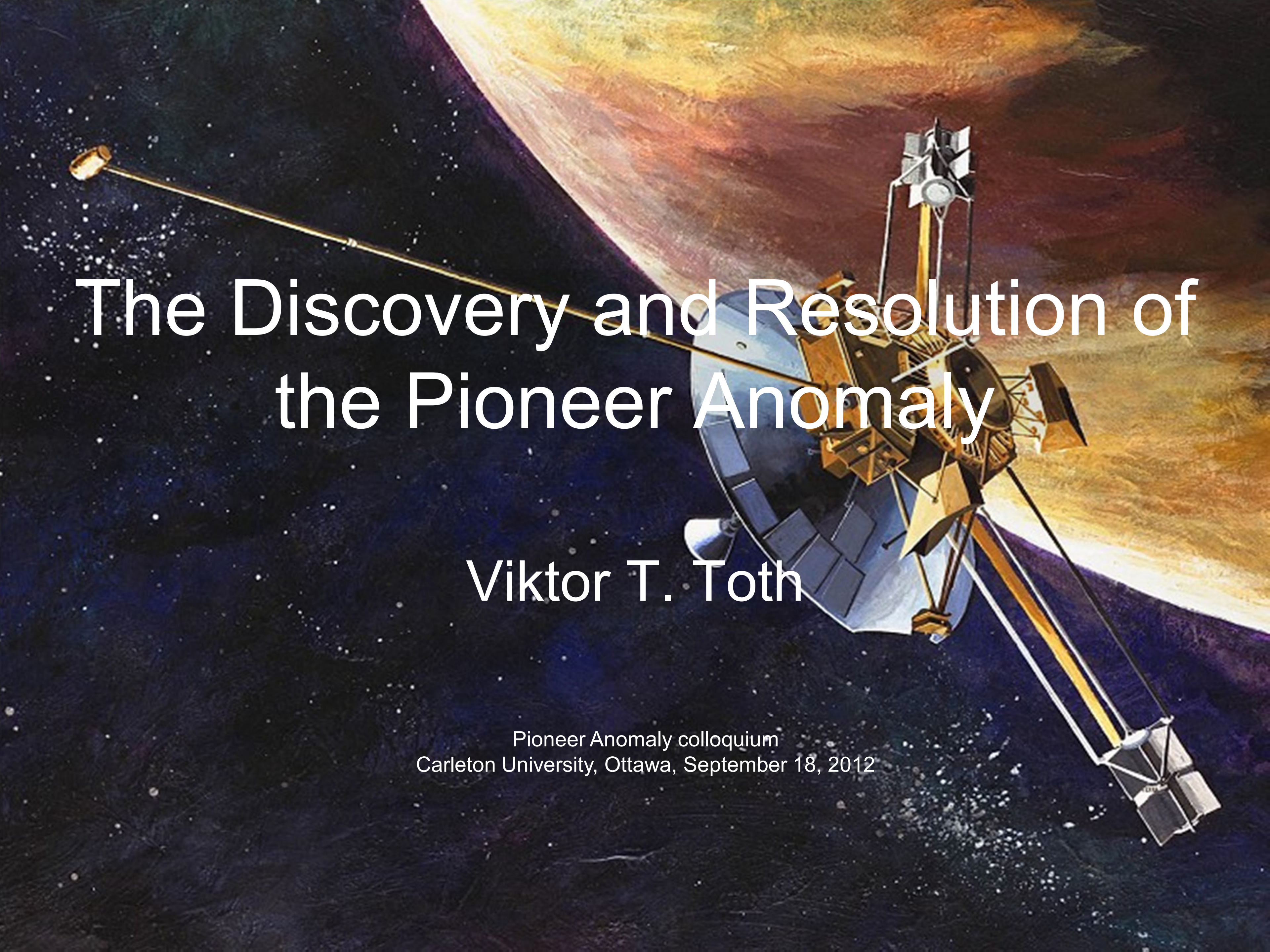


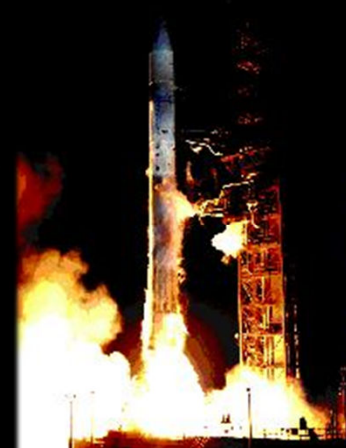
The Discovery and Resolution of the Pioneer Anomaly

