Cosmology

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Goal

- Broad overview of current cosmology
  - Cosmic Expansion

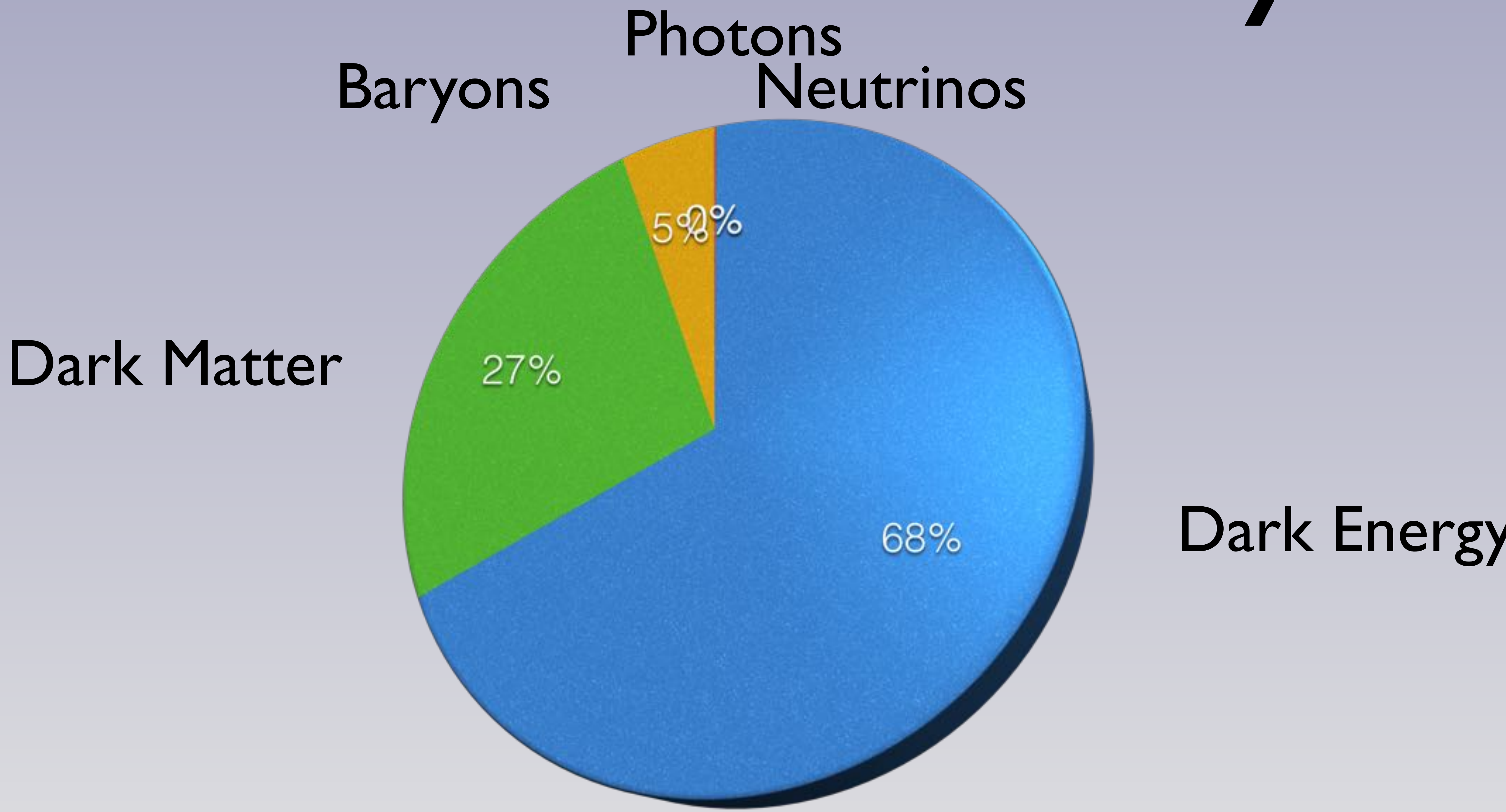
Broad overview of current cosmology

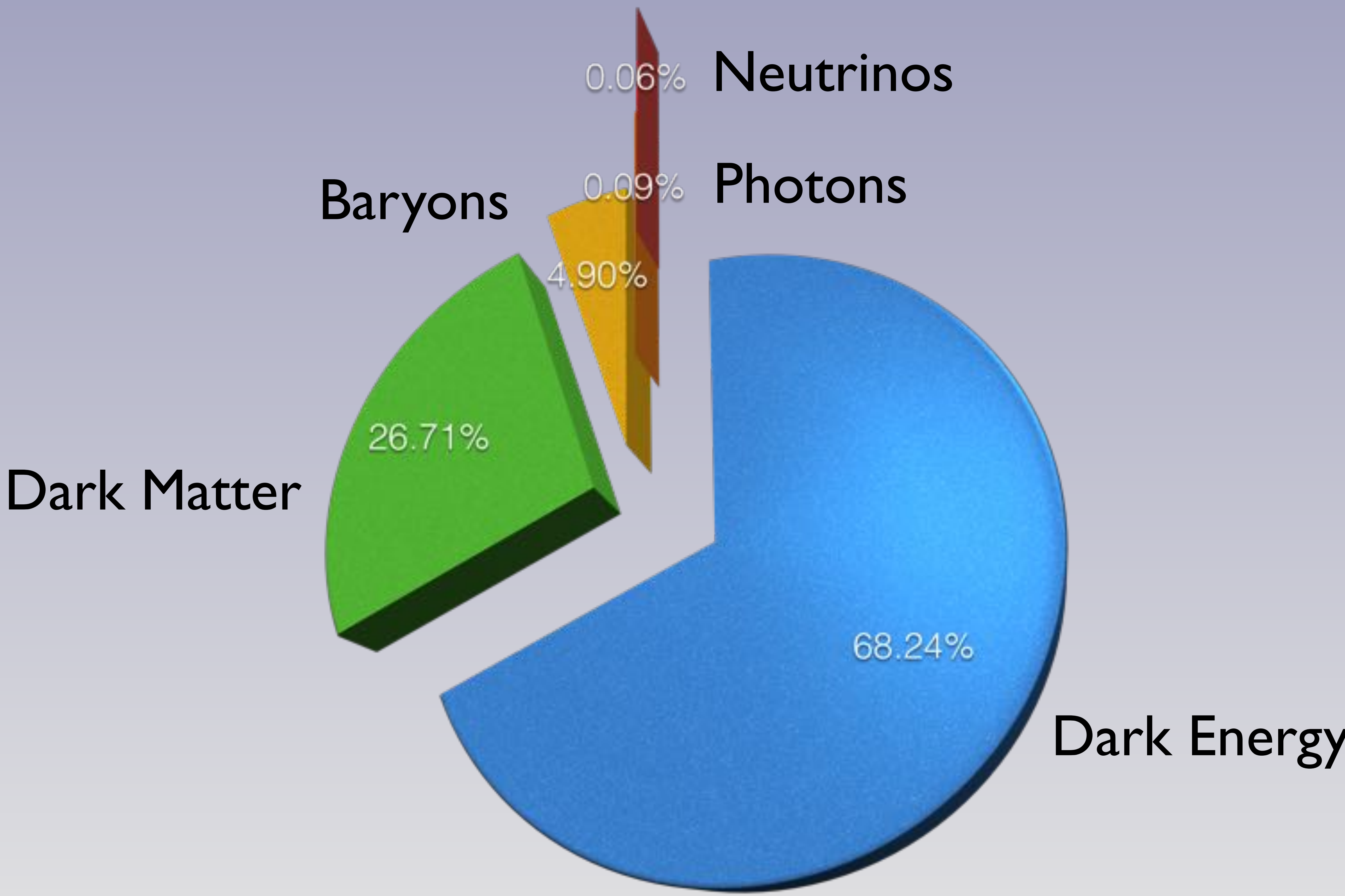
I. Universe today: ingredients and why.
II. CMB physics: understanding Planck, Bicep2, and others.
III. Large scale structure: galaxies and clusters.
IV. Inflation
V. Pitfalls for cosmologists

I. Universe today: ingredients and why.

- Very untechnical
  - What are the sources of information in cosmology
  - Cosmic expansion

The Universe today




0.06%
Neutrinos
0.09%
Photons
Baryons
4.90%
26.71%
Dark Matter
68.24%
Dark Energy

Goal

- Broad overview of current cosmology
- Explain why we believe 94.95% is unknown matter

The absolute fundament to keep in mind

- Every observation goes via light (even at LHC).
- Cosmologists can only observe 2 dimensions:
  - two angles

