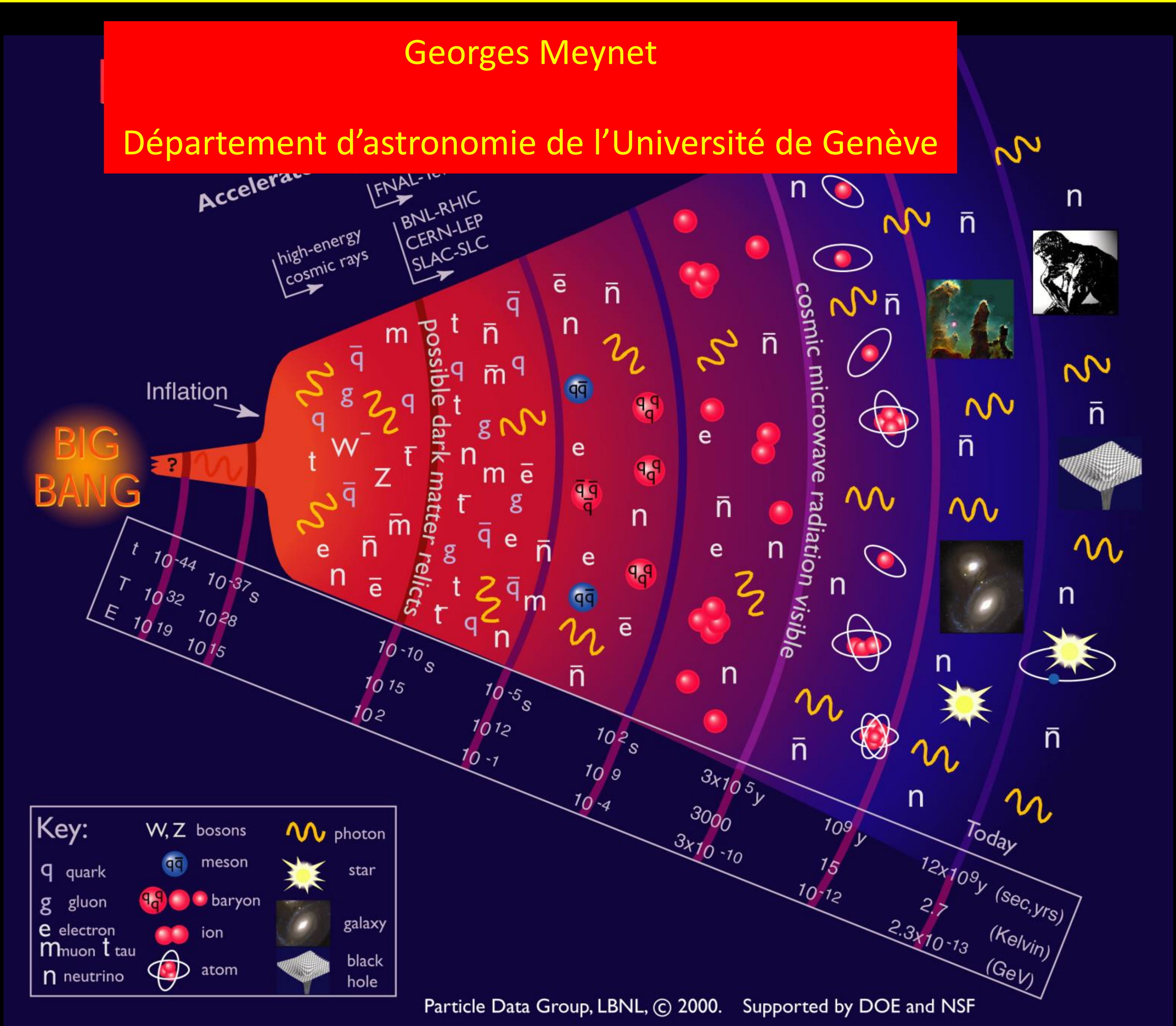
QUELQUES NOMBRES POUR UN UNIVERS

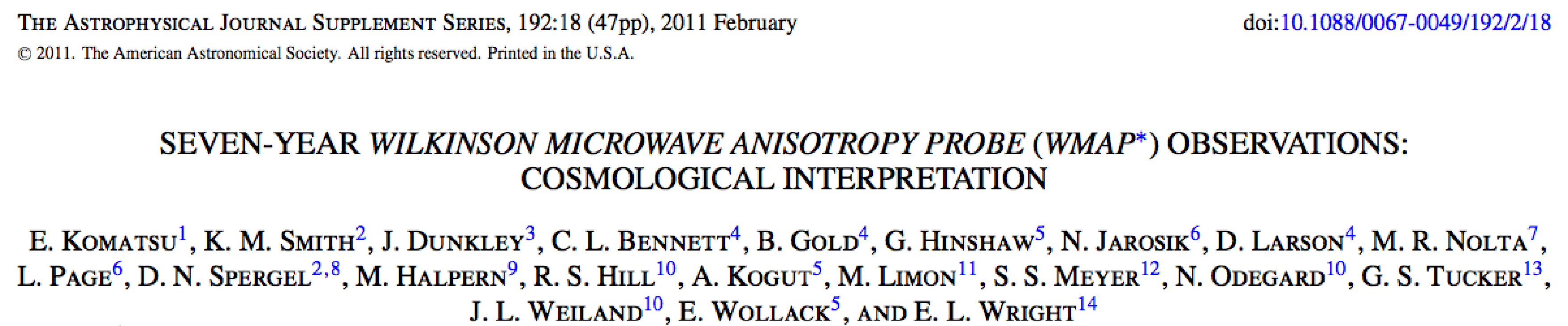
http://solar.physics.montana.edu/scott/strings/standard_universe.html



Georges Meynet

Département d’astronomie de l’Université de Genève

Particle Data Group, LBNL, © 2000. Supported by DOE and NSF



The Astrophysical Journal Supplement Series, 192:18 (47pp), 2011 February
doi:10.1088/0067-0049/192/2/18

SEVEN-YEAR *WILKINSON MICROWAVE ANISOTROPY PROBE* (*WMAP**) OBSERVATIONS: COSMOLOGICAL INTERPRETATION

E. Komatsu[1], K. M. Smith[2], J. Dunkley[3], C. L. Bennett[4], B. Gold[4], G. Hinshaw[5], N. Jarosik[6], D. Larson[4], M. R. Nolta[7], L. Page[6], D. N. Spergel[2,8], M. Halpern[9], R. S. Hill[10], A. Kogut[5], M. Limon[11], S. S. Meyer[12], N. Odegard[10], G. S. Tucker[13], J. L. Weiland[10], E. Wollack[5], and E. L. Wright[14]

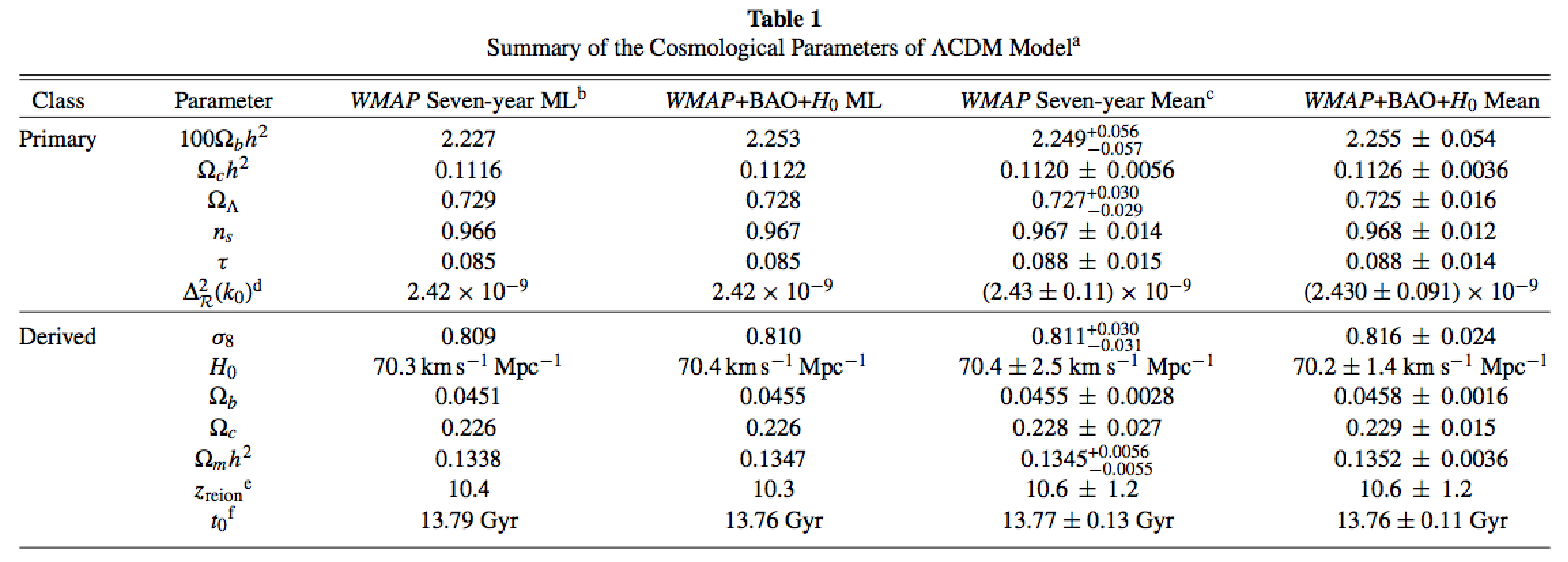
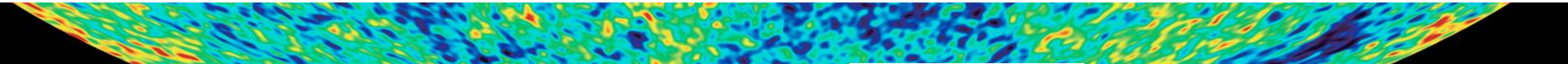
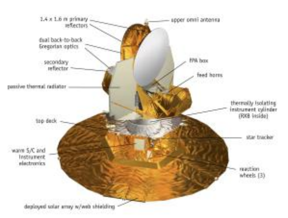


Table 1

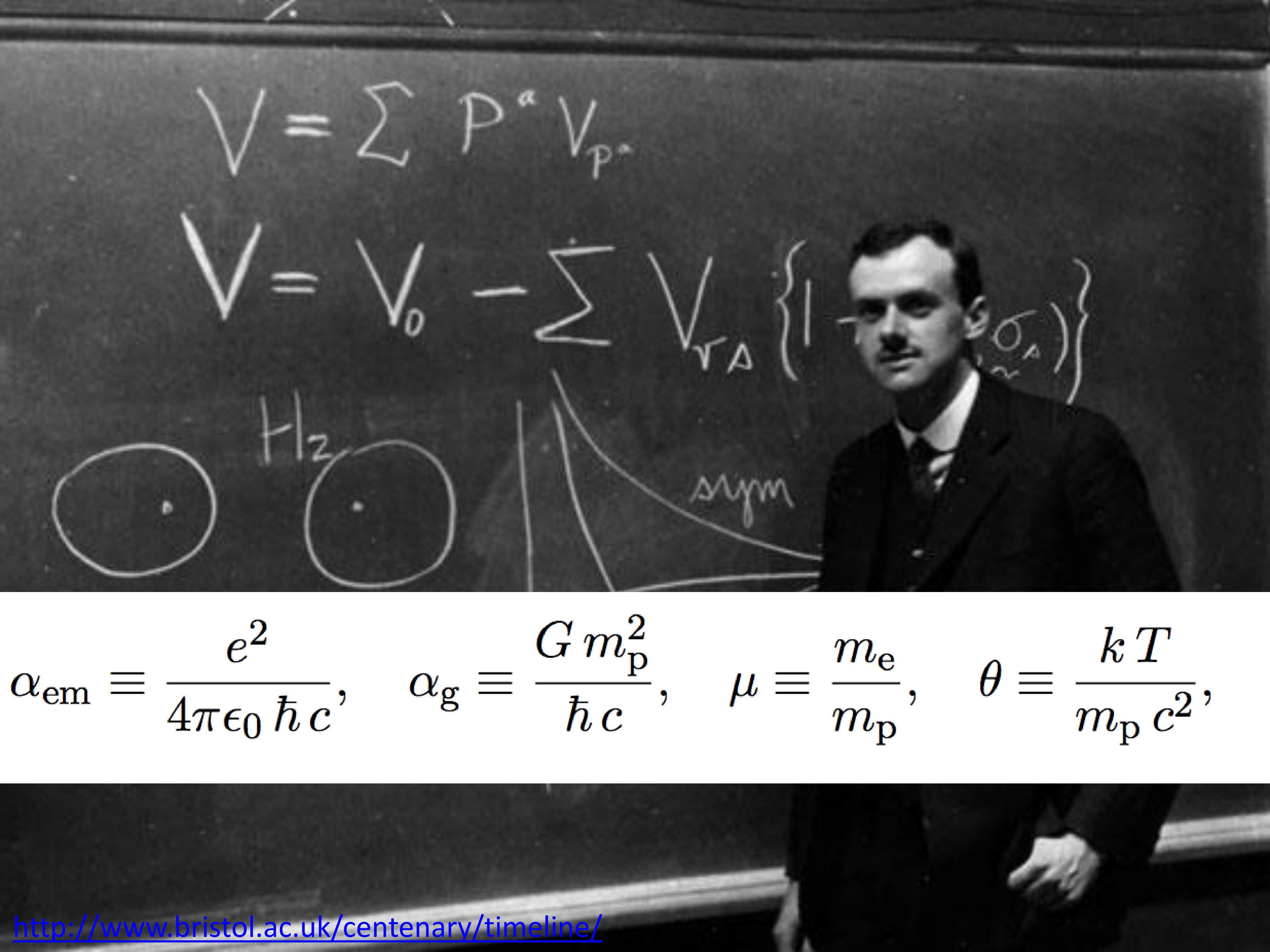
Summary of the Cosmological Parameters of ΛCDM Model[a]

Class	Parameter	*WMAP* Seven-year ML[b]	*WMAP*+BAO+H_0 ML	*WMAP* Seven-year Mean[c]	*WMAP*+BAO+H_0 Mean
Primary	$100\Omega_b h^2$	2.227	2.253	$2.249^{+0.056}_{-0.057}$	2.255 ± 0.054
	$\Omega_c h^2$	0.1116	0.1122	0.1120 ± 0.0056	0.1126 ± 0.0036
	Ω_Λ	0.729	0.728	$0.727^{+0.030}_{-0.029}$	0.725 ± 0.016
	n_s	0.966	0.967	0.967 ± 0.014	0.968 ± 0.012
	τ	0.085	0.085	0.088 ± 0.015	0.088 ± 0.014
	$\Delta^2_{\mathcal{R}}(k_0)$[d]	2.42×10^{-9}	2.42×10^{-9}	$(2.43 \pm 0.11) \times 10^{-9}$	$(2.430 \pm 0.091) \times 10^{-9}$
Derived	σ_8	0.809	0.810	$0.811^{+0.030}_{-0.031}$	0.816 ± 0.024
	H_0	$70.3\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$	$70.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$	$70.4 \pm 2.5\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$	$70.2 \pm 1.4\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$
	Ω_b	0.0451	0.0455	0.0455 ± 0.0028	0.0458 ± 0.0016
	Ω_c	0.226	0.226	0.228 ± 0.027	0.229 ± 0.015
	$\Omega_m h^2$	0.1338	0.1347	$0.1345^{+0.0056}_{-0.0055}$	0.1352 ± 0.0036
	z_{reion}[e]	10.4	10.3	10.6 ± 1.2	10.6 ± 1.2
	t_0[f]	13.79 Gyr	13.76 Gyr	13.77 ± 0.13 Gyr	13.76 ± 0.11 Gyr





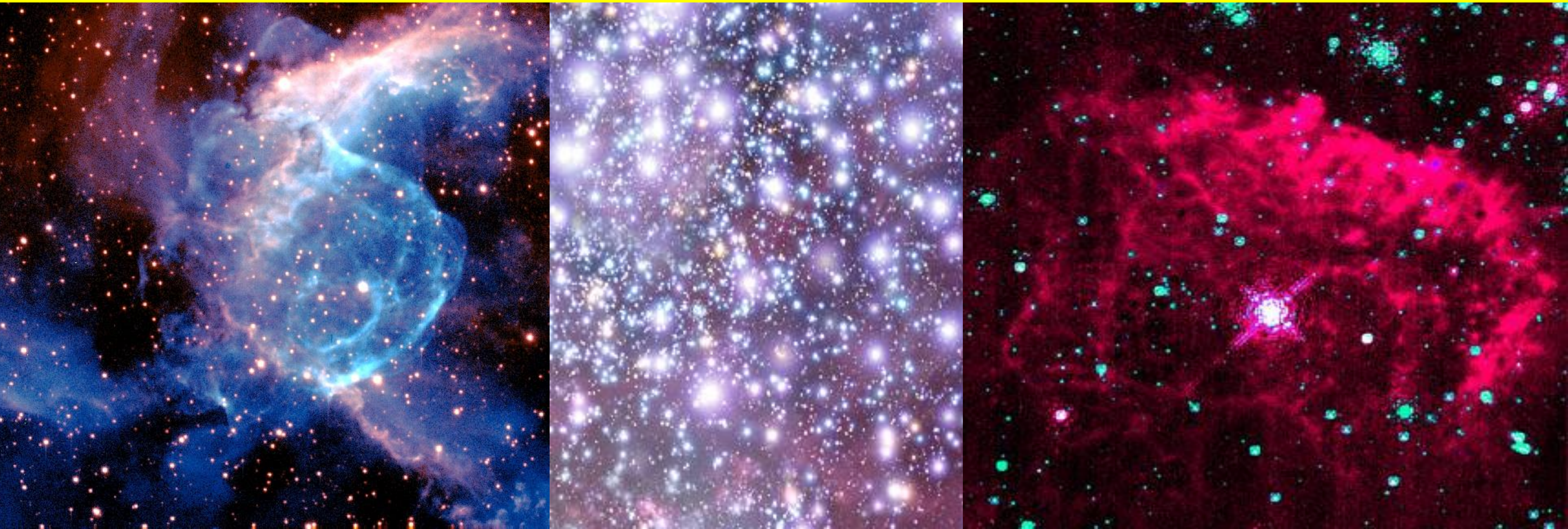
http://commons.wikimedia.org/wiki/File:WMAP_spacecraft_diagram.jpg



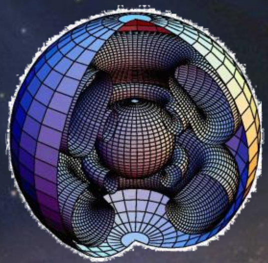
$$\alpha_{\rm em} \equiv \frac{e^2}{4\pi\epsilon_0\,\hbar\,c}, \quad \alpha_{\rm g} \equiv \frac{G\,m_{\rm p}^2}{\hbar\,c}, \quad \mu \equiv \frac{m_{\rm e}}{m_{\rm p}}, \quad \theta \equiv \frac{k\,T}{m_{\rm p}\,c^2},$$

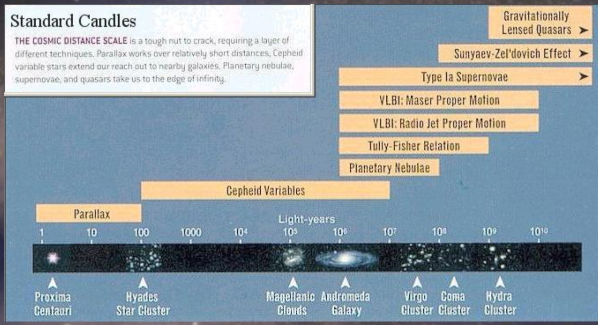
http://www.bristol.ac.uk/centenary/timeline/

Les étoiles pour sonder l’UNIVERS



1) La Physique stellaire en quelques mots

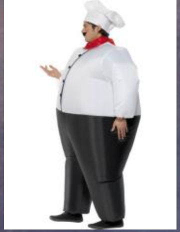



Standard Candles

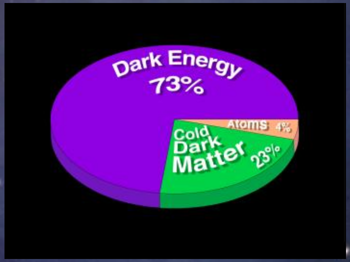
THE COSMIC DISTANCE SCALE is a tough nut to crack, requiring a layer of different techniques. Parallax works over relatively short distances, Cepheid variable stars extend our reach out to nearby galaxies. Planetary nebulae, supernovae, and quasars take us to the edge of infinity.

http://universe-review.ca/R02-07-candle.htm

2) Les étoiles comme chandelle standard



3) Les étoiles et la cuisine cosmique



4) La nucléosynthèse et la matière sombre

5) Les étoiles et les constantes fondamentales

1) Quelques mots sur la physique stellaire

Chandra poster

PHYSICAL INTERACTIONS IN STARS

GRAVITATION

STRONG NUCL.

Energy production

contraction

Nuclear energy

WEAK NUCL.

ELECTRO.

Energy transport

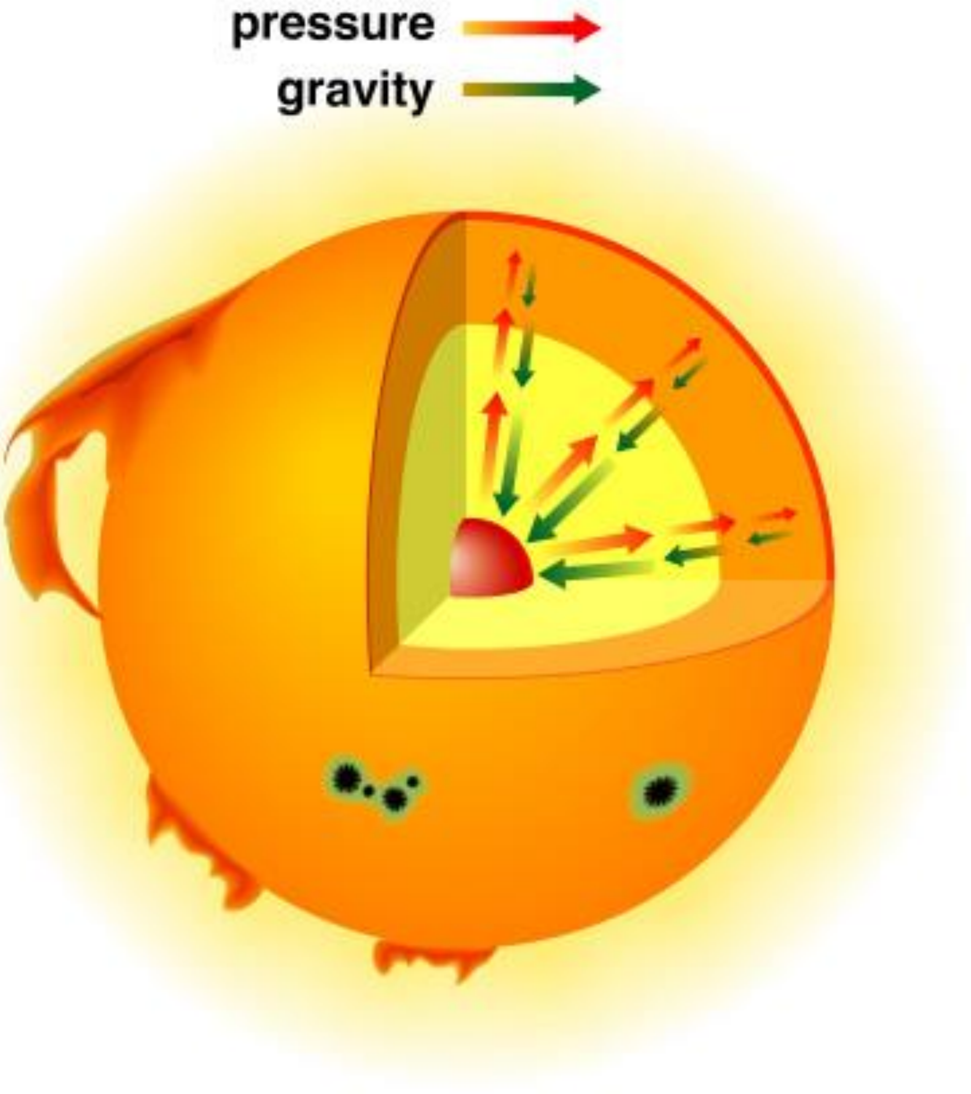
radiation

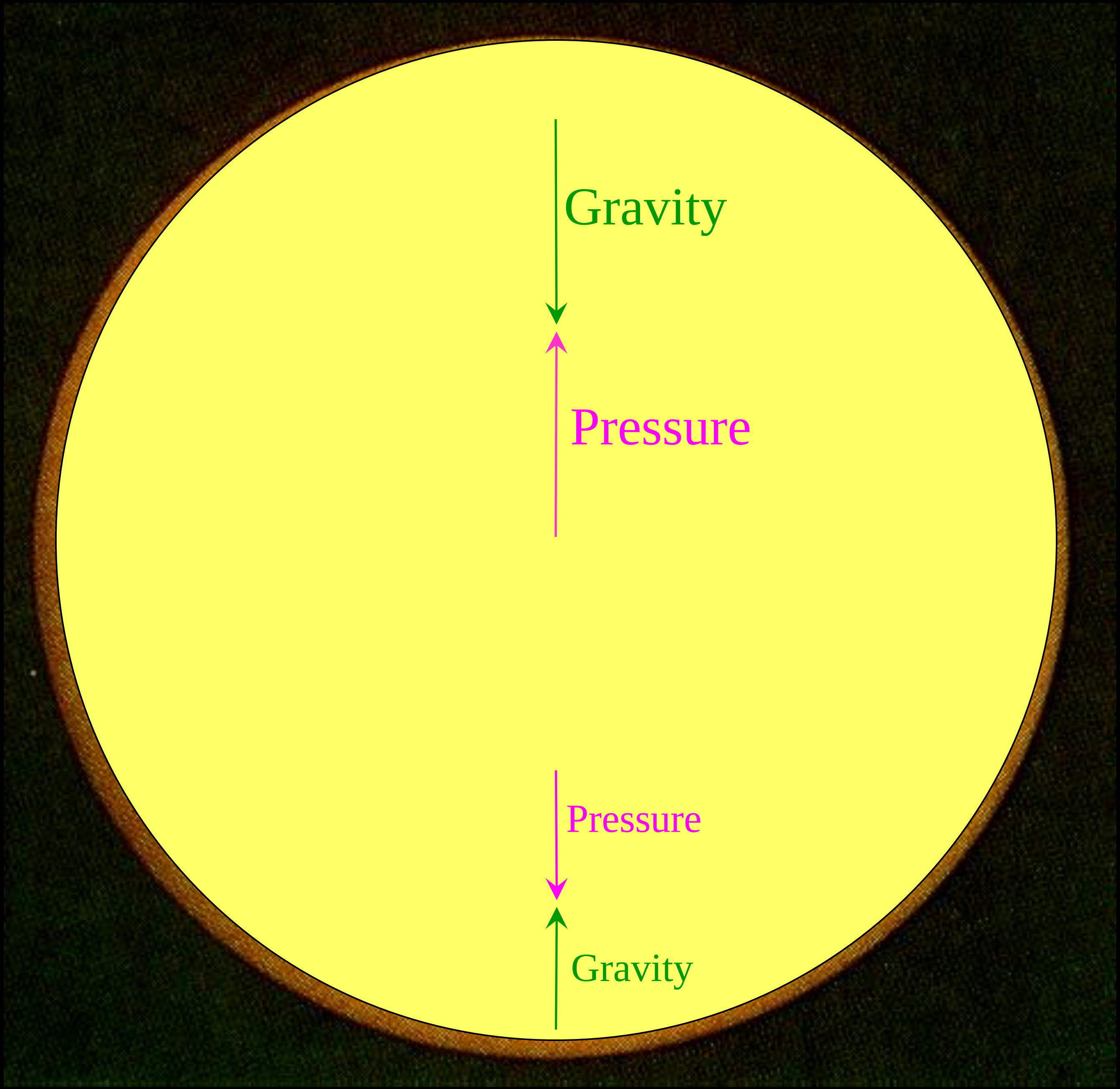
ν-emission

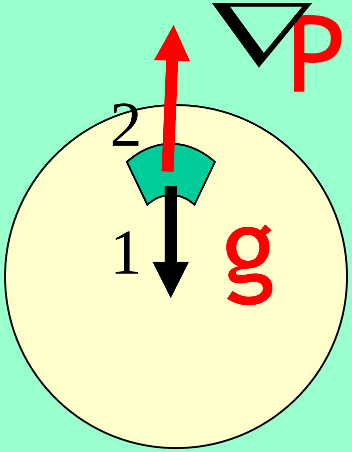
Intervene through numerous physical mechanisms

- **equation of state**
- **Thermodynamic properties**
- **Opacities, atomic, molecular**
- **nuclear reaction rates**
- **neutrino emissions**
- **Hydrodynamics**
- **…………….**

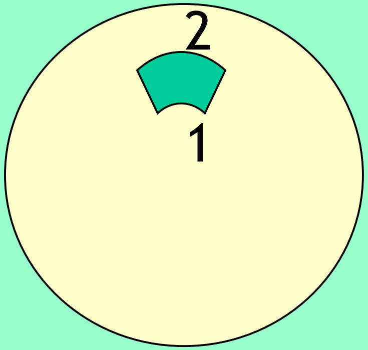
Maintain equilibrium has a price




Gravity
Pressure
Pressure
Gravity

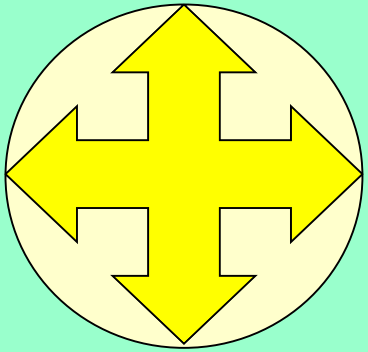


P1 > P2



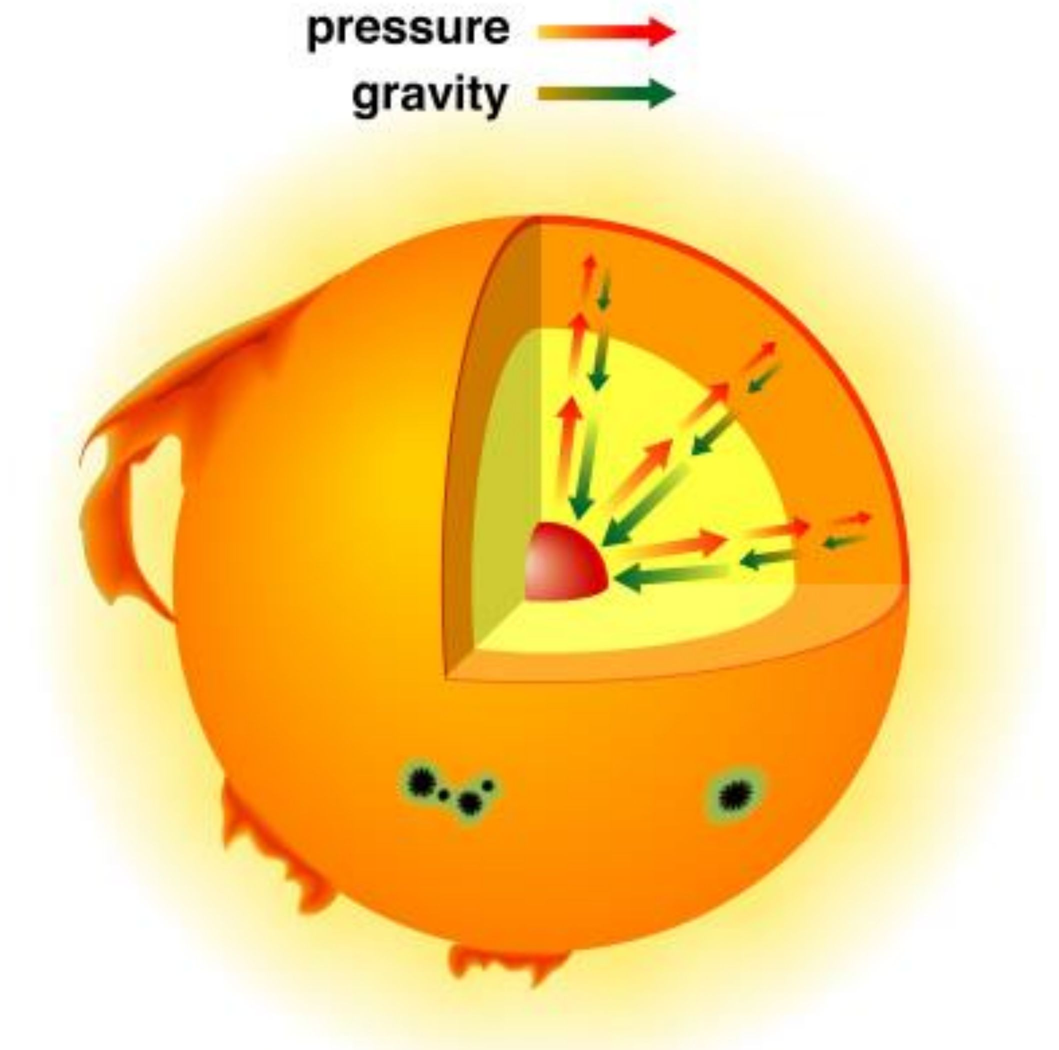
T1> T2

$U=aT^4$



U1 >>U2

Maintain equilibrium has a price



A few estimates

- Central pressure in the SUN
- Central temperature in the SUN

$$\boxed{\frac{dP}{dr} = -\rho g}$$

$$\frac{P_s - P_c}{R} \approx -\frac{M}{\frac{4}{3}\pi R^3}\,\frac{GM/2}{(R/2)^2}$$

$$\boxed{P_c \approx \frac{1}{2} G \frac{M^2}{R^4}}$$

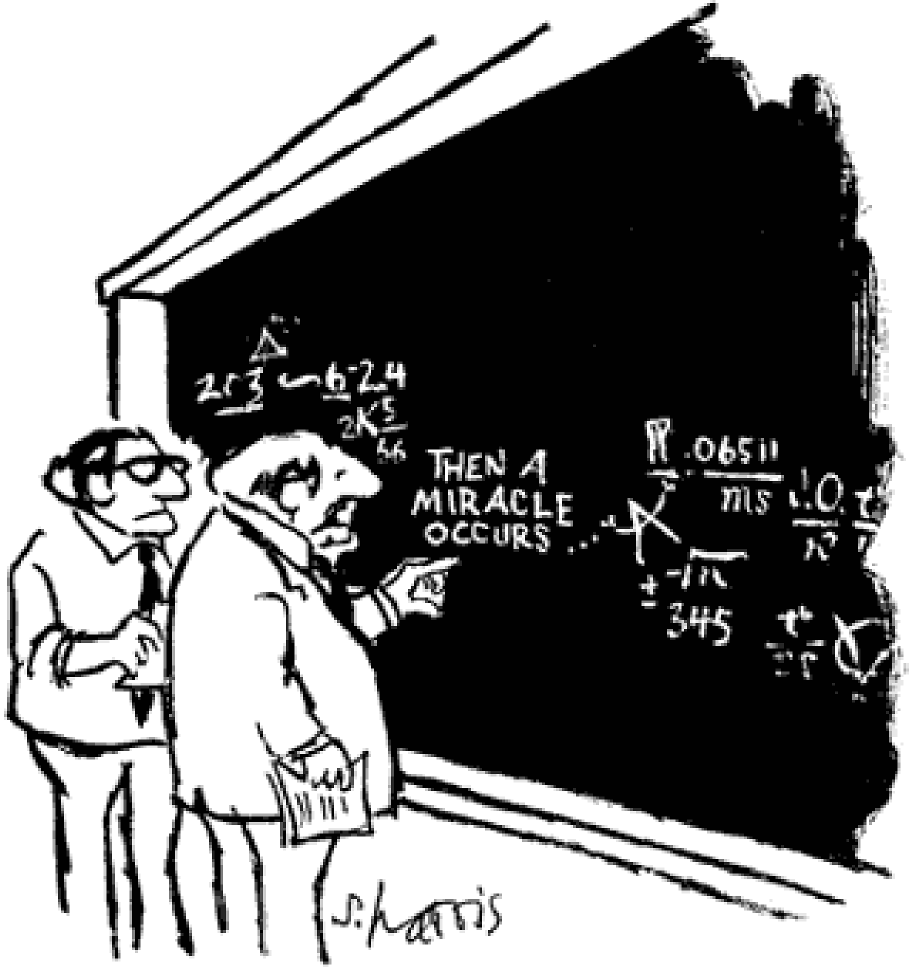
$$\boxed{P_c \approx \frac{1}{2} G \frac{M^2}{R^4}}$$

$$\boldsymbol{P = \frac{k}{\mu m_H} \rho T}$$

$$\rho_c = f\rho$$

$$\boxed{T_c = \frac{2Gm_H}{k} \frac{\mu_c M}{fR}}$$

A PROBLEM WITH THESE ESTIMATES…



"I think you should be more explicit here in step two."

http://www.sciencecartoonsplus.com/gallery/

J. Homer Lane 1870

Temperature → 10^7 K

Density → 150 000 $\mathrm{kg/m^3}$

PROBLEM !!!

