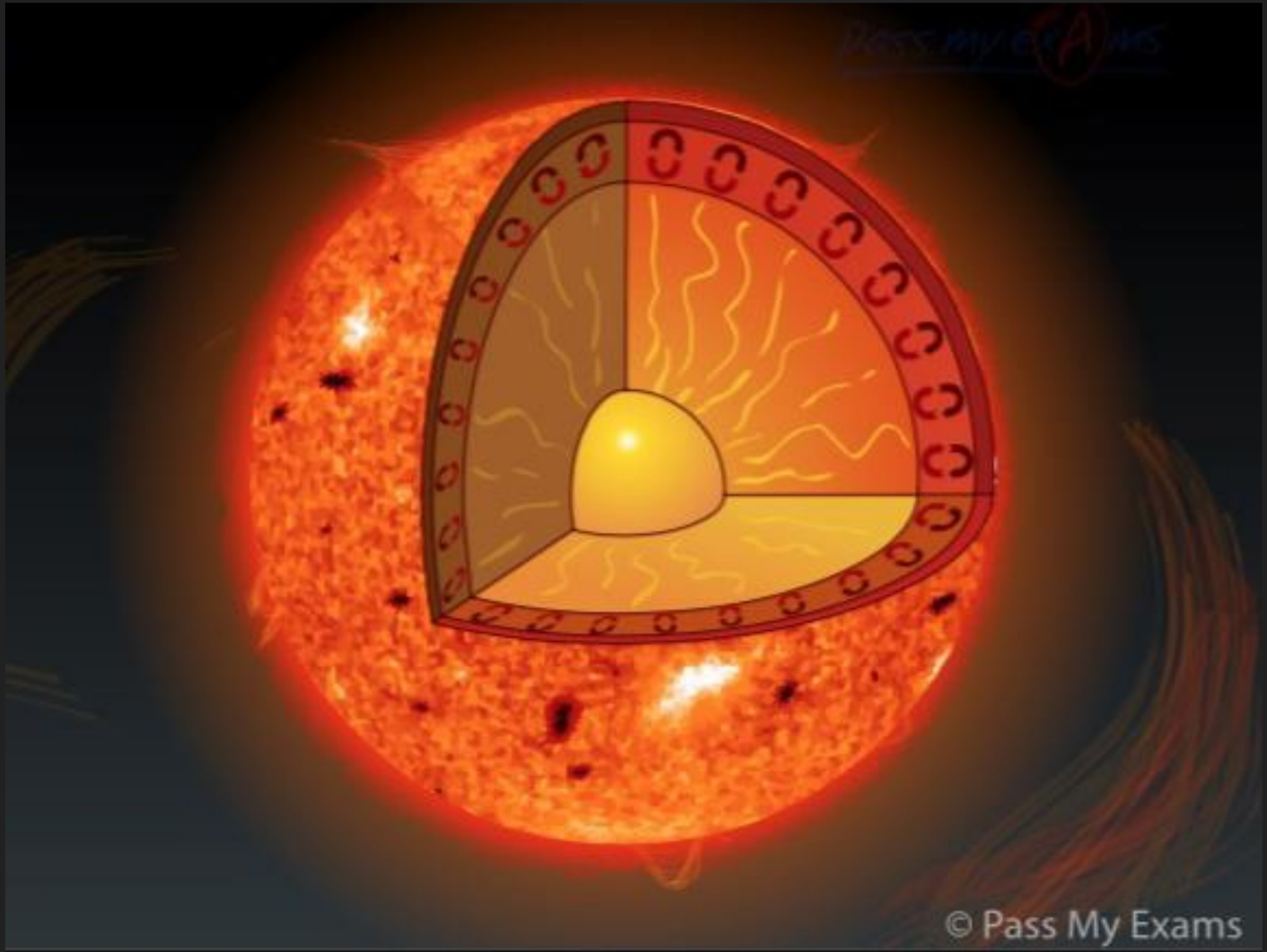
Современная астрофизика: обзор

Сергей Попов

Солнце

- Гидростатическое равновесие
- Термоядерные реакции
- Нейтрино
- Конвекция и перенос излучения
- Магнитогидродинамика
- Гелиосейсмология

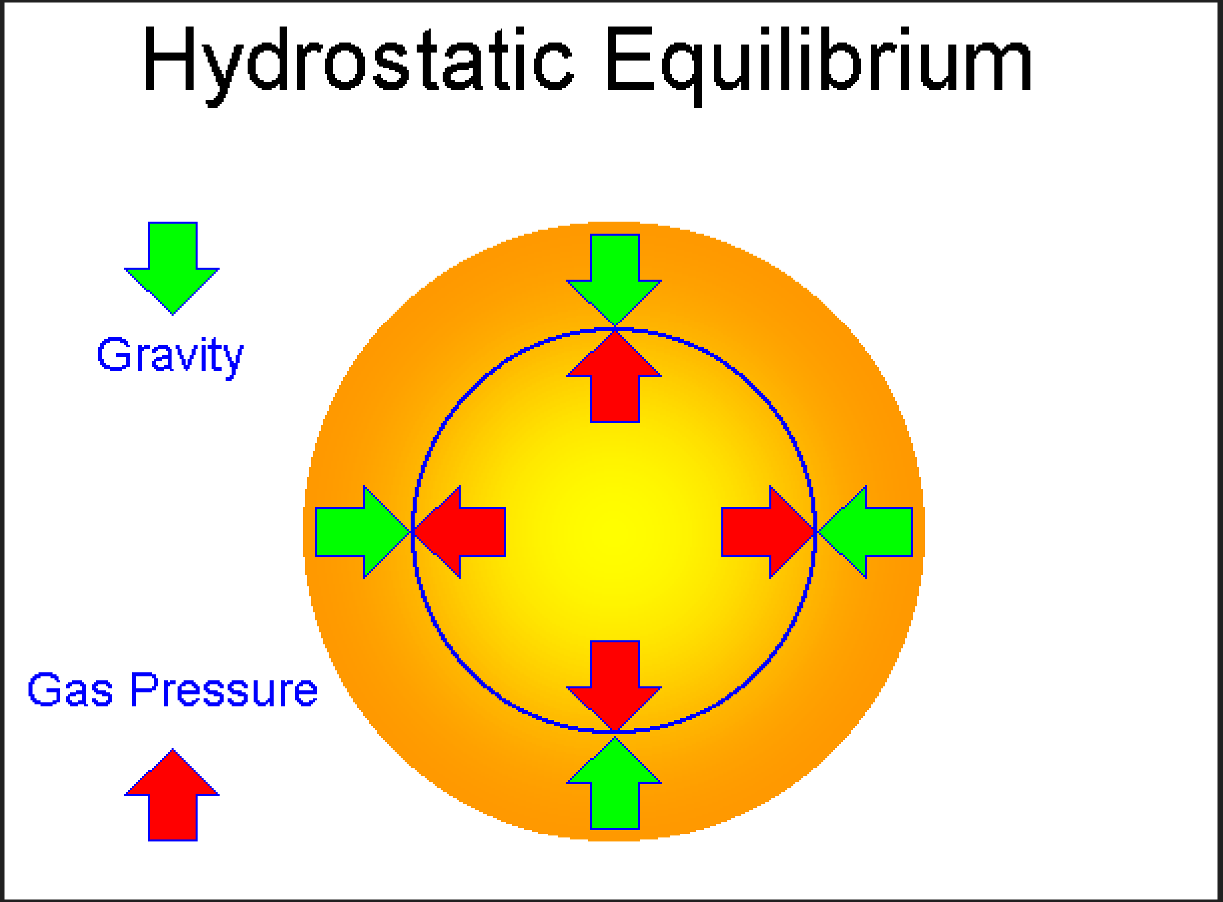


Гидростатическое равновесие

$$\frac{dP}{dr} = -\rho(r)g(r)$$

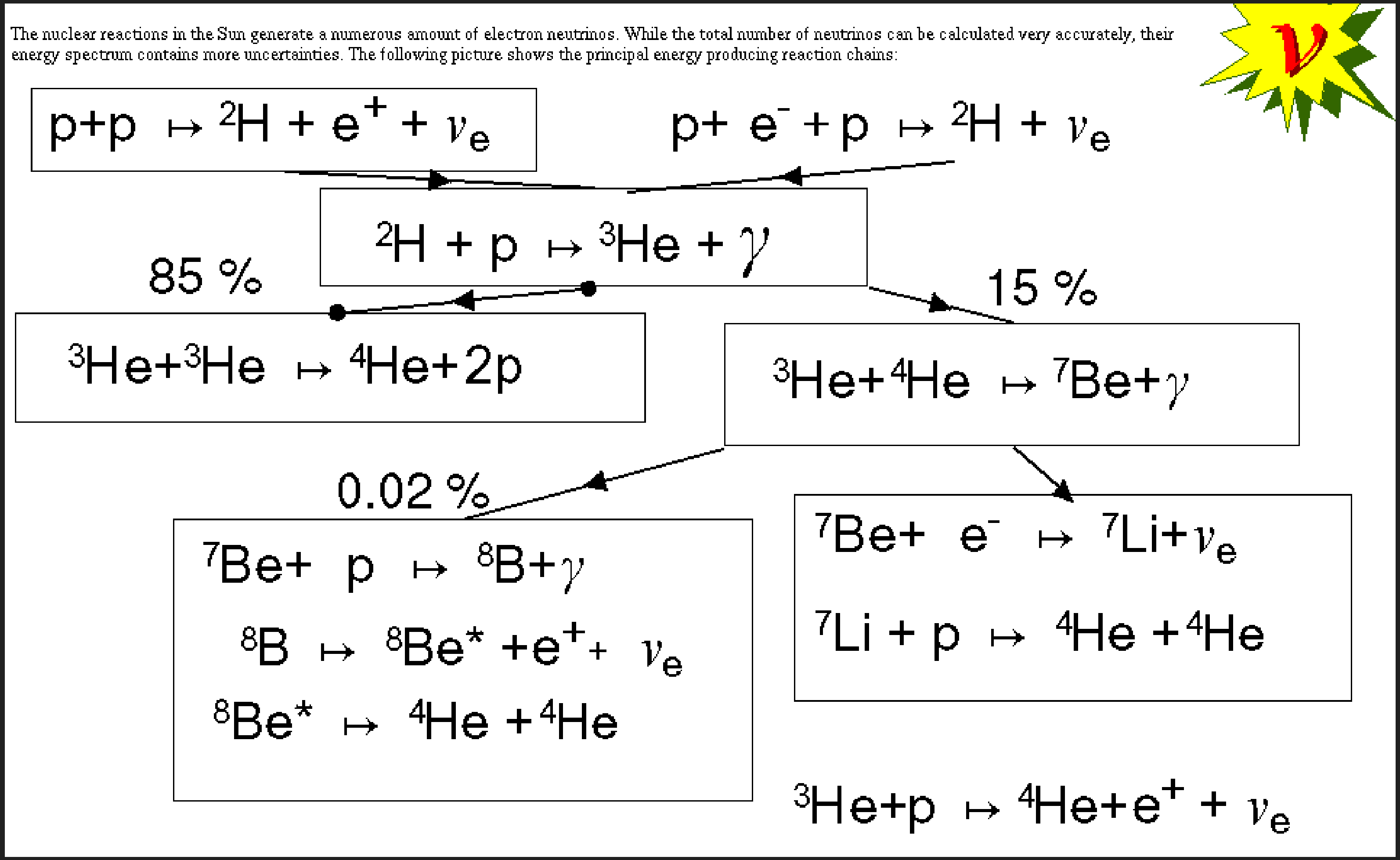
or,

$$\frac{dP}{dr} = -\frac{GM(r)\rho(r)}{r^2}$$


Hydrostatic Equilibrium
Gravity
Gas Pressure

Термоядерные реакции

pp-цикл



The nuclear reactions in the Sun generate a numerous amount of electron neutrinos. While the total number of neutrinos can be calculated very accurately, their energy spectrum contains more uncertainties. The following picture shows the principal energy producing reaction chains:

$p+p \mapsto {}^2H + e^+ + \nu_e$

$p+ e^- + p \mapsto {}^2H + \nu_e$

${}^2H + p \mapsto {}^3He + \gamma$

85 %

${}^3He+{}^3He \mapsto {}^4He+2p$

15 %

${}^3He+{}^4He \mapsto {}^7Be+\gamma$

0.02 %

${}^7Be+ p \mapsto {}^8B+\gamma$

${}^8B \mapsto {}^8Be^* +e^+ + \nu_e$

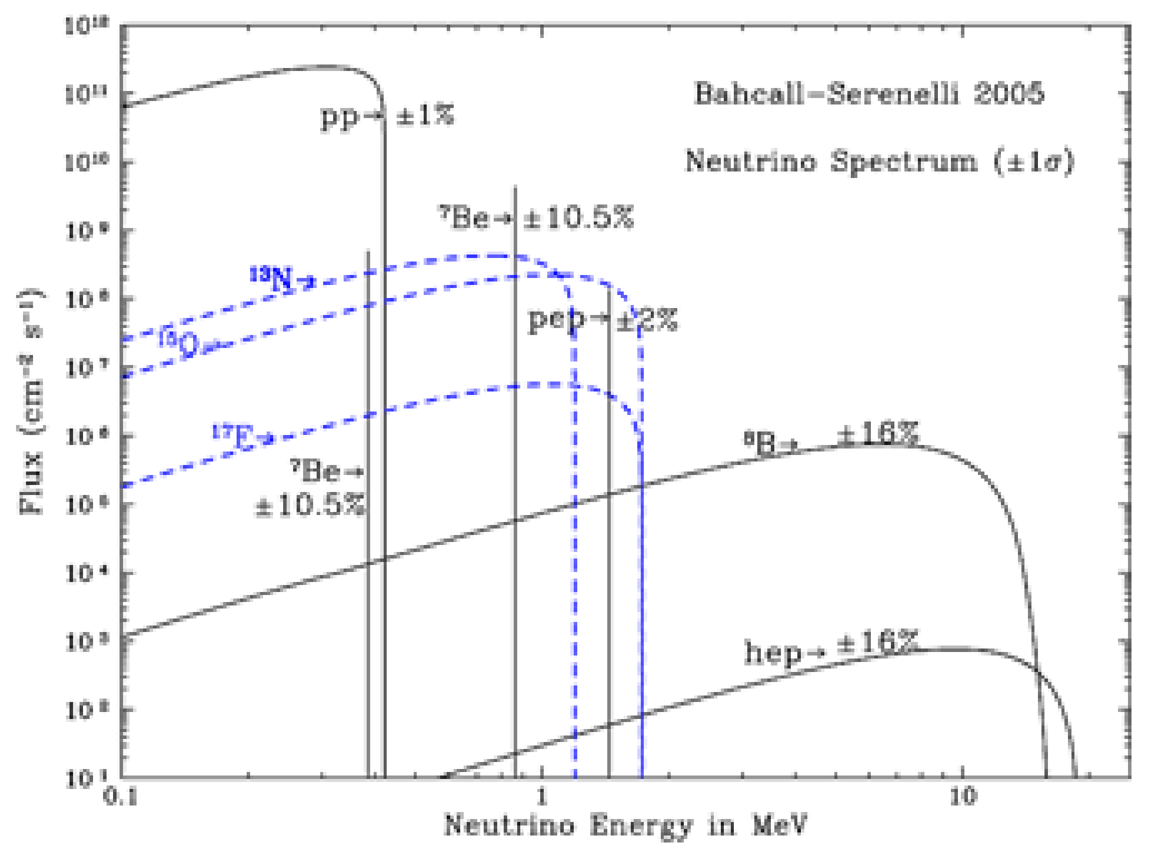
${}^8Be^* \mapsto {}^4He + {}^4He$

${}^7Be+ e^- \mapsto {}^7Li+\nu_e$

${}^7Li + p \mapsto {}^4He + {}^4He$

${}^3He+p \mapsto {}^4He+e^+ + \nu_e$

Солнечные нейтрино

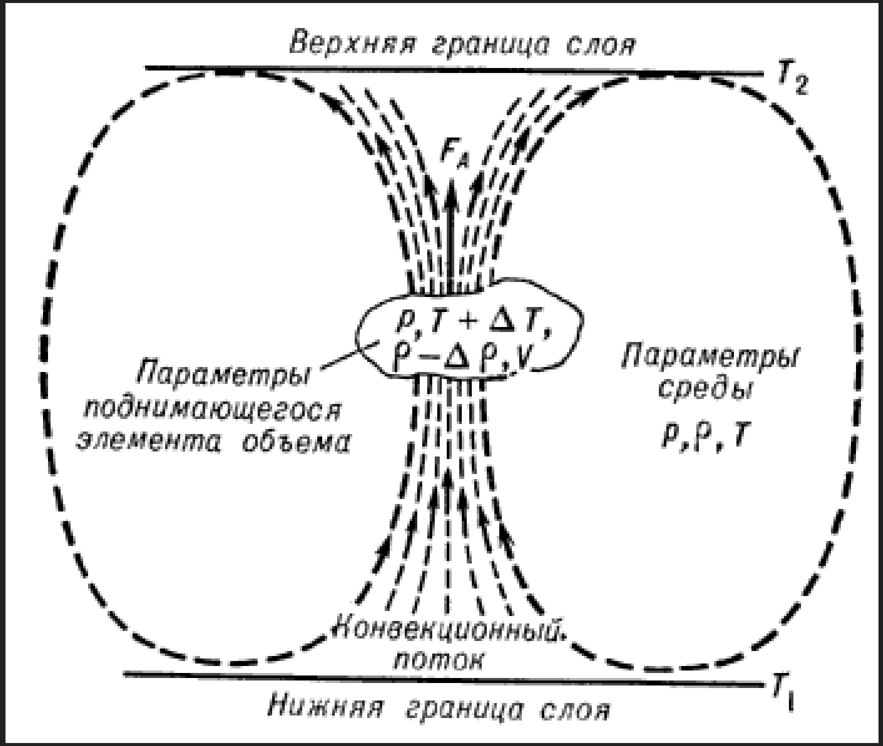


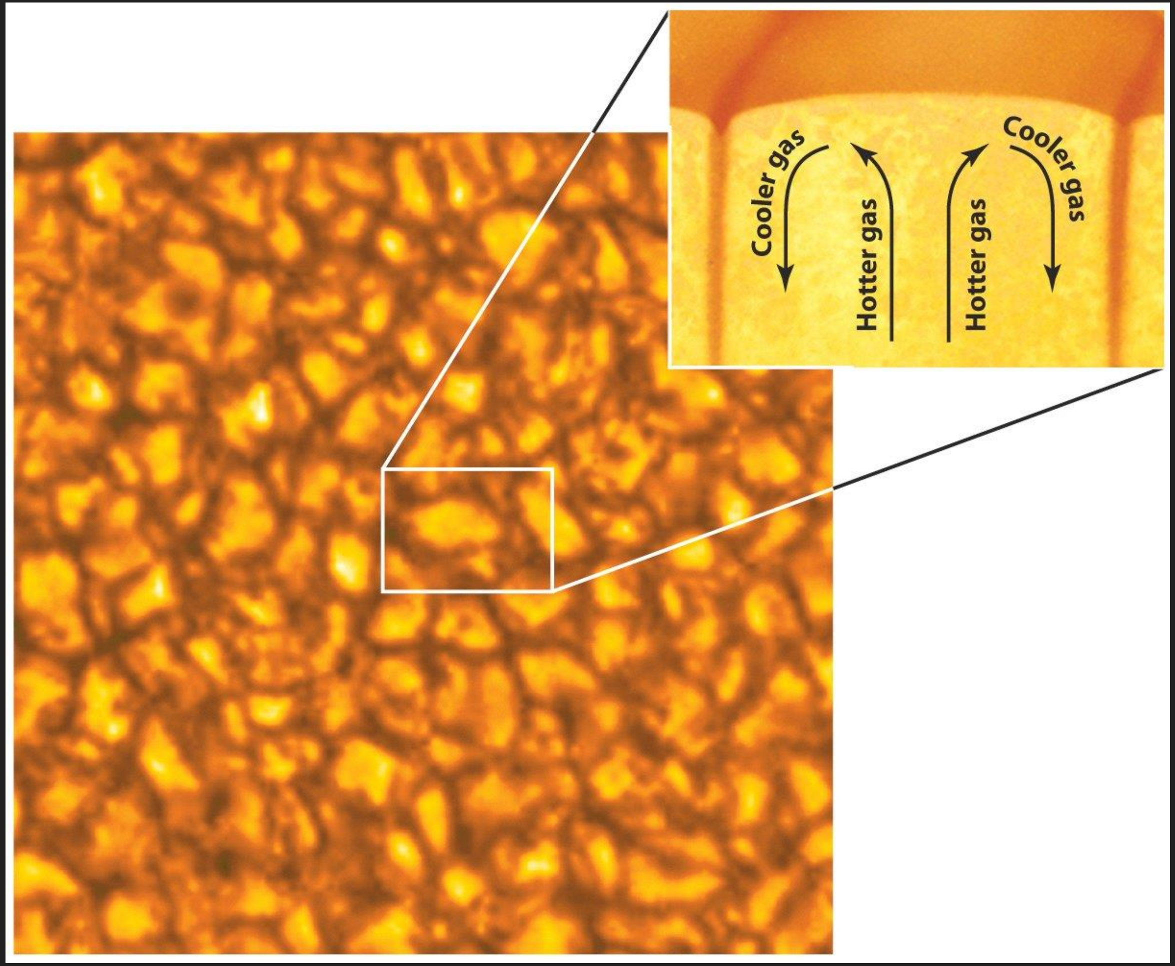
Конвекция

$R > R_{кр}$

$$R = \frac{d^4 \beta g}{\nu \xi} \left(\nabla T - \nabla T_{ад}\right)$$

Критерий Рэлея


Верхняя граница слоя
T_2
F_A
$p, T + \Delta T,$
$\rho - \Delta \rho, V$
Параметры поднимающегося элемента объема
Параметры среды
p, ρ, T
Конвекционный поток
T_1
Нижняя граница слоя


