KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Beyond the Standard Model

Hitoshi Murayama (Berkeley, Kavli IPMU Tokyo)

Invisibles School, June 17, 2015

BERKELEY CENTER FOR THEORETICAL PHYSICS

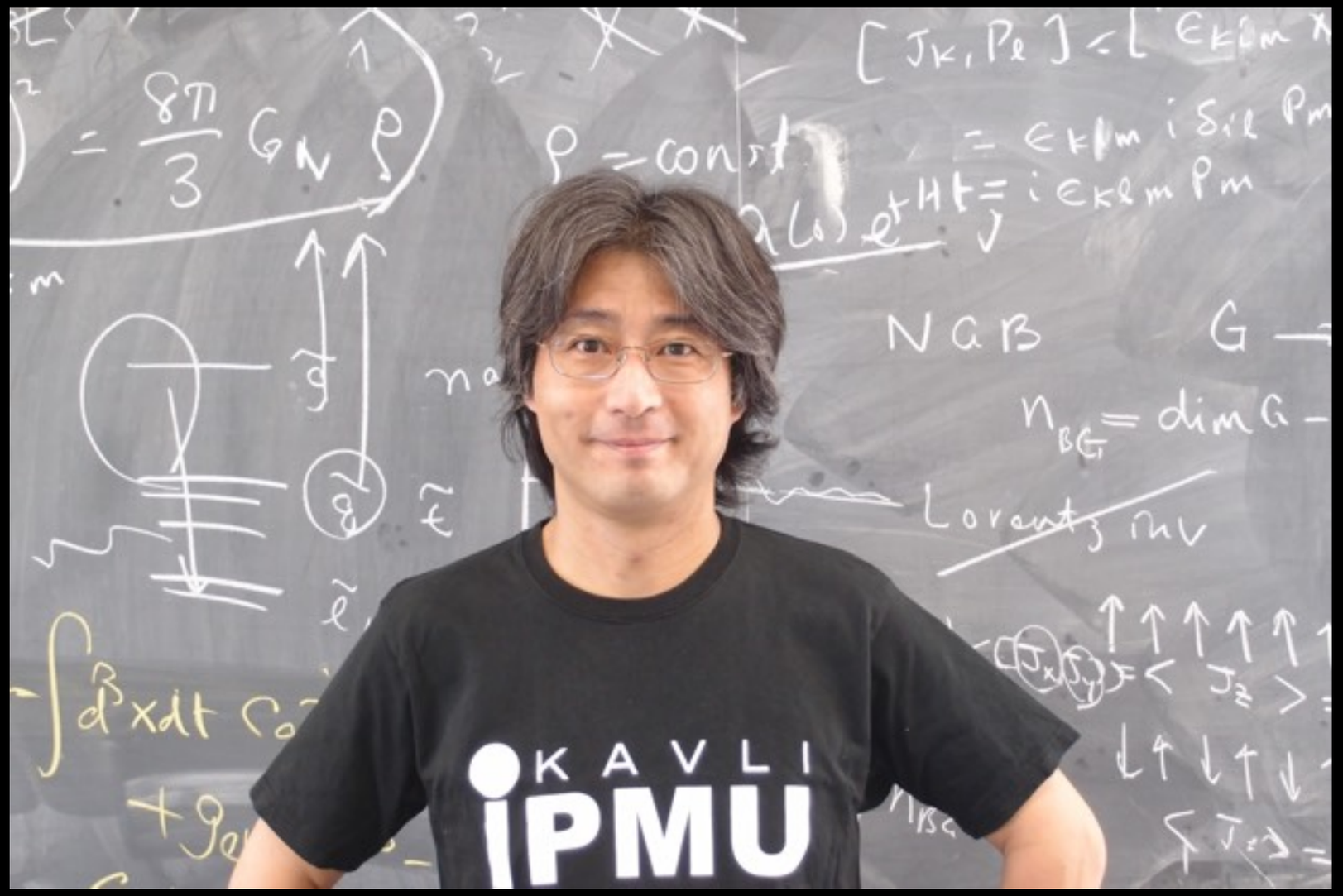
BERKELEY LAB

KAVLI IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Director of the Kavli Institute for the Physics

and Mathematics of the Universe

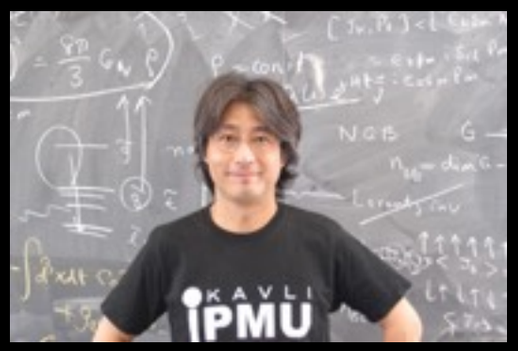
A lot of responsibility!



Director of the Universe

Not high enough authority

Voice of God



Director of the Universe

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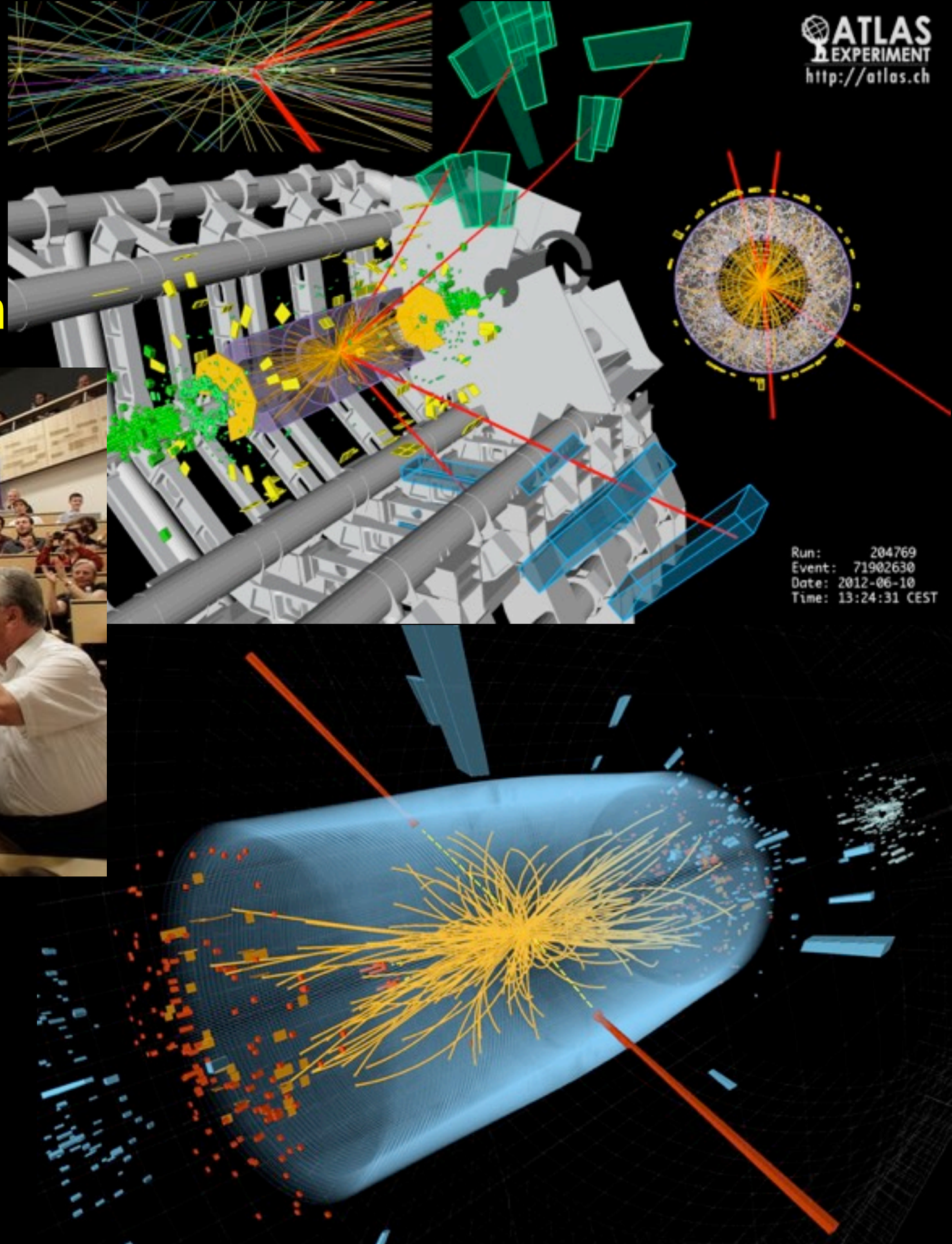
2012.7.4

discovery of Higgs boson



theory：1964

design：1984

construction：1998

Higgsdependence Day
July 4, 2012

Standard Model is extreeemely successful

- Take Particle Data Group "Reviews of Particle Physics" with 1676 pages
- With only a few exceptions, all numbers in the book are consistent with the Standard Model with suitably chosen 19 parameters
- add neutrinos: 5 more parameters
- Some of them tested at 10^{-9}–10^{-12} level
- Many at 10^{-3} level

Standard Model is extreeemely successful

- baryon and lepton number conserved (apart from anomaly $\propto e^{-8\pi^2/g^2}$)
- flavor approximately conserved (apart from small mixing in V_{CKM})
- especially flavor-changing neutral current small (e.g., $s \to d$ vanishes at tree-level, suppressed by m_c^2/m_W^2 at one-loop)

Rare effects from high energies

- Effects of high-energy physics as effective operators added to the standard model

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots$$

- can be classified systematically

$$\mathcal{L}_5 = (LH)(LH) \to \frac{1}{\Lambda}(L\langle H\rangle)(L\langle H\rangle) = m_\nu \nu\nu$$

$$\mathcal{L}_6 = QQQL, \bar{L}\sigma^{\mu\nu}W_{\mu\nu}Hl, \epsilon_{abc}W_\nu^{a\mu}W_\lambda^{b\nu}W_\mu^{c\lambda},$$
$$(H^\dagger D_\mu H)(H^\dagger D^\mu H), B_{\mu\nu}H^\dagger W^{\mu\nu}H, \ldots$$

So,
what's the problem?

Five empirical evidences for physics beyond SM

- Since 1998, it became clear that there are at least five missing pieces in the SM
  - non-baryonic dark matter
  - neutrino mass
  - accelerated expansion of the Universe
  - apparently acausal density fluctuations
  - baryon asymmetry

We don't really know their energy scales...

Physicists ask simple and profound questions

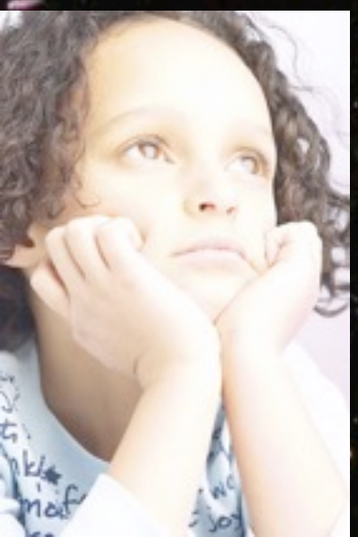
How did the Universe begin?

What is its fate?

What is it made of?

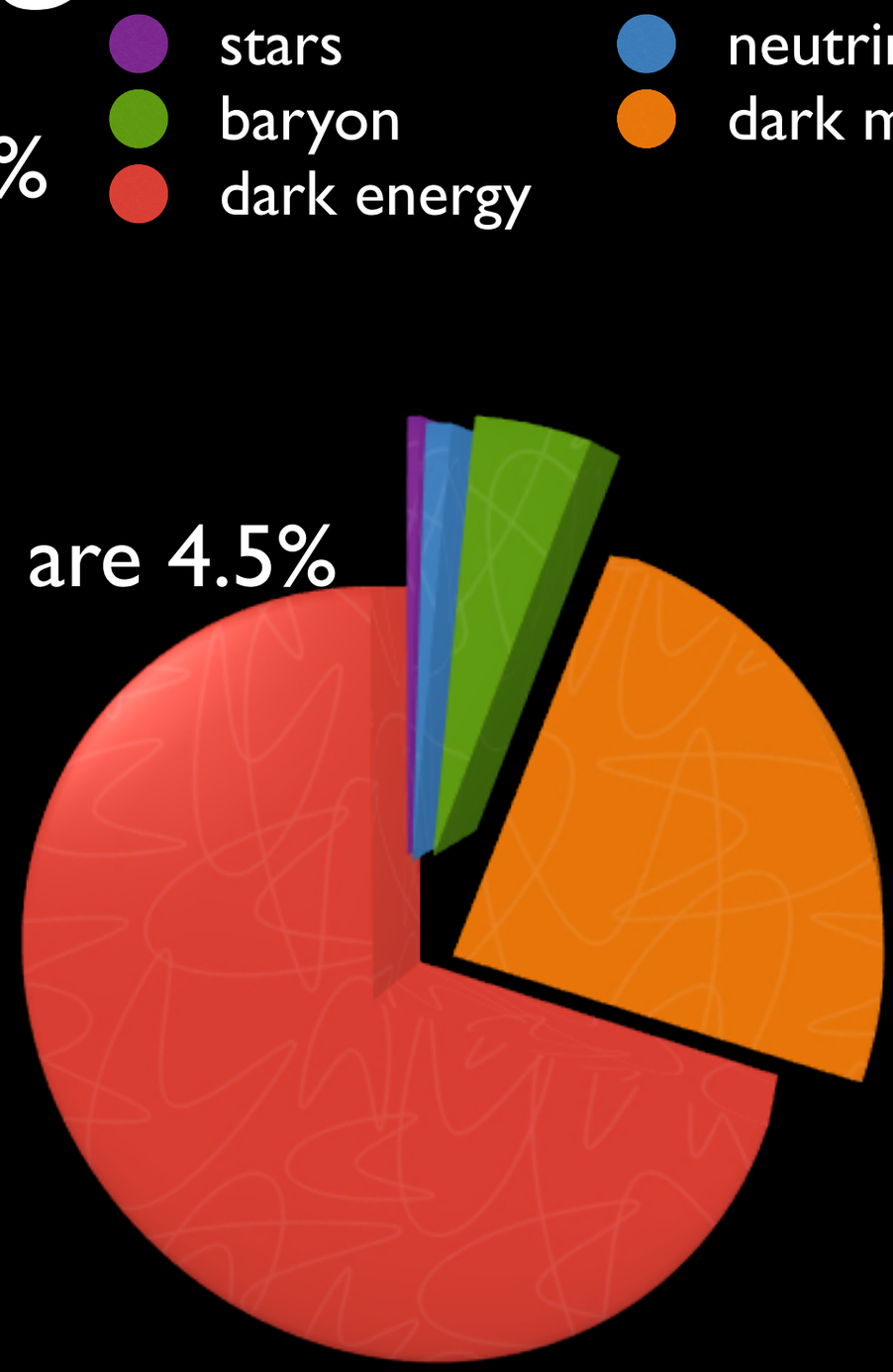
What are its basic laws?

Where do we come from?



Energy budget of Universe

- Stars and galaxies are only ~0.5%
- Neutrinos are ~0.1–0.5%
- Rest of ordinary matter (electrons, protons & neutrons) are 4.5%
- Dark Matter 27%
- Dark Energy 67%
- Anti-Matter 0%
- Higgs ~10^{62}%??



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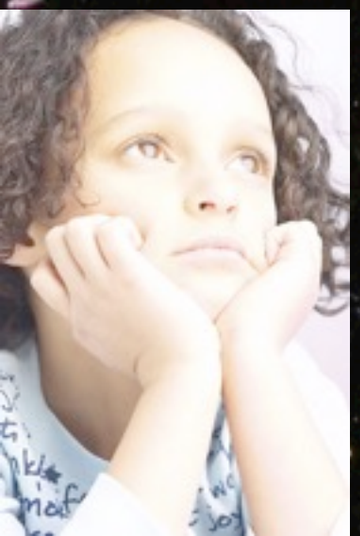
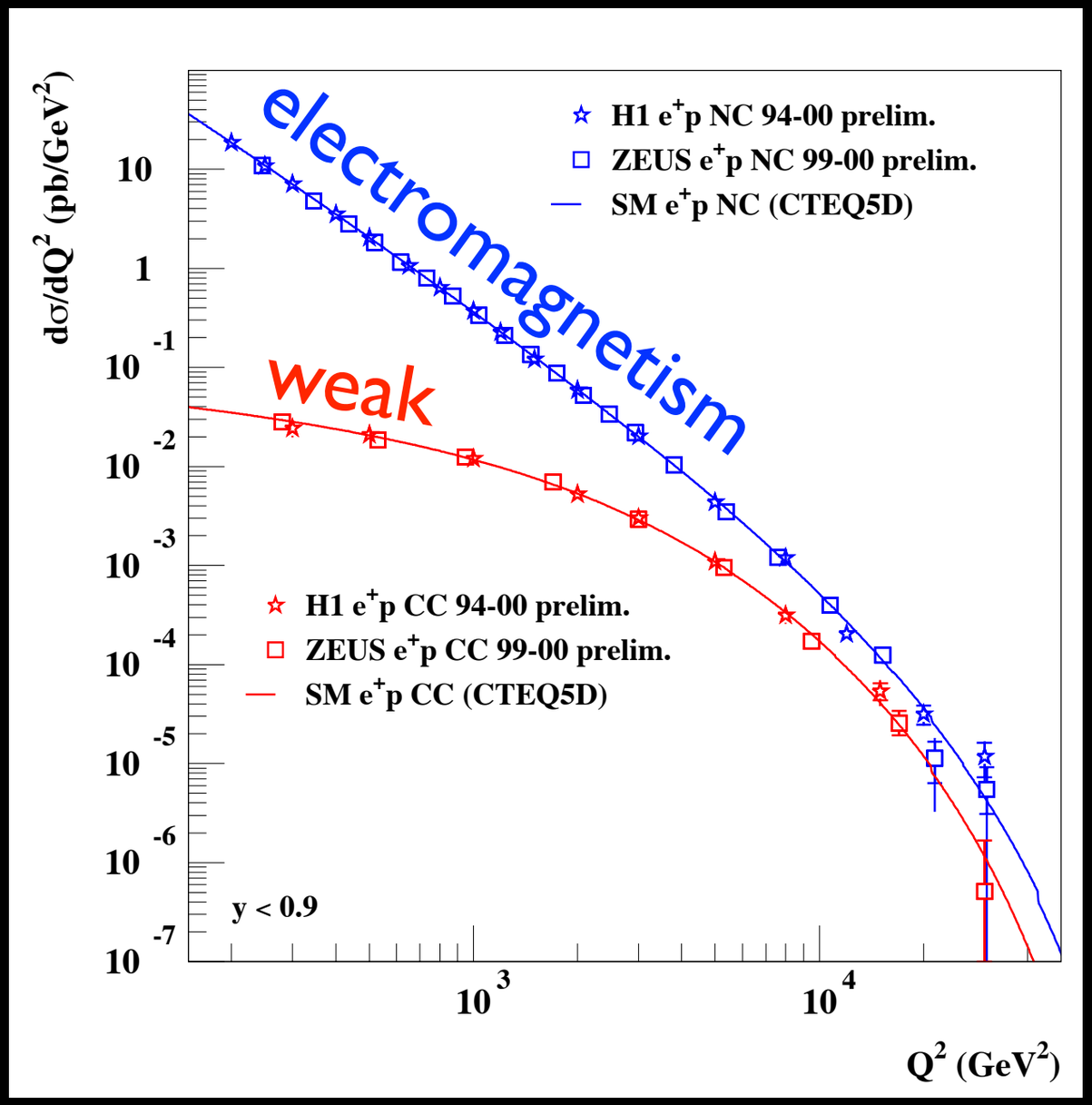


Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)

a new layer of unification

HERA ep collider



- Unification of electromagnetic and weak forces

⇒ electroweak theory

- Long-term goal since ‘60s

We are finally getting there!

- If they are unified, what makes them so different?

⇒ Higgs boson!

History of Unification

planets apple

gravity mechanics

electric magnetic

atoms

Quantum mechanics

electromagnetism

Special relativity

GR

Quantum ElectroDynamics

γ-decay

β-decay

Weak force

Electroweak theory

α-decay

Strong Force

String theory? Grand Unification?

Physicists ask simple and profound questions

How did the Universe begin?

