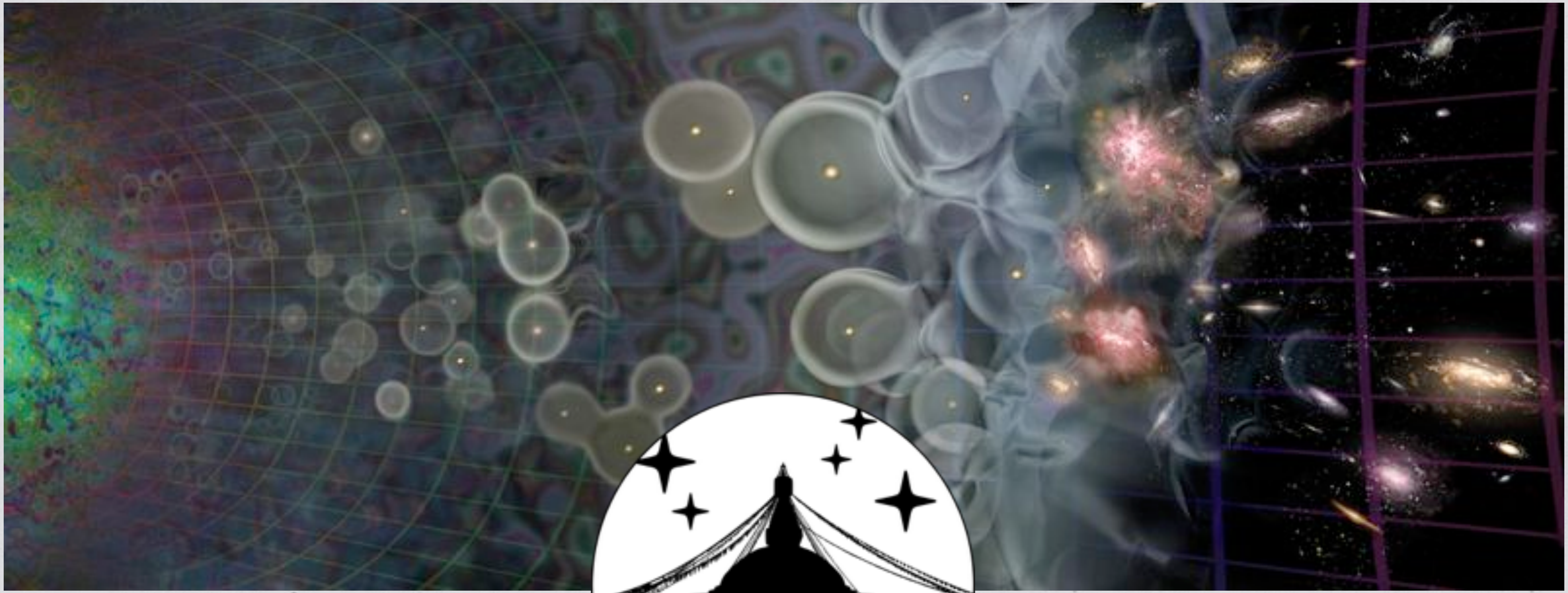
Introduction to Cosmology

POSTERA CRESCAM LAUDE

Michele Trenti

Australian Government
Australian Research Council



FIRST
KATHMANDU ASTROPHYSICS SCHOOL
KAS16

My (scientific) path around the world

★ Born and raised in Italy

★ Undergrad. & Ph.D. in Pisa

★ Postdoc at STScI, Baltimore, MD

★ Postdoc at University of Colorado, Boulder

★ Kavli Institute Fellow (lecturer) at the University of Cambridge

★ Senior Lecturer at the University of Melbourne

SCUOLA
NORMALE
SUPERIORE

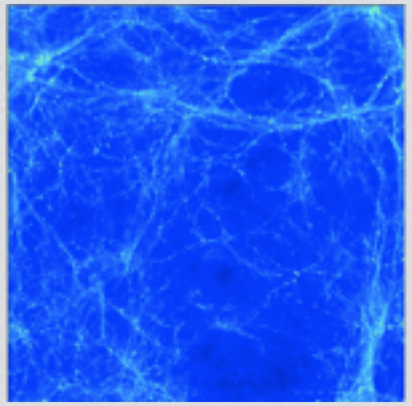
SPACE
TELESCOPE
SCIENCE
INSTITUTE
Operated for NASA by AURA

Kavli Institute for Cosmology
KICC
Cambridge

THE UNIVERSITY OF
MELBOURNE

At the crossroad of modeling and observations

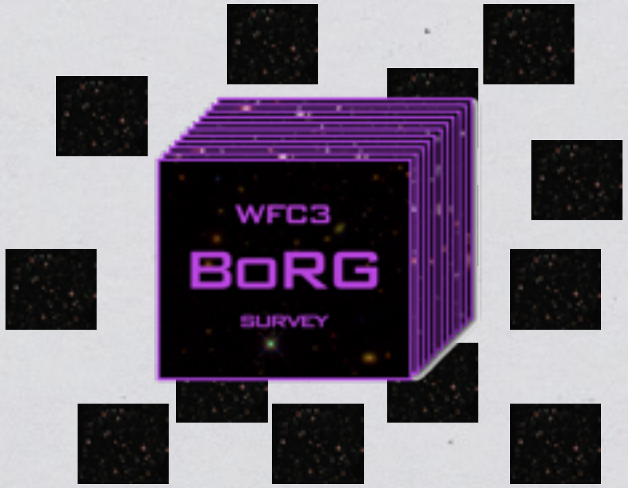
★ Models & simulations of dark matter, star/galaxy formation, metal enrichment



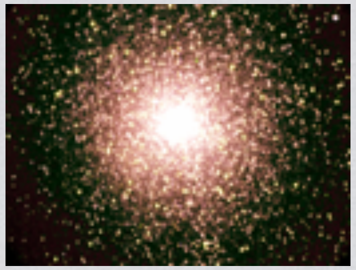
★ Observations of distant galaxies:

  ★ Ultra-faint

  ★ Bright



★ Star cluster dynamics/black holes



Outside the office

★Keen to go out and play (especially mountain “running”)

★Cooking

★Boardgames

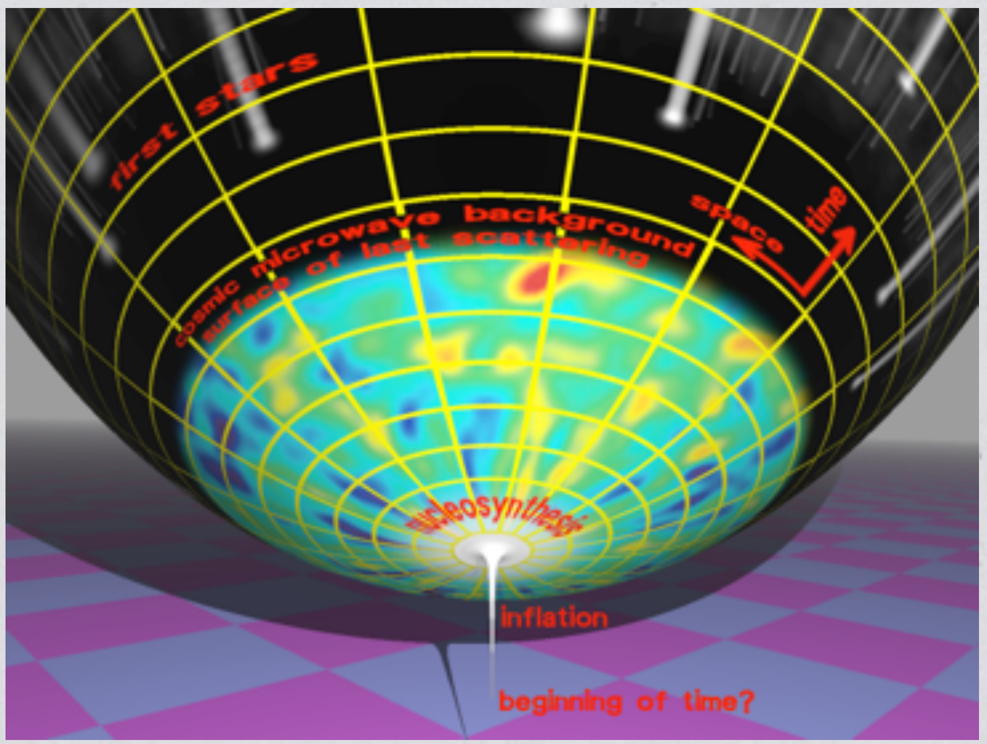
★ScienceFiction/Fantasy reading

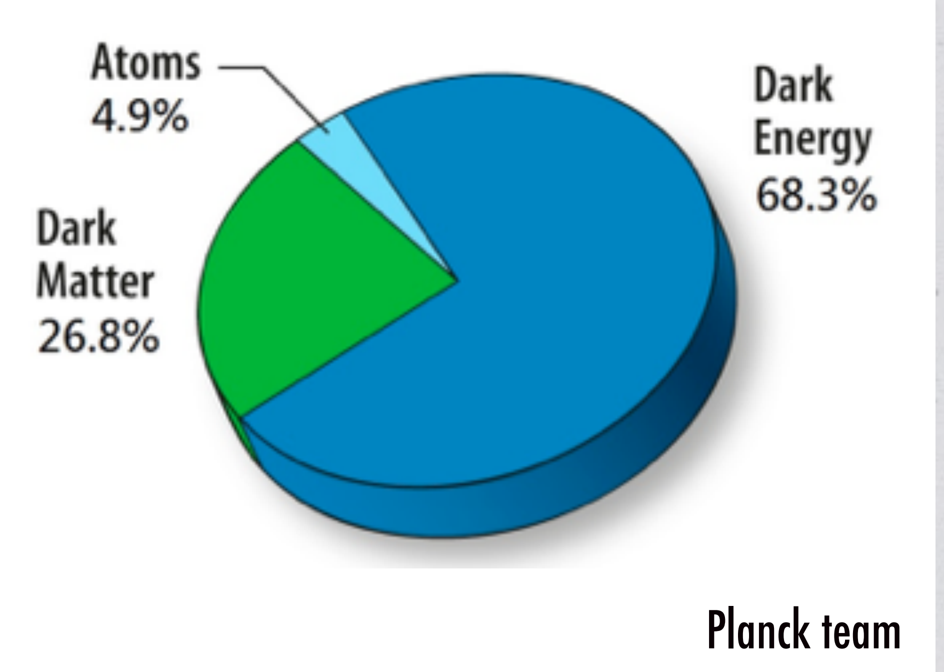
Outline

- ★ The Friedman-Robertson-Walker model
- ★ Observational evidence for expansion
- ★ A brief history of the Universe
- ★ Gravitational Lensing

A simple model for the Universe

- ★ Standard model: homogeneous, isotropic, expanding Universe
  - ★ Astronomer's time unit: redshift z [z+1: inverse of expansion factor]
- ★ Simple composition:
  - ★ Dark Energy
  - ★ Dark Matter
  - ★ Baryons

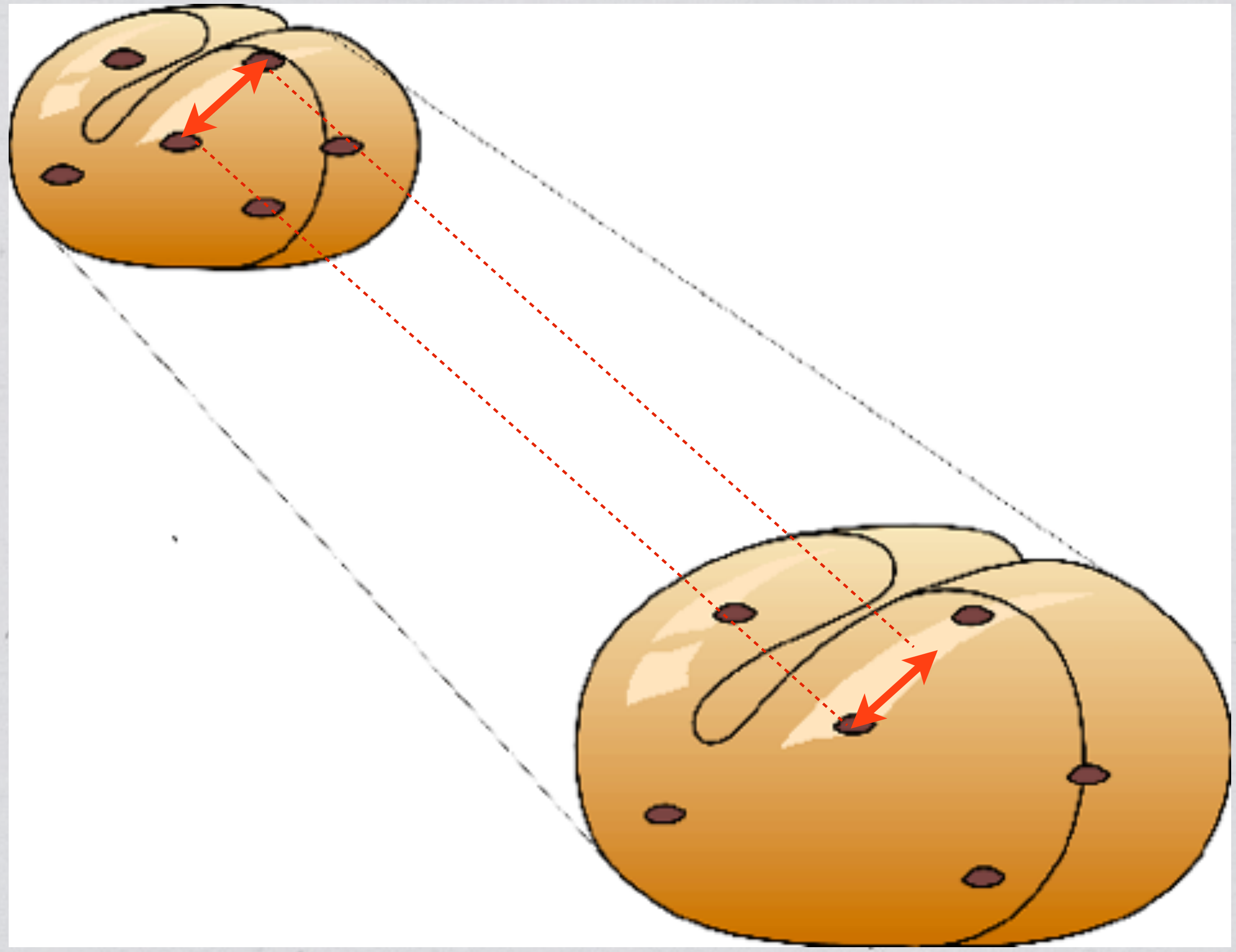




Planck team

The raisin bread analogy

★ All raisins are moving away from each other as the loaf grows during raising/baking



