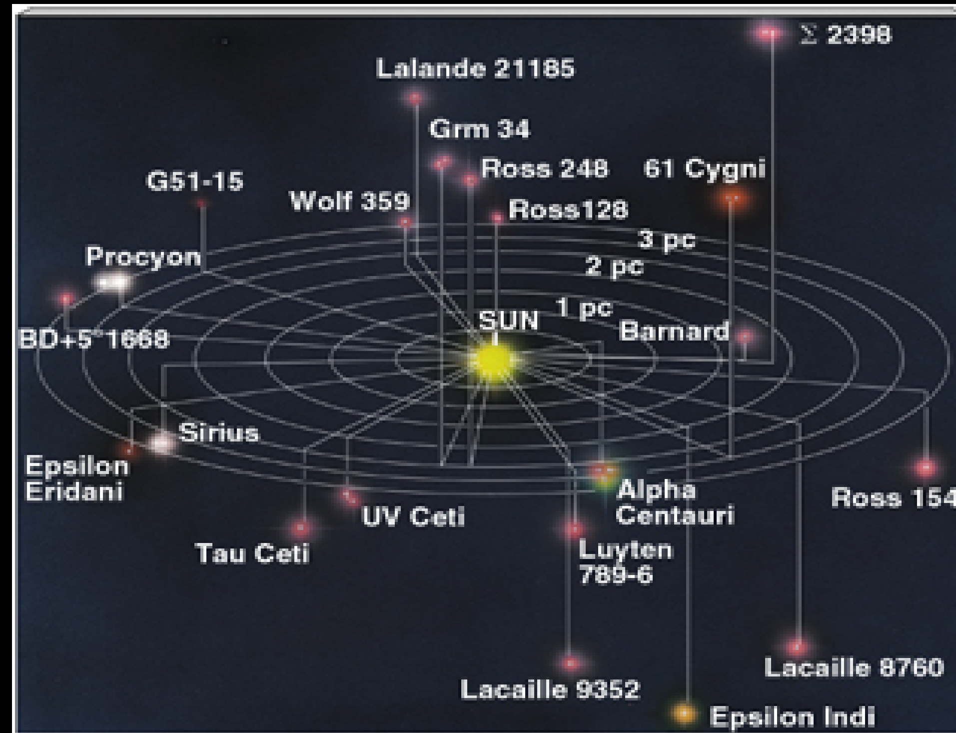
Standard Candles: Distance Measurement in Astronomy

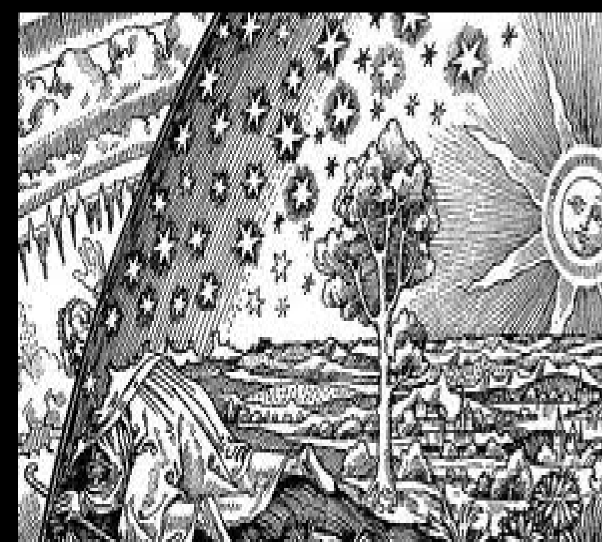
Farley V. Ferrante

Southern Methodist University

OUTLINE

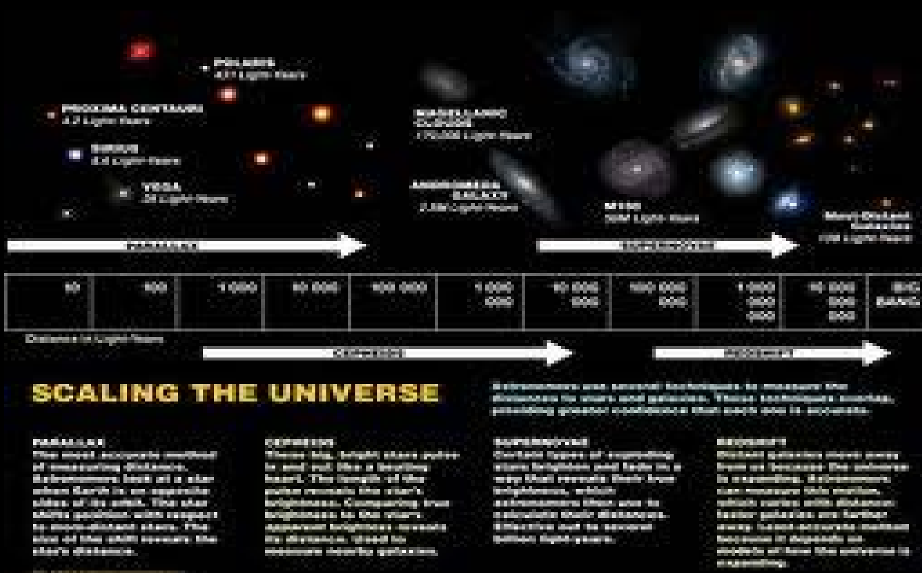
- Cosmic Distance Ladder
- Standard Candles
  - ❑Parallax
  - ❑Cepheid variables
  - ❑Planetary nebula
  - ❑Most luminous supergiants
  - ❑Most luminous globular clusters
  - ❑Most luminous H II regions
  - ❑Supernovae
  - ❑Hubble constant & red shift
- Standard Model of Cosmology

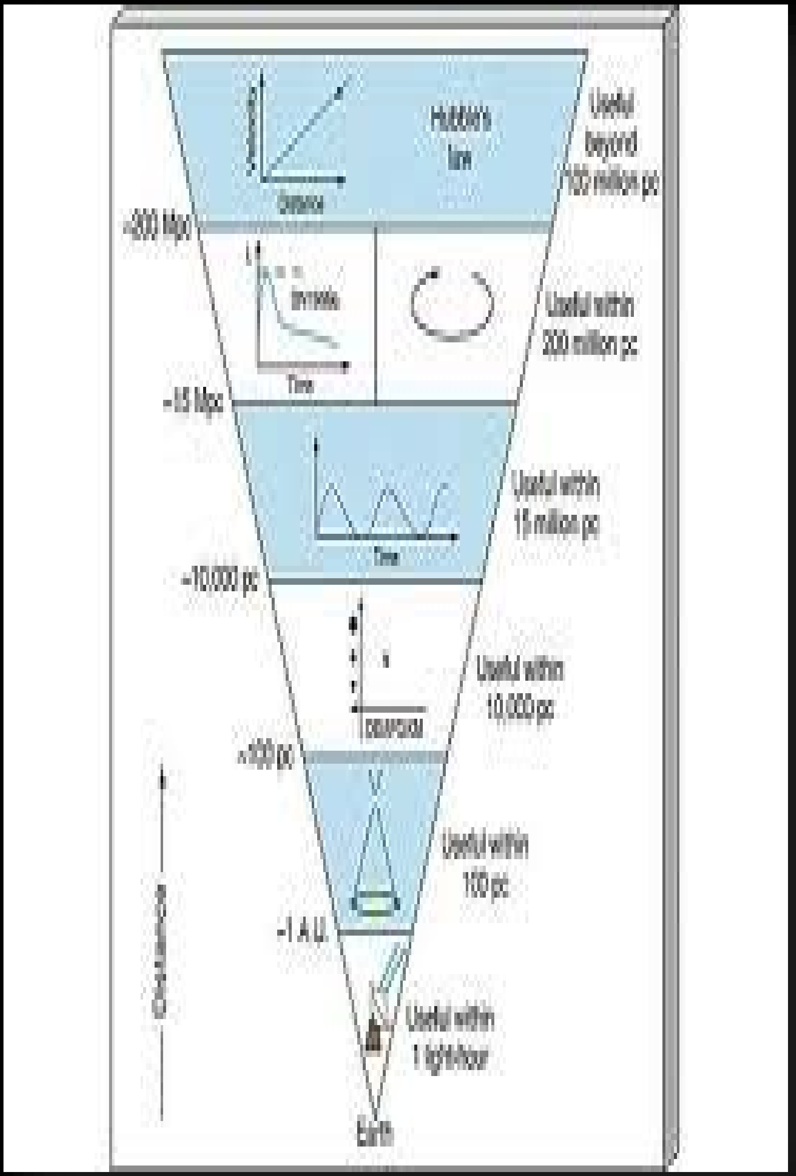




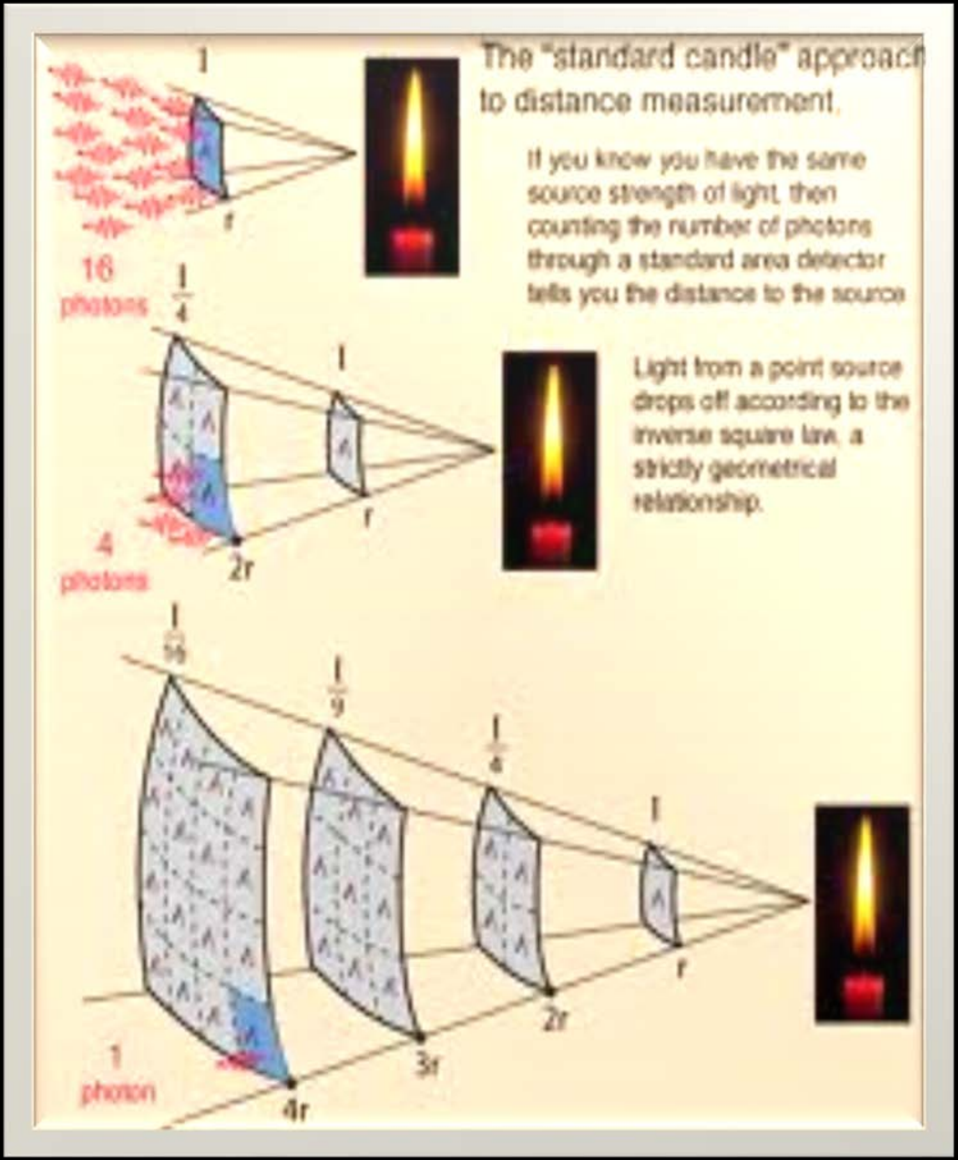
The Cosmic Distance Ladder

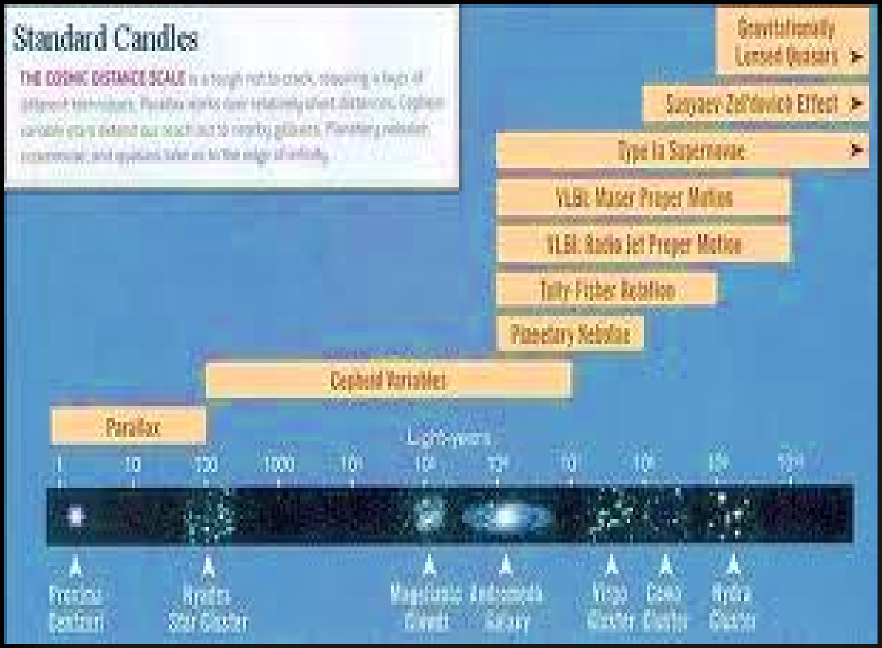
- Distances far too vast to be measured directly
- Several methods of indirect measurement
- Clever methods relying on careful observation and basic mathematics
- Cosmic distance ladder: A progression of indirect methods which scale, overlap, & calibrate parameters for large distances in terms of smaller distances



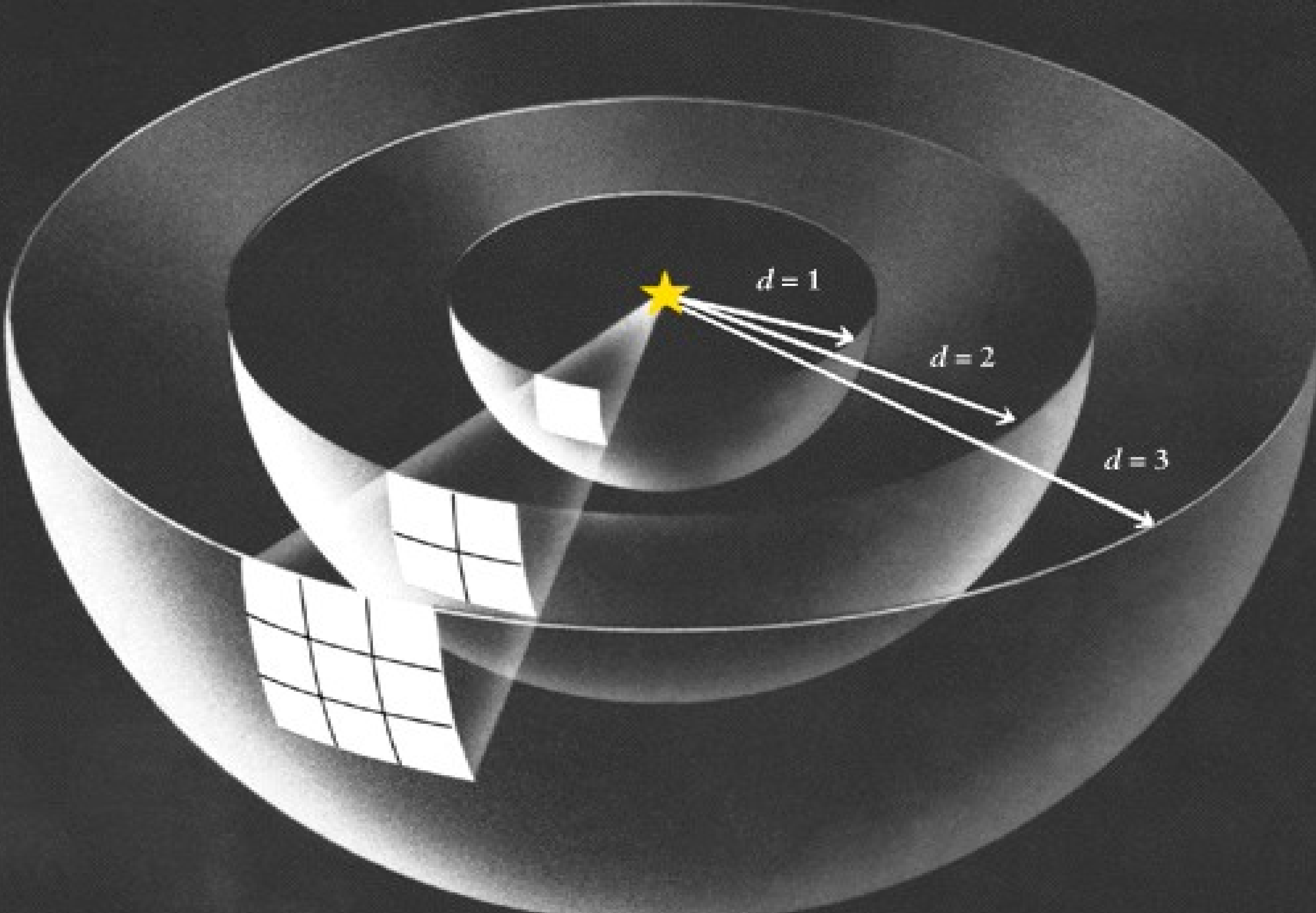


Standard Candles

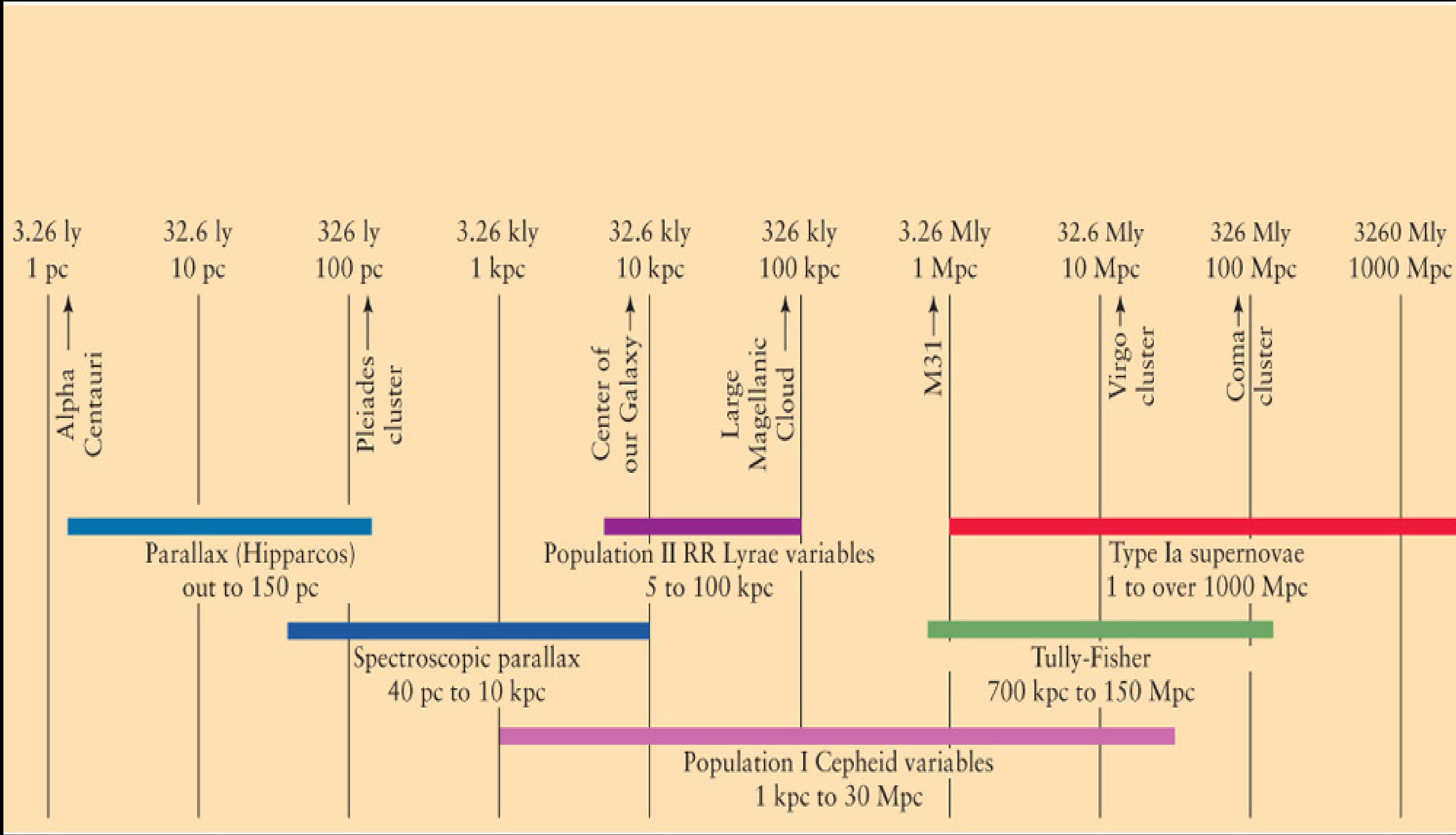




- Magnitude: Historical unit (Hipparchus) of stellar brightness such that 5 magnitudes represents a factor of 100 in intensity
- Apparent magnitude: Number assigned to visual brightness of an object; originally a scale of 1-6
- Absolute magnitude: Magnitude an object would have at 10 pc (convenient distance for comparison)
- List of most luminous stars

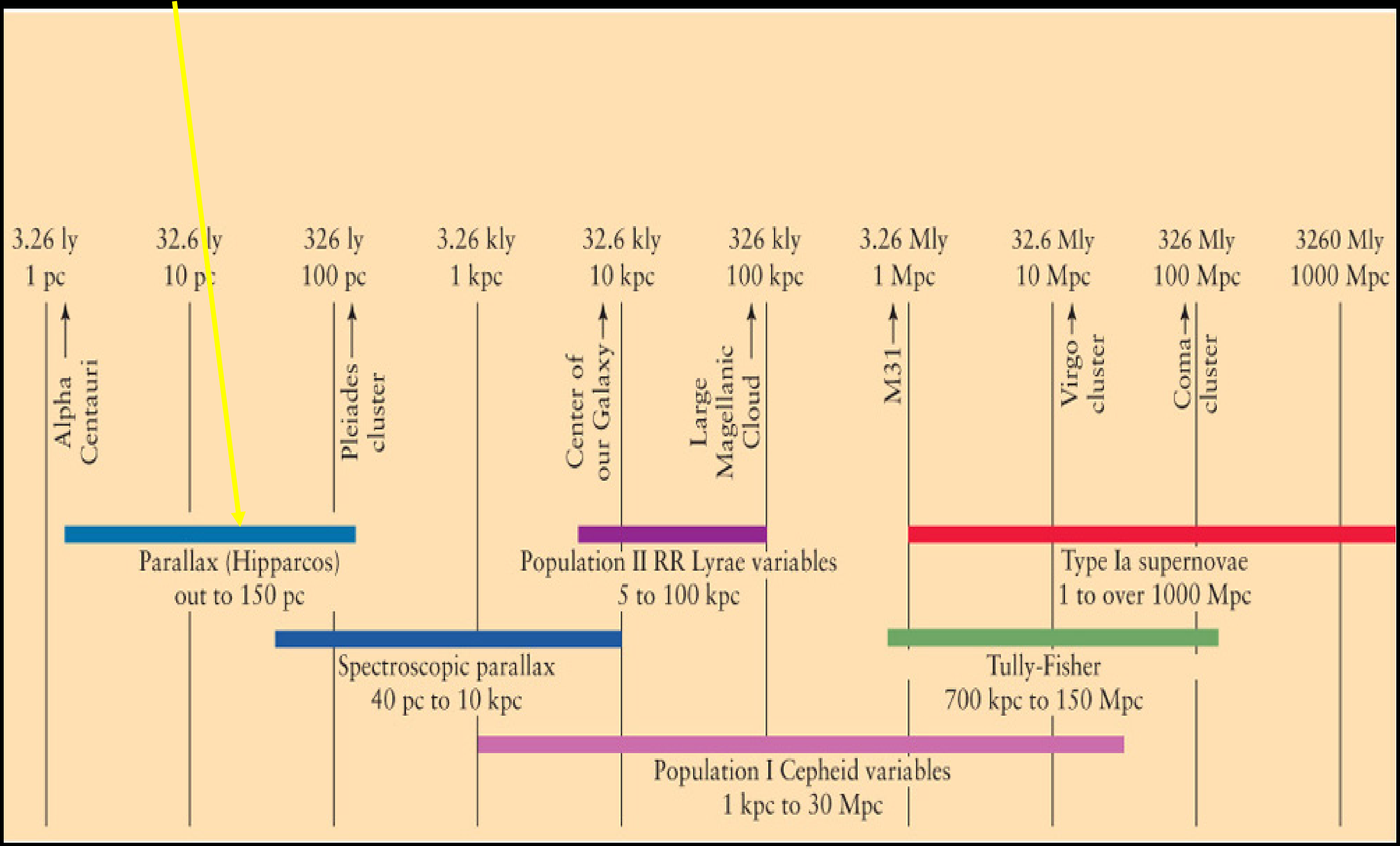

d = 1
d = 2
d = 3

The Cosmic Distance Ladder



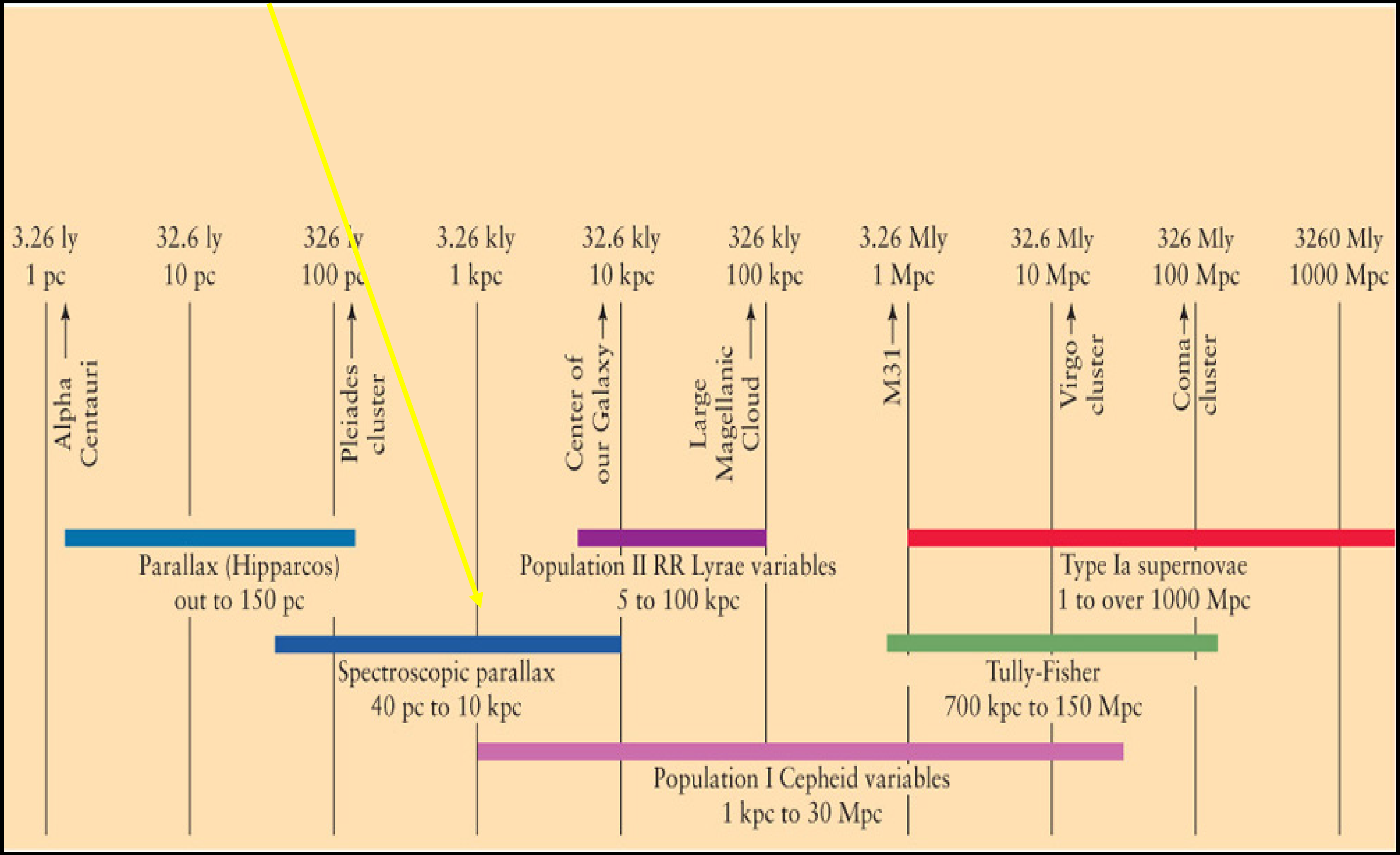
The Cosmic Distance Ladder

Parallax to nearby stars ***~150 pc***



The Cosmic Distance Ladder

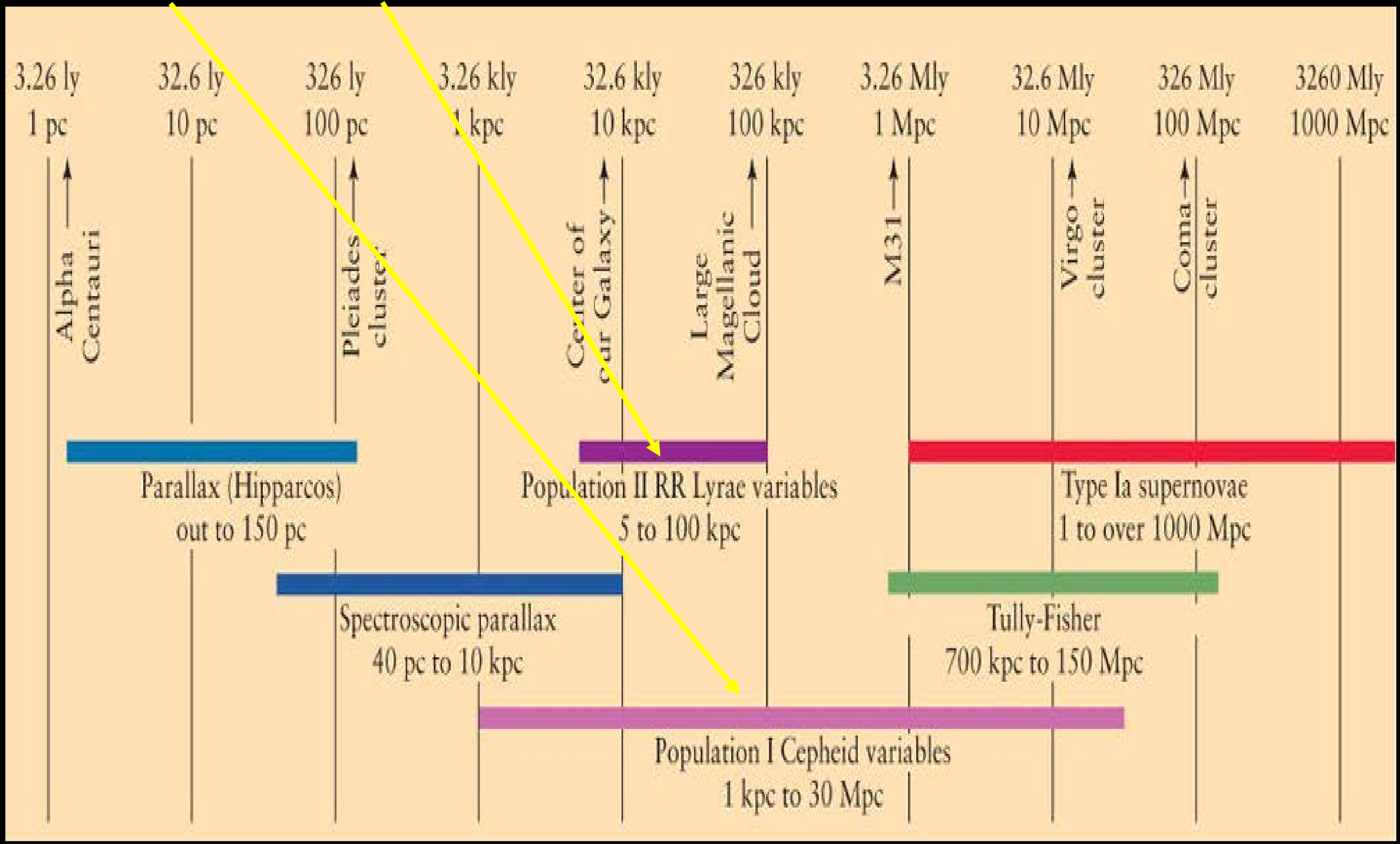
Spectroscopic parallax to stars in galaxy ***~10 kpc***



