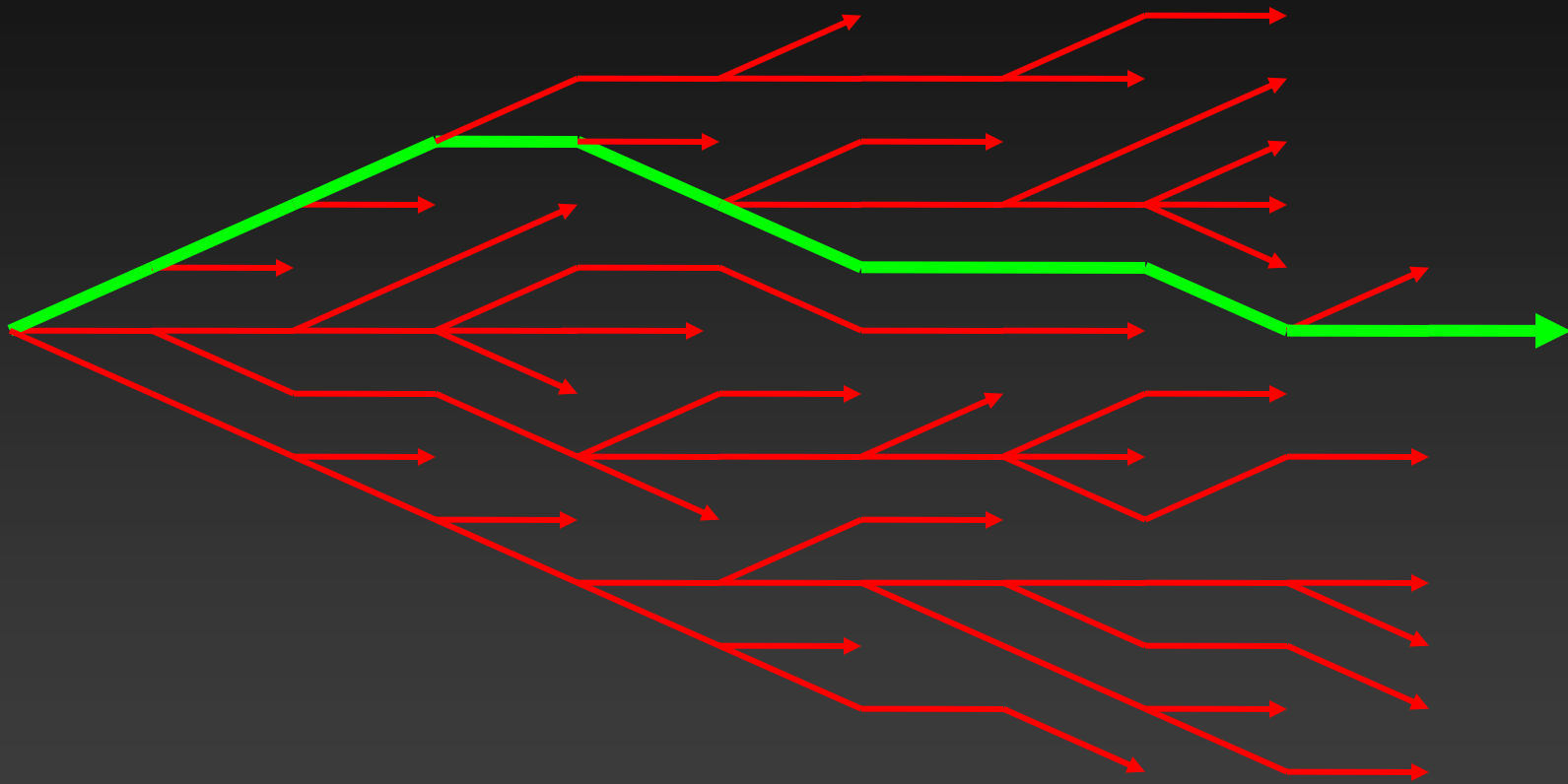
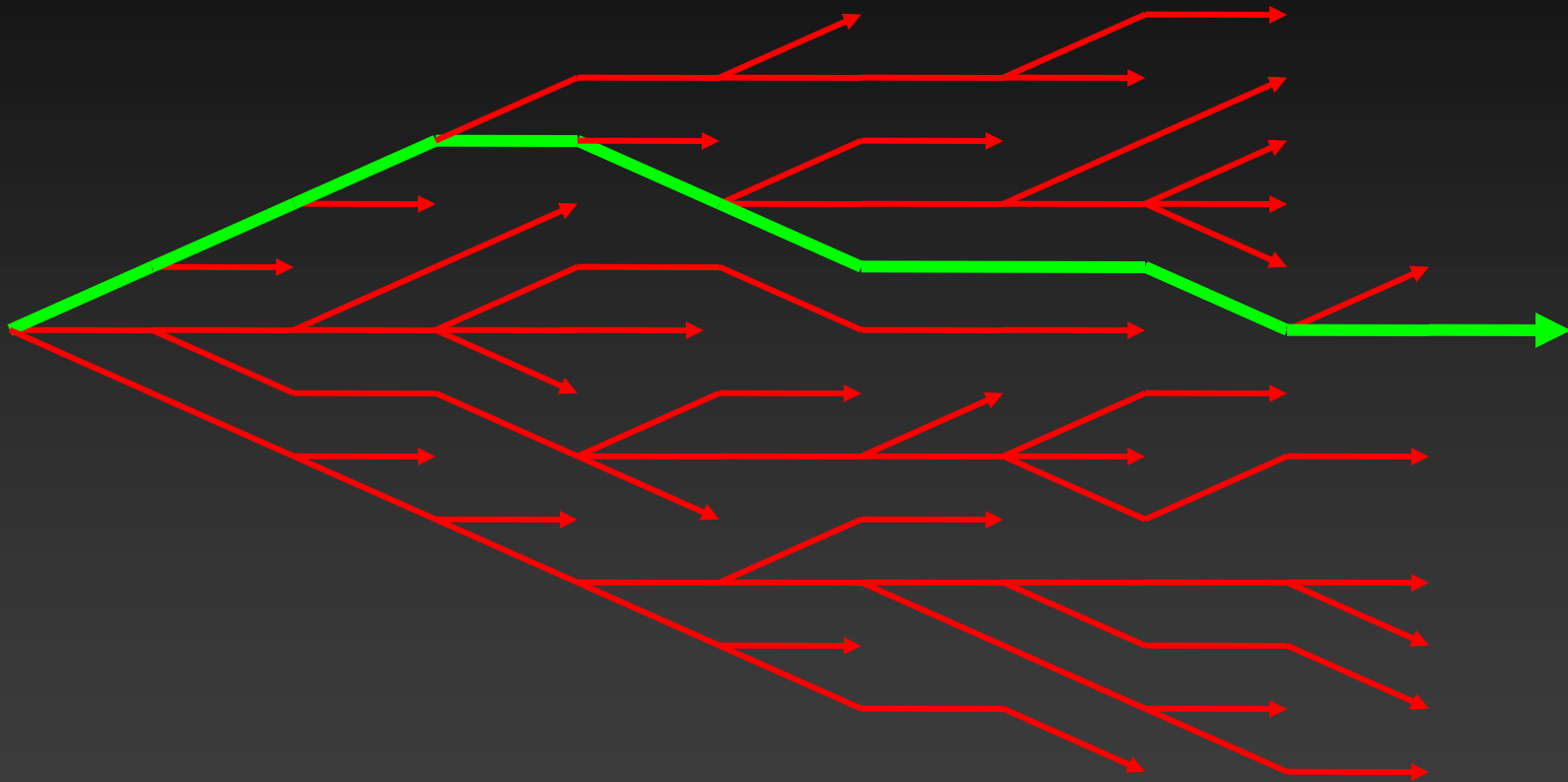


