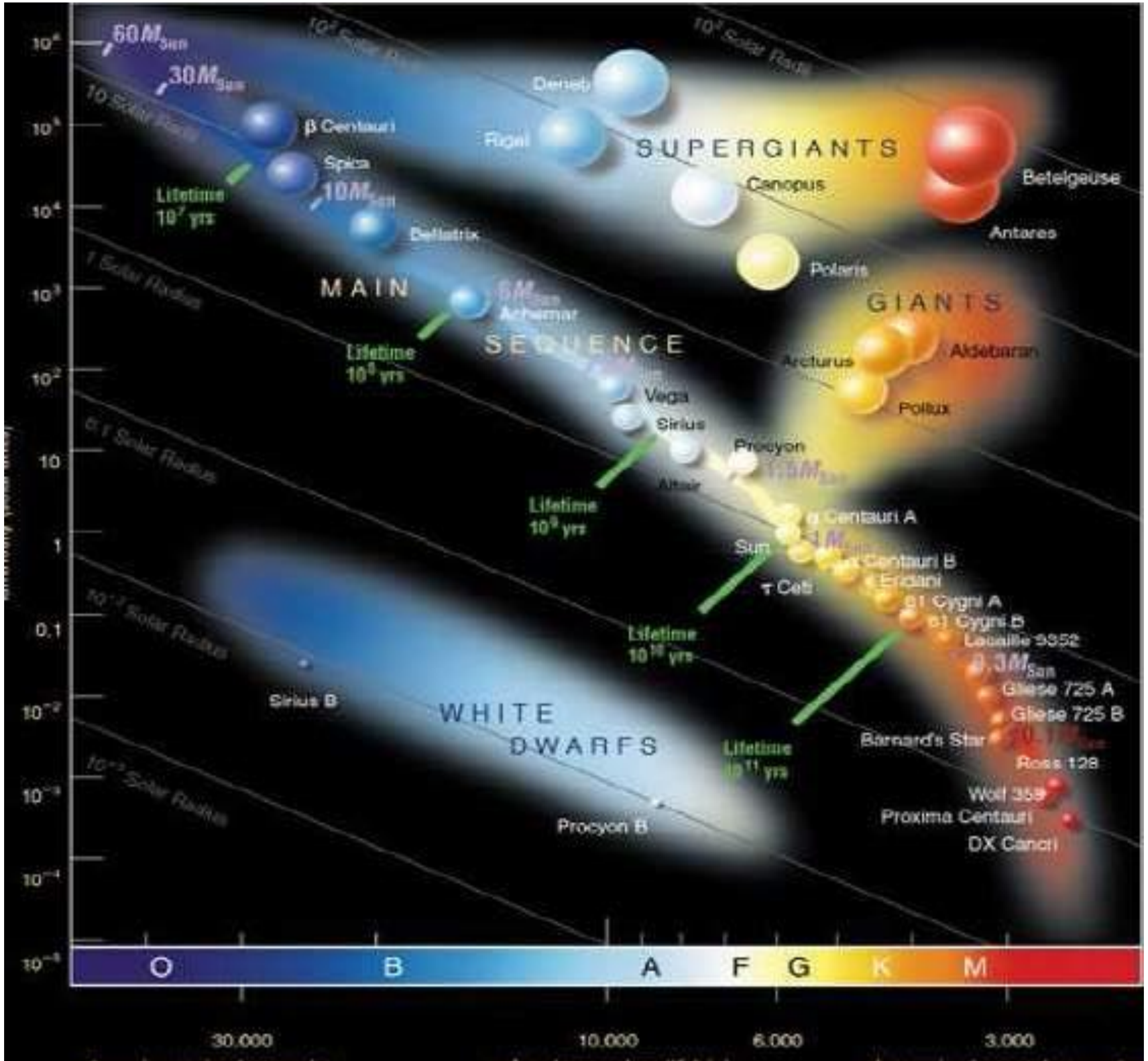
«Космологи часто ошибаются,
но никогда не сомневаются.»
Л.Ландау

«Дозвездный нуклеосинтез, рекомбинация и состав Вселенной.».

В.Н. Кондратьев
ЛТФ, ОИЯИ

1. Обоснование необходимости дозвездного нуклеосинтеза.
2. Праймодиал нуклеосинтез. Эпохи :
   - Термодинамическое равновесие нуклонов по изоспину.
   - Отщепление нейтрино от термодинамического равновесия и замерзание слабого взаимодействия.
   - Замерзание дейтрона.
   - Ядерные циклы при дозвездном синтезе альфа-частиц.
3. Рекомбинация Вселенной
4. Состав Вселенной
5. Астрофизические ограничения на свойства темной материи

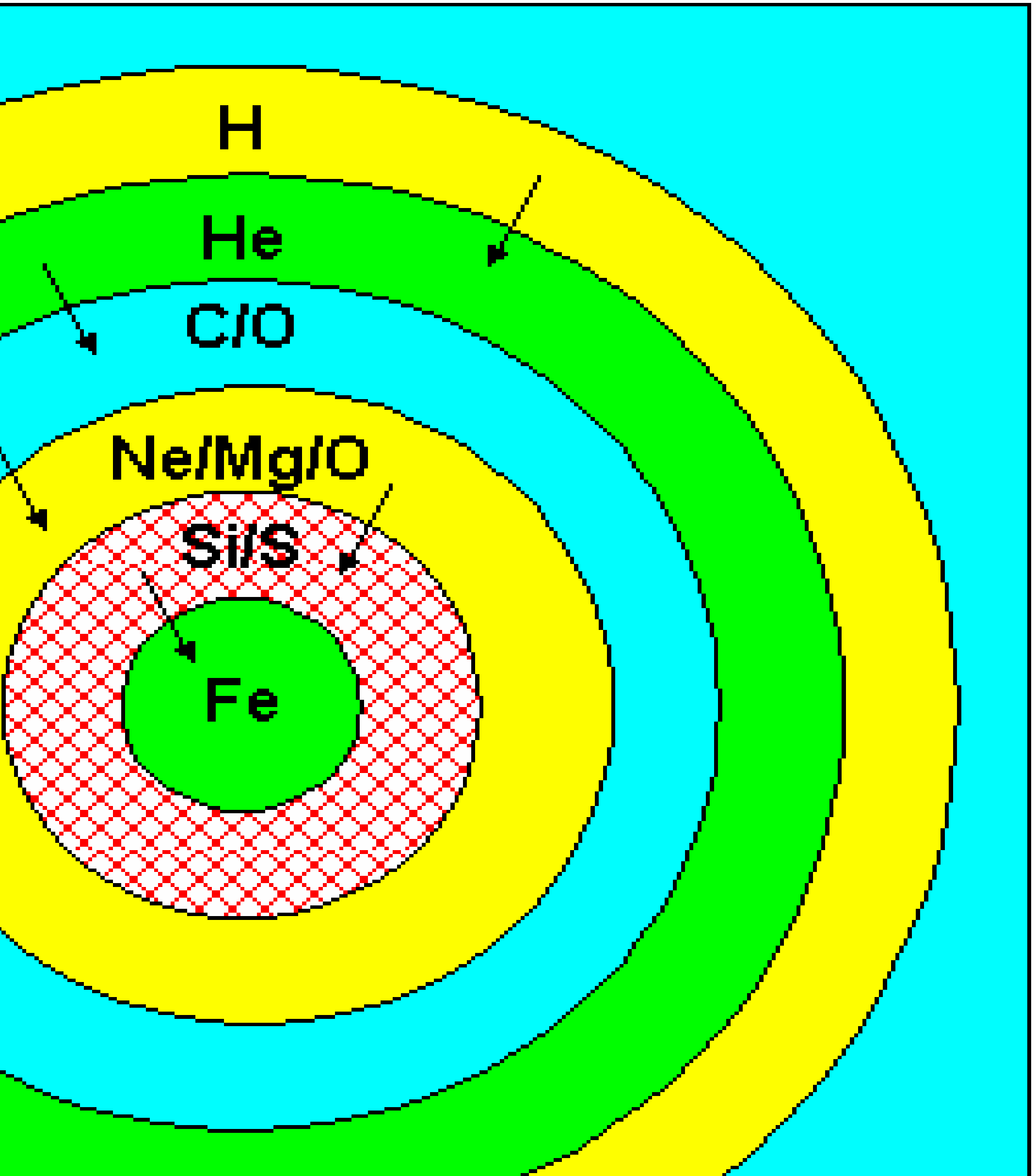
Hertzsprung- Russell (H-R) diagram



Stefan-Boltzmann
Law for flux

luminosity L
of a star with
radius R **&**
surface temperature T
$L \sim (\text{Surface})T^4 \sim R^2T^4$

Massive Star, $M > 10\ M_o$ *onion*



$4H \rightarrow {}^{4}_{2}He$

$3\ {}^{4}_{2}He \rightarrow {}^{12}_{6}C$

${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{20}_{10}Ne + {}^{4}_{2}He$

${}^{12}_{6}C + {}^{12}_{6}C \rightarrow {}^{24}_{12}Mg + \gamma$

${}^{12}_{6}C + {}^{16}_{8}O \rightarrow {}^{28}_{14}Si + \gamma$

${}^{16}_{8}O + {}^{16}_{8}O \rightarrow {}^{32}_{16}S + \gamma$

${}^{28}_{14}Si + {}^{16}_{8}O \rightarrow {}^{44}_{22}Ti(\beta^{+})$

${}^{44}_{21}Sc(\beta^{+})\ {}^{44}_{20}Ca$

${}^{28}_{14}Si + {}^{28}_{14}Si \rightarrow {}^{56}_{28}Ni(\beta^{+})$

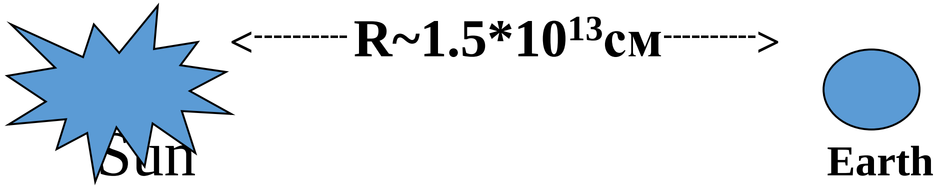
${}^{56}_{27}Co(\beta^{+})\ {}^{56}_{26}Fe$

Source of Sun’s energy

Edington first proposed the reaction

$4p \to {}^4He + 2e^+ + 2\nu_e$,   Q=25.8 MeV

solar constant **(at the Earth): 0.033 cal/sec/cm^2**


<---------- $R \sim 1.5 \cdot 10^{13}$ см ---------->

Persistent Luminocity : **$4\pi R^2 \cdot 0.033 = 4 \cdot 3.14 \cdot 2.25 \cdot 10^{26} \cdot 0.033$**

$0.92 \cdot 10^{26}$ cal/s $= 2.4 \cdot 10^{39}$ MeV/s

Burning rate: **$P = 4 \cdot 2.4 \cdot 10^{39} / 25 = 4 \cdot 10^{38}$ protons/sec**

Sun’s mass**$= 2 \cdot 10^{30}$ kg $= 1.2 \cdot 10^{57}$ protons**

Mass$_p$=$1.7 \cdot 10^{-27}$kg

Time: $1.2 \cdot 10^{57} / 4 \cdot 10^{38} = 3 \cdot 10^{18} = 10^{11}$ years=100 b.y.

In 5 b.y. :   5% H mass is converted to ^{4}He

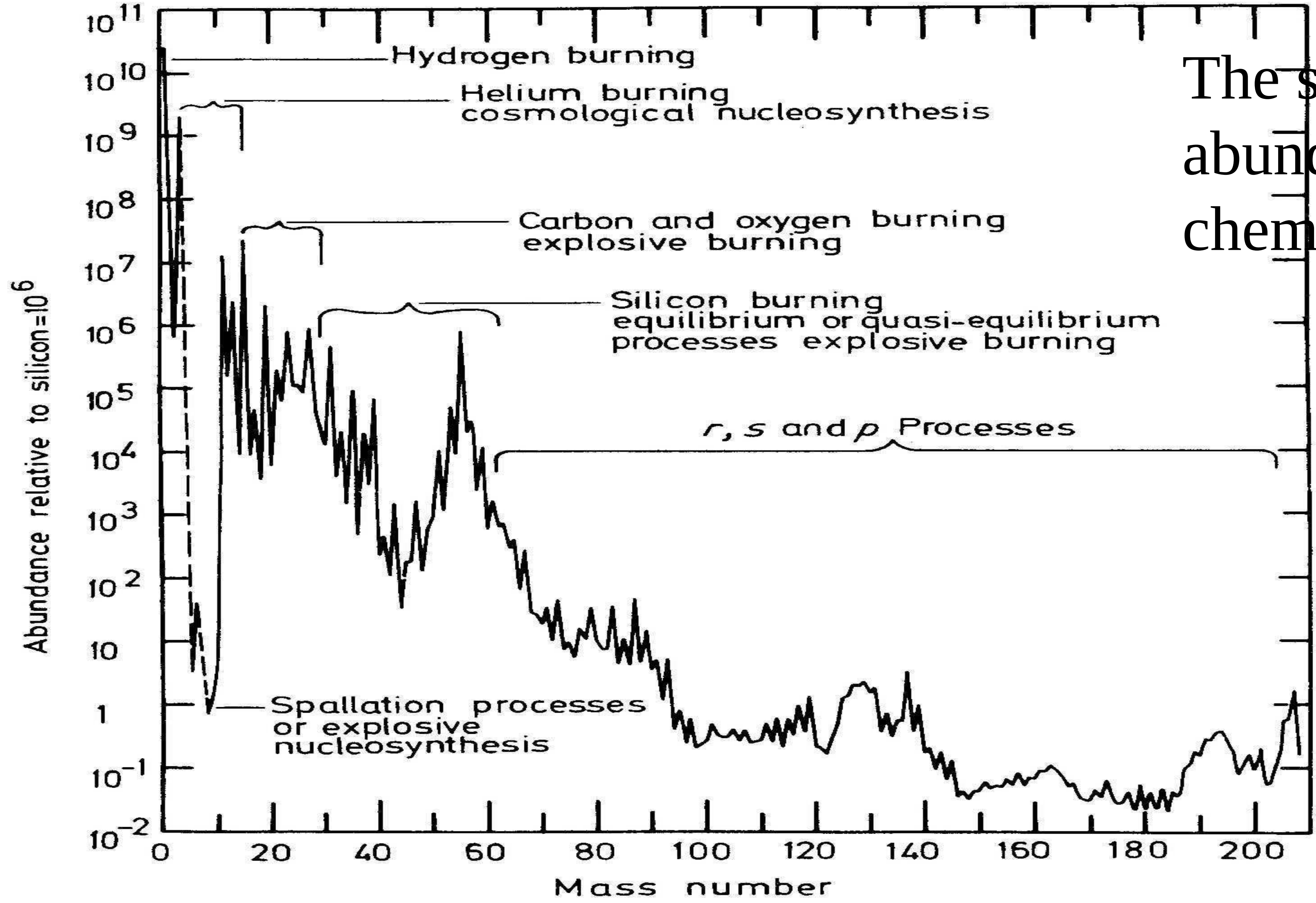
at *hydrostatic burning of stars*

In 5 b.y. : 5% H mass is converted to ^{4}He

95%-^{1}H; 5%-^{4}He

- Mass: 1 - ^{4}He (2p, 2n) = 4N
- 19 - ^{1}H (p) $\rightarrow$ 76p
- [n/p] = 2/(76+2) =1/39