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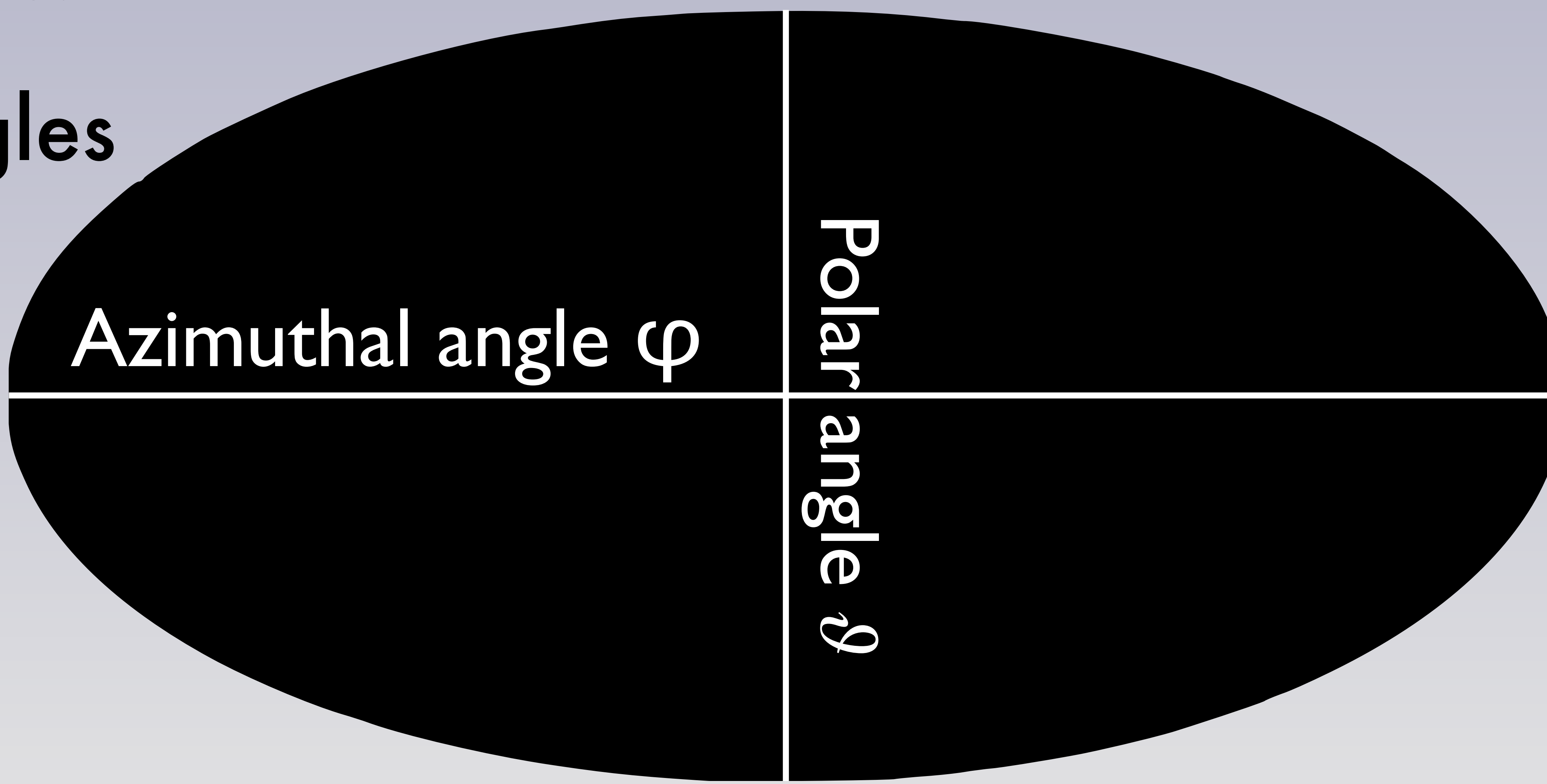
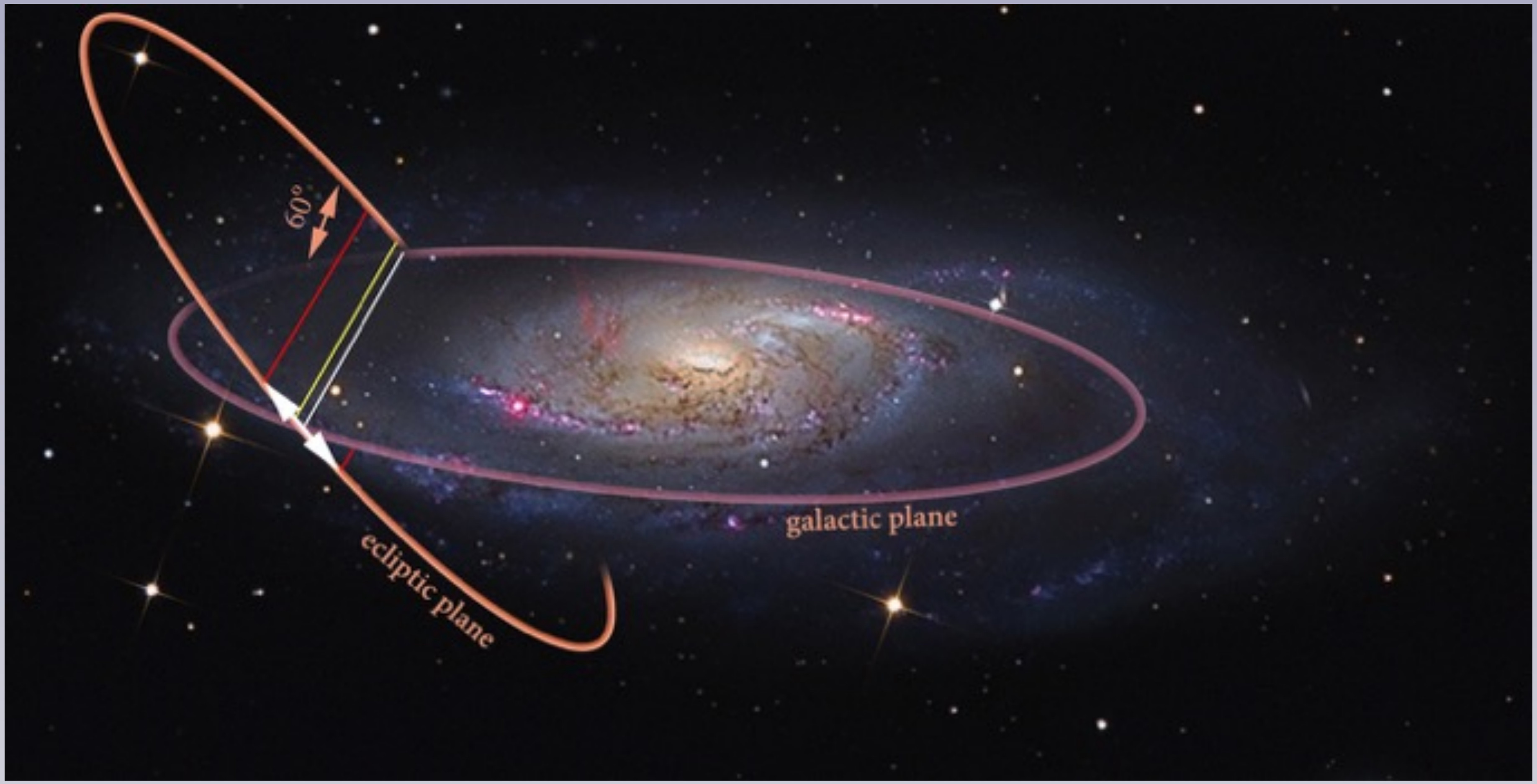
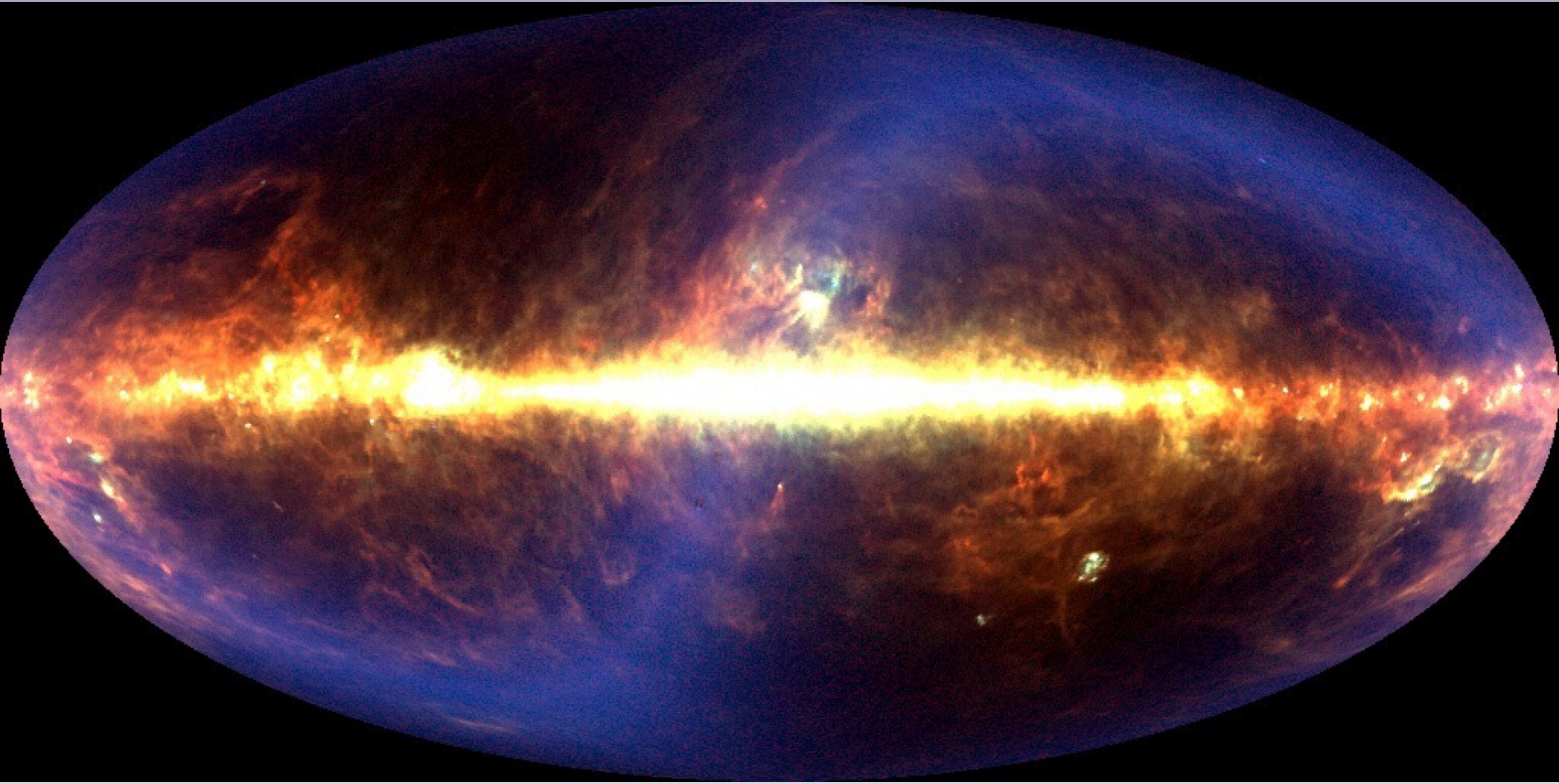


