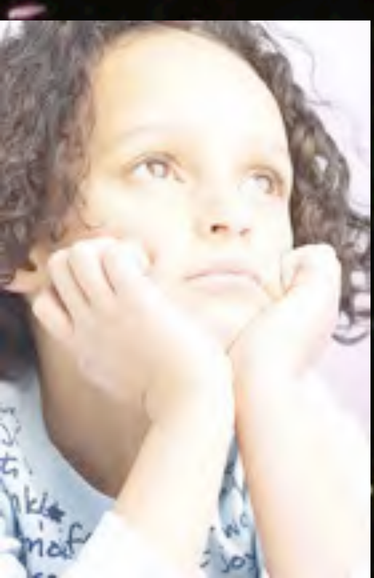
Cosmology
Dark Matter

AESHEP 2012年10月25日

Kavli IPMU, University of Tokyo
UC Berkeley, Lawrence Berkeley Laboratory
Hitoshi Murayama

How did the Universe begin?
What is its fate?
What is it made of?
What are its fundamental laws?
Why do we exist?

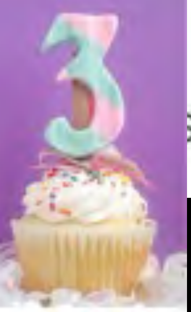
interdisciplinary institute of
astronomy, physics and mathematics
10-year program by Japanese
government since 2007



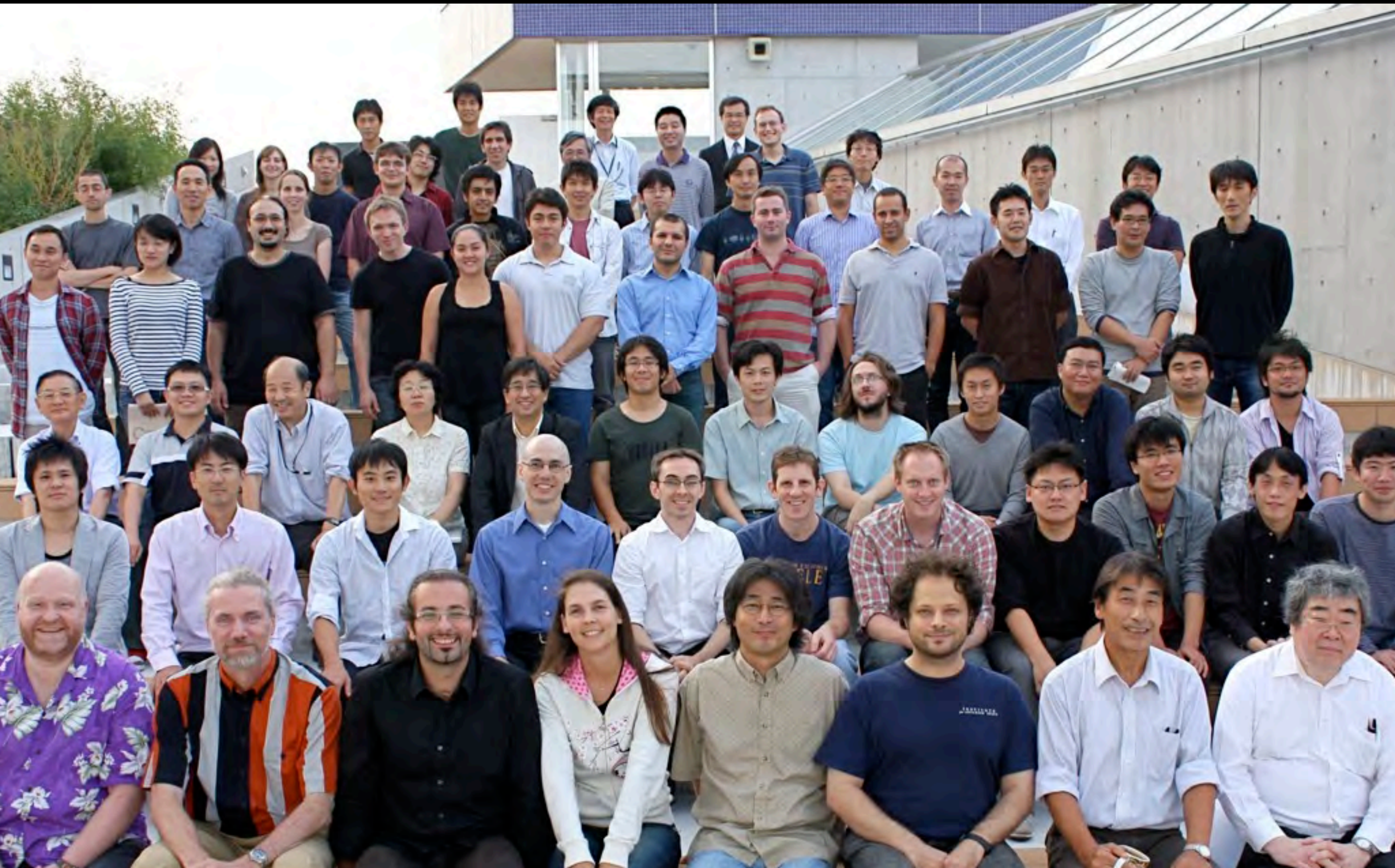
Oct 2007

Oct 2008

Oct 2009



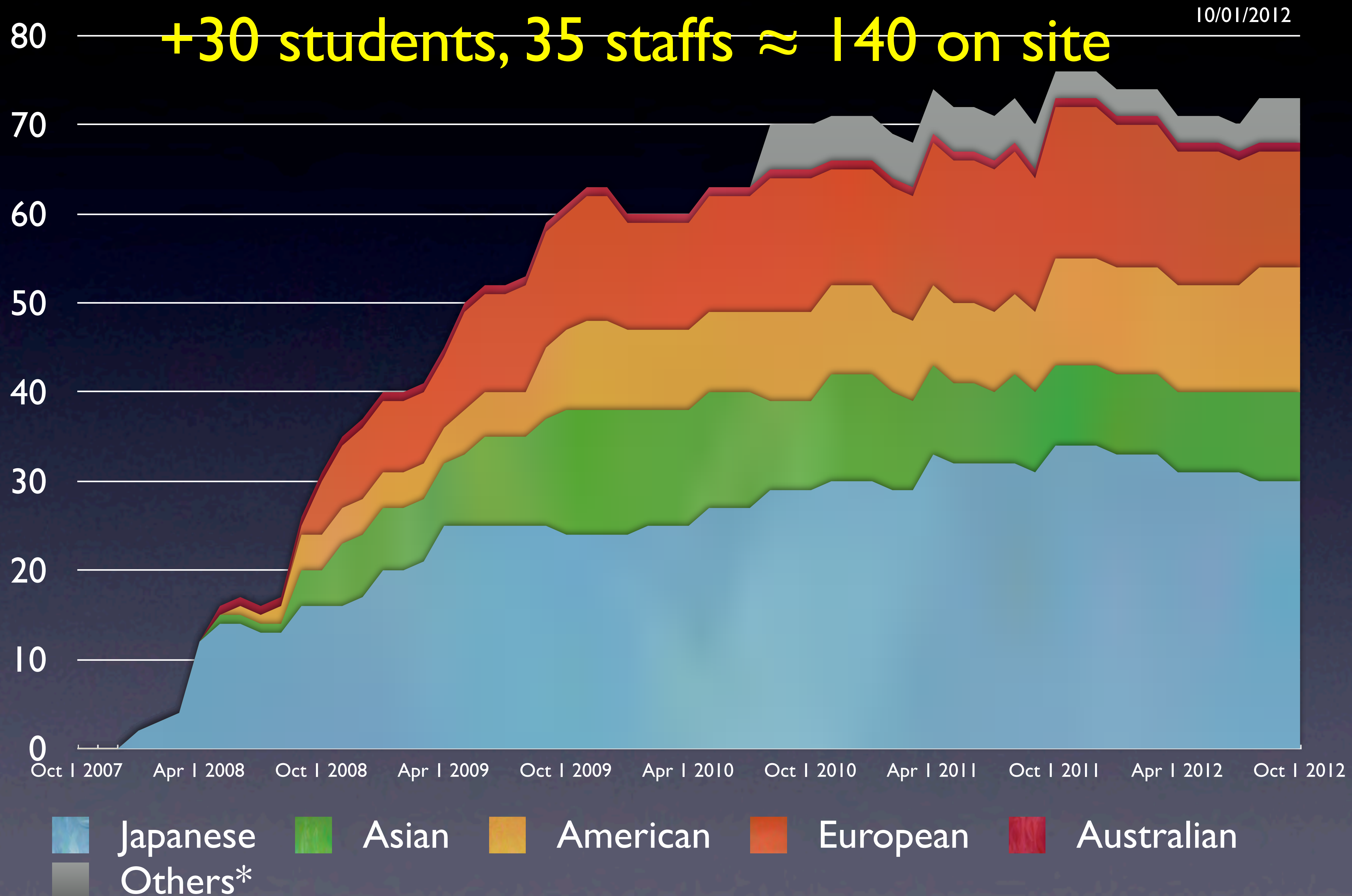
Oct 2010



Oct 2011

Oct 2012

Full-time Scientists paid by IPMU



*Argentina, Chile, Canada

brand-new building 2010


"European town square"
obelisk
"L'Universo é scritto in
lingua matematica"


日本の頭脳
iPMU
Institute for the Physics and Mathematics of the Universe
2007年設立
東京大学国際高等研究所数物連携宇宙研究機構
Institute for the Physics and Mathematics of the Universe

Asahi TV

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

THE KAVLI FOUNDATION

officially Kavli IPMU on April 1, 2012
First research institute in Japan named after a donor, breaking new grounds

May 9, meeting with Prime Minister Noda

http://www.kantei.go.jp/jp/noda/actions/201205/09kavli.html

- *Basic research is very important, because it is a common resource shared by the whole humanity.*

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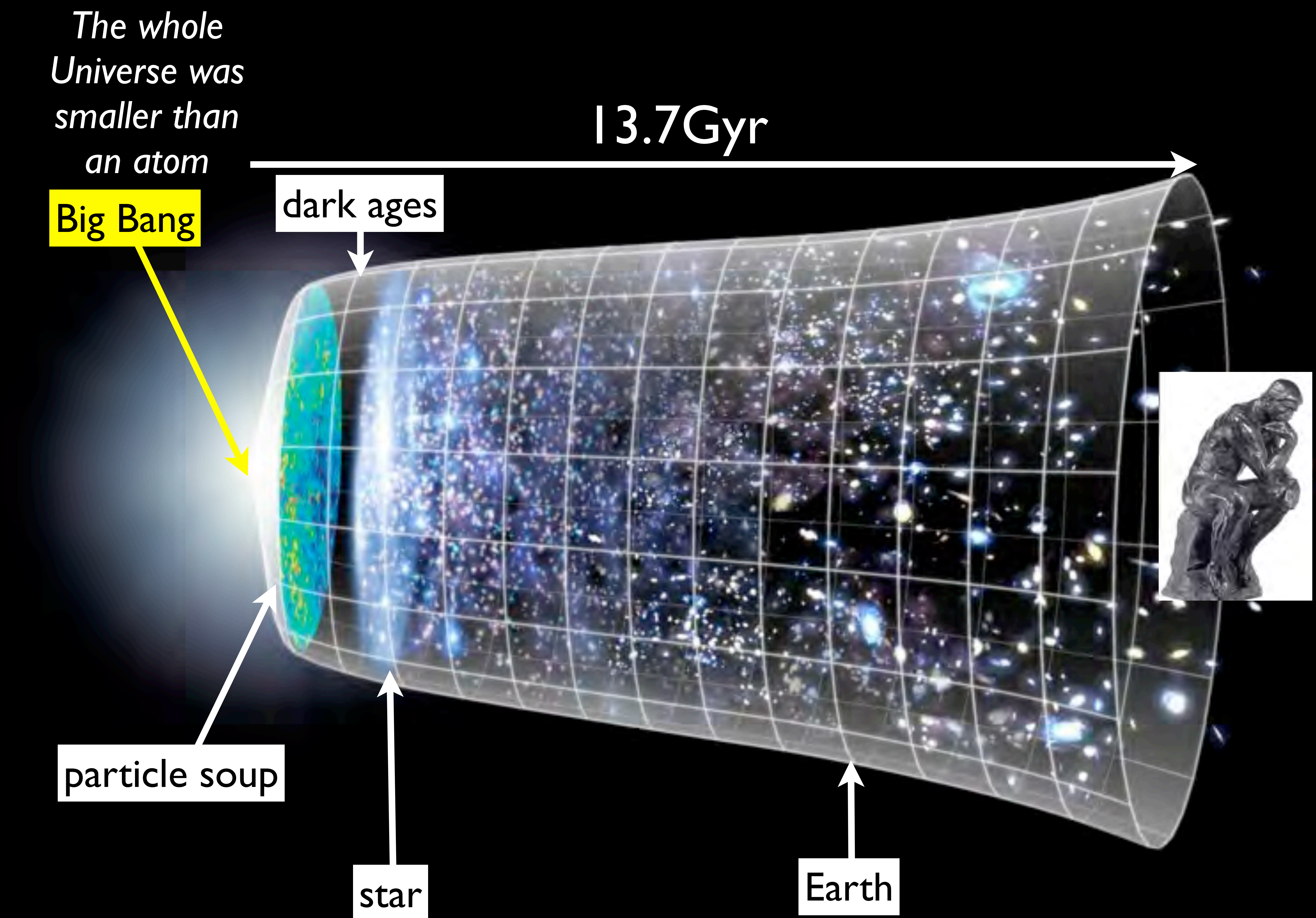
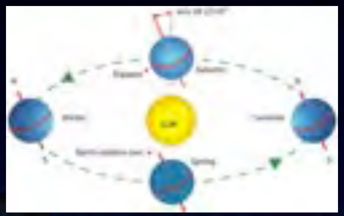

The whole Universe was smaller than an atom
13.7Gyr
Big Bang
dark ages
particle soup
star
Earth

ものの大きさ

10^{27}m

10^{23}m

10^{20}m

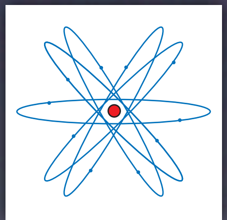


10^{11}m

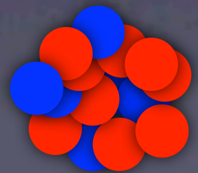
10^{7}m

10^{3}m

0.1m



10^{-10}m

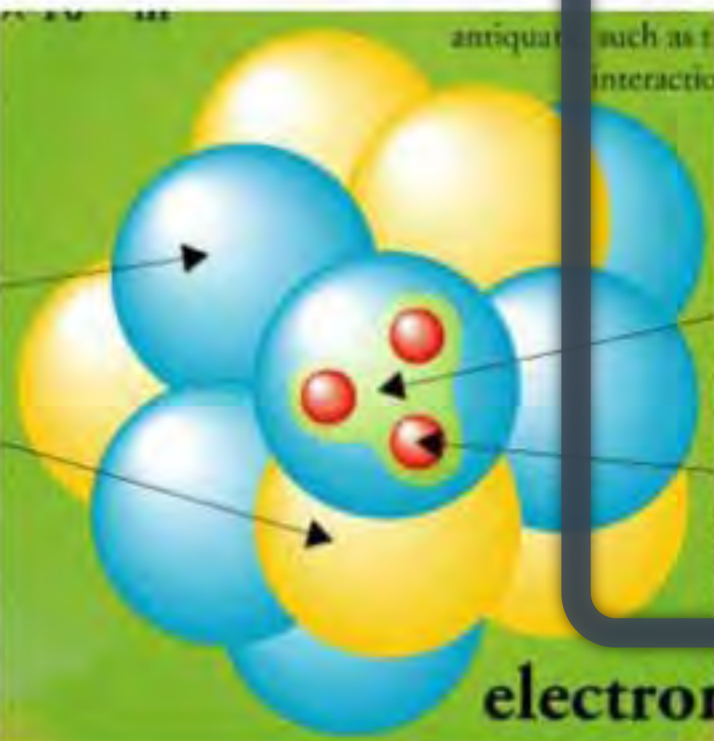


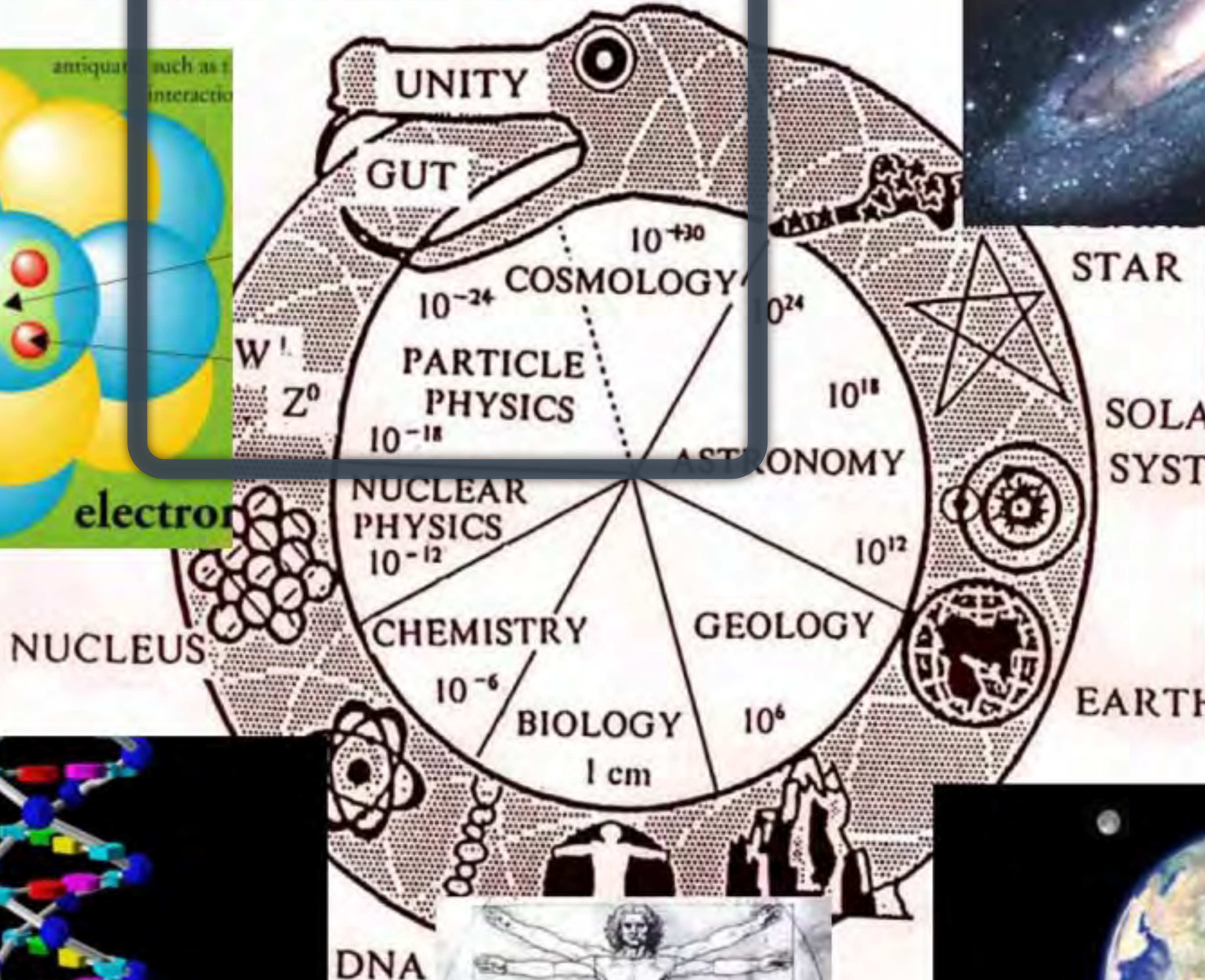
10^{-15}m

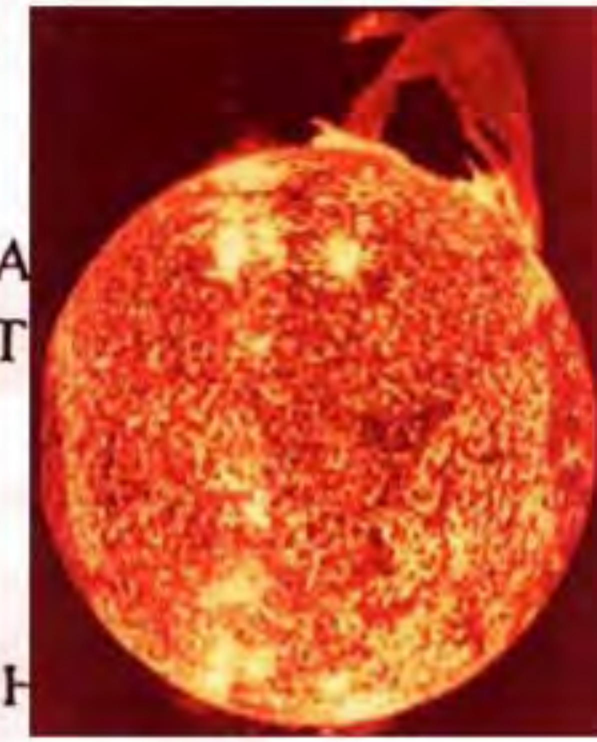
10^{-19}m

- 自然界のスケール

ウロボロスの蛇

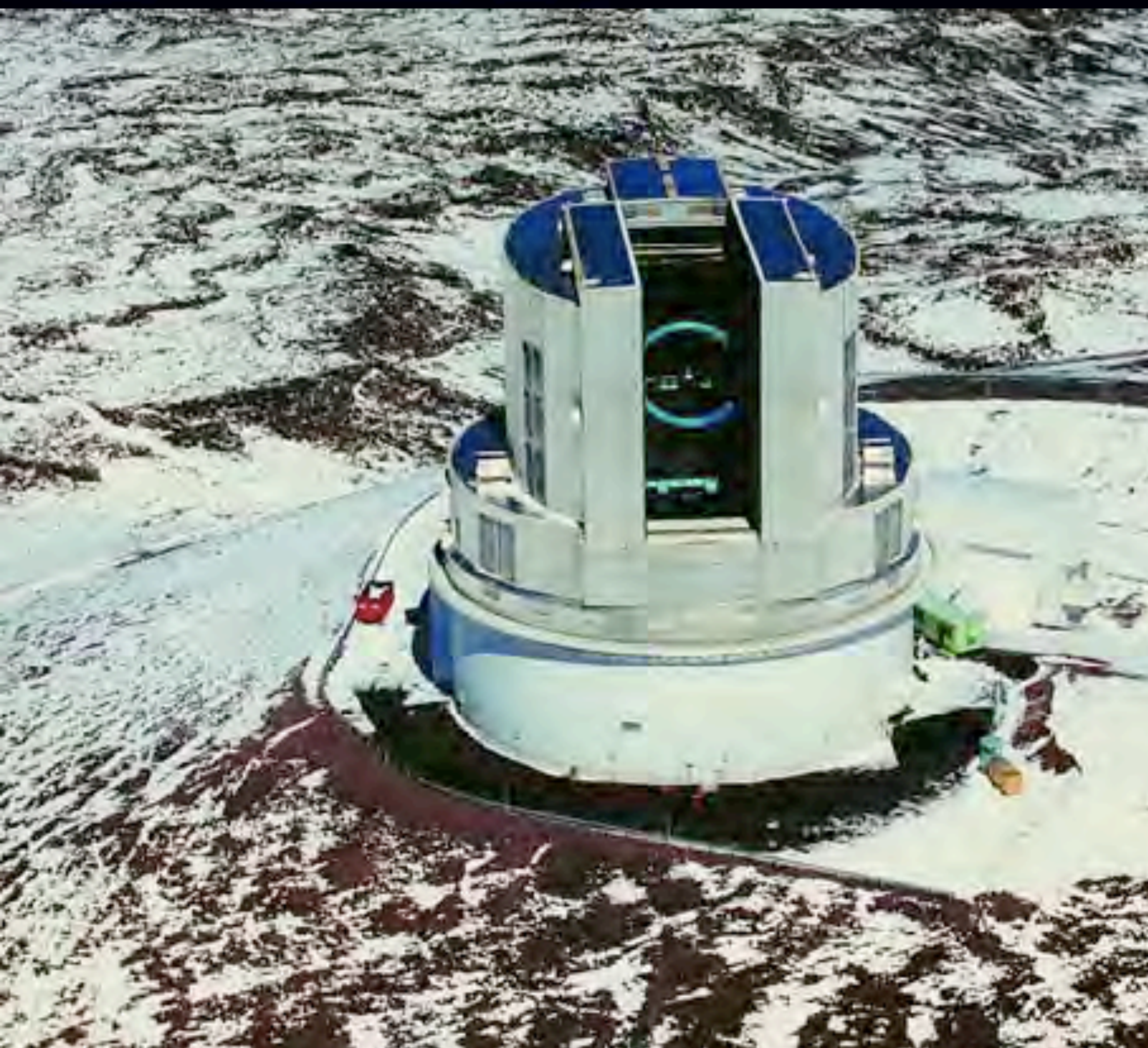


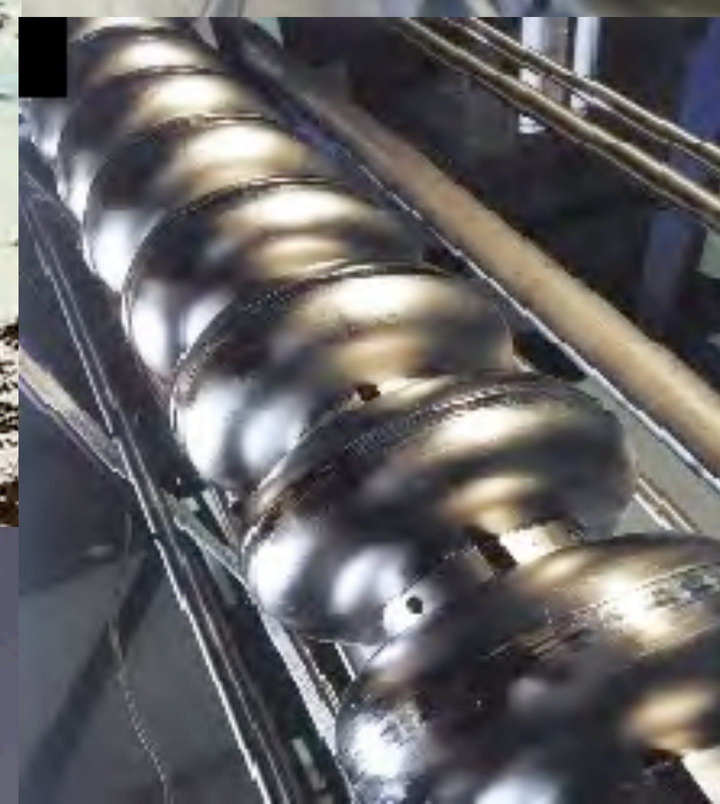

UNITY
GUT
10^{+30}
COSMOLOGY
10^{-24}
10^{24}
PARTICLE PHYSICS
W
Z^0
10^{-18}
10^{18}
ASTRONOMY
NUCLEAR PHYSICS
10^{-12}
10^{12}
CHEMISTRY
GEOLOGY
10^{-6}
BIOLOGY
1 cm
10^6
STAR
EARTH
NUCLEUS
DNA



タイムマシン

タイムマシン






Solar System

2010年4月7日

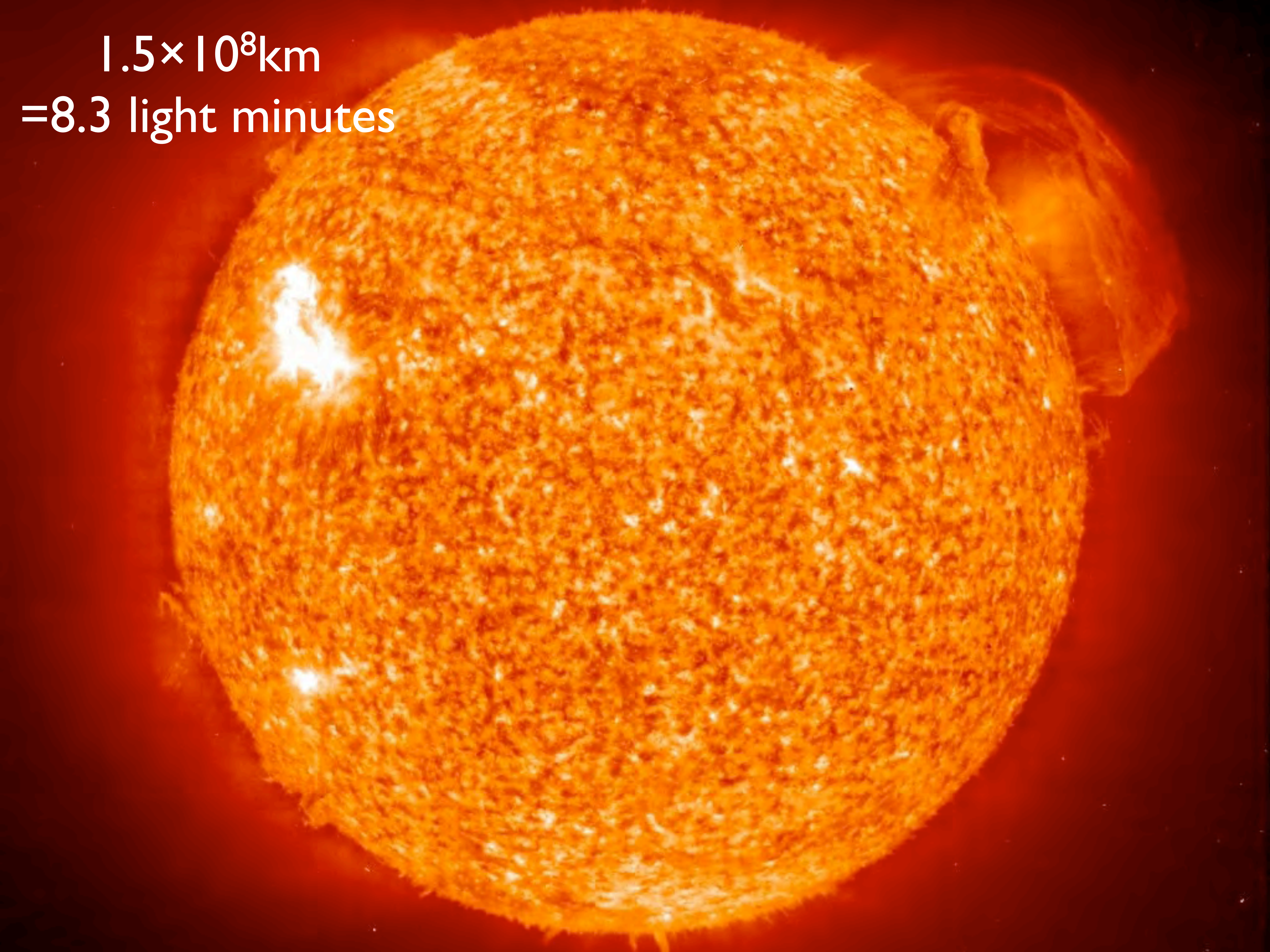
375 km 上空

ももの皮

Sep 30, 2008
Kaguya

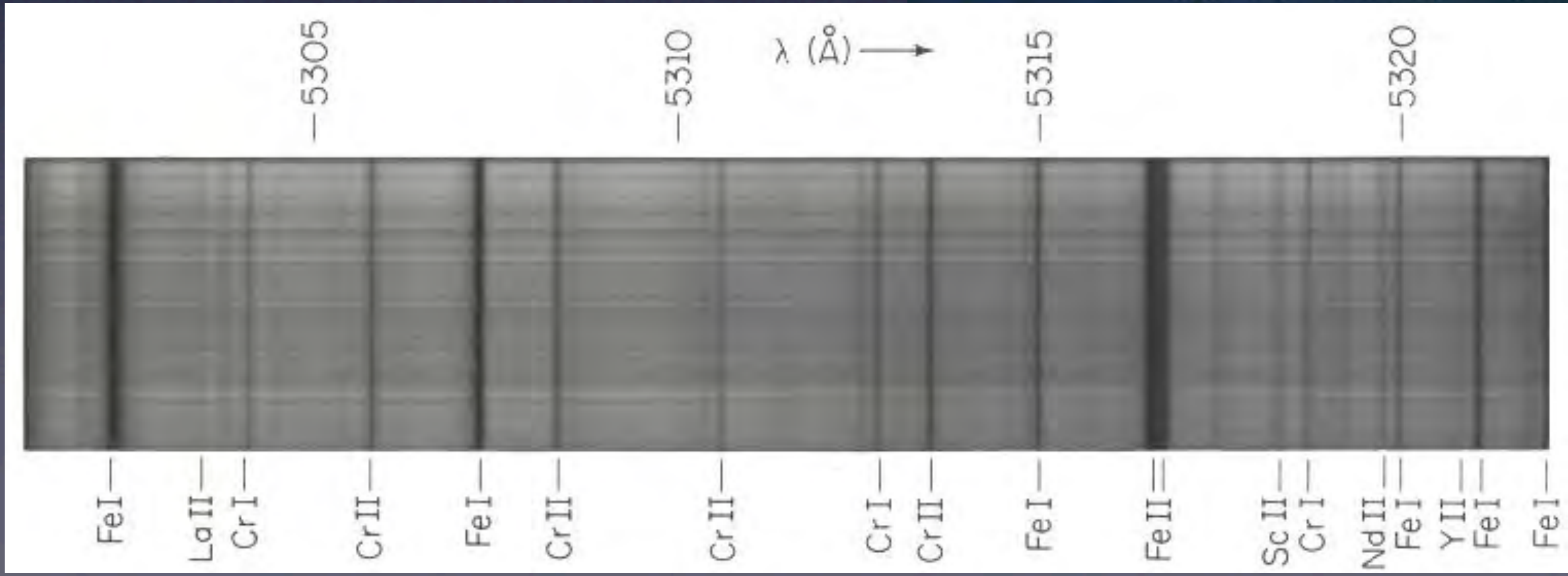
380,000km
=1.3 light seconds

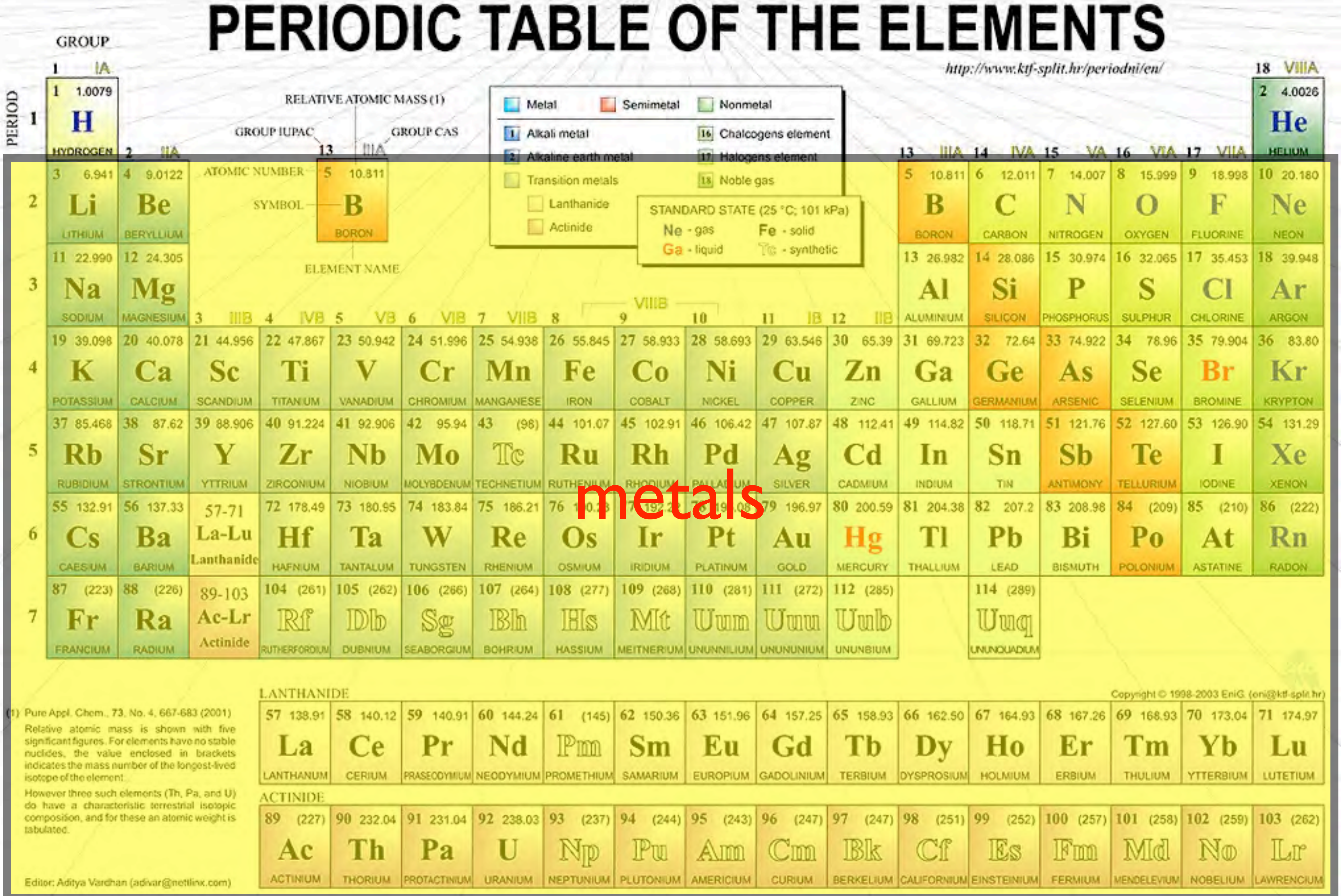

380,000km
=1.3 light seconds
©JAXA/NH

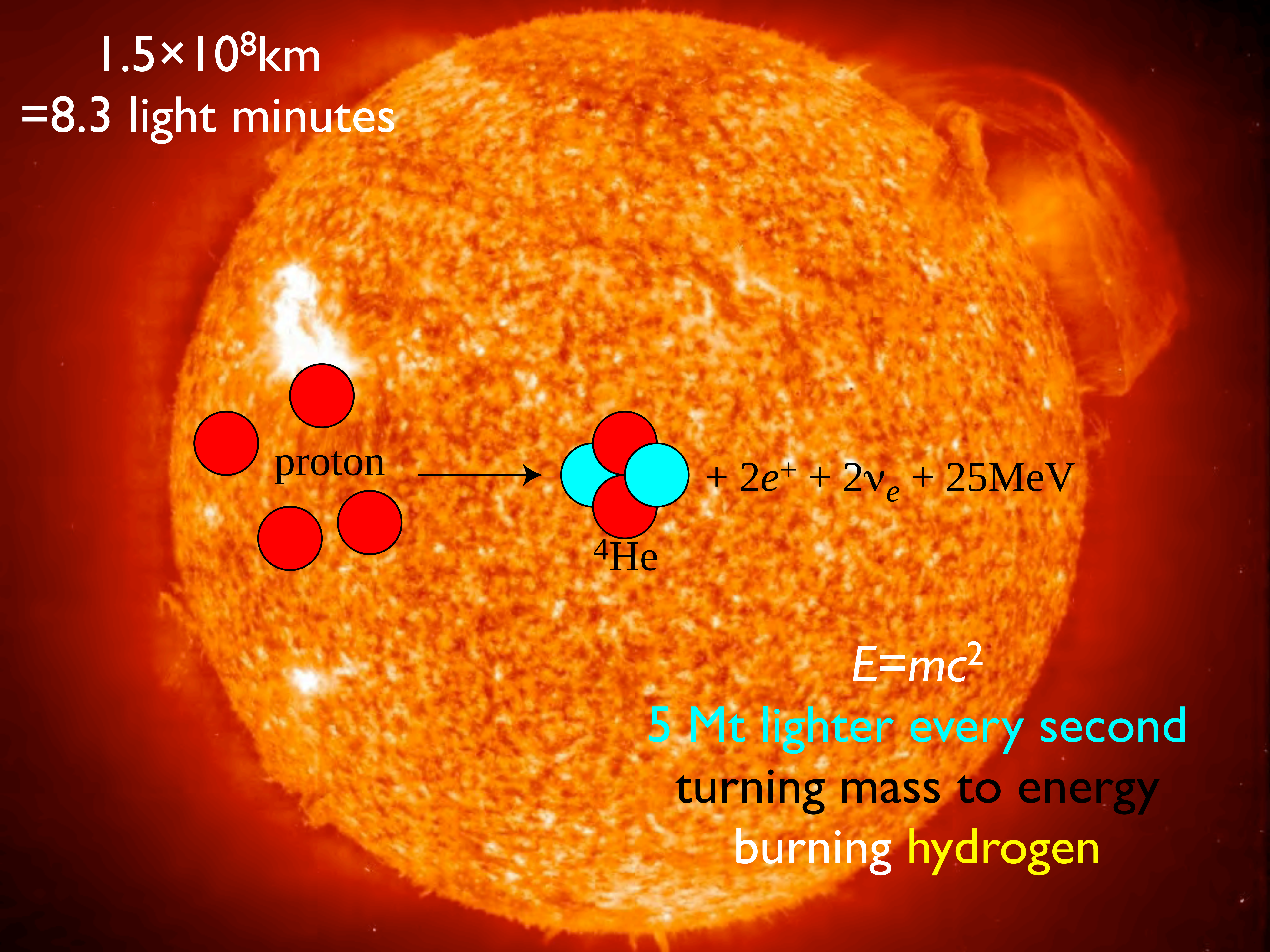

1.5×10^8km
=8.3 light minutes

Made of atoms

- everything around us is made of atoms
- stars are made of atoms, too
- spectroscopy




