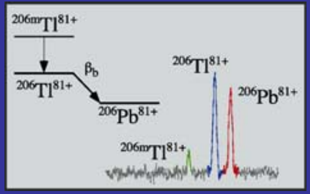
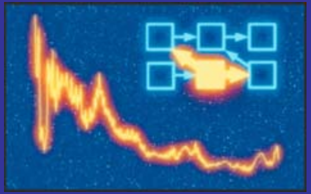
Are nuclear cosmic "clocks" reliable?

What happened at the early solar system?

Fritz Bosch, GSI Helmholtzzentrum





1. The "new cosmology"

2. Stellar and nuclear cosmic clocks

3. The ^{187}Rhenium/^{187}Osmium nuclear cosmic clock and its dependence on the atomic charge state

4. The s-process nuclear clock ^{205}Pb and the early solar system

The past and the fate of our Universe

Two hints on a "birth" of the Universe

→ The cosmic expansion: **Redshift** proportional to distance

→ The **3K** Cosmic Microwave Background (CMB) from decoupling of matter and radiation

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team
STScI-PRC04-07a

Honey, how old is the Universe ?

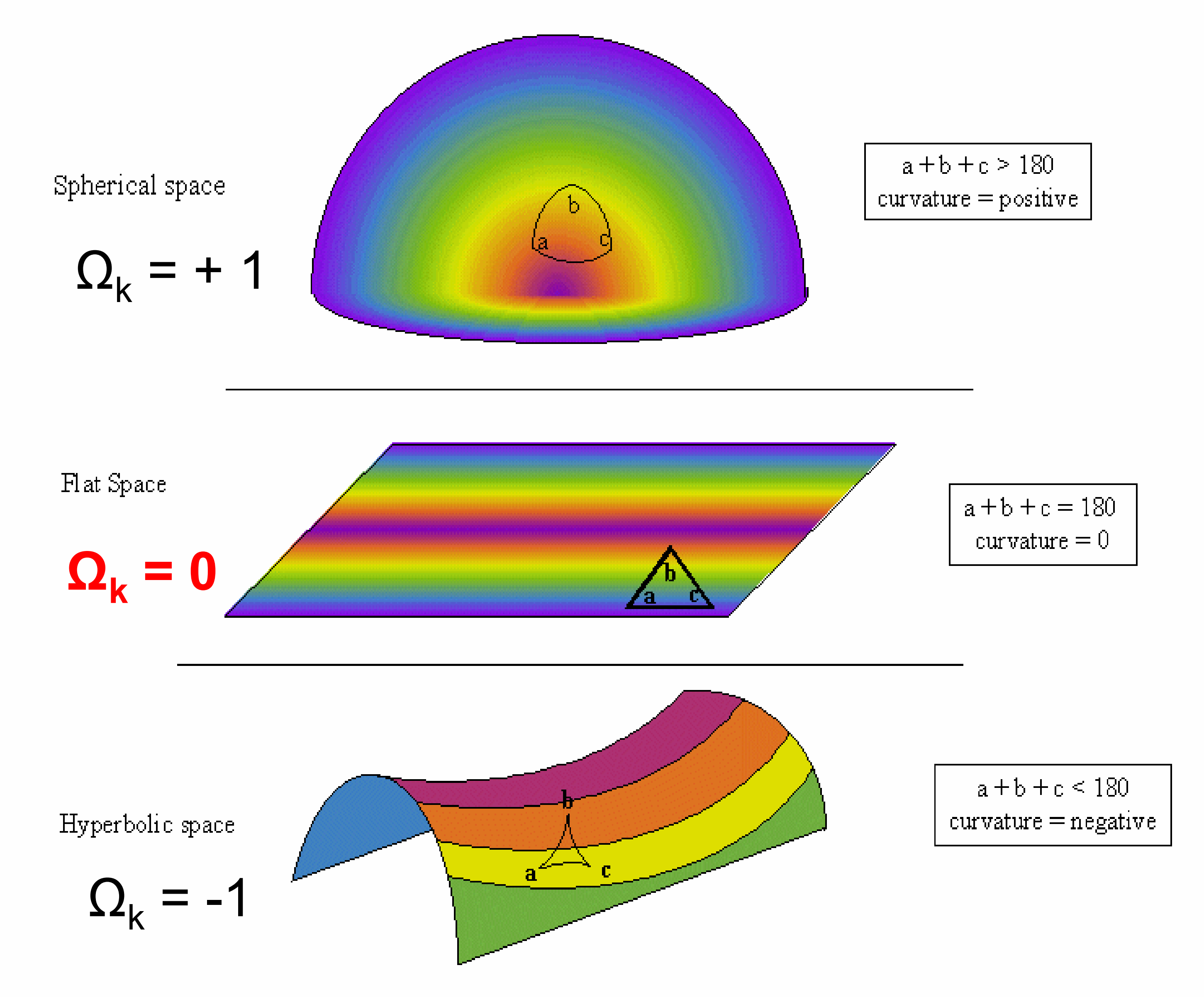
..I do'nt know, honey

Oh! It sounds strange – I think you're a physicist ??

That's true – but I had neither help nor money for looking to the secrets of the Universe...

My thanks are to the ESR accelerator crew, the Atomic Physics and (former) KPII division and to all other colleagues for their invaluable support

Only **three geometries possible** if the Universe is homogeneous and isotropic ("cosmological principle")



$\Omega_k = +1$

$a + b + c > 180$
curvature = positive

$\Omega_k = 0$

$a + b + c = 180$
curvature = 0

$\Omega_k = -1$

$a + b + c < 180$
curvature = negative

A homogeneous and isotropic Universe is described by the

Friedmann-Lemaitre equation(s)

from Einsteins field equation: $R_{\mu\nu} - 1/2\, g_{\mu\nu} R\, (-\Lambda\, g_{\mu\nu}) = - 8\pi\, T_{\mu\nu}$

$$(da/dt)^2 = H_0^2\, [1 + \Omega_m\, (1/a - 1) + \Omega_\Lambda\, (a^2 - 1)]$$

Relative "size" **$a(t)$** = $R(t) / R_0$= **$(1+z)^{-1}$** vs. time t

H_0 = today's Hubble constant; **z** = redshift = $\Delta\lambda / \lambda_0 = 1/a(t) - 1$

Ω_m = mass density; **Ω_Λ**= "cosmological constant"; $\Omega_m + \Omega_\Lambda + \Omega_k = 1$

Today ($a = 1$, $t = T_U$) : $da/dt =$ **$+ H_0$**

Future ($t > T_U$, $a > 1$) dominated by **Ω_m** for $\Omega_\Lambda = 0$
or by the **sign (+-) of Ω_Λ** for $\Omega_\Lambda \neq 0$

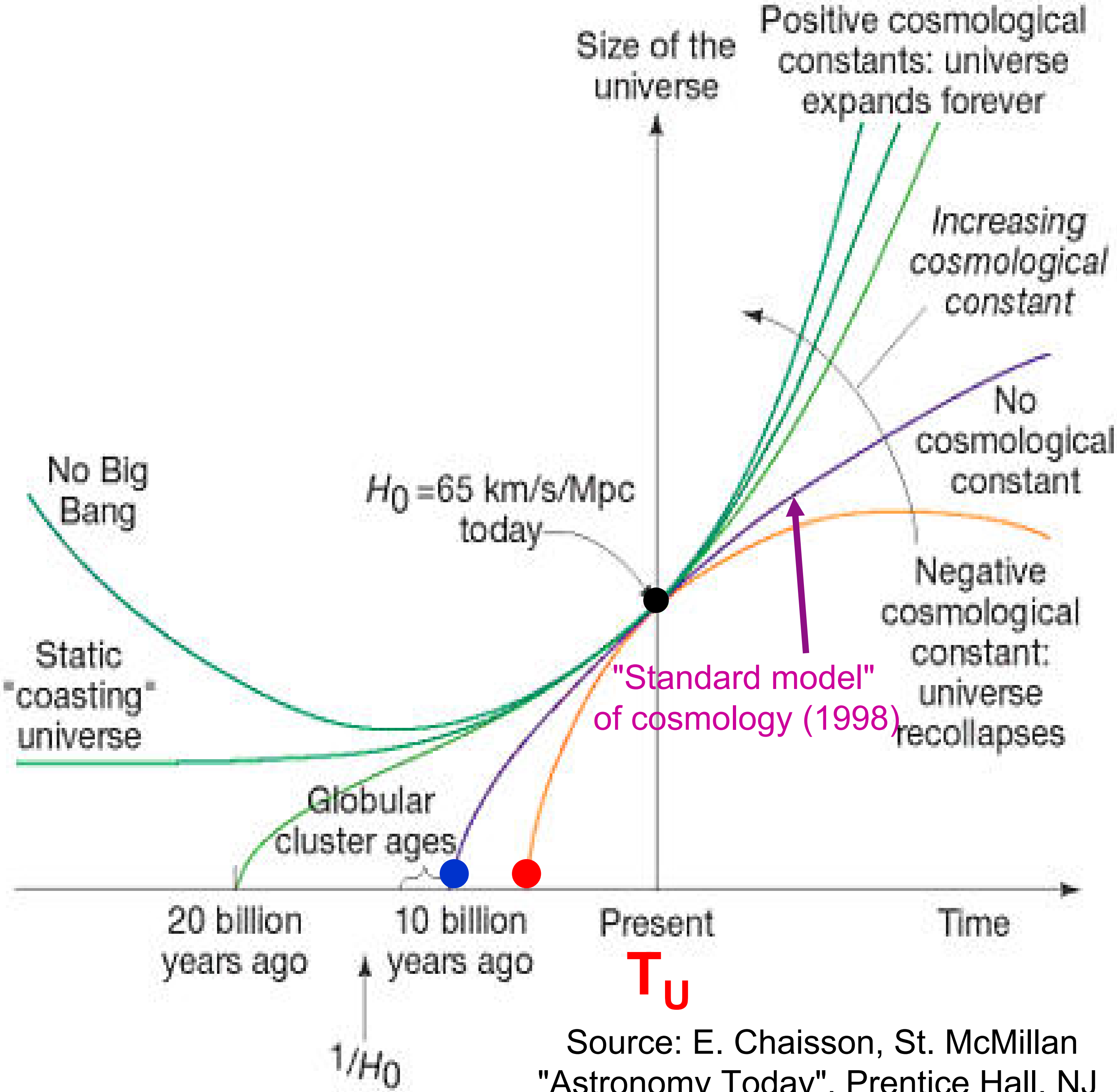
→ Data for Ω_m, **H_0**, **H ($a < 1$)**, lower and upper limit for **T_U** needed

"Standard model" of cosmology "valid" until 1998

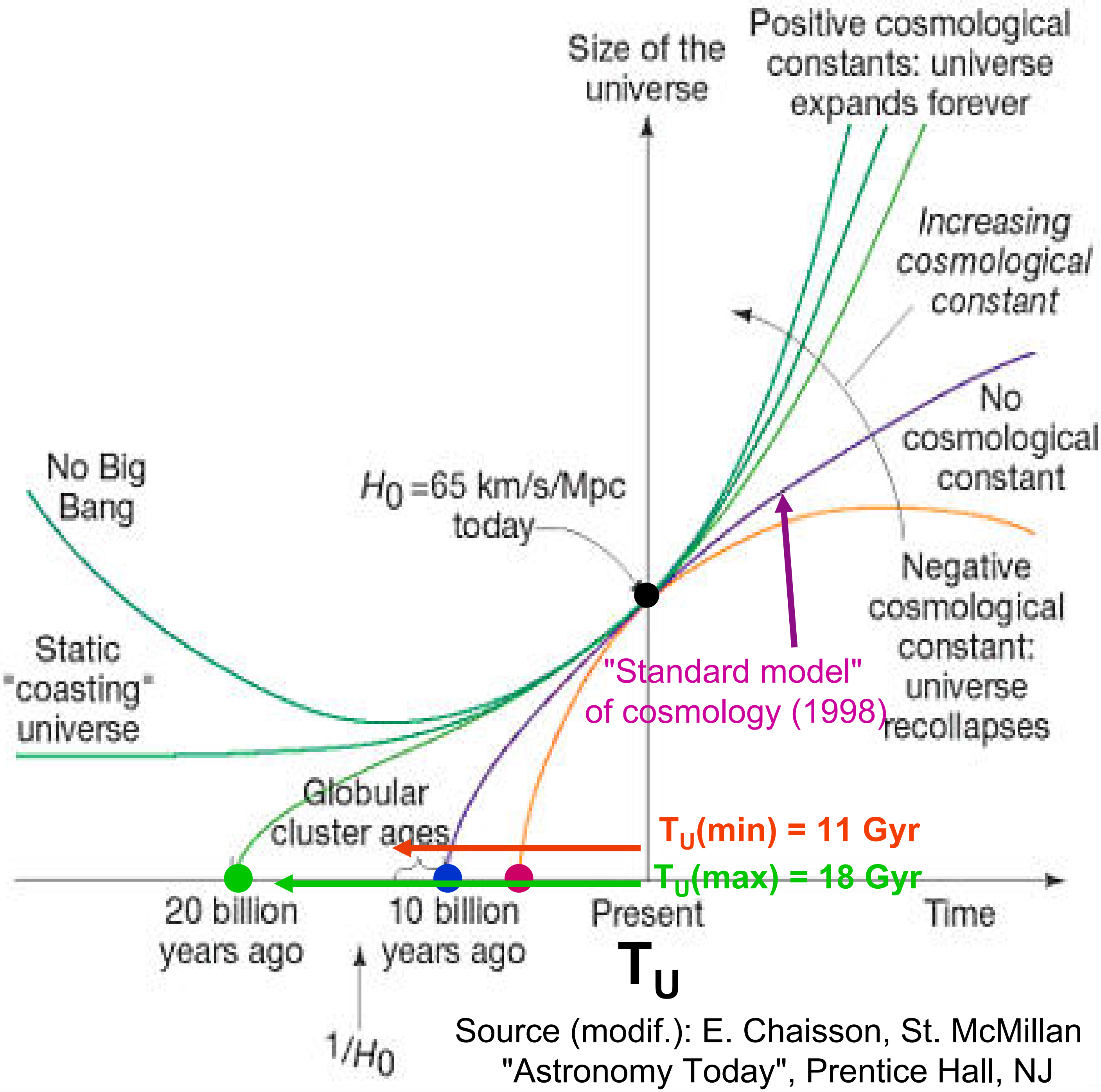
1. "Critical" mass density: $\Omega_m = 1$
2. No cosmological constant: $\Omega_\Lambda = 0$
3. Euclidian (flat) Universe: $\Omega_k = 0$ (follows from "inflation")

$$\rightarrow (da/dt)^2 = H_0^2 \; 1/a \rightarrow \int^{1} a^{1/2} \, da = H_0 \int^{T_U} dt$$

- → Age of the universe: $T_U = 2/3 \cdot 1/H_0$
- for $H_0 = 72$ (7) km /s/ Mpc [1994] → $T_U = 9$ (1) · 10^9 yr



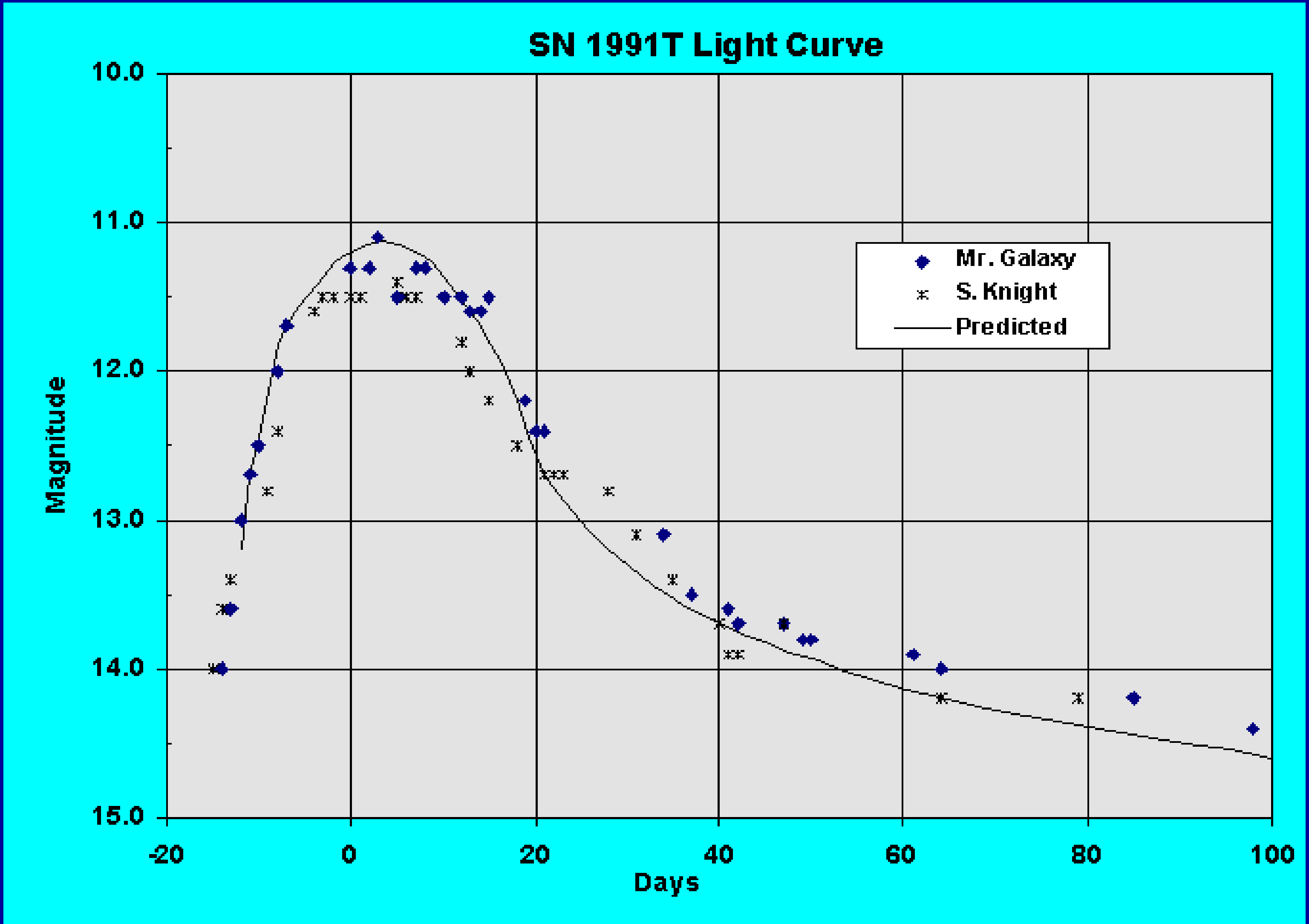
Source: E. Chaisson, St. McMillan "Astronomy Today", Prentice Hall, NJ



Source (modif.): E. Chaisson, St. McMillan "Astronomy Today", Prentice Hall, NJ

1. The new cosmology from 1998

Detection of "standard chandles" **Supernovae Ia** (Perlmutter, Leibundgut)
at a **redshift z = 0.5**; since z = 1/a - 1→ **a = 2/3**

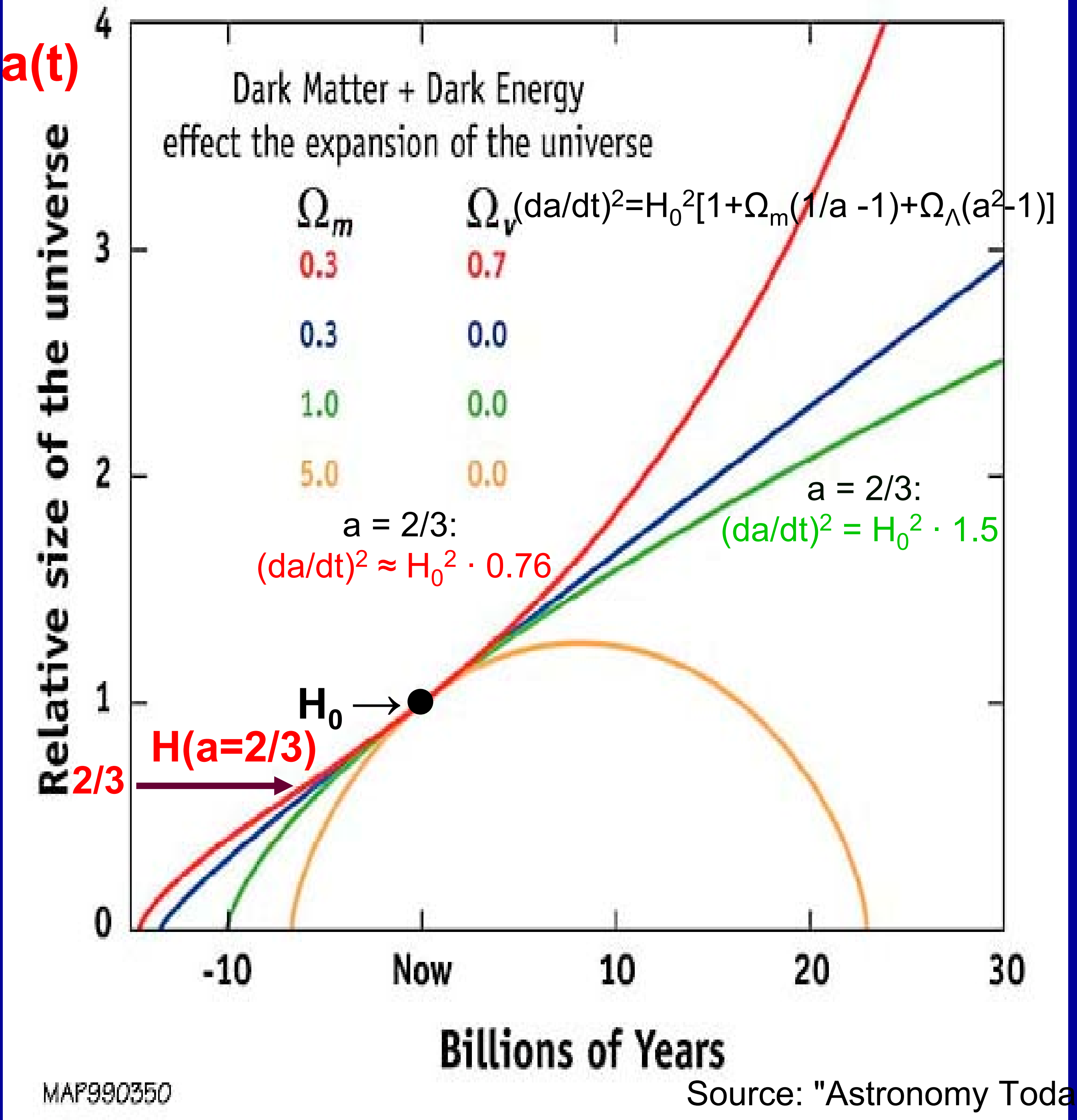


Die Augen der Unendlichkeit

Keck I/II of Caltech on the
Mauna Kea, Hawaii:
Twin (10 meter) mirrors

Very Large Telescope of ESO on the
Cerro Paranál, Chile:
Four connected 8.2 meter mirrors

