Nikolai Kolachevsky

Lecture 6

- Pulsars as astrophysical sources of periodic pulses. Physics of pulsars.
- Drift of periastrium and General relativity tests. Radiation of gravitational waves.
- Quasar spectra. Search for drift of the fine structure constant.
- Calibration of astrophysical spectrometers. Search for exasolar planets.

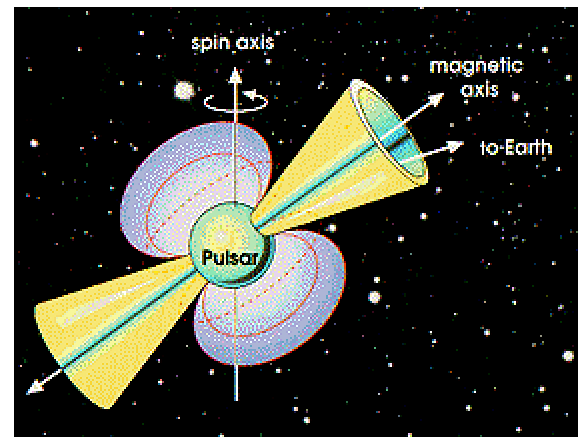
ФИАН

Pulsars – precise natural clocks in the Universe

Shortest observed pulse period **1.3ms**

PSR B1937+21

Speed on the surface < c!
=> R_{max}=50 km



Angular velocity:

$$\Omega = \sqrt{GM/R^3}$$

Mass:

$$M = 4\pi R^3 \rho/3$$

Highest density – neutron star density

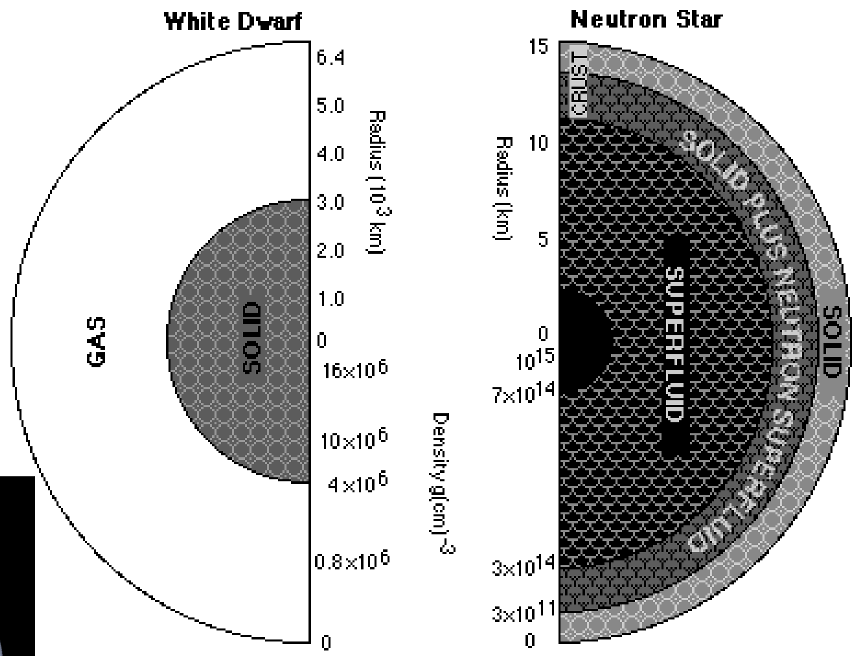
$$\rho \approx 10^{17}\ \mathrm{kg/m^3}$$

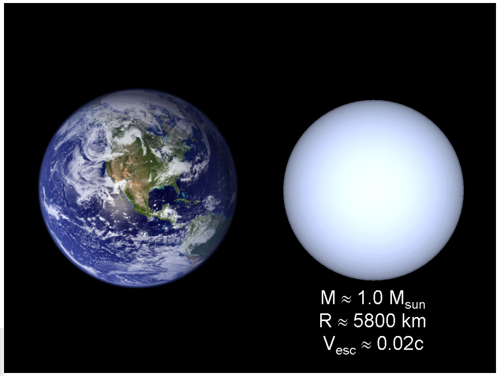
Rotation period ~ 1 ms – seems to be true!

Neutron stars and white dwarfs

Electron-degenerate matter

Neutron star – neutron-proton Fermi liquid





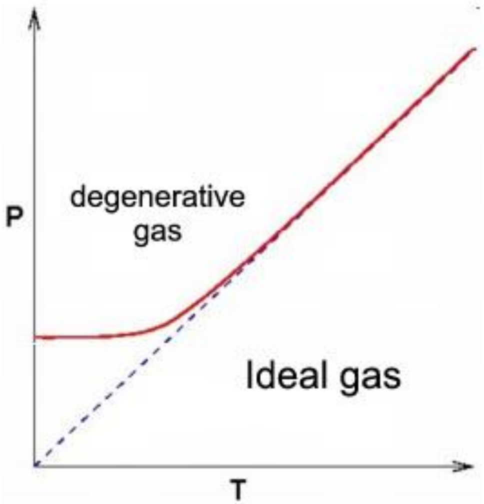
Equations of state a white dwarf

Electron-degenerate matter (electron-nuclei plasma)

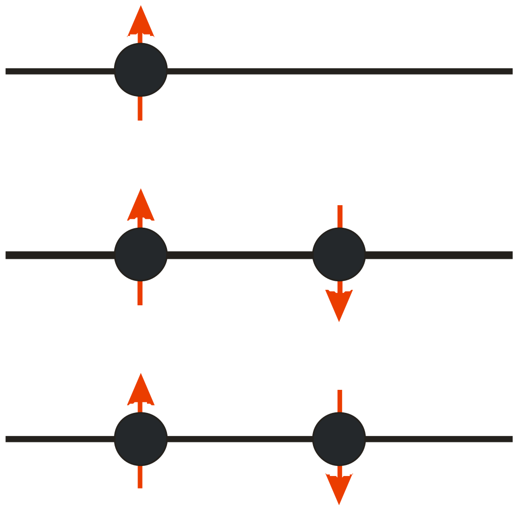
$\rho = 10^5 - 10^9$ g/cm^3

Non-relativistic case

$$P = K_1 \rho^{5/3}$$



High-energy electron move very fast



Relativistic regime!

Equations of state a white dwarf

Electron gas pressure

Relativistic case

$P = K_2 \rho^{4/3} \qquad \rho \sim M/R^3$

Pressure:

$P \sim M^{4/3}/R^4$

Gradient:

$$\frac{P}{R} \sim \frac{M^{4/3}}{R^5}$$

$$\sim M^{4/3}$$

Gravity

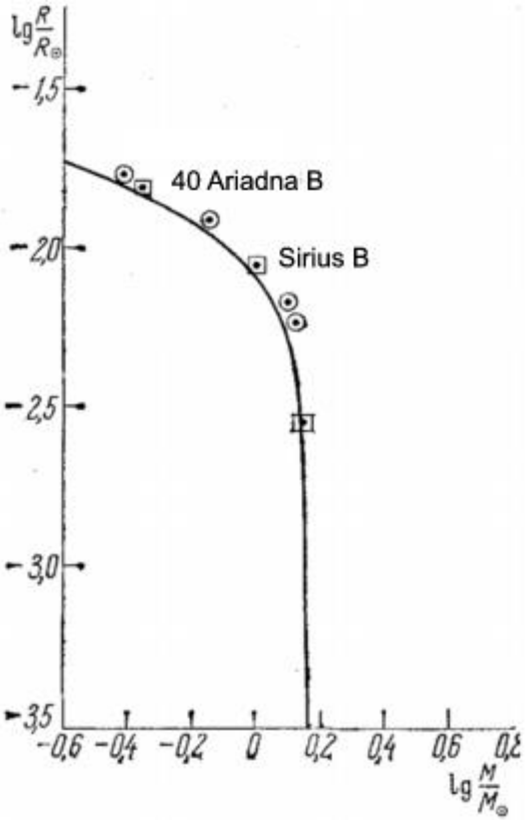
$$\frac{\rho G M}{R^2} \sim \frac{M^2}{R^5}$$

