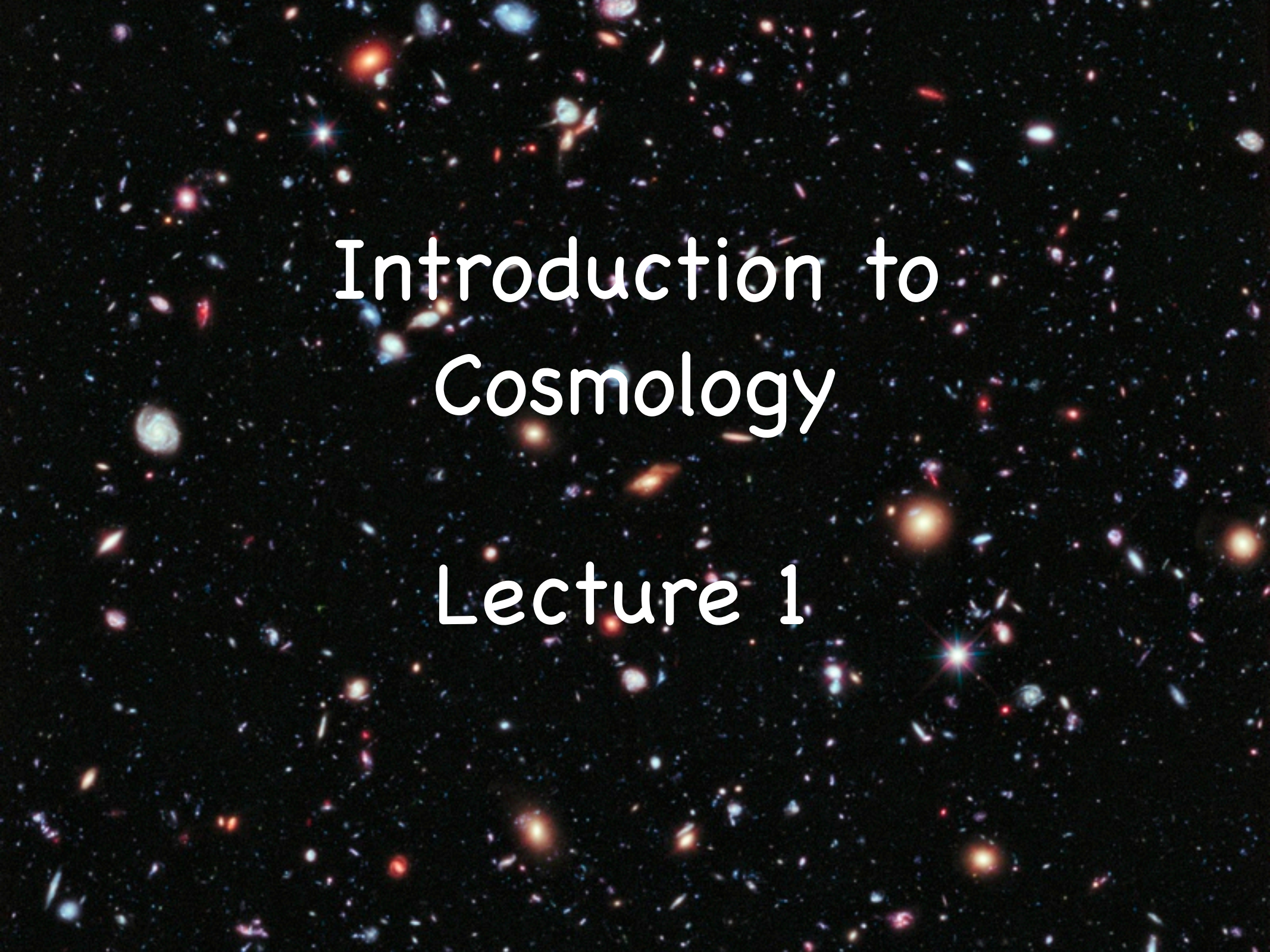


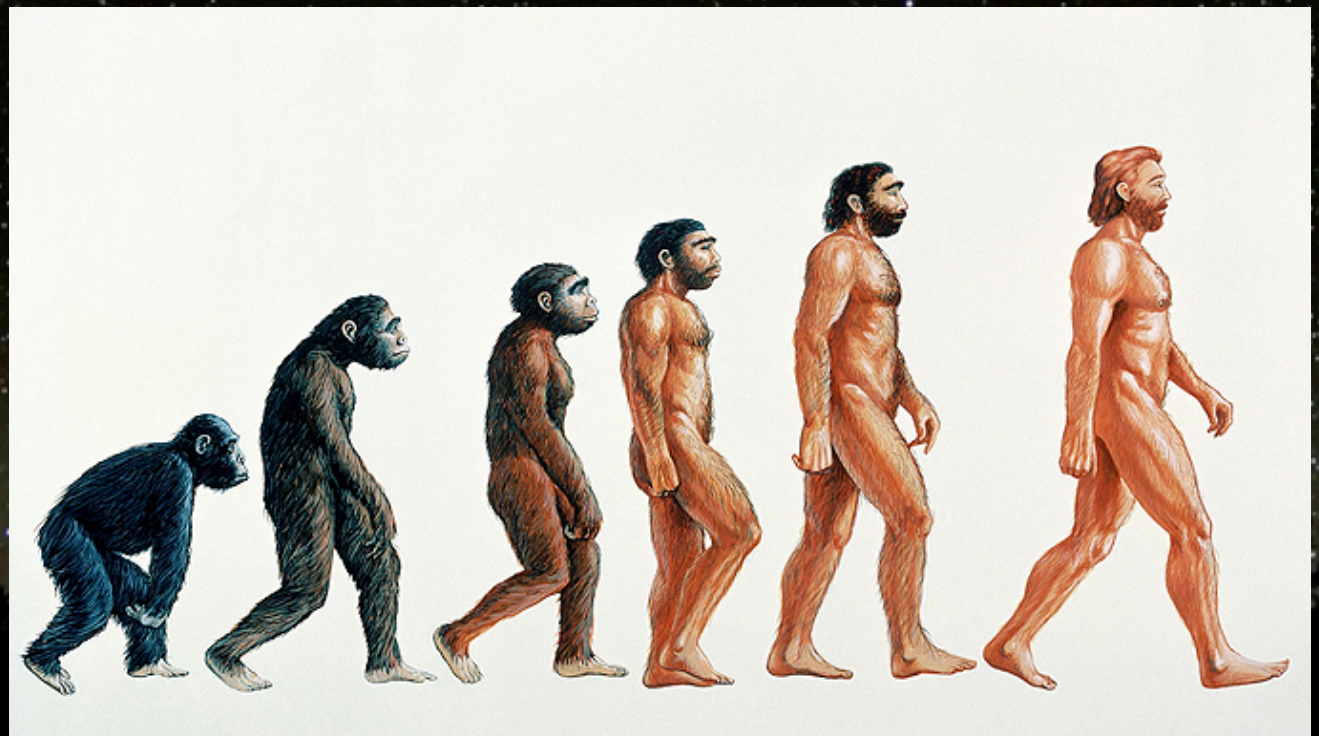
Introduction to Cosmology

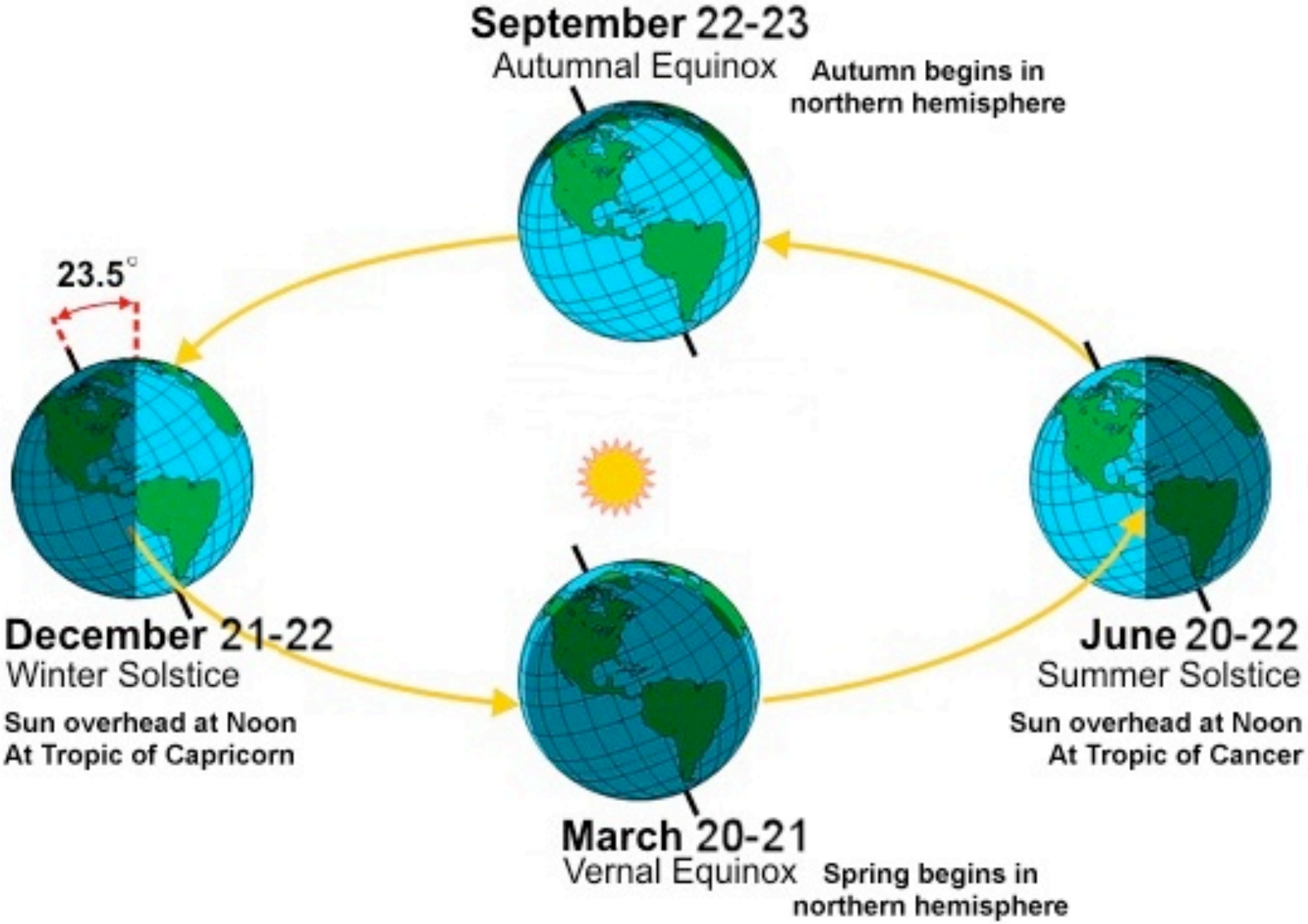
Lecture 1

"A cosmological model is a mathematical representation of our universe that is based on the laws of nature that have been validated locally in our Solar system and on their extrapolations.

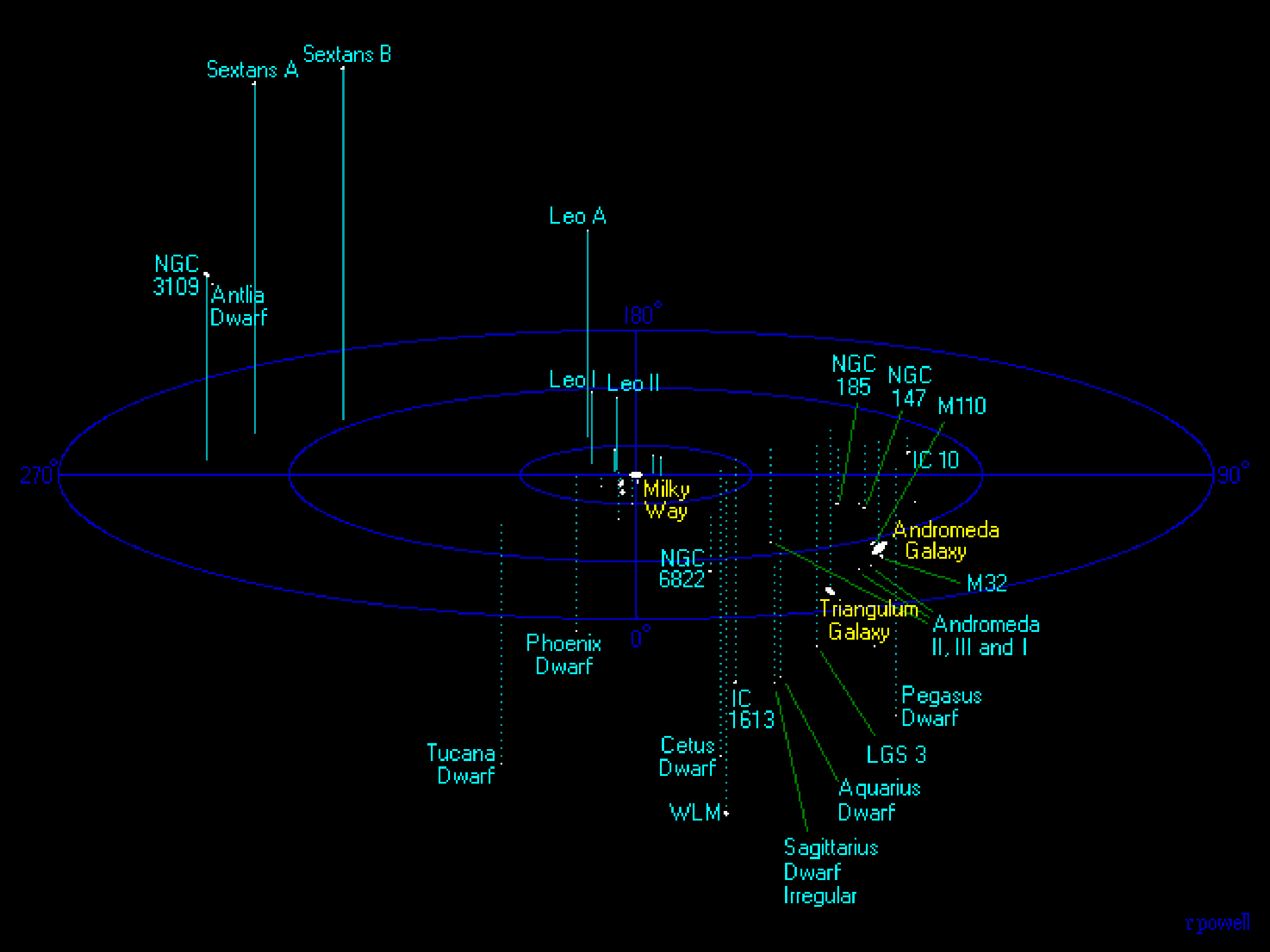
It thus seats at the crossroad between theoretical physics and astronomy. Its basic enterprise is to use tested physical laws to understand the properties and evolution of our universe and of the matter and the astrophysical objects it contains."