Do we still have a gaz at such a high density?

Density obtained in matter composed of H atomes adjacent to each other

13 600 $\mathrm{kg/m^3}$

Estimate for the luminosity

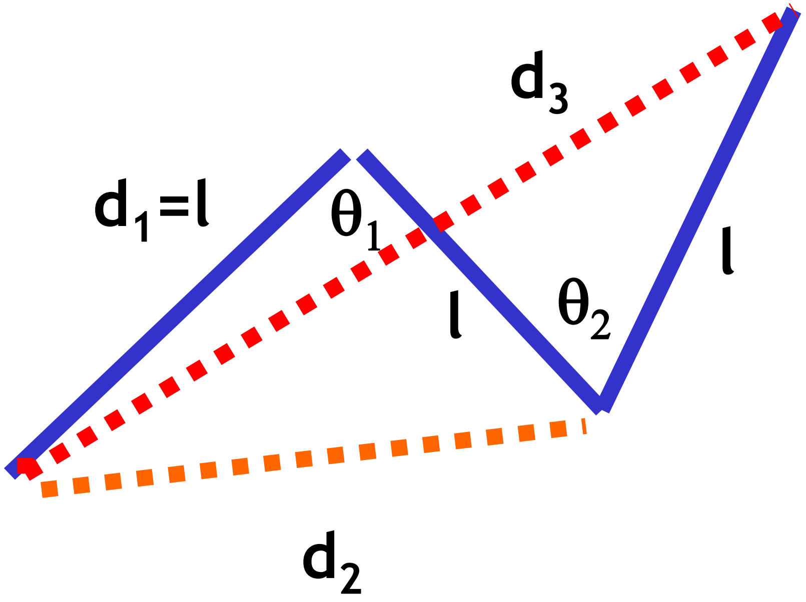
L=A/B

A=Quantity of energy under the form of radiation

$$\boxed{a < T^4 > \frac{4}{3}\pi R^3}$$

B=Time for a photon at the centre to reach the surface

$$\boxed{\frac{l}{c} N_{diff}}$$



$$\boxed{N_{diff} = \frac{R^2}{l^2}}$$

$$\boxed{l = \frac{1}{\kappa\rho}}$$

$$d_1^2 = l^2$$

$$d_2^2 = l^2 + l^2 - 2l^2 \cos\theta_1$$

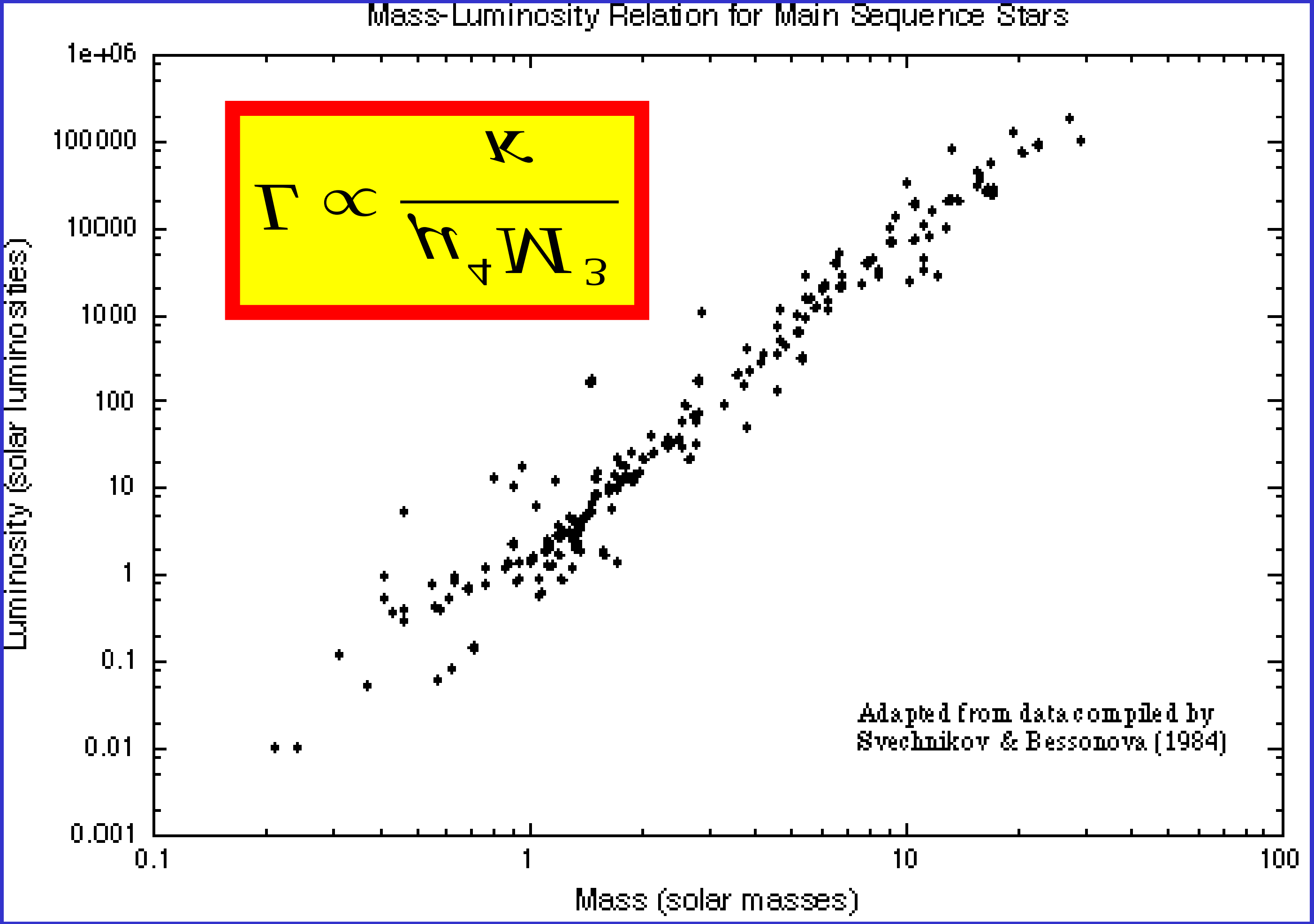
$$d_n^2 = nl^2 - 2l\left(\sum_{i=2}^{n} d_{i-1}\cos\theta_{i-1}\right) \approx nl^2$$

$$\mathrm{L} = \frac{a < T^4 > \frac{4}{3}\pi R^3}{\frac{l}{c} N_{diff}}$$

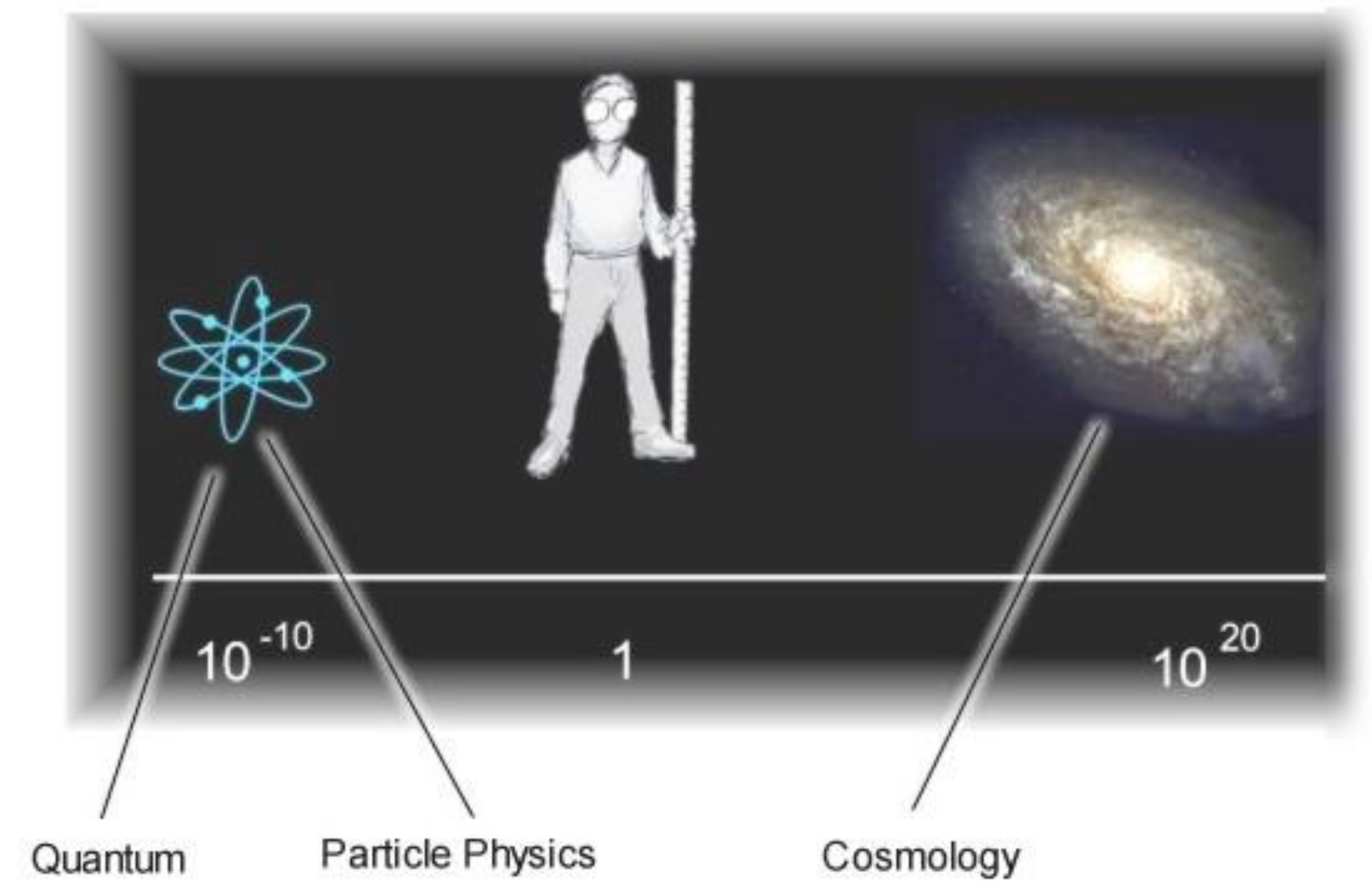
$$\mathrm{L} \sim \frac{T^4 R^3}{R^2 \frac{M}{R^3} \kappa}$$

$$T \approx C\mu \frac{M}{R}$$

The mass-luminosity relation for 192 stars in double-lined spectroscopic binary systems.

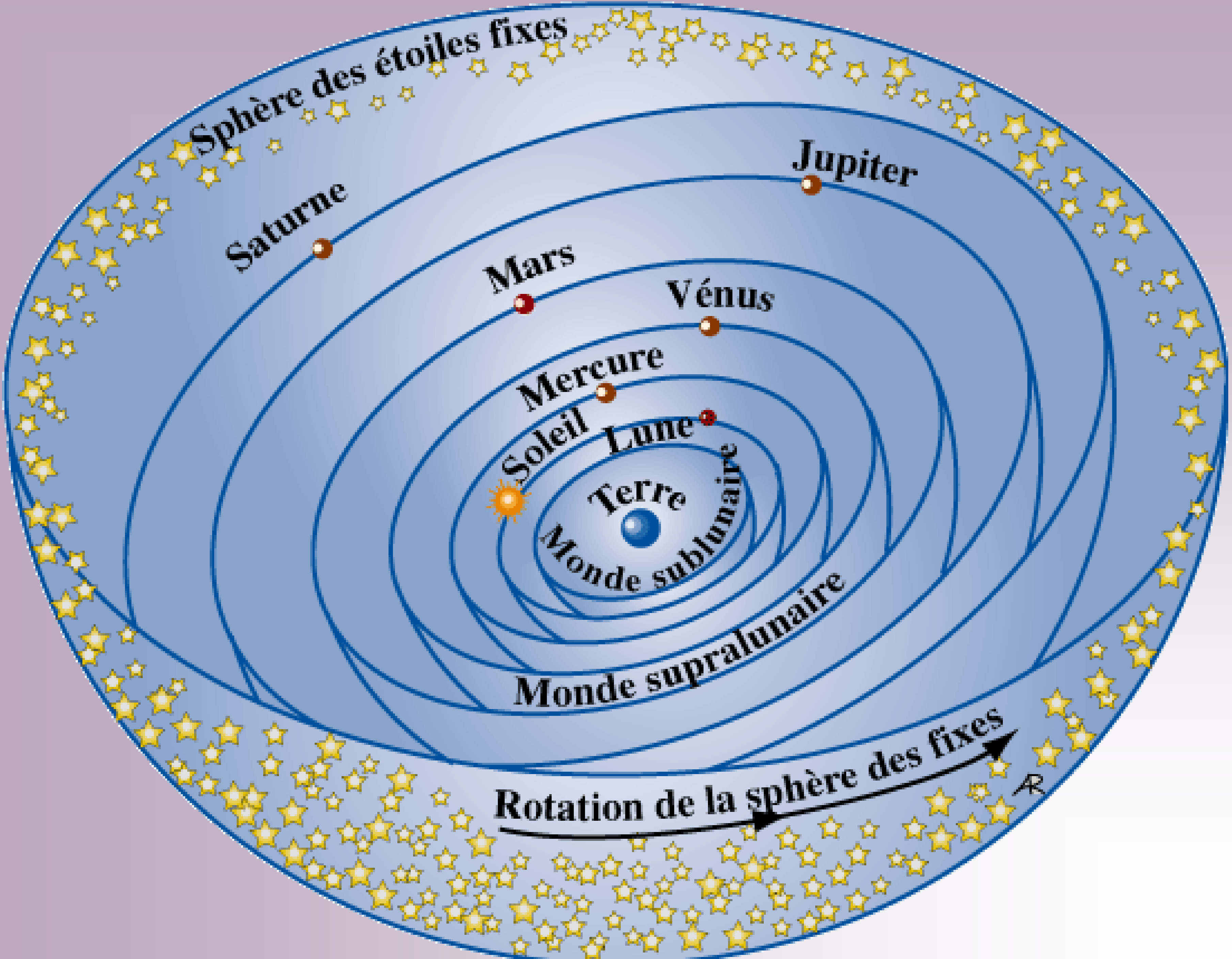


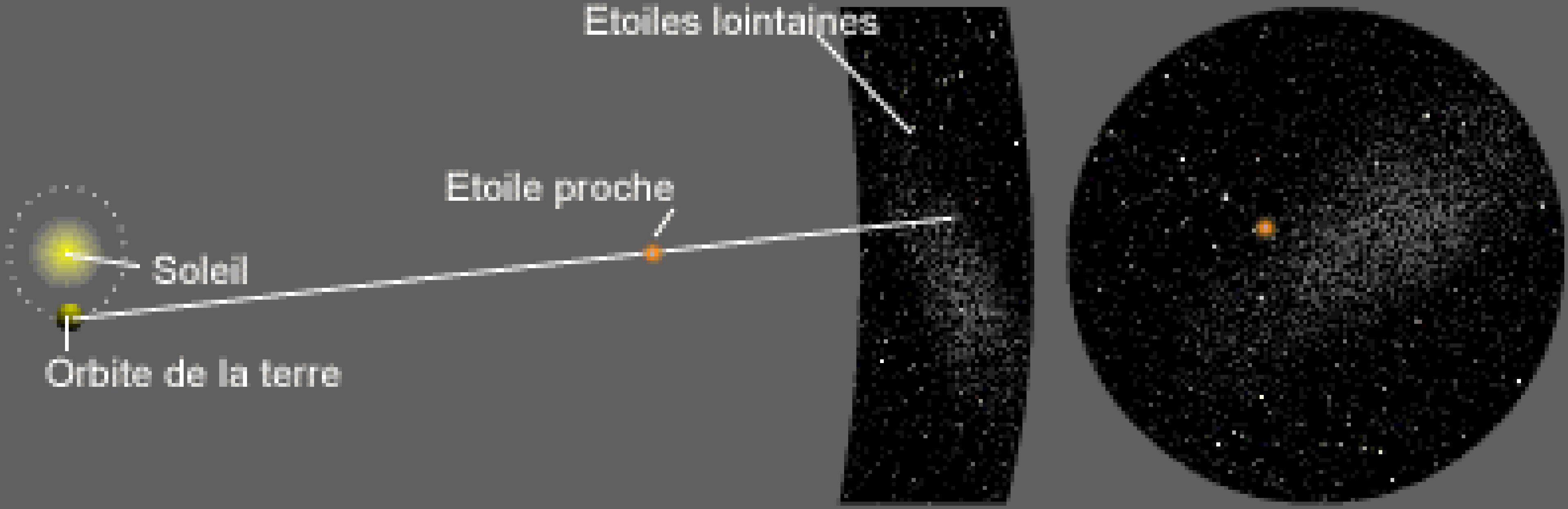
2) Les étoiles comme chandelles standards



http://www.phy.bris.ac.uk/allegory/

ster


Sphère des étoiles fixes
Jupiter
Saturne
Mars
Vénus
Mercure
Soleil
Lune
Terre
Monde sublunaire
Monde supralunaire
Rotation de la sphère des fixes

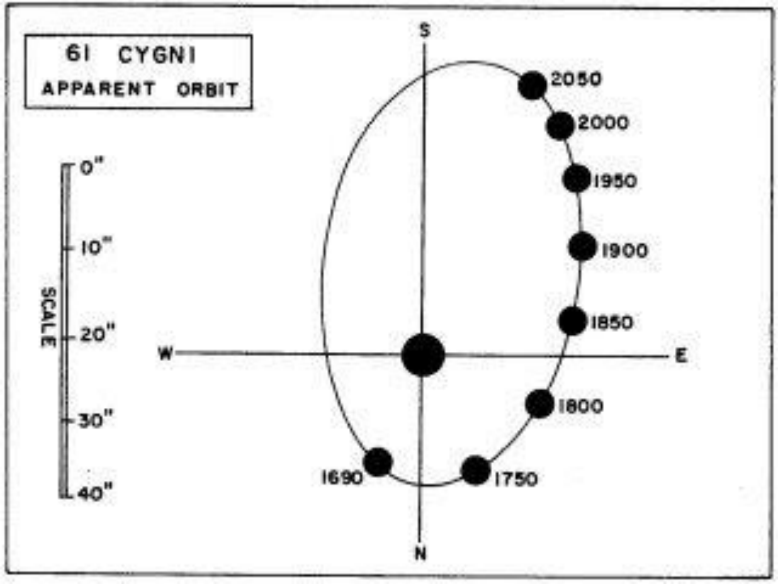


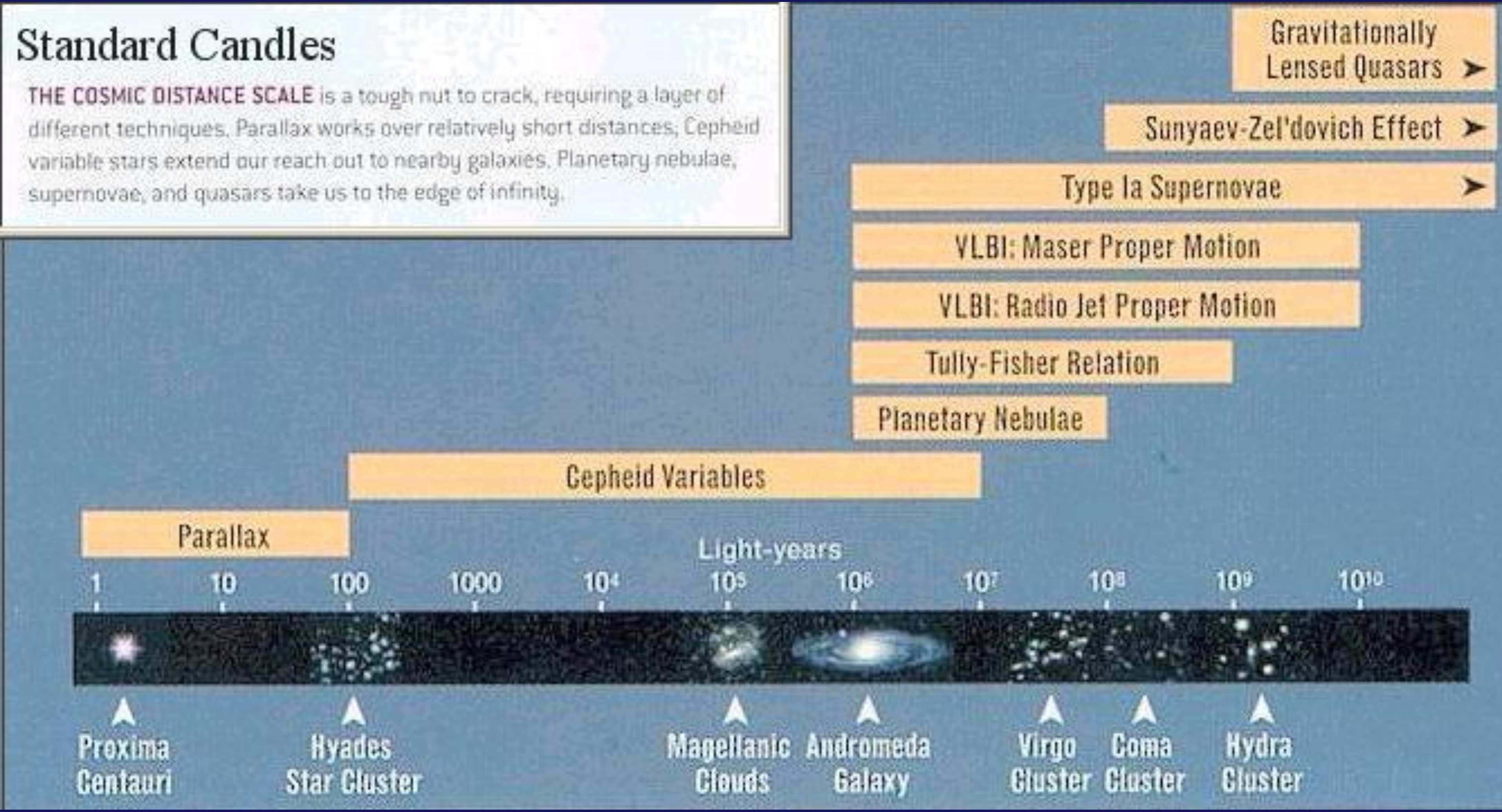
Première observation

Friedrich Bessel
1838

Distance 10.5 a.l.
Parallaxe 0’’31
1/4737 de l’angle
sous-tendu par
la pleine Lune

Système binaire
Prev=653.2 ans





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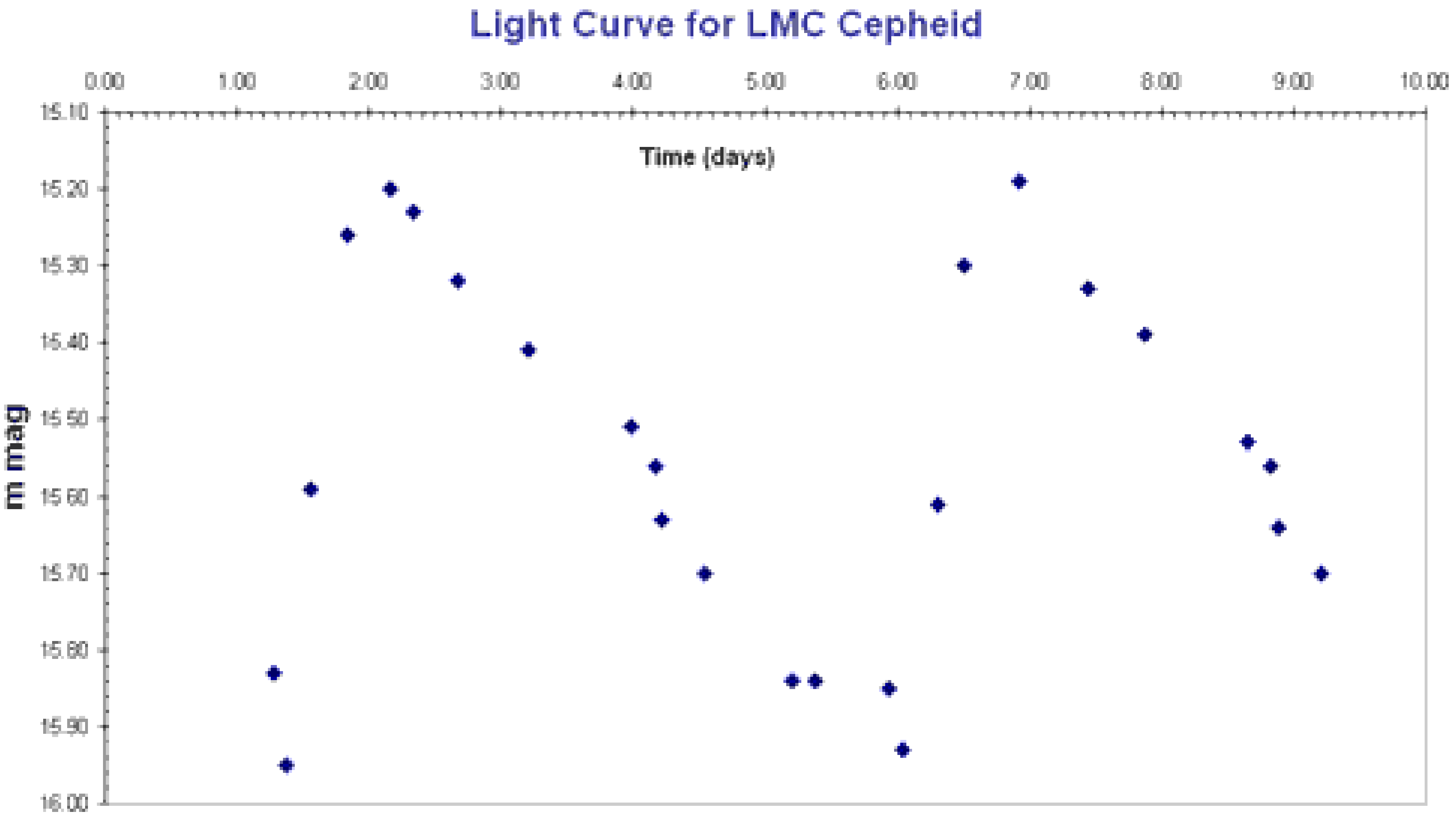
http://universe-review.ca/R02-07-candle.htm

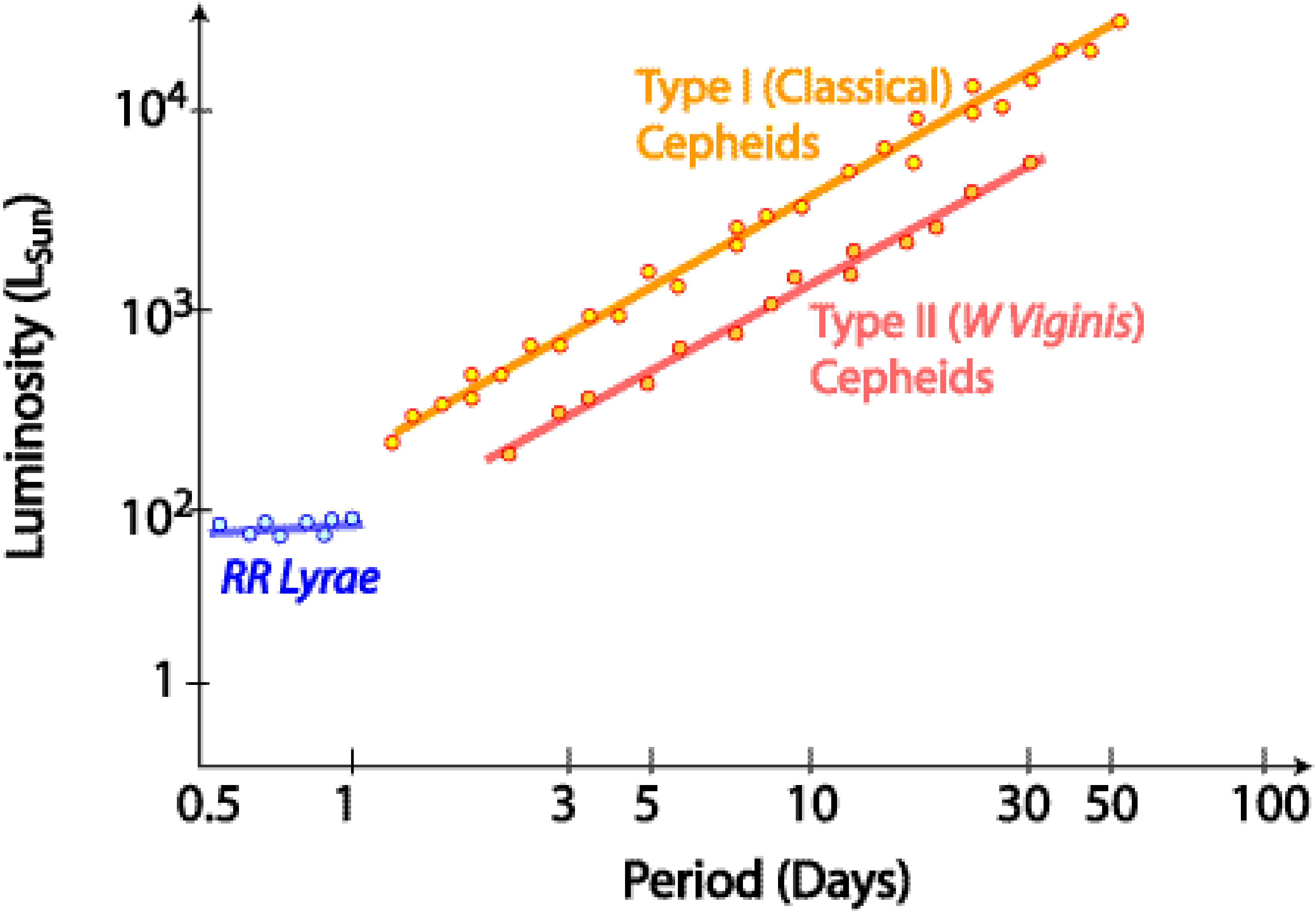
HENRIETTA LEAVITT

1868 - 1921

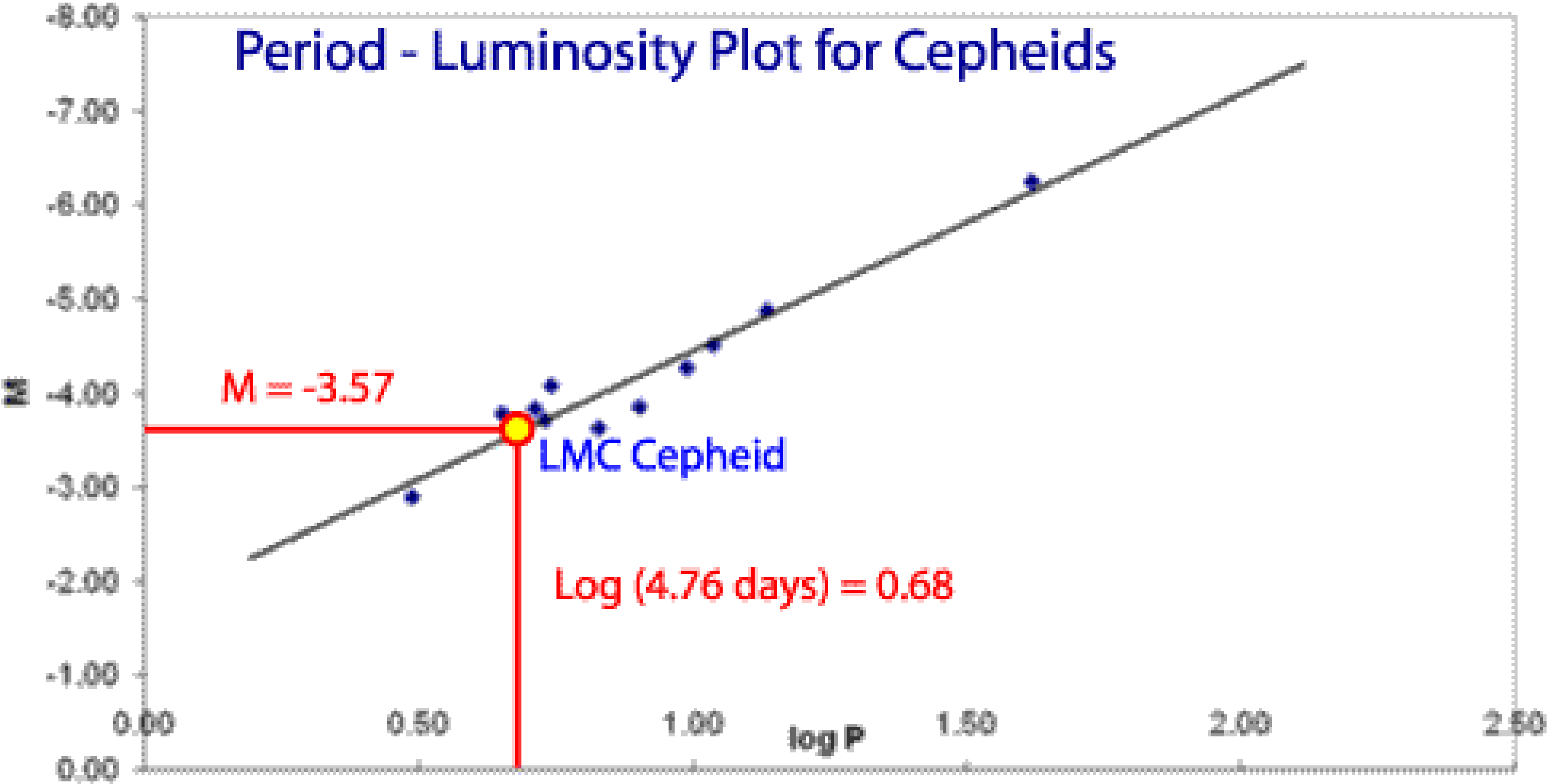
- En 1911, Henrietta Swan Leavitt, qui travaillait à Harvard, utilisa les Cépheides pour mesurer la distance au Petit Nuage de Magellan


Light Curve for LMC Cepheid
Time (days)
m mag
0.00
1.00
2.00
3.00
4.00
5.00
6.00
7.00
8.00
9.00
10.00
15.10
15.20
15.30
15.40
15.50
15.60
15.70
15.80
15.90
16.00

PERIOD - LUMINOSITY RELATIONSHIP



http://outreach.atnf.csiro.au/education/senior/astrophysics/variable_cepheids.html


Period - Luminosity Plot for Cepheids
M = -3.57
LMC Cepheid
Log (4.76 days) = 0.68
M
-8.00
-7.00
-6.00
-5.00
-4.00
-3.00
-2.00
-1.00
0.00
0.00
0.50
1.00
1.50
2.00
2.50
log P

Distances des Cepheides

Distance à la Cepheide la plus proche (Delta Cephei) peut être déterminée par la méthode des parallaxes. Cela détermine K dans la relation $L = KP^{1.3}$

Puisque la période d'une Cépheide est reliée à sa luminosité absolue, si on observe sa période et sa luminosité apparente, on peut dériver sa distance (avec une erreur d'~ 10%)

$$\text{Eclat apparent} = \frac{\text{Eclat absolu}}{4\,\pi\,\text{distance}^2}$$

Les trois piliers observationnels de la cosmologie du Modèle Standard (Hot Big Bang)

- Expansion de l'univers
  (Hubble 1929)

- Nucléosynthèse cosmologique
  (Chandrasekhar & Henrich 1942, Gamow 1946,
  Taylor & Hoyle 1964, Wagoner, Fowler, Hoyle 1967)

- Fond de rayonnement thermique à $T_{bb} = 2.728 \pm 0.004$ K
  (Tolman 1934, Alpher, Bethe, Gamow 1948, Sachs & Wolfe 1967,
  Penzias & Wilson 1965, Mather et al. 1990, Smoot et al. 1992)

Durant la seconde moitié du 20^{e} siècle,
la cosmologie est devenue une science quantitative.

