Cosmology
Dark Matter

AESHEP Oct 25, 2012

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?

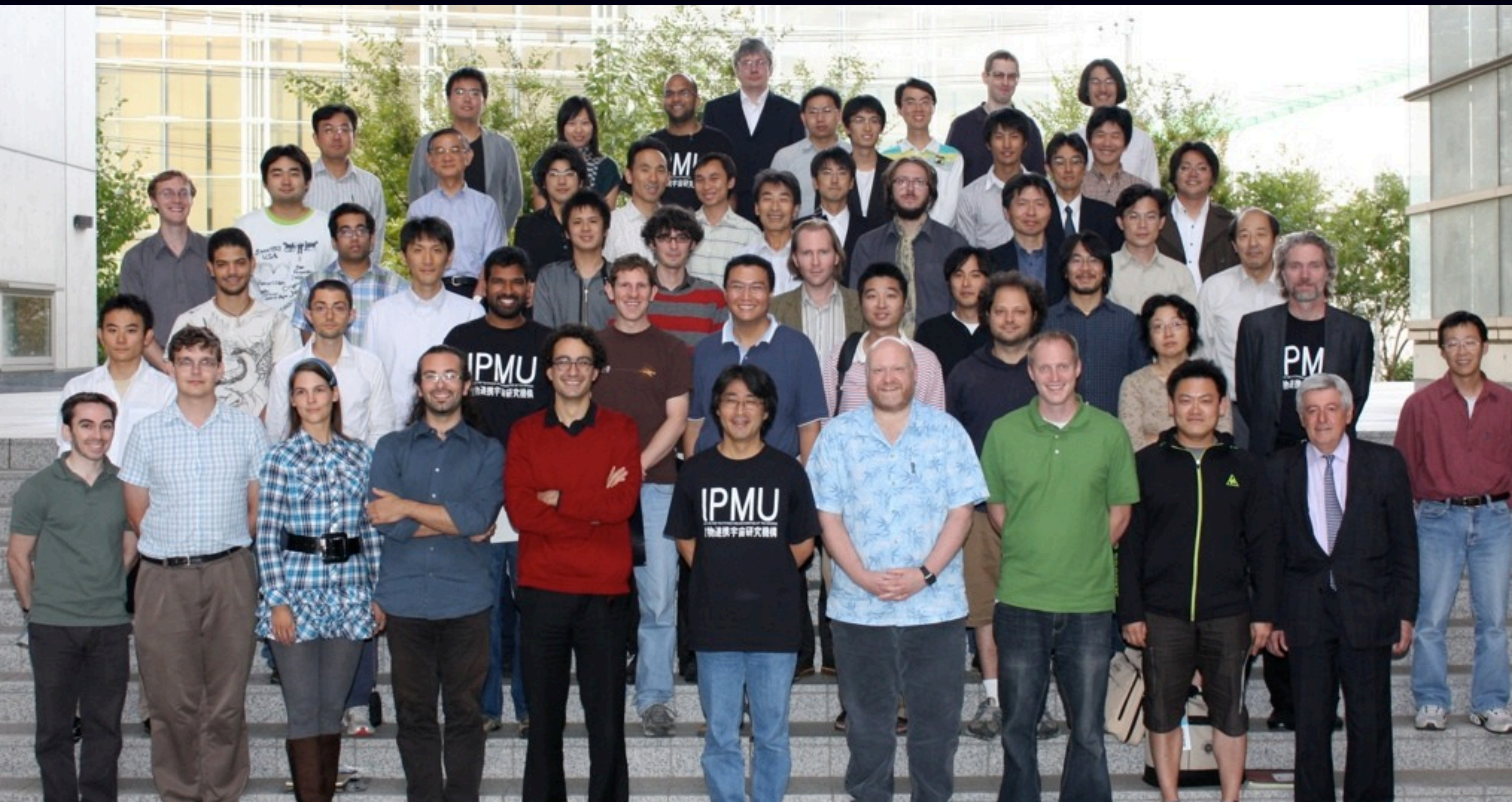
interdisciplinary institute of
astronomy, physics and mathematics
10-year program by Japanese
government since 2007

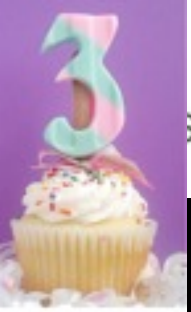
Oct 2007

Oct 2008

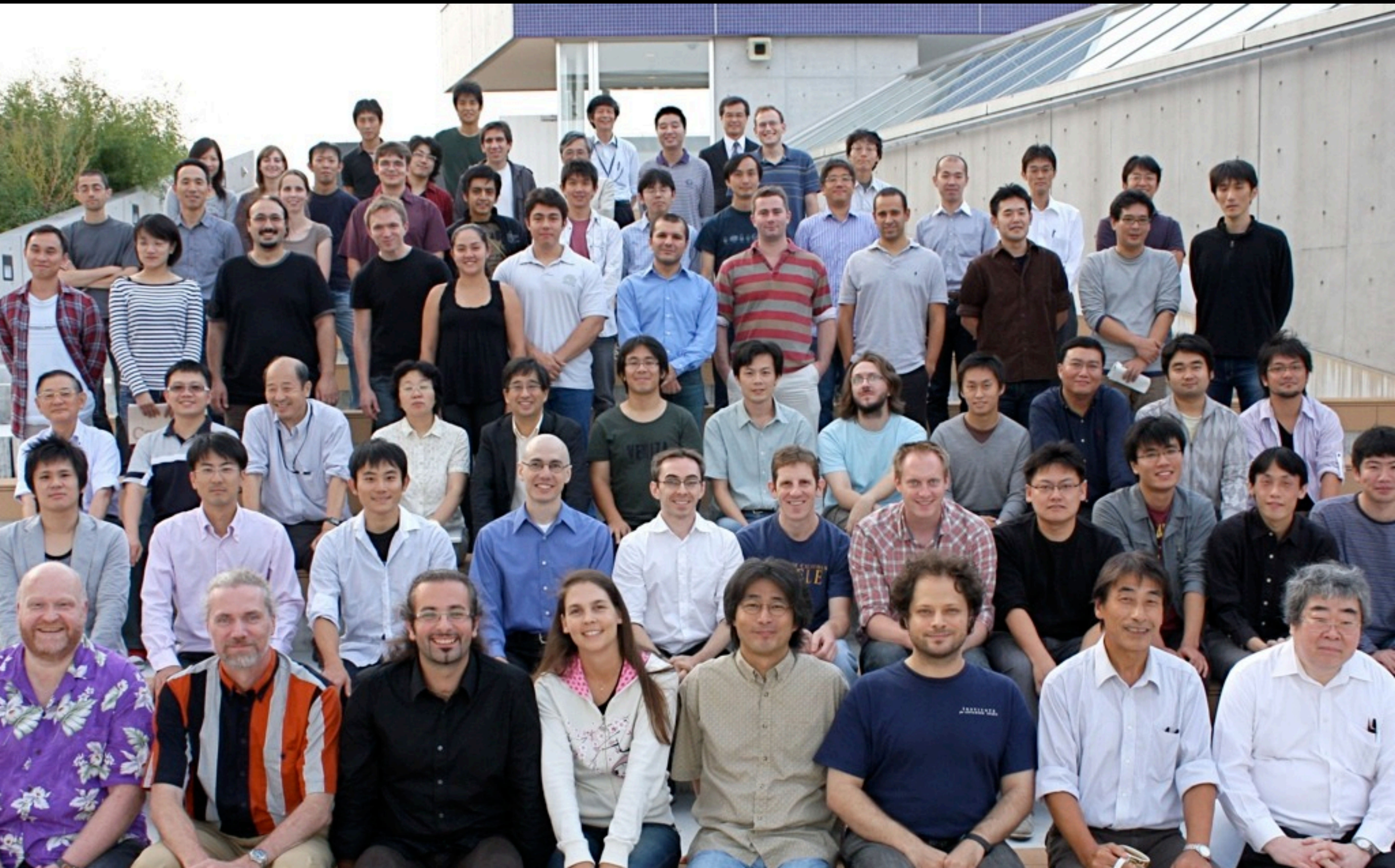
KAVLI IPMU

Oct 2009





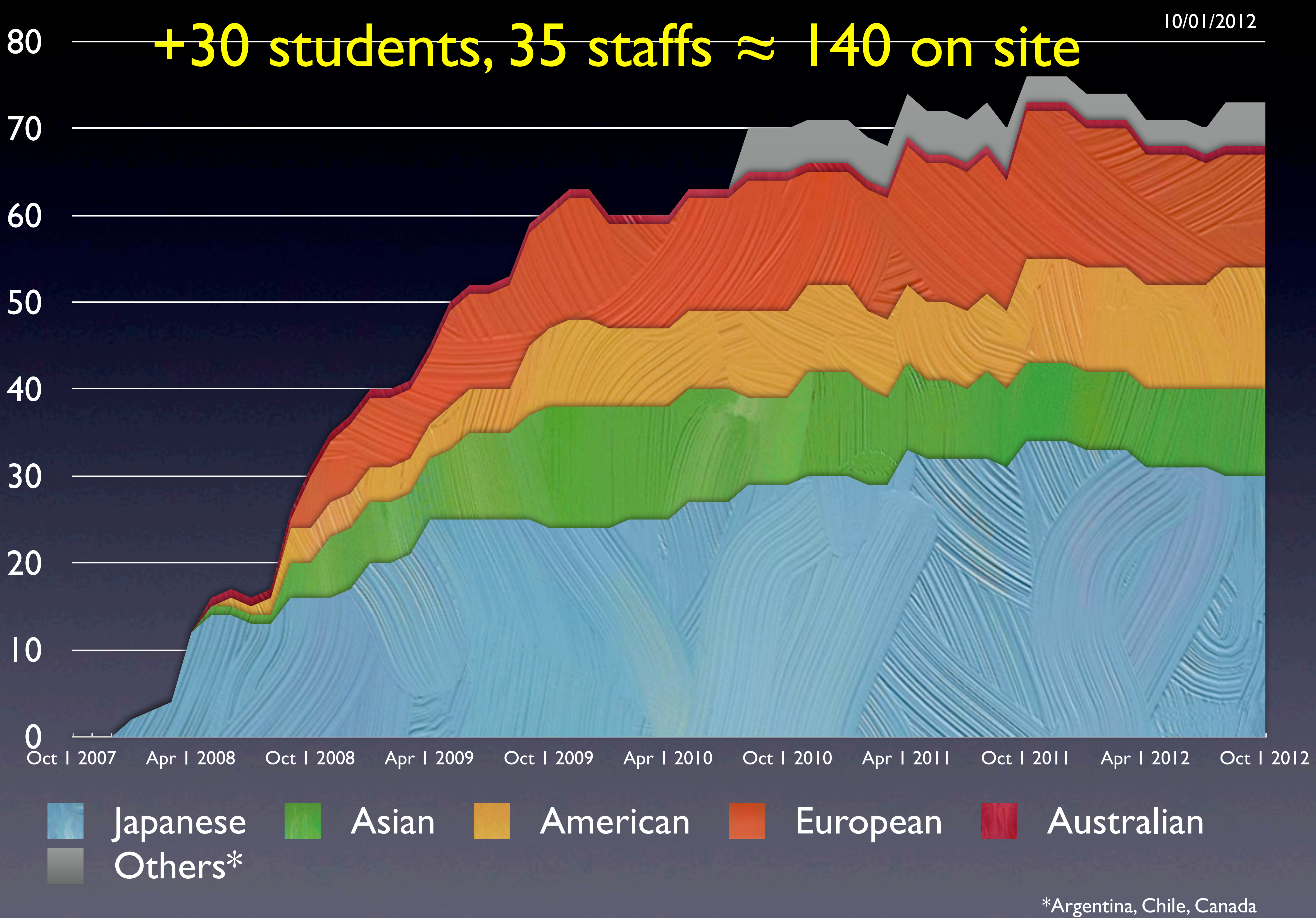
Oct 2010



Oct 2011

Oct 2012

Full-time Scientists paid by IPMU




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

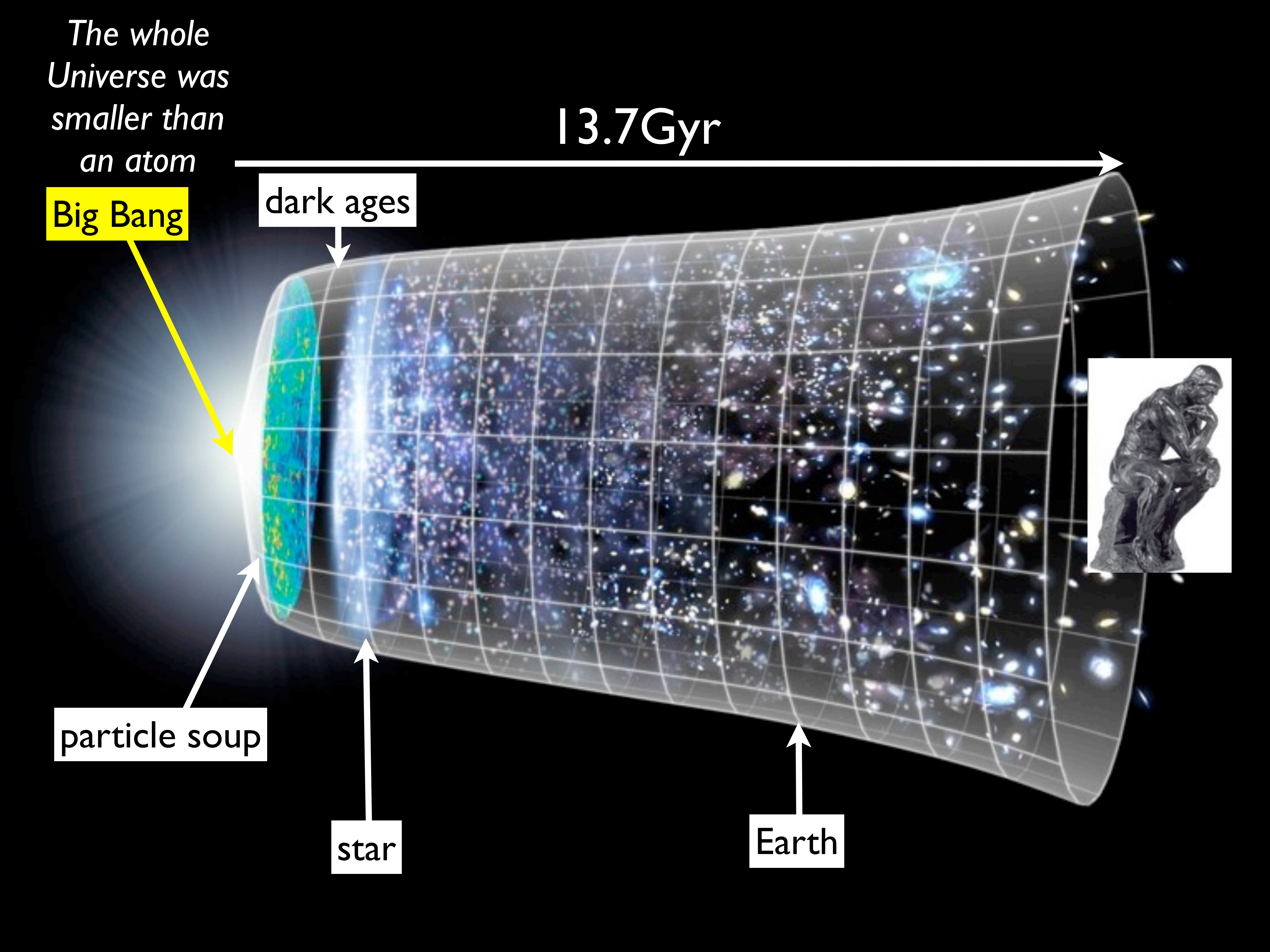
May 9, meeting with Prime Minister Noda

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.*

Cosmology
Dark Matter

AESHEP Oct 25, 2012
Kavli IPMU, University of Tokyo
UC Berkeley, Lawrence Berkeley Laboratory
Hitoshi Murayama



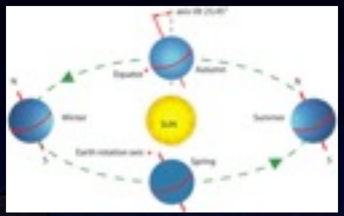
The whole Universe was smaller than an atom
13.7Gyr
Big Bang
dark ages
particle soup
star
Earth

scales


10^{27}m


10^{23}m

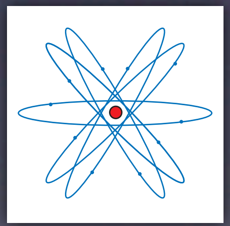

10^{20}m

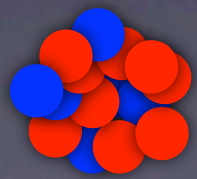

10^{11}m


10^{7}m


10^{3}m


0.1m

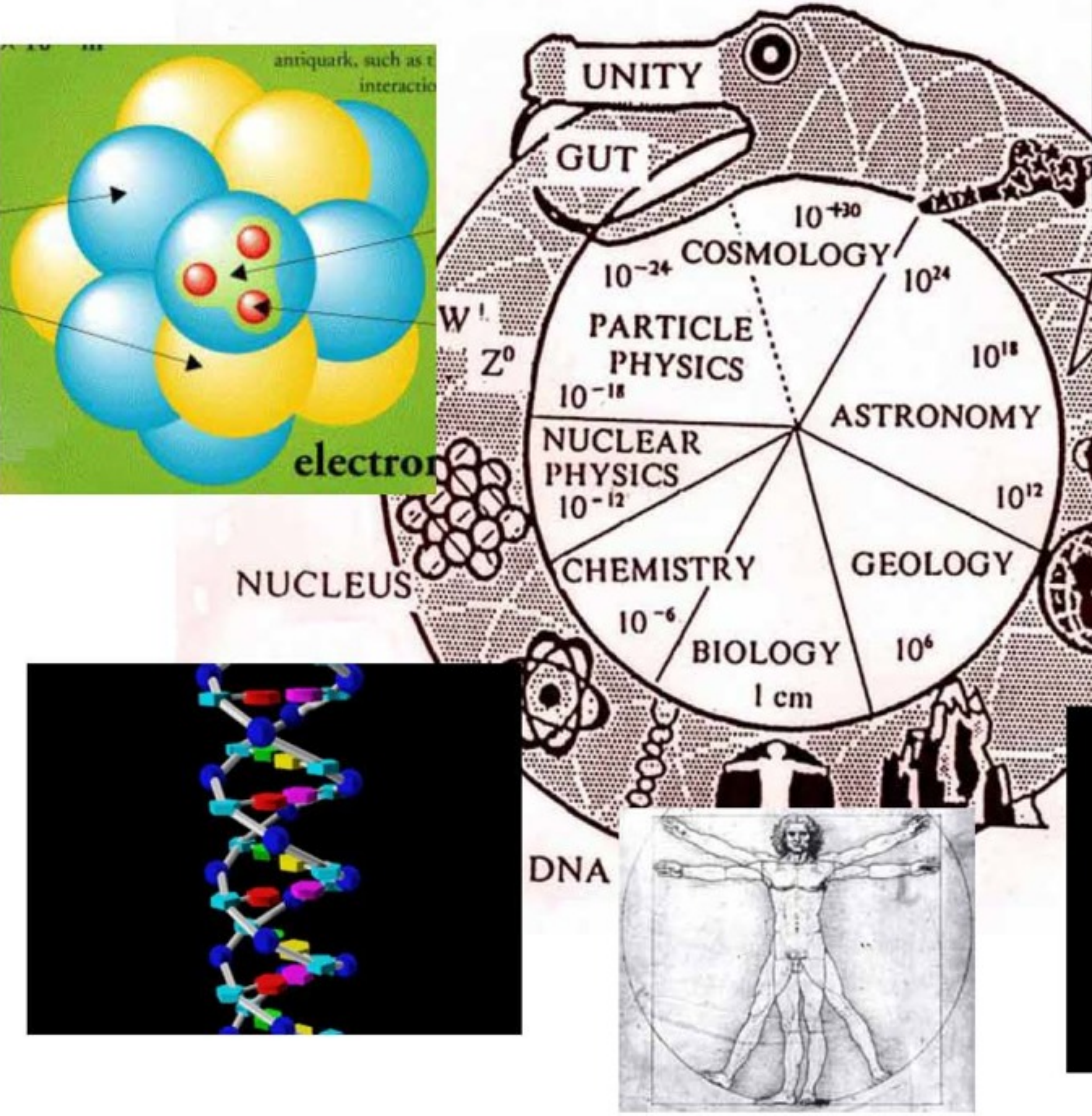

10^{-10}m

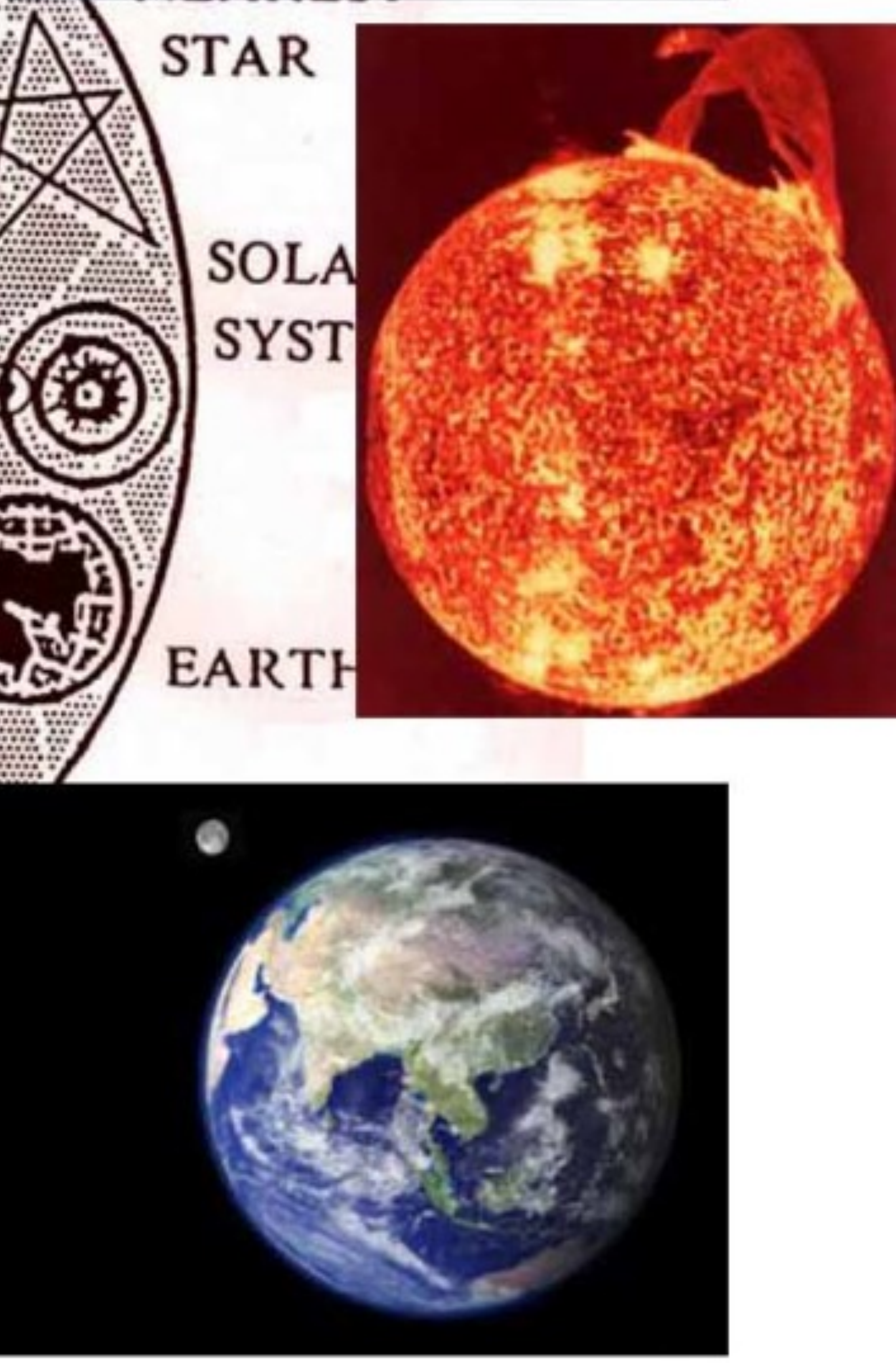

10^{-15}m

10^{-19}m

- distance scales in nature

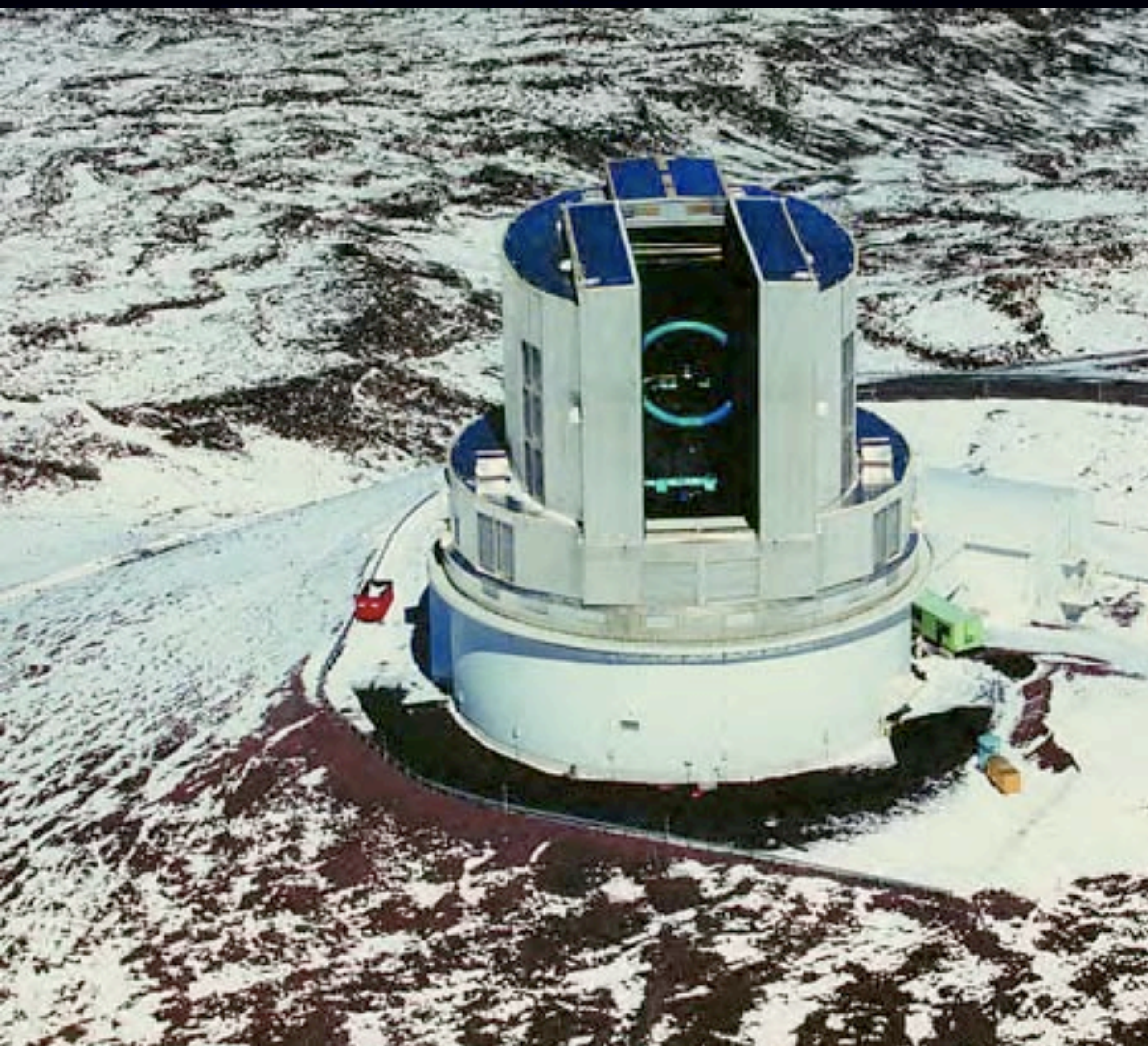
Snake of Sizes





Time Machine

Time Machine




Solar System

375 km above ground

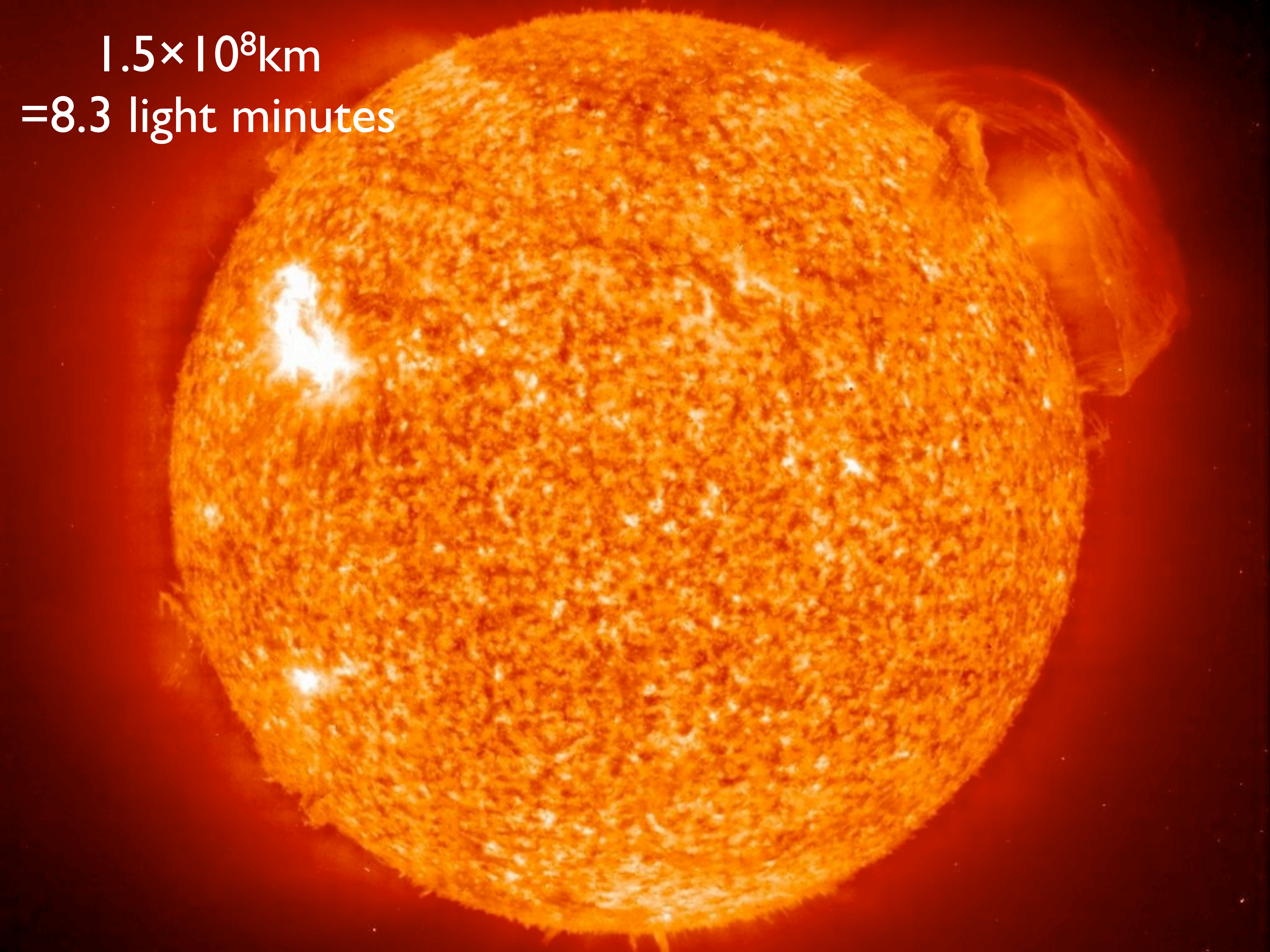
Apr 7 2012

skin of peach

Sep 30, 2008
Kaguya

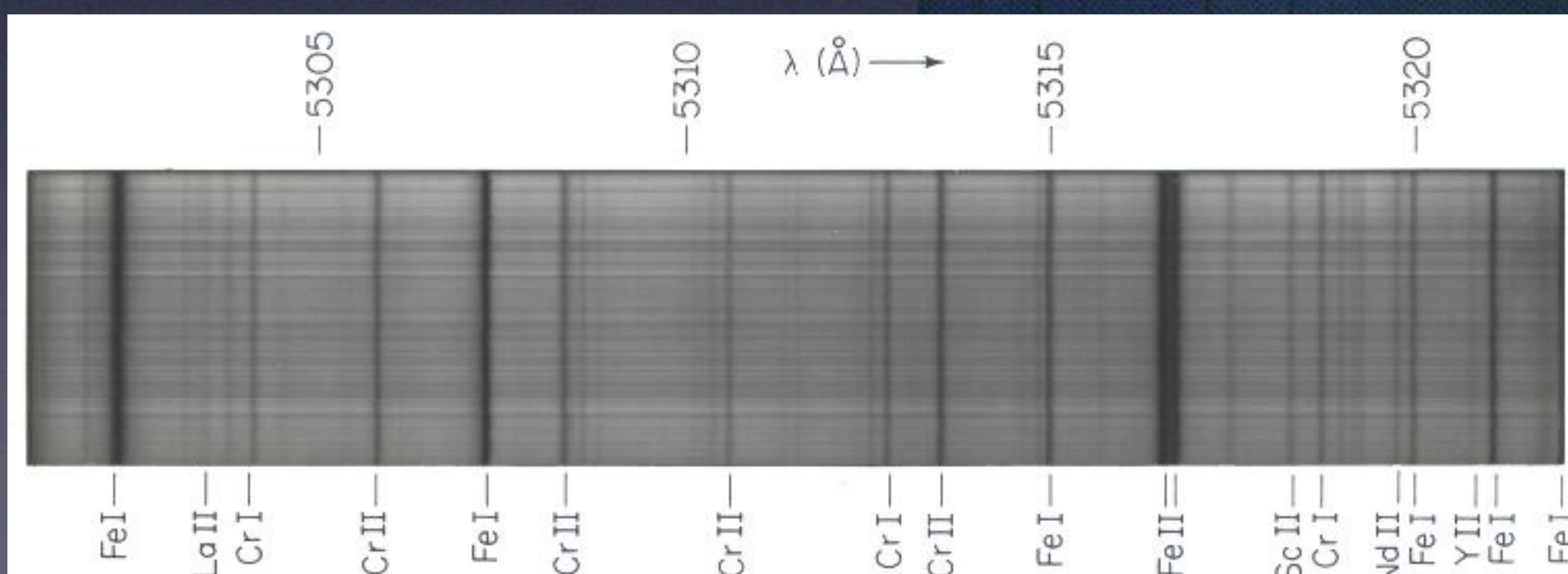
380,000km
=1.3 light seconds

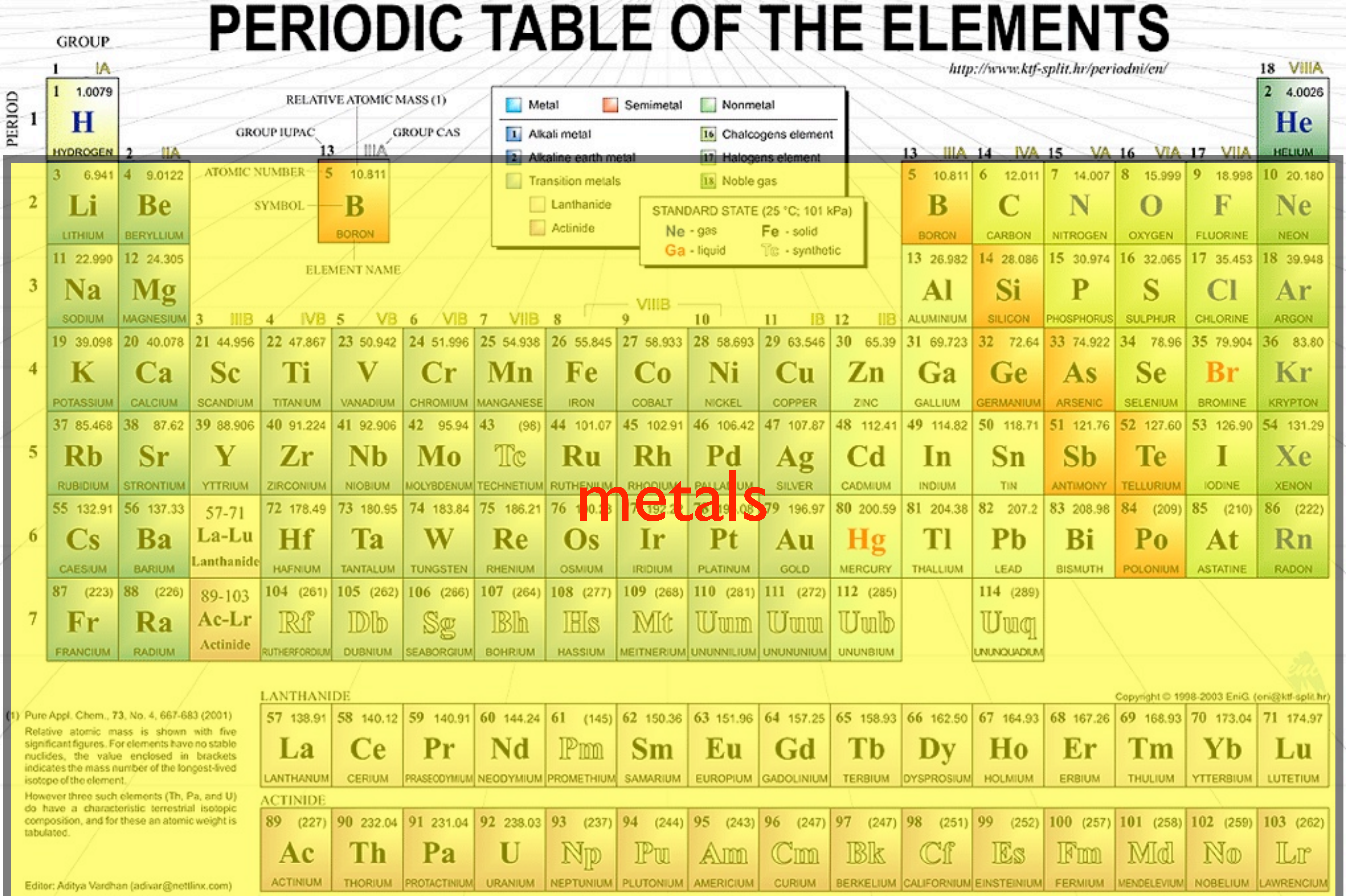

380,000km
=1.3 light seconds
©JAXA/NH


1.5×10^8km
=8.3 light minutes

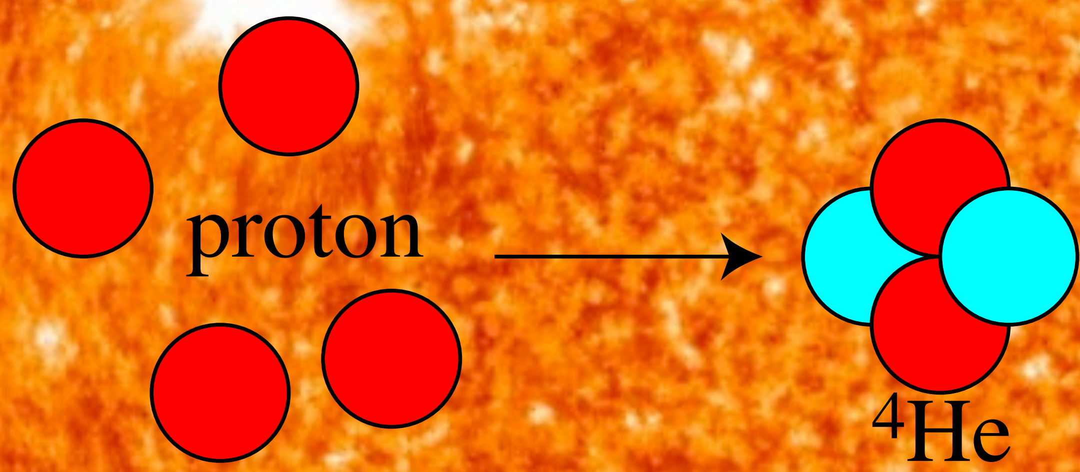
Made of atoms

- 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/
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
LANTHANIDE
ACTINIDE
Copyright © 1998-2003 EniG. (eni@ktf-split.hr)
Editor: Aditya Vardhan (adivar@netlinx.com)
metals

1.5×10^{8}km
=8.3 light minutes



$+\ 2e^{+} + 2\nu_e + 25\text{MeV}$

$E=mc^2$

5 Mt lighter every second

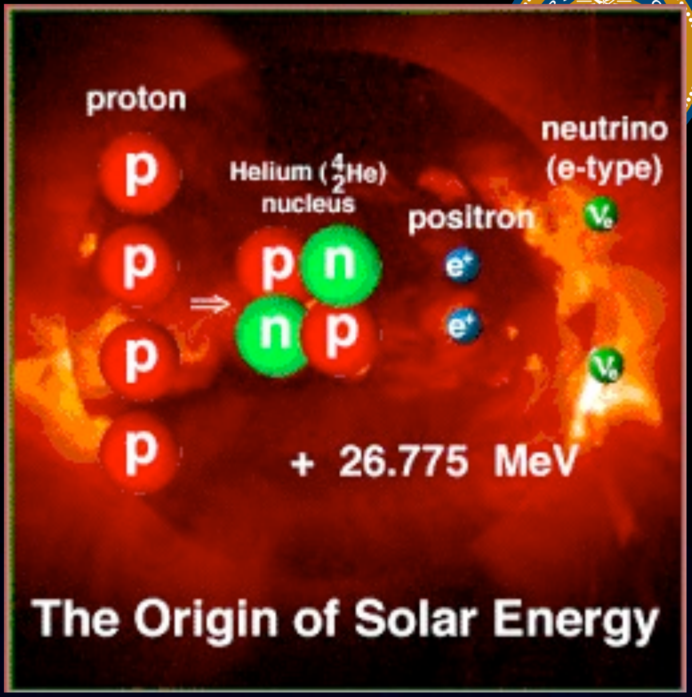
turning mass to energy

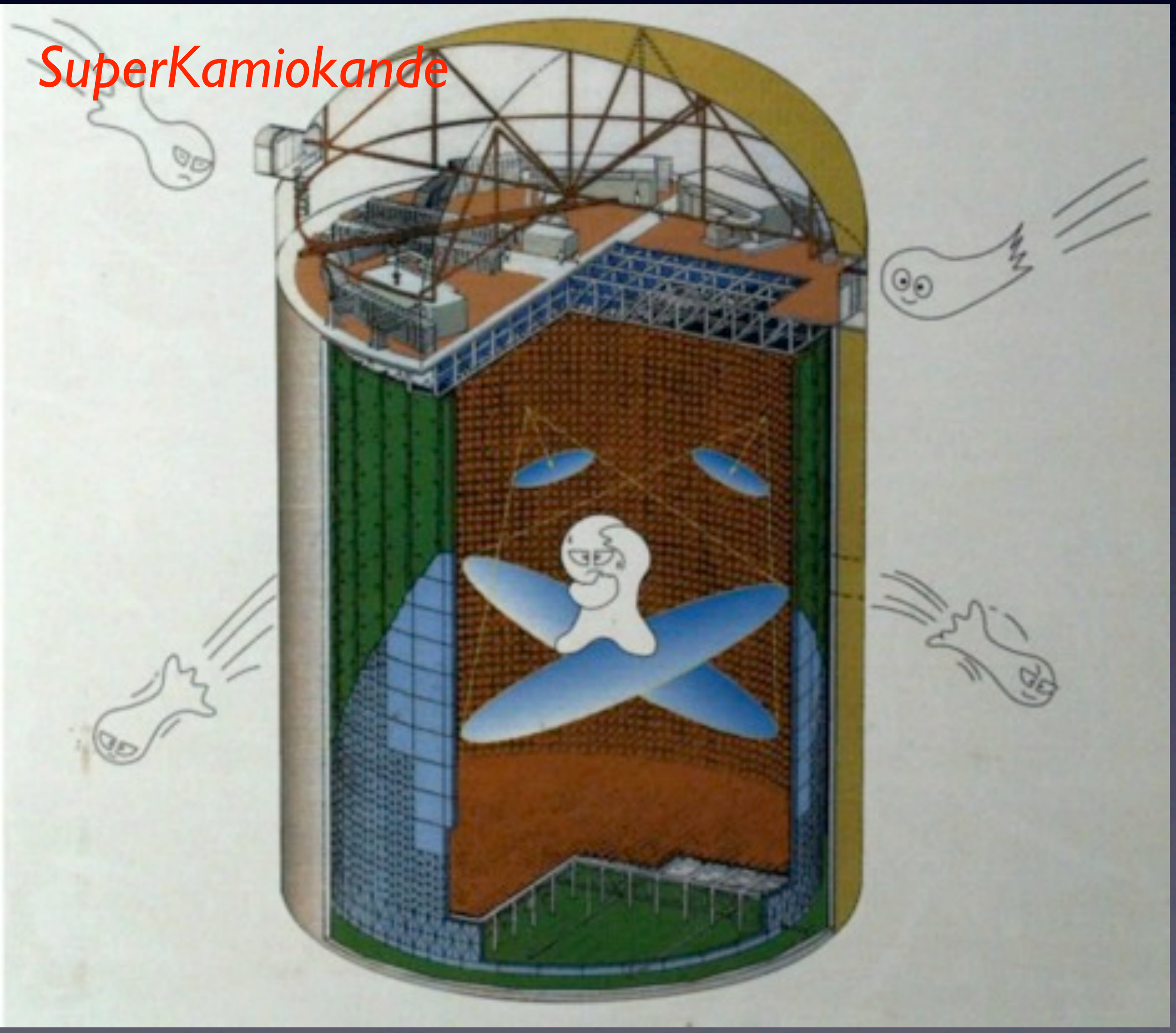
burning hydrogen

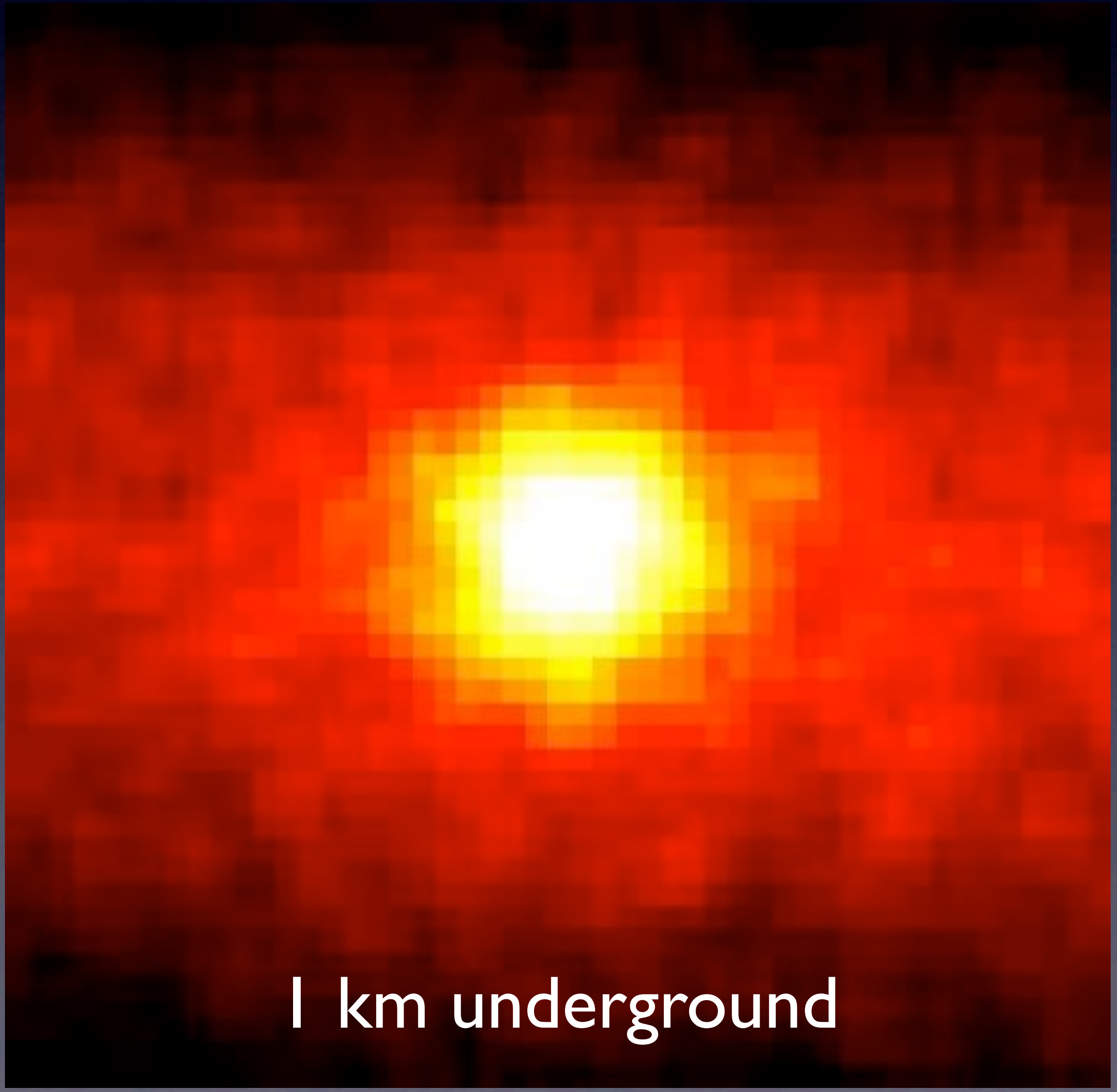
proof

nuclear fusion also produces neutrinos

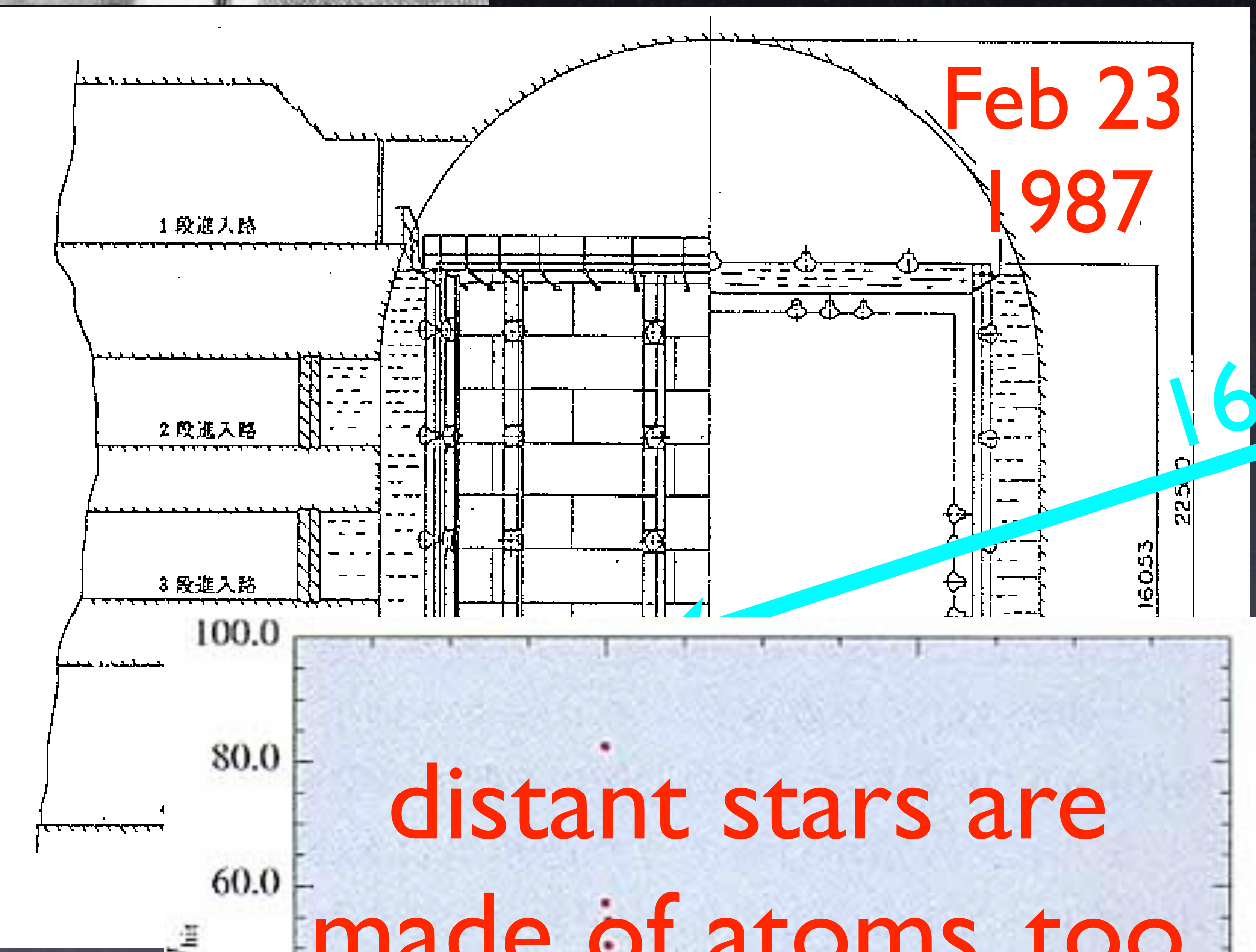
tens of trillions of neutrinos going through our body every second

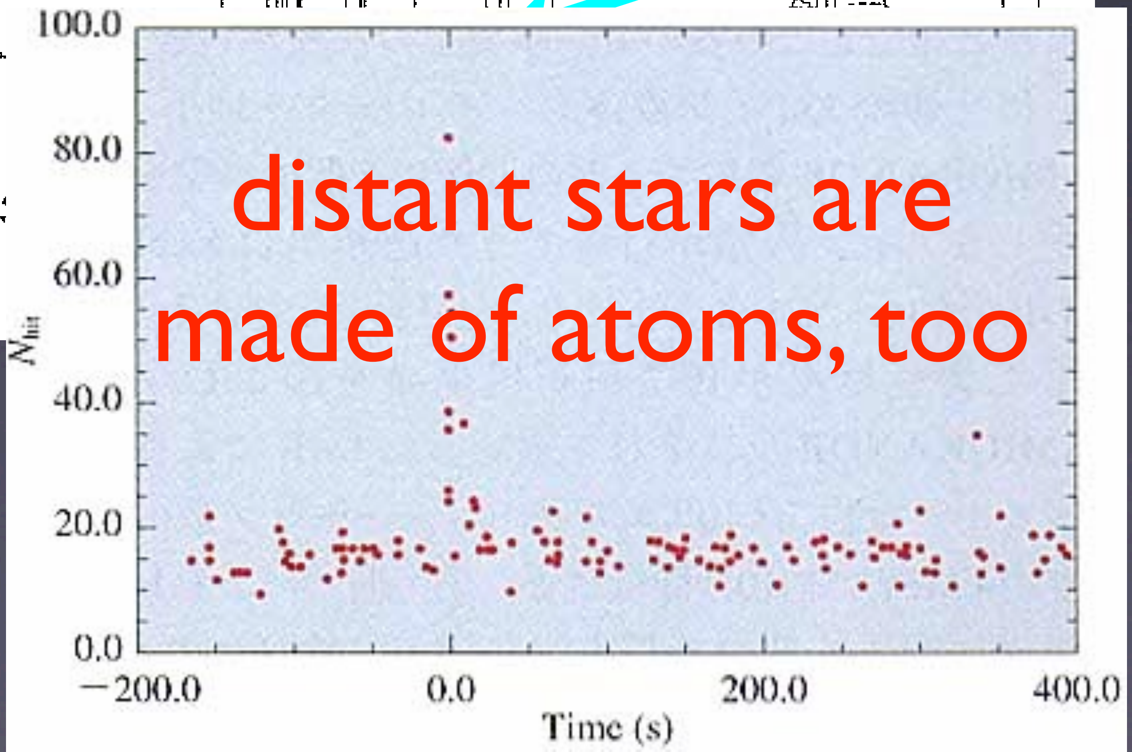


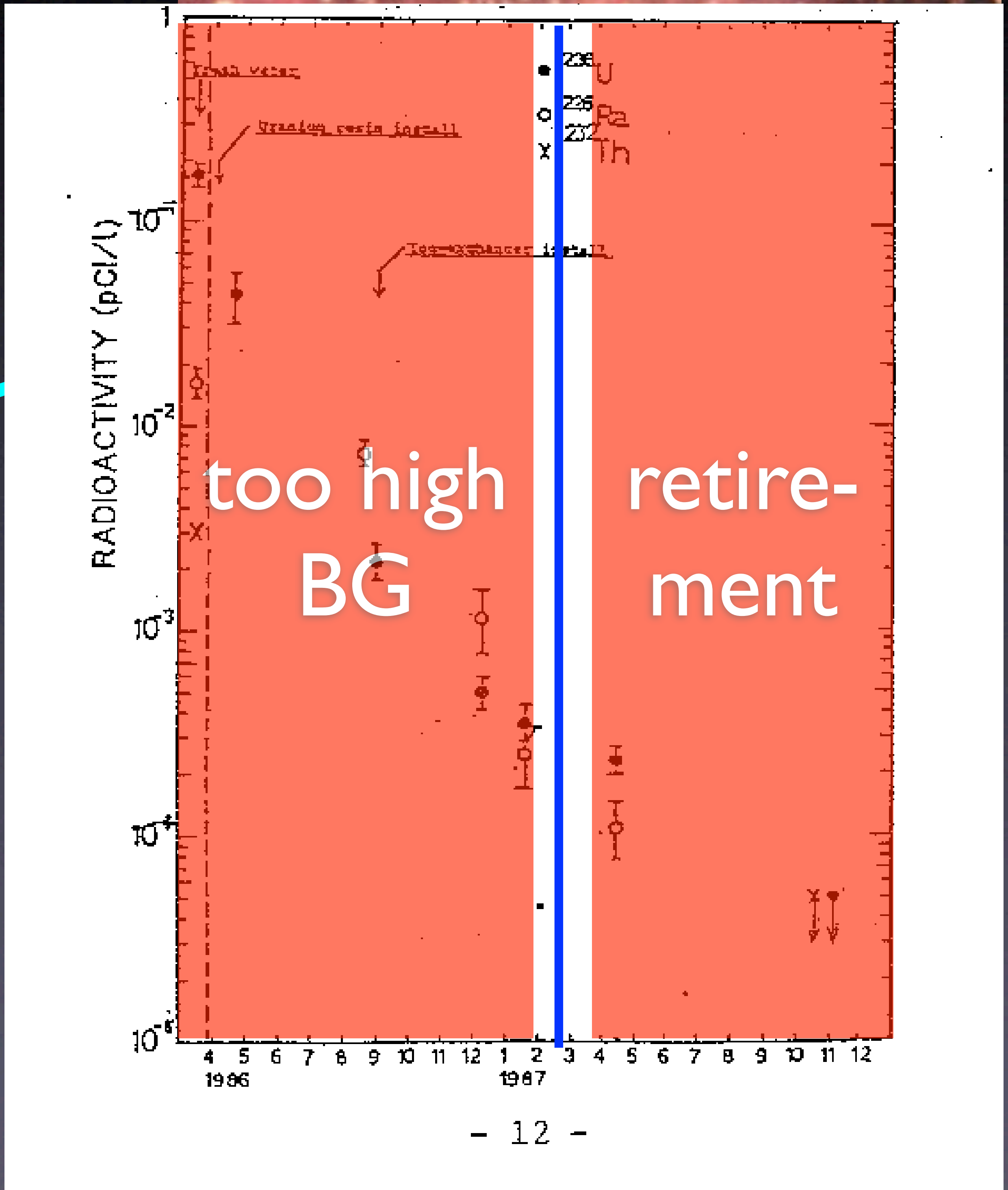




luck

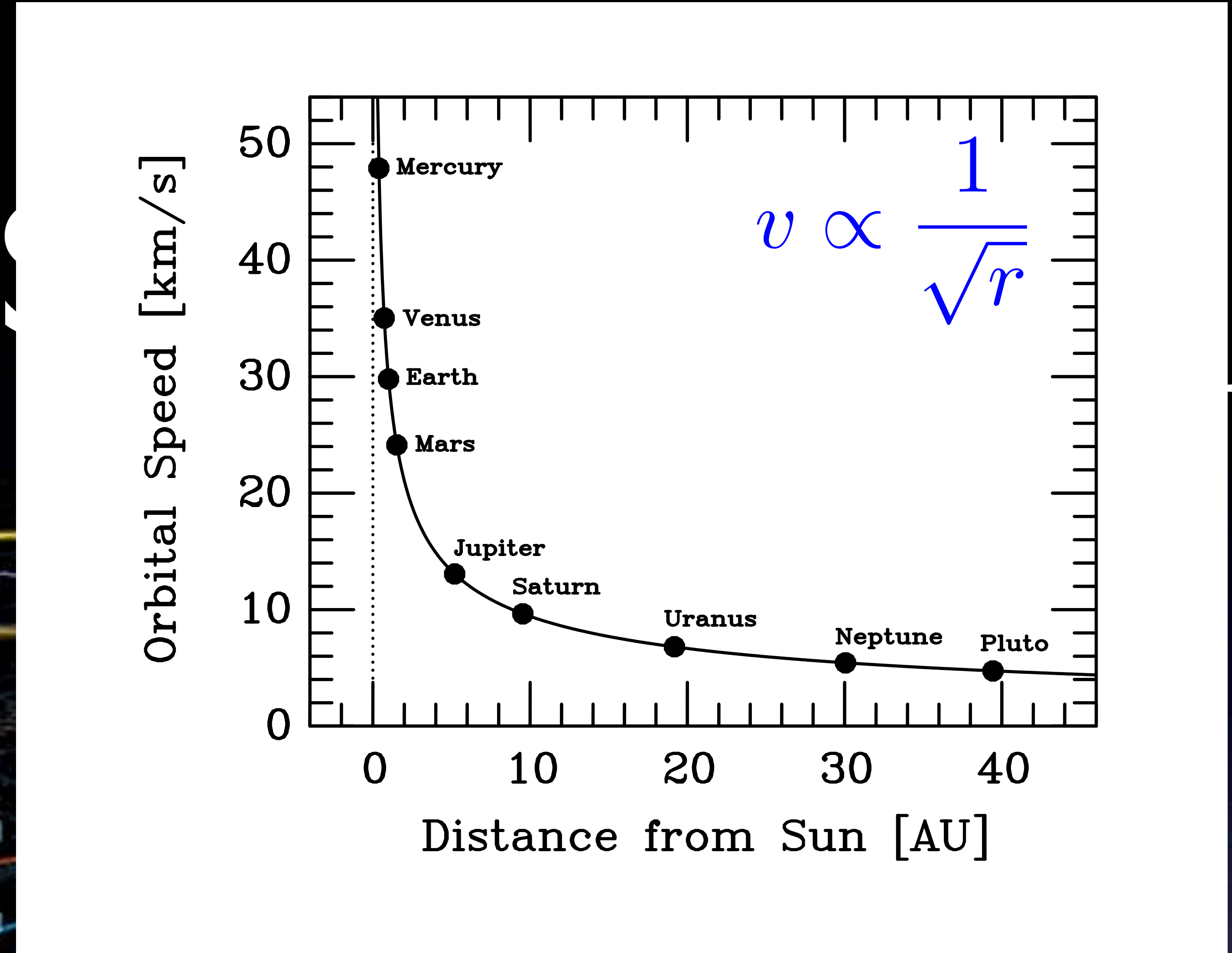

Feb 23
1987
160,000
1 段進入路
2 段進入路
3 段進入路
16053
2250

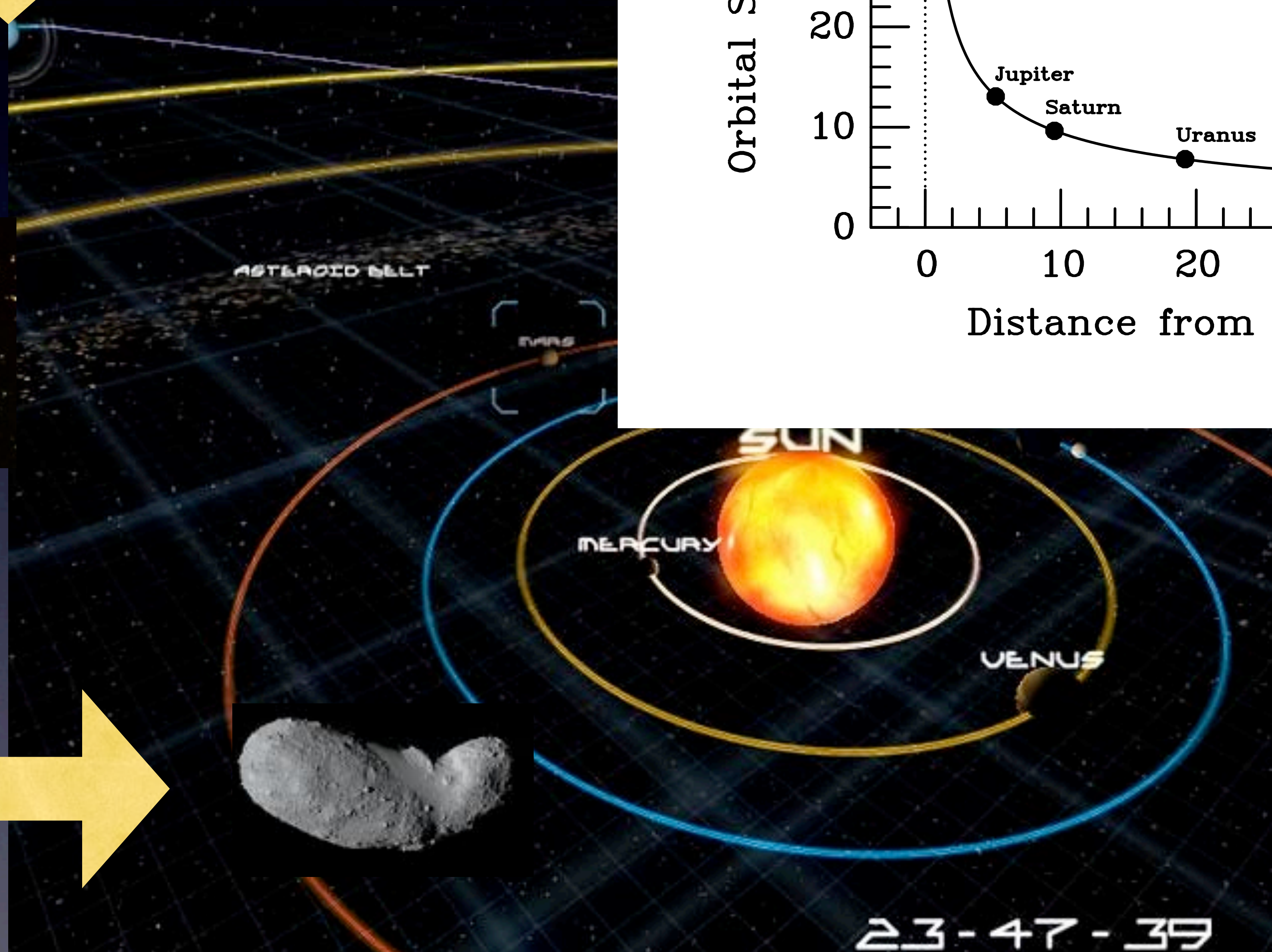

distant stars are
made of atoms, too
100.0
80.0
60.0
40.0
20.0
0.0
−200.0
0.0
200.0
400.0
Time (s)
N_{hit}