Cooler gas
Hotter gas
Hotter gas
Cooler gas

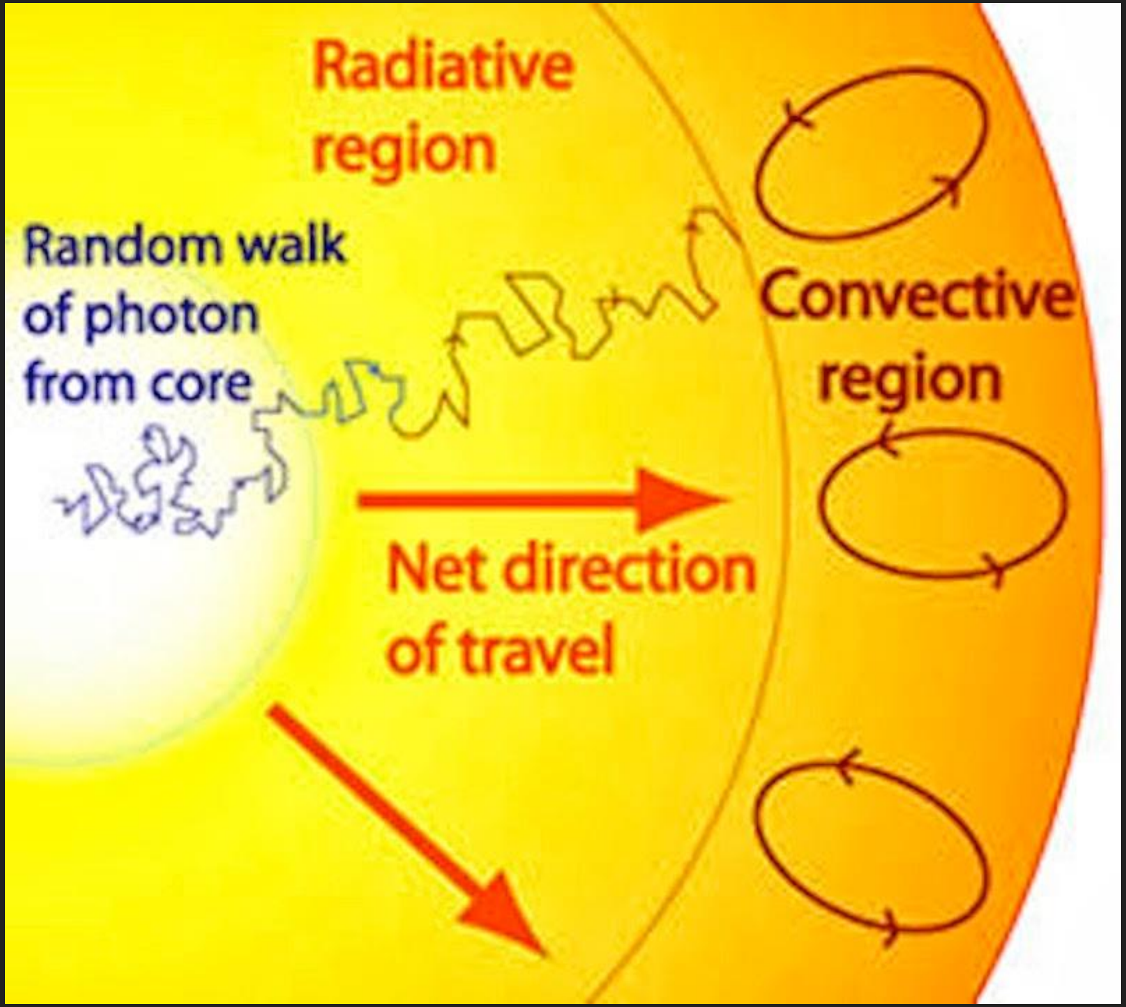
Перенос энергии излучением

$$L(r) = -4\pi r^2 D_\gamma 4a_r T^3 \nabla T$$

$$\varepsilon_r = a_r T^4$$

$$\frac{dT}{dr} = -\frac{3\kappa\rho}{4ca_r T^3}\frac{L(r)}{4\pi r^2}$$

$$\kappa = (\kappa_T + \kappa_{ff} + \kappa_{bf} + \kappa_{bb}\ldots)$$


Radiative region
Random walk of photon from core
Convective region
Net direction of travel

Магнитогидродинамика

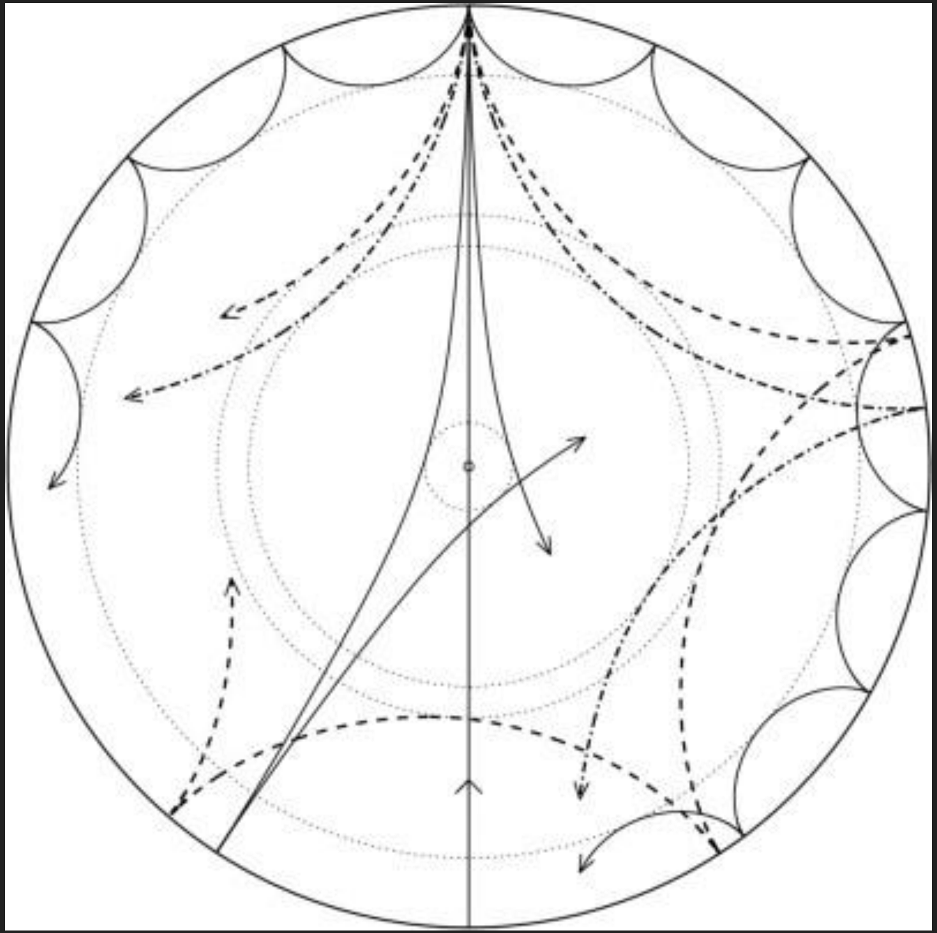
$$\frac{\partial \varrho}{\partial t} + \nabla \cdot (\varrho \boldsymbol{V}) = 0,$$

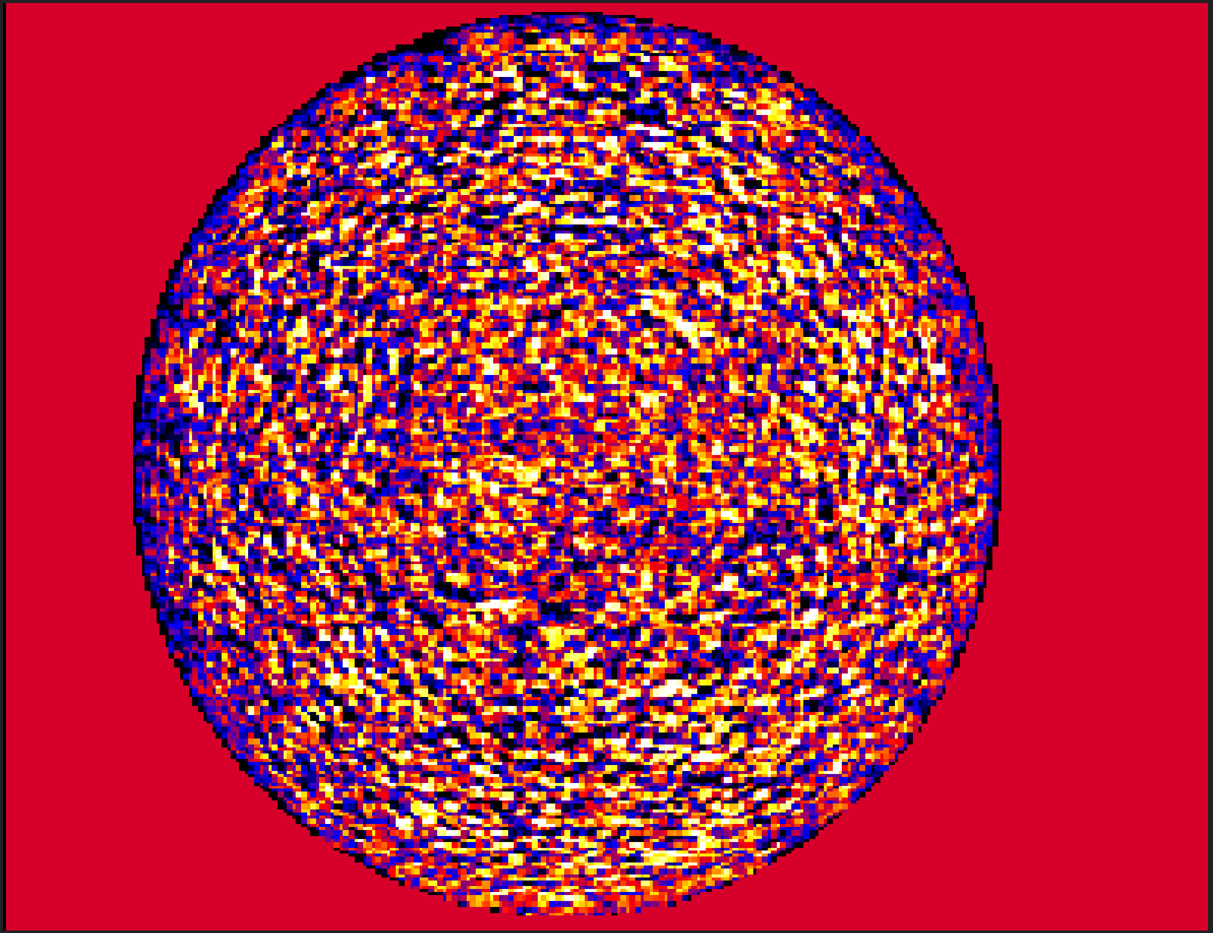
$$\varrho \frac{\partial \boldsymbol{V}}{\partial t} + \varrho (\boldsymbol{V} \cdot \nabla) \boldsymbol{V} = -\nabla p + \frac{1}{\mu} (\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \varrho \boldsymbol{g}$$

$$\frac{\partial p}{\partial t} + \boldsymbol{V} \cdot \nabla p = -\gamma p \nabla \cdot \boldsymbol{V},\ p = \frac{k_{\mathrm{B}}}{m} \varrho T,$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{V} \times \boldsymbol{B}), \nabla \cdot \boldsymbol{B} = 0,$$

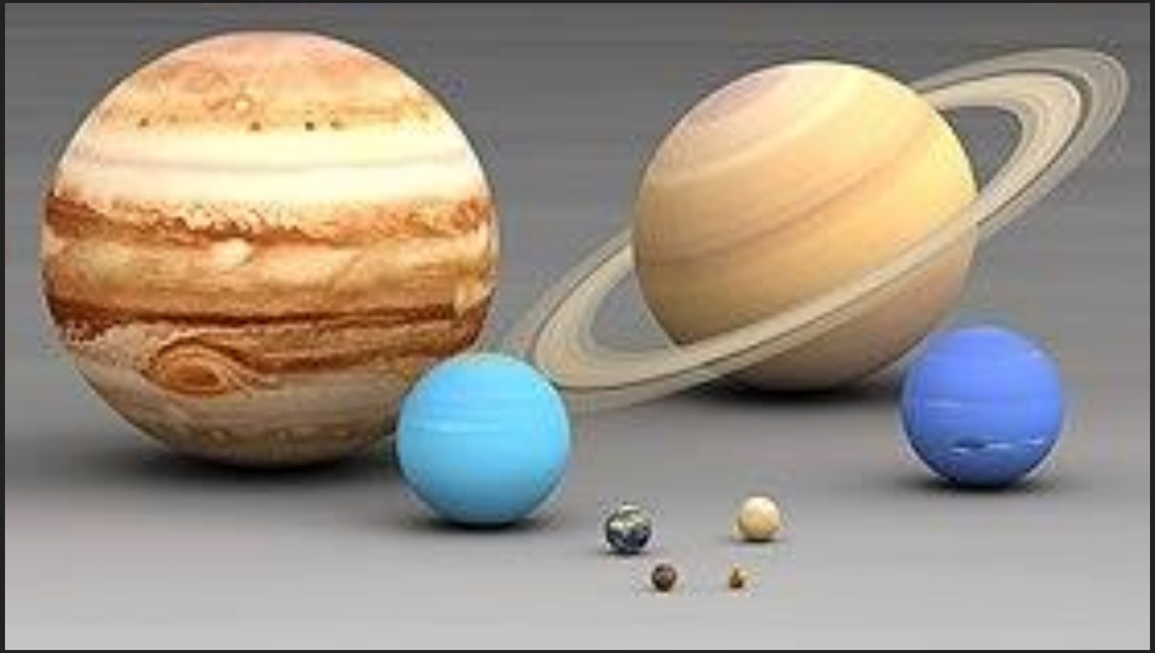
Гелиосейсмология

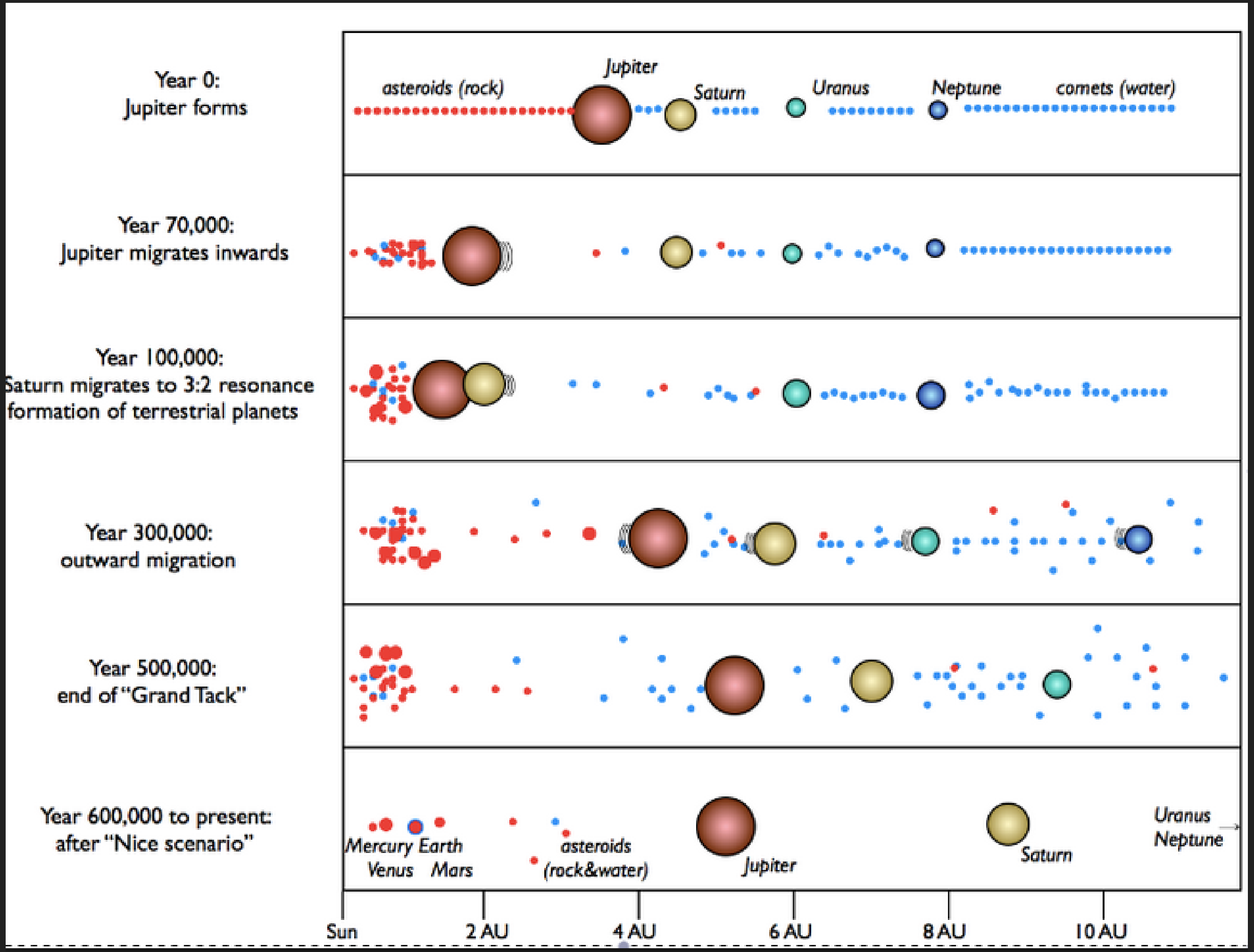




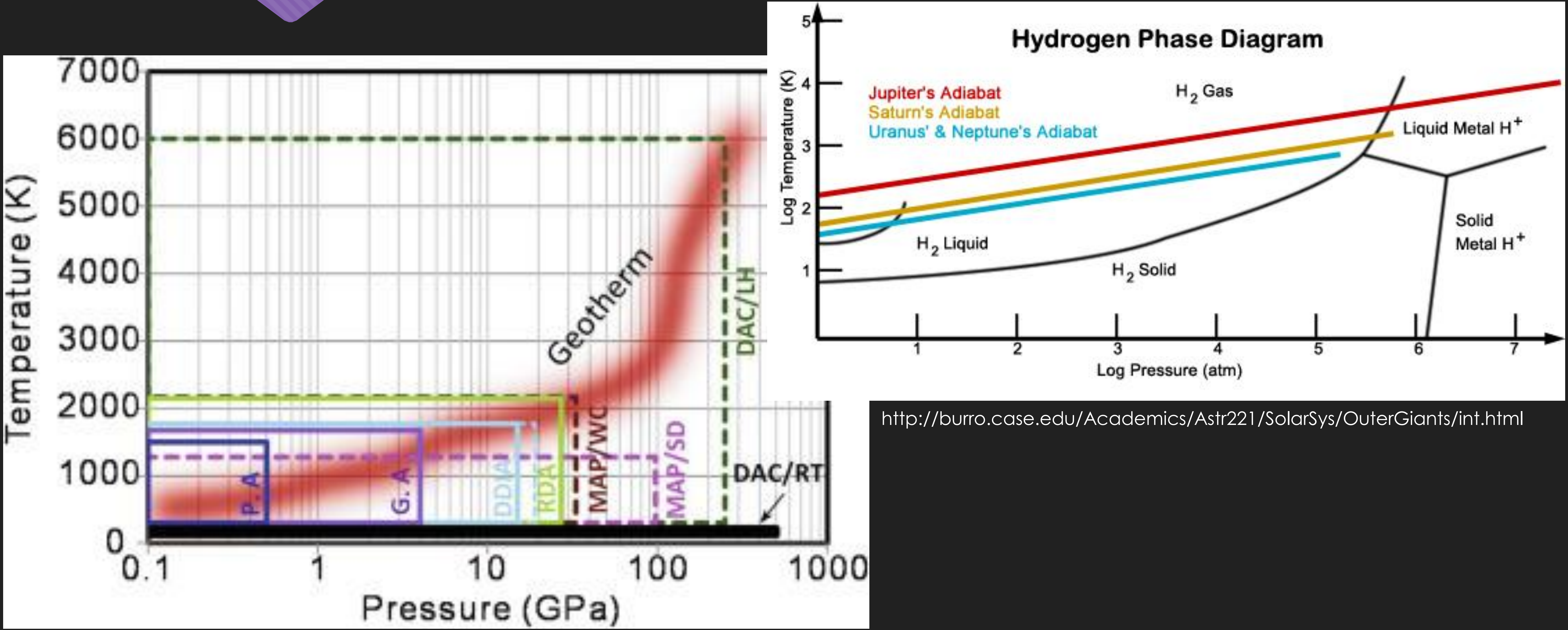
https://www.stat.berkeley.edu/~stark/Seminars/Aaas/helio.htm

Солнечная система




Year 0:
Jupiter forms
asteroids (rock)
Jupiter
Saturn
Uranus
Neptune
comets (water)
Year 70,000:
Jupiter migrates inwards
Year 100,000:
Saturn migrates to 3:2 resonance
formation of terrestrial planets
Year 300,000:
outward migration
Year 500,000:
end of "Grand Tack"
Year 600,000 to present:
after "Nice scenario"
Mercury Earth
Venus Mars
asteroids
(rock&water)
Jupiter
Saturn
Uranus
Neptune
Sun
2 AU
4 AU
6 AU
8 AU
10 AU