# The Evolution of the Universe - an Overview

EIROforum Teacher School  
CERN - November 2009  
Julien Lesgourgues (CERN)





- **standard cosmological model** = simplest model explaining most current observations in a satisfactory way

# Global description of the Universe

- Einstein's theory of gravitation (General Relativity)
  - Consistent with all experiments...
- Issue of composition and evolution are related
- Large scale homogeneity
  - Observation of galaxy clusters, Cosmic Microwave Background...
- Friedmann - Lemaître model
  - Homogeneous spatial curvature (euclidian, spherical, hyperbolic)
  - Homogeneous expansion  $a(t)$
  - Curvature and expansion related to content (non-relativistic particles, relativistic particles, cosmological constant...)



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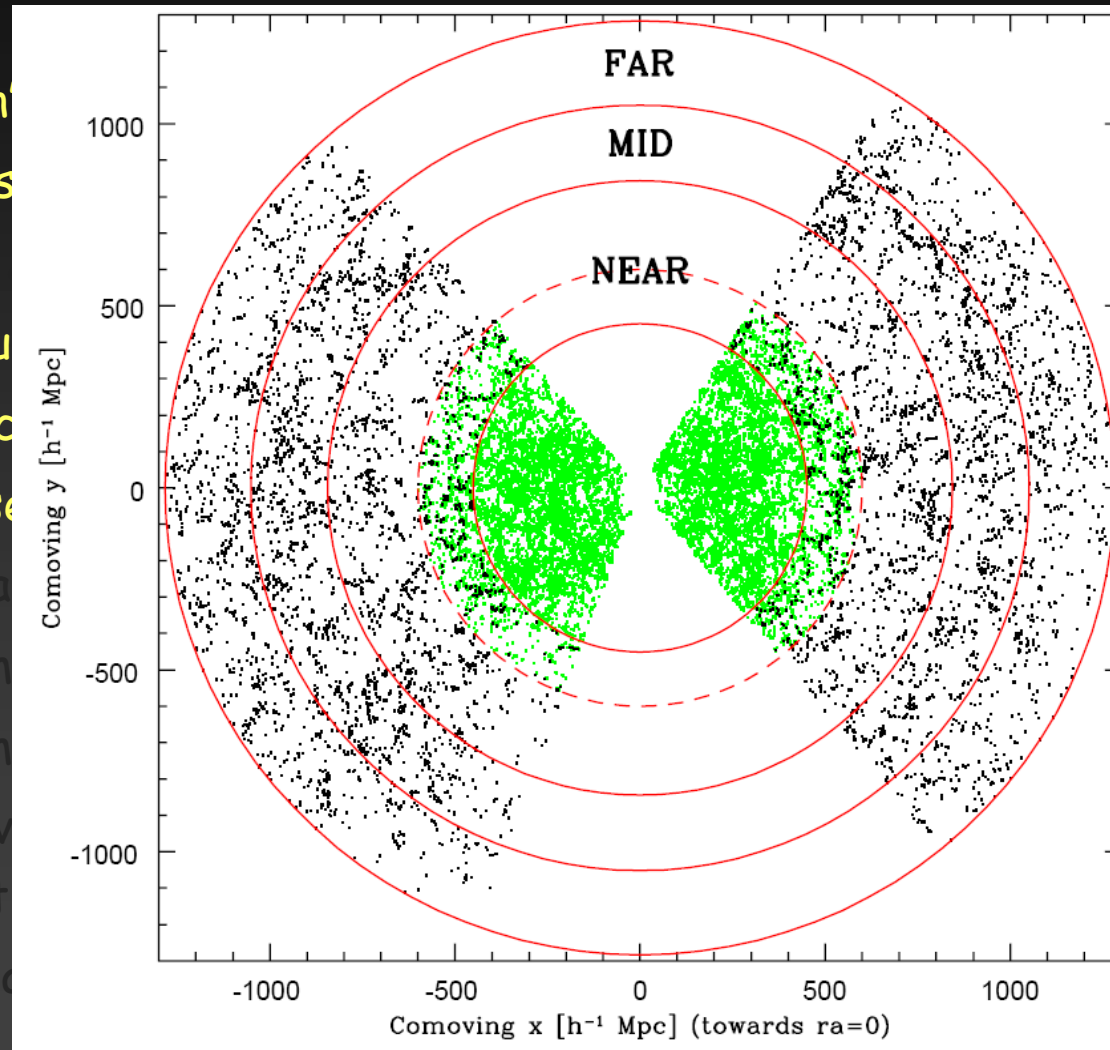


