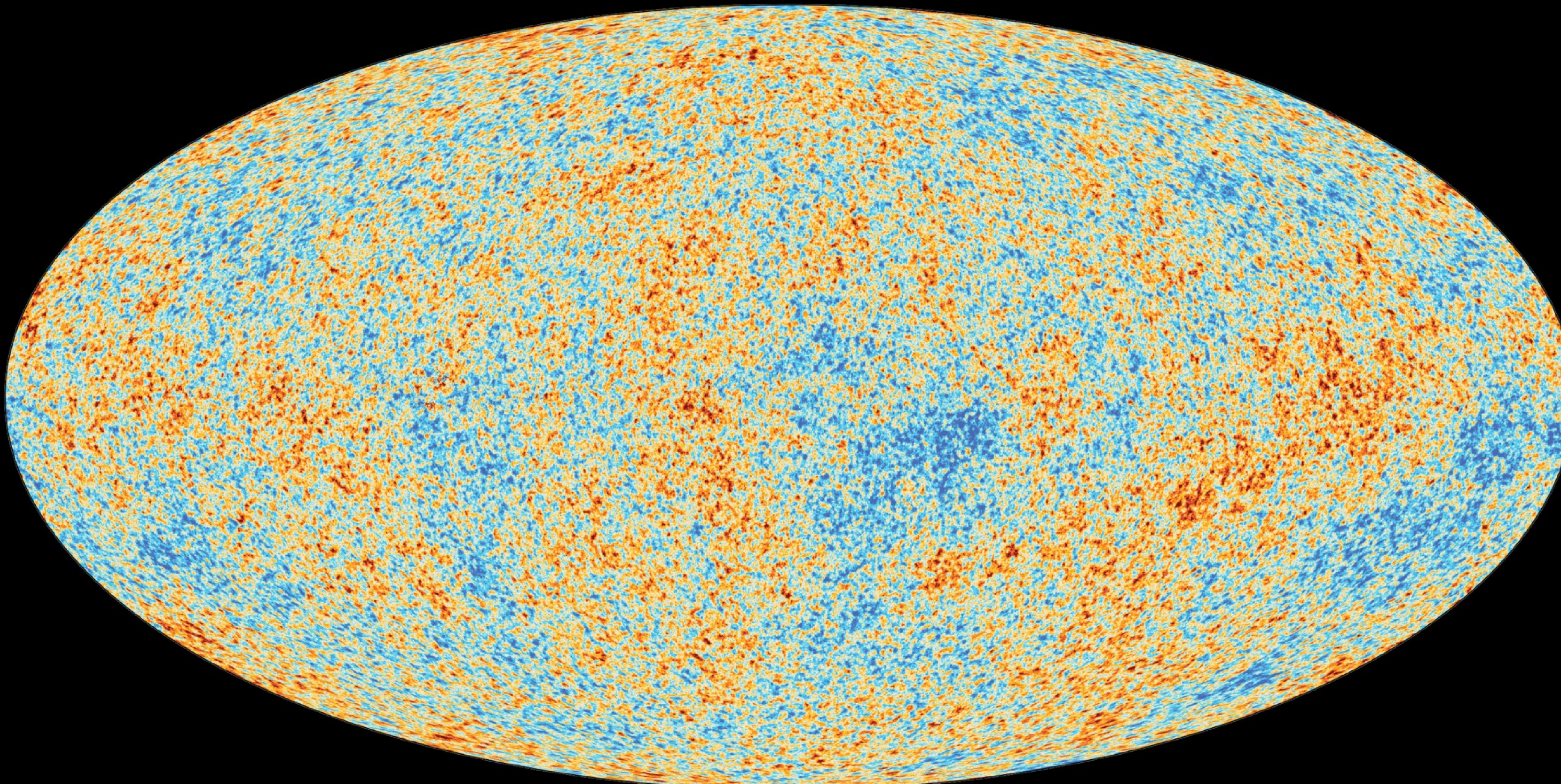
Session ID: diemer

30 seconds

The ΛCDM model

- Λ = Cosmological constant
- CDM = Cold Dark Matter
- ΛCDM = A Big Bang cosmology that contains cold dark matter, baryons, and a cosmological constant

Planck CMB Map



ESA / Planck

Participation: CMB

TurningPoint:
What are the spots in the CMB?

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30 seconds

Parameters of the ΛCDM model

$\Omega_{\mathrm{m},0}$	Matter density in units of crit. dens. today
$\Omega_{\mathrm{b},0}$	Baryon density in units of crit. dens. today
$\Omega_{\mathrm{k},0}$	Curvature density in units of crit. dens. today
$\Omega_{\Lambda,0}$	Cosmological constant dens. in units of crit. dens. today
H_0	Hubble expansion rate today
t_0	Age of Universe
z_{rec}	Redshift of recombination
τ	How many CMB photons are absorbed on the way to us
A_{s}	Strength of quantum fluctuations
n_{s}	Dependence of quantum fluctuations on scale

Density parameters are not all independent:

$$\Omega_{\mathrm{m},0} + \Omega_{\mathrm{k},0} + \Omega_{\Lambda,0} = 1$$

Matter includes dark matter and baryons:

$$\Omega_{\mathrm{m},0} = \Omega_{\mathrm{dark},0} + \Omega_{\mathrm{b},0}$$

Related via Ω_{X}

We did not talk about these parameters in detail. The fluctuation parameters refer to the original fluctuations present after inflation, their strength is

$$P(k) = A_{\mathrm{s}} \left(\frac{k}{k_0} \right)^{n_{\mathrm{s}}}$$

k = inverse wavelength

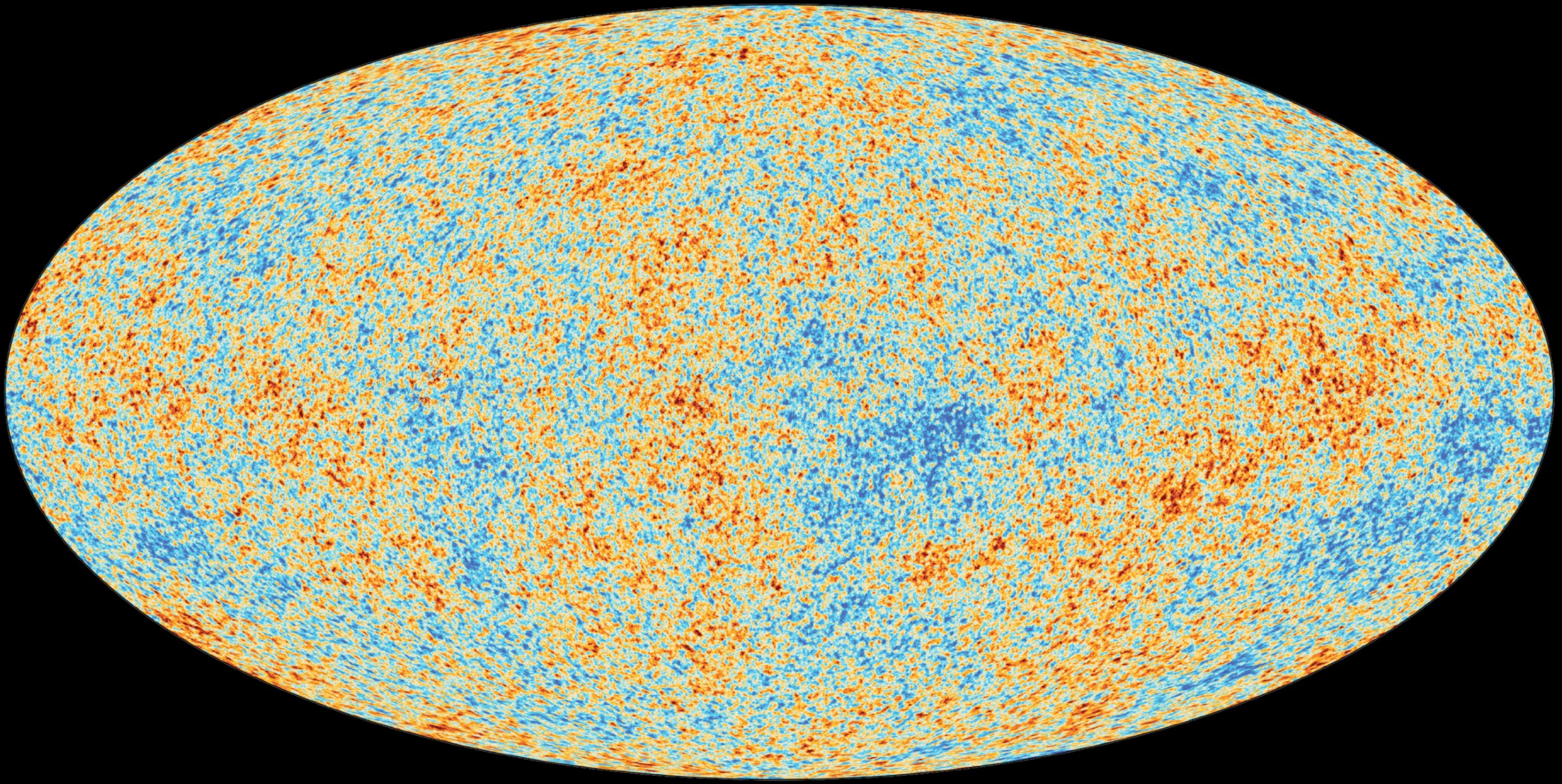
Parameters (flat ΛCDM)

$\Omega_{\mathrm{m},0}$	Matter density in units of crit. dens. today	CMB, rotation curves, Supernovae, lensing...
$\Omega_{\mathrm{b},0}$	Baryon density in units of crit. dens. today	CMB, Big Bang nucleosynthesis, baryons in clusters
H_0	Hubble expansion rate today	CMB, low-z redshift-distance diagram...
τ	How many CMB photons are absorbed on the way to us	CMB
A_s	Strength of quantum fluctuations	CMB
n_s	Dependence of quantum fluctuations on scale	CMB
$\Omega_{\Lambda,0}$	Cosmological constant dens. in units of crit. dens. today	$\Omega_{\Lambda,0} = 1 - \Omega_{\mathrm{m},0}$
$\Omega_{\mathrm{k},0}$	Curvature density in units of crit. dens. today	$\text{Flat} \implies \Omega_k = 0$
t_0	Age of Universe	Derived
z_{rec}	Redshift of recombination	Derived