Недра планет



https://www.sciencedirect.com/science/article/pii/S2468080X16000078

http://burro.case.edu/Academics/Astr221/SolarSys/OuterGiants/int.html

Экзопланеты

Миграция планет в диске

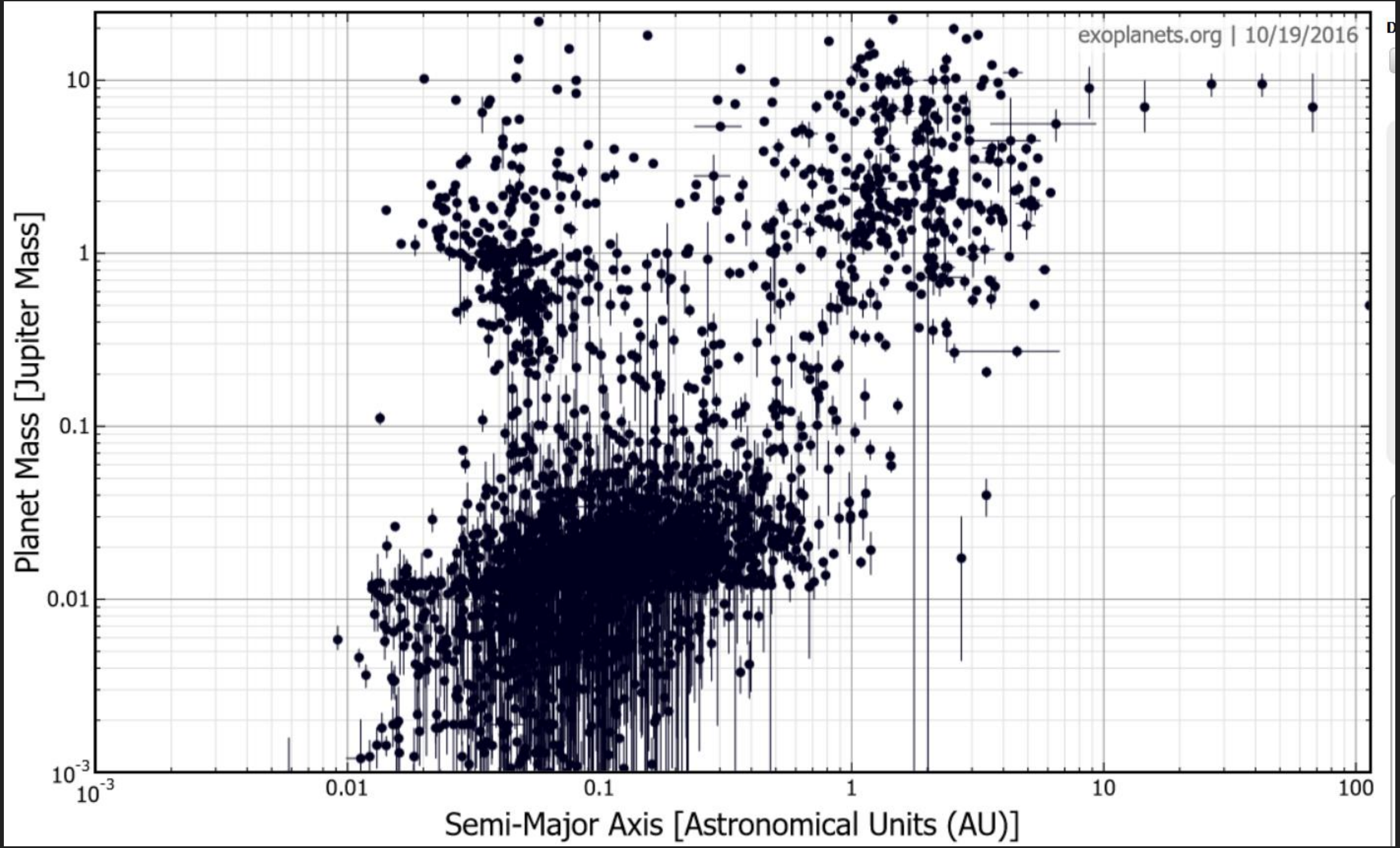
Type I

$$\frac{dJ_{\rm p}}{dt} = -(1.36 + 0.54\bar{\alpha}) \left(\frac{M_{\rm p}}{M_2}\right)^2 \left(\frac{H}{r_{\rm p}}\right)^{-2} \Sigma r_{\rm p}^4 \Omega_{\rm p}^2,$$

$$\frac{dr_{\rm p}}{dt} = -(2.72 + 1.08\bar{\alpha}) \frac{M_{\rm p}}{M_2^2} \left(\frac{H}{r_{\rm p}}\right)^{-2} \Sigma r_{\rm p}^3 \Omega_{\rm p}.$$

Type II

$$\frac{dr_{\rm p}}{dt} = -\frac{3}{2}\alpha \left(\frac{H}{r_{\rm p}}\right)^2 f^{-1} \nu_{\rm K},$$



Звезды

$$P = K\rho^{\gamma}, \quad K, \gamma = \mathrm{const}, \quad \gamma = 1 + \frac{1}{n}$$

$$\frac{dP}{dr} = -\frac{Gm\rho}{r^2} = g\rho, \quad g = -\frac{Gm}{r^2} = -\frac{d\varphi}{dr}$$

$$\frac{dP}{dr} = -\rho \, \frac{d\varphi}{dr}, \qquad \Delta\varphi = 4\pi G\rho$$

$$\rho = \rho_c \, \Theta^n, \qquad \Theta = 1 \text{ при } r = 0$$

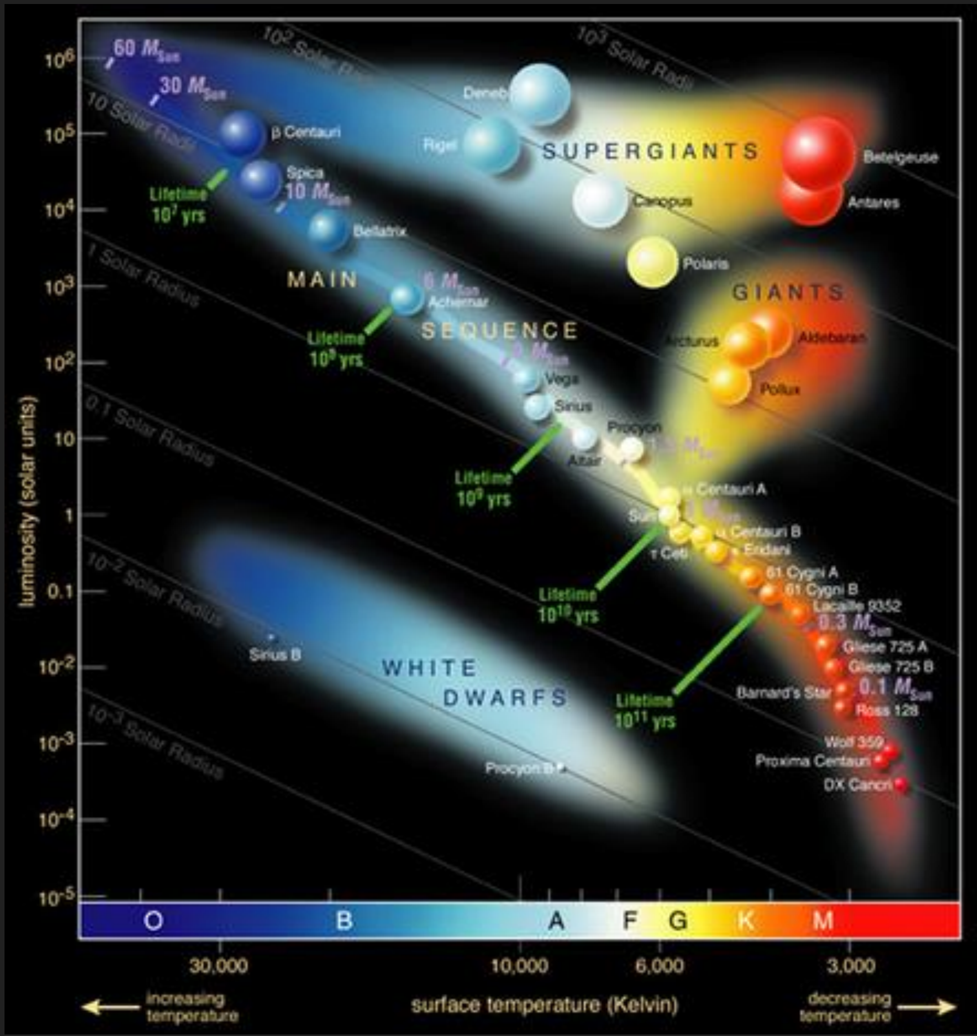
$$P = K\rho_c^{1+1/n} \, \Theta^{1+n}, \quad \frac{dP}{dr} = (n+1)K\rho_c^{1+1/n} \, \Theta^n \, \frac{d\Theta}{dr}$$

$$\frac{d\varphi}{dr} = -(n+1)K\rho_c^{1/n} \, \frac{d\Theta}{dr}$$

$$\Delta\Theta = -\frac{4\pi G\rho_c^{1-1/n}}{(n+1)K} \, \Theta^n$$

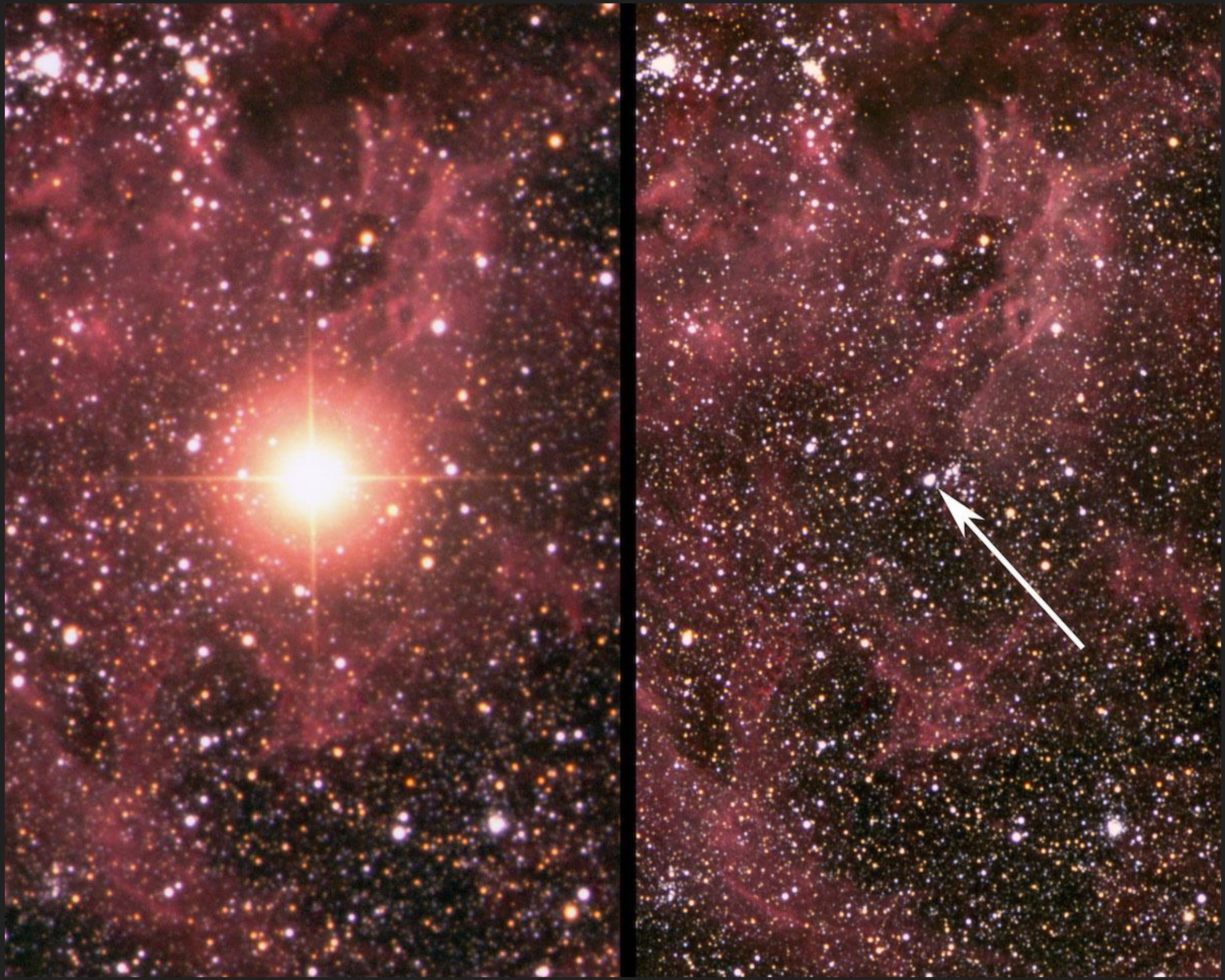
$$\xi = r/a, \quad a^2 = (n+1)K\rho_c^{1/n-1}/(4\pi G)$$

$$\frac{1}{\xi^2}\frac{d}{d\xi}\xi^2\frac{d}{d\xi}\Theta = -\Theta^n$$

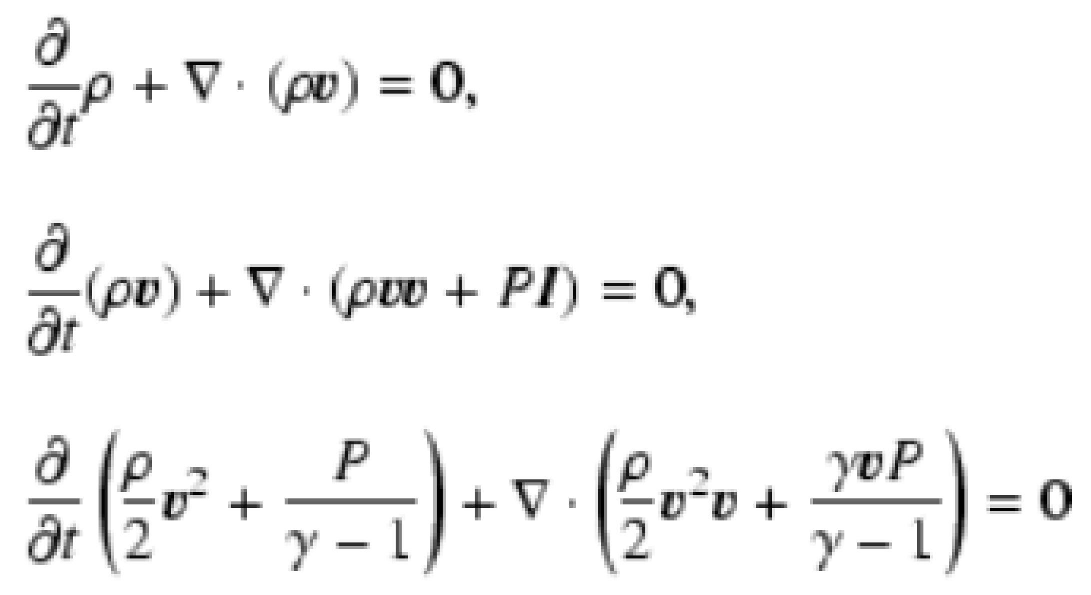


Сверхновые

- Трехмерная гидродинамика
- Нейтрино
- Магнитные поля
- Ядерные реакции
- Перенос излучения
- Уравнение состояния сверхплотного вещества



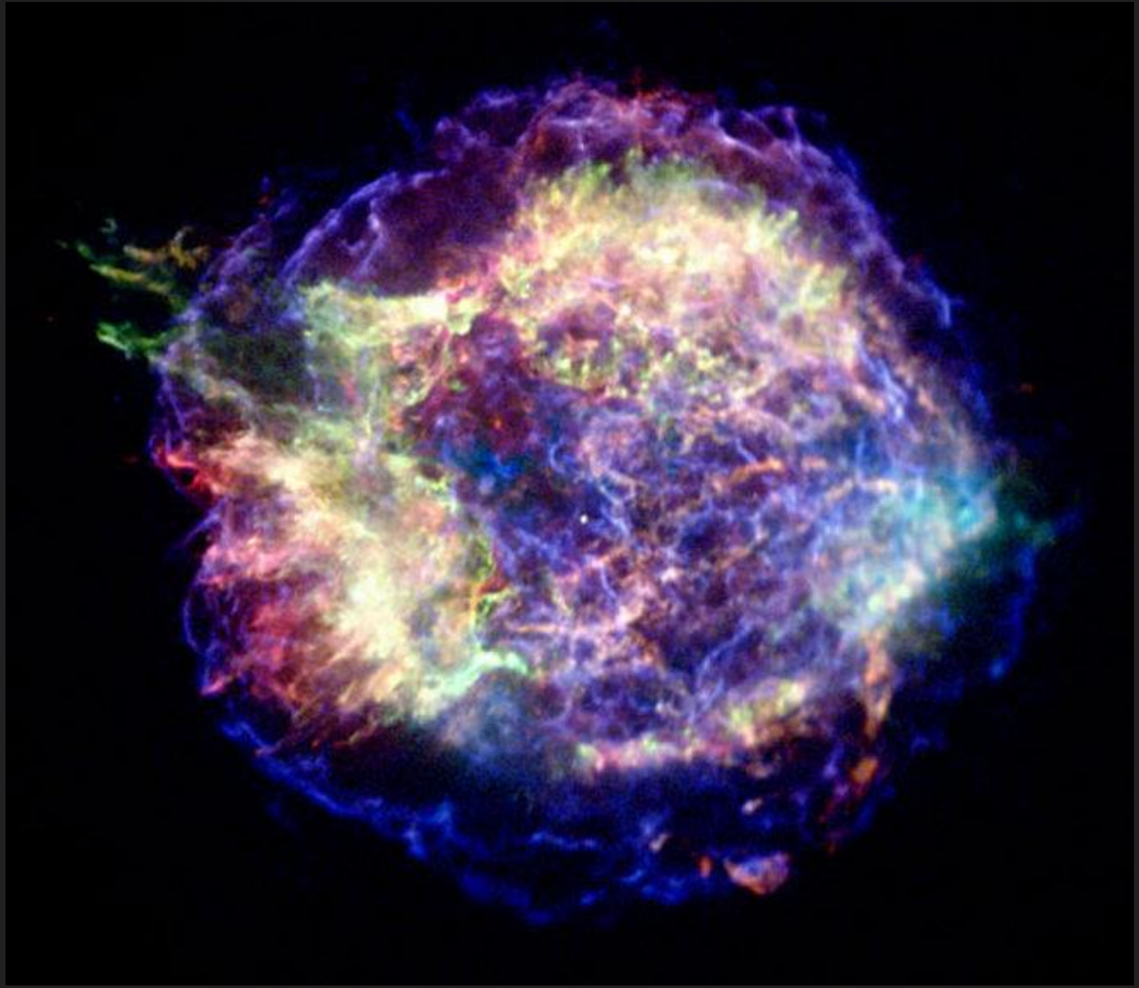
Остатки сверхновых



$$\frac{\partial}{\partial t}\rho + \nabla \cdot (\rho \boldsymbol{v}) = 0,$$

$$\frac{\partial}{\partial t}(\rho \boldsymbol{v}) + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v} + P\boldsymbol{I}) = 0,$$

$$\frac{\partial}{\partial t}\left(\frac{\rho}{2}v^2 + \frac{P}{\gamma - 1}\right) + \nabla \cdot \left(\frac{\rho}{2}v^2\boldsymbol{v} + \frac{\gamma \boldsymbol{v} P}{\gamma - 1}\right) = 0$$