La loi de Hubble

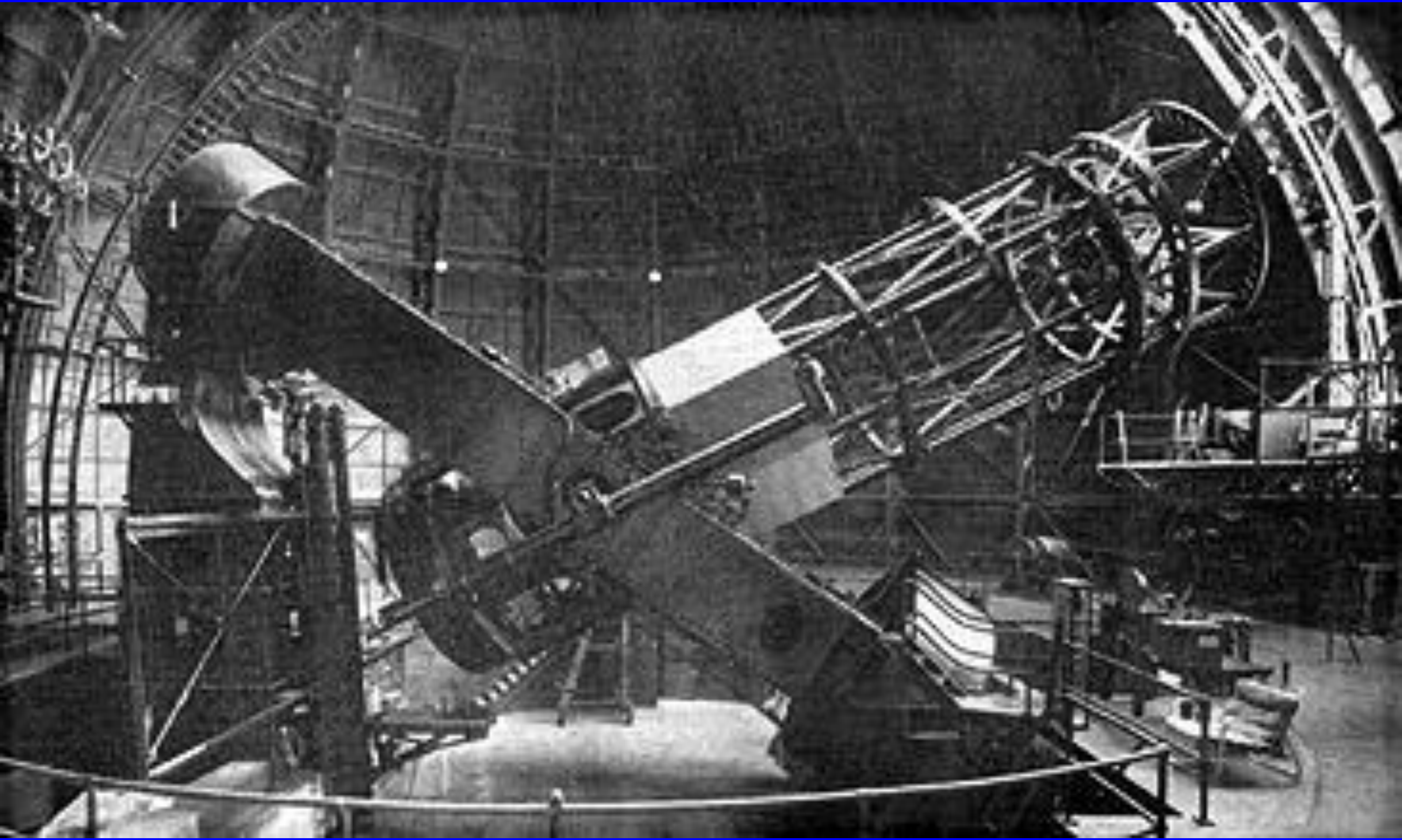
EDWIN

POWELL

HUBBLE

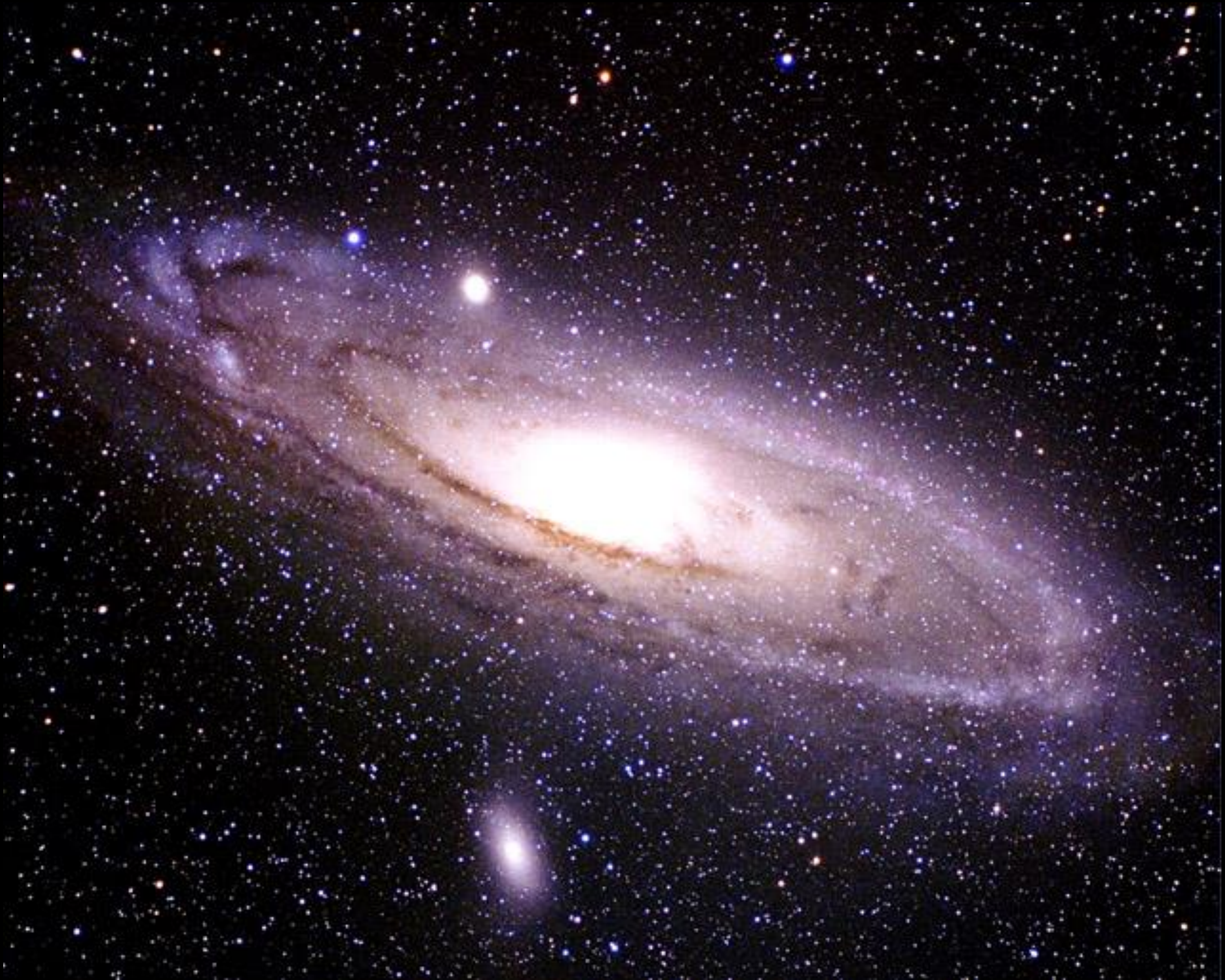
1889 - 1953

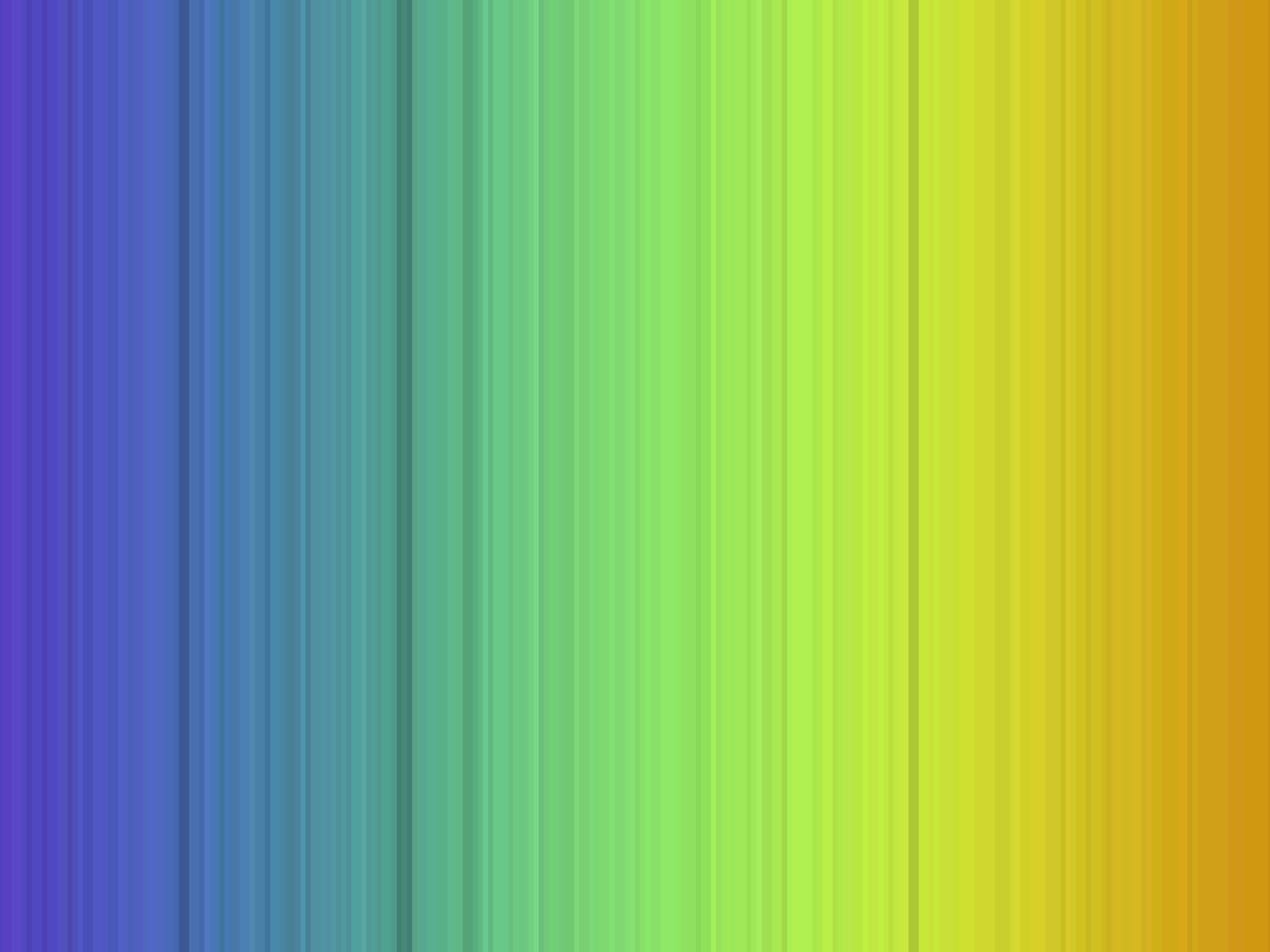
Hooker 100” Telescope

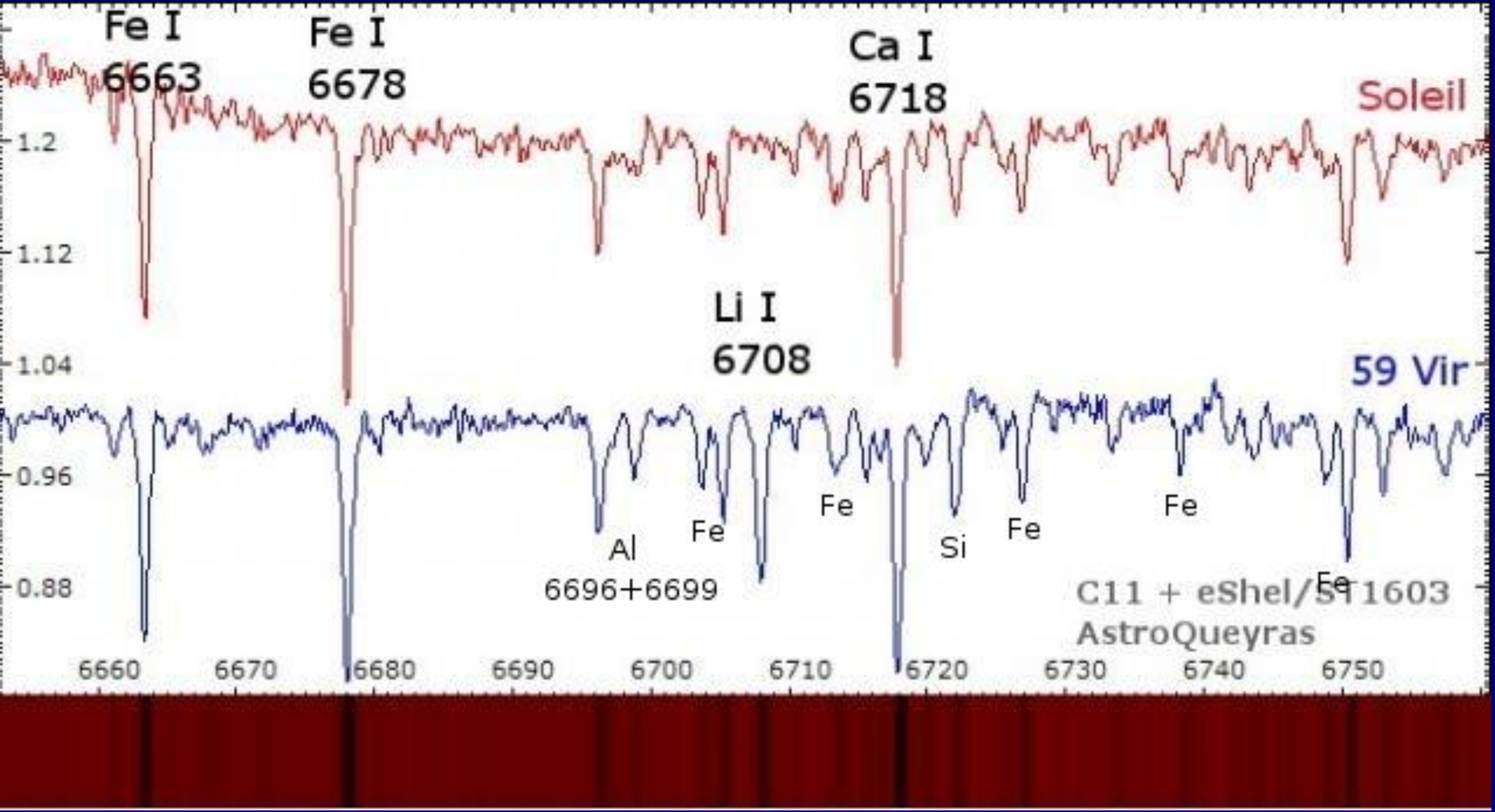


Observatoire du Mont Wilson

Andromeda Nebula (M31)






Fe I
6663
Fe I
6678
Ca I
6718
Soleil
Li I
6708
59 Vir
Al
6696+6699
Fe
Fe
Si
Fe
Fe
Fe
C11 + eShel/ST1603
AstroQueyras
1.2
1.12
1.04
0.96
0.88
6660
6670
6680
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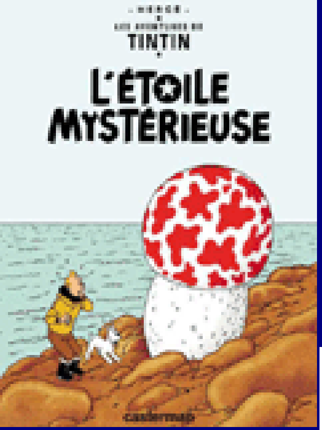
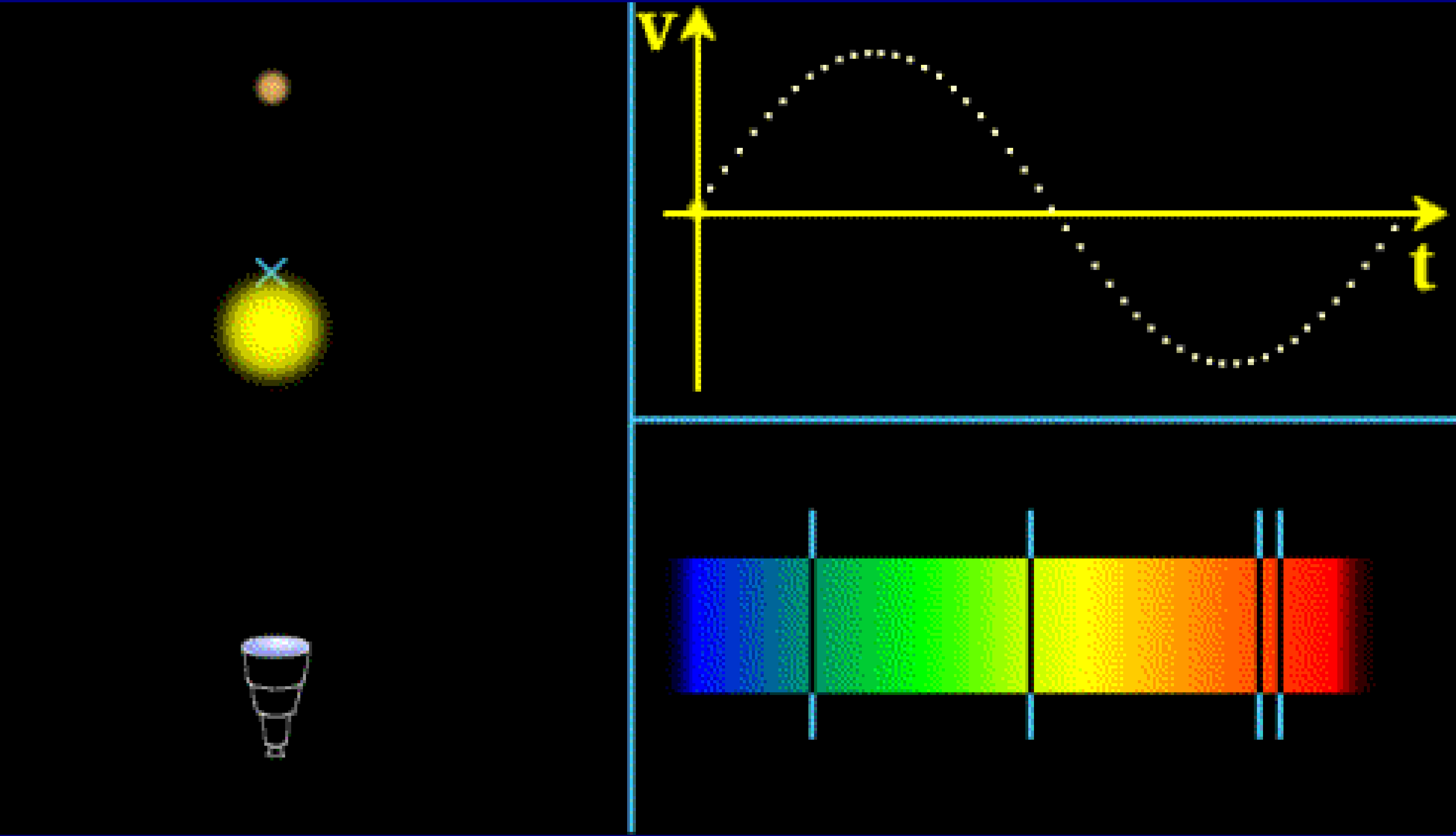
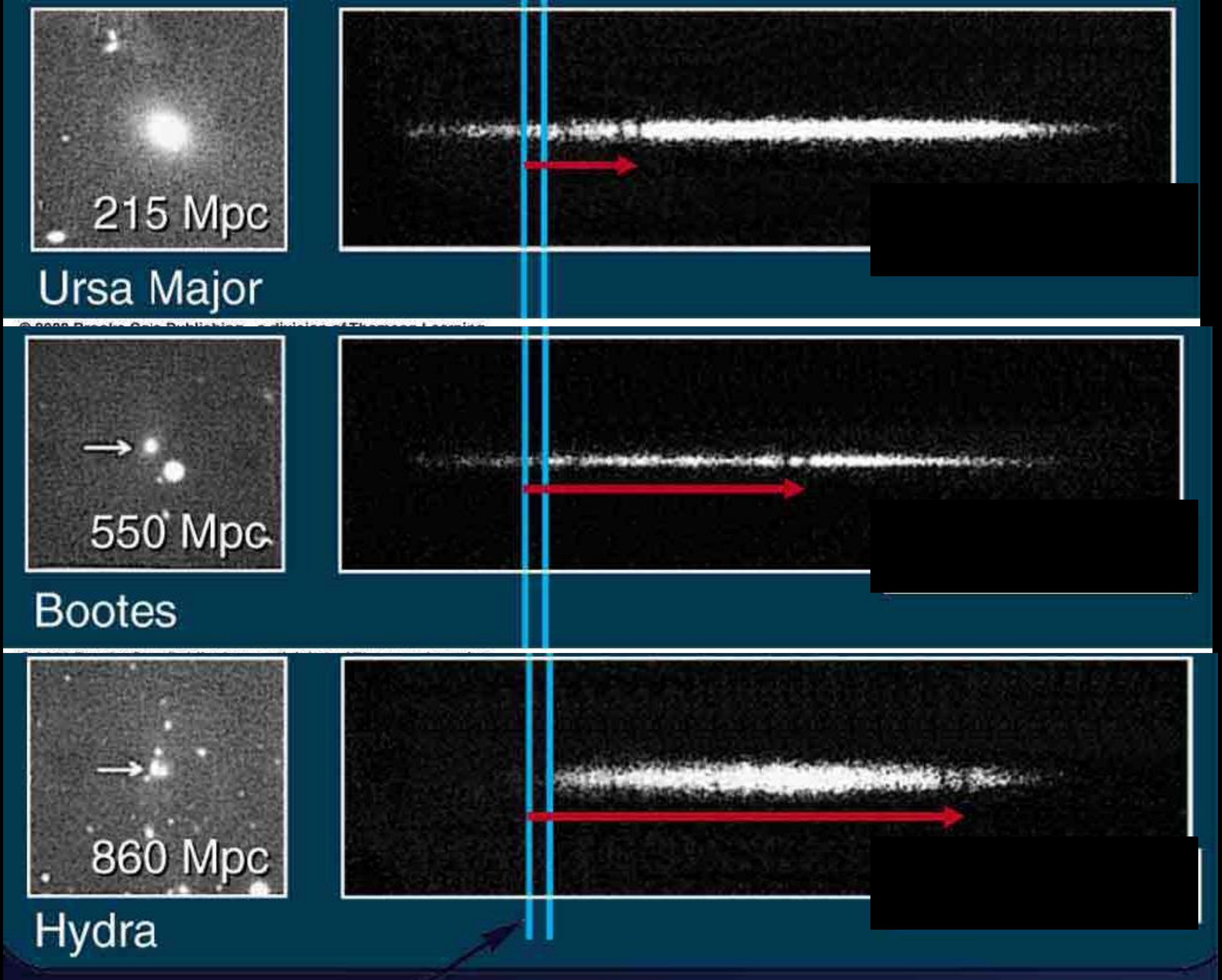
6700
6710
6720
6730
6740
6750


HERGÉ
LES AVENTURES DE TINTIN
L'ÉTOILE MYSTÉRIEUSE
casterman


Vous connaissez le spectroscope, cet instrument qui permet de découvrir dans les astres des éléments qui n'ont pas encore pu être isolés sur terre. Ceci est une photographie spectroscopique du bolide qui nous a frôlés cette nuit. Chacune de ces lignes, ou chacun de ces groupes de lignes, est caractéristique d'un métal. Ces lignes, là, au milieu, sont celles d'un métal inconnu, qui se trouvait dans ce bolide. Vous saisissez?...
Euh... A peu près .....
Scanned by E-Tintin


v
t

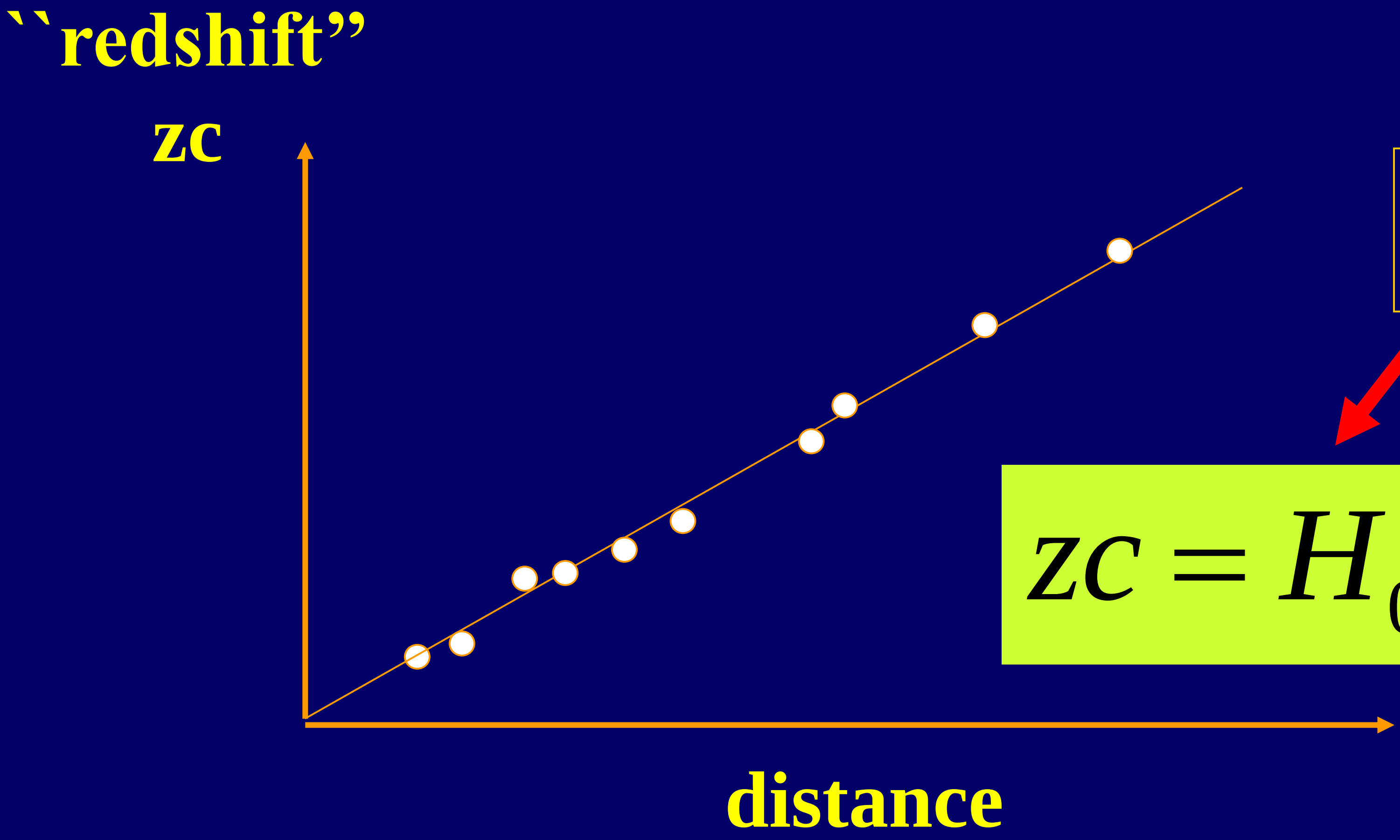


[redacted]

[redacted]

[redacted]

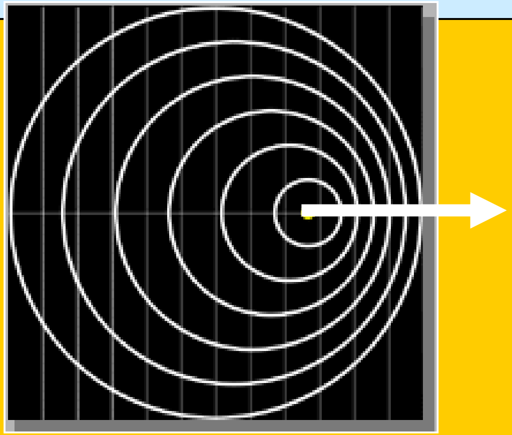
La loi de Hubble



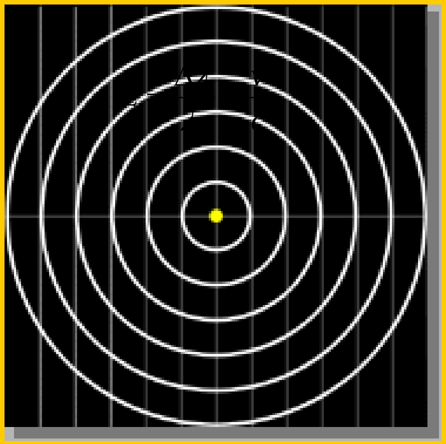
Constante De Hubble

$$zc = H_0 d$$

Une interprétation possible: décalage Doppler

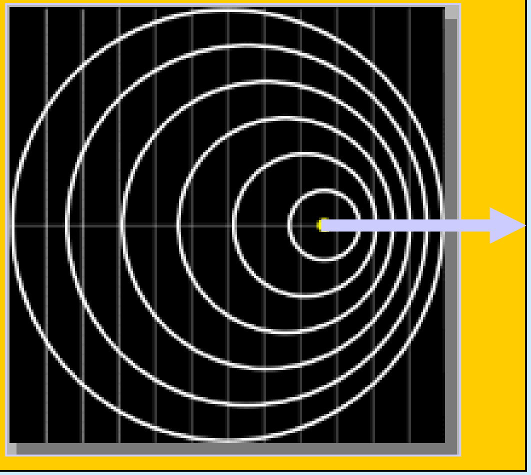


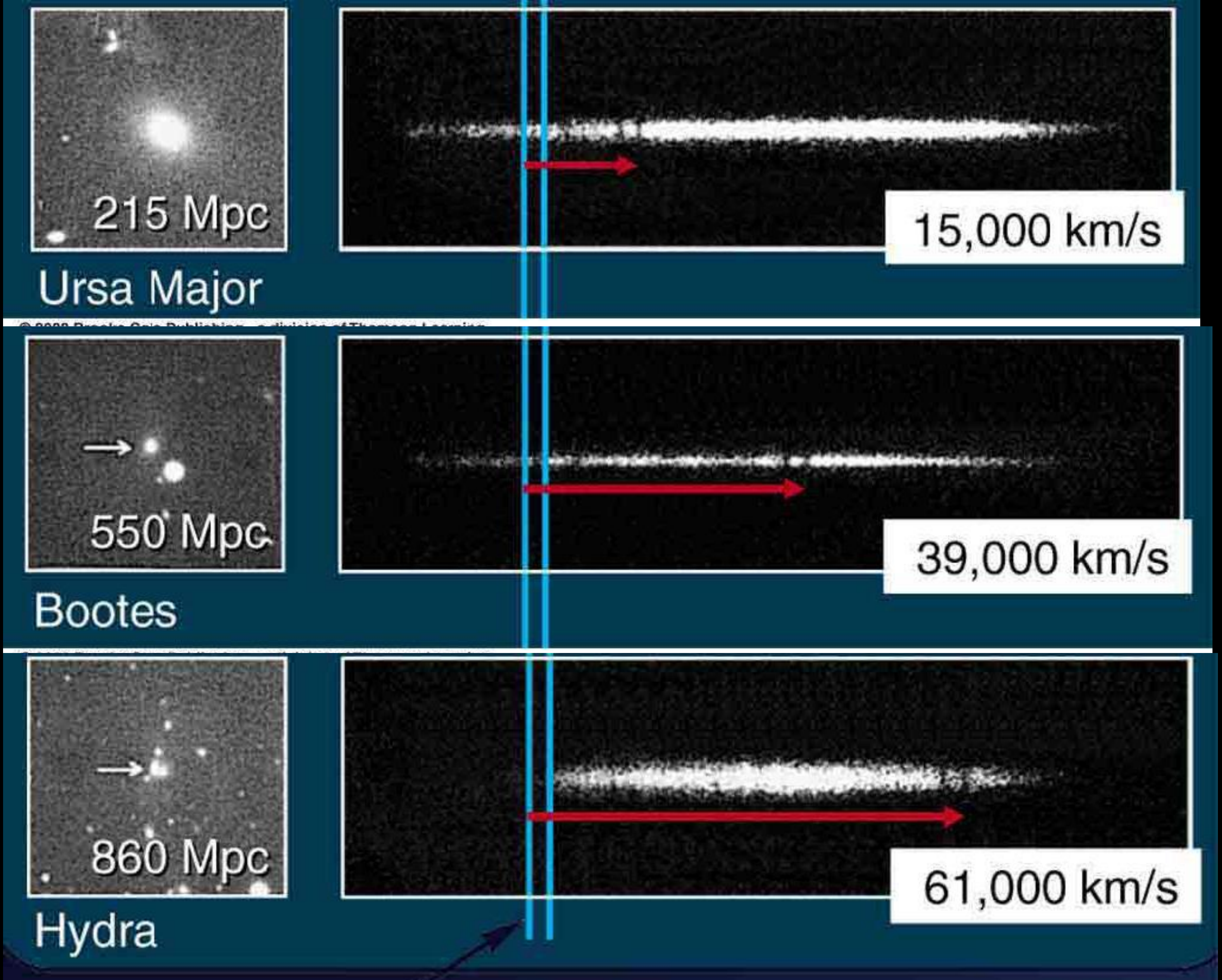
Longueur d’onde plus courte perçue



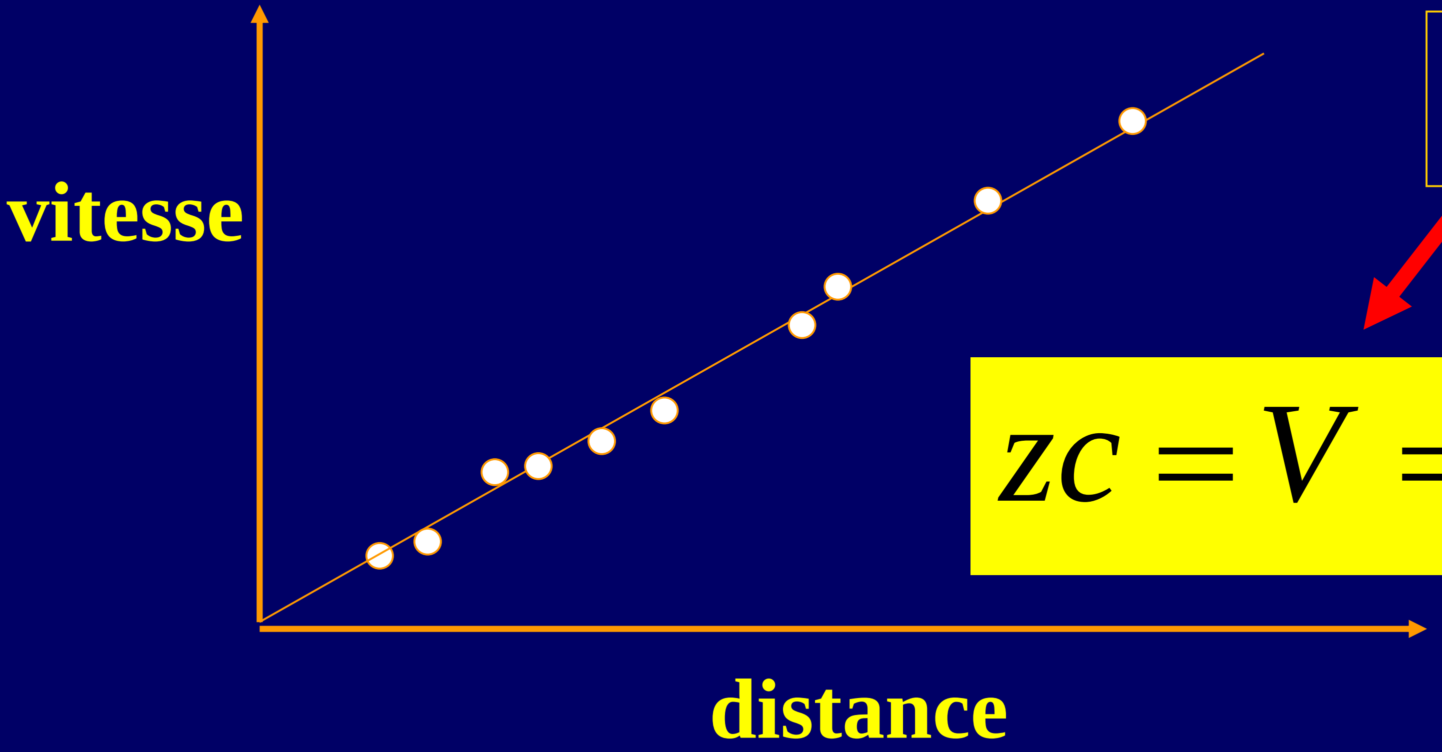
$$z = \frac{\Delta\lambda}{\lambda_e} = \frac{v}{c}$$