Choices of plane



- Ecliptic
- Galactic

Actual IR sky (COBE)



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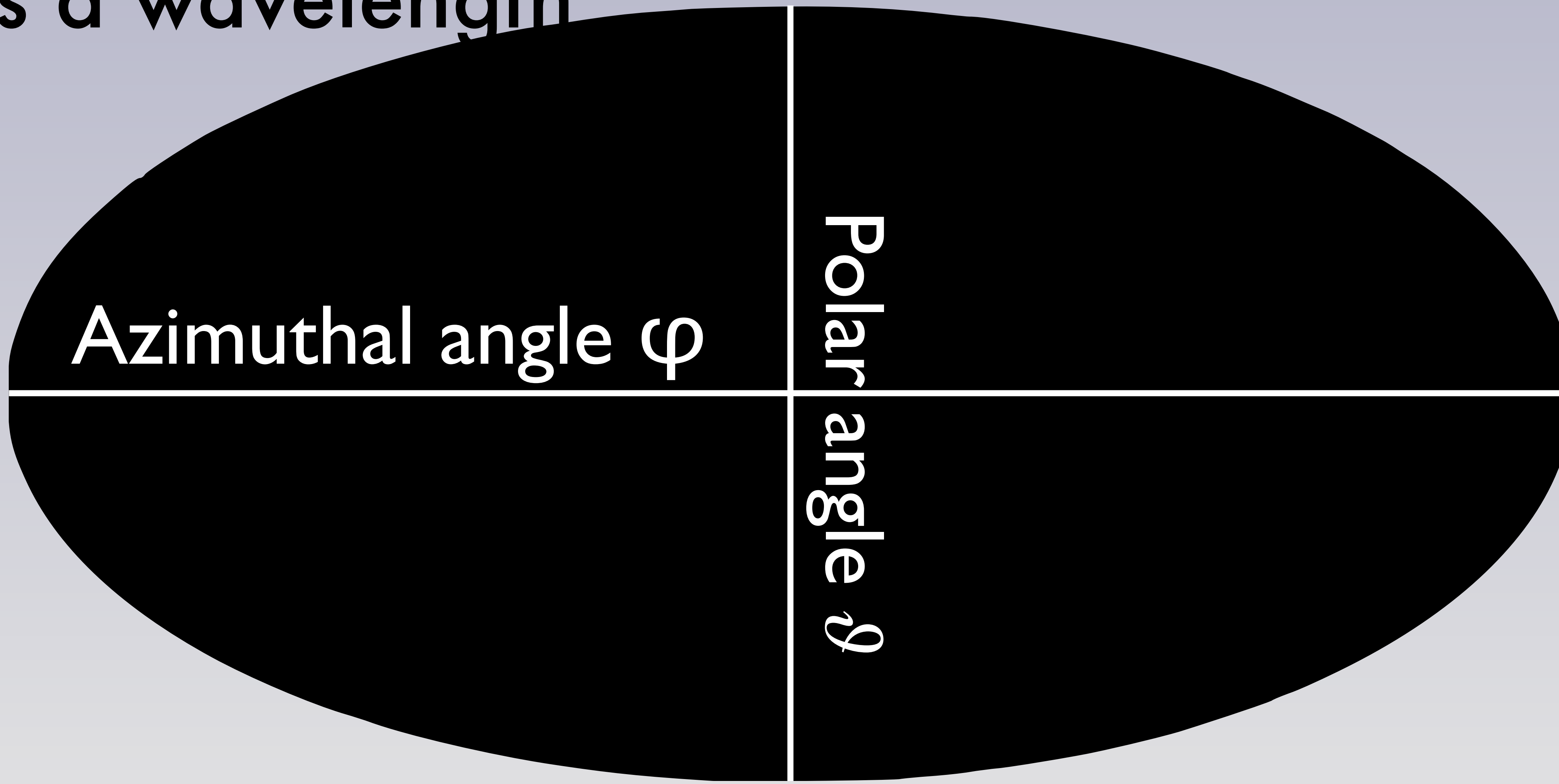

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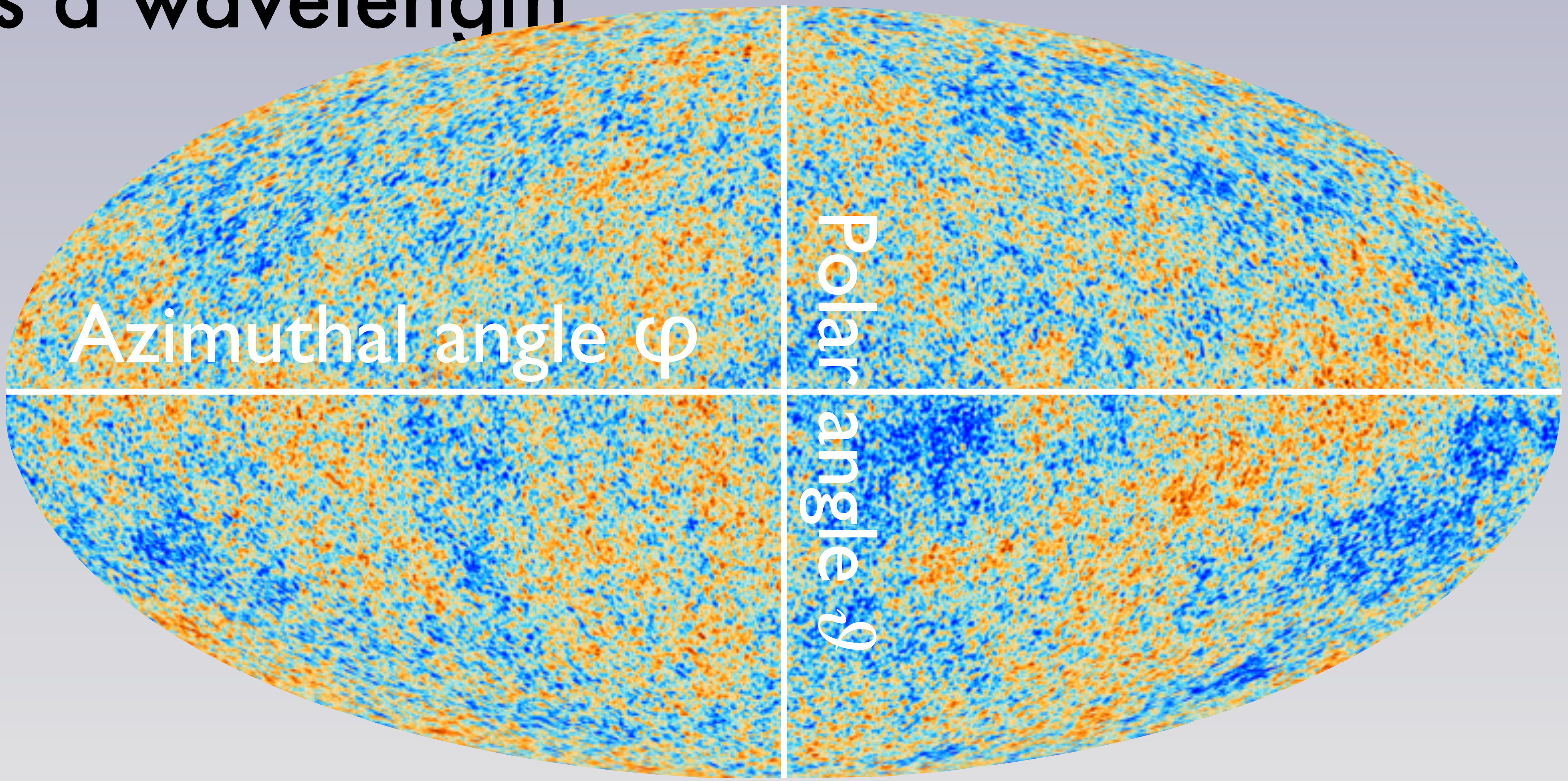
Sky at 143 GHz



But Astronomers:

- Cosmologists can only observe 2 dimensions:
  - two angles
- Astronomers can observe three dimensions:
  - two angles, two eyes

