Clocks and Gravity

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Airlie
From Quantum to Cosmos, May 22. – 24. 2006

Clocks and Gravity

Well known issues

- Gravitational redshift
  - Important effect within Einstein's General Relativity
  - Needed for clock synchronization on Earth
  - Needed for GPS
- Universality of gravitational redshift
  - Important for the structure of General Relativity

Points made here

- Clocks are a universal tool
- Clocks have many important practical applications
- Most space missions may profit from clocks onboard
- Time and position are independent observables
- Technology and Fundamental Physics

Outline

1. The situation of standard physics
   - The status
   - Applications
   - Problems?

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   - On strategies for the search for QG effects
   - Observation vs. Experiment

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   - Observation vs. Experiment
3. Space conditions
4. Gravity anomalies (in Universe and within Solar system)
   - Anomalies
   - Solar system anomalies

Outline

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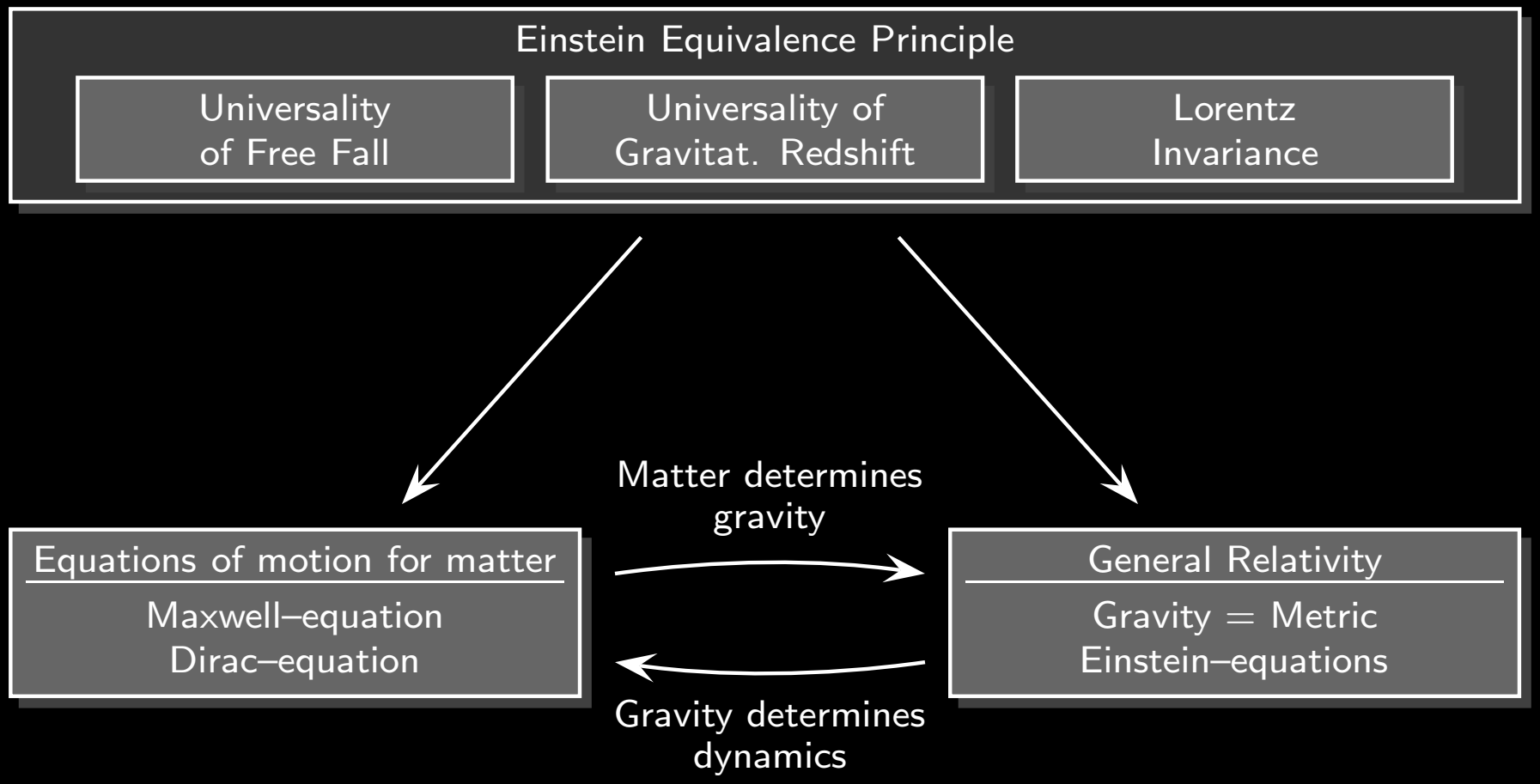
Structure of standard physics



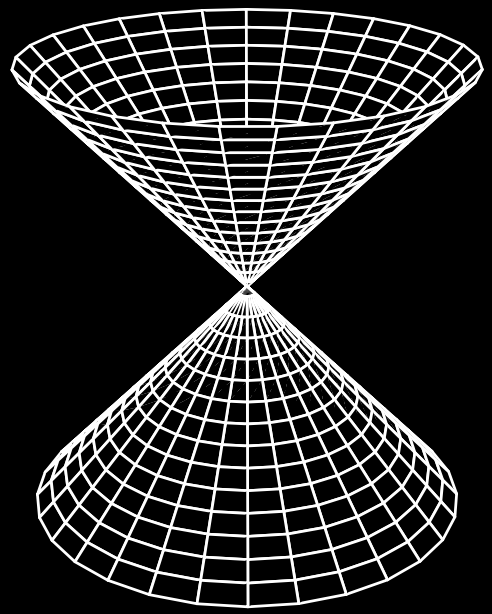
The present situation

All aspects of Lorentz invariance are experimentally well tested and confirmed

Foundations

Postulates

- $c = const$
- Principle of Relativity



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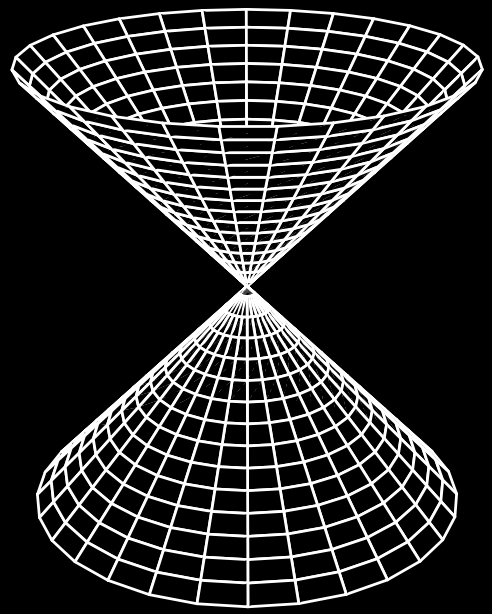


Tests = Clock tests

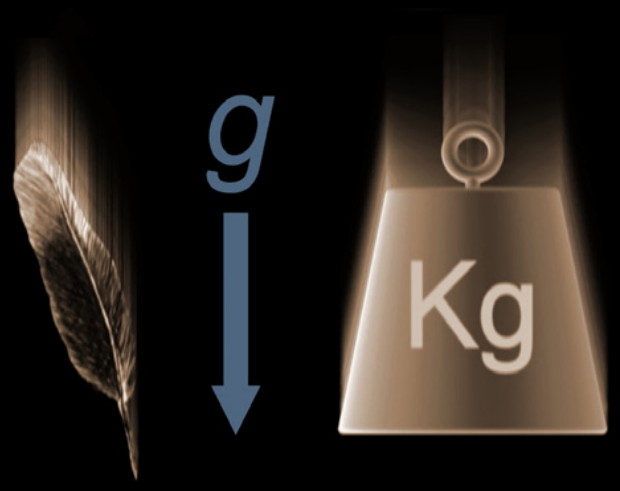
- Independence of c from velocity of the source
- Universality of c
- Isotropy of c
- Independence of c from velocity of the laboratory
- Time dilation
- Isotropy of physics (Hughes–Drever experiments)
- Independence of physics from the velocity of the laboratory

The present situation

Many aspects of the Universality of Free Fall are experimentally well tested and confirmed

Postulate

In a gravitational field all structureless test particles fall in the same way



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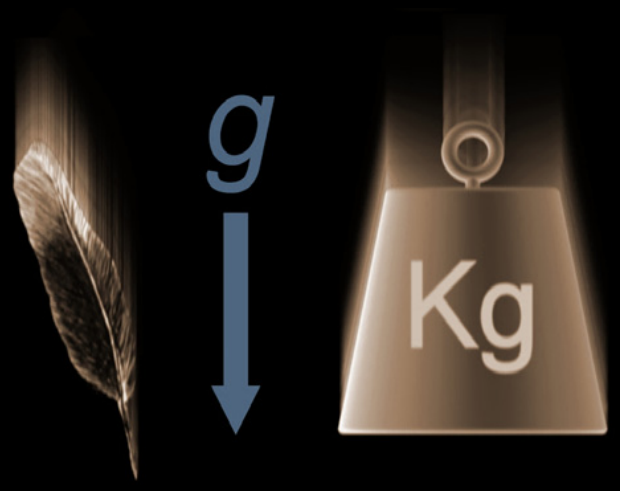