Longueur d’onde plus longue perçue




215 Mpc
15,000 km/s
Ursa Major
550 Mpc
39,000 km/s
Bootes
860 Mpc
61,000 km/s
Hydra

La loi de Hubble



Constante
De Hubble

$$zc = V = H_0 d$$

La loi de Hubble

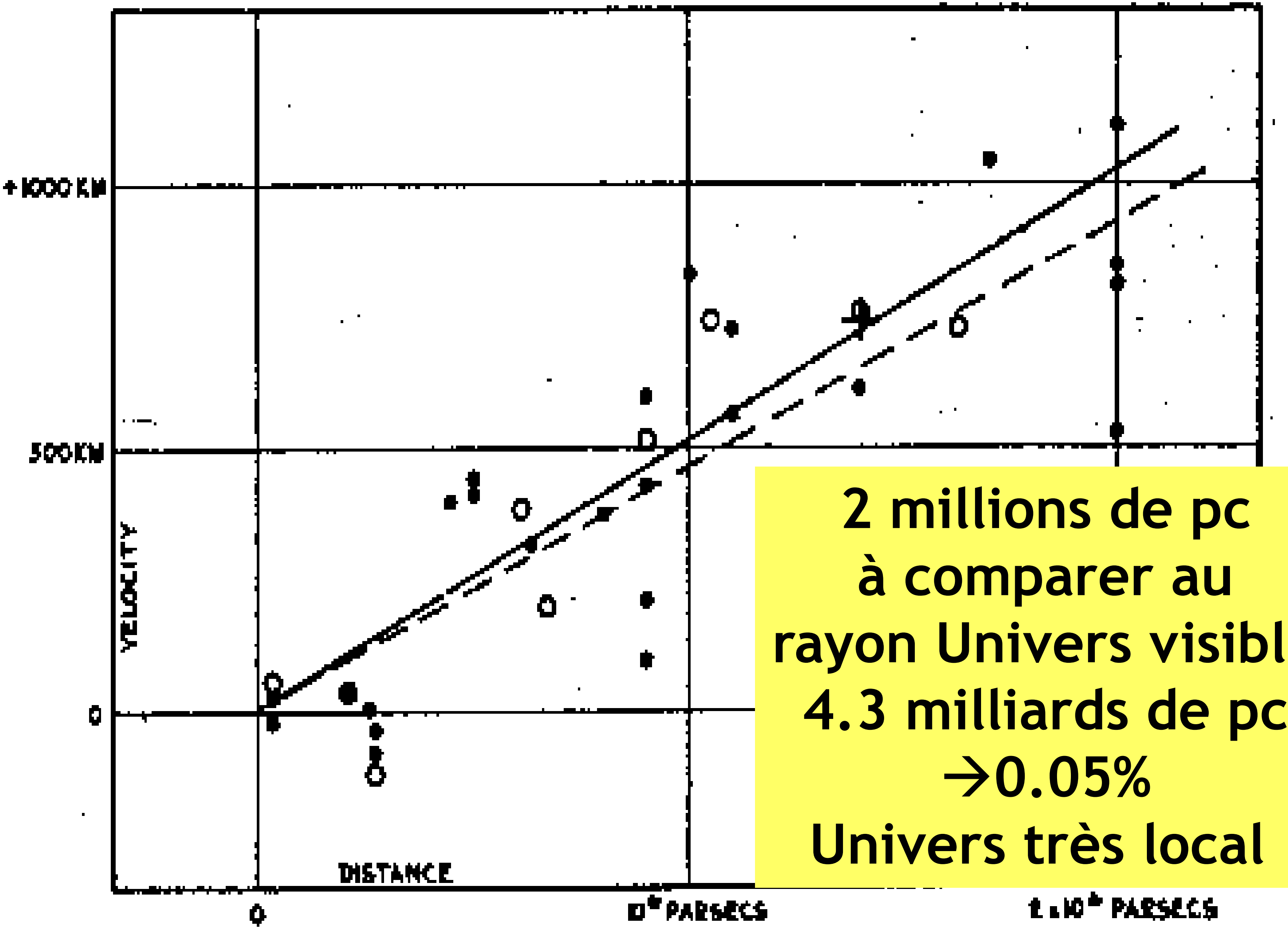
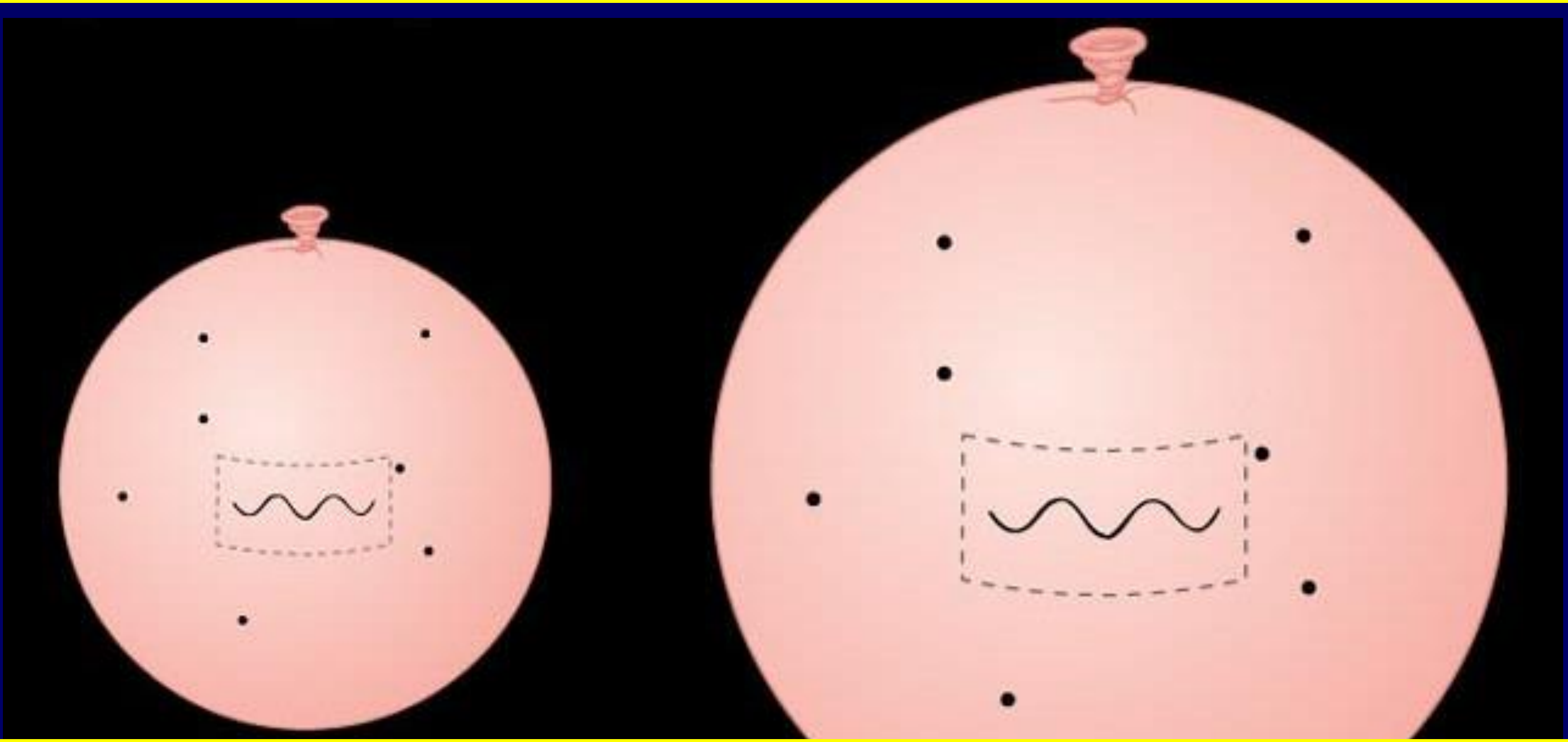


FIGURE 1

2 millions de pc
à comparer au
rayon Univers visible
4.3 milliards de pc
→0.05%
Univers très local

Comment le décalage vers le rouge est-il relié au mouvement d’expansion ?

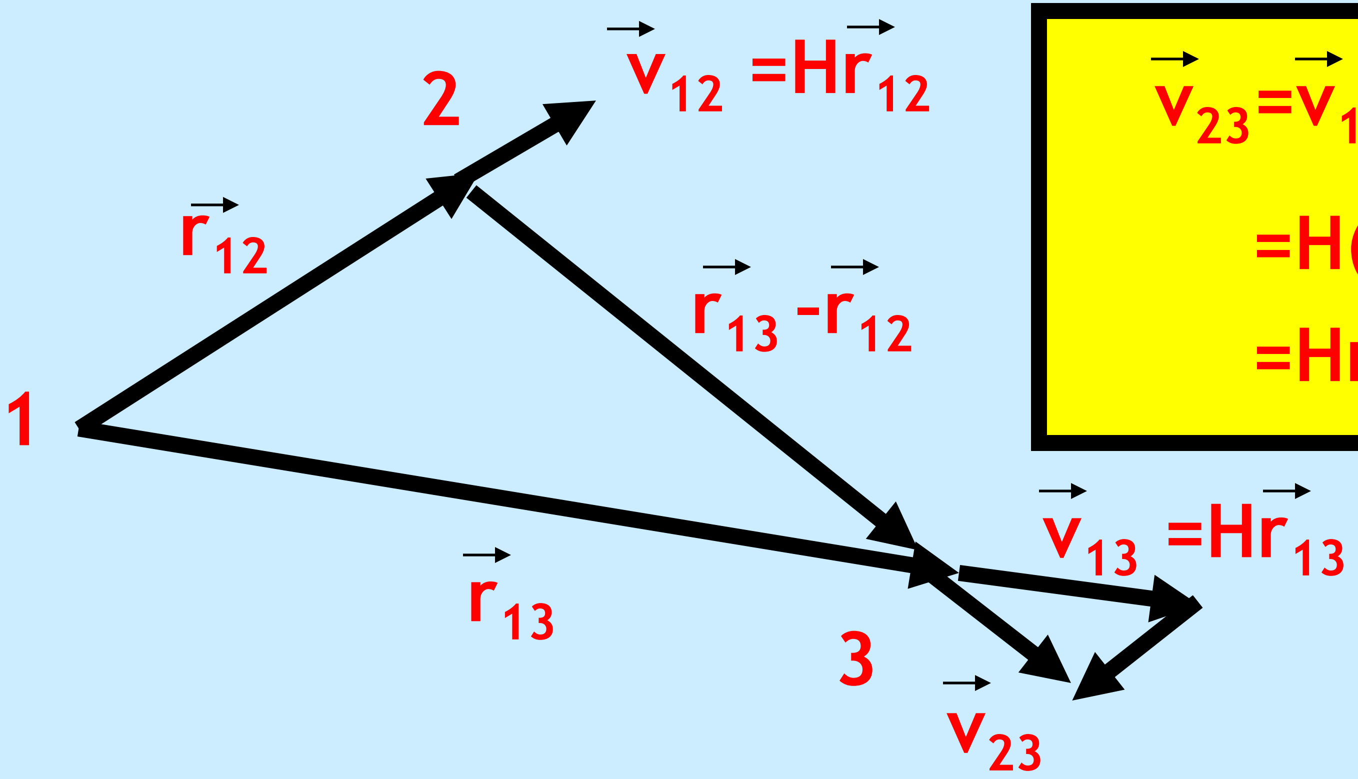


LE REDSHIFT EST UNE CONSEQUENCE DE L’EXPANSION DE L’ESPACE

DANS UN UNIVERS EN EXPANSION PURE → PAS DE POSITION PRIVILEGIEE

Pas de direction privilégiée

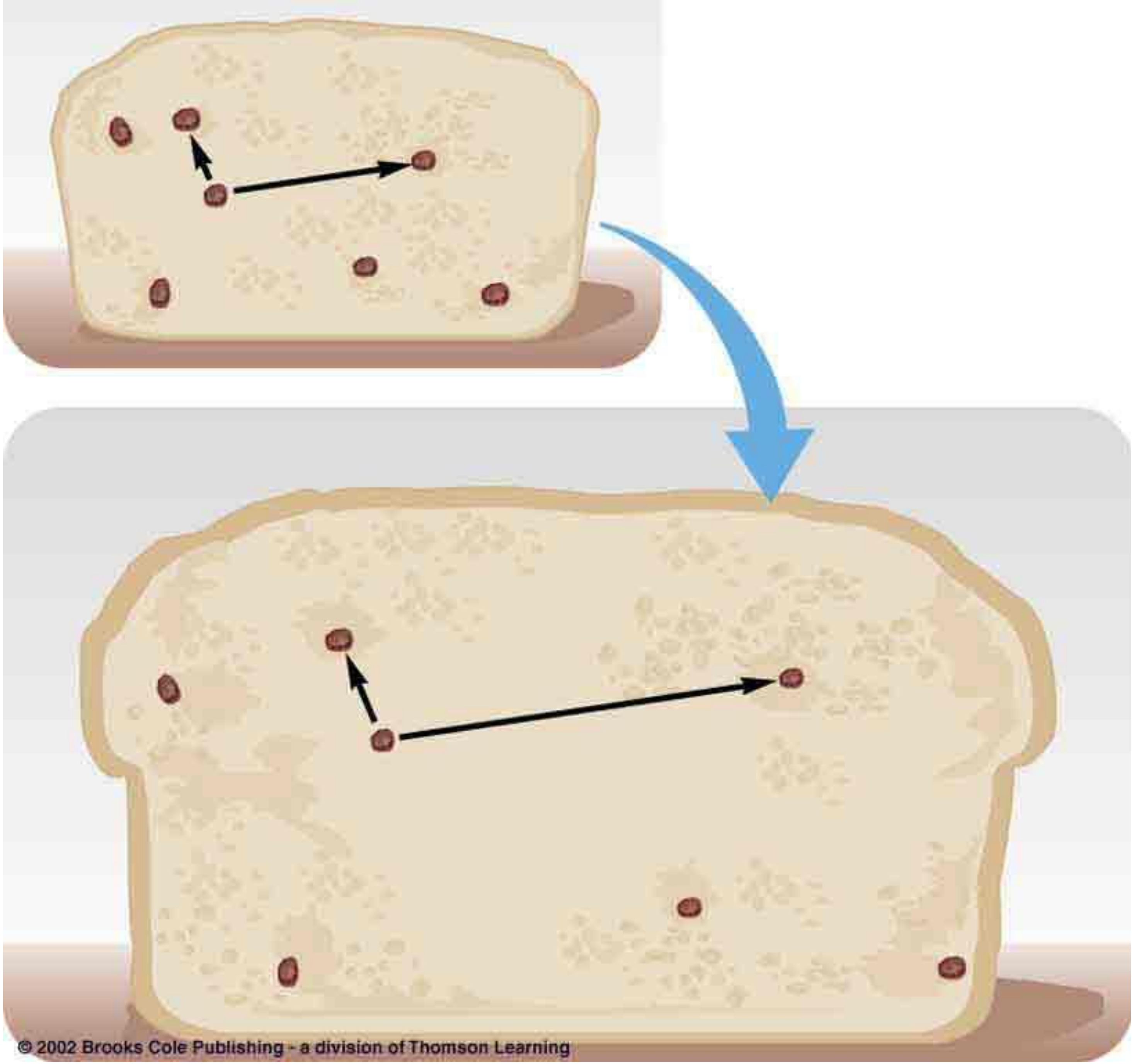
Pas de points privilégiés, pas de centre

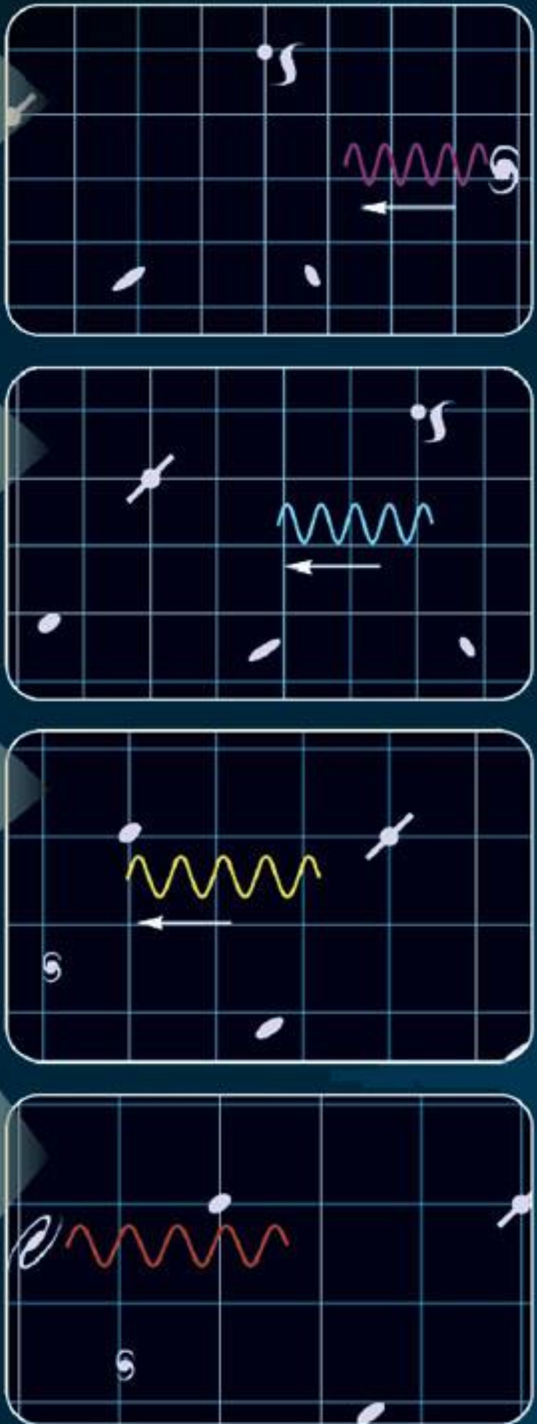


$$\vec{v}_{23} = \vec{v}_{13} - \vec{v}_{12}$$

$$= H(\vec{r}_{13} - \vec{r}_{12})$$

$$= H\vec{r}_{23}$$





A distant galaxy emits a short-wavelength photon toward our galaxy.

The expansion of space-time stretches the photon to longer wavelength as it travels.

The farther the photon has to travel, the more it is stretched.

When the photon arrives at our galaxy, you see it with a longer wavelength — a redshift that is proportional to distance.

La loi de Hubble

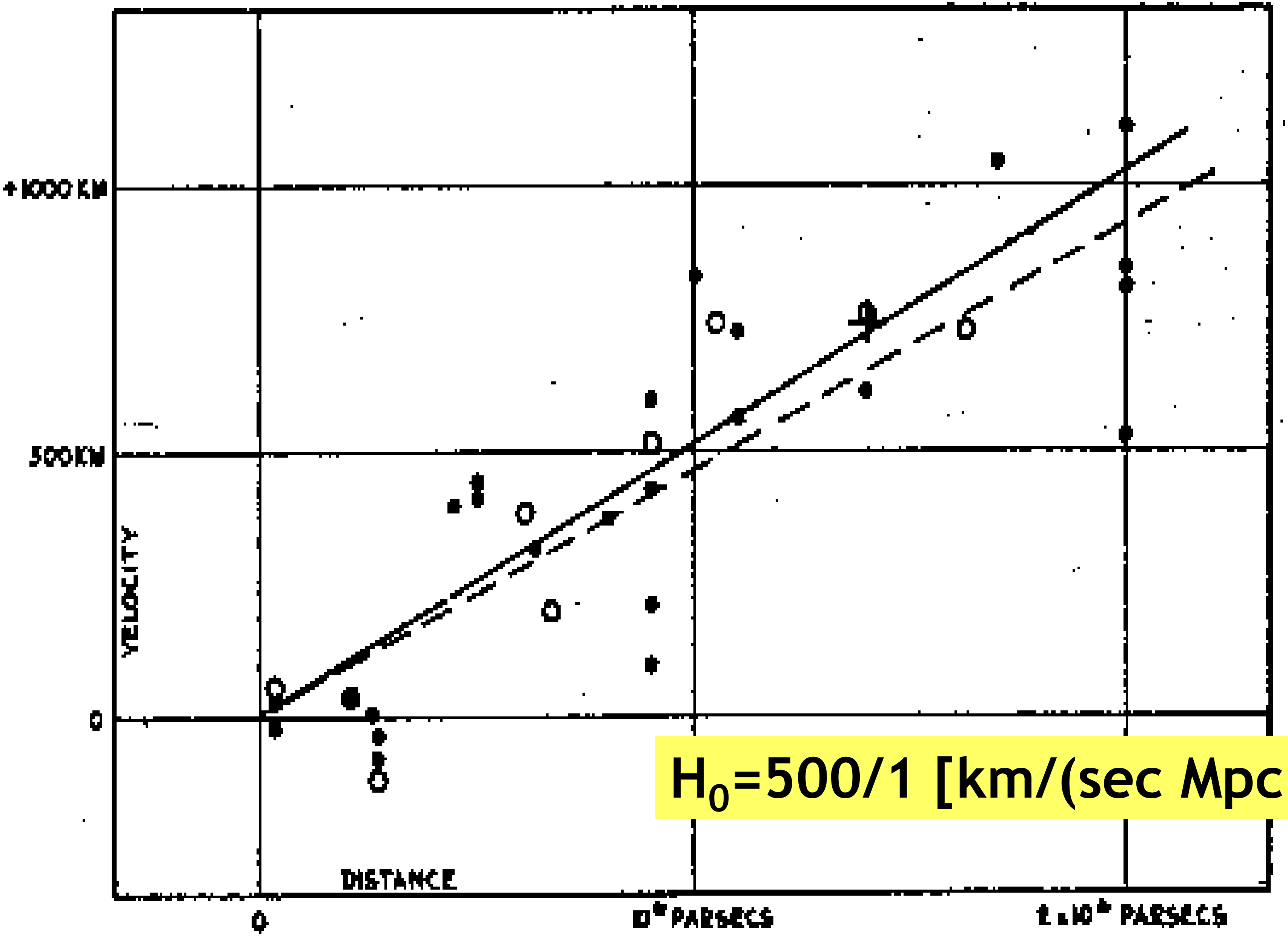
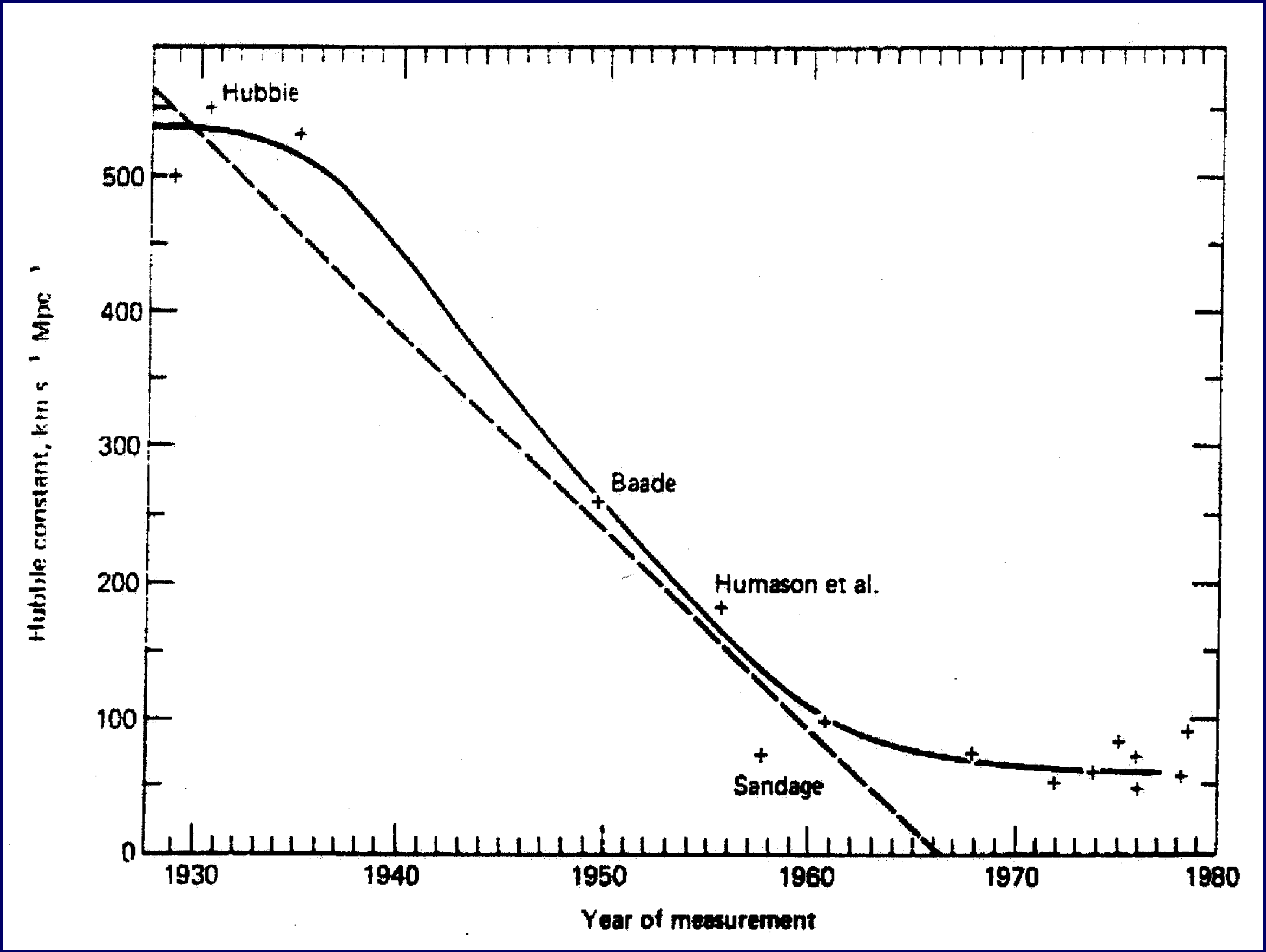
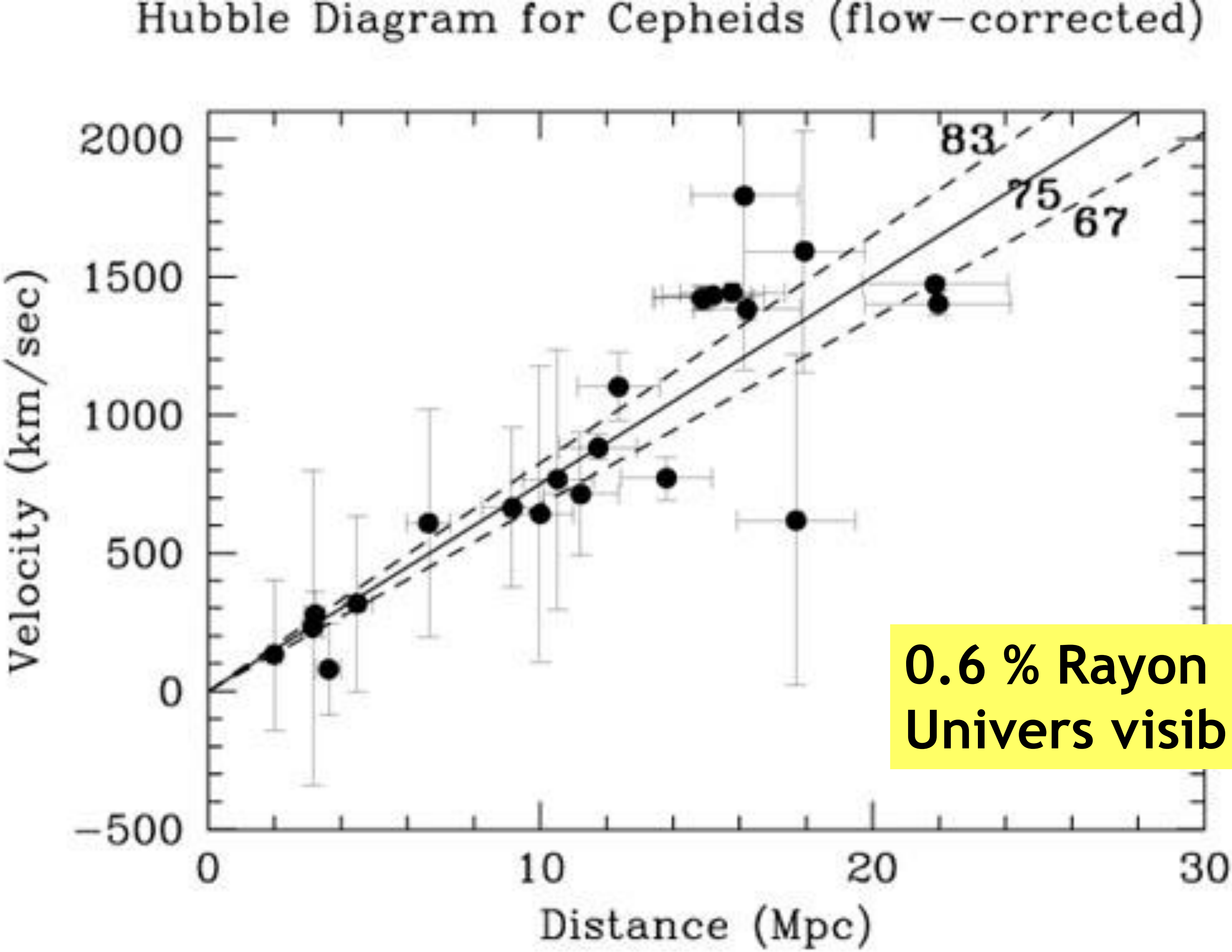


FIGURE 1

$H_0 = 500/1$ [km/(sec Mpc)]


Hubble constant, km s⁻¹ Mpc⁻¹
500
400
300
200
100
0
1930
1940
1950
1960
1970
1980
Year of measurement
Hubble
Baade
Humason et al.
Sandage



