Pulsars and Terrestrial Time Standards

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Overview

- Technology behind terrestrial time standards
- Formation & accuracy of ensemble TT
- Pulsars as clocks
- Prospects for the PTA and SKA

The scale of time and space

- Space-time events described by $\boldsymbol{x}$, ct
- SI: c = 299,792,458 m s^{-1} (exactly)
    - Time standards are length standards
- SI: f = 9.192631770 GHz (exactly) for Cs hyperfine

Short term: HI Maser

- Masing at 21 cm line
- Best available short-term stability (10^{-15} @ 1 day)
- Needs adjustment on longer intervals
- Common as observatory clock / frequency reference

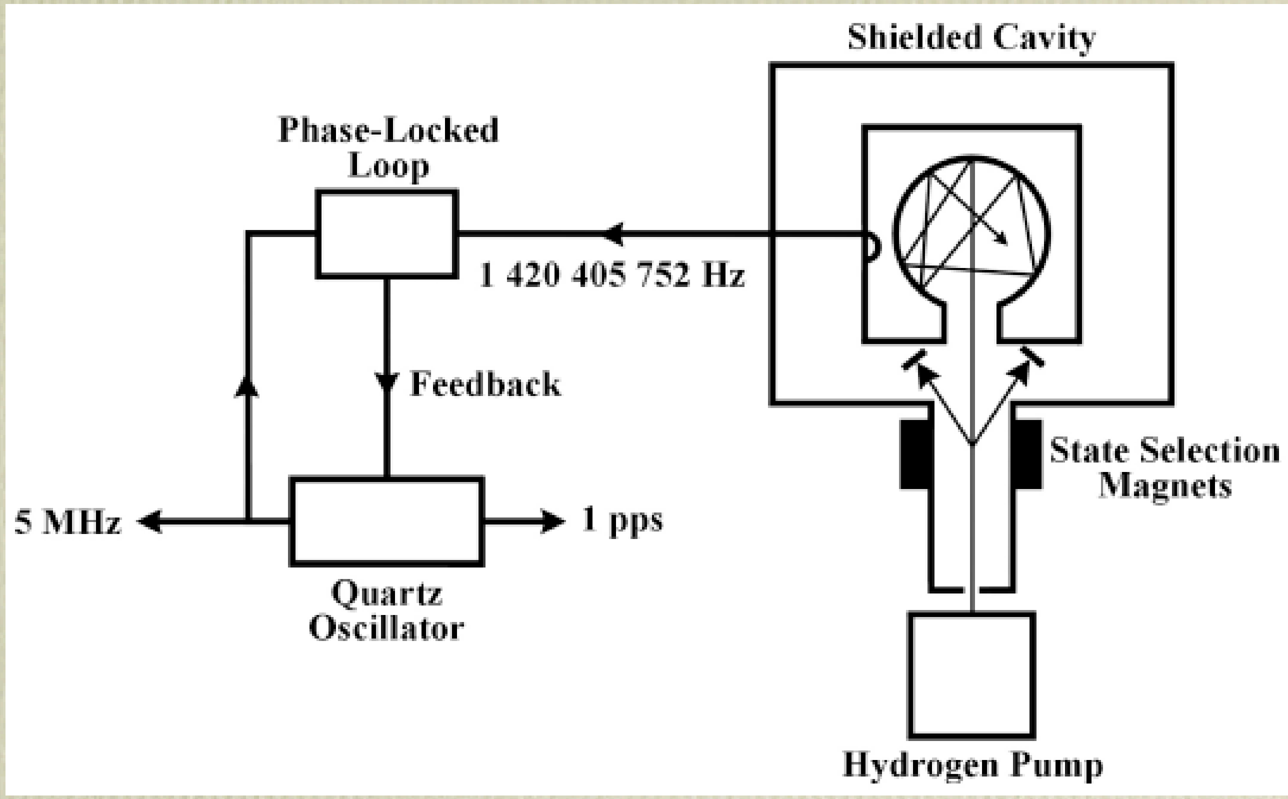
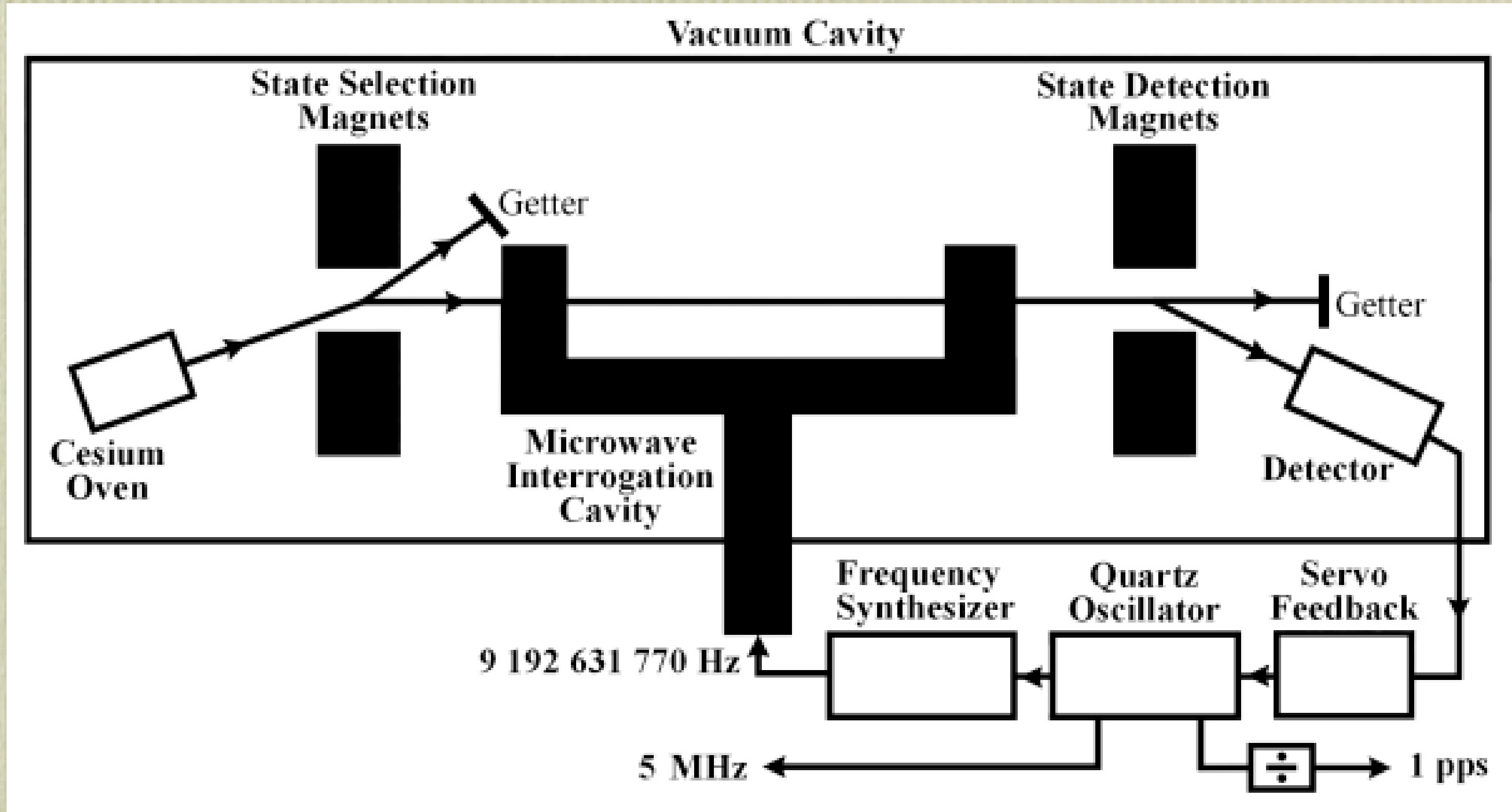