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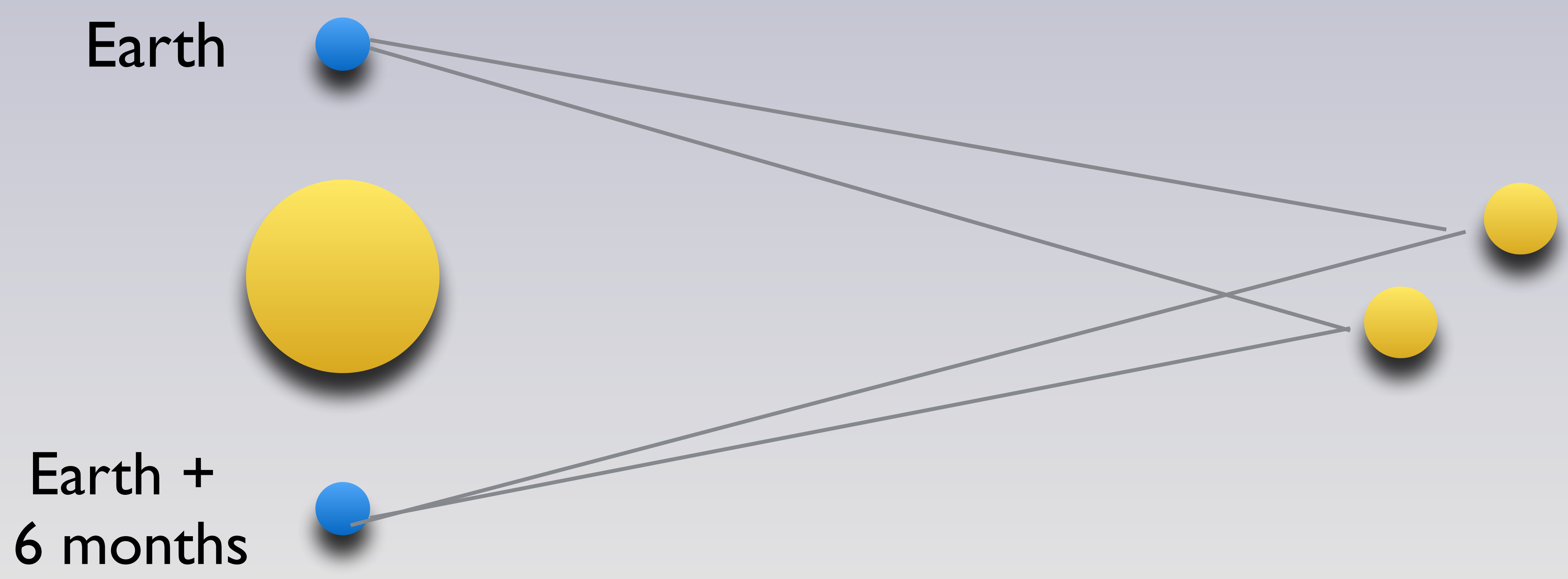
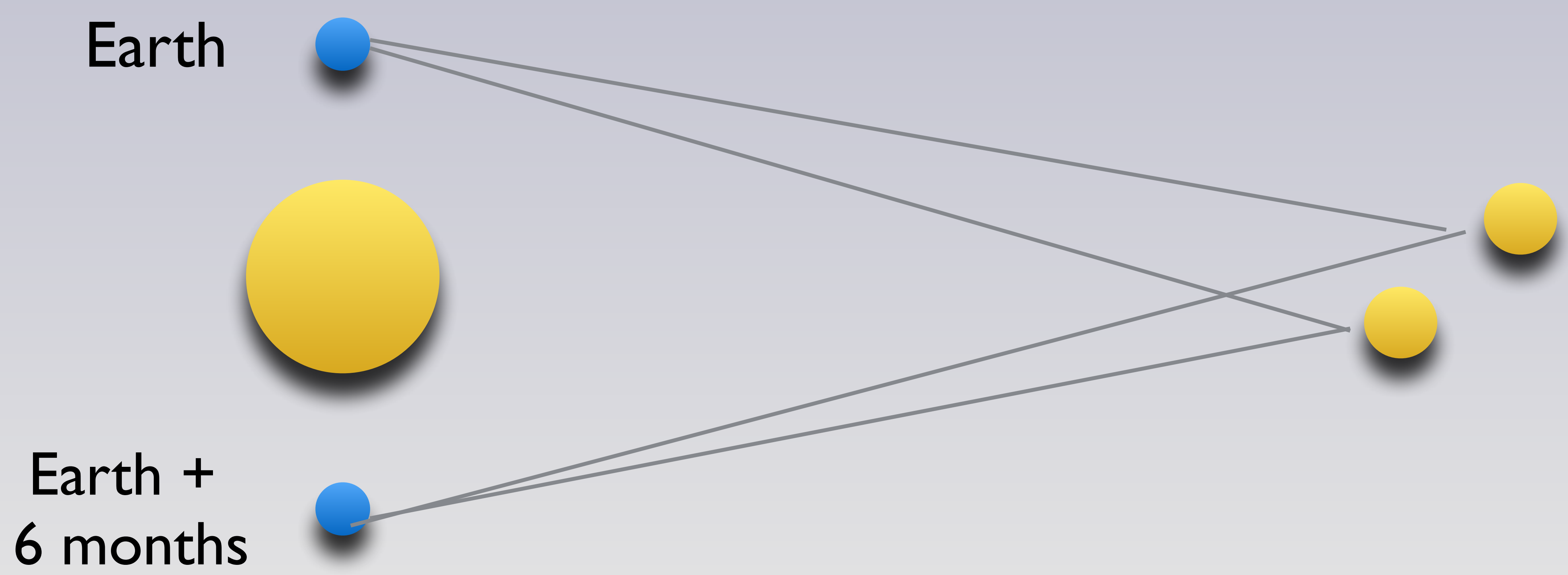


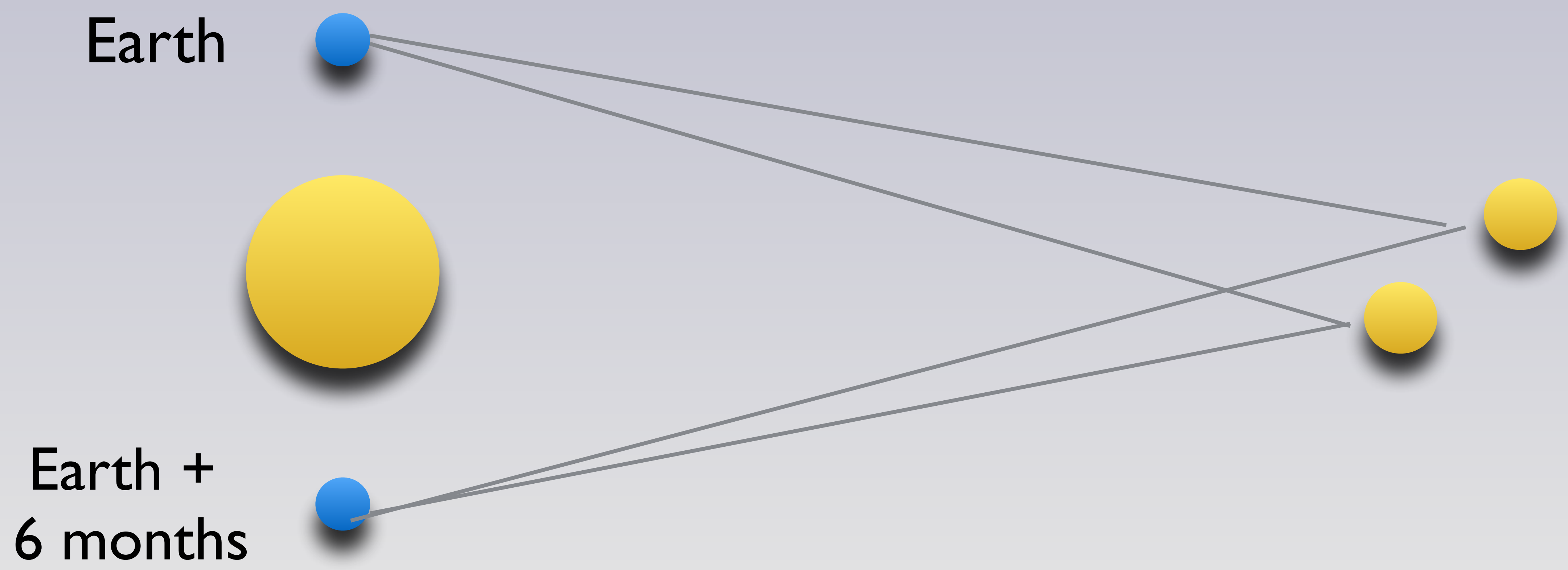
But Astronomers:

- If you know AU
  - Astronomical Unit = Earth-Sun dist.
- You know distance to star.



But Astronomers:

- If you do not know AU
- Measure distance in parallax angles:
  - 1pc = 1 parsec = distance to parallax of 1 arcsecond
- Given AU: 1 pc = 3.26 lightyears



The absolute fundament to keep in mind

- Every observation goes via light (even at LHC).
  - Light has a wavelength
  - Light has an intensity
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The absolute fundament to keep in mind

- Every observation goes via light (even at LHC).
  - Light has a wavelength
  - Light has an intensity
- Known distance to nearby objects
- Compute emitted luminosity from measured intensity
  - Turns out, some objects are “Standard Candles”: luminosity related to other observables, e.g. periodicity of Cepheids.