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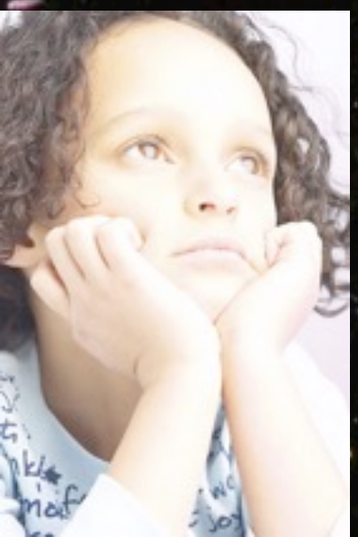
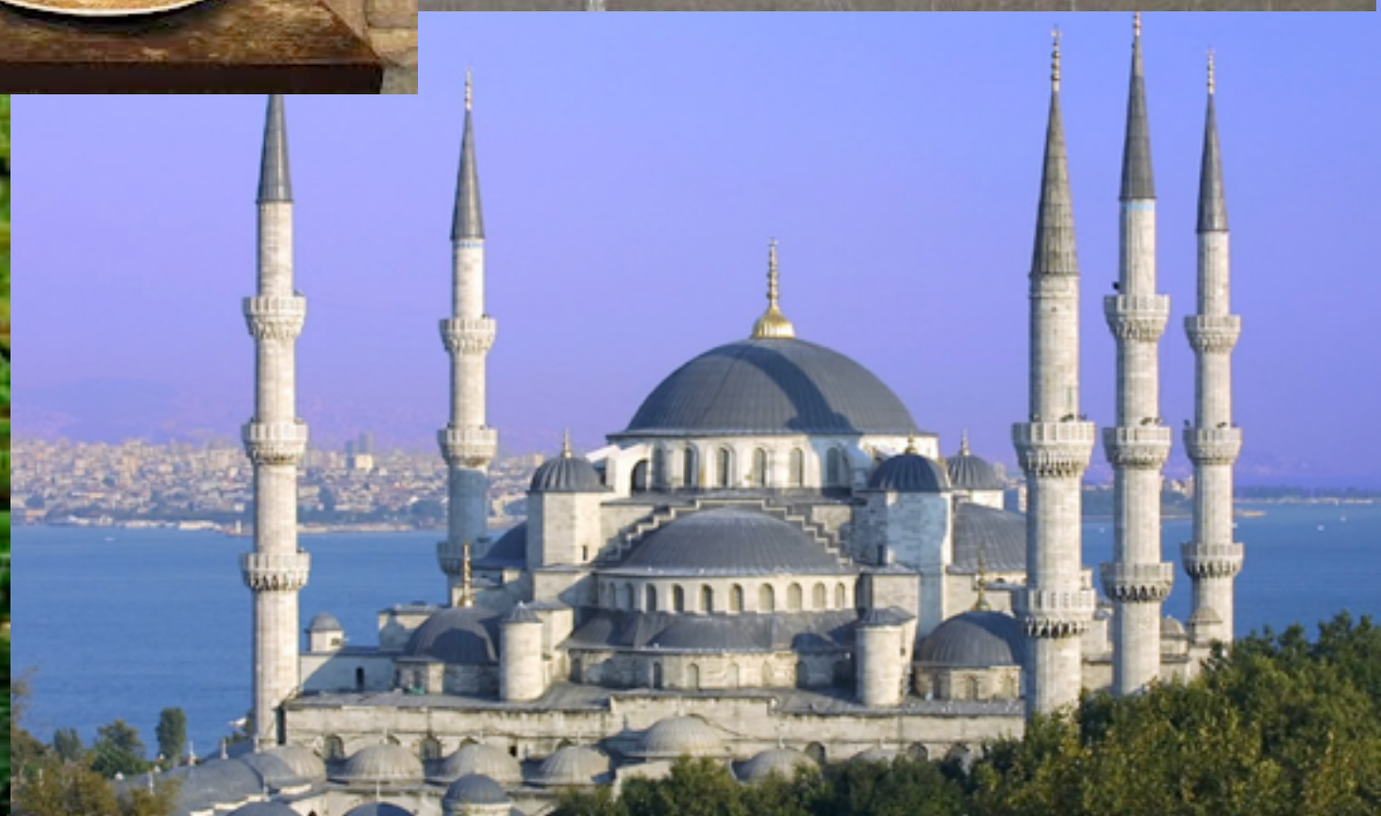
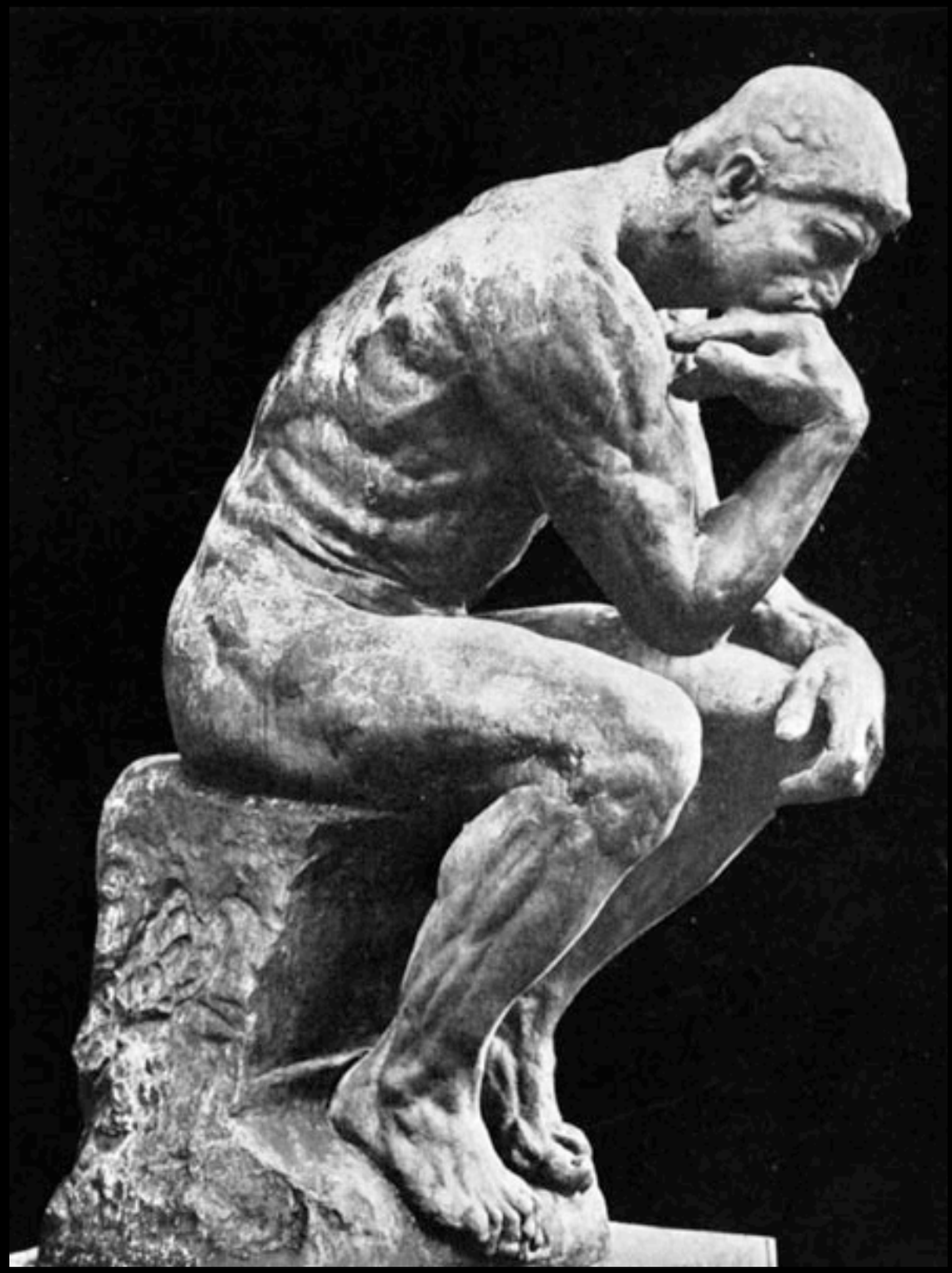



Where do we come from?


Religions



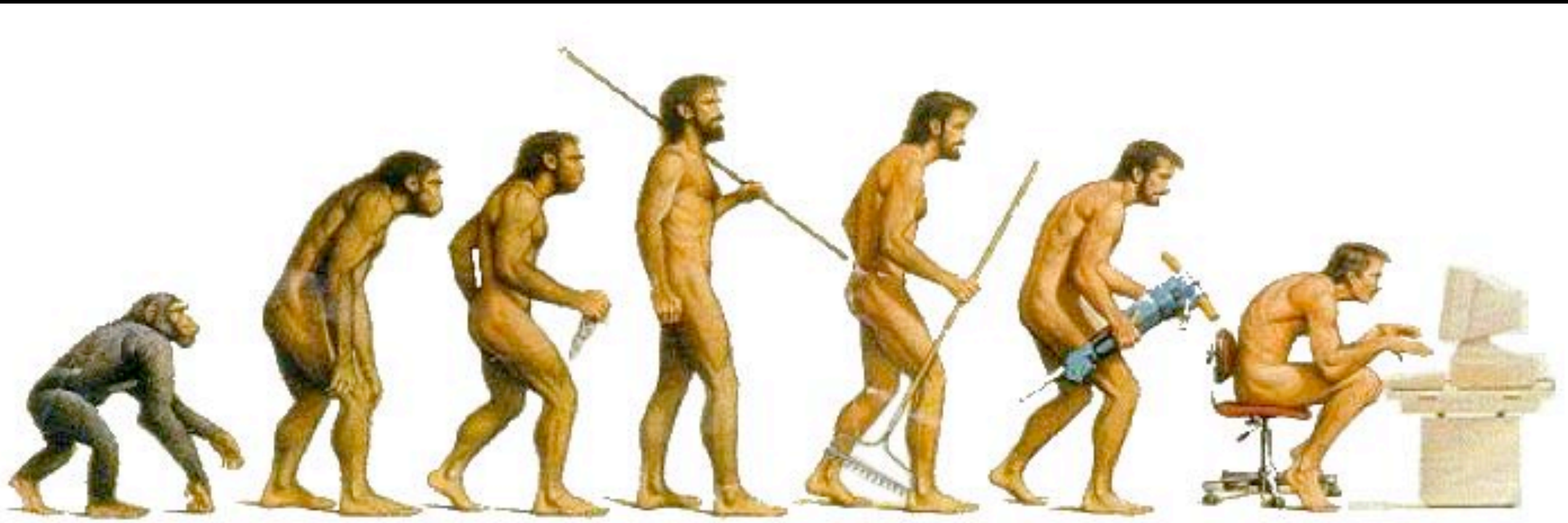
Where do we come from?



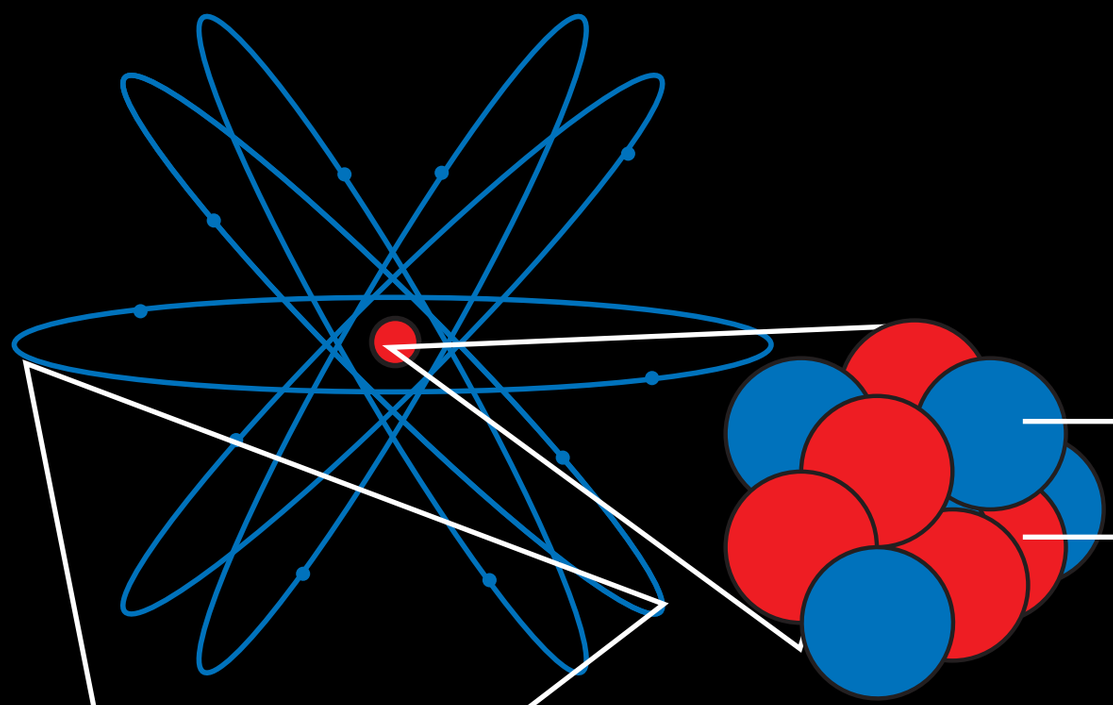
Philosophy

Where do we come from?

Evolutionary biology



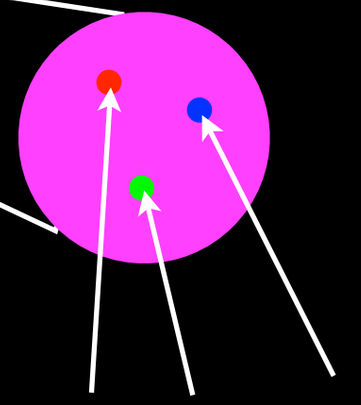
atom



nucleus

neutron

proton



quarks

Where did
a variety of nuclei
come from?

DANIEL CARDLE 2003

Subaru
8.2m diameter mirror

LHC
27km all around

Andromeda
2.3 million light years

HSC team
Subaru
telescope

cluster of galaxies
2.1 billion light years

Abell 2218

Galaxy Cluster MACS J1149+2223

galaxy @ 13.3 billion light years

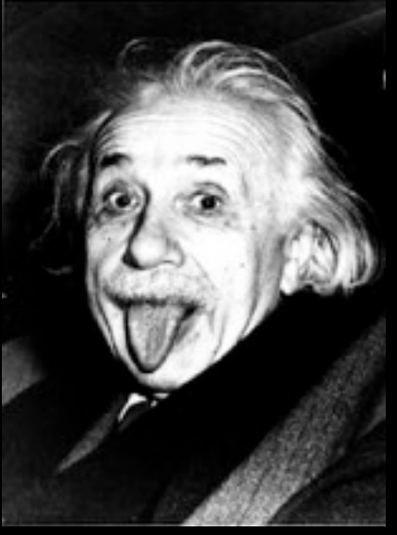
High-Redshift Galaxy MACS1149-JD

A Distant Gravitationally-Lensed Galaxy at Redshift = 9.6

Hubble Space Telescope • ACS • WFC3

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

ssc2012-12a



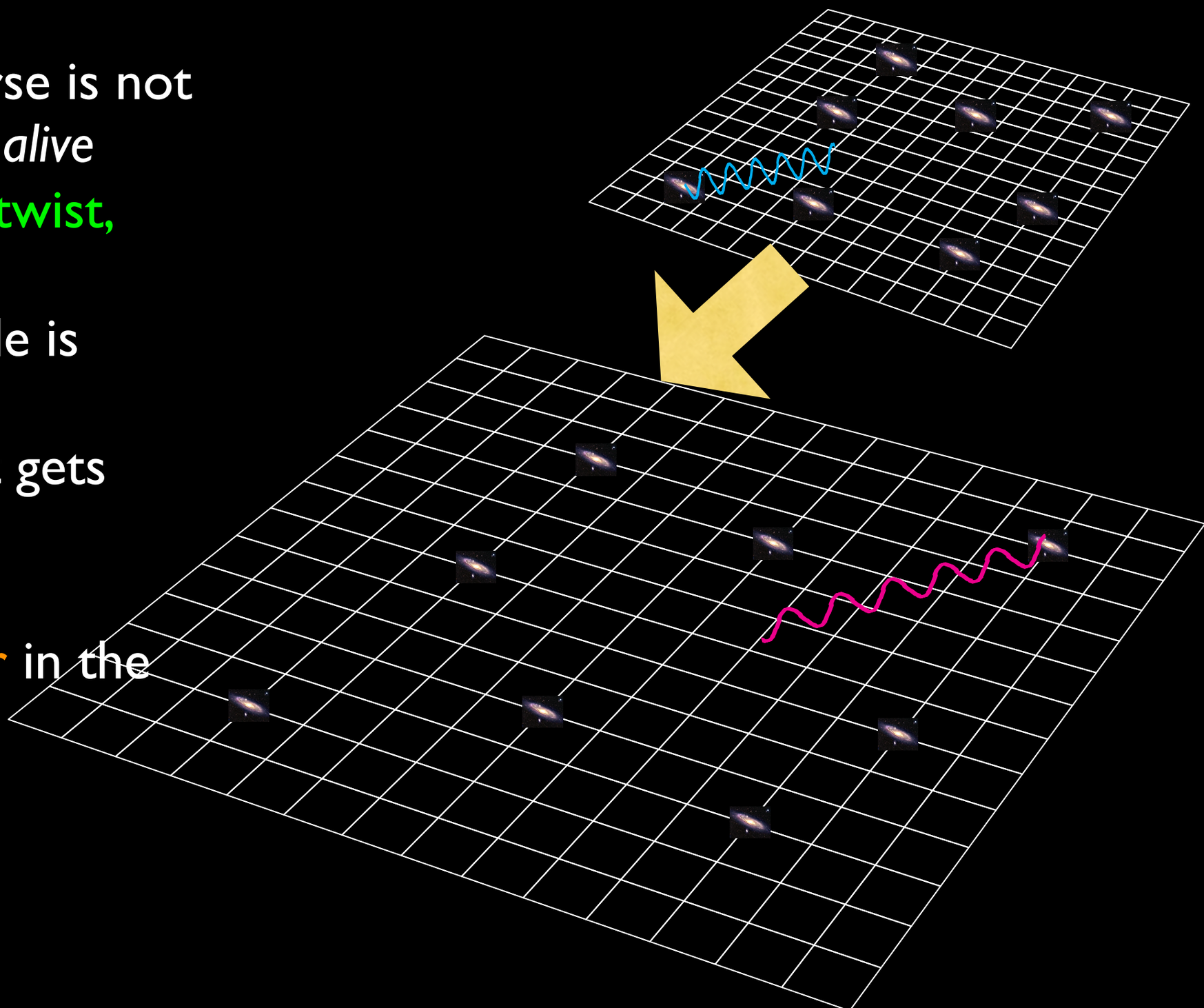
$$E = h\nu = \frac{hc}{\lambda}$$

expanding space

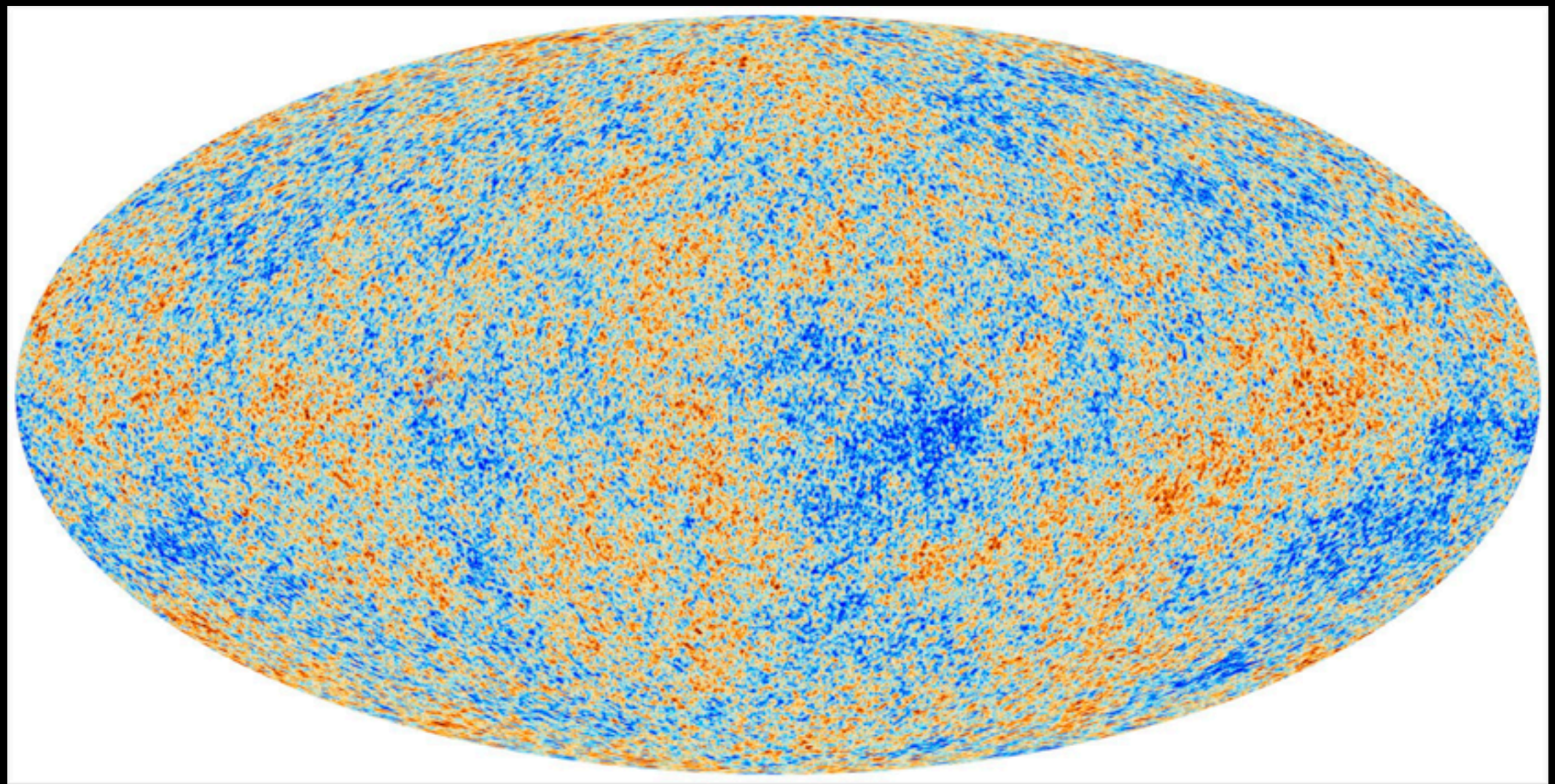
- Einstein: the universe is not just a box, actually *alive*
- the box can warp, twist, expand
- Universe as a whole is getting bigger
- at the same time it gets colder

- it was smaller, hotter in the past

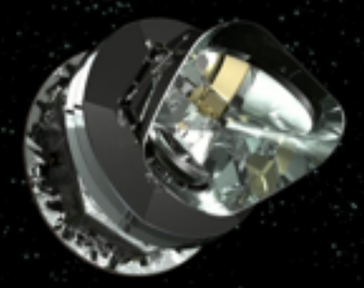
Big Bang!