★ *First evidence of expansion from Hubble (~1920)*

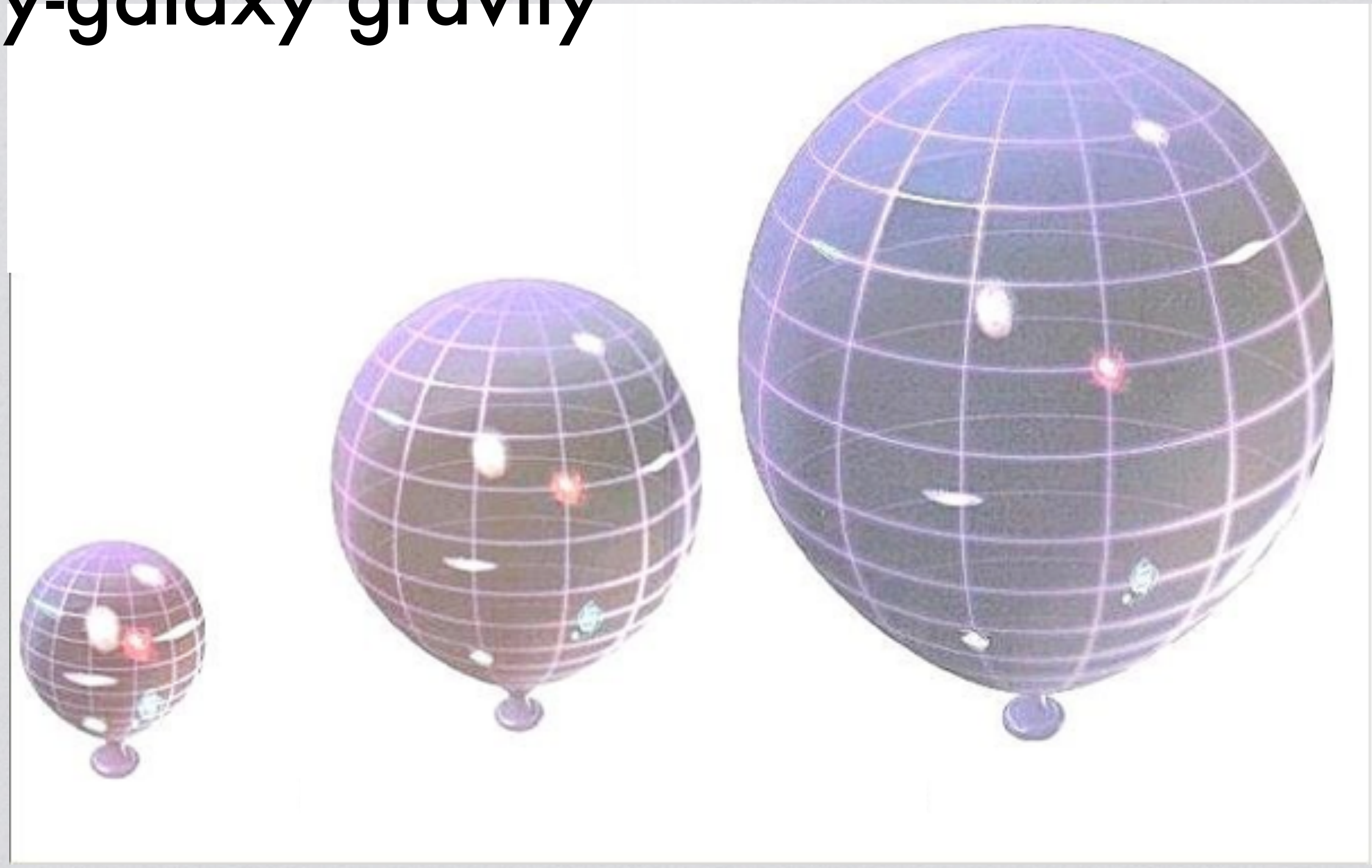
Homogeneity and Isotropy

★ What does it mean?

- ★ Homogeneity: Universe looks the same at all points
- ★ Isotropy: Universe looks the same in all directions
- ★ *Can you think of examples of systems that meet one but not the other property?*

The idea of comoving coordinates

- ★ Comoving coordinate system carried along with expansion:
  - ★ Treat separately global expansion vs. local motion such as galaxy-galaxy gravity



- ★ Newtonian gravity is exact in comoving coordinates [for homogeneous Universe]

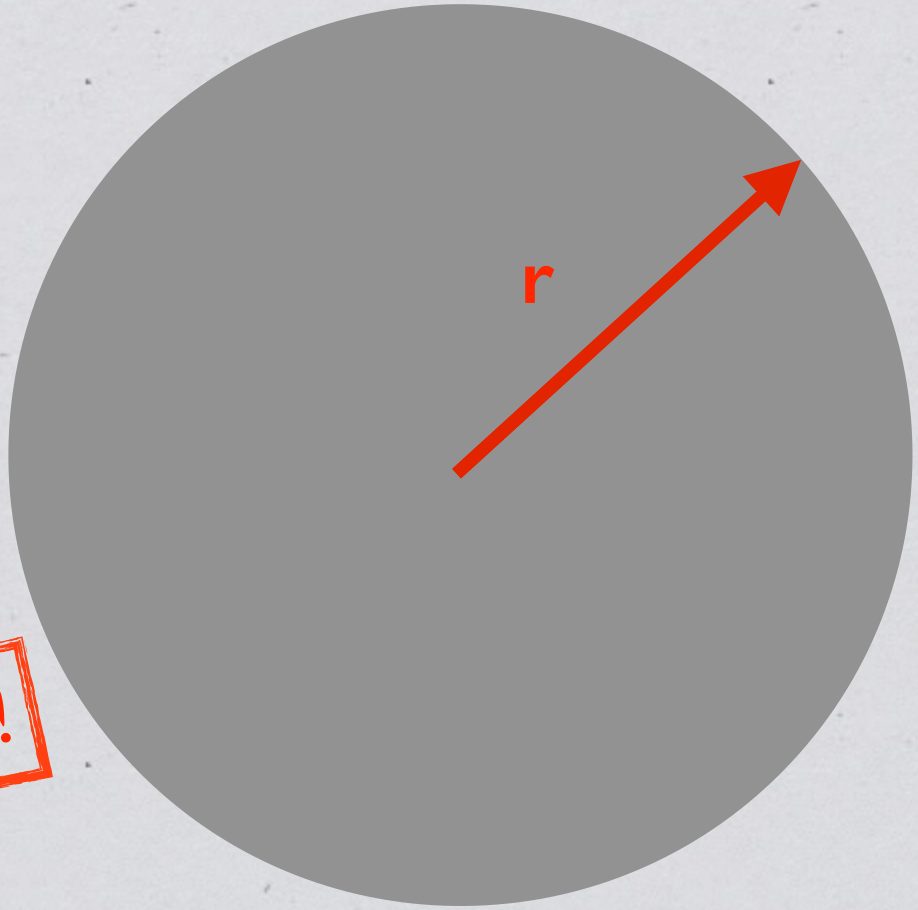
The Friedman equation

- How do we describe the expansion of the Universe?
  - Expansion factor: $a(t)=1/(1+z)$
    - $a(t=0) = 0$
    - $a(t_{now}) = 1$
  - Equation for $a(t)$ derived from energy conservation of a uniform expanding medium

No worries: No derivation today!

comoving

$$\overrightarrow{r(t)} = a(t)\ \vec{x}$$



The Friedman equation

Curvature

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

Density

Cosmological constant

Expansion rate

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

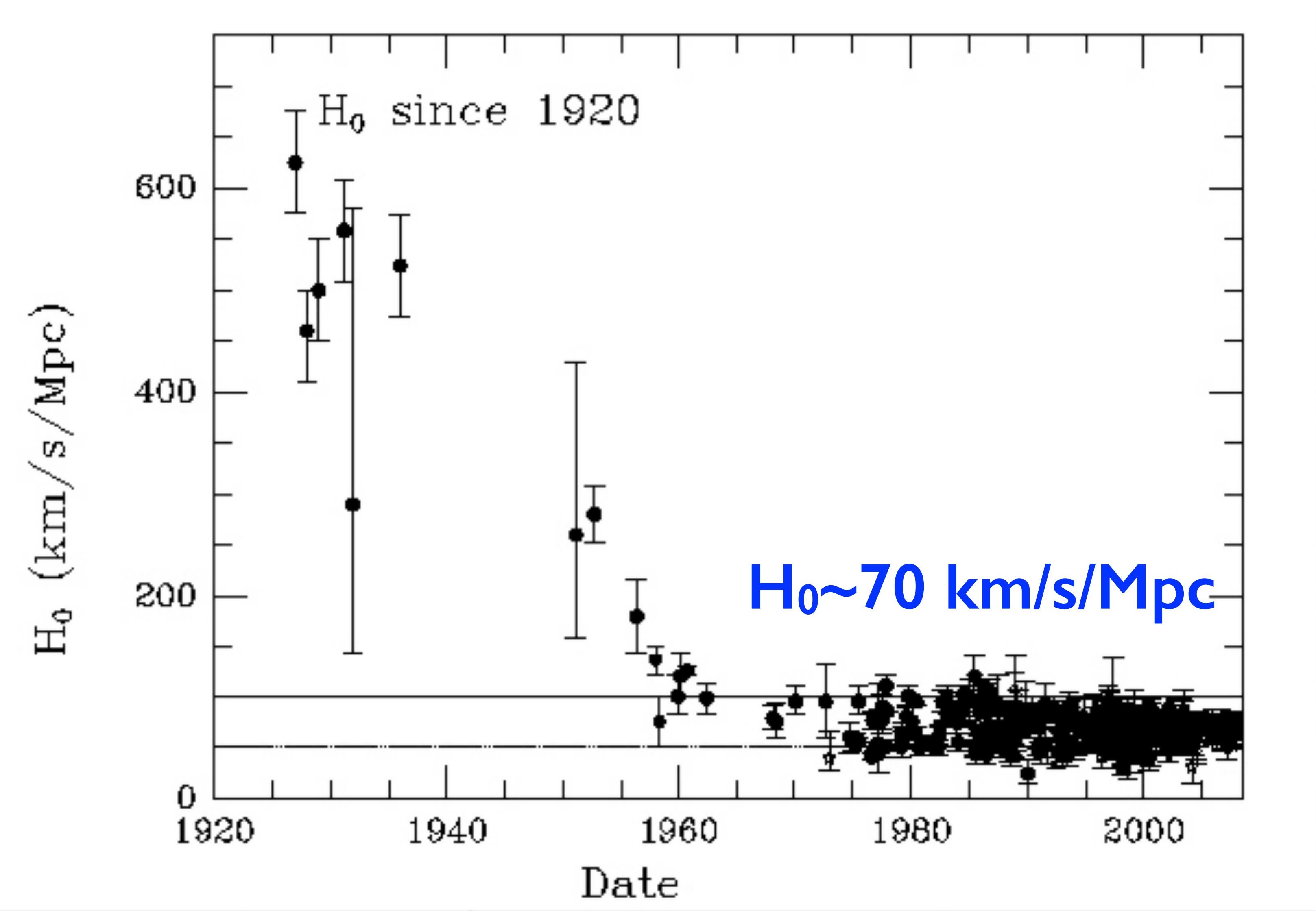
- Friedman equation: Density scaling as
  - Matter: $1/a^3$
  - Radiation: $1/a^4$ [IDEA of WHY extra a?]
- For a flat Universe
  - Matter Dominated: $a(t) \propto t^{2/3}$
  - Radiation Dominated: $a(t) \propto t^{1/2}$
  - Λ Dominated: $\left(\frac{\dot{a}}{a}\right)^2 = \frac{\Lambda}{3}$