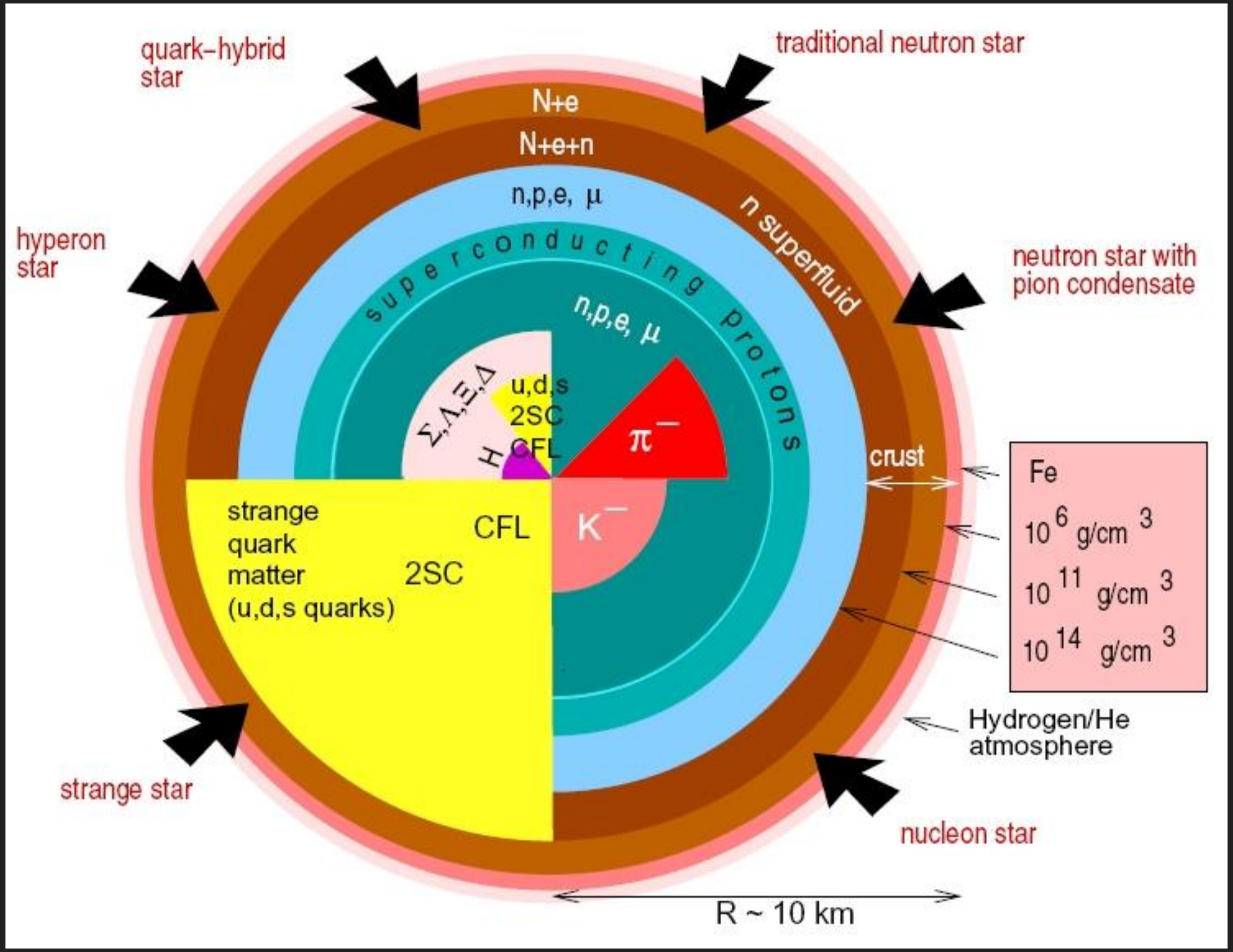
Нейтронные звезды

$$(1)\quad \frac{dP}{dr} = -\frac{G\rho m}{r^2}\left(1+\frac{P}{\rho c^2}\right)\left(1+\frac{4\pi r^3 P}{mc^2}\right)\left(1-\frac{2Gm}{rc^2}\right)^{-1}$$

$$(2)\quad \frac{dm}{dr} = 4\pi r^2 \rho$$

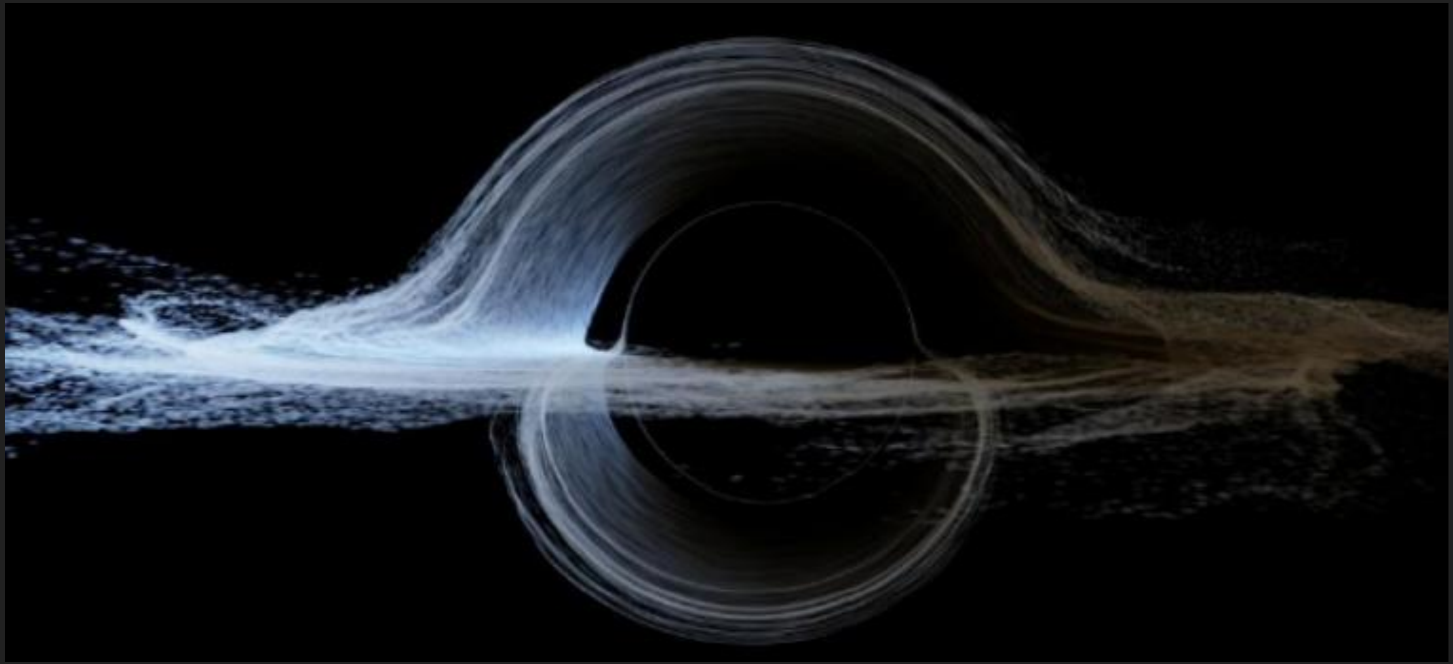
$$(3)\quad \frac{d\Phi}{dr} = -\frac{1}{\rho c^2}\frac{dP}{dr}\left(1+\frac{P}{\rho c^2}\right)^{-1}$$

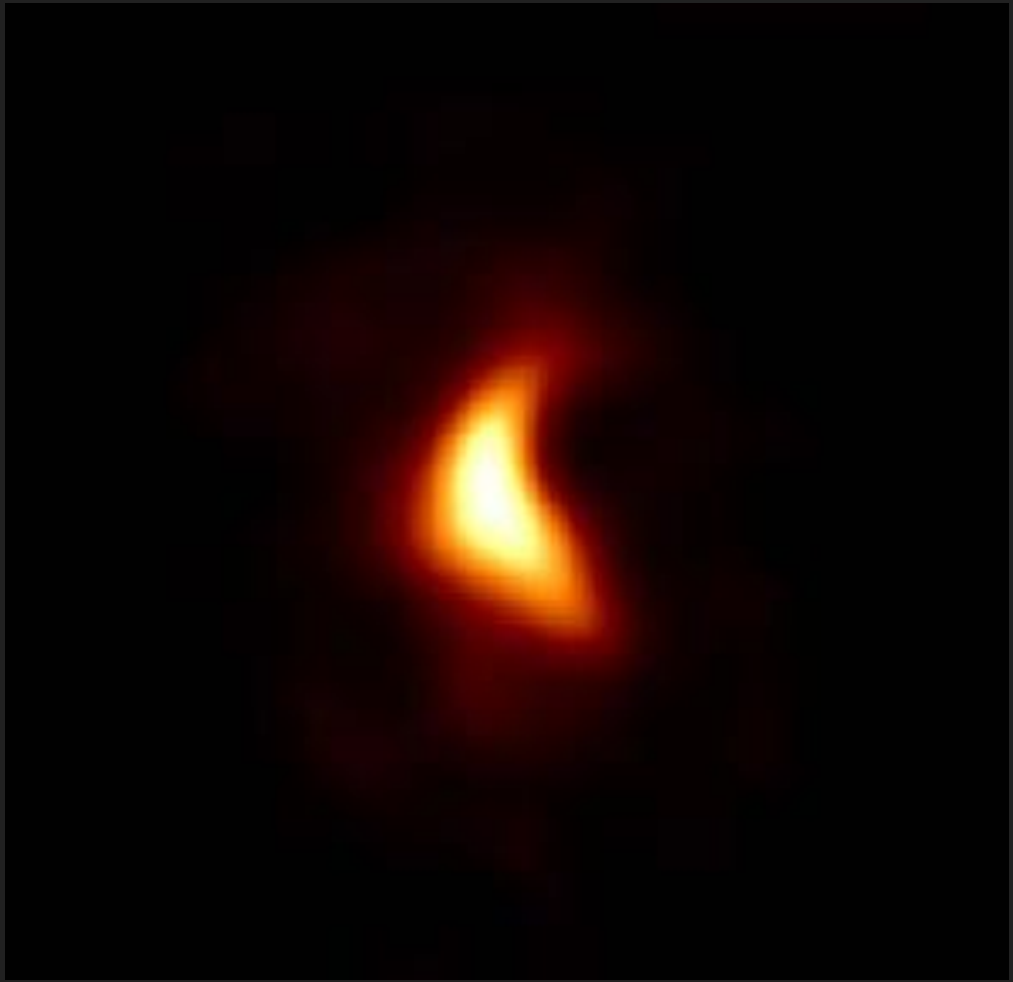
$$(4)\quad P = P(\rho)$$


quark–hybrid star
traditional neutron star
N+e
N+e+n
n,p,e, μ
n superfluid
superconducting protons
n,p,e, μ
hyperon star
neutron star with pion condensate
Σ,Λ,Ξ,Δ
u,d,s
2SC
CFL
H
π⁻
K⁻
crust
Fe
10^6 g/cm^3
10^11 g/cm^3
10^14 g/cm^3
strange quark matter (u,d,s quarks)
CFL
2SC
Hydrogen/He atmosphere
strange star
nucleon star
R ~ 10 km

Черные дыры

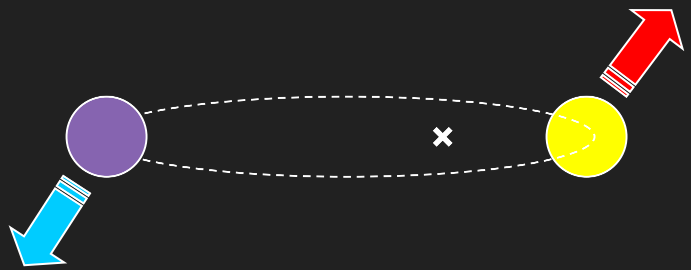
$$R = \frac{2GM}{c^2}$$

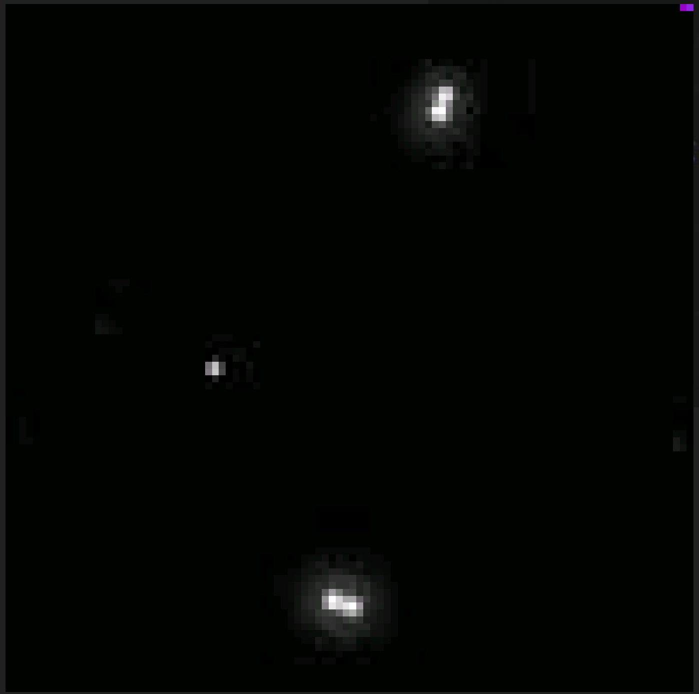


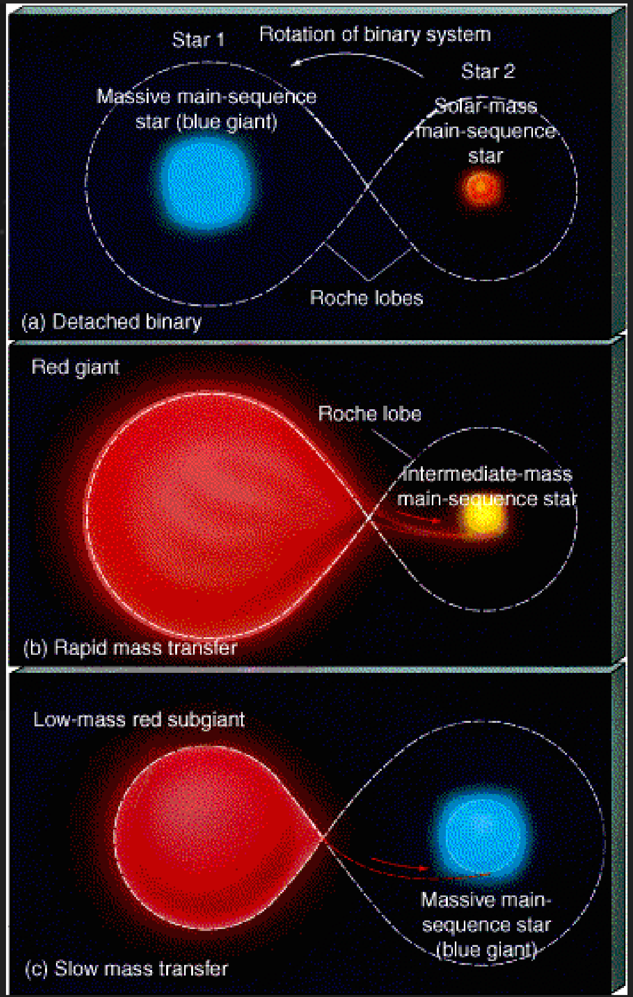


Двойные системы

$$m_x = f_v(m)\left(1+\frac{m_v}{m_x}\right)^2 \frac{1}{\sin i^3}\,.$$



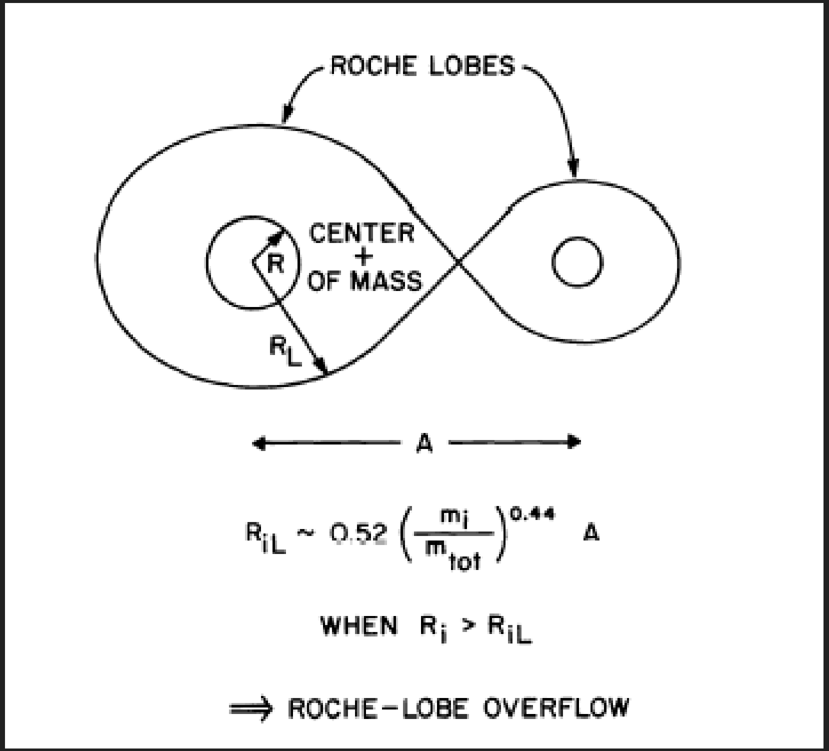


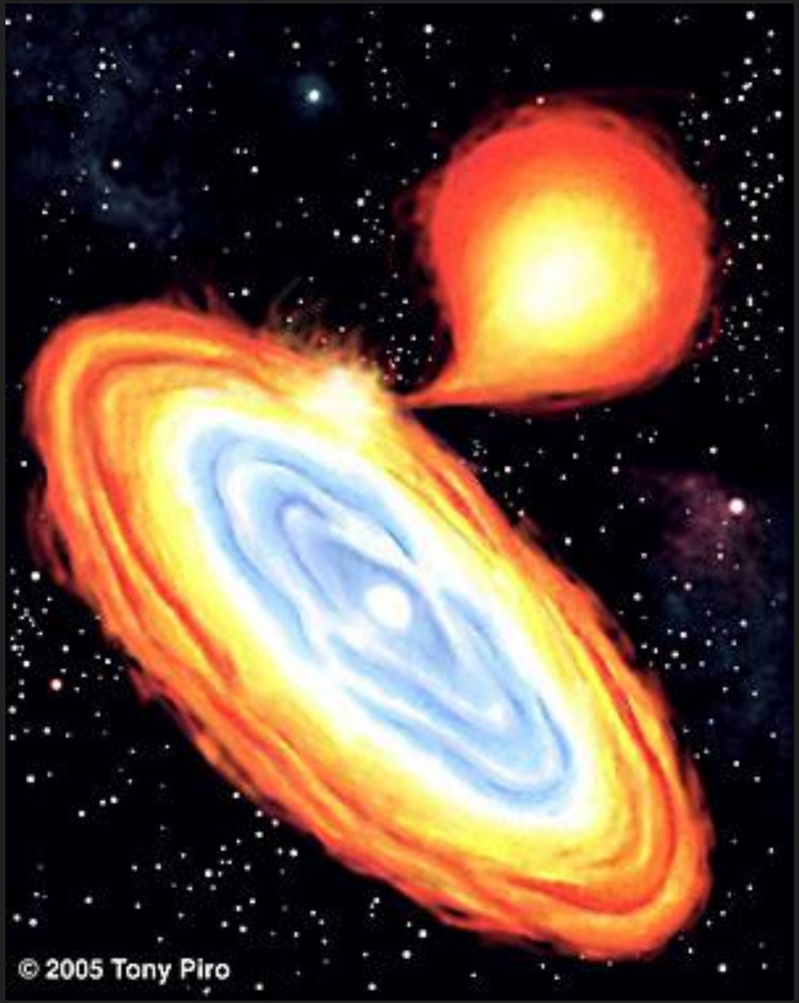

Star 1
Rotation of binary system
Star 2
Massive main-sequence star (blue giant)
Solar-mass main-sequence star
Roche lobes
(a) Detached binary
Red giant
Roche lobe
Intermediate-mass main-sequence star
(b) Rapid mass transfer
Low-mass red subgiant
Massive main-sequence star (blue giant)
(c) Slow mass transfer

Аккреция в двойных

$$\dot{M}_{\mathrm{HL}} = \pi\zeta_{\mathrm{HL}}^2 v_\infty \rho_\infty = \frac{4\pi G^2 M^2 \rho_\infty}{v_\infty^3}$$

$$\zeta_{\mathrm{HL}} = \frac{2GM}{v_\infty^2}$$


ROCHE LOBES
CENTER + OF MASS
R
R_L
A
$R_{iL} \sim 0.52 \left(\frac{m_i}{m_{tot}}\right)^{0.44} A$
WHEN $R_i > R_{iL}$
⟹ ROCHE–LOBE OVERFLOW


© 2005 Tony Piro

Слияния компактных объектов

$$\frac{\mathrm{d}r}{\mathrm{d}t} = -\frac{64}{5}\frac{G^3}{c^5}\frac{(m_1 m_2)(m_1+m_2)}{r^3}$$

$$t = \frac{5}{256}\frac{c^5}{G^3}\frac{r^4}{(m_1 m_2)(m_1+m_2)}$$

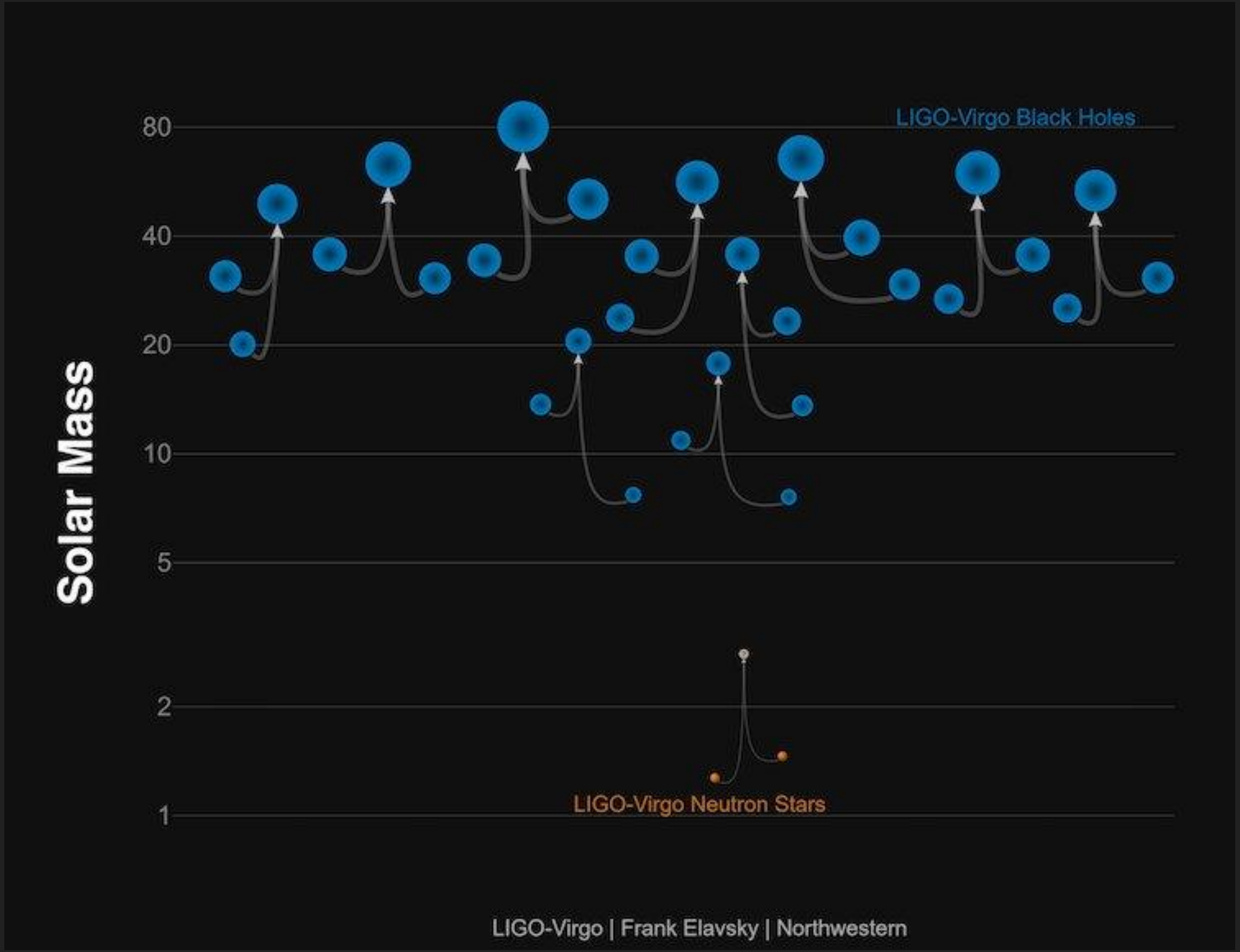
$$f_{\rm GW}^{\rm max} \sim \frac{c^3}{\pi 6^{3/2} G M_{\rm BBH}} = 4.4\times 10^3 \left(\frac{\mathrm{M}_\odot}{M_{\rm BBH}}\right) \mathrm{Hz}.$$

$$\dot{E}_{\rm gw}^{\rm circ} = \frac{32}{5}\frac{c^5}{G}\left(\frac{G M_{\rm c}}{c^3}\pi f\right)^{10/3} = \frac{32}{5\cdot 6^5}\frac{c^5}{G}\nu^2 \tilde{f}^{10/3}$$

$$\tilde{f} = f/f_{\rm coal}$$

$$M_{\rm c} \equiv \frac{(m_1 m_2)^{3/5}}{(m_1+m_2)^{1/5}} = \nu^{3/5} M = \mu^{3/5} M^{2/5}$$