RADIOACTIVITY (pCi/l)
too high
BG
retire-
ment
238U
226Ra
232Th
1986
1987
- 12 -

Solar S

Neptune
4 light hours

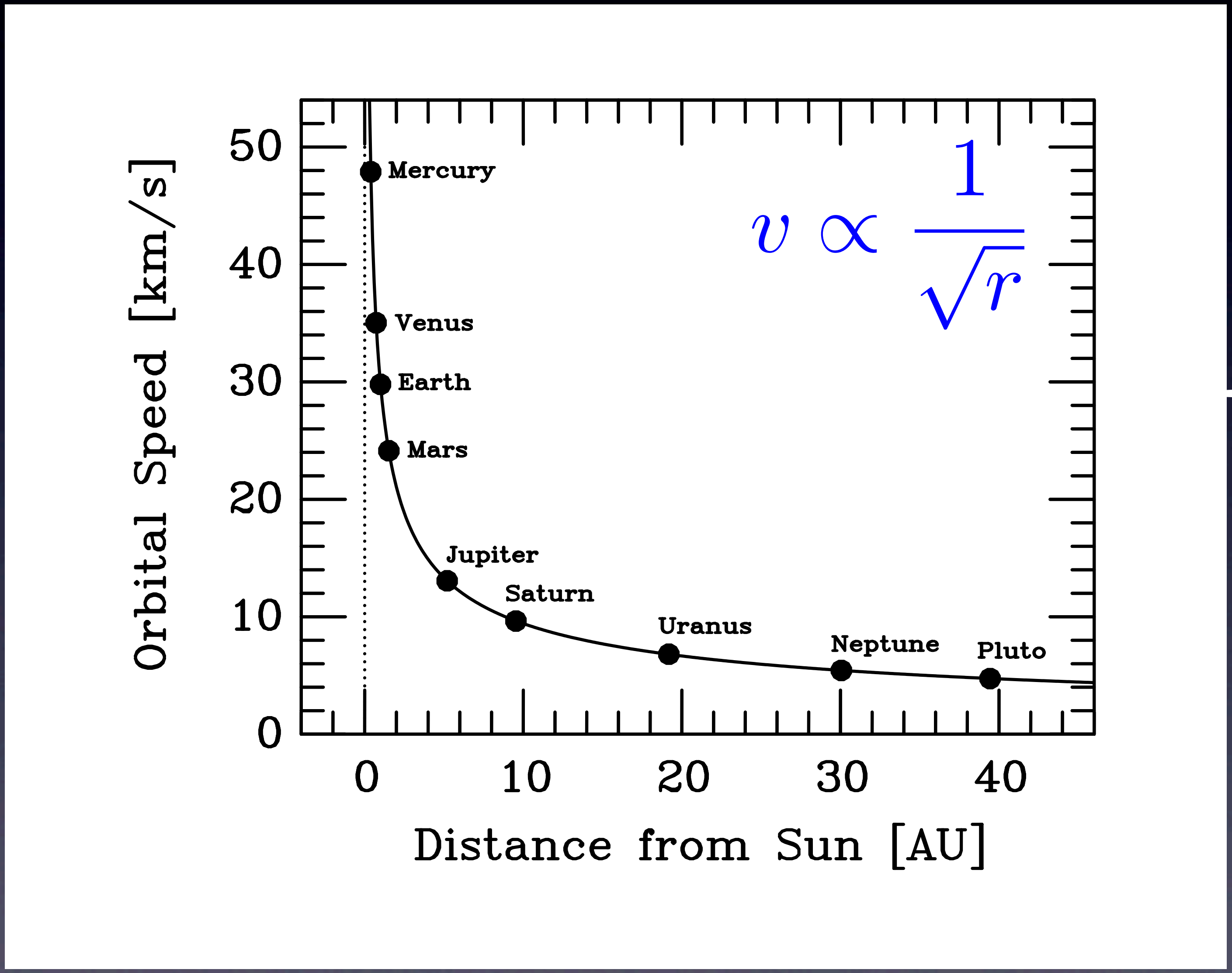




Itokawa
20 light minutes

Earth resolves around the Sun with 30km/sec

High School physics



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

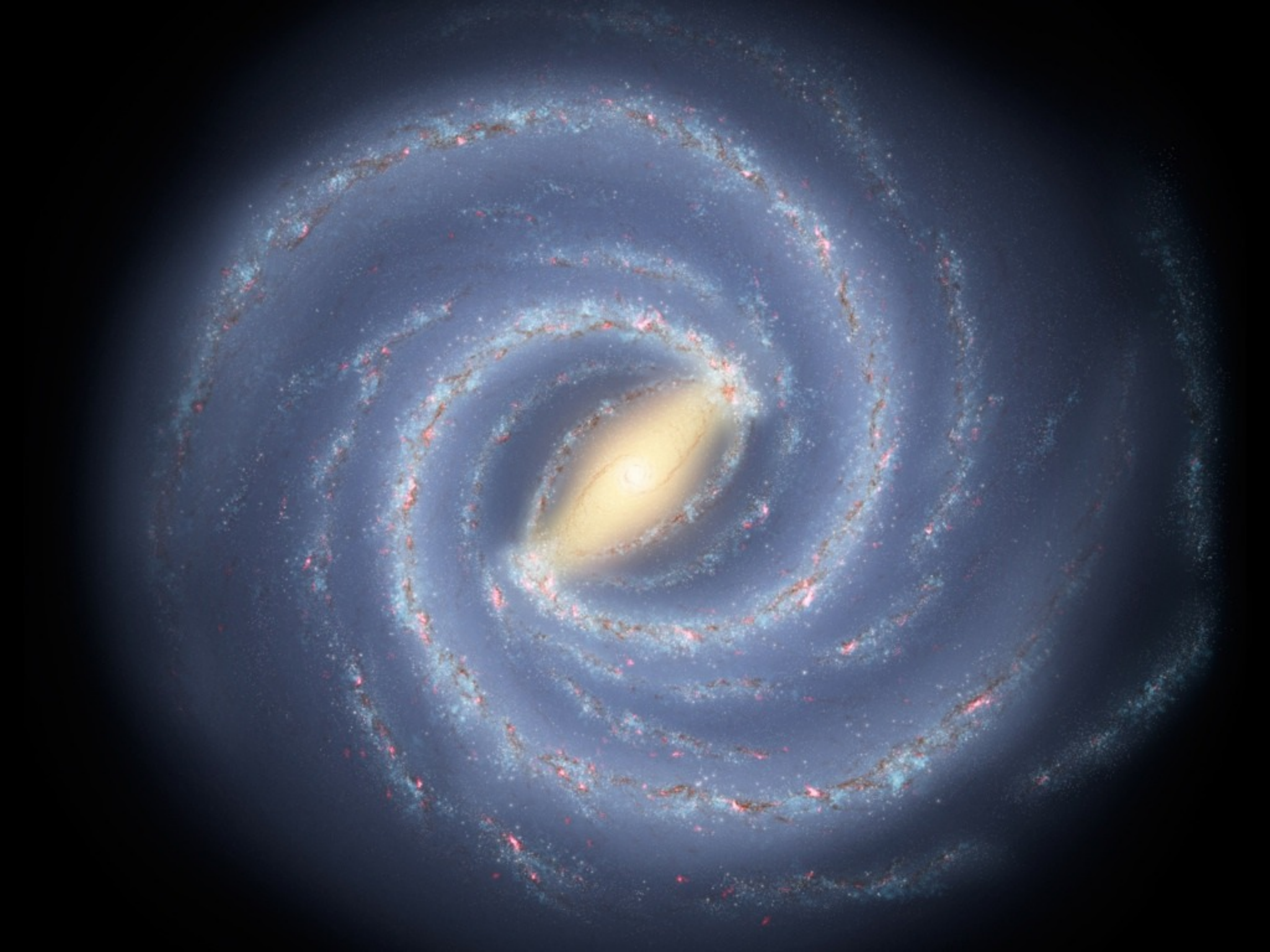
$$ma = m\frac{v^2}{r}$$

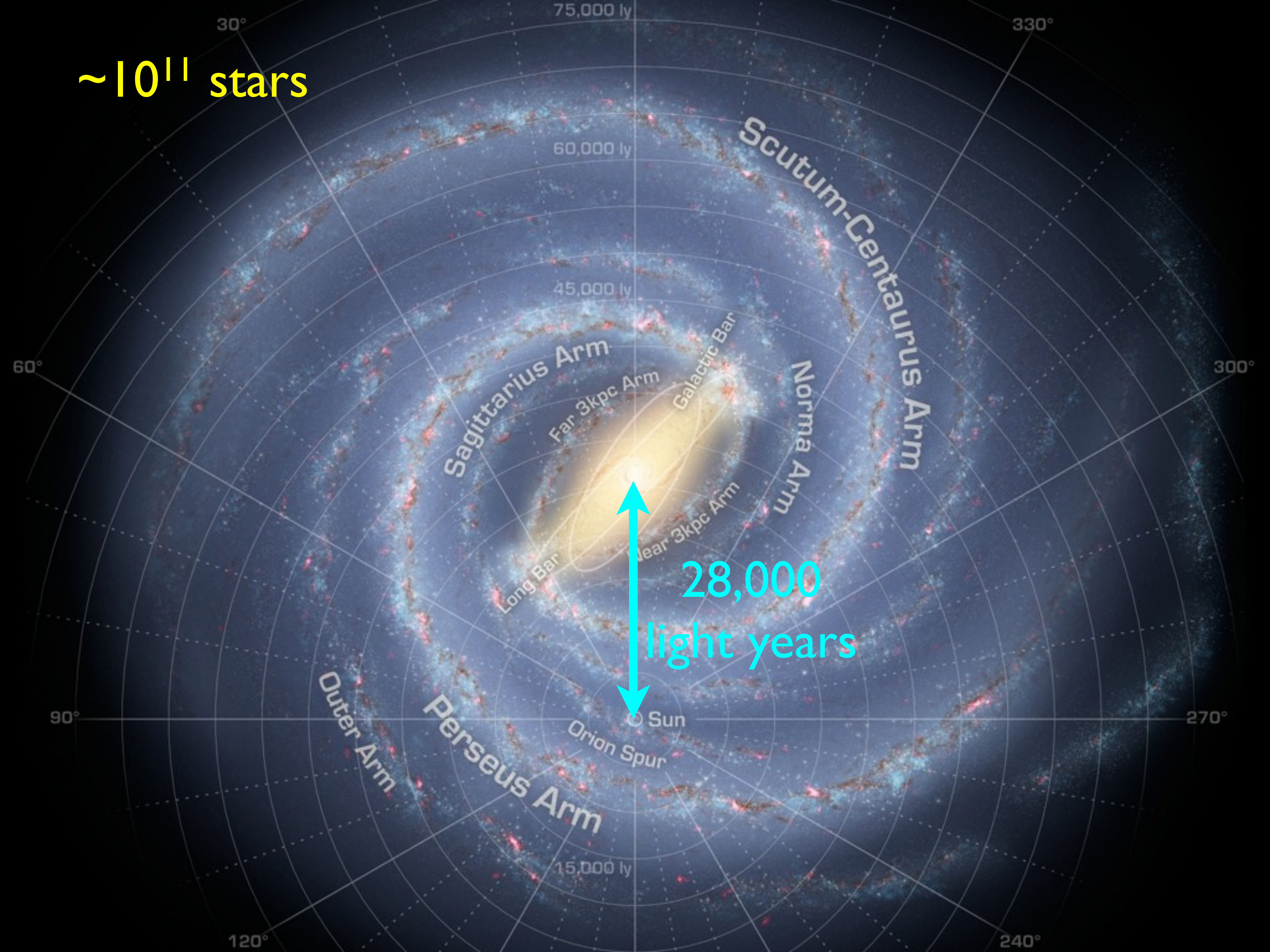
$$\frac{GM_\odot m}{r^2} = m\frac{v^2}{r}$$

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

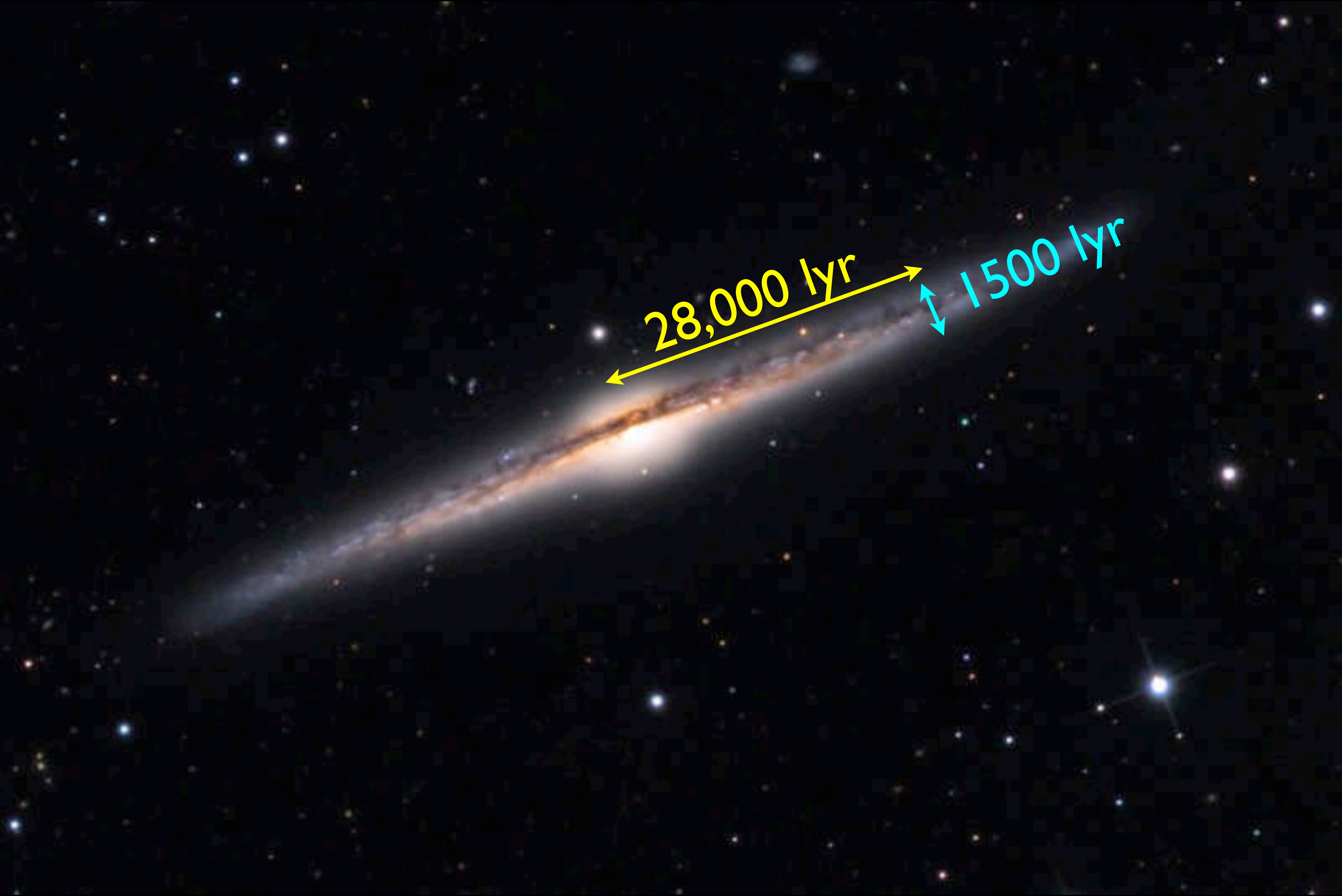

closest star
Proxima Centauri
4.2 light years

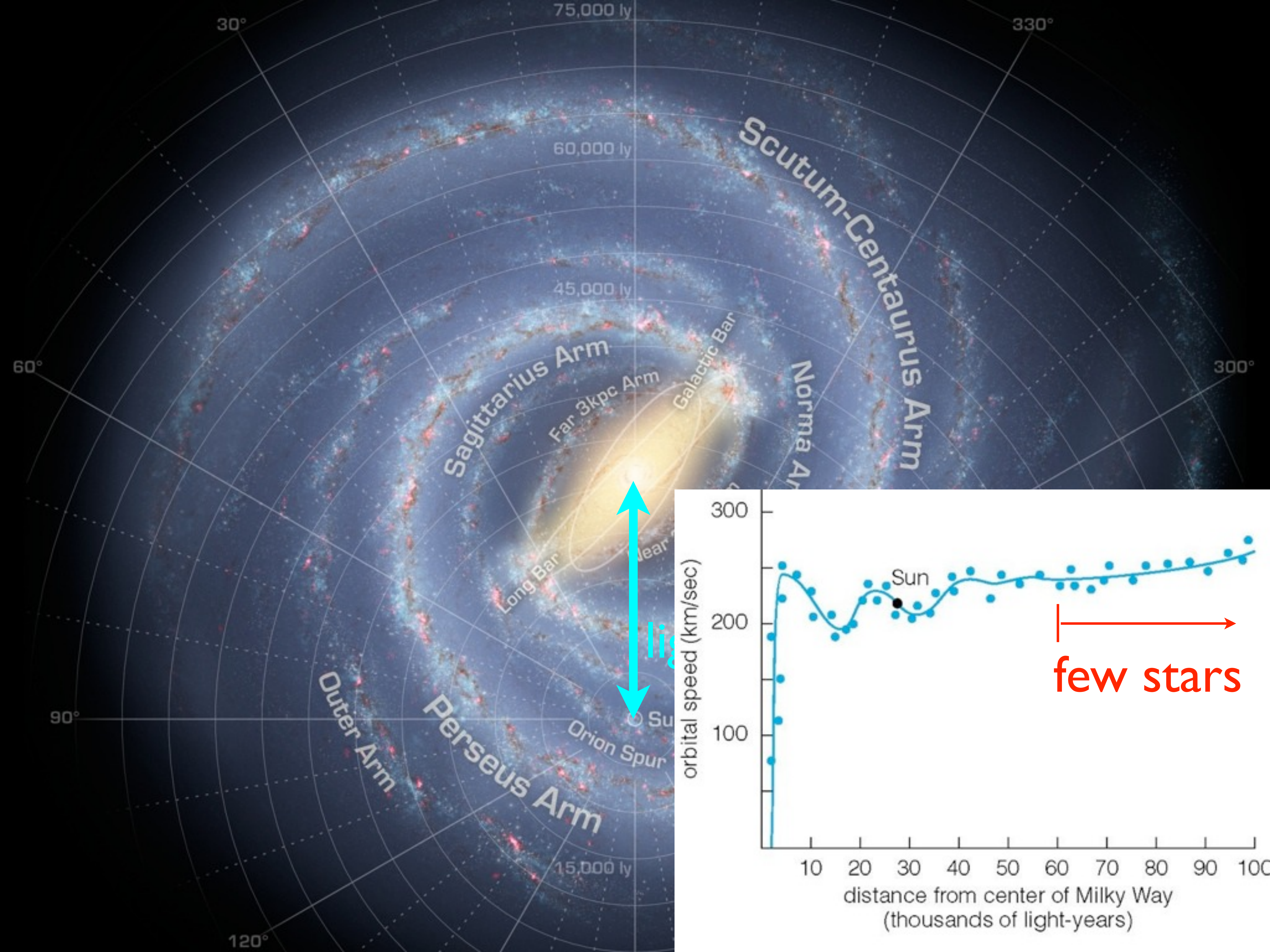
Milky Way and Galaxies



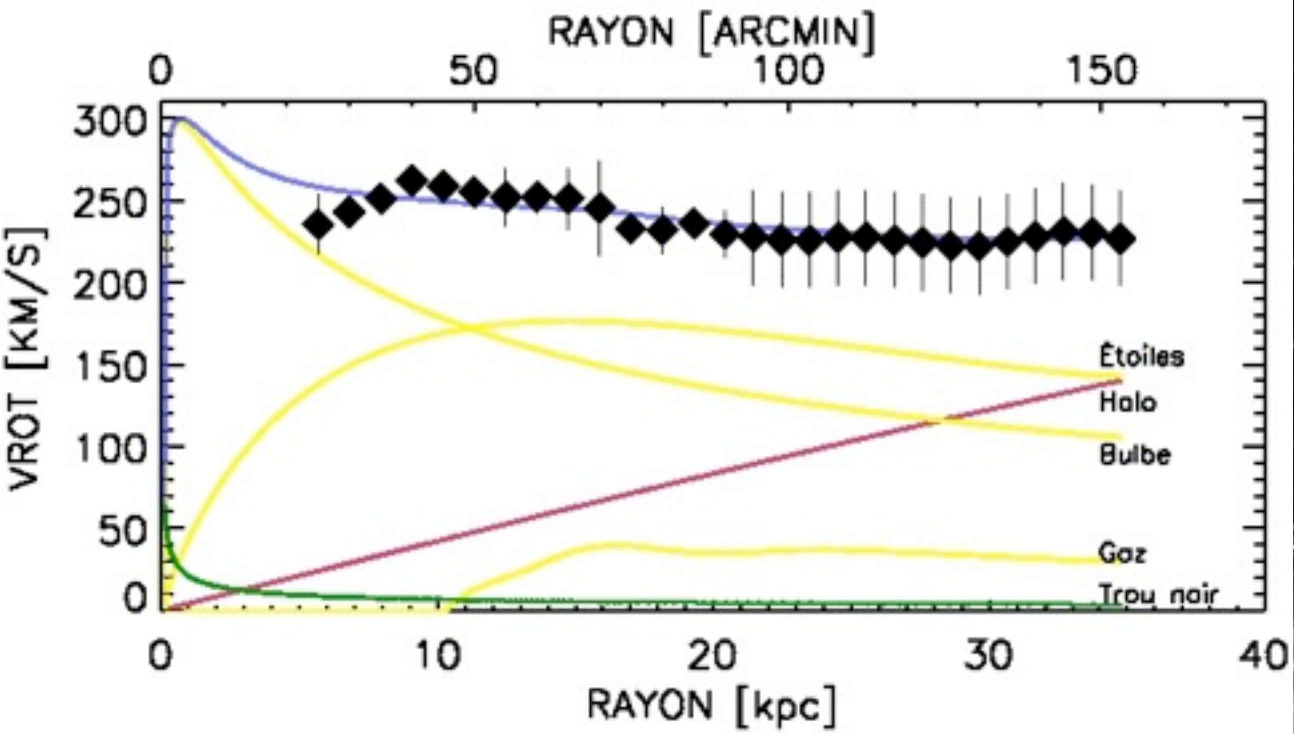


~10¹¹ stars
75,000 ly
60,000 ly
45,000 ly
15,000 ly
30°
330°
60°
300°
90°
270°
120°
240°
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar
28,000
light years
Sun
Orion Spur
Outer Arm
Perseus Arm


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
Long Bar
Outer Arm
Perseus Arm
Orion Spur
300
200
100
orbital speed (km/sec)
Sun
10
20
30
40
50
60
70
80
90
distance from center of Milky Way
(thousands of light-years)
few stars


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

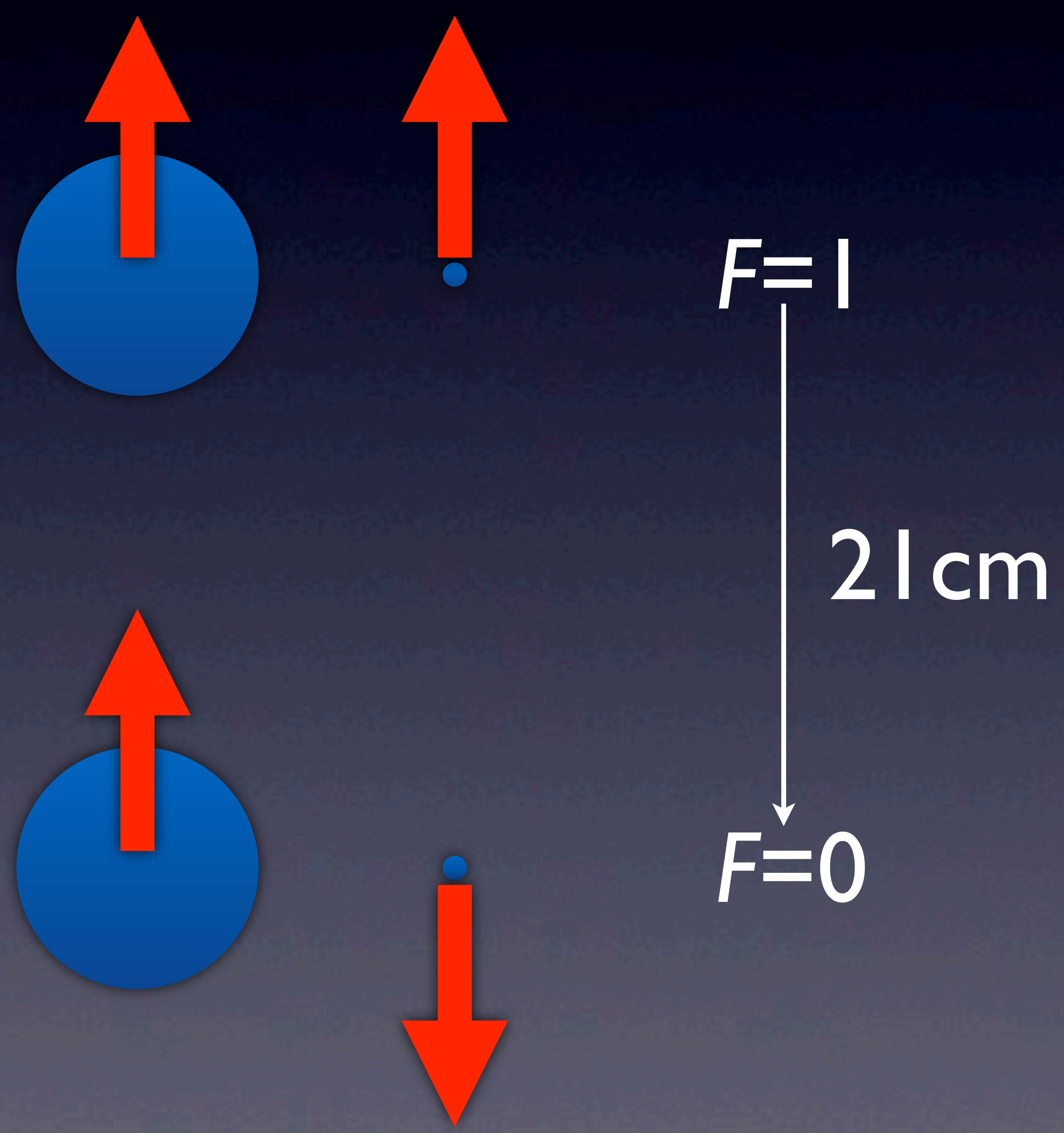

will collide with us
in 4.5 billion years
Andromeda M33 = 2.5M lyr

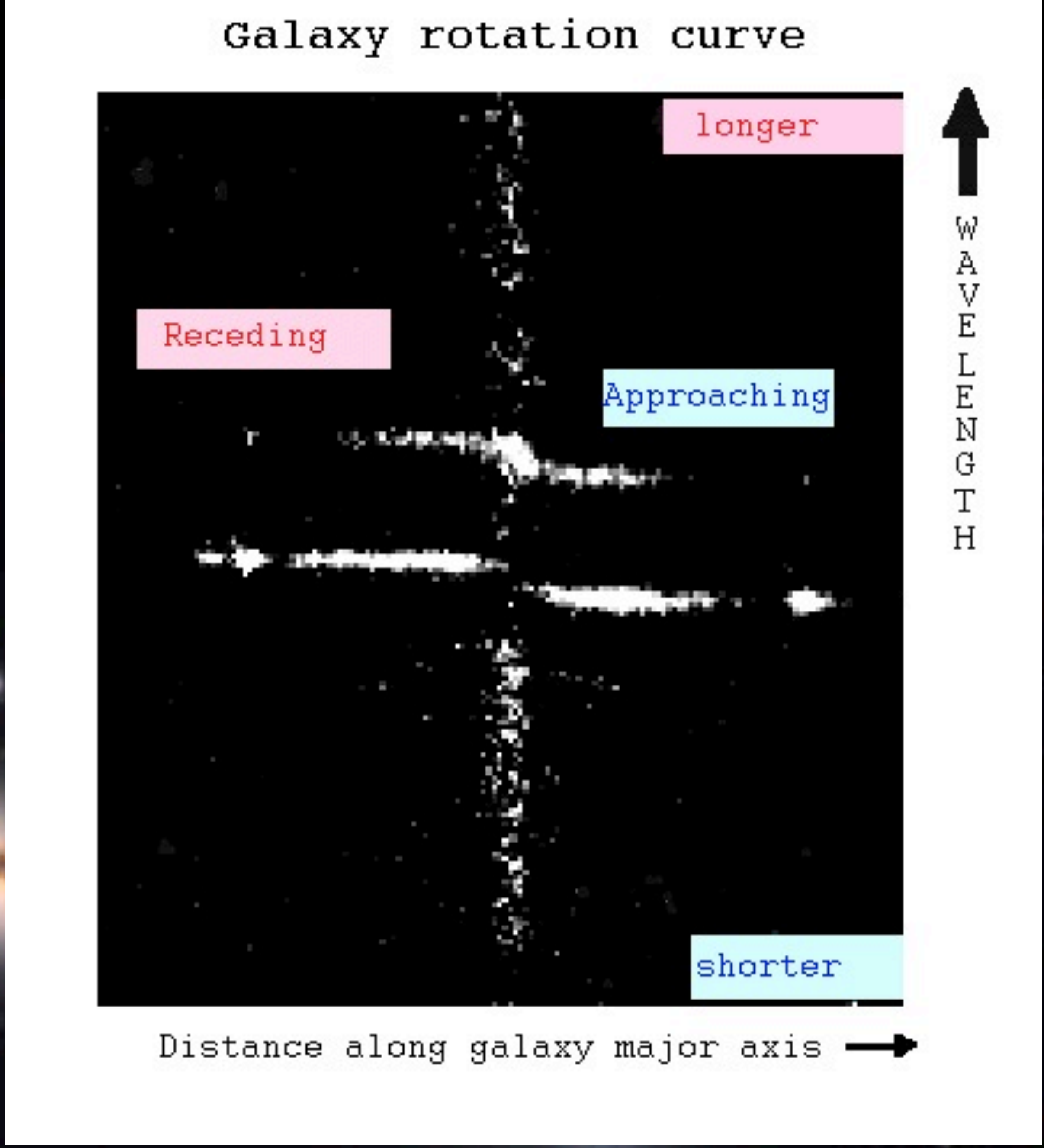
How do we measure the rotation curve?

- 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

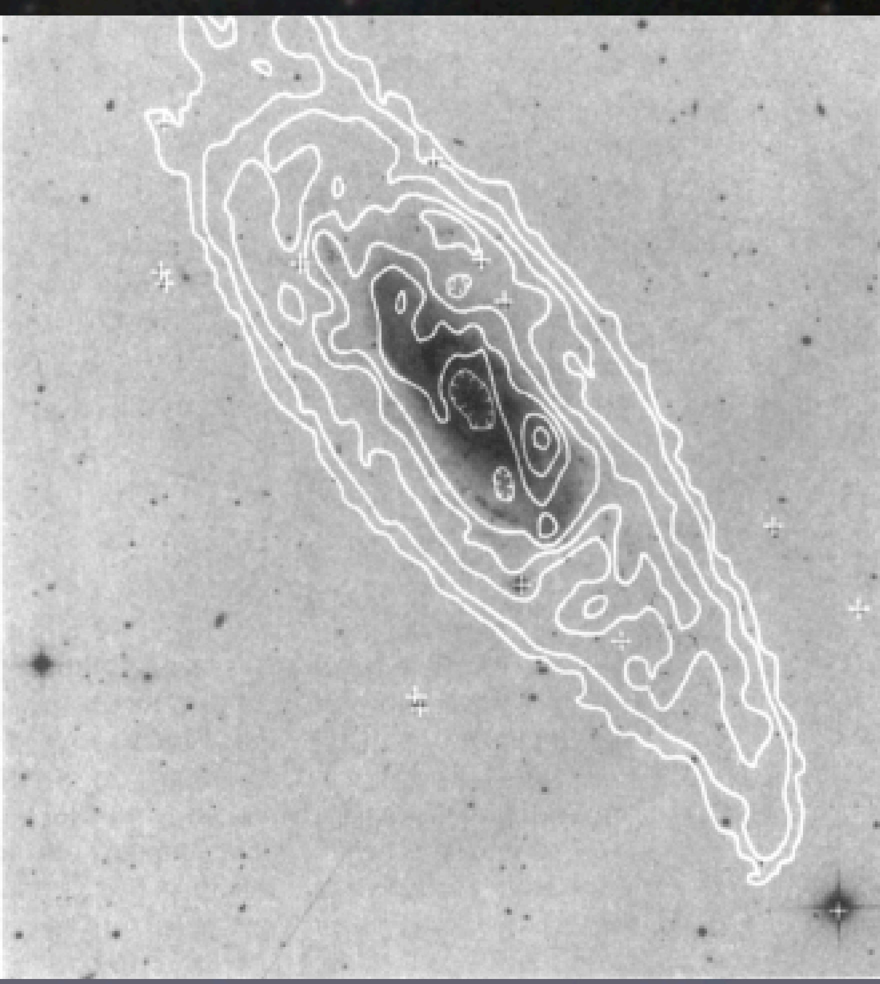


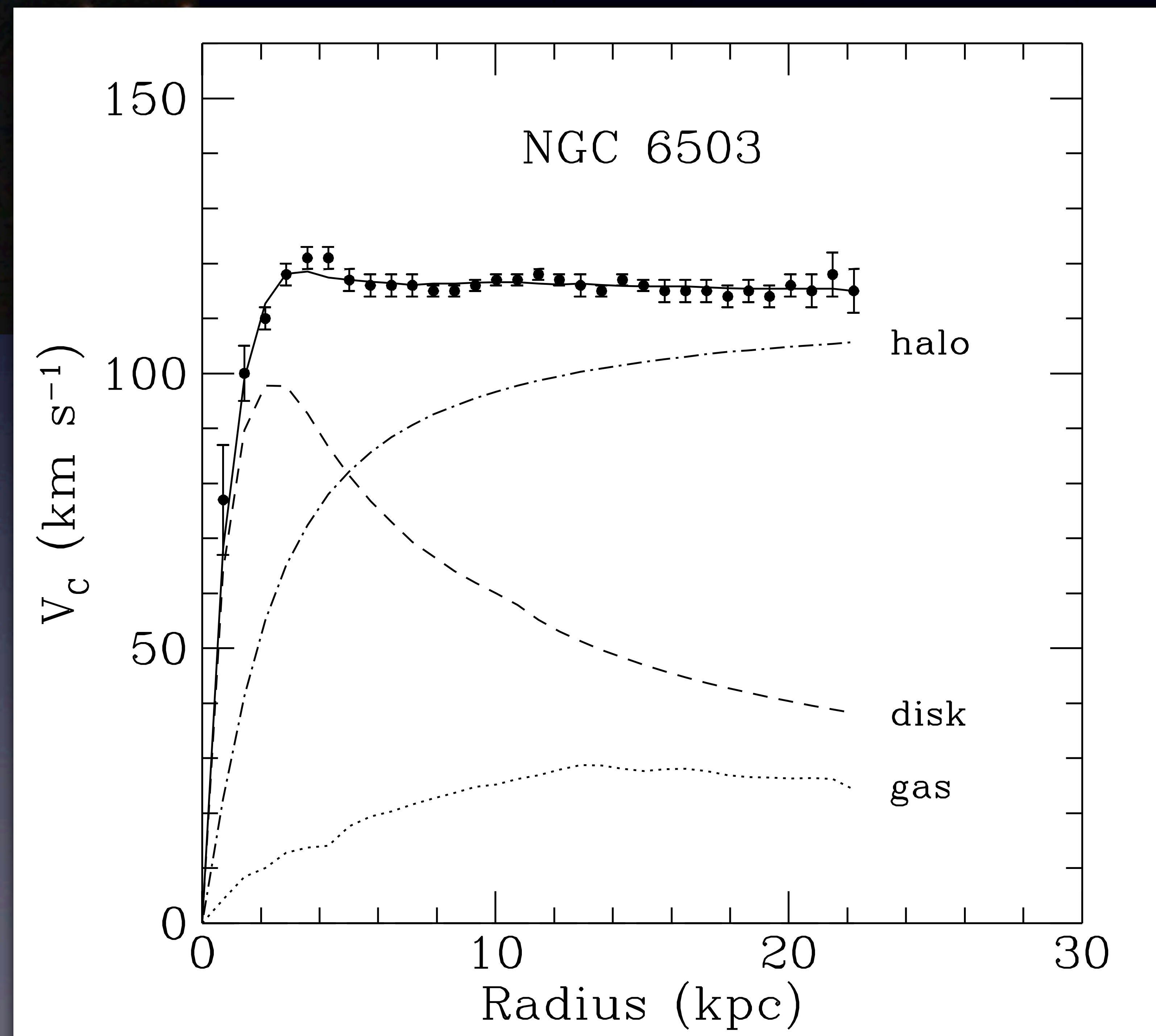


Galaxy rotation curve
longer
Receding
Approaching
shorter
WAVELENGTH
Distance along galaxy major axis

Vera
Rubin

1960s




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

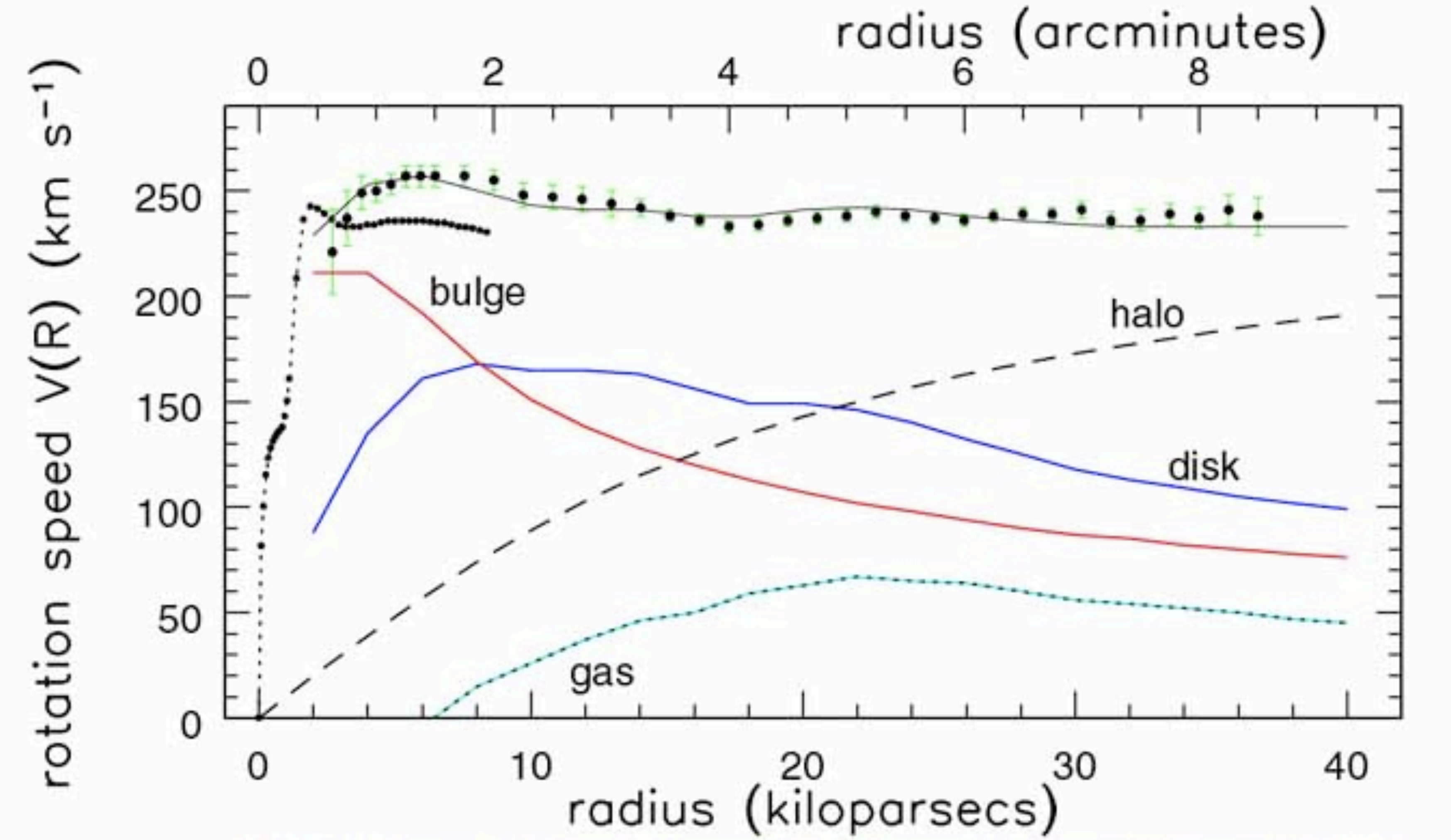
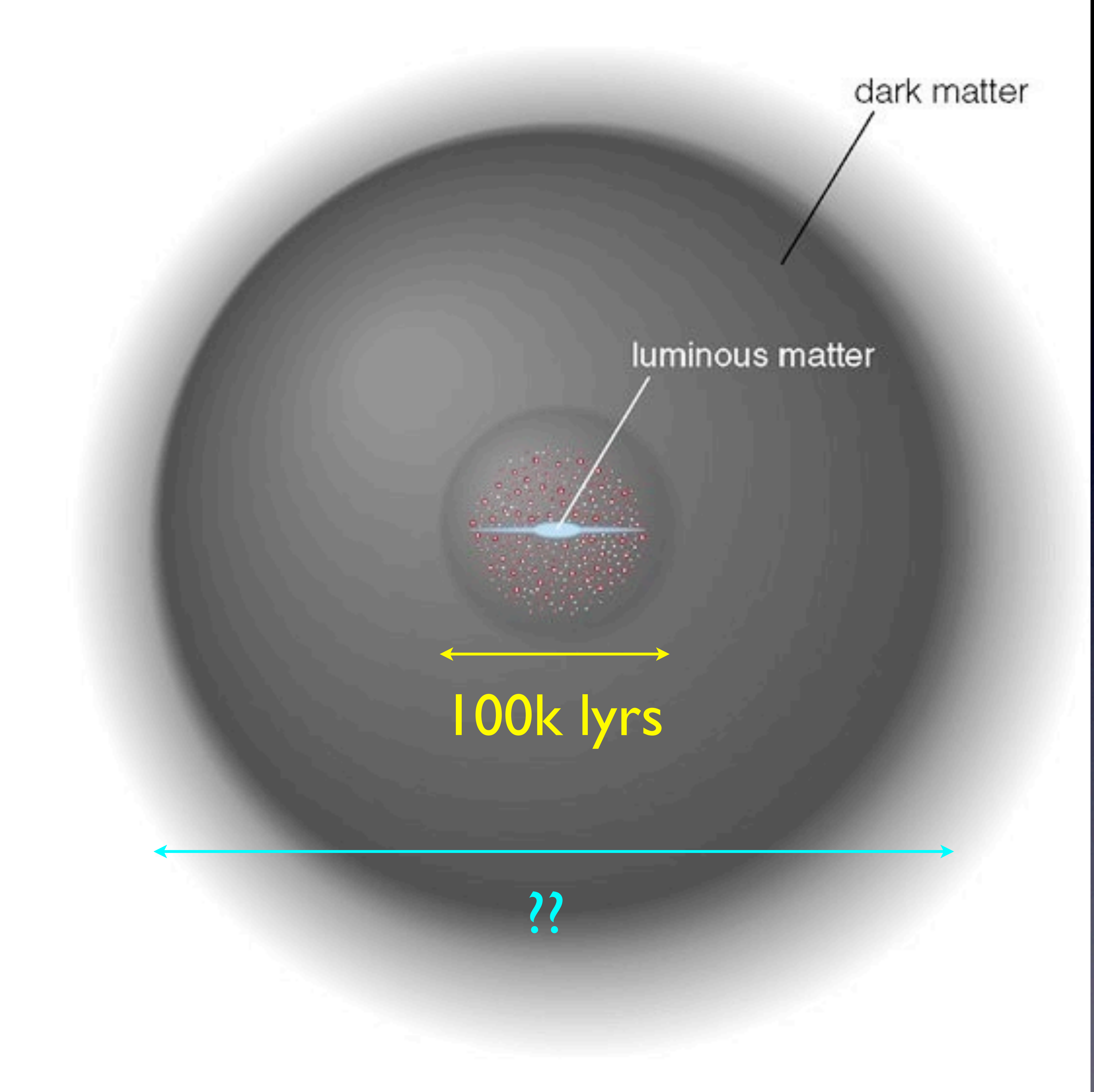


Fig 5.20 (Begeman, Sofue) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007


dark matter
luminous matter
100k lyrs
??

connects galaxies

stacking 85k quasars near 20M galaxies

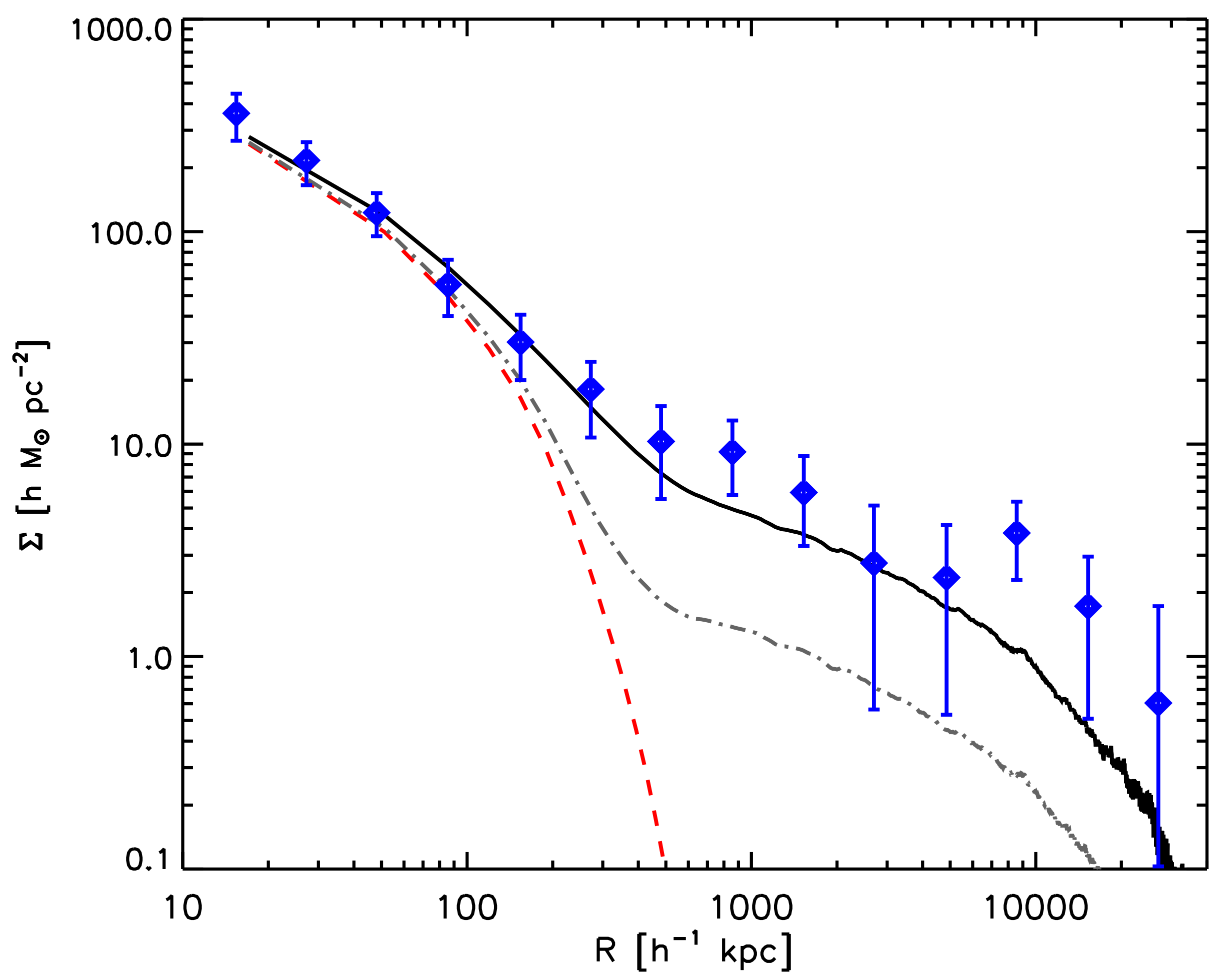


Fig. 2.— The mean surface mass density profile as a function of the distance from the centre of galaxies. The thick solid curve is the mean of all haloes above the mass threshold. The dash-dotted curve represents the contribution from particles bound to haloes, i.e., particles that reside within the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

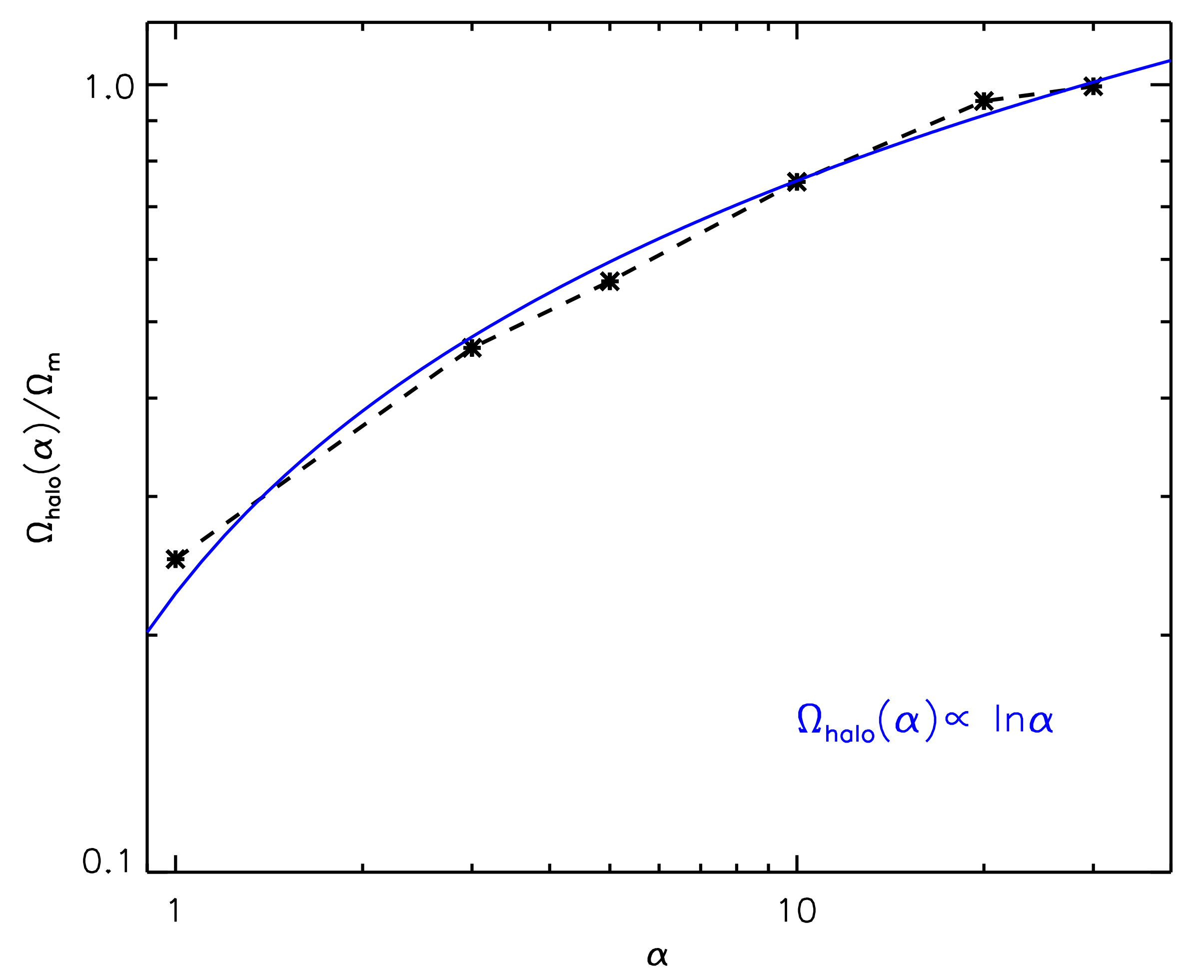
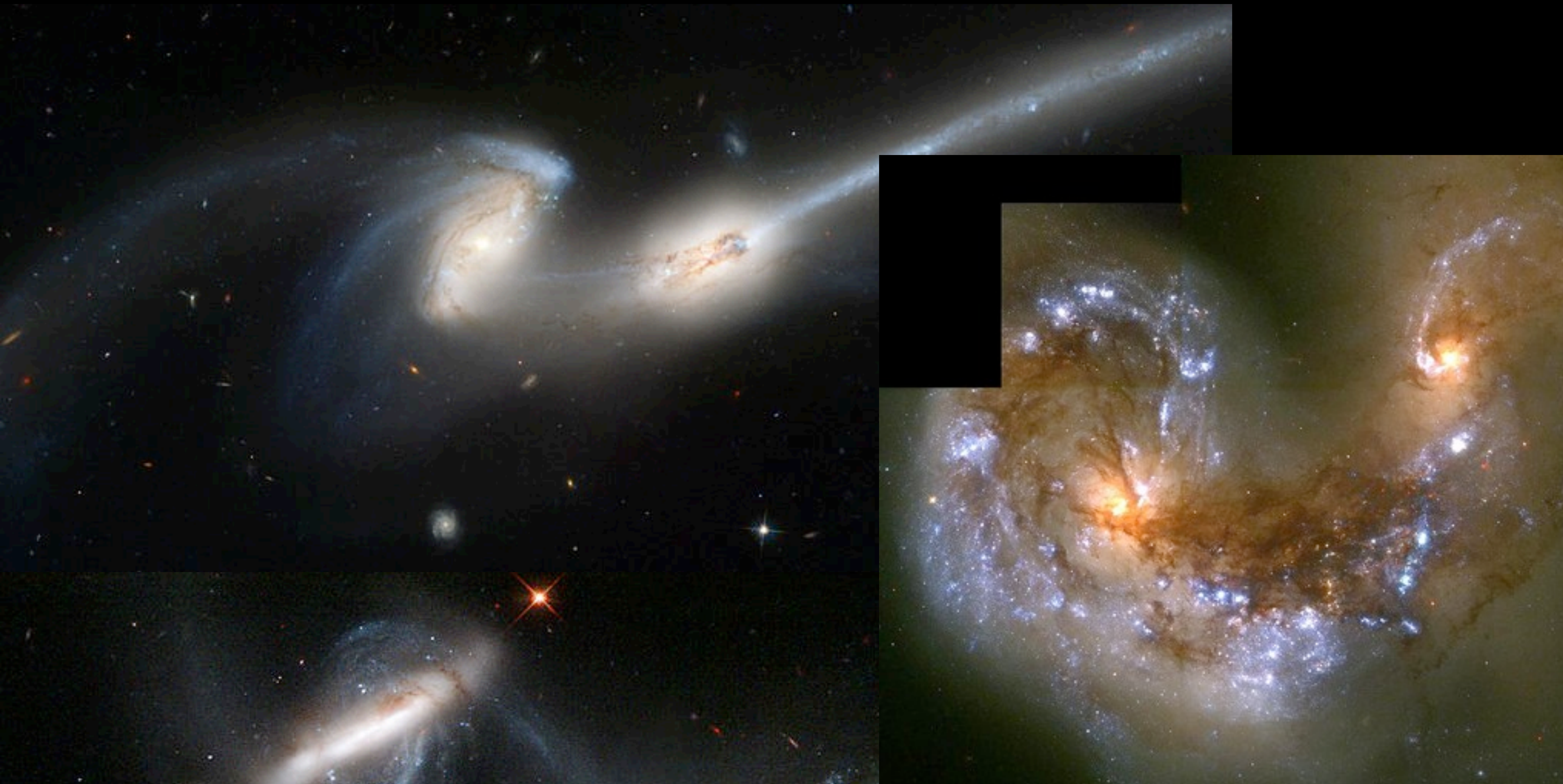


Fig. 4.— Fraction of mass contained in the sphere centred on individual haloes with radius $\alpha R_{\rm vir}$, where $R_{\rm vir}$ is the pseudovirial radius and α is the multiplier represented in the abscissa. The solid curve is $0.23 \ln +0.23$ given in the text.

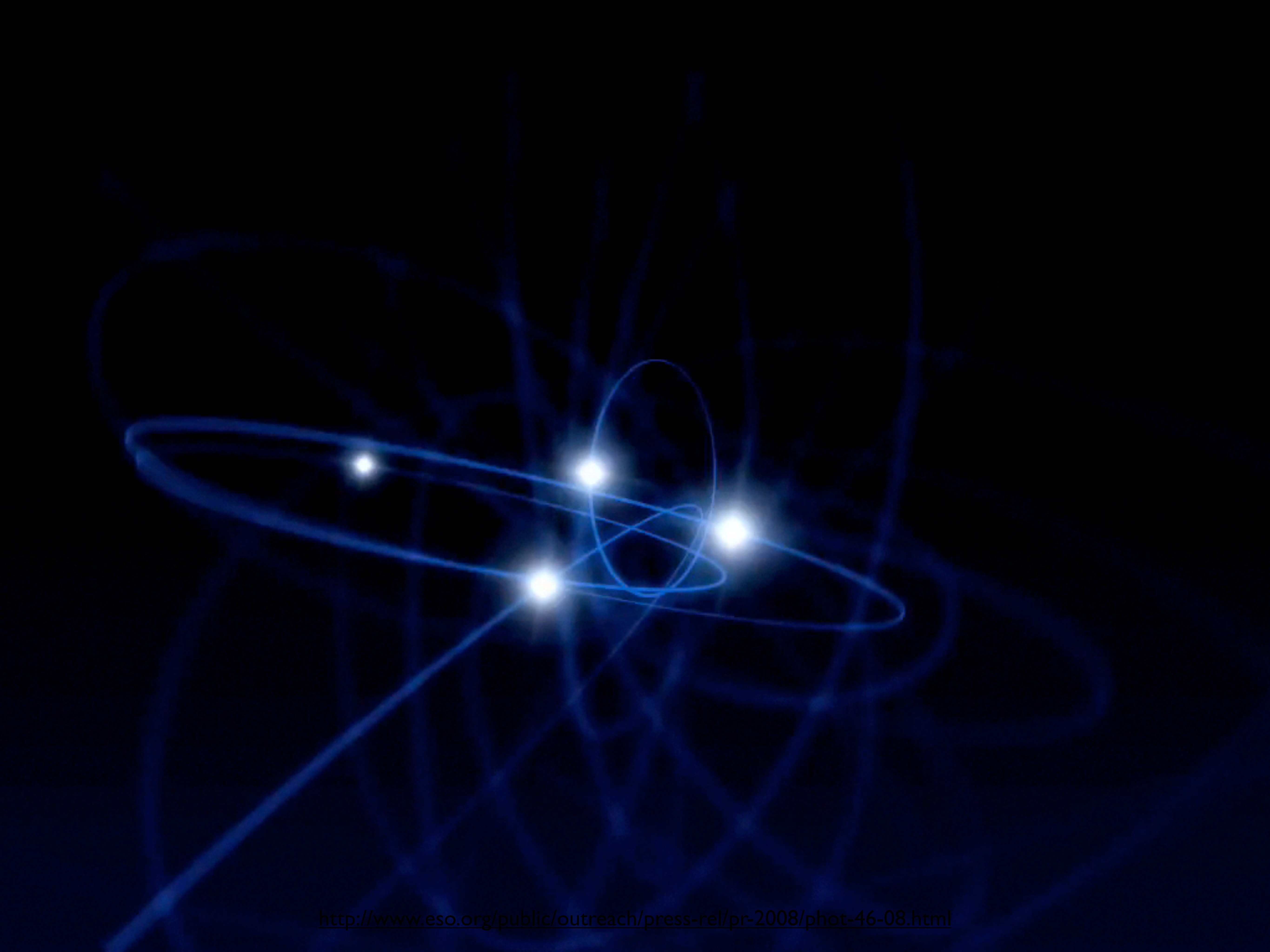
Ménard et al 2009

Masaki Fukugita Yoshida 2011




galaxies
rejuvenated
after mergers

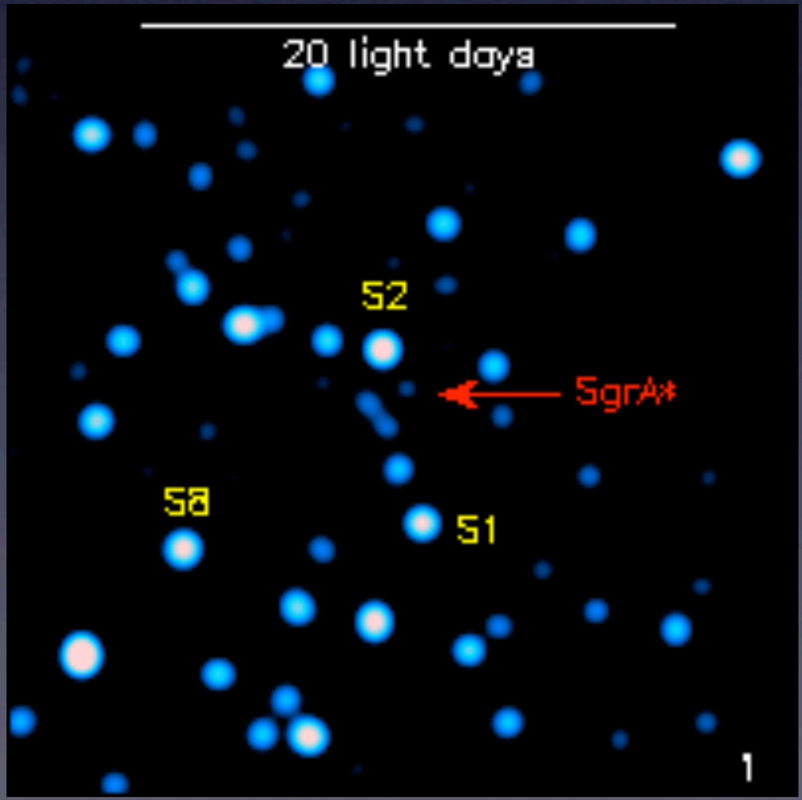
Center of Milky Way



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

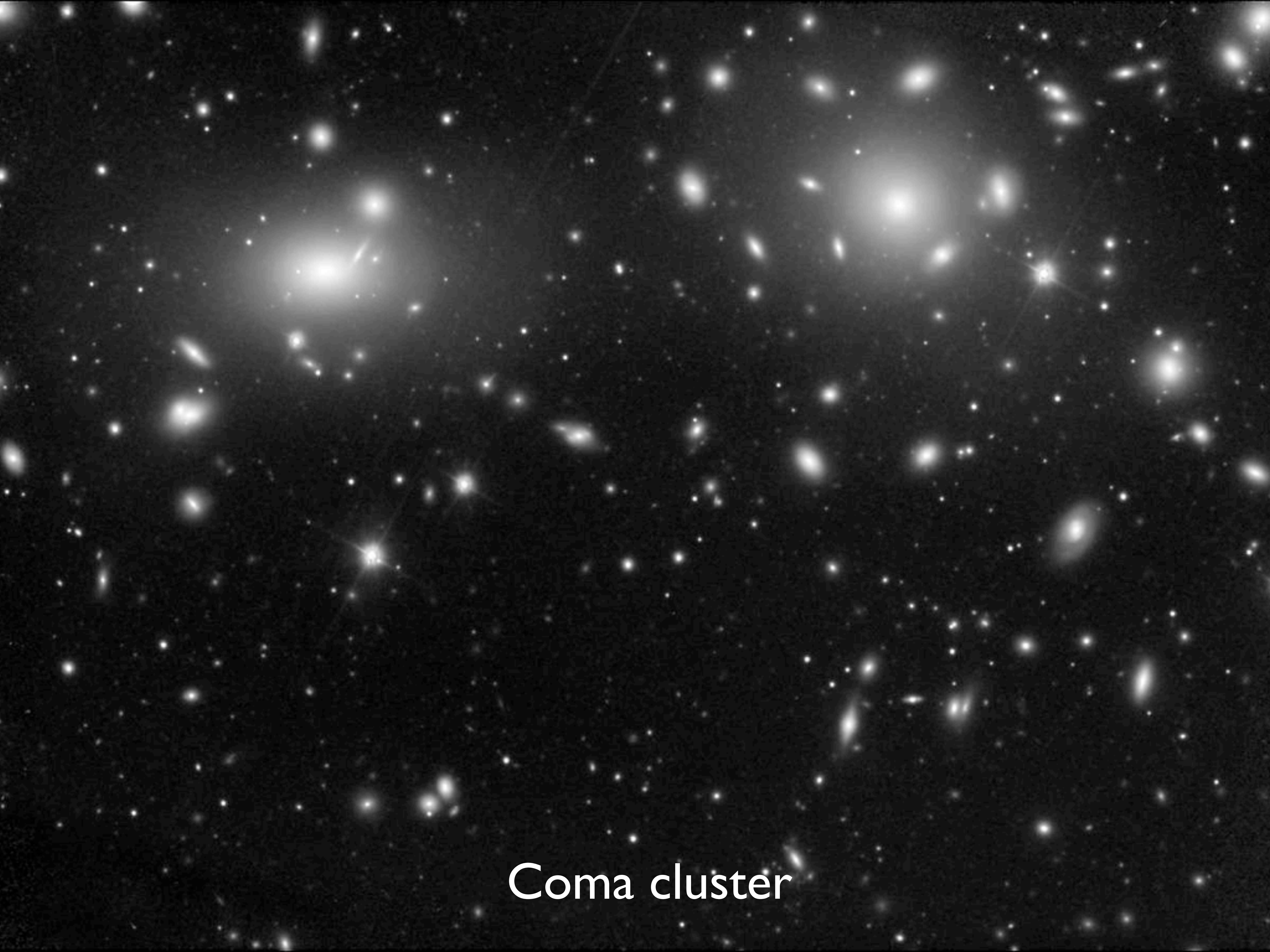
Supermassive Black Hole

- 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



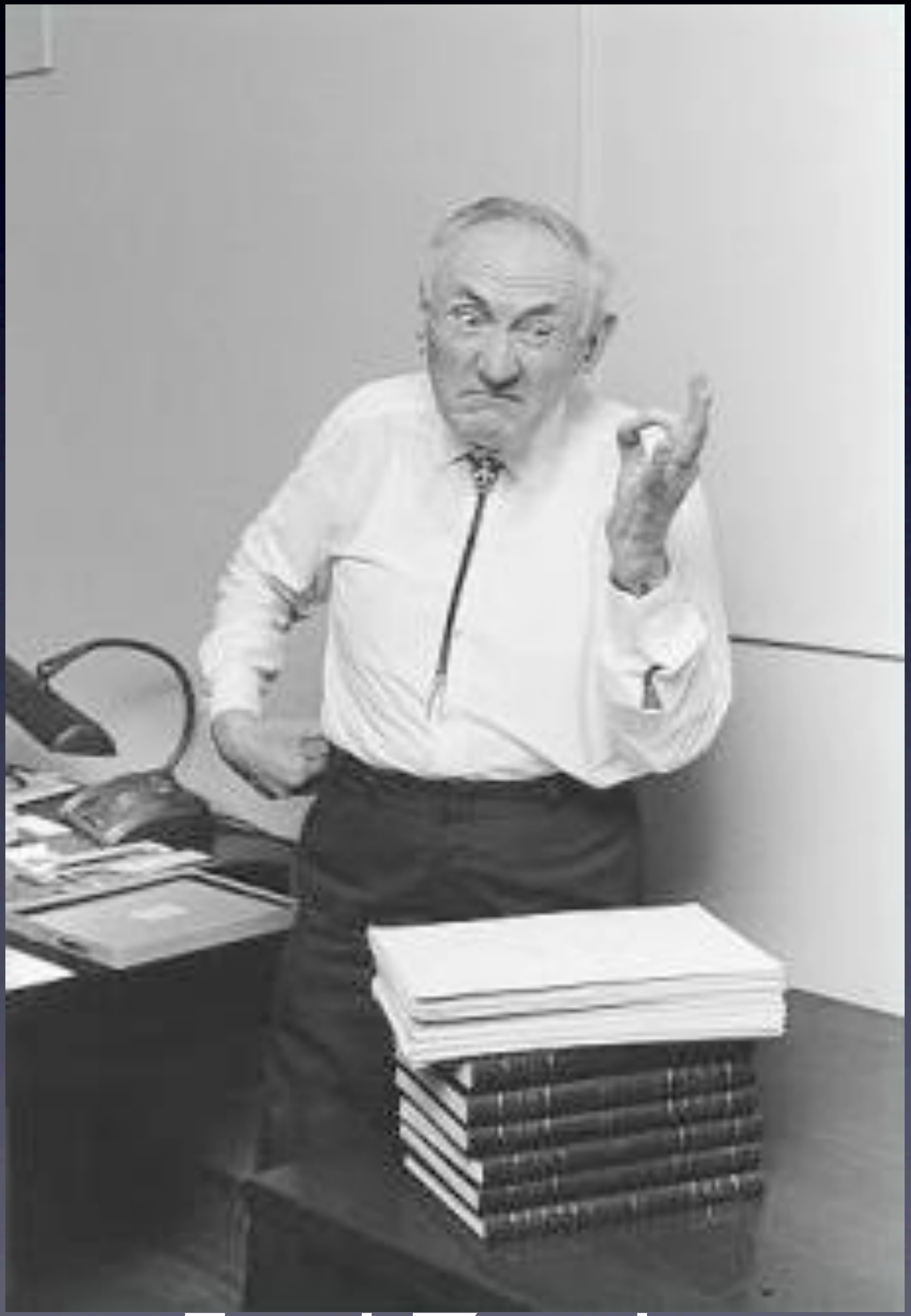
http://www.eso.org/public/outreach/press-rel/pr-2008/phot-46-08.html


Cluster of Galaxies


Coma cluster

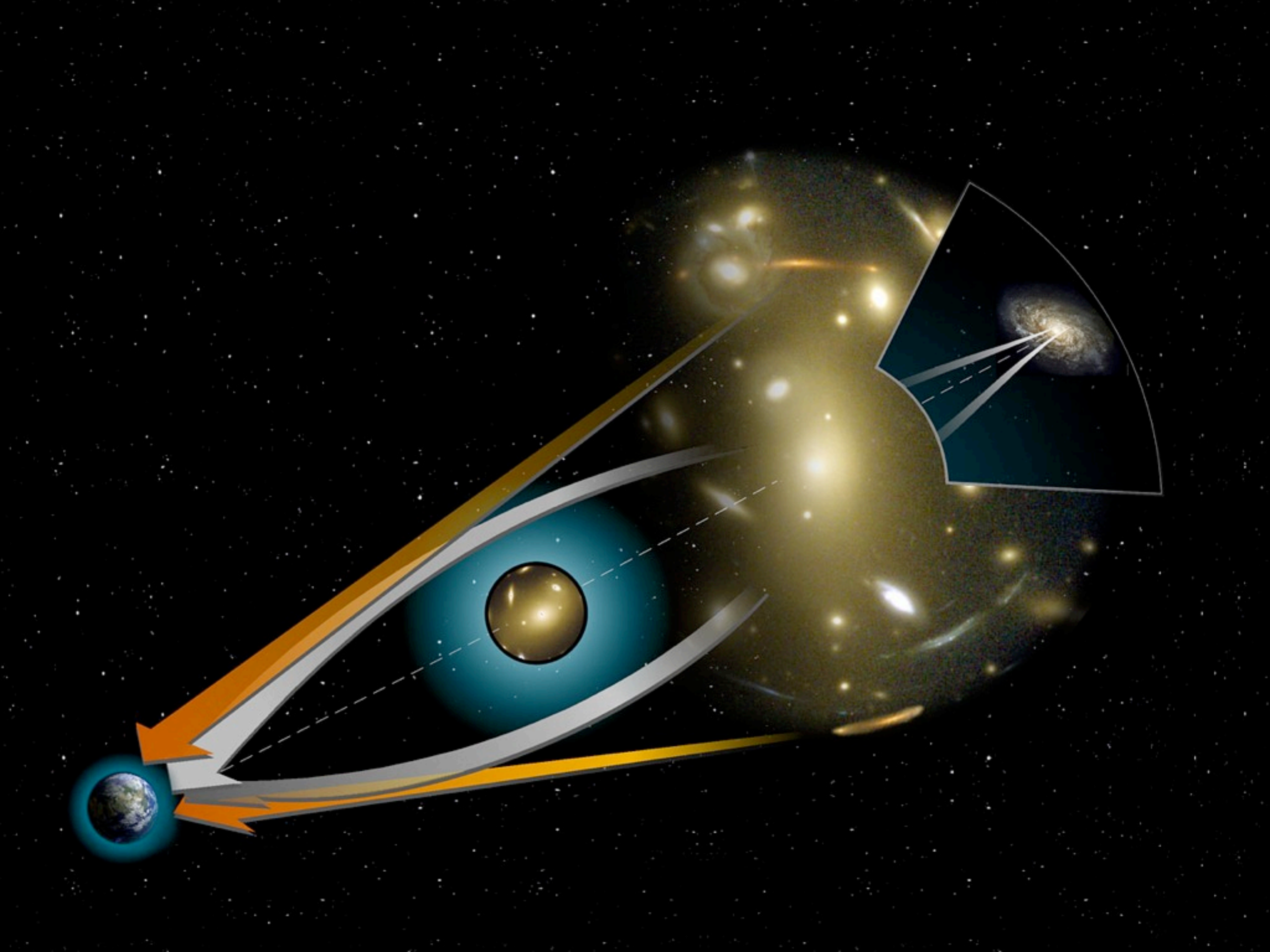
motion of galaxies

- 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"