Acceleration

A basic parameter: Hubble Constant

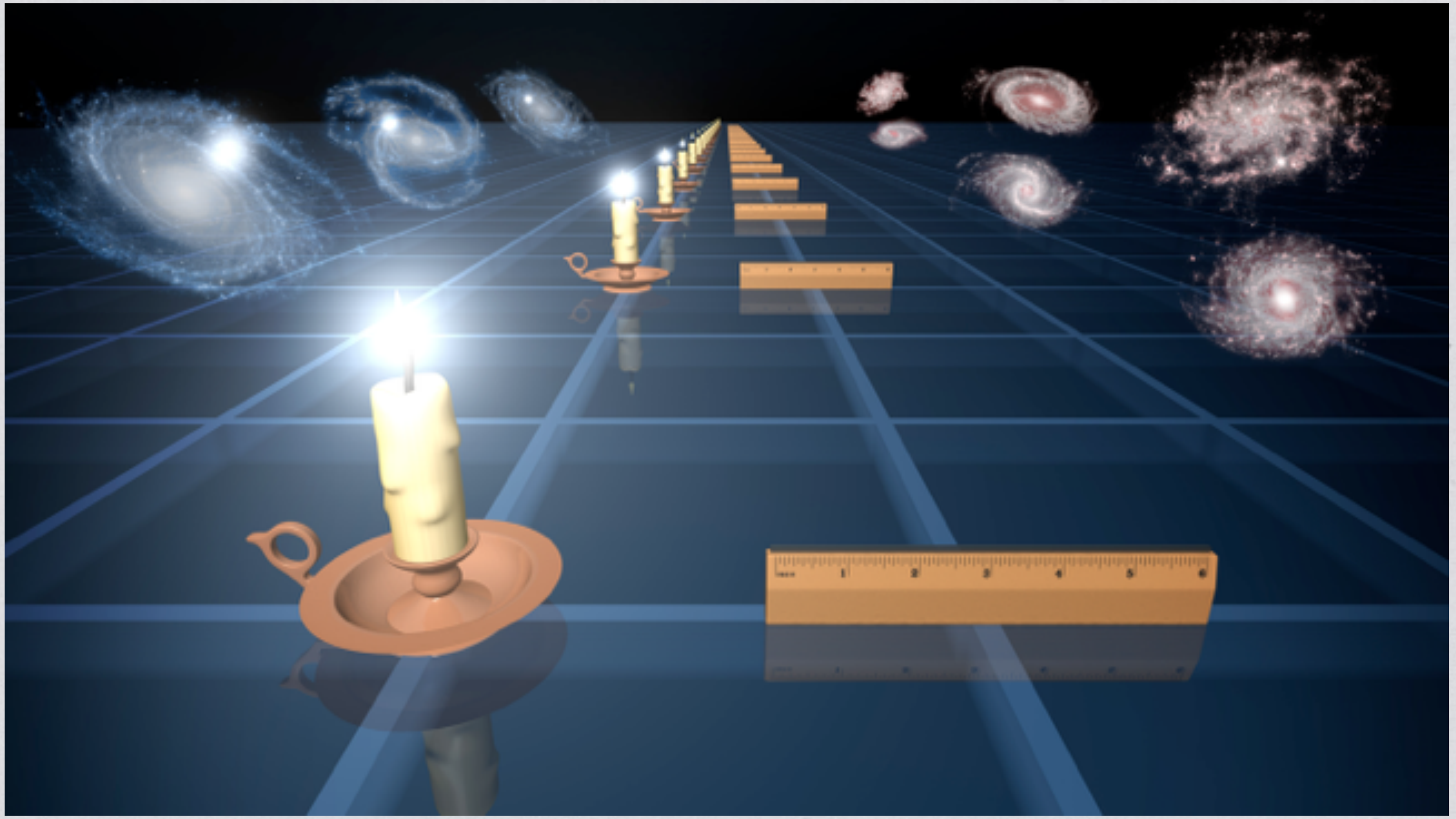
$$\frac{a(t)}{a(t_0)} = 1 + H_0[t - t_0] + O[(t - t_0)^2]$$

- ★ Hubble was only qualitatively right

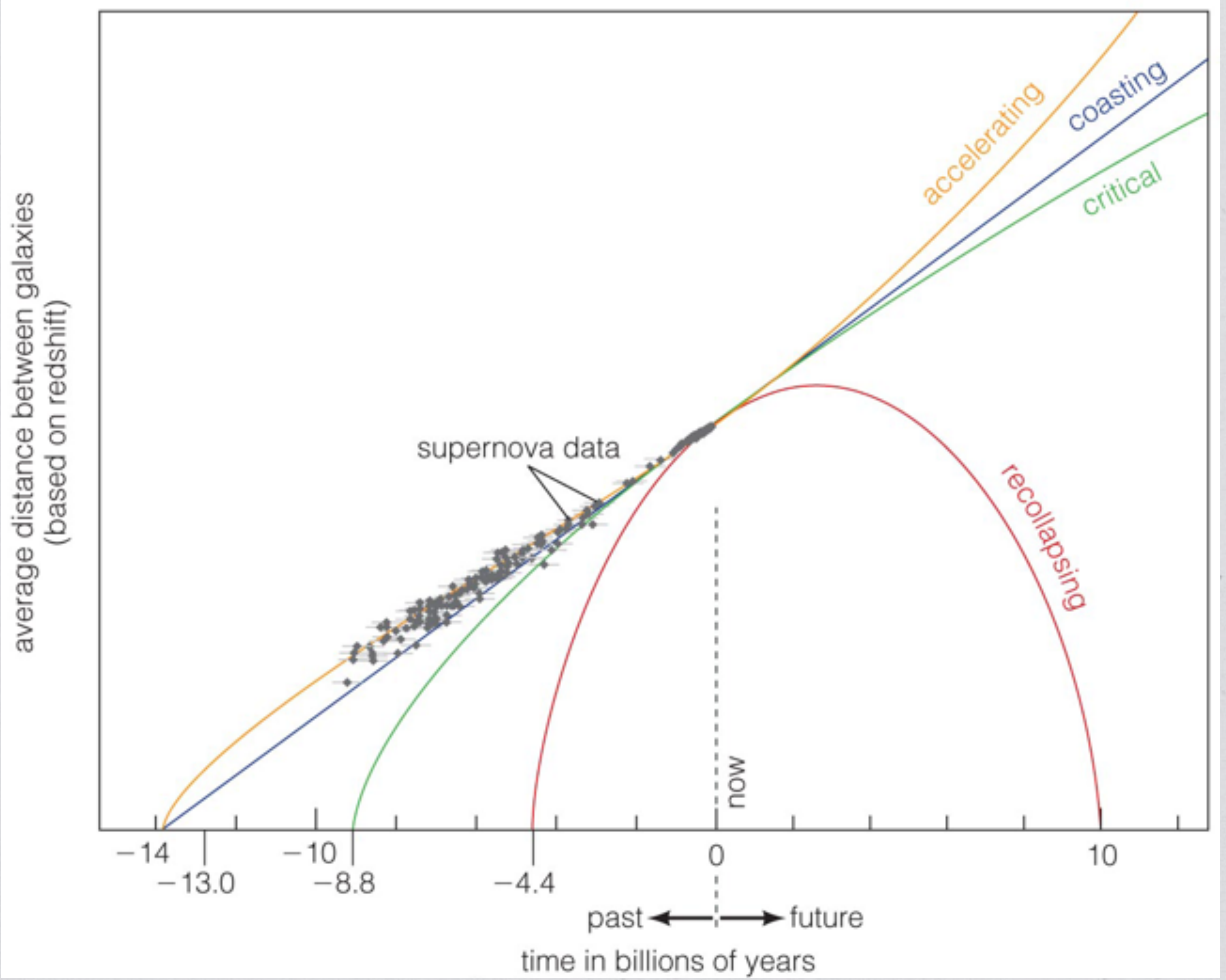


Measuring expansion with standard candels

- ★ Measure redshift and observed luminosity
- ★ If we know absolute luminosity, we infer luminosity distance (cosmology dependent)



Observational evidence for an accelerating universe



Alternative cosmological probes: Oldest stellar populations

- ★ Globular clusters have oldest stars in the MW
- ★ What do they tell us about H_0?