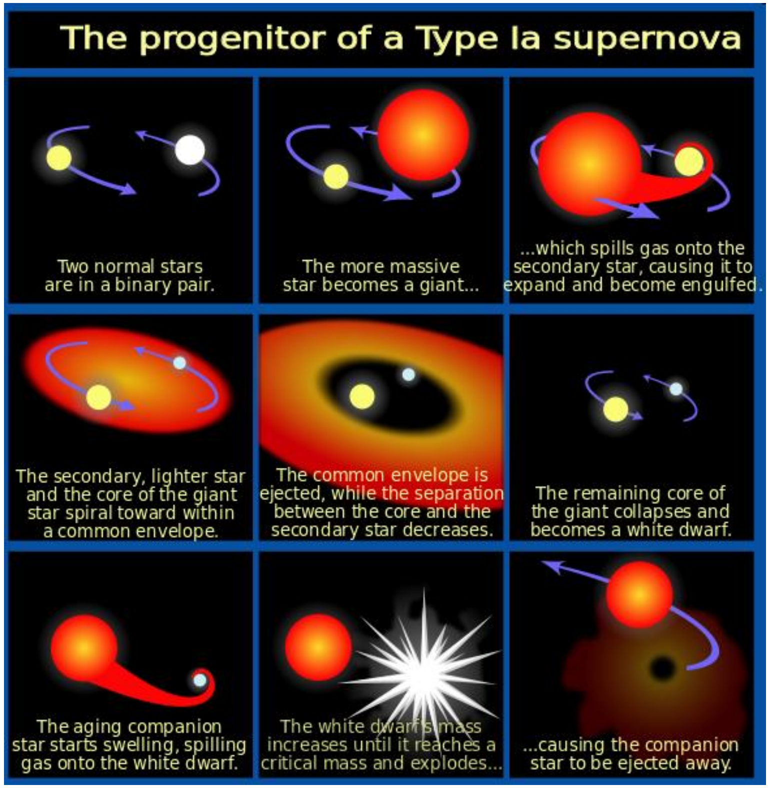
$$\sim M^2$$

Chandrasekar limit

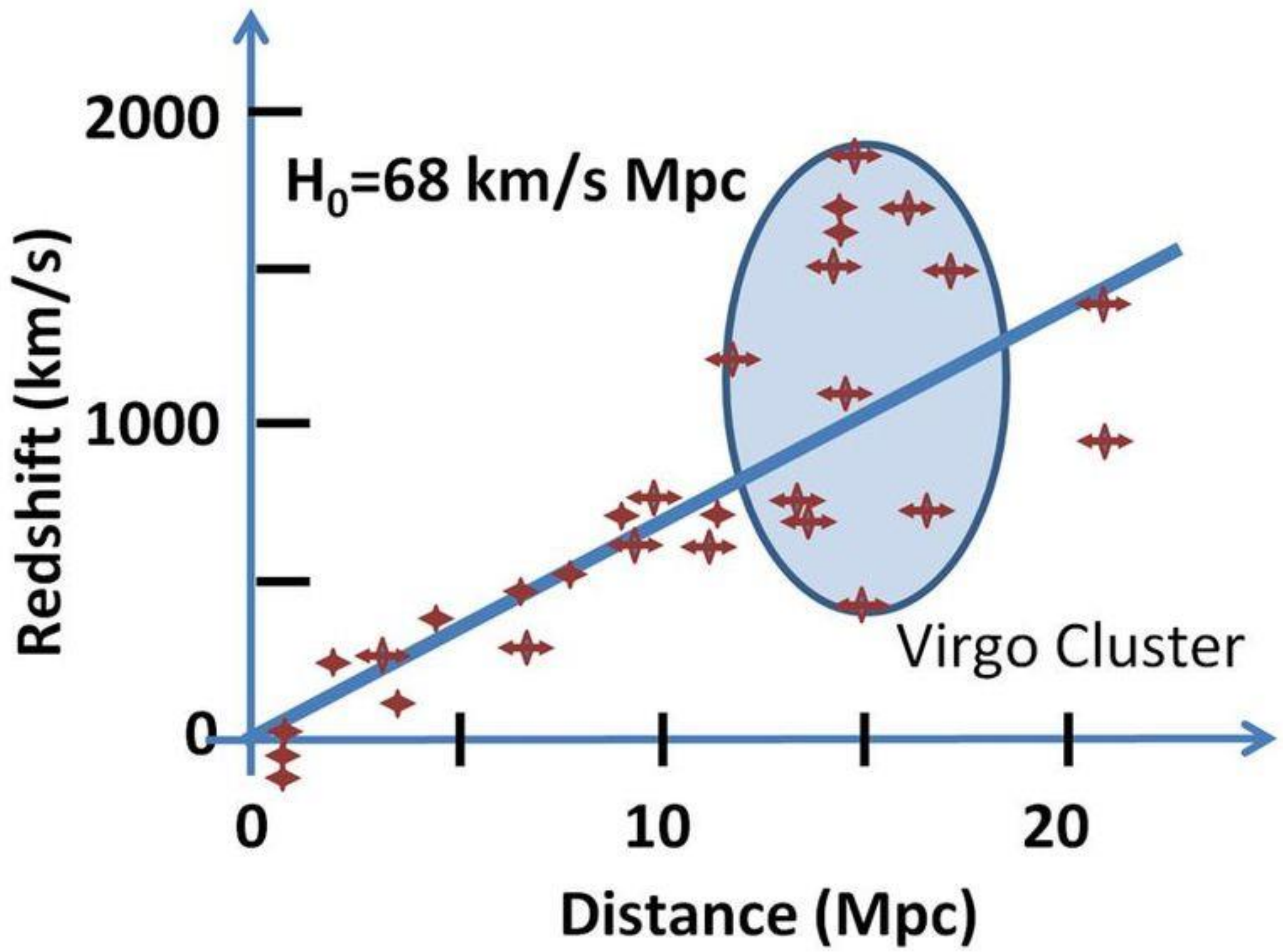
1.44 solar mass !

If mass becomes higher -> supernova class Ia
Standard candle



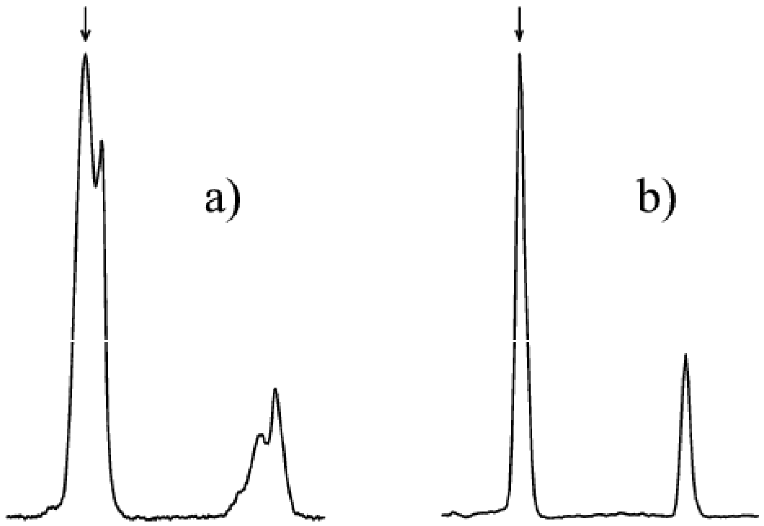


Hubble constant determination



Emission pattern

Pulsar’s “fingerprints”



Slow pulsars $(33 \text{ ms} < P < 5 \text{ s})$

Millisecond pulsars $1{,}5\,\text{ms}$ to $30\,\text{ms}$.

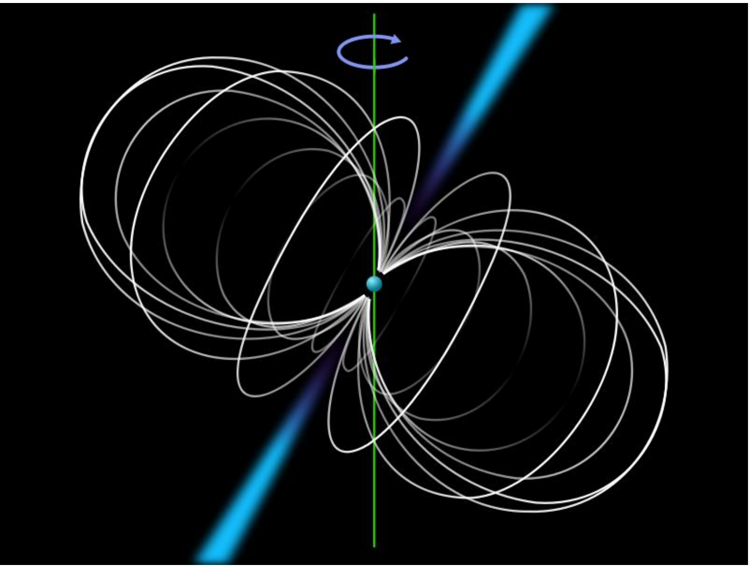
Millisecond pulsars are old (billion years), rather weak magnetic field

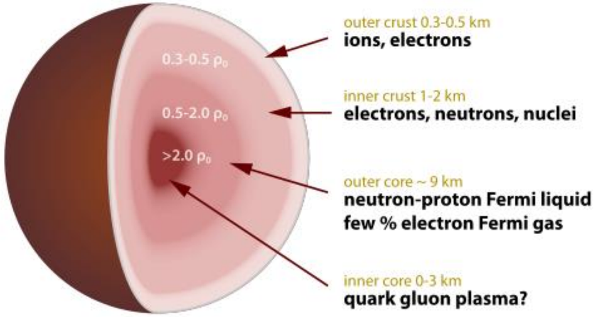
Period variation $\dot{P} \approx 10^{-19}\,\text{s/s}.$

Have orbital twins!

Pulsars: magnetic field increases!

$(p^+ + e^- \to n + \nu)$





Initial star (Solar radius)

$$R_i \approx 7 \cdot 10^8 \text{ m}$$

Pulsar

$$R_f \approx 5 \cdot 10^4 \text{ m}$$

Magnetic flow is conserved

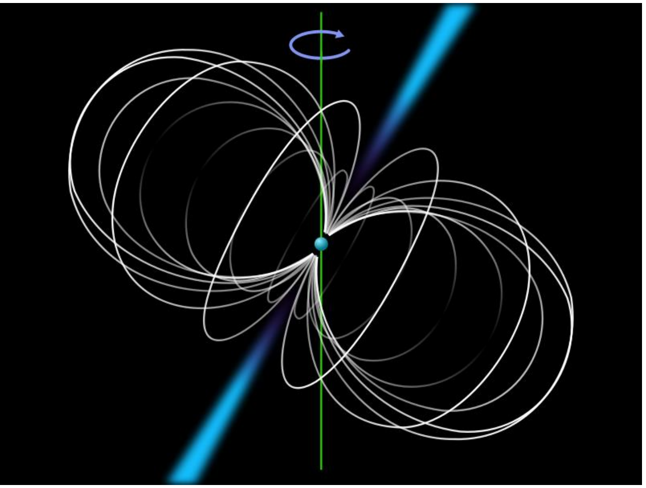
$$B_i 4\pi R_i^2 = B_f 4\pi R_f^2$$

Magnetic field can reach

$$B_f = 10^8 \text{ T}$$

Or even higher

Deceleration due to electromagnetic radiation emission



Rotating magnetic dipole $$\frac{dE}{dt} = \frac{2(M\sin\alpha)^2\Omega^4}{3c^2}$$