The solar system abundances of chemical elements



75%-^{1}H; 25%-^{4}He

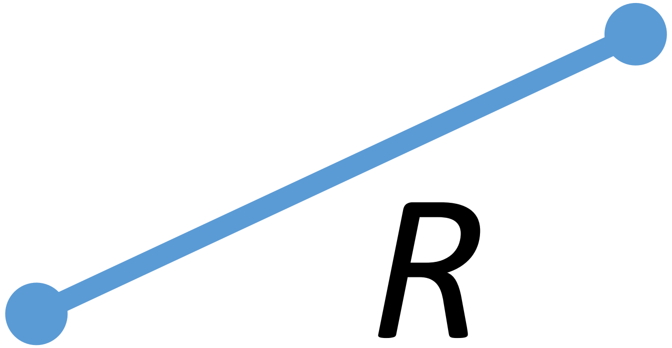
- Mass: 1 - ^{4}He (2p, 2n) = 4N
- 3 - ^{1}H (p) $\rightarrow$ 12p
- [n/p] = 2/(12+2) =1/7

Cosmology: *homogeneous, isotropic universe*

Friedmann–Lemaître–Robertson–Walker (FLRW) metric

$$d\tau^2 = dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2\right]$$

$$\left|0,(r,\theta,\phi)\right| = R(t)\int_0^r \frac{dr^2}{\sqrt{1-kr^2}}$$



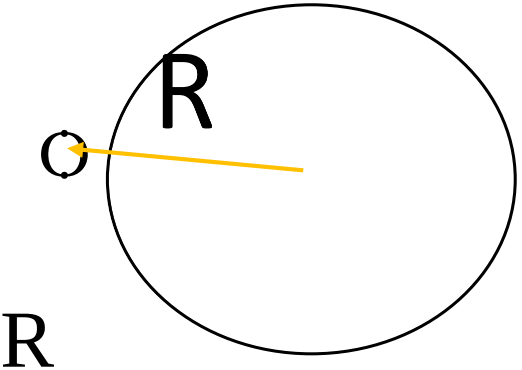
$$V_R = H\,R$$

Hubble law

Hubble expansion

homogeneous & isotropic universe

the test mass m



potential energy

$$U = -G\, M(R)\, m/R \qquad \text{(HE1)}$$

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

kinetic energy

$$T = 1/2\, mv^2$$

Hubble's Law: $v = HR$ (HE2)

Hubble constant

Today’s value

$$H = (1/R)\,(dR/dt) = [71 \text{ +/- } 4] \text{ km/s/Mpc} \qquad \text{(HE3)}$$

total energy of test particle

$$E_{\mathrm{tot}} = T + U = \frac{1}{2} m R^2 (H^2 - \frac{8}{3} \pi\rho G) \qquad \text{(HE4)}$$

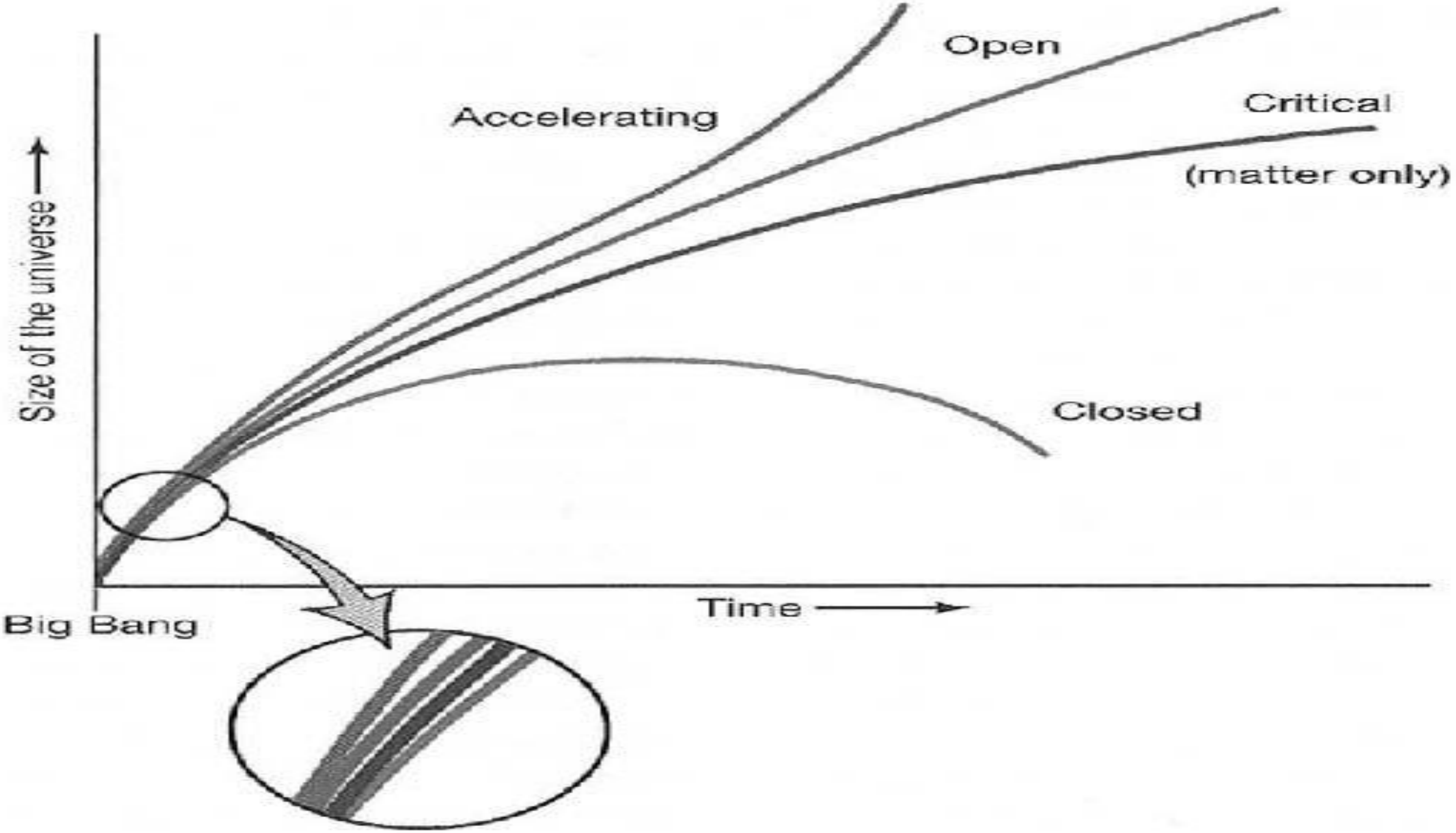
critical density

$$\rho_{\mathrm{crit}} = \frac{3H^2}{8\pi G} \approx 1.88 \cdot 10^{-29} h^2 \mathrm{g/cm}^3 \qquad \text{(HE5)}$$

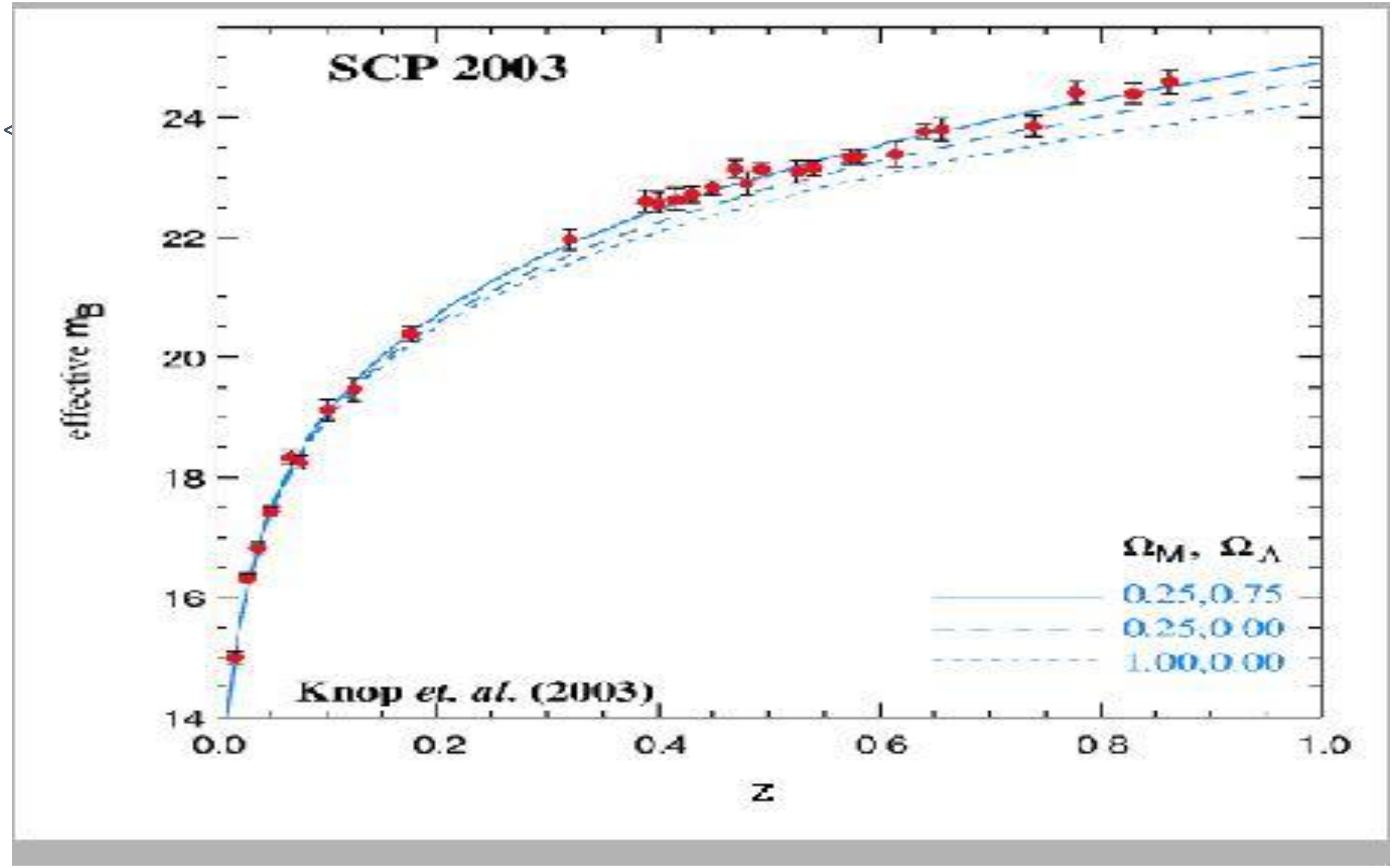
$h = 0.71 \pm 0.04$ [100km/s/Mpc]

$\rho < \rho_{\mathrm{crit}}$ → continued expansion

$\rho > \rho_{\mathrm{crit}}$ → ultimate contraction (HE6)



▲ **FIGURE 27.9 Flatness Problem** If the universe deviates even slightly from critical density, that deviation grows rapidly in time. For the universe to be as close to critical as it is today, it must have differed from the critical density in the past by only a tiny amount.



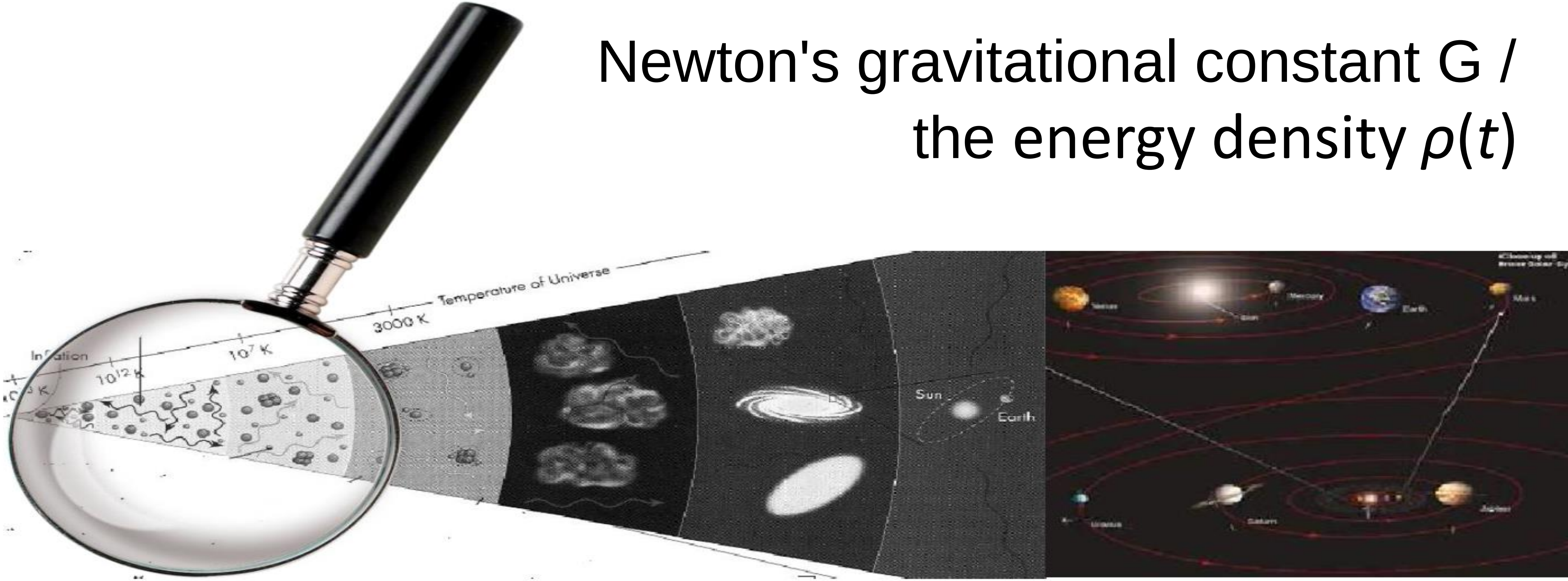
- Effective luminosity of SNIa versus red shift. The best fit flat Universe model is shown by solid curve. Distant SNe are seen to be fainter than expected fom decelerating Universe indicating the presence of a cosmological constant or **dark energy**.