The Cosmic Distance Ladder

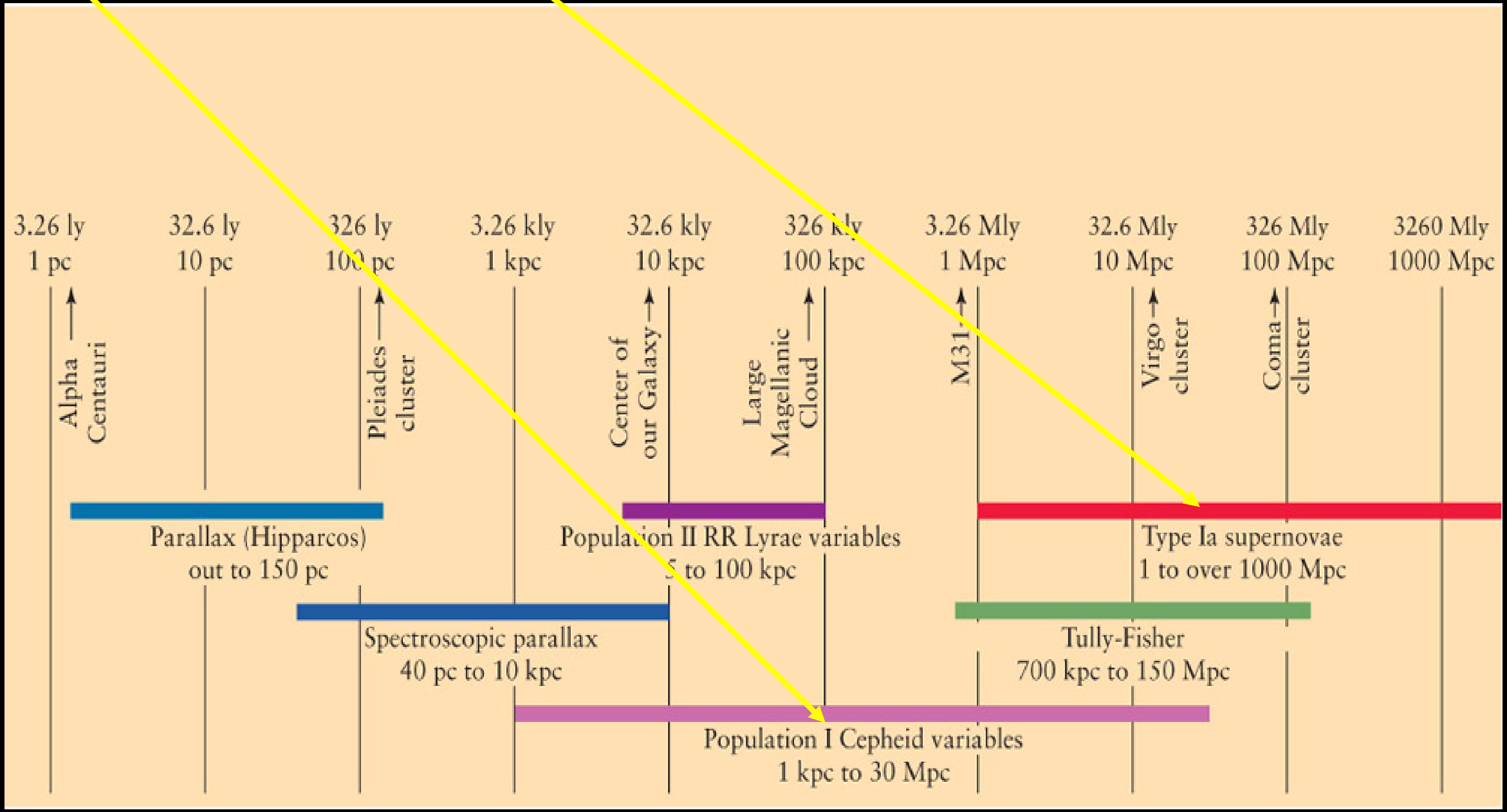
Calibrated variable stars in MW galaxy

~30 kpc



The Cosmic Distance Ladder

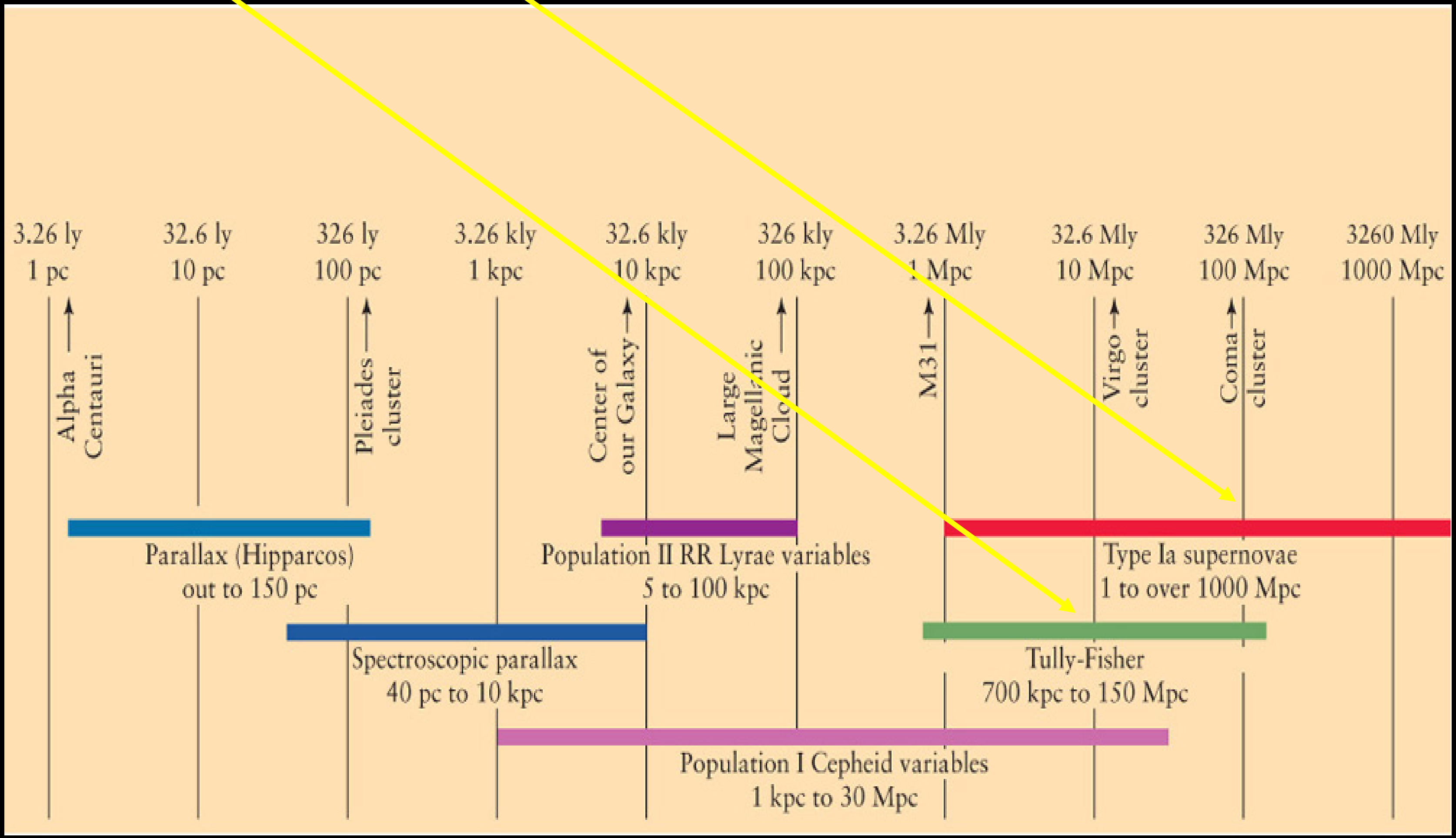
Calibrated variable stars, supernovae in 'nearby' galaxies ***~3 Mpc***



The Cosmic Distance Ladder

Calibrated variable stars, supernovae, most massive galaxies in 'distant' clusters

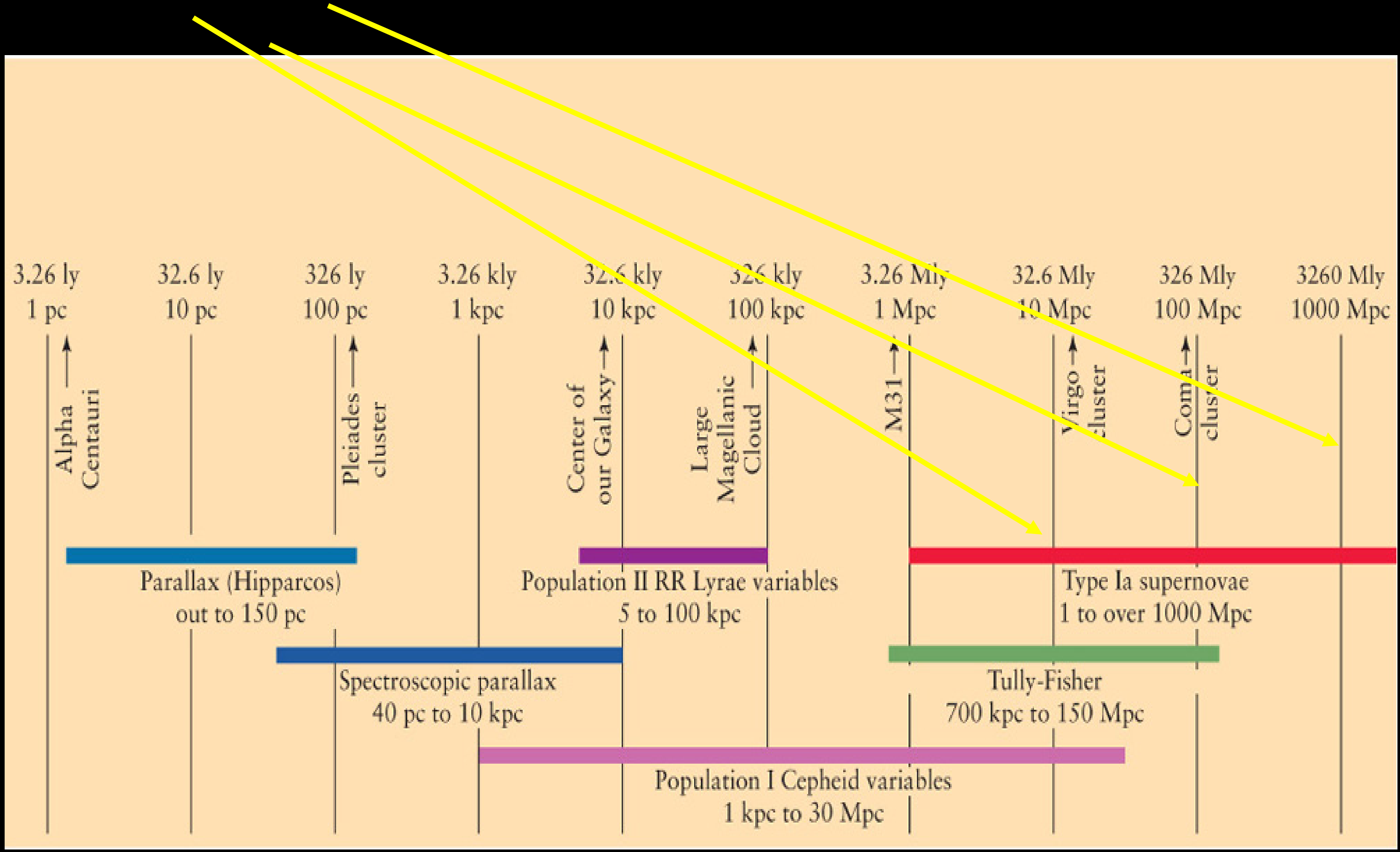
~150 Mpc to 1 Gpc



The Cosmic Distance Ladder

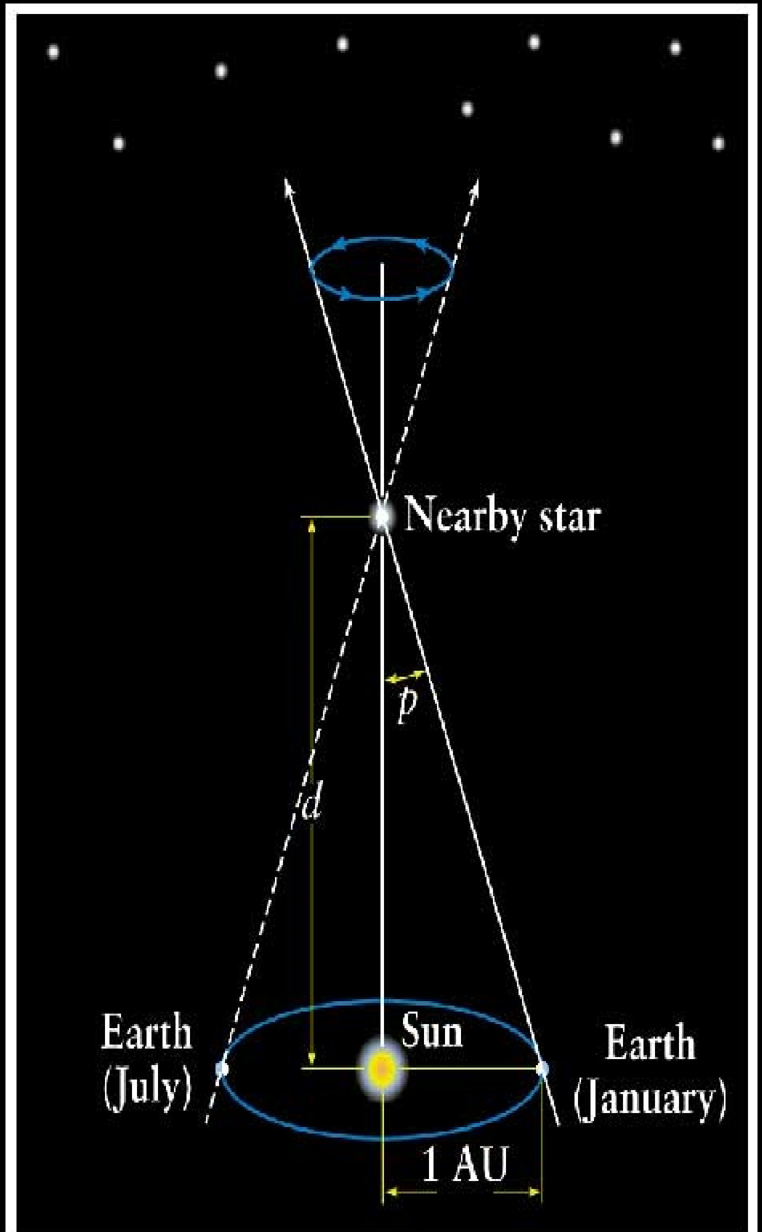
Hubble's Law

~3 Gpc



Parallax

- Distance Units:
  - ❑ 1 AU = 1.49597870700 x 10^{11} m
  - ❑ 1 ly = 9.46 053 x 10^{15} m = 6.324 x 10^{4} AU
  - ❑ 1 pc = 3.085678 x 10^{16} m = 3.261633 ly = 206 264.81 AU
- 1 parsec (pc): Distance from the Sun to an astronomical object for which the parallax angle is one arcsecond
- Stellar parallax: A nearby star's apparent movement against the background of more distant stars as the Earth revolves around the Sun
- By taking measurements of the same star 6 months apart and comparing the angular deviation, distance to the star can be calculated
- 1st performed by Friedrich Wilhelm Bessel (1838)
- Limit of measurement with Earth based telescopes is about 20 pc (includes around 2000 stars)
- Hipparcos satellite (1989-1993) measured parallax accurately to about 200 pc (nearly a million stars)
  - ❑ Precision parallax measurements of 273 Cepheid variables; 2 of them not previously observed

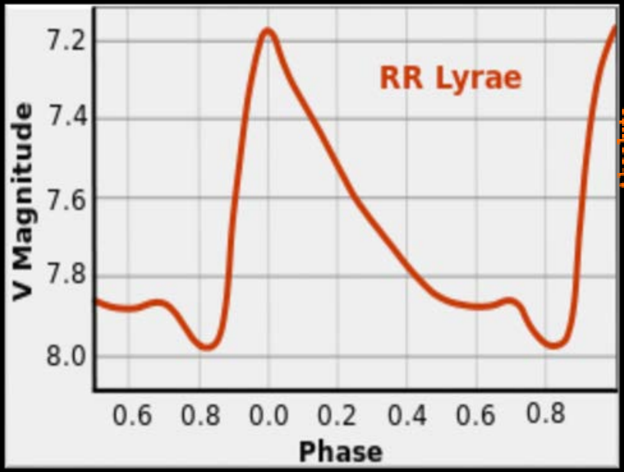


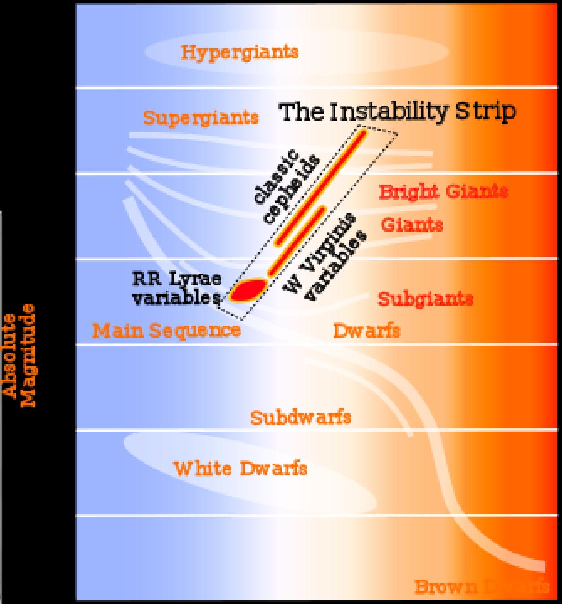
a

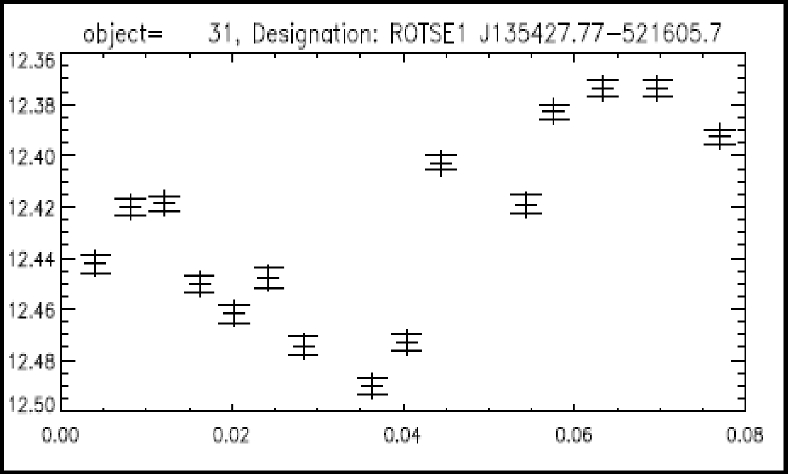
$$d = \frac{1}{}$$

RR Lyrae Variables

- Short period variable stars (< 1 day)
- Commonly found in globular clusters
- Named after prototype RR Lyrae in Lyra
  - ❑ Consumed H at core
  - ❑ Evolved off of main sequence & passed through red giant stage
  - ❑ He fusion in core
- Pulsating horizontal branch stars
  - ❑ Spectral class A (F occasionally)
  - ❑ Mass ≈ 0.5 solar mass; originally about 0.8 solar mass but shed mass during evolution
- Pulse in a manner similar to Cepheids
  - ❑ Old, low mass, metal–poor, Population II stars
  - ❑ More common but less luminous than Cepheids
  - ❑ Absolute mag = 0.75 (40-50 times $L_\odot$)
- Good standard candles for relatively near objects (within Milky Way)
- Also used in globular cluster studies & to study chemical properties of older stars

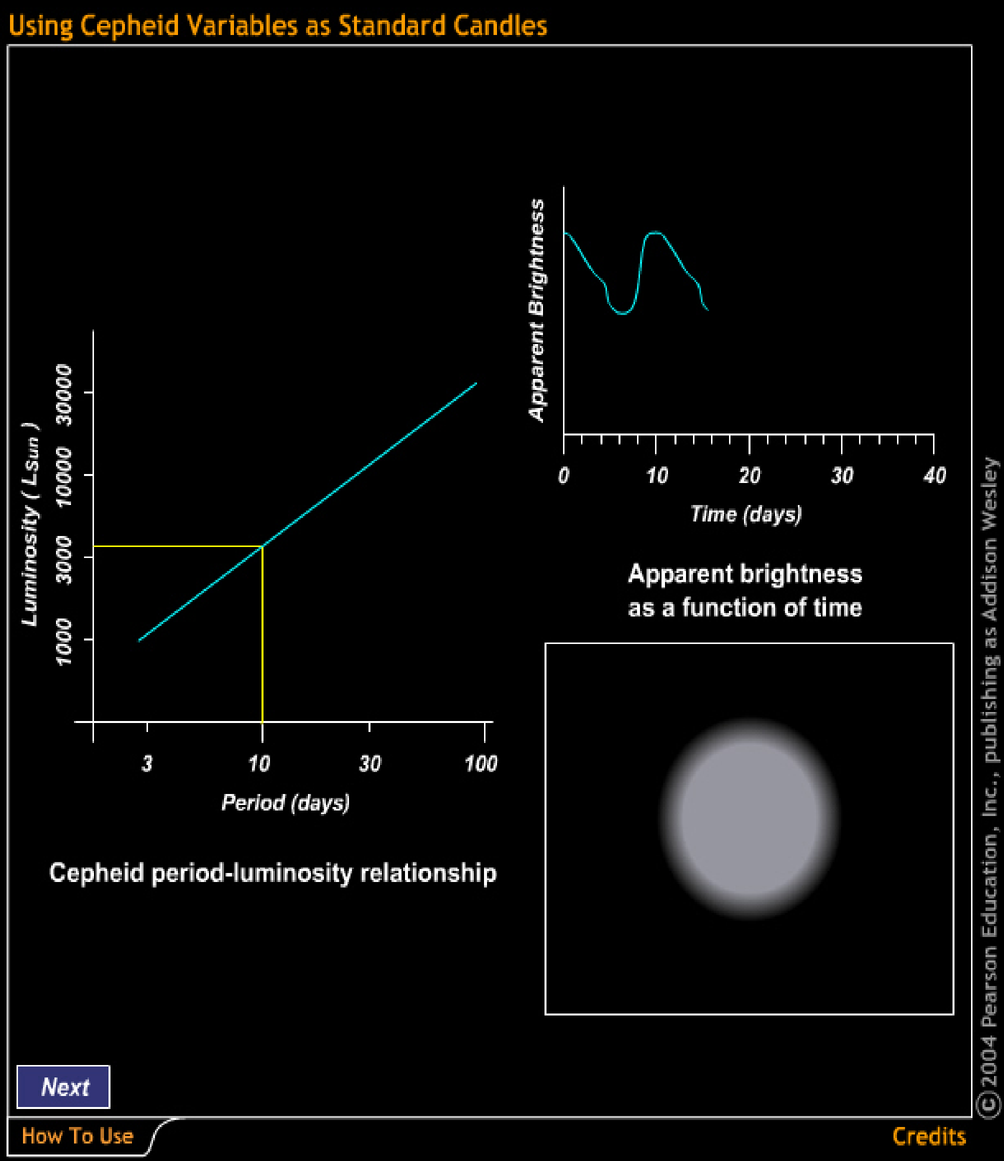




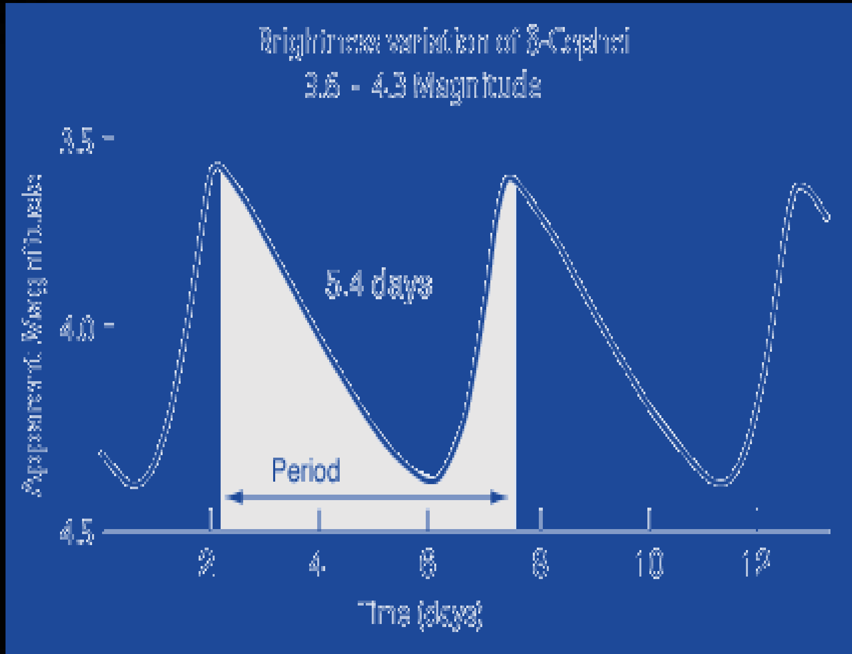


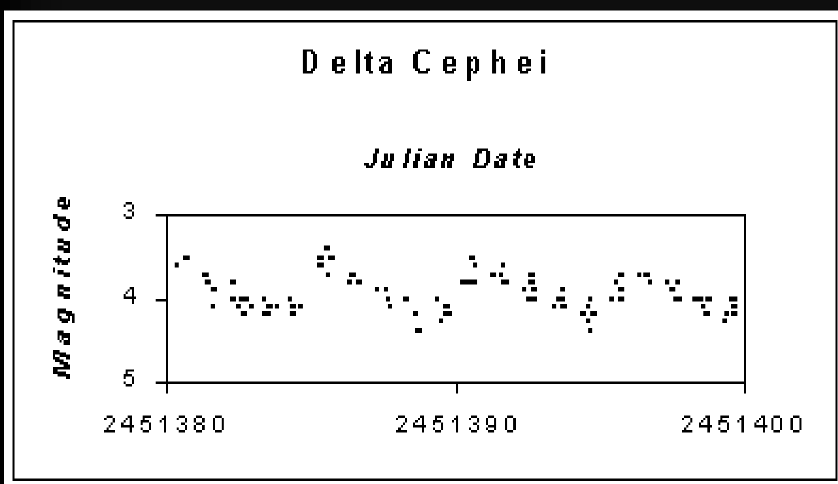
Cepheid Variables

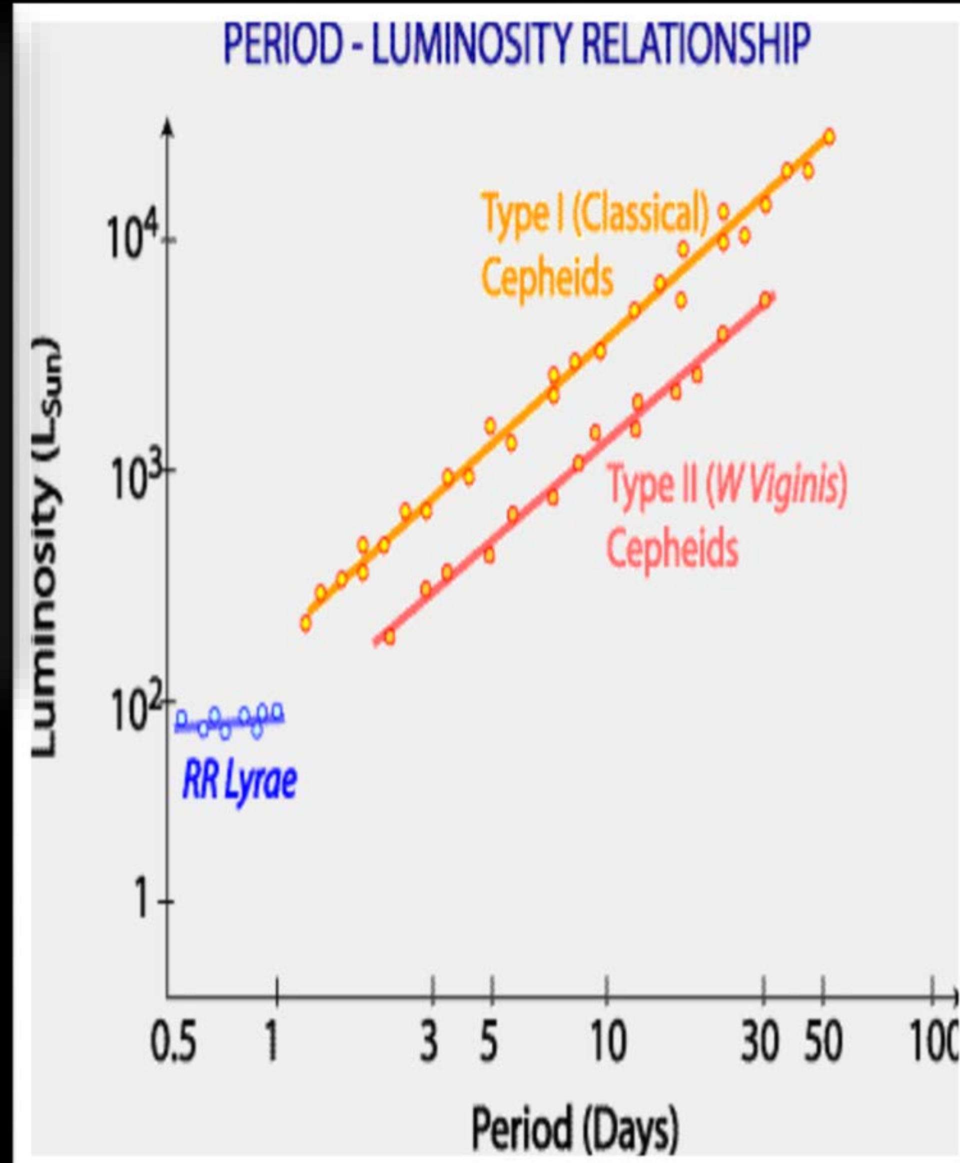
- Cepheid variables (Population I stars) make good standard candles because:
  - ❑ Long period variables
  - ❑ Follow a well-defined period-luminosity relationship
  - ❑ Bright giants -- luminous enough to see at great distances
- Henrietta Swan Leavitt (1868-1921): Observed a certain class of stars that oscillated in brightness periodically (1908)
- Plotting absolute magnitude (luminosity) vs period yielded a precise relationship
- Provided another way to obtain absolute brightness, & hence observed distances
- Because Cepheids are so bright, this method works up to ~5 Mpc
- Most galaxies have at least one Cepheid in them, so distances to 'nearby' galaxies can be determined