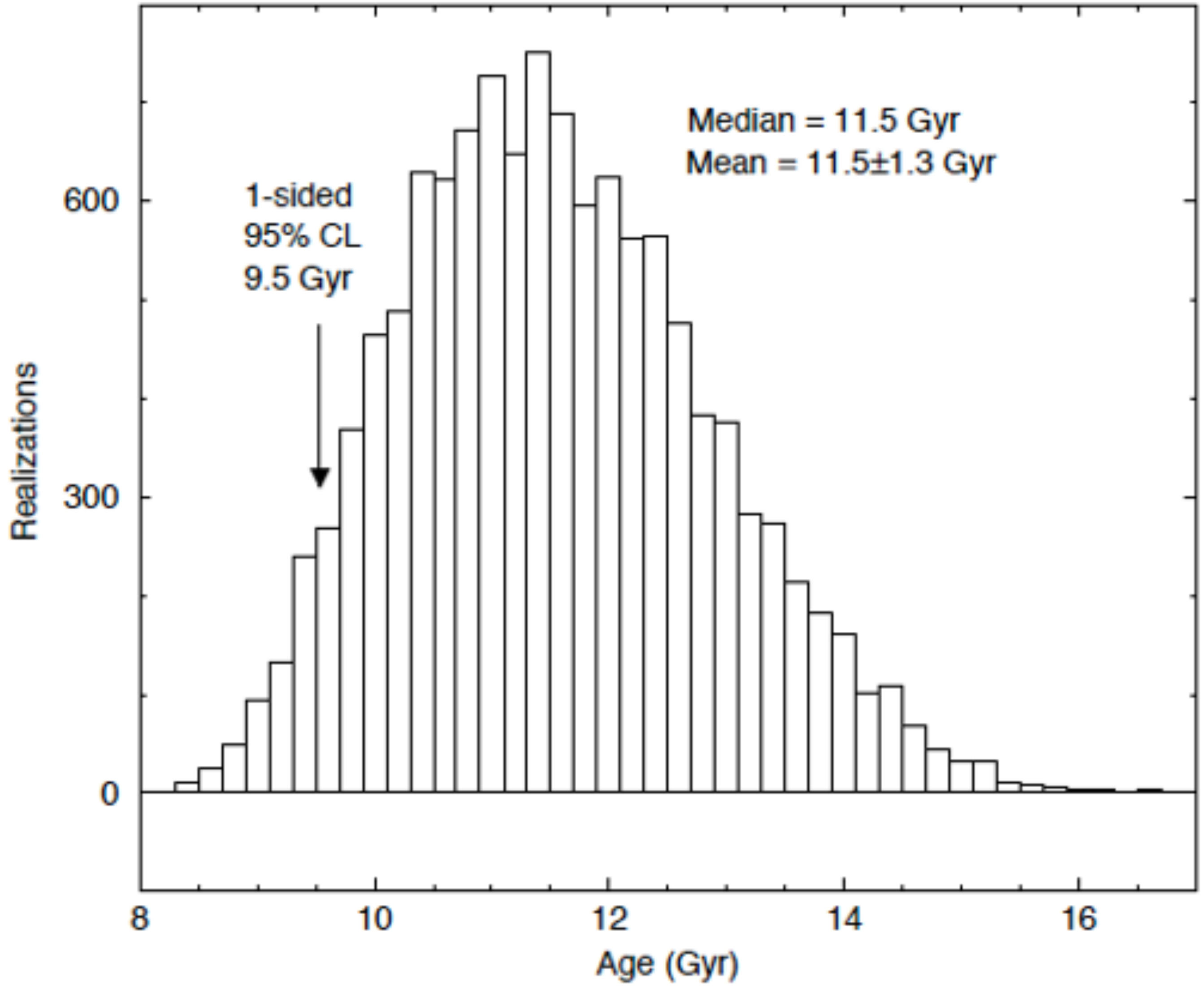


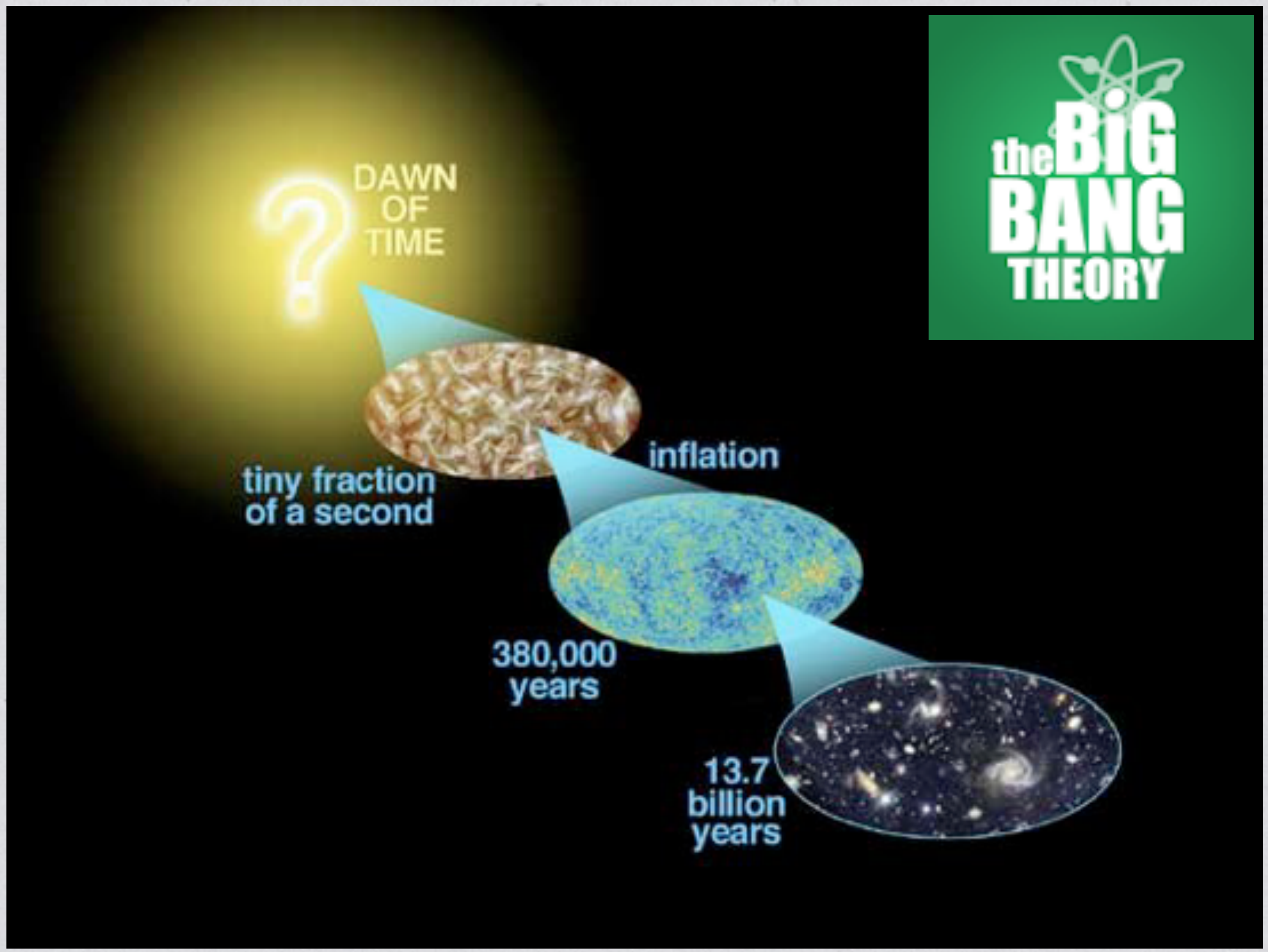
FIG. 2.—Histogram of globular cluster (GC) ages. The median, mean, standard deviation and one-sided 95% confidence level lower limit are all indicated on the figure.

Consistent evidence that standard cosmological model provides a good description of the Universe

What are its basic predictions for the history of the Universe?

A brief history of the Universe: The Beginning

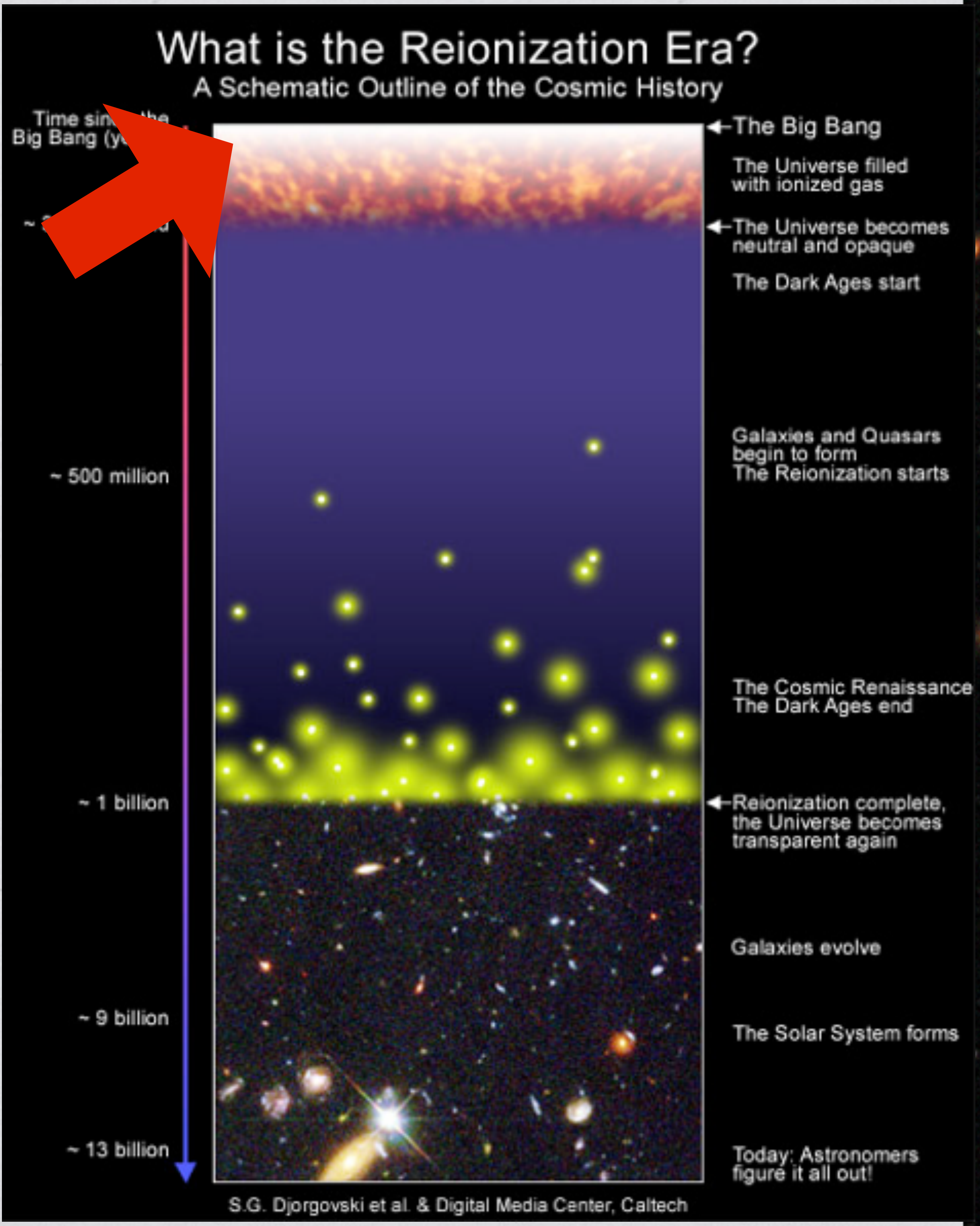
Our whole Universe was in a hot dense state, then nearly fourteen billion years ago expansion started...



Hot and dense

The first steps

- ★ $t<10^{-10}$ s: Fairly open to speculation
  - ★ $t<10^{-43}$ s: Planck epoch [gravity is unified]
  - ★ $t<10^{-34}$ s: Forces (except gravity) unified [$T>10^{16}$ GeV]



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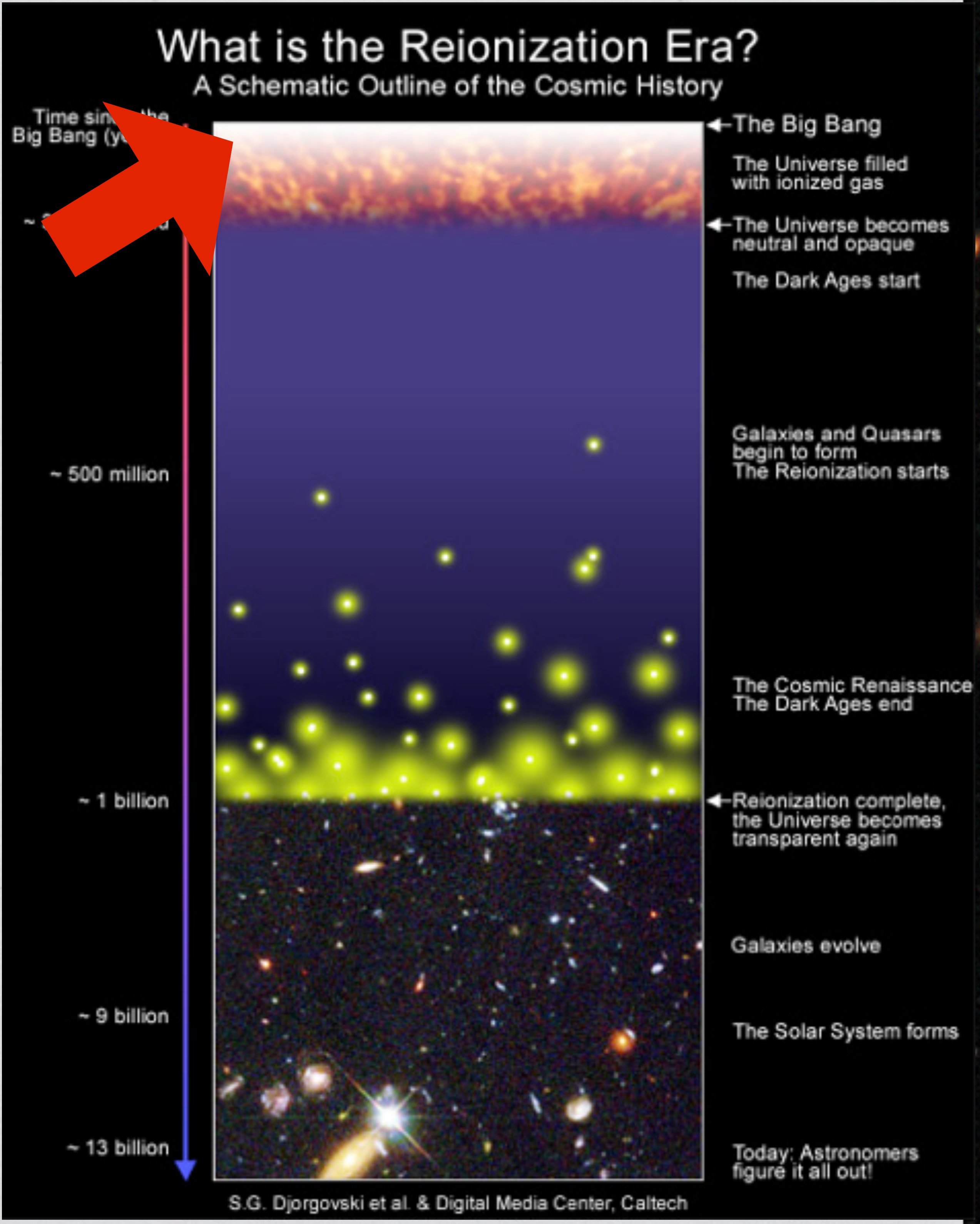
Hot and dense

The first steps

- ★ t~10^{-40}-10^{-34}s: Inflation [Universe expands by factor ~e^{99}]
- ★ Inflation conveniently solves:
  - ★ Flatness problem (Ω=1)
  - ★ Horizon problem (isotropy)
  - ★ Relic particle abundances



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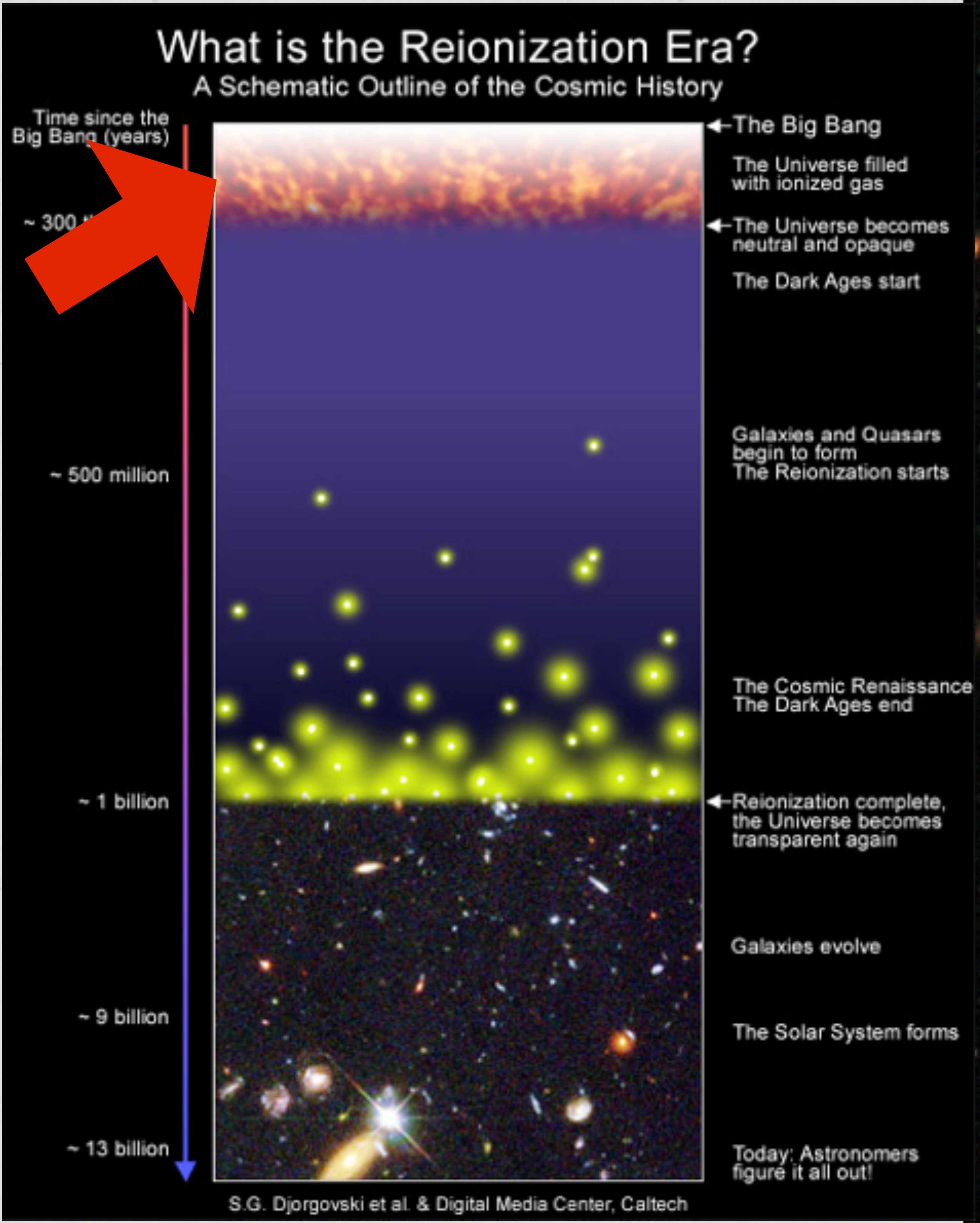
Hot and dense