Hubble Expansion

$\rho(t)$

$$\frac{dR(t)}{dt}R^{-1}(t) = \text{Hubble"}\overset{\textbf{Parameter}}{\cancel{\text{constant}}}\text{"} = \sqrt{\frac{8\pi G\rho(t)}{3}}$$

Newton's gravitational constant G /
the energy density $\rho(t)$



Energy density

$$\rho(T) =$$

$$\frac{g_\gamma}{h^3}\int_0^\infty \frac{d^3k}{(2\pi)^3}\frac{ck}{\exp\{ck/T\}-1}$$

Photons

$$\frac{g_\nu}{h^3}\int_0^\infty \frac{d^3k}{(2\pi)^3}\frac{ck}{\exp\{ck/T\}+1}$$

Fermions

$$\rho(t) = N\frac{\pi^2}{30}T^4$$

$N_\gamma = 2$

$N_F = 7/4$

$$[n, p], e^{-/+}, \gamma, \text{ and } \nu_{e,\mu,\tau}$$

$N_t = 2 + (2+3)7/4 = 43/4$

$$R \sim T^{-1} \sim t^{1/2}$$

$$H \approx \frac{0.67}{\sec}\left(\frac{kT}{MeV}\right)^2$$

	T(K)	R/Ro	t(sec)
10 MeV	10^{11}	$1.9 * 10^{-11}$	.0108
1 MeV	10^{10}	$1.9 * 10^{-10}$	1.10
100 keV	10^{9}	$2.6 * 10^{-9}$	182
10 keV	10^{8}	$2.7 * 10^{-8}$	19200

Epoch I. chemical equilibrium

t ~.01 sec | T ~ 10^{11} K : kT~ 10 MeV>>$2m_ec^2$

$$[n \leftrightarrow p], e^{-/+},\ \gamma,\ \text{and}\ \nu_{e,\mu,\tau}$$

chemical equilibrium

due to neutral- and charged current interactions

$$[p \leftrightarrow n] \text{ -equilibrium } : \begin{cases} p + e^- \leftrightarrow n + \nu_e \\ n + e^+ \leftrightarrow p + \tilde{\nu}_e \\ p \leftrightarrow n + e^+ + \nu_e \\ n \leftrightarrow p + e^- + \tilde{\nu}_e \end{cases}$$

occup $\propto$ $g_i \exp\{-E_i / kT\}$: ->

$$\left[\frac{n}{p}\right] = \frac{\exp\{-m_n / kT\}}{\exp\{-m_p / kT\}} = \exp\{-\Delta m / kT\}$$

$$\Delta m = m_n - m_p = 1.294 \text{ MeV}$$

T = 10^{11} °K

[n/p] = 0.86

Epoch II. Neutrino decoupling

- t ~ 0.1 sec T ~ 3 $*10^{10}$ K ~ 3 MeV

To estimate the time scale for n ↔ p

Via reaction $n + \nu_e \leftrightarrow p + e^-$

$$\Lambda(T) = <\sigma v> n \approx \frac{0.76}{\sec}\left(\frac{kT}{MeV}\right)^5$$

Epoch III. Freezing weak interaction

$$\Lambda(T) = H$$

$$\frac{0.76}{\sec}\left(\frac{kT}{MeV}\right)^5 \approx \frac{0.67}{\sec}\left(\frac{kT}{MeV}\right)^2$$

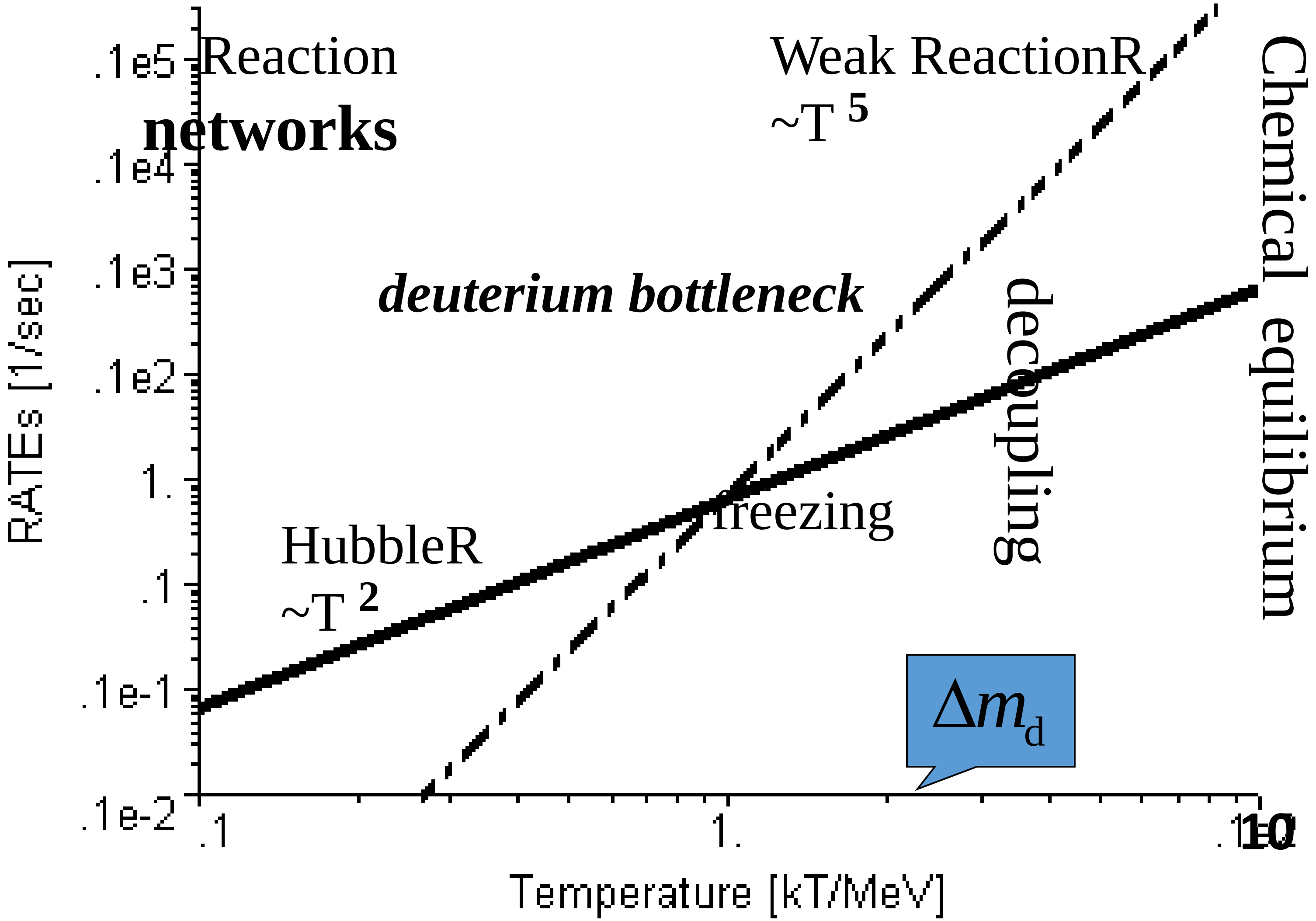
$T \approx 0.8$ MeV

$$[n/p] = \exp\{-\Delta m/T\}$$

$$\approx 1/5$$

$[n, p], e^{-/+}, \gamma, \text{ and } \nu_{e,\mu,\tau}$

time



Reaction **networks**

Weak ReactionR ~T $^{\mathbf{5}}$

deuterium bottleneck

HubbleR ~T $^{\mathbf{2}}$

freezing

decoupling

Chemical equilibrium

Δm_d

10

Epoch IV. Deuteron freezing

Baryons [n & p] $n + p \leftrightarrow d + \gamma$

$$n_{n+p} \left|\langle d\gamma | H_\gamma | np\rangle\right|^2 \approx n_{d+\gamma} \left|\langle np | H_\gamma | d\gamma\rangle\right|^2$$

$$n_{p+n} = n_p\, n_n \approx n_{d+\gamma} = n_d\, n_\gamma^{\mathrm{ef}}$$

$$n_\gamma^{eff} = \int_{\Delta m_d}^{\infty} \frac{8\pi\varepsilon^2 d\varepsilon}{\exp(\varepsilon / kT) - 1} \approx \exp\{-\Delta \mathrm{m}_d/T\}\, n_\gamma$$

EQUILIBRIUM CONDITION

$$n_p\, n_n \approx \exp\{-\Delta m_d/T\}\, n_d\, n_\gamma$$

$$n_p / n_\gamma \approx \eta$$

$$\approx \exp\{-\Delta m_d/T\}\, n_d / n_n$$

Deuteron formation

$$n_d / n_n \approx 1$$

$$\eta \approx \exp\{-2.24\ \mathrm{MeV}/T_d\}$$

^{4}He abundance → [n/p]= 1/7 at T_d – determines T_d

$n \rightarrow p + e^- + \nu_e$

Effective reactions

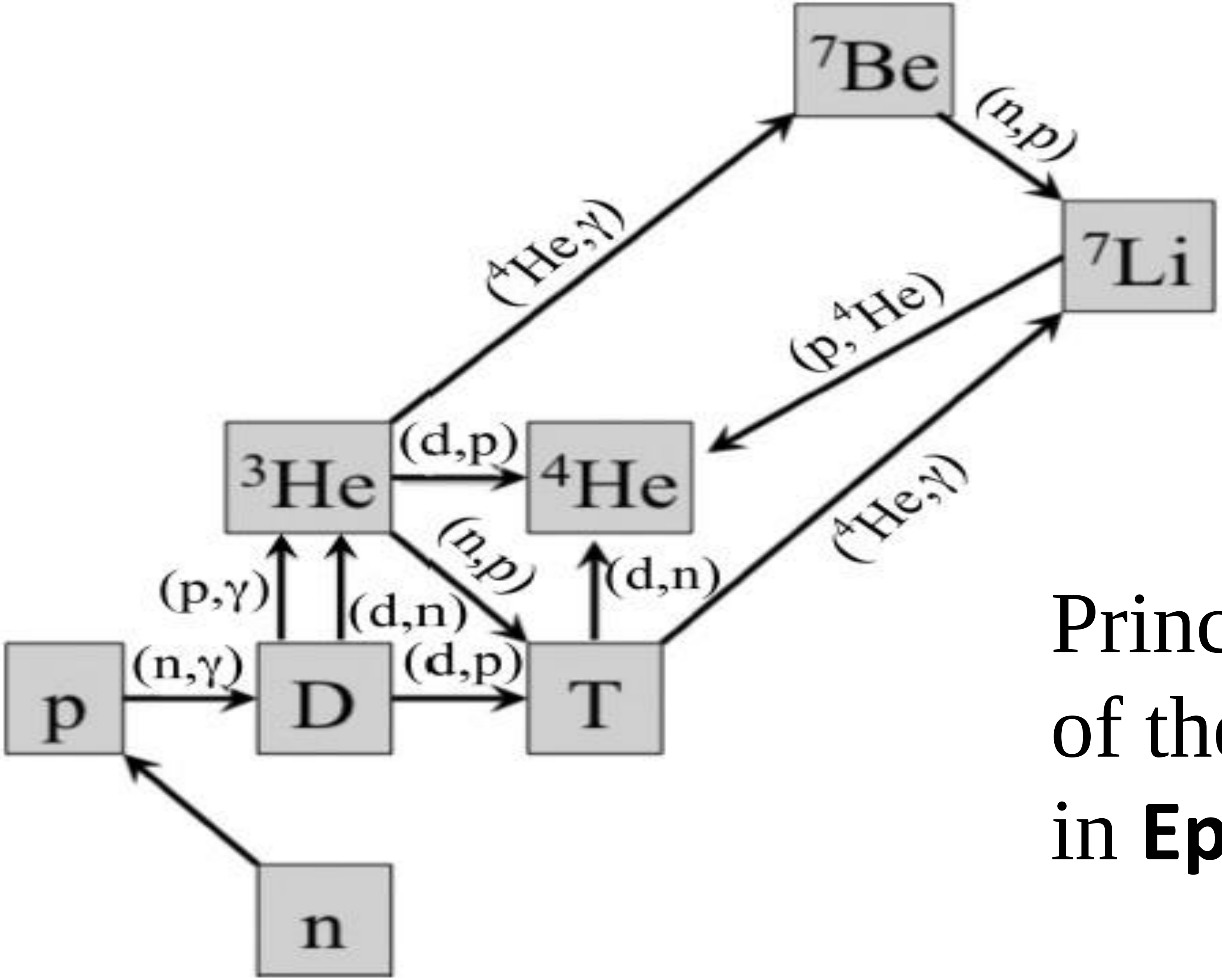
$\nu_e + n \rightarrow p + e^-$

To reduce (n/p)-ratio from $[n/p]_1 = 0.25$ to $[n/p]_2 = 1/7$

Neutron number N_n is smaller on $N_{n1}/N_{n2} = 0.62$

$t \sim 3.0$ minutes → $T_d \approx 1.1 * 10^9$ K ≈ 95 keV $<< \Delta m_d$

$$\eta \approx \exp\{-2.24/0.095\} \approx 10^{-10}$$



?(p,γ)

