HUMINANITY

Series of PowerPoint Presentations by J. W. Gardner

- Misbeliefs – Acquisition & Probable Examples
- Big Picture Science – Observable Universe
- Big Picture Science – Planet Earth
- Big Picture Science – Life on Earth
- Basic Science Sampler – Quantum Physics, Relativistic Physics and Thermodynamics

One of Three Presentations on Big Picture Science

Subject	Key Theory
Observable Universe	Big Bang
Planet Earth	Plate Tectonics
Life on Earth	Evolution

Brief History of Universe

Cosmic Expansion

Changes in Content

ΛCDM Model

Shortcuts to topics underlined

Brief History of Universe

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Motivations for inflation

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Evidence of dark energy

Precision cosmology

Brief History of Observable Universe

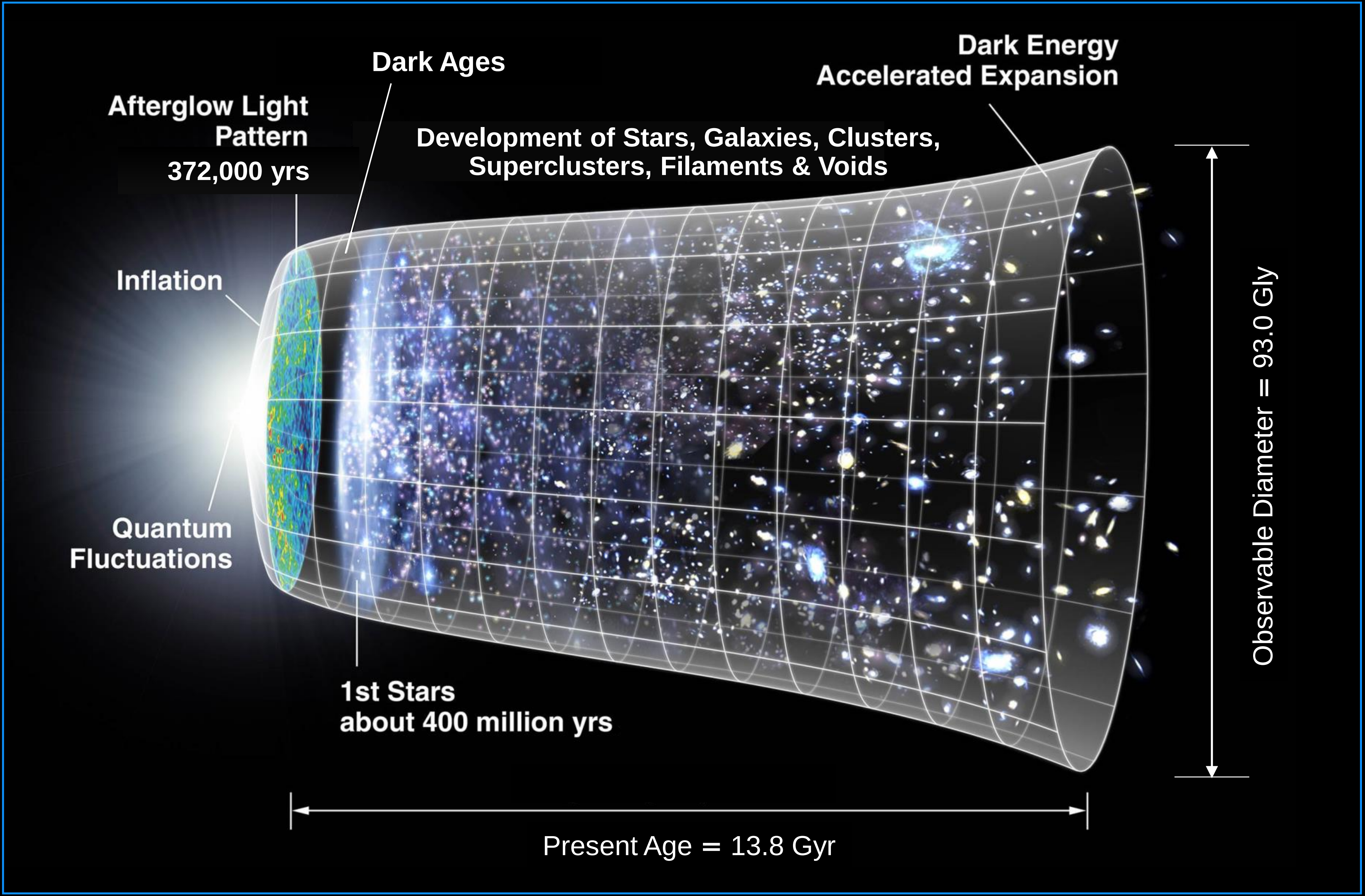

Image from NASA. Slightly modified. Artistic liberties taken in the picture (e.g., suggestion of expansion within black void). Above picture employed (with slight modifications) multiple times in this presentation

Brief History of Observable Universe

- Our observable universe has been expanding for about 13.8 Gyr from a once tiny, staggeringly dense ball of energy
- Very early on, quantum fluctuations might have been stretched to astrophysical scales by an exponential expansion or cosmic inflation, with resulting higher density regions providing seeds from which large-scale structure would eventually grow
- Variety of elementary particles and antiparticles were present in early universe. By the time the universe was about 1 minute old, those entities had been reduced by combinations & annihilations to protons, neutrons, electrons, neutrinos & photons. Negligible antiparticles remained
- Several light nuclei formed within next couple of minutes by BBN. All other nuclei created much later (some in stars, for example)
- Universe became transparent at age 372 kyr, when electrons and atomic nuclei combined. Photons set free to stream observed on Earth today as cosmic microwave background (CMB). Variations in CMB reflective of density variations mentioned above

Observable universe probably contiguous part of much larger universe. 1 Gyr = 1 billion years

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Such inflation would have made observable universe an even smaller potion of total universe

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Elementary particles included quarks and antiquarks, leptons and antileptons, and various bosons

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BBN = Big Bang Nucleosynthesis

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1 kyr = 1 thousand years

Brief History of Observable Universe

- Large-scale structure, or cosmic web, began to form few 100 million years after photon decoupling through gravitational instability
- Observable universe today has proper radius of 46.5 Gly and contains about 10^{22} or 10 billion trillion stars
- According to current ΛCDM model of cosmos, stars and other ordinary matter account for only 4.9% of total universe energy. Dominant contributors are cold dark matter (CDM, 26.0 %) and dark energy (Λ, 69.1%)
- Data supporting ΛCDM model include Hubble plots (standard and extended), galaxy redshift surveys, and CMB anisotropies. Particle evidence of dark matter & dark energy is missing (e.g. no detection in Large Hadron Collider)

Higher density regions steal matter from lower density regions

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1 Gly = distance light travels in 1 billion years. 10^{22} also is a rough approximation of the number of sand grains on all the beaches of Earth

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Such supporting data covered later

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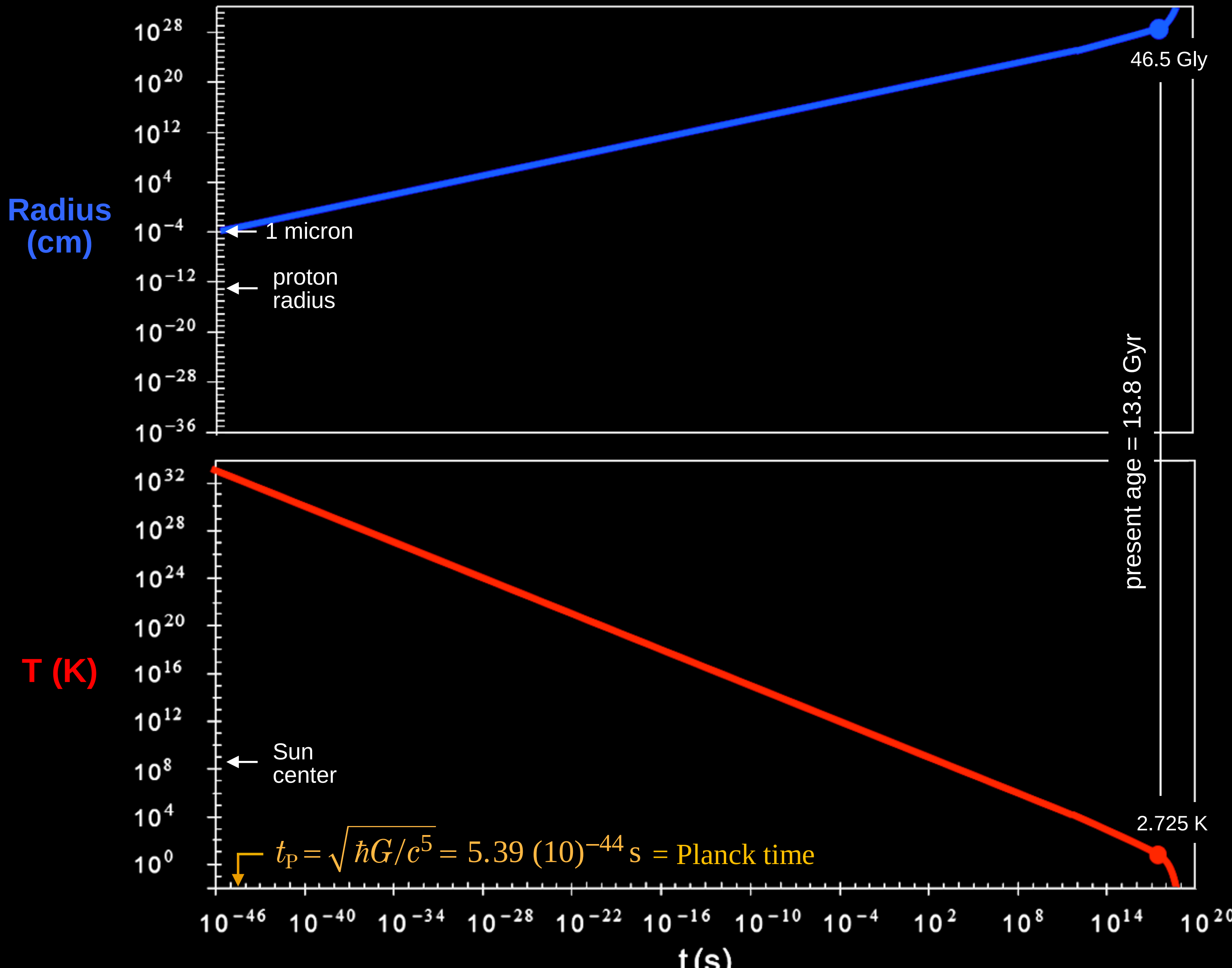
Simple Expansion of Observable Universe



Radius and temperature of observable universe vs cosmic time. Here "simple" means w/o inflation

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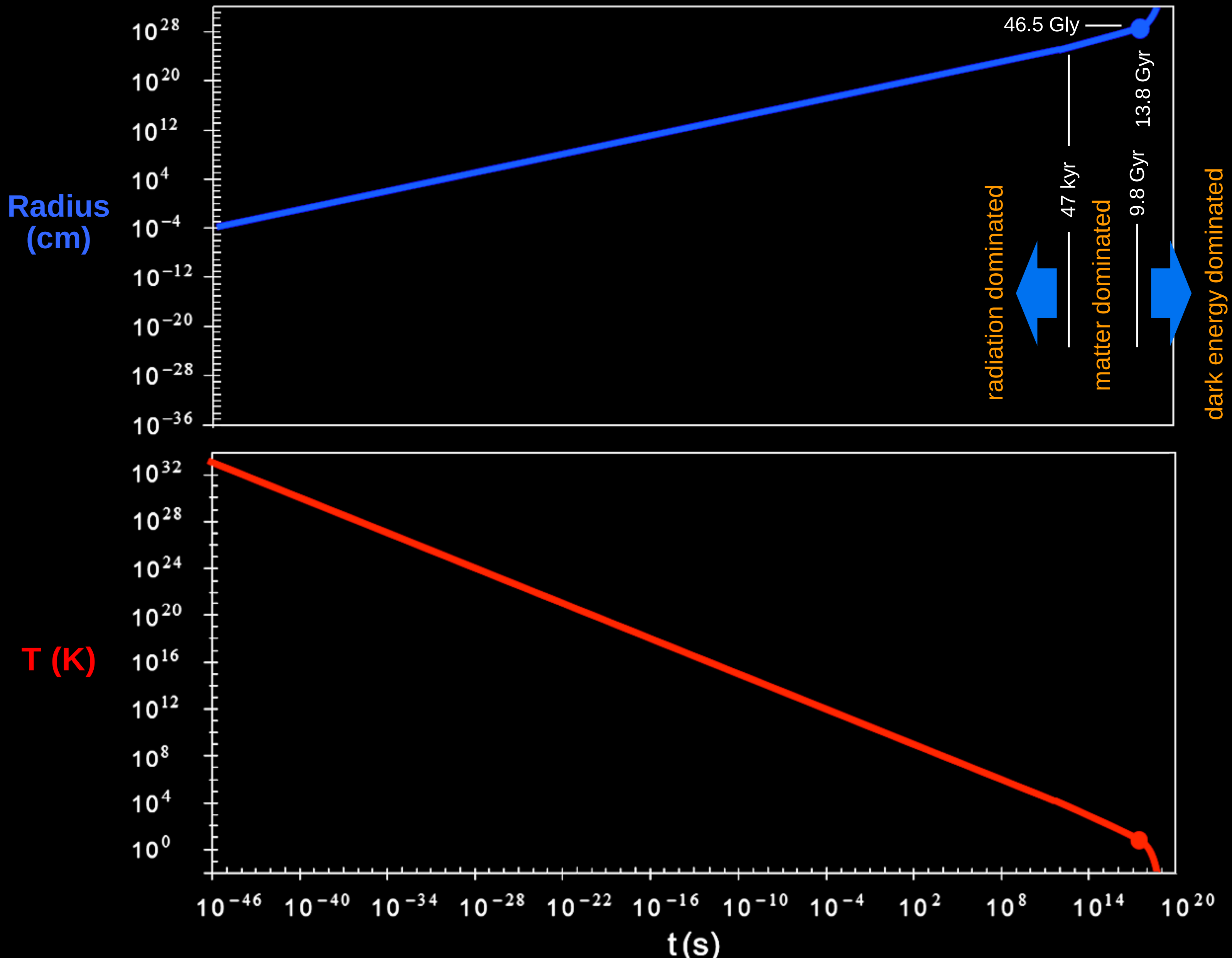
Stages of Simple Expansion



Expansion dominated first by radiation, then by matter (mostly dark), then by dark energy

Calculation of expansion covered under ΛCDM model

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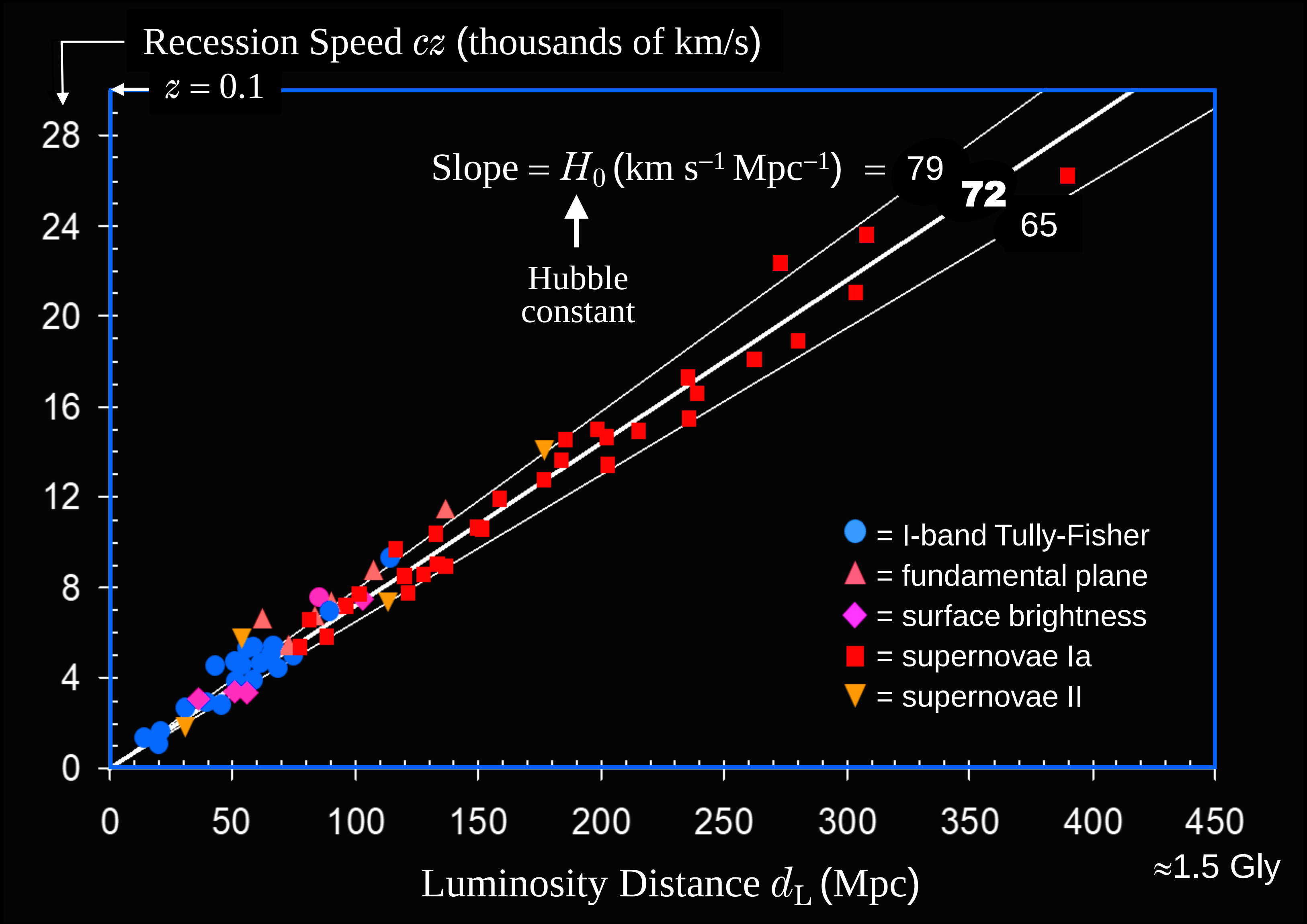
Evidence of Expansion – Hubble Plot

- Galaxy separation rate versus distance
- Slope provides estimate of universe age
- Age favored most recently – 13.8 Gyr – comes from matching a mix of data with the ΛCDM model

For galaxies not close enough to be bound by gravity (excludes members of our Local Group)

Hubble Plot

Freedman et al, Astrophysical Journal, 553:47-72, May 2001



First Hubble plot created by Edwin Hubble in 1929, but accurate plot unavailable throughout 20th century. Hubble Space Telescope was justified in part to remedy situation. Use of such yielded the above plot

Evidence of Expansion – Hubble Plot

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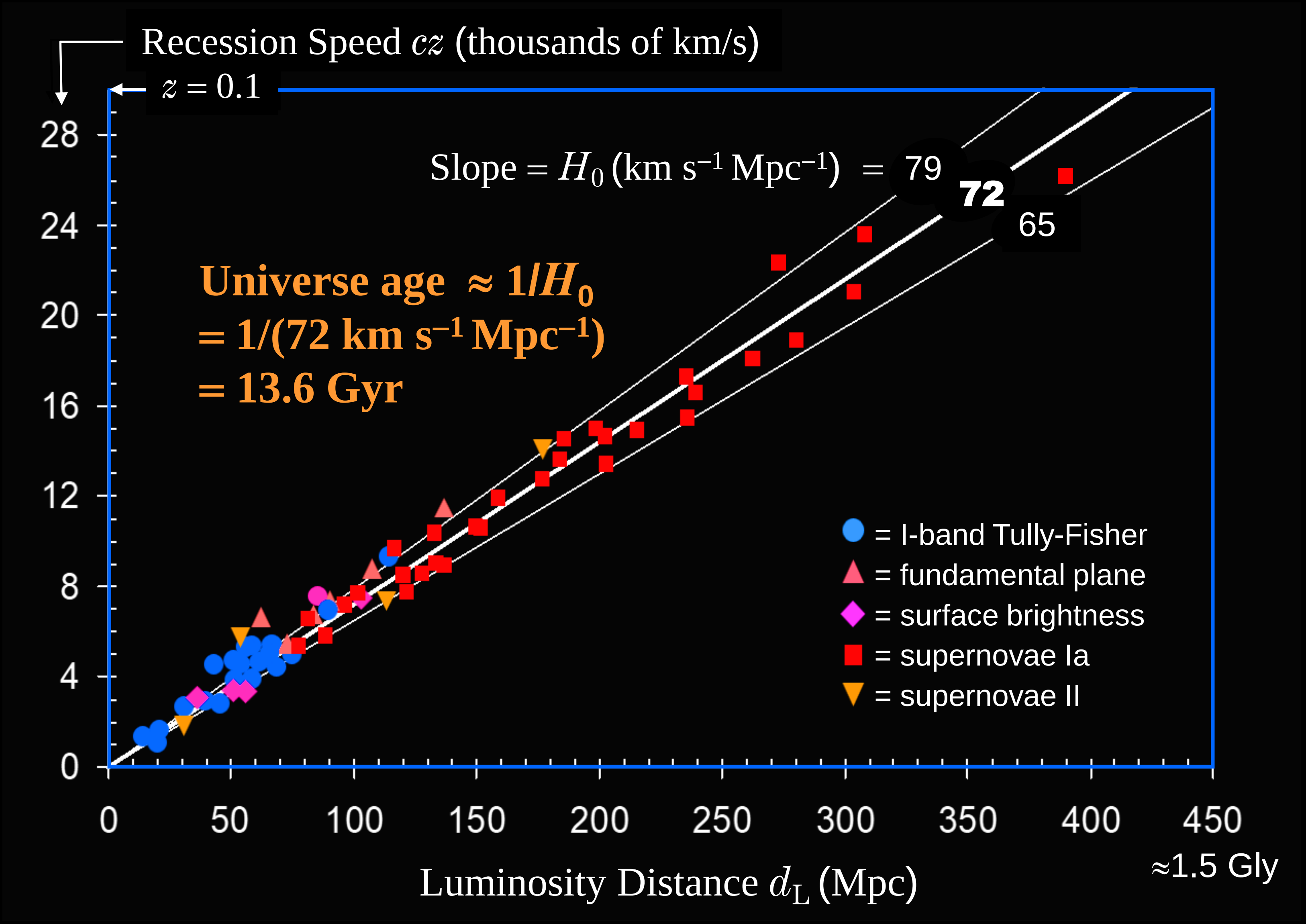
Hubble Plot

Estimate of Universe Age



Evidence of Expansion – Hubble Plot

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Covered below under ΛCDM model

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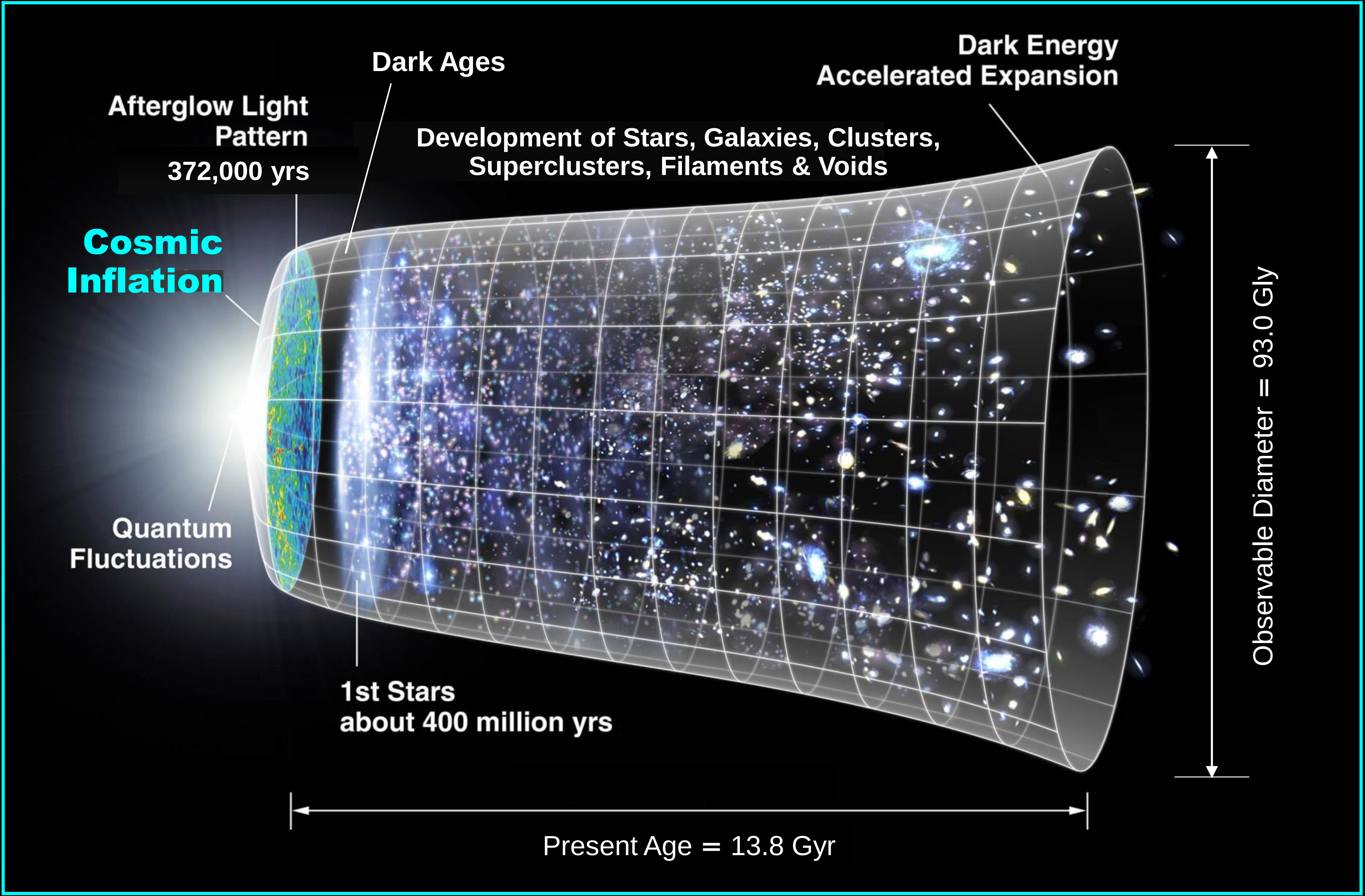
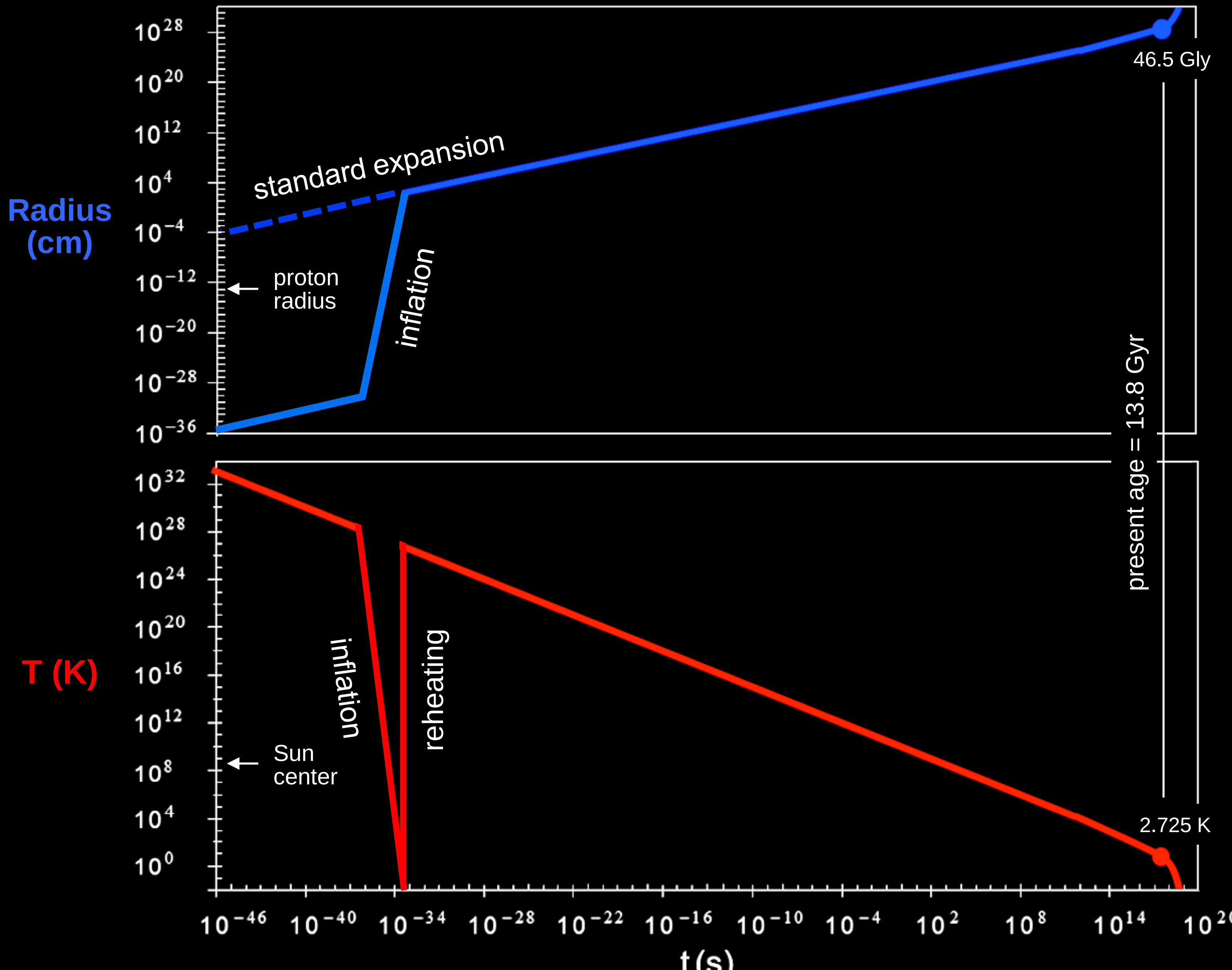
Cosmic Inflation