Cepheid Variables

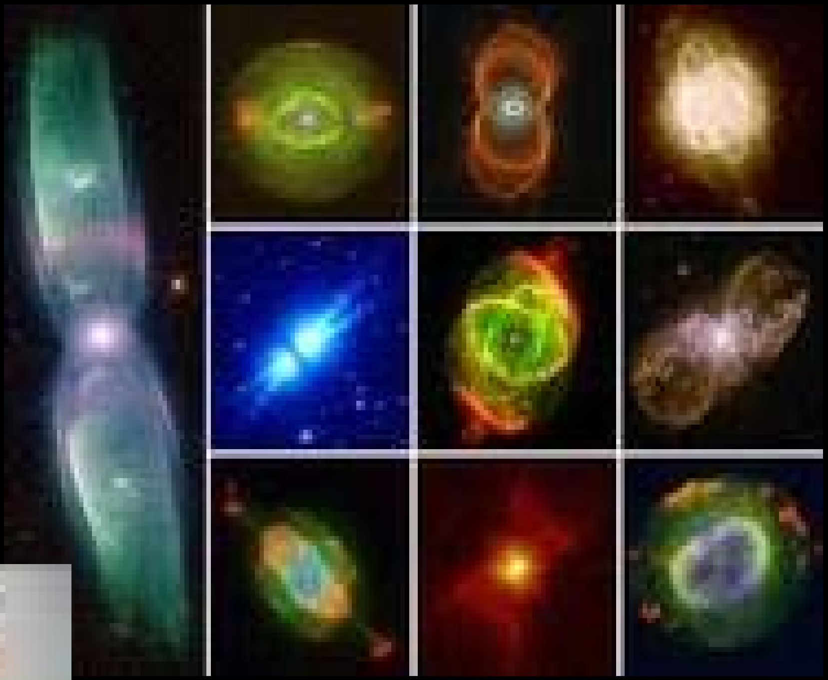


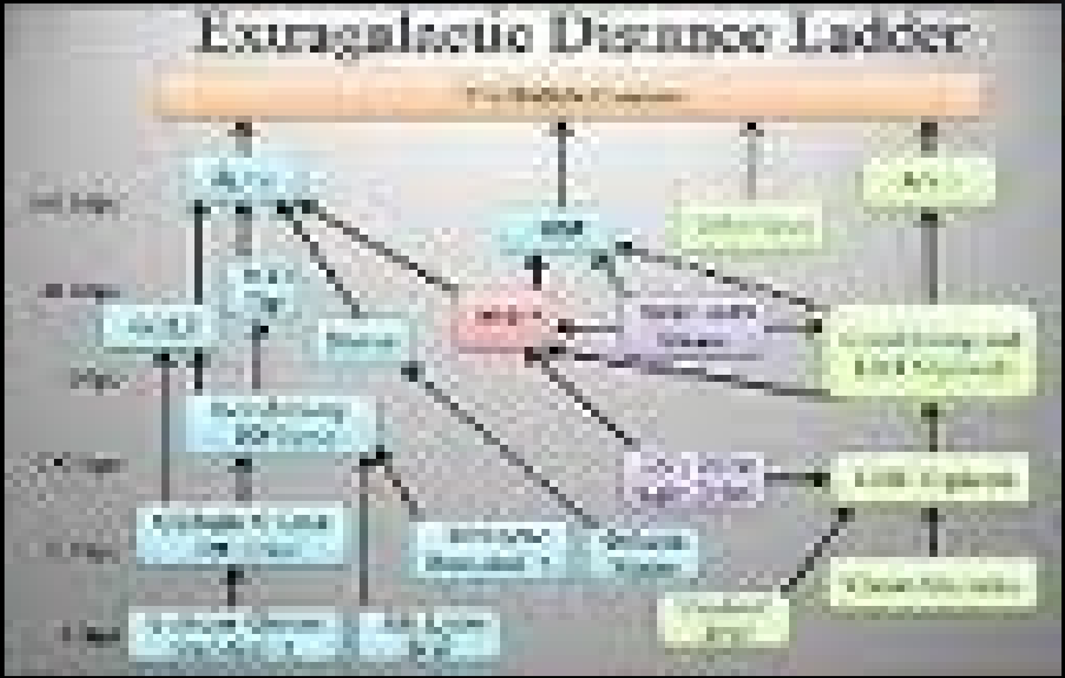




Planetary Nebulae

- Planetary nebula luminosity function (PNLF) is a secondary distance indicator
- Uses the [O III] λ5007 forbidden line found in all planetary nebula which are members of old stellar populations (Population II)
- Works well for both spiral and elliptical galaxies despite completely different stellar populations
- Part of the Extragalactic Distance Scale





The Ring Nebula (NGC 6720)

Most Luminous Supergiants

- Brightest supergiants in a given galaxy will have about the same absolute magnitudes:
  - ❑ About -8 for red supergiants
  - ❑ About -9 for blue supergiants
- These two types of supergiants can be seen out to about 15 Mpc & 25 Mpc respectively
- Compared to a maximum distance of ~ 5 Mpc for Cepheid variables

Galactic center: Sgr A^* is located near the center of this image. Most of these stars are very young and massive and heavily reddened . Spectroscopic studies indicate that the stars are luminous super giants and only a few 10s of millions years old.

VY Canis Majoris (Class M hypergiant) : 3×10^5 times solar luminosity; about 25 times solar mass.

Most Luminous Globular Clusters

- Beyond 25 Mpc, even the brightest blue supergiants fade from view
- Use entire star clusters & nebulae for luminosity measurement
- Brightest globular clusters: total luminosity of ~ magnitude -10; observable out to ~40 Mpc

The M80 globular cluster in the constellation Scorpius is located ~ 28,000 ly from the Sun and contains hundreds of thousands of stars.

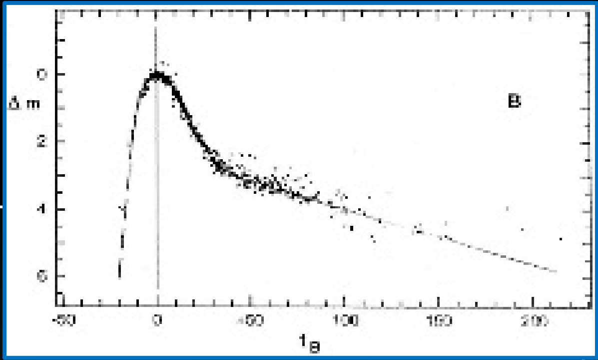
H II Regions

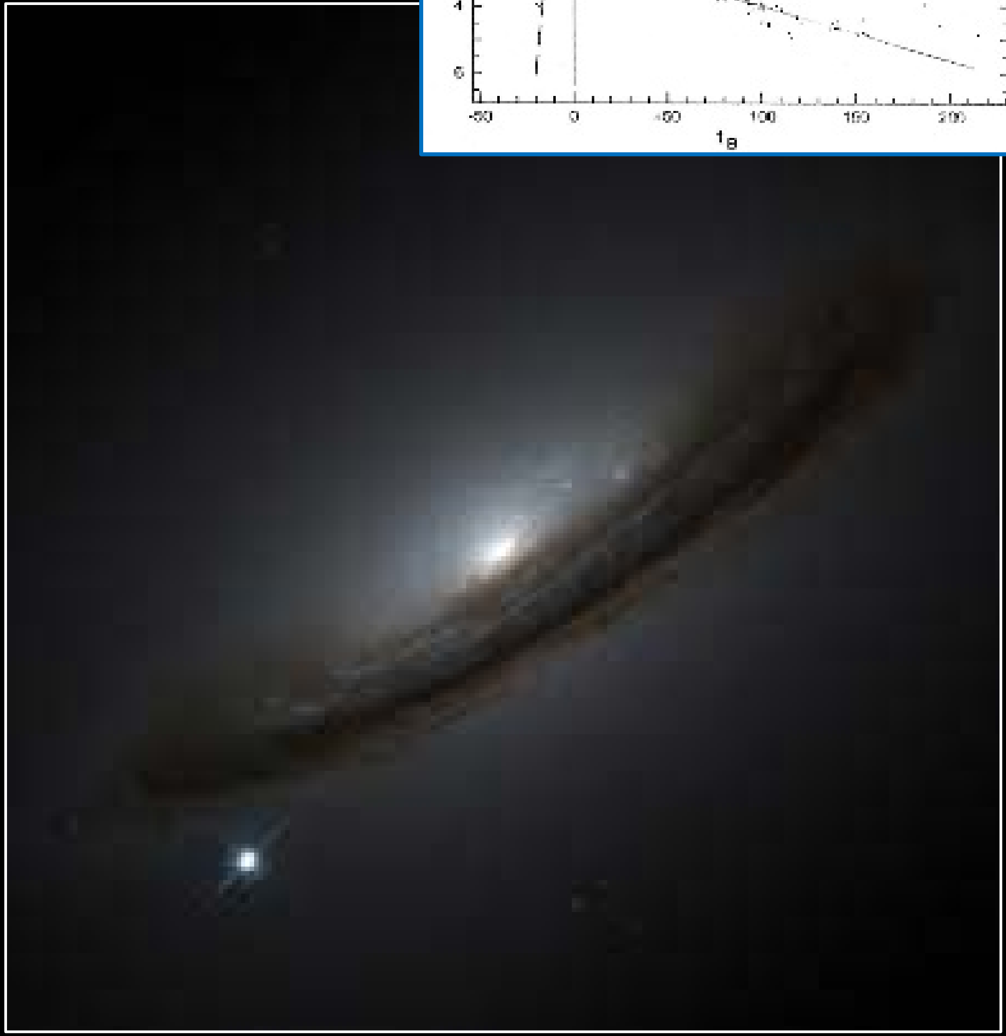
- H II regions: Areas in space which are luminous with the emission spectrum of ionized
- Brightest H II regions: absolute magnitudes of ~ -12; observable to ~ 100 Mpc
- Compared to ~ 40 Mpc for brightest globular clusters
- Associated with massive O-type & B-type stars
  - ❑ Surface temperatures in the range 15 000 – 60 000 K
  - ❑ Characteristic blackbody radiation curves peak in UV
- Often surrounded by vast clouds of H gas
- UV can ionize the H atoms:
  - ❑ H atoms tend to attract electrons & reassemble
  - ❑ Captured electrons cascading down through the quantum states of the H atom
  - ❑ Emit characteristic photons of light upon each downward jump

Eagle Nebula (M16): "The Pillars of Creation"

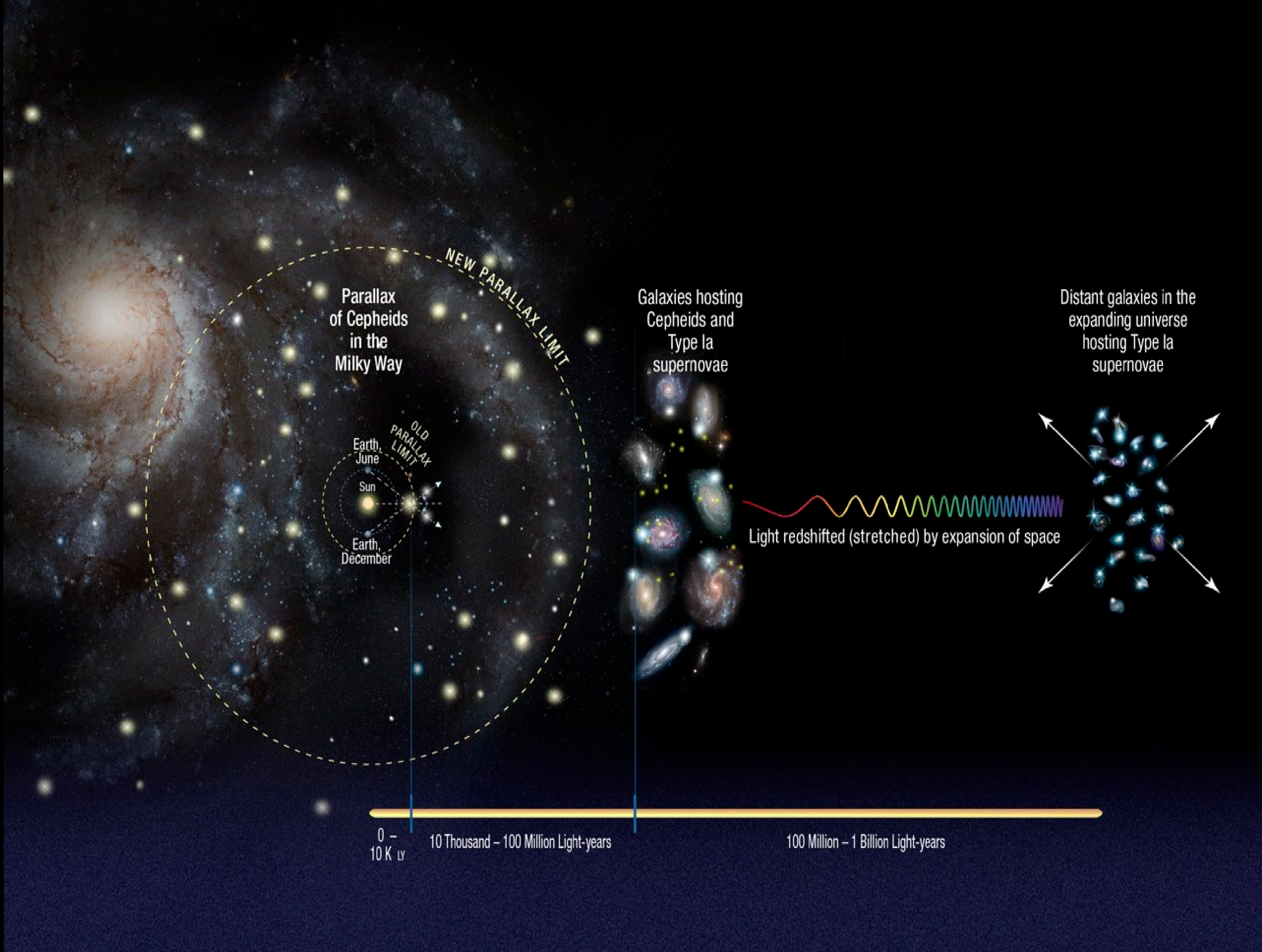
Supernovae (SNe)

- Beyond 100 Mpc even the brightest HII regions are indistinct
- SNe types Ib, Ic & II (core collapse)
  - Show large brightness variations
  - Intervening matter absorbs light
- Type 1a SNe
  - Only individual ‘standardizable’ candles are SNe which can reach a peak magnitude = -19.3 ± 0.3
  - Not as uniform in absolute magnitude as once believed
  - Period-luminosity relationship (period of decline in magnitude as SN fades)
  - Provide a distance measurement uncertainty approaching 5% over vast distance ranges of ~ 1 000 Mpc (1 Gpc)



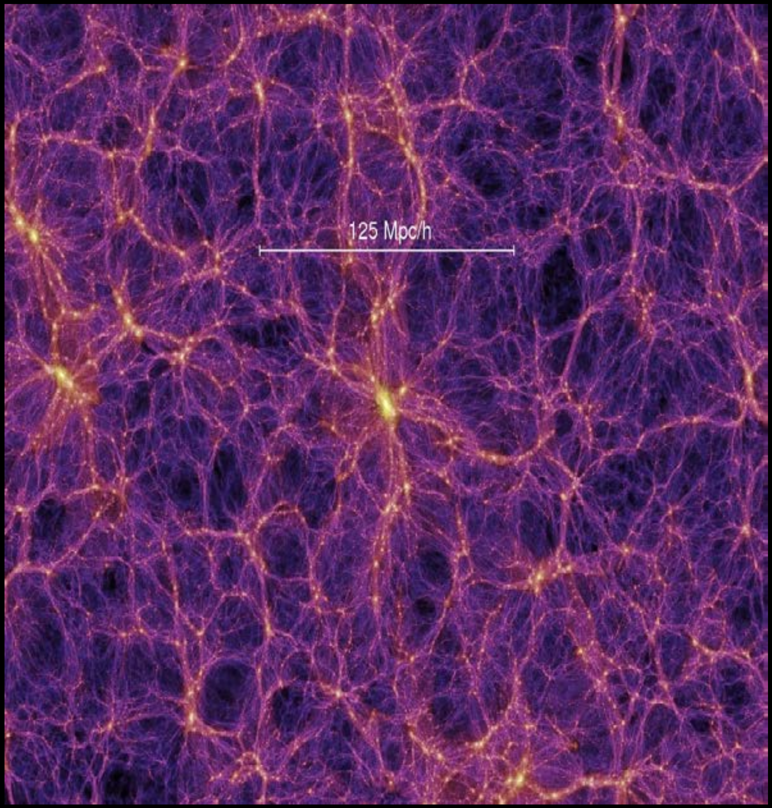


SN 1994D (NGC 4526)


NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Distant galaxies in the expanding universe hosting Type Ia supernovae
Light redshifted (stretched) by expansion of space
0 – 10 K LY
10 Thousand – 100 Million Light-years
100 Million – 1 Billion Light-years

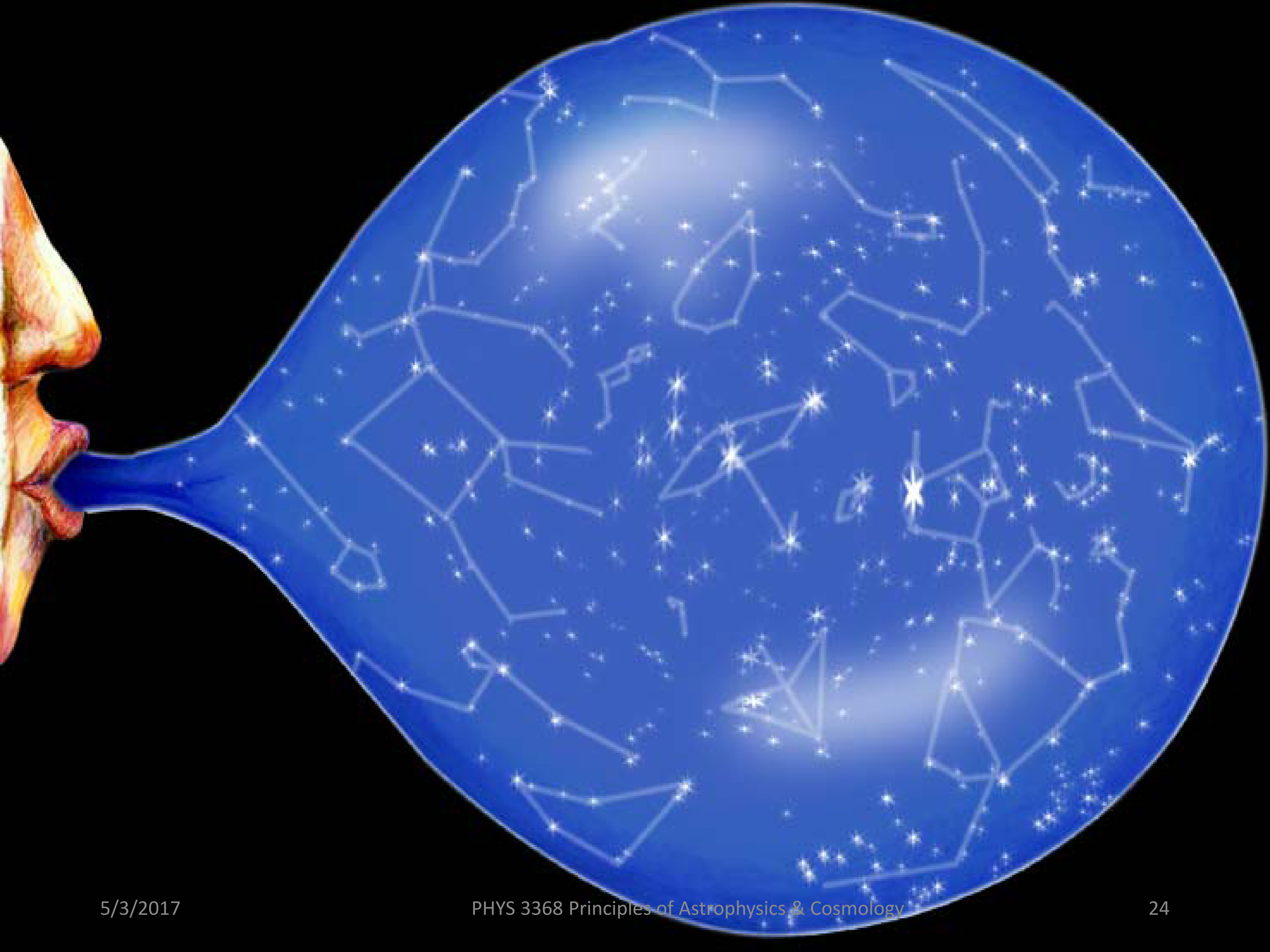
The Standard Model *of Cosmology*

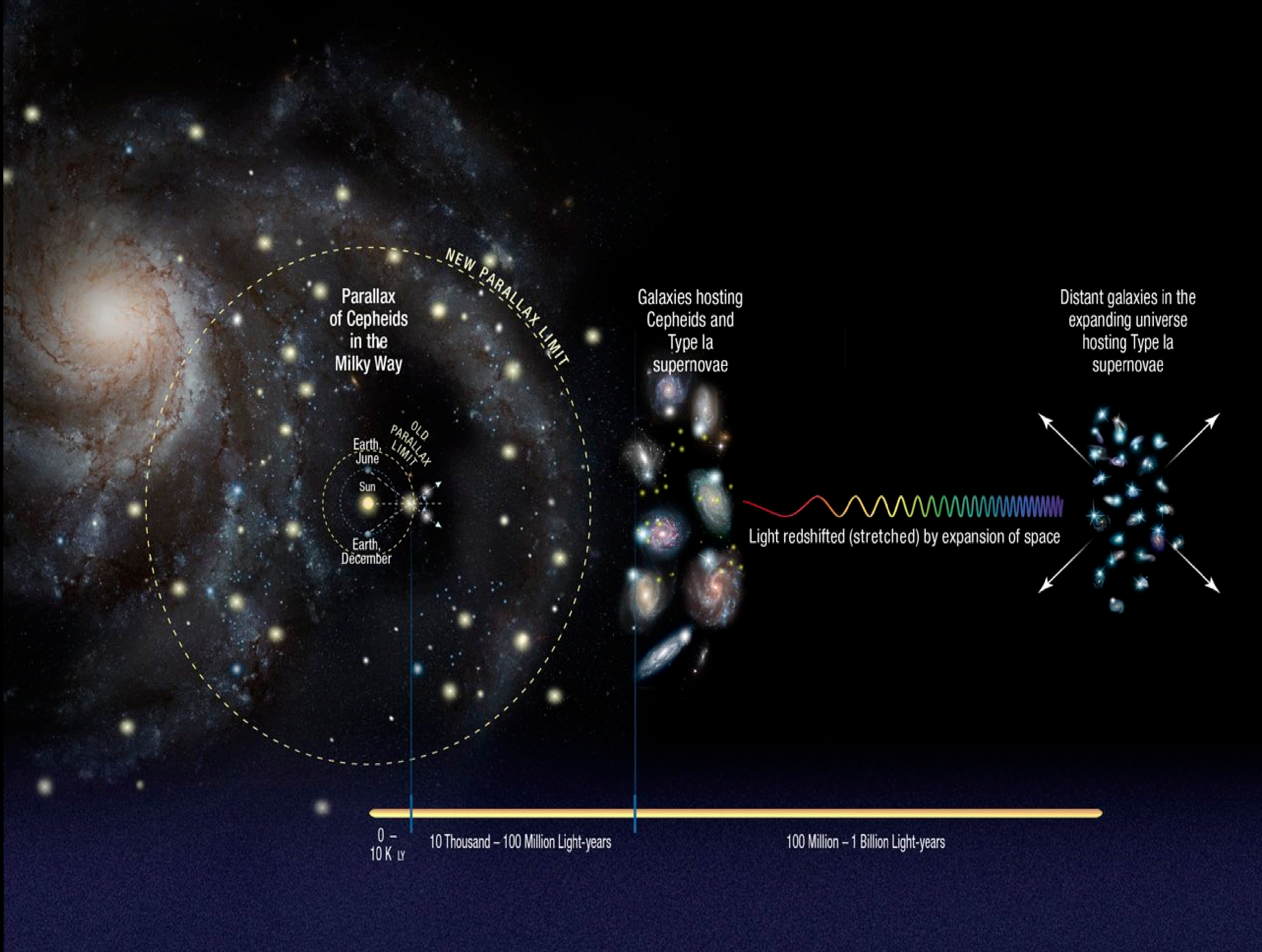
Hubble Ultra Deep Field



[The Universe Adventure](#)

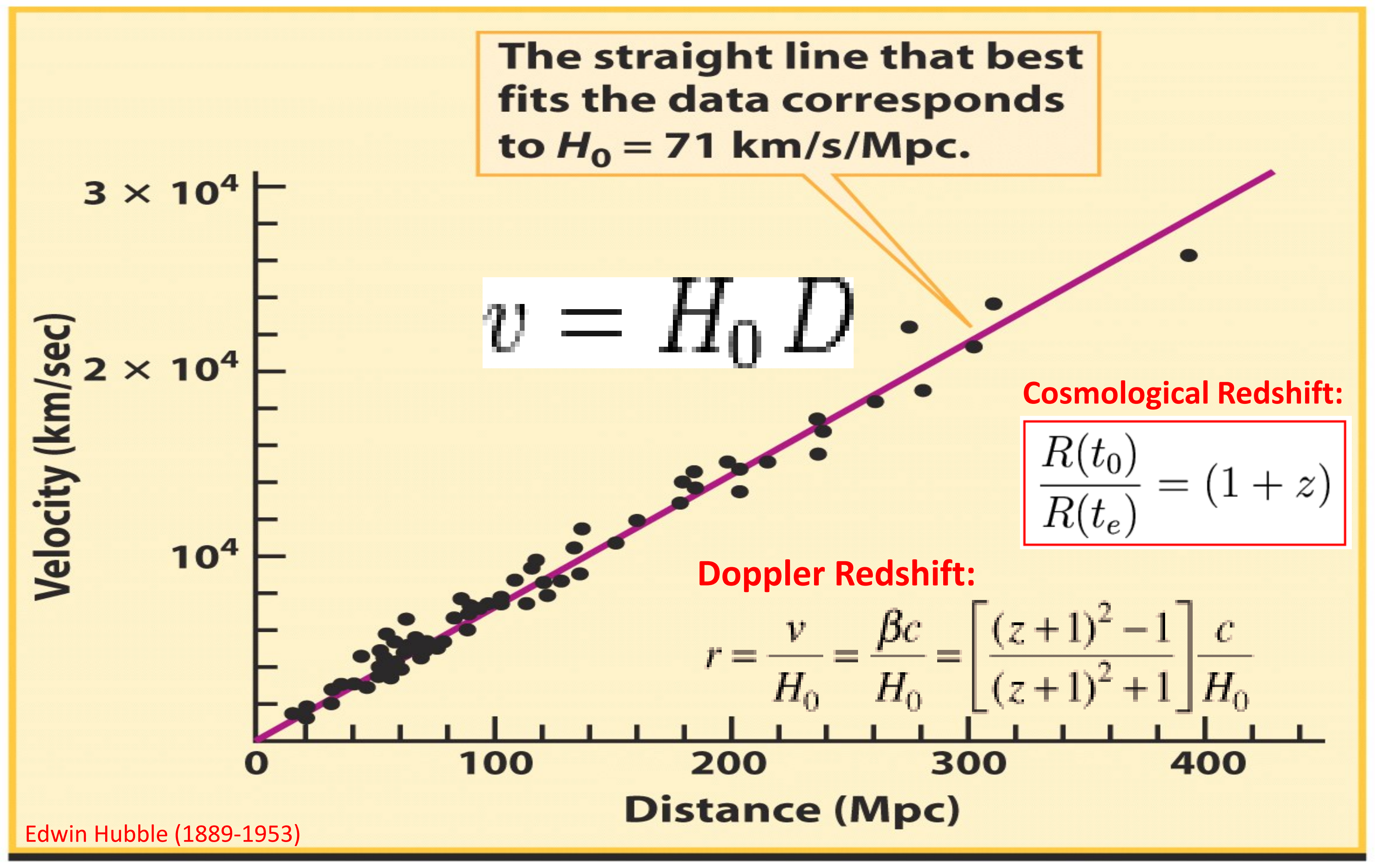
[The Standard Model of Cosmology](#)