0.6 % Rayon Univers visible

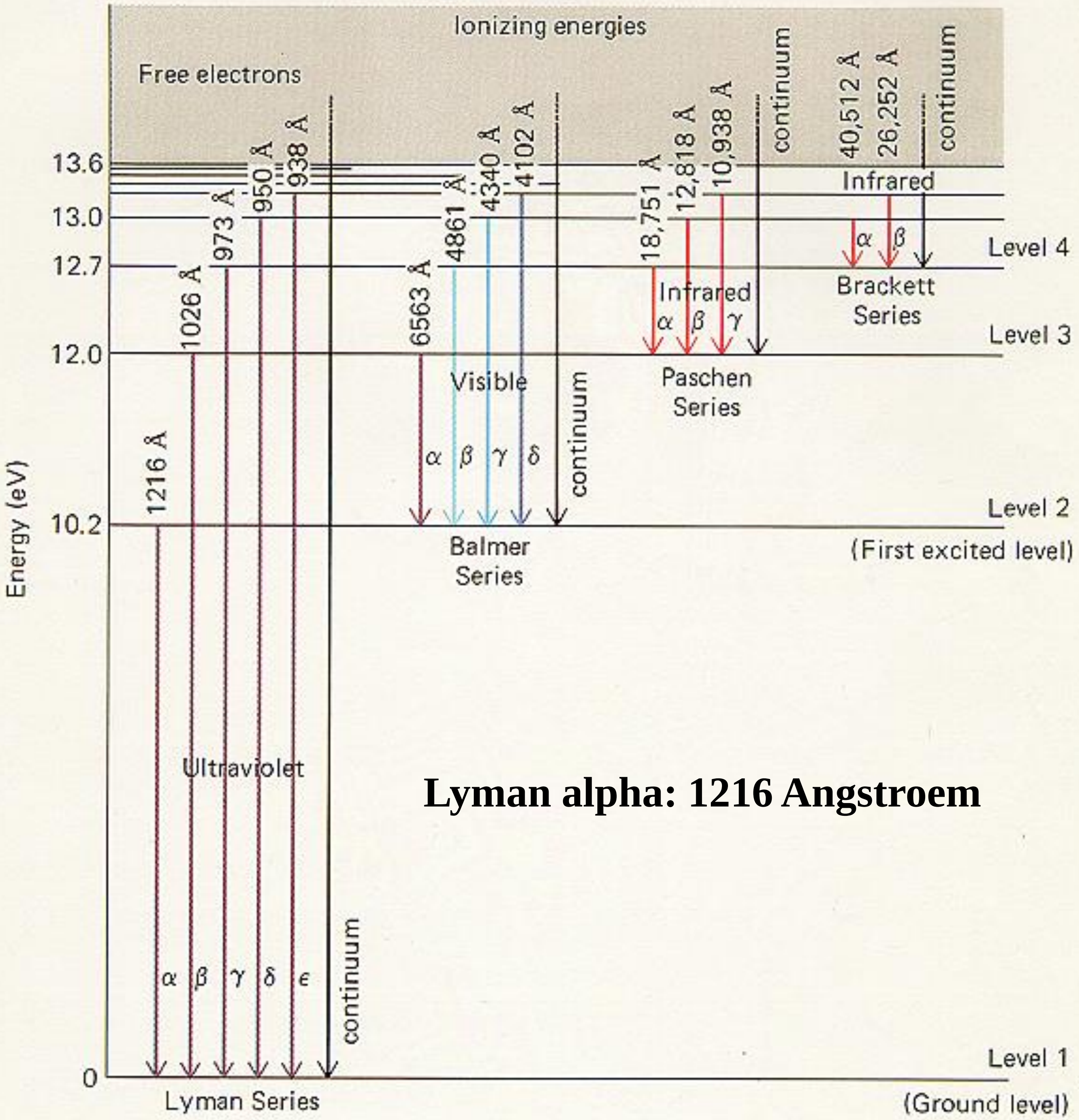
Freedman et al. 2001

Le décalage vers le rouge z est relié aux facteurs d'échelles au temps de l'émission et de la réception du signal

$$z+1=\frac{\lambda_o}{\lambda_e}=\frac{R_o}{R_e}$$

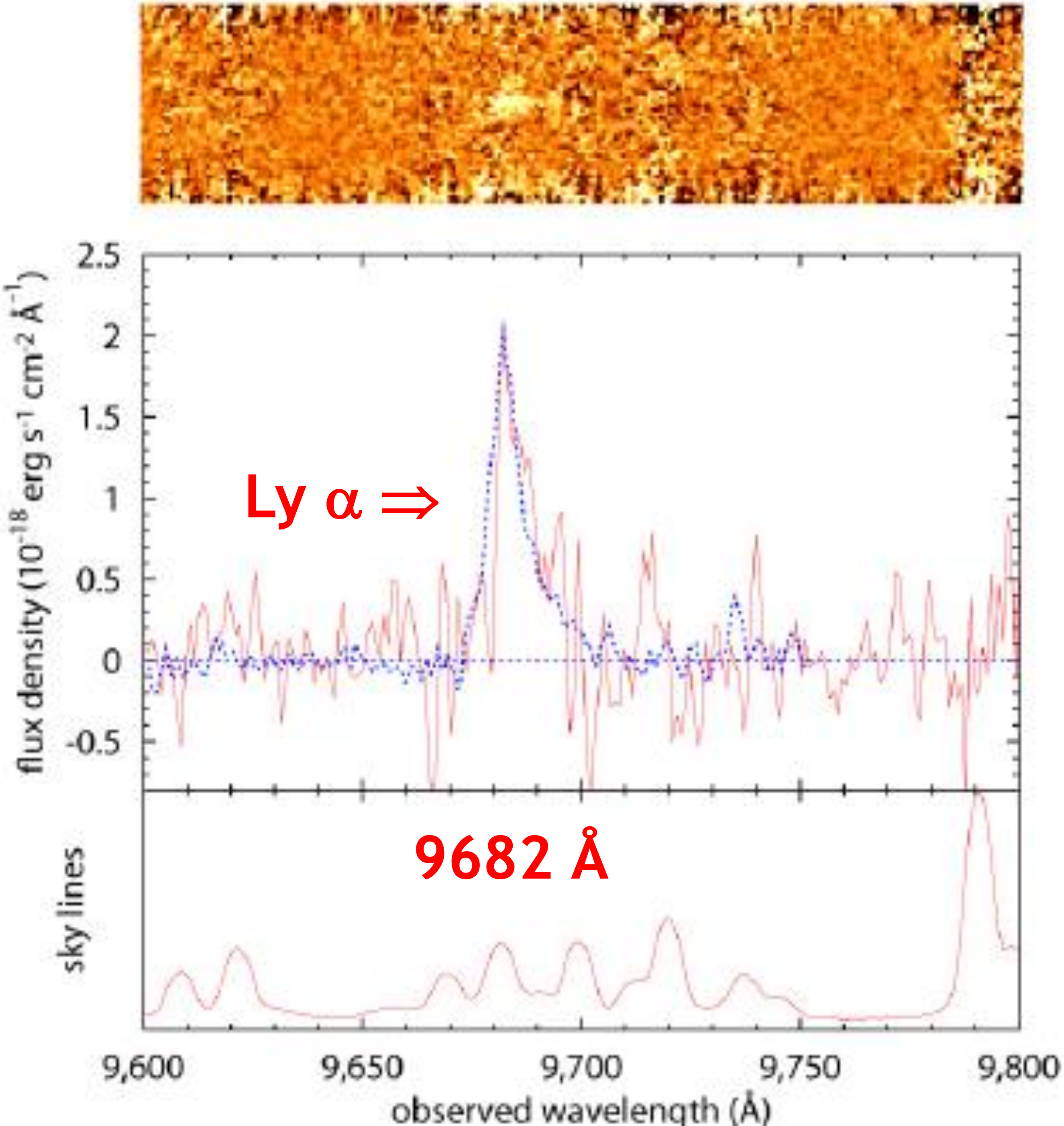
Pour un objet observé à z = 4.3, les distances dans l'univers étaient 5.3 fois plus petites que maintenant:

λ croît comme R



Lyman alpha: 1216 Angstroem

Chaque transition est associée à l’émission, l’absorption d’un photon d’une certaine longueur d’onde


2.5
2
1.5
1
0.5
0
-0.5
flux density (10^{-18} erg s^{-1} cm^{-2} Å^{-1})
sky lines
9,600
9,650
9,700
9,750
9,800
observed wavelength (Å)

Ly α ⇒

9682 Å

$$z + 1 = \frac{\lambda_o}{\lambda_e} = \frac{R_o}{R_e}$$

Longueur d’onde observée 9682 Å

Z=6.96

Longueur d’onde à l’émission 1216 Å

$$d(t_0) = R(t_0)C$$

$$V(t_0) = \dot{R}(t_0)C$$

$$V(t_0) = \frac{\dot{R}(t_0)}{R(t_0)} d(t_0)$$

LA CONSTANTE DE HUBBLE EST UNE MESURE DU TAUX ACTUEL D’EXPANSION DE L’UNIVERS

$$H_0 = \frac{\dot{R}(t_0)}{R(t_0)}$$

DEUX RELATIONS IMPORTANTES

Décalage vers le rouge → indication du facteur d'échelle au moment où la lumière a été émise

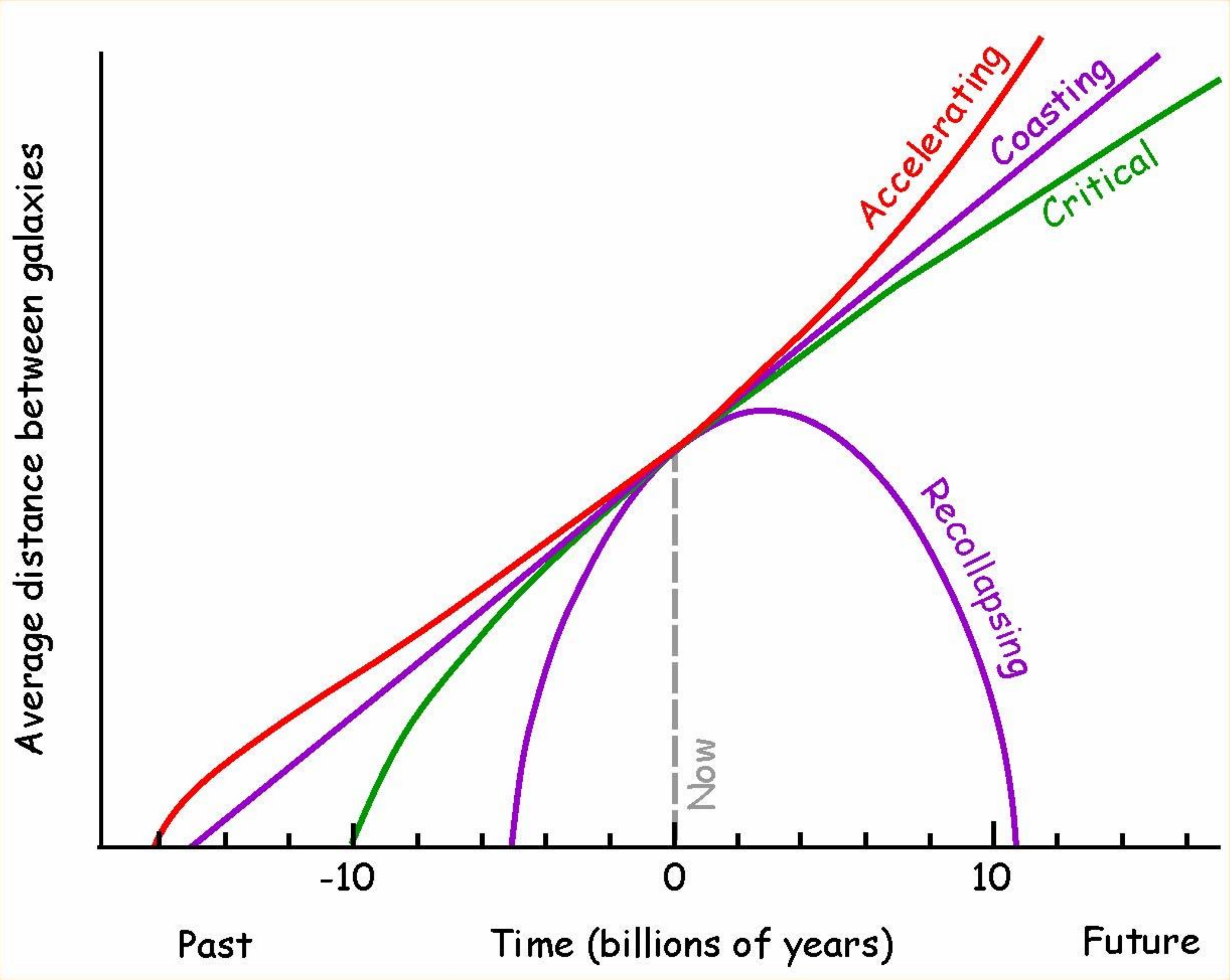
$$z+1=\frac{\lambda_o}{\lambda_e}=\frac{R_o}{R_e}$$

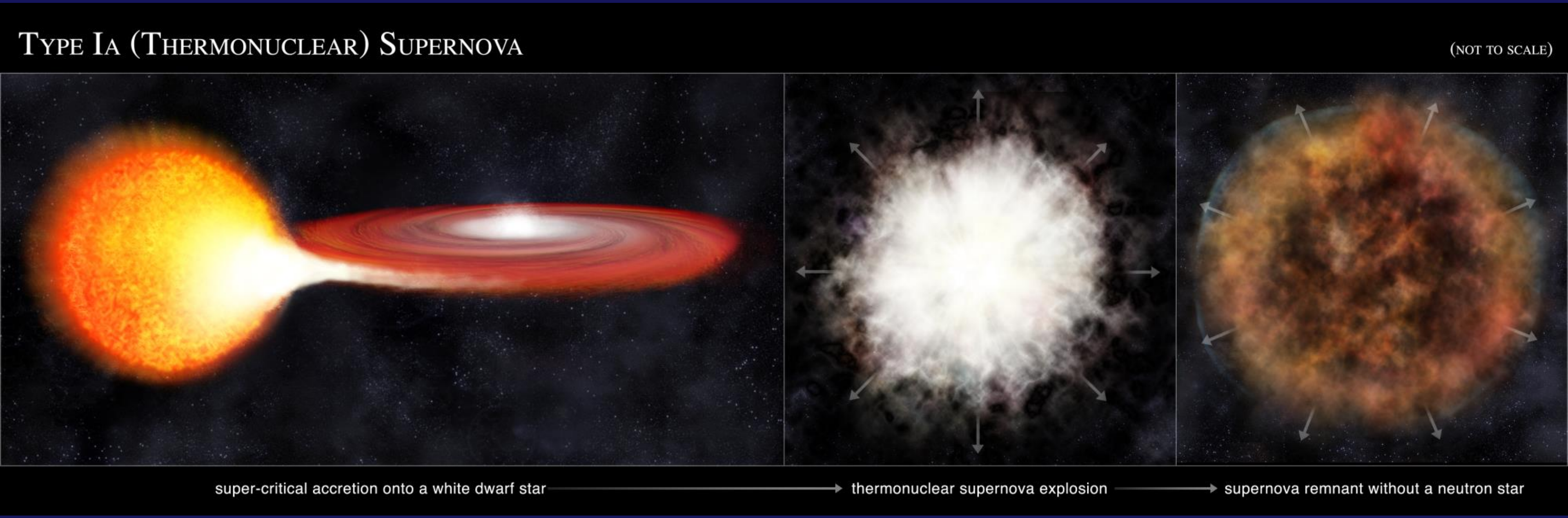
Constante de Hubble → taux d'expansion actuel

$$H_0=\frac{\dot{R}(t_0)}{R(t_0)}$$

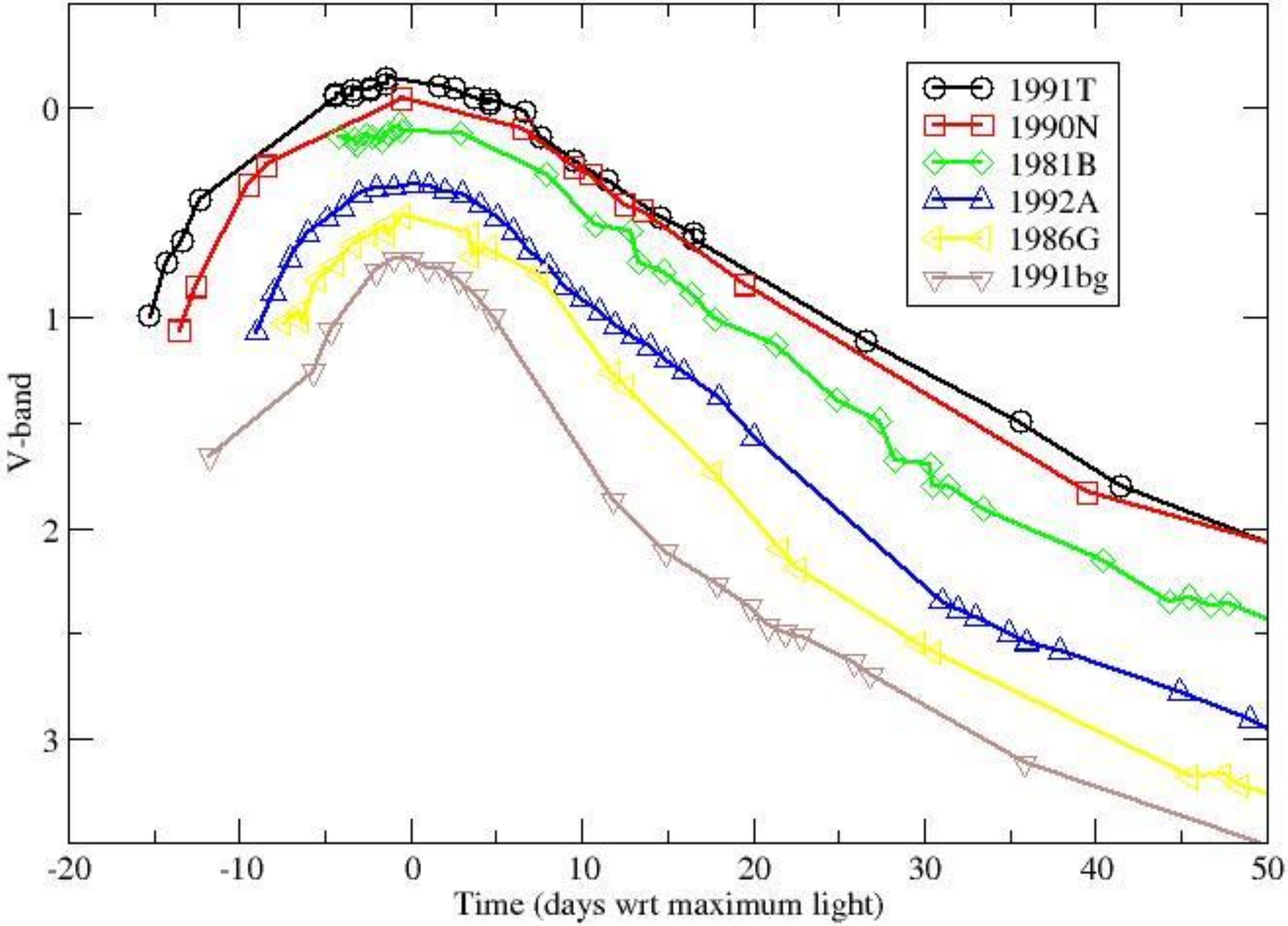
Pour décrire l'histoire de l'Univers, soit entre autre la fonction R(t) il est nécessaire d'établir les équations qui gouvernent son évolution

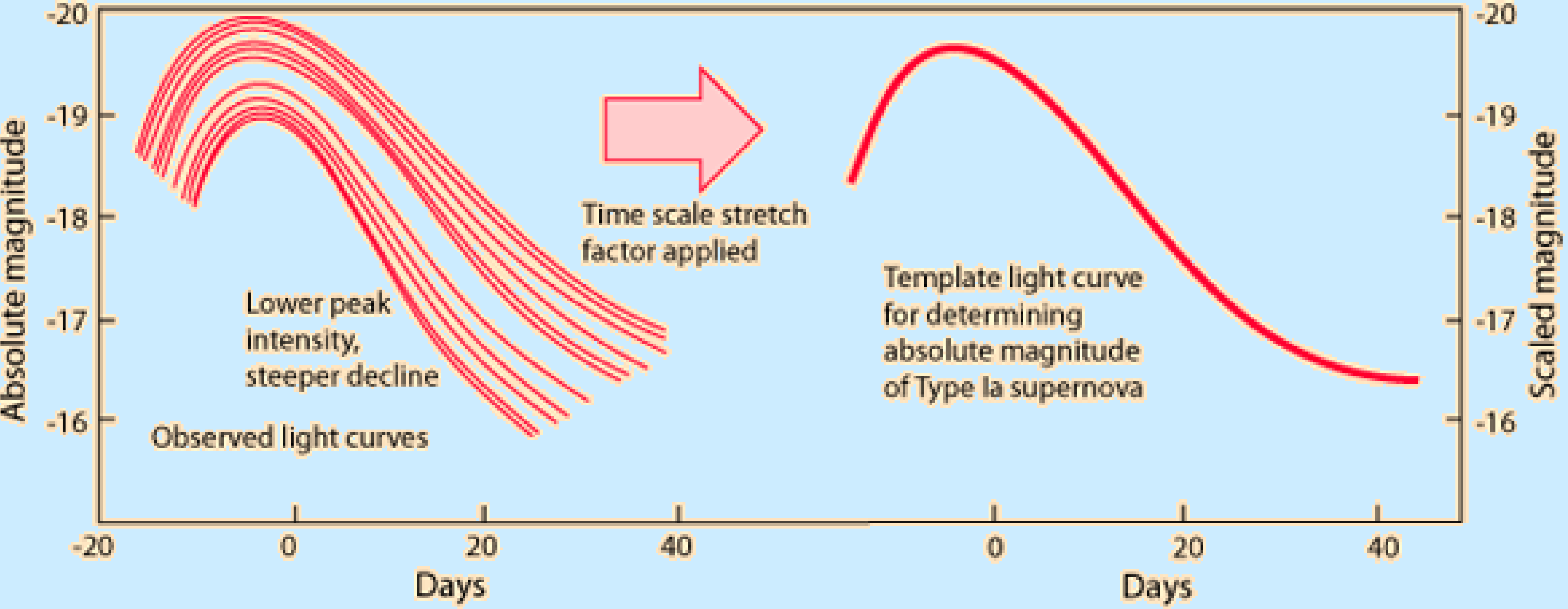
Evolution des distances



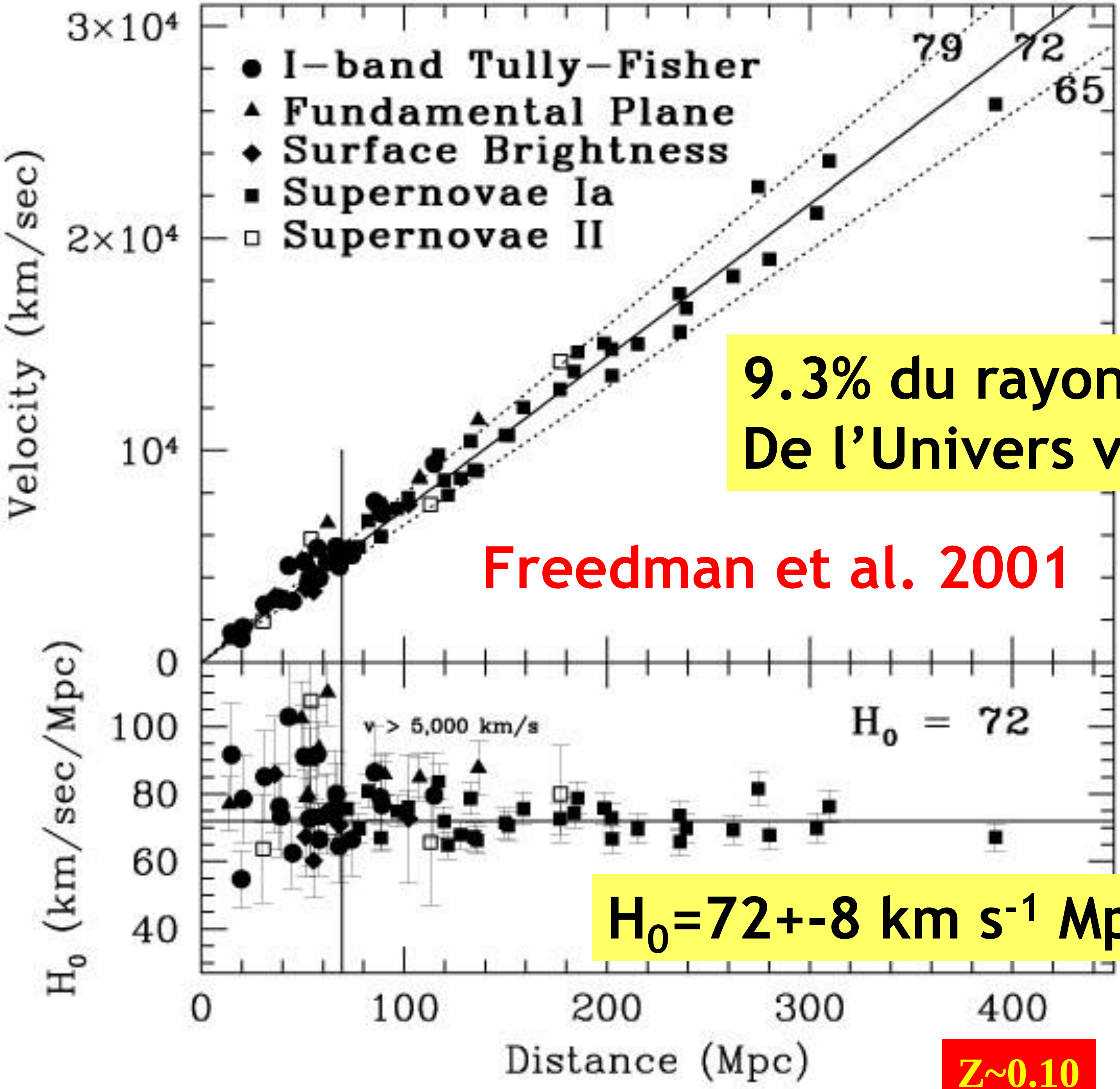


http://chandra.harvard.edu/xray_sources/supernovas.html


1991T
1990N
1981B
1992A
1986G
1991bg
V-band
0
1
2
3
-20
-10
0
10
20
30
40
50
Time (days wrt maximum light)



http://hyperphysics.phy-astr.gsu.edu/hbase/astro/snovcn.html



Freedman et al. 2001

9.3% du rayon
De l'Univers visible

H_0=72+-8 km s^{-1} Mpc^{-1}

Z~0.10

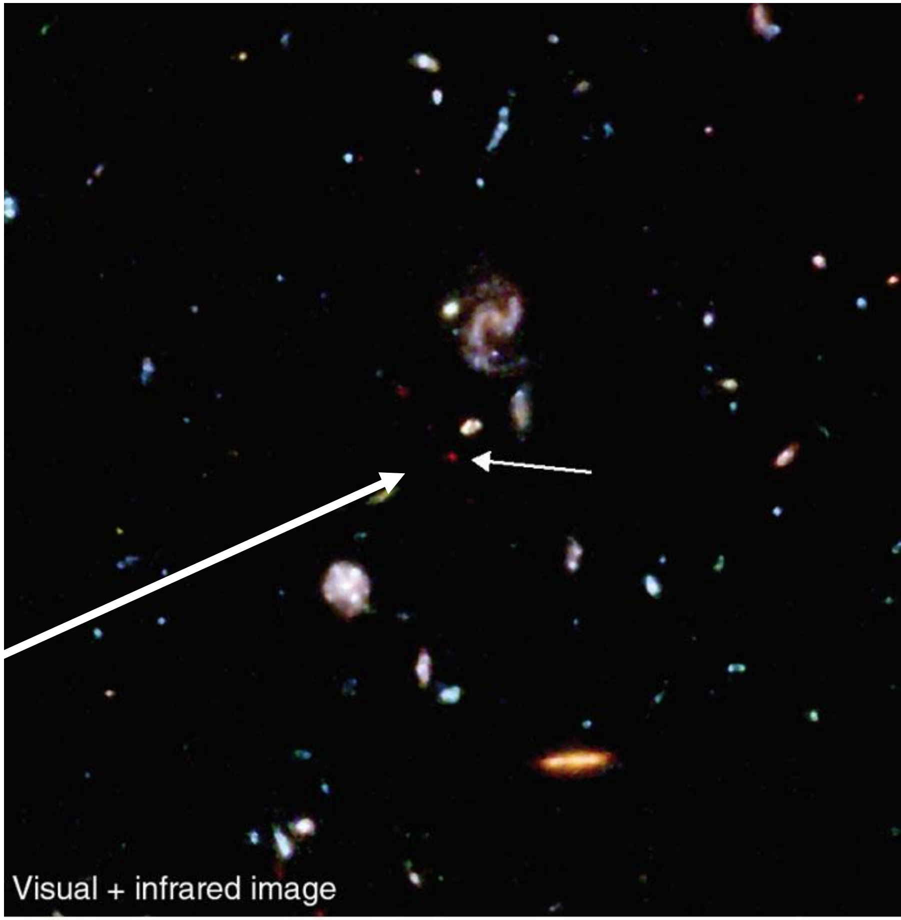
L’âge de l’Univers

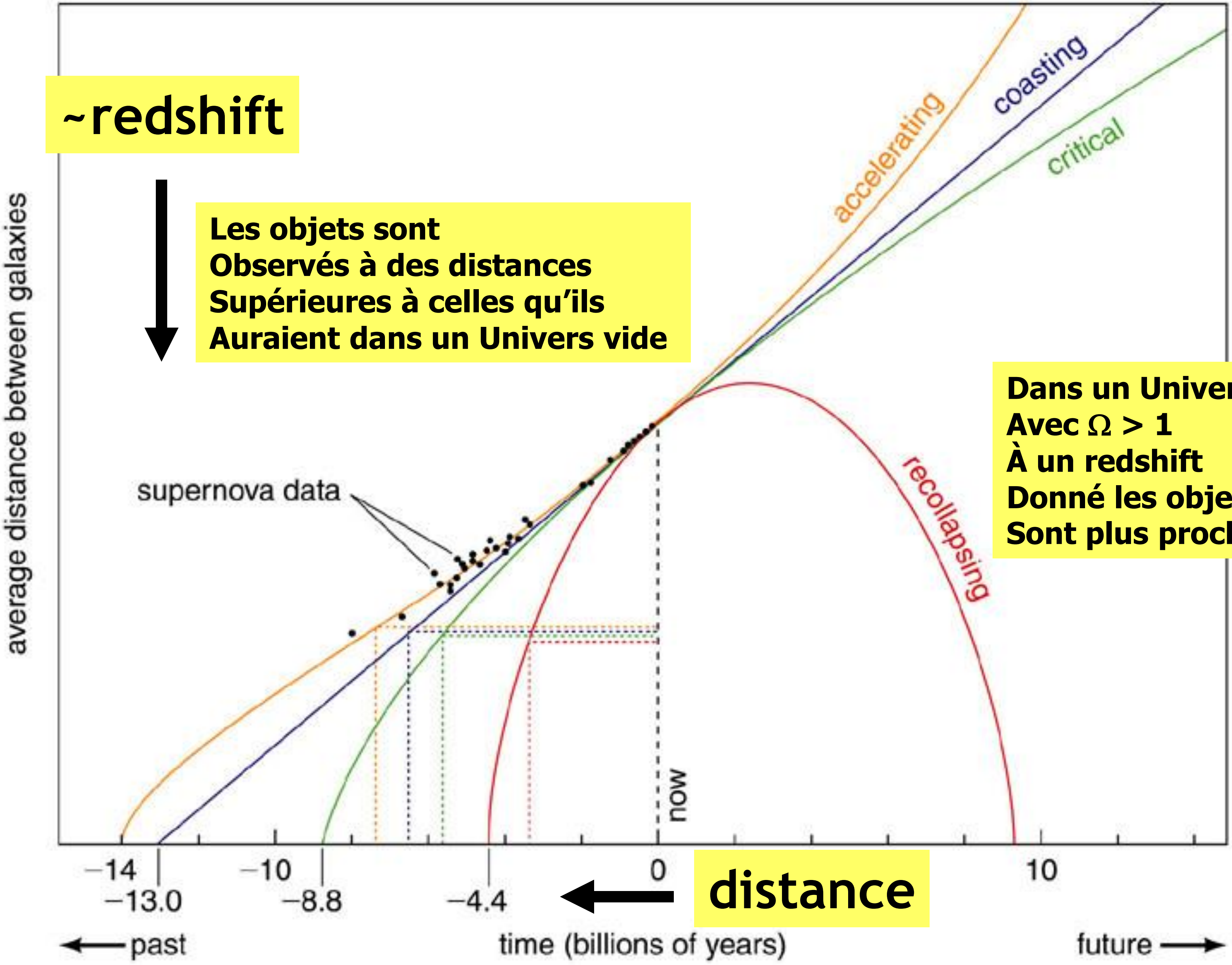
Temps = distance / vitesse

vitesse = H x d

$T \approx d/v = 1/H \sim$ 13.7 milliards d’années

La lumière que nous voyons aujourd’hui provenant de cette galaxies a quitté cette galaxie alors que l’Univers n’était âgé que d’environ 1 milliard d’années.