Tests

UFF for

- Neutral bulk matter
- Charged particles
- Particles with spin

No test so far for

- Anti particles

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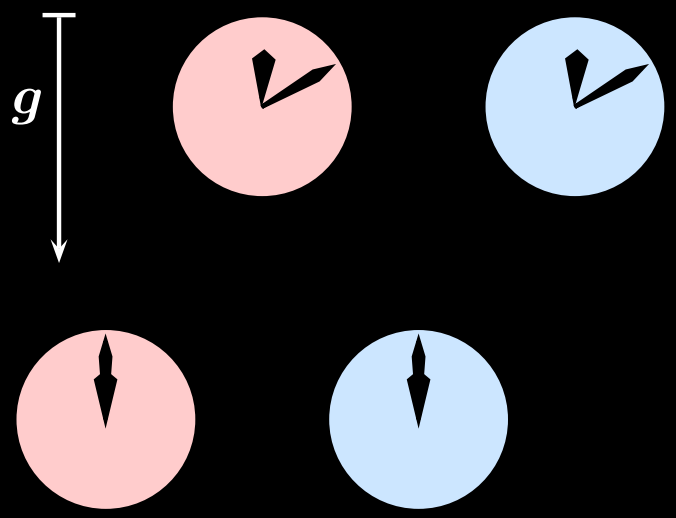
Many aspects of the Universality of the Gravitational Redshift are experimentally well tested and confirmed

Postulate

In a gravitational field all clocks behave in the same way



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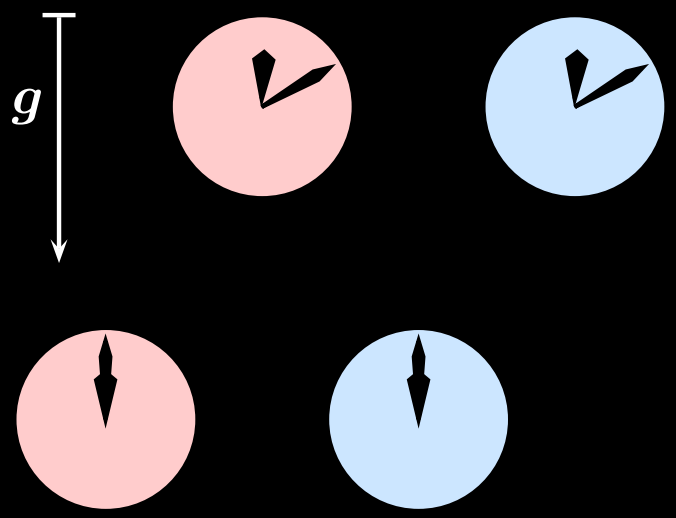


Tests (= Clock tests)

UGR for

- Atomic clocks: electronic
- Atomic clocks: hyperfine
- Molecular clocks: vibrational
- Molecular clocks: rotational
- Resonators
- Nuclear transitions (Mössbauer effect)

No test so far for

- Anti clocks

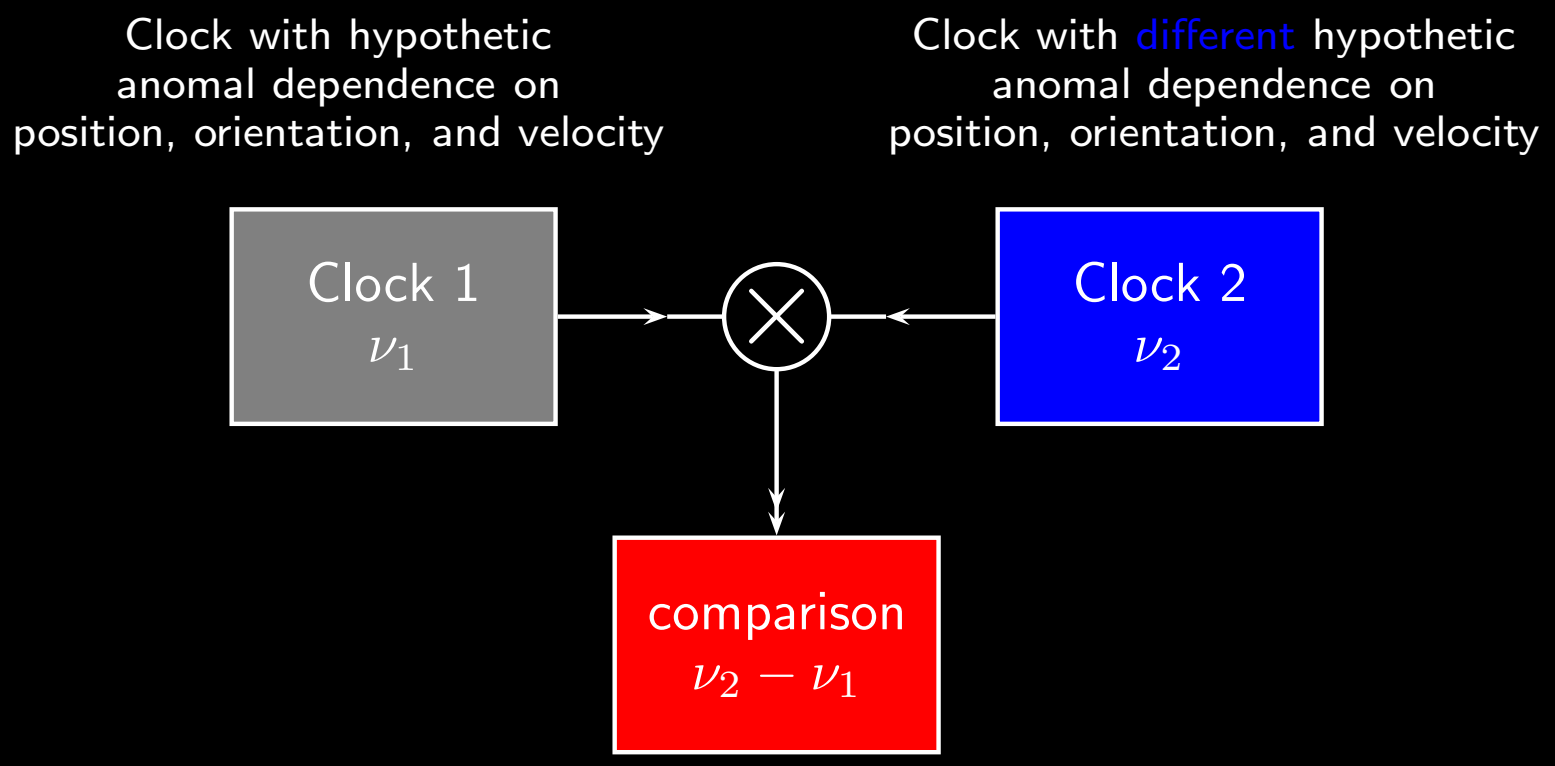
Universal tool

Clocks are a universal tool for testing space–time properties

GR: Physics of position and time (trajectories of particles and light rays)

SR: Based solely on clock camparison experiments

UGR: clock comparison experiment



Clocks

Clocks of different nature exhibit a different dependence on fundamental constants

Scaling of transition energies (in units of Rydberg energy)

Hyperfine energies $g(m_e/m_p)\alpha^2 f(\alpha)$

Vibrational energies in molecules $\sqrt{m_e/m_p}$

Rotational energies in molecules m_e/m_p

Fine-structure energies α^2

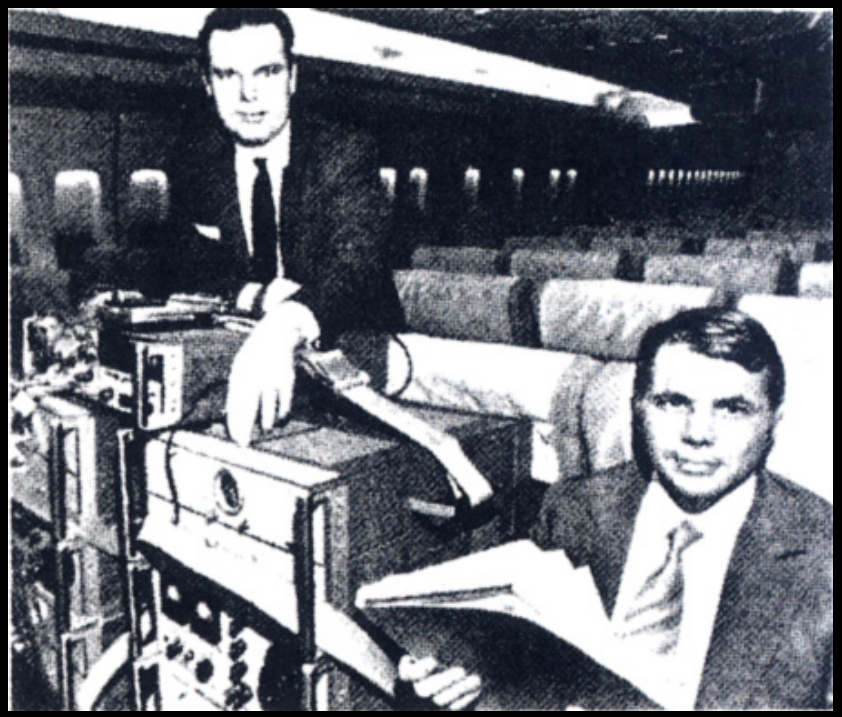
Electronic energies (incl. relativistic effects) $f(\alpha)$

Cavity frequency $1/\alpha$

Weak interaction splitting/Zeeman frequency G_{F}

Test of time–dilation: Transport of clocks

Development of good clocks ⇒ clocks on aircraft: Experiment by Hafele and Keating 1968 to test time dilation



We shall do the same today: Put the best clocks on spacecraft and test clock effects!