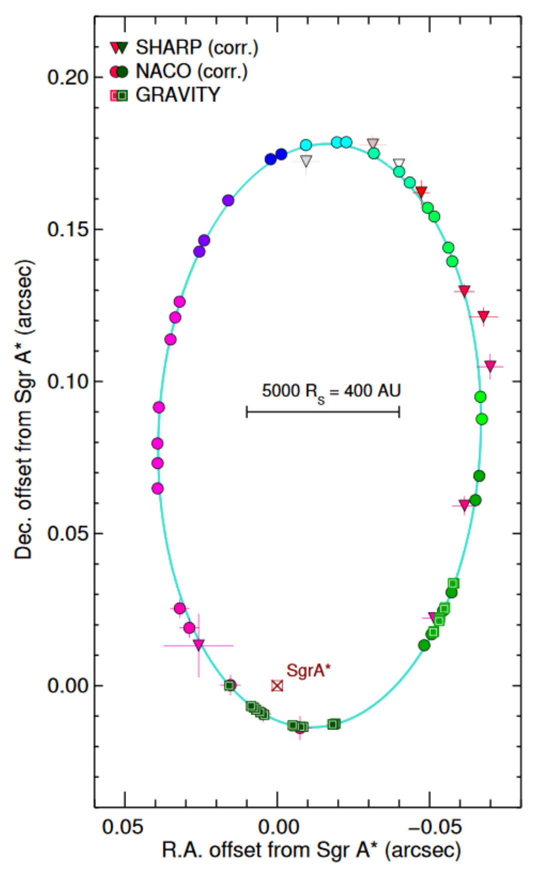
$$\nu^2(c^5/G) \sim \nu^2(3.6\times 10^{59})\,\mathrm{erg\,s^{-1}}$$

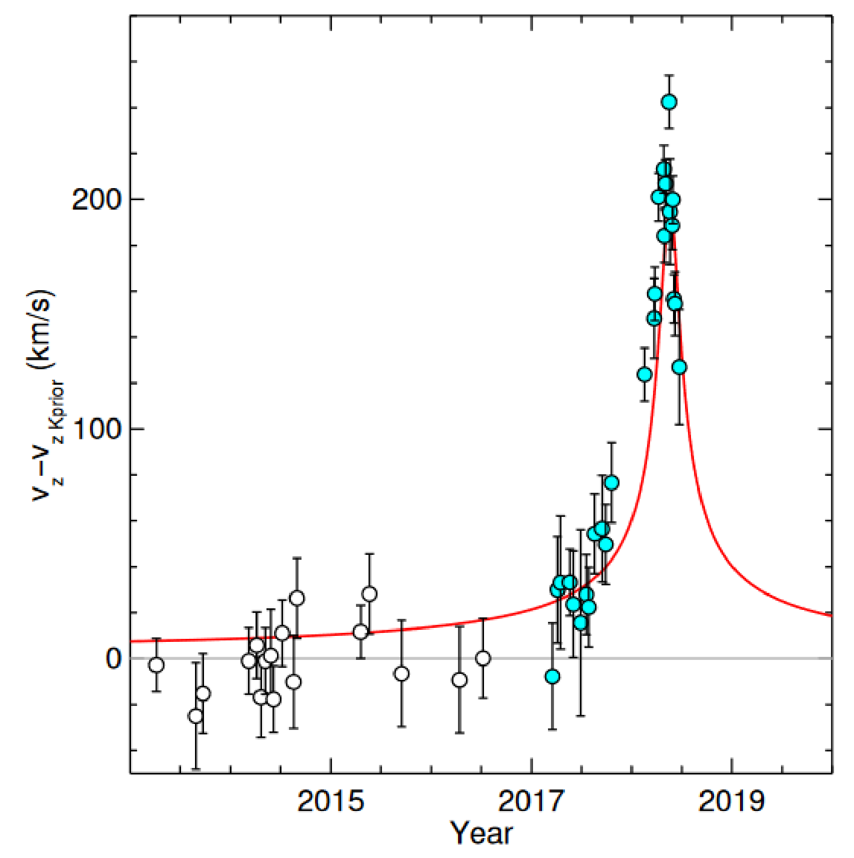


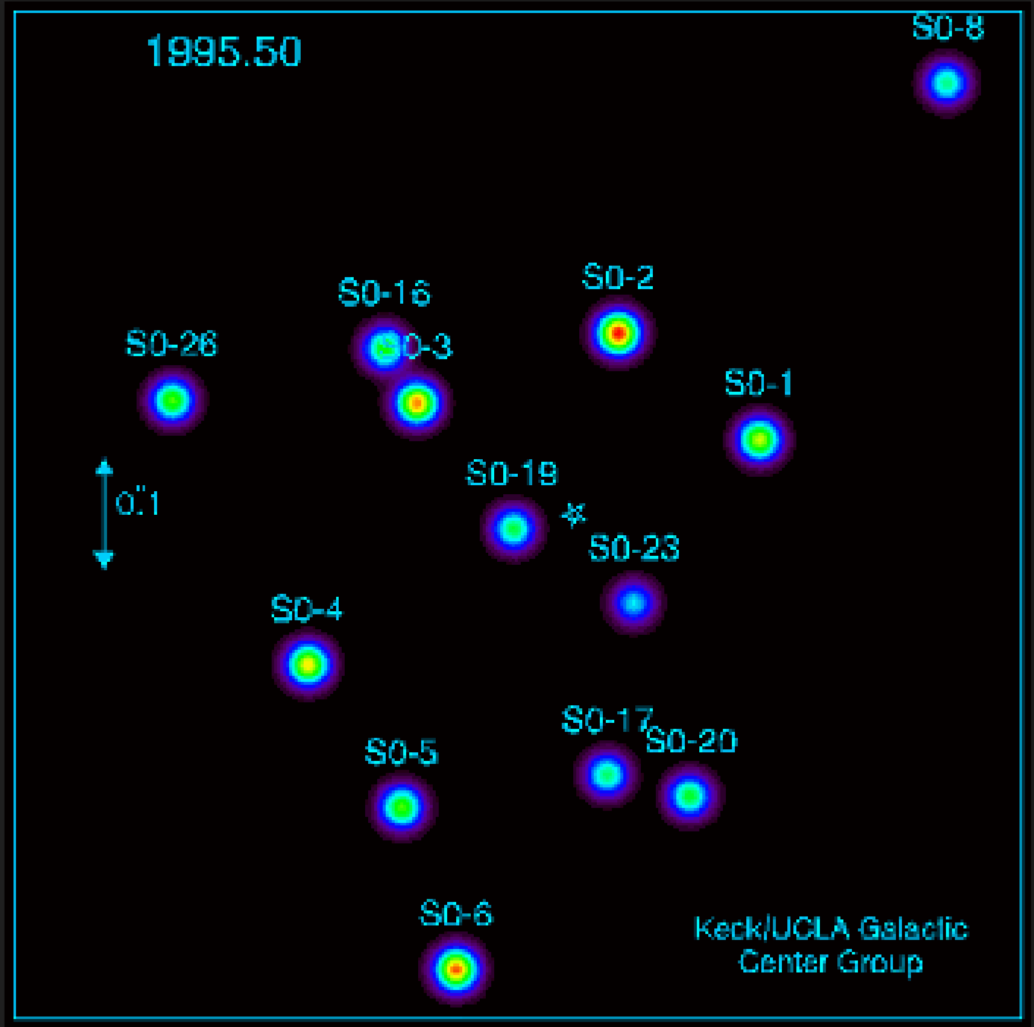
LIGO-Virgo | Frank Elavsky | Northwestern

Sgr A* - наша черная дыра

$$z = \frac{\Delta\lambda}{\lambda} = B_0 + B_{0.5}\beta + B_1\beta^2 + O(\beta^3),$$



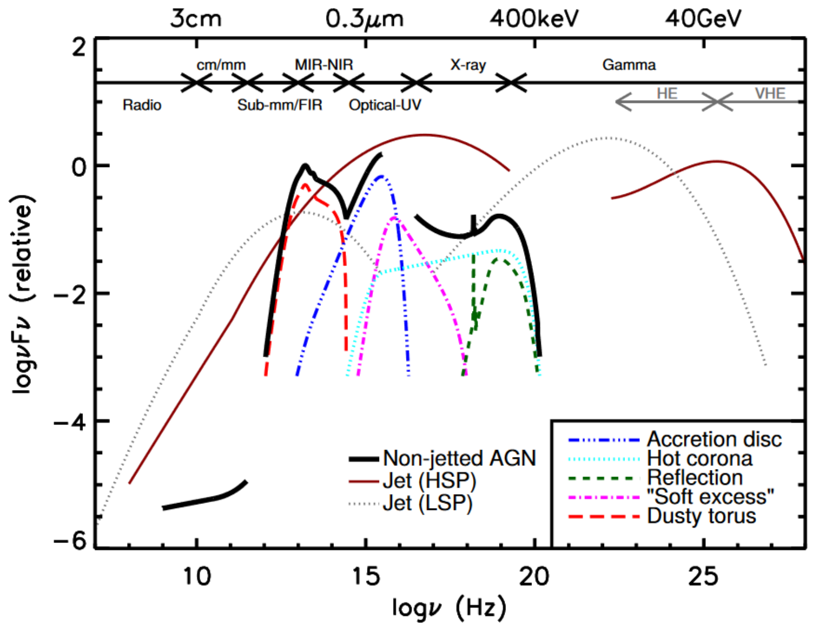


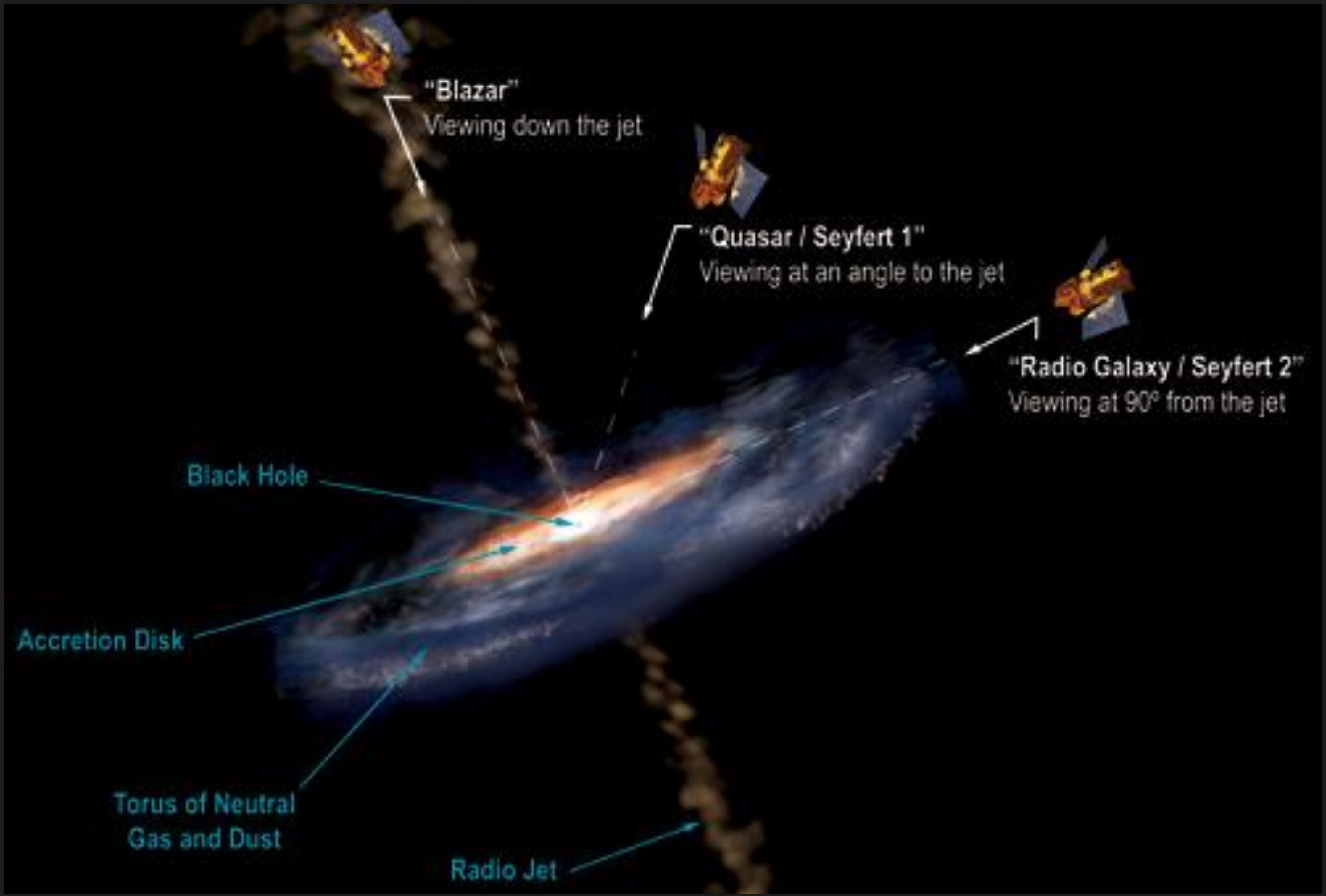

1995.50
S0-8
S0-16
S0-2
S0-26
S0-3
S0-1
0.''1
S0-19
S0-23
S0-4
S0-17
S0-20
S0-5
S0-6
Keck/UCLA Galactic
Center Group

Сверхмассивные черные дыры

$$L_{\mathrm{Edd}} = \frac{4\pi G M m_{\mathrm{p}} c}{\sigma_{\mathrm{T}}}$$

$$= 1.26 \times 10^{38} \left(\frac{M}{M_\odot}\right) \mathrm{erg/s} = 3.2 \times 10^{4} \left(\frac{M}{M_\odot}\right) L_\odot$$



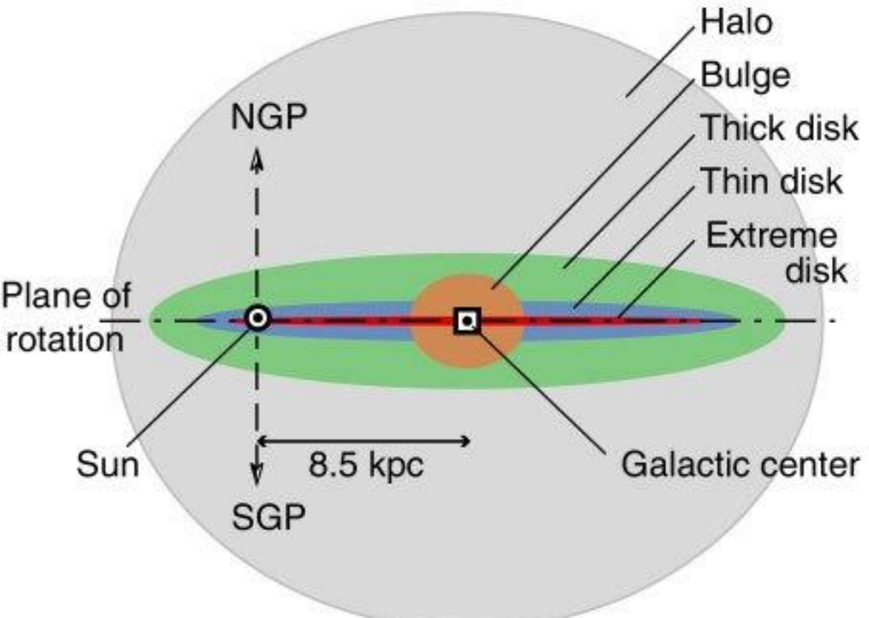

"Blazar"
Viewing down the jet
"Quasar / Seyfert 1"
Viewing at an angle to the jet
"Radio Galaxy / Seyfert 2"
Viewing at 90° from the jet
Black Hole
Accretion Disk
Torus of Neutral Gas and Dust
Radio Jet

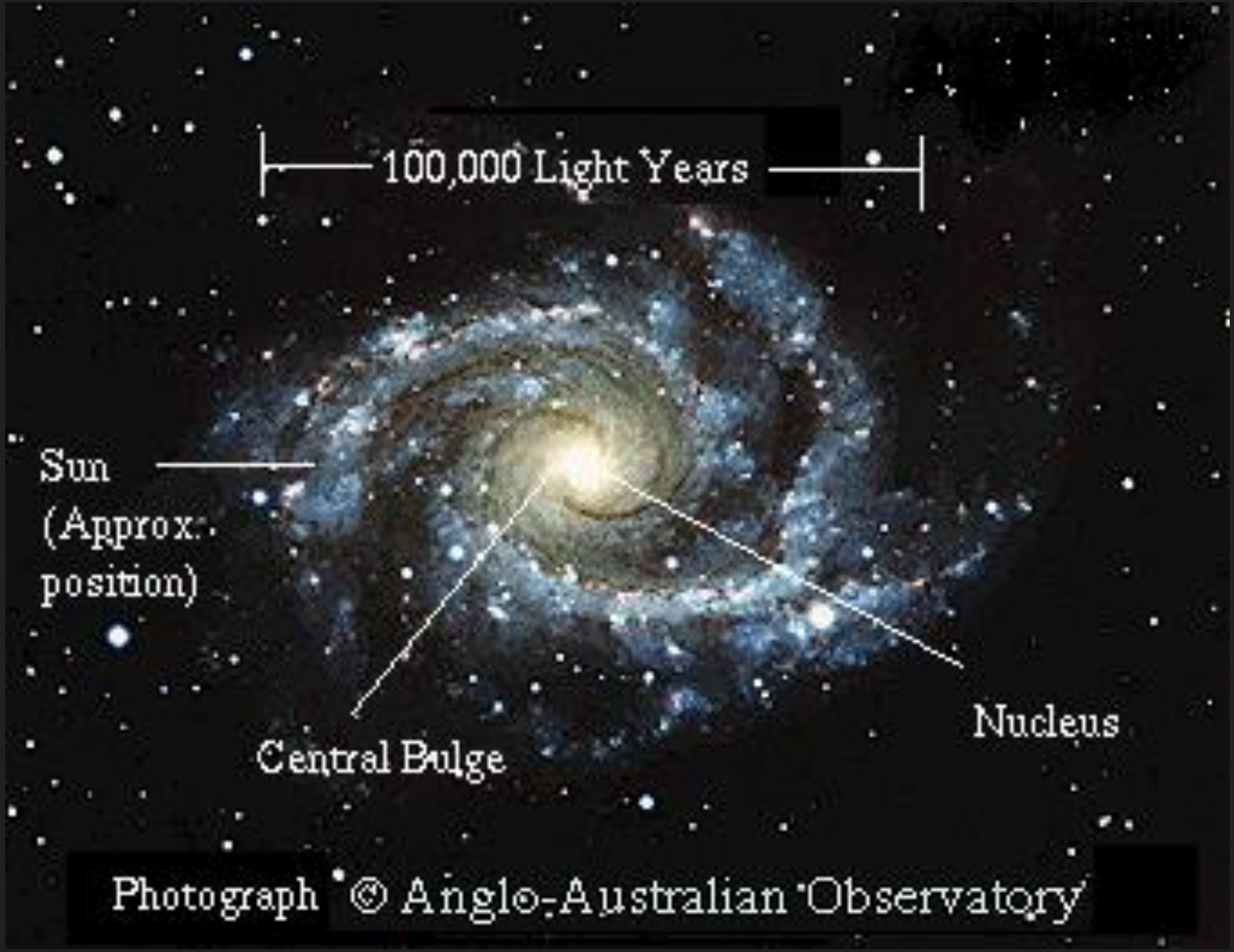
Галактика

$$\Phi_i(R, z) = \frac{GM_i}{\{R^2 + [a_i + (z^2 + b_i{}^2)^{1/2}]^2\}^{1/2}}, \quad R^2 = x^2 + y^2$$