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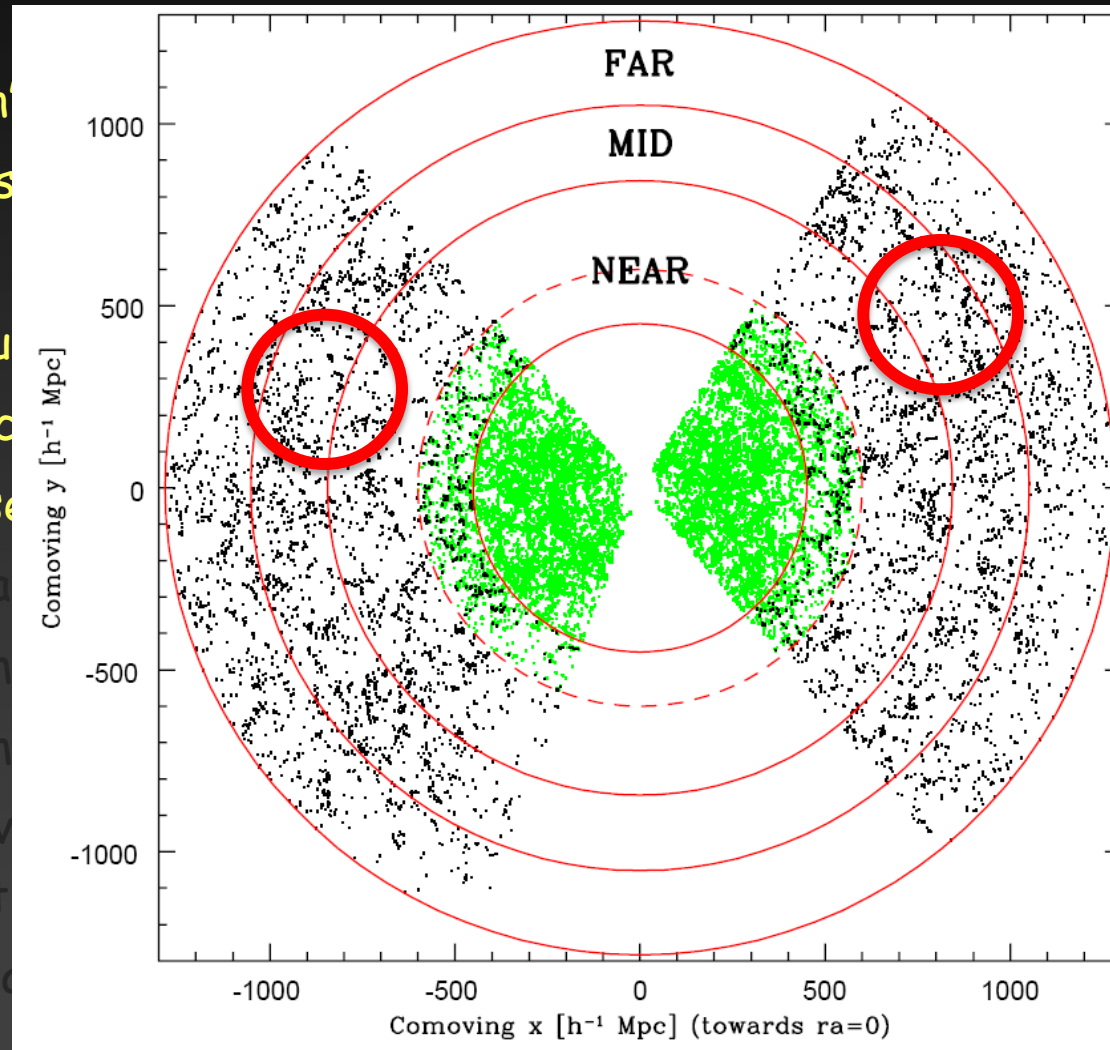
background...

(parabolic)

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- Ordinary matter (stars, galaxies, gaz clouds) = non-relativistic = « matter » (includes dark matter)
- Assumption of matter domination is necessary !  
Explains transition homogeneous -> inhomogeneous (gravitational clustering). Time scale : ~ 10 billion years
- Decelerated expansion of the universe
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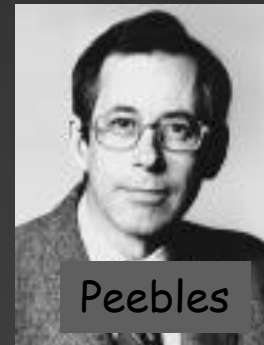
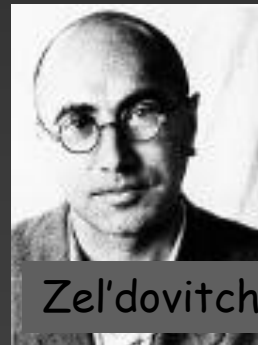
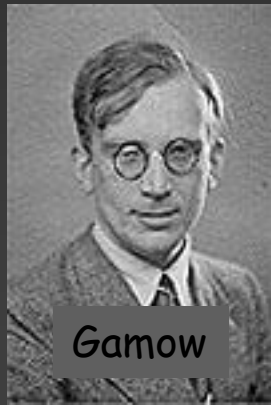
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Guth



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# Inflation + radiation + matter cannot do it alone !!

- Problems :
  - Some objects look older than the theoretical age of the universe in this scenario
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  - Spatial curvature of hyperbolic type
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# Inhomogeneities