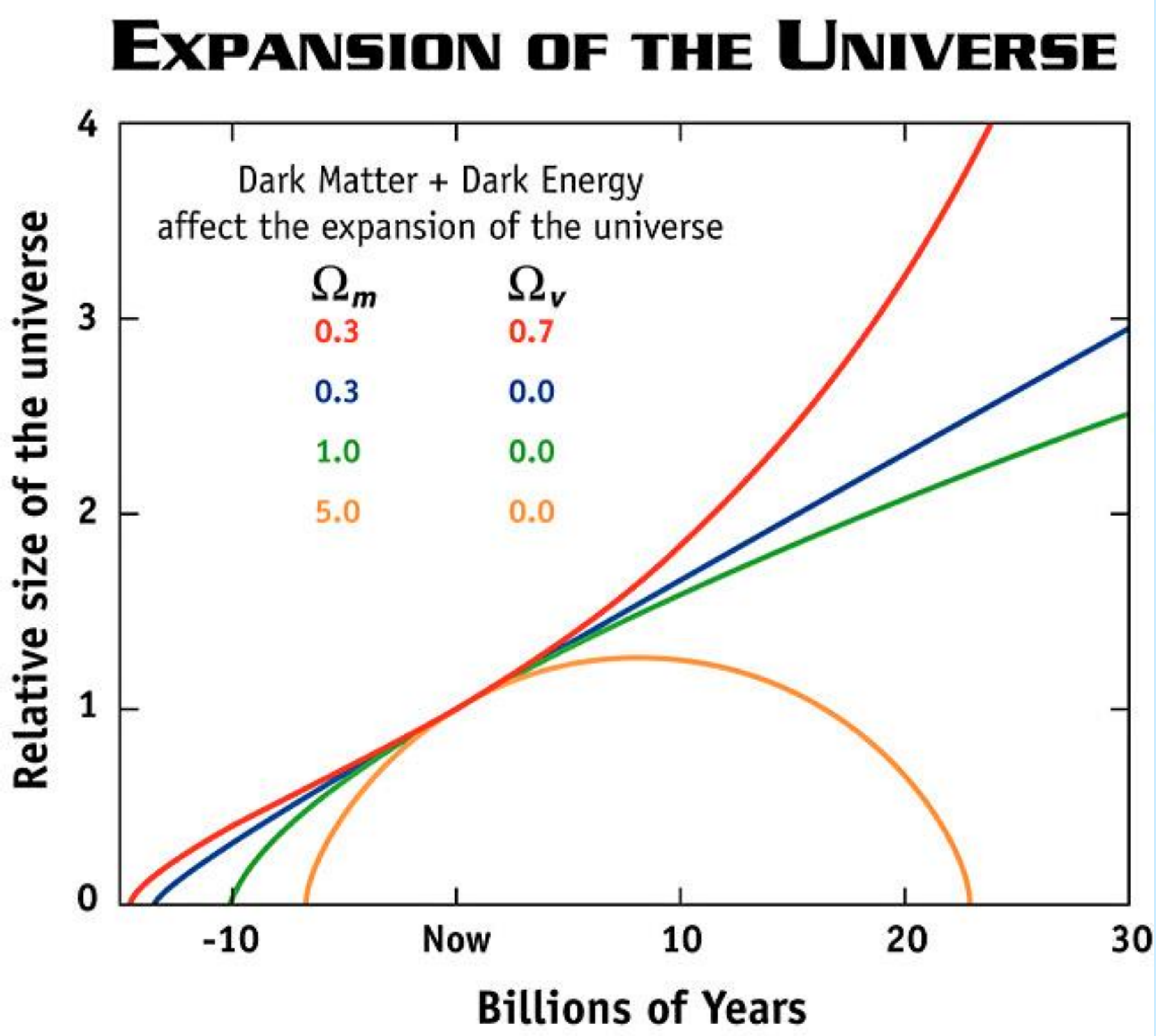


~redshift

Les objets sont
Observés à des distances
Supérieures à celles qu'ils
Auraient dans un Univers vide

Dans un Univers
Avec Ω > 1
À un redshift
Donné les objets
Sont plus proches

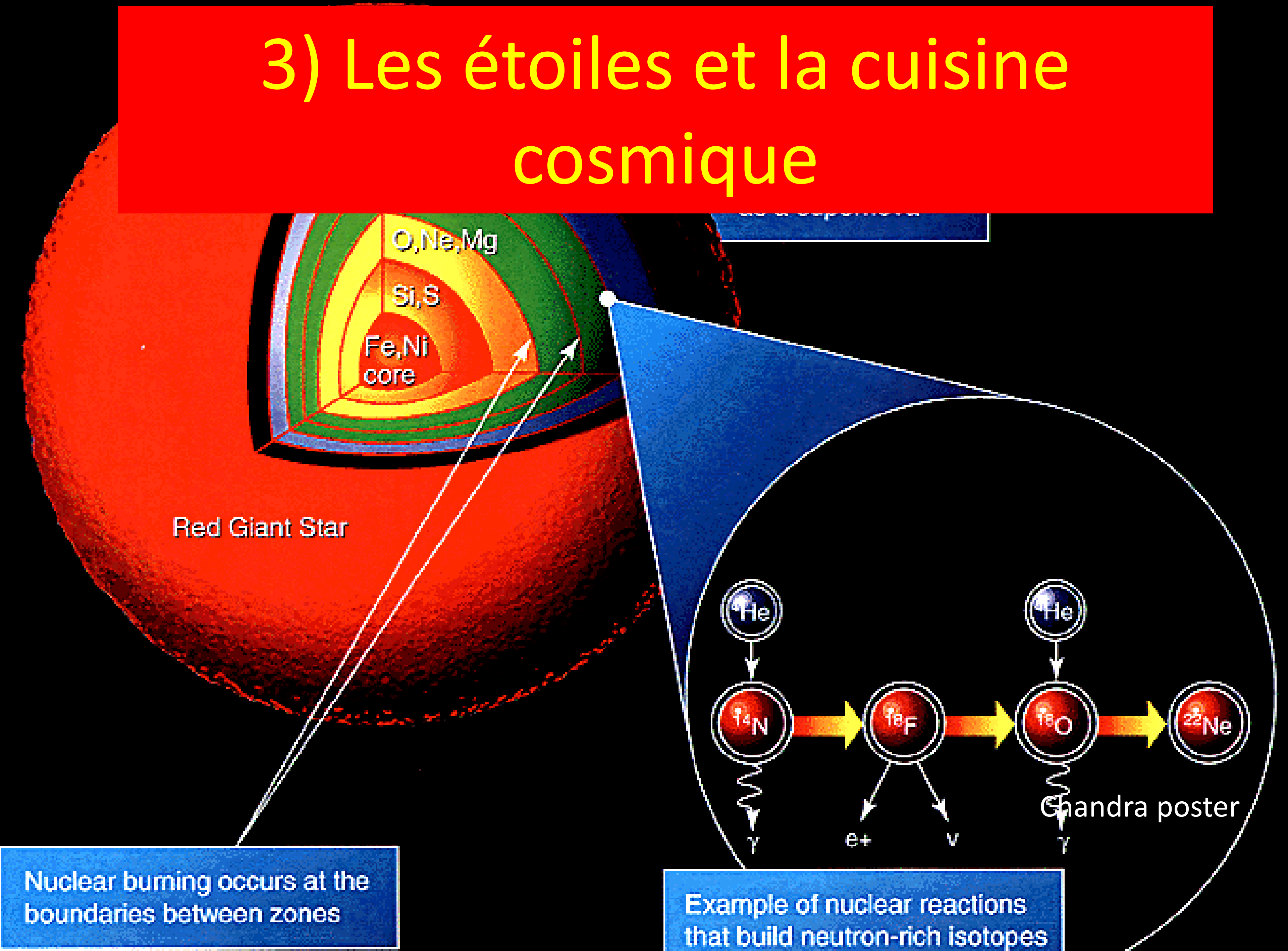
distance


EXPANSION OF THE UNIVERSE
Dark Matter + Dark Energy
affect the expansion of the universe
Ω_m
Ω_v
0.3
0.7
0.3
0.0
1.0
0.0
5.0
0.0
Relative size of the universe
0
1
2
3
4
-10
Now
10
20
30
Billions of Years

La matière émettant de la lumière n’est qu’une toute petite partie du contenu de l’Univers en matière/énergie

0.5%

3) Les étoiles et la cuisine cosmique

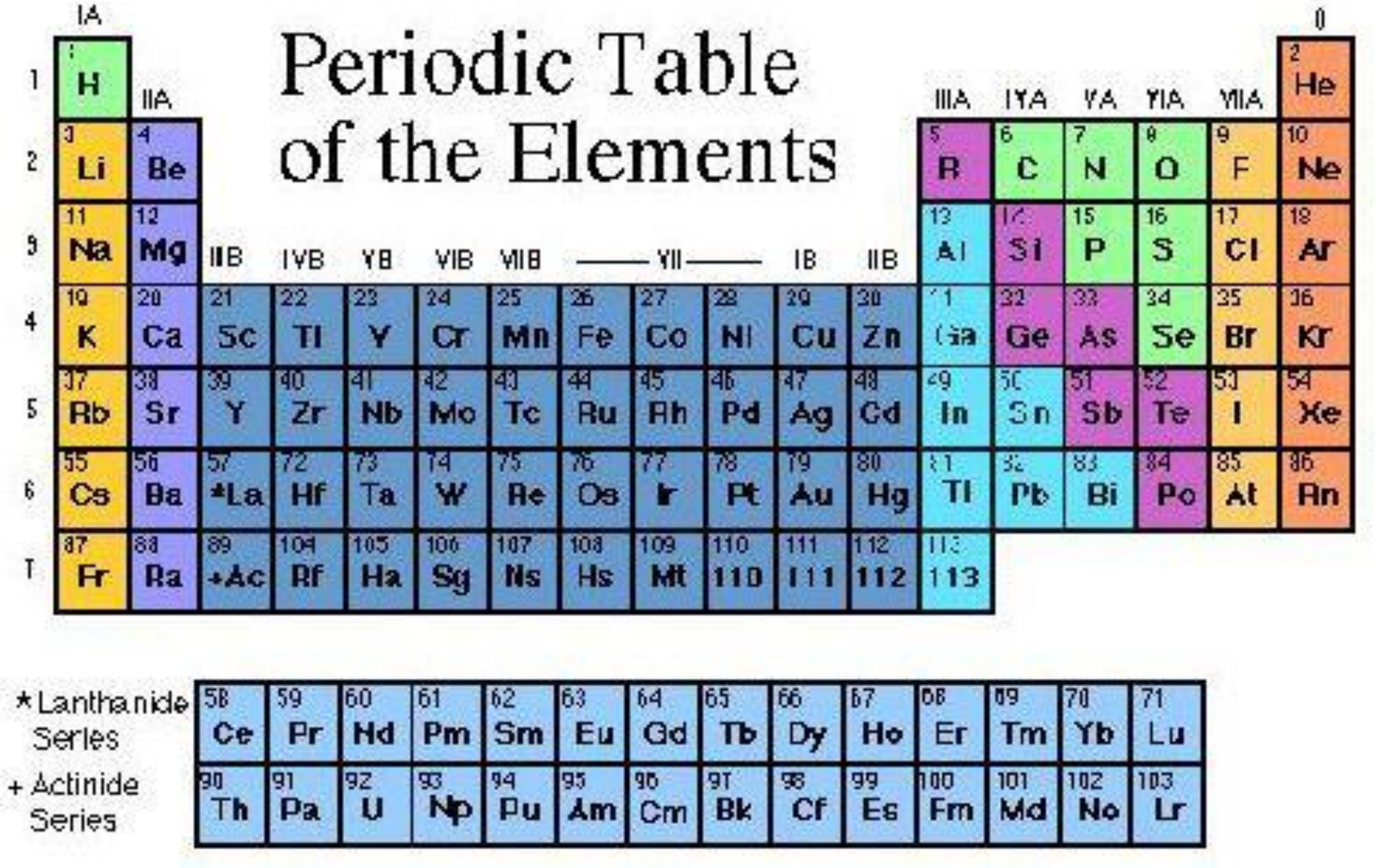


Nuclear burning occurs at the boundaries between zones

Example of nuclear reactions that build neutron-rich isotopes

Chandra poster

Tous différents, mais tous parents



Periodic Table of the Elements

	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	0
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57 *La	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89 +Ac	104 Rf	105 Ha	106 Sg	107 Ns	108 Hs	109 Mt	110 110	111 111	112 112	113 113					

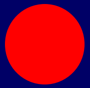
* Lanthanide Series	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu
+ Actinide Series	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

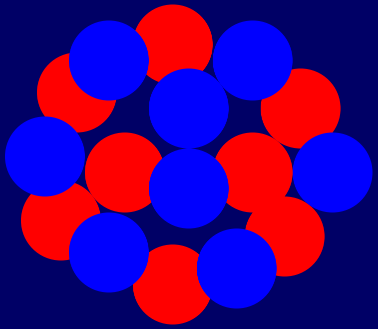
Hydrogène

Oxygène

H

O





1 proton

8 protons
8 neutrons

EAU= 2 atomes d’hydrogène + 1 atome d’oxygène

Aventure intellectuelle extraordinaire…

Destin de

15 747 724 136 275 002 577 605 653 961 181 555 468 044 717 914 527 116 709 366 231 425 076 185 631 031 296

$$1.6\ 10^{79}$$

Protons et d’autant d’électrons dans l’Univers

Arthur Stanley Eddington (1939)

$$\boxed{L \propto \frac{\mu^4 M^3}{\kappa}}$$

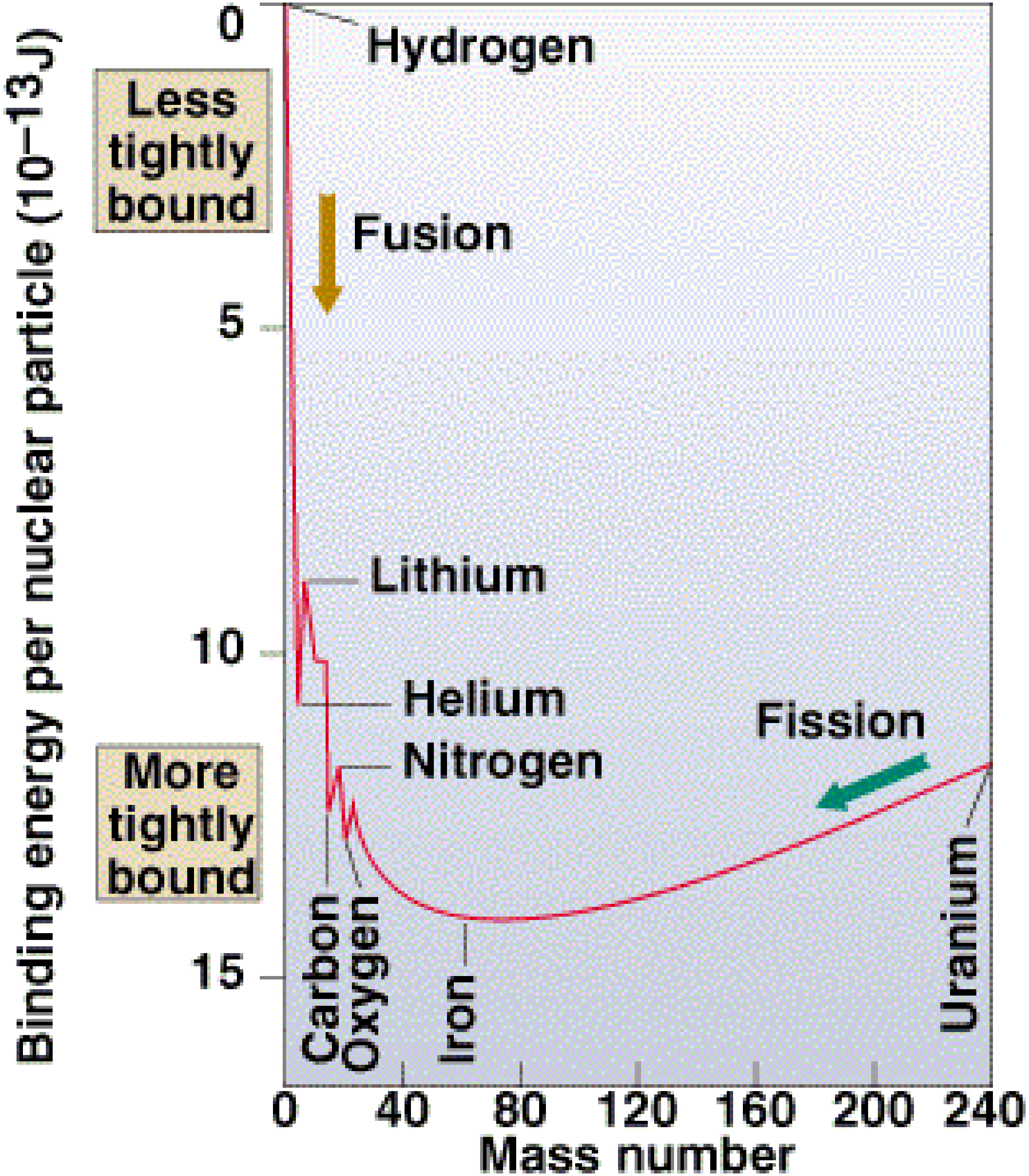
Luminosity is a consequence of equilibrium

More a star massive is, more luminous it is

Higher the averaged opacity, lower the luminosity

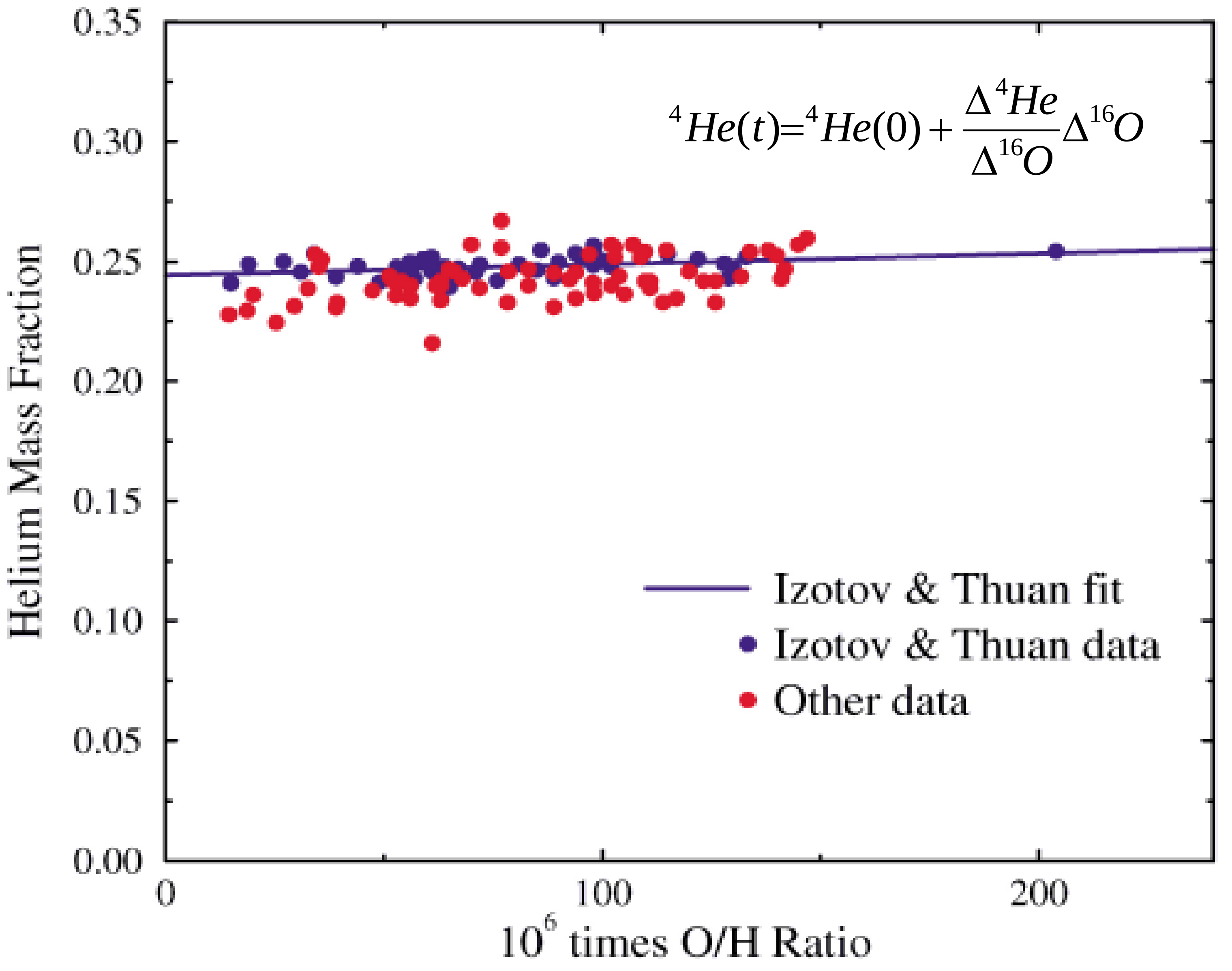
A Helium star is more luminous than a hydrogen stars (given a mass and opacity)

Where does this energy come from ?



©Brooks/Cole Publishing Company/ITP

^{4}He


$^4He(t) = {}^4He(0) + \frac{\Delta^4He}{\Delta^{16}O}\Delta^{16}O$
Helium Mass Fraction
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
100
200
10^6 times O/H Ratio
Izotov & Thuan fit
Izotov & Thuan data
Other data

4) La nucléosynthèse et la matière sombre

Chandra poster

http://bccp.lbl.gov/research3.html

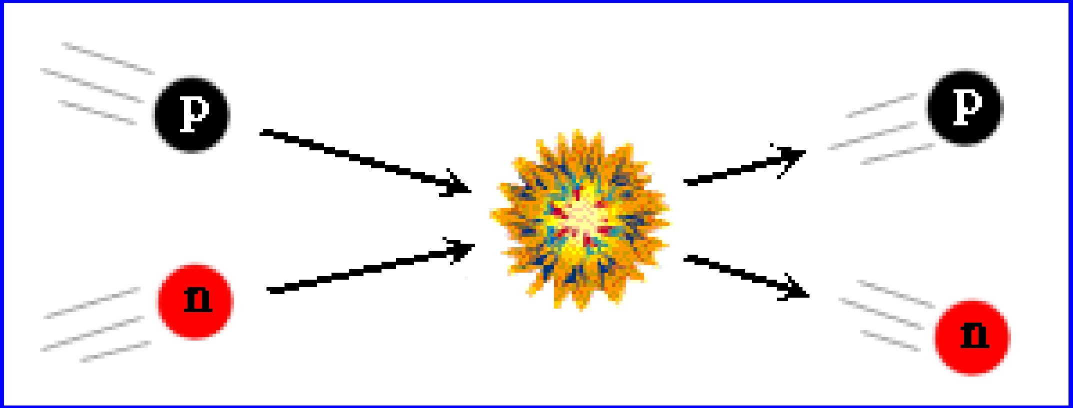
La nucléosynthèse primordiale

- 1940s: Gamow, Alpher & Herman proposèrent que tous les éléments chimiques étaient synthétisés alors que l'Univers n'était âgé que de quelques minutes
- Prédiction du rayonnement de fond cosmologique

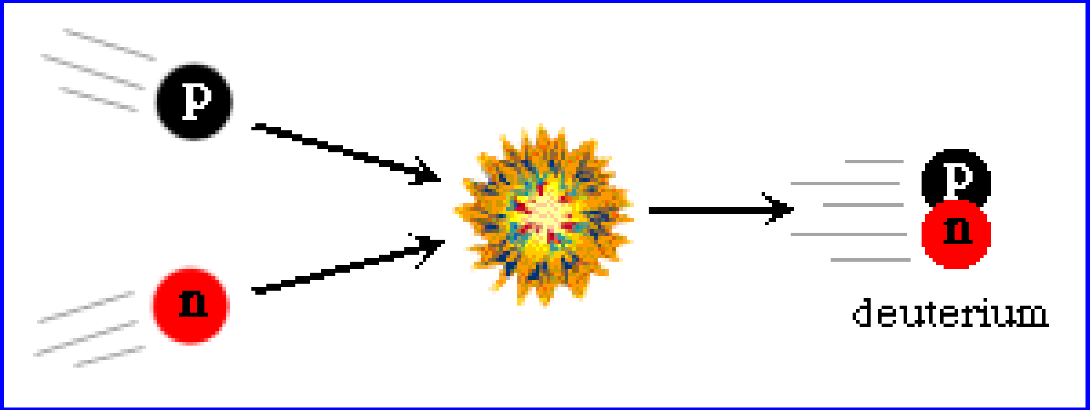
George Gamow (1904-1975)

Formation du Deutérium (D)

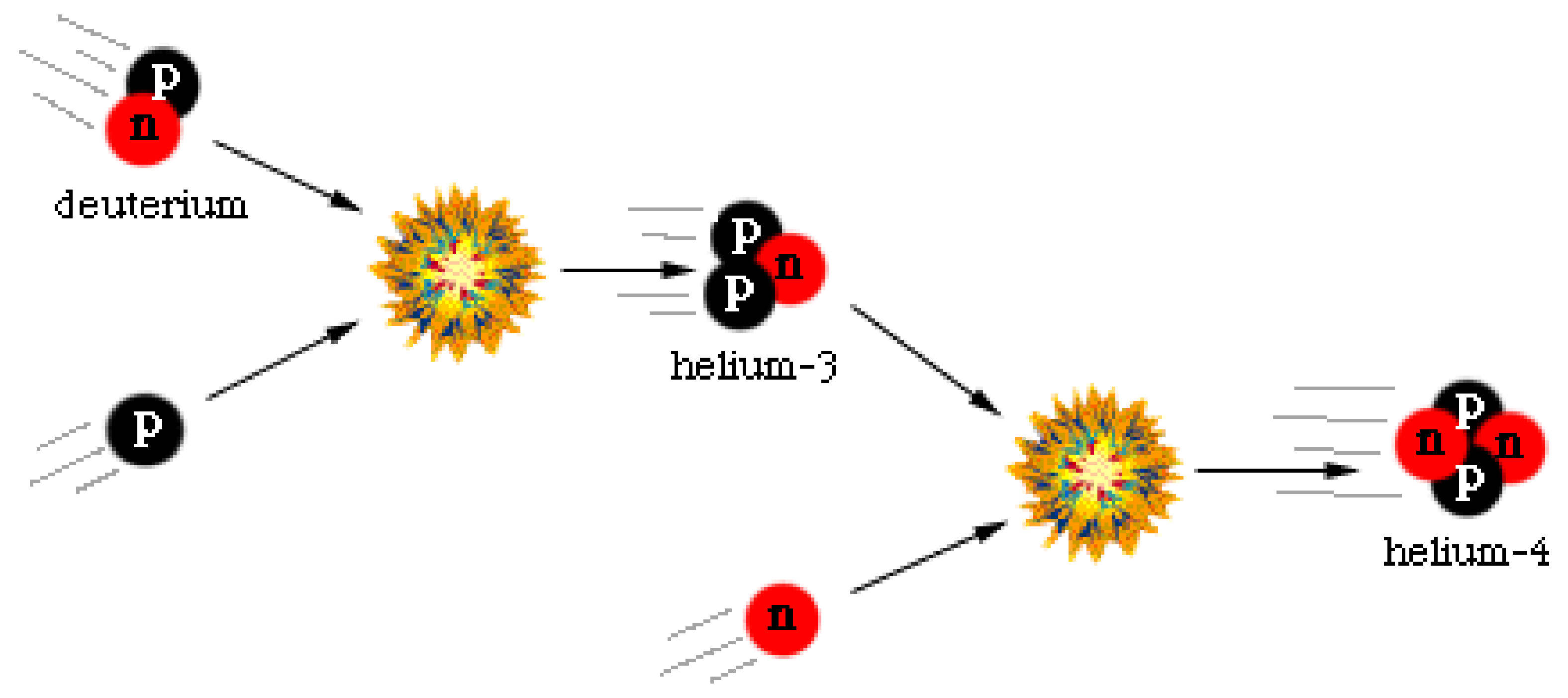
$T > 10^9$ K



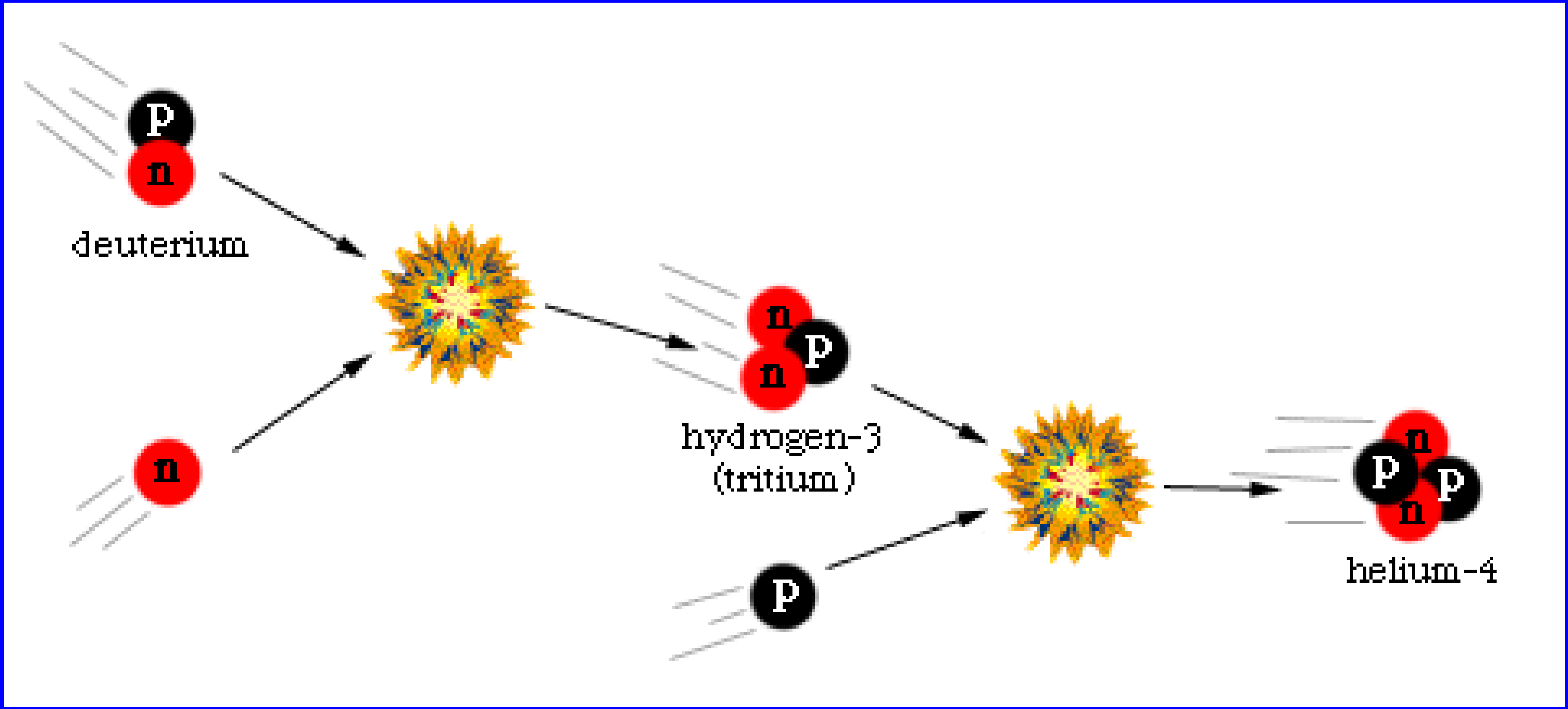
$T < 10^9$ K



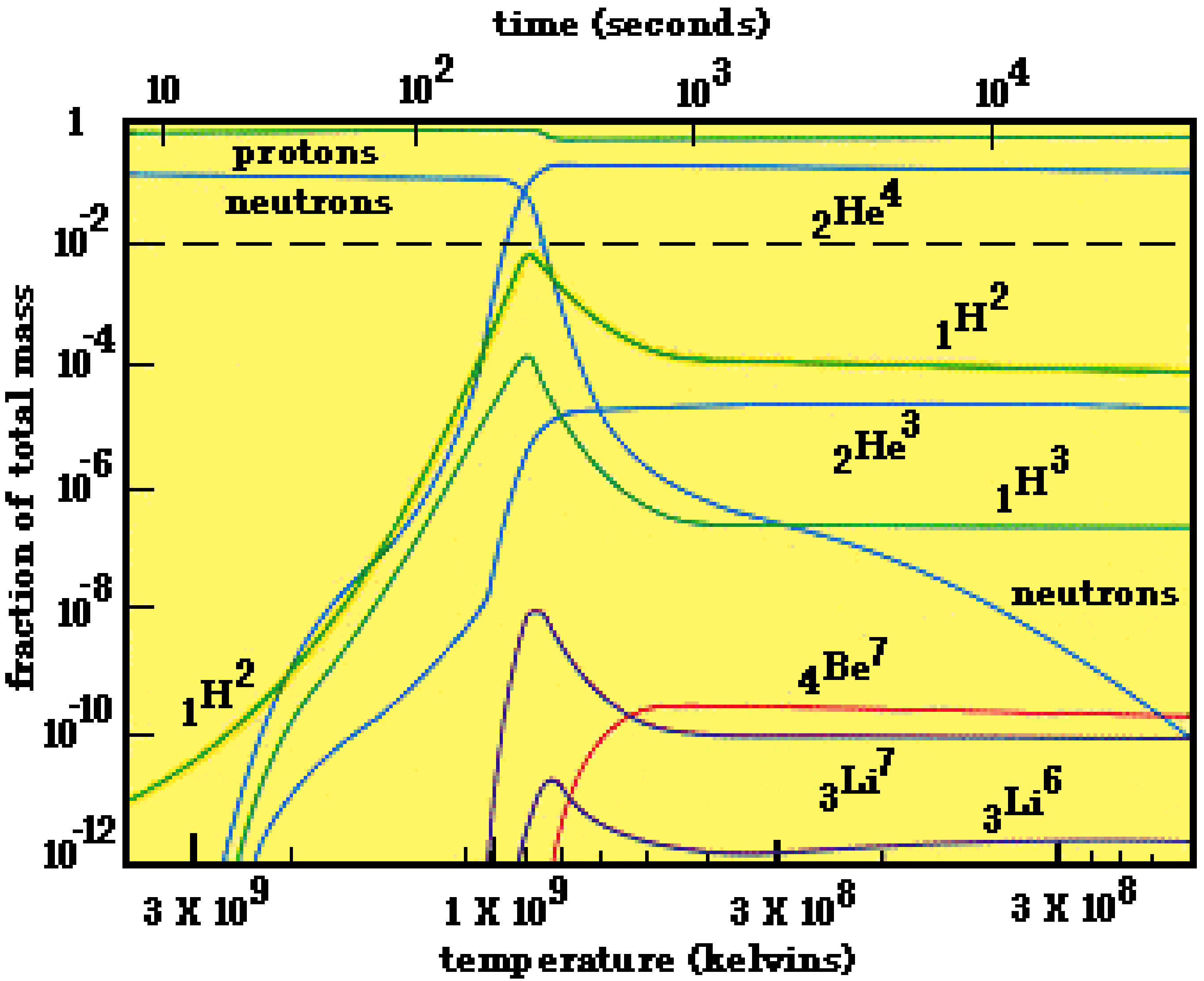
Formation de l'Helium (He): chaîne de réactions 1



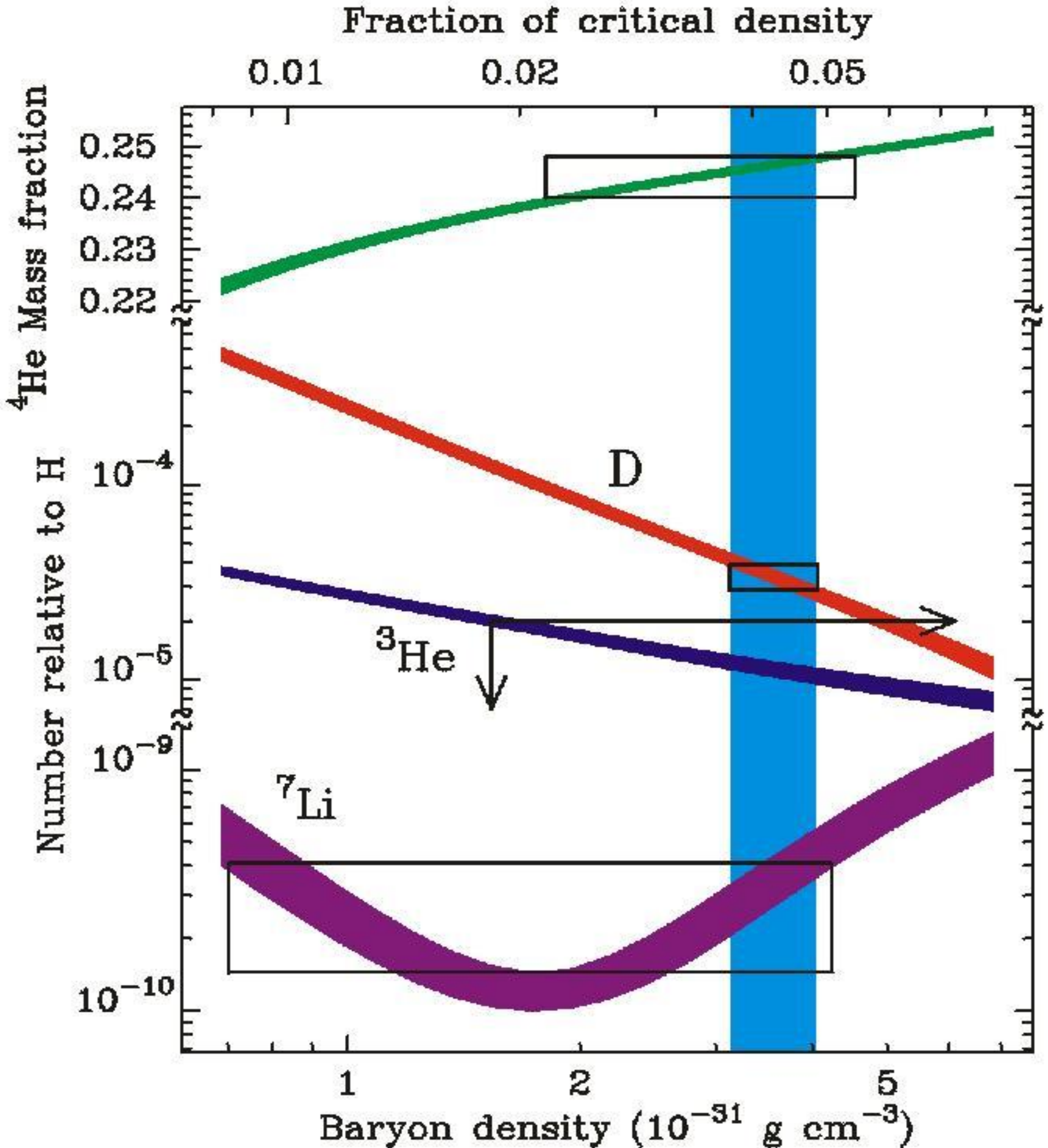
Formation de l’Hélium (He): chaîne de réactions 2



Abundance Evolution



Les résultats de la nucléosynthèse cosmologique dépendent d'un seul paramètre



Matière émettant de la lumière

$\Omega_{\text{étoiles}} \sim 0.005$ (0.5%)

Nucléosynthèse cosmologique

Matière baryonique: $\Omega_B \sim 0.05$ (5%)

↓

La plupart des baryons dans l'Univers sont sombres

Matière émettant de la lumière

$\Omega_{\text{étoiles}} \sim 0.005$ (0.5%)

Nucléosynthèse cosmologique

Matière baryonique: $\Omega_B \sim 0.05$ (5%)