Diagram: NIST

Long term: Cs Beam

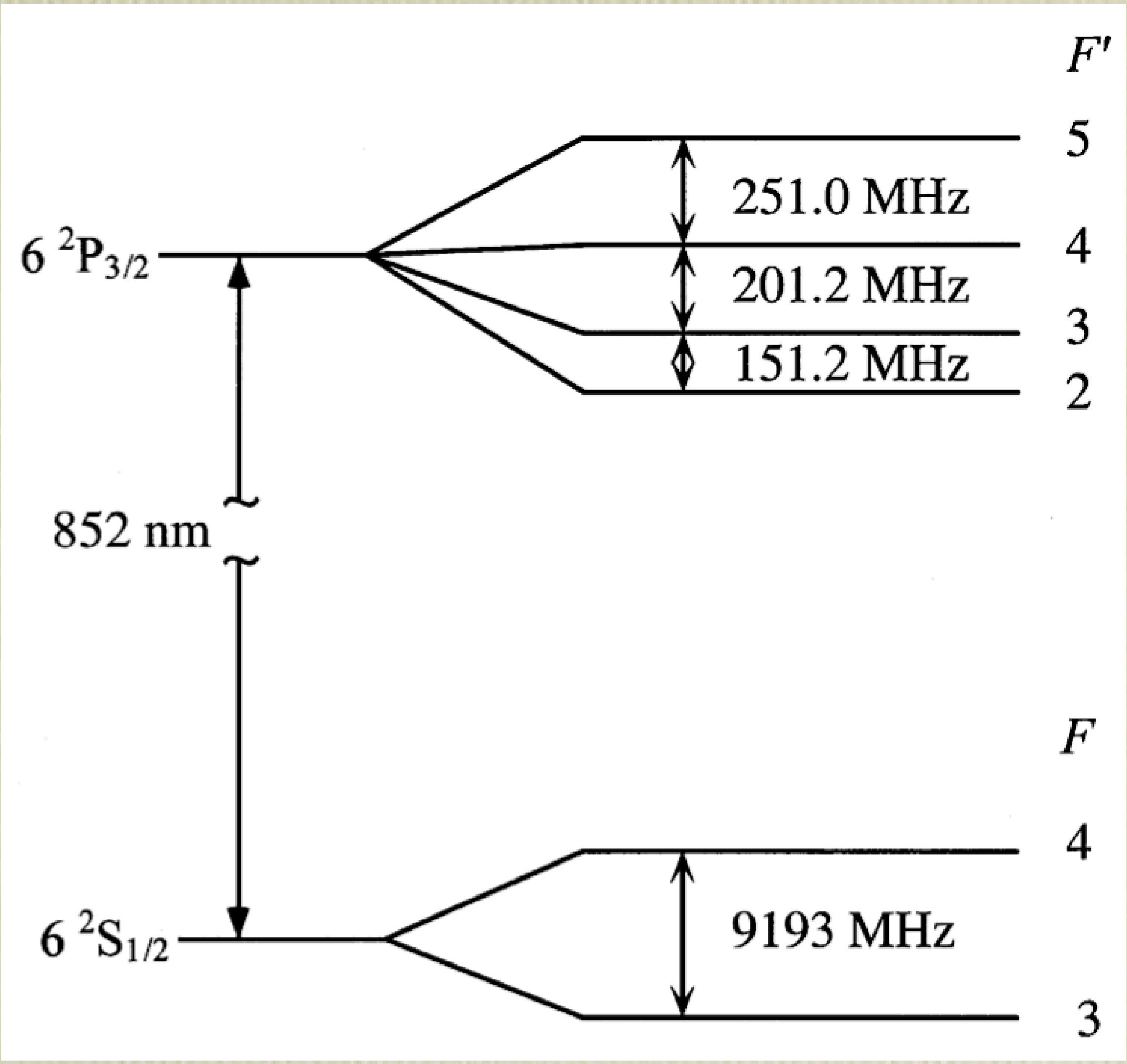


- Stimulated hyperfine state transition
- Tuned to maximise transition efficiency
- Stability ~$10^{-13 - 14}$ over weeks-months
- Sold commercially (cheaper than masers!)

Diagram: NIST

Optical pumping & detection

- Pumping:
  - $F = 4 \rightarrow F' = 3$ (pump)
    $F'=3 \rightarrow F = 3$ or 4 (relax)
  - High conversion efficiency
- Detection:
  - $F = 4 \leftrightarrow F' = 5$
  - 100% detection efficency
- 1990s: 4.4×10^{-14}



Optical cooling: Cs fountain

- Cs beam limited by time of flight in microwave cavity ($\Delta f \sim 1/\Delta t$)
- Directed pumping + random re-emission = directional cooling
- 3D version: "optical molasses" containment @ ~1 μK
- De-tune to move ball