Energy taken from rotation $$E_{\rm rot} = \frac{1}{2}\Theta\Omega^2$$

Huge inertia moment $$8/15\pi\rho R^5 \approx 1,3\cdot 10^{38}\,\mathrm{kg\,m^3}$$

$$\frac{dE_{\rm rot}}{dt} = \Theta\Omega\dot{\Omega} = -4\pi^2\Theta\frac{\dot{P}}{P^2}$$

Energy dissipation $10^{23}\ \mathrm{W} \le \dot{E}_{\rm rot} \le 10^{26}\ \mathrm{W}$. Comparable to the Sun radiation

One can evaluate magnetic moment

$$\dot{\Omega} = \frac{2(M\sin\alpha)^2}{3\Theta c^3}\Omega^3$$

Pulsar chronometry

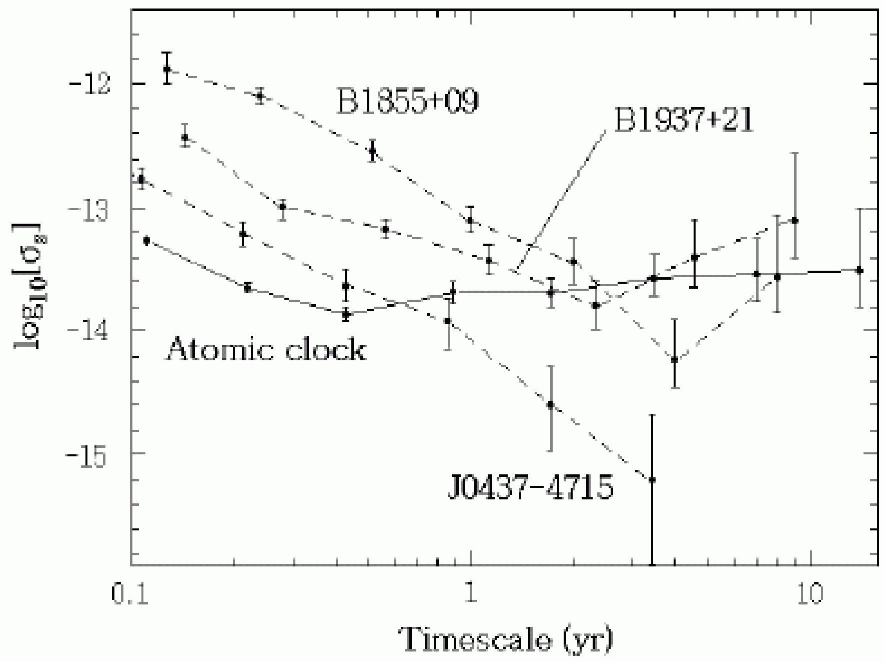
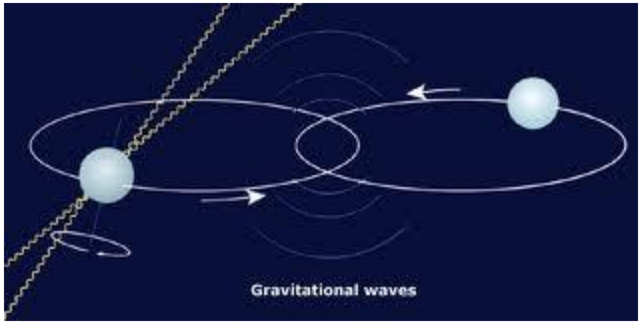
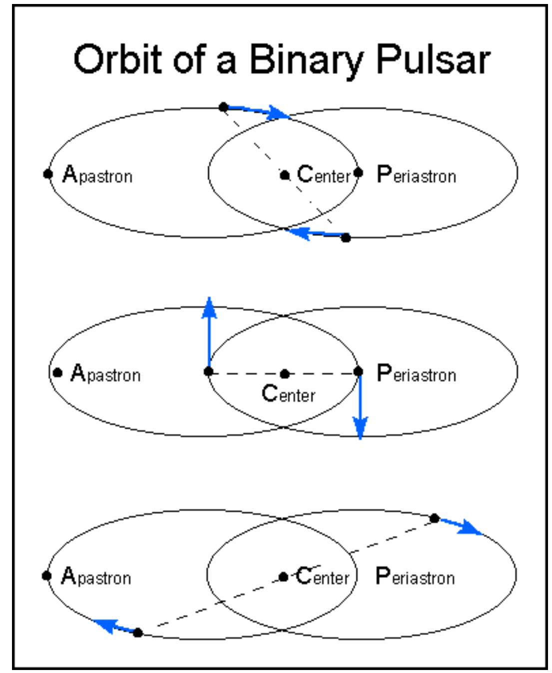


Fig. 1. Timing stability of radio signals from pulsars B1937+21, B1855+09, and J0437-4715, compared with that of an atomic clock.

Binary star system (binary pulsars)

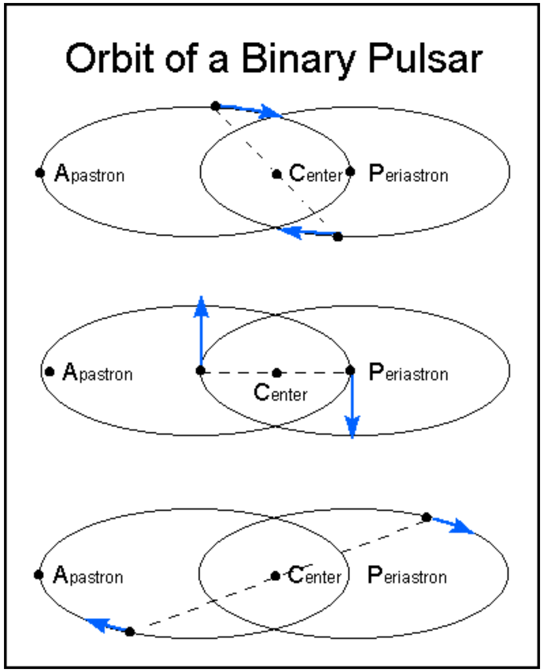


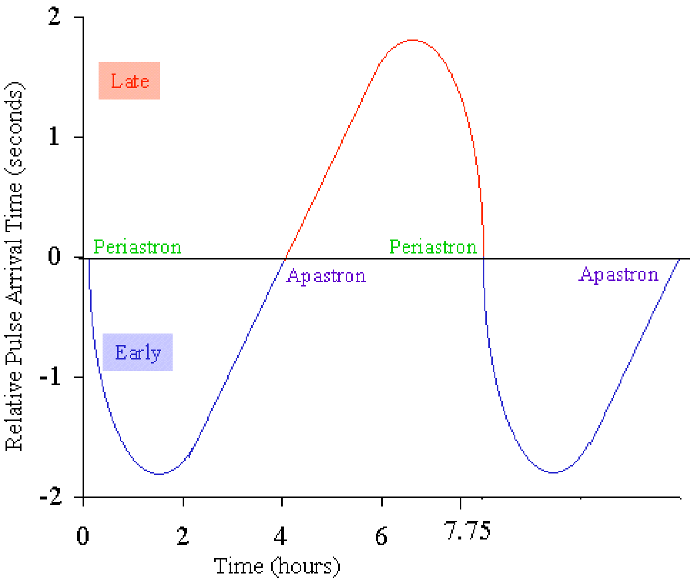
Hulse and Taylor -> Nobel Prize 1993



The period of the orbital motion is 7.75 hours, and the stars are believed to be nearly equal in mass, about 1.4 solar masses.

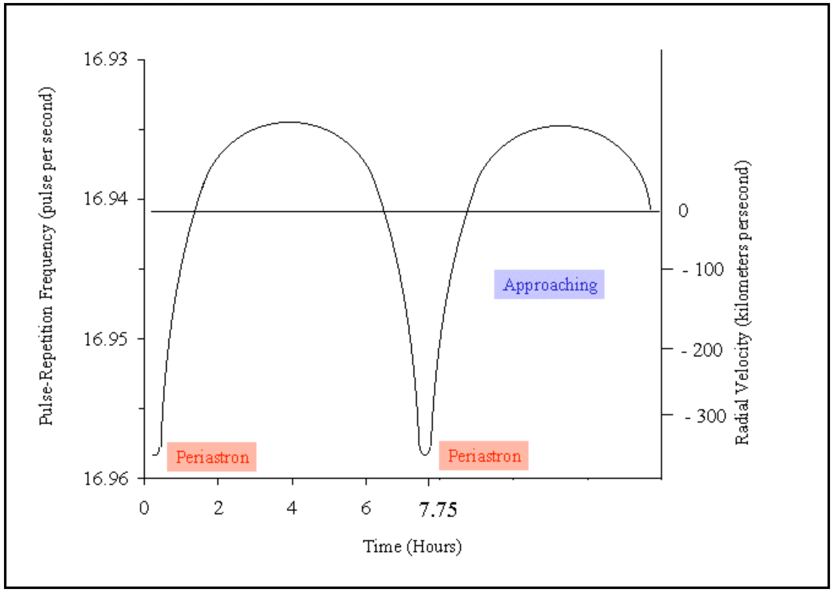
Arrival time variation



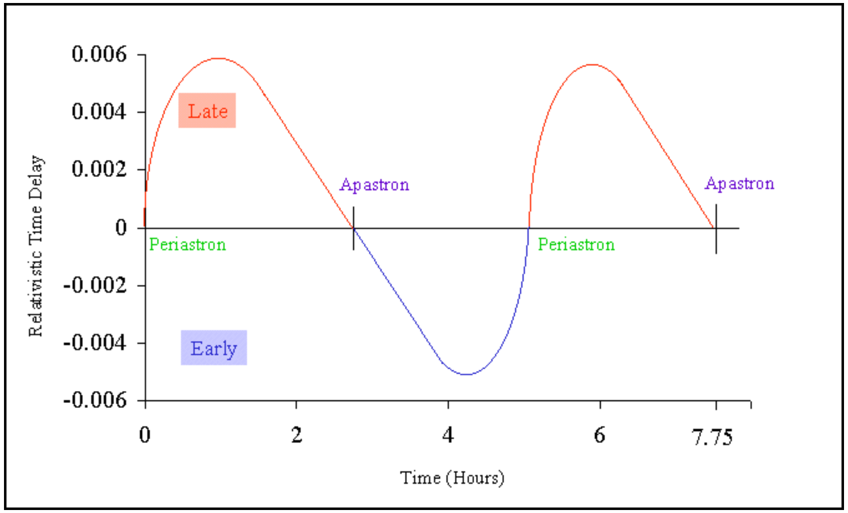


When the pulsar is on the side of its orbit closest to the Earth, the pulses arrive more than 3 seconds earlier that they do when it is on the side furthest from the Earth. The difference is caused by the shorter distance from Earth to the pulsar when it is on the the close side of its orbit. The difference of 3 light seconds implies that the orbit is about 1 million kilometers across.