(e,ν)

Principal reactions of the BBN network in **Epoch V.**

Main nuclear reactions

$p + n \rightarrow {}^{2}H + \gamma$ (Q = +2.22 МэВ),

$$ {}^{2}H + {}^{2}H = \begin{cases} {}^{3}H + p & (Q = 4.03\ \text{МэВ}), \\ {}^{3}He + n & (Q = 3.27\ \text{МэВ}), \end{cases} $$

$$\lambda_{ij} = \frac{< \sigma_{ij} v_{ij} >}{1 + \delta_{ij}}$$

$$\frac{\partial n_d}{\partial t} + 3Hn_d = \lambda_{pn}\, n_p\, n_n - \lambda_{pd}\, n_p n_d - \lambda_{dd}\, n_d\, n_d$$

$$\frac{\partial n_T}{\partial t} + 3Hn_T = \lambda_{pd}\, n_p\, n_d - \lambda_{dT}\, n_d n_T - \lambda_{THe}\, n_T\, n_{He} + \cdots$$

Main nuclear reactions

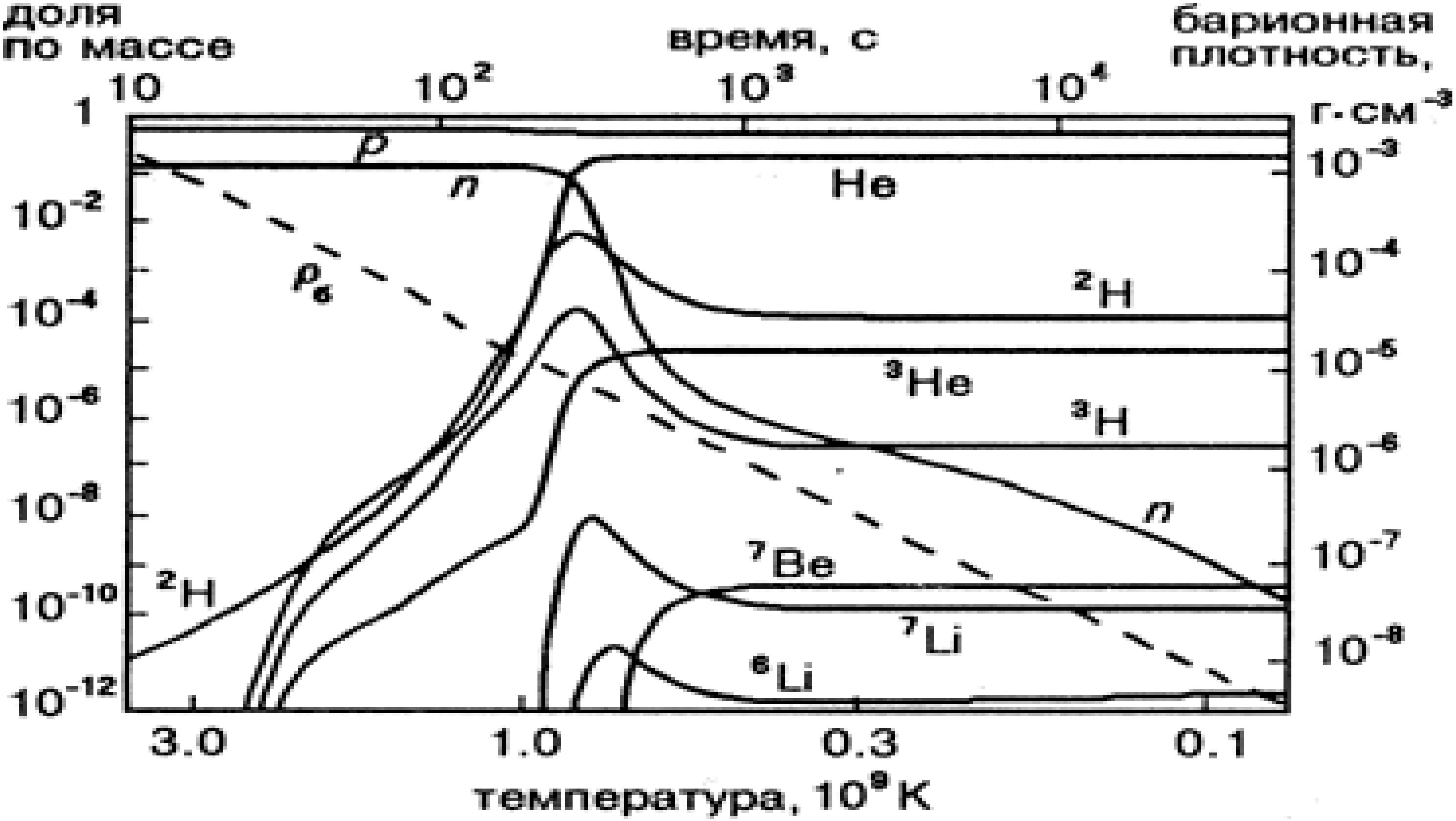
$^{2}H + ^{3}H \rightarrow ^{4}He + n$ (Q = 17.59 МэВ),

$^{2}H + ^{3}He \rightarrow ^{4}He + p$ (Q = + 18.35 МэВ

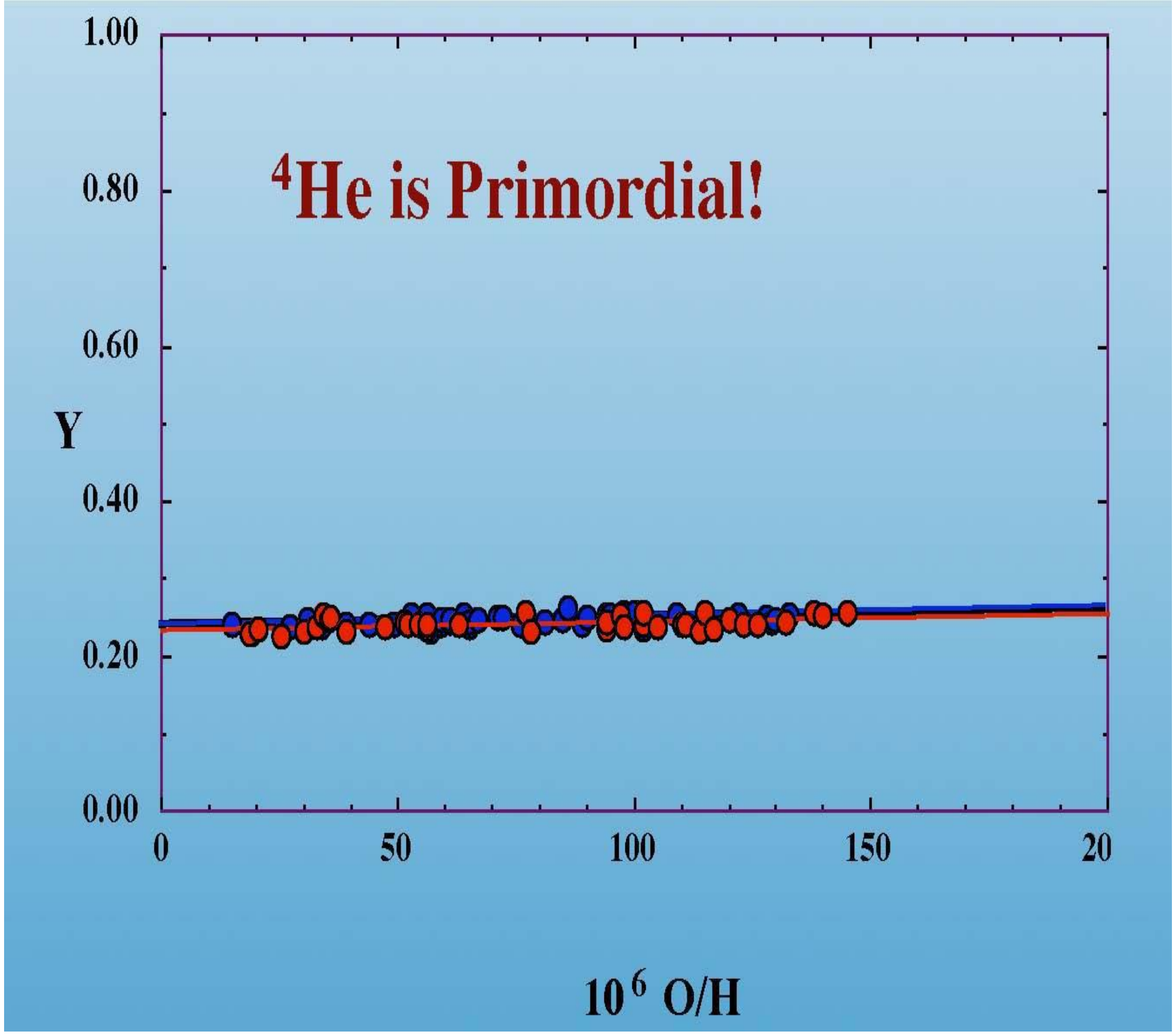
$^{7}Be + n \rightarrow ^{7}Li + p$, ? $^{7}Be + e \rightarrow ^{7}Li + \nu e$

$^{7}Be + n \rightarrow 2\ ^{4}He + \gamma$

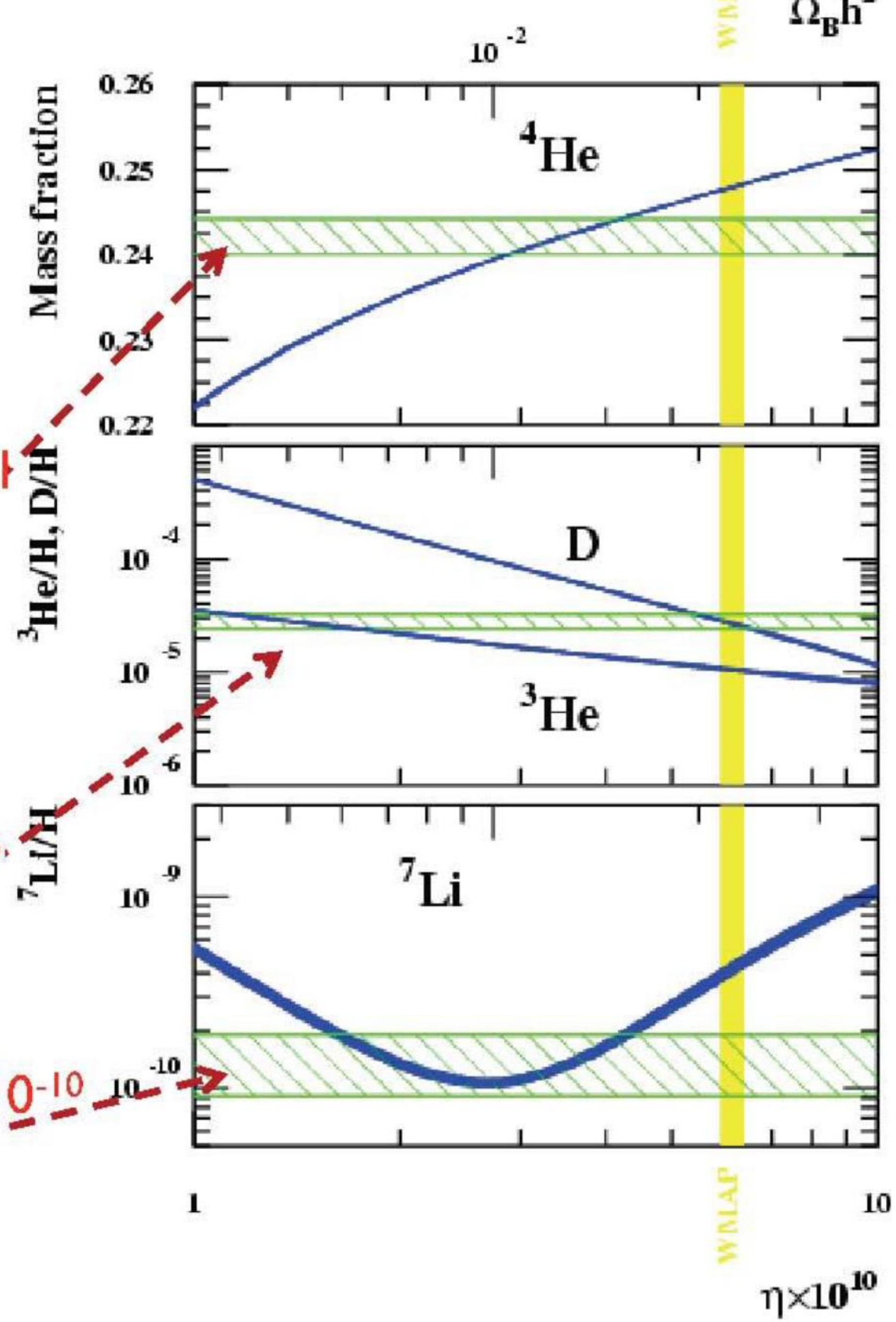
$^{7}Li + p \rightarrow 2\ ^{4}He + \gamma$



доля по массе
время, с
барионная плотность, г·см⁻³
10
10²
10³
10⁴
1
10⁻²
10⁻⁴
10⁻⁶
10⁻⁸
10⁻¹⁰
10⁻¹²
10⁻³
10⁻⁴
10⁻⁵
10⁻⁶
10⁻⁷
10⁻⁸
p
n
He
ρб
²H
³He
³H
n
⁷Be
⁷Li
⁶Li
²H
3.0
1.0
0.3
0.1
температура, 10⁹ K



Measurements of $_4$He from extragalactic metal-poor HII regions, showing no correlation with metallicity



$X(^4\mathrm{He}) = 0.2421 \pm 0.0021$

$D/H=(2.78 \pm 0.41)\times 10^{-5}$,

$D/H=(1.23 + 0.68 - 0.32)\times 10^{-10}$

Observational Evidence Supporting the Big Bang

- Elemental abundances
- Cosmic Microwave Background (CMB) or Relict Radiation
- Hubble’s law for expansion of the Universe

Universe recombination

380,000 years after the Big Bang

$\boldsymbol{p} + \boldsymbol{e}^{-} \leftrightarrow \boldsymbol{H} + \boldsymbol{\gamma}$ equilibrium with $B_H = 13.6$ eV