The present situation

All predictions of Einstein's General Relativity are experimentally well tested and confirmed

Foundations

The Einstein Equivalence Principle

- Universality of Free Fall
- Universality of Gravitational Redshift
- Local Lorentz Invariance

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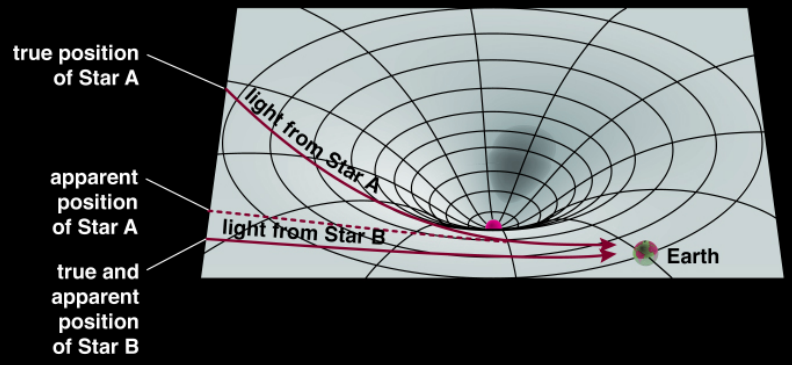
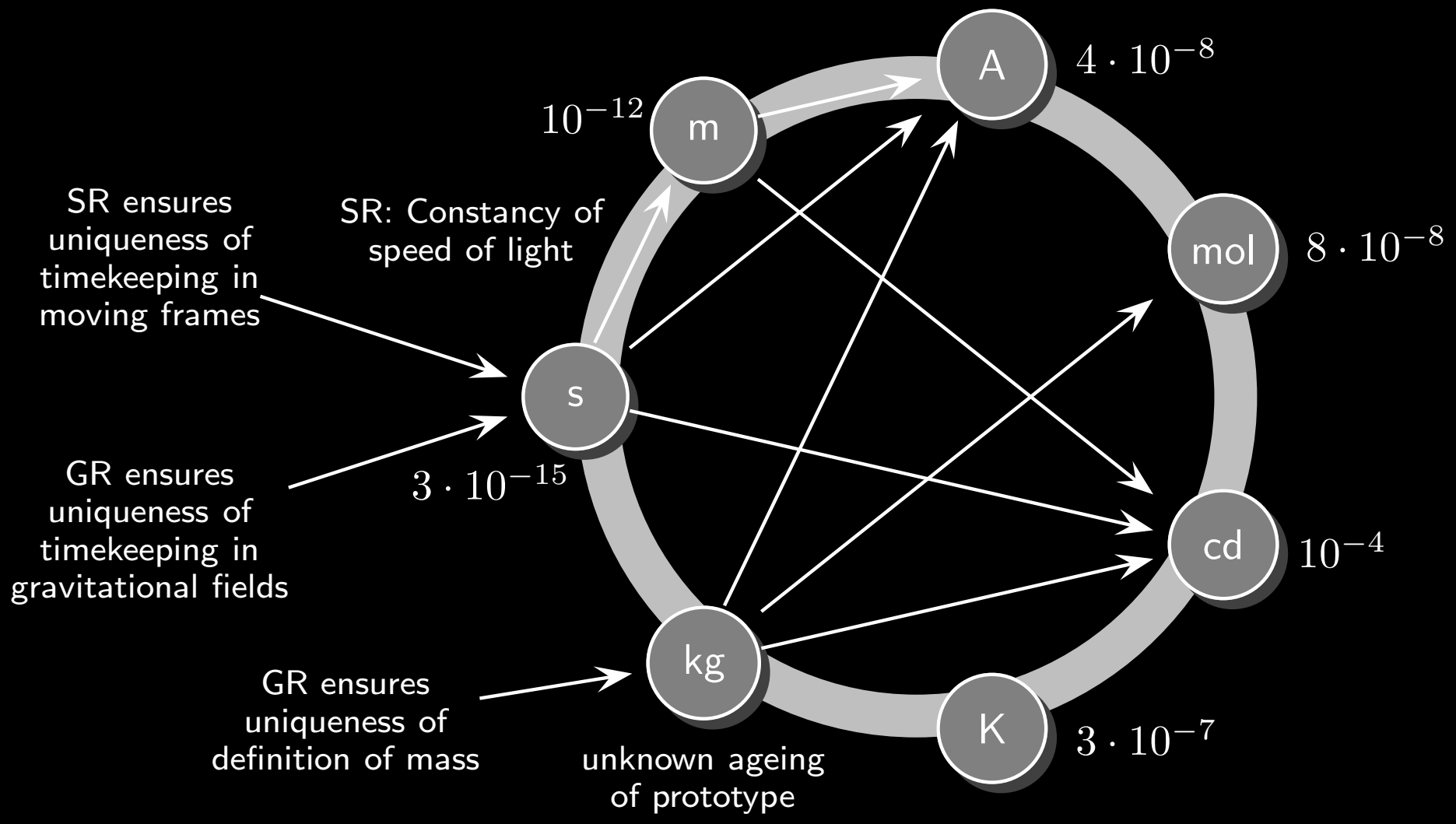


Predictions from GR

- Solar system effects
  - Perihelion shift
  - Gravitational redshift
  - Deflection of light
  - Gravitational time delay
  - Lense–Thirring effect
  - Schiff effect
- Strong gravitational fields
  - Binary systems
  - Black holes
- Gravitational waves
- Cosmology