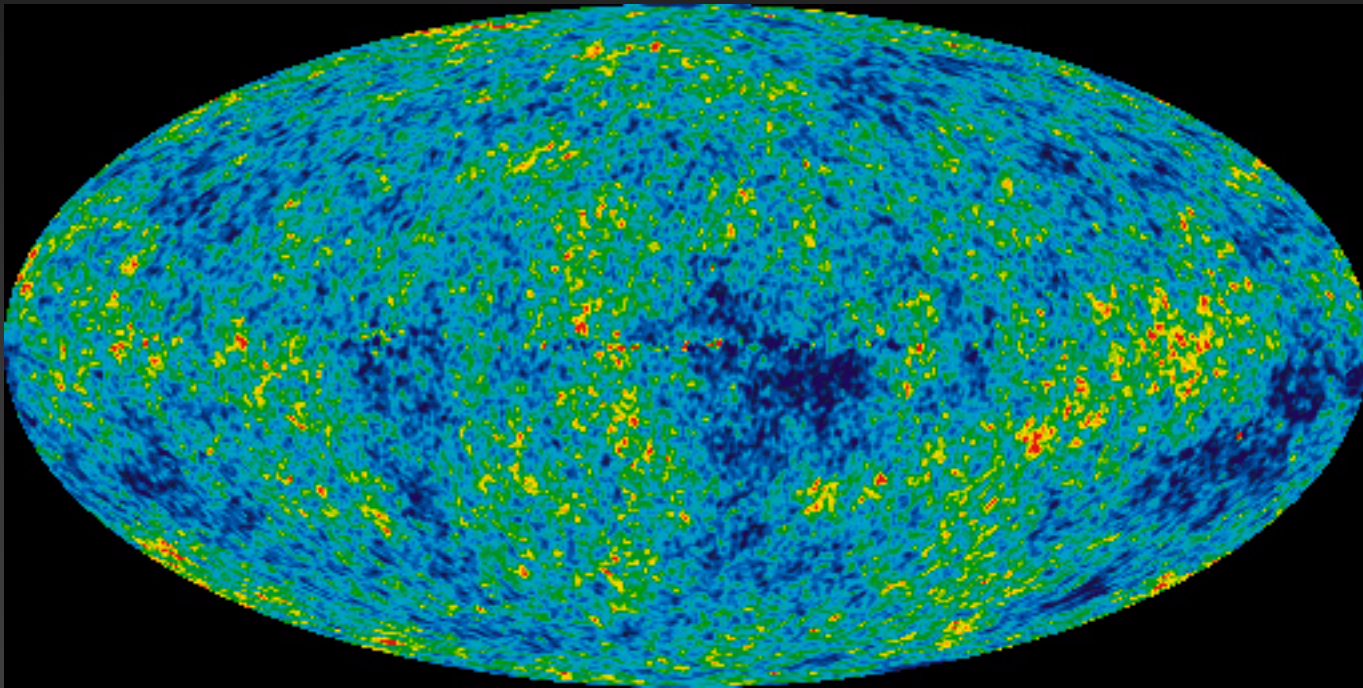
- Model for inhomogeneities:
  - Small statistical fluctuations in the primordial universe
  - Propagation of acoustic waves during radiation domination
  - Formation of structures (galaxies, clusters) during matter domination

# Inhomogeneities

- How could we test this model ?
  - Galaxy/cluster surveys : evolution of fluctuations over last billion years
  - Map of Cosmic Microwave Background (CMB) anisotropies : picture of fluctuations after 320'000 years of matter domination (when universe becomes transparent)

# CMB anisotropies

- from COBE and WMAP to Planck...



# CMB anisotropies

- Theoretical predictions : spectrum of the map :

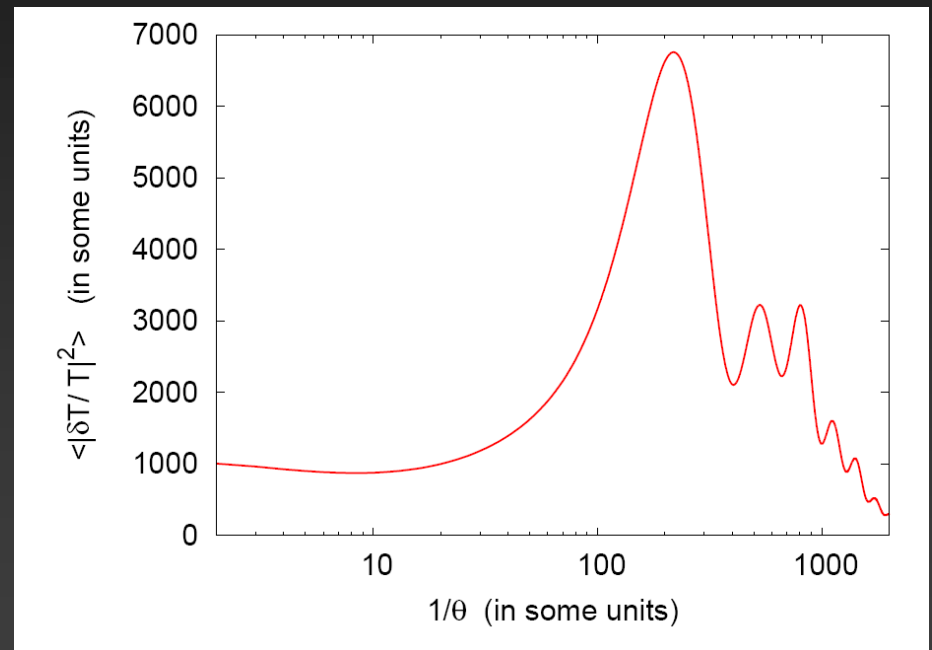
- Peaks = acoustic waves of frequency  $\sim 1 / 100'000$  yrs