measured by CMB

fixed or derived

Planck CMB Map



ESA / Planck

Power spectrum

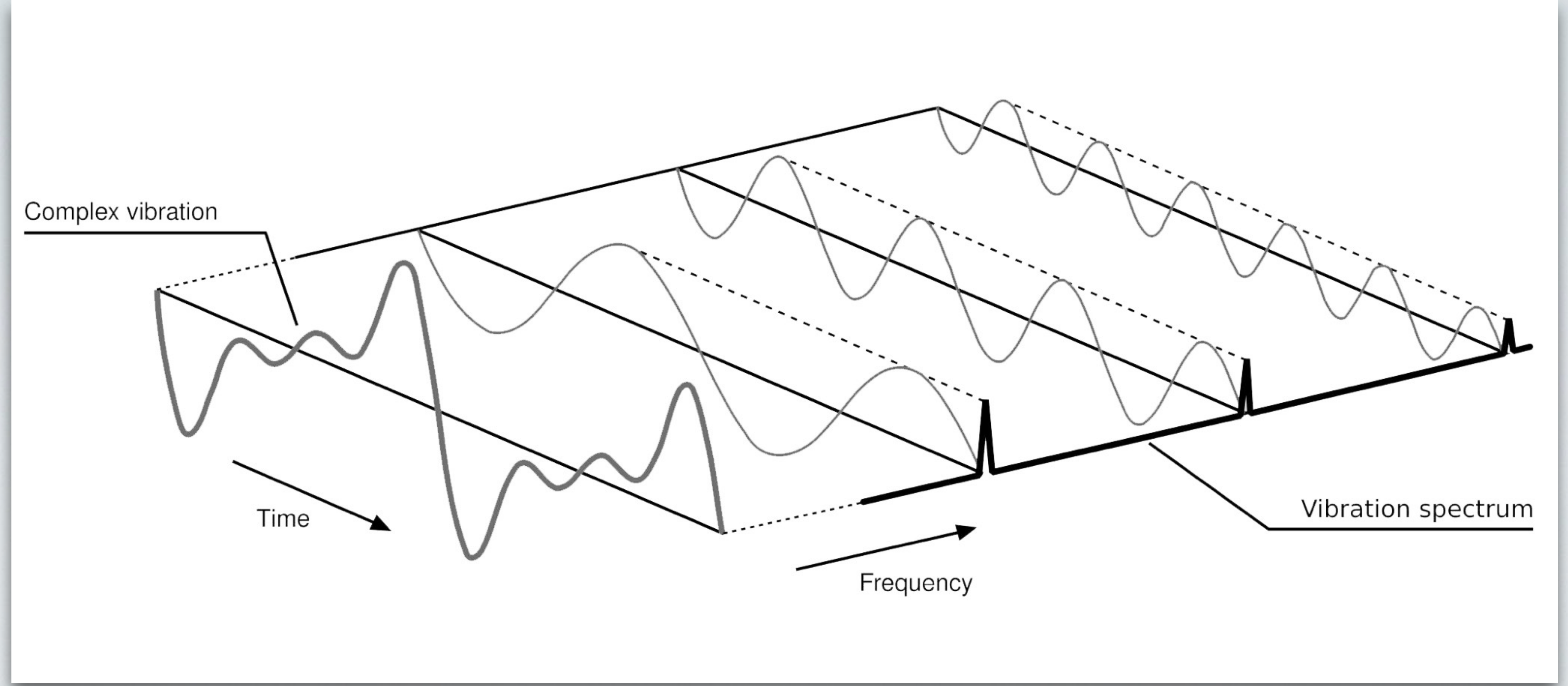


Image: Power-MI

Multipoles

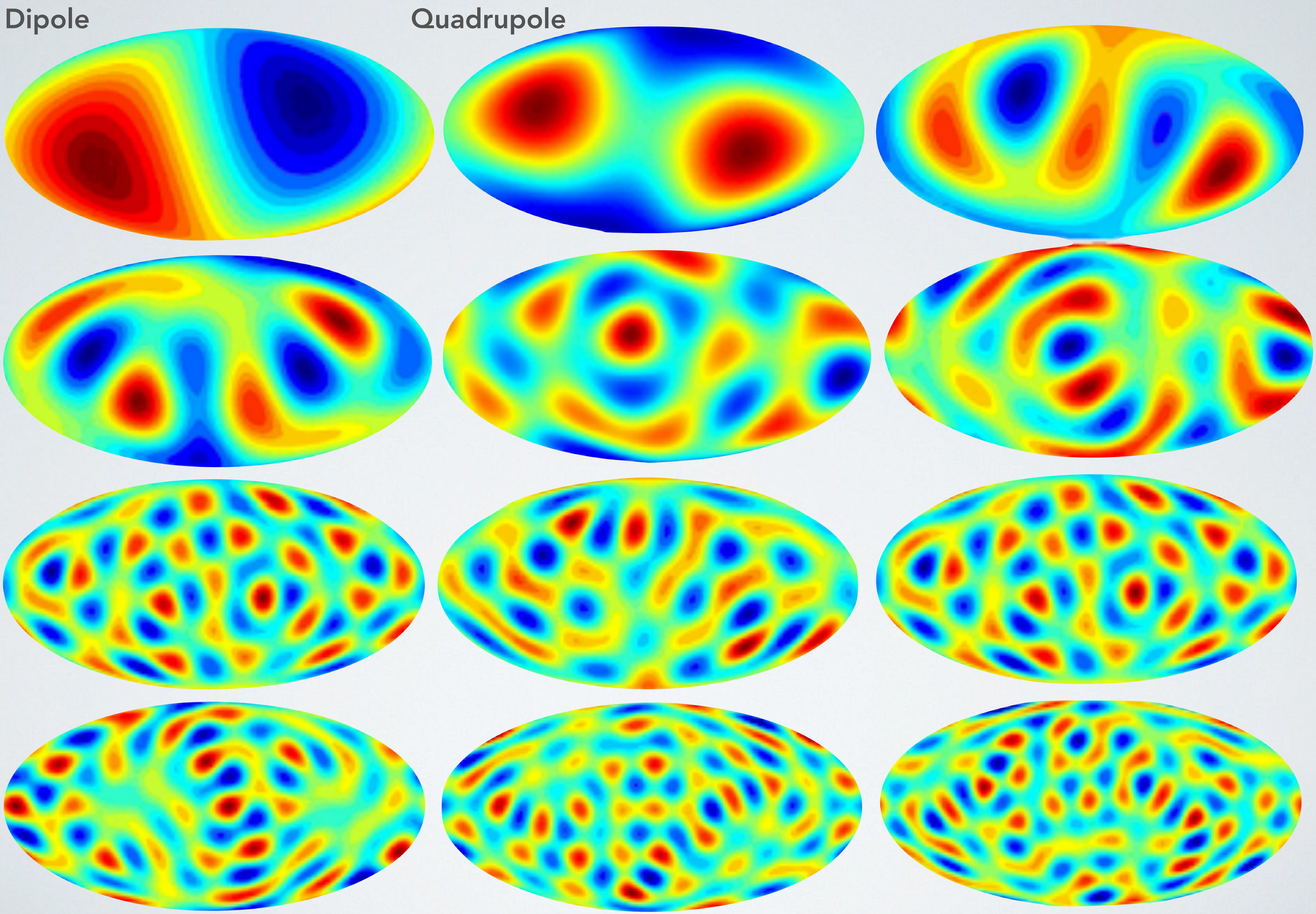
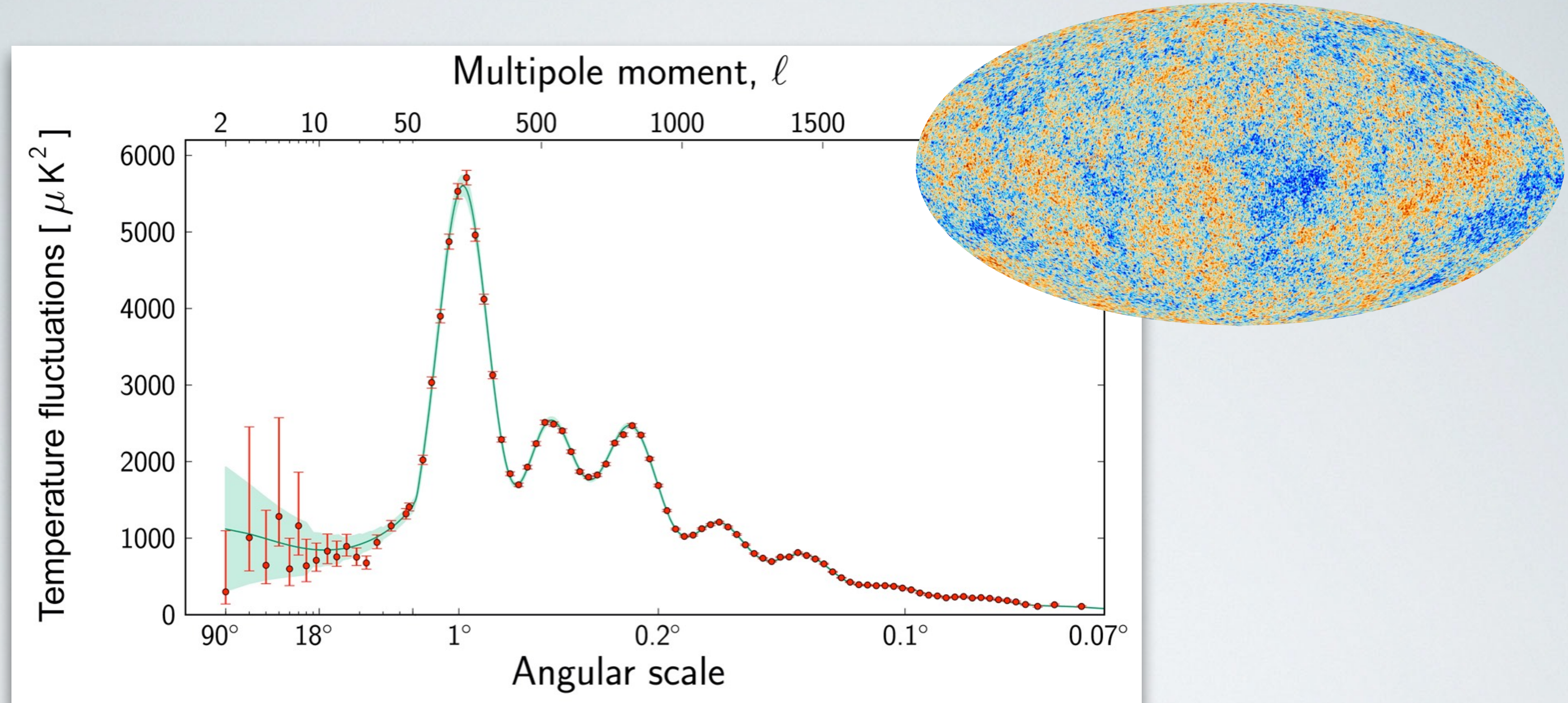