Near time zero, if it occurred. Some cosmologists consider inflation to be the "bang" in Big Bang

Expansion with Inflation – A Scenario



From Lineweaver (arXiv:astro-ph/0305179 v1. 12 May 2003)

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Standard Big Bang Problems Solved by Inflation

Problem	Inflation Solution
Large-scale homogeneity problem (a.k.a. large-scale smoothness or horizon problem) Measured CMB temperatures deviate from average value by less than 1 hundredth of a percent But causal contact possible over only 1 degree of sky	Tiny, causally connected volume stretched to size bigger than observable universe
Flatness problem (a.k.a. fine-tuning or oldness problem) Curvature, if not identically zero, varies with time according to the Friedmann equation	Observable universe becomes tiny fraction of much larger universe. Curvature not detectable within that fraction
Relic problem (a.k.a. magnetic monopole problem) Supersymmetric extensions of the standard model of particle physics predict formation in early universe of massive, stable particles in sufficient concentrations to be observable today	Relic particles too sparse to be detected after inflation
Structure problem (a.k.a. small-scale inhomogeneity problem) Large-scale structure in present universe is traceable to nearly scale-invariant density perturbations revealed by CMB. But what was origin of perturbations?	Quantum fluctuations, stretched to astrophysical scales, serve as seeds of structure growth. **Now considered most important feature of inflation**

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Changing Contents of Universe

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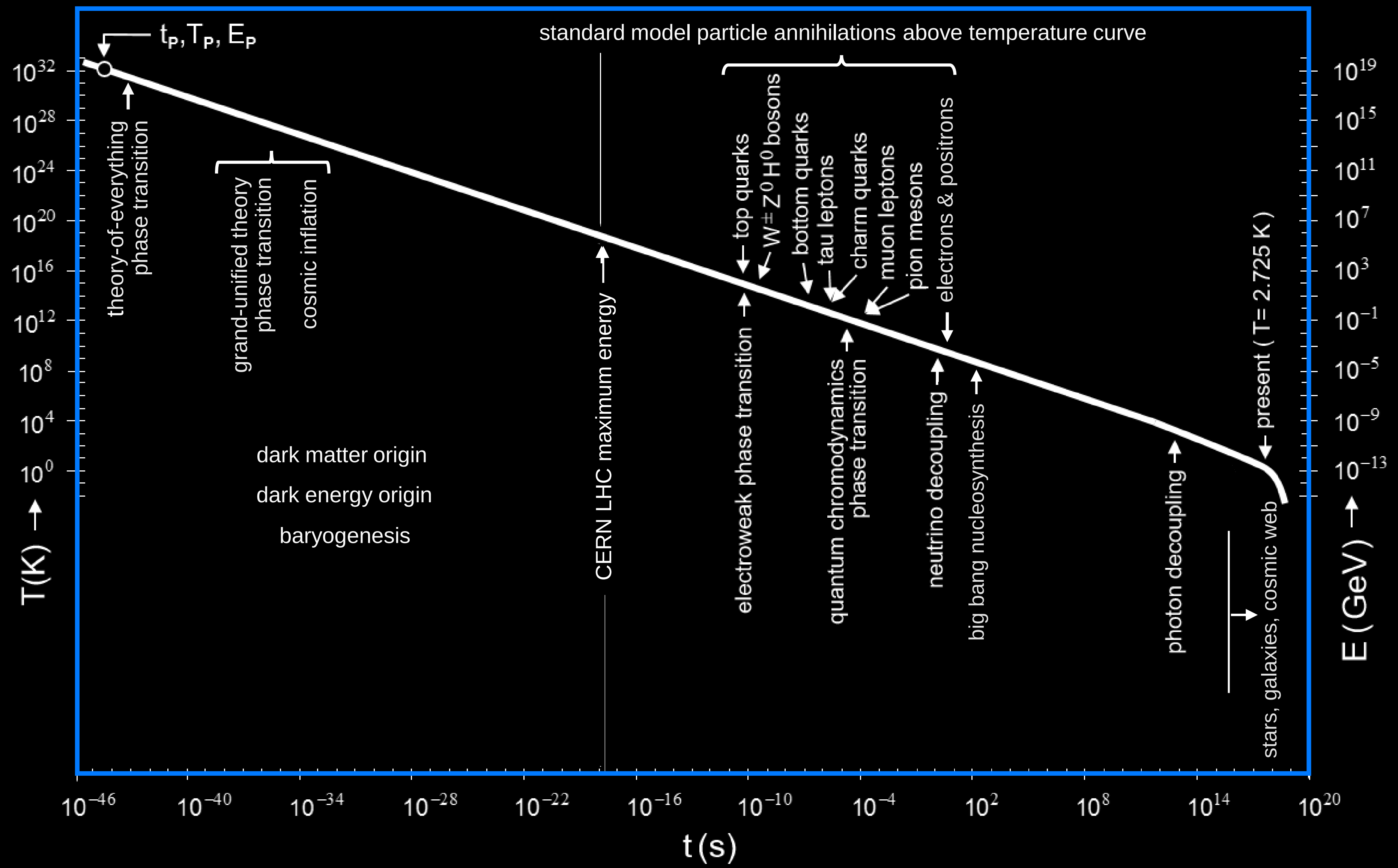
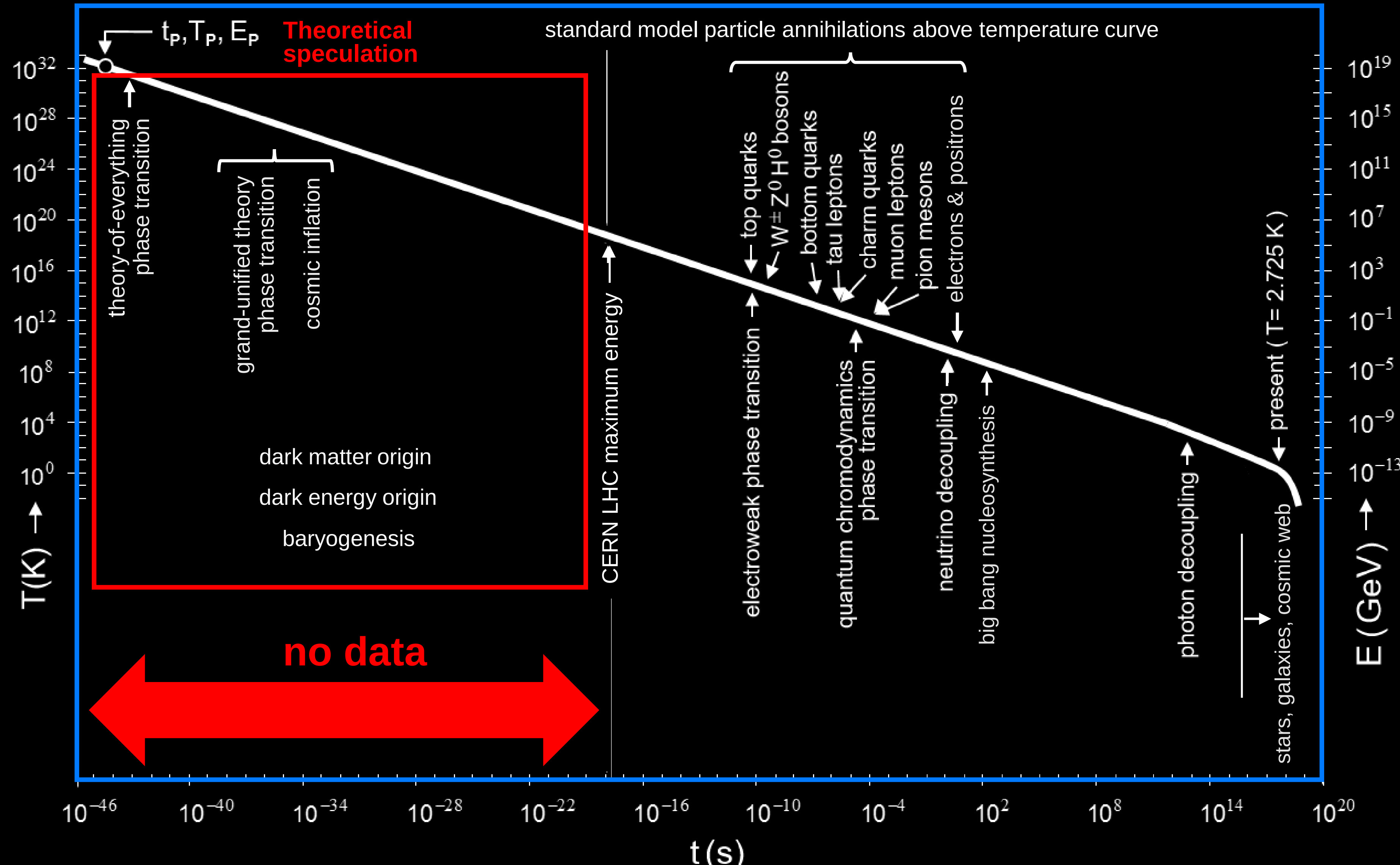


From Wikipedia "Chronology of Universe" article and other sources

Changing Contents of Universe

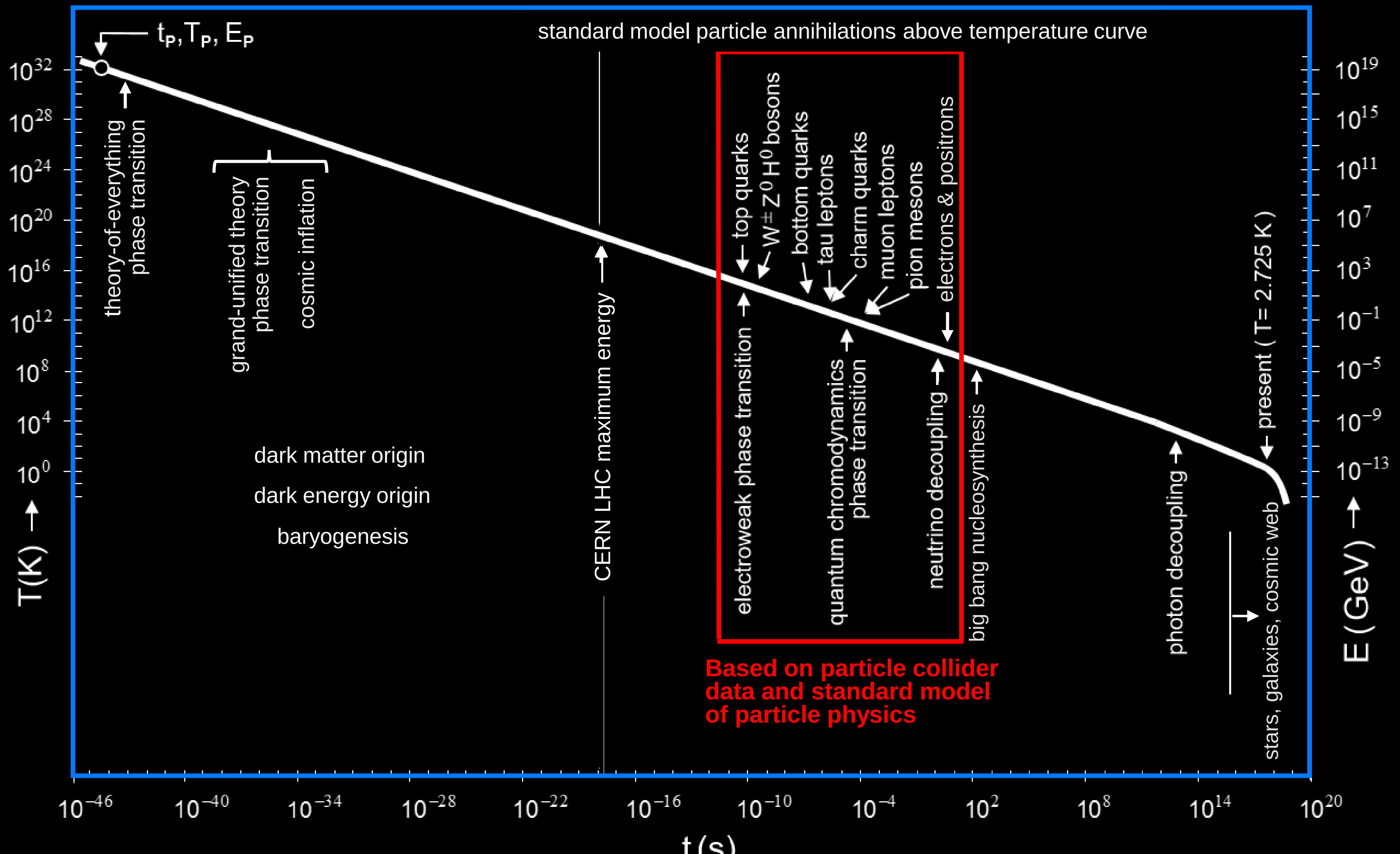
Overview



Theory-of-everything phase transition separates gravity & grand-unified forces. Grand-unified theory phase transition separates strong nuclear & weak nuclear forces. Baryogenesis leads to more matter than antimatter

Changing Contents of Universe

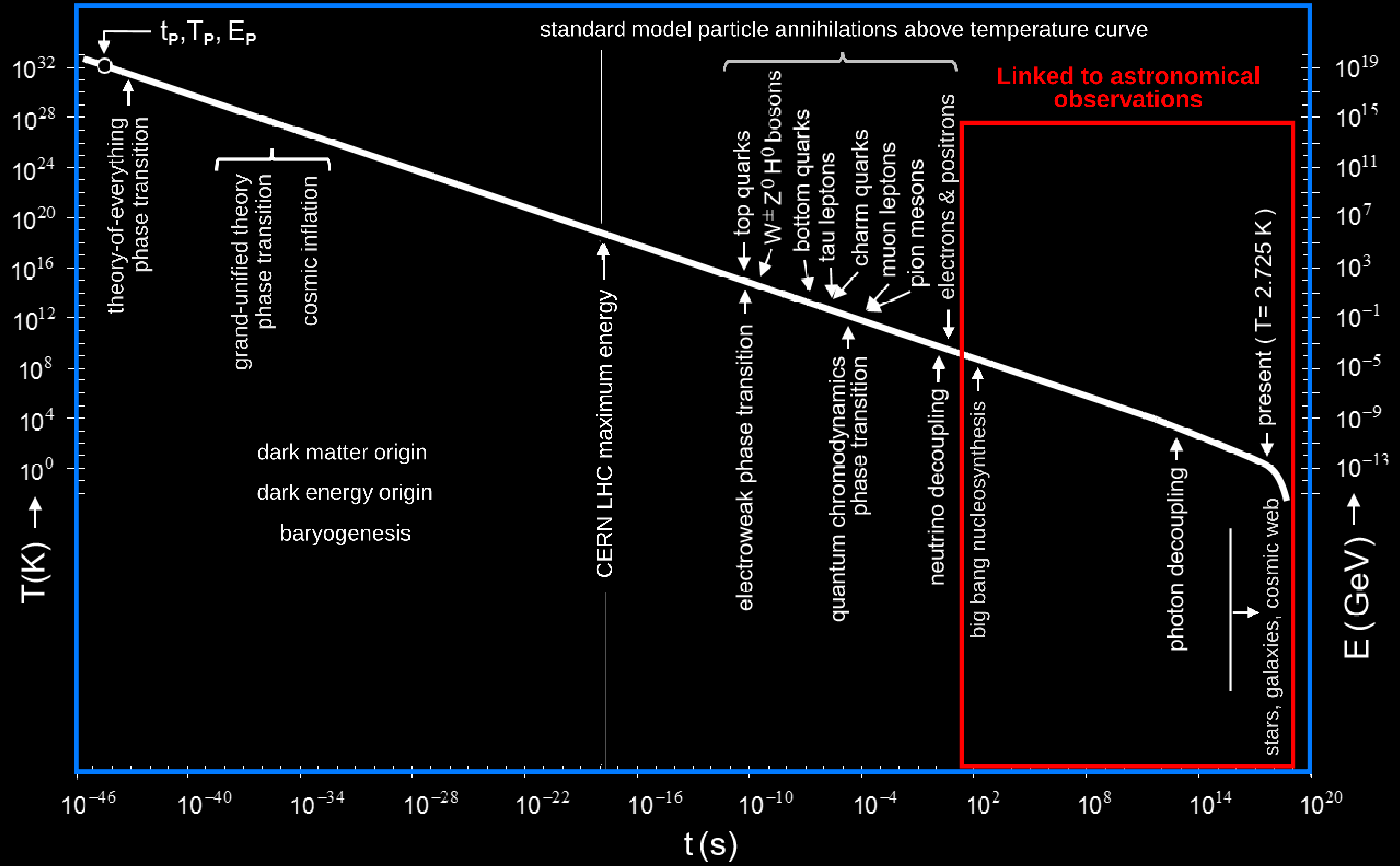
Overview



Electroweak phase transition separates electromagnetic & weak nuclear forces. Quantum chromodynamics phase transition confines quarks to hadrons

Changing Contents of Universe

Overview



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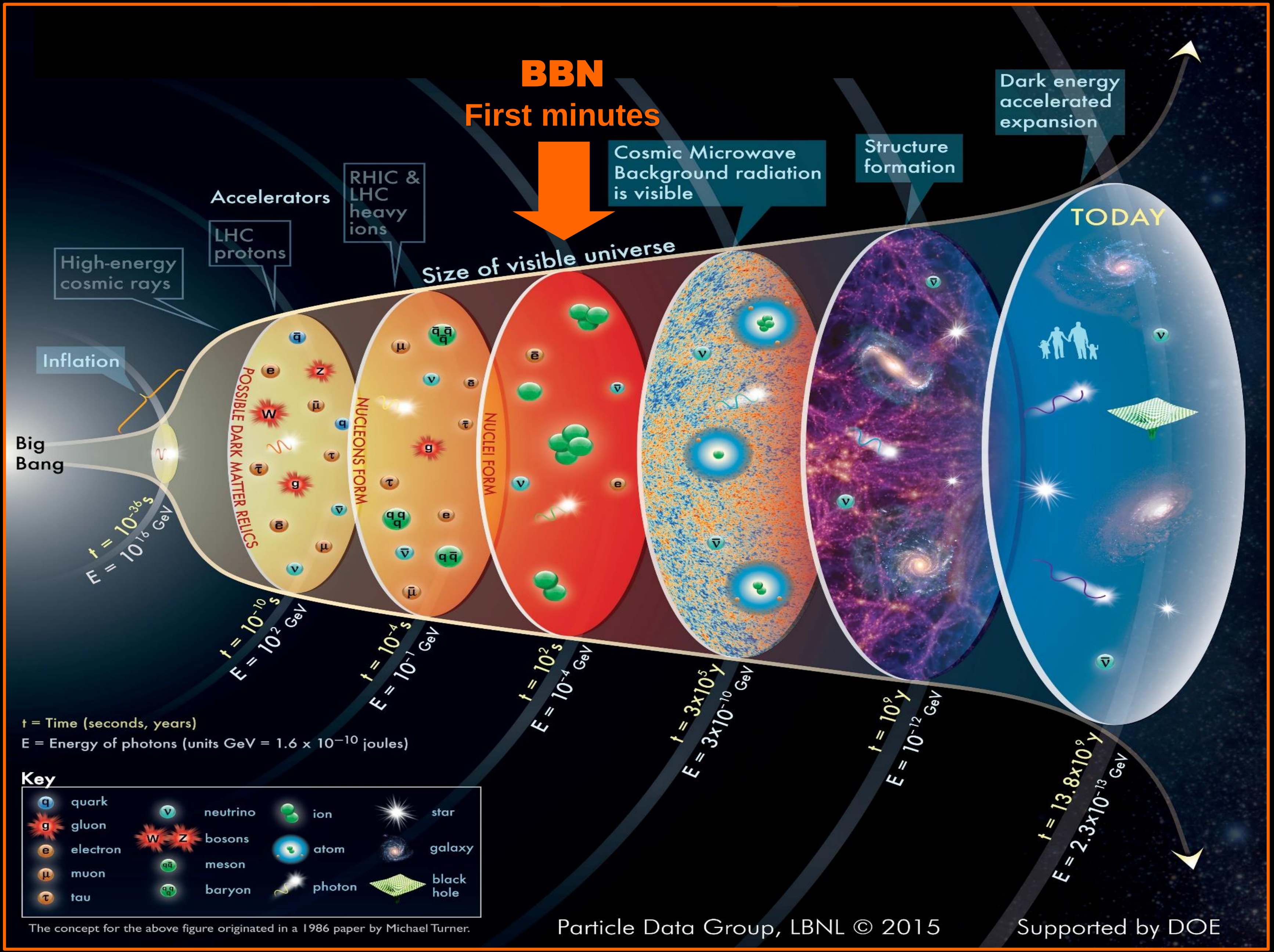
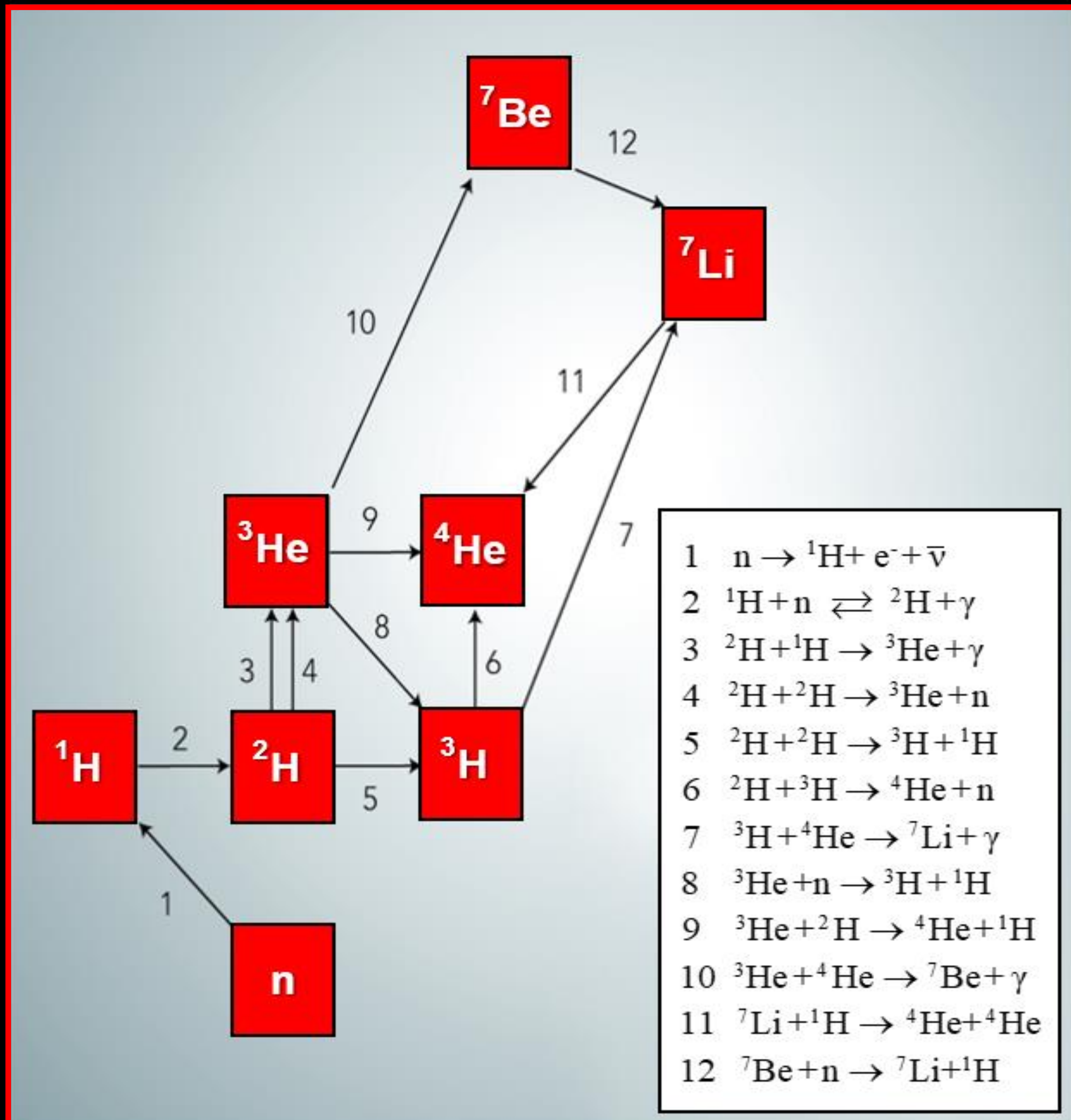
Big Bang Nucleosynthesis



Big Bang Nucleosynthesis (BBN)