Period variation

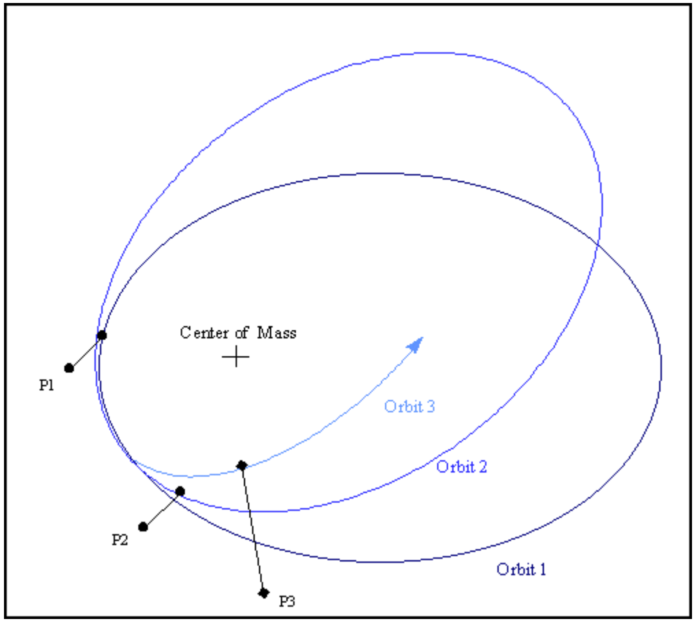


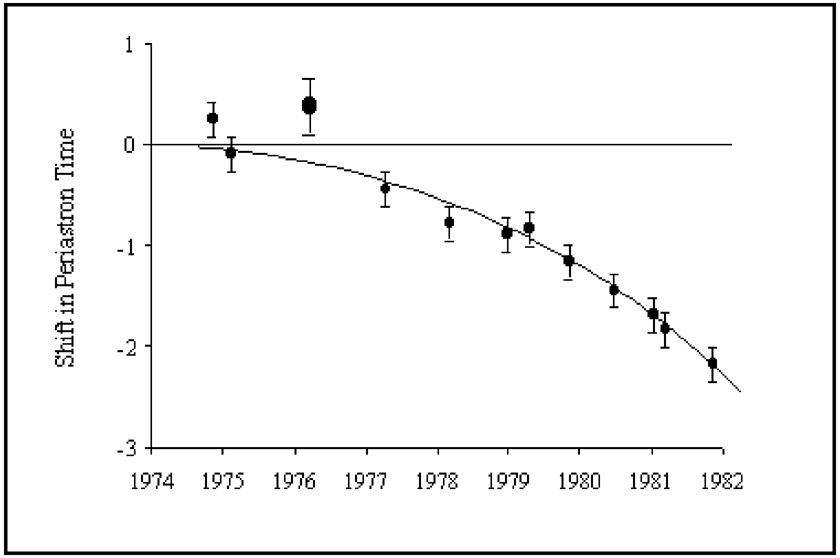
Velocity of the pulsar changes as it moves through its orbit. When the pulsar is moving towards us and is close to its periastron, the pulses should come closer together.



Gravitational field is stronger => the pasage of time is slowed down
The time between pulses (ticks) lengthens just as Einstein predicted.
The pulsar clock is slowed down when it is travelling fastest and in the strongest part of the gravitational field

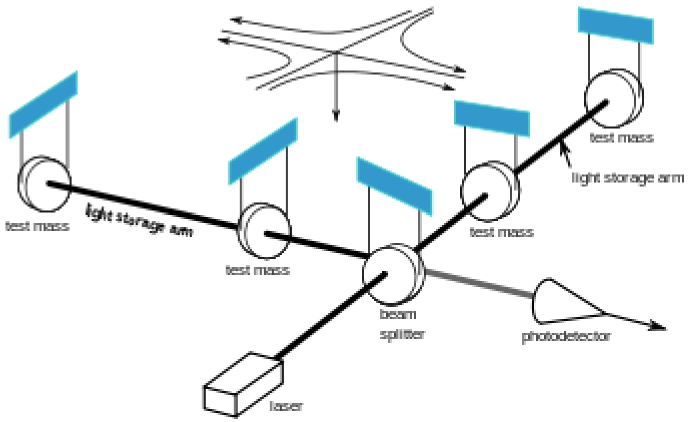
Rotation of periastron

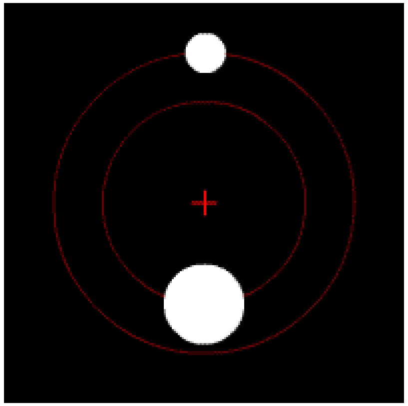


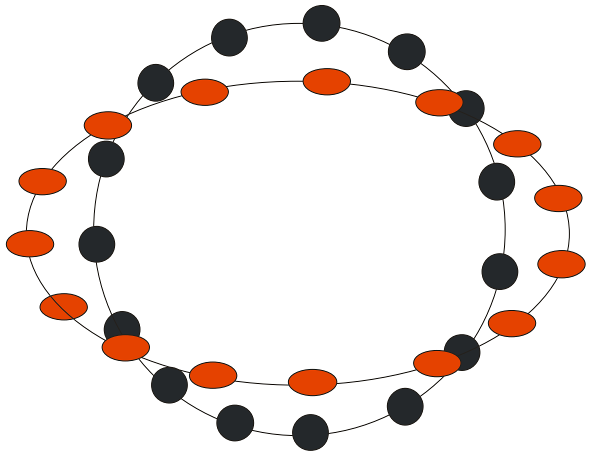


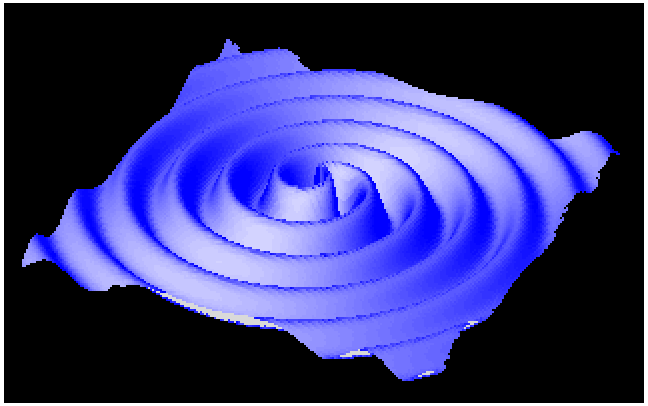
The observed advance for PSR 1913+16 is about 4.2 degrees per year; the pulsar's periastron advances in a single day by the same amount as Mercury's perihelion advances in a century.

Gravitational waves emission?









Power radiated by Gravitational waves emission?

Earth-Sun system

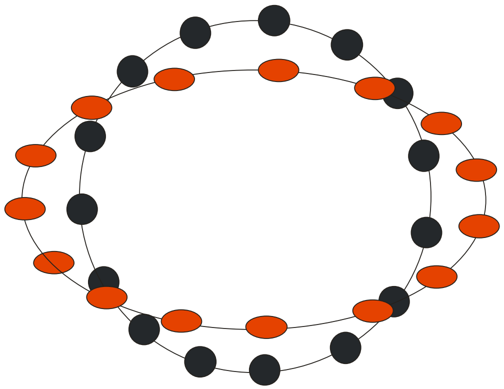
$$P = \frac{dE}{dt} = -\frac{32}{5}\frac{G^4}{c^5}\frac{(m_1 m_2)^2(m_1+m_2)}{r^5}$$

200 W power in gravitational waves

Wave amplitude

$$h_+ = -\frac{1}{R}\frac{G^2}{c^4}\frac{4m_1 m_2}{r} = -\frac{1}{R}1.7\times 10^{-10}\ \text{meters}$$

For the distance of 1 light year $h \sim 10^{-26}$



Search for the possible variation of the fine structure constant

Fundamental Constants in Quantum Mechanics

Schrödinger in atomic units:

$$E_{\mathrm{Bohr}} = -\frac{1}{n^2}$$

Use atomic units → no adjustable parameters !