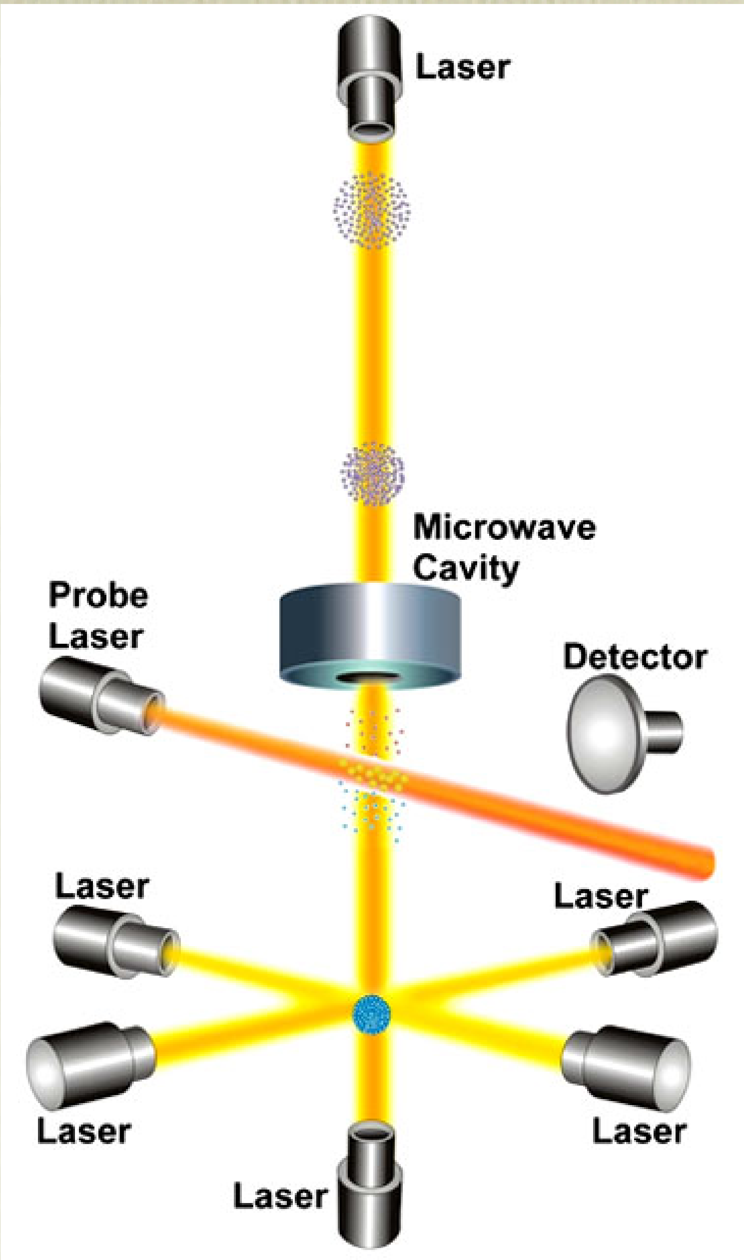


Diagram: NIST

Optical cooling: Cs fountain

- Cs beam limited by time of flight in microwave cavity ($\Delta f \sim 1/\Delta t$)
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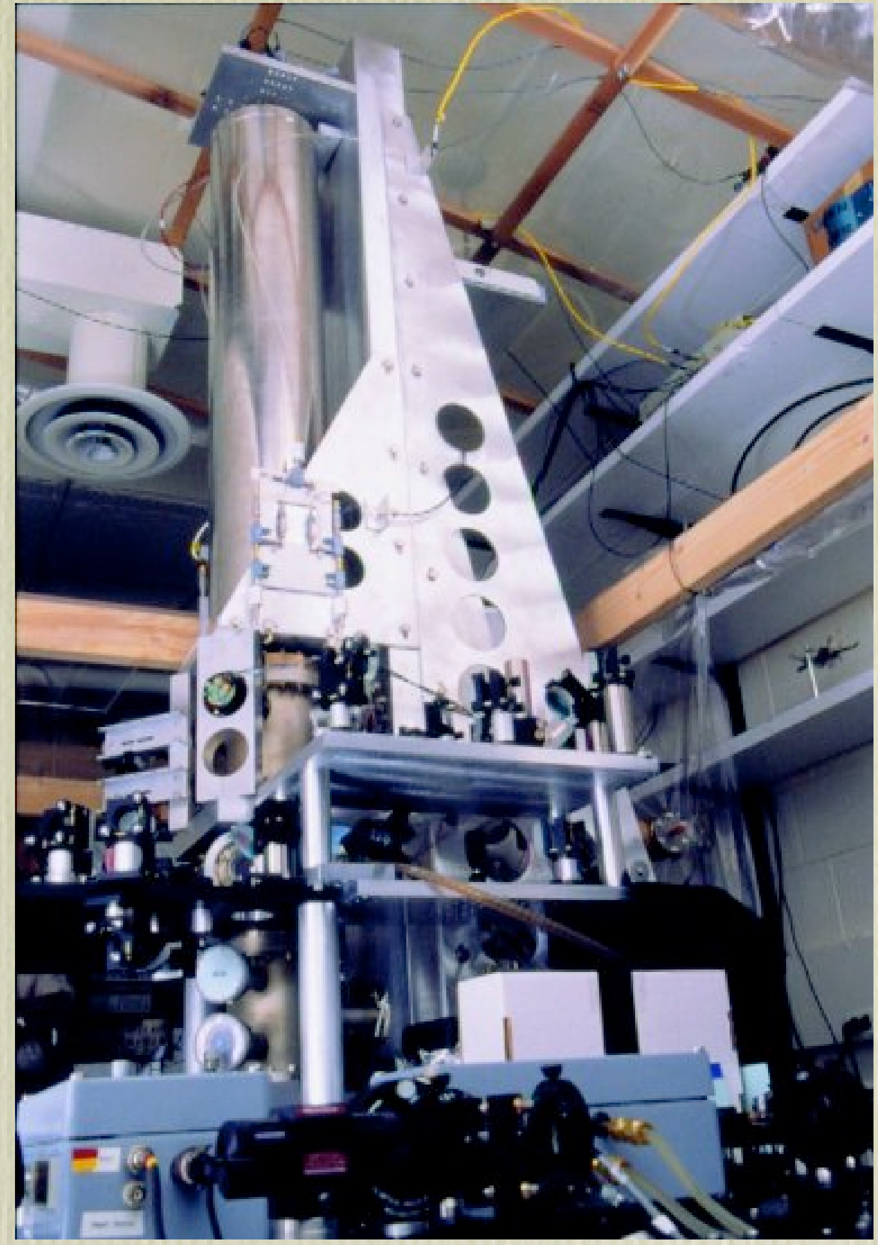
Animation: NIST