Source: homepages ESO, CALTECH

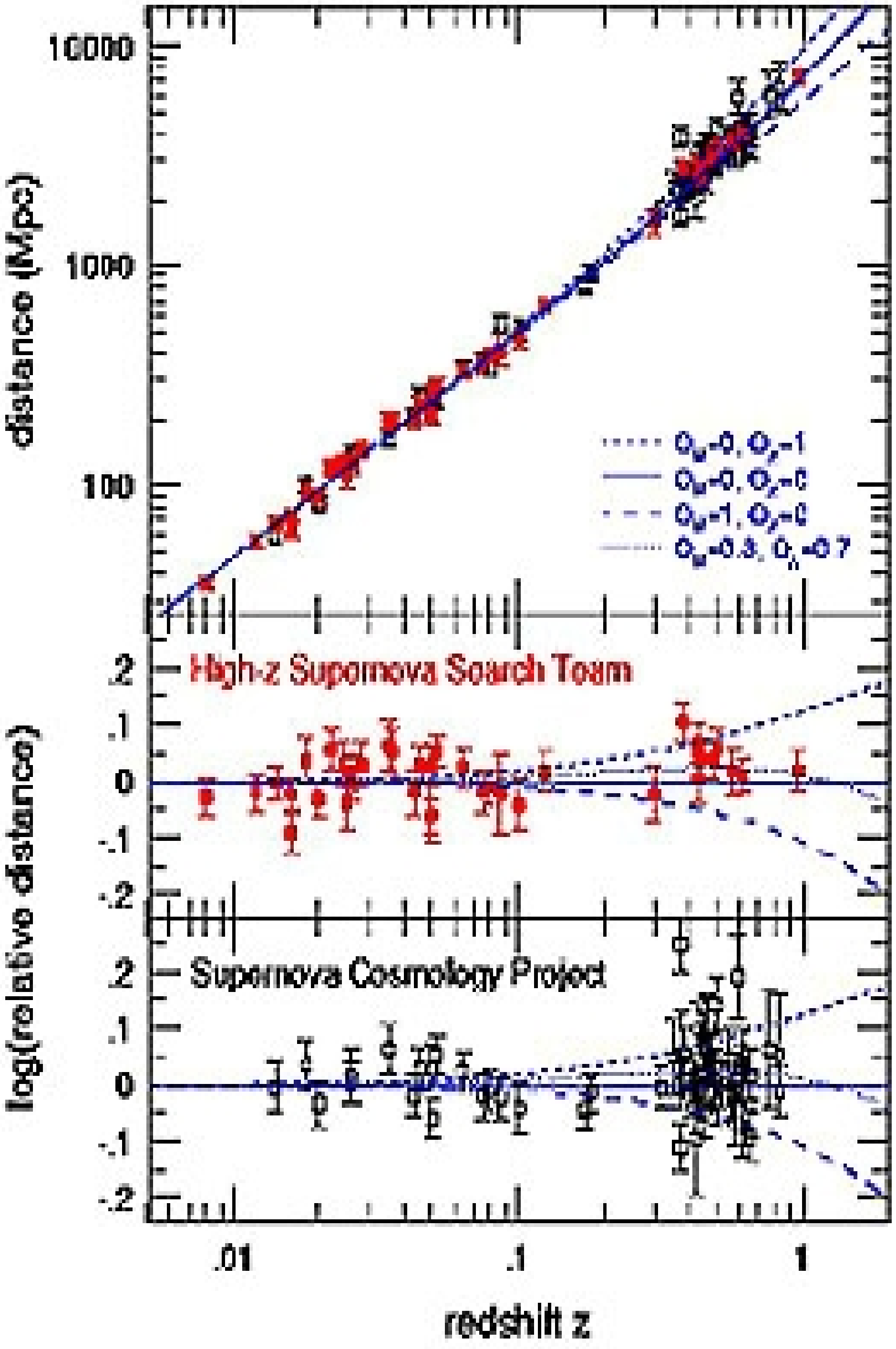


$(da/dt)^2=H_0^2[1+\Omega_m(1/a -1)+\Omega_\Lambda(a^2-1)]$

a = 2/3: $(da/dt)^2 \approx H_0^2 \cdot 0.76$

a = 2/3: $(da/dt)^2 = H_0^2 \cdot 1.5$

Source: "Astronomy Today"



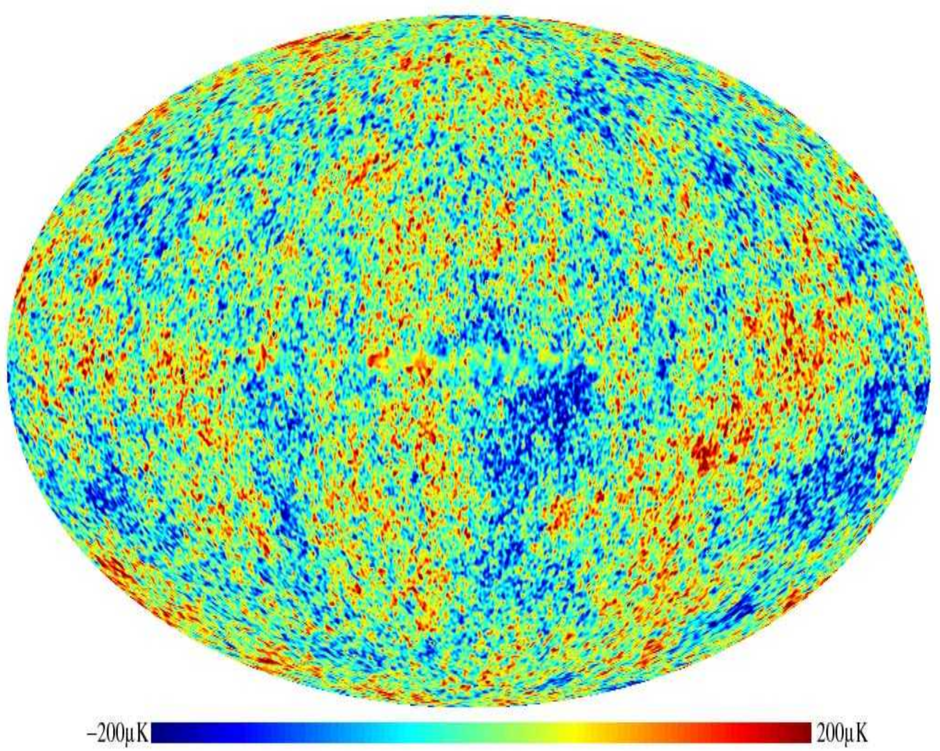
Hubble constant **H(a =2/3) smaller than expected** by a factor of ≈ √2

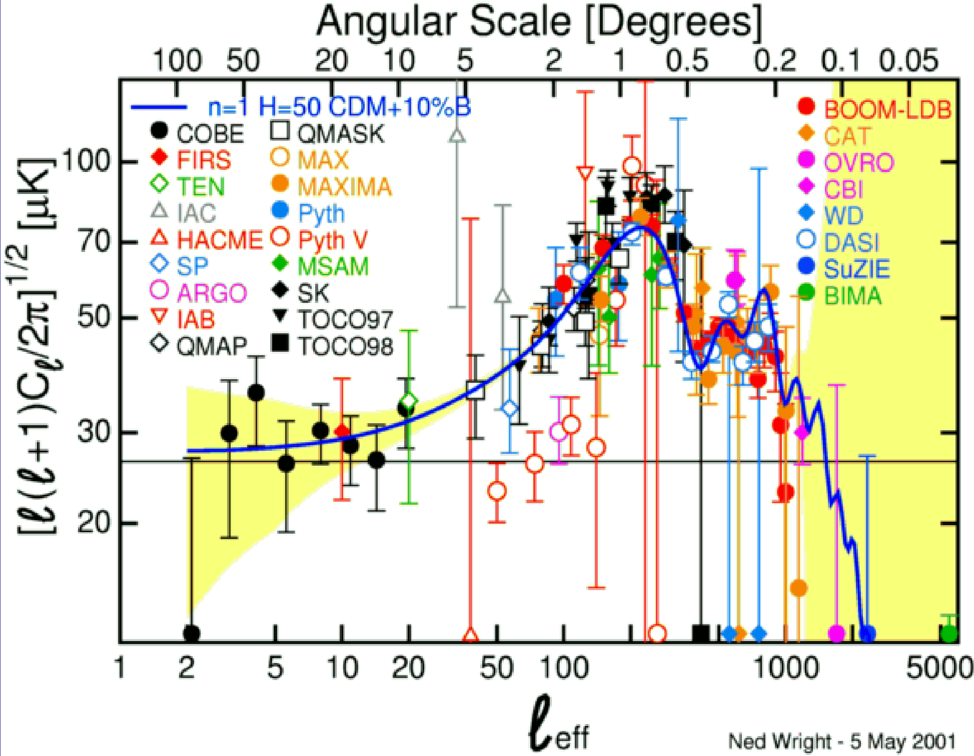
Perlmutter, Leibundgut 1998
Ap. J. **517** (1999) 565

→ There is an $\boldsymbol{\Omega_\Lambda \approx +0.7}$
the Universe expands forever
faster and faster,
due to this puzzling
"cosmological constant"
("dark energy")

Source: Ap. J. **517** (1999) 569

From the autocorrelation of the 3K Cosmic Microwave Background (CMB) → Universe is flat ($\Omega_k = 0$)



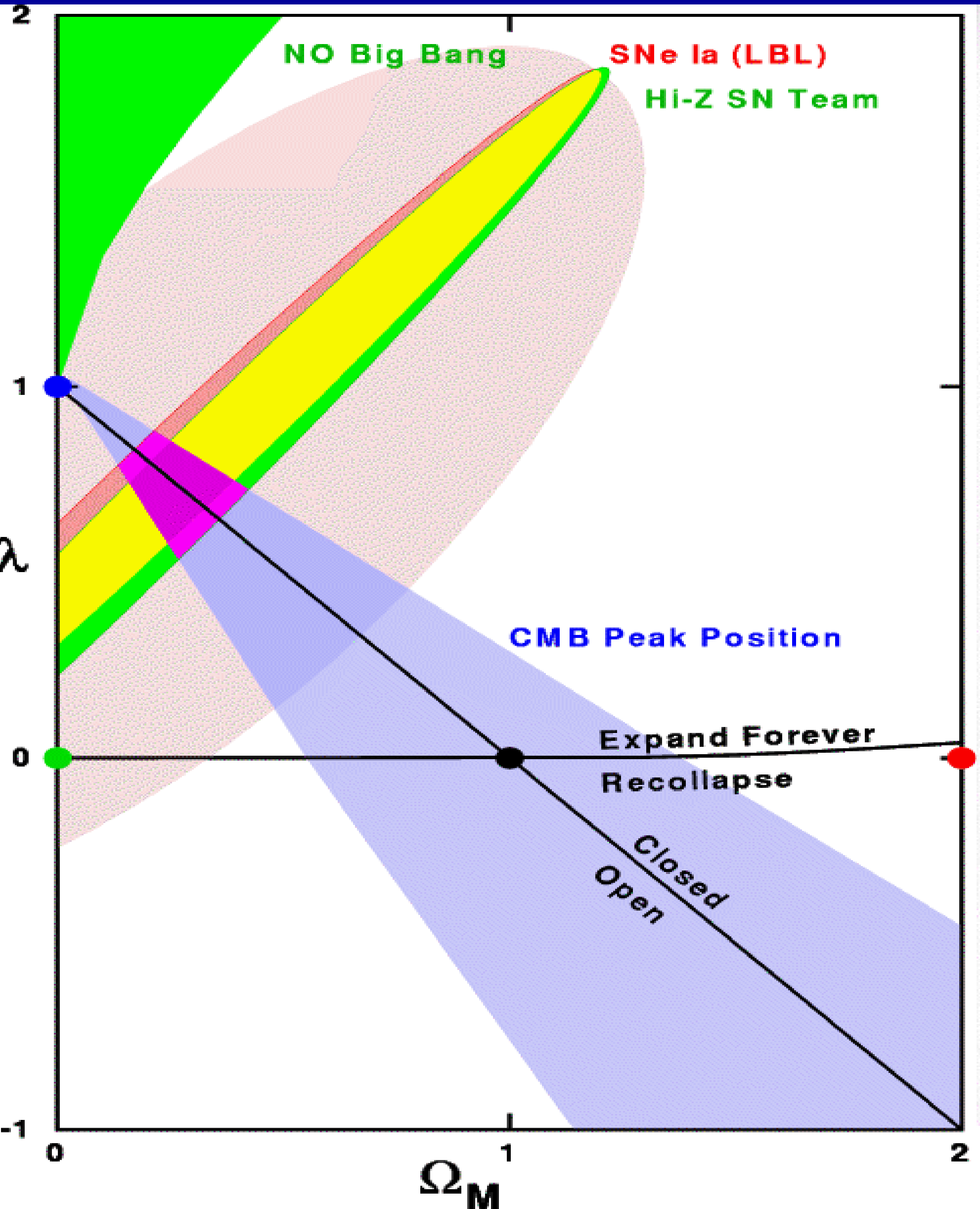


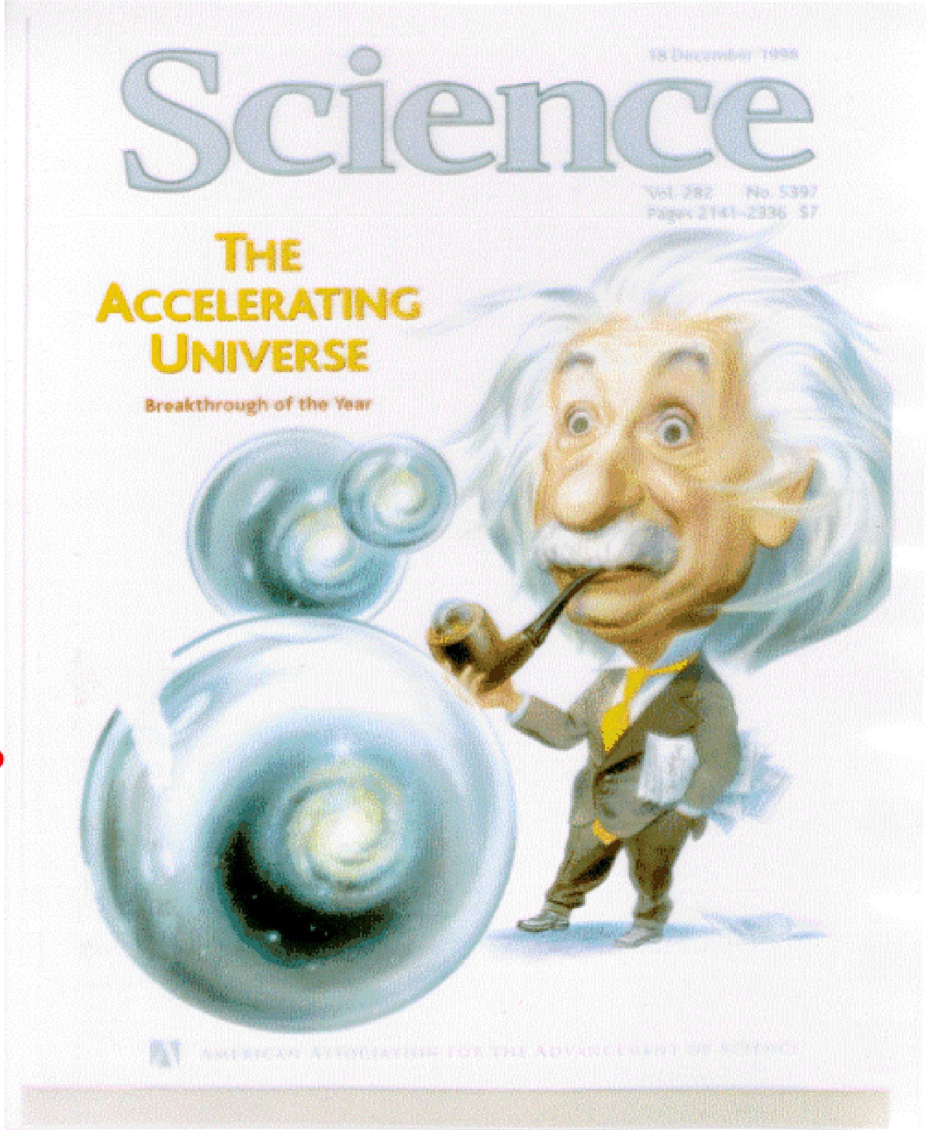
3K CMB from decoupling of matter and radiation, 300 000 yr after BB

Small-angle autocorrelation of 3K CMB (WMAP)

Source: WMAP, homepage

The inauguration of the new cosmology in 1998





Source: Science, December 18, 1998

Is the "new cosmology" already confirmed ?

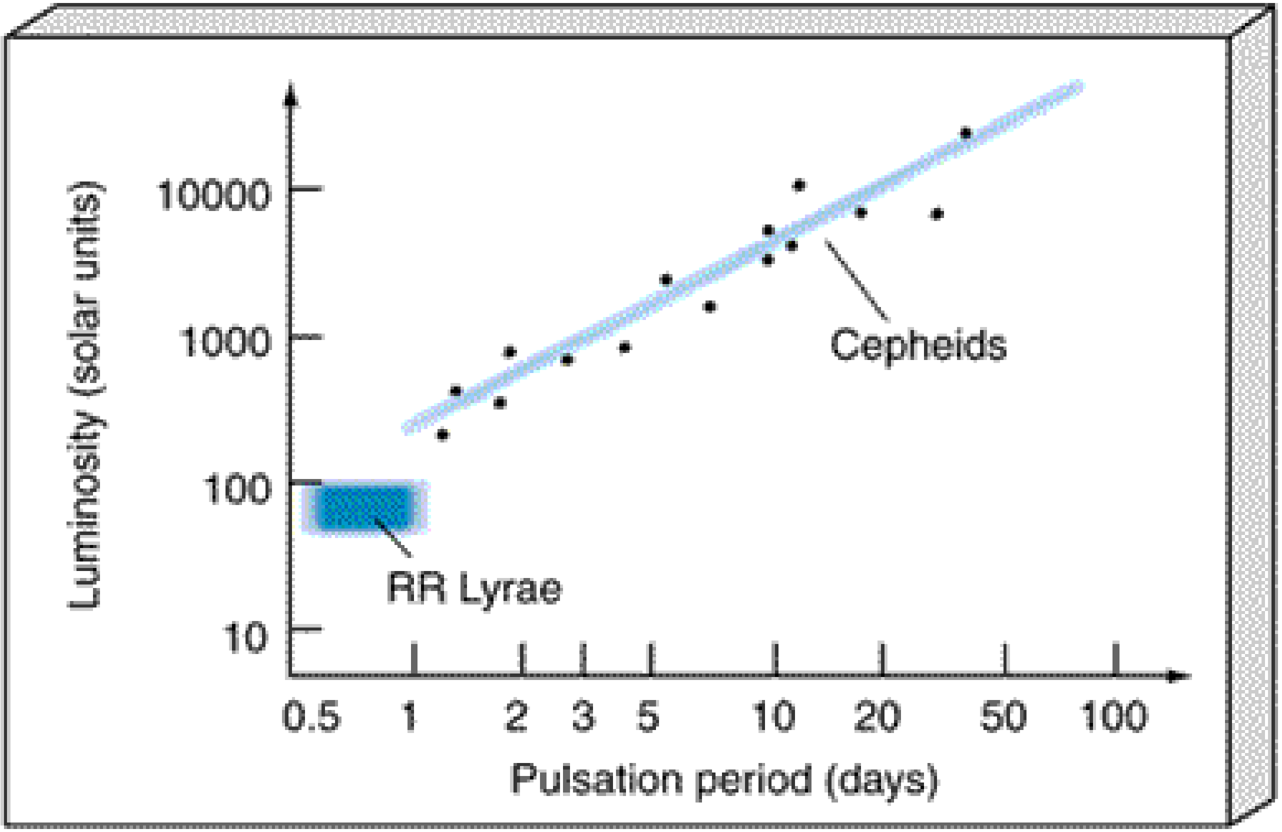
- Are the **old** (**- 4 · 10^9 yr**) Supernovae Ia calibrated chandles ?
- Is the **absorption** on the long way to us really understood ?
- Are there any other hints on an **$\Omega_\Lambda > 0$**, or "dark energy" ?