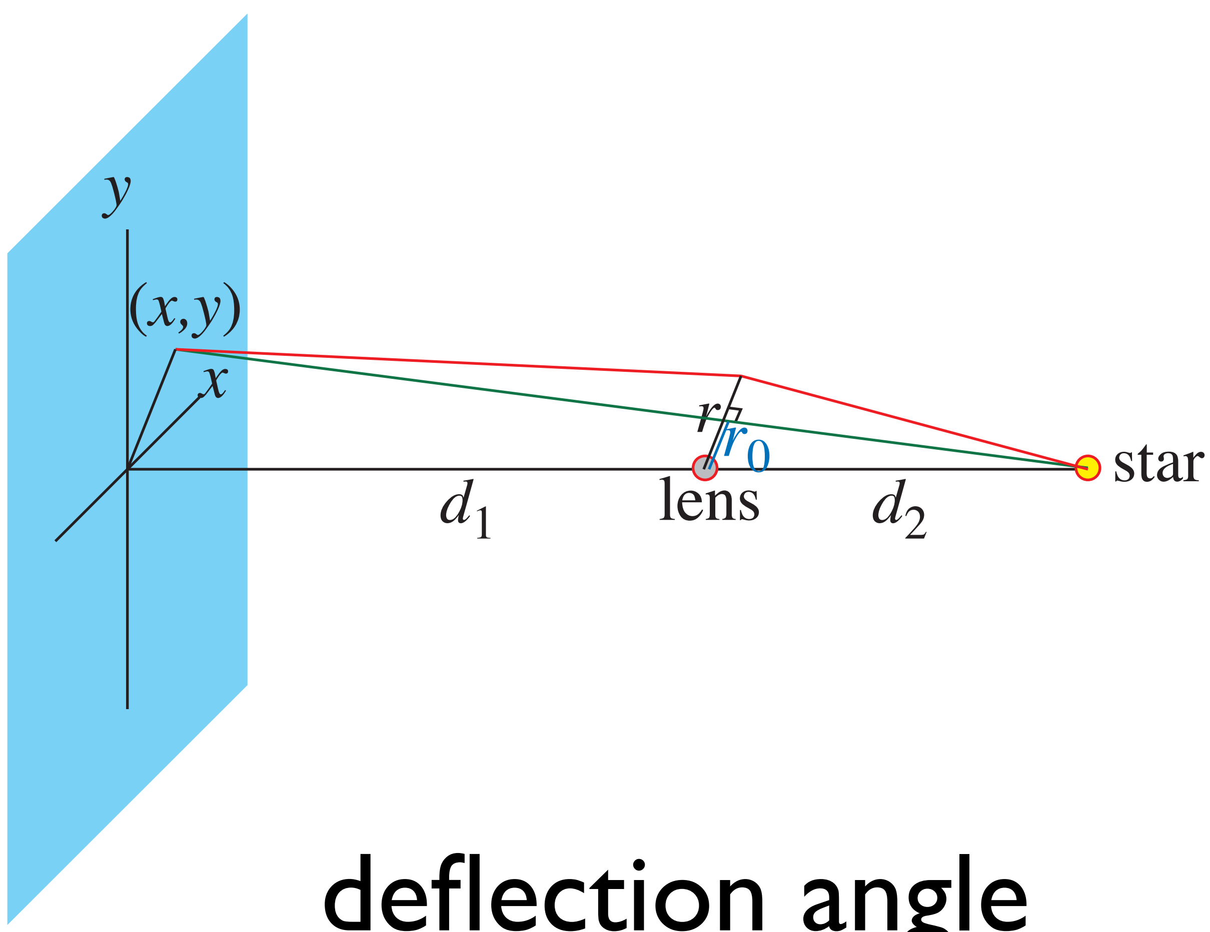


Fred Zwicky

gravitational lensing

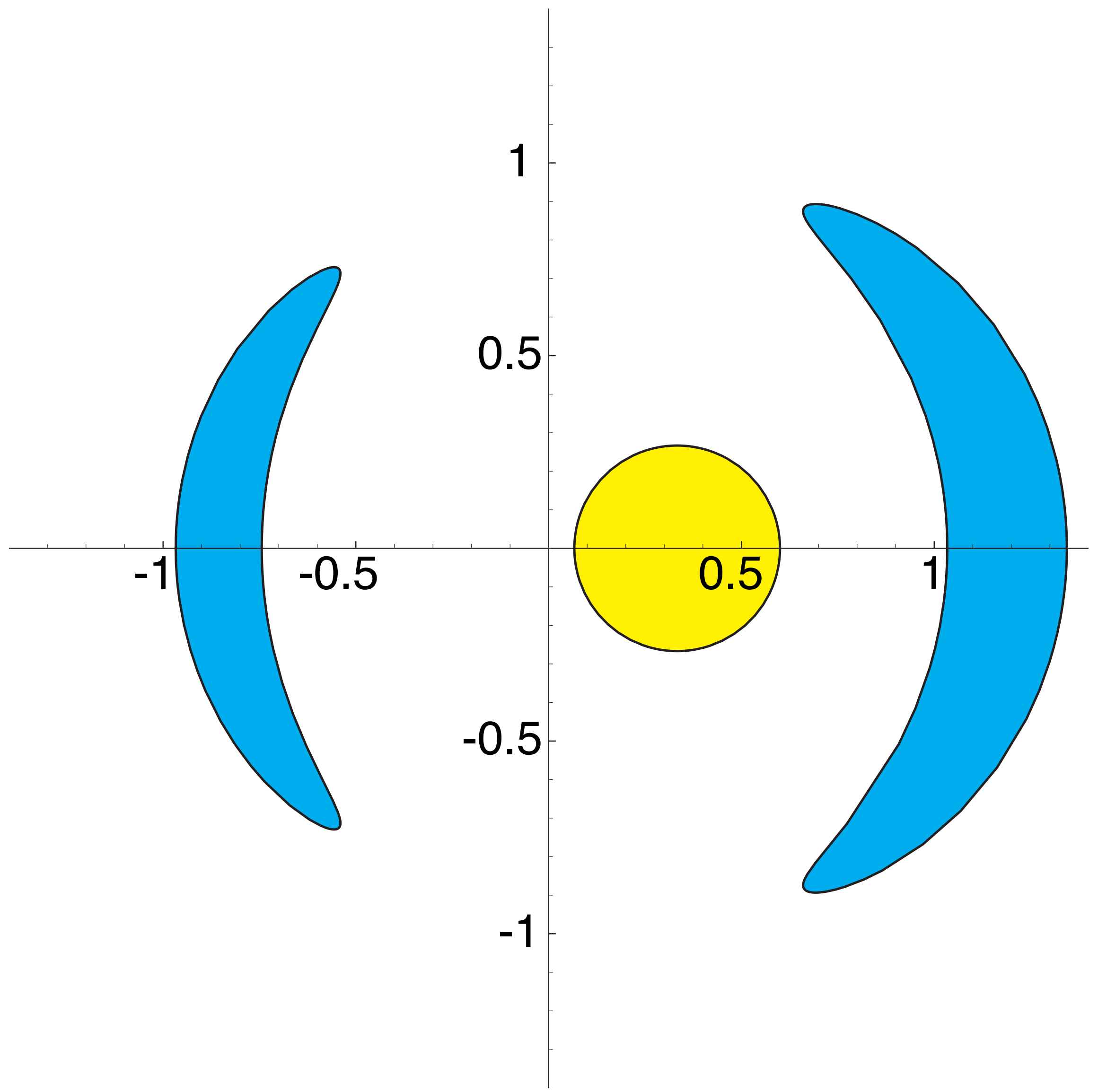


gravitational lensing



deflection angle

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



gravitational lensing

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

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

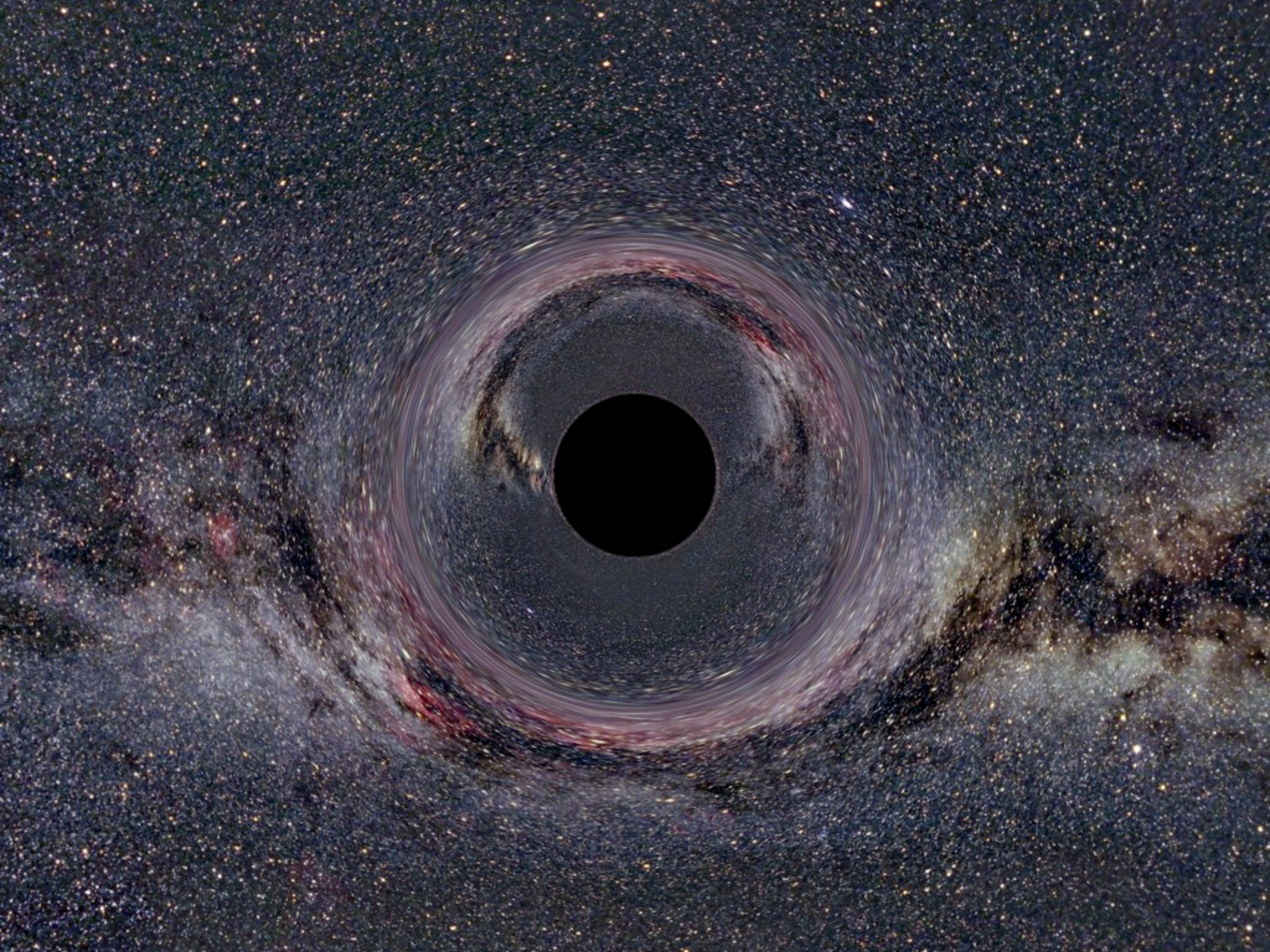
$$S(t, r, \theta) = Et - L\theta + W(E, r, L)$$

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

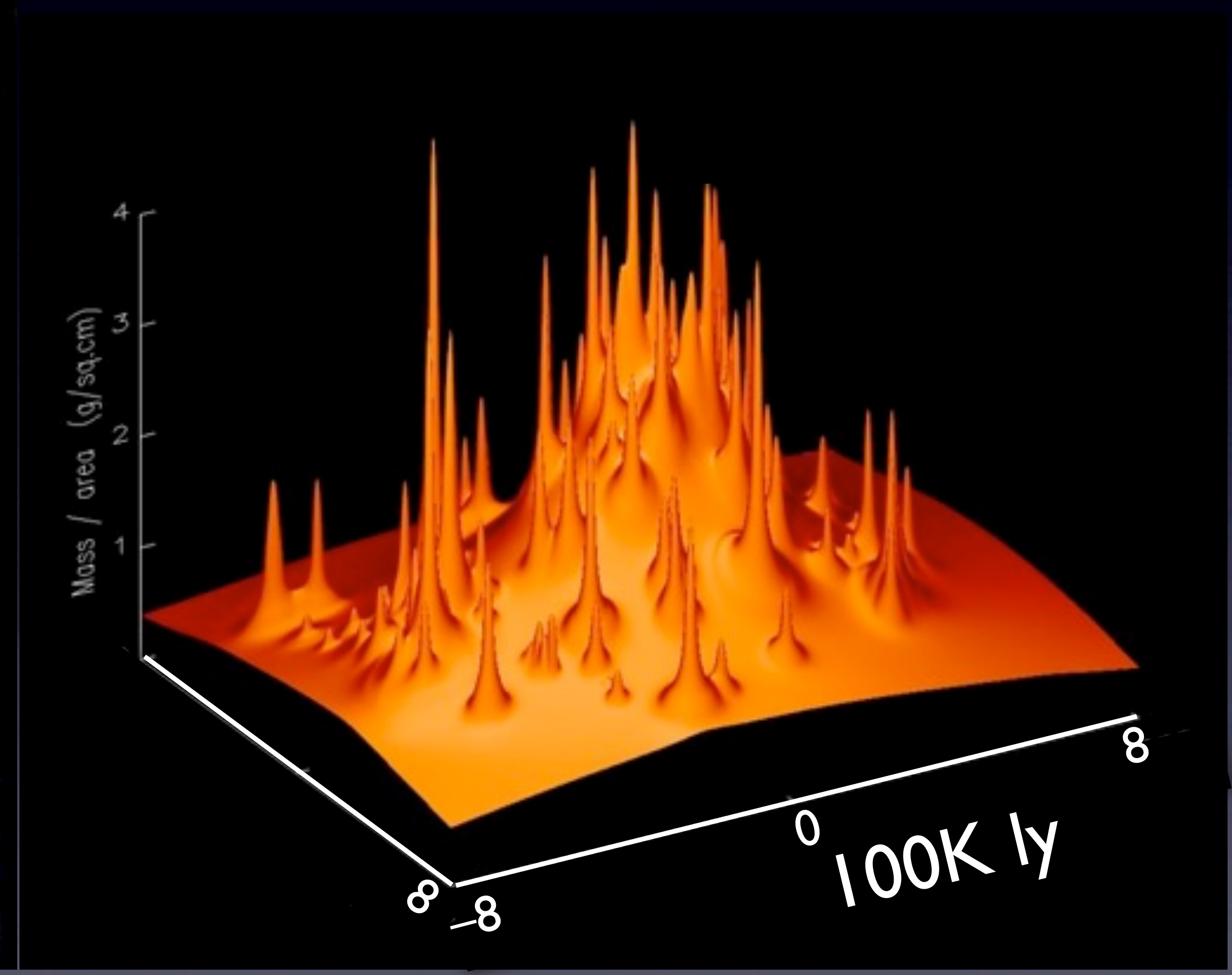
The closest approach r_c is where $\partial_r W = 0$

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

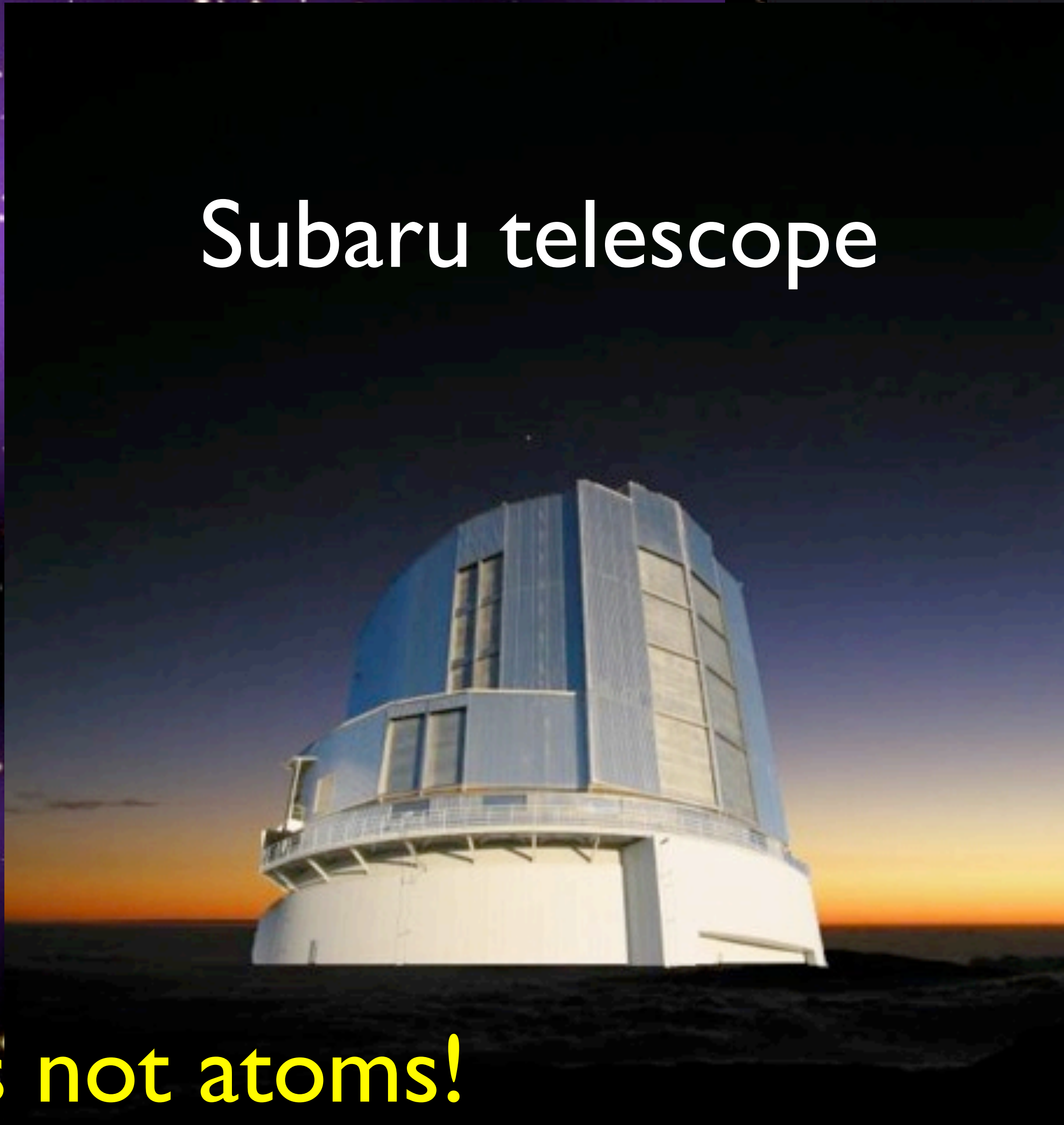
$$\pi + \Delta\theta = \partial_L W = 2\int_{r_c}^{\infty} \frac{dr}{r\sqrt{(1 - \frac{r_S}{r_c})\frac{r^2}{r_c^2} - (1 - \frac{r_S}{r})}} = \pi + \frac{2r_S}{r_c} + O(r_S^2)$$



Clusters of galaxies

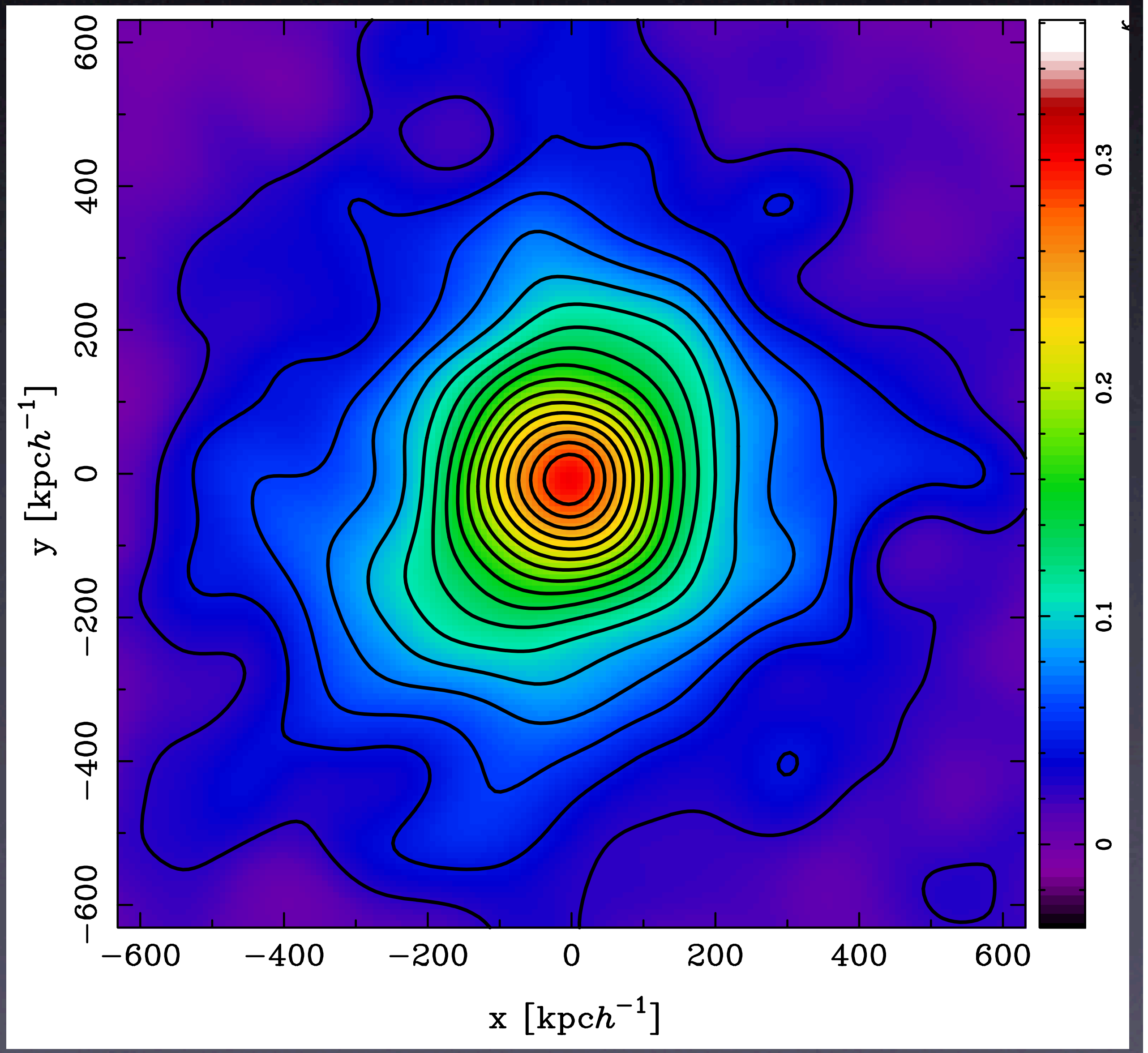


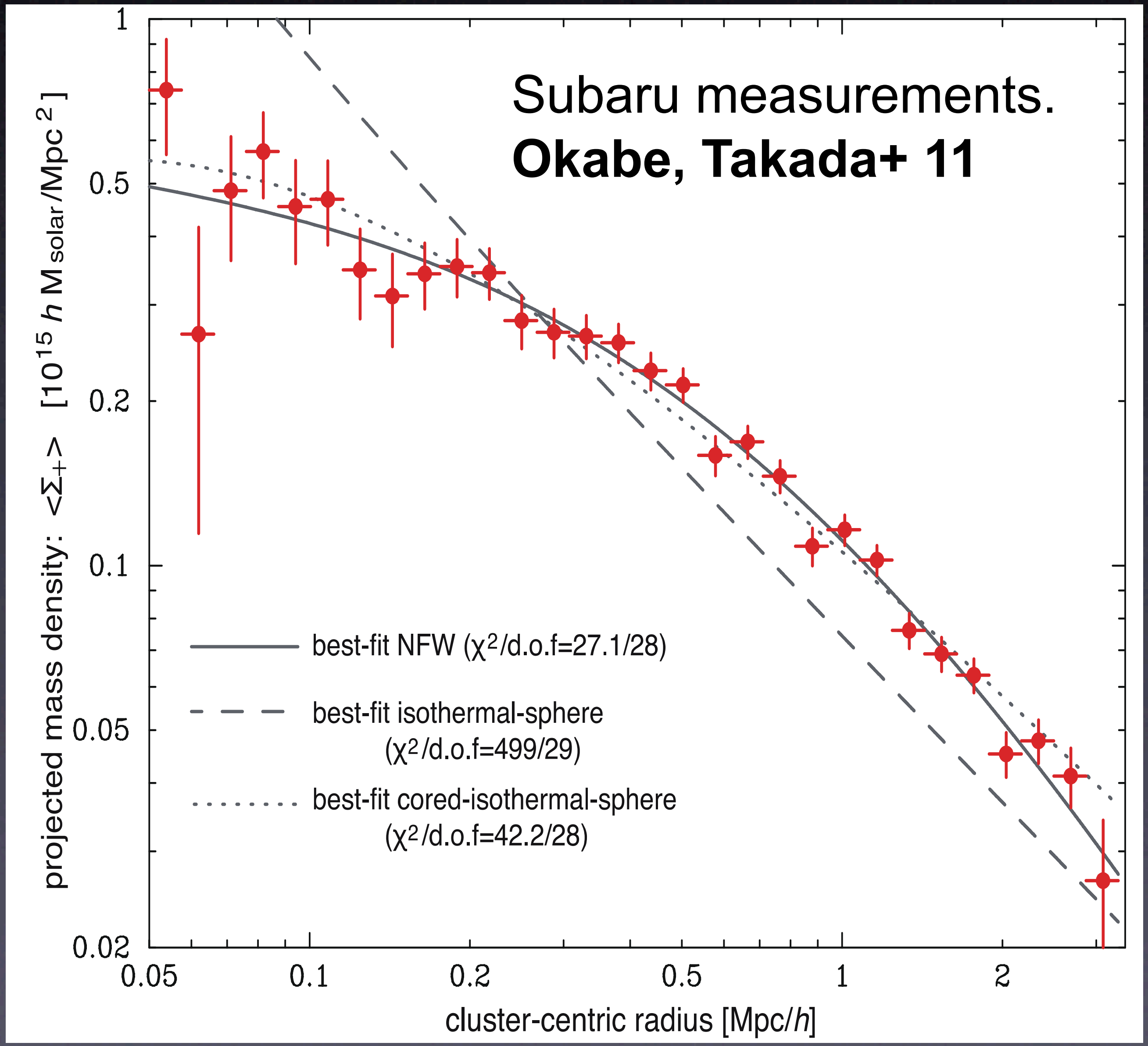
distortion in images of BG galaxies → 2D map of dark matter “see” invisible dark mat



more than 80% of matter is not atoms!

as expected by theory

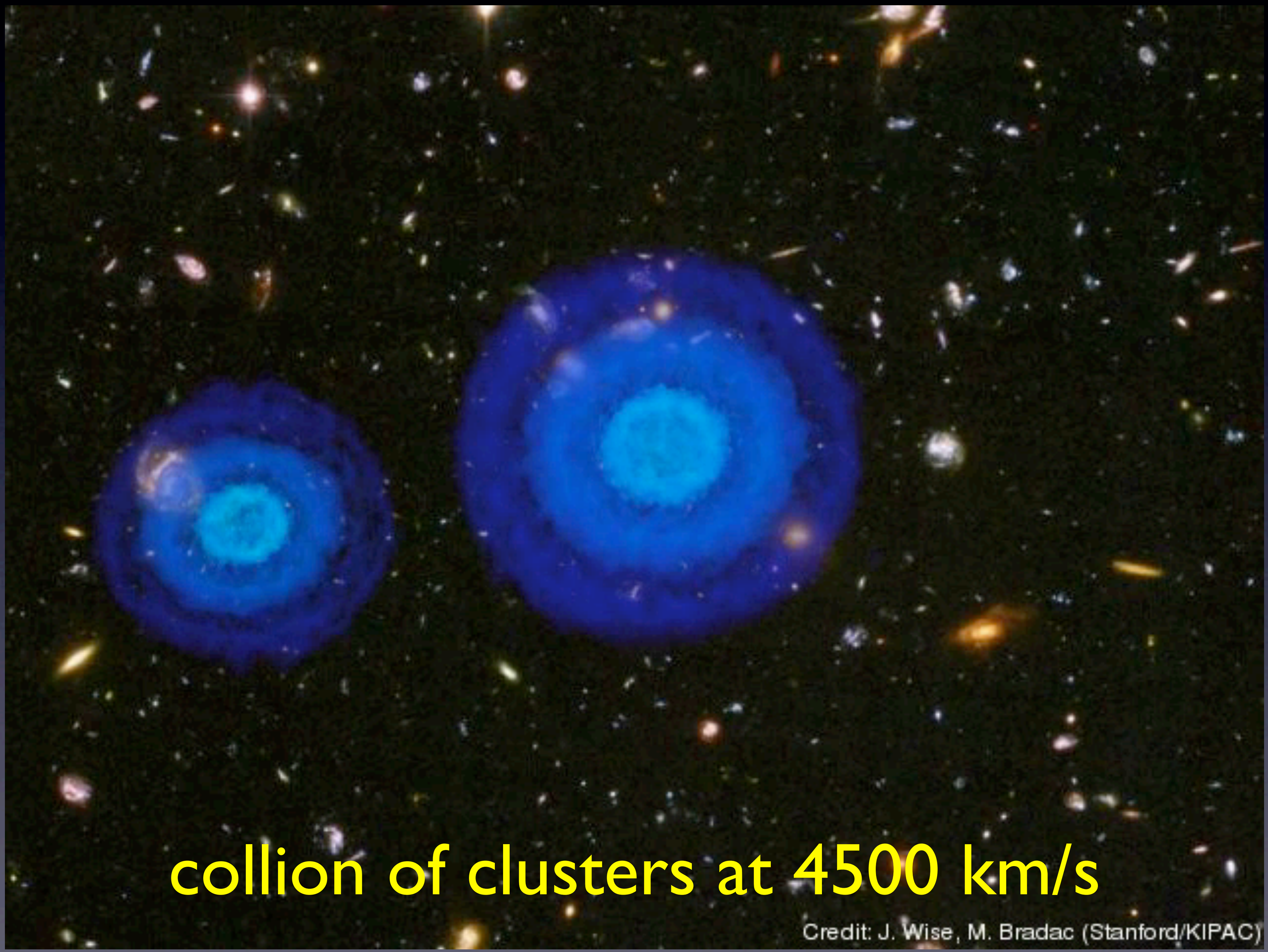




45 clusters stacked

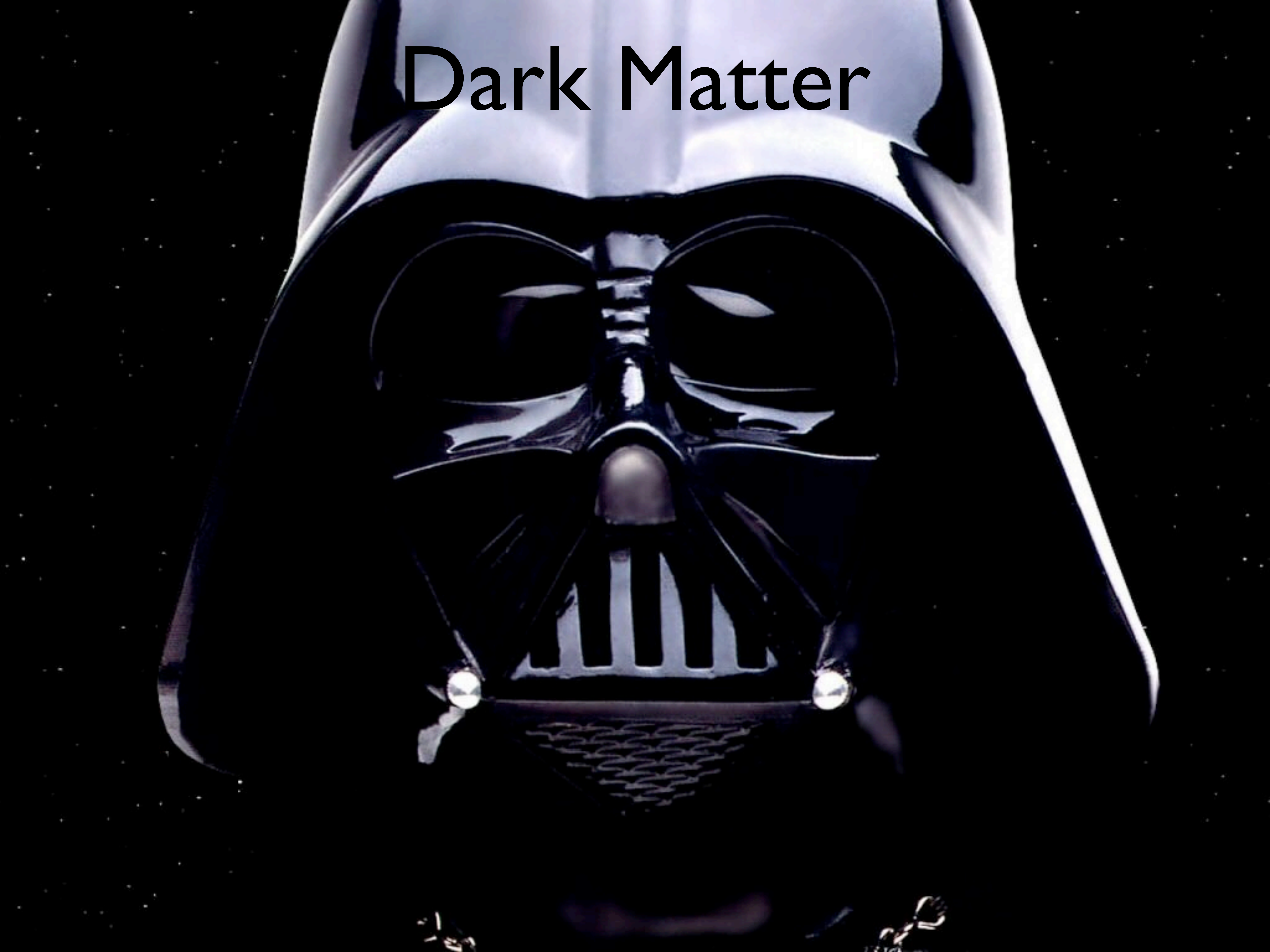
consistent with NFW profile

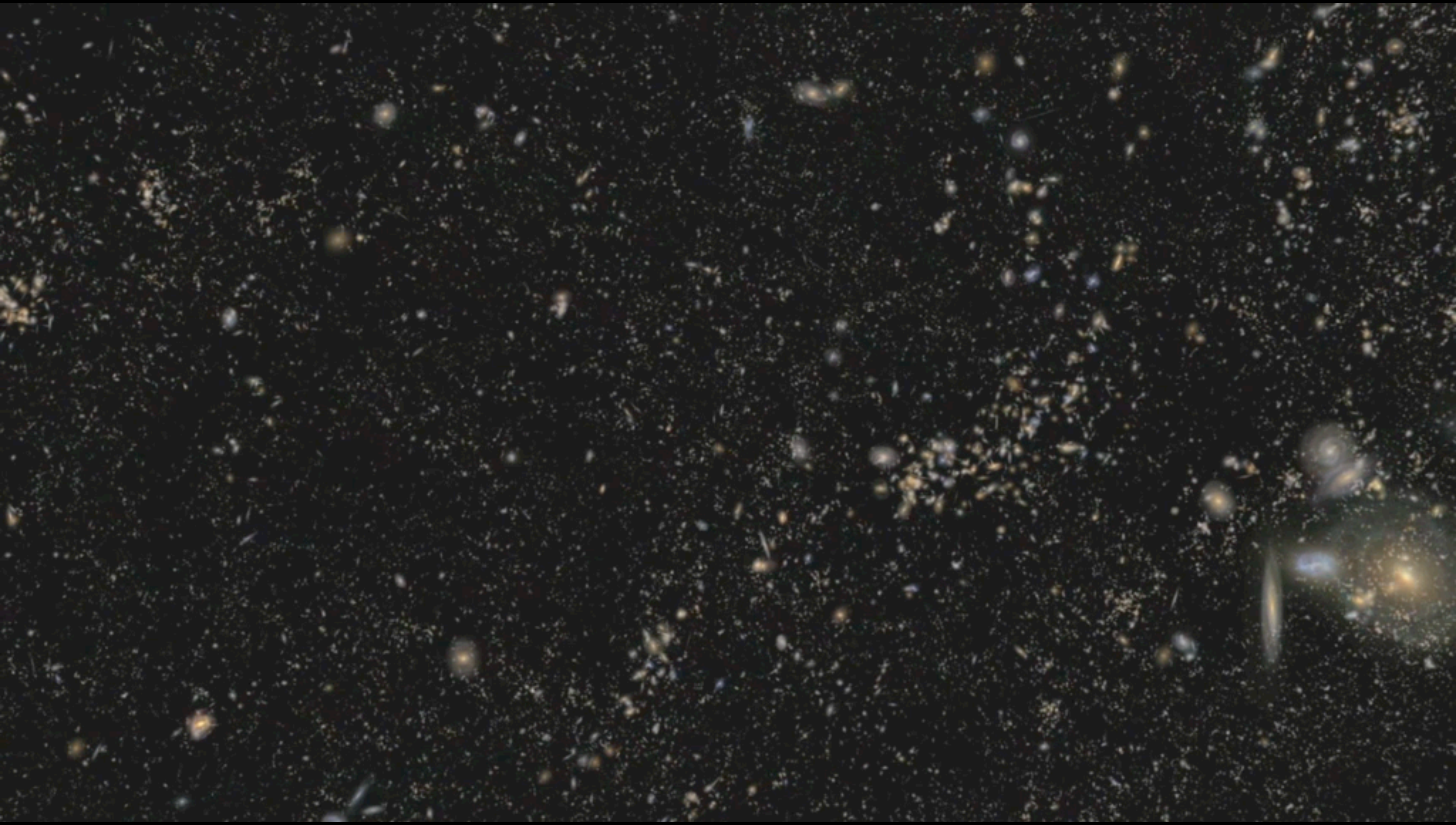
lucky we are not here



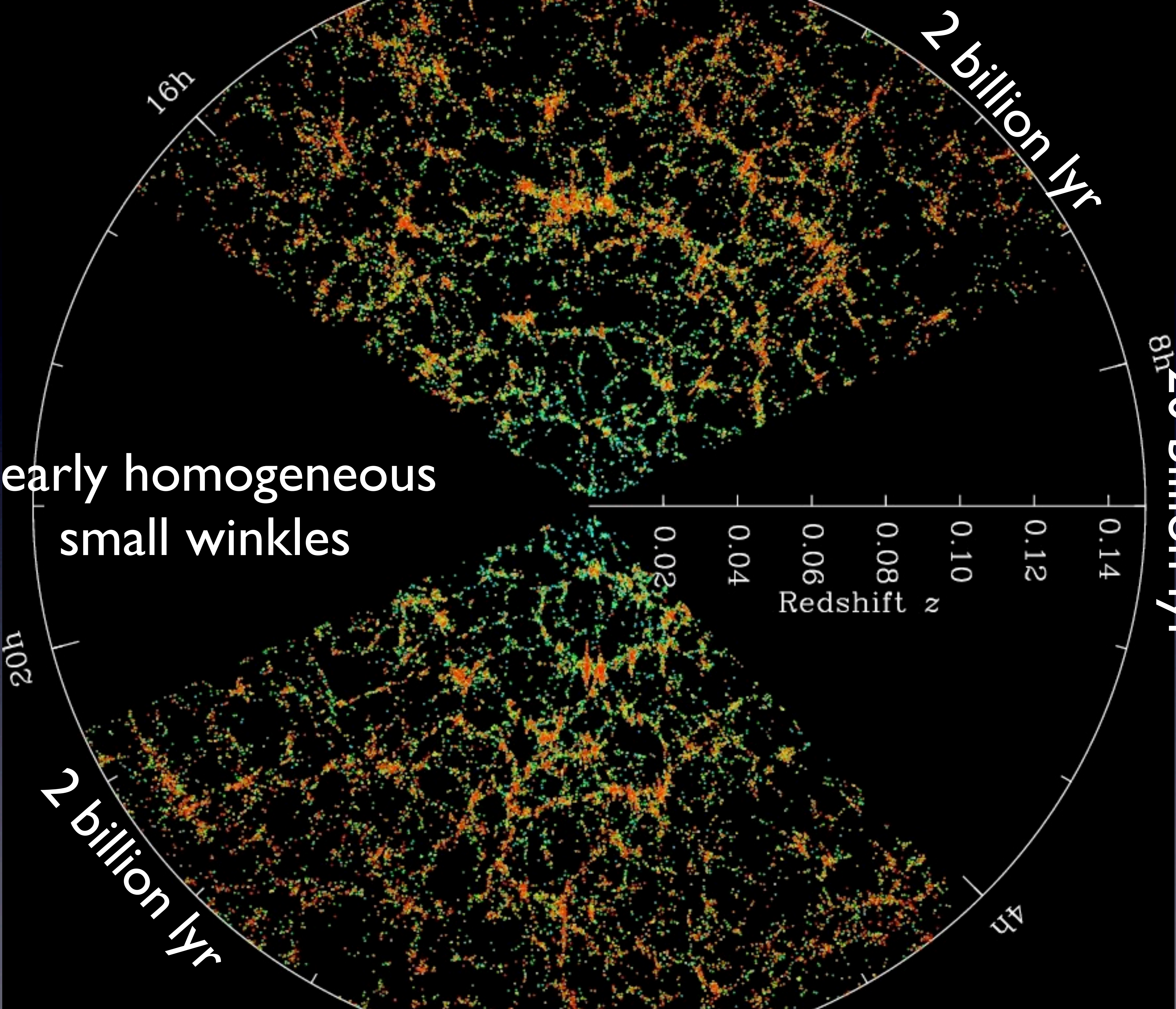
4 billion lyr away

Dark Matter

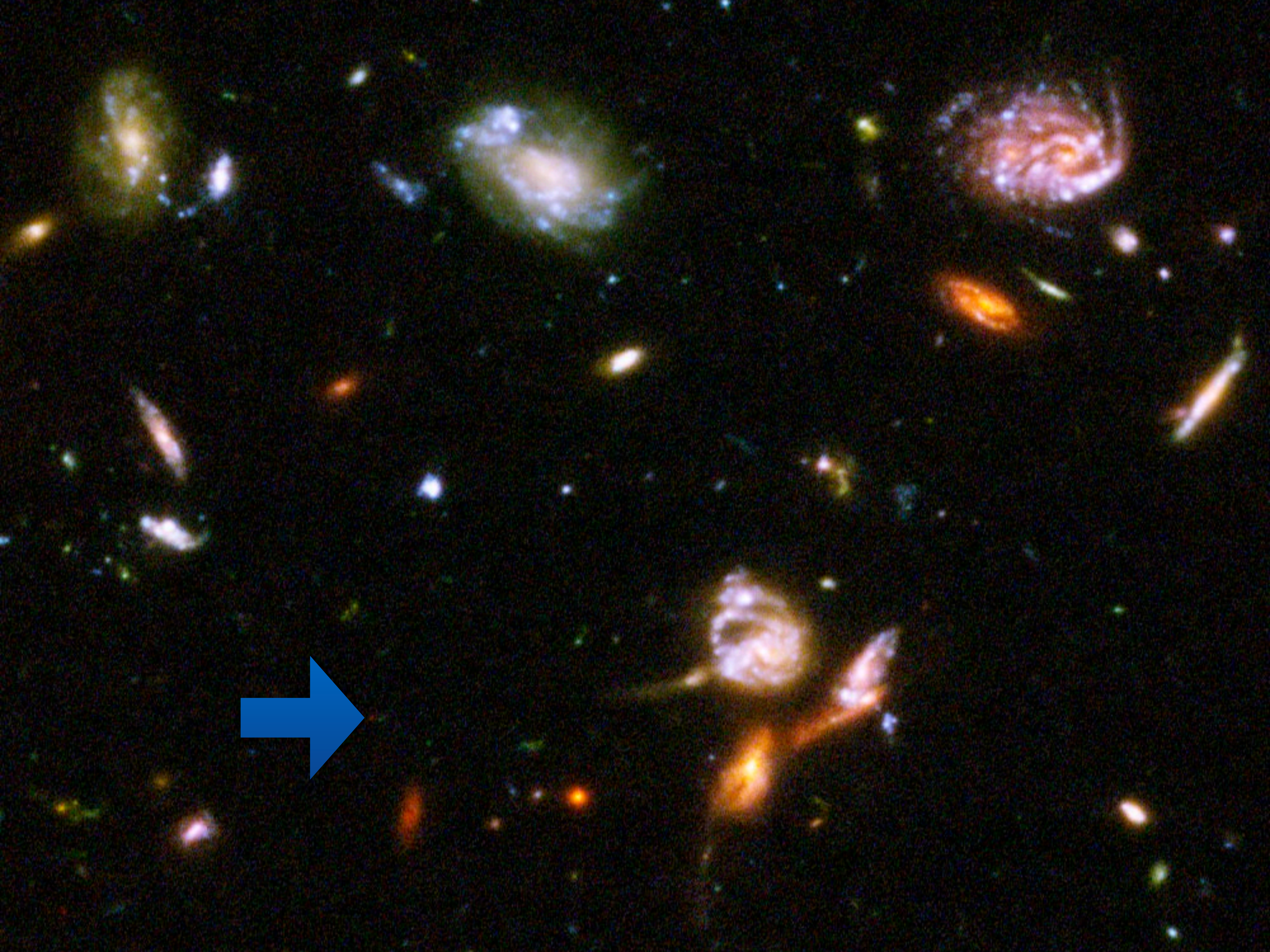


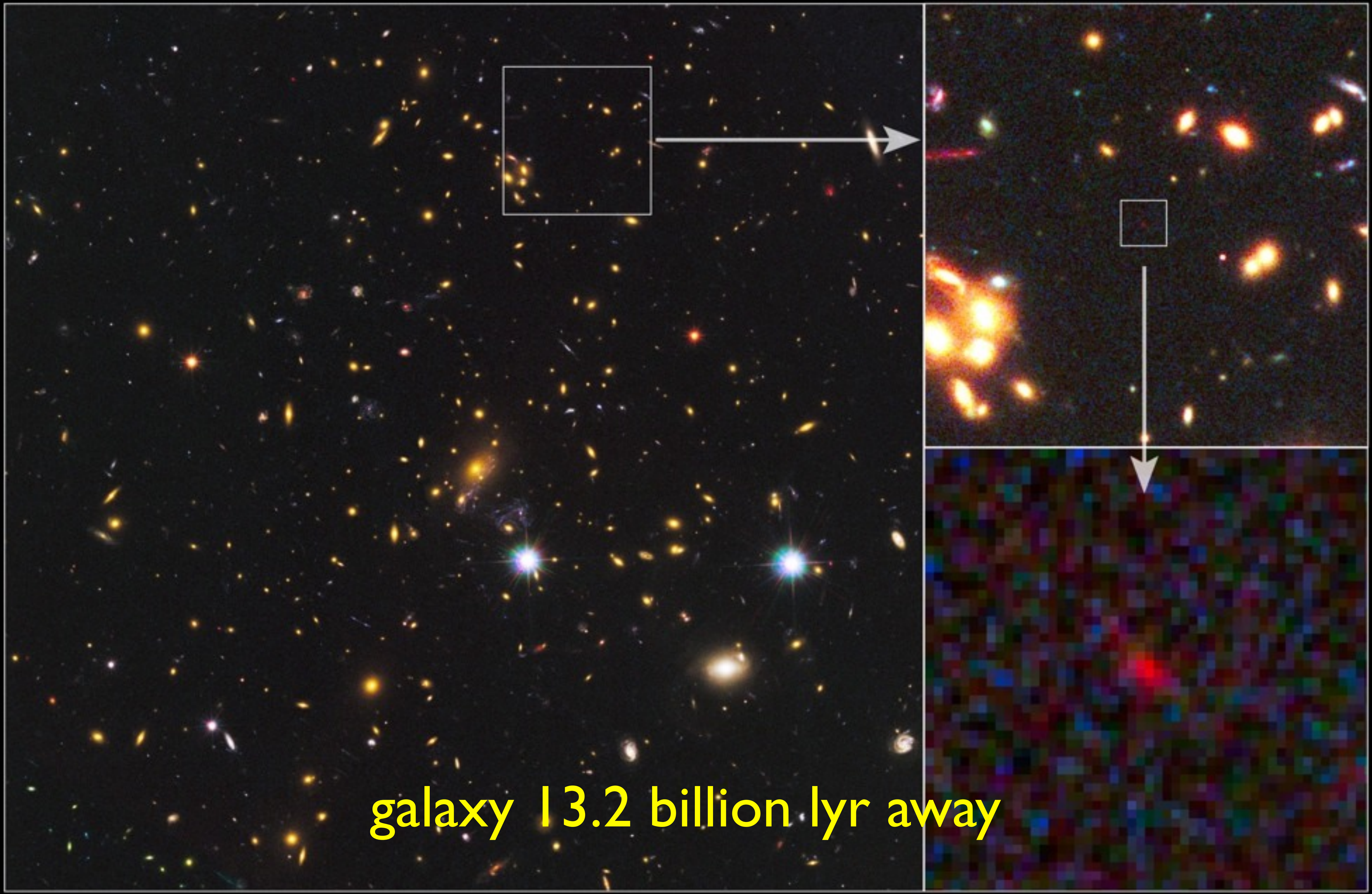


fly-through based on SDSS-III data



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
4h
2 billion lyr





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)

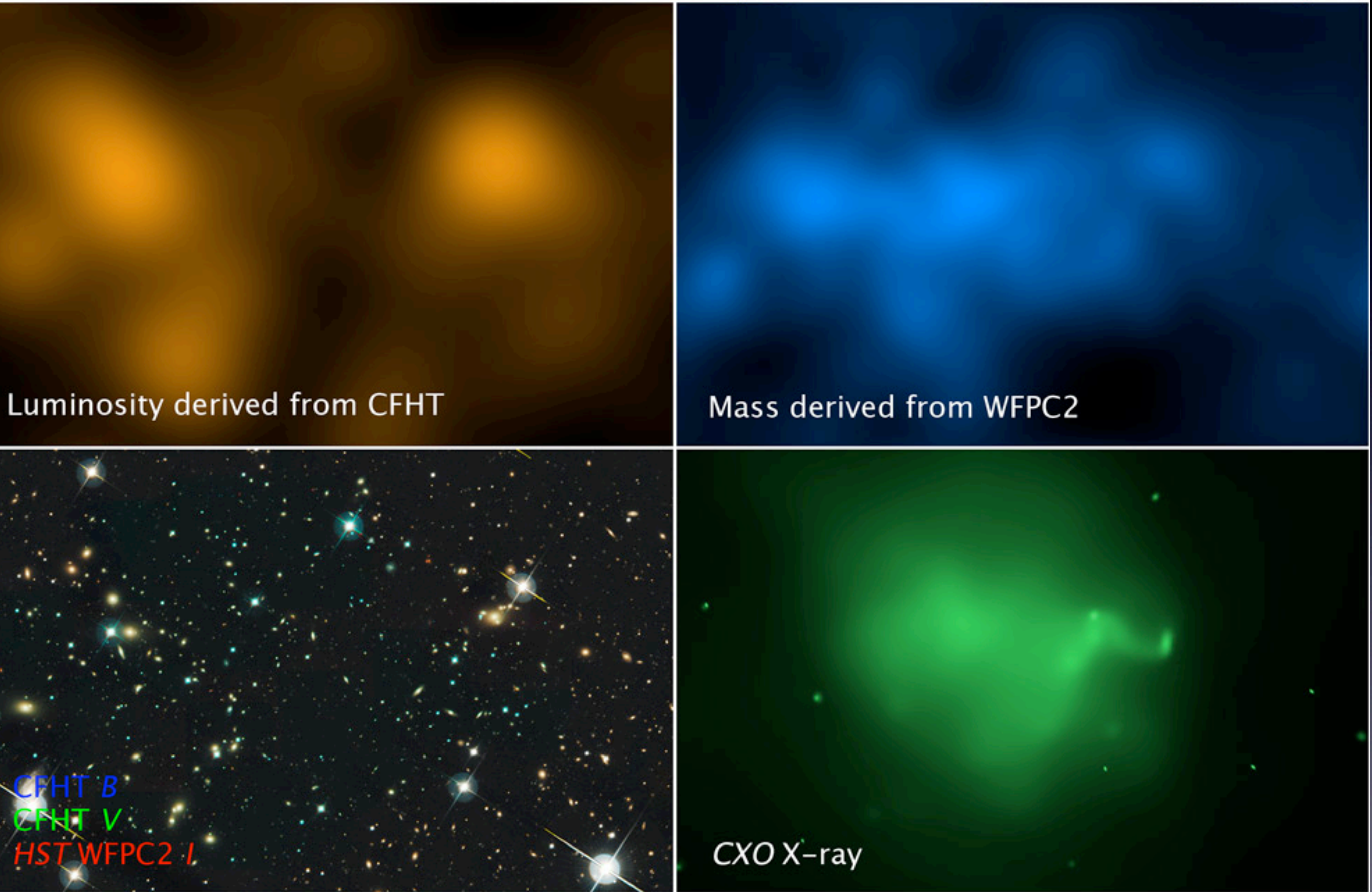
Hubble Space Telescope • ACS • WFC3

ssc2012-12a

dark ages
13.6 billion lyr away

Train Wreck Cluster

Train Wreck Cluster



Friedmann Universe

Expanding space

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

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

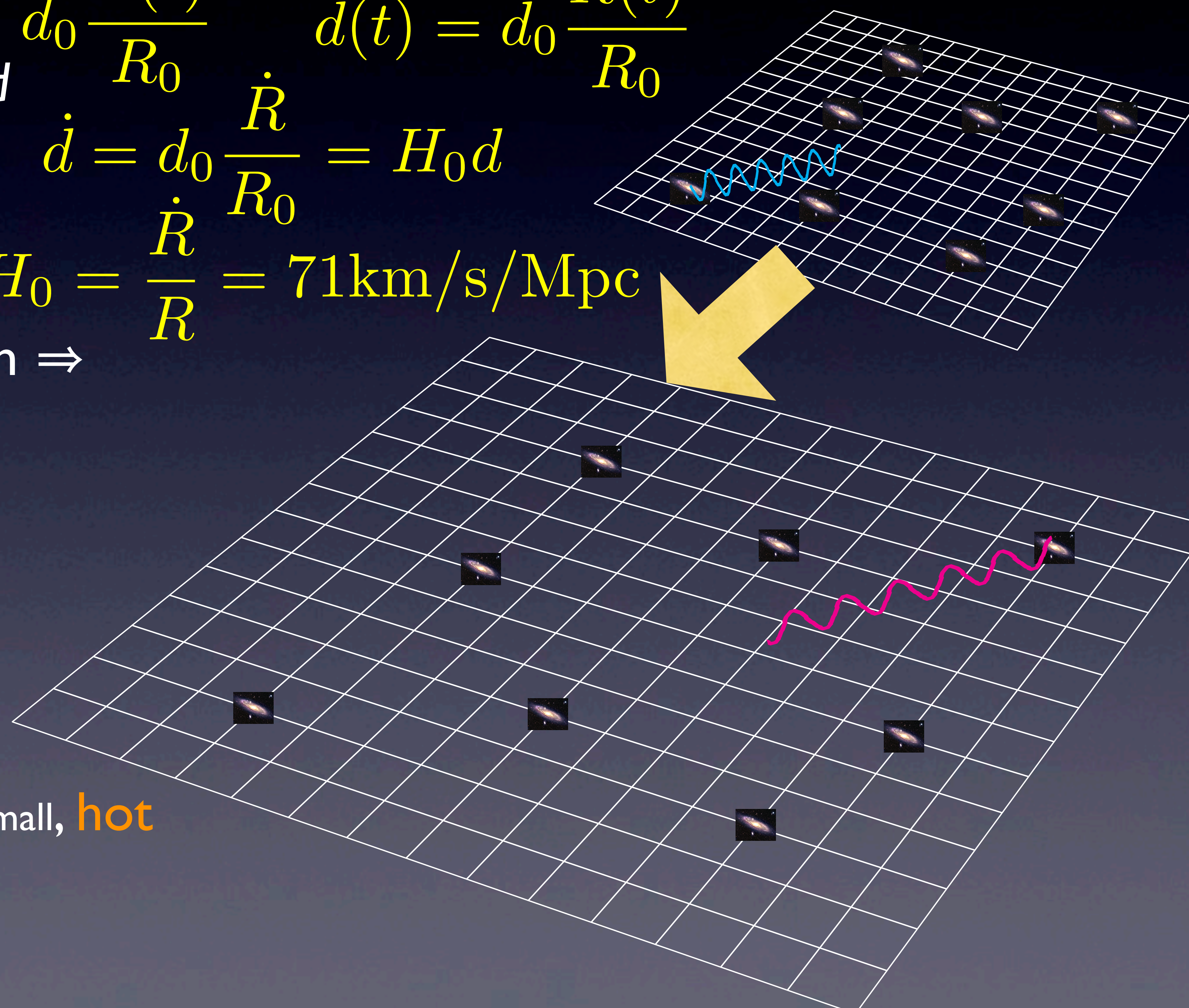
$$H_0 = \frac{\dot{R}}{R} = 71\mathrm{km/s/Mpc}$$

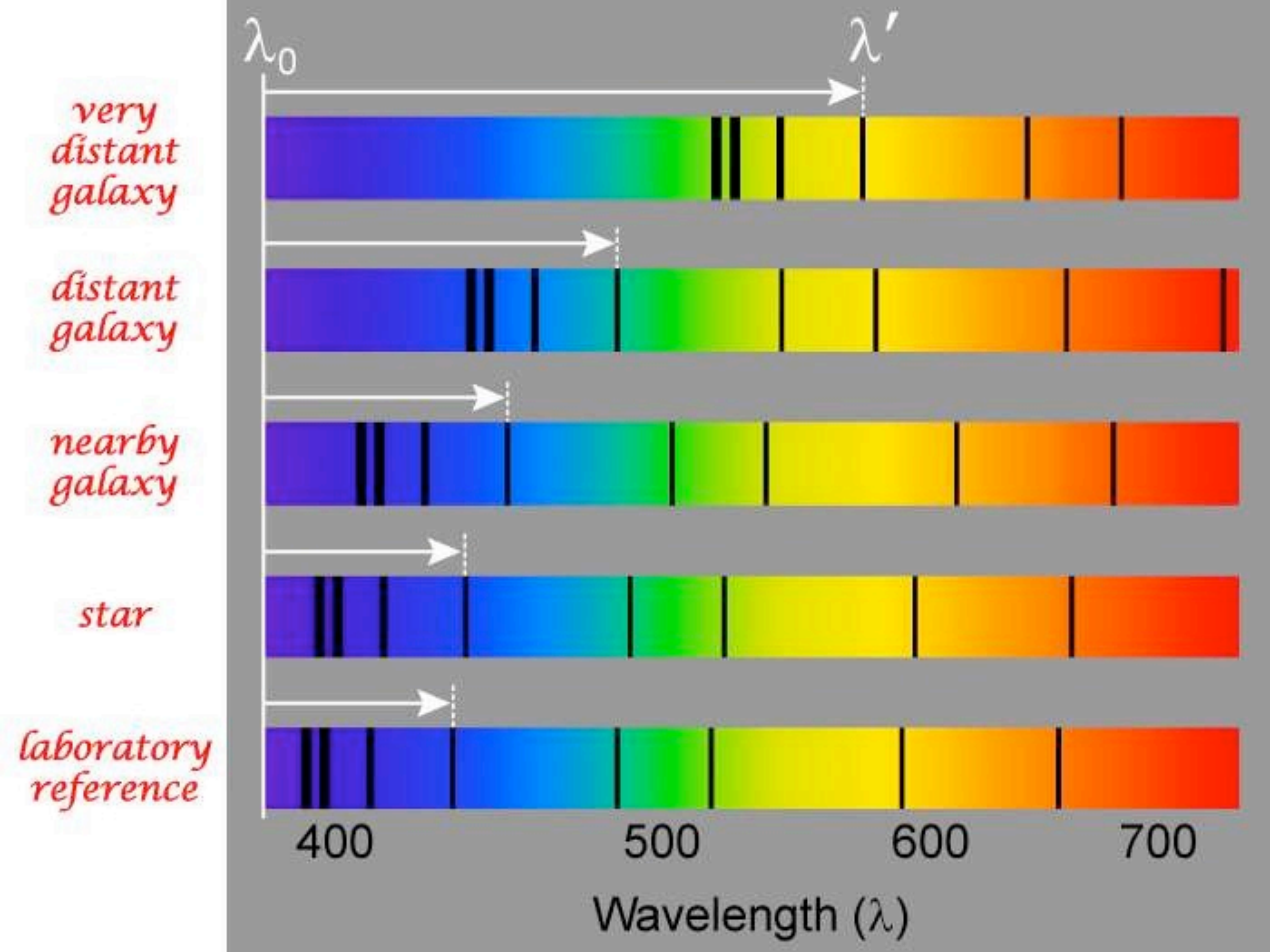
- Hubble law: $v=H_0\, d$
- $\lambda=\lambda_0(1+z)$
- z: redshift = R_0/R
- adiabatic expansion ⇒

  $T \propto R^{-1}$
- $T=T_0(1+z)$
- bigger and colder

- Universe started small, hot

Big Bang!





λ_0
λ'
very distant galaxy
distant galaxy
nearby galaxy
star
laboratory reference
400
500
600
700
Wavelength (λ)

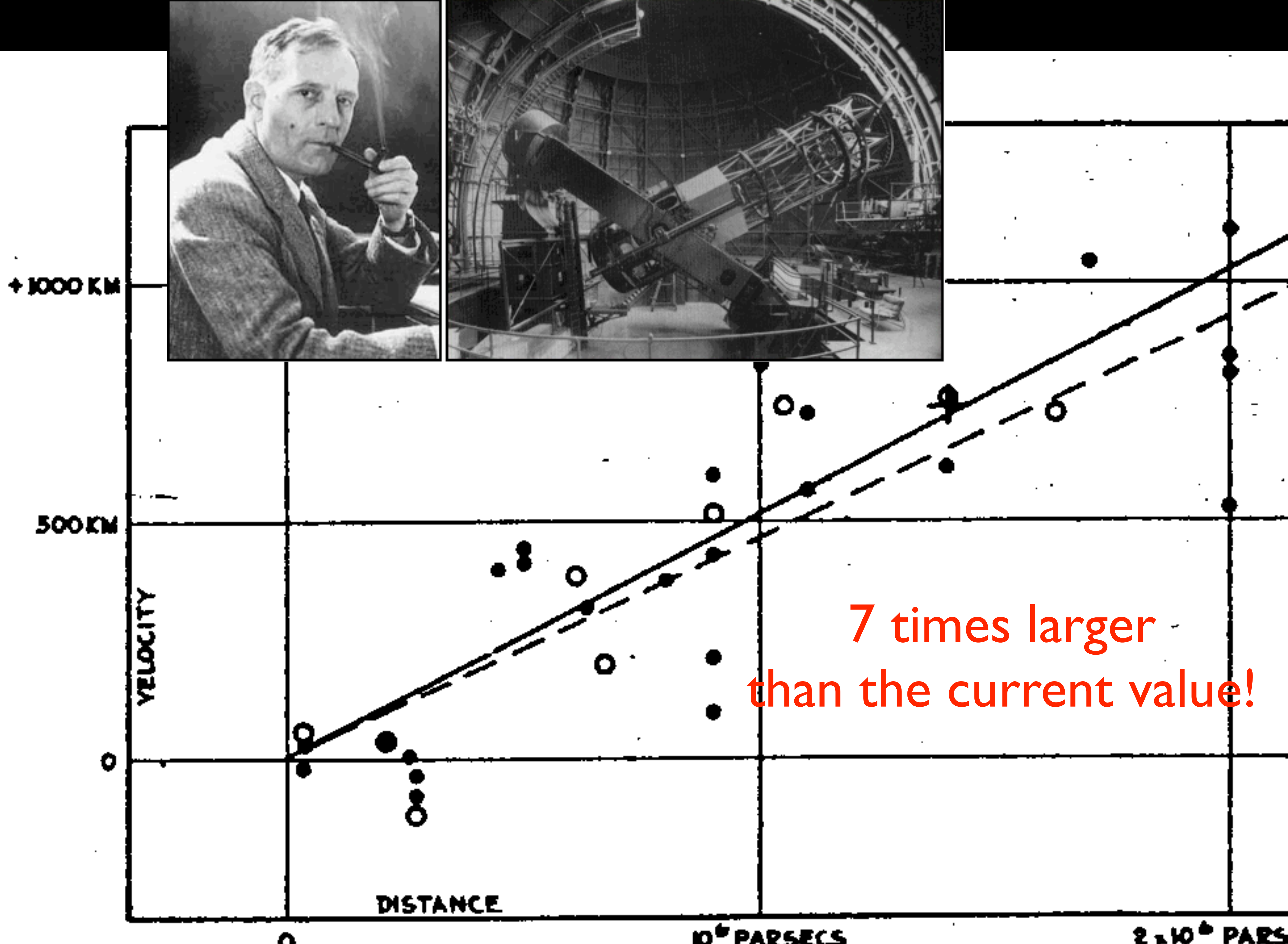
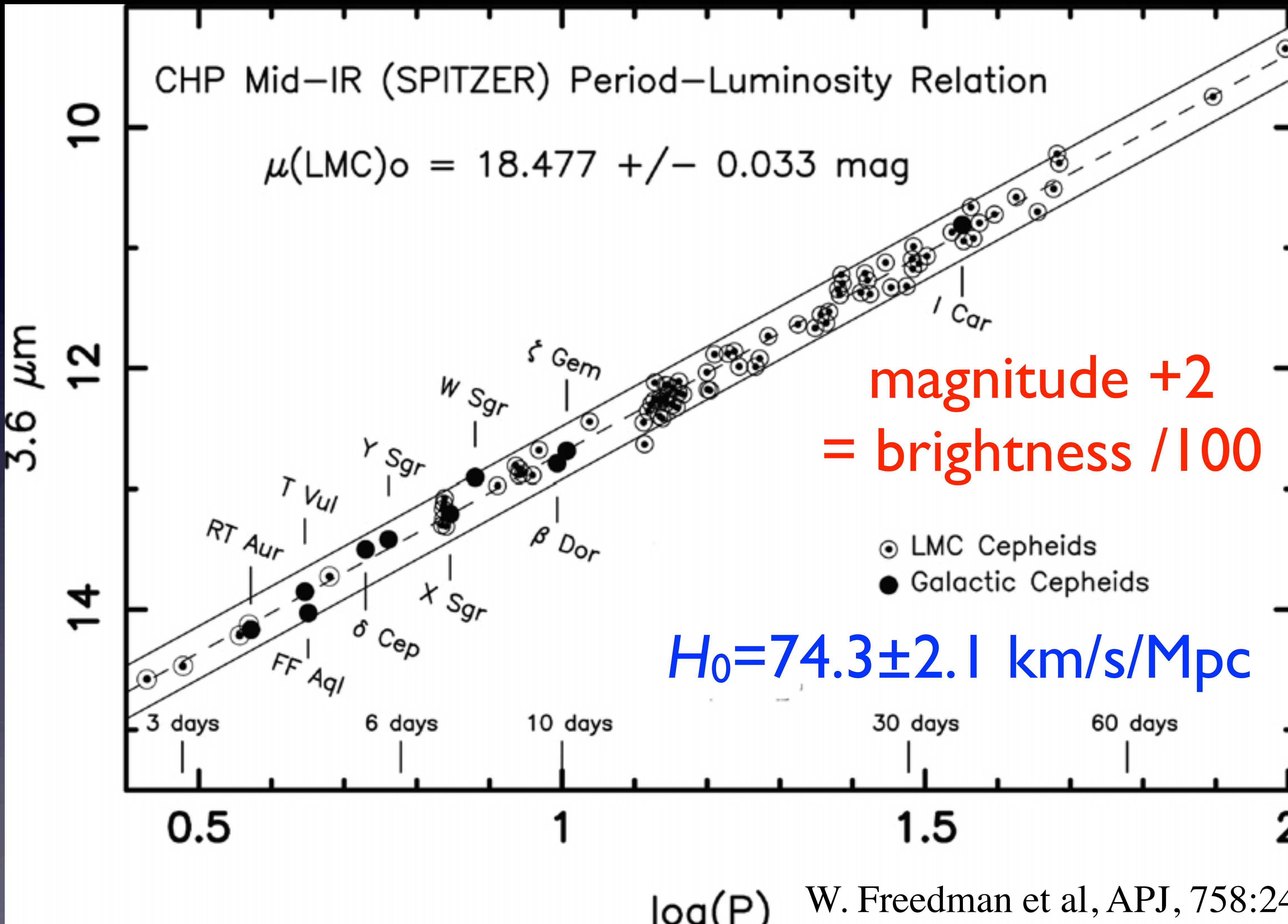


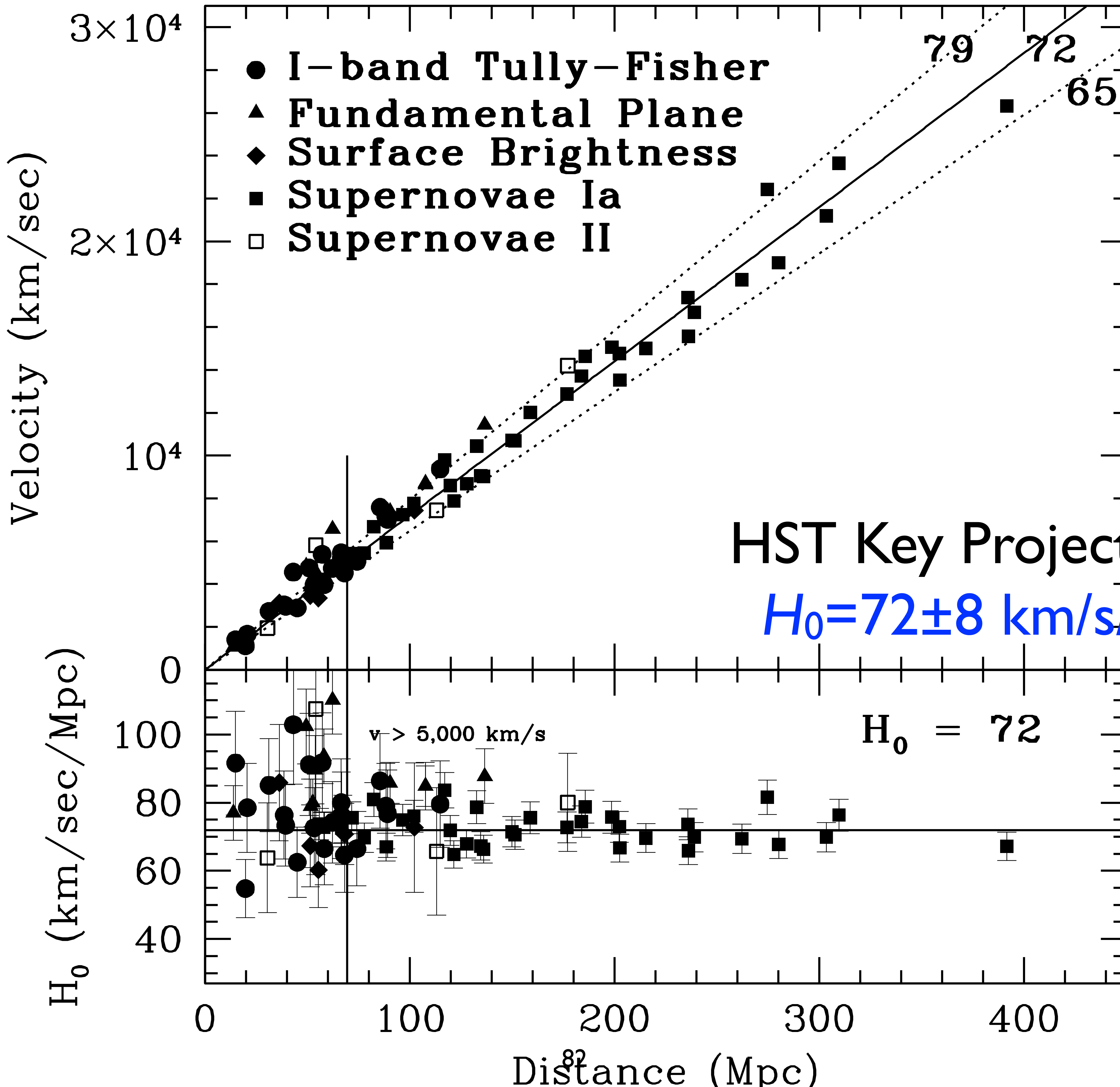
FIGURE 1

7 times larger
than the current value!