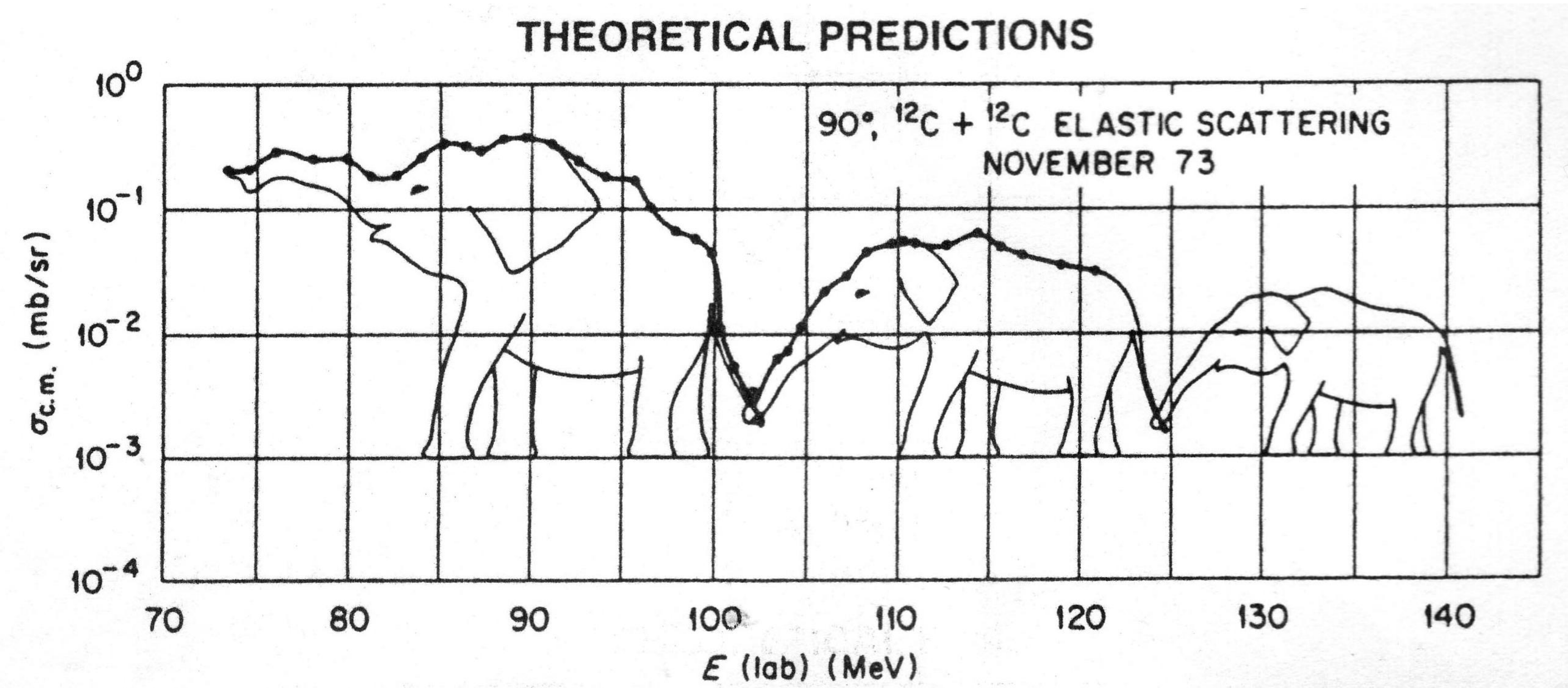
Full recoil and QED:

$$E_{\mathrm{QED}} = -\frac{1}{n^2} + \frac{3(2j+1) - 8n}{4(2j+1)n^4}\,\alpha^2 + \ldots$$

$$= -\frac{1}{n^2} + a_2\alpha^2 + a_4\alpha^4 + a_{50}\alpha^5 + a_{51}\alpha^5 ln(\alpha^{-2}) + \ldots$$

→ Adjust parameter α to match observations.

The Role of Parameters



- Parameters express our ignorance.
- The standard model has 18 of them.

What‘s the Problem
with the
Fundamental Constants ?

Fundamental Constants

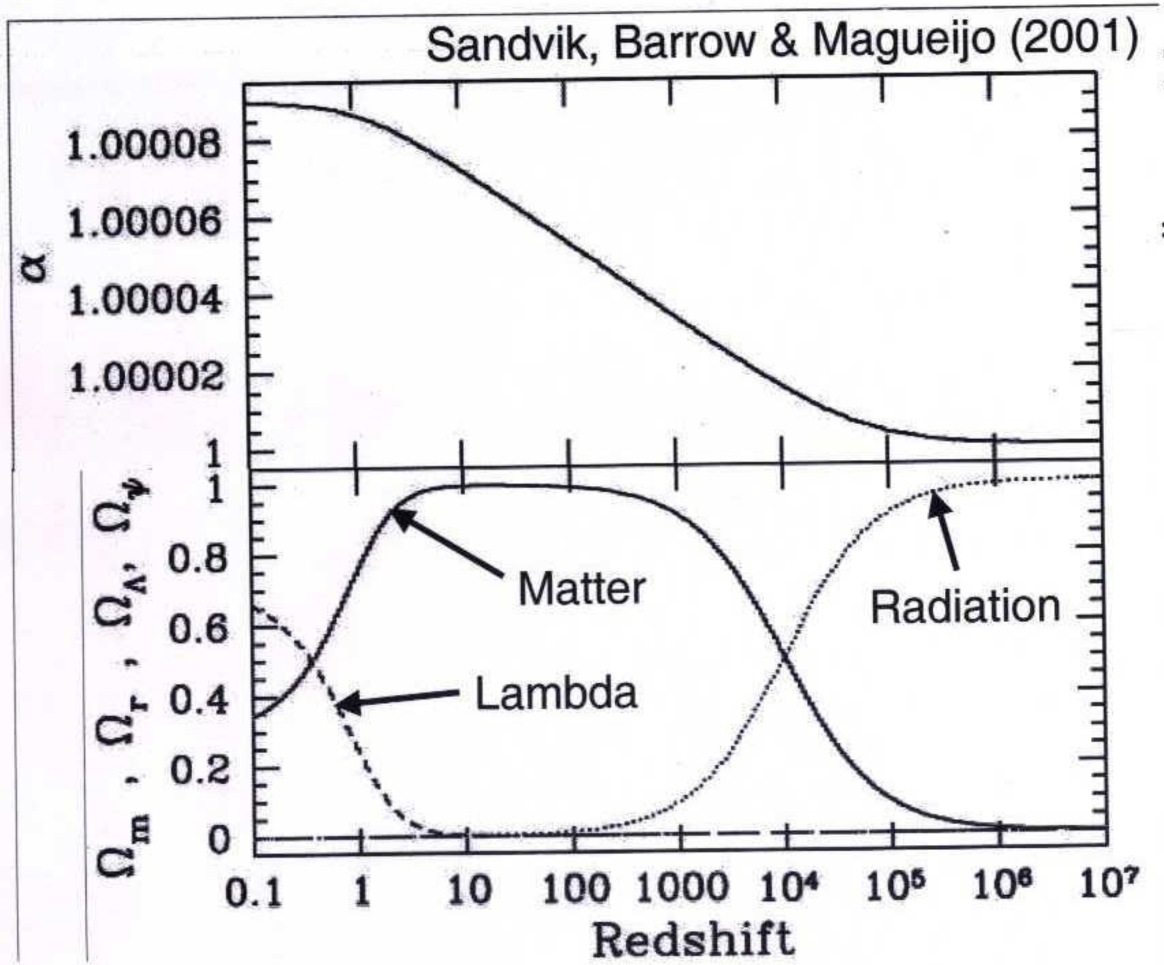
- Why do the constants have the observed values?
- Can‘t be calculated ⇒ standard model is incomplete.
- Look for phenomena beyond the standard model.
- A complete theory should produce small numbers. small numbers

Dirac 1937: The age of the universe in atomic units divided by the electromagnetic force between an electron and a proton measured in units of their gravitational force is such a small number (believed to be ≈ 3 in 1937).

⇒ Almost every „constant“ could vary in time.

Evolution of the Universe

Bekenstein model. Olive, Pospelov - driven by dark matter



$=e^2/\hbar c$

Search for Drift

$\Theta(t_1)$ $\Theta(t_2)$

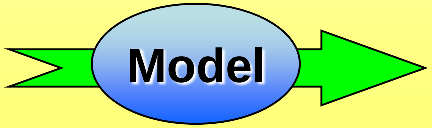
t_1 t_2 t

Θ - stable value (dimensionless)

$\Theta(\alpha_1, \alpha_2, \ldots)$ **depends on a set of fundamental parameters**

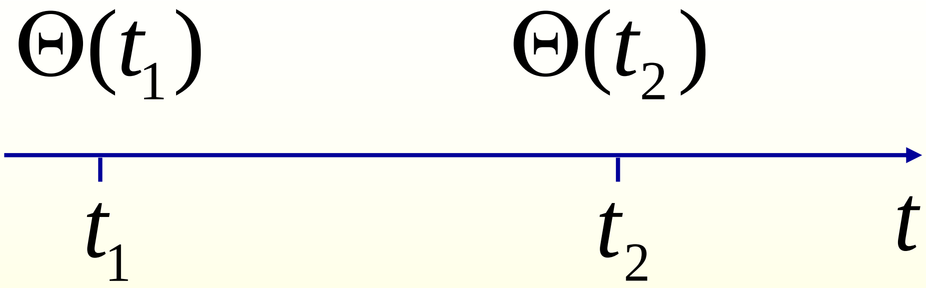
e.g.
cross-section ratio,
mass ratio,
frequency ratio, ...

$$\frac{\Theta(t_2) - \Theta(t_1)}{t_2 - t_1}$$



$$\frac{\partial \alpha_i}{\partial t}$$

Search for Drift



Θ - stable value (dimensionless)

e.g. cross-section ratio, mass ratio, frequency ratio, ...