→ Independent constraints for Ω_m, Ω_Λ, **$H(a)$** and **T_U** are mandatory

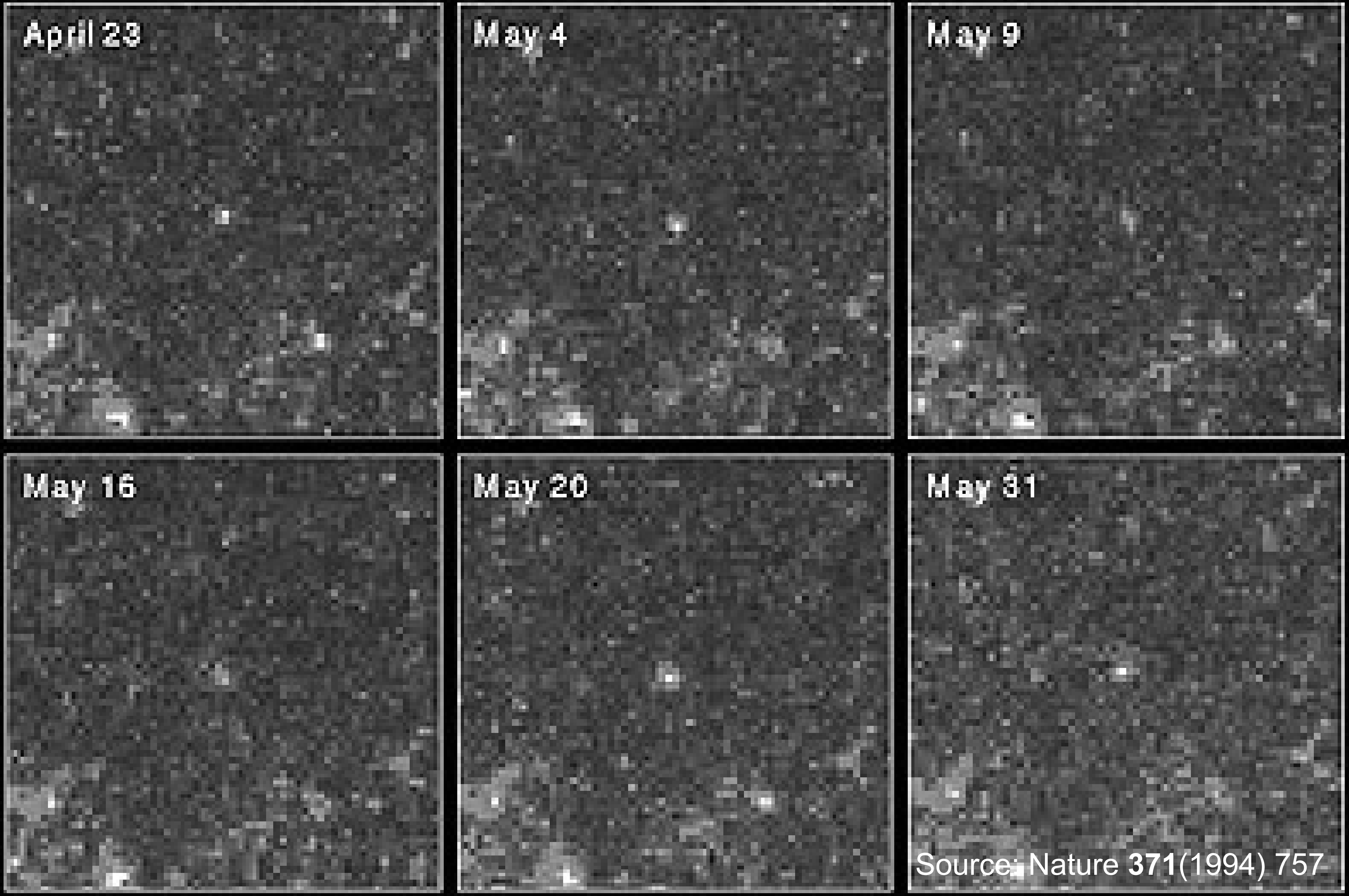
Henrietta Leavitt detects in 1908 new calibration chandels for large distances (many Megaparsec), the **δ Cepheids**: Pulsation period proportional to absolute luminosity

After 70 years of Hubble-war (Sandage vs.de Vaucouleurs) this problem is now solved by the "Hubble key project" (W.L. Freedman and coworkers 1994-2000)

Henrietta Leavitt 1910
Harvard Smithonian



Cepheid Variable Star in Galaxy M100 1994 HST•WFPC2



Source: Nature **371**(1994) 757

H_0 = 72(7) km/s/Megaparsec (Mpc)

W.L. Freedman et al., Nature **371** (1994) 757

M100 in the Virgo cluster

From the **period** of the δ Cepheids
→ **distance** = 15 Mpc

From the **redshift**
→ **expansion velocity**
= 1080 km/s

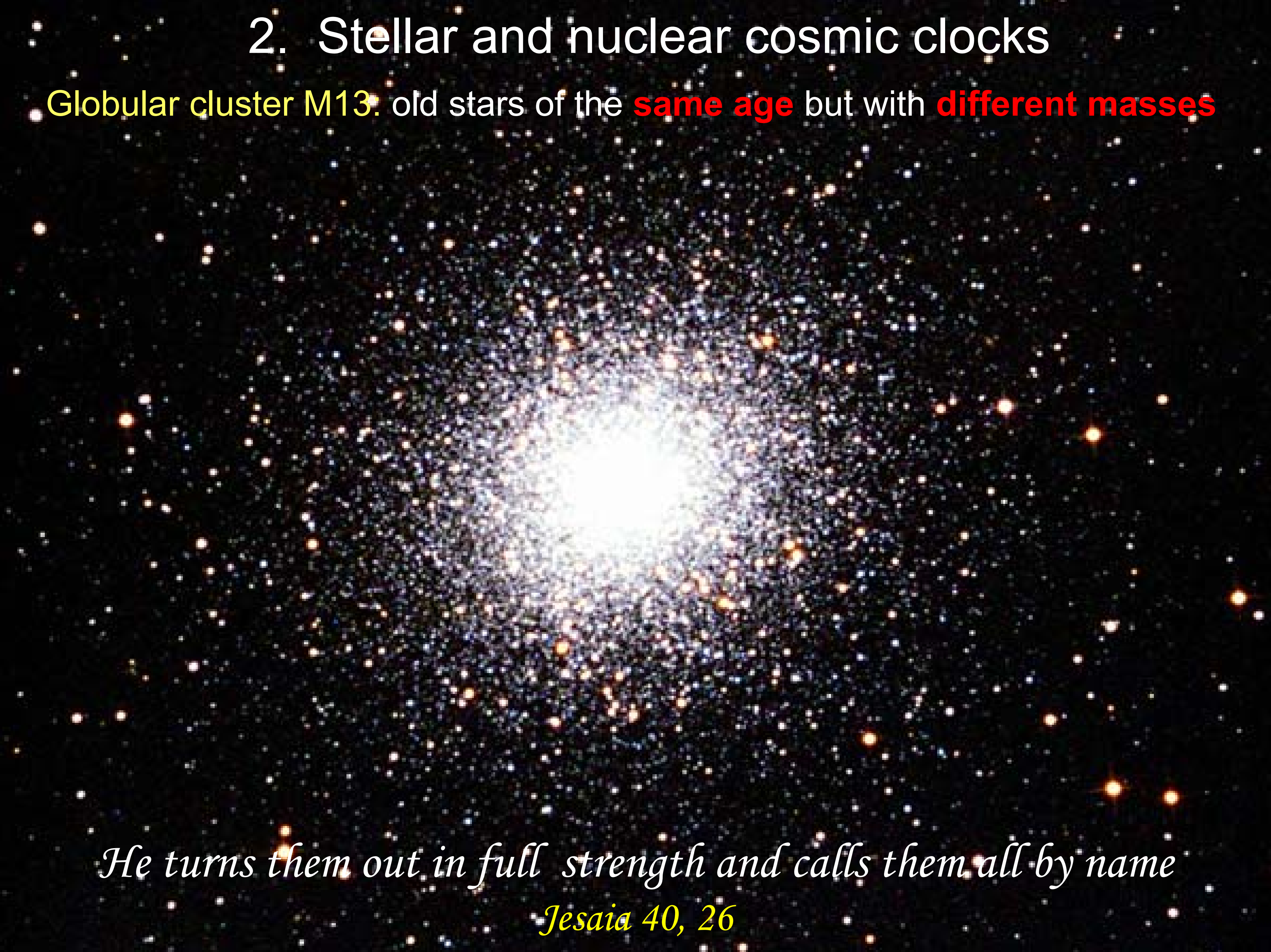
→ H_0 = 1080 km/s/15 Mpc

$1/H_0$ = 'age' **T_U** of the Universe
for constant expansion

→ $T_U = 13.5 \cdot 10^9$ yr

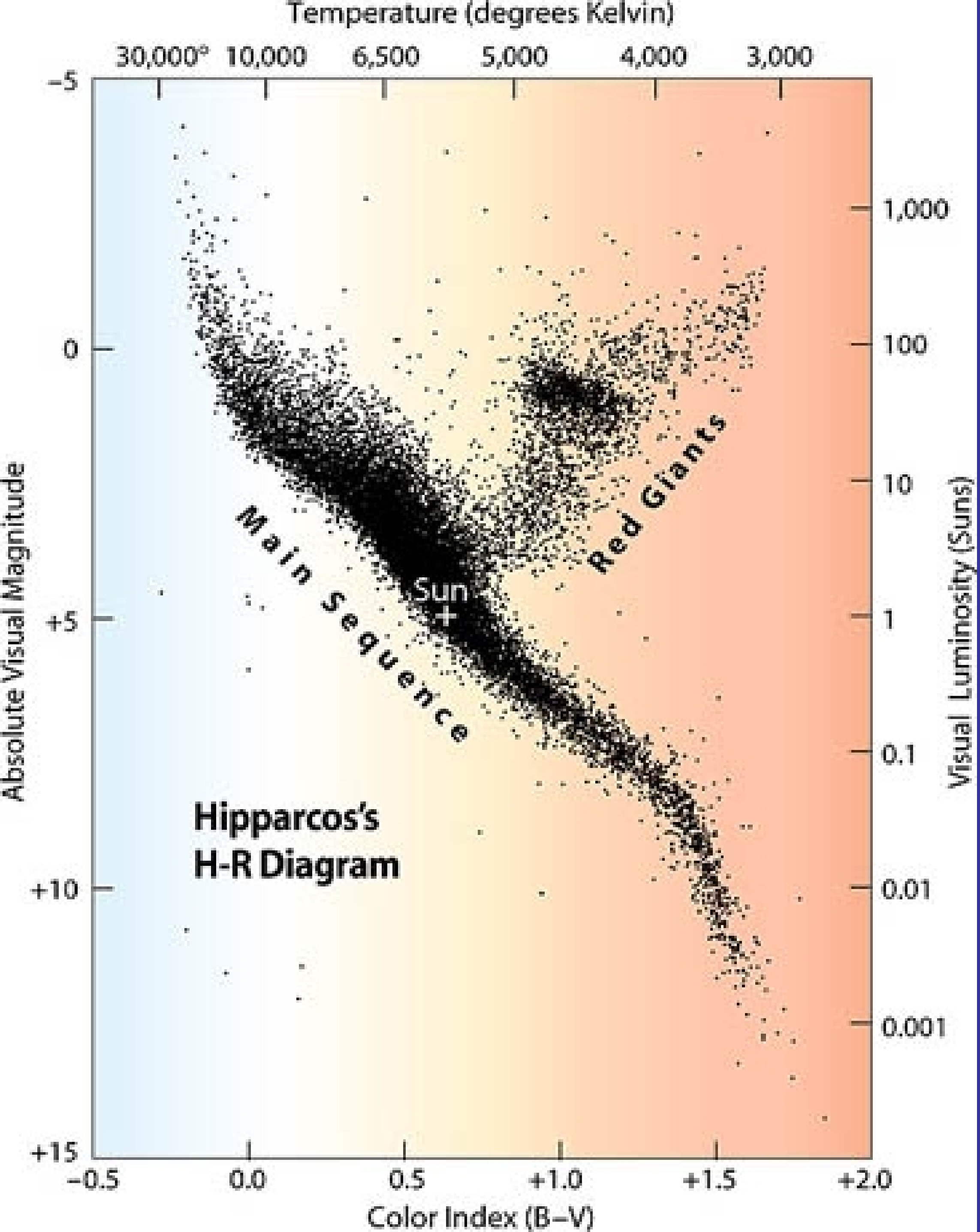
2. Stellar and nuclear cosmic clocks

Globular cluster M13: old stars of the **same age** but with **different masses**



He turns them out in full strength and calls them all by name

Jesaia 40, 26



'Hertzsprung-Russell-diagram' of all stars up to a distance of **300 parsec (975 light years) taken by Hipparcos (1995)**

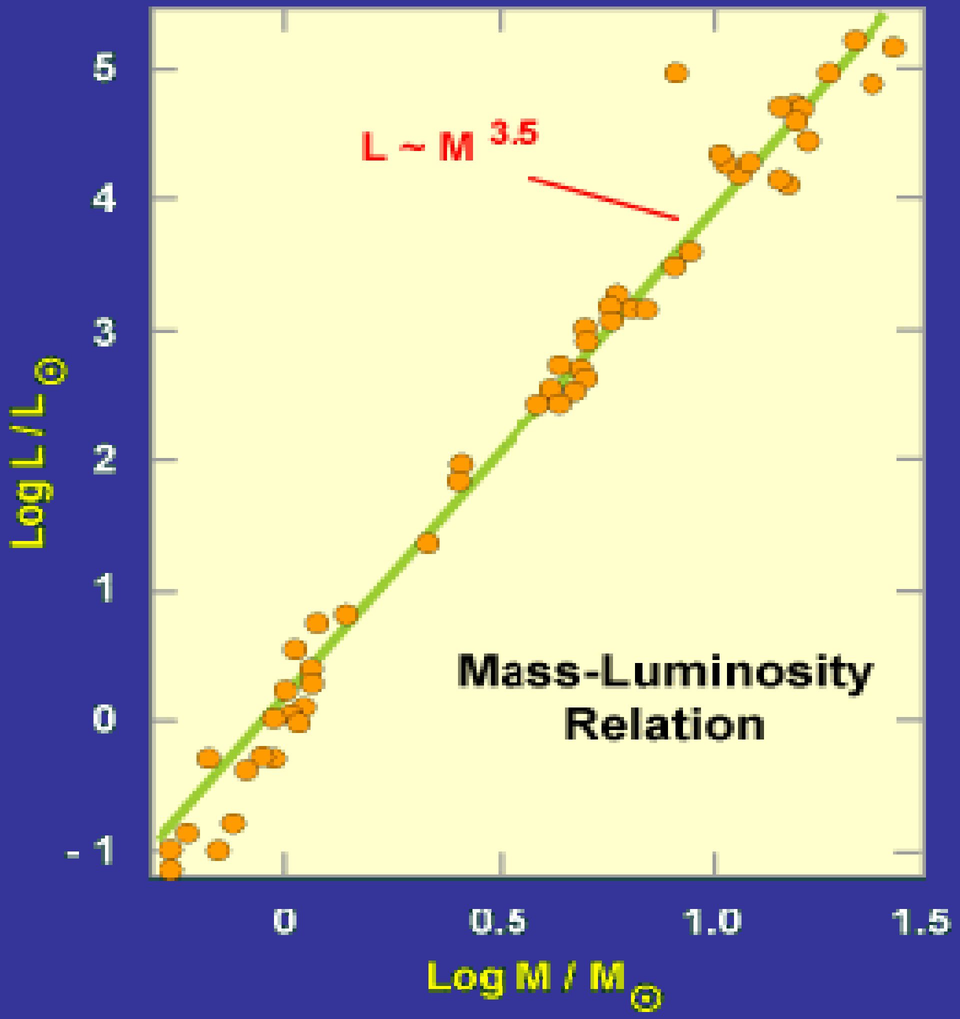
Absolute luminosity versus temperature

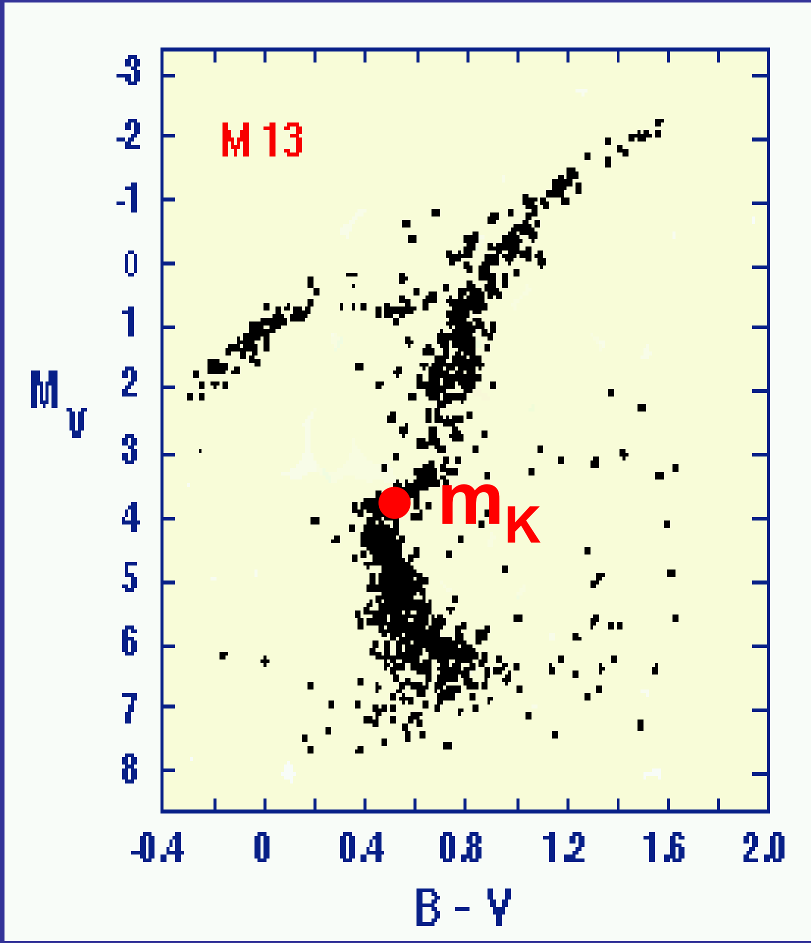
The stars are stationary on the **'Main Sequence' during** the fusion of protons to helium

This time depends very sensitively on the **mass** of the individual stars

Source: homepage Hipparcos

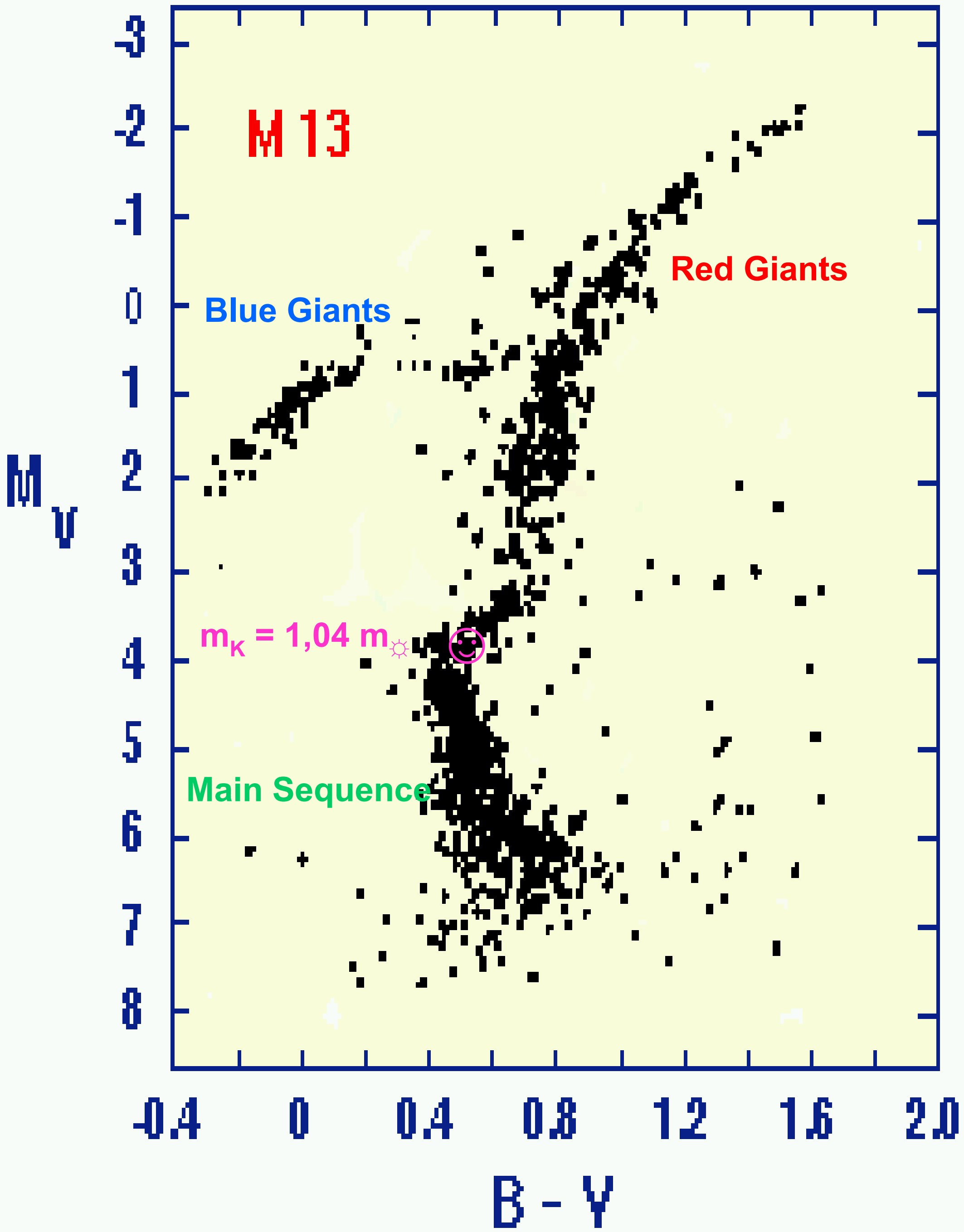
Age of GC from 'kink' at Main Sequence





Stay on the Main Sequence: $\tau_{MS} = M/L \propto M^{-2.5}$

$\tau_{GC}/\tau_{\odot} = [M_{\odot}/M_{GC}]^{2.5}$



For our **Sun** this time is calculated as $\tau_{¤} = \mathbf{9.4 \cdot 10^9}$ **yr**, for lighter stars longer, for heavier ones shorter:

$$\tau_{HR} = 9.4 \cdot 10^9 \text{ yr } (m_☼/m)^{2,5}$$

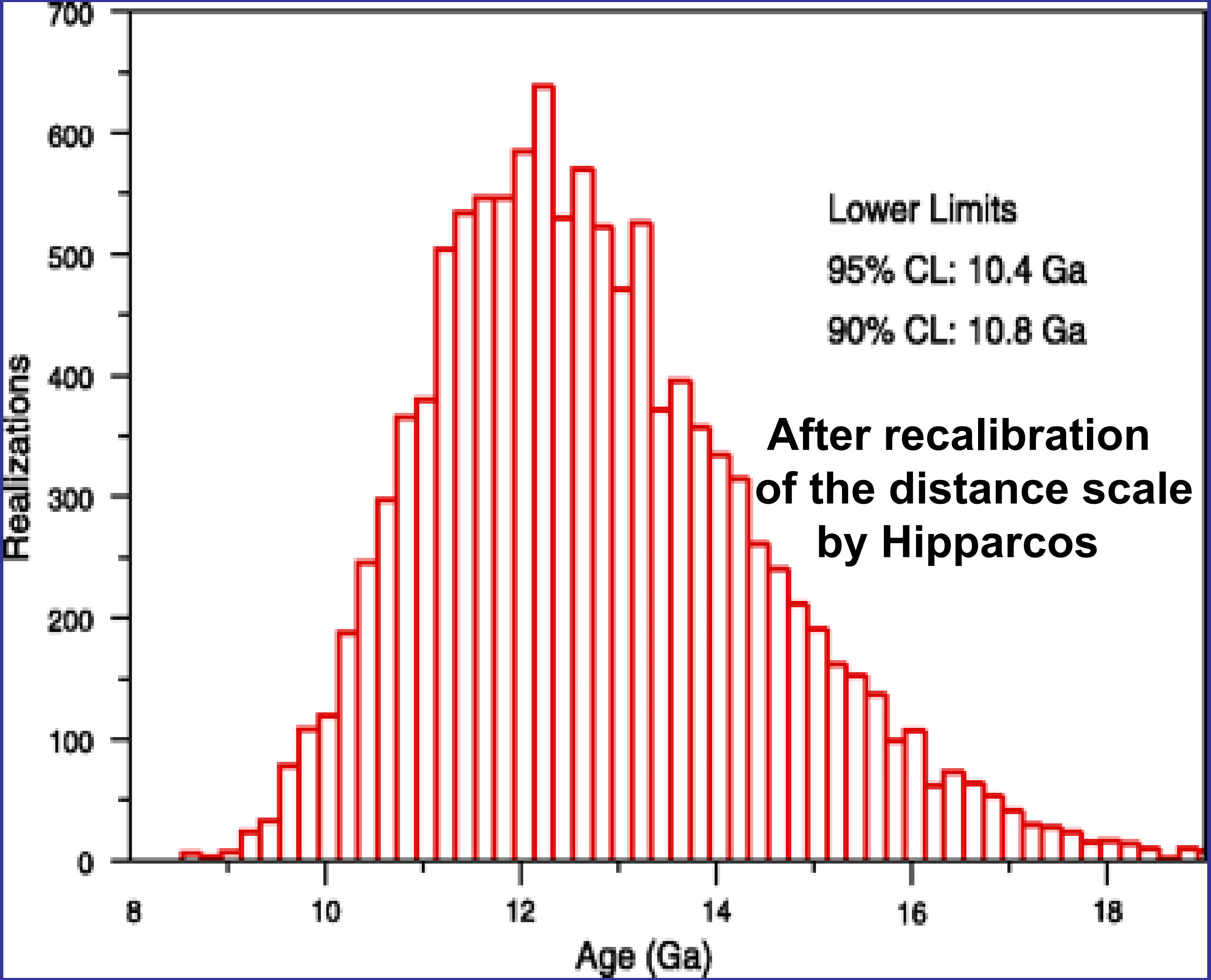
Observing **at which mass m_K the stars of M13 are leaving the main sequence**

One can determine **the age of M13** – and therewith a lower limit **for the age T_G of our galaxy**.

from **m_K = 1,04 $m_☼$**

→ T_G > 8 Gyr

Lower limit of the age T_G of our galaxy $\approx 11 \cdot 10^9$ yr



After recalibration of the distance scale by Hipparcos

B. Charboyer, L.M. Krauss, Science 299 (2003) 65


Die gibt's seit über 12 Milliarden Jahren ....

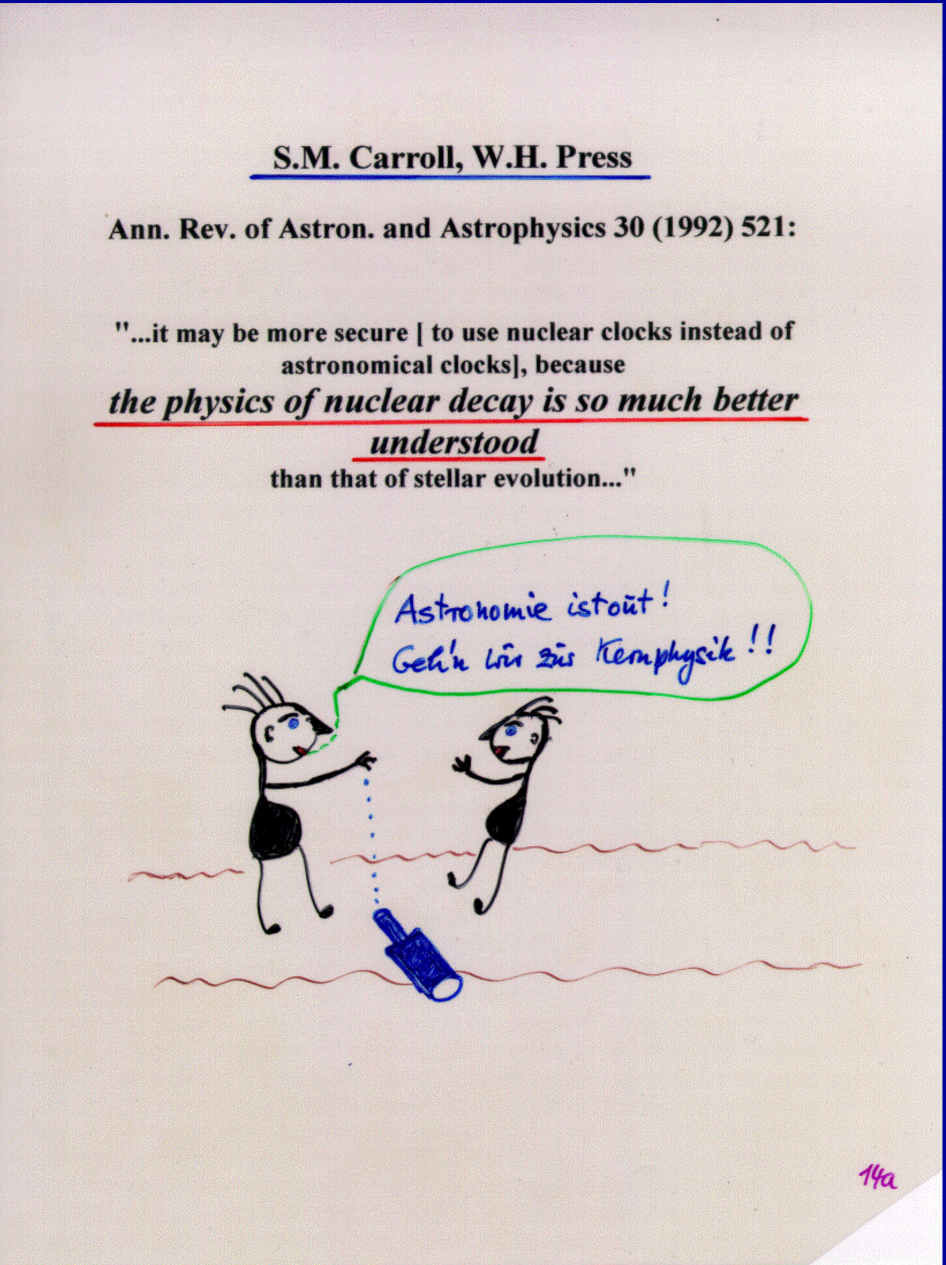
The reliability of the (lower) limit of ~**$11 \cdot 10^9$ yr**
for the age of our Milky Way galaxy depends on

How trustworthy is the chemical evolution model ?
of stars and, in particular, of our Sun, and

How precisely can the mass at the "kink"
be determined ? (distance problem of the HRD!)

→ Other chronometers are urgently needed with an
independent "clockwork"

Nuclear cosmic 'clocks'



S.M. Carroll, W.H. Press

Ann. Rev. of Astron. and Astrophysics 30 (1992) 521:

"...it may be more secure [to use nuclear clocks instead of astronomical clocks], because *the physics of nuclear decay is so much better understood* than that of stellar evolution..."

14a

1. Select a long-lived radioactive mother (m) / β-daughter (d) couple

2. **Determine N(m), N(d) at time t**

3. $N(m)\,(t) = N(m)\,(t_0)\exp[-\Lambda\,(t-t_0)]$
   $N(d)\,(t) = N(m)\,(t_0)\,[1 - \exp[-\Lambda\,(t-t_0)]$

→ **$[N(d)/N(m)]\,(t) = \exp[\,\Lambda\,(t-t_0)] - 1$**

One has to measure 'only'

The relative amount at time t and the **decay probability Λ** of the mother ion

→ **Nuclear cosmic clocks should be independent on stellar/galactic evolution models**

Only 4 nuclear clocks for the age of our galaxy / the Universe

Long half-life (many 10^9 yr) → small Q value and/or large ΔI^π

1. ^{87}Rb/^{87}Sr (β) $T_{1/2}$ = 50 Gyr Q_β = 273 keV ($3/2^- \rightarrow 9/2^+$)

2. ^{176}Lu/^{176}Hf (β) $T_{1/2}$ = 30 Gyr Q_β = 1186 keV ($7^- \rightarrow 0^+$)

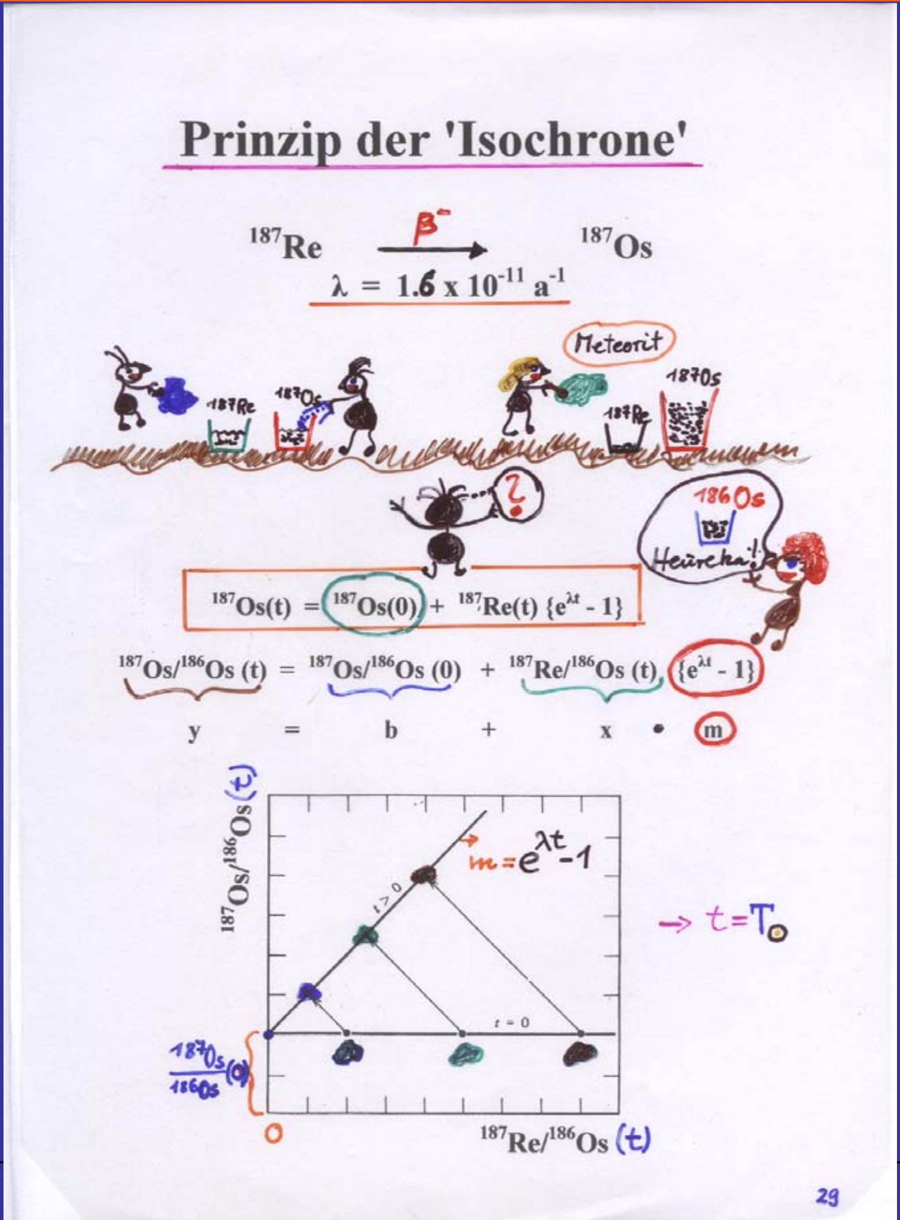
3. ^{187}Re/^{187}Os (β) $T_{1/2}$ = 42 Gyr Q_β = 2.6 keV ($5/2^+ \rightarrow 1/2^-$)

4. ^{238}U...^{206}Pb (α, β) $T_{1/2}$ = 4.5 Gyr

4a. ^{232}Th...^{208}Pb (α, β) $T_{1/2}$ = 14 Gyr

From measured mother/daughter abundance and known half-life
→ Age of the sample

Age of the solar system $T_{\odot} = 4.6 \cdot 10^9$ yr; the "isochrones"



Prinzip der 'Isochrone'

$$^{187}\mathrm{Re} \xrightarrow{\beta^-} {}^{187}\mathrm{Os}$$

$$\lambda = 1.6 \times 10^{-11}\ \mathrm{a}^{-1}$$

$$\boxed{^{187}\mathrm{Os}(t) = {}^{187}\mathrm{Os}(0) + {}^{187}\mathrm{Re}(t)\,\{e^{\lambda t} - 1\}}$$

$$\underbrace{^{187}\mathrm{Os}/^{186}\mathrm{Os}\,(t)}_{y} = \underbrace{^{187}\mathrm{Os}/^{186}\mathrm{Os}\,(0)}_{b} + \underbrace{^{187}\mathrm{Re}/^{186}\mathrm{Os}\,(t)}_{x} \bullet \underbrace{\{e^{\lambda t} - 1\}}_{m}$$

→ $t = T_{\odot}$

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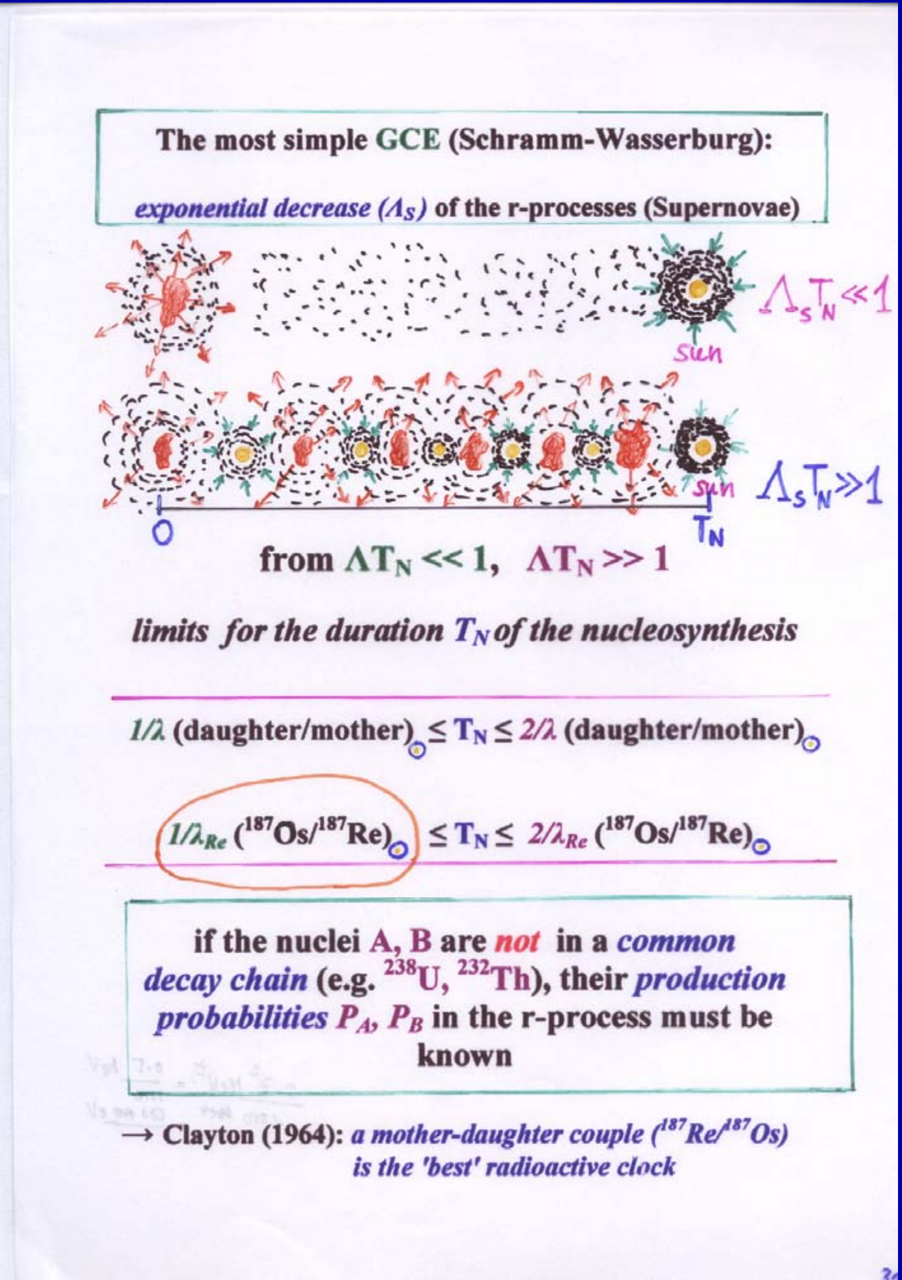
Constraints for the pre-solar age T_N of our galaxy



The most simple GCE (Schramm-Wasserburg):

***exponential decrease (Λ_S)* of the r-processes (Supernovae)**

from $\Lambda T_N << 1$, $\Lambda T_N >> 1$

limits for the duration T_N of the nucleosynthesis

$1/\lambda$ (daughter/mother)$_\odot \leq T_N \leq 2/\lambda$ (daughter/mother)$_\odot$

$1/\lambda_{Re}$ $({}^{187}Os/{}^{187}Re)_\odot \leq T_N \leq 2/\lambda_{Re}$ $({}^{187}Os/{}^{187}Re)_\odot$

if the nuclei A, B are *not* in a *common decay chain* (e.g. ^{238}U, ^{232}Th), their *production probabilities* P_A, P_B in the r-process must be known

→ **Clayton (1964):** ***a mother-daughter couple ($^{187}Re/^{187}Os$) is the 'best' radioactive clock***

1. Measure **R $({}^{187}Os/{}^{187}Re)_d$ and Λ(Re)**

The two extreme cases:*

1. all ^{187}Re (r-made) due to **one** Supernova

$$dN_{Re}(t)/dt = - \Lambda N_{Re}(t); \; dN_{Os}(t)/dt = \Lambda N_{Re}(t)$$

2. ^{187}Re due to **infinitely many** Supernovae

$$dN_{Re}(t)/dt = - \Lambda N_{Re}(t) + p; \; dN_{Os}(t)/dt = \Lambda N_{Re}(t)$$

$$\rightarrow T_N \geq 1/\Lambda \cdot R({}^{187}Os/{}^{187}Re)_d \quad (1)$$
$$\rightarrow T_N \leq 2/\Lambda \cdot R({}^{187}Os/{}^{187}Re)_d \quad (2)$$

$1/\Lambda = 61.3$ Gyr, $R({}^{187}Os/{}^{187}Re)_d = 0.137$

$$\rightarrow 8.4 \leq T_N \leq 16.8 \text{ [Gyr]}$$

$$\rightarrow 13 \leq T_G = T_N + T_☻ \leq 21.4 \text{ [Gyr]}$$

* E.M.D. Symbalisty et al., Rep.Prog.Phys. **44** (1981) 293

3. The ^{187}Re/^{187}Os nuclear cosmic clock

$T_N \geq \quad \tau(^{187}\mathrm{Re}) \quad \cdot \quad R\,(^{187}\mathrm{Os}/^{187}\mathrm{Re})_d$

$61.3\ \mathrm{Gyr} \quad \cdot \quad 0.137$

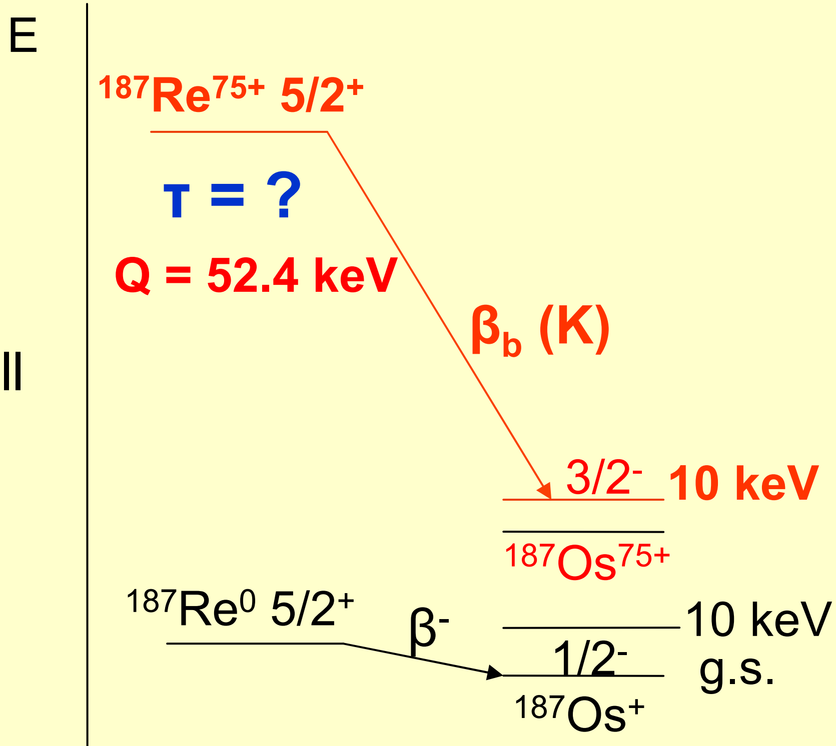
$= 8.4\ \mathrm{Gyr}$

but...