- Details of the curve



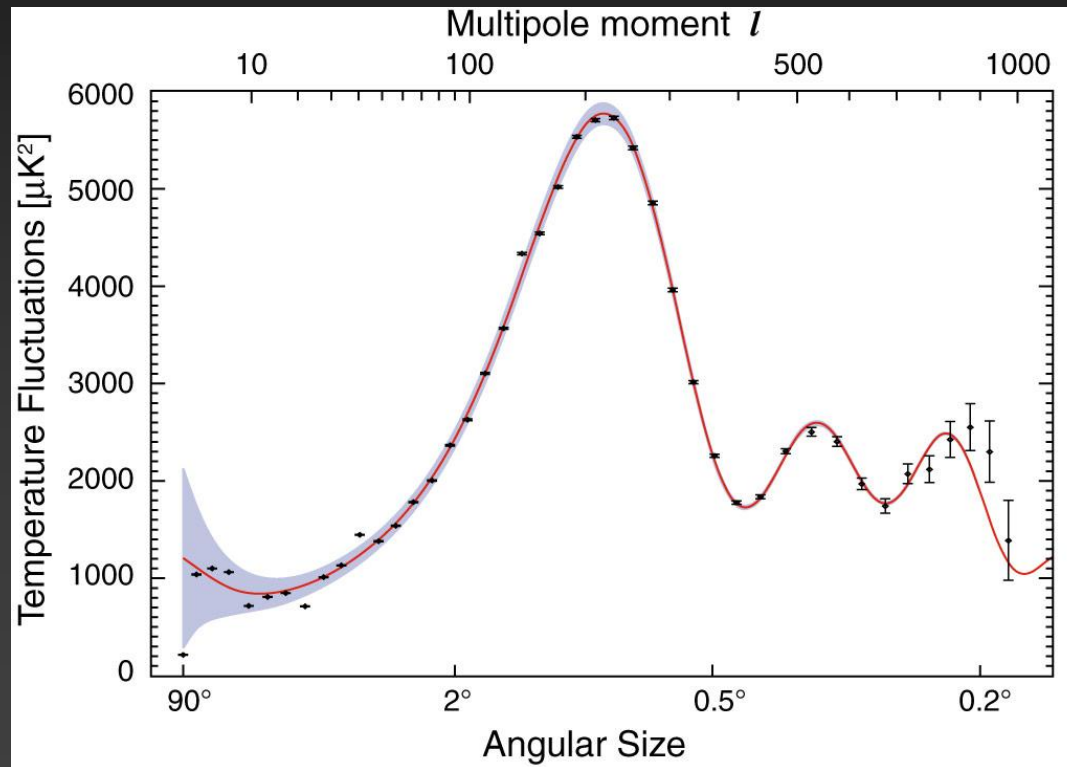
model parameters

(composition, age, curvature, initial fluctuations)



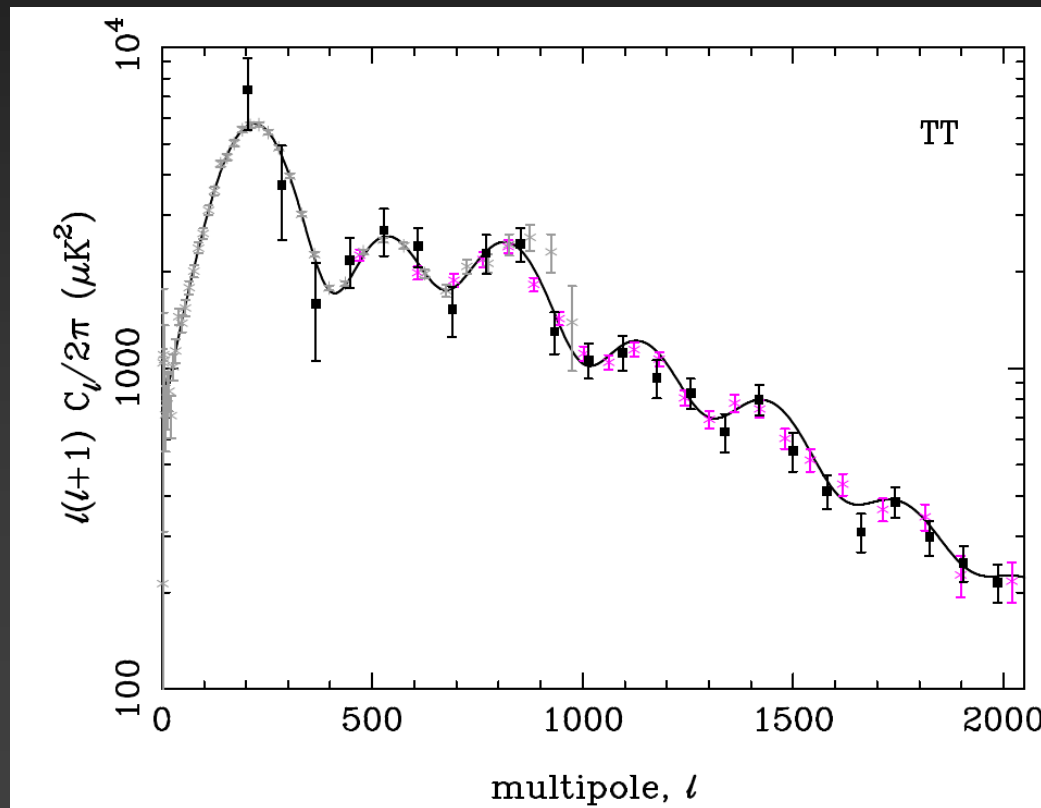
# CMB anisotropies

- Spectrum of WMAP's map (zoom on first 3 peaks)



# CMB anisotropies

- Spectrum from all currently available data





# Perturbation analysis : results

- Confirmation of radiation / matter domination, of primordial nucleosynthesis
- Univers très plat et en accélération (preuve indépendante des supernovae)
  - Modification gravité?
  - Matière avec pression négative = « énergie noire » ?
  - Constante cosmologique (pression = - densité) ?

# Perturbation analysis : results

- Confirmation of radiation / matter domination, of primordial nucleosynthesis
- Universe close to euclidean, in acceleration (proof independant of supernovae)
  - Modified gravity ?
  - Negative pressure fluid = « dark energy » ?
  - Cosmological constant (pressure = - density) ?