$\Theta(\alpha_1, \alpha_2, \ldots)$ **depends on a set of fundamental parameters**

---

the value of α is known to 4·10^{-10} (40 years => $\frac{\dot{\alpha}}{\alpha} = 10^{-11}\ \text{yr}^{-1}$**)**

D.Hanneke et al., PRL 100, 120801 (2008)

Sensitivity to the DRIFT is much higher! $\frac{\Delta\Theta}{\Theta} = 10^{-17}$

Sensitivity to α variations for different methods

Oklo Phenomenon

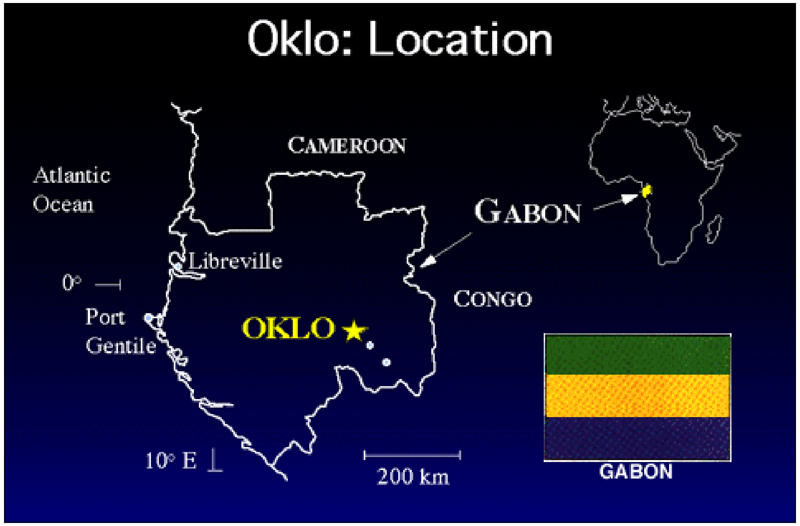
Natural fission $^{235}U/^{238}U$ reactor

$2 \cdot 10^9$ years ago

$$n + {}^{149}_{62}\mathrm{Sm} \rightarrow {}^{150}_{62}\mathrm{Sm} + \gamma$$

resonance by 0.1 eV

A.I. Shlyakhter, *Nature* (London), **264**, 340 (1976)



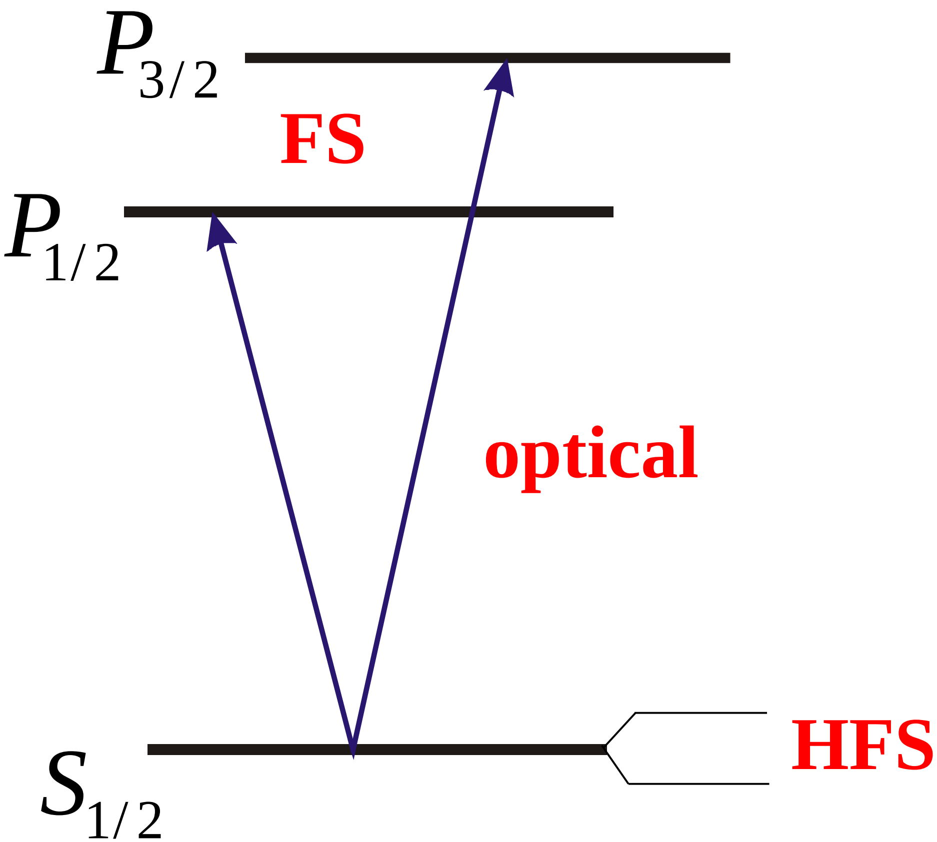
Abundance ratio:

$${}^{149}_{62}\mathrm{Sm} / {}^{147}_{62}\mathrm{Sm} \quad \rightarrow \quad \textbf{0.02} \text{ (Oklo)}, \quad \textbf{0.9} \text{ (typical)}$$

$$\Delta\alpha/\alpha = (-0.36 \pm 1.44) \cdot 10^{-8}$$

Y.Fujii *et al.*, *Nucl. Phys.* B, **573, 377 (2000)**

Atomic Spectra



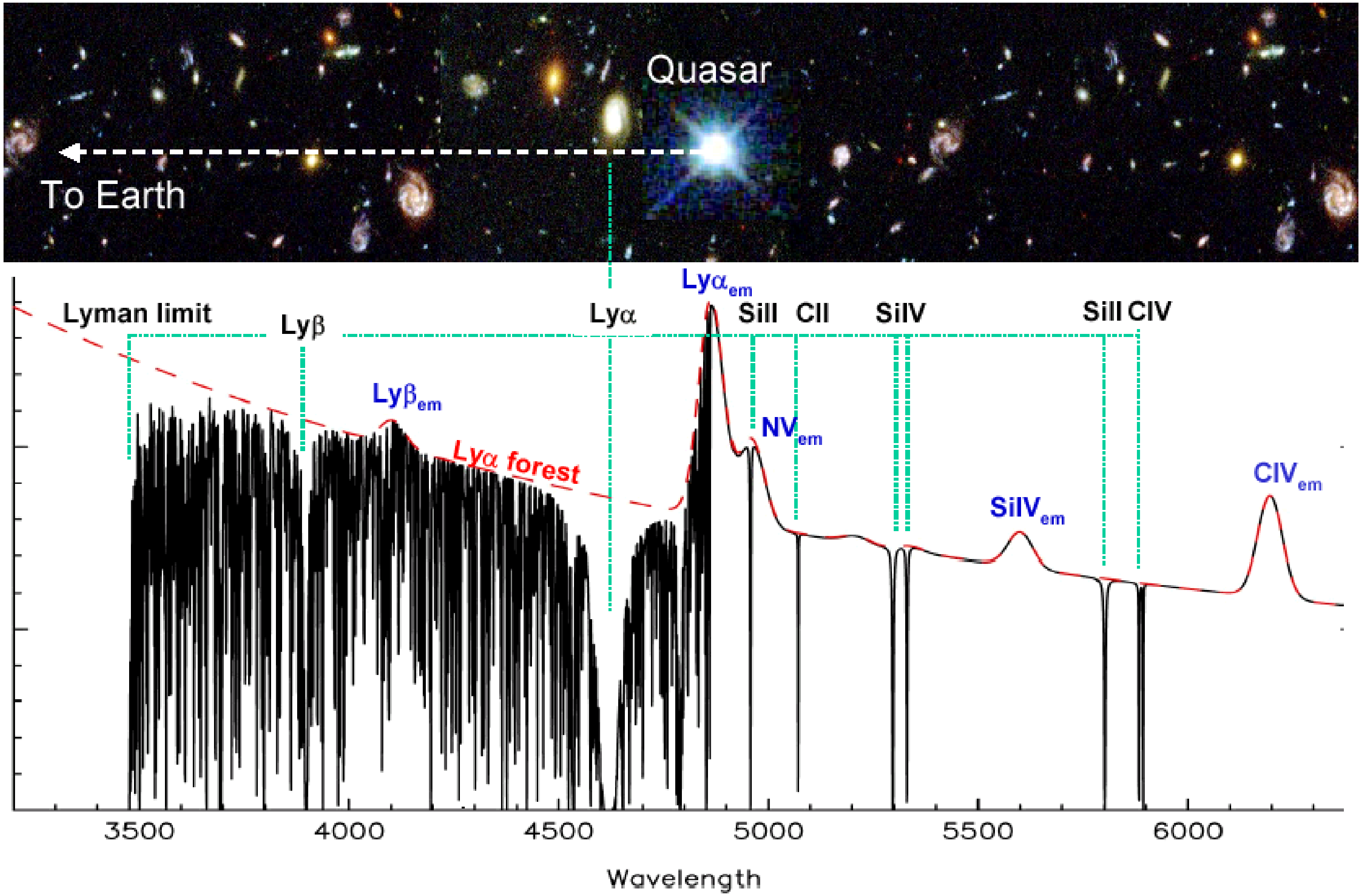
$$z = \frac{\nu_{emission}}{\nu_{today}} - 1$$

Transition	Scaling
Optical	Ry
Fine structure	$\alpha^2 Ry$
Hyperfine structure	$\mu_{nucl} / \mu_B \, \alpha^2 Ry$

$$\frac{\text{FS}}{\text{optical}} \sim \alpha^2$$

M.P. Savedoff, *Nature*, **178,** 689 (1956)