NIST-F1 Cs fountain

- 10^7 Caesium atoms
- 2 μK cooling
- 1 Hz line width
- Accuracy < 10^{-15}

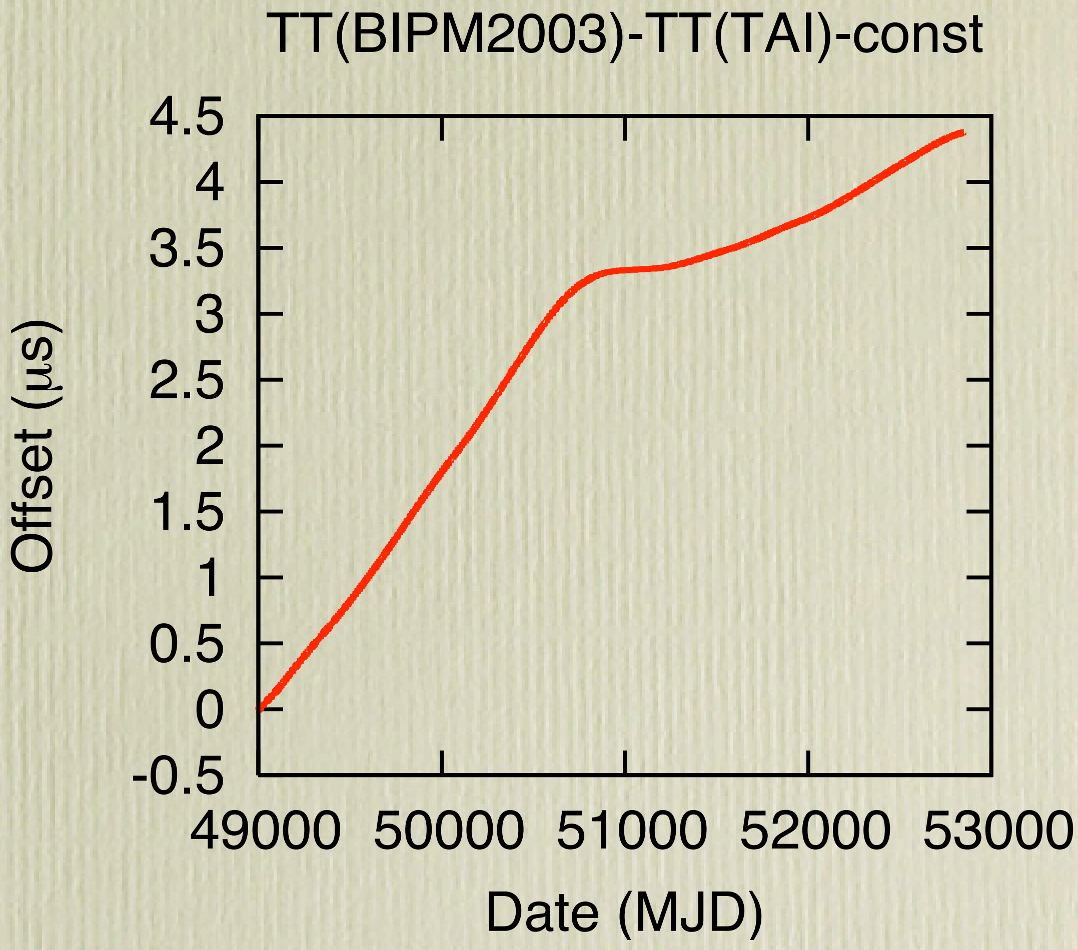


Ensemble time: EAL & TAI

- EAL = weighted average of 200 atomic clocks
- TAI = EAL, “steered” towards uniform SI time for timescales > 0.5 year
  - Uses 9 Primary Frequency Standards, including 5 Caesium fountains
- UTC = TAI + leap seconds

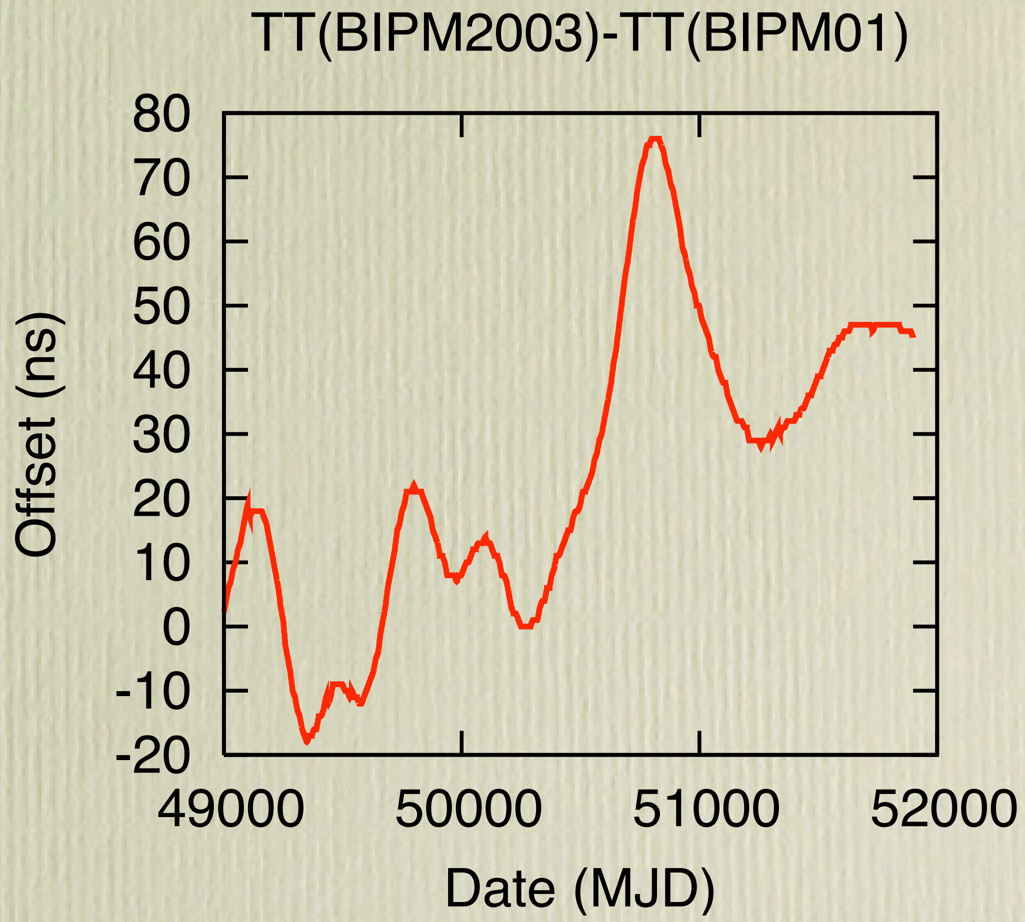
TT(BIPM): most accurate clock on Earth

- TT(TAI) = TAI + 32.184 s
- TT(BIPM) = retrospectively steered TT(TAI)
- TAI-BIPM = microseconds



TT(BIPM): most accurate clock on Earth

- TT(TAI) = TAI + 32.184 s
- TT(BIPM) = retrospectively steered TT(TAI)
- BIPM2003 - BIPM01 = 10s of nanoseconds



Prospects for TT

- Factor 10 / decade
- But also need better:
    - Time transfer
    - Short term stability