NEW PARALLAX LIMIT
Parallax of Cepheids in the Milky Way
OLD PARALLAX LIMIT
Earth, June
Sun
Earth, December
Galaxies hosting Cepheids and Type Ia supernovae
Distant galaxies in the expanding universe hosting Type Ia supernovae
Light redshifted (stretched) by expansion of space
0 – 10 K LY
10 Thousand – 100 Million Light-years
100 Million – 1 Billion Light-years

Hubble Constant & Redshift



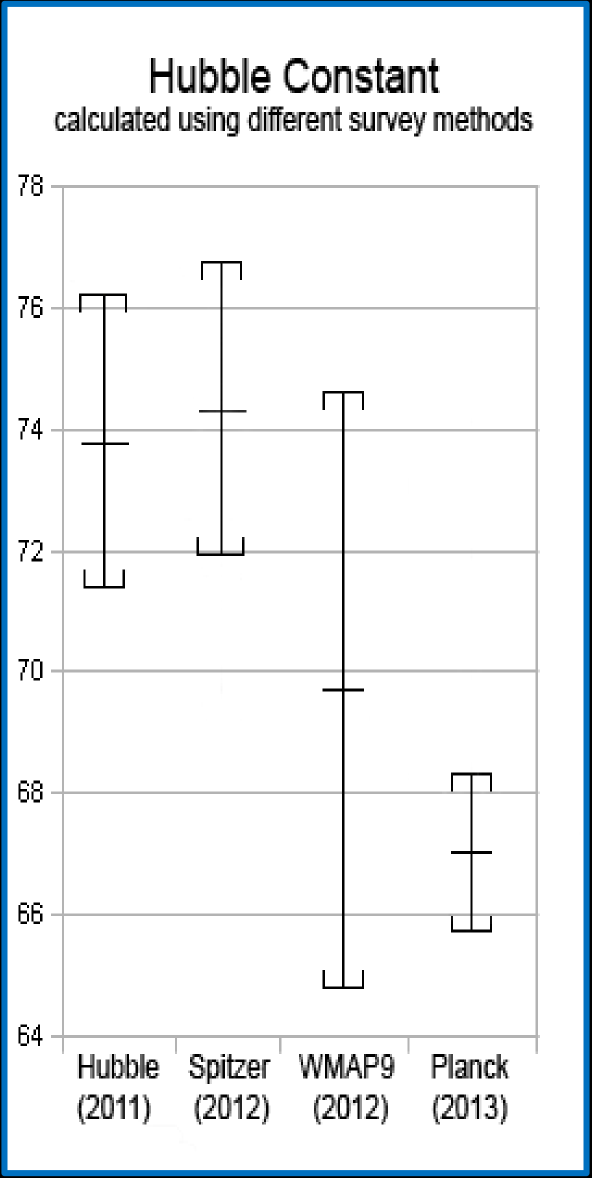
Hubble Time: $t_H = 1/H_0$ = 13.77 Gyr ± 0.11 Gyr

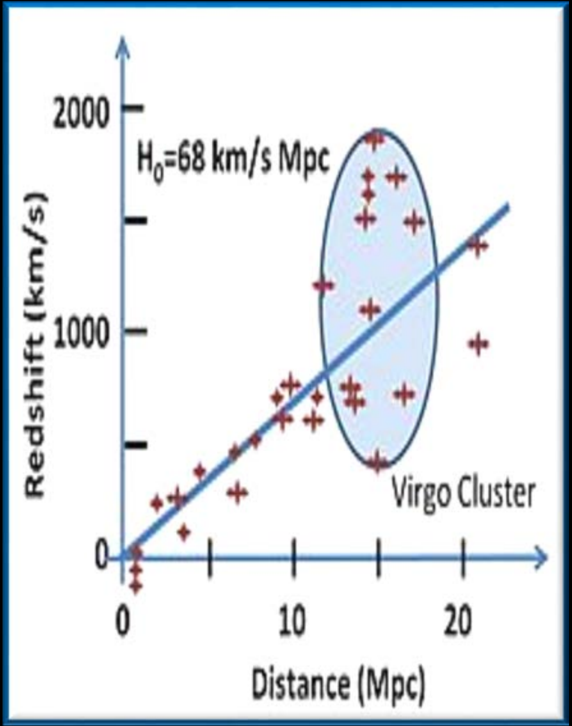
Age of Universe: $t_0 = 0.957 * t_H$ = 13.18 Gyr ± 0.11 Gyr (ΛCDM)

Hubble Constant & Redshift

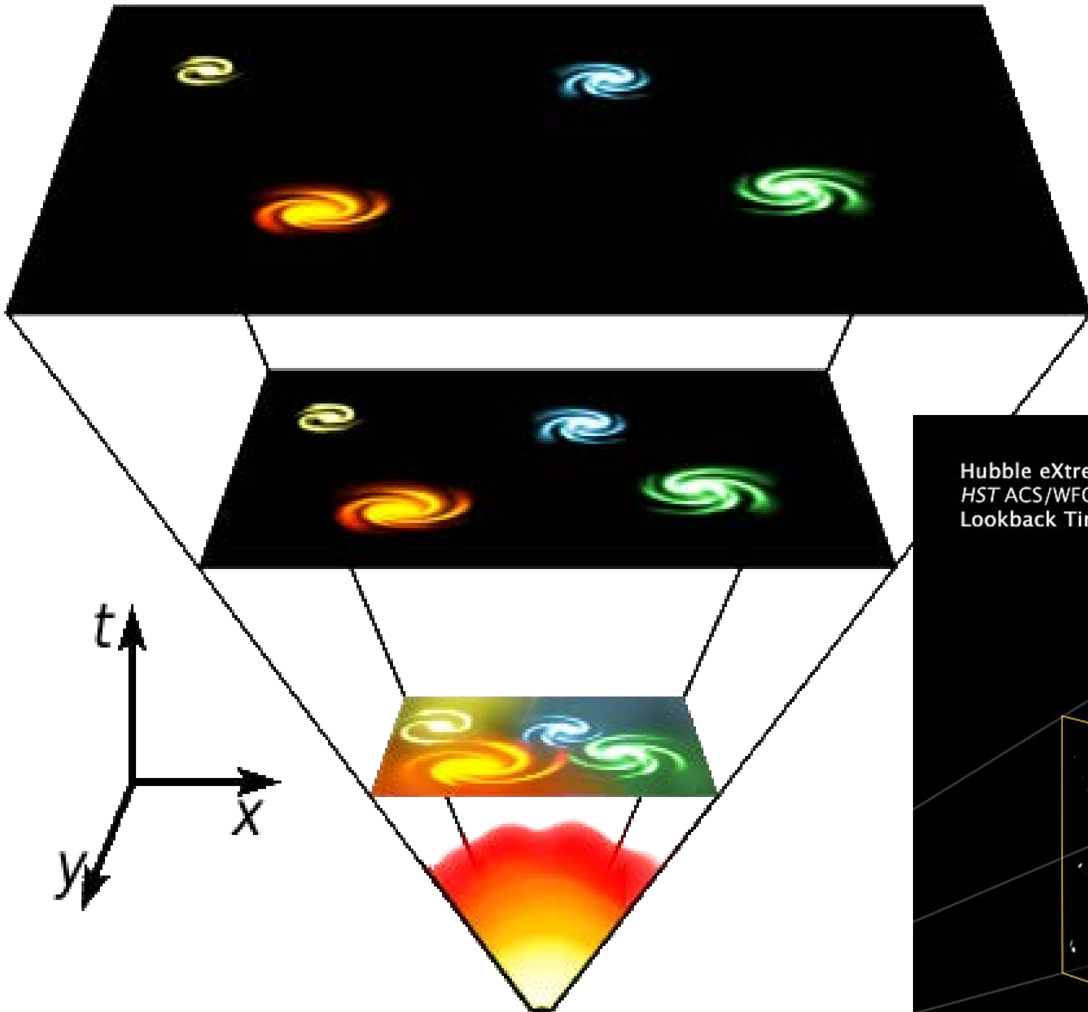
Hubble Constant:

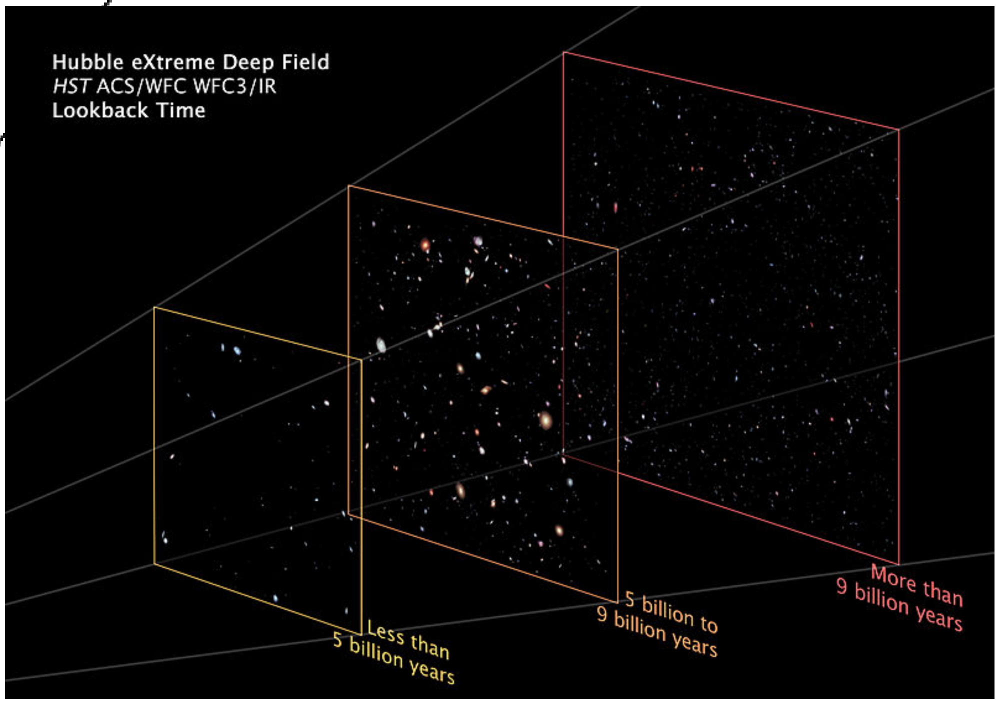
- HST (2001 – 2005):
  - ❑ Type Ia supernovae (yield relative distances to ~ 5%) along with data from Cepheids
  - ❑ H_0 = 72 km/s/Mpc ± 8 km/s/Mpc
  - ❑ t_H = 13.6 Gyr
  - ❑ t_0 = 13.0 Gyr
- WMAP (2010):
  - ❑ H_0 = 71.0 ± 2.5 km/s/Mpc
  - ❑ t_H = 13.75 Gyr ± 0.11 Gyr
  - ❑ t_0 = 13.16 Gyr ± 0.11 Gyr
- Planck (2013):
  - ❑ H_0 = 67.74 ± 0.46 km/s/Mpc
  - ❑ t_H = 14.43 ± 0.05 Gyr
  - ❑ t_0 = 13.81 Gyr ± 0.05 Gyr
- HST (2016):
  - ❑ H_0 = 73.00 km/s/Mpc ± 1.75 km/s/Mpc
  - ❑ t_H = 13.39 Gyr
  - ❑ t_0 = 12.81 Gyr
- SDSS III BOSS (2016):
  - ❑ H_0 = 67.6 km/s/Mpc ± 0.7 km/s/Mpc
  - ❑ t_H = 14.46 Gyr
  - ❑ t_0 = 13.84 Gyr



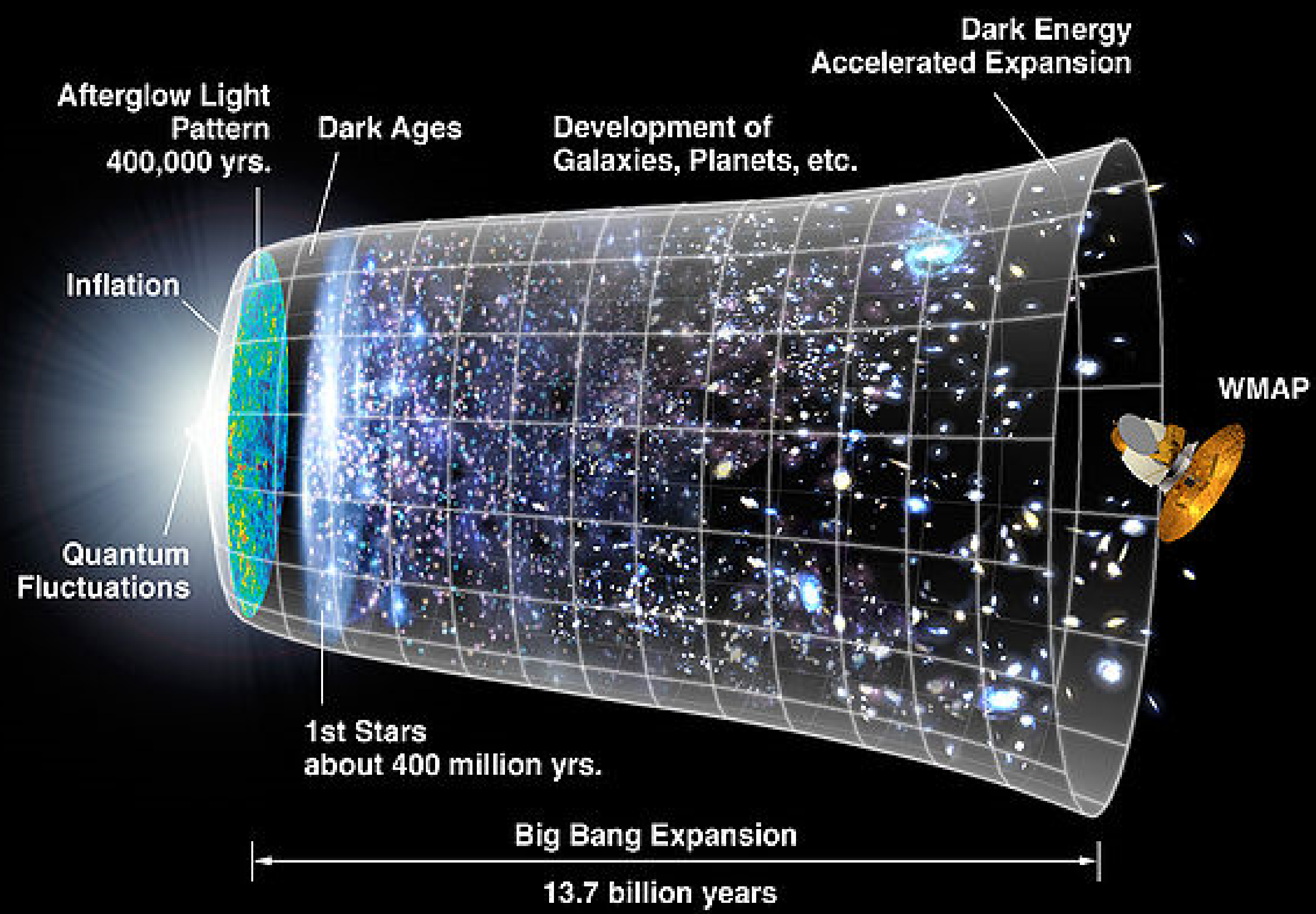


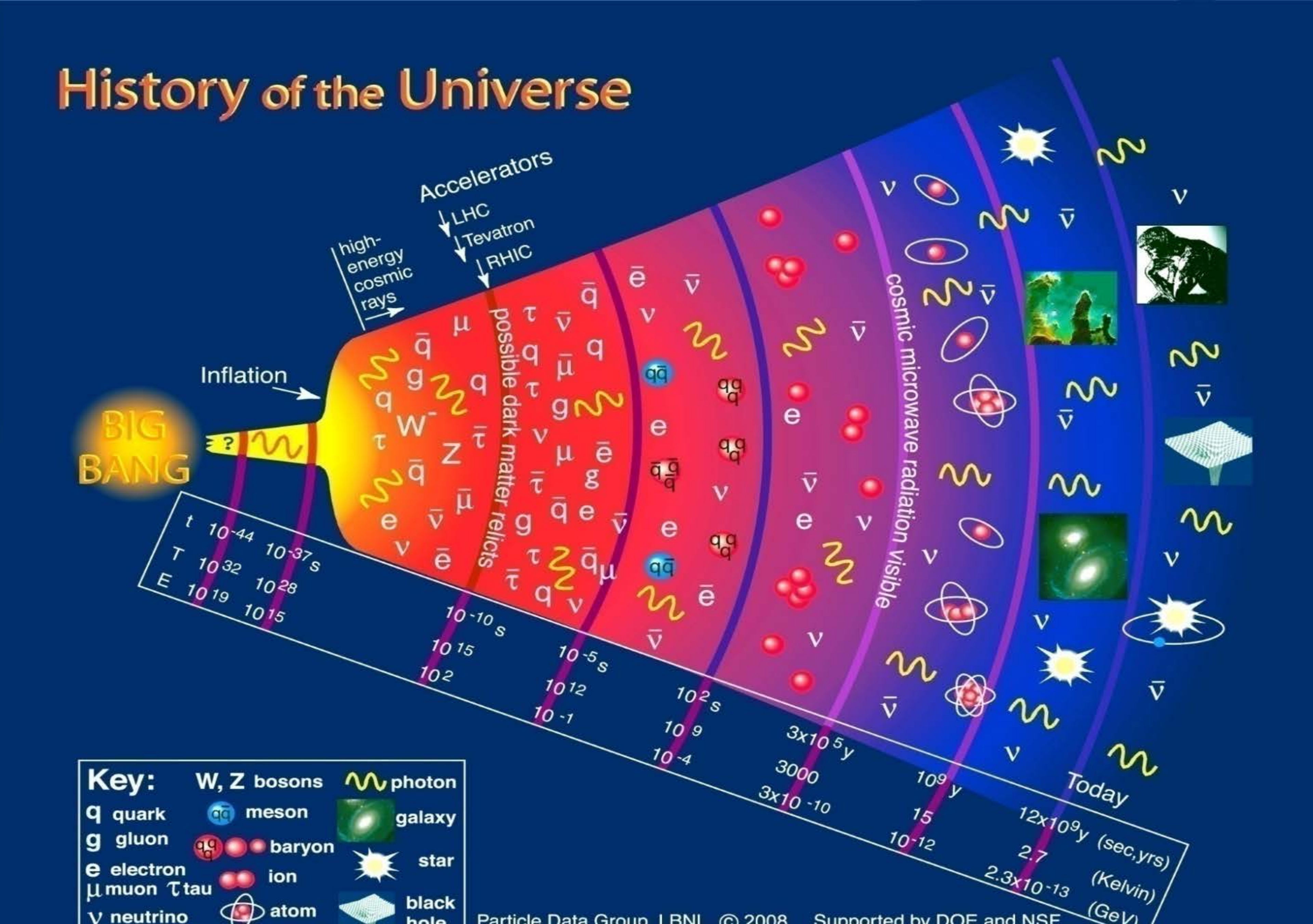
Evidence for Big Bang and Problems with Big Bang Model



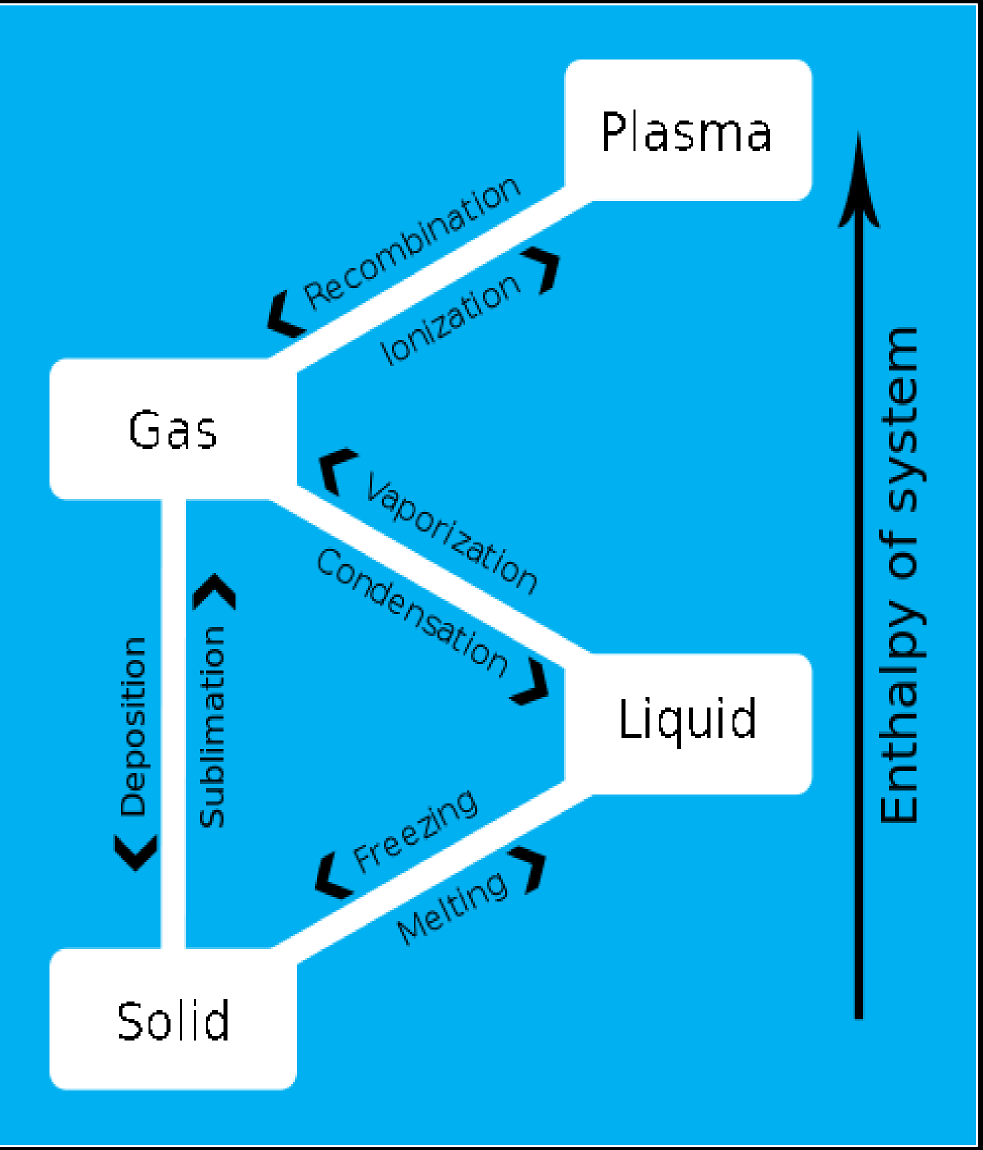


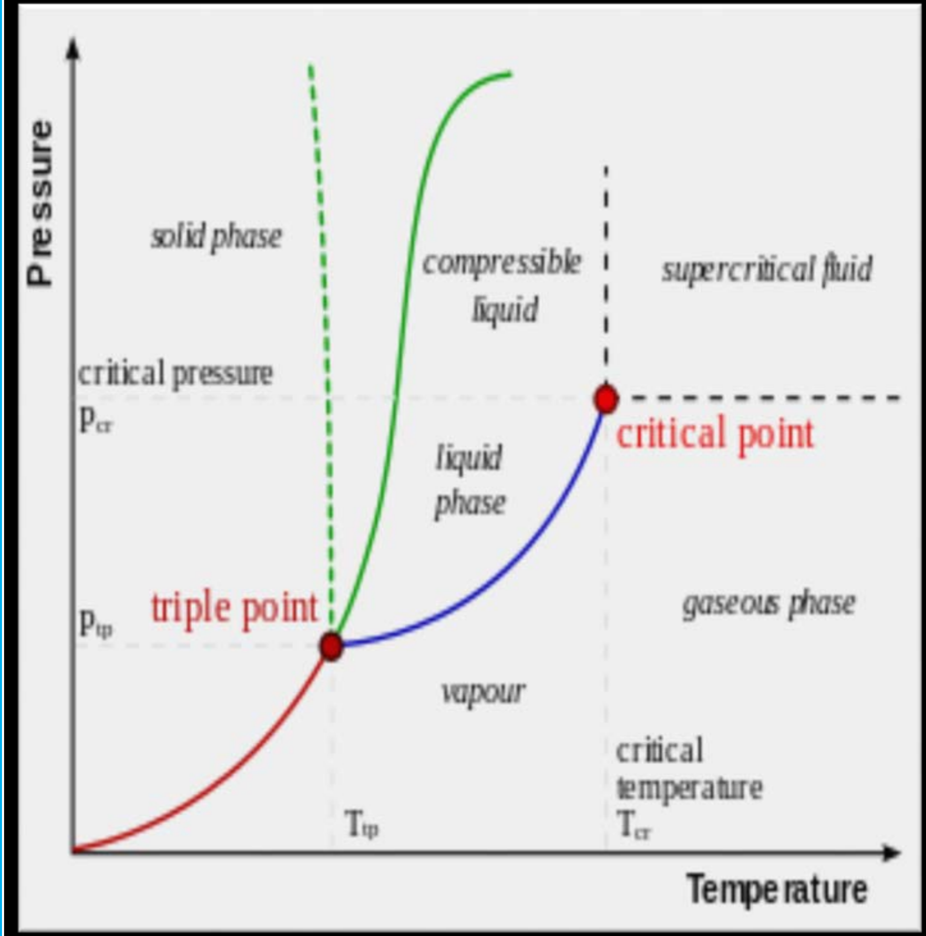
Standard Model of Cosmology (ΛCDM)

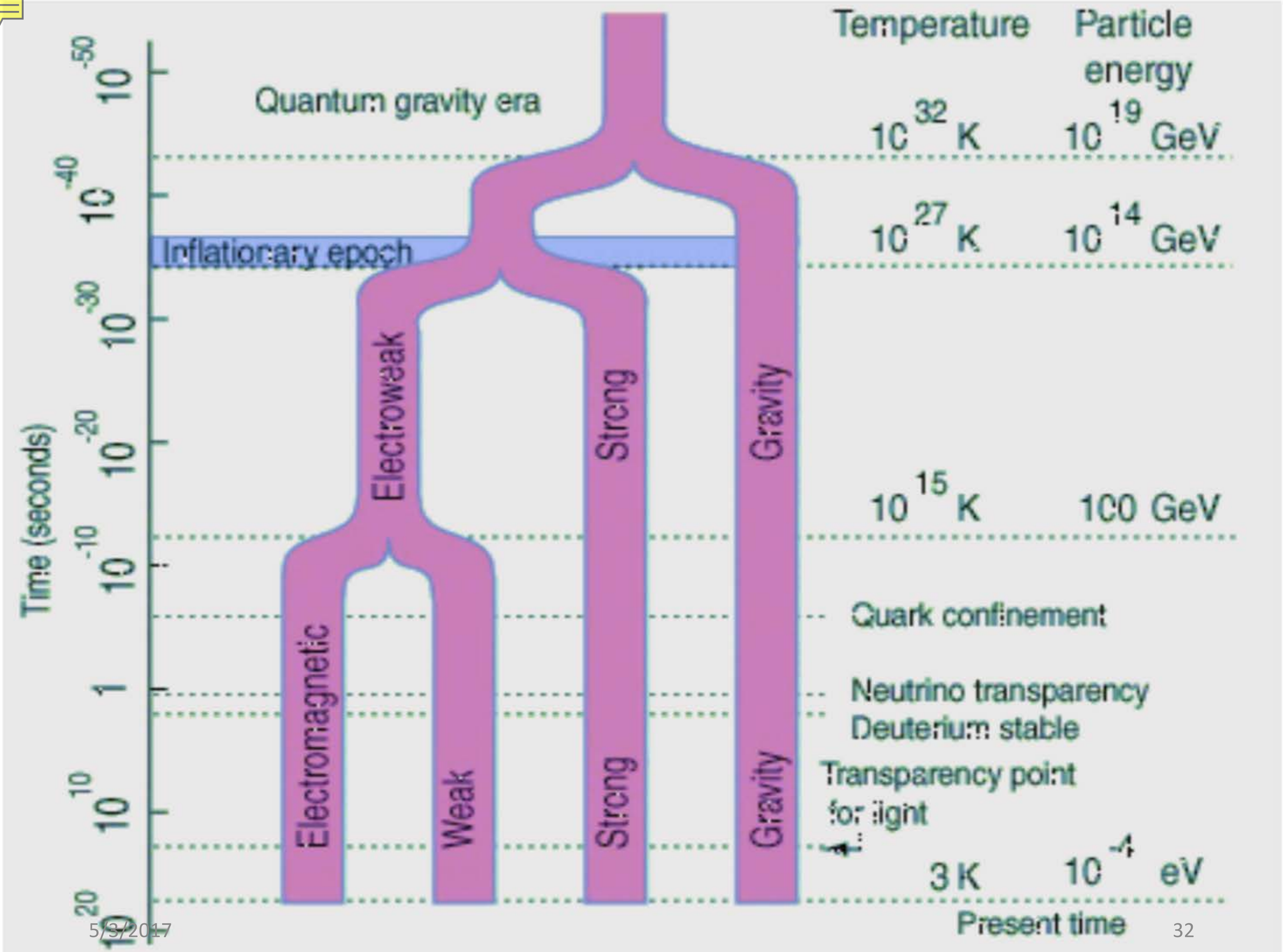



History of the Universe
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
meson
baryon
ion
atom
photon
galaxy
star
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Phase Change