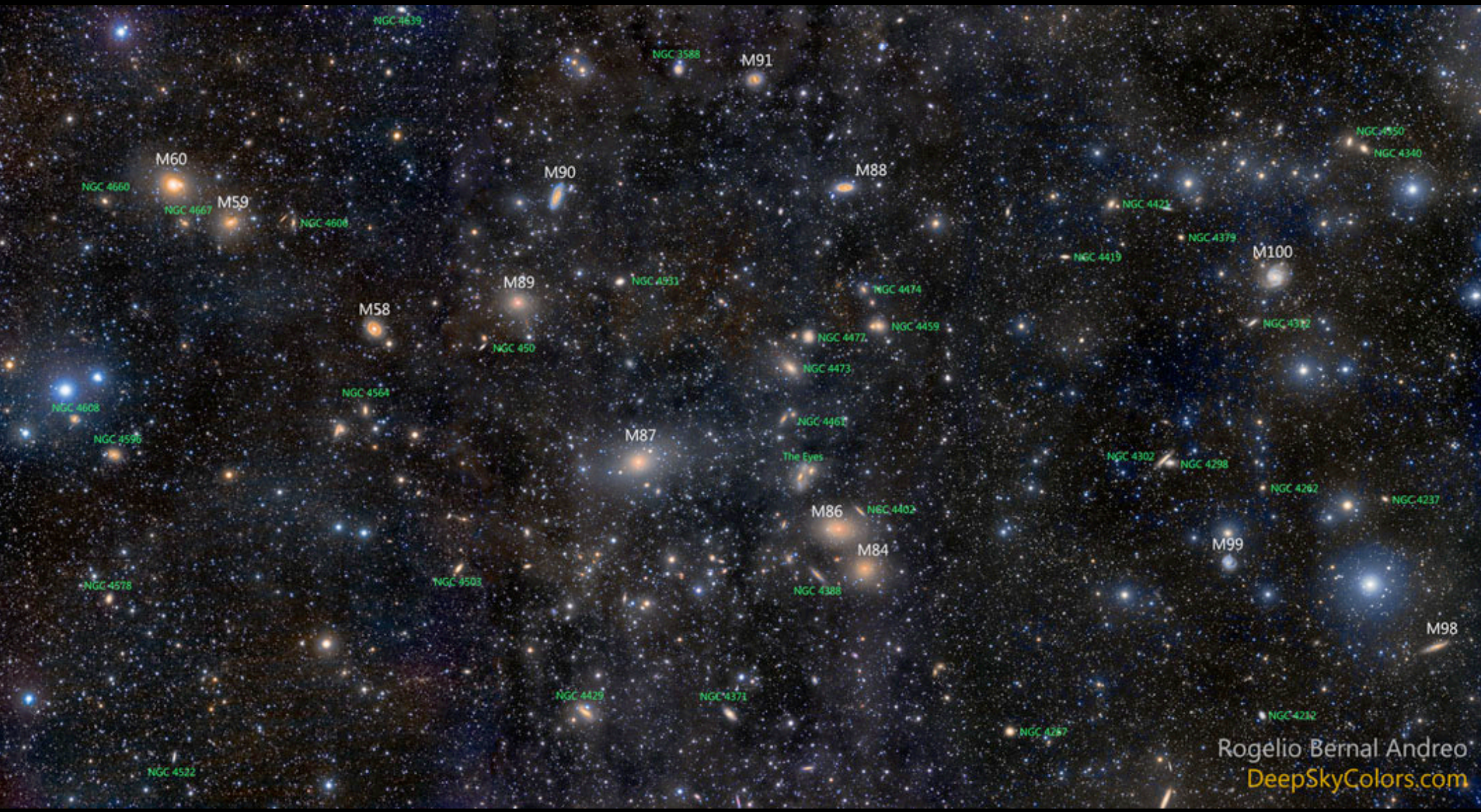
J-P Uzan arXiv:1606.06112

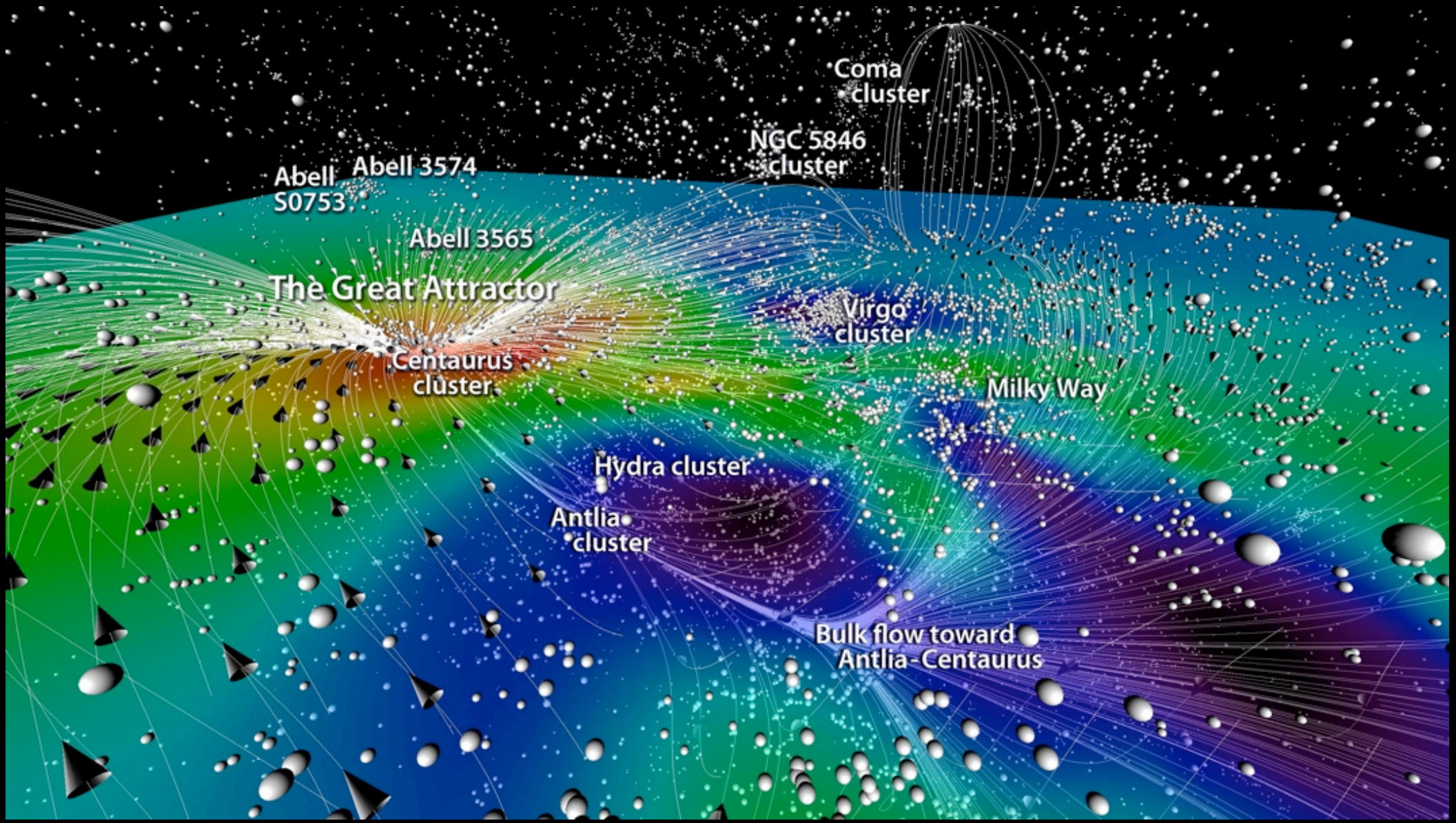


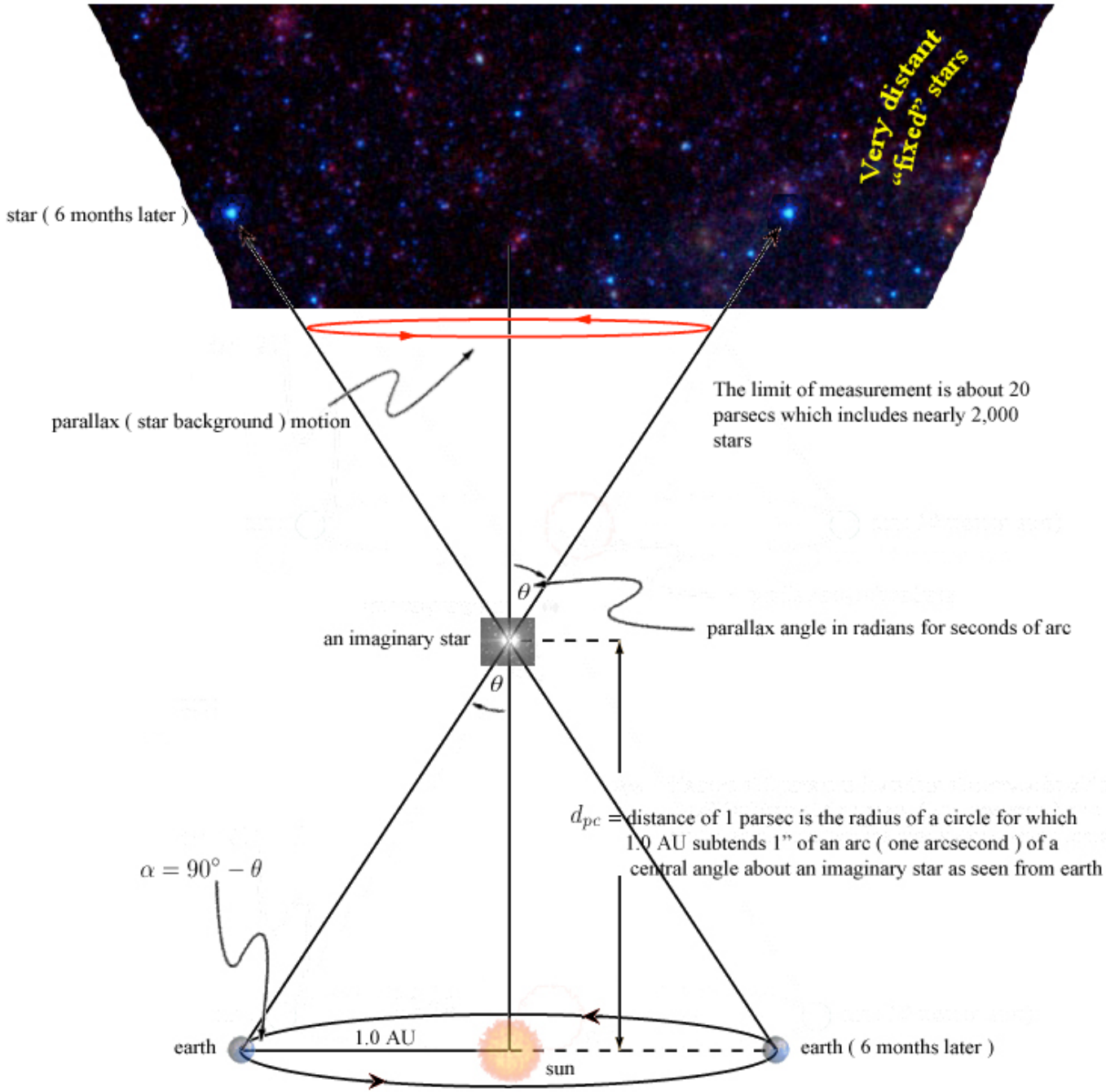

September 22-23
Autumnal Equinox
Autumn begins in
northern hemisphere
23.5°
December 21-22
Winter Solstice
Sun overhead at Noon
At Tropic of Capricorn
June 20-22
Summer Solstice
Sun overhead at Noon
At Tropic of Cancer
March 20-21
Vernal Equinox
Spring begins in
northern hemisphere


Galactic Longitide
0°
30°
330°
60°
300°
90°
270°
120°
240°
150°
210°
180°
75,000 ly
60,000 ly
45,000 ly
30,000 ly
15,000 ly
Scutum-Centaurus Arm
Sagittarius Arm
Norma Arm
Perseus Arm
Outer Arm
Far 3kpc Arm
Near 3kpc Arm
Galactic Bar
Long Bar
Sun
Orion Spur
We are here!