Cepheids calibration



W. Freedman et al, APJ, 758:24, 2012

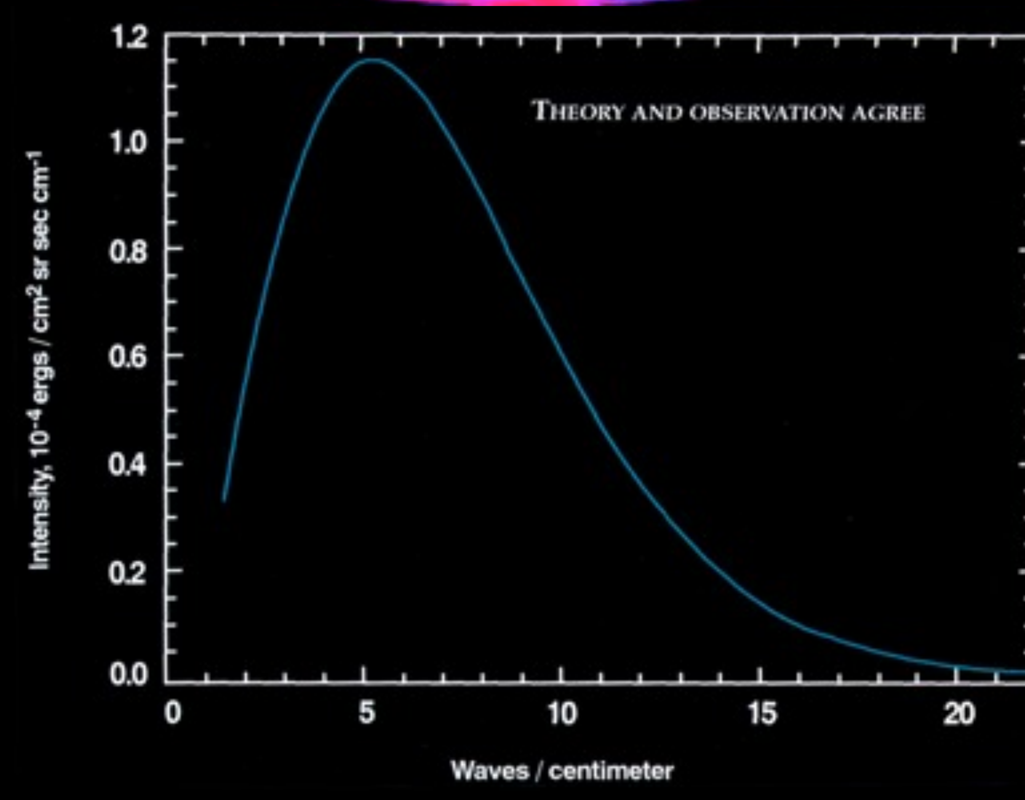


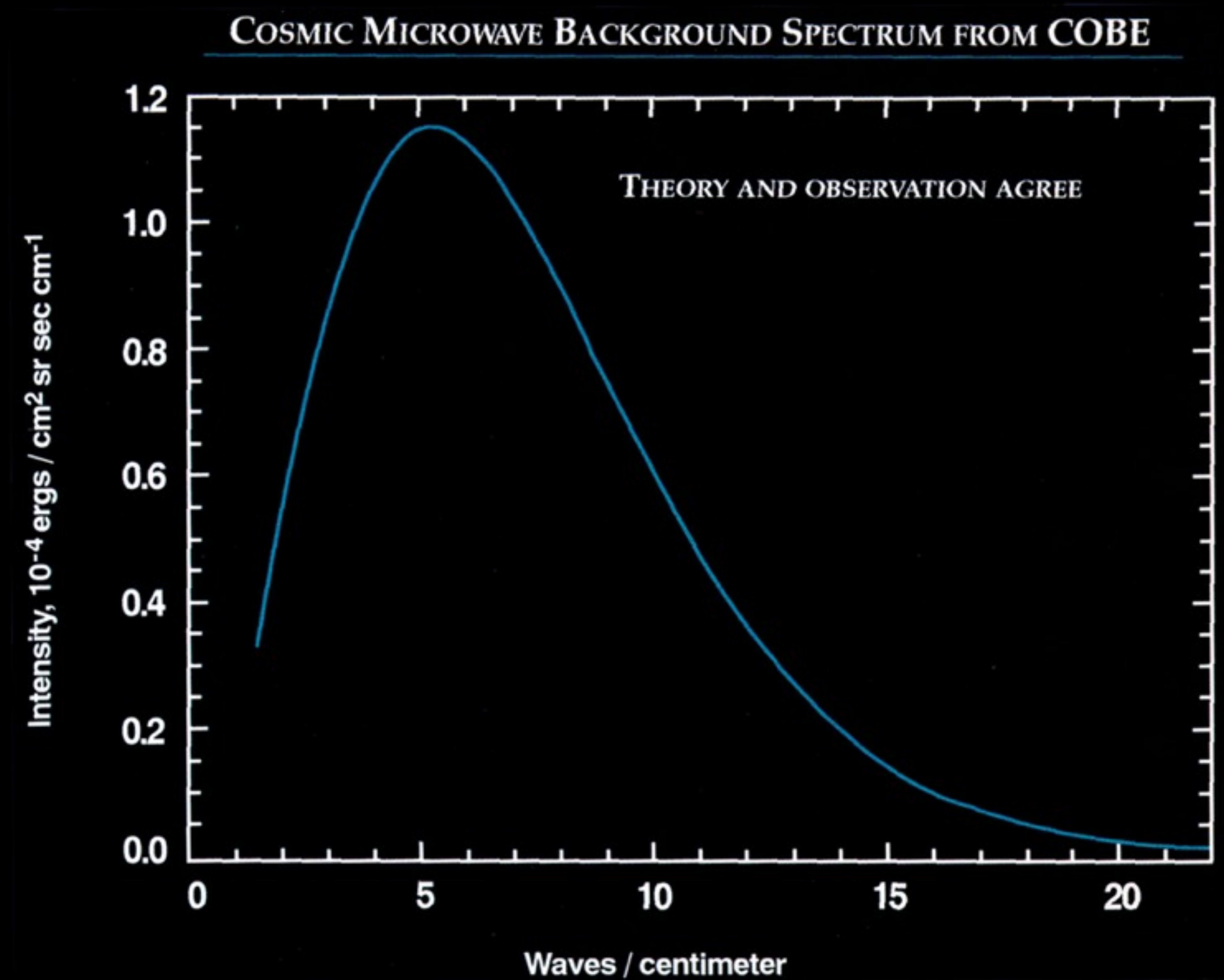
HST Key Project 2001

H_0=72±8 km/s/Mpc

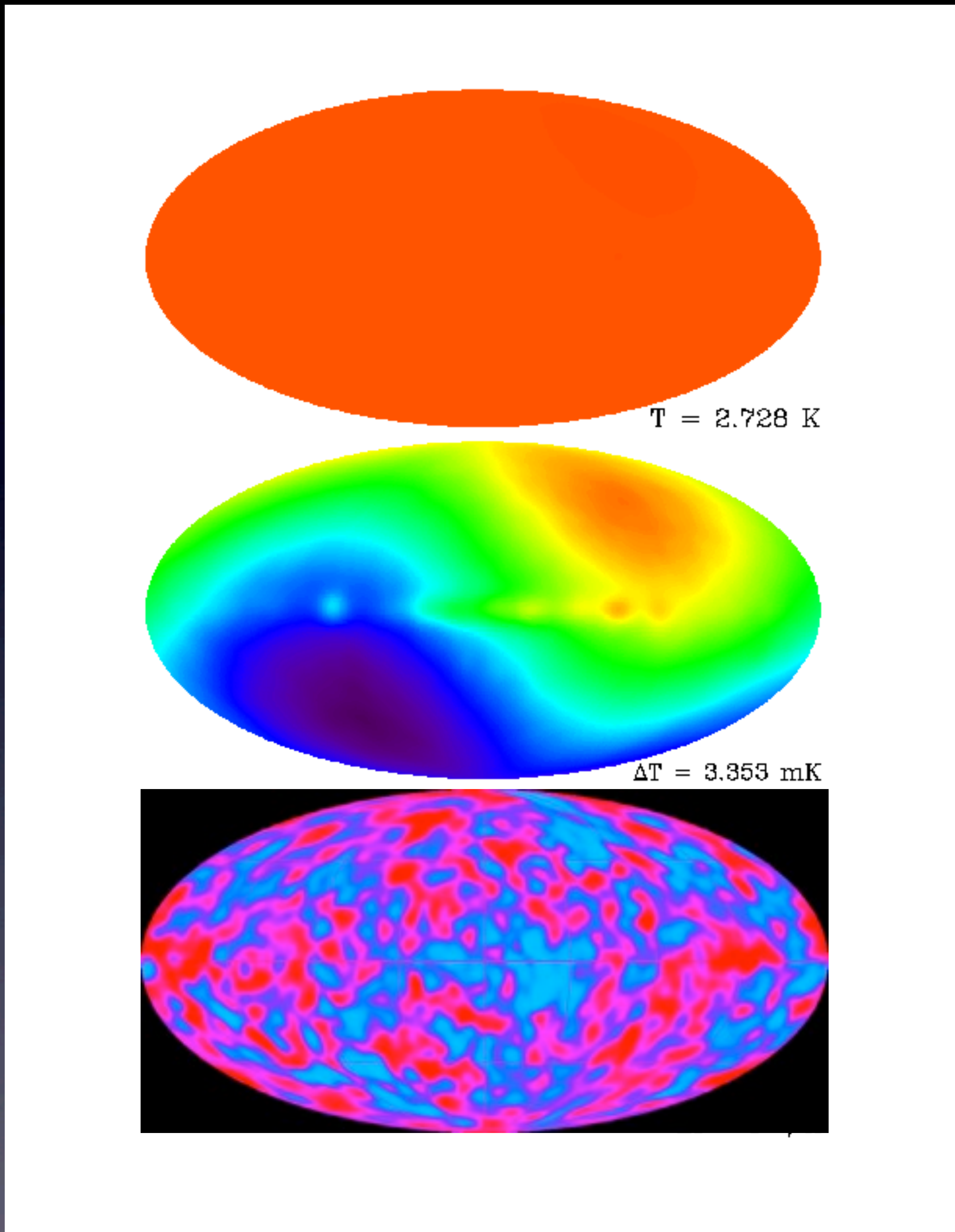
13.7 G lyr away
= 13.7 Gyr ago

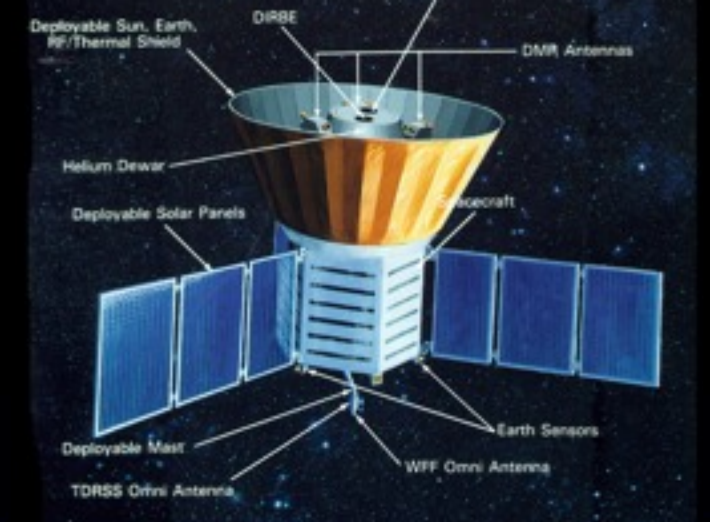
You can still see the Big Bang





COSMIC MICROWAVE BACKGROUND SPECTRUM FROM COBE
THEORY AND OBSERVATION AGREE
Intensity, 10^{-4} ergs / cm^2 sr sec cm^{-1}
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
5
10
15
20
Waves / centimeter



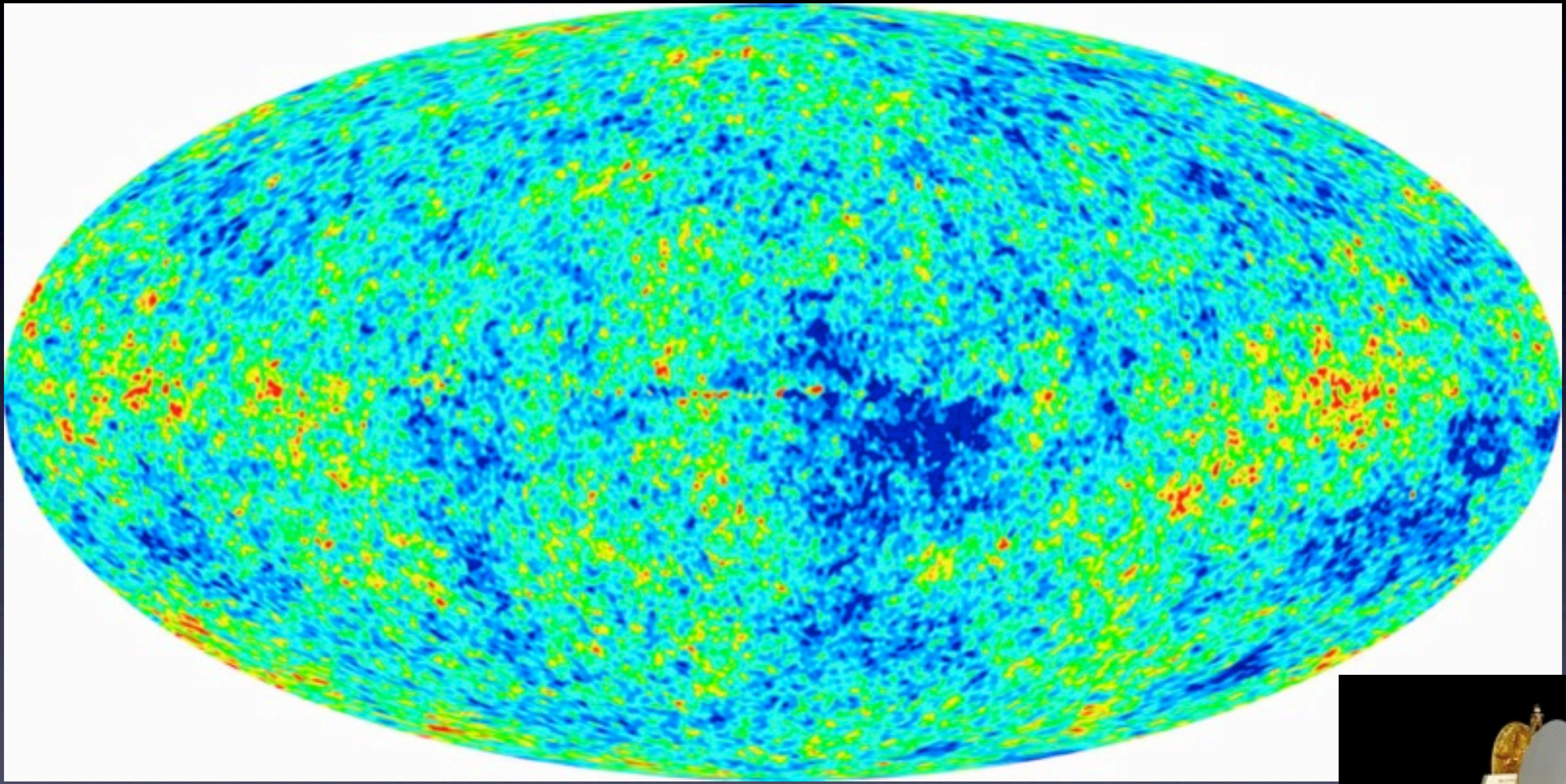


CMB temperature

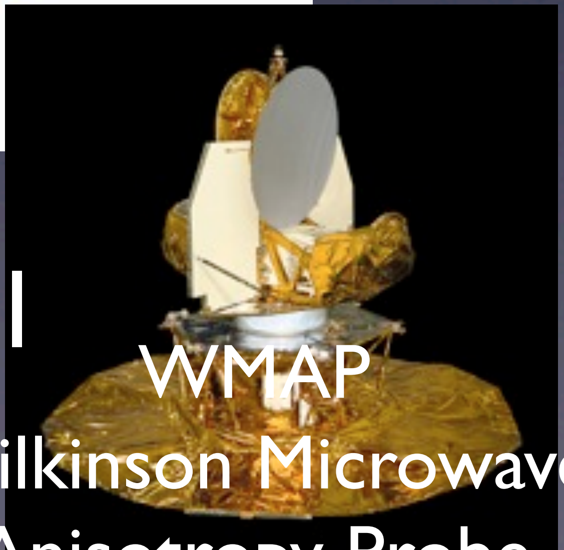
CMB dipole
we are moving at
~1% of *c* relative to CMB

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

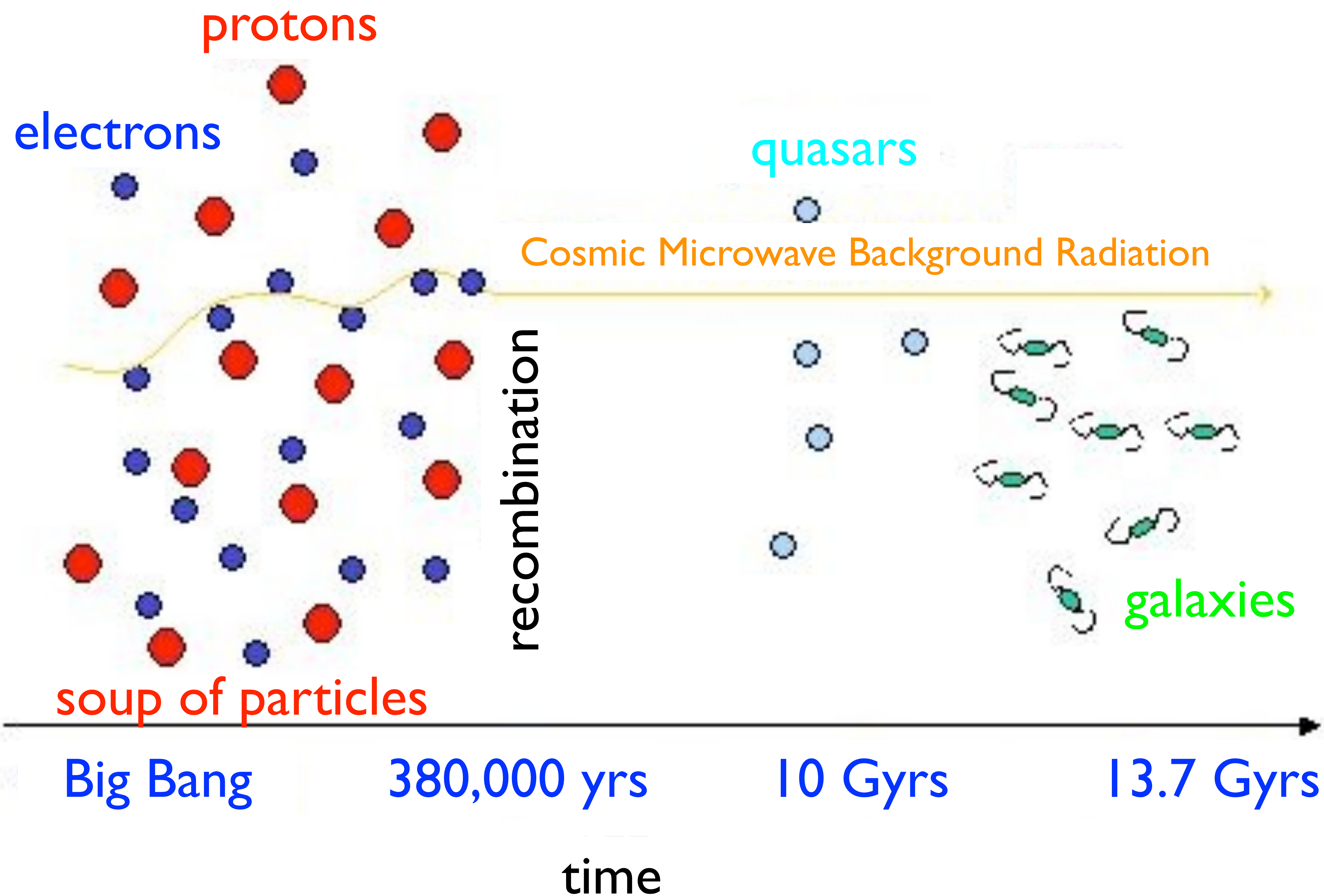
wall @ 13.7Glyr away

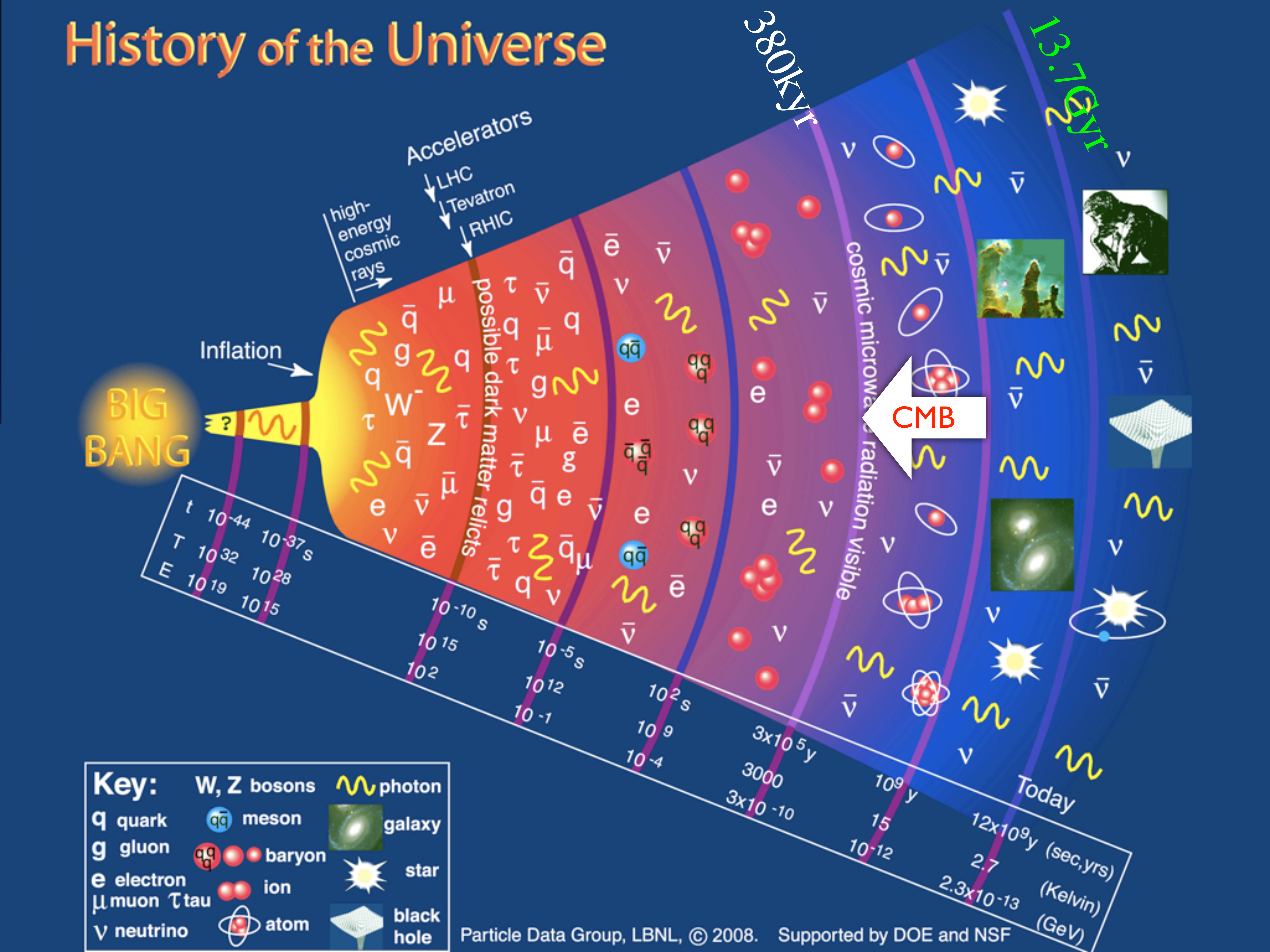


You can never see beyond this wall using light



WMAP
Wilkinson Microwave Anisotropy Probe


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

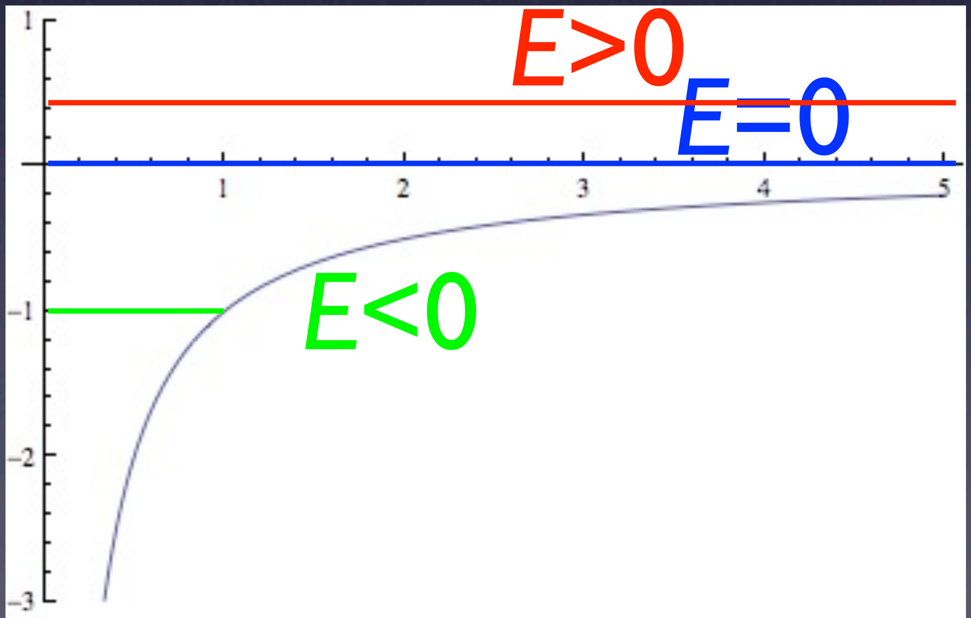

History of the Universe
380kyr
13.7Gyr
Accelerators
LHC
Tevatron
RHIC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
CMB
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -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

Friedmann Equation

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

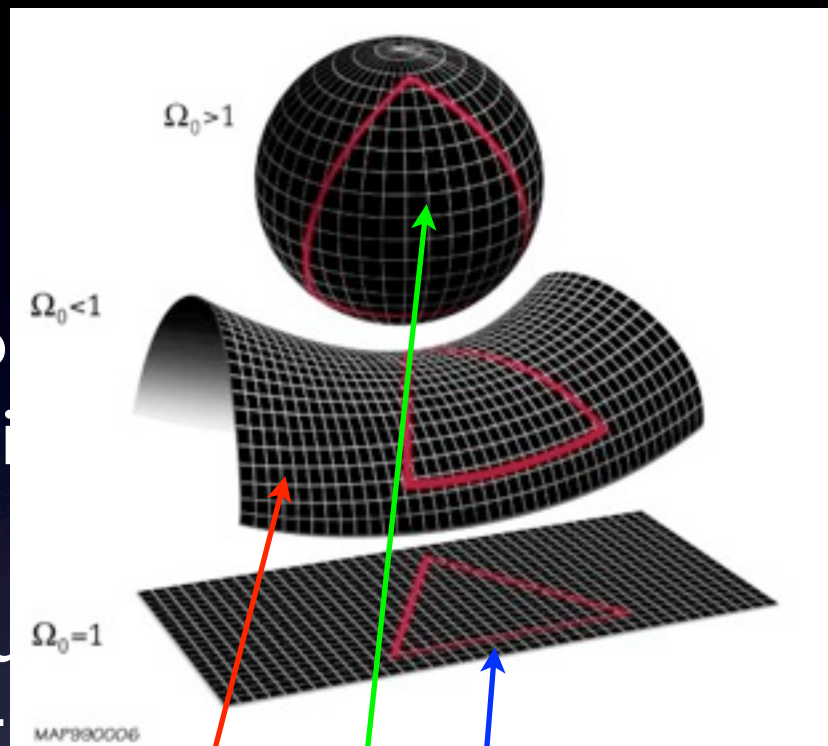
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G_N\rho - \frac{k}{R^2}$$

- "non-relativistic derivation"
- assume spherical distribution of mass density ρ
- *same as full relativistic equation with a curvature term k*=–1, 0, 1



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

Friedmann Equation



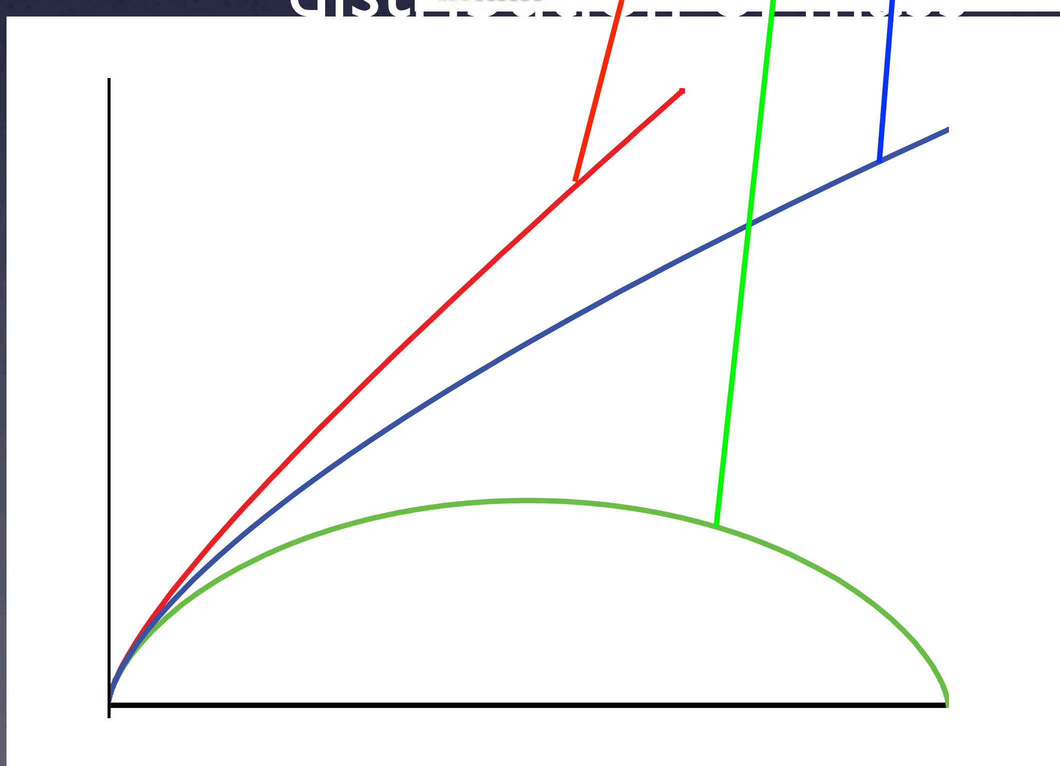
$$E = \frac{m}{2}\dot{R}^2 - G_N\left(\frac{4\pi}{3}\rho R^3\right)\frac{m}{R}$$

- “no
deri
- assu
dist

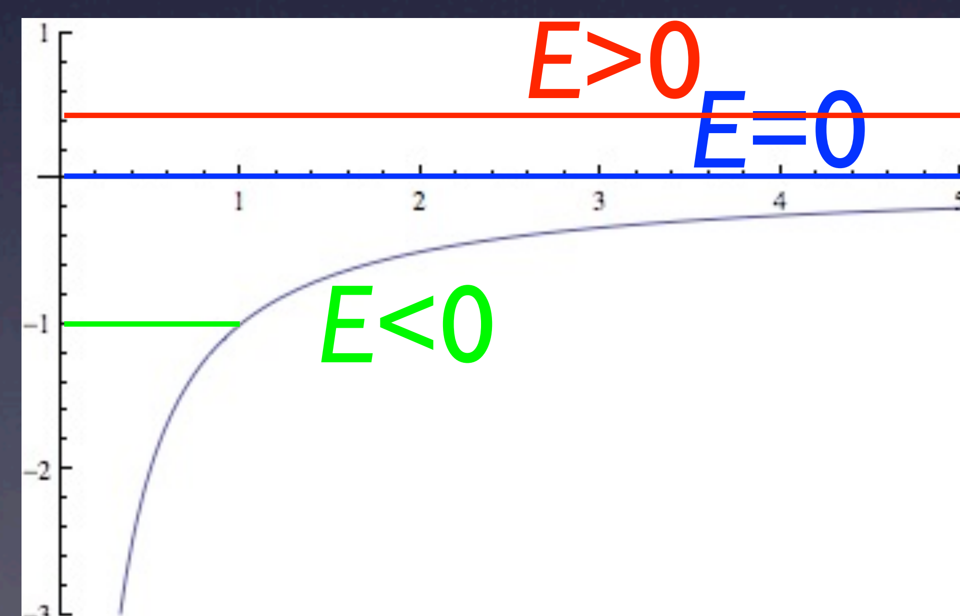
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G_N\rho - \frac{k}{R^2}$$

re

size of the Universe



time



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

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

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

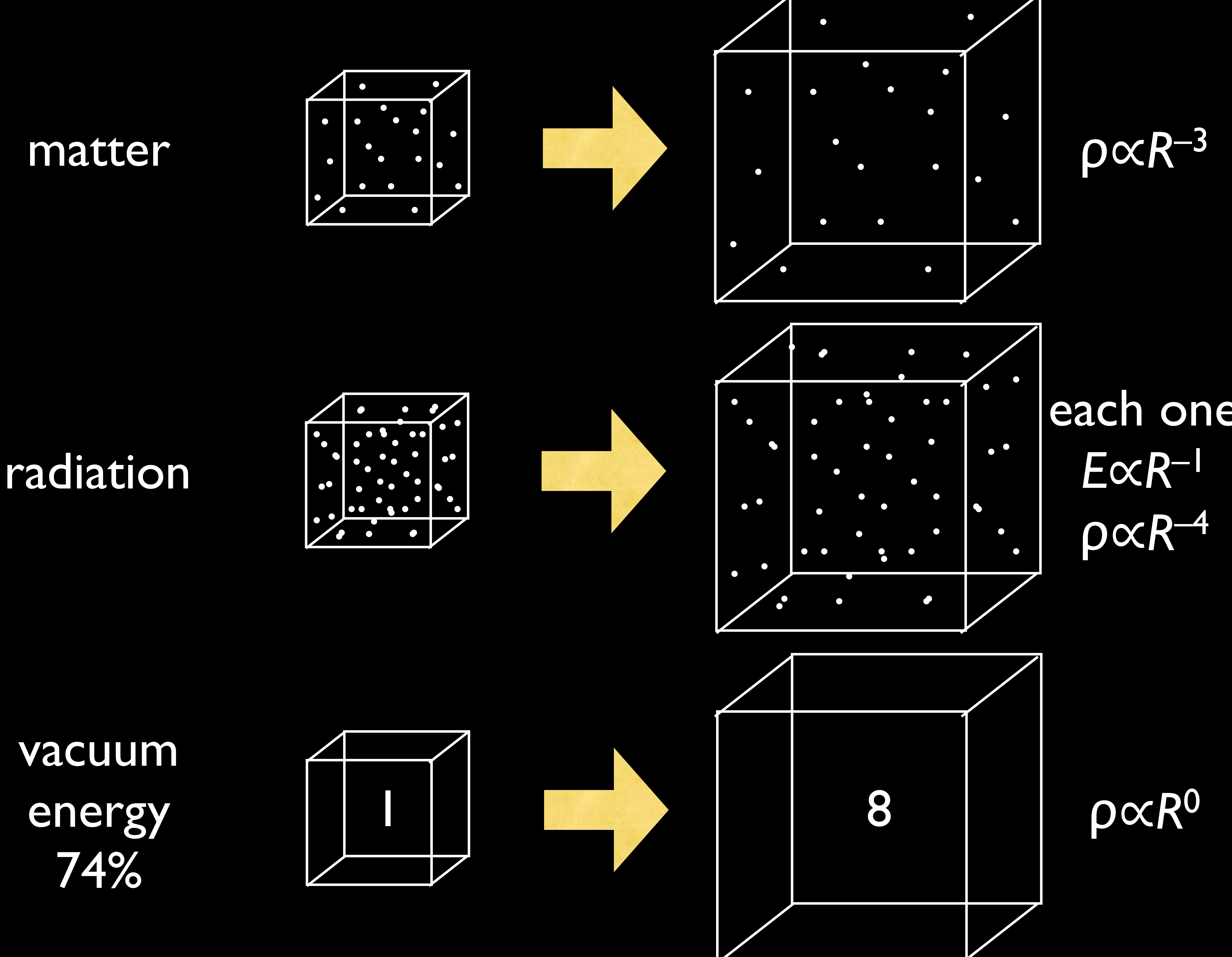
$$H_0 = \frac{\dot{R}}{R} = 71\mathrm{km/s/Mpc}$$

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

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

$$1 = \Omega_{\mathrm{rad}} + \Omega_{\mathrm{matter}} + \Omega_k + \Omega_\Lambda$$

$$\rho(z) = \rho_c(\Omega_{\mathrm{rad}}(1+z)^4 + \Omega_{\mathrm{matter}}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

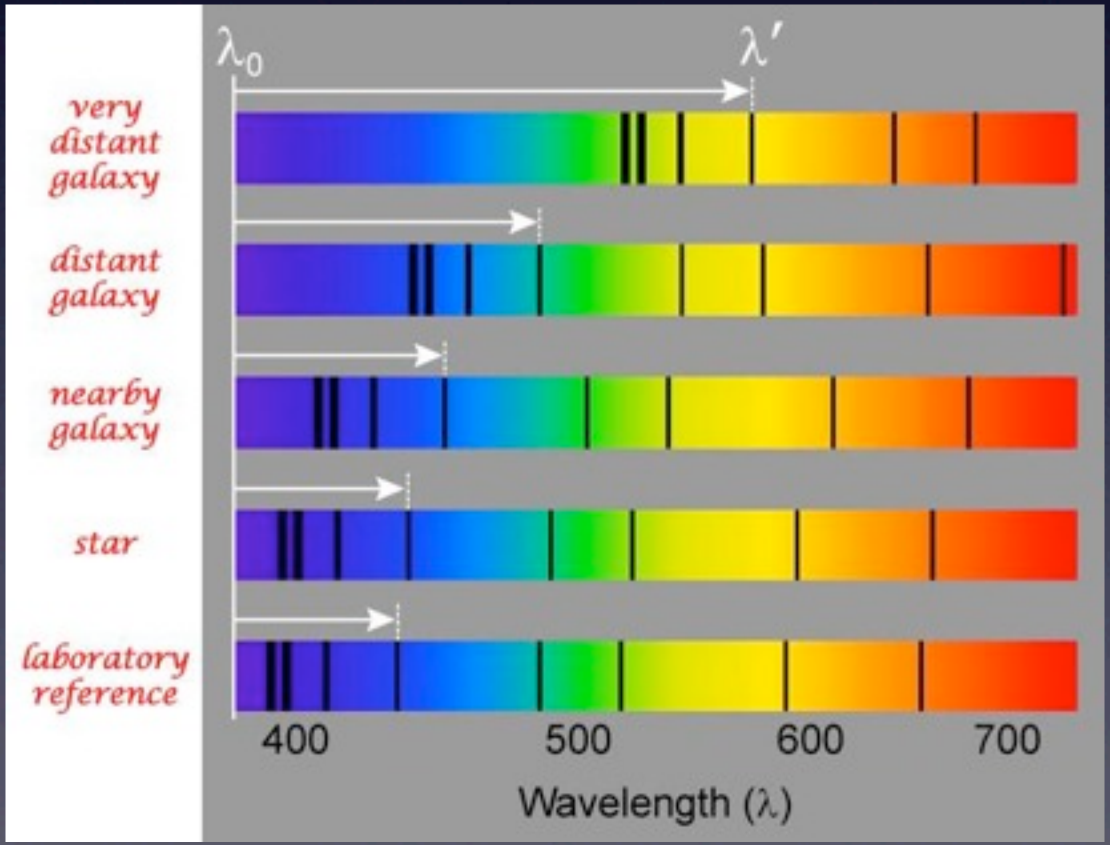

matter
$\rho \propto R^{-3}$
radiation
each one
$E \propto R^{-1}$
$\rho \propto R^{-4}$
vacuum
energy
74%
1
8
$\rho \propto R^{0}$

Expanding Universe

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

- $\lambda = \lambda_0(1+z)$
- z: redshift
- $1+z = R_0/R = a(t)^{-1}$
- adiabatic expansion ⇒

  $T \propto R^{-1}$
- $T = T_0(1+z)$



$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

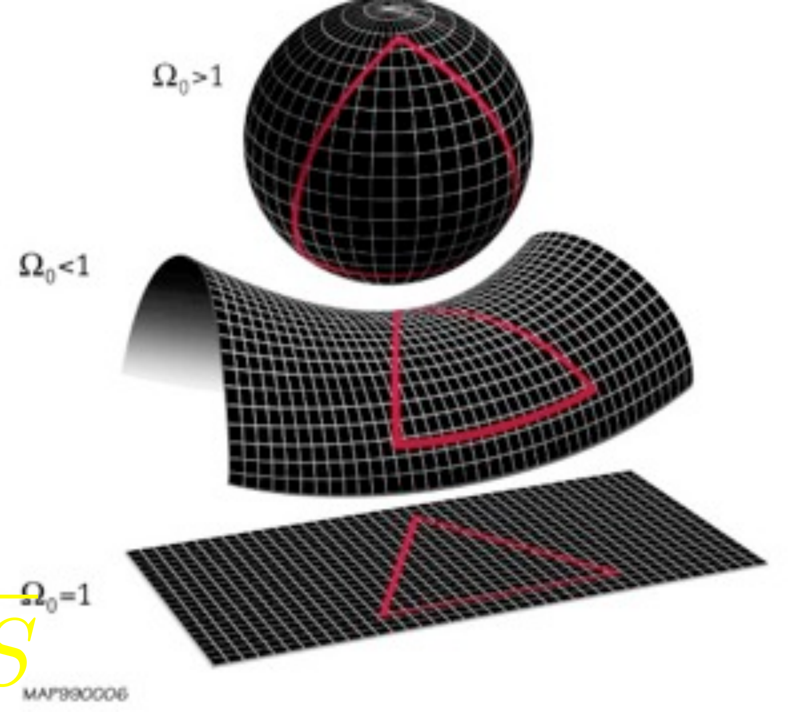
distance

- luminosity distance $d_L = \sqrt{L/4\pi S}$
- comoving distance $d_C(z) = c\int_t^{t_0} \frac{dt'}{a(t')}$
- light travel distance $c(t_0 - t)$
- angular diameter distance $d_A = x/\theta$

$$\frac{\dot{a}}{a} = H \qquad dt = \frac{1}{H}\frac{da}{a} = \frac{1}{H}\frac{dz}{1+z}$$

$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

distance



- luminosity distance $$d_L = \sqrt{L/4\pi S}$$
- comoving distance $$d_C(z) = c\int_0^z \frac{dz'}{H(z)}$$
- light travel distance $$d_T(z) = c\int_0^z \frac{dz'}{(1+z')H(z)}$$
- angular diameter distance $$d_A = x/\theta$$
- transverse comoving distance $$d_M(z) = \frac{c}{H_0}\frac{1}{\sqrt{\Omega_k}}\sinh\frac{\sqrt{\Omega_k}H_0 d_C(z)}{c}$$

$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

distance

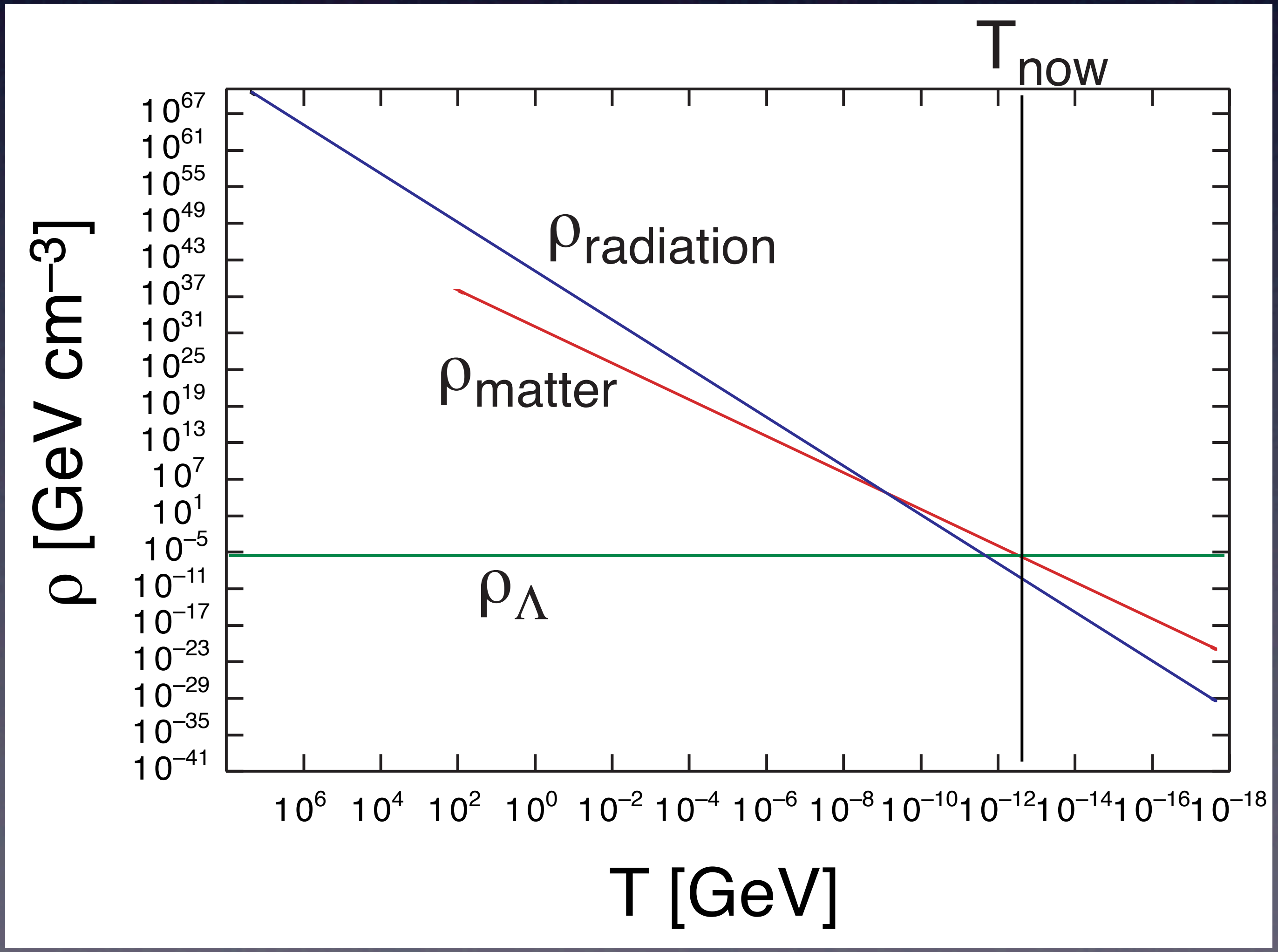
- luminosity distance $$d_L(z) = (1+z)d_M(z)$$
- comoving distance $$d_C(z) = c\int_0^z \frac{dz'}{H(z)}$$
- light travel distance $$d_T(z) = c\int_0^z \frac{dz'}{(1+z')H(z)}$$
- angular diameter distance $$d_A(z) = \frac{d_M(z)}{(1+z)}$$
- transverse comoving distance $$d_M(z) = \frac{c}{H_0}\frac{1}{\sqrt{\Omega_k}}\sinh\frac{\sqrt{\Omega_k}H_0 d_C(z)}{c}$$

$$H(z)^2 = H_0^2(\Omega_{\rm rad}(1+z)^4 + \Omega_{\rm matter}(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda)$$

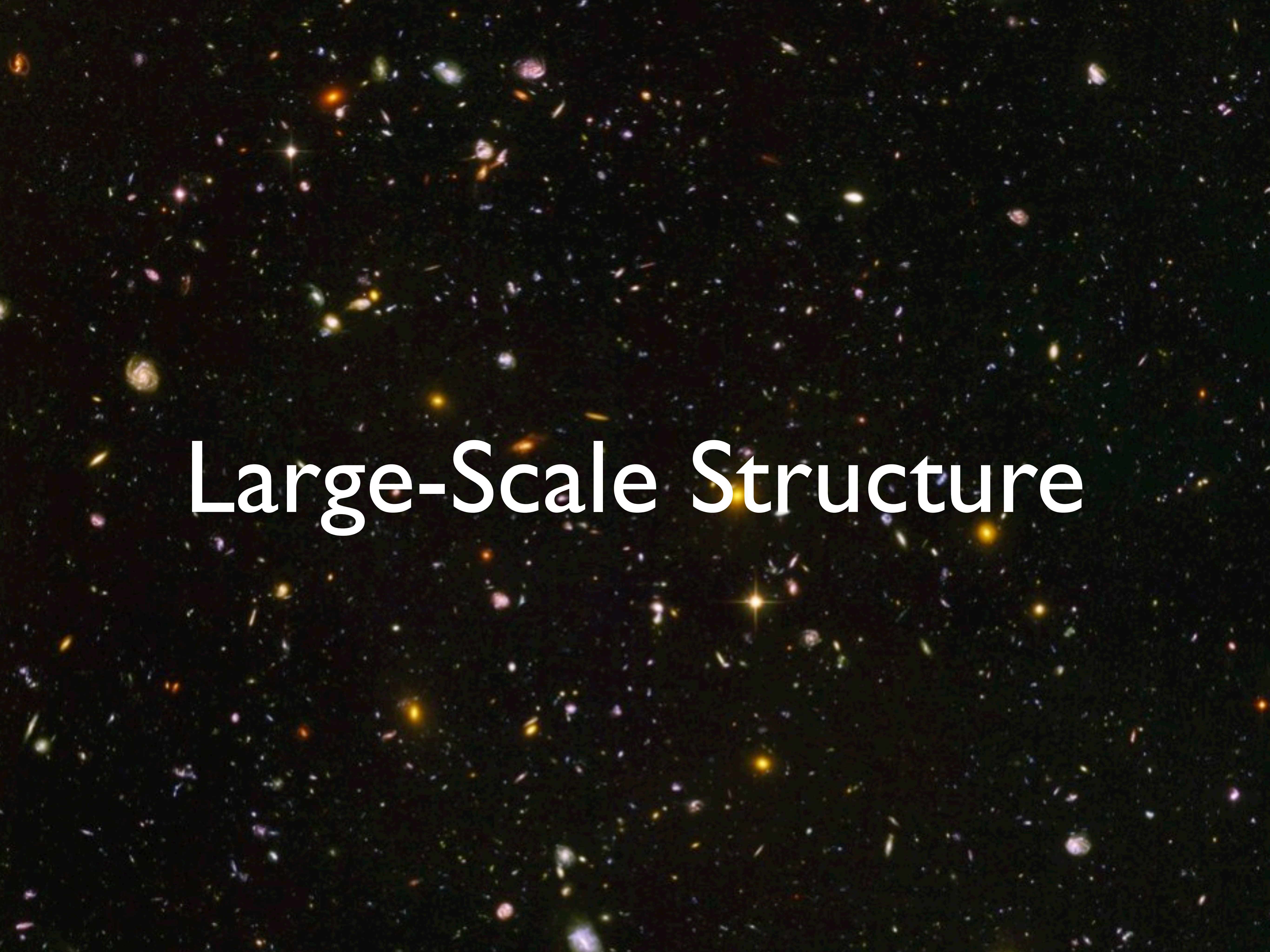
Early Universe

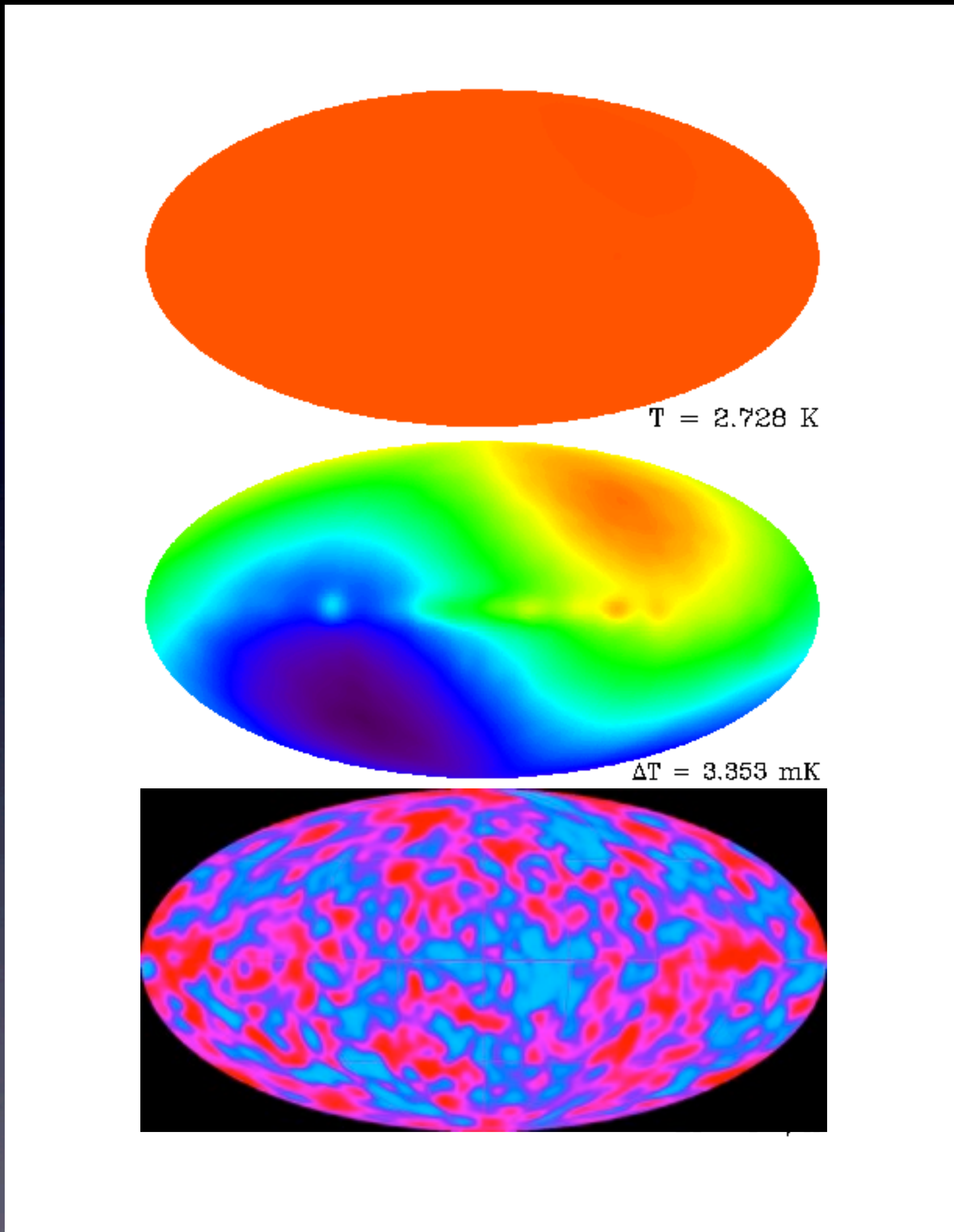
- temperature: $T \propto (1+z)$
- matter: $\rho \propto (1+z)^3$
- radiation (massless particles): $\rho \propto (1+z)^4$ matter-radiation equality: $z \approx 3300$
- recombination: $z \approx 1300$

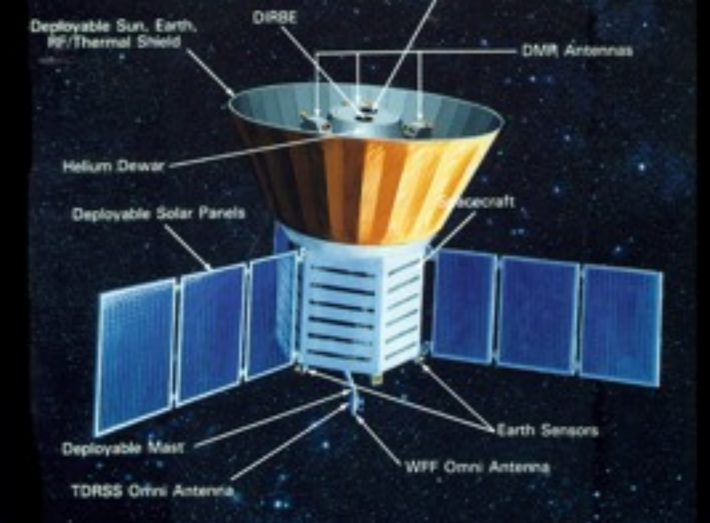
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3} G_N \rho - \frac{k}{R^2}$$



Large-Scale Structure



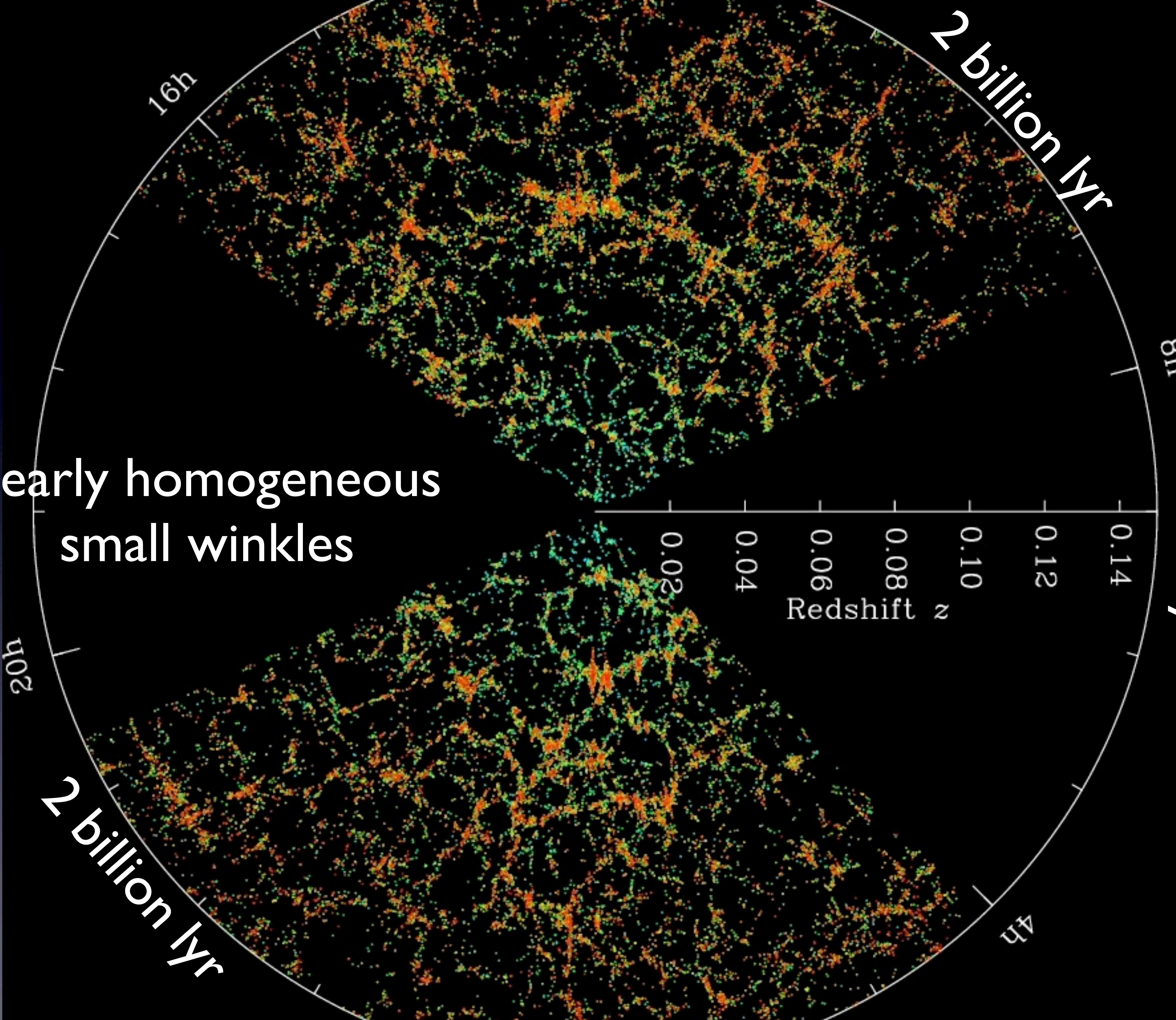




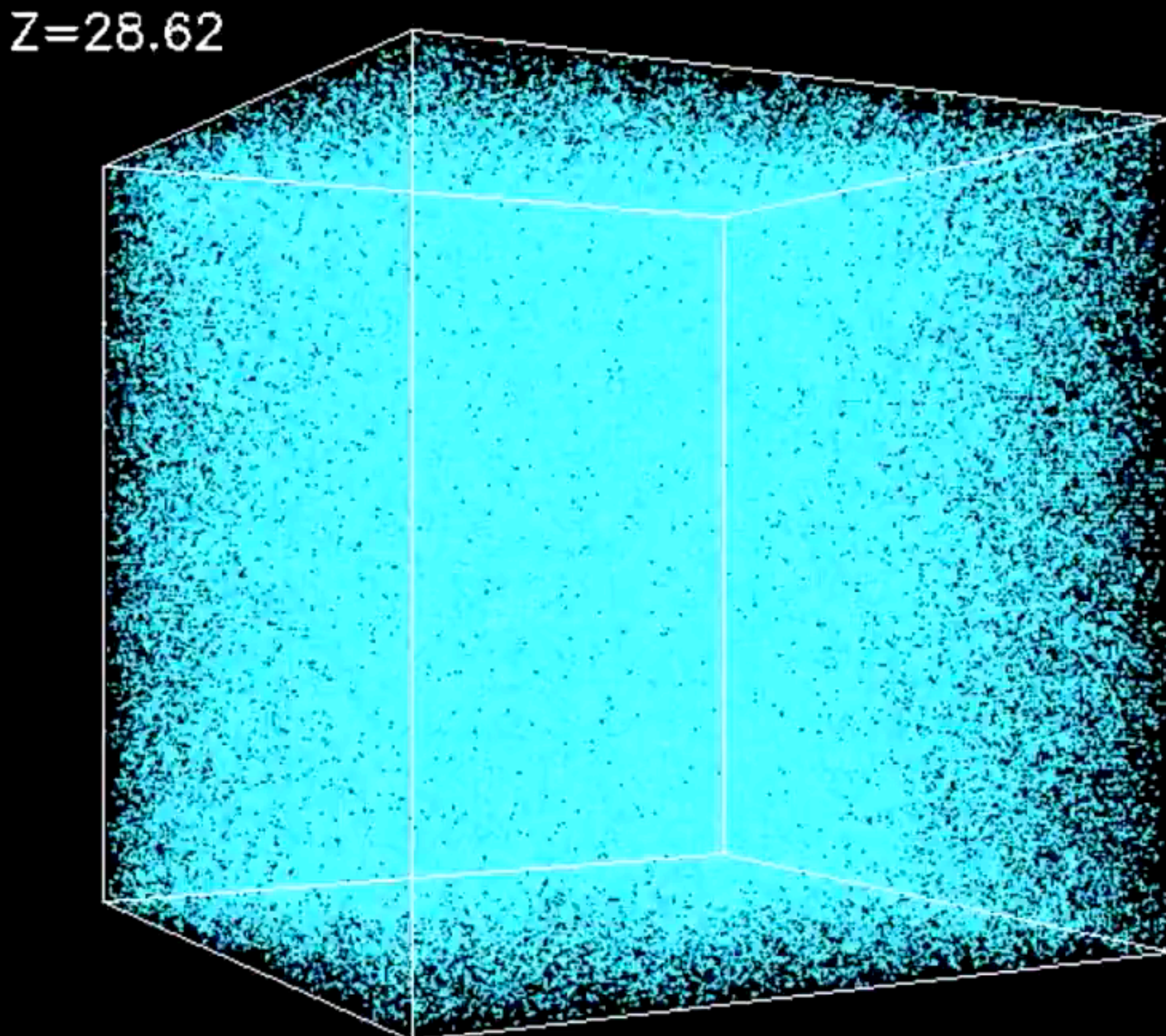
CMB temperature

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

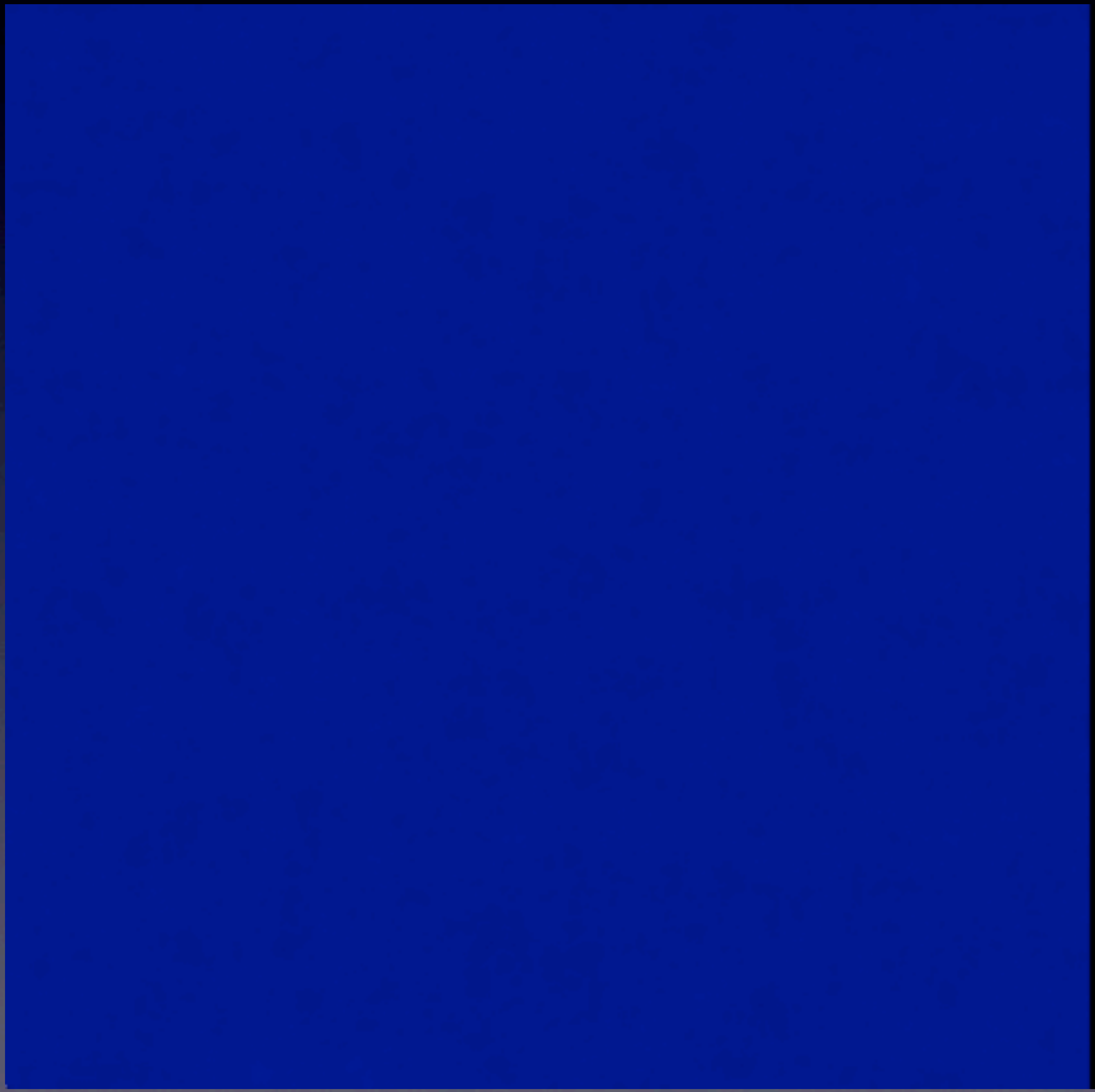
CMB anisotropy
at $\sim 10^{-5}$
1mm ripple on 100m sea



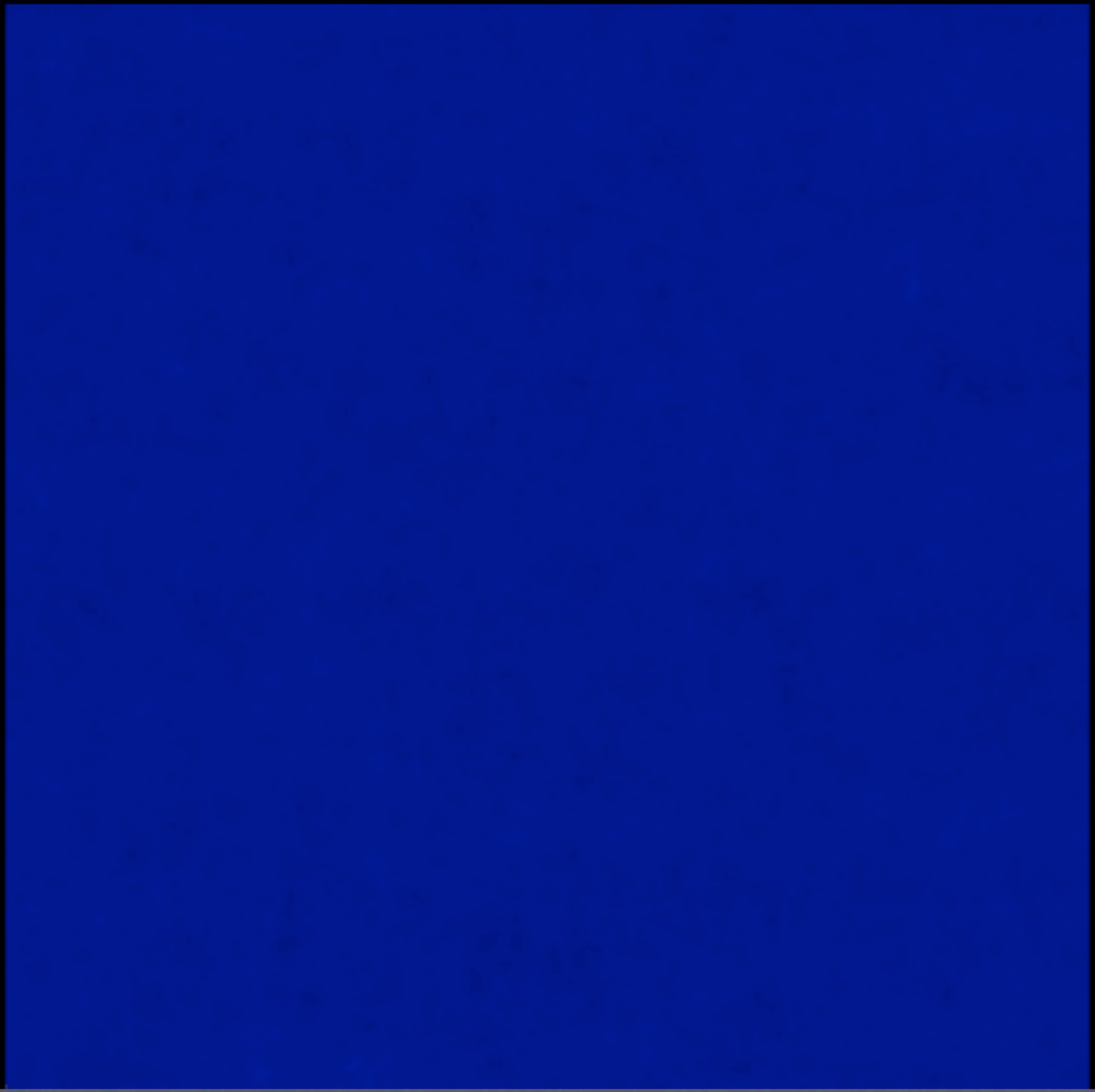
nearly homogeneous
small winkles


Z=28.62

Dark Matter is our birth mother

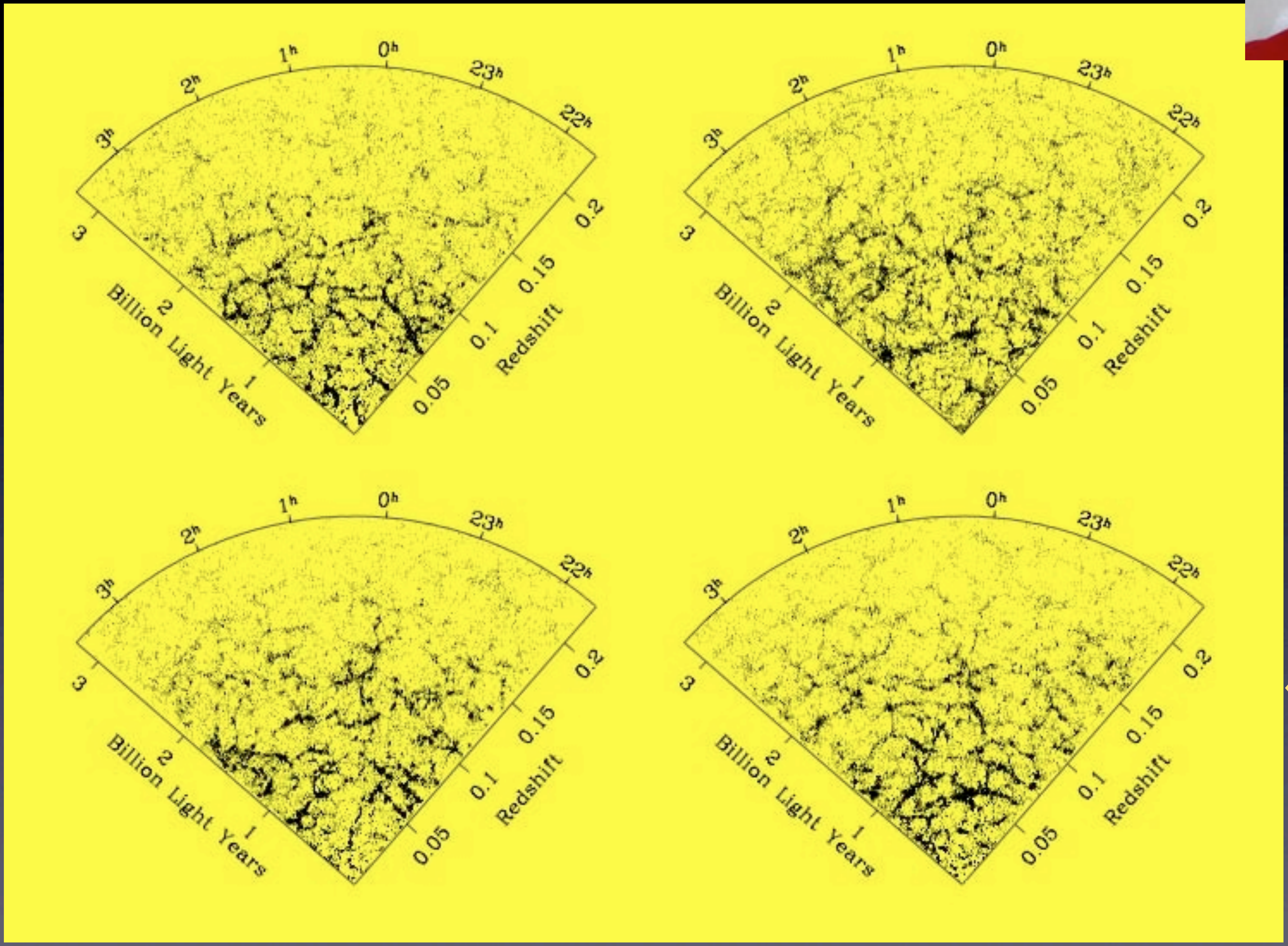


no dark matter



with dark matter

one is real



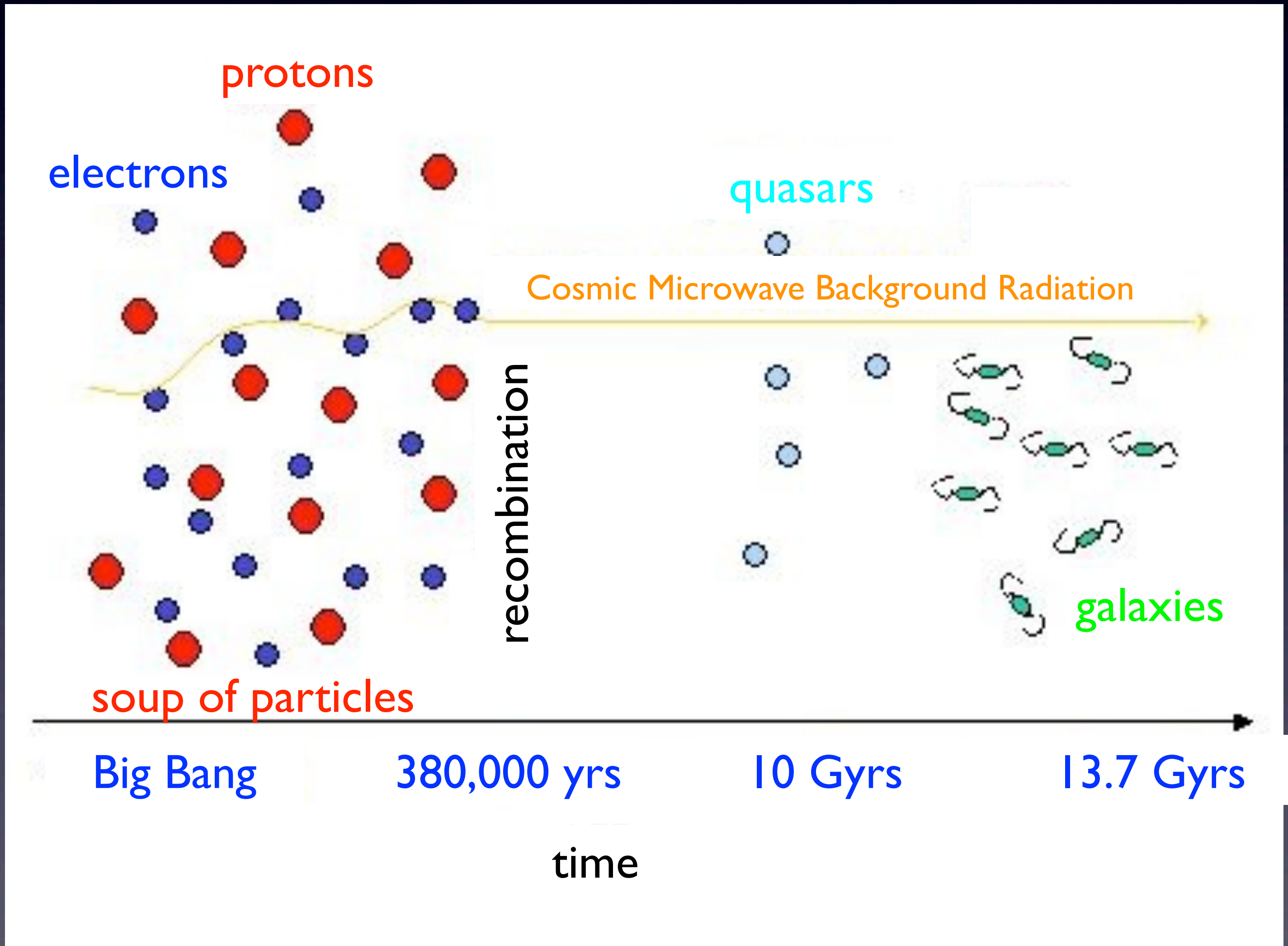
3h
2h
1h
0h
23h
22h
3
2
1
Billion Light Years
0.05
0.1
0.15
0.2
Redshift

reenacting Big Ban with Cal Band

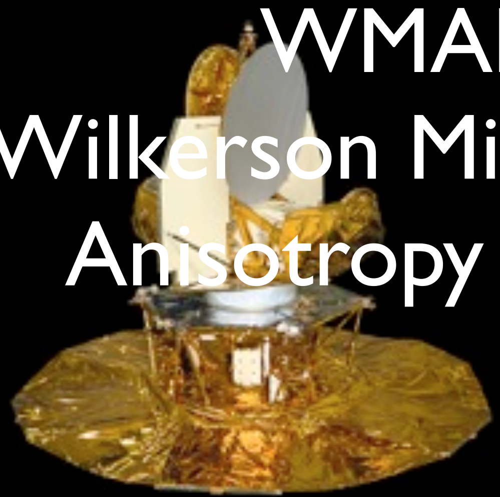

power spectrum

CMB

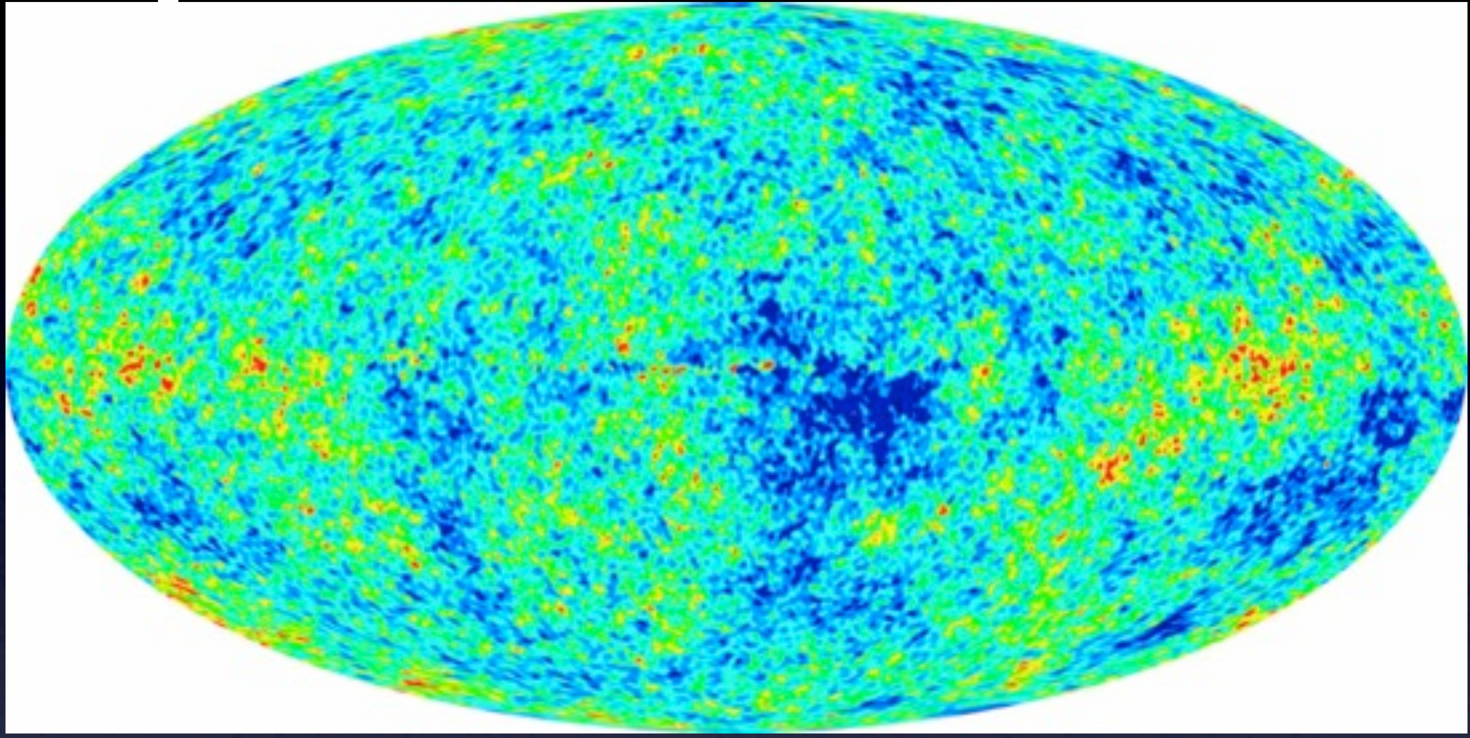
- before recombination, there was a fluid of protons, electrons, photons, dark matter (and neutrinos)
- photon pressure ⇒ "sound waves"