PERIODIC TABLE OF THE ELEMENTS
http://www.ktf-split.hr/periodni/en/
GROUP
PERIOD
RELATIVE ATOMIC MASS (1)
GROUP IUPAC
GROUP CAS
ATOMIC NUMBER
SYMBOL
ELEMENT NAME
Metal
Semimetal
Nonmetal
Alkali metal
Alkaline earth metal
Transition metals
Lanthanide
Actinide
Chalcogens element
Halogens element
Noble gas
STANDARD STATE (25 °C; 101 kPa)
Ne - gas
Fe - solid
Ga - liquid
Tc - synthetic
1 1.0079 H HYDROGEN
2 4.0026 He HELIUM
3 6.941 Li LITHIUM
4 9.0122 Be BERYLLIUM
5 10.811 B BORON
6 12.011 C CARBON
7 14.007 N NITROGEN
8 15.999 O OXYGEN
9 18.998 F FLUORINE
10 20.180 Ne NEON
11 22.990 Na SODIUM
12 24.305 Mg MAGNESIUM
13 26.982 Al ALUMINIUM
14 28.086 Si SILICON
15 30.974 P PHOSPHORUS
16 32.065 S SULPHUR
17 35.453 Cl CHLORINE
18 39.948 Ar ARGON
19 39.098 K POTASSIUM
20 40.078 Ca CALCIUM
21 44.956 Sc SCANDIUM
22 47.867 Ti TITANIUM
23 50.942 V VANADIUM
24 51.996 Cr CHROMIUM
25 54.938 Mn MANGANESE
26 55.845 Fe IRON
27 58.933 Co COBALT
28 58.693 Ni NICKEL
29 63.546 Cu COPPER
30 65.39 Zn ZINC
31 69.723 Ga GALLIUM
32 72.64 Ge GERMANIUM
33 74.922 As ARSENIC
34 78.96 Se SELENIUM
35 79.904 Br BROMINE
36 83.80 Kr KRYPTON
37 85.468 Rb RUBIDIUM
38 87.62 Sr STRONTIUM
39 88.906 Y YTTRIUM
40 91.224 Zr ZIRCONIUM
41 92.906 Nb NIOBIUM
42 95.94 Mo MOLYBDENUM
43 (98) Tc TECHNETIUM
44 101.07 Ru
45 102.91 Rh
46 106.42 Pd
47 107.87 Ag SILVER
48 112.41 Cd CADMIUM
49 114.82 In INDIUM
50 118.71 Sn TIN
51 121.76 Sb ANTIMONY
52 127.60 Te TELLURIUM
53 126.90 I IODINE
54 131.29 Xe XENON
55 132.91 Cs CAESIUM
56 137.33 Ba BARIUM
57-71 La-Lu Lanthanide
72 178.49 Hf HAFNIUM
73 180.95 Ta TANTALUM
74 183.84 W TUNGSTEN
75 186.21 Re RHENIUM
76 Os OSMIUM
Ir IRIDIUM
Pt PLATINUM
79 196.97 Au GOLD
80 200.59 Hg MERCURY
81 204.38 Tl THALLIUM
82 207.2 Pb LEAD
83 208.98 Bi BISMUTH
84 (209) Po POLONIUM
85 (210) At ASTATINE
86 (222) Rn RADON
87 (223) Fr FRANCIUM
88 (226) Ra RADIUM
89-103 Ac-Lr Actinide
104 (261) Rf RUTHERFORDIUM
105 (262) Db DUBNIUM
106 (266) Sg SEABORGIUM
107 (264) Bh BOHRIUM
108 (277) Hs HASSIUM
109 (268) Mt MEITNERIUM
110 (281) Uun UNUNNILIUM
111 (272) Uuu UNUNUNIUM
112 (285) Uub UNUNBIUM
114 (289) Uuq UNUNQUADIUM
LANTHANIDE
57 138.91 La LANTHANUM
58 140.12 Ce CERIUM
59 140.91 Pr PRASEODYMIUM
60 144.24 Nd NEODYMIUM
61 (145) Pm PROMETHIUM
62 150.36 Sm SAMARIUM
63 151.96 Eu EUROPIUM
64 157.25 Gd GADOLINIUM
65 158.93 Tb TERBIUM
66 162.50 Dy DYSPROSIUM
67 164.93 Ho HOLMIUM
68 167.26 Er ERBIUM
69 168.93 Tm THULIUM
70 173.04 Yb YTTERBIUM
71 174.97 Lu LUTETIUM
ACTINIDE
89 (227) Ac ACTINIUM
90 232.04 Th THORIUM
91 231.04 Pa PROTACTINIUM
92 238.03 U URANIUM
93 (237) Np NEPTUNIUM
94 (244) Pu PLUTONIUM
95 (243) Am AMERICIUM
96 (247) Cm CURIUM
97 (247) Bk BERKELIUM
98 (251) Cf CALIFORNIUM
99 (252) Es EINSTEINIUM
100 (257) Fm FERMIUM
101 (258) Md MENDELEVIUM
102 (259) No NOBELIUM
103 (262) Lr LAWRENCIUM
(1) Pure Appl. Chem., 73, No. 4, 667-683 (2001)
Relative atomic mass is shown with five significant figures. For elements have no stable nuclides, the value enclosed in brackets indicates the mass number of the longest-lived isotope of the element.
However three such elements (Th, Pa, and U) do have a characteristic terrestrial isotopic composition, and for these an atomic weight is tabulated.
Copyright © 1998-2003 EniG. (eni@ktf-split.hr)
Editor: Aditya Vardhan (adivar@netlinx.com)
metals

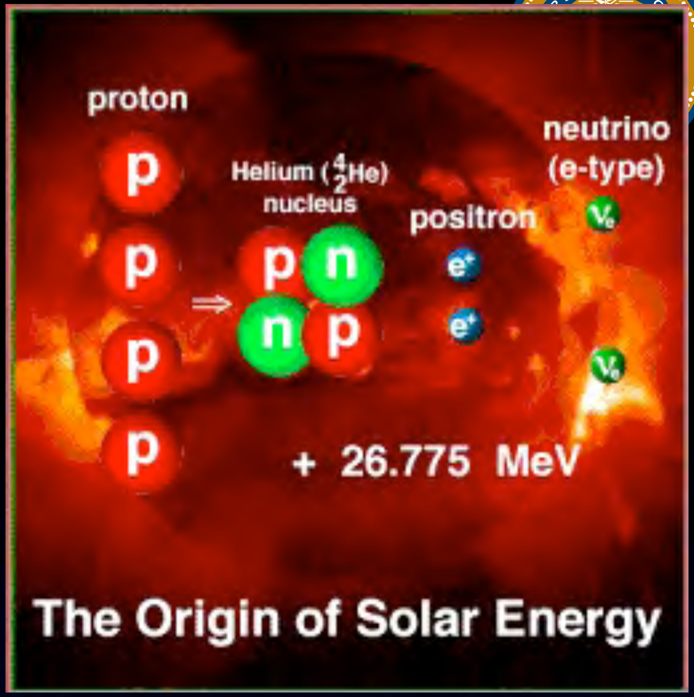


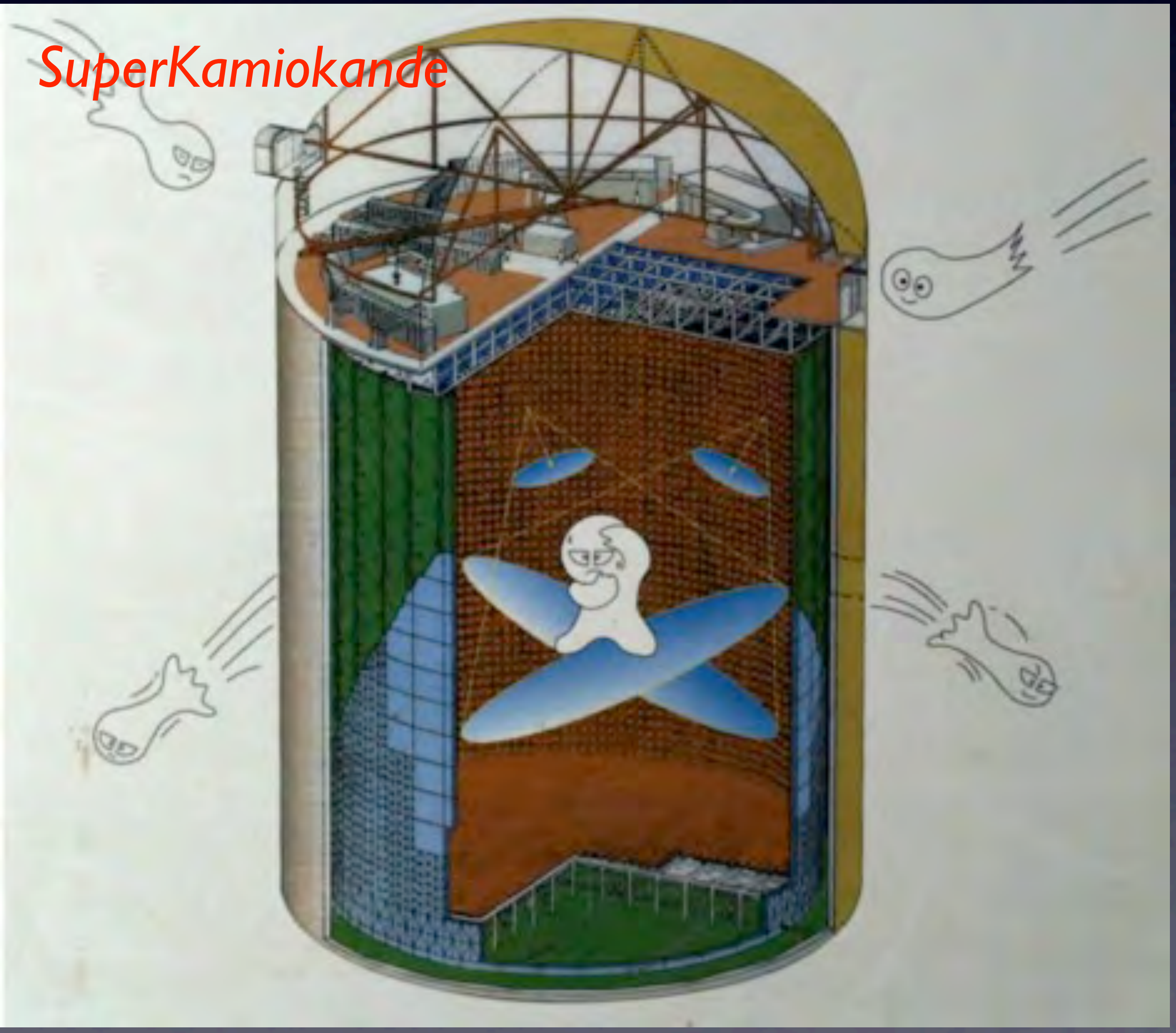
1.5×10⁸km
=8.3 light minutes
proton
^{4}He
$+\ 2e^+ + 2\nu_e + 25\mathrm{MeV}$
$E=mc^2$
5 Mt lighter every second
turning mass to energy
burning hydrogen

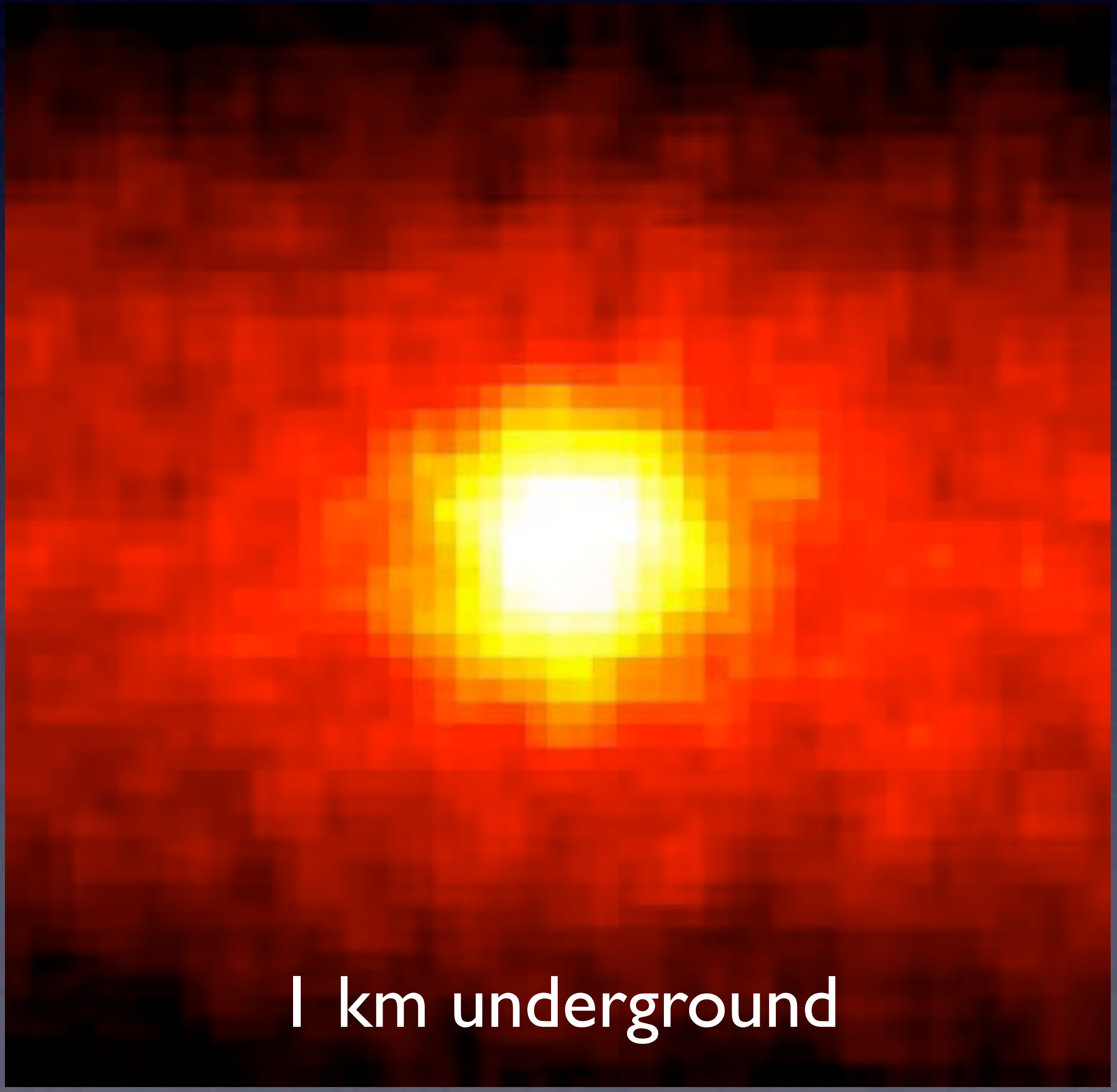
proof

nuclear fusion also produces neutrinos

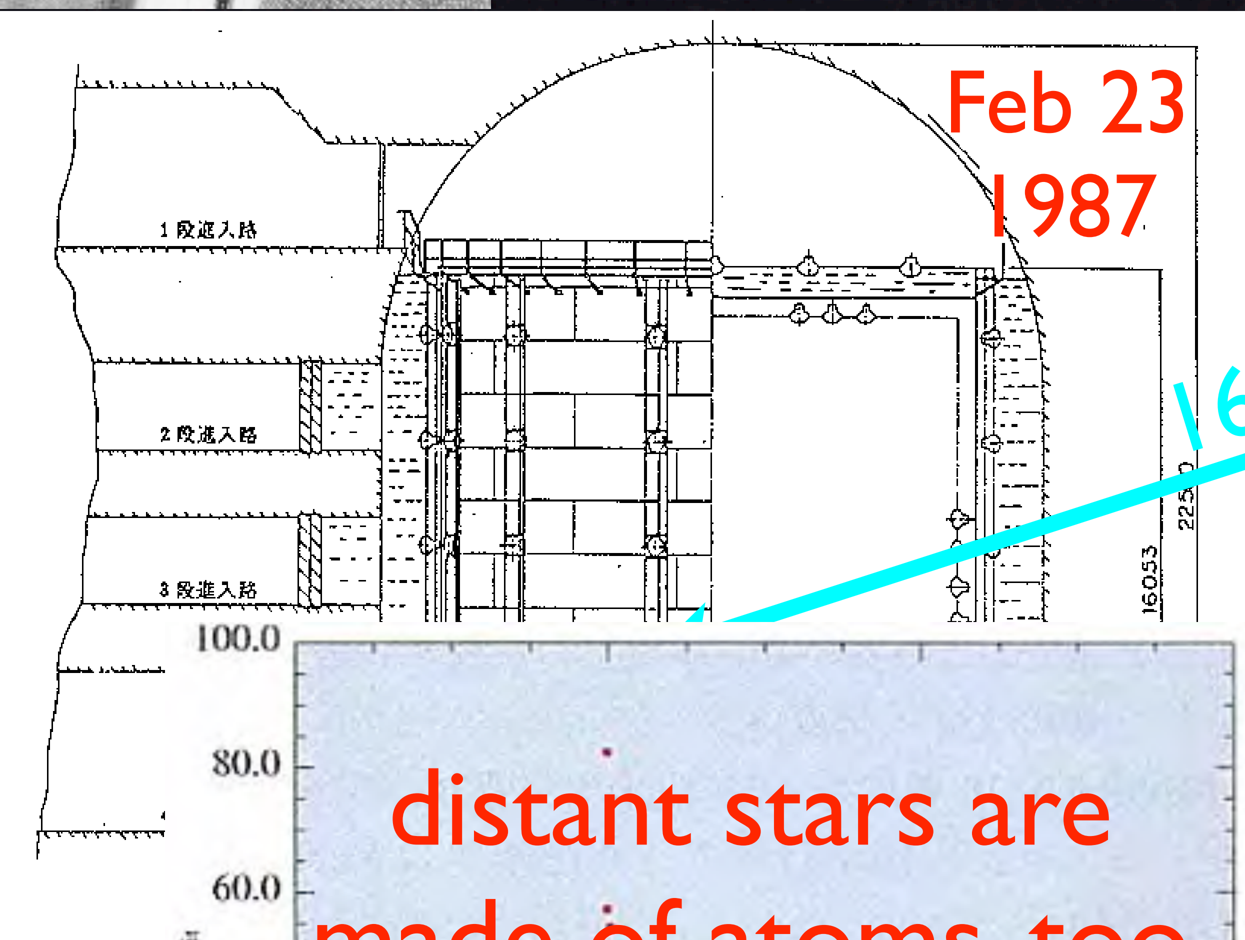
tens of trillions of neutrinos going through our body every second



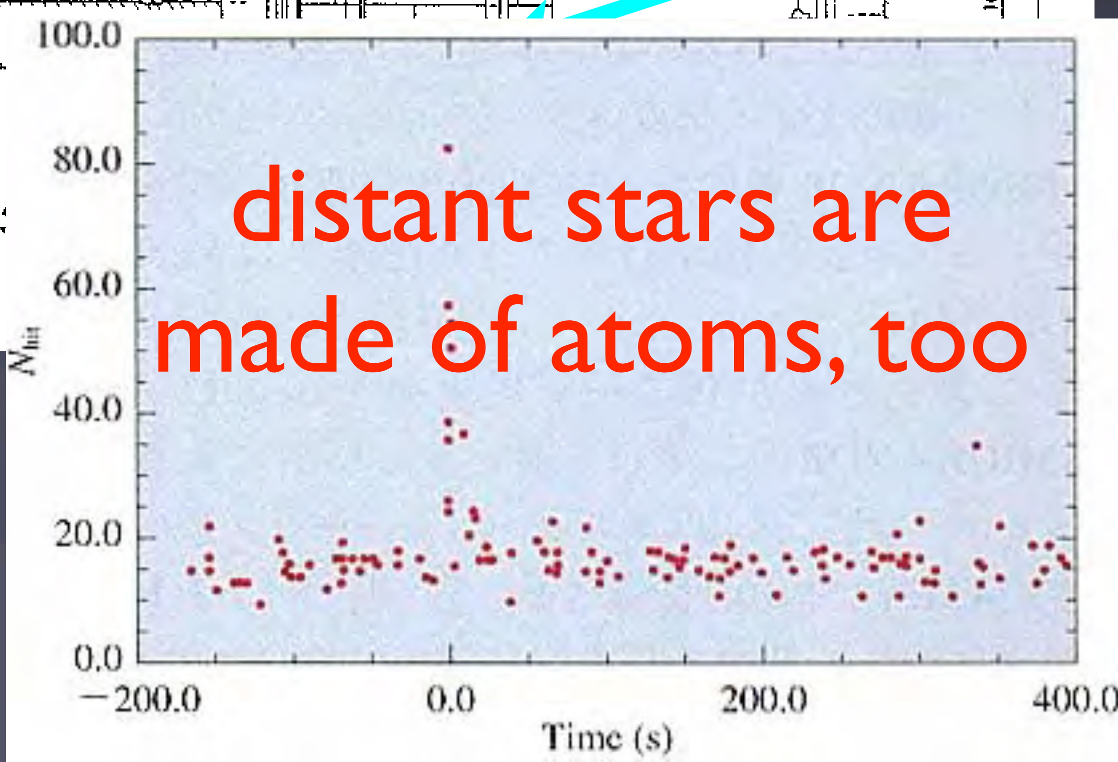




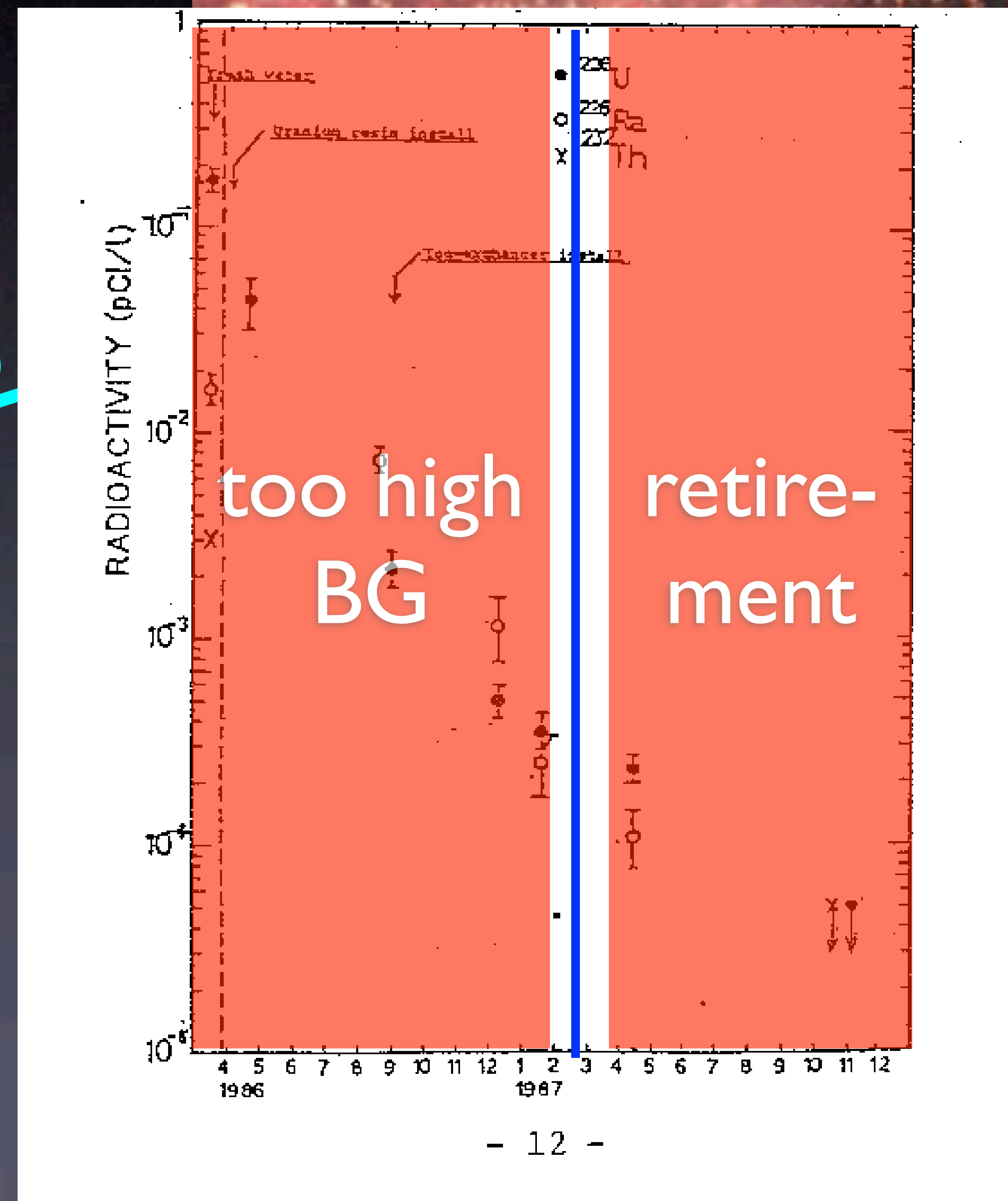
luck



1 段進入路
2 段進入路
3 段進入路
16053
2250
Feb 23
1987
160,000



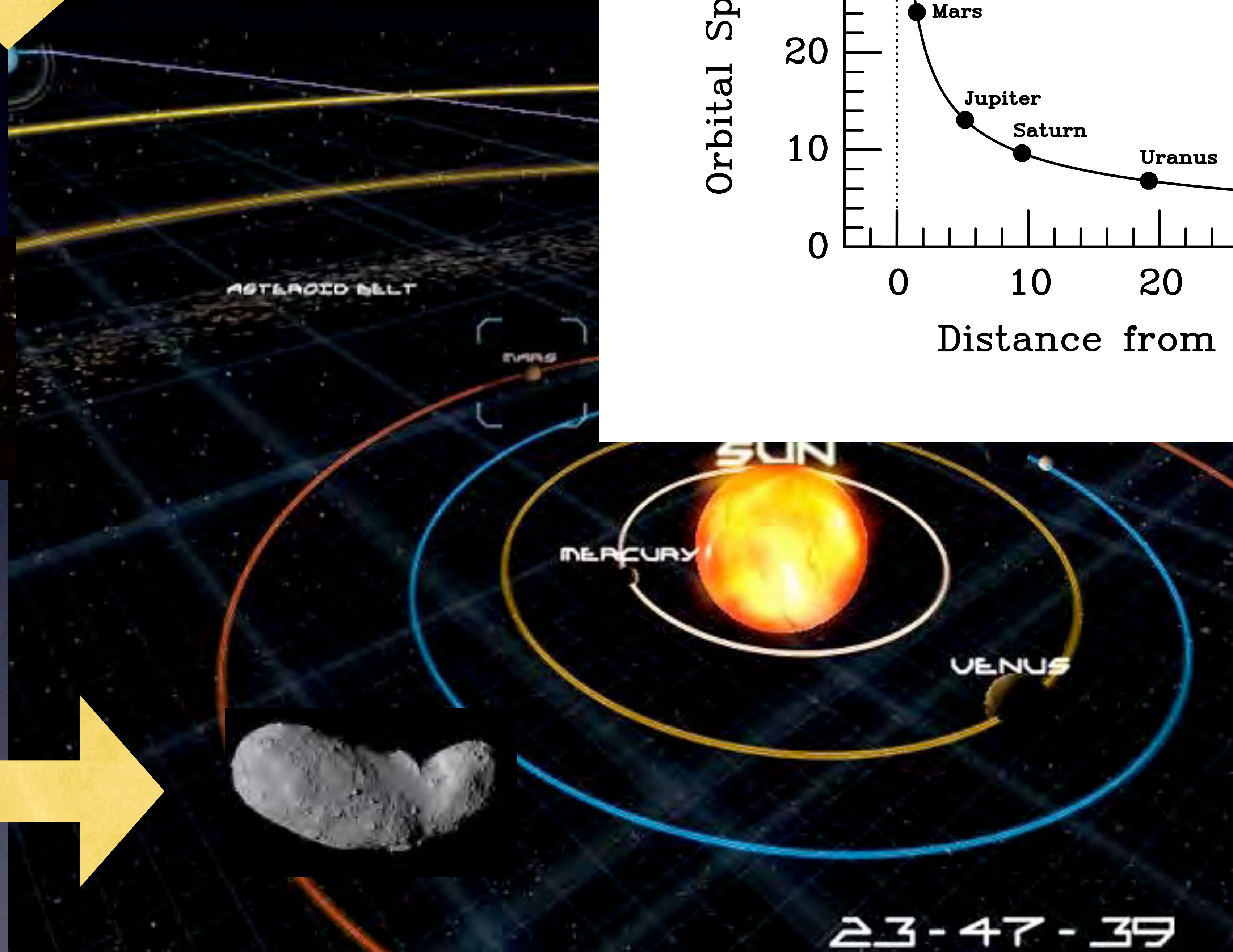
distant stars are
made of atoms, too
100.0
80.0
60.0
40.0
20.0
0.0
−200.0
0.0
200.0
400.0
Time (s)

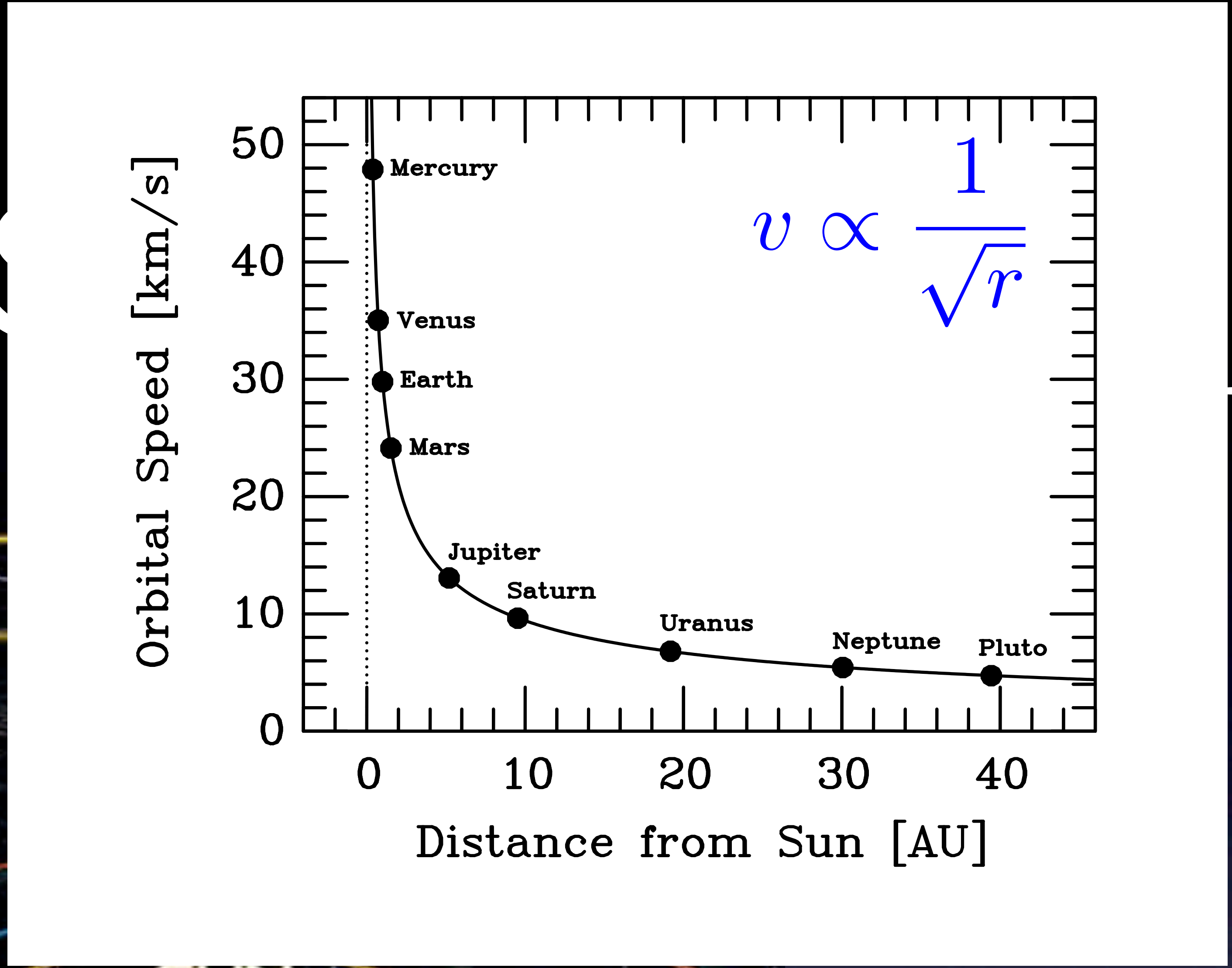


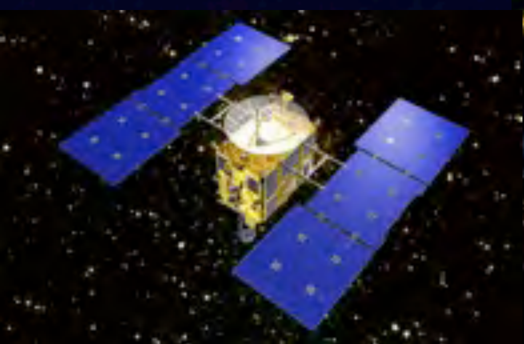
RADIOACTIVITY (pCi/l)
226U
226Ra
232Th
too high
BG
retire-
ment
4 5 6 7 8 9 10 11 12 1 2 3 4 5 6 7 8 9 10 11 12
1986
1987
- 12 -