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


NGC 4639
NGC 3588
M91
M60
M90
M88
NGC 4660
M59
NGC 4667
NGC 4606
NGC 4421
NGC 4379
M100
NGC 4419
M89
NGC 4311
NGC 4474
M58
NGC 4459
NGC 4477
NGC 450
NGC 4473
NGC 4564
NGC 4608
NGC 4461
NGC 4596
M87
The Eyes
NGC 4302
NGC 4298
NGC 4262
NGC 4237
M86
NGC 4402
M84
M99
NGC 4578
NGC 4503
NGC 4388
M98
NGC 4429
NGC 4371
NGC 4292
NGC 4267
NGC 4522
Rogelio Bernal Andreo
DeepSkyColors.com


Coma
cluster
NGC 5846
cluster
Abell
S0753
Abell 3574
Abell 3565
The Great Attractor
Virgo
cluster
Centaurus
cluster
Milky Way
Hydra cluster
Antlia
cluster
Bulk flow toward
Antlia-Centaurus

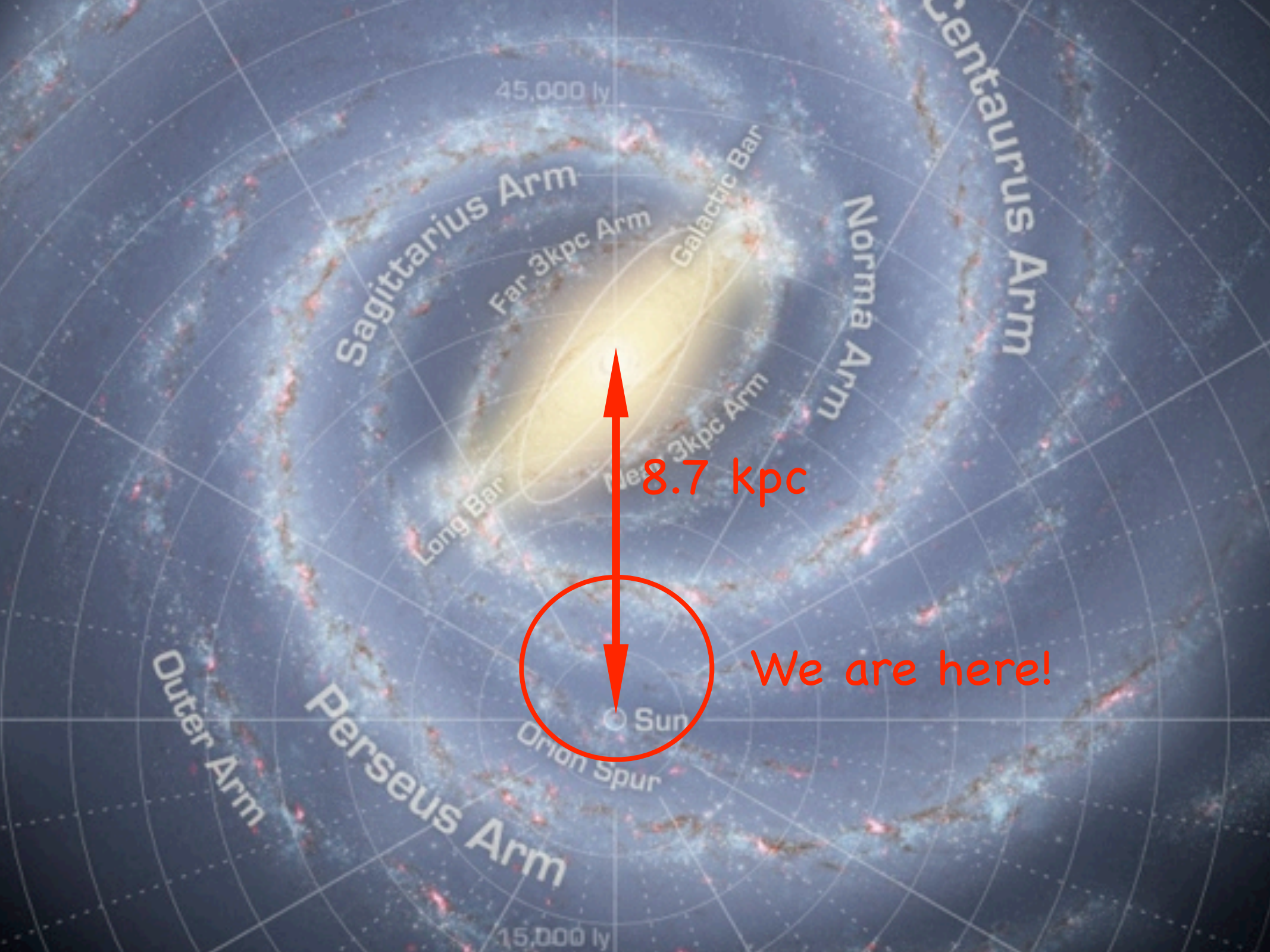


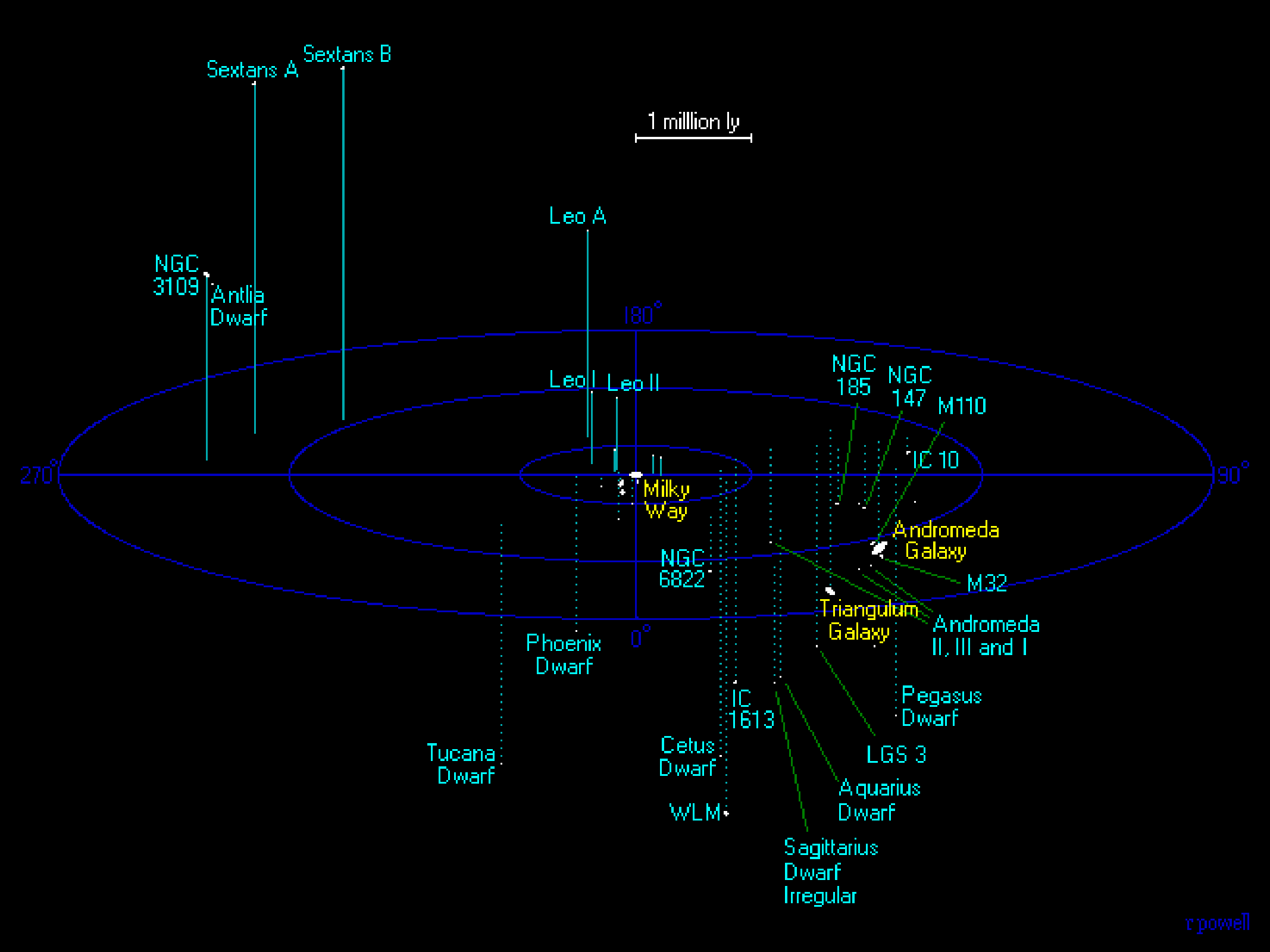
Where:

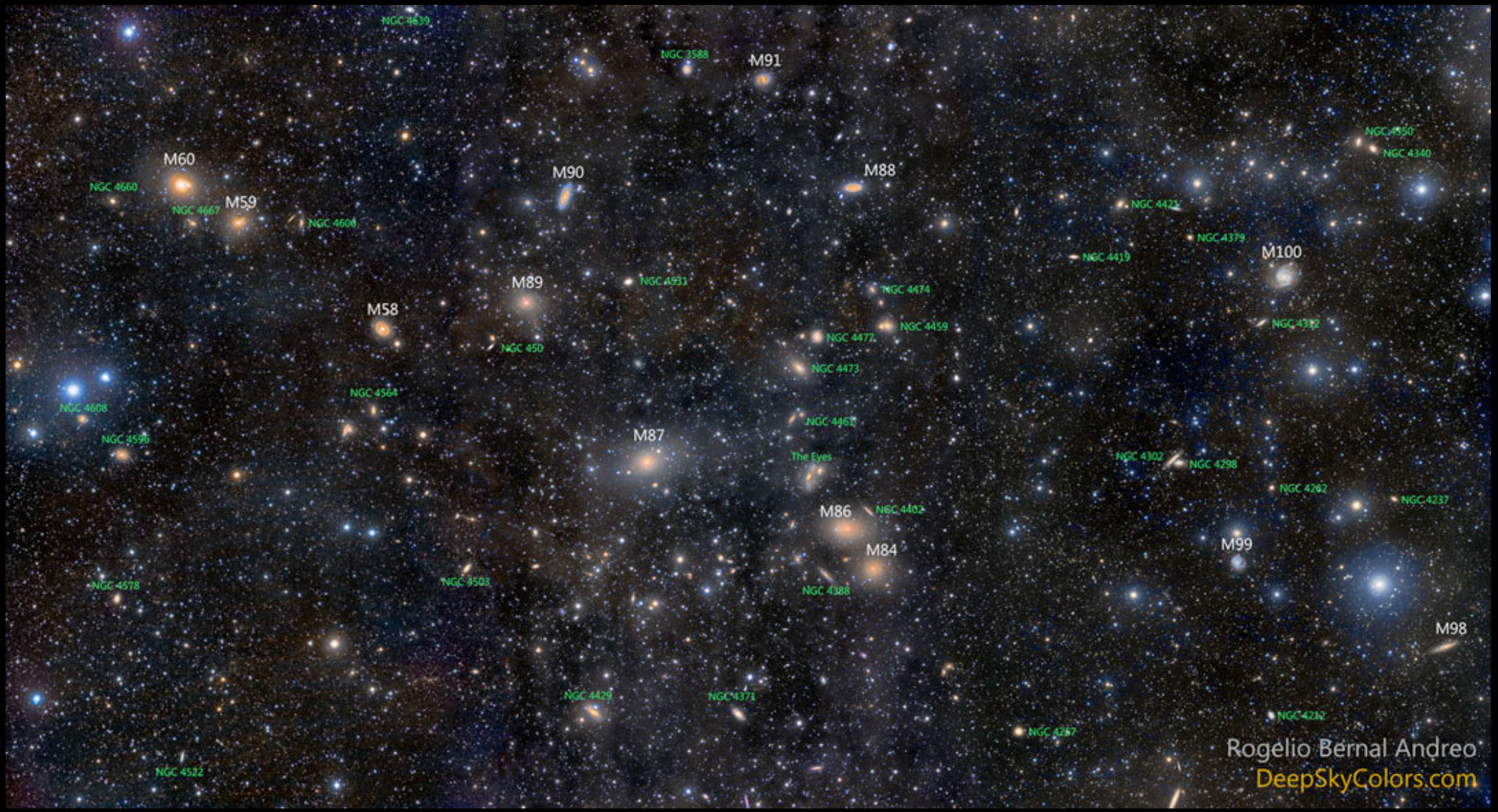
θ = angle of parallax in radians for seconds of arc

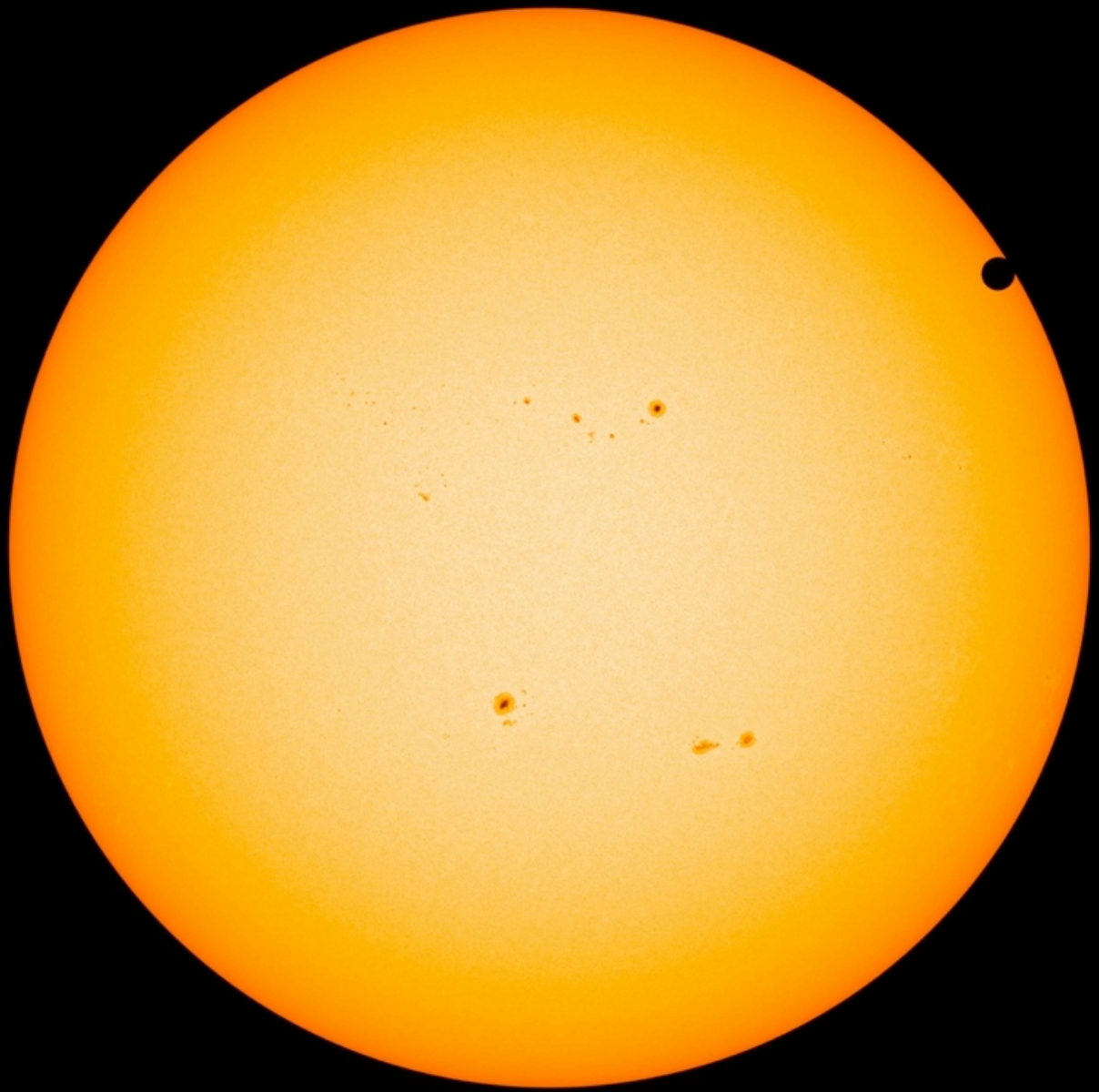
$d_{pc} = 1/\theta$, distance to an imaginary star in parsecs and is the radius of a circle for which 1.0 AU subtends 1.0" (one second) of arc of a central angle about an imaginary star as seen from earth