“Wall” @ 13.8 Blyrs

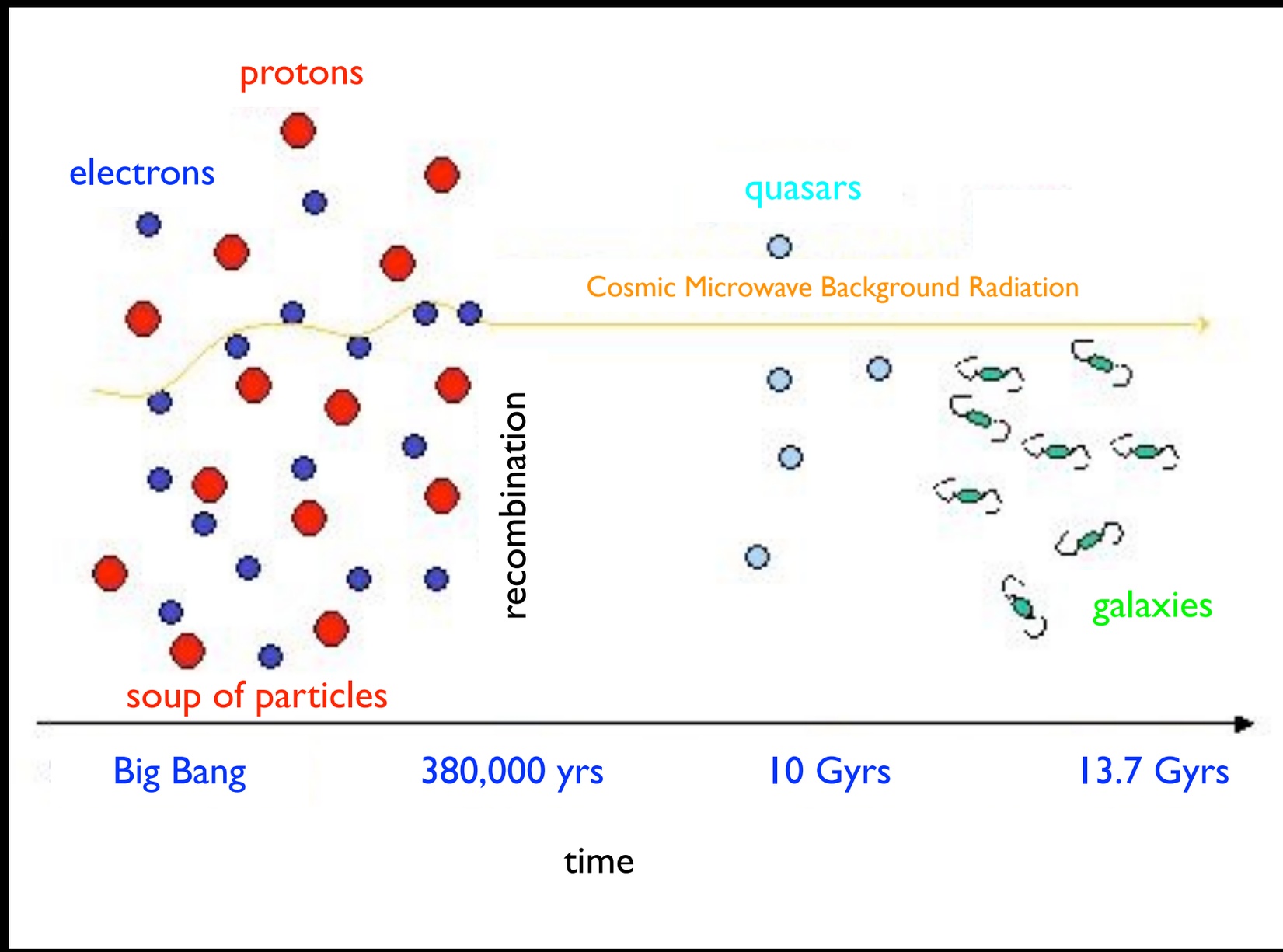


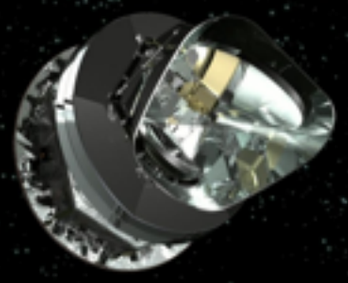
You can never “see” beyond this wall
with a telescope



CMB

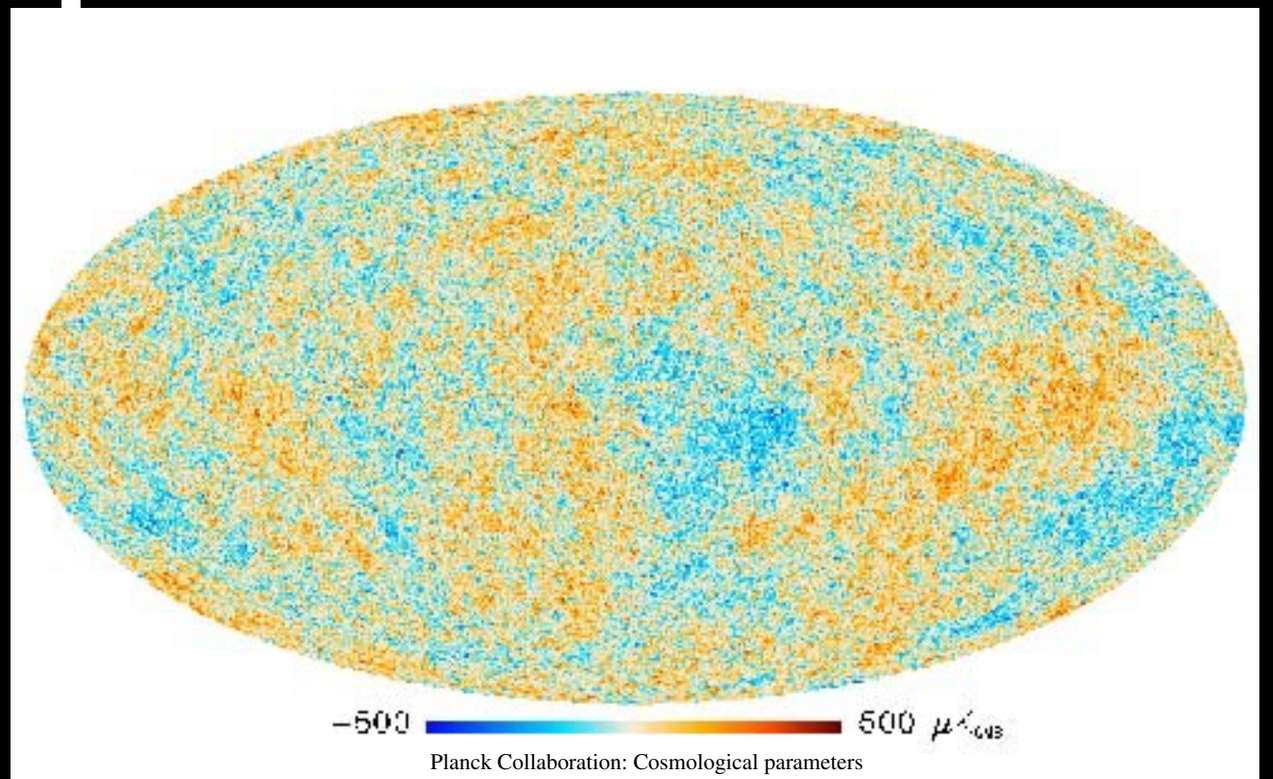
- before recombination, there was a fluid of protons, electrons, photons, dark matter (and neutrinos)
- photon pressure ⇒ "sound waves"





assumption

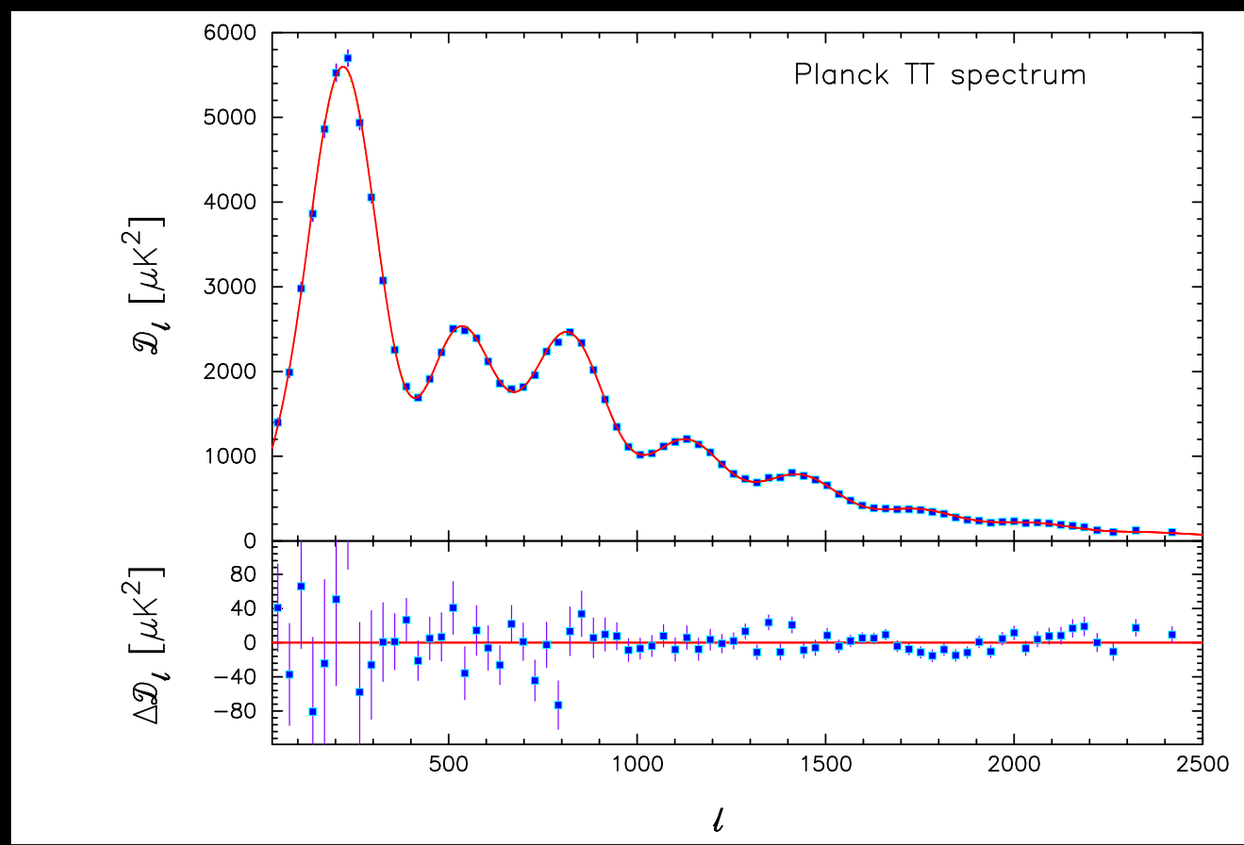
- a random density fluctuations ~O(10^{-5}) more-or-less scale invariant $P(k) \propto k^{ns-1}$



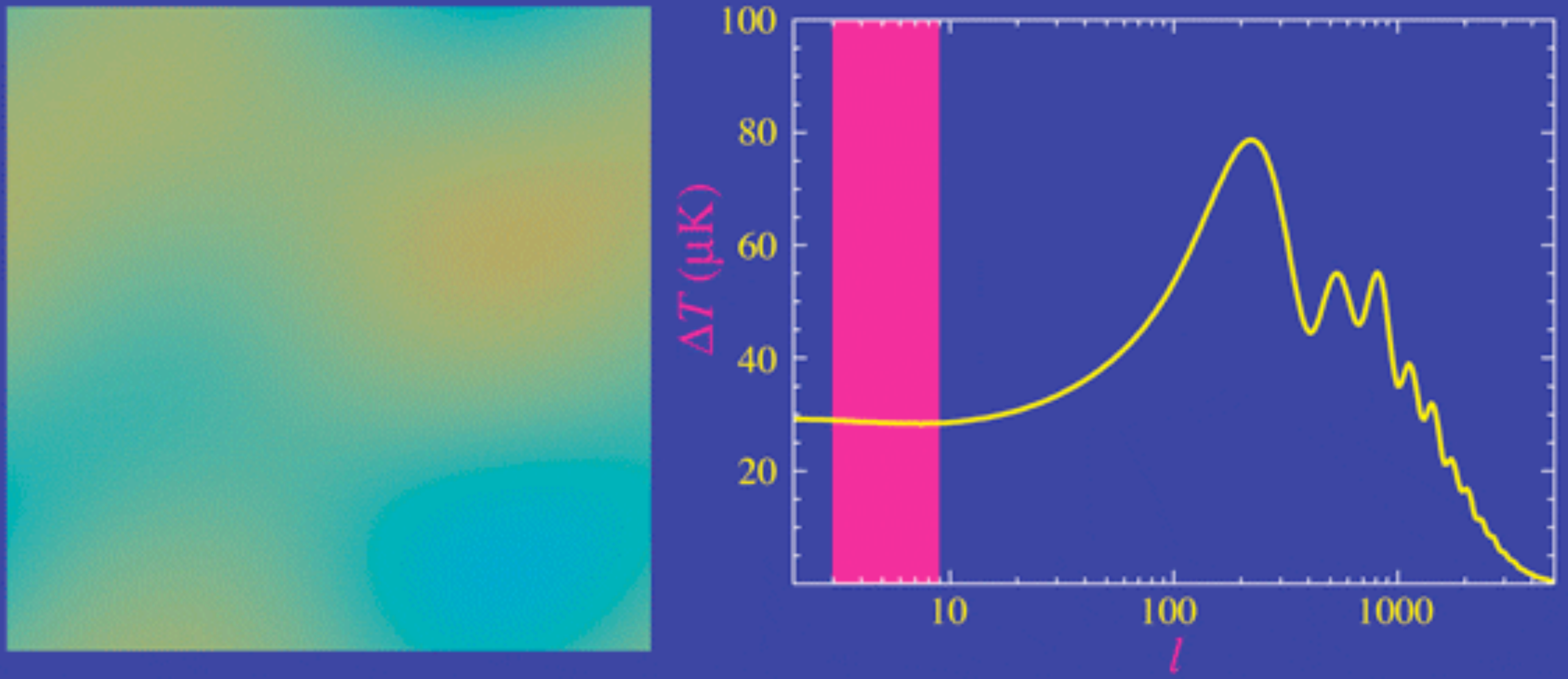
- starts acoustic oscillation, amplified by gravitational attraction
- "knows" about everything between 0<z<1300