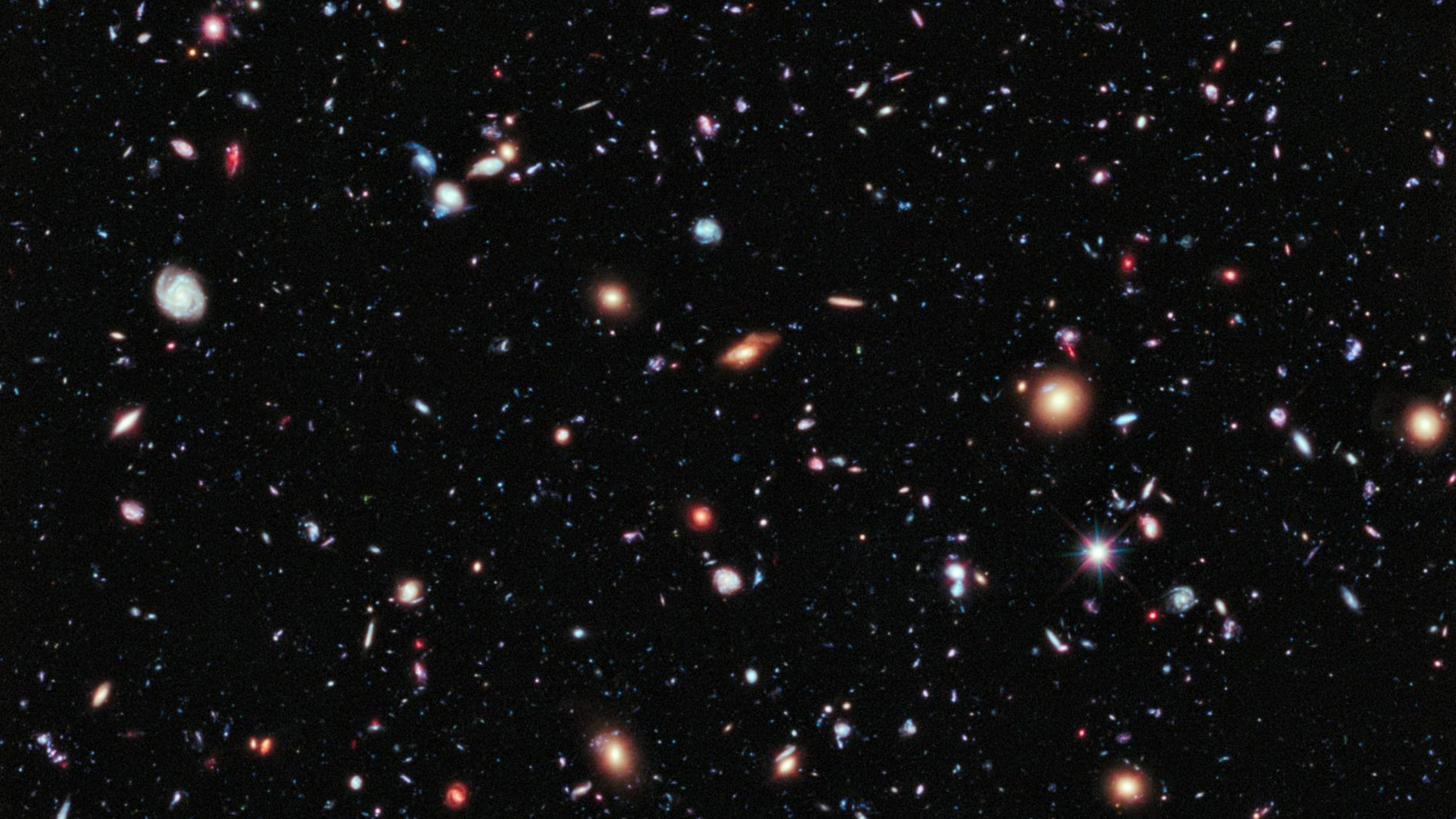
$$\Phi_h = -\frac{GM_c}{r_c}\left[\frac{1}{2}\ln\left(1 + \frac{r^2}{r_c{}^2}\right) + \frac{r_c}{r}\,\mathrm{atan}\left(\frac{r}{r_c}\right)\right],$$

$$M_c \equiv 4\pi\rho_c r_c{}^3$$

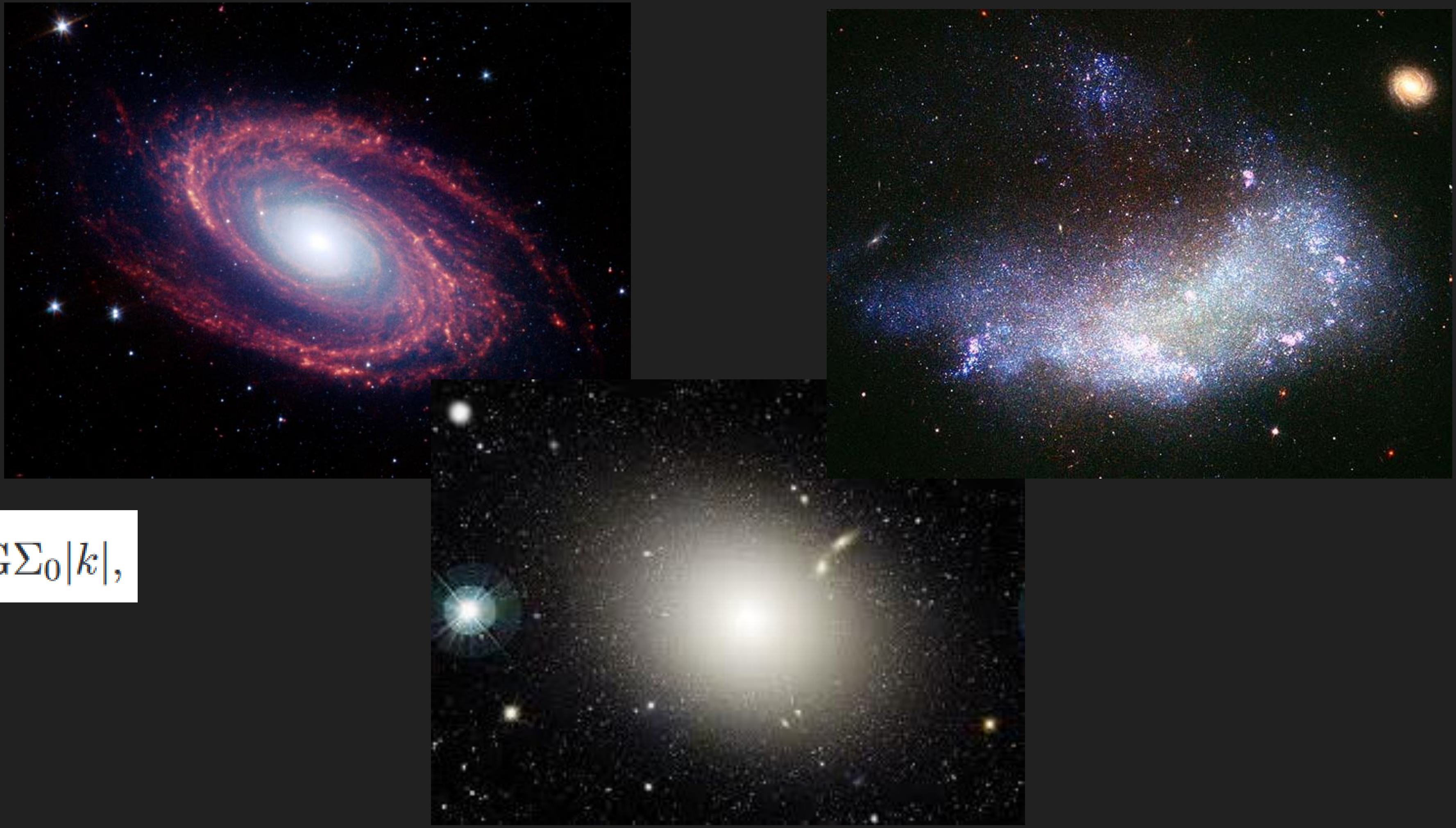

Halo
Bulge
Thick disk
Thin disk
Extreme disk
NGP
Plane of rotation
Sun
8.5 kpc
Galactic center
SGP


100,000 Light Years
Sun (Approx. position)
Central Bulge
Nucleus

Photograph © Anglo-Australian Observatory



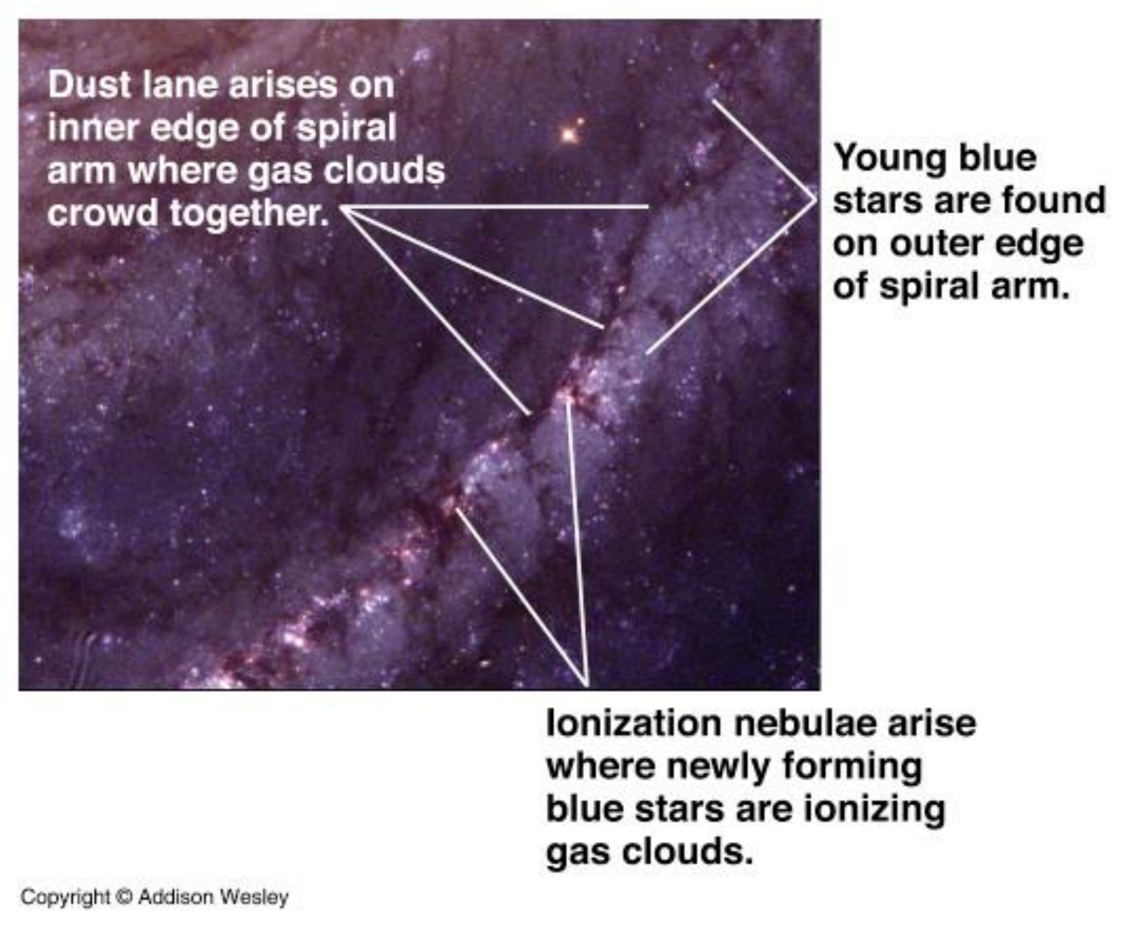
Галактики



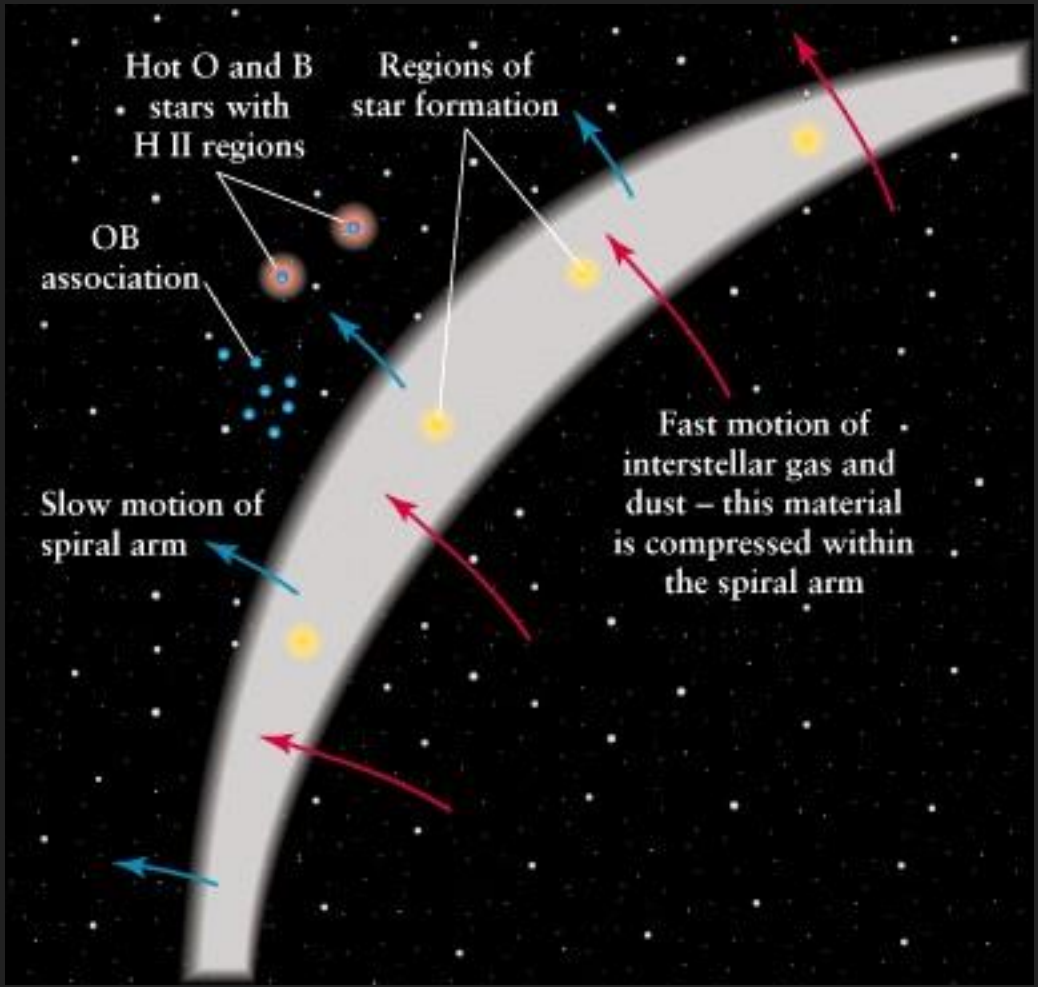
$$(\omega - m\Omega)^2 = c_s^2 k^2 + \kappa^2 - 2\pi G \Sigma_0 |k|,$$

$$\kappa = \sqrt{R\frac{\partial \Omega^2}{\partial R} + 4\Omega^2}$$

Рукава и звездообразование


Dust lane arises on inner edge of spiral arm where gas clouds crowd together.
Young blue stars are found on outer edge of spiral arm.
Ionization nebulae arise where newly forming blue stars are ionizing gas clouds.
Copyright © Addison Wesley

http://cse.ssl.berkeley.edu


Hot O and B stars with H II regions
Regions of star formation
OB association
Slow motion of spiral arm
Fast motion of interstellar gas and dust – this material is compressed within the spiral arm

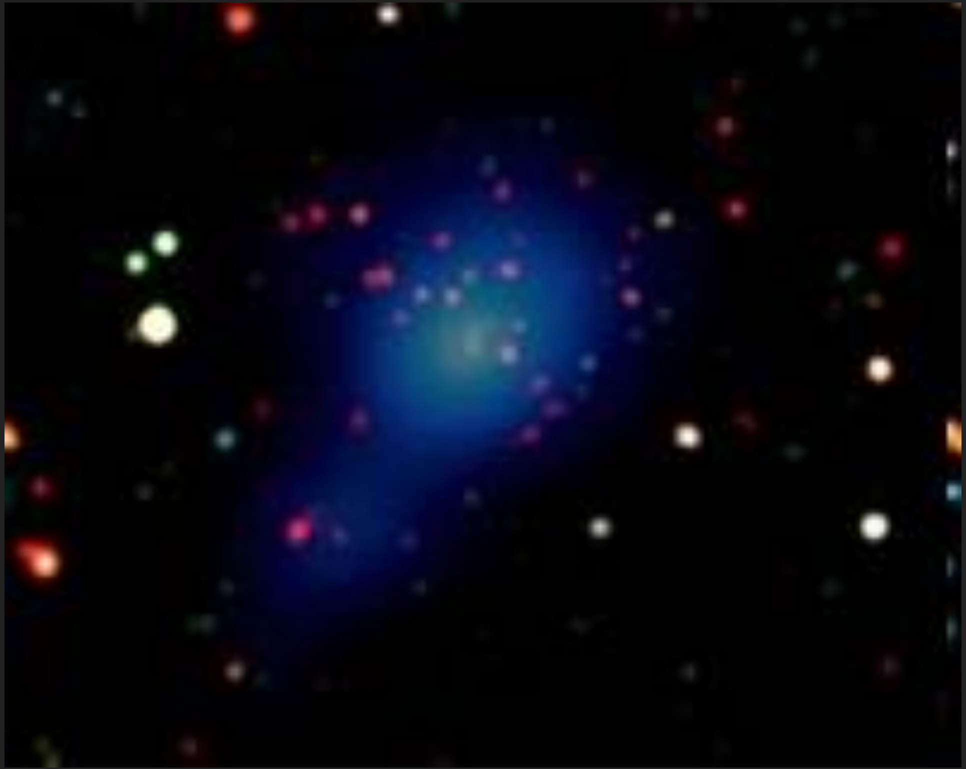
http://frigg.physastro.mnsu.edu

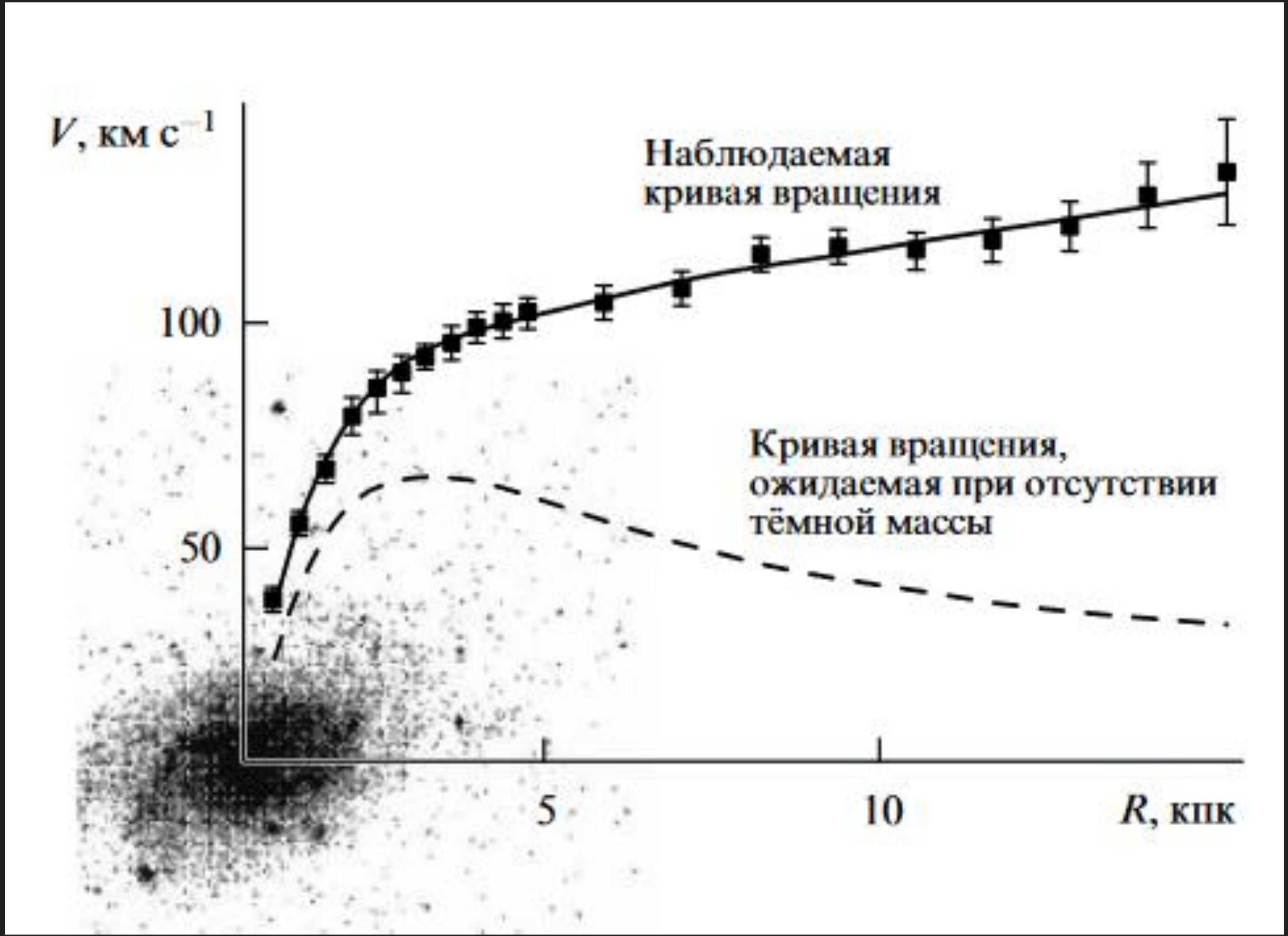
Межзвездная среда

$$M_J = \left(\frac{5kT}{Gm}\right)^{3/2}\left(\frac{3}{4\pi\rho}\right)^{1/2}$$

Темное вещество

$$-\frac{1}{\rho}\frac{\mathrm{d}P}{\mathrm{d}r} = \frac{V_{\mathrm{c}}^2}{r} = \frac{GM(r)}{r^2}$$




