Cosmology

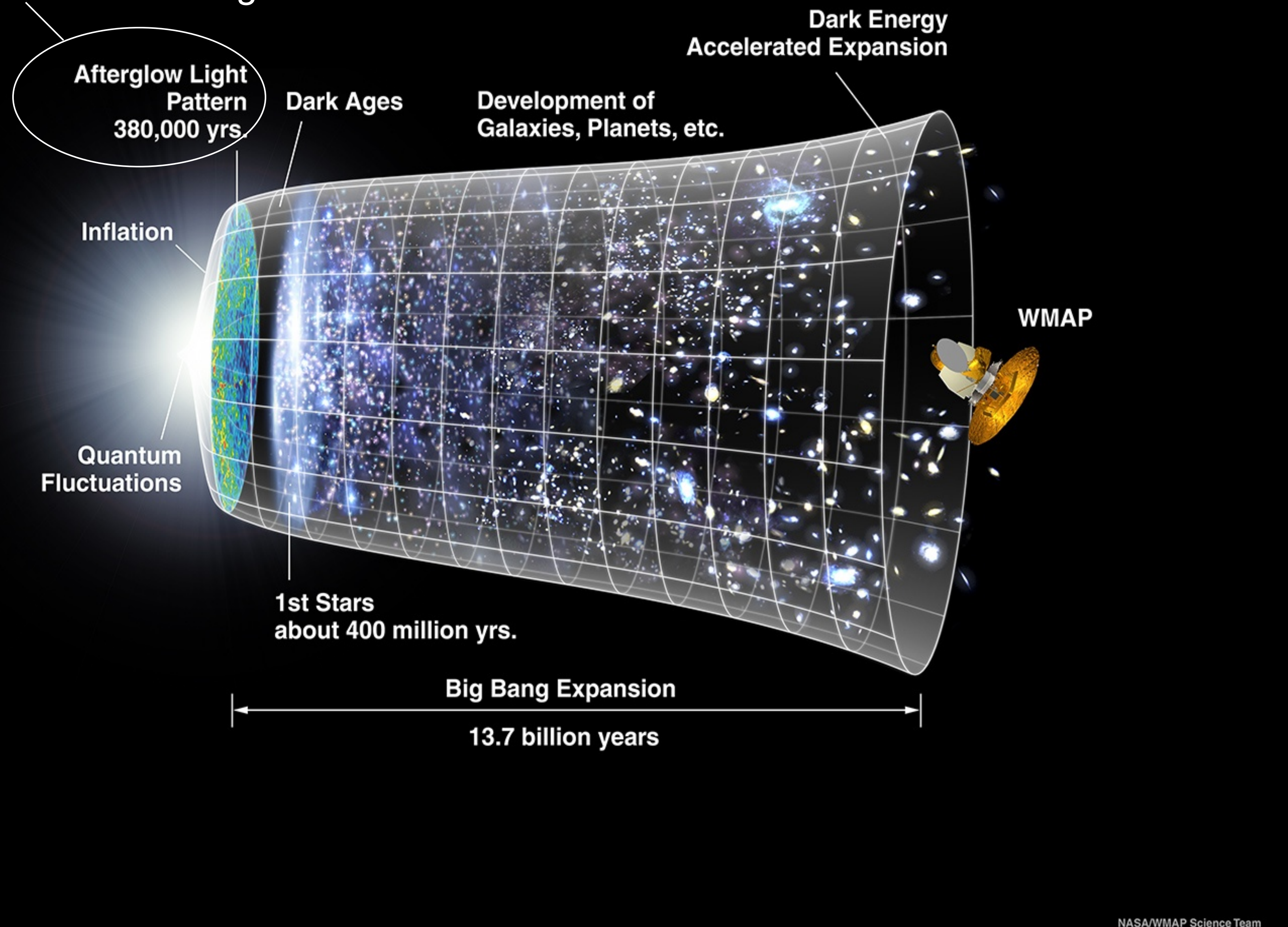
and the

Particle Physics Connection

Richard Talaga

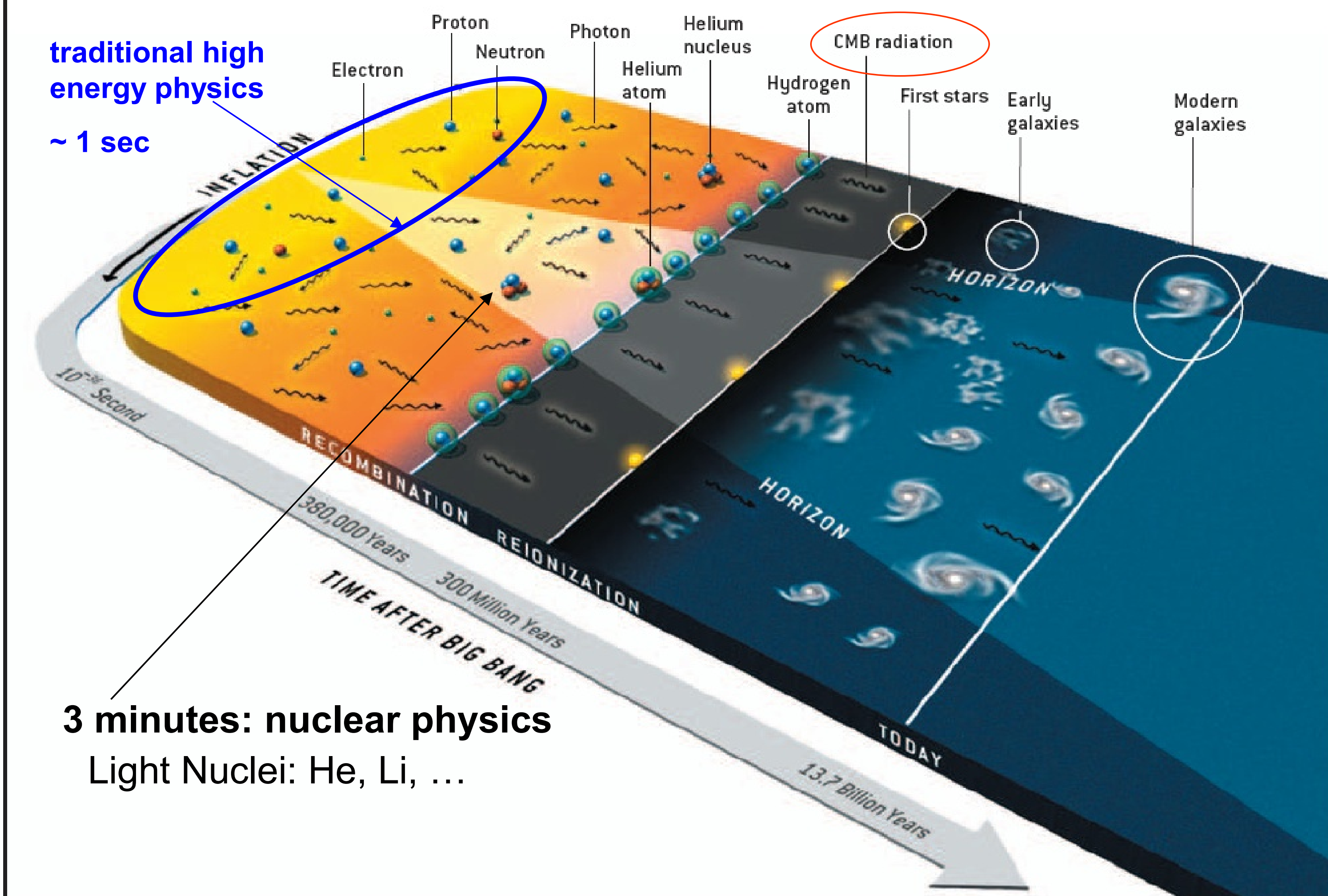
Argonne National Laboratory

Cosmic Microwave Background



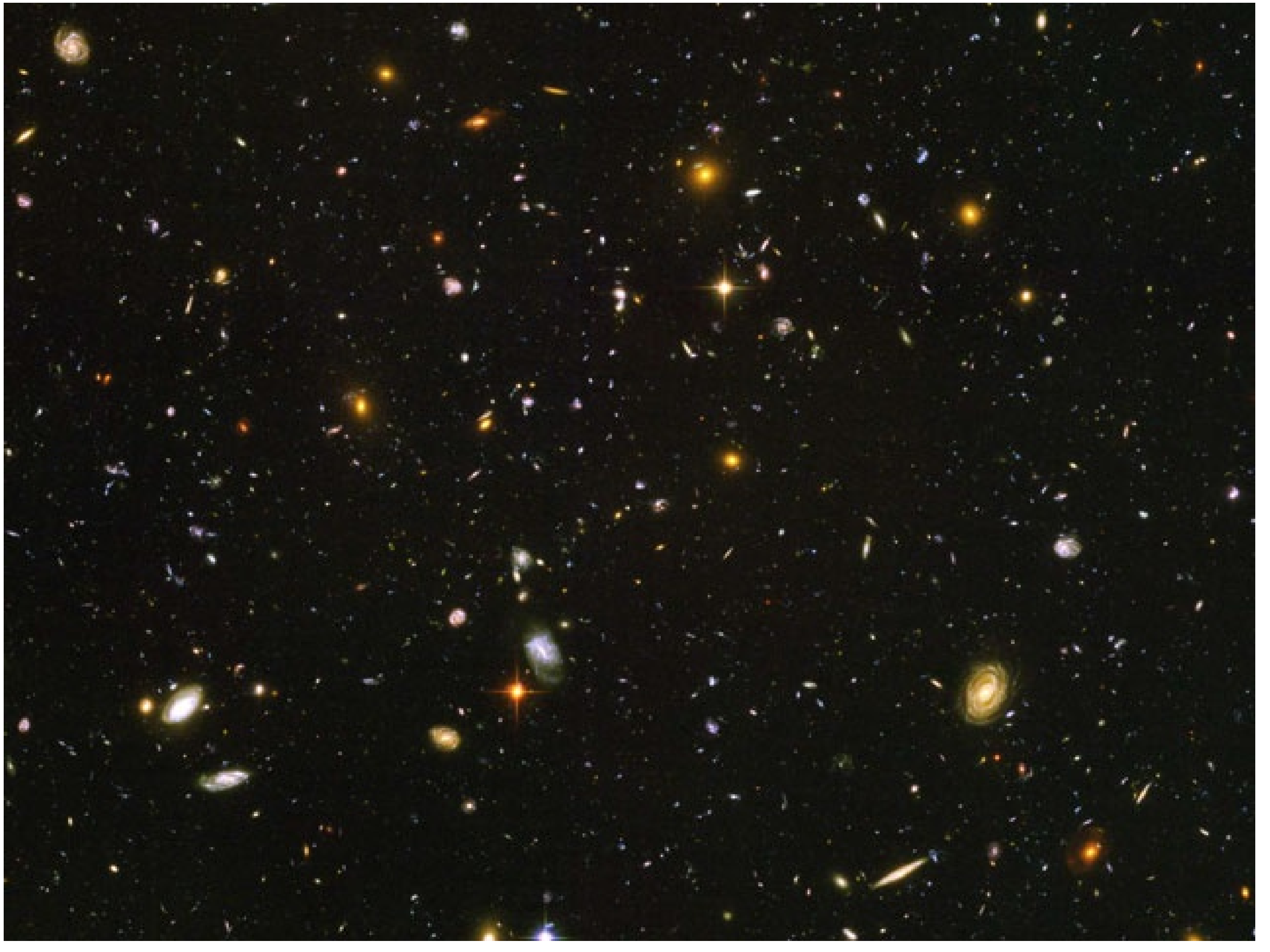
TIMELINE OF THE UNIVERSE

AS INFLATION EXPANDED the universe, the plasma of photons and charged particles grew far beyond the horizon (the edge of the region that a hypothetical viewer after inflation would see as the universe expands). During the recombination period about 380,000 years later, the first atoms formed and the cosmic microwave background (CMB) radiation was emitted. After another 300 million years, radiation from the first stars reionized most of the hydrogen and helium.



Scientific American Feb 2004 pp 44-53

First Galaxies 13 Billion Years Ago



Hubble Ultra Deep Field: 3-month long exposure!

Cosmology & Particle Physics

- **Cosmology: Huge Distances, size of the Universe**
  - The discipline of Physical Cosmology began in the early 20th century
  - Attempts to explain the evolution of the Universe and the large-scale structures such as galaxy clusters from (almost) the very beginning ~13.8 Billion years ago
  - Investigation of the Cosmic Microwave background has provided a tremendous amount of information on the Early Universe
    - Satellite and earth-based microwave bolometers
- **Particle Physics: Tiny distances, of sub-atomic proportions**
  - Also called **High Energy Physics** or **Elementary Particle Physics**
  - Began ~1947-1950 with discoveries of the pion in cosmic rays and the delta "resonance" at the University of Chicago
  - Attempts to find the fundamental building blocks of nature and their interactions
    - So far, we have
      - Building blocks: Quarks, electrons, neutrinos
      - Interactions: Strong (QCD) and electroweak (weak nuclear and electromagnetic unified into one theory ~1967-1970's)
      - Note that gravity is not included
  - Ongoing searches for "Supersymmetric" particles (perhaps source of Dark Matter) and signs of Grand Unified Interactions (all forces have the same strength at extremely high energies). Also searching for the Higgs particle, which has a tie-in to cosmological "inflation".

The Connection, page 1

Up to about **1 second** after the Big Bang

- The enormous temperature at that time provided energy for particle creation
  - $E \sim k_B T$ **Energy is directly proportional to temperature**
    - Example: An ideal gas molecule has K.E. = $3/2 k_B T$
  - $E = mc^2$ Mass has an equivalent energy
    - Example: Two gamma rays (no mass) with 1.02 MeV energy collide to produce one electron and one positron; each has a mass of 0.51 MeV
- Particle physicists have built accelerators to replicate the impact energies in the very early Universe
  - Investigate what kinds of particles were present at that time and how they interacted with each other

The Connection, page 2

- Particle Physics seeks an understanding of all the "elementary" particles and fundamental forces in nature

- It turns out that the particles we have studied so far comprise about **5%** of all the mass (or energy) in the Universe!
  - This fact has been creeping up on us for the past ~ 30 years
    - Dark Matter (~1970s) now ~23% of the mass energy
    - Dark Energy (1998) now ~72% of the mass energy

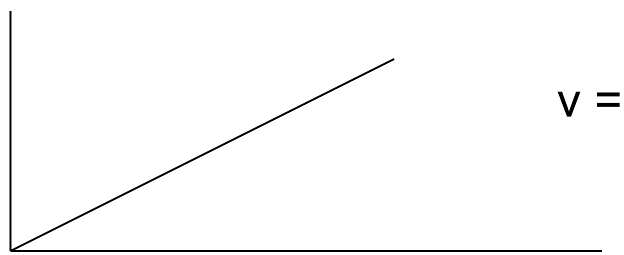
- A number of Particle Physicists are engaged in the investigation of dark matter with accelerators and also in space; we are also beginning to investigate dark energy.