Bare (and H-like) **^{187}Re** can undergo **bound-state β decay (β_b)** to the K shell **and the first excited state at 10 keV** of $^{187}\mathrm{Os}^{75+}$ ($I^\pi = 3/2^-$)

Nuclear matrix element (**log ft**) **not known**

Measurement of the **lifetime τ of bare ^{187}Re** provides **log ft.** Then the lifetime for **all charge states q** can be calculated reliably



E

$^{187}\mathrm{Re}^{75+}$ $5/2^+$

τ = ?

Q = 52.4 keV

β_b (K)

$3/2^-$ **10 keV**

$^{187}\mathrm{Os}^{75+}$

$^{187}\mathrm{Re}^0$ $5/2^+$

β^-

10 keV

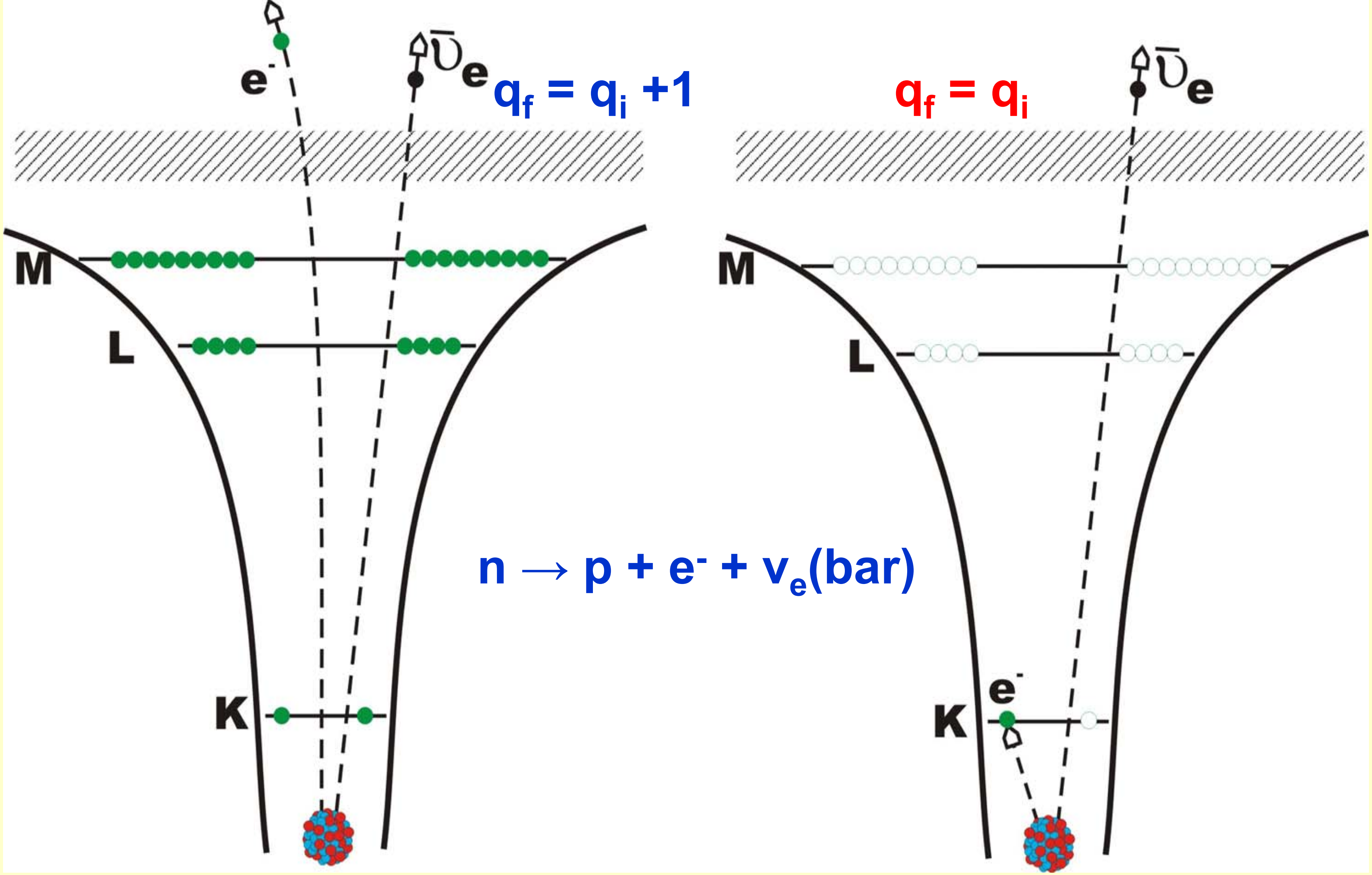
$1/2^-$

g.s.

$^{187}\mathrm{Os}^+$

τ = 61 Gyr;

Q = 2.6 keV



$q_f = q_i + 1$

$q_f = q_i$

$n \rightarrow p + e^- + \nu_e(bar)$

Continuum β decay (β_c)

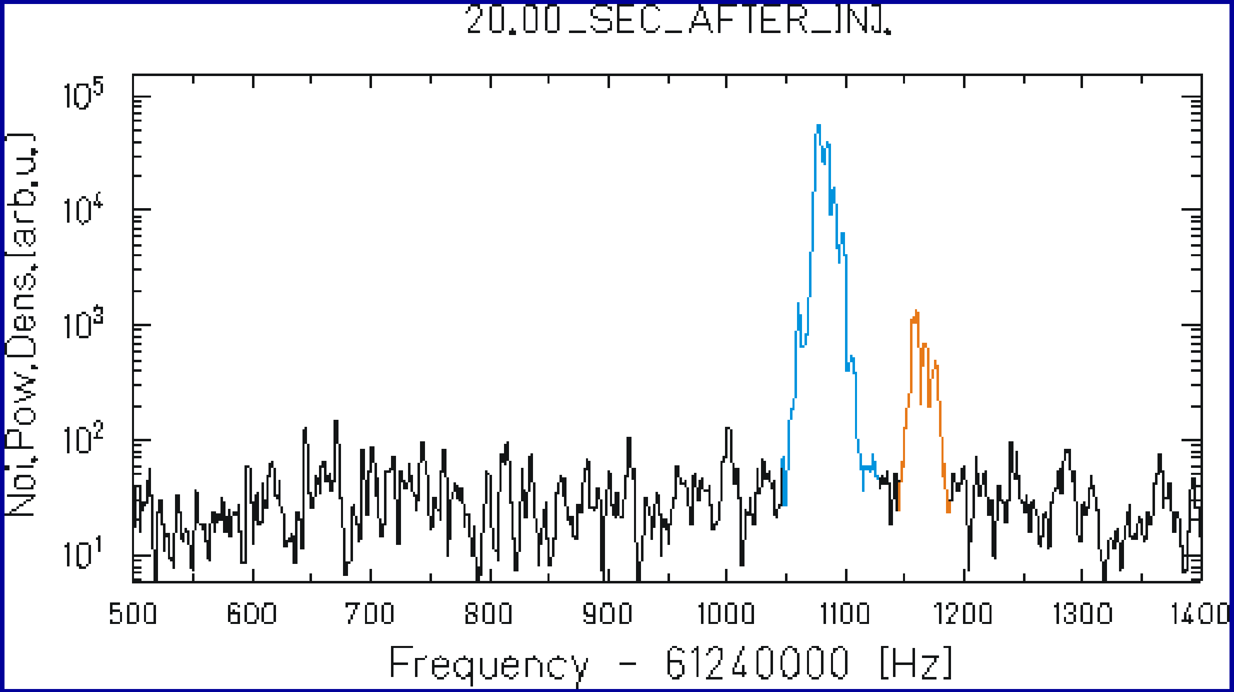
Bound-state β decay (β_b) to K shell

K binding energy saved → Q value gets much larger ($\lambda \infty Q^5$)

$$Q_{\beta b}\,({}^{187}\mathrm{Re}^{75+} \rightarrow {}^{187}\mathrm{Os}^{75+}\ \mathrm{g.s.,K}) = Q_{\beta c} - |\Delta B_e| + |E_B(K)_{Os}|$$

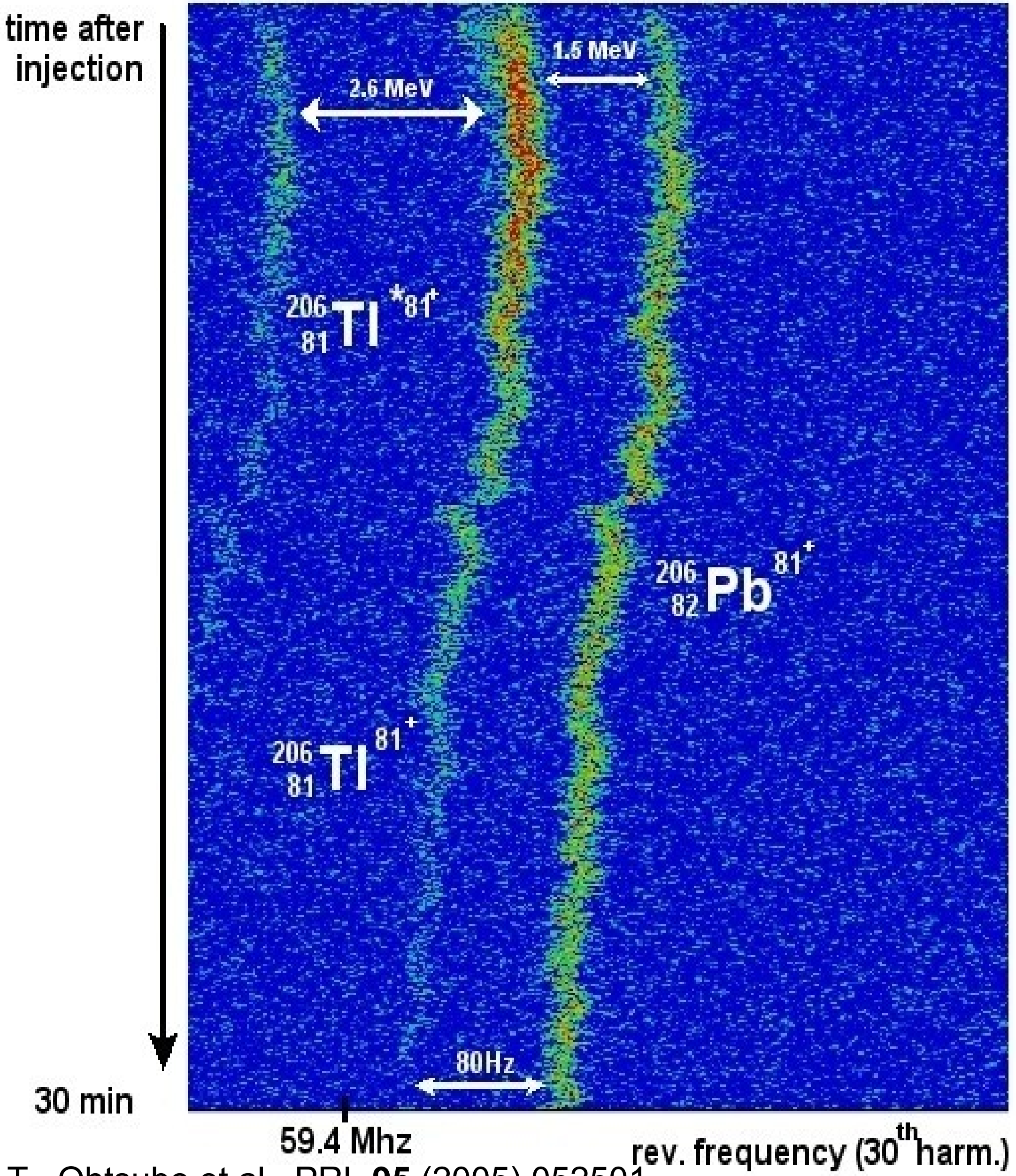
2.6 keV - 21 keV + 80.8 keV = **+ 62.4 keV**

Cooling



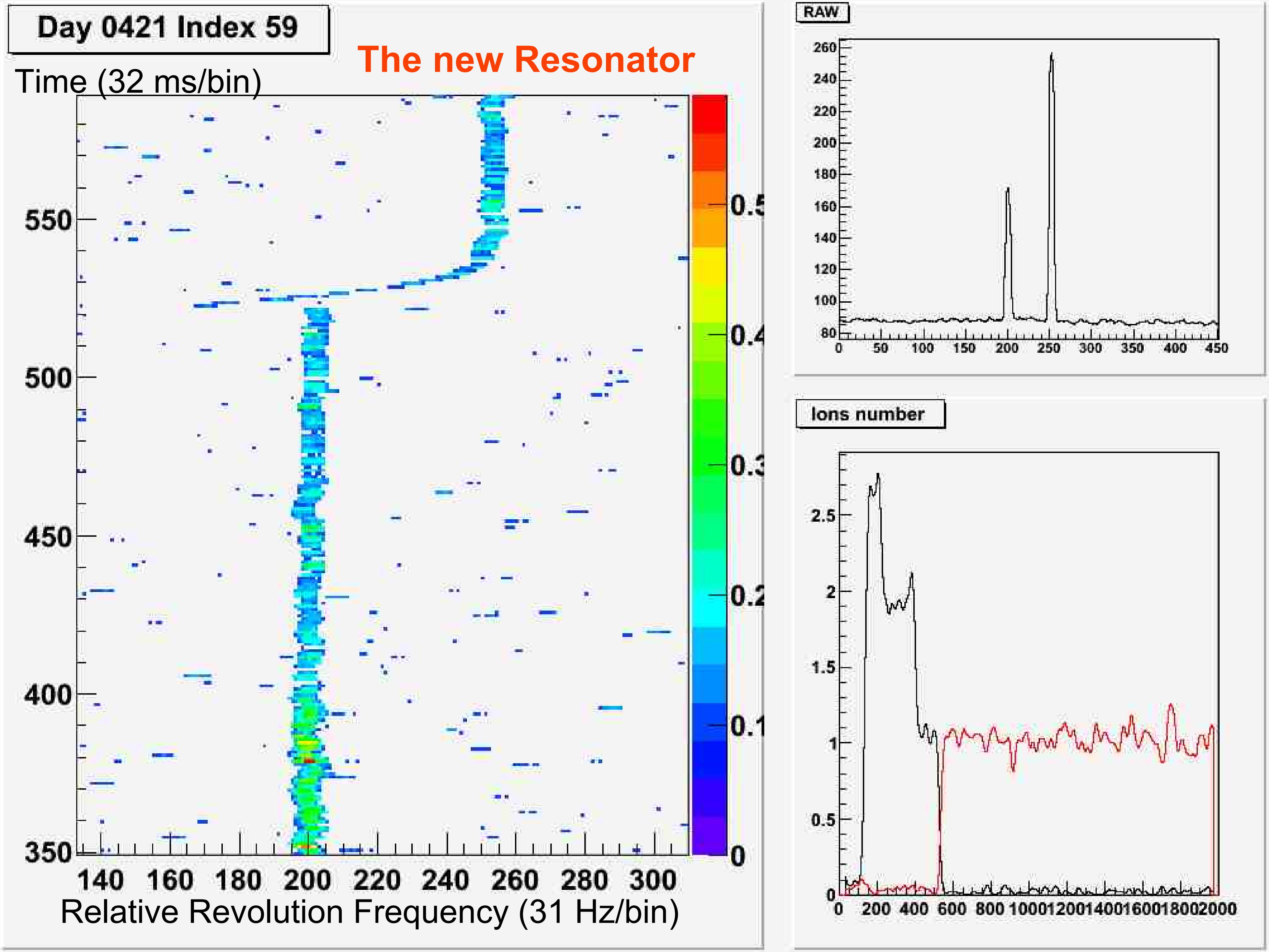
D. Boutin

First **direct** observation of β_b decay

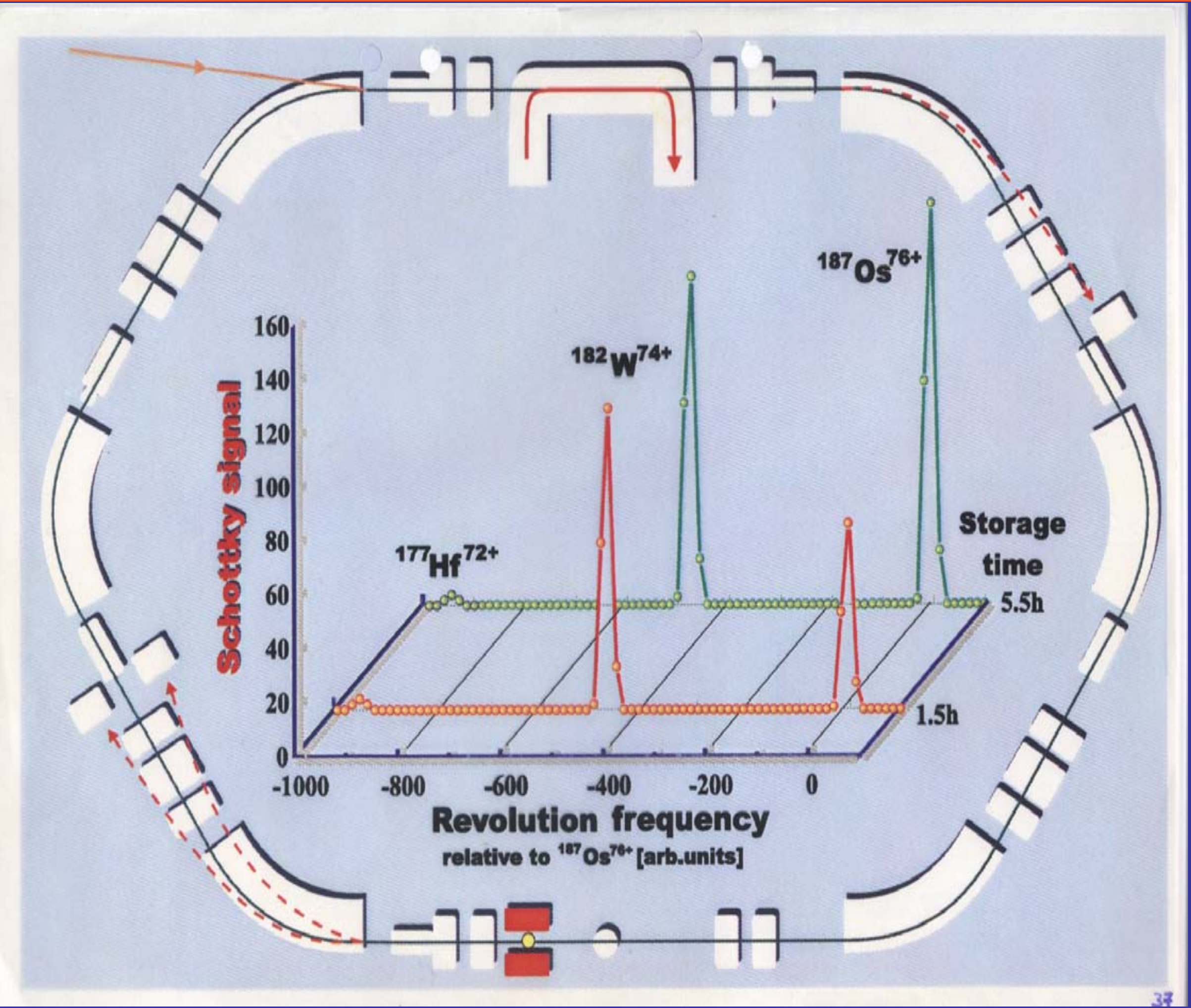


T. Ohtsubo et al., PRL **95** (2005) 052501

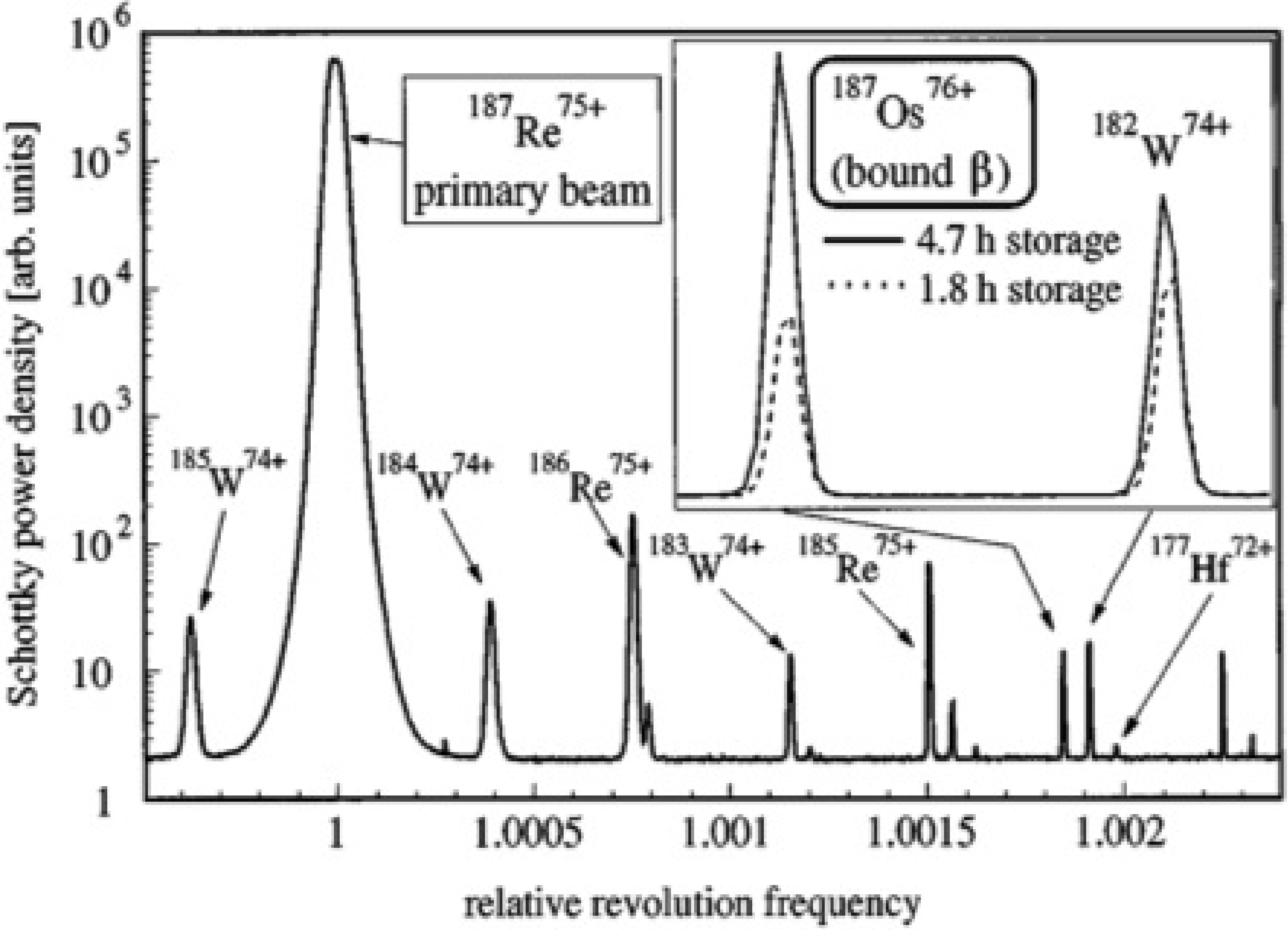
The new Resonator



How to determine a β_b lifetime τ at a Q value of 62 keV?