The first few minutes

- ★ t~400s: Nucleosynthesis [T~1MeV]
  - ★ Radiation becomes unable to dissociate nuclei
  - ★ Primordial chemical elements are formed (H, He, + traces of Li)



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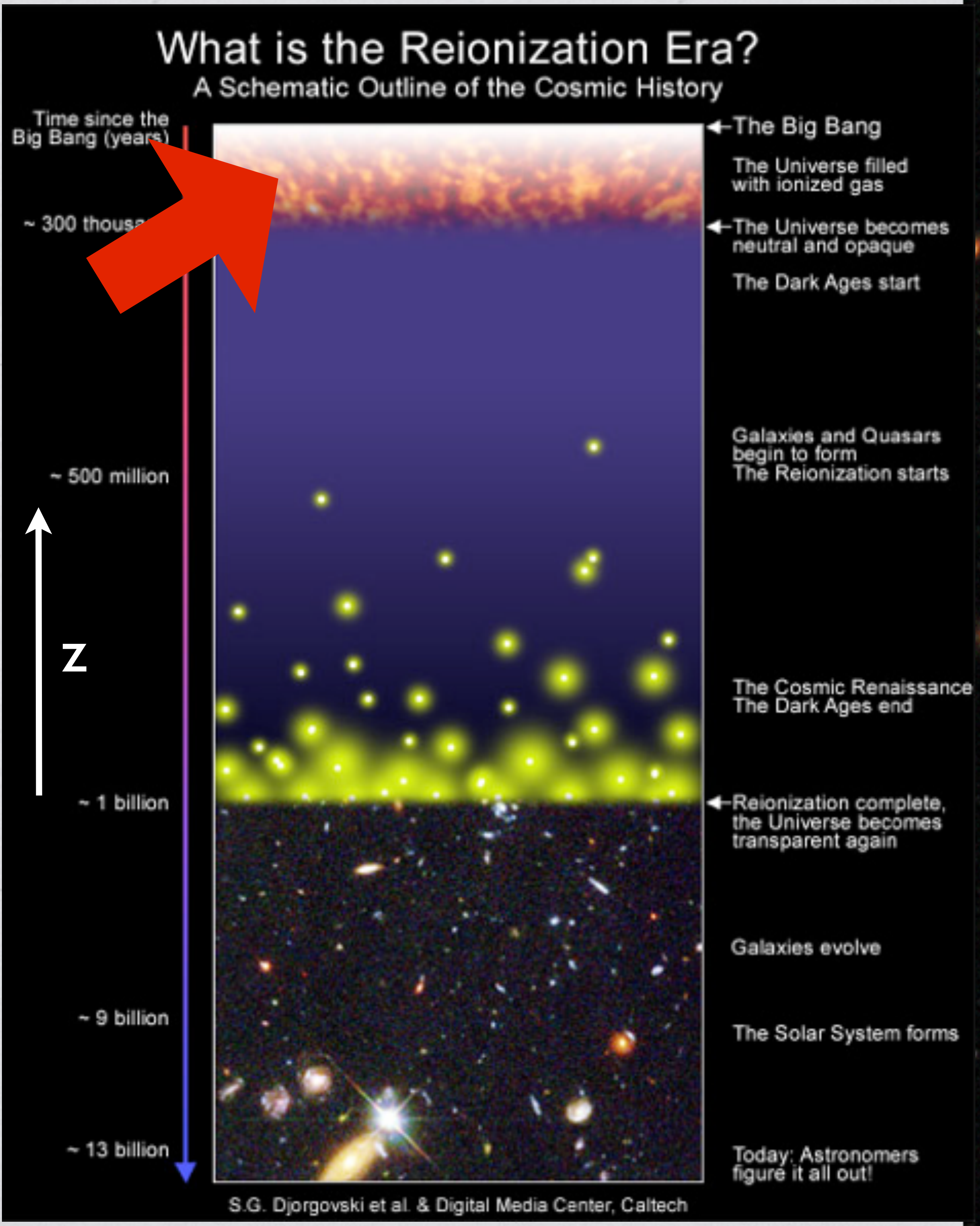
The infancy of the Universe

- ★ Plasma temperature is decreasing with decreasing redshift (expansion-induced cooling)
  - ★ $z \gtrsim 1500$ [~$3x10^5$ yr]: The Universe is ionized



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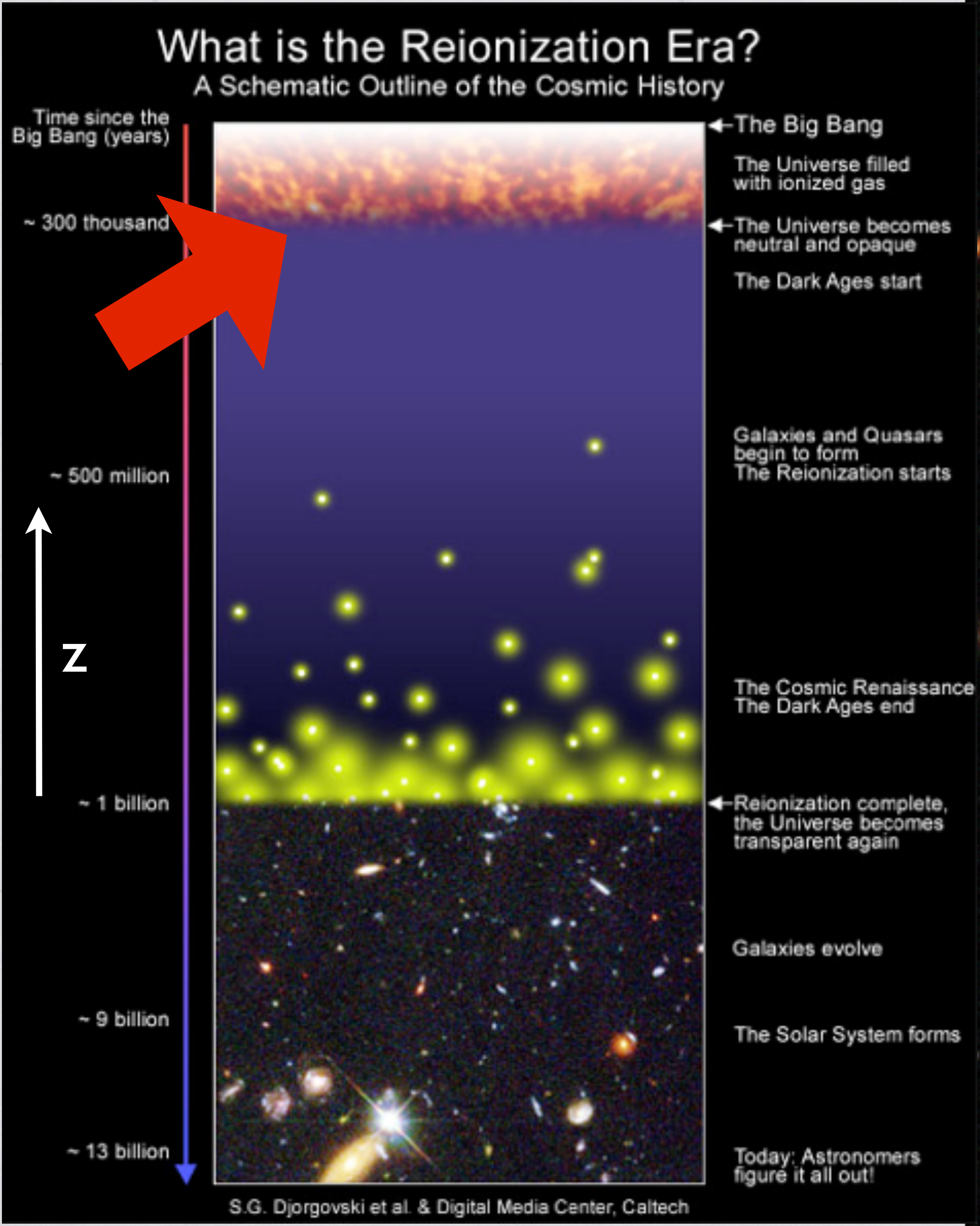
The Dark Ages

- $z \lesssim 1500$ [~3e5 yr]: Gas in the Universe becomes neutral (opaque)
  - Temperature has decreased sufficiently to allow efficient recombination
- The Dark Ages begin



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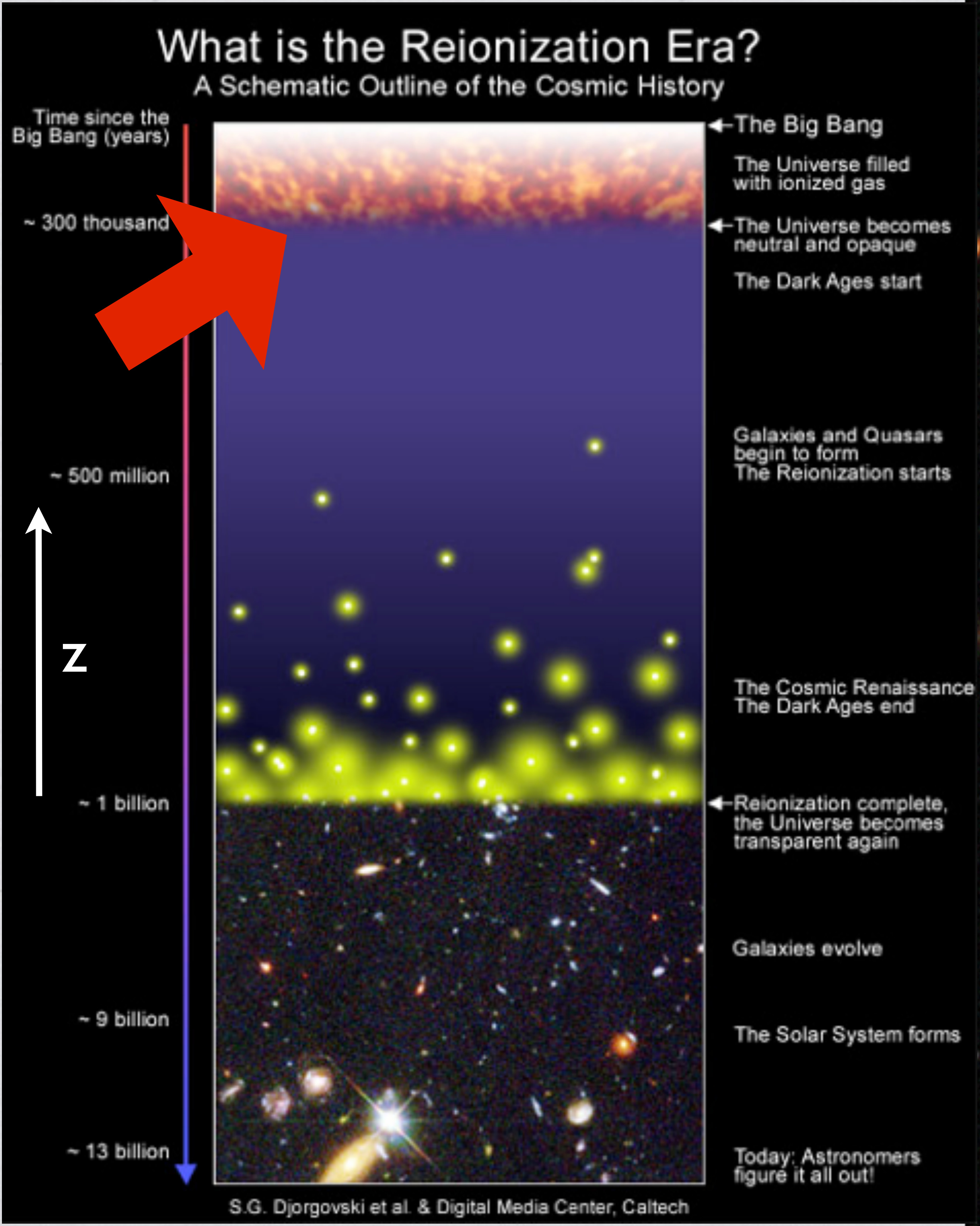
Cosmic microwave background

- ★ z~1100 [~3.5e5 yr]: Decoupling between radiation and matter
  - ★ Radiation can travel freely without further scattering
- ★ Cosmic Microwave Background gives us image of the last scatter surface



What is the Reionization Era?