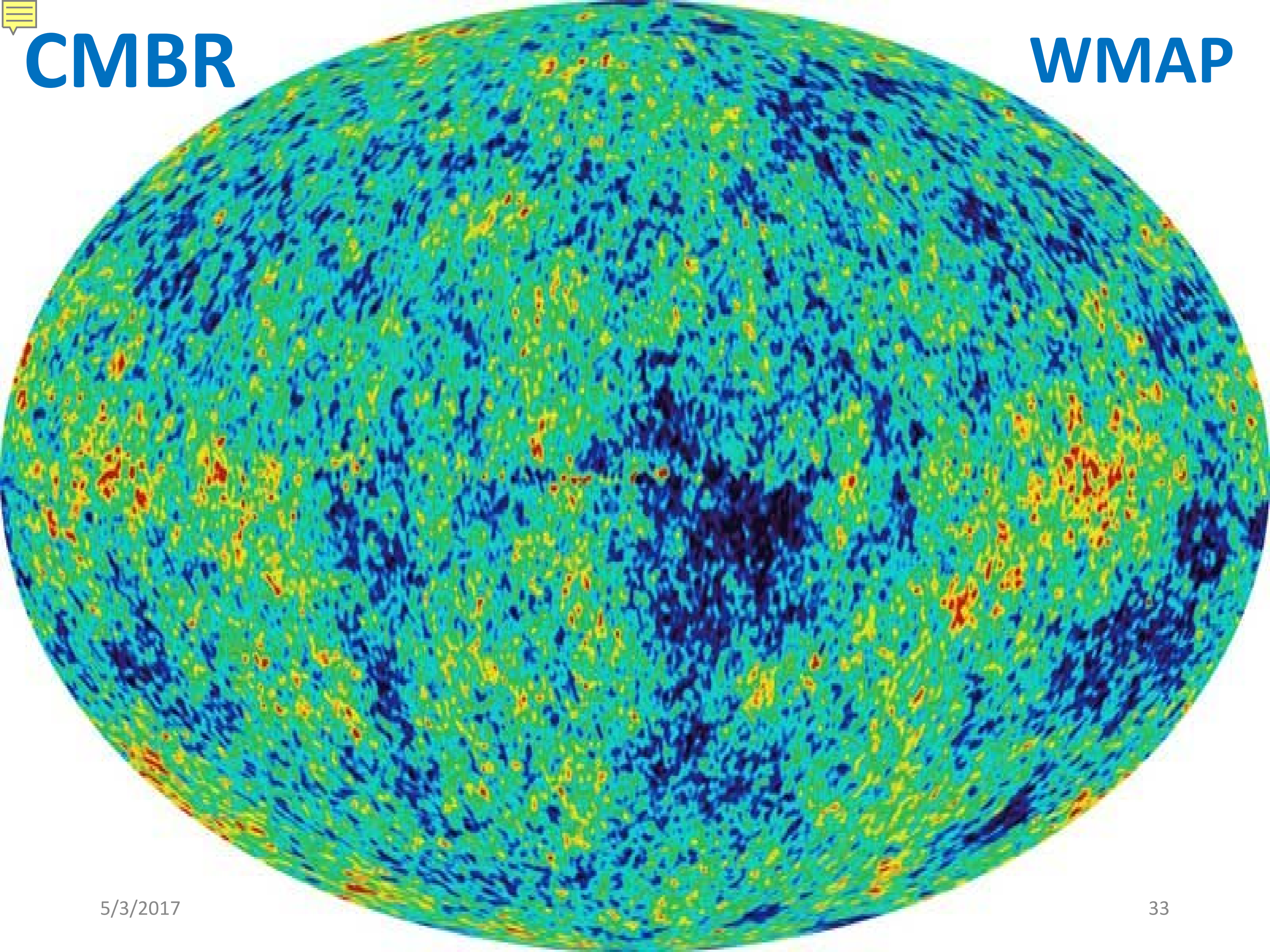




Temperature
Particle energy
Quantum gravity era
10^32 K
10^19 GeV
10^27 K
10^14 GeV
Inflationary epoch
Electroweak
Strong
Gravity
10^15 K
100 GeV
Quark confinement
Neutrino transparency
Deuterium stable
Transparency point for light
Electromagnetic
Weak
Strong
Gravity
3 K
10^-4 eV
Present time
Time (seconds)
10^-50
10^-40
10^-30
10^-20
10^-10
1
10^10
10^20

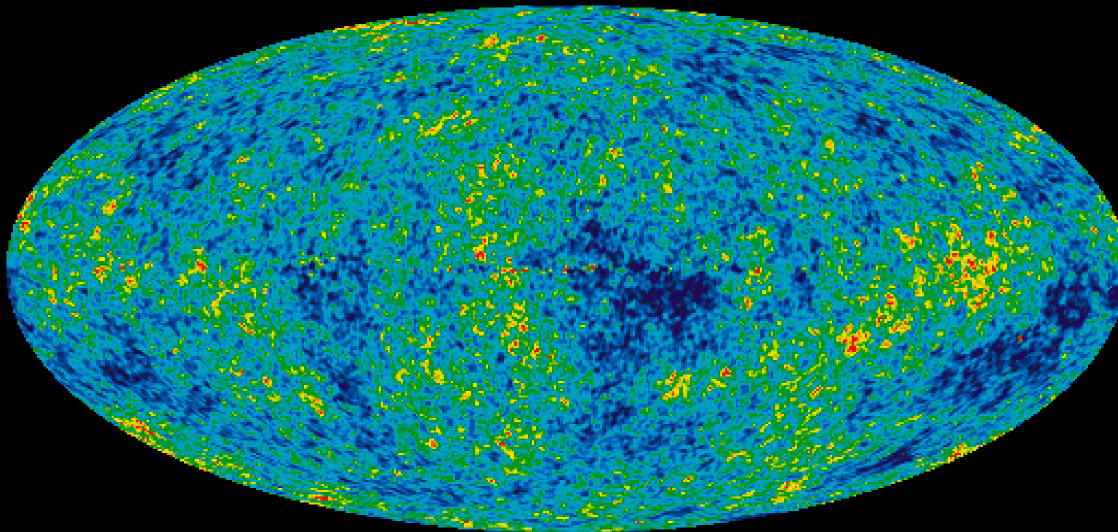
CMBR

WMAP



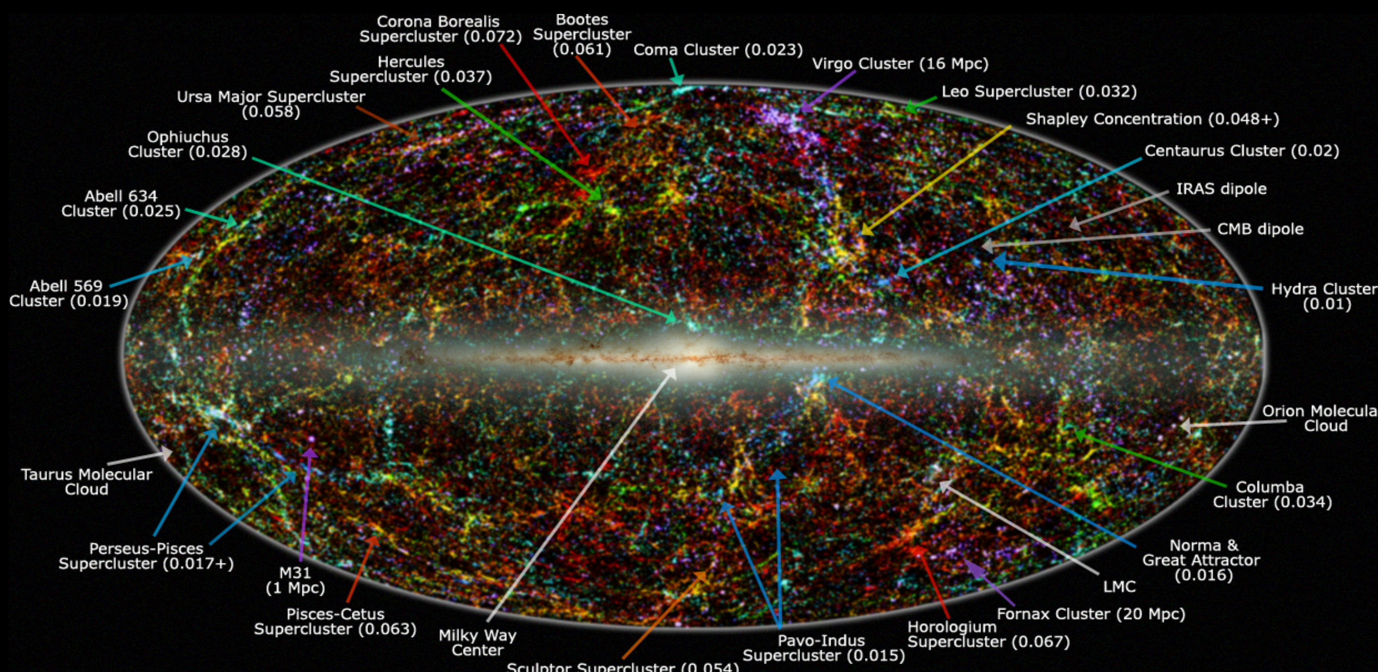
We’re just trying to get from Point A to Point B

Universe as it appeared 13.5 billion years ago

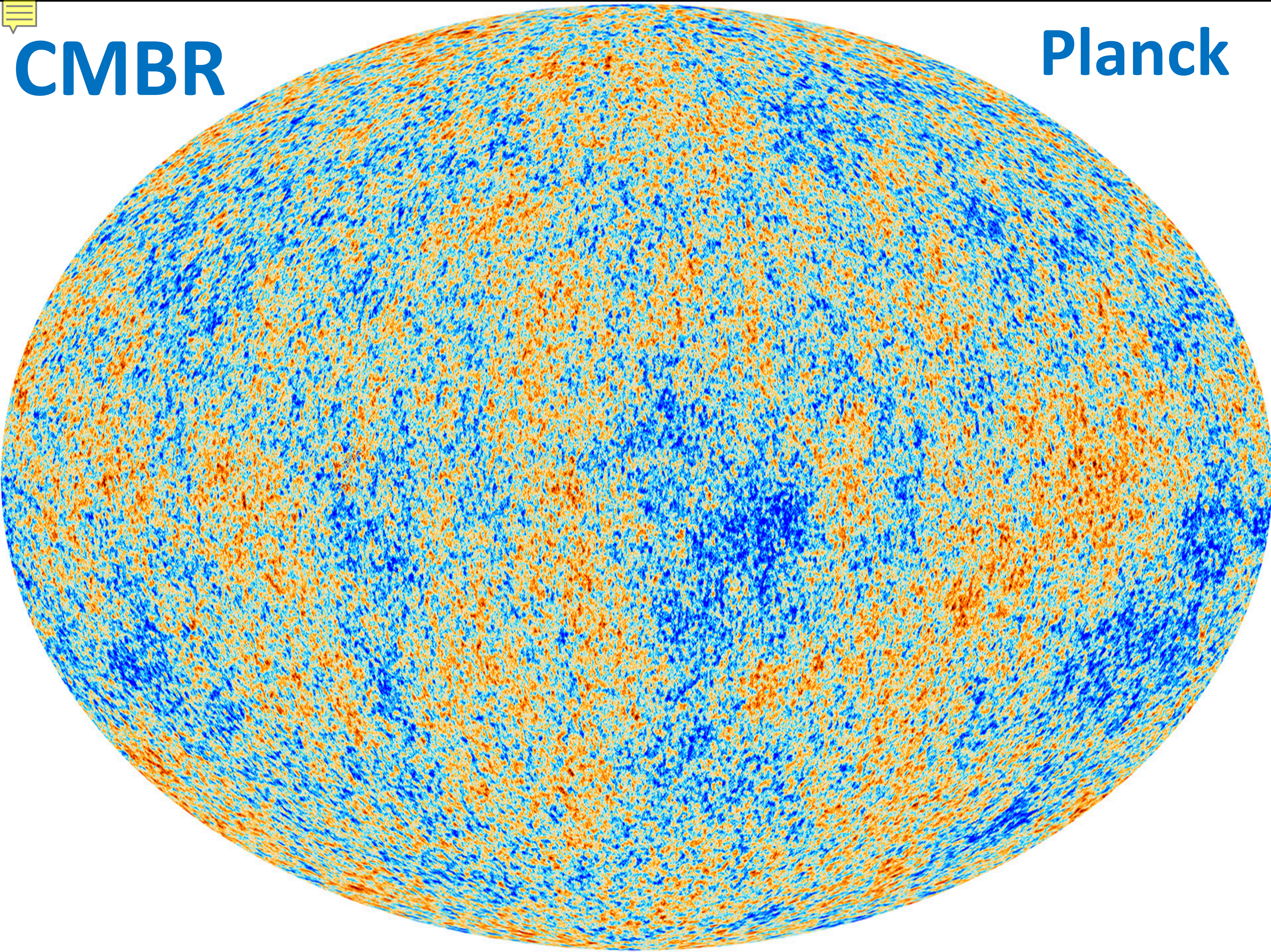


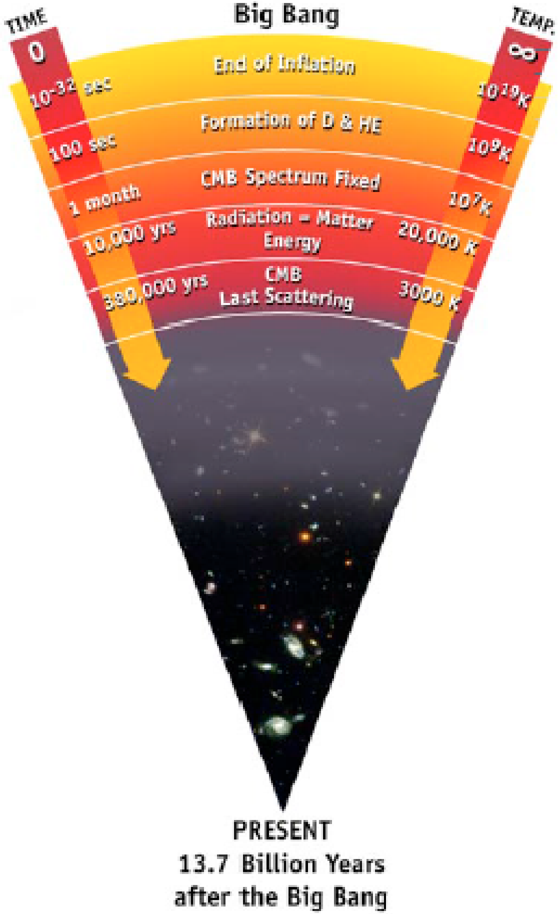
Time

Today

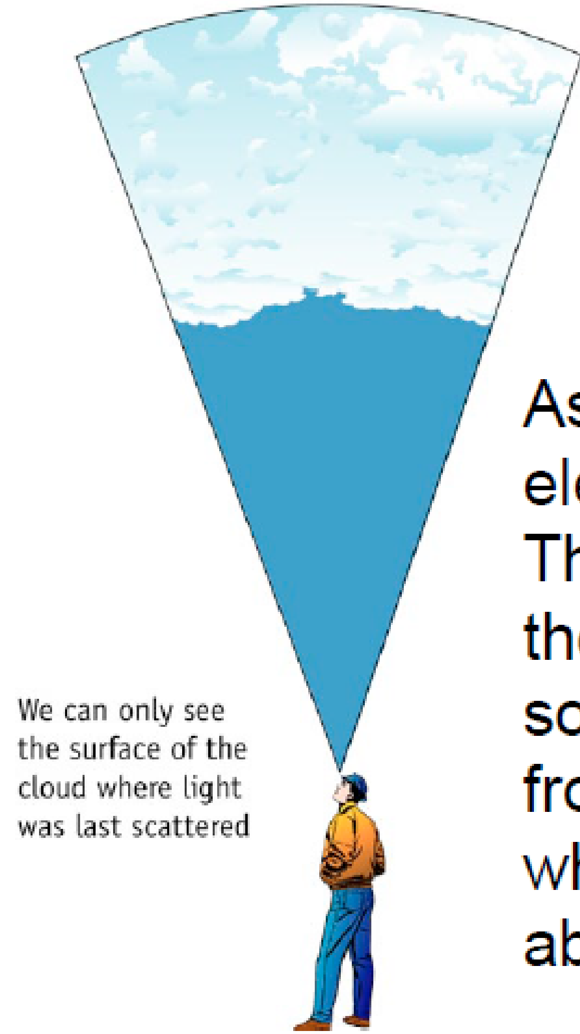


CMBR





The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



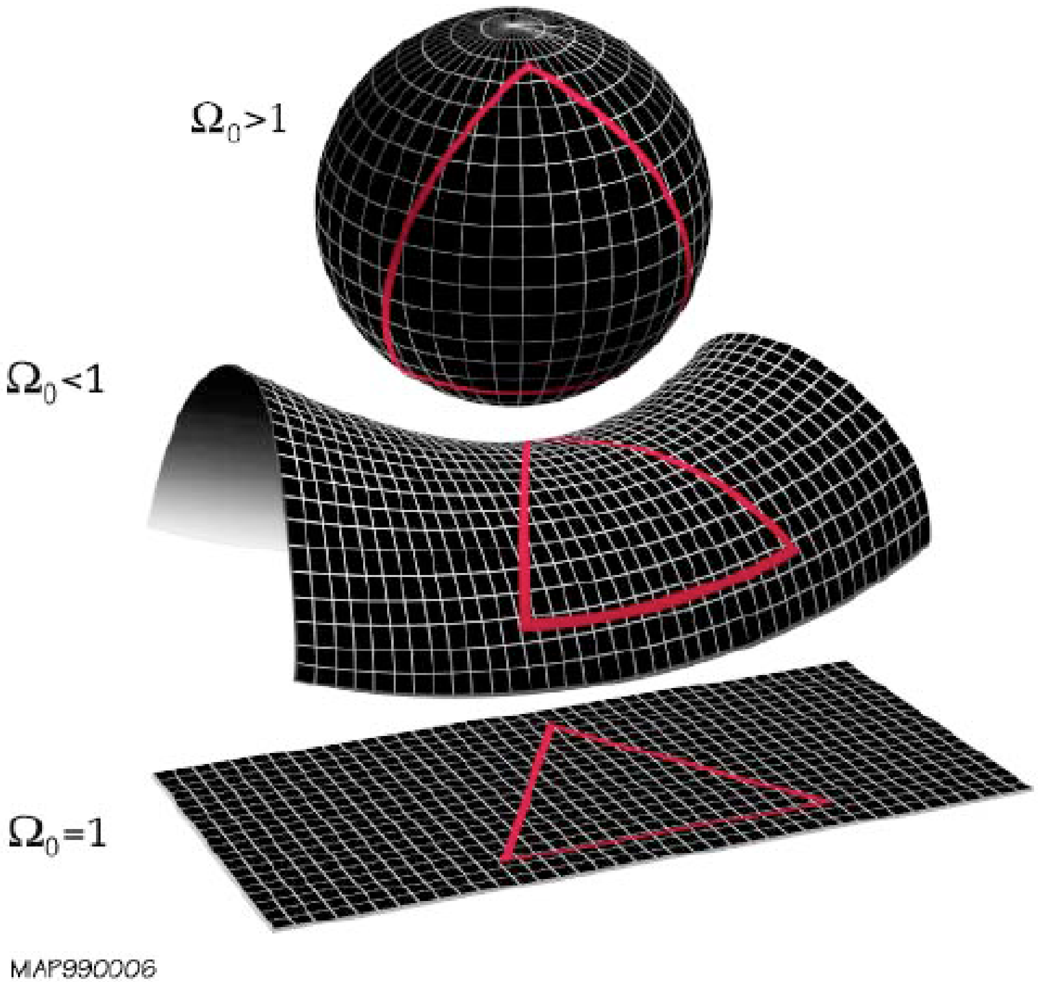
As T drops nuclei capture electrons and form atoms. This results in a big drop in the ionization fraction and so the photons decouple from the matter at this time when the universe was about 400,000 years old.

CMB anisotropy: Along with initial last-scattering surface irregularities, as the CMB propagates to us, metric irregularities along the line of sight make it more anisotropic.

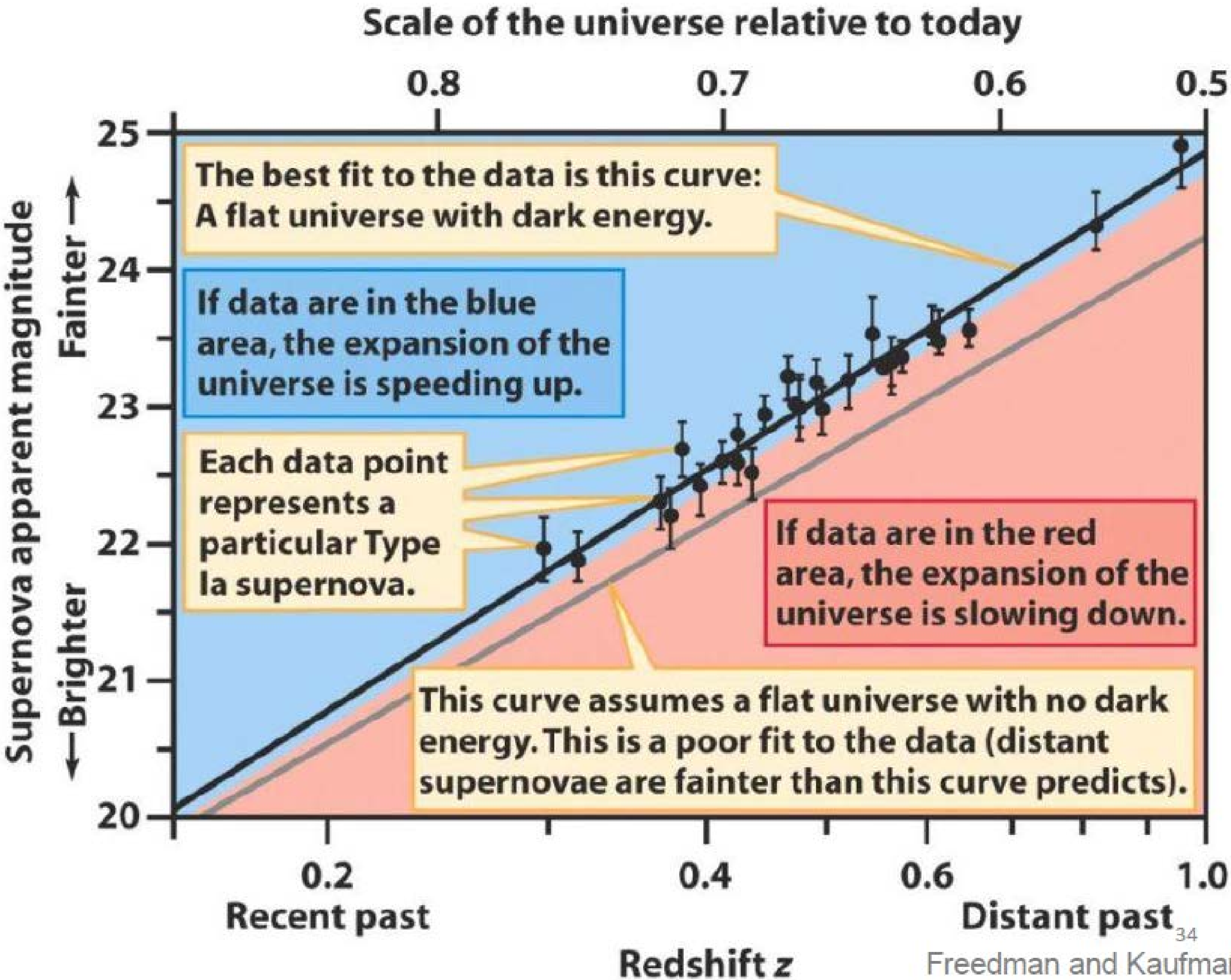
Geometry of Universe

$$ds^2 = dt^2 - a^2(t)\,[dr^2 + S_K{}^2(r)\,\{d\theta^2 + \sin^2(\theta)d\phi^2\}]$$

(2 dimensional analogs)



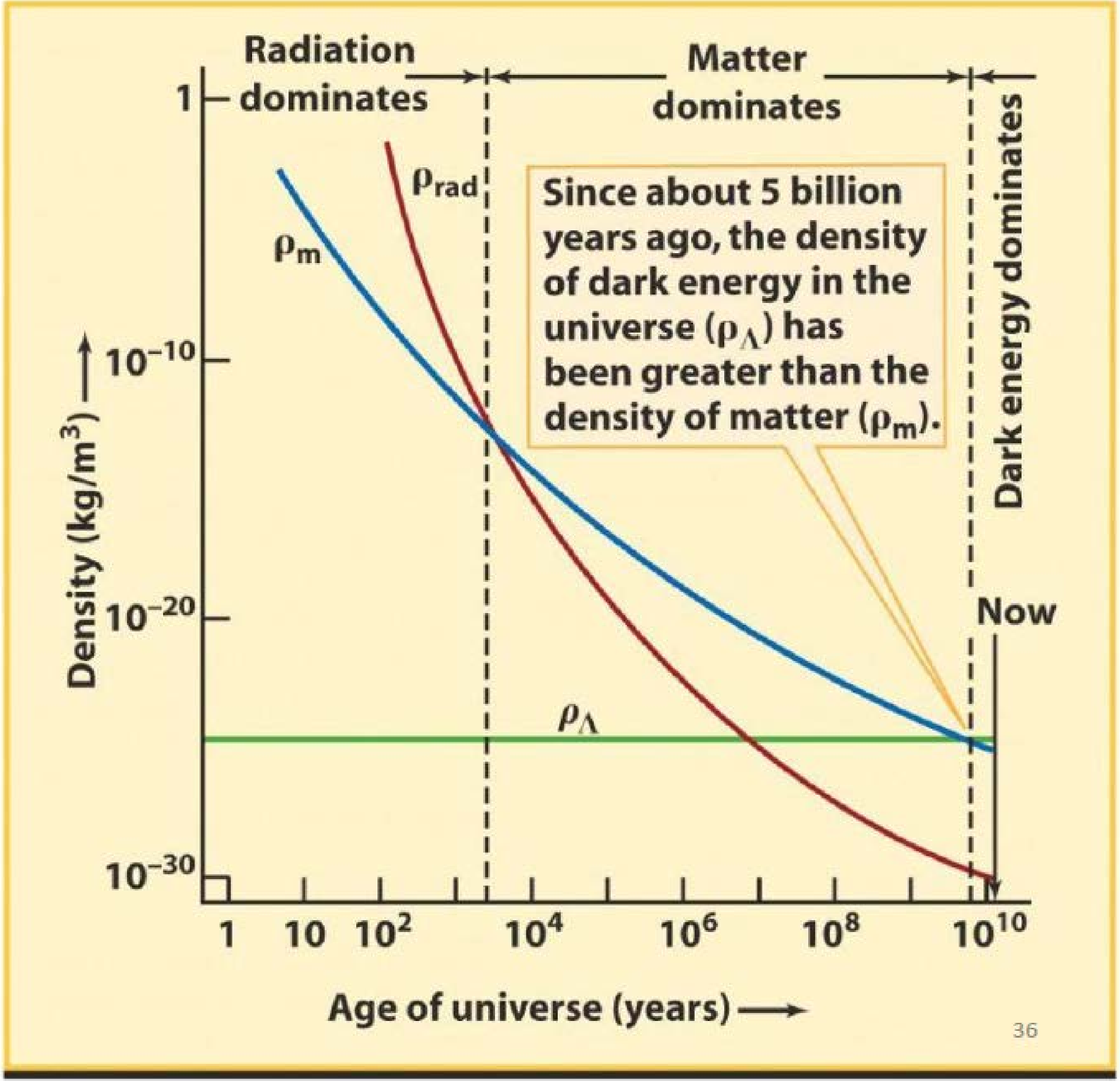
	$S_K(r)$	K^2
closed	sin(r)	>0
open	sinh(r)	<0
flat	r	=0



Freedman and Kaufmann

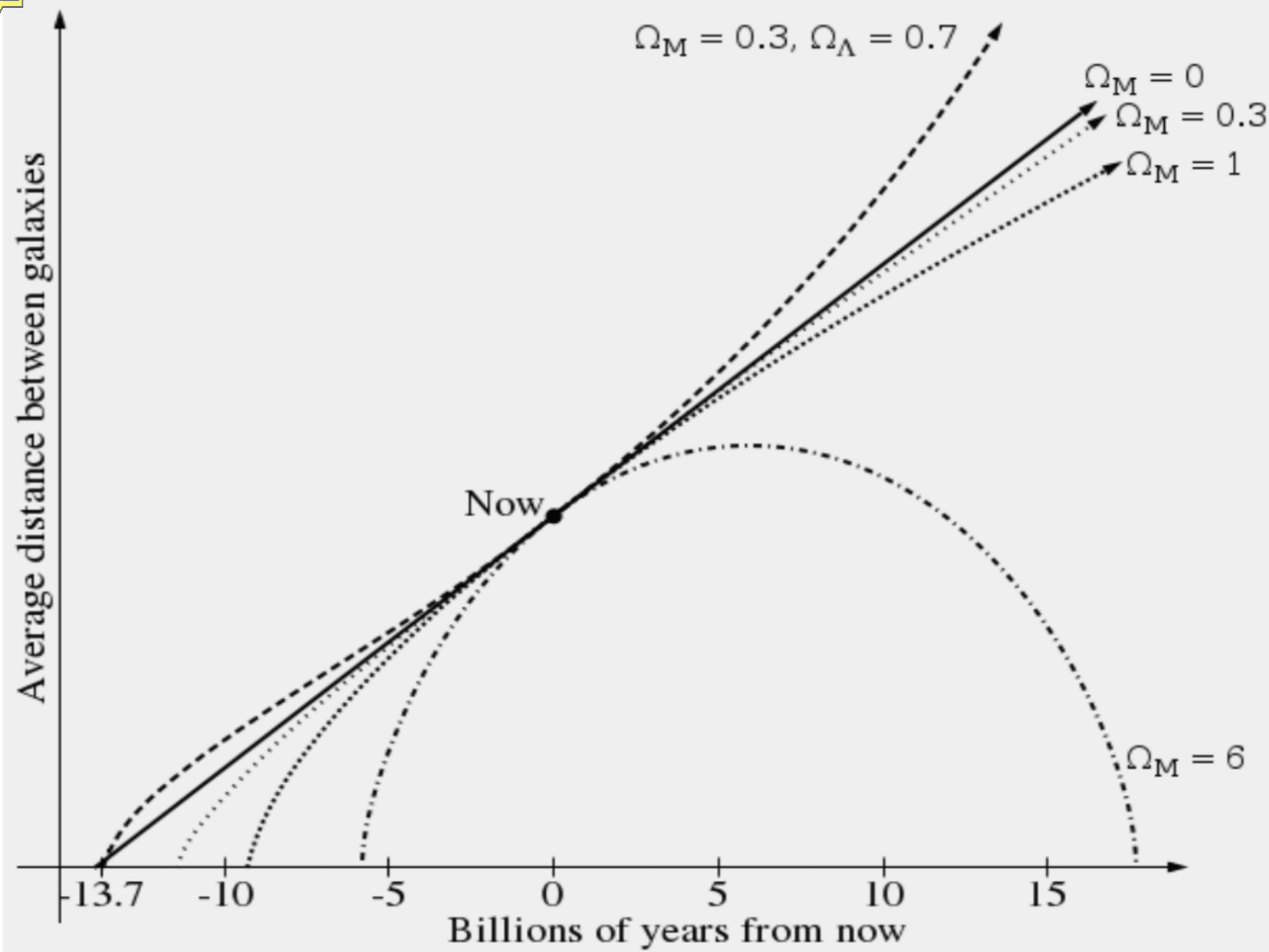
Flat ΛCDM

(Concordance Model)