Viktor T. Toth

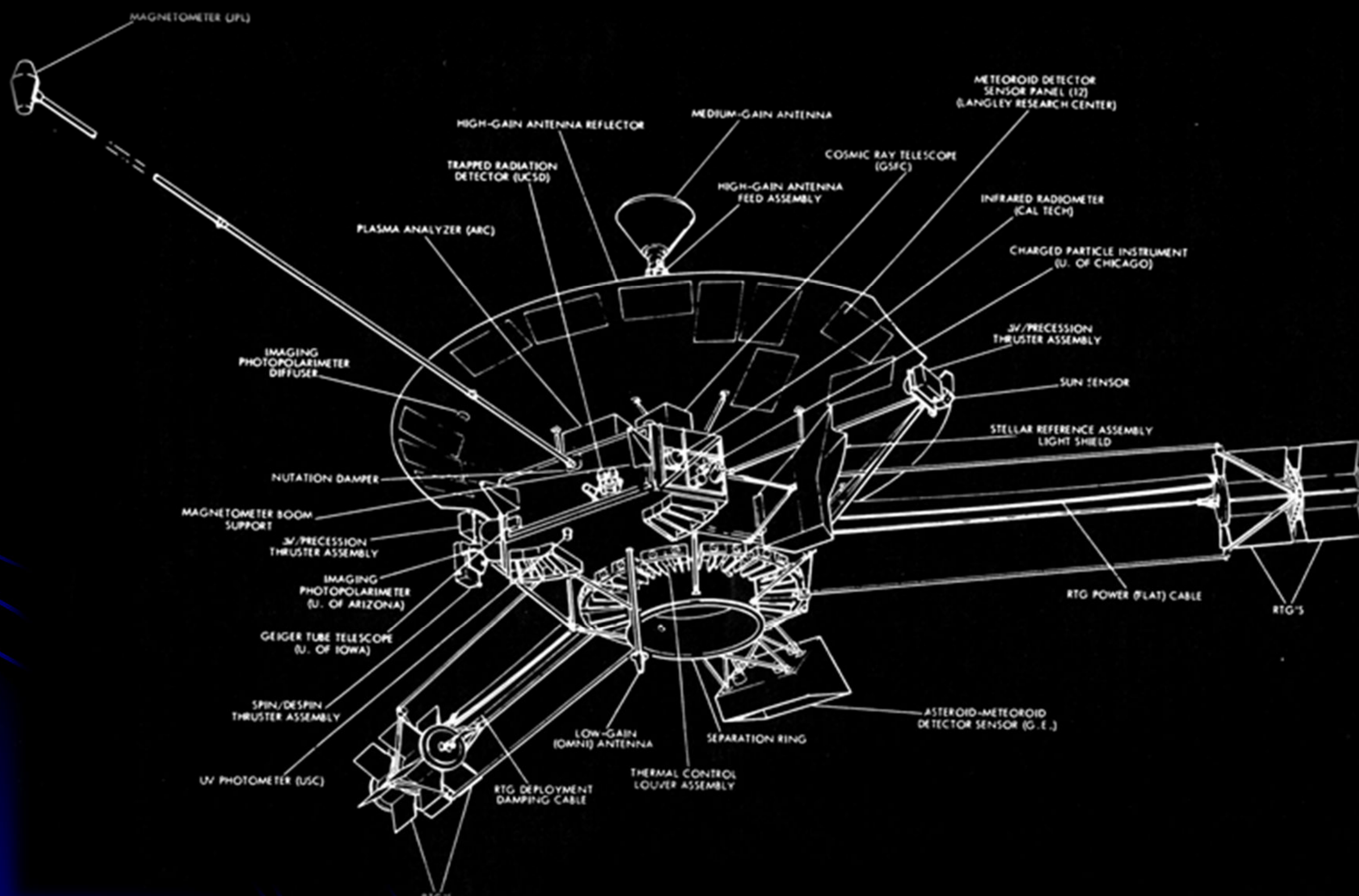
Pioneer Anomaly colloquium
Carleton University, Ottawa, September 18, 2012