Chronology of Major Events in Modern Cosmology

- 1917 Einstein published "Cosmological Considerations of the General Theory of Relativity"
  - Equations show that space-time is curved by matter (or energy)
  - 1922 Alexander Friedmann uses General Relativity to show that the Universe might be expanding
    - Einstein believed the Universe was static, so he added constant to keep his equations from disagreeing with his belief: the **Cosmological Constant** **(he later called this his greatest blunder)**

- 1920 National Academy of Sciences Debate: are Spiral Nebulae Outside the Milky Way?
  - Harlow Shapley (within Milky Way) vs. Heber Curtis (outside, other galaxies)
  - 1923-24 Edwin Hubble resolves the debate by observing Cepheids* in Andromeda
    - Distance was well beyond the stars of the Milky Way

- 1929 Hubble discovered that distant galaxies move away faster
  - Hubble's law: recession speed of a galaxy is proportional to its distance

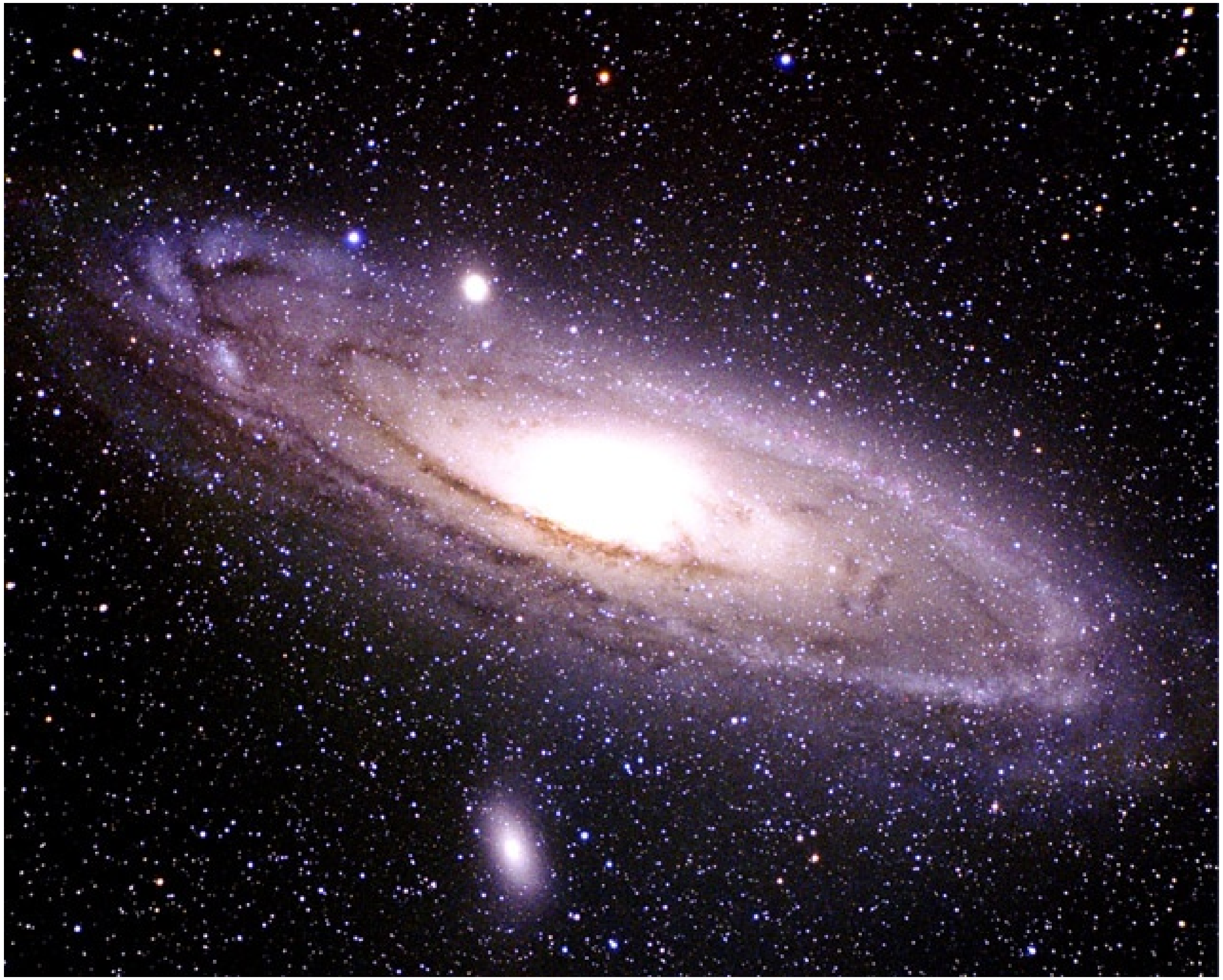


$v = H_0 d$ $H_0 =\sim 70$ (km/s)/Mpc

Mpc = 3.3 Million Light Years

* Cepheid: variable star whose absolute brightness is proportional to period of variation

Andromeda Galaxy



2.5 Million Light Years Away

About 2.5º Wide (5 x Moon)

Visible to the un-aided eye

Chronology, continued

- **1948** Fred Hoyle, Thomas Gold and Hermann Bondi proposed the **Steady State Theory** of the Universe
  - Although the Universe is expanding, it does not change its look over time
    - New matter is created continuously, perceptible on the large scale of the Universe but not on small scales
- **1948** George Gamow and Ralph Alpher wrote "The Origin of Chemical Elements" showing how the levels of H and He in the Universe could be explained by reactions in the **Big Bang Theory**
  - Also predicted a *cosmic microwave background* (with R. Herman)
    - Not too many people were paying attention at that time
- **1963-5** Arno Penzias and Robert Wilson detect cosmic microwave background

Receiver was built to detect radio signals bounced off **balloons** for communications.

Satellite communication began in the early '60s and the receiver became available for astronomical research.

Big Bang Wins

- Wilson and Penzias didn't understand the nature of their detection, at first
  - Noise from terrestrial sources
    - New York City (they were in New Jersey)
    - Pigeon droppings in the antenna (no change after cleanup)
    - Eliminated all possible sources of noise and **PUBLISHED**!

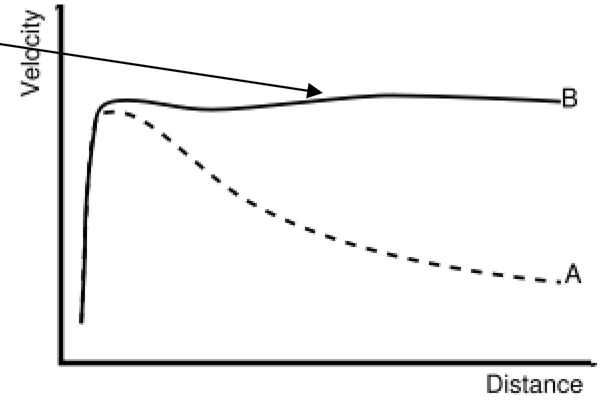
"They had been using an ultra-sensitive microwave receiving system to study radio emissions from the Milky Way when they found an unexpected background of radio noise with no obvious explanation. It came from all directions and, after repeated checks, it appeared to emanate from outside the Galaxy.

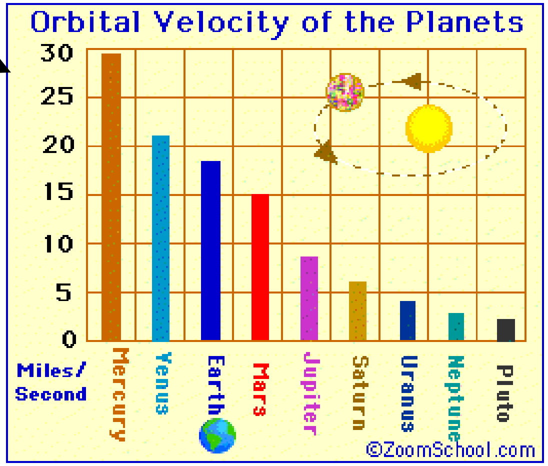
Penzias and Wilson consulted with Princeton physicist Robert H. Dicke, who had theorized that if the universe was created according to the Big Bang theory, a background radiation at 3-degree Kelvin would exist throughout the universe. Dicke visited Bell Labs and confirmed that the mysterious radio signal Penzias and Wilson detected was, indeed, the cosmic radiation that had survived from the very early days of the universe. It was proof of the Big Bang."

Excerpted from Bell Labs web site

Chronology

- **1975** Vera Rubin discovered that stars orbit around galaxies at speeds that are independent of distance from the galactic center
  - Using Newton's Laws and an appropriate star (mass) distribution function, one expects stellar velocities to decrease with distance from the galactic center
  - Simple example: solar system



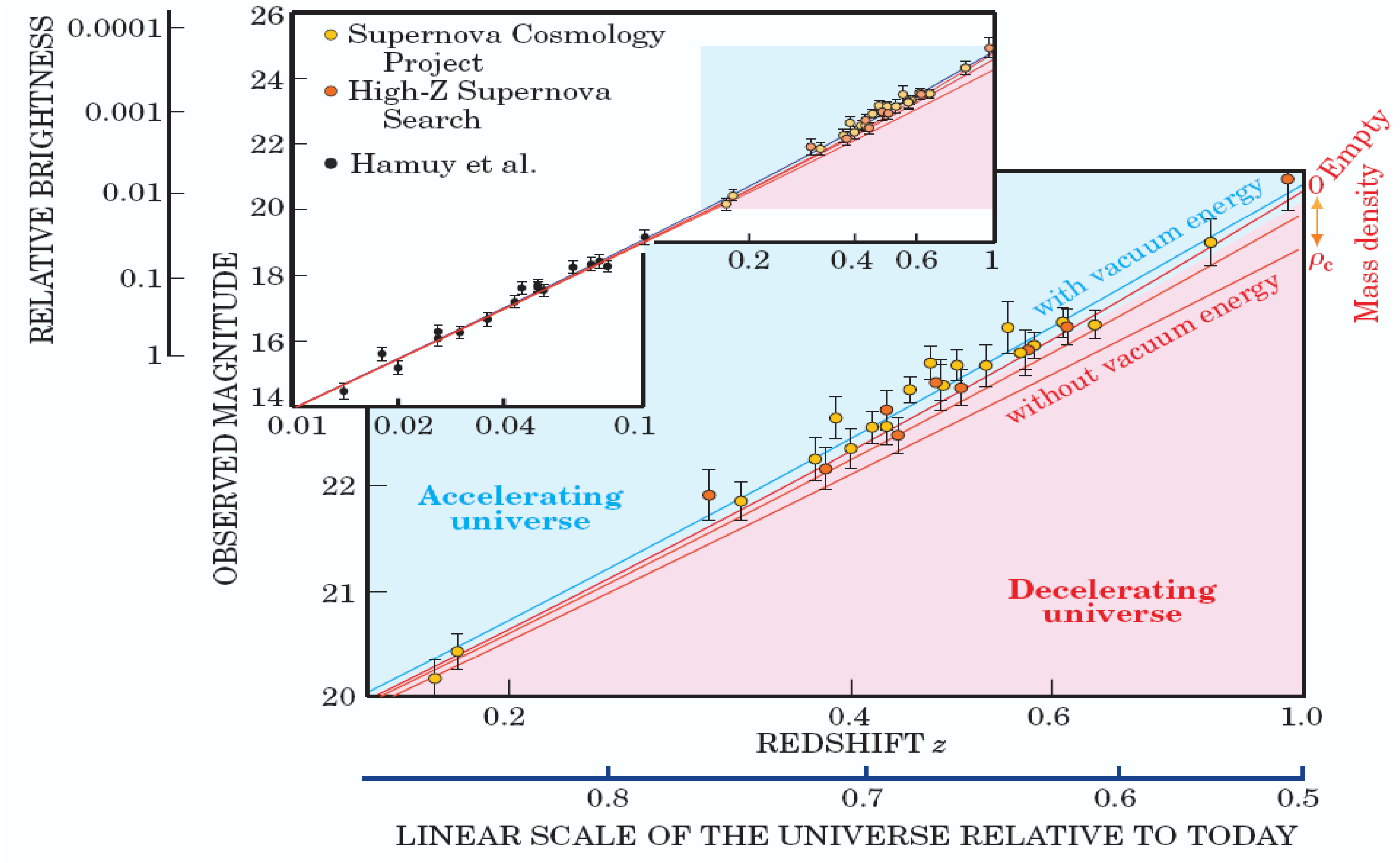


- Dark matter is non-baryonic: not protons, neutrons or electrons. It's interactions are very weak! On large scales, it is thought to interact gravitationally.
- We don't know what it is!!!! But we have some ideas and are looking for it in the lab (and in the galaxy).