A Schematic Outline of the Cosmic History

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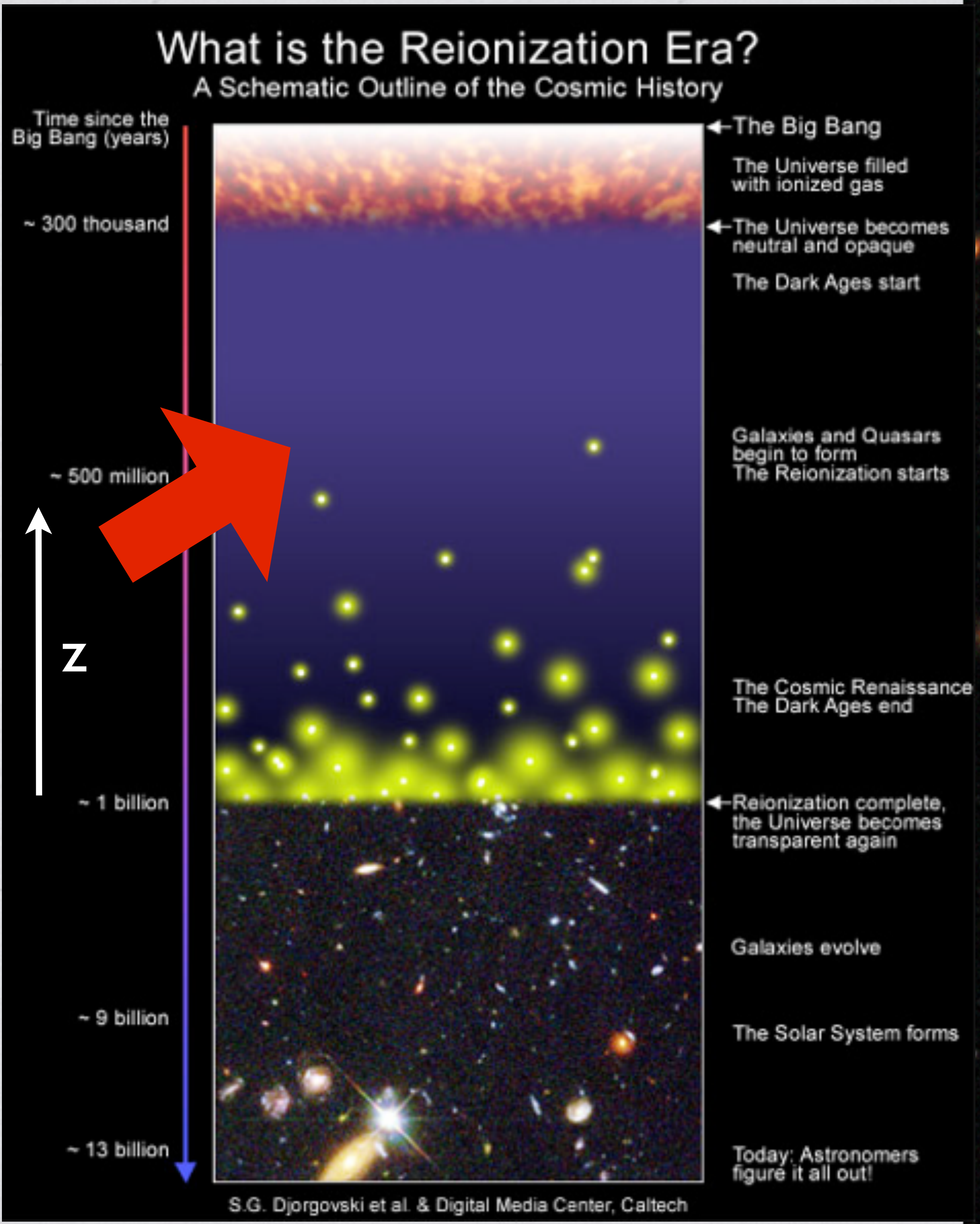
The First Light

- $z \lesssim 30$ [~1e8 yr]: First dark matter halos with 10^6-10^8 M_{sun} form from non-linear growth of primordial density fluctuations
  - Gas cooling possible within these halos:
    - First Stars and Galaxies are born



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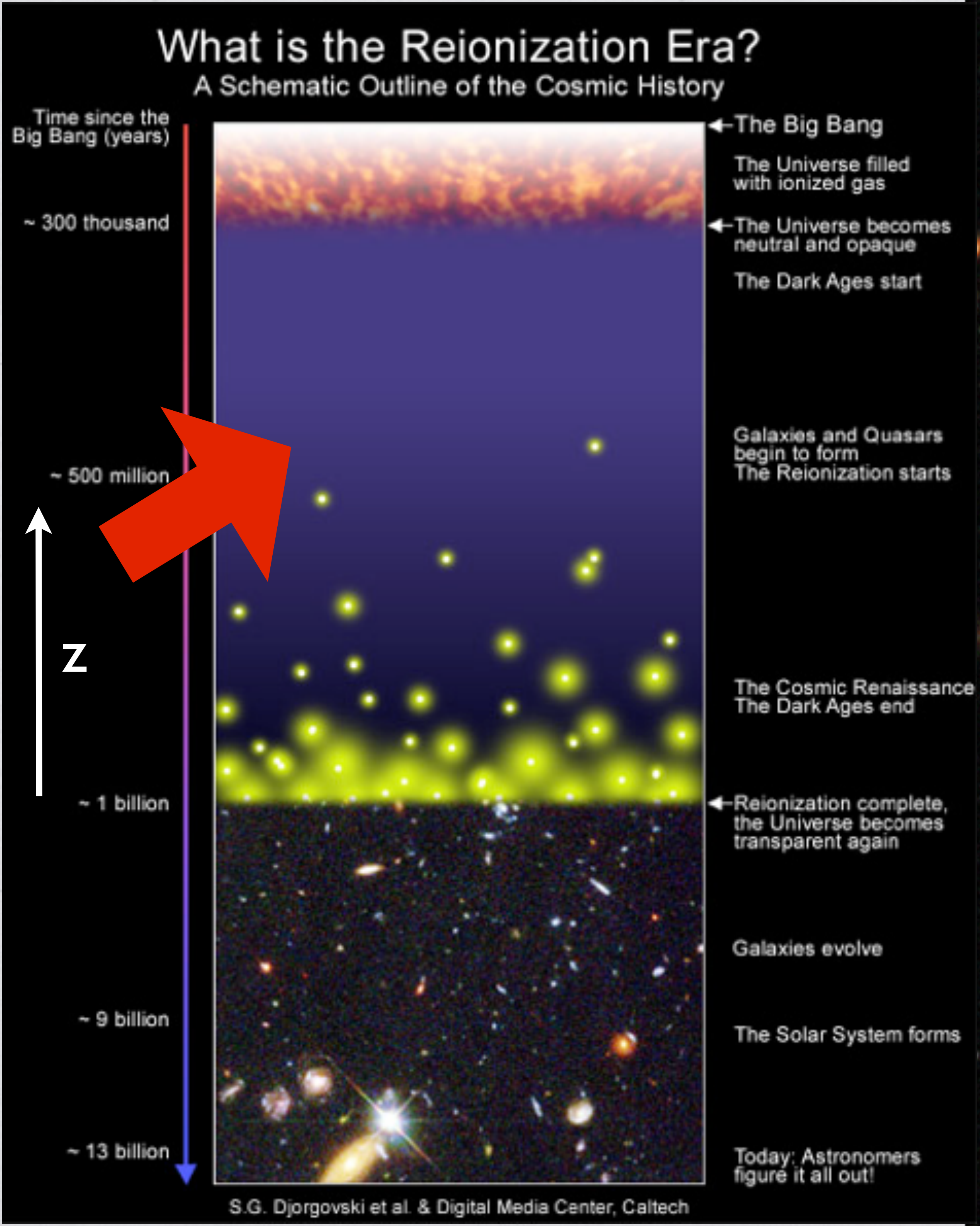
The beginning of reionization

- ★ $z \lesssim 30$ [~1e8 yr]: First light sources emit energetic photons (E>13.6 eV)
  - ★ Hydrogen (re)ionization begins
  - ★ Star formation rate, and therefore ionization fraction, increases with decreasing redshift



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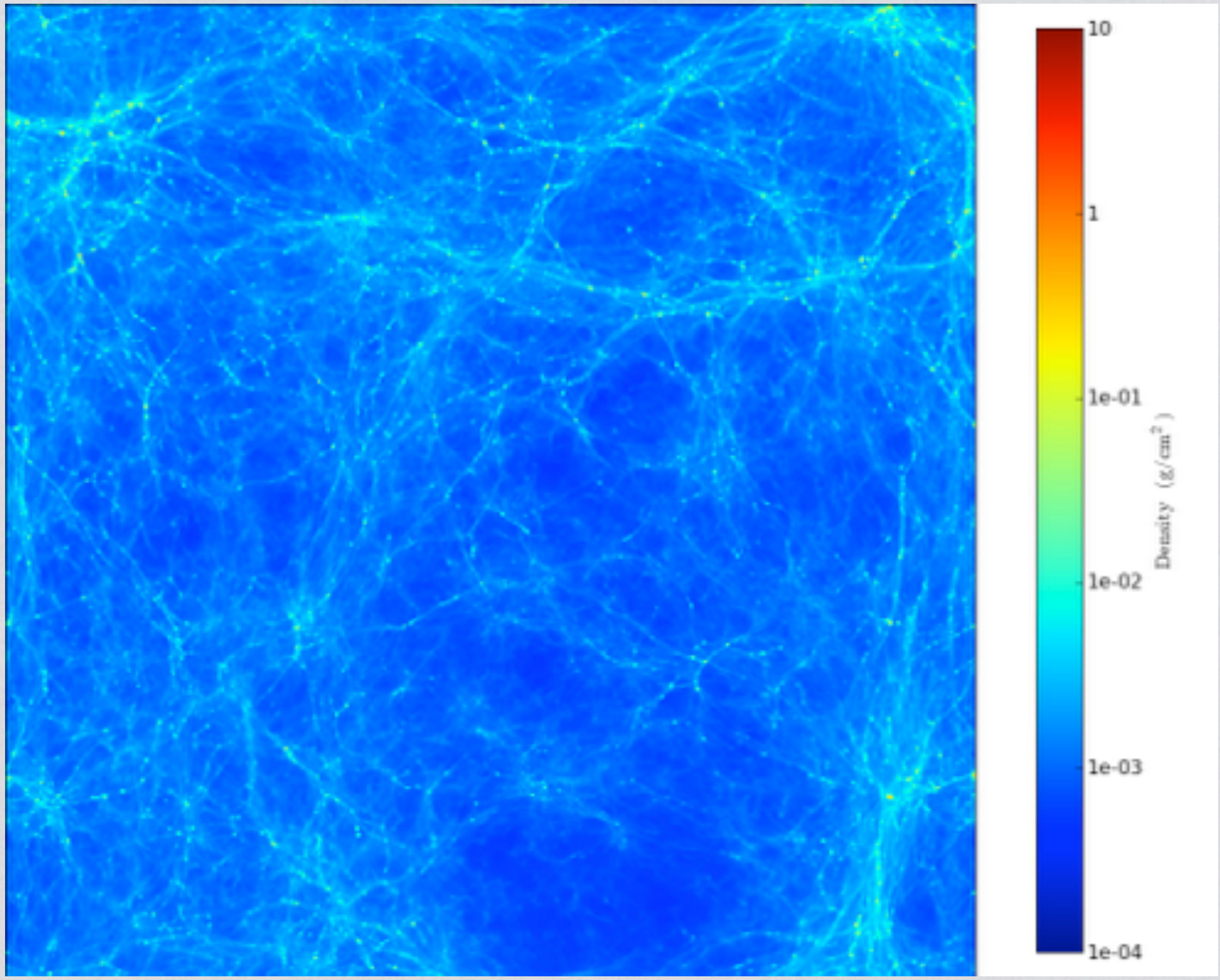
Clustering of First Galaxies

- ★Formation of first galaxies (ionizing sources) is spatially biased
- ★Large scale structure (cosmic web) already present at z~6-10
- ★Overdensities: Locations of first galaxies

Structure at early times: density projection



10^3 Mpc^3 box, N=2x1024^3, z_{end}=6

Trenti, Stiavelli & Shull (2009)