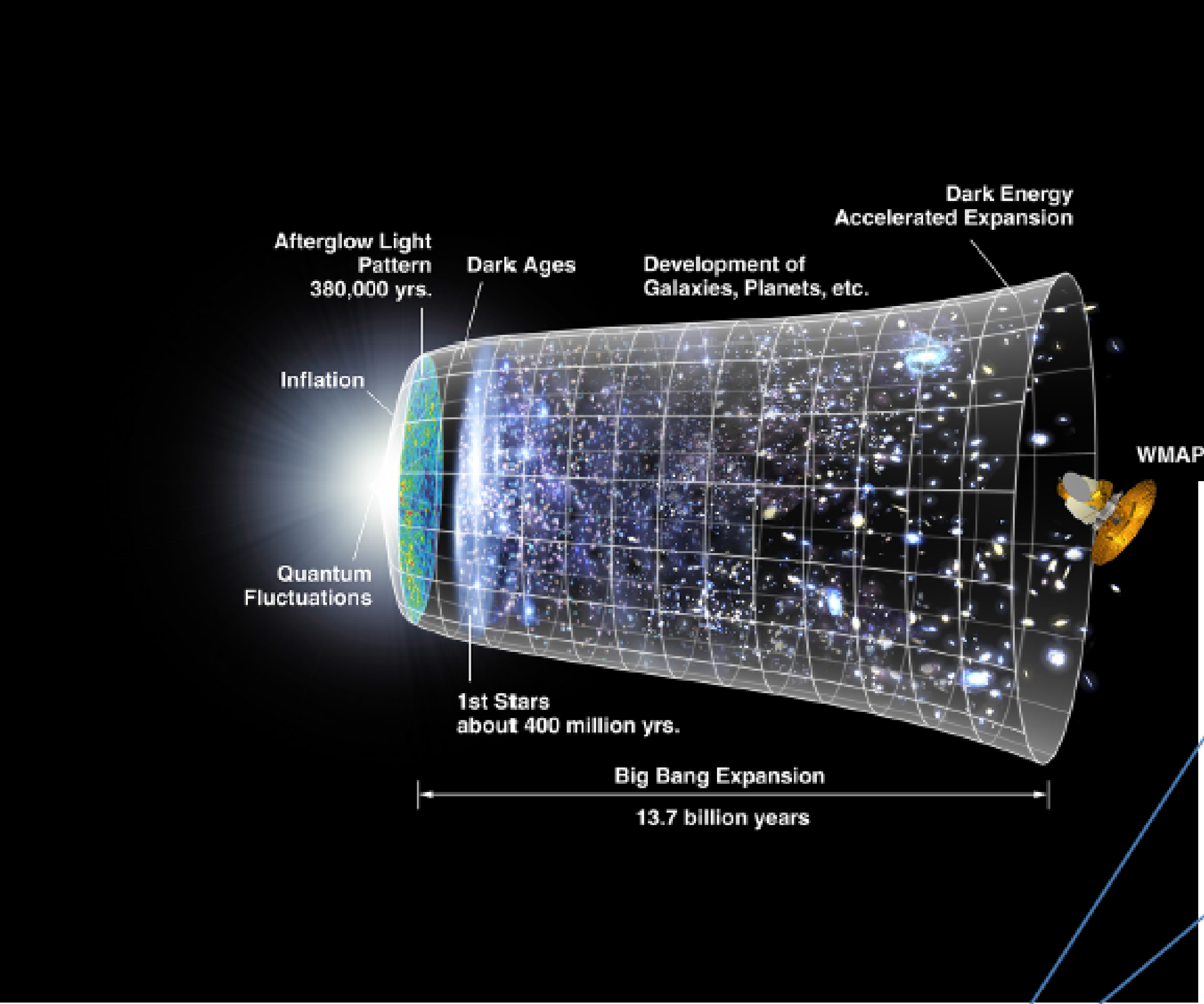


[Cosmology Calculator]

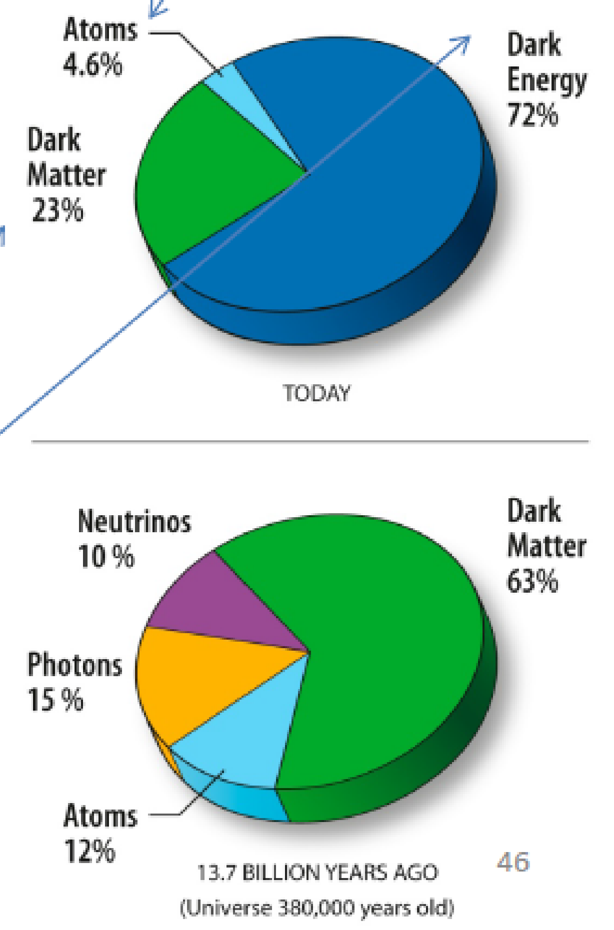
Freedman and Kaufmann



$\Omega_M = 0.3, \Omega_\Lambda = 0.7$
$\Omega_M = 0$
$\Omega_M = 0.3$
$\Omega_M = 1$
$\Omega_M = 6$
Now
Average distance between galaxies
-13.7
-10
-5
0
5
10
15
Billions of years from now

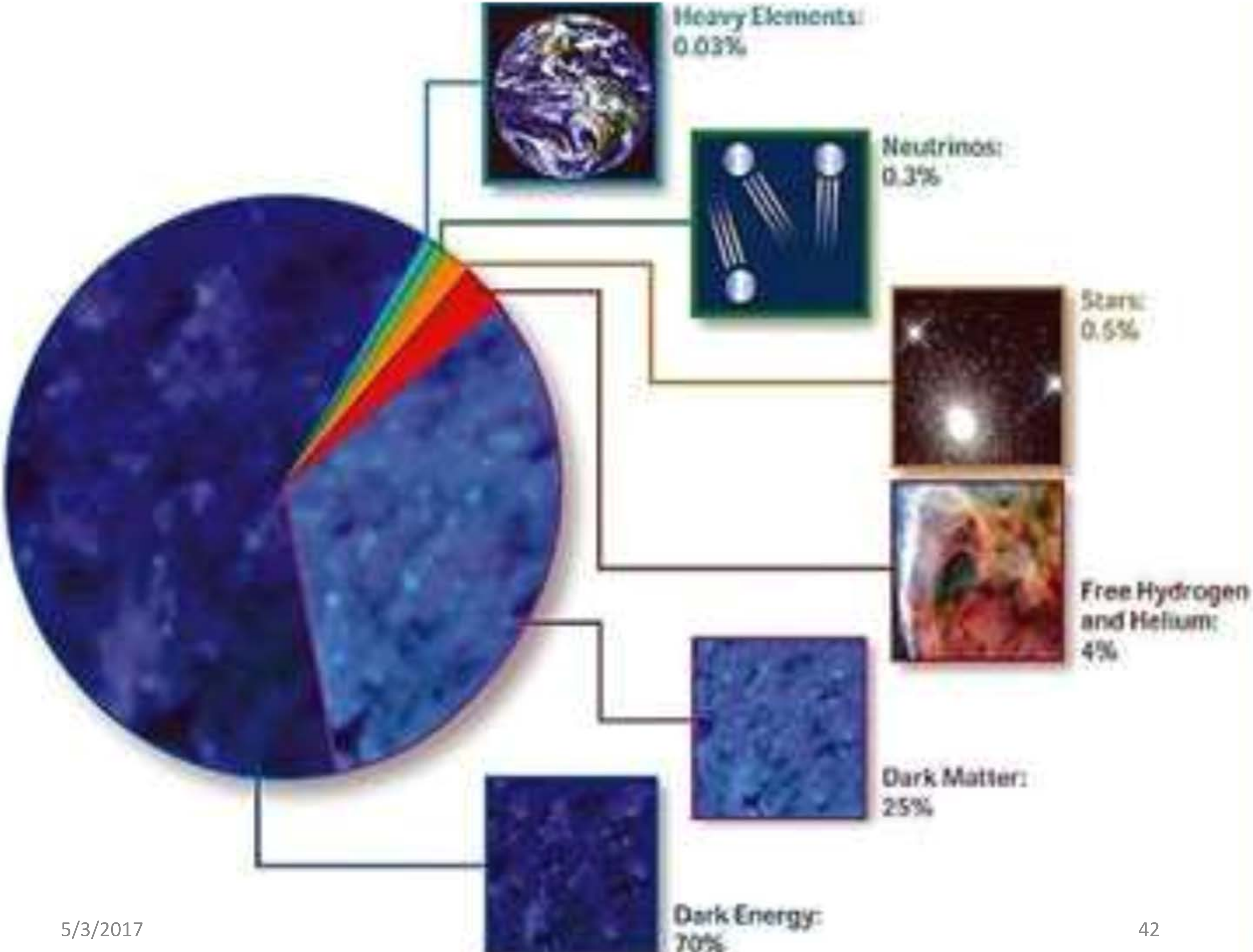


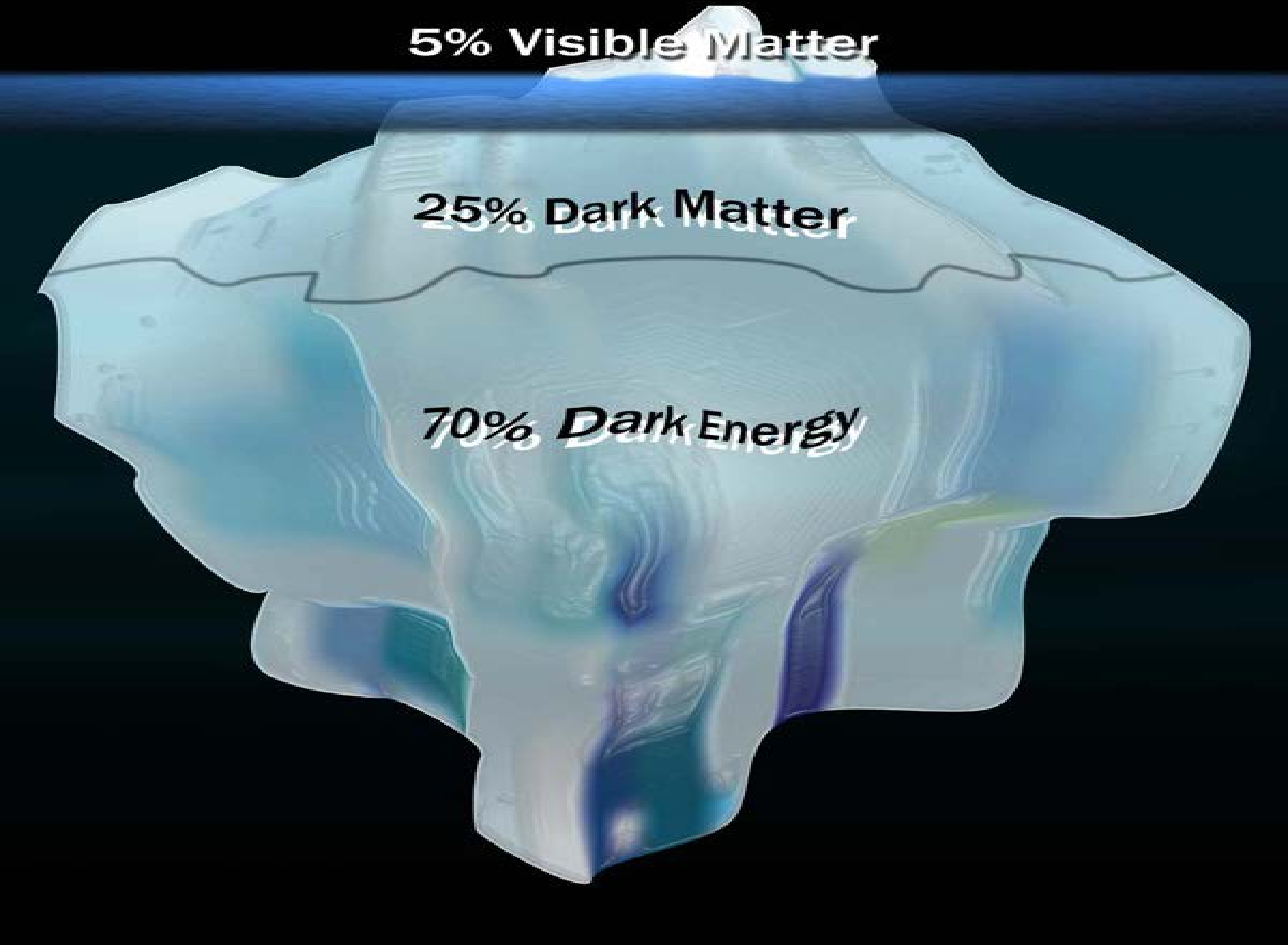
We almost understand < 5% of the current energy budget.



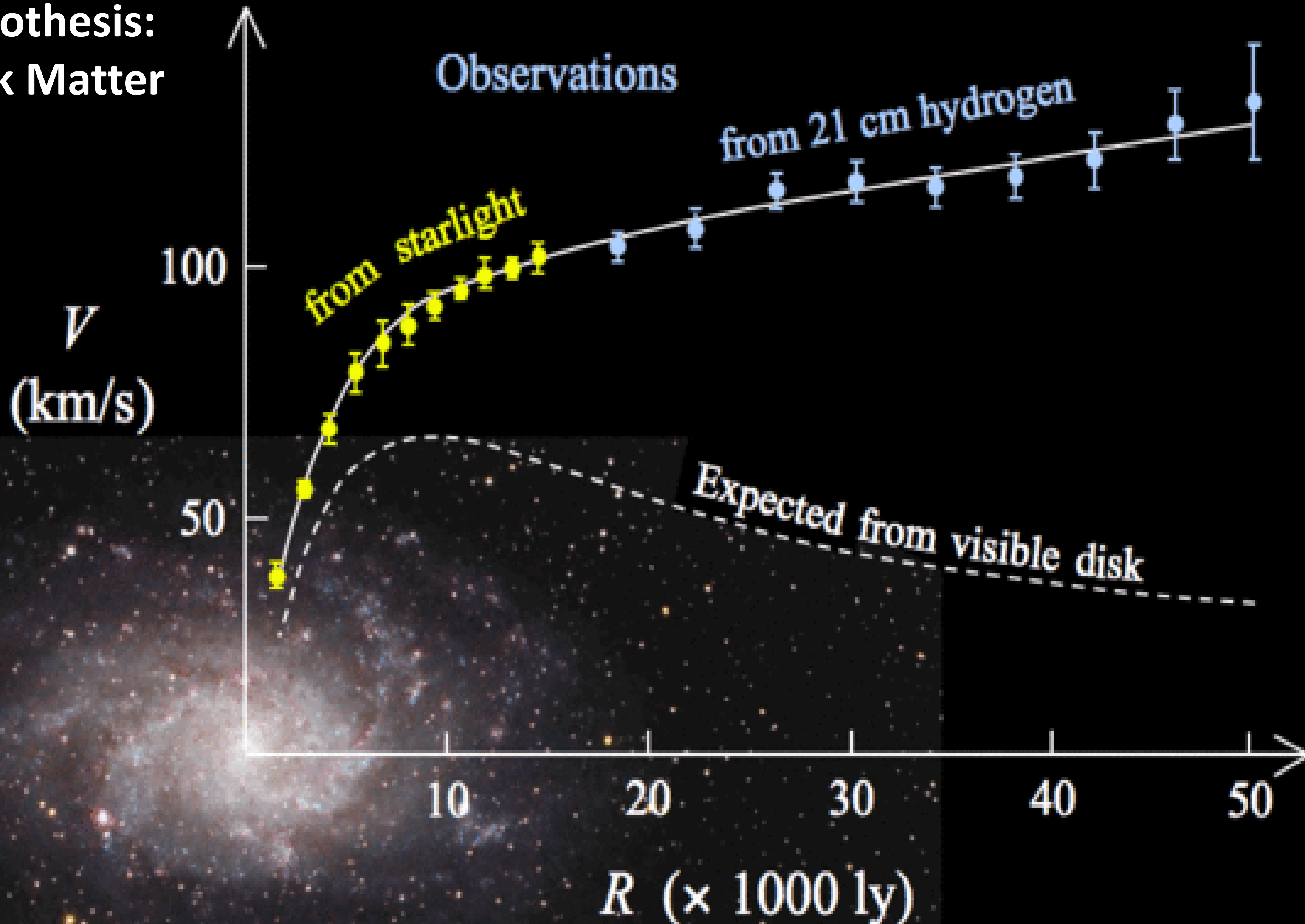
We do not understand > 95% of the current energy budget.

But we do have a good “standard” model of cosmology, flat ΛCDM.

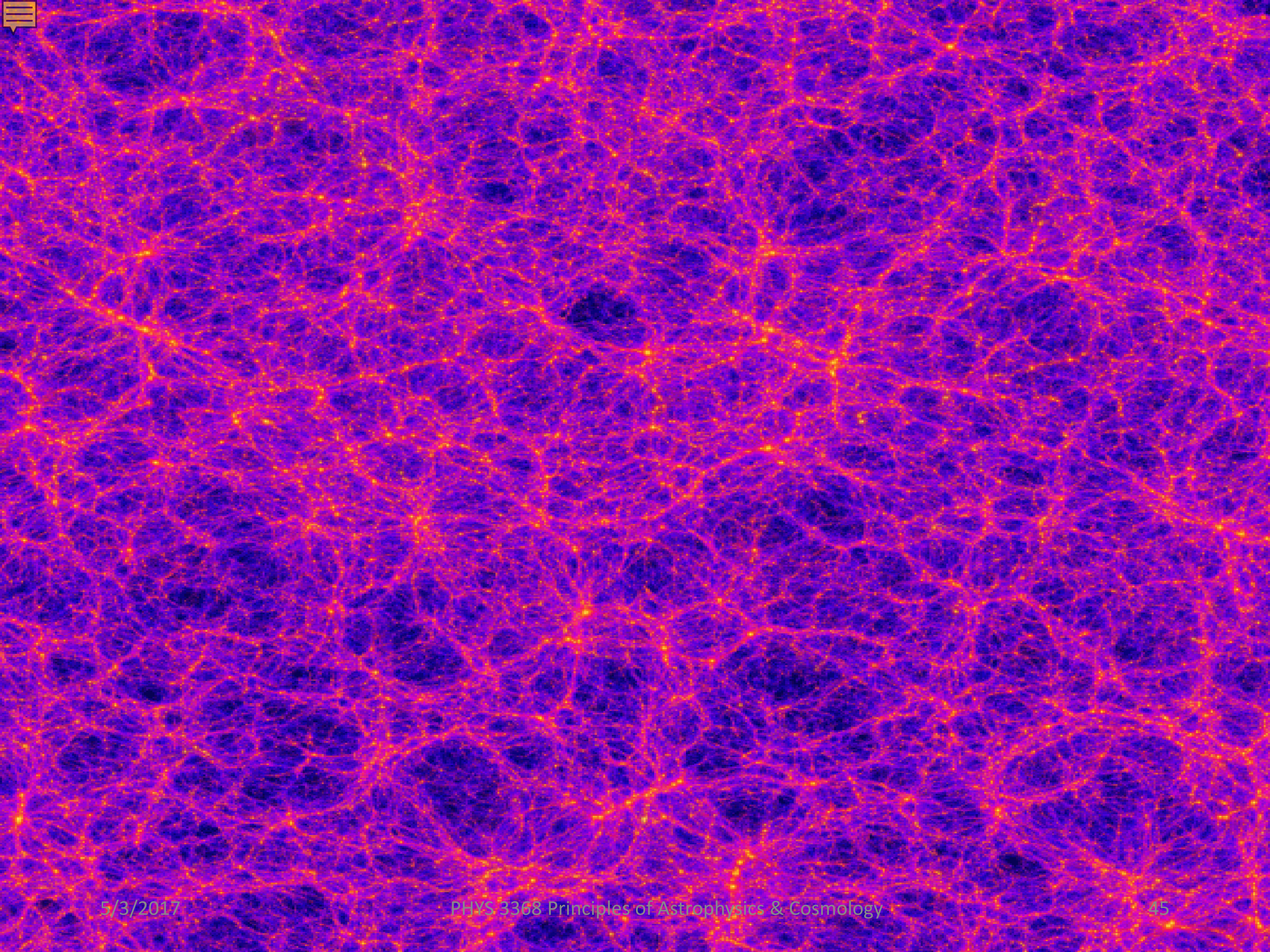

Heavy Elements:
0.03%
Neutrinos:
0.3%
Stars:
0.5%
Free Hydrogen
and Helium:
4%
Dark Matter:
25%
Dark Energy:
70%

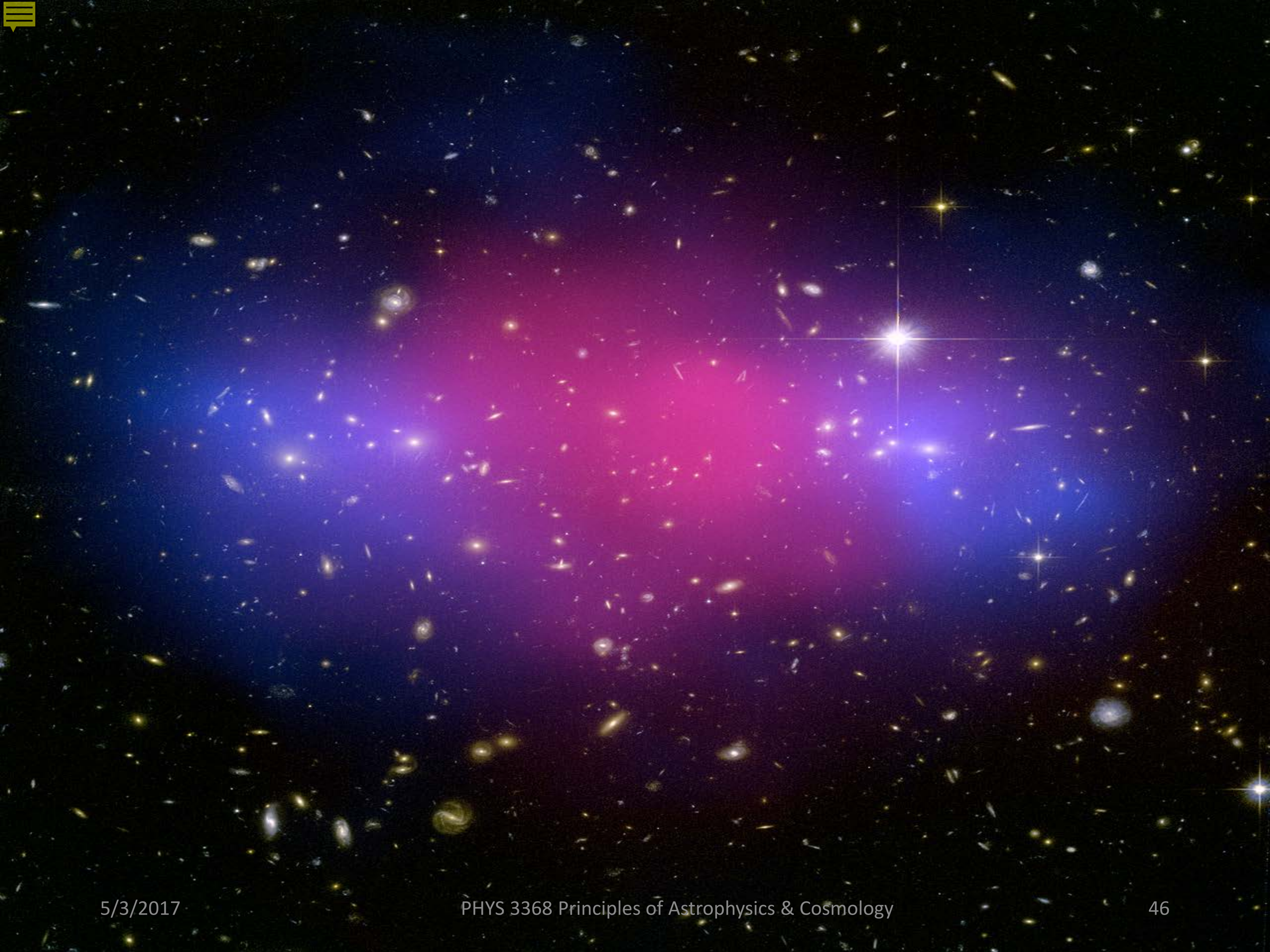

5% Visible Matter
25% Dark Matter
70% Dark Energy

Hypothesis:
Dark Matter



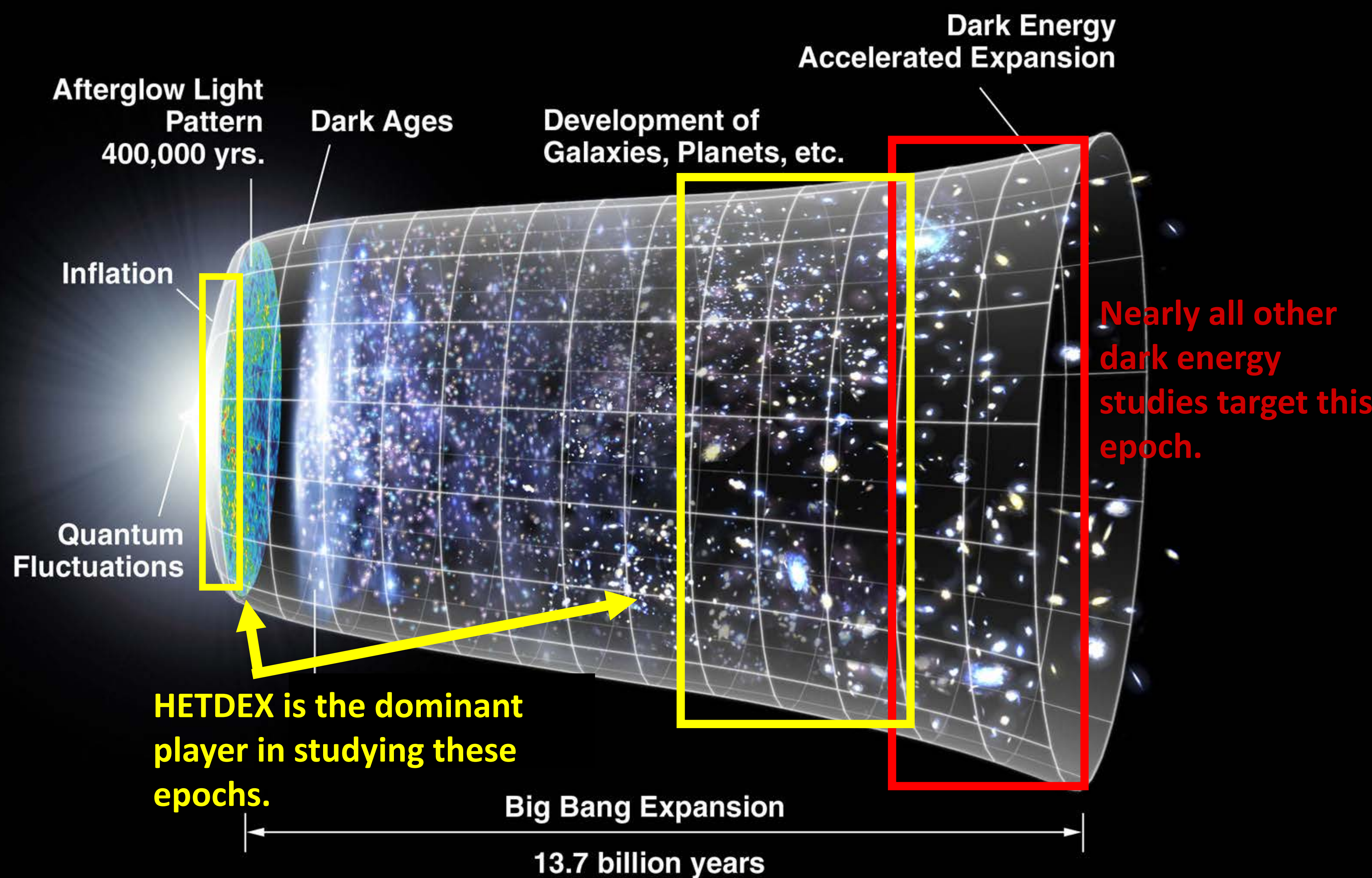
Alternative Hypothesis:
Modified Newtonian Dynamics (MOND)

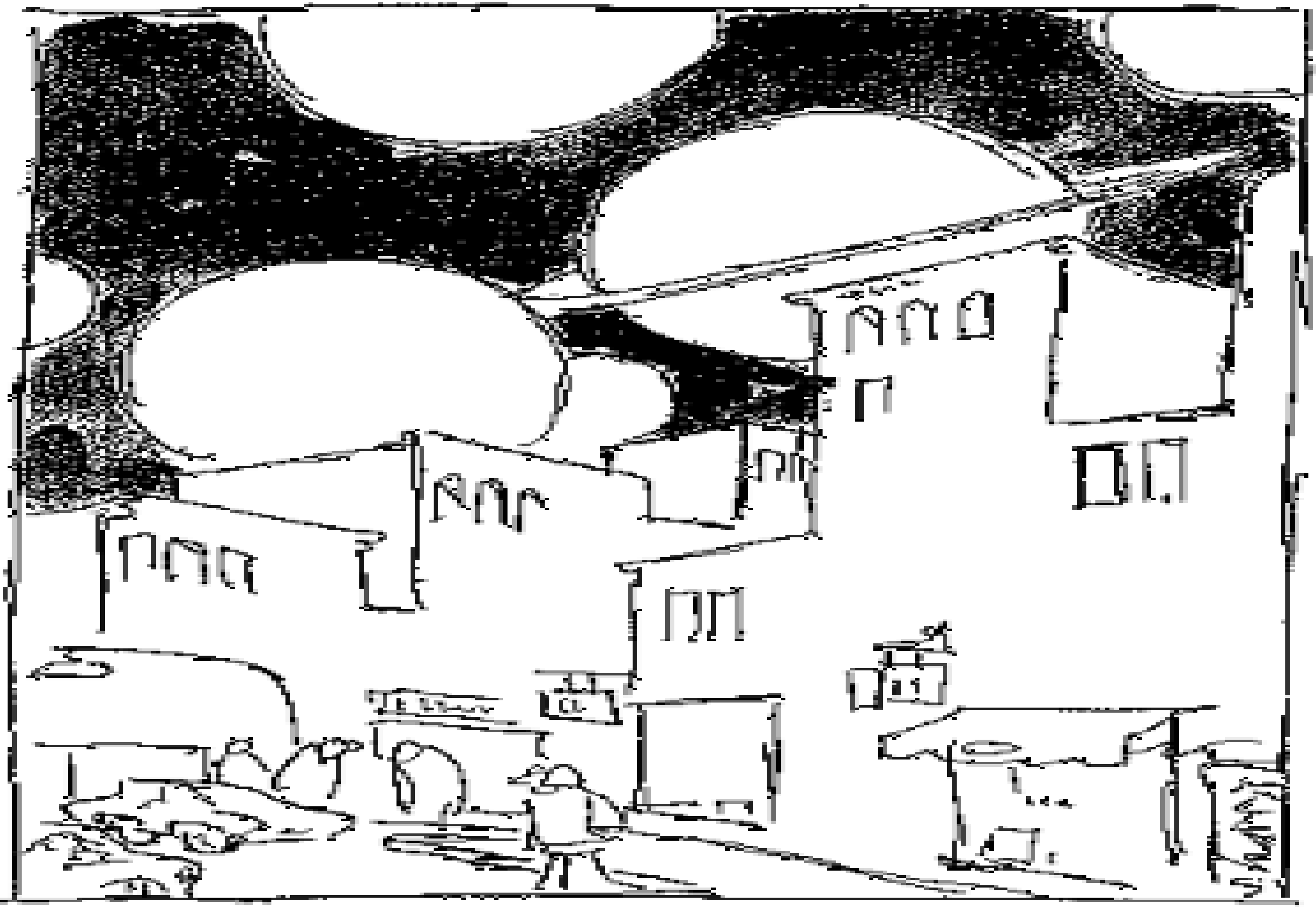




Walk Softly but Carry a Huge Number of Spectrographs (when exploring the dark side)

HETDEX and the Expansion History of the Universe





AS THE UNIVERSE CONTINUED TO CONTRACT...