Saha equality

$$n_p\, n_e \approx [2\pi/m_e\, T]^{3/2} \exp\{B_H/T\}\, n_H$$

Neutral Universe $n_p = n_e$

Recombination $n_p = n_e \approx 2n_H$

$$n_\gamma = 2\int \frac{dq^3}{(2\pi)^3}\frac{1}{\exp\{q/T_\gamma\}-1} = 2\varsigma(3)T_\gamma^3/\pi^2$$

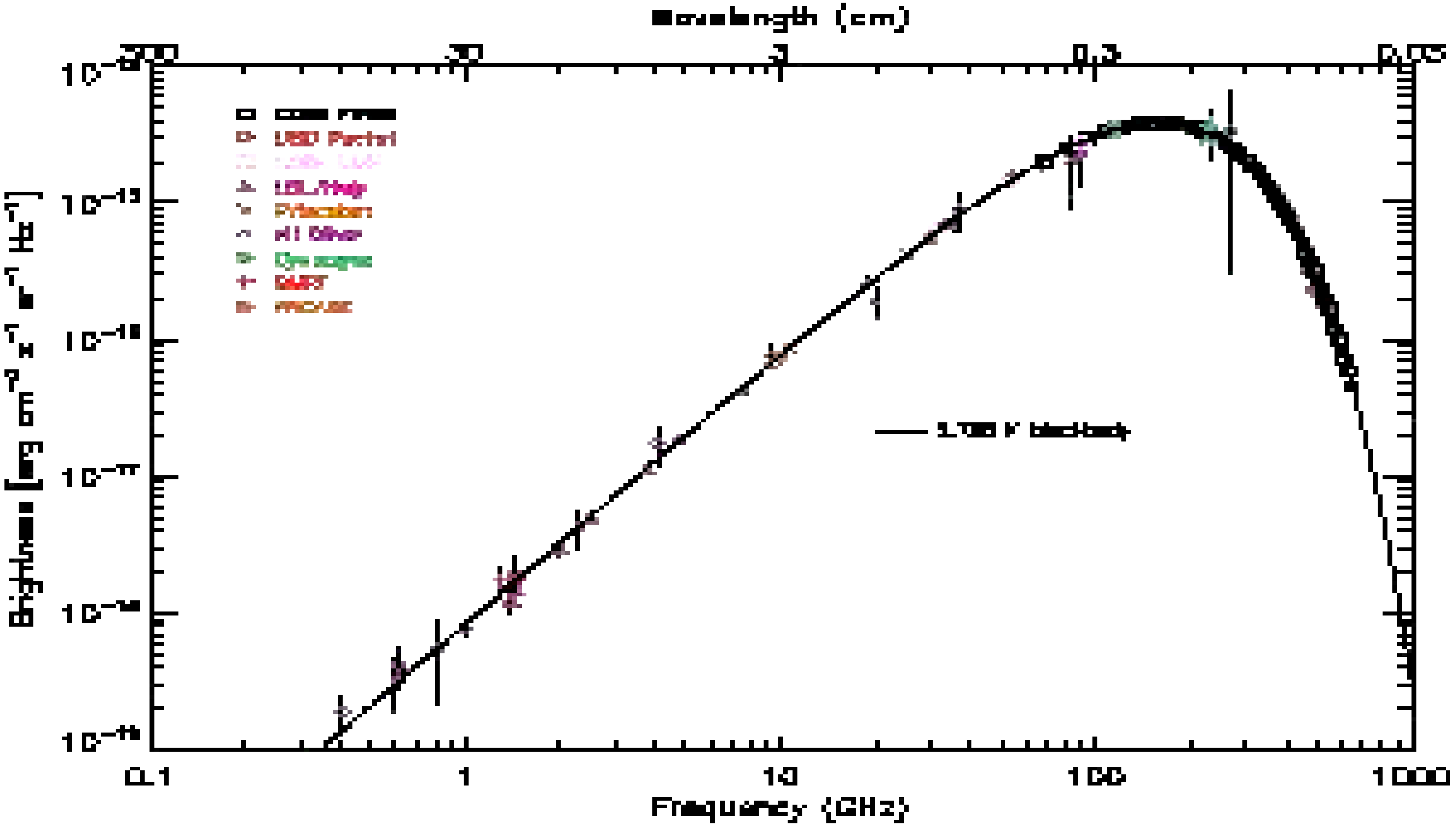
→

$$1 \approx [m_e T_R/2\pi]^{3/2} \exp\{B_H/T_R\}\,\eta$$

Recombination $T_R \approx 3500\ \mathrm{K}$

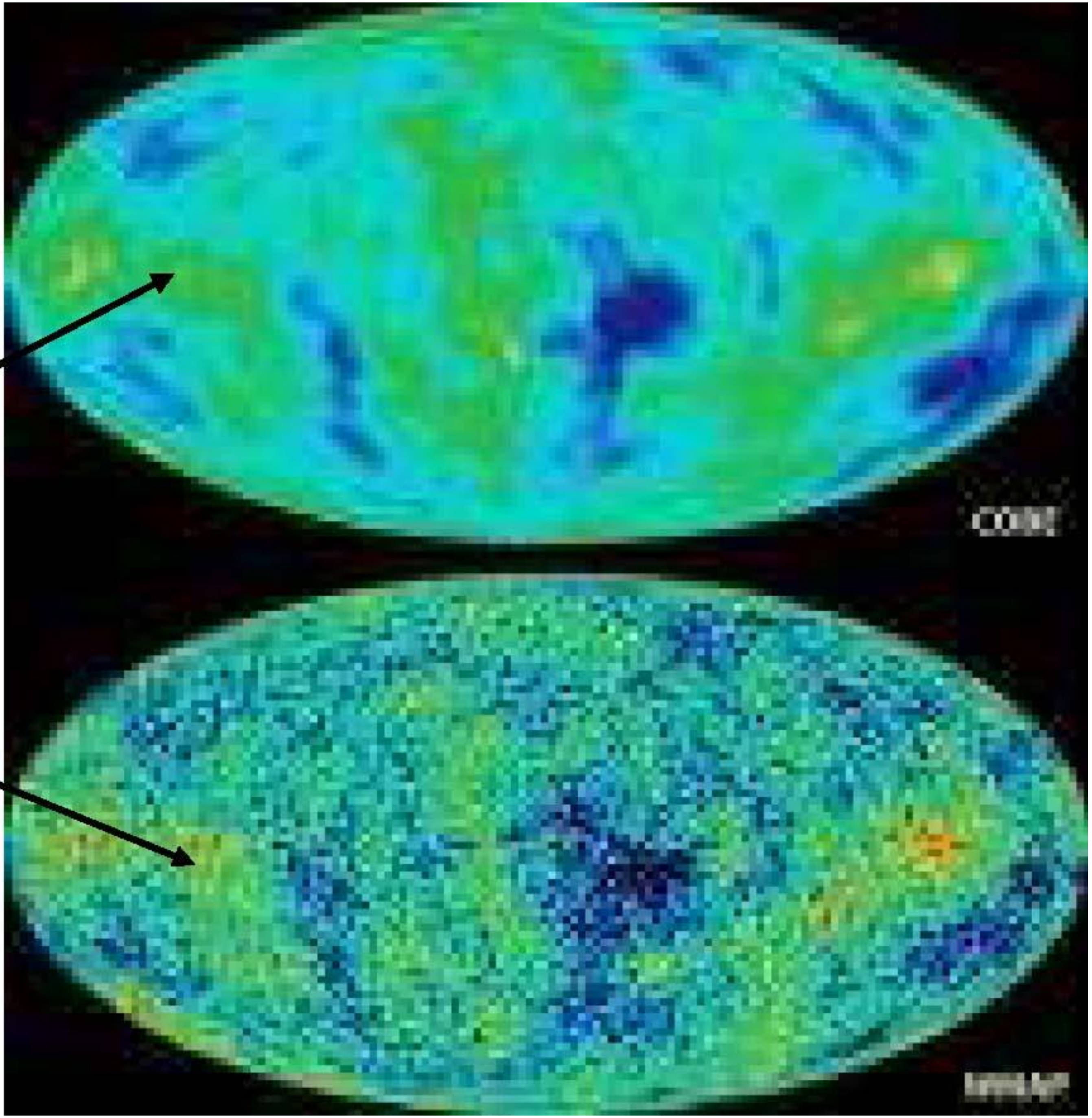
Detection of Cosmic Microwave Background

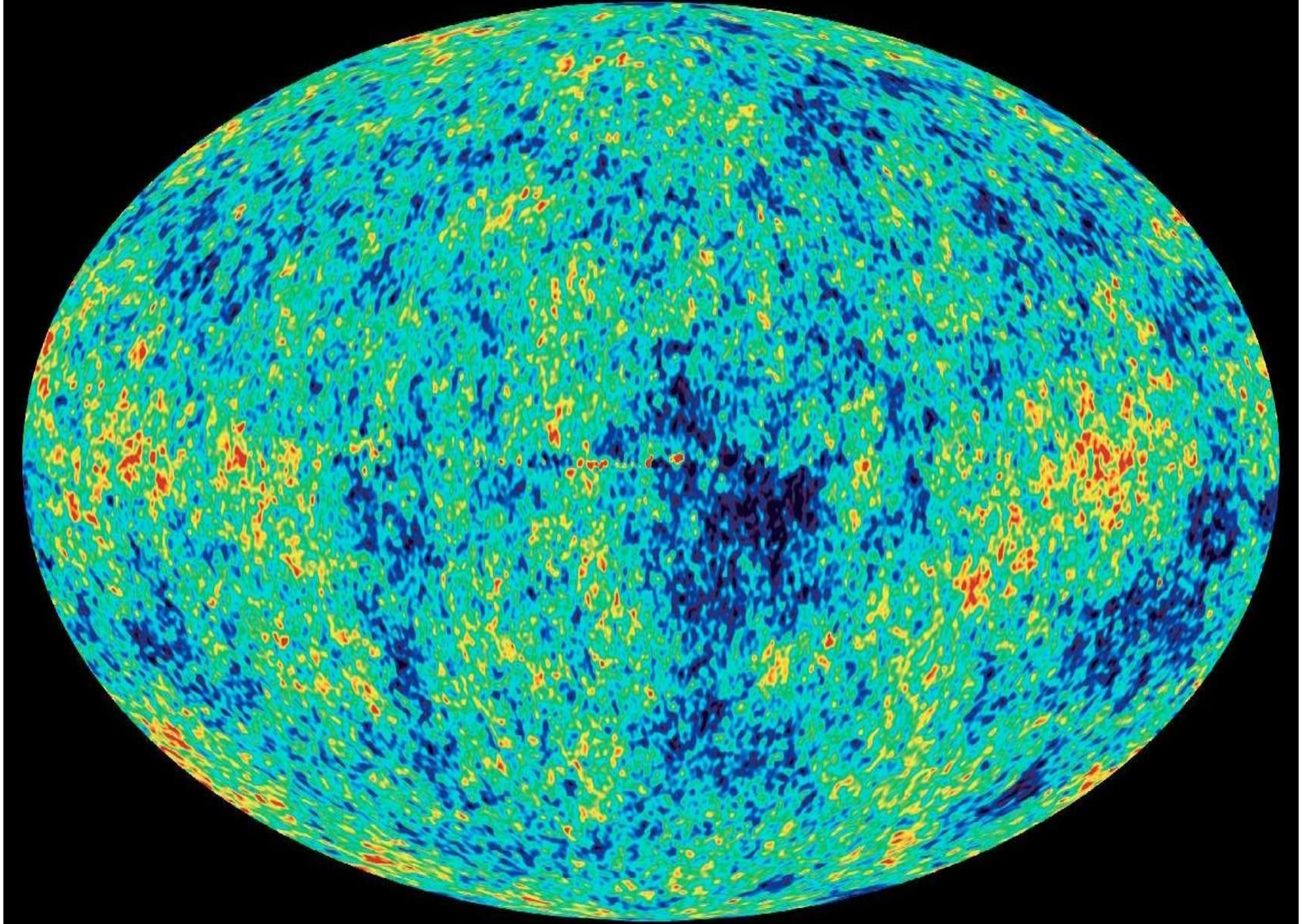
Arno Penzias & Robert Wilson, at Bell Labs in NJ, scooped CMD *by accident* In 1965.