WMAP
Wilkerson Microwave
Anisotropy Probe



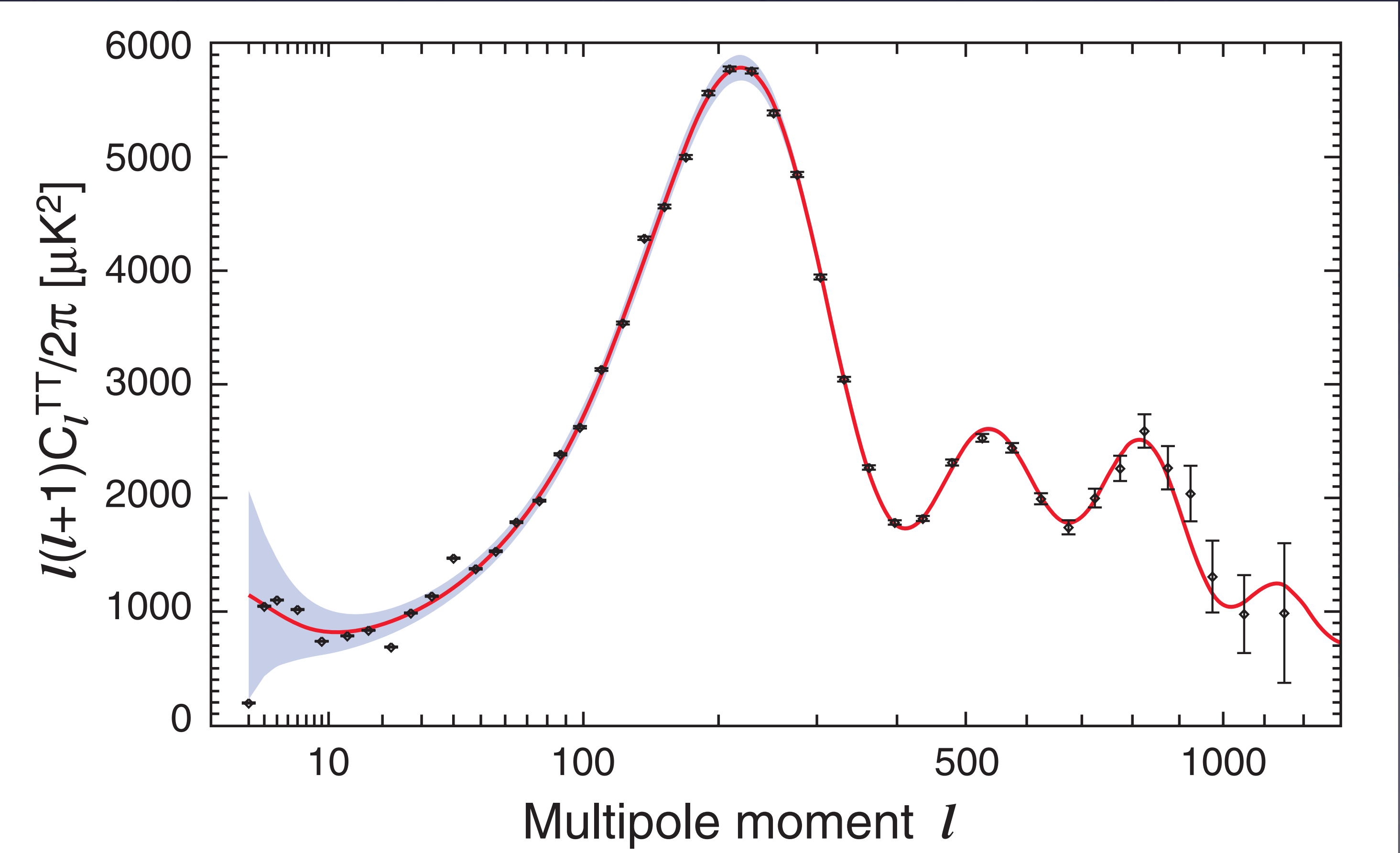
assumption

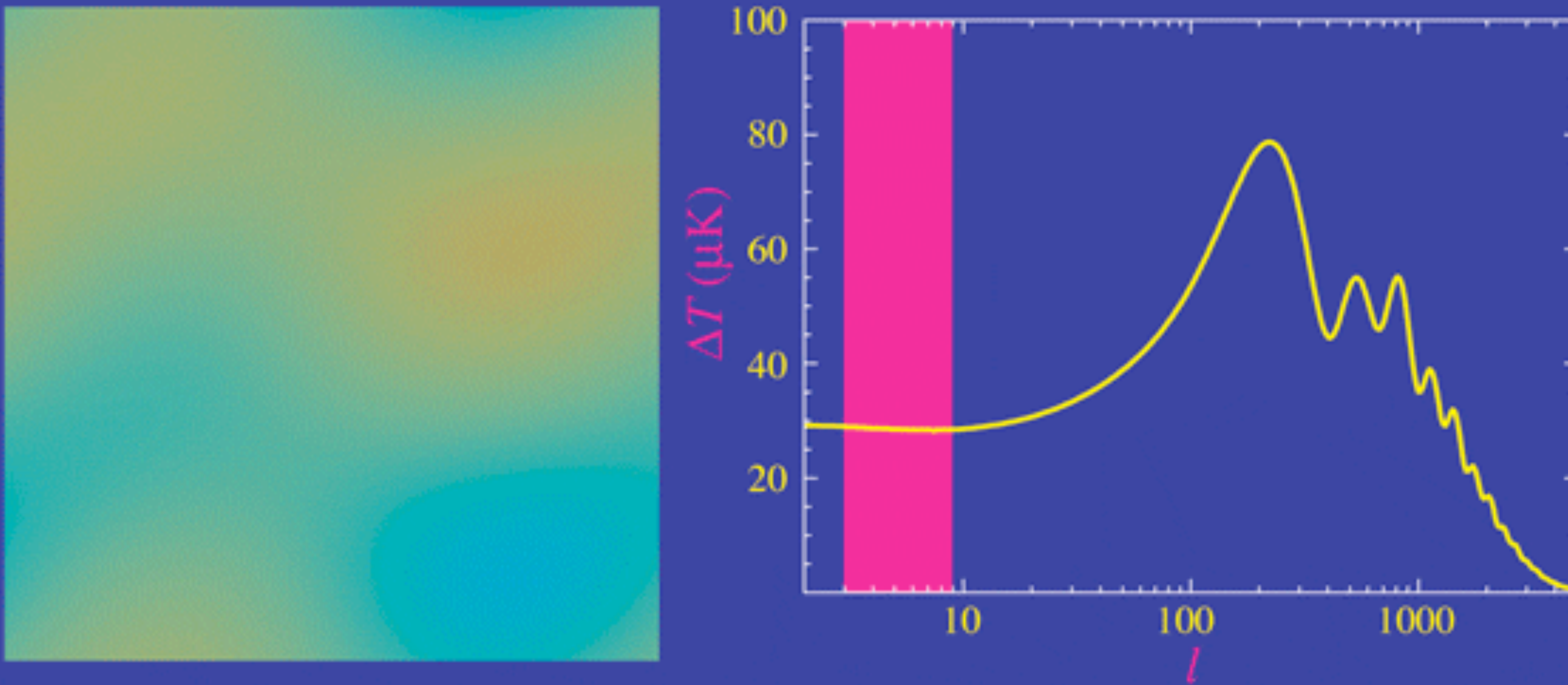


- a random density fluctuations ~$O(10^{-5})$ more-or-less scale invariant $P(k) \propto k^{ns-1}$
- starts acoustic oscillation, amplified by gravitational attraction
- "knows" about everything between $0<z<1300$

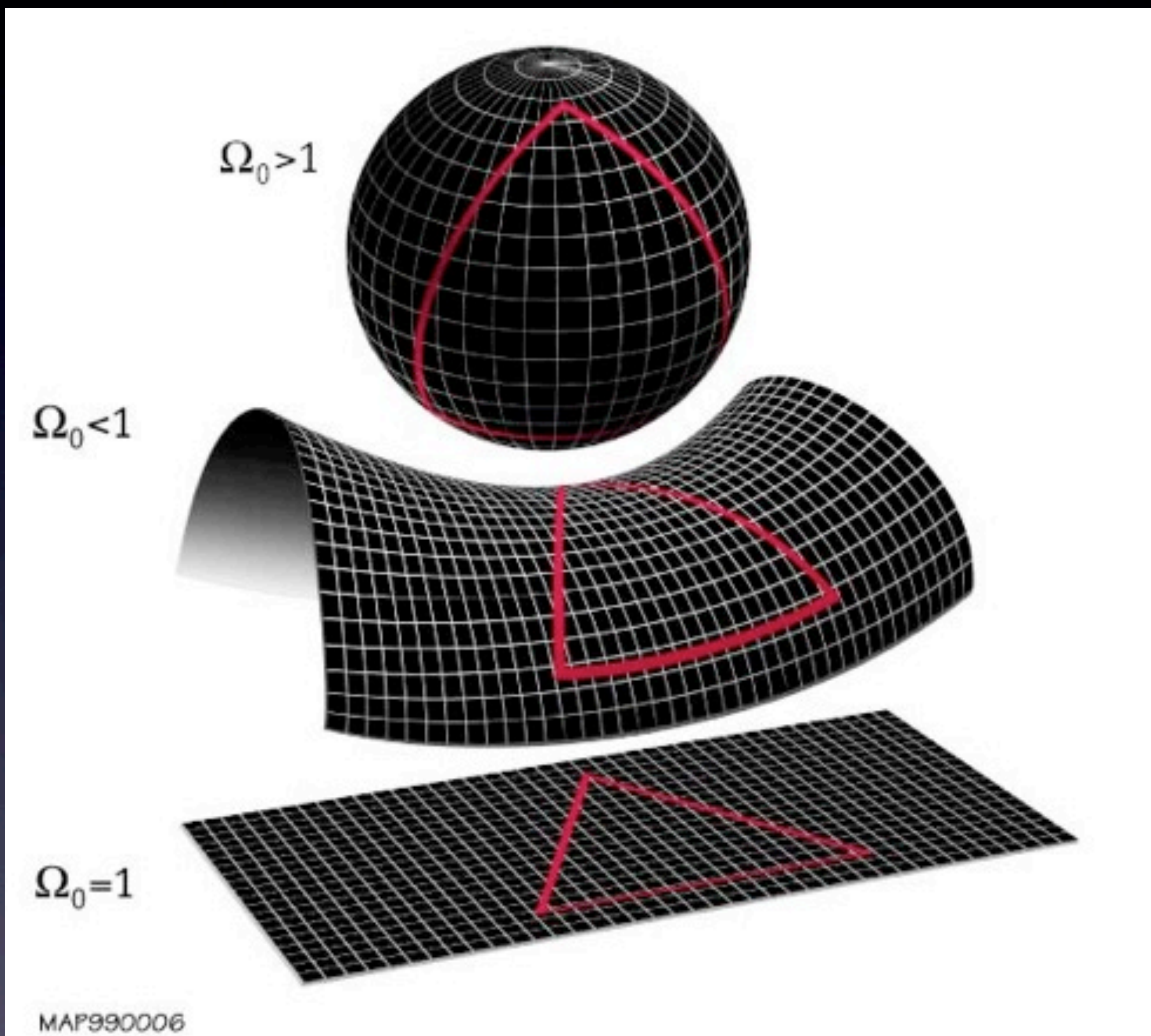
$$\delta T/T = a_{lm}\, Y_l^m$$

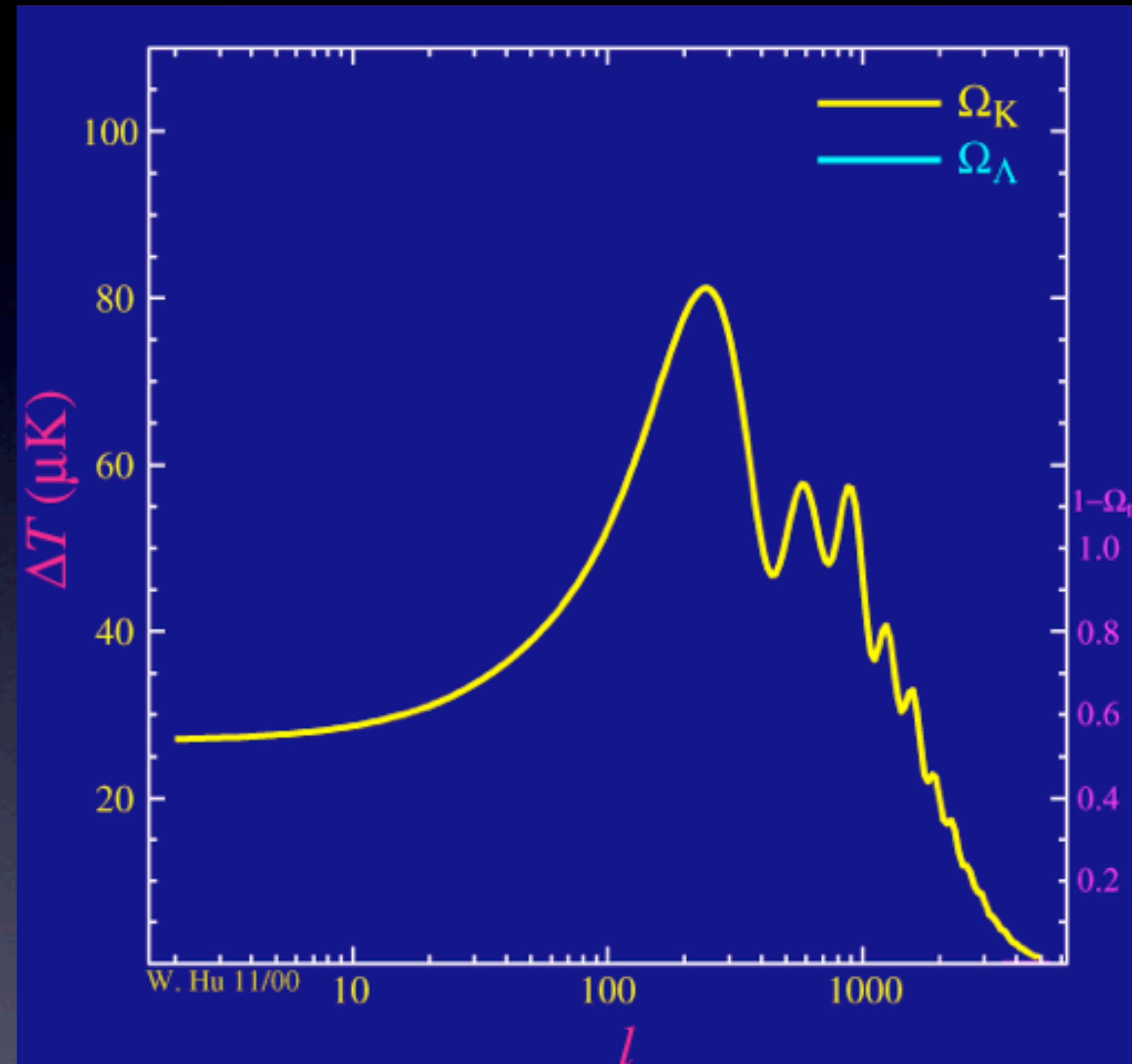
$$(2l+1)c_{lm} = \Sigma_m\, a_{lm}^*a_{lm}$$



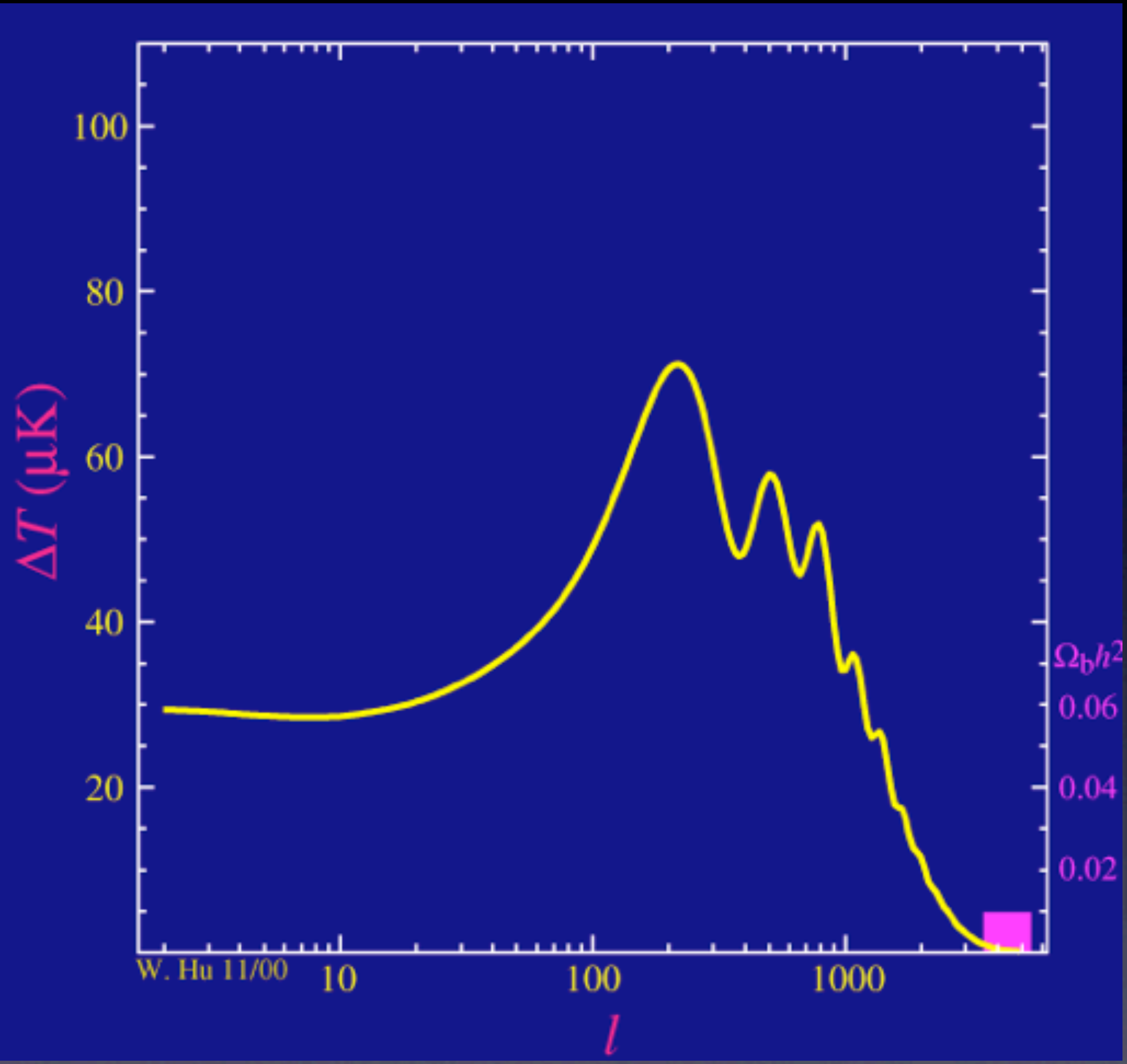


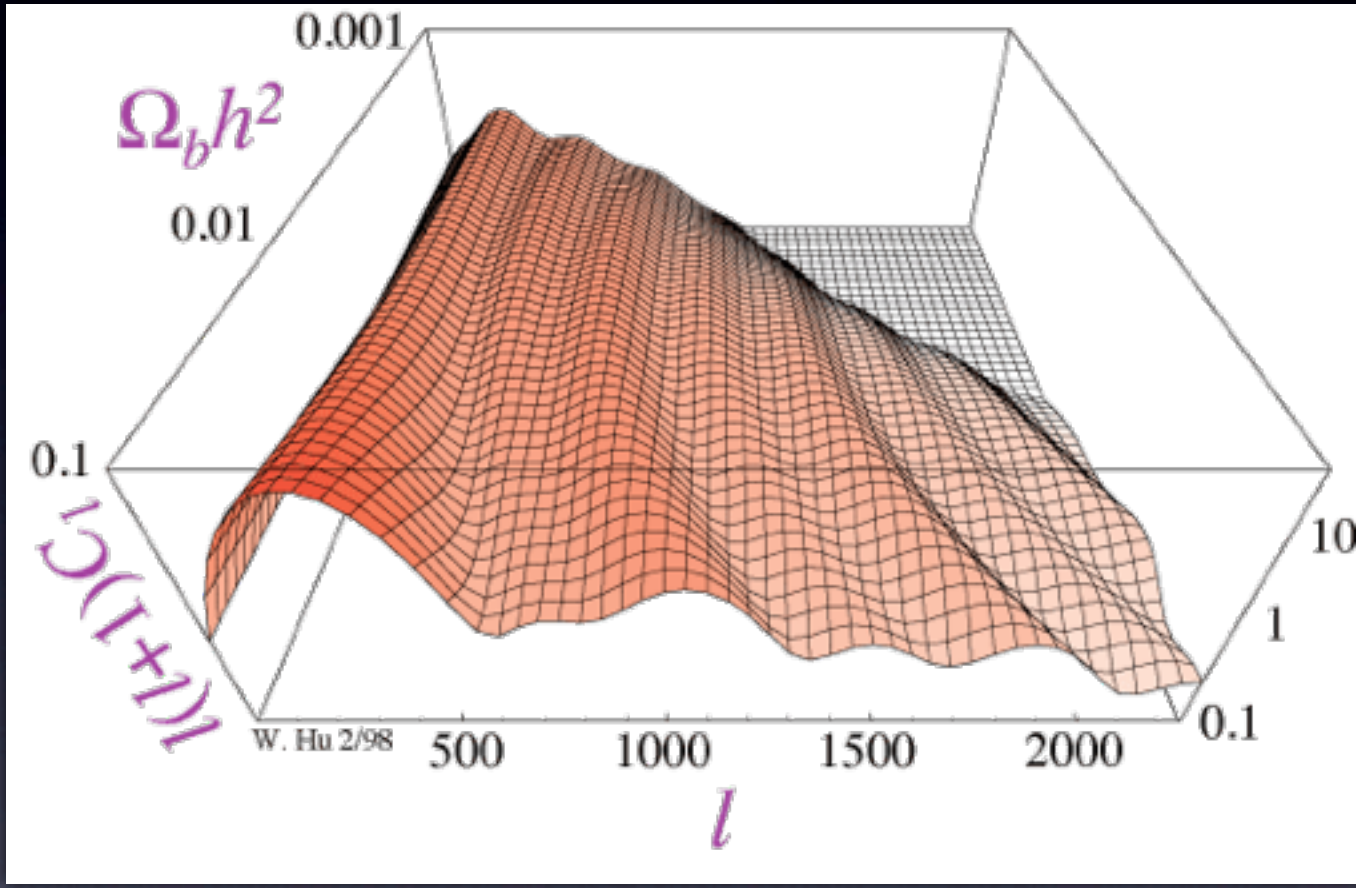
Wayne Hu





Ω_k changes
the apparent angular size
of the peak positions

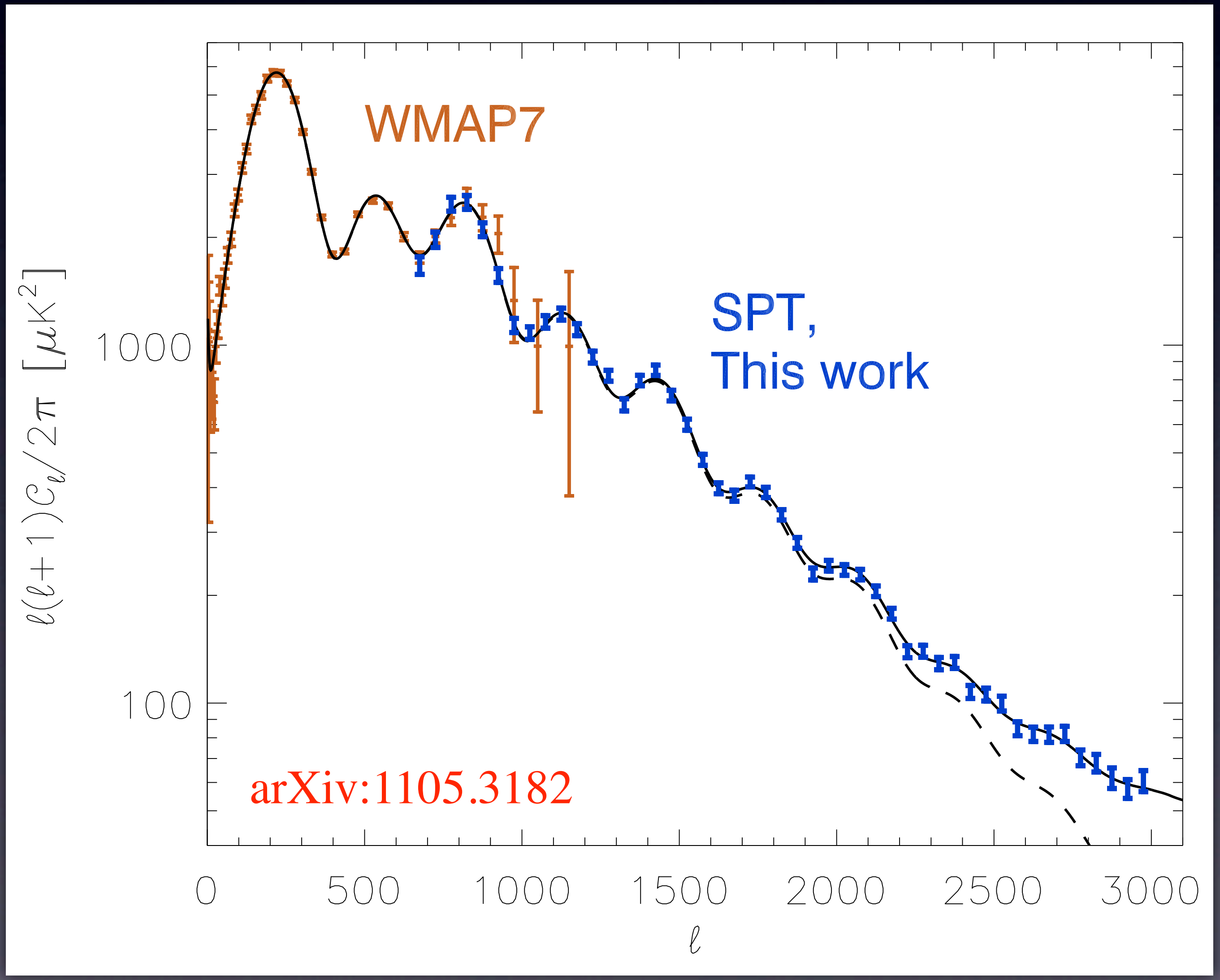




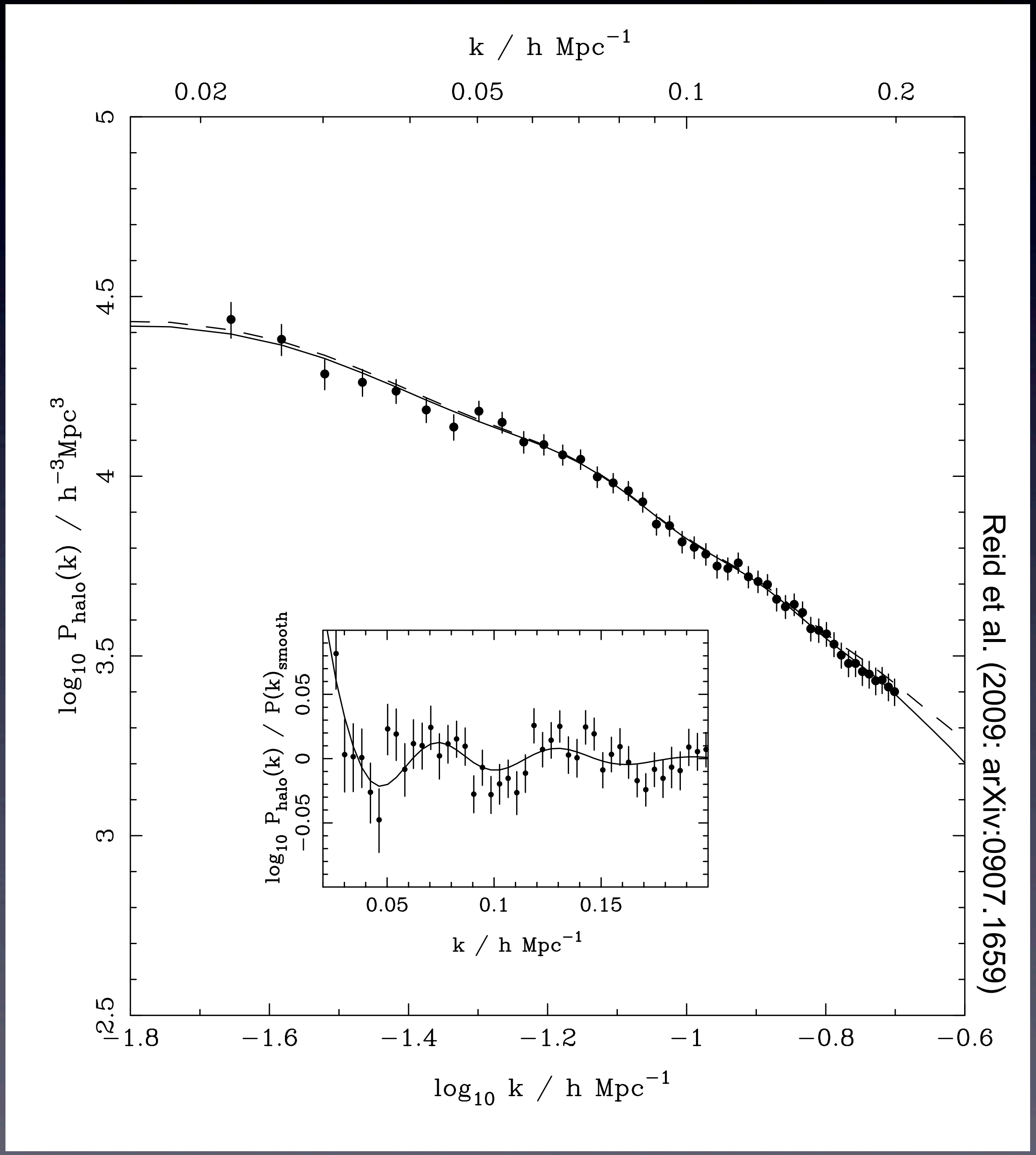
Ω_b changes
the relative size of
even and odd peaks

standard cosmology
ΛCDM

works like SM @ LEP



CMB power spectrum



galaxy power spectrum

standard cosmology
ΛCDM

- flat universe Ω_k=0
- perturbation $P(k) \propto k^{ns-1}$ with single exponent n_s for both scalar and tensor modes
- three massless neutrinos

Table 3
Six-parameter ΛCDM Fit[a]

Parameter	Seven-year Fit
Fit parameters	
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$
$\Omega_c h^2$	0.1109 ± 0.0056
Ω_Λ	0.734 ± 0.029
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$
n_s	0.963 ± 0.014
τ	0.088 ± 0.015
Derived parameters	
t_0	13.75 ± 0.13 Gyr
H_0	71.0 ± 2.5 km s^{-1} Mpc^{-1}
σ_8	0.801 ± 0.030
Ω_b	0.0449 ± 0.0028
Ω_c	0.222 ± 0.026
z_{eq}	3196^{+134}_{-133}
z_{reion}	10.5 ± 1.2

Note. [a] Models fit to *WMAP* data only. See Komatsu e
constraints.

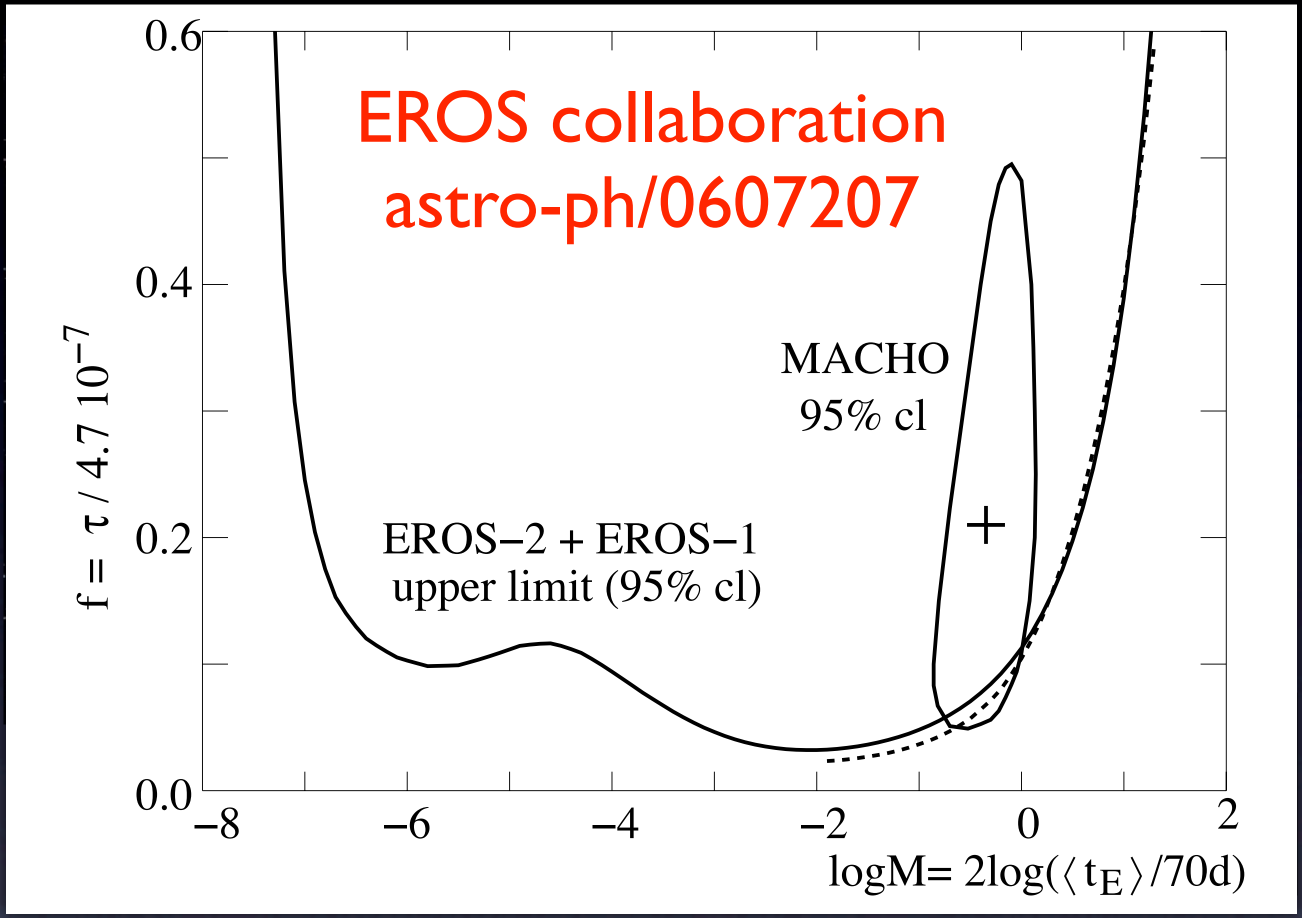
Known Facts about Dark Matter

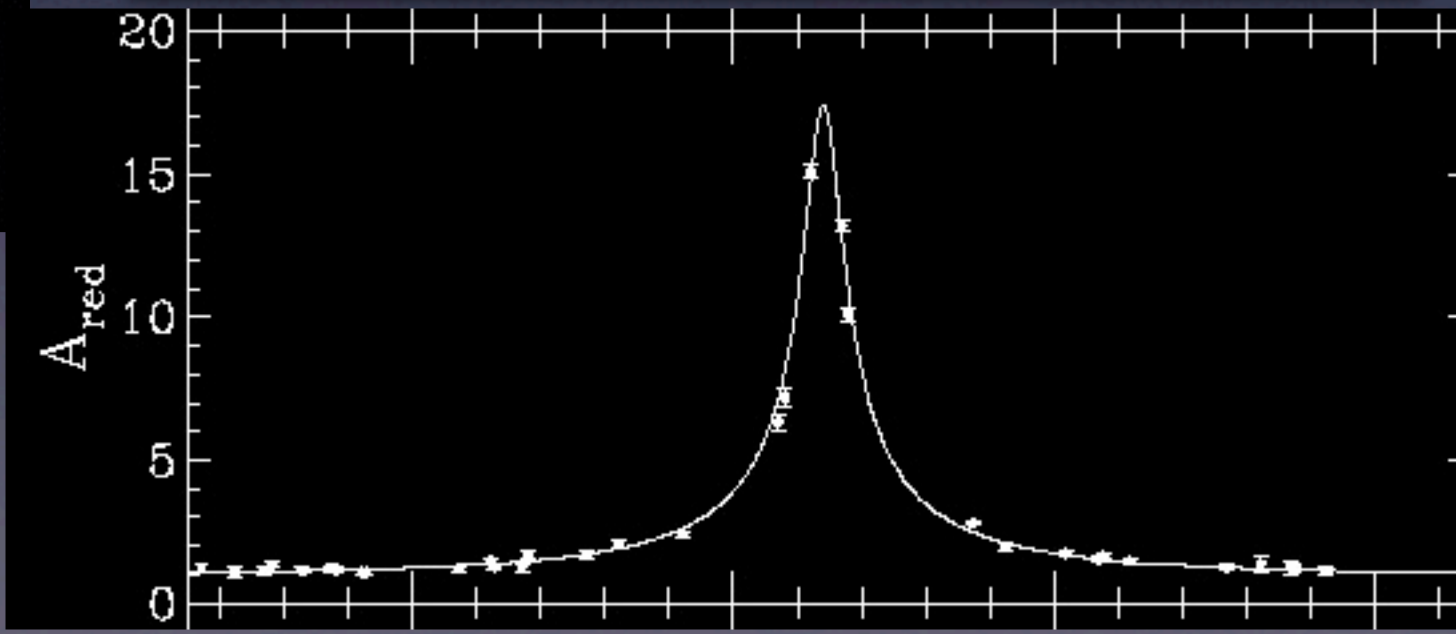
Cold and Neutral

- 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)





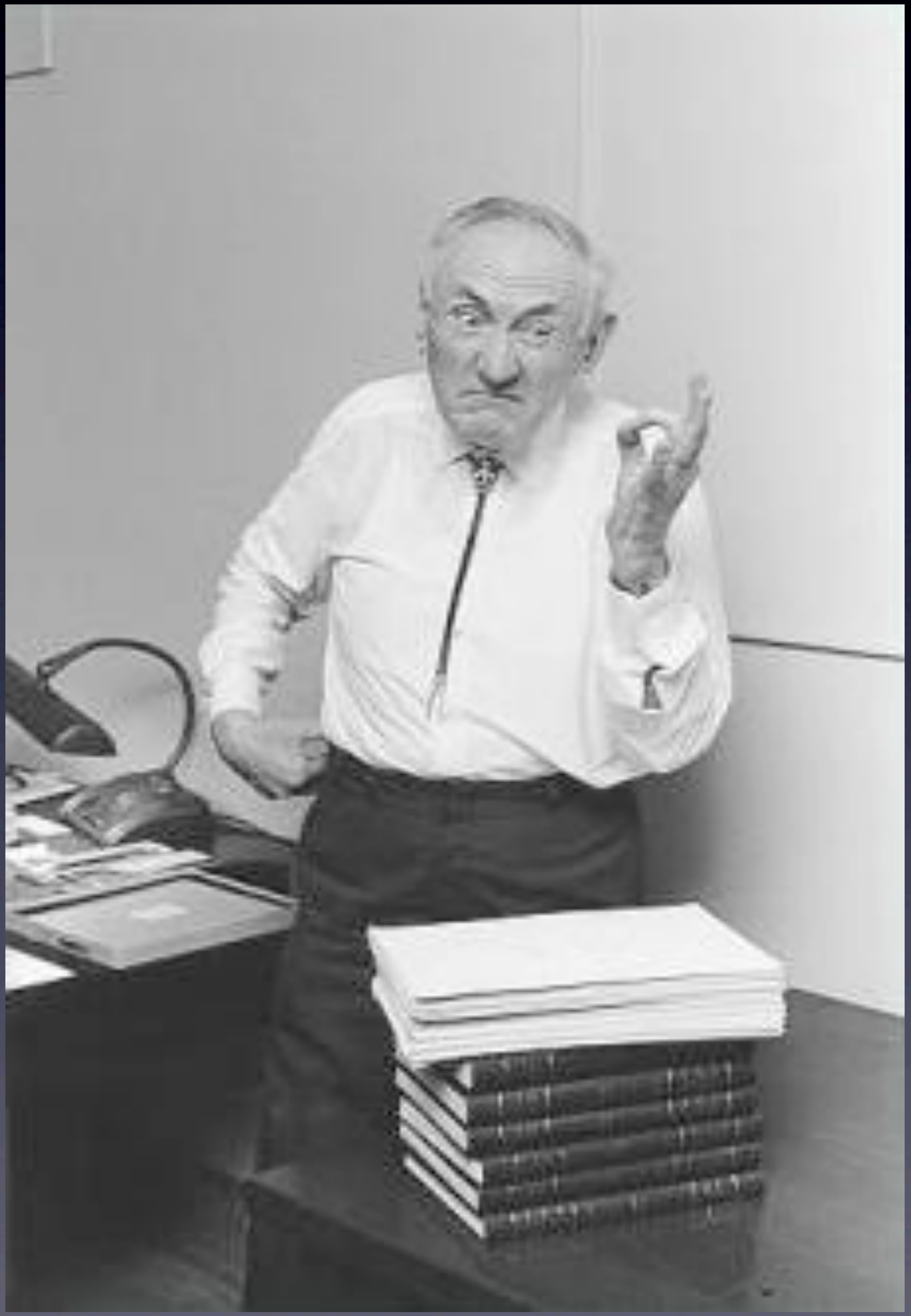
Not enough of them!

Mass Limits
"Uncertainty Principle"

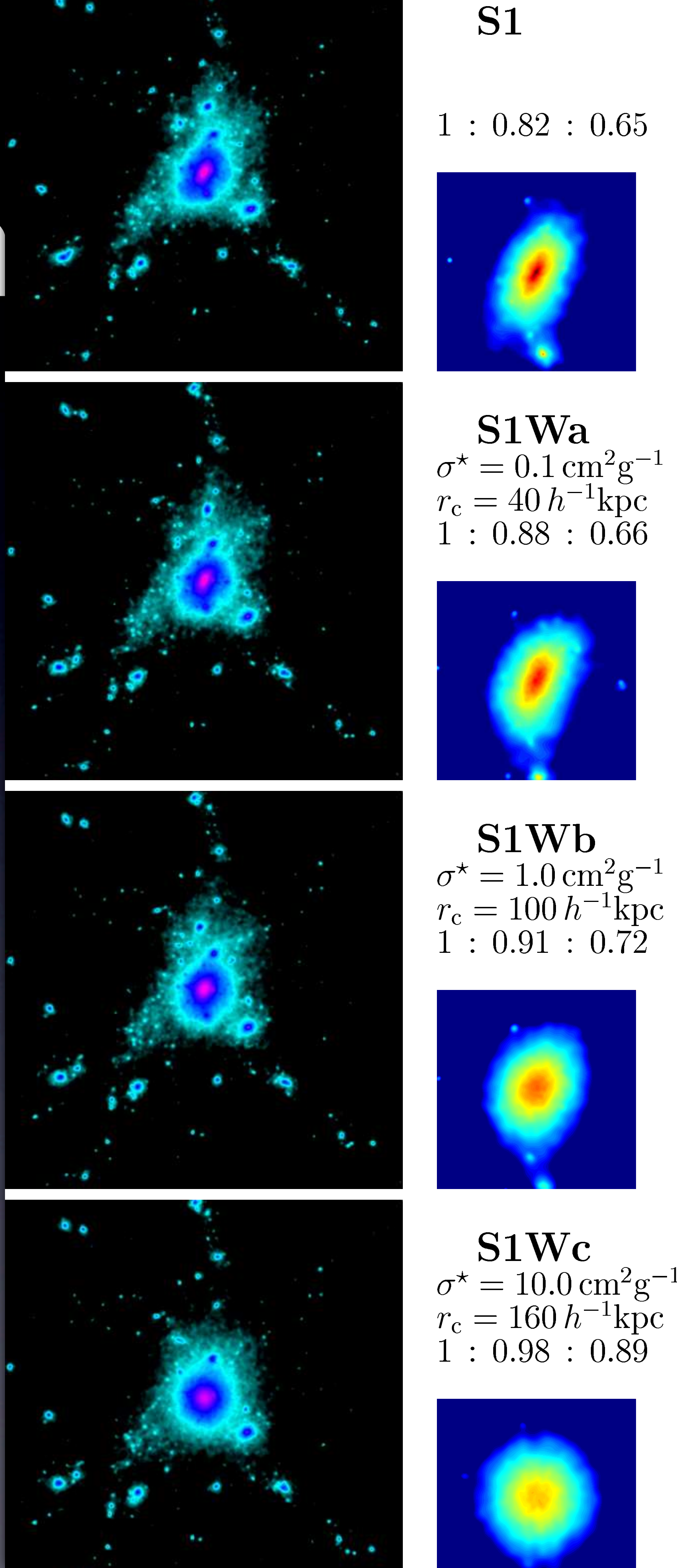
- Clumps to form structure
- imagine $V = G_N \frac{Mm}{r}$
- "Bohr radius": $r_B = \frac{\hbar^2}{G_N M m^2}$
- too small m ⇒ won't "fit" in a galaxy!
- m >10^{-22} eV "uncertainty principle" bound
(modified from Hu, Barkana, Gruzinov, astro-ph/0003365)

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:

  $\sigma < 1.7\times10^{-24}$ cm^2 (m/GeV)
  (Markevitch et al, astro-ph/0309303)

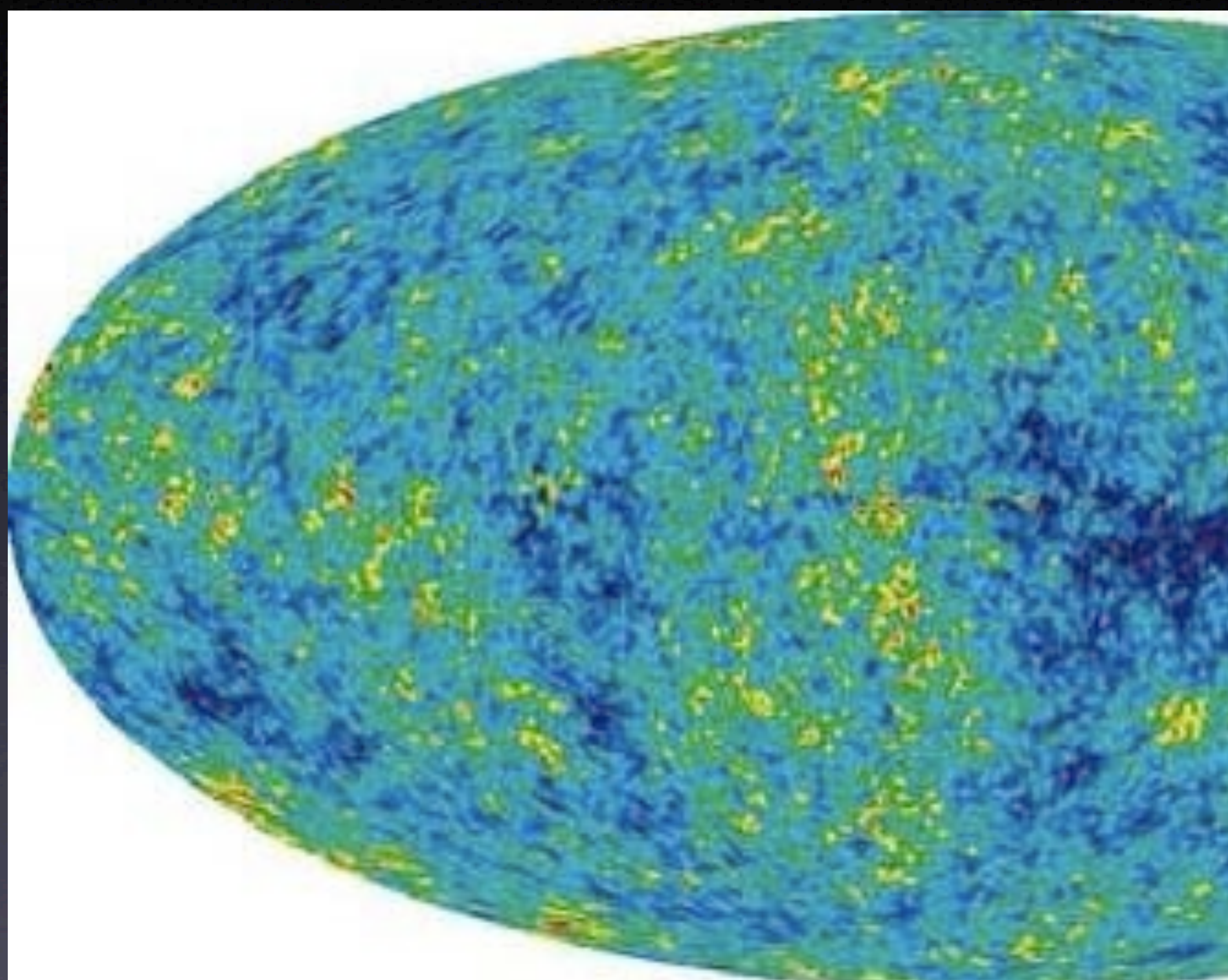
Lifetime

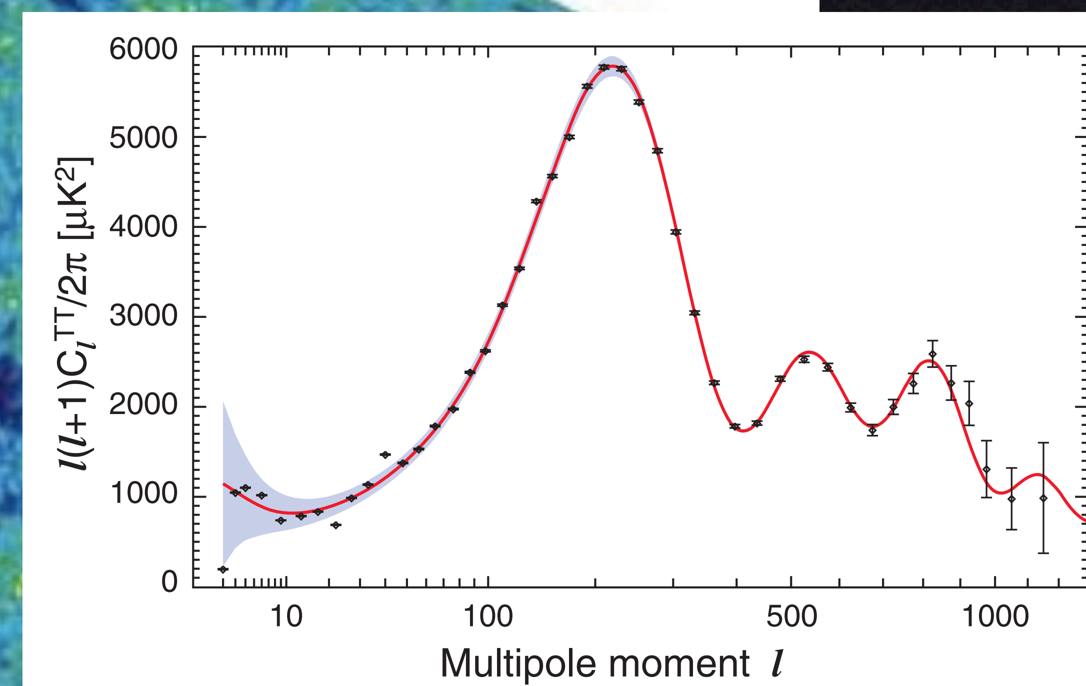
- At least of the order of age of the universe 14Gyr
- Beyond that, it depends on decay modes, branching fractions, all model-dependent

KAVLI IPMU

BERKELEY CENTER FOR THEORETICAL PHYSICS

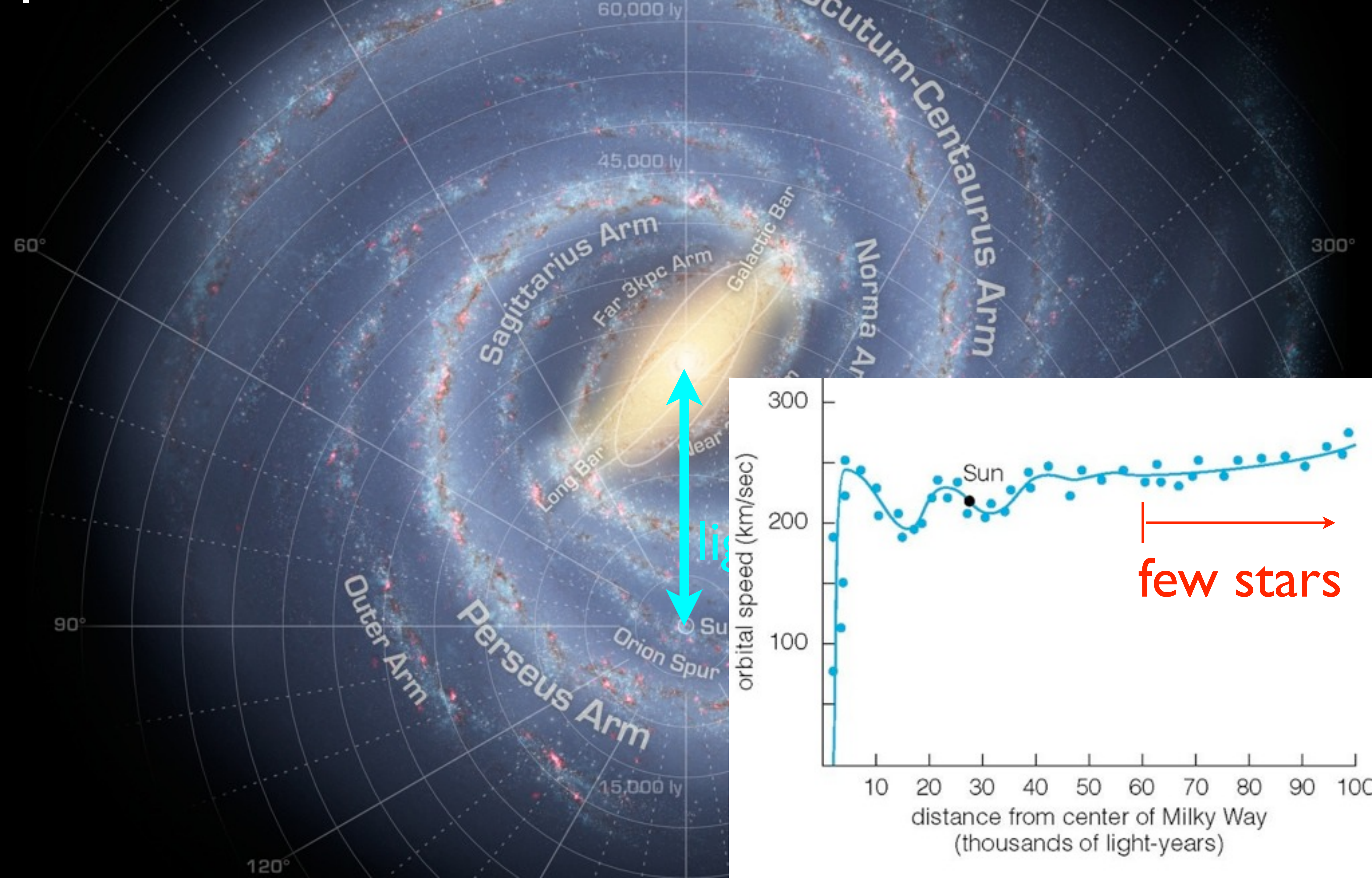
Cosmological scales





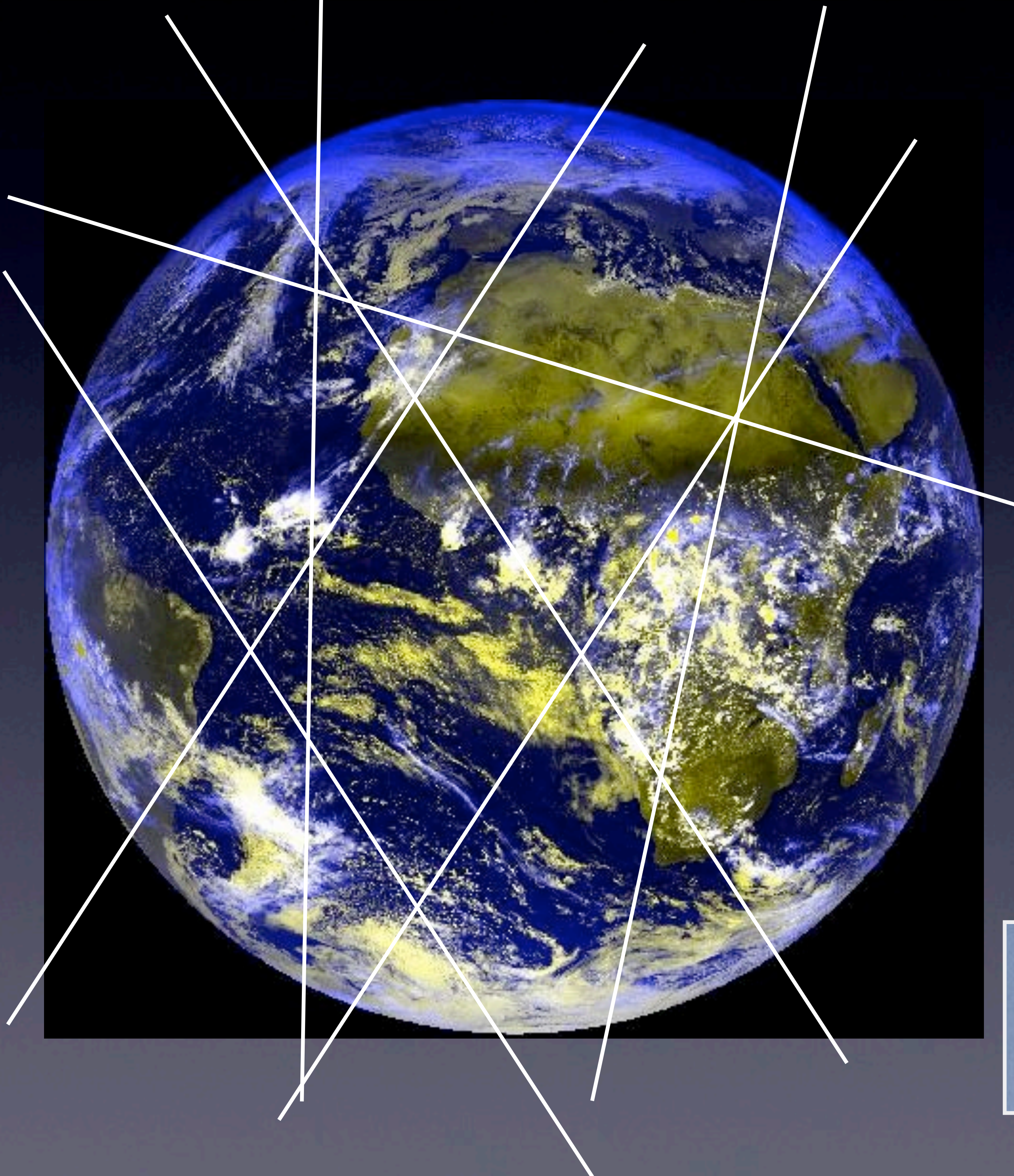
$$\frac{\text{matter}}{\text{all atoms}} = 5.70^{+0.39}_{-0.61}$$

$\rho \approx 0.3\text{–}0.4\ \mathrm{GeV/cm^3}$




WIMP paradigm

MACHOs to WIMP

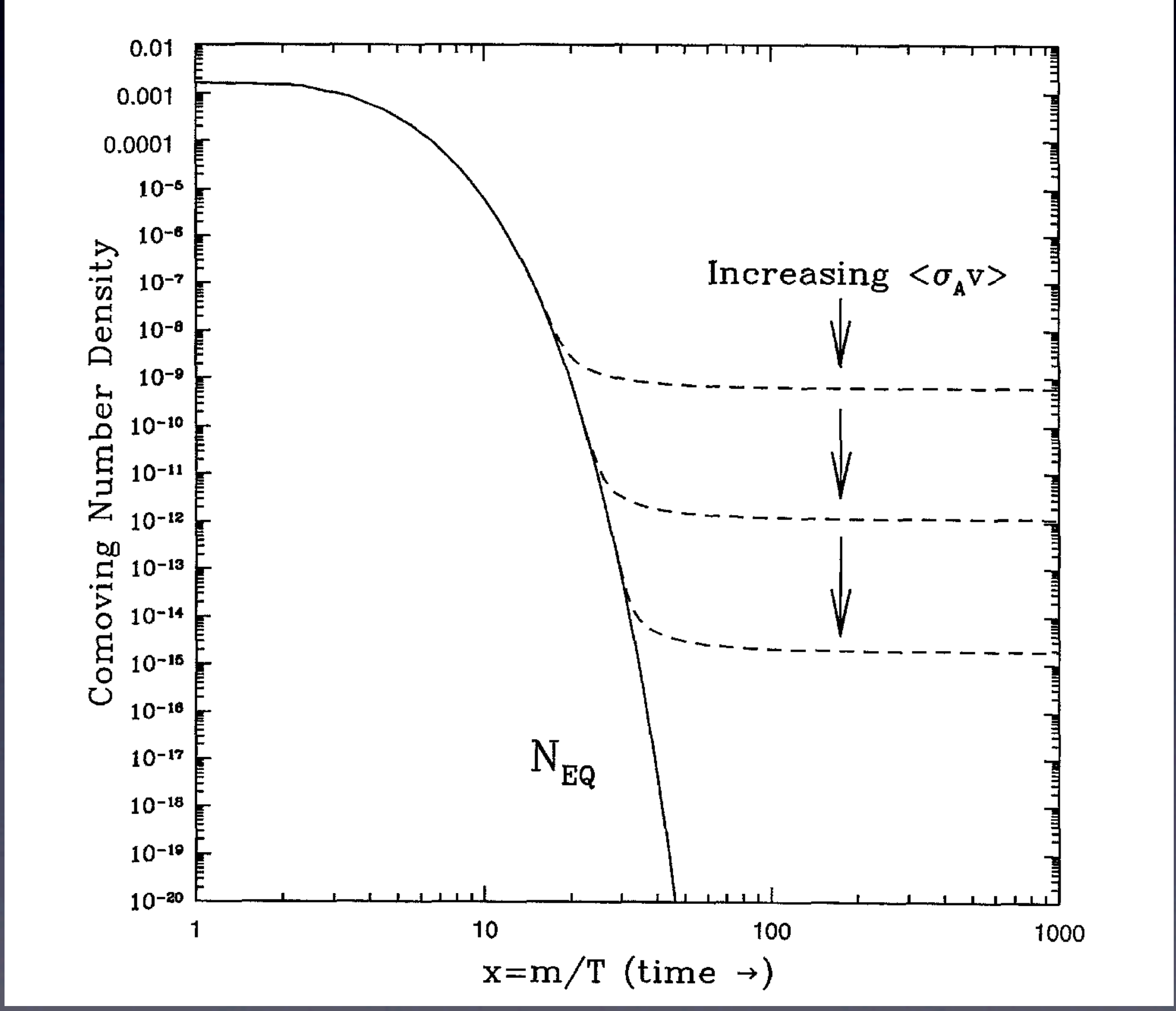


- *The dominant paradigm: WIMP (Weakly Interacting Massive Particle)*
- *Stable heavy particle produced in early Universe, left-over from near-complete annihilation*

$$\Omega_M = \frac{0.756(n+1)x_f^{n+1}}{g^{1/2}\sigma_{ann}M_{Pl}{}^3}\frac{3s_0}{8\pi H_0^2} \approx \frac{\alpha^2/(TeV)^2}{\sigma_{ann}}$$

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!!!