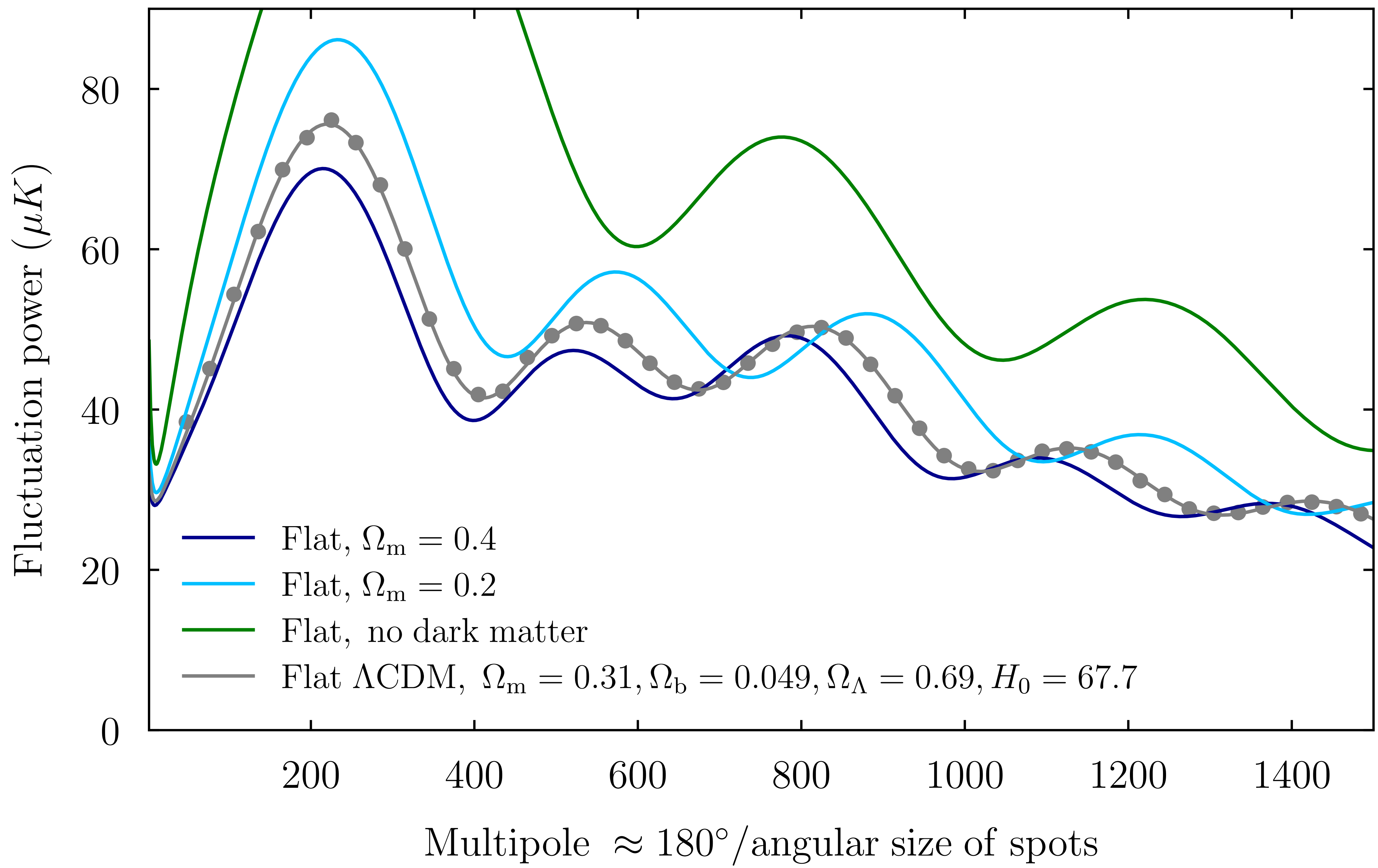
Figure by Ville Heikkilä

Power spectrum of fluctuations



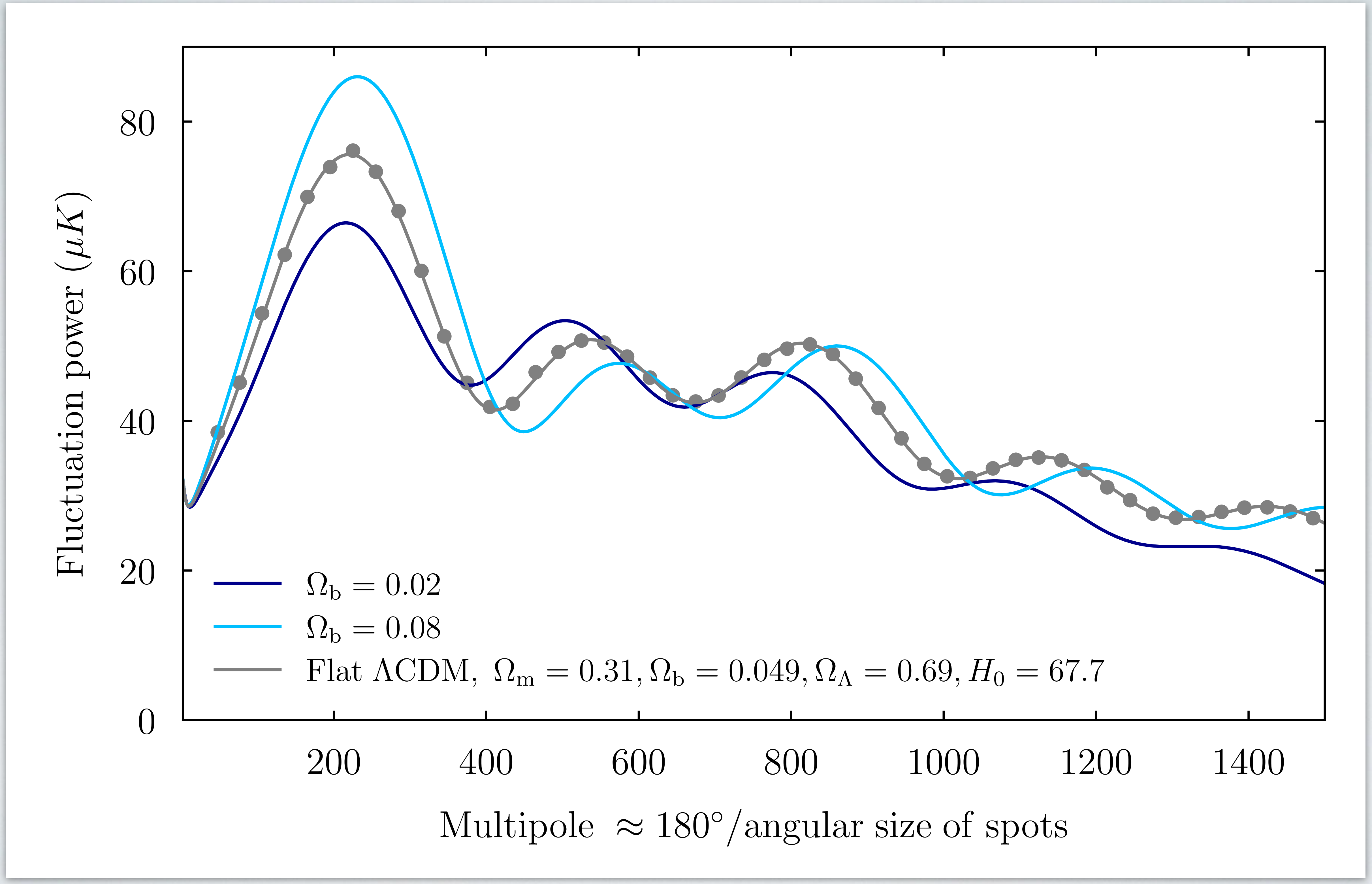
- Power spectrum = "how strong are fluctuations at a given scale"
- Most prominent fluctuation scale is about **1 degree**
- Our **model of cosmology matches the data extremely well** (green line)
- Compute model predictions with a **computer code**

CMB with different amounts of dark matter



Made with CAMB • Planck data

CMB with different amounts of baryons



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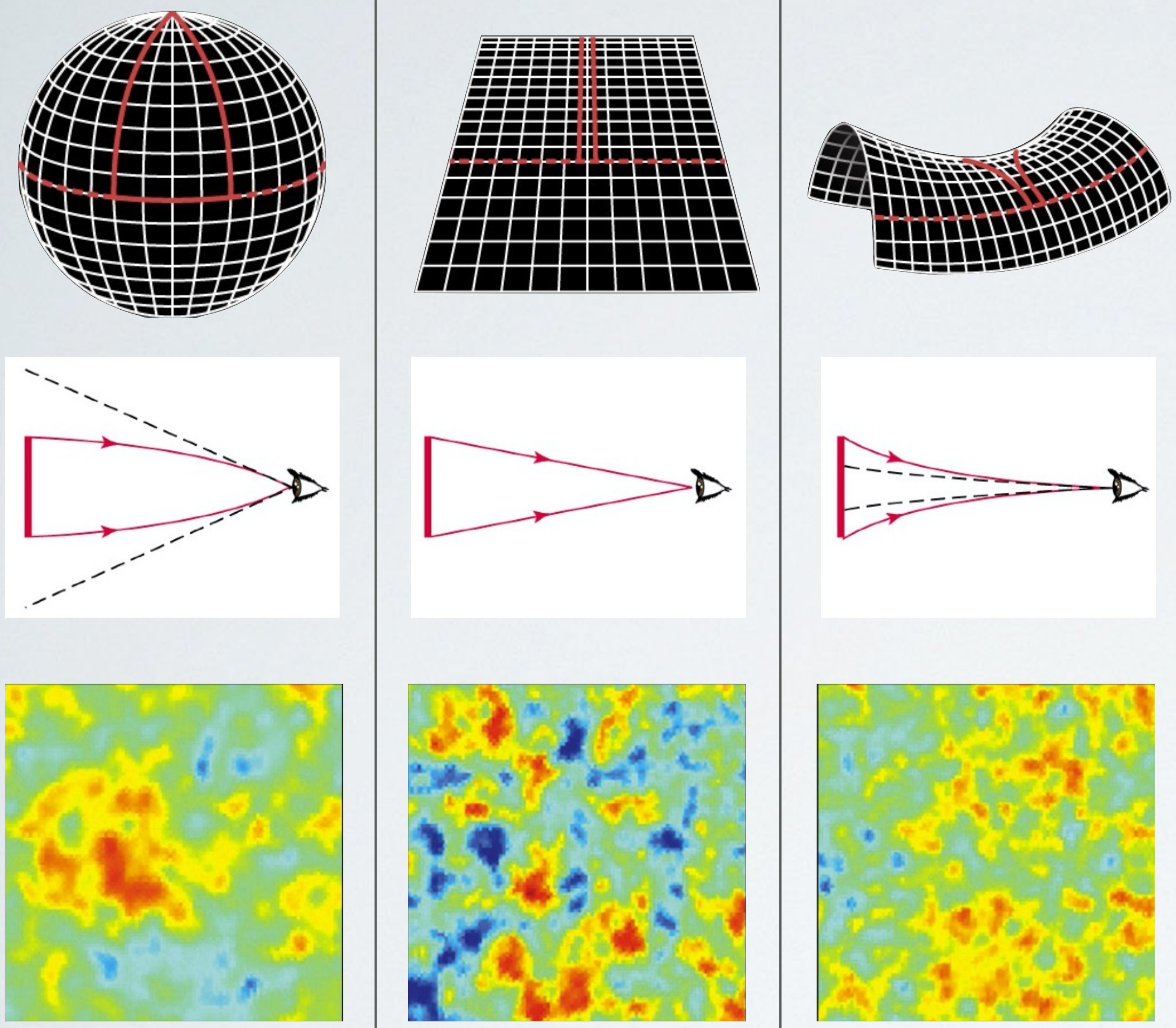
Curvature of the Universe



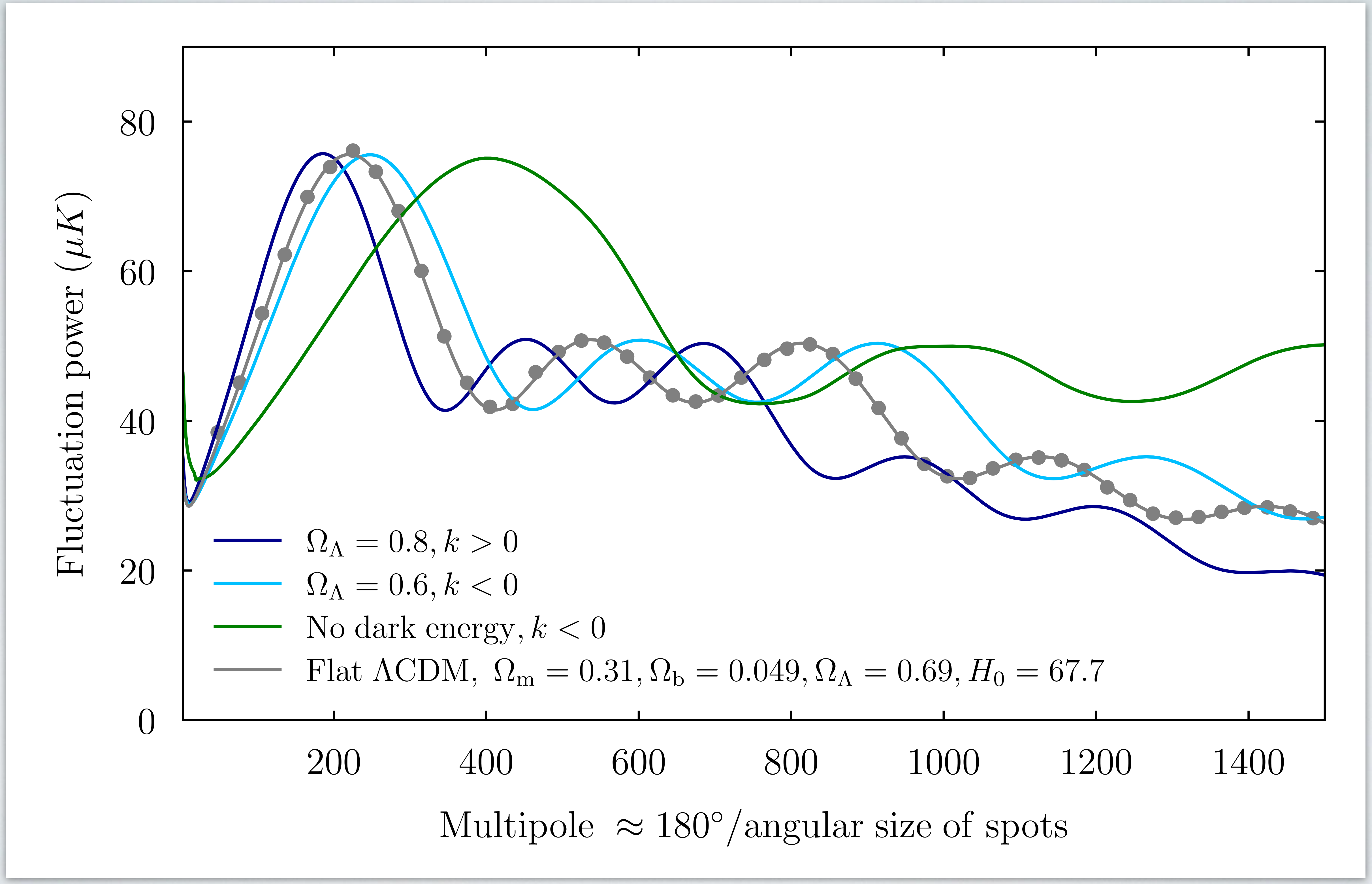
Closed (k > 0), spots appear larger

Flat (spots appear in actual size)