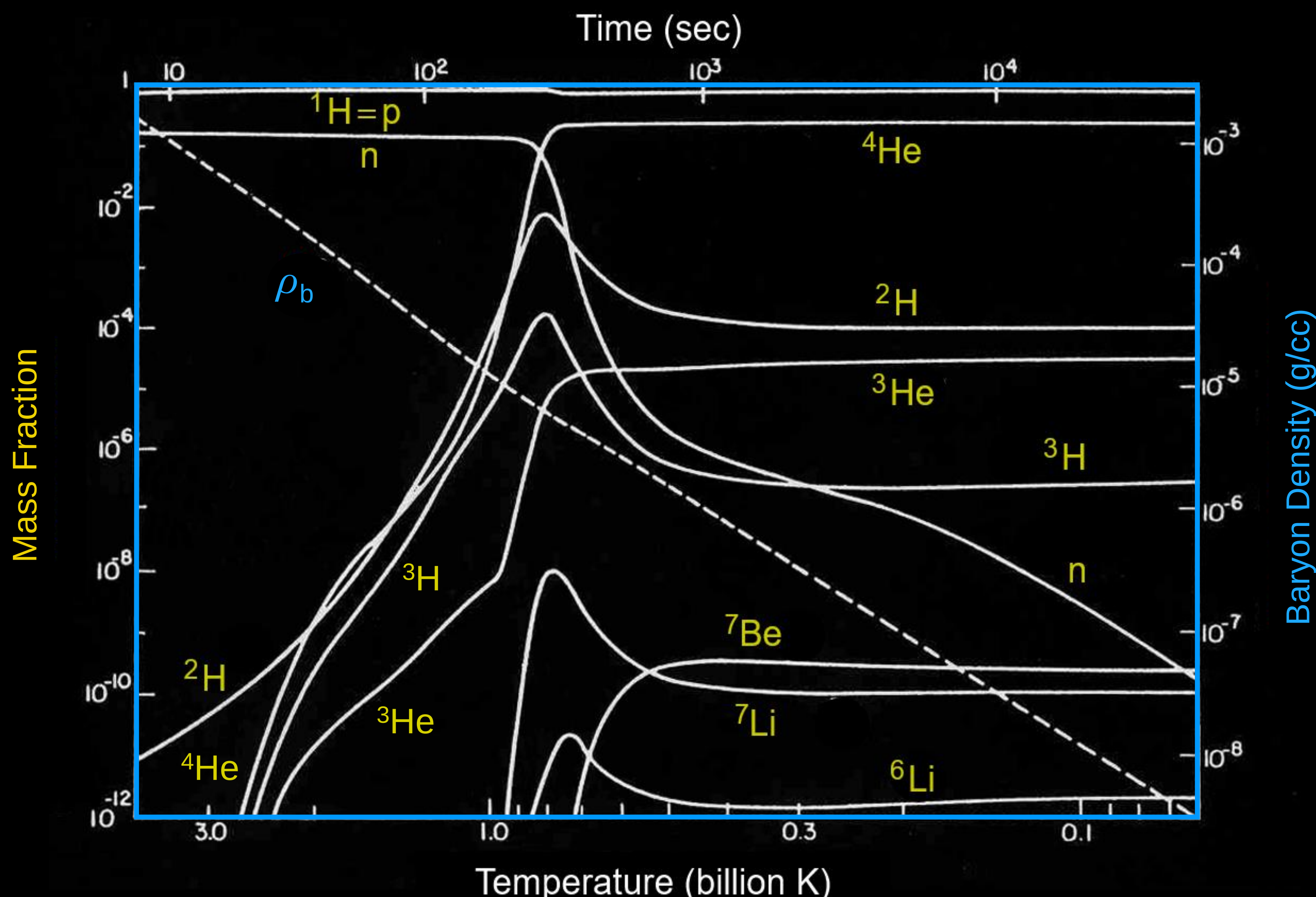
- Formation throughout universe of few light nuclei (primarily helium) in first few minutes of Big Bang
- Earliest window on universe via comparison between predicted and observed light nuclei abundances in pristine regions of cosmos

BBN – Nuclear Reactions



${}^1H$ = p = proton (2 up quarks + 1 down quark). n = neutron (2 down quarks + 1 up quark).
Based on http://physicsworld.com/cws/article/print/30680/1/PWfea4_08-07

BBN – Species Abundance vs Time & Temperature



Narrow window in time and temperature when conditions right for BBN.
From http://burro.case.edu/Academics/Astr222/Cosmo/Early/bbn.html

Big Bang Nucleosynthesis (BBN)

- Formation throughout universe of few light nuclei (primarily helium) in first few minutes of Big Bang
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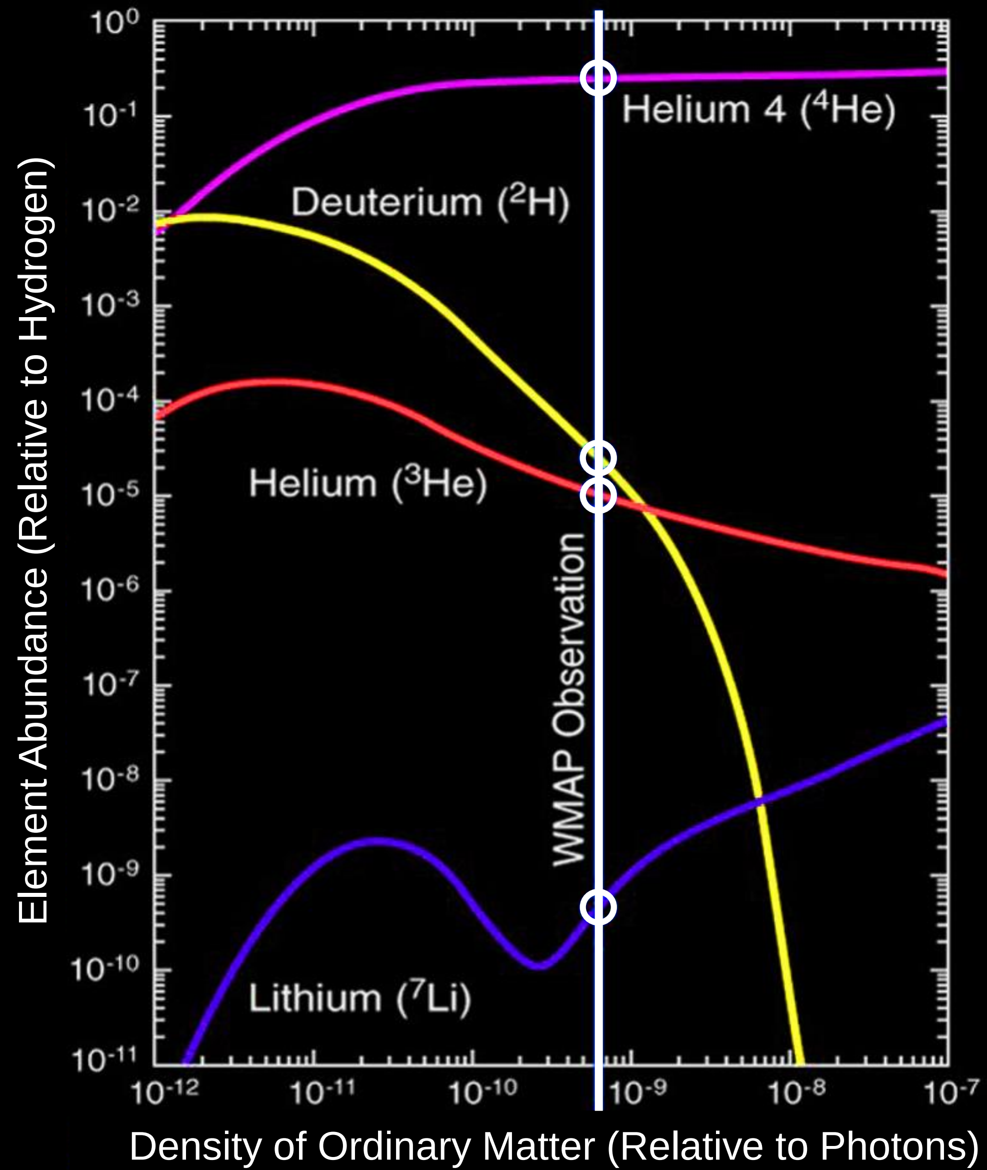
Earliest status would change if smoking gun evidence of inflation were discovered

BBN – Predicted & Observed Abundances



NASA/WMAP Science Team
WMAP 101078

"Light Element Nucleosynthesis," G. Steigman, Encyclopedia of in Astronomy and Astrophysics (2000)

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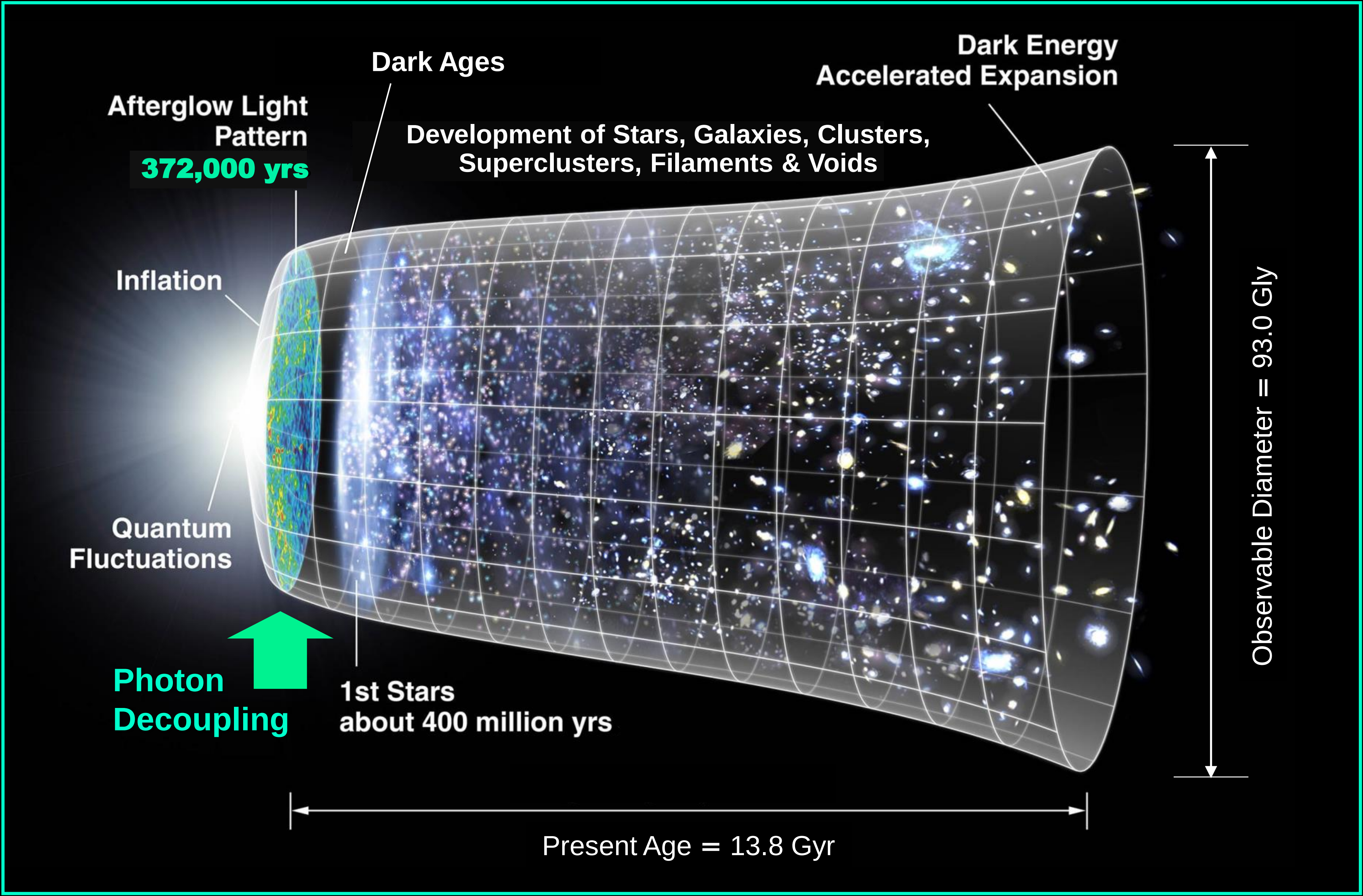
Photon Decoupling / CMB Creation



CMB = Cosmic Microwave Background

Photon Decoupling / CMB Creation

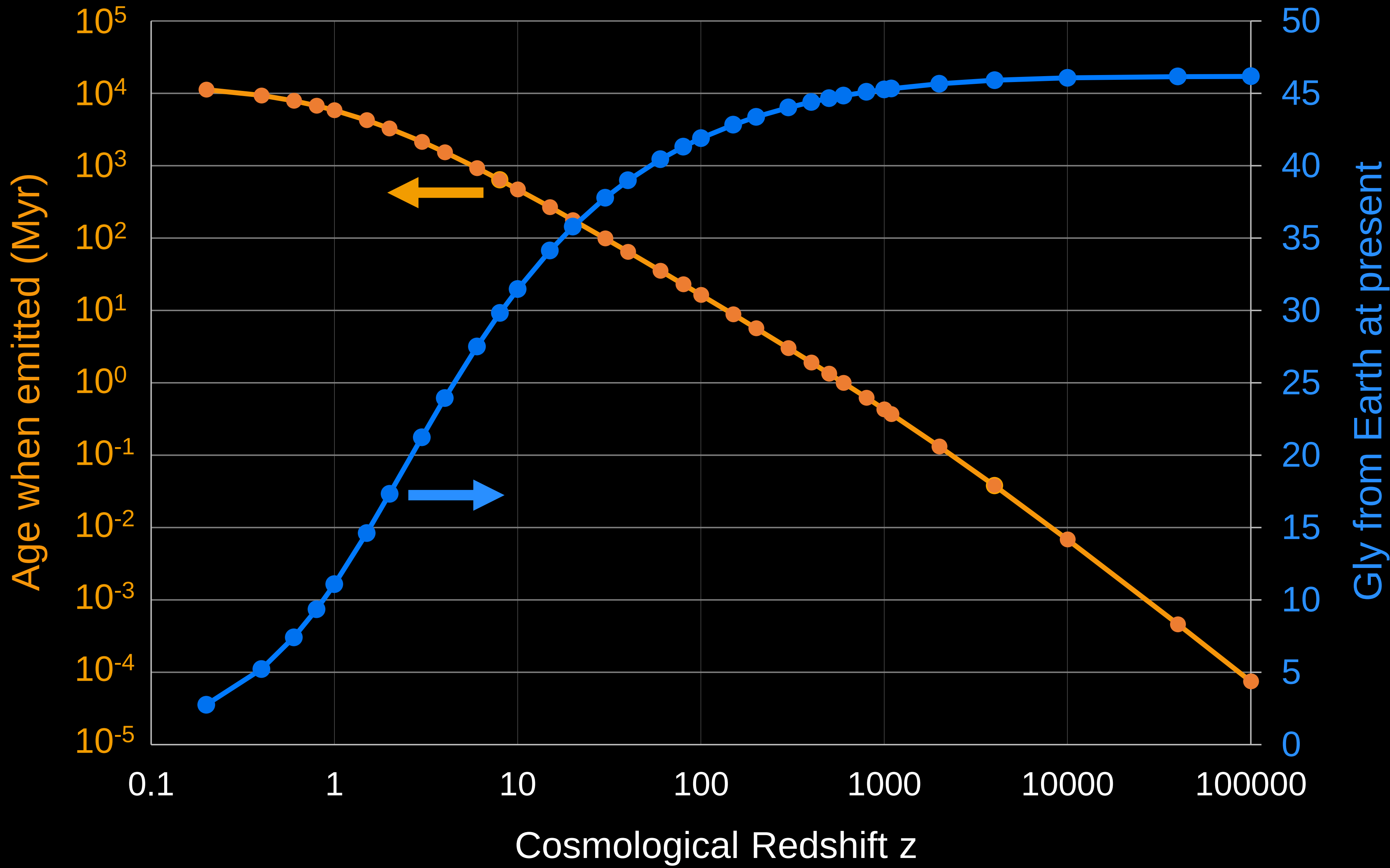
- When universe is roughly 372,000 yr old, kinetic energy of electrons drops to level where they can be bound by oppositely charged nuclei
- Photons, previously being almost continuously deflected by electrons, are then free to travel in whichever direction they were going
- Those photons just now reaching Earth (greatly redshifted) constitute the cosmic microwave background

Above description simplified. Note also that when you are between active channels on an analog television, part of the "snow" on the screen and part of the hiss that you hear ("white noise") is CMB radiation

Digression: Telescopes as Time Machines

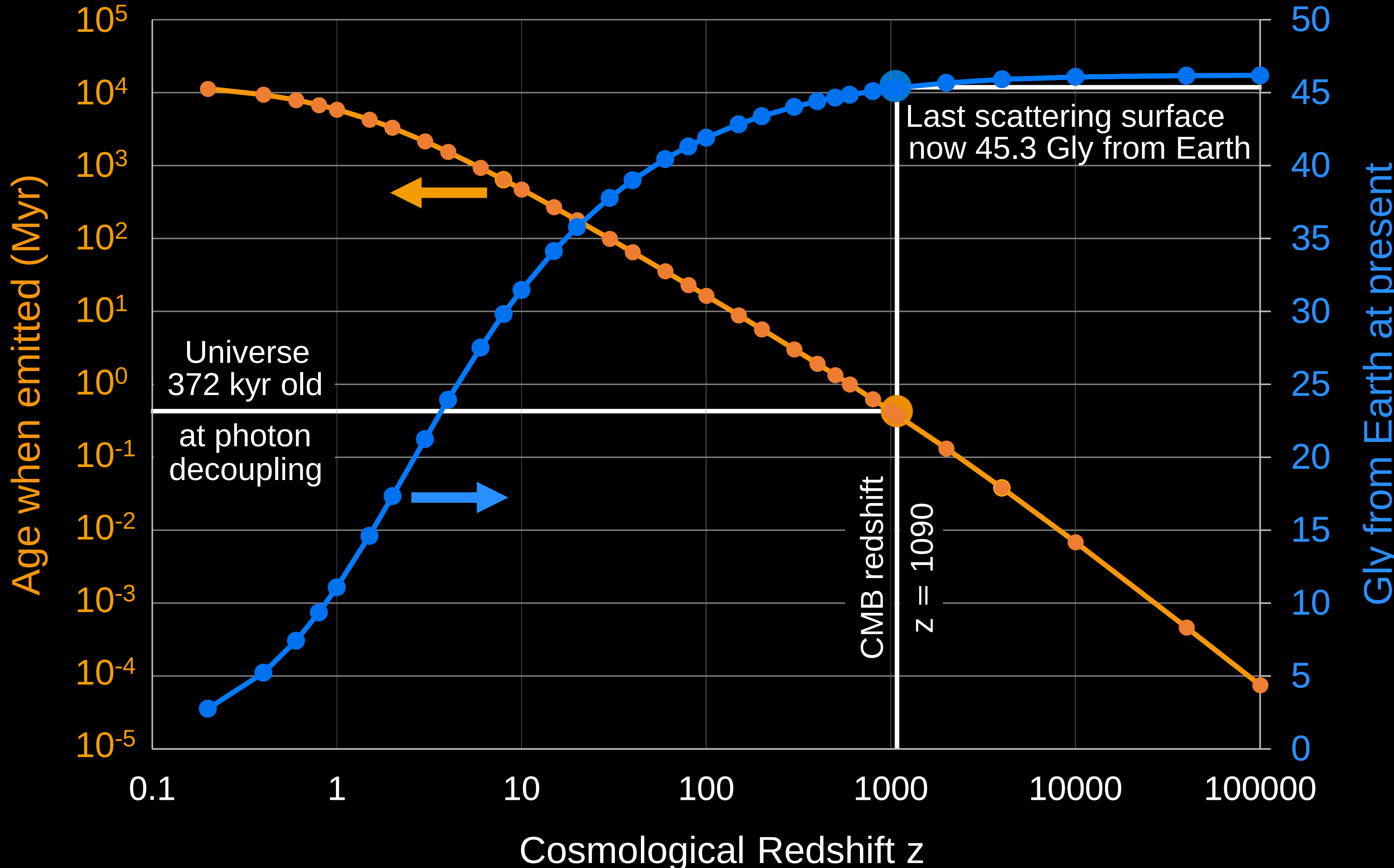
- Powerful telescopes see things far, far away
- Not things as they are now, but as they were long, long ago (apart from redshift)
- Telescopes therefore are like time machines
- Observations often characterized by redshift, which can be related to age & present proper distance from Earth

Age & Present Proper Distance vs Redshift



Point values obtained using Ned Wright's Cosmology Calculator I with H_0 = 67.74 km s^{-1} Mpc^{-1}, Ω_M = .309 and Ω_Λ = .691. Present proper distance also known as comoving radial distance

Application of Last Chart to CMB



The last scattering surface is the spherical shell centered about the Earth from which the CMB was emitted

Value of CMB

- **Accidental discovery (Penzias and Wilson, 1964) provided smoking gun evidence of Big Bang**
- **Anisotropies in CMB keys to understanding large scale structure and determining cosmological parameters**

Essentially ended serious consideration of the competing steady-state universe theory

Value of CMB

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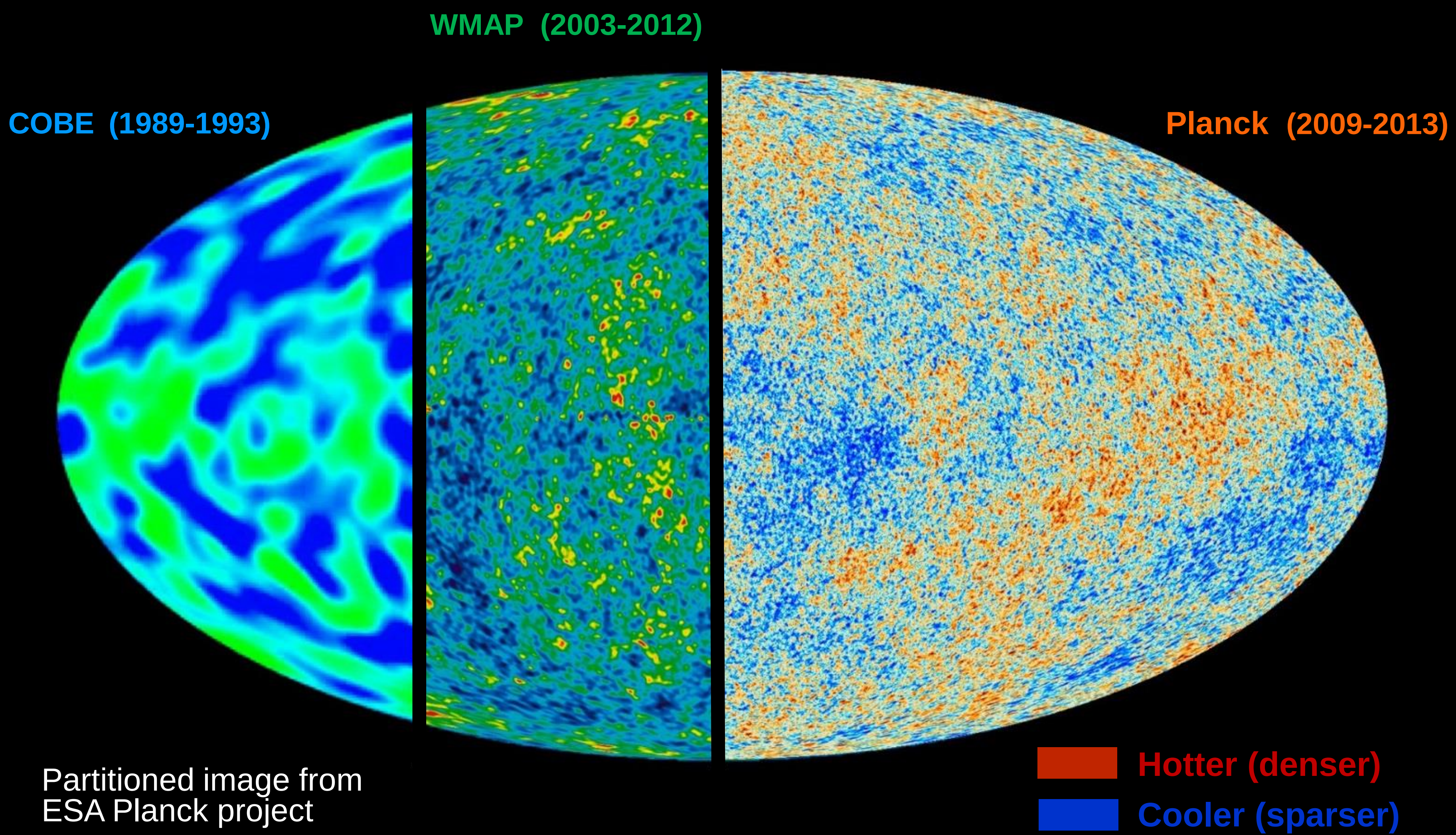
Full-Sky Cosmic Microwave Background Map

Indicative of Density Variations When Universe Became Transparent



Baby pictures of universe (age 372 kyr). Higher density regions are seeds from which structure has grown. Detailed analysis of variations a key component of precision cosmology. WMAP = Wilkinson Microwave Anisotropy Probe. ESA = European Space Agency