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

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

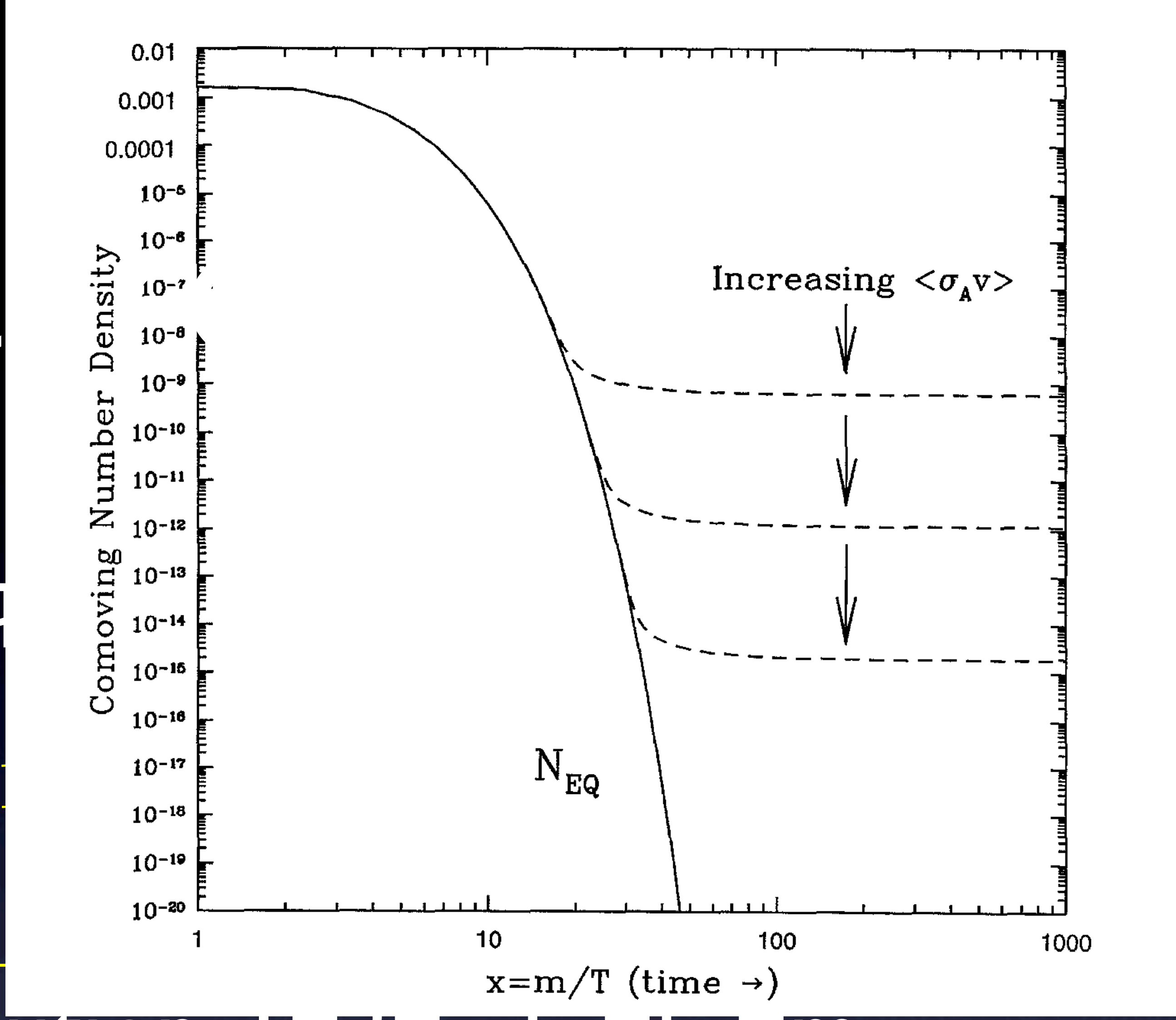
$$\sim 10^{-9} \mathrm{GeV}^{-2}$$

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

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

WIMP miracle

therma



- Solve the Boltzmann eq

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

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

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

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

- 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

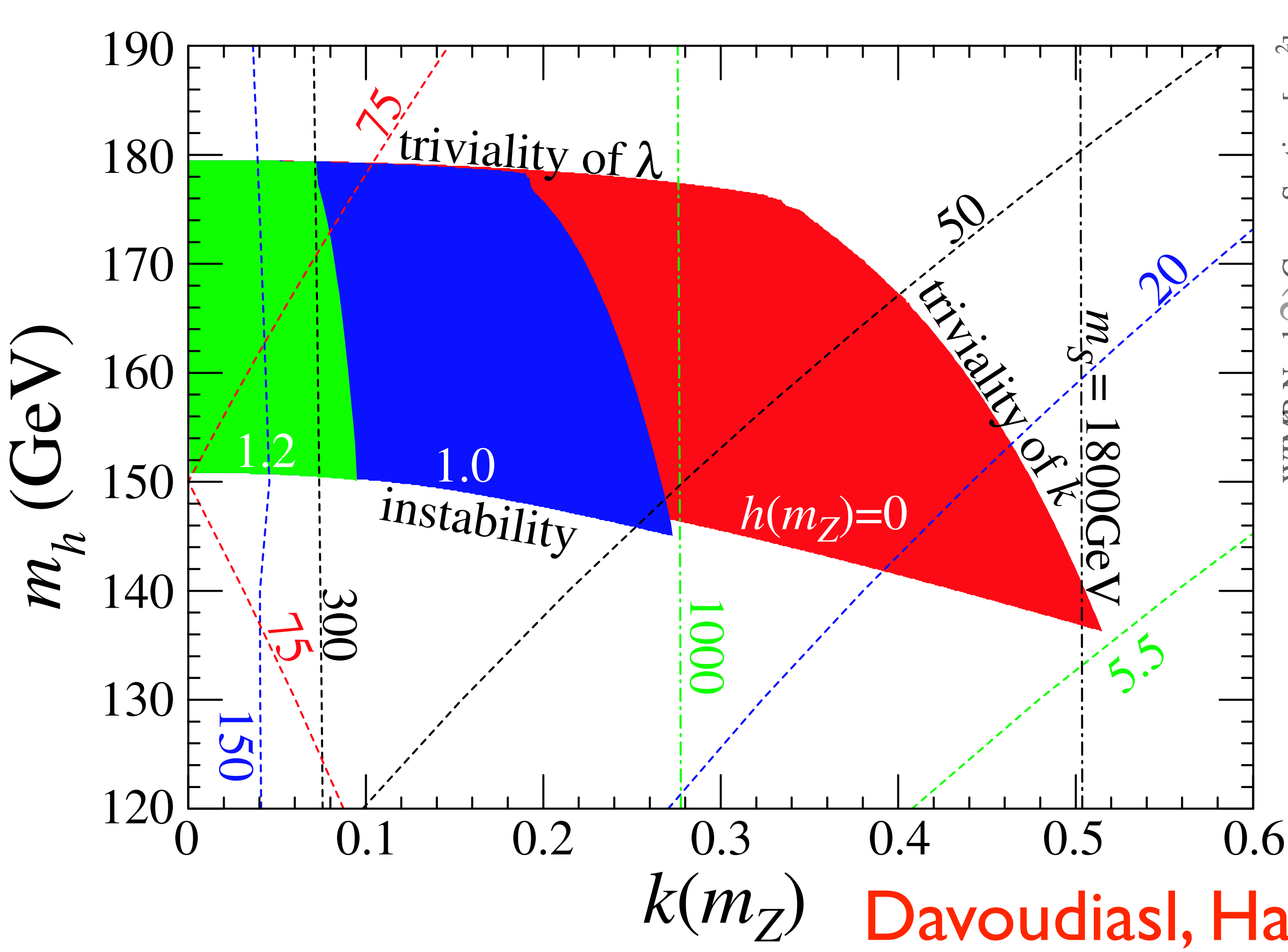
- Dark Matter clearly a new degree of freedom
- The smallest degree of freedom you can add to the QFT is a real Klein-Gordon field S: dof=1
- assign odd Z_2 parity to S, everything else even
- Most general renormalizable coupling

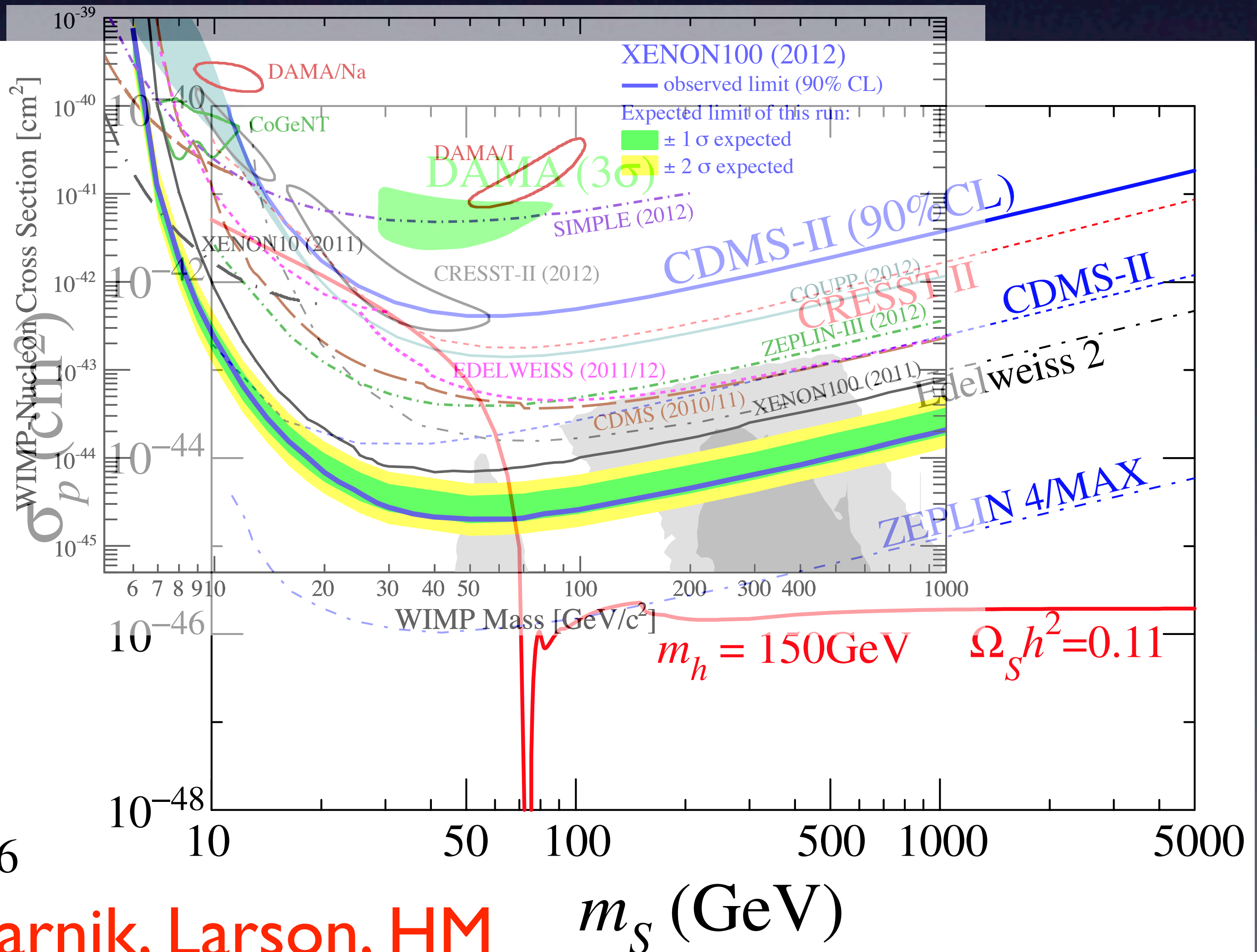
$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4 .$$

Davoudiasl, Harnik, Larson, HM

Consistency check

- correct Dark Matter abundance 5.5–1800 GeV
- evades direct detection limits >60 GeV
- satisfies triviality/instability limits from RGE
- consistent with precision electroweak data





Davoudiasl, Harnik, Larson, HM

Higgs as a portal

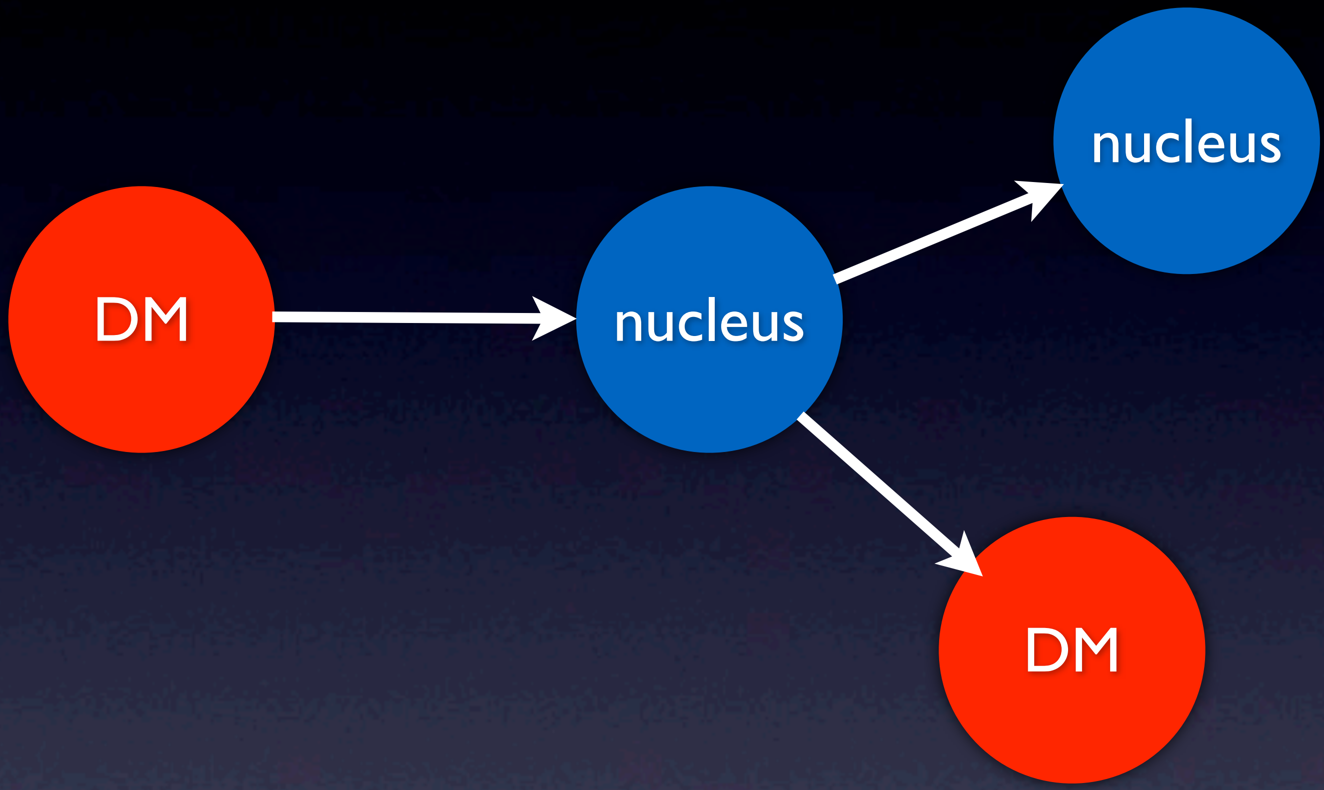
$$L_S = \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2} m_S^2 S^2 - \frac{k}{2}|H|^2 S^2 - \frac{h}{4!} S^4.$$

- having discovered the Higgs?
- Higgs boson may connect the Standard Model to other "sectors" via lowest-dim operators

$$\mathcal{L} = \mathcal{O}_{hidden} H^\dagger H$$

basic idea

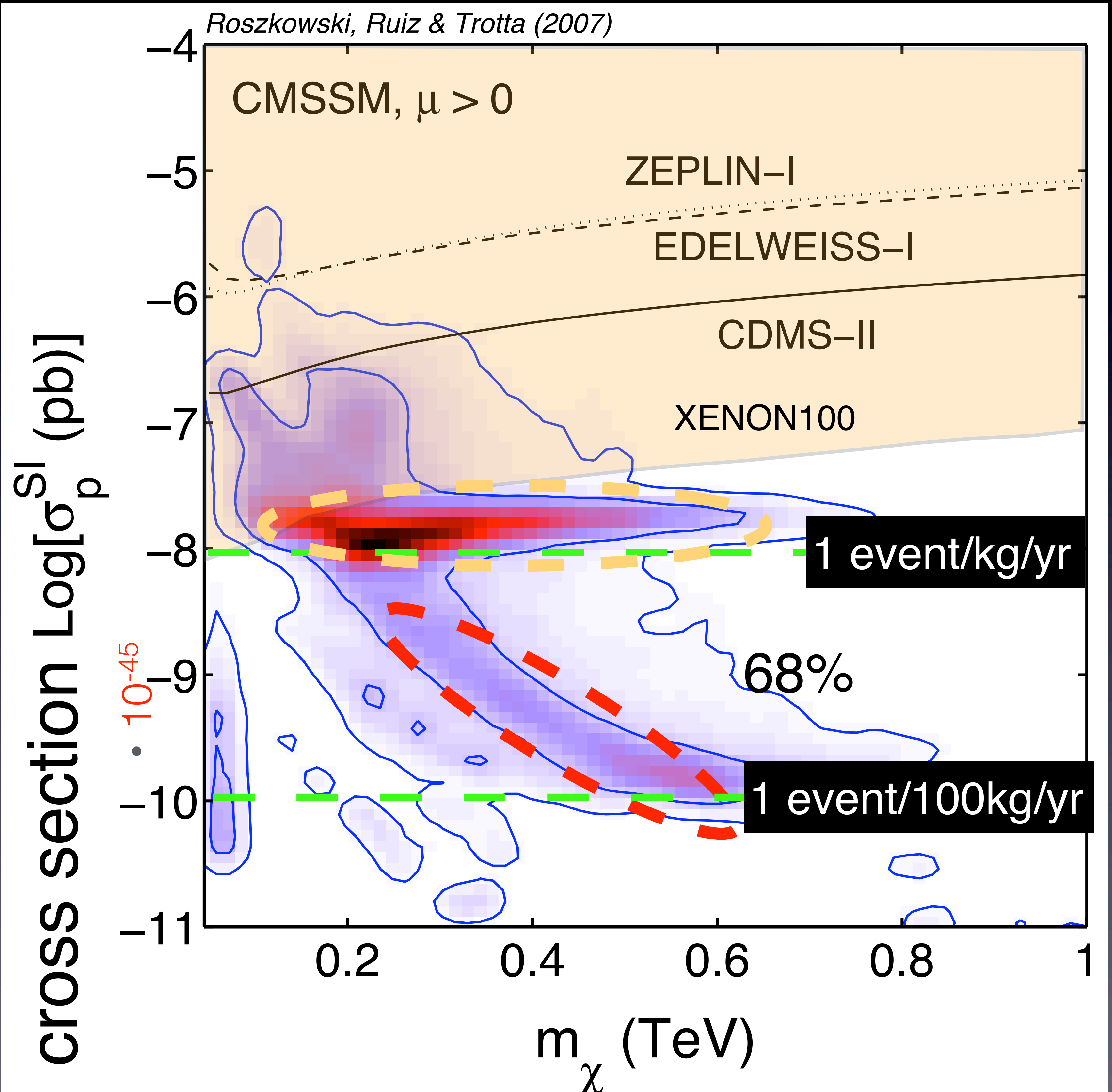
- maximum energy transfer to nucleus when $m_\chi \sim M_A$
- energy of the nucleus leads to a combination of
  - ionization
  - phonon
  - scintillation



$$E_f = \frac{1}{2} m_\chi \frac{m_\chi M_A}{(m_\chi + M_A)^2} 2(1 - \cos\hat{\theta})$$

Sensitivity and SUSY Parameter

Masaki Yamashita



CMSSM in 2007
hep-ph 0705.2012v1
Roszkowski et al.

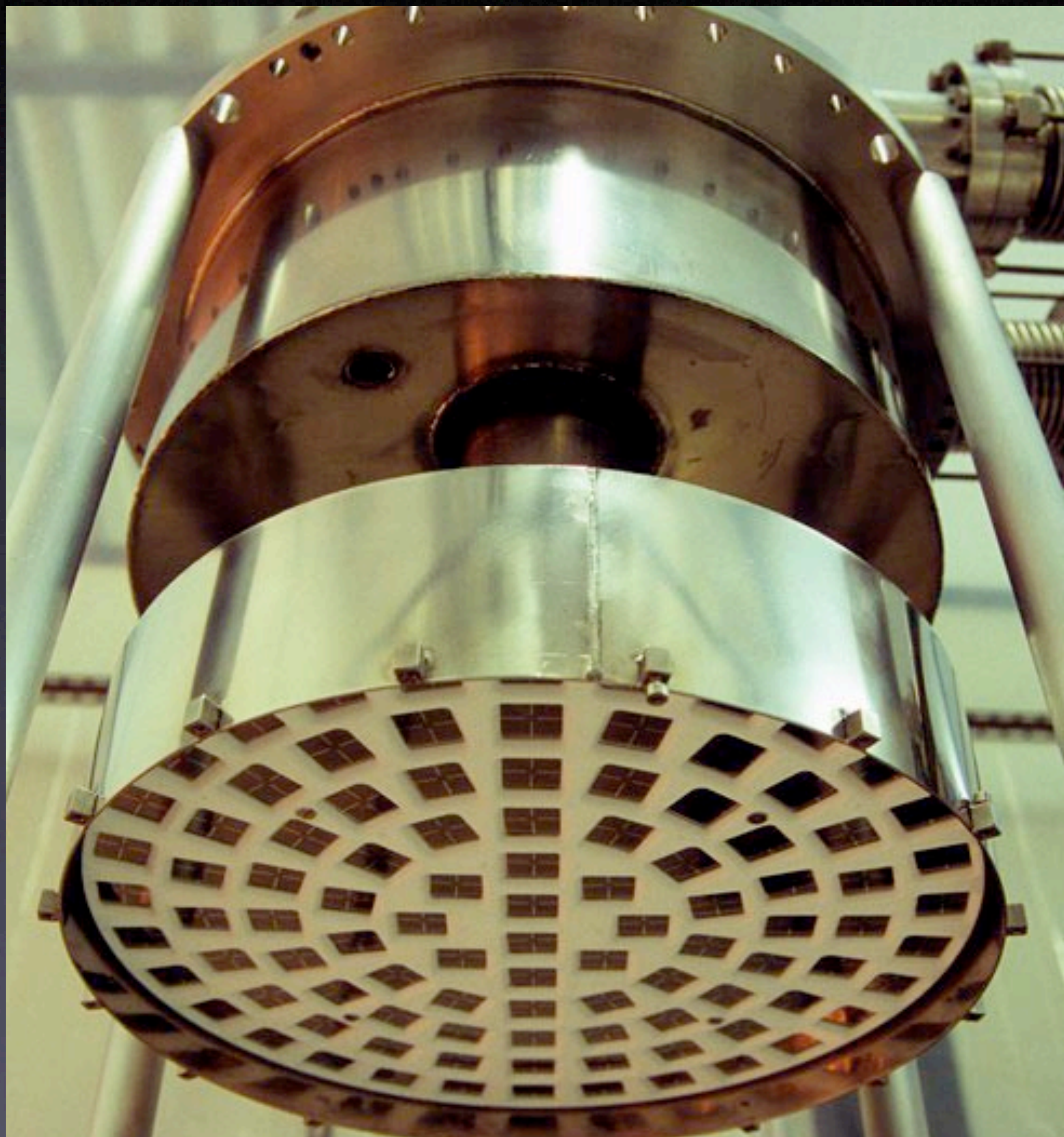
near future

Super CDMS, XENON100, LUX, XMASS, COUPP, CRESST-II, EDELWEISS-II, ZEPLIN-III,...

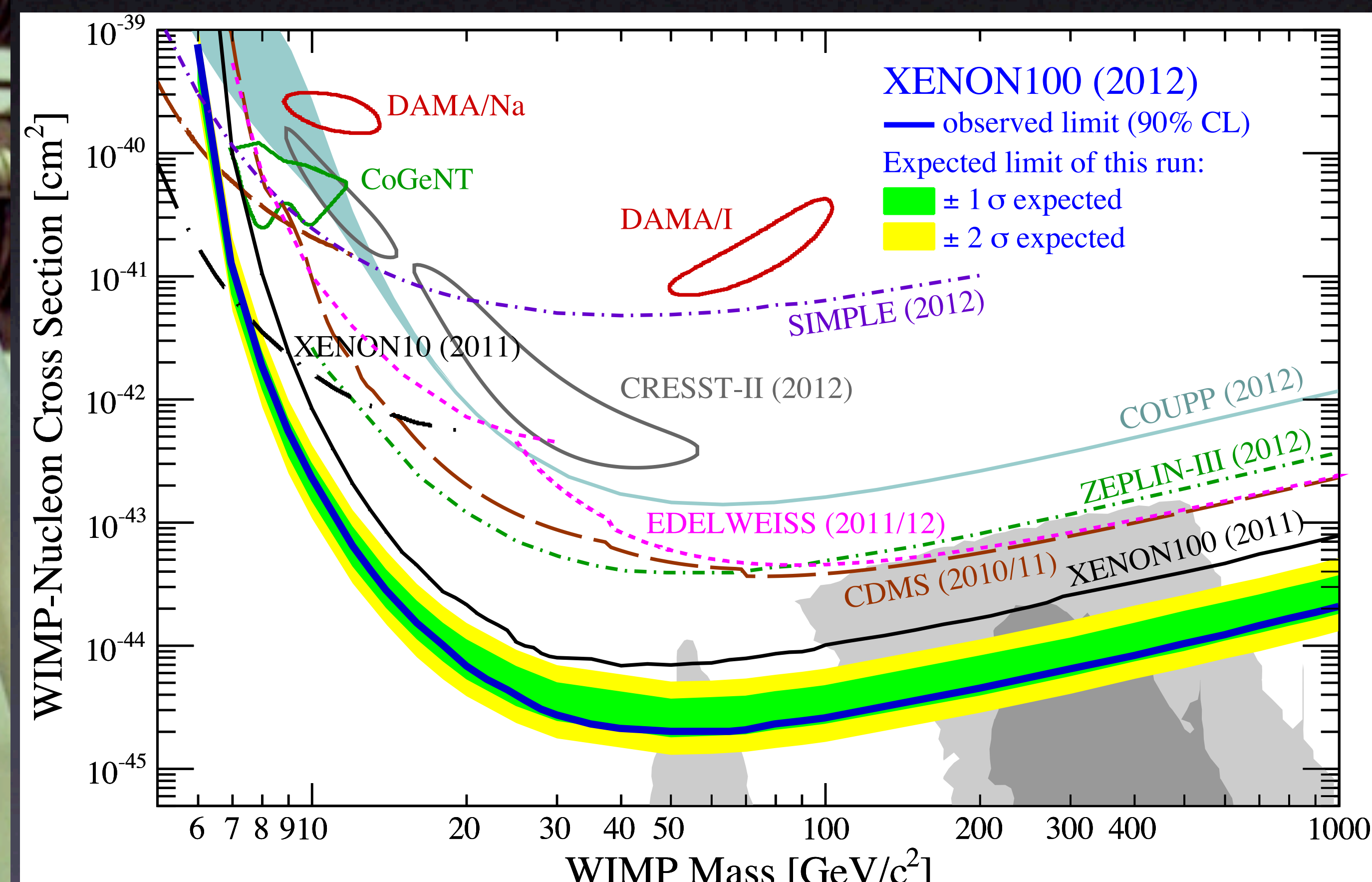
Future experiments

SuperCDMS1t, XENON1t, LZ, Darwin ArDM ,XMASS 20T, ...

direct search



XENON 100

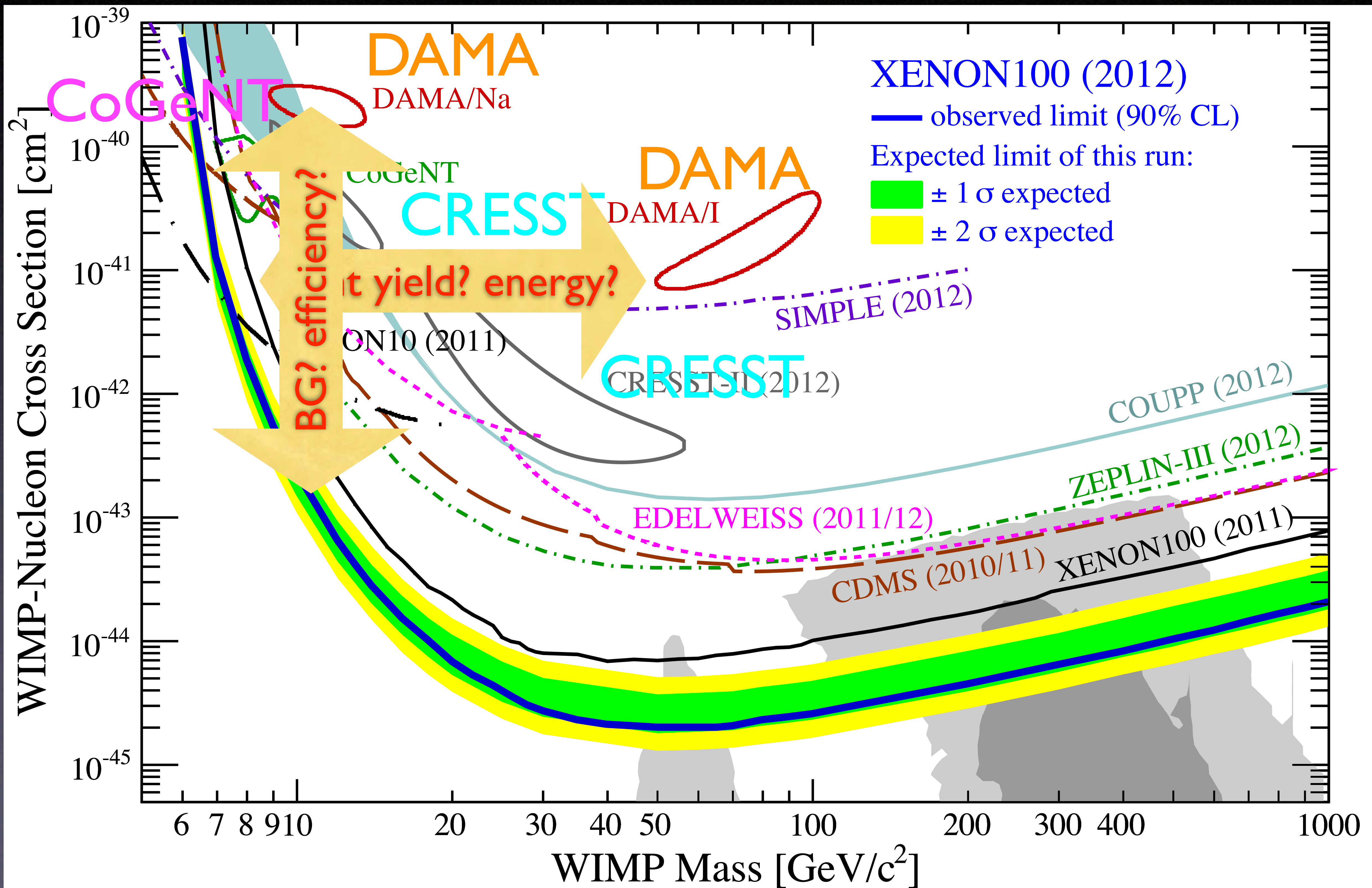


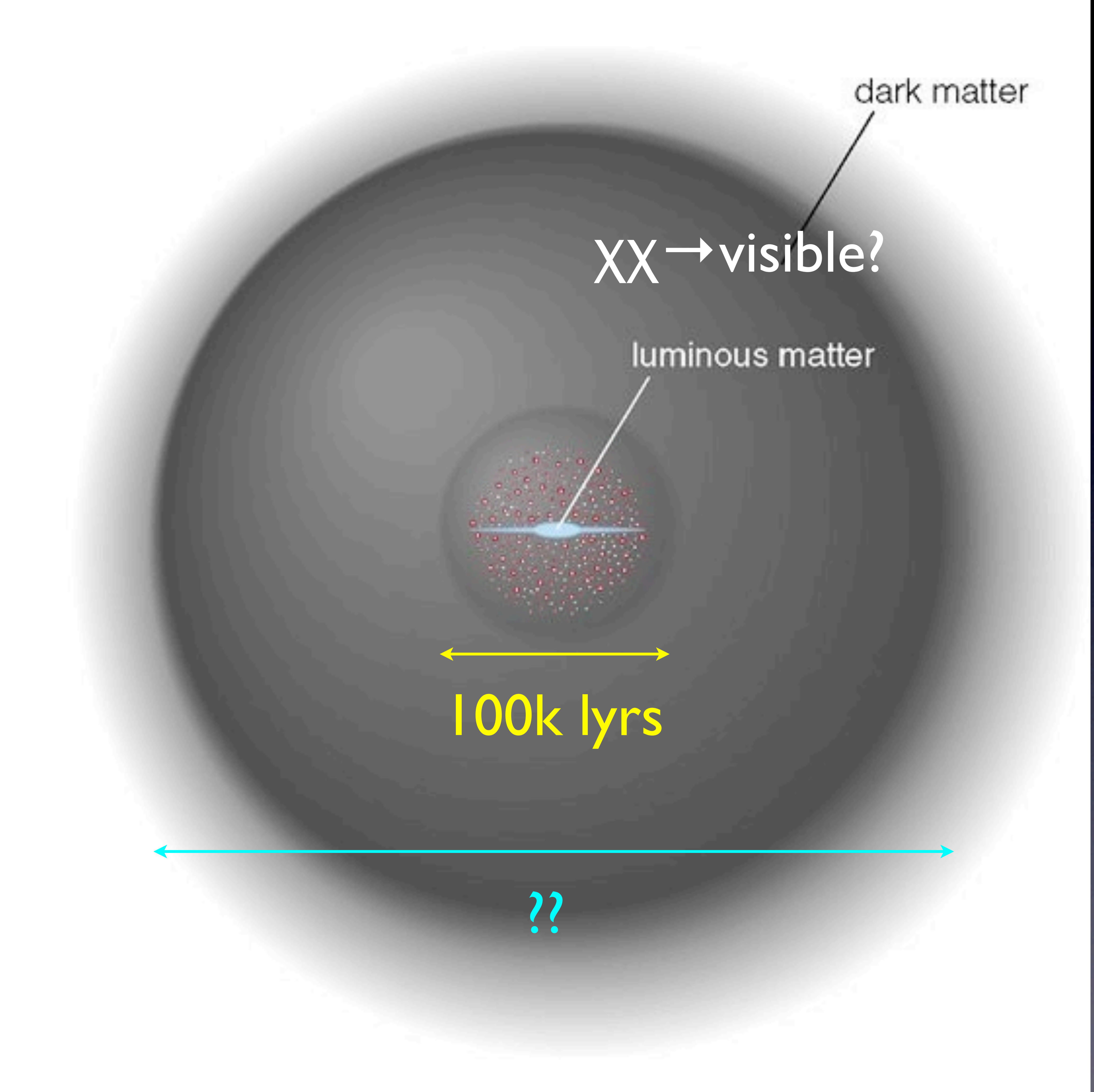
cf. $\sigma \sim 10^{-36}$ cm^2
for a heavy neutrino

KAVLI IPMU

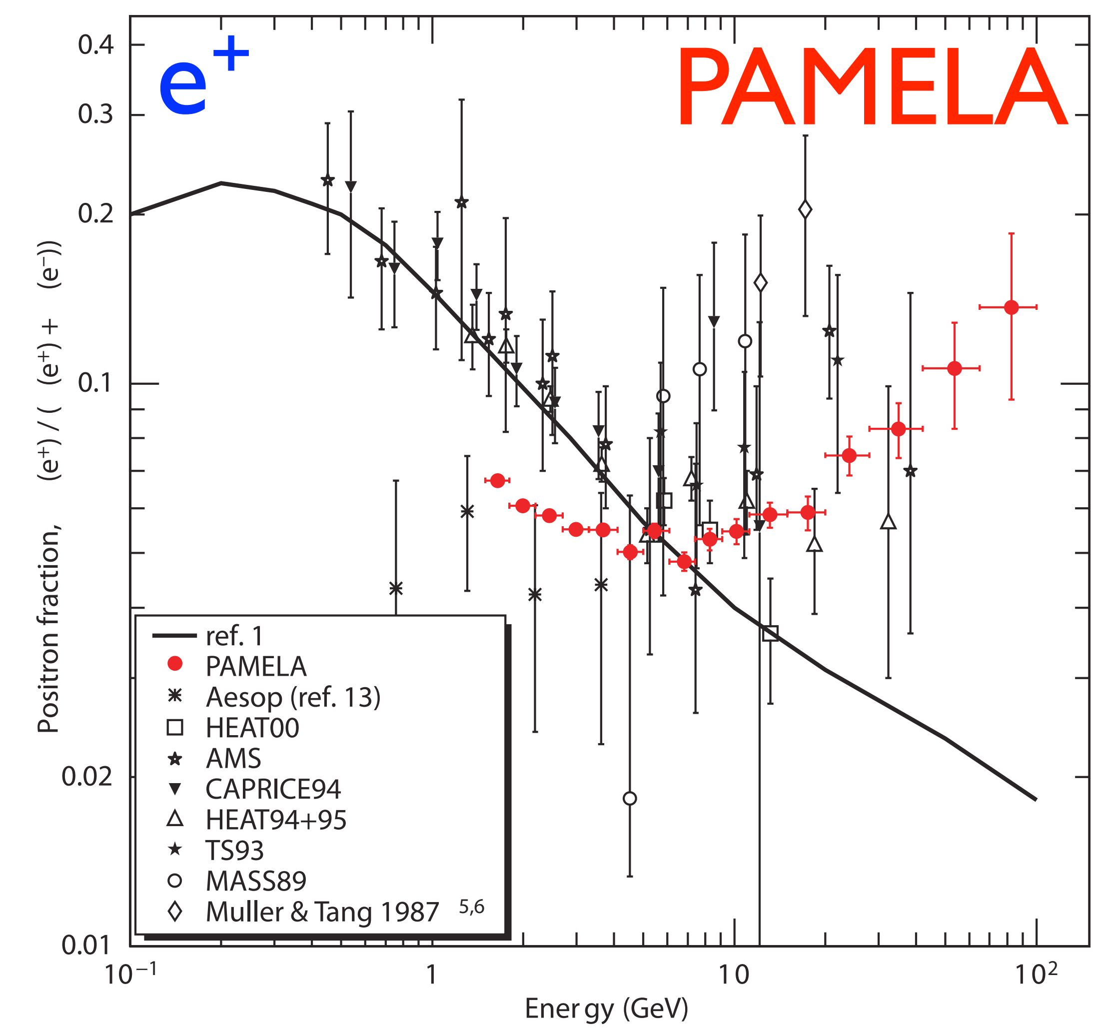
BERKELEY CENTER FOR THEORETICAL PHYSICS

confusing

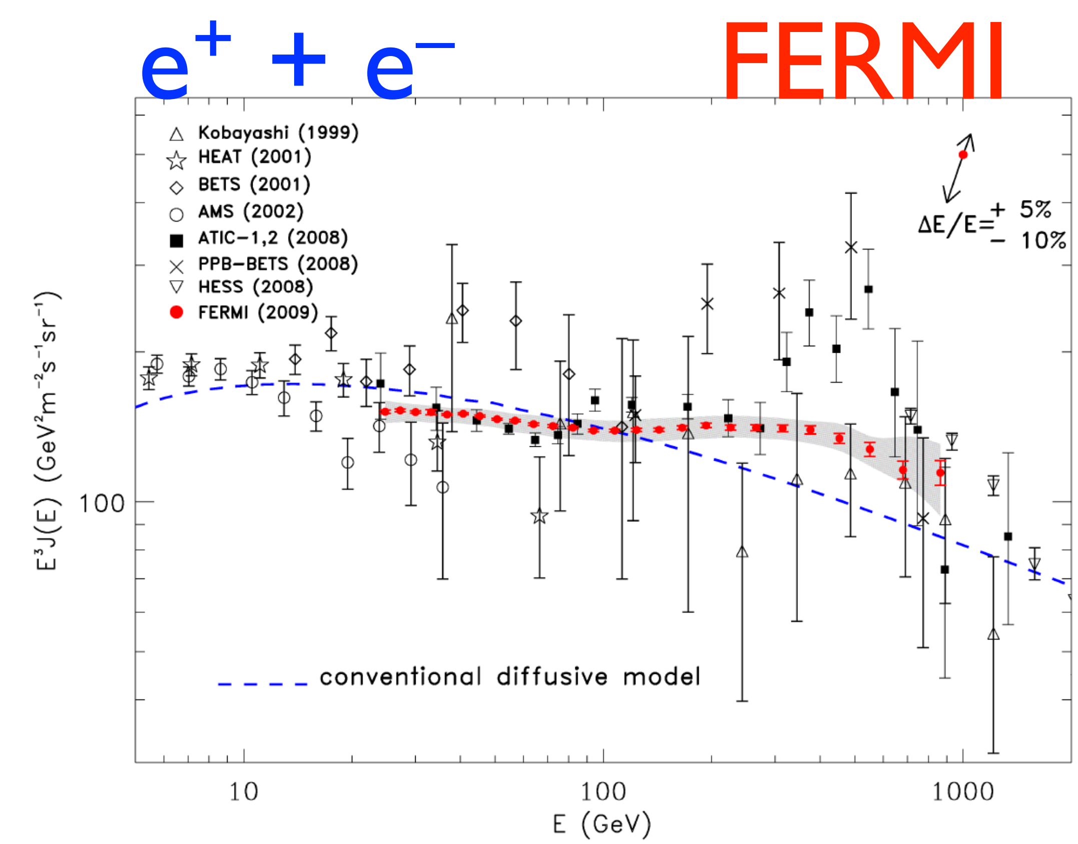



dark matter
XX→visible?
luminous matter
100k lyrs
??

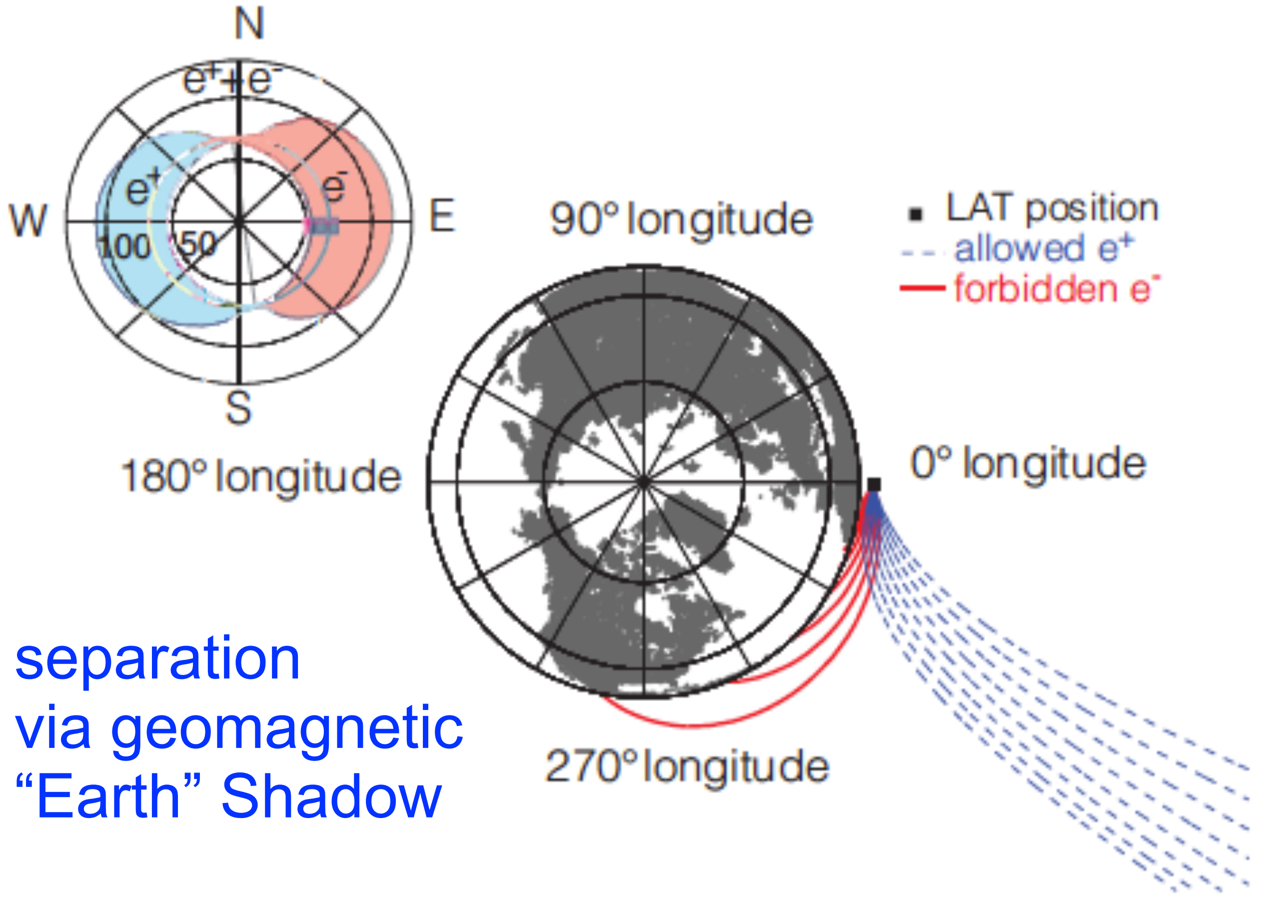
PAMELA



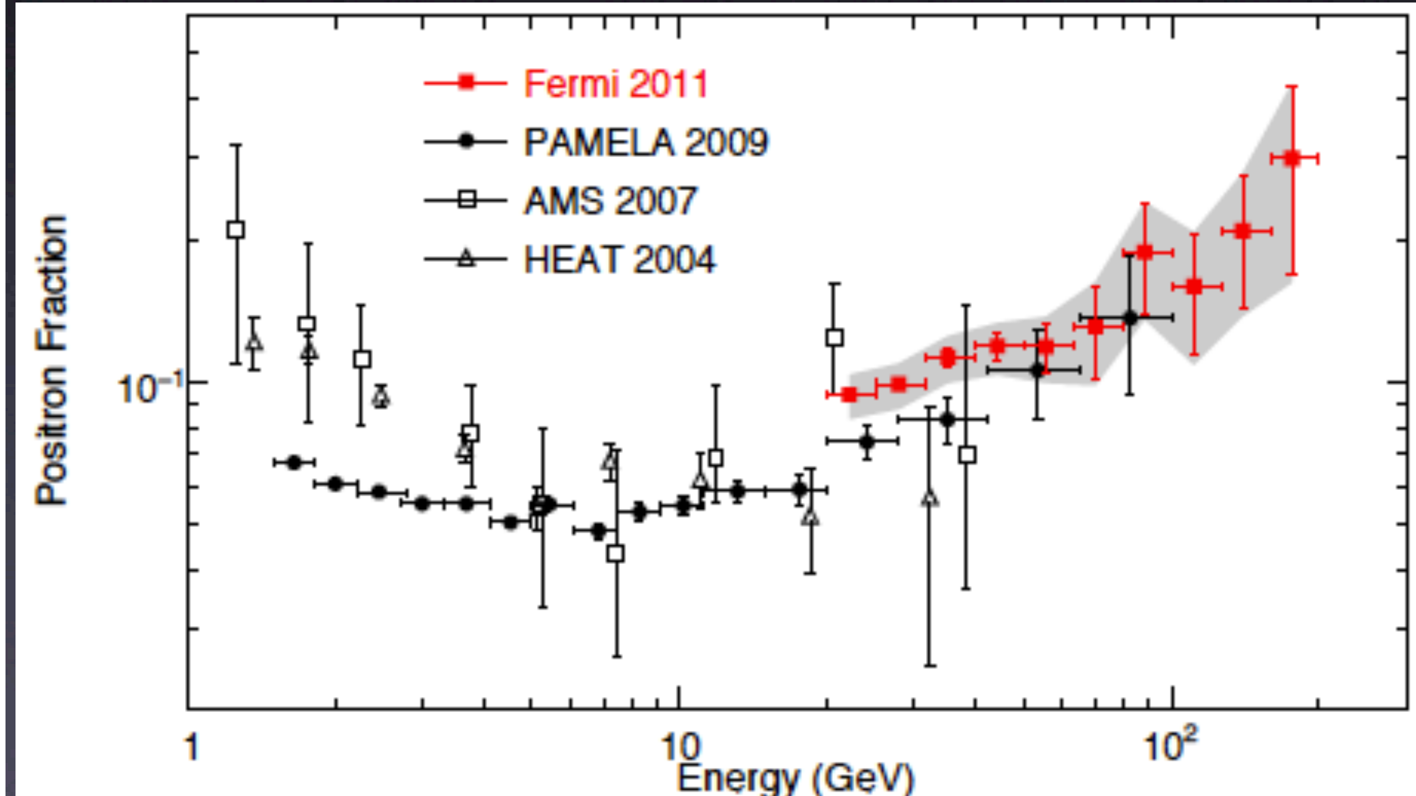
dark matter annihilation or decay in the galactic halo?



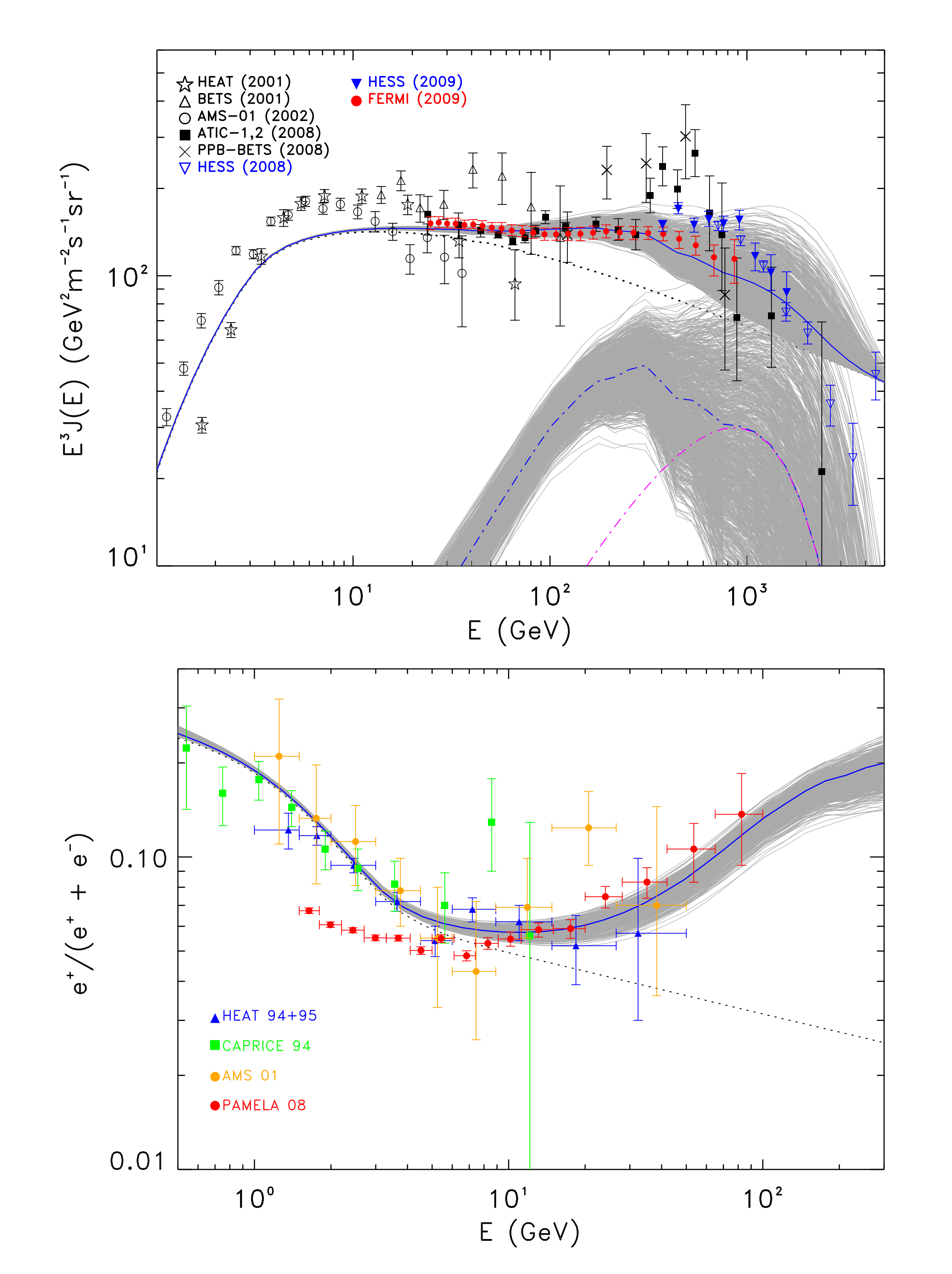
rise in e^+ fraction confirmed by Fermi



separation
via geomagnetic
“Earth” Shadow

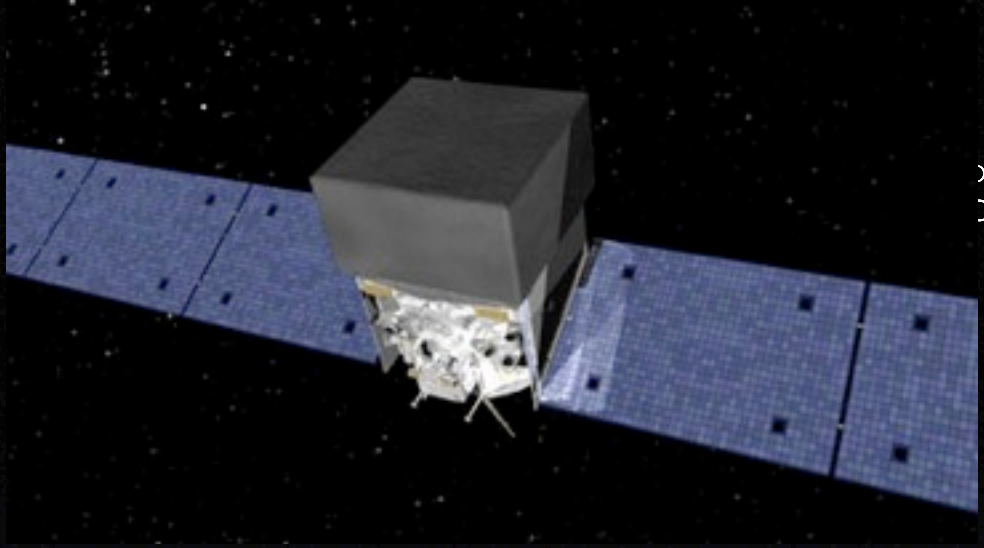


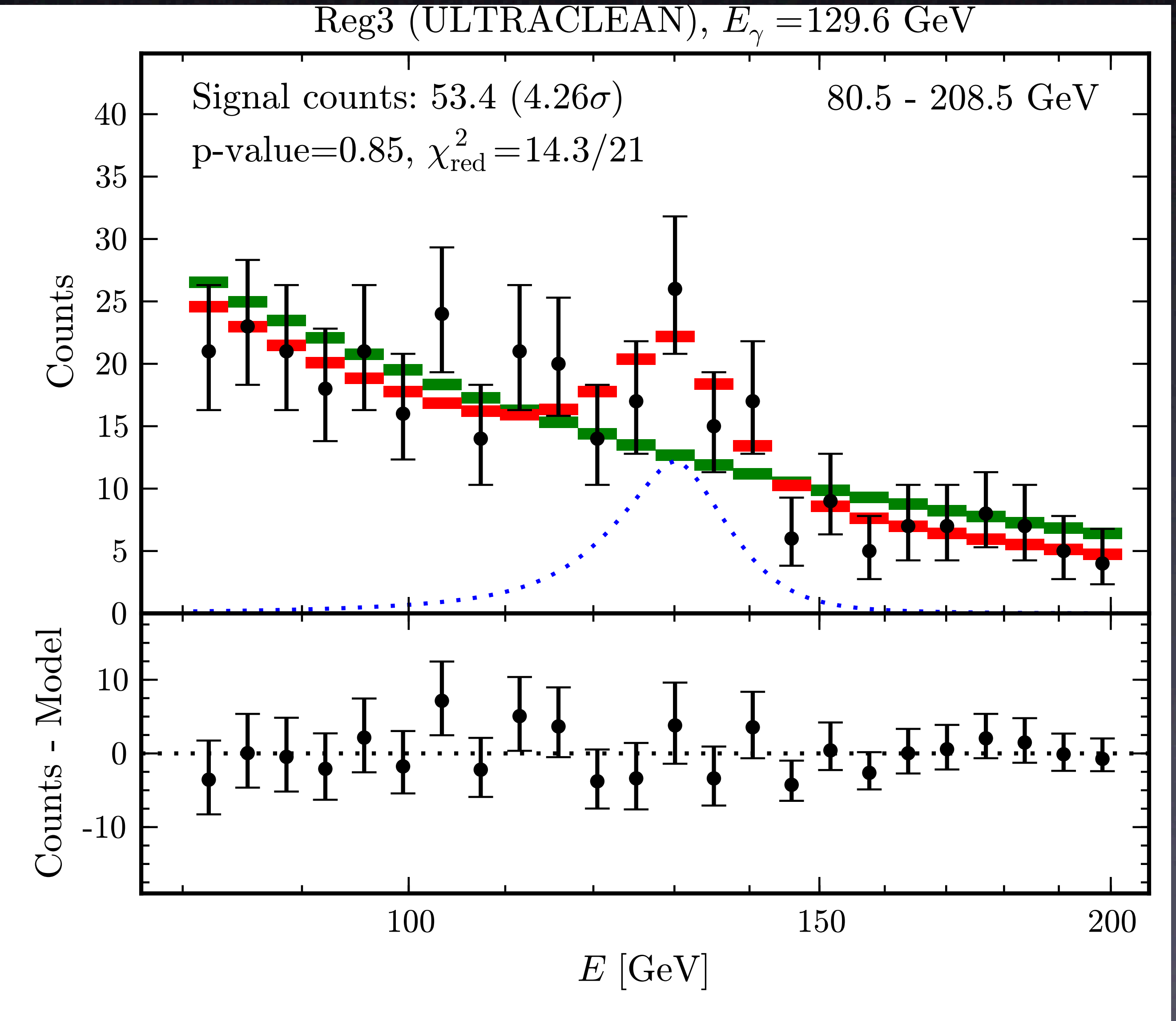
pulsars?

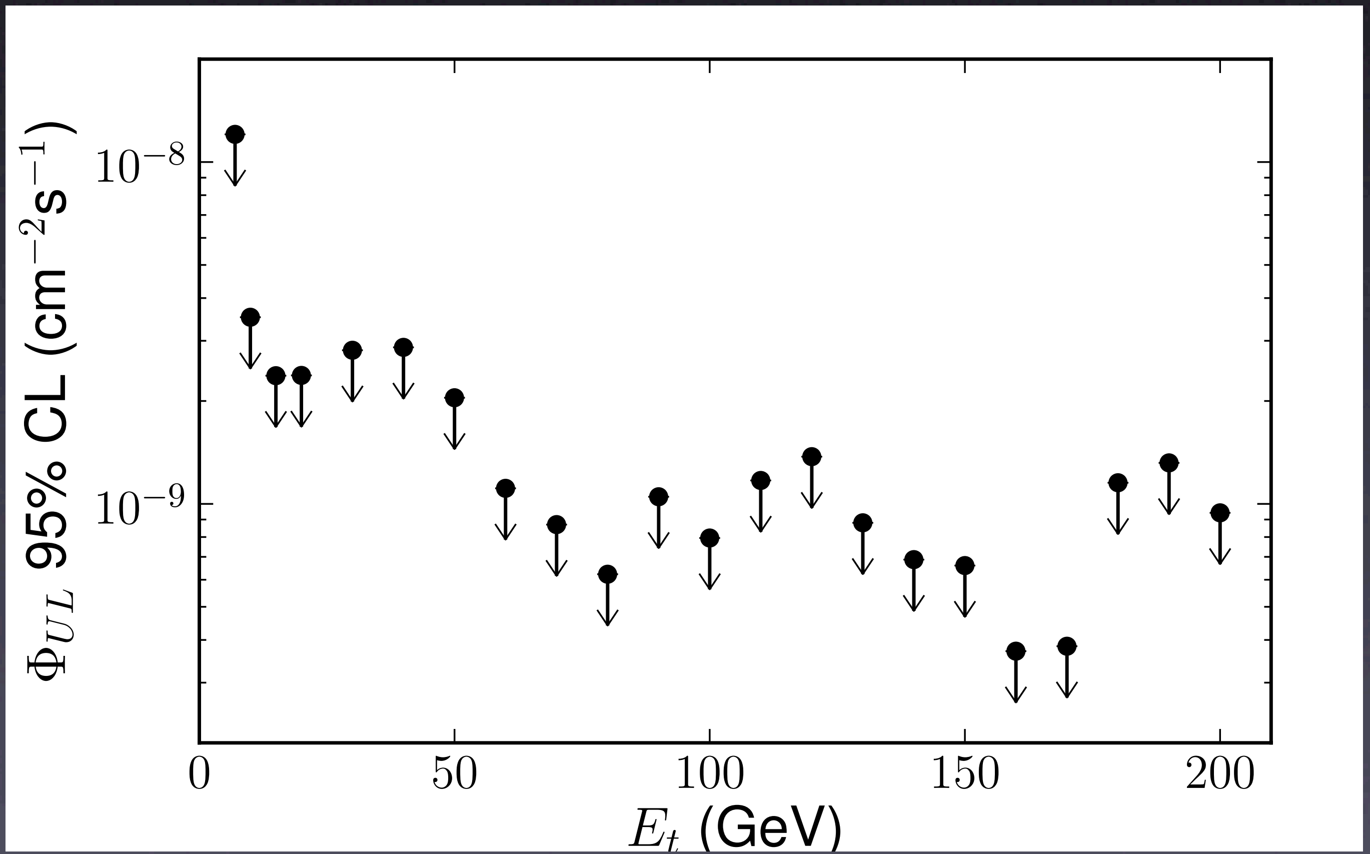


HEAT (2001)
BETS (2001)
AMS-01 (2002)
ATIC-1,2 (2008)
PPB-BETS (2008)
HESS (2008)
HESS (2009)
FERMI (2009)
$E^3J(E)$ $(GeV^2m^{-2}s^{-1}sr^{-1})$
E (GeV)
HEAT 94+95
CAPRICE 94
AMS 01
PAMELA 08
$e^+/(e^+ + e^-)$
E (GeV)

bump?





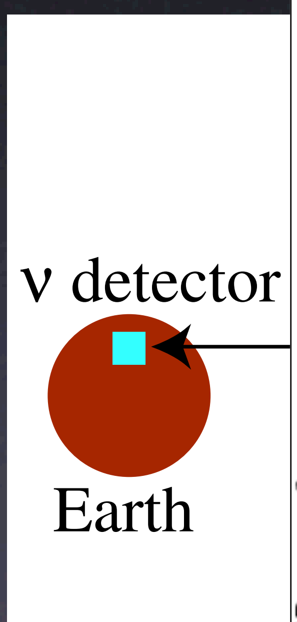


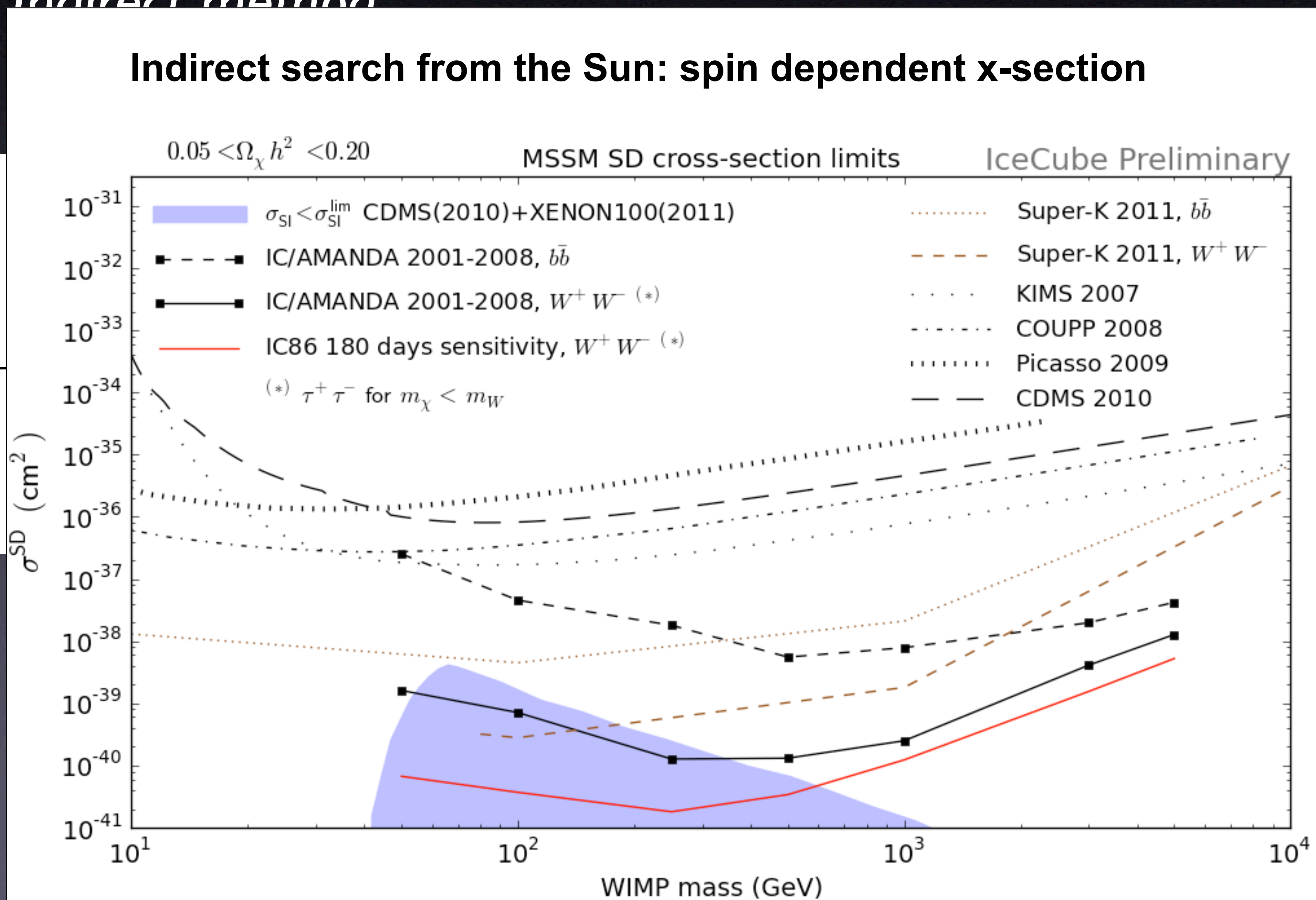
Christoph Weniger

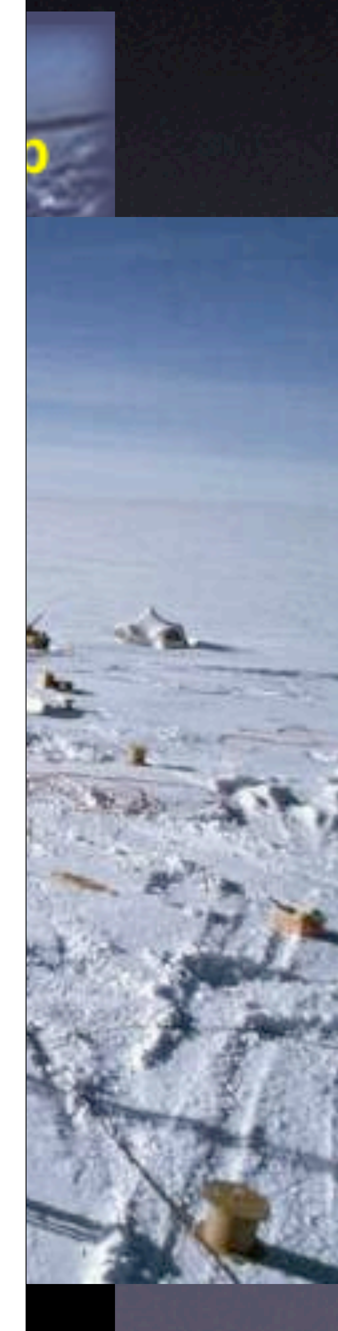
Fermi-LAT collab

Finding Dark Matter

Indirect method







adron Collider (LHC)

BERKELEY CENTER FOR THEORETICAL PHYSICS

Recreating Big Bang

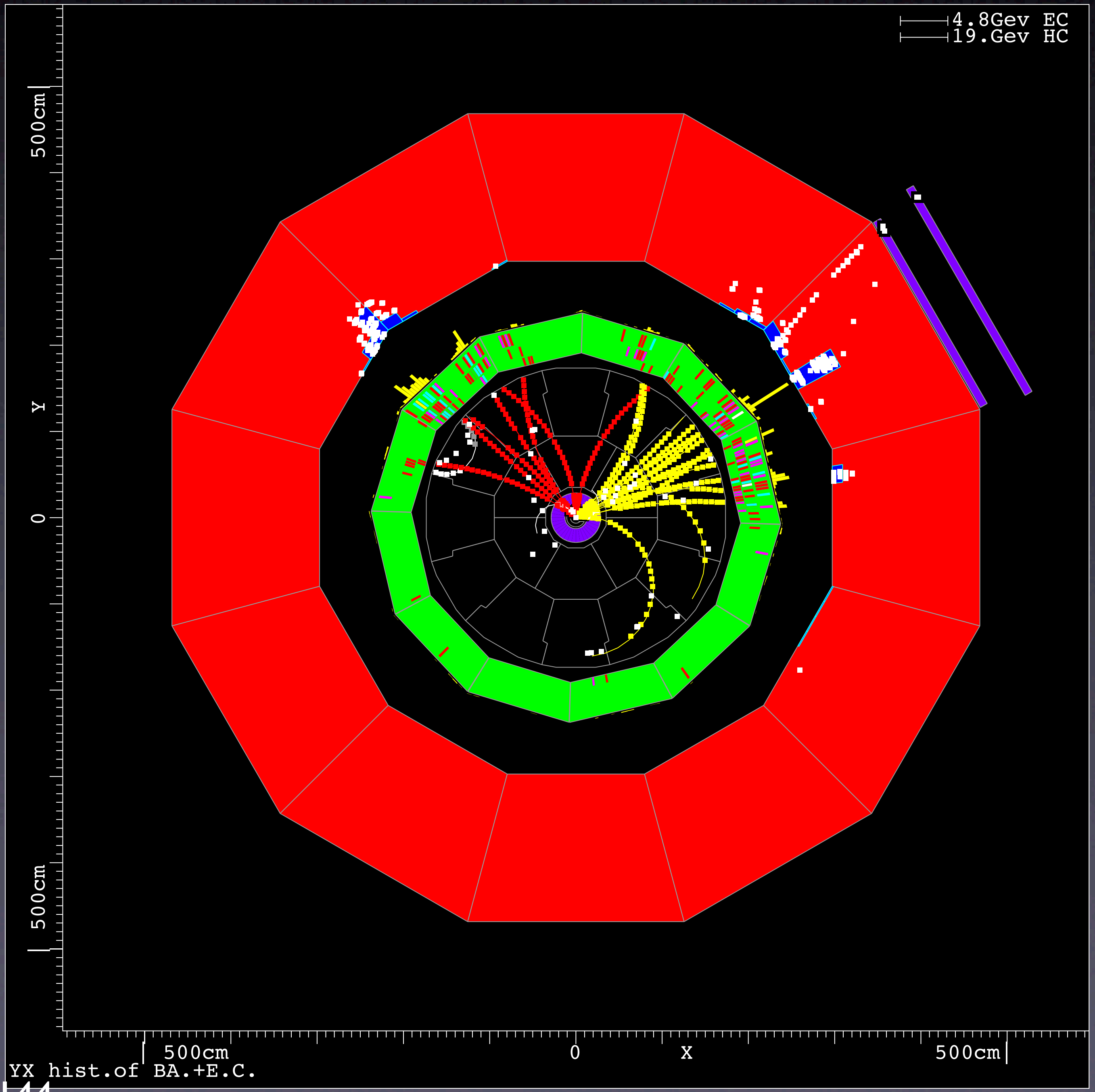
Producing Dark Matter in the laboratory

- Mimic Big Bang in the lab
- Hope to create invisible Dark Matter particles
- Look for events where energy and momenta are unbalanced

"missing energy" E_{miss}

- Something is escaping the detector

⇒Dark Matter!?

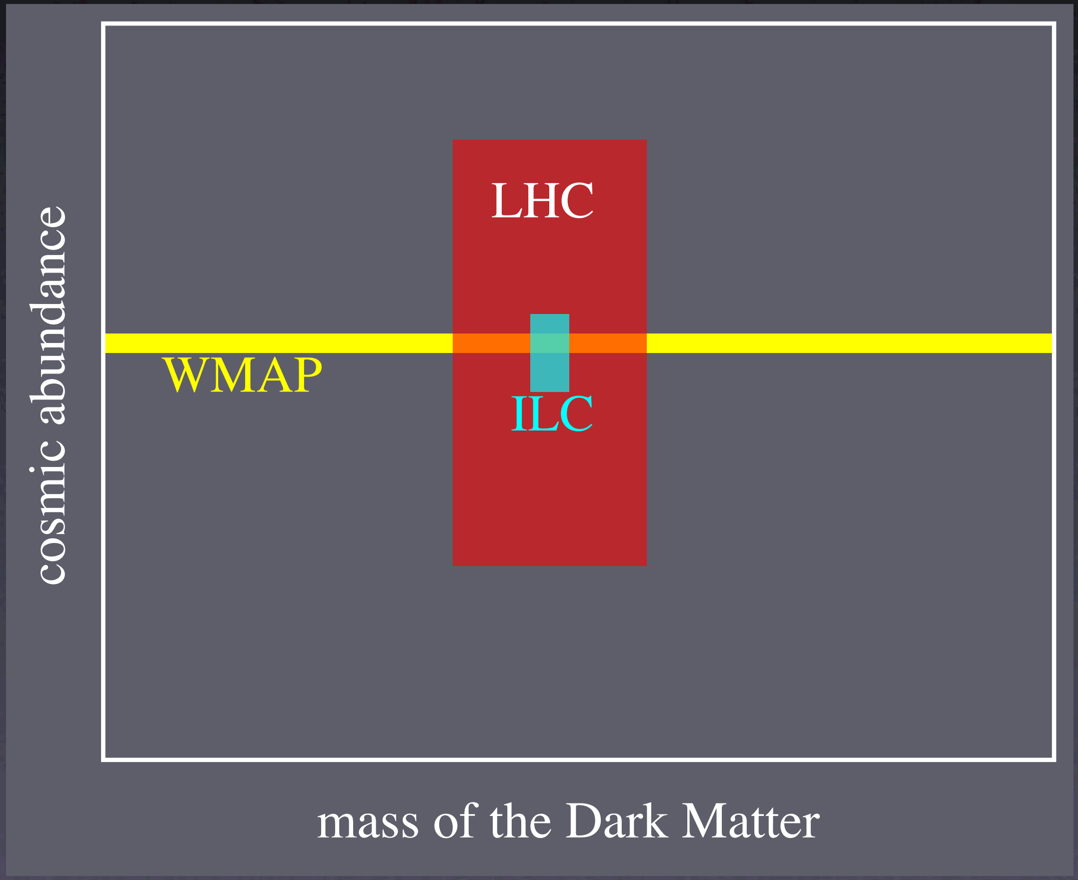


How do we know what Dark Matter *is*?