Hubble (1929) [after Lemaître (1927)]

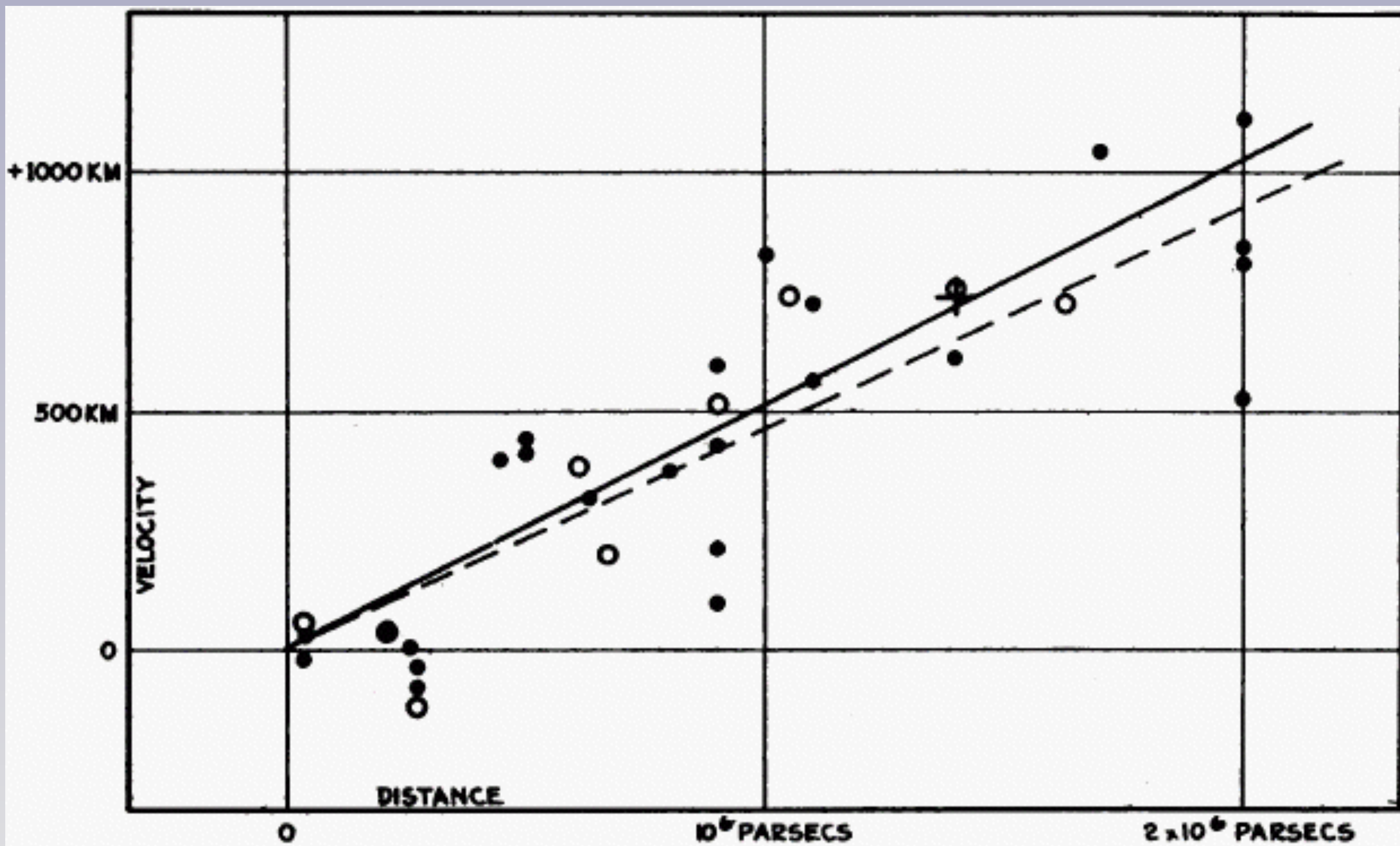
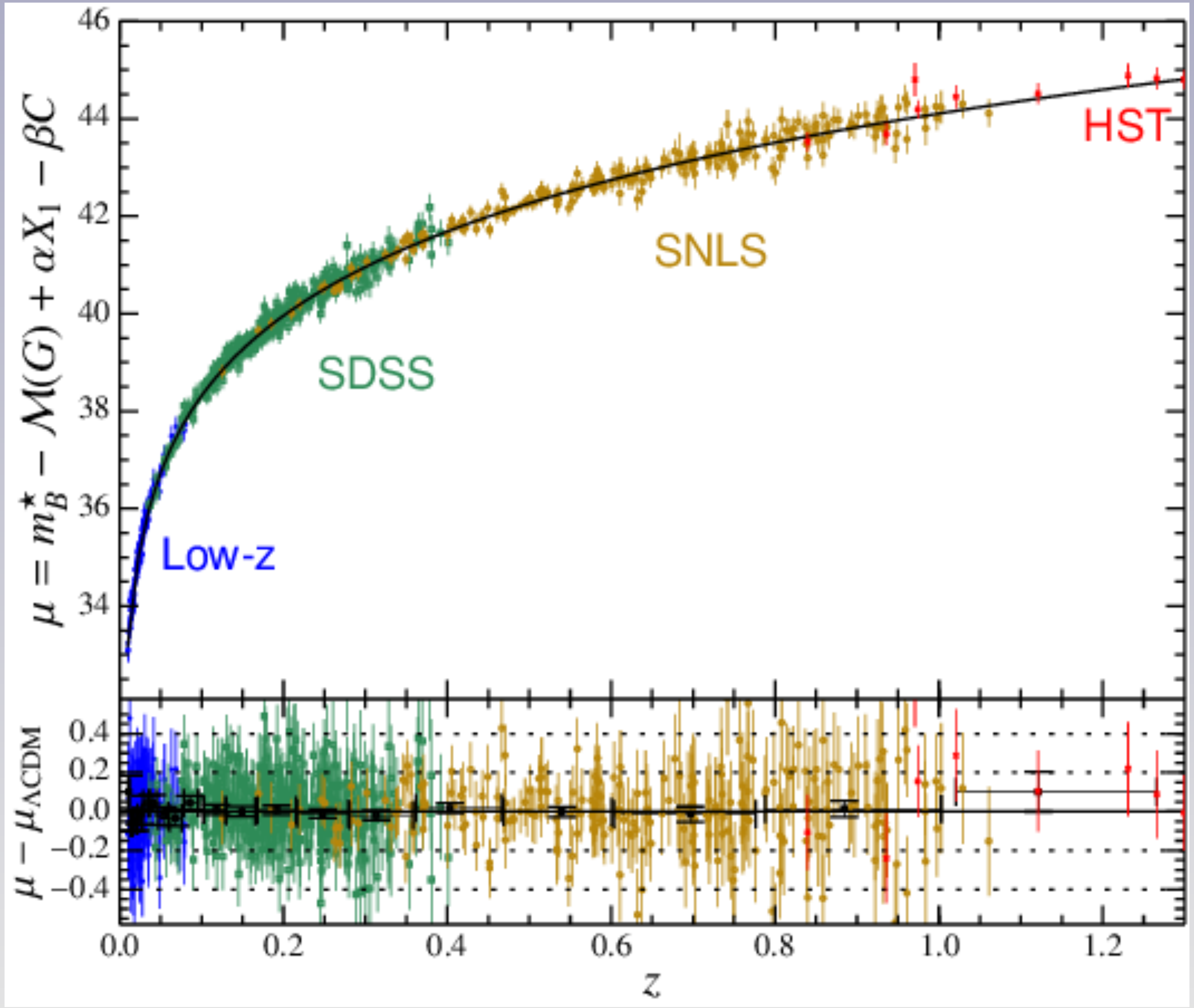


FIGURE 1

Velocity-Distance Relation among Extra-Galactic Nebulae.

Hubble diagram today



http://supernovae.in2p3.fr

Expansion observed

- Relation measured between redshift of spectra (e.g. specific emission lines) and luminosity distance.
- Inferred from:
  - Parallax to near objects
    - period - luminosity relation of Cepheids
  - Interpretation of redshift as Doppler effect

That was no coincidence

— 49 —

UN UNIVERS HOMOGÈNE DE MASSE CONSTANTE ET DE RAYON CROISSANT, RENDANT COMPTE DE LA VITESSE RADIALE DES NÉBULEUSES EXTRA-GALACTIQUES

Note de M. l'Abbé G. LEMAÎTRE

1. GÉNÉRALITÉS.

La théorie de la relativité fait prévoir l'existence d'un univers homogène où non seulement la répartition de la matière est uniforme, mais où toutes les positions de l'espace sont équivalentes, il n'y a pas de centre de gravité. Le rayon R de l'espace est constant, l'espace est elliptique de courbure positive uniforme $1/R^2$, les droites issues d'un même point repassent à leur point de départ après un parcours égal à πR, le volume total de l'espace est fini et égal à $\pi^2 R^3$, les droites sont des lignes fermées parcourant tout l'espace sans rencontrer de frontière (1).

1927

Friedmann-Lemaître metric

- If we are not in a special position
- Universe must be everywhere similar to here*
- First approximation: no space dependence, only time.
  - Invariant under rotations and translations

* realize how revolutionary that idea was (still is)

Friedmann-Lemaître metric

- First approximation: no space dependence, only time.
- Put that in the metric and in the Einstein equation

$$R_{\mu\nu} - \frac{1}{2} R\, g_{\mu\nu} = 8\pi G_{\mathrm{N}} T_{\mu\nu}$$

$$\begin{aligned} ds^2 &= -dt^2 + a(t)^2 \left[dx^2 + dy^2 + dz^2 \right] \\ &= g_{\mu\nu} dx^\mu dx^\nu \end{aligned}$$

General Relativity in a nut shell

- SR: relative velocities of inertial frames affect relative perception of space and time
- GR: acceleration indistinguishable from gravitational pull. Gravity = curvature of space and time
- For symmetrists:
  - SR = global symmetry under Lorentz transformations
  - GR = local Lorentz symmetry, hence a force emerges (and a particle!).

Function of $g_{\mu\nu}$ and its derivatives up to second order

Stress energy tensor: matter content

$$R_{\mu\nu} - \frac{1}{2} R \, g_{\mu\nu} = 8\pi G_{\rm N} T_{\mu\nu}$$

$$ds^2 = -dt^2 + a(t)^2 \left[dx^2 + dy^2 + dz^2 \right]$$

$$= g_{\mu\nu} dx^{\mu} dx^{\nu}$$

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

$$\left(\frac{\dot{a}(t)}{a(t)}\right)^2 = \frac{8\pi G_{\mathrm{N}}}{3}\rho + \frac{\Lambda}{3} - \frac{k^2}{a(t)^2} \qquad \dot{a}(t) \equiv \frac{da(t)}{dt}$$

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Big Bang model

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But...

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- time = space: no special position, then no special time either?
- Einstein's static universe was arguably more humble.