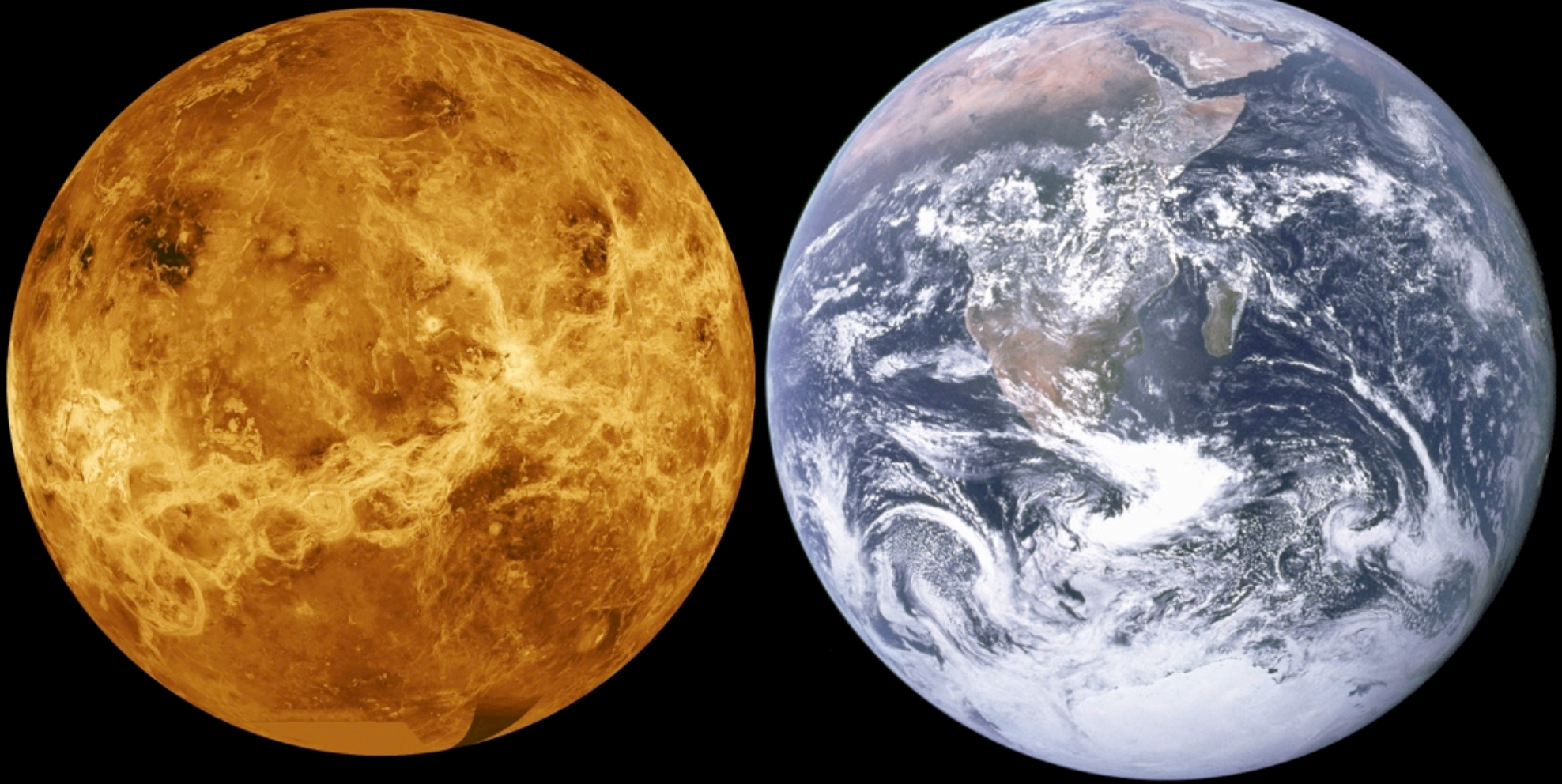
note: the word parsec stands for "Parallax of one arcsecond"

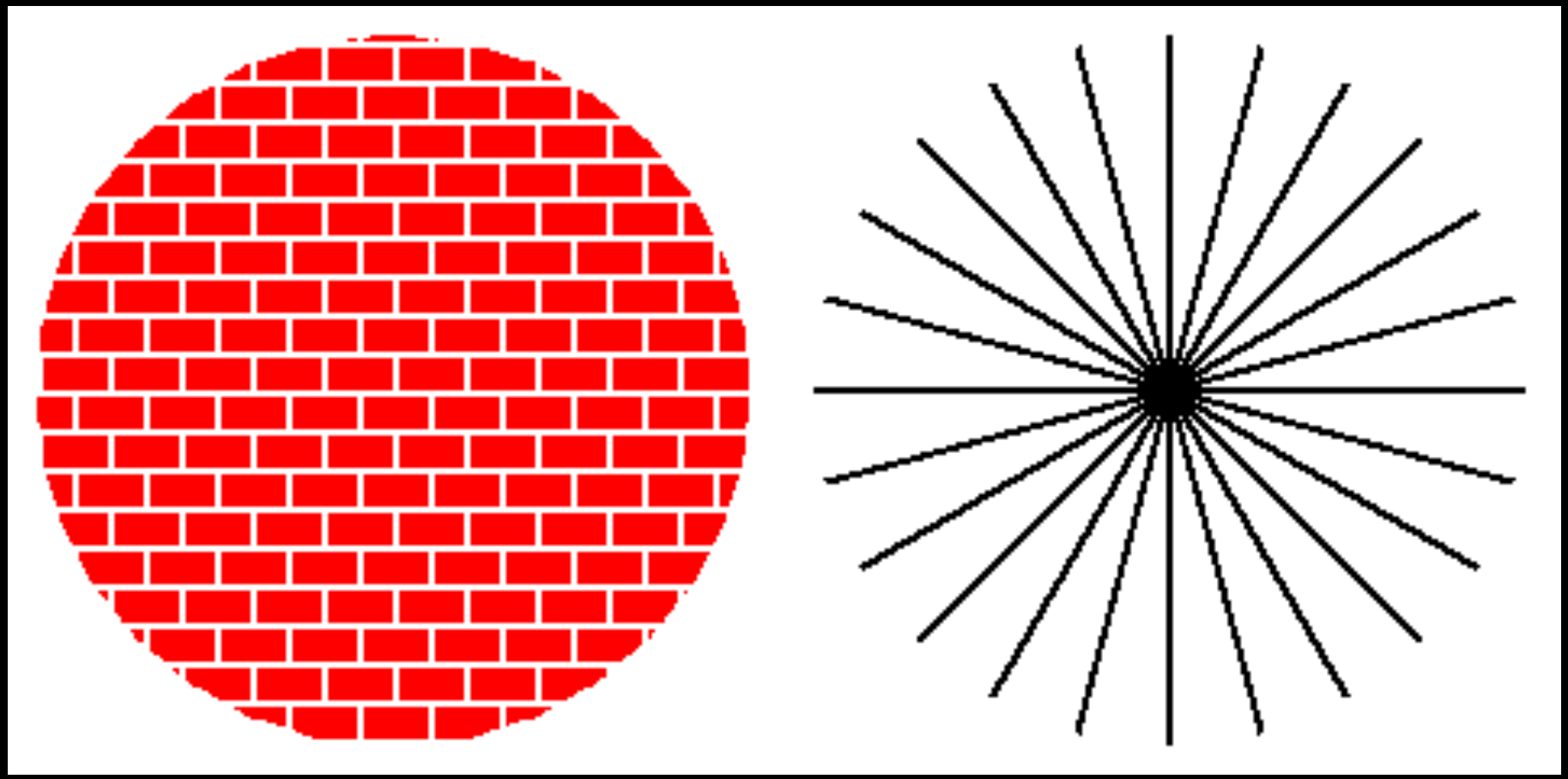

45,000 ly
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Centaurus Arm
Long Bar
Near 3kpc Arm
8.7 kpc
We are here!
Sun
Orion Spur
Outer Arm
Perseus Arm
15,000 ly


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

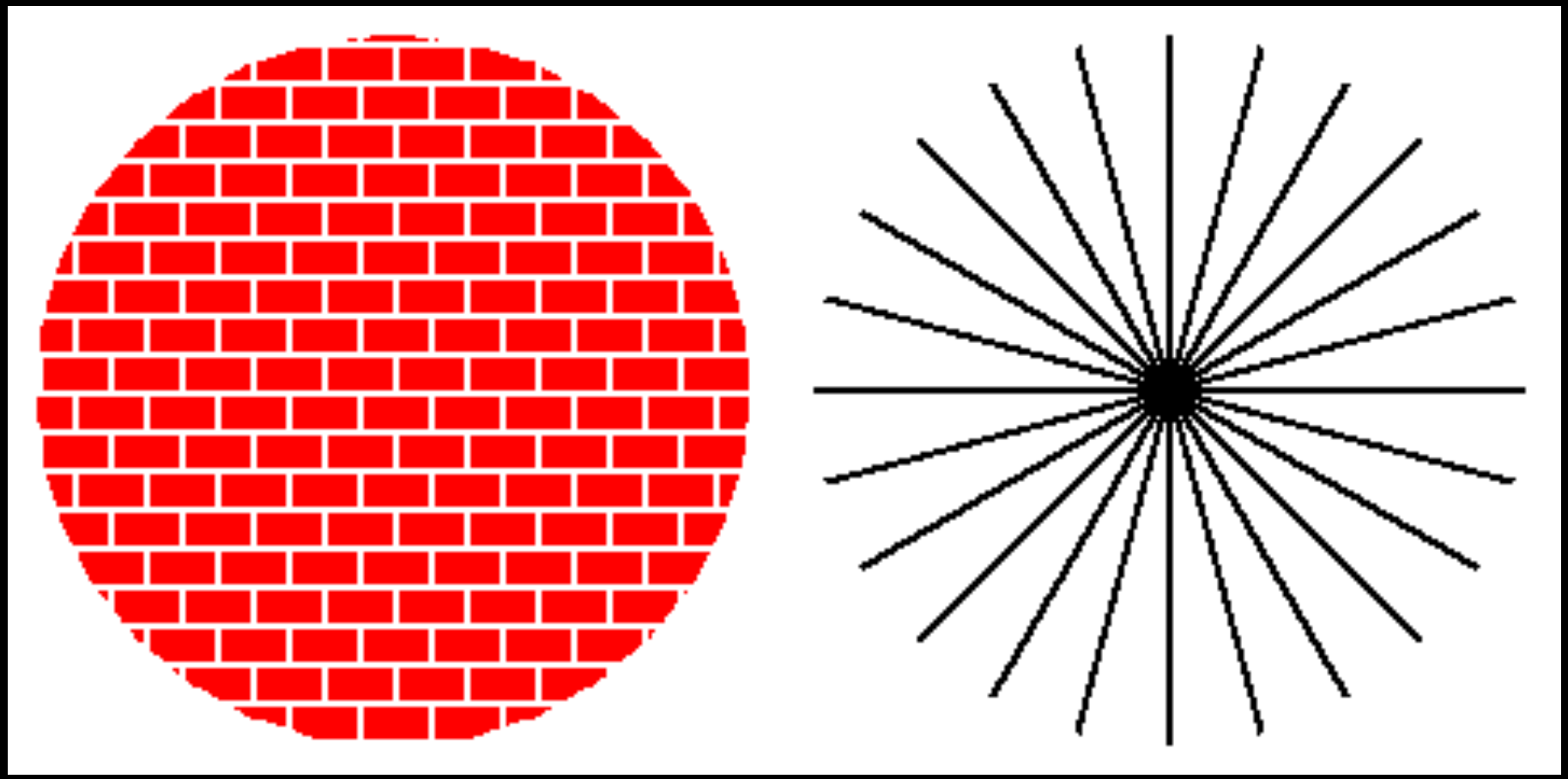

NGC 4639
NGC 3588
M91
NGC 4550
NGC 4340
M60
M90
M88
NGC 4660
M59
NGC 4667
NGC 4606
NGC 4421
NGC 4379
M100
NGC 4419
M89
NGC 4531
NGC 4474
M58
NGC 4459
NGC 4382
NGC 4477
NGC 450
NGC 4473
NGC 4564
NGC 4608
NGC 4461
NGC 4596
M87
The Eyes
NGC 4302
NGC 4298
NGC 4262
NGC 4237
M86
NGC 4402
M84
M99
NGC 4578
NGC 4503
NGC 4388
M98
NGC 4429
NGC 4371
NGC 4212
NGC 4267
NGC 4522
Rogelio Bernal Andreo
DeepSkyColors.com