V, км с$^{-1}$
100
50
5
10
R, кпк
Наблюдаемая кривая вращения
Кривая вращения, ожидаемая при отсутствии тёмной массы

Скопления галактик

$\delta(\mathbf{x}) = (\rho(\mathbf{x}) - \bar{\rho}_{\mathrm{m}})/\bar{\rho}_{\mathrm{m}}$ $\delta_R(\mathbf{x}) \equiv \int \delta(\mathbf{x} - \mathbf{r}) W(\mathbf{r}, R) d^3 r$

$$\langle \delta_R^2 \rangle \equiv \sigma^2(R) = \frac{1}{(2\pi)^3} \int P(k) |\tilde{W}(\mathbf{k}, R)|^2 d^3 k,$$

$\delta_R(\mathbf{k}) = \delta(\mathbf{k}) \tilde{W}(\mathbf{k}, R)$

$P(k) \propto k^n$ $\sigma^2(R) \propto R^{-(n+3)}$

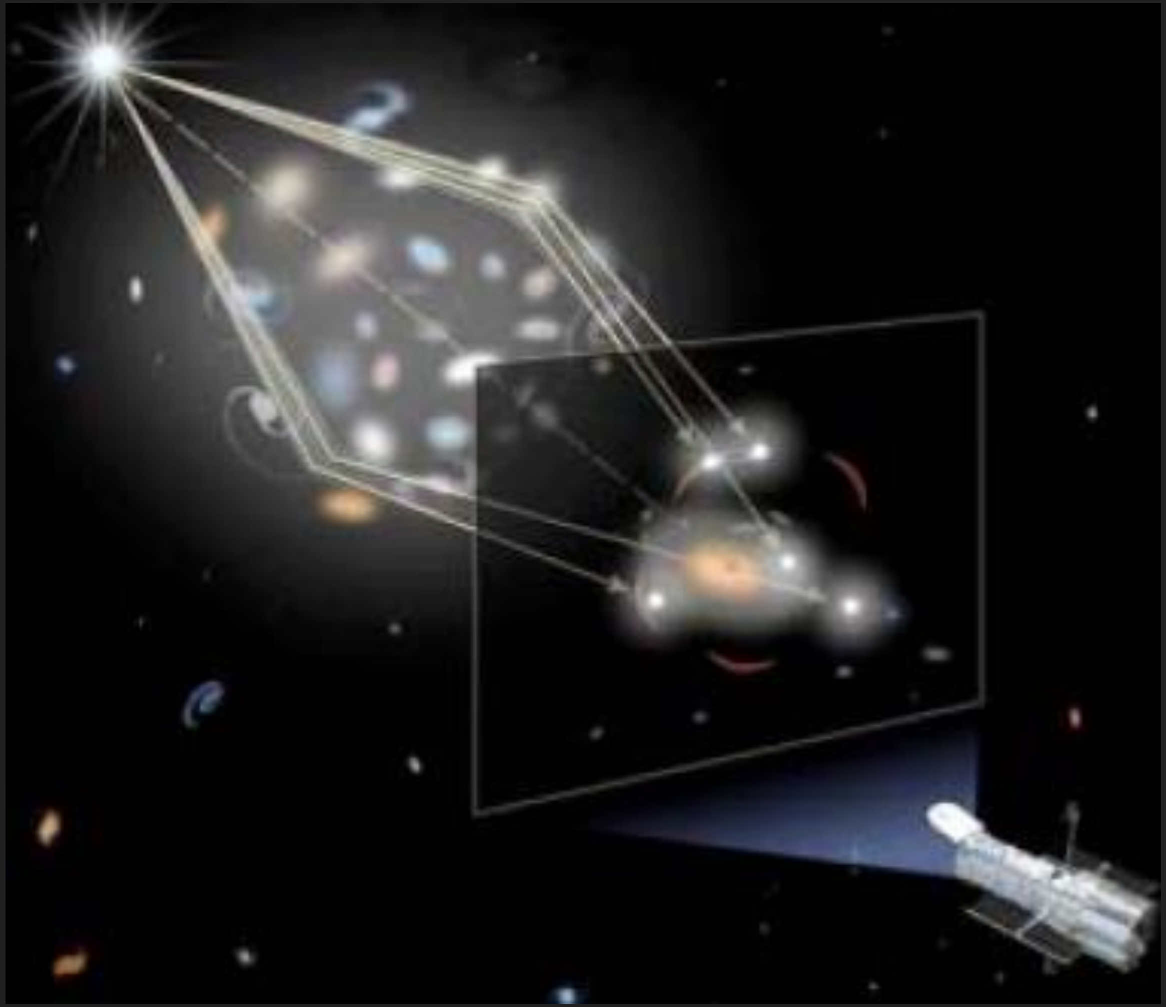
$M = 4\pi/3 \rho_{\mathrm{m}}(\mathrm{z}) R^3$

$$p(\delta_M) = \frac{1}{\sqrt{2\pi}\sigma(M)} \exp\left[-\frac{\delta_M^2}{2\sigma^2(M)}\right]$$

Линзирование на скоплениях галактик

$$f^{\rm obs}(\theta_i) = f^{\rm s}(\mathcal{A}_{ij}\theta_j)$$

$$\mathcal{A} = \frac{\partial(\delta\theta_i)}{\partial\theta_j} = (\delta_{ij} - \Psi_{,ij}) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$



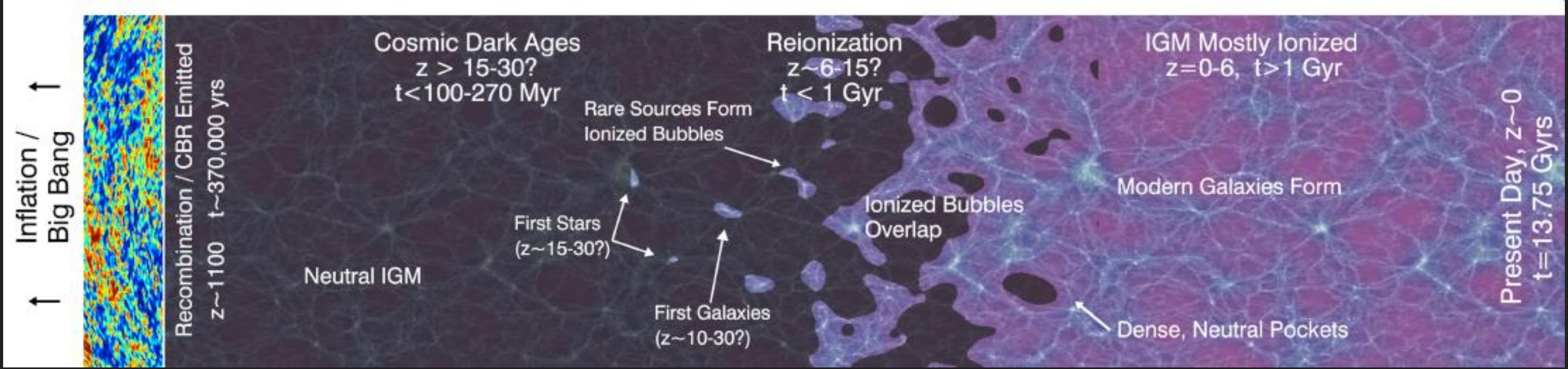
Космология (на четырех китах)

Динамика расширения

Крупномасштабная структура

Реликтовое излучение

Нуклеосинтез



Inflation / Big Bang
Recombination / CBR Emitted
z~1100 t~370,000 yrs
Cosmic Dark Ages
z > 15-30?
t<100-270 Myr
Rare Sources Form
Ionized Bubbles
First Stars
(z~15-30?)
Neutral IGM
First Galaxies
(z~10-30?)
Reionization
z~6-15?
t < 1 Gyr
Ionized Bubbles
Overlap
IGM Mostly Ionized
z=0-6, t>1 Gyr
Modern Galaxies Form
Dense, Neutral Pockets
Present Day, z~0
t=13.75 Gyrs

Расширение вселенной

$v=Hd$

H – постоянная Хаббла.

73 +/- 7 км/с/Мпк

$$ds^2 = c^2dt^2 - a(t)^2dl^2.$$

$$H = \dot{a}/a$$

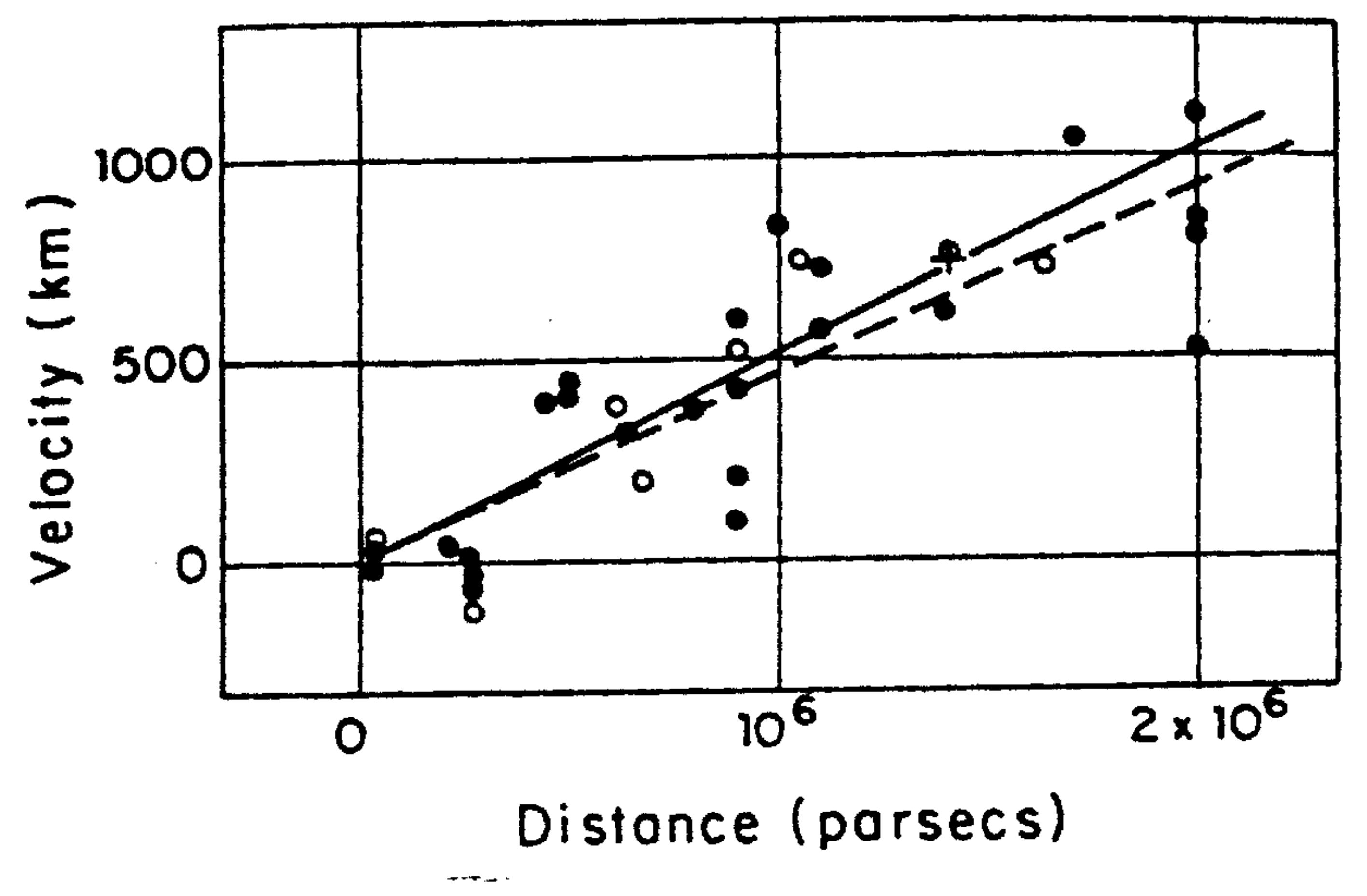
$a^2(t)dl^2=dd^2$

$dd=a(t)dl$

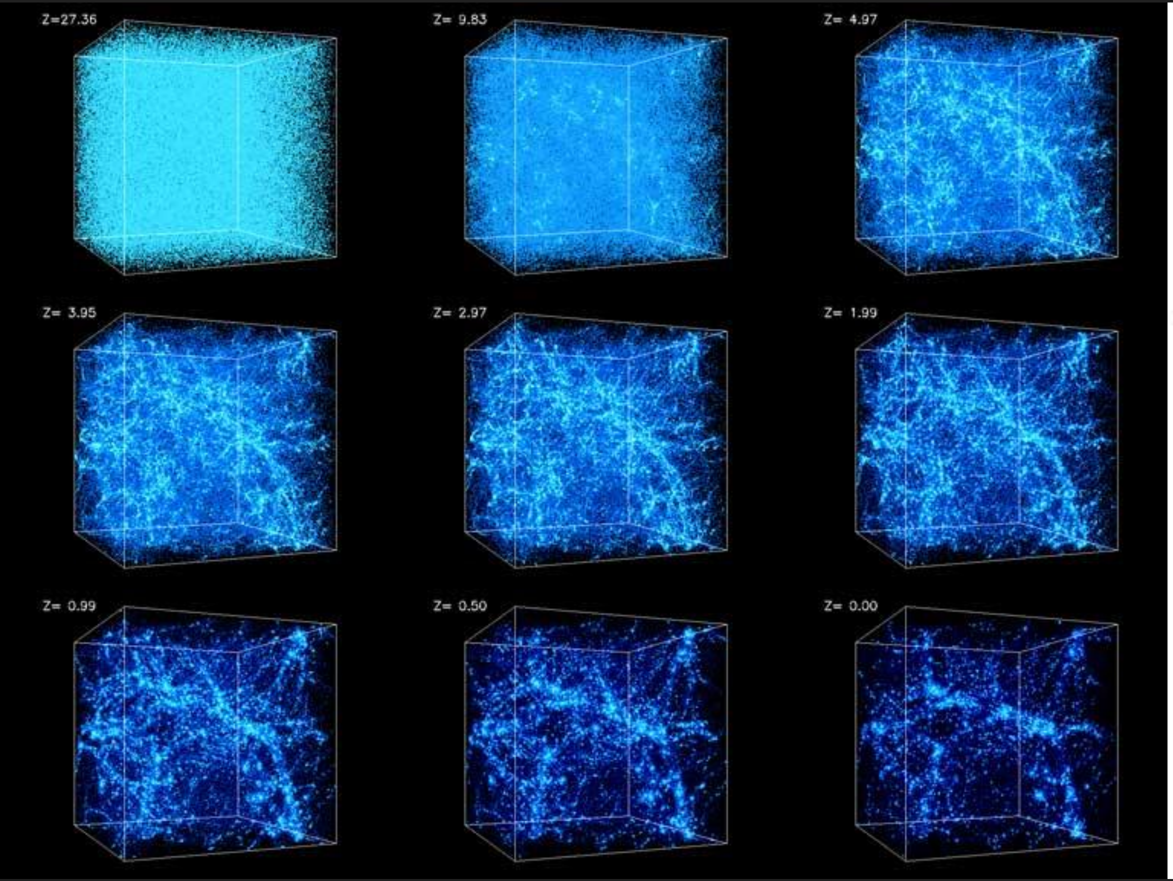
$d=a(t)\int dl=a\chi$

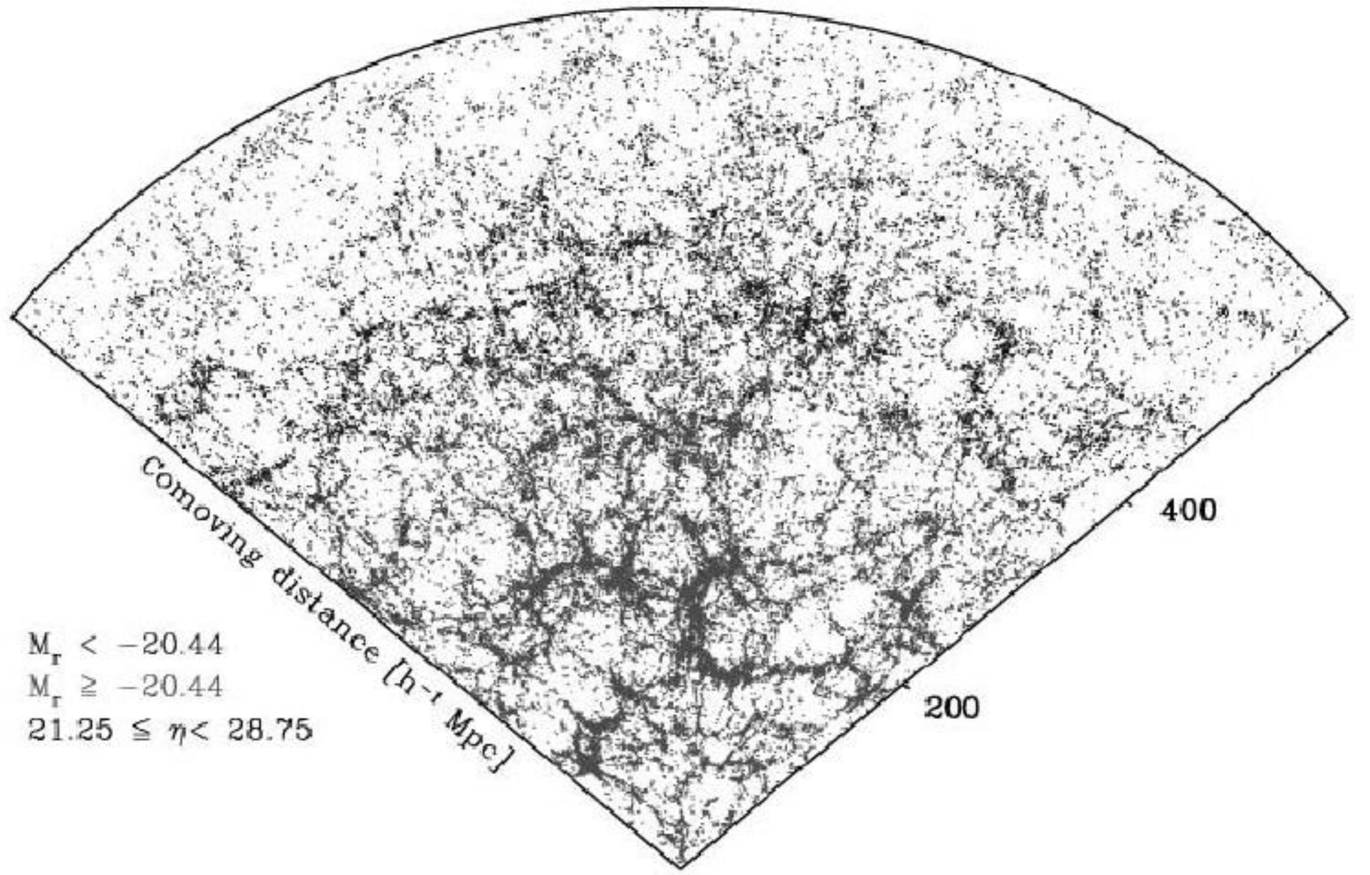
$v=dd/dt=(da/dt)\chi = [(da/dt)/a](a\chi)=Hd$

$$H^2(z)=H_0^2\left(\Omega_r(1+z)^4+\Omega_m(1+z)^3+\Omega_c(1+z)^2+\Omega_\Lambda\right)$$



Крупномасштабная структура


Z=27.36
Z= 9.83
Z= 4.97
Z= 3.95
Z= 2.97
Z= 1.99
Z= 0.99
Z= 0.50
Z= 0.00



Темная энергия

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3},$$

$$\Omega_k \equiv \frac{-kc^2}{(a_0 H_0)^2}$$

$$\Omega_\Lambda \equiv \frac{\Lambda c^2}{3H_0^2},$$

$$H^2(z) = H_0^2\left(\Omega_M(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right).$$