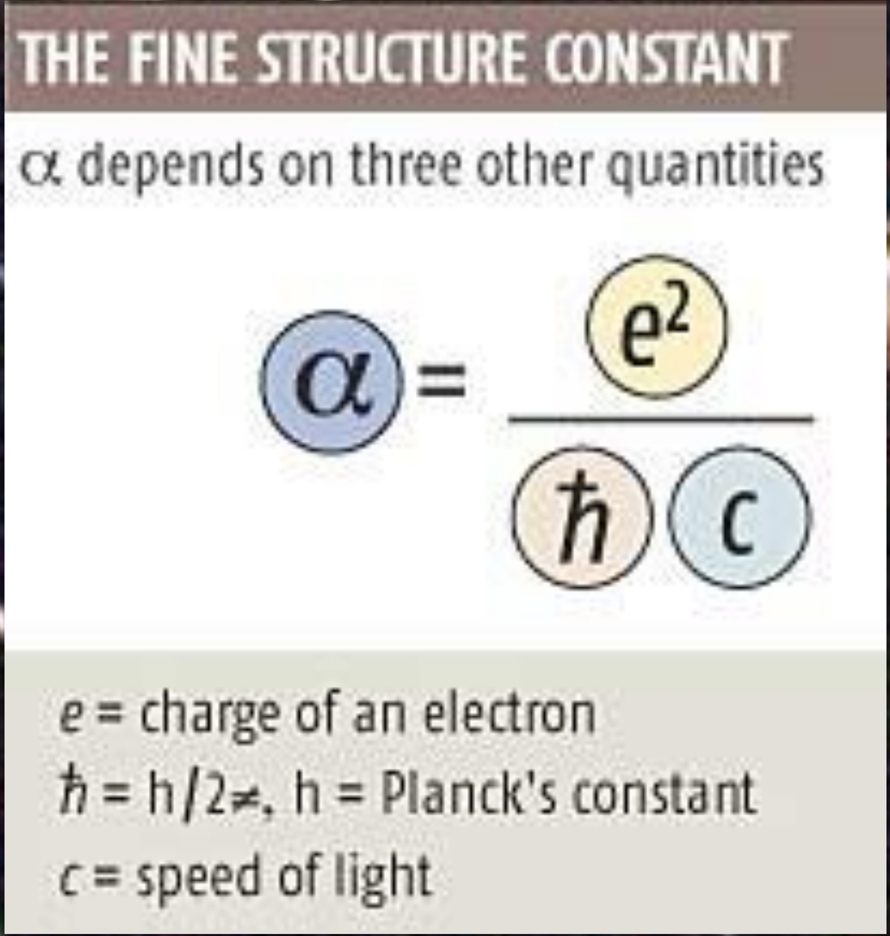
↓

La plupart des baryons dans l'Univers sont sombres

La plus grande partie de la matière sombre est non baryonique

Pas de charges électriques, non soumise aux interactions nucléaires fortes

5) Les étoiles et les constantes fondamentales



THE FINE STRUCTURE CONSTANT

α depends on three other quantities

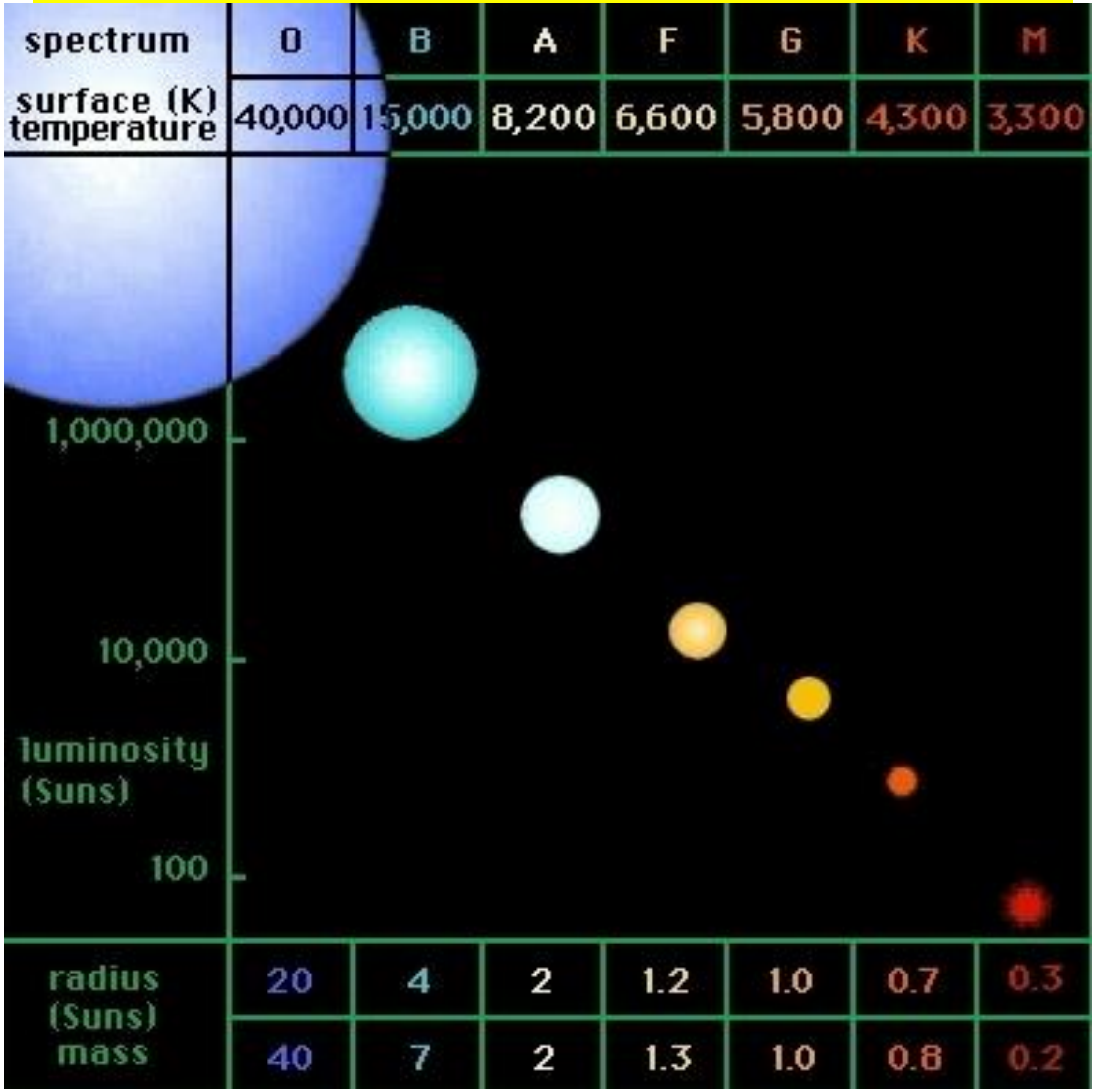
$$\alpha = \frac{e^2}{\hbar c}$$

e = charge of an electron

$\hbar$ = h/2≠, h = Planck's constant

c = speed of light

A NATURAL SCALE FOR THE MASS OF STARS…



spectrum	O	B	A	F	G	K	M
surface (K) temperature	40,000	15,000	8,200	6,600	5,800	4,300	3,300
radius (Suns)	20	4	2	1.2	1.0	0.7	0.3
mass	40	7	2	1.3	1.0	0.8	0.2

https://ca-science7.wikispaces.com/Alli_Astro

IMPORTANCE OF THE RADIATION PRESSURE

Eddington

The parable of the physicist on a cloud Bound planet Eddington 1926

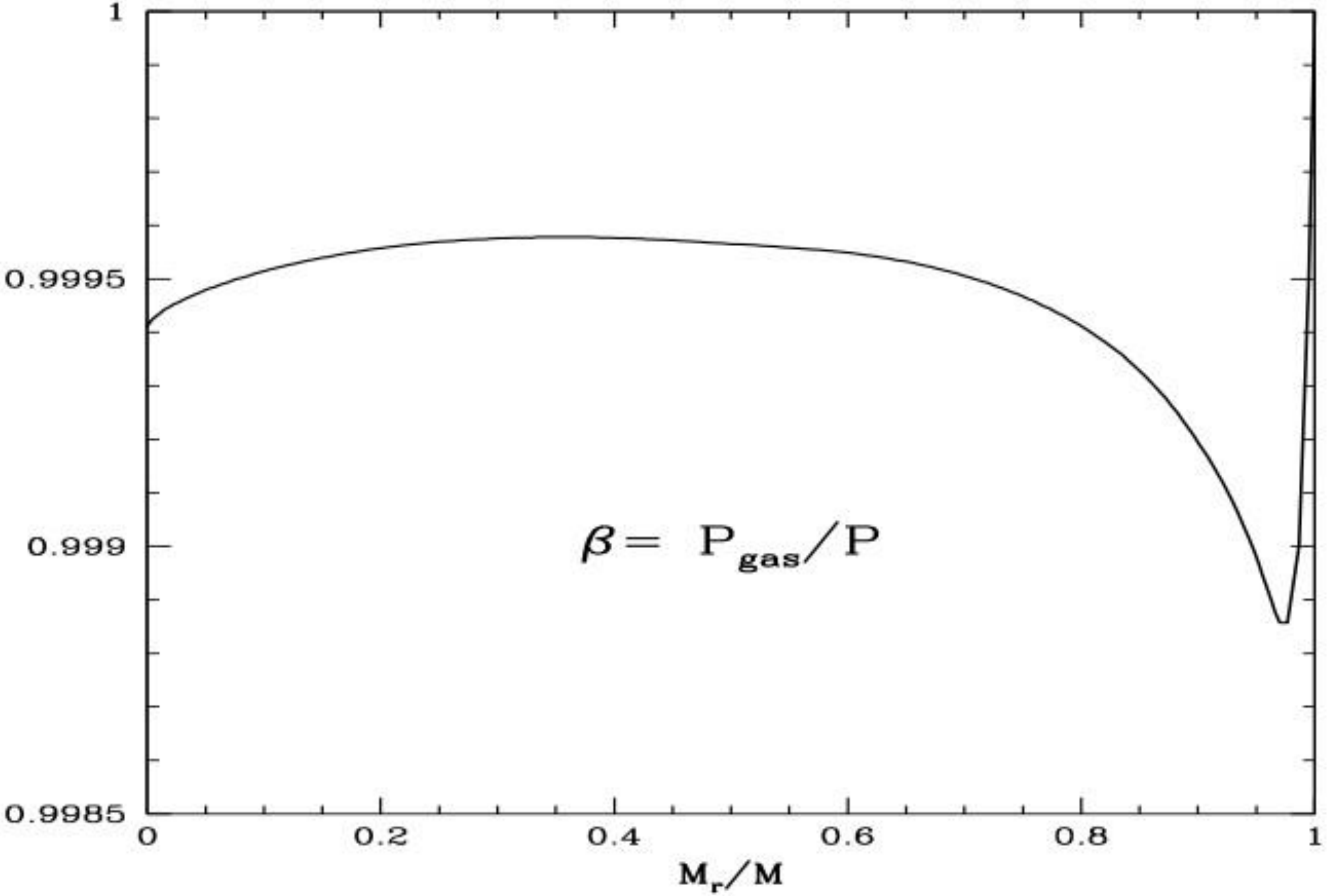
Reported by Srinivasan, Saas-Fee Advanced Course 25 (1995)

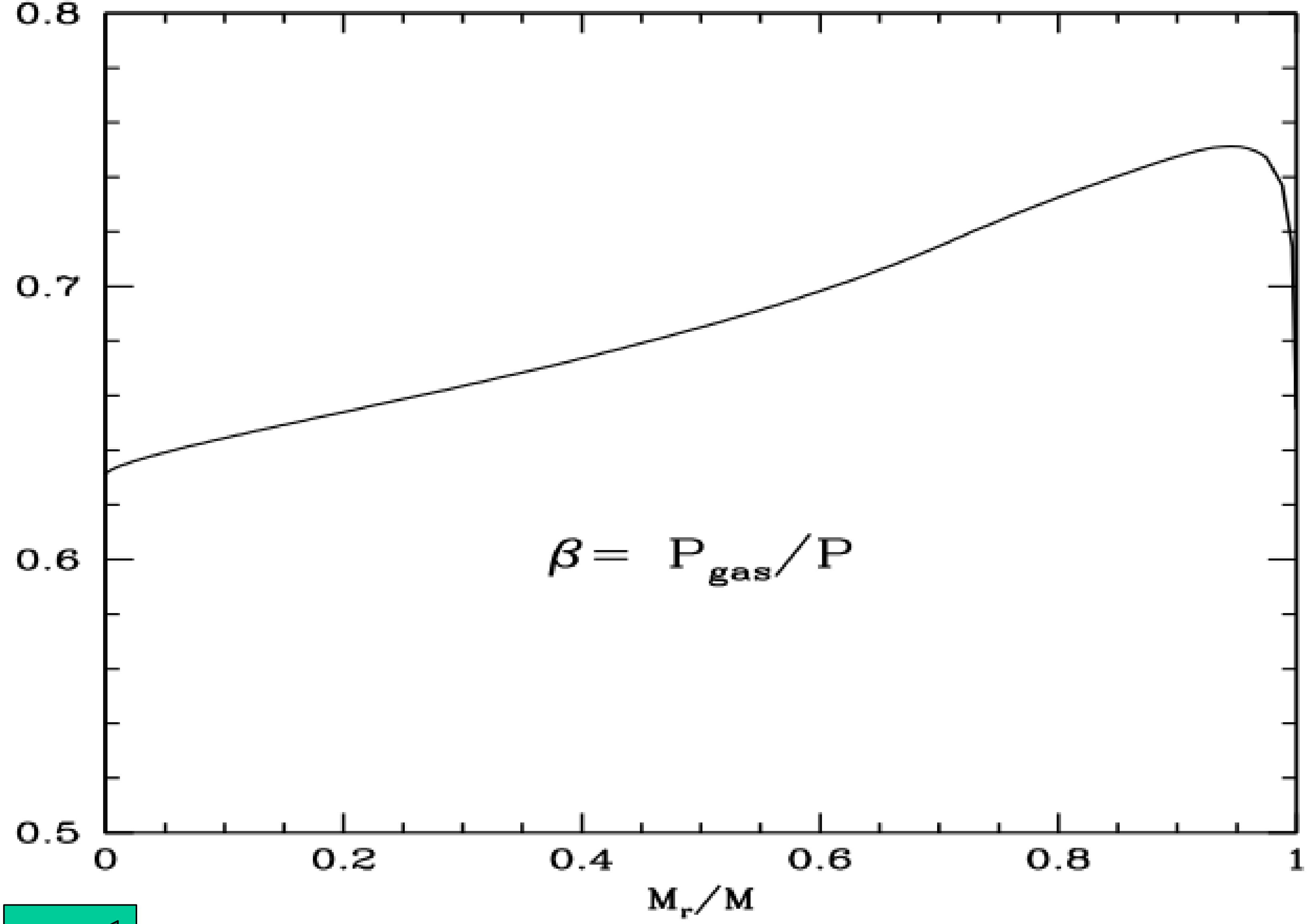
``The outward flowing radiation may be compared to a wind blowing through the star and helping to distend it against gravity.''

- Possible to compute what proportion of the weight is borne by radiation the rest being supported by the gaz
- To a first approximation, this proportion is the same at all parts of the star

``We can imagine a physicist on a cloud-bound planet who has never heard tell of the star, calculating the ratio of Radiation pressure to gas pressure for a series of globes of gas of various sizes, starting, say, with a globe of mass 10 g, then 100g, 1000g and so on, so that his n^{th} *globe contains* 10^{n}*g.''*

The results →


1
0.9995
0.999
0.9985
0
0.2
0.4
0.6
0.8
1
M_r/M
$\beta = P_{gas}/P$


0.8
0.7
0.6
0.5
0
0.2
0.4
0.6
0.8
1
M_r/M
$\beta = P_{gas}/P$

For Low Mass ⇒ P_{gas}

For High Mass ⇒ P_{rad}

Only for a relatively narrow mass interval the table becomes interesting (with numbers different from 0 or 1

n	Prad/P	Pgas/P
…	….	…
32	0.0016	0.9984
33 1Ms	0.106	0.894
34 10Ms	0.570	0.430
35 100Ms	0.850	0.150
36	0.951	0.049
37	0.984	0.016
38	0.9951	0.0049
39	0.9984	0.0016
….	…	…

We may
Expect
Something
To happen

What happens is the stars !

The observed masses of the stars are in majority between 10^{33} - 10^{34} g where the serious challenge of radiation pressure to compete with gaz pressure is beginning

AIP Niels Bohr Library

NATURAL SCALES OF THE STELLAR MASSES

Chandrasekhar 1936

In any equilibrium configuration in which the mean density inside decreases outwards we have the inequality

$$\frac{1}{2}G\left(\frac{4}{3}\pi\right)^{1/3}\bar{\rho}^{4/3}(r)M^{2/3}(r)\leq P_c-P\leq\frac{1}{2}G\left(\frac{4}{3}\pi\right)^{1/3}\rho_c^{4/3}M^{2/3}(r)$$

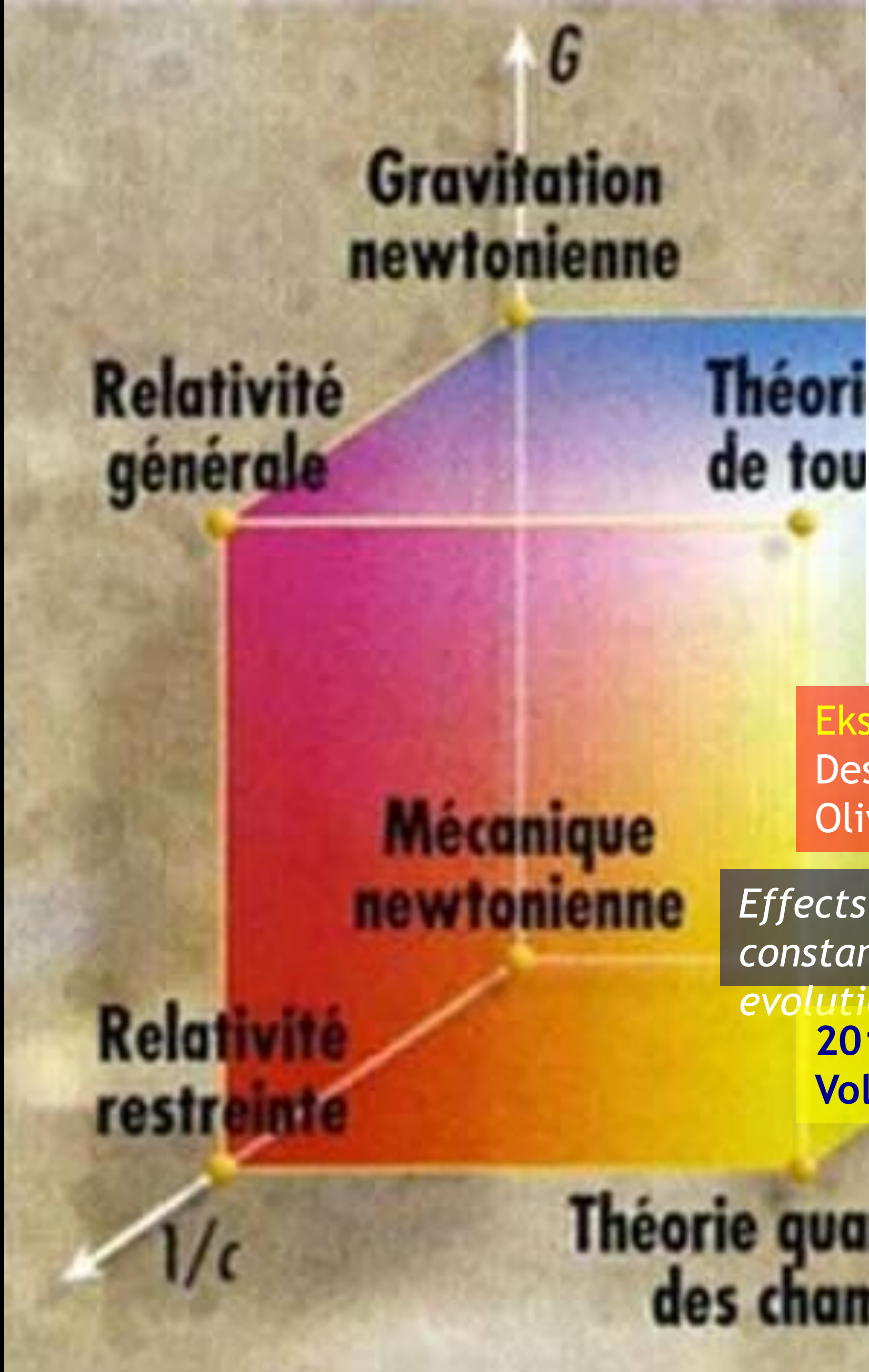
where $\bar{\rho}(r)$ denotes the mean density inside r, and ρ_c the central density and P_c the central pressure

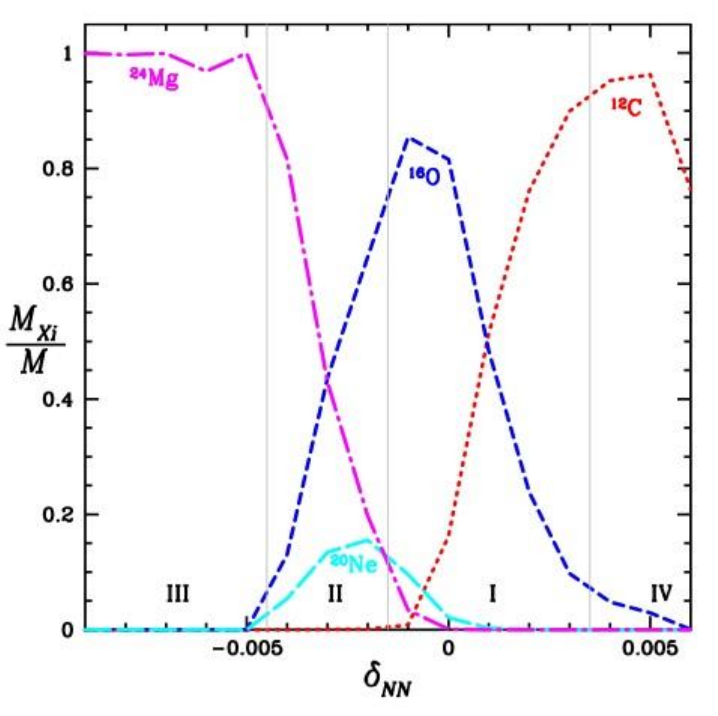
$$P=\underbrace{\frac{k}{\mu m_H}\rho T}_{P_{gaz}}+\frac{1}{3}aT^4,\beta=P_{gaz}/P,a=\frac{8\pi^5k^4}{15h^3c^3}$$

$$\mu^2M\left(\frac{\beta_c^4}{1-\beta_c}\right)^{1/2}\geq\underbrace{0.1873\left(\frac{hc}{G}\right)^{3/2}\frac{1}{m_H^2}}_{5.48M_{sol}}$$

$$\mu^2 M \left(\frac{\beta_c^4}{1-\beta_c}\right)^{1/2} \geq \underbrace{0.1873\left(\frac{hc}{G}\right)^{3/2}\frac{1}{m_H^2}}_{5.48 M_{sol}}$$

Supposing the mechanical equilibrium is maintained by both the gaz and radiation pressure, one obtains a combination of physical constants providing a natural scale for the masses of the stars.





Ekström, S.; Coc, A.;
Descouvemont, P.; Meynet, G.;
Olive, K. A.; Uzan, J.-P.; Vangioni, E.

Effects of the variation of fundamental constants on Population III stellar evolution

2010, Astronomy and Astrophysics, Volume 514, id.A62

Roland Lehoucq

Il y a plus de choses dans le ciel et
la terre, Horatio,
Qu'il est rêvé dans votre
philosophie.

Hamlet, acte I, scène V.
Hamlet s'adresse à Horatio

William Shakespeare

Old Universe – *New* Numbers

$\Omega_{tot} = 1.02^{+0.02}_{-0.02}$

$w < -0.78$ (95% CL)

$\Omega_\Lambda = 0.73^{+0.04}_{-0.04}$

$\Omega_b h^2 = 0.0224^{+0.0009}_{-0.0009}$

$\Omega_b = 0.044^{+0.004}_{-0.004}$

$n_b = 2.5 \times 10^{-7}{}^{+0.1\times10^{-7}}_{-0.1\times10^{-7}}$ cm^{-3}

$\Omega_m h^2 = 0.135^{+0.008}_{-0.009}$

$\Omega_m = 0.27^{+0.04}_{-0.04}$

$\Omega_\nu h^2 < 0.0076$ (95%CL)

$m_\nu < 0.23$ eV (95% CL)

$T_{cmb} = 2.725^{+0.002}_{-0.002}$ K

$n_\gamma = 410.4^{+0.9}_{-0.9}$ cm^{-3}

$\eta = 6.1 \times 10^{-10}{}^{+0.3\times10^{-10}}_{-0.2\times10^{-10}}$

$\Omega_b \Omega_m^{-1} = 0.17^{+0.01}_{-0.01}$

$\sigma_8 = 0.84^{+0.04}_{-0.04}$ Mpc

$\sigma_8 \Omega_m^{0.5} = 0.44^{+0.04}_{-0.05}$

$A = 0.833^{+0.086}_{-0.083}$

$n_s = 0.93^{+0.03}_{-0.03}$

$dn_s/d\ln k = -0.031^{+0.016}_{-0.018}$

$r < 0.71$ (95% CL)

$z_{dec} = 1089^{+1}_{-1}$

$\Delta z_{dec} = 195^{+2}_{-2}$

$h = 0.71^{+0.04}_{-0.03}$

$t_0 = 13.7^{+0.2}_{-0.2}$ Gyr

$t_{dec} = 379^{+8}_{-7}$ kyr

$t_r = 180^{+220}_{-80}$ Myr (95% CL)

$\Delta t_{dec} = 118^{+3}_{-2}$ kyr

$z_{eq} = 3233^{+194}_{-210}$

$\tau = 0.17^{+0.04}_{-0.04}$

$z_r = 20^{+10}_{-9}$ (95% CL)

$\theta_A = 0.^\circ598^{+0.002}_{-0.002}$

$d_A = 14.0^{+0.2}_{-0.3}$ Gpc

$l_A = 301^{+1}_{-1}$

$r_s = 147^{+2}_{-2}$ Mpc

$$H^2 \equiv \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho_m + \frac{\Lambda}{3} - \frac{k}{R^2}$$

Let us first consider a uniform contraction of a mass M. In that case a variation in radius ΔR corresponds to a variation in pressure ΔP and to a variation in density $\Delta\rho$ so that we have the following relations:

$$\frac{\Delta P}{P} = -4\frac{\Delta R}{R}, \quad \text{and} \quad \frac{\Delta\rho}{\rho} = -3\frac{\Delta R}{R}.$$

The first equality is deduced from the hydrostatic equilibrium equation and the second from the continuity equation. From these two relations, we can write

$$\Delta \ln P = \frac{4}{3}\Delta \ln \rho.$$

Let us now write the equation of state as follows

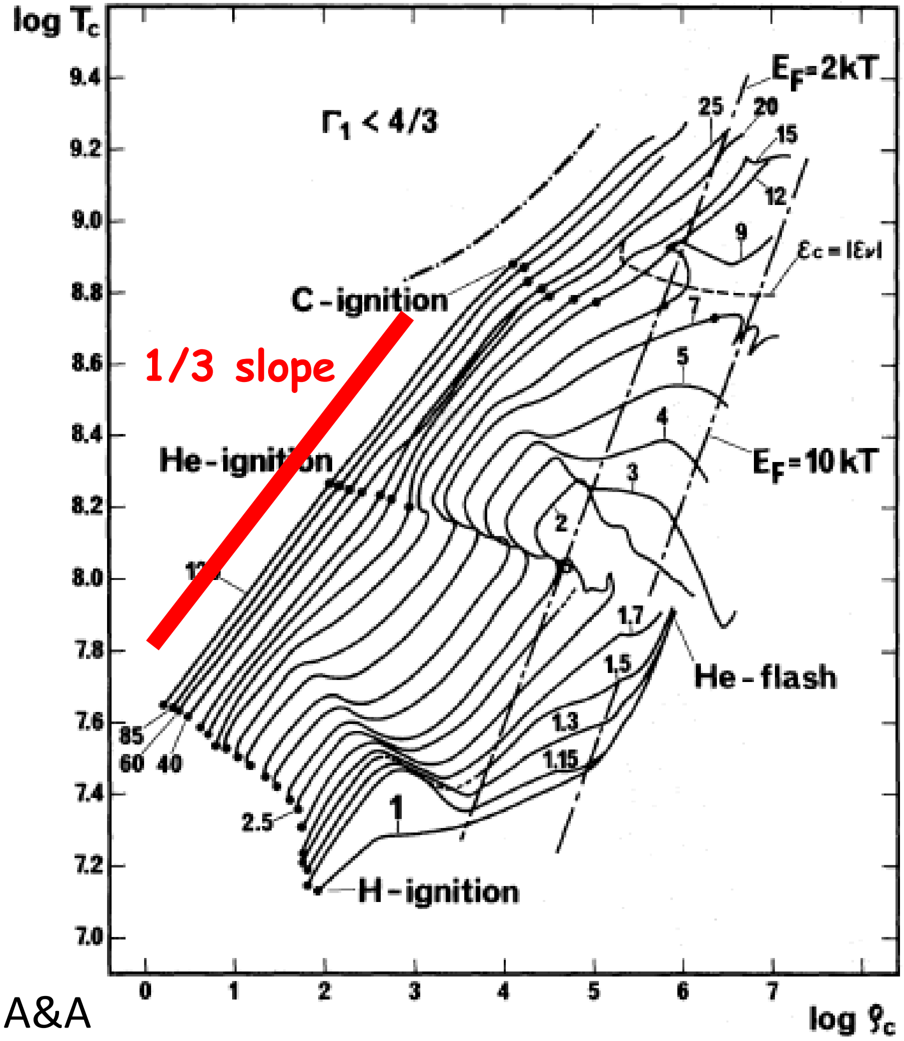
$$\Delta \ln \rho = \alpha \Delta \ln P - \delta \Delta \ln T,$$

where α and δ are defined by $\alpha = \left(\frac{\partial \ln \rho}{\partial \ln P}\right)_{T,\mu}$ and $\delta = -\left(\frac{\partial \ln \rho}{\partial \ln T}\right)_{P,\mu}$, and where μ, the mean molecular weight, is supposed to remain constant. From these two relations one obtains, by eliminating ΔP the two following relations between a variation in log T and log ρ:

$$\Delta \ln T = \left(\frac{4\alpha - 3}{3\delta}\right)\Delta \ln \rho. \tag{1}$$

For a perfect gas law we have $\alpha = \delta = 1$. Therefore an increase of, for instance, 30% in density implies an increases of 10% in temperature.

Stars=system with a negative specific heat!



Maeder & Meynet 1989, A&A

. GRAVITATIONAL ENERGY

HOW LONG CAN IT LAST?

$$\tau_{KH} = \frac{GM^2}{RL} \rightarrow \tau_{KH} = 10^7\ years$$

- **NUCLEAR ENERGY**

HOW LONG CAN IT LAST?

$$\tau_{nucl} \approx \frac{MqX\,0.007c^2}{L} \rightarrow \tau_{nucl} \approx 10^{10}\ years$$

THE RESERVOIRS OF ENERGY

- **GRAVITATIONAL ENERGY**

$$\tau_{KH} = \frac{GM^2}{RL} \rightarrow \tau_{KH} = 10^7\ years$$

- **NUCLEAR ENERGY**

$$\tau_{nucl} \approx \frac{MqX\,0.007c^2}{L} \rightarrow \tau_{nucl} \approx 10^{10}\ years$$

The mechanisms of extraction of the energy from these reservoirs are responsible for the evolution of the stars.

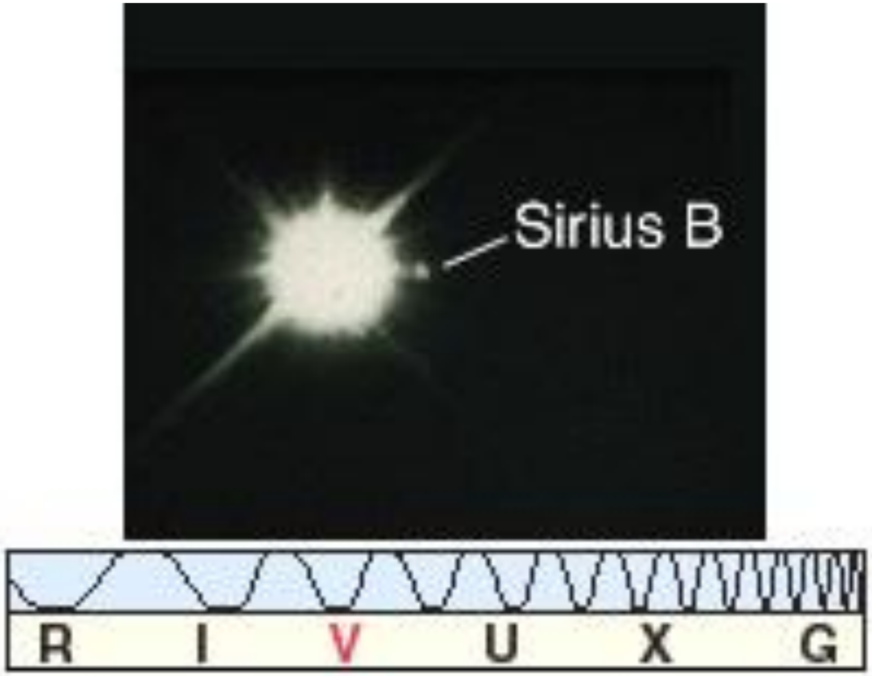
EQUILIBRIUM→EVOLUTION

- Hyrostatic equilibrium→loss of energy
- Energy produced by contraction

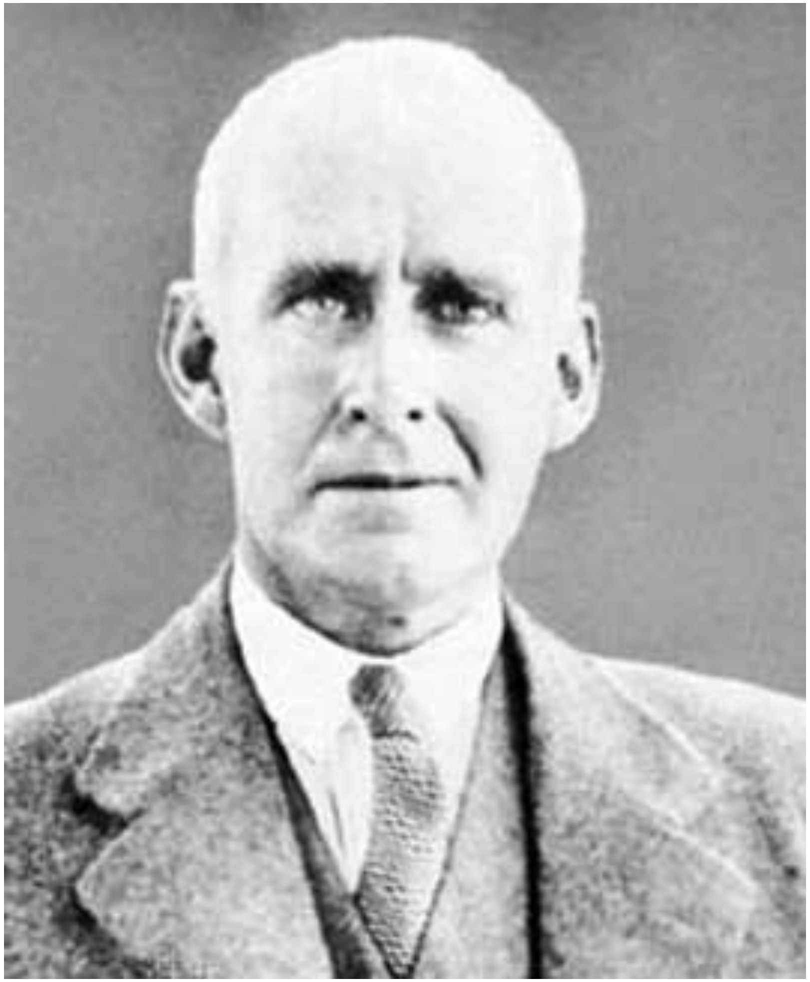
  nuclear reactions
- The state of the stars evolve.
- **Can it continue for ever?**

Sirius B

Mass	1.1 solar masses
Radius	0.008 solar radii (5500 km)
Luminosity (total)	0.04 solar luminosities (1.6 x10^{25} W)
Surface temperature	24,000 K
Average density	3x10^9 kg/m^3



TOO LITTLE ENERGY TO COOL!!!