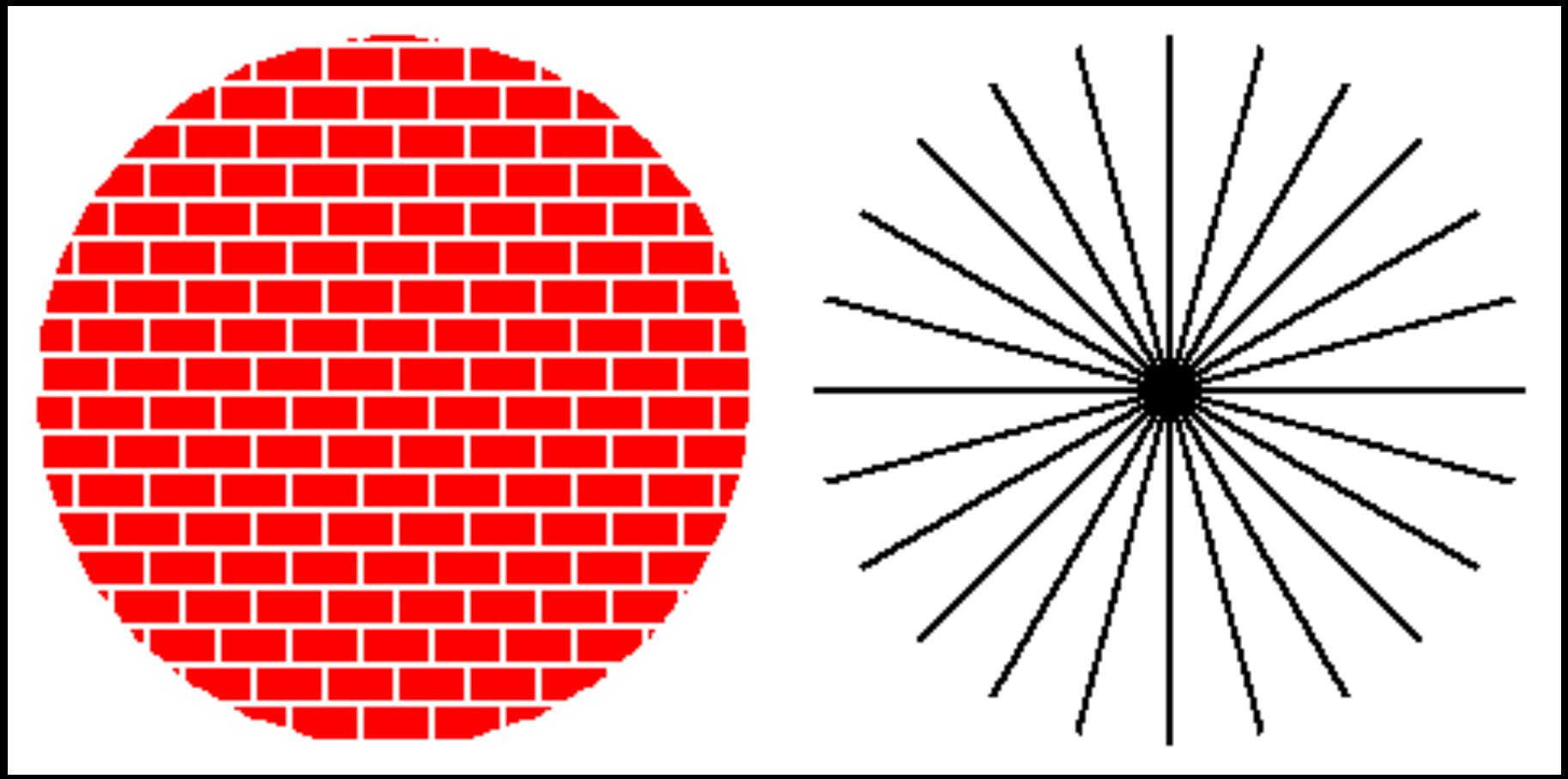




homogeneous



homogeneous



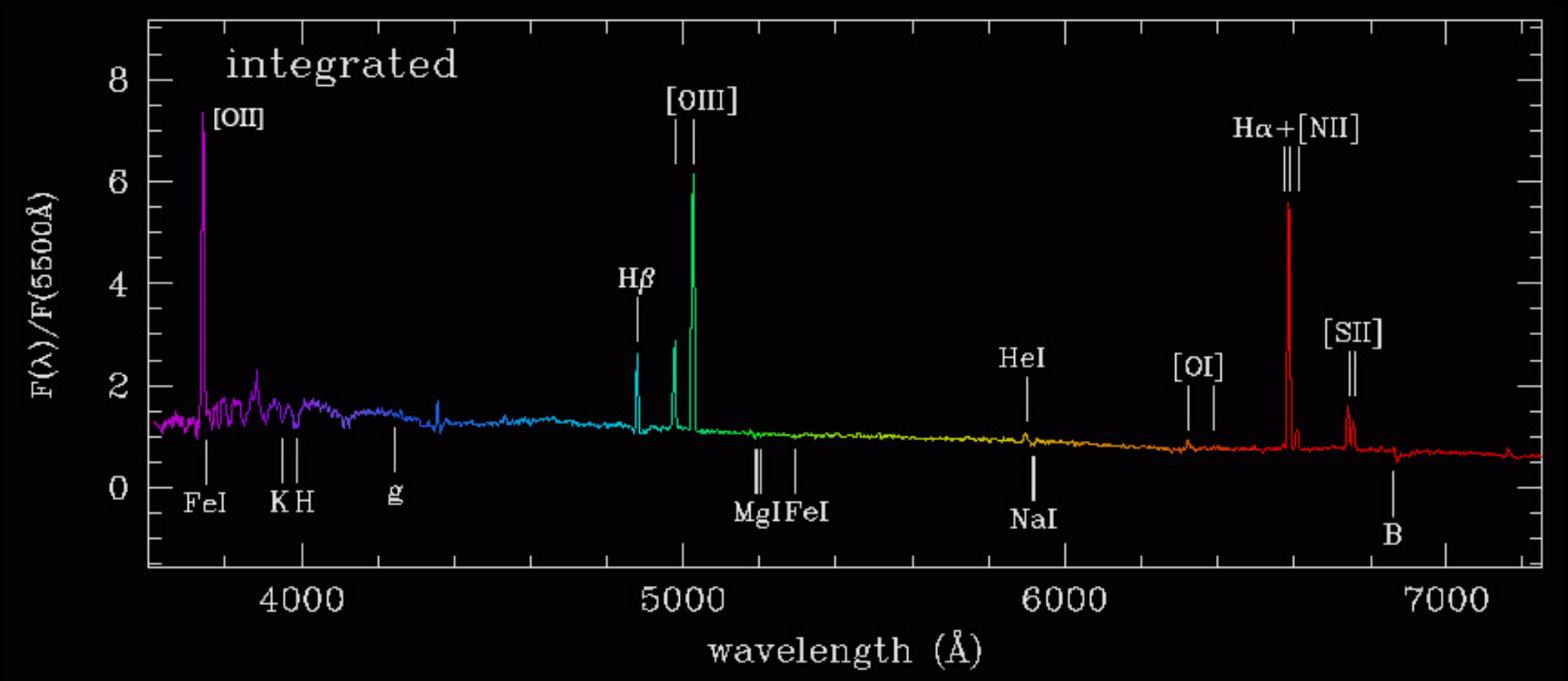
isotropic

12h
8h
4h
0h
20h
16h
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z

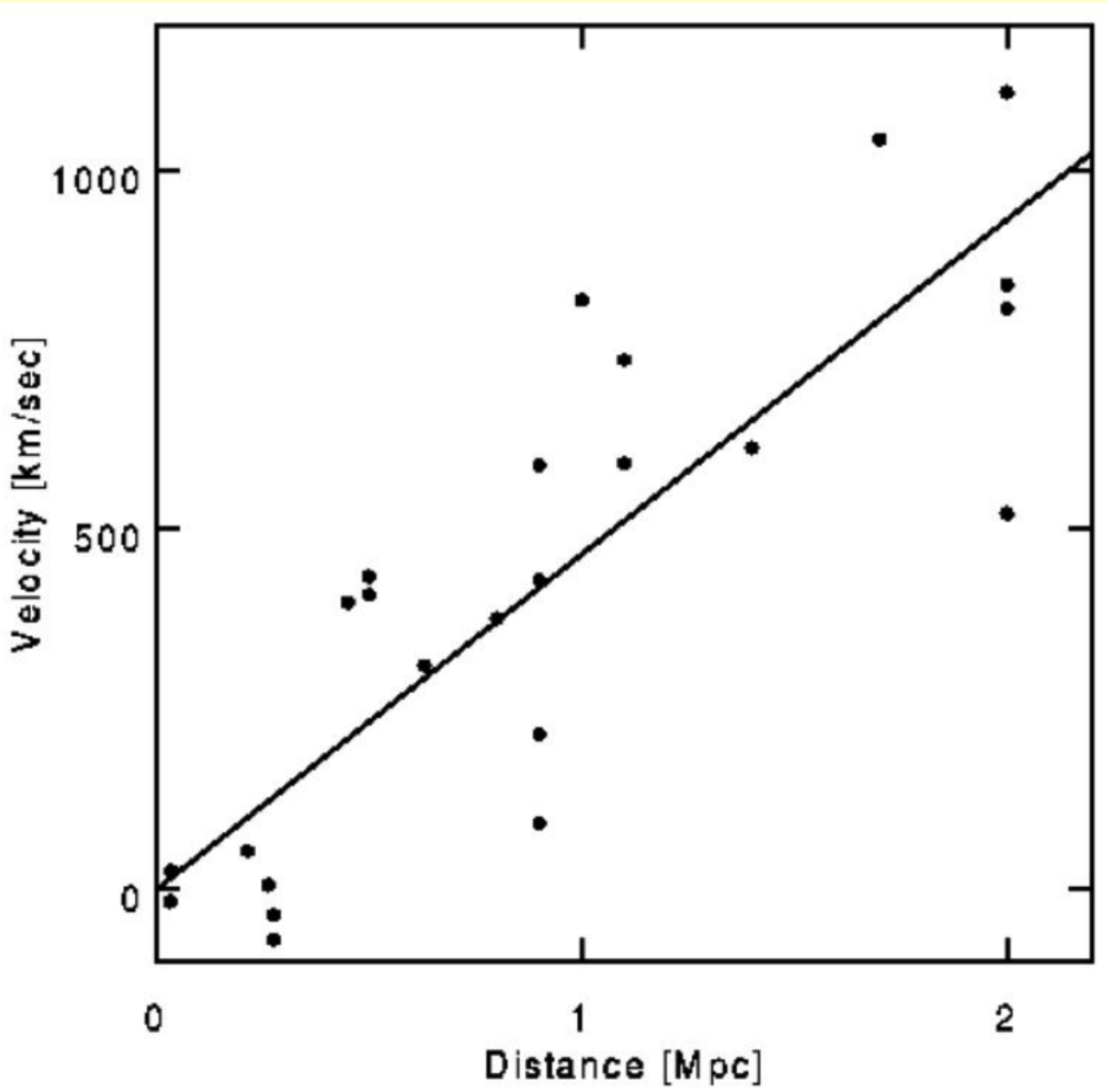
"There is no absolute up or down, as Aristotle taught; no absolute position in space; but the position of a body is relative to that of other bodies. Everywhere there is incessant relative change in position throughout the universe, and the observer is always at the center of things."

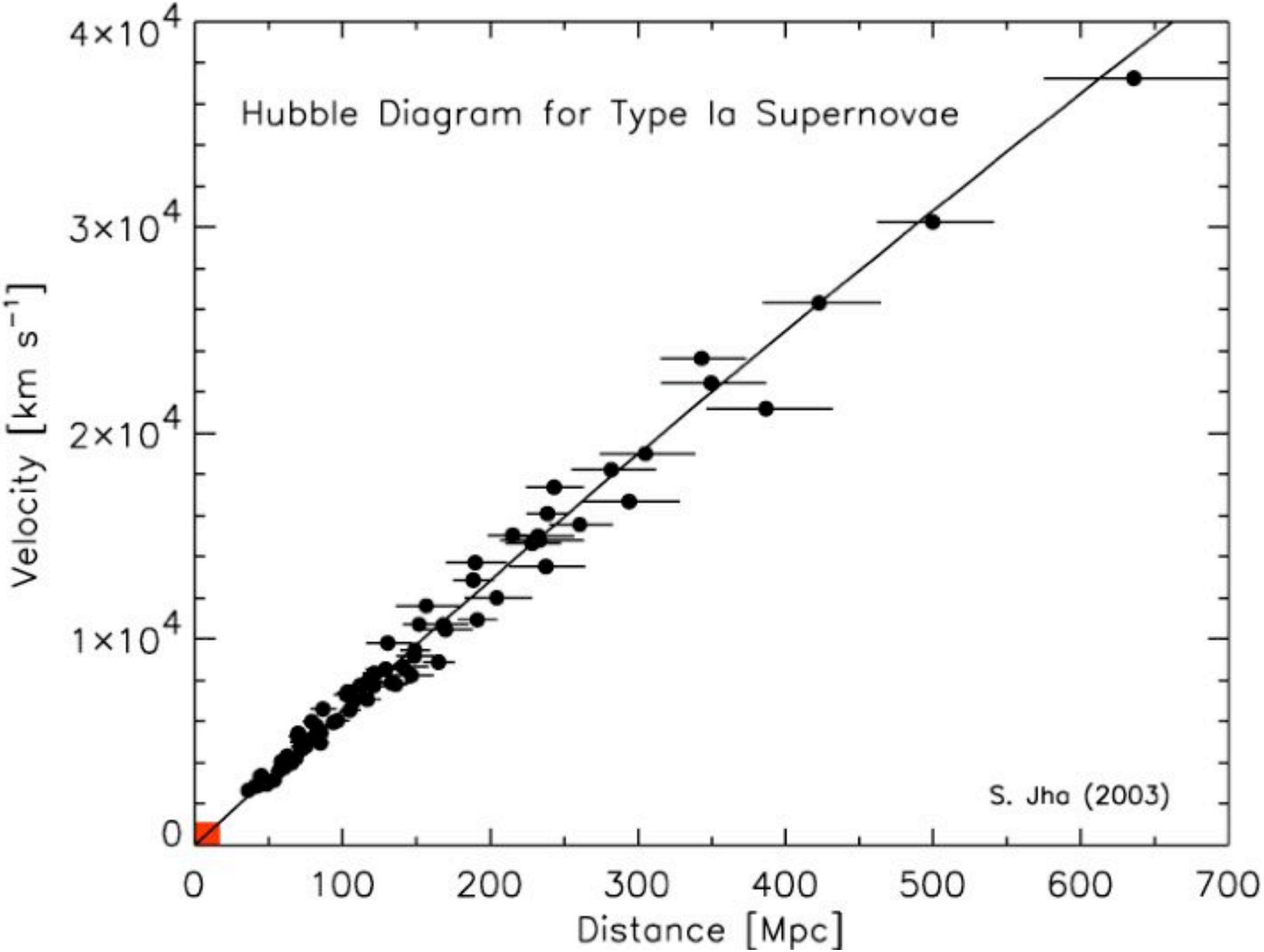
Giordano Bruno in
De la causa, principio, et uno (1584)