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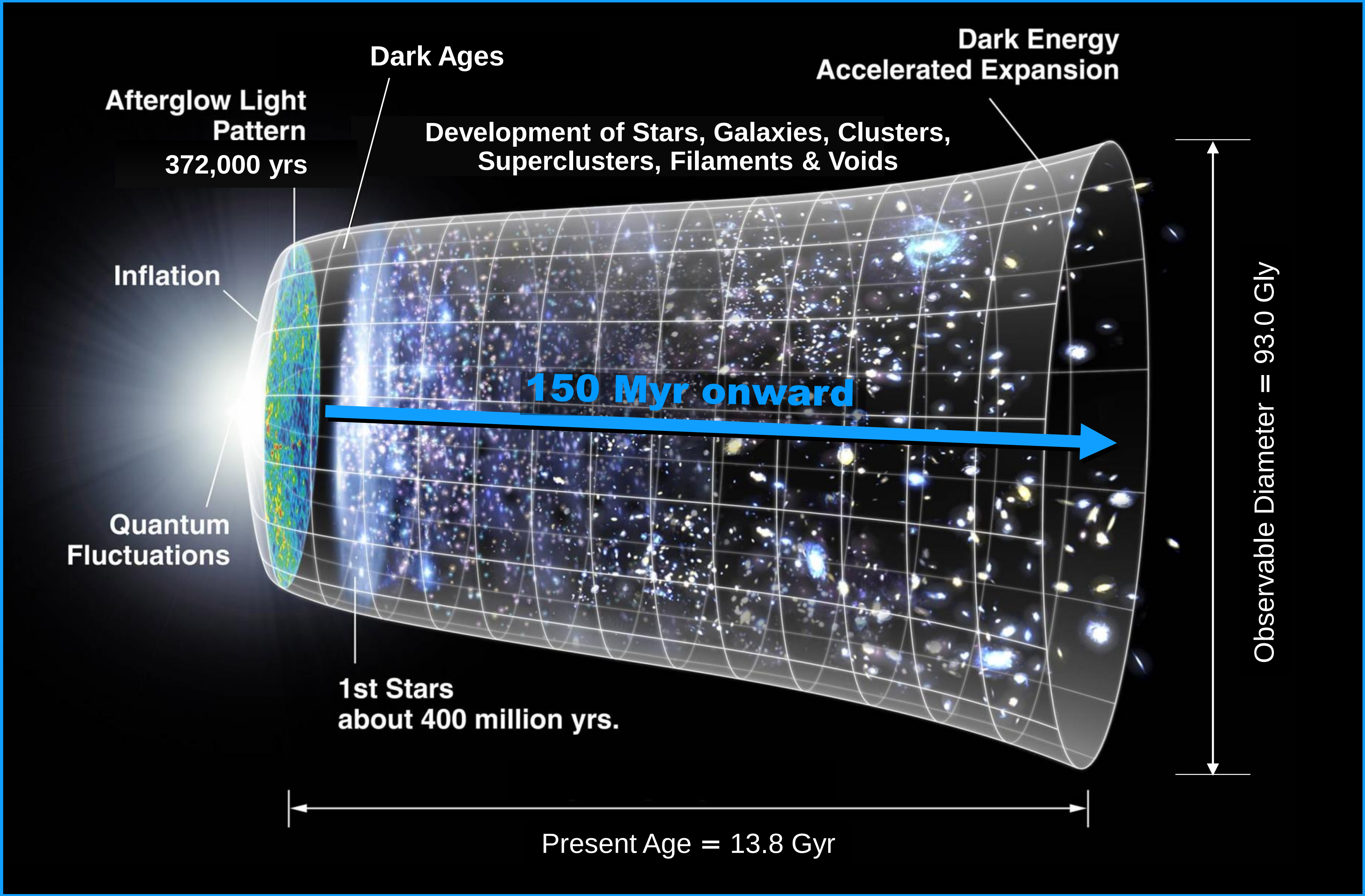
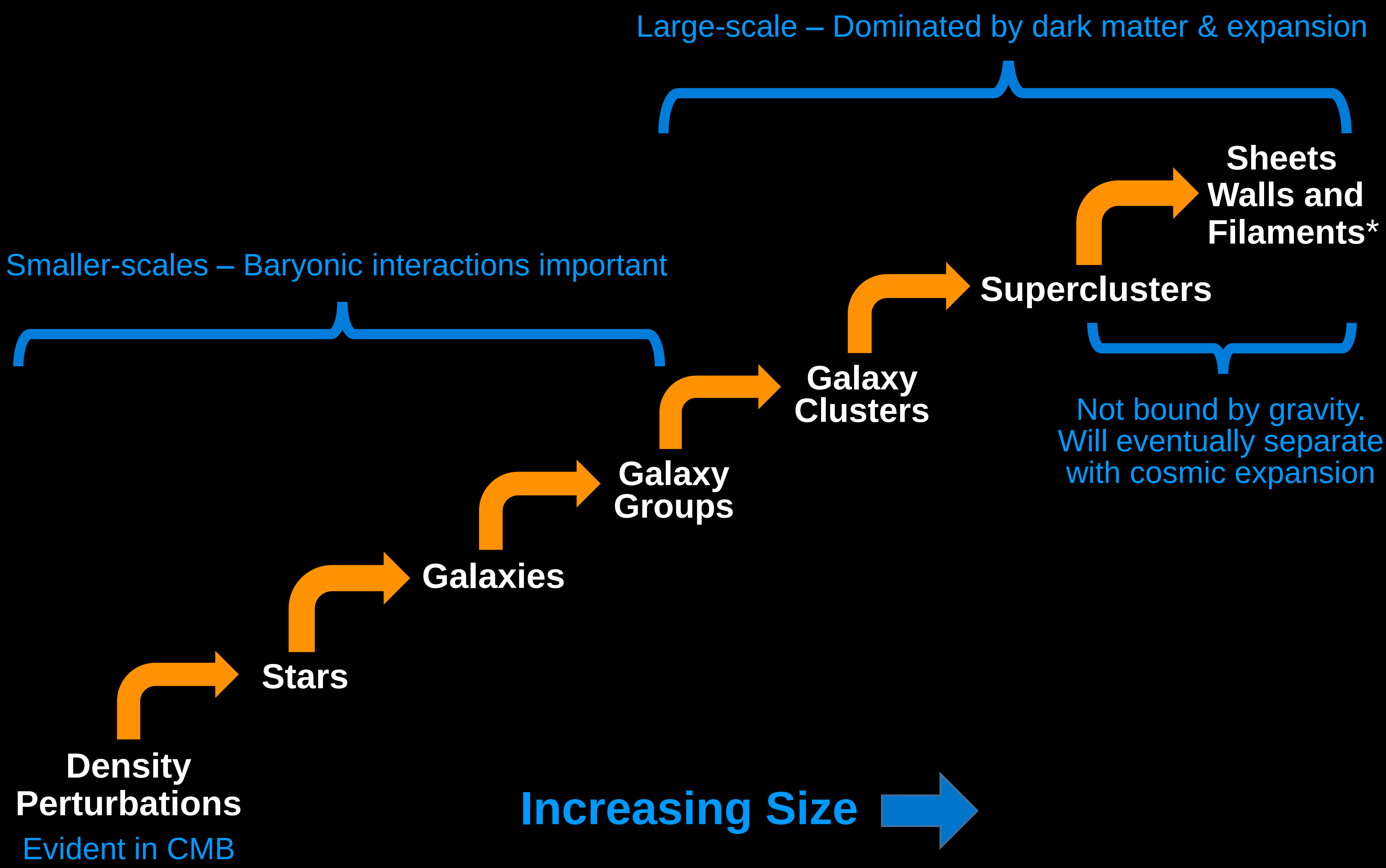
Large-Scale Structure (Cosmic Web) Formation



Hierarchy of Cosmic Structure



*Sheets walls & filaments separated by immense voids. Based on Wikipedia "Observable Universe" article

Large-Scale Structure or Cosmic Web

- Structure growth begins about 150 Myr after bang
- Seeds are higher density regions apparent in CMB
- Growth by means of gravitational instability
- Maps of Web obtainable from galaxy redshift surveys
- As with CMB, analysis of GRSs can help determine values of cosmological parameters
- Structure growth can be simulated mathematically

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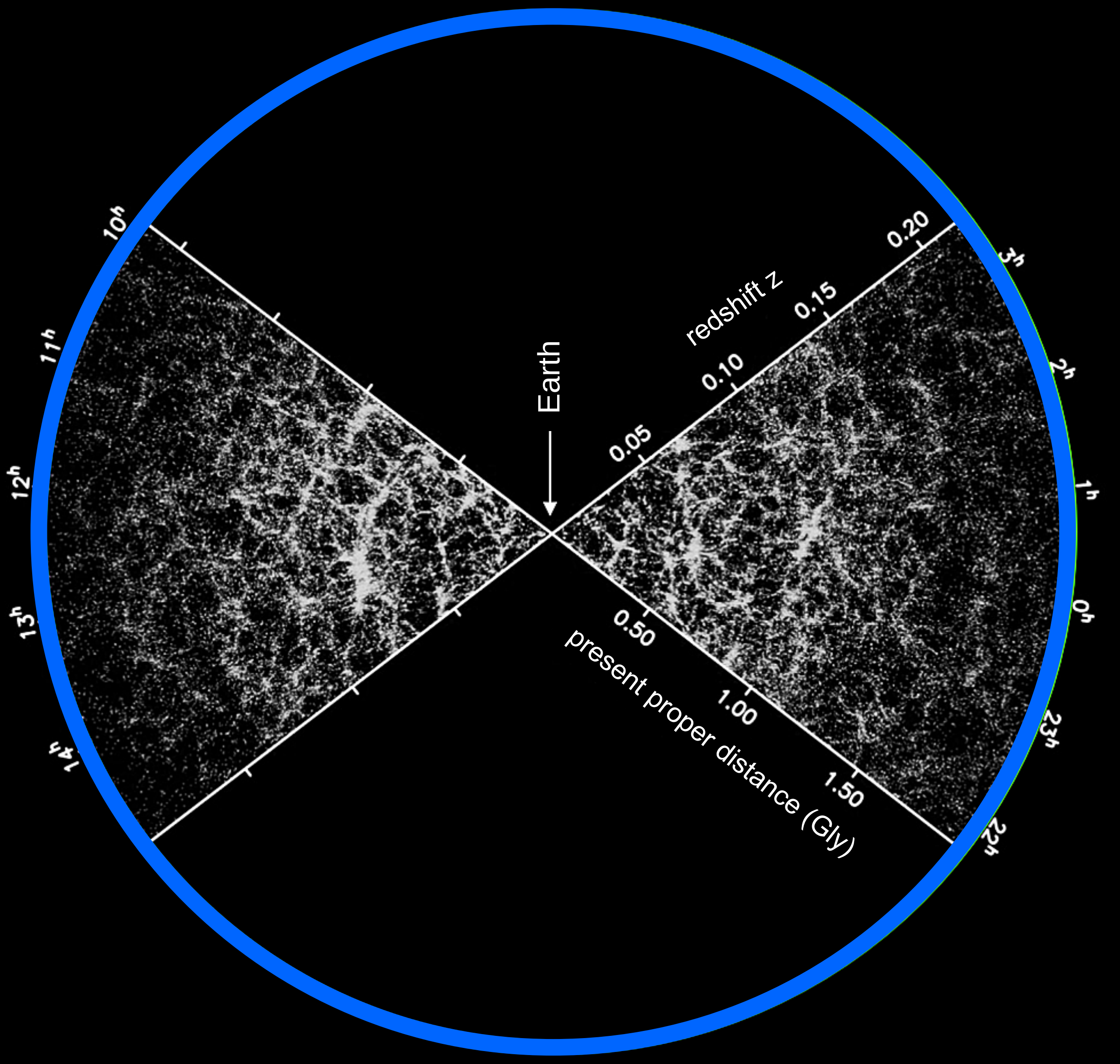
or GRSs

Cosmic Web – "Near" Earth

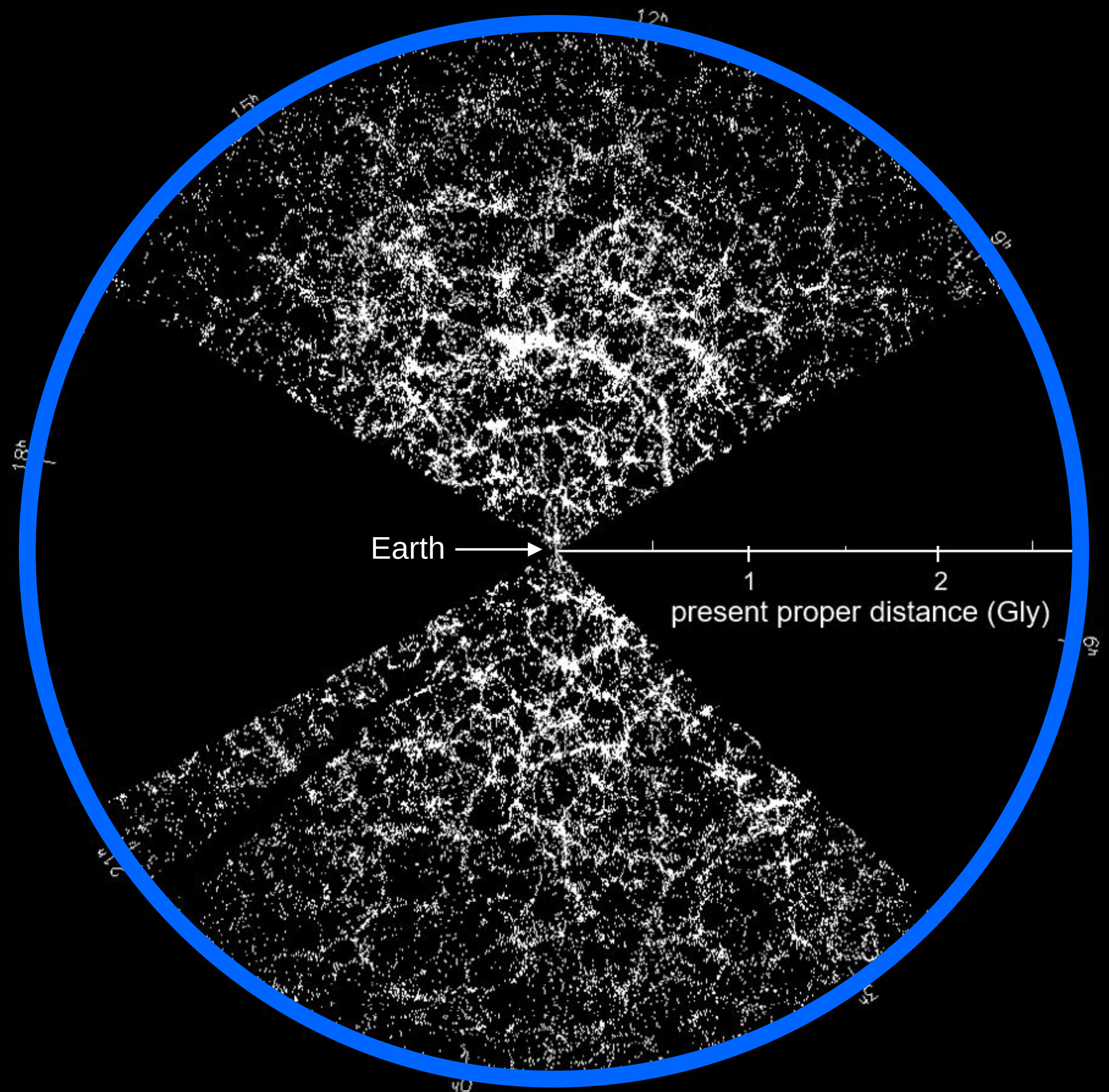
2dF Galaxy Redshift Survey



From Colless (2003) arXiv:astro-ph/0306581v1. Each point represents galaxy, galaxy cluster or quasar

Cosmic Web – "Near" Earth

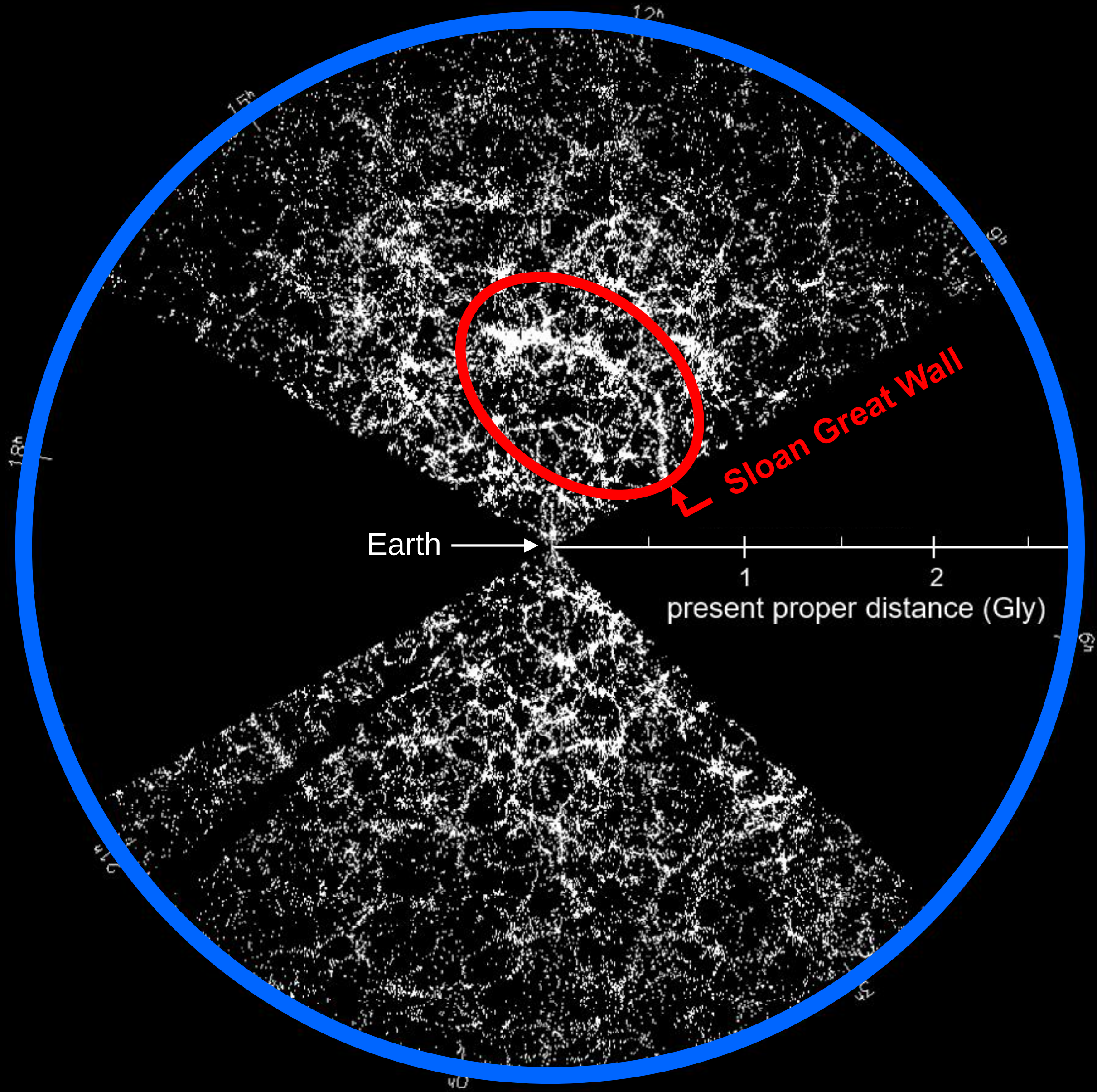
SDSS Galaxy Redshift Survey



From Gott, J. R. III, et al. (2005), A Map of the Universe, Astron. J. 624, 463. SDSS = Sloan Digital Sky Survey

Cosmic Web – "Near" Earth

SDSS Galaxy Redshift Survey



Sloan Great Wall is largest structure in known universe

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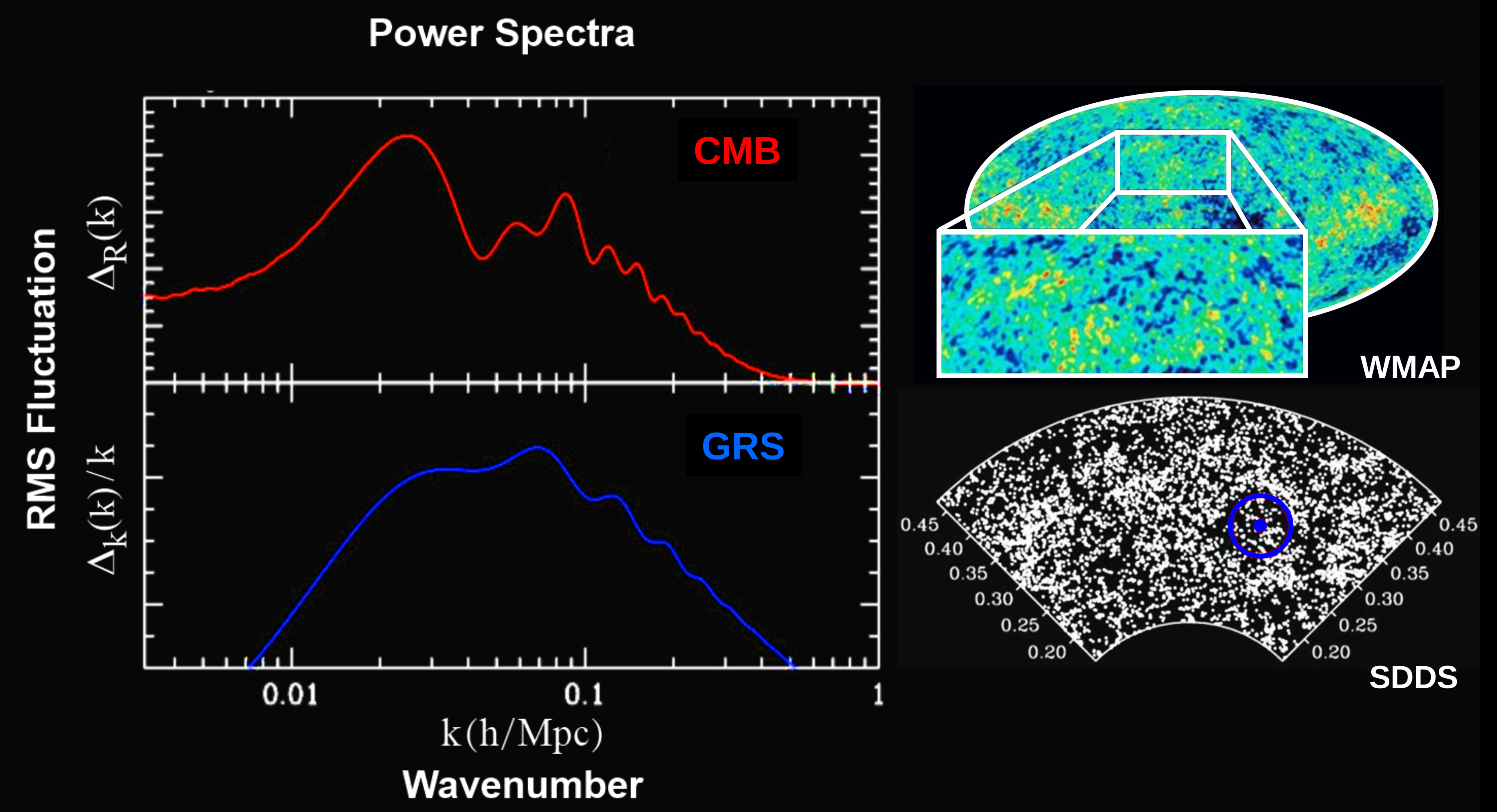
Touched on under ΛCDM model below

Baryon Acoustic Oscillations

Evidenced in Both CMB and GRS Power Spectra



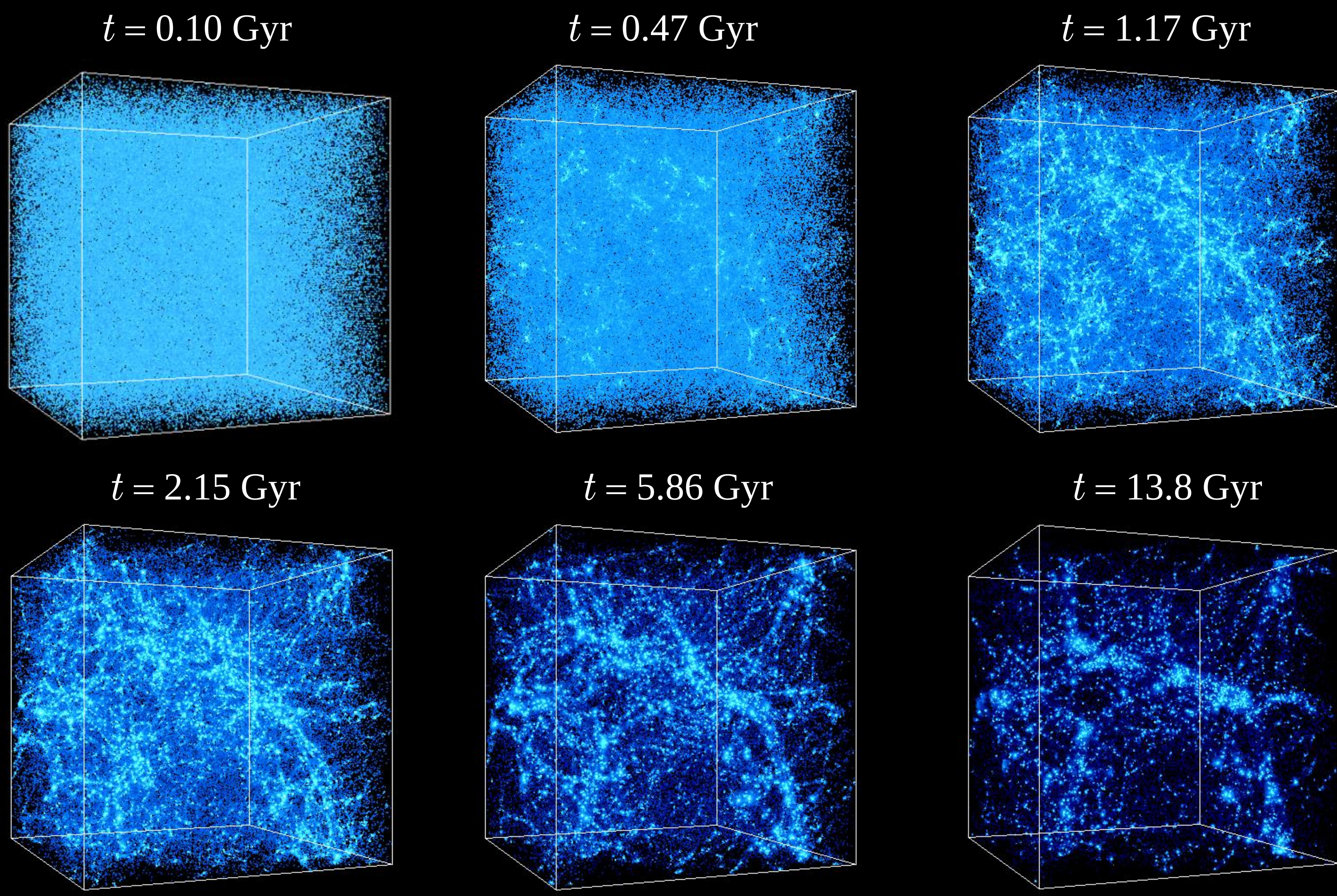
Analysis helps determine ΛCDM parameter values. Peaks are reflective of standing acoustic waves in the early universe. Source: Martin White

Large-Scale Structure or Cosmic Web

- Structure growth begins about 150 Myr after bang
- Seeds are higher density regions apparent in CMB
- Growth by means of gravitational instability
- Maps of Web obtainable from galaxy redshift surveys
- As with CMB, analysis of GRSs can help determine values of cosmological parameters
- Structure growth can be simulated mathematically

Simulated Large-Scale Structure Development

Dark Matter Distributions at Various Times

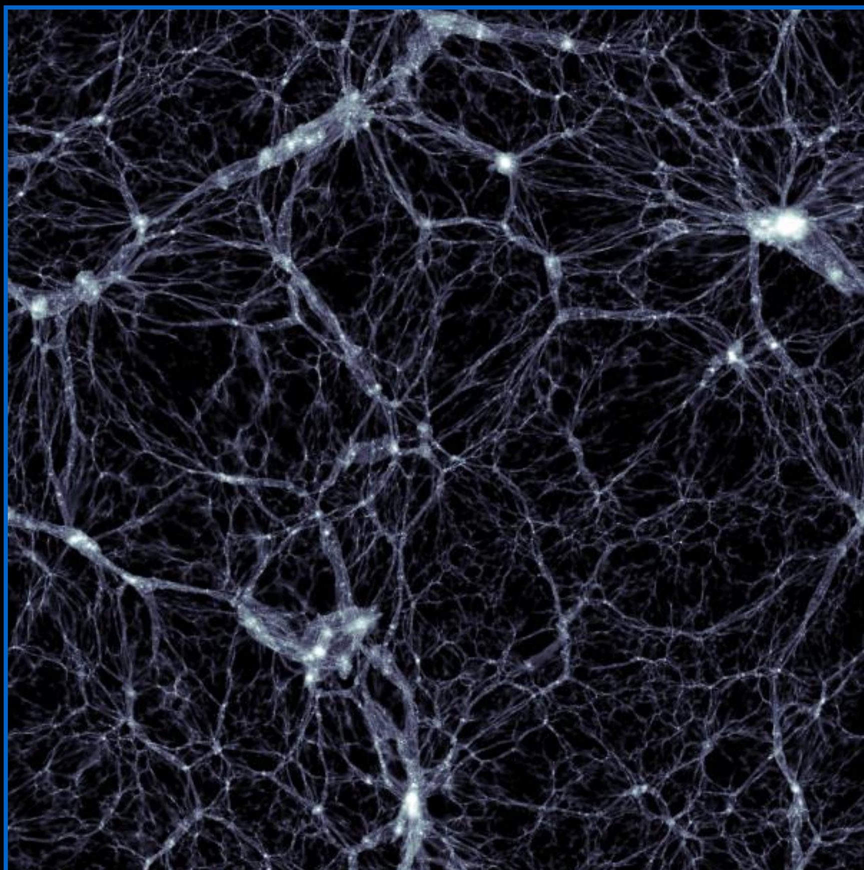


Simulations performed at the National Center for Supercomputer Applications by Andrey Kravtsov (University of Chicago) and Anatoly Klypin (New Mexico State University). Visualizations by Andrey Kravtsov