1. Store and cool bare ^{187}Re for various times (hours)
2. The β_b daughters, H-like ^{187}Os, at the **same** atomic charge state are **not resolved** Q value only **62 keV**
3. After the (long) storage time **strip the one electron** of ^{187}Os in an intense gas jet, acting for two minutes only
4. The **bare ^{187}Os ions** are **well-resolved** now, at **$q = 76^+$**
5. The number of nuclear reaction products (Hf, W,..) does **not** depend on storage time

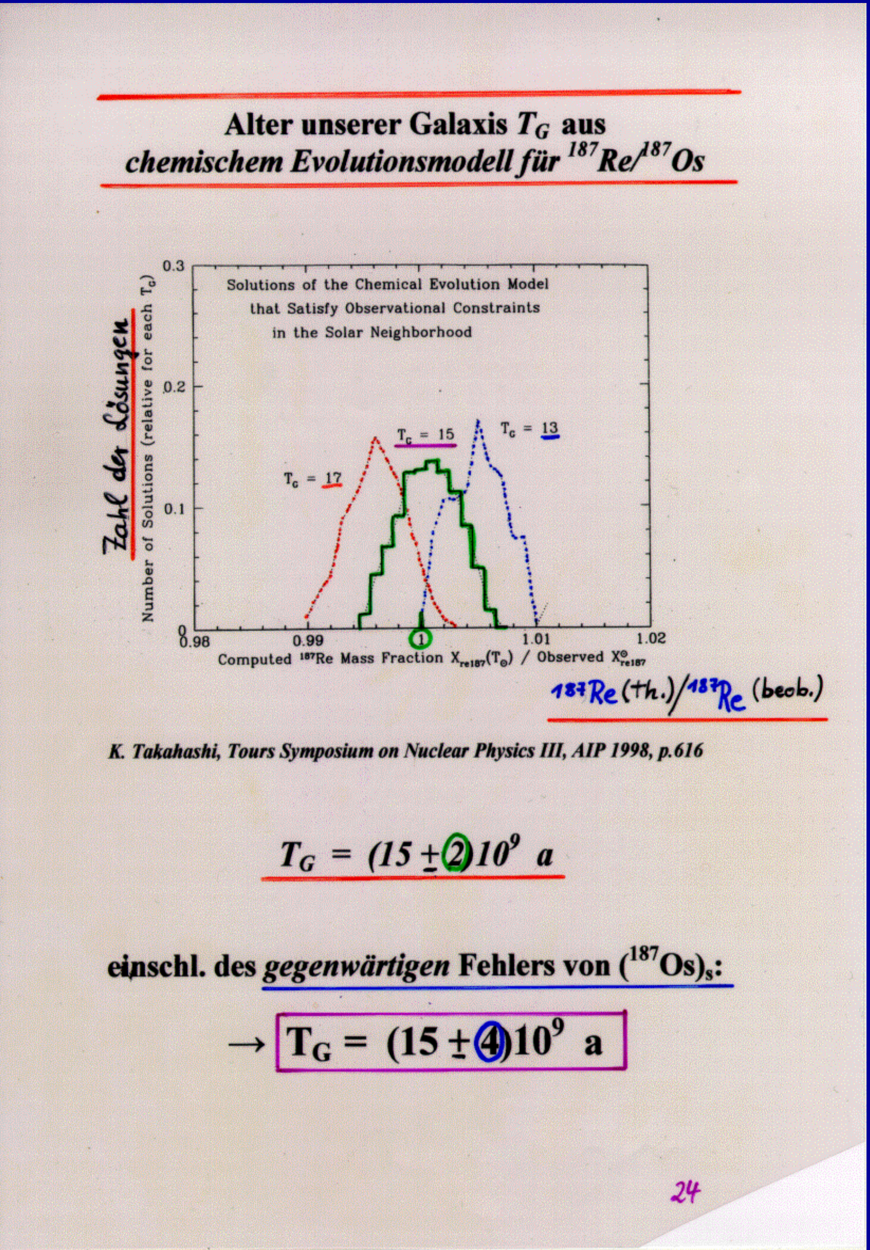


τ(bare $^{187}Re^{75+}$) = 48(3) yr

τ(neutral $^{187}Re^{0}$) = 61(2) ·10^9 yr

F. Bosch et al., PRL **77** (1996) 5170

The abundance of ^{187}Re/^{187}Os depends on the galactic history



Alter unserer Galaxis T_G aus
chemischem Evolutionsmodell für $^{187}Re/^{187}Os$

K. Takahashi, Tours Symposium on Nuclear Physics III, AIP 1998, p.616

$$T_G = (15 \pm 2) 10^9\ a$$

einschl. des *gegenwärtigen* Fehlers von $(^{187}Os)_s$:

$$\rightarrow \boxed{T_G = (15 \pm 4) 10^9\ a}$$

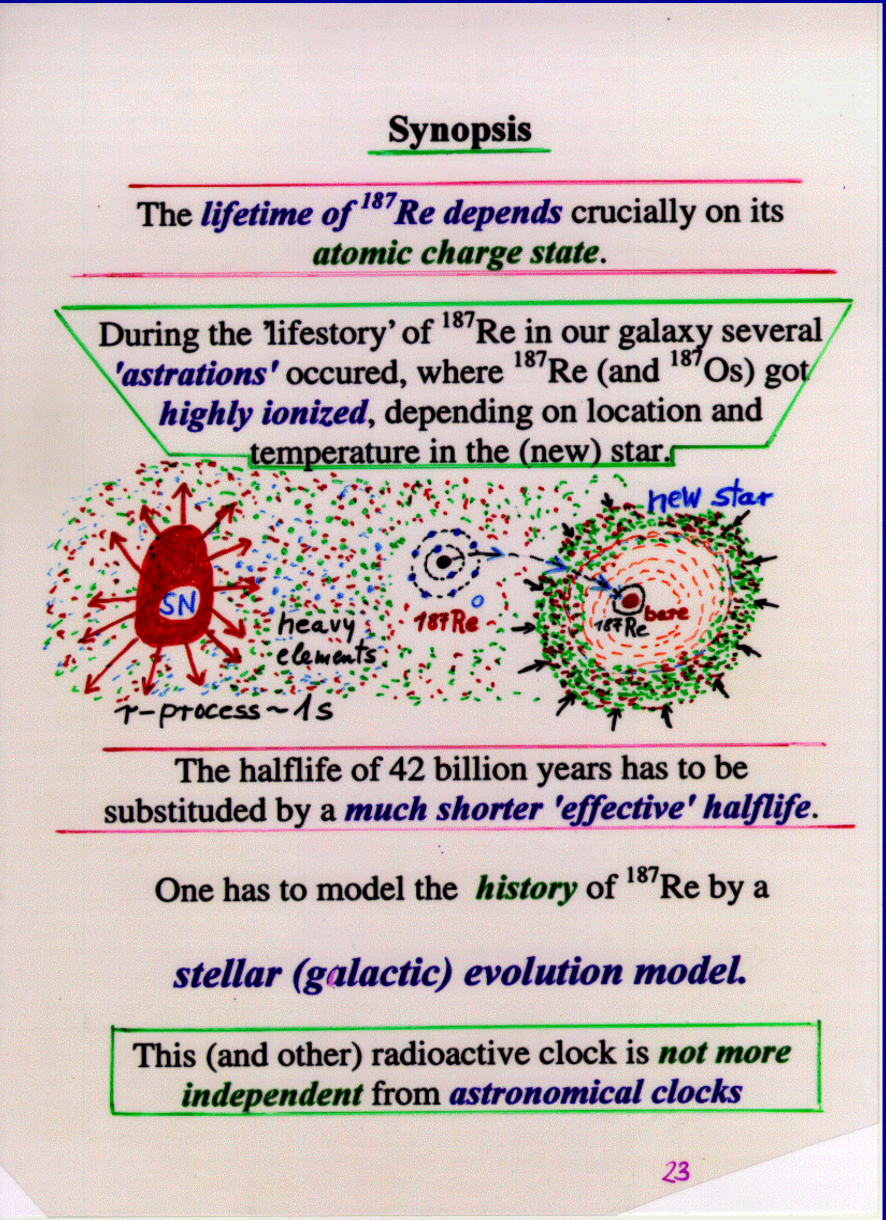
Sorry! or -

Try, to figure out the galactic history of ^{187}Re/^{187}Os with the **known lifetimes τ(q) of ^{187}Re for all charge states q***

→ T_G = 15(4) · 10^9 yr

* K. Takahashi, Tours Symp. on Nucl. Physics III, AIP 1998, 616

Six snap-shots from the galactic fate of a randomly chosen ^{187}Re



Synopsis

The ***lifetime of ^{187}Re depends*** crucially on its ***atomic charge state.***

During the 'lifestory' of ^{187}Re in our galaxy several ***'astrations'*** occured, where ^{187}Re (and ^{187}Os) got ***highly ionized***, depending on location and temperature in the (new) star.

The halflife of 42 billion years has to be substituded by a ***much shorter 'effective' halflife.***

One has to model the ***history*** of ^{187}Re by a

stellar (galactic) evolution model.

This (and other) radioactive clock is ***not more independent*** from ***astronomical clocks***

23

1. Produced in the outbreak of a Supernova
2. After some 100 million years of free galactic self-determination, citizenship in a 9-solar-mass star near a C-burning shell.
3. During some boring years in various charge states q; decaying some day to ^{187}Os by β_b
4. Re-born by free-electron-capture of ^{187}Os.
5. Surviving the outbreak of its home-star, but again in the interstellar space, waiting...
6. ..Awaking in a deep-lying rock on the earth; disturbed there by a curious physicist...

→ The one decay constant λ_{Re} has to be substituted by a $< \lambda (q) >_{eff}$, properly weighted over its galactic 'history'...

What's about the other nuclear cosmic clocks ?

^{87}Rb/^{87}Sr:

Production ratio of ^{87}Rb in the s- and r-process **not clear**

^{176}Lu/^{176}Hf:

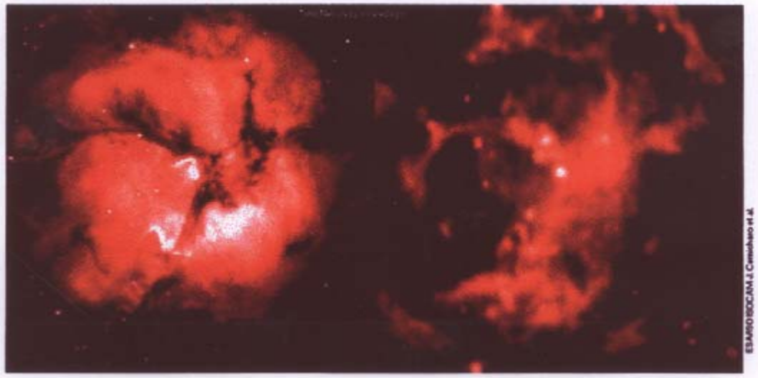
Excited state at 127 keV, **$T_{1/2}$ = 3.7 h**
populated in **s- process** ($T_s \approx$ 30 keV)

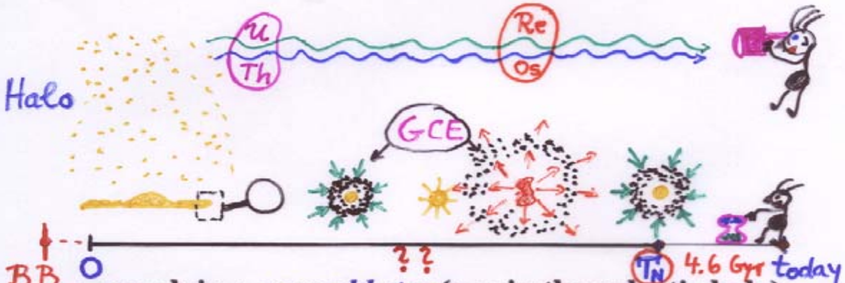
^{238}U/^{232}Th:

Relative **r- production probabilities not known**

U/Th absorption lines from metal-poor stars of galactic halo

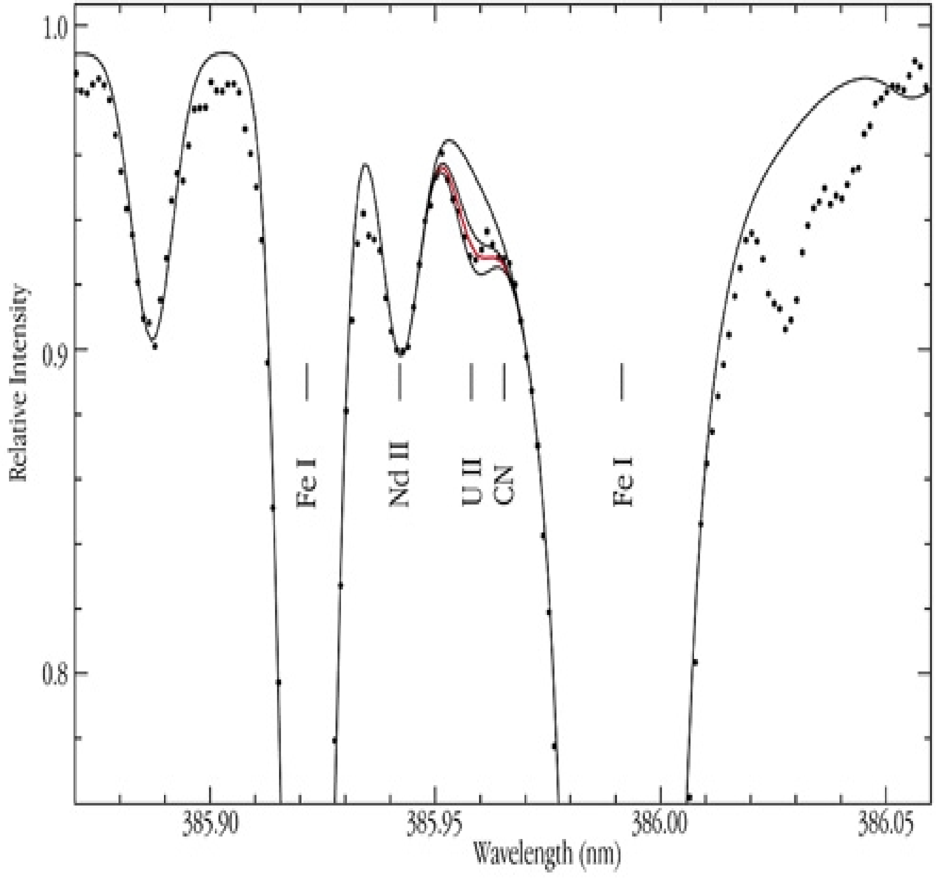
How can we estimate the *age of our galaxy* *before* the formation of the solar system?





→ **search in a *very old star* (e.g. in the galactic halo) for a *radioactive couple* (e.g. via spectral lines)**

→ **try, based on a model for the *chemical evolution of the galaxy* (GCE), to determine the age of your *present radioactive 'clock'***



Uranium Line in the Spectrum of the Old Star CS 31082-001
(VLT KUEYEN + UVES)

ESO PR Photo 05b/01 (7 February 2001)

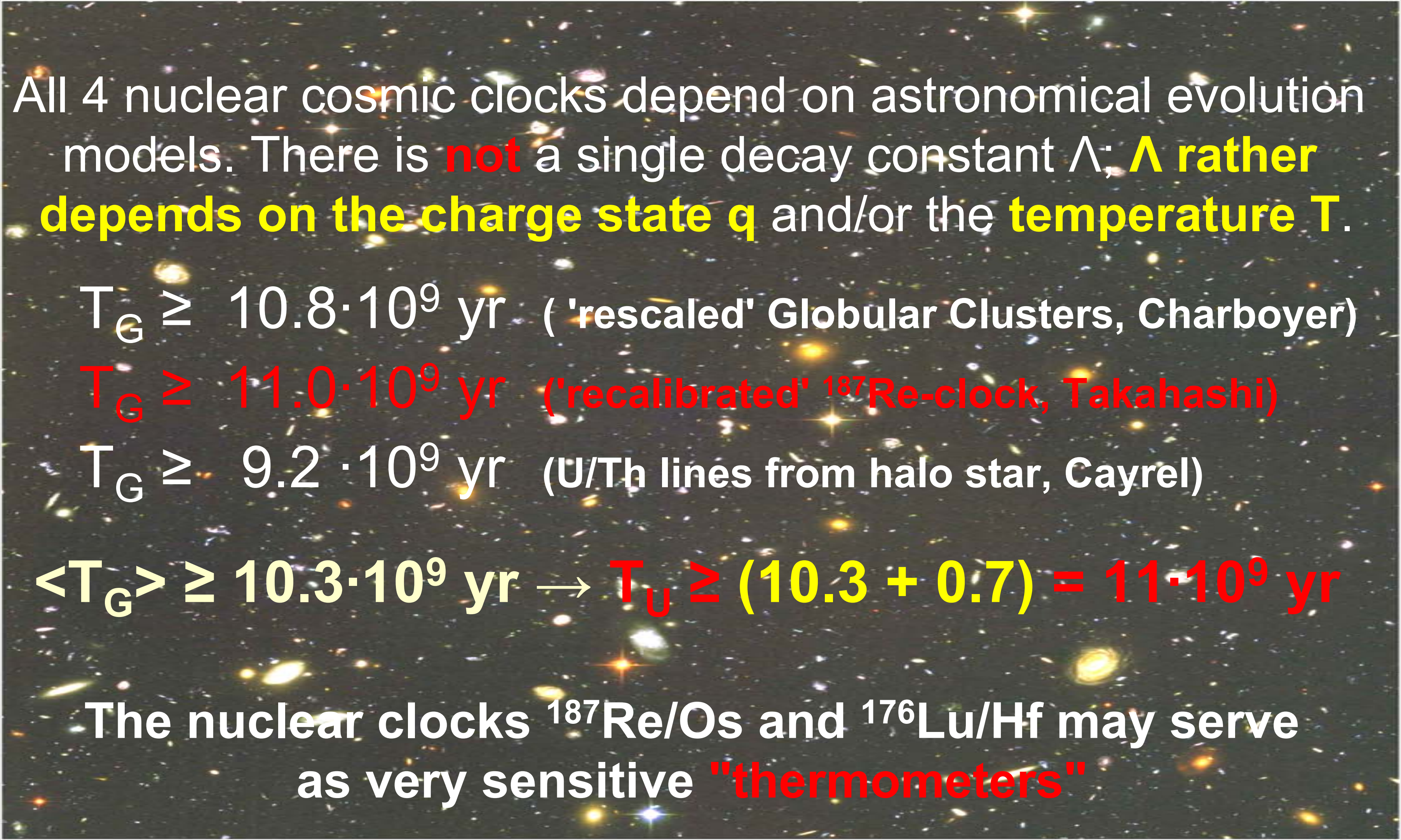
© European Southern Observatory

B. Cayrel et al., Nature **409** (2001) 691

$T_G \geq 9.2$ Gyr

(problems: r-production, oscillator strengths)

Conclusion



All 4 nuclear cosmic clocks depend on astronomical evolution models. There is **not** a single decay constant Λ; **Λ rather depends on the charge state q** and/or the **temperature T**.