The Pioneer 10/11 missions

- Launched in 1972 and 1973
- First to explore beyond Mars
- First to visit Jupiter and Saturn
- Planned duration: 600-900 days



The Pioneer spacecraft



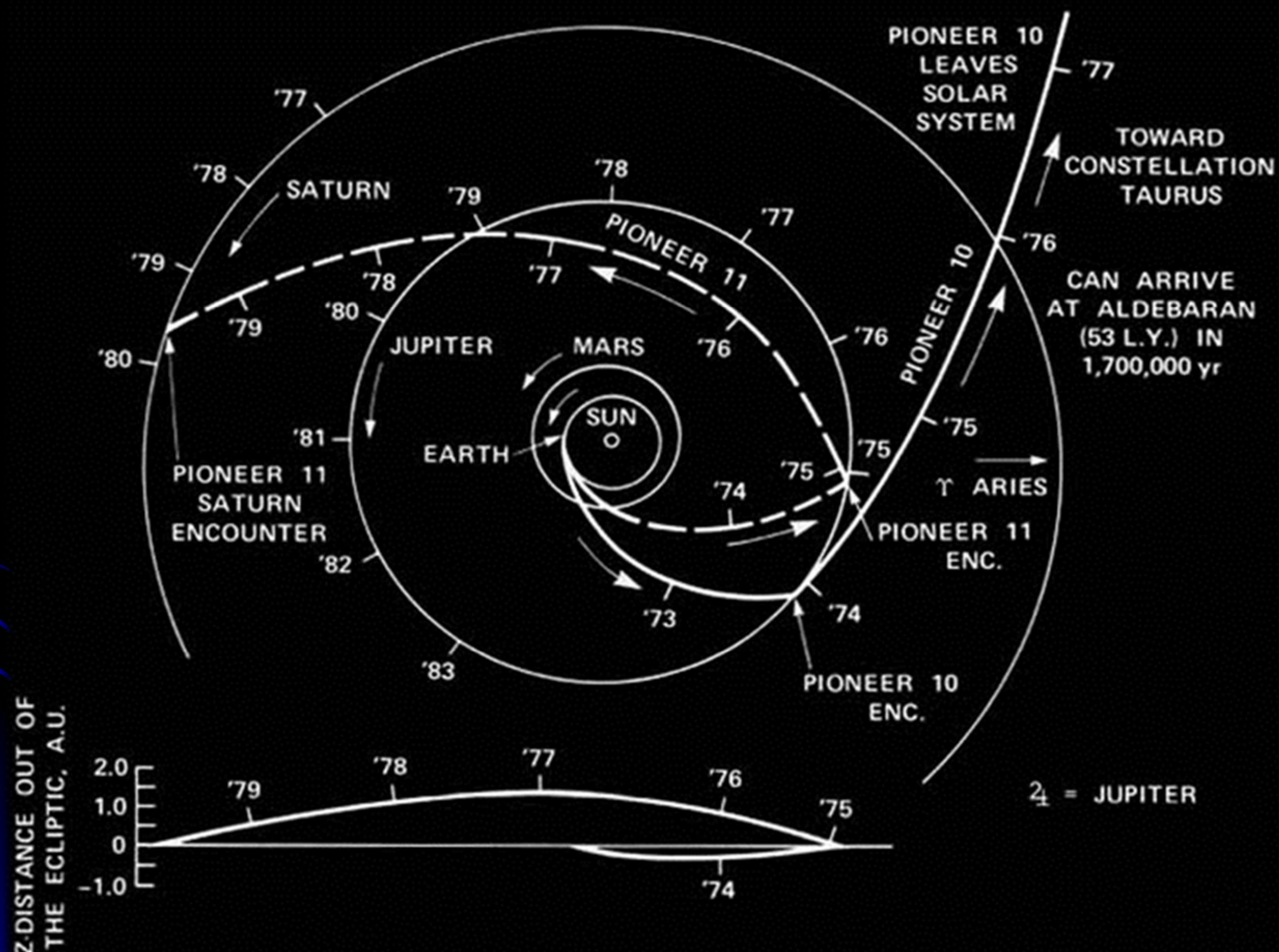
The Pioneer spacecraft

- Mass: ~250 kg
- Radioisotope Thermoelectric Generators
- Electrical Power: ~160 W (at launch)
- 11 Scientific Instruments
- 2.75 m High Gain Antenna
- Transmitter: 8 W
- Data rate: 16-2048 bps
- Spin stabilized (4.8 rpm nominal)