Chronology

- 1998 *Supernova Cosmology Project* and *High-z Supernova Search Team* find evidence that the expansion of the Universe is accelerating!
  - After an explosion, you expect expansion. But the expansion should slow down- decelerate- due to attraction of the mass and energy in the Universe.
- **First evidence for acceleration of expansion of the Universe**
  - Type 1a supernovae have a well-known absolute brightness
    - Redshift determines recession velocity
    - Hubble's law determines distance
    - Divide absolute brightness by $(\text{distance})^2$ to predict the observed brightness
  - But observed brightness is **fainter** than predicted

Evidence for Dark Energy



Source: Physics Today April 2003 pp 53 - 60

Gravitational Redshift and Distance/Time

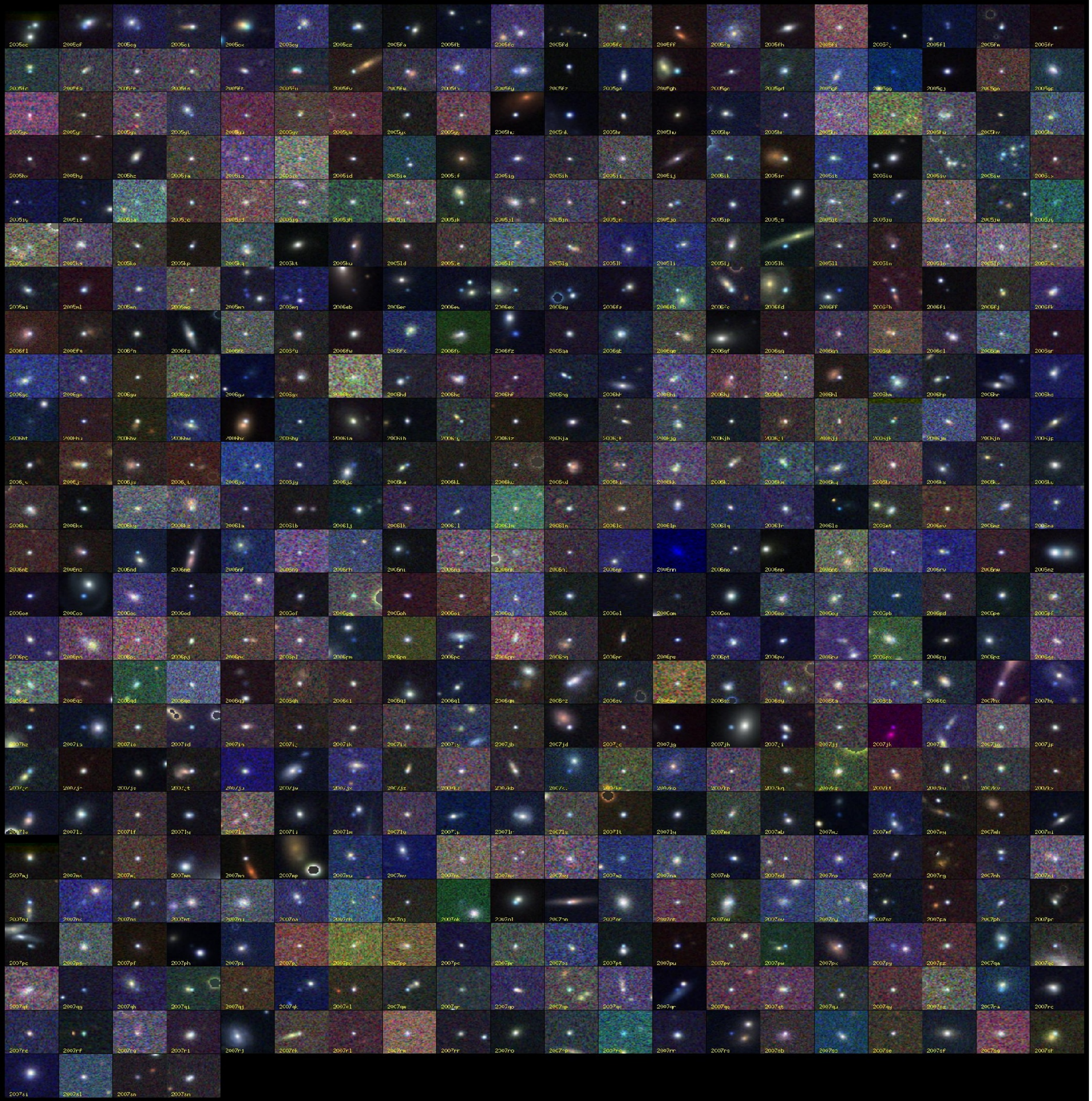
- Not the same as Doppler Shift
  - Doppler shift is caused by motion through space

- Gravitational Redshift is caused by expansion of space

  Redshift parameter $z = (\lambda - \lambda_0)/ \lambda_0$

- Relating z to distance or age since the BB *depends on cosmology*: H_0, Dark energy, dark matter and the curvature of the Universe
  - Try Ned Wright's Cosmic Calculator at
    - http://www.astro.ucla.edu/~wright/CosmoCalc.html
- Examples with $H_0 = 72$ $\Omega_m = 0.28$ and a Flat Universe

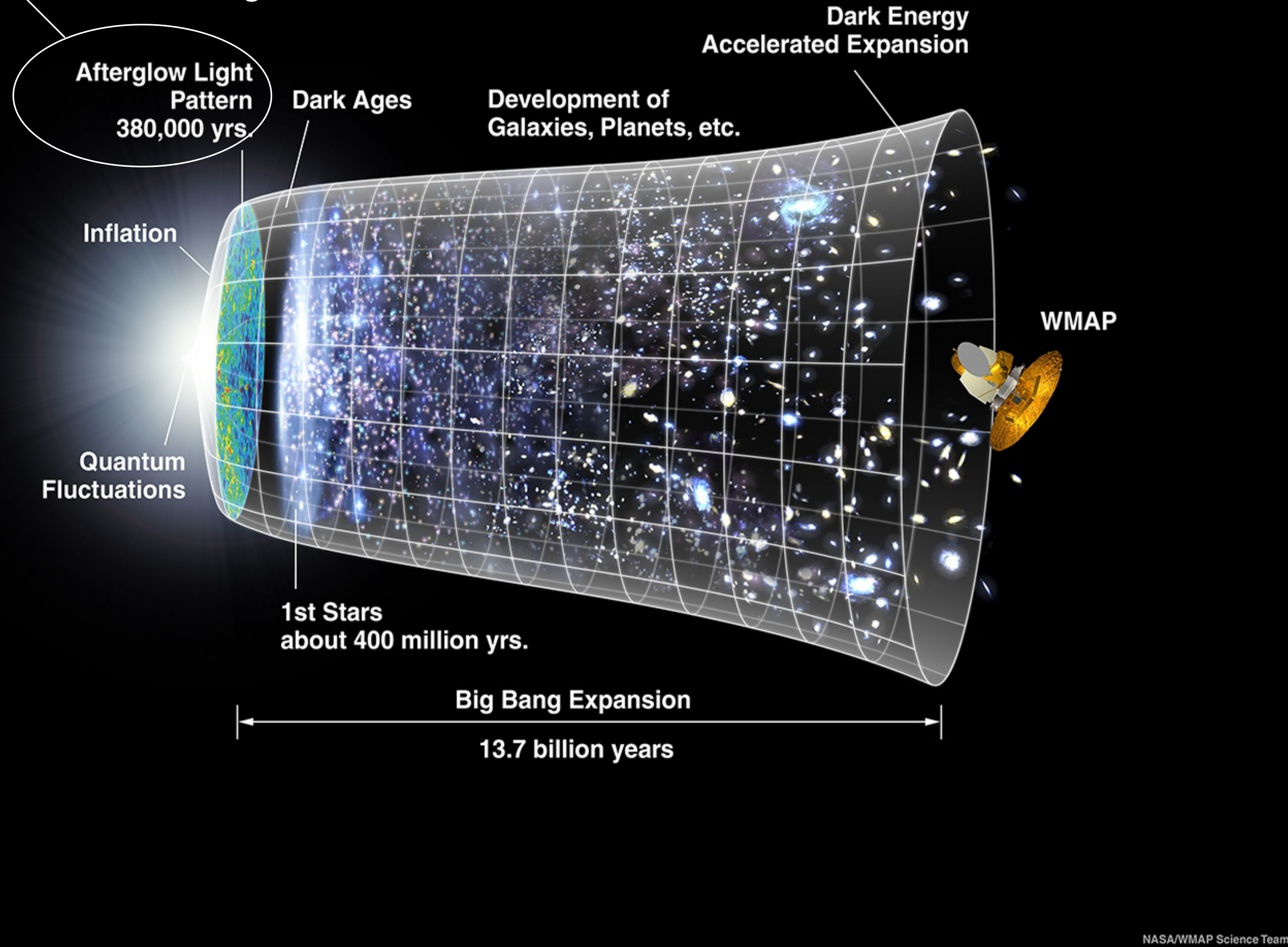
Z	Age, Millions of years since BB
0	13,722 (now)
0.1	12,420
1.0	5,920
2.0	3,330
5.0	1,190
10.0	480 (first stars)
1000	0.435
1080	0.382 (Recombination)



Galaxies and Supernovae seen by the Sloan Digital Sky Survey

Inflation and the Cosmic Microwave Background

Cosmic Microwave Background



Events Right After the Big Bang

- t = 0 Big Bang

- **t = 10^{-39} s** Temp = 10^{29} K
  - 10^{16} GeV per particle
    - Note: Highest energy cosmic rays today have energy ~ 10^{11} GeV
  - Strong and Electroweak Interactions are unified: they have the same strength (this is still a hypothesis)

- **t = 10^{-37} s** Observed universe has come to thermal equilibrium
  - The Universe we observe now was very small back then, all regions were in thermal contact

- **t = 10^{-37} to 10^{-35} s Inflation (this is still a theory that's being tested)**
  - Radius of Universe goes from ~ **10^{-50} m ➔ 1 m**
    - **That's like expanding the size of a proton to 10^{35} meters or 10 Million Billion Light Years**
  - **The observable Universe after inflation is in exquisite thermal equilibrium (inflation theory helps explain CMB observations)**
  - Small fluctuations in the inflation process produce **density variations** in the otherwise uniform Universe

Events up to "Recombination"

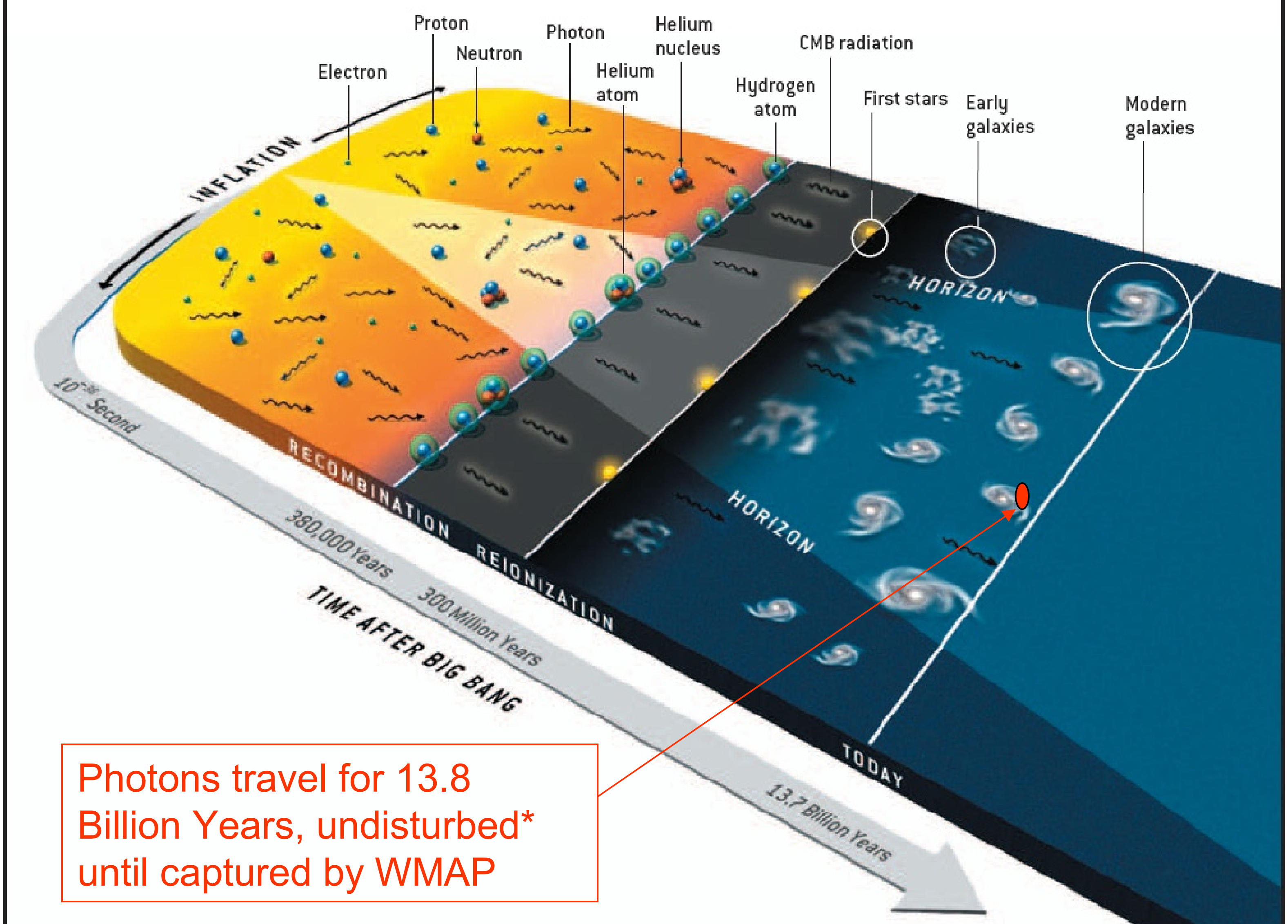
A dense and hot plasma occupies the Universe

- Photons scatter off charged particles
  - analogous to a gas: compression and rarefaction
- as space-time expands, the plasma is cooled

- $t = 5 \times 10^{-15}$ s $T = 8 \times 10^{16}$ K
  - Energy scale that will be reached at the Large Hadron Collider (LHC) note: 1 GeV = 10^{13} K
- t = 1 s T = 10 Billion K
  - Mass density = **500,000** Pressure 10^{21} atmospheres
  - Conditions are like those in the core of a Super Nova explosion
    - The hottest and most dense conditions in the Universe nowadays, since the Big bang
- t = 3.5 minutes Deuterium is formed, then Helium: "Big Bang Nucleosynthesis"
- t = 7 days T = 17 Million K (1 million K hotter than solar core)
  - Mass density 10^{-6} pressure 10^{9} Atmospheres (air density ~ 10^{-3} for comparison)
- t = 1 year T = 2 Million K (~ temp in solar corona)
  - Mass density < 10^{-9} p ~ 10^{6} Atmospheres
- t = 100,000 years
  - Mass density = 10^{-19} T = 5,800 K
- t = 380,000 years T = 3,000 K
  - Not enough energy to keep hydrogen ionized! ➔ Recombination to neutral hydrogen
  - **The Universe, for the first time, is transparent and photons travel without any further collisions**

TIMELINE OF THE UNIVERSE

AS INFLATION EXPANDED the universe, the plasma of photons and charged particles grew far beyond the horizon (the edge of the region that a hypothetical viewer after inflation would see as the universe expands). During the recombination period about 380,000 years later, the first atoms formed and the cosmic microwave background (CMB) radiation was emitted. After another 300 million years, radiation from the first stars reionized most of the hydrogen and helium.