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

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



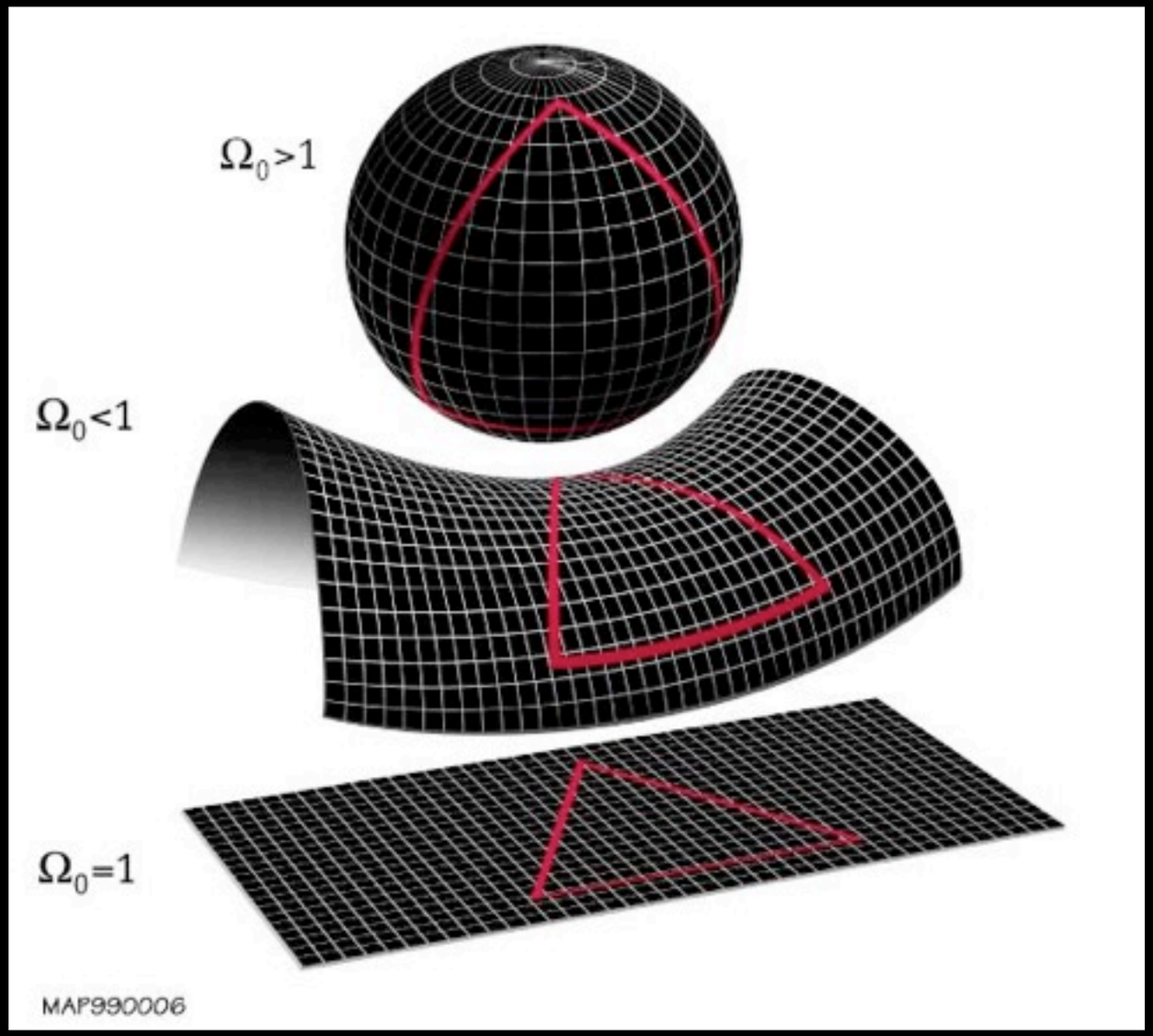
angular resolution

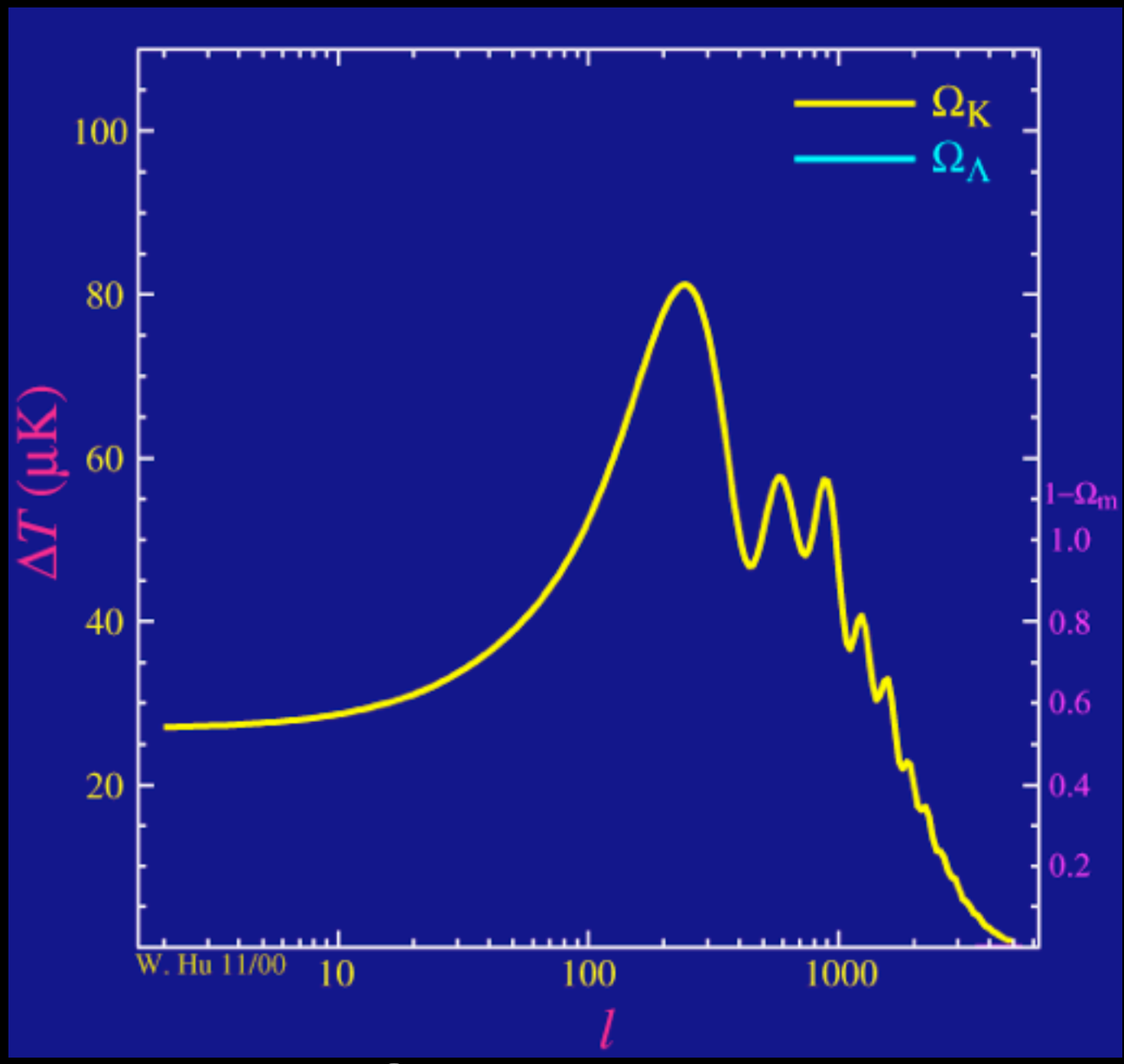


Wayne Hu

http://background.uchicago.edu/~whu/metaanim.html

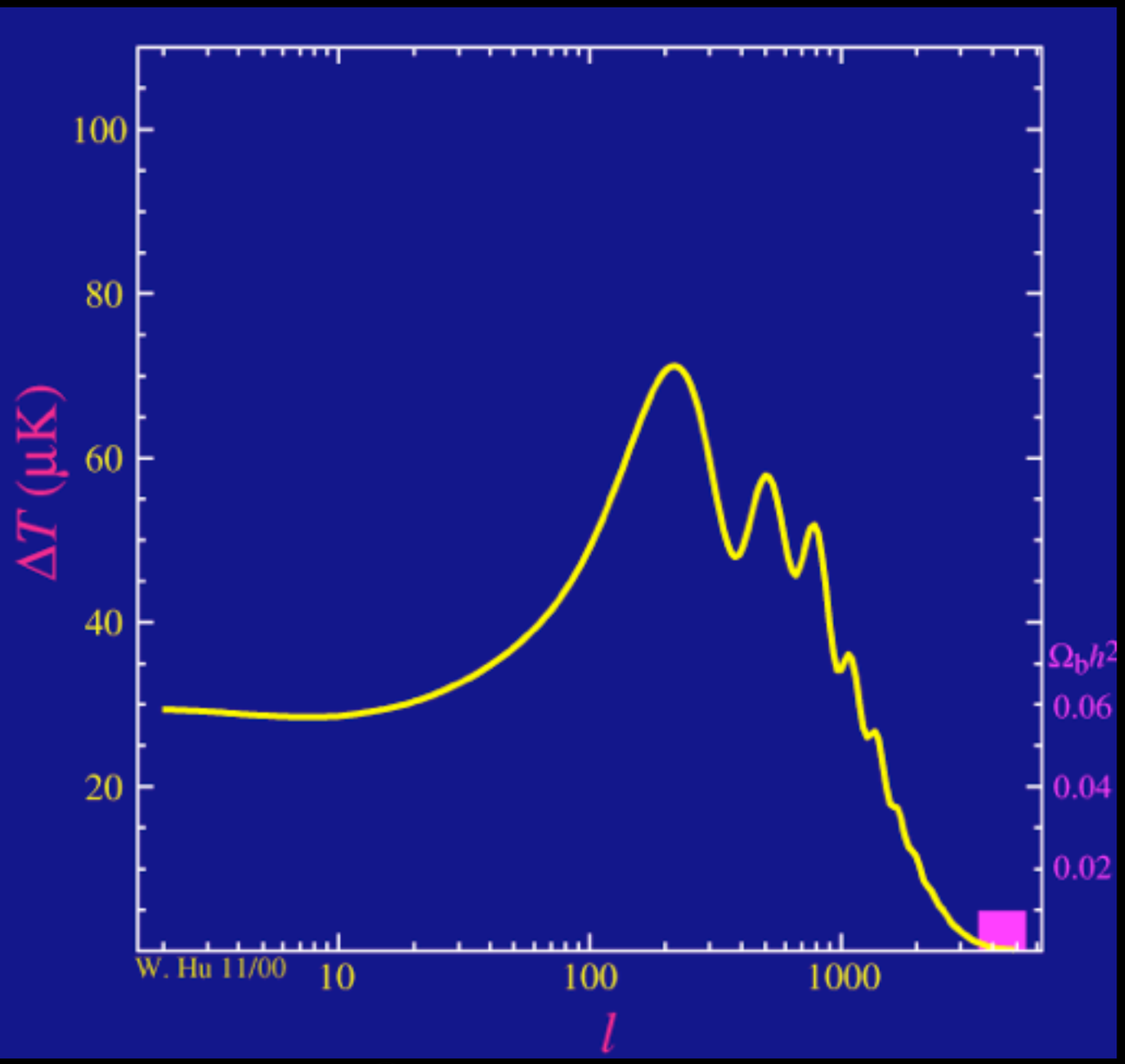
spatial curvature

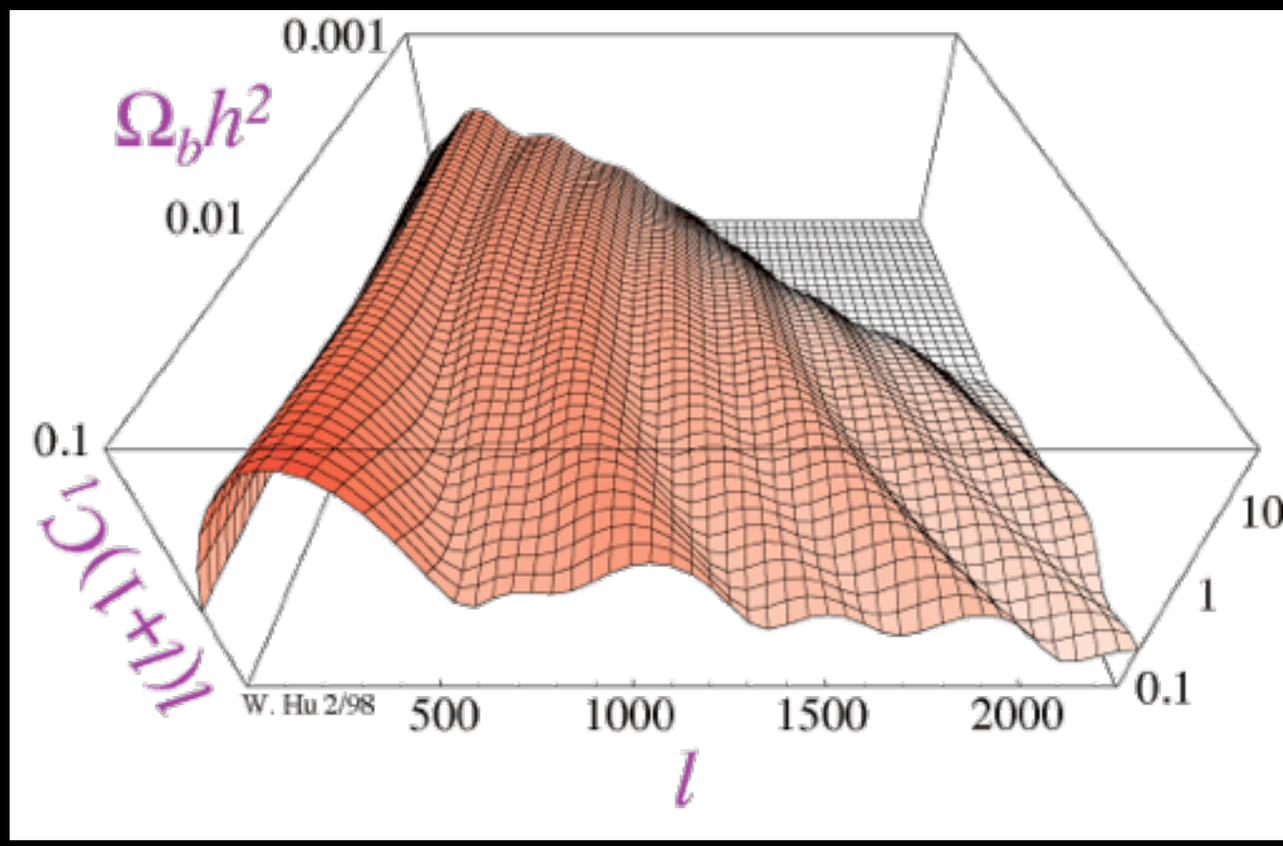




Ω_k changes
the apparent angular size
of the peak positions

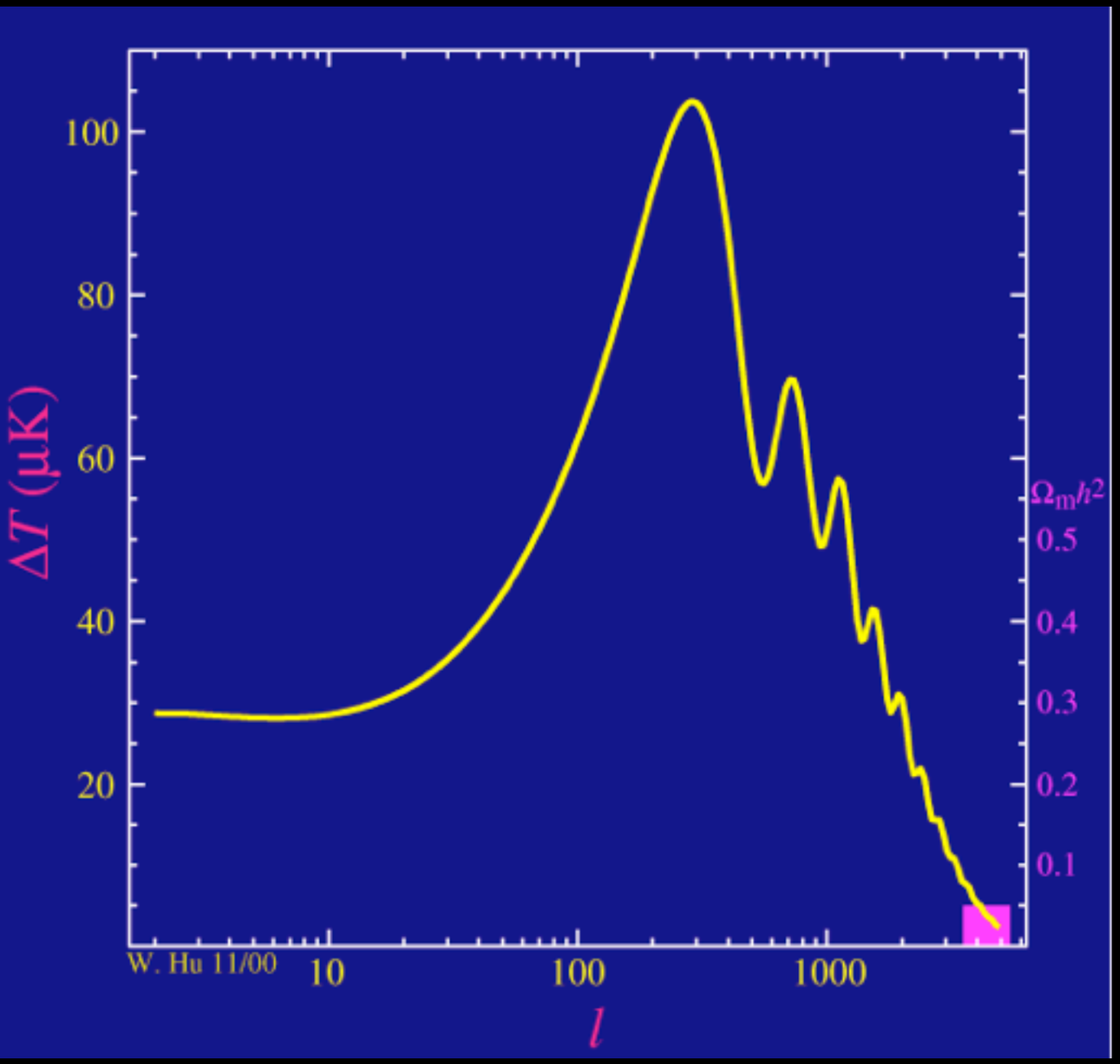
atoms

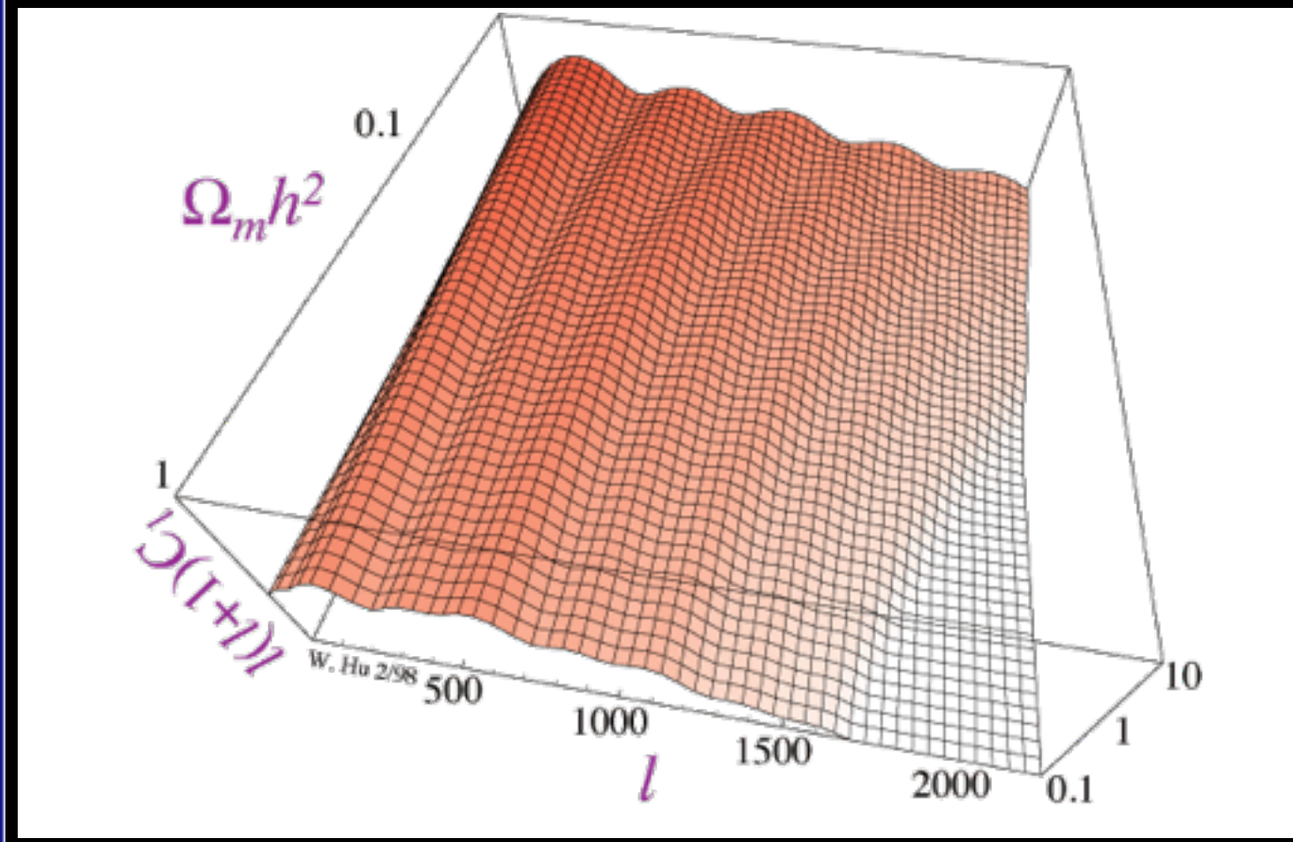




Ω_b changes
the relative size of
even and odd peaks

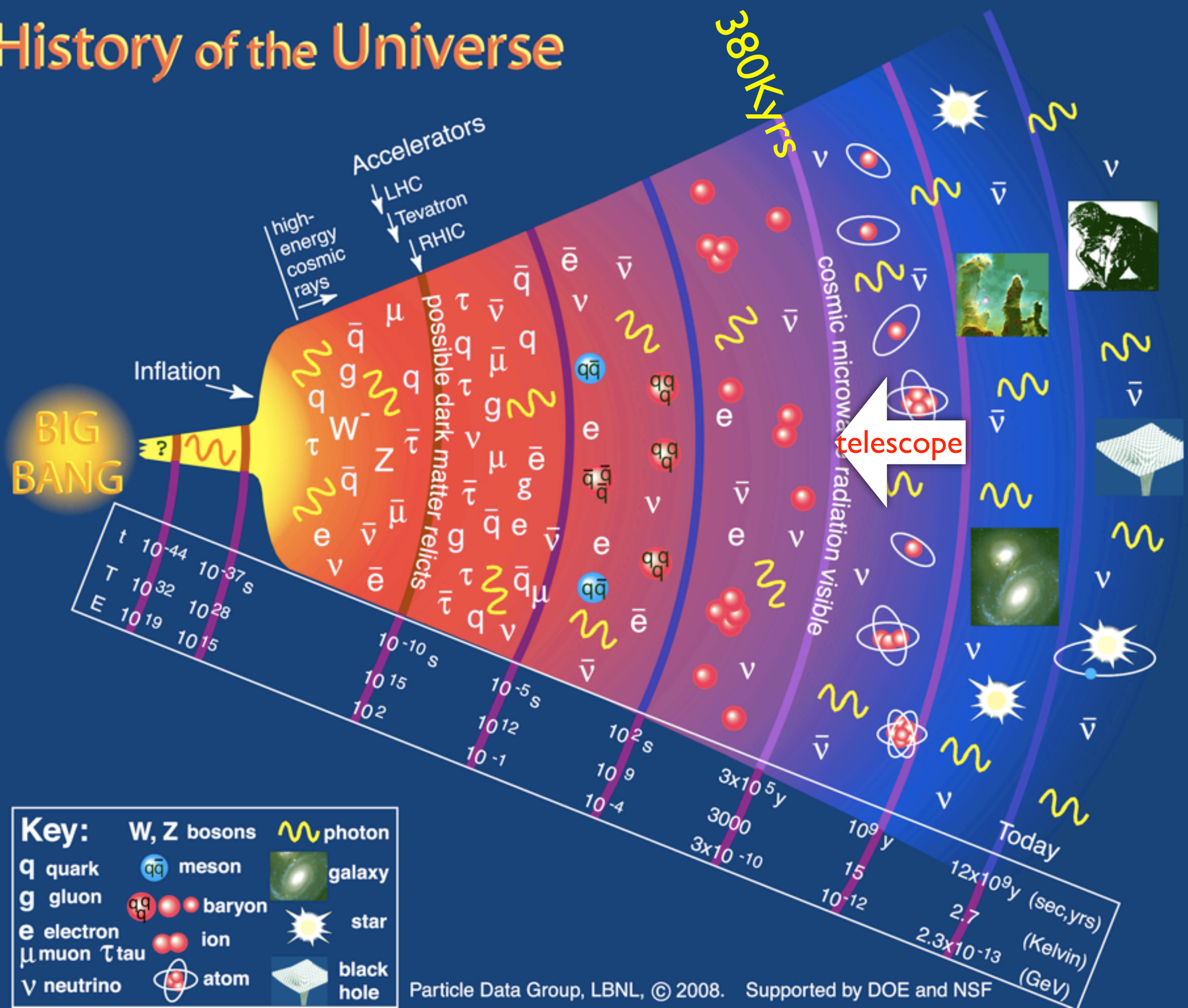
dark matter





Ω_m changes
overall power

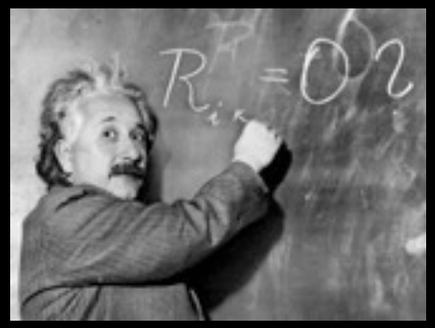
History of the Universe

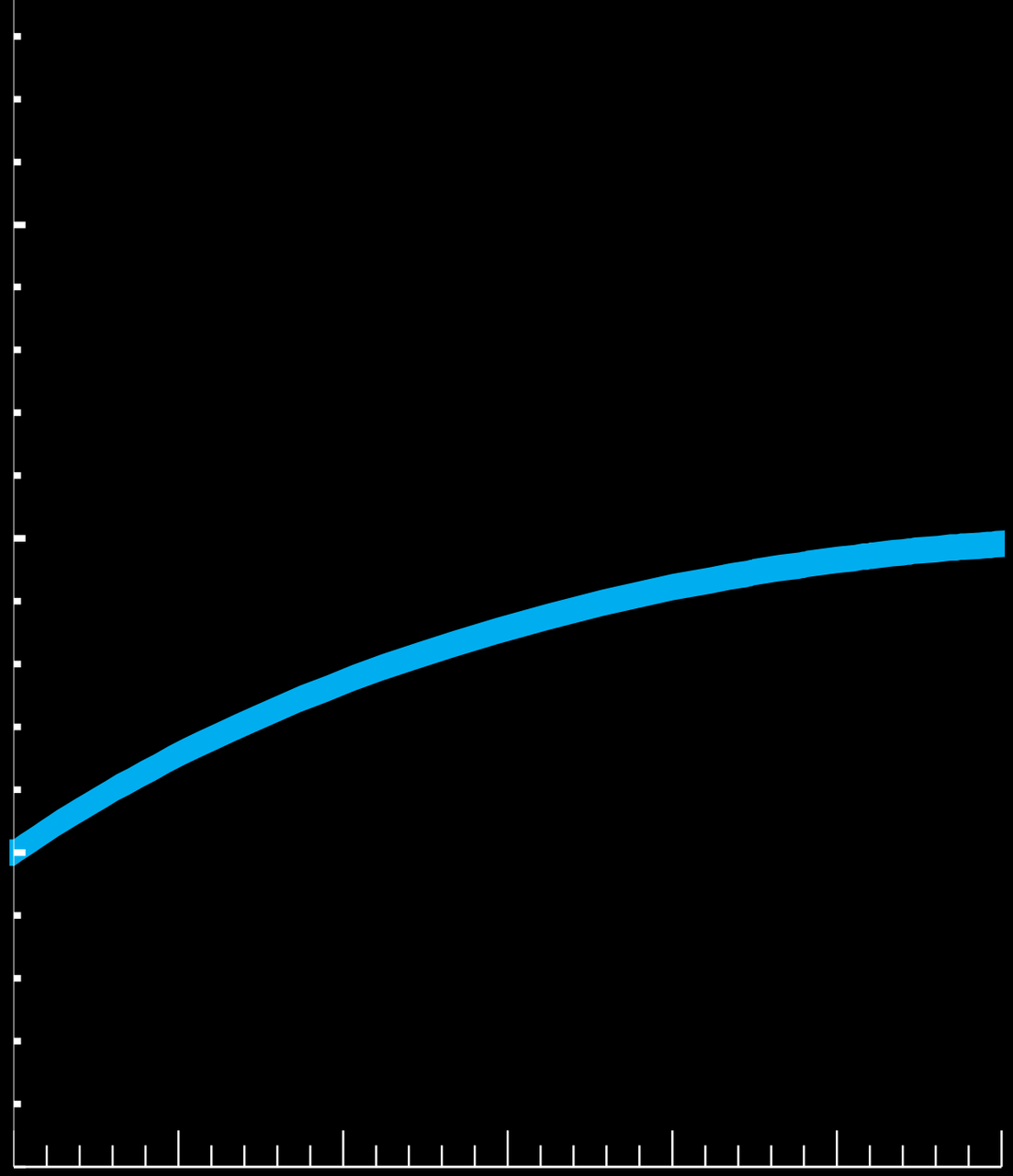


Key:

- q quark
- g gluon
- e electron
- μ muon τ tau
- ν neutrino
- W, Z bosons
- qq̄ meson
- qqq baryon
- ion
- atom
- photon
- galaxy
- star
- black hole

expansion





should
slow down

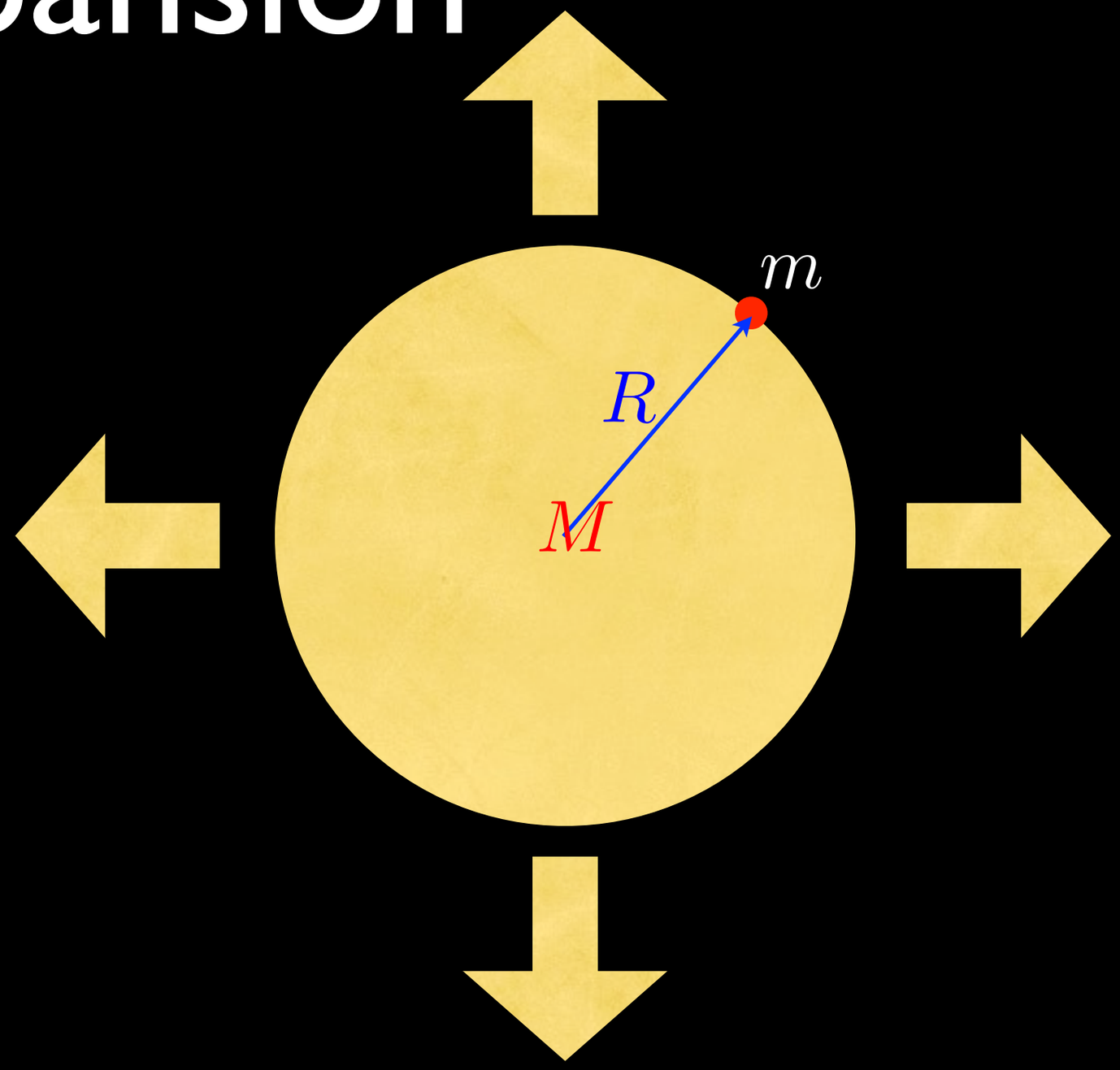
equation for cosmic expansion

$$F = ma$$

$$F = -G\frac{Mm}{R^2}$$

$$a = \frac{d^2}{dt^2}R$$

$$\frac{d^2}{dt^2}R = -G\frac{M}{R^2}$$

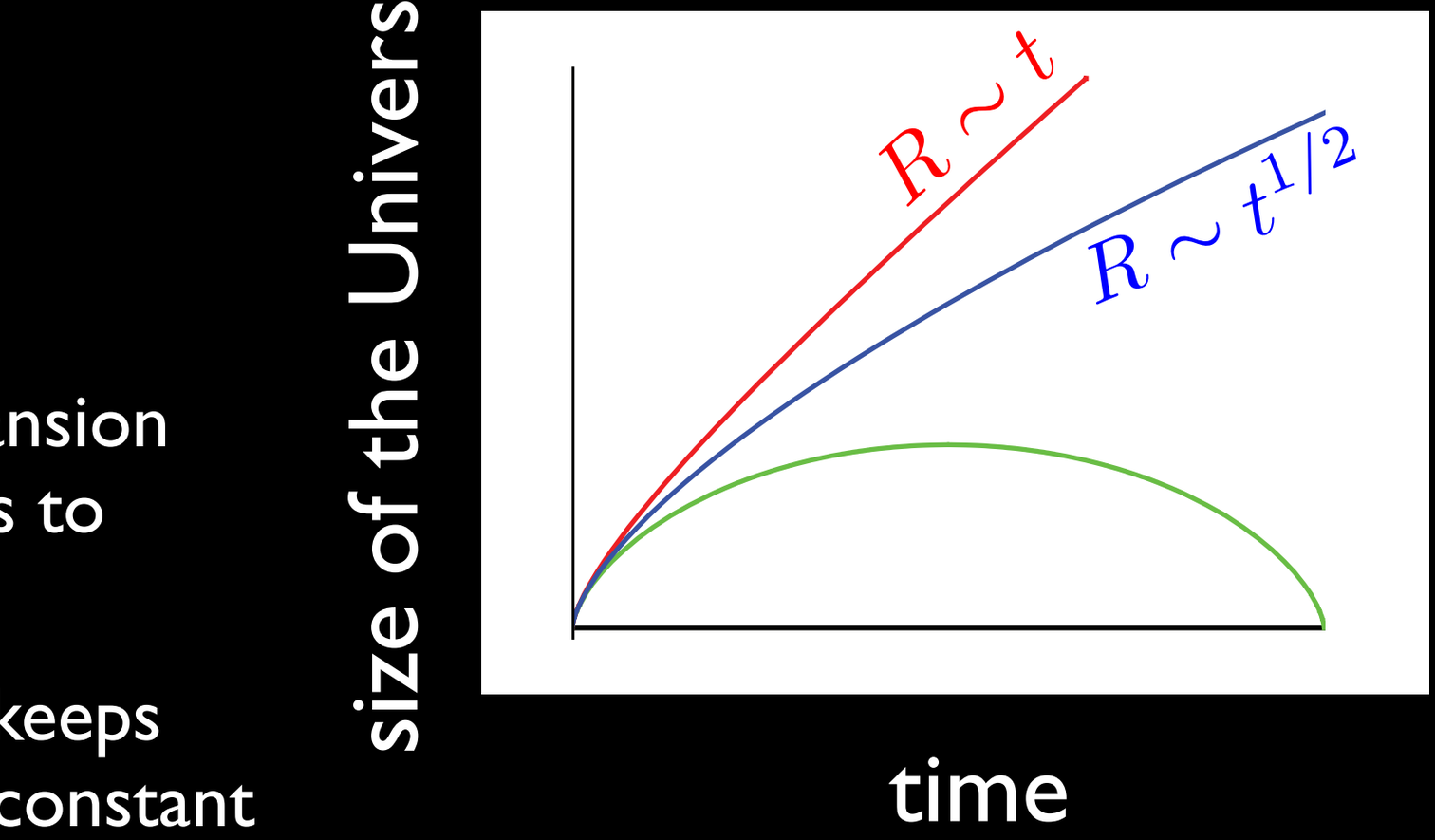


three possible fates

the same equation

$$\frac{d^2}{dt^2}R = -G\frac{M}{R^2}$$

- if enough matter, expansion slows and stops, starts to contract, Big Crunch
- if not enough matter, keeps expanding, eventually constant speed



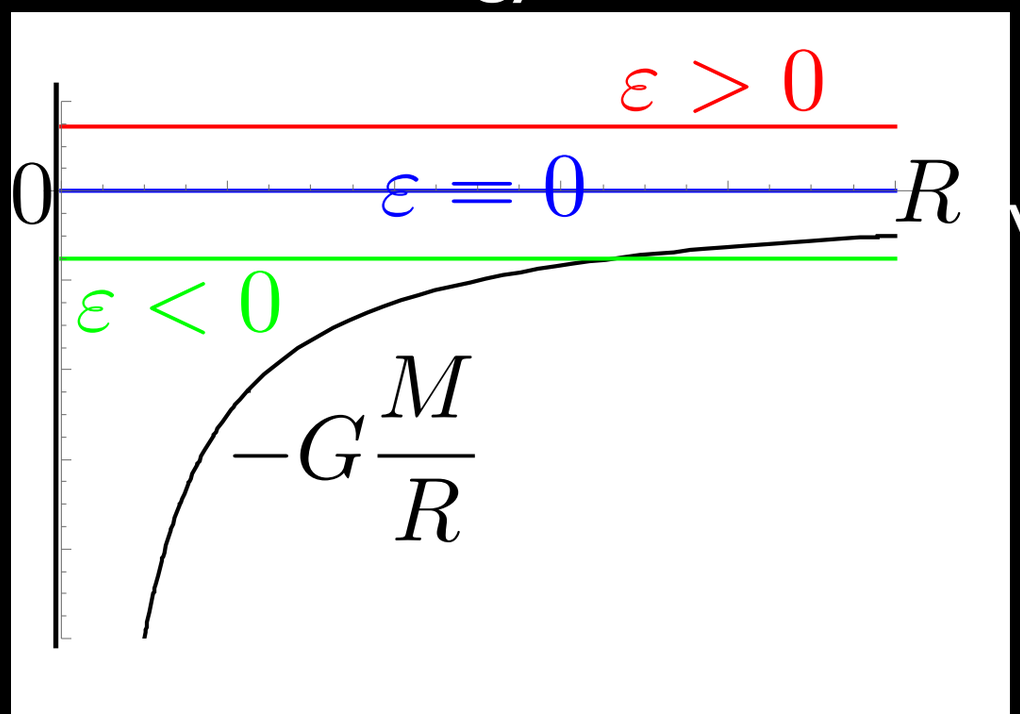
three possible fates

$$\frac{d^2}{dt^2}R = -G\frac{M}{R^2}$$

- This quantity is conserved (*i.e.* time-independent)

$$\varepsilon = \frac{1}{2}\left(\frac{dR}{dt}\right)^2 - G\frac{M}{R}$$

- it has the interpretation of "total energy"



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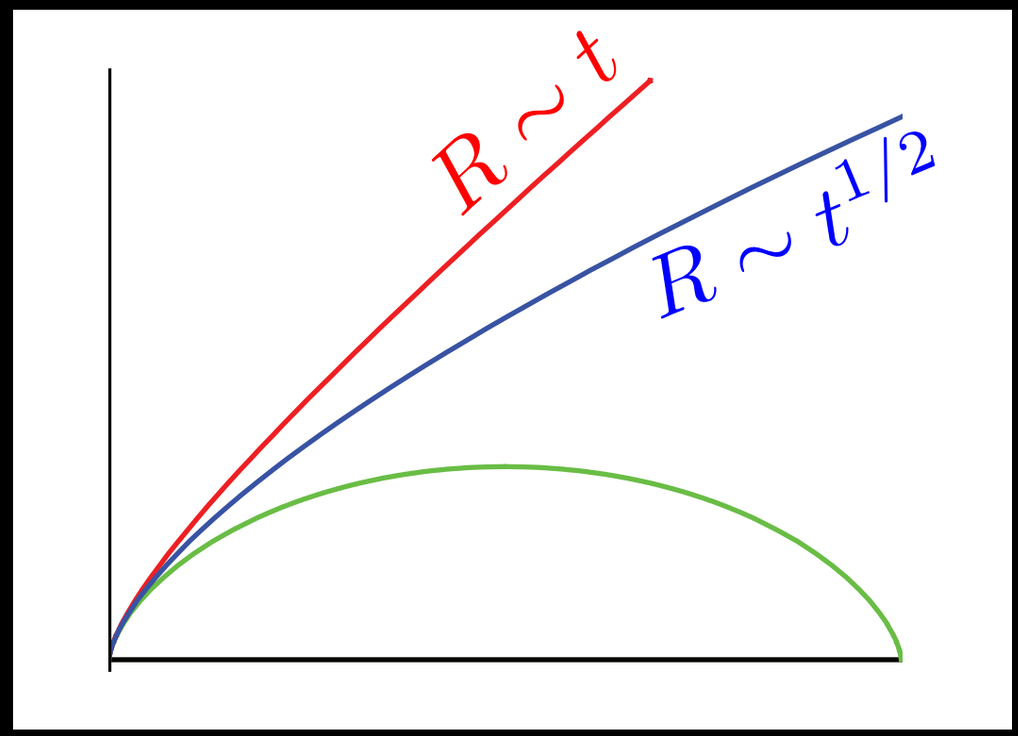
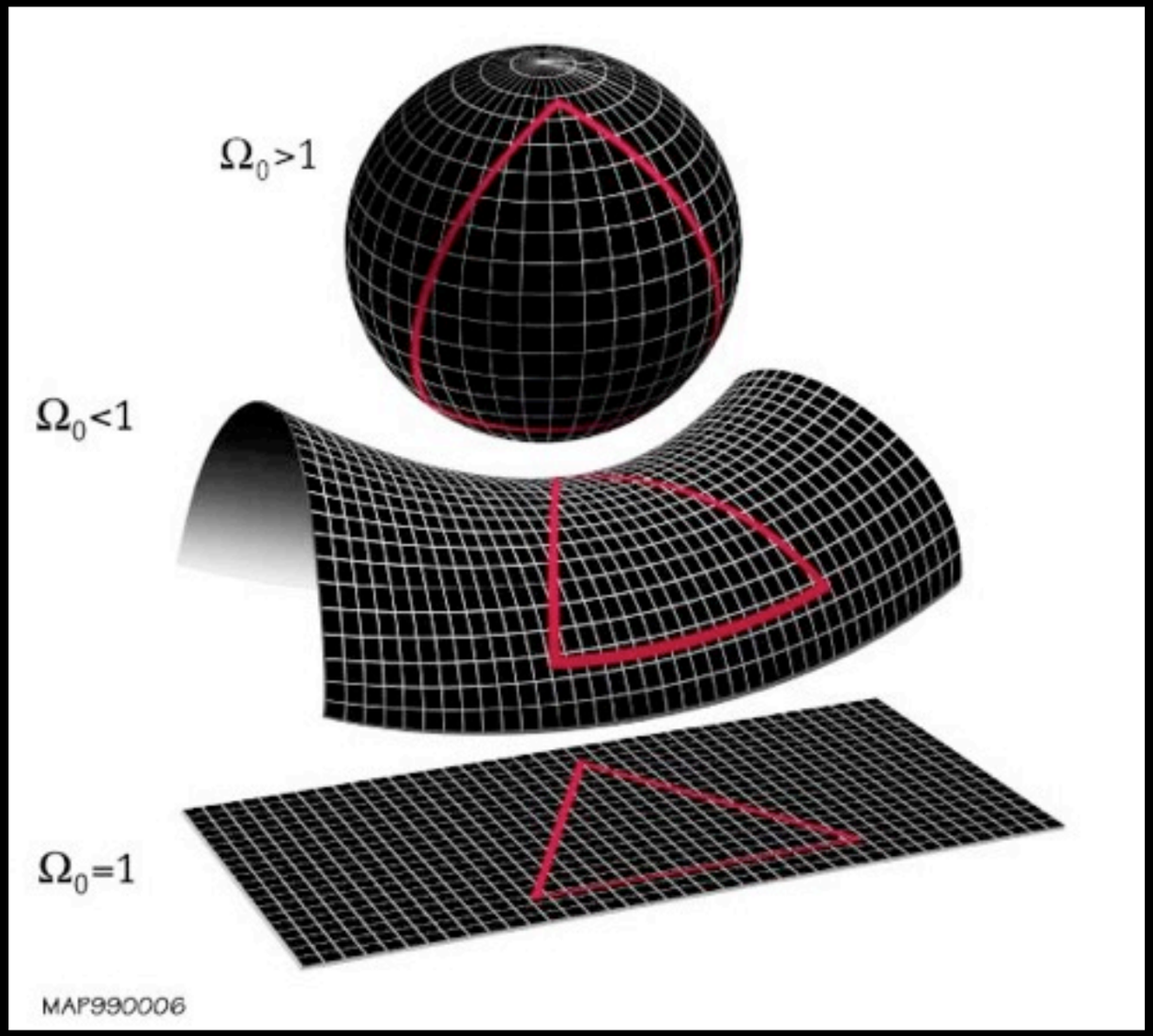
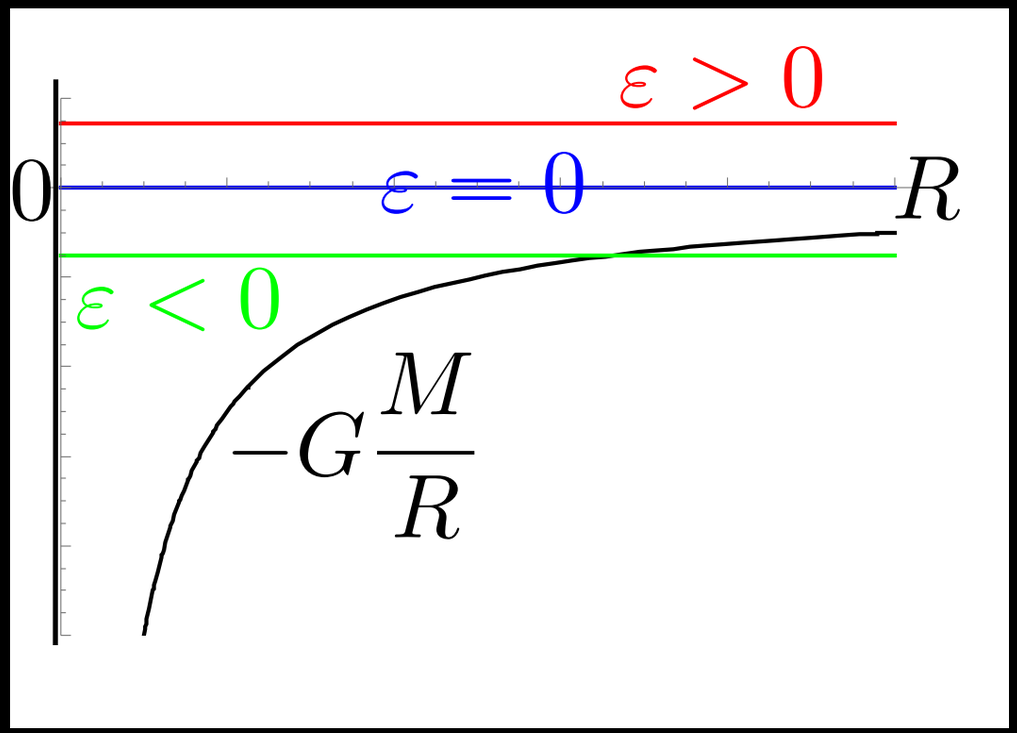


need GR for this





generalize

- so far assumed total mass is constant ("matter")
- if it changes as the Universe expands, generalize it
- Simplify the equation
- write $k = -2\varepsilon$

$$\varepsilon = \frac{1}{2}\left(\frac{dR}{dt}\right)^2 - G\frac{M}{R}$$

$$\varepsilon = \frac{1}{2}\left(\frac{dR}{dt}\right)^2 - G\frac{\rho}{R}\frac{4\pi}{3}R^3$$

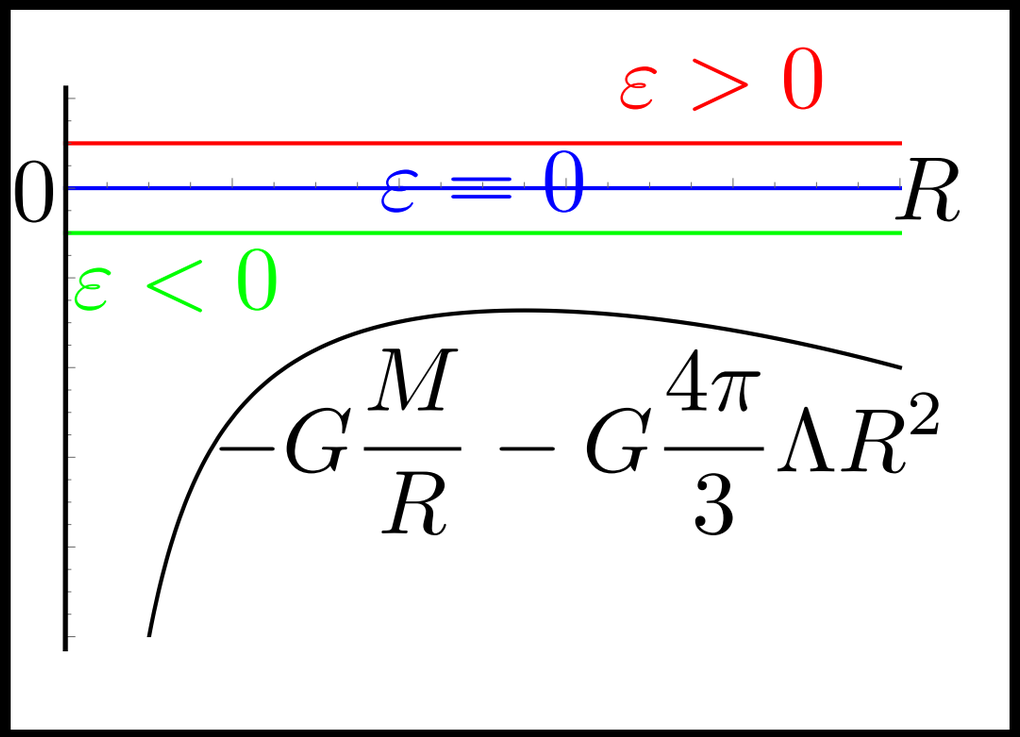
$$\left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi}{3}G\rho + \frac{2\varepsilon}{R^2}$$

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

Homework

- we have at least three components
- radiation: $\rho \propto R^{-4}$
- matter: $\rho \propto R^{-3}$
- vacuum energy: $\rho \propto R^{0}$
- it appears $k=0$
- current value: H_0
- Solve this differential equation with Planck data to compute the age of the Universe