Open (k < 0), spots appear smaller

- We understand the physics of the CMB patches very well, so we know what size they should be
- If the Universe was strongly curved, the apparent size of the patches would change
  - Larger if positively curved, because lines converge
  - Smaller if negatively curved, because lines diverge
- All CMB measurements are compatible with k = 0 (flat)

CMB with different amounts of dark energy



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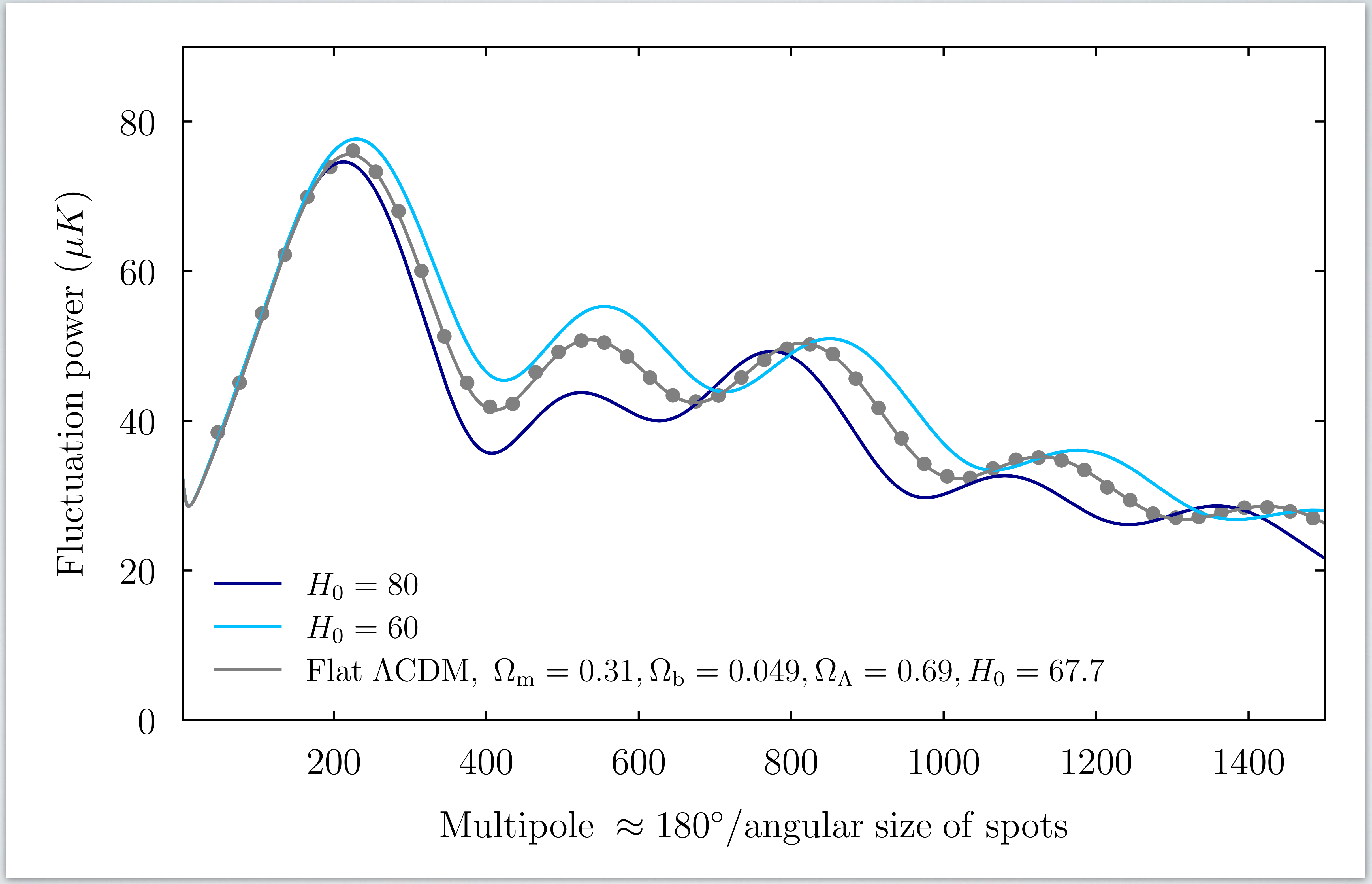
CMB with different H0



Made with CAMB • Planck data

Part 3: Combining experiments: Concordance

Participation: Distance ladder

TurningPoint:
What are the steps of the distance ladder (from nearby to far)?

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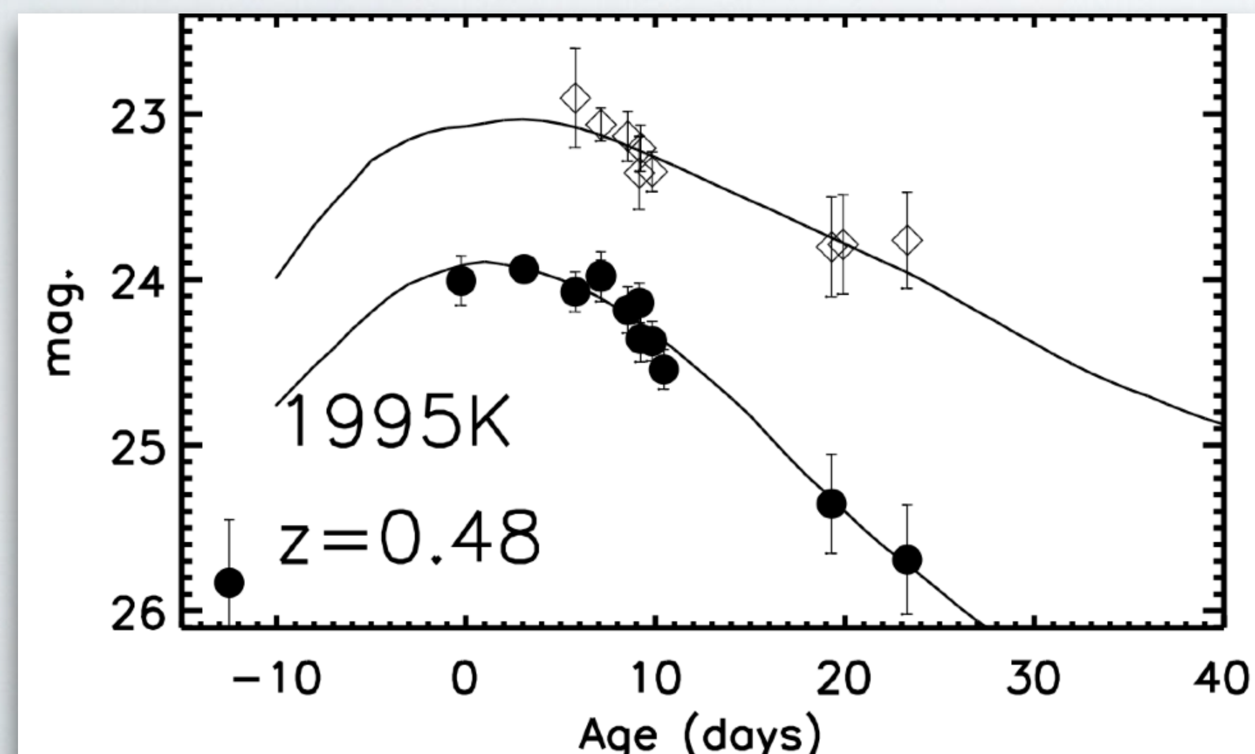
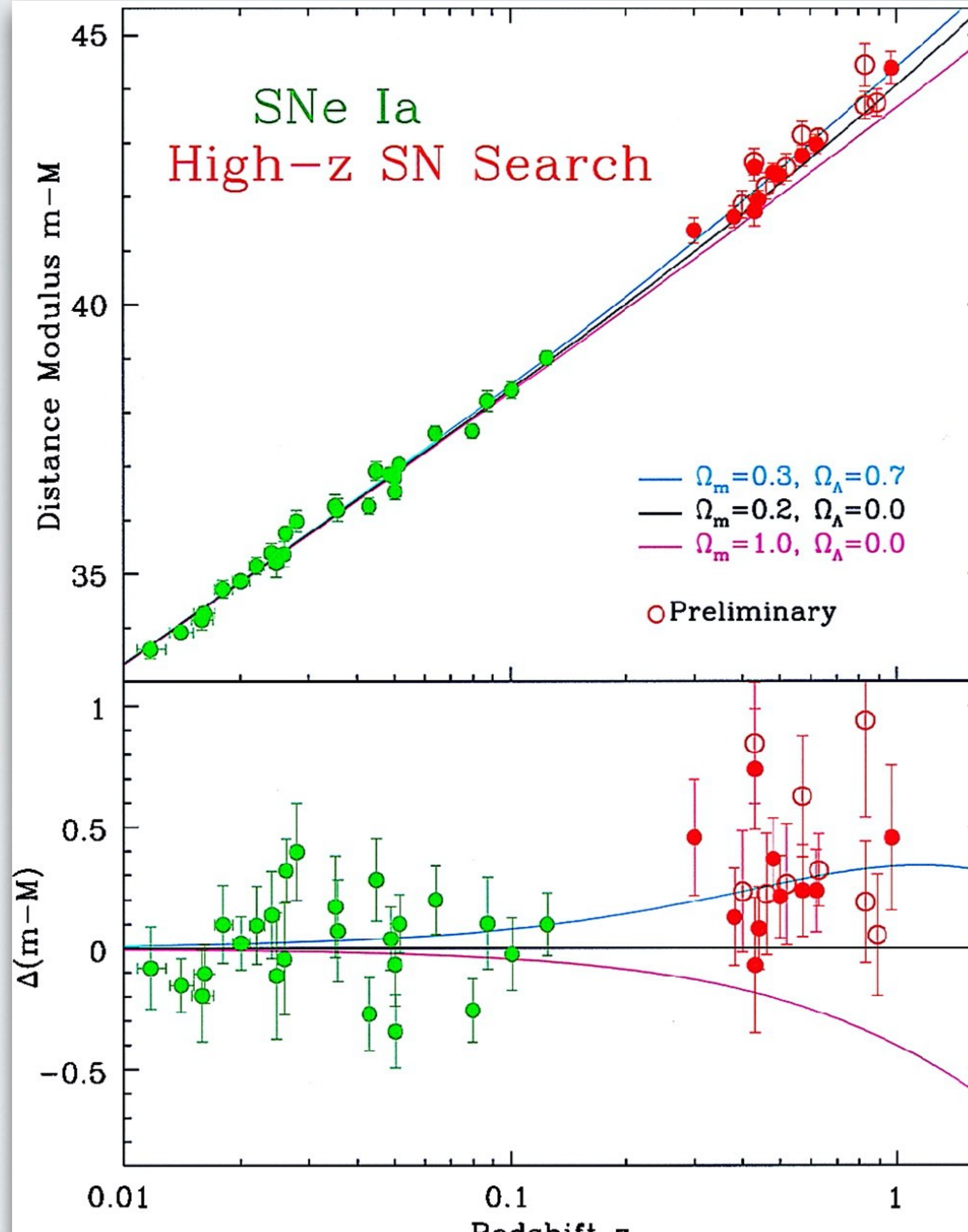
30 seconds