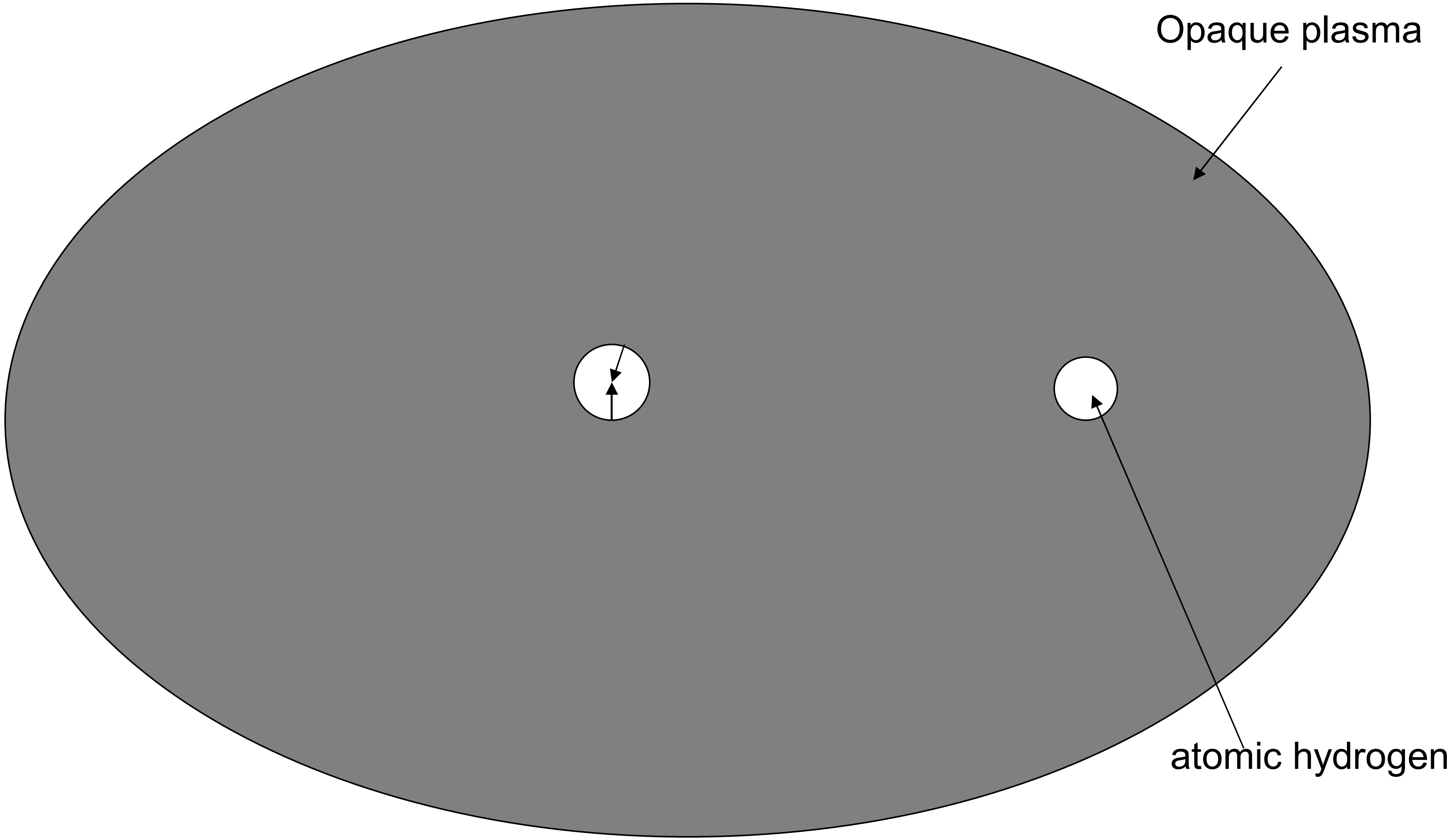
Scientific American Feb 2004 pp 44-53

* **Photons lose energy due to expanding Universe.**

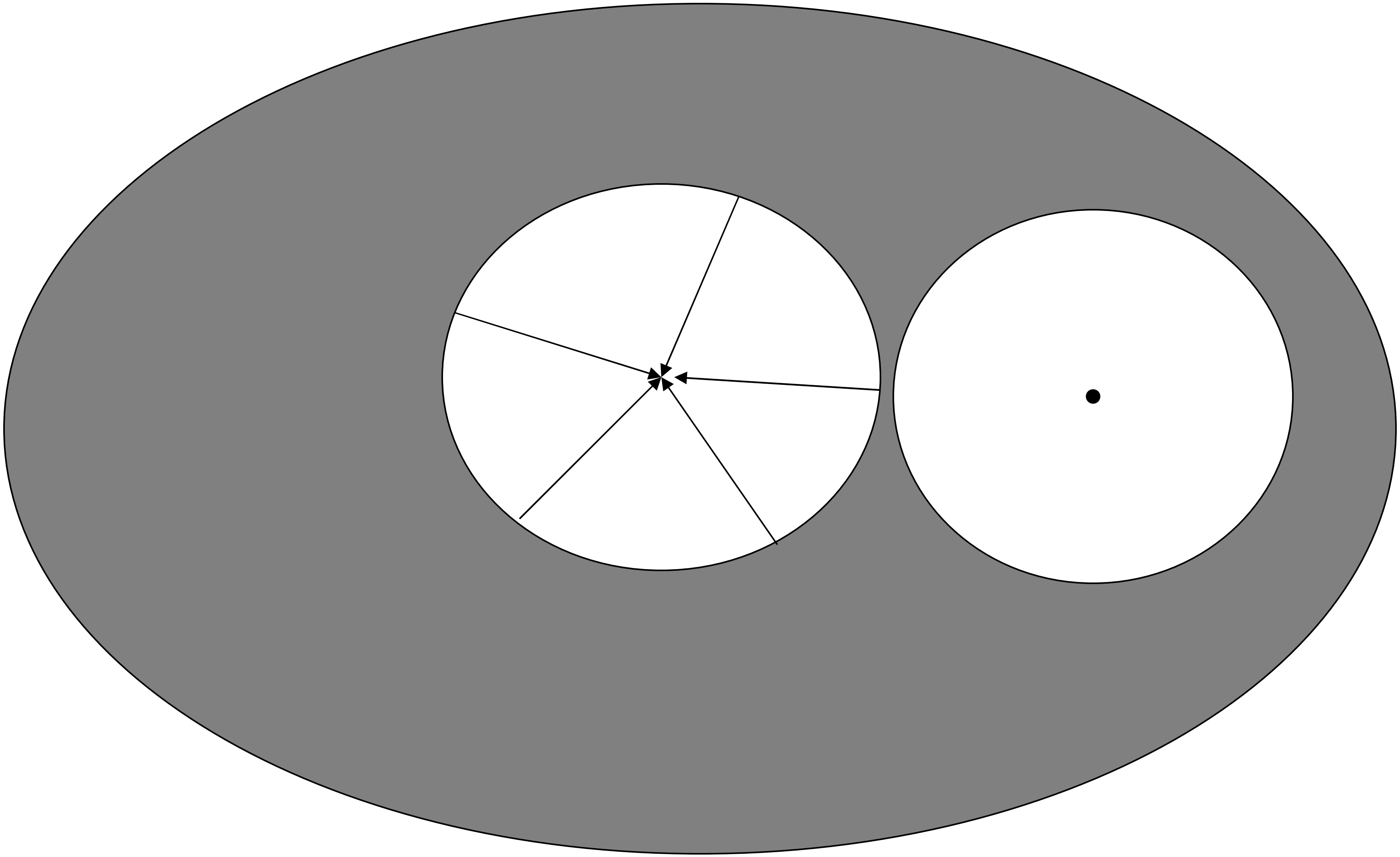
Initial T = 3,000 K

Final **T = 2.7** K

The Plasma Was Everywhere



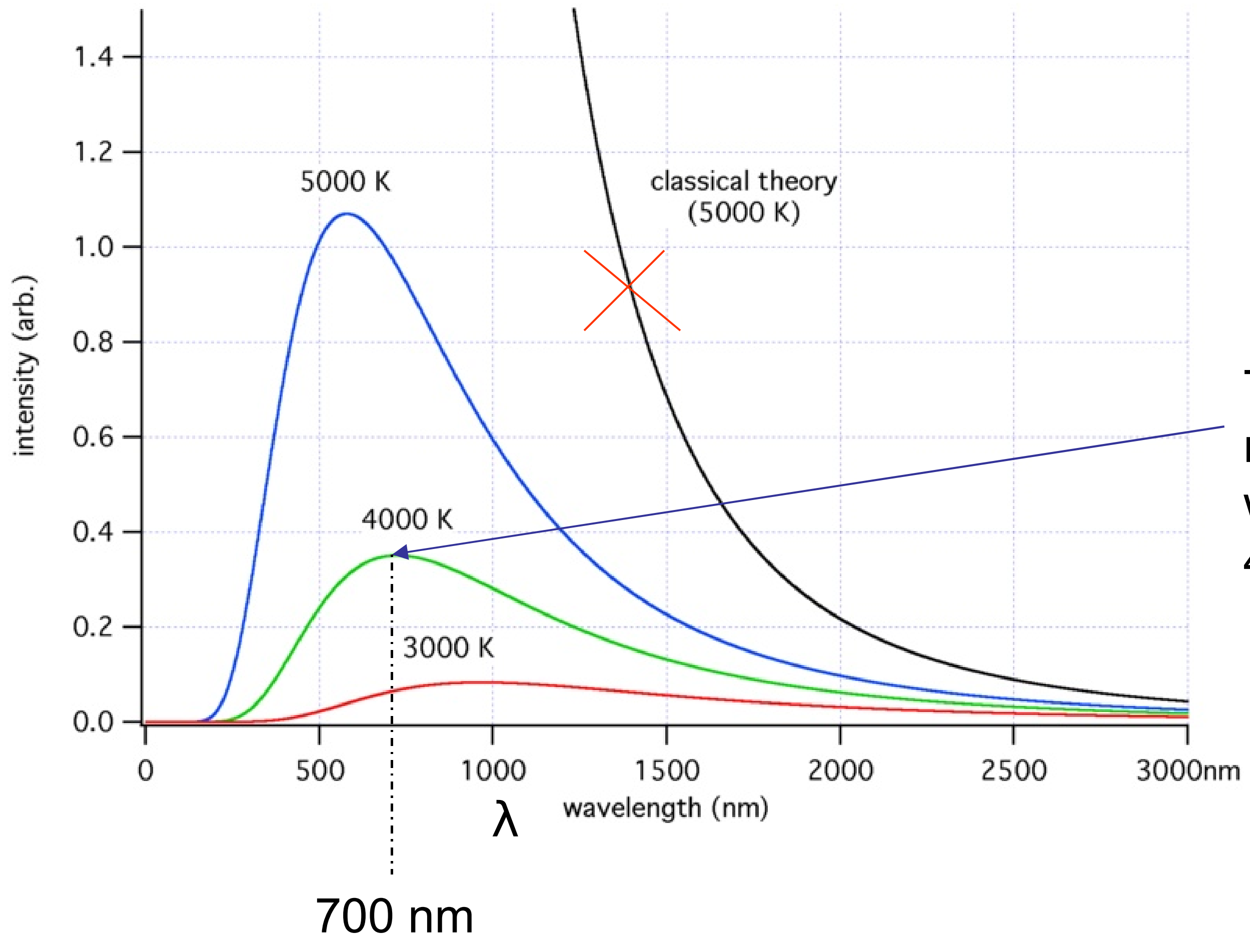
Our View is Expanding



Black Body Radiation

Relate Temperature to Light Spectrum

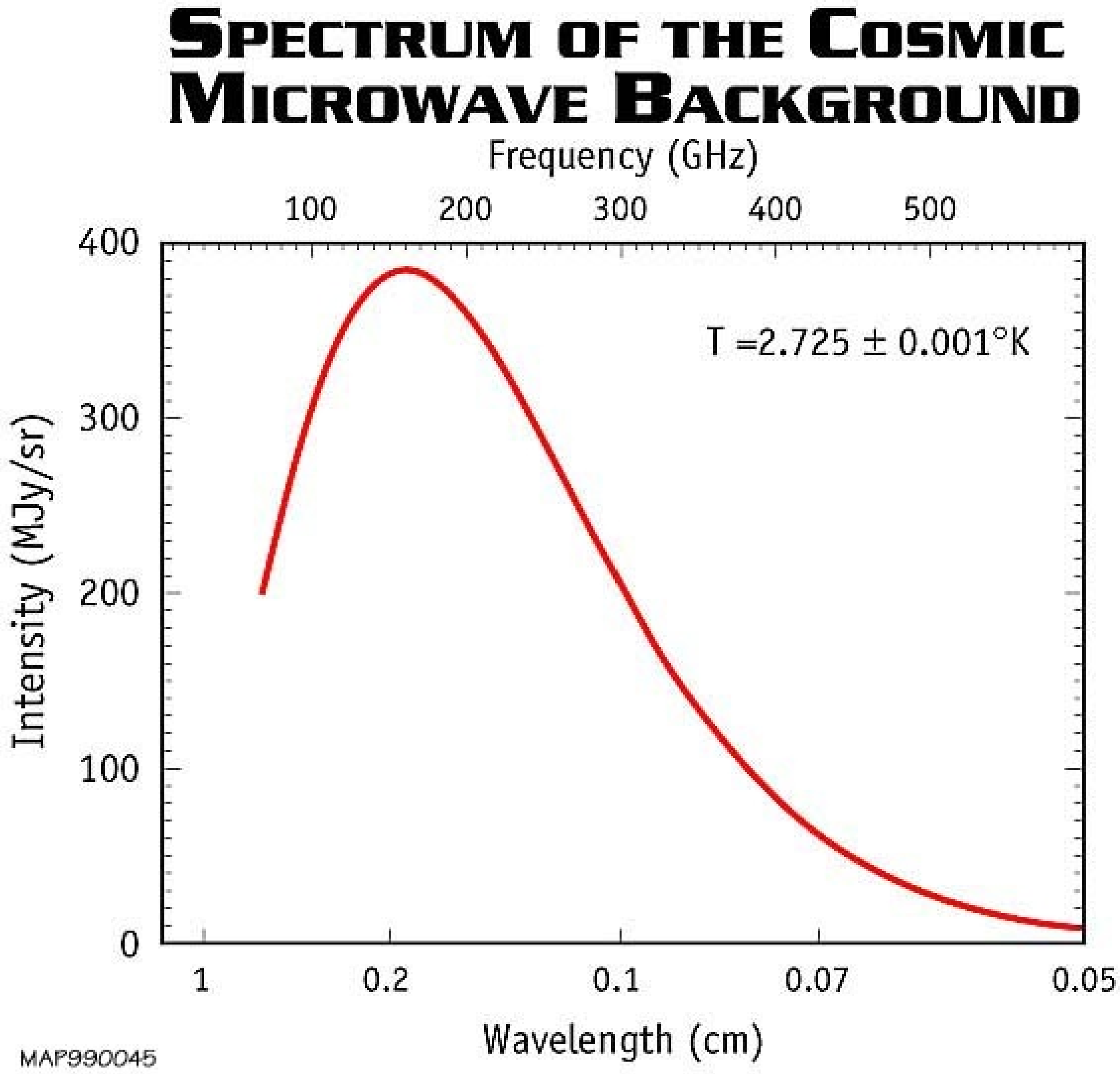
Primordial Plasma Acted as a Black Body



Peak of curve

$\boxed{hc/\lambda = 2.8\ k_B T}$

The peak at λ = 700 nm represents a blackbody with a temperature of 4000 K

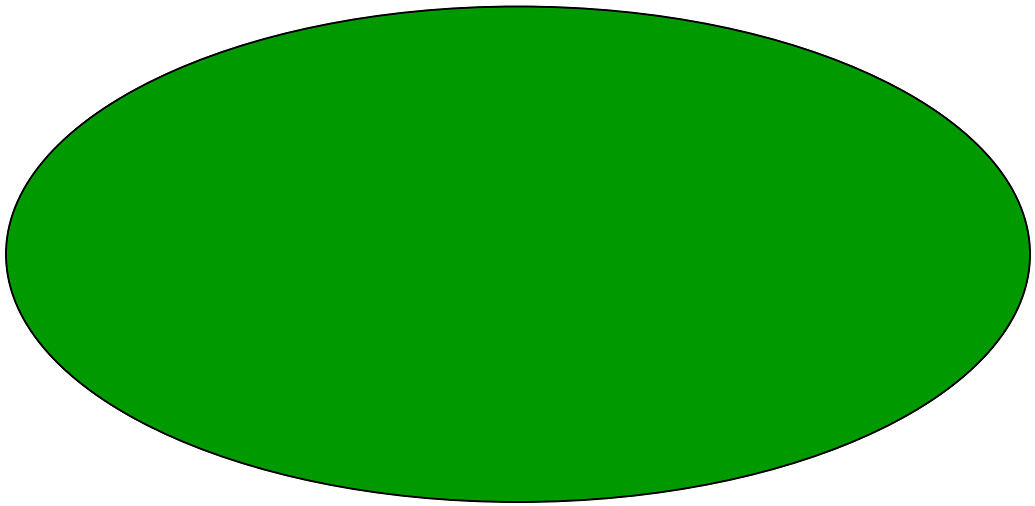


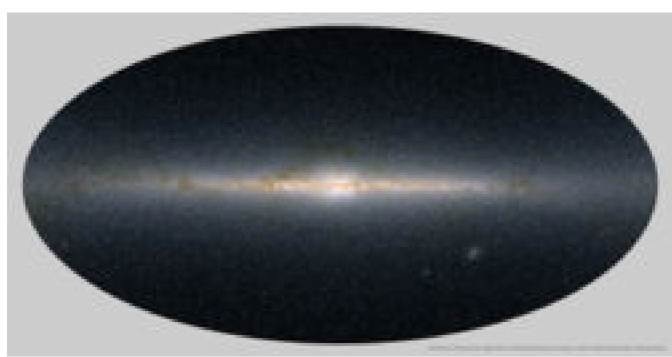
Data fits ideal black body curve to better than 1 part in 10,000