Score so far

- Theory of gravity that allows for expanding universe
- Observations of:
  - correlated periodicity and luminosity, when corrected for nearby distances
    - correlated received flux and redshift
      - inferred expansion of universe

Given expansion:

- Universe must once have been small, dense and hot
- Cooling by expansion
- Hierarchy of temperatures in the history of the universe

Event	time t	redshift z	temperature T
Inflation	10^{-34} s (?)	–	–
Baryogenesis	?	?	?
EW phase transition	20 ps	10^{15}	100 GeV
QCD phase transition	20 μs	10^{12}	150 MeV
Dark matter freeze-out	?	?	?
Neutrino decoupling	1 s	6×10^9	1 MeV
Electron-positron annihilation	6 s	2×10^9	500 keV
Big Bang nucleosynthesis	3 min	4×10^8	100 keV
Matter-radiation equality	60 kyr	3400	0.75 eV
Recombination	260–380 kyr	1100–1400	0.26–0.33 eV
Photon decoupling	380 kyr	1000–1200	0.23–0.28 eV
Reionization	100–400 Myr	11–30	2.6–7.0 meV
Dark energy-matter equality	9 Gyr	0.4	0.33 meV
Present	13.8 Gyr	0	0.24 meV

[from lecture notes by Daniel Baumann
http://www.damtp.cam.ac.uk/user/db275/Cosmology/Chapter3.pdf]

Given expansion:

- Universe must once have been small, dense and hot
- Very much like interior of star
- Opaque (think of sun)
  - transition to transparent

The Cosmic Microwave Background

- Transition from opaque to transparent at T ≃ 3000 K
- At any later time Δt, an observer sees CMB at distance $c\Delta t$
- Observed in 1964:

Timeline of the discovery of the CMB

Important dates and persons

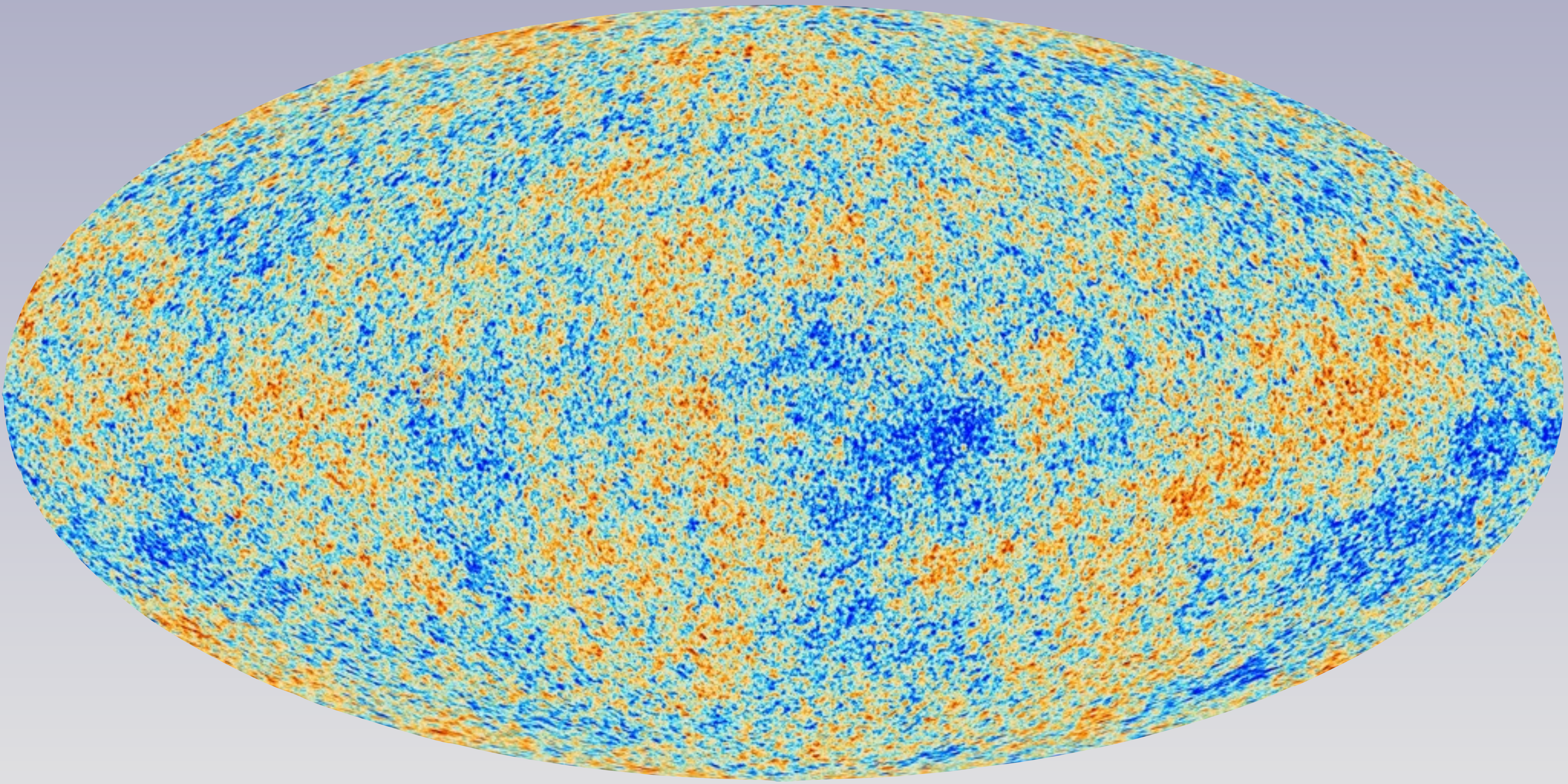
1946	George Gamow estimates a temperature of 50K
1946	Robert Dicke predicts a microwave background radiation temperature of "less than 20K" (ref: Helge Kragh), but later revised to 45K (ref: Stephen G. Brush)
1948	Ralph Alpher and Robert Herman re-estimate Gamow's estimate at 5K.
1949	Alpher and Herman re-re-estimate Gamow's estimate at 28K.
1960s	Robert Dicke re-estimates an MBR (microwave background radiation) temperature of 40K (ref: Helge Kragh)
1964	A. G. Doroshkevich and Igor Novikov publish a brief paper, where they name the MBR phenomenon as detectable.
1960s	Arno Penzias and Robert Woodrow Wilson measure the temperature to be approximately 3 K.

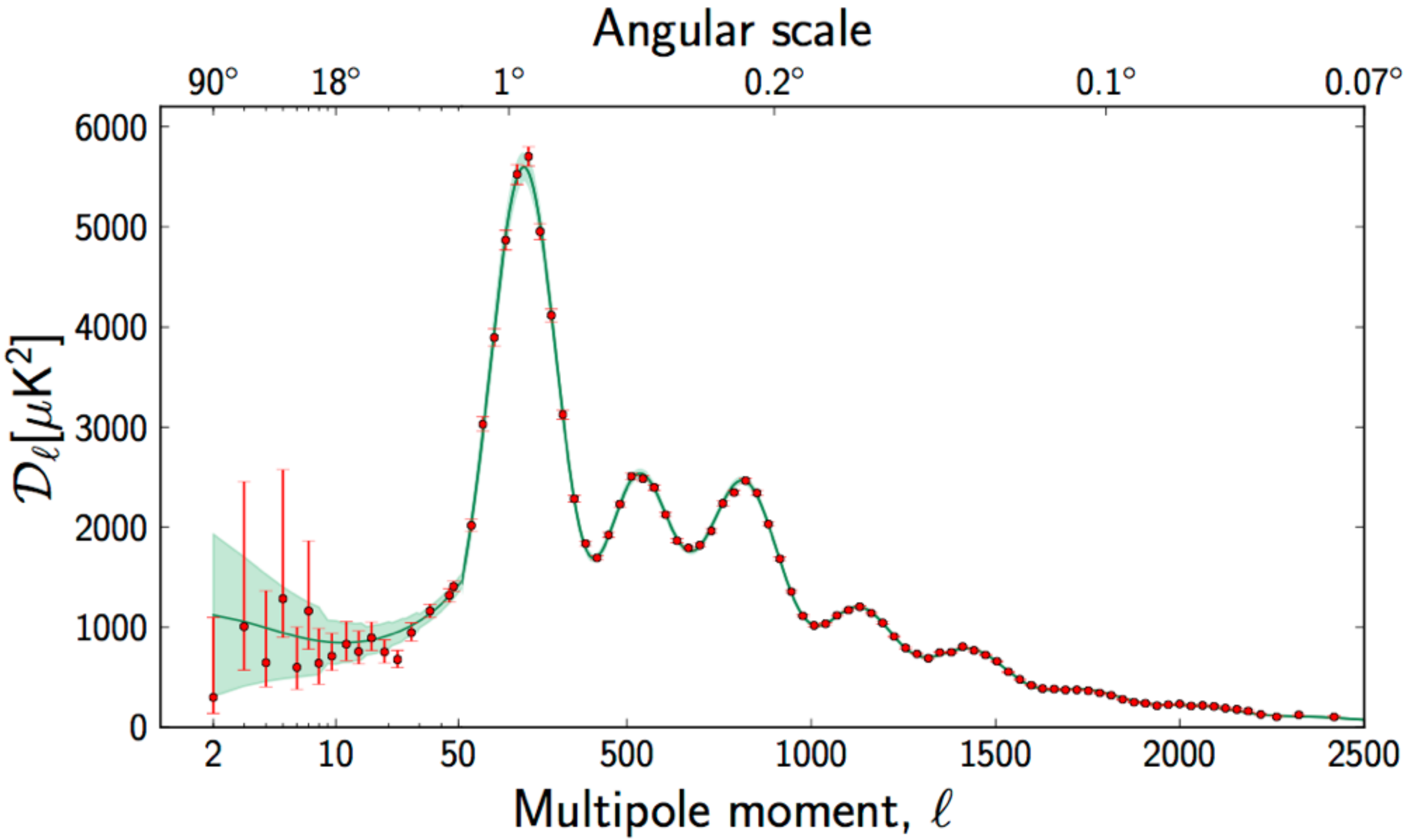
[wikipedia]