First measurement of accelerating expansion

- Not always easy to even find the peak luminosity of a supernovae
- Data shows very slim preference for model with dark energy

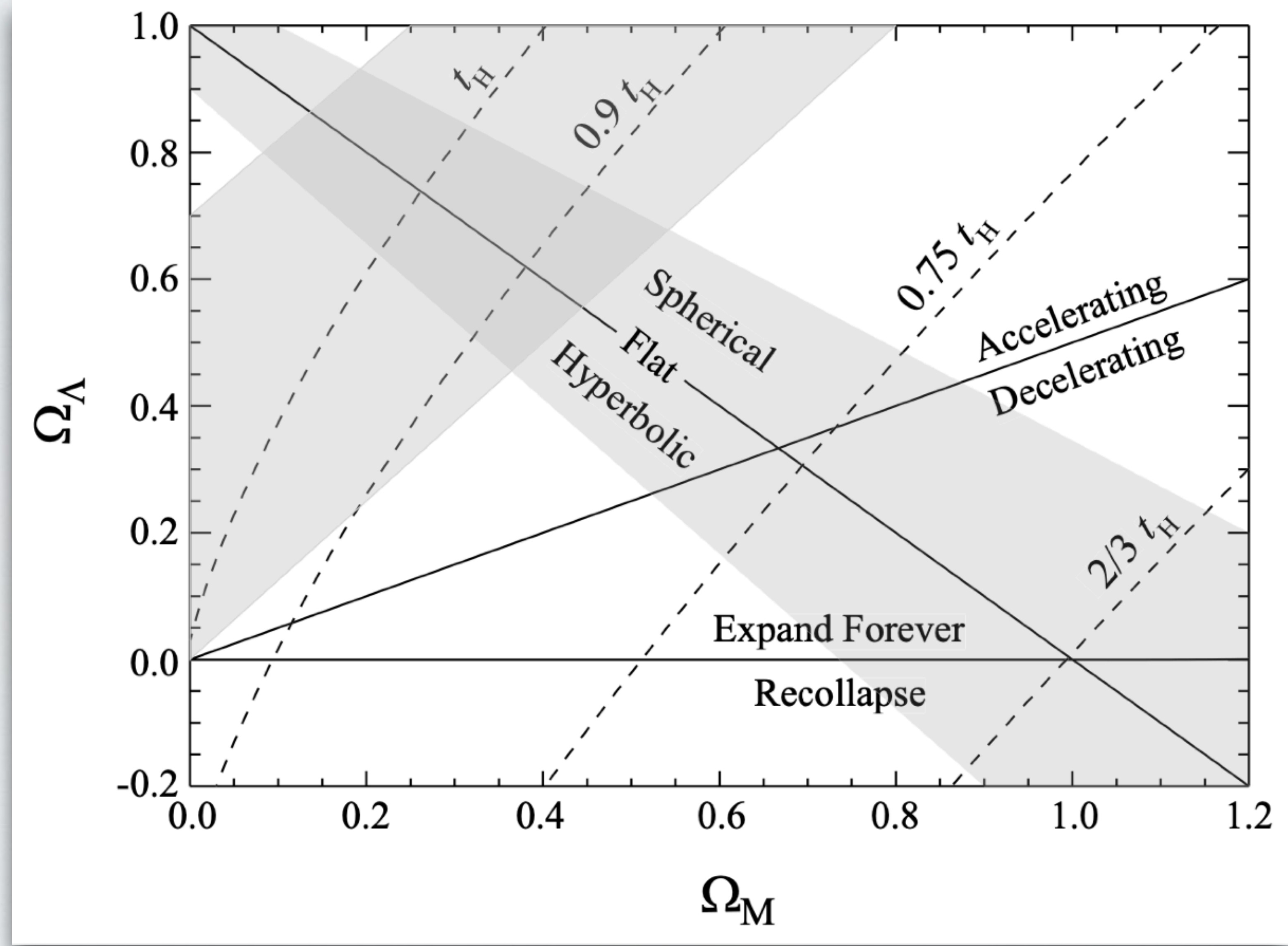




Riess et al. 1998 • Perlmutter et al. 1999

Relationships between parameters

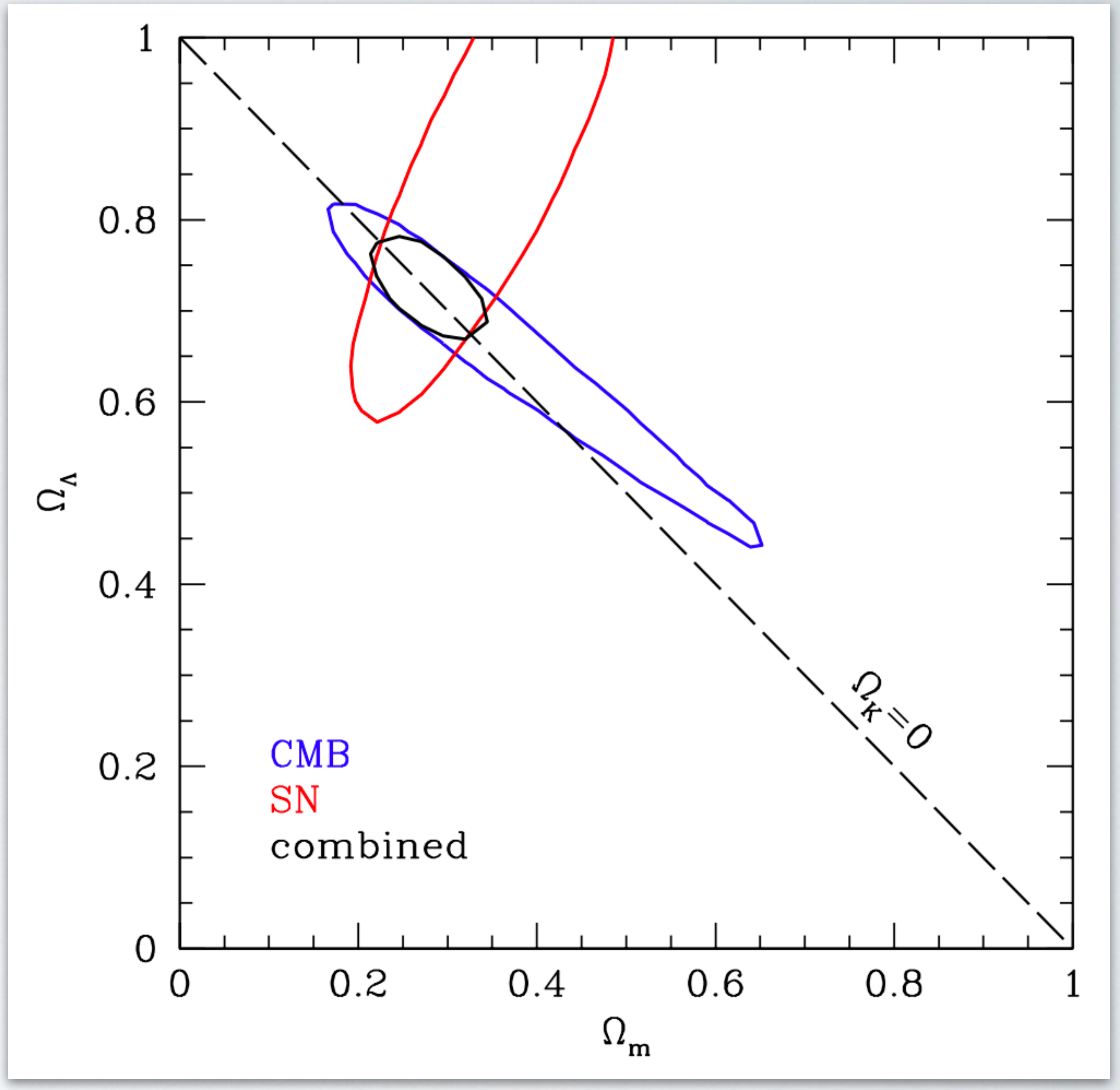
- We cannot plot all 6 parameters in one graph, but we can consider two
- The $\Omega_m - \Omega_\Lambda$ plane is particularly instructive



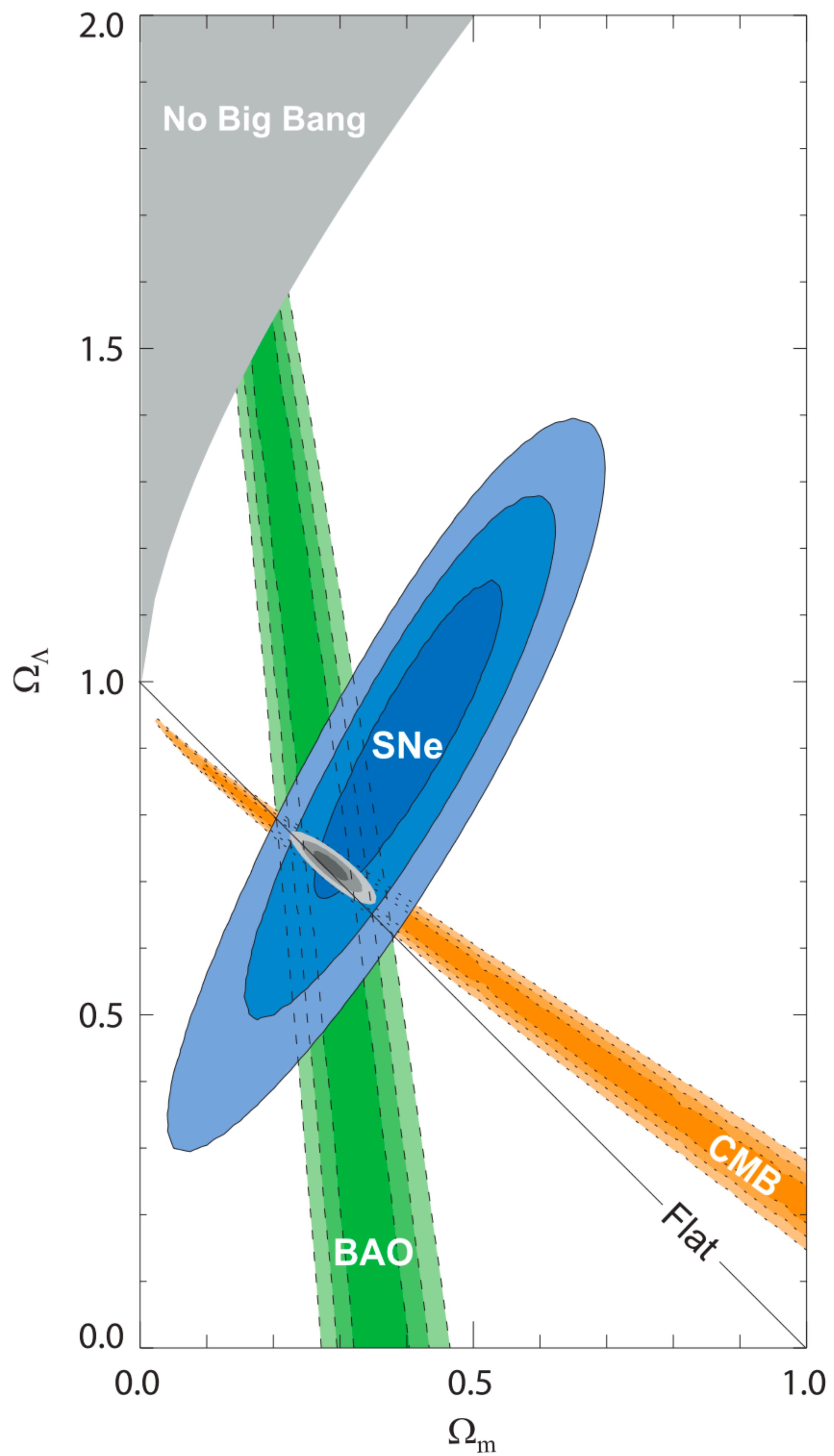
Hawley & Holcomb

Combining measurements

- CMB strongly prefers a flat (or close to flat) Universe
- There is **flexibility** in Ω_m and Ω_Λ, as long as the other adjusts
- Supernovae don't tell us about flatness but about balance between matter (gravity) and expansion
- **Combining** the two measurements gives much **tighter constraints**



Weinberg et al. 2013



Concordance

- **Concordance = agreement between different ways to measure cosmological parameters**
- BAO = "baryon acoustic oscillations", signature of sound waves from the early Universe
- All three probes can agree on a narrow area in the $\Omega_m - \Omega_\Lambda$ "parameter space"
- That is not obvious, and gives us confidence!