Deviations from black body curve on the order of a few parts in 100,000 reveal important information about our Universe

Isotropy of the Cosmic Microwave background

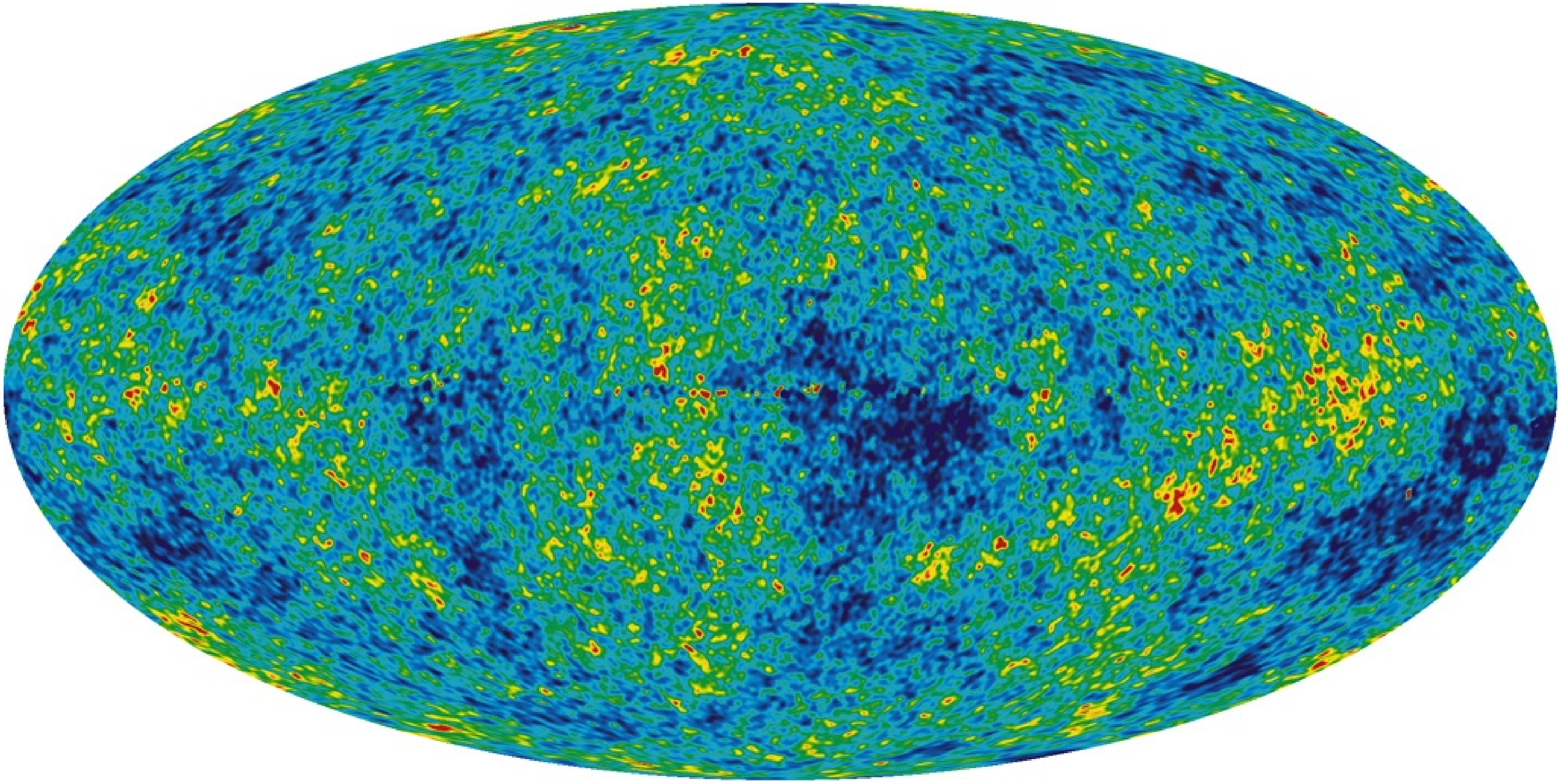
CMB view of the Universe: T =2.725°

360°  0°



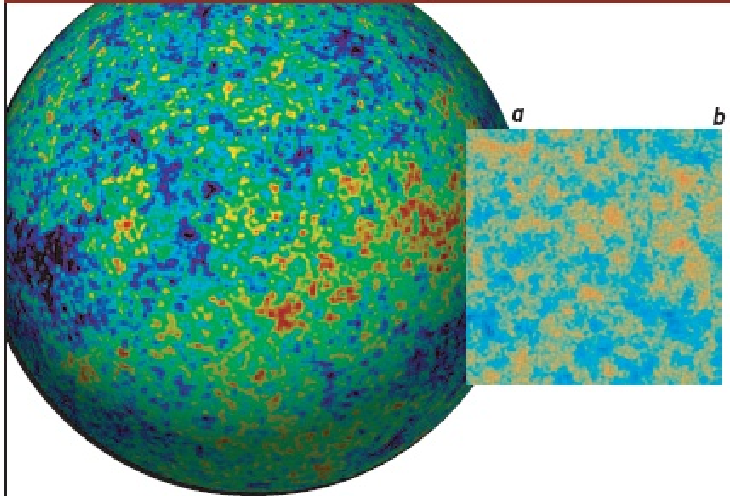
Optical view of the Universe

WMAP 2008
Cosmic Microwave Background

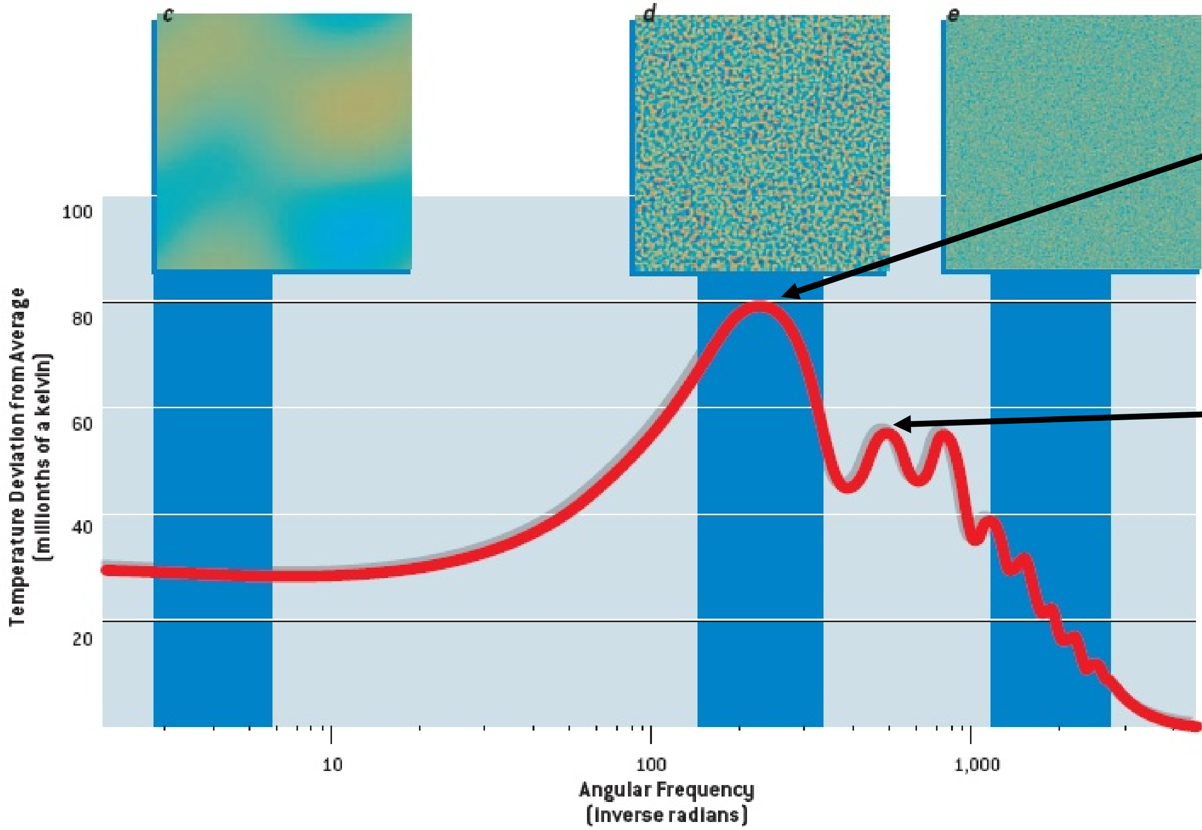


Tiny Temperature Deviations from 2.725 K

THE POWER SPECTRUM



OBSERVATIONS OF THE CMB provide a map of temperature variations across the whole sky (*a*). When researchers analyze portions of that map (*b*), they use band filters to show how the temperature of the radiation varies at different scales. The variations are barely noticeable at large scales corresponding to regions that stretch about 30 degrees across the sky (*c*) and at small scales corresponding to regions about a tenth of a degree across (*e*). But the temperature differences are quite distinct for regions about one degree across (*d*). This first peak in the power spectrum (*graph at bottom*) reveals the compressions and rarefactions caused by the fundamental wave of the early universe; the subsequent peaks show the effects of the overtones.