Neptune
4 light hours

Solar S





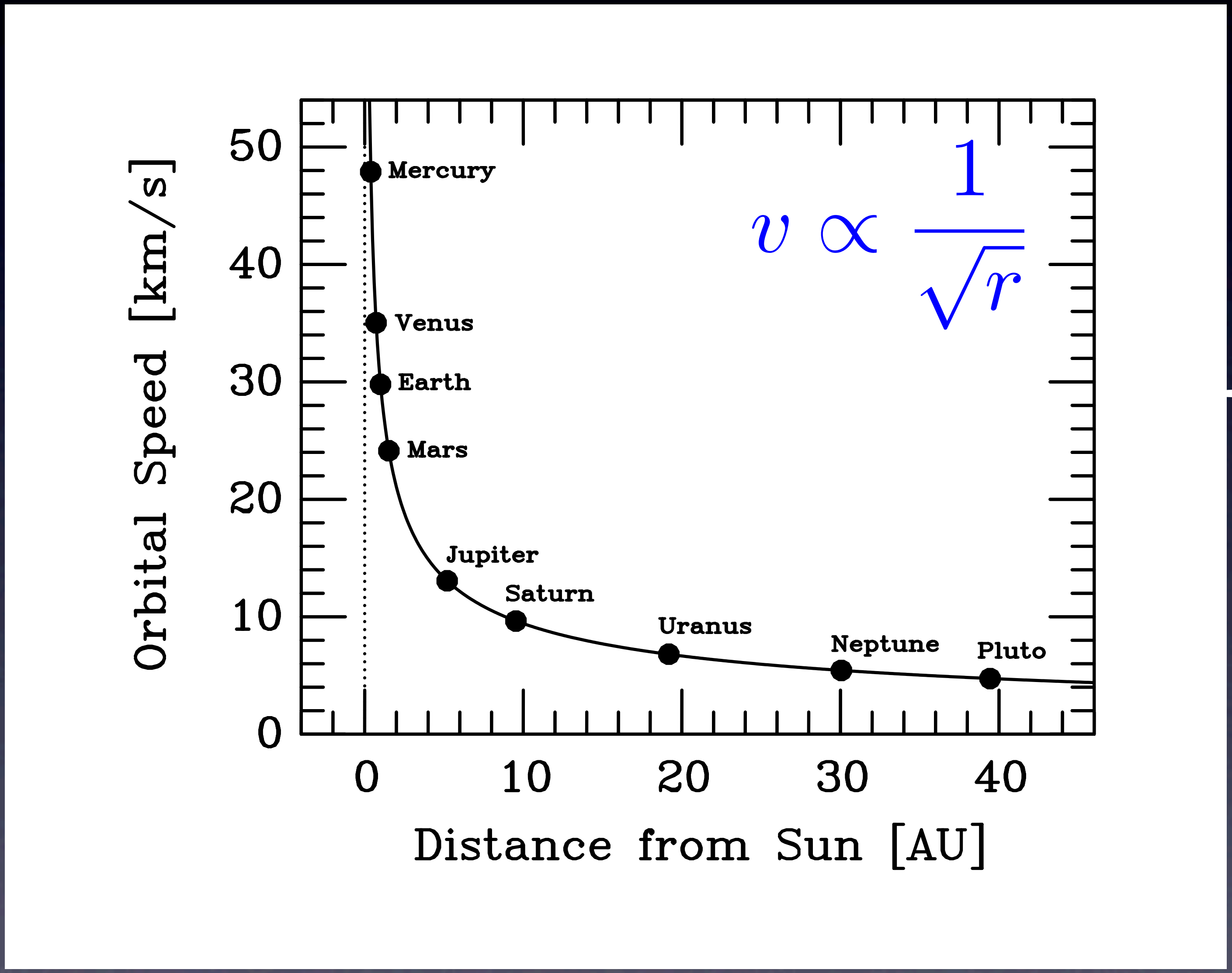


Itokawa

20 light minutes

Earth resolves around the Sun with 30km/sec

High School physics



$$F = \frac{GM_\odot m}{r^2}$$

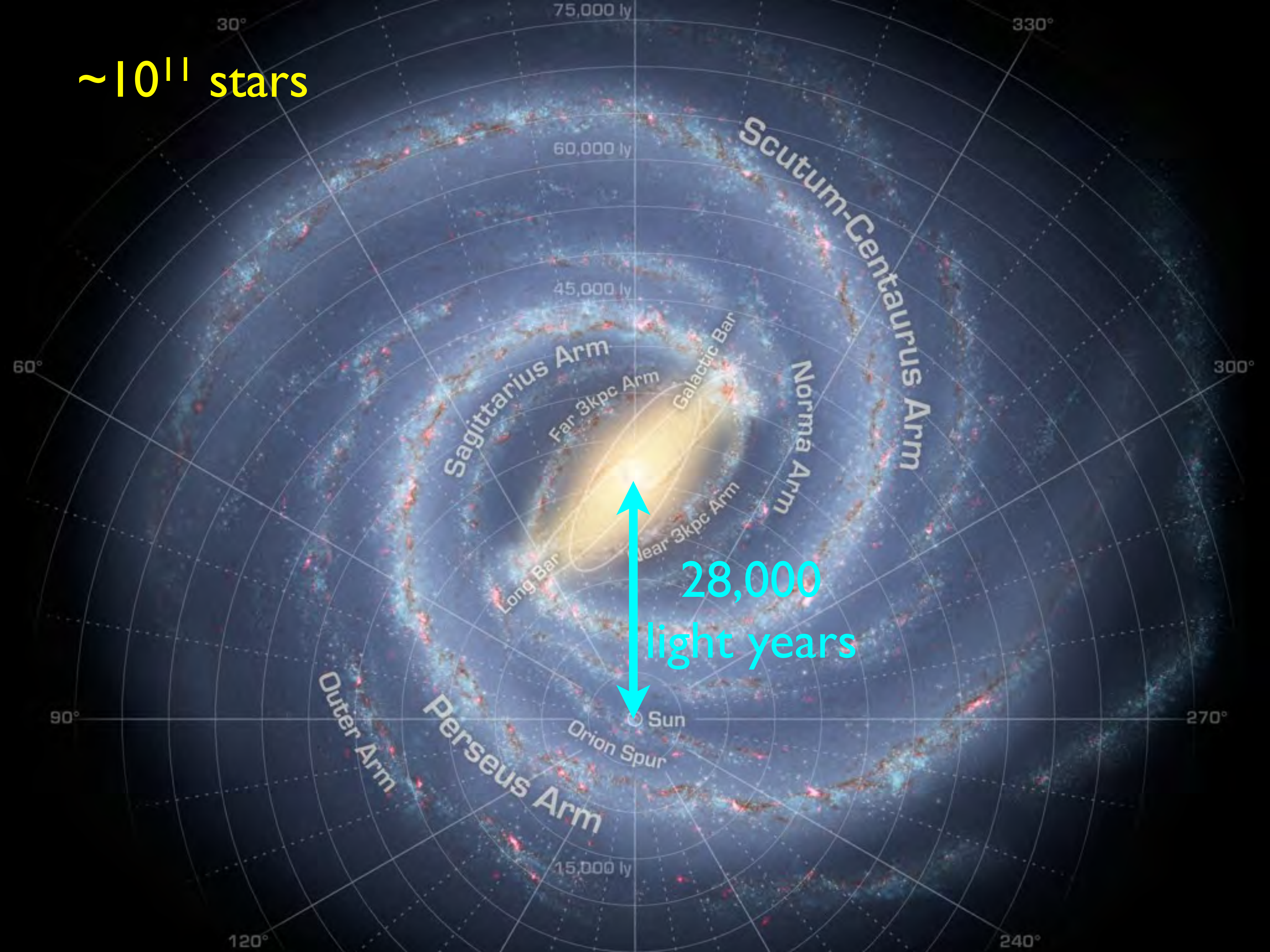
$$ma = m\frac{v^2}{r}$$

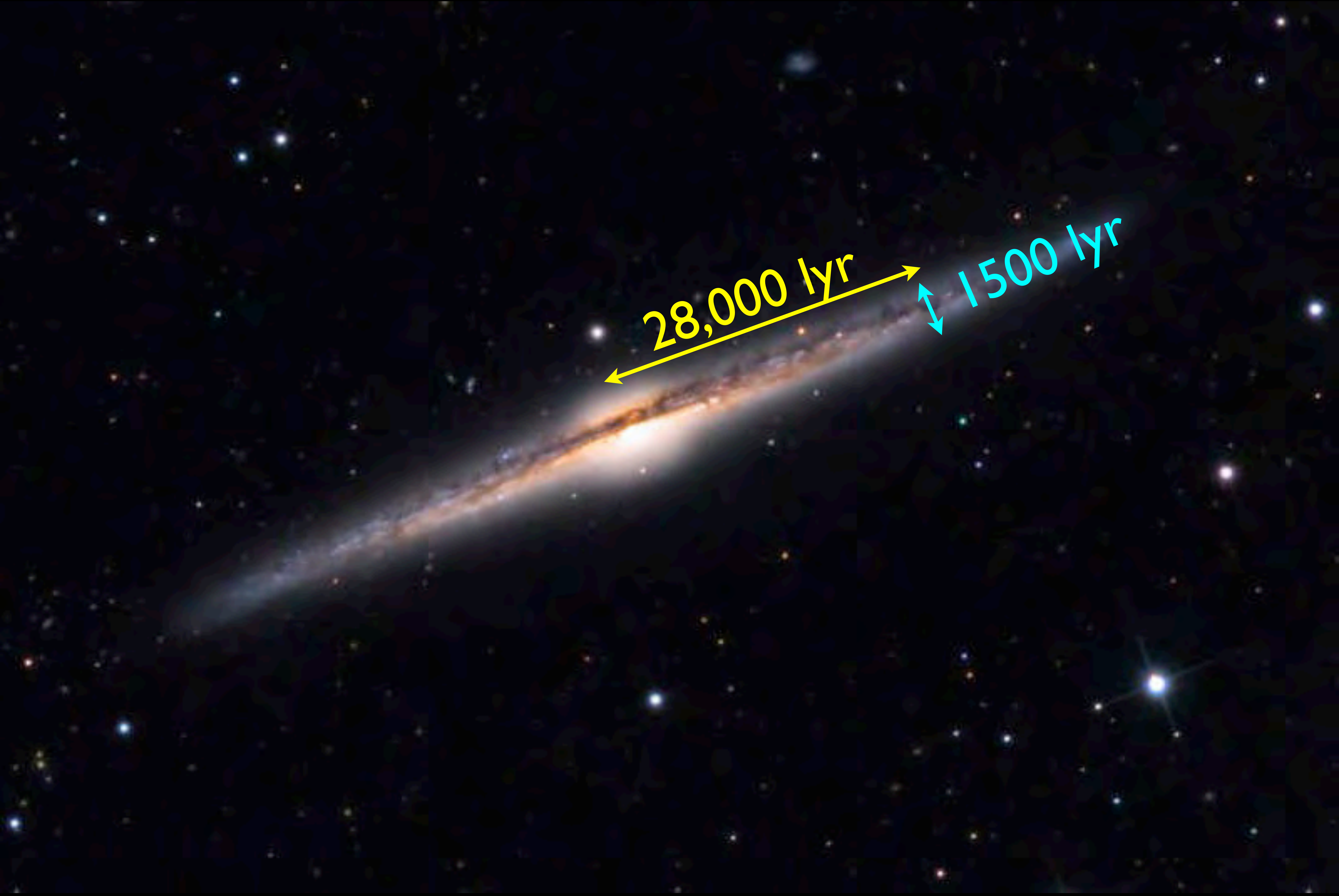
$$\frac{GM_\odot m}{r^2} = m\frac{v^2}{r}$$

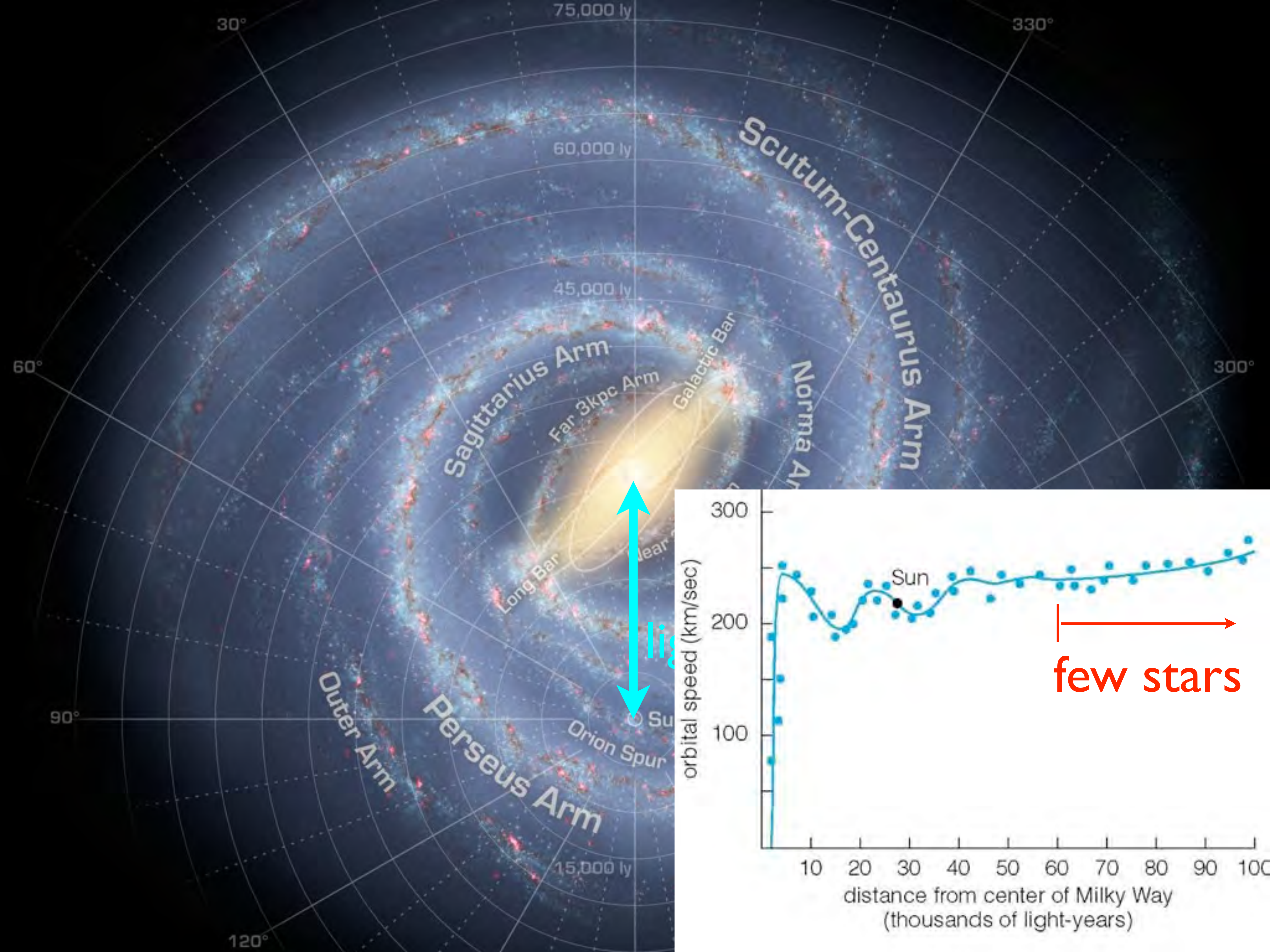
$$v = \sqrt{\frac{GM_\odot}{r}} \propto \frac{1}{\sqrt{r}}$$


closest star
Proxima Centauri
4.2 light years

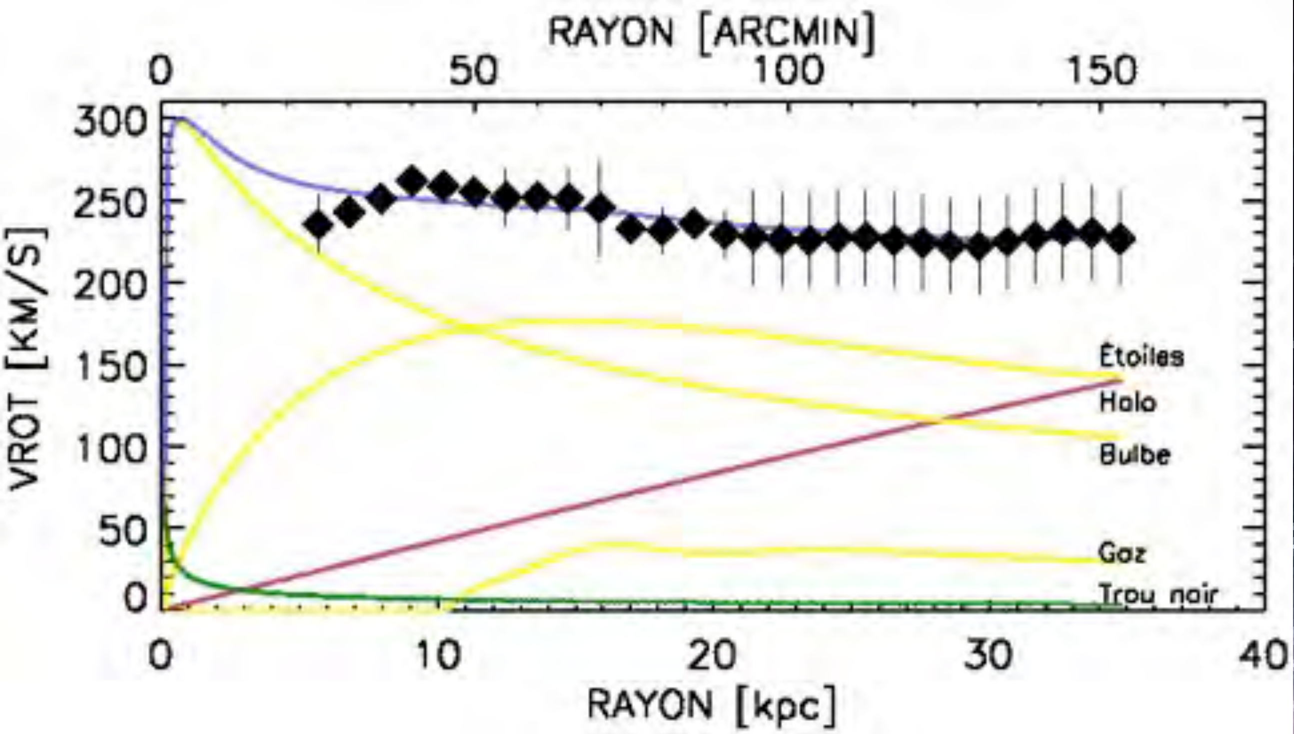
Milky Way and Galaxies


~10^{11} stars
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
28,000
light years
Sun
Orion Spur
Outer Arm
Perseus Arm


28,000 lyr
1500 lyr



75,000 ly
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
120°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Ar
Long Bar
Outer Arm
Perseus Arm
Orion Spur
orbital speed (km/sec)
300
200
100
Sun
few stars
10
20
30
40
50
60
70
80
90
distance from center of Milky Way
(thousands of light-years)


RAYON [ARCMIN]
0
50
100
150
VROT [KM/S]
300
250
200
150
100
50
0
Étoiles
Halo
Bulbe
Gaz
Trou noir
10
20
30
40
RAYON [kpc]

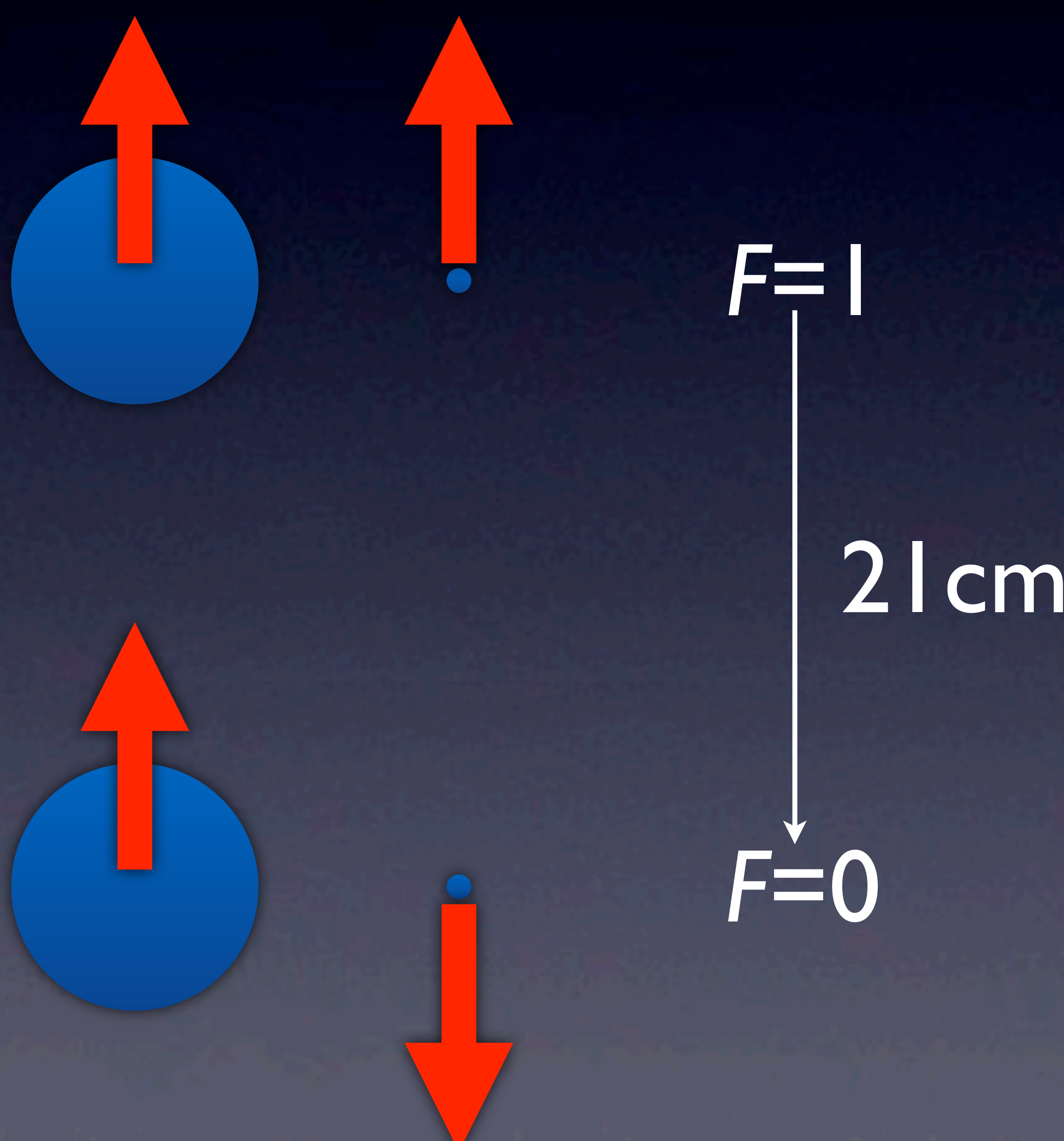

will collide with us
in 4.5 billion years
Andromeda M33 = 2.5M lyr

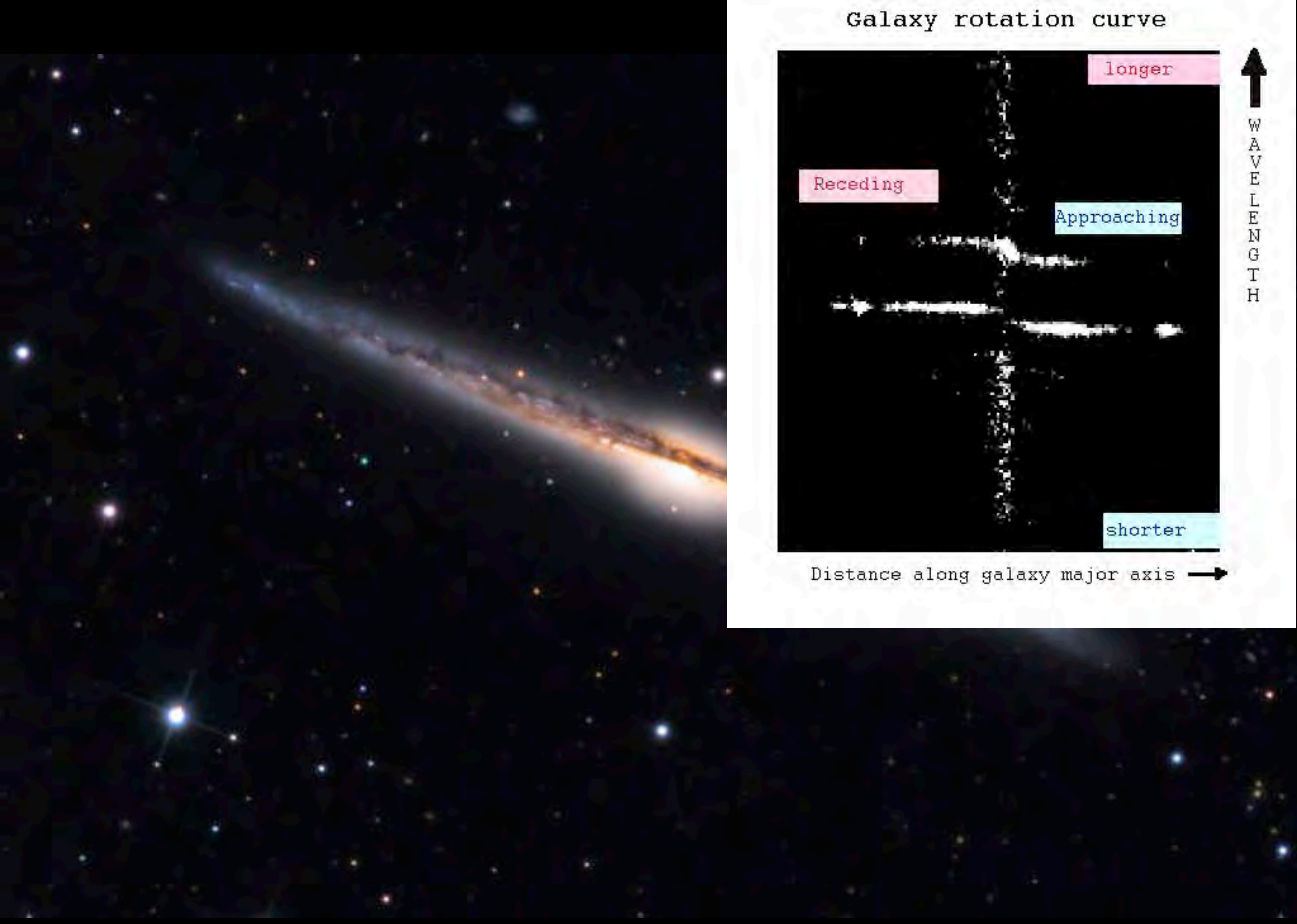
How do we measure the rotation curve?

- Special relativity

$$f' = \sqrt{\frac{c \mp v}{c \pm v}}\, f \approx \left(1 \mp \frac{c}{v}\right) f$$

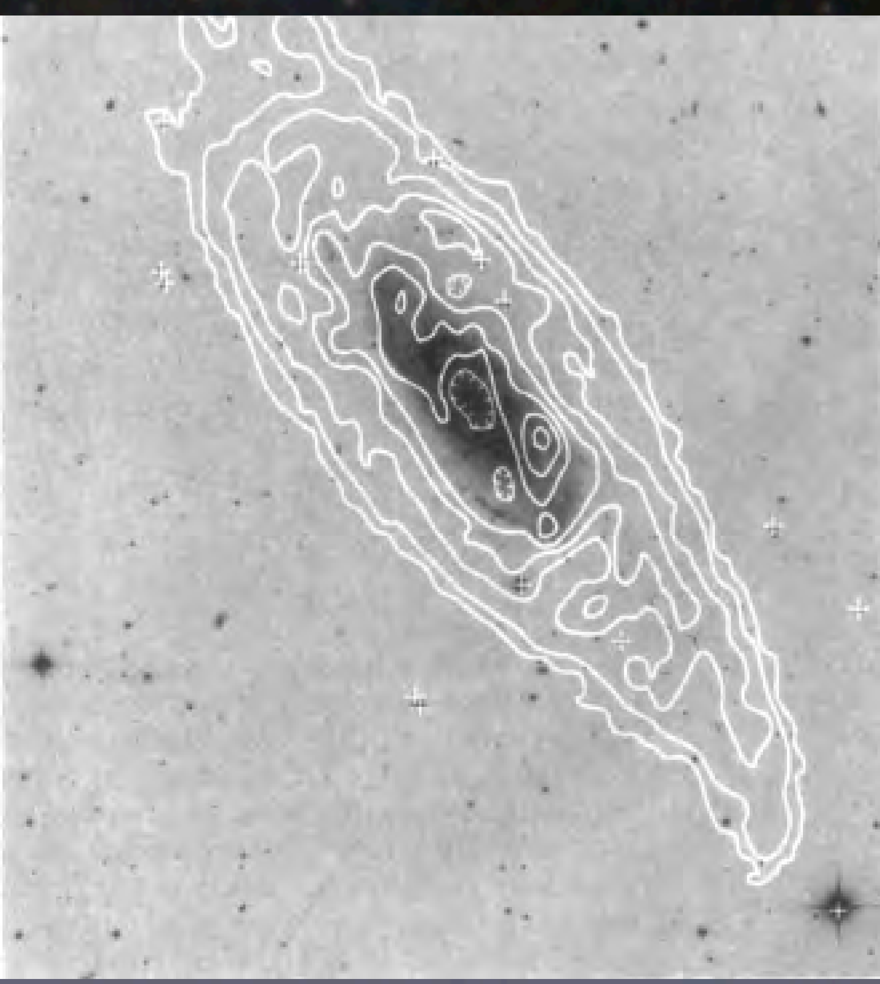
- hyperfine splitting in neutral hydrogen
- 21cm line can be excited by the cosmic microwave background
- kT_0=0.23 meV
- $h\,c$/21cm = 0.94 μeV

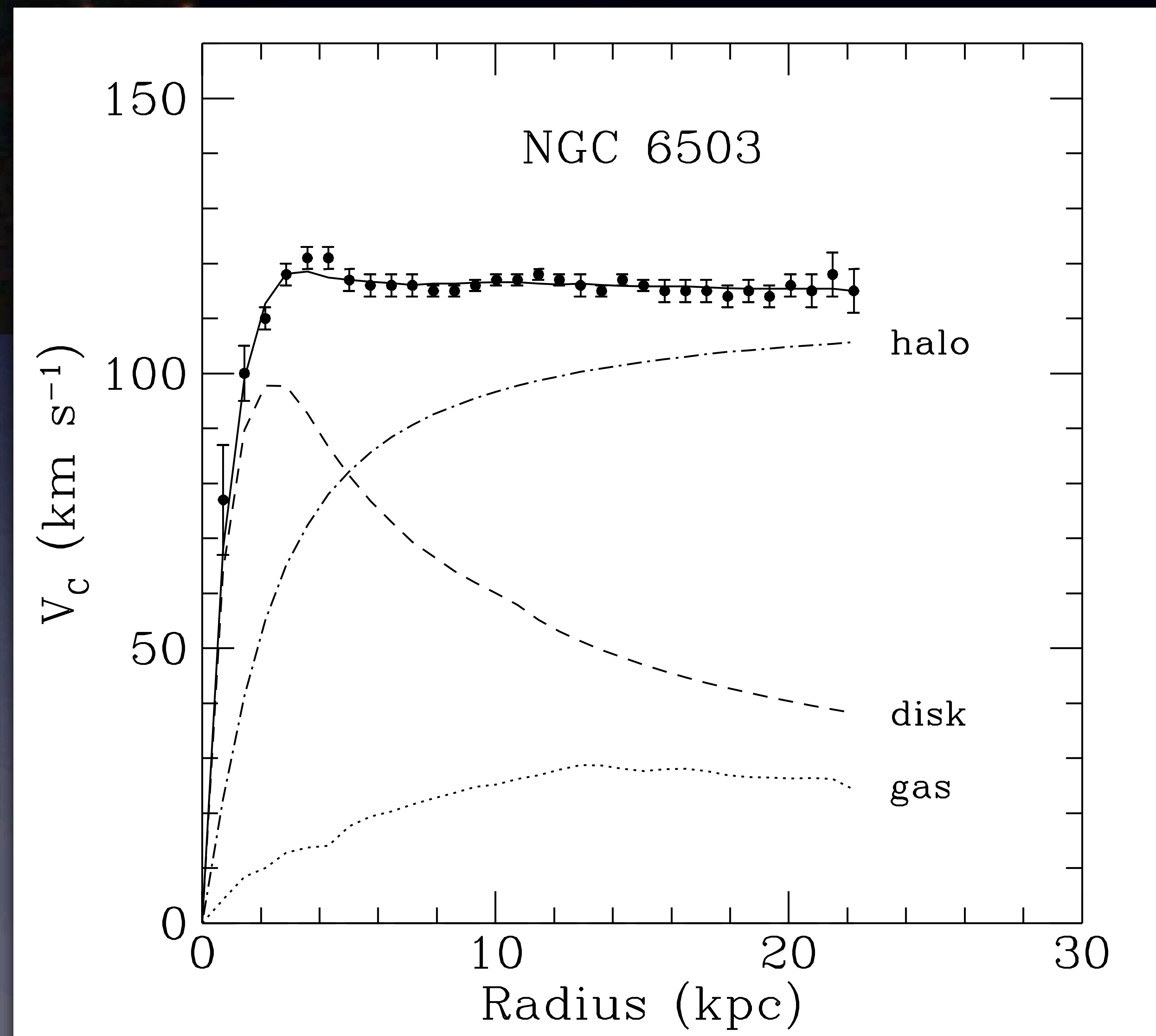



Galaxy rotation curve
longer
Receding
Approaching
shorter
WAVELENGTH
Distance along galaxy major axis