CMB Satellites

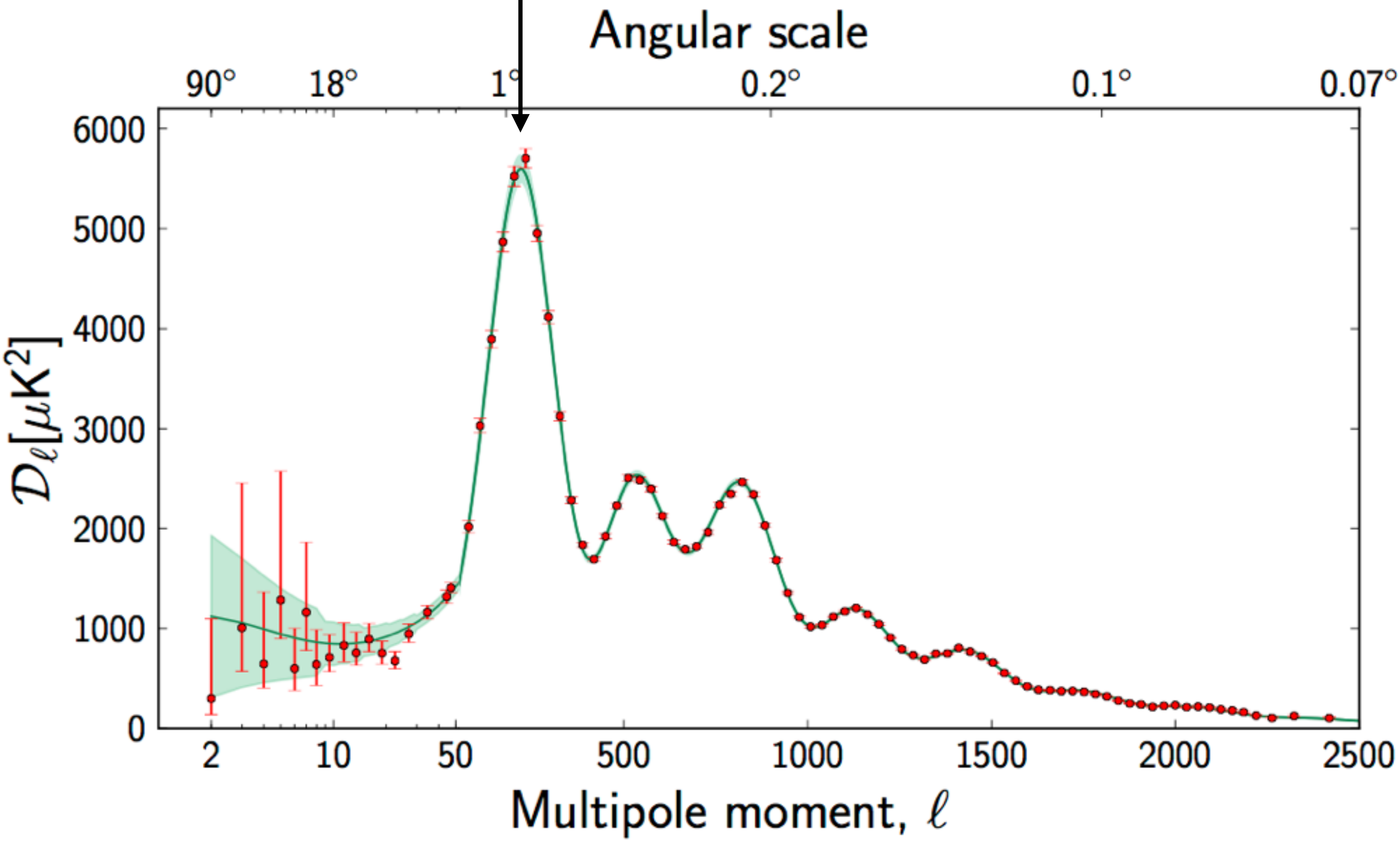
- COBE: Cosmic Background Explorer (1989-1993)
  - Measured absolute temperature (2.7255 K)
  - First full sky spectrum of anisotropies
- WMAP: Wilkinson Microwave Anisotropy Probe (2001-2014) – only anisotropies, not temperature
- Planck (2009-2013) – only anisotropies, not temperature

Planck's temperature map (galactic coordinates)




Angular scale
90°
18°
1°
0.2°
0.1°
0.07°
6000
5000
4000
3000
2000
1000
0
$\mathcal{D}_\ell [\mu K^2]$
2
10
50
500
1000
1500
2000
2500
Multipole moment, ℓ

Angle and wavelength (T_{CMB})



Distance measures

$$
\begin{aligned}
ds^2 &= -dt^2 + a(t)^2\left[dx^2 + dy^2 + dz^2\right] \\
&= -dt^2 + a(t)^2\left[dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]
\end{aligned}
$$

Luminosity distance

$$\begin{aligned} ds^2 &= -dt^2 + a(t)^2\left[dx^2 + dy^2 + dz^2\right] \\ &= -dt^2 + a(t)^2\left[dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right] \end{aligned}$$

$$\begin{aligned} \mathcal{F}(r) &\equiv \frac{\mathcal{L}}{\text{surface of imaginary sphere}} \\ &= \frac{\mathcal{L}}{4\pi d_L^2} \\ &= \frac{a(t)^{-4}\mathcal{L}}{4\pi a(t)^2 r^2} \\ d_L &= a(t)^-1r \end{aligned}$$

Angular diameter distance

$$
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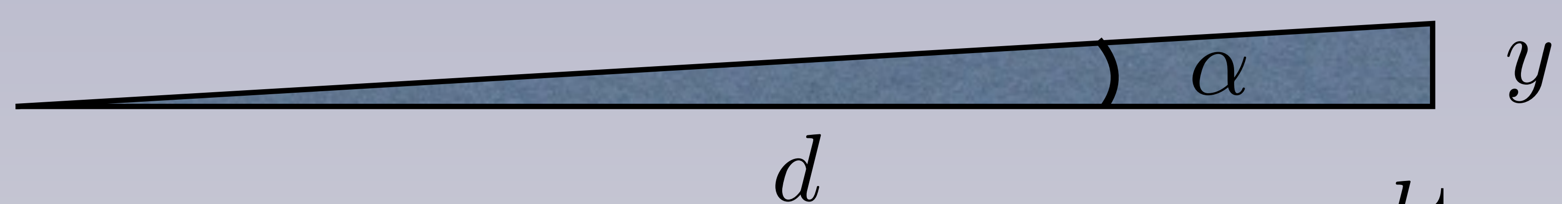

$$y = d\tan\alpha \simeq d\,\alpha$$

or in 2D:

$$
\begin{aligned}
d_A &\equiv \sqrt{\frac{dA}{d\Omega}} \\
&= \sqrt{\frac{\sqrt{g^{(2)}}}{d\Omega}} \\
&= a(t) r
\end{aligned}
$$

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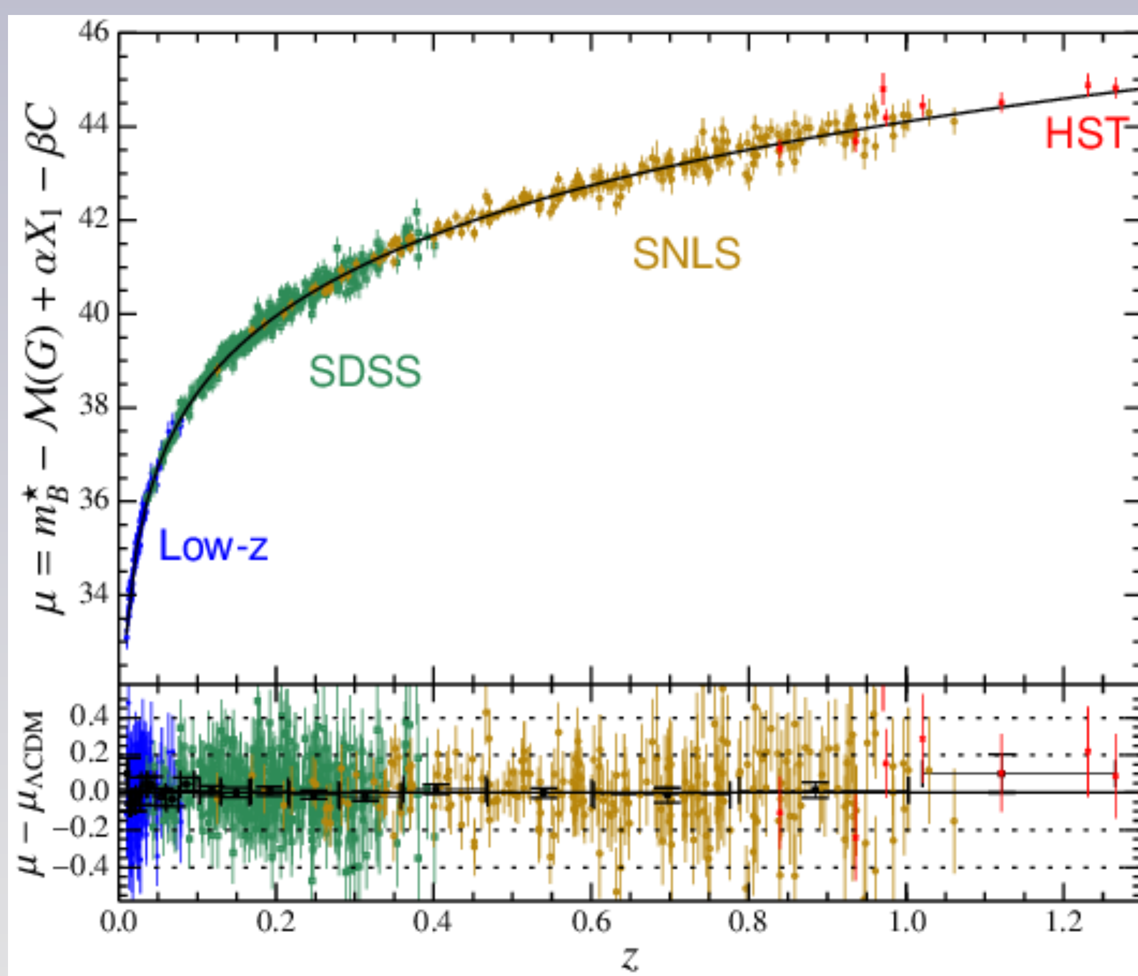
$$d_L = \frac{d_A}{a(t)^2} = (1+z)^2 d_A$$