Outline

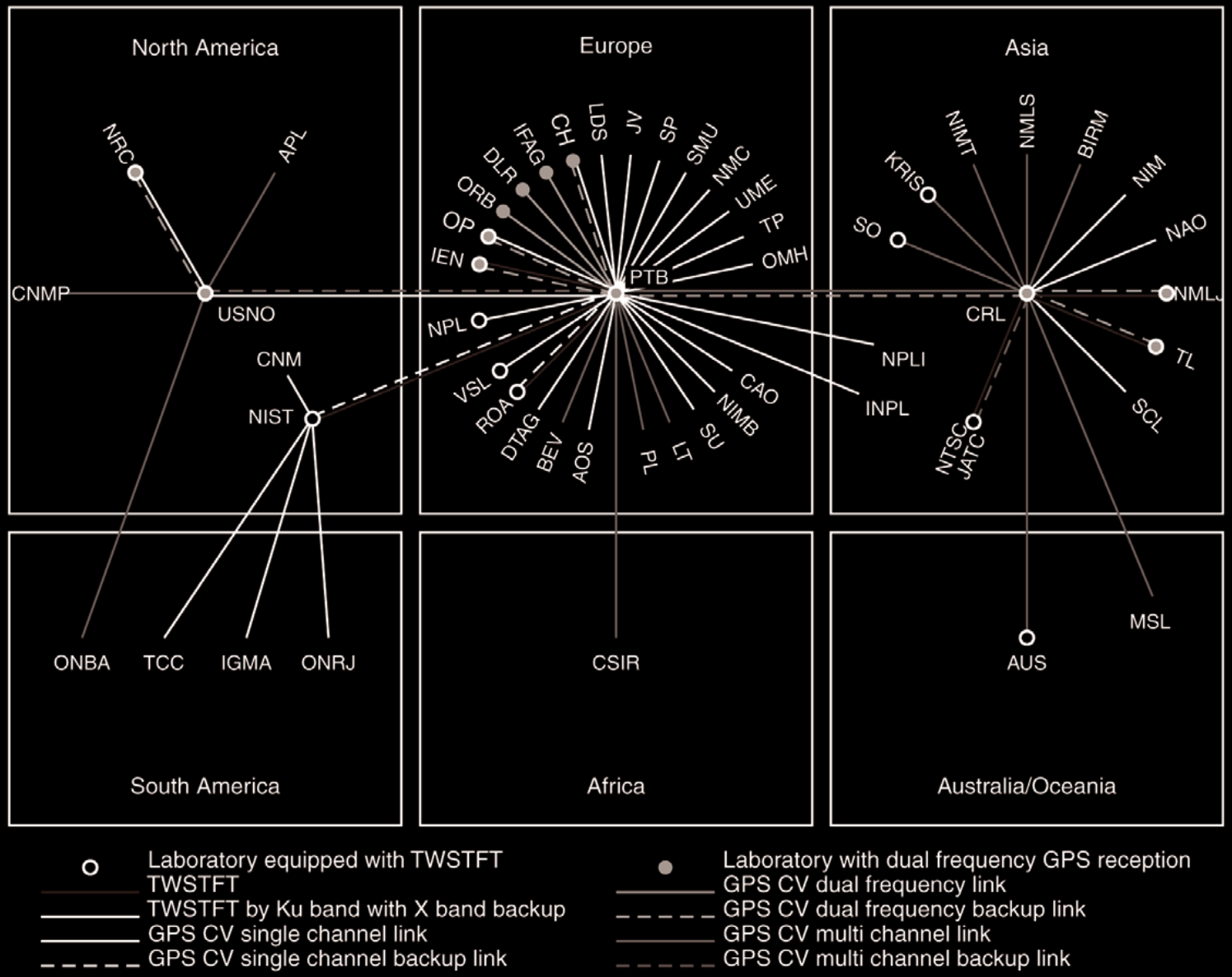
Metrology



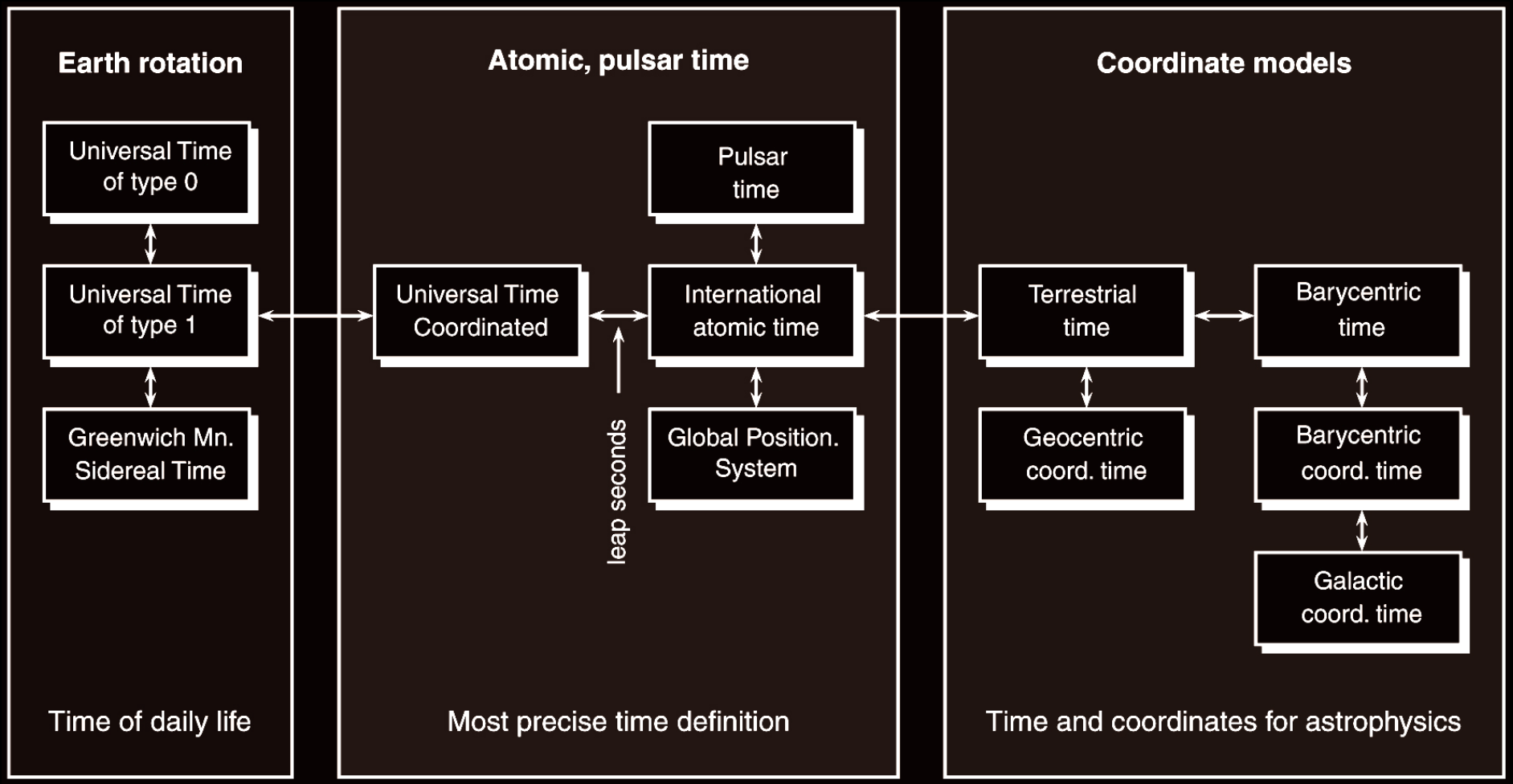
SR & GR = Physics of space and time ≡ fundamental metrology

Metrology

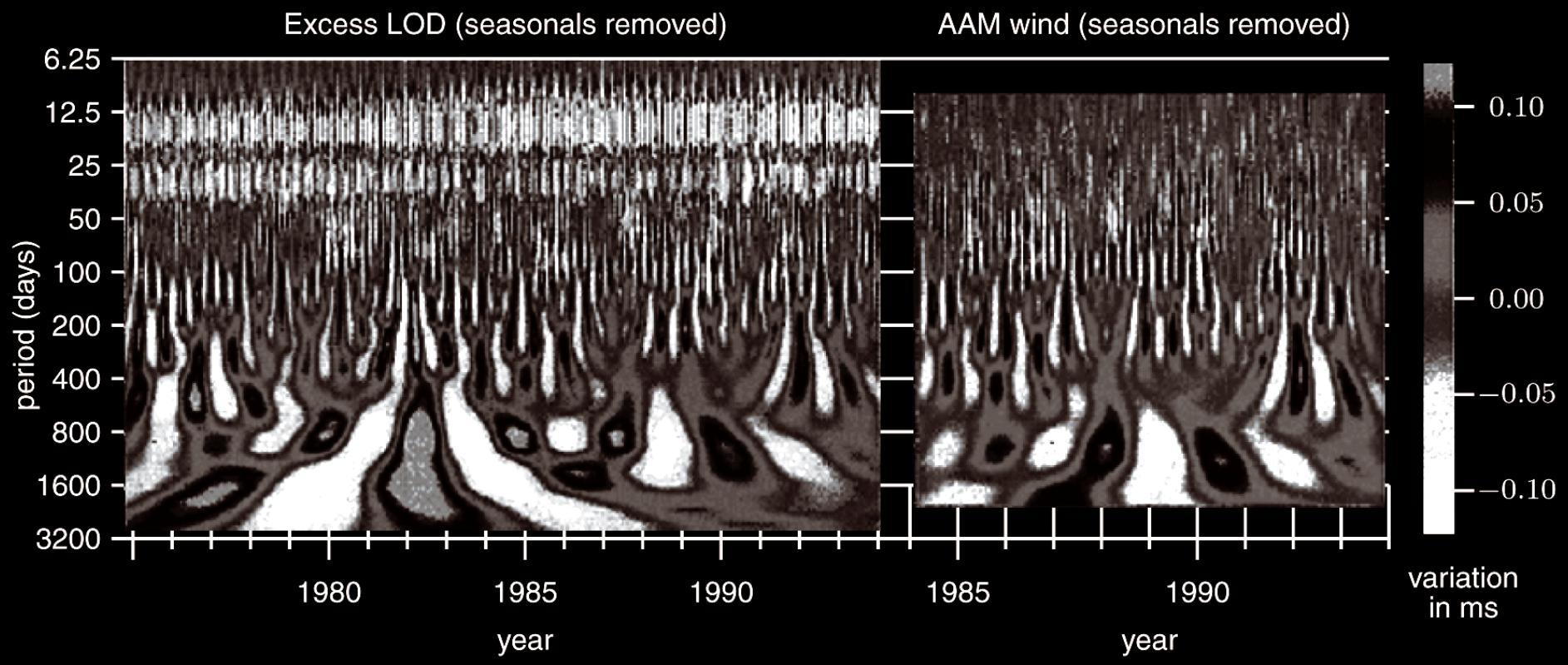
TAI


North America
NRC
APL
CNMP
USNO
CNM
NIST
ONBA
TCC
IGMA
ONRJ
South America
Europe
IFAG
CH
LDS
JV
SP
SMU
NMC
UME
TP
OMH
DLR
ORB
OP
IEN
PTB
NPL
VSL
ROA
DTAG
BEV
AOS
PL
LT
SU
NIMB
CAO
Africa
CSIR
Asia
NIMT
NMLS
BIRM
KRIS
NIM
SO
NAO
NMLJ
CRL
TL
NPLI
INPL
SCL
NTSC
JATC
MSL
AUS
Australia/Oceania
Laboratory equipped with TWSTFT
TWSTFT
TWSTFT by Ku band with X band backup
GPS CV single channel link
GPS CV single channel backup link
Laboratory with dual frequency GPS reception
GPS CV dual frequency link
GPS CV dual frequency backup link
GPS CV multi channel link
GPS CV multi channel backup link

Time scales


Earth rotation
Universal Time of type 0
Universal Time of type 1
Greenwich Mn. Sidereal Time
Time of daily life
Atomic, pulsar time
Pulsar time
Universal Time Coordinated
International atomic time
leap seconds
Global Position. System
Most precise time definition
Coordinate models
Terrestrial time
Barycentric time
Geocentric coord. time
Barycentric coord. time
Galactic coord. time
Time and coordinates for astrophysics