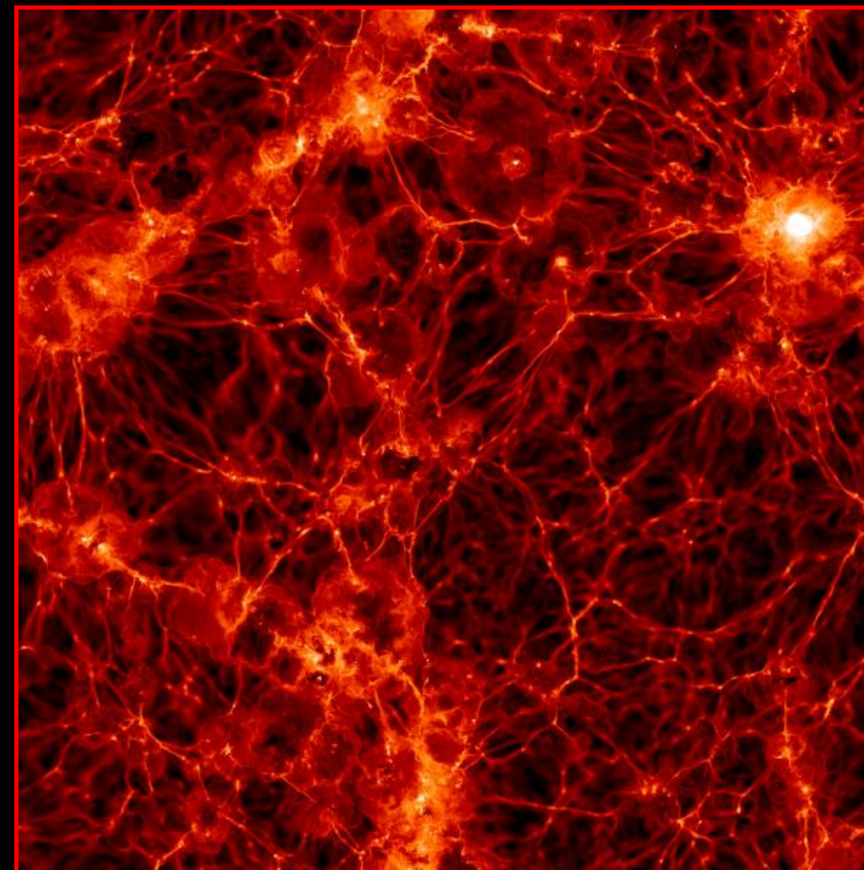
Cosmic Web – Detailed Simulation

Distributions of Ordinary and Dark Matter

Ordinary (Baryonic) Matter

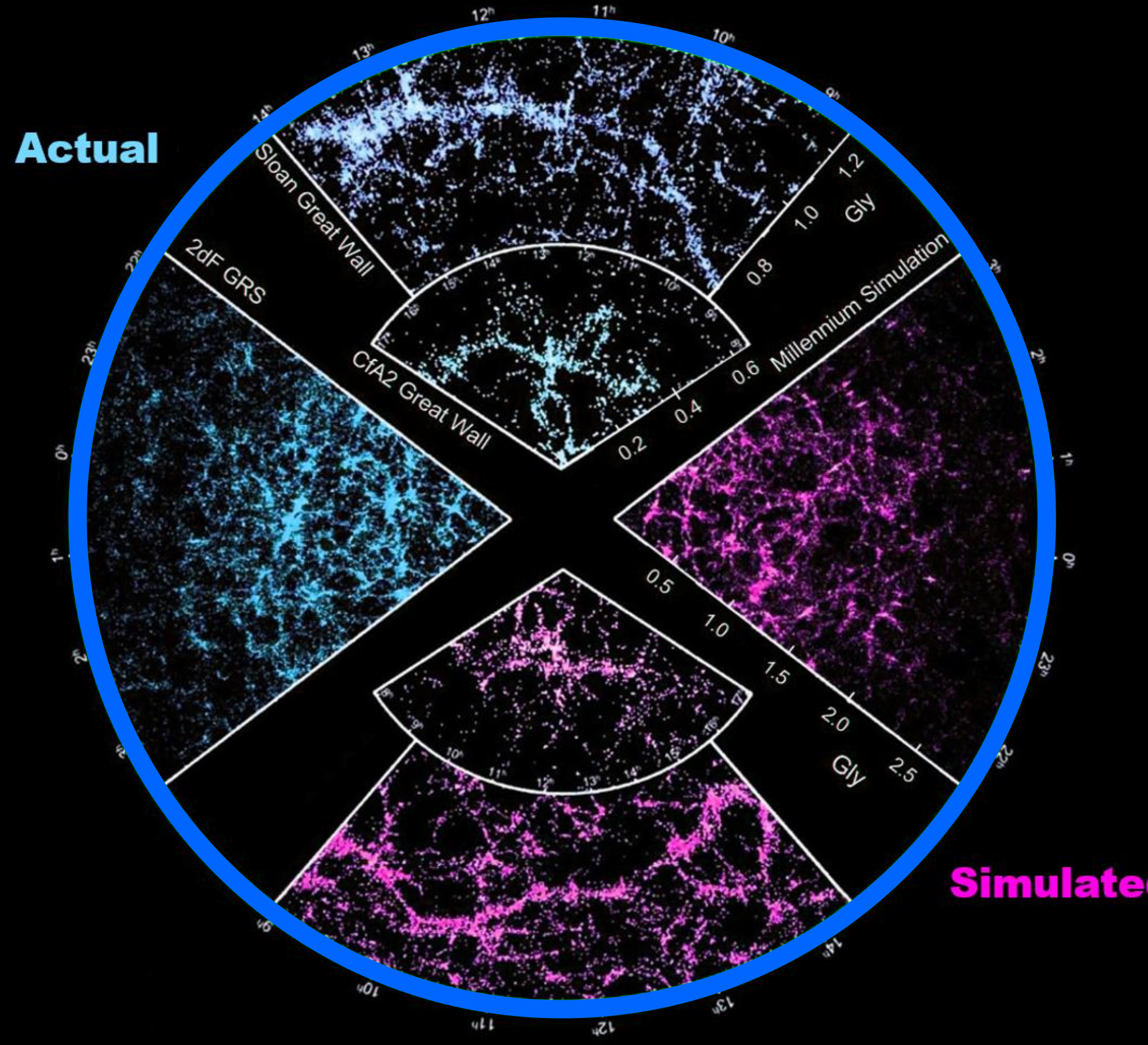


Dark Matter



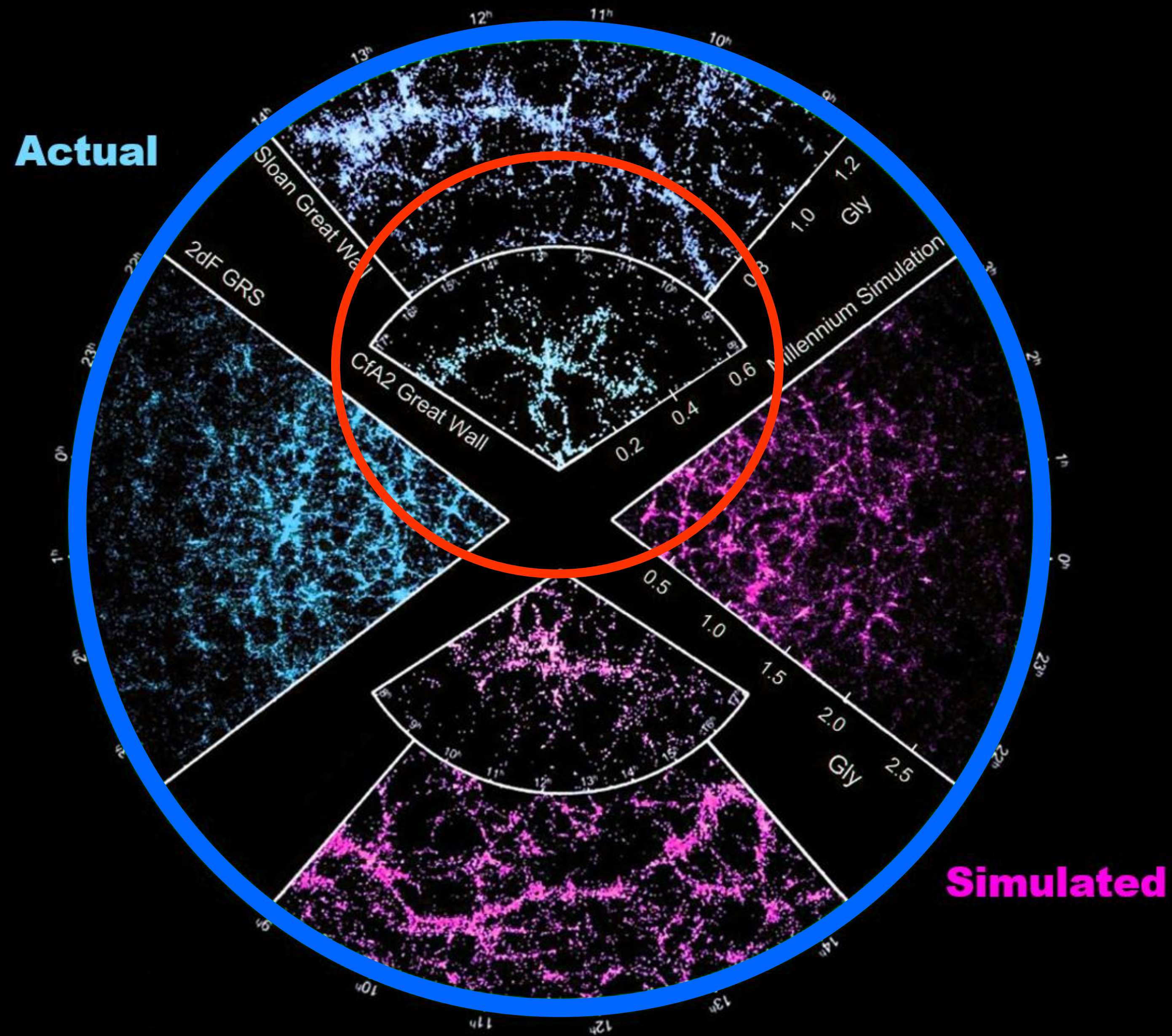
Slab 350 Mly x 350 Mly in page plane and 300 kly perpendicular to page plane. Ordinary matter (left panel) clumps more tightly than dark matter (right panel). Haider et al, Feb 24, 2016, *Monthly Notices of Royal Astronomical Society*. As others have noted, Web bears striking resemblance to network of brain neurons

Cosmic Web – "Near" Earth – Actual & Simulated



Actual (CfA2, 2dF, SDSS) vs Millenium simulation cosmic web slices. Springel et al arXiv:astro-ph/0604561

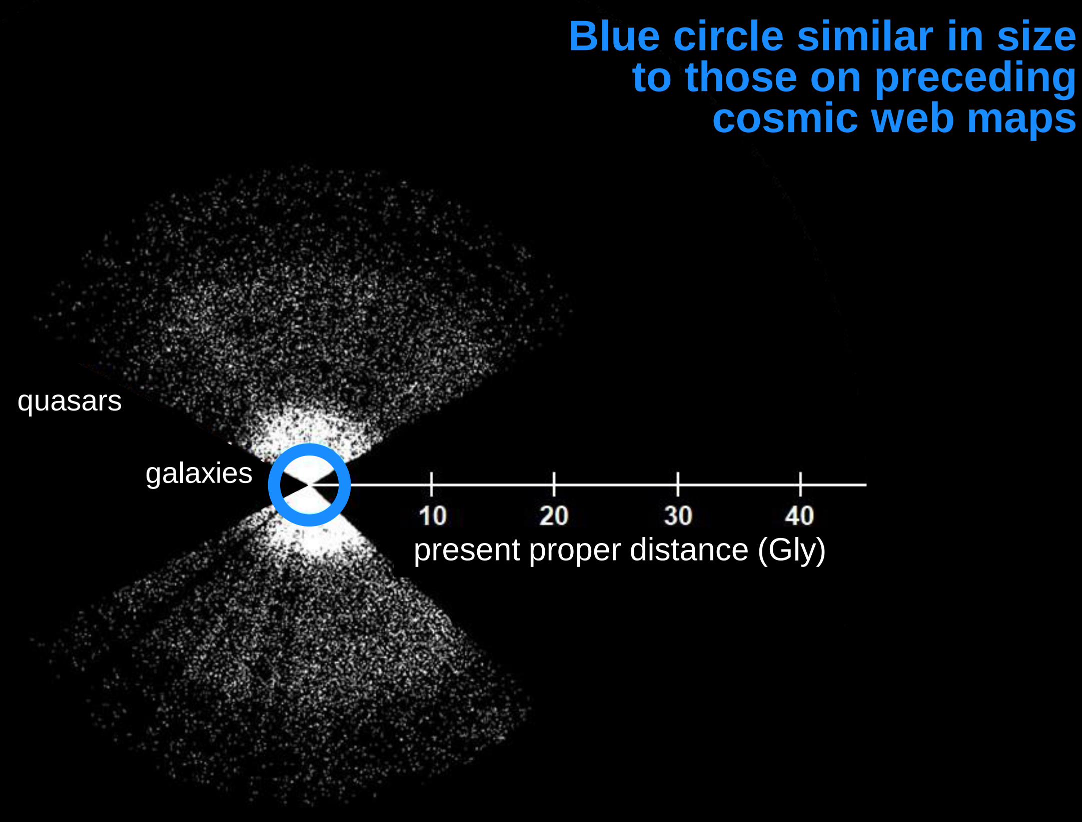
Cosmic Web – "Near" Earth – Actual & Simulated



CfA2 was first galaxy redshift survey (1987)

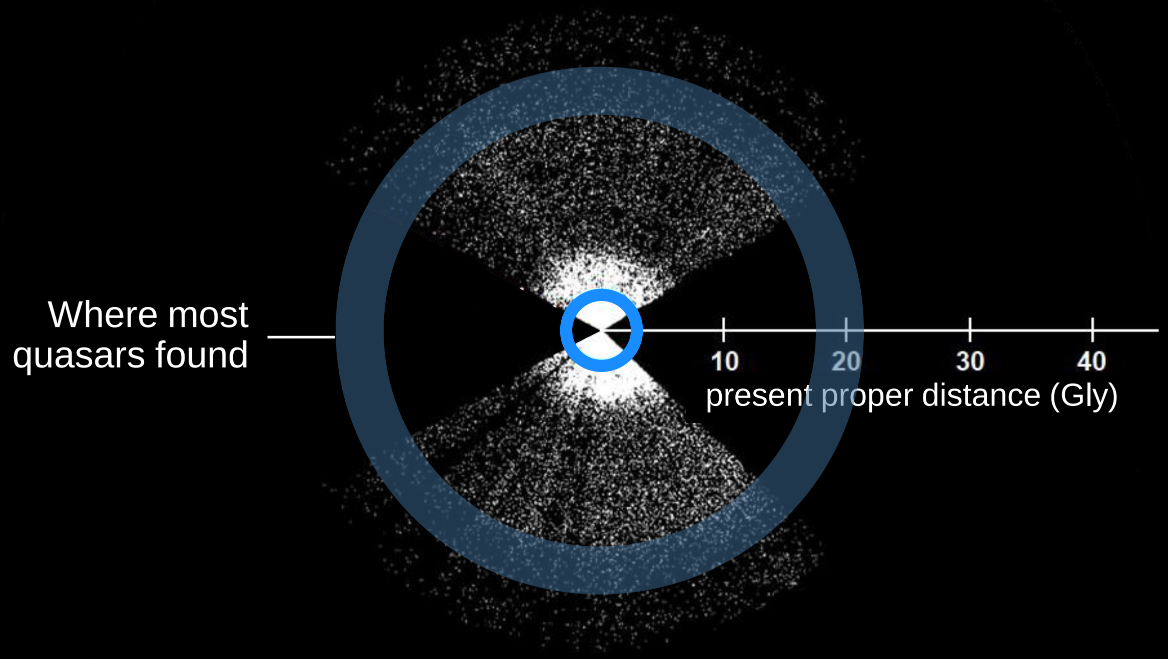
Prior to CfA2 survey, matter generally assumed to be distributed more or less uniformly throughout cosmos

Scale of Observable Universe



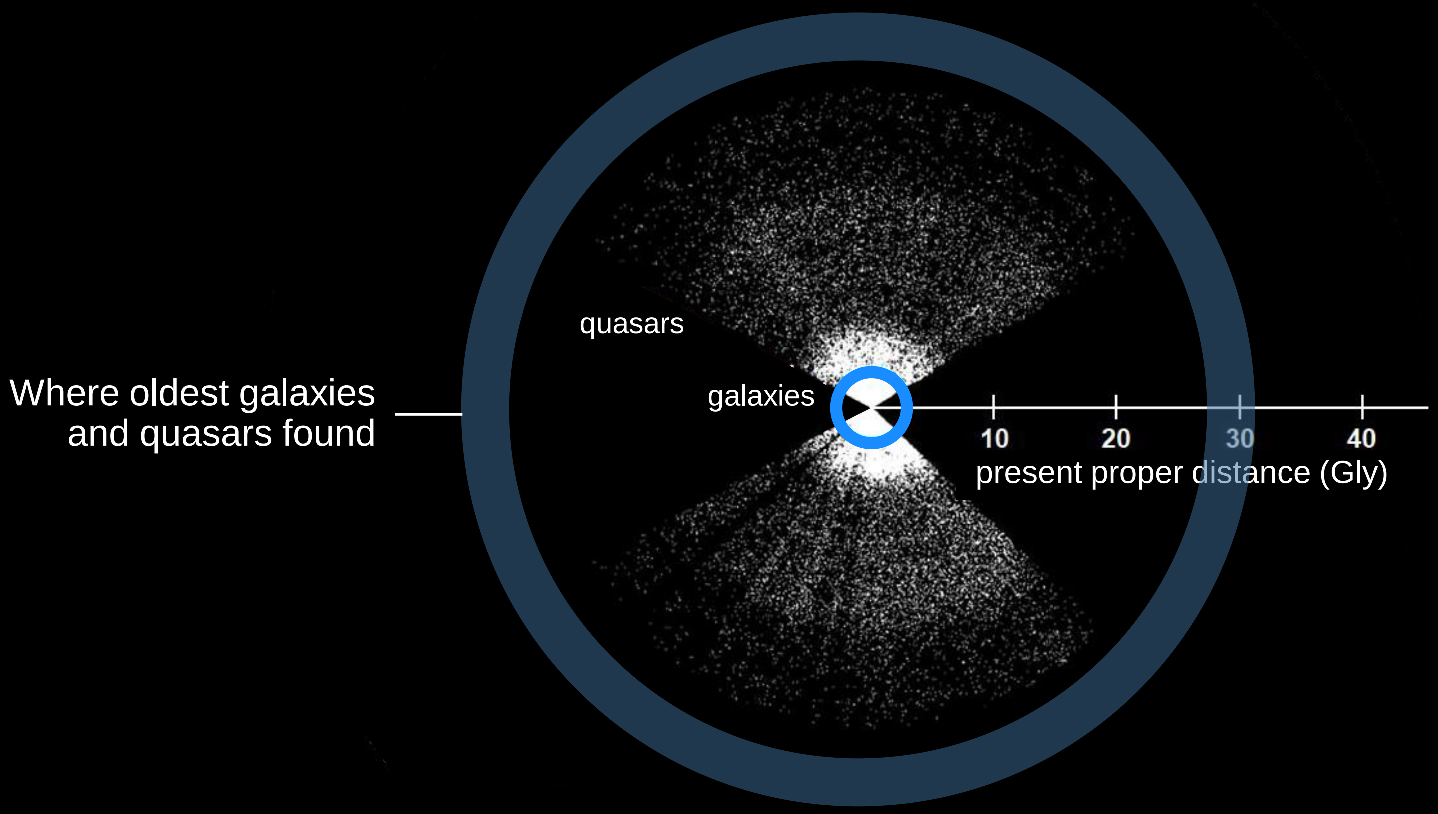
SDSS map from Gott, J. R. III, et al. (2005), A Map of the Universe, *Astron. J*. 624, 463. Where quasars dominate, most galaxies are too faint to be seen

Scale of Observable Universe

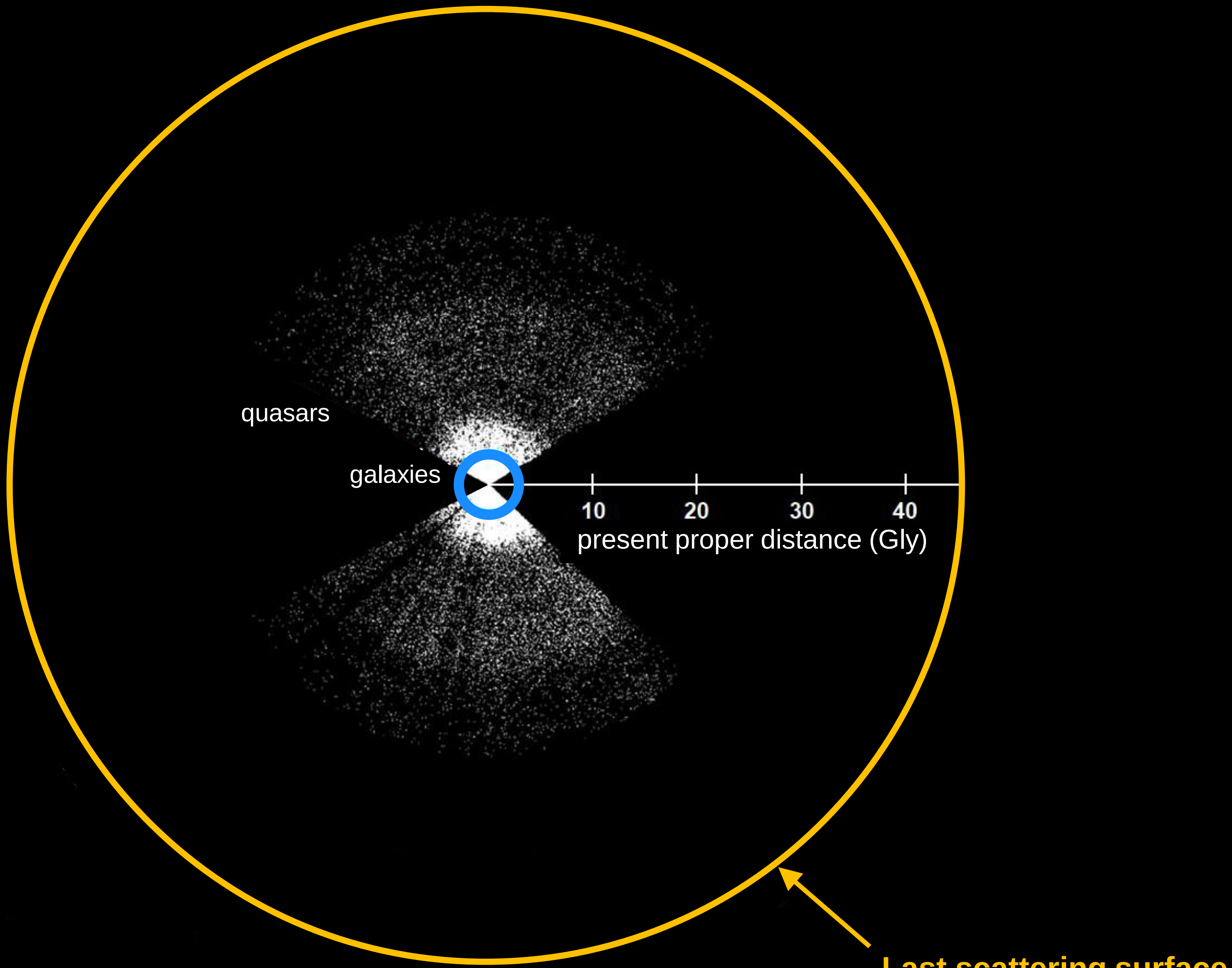


Most quasars were created when the universe was older and denser. Quasar density peaks at $z = 2–3$ (Richards et al, 2006, arXiv:astro-ph/0601434v2) or 17.3–21.2 Gly away or 10.5-11.6 Gyr ago

Scale of Observable Universe

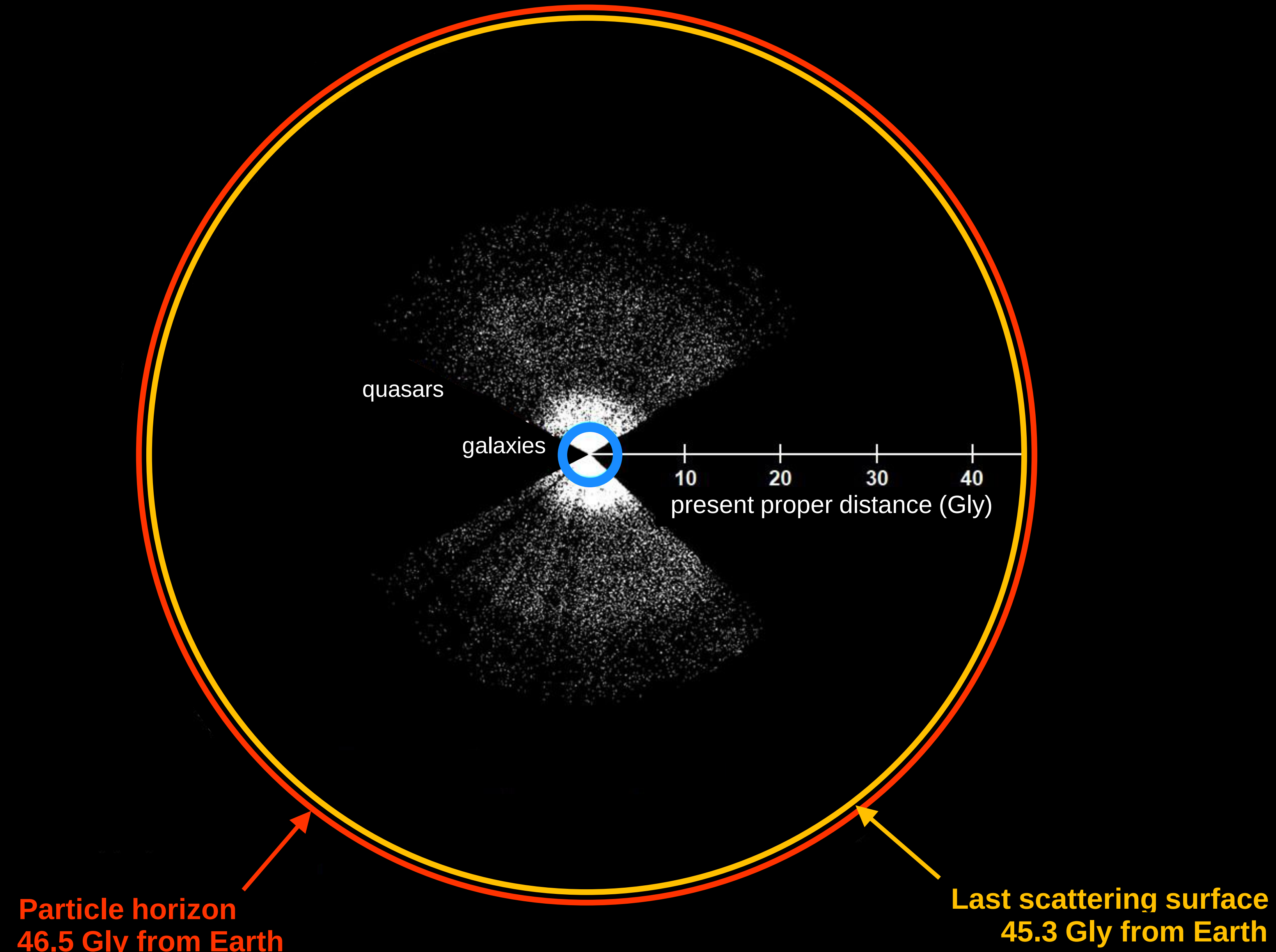


Scale of Observable Universe



At photon decoupling surface was only 42 Mly away (well inside blue circle)

Scale of Observable Universe



The particle horizon is the farthest distance light could have traveled since the expansion began