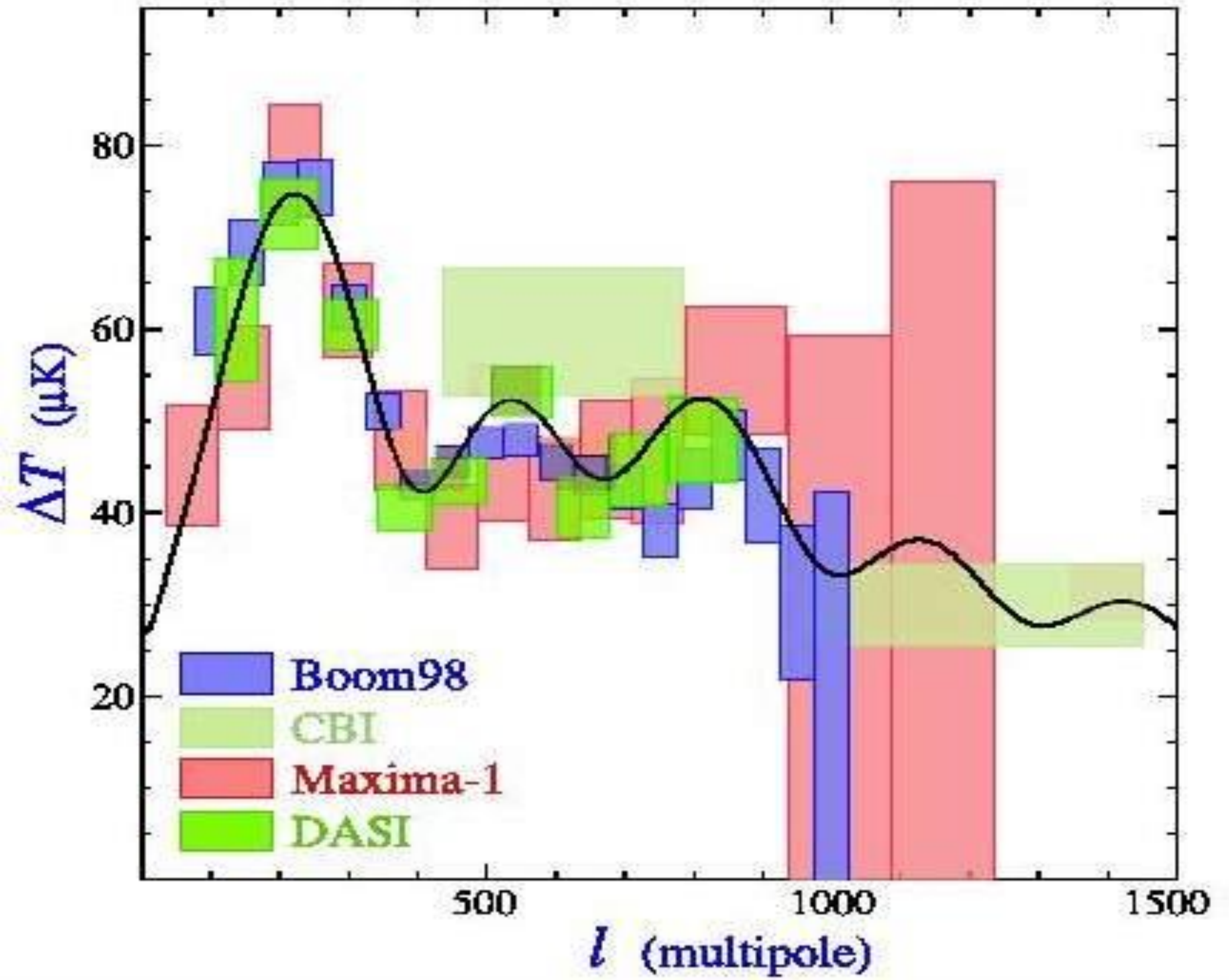


COBE

WMAP






80
60
40
20
500
1000
1500
ΔT (μK)
l (multipole)
Boom98
CBI
Maxima-1
DASI

mass/energy density

Photon, baryon, & neutrino contributions

$T_\gamma \approx 2.785\ \mathrm{K}$ → *photon number density*

$$n_\gamma = 2\int \frac{dq^3}{(2\pi)^3} \frac{1}{\exp\{q/T_\gamma\} - \underset{\approx}{1}} = 2\varsigma(3)T_\gamma^3/\pi^2 \approx 411/\mathrm{cm}^3$$

$$\rho_\gamma = \pi^2\ T^4/\ 15 \approx 4.64\ 10^{-34}\ \mathrm{g/cm^3} \approx 0.26\ \mathrm{eV/cm^3}$$

$$\rho_\gamma \sim 10^{-5.5}\ \rho_{crit}$$

γ

mass/energy density

Photon, baryon, & neutrino contributions

$$\eta_{\mathrm{BBN}} \approx (5.9 \pm 0.8) * 10^{-10}$$

$$\eta_{\mathrm{CMB}} \approx (6.14 \pm 0.25) * 10^{-10}$$

$$n_{barion} = \eta\, n_{\gamma} \approx 2.5\ 10^{-7}\ /\mathrm{cm}^3$$

$$\rho_b = n_{\mathrm{nucleons}}\, M_N \approx 4.19 * 10^{-31} \mathrm{g/cm}^3$$

$$\approx 0.0442 \rho_{\mathrm{crit}}$$

$$\rho_e \approx (6 m_e / 7 M_N) \rho_b \approx 2 \times 10^{-5} \rho_{crit}$$

mass/energy density neutrino contributions

Contributions of each neutrino flavor (e.g., ν_e and $\underline{\nu}_e$)

$$n_\upsilon = 2\int \frac{dq^3}{(2\pi)^3} \frac{1}{\exp\{q/T_\upsilon\}+1} = 2\varsigma(3)T_\upsilon^3/(2\pi^2)$$

$$n_\upsilon = \frac{3}{4}\left(\frac{T_\upsilon}{T\gamma}\right)^3 n_\gamma \qquad \text{(ME5)}$$

constancy of entropy

$$\frac{T_\upsilon}{T_\gamma} = \left(\frac{\rho_\gamma^T}{\rho_\gamma^T + \rho_{e^+}^T + \rho_{e^-}^T}\right)^{1/3}$$

$$\rho_{e^-} = 2\int \frac{dq^3}{(2\pi)^3} \frac{q}{\exp\{q/T_\upsilon\}-1} = \frac{7}{8}\rho_\gamma$$

$$\frac{T_\upsilon}{T_\gamma} = \left(\frac{4}{11}\right)^{1/3}$$

$$n_\upsilon = \frac{3}{4}\frac{7}{11} n_\gamma = \frac{3}{11} n_\gamma \qquad \text{(ME6)}$$

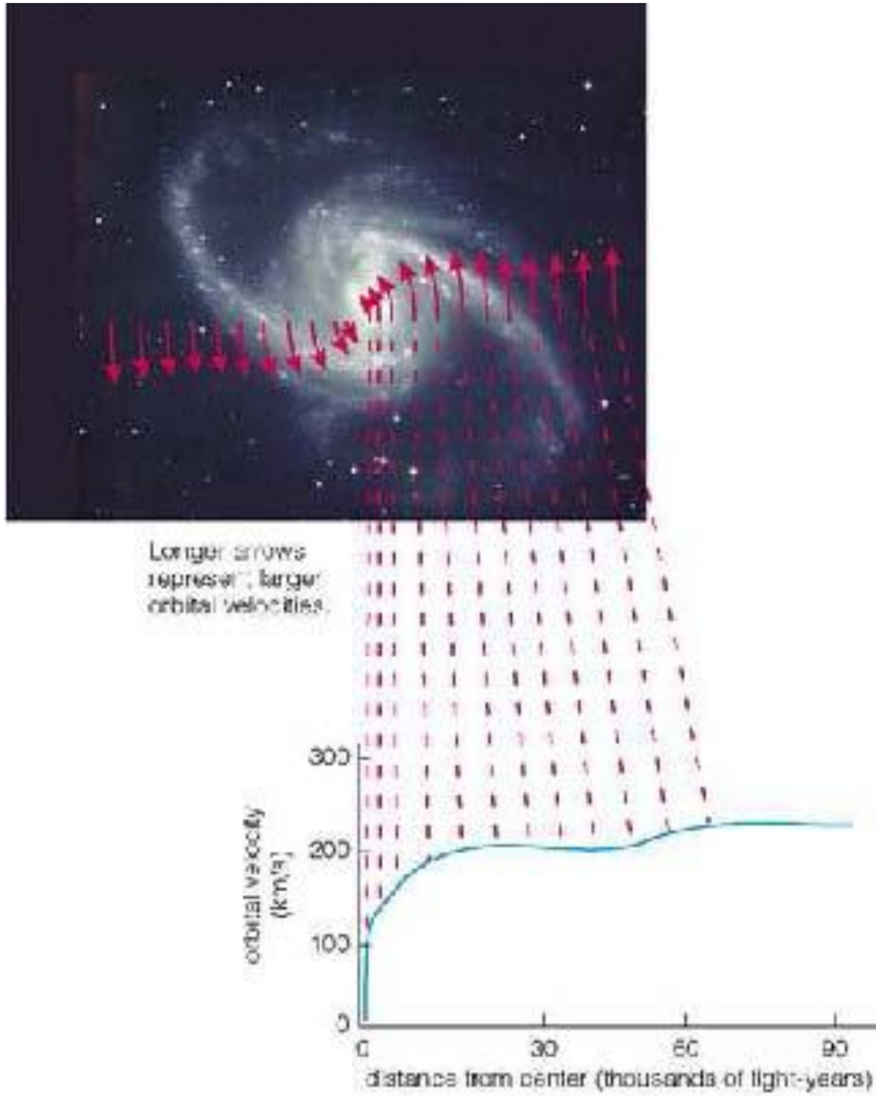
$$\rho_\upsilon = \frac{3}{11} n_\gamma \sum\nolimits_i m_\upsilon(i) = 0.0106\,\frac{\rho_{\text{crit}}}{h^2}\sum\nolimits_i m_\upsilon(i) \qquad \text{(ME7)}$$

$$0.055 \text{ eV} \leq \sum\nolimits_i m_\upsilon(i) \leq 1 \text{ eV}$$

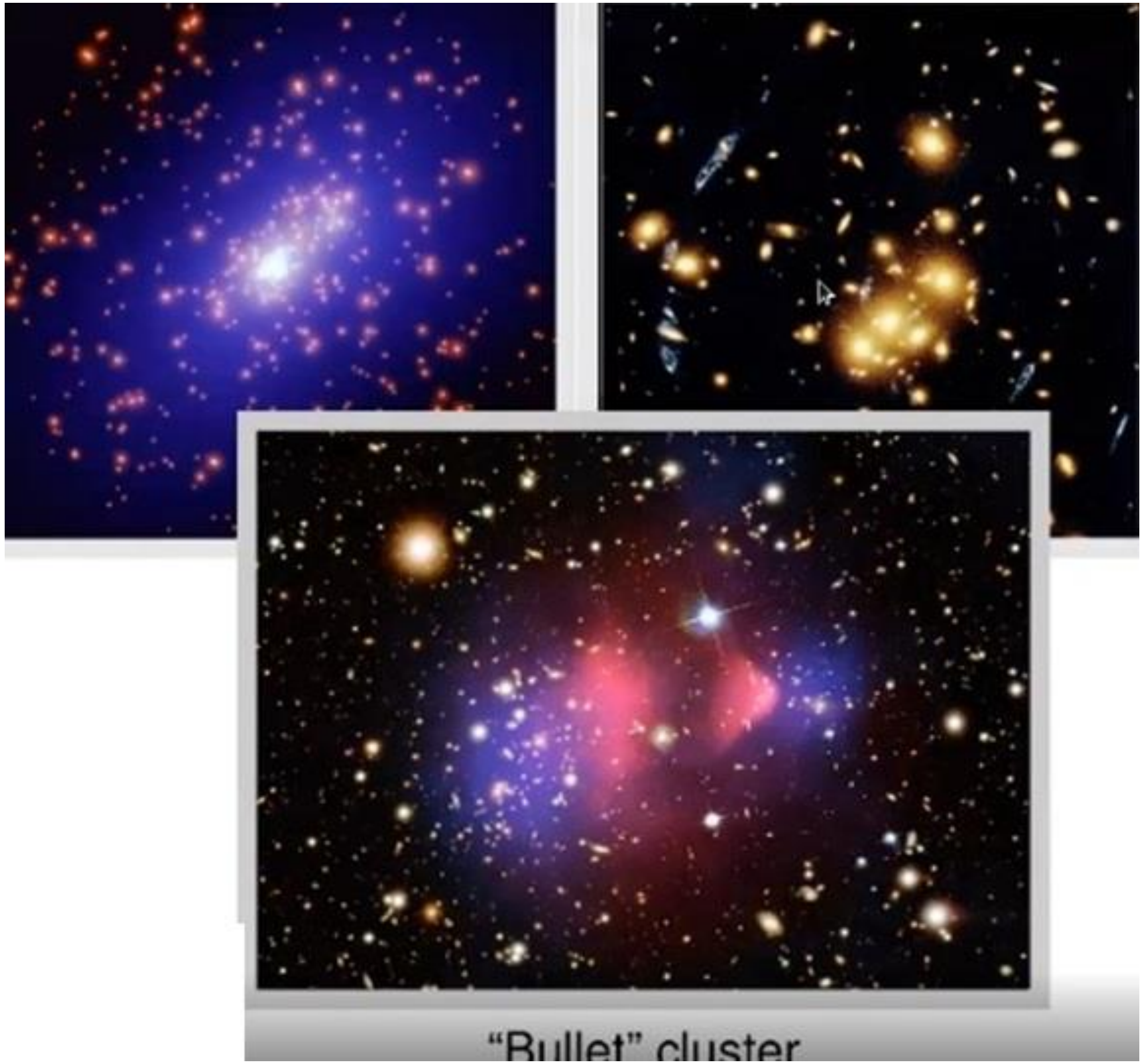
$$0.0011 < \rho_\nu/\rho_{\text{crit}} < 0.026 \qquad \text{(ME8)}$$