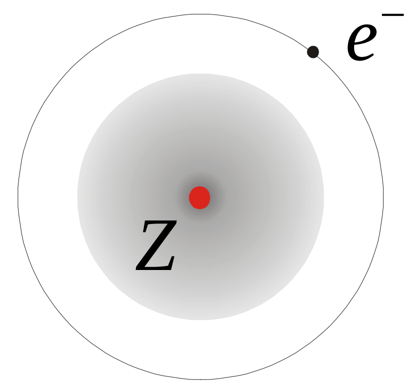
Quasar Absorption Spectra



J.K. Webb *et al.*, *Phys. Rev. Lett.* **87**, 091301 (2001)

"Many-Multiplet" Method

$$f = f_{NR} \cdot F_{rel}(Z\alpha)$$



$F_{rel}(Z\alpha)$ **depends only on** α

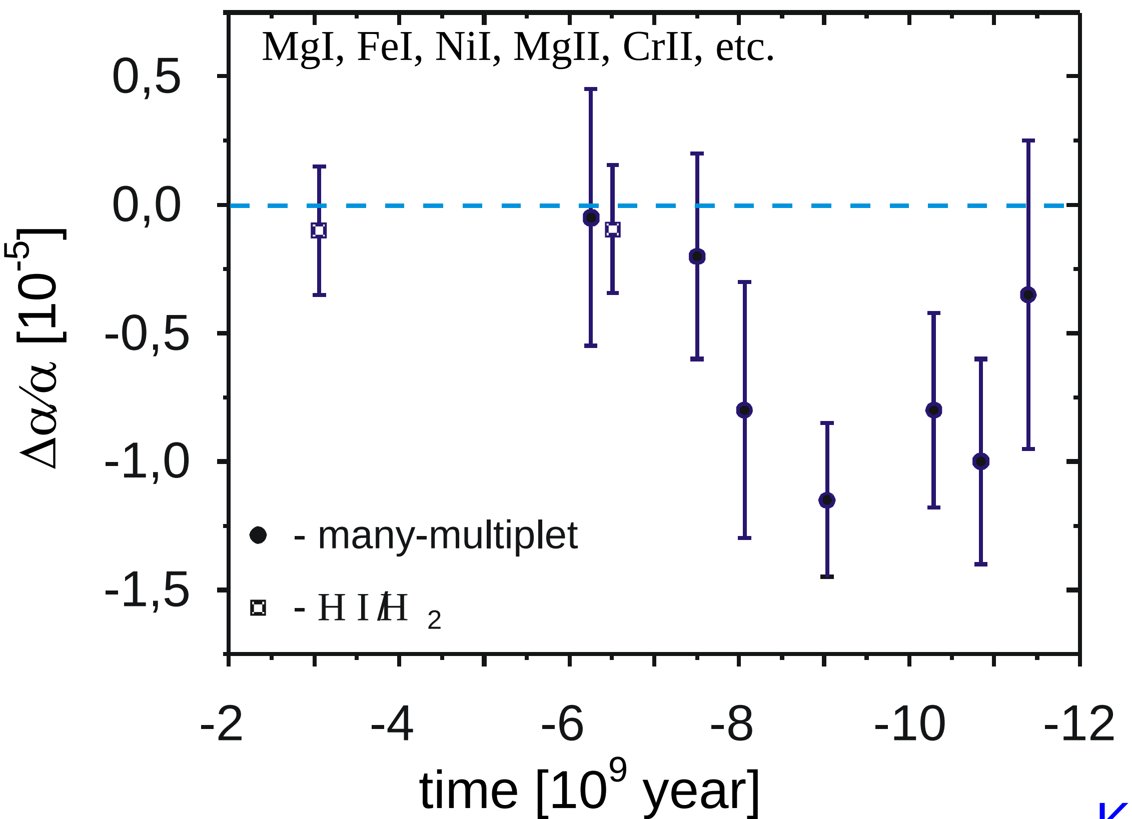
$$\frac{\partial}{\partial t} \ln \frac{f_1}{f_2} = \frac{\partial \ln \alpha}{\partial t} \times \frac{\partial}{\partial \ln \alpha} \ln \frac{F_{rel}(1)}{F_{rel}(2)}$$

measurable value

to be determined

calculated from basic principles

Keck/HIRES results



Keck / HIRES (72 systems):

$$\Delta\alpha/\alpha = (-0.57 \pm 0.1)\cdot 10^{-5}$$

$$\dot{\alpha}/\alpha \;\square\; 0.5\cdot 10^{-15}\ \text{yr}^{-1}$$

J.K. Webb *et al.*, *Phys. Rev. Lett.* **87**, 091301 (2001)

Recent astrophysical results

- Murphy et al, 2003: **Keck telescope,** 143 systems, 23 lines, $0.2<z<4.2$

  $$\Delta\alpha/\alpha = -0.543(0.116) \times 10^{-5}$$

- Quast et al, 2004: **VLT telescope,** 1 system, Fe II, 6 lines, z=1.15

  $$\Delta\alpha/\alpha = -0.4(1.9)(2.7) \times 10^{-6}$$

- Srianand et al, 2004: **VLT telescope,** 23 systems, 12 lines, Fe II, Mg I, Si II, Al II, $0.4<z<2.3$

  $$\Delta\alpha/\alpha = -0.6(0.6) \times 10^{-6}$$

Comparison of sensitivities

Astrophysical

(many-multiplet)

$\Delta\alpha/\alpha \sim 10^{-6}$

$\Delta T \sim 10^{10}$ yr

J.K. Webb *et al.*, *Phys. Rev. Lett.* **87**, 091301 (2001)

Geological

(Oklo)

$\Delta\alpha/\alpha \sim 10^{-8}$

Y.Fujii *et al.*, *Nucl. Phys.* B, **573**, 377 (2000)

Laboratory

$\Delta\alpha/\alpha < 10^{-16}$

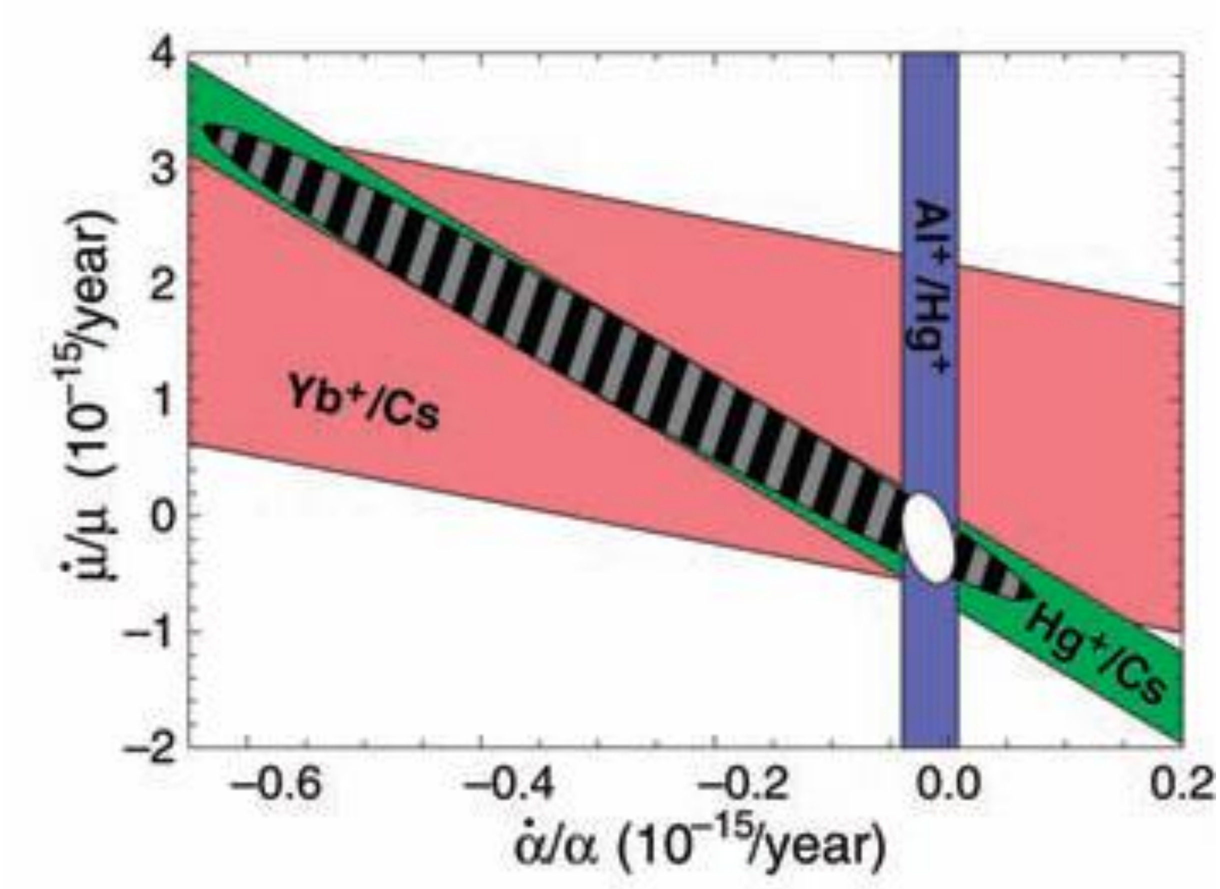
$\Delta T \sim 10$ yr

Optical Frequency Metrology

Laboratory experiments

- **high sensitivity to drift (< 10^{-16})**
- **short time intervals (~10 yrs)**
- **high reproducibility, big variety of samples**
- **straightforward analysis of systematics**
- **weak model dependence**