Vera
Rubin

1960s





NGC 6503
halo
disk
gas
V_c (km s^{-1})
Radius (kpc)
0
50
100
150
0
10
20
30

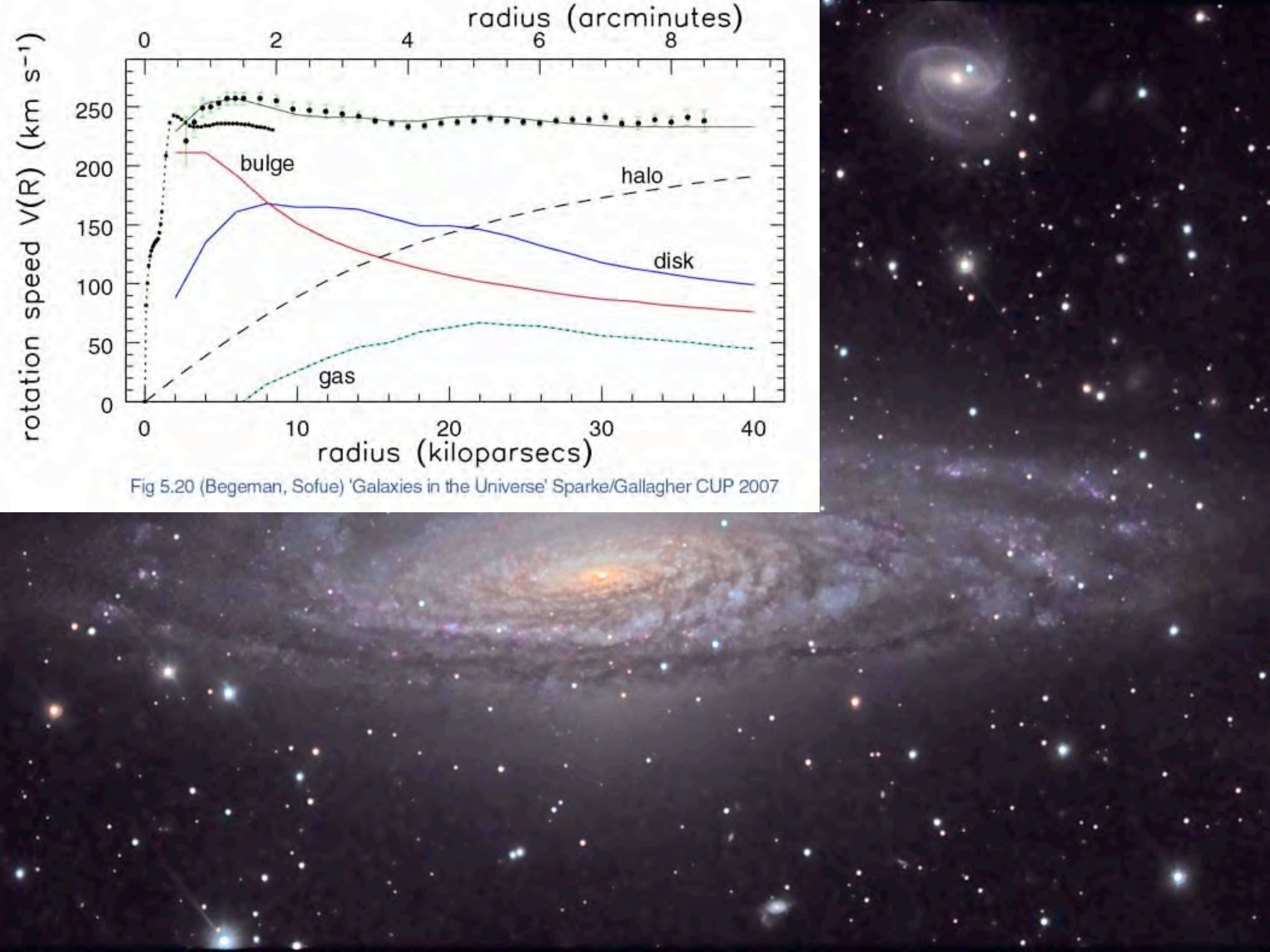
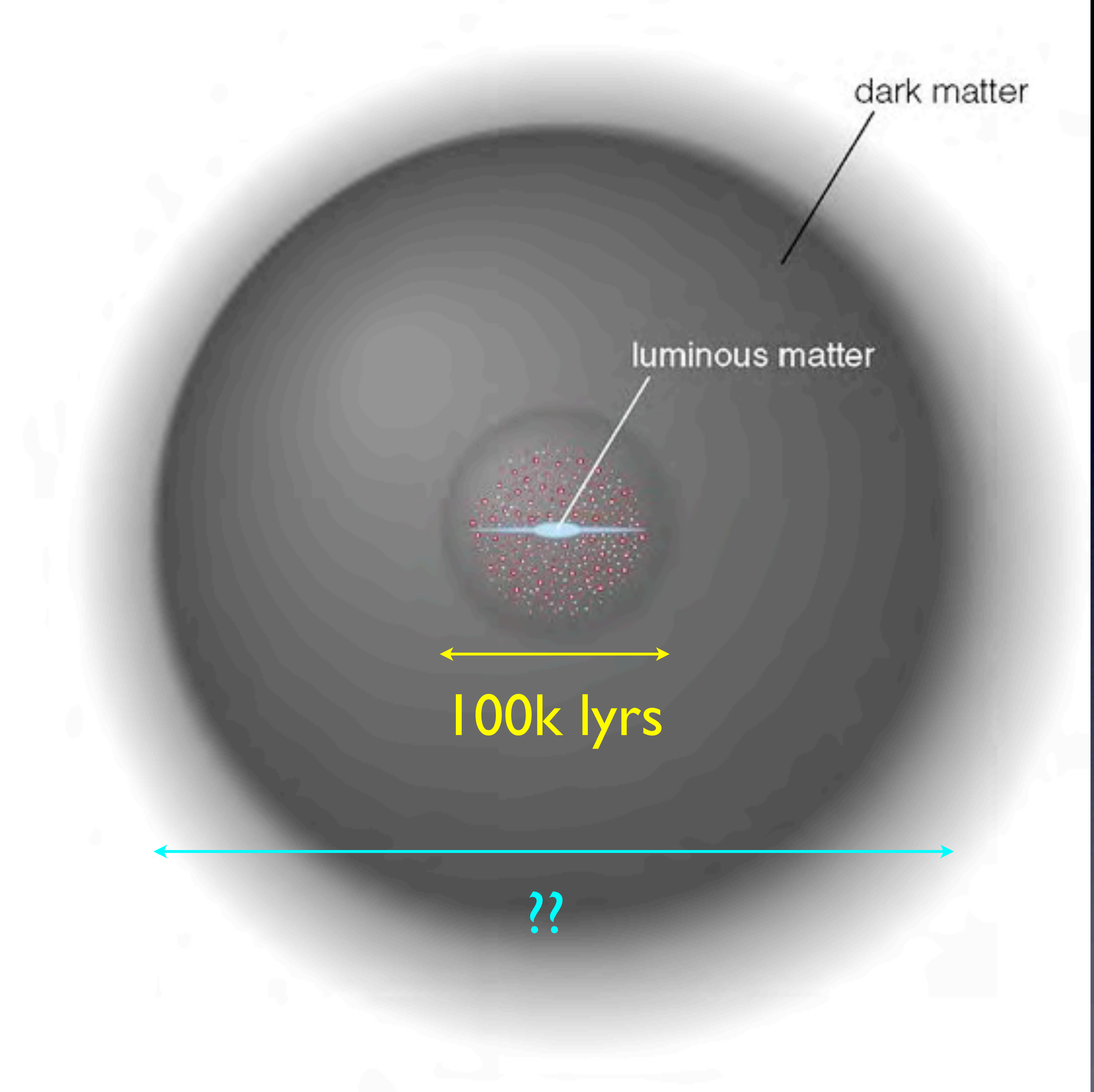
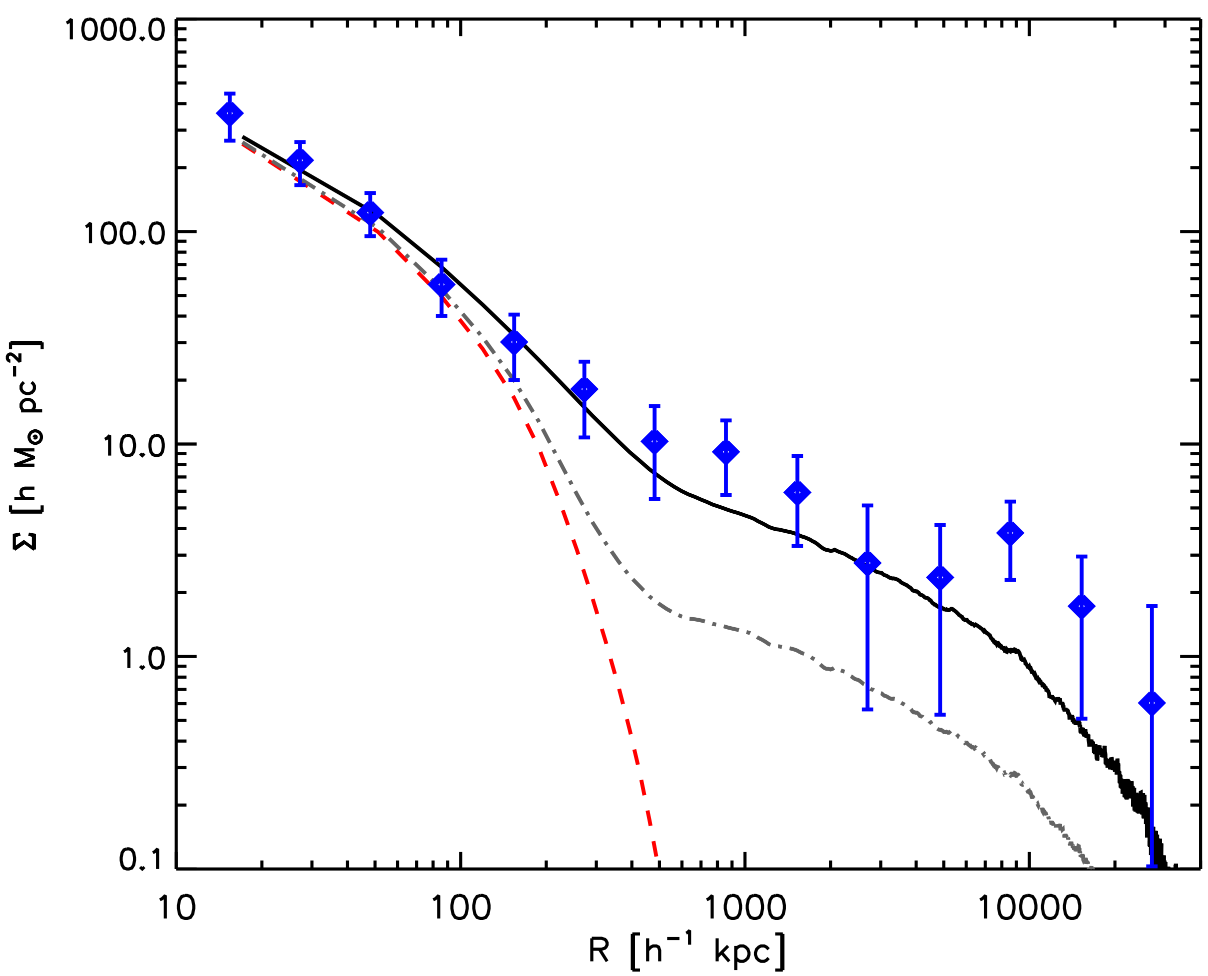


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007


dark matter
luminous matter
100k lyrs
??

connects galaxies

stacking 85k quasars near 20M galaxies



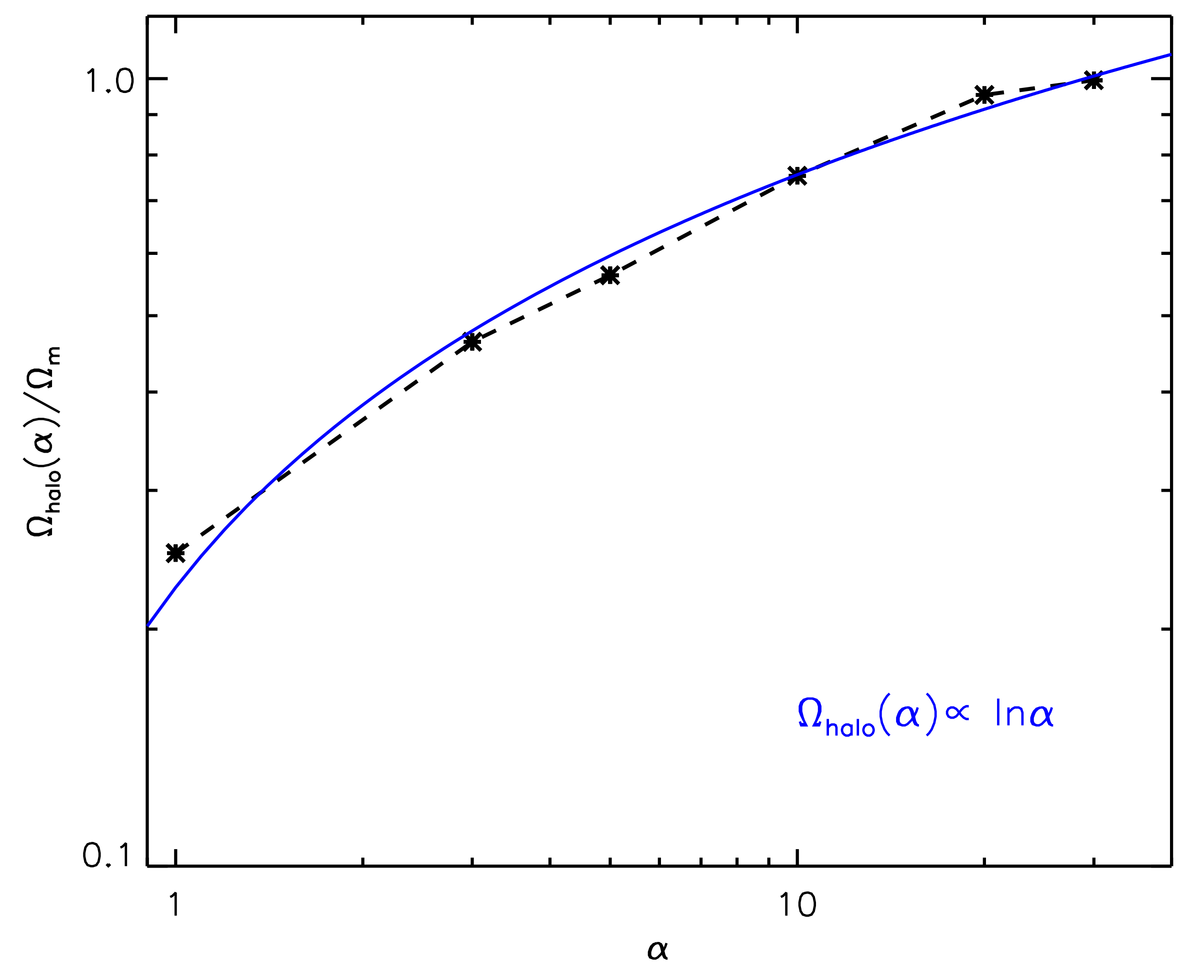
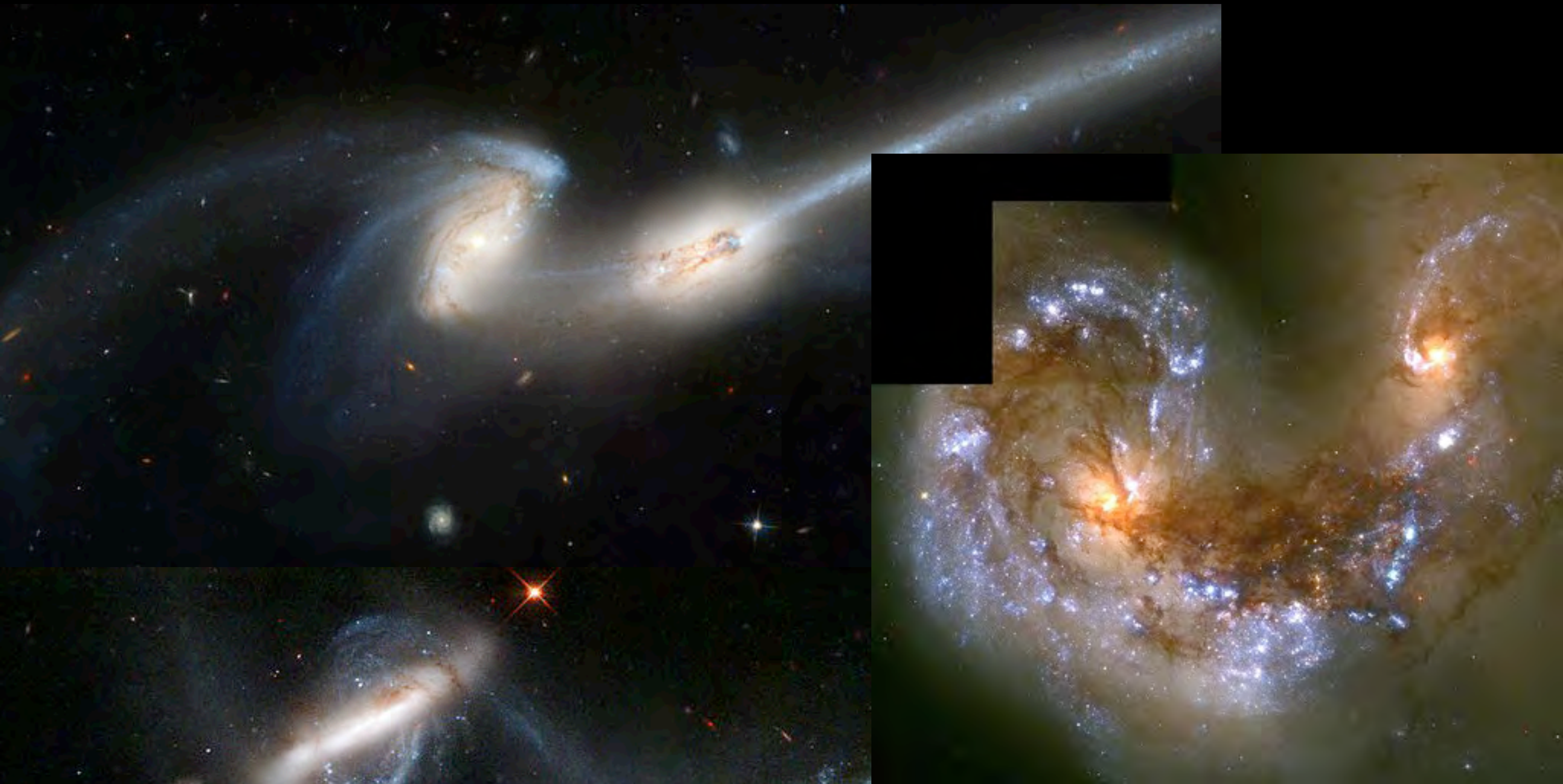


Fig. 2.— The mean surface mass density profile as a function of the distance from the centre of galaxies. The thick solid curve is the mean of all haloes above the mass threshold. The dash-dotted curve represents the contribution from particles bound to haloes, i.e., particles that reside within the virial radius of all haloes. The data with error bars are the observational estimate by MSFR as in the previous figure.

Fig. 4.— Fraction of mass contained in the sphere centred on individual haloes with radius $\alpha R_{\rm vir}$, where $R_{\rm vir}$ is the pseudovirial radius and α is the multiplier represented in the abscissa. The solid curve is $0.23\ln + 0.23$ given in the text.

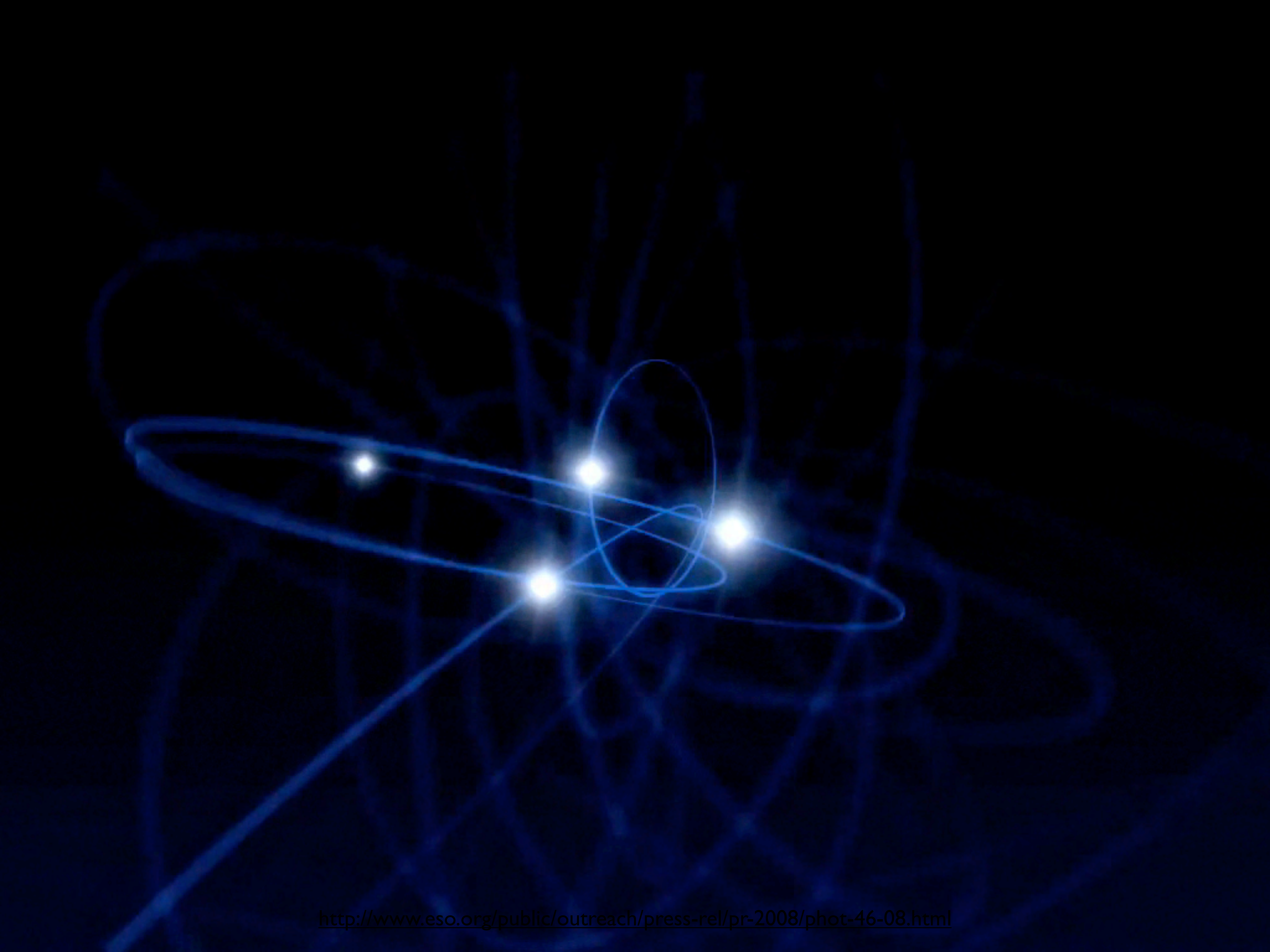
Ménard et al 2009

Masaki Fukugita Yoshida 2011



galaxies rejuvenated after mergers

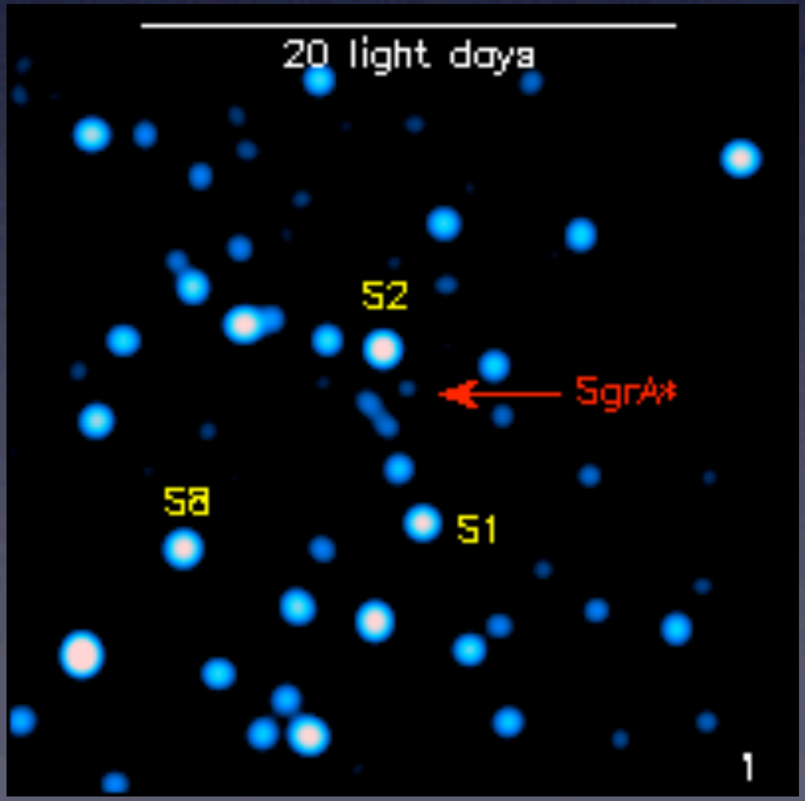
Center of Milky Way



http://www.eso.org/public/outreach/press-rel/pr-2008/phot-46-08.html

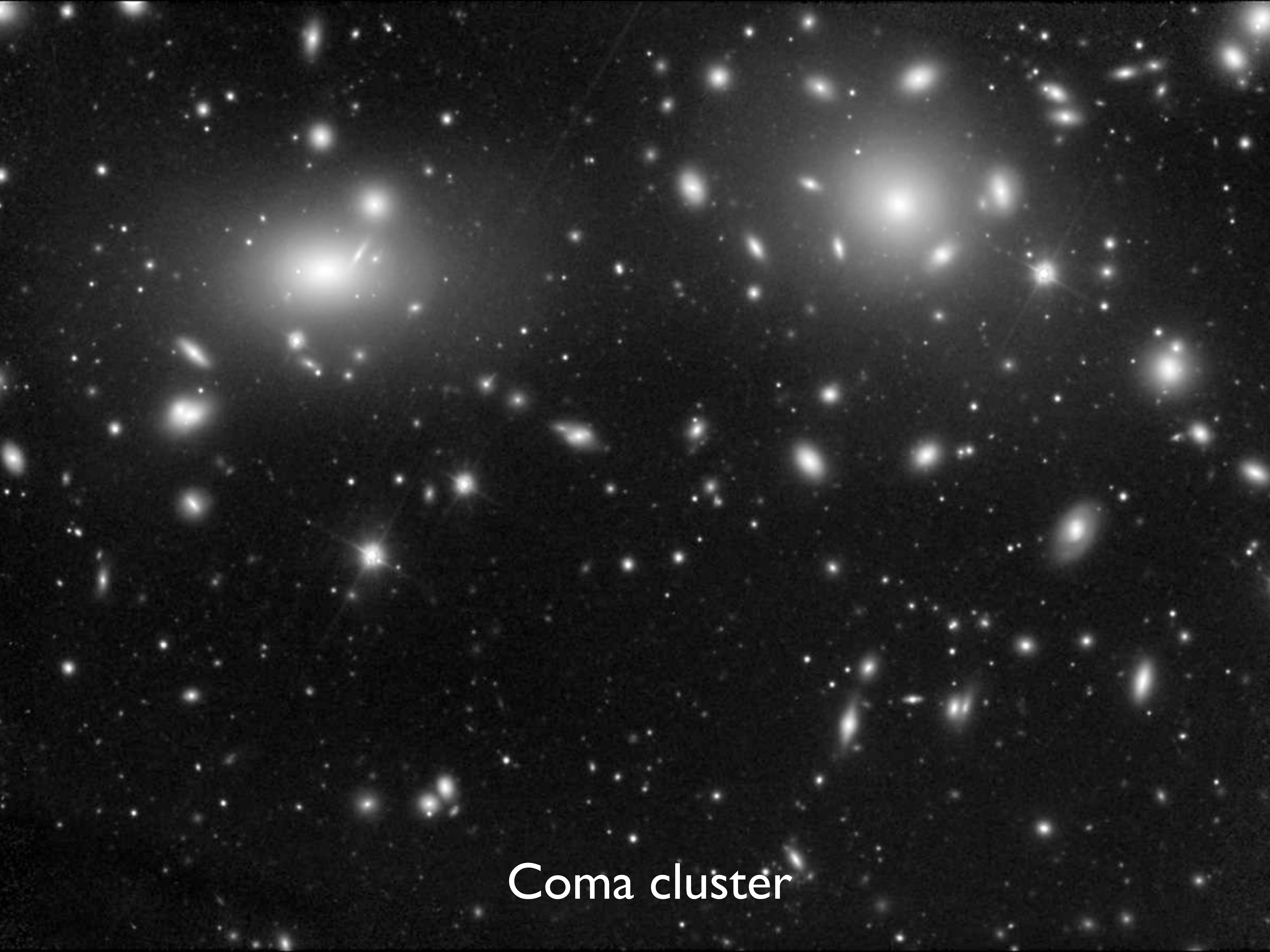
Supermassive Black Hole

- supermassive blackhole of mass ~4M M_{sun} at the center of Milky Way
- swallows gas around it
- "death cry" for about 30 min
- but can't be dark matter, far less than 100billion stars



http://www.eso.org/public/outreach/press-rel/pr-2008/phot-46-08.html

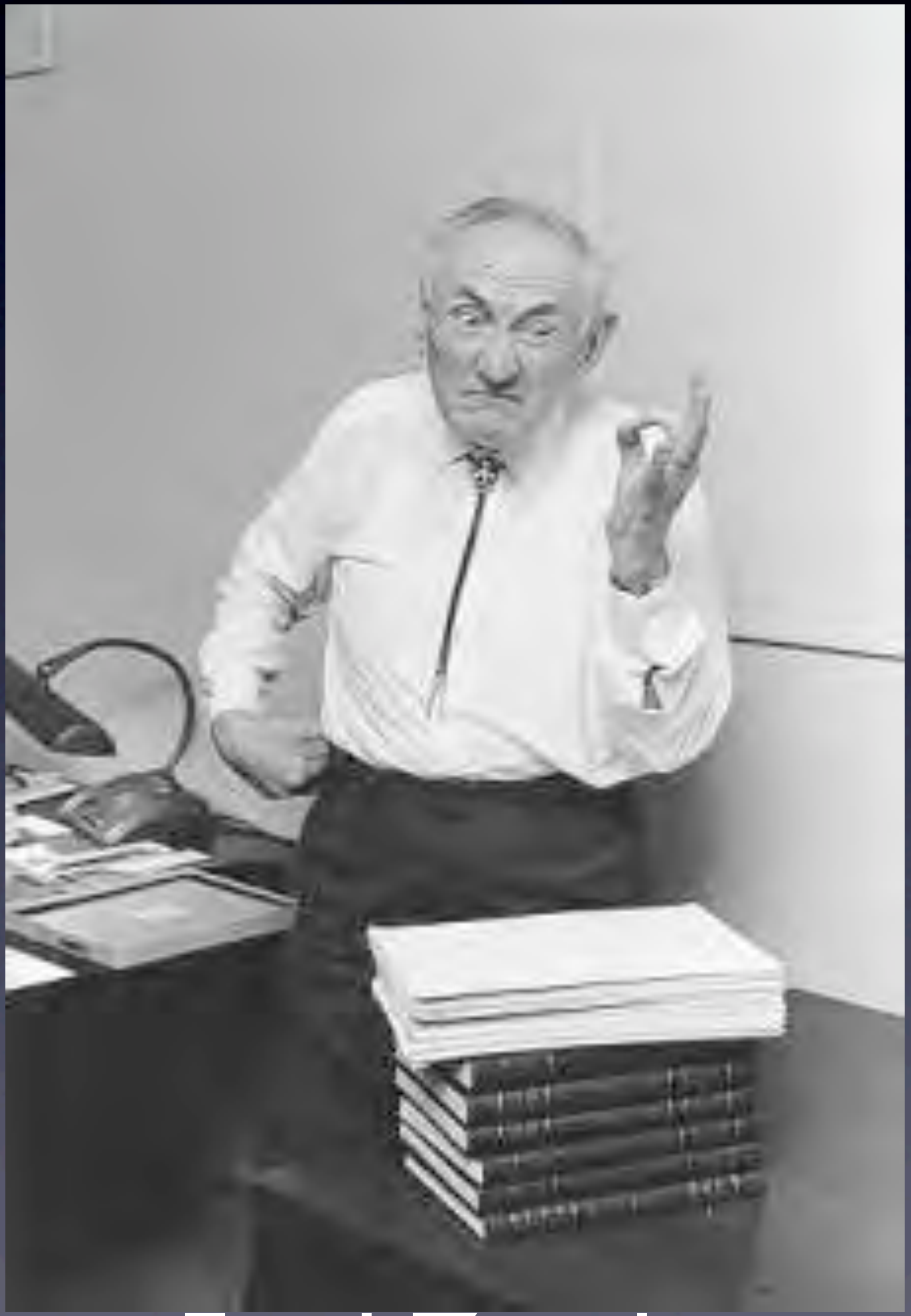

Cluster of Galaxies



Coma cluster

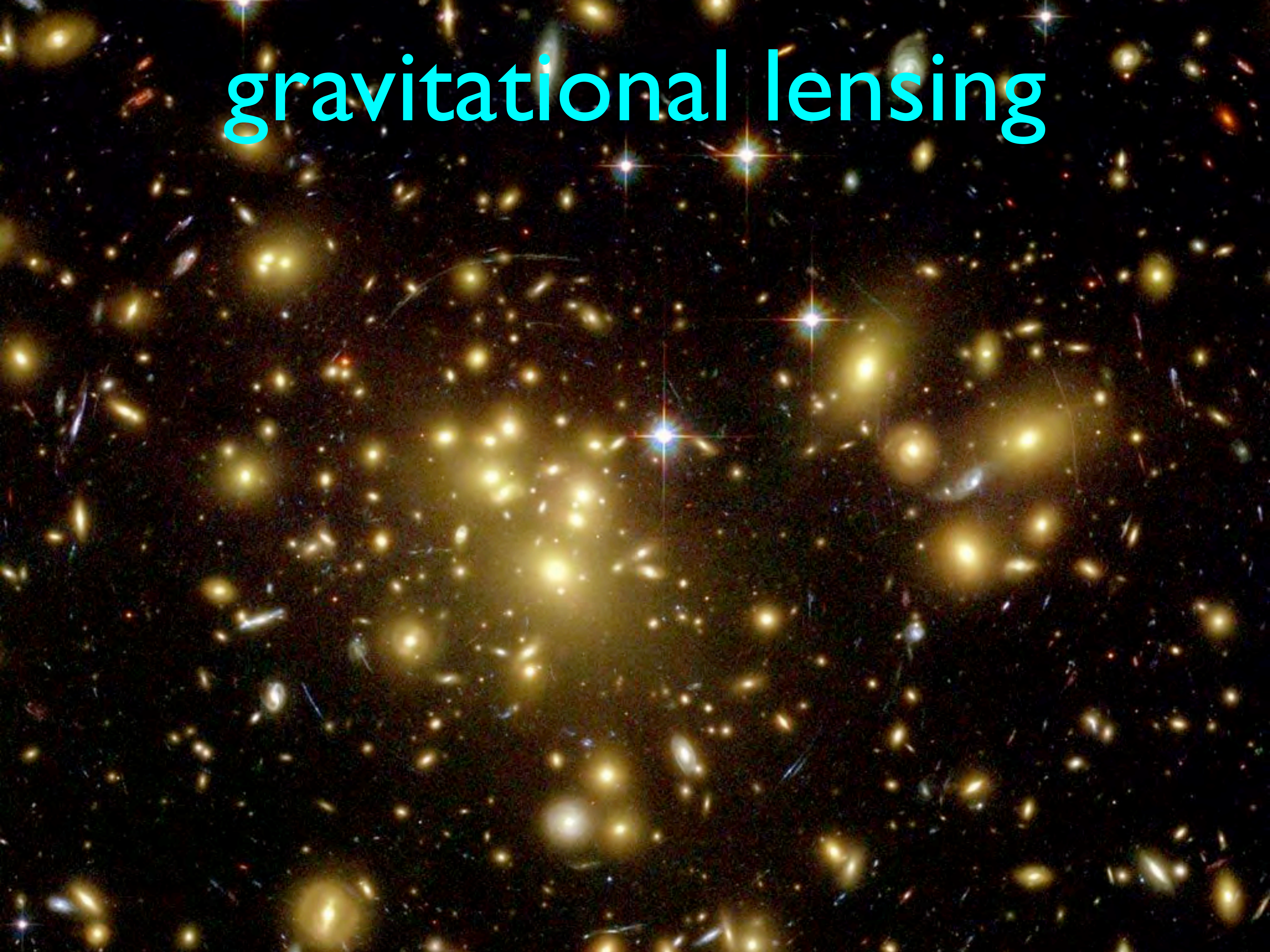
motion of galaxies

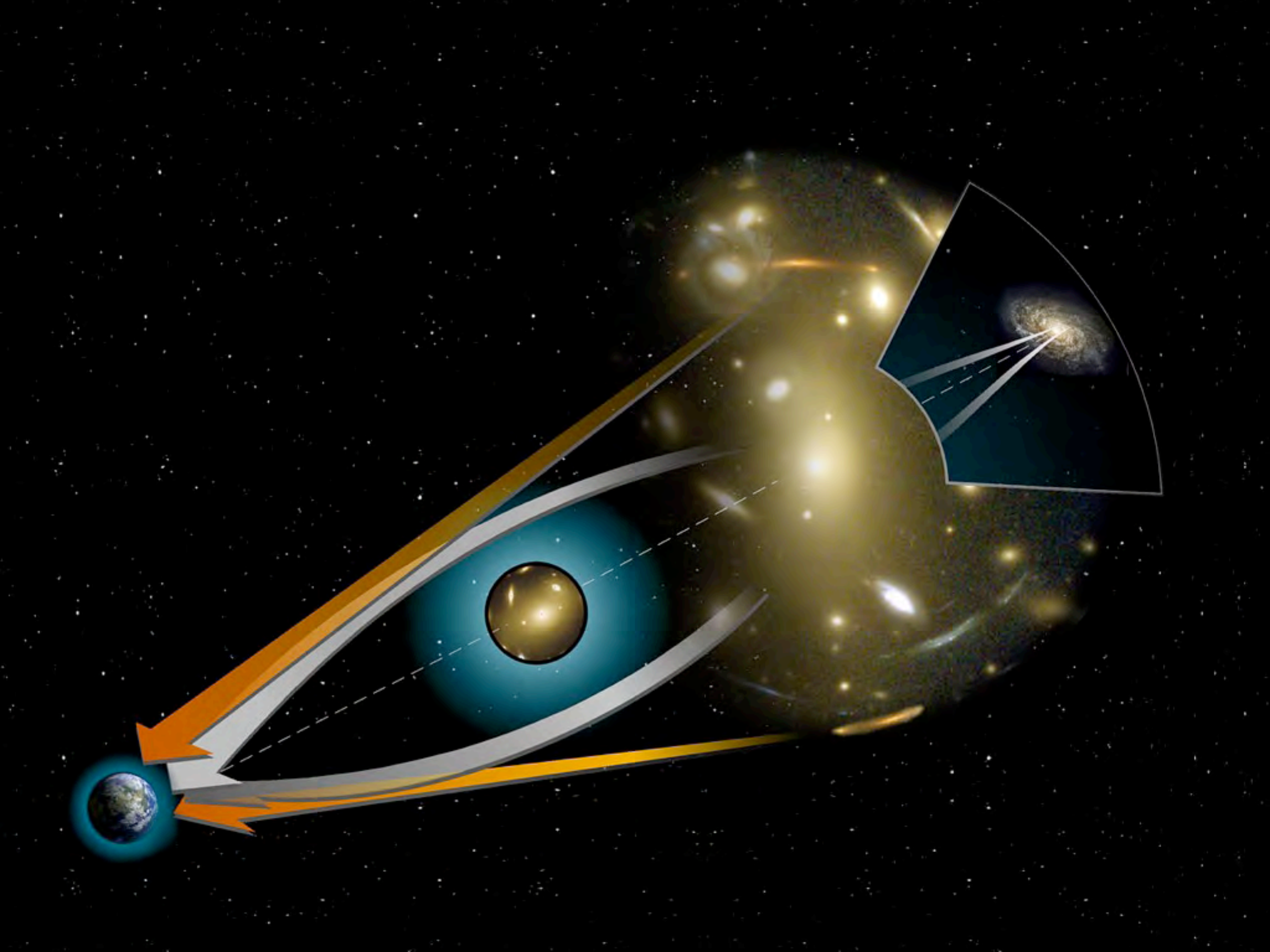
- galaxies are moving in the mutual gravitational potential
- assume virialized motion $\langle v^2 \rangle = G_N M/r$
- but they are too fast, too
- first proposal of "dark matter"