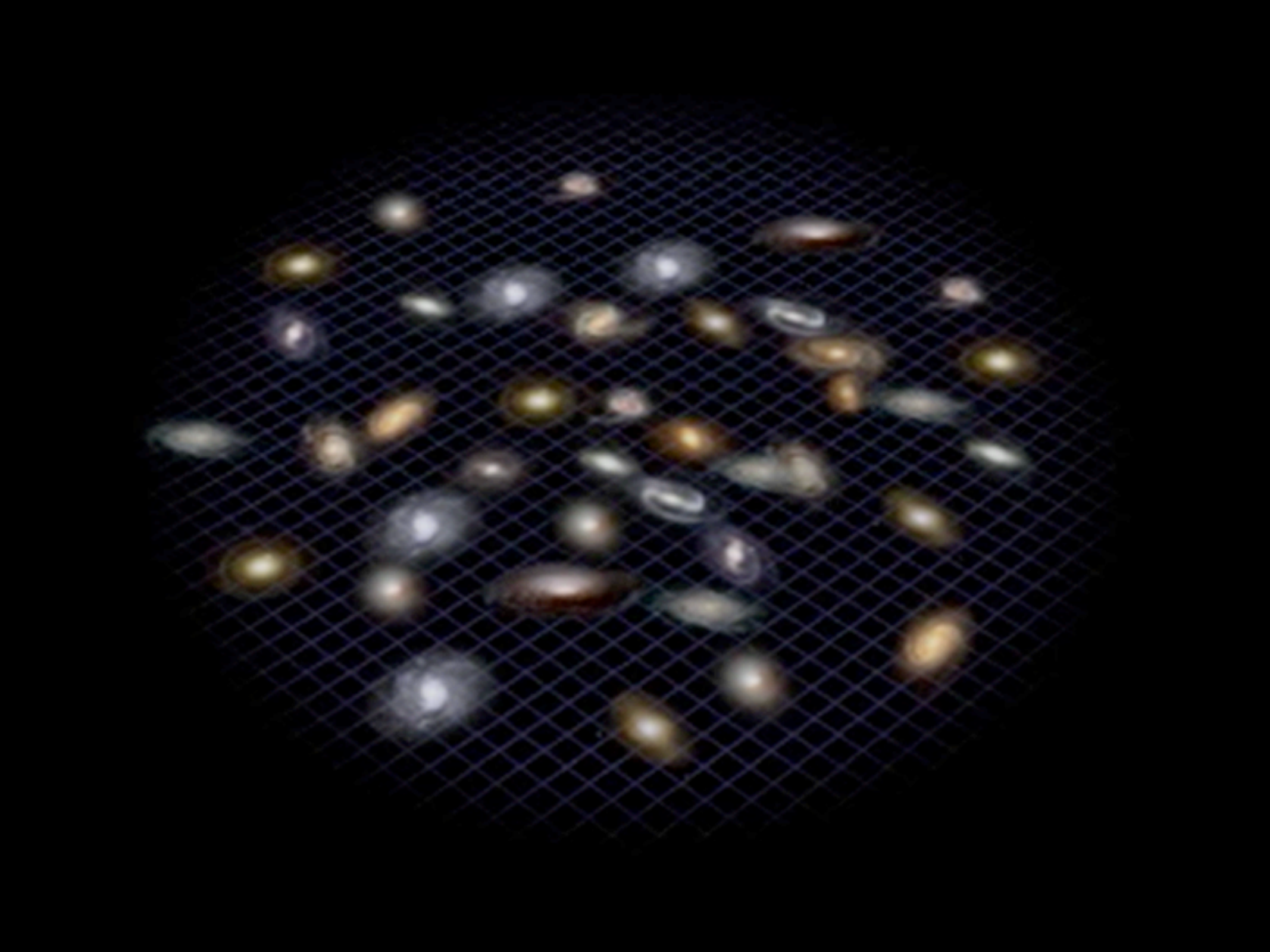

150 JAHRE DOPPLER-PRINZIP
PHYSIKER
s6
REPUBLIK ÖSTERREICH
H. HERGER
1992

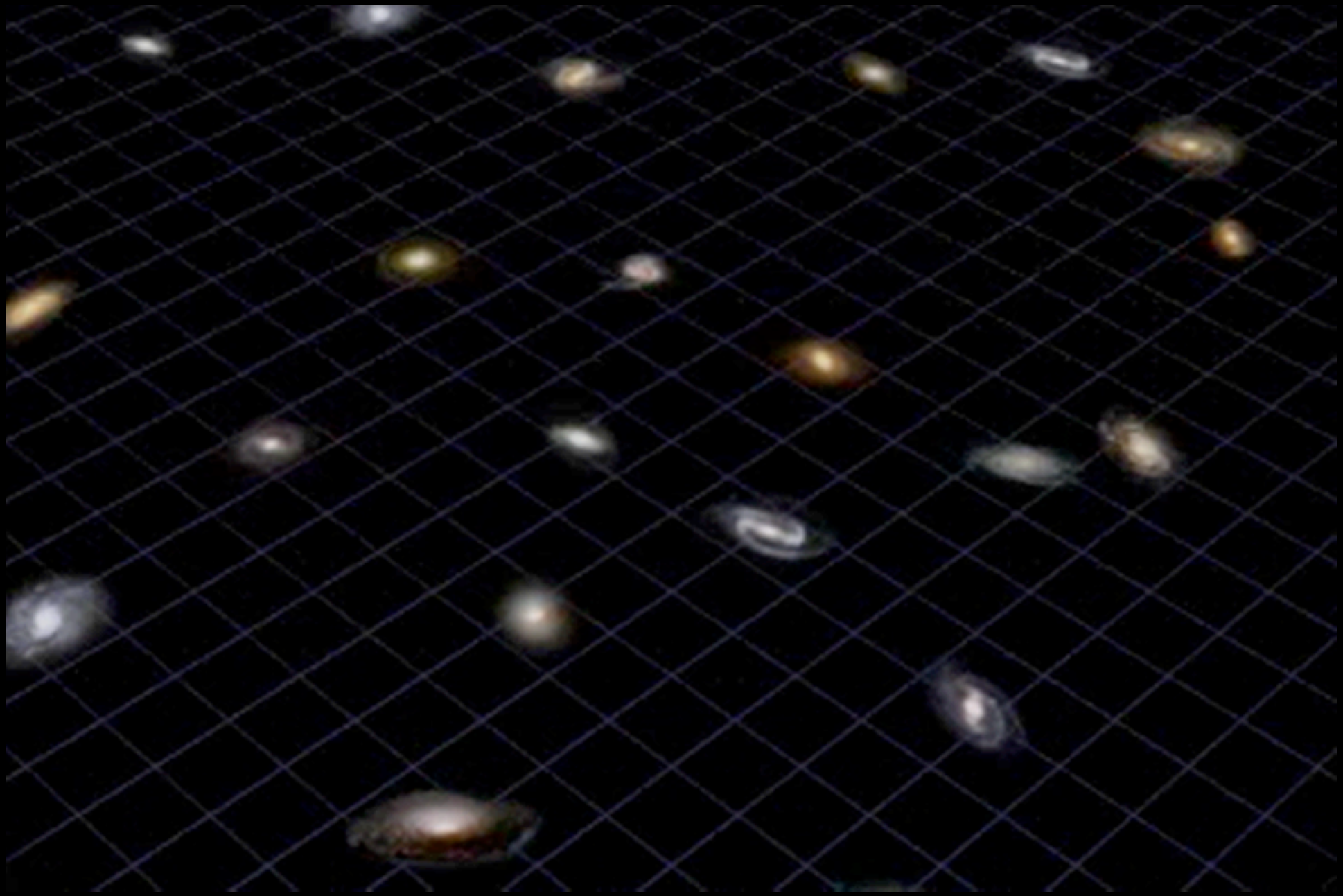

integrated
[OII]
[OIII]
Hα+[NII]
Hβ
HeI
[OI]
[SII]
FeI
K H
g
MgI FeI
NaI
B
F(λ)/F(5500Å)
wavelength (Å)
0
2
4
6
8
4000
5000
6000
7000