# Perturbation analysis : results

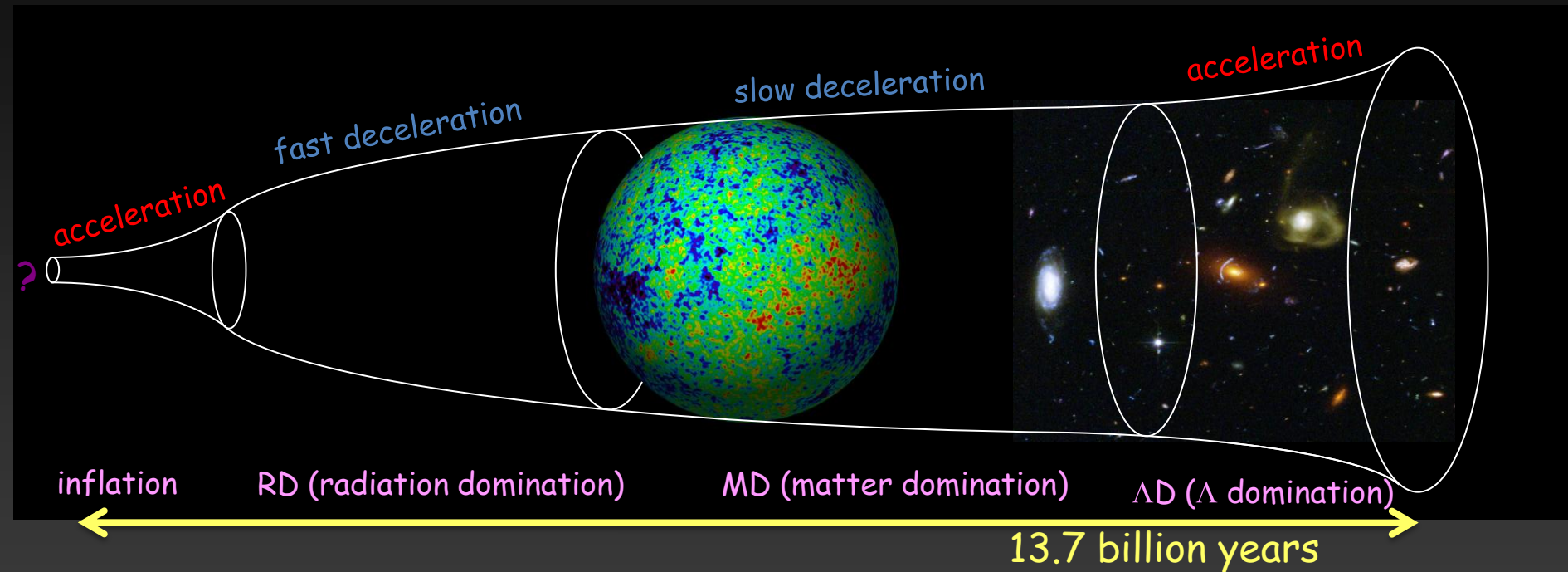
- Confirmation of dark matter (model coming from astrophysics : Zwicky 1933) = non-relativistic matter which interacts only gravitationally



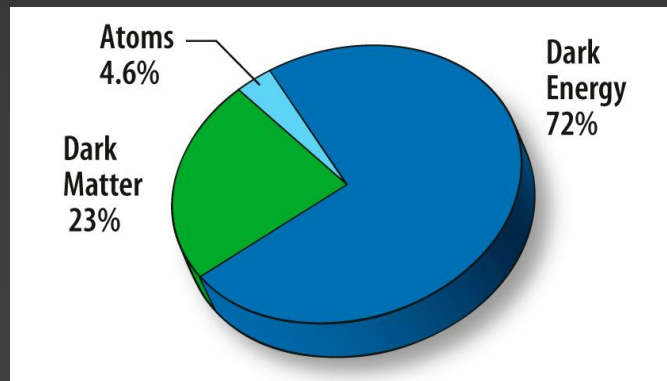
# Perturbation analysis : results

- Properties of primordial fluctuations coincide with predictions of inflation
  - Quantum fluctuations  $\rightarrow$  density fluctuations in primordial universe
  - Special properties (passive, gaussian, adiabatic, nearly scale-invariant)
  - Indirect proof : no satisfactory alternative model; better proofs possible with future CMB experiments...

# Standard cosmological model



currently :



+ 0.1% to 1% neutrinos  
+ 0.01% photons

# Limits of the model

- Simplest model in agreement with most observations. Various possible extensions known and studied.
- Few observations disagree. To be confirmed.
- Theoretical limits of cosmology !!!!