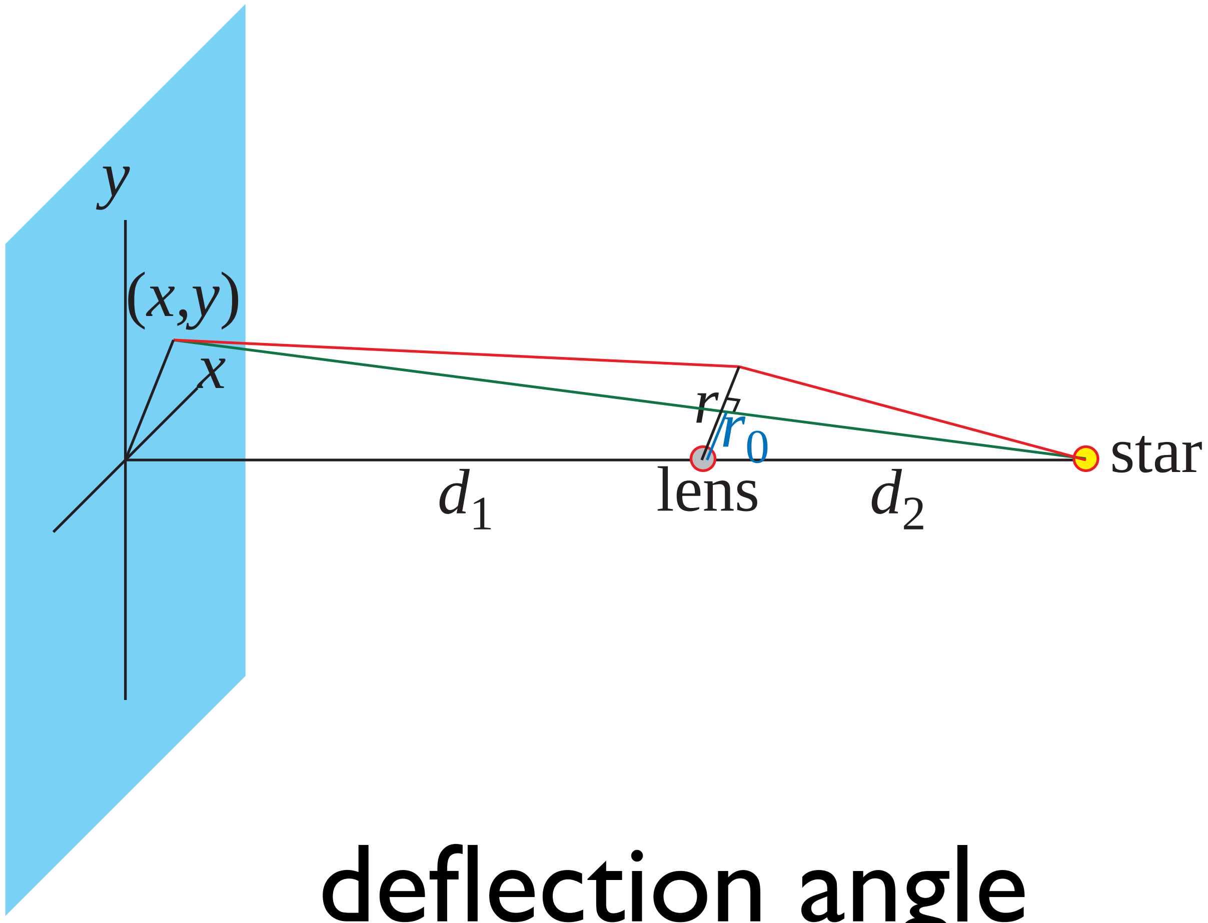
Fred Zwicky

gravitational lensing



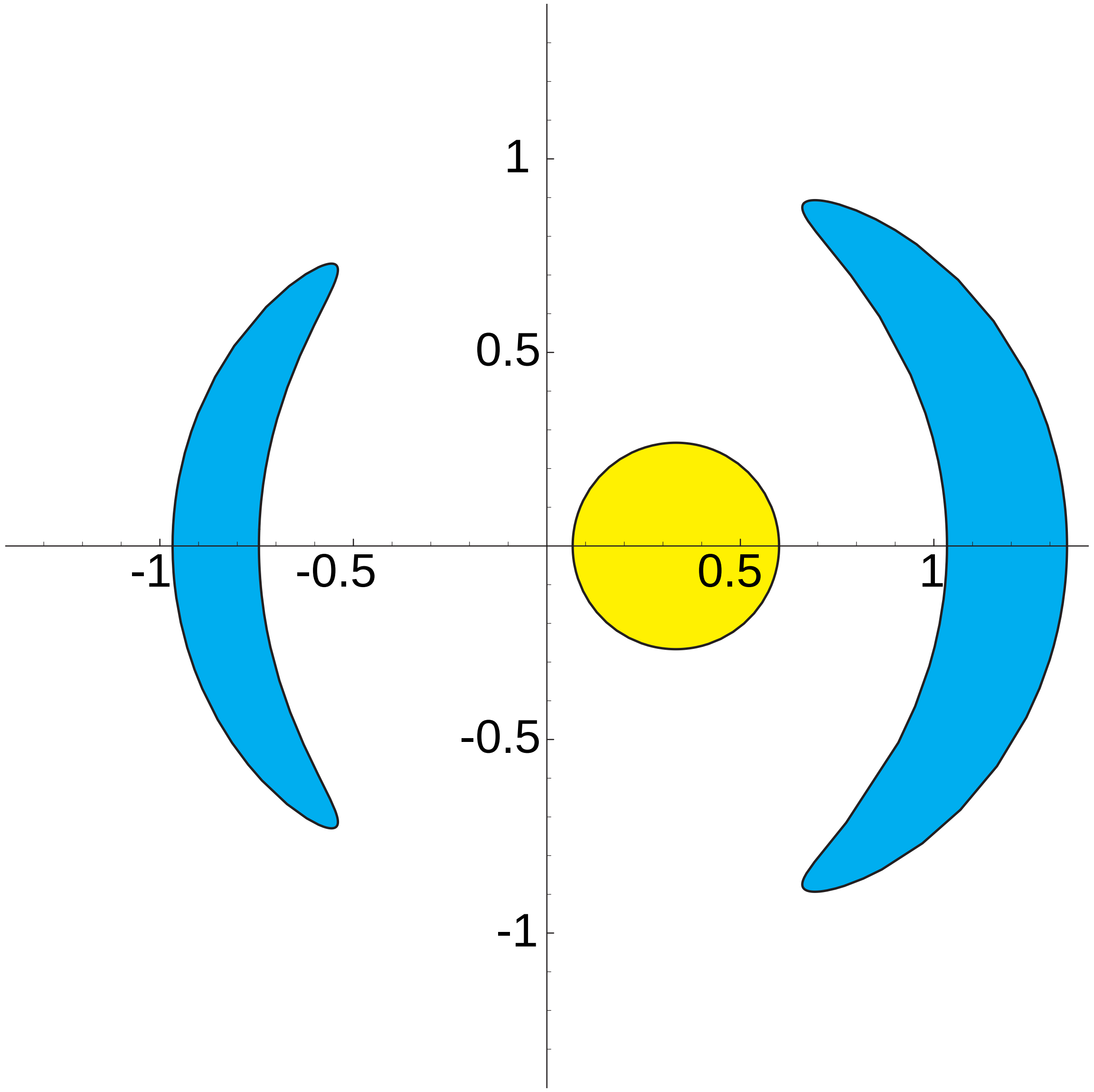


gravitational lensing



deflection angle

$$\theta = 2\frac{r_S}{r} = 4\frac{G_N M}{c^2 r}$$



gravitational lensing

$$ds^2 = \left(1 - \frac{r_S}{r}\right) c^2 dt^2 - \frac{dr^2}{1 - r_S/r} - r^2 d\theta^2 - r^2 \sin^2\theta d\phi^2$$

$$g^{\mu\nu}\partial_\mu S \partial_\nu S = mc^2 = 0$$

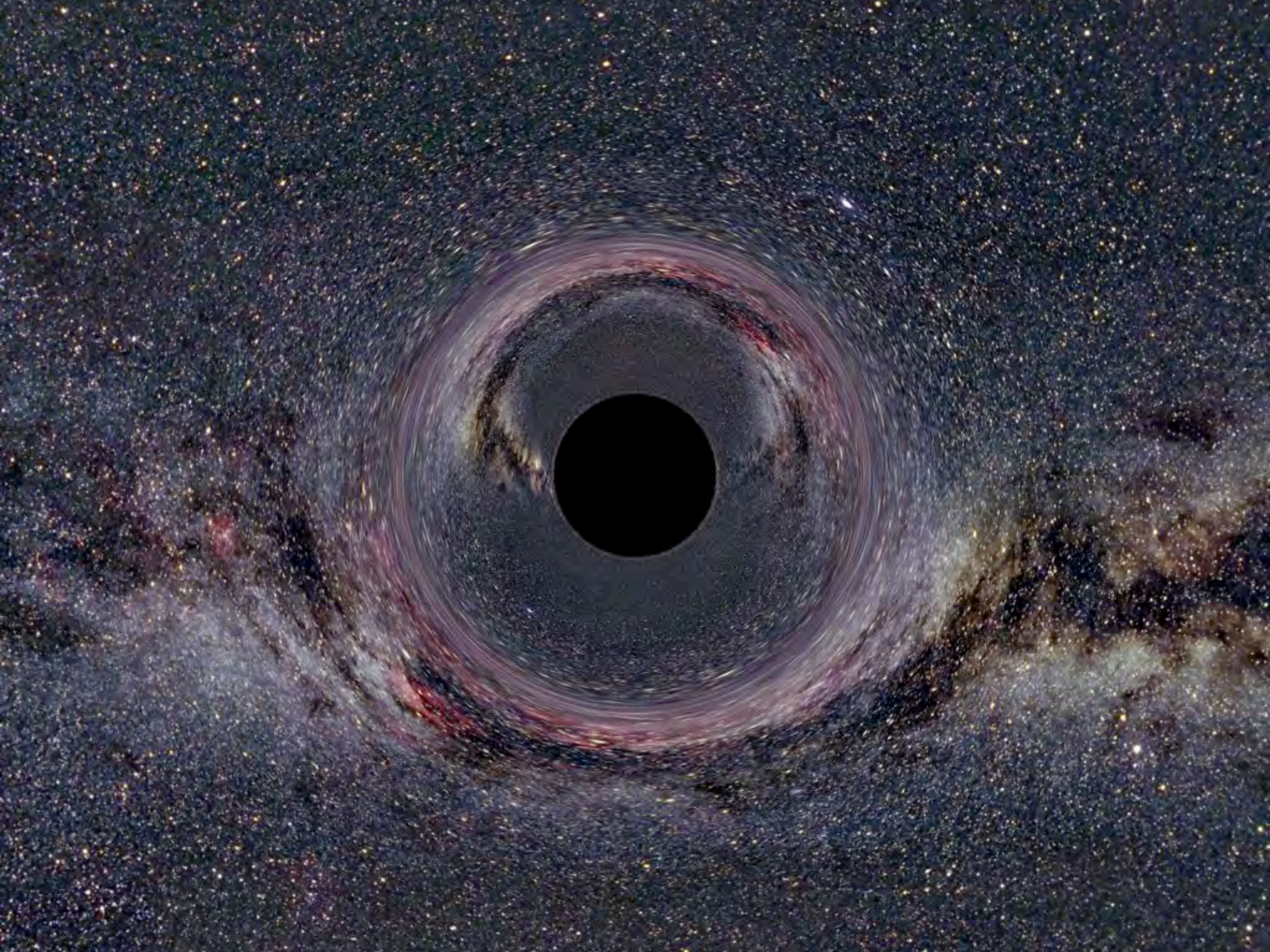
$$S(t, r, \theta) = Et - L\theta + W(E, r, L)$$

$$(\partial_r W)^2 = \left(1 - \frac{r_S}{r}\right)^{-2} \frac{E^2}{c^2} - \left(1 - \frac{r_S}{r}\right)^{-1} \frac{L^2}{r^2}$$

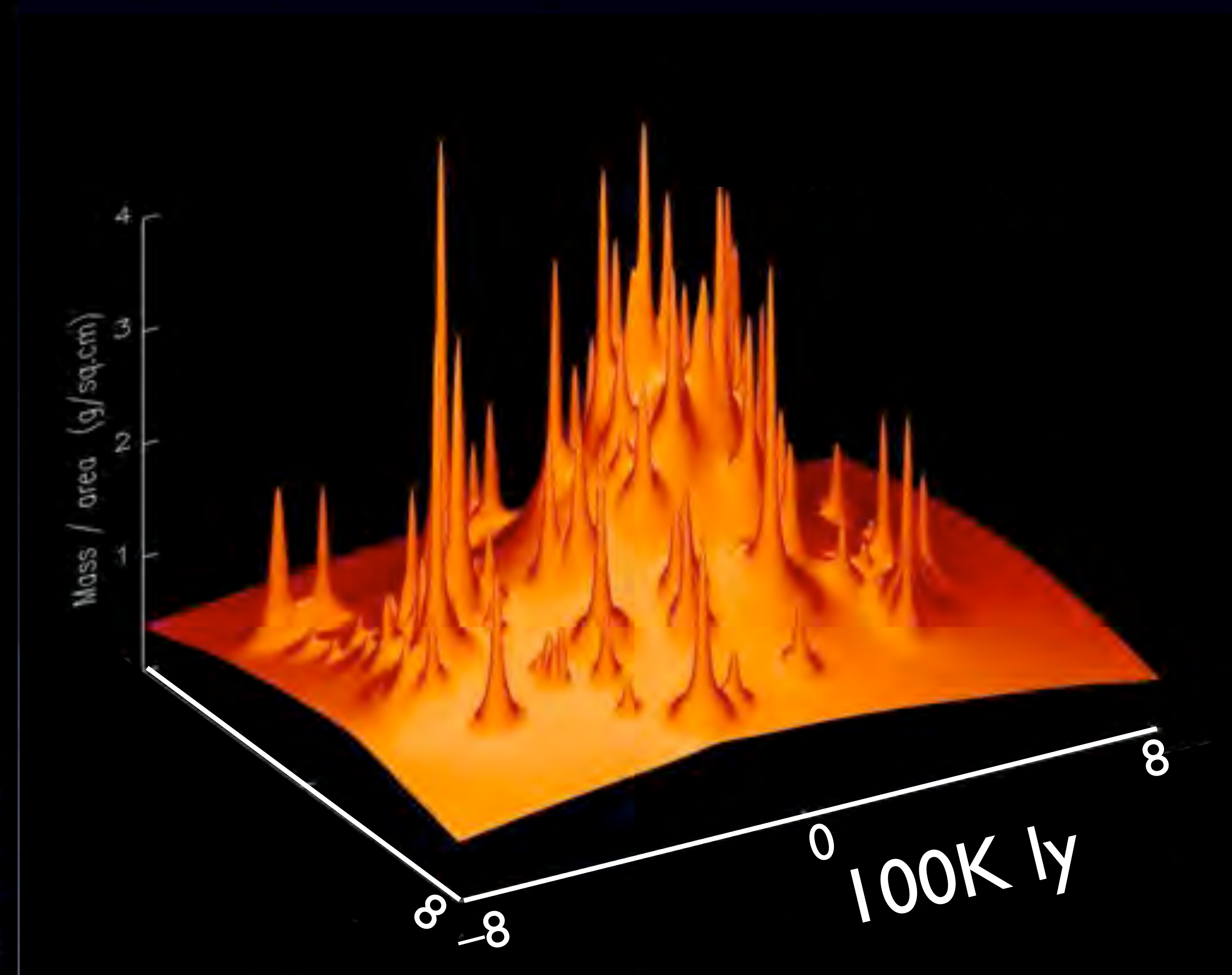
The closest approach r_c is where $\partial_r W = 0$

$$E^2 = c^2 \left(1 - \frac{r_S}{r_c}\right) \frac{L^2}{r_c^2}$$

$$\pi + \Delta\theta = \partial_L W = 2\int_{r_c}^{\infty} \frac{dr}{r\sqrt{(1 - \frac{r_S}{r_c})\frac{r^2}{r_c^2} - (1 - \frac{r_S}{r})}} = \pi + \frac{2r_S}{r_c} + O(r_S^2)$$



Clusters of galaxies

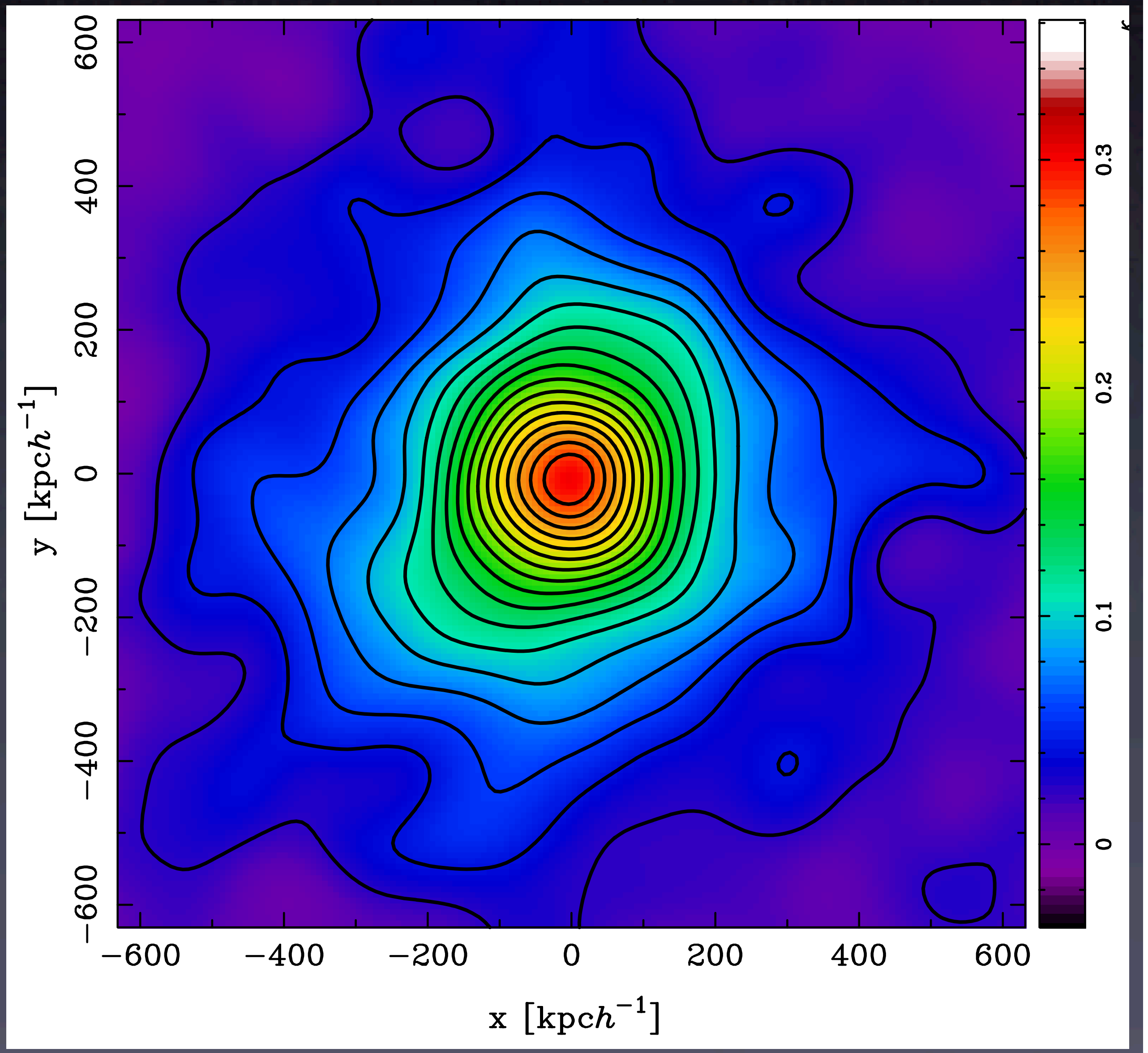


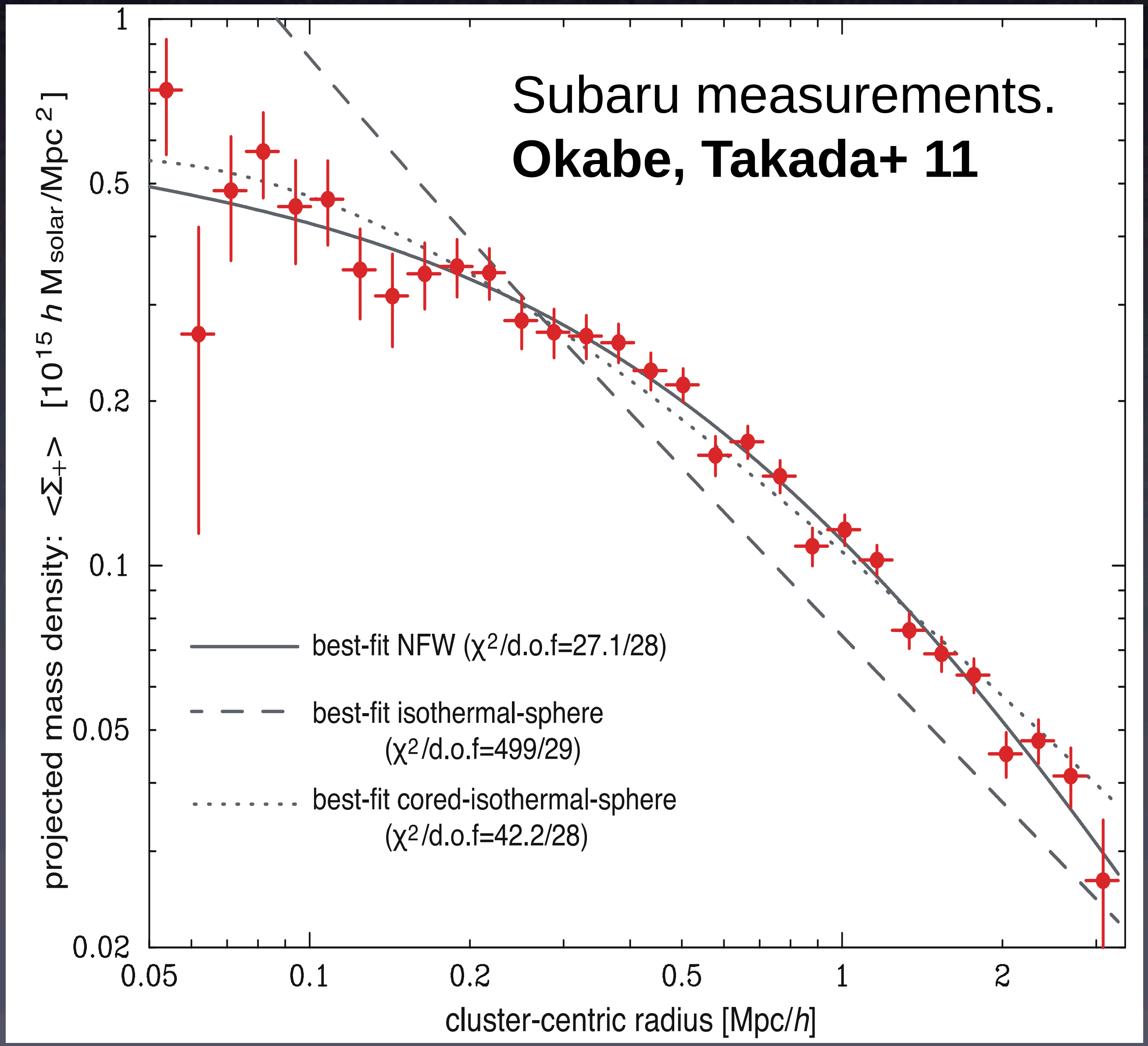
distortion in images of BG galaxies ➡ 2D map of dark matter “see” invisible dark mat

Subaru telescope

more than 80% of matter is not atoms!

as expected by theory

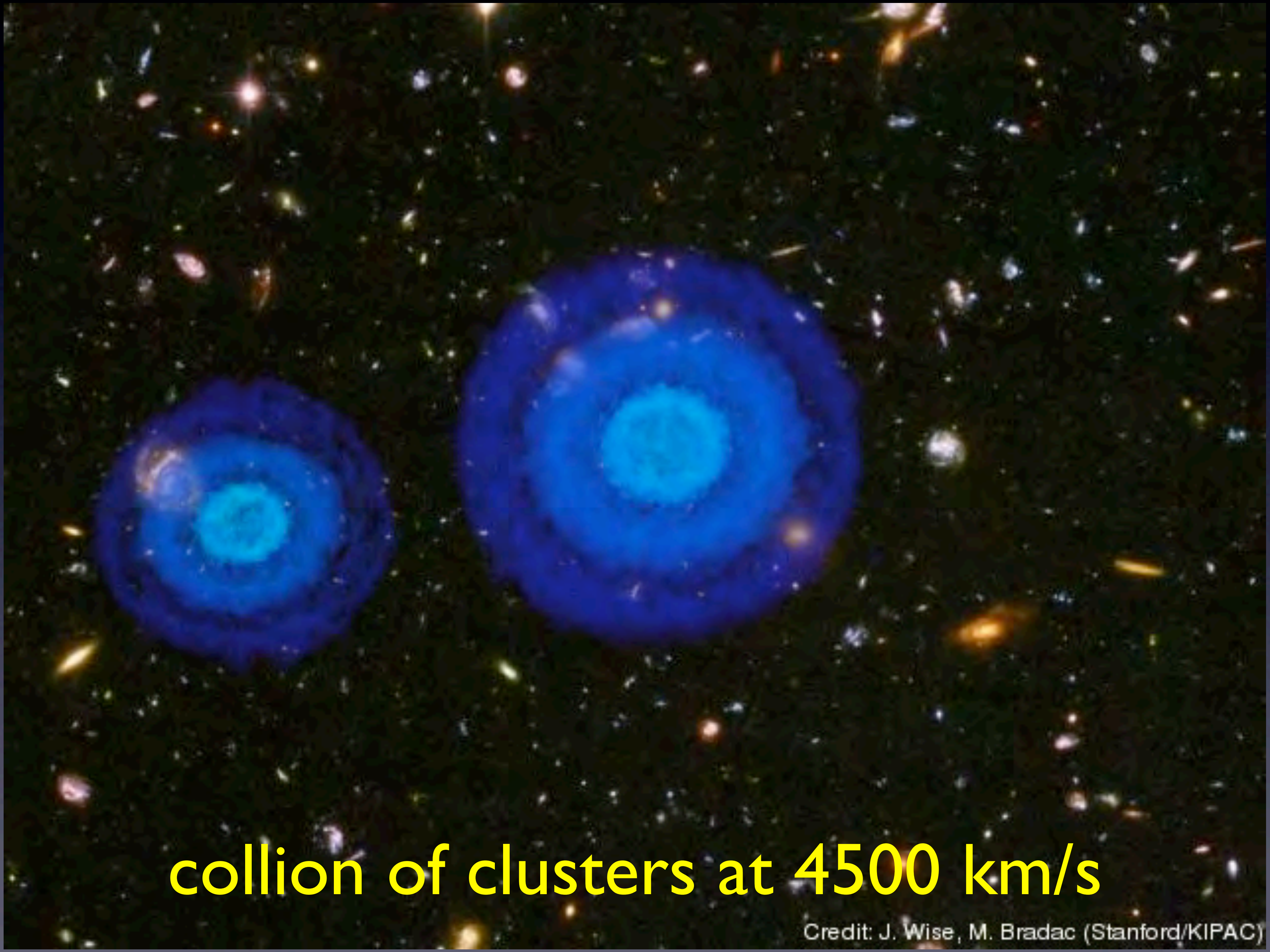




45 clusters stacked

consistent with NFW profile

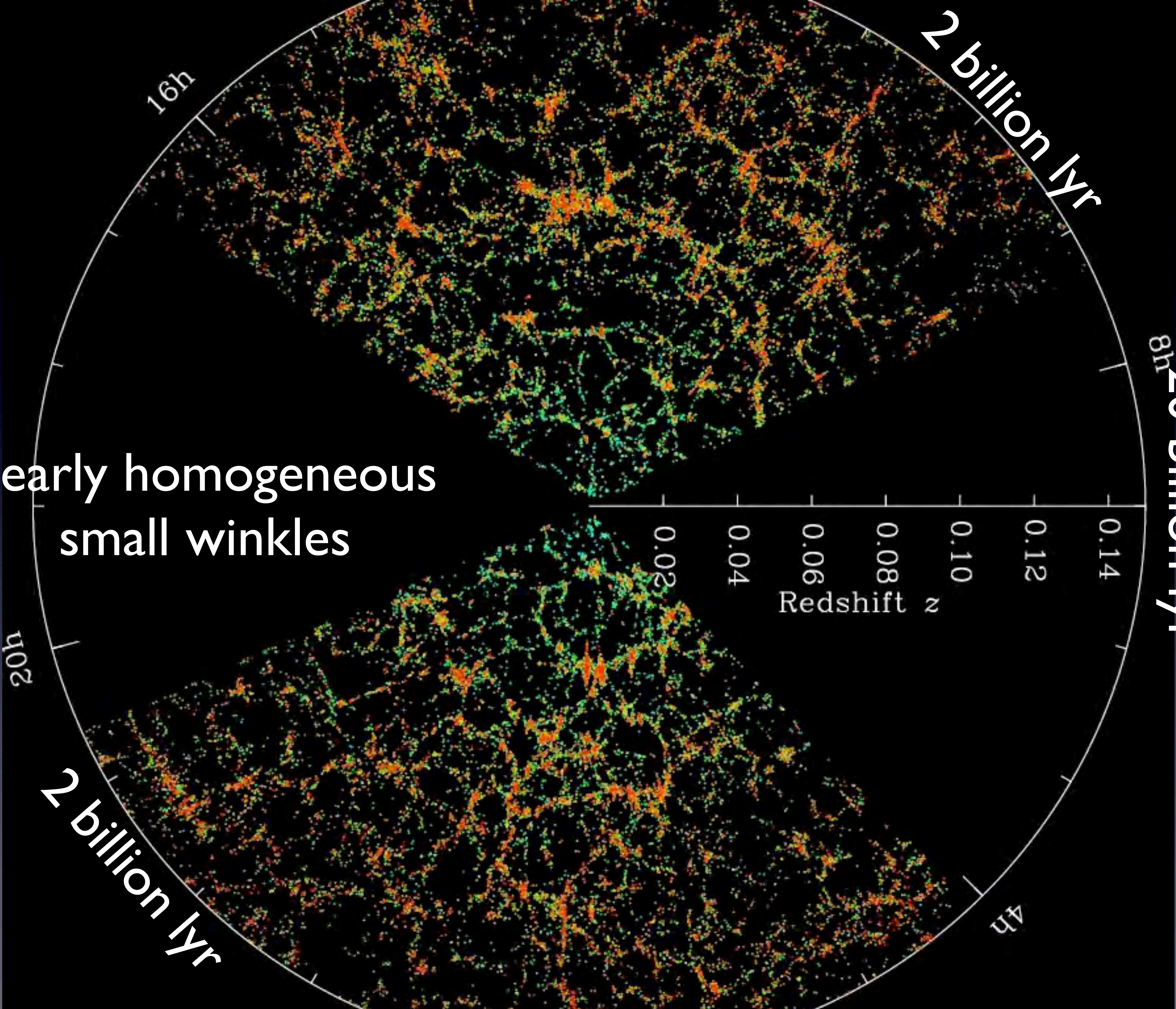
lucky we are not here

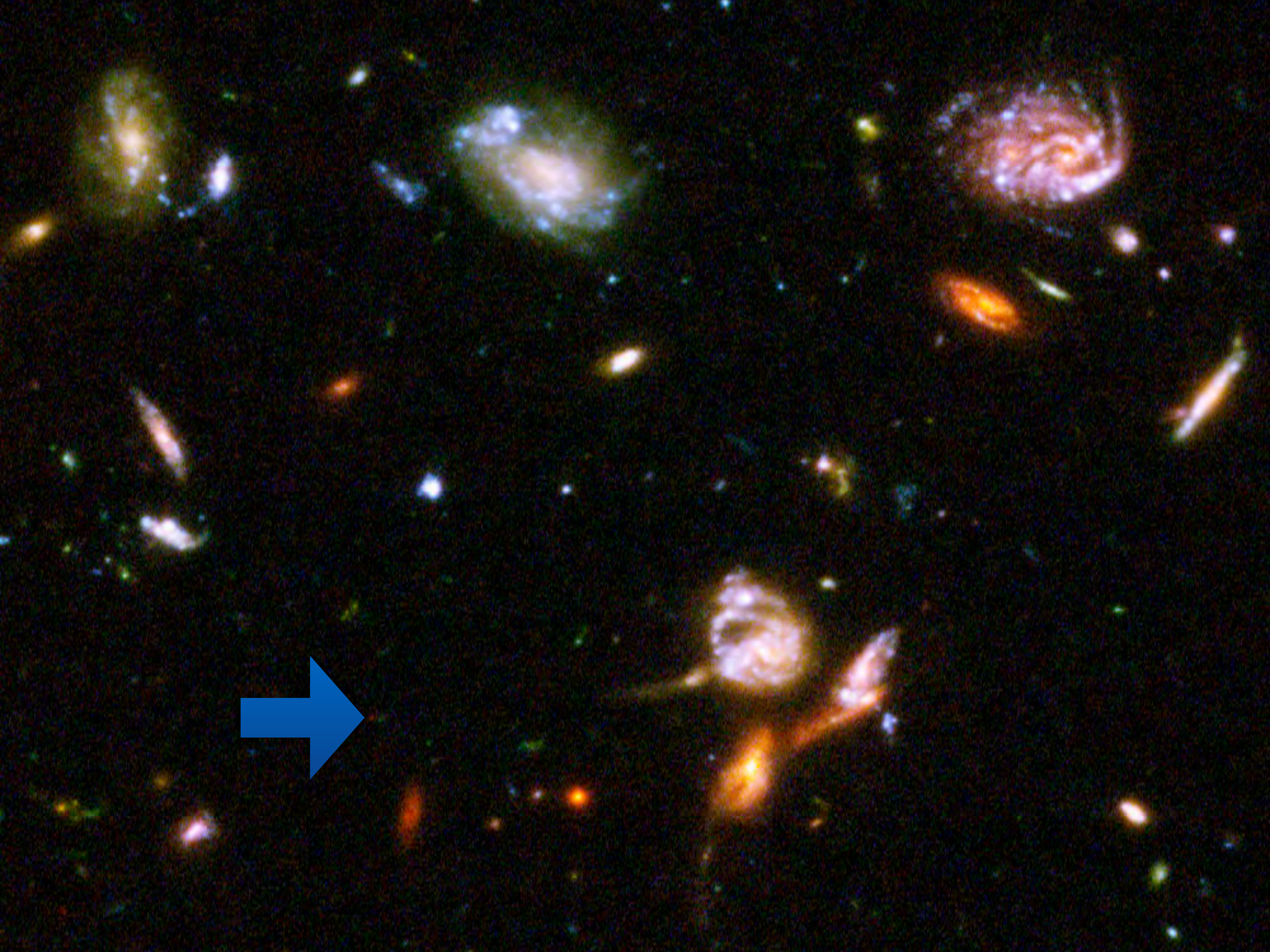


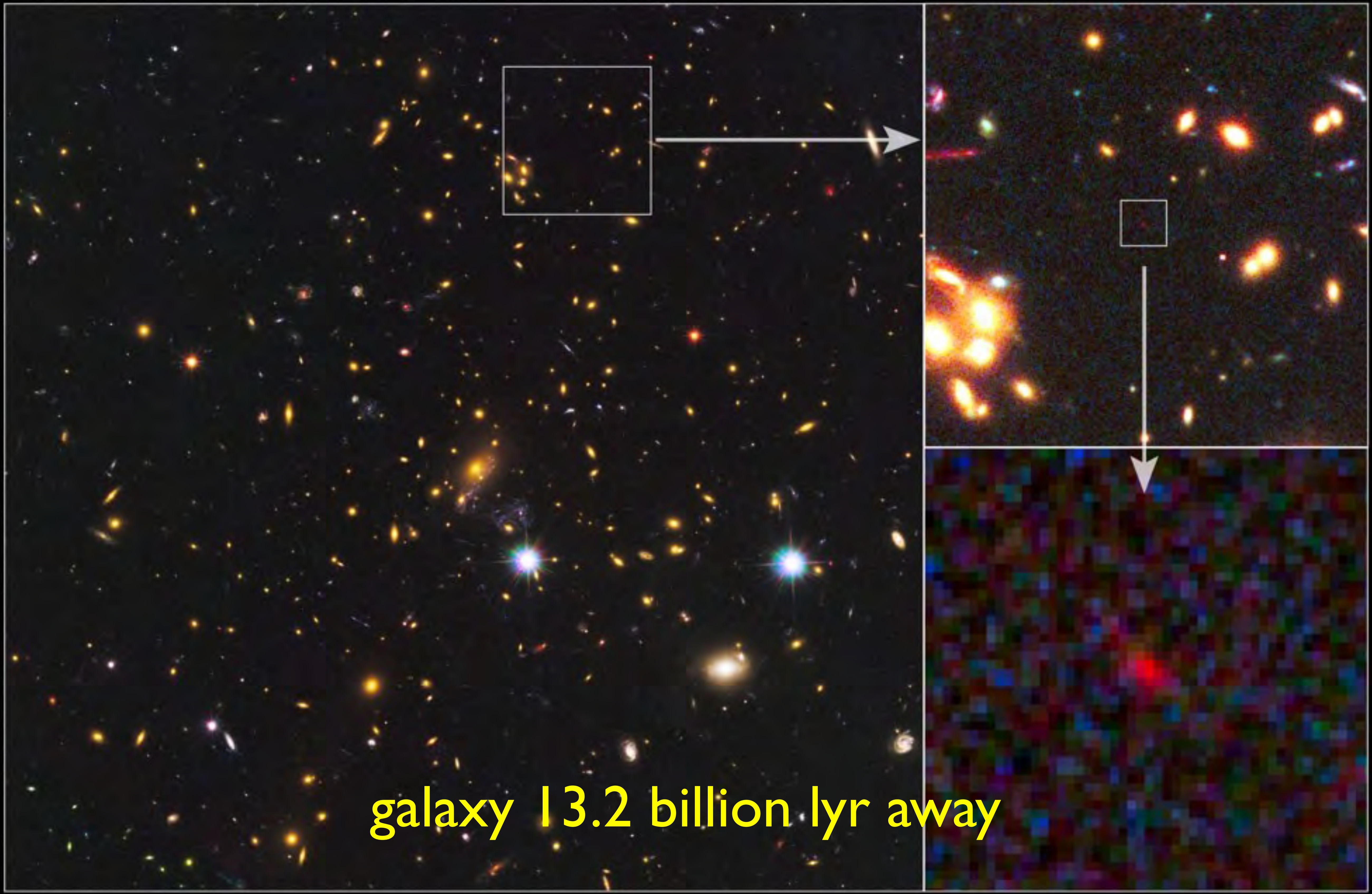
4 billion lyr away

Dark Matter

fly-through based on SDSS-III data


2 billion lyr
16h
8h
20 billion lyr
nearly homogeneous
small winkles
0.02
0.04
0.06
0.08
0.10
0.12
0.14
Redshift z
20h
2 billion lyr
4h