Kowalski et al. 2008

Concordance cosmology (Planck 2018 + BAO)

$\Omega_{\rm m,0}$	0.31	Matter density in units of crit. dens. today	CMB, rotation curves, Supernovae, lensing…
$\Omega_{\rm b,0}$	0.049	Baryon density in units of crit. dens. today	CMB, Big Bang nucleosynthesis, baryons in clusters
$\Omega_{\Lambda,0}$	0.69	Cosmological constant dens. in units of crit. dens. today	$\Omega_{\Lambda,0} = 1 - \Omega_{\rm m,0}$
$\Omega_{\rm k,0}$	0	Curvature density in units of crit. dens. today	Flat $\implies \Omega_k = 0$
H_0	$67.7 \ \frac{\rm km/s}{\rm Mpc}$	Hubble expansion rate today	CMB, low-z redshift-distance diagram…
t_0	13.79 Gyr	Age of Universe	Derived
$z_{\rm rec}$	1090	Redshift of recombination	Derived
τ	0.056	How many CMB photons are absorbed on the way to us	CMB
$A_{\rm s}$	2.1×10^{-9}	Strength of quantum fluctuations	CMB
$n_{\rm s}$	0.967	Dependence of quantum fluctuations on scale	CMB

measured by CMB

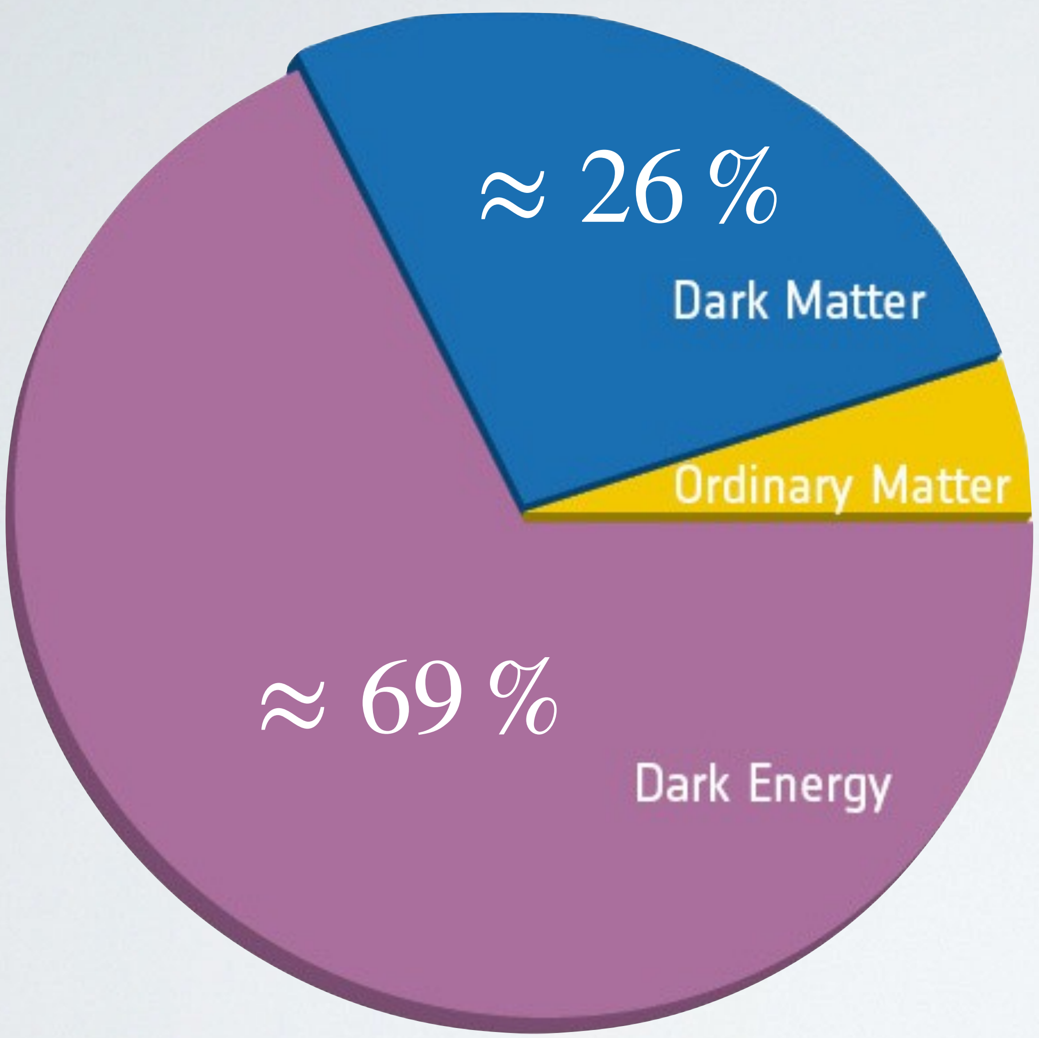
fixed or derived

Part 4: Checks, consequences, extensions

Age of the Universe

- We got an age of the Universe of $t_0 \approx 13.8\ \mathrm{Gyr}$
- That means we should not find anything older in the Universe
- Old (pre-1998) models that did not include dark energy gave $t_0 \approx 9\ \mathrm{Gyr}$
- But there are globular star clusters whose estimated ages are 12-14 Gyr
- Resolved by adding dark energy to the model