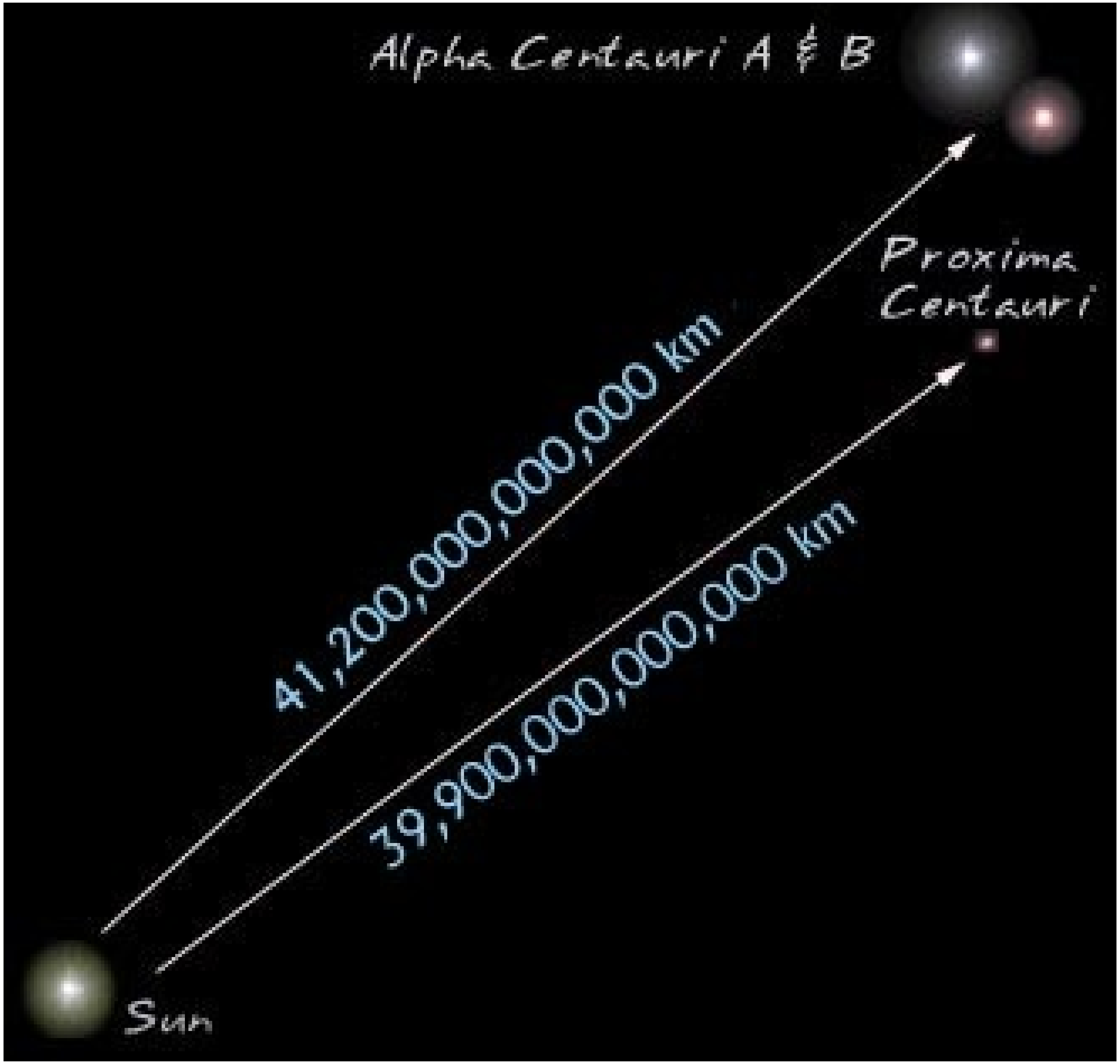


Scientific American Feb 2004 pp 44-53

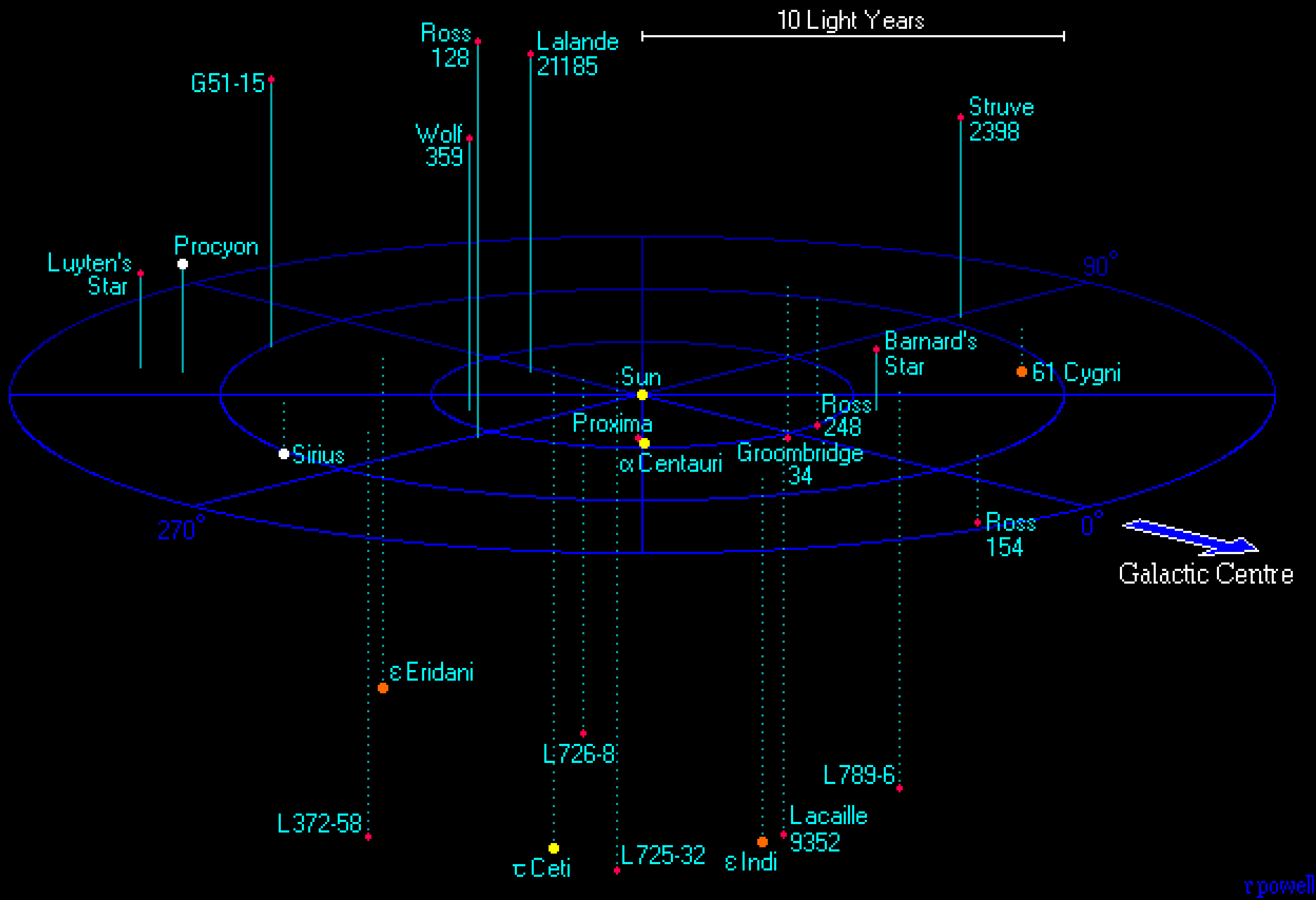
Peak at this frequency shows that the Universe is not curved

Ratio of 2nd and 3rd peaks measures the amount of dark matter in Universe

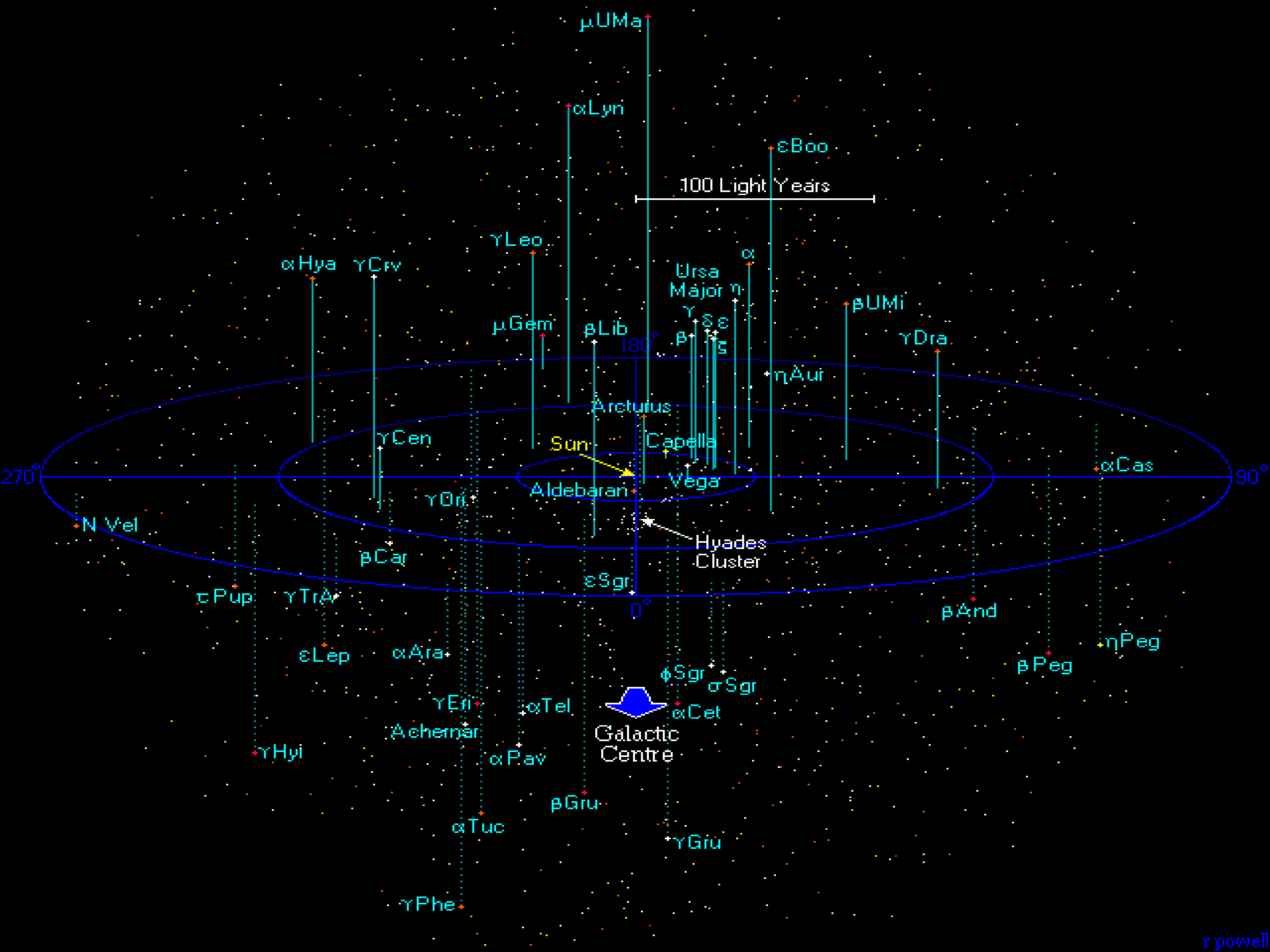
Large Scale Structure of the Universe

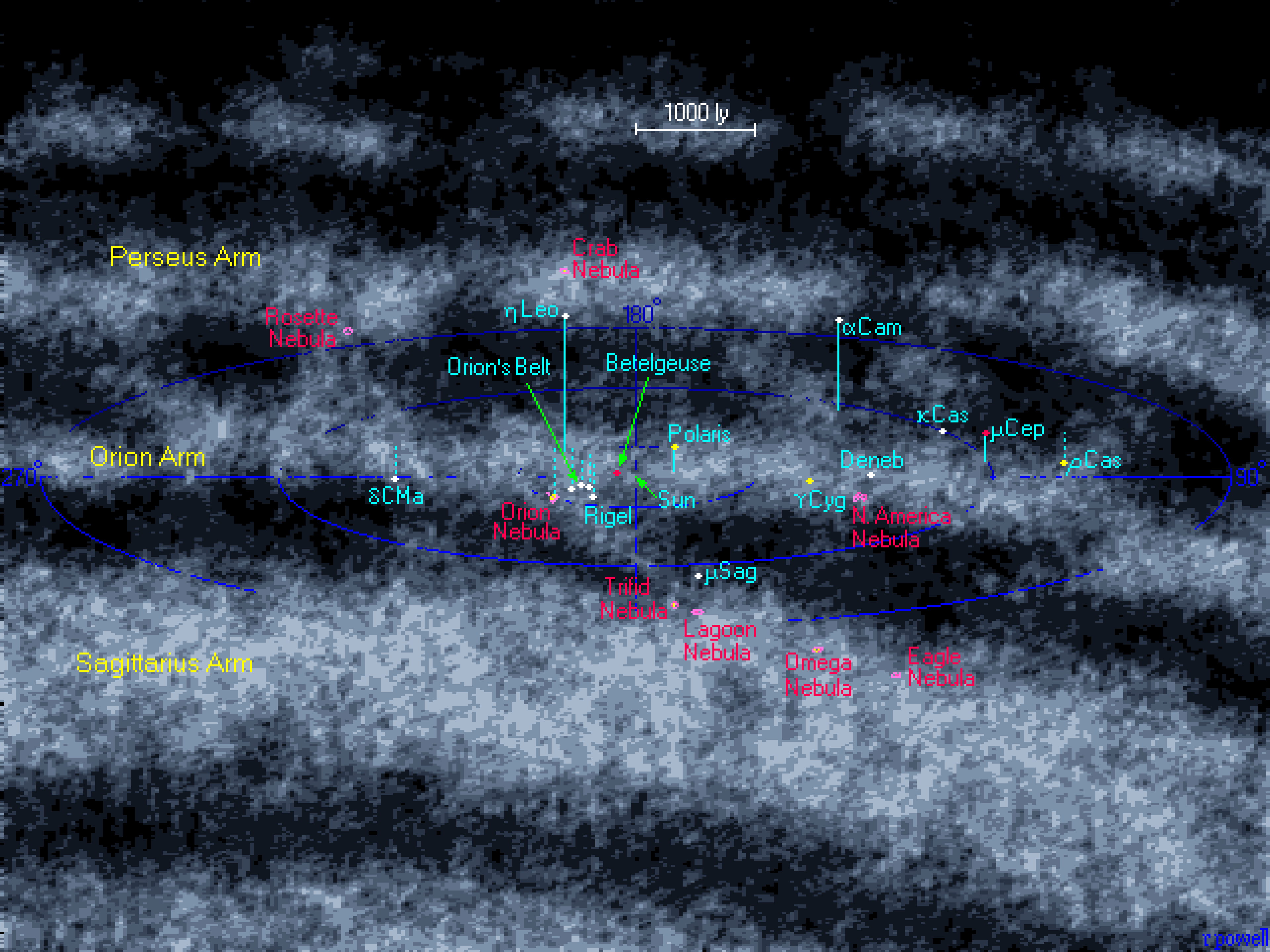


1 light year = 9.5x10**12 km

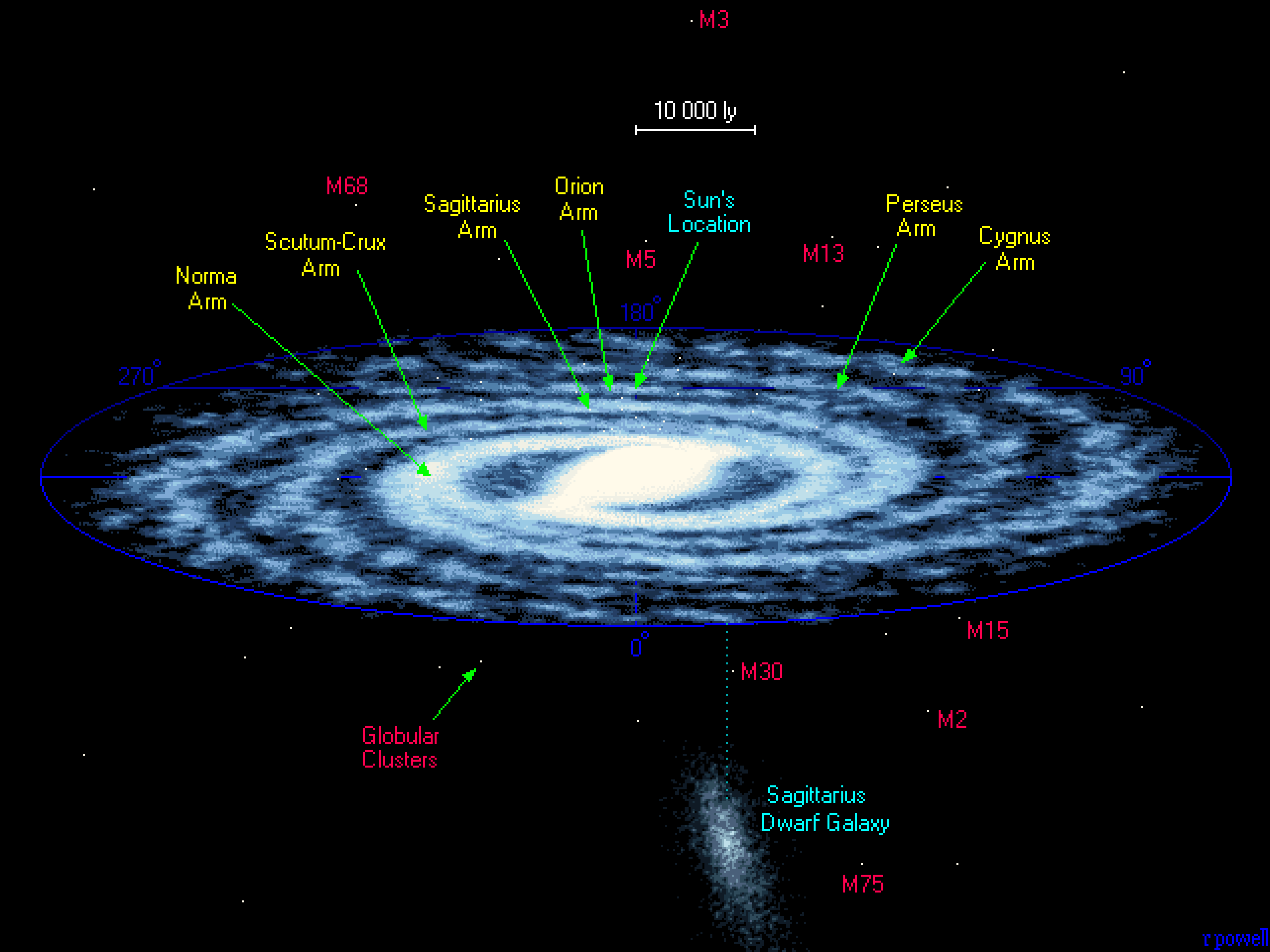


10 Light Years
Ross 128
Lalande 21185
G51-15
Wolf 359
Struve 2398
Procyon
Luyten's Star
90°
Barnard's Star
61 Cygni
Sun
Ross 248
Proxima
Sirius
α Centauri
Groombridge 34
270°
Ross 154
0°
Galactic Centre
ε Eridani
L726-8
L789-6
L372-58
Lacaille 9352
τ Ceti
L725-32
ε Indi
r powell