Galaxy Cluster MACS J1149+2223

High-Redshift Galaxy MACS1149-JD

A Distant Gravitationally-Lensed Galaxy at Redshift = 9.6

NASA / ESA / STScI/ J. Hora (Harvard-Smitsonian CfA)

Hubble Space Telescope • ACS • WFC3

ssc2012-12a

dark ages
13.6 billion lyr away

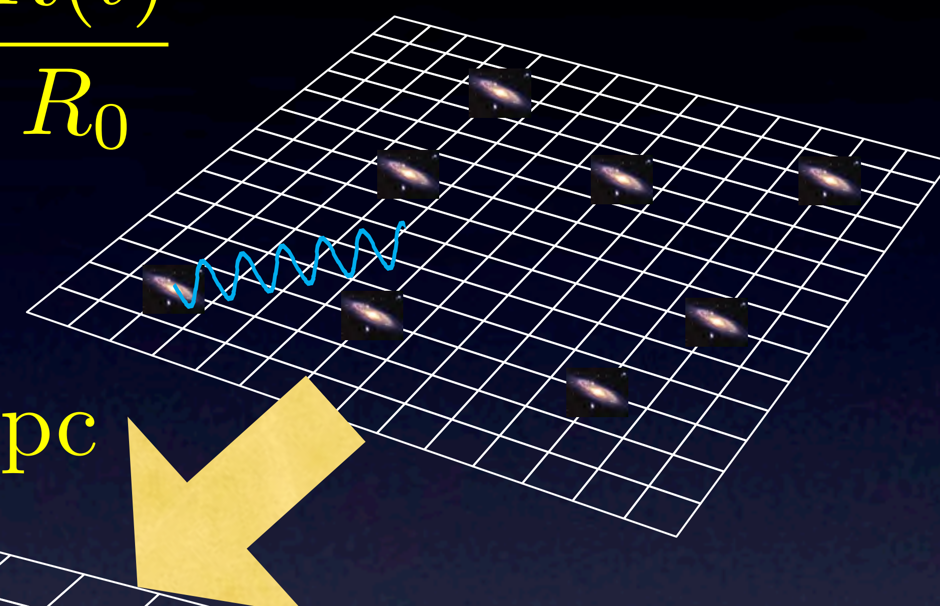
Expanding space

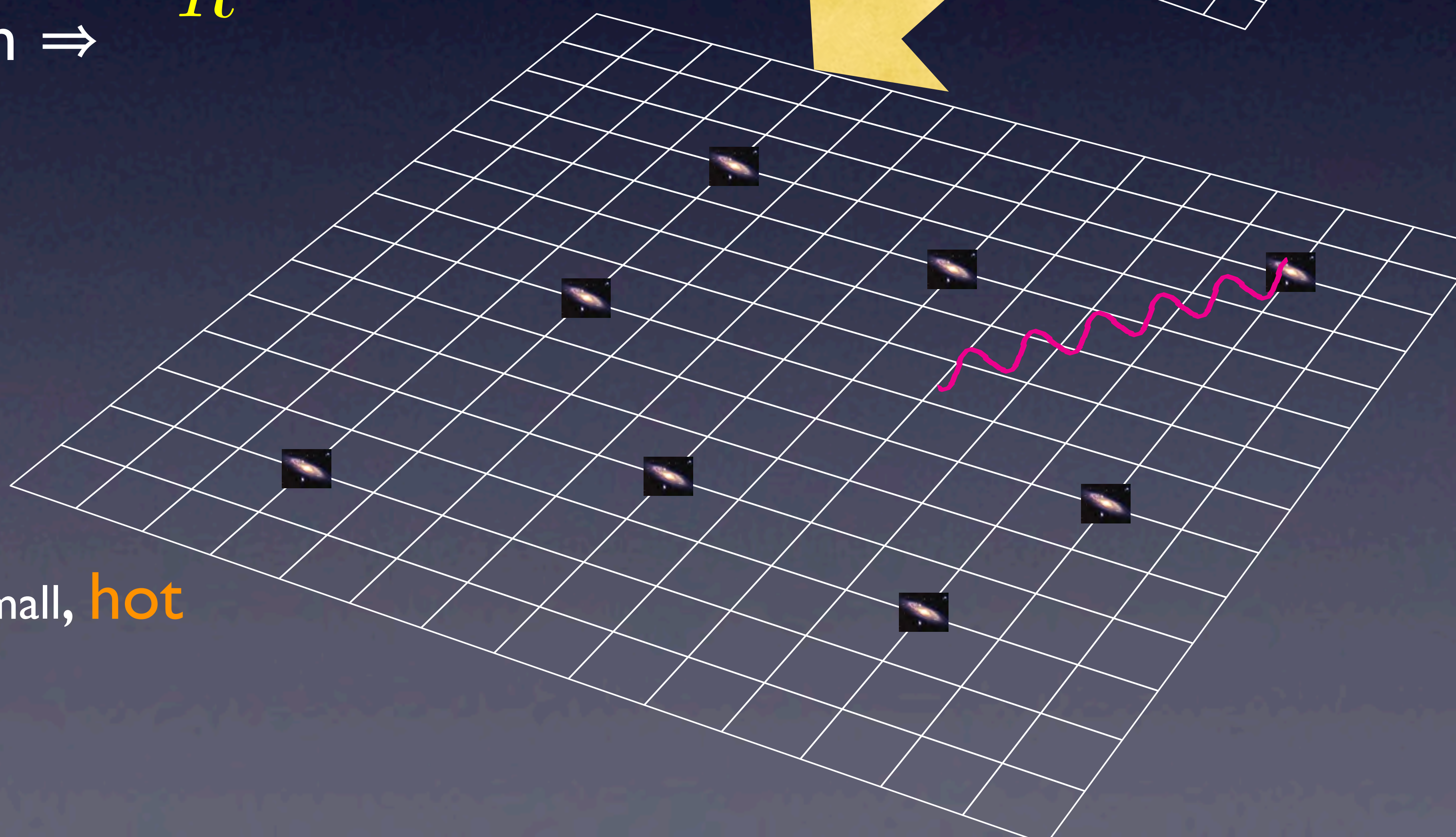
$$d = d_0 \frac{R(t)}{R_0} \qquad \dot{d}(t) = d_0 \frac{\dot{R}(t)}{R_0}$$

$$\dot{d} = d_0 \frac{\dot{R}}{R_0} = H_0 d$$

$$H_0 = \frac{\dot{R}}{R} = 71 \mathrm{km/s/Mpc}$$

- Hubble law: $v = H_0 d$
- $\lambda = \lambda_0(1+z)$
- z: redshift = R_0/R
- adiabatic expansion ⇒ $T \propto R^{-1}$
- $T = T_0(1+z)$
- bigger and colder

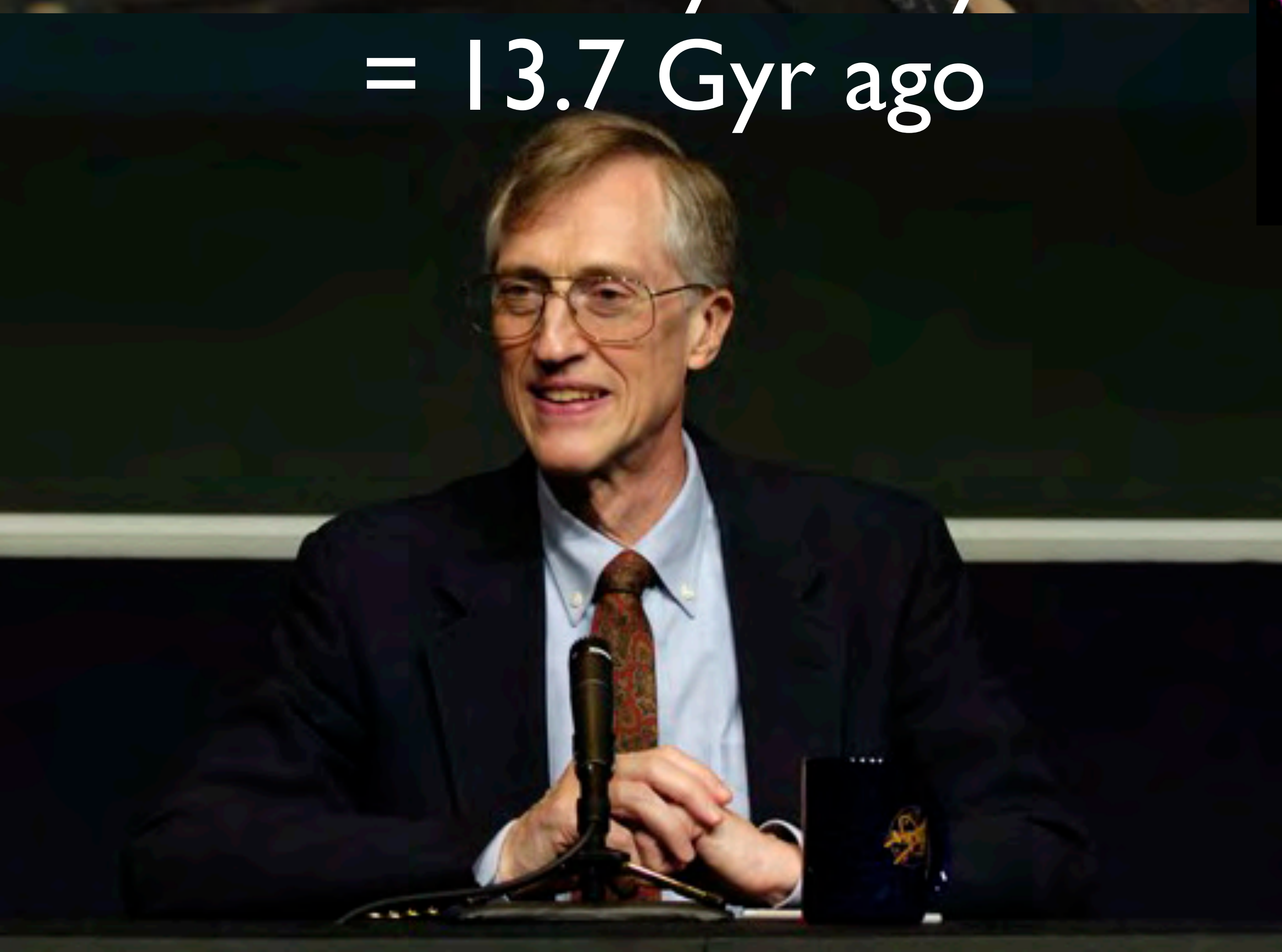




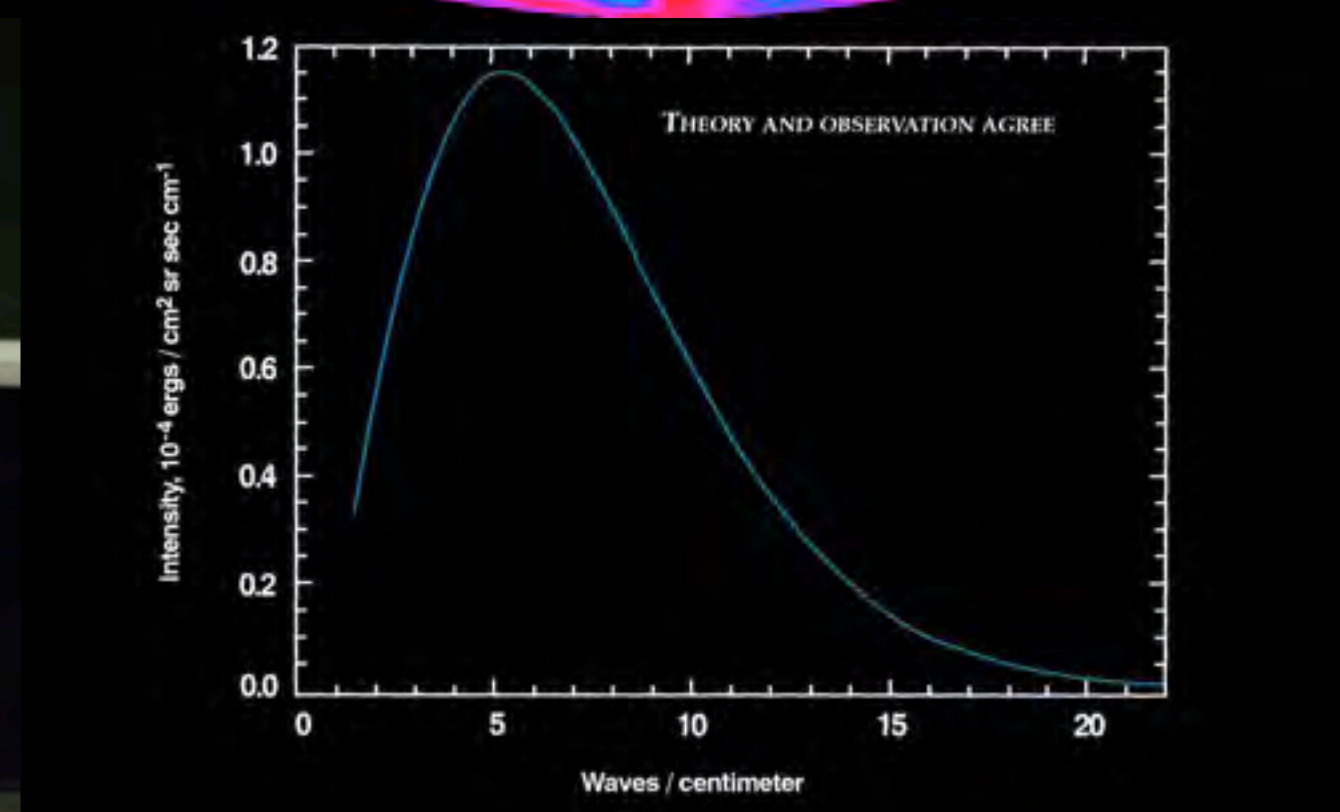
- Universe started small, hot

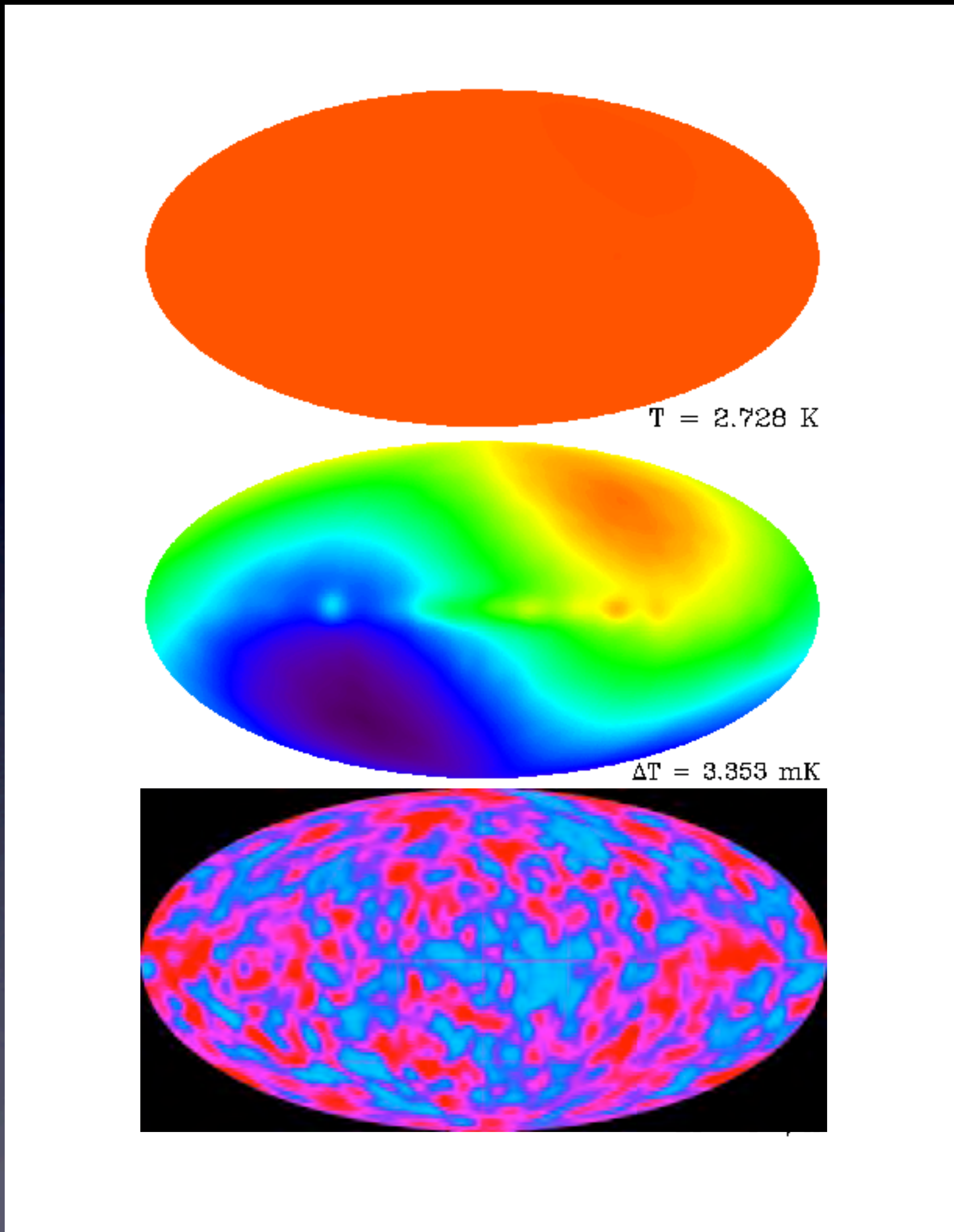
Big Bang!

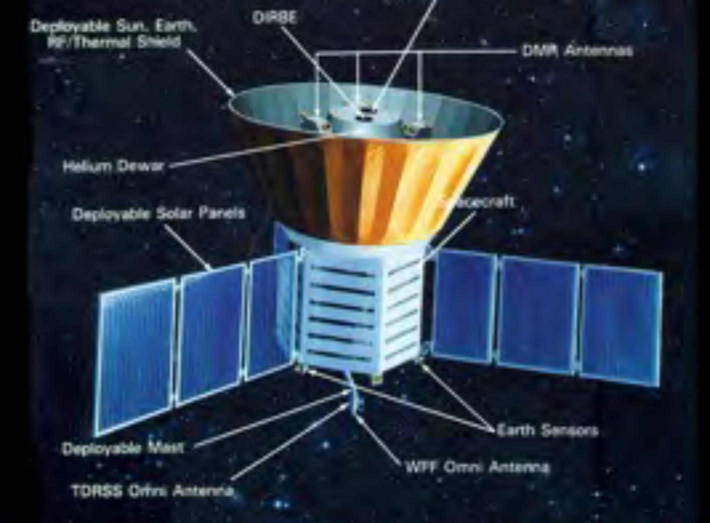
13.7 G lyr away
= 13.7 Gyr ago



You can still see the Big Bang





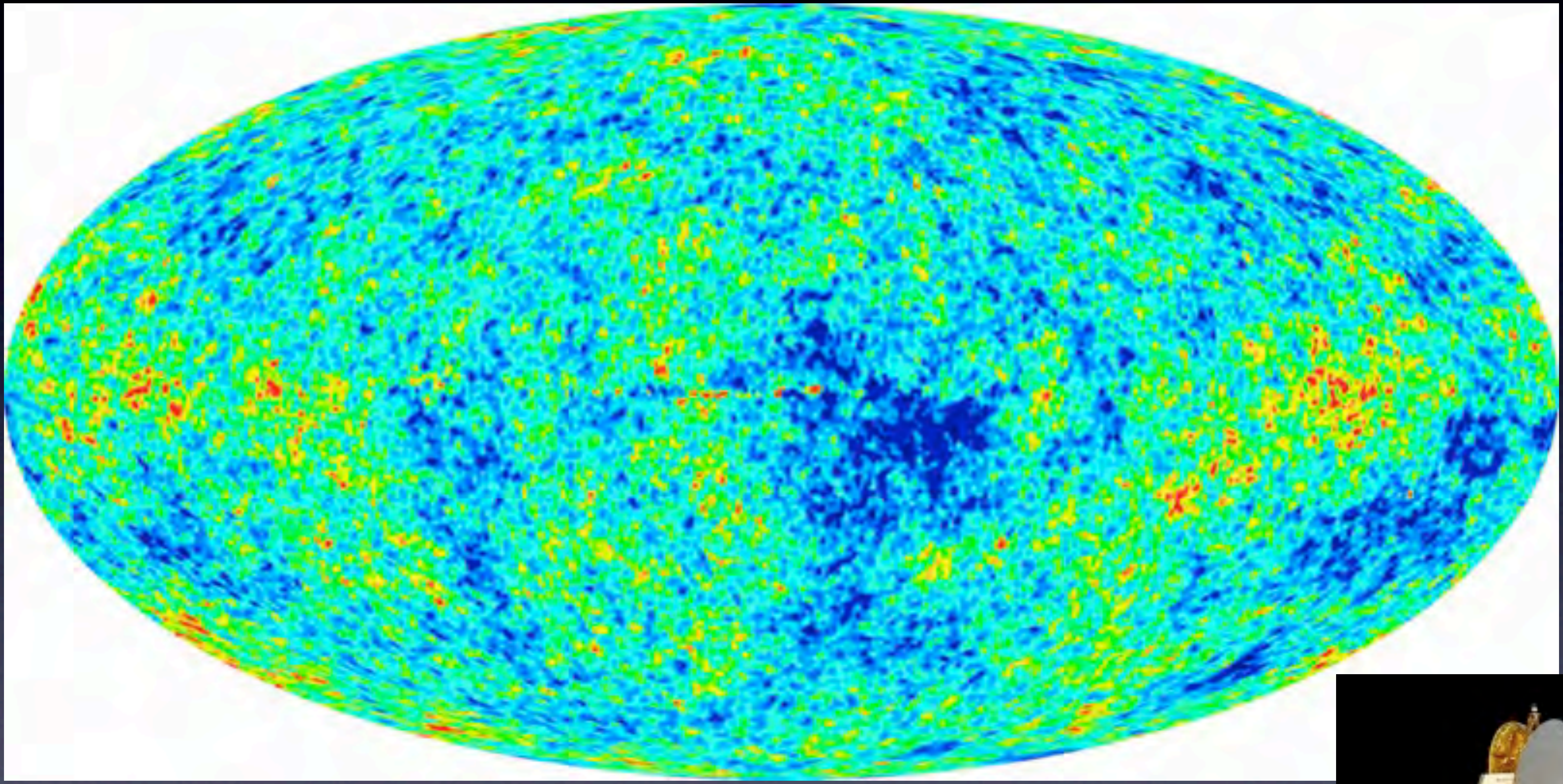


CMB temperature

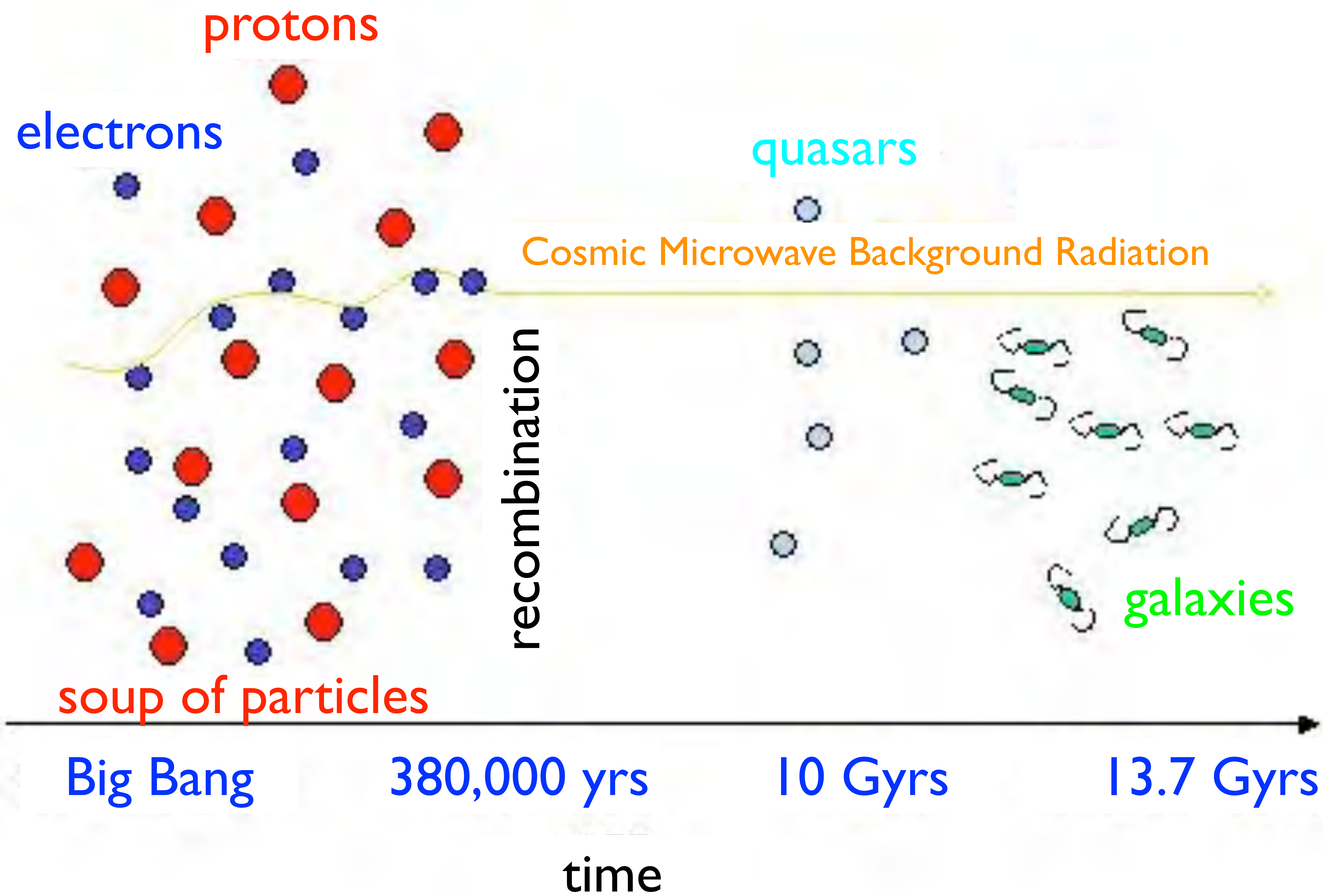
CMB dipole
we are moving at
~1% of *c* relative to CMB

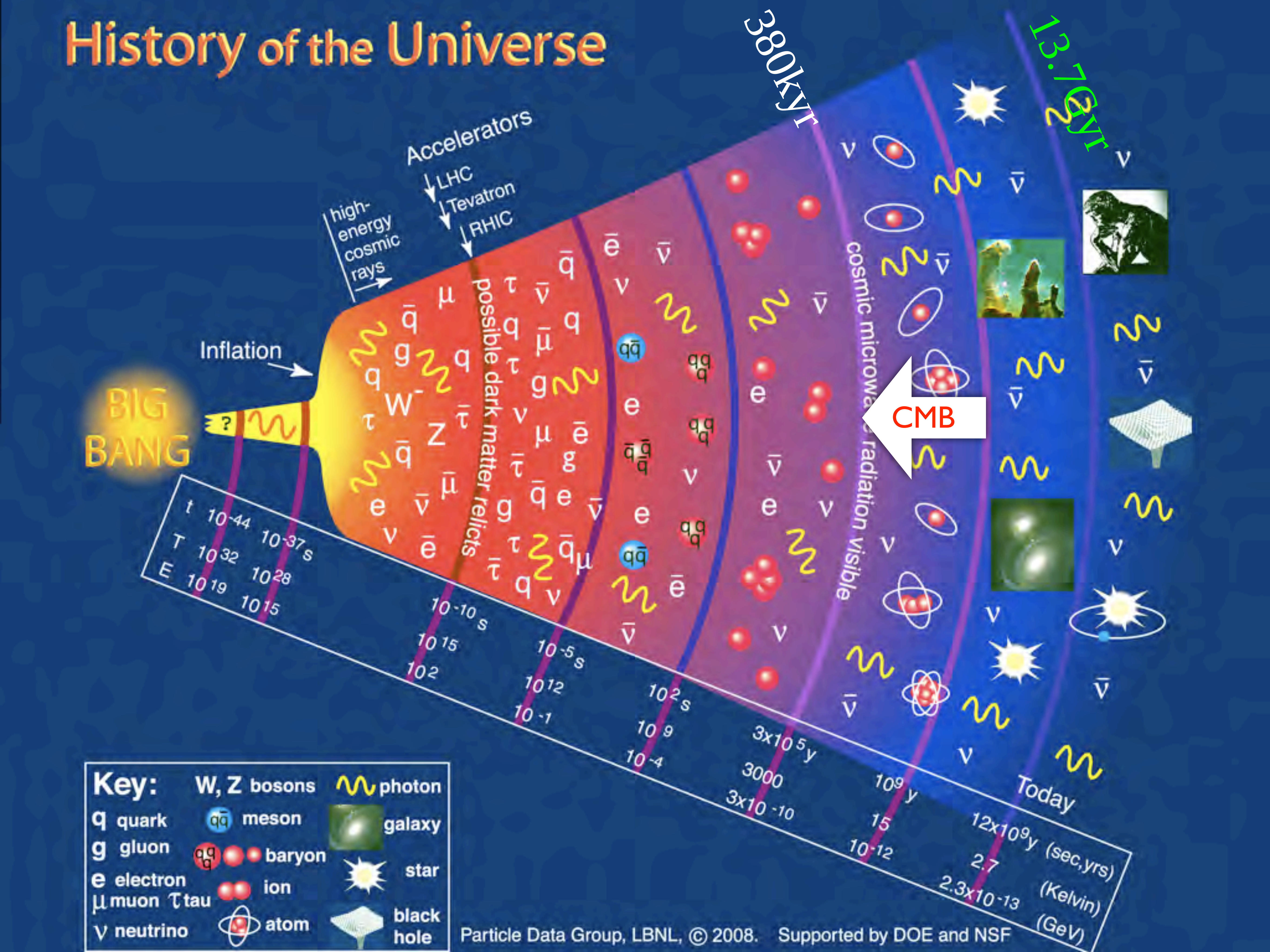
CMB anisotropy
at ~10^{-5}
1mm ripple on 100m sea

wall @ 13.7Glyr away



You can never see beyond this wall
using light


protons
electrons
quasars
Cosmic Microwave Background Radiation
recombination
galaxies
soup of particles
Big Bang
380,000 yrs
10 Gyrs
13.7 Gyrs
time


History of the Universe
380kyr
13.7Gyr
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
CMB
t 10-44 10-37s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
star
μ muon τ tau
ion
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

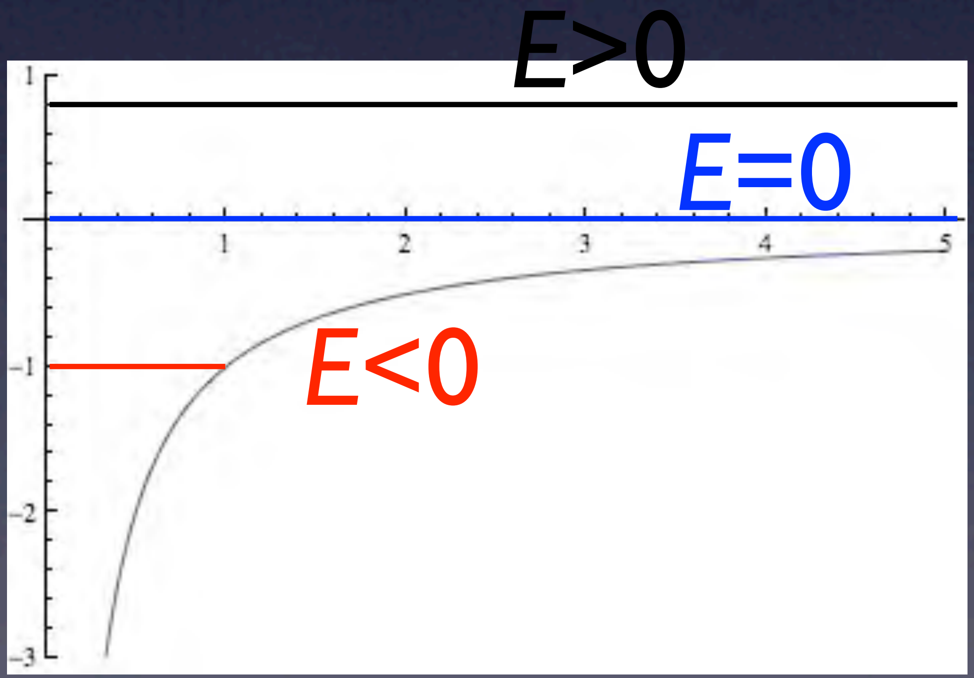

Friedmann Universe

Friedmann Equation

$$E = \frac{m}{2}\dot{R}^2 - G_N\left(\frac{4\pi}{3}\rho R^3\right)\frac{m}{R}$$

- "non-relativistic derivation"
- assume spherical distribution of mass density ρ
- *same as full relativistic equation with a curvature term*

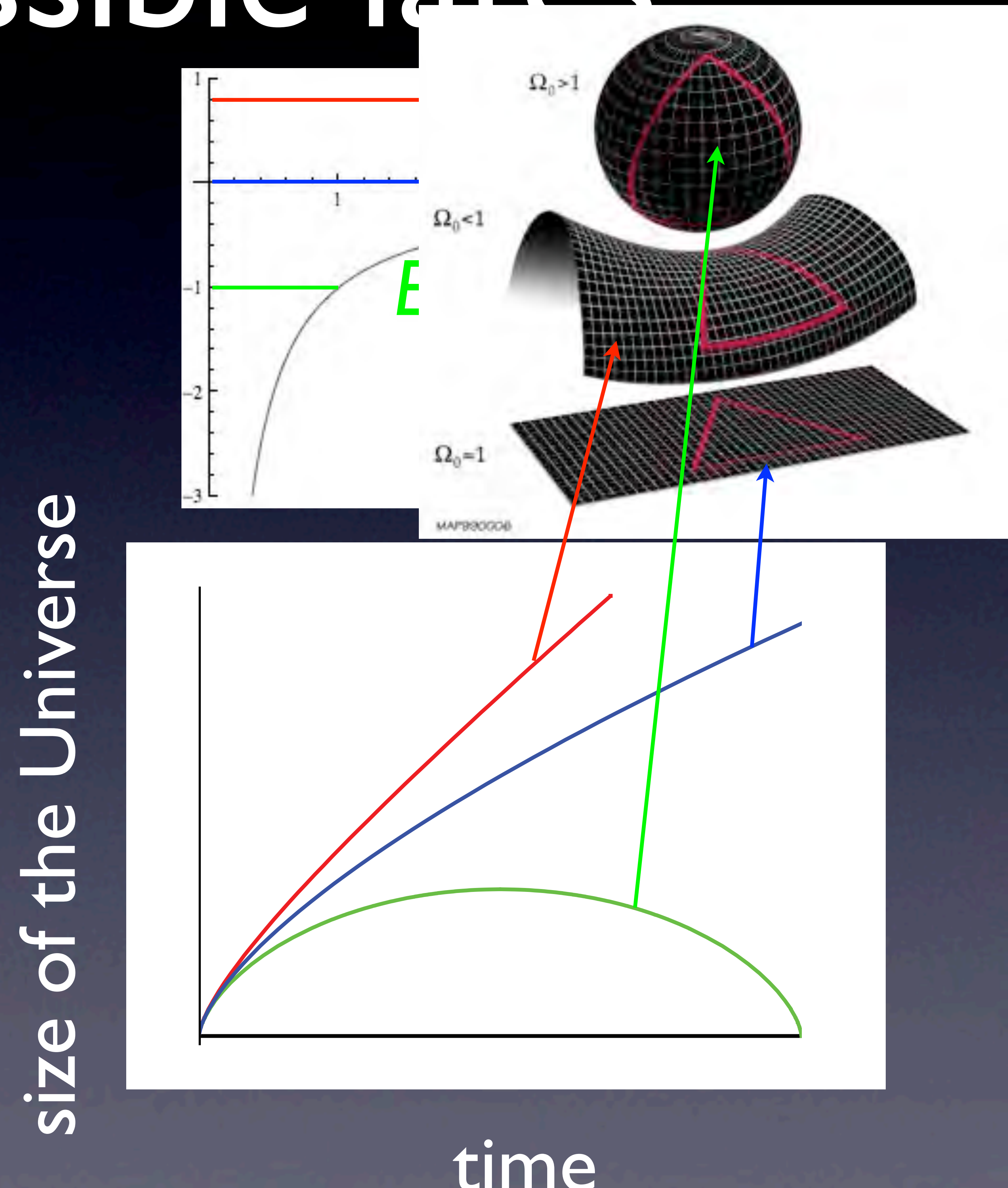
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G_N\rho - \text{const}$$



$$\frac{4\pi}{3}\rho R^3 = M$$

three possible fates

- depending on the "energy", there are three possible fates of the Universe
- adiabatic expansion ⇒ $T \propto R^{-1}$
- past universe was smaller and hotter
- "energy" corresponds to the *curvature* of space
- actually, it is *flat*