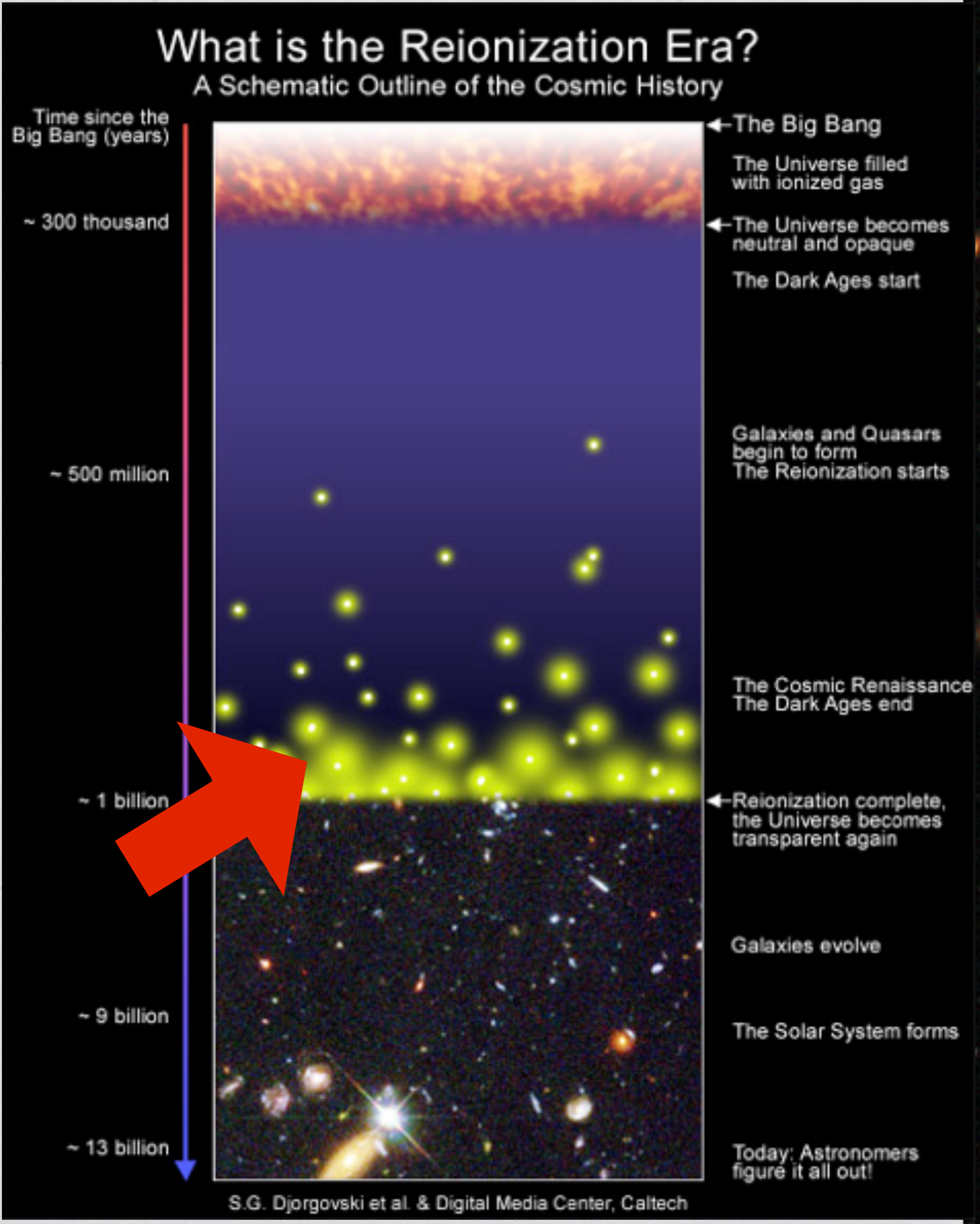
The end of reionization

★By z~6 [10^9 yr] hydrogen reionization is completed:

  ★In fact, the Universe is observed to be mostly transparent to ionizing photons

★How does the process proceed from z~30 to z~6? What is its topology?

★What are the sources responsible? And their properties?



What is the Reionization Era?

A Schematic Outline of the Cosmic History

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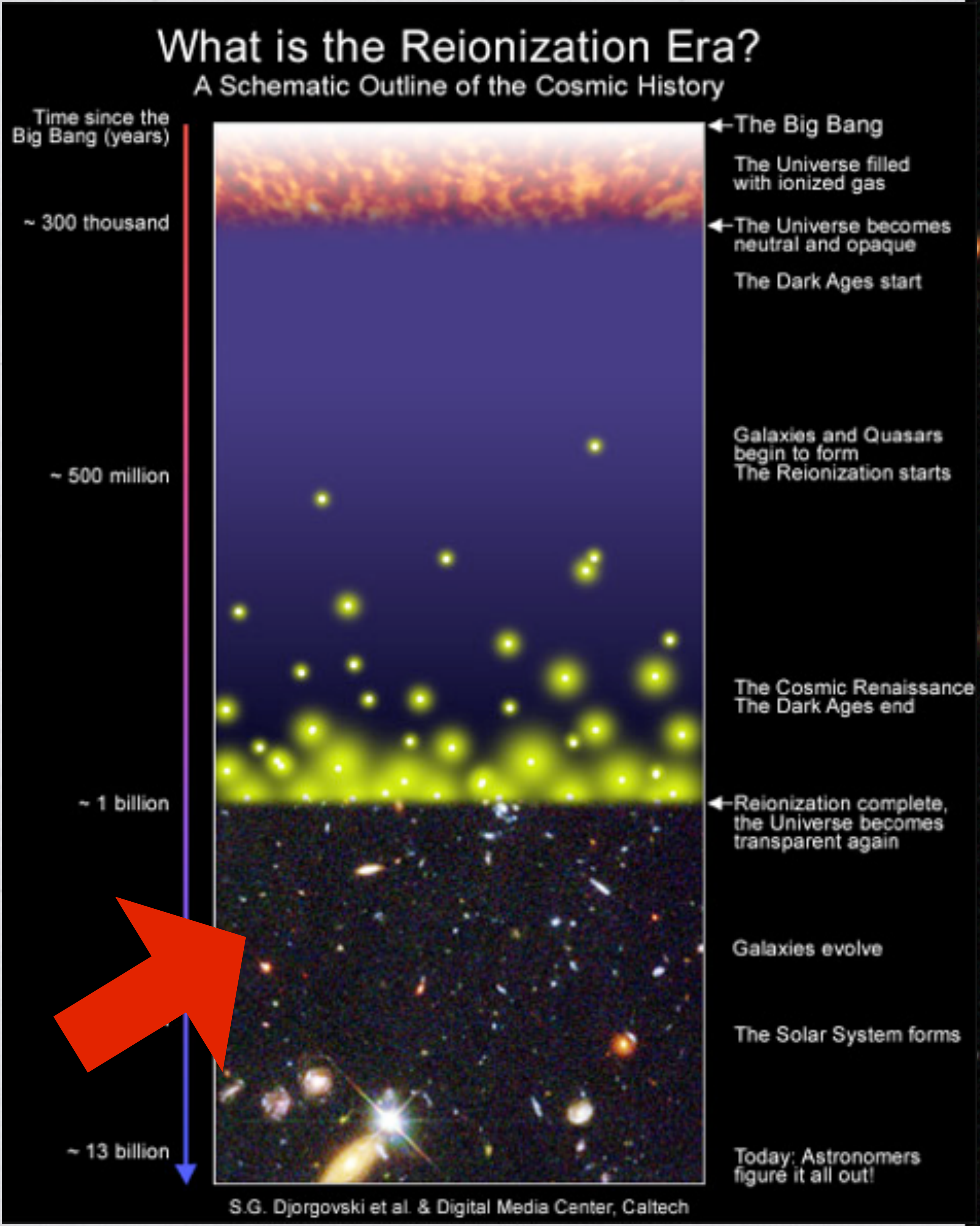
The golden age of galaxies

- ★z~6 [1Gyr] to z~2 [3Gyr]:
  - ★Star formation rate increases with decreasing redshift
  - ★Galaxies are assembled
  - ★Heavy chemical elements ("metals") produced in good numbers by SNe



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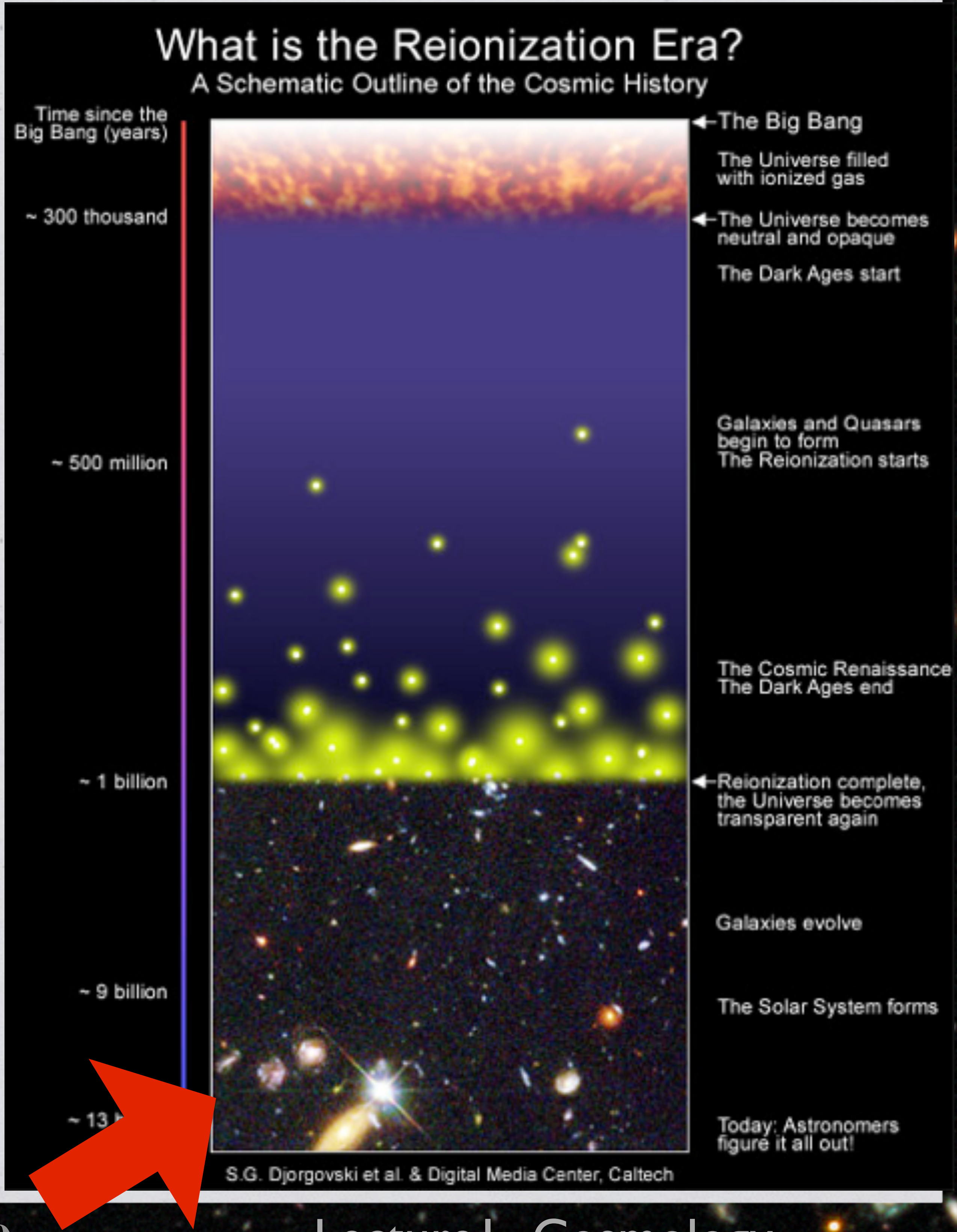
The golden age of galaxies

- ★z<1 [t~8Gyr]:
  - ★Star formation rate decreases steadily with decreasing redshift
  - ★Galaxies become progressively passive
- ★z=0:



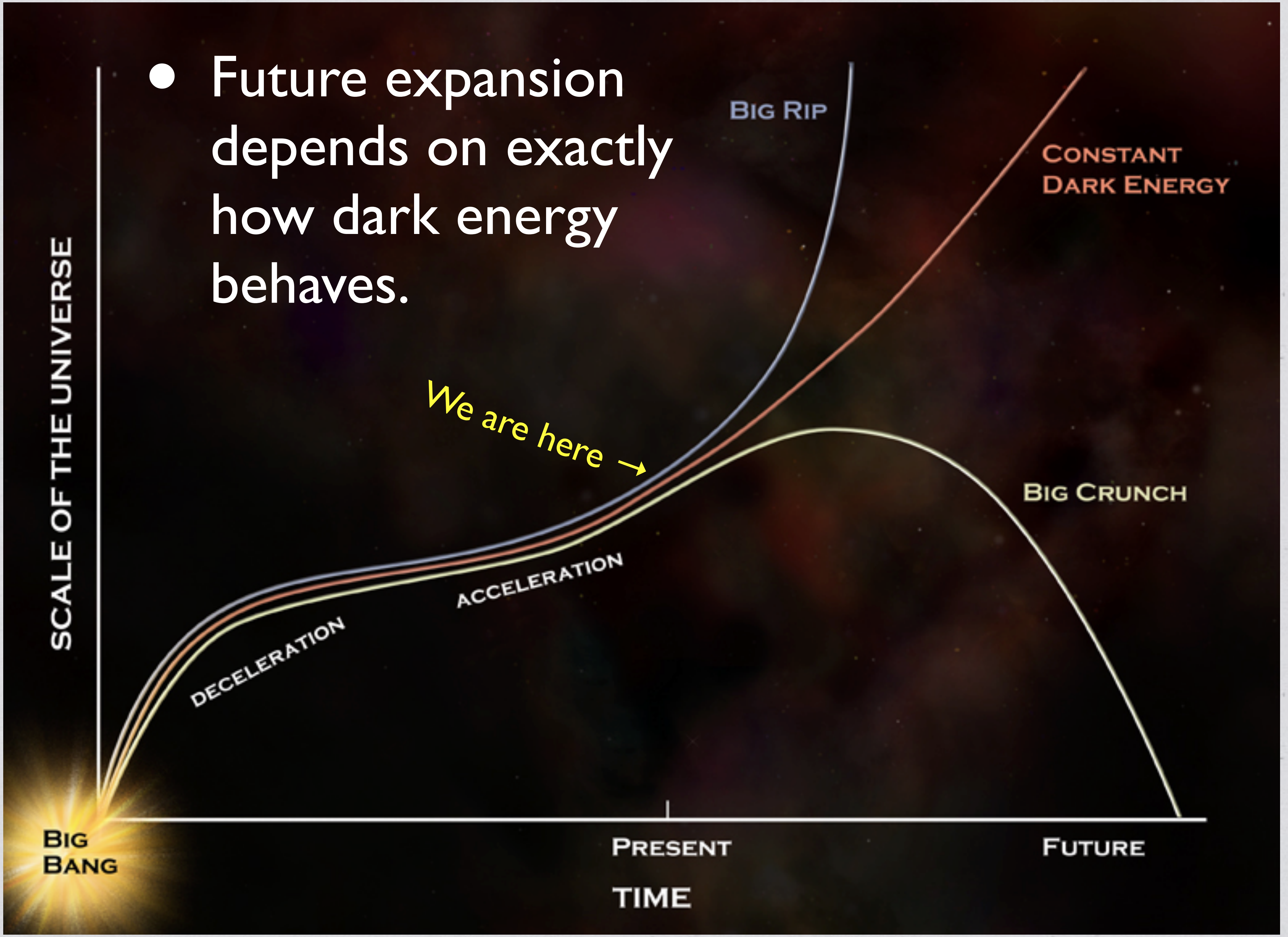
What is next?

It's difficult to make predictions, especially about the future.
- Yogi Berra

- Universe is expanding now and that expansion is speeding up because of Dark Energy
  - *But will expansion continue to speed-up?*
  - *Or will the Universe stop expanding and re-collapse?*
- *How long do we have?*

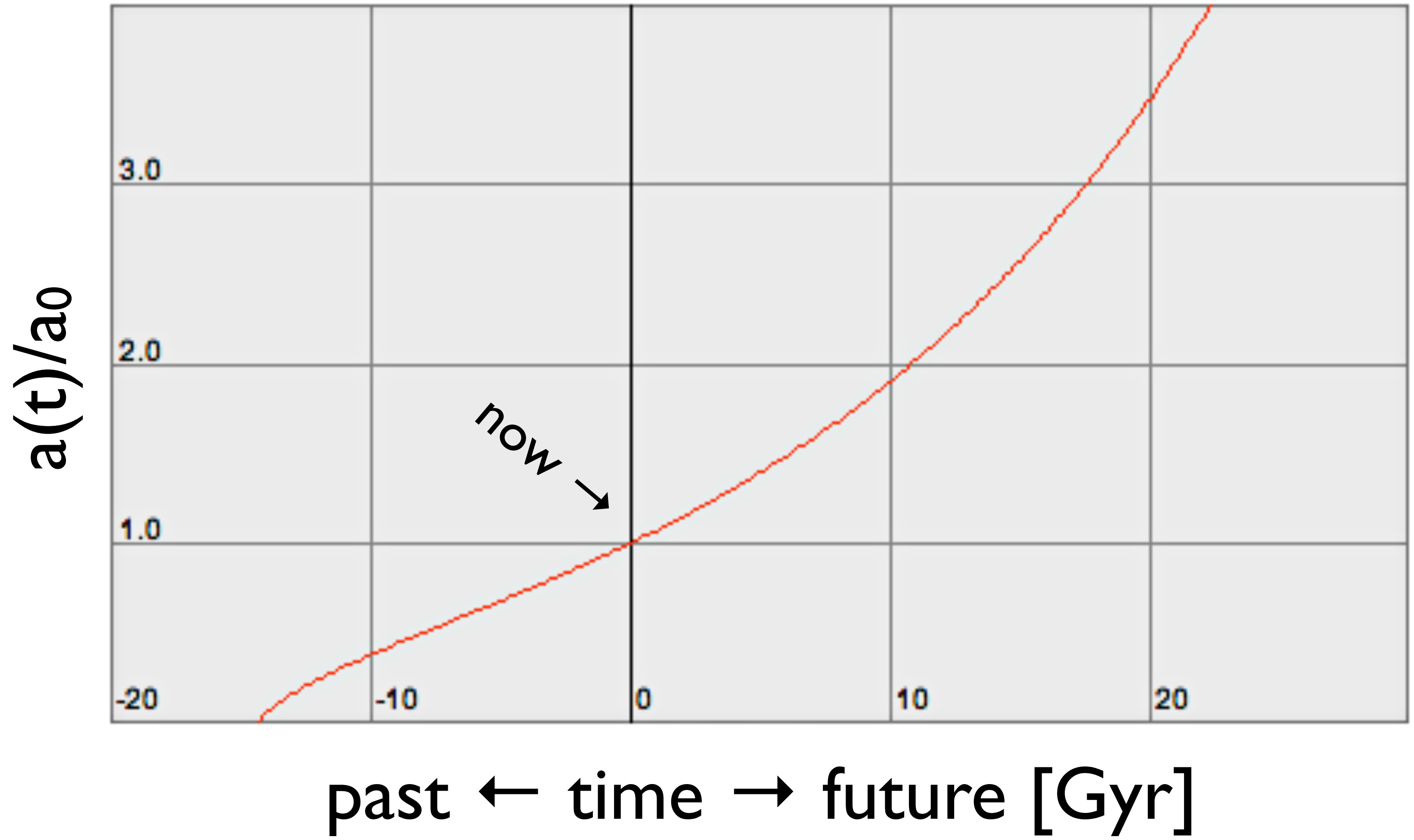
What is next?

- Future expansion depends on exactly how dark energy behaves.



A simple possibility - Heat Death

- Constant Dark Energy continues to accelerate the universe
  - ★ What are the consequences?

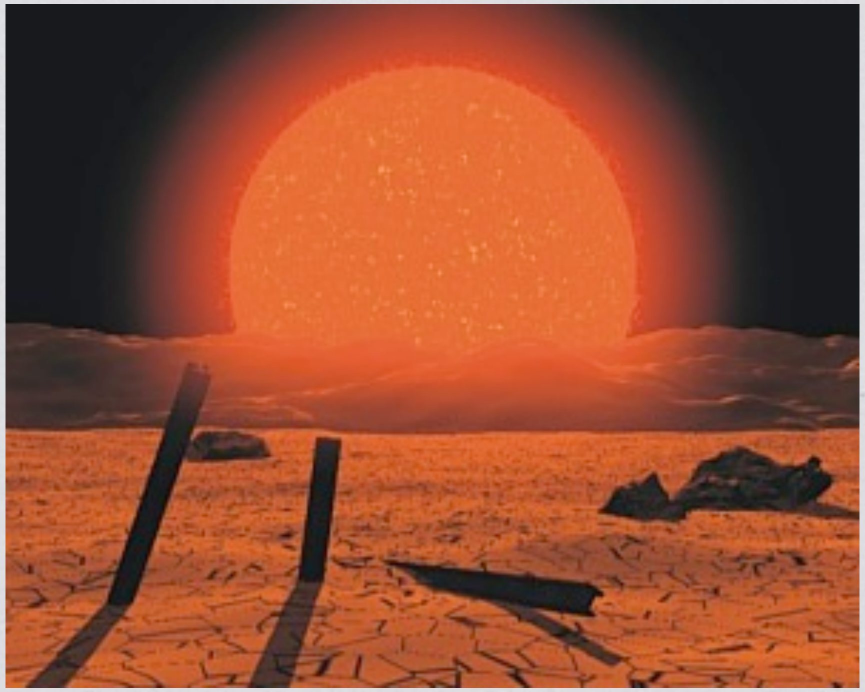


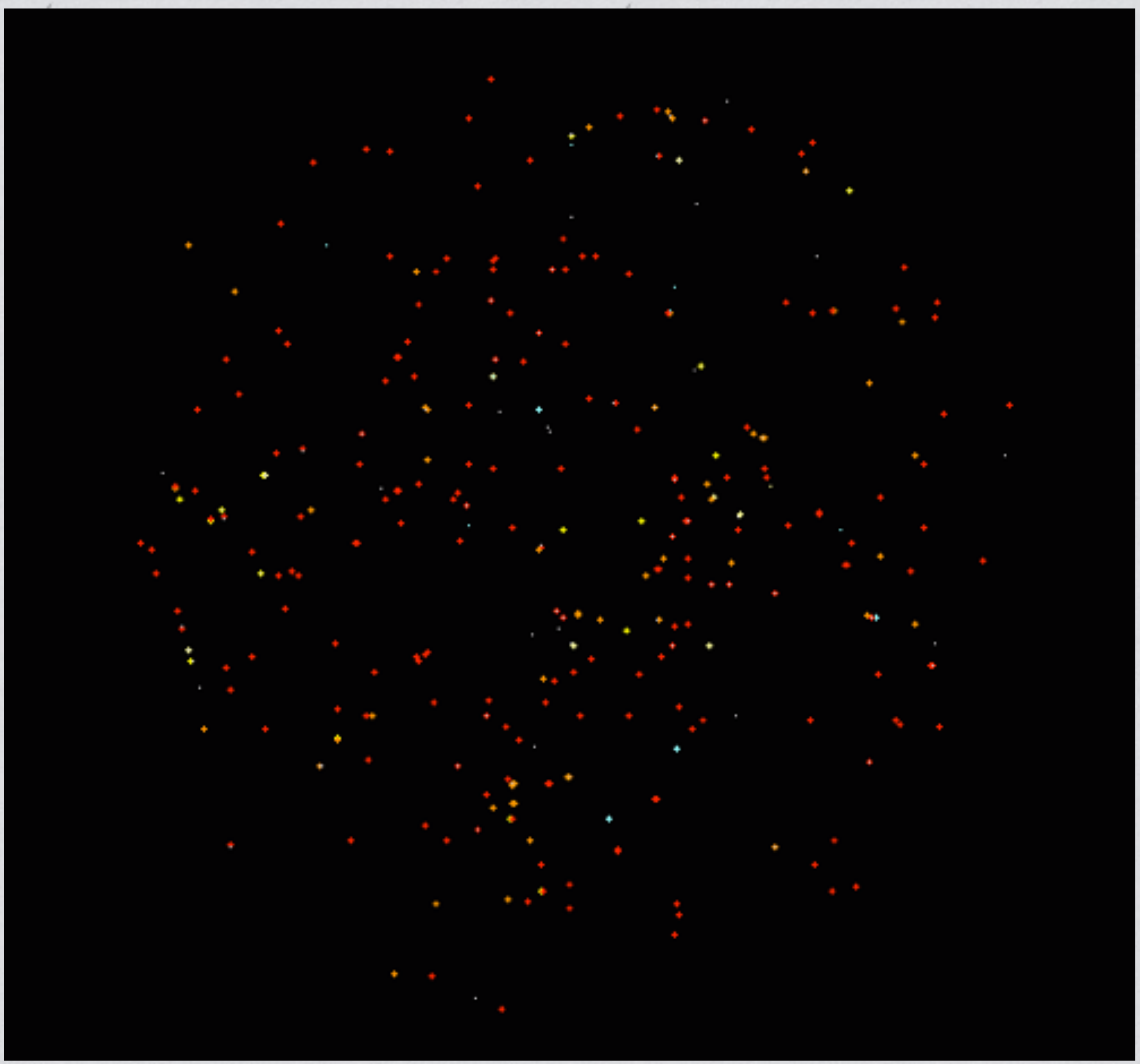
How does it end?

~2-4 Gyr: Milky Way and Andromeda collide, become a single elliptical galaxy

How does it end?

~5 Gyr: Sun becomes red giant, planetary nebula, white dwarf





- ~100 Gyr: Expansion accelerated so fast that all other galaxies beyond our horizon
- Only red dwarf stars remain.
- Not much to see

- ~10^{12} years: end of the stellar era.
  All stars have evolved into their end stages (WD, NS, BH). Universe is dark. Proton decay?

- ~10^{37} years: Only black holes remain and they are evaporating.

- ~10^{100} years: Even the black holes are gone. Only electrons, neutrinos, proton decay products, and photons exist.

  Temperature → 0 K.

  It is over.

Summary

★ Homogenous, Isotropic Universe (FRW model)

★ Some measurements of cosmological parameters (H_0, Λ)

★ Expansion history of the Universe

Readings/useful material

- ★ "Foundations of Astrophysics" B. Ryden & B.M. Peterson, Addison-Wesley
- ★ "An introduction to modern cosmology" A. Liddle
- ★ "Distance Measures in Cosmology" D. Hogg, 1999, http://arxiv.org/abs/astroph/9905116
- ★ Cosmology calculator by Nick Gnedin http://home.fnal.gov/~gnedin/cc/

★ Next class: Dark Matter