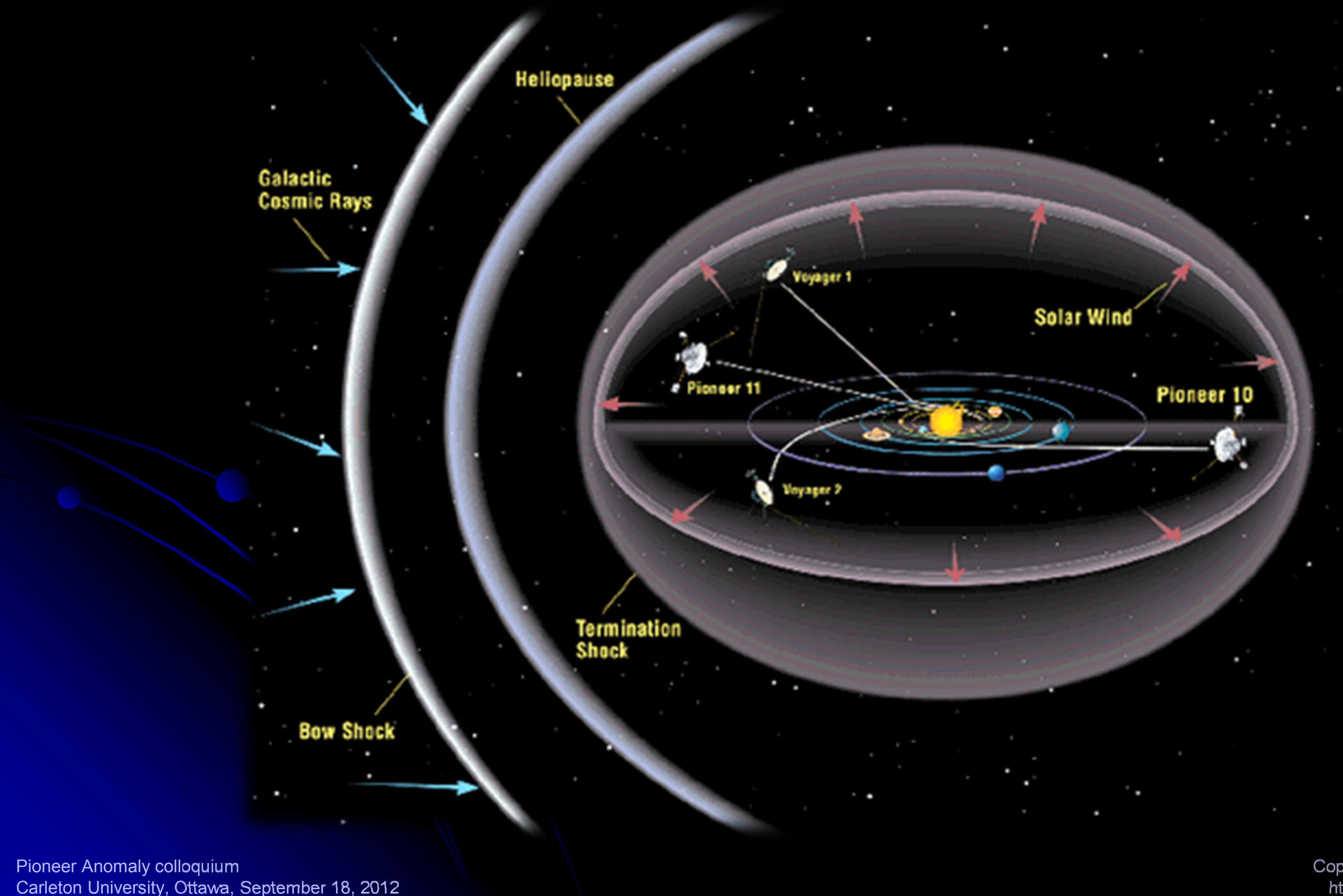
Mission objectives

- Primary Objectives
  - Explore the asteroid belt
  - Explore beyond Mars
  - Close-up observations of Jupiter
- Secondary Objectives
  - Explore the outer solar system
  - Search for gravity waves
  - Search for “Planet X”