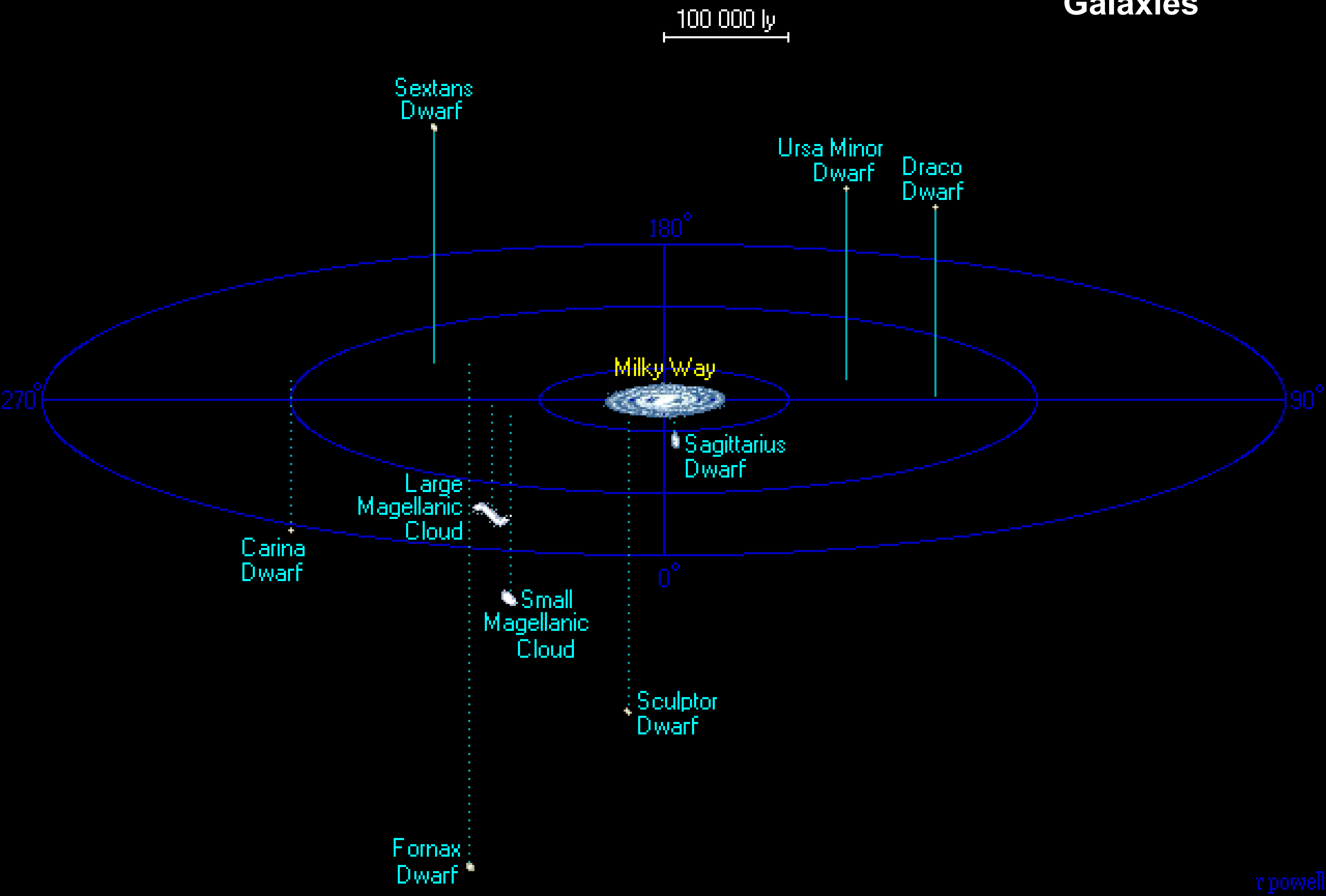

μUMa
αLyn
εBoo
100 Light Years
γLeo
αHya
γCrv
α
Ursa
Major
η
γ
δ
ε
β
ζ
βUMi
μGem
βLib
180°
γDra
ηAur
Arcturus
γCen
Sun
Capella
270°
Vega
90°
αCas
Aldebaran
γOri
N Vel
Hyades
Cluster
βCar
εSgr
τPup
γTrA
0°
βAnd
ηPeg
εLep
αAra
φSgr
σSgr
βPeg
γEri
αTel
αCet
Achernar
Galactic
Centre
γHyi
αPav
βGru
αTuc
γGru
γPhe
r powell



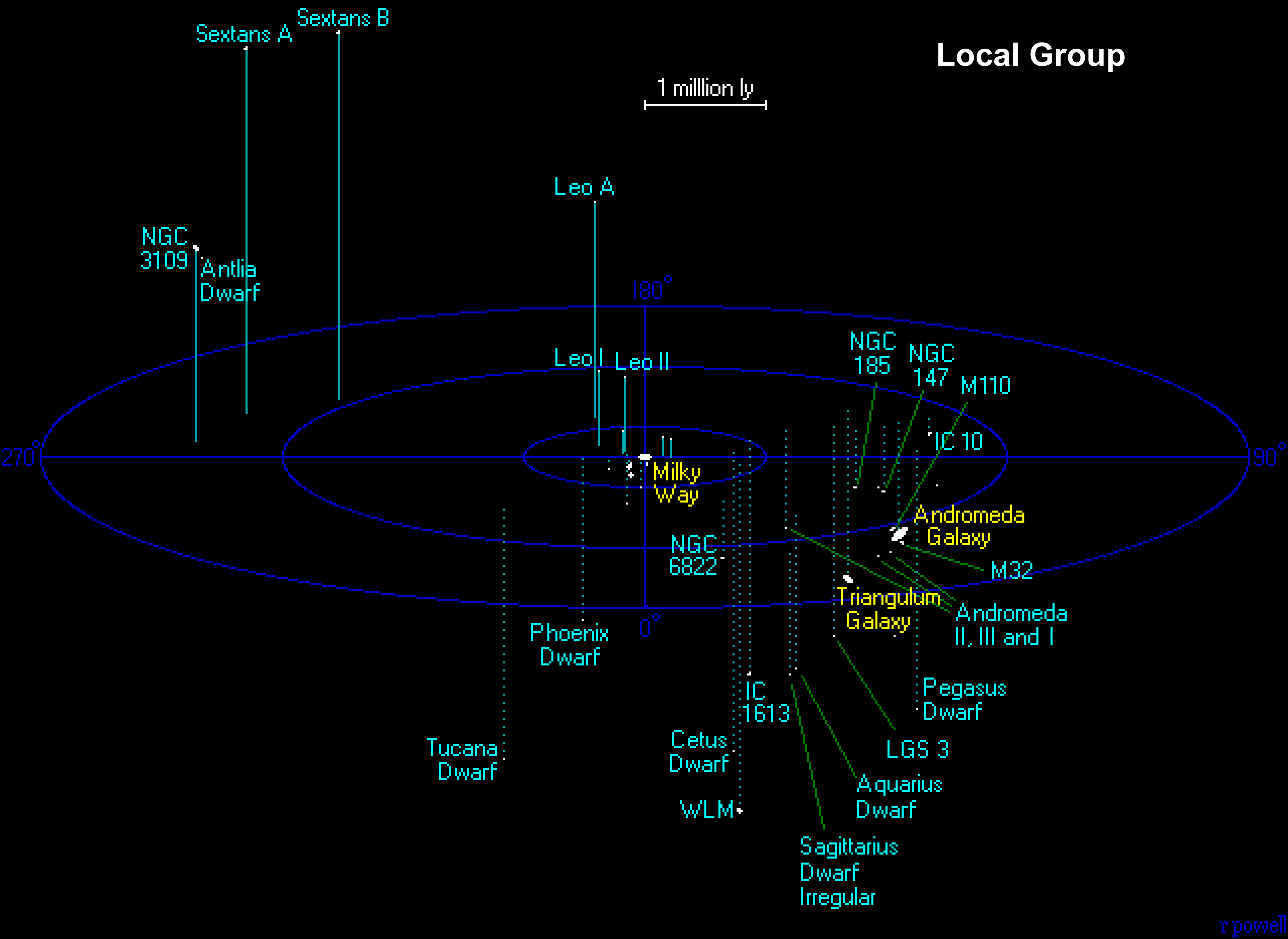
1000 ly
Perseus Arm
Crab Nebula
Rosette Nebula
η Leo
180°
α Cam
Orion's Belt
Betelgeuse
κ Cas
μ Cep
Polaris
Orion Arm
270°
δ CMa
Deneb
ρ Cas
90°
Orion Nebula
Rigel
Sun
γ Cyg
N. America Nebula
μ Sag
Trifid Nebula
Lagoon Nebula
Omega Nebula
Eagle Nebula
Sagittarius Arm
r.powell


M3
10 000 ly
M68
Sagittarius
Arm
Orion
Arm
Sun's
Location
Perseus
Arm
Cygnus
Arm
Scutum-Crux
Arm
Norma
Arm
M5
M13
180°
270°
90°
0°
M15
M30
M2
Globular
Clusters
Sagittarius
Dwarf Galaxy
M75
r powell