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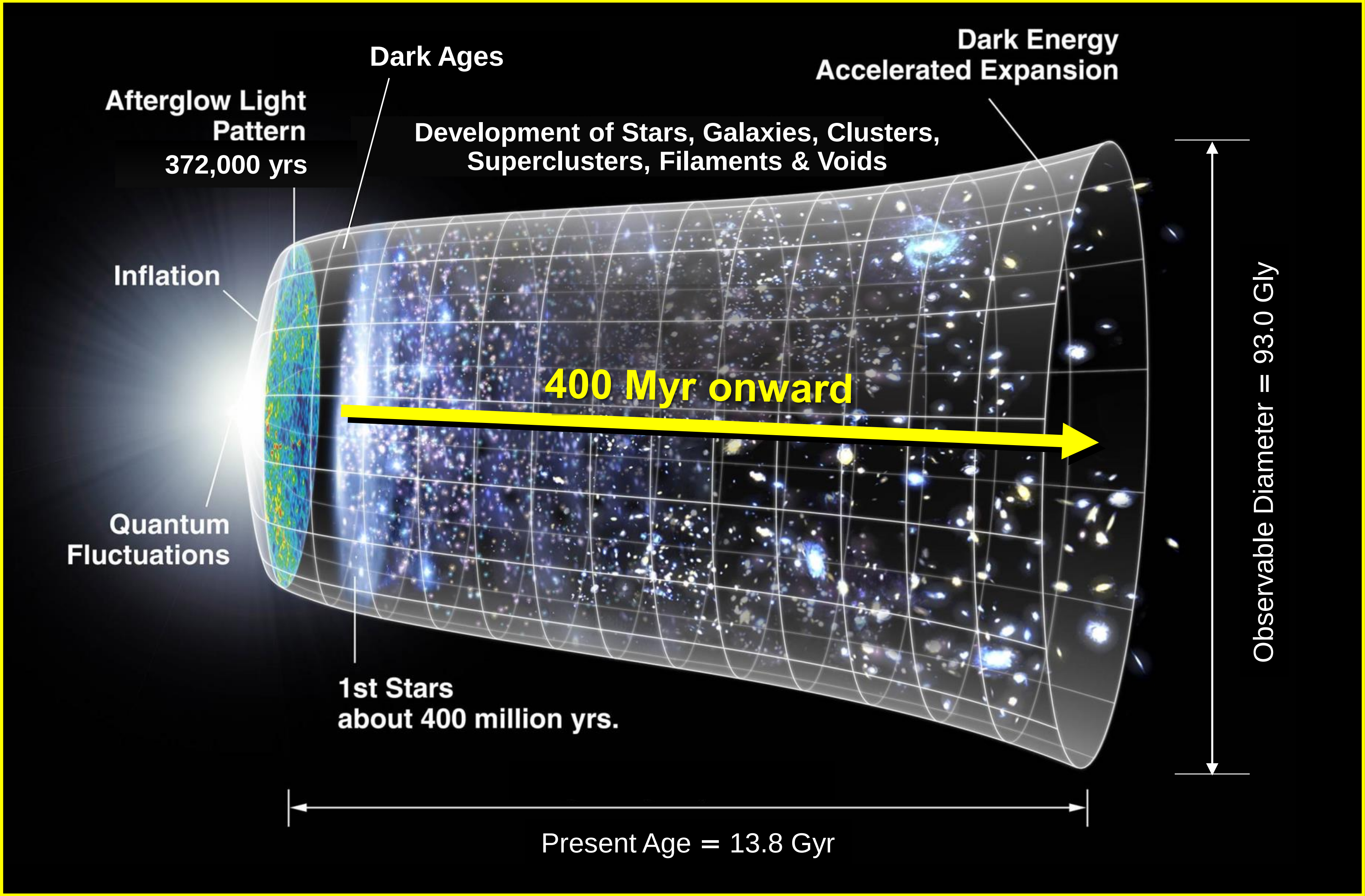
Stellar Evolution



Stellar Evolution

- Stars have formed, evolved and died since the universe was about 400 Myr old
- Small ones have predicted lifespans greater than the current age of the universe
- Number of elements created in burning stars and their explosions

Stellar Evolution

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- Number of elements created in burning stars and their explosions

Such long-lived small stars known as red dwarves

Stellar Evolution

- Stars have formed, evolved and died since the universe was about 400 Myr old
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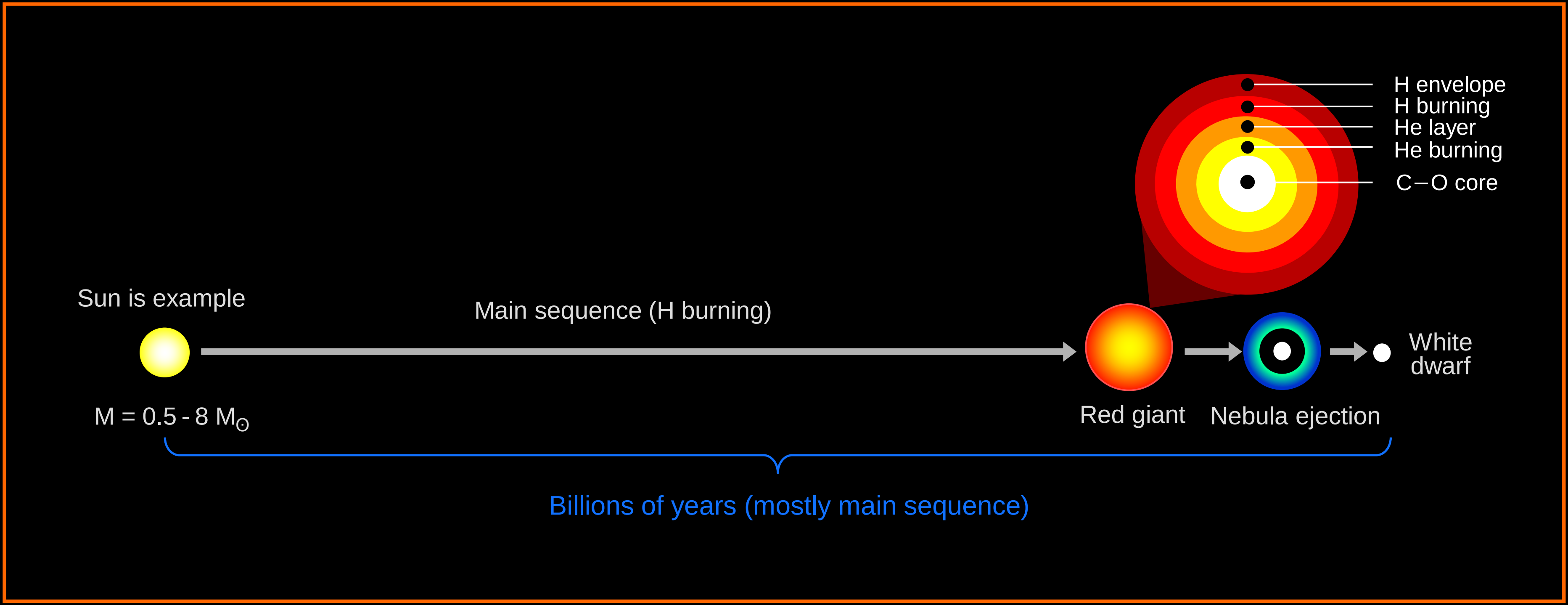
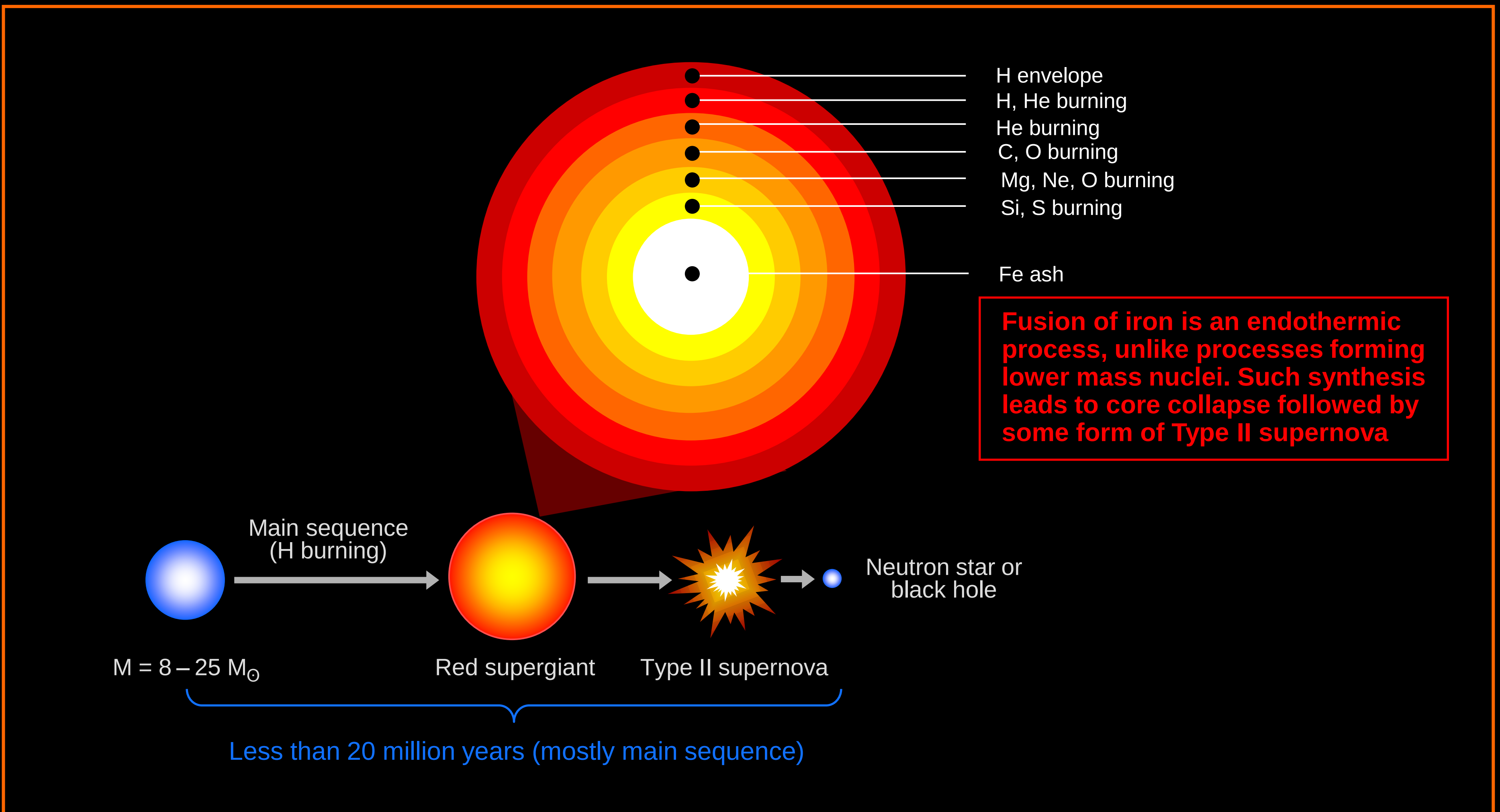
Evolution of Low Mass Star



Highly simplified. Layers from *Astronomy* (Openstax). Red dwarfs not included in low mass category here.
Sun is currently 4.6 Gyr old and will become a red giant in another 5-7 Gyr

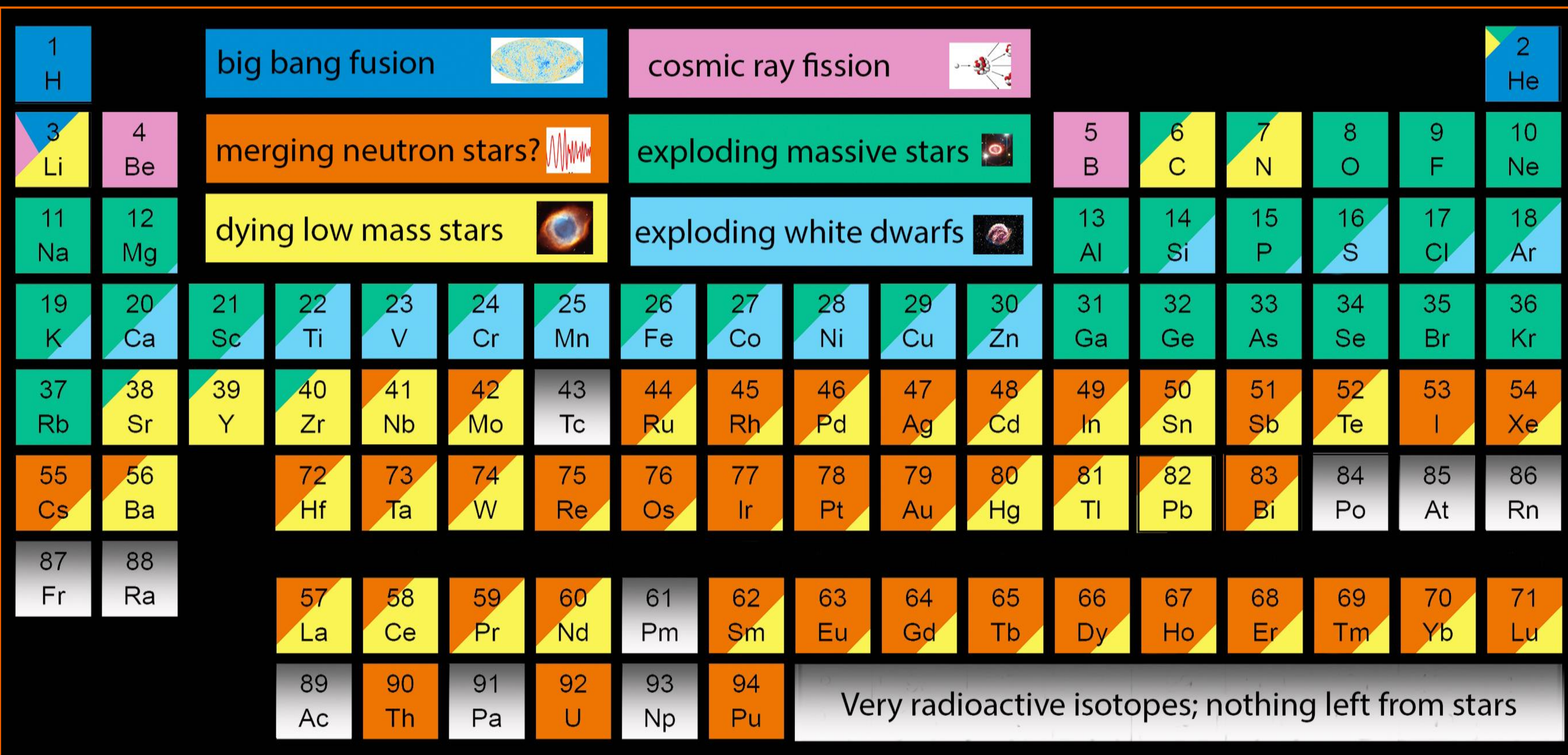
Evolution of High Mass Star



Highly simplified. Layers from *Astronomy* (Openstax). High mass star ends its time as element factory in massive nuclear explosion

Nucleosynthesis in General

Cosmogenic Origin of Each Element



As indicated above, creation of all elements in the periodic table involves more than BBN and the stellar evolution processes depicted on the last two slides. See Wikipedia "Nucleosynthesis" article. Above chart created by Jennifer Johnson, www.astronomy.ohio-state.edu/~jaj/nucleo/

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Lambda CDM (ΛCDM*) Model

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- Current "standard model" of observable universe**
- Based on general relativity***
- Accommodates precision fits of essentially all data
- Major components (dark matter and dark energy) not tied to any known particles
- Cosmic inflation not integral part of model

*Λ = Einstein cosmological constant. CDM = Cold Dark Matter. **Not to be confused with the Standard Model of Particle Physics. ***Therefore a classical – as opposed to a quantum – theory

Without extensions, the ΛCDM model describes the simple (no inflation) expansion shown early in the presentation

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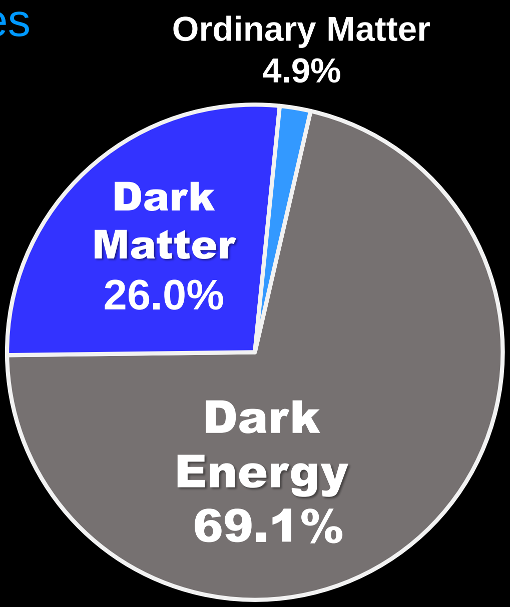
Components of Universe – ΛCDM Model

- **Radiation (negligible portion of current energy)**
  - Consists of photons and neutrinos
  - Once dominant component
- **Ordinary or baryonic matter**
  - Principal portion: invisible intergalactic gas
  - Smaller, visible portion: stars, planets, galaxies
  - Interacts through all four fundamental forces
  - Pressureless on cosmological scale ("dust")
  - Stuff of life
- **Dark matter or CDM**
  - Particle nature unknown
  - Interacts only through gravity
- **Dark energy (Λ component)**
  - Particle nature unknown
  - Small but constant energy density
  - Negative pressure !
  - Dominates current expansion



Current Energy Breakdown

Energy breakdown from Planck Project (2015, DOI: 10.1051/0004-6361/201525830) to nearest 0.1%

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Isotropic, Homogeneous Universe

- With a little smoothing, our observable universe is isotropic and homogeneous
- An isotropic universe looks the same in every direction
- A homogeneous universe looks isotropic from every location

For an isotropic, homogeneous universe the Einstein field equation reduces to an ordinary differential equation that can easily be integrated numerically

At least in the simple case without inflation

Einstein Field Equation

Basic Equation of General Relativity

Constant

$$\mathbf{G} = \kappa \mathbf{T}$$

Einstein curvature 4-tensor

Energy-momentum 4-tensor

$\kappa = 8\pi G/c^4$. Divergence of curvature tensor identically zero, whereby $\nabla \cdot \mathbf{T} = \mathbf{0}$ (energy-momentum conservation)

Expansion Equation – ΛCDM Model

Einstein Field Equation

$\mathbf{G} = \kappa \mathbf{T}$

Large-scale Isotropy & Homogeneity

Energy-Momentum Conservation

$\nabla \cdot \mathbf{T} = \mathbf{0}$

$$3\frac{\dot{a}^2 + kc^2}{a^2c^2} = \kappa \mathcal{E}$$

Time Components

$$\mathrm{d}(\mathcal{E}a^3) = -P\,\mathrm{d}a^3$$

First law of thermodynamics

or, equivalently

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{\kappa c^2}{3}\mathcal{E} - \frac{kc^2}{a^2}$$

Friedmann Equation

$$\mathcal{E} = \mathcal{E}_\mathrm{R} + \mathcal{E}_\mathrm{M} + \mathcal{E}_\Lambda$$

Flat Universe $k = 0$

Radiation (photons + neutrinos): $P_\mathrm{R} = \frac{1}{3}\mathcal{E}_\mathrm{R}$ $\quad \mathcal{E}_\mathrm{R} = \mathcal{E}_\mathrm{R0}\,\tilde{a}^{-4}$

Matter (ordinary + dark): $P_\mathrm{M} = 0$ $\quad \mathcal{E}_\mathrm{M} = \mathcal{E}_\mathrm{M0}\,\tilde{a}^{-3}$

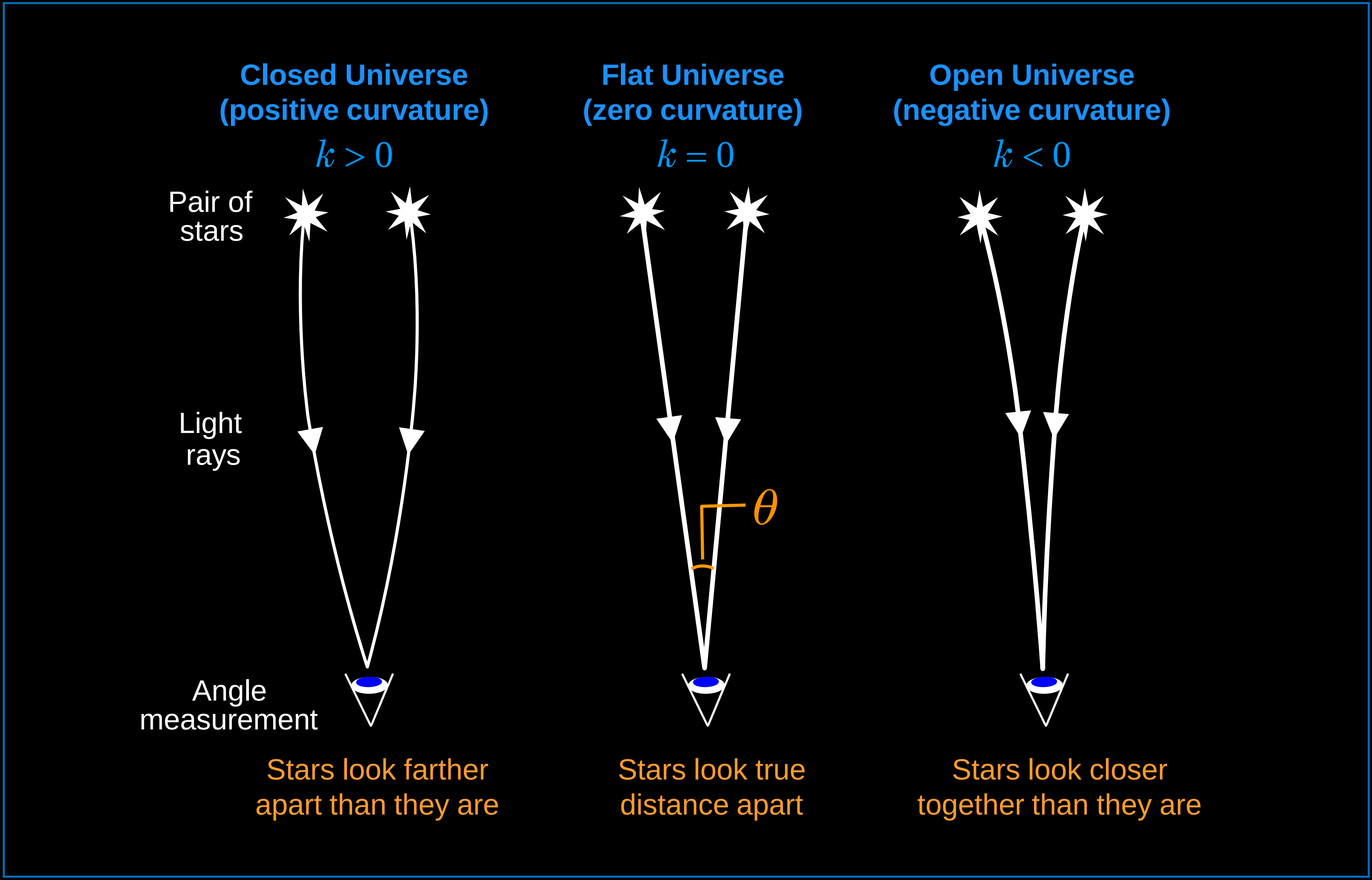
Dark Energy: $P_\Lambda = -\mathcal{E}_\Lambda$ $\quad \mathcal{E}_\Lambda = \Lambda/\kappa$

Expansion Equation

$$t(\tilde{a}) = \frac{1}{H_0}\int_0^{\tilde{a}} \frac{\mathrm{d}\tilde{a}}{\sqrt{\Omega_\mathrm{R0}\tilde{a}^{-2} + \Omega_\mathrm{M0}\tilde{a}^{-1} + \Omega_{\Lambda 0}\tilde{a}^{2}}}$$

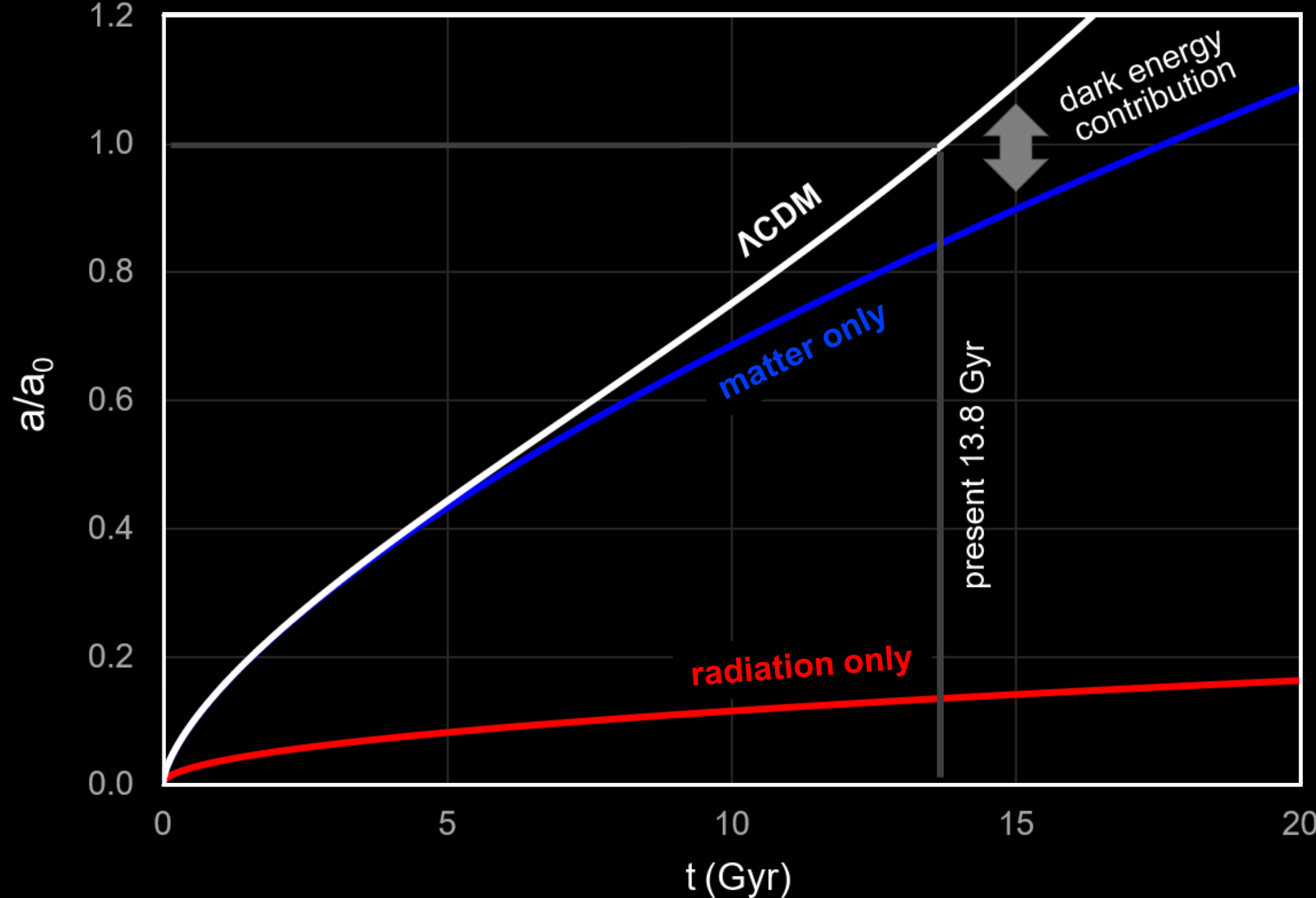
a = radius of observable universe, t = time, $\tilde{a} = a/a_0$, 0 subscript means present time, $\mathcal{E}$ = energy density, P = pressure, k = curvature, Λ = cosmological constant, $\Omega_{\mathrm{X}0}$ = component X fraction of universe energy

Flat and Curved Universes



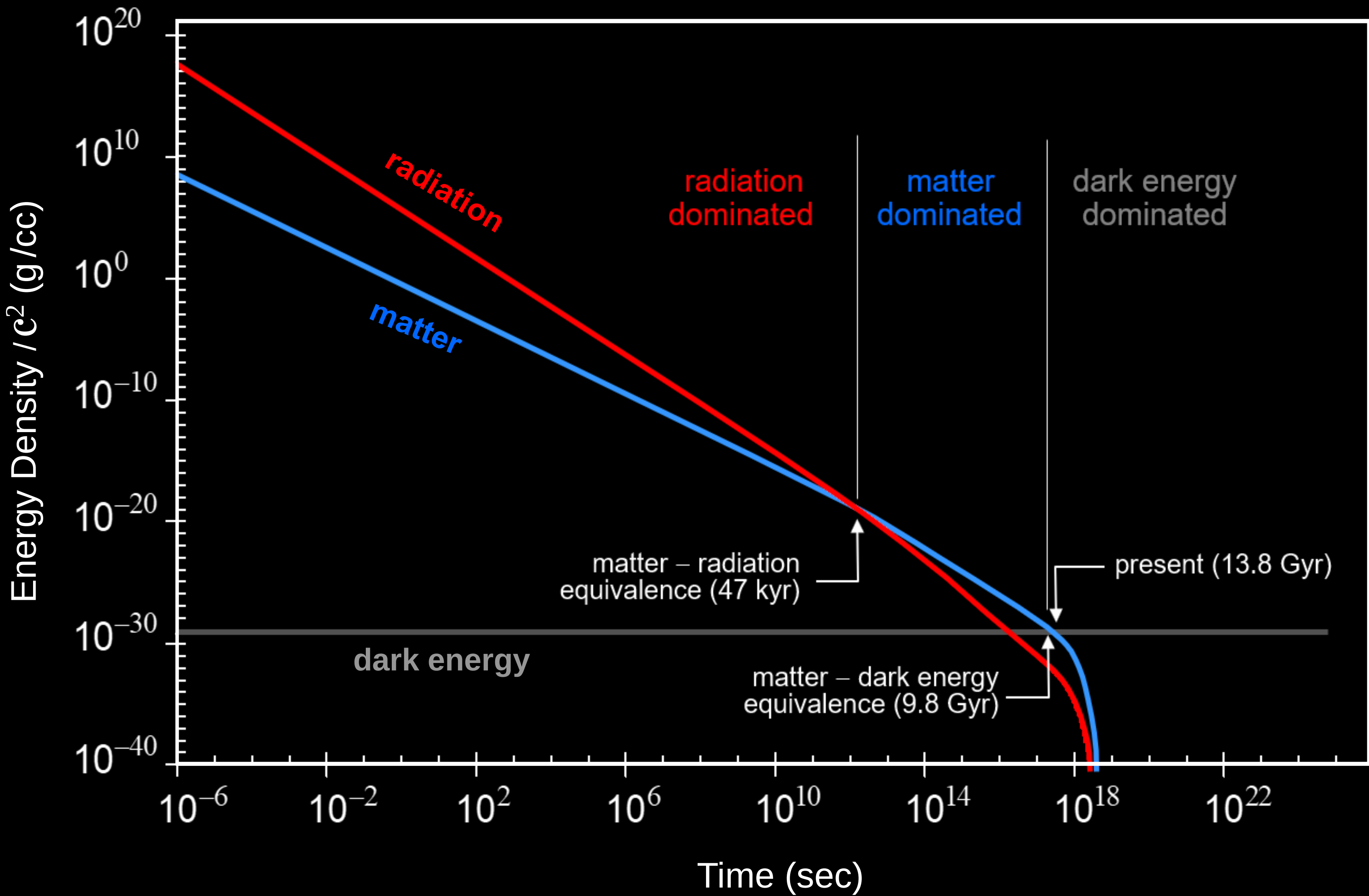
In a closed universe, travel far enough along a geodesic and you get back to where you started. Our observable universe appears to be flat

Expansion of Flat Universe – ΛCDM Model



Inflation, if it occurred, would mean that the universe was incredibly small at very early times and that the universe beyond our observable portion now is very much larger. But it would not impact this graph

Energy Densities Over Time



Acceleration Equation – ΛCDM Model

Space component of Einstein field equation

$$\frac{\ddot{a}}{a} = -\frac{\kappa c^2}{6}\left(\mathcal{E} + 3P\right)$$

Currently, under dark energy domination,

$$\frac{\ddot{a}}{a} = \frac{\Lambda c^2}{3}$$

The expansion of our observable universe does indeed appear to be accelerating

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Why Dark Matter?