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



History of the Universe

3min

380Kyrs

Accelerators
LHC
Tevatron
RHIC

high-energy cosmic rays

Inflation

BIG BANG

possible dark matter relicts

cosmic microwave radiation visible

telescope

accelerators

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

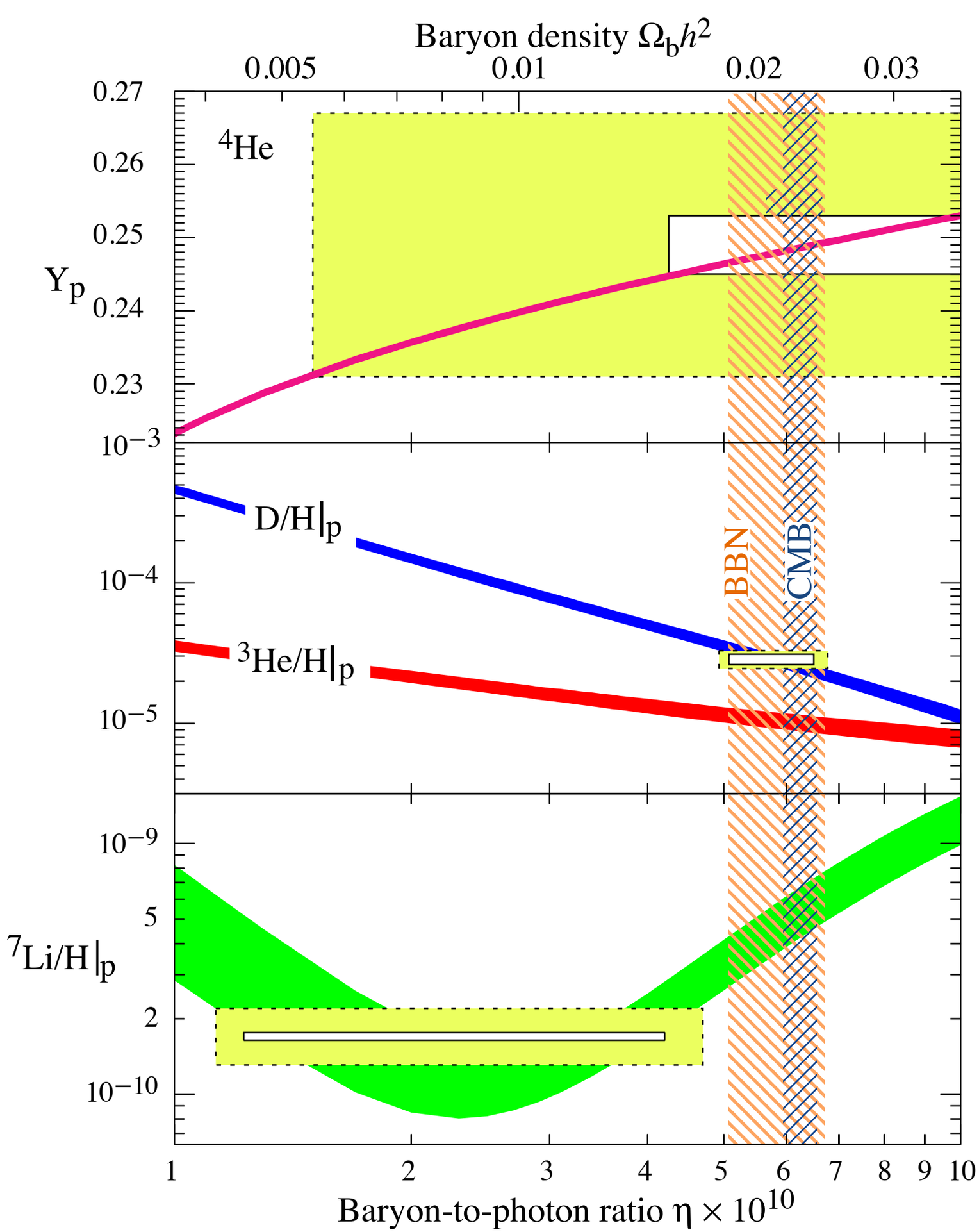
3x10^5 y

Big Bang made only H and He

Key:
q quark
g gluon
e electron
μ muon τ tau
ν neutrino
W, Z bosons
qq meson
baryon
ion
atom
photon
galaxy
star
black hole

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

PDG

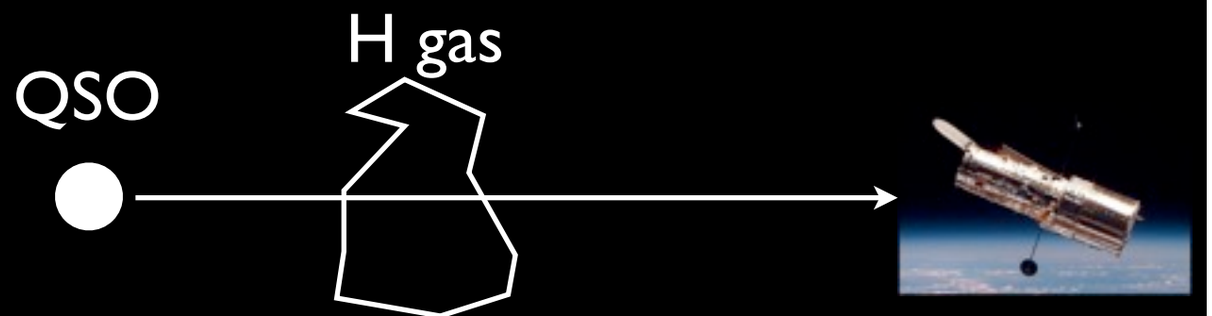

Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
^{4}He
10^{-3}
10^{-4}
10^{-5}
D/H$|_p$
^{3}He/H$|_p$
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H$|_p$
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{10}$

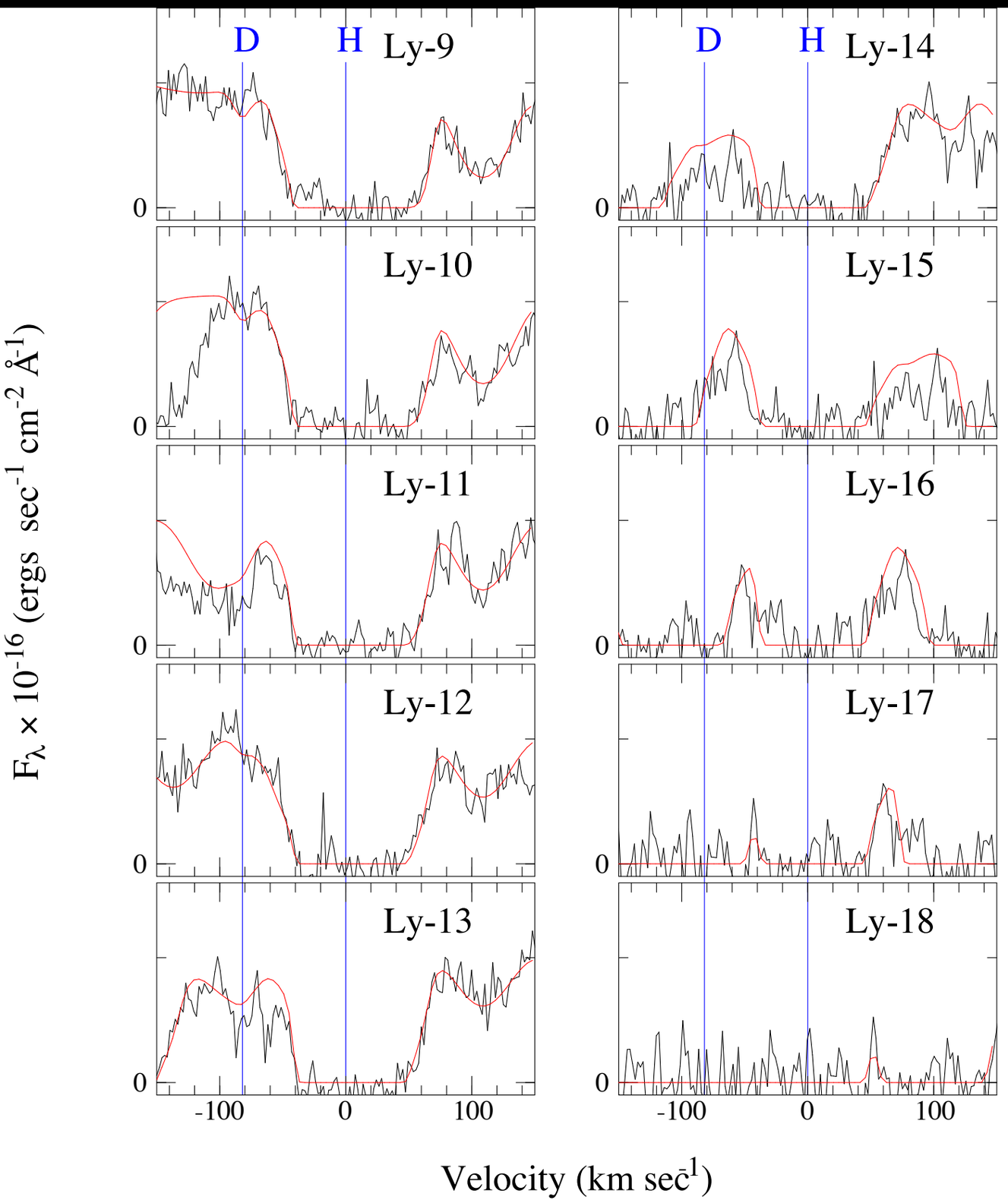
deuterium abundance

Kirkman, Tytler, Suzuki, O'Meara, Lubin

$$\frac{1}{\mu} = \frac{1}{m_e} + \frac{1}{m_{\rm nuc}} \qquad E_n = -\frac{\alpha^2 \mu}{2n^2}$$

- believed to be the most accurate, most primordial
- hydrogen backlit by quasar, Lyman absorption lines
- reduced mass different by 1/4000 between H and D



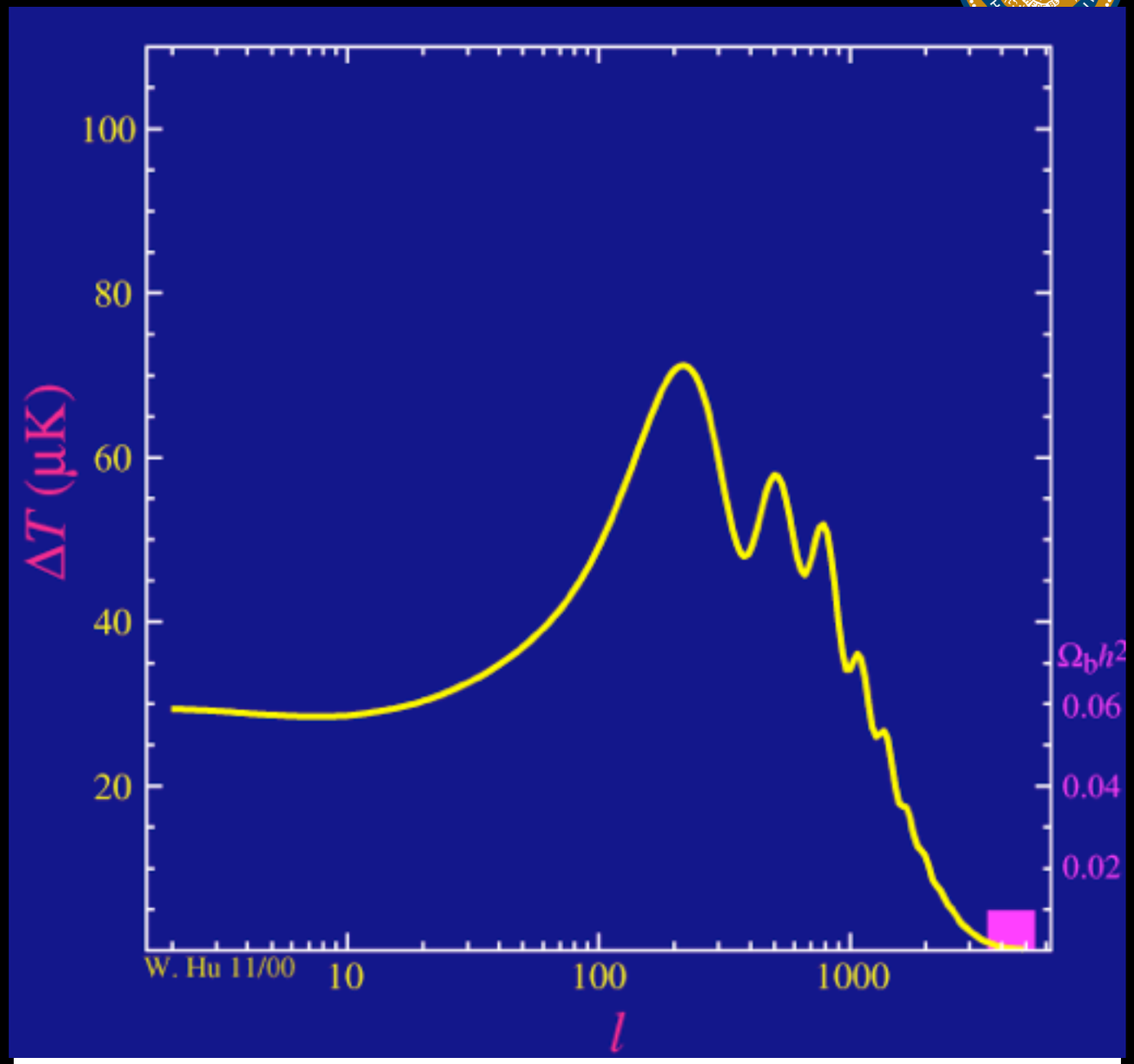


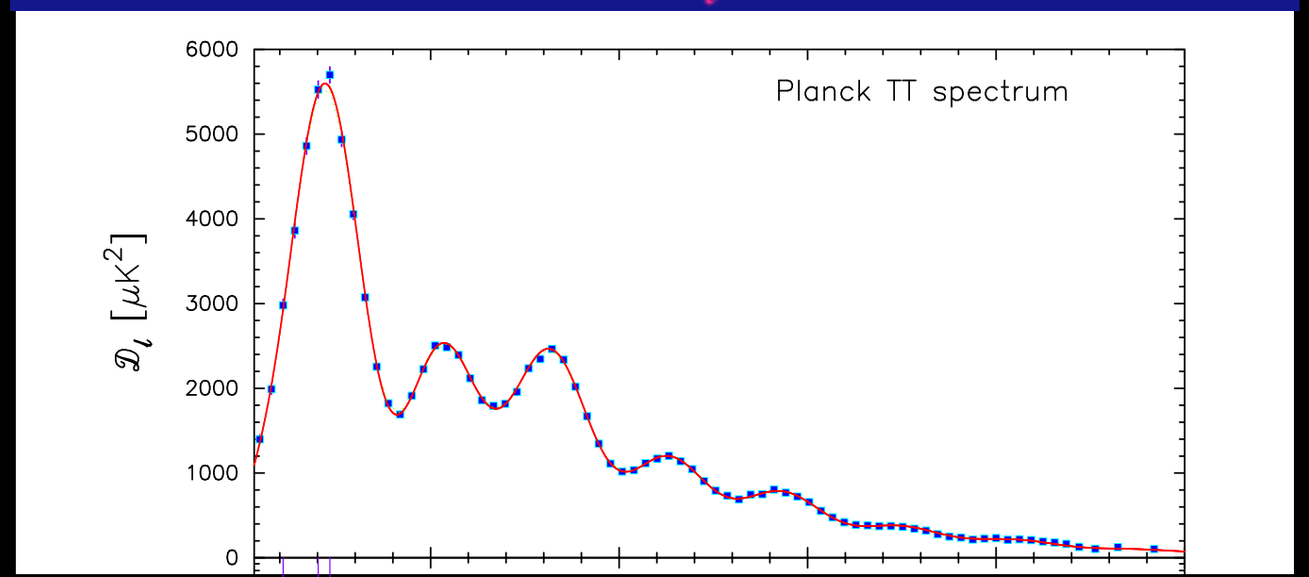
CMB

- acoustic peaks in the CMB anisotropy power spectrum are due to the sound waves (oscillations) in photon-baryon fluid at T~3000K

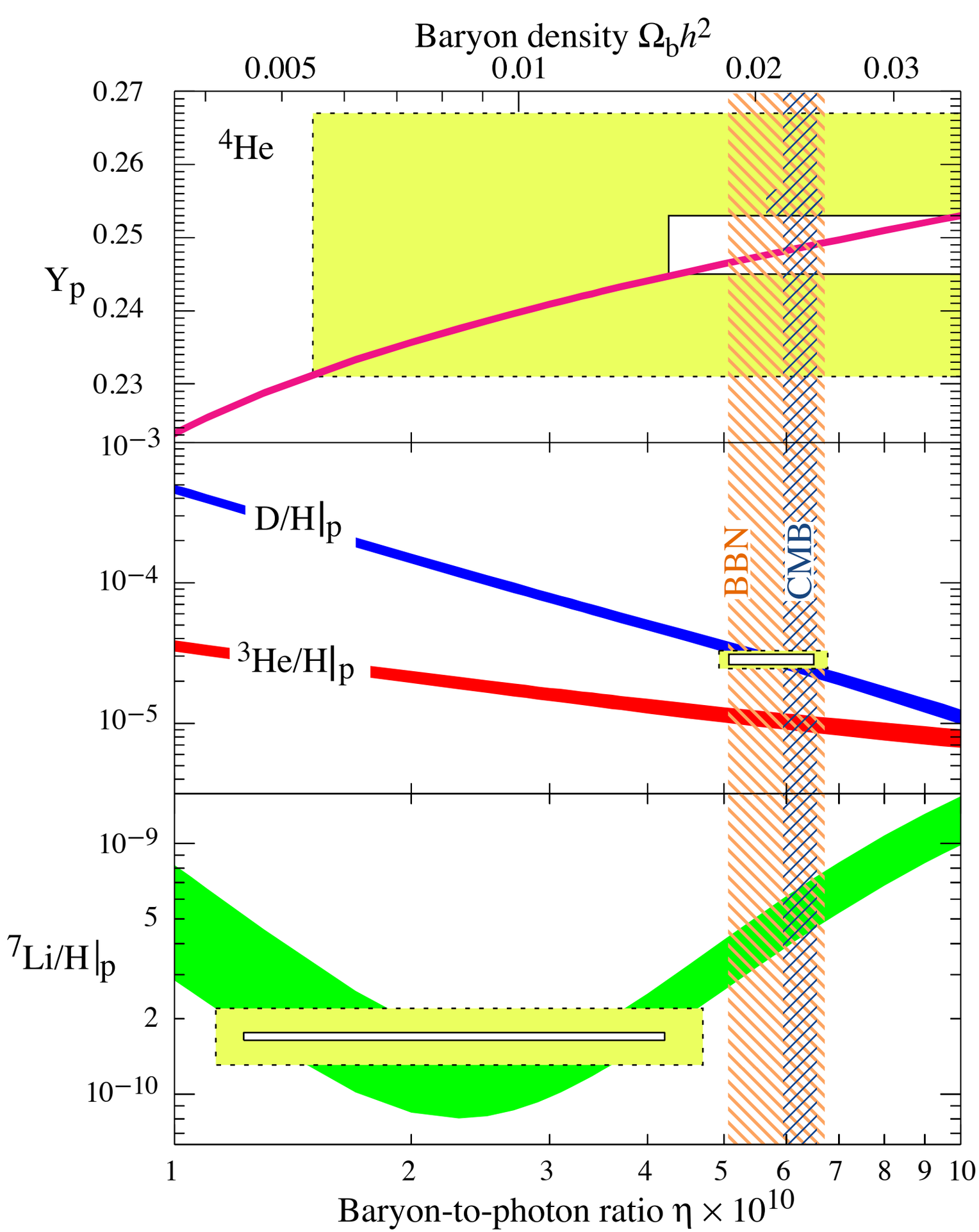
- amount of baryon particularly affects the ratio of even and odd peaks