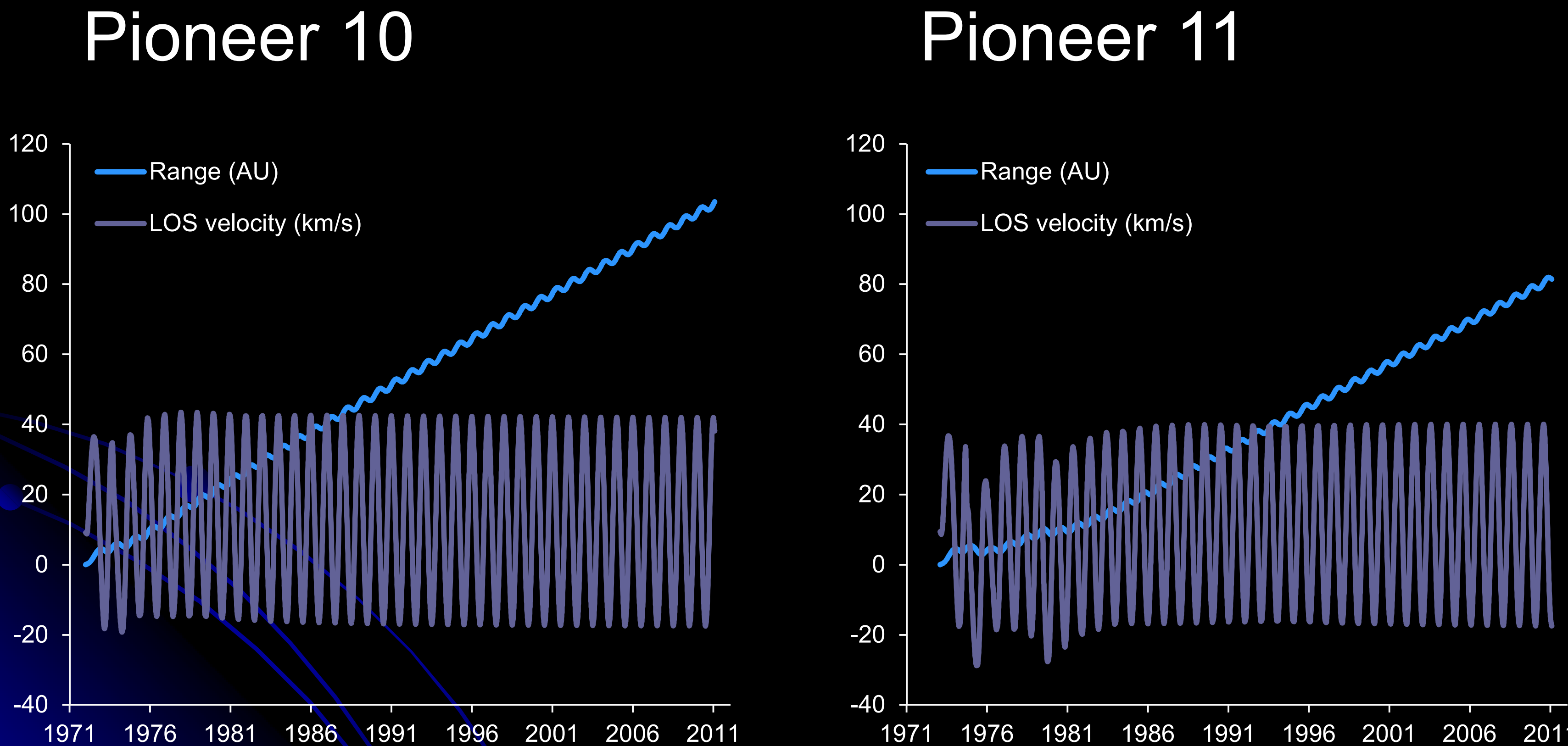
Pioneer orbits – early years



Pioneer and Voyager orbits through the outer solar system



Distance and geocentric velocity



Orientation maneuvers

- Few maneuvers needed for spinning spacecraft
- Few maneuvers → clean data
- Ingenious "Closed loop" CONSCAN maneuver lets the spacecraft "home in" on DSN signal
- Late in the mission, ~2 CONSCANs a year were performed

Pioneer 10 after 30 years

- Distance from Sun: ~80 AU
- Round-trip light time: ~21 hours
- Speed relative to the Sun: ~12 km/s

Pioneer 10 after 30 years