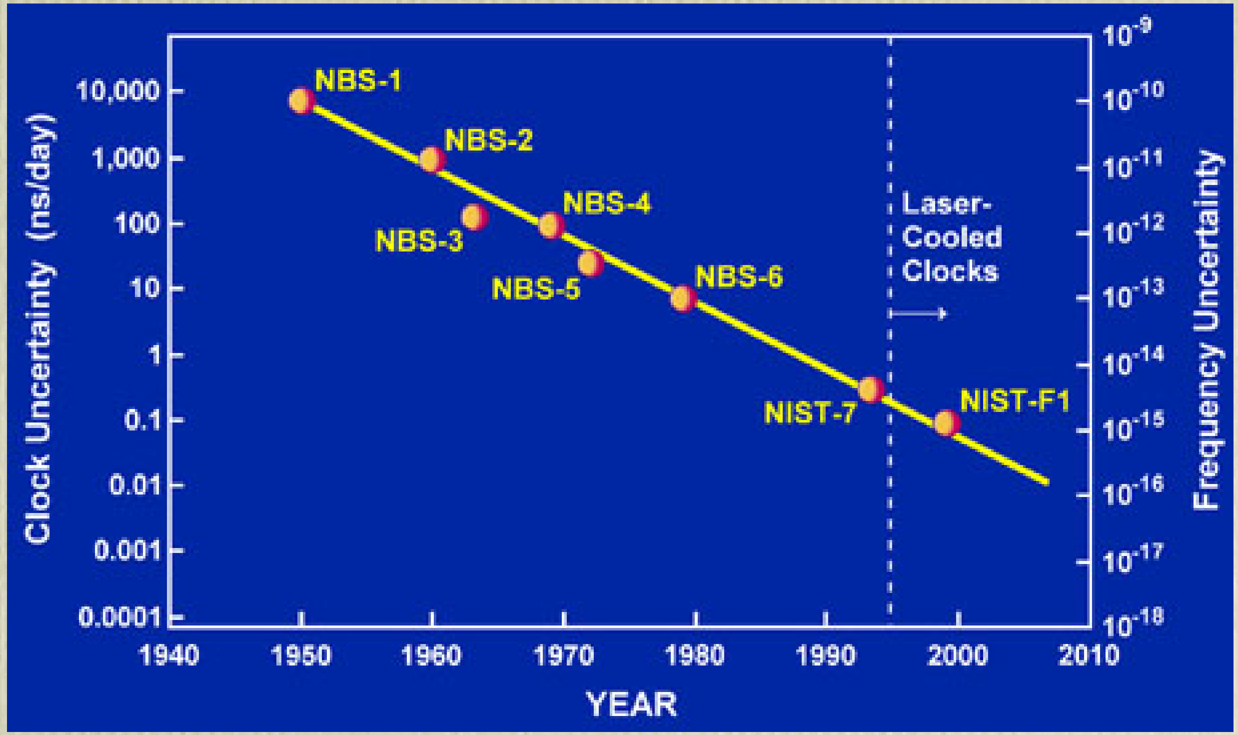


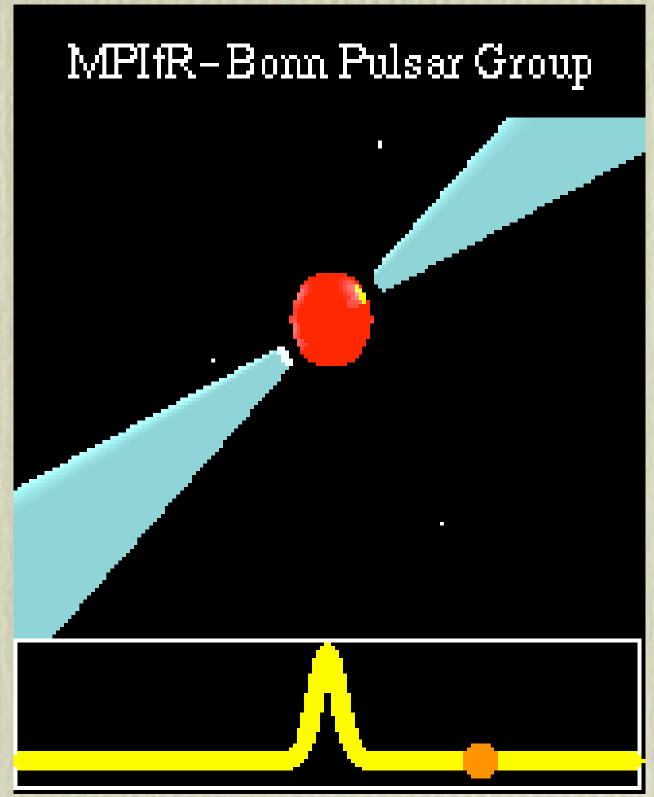
Diagram: NIST

Next generation clocks

- Trapped ion, e.g. $^{199}Hg^{+}$
- 40 GHz hyperfine ground state transition, or
- 1.07×10^{15} Hz (2860 Å) quadrupole transition + femtosecond laser
- Redefinition of SI second?

MSPs: most accurate clocks in the Universe?

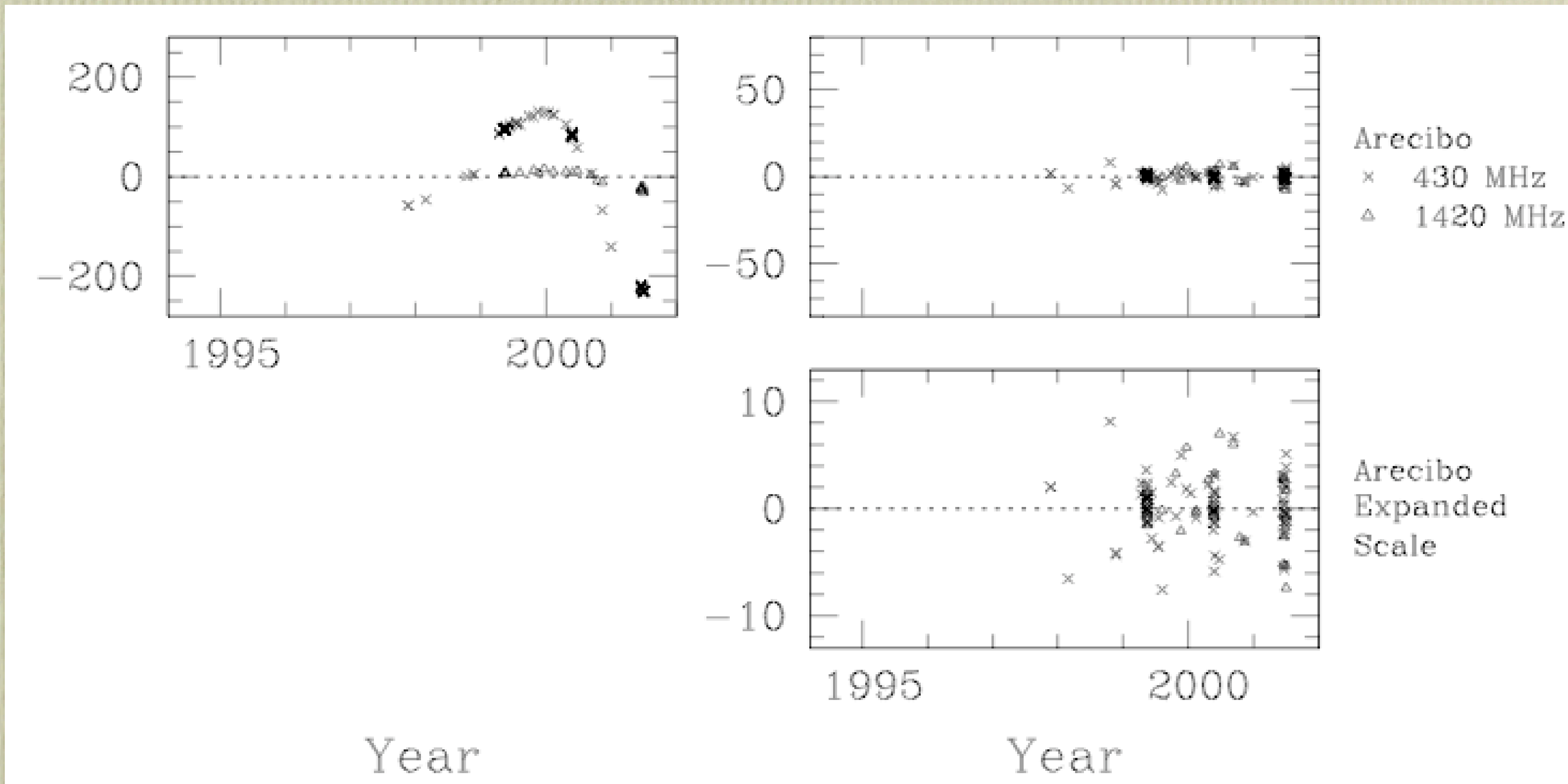
- Limit on rotational stability not known
- $I \sim 10^{45}$ g cm^2
- $\omega \sim 10^3$ rad s^{-1}
- Several sources of observational error