$\Omega_b h^2 = 0.02207 \pm 0.00033$

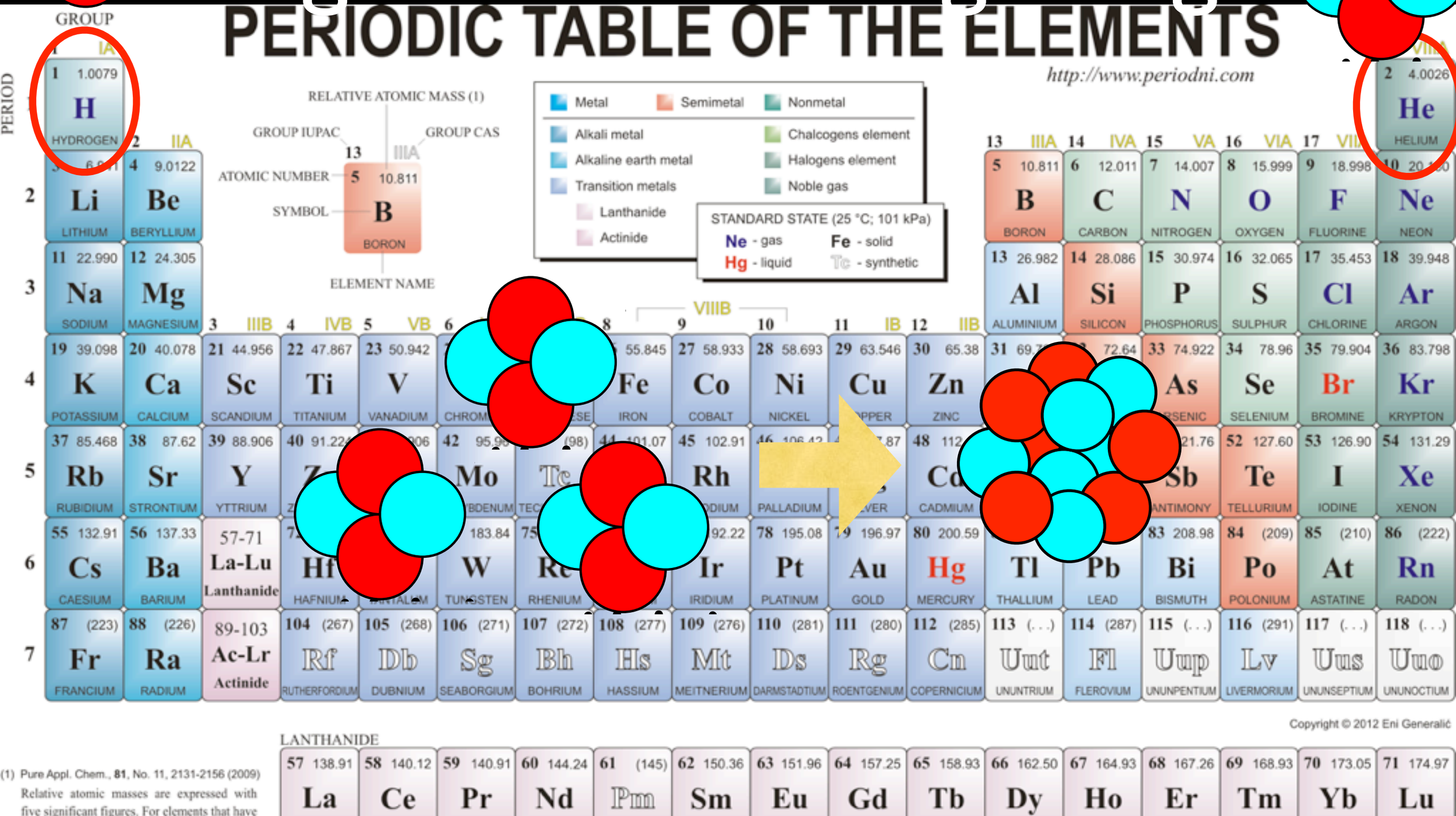




PDG

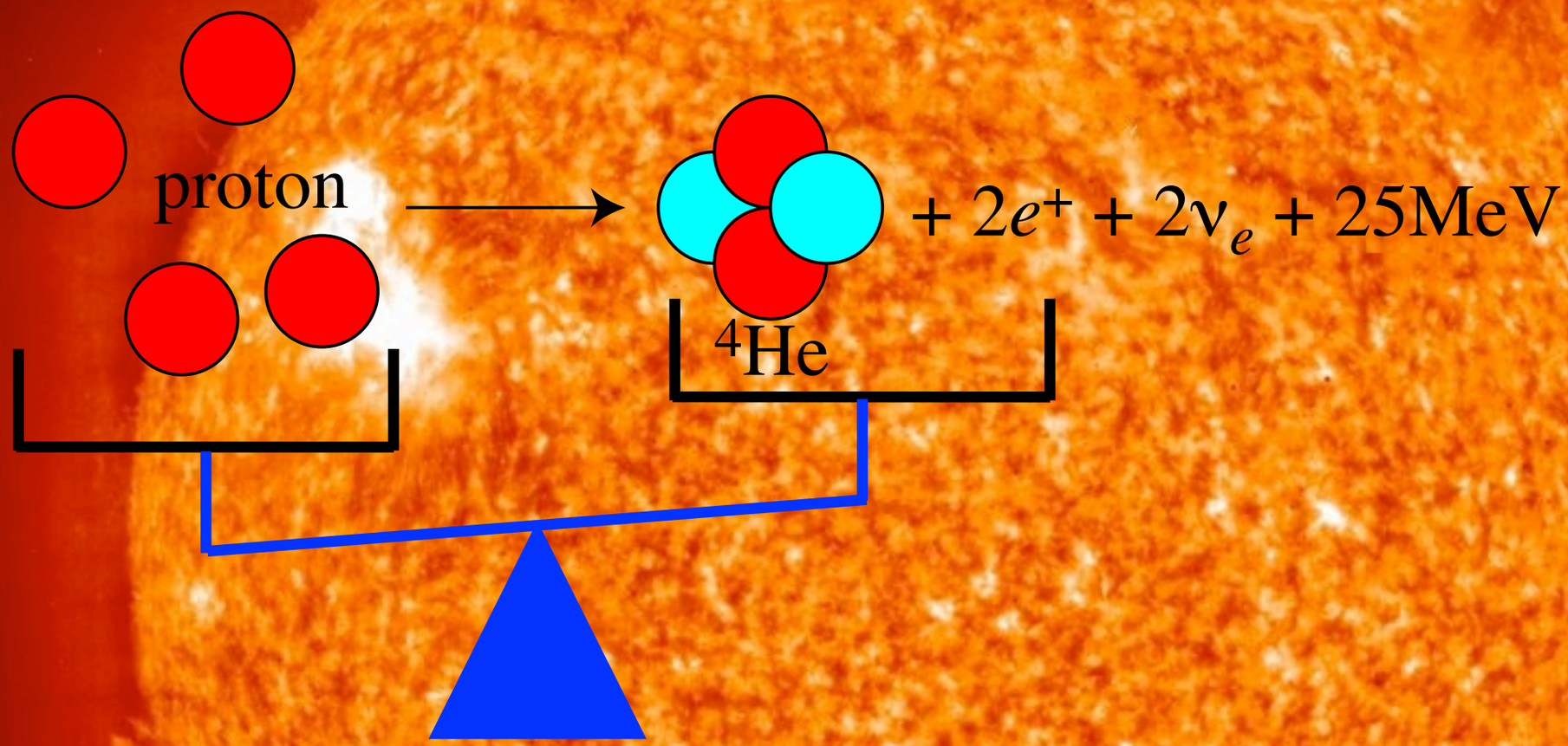

Baryon density $\Omega_b h^2$
0.005
0.01
0.02
0.03
0.27
0.26
0.25
0.24
0.23
Y_p
^{4}He
10^{-3}
10^{-4}
10^{-5}
D/H$|_p$
^{3}He/H$|_p$
BBN
CMB
10^{-9}
5
2
10^{-10}
^{7}Li/H$|_p$
1
2
3
4
5
6
7
8
9
10
Baryon-to-photon ratio $\eta \times 10^{10}$

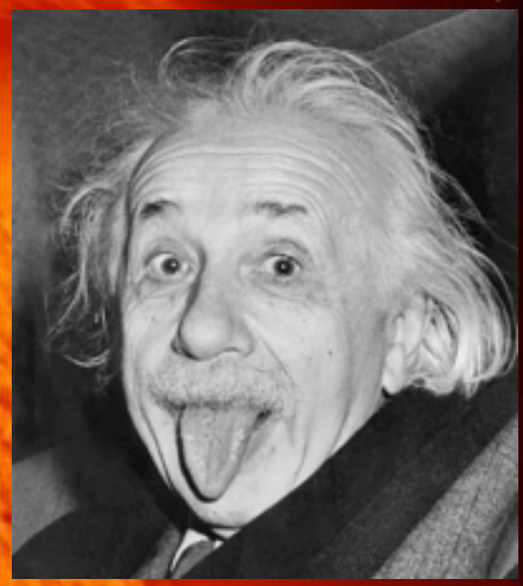
only hydrogen and helium right after the Big Bang



(1) Pure Appl. Chem., **81**, No. 11, 2131-2156 (2009)
Relative atomic masses are expressed with five significant figures. For elements that have no stable nuclides, the value enclosed in

Why does the Sun shine?





$E=mc^2$

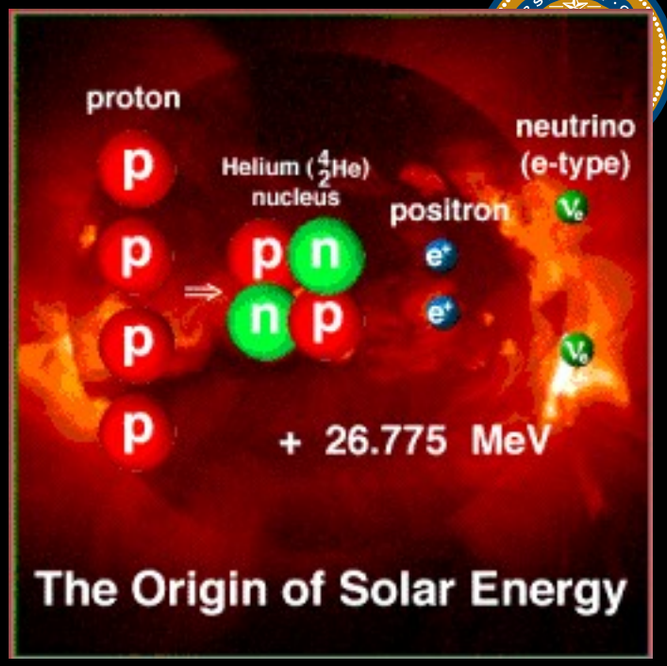
the Sun is getting
lighter by
4 million tons
every second

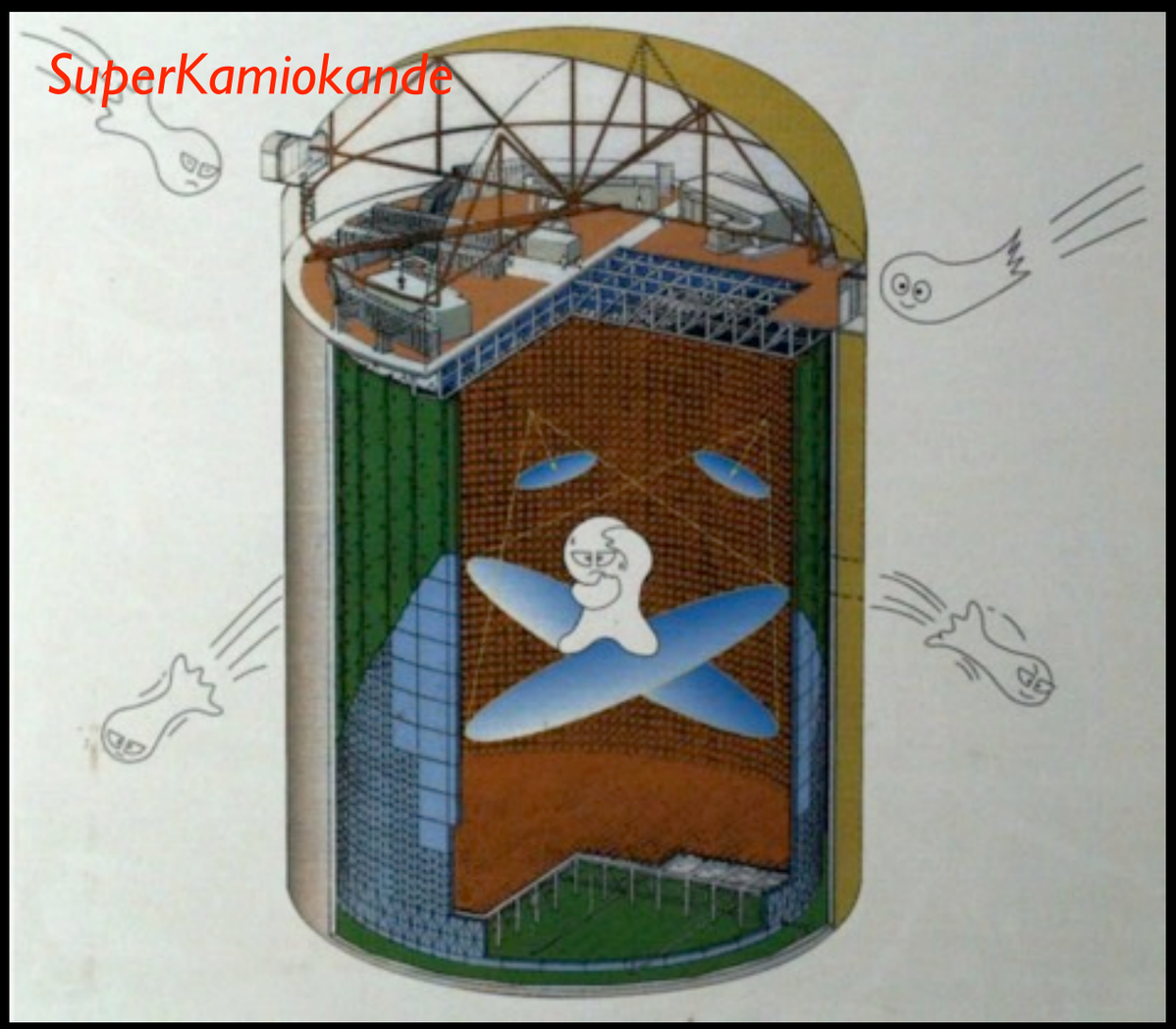
a hundred trillion
neutrinos go through
our body every second

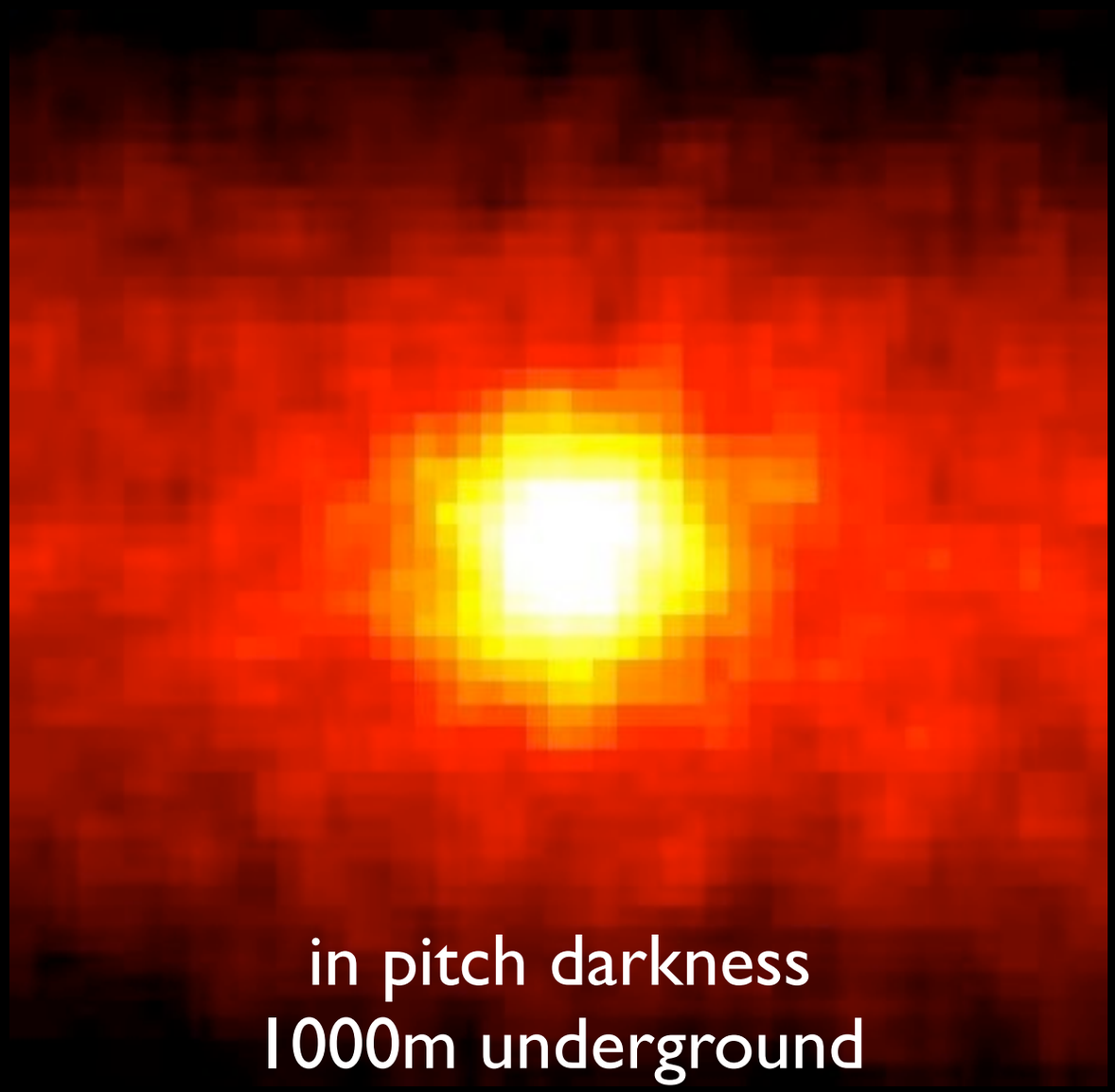
Super-Kamiokande

evidence

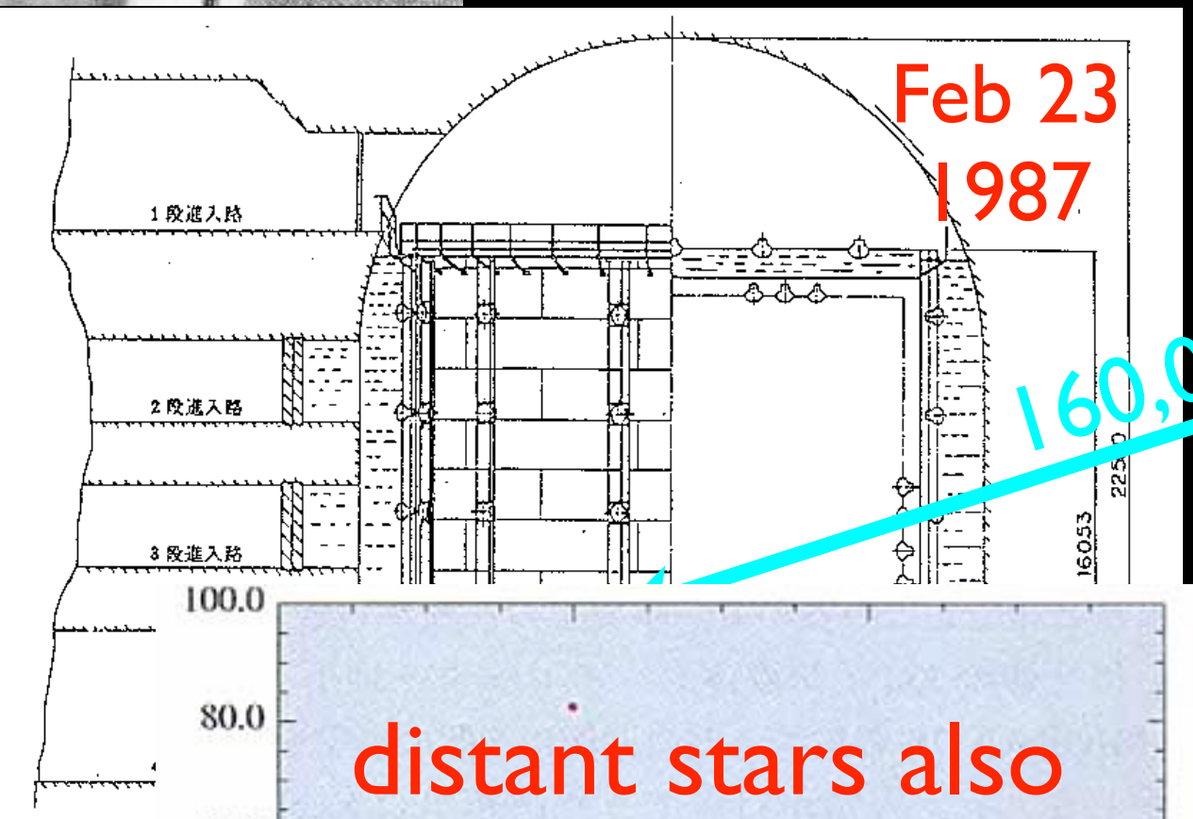
burning atoms in the Sun produces neutrinos
trillions through our body every second