Universe compositi0n based on astrophysics

Rotating galaxies

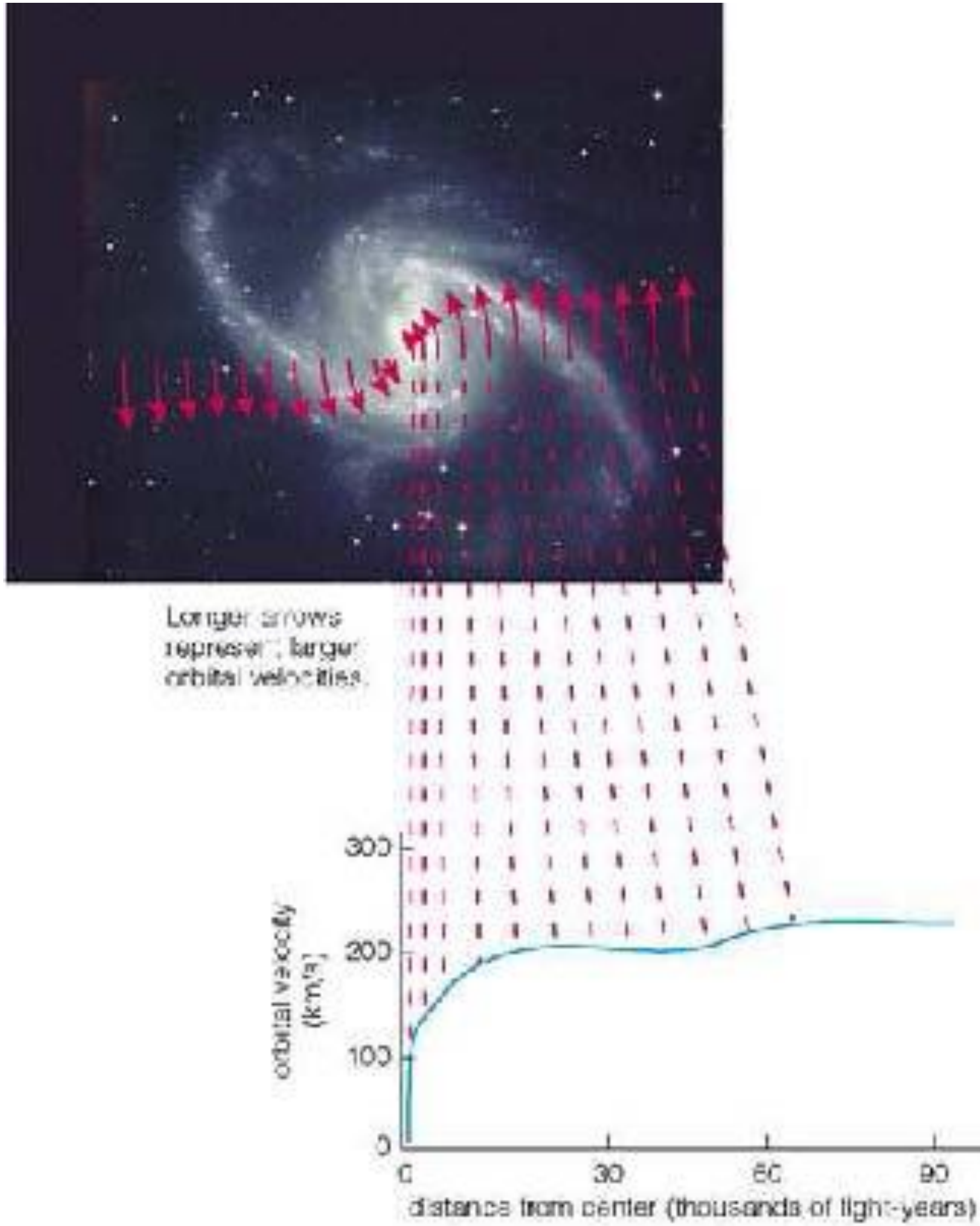


Lensing due to gravitation



Dark Matter. How to Measure

- emit no radiation & invisible at electromagnetic wavelengths
- detected through the force of gravity
- **dark matter** mass =
  Total Mass -Luminous Mass
- **dark fraction**:
- Spirals/ Ellipticals:
  90% total mass
  within R=150,000 ly
- Cluster of galaxies:
  90% of total mass
  within cluster



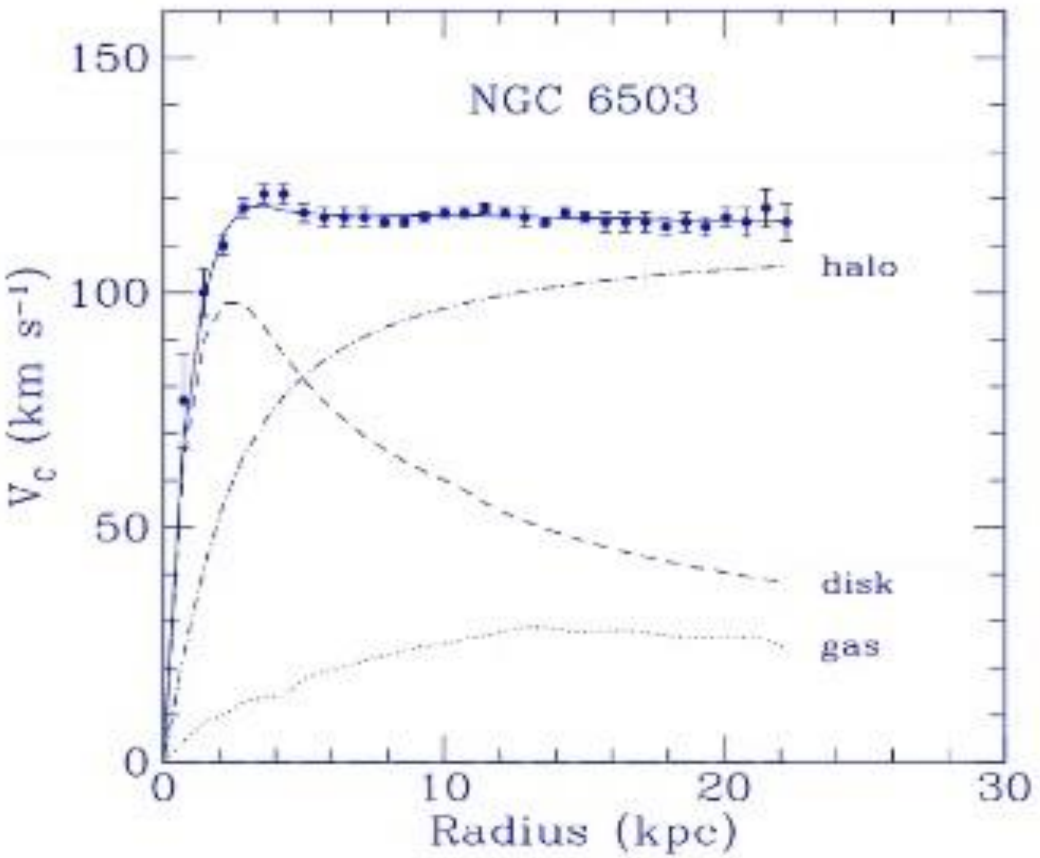
Galactic dark halos: flat rotation curves

Newtonian dynamics

$$\frac{V^2(R)}{R} m = G\frac{mM(R)}{R^2}$$

$$v(R) = \sqrt{G\frac{M(R)}{R}}$$

$$M(R) = 4\pi\int_0^R \rho(r) r^2 dr$$



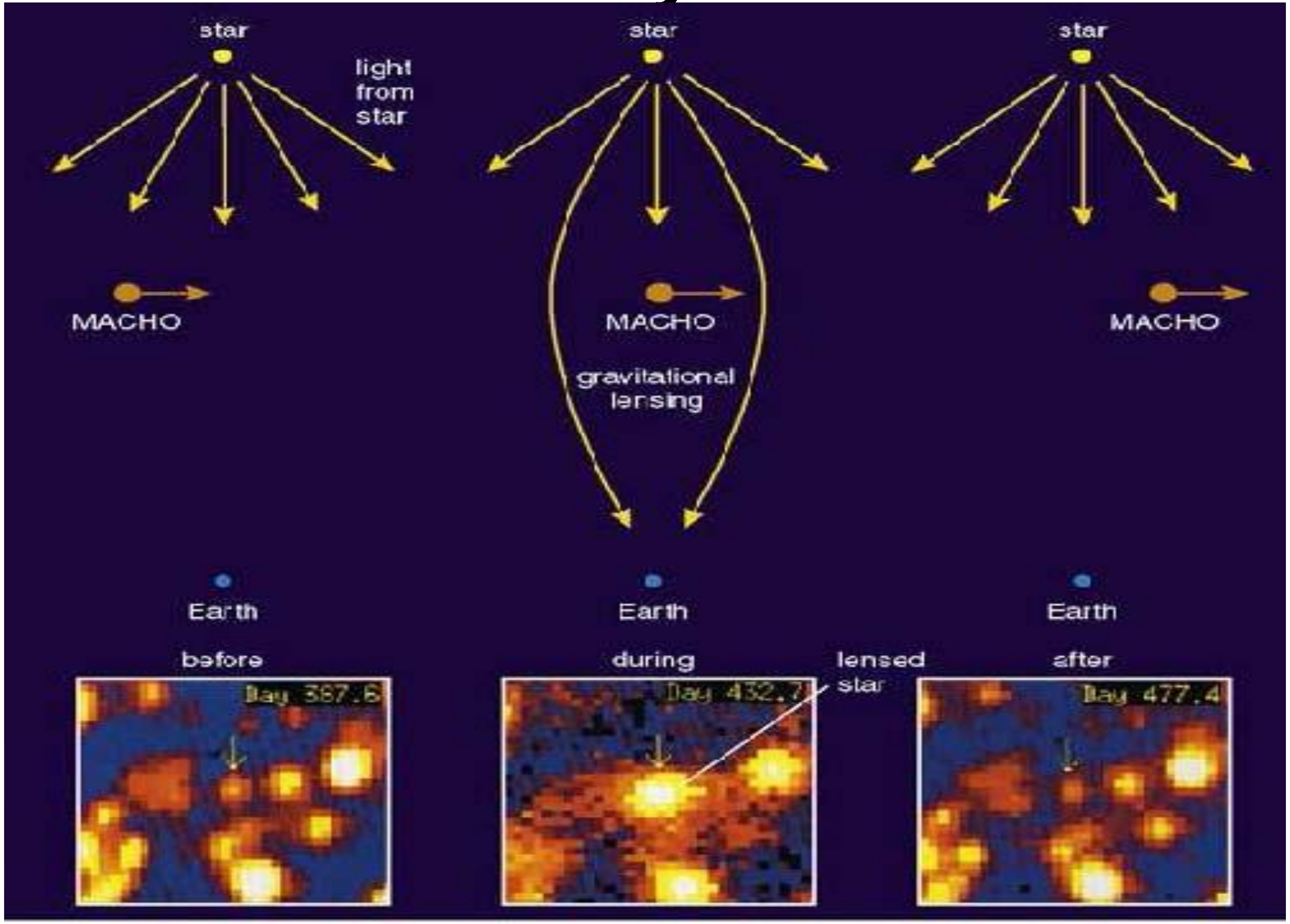
observations: $v(R) \simeq$ const

visible matter: internal regions $v(R) \propto \sqrt{R}$

external ("empty") regions $v(R) \propto 1/\sqrt{R}$

Detecting Dark Matter Candidates?

MACHOS in our Galaxy via Microlensing



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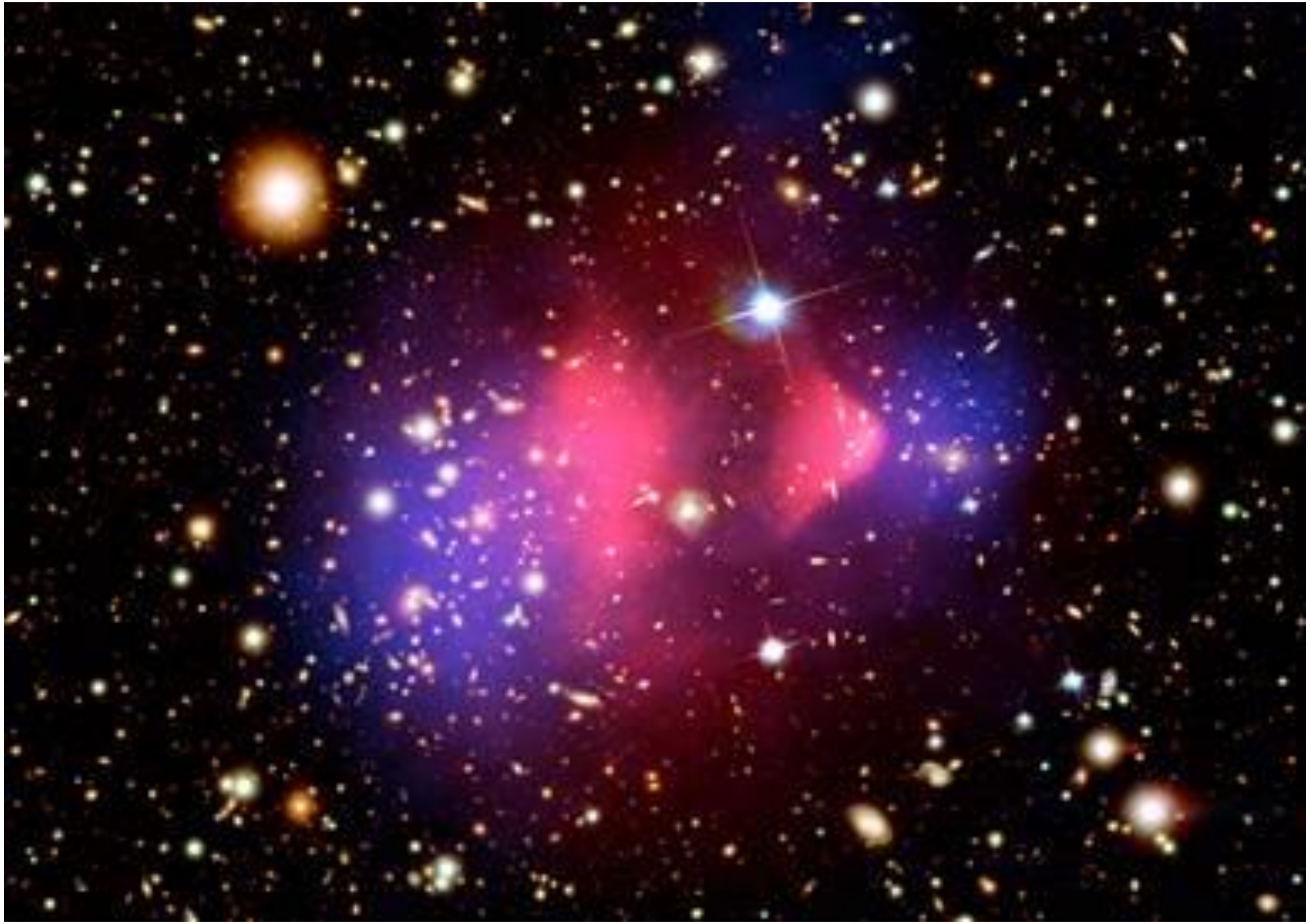
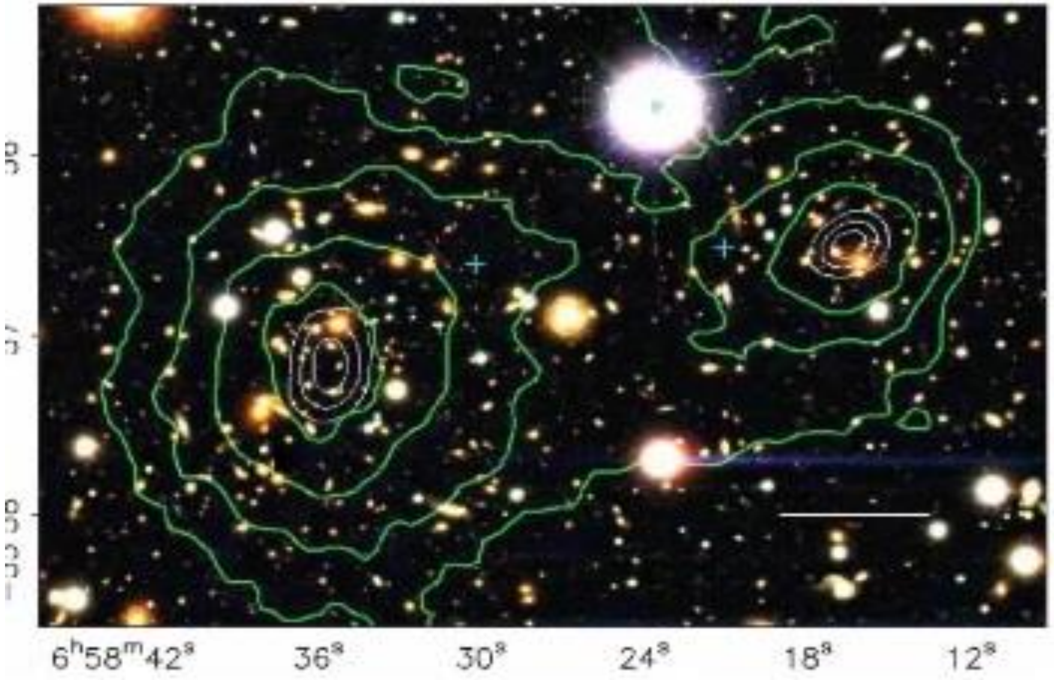
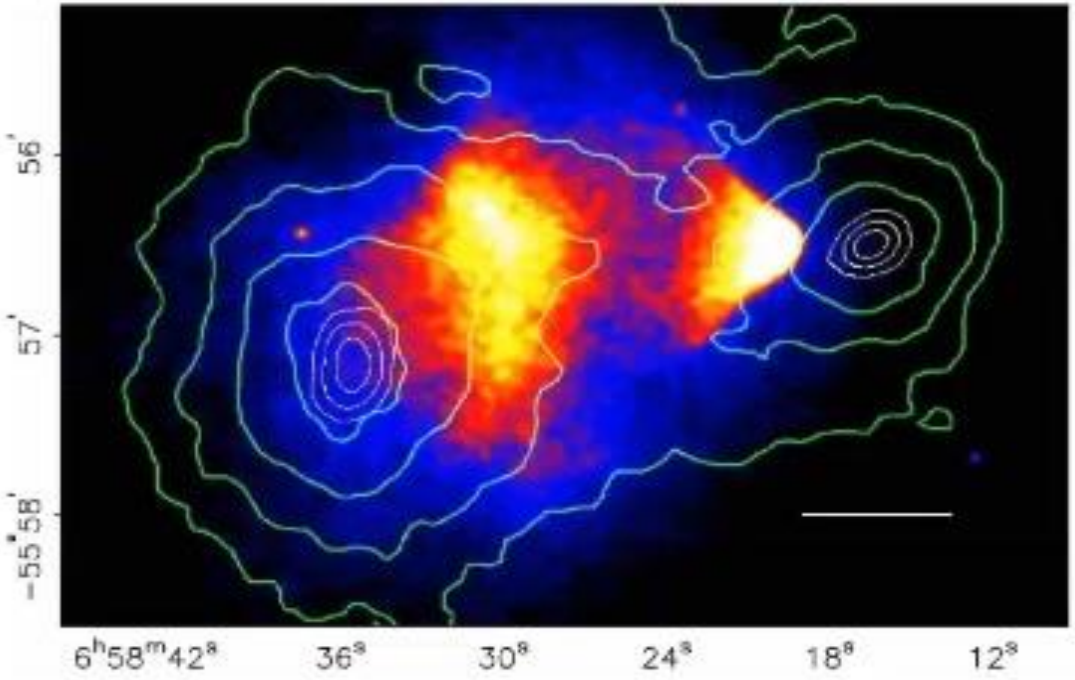