Current Universe

- knowing the l.h.s. tells us the current energy density
- l.h.s. = H_0^2 from Hubble law $v=H_0\, d$
- r.h.s. defines the *critical density* ρ_c

$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho - \cancel{\mathrm{const}}$$

$$H_0 = \frac{\dot{R}}{R} = 71\mathrm{km/s/Mpc}$$

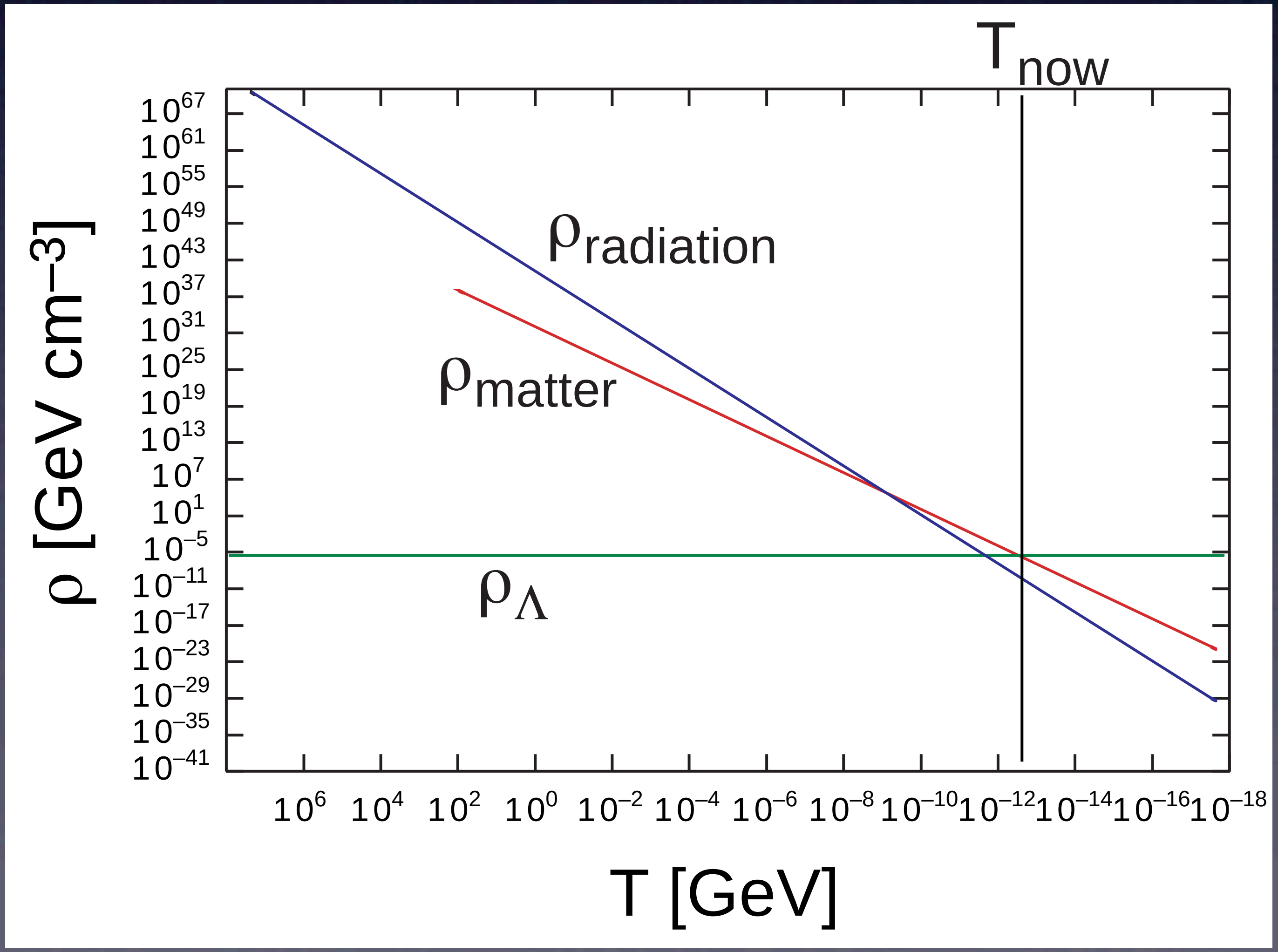
$$\rho_c = \frac{3}{8\pi} G + N^{-1} H_0^2 = 5.3 \times 10^{-6} \mathrm{GeV cm}^{-3}$$

- define $\Omega_i = \rho_i / \rho_c$
- $\Sigma_i\, \Omega_i = 1$

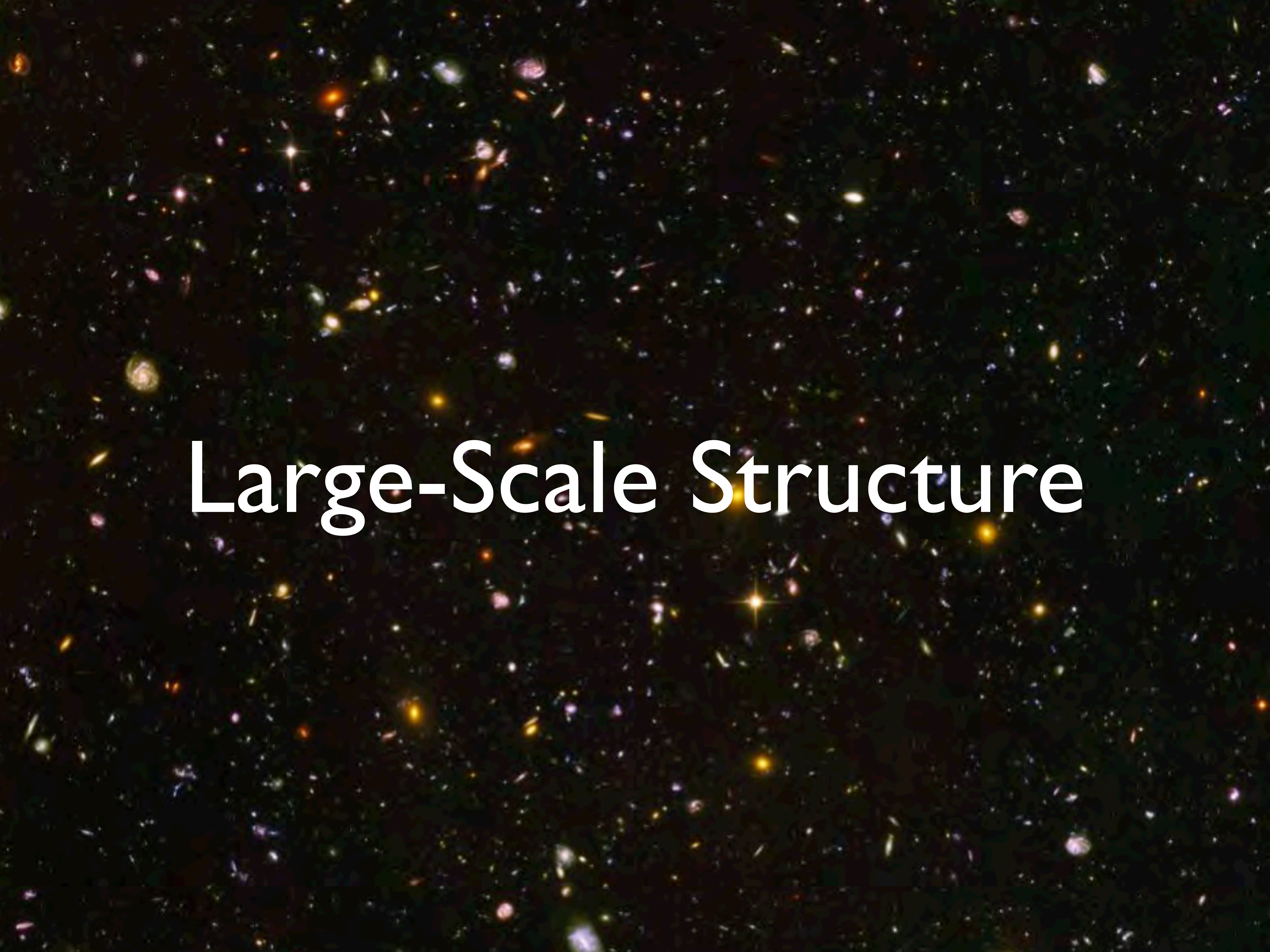
Early Universe

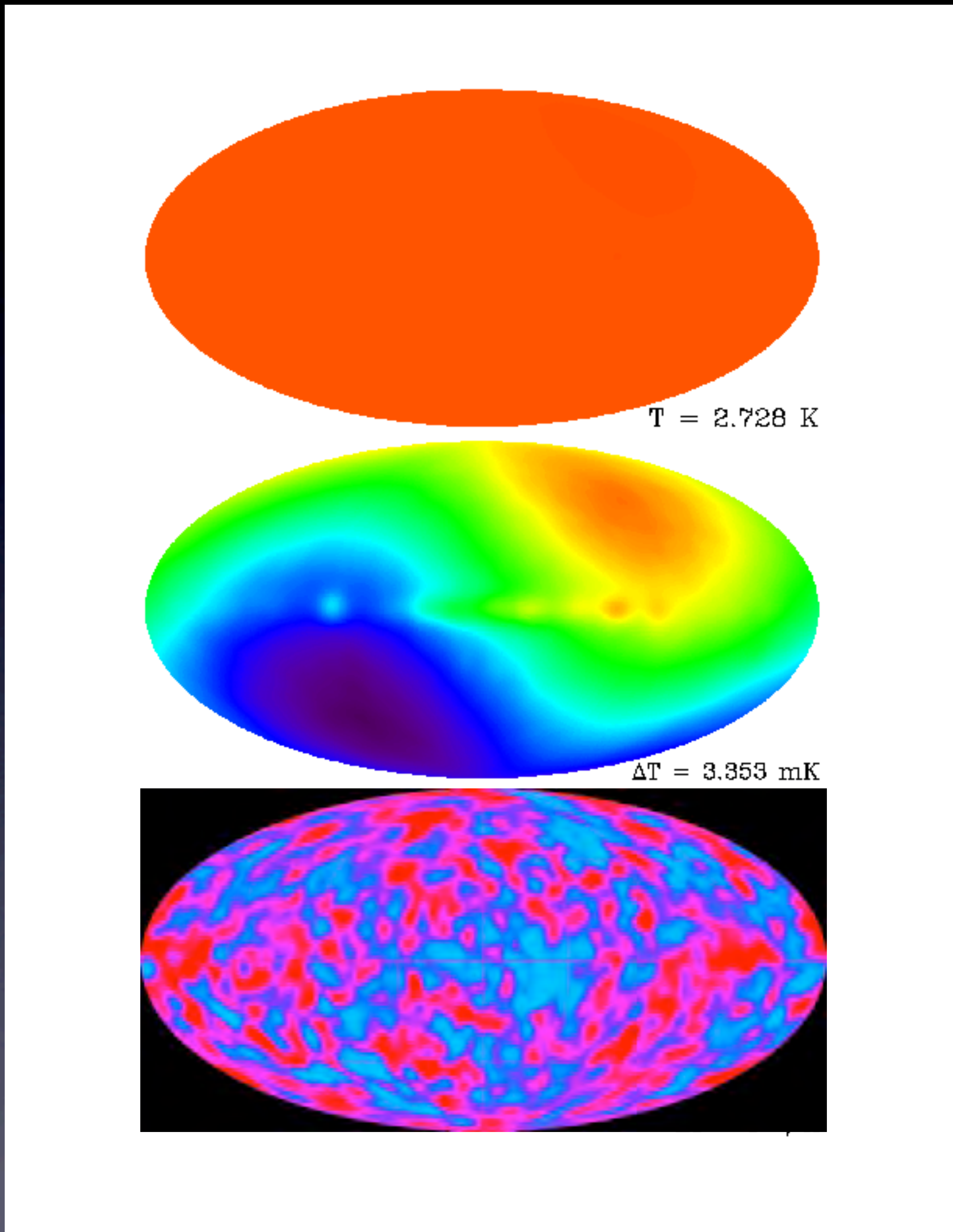
- adiabatic expansion ⇒ $T \propto R^{-1}$
- $T = T_0(1+z)$
- z: redshift = R_0/R
- $\lambda = \lambda_0(1+z)$
- matter: $\rho \propto R^{-3}$
- radiation (massless particles): $\rho \propto R^{-4}$
- matter-radiation equality: $z \approx 3300$
- recombination: $z \approx 1300$

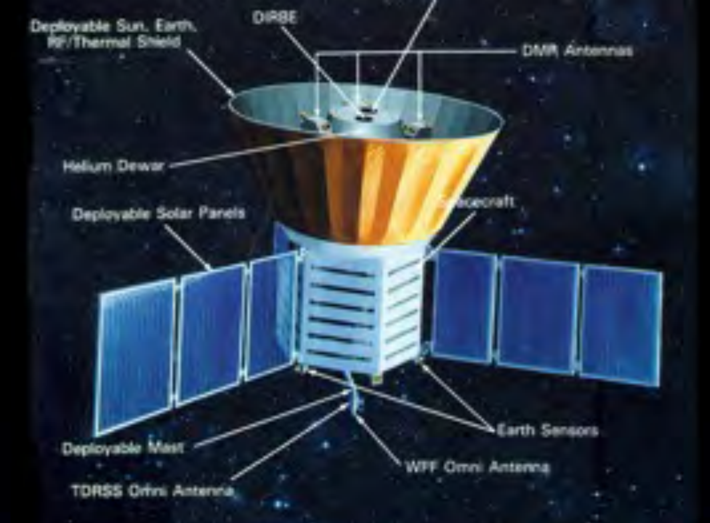
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho - \cancel{\text{const}}$$



Large-Scale Structure





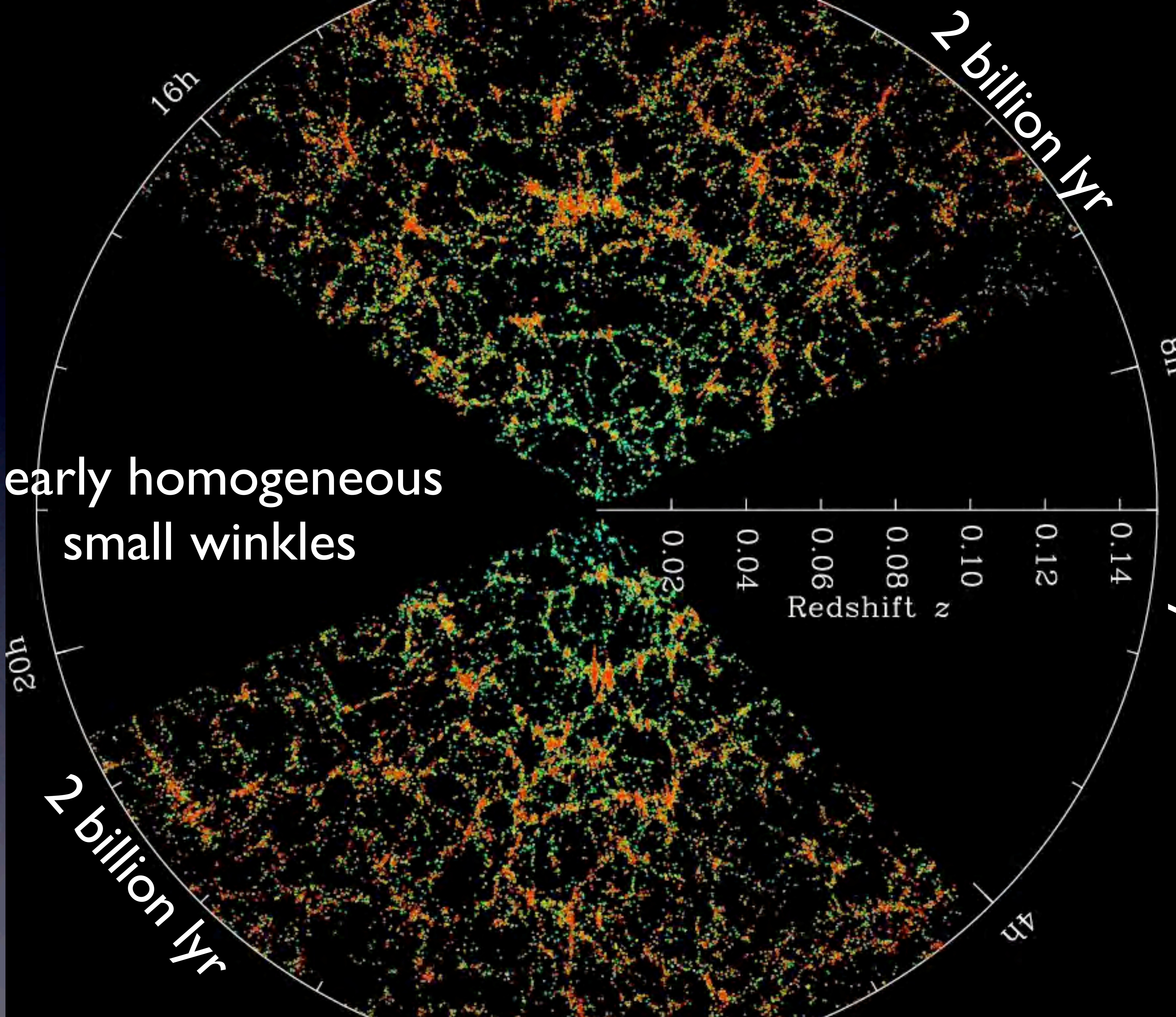


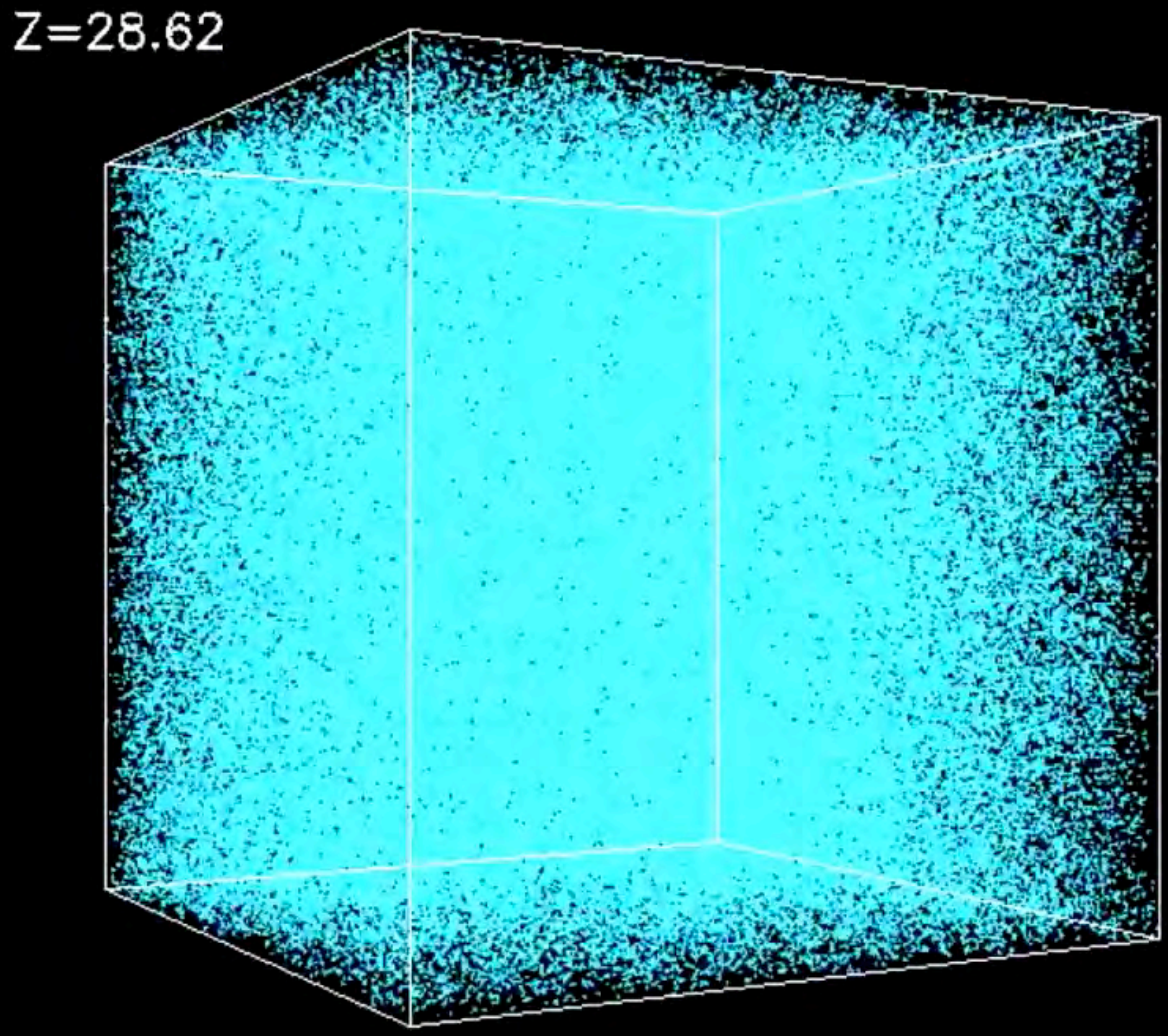
CMB temperature

CMB dipole
we are moving at
~1% of *c* relative to CMB

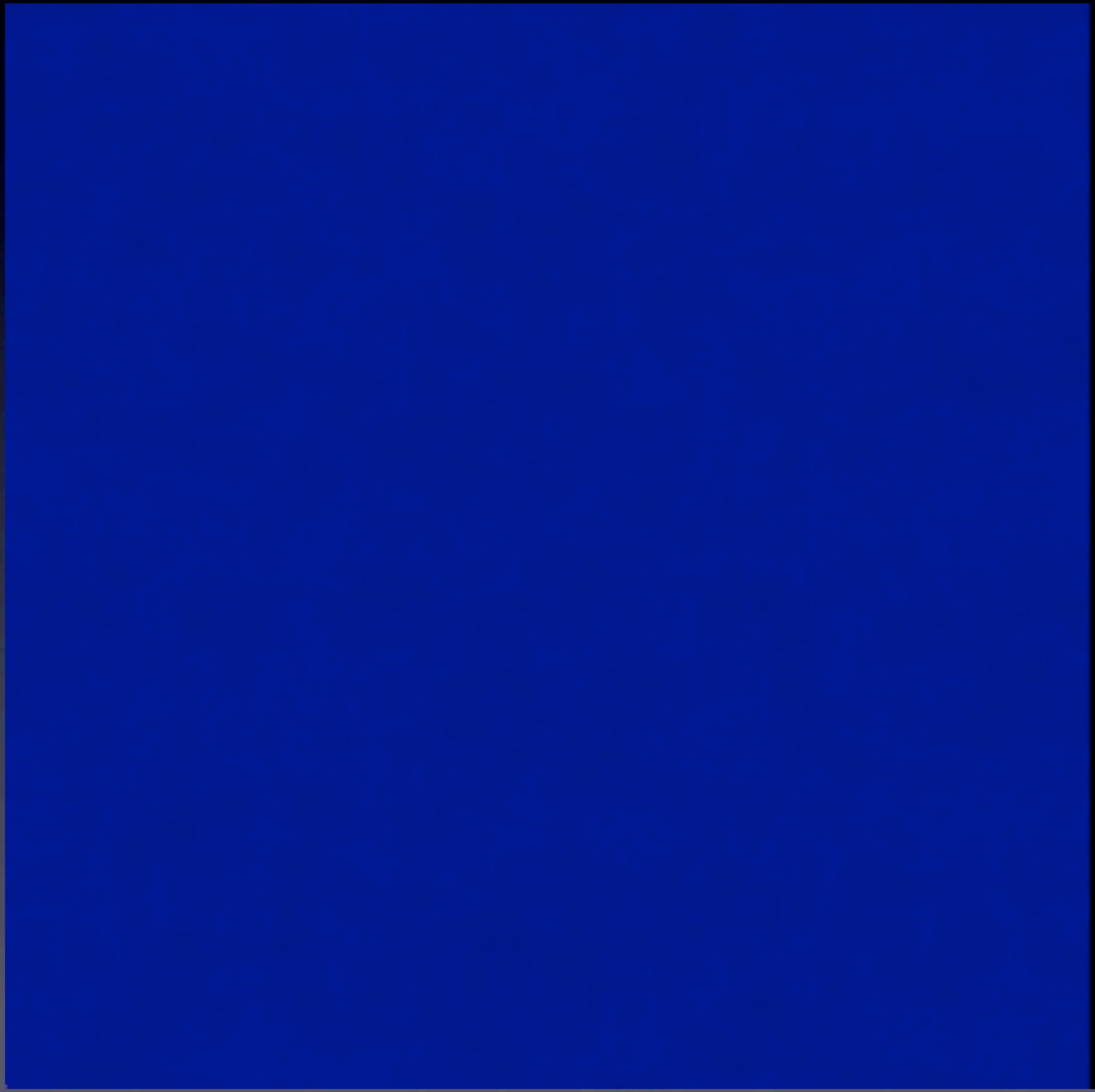
CMB anisotropy
at $\sim 10^{-5}$
1mm ripple on 100m sea

nearly homogeneous
small winkles

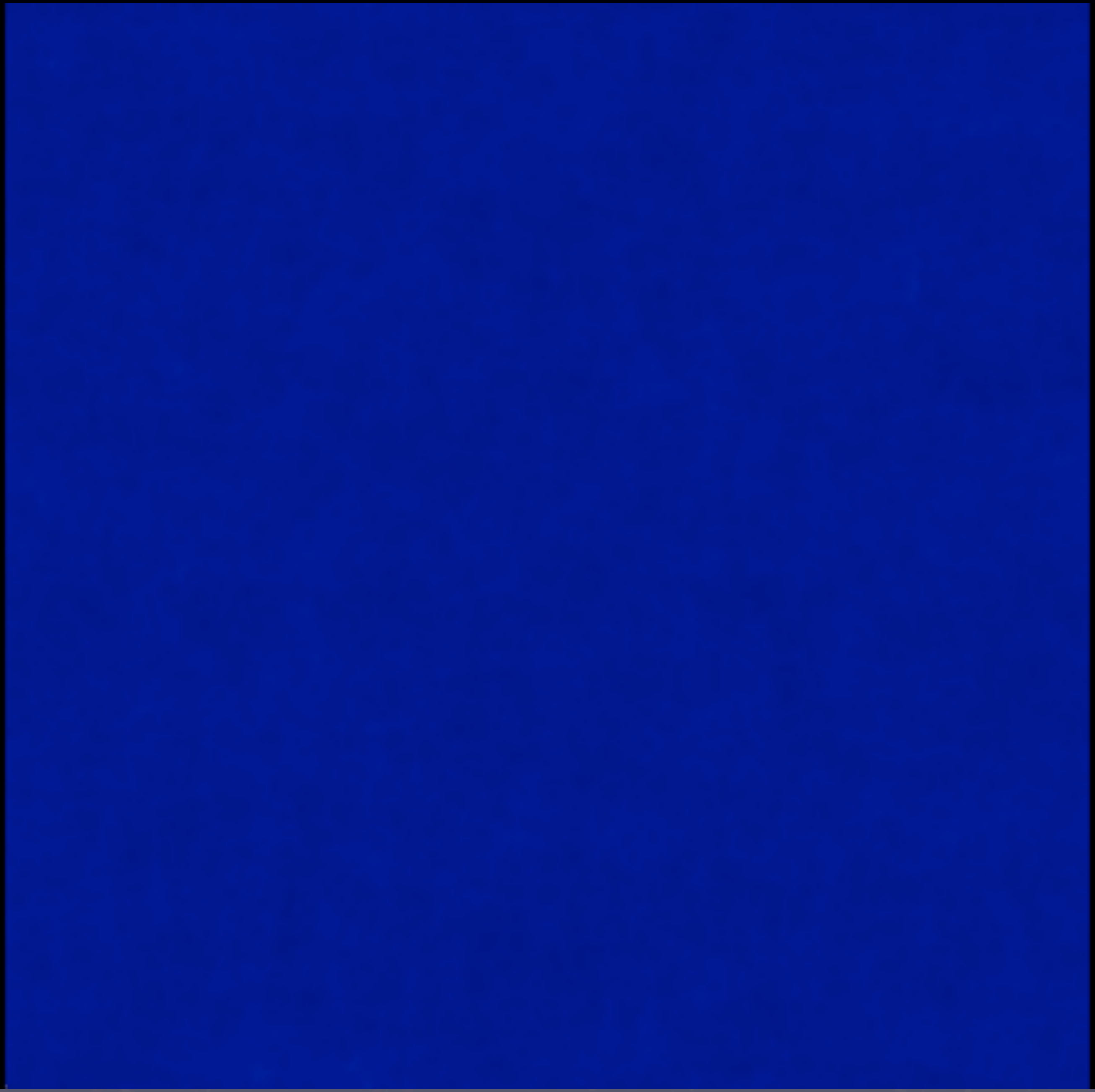



Z=28.62

Dark Matter is our birth mother

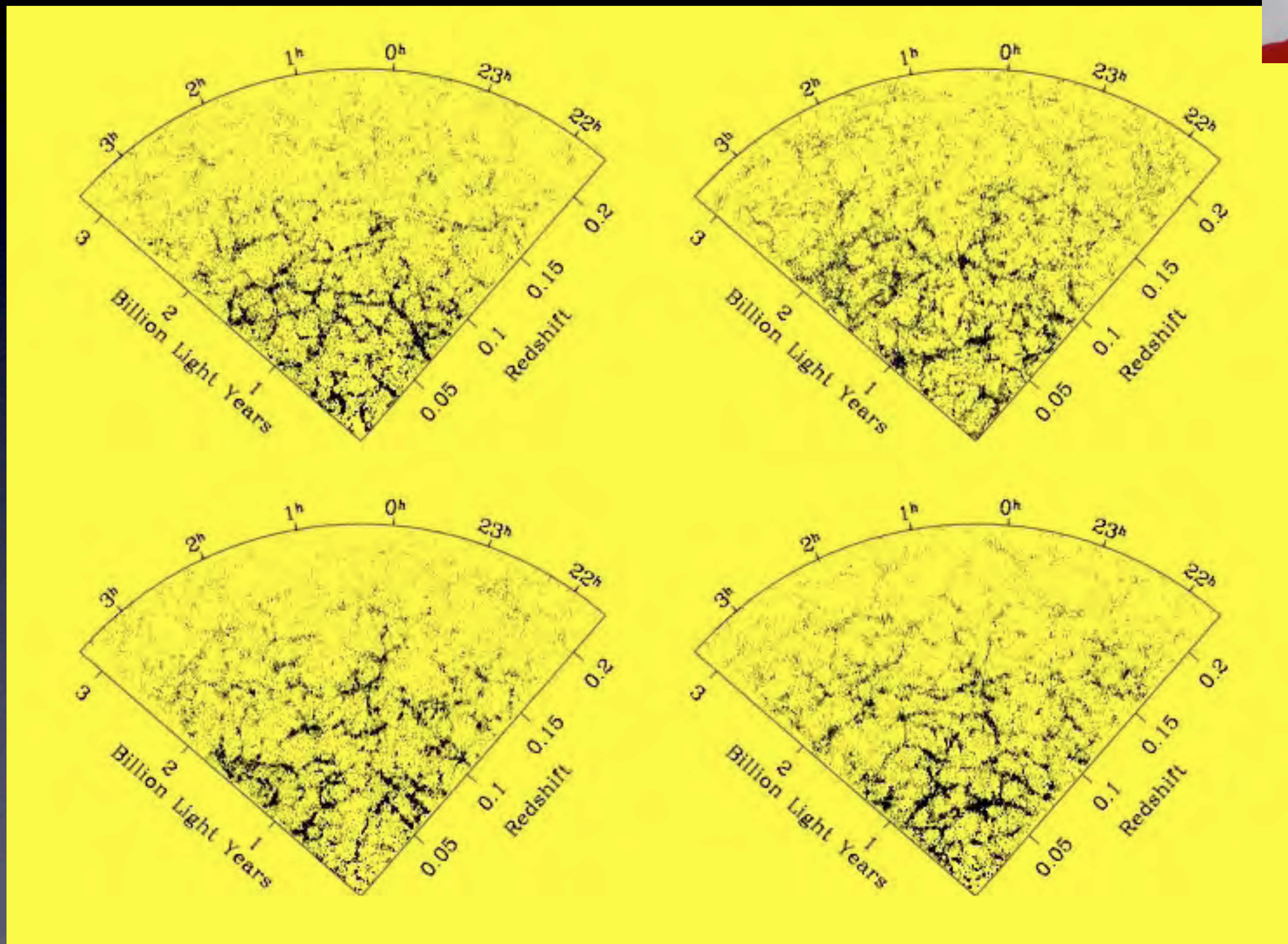


no dark matter



with dark matter

one is real


3h
2h
1h
0h
23h
22h
3
2
1
Billion Light Years
0.05
0.1
0.15
0.2
Redshift

reenacting Big Ban with Cal Band

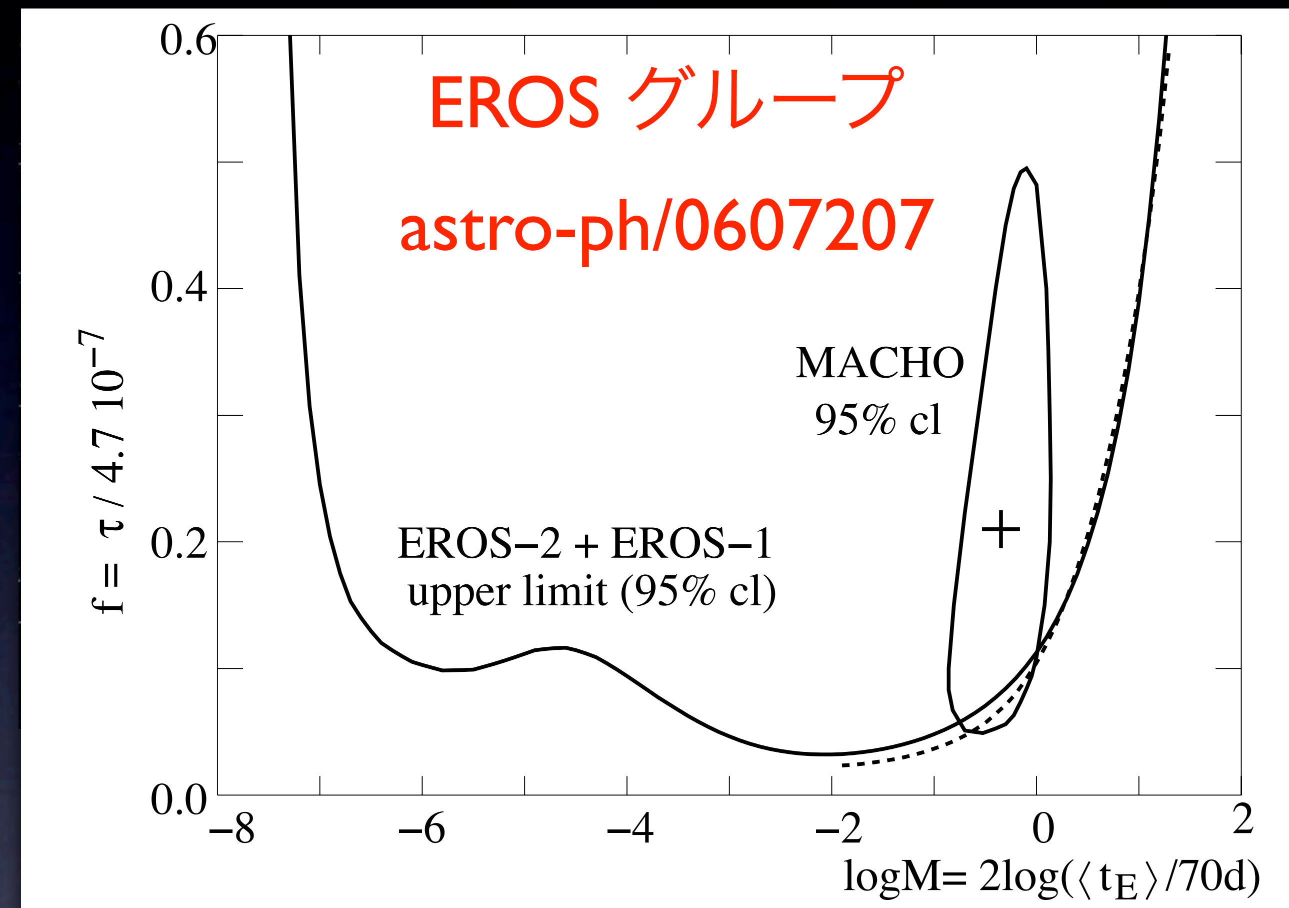
Known Facts about Dark Matter

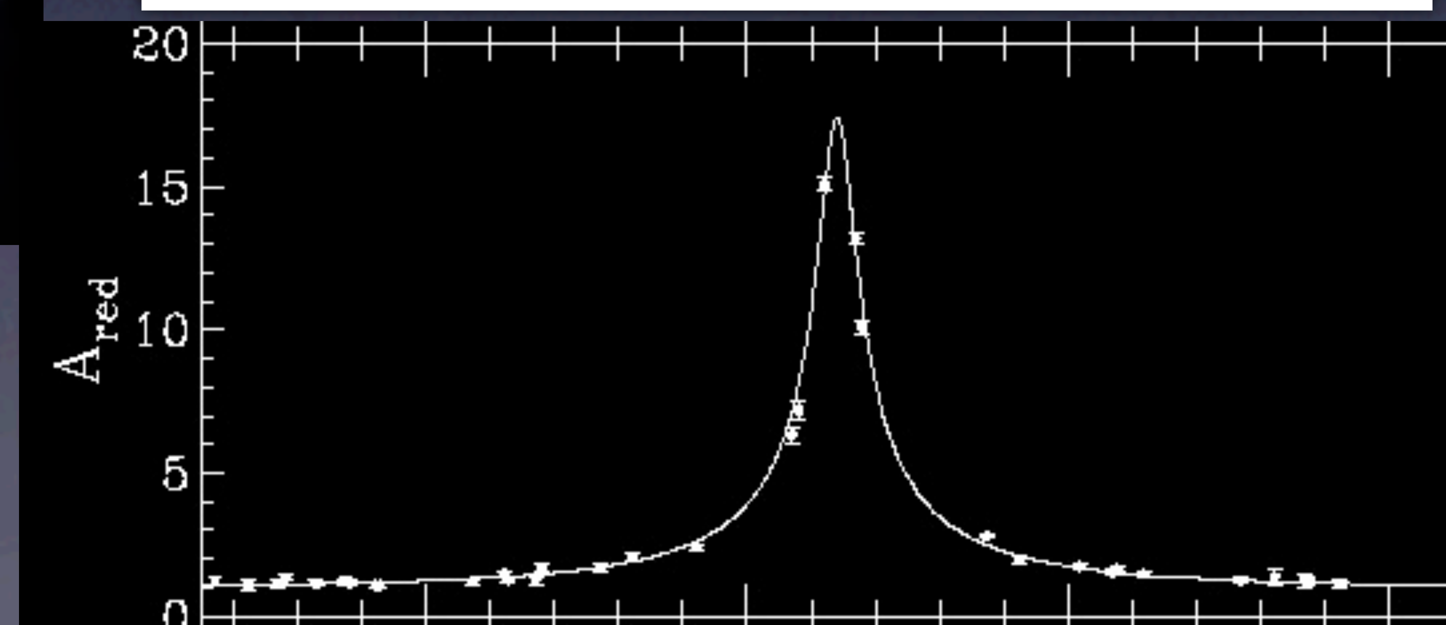
Cold and Neutral

- By the time of matter-radiation equality and until now, dark matter must be non-relativistic and clump together by gravitational attraction
- must be electrically neutral

Dim Stars?