[Cosmological Constant]

[Quantum Universe]

Open questions, missing links

B.R. & M. Vogeley, PASP120,235 (2008)

What is dark energy?

Is it a cosmological constant, or does it vary with space and in time?

Is the general theory of relativity correct on large scales?

Are the astronomy observations for dark energy secure?

Is it really decoupled (except gravitationally) from everything else?

What is dark matter?

Supersymmetry? Axions?

Will the Large Hadron Collider at CERN tell us?

Laboratory searches for dark matter.

Dwarf galaxy abundances, galactic nuclear profiles might be problems for “pure” CDM.

What are the masses of neutrinos?

Are the constraints on baryon density consistent?

When and how was the baryon excess generated?

What is the topology of space?

What are the initial seeds for structure formation?

Did the early universe inflate and reheat?

When, how, and what were the first structures formed?

How do baryons light up galaxies and what is their connection to mass?

How do galaxies and black holes co-evolve?

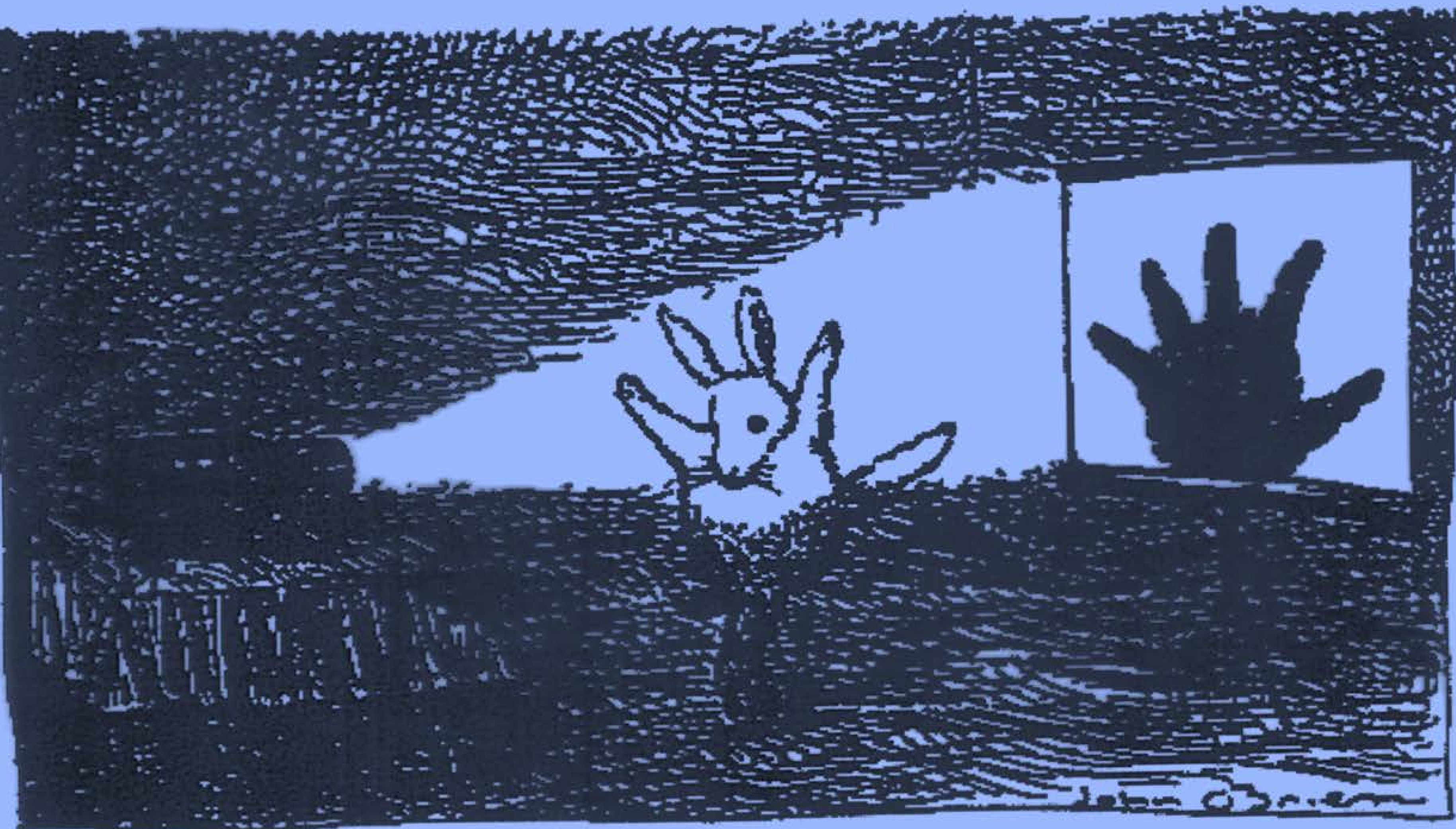
Does the Gaussian, adiabatic CDM structure formation model have a real flaw?

Is the low quadrupole moment of the CMB anisotropy a problem for flat ΛCDM?

Are the largest observed structures a problem for flat ΛCDM?

...when you have eliminated the impossible, whatever remains, however improbable, must be the truth.

Sherlock Holmes (Arthur Conan Ignatius Doyle)



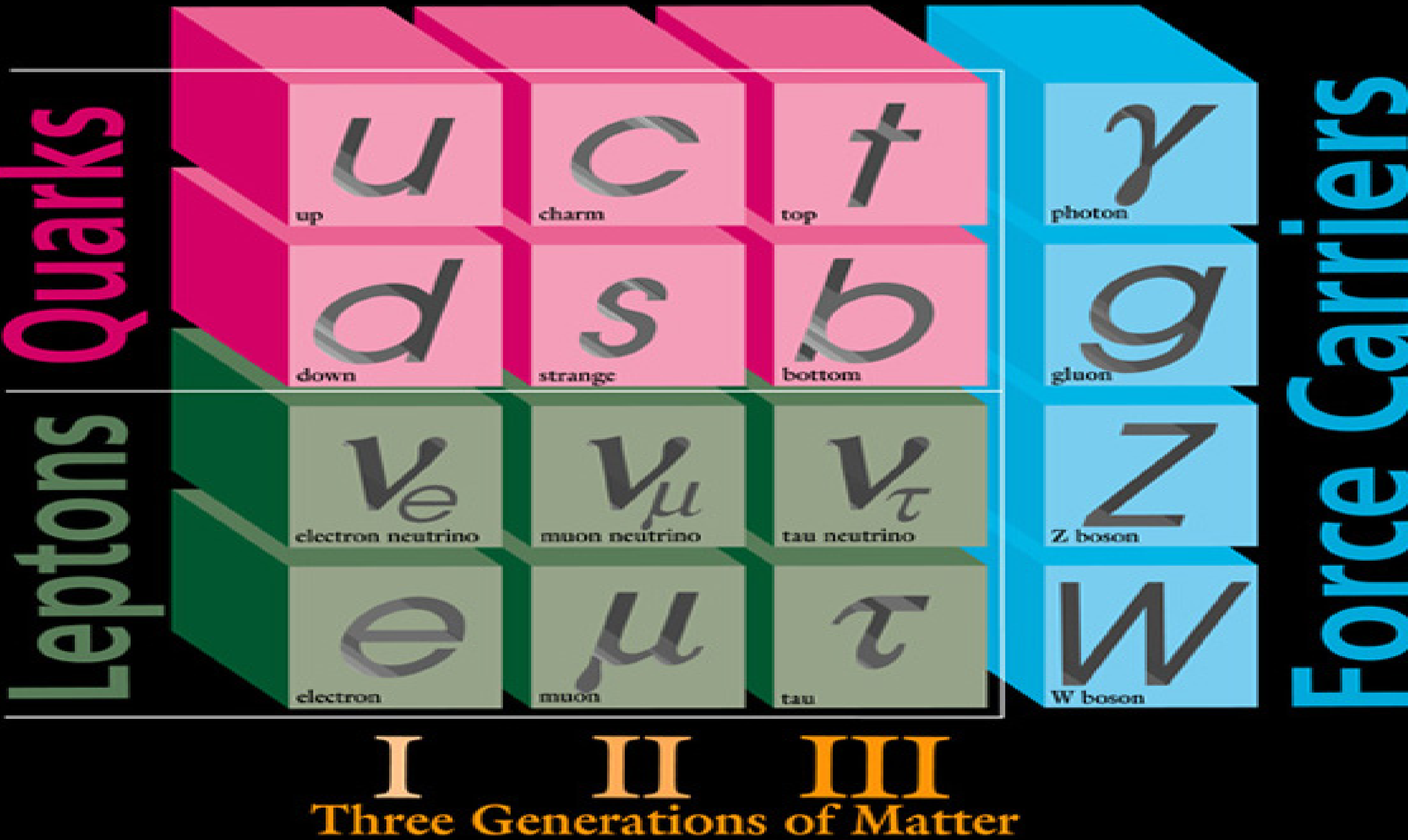
What you see is not always what you get.

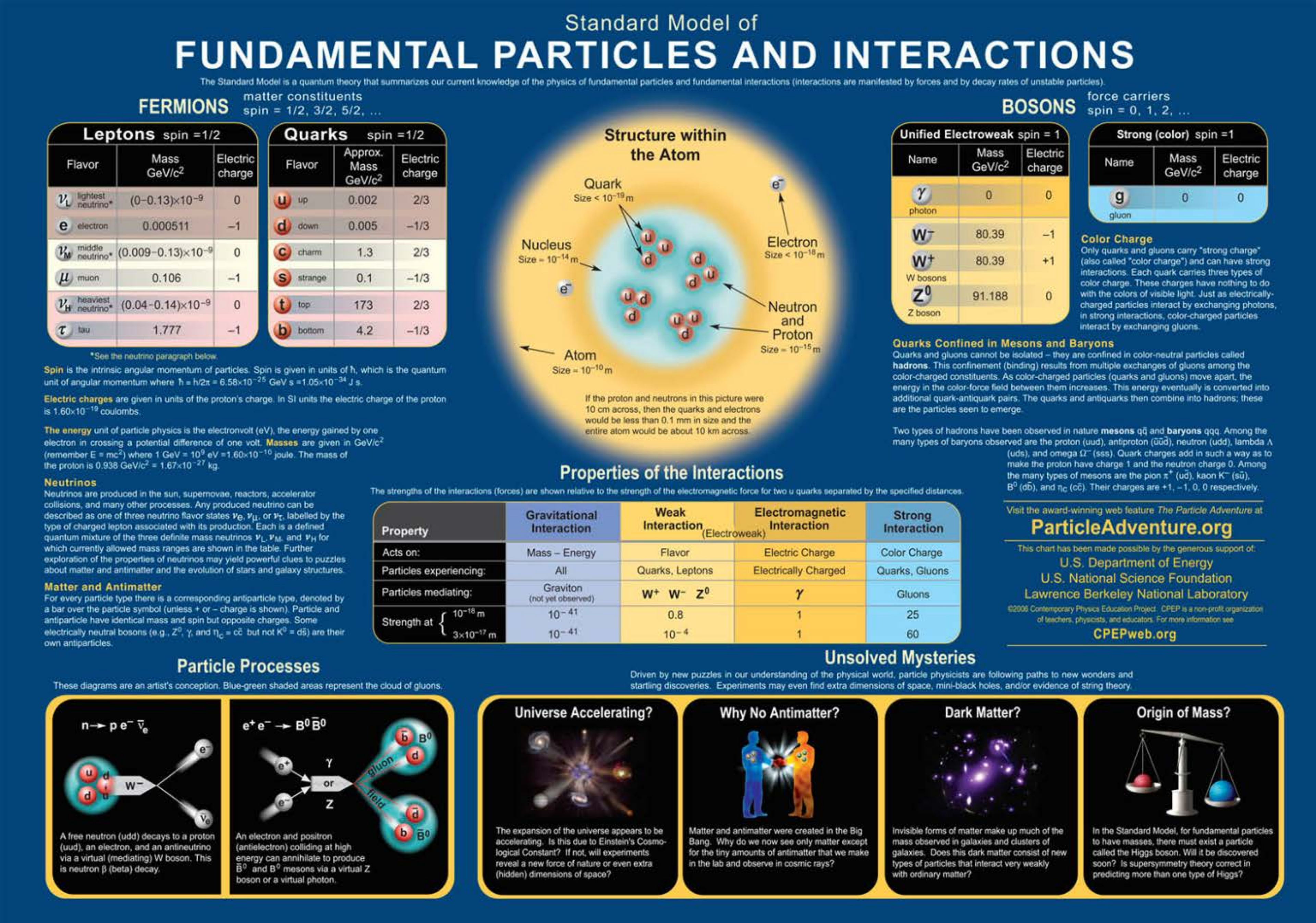
The Standard Model

of Elementary Particle Physics

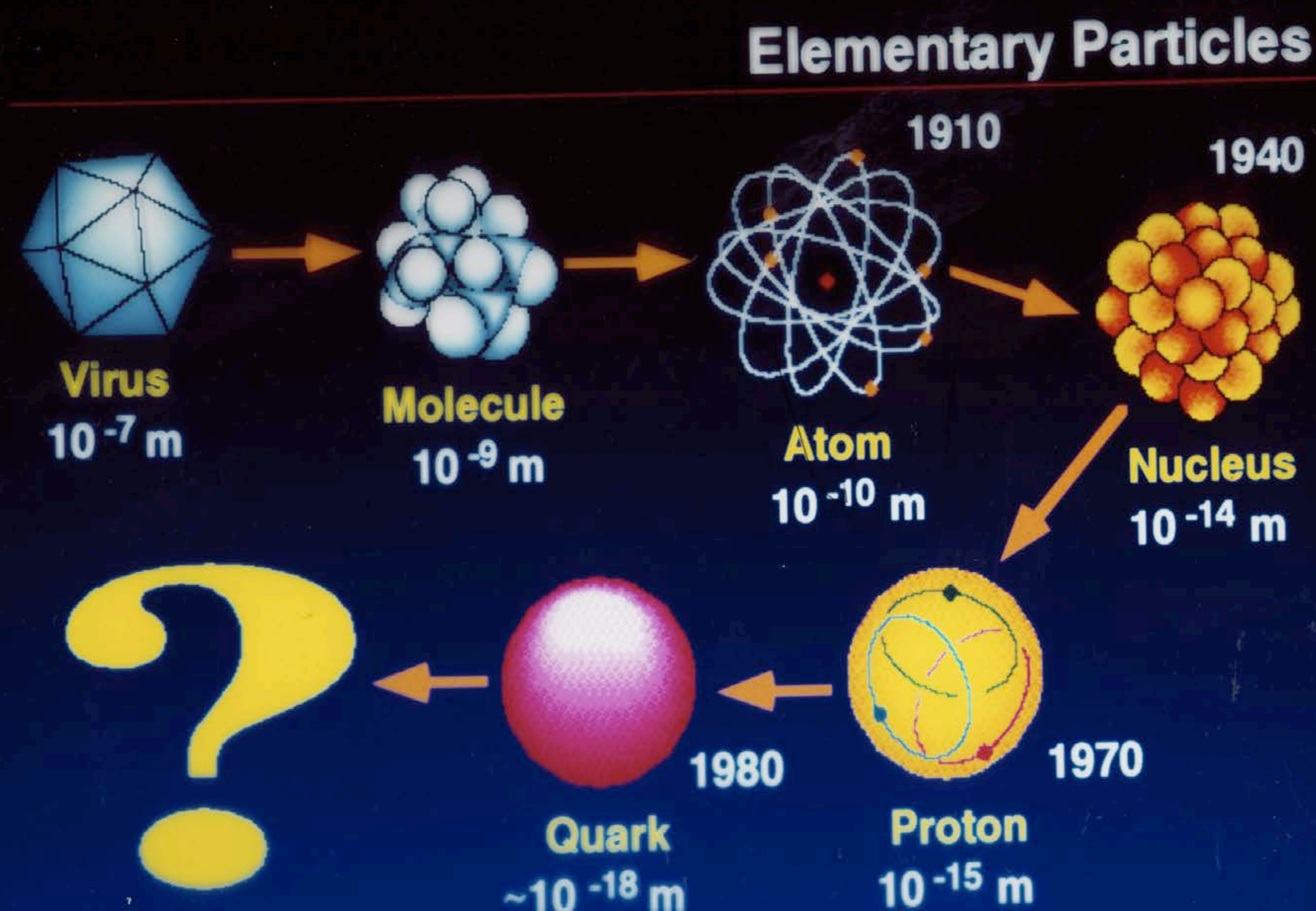
The Particle Adventure

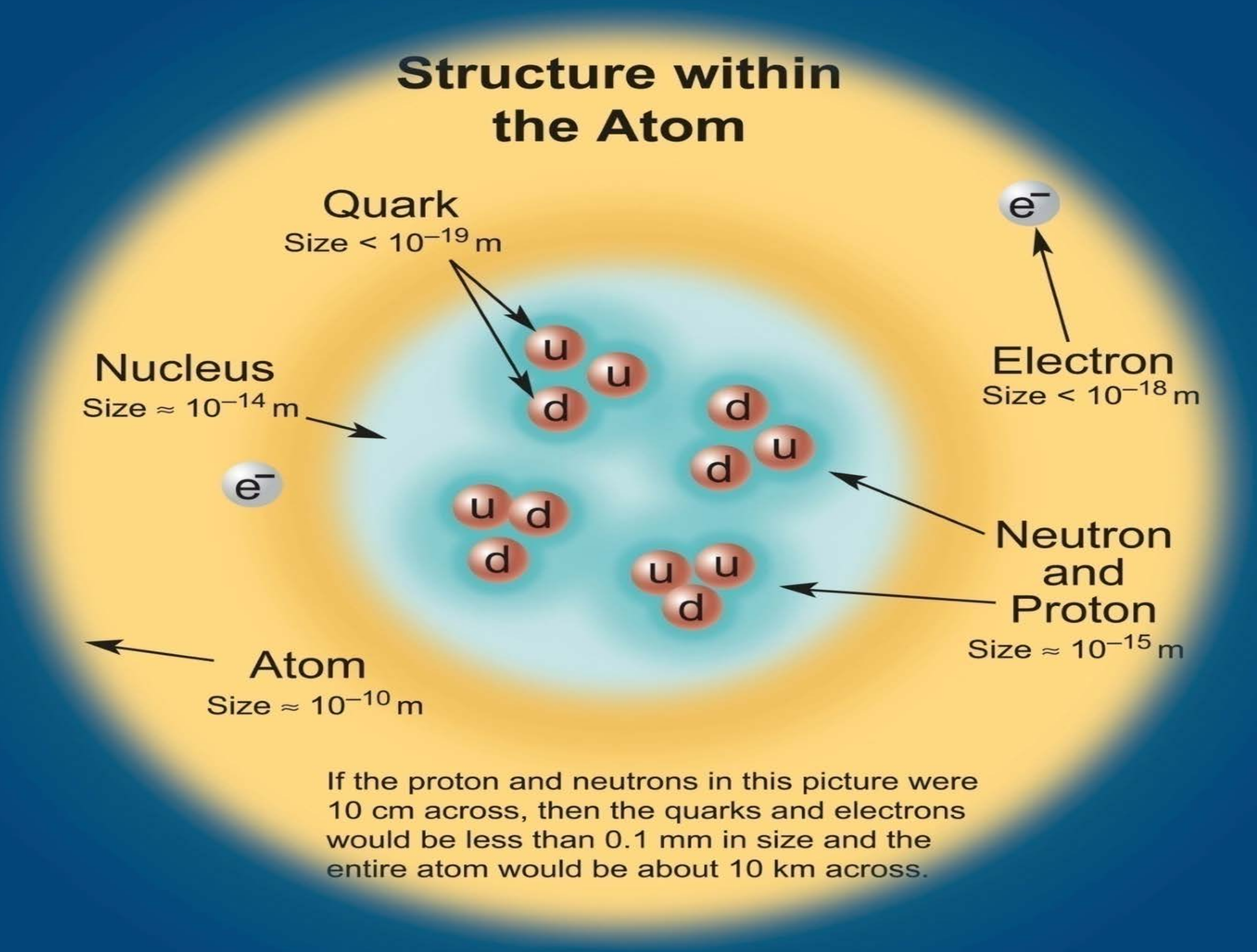
ELEMENTARY PARTICLES





Standard Model of
FUNDAMENTAL PARTICLES AND INTERACTIONS
The Standard Model is a quantum theory that summarizes our current knowledge of the physics of fundamental particles and fundamental interactions (interactions are manifested by forces and by decay rates of unstable particles).
FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...
Leptons spin =1/2
Flavor | Mass GeV/c² | Electric charge
νL lightest neutrino* | (0-0.13)×10⁻⁹ | 0
e electron | 0.000511 | -1
νM middle neutrino* | (0.009-0.13)×10⁻⁹ | 0
μ muon | 0.106 | -1
νH heaviest neutrino* | (0.04-0.14)×10⁻⁹ | 0
τ tau | 1.777 | -1
Quarks spin =1/2
Flavor | Approx. Mass GeV/c² | Electric charge
u up | 0.002 | 2/3
d down | 0.005 | -1/3
c charm | 1.3 | 2/3
s strange | 0.1 | -1/3
t top | 173 | 2/3
b bottom | 4.2 | -1/3
*See the neutrino paragraph below.
Spin is the intrinsic angular momentum of particles. Spin is given in units of ħ, which is the quantum unit of angular momentum where ħ = h/2π = 6.58×10⁻²⁵ GeV s =1.05×10⁻³⁴ J s.
Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10⁻¹⁹ coulombs.
The energy unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. Masses are given in GeV/c² (remember E = mc²) where 1 GeV = 10⁹ eV =1.60×10⁻¹⁰ joule. The mass of the proton is 0.938 GeV/c² = 1.67×10⁻²⁷ kg.
Neutrinos
Neutrinos are produced in the sun, supernovae, reactors, accelerator collisions, and many other processes. Any produced neutrino can be described as one of three neutrino flavor states νe, νμ, or ντ, labelled by the type of charged lepton associated with its production. Each is a defined quantum mixture of the three definite mass neutrinos νL, νM, and νH for which currently allowed mass ranges are shown in the table. Further exploration of the properties of neutrinos may yield powerful clues to puzzles about matter and antimatter and the evolution of stars and galaxy structures.
Matter and Antimatter
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or - charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z⁰, γ, and ηc = cc̄ but not K⁰ = ds̄) are their own antiparticles.
Structure within the Atom
Quark Size < 10⁻¹⁹ m
Nucleus Size ≈ 10⁻¹⁴ m
Electron Size < 10⁻¹⁸ m
Neutron and Proton Size ≈ 10⁻¹⁵ m
Atom Size ≈ 10⁻¹⁰ m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.
BOSONS force carriers spin = 0, 1, 2, ...
Unified Electroweak spin = 1
Name | Mass GeV/c² | Electric charge
γ photon | 0 | 0
W⁻ | 80.39 | -1
W⁺ W bosons | 80.39 | +1
Z⁰ Z boson | 91.188 | 0
Strong (color) spin =1
Name | Mass GeV/c² | Electric charge
g gluon | 0 | 0
Color Charge
Only quarks and gluons carry "strong charge" (also called "color charge") and can have strong interactions. Each quark carries three types of color charge. These charges have nothing to do with the colors of visible light. Just as electrically-charged particles interact by exchanging photons, in strong interactions, color-charged particles interact by exchanging gluons.
Quarks Confined in Mesons and Baryons
Quarks and gluons cannot be isolated – they are confined in color-neutral particles called hadrons. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs. The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge.
Two types of hadrons have been observed in nature mesons qq̄ and baryons qqq. Among the many types of baryons observed are the proton (uud), antiproton (ūūd̄), neutron (udd), lambda Λ (uds), and omega Ω⁻ (sss). Quark charges add in such a way as to make the proton have charge 1 and the neutron charge 0. Among the many types of mesons are the pion π⁺ (ud̄), kaon K⁻ (sū), B⁰ (db̄), and ηc (cc̄). Their charges are +1, -1, 0, 0 respectively.
Visit the award-winning web feature The Particle Adventure at
ParticleAdventure.org
This chart has been made possible by the generous support of:
U.S. Department of Energy
U.S. National Science Foundation
Lawrence Berkeley National Laboratory
©2006 Contemporary Physics Education Project. CPEP is a non-profit organization of teachers, physicists, and educators. For more information see
CPEPweb.org
Properties of the Interactions
The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.
Property | Gravitational Interaction | Weak Interaction (Electroweak) | Electromagnetic Interaction | Strong Interaction
Acts on: | Mass – Energy | Flavor | Electric Charge | Color Charge
Particles experiencing: | All | Quarks, Leptons | Electrically Charged | Quarks, Gluons
Particles mediating: | Graviton (not yet observed) | W⁺ W⁻ Z⁰ | γ | Gluons
Strength at 10⁻¹⁸ m | 10⁻⁴¹ | 0.8 | 1 | 25
Strength at 3×10⁻¹⁷ m | 10⁻⁴¹ | 10⁻⁴ | 1 | 60
Particle Processes
These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.
n → p e⁻ ν̄e
A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.
e⁺ e⁻ → B⁰ B̄⁰
γ or Z
gluon field
An electron and positron (antielectron) colliding at high energy can annihilate to produce B̄⁰ and B⁰ mesons via a virtual Z boson or a virtual photon.
Unsolved Mysteries
Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.
Universe Accelerating?
The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?
Why No Antimatter?
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?
Dark Matter?
Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?
Origin of Mass?
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?


Elementary Particles
1910
1940
Virus
10 -7 m
Molecule
10 -9 m
Atom
10 -10 m
Nucleus
10 -14 m
?
Quark
~10 -18 m
1980
Proton
10 -15 m
1970


Structure within the Atom
Quark
Size < 10^{-19} m
Nucleus
Size ≈ 10^{-14} m
Electron
Size < 10^{-18} m
e⁻
u
d
Neutron and Proton
Size ≈ 10^{-15} m
Atom
Size ≈ 10^{-10} m
If the proton and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

BOSONS

force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.

These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	**uud**	1	0.938	1/2
$\bar{\mathbf{p}}$	antiproton	$\bar{\mathbf{u}}\bar{\mathbf{u}}\bar{\mathbf{d}}$	–1	0.938	1/2
n	neutron	**udd**	0	0.940	1/2
Λ	lambda	**uds**	0	1.116	1/2
Ω^-	omega	**sss**	–1	1.672	3/2

Mesons $q\bar{q}$

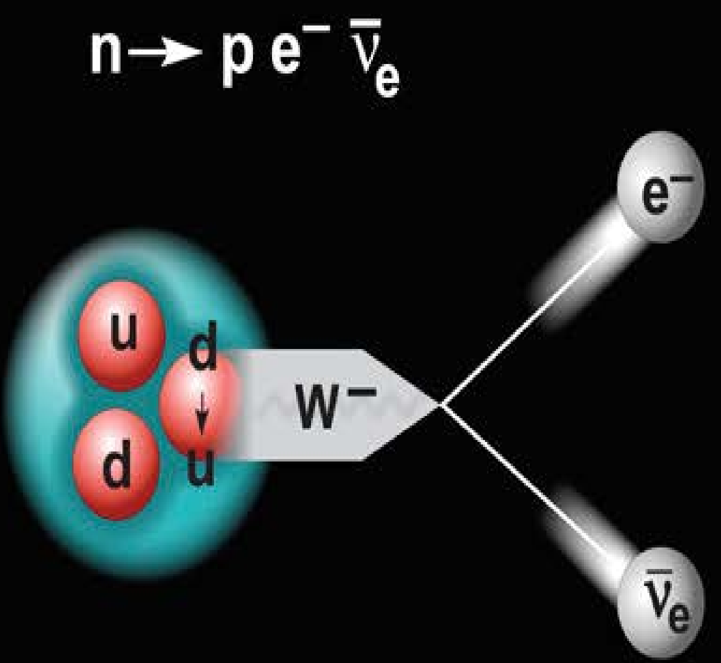
Mesons are bosonic hadrons

These are a few of the many types of mesons.

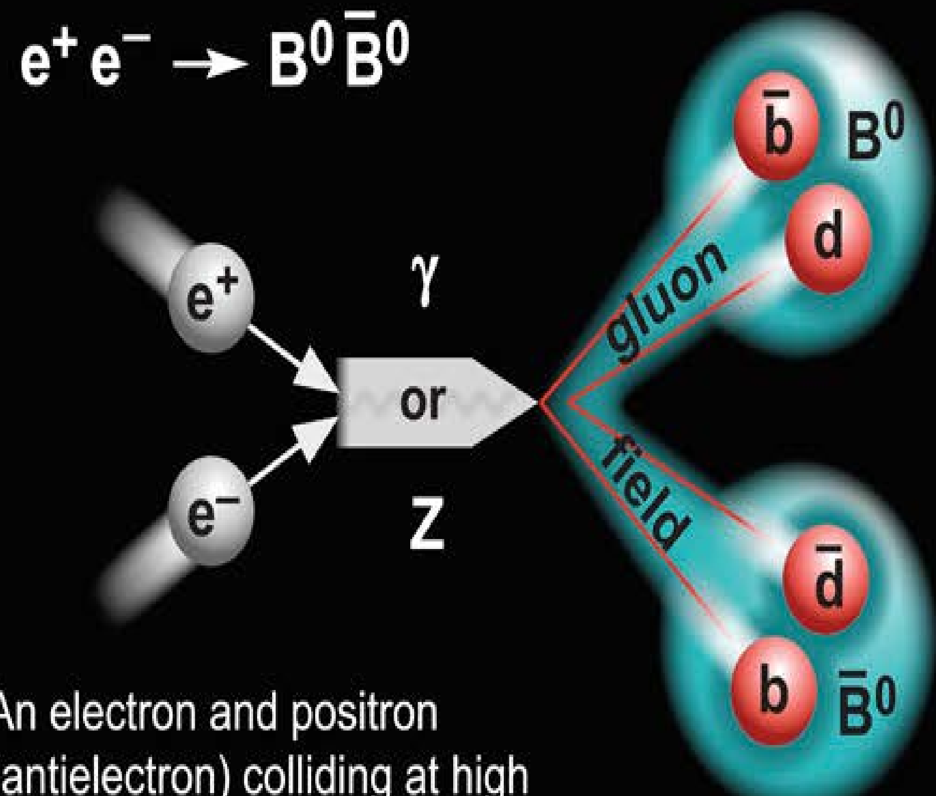
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$\mathbf{u\bar{d}}$	+1	0.140	0
K^-	kaon	$\mathbf{s\bar{u}}$	–1	0.494	0
ρ^+	rho	$\mathbf{u\bar{d}}$	+1	0.776	1
B^0	B-zero	$\mathbf{d\bar{b}}$	0	5.279	0
η_c	eta-c	$\mathbf{c\bar{c}}$	0	2.980	0

Particle Processes

These diagrams are an artist's conception. Blue-green shaded areas represent the cloud of gluons.