Deterministic effects

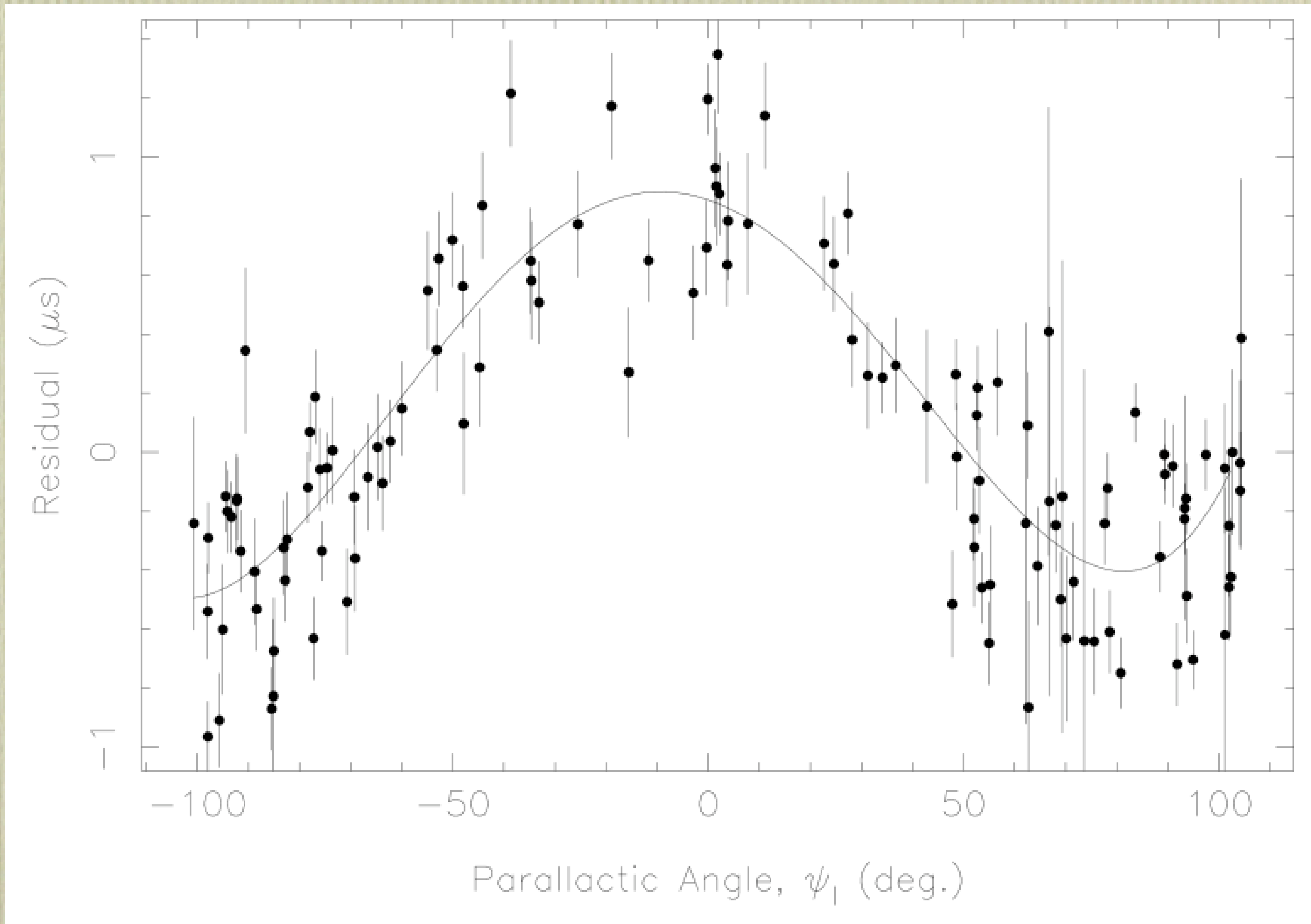
- Rotation period & first derivative (magnetic dipole radiation) {2}
- Binary motion (Kepler, Kepler+derivatives, Einstein) {5-8}
- Proper motion {2}
- Shklovskii effect {1:*d*}
- Interstellar dispersion {1+}
- Solar system dispersion {0+}
- Solar Shapiro delay {0}
- Earth orbital motion {3:α, δ, *d*}
- Gravitational time dilation {0}
- Precession, nutation, polar motion {0}
- Instrumental response (linear) {7+time-variable}