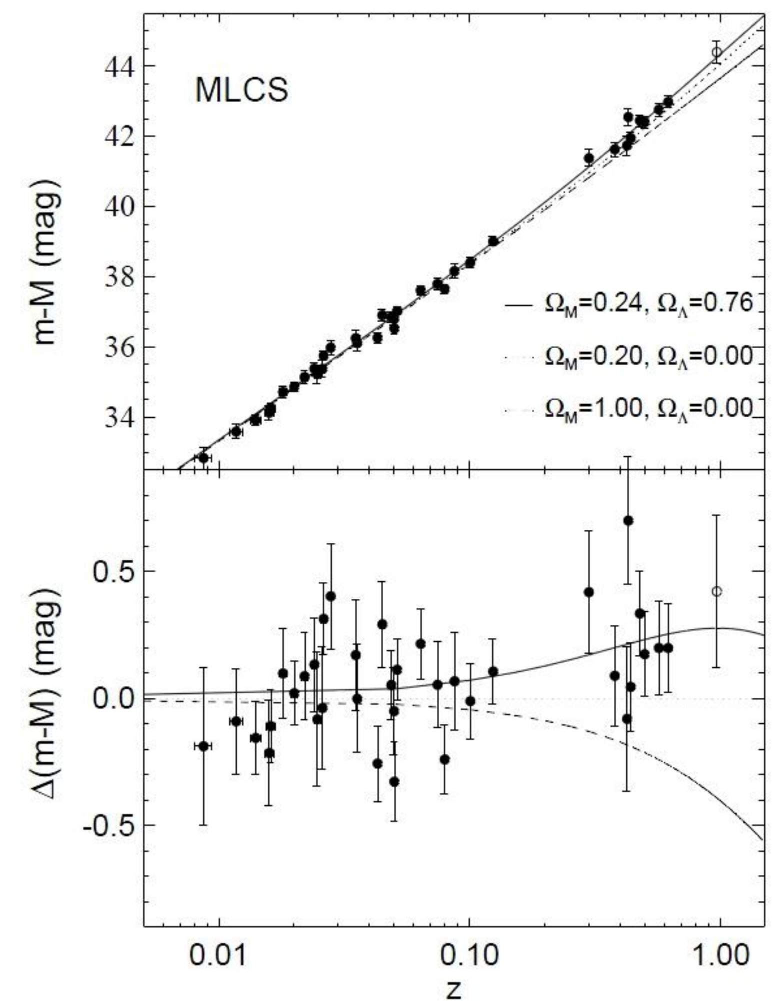
Параметр замедления q

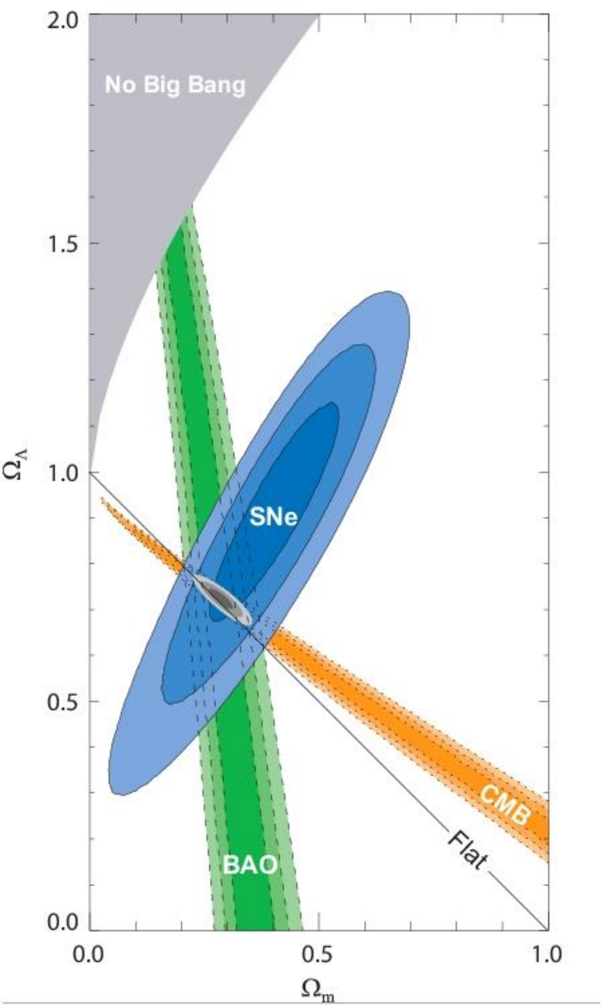
$$q = -\left(1 + \frac{\dot{H}}{H^2}\right).$$

q=0 t=1/H

q=1/2 t=(2/3H)

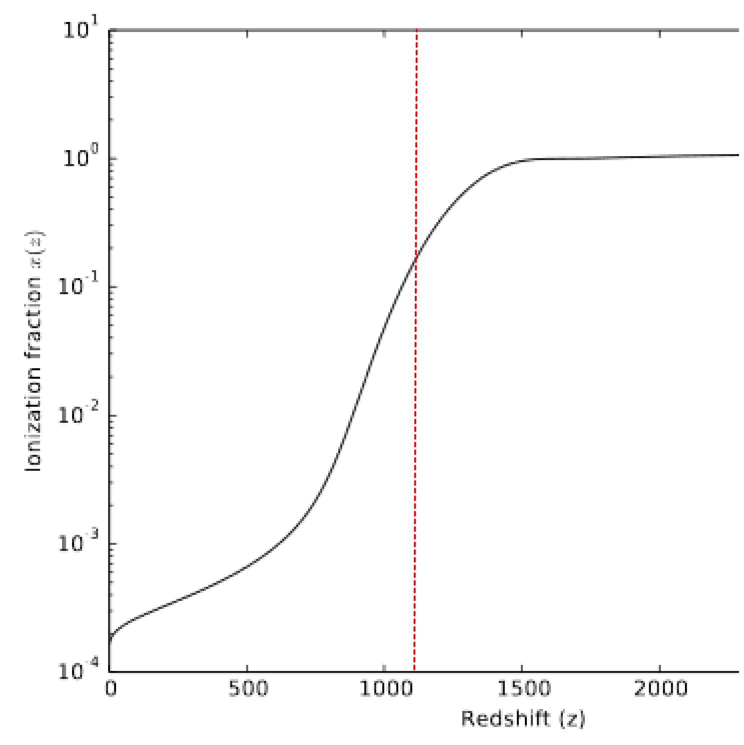
Сейчас q<0.

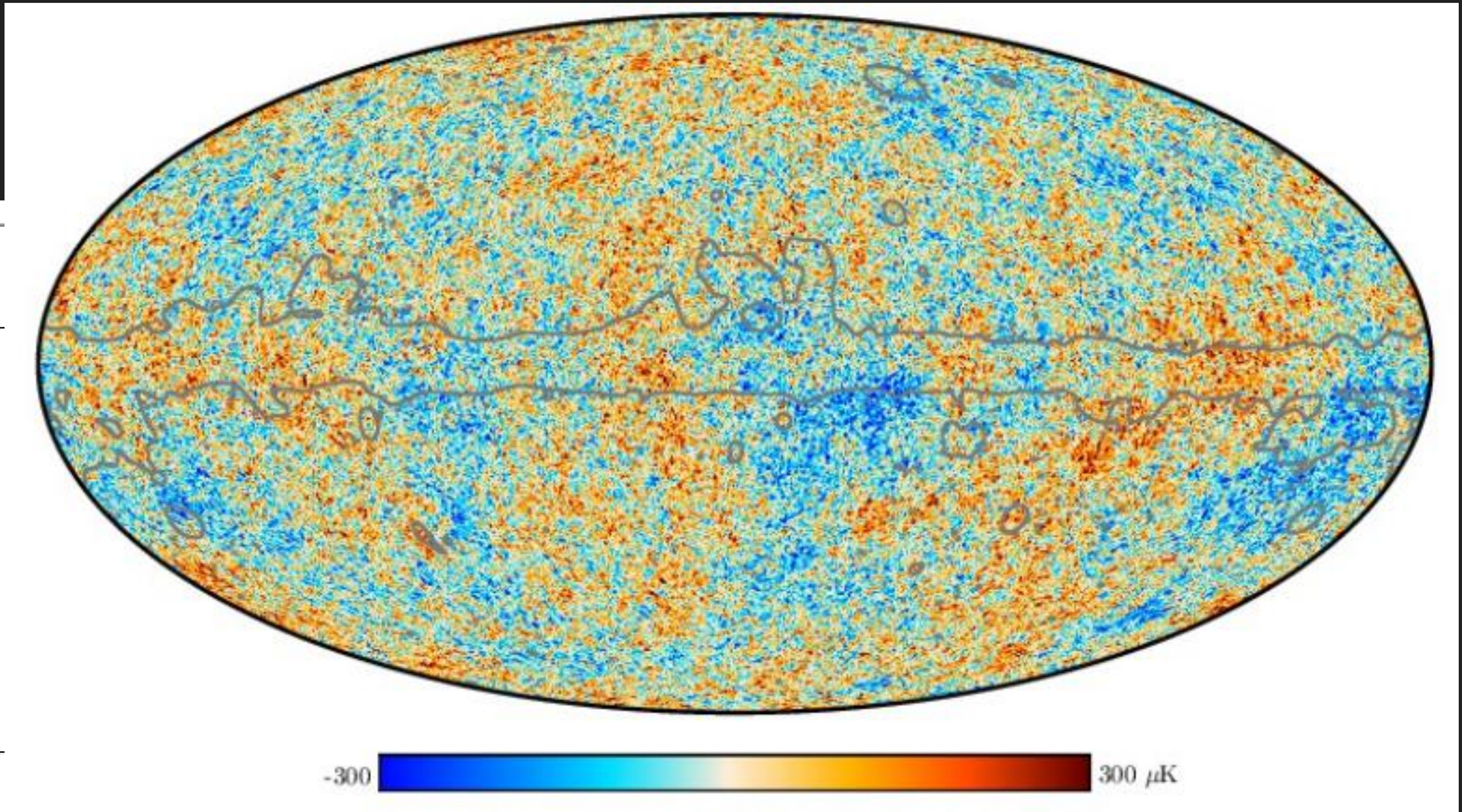




Реликтовое излучение

$$T(z) = T_0 \times (1 + z)$$





Барионные акустические осцилляции

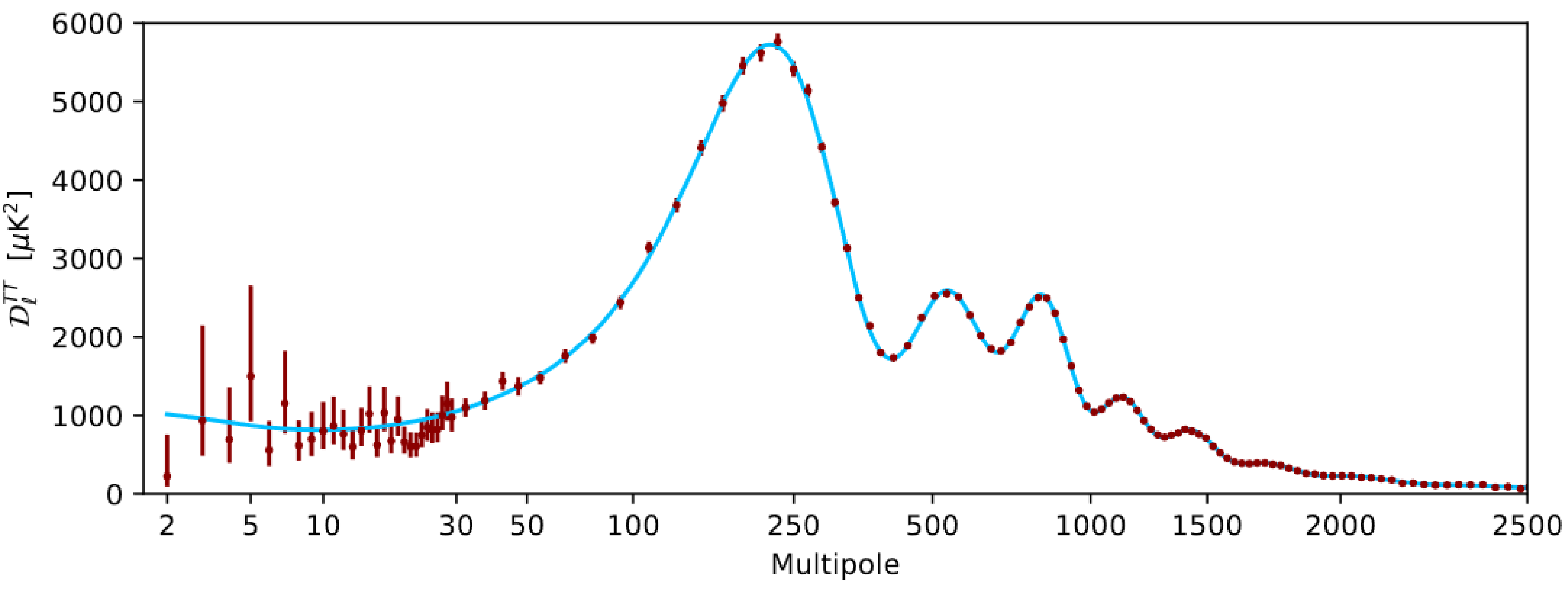
$$c_s = c/\sqrt{3(1+R)}$$

$$R \equiv 3\rho_b/4\rho_\gamma \propto \Omega_b/(1+z)$$

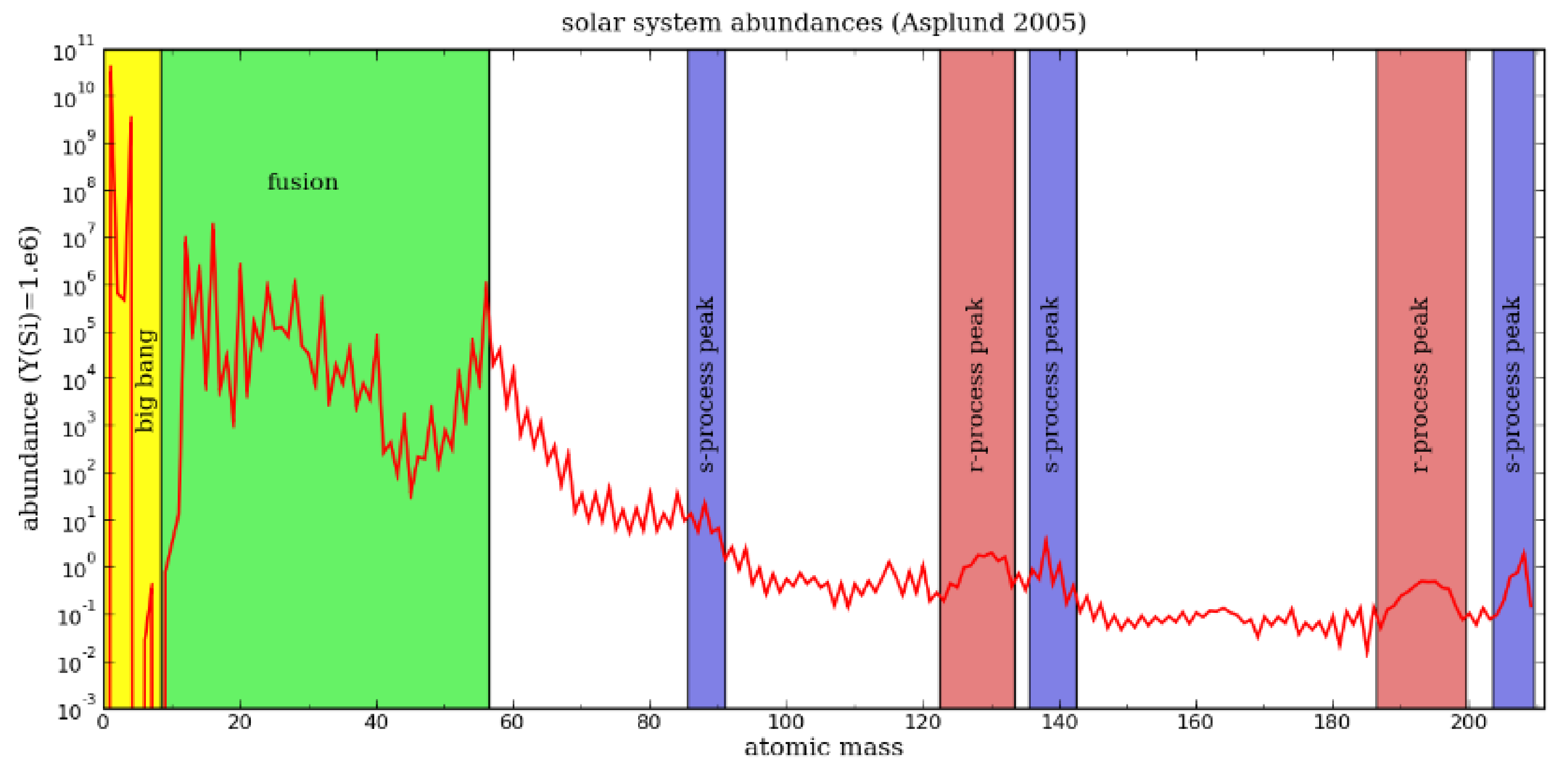
$$\Delta\theta = \frac{\Delta\chi}{d_A(z)}$$

$$d_A(z) \propto \int_0^z \frac{dz'}{H(z')}$$

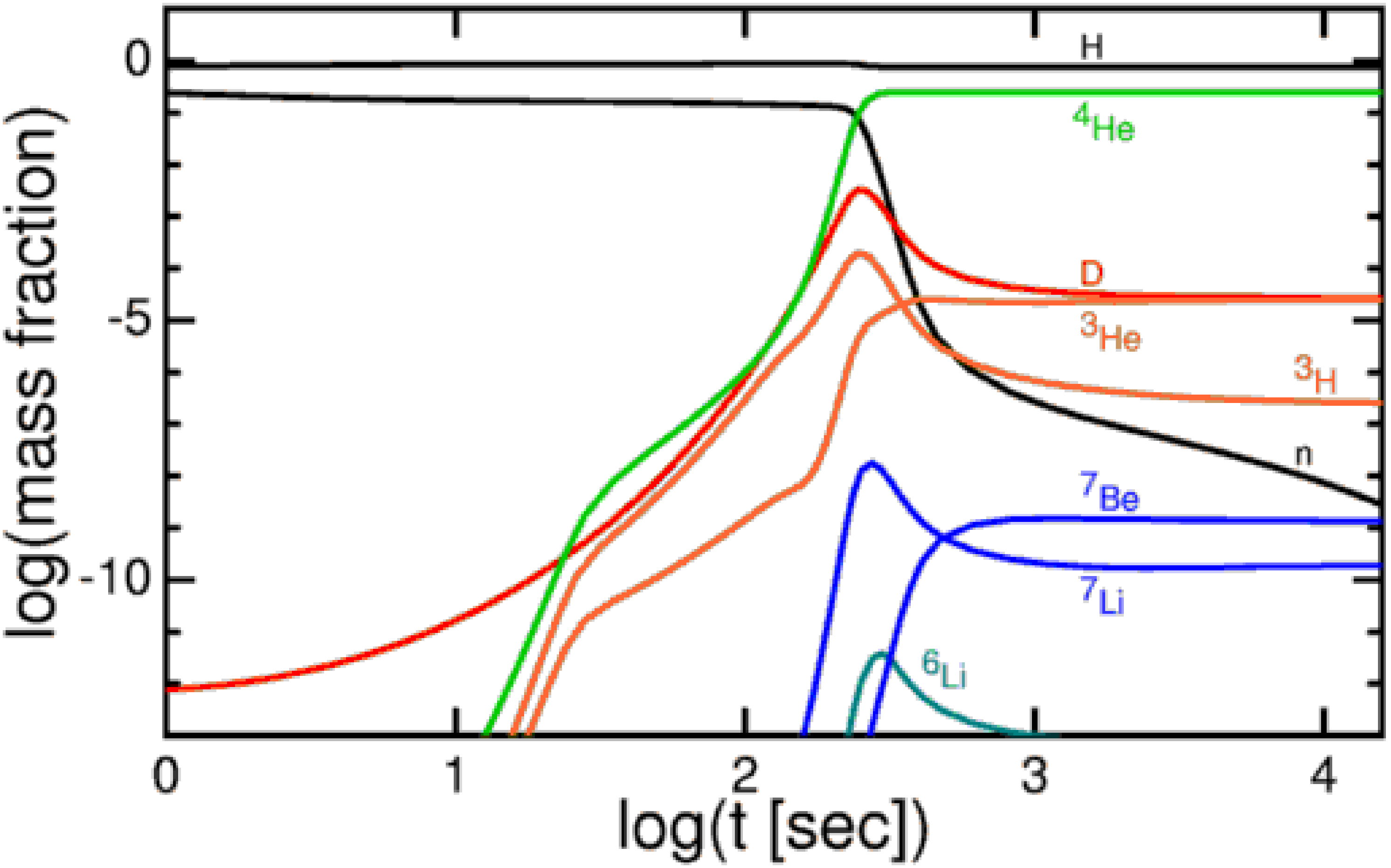
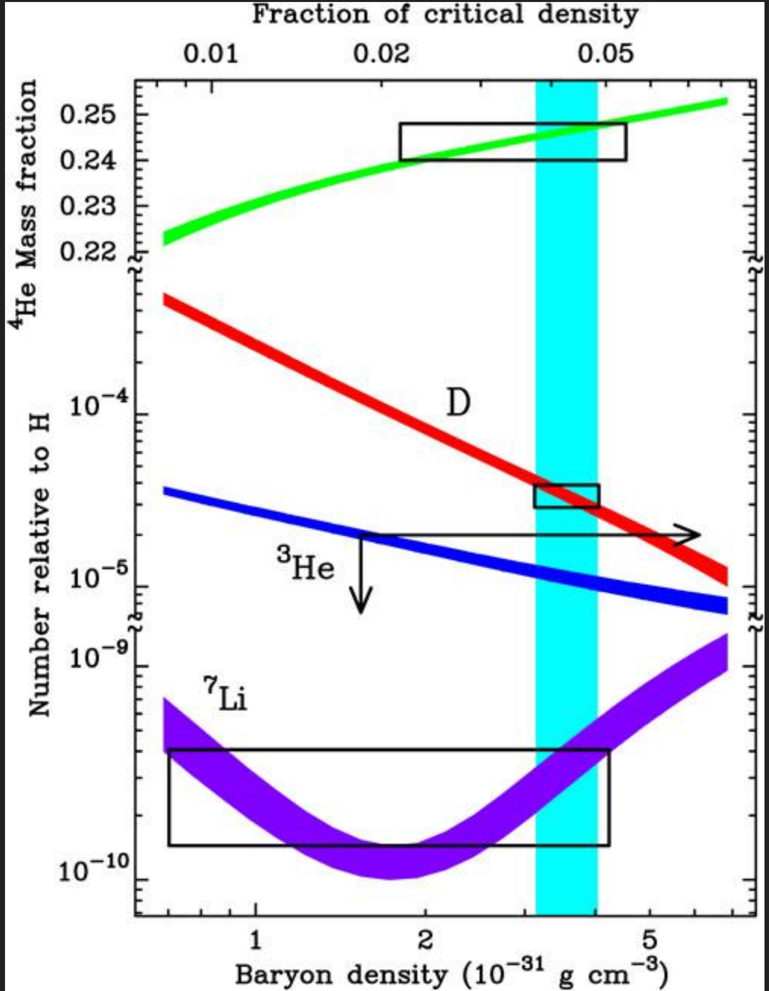
$$c\Delta z = H(z)\Delta\chi$$



Обилие элементов



1901.01410

Первичный нуклеосинтез