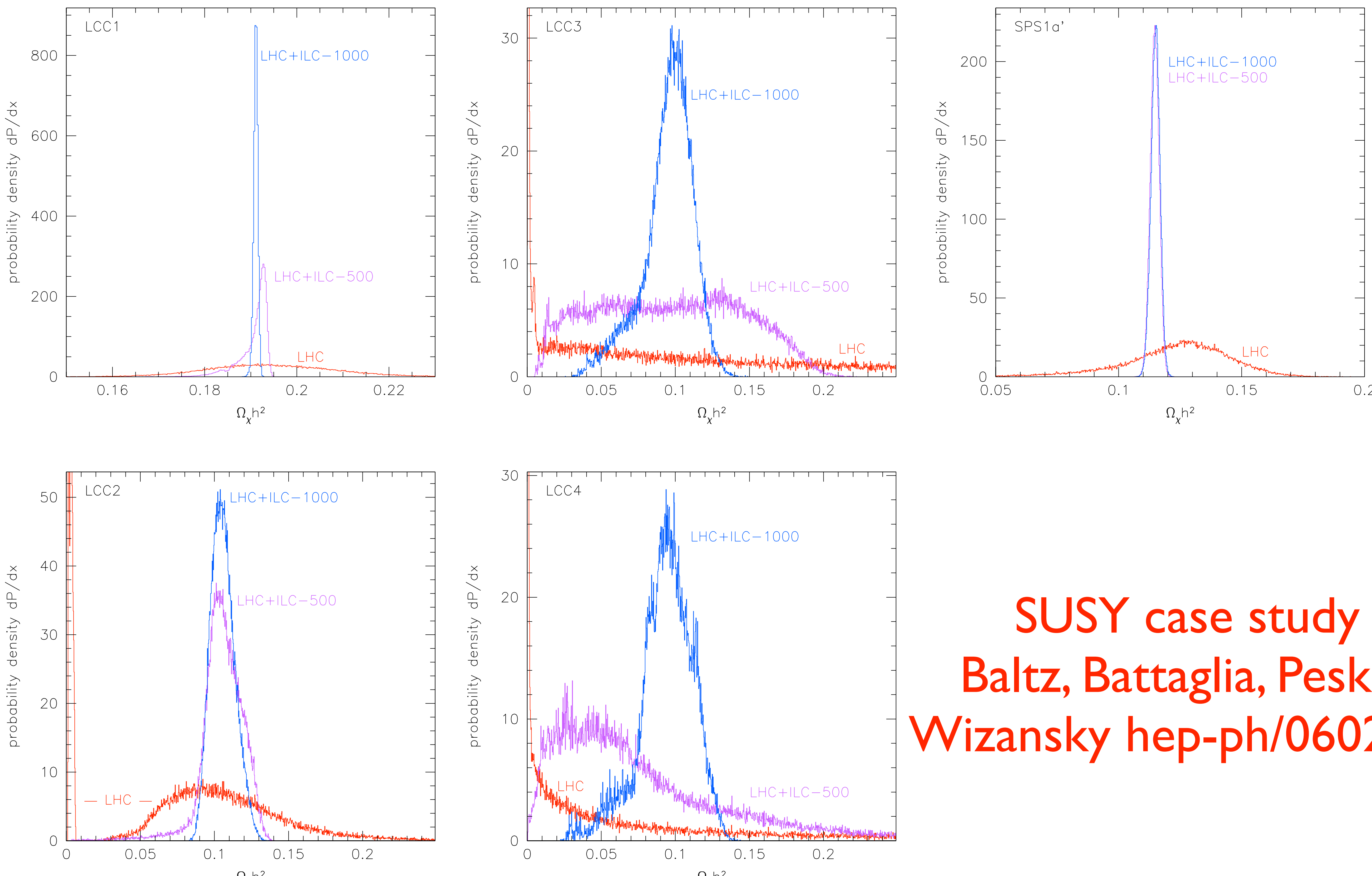
- cosmological measurement of dark matter
  - abundance $\propto \sigma_{ann}^{-1}$
- detection experiments
  - scattering cross section
- production at colliders
  - mass, couplings
  - can calculate cross sections
- If they agree with each other:

$\Longrightarrow$ Will know *what Dark Matter is*

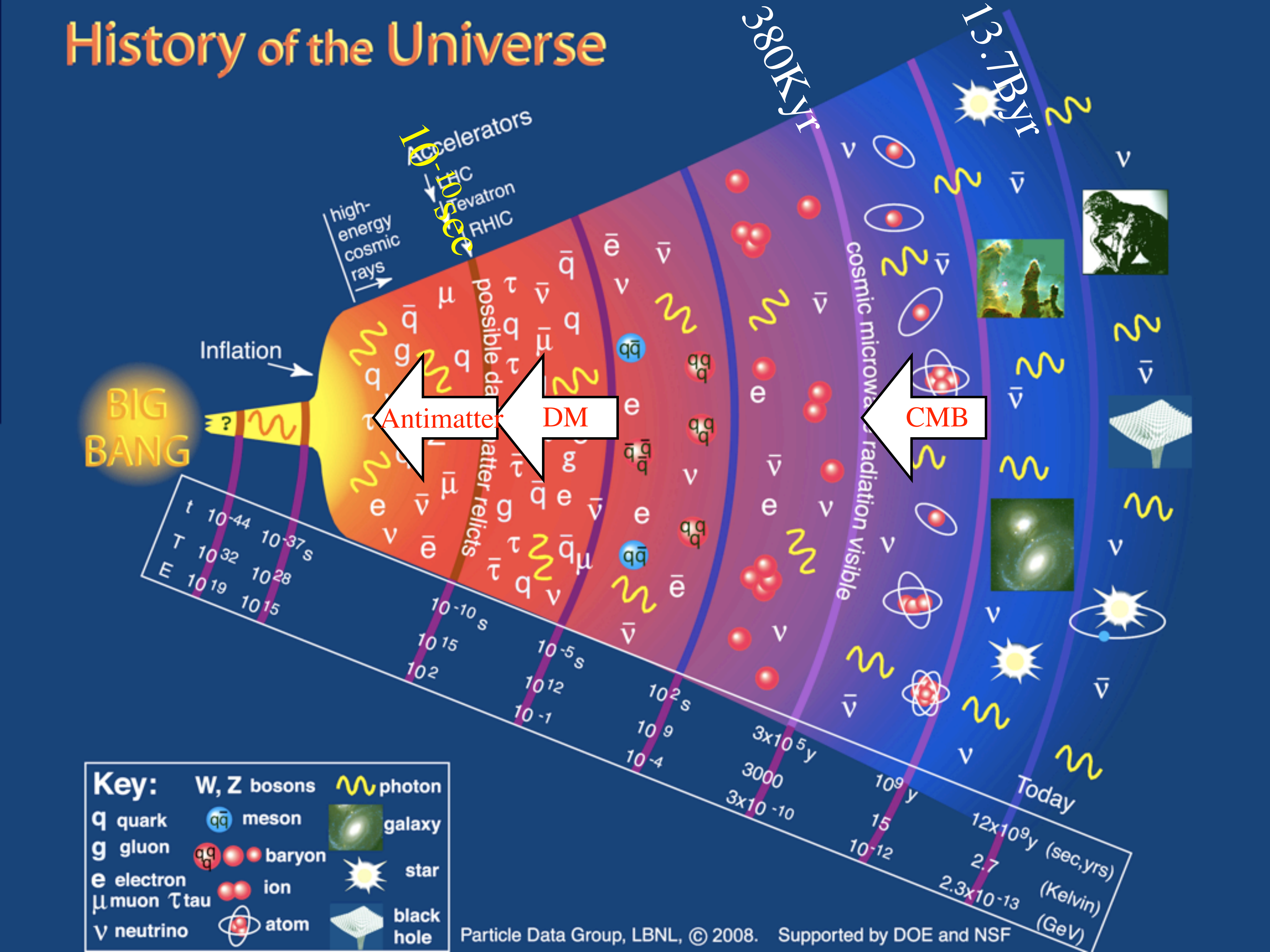
$\Longrightarrow$ Will understand universe back to t~10^{-10} sec



Omega from colliders



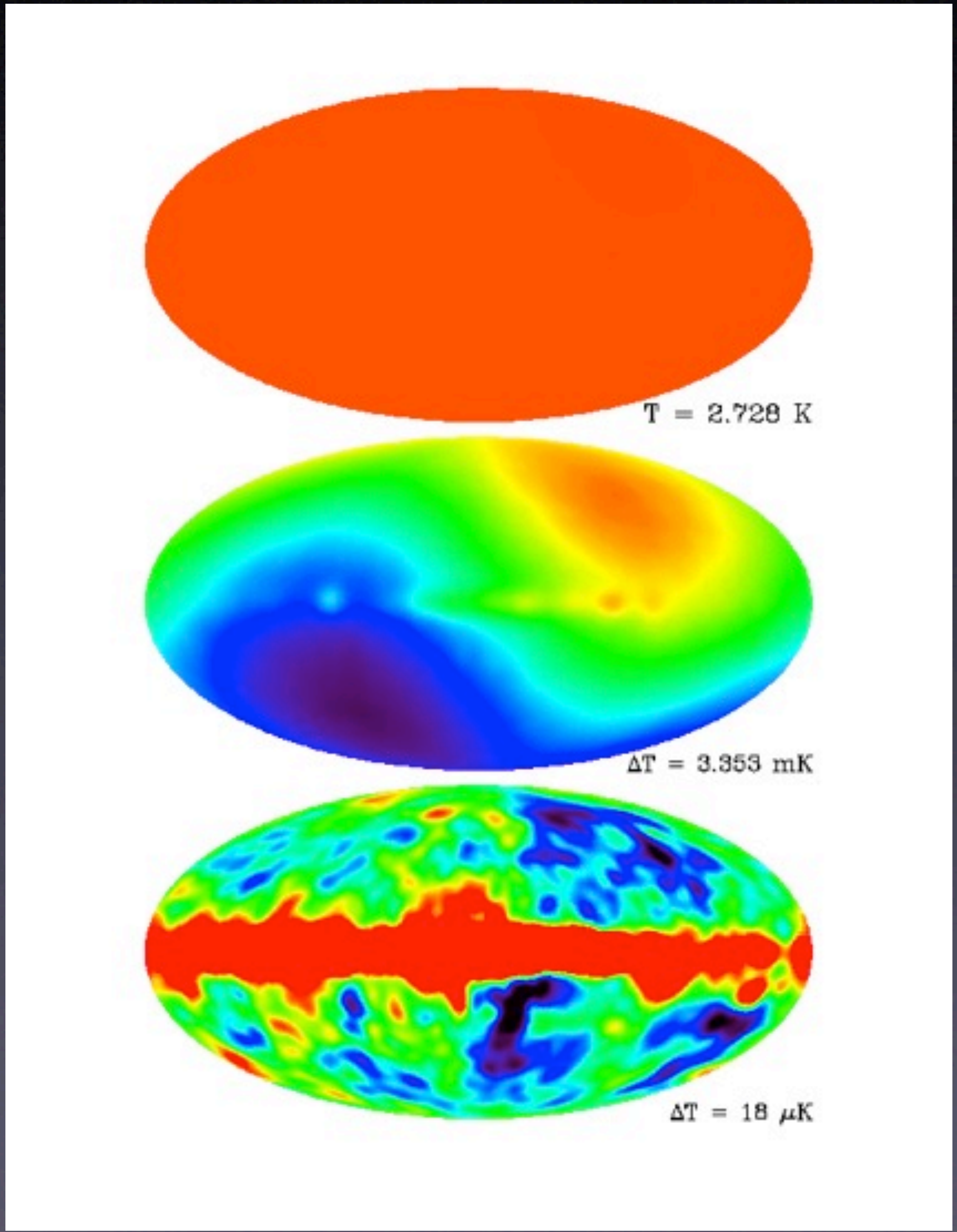
SUSY case study
Baltz, Battaglia, Peskin, Wizansky hep-ph/0602187



History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
10-10 sec
380Kyr
13.7Byr
possible dark matter relicts
cosmic microwave radiation visible
Antimatter
DM
CMB
t 10-44 10-37 s 10-10 s 10-5 s 10 2 s 3x10 5 y 10 9 y Today 12x10 9 y (sec,yrs)
T 10 32 10 28 10 15 10 12 10 9 3000 15 2.7 (Kelvin)
E 10 19 10 15 10 2 10 -1 10 -4 3x10 -10 10 -12 2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
star
e electron
ion
μ muon τ tau
atom
black hole
ν neutrino
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

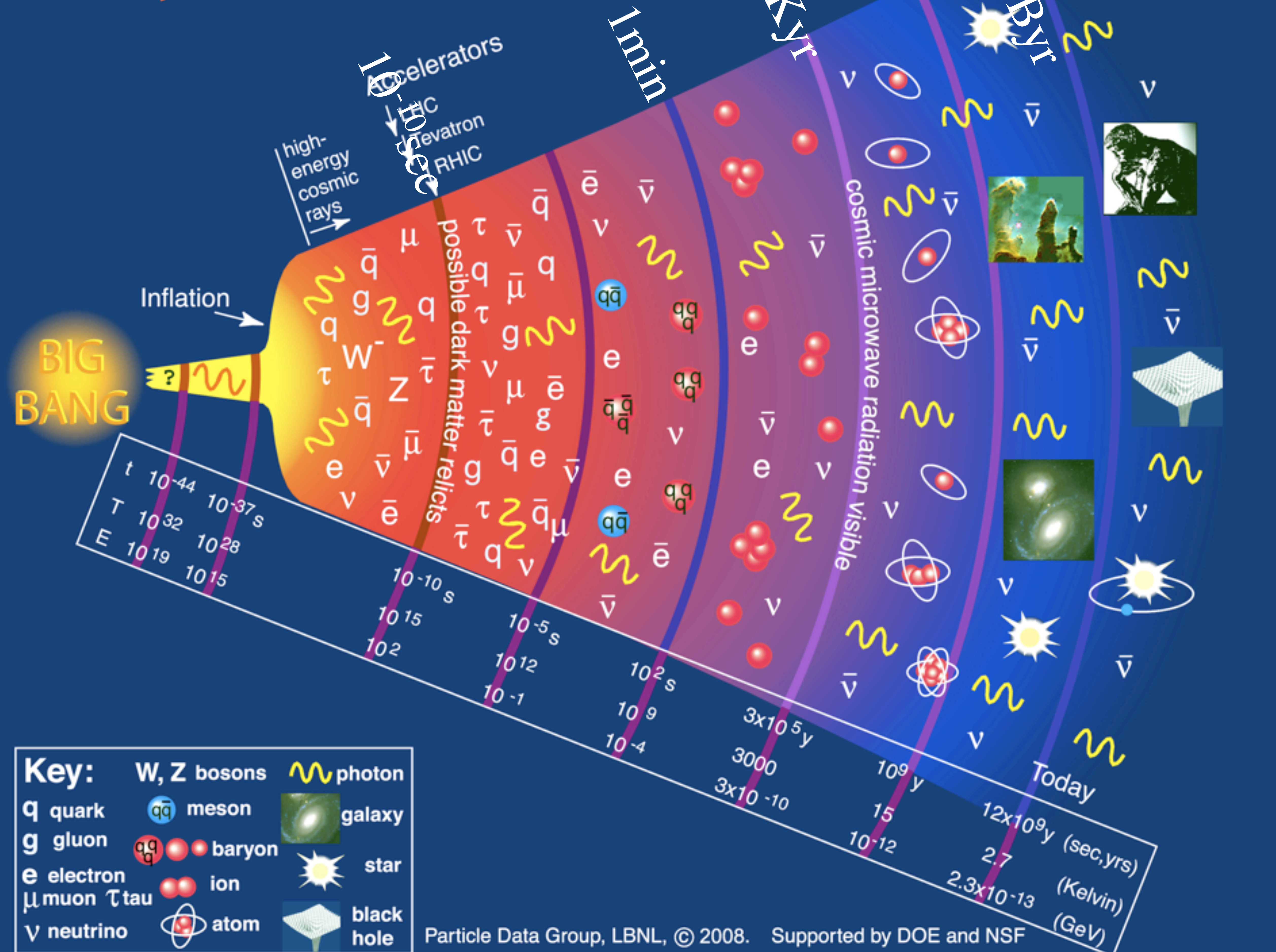

Inflation

Why do they all look the same?



- Like having discovered two remote islands in very different parts of the world, speaking the same language
- even the accents are nearly the same: one part in 100,000
- we suspect they had communication

History of the Universe



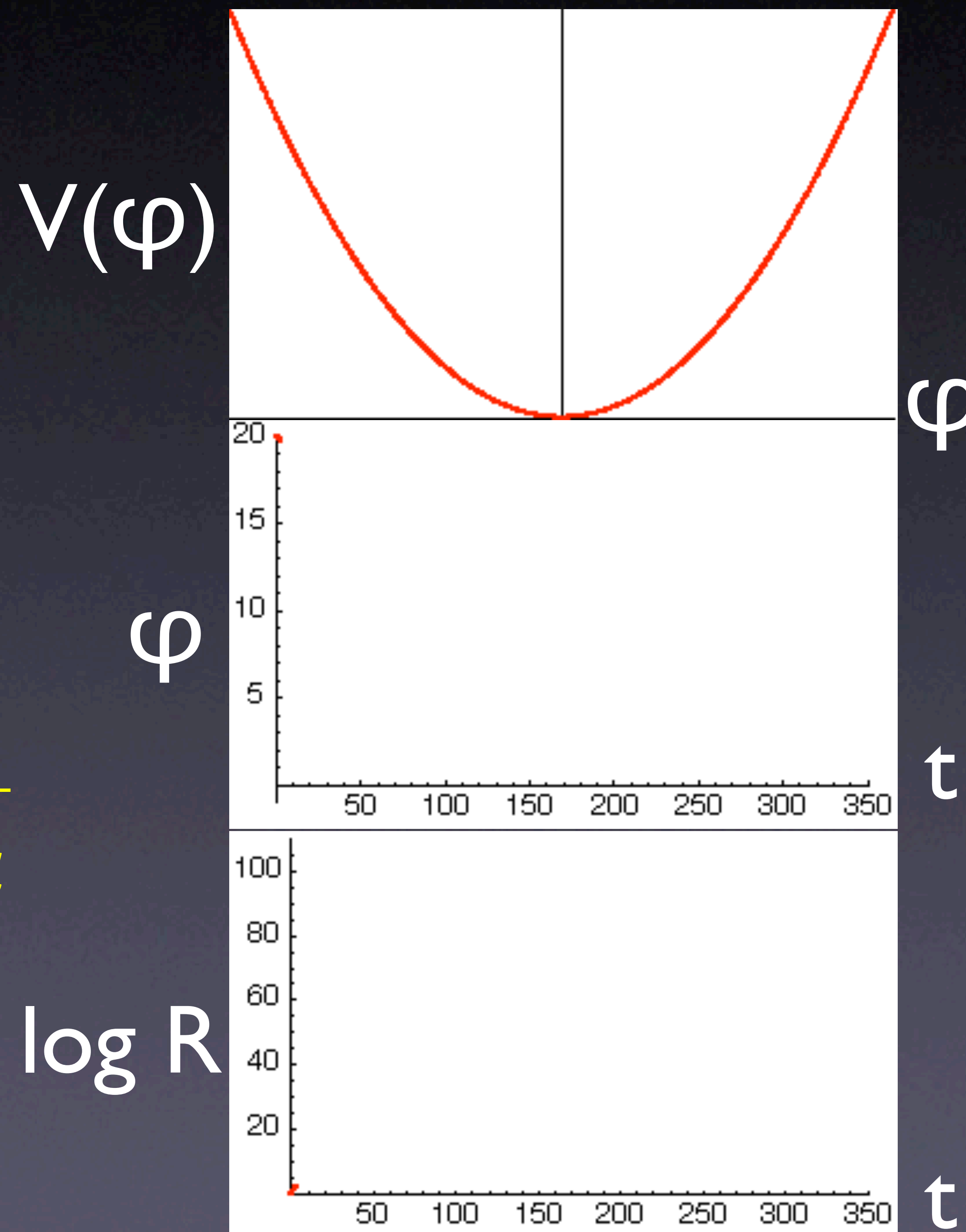
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

inflaton

- scalar field with rather flat potential (compared to the Planck scale), $\lambda \approx 10^{-11}$
- the equation of motion has a "friction term"
  $$\ddot{\phi} + 3H\dot{\phi} = V'(\phi)$$
- slow-roll solution with more or less constant *H*

$$|\ddot{\phi}| \ll |\dot{\phi}| = V'(\phi) \quad H^2 = \frac{8\pi}{3}\frac{V}{M_{Pl}^2}$$

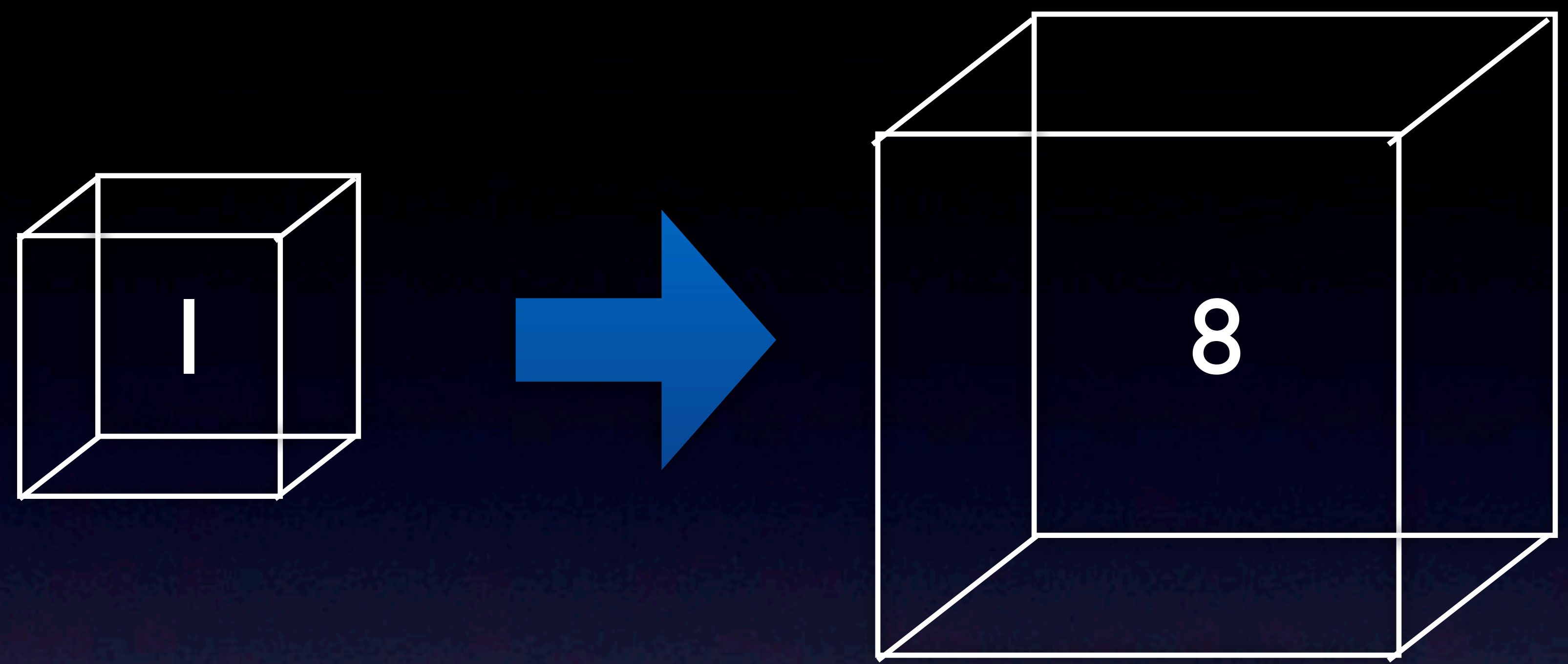
- Universe expands exponentially $R(t) \propto e^{Ht}$
- need *e-folding* $N=Ht > 60$ to solve the problem



HM, Suzuki, Yanagida, Yokoyama

Ultimate Free Lunch!

vacuum
energy
74%



$\rho \propto R^0$

total energy keeps growing like volume $R(t)^3 \propto e^{3Ht}$

near sighted

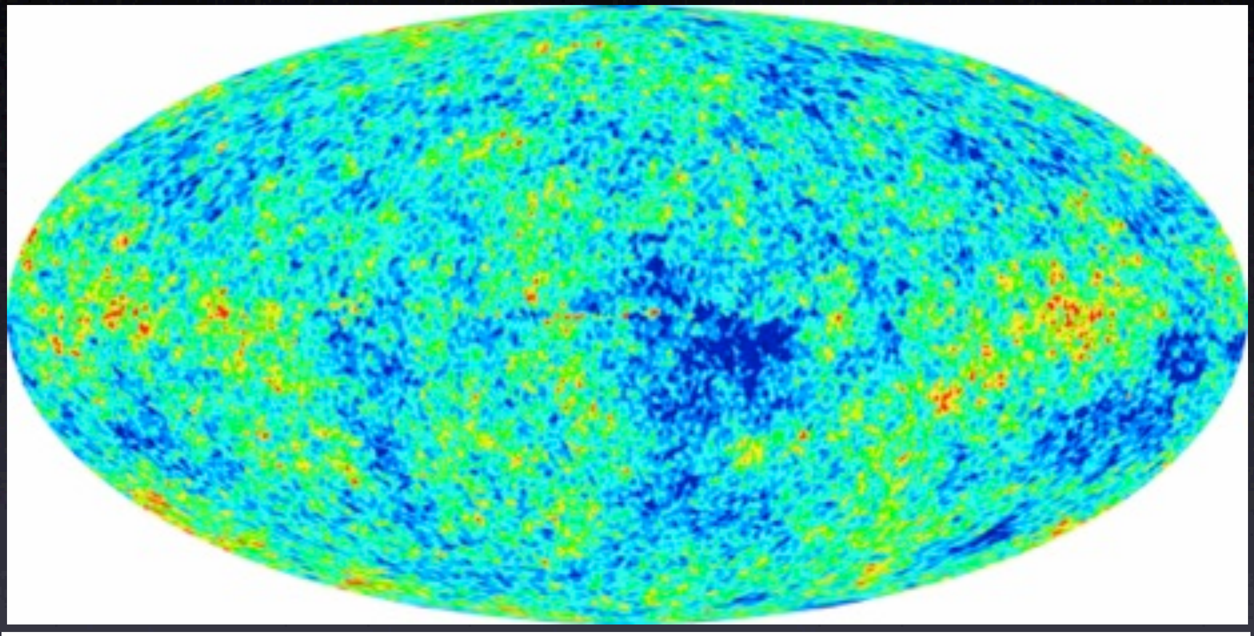
- What you are seeing one moment is *gone* by inflation the next moment
- feel very near-sighted
- "horizon" ≈ H_I^{-1}
- uncertainty principle: quatum fluctuation $\delta\varphi \approx H_I / 2\pi$

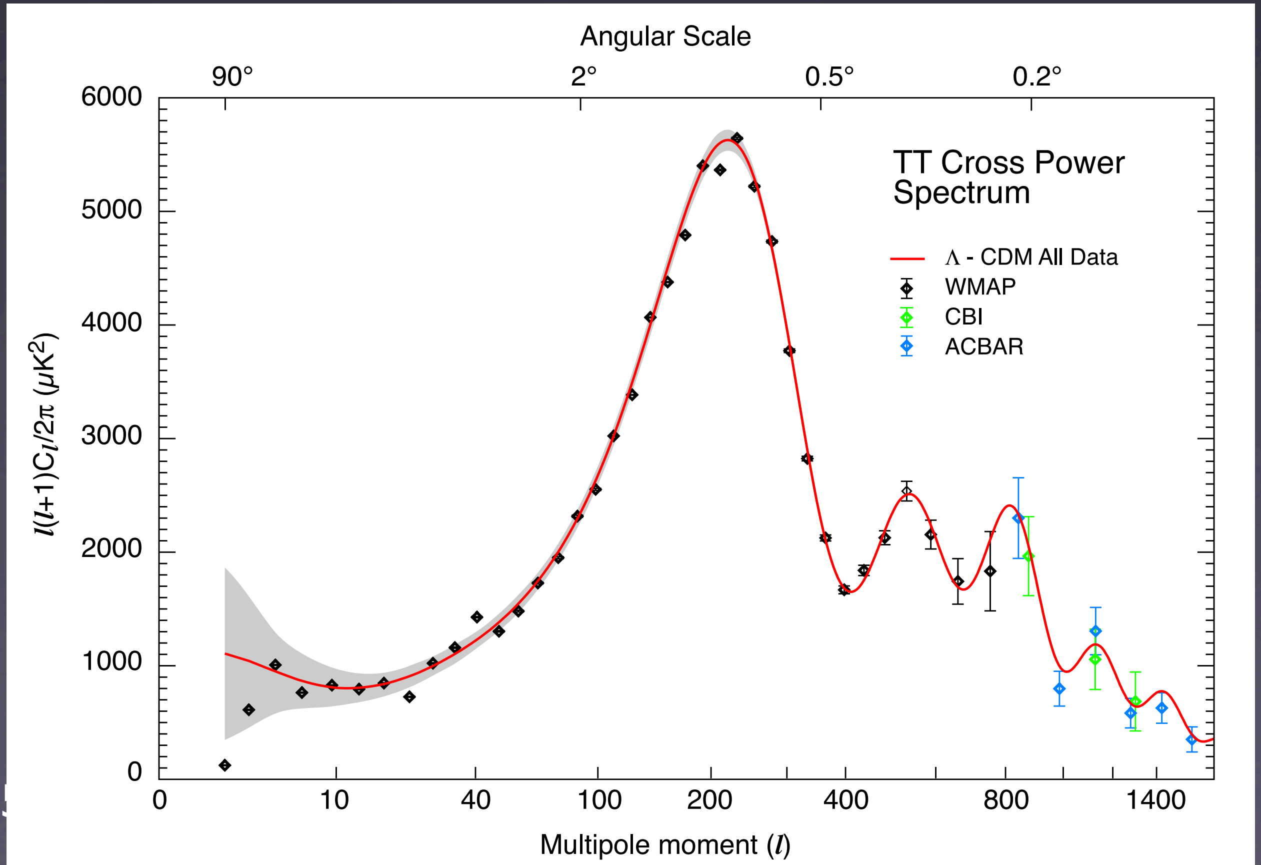
$$\zeta = \frac{\delta\rho}{\rho + p} = \frac{V'\delta\varphi}{\dot{\phi}^2} = \frac{V'}{\dot{\phi}^2}\frac{H}{2\pi}$$

- nearly scale-invariant density fluctuation

Seeds for structure

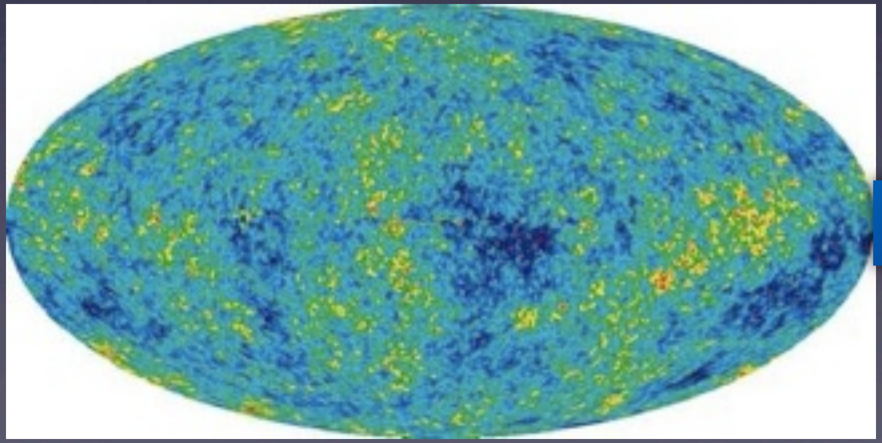
- Cosmic Inflation stretched the new-born microscopic space to our entire visible universe
- Observed structure originates from quantum fluctuation of inflaton
- Large-Scale Structure, CMB E-mode polarization consistent with this picture

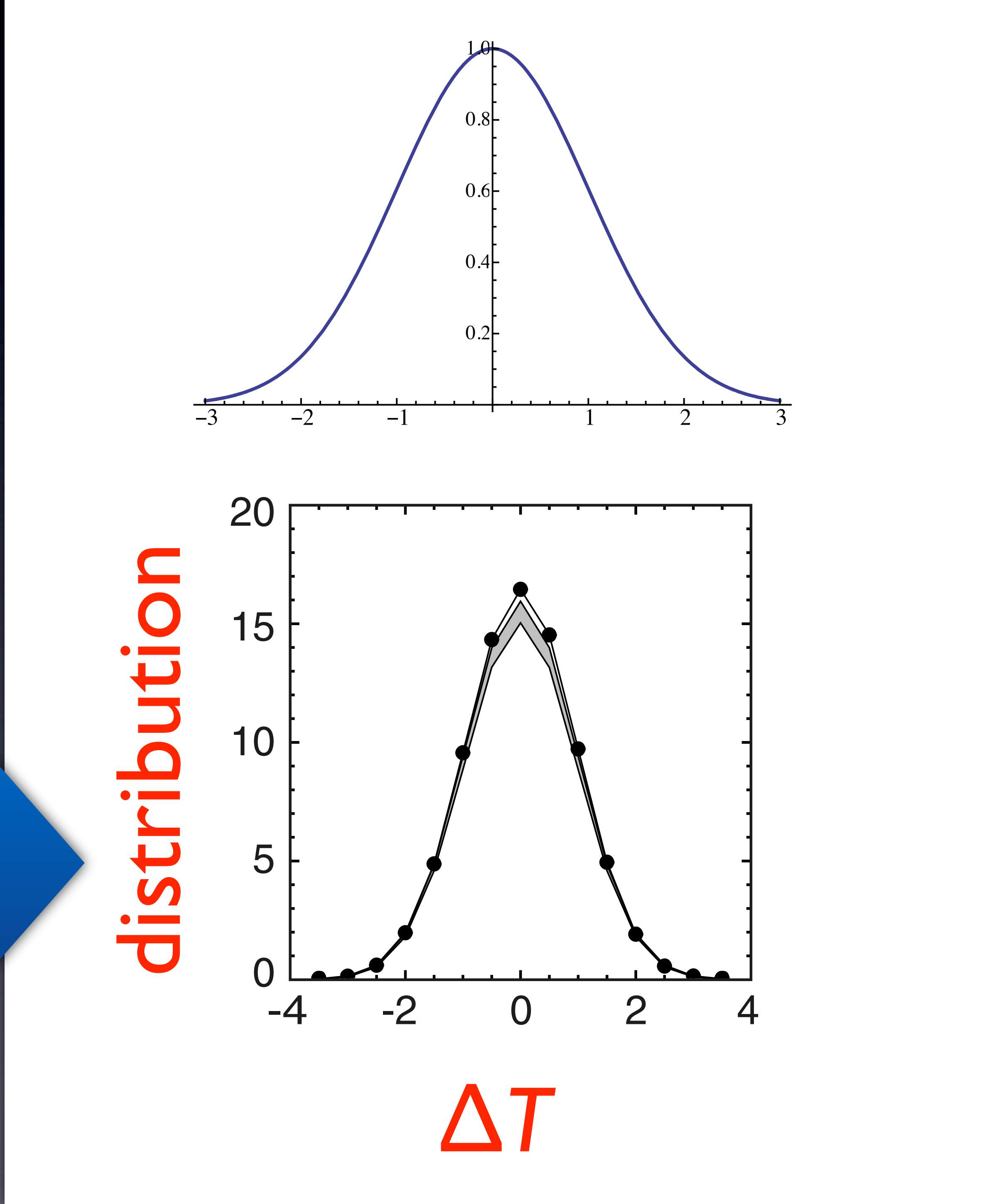




Getting stronger

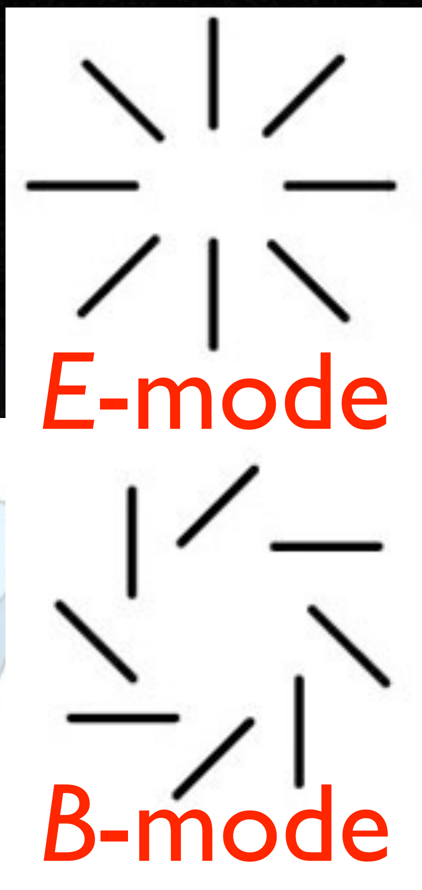
- If simple quantum fluctuation, it must be distributed as Gaussian
- Indeed!
- further tests of non-Gaussianity at Planck

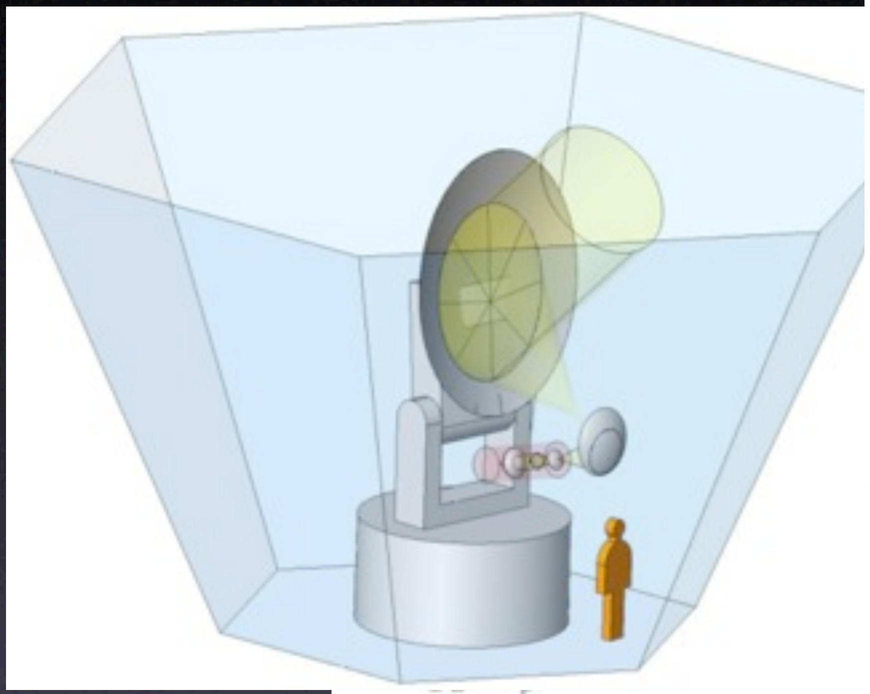


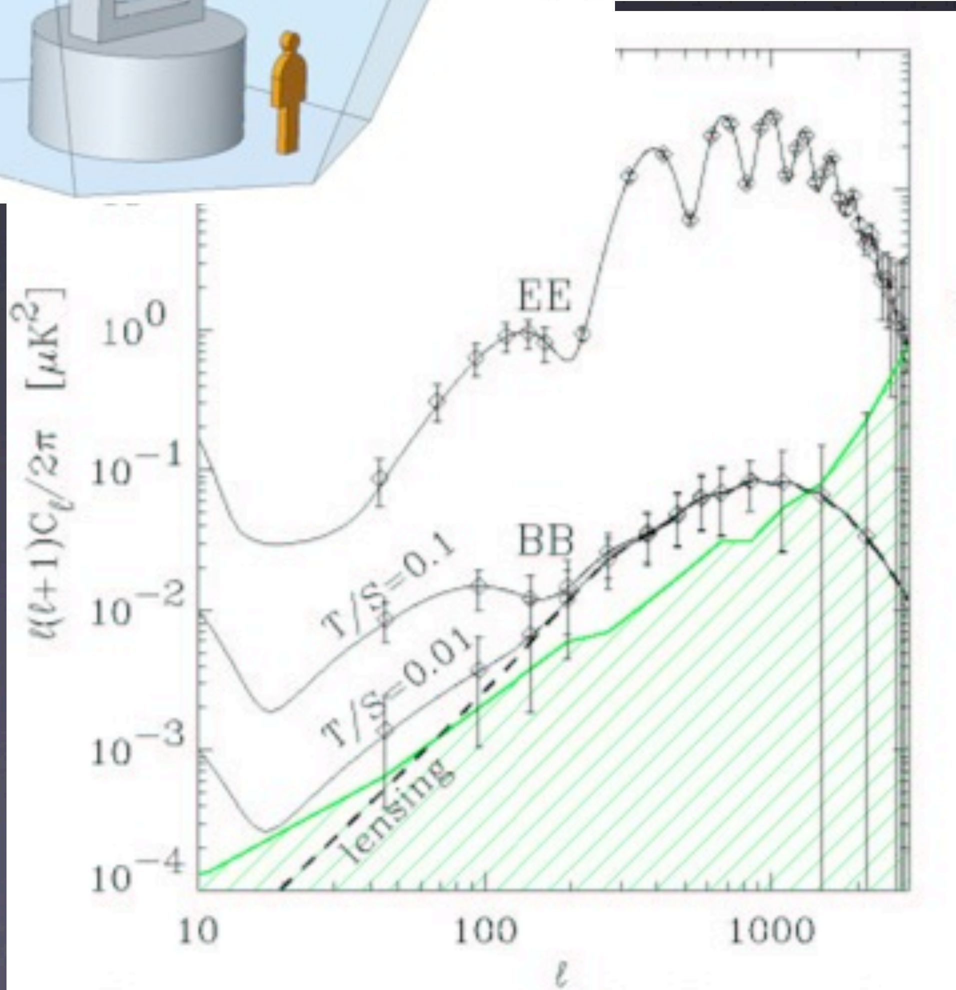


How do we know it really happened?

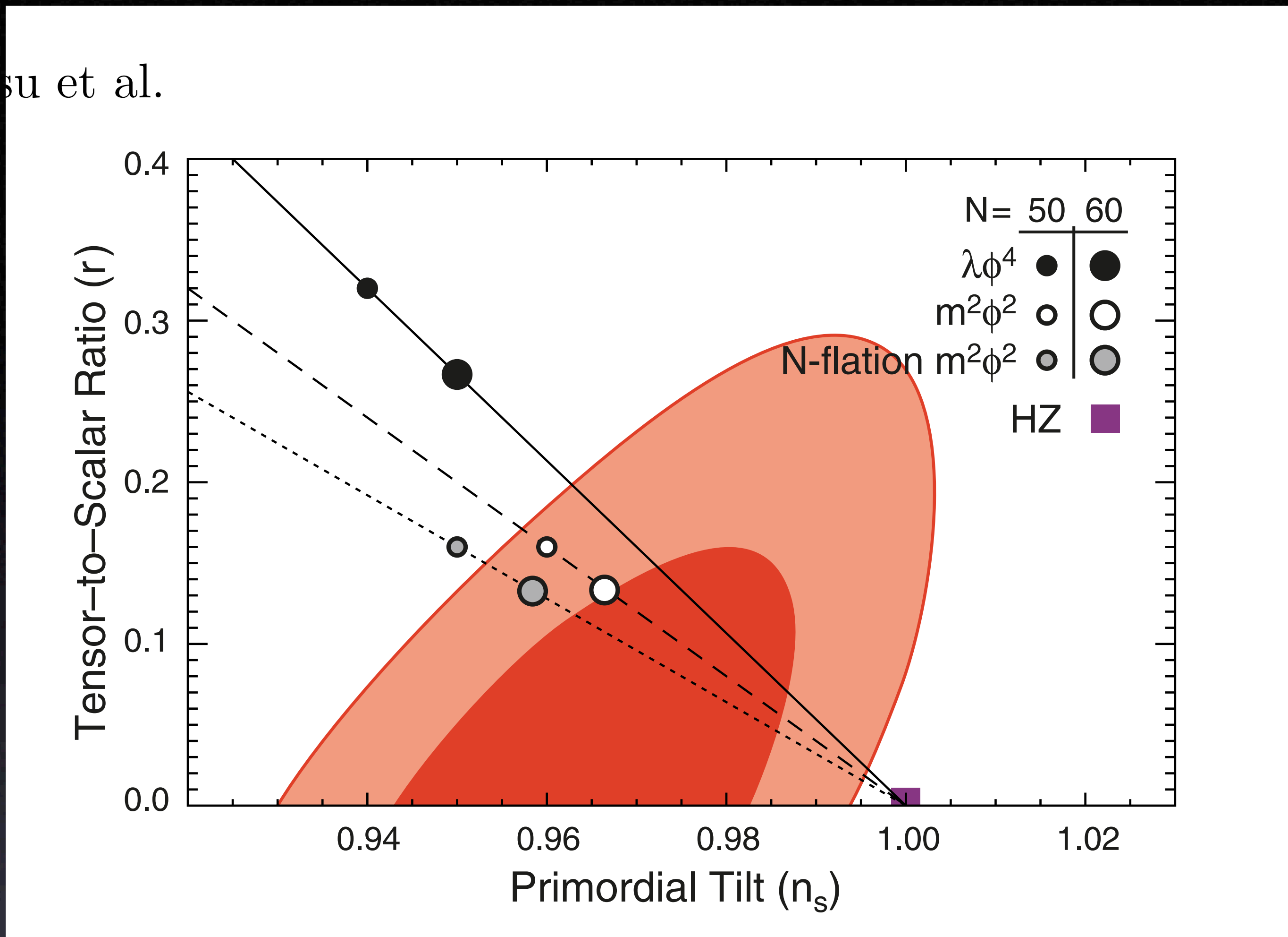
- everything gets quantum fluctuation, including gravitons
- Gravitons from quantum fluctuation gives B-mode polarization in CMB
- The size is directly proportional to the inflationary energy scale
  $\Rightarrow$ e.g., Planck, POLARBEAR, Quiet



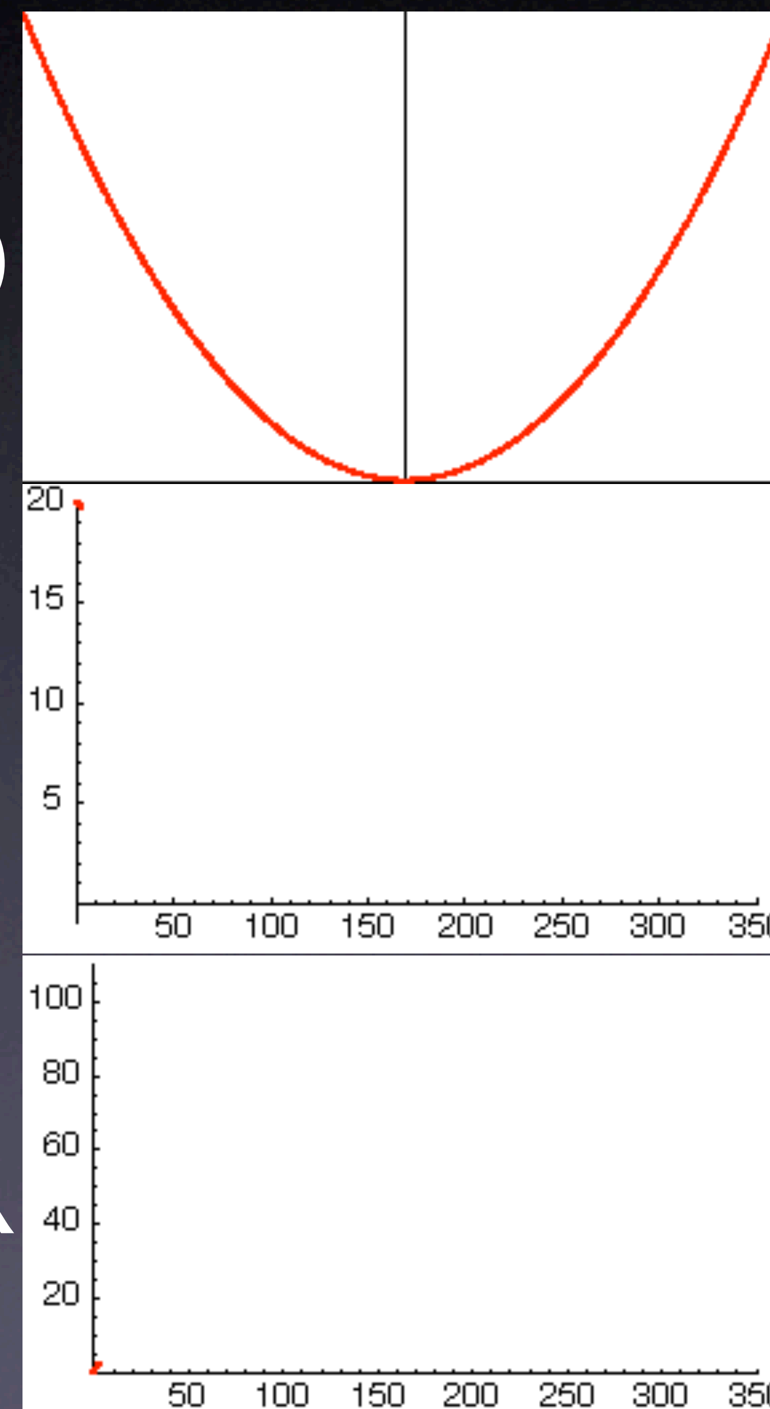




m together



/(φ)



φ

φ

t

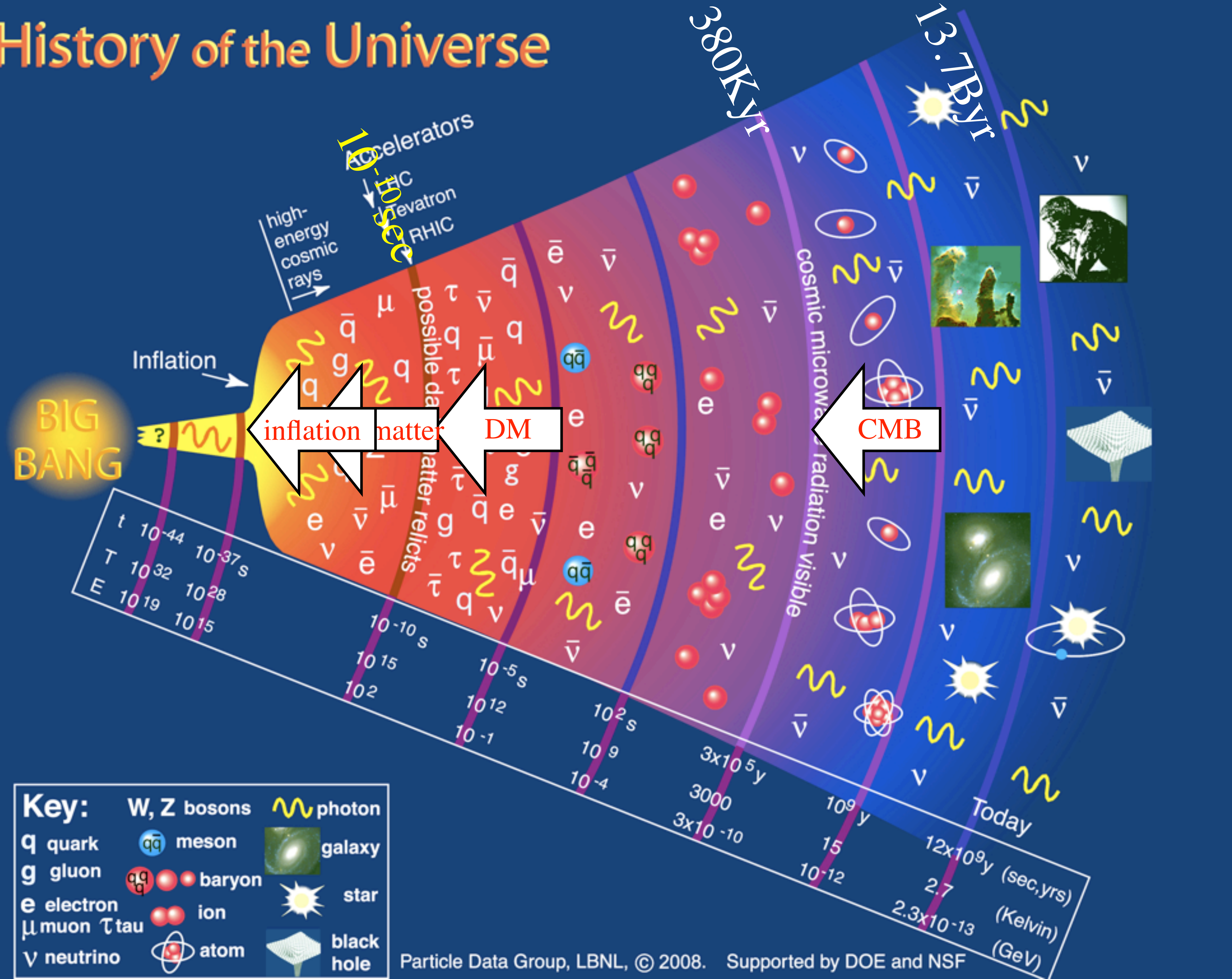
log R

t

- quantum fluctuation source of later structure
- decays into both matter and anti-matter, but with a slight preference to matter
- decay products contain supersymmetry and hence Dark Matter

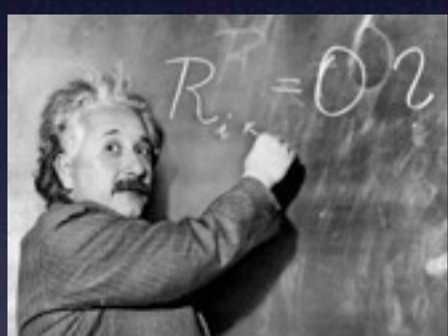
HM, Suzuki, Yanagida, Yokoyama

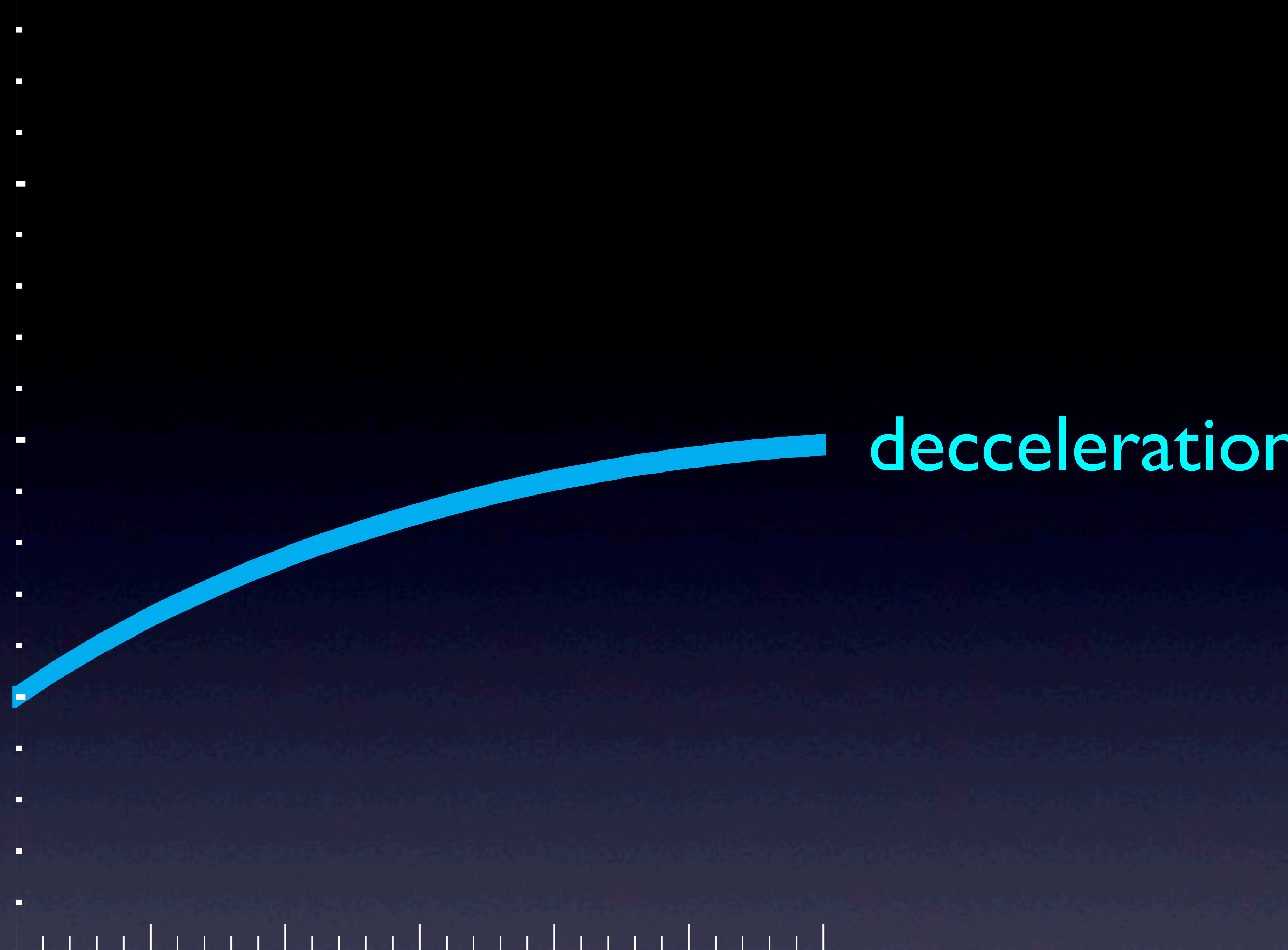
History of the Universe



fate of the Univese

expansion



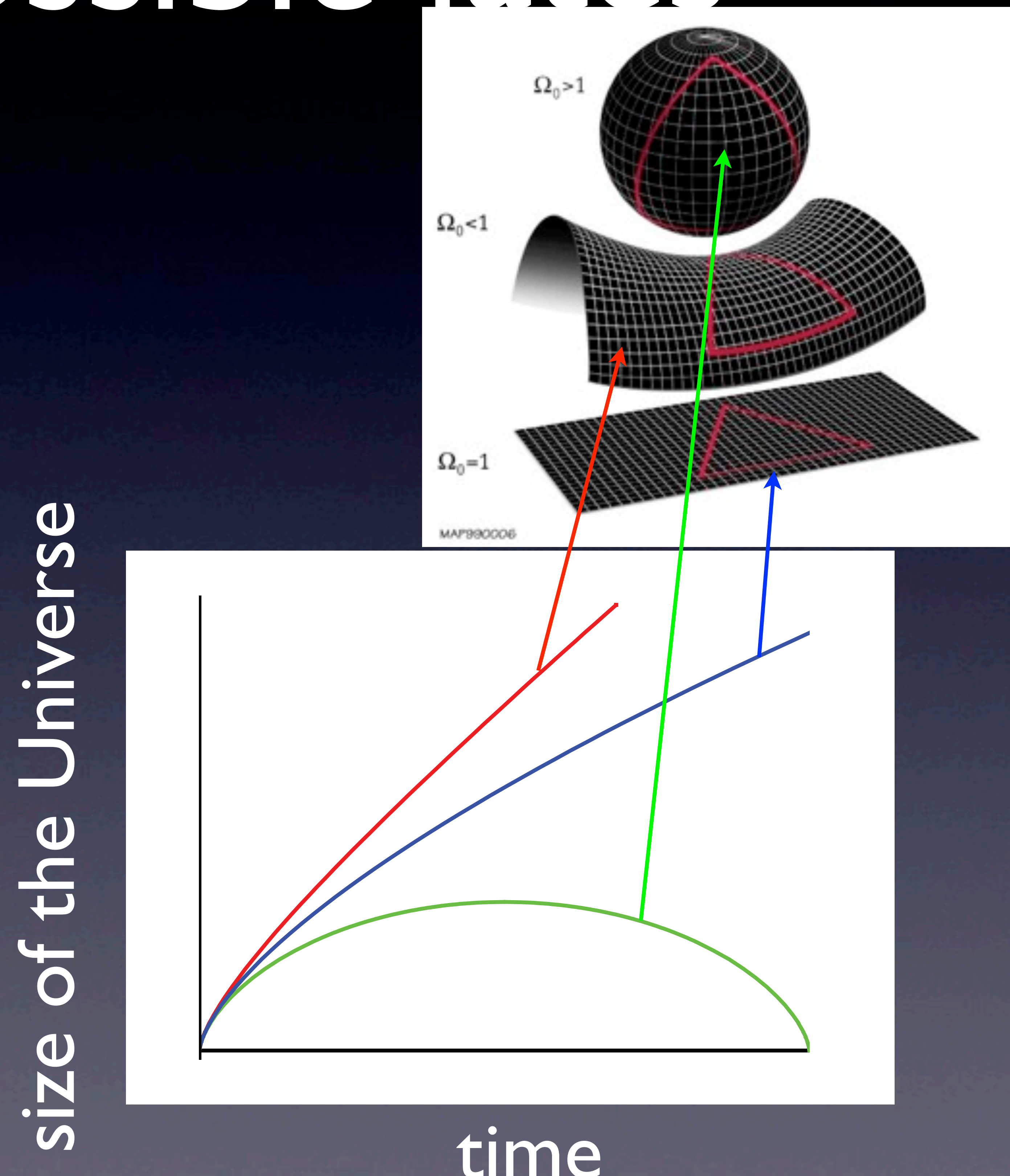


three possible fates

- if large amount of matter, expansion stops and heads back to a Big Crunch

- if small amount of matter, expansion will go on forever

- study the expansion history and predict the future!



future observers

- as the Universe gets better, more and more galaxies come into sight
- observation becomes more fun!

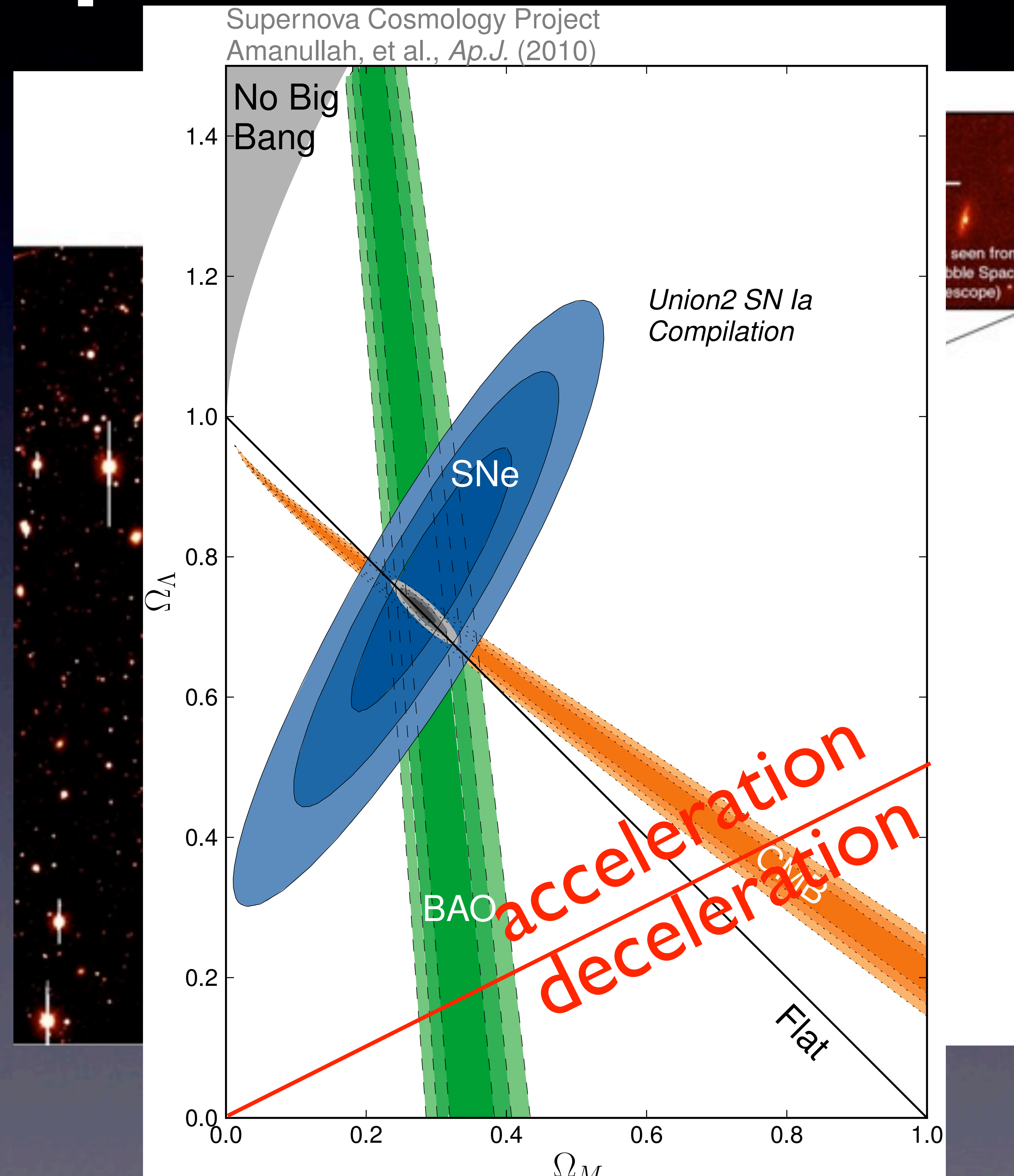

Dark Energy

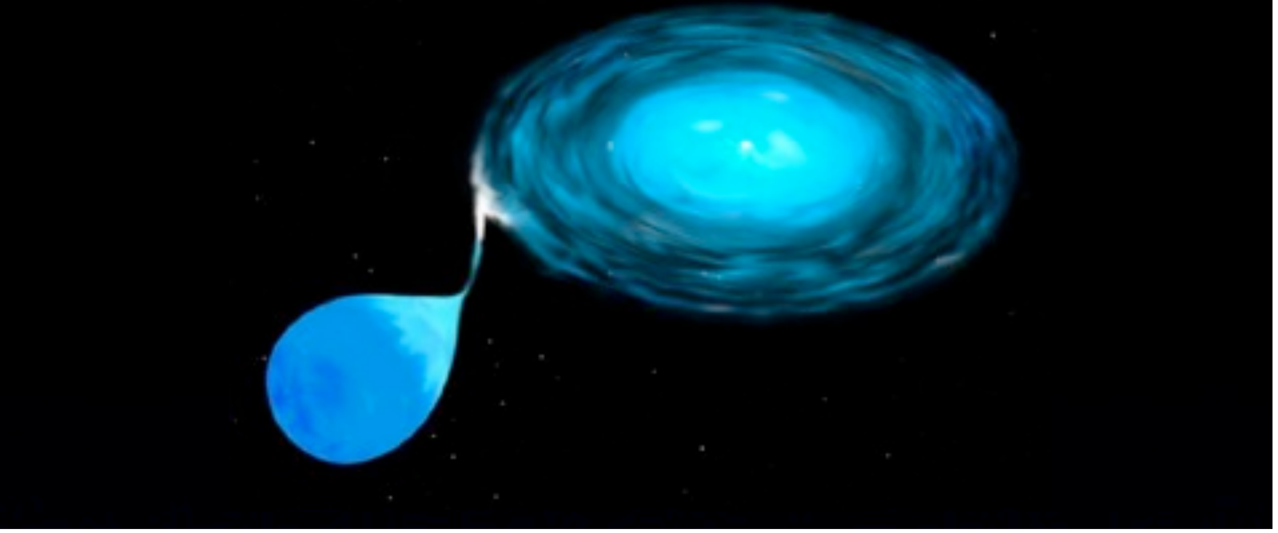

Dark Energy
Dark Energy
Dark Energ
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Energy
Dark Ener
Dark Energy

Type-Ia supernovae

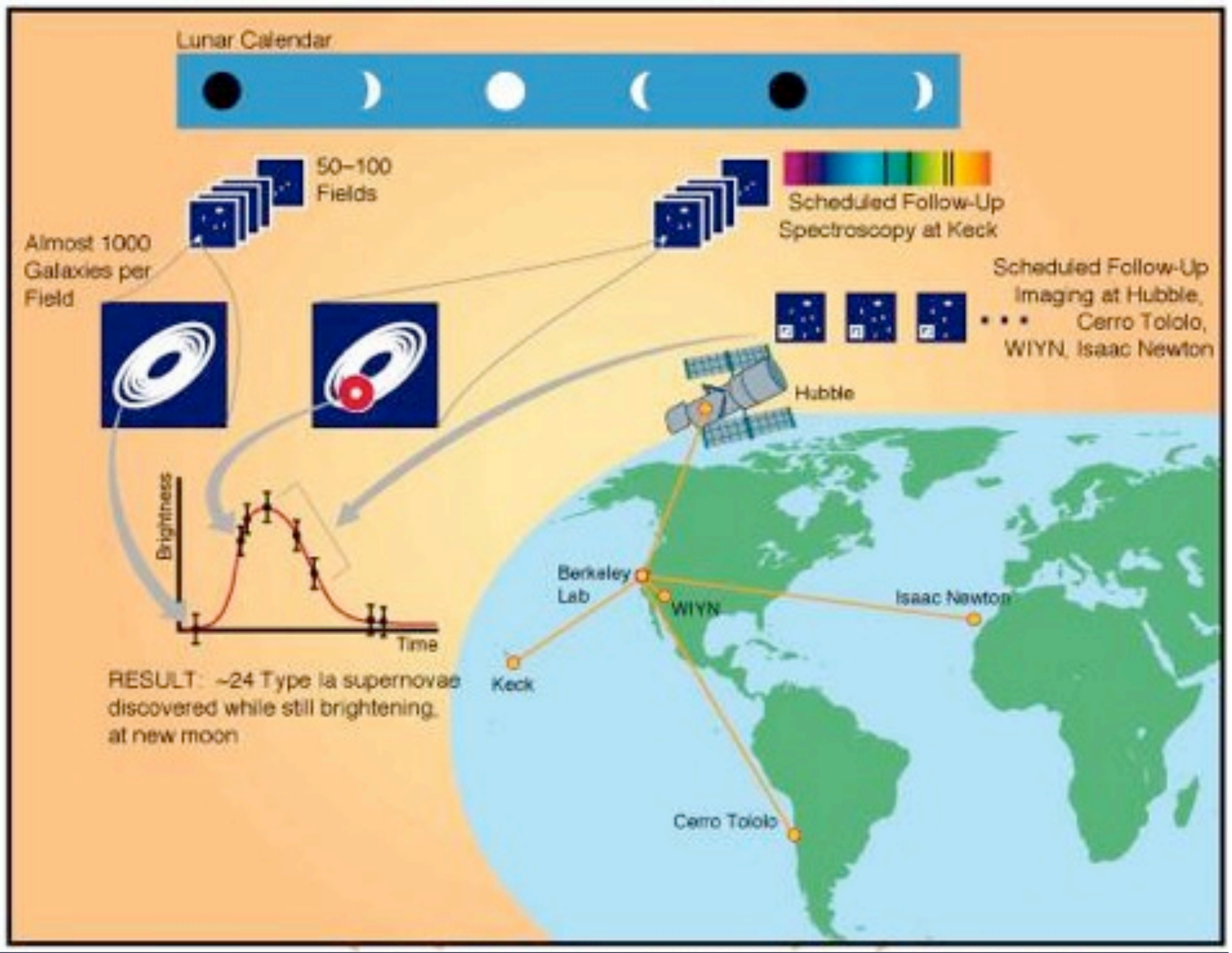
- Type-Ia supernova becomes brighter than the whole galaxy
- *How bright it looks*
  ⇒ How far away

  ⇒ How far back in time
- *How red it looks*
  ⇒ How much expansion
- Expansion of the Universe is getting faster!