Practical application: Clocks and climate research



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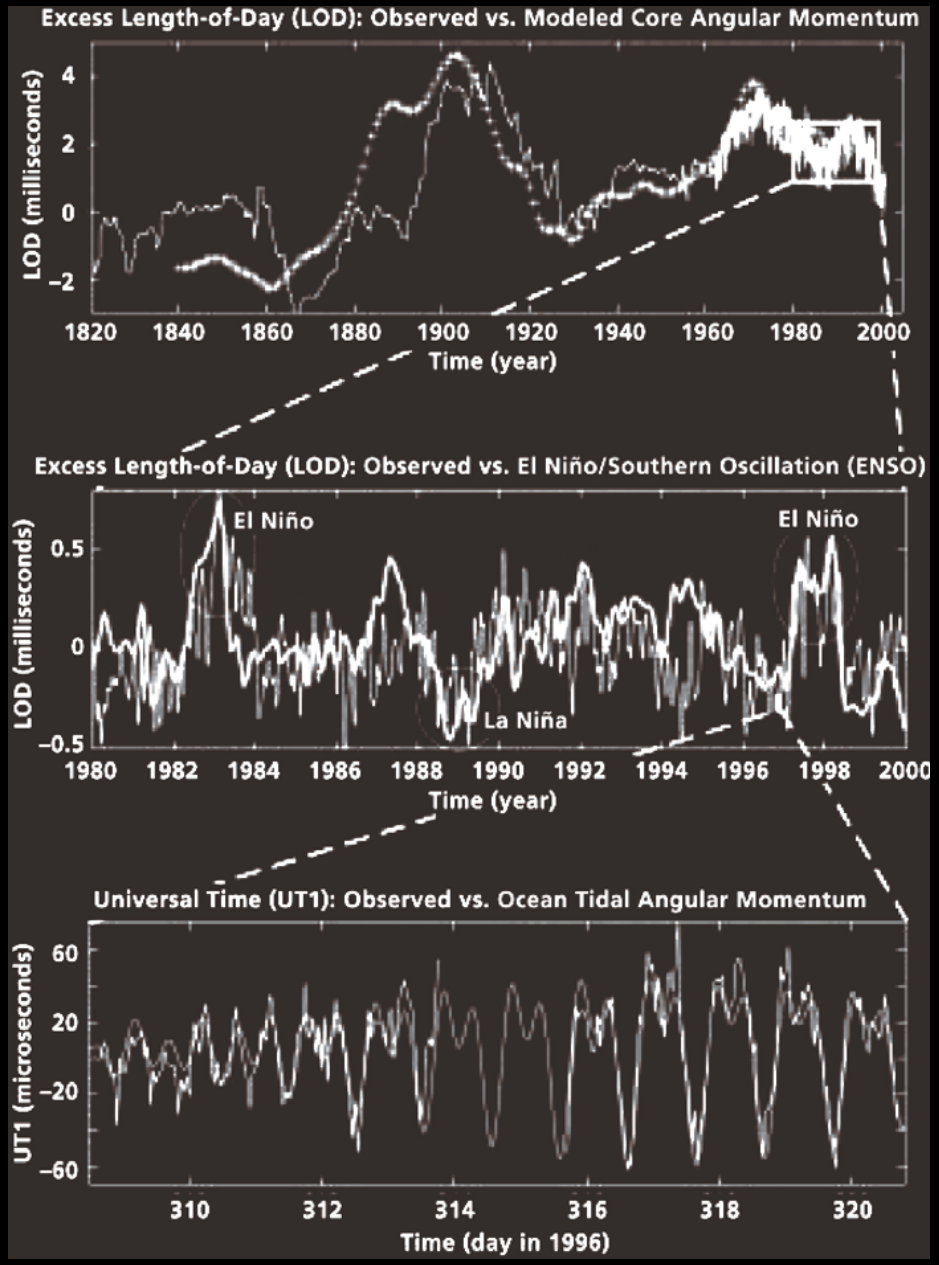
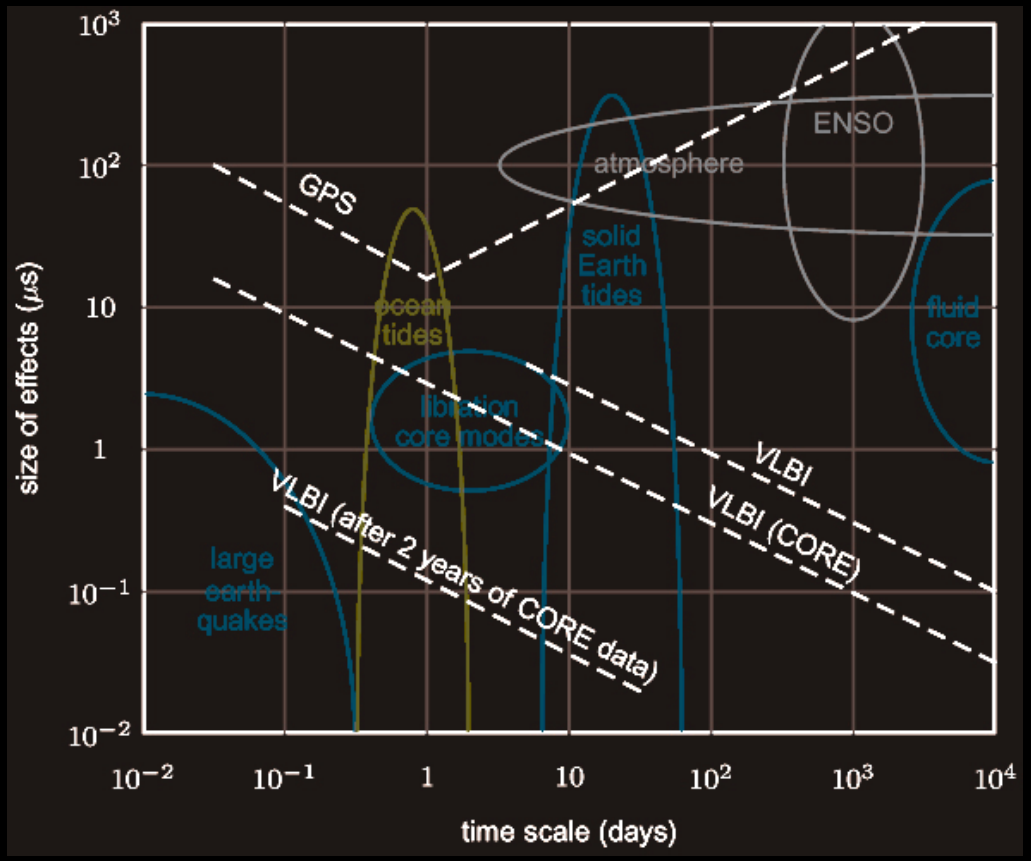


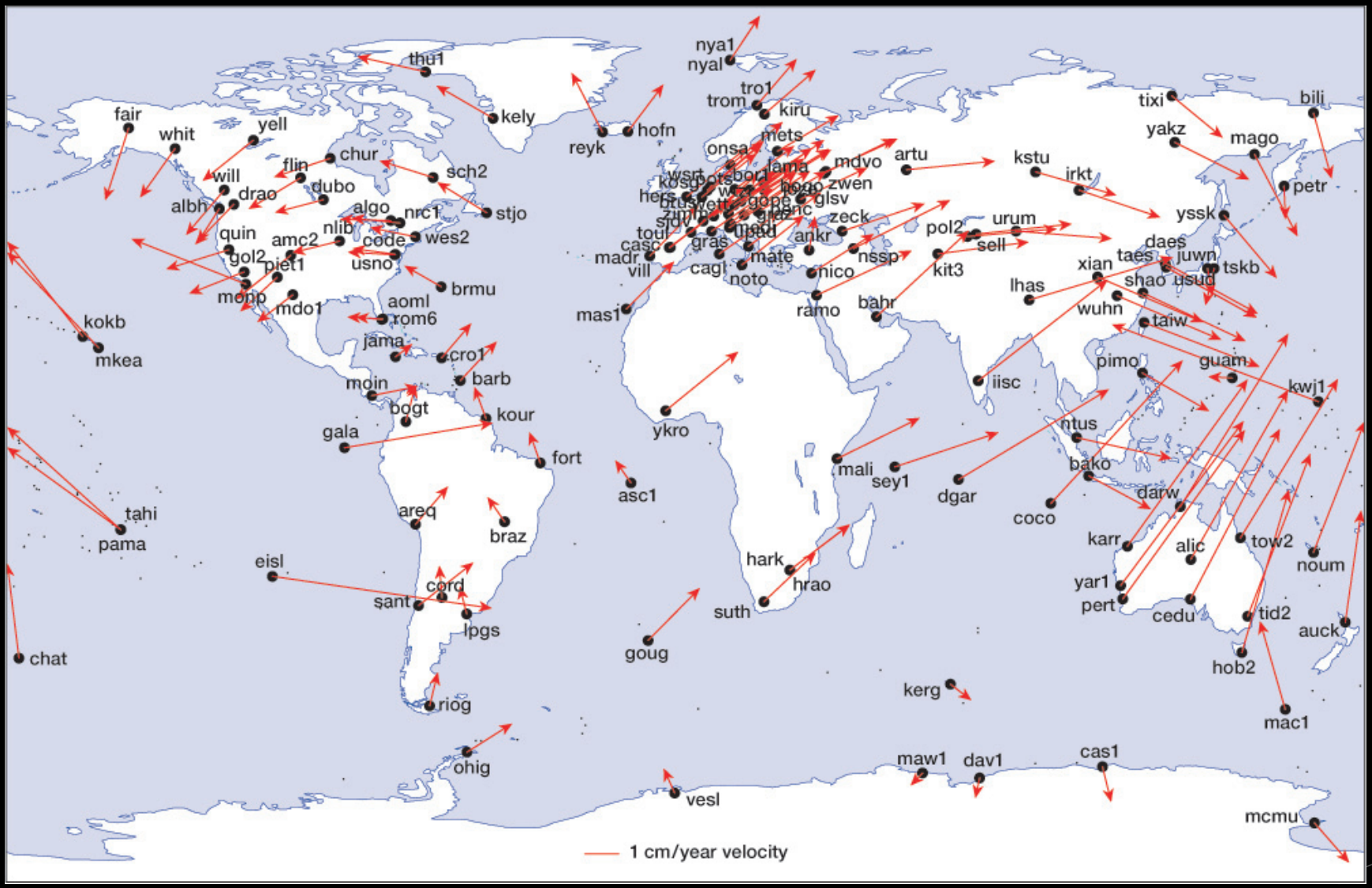
Practical application: Clocks and Earth dynamics



Clocks are of help to measure:

- warming of oceans
- motion of Earth's crust, ...
- ...

Practical application: Clocks and positions



1 cm/year velocity

Outline

Problems?

Issues to be resloved

- Need for Quantum Gravity
- Gravity "anomalies"

Outline

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The need for Quantum Gravity

Frame theories	Interactions
Quantum theory	Electrodynamics
Special Relativity	Gravity
General Relativity	Weak interaction
Statistical mechanics	Strong interaction
Problem	**Wish**
Incompatibility of quantum theory and General Relativity	Unification of all interactions

- Avoiding Singularities
- Resolving the problem of time

Need of modifications of standard physics → search for modifications

Possible effects

Possible geometry relevant effects

- Anisotropic speed of light
- Anisotropy in quantum fields
- Violation of UFF, UGR
- Birefringence
- Anomalous spin–coupling
- Anomalous coupling of charge
- Anomalous dispersion
- Newton / Coulomb potential
- Nonlinearities
- Charge non–conservation
- Active – passive mass and charge

Other possible effects

- Decoherence
- Modified interference
- Non–localities

Structure of parameters

- Usually: parameters are asumed to be constant
- In unification scenarios: parameters depend on time and position, through scalar fields (dilaton, quintessence, varying e) $\longrightarrow$ scalar–tensor theories

Many of them typically clock tests

Clocks are an important device in the search for QG

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Strategy: Exploration of new regimes

Standard physics experimentally well proven for standard energies, velocities, distances, ...
Search for new effects $\Rightarrow$ need to go to non–standard situations:

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Extreme large distances.