$T_G \geq 10.8 \cdot 10^9$ yr **('rescaled' Globular Clusters, Charboyer)**

$T_G \geq 11.0 \cdot 10^9$ yr **('recalibrated' ^{187}Re-clock, Takahashi)**

$T_G \geq 9.2 \cdot 10^9$ yr **(U/Th lines from halo star, Cayrel)**

$$\langle T_G \rangle \geq 10.3 \cdot 10^9 \text{ yr} \rightarrow T_U \geq (10.3 + 0.7) = 11 \cdot 10^9 \text{ yr}$$

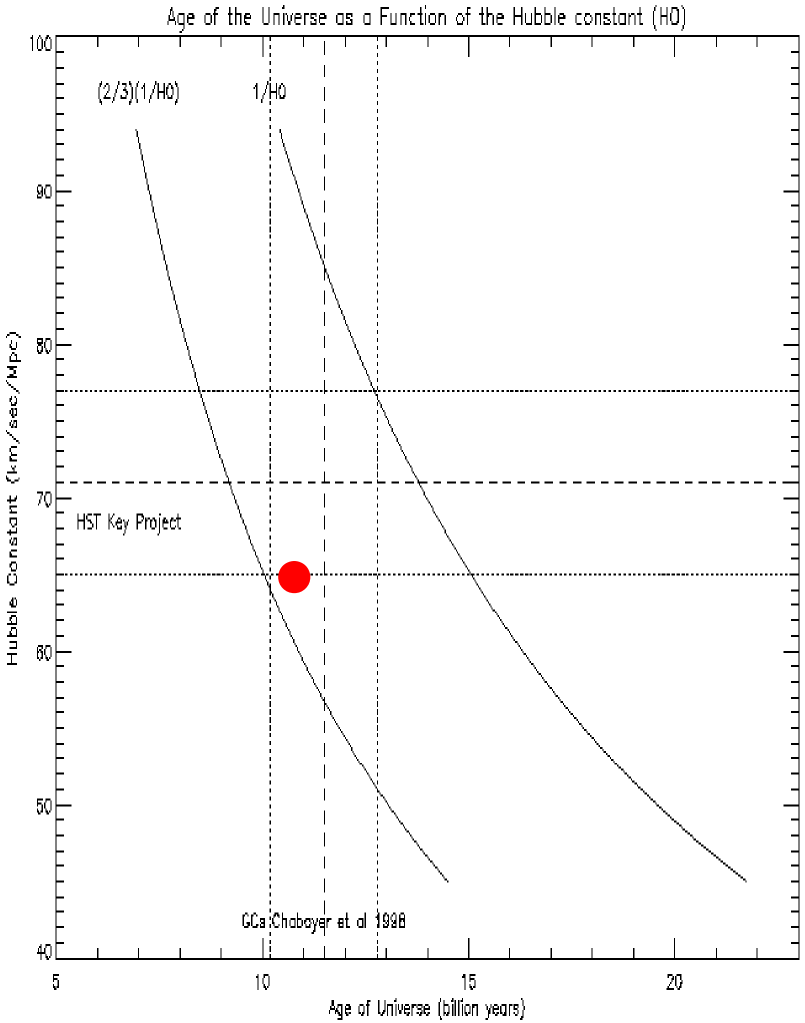
The nuclear clocks ^{187}Re/Os and ^{176}Lu/Hf may serve as very sensitive "thermometers"

Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

Today's lower limits for H_0 and T_U already in conflict to the Standard Model of cosmology



Standard model ($\boldsymbol{\Omega_m = 1, \Omega_\lambda = 0}$):

$T_U H_0 = 2/3$ (652 [Gyr] · [km/s/Mpc])

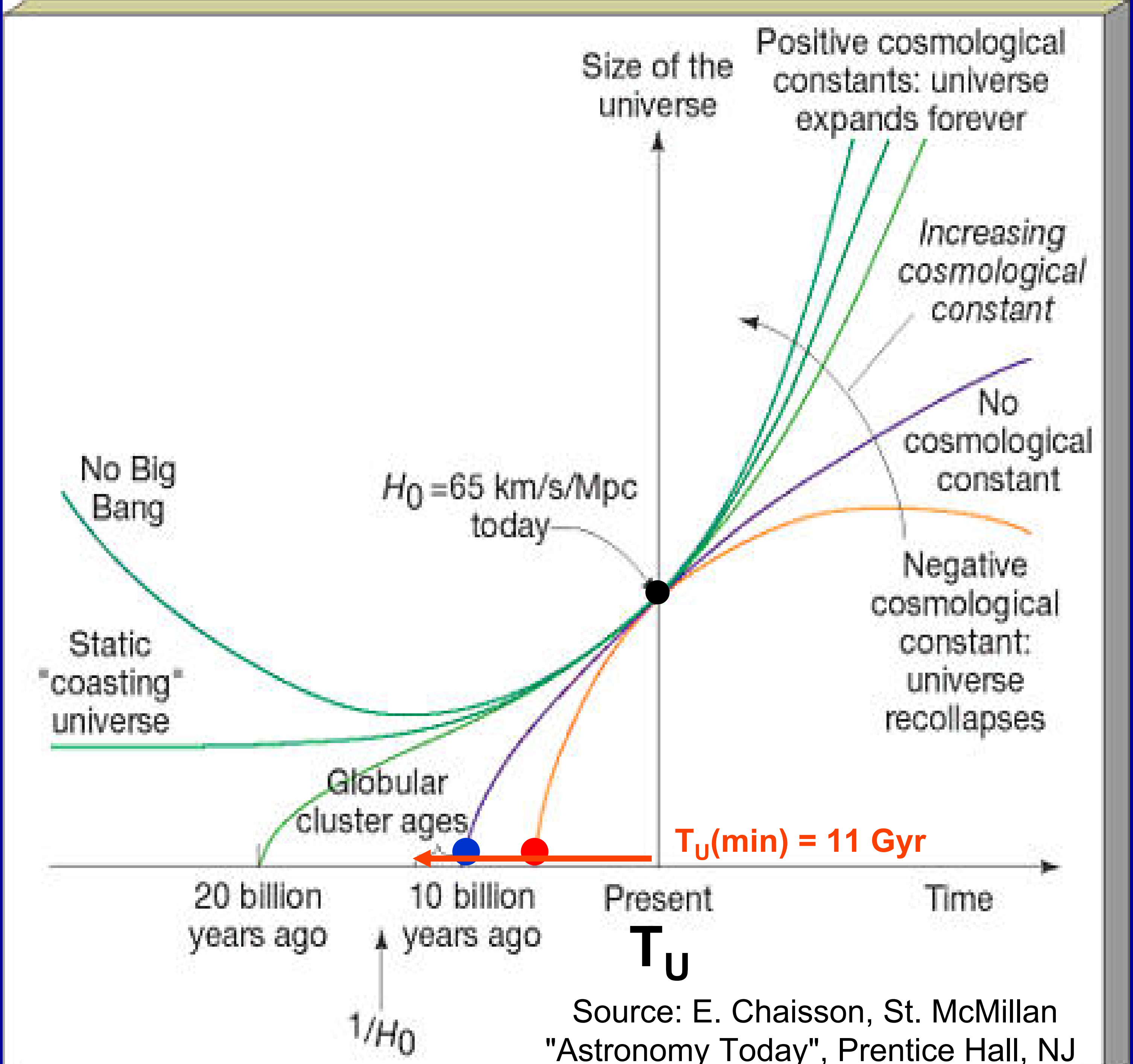
'Empty' universe: $T_U H_0 = 1$ (978)

$H_0 = 72$ (7) km/s/Mpc ≥ 65

W.L. Freedman et al., Nature **371**(1994) 757

$T_U \geq 11$ Gyr

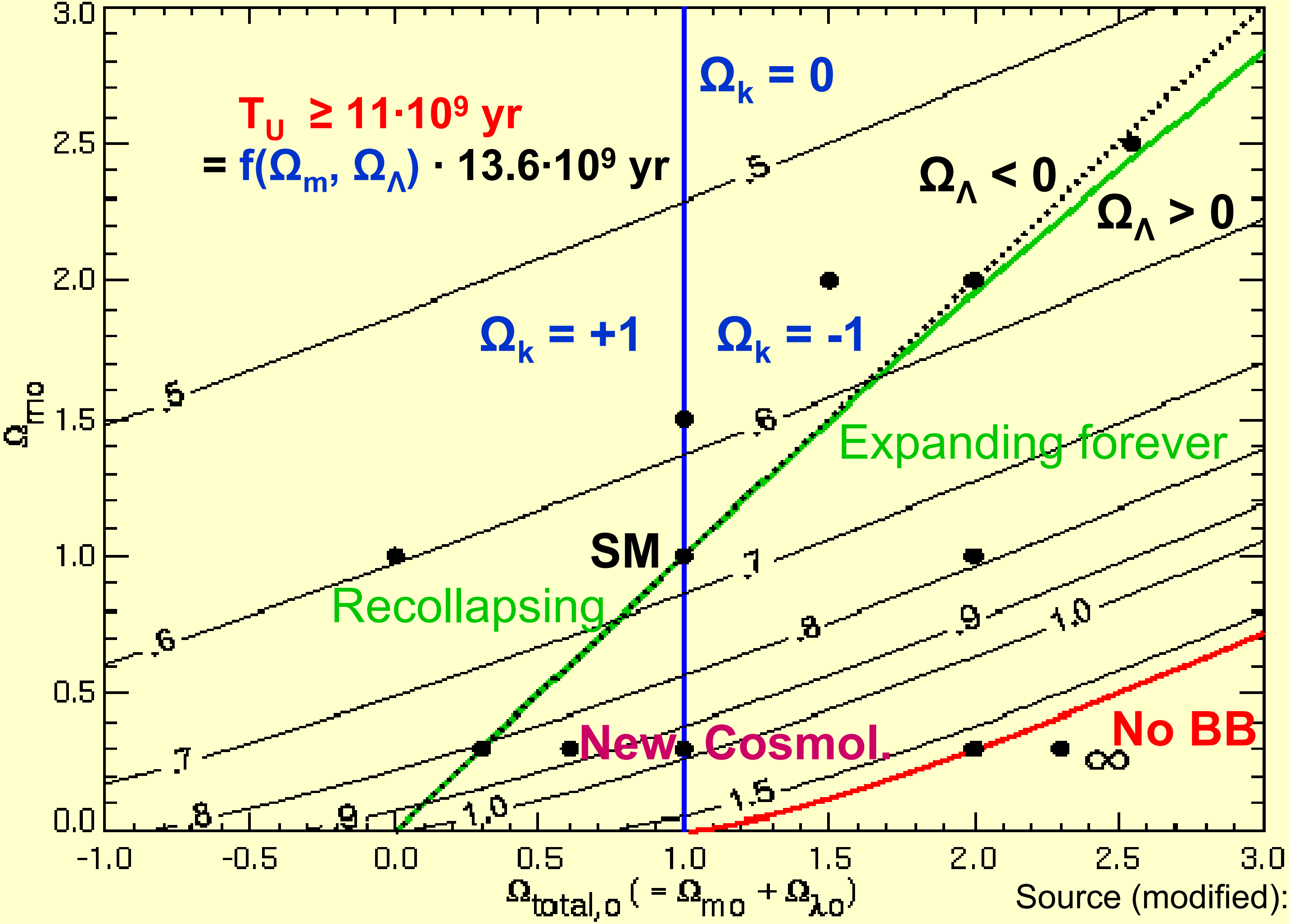
→ $H_0 T_U \geq 65 \cdot 11 = 715$



Source: E. Chaisson, St. McMillan "Astronomy Today", Prentice Hall, NJ

Mass density Ω_{m0} vs. $\Omega_{total,0} = \Omega_{m0} + \Omega_{\Lambda 0}$; $\Omega_{m0} + \Omega_{\Lambda 0} + \Omega_k = 1$

$H_0 = 72$ (7) km/s/Mpc age contours in units of $H_0^{-1} = 13.6$ (1.4) · 10^9 yr



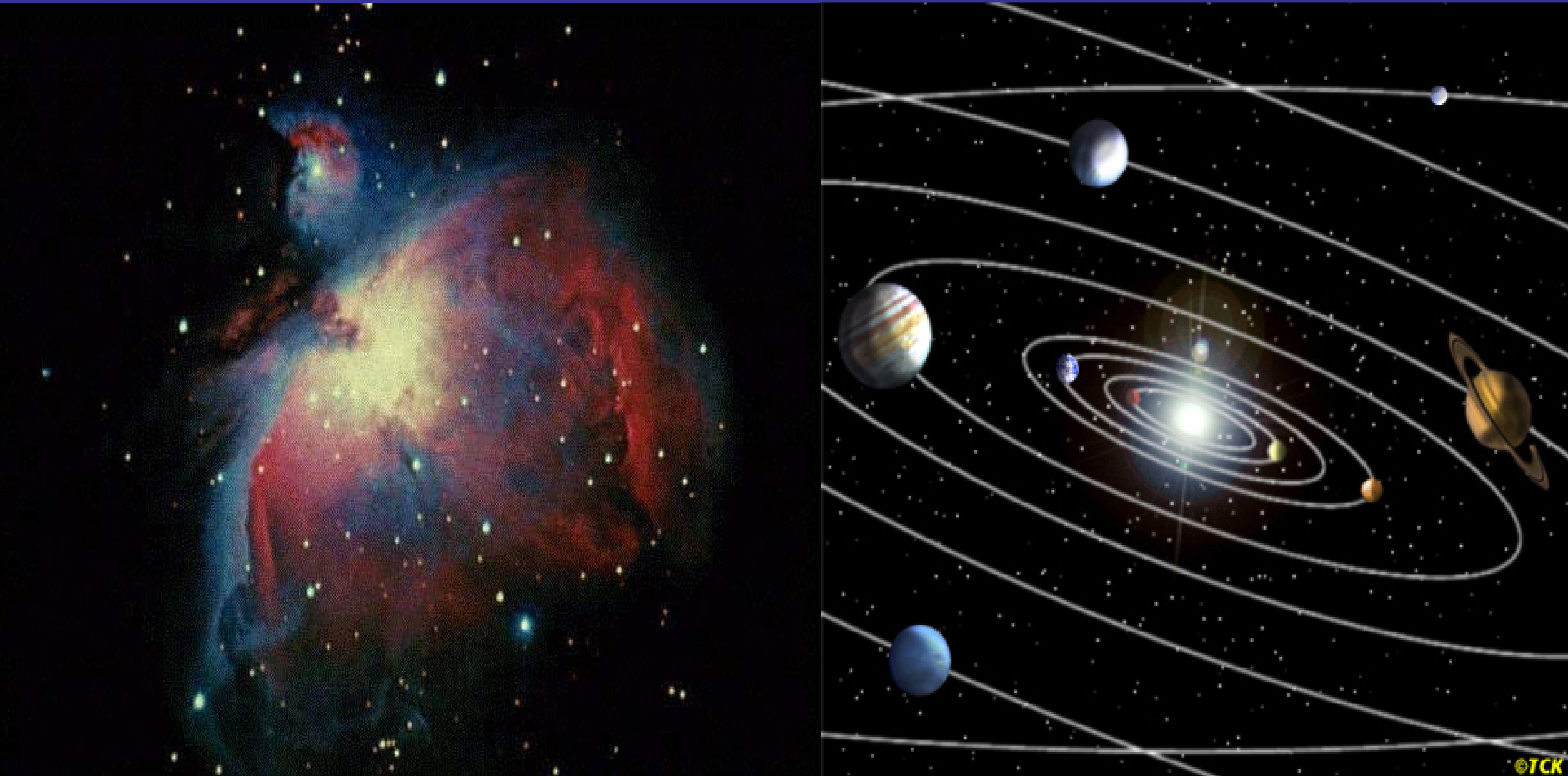
Source (modified):
S.M.Carroll, A&A **30** (1992)499

We shall never go for a second time into the same river

Herakleitos

4. The s-process nuclear cosmic clock ^{205}Pb and the bound-state β decay of bare ^{205}Tl (# E019 and # E100)

What happened between the decoupling of the Solar system from the galactic interstellar matter and its solidification ?



Physics case

^{205}Pb is the **only purely s-process** short-lived (10^7 y) radioactivity (**SLR**) alive in the early solar system

SLR provides insight on **nucleosynthesis just prior to the Sun's birth**

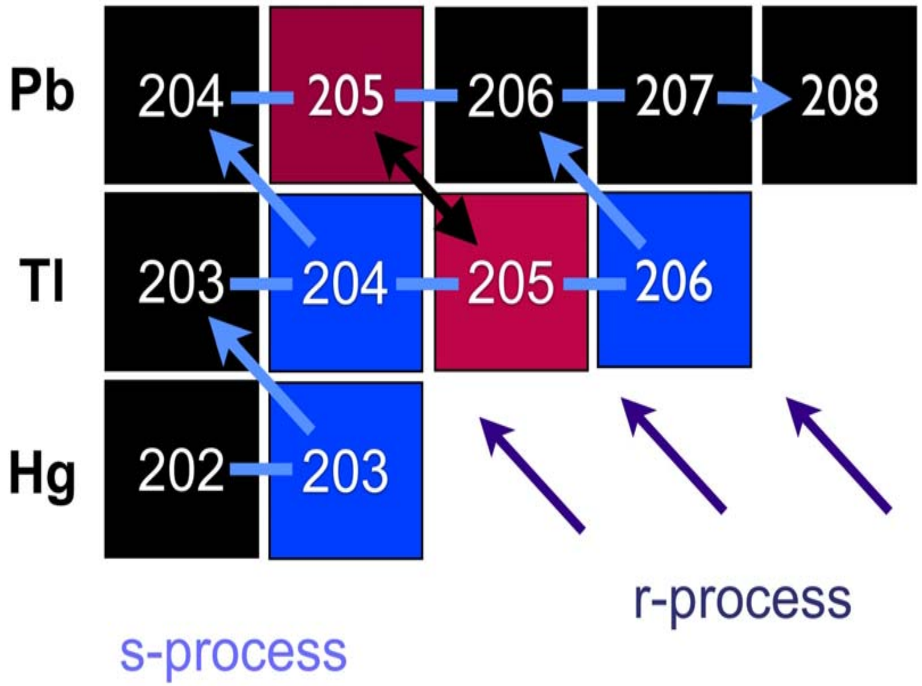
$$N(^{205}Pb)/N(^{204}Pb) \;=\; \mathbf{P(^{205}Pb)/(P^{204}Pb)} \;\cdot\; \tau_{205}/T_G$$

abundances in ISM	s-production rates	$2 \cdot 10^7 / 8 \cdot 10^9$
≈ 10^{-3} (measured)*	**≈ 1 (assumed)**	**≈ $2 \cdot 10^{-3}$**

*R.G.A. Baker et al., Earth Pl. Sc. **291** (2010) 39

^{205}Pb strongly reduced by free EC from 2.3 keV state
injection of s-matter needed from a star to get the ratio of 10^{-3}

J J.B. Blake et al., Ap.J. **197** (1975) 615



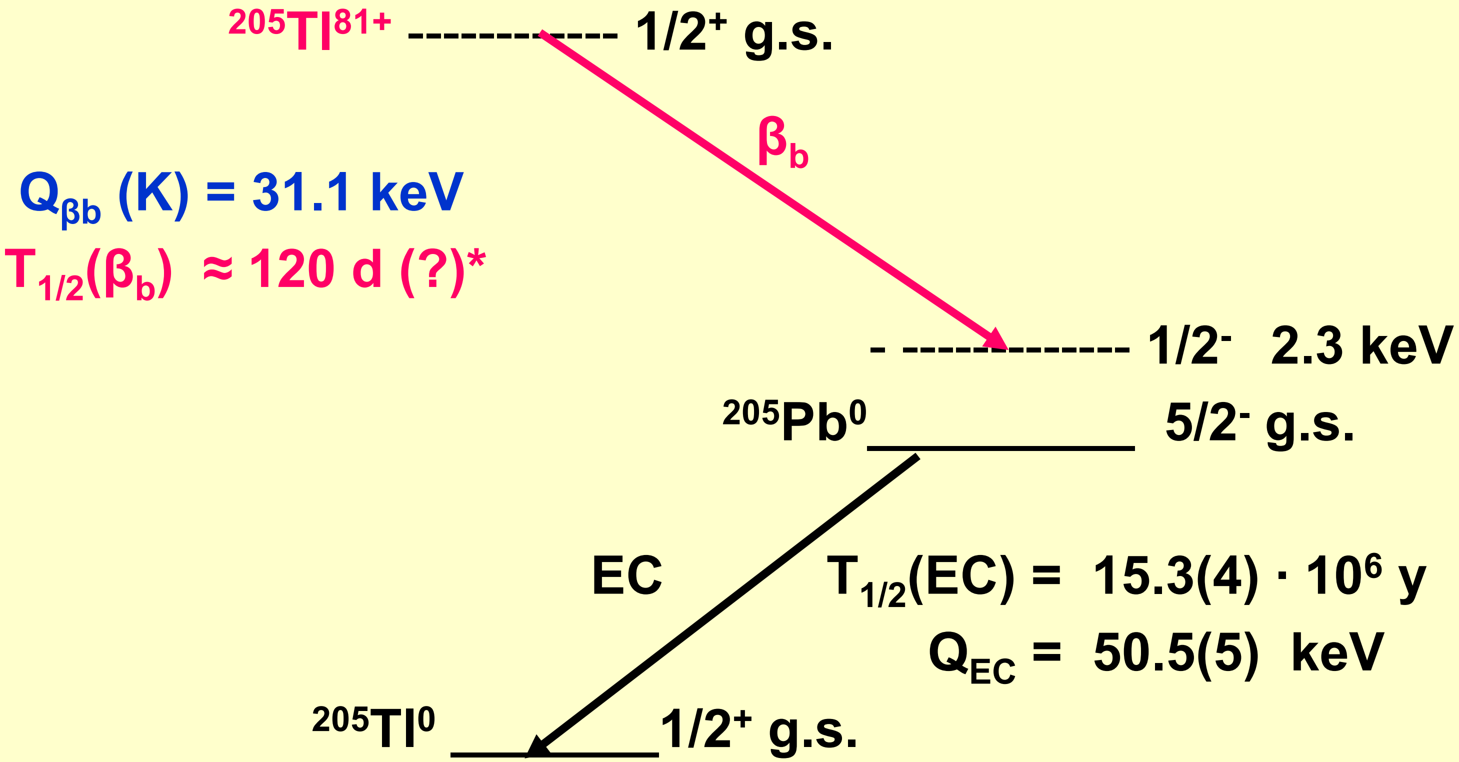
Sunday, April 18, 2010

Counter-balanced by β_b decay of highly ionized ^{205}Tl?

K. Yokoi, A.+ A. **145** (1985) 339

$\lambda_{\beta b}$ of bare ^{205}Tl provides the additional production rate of ^{205}Pb in the s-environment. It "decides" whether or not an additional source of ^{205}Pb (AGB star, Supernova) **was acting at the onset of our Solar system.**

Lifetime of **bare** (or H-like) ^{205}Tl ?