Search for MACHOs
(Massive Compact Halo Objects)





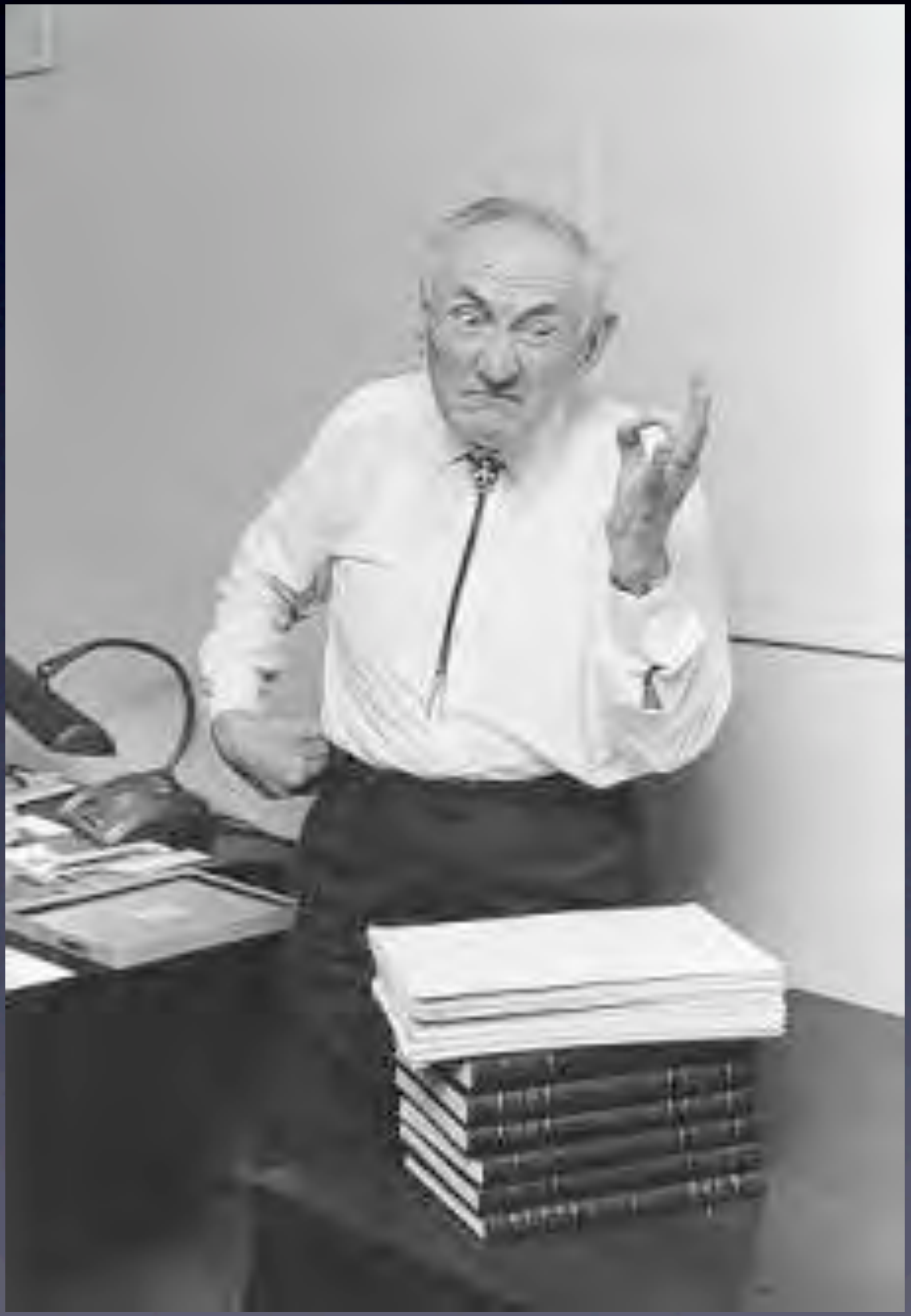
Not enough of them!

Mass Limits
"Uncertainty Principle"

- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
  (modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

Mass Limits

- 10^{-31} GeV to 10^{50} GeV
- we narrowed it down to within 81 orders of magnitude
- a big progress in 70 years since Zwicky



Self-Couplin

- if self-coupling too big, will “smooth out” cuspy profile at the galactic center
- some people want it

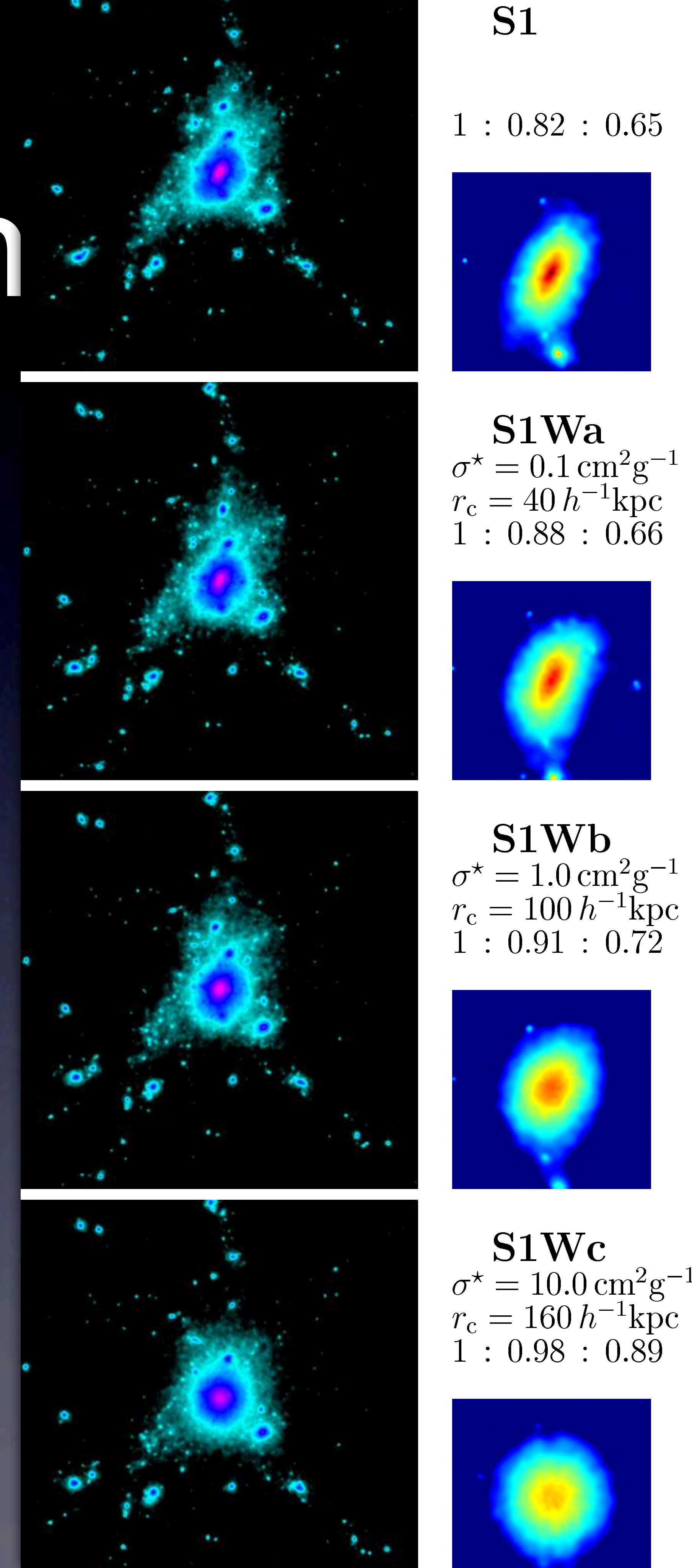
  (Spergel and Steinhardt, astro-ph/9909386)
- need core < 35 kpc/h from data

  $\sigma < 1.7 \times 10^{-25}$ cm^2 (m/GeV)

  (Yoshida, Springel, White, astro-ph/0006134)
- bullet cluster:

  $\sigma < 1.7 \times 10^{-24}$ cm^2 (m/GeV)

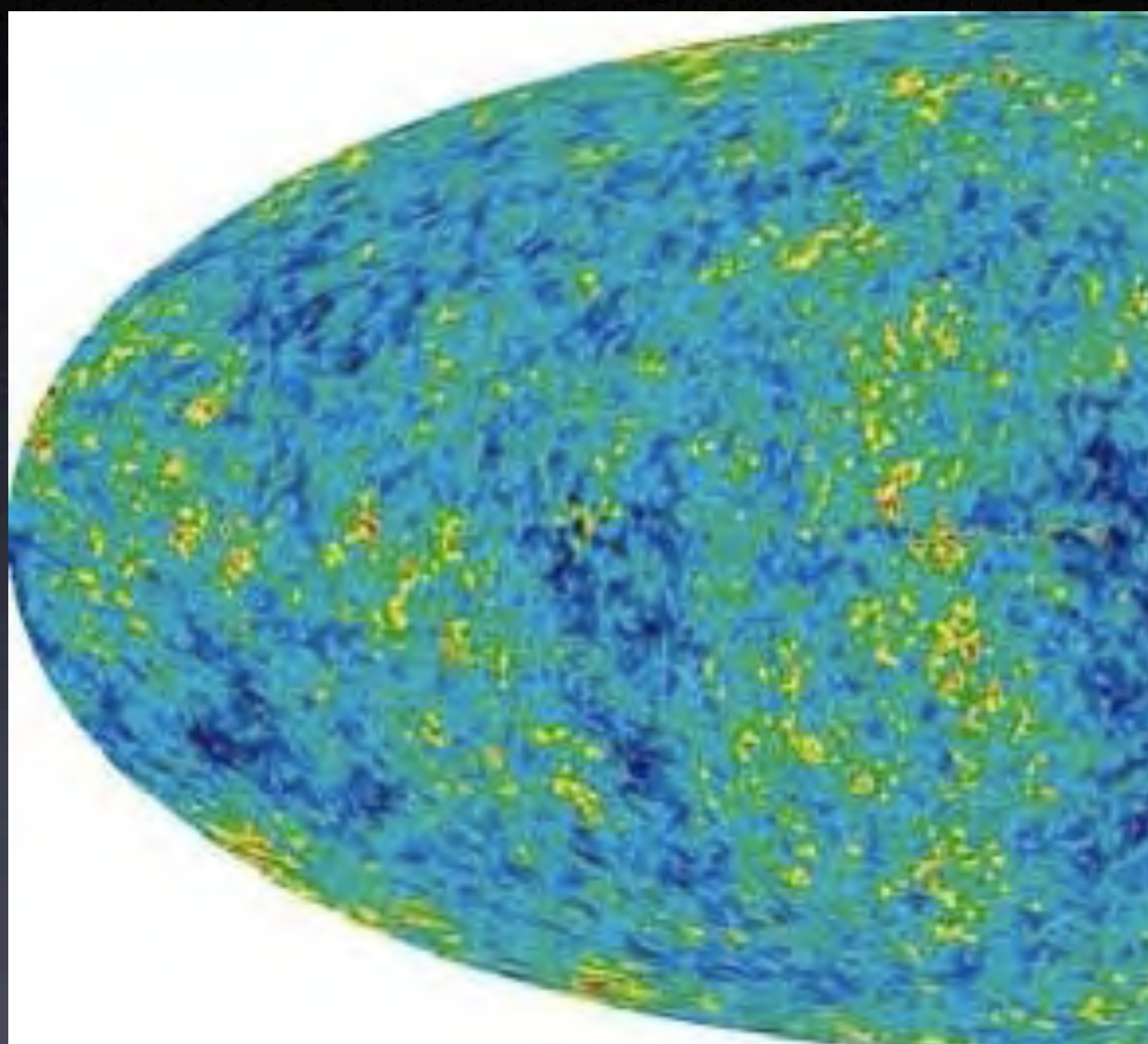
  (Markevitch et al, astro-ph/0309303)

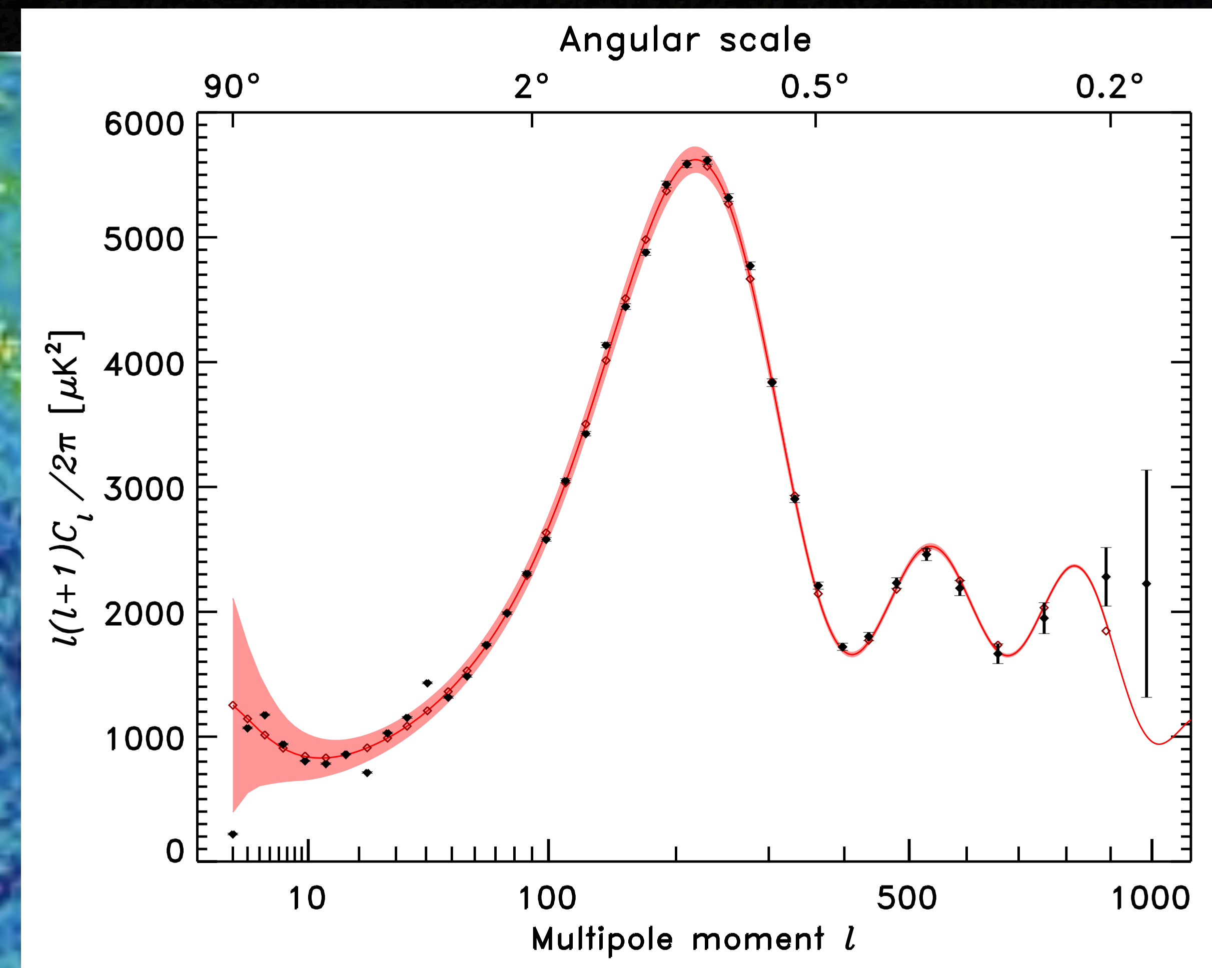


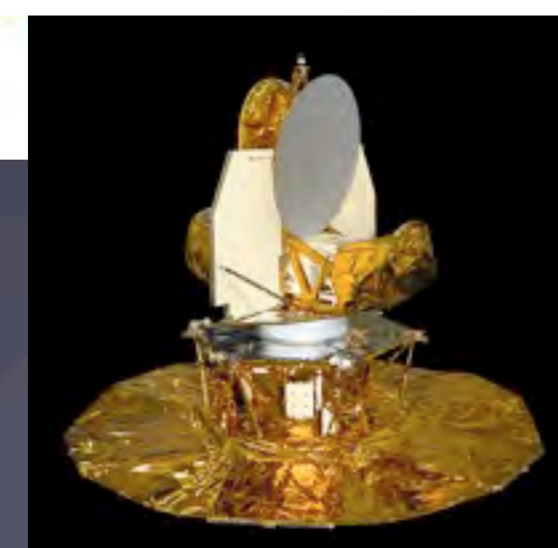
Lifetime

- At least of the order of age of the universe 14Gyr
- Beyond that, it depends on decay modes, branching fractions, all model-dependent

Cosmological scales





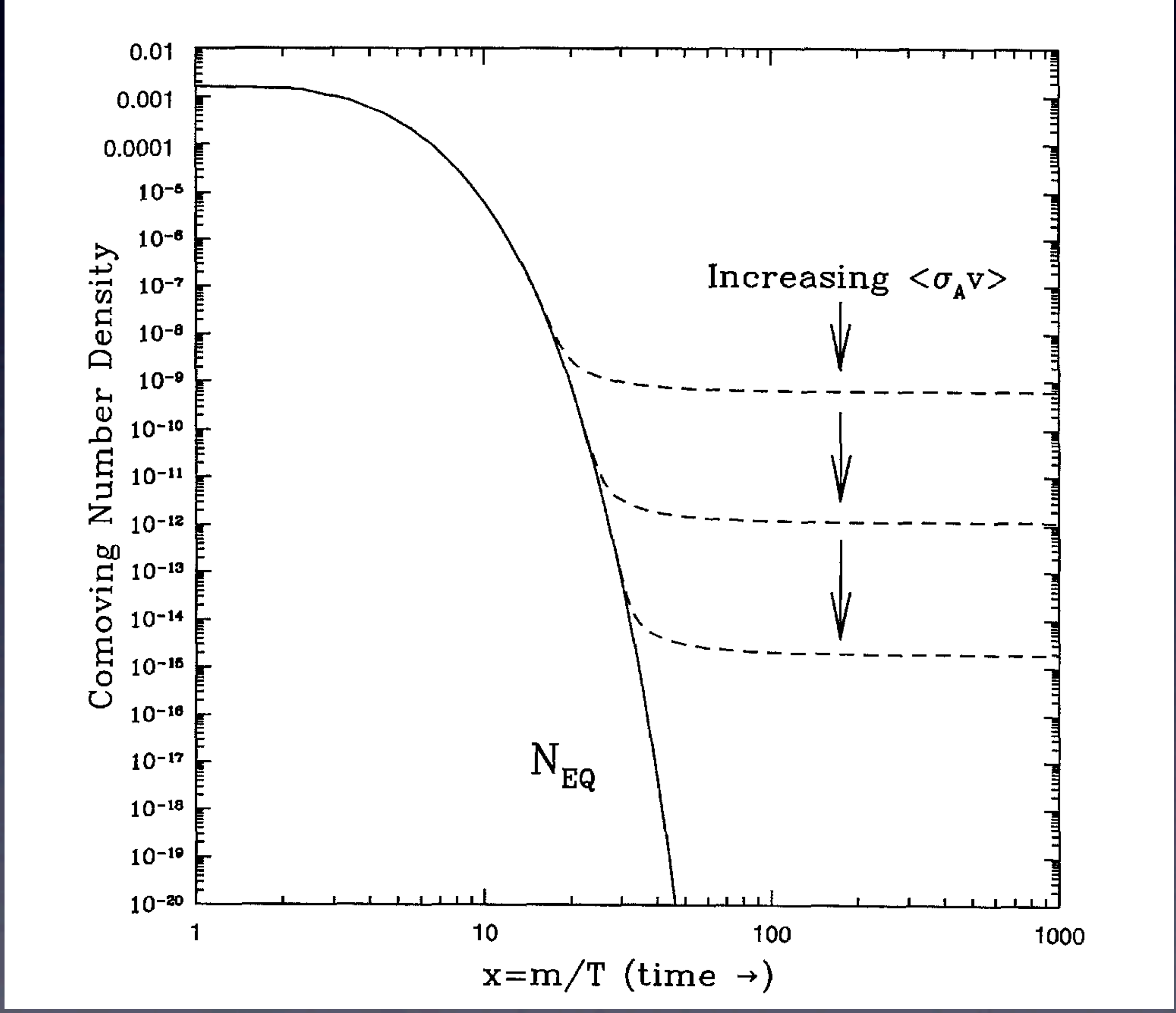


$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

WIMP paradigm

thermal relic

- thermal equilibrium when $T > m_\chi$
- Once $T < m_\chi$, no more χ created
- if stable, only way to lose them is annihilation
- but universe expands and χ get dilute
- at some point they can't find each other
- their number in comoving volume "frozen"



Freeze-out

- WIMP freezes out when the annihilation rate drops below the expansion rate
- Yield Y=n/s constant under expansion
- stronger annihilation ⇒ less abundance

$$H \approx g_*^{1/2} \frac{T^2}{M_{Pl}}$$

$$\Gamma_{\rm ann} \approx \langle \sigma_{\rm ann} v \rangle n$$

$$H(T_f) = \Gamma_{\rm ann}$$

$$n \approx g_*^{1/2} \frac{T_f^2}{M_{Pl} \langle \sigma_{\rm ann} v \rangle}$$

$$s \approx g_* T^3$$

$$Y = \frac{n}{s} \approx g_*^{-1/2} \frac{1}{M_{Pl} T_f \langle \sigma_{\rm ann} v \rangle}$$

$$\Omega_\chi = \frac{m_\chi Y s_0}{\rho_c}$$

$$\approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

Order of magnitude

- "Known" Ω_χ=0.23 determines the WIMP annihilation cross section
- simple estimate of the annihilation cross section
- weak-scale mass!!!

$$\Omega_\chi \approx g_*^{-1/2} \frac{x_f}{M_{Pl}^3 \langle \sigma_{\rm ann} v \rangle} \frac{s_0}{H_0^2}$$

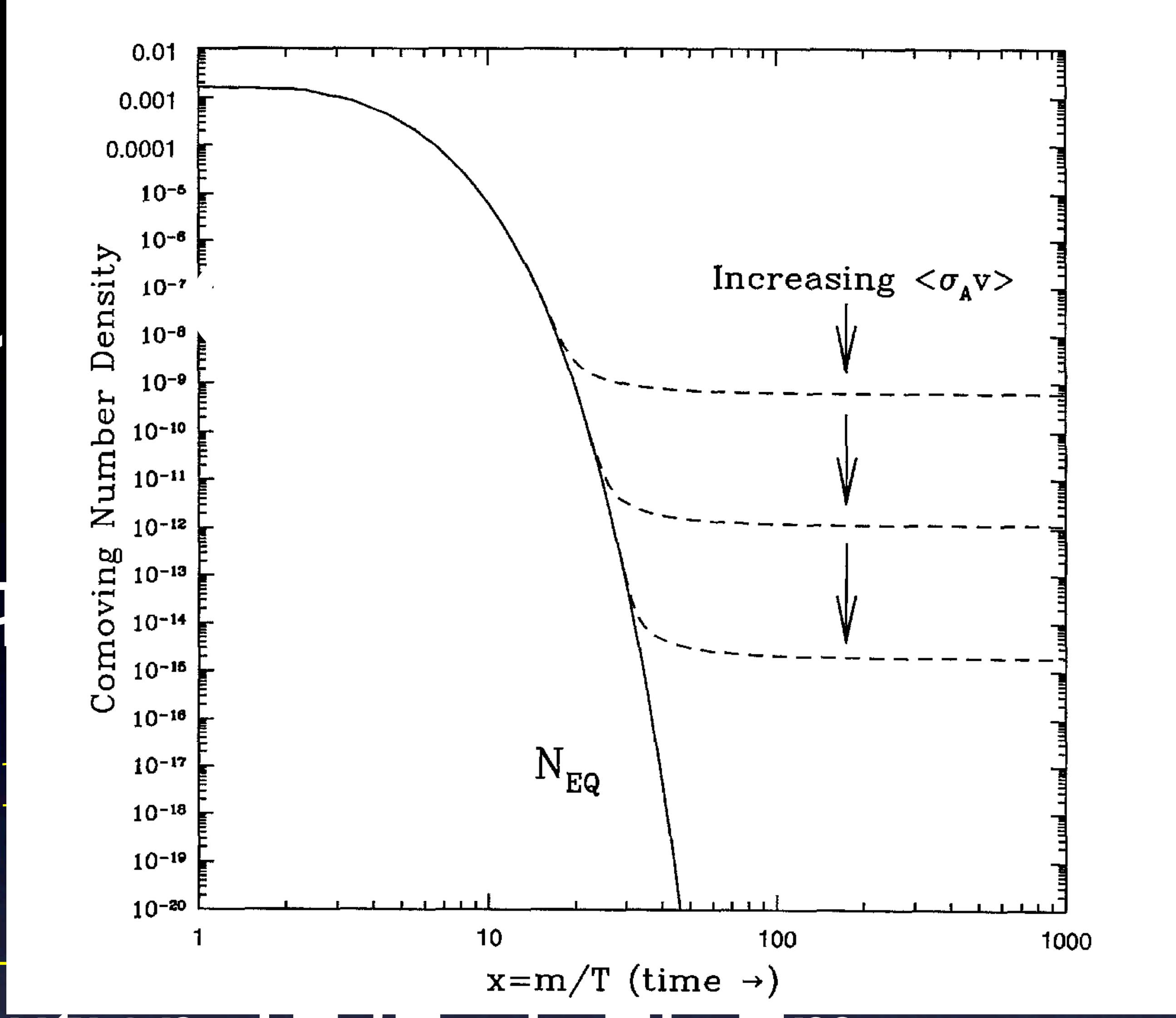
$$\langle \sigma_{\rm ann} v \rangle \approx \frac{1.12 \times 10^{-10} \mathrm{GeV}^{-2} x_f}{g_*^{1/2} \Omega_\chi h^2}$$

$$\sim 10^{-9} \mathrm{GeV}^{-2}$$

$$\langle \sigma_{\rm ann} v \rangle \approx \frac{\pi \alpha^2}{m_\chi^2}$$

$$m_\chi \approx 300 \text{ GeV}$$

therma



- Solve the Boltzmann eq

$$\frac{dn_1}{dt} + 3Hn_1 = -\int \prod_{i=1}^{4} \frac{d^3p_i}{(2\pi)^3 2E_i} |\mathcal{M}(\ldots$$

$$[f_1 f_2 (1 \pm f_3)(1 \pm f_4) - \ldots$$

- assume Maxwell distribution, 1=2=χ, $E_1=E_2=m_\chi$

$$\frac{dn}{dt} + 3Hn = -\langle \sigma_{\rm ann} v \rangle (n^2 - n_{eq}^2)$$

- Note momentum dependence may be important close to thresholds, resonances
- reproduce the estimate with

$$x_f \approx 24 + \ln \frac{m_\chi}{100\mathrm{GeV}} + \ln \frac{\langle \sigma_{\rm ann} v \rangle}{10^{-9}\mathrm{GeV}^{-2}} - \frac{1}{2} \ln \frac{g_*}{100}$$

WIMP

- A stable particle at the weak scale with "EM-strength" coupling naturally gives the correct abundance
- This is where we expect new particles because of the hierarchy problem!
- Many candidates of this type: SUSY, little Higgs with T-parity, Universal Extra Dimensinos, etc
- If so, we may even create dark matter at accelerators

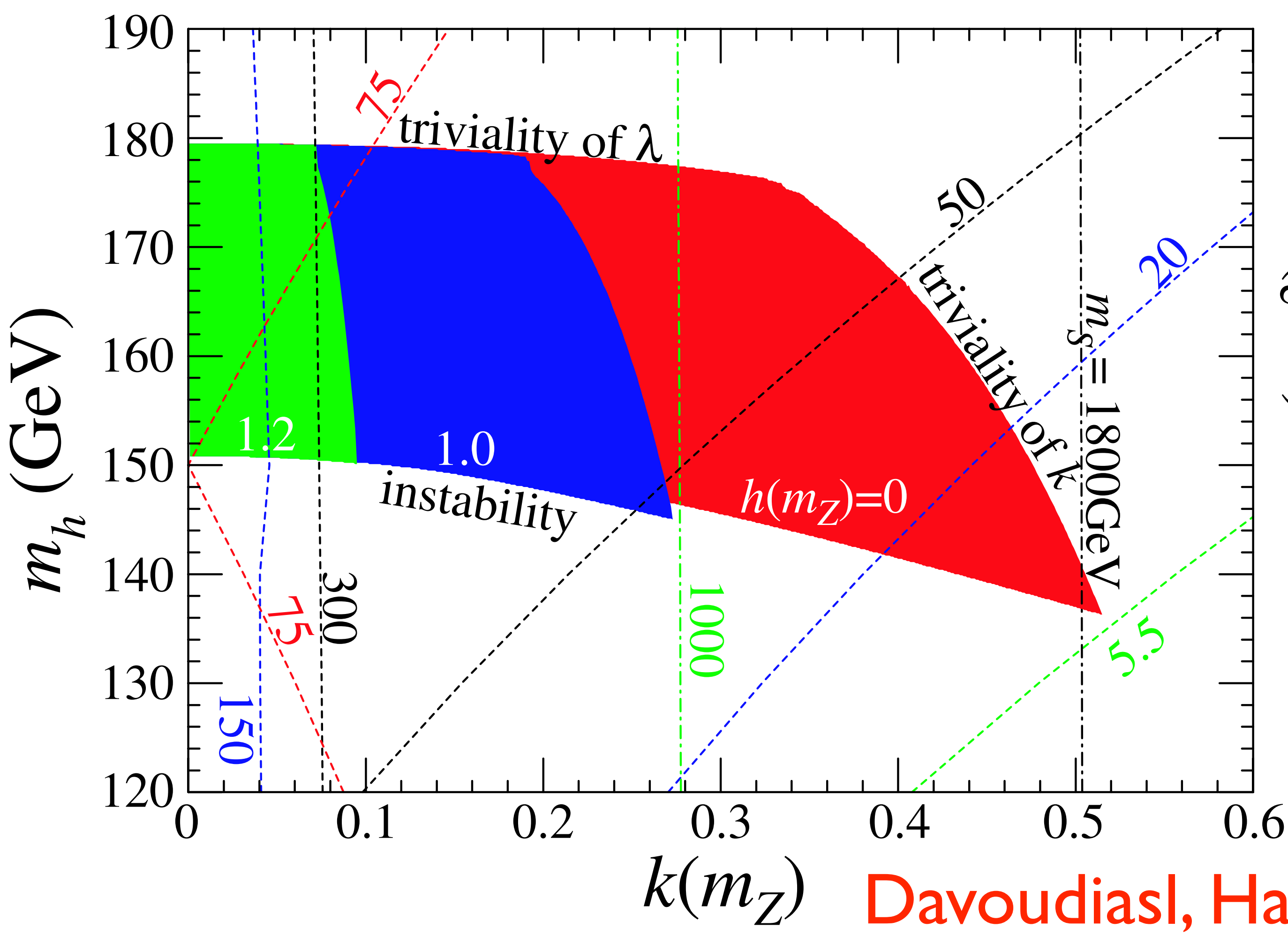
Minimal Model

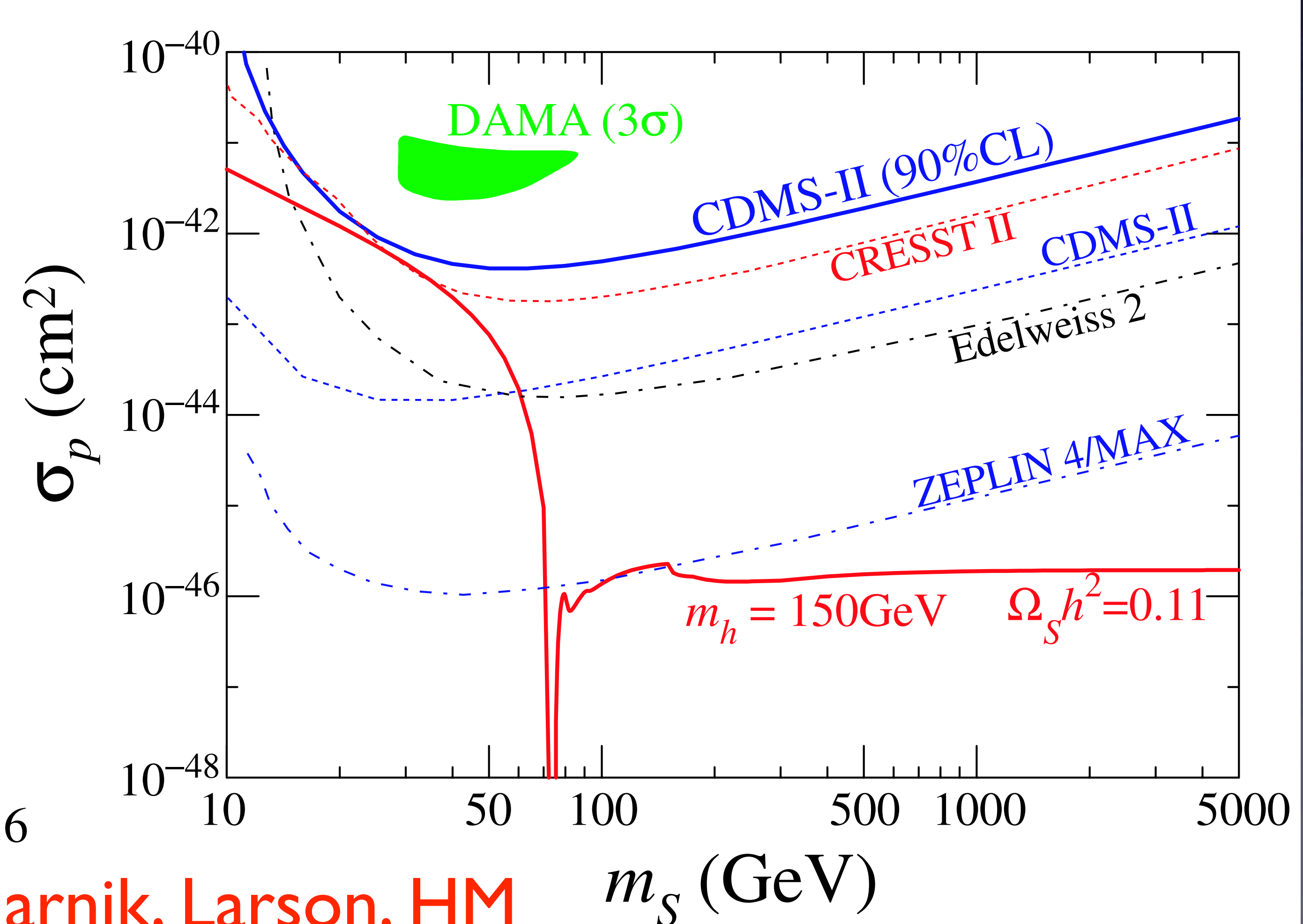
- Dark Matter clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field S: dof=1
- assign odd Z_2 parity to S, everything else even
- Most general renormalizable coupling

$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!}S^4.$$

Consistency check

- correct Dark Matter abundance
- evades direct detection limits
- satisfies triviality/instability limits from RGE
- consistent with precision electroweak data





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