Contents of the Universe



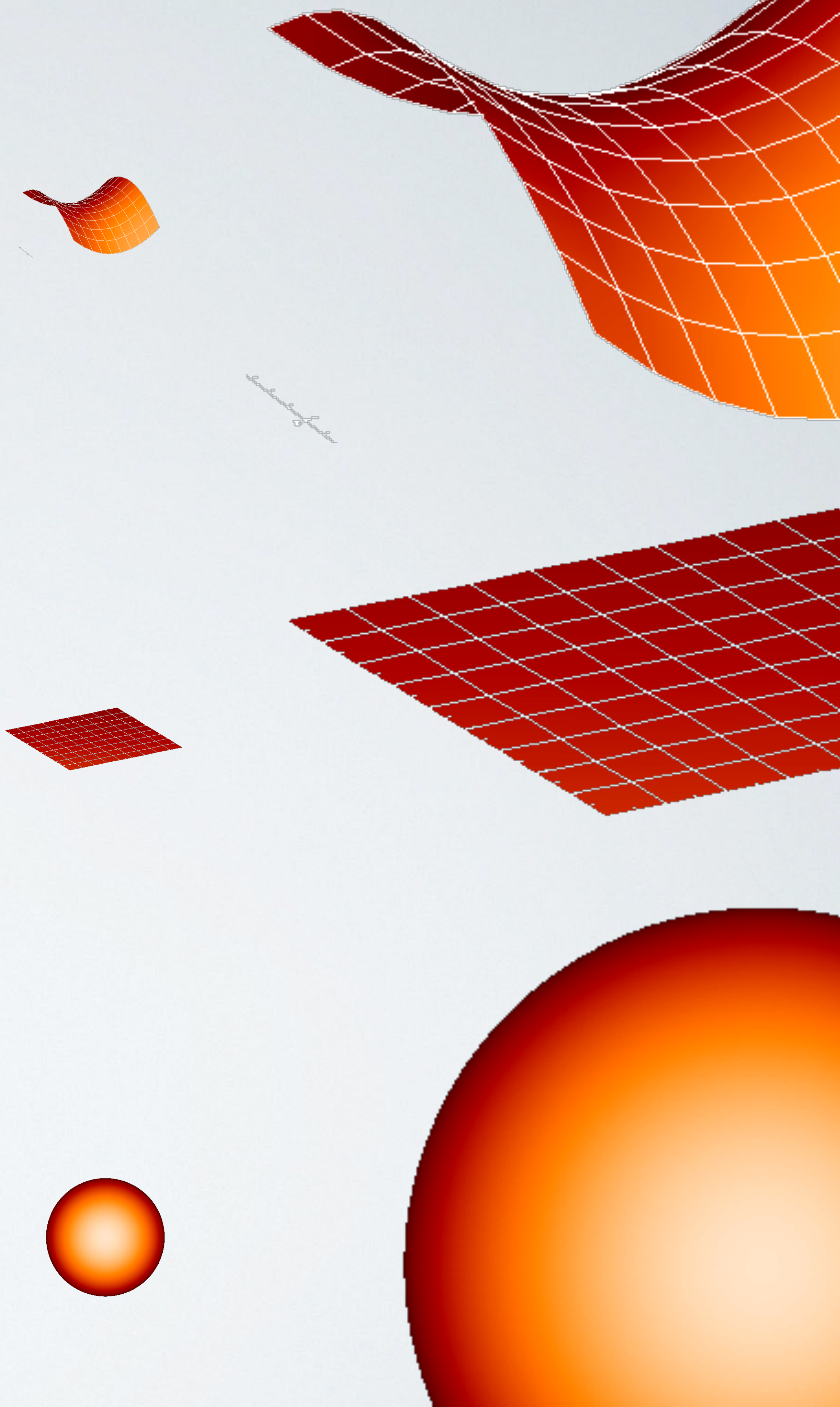
≈ 4.9 % baryons

- ≈ 4.6 % gas
- ≈ 0.3 % stars & remnants

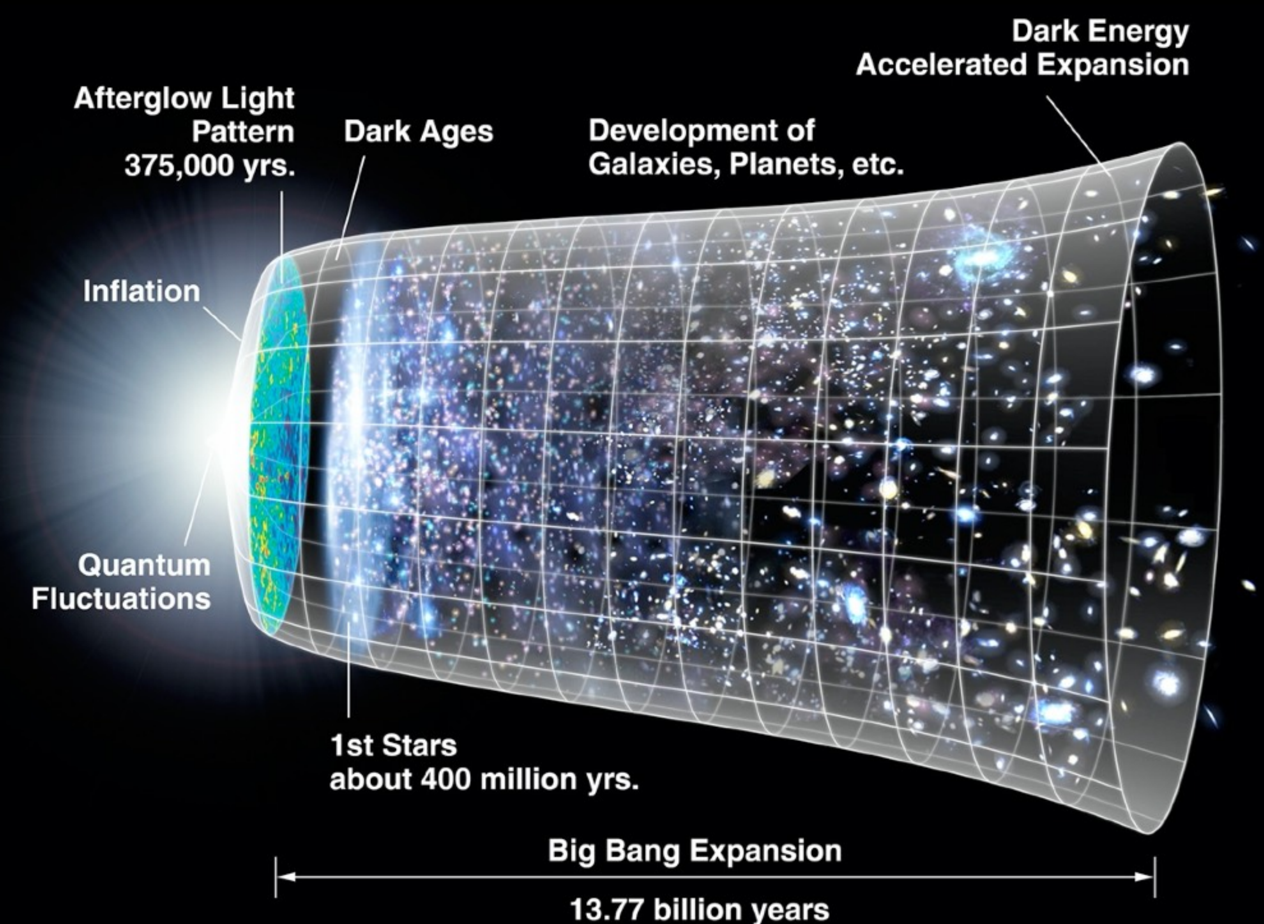
Walter et al. 2020

Flatness problem

- Why is the Universe flat?
- Must have been **even flatter** in the past
- One second after the Big Bang, $\Omega_k \leq 10^{-16}$ or so!
- Solved by **inflation** (see later lecture)



Possible extensions to ΛCDM model



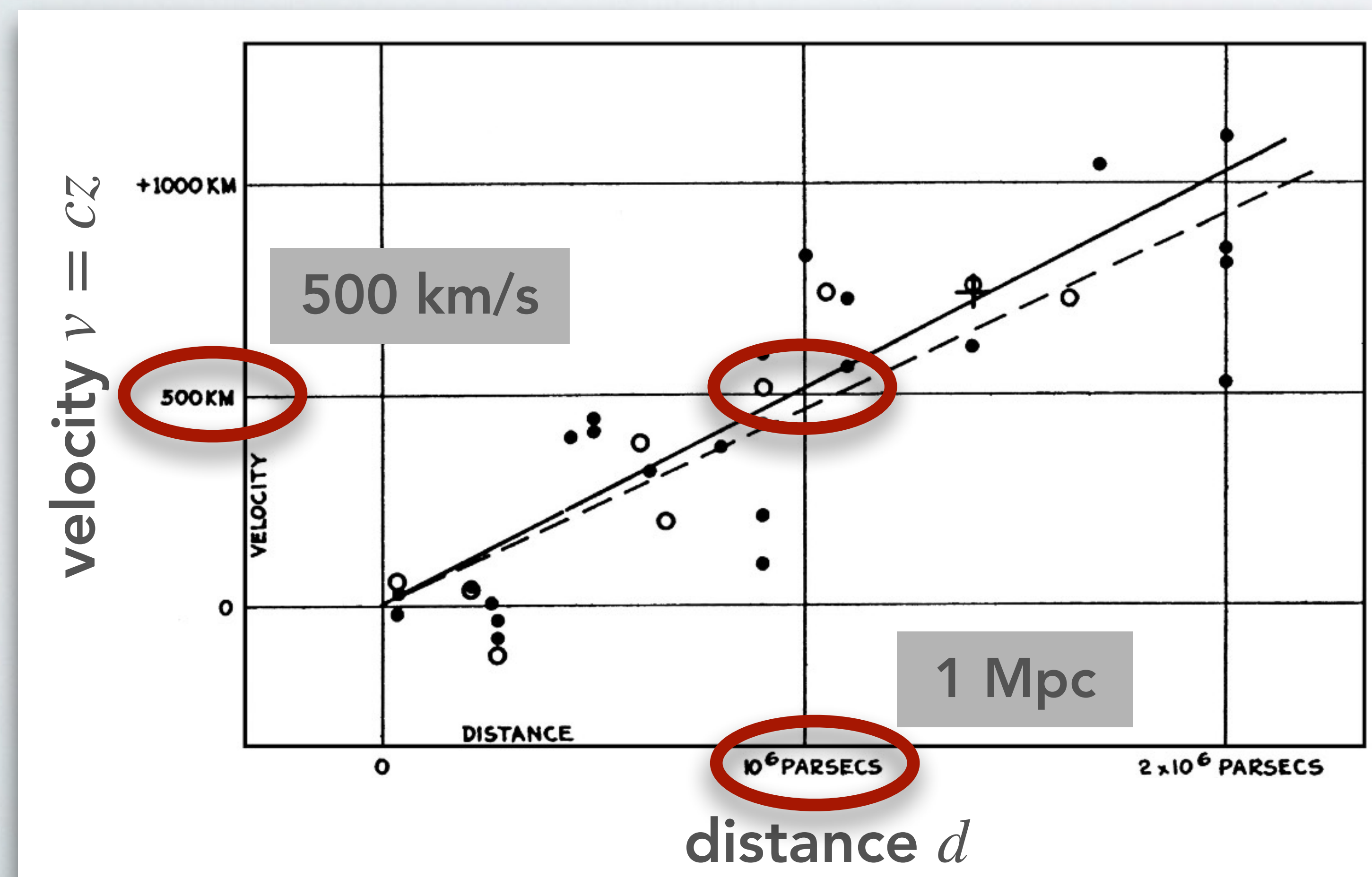
- Curvature ($\Omega_k \neq 0$)
- Non-Λ solutions for acceleration
  - Other dark energy models
  - Modified gravity (non-GR)
- Different spectrum of fluctuations after inflation
- Cosmic neutrinos
- Currently, there is **no convincing evidence** for any of these
- Remarkable given that flat ΛCDM has only **six free parameters!**

NASA / WMAP

Part 5: The Hubble tension

Hubble-Lemaitre law

- Slipher (1912) measured redshifts of some spiral nebulae, found **large velocities** (>1000 km/s) relative to MW
- Hubble and Humason systematically studied galaxies
  - Obtained **redshifts** from stellar spectra
  - Obtained **distances** using Cepheids and other estimates
- Interpreted redshift as Doppler shift, v/c (valid at low redshift)
- **Linear** relationship!
- Published in 1929; Lemaitre published same result in 1927 (in low-impact journal)



$$v = H_0 \times d$$

$$H_0 \approx 500 \frac{\text{km/s}}{\text{Mpc}}$$?


Vesto Slipher


Milton Humason


Georges Lemaitre

The first standard candle: Cepheid Variables

- Hubble got unlucky: there are **multiple types of Cepheids** with different period-luminosity relations!
- Combined with other observational errors, this gave very **wrong Hubble constant**

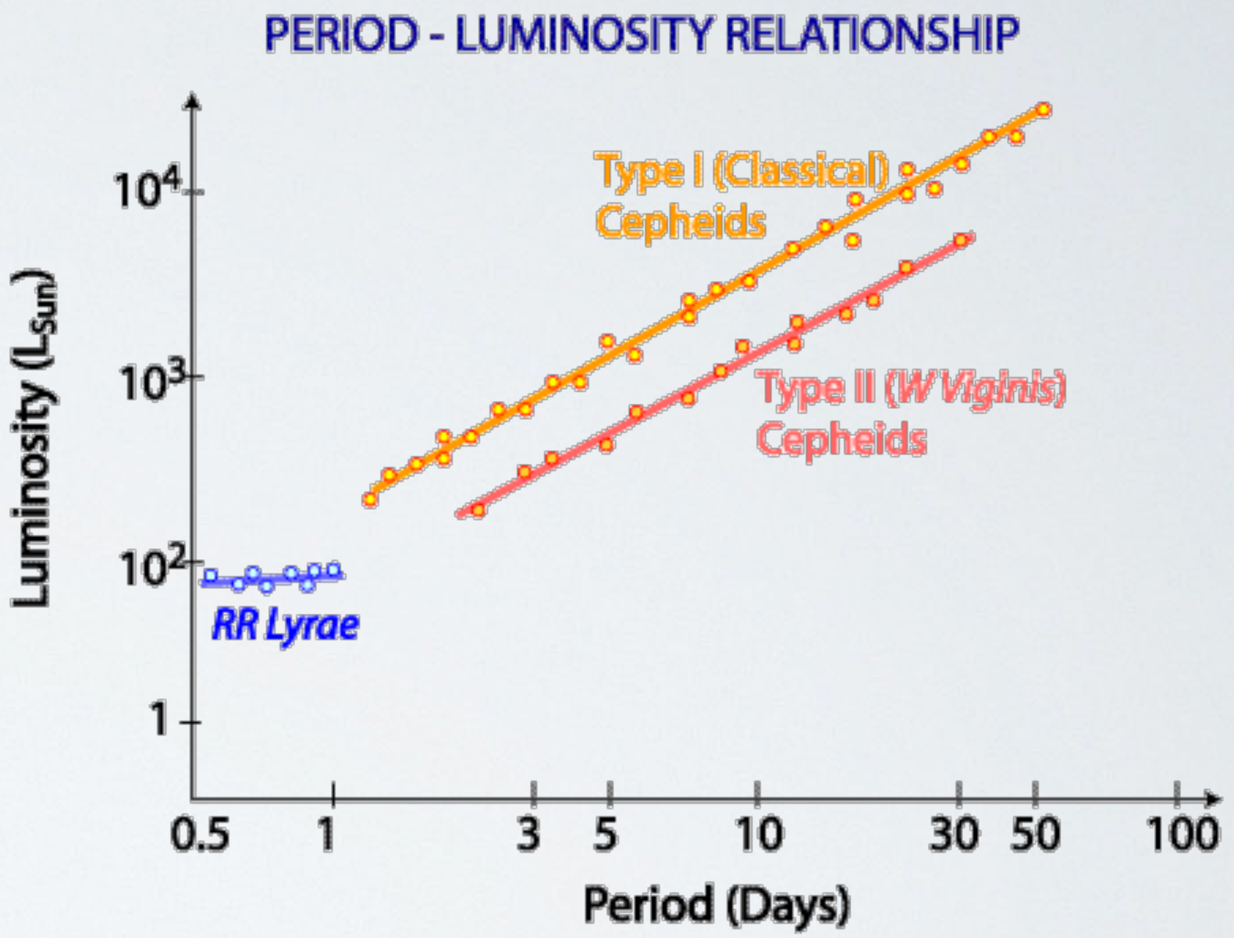
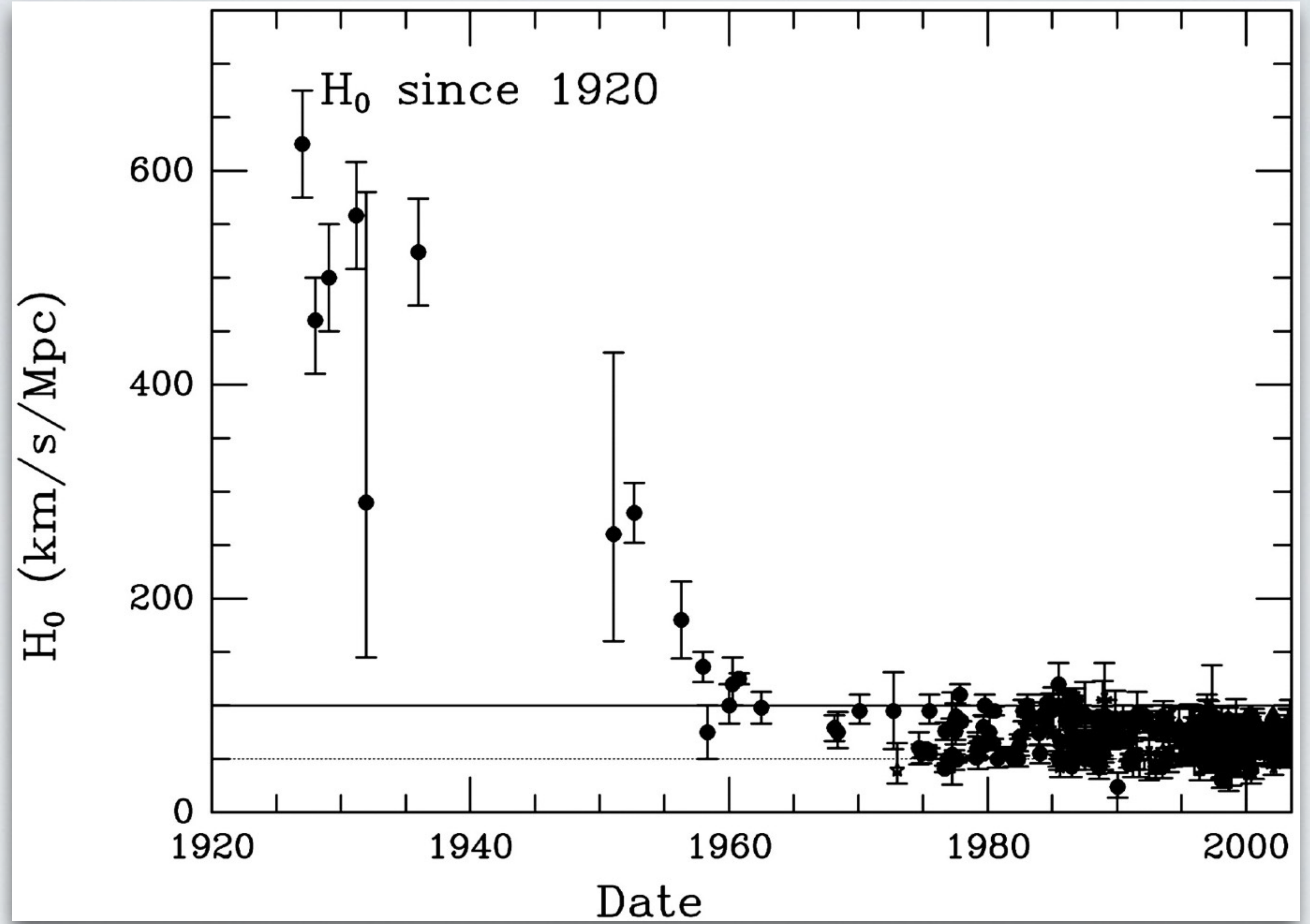