A free neutron (udd) decays to a proton (uud), an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β (beta) decay.

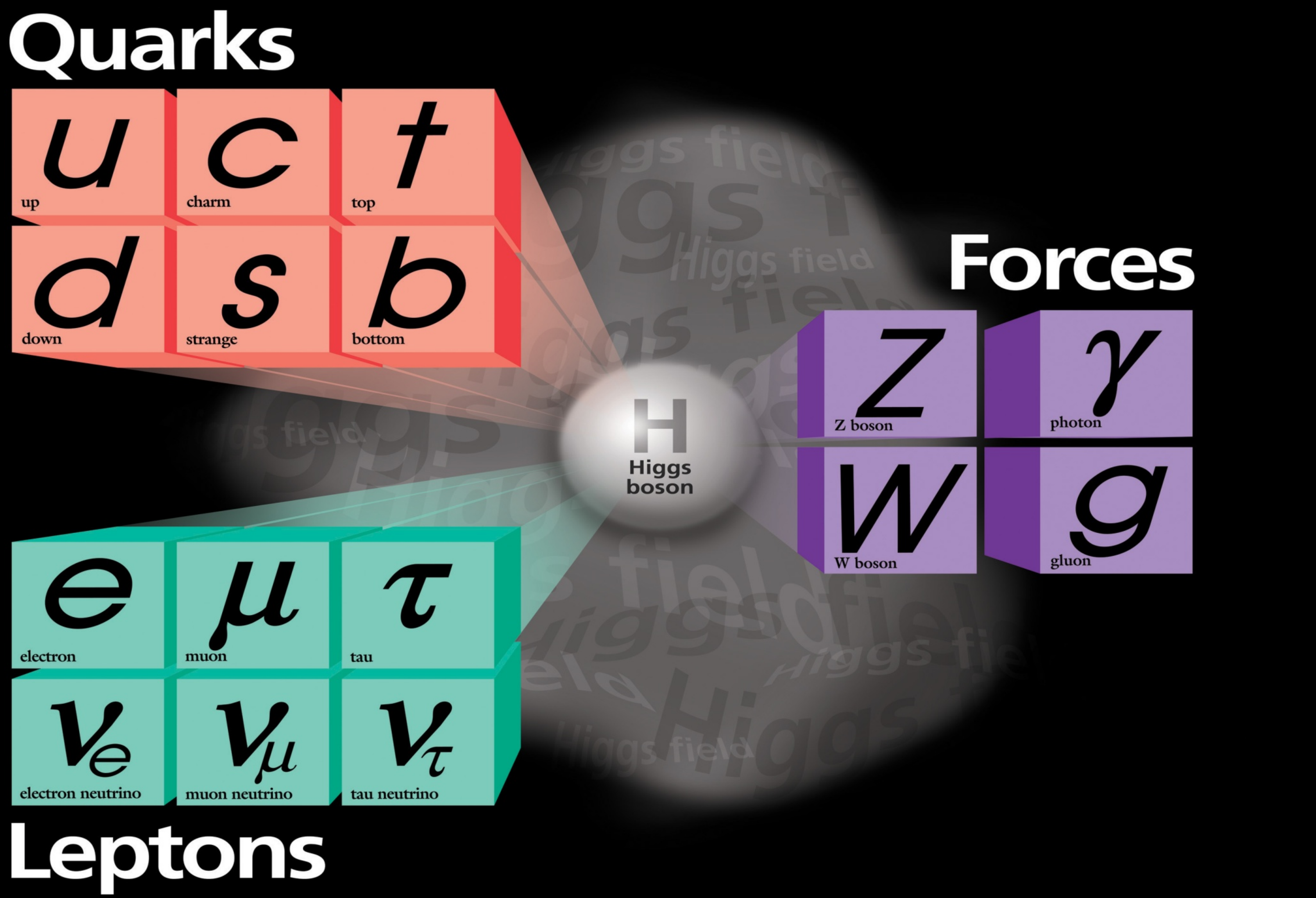


An electron and positron (antielectron) colliding at high energy can annihilate to produce $\bar{B}^0$ and B^0 mesons via a virtual Z boson or a virtual photon.

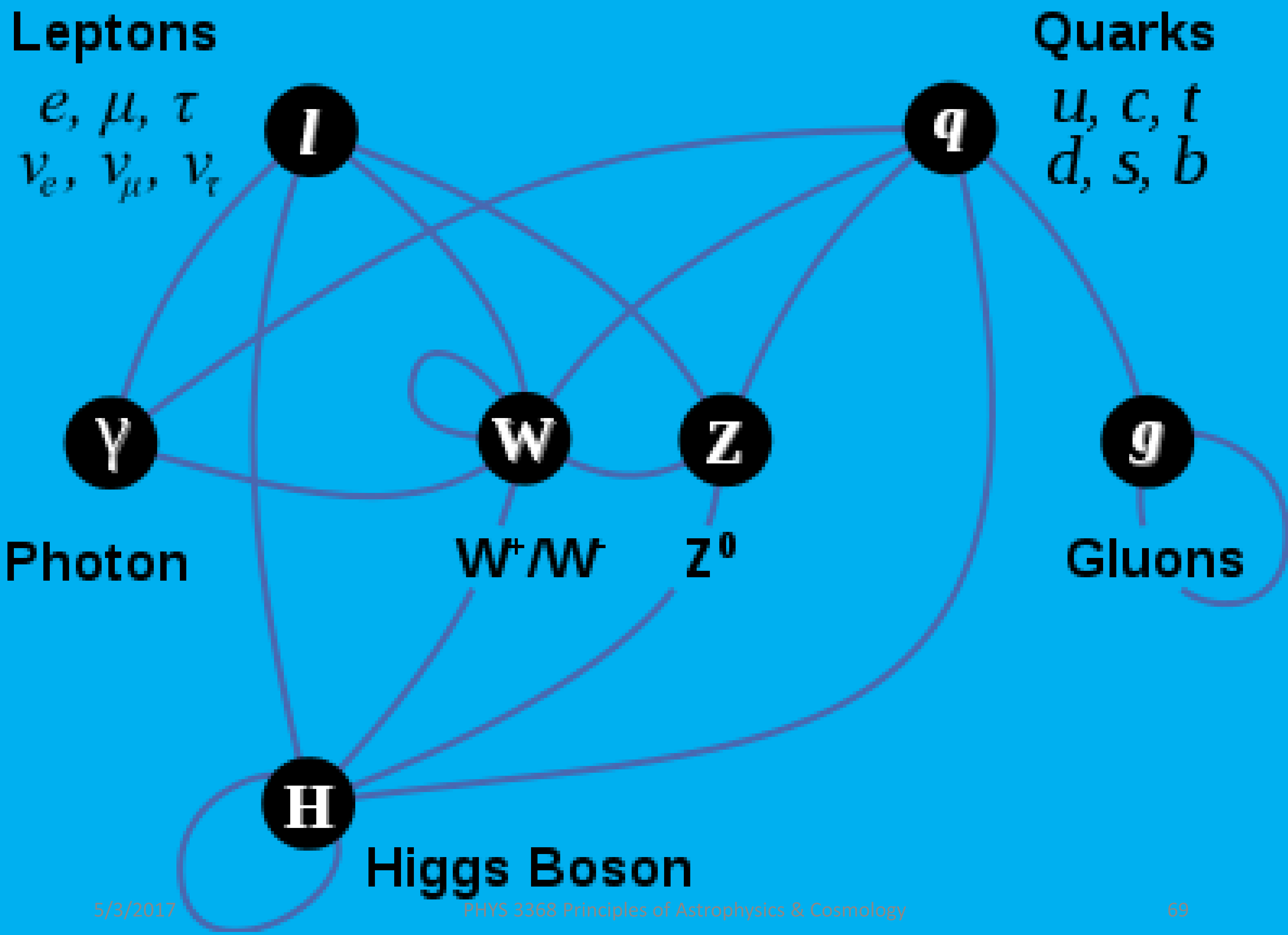
Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

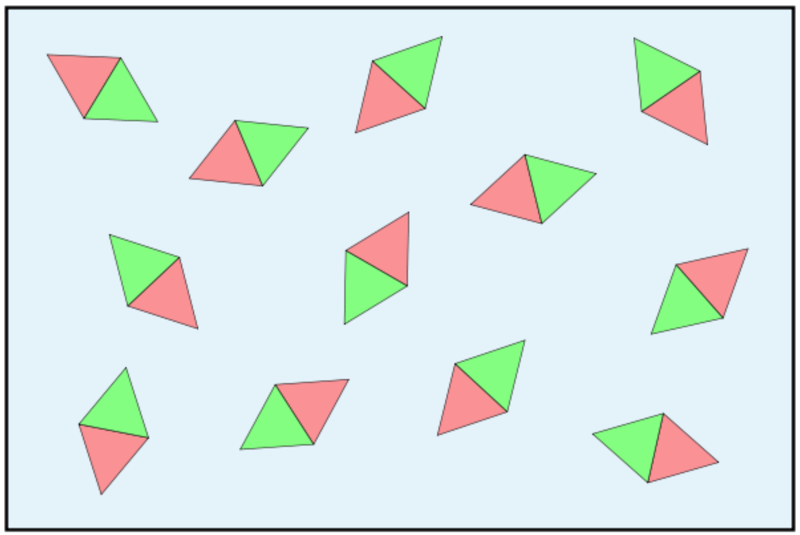
Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

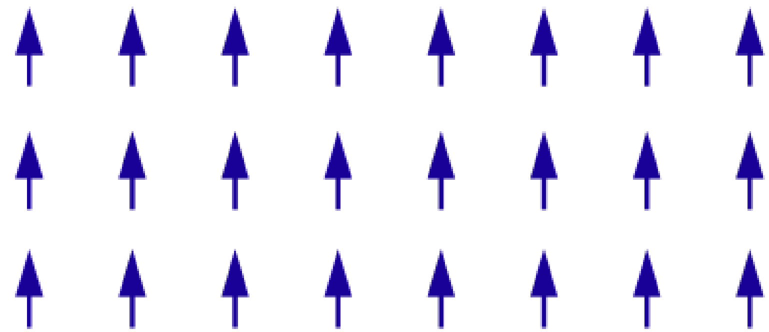


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Forces
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs
boson
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons


Leptons
e, μ, τ
νe, νμ, ντ
l
Quarks
u, c, t
d, s, b
q
γ
W
Z
g
Photon
W+/W-
Z0
Gluons
H
Higgs Boson

Arrangement of molecules in ferromagnet



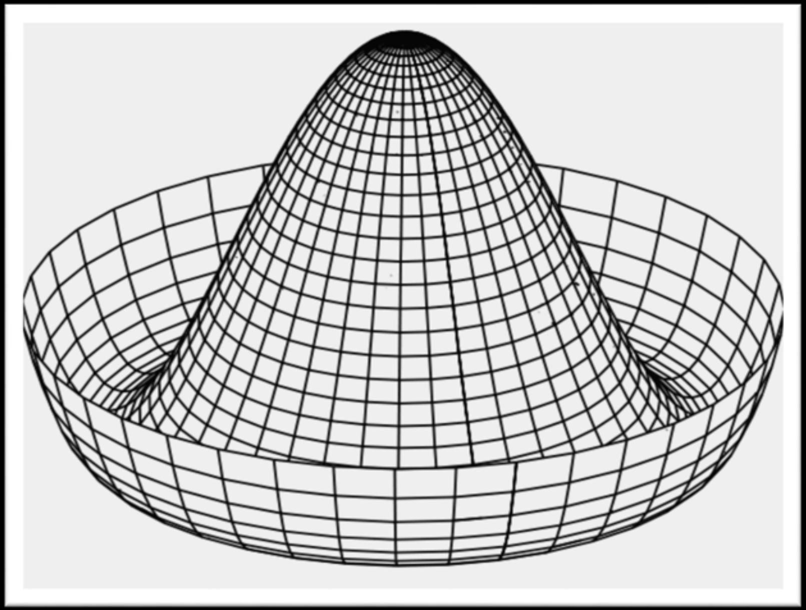


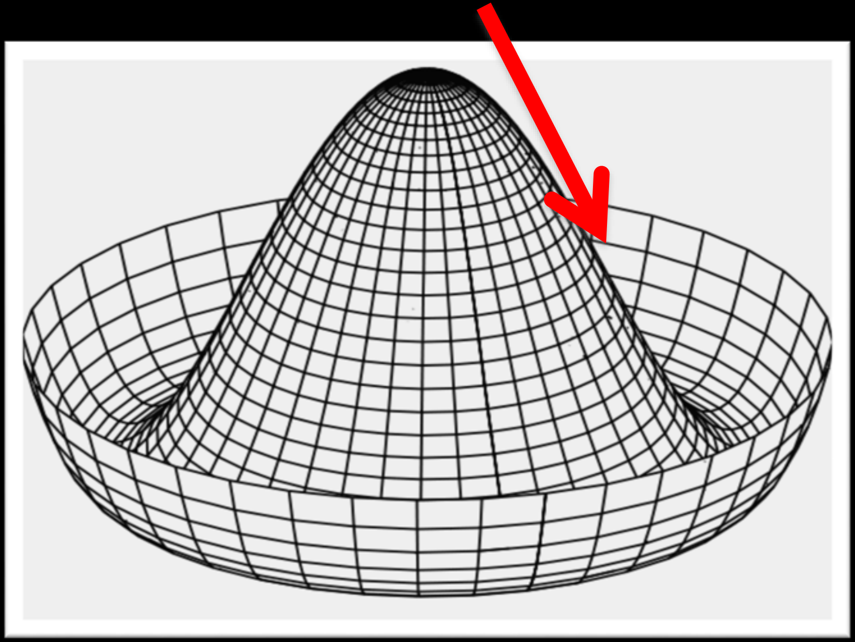
Above Tc rotational invariance

Below Tc rotational invariance is spontaneously broken

Higgs Field

Higgs mechanism – add the "Mexican hat" potential, which respects the electroweak symmetry (symmetric but unstable).





Ground state with symmetry spontaneously broken (Nambu-Goldston boson)

Higgs mechanism and Higgs Boson to the rescue

- **The credit is due to:**
- **Englert, Brout, Higgs, Guralnik, Hagen and Kibble**
  +
  Phil Anderson
- **Universe is filled with the condensate of the Higgs boson**
- **When the electron moves through this condensate it picks up a mass!**
- **Mechanism related to the notion of spontaneously broken symmetry. The underlying theory may have symmetry property, but the ground state may not e.g., theory of ferromagnetism respects rotational invariance.**


Standard
Model

Unsolved Mysteries

Driven by new puzzles in our understanding of the physical world, particle physicists are following paths to new wonders and startling discoveries. Experiments may even find extra dimensions of space, mini-black holes, and/or evidence of string theory.

Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmological Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

Why No Antimatter?

Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

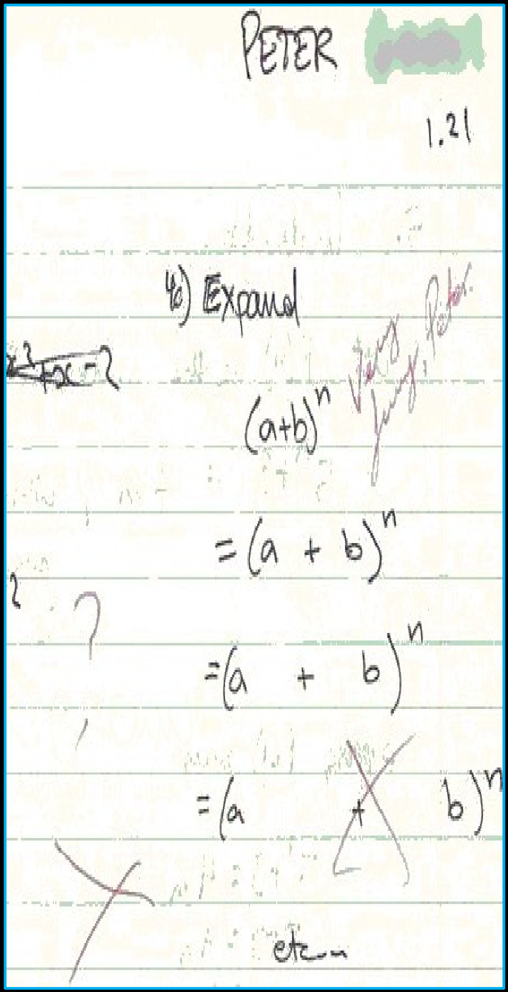
Origin of Mass?

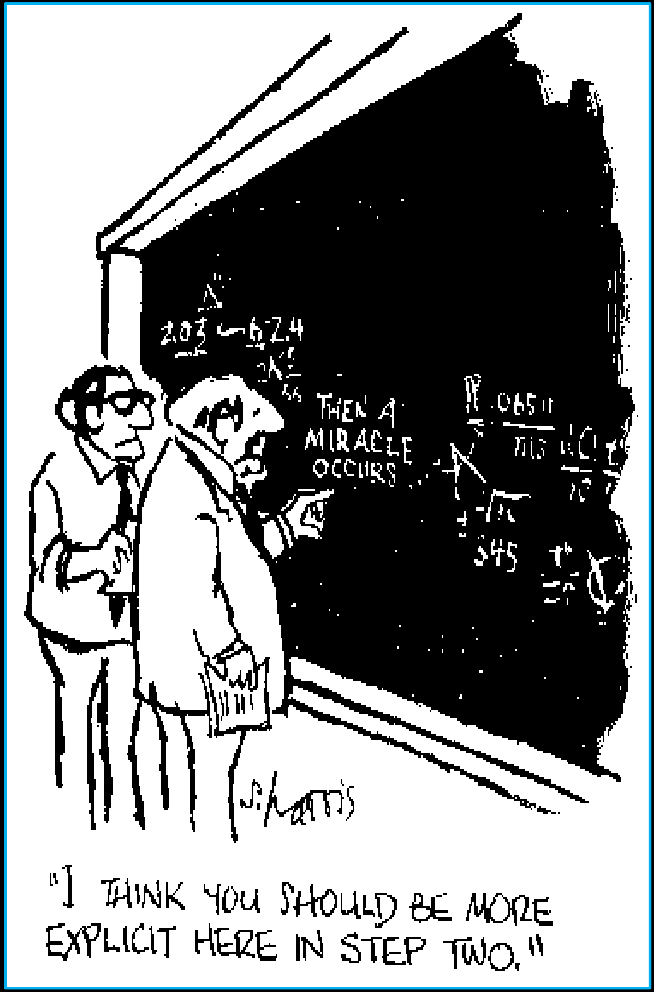
In the Standard Model, for fundamental particles to have masses, there must exist a particle called the Higgs boson. Will it be discovered soon? Is supersymmetry theory correct in predicting more than one type of Higgs?

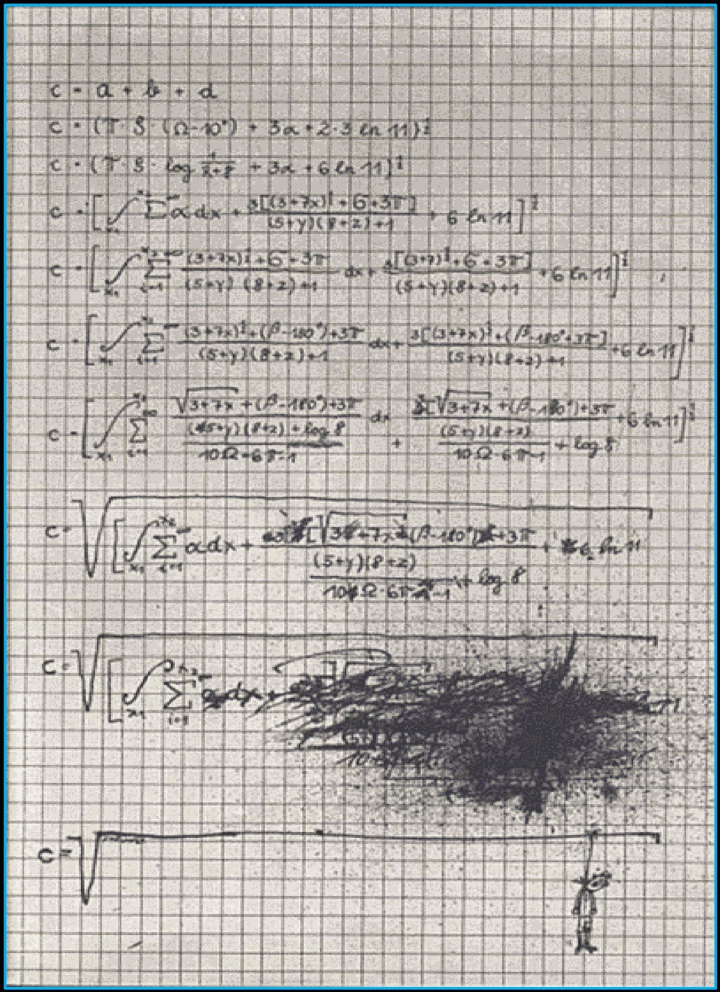
References

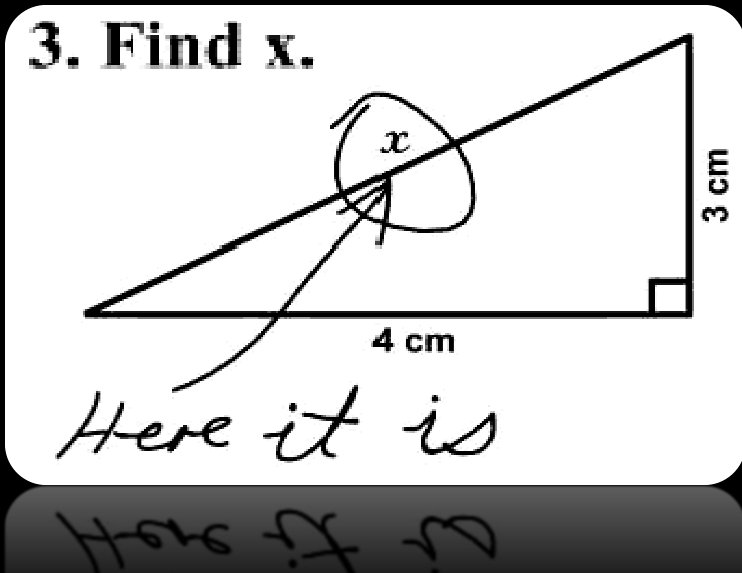
- AAVSO: www.aavso.org
- Astronomy Magazine: www.astronomy.com
- Astronomy Picture of the Day: http://apod.nasa.gov/apod/
- Astrophysics in a Nutshell, D. Maoz, Princeton University Press (2007)
- Astrophysics papers: http://www.physics.smu.edu/kehoe/astro/papers/
- Cornell University Library Astrophysics: http://xxx.lanl.gov/archive/astro-ph
- Hyperphysics: http://hyperphysics.phy-astr.gsu.edu/hbase/hph.html
- Introduction to CCDs (PowerPoint), Simon Tulloch (2007)
- Introduction to Cosmology, B. Ryden, Addision-Wesley (2003)
- McDonald Observatory: http://mcdonaldobservatory.org/
- ROTSE: www.rotse.net
- SIMBAD Astronomical Database: http://simbad.u-strasbg.fr/simbad/
- Star Charts & Astronomy Software: http://www.midnightkite.com/binstar.html
- The CCD Detector (PowerPoint), Sami Dib, **Jean Surdej (2006)**
- Theory and Observation of Pulsating Stars: http://www.univie.ac.at/tops
- Wikipedia: http://en.wikipedia.org/wiki/Main_Page

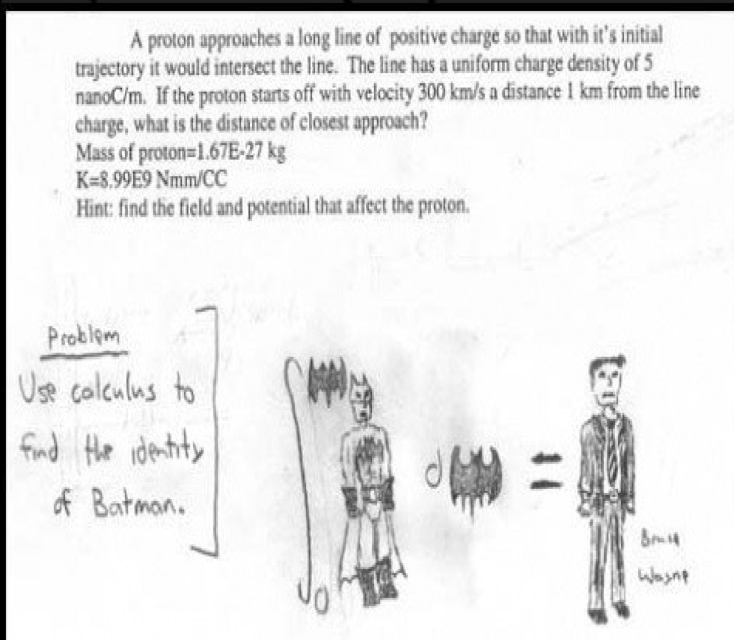
Humorous Interlude

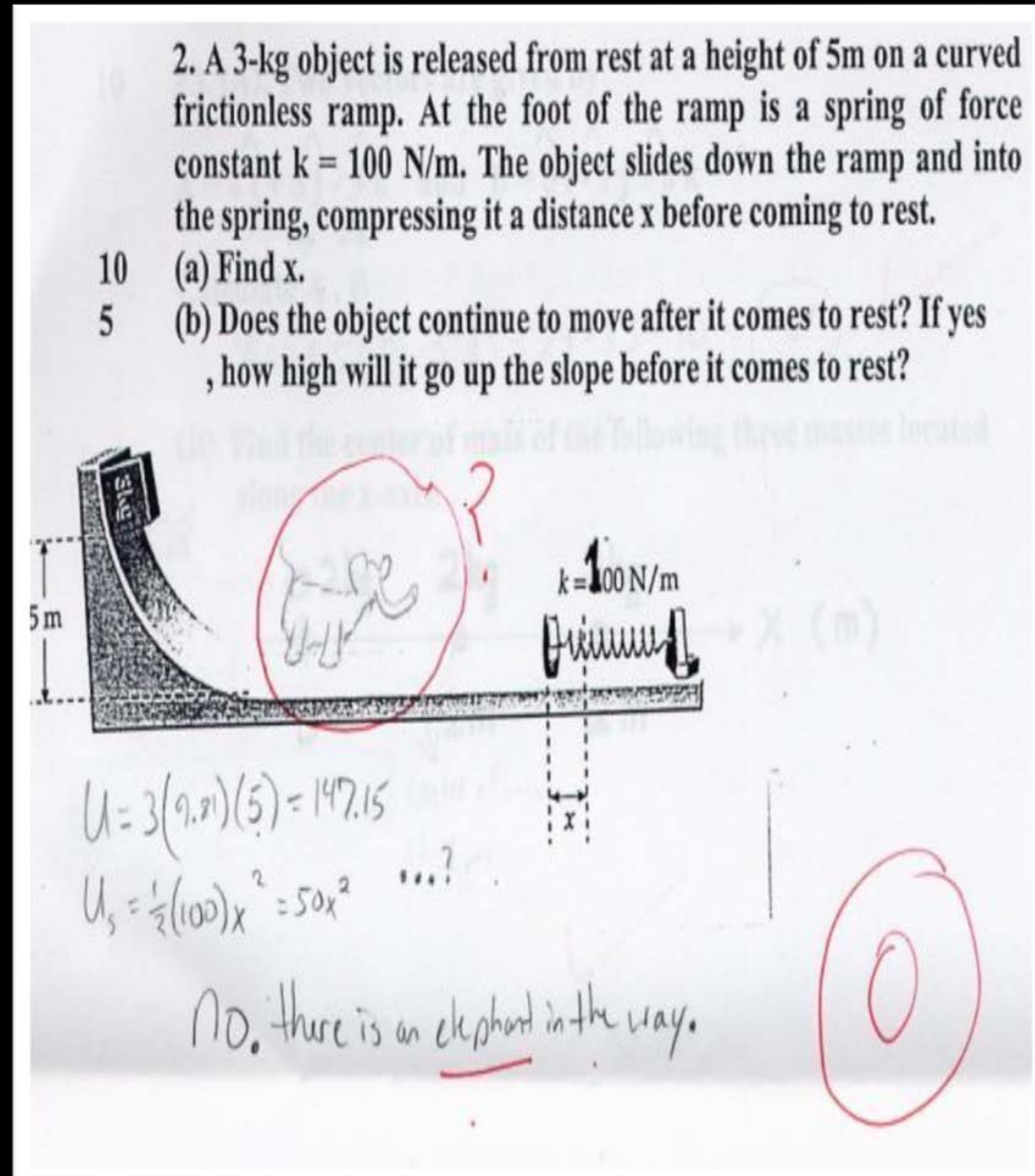







3. Find x.
x
3 cm
4 cm
Here it is


A proton approaches a long line of positive charge so that with it's initial trajectory it would intersect the line. The line has a uniform charge density of 5 nanoC/m. If the proton starts off with velocity 300 km/s a distance 1 km from the line charge, what is the distance of closest approach?
Mass of proton=1.67E-27 kg
K=8.99E9 Nmm/CC
Hint: find the field and potential that affect the proton.
Problem
Use calculus to find the identity of Batman.


2. A 3-kg object is released from rest at a height of 5m on a curved frictionless ramp. At the foot of the ramp is a spring of force constant k = 100 N/m. The object slides down the ramp and into the spring, compressing it a distance x before coming to rest.
10 (a) Find x.
5 (b) Does the object continue to move after it comes to rest? If yes , how high will it go up the slope before it comes to rest?
5 m
k = 100 N/m
x
U = 3(9.81)(5) = 147.15
Us = ½(100)x² = 50x²
...?
No, there is an elephant in the way.
0