$$
\begin{aligned}
d_L &= \frac{d_A}{a(t)^2} = (1+z)^2 d_A \\
d_A(z) &= a(t) r \\
ds^2 &= 0 \rightarrow dt = a(t) dr \\
\int dr &= \int dt/a(t) \\
r &= \int dt/a(t) = \int da/(a\dot{a}) \\
&= \int da/(a^2 H(z)) = \int dz/H(z) \\
H_0 d_A(z) &= \frac{1}{1+z} \int \frac{dz}{\sqrt{\Omega_m (1+z)^3 + \Omega_r (1+z)^4 + \Omega_k (1+z)^2 + \Omega_\Lambda}}
\end{aligned}
$$

CMB as a distance measure

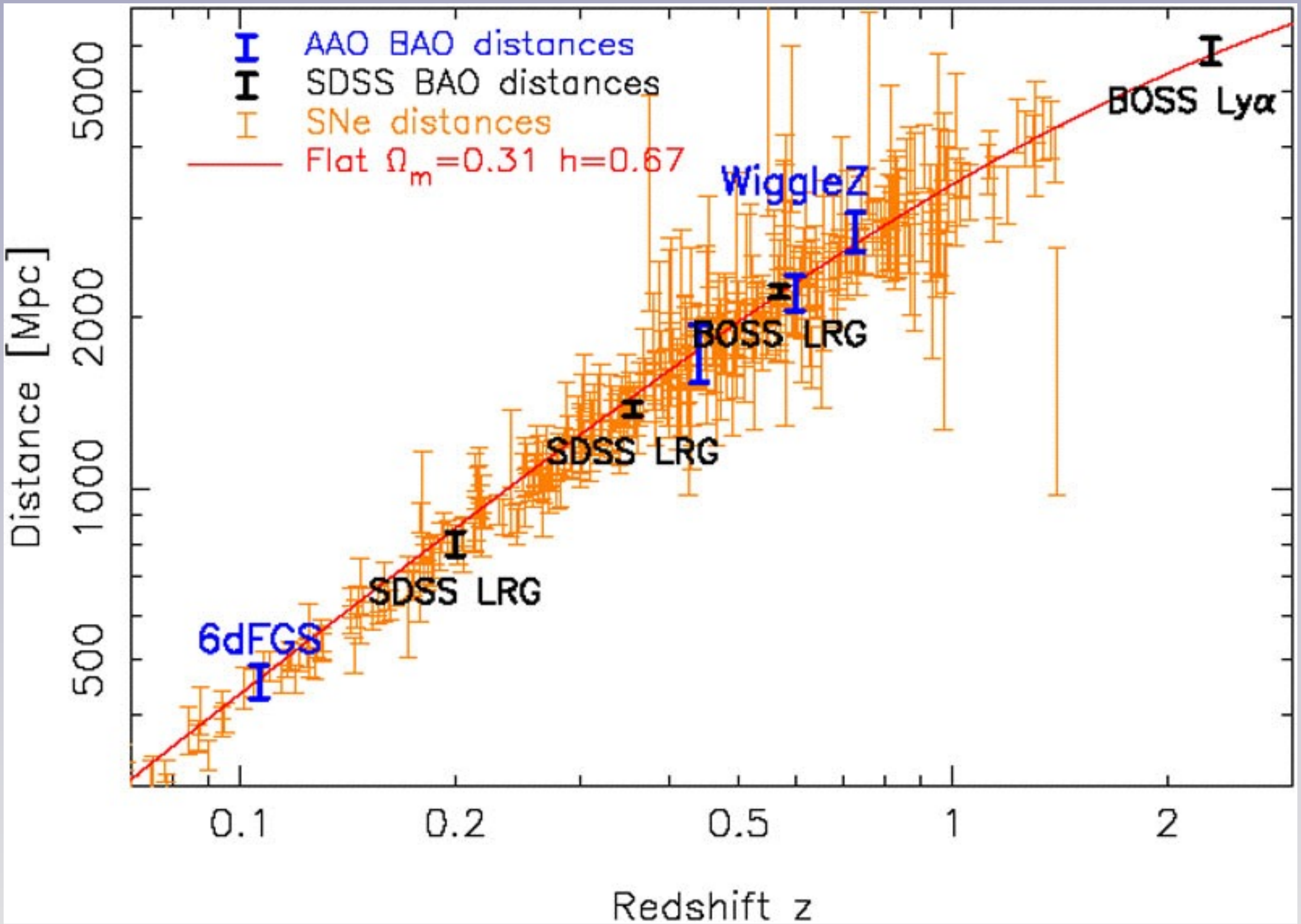
- assume for the moment that you know the physical distance of this characteristic scale 1°



CMB

z=1100

BAO as a distance measure



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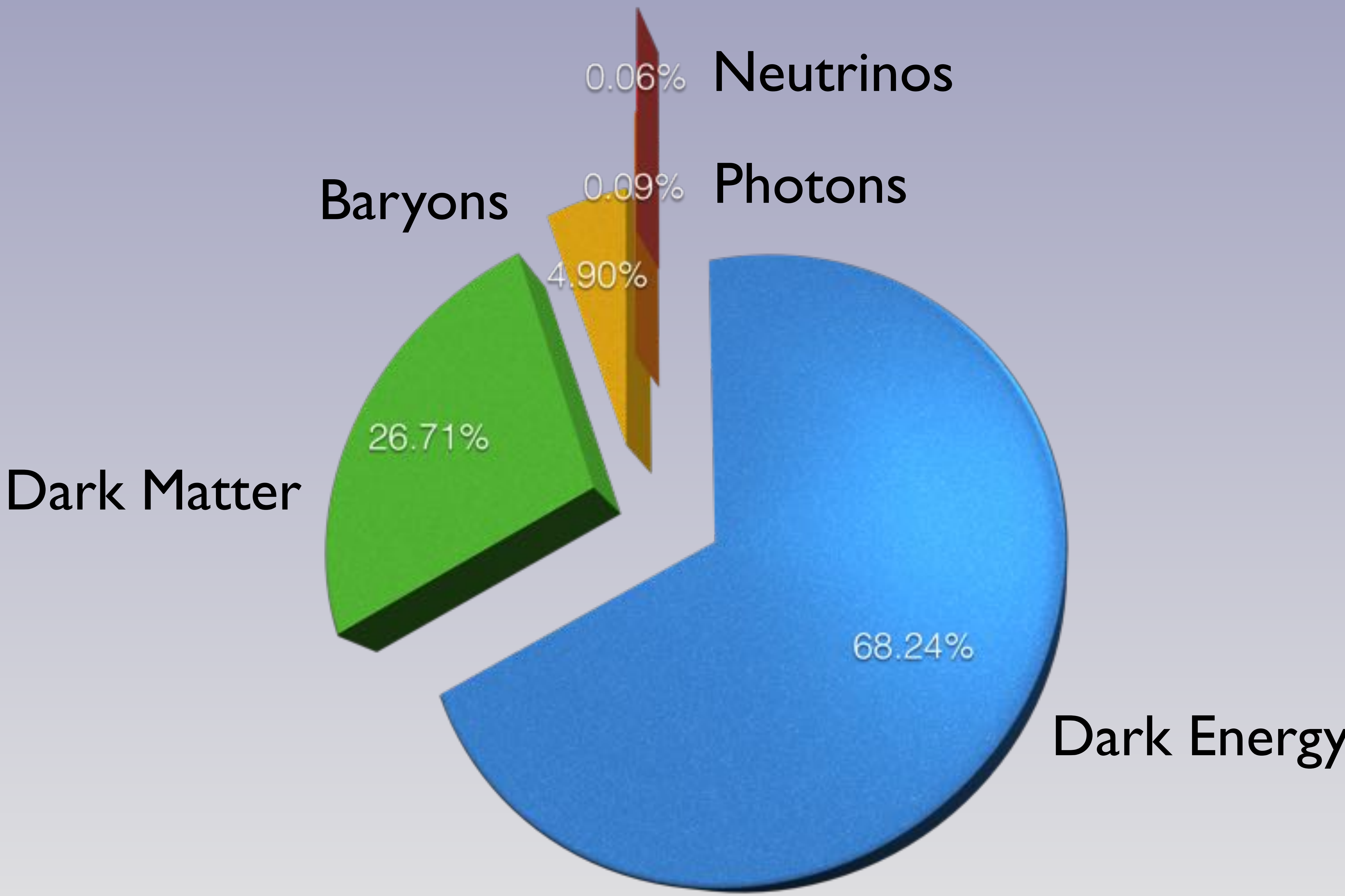
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What's next?

- Where does the structure come from?
- How does structure grow in an expanding universe?
- What would the CMB look like?
- How can this all be used to learn about fundamental physics?