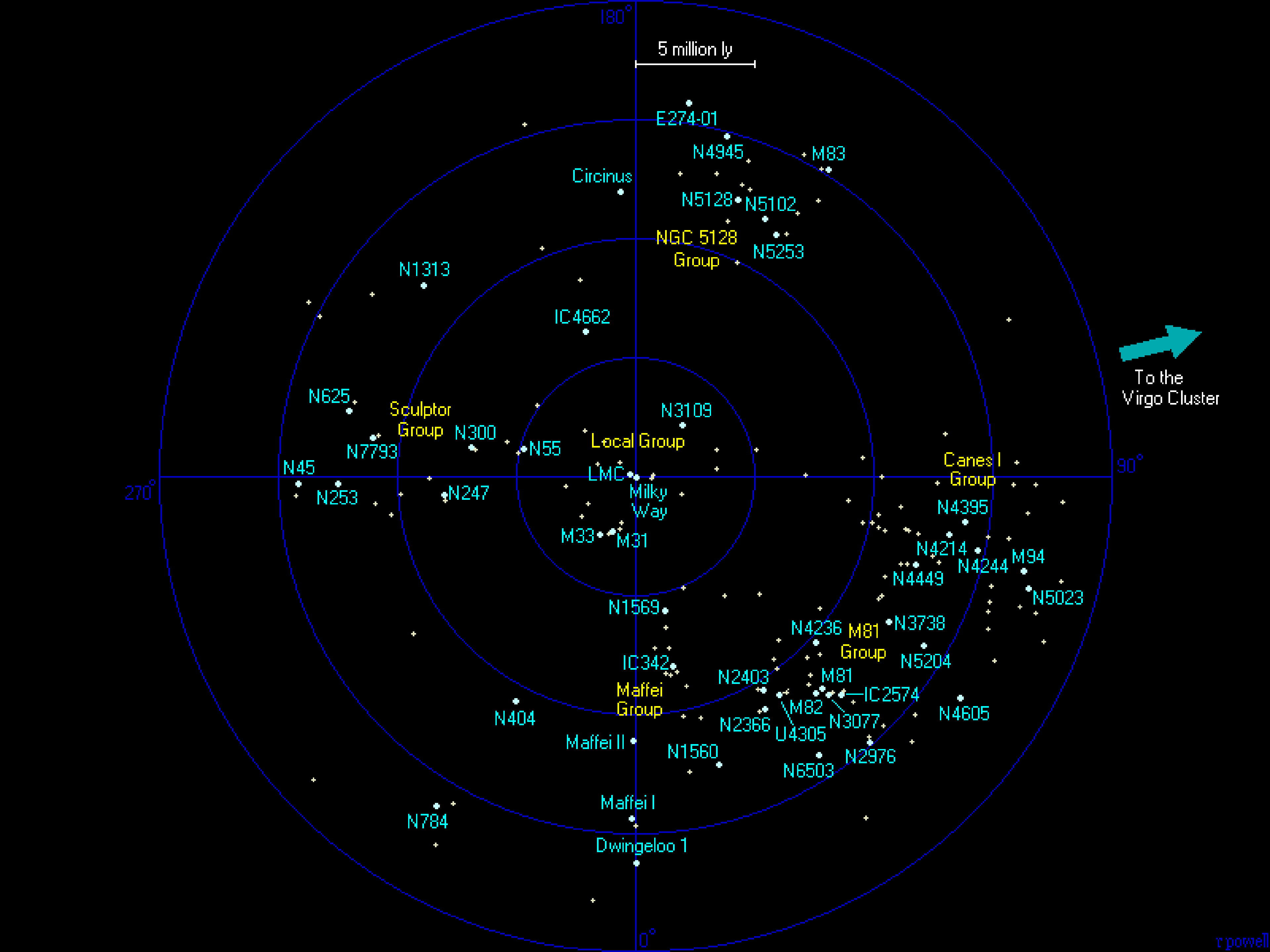
Satellite Galaxies



Local Group

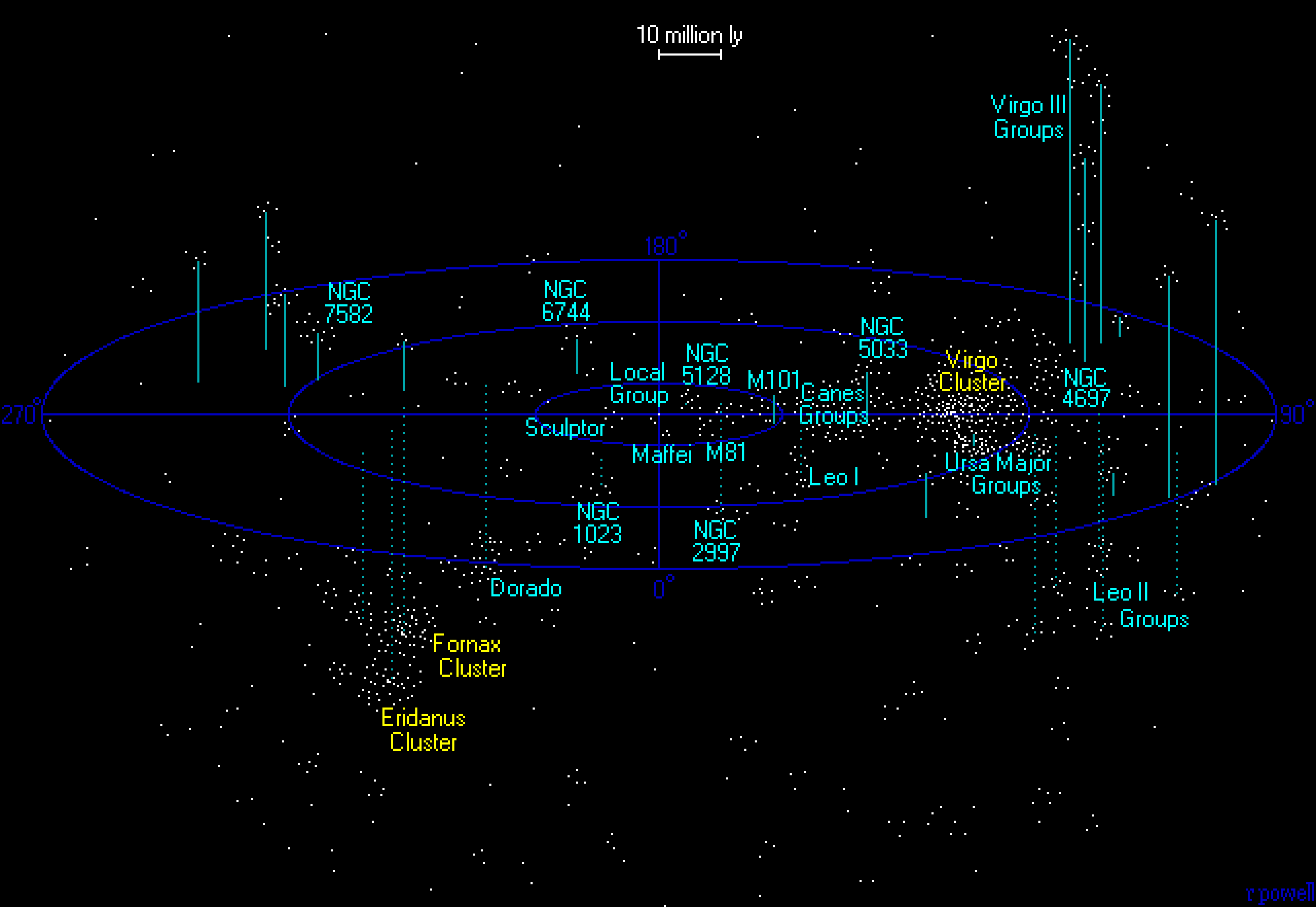


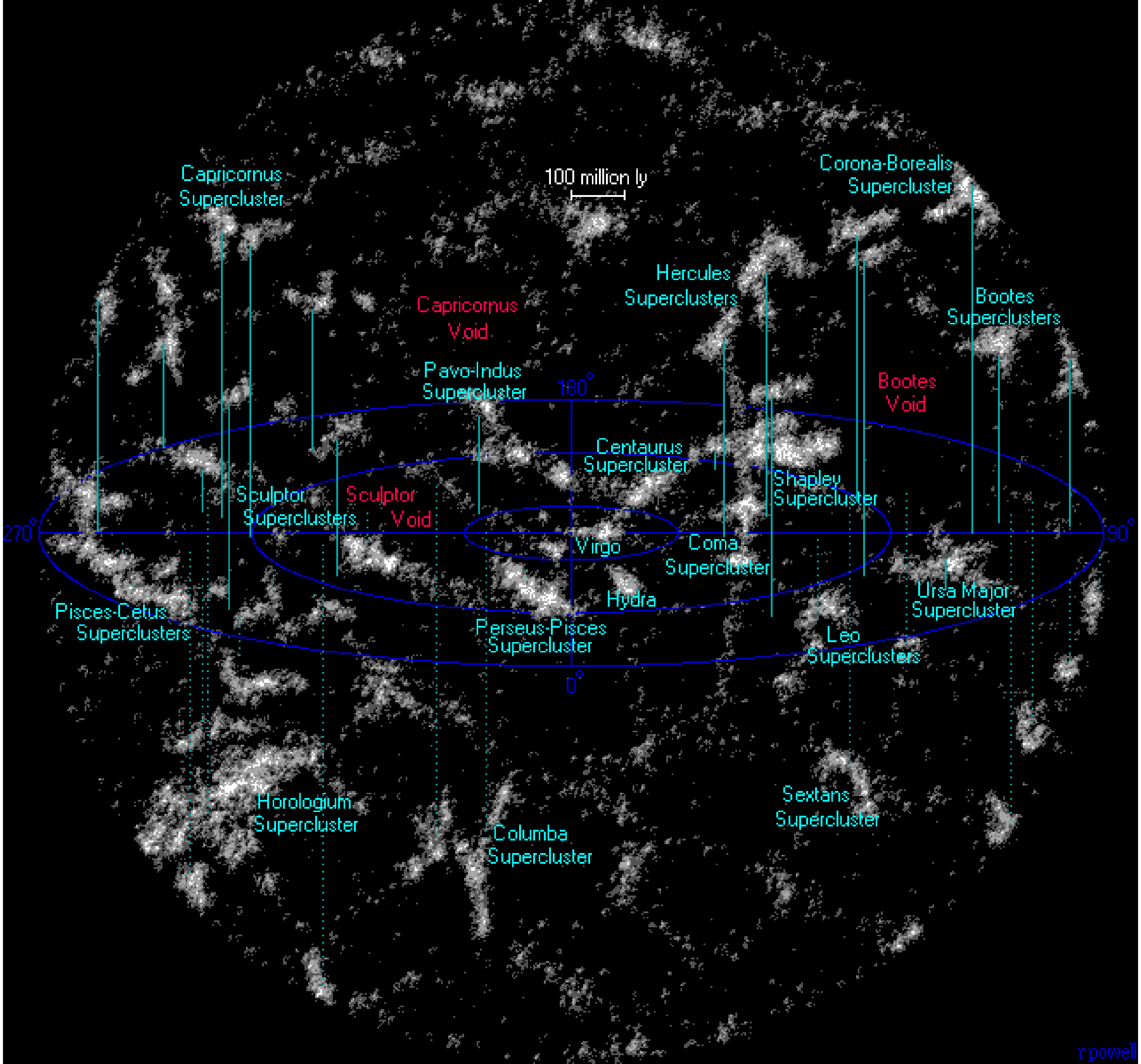
1 milllion ly
Sextans A
Sextans B
Leo A
NGC 3109
Antlia Dwarf
180°
270°
90°
0°
Leo I
Leo II
NGC 185
NGC 147
M110
IC 10
Milky Way
Andromeda Galaxy
M32
NGC 6822
Triangulum Galaxy
Andromeda II, III and I
Phoenix Dwarf
Pegasus Dwarf
IC 1613
LGS 3
Tucana Dwarf
Cetus Dwarf
Aquarius Dwarf
WLM
Sagittarius Dwarf Irregular
r powell

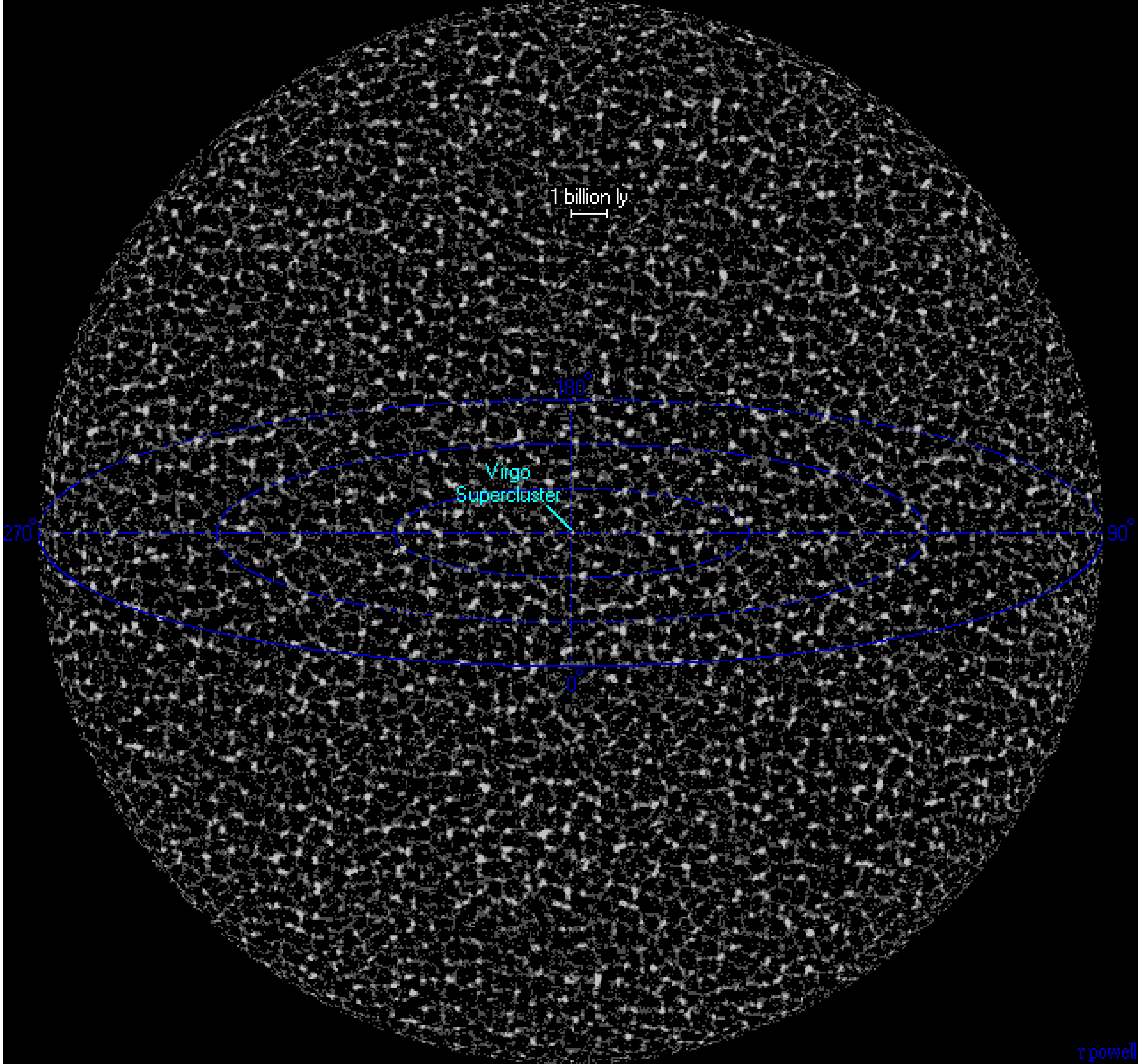


180°
5 million ly
E274-01
N4945
M83
Circinus
N5128
N5102
NGC 5128
Group
N5253
N1313
IC4662
N625
Sculptor
Group
N300
N7793
N55
N3109
Local Group
To the
Virgo Cluster
N45
N253
N247
LMC
Milky
Way
270°
90°
Canes I
Group
N4395
M33
M31
N4214
N4244
M94
N4449
N5023
N1569
N4236
M81
Group
N3738
N5204
IC342
N2403
M81
Maffei
Group
IC2574
M82
N404
N3077
N4605
N2366
U4305
Maffei II
N1560
N2976
N6503
Maffei I
N784
Dwingeloo 1
0°
r powell

Virgo SuperCluster



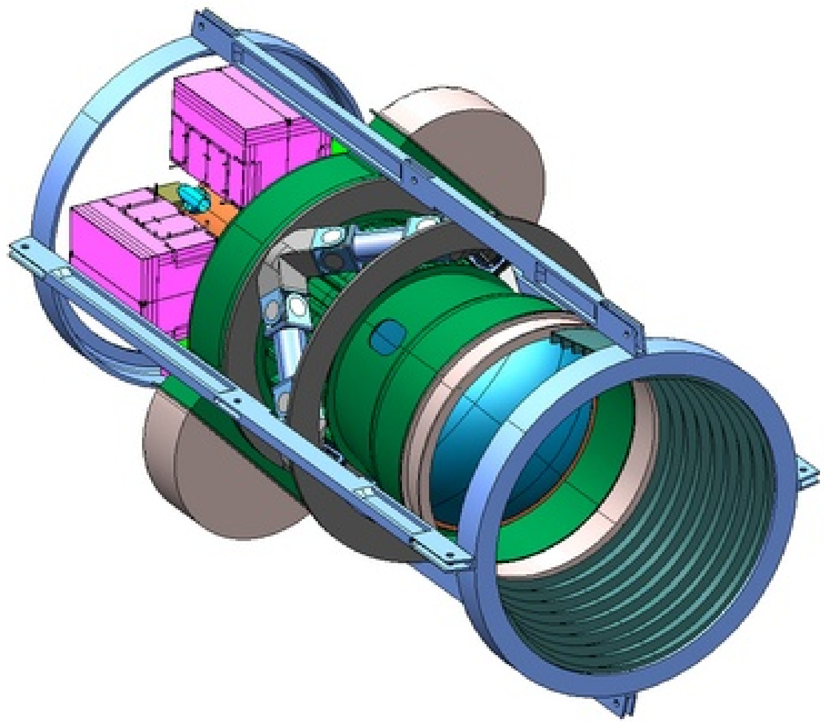

100 million ly
Capricornus Supercluster
Corona-Borealis Supercluster
Hercules Superclusters
Bootes Superclusters
Capricornus Void
Pavo-Indus Supercluster
180°
Bootes Void
Centaurus Supercluster
Shapley Supercluster
Sculptor Superclusters
Sculptor Void
270°
90°
Virgo
Coma Supercluster
Hydra
Ursa Major Supercluster
Pisces-Cetus Superclusters
Perseus-Pisces Supercluster
Leo Superclusters
0°
Horologium Supercluster
Columba Supercluster
Sextans Supercluster
r powell


1 billion ly
180°
Virgo
Supercluster
270°
90°
0°
r powell

Conclusion

- Particle Physicists are studying the remaining 95% of matter-energy in the Universe
- Joining forces with Cosmologists and Astronomers
- Argonne HEP Division is working on the Dark Energy Survey
  - Part of a collaboration to make the biggest CCD Camera in the world for the 4m Blanco telescope on Cerro Tololo in Chile. Investigate the expansion of the Universe by observing formation of large-scale structures and by observing distant supernovae.

DES Camera and Telescope



Edwin Hubble

- Hubble grew up in Wheaton IL and attended the U of Chicago (class of 1910)
  - 1906 Illinois state record high jump while in high school
- Rhodes Scholar; studied jurisprudence then switched to Spanish
- Taught and coached basketball in New Albany High School, Indiana
- Returned to U Chicago’s Yerkes Observatory for PhD in 1917