$^{205}\mathrm{Tl}^{81+}$ ------------- $1/2^+$ g.s.

β_b

$Q_{\beta b}$ (K) = 31.1 keV

$T_{1/2}(\beta_b) \approx 120$ d (?)*

- -------------- $1/2^-$ 2.3 keV

$^{205}\mathrm{Pb}^0$ $5/2^-$ g.s.

EC

$T_{1/2}(\mathrm{EC}) = 15.3(4) \cdot 10^6$ y

$Q_{EC} = 50.5(5)$ keV

$^{205}\mathrm{Tl}^0$ $1/2^+$ g.s.

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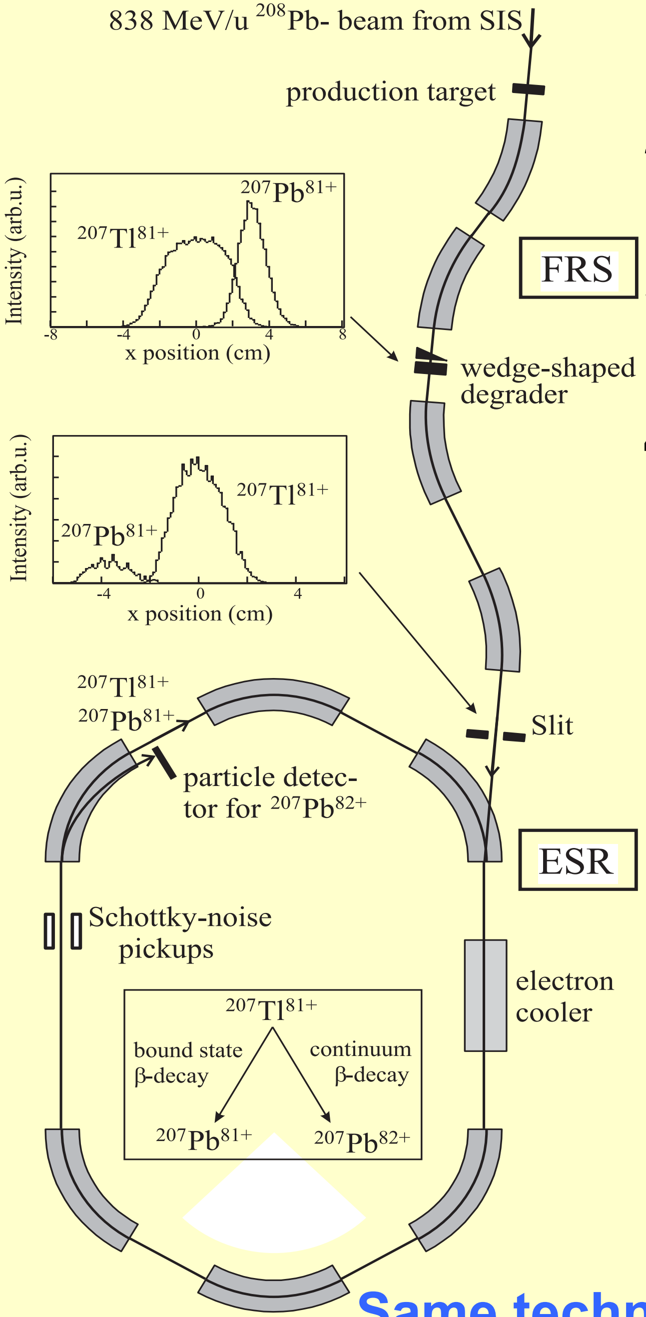
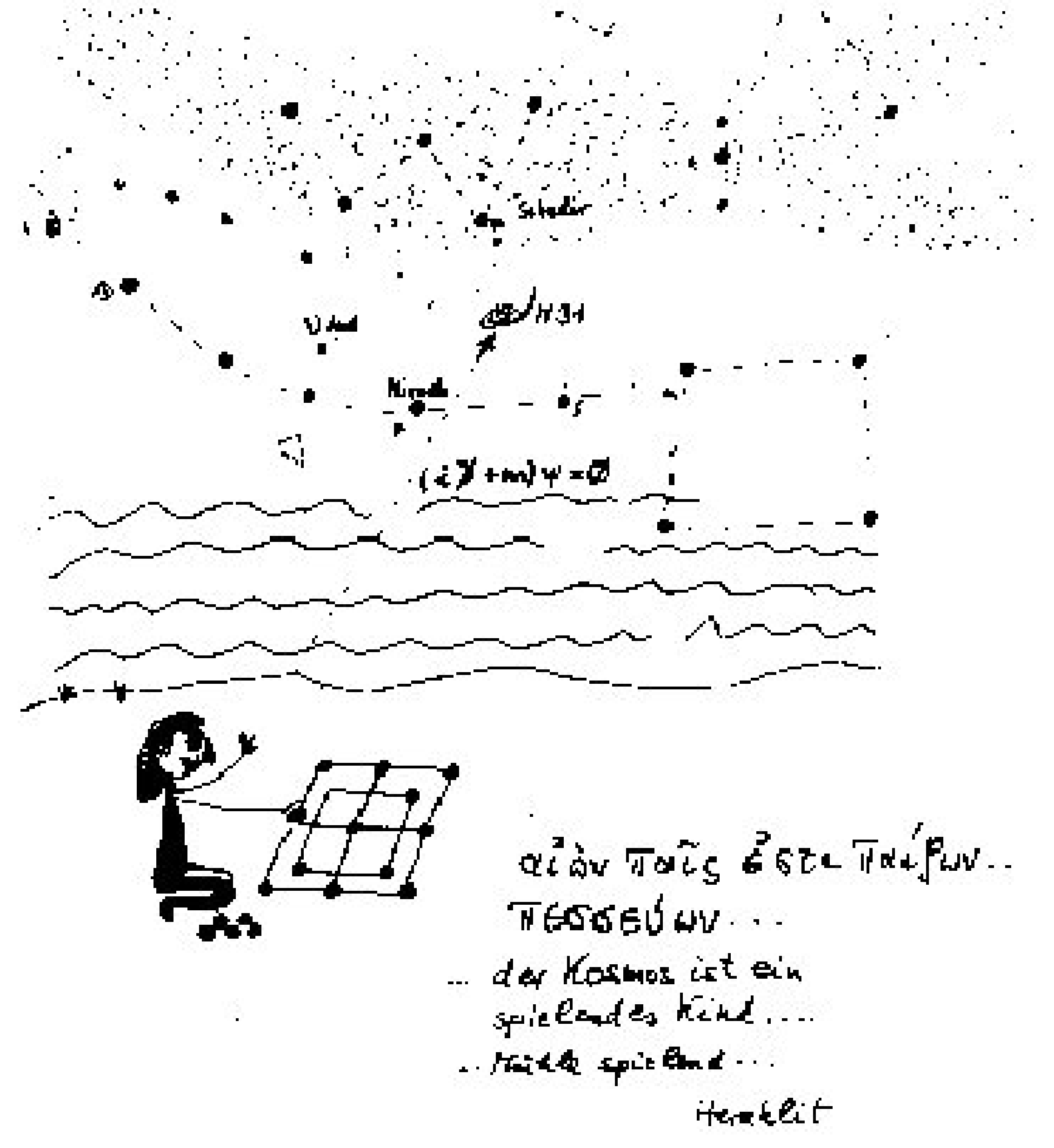
* K. Yokoi et al., Astron. + Astroph. **145** (1985) 339



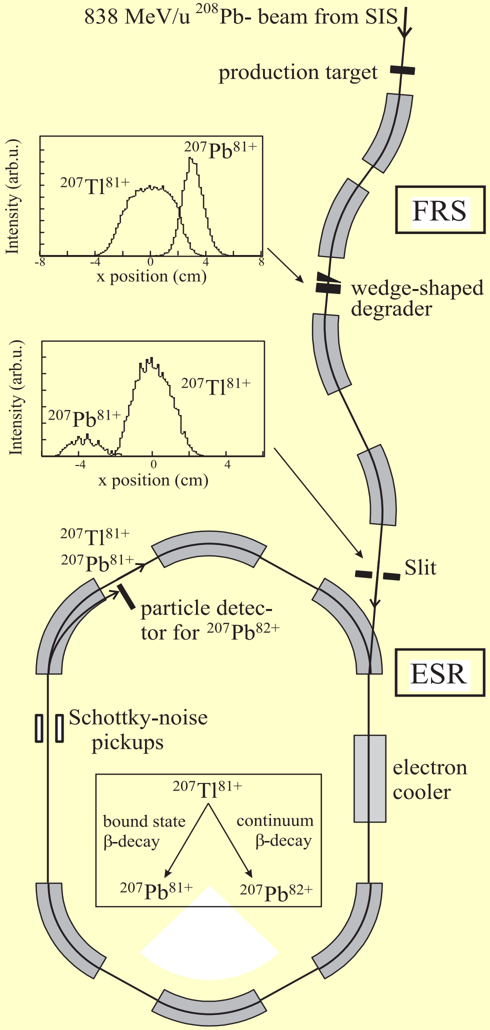
1. **Injection of bare ^{205}Tl from FRS**
2. **Accumulation in ESR to $5 \cdot 10^5$ ions**
3. **Storage for different times t**
4. **Parent- (bare ^{205}Tl^{81+}) and daughter (H-like ^{205}Pb^{81+}) line not separated in Schottky spectrum**
5. **Gas jet (Argon) turned-on for about 2 minutes**
   K electron of ^{205}Pb^{81+} stripped-off
6. **Get bare ^{205}Pb, well-resolved**

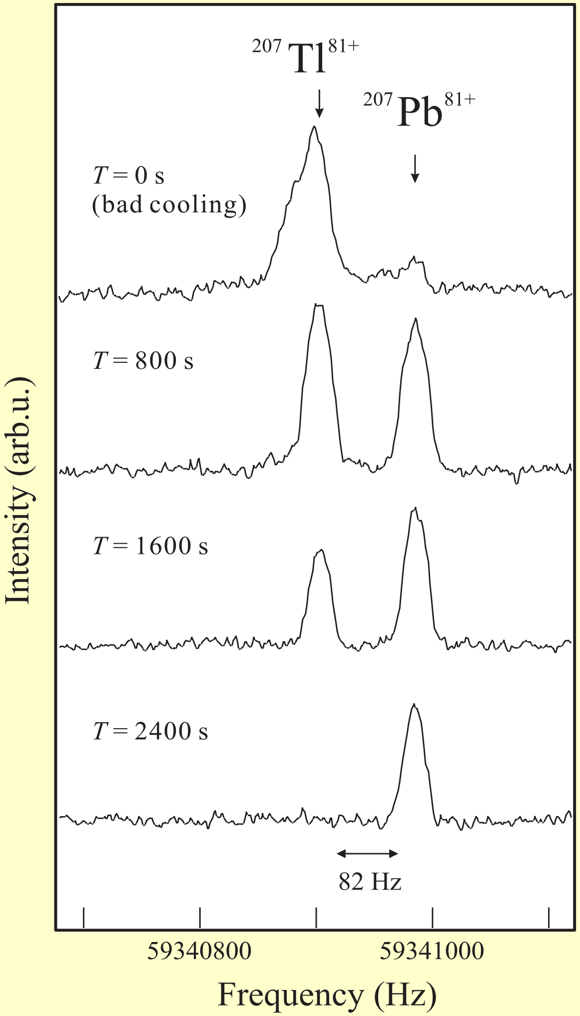
Same technique as applied for β_b decay of ^{163}Dy and ^{187}Re

The cosmos is like a child playing at dominoes...



Direct life-time determination of β_b decay





Projectile fragmentation

stochastic + e$^-$ cooling

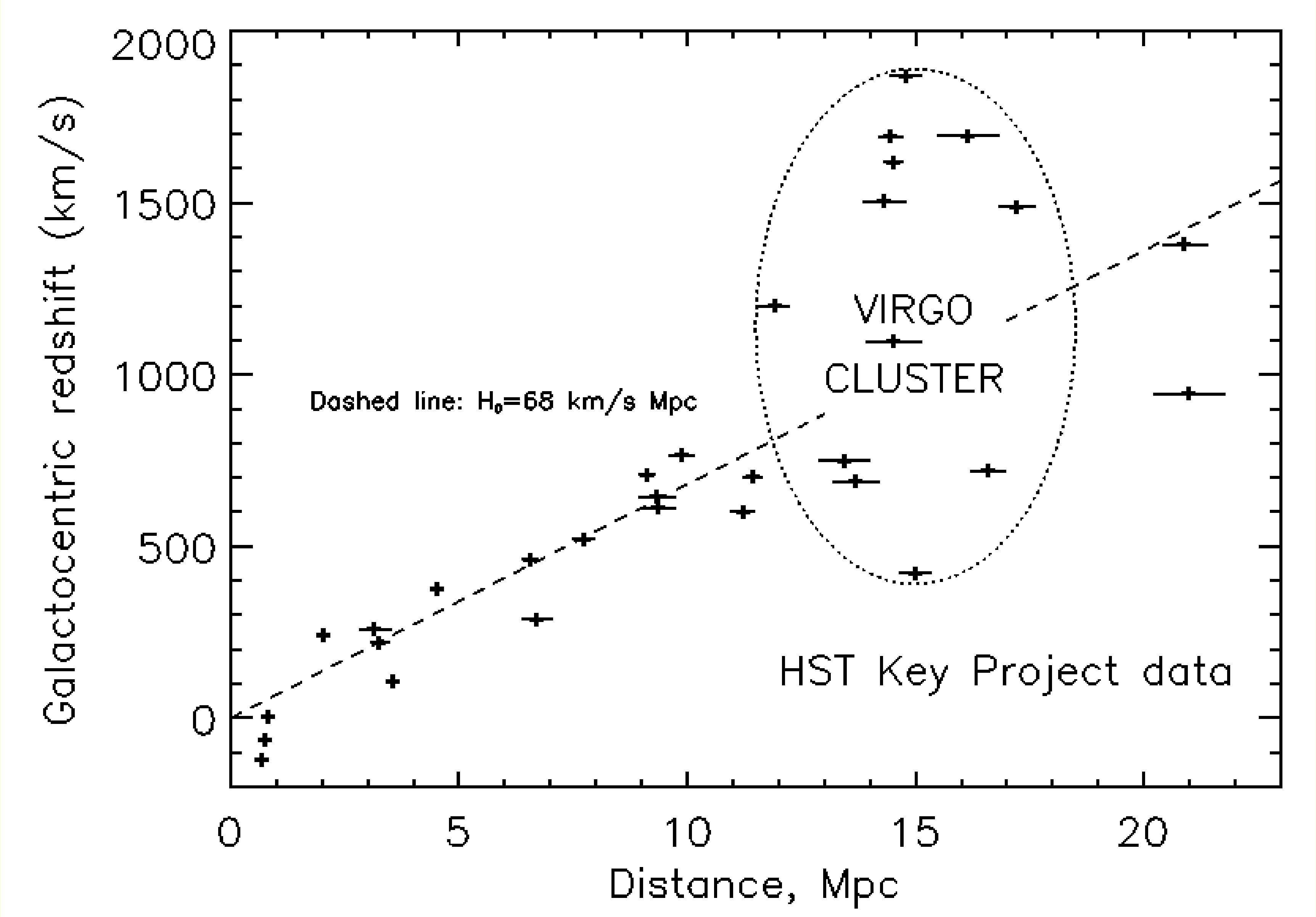
Schottky analysis

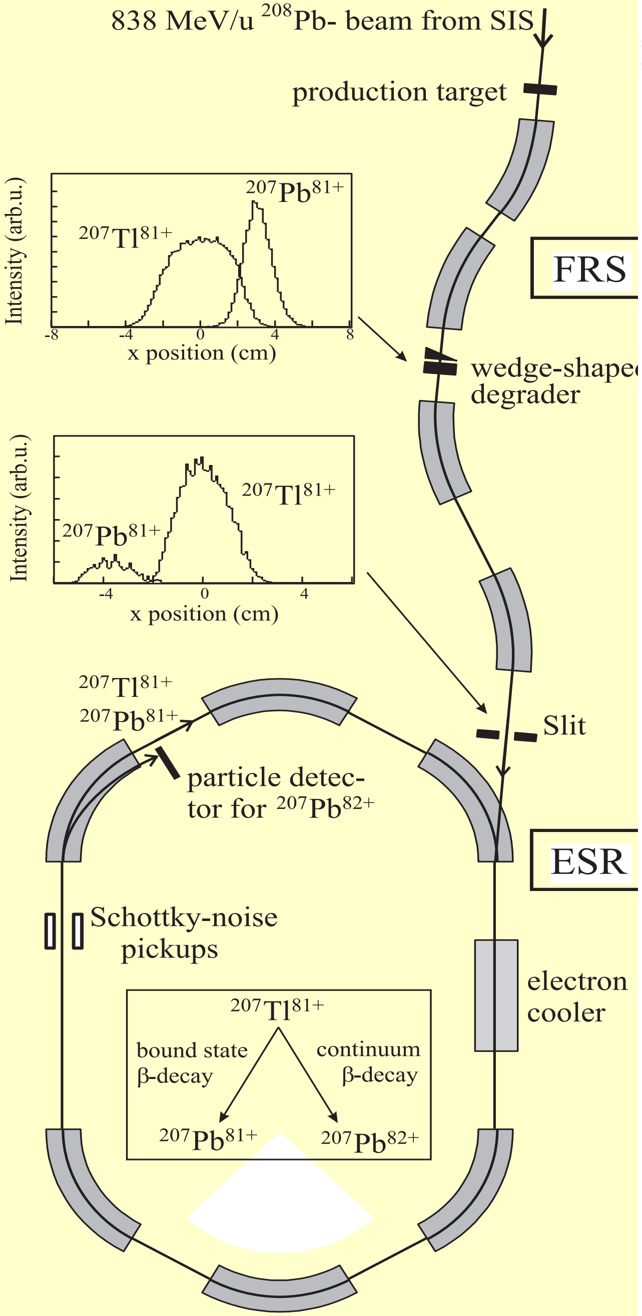
Mother and daughter in the **same** spectrum

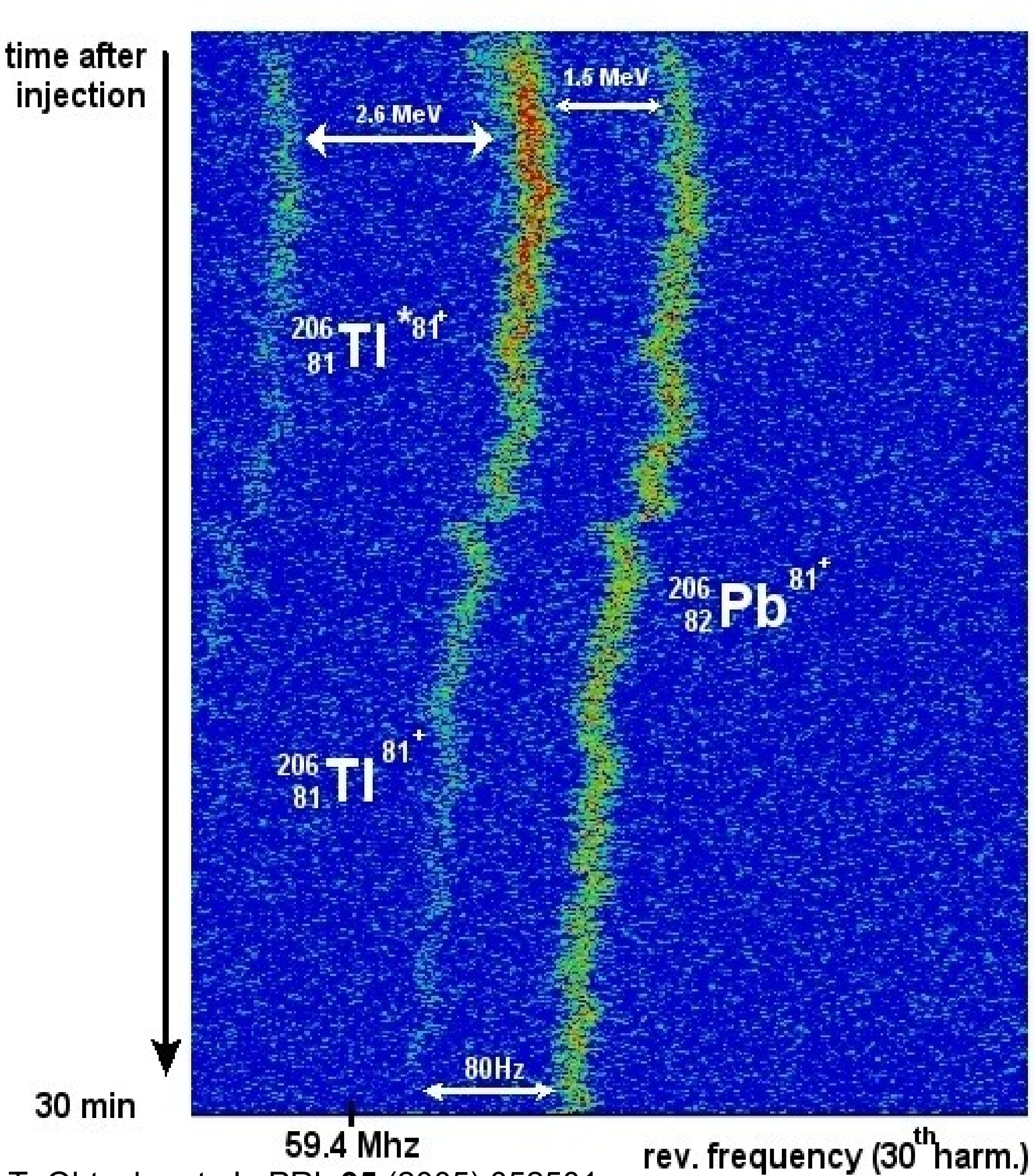
First **direct** observation of β_b decay

T. Ohtsubo et al., PRL **95**, 052501 (2005)

Hubble Space Telescop key project: δ Cepheids in M100 (Virgo)
W.L. Freedman 1994 (2000) → **H_0 = 72(7) km/s/Mpc**







T. Ohtsubo et al., PRL **95** (2005) 052501