ISM effects



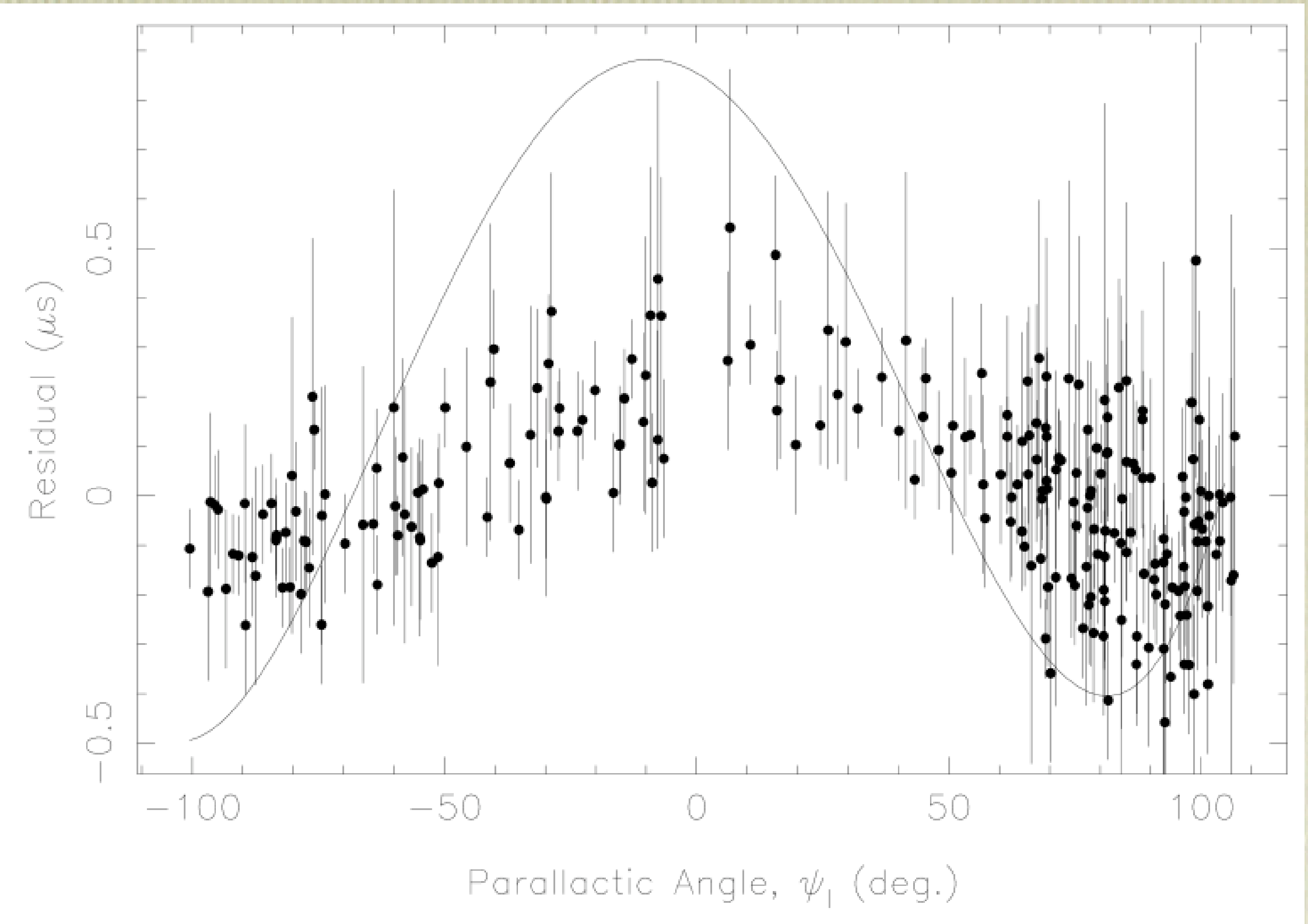
Splaver et al. 2002

Instrumental effects



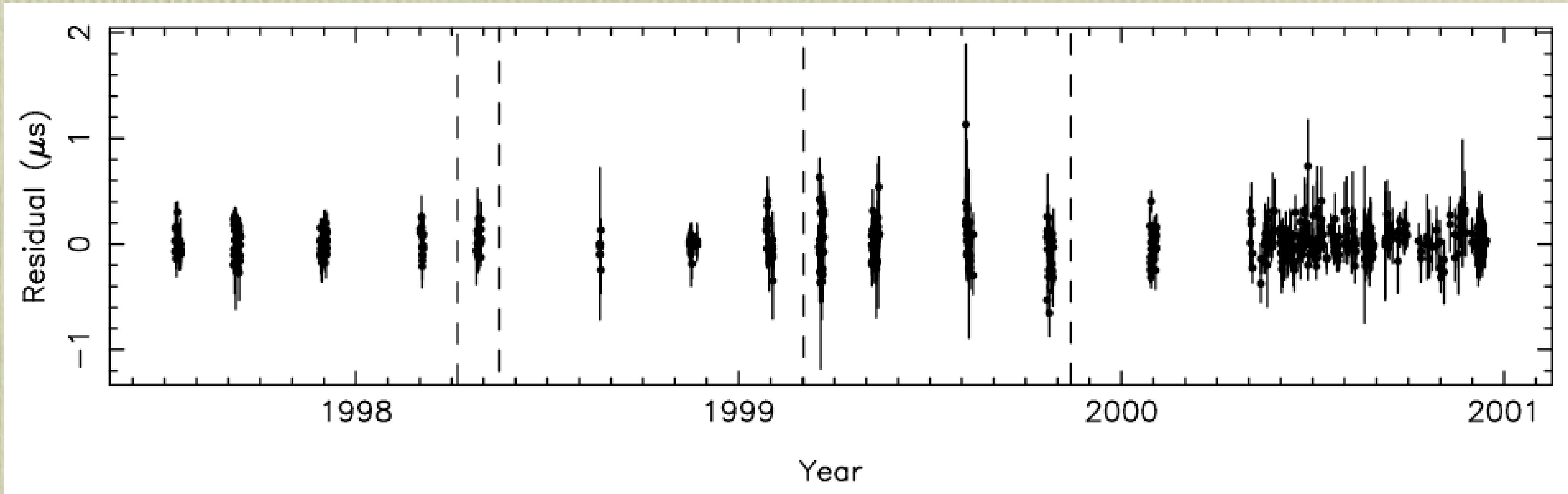
Van Straten 2003

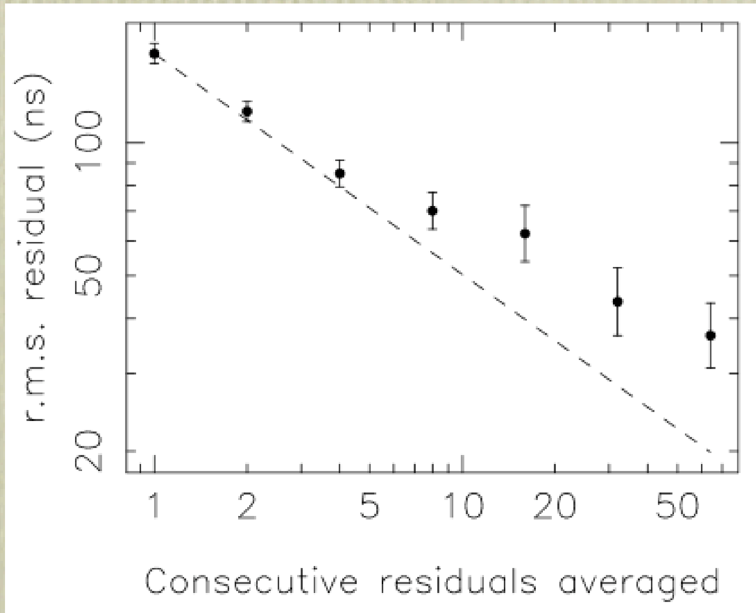
Instrumental effects



Van Straten 2003

Radiometer noise

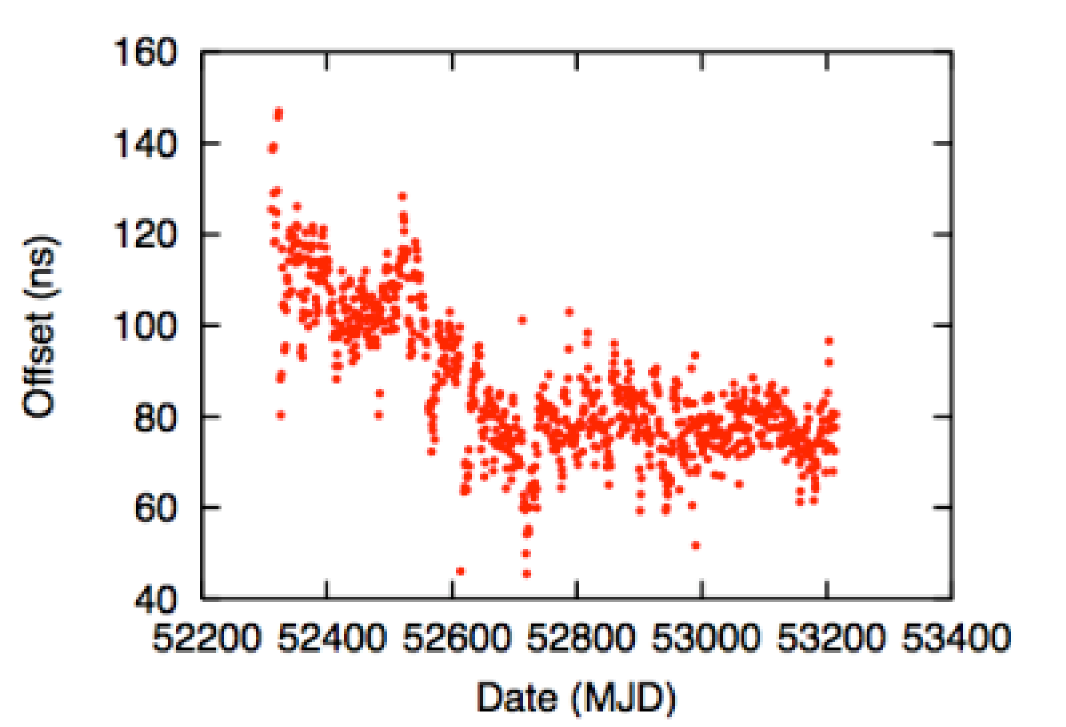




Van Straten 2003

Time transfer

- Comparison to TT suffers same transfer problems as formation of TT
- PKS GPS UTC ...
- PKS UTC(AUS) UTC ..



TT(BIPM) vs PT(PKS)

- 100 ns / 5 y = 6×10^{-16}
  - Multiple pulsars (cf. Kaspi et al)