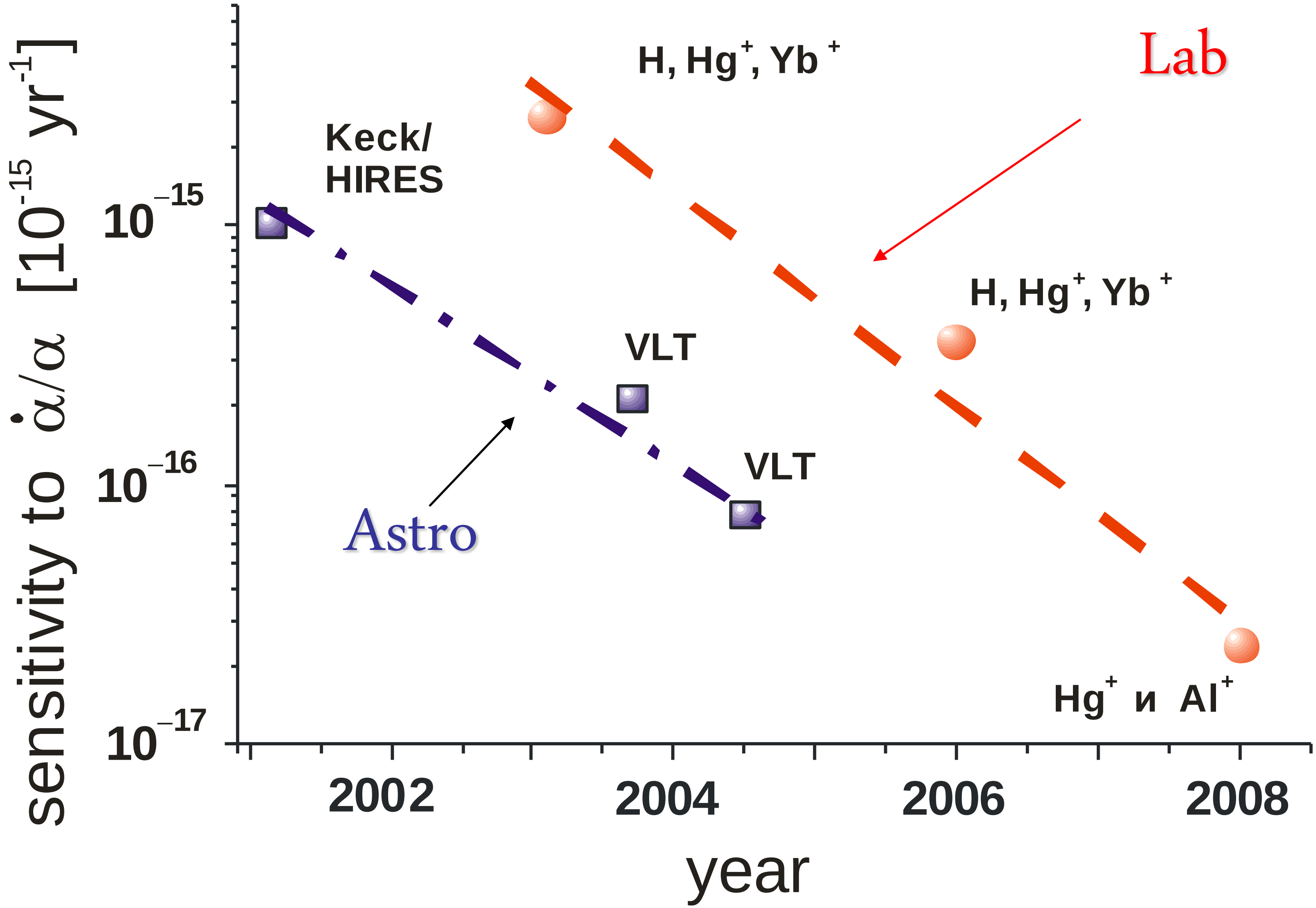
Ellipse Plot



$$\dot{\mu}/\mu = (-1.9 \pm 4.0)\cdot 10^{-16}\ \ \mathrm{yr}^{-1}$$

T. Rosenband et al. SCIENCE 319, 1808 (2008)

Sensitivity to linear drift



Laser Frequency Combs for Astronomical Observations

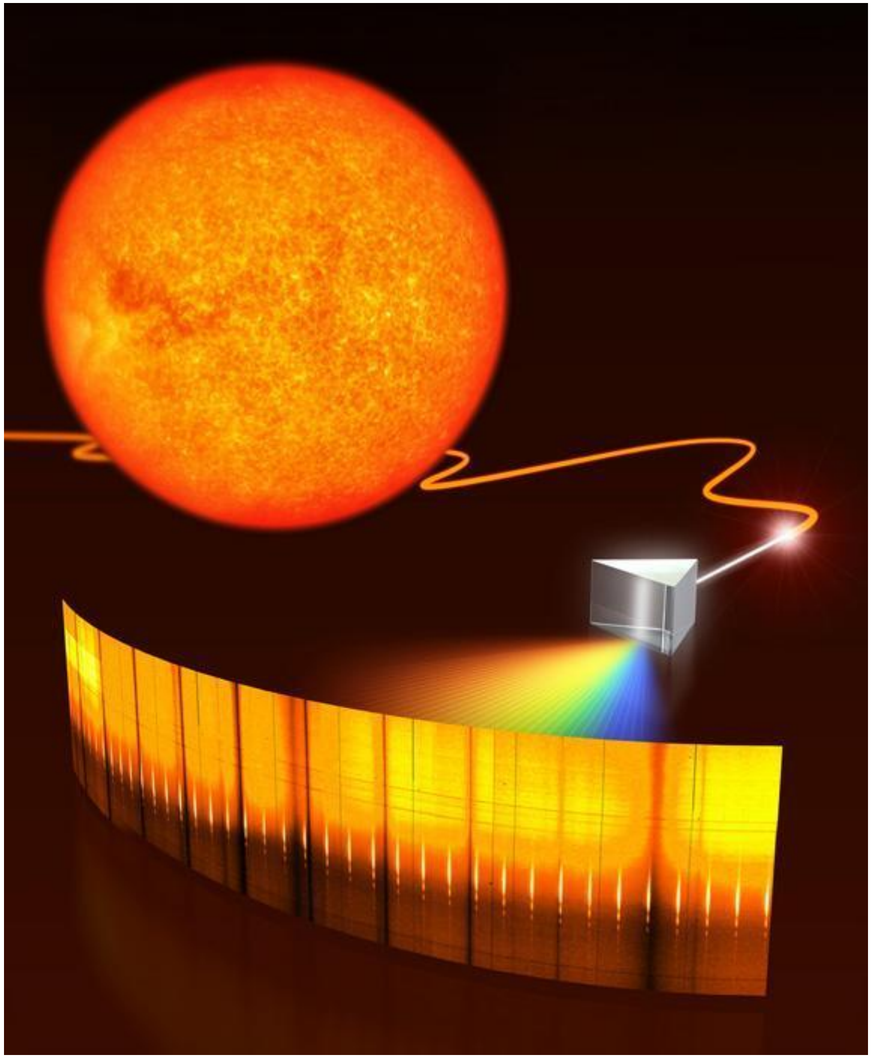
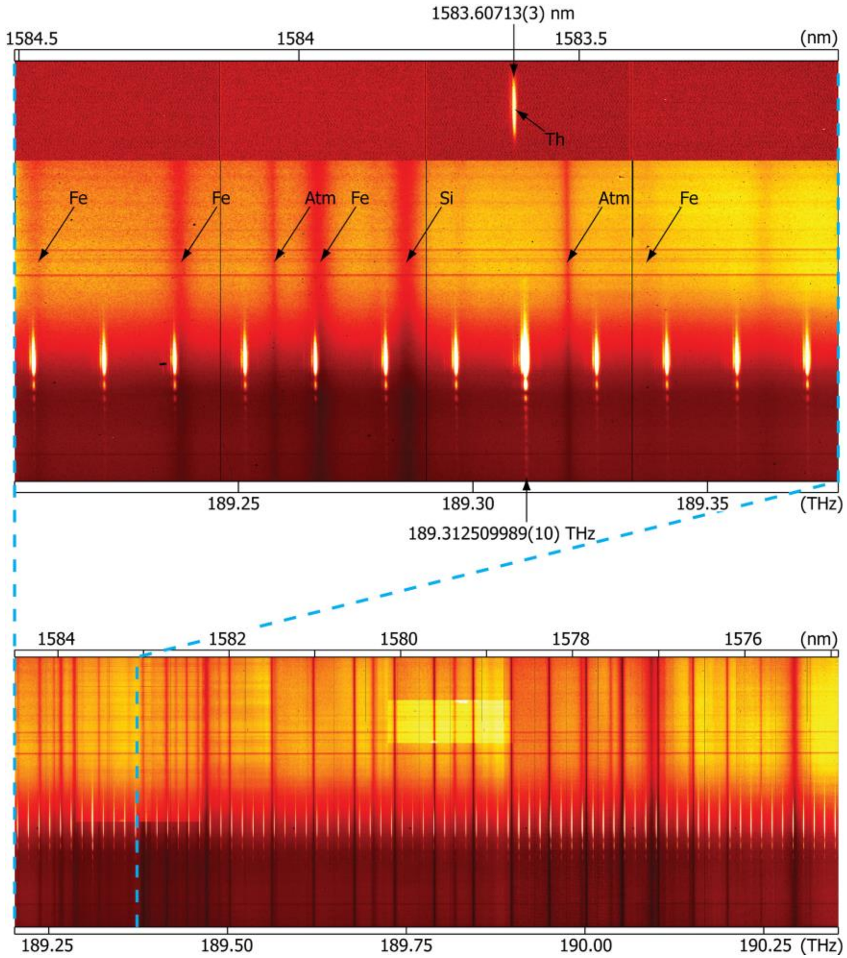


Image: ESO



T. Steinmetz et al, SCIENCE 321, 5894 (2008)