- **Dark matter between galaxies in galaxy clusters helps explain otherwise anomalously high galaxy speeds within clusters**
- **Dark matter around galaxies accounts for plateaus often seen in galaxy rotation curves**
- **Dark matter helps bring calculated CMB power spectrum into agreement with measured spectrum, particularly second and third acoustic peaks**
- **Dark matter helps bring calculated large-scale structure into agreement with measured structure**
- **Existence helps explain the Bullet Cluster**

Behavior first noticed by Fred Zwicky in the 1930s

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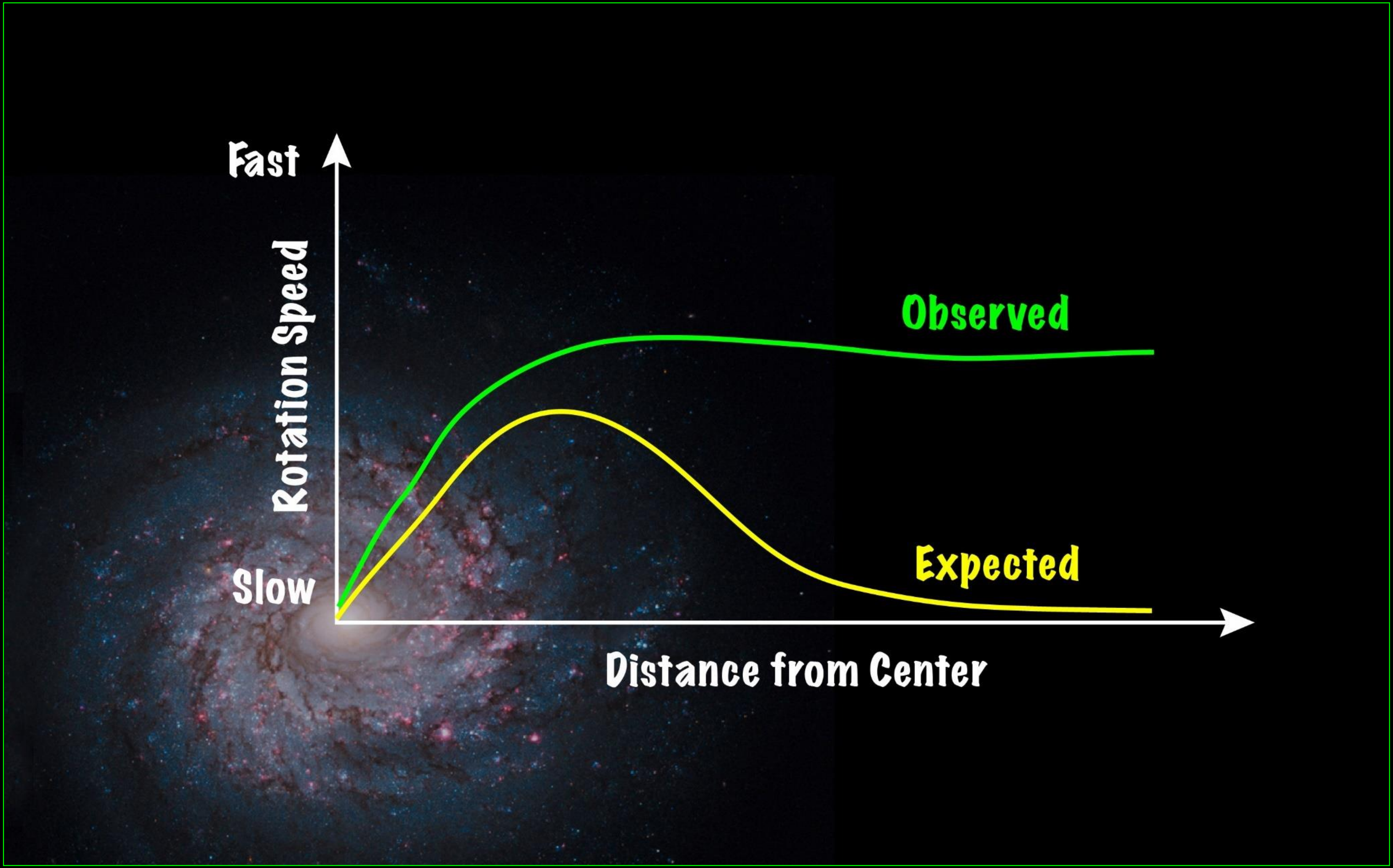
Dark Matter and Galaxy Rotation Curve Plateau



First group of "flat" rotation curves measured by Vera Rubin and coworkers, primarily in 1970s. Plateaus explained by dark matter halos beyond visible portions of galaxies (next slide). Image source unknown

Dark Matter Halo Surrounding Galaxy

Artist impression of Milky Way dark matter halo (shown in blue; actually invisible). National Geographic

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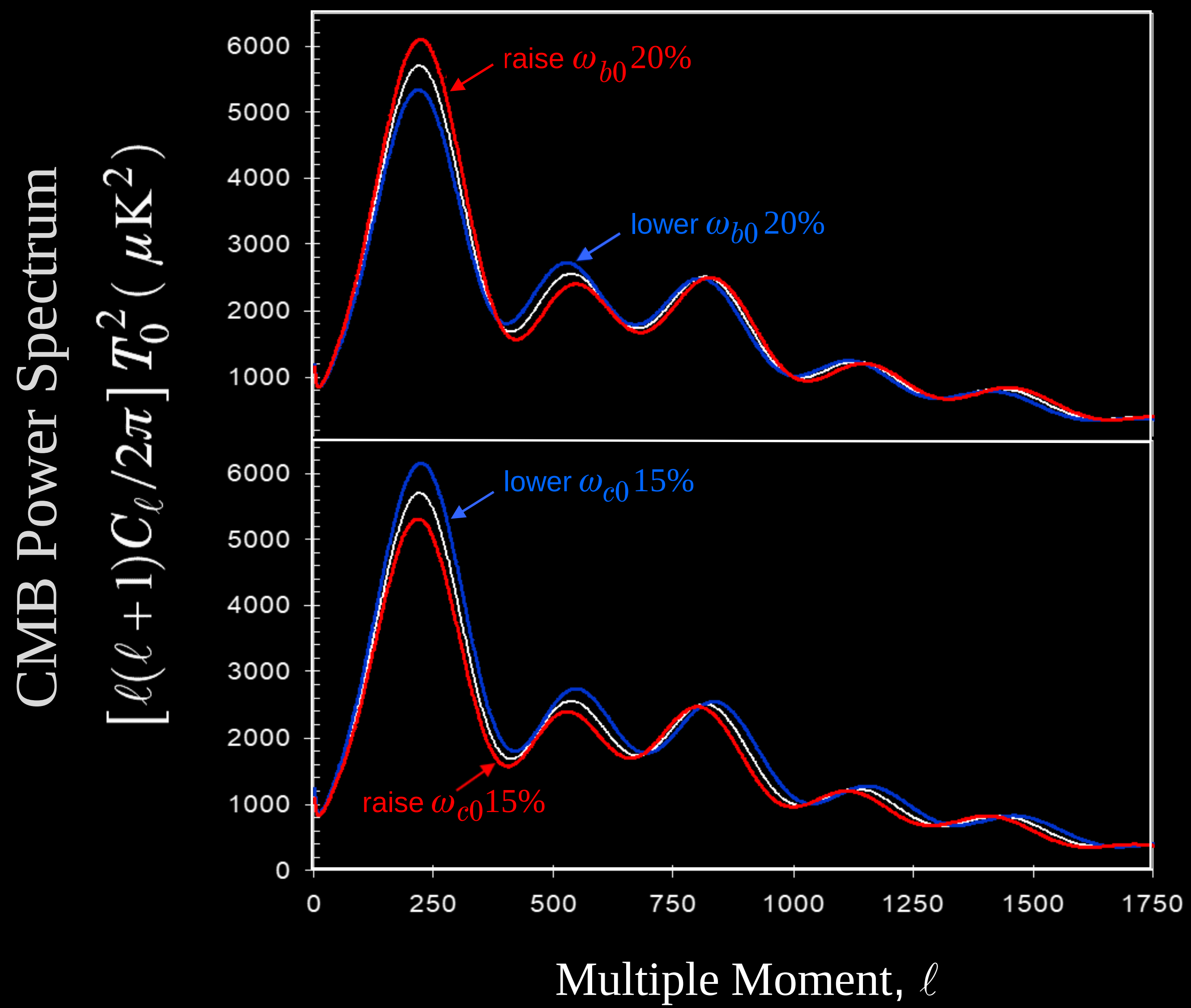
CMB Power Spectrum – Sensitivity to Parameters

Baryonic Matter & Cold Dark Matter



Theoretical spectrums generated using CAMB, one of the computer programs used by NASA to analyze WMAP data. White curves best fit of WMAP data. Red and blue curves perturbations

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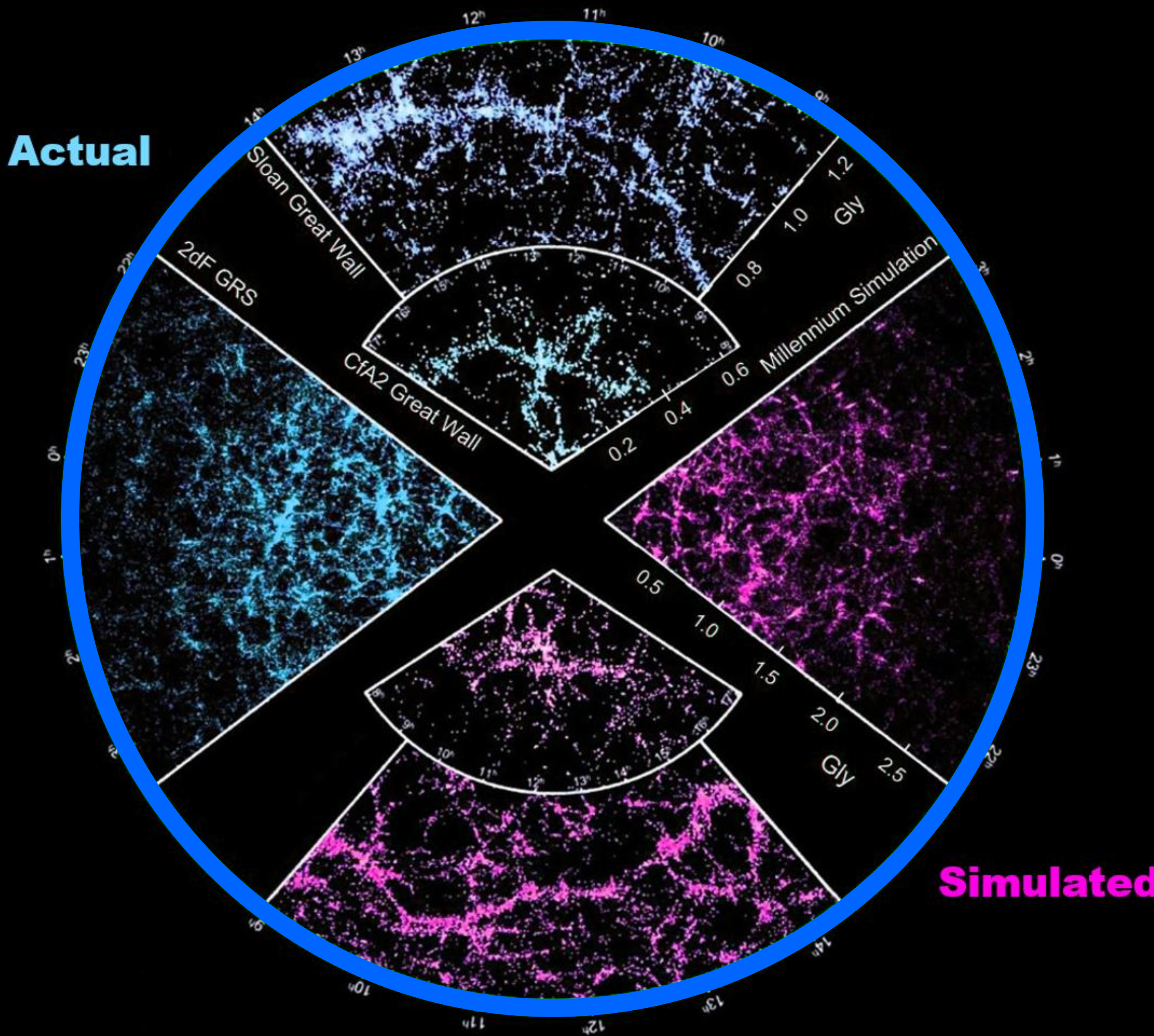
Cosmic Web – "Near" Earth – Actual & Simulated



Actual (CfA2, 2dF, SDSS) vs Millenium simulation cosmic web slices. Springel et al arXiv:astro-ph/0604561

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Involves most energetic event known outside of Big Bang: namely a high-speed "collision" of two galaxy clusters. More immediately below. See also Wikipedia article on Bullet Cluster

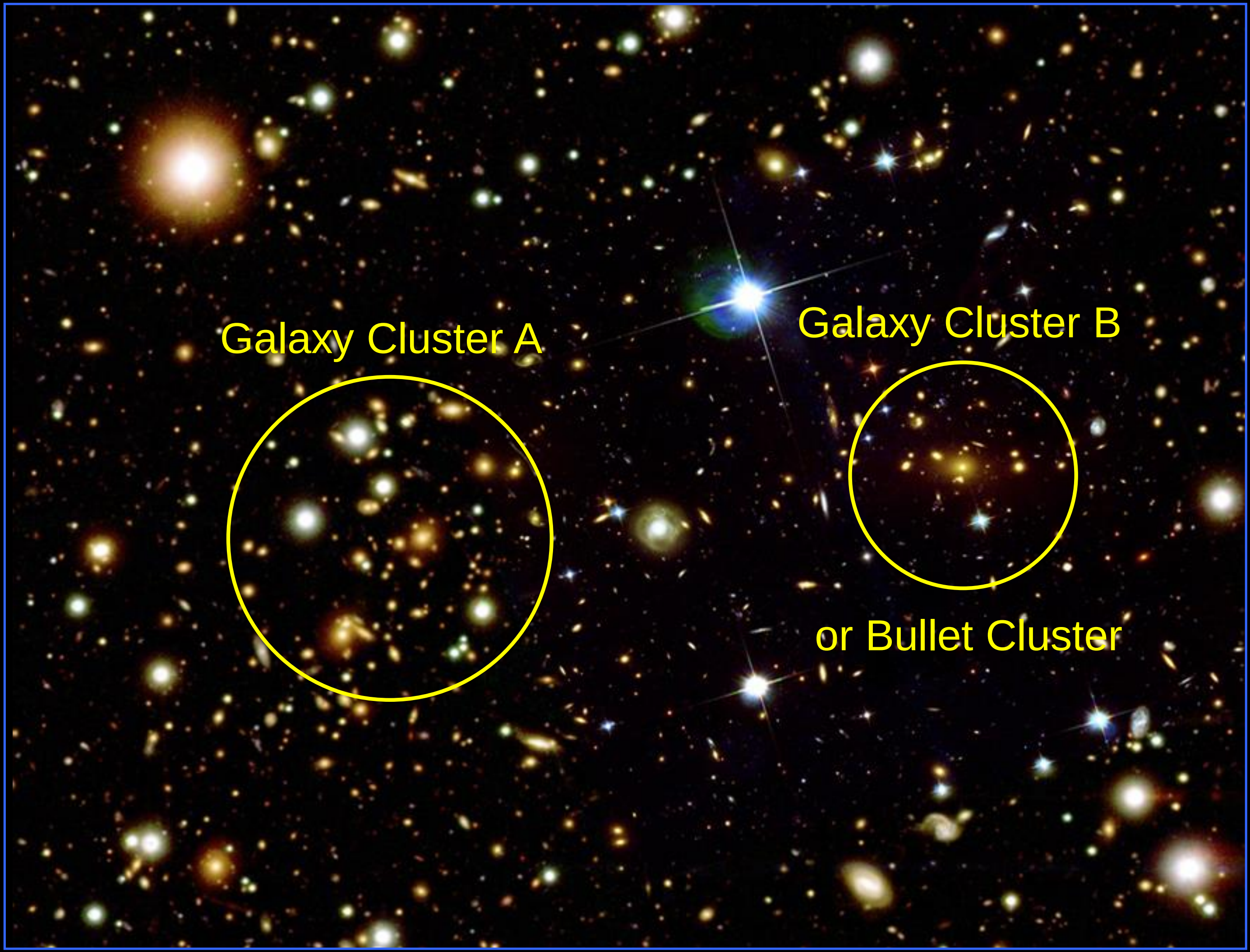
Bullet Cluster

Visible Light Image

Three types of matter are present above: (i) galaxies, visible as starlight, although individual stars too small to see, (ii) intergalactic gas and (iii) dark matter. Mass content, from smallest to largest, is in the same order. Second and third matter types not visible with optical telescope. Above and next three images from NASA

Bullet Cluster

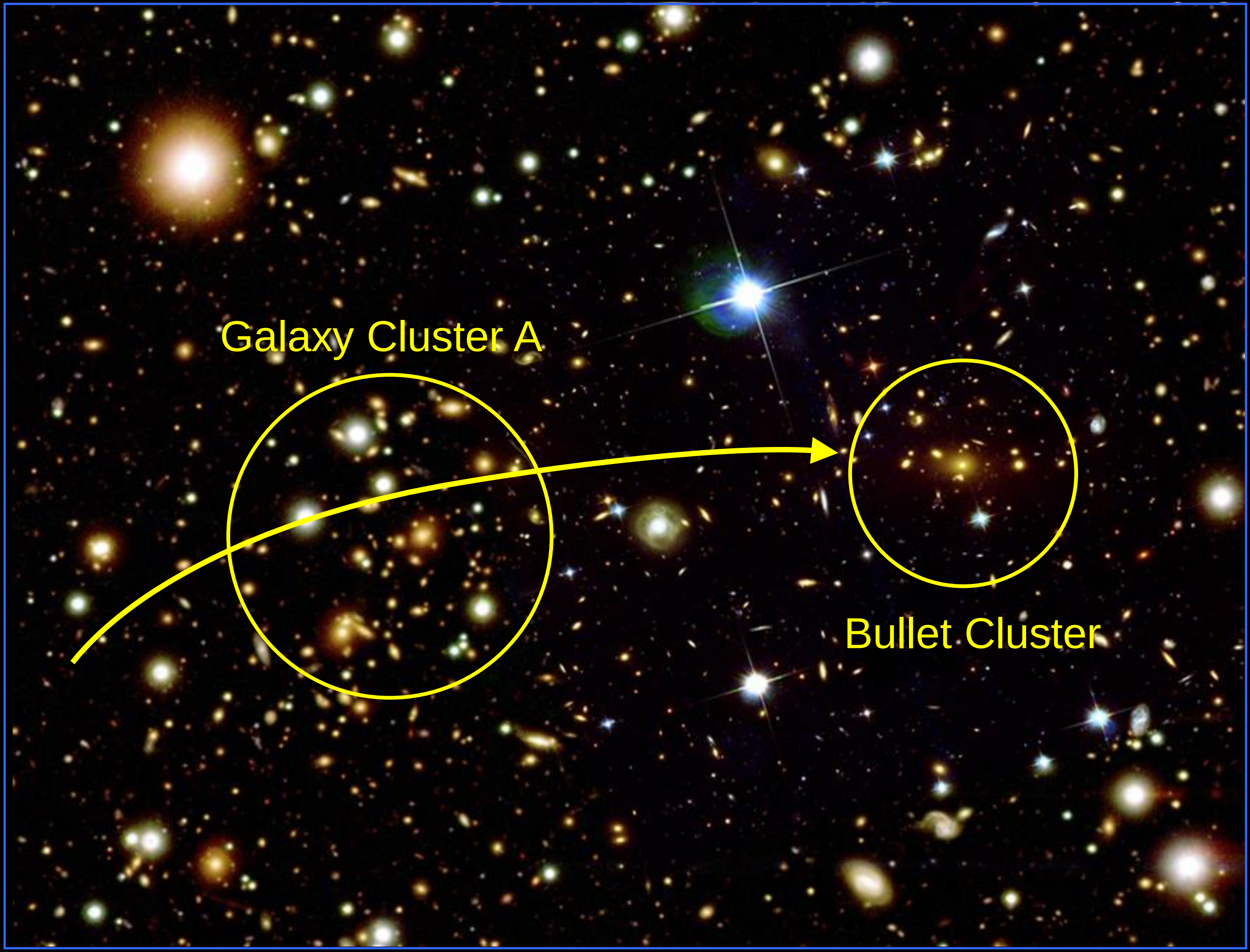
Visible Light Image



Of particular interest are the two circled galaxy clusters

Bullet Cluster

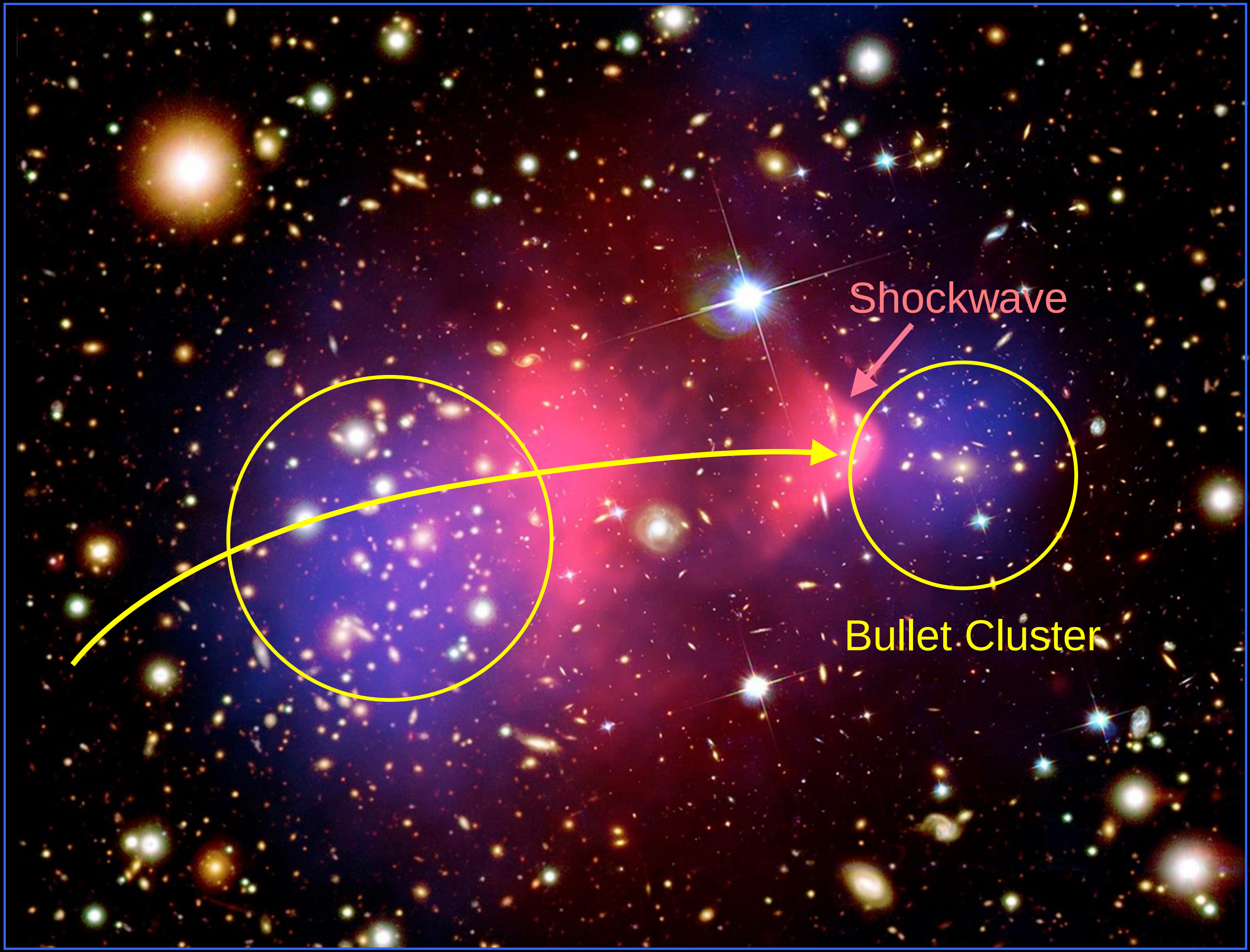
Visible Light Image



Bullet Cluster once passed through Galaxy Cluster A at 10 million mph to reach its present location (path estimate mine)