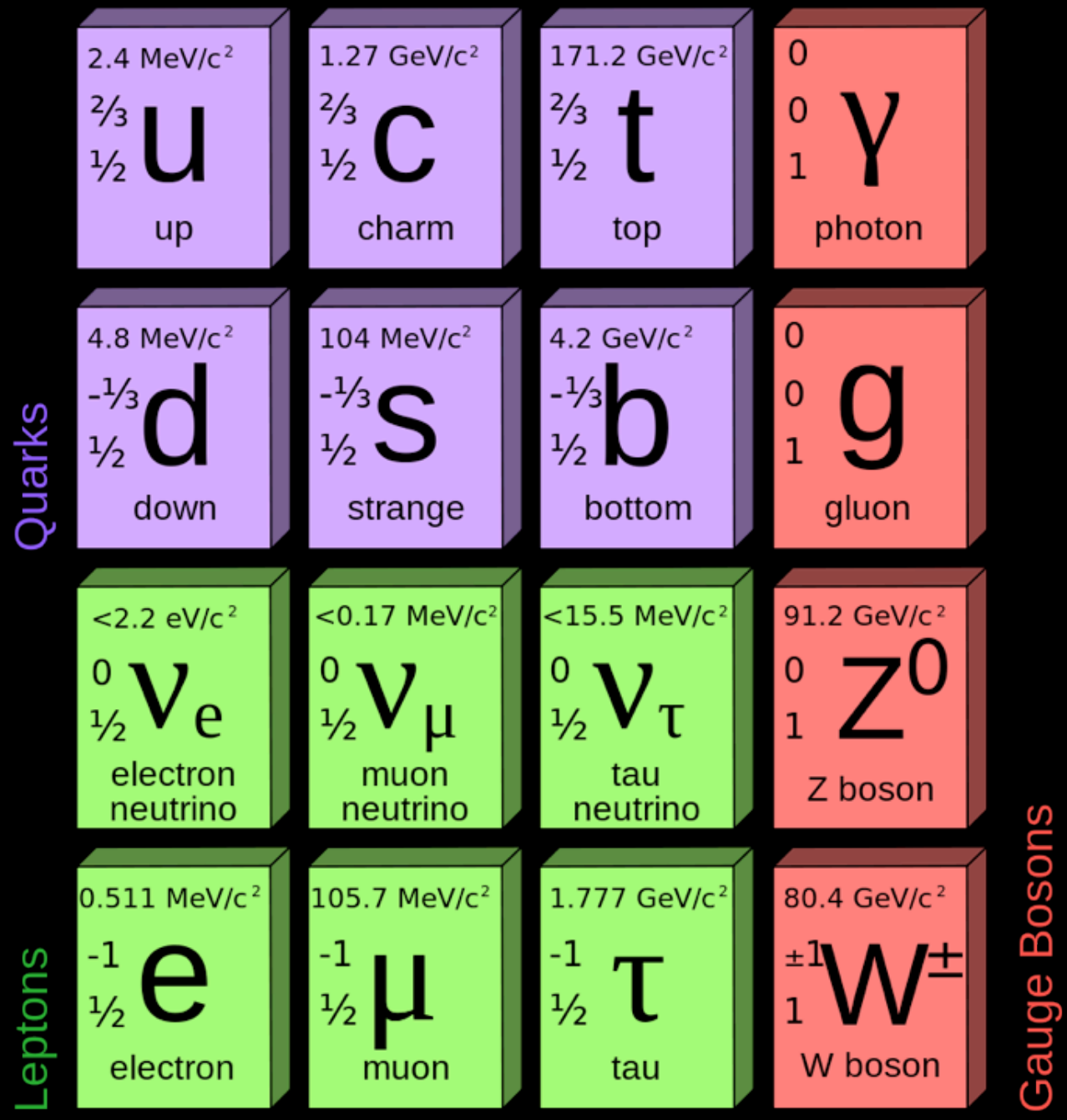
HUBBLE'S ORIGINAL DIAGRAM

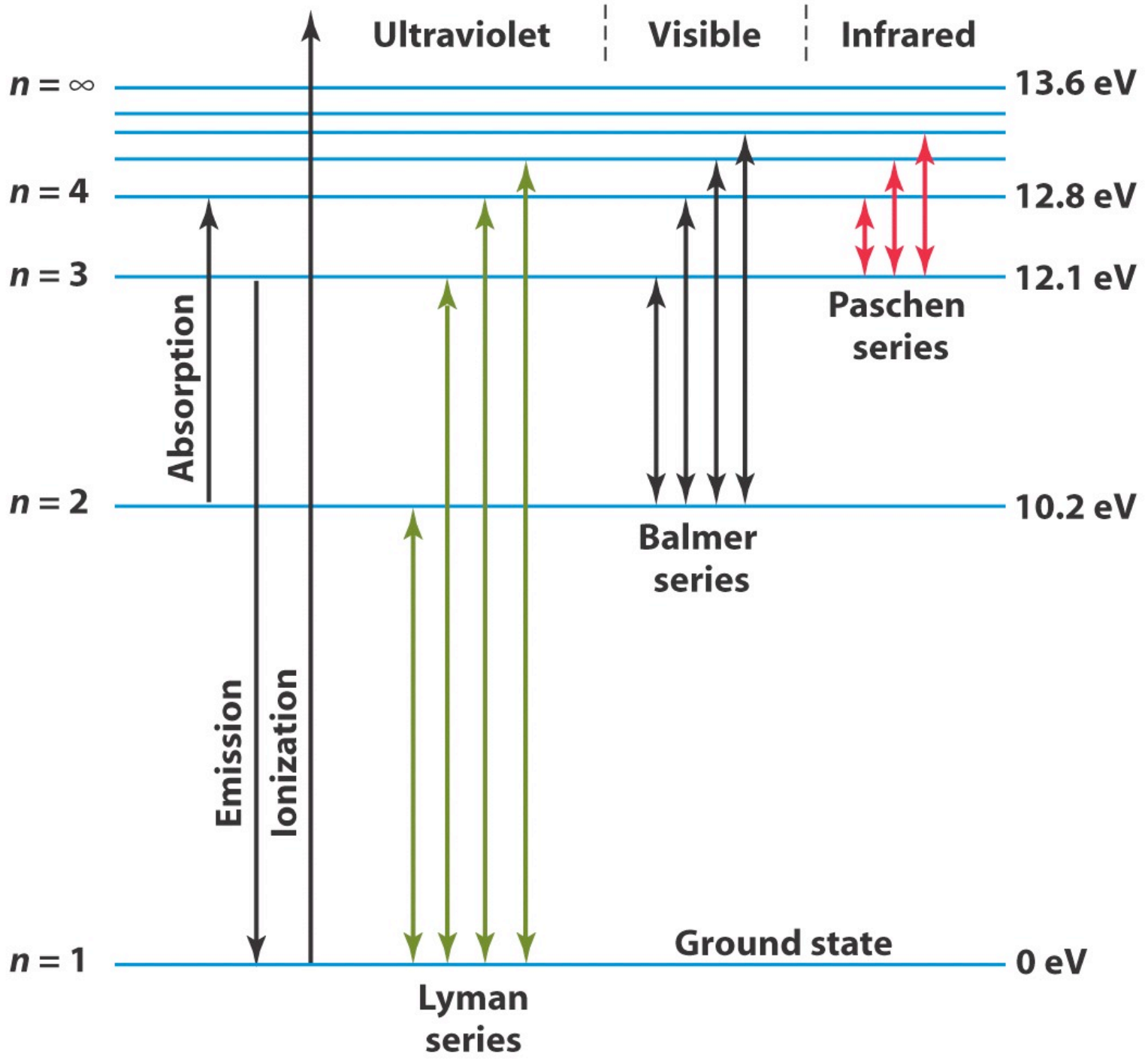


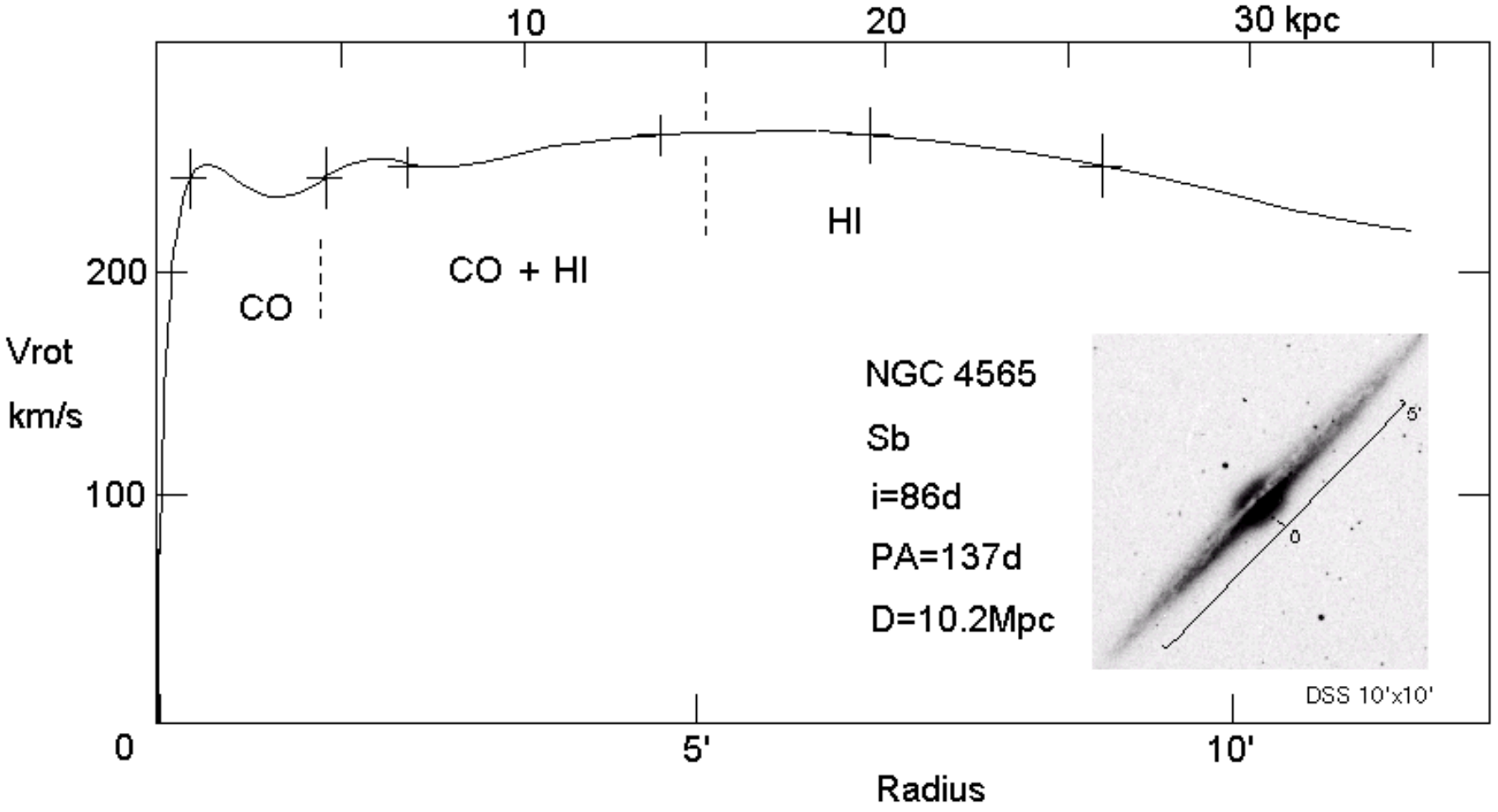

Hubble Diagram for Type Ia Supernovae
Velocity [km s^{-1}]
Distance [Mpc]
0
1×10^4
2×10^4
3×10^4
4×10^4
0
100
200
300
400
500
600
700
S. Jha (2003)

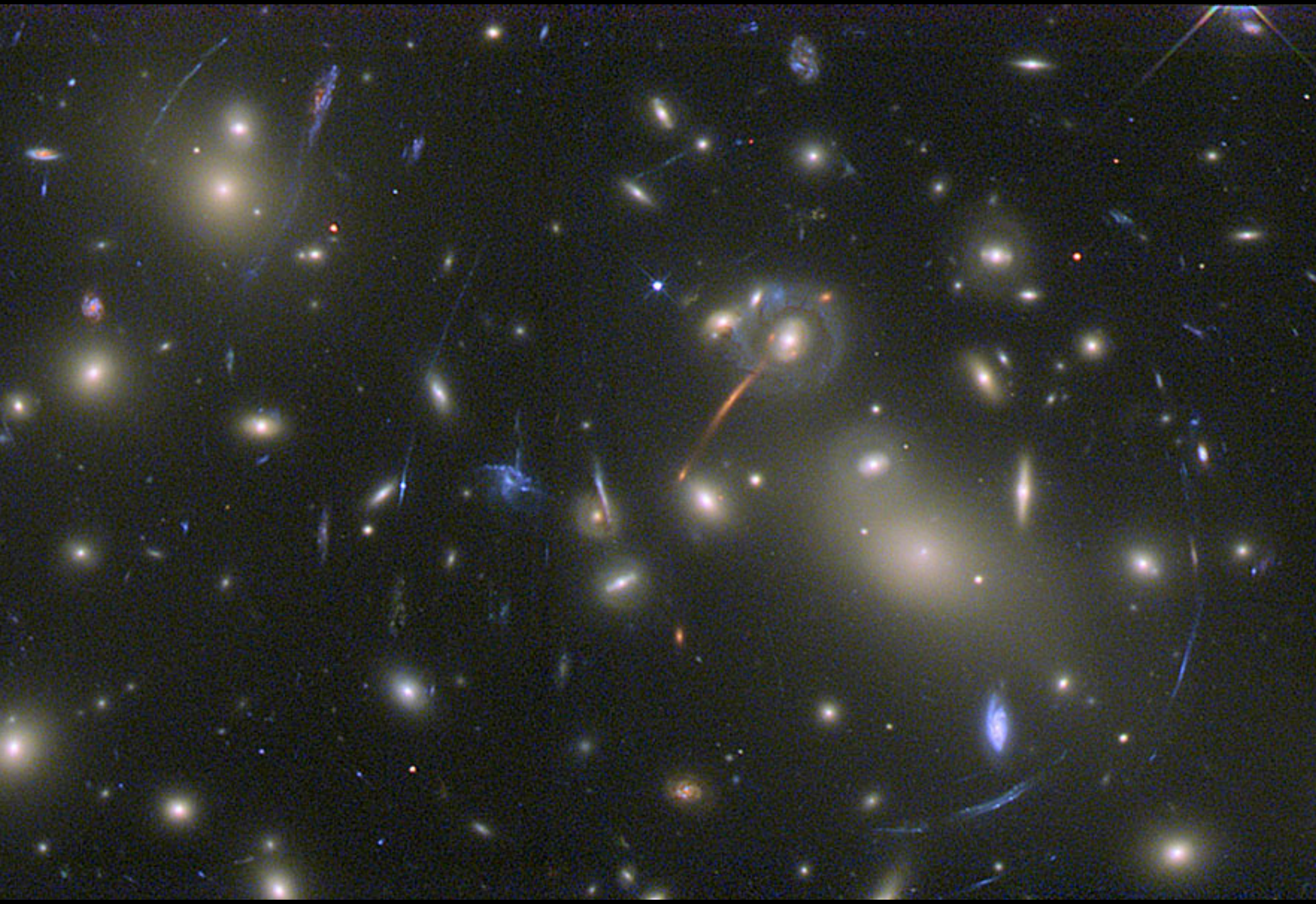





Quarks
Leptons
Gauge Bosons
2.4 MeV/c²
⅔
½
u
up
1.27 GeV/c²
⅔
½
c
charm
171.2 GeV/c²
⅔
½
t
top
0
0
1
γ
photon
4.8 MeV/c²
-⅓
½
d
down
104 MeV/c²
-⅓
½
s
strange
4.2 GeV/c²
-⅓
½
b
bottom
0
0
1
g
gluon
<2.2 eV/c²
0
½
νe
electron neutrino
<0.17 MeV/c²
0
½
νμ
muon neutrino
<15.5 MeV/c²
0
½
ντ
tau neutrino
91.2 GeV/c²
0
1
Z⁰
Z boson
0.511 MeV/c²
-1
½
e
electron
105.7 MeV/c²
-1
½
μ
muon
1.777 GeV/c²
-1
½
τ
tau
80.4 GeV/c²
±1
1
W±
W boson


Ultraviolet
Visible
Infrared
n = ∞
n = 4
n = 3
n = 2
n = 1
13.6 eV
12.8 eV
12.1 eV
10.2 eV
0 eV
Absorption
Emission
Ionization
Paschen series
Balmer series
Lyman series
Ground state


10
20
30 kpc
200
100
0
Vrot
km/s
CO
CO + HI
HI
NGC 4565
Sb
i=86d
PA=137d
D=10.2Mpc
5'
0
DSS 10'x10'
0
5'
10'
Radius