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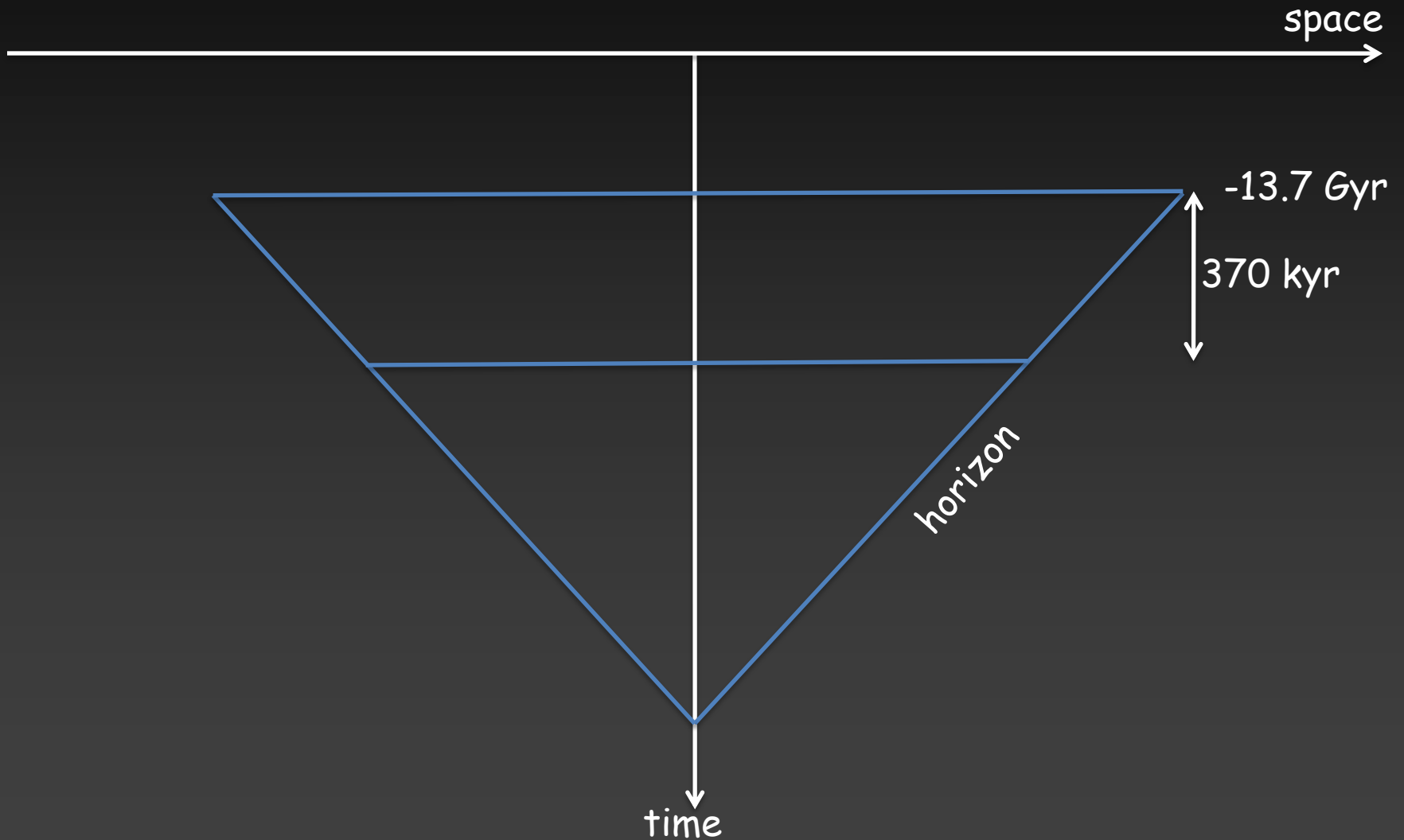
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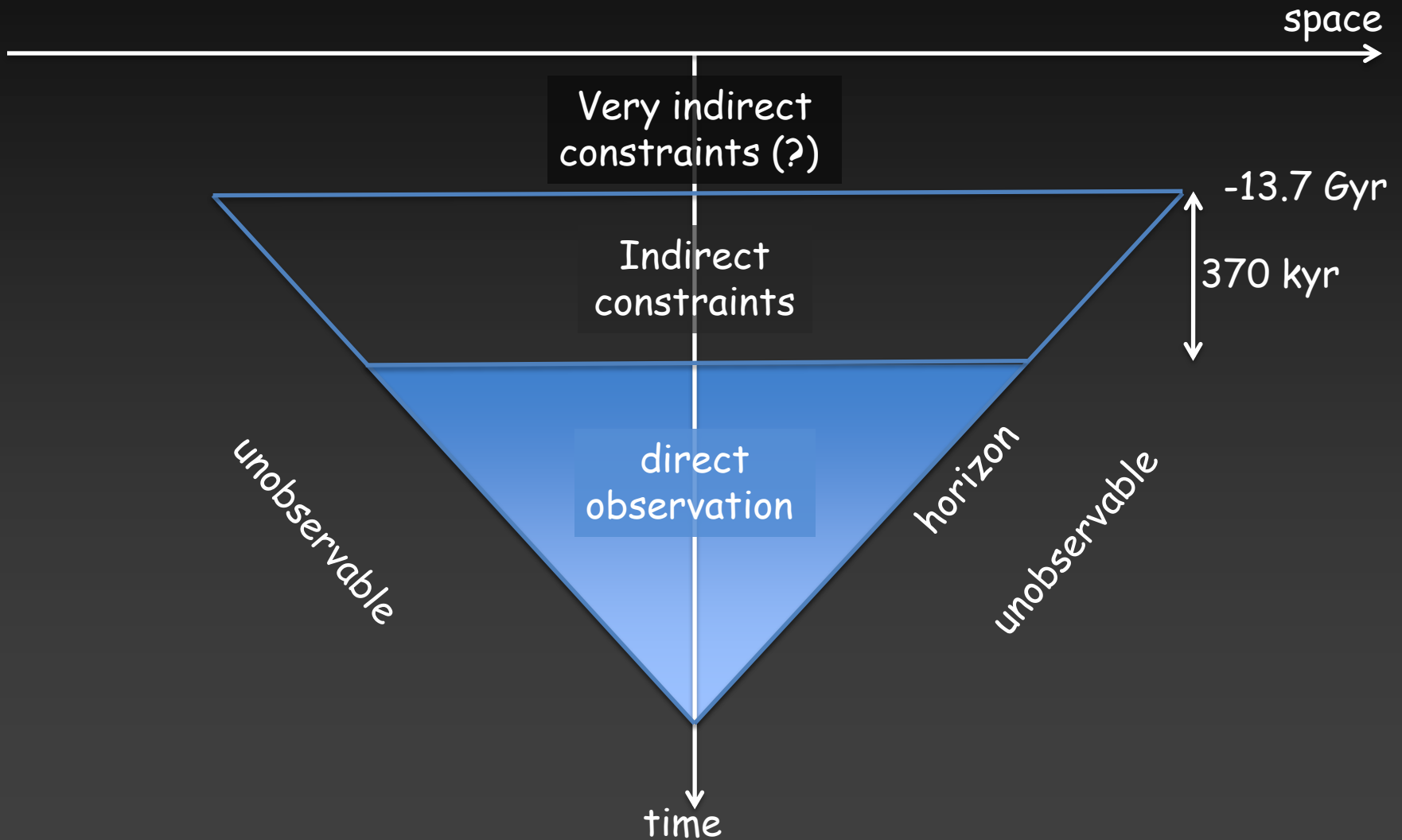
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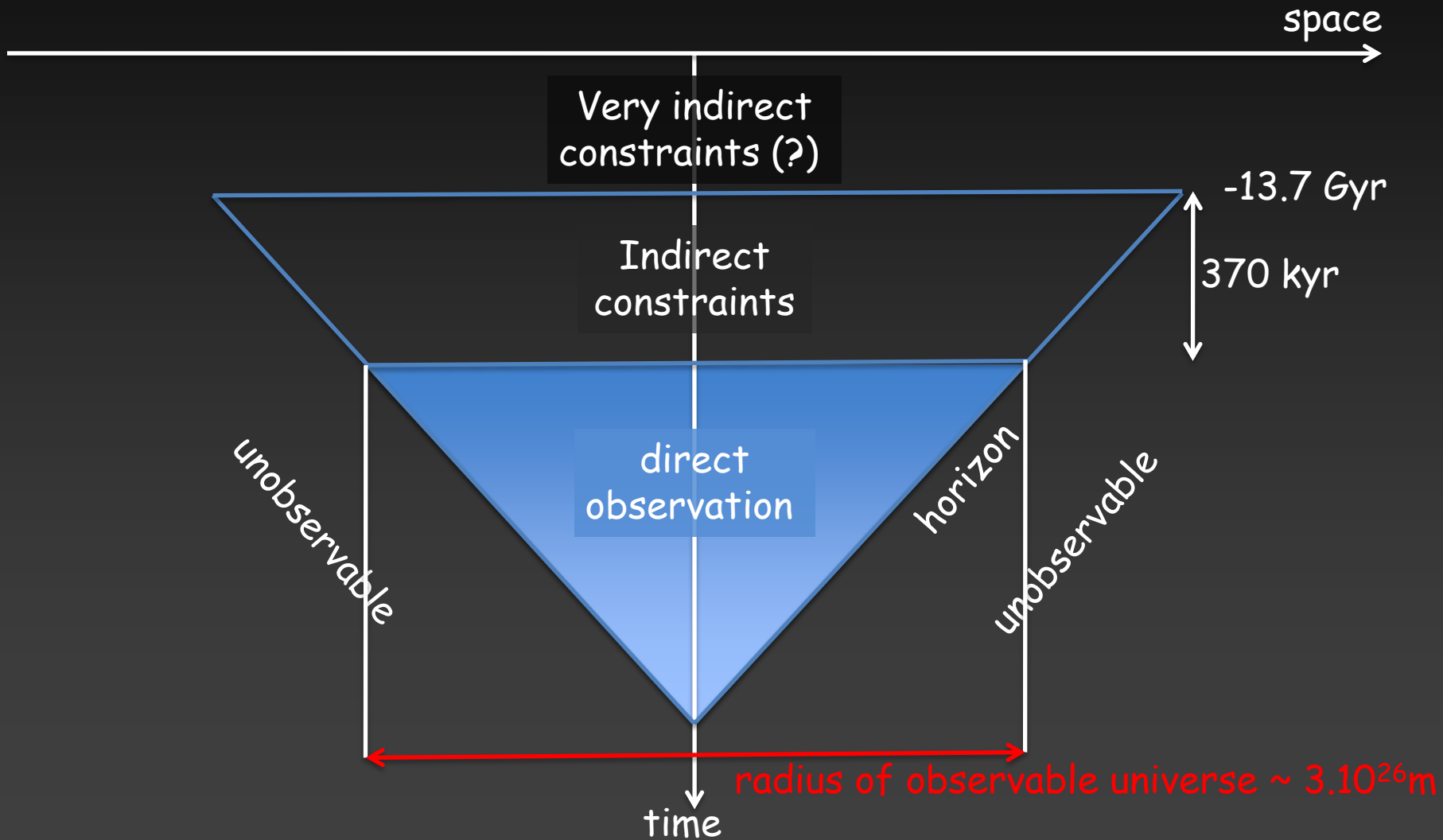
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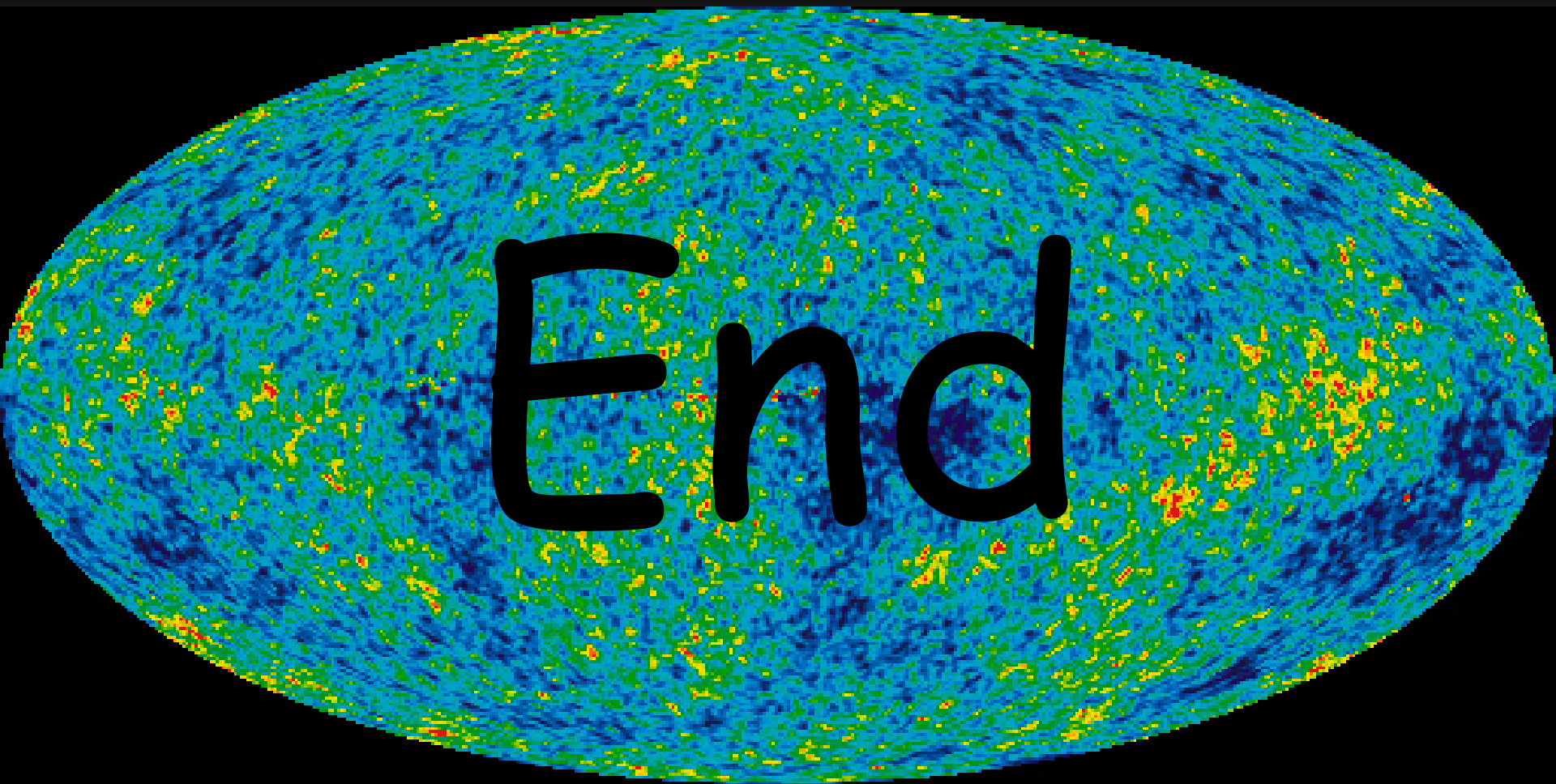
- Standard cosmological model = approximation valid in the observable part of the universe
- Doesn't say whether universe globally finite/infinite, euclidean, homogeneous, etc.
- Exemple of global topology
  - if actual radius < observable radius (fake) : multiple images
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