Eddington

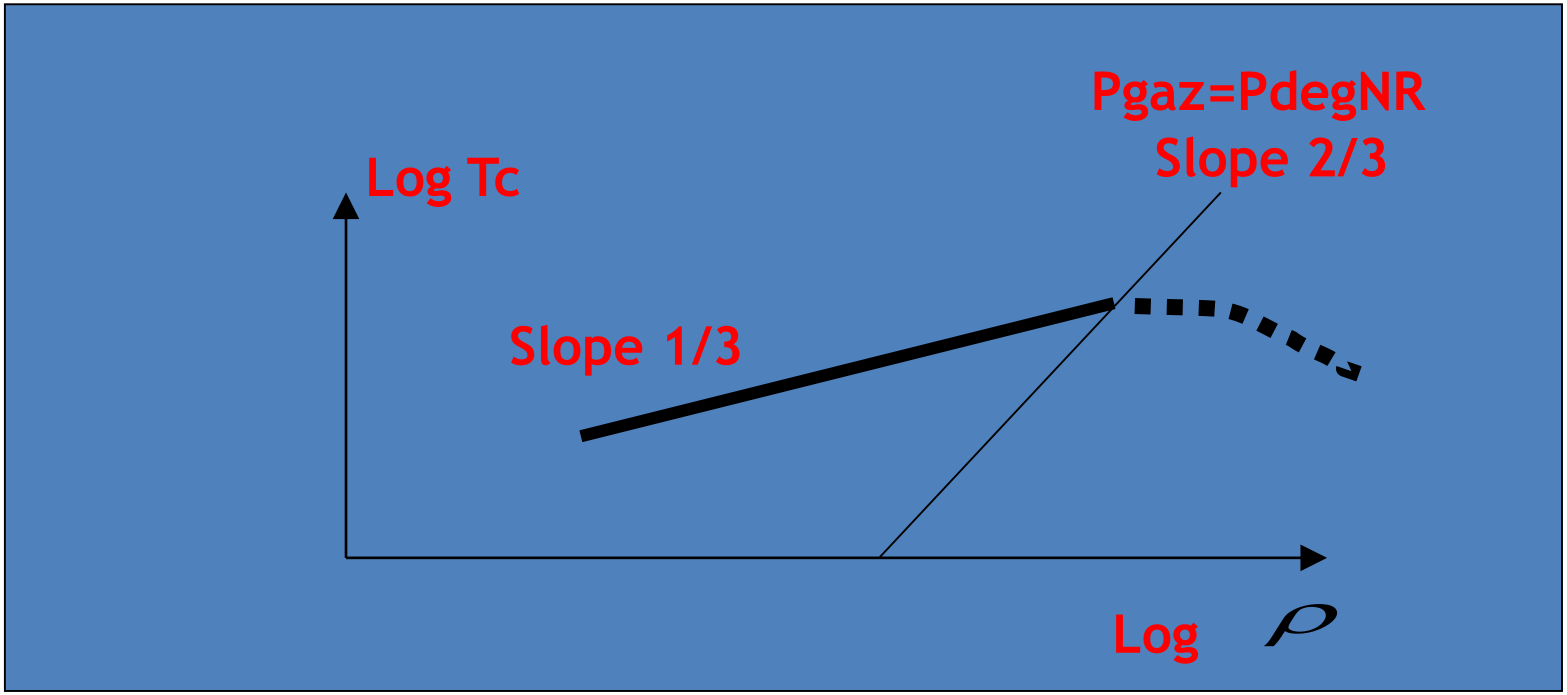
$$\Delta \ln T = \left(\frac{4\alpha - 3}{3\delta}\right) \Delta \ln \rho.$$

$$P \propto \rho^{5/3}$$

$$\alpha = 3/5 \text{ and } \delta = 0$$

no longer valid, but if during the course of evolution, when the central conditions pass from the non-degenerate region to the degenerate one, α becomes inferior to three quarters before δ is equal to zero, then a contraction can produce a cooling! This can be understood as due to the fact that, in order to allow electrons to occupy still higher energy state, some energy has to be extracted from the non degenerate nuclei which, as a consequence, cool down.

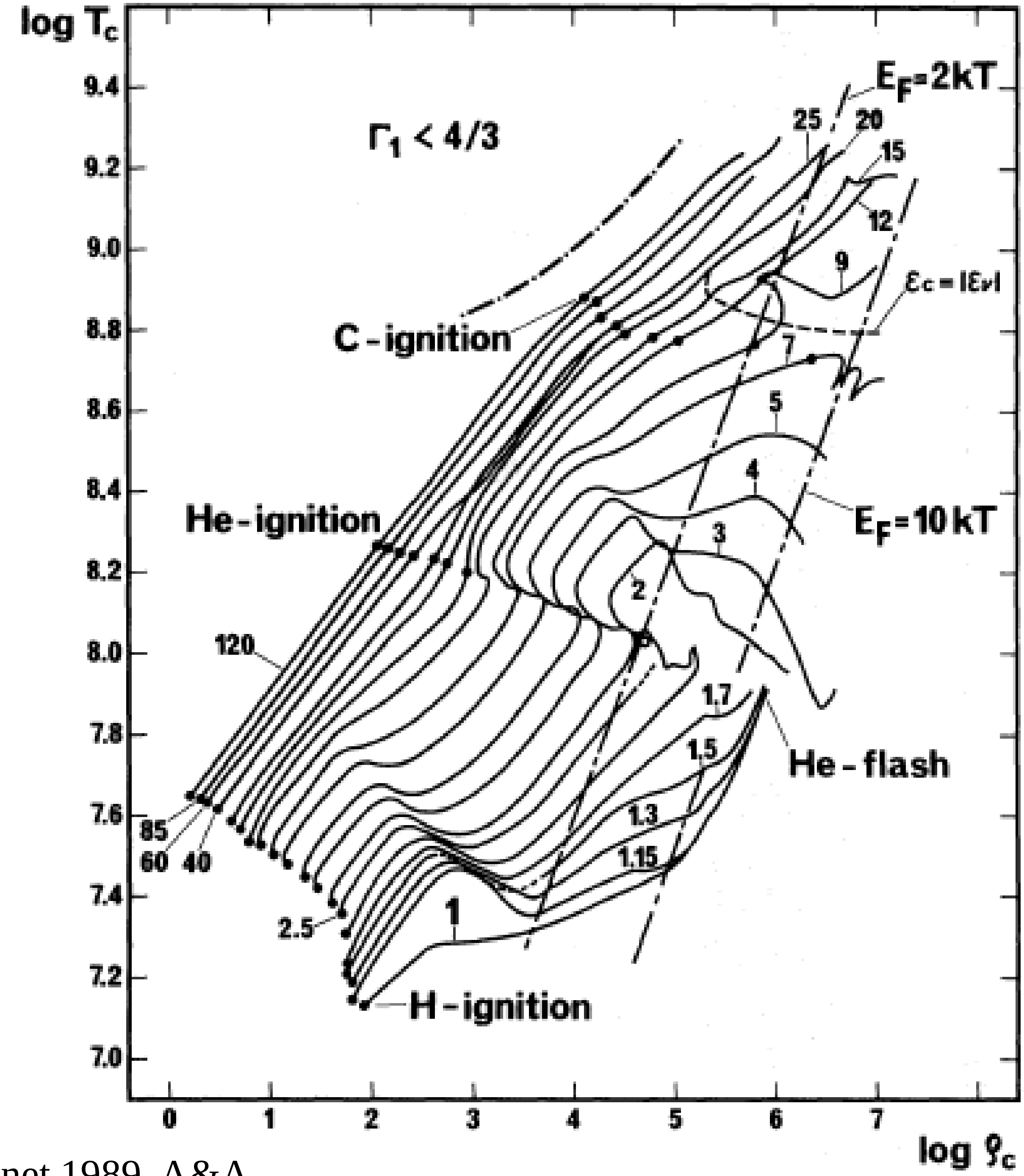
Evolution of the temperature and density at the centre



Pgaz=PdegNR

$$\boxed{\frac{k}{\mu m_H}\rho T = K_1\left(\frac{\rho}{\mu e}\right)^{5/3}}$$

$$\boxed{\rightarrow T = K_1 \frac{\mu m_H}{k}\frac{1}{\mu_e^{5/3}}\rho^{2/3}}$$

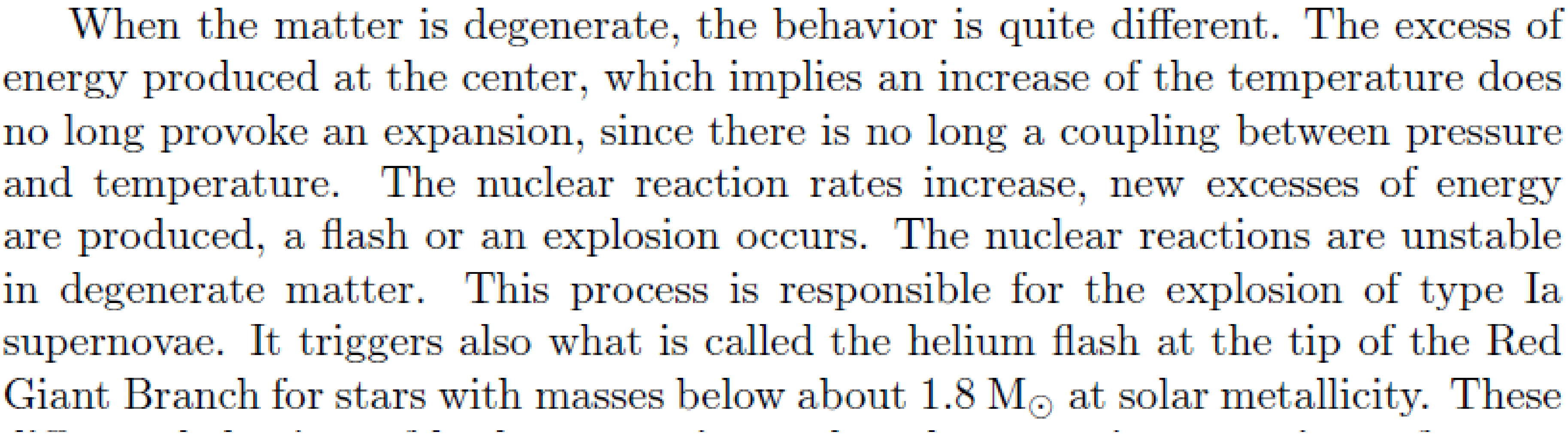


Maeder & Meynet 1989, A&A

Nuclear reaction in PG conditions

Let us now study the nuclear source in degenerate conditions. Let us imagine that for whatever reason an excess of energy is produced at the center of the star. This will produce a heating of the matter. When the perfect gas law prevails, an increase of temperature will produce an increase of pressure and therefore an expansion. This implies an increase of the potential energy and through the Virial theorem a decrease of the internal energy, therefore the temperature decreases as well as the nuclear reaction rates. We see that in perfect gas conditions, there is a negative feedback which stops the runaway. The nuclear reactions are stable when the perfect gas law prevails.

Nuclear reactions in DG conditions



When the matter is degenerate, the behavior is quite different. The excess of energy produced at the center, which implies an increase of the temperature does no long provoke an expansion, since there is no long a coupling between pressure and temperature. The nuclear reaction rates increase, new excesses of energy are produced, a flash or an explosion occurs. The nuclear reactions are unstable in degenerate matter. This process is responsible for the explosion of type Ia supernovae. It triggers also what is called the helium flash at the tip of the Red Giant Branch for stars with masses below about 1.8 $M_\odot$ at solar metallicity. These

Stellar evolution in a nutshell

When perfect gaz prevails→ hydrostatic equilibrium implies continuous loss of energy

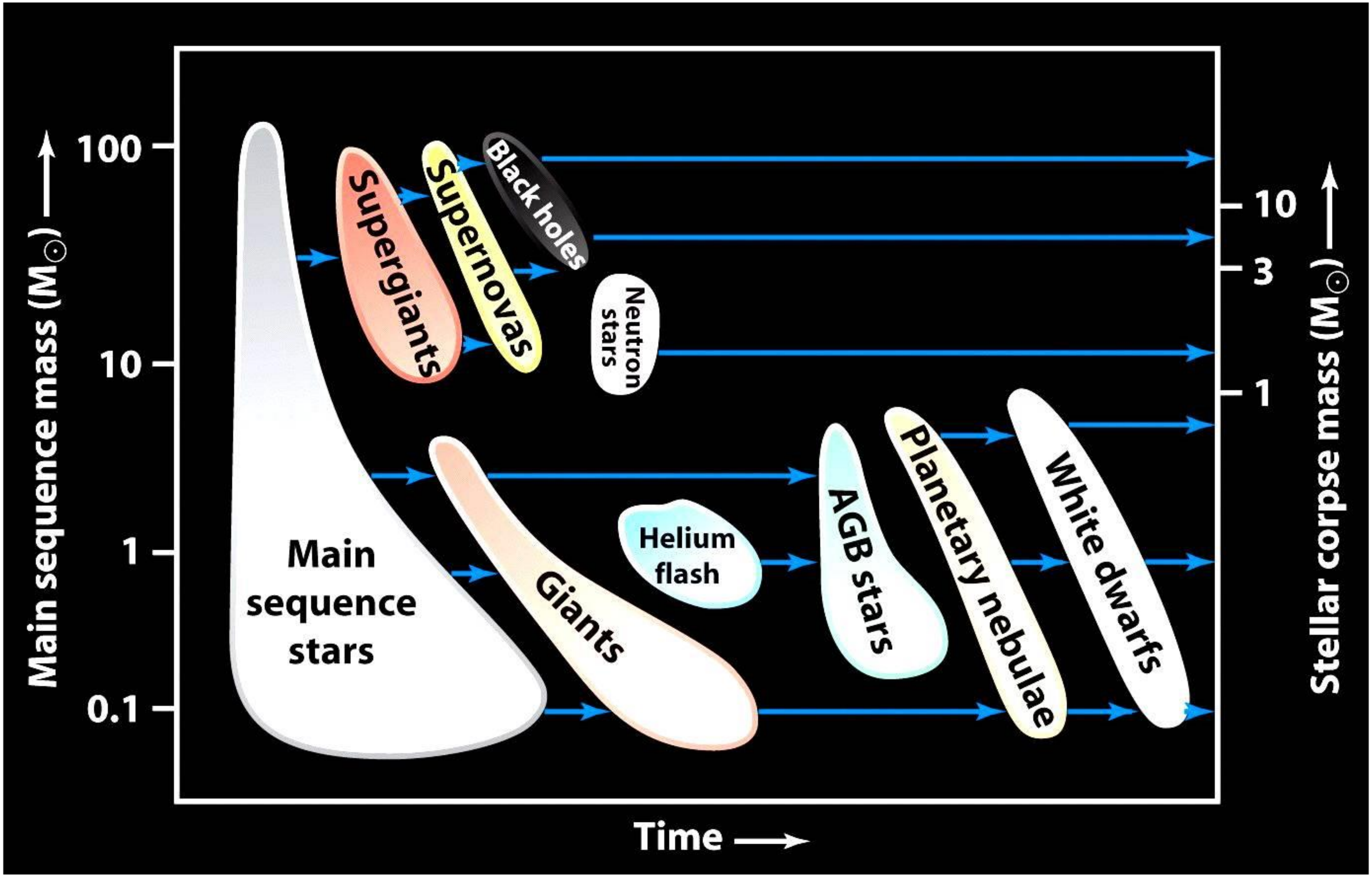
Star compensate for this loss either by macroscopic contraction or microscopic ones

This changes the structures and the composition of the star

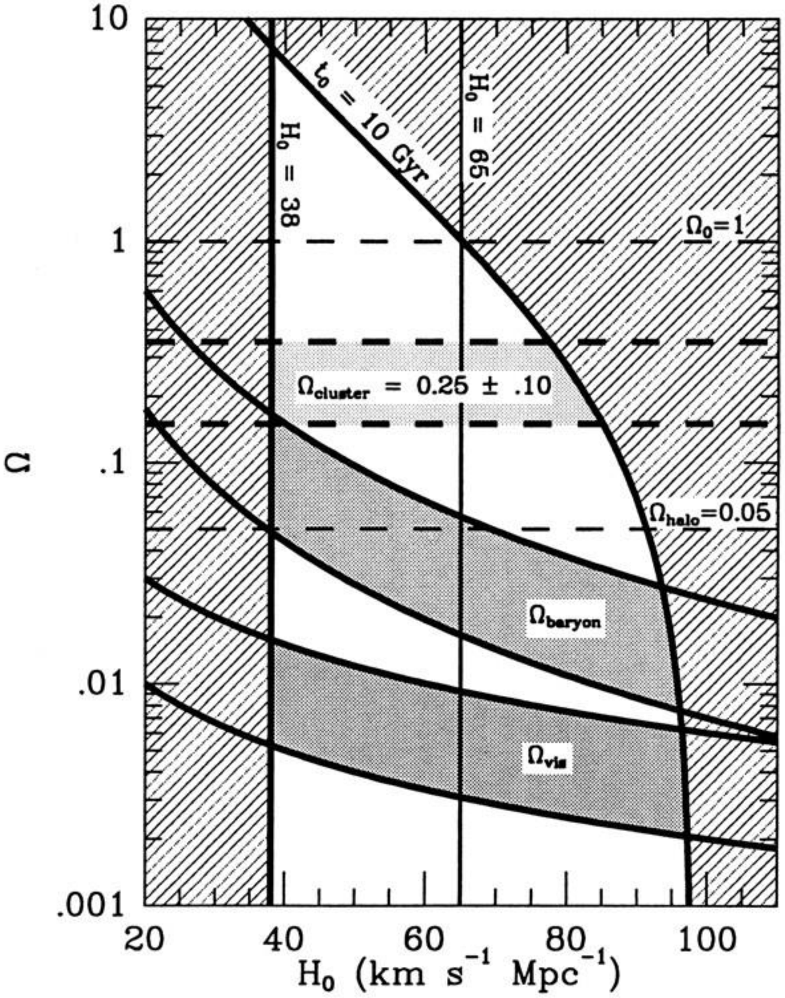
These processes drive the central regions in degenerate regimes

In degenerste regime: nuclear reaction unstable, contraction may lead to cooling

Hydrostatique equilibrium is for free! No long evolution


Main sequence mass (M☉)
100
10
1
0.1
Stellar corpse mass (M☉)
10
3
1
Main sequence stars
Supergiants
Supernovas
Black holes
Neutron stars
Giants
Helium flash
AGB stars
Planetary nebulae
White dwarfs
Time

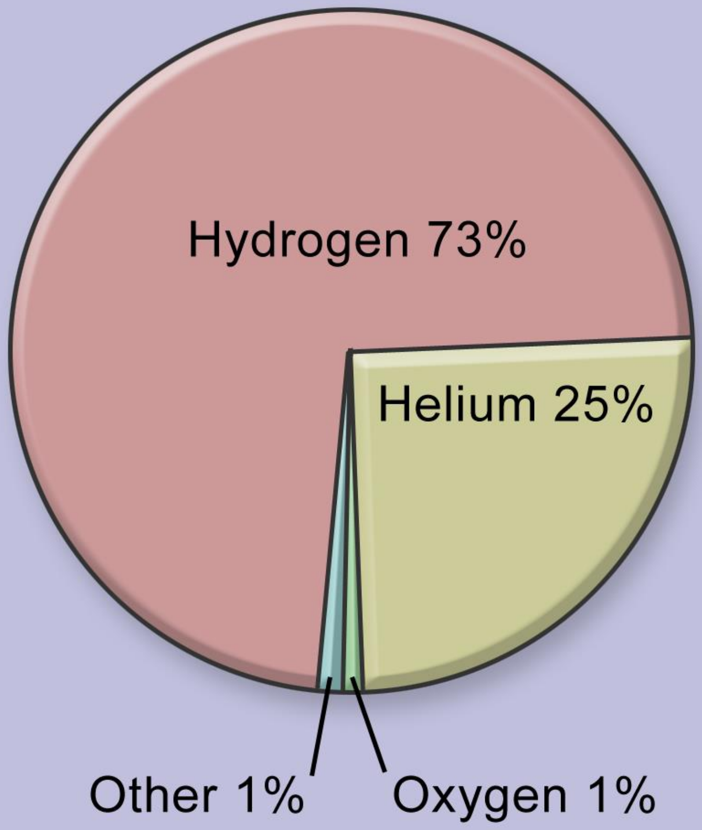
An updated version of H0-Ω diagram of Gott, Gunn, Schramm, and Tinsley (32) showing that Ωb does not intersect ΩVISIBLE for any value of H0 and that ΩTOTAL > 0.1, so nonbaryonic dark matter also is needed (33).



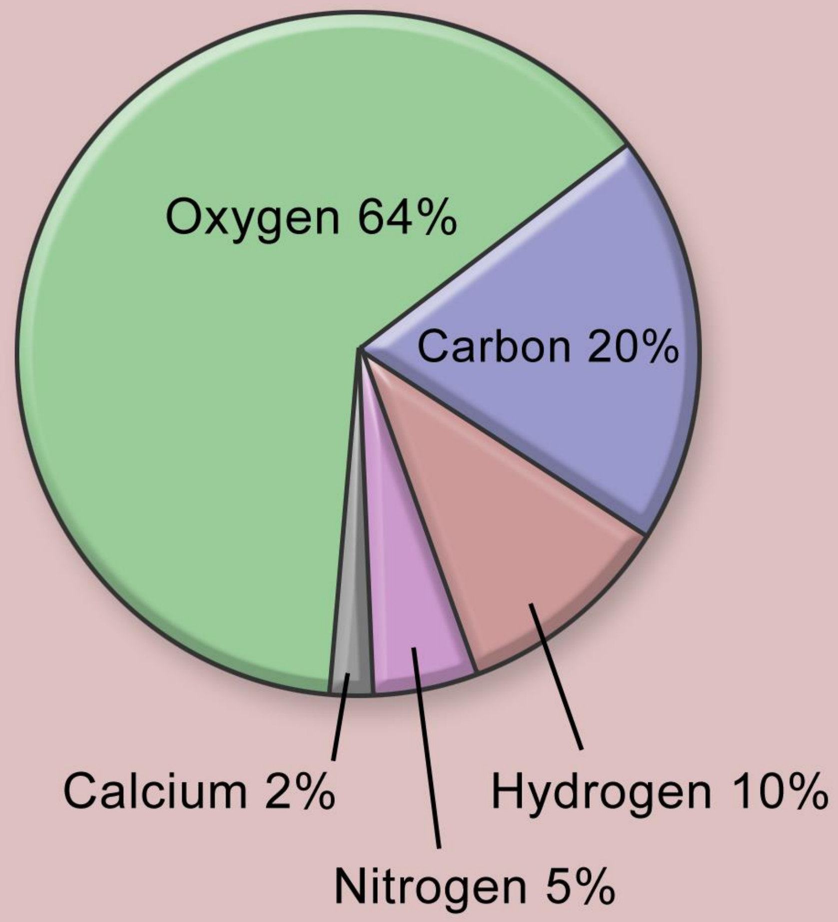
Schramm D N PNAS 1998;95:42-46

RELATIVE ABUNDANCE BY WEIGHT

Universe



Humans

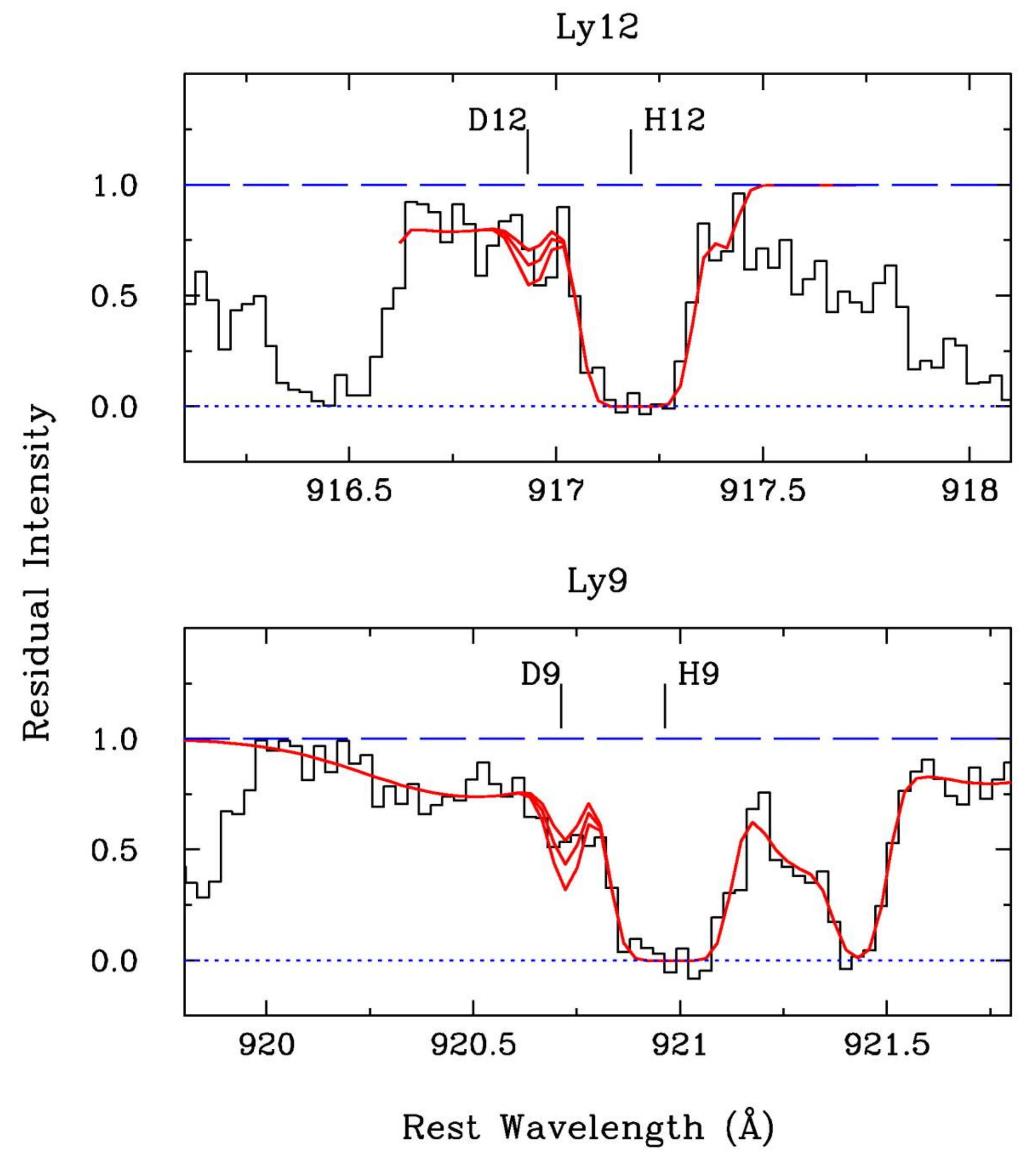


$(D/H)_P \sim 3\ 10^{-5}$

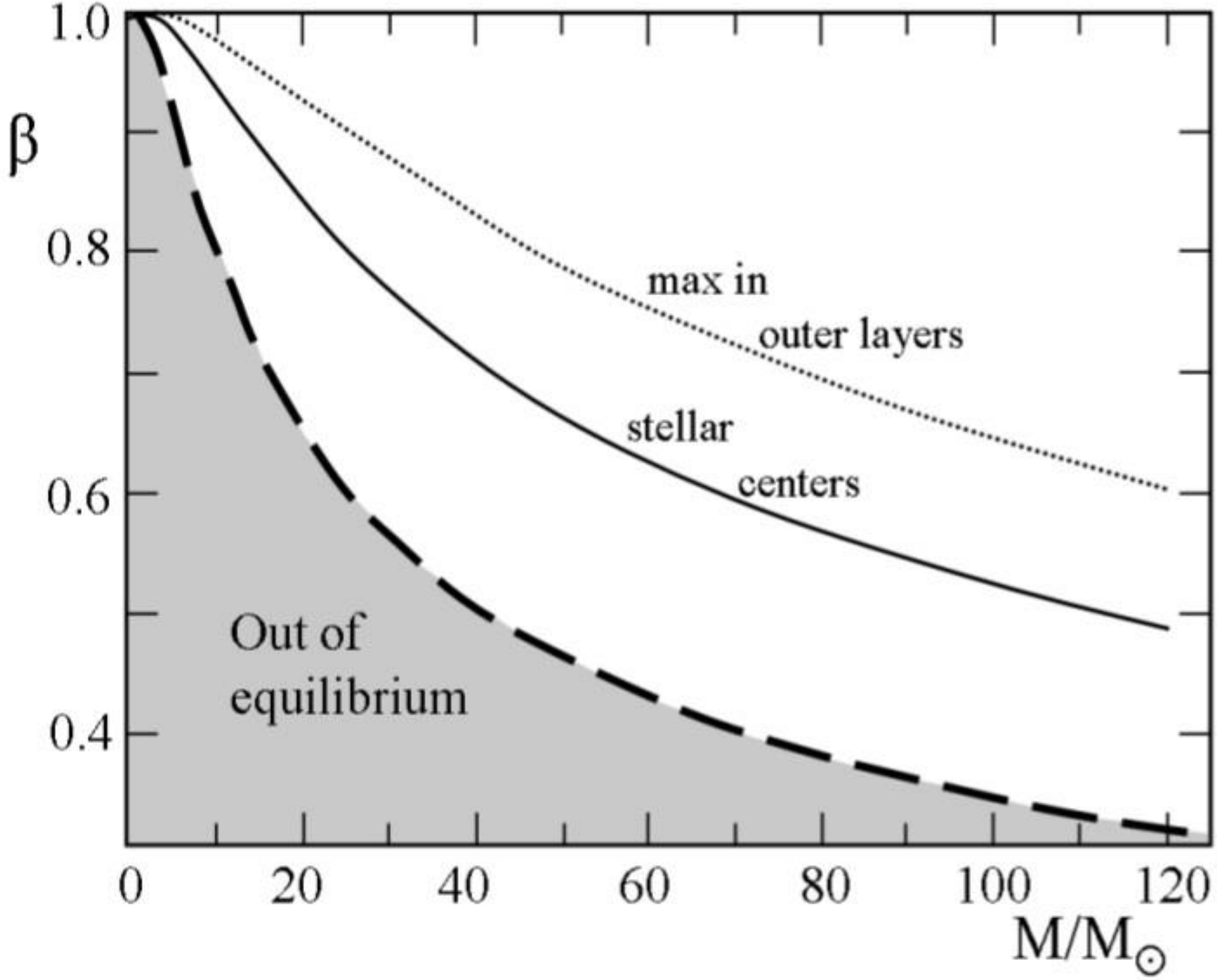
$\Omega_B h^2 = 0.020$

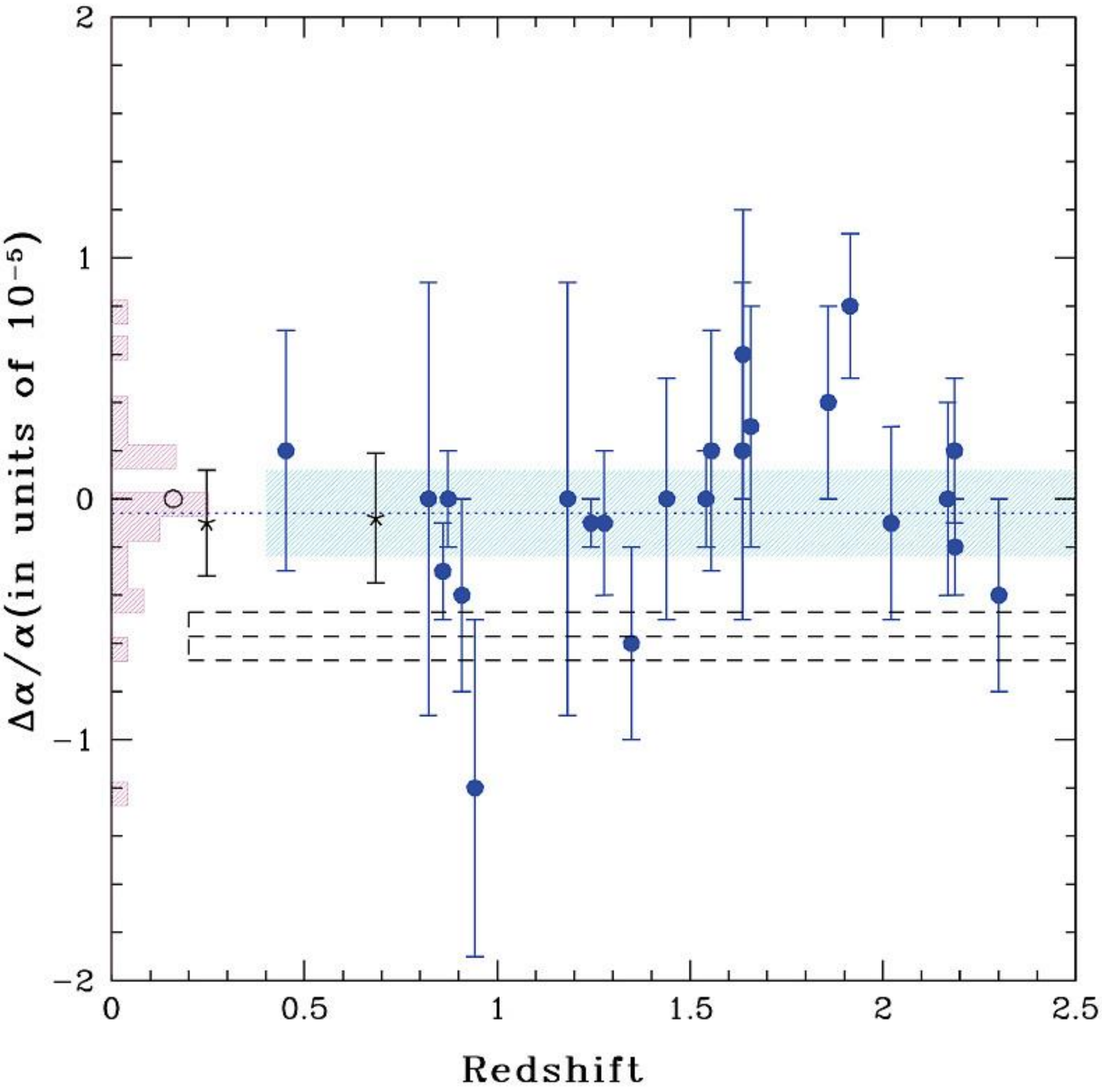
$\Omega_B \sim 0.04$

Steigman 2002



Pettini and Bowen 2001


β
1.0
0.8
0.6
0.4
0
20
40
60
80
100
120
$M/M_\odot$
max in
outer layers
stellar
centers
Out of
equilibrium



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TWO RECENT BOOKS

Physics, Formation and Evolution of Rotating Stars, Maeder, A&A Library, Springer 2009

Stars and Stellar Evolution, K.S. de Boer & W. Seggewiss, EDP Sciences, 2008

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From stars to nuclei, Meynet 2008, The European Physical Journal Special Topics, Volume 156, Issue 1, pp.257-263