  - Should be able to out-do TT(BIPM) by factor few,
  - Only for 1 y < $\Delta t < t_{total}$
- SKA: 150× better by 2020
  - Just keeping up with atomic clocks
- Ultimate menace: GR !?

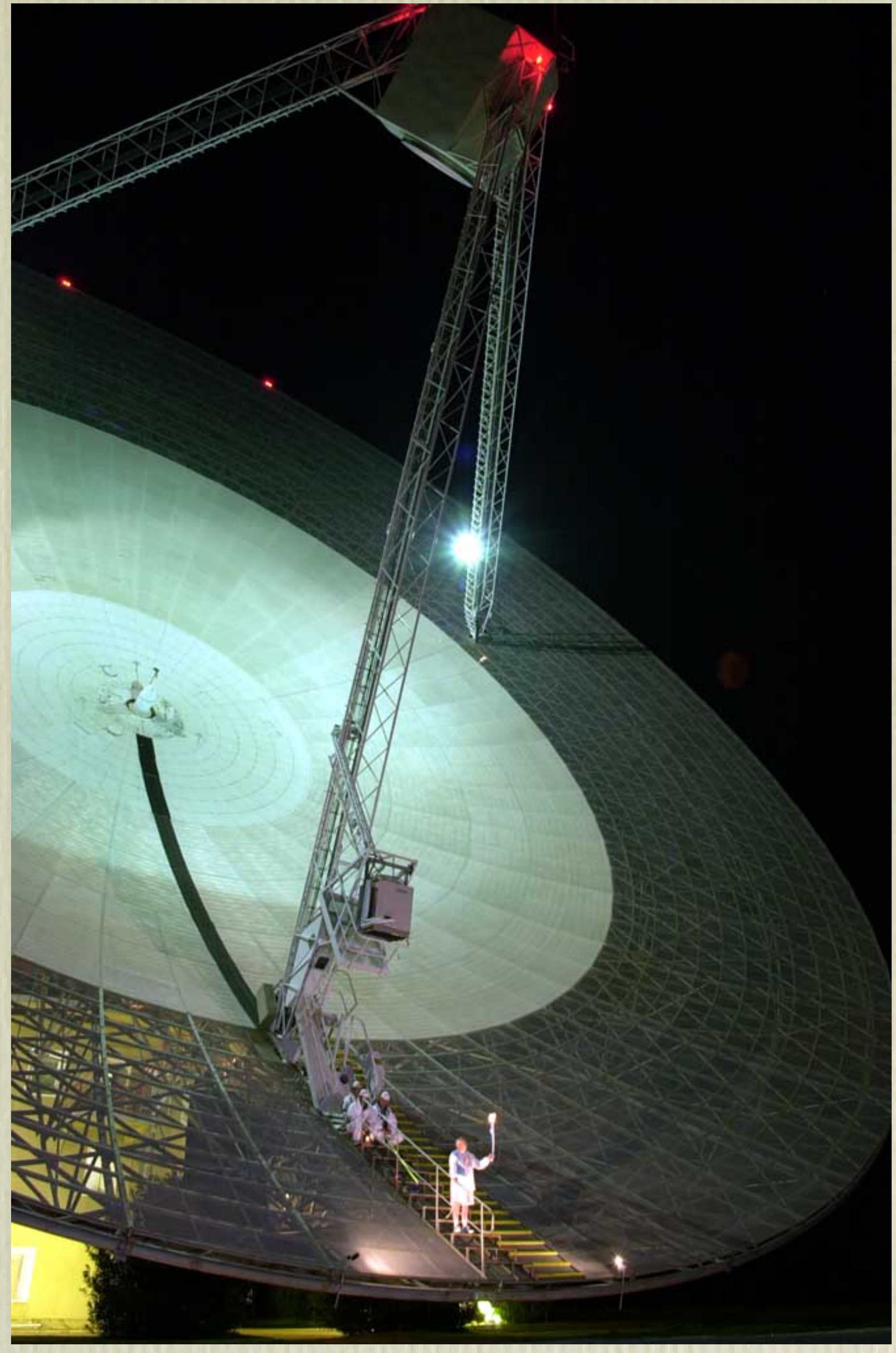


Photo: Stewart Duff

Summary

- Continued improvement in terrestrial time, via
  - Caesium fountains (present)
  - Trapped ion optical frequency standards
- Continued improvements in pulsar timing, via
  - Pulsar Timing Array
  - Square Kilometre Array
- Pulsars win on few-year timescales