Bullet Cluster

Visible, X-ray and Gravity-Lensed Images



Dark matter (false blue) revealed by gravitational lensing analysis. Neither dark matter nor galaxy stars were much affected by the "collision." But intergalactic gas was. Portions heated to a hundred million degrees are revealed in X-ray image (false pink). Frictional momentum exchange dragged large cluster gas rightward and retarded motion of small cluster gas, thus separating intergalactic gas from other components

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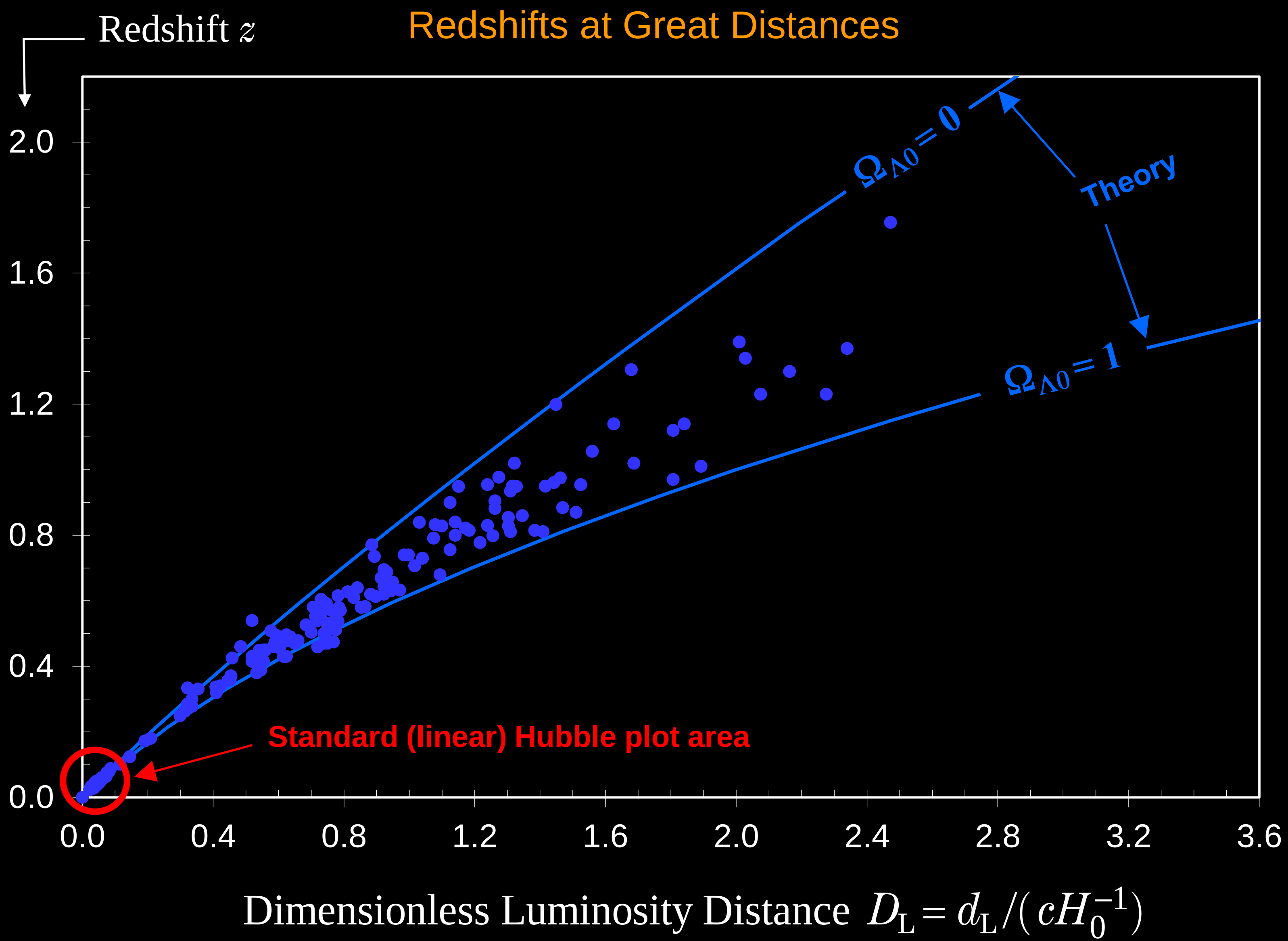
- Needed to account for shape of extended Hubble plot (EHP)
- Enables concordance of three major types of data within flat observable universe

Extended Hubble Plot

Redshifts at Great Distances



From Type Ia supernova data compiled by Riess et al, *Astrophysical Journal* 659:98Y121 (2007). $\Omega_{\Lambda 0}$ is the current dark energy fraction of the observable universe. Evidence of accelerated expansion discovered by Riess et al (1998) and Perlmutter et al (1999). Standard (linear) Hubble plot would fit in small red circle

Why Dark Energy?

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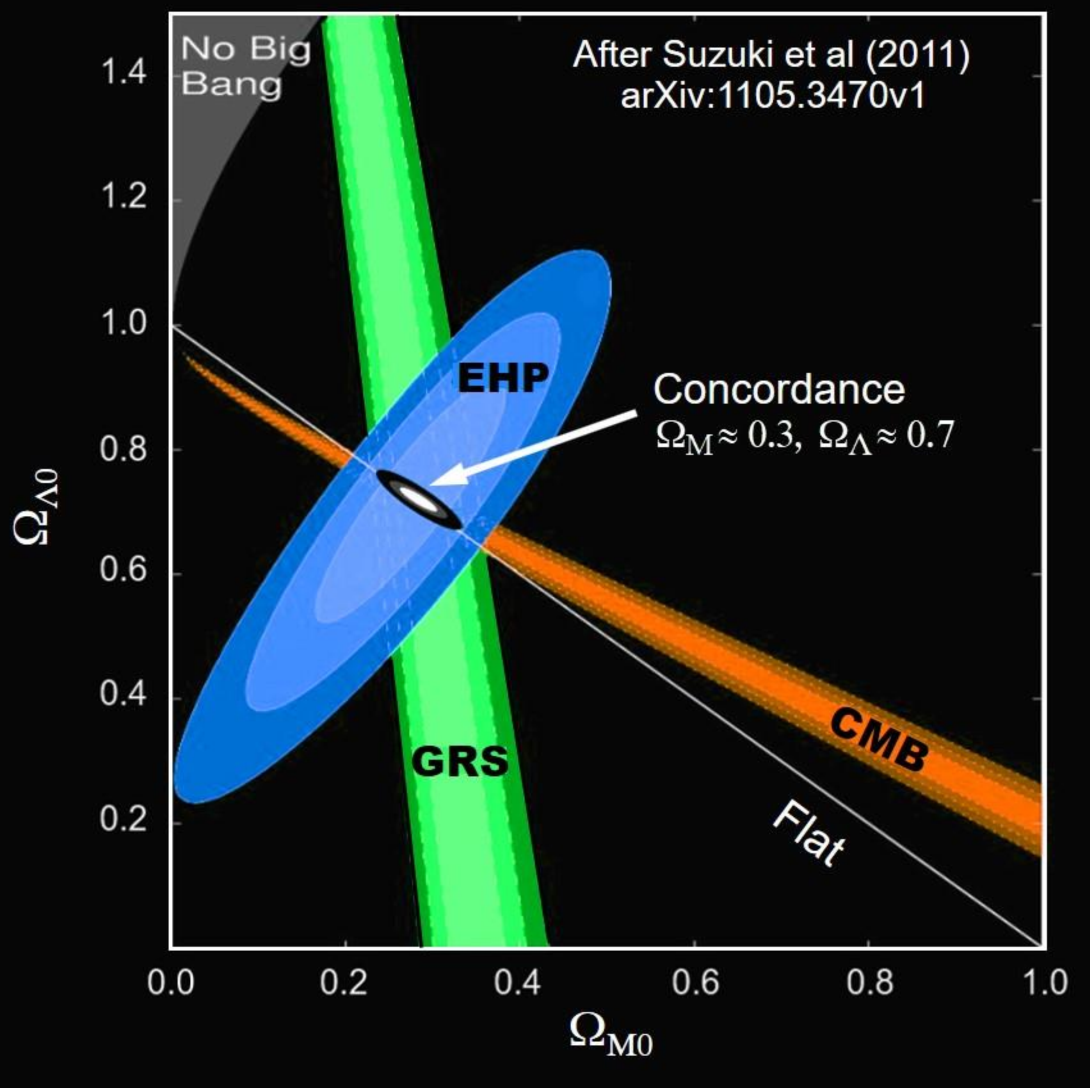
Extended Hubble Plot, Cosmic Microwave Background, Galaxy Redshift Survey

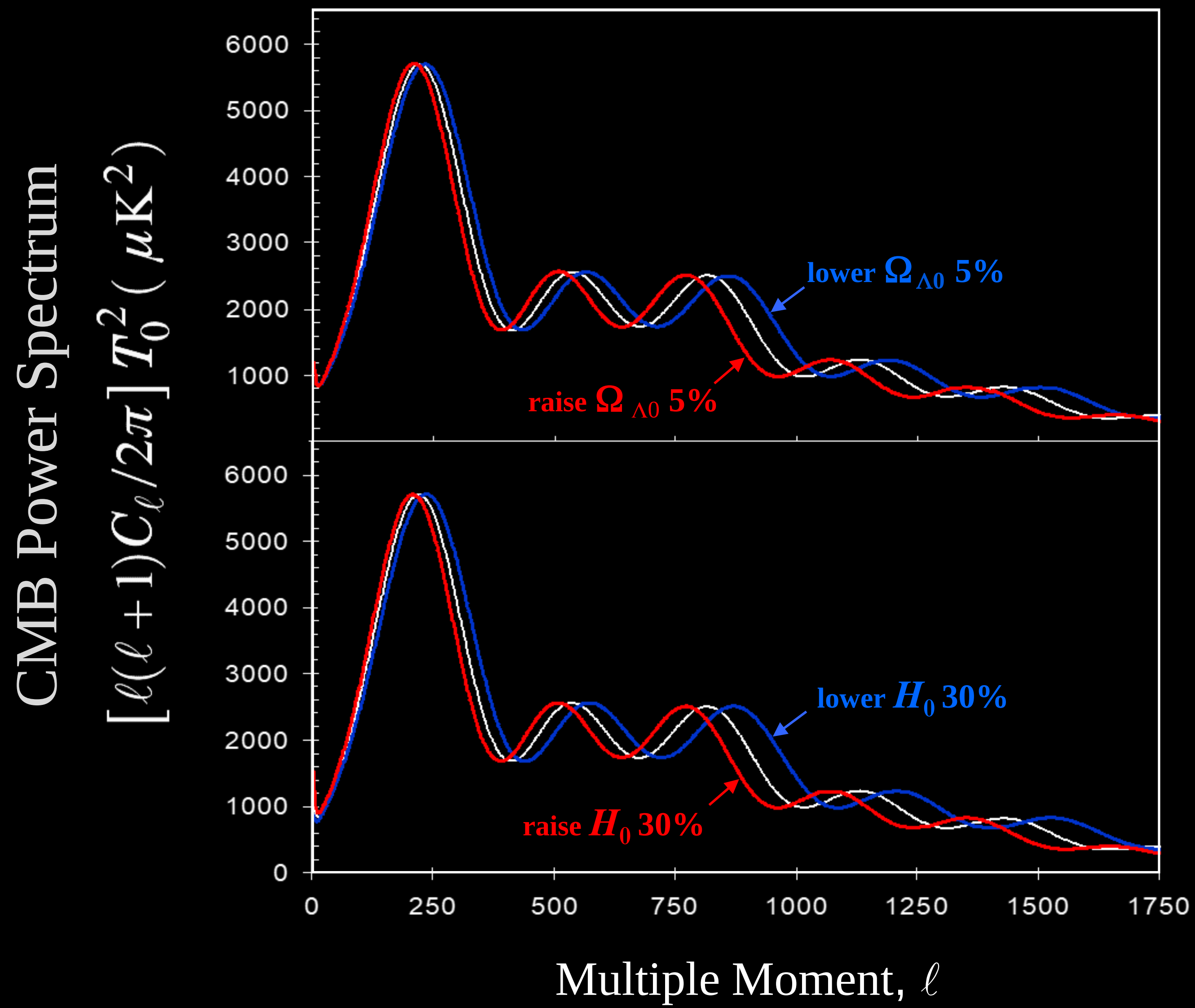
Cosmic Concordance



Probable dark energy and (mostly dark) matter fractions of observable universe indicated by analyses of (i) extended Hubble plot (EHP) from Ia SN, (ii) CMB angular power spectrum from CMB anisotropies, and (iii) matter power spectrum from galaxy redshift surveys (GRS). Flat universe strongly supported

Example of Why Multiple Data Types Needed

Dark Energy & Hubble Constant Degeneracy



Theoretical spectrums generated using CAMB, one of the computer programs used by NASA to analyze WMAP data. White curves best fit of WMAP data. Red and blue curves perturbations

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Precision Cosmology

- Precision cosmology began in earnest with the 1st release of WMAP CMB data (2003). It continued to evolve with additional WMAP data releases / analyses and then with those of the Planck Project
- CMB-based values of H_0 and $\Omega_{\Lambda 0}$ have drifted toward low ends of ranges obtained just prior to availability of CMB data
- In the case of H_0 the explanation is not that the prior (HST Key Project) range was in error on the high side. H_0 has been been remeasured using the HST and standard candles calibrated via parallax and found to have a most likely value slightly higher than that obtained by the Key Project
- Consensus regarding difference has yet to be established

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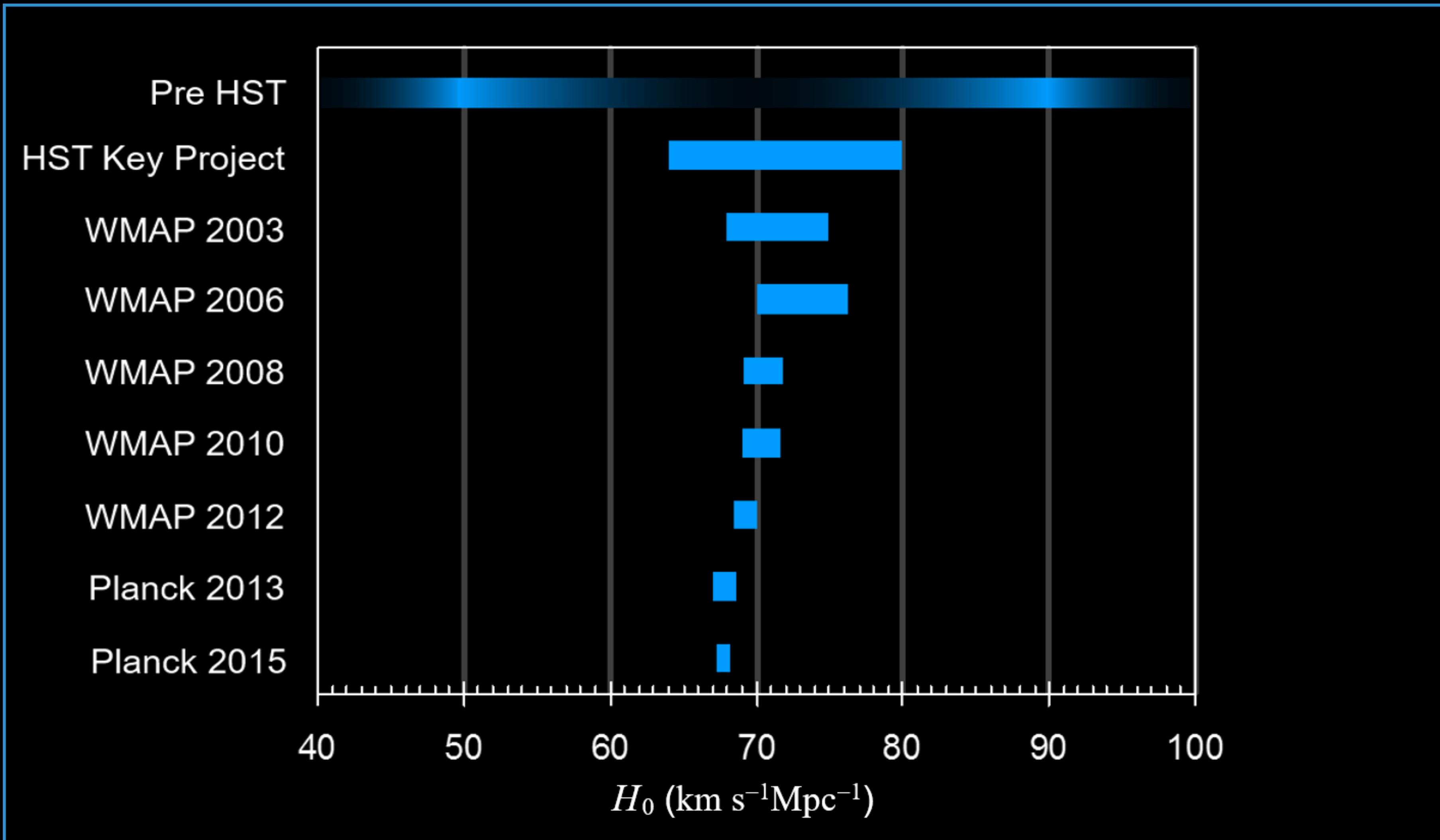
Precision Cosmology

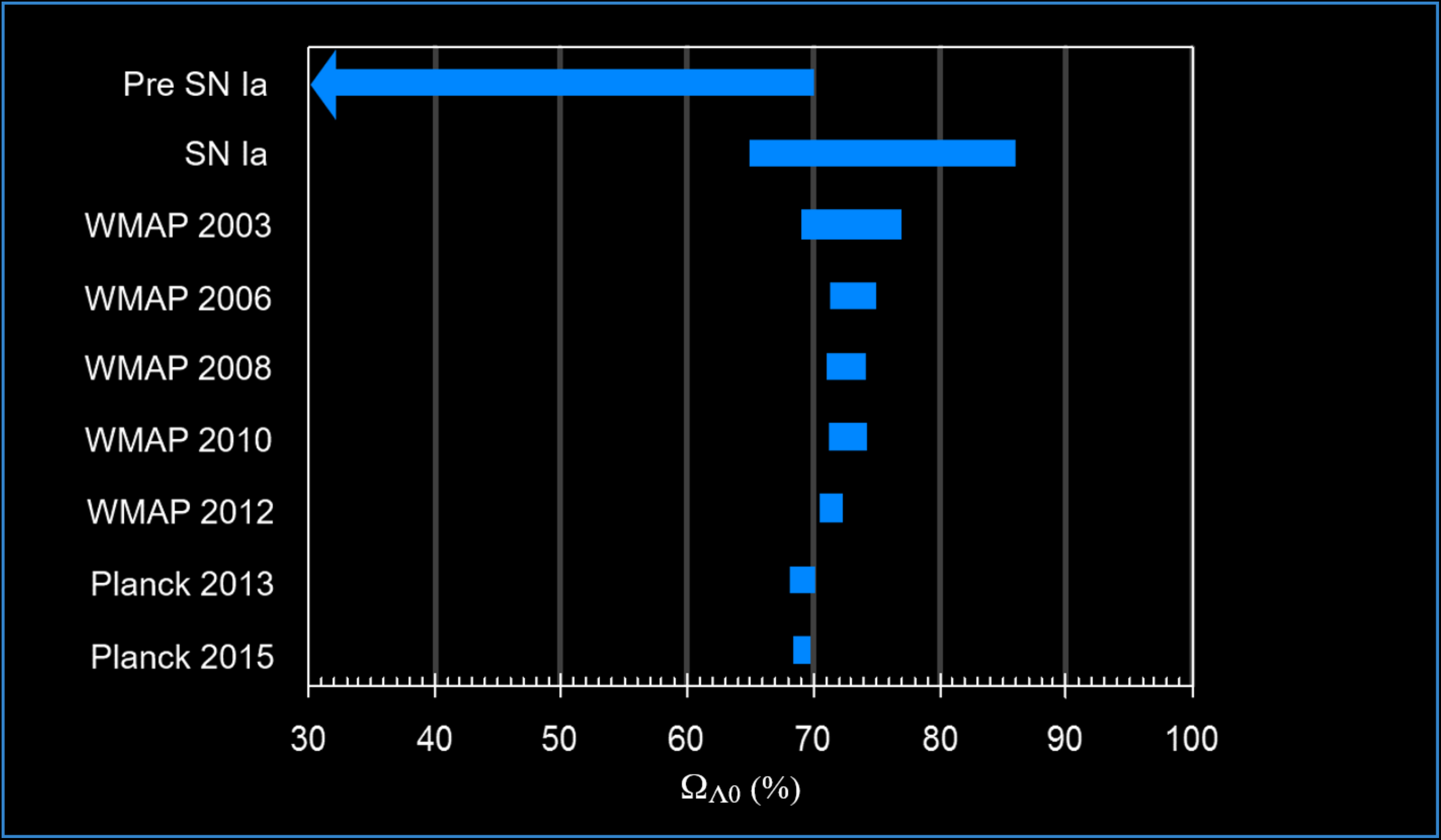
Homing In On Hubble Constant ?



Pre-HST (before Hubble Space Telescope) means the 1980s and most of the 1990s. During that time there were two prominent views on the value of H_0 : ≈ 50 and ≈ 90 km $s^{-1}Mpc^{-1}$. About the only thing researchers agreed on was that the correct value could not be in the middle. But that is essentially what the Key Project revealed (72±8 km $s^{-1}Mpc^{-1}$). Early WMAP values agreed, but then trended downward, as did Planck values

Precision Cosmology

Dialing In On Dark Energy ?



Arrow indicates $\Omega_{\Lambda 0}$ smaller than 70% or simply not considered. SN Ia refers to $\Omega_{\Lambda 0}$ estimates based on Type Ia supernova data such as gathered by Riess et al (1998) and Perlmutter et al (1999). As with Hubble constant, values of $\Omega_{\Lambda 0}$ have trended downward with more recent CMB data analyses (WMAP and Planck)

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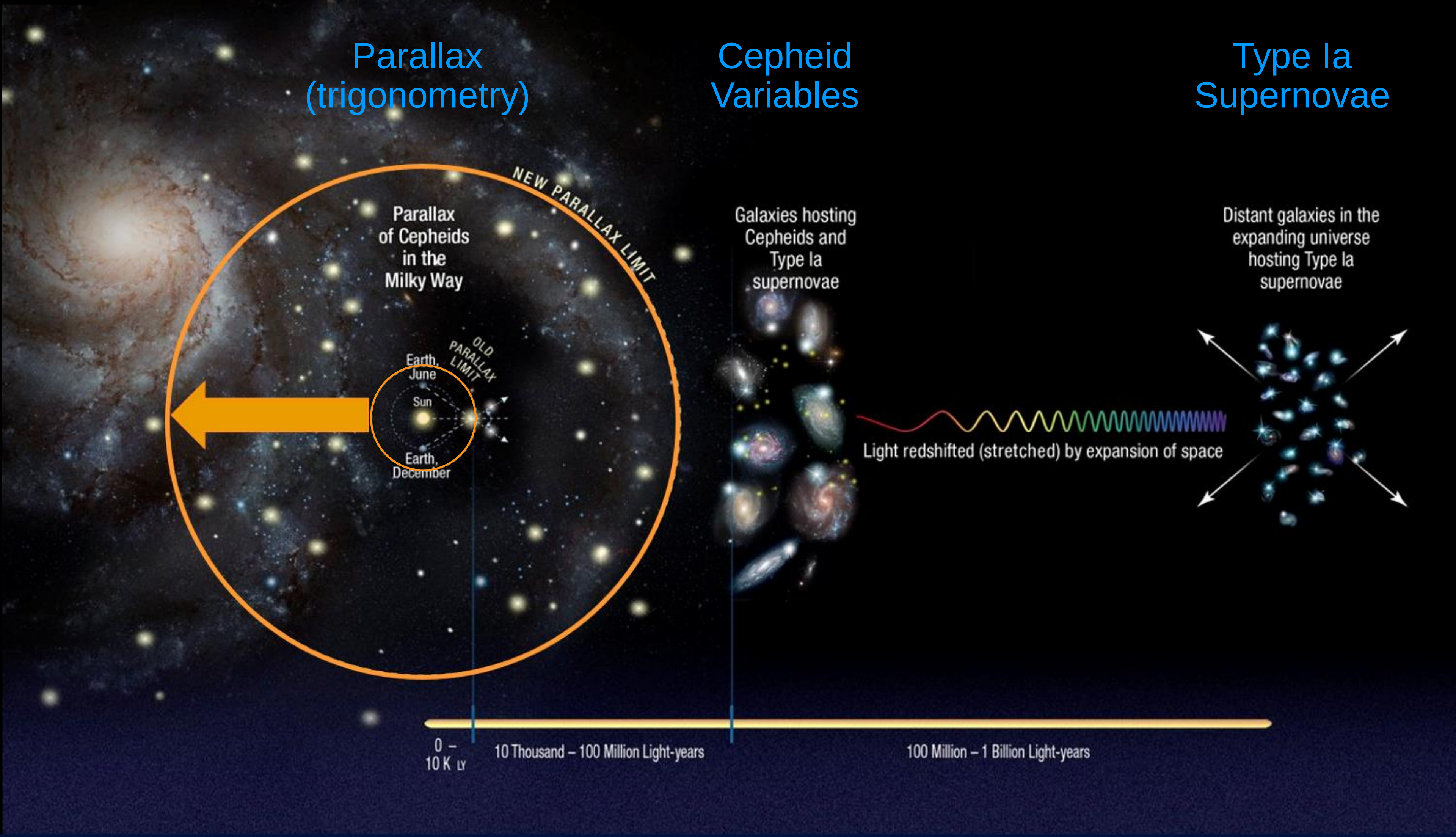
*Using the ESA Gaia satellite

Astronomical Distance Measurements

Three Key Components of Cosmic Distance Ladder



ESA Gaia space observatory dramatically increases distances based on parallax ("new parallax limit" above).
From Wikipedia "Cosmic Distance Ladder" article

Hubble Constant from HST & Gaia

$$H_0 = 73.24 \pm 1.7 \text{ km s}^{-1}\text{Mpc}^{-1}$$

Value larger & more tightly constrained than the 72±8 km $s^{-1}Mpc^{-1}$ from HST Key Project, but farther from latest CMB-based values

Blue value from Riess et al, *The Astrophysical Journal*, 861:126 (13pp), 2018 July 10.

Precision Cosmology

- Precision cosmology began in earnest with the 1st release of WMAP CMB data (2003). It continued to evolve with additional WMAP data releases / analyses and then with those of the Planck Project
- CMB-based values of H_0 and $\Omega_{\Lambda 0}$ have drifted toward low ends of ranges obtained just prior to availability of CMB data
- In the case of H_0 the explanation is not that the prior (HST Key Project) range was in error on the high side. H_0 has been been remeasured using the HST and standard candles calibrated via parallax* and found to have a most likely value slightly higher than that obtained by the Key Project
- Consensus regarding difference has yet to be established

For some discussion see (i) "The Universe's Fate Rests on the Hubble Constant – Which Has So Far Eluded Astronomers" Jim Daley, *Scientific American*, Jan 20, 2019 and (ii) "Surprise! The Hubble Constant Changes Over Time" Eric Siegel, *Forbes*, June 29 2018

Other Loose Ends

- **Theory-of-everything phase transition**
  Separation of gravity & grand unified force
- **Grand-unified theory phase transition**
  Separation of strong nuclear & weak nuclear forces
- **Cosmic inflation**
  Did it actually happen? If so, how and when?
- **Baryogenesis**
  Slight imbalance of matter and antimatter such that only matter survived annihilation
- **Nature of dark matter**
- **Nature of dark energy**

The End