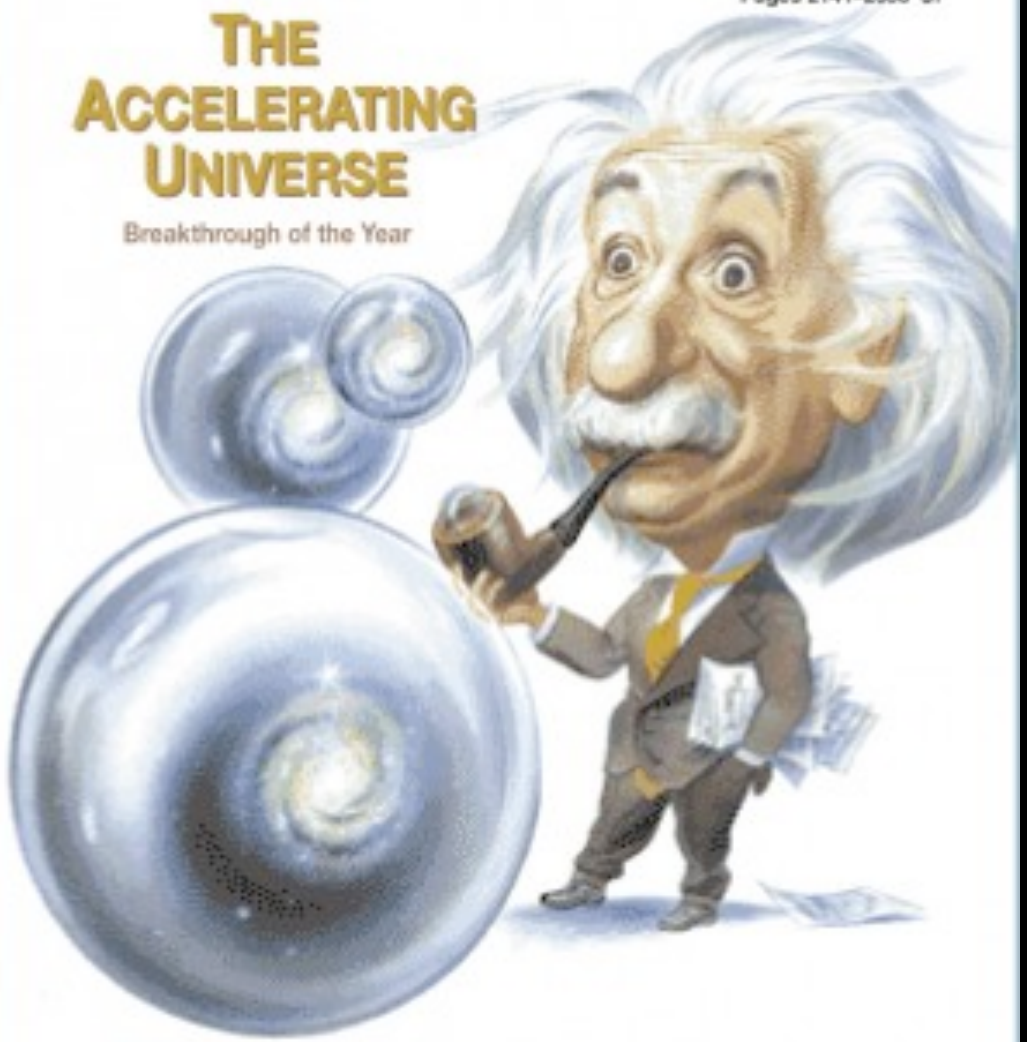
Science

18 December 1998

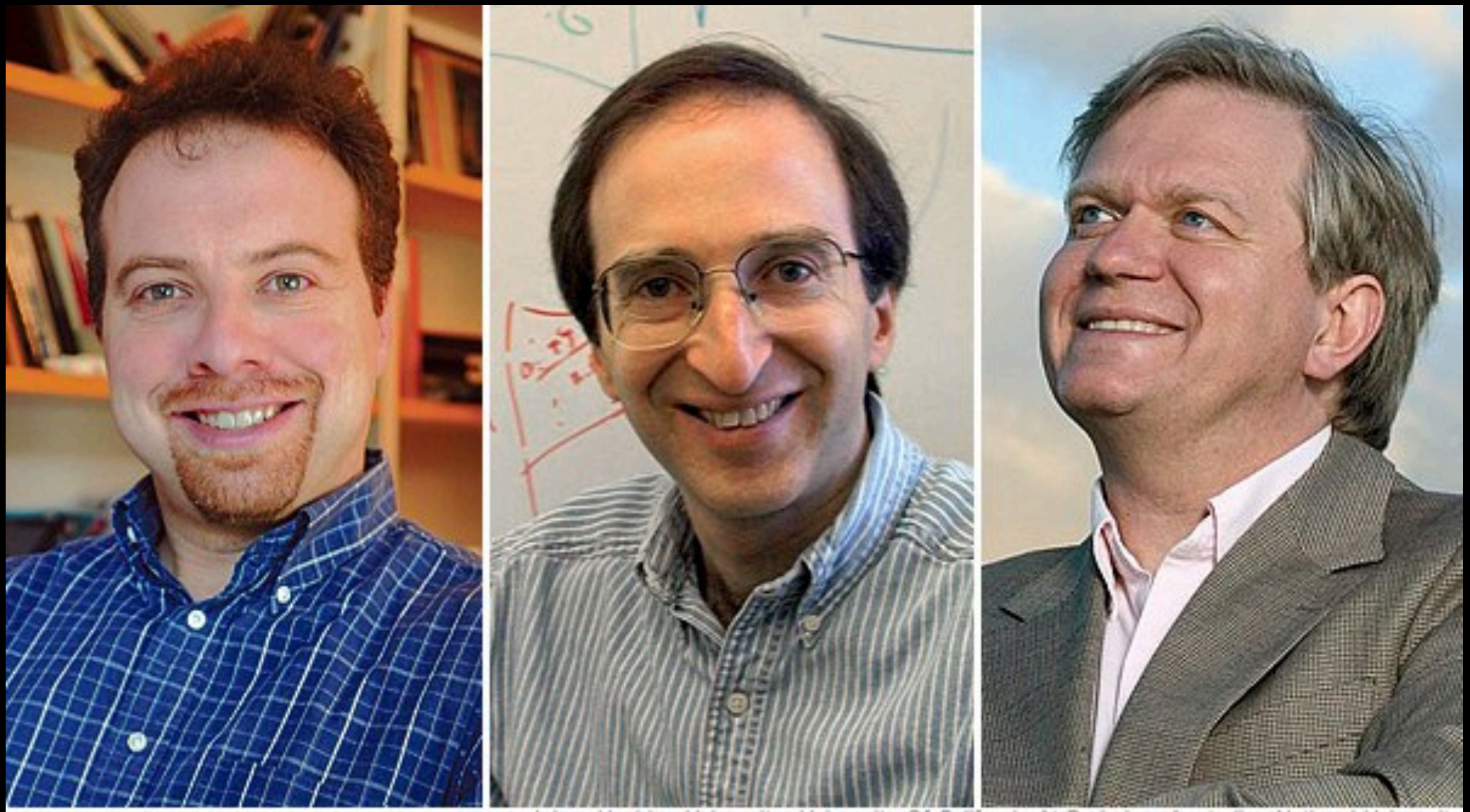
Vol. 282 No. 5397
Pages 2141–2336 $7

THE ACCELERATING UNIVERSE

Breakthrough of the Year



AMERICAN ASSOCIATION FOR THE ADVANCEMENT OF SCIENCE

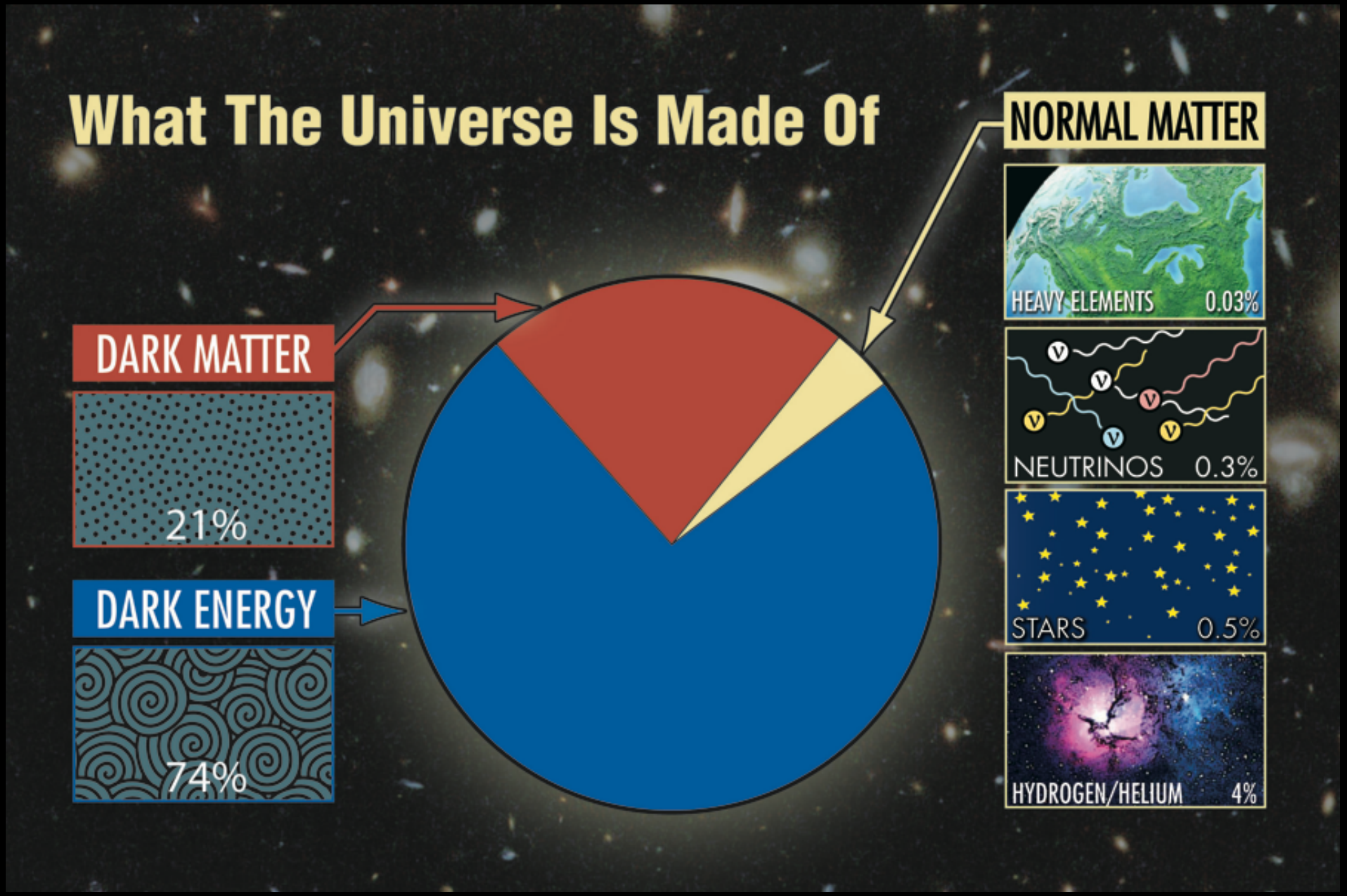


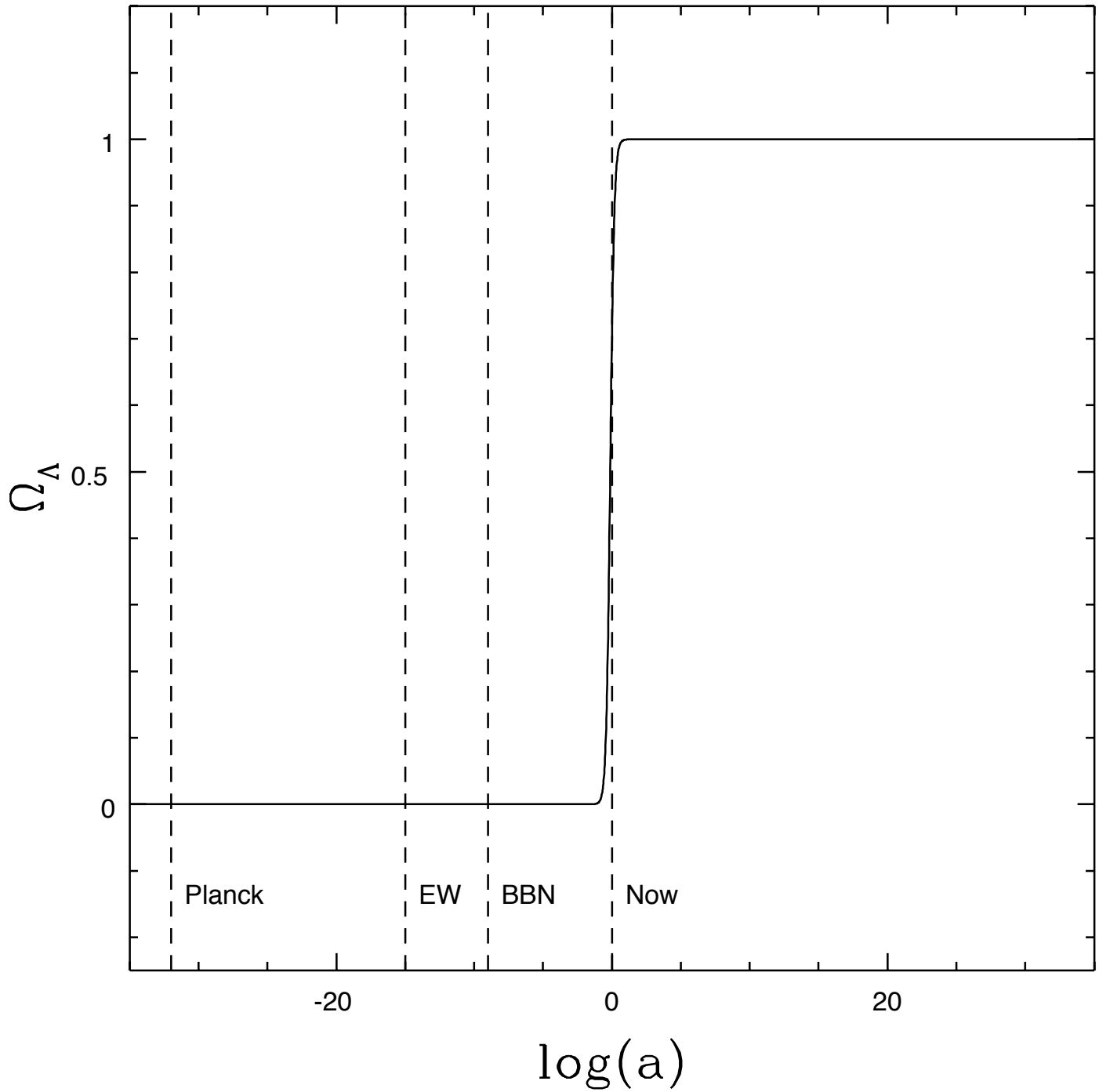
Johns Hopkins University; University Of California At Berkeley; Australian National University

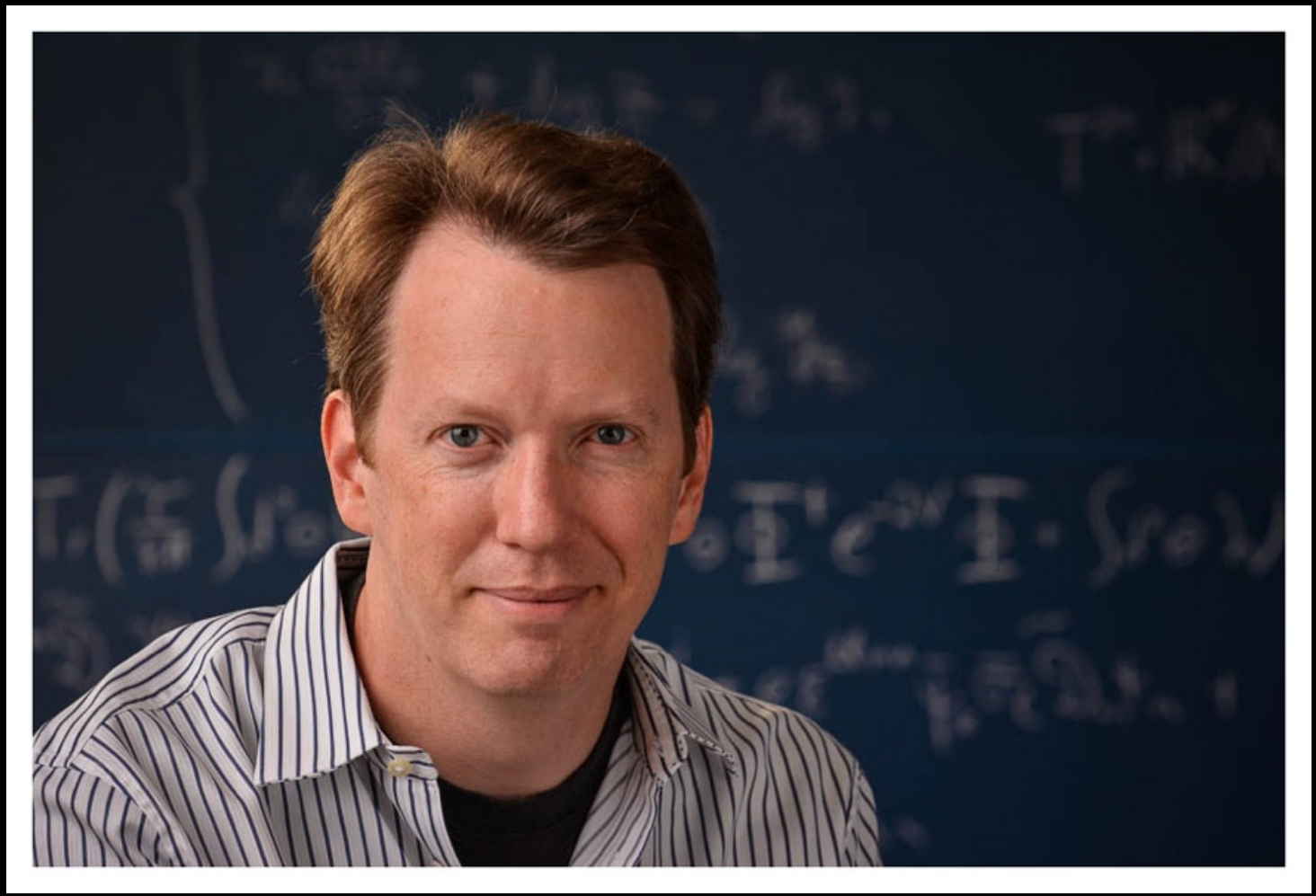
From left, Adam Riess, Saul Perlmutter and Brian Schmidt shared the Nobel Prize in physics awarded Tuesday.

Table 1.1: Cosmic Inventory

Component	$\boldsymbol{\Omega}$ (ρ/ρ_c)
Dark Energy	$\mathbf{0.691 \pm 0.006}$
Matter (baryonic and non-baryonic)	$\mathbf{0.312 \pm 0.009}$
Baryons (Total)	$\mathbf{0.0488 \pm 0.0004}$
Baryons in stars and stellar remnants	$\mathbf{\sim 0.003}$
Neutrinos	$\mathbf{\sim 0.001}$
Photons (CMB)	$\mathbf{5 \times 10^{-5}}$


What The Universe Is Made Of
NORMAL MATTER
HEAVY ELEMENTS 0.03%
NEUTRINOS 0.3%
STARS 0.5%
HYDROGEN/HELIUM 4%
DARK MATTER
21%
DARK ENERGY
74%


1
0.5
0
Ω_Λ
Planck
EW
BBN
Now
-20
0
20
log(a)



Sean Carroll: "We live in a preposterous Universe."

The challenge is to understand if these numbers are simply coincidences, or actually reflect a beautiful underlying reality that we do not as yet comprehend.