- Composite image of the **Bullet cluster (1E 0657-56)** shows distribution of ordinary matter, inferred from X-ray emissions, in red and total mass, inferred from gravitational lensing, in blue

Colliding clusters (Bullet clusters 1E0657-558)



gravitational lensing



Observations in X-rays

$M \simeq 10 \times m$

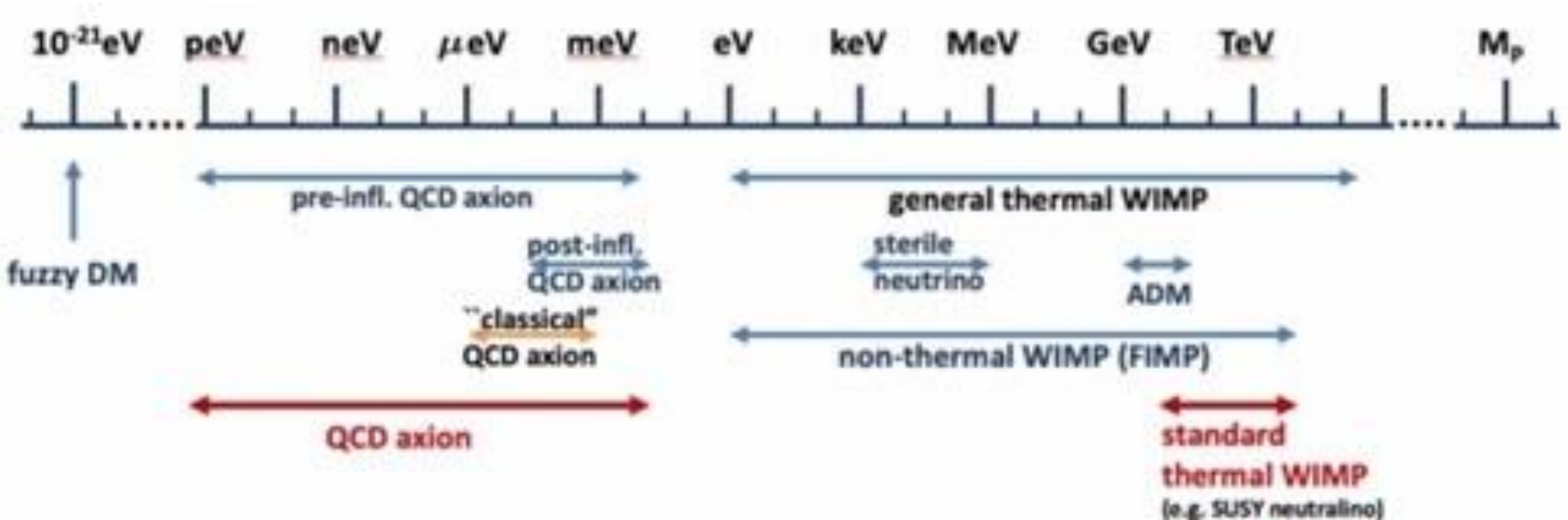
scale is 200 kpc

clusters are at 1.5 Gpc

Astrophysical constraints for Dark Matter

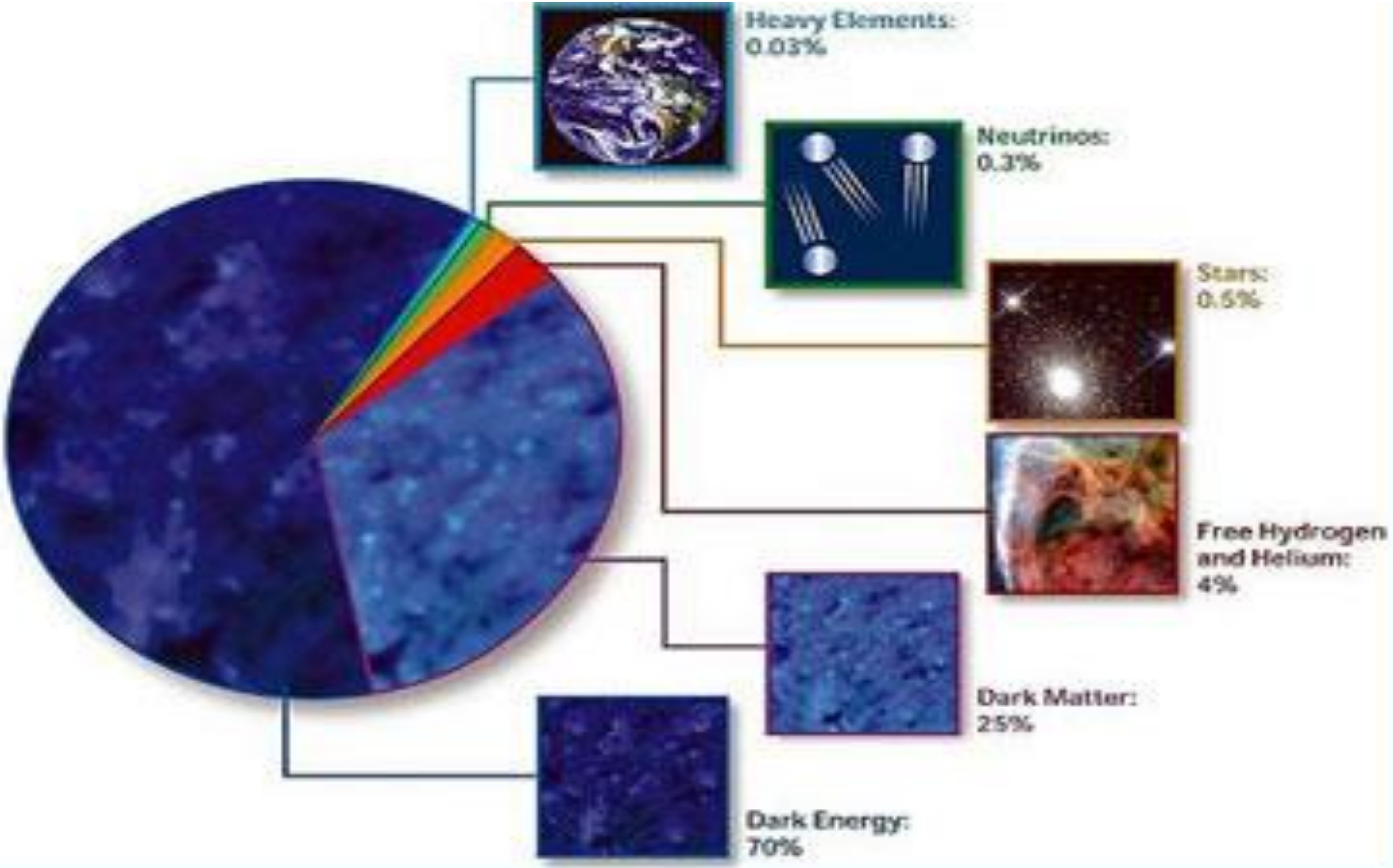
- Stable on the Universe time-scale
- Practically non collisional
- No electric charge

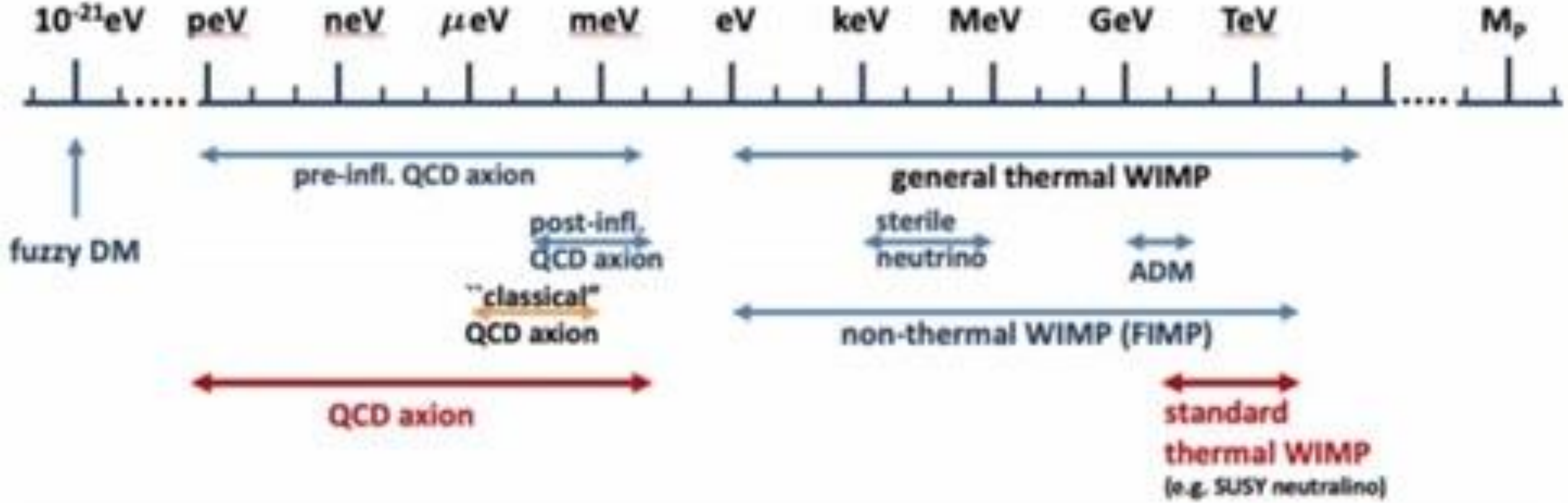
Form ellipsoidal hallo
being invisible



Astrophysical constraints for Dark Matter

- Stable global stellar clusters $M_{\mathrm{dm}} < 10^3 M_{\mathrm{Sun}} \approx 10^{61}$ GeV
- Confined in galaxy quantum effects
- Wavelength $\lambda = 2\pi / M_{\mathrm{dm}} V_{\mathrm{dm}} < l_{\mathrm{galaxy}}$
- Bosons $M_{\mathrm{dm}} > 10^{-22}$ eV
- Fermions $M_{\mathrm{dm}} > 750$ eV
- If present at prestellar nucleosynthesis $M_{\mathrm{dm}} > 10$ MeV


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



10^{-21}eV peV neV μeV meV eV keV MeV GeV TeV M_P

fuzzy DM

pre-infl. QCD axion

post-infl. QCD axion

"classical" QCD axion

QCD axion

general thermal WIMP

sterile neutrino

ADM

non-thermal WIMP (FIMP)

standard thermal WIMP
(e.g. SUSY neutralino)