- Dark energy, dark matter, Pioneer anomaly
- Ultra–low frequency gravitational waves (early universe)

Extreme small distances. Higher dimensional theories: violation of Newton's law at small (sub–mm) distances

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Extreme long timescales.

- Search for space–time fluctuations in terms of $1/f$–noise
- Time dependence of constants

Extreme short timescales. Short time scales ↔ large energies

Outline

Observations vs. Experiment

Comparison: high energy cosmic ray observation $\leftrightarrow$ low energy laboratory exp.

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Astrophysical observations

- \+ Availability of ultra high energies of more than 10^{21} eV
- – No systematic repeatability
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Laboratory search (including space)

– Only small energies are available
+ Repeatability of the experiment, systematic variation of initial and boundary conditions, used for:
  - Identification of cause
  - Improvement of precision of result
+ Ultra–low temperatures, ultrastable devices like optical resonators can be obtained in the laboratory / in space only

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Due to stability and repeatability of experiments, laboratory searches for quantum gravity effects may be as promising as astrophysical observations

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Space conditions

Particular space conditions and corresponding tests

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- Free fall – no gravitational force

Tests

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- Long time for accumulating small forces

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- Test of Universality of Free Fall
- Test of Universality of Gravitational Redshift
- Measurement of absolute gravitational redshift
- Long time for accumulating small forces

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- Free fall – no gravitational force
- Large differences in the gravitational potential
- Huge distances
- Large velocities
- Low noise
- Well–defined clocks

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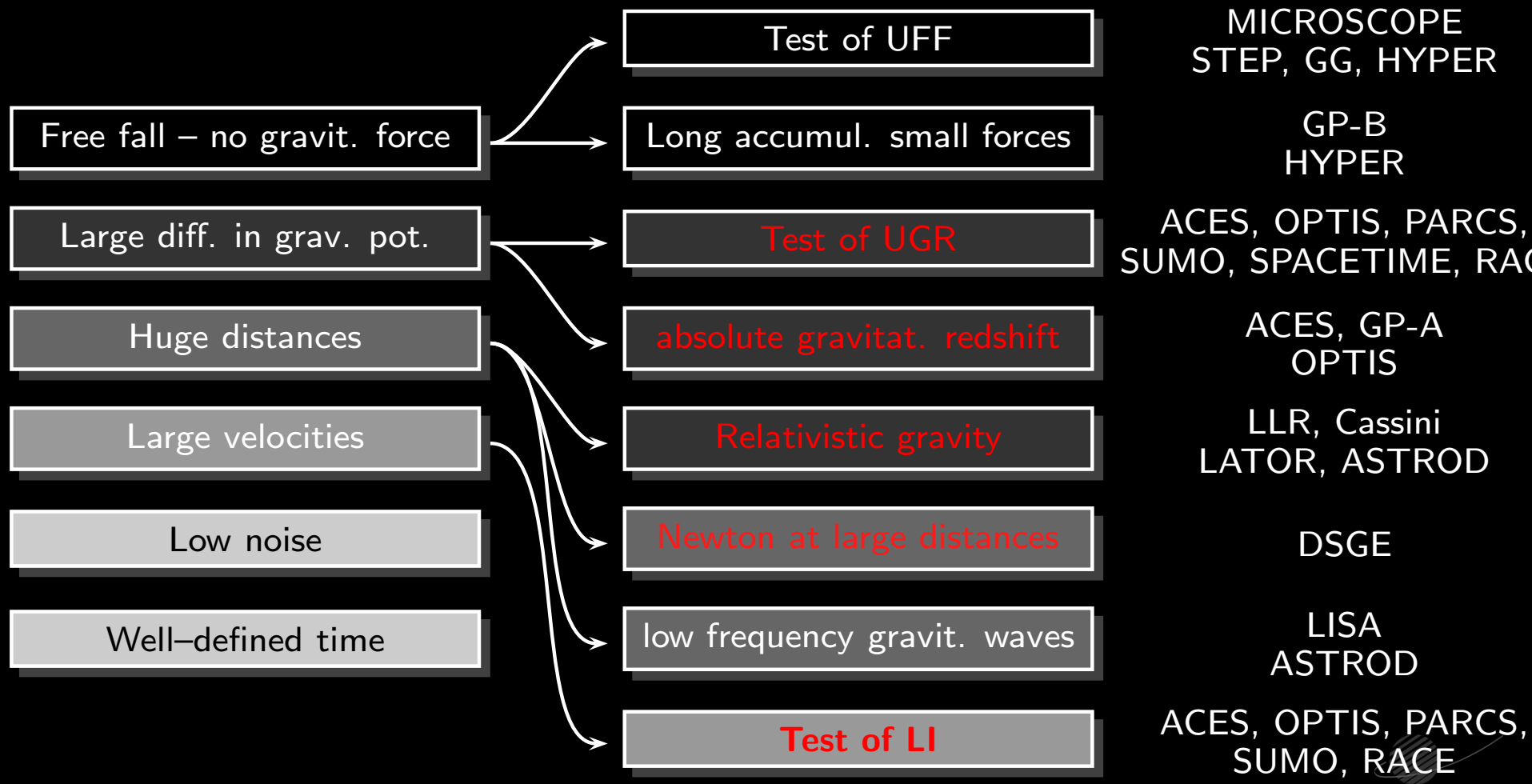
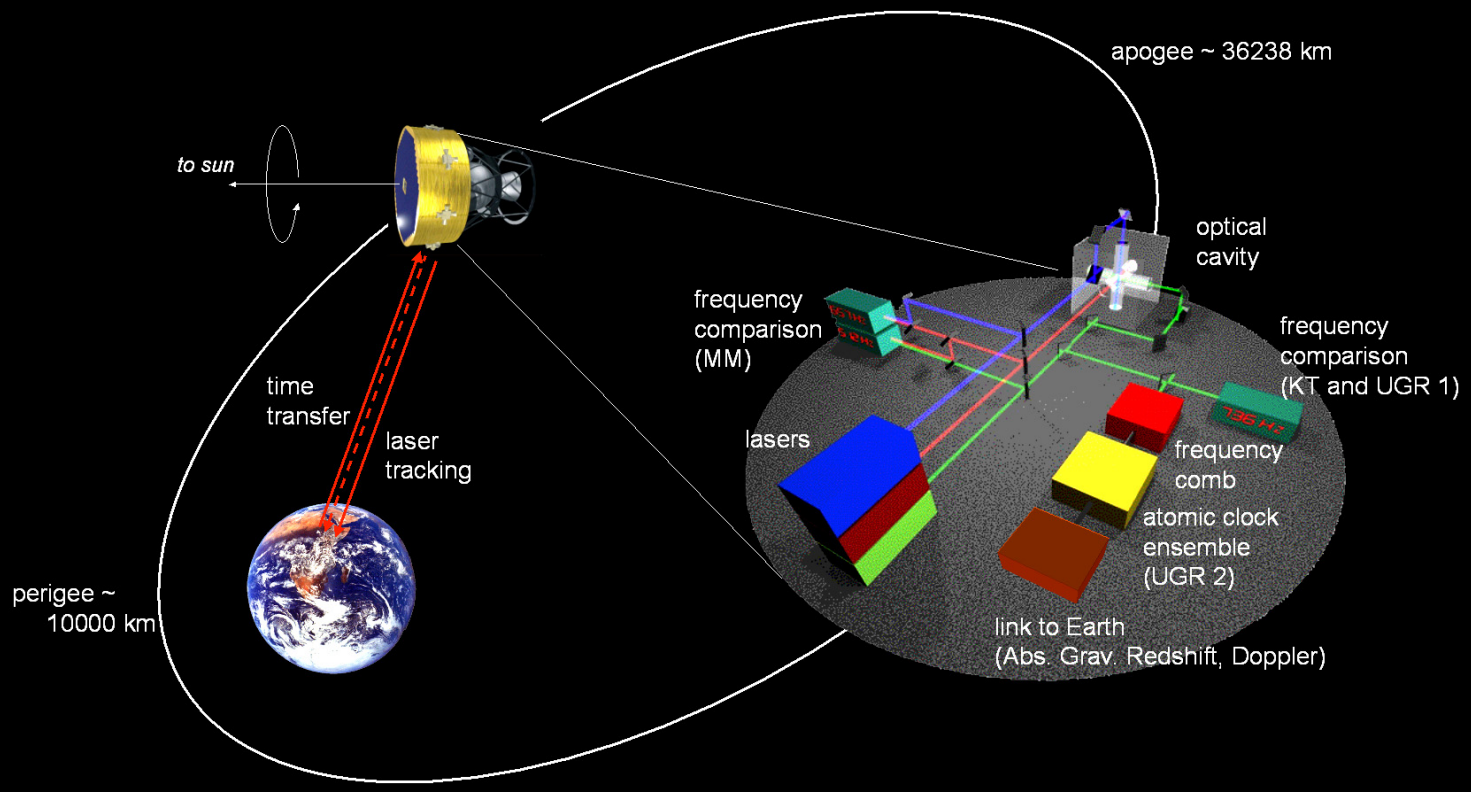


Example: OPTIS

OPTIS = OPtical Tests of the Isotropy of Space
Mission for improved tests of Special and General Relativity



Objectives: Michelson–Morley, Kennedy–Thorndike, time dilation, UGR, absolute redshift, perihelion shift, Lense–Thirring, Yukawa (→ poster)

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But: Dark clouds over General Relativity?