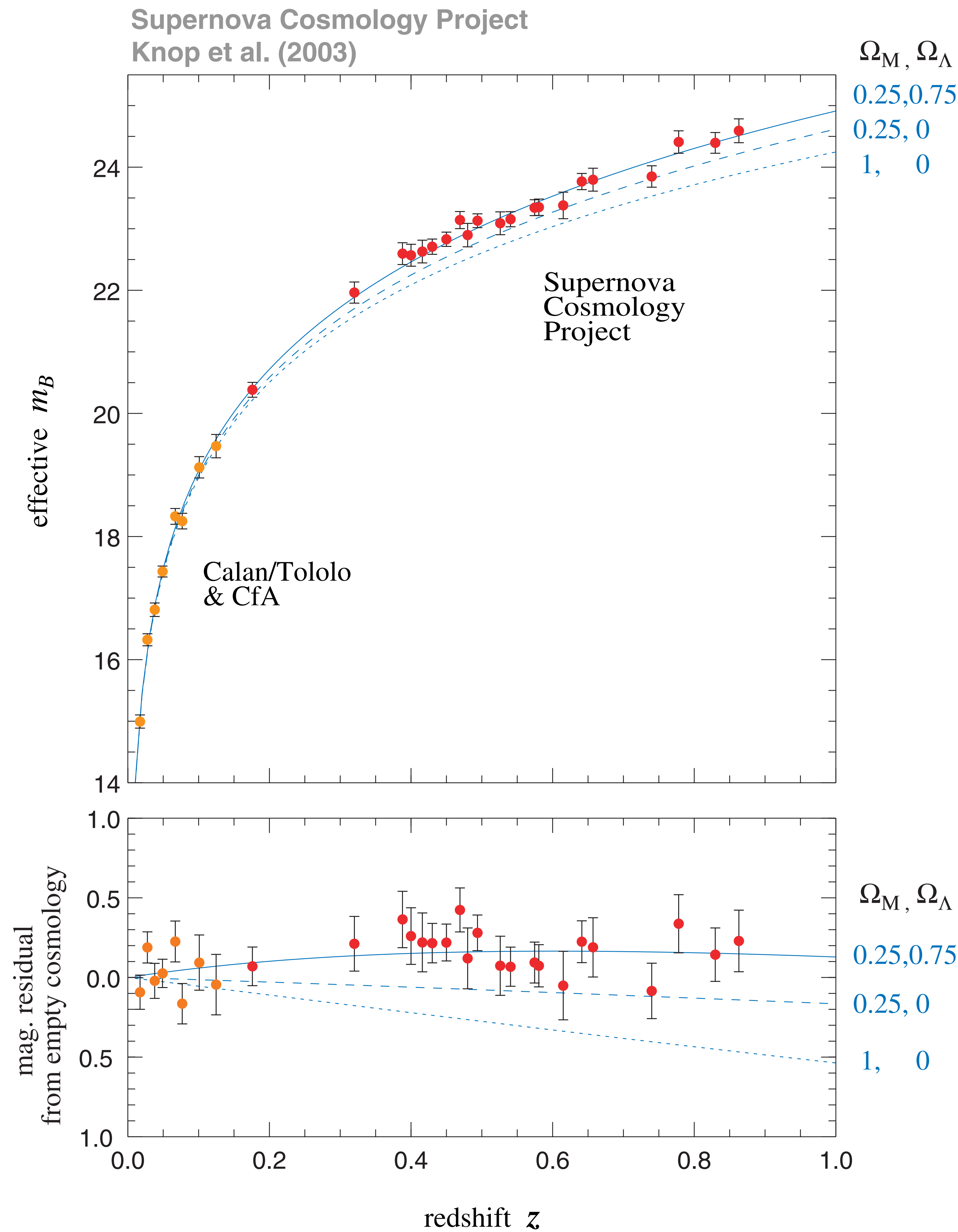




Strategy

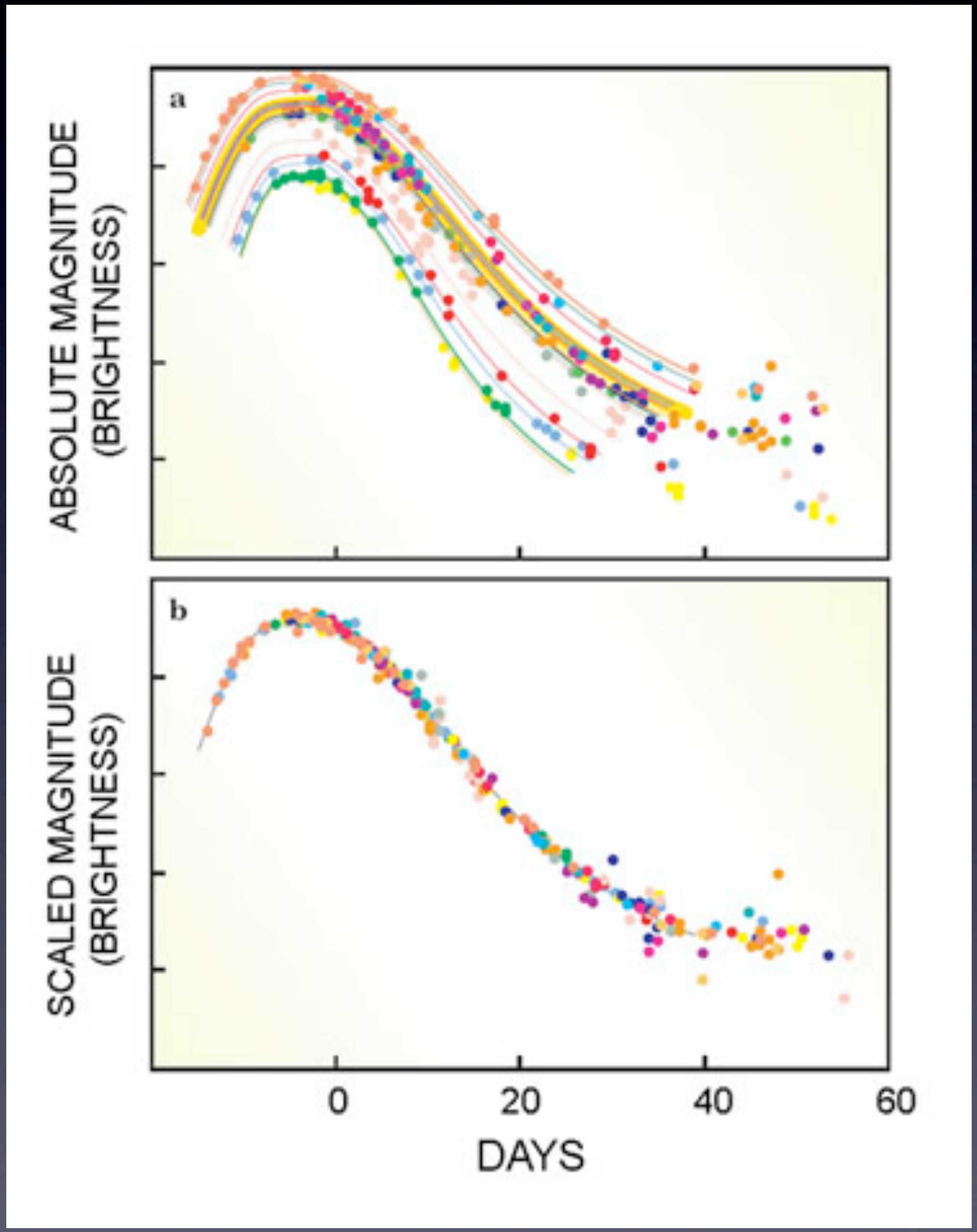


supernovae on demand



stretch factor

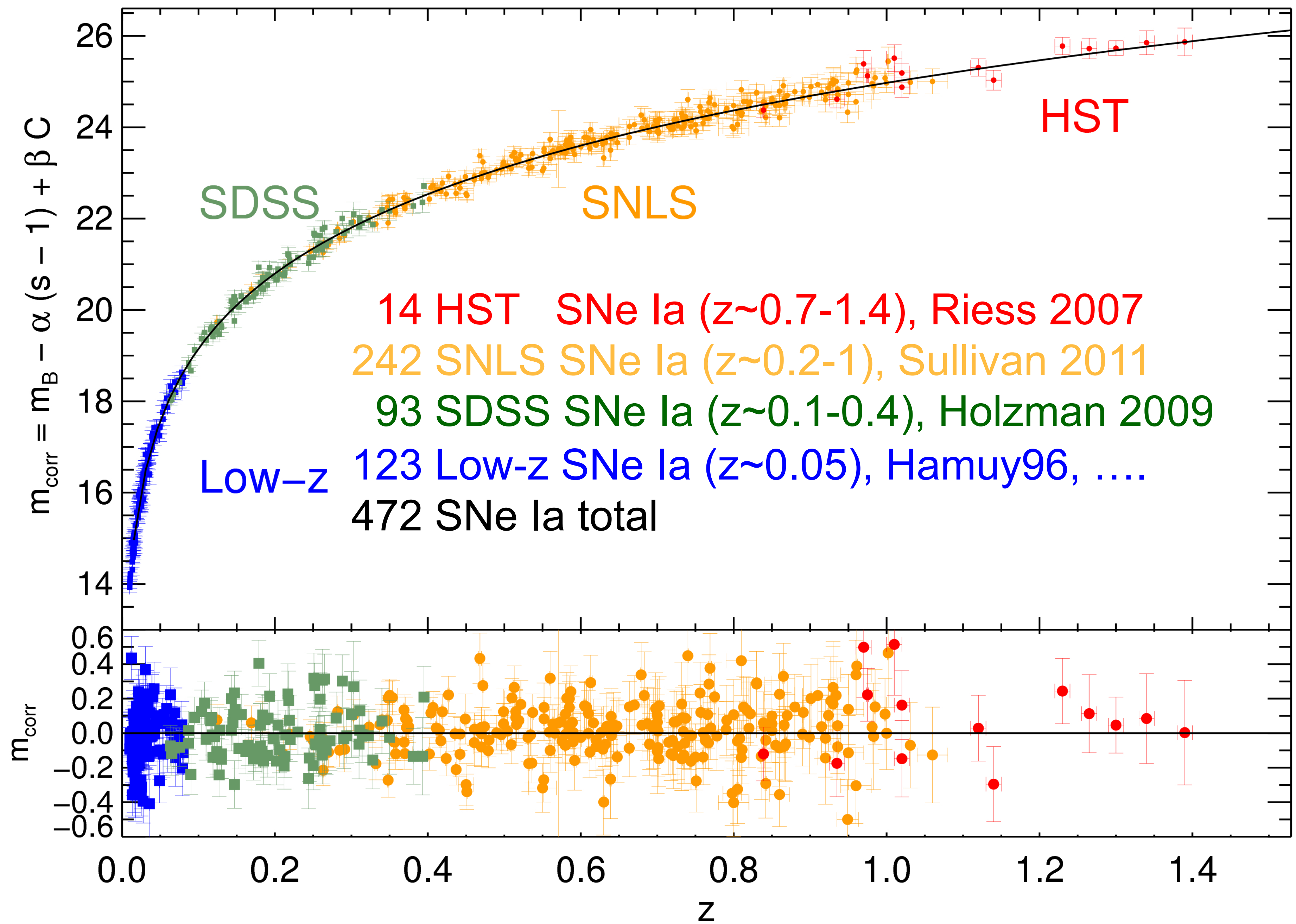
- it is not quite standard
- correlation between duration time and the absolute brightness
- can be “fixed” by a “stretch factor”
- other smaller concerns with environment (metallicity), dust extinction, etc



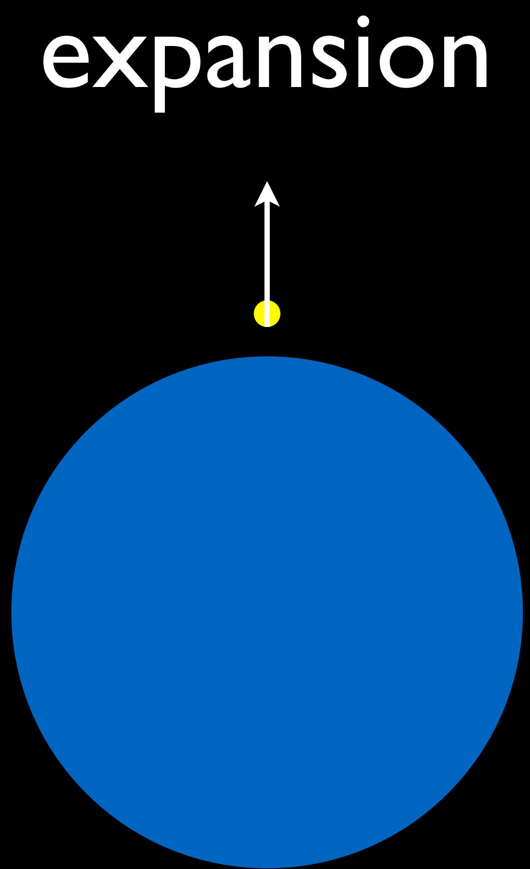
SNLS-3 years Combined Hubble diagram

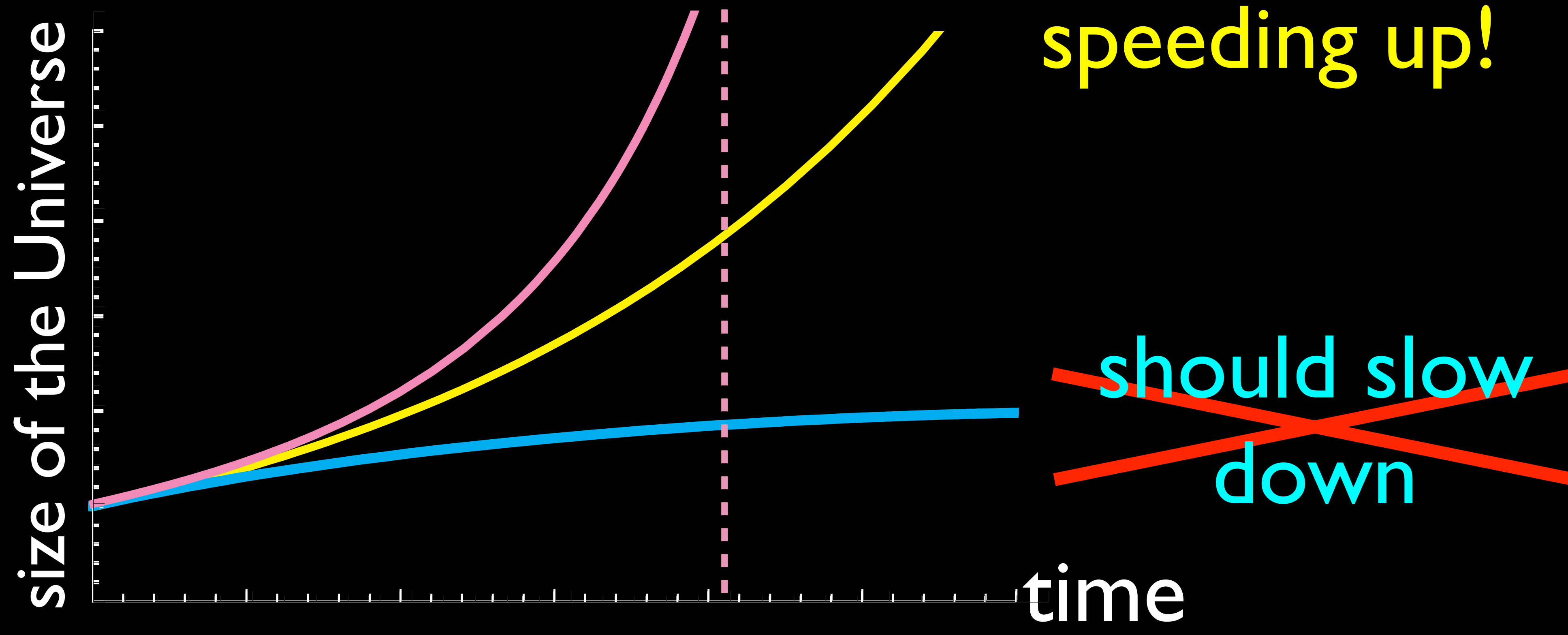
Pierre Antilogus
Marc Betoule

Stat ~ x 10 since the 1998 discovery papers

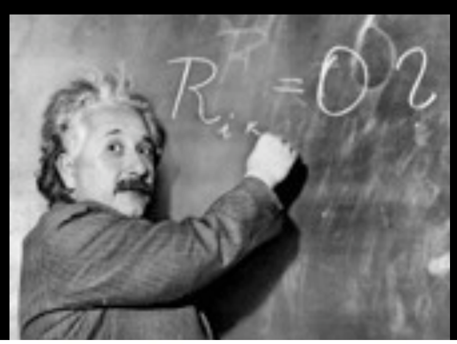


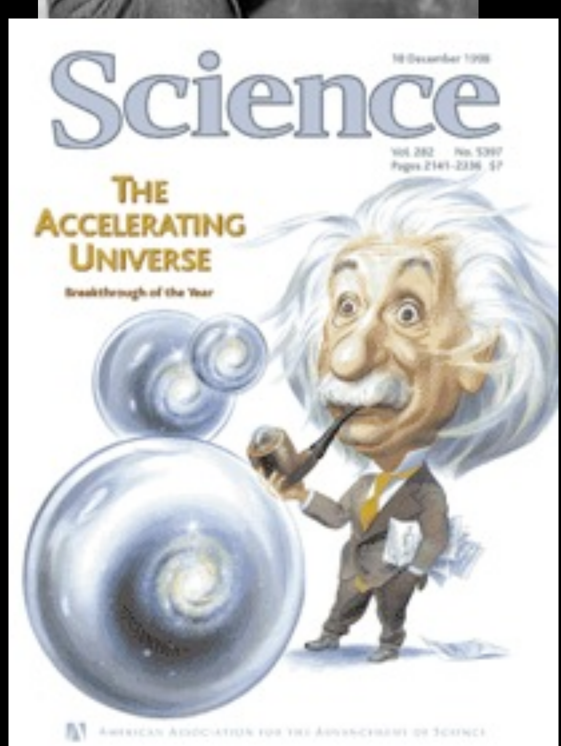
Guy et al, 2010 – Conley et al 2010, Sullivan et al, 2011





- expansion started to speed up recently (~7Byr)
- energy is increasing!
- infinite source of energy?? dark energy
- Was Einstein wrong?
- new paradigm of the Universe, fundamental laws
- If the rate of energy increase very quick, eventually the expansion becomes infinitely fast
  ⇒ Will the Universe end??
- Need to measure the rate of energy increase!





Acceleration

- *w*: equation of state parameter
- radiation: *w*=1/3
- matter: *w*=0
- vacuum energy: *w*=–1
- acceleration: *w*<–1/3

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

$$\rho = wp$$

$$dU = d(\rho R^3) = -pdV = -w\rho dR^3$$

$$\rho \propto R^{-3(1+w)}$$

$$\ddot{R} \propto -(1-3w)$$

Does the Universe end?

- If $w<-1$, the Universe ends in a Big Rip
- Expansion becomes so fast that galaxies, stars, eventually atoms and even nuclei get ripped apart
- Universe ends with an infinite speed and empty!
- or it may be “Inflation Strikes Back”, $w>-1$
- We need to know the equation of state

NHK Science Zero 2010.9.4

Embarrassment

- A naïve estimate of the cosmological constant in Quantum Field Theory:

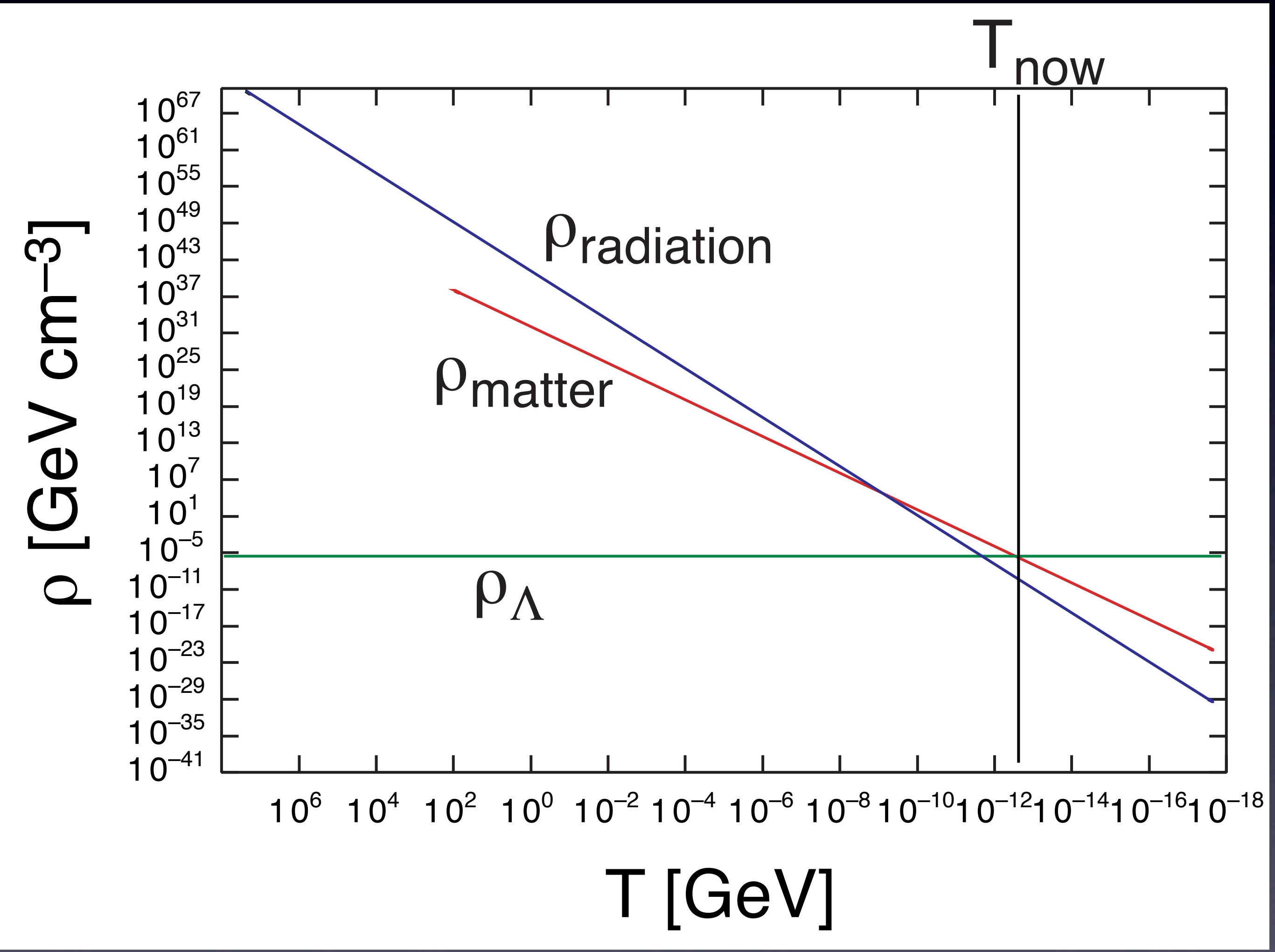
$$\rho_\Lambda \sim M_{Pl}{}^4 = G_N{}^{-2} \sim 10^{120} \textit{ times observation}$$

The worst prediction in theoretical physics!

- People had argued that there must be some mechanism to set it zero
- But now it seems finite???

Cosmic Coincidence Problem

- Why do we see matter and cosmological constant almost equal in amount?
- "Why Now" problem
- *Actually a triple coincidence problem including the radiation*
- If there is a deep reason for $\rho_\Lambda \sim ((\mathrm{TeV})^2/M_{Pl})^4$, coincidence natural

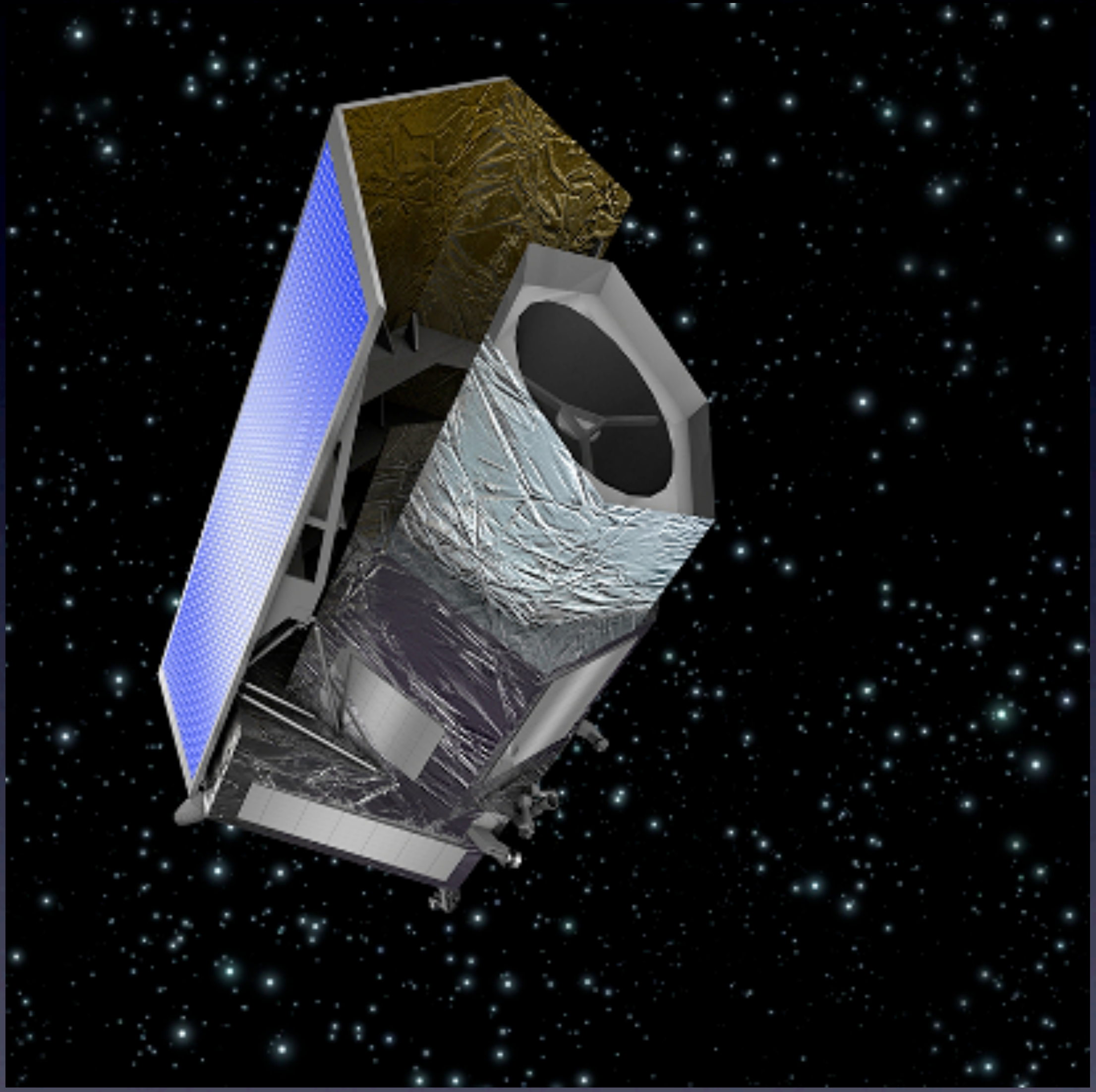


Arkani-Hamed, Hall, Kolda, HM

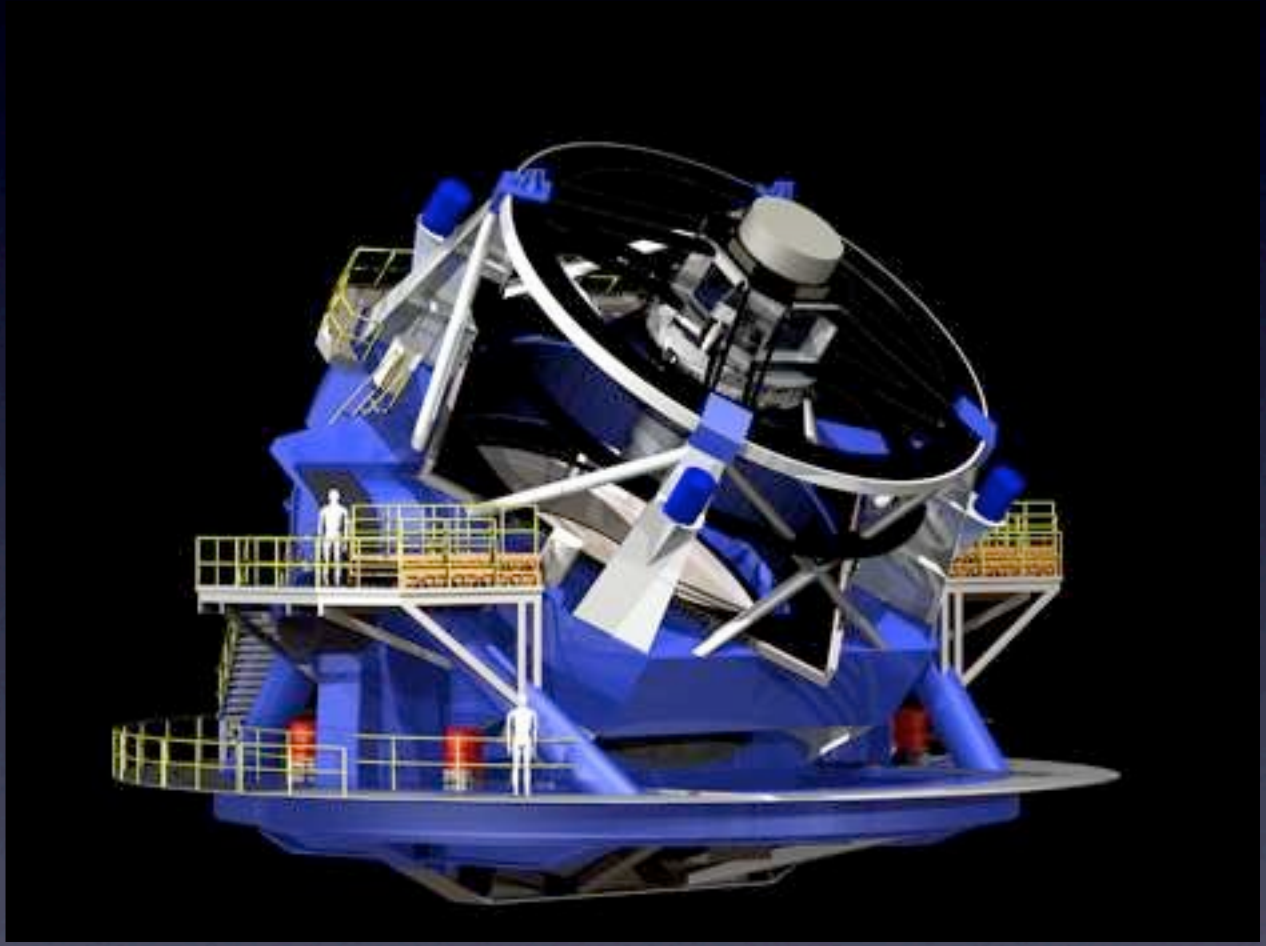
We can study cosmology only now.

Need funding ASAP.

big future players



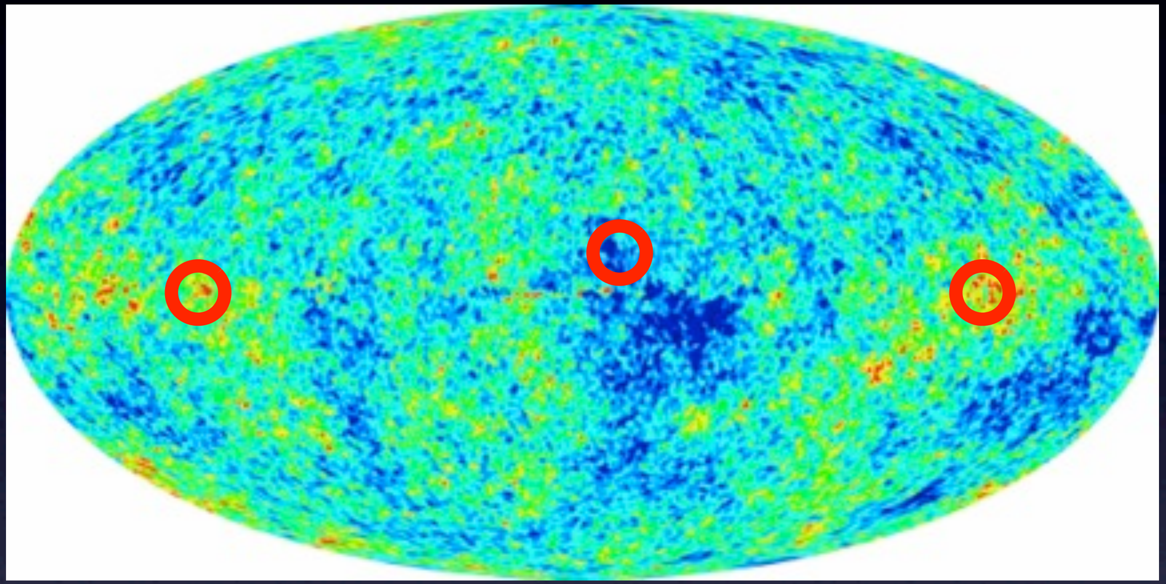
EUCLID

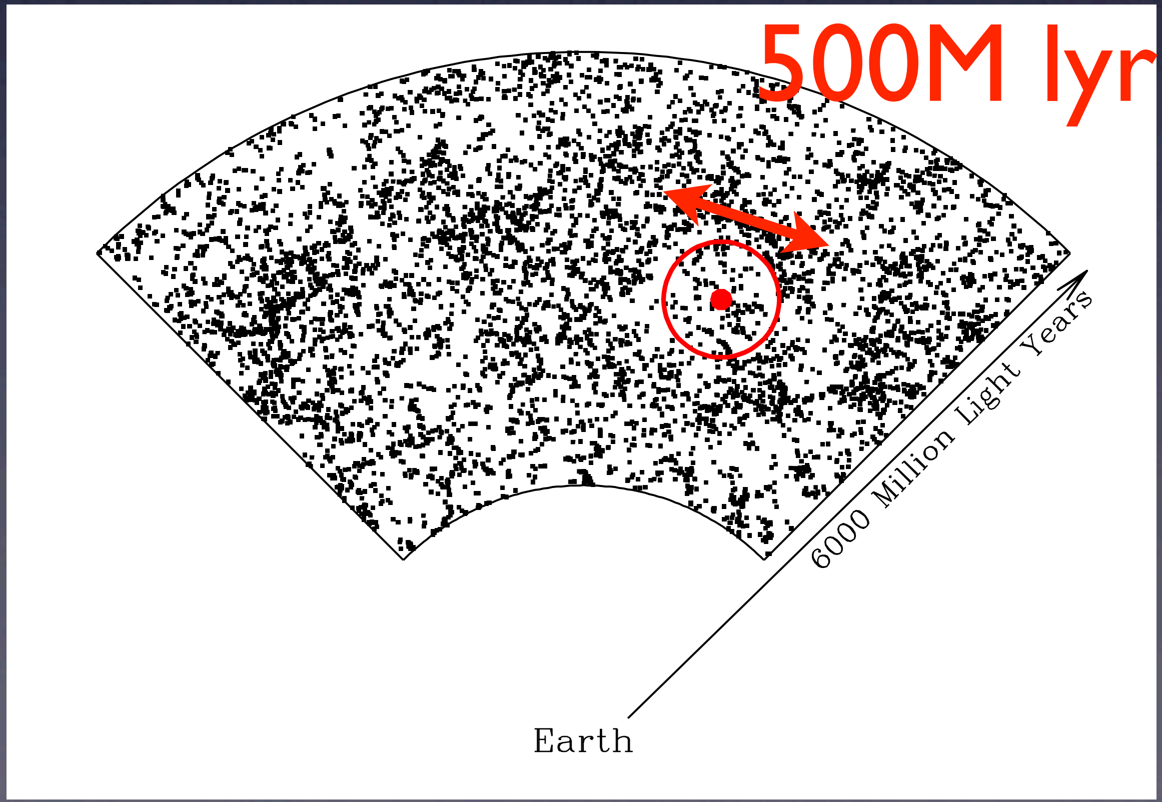


LSST

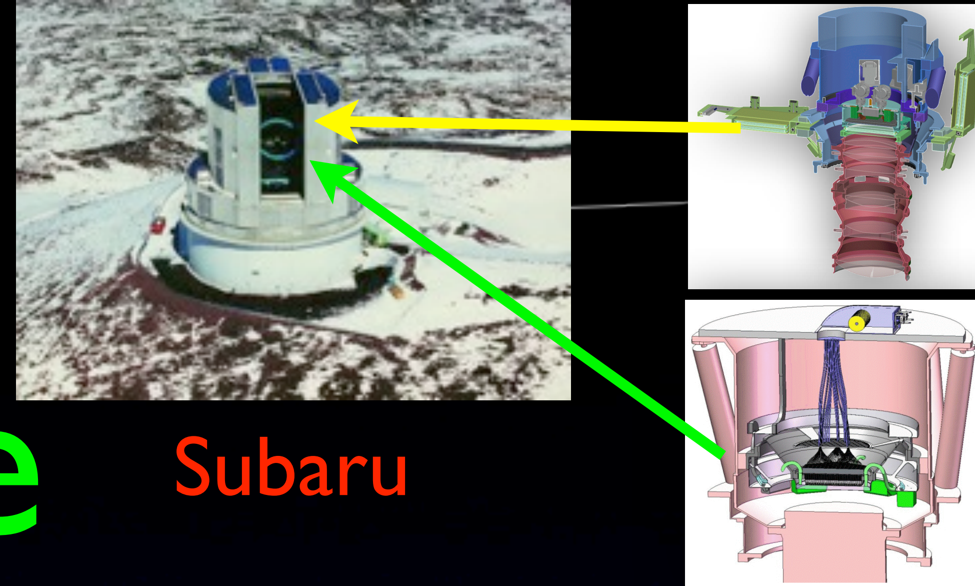
Standard Ruler

- characteristic scales for acoustic peaks
- acoustic peak shows up in galaxy distributions, too, at ~500M lyr
- use this scale as a "standard ruler" to measure distances accurately
- Will the Universe end?





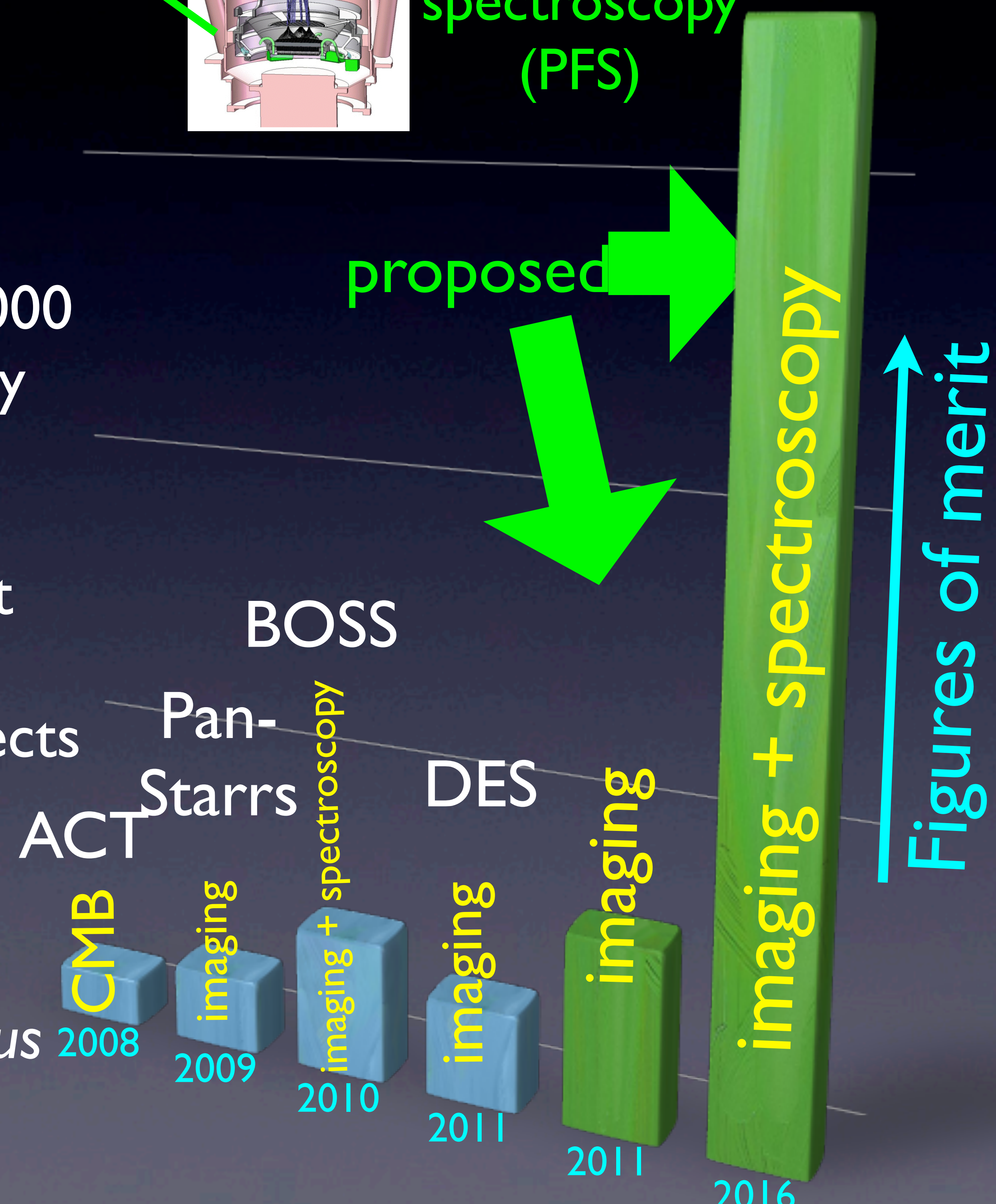
SuMIRe



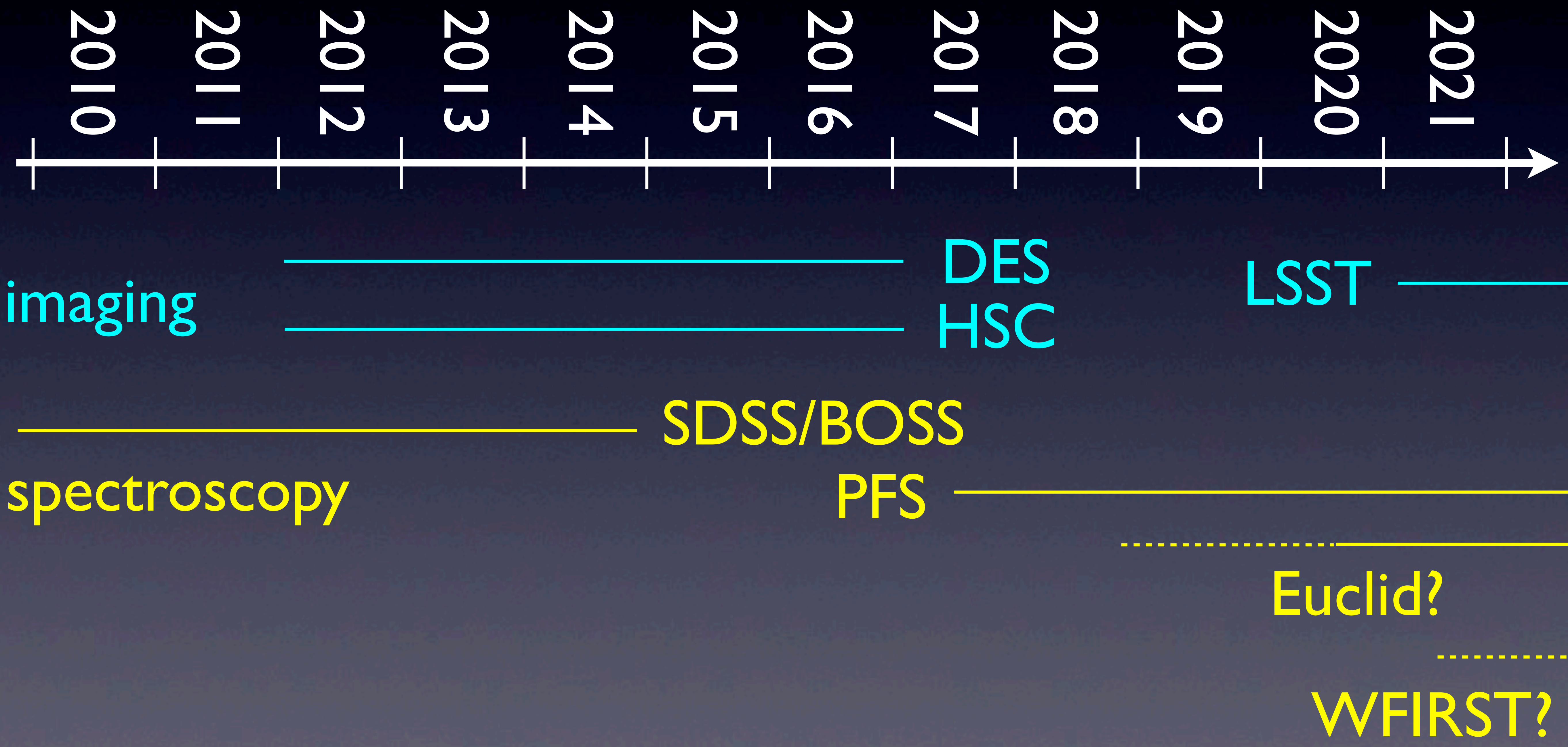
- *cosmic census*
- field of view ~ Hubble x1000
- Major study of dark energy
- Subaru Measurement of Images and Redshifts

1. imaging with 0.9B-pixels 3t CCD camera from 2012
2. spectroscopy of 2400 objects from 2017

- same telescope for both imaging and spectroscopy
- *galaxy survey with continuous redshift coverage*



Timeline



2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
imaging
DES
HSC
LSST
SDSS/BOSS
spectroscopy
PFS
Euclid?
WFIRST?

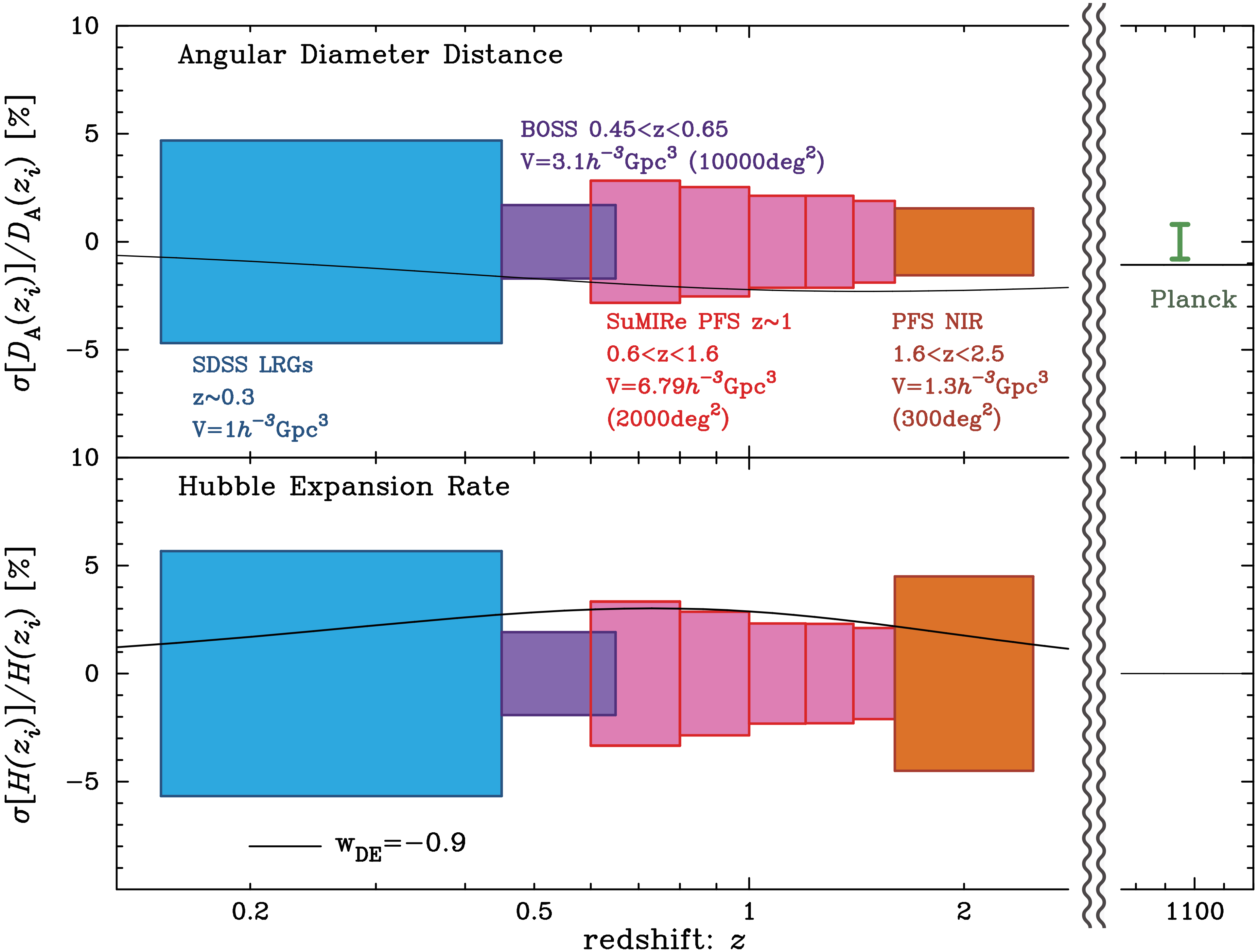
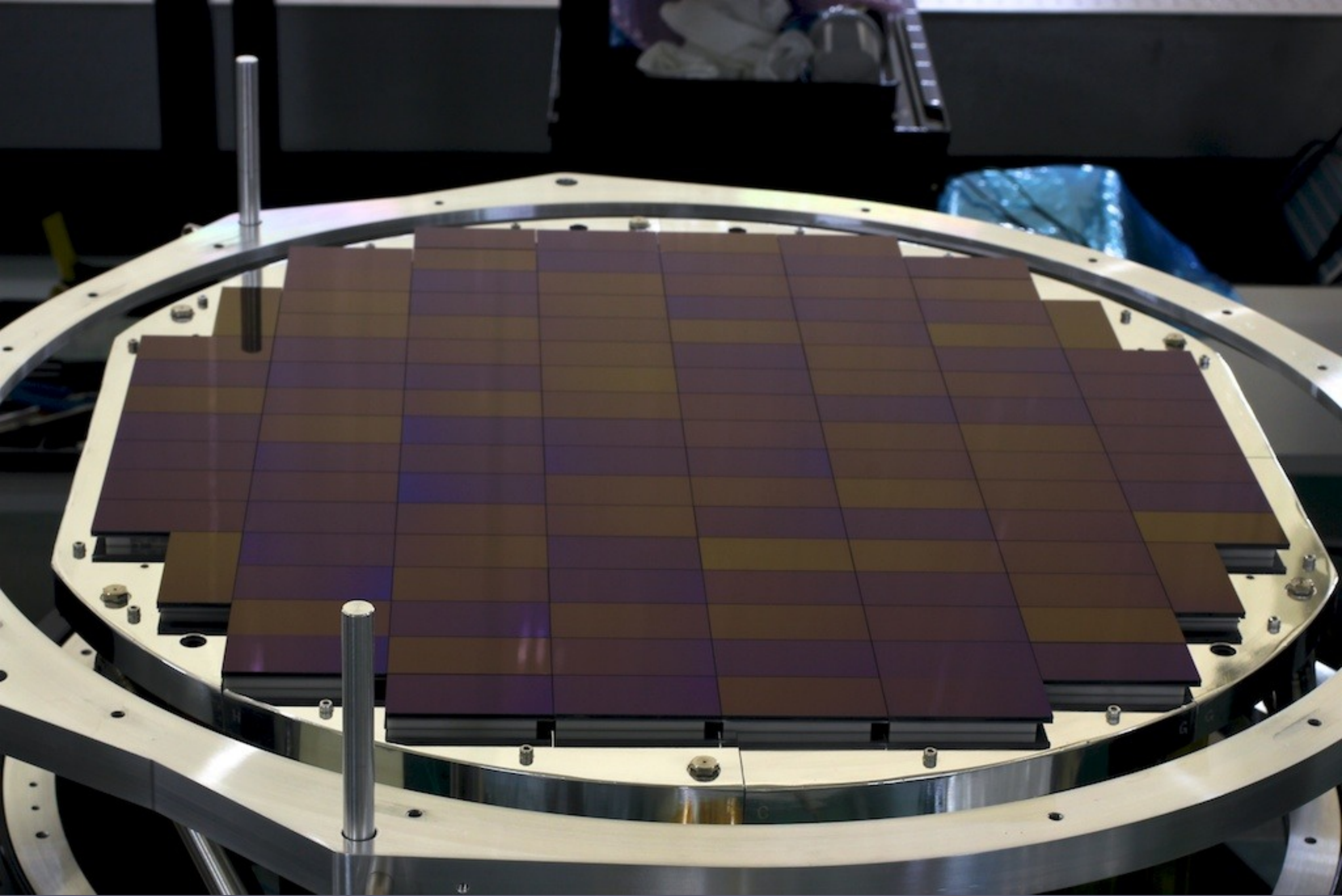
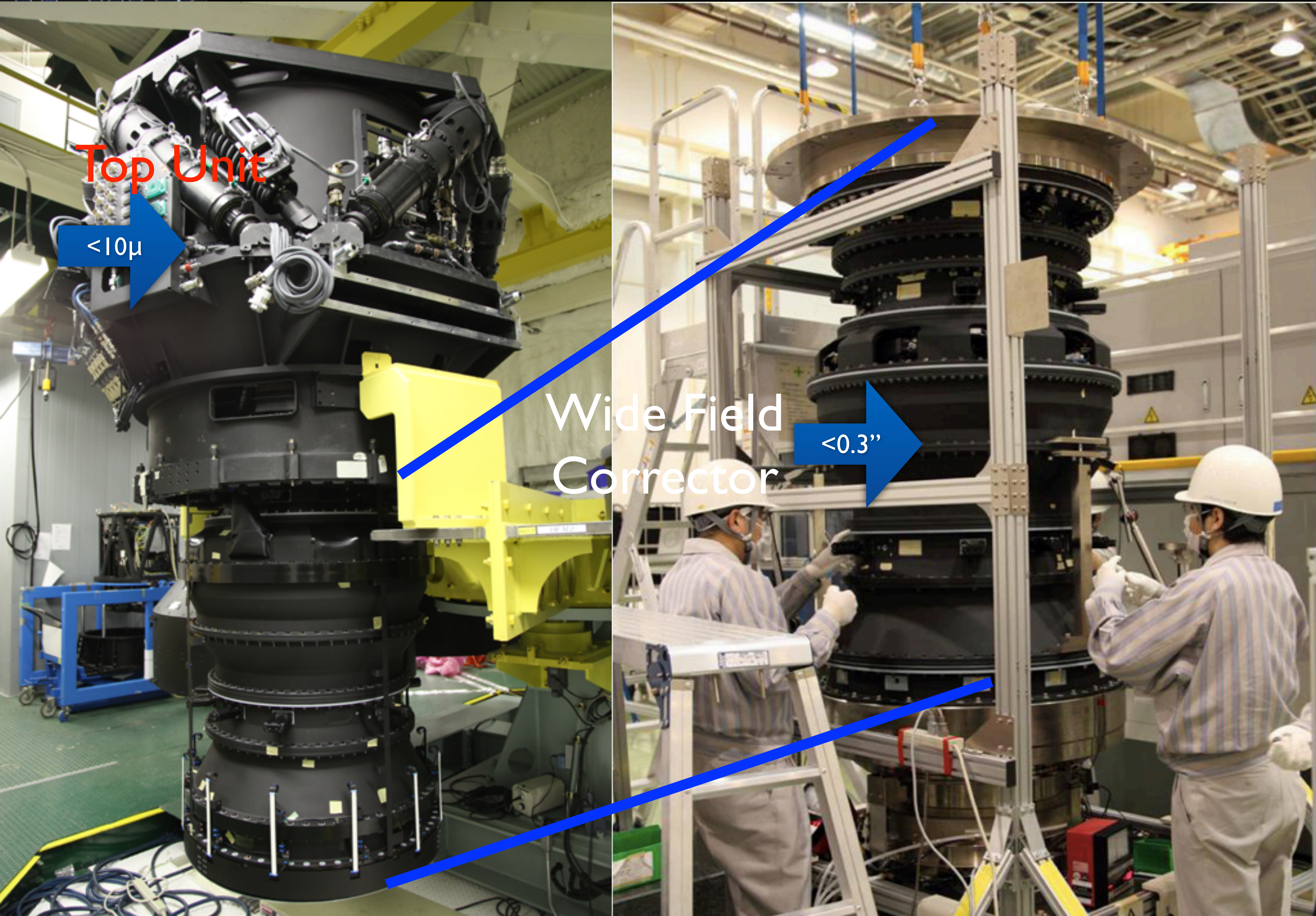


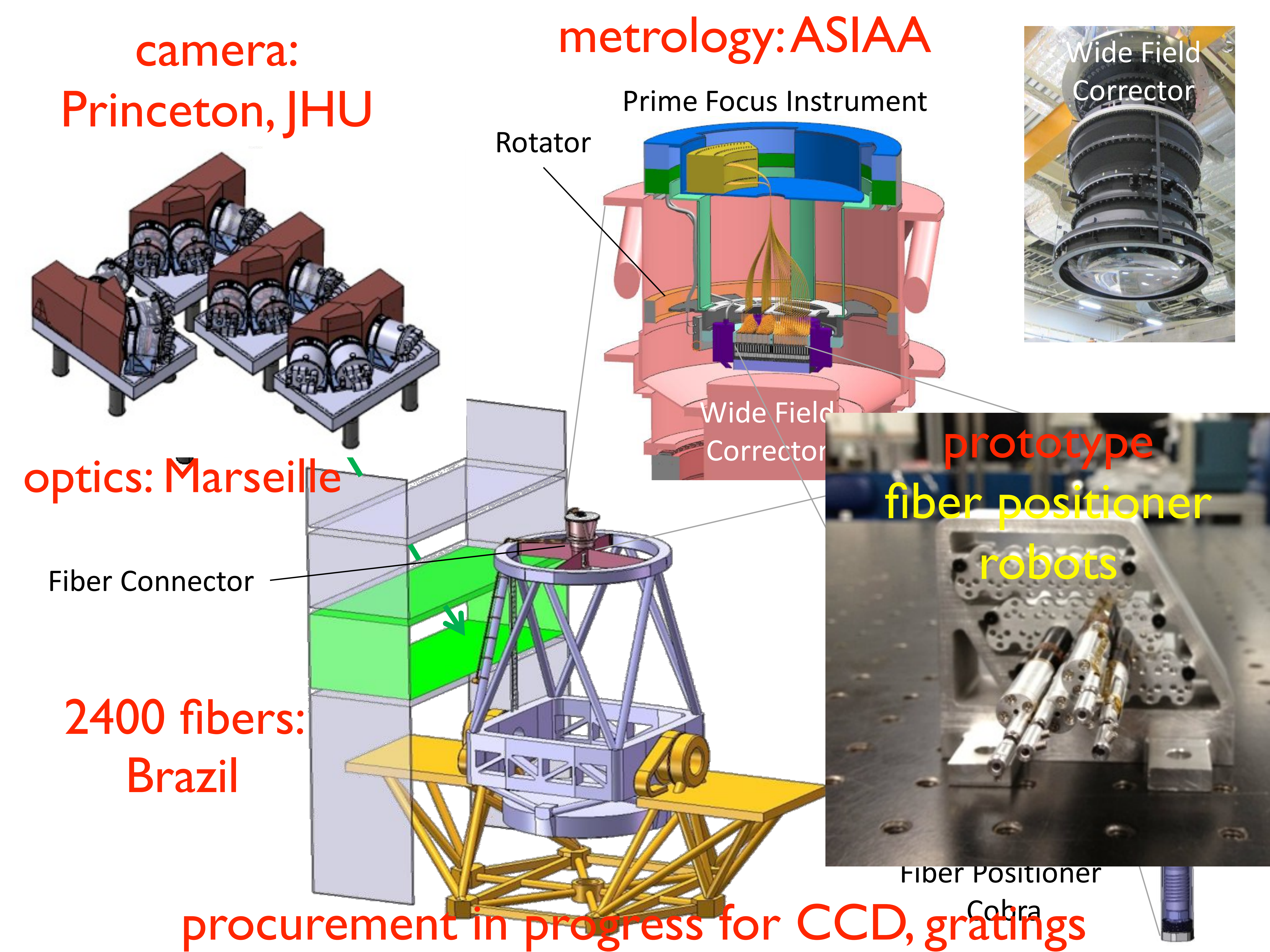
Figure 4.6: Fractional errors in measuring the angular diameter distance and the Hubble expansion rate for each redshift slices for the different BAO surveys, SDSS, BOSS and PFS. For the PFS survey we assumed survey parameters given in Table 4.3. The solid curves in each panel shows the fractional difference of $D_A(z)$ or $H(z)$ when changing the dark energy equation of state w to $w = -0.9$ from $w = -1$ (ΛCDM model).



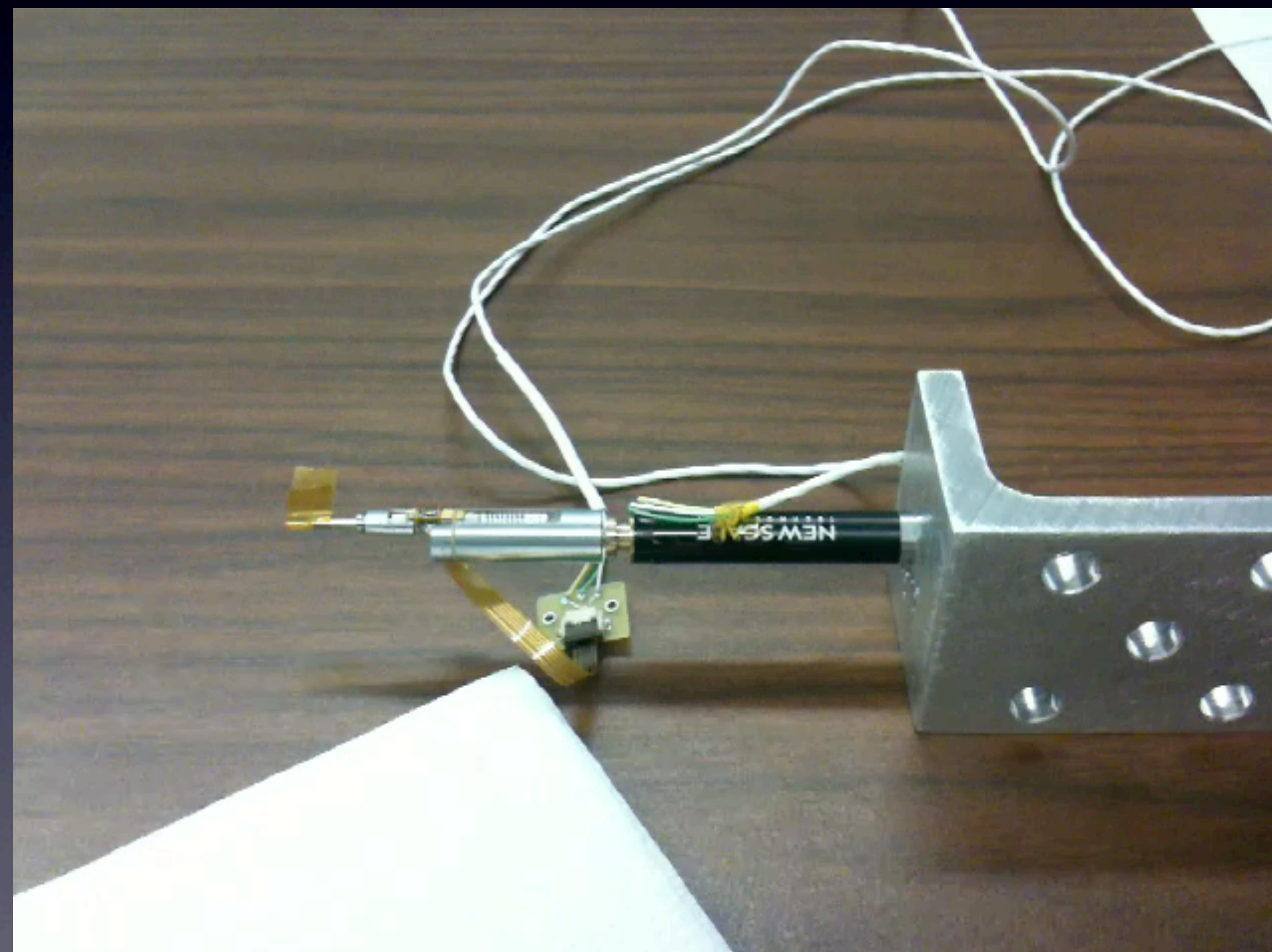
First Light later this year!

World's Best Digital Camera: 3tons!




camera:
Princeton, JHU
metrology: ASIAA
Prime Focus Instrument
Rotator
Wide Field
Corrector
Wide Field
Corrector
prototype
fiber positioner
robots
optics: Marseille
Fiber Connector
2400 fibers:
Brazil
Fiber Positioner
Cobra
procurement in progress for CCD, gratings

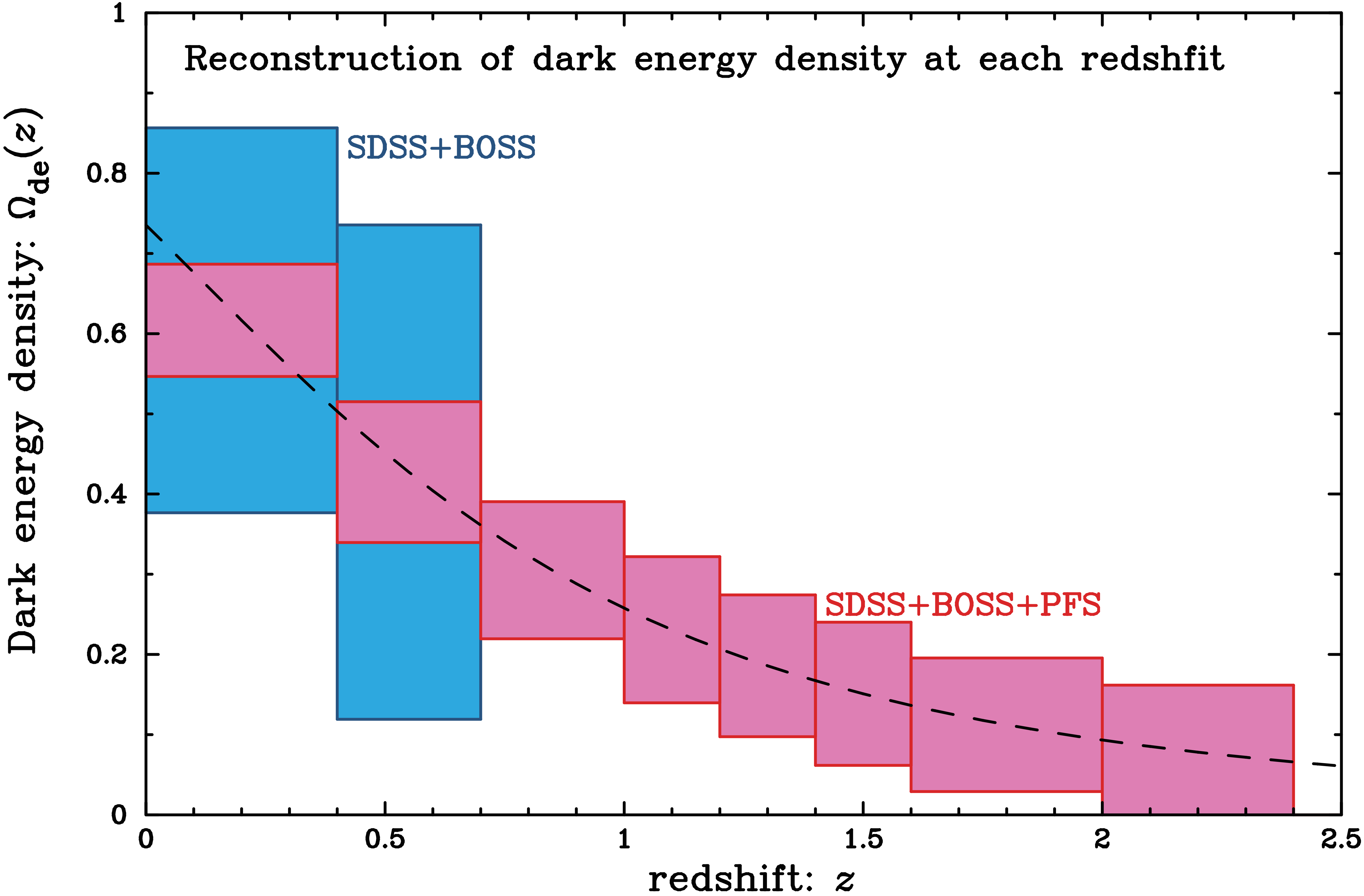
fiber positioner JPL Cobra design



pointing accuracy ~10μ in ~40 seconds

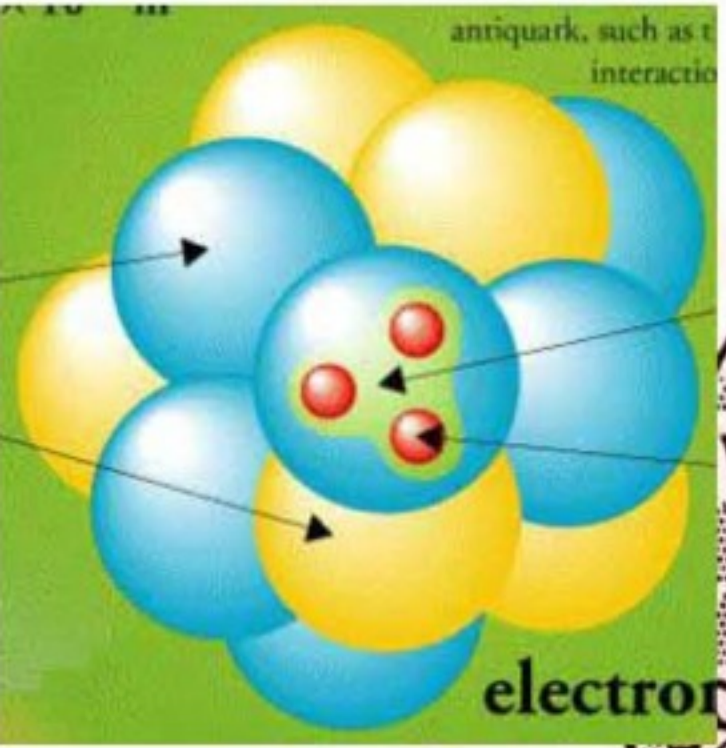
2nd PFS collaboration meeting 1/8, 9, 2012
a big momentum building up!

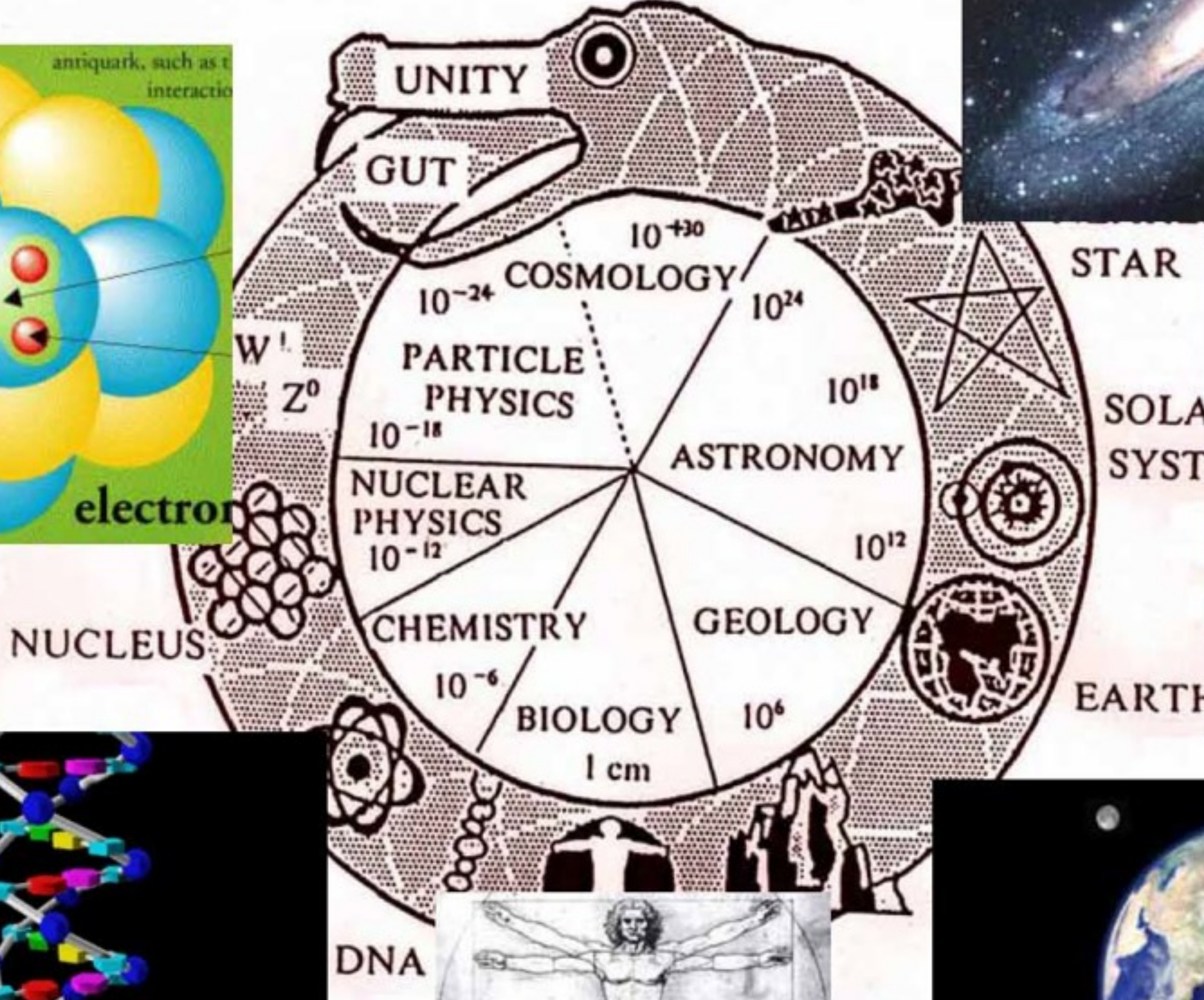
map out evolution history

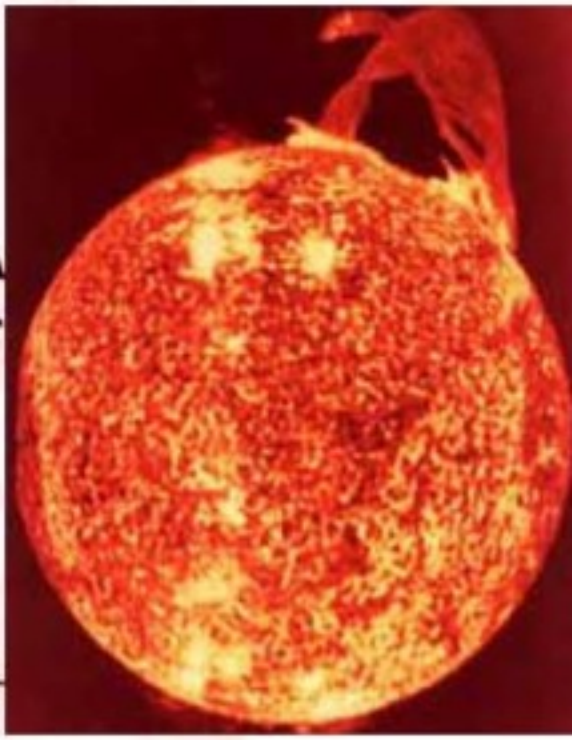


http://sumire.ipmu.jp/pfs/intro.html

Snake of Sizes








dark side
HEP
astro