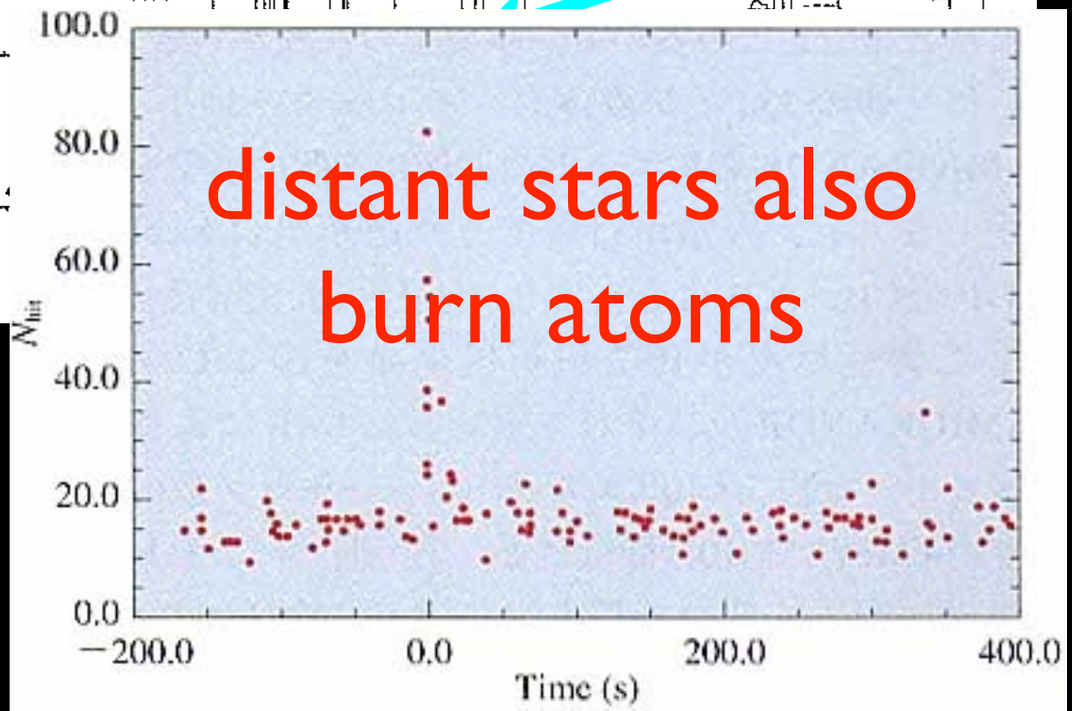




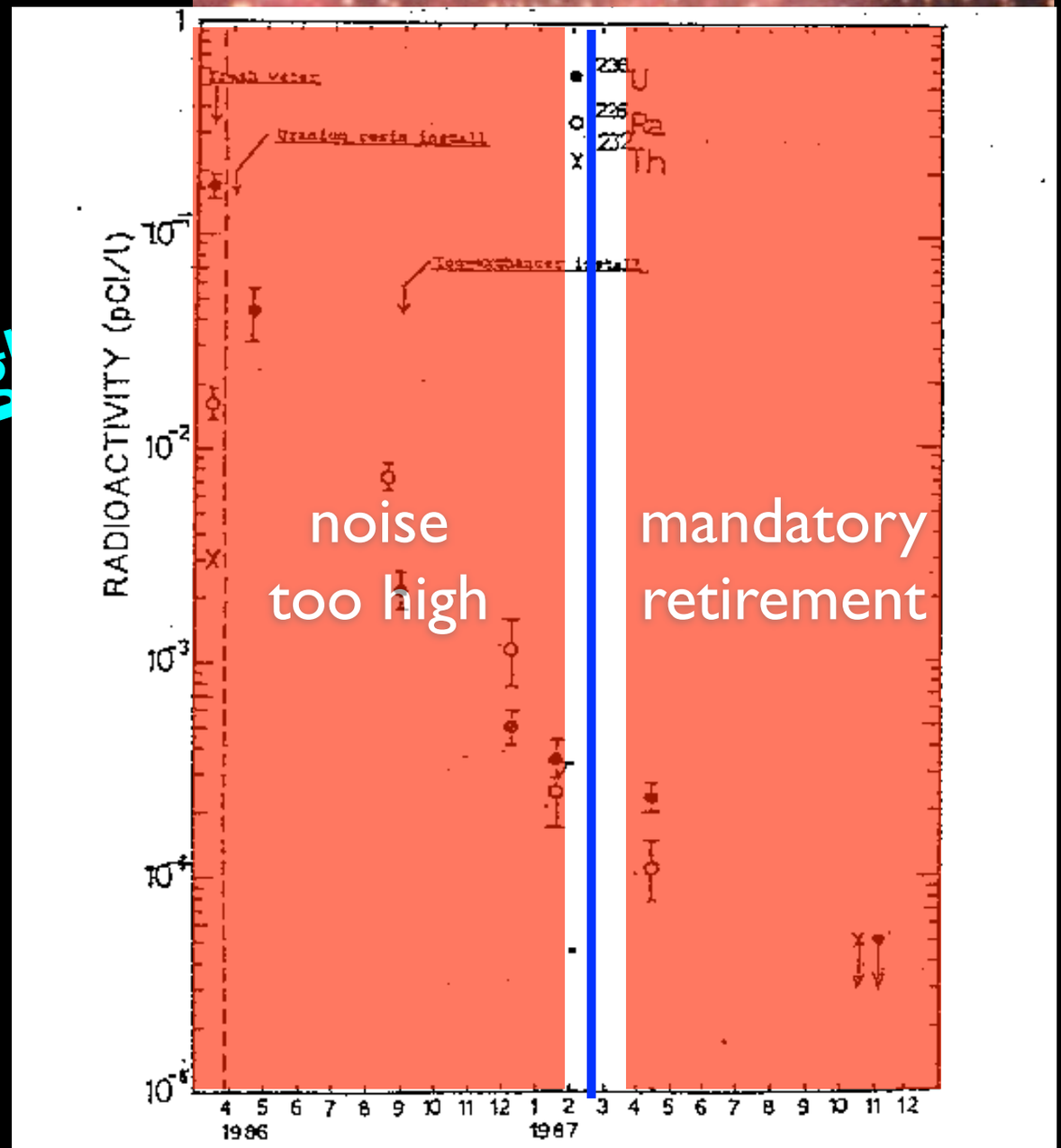
tremendous luck



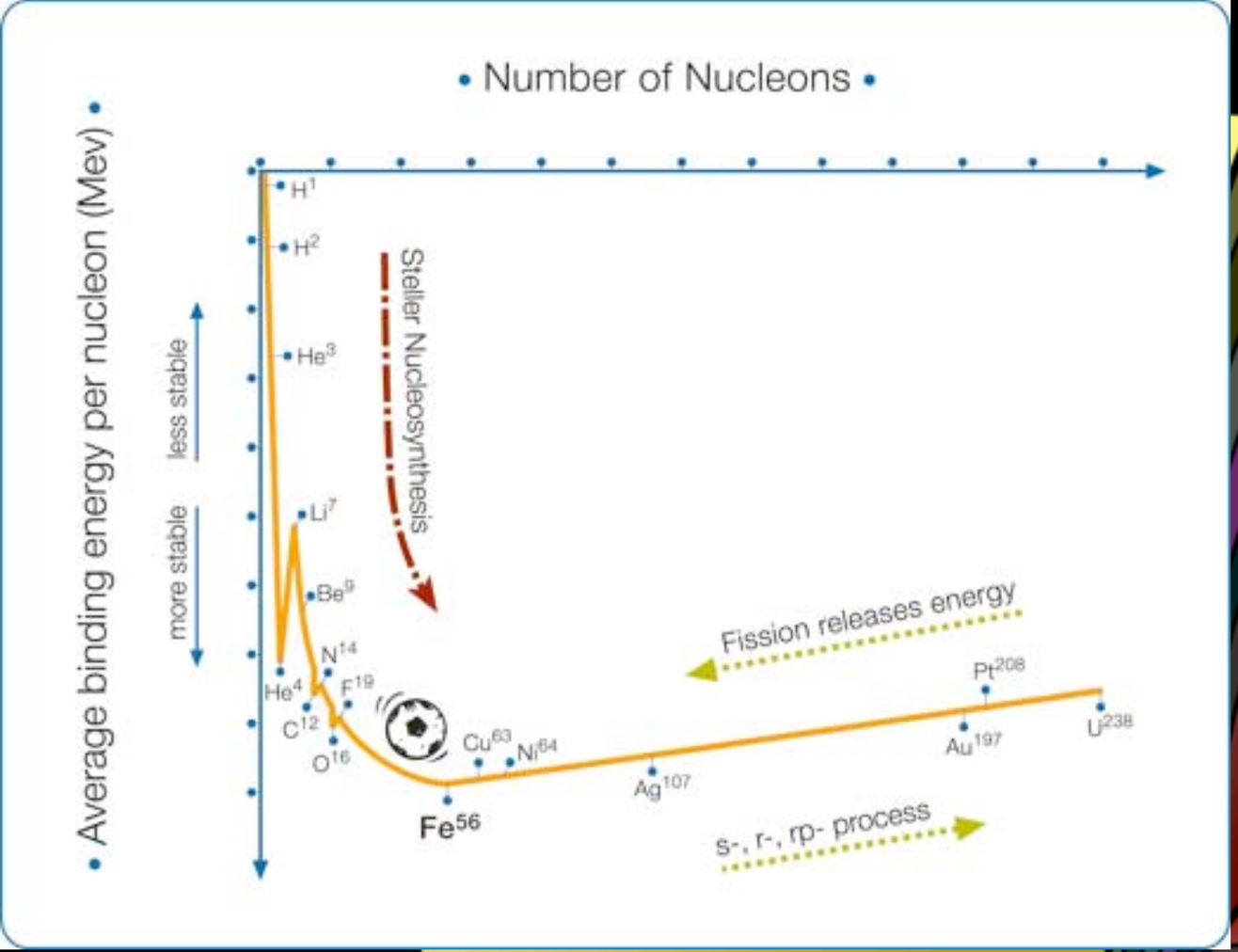
Feb 23
1987

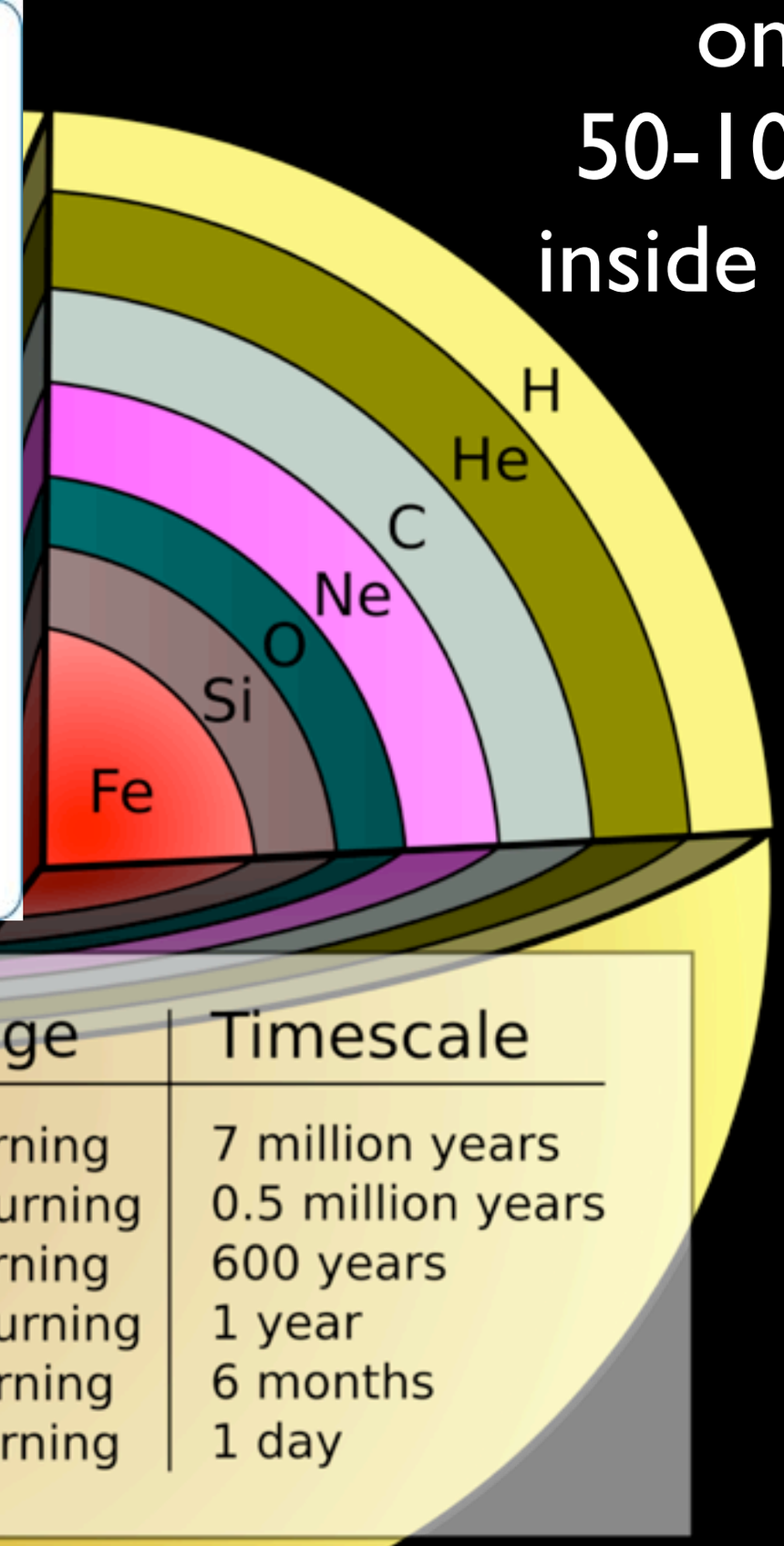


distant stars also
burn atoms



once in
50-100 years
inside the MW





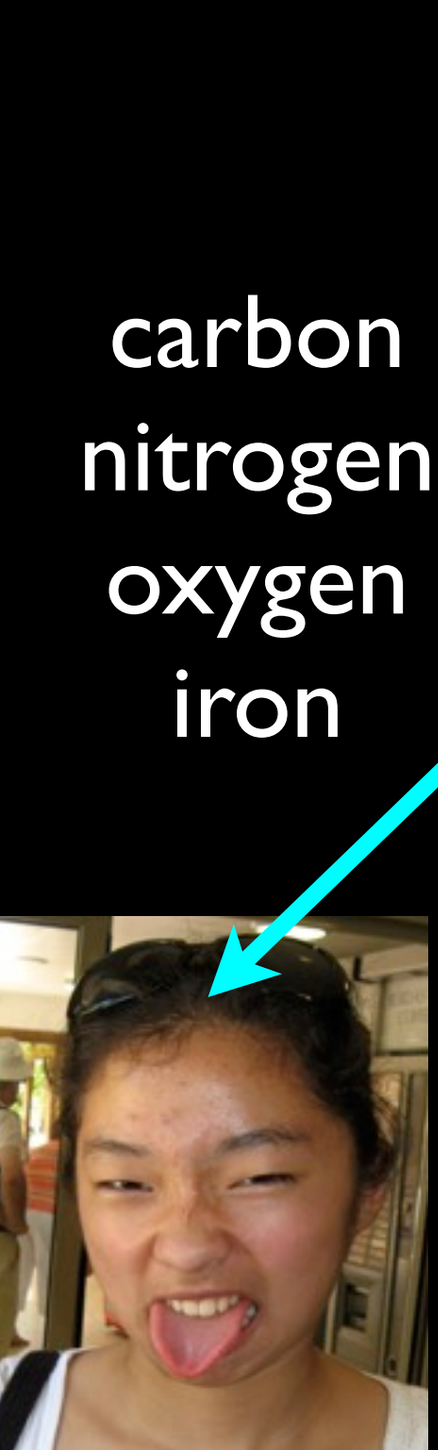
Stage	Timescale
H burning	7 million years
He Burning	0.5 million years
C Burning	600 years
Ne Burning	1 year
O Burning	6 months
Si Burning	1 day

an example of
time scales for a
quite massive star

hydrogen
helium

carbon
nitrogen
oxygen
iron

neutrinos
160,000 light years



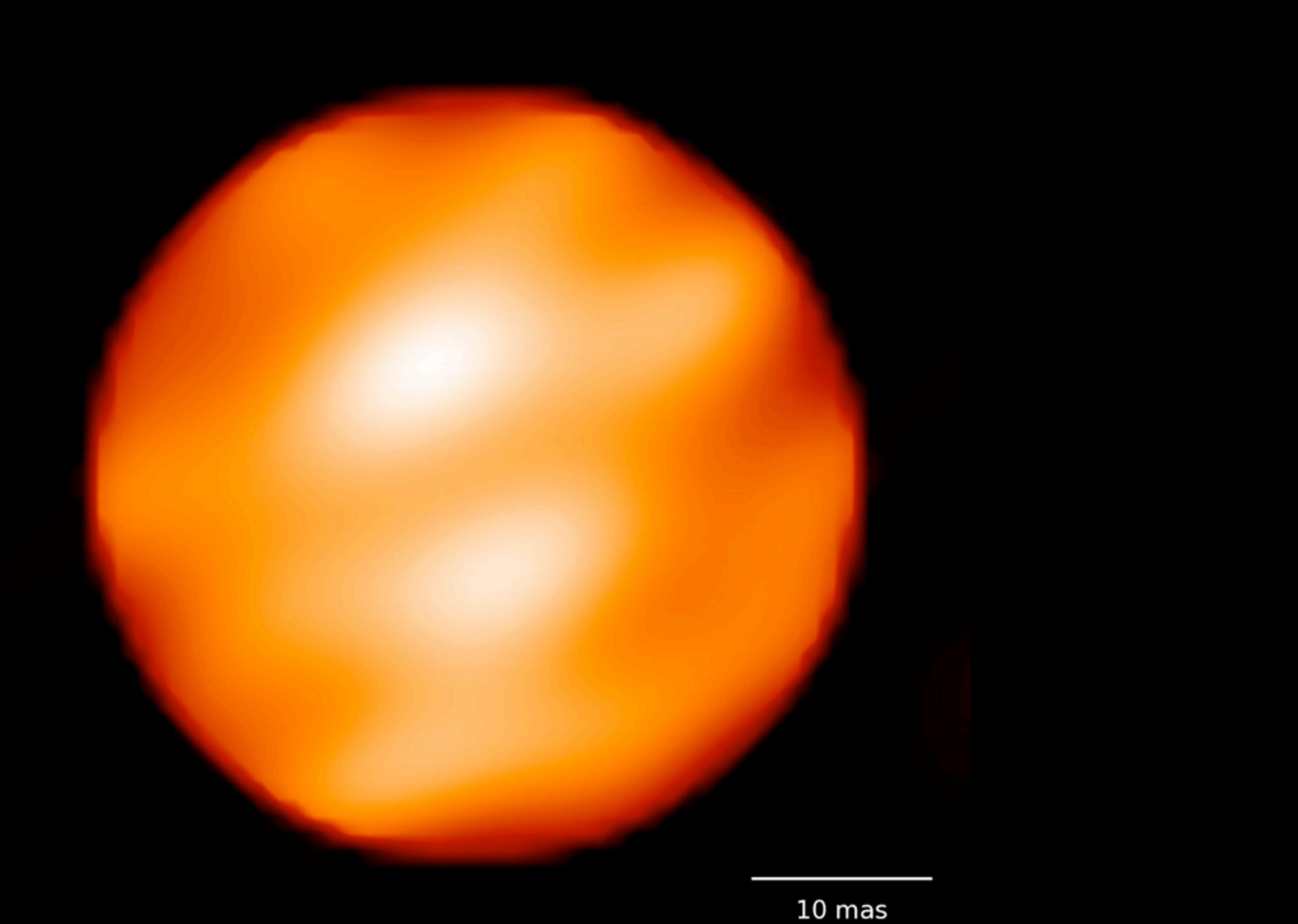
We are star dust

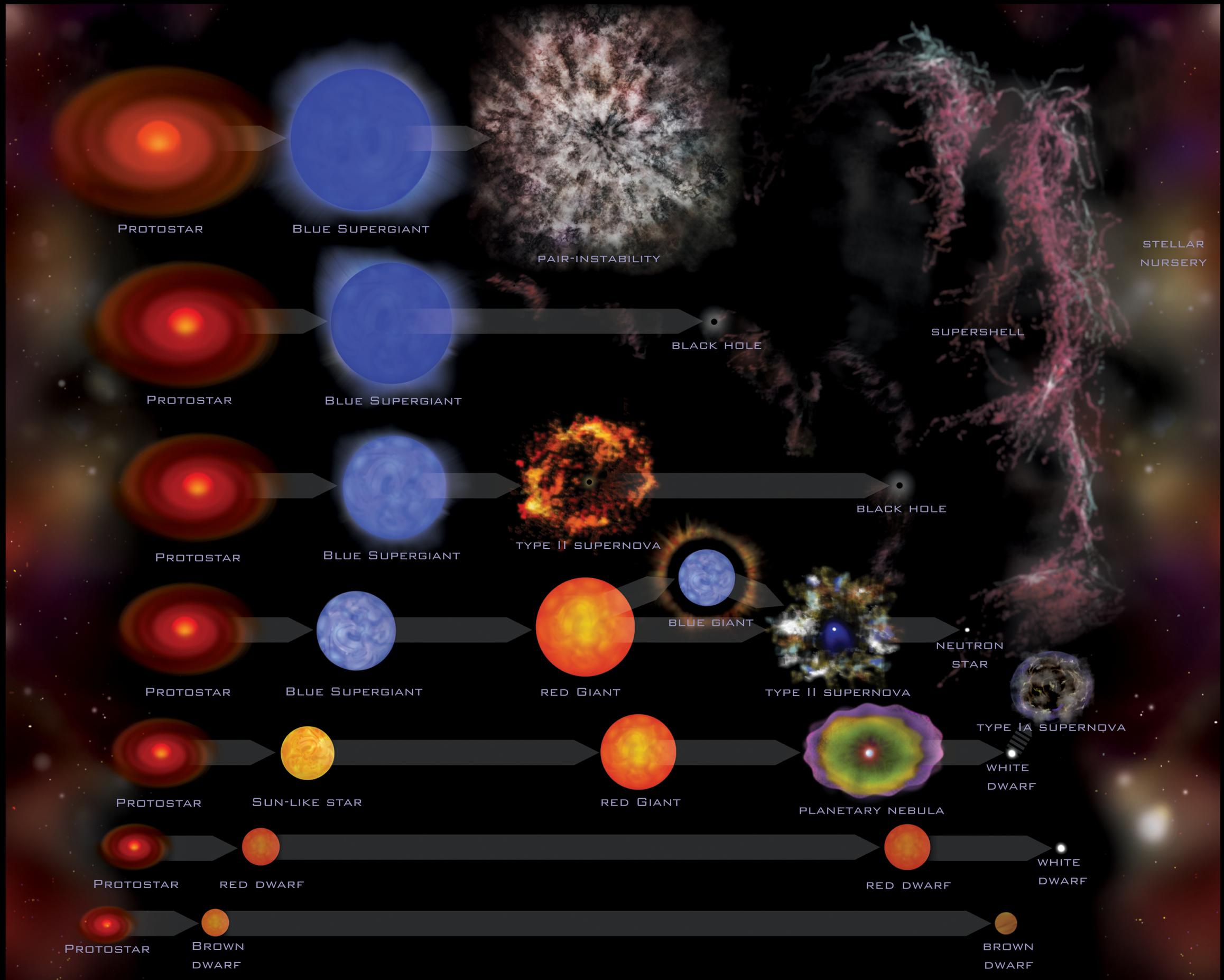
640 lyr

Betelgeuse
$20M_\odot$

Constellation Orion

Constellation: Orion

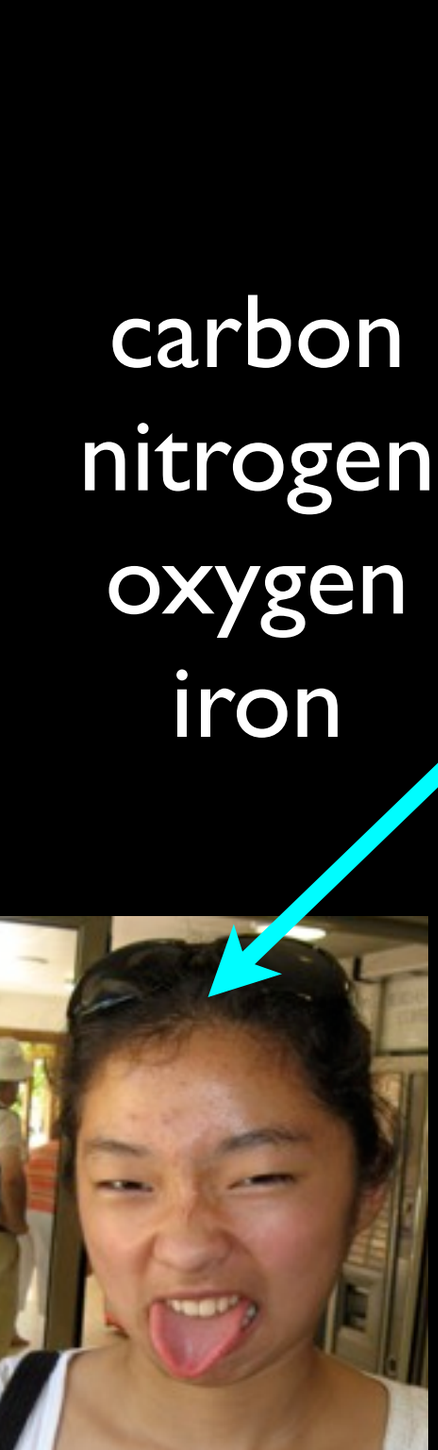

10 mas


PROTOSTAR
BLUE SUPERGIANT
PAIR-INSTABILITY
STELLAR NURSERY
SUPERSHELL
PROTOSTAR
BLUE SUPERGIANT
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
TYPE II SUPERNOVA
BLACK HOLE
PROTOSTAR
BLUE SUPERGIANT
RED GIANT
BLUE GIANT
TYPE II SUPERNOVA
NEUTRON STAR
PROTOSTAR
SUN-LIKE STAR
RED GIANT
PLANETARY NEBULA
TYPE IA SUPERNOVA
WHITE DWARF
PROTOSTAR
RED DWARF
RED DWARF
WHITE DWARF
PROTOSTAR
BROWN DWARF
BROWN DWARF

hydrogen
helium

carbon
nitrogen
oxygen
iron

neutrinos
160,000 light years



We are star dust