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Distance Earth–Sun increases by ~ 10 m/cy

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Is the gravitational physics in the Solar system really well understood?
Gravity on large scales? $\leftrightarrow$ influence of DM and/or DE?
Additional exploration with clocks!

Outline

The Pioneer anomaly

The observation (Anderson et al 1998, 2002)

- Measured constant acceleration

$$a_{\mathrm{Pioneer}} = (8.74 \pm 1.33) \cdot 10^{-10}\ \mathrm{m/s^2}$$

- Acceleration constant and toward the Sun

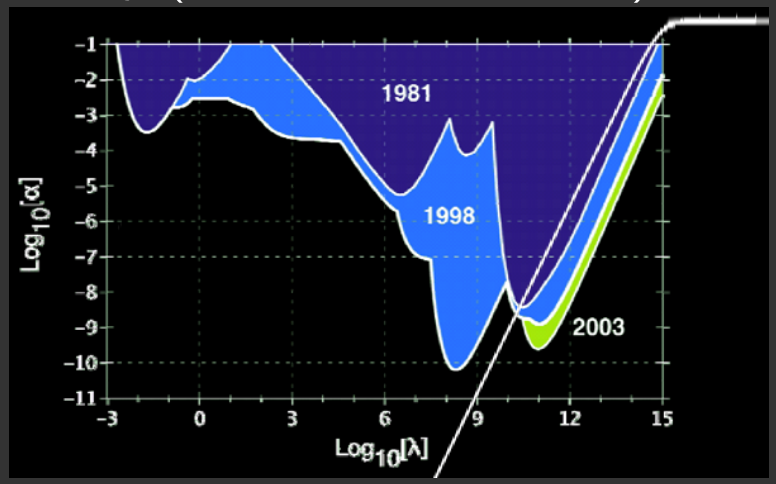
New information from

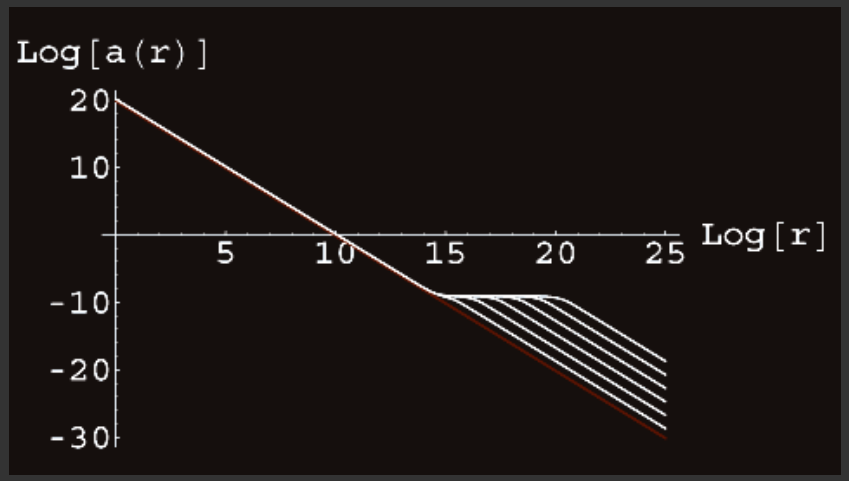
- Clock on new DSGE
- Drift of clocks on Earth may simulate the effect → clock comparison

Theory

Theoretical considerations

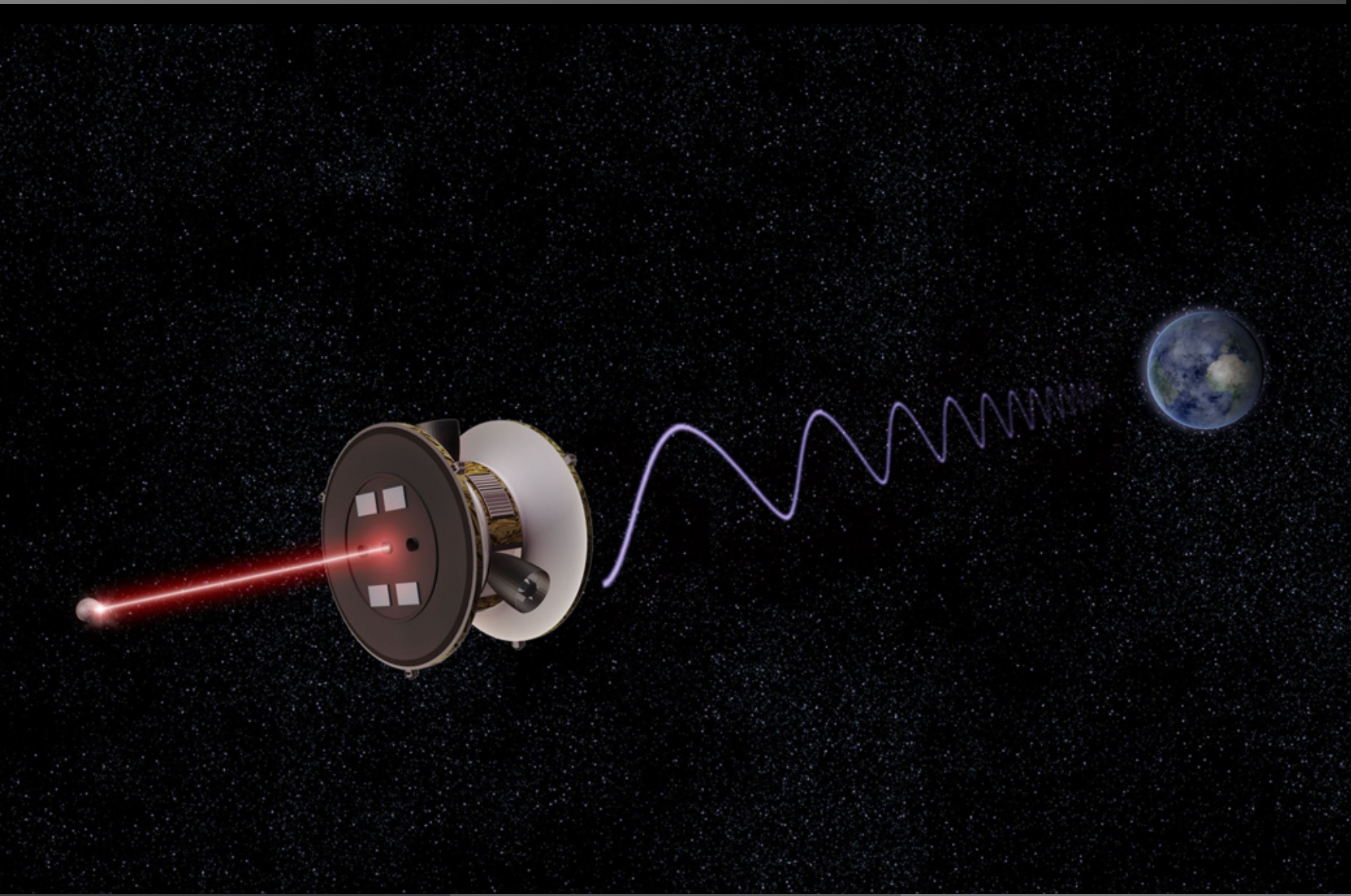
- Cosmological influence orders of magnitude too small in order to explain the Pioneer anomaly (e.g. C.L. & Dittus 2005, Giulini & Matteo 2006)
- Yukawa describing galactic rotation curve can be used to describe Pioneer anomaly (Dittus & C.L. 2005)





- Cosmological constant cannot be responsible for Pioneer anomaly (Kagramanova, Kunz & C.L. 2006)

Outlook: New mission



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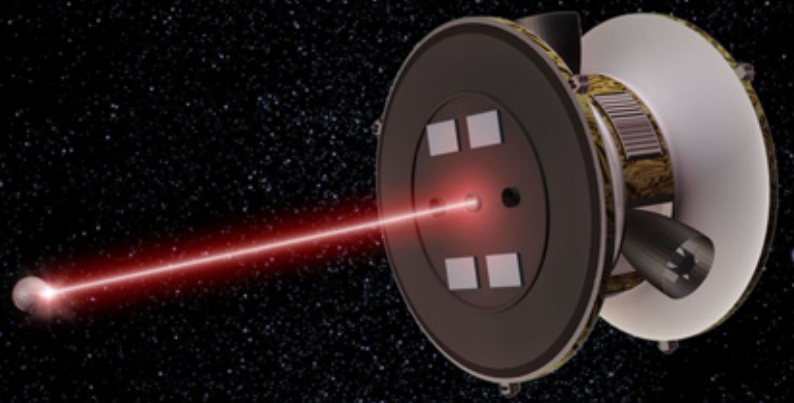


- Active spacecraft, passive test mass
- Accurate tracking of test mass
- 2–step–tracking
  - Radio: Earth — spacecraft
  - Laser: spacecraft — test mass
- Flexible formation: varying distance
- Test mass is at environmentally quiet distance from spacecraft $\sim$ 200 m
- Occasional manoeuvres to maintain formation

New Pioneer Explorer should be equipped with stable clock

For Pioneer anomaly:

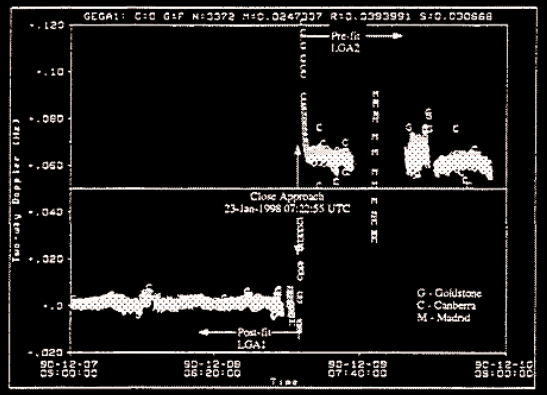
$$\frac{\Delta_{\mathrm{Pioneer}}\nu}{\nu} = \frac{1}{c^2}\int_{\mathrm{Jupiter}}^{90\ \mathrm{AU}} a_{\mathrm{Pioneer}}dx = 10^{-13}$$

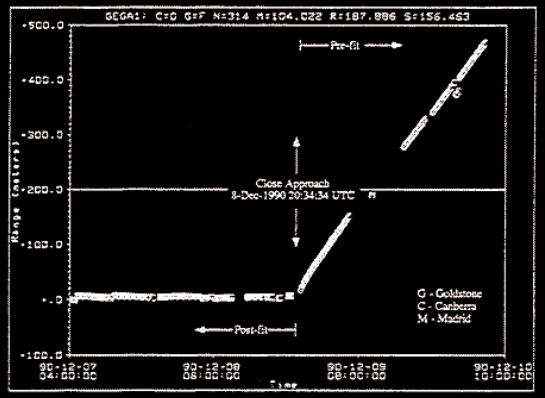
The flyby anomaly

Observation

- After satellite flybys at Earth the velocity is too large by a few mm/s
- First Galileo flyby 1990, NEAR flyby 1998, Cassini flyby 1999, Rosetta flyby 2005,Messenger flyby 2005

GEGA1:
Two–way S–band
Doppler residuals &
range residuals





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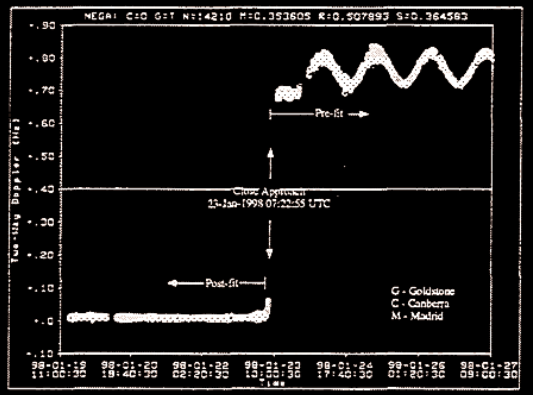
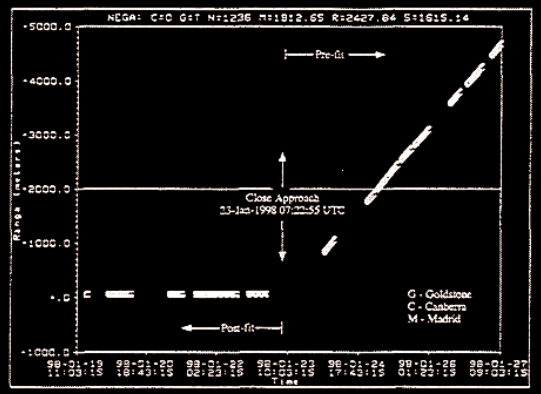
NEGA:
Two–way X–band Doppler residuals & range residuals





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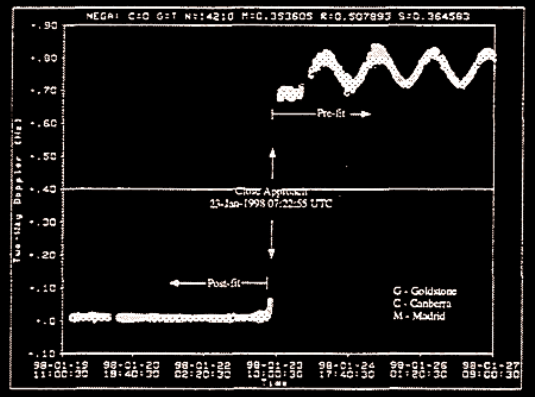

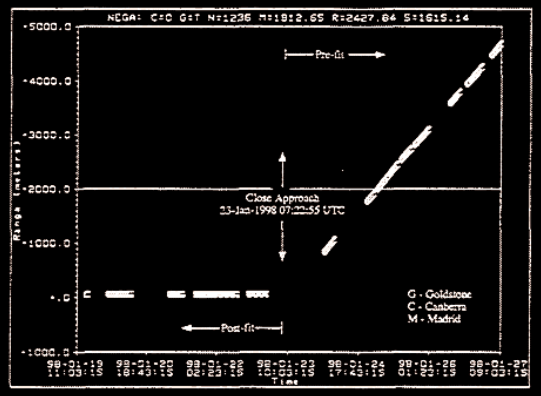

New information from:

- Better time resolution of velocity increase: continuous observation
- Clock on spacecraft
- Observation of Mars flyby (Rosetta)

Increase of Astronomical Unit

Observation

Various groups reported

- Krasinsky & Brumberg 2005: 15 ± 4 m/cy
- Pitjeva 2005: 7 ± 1 m/cy

Remarks / Questions

- $\dot{G}$ excluded by LLR
- Mass loss of Sun leads only to 1 m/cy
- Influence of cosmic expansion by many orders of magnitude too small
- Interplanetary plasma?
- Effect can again be simulated by drift of clocks

Summary

Possible questions

- Influence of cosmic expansion? ($a_{\mathrm{Pioneer}} \approx cH$)
- Something wrong with weak gravity?
- Do clocks on Earth behave properly?

Clocks

Clocks are essential in helping to explore

- Pioneer anomaly
- Flyby anomaly
- Secular increase of AU

Outline

Gravity, geometry, clocks, and particle motion

Gravity = geometry = metric + connection = clock and particle motion
For the full exploration of gravity one needs position and time

Measurement of time

- Clocks measure proper time related to dx^μ

$$T = \int_{\text{worldline}} ds \qquad \text{with} \qquad ds^2 = g(x, dx)\,, \quad g(x, \lambda dx) = \lambda^2 g(x, dx)$$

- For Riemanian space–time metric $ds^2 = g_{\mu\nu} dx^\mu dx^\nu$

$$T = \int_{\text{worldline of clock}} \sqrt{g_{\mu\nu} dx^\mu dx^\nu} \approx \int (1 - U + \dot{x}^2) dx^0 + \int g_{0i} dx^i$$

- Two clocks at different positions: gravitational redshift

Gravity, geometry, clocks, and particle motion

Motion of particles

- Equation of motion for particles: Weak Equivalence Principle $\Rightarrow$

$$0 = v^\nu \partial_\mu v^\nu + H^\mu(x,v) = \left\{ {\mu \atop \rho\sigma} \right\} v^\mu v^\sigma + h^\mu(x,v)$$

- 3–acceleration

$$\ddot{x}^i = \underbrace{\partial_i U}_{\text{Newton}} + \underbrace{(\partial_i h_j - \partial_j h_i)\dot{x}^j}_{\text{Lense-Thirring}} + \Upsilon^i + \Upsilon^i_j \dot{x}^j + \Upsilon^i_{jk} \dot{x}^j \dot{x}^k + \ldots$$

- Equation of motion respects UFF but violates Einstein's elevator
- Such terms may play a role in Pioneer anomaly or flyby anomaly
- Need of precise clocks for tracking of satellites in oder to determine these terms

Time and orbit of spacecraft are independent observables
Only in Einstein's General Relativity both are governed by the space–time metric
Spacecraft should carry clocks onboard

Outline

Summary

Summary

- Clocks are needed for most space projects
- Clocks are essential for the search of quantum gravity effects
- Clocks will play an important role in resolving current gravity puzzles

- C.L. & Dittus 2000
- Dittus & C.L. (eds) 2003: Special Issue of *Gen. Rel. Grav.* on Fundamental Physics on the ISS
- Dittus, C.L & Turyshev 2007 (forthcoming book (Springer) on space technologies and missions)

Gravity plays a major role in modern physics

Outlook: experiment/observation in gravitational physics

Data basis improves

- New gravitating systems: binary pulsar $\rightarrow$ new tests of GR, non–linearities, ...
- Longer data span: LLR $\rightarrow \dot{G}/G$, equivalence principle, ...
- Longer data span: ephemerides $\rightarrow$ increase of AU
- Improved data from new measurements: Planck $\rightarrow$ cosmology, quadrupole, ...
- UHECR: Auger, ... $\rightarrow$ dispersion relation, search for QG, ...
- Gravitational waves $\rightarrow$ black holes, binary systems, ...
- Satellite navigation $\rightarrow$ flyby
- New Horizon mission
- New Pioneer mission ....

Vastly increasing knowledge about gravity ...

Gravity is a very dynamic field – new important applications for daily life

Outline

Technology vs. Fundamental Phyiscs

From Philosophy of Science:

- $\Rightarrow$ "Fundamental Physics makes technological progress possible"
- $\Leftarrow$ "Technology stimulates scientific inventiveness", e.g. Einstein–Poincaré simultaneity (Gallison 2003)

Not possible: To have solely technological development (Carrier 2006):

- $\Leftrightarrow$ "... practical challenges cannot appropriately be met without treating problems in basic science ... applied research naturally grows into basic science ... Applied research tends to transcend applied questions for methodological reasons. A lack of deeper understanding of a phenomenon eventually impairs the prospects of its technological use. ... Uncovering the relevant mechanisms and embedding them in a theoretical framework is of some use typically for ascertaining or improving the applicability of a finding. Scientific understanding makes generalizations robust ... Treating applied questions appropriately requires not treating them exclusively as applied questions."

Even the demand of mere technology needs Fundamental Physics.

Final Conclusion