Image: hyperphysics.phy-astr.gsu.edu

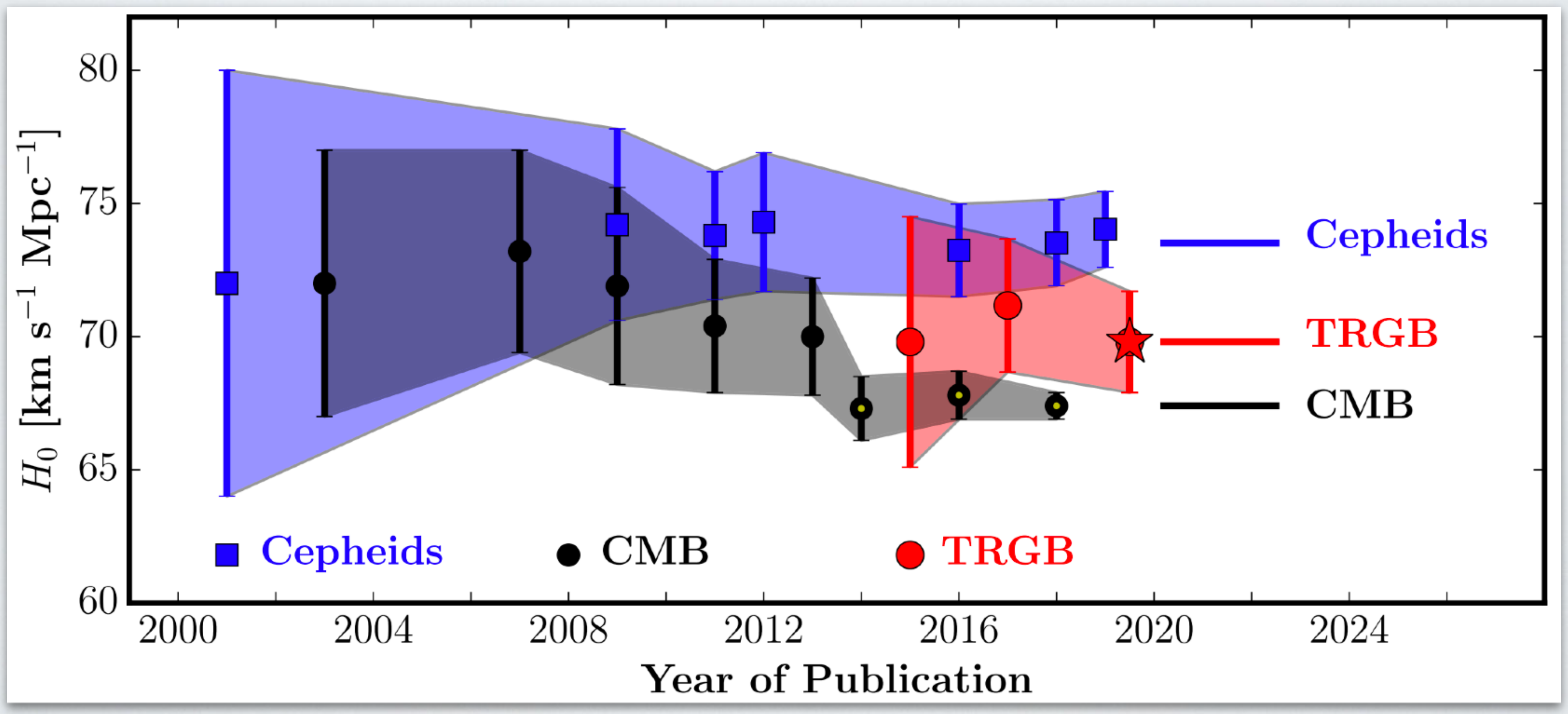
History of H_0 measurements



Kirschner 2004

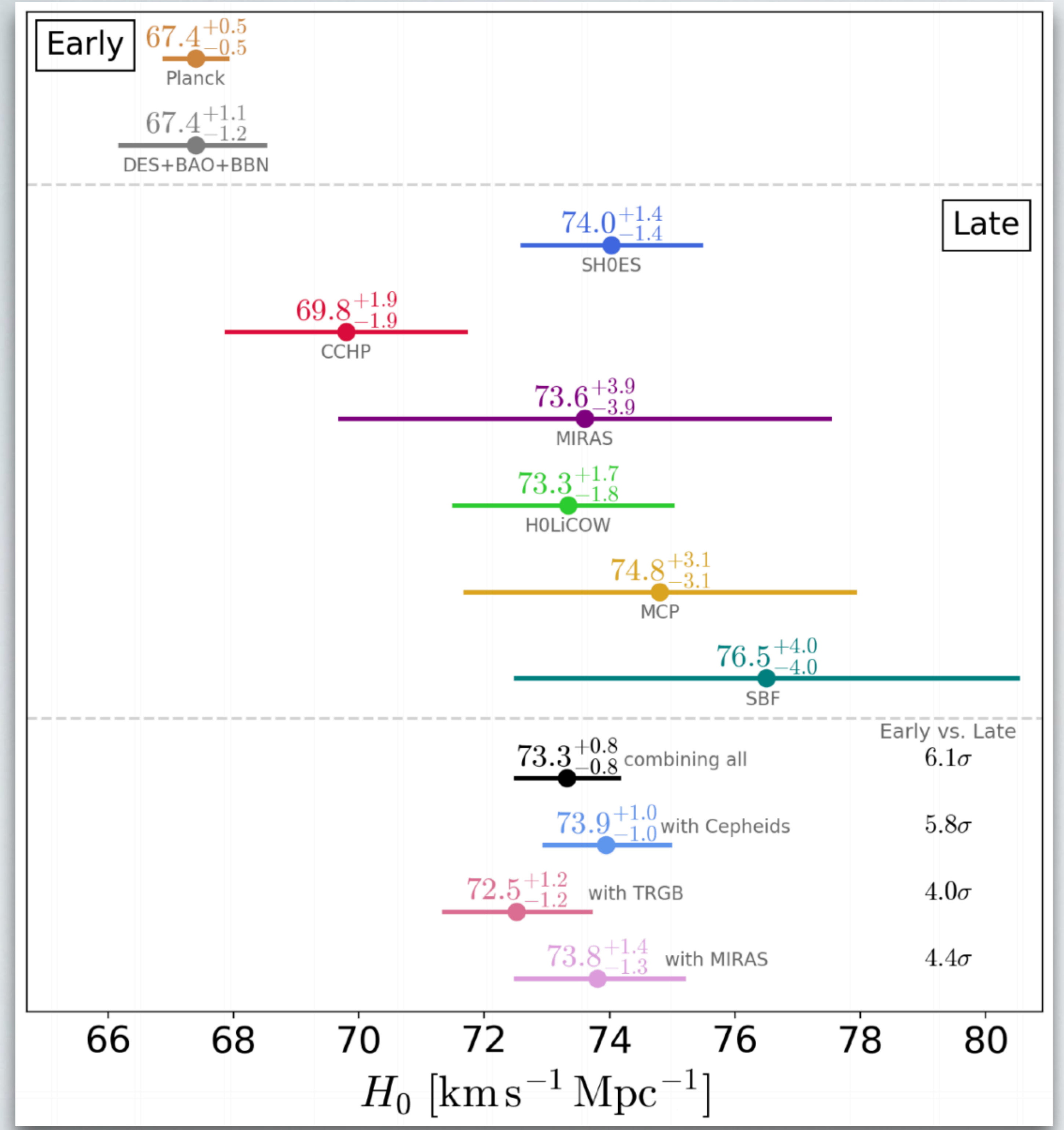
The Hubble tension

- TRGB = "Tip of red giant branch" (new method to measure distances without Cepheids)
- CMB = WMAP & Planck measurements
- Planck prefers lower H_0 than WMAP did
- Measurements from **local Universe and CMB prefer different values!**



Freedman et al. 2019

The Hubble tension



- CMB measures early Universe physics, H_0 is inferred via ΛCDM model
- Many different techniques to measure H_0 locally (from galaxies near Milky Way) seem to agree on higher values
- Measurement error in CMB?
- Error in local measurements?
- New physics?

Verde et al. 2019

Take-aways

- The flat Λ**CDM model** explains observed data remarkably well with only **six free parameters**
- When we **combine data** from different measurement techniques, we largely find **agreement** (concordance)
- There are some remaining issues such as the **Hubble tension** between CMB and local measurements of H_0

Next time…

We'll talk about:

- The cosmic web of dark matter

Assignments

- Post-lecture quiz (by tomorrow night)
- Homework #4 (due 11/11)

Reading:

- H&H Chapter 15