- One instrument (GTT) was still operating (power-down command sent last track, but never confirmed)
- Bus voltage ~ 26VDC instead of nominal 28VDC
- Transmitter XCO failed (probably due to cold)
- Transmitter still operating in coherent mode
- Many temperature readings “off scale” or outside calibrated ranges
- Propellant lines frozen (no maneuvers possible)

Discovery of the Anomaly

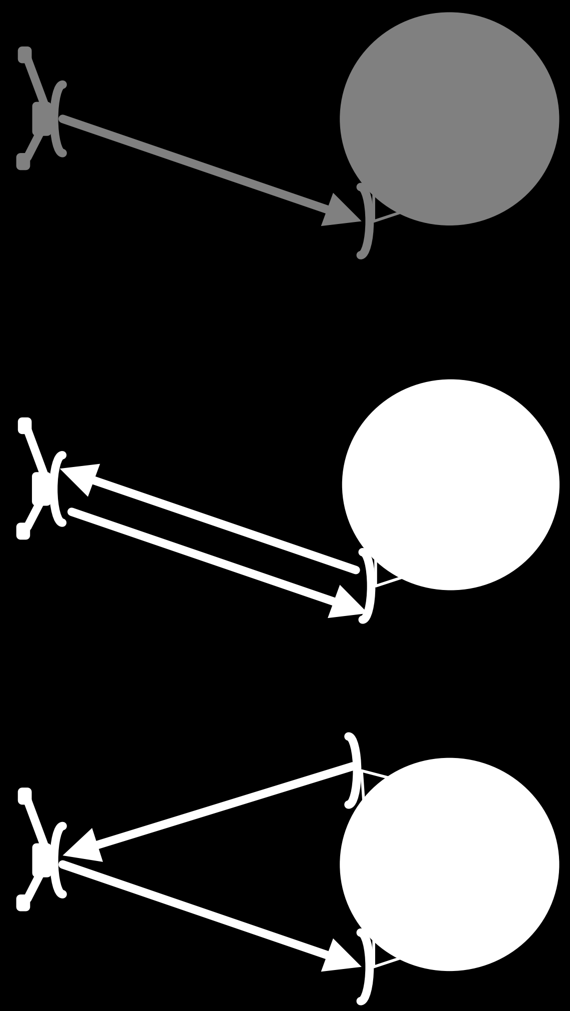
- Search began in 1979 (for “Planet X”)
- Anomaly first detected in 1980
- Initial JPL ODP analysis in 1990-95
- Aerospace Corporation confirms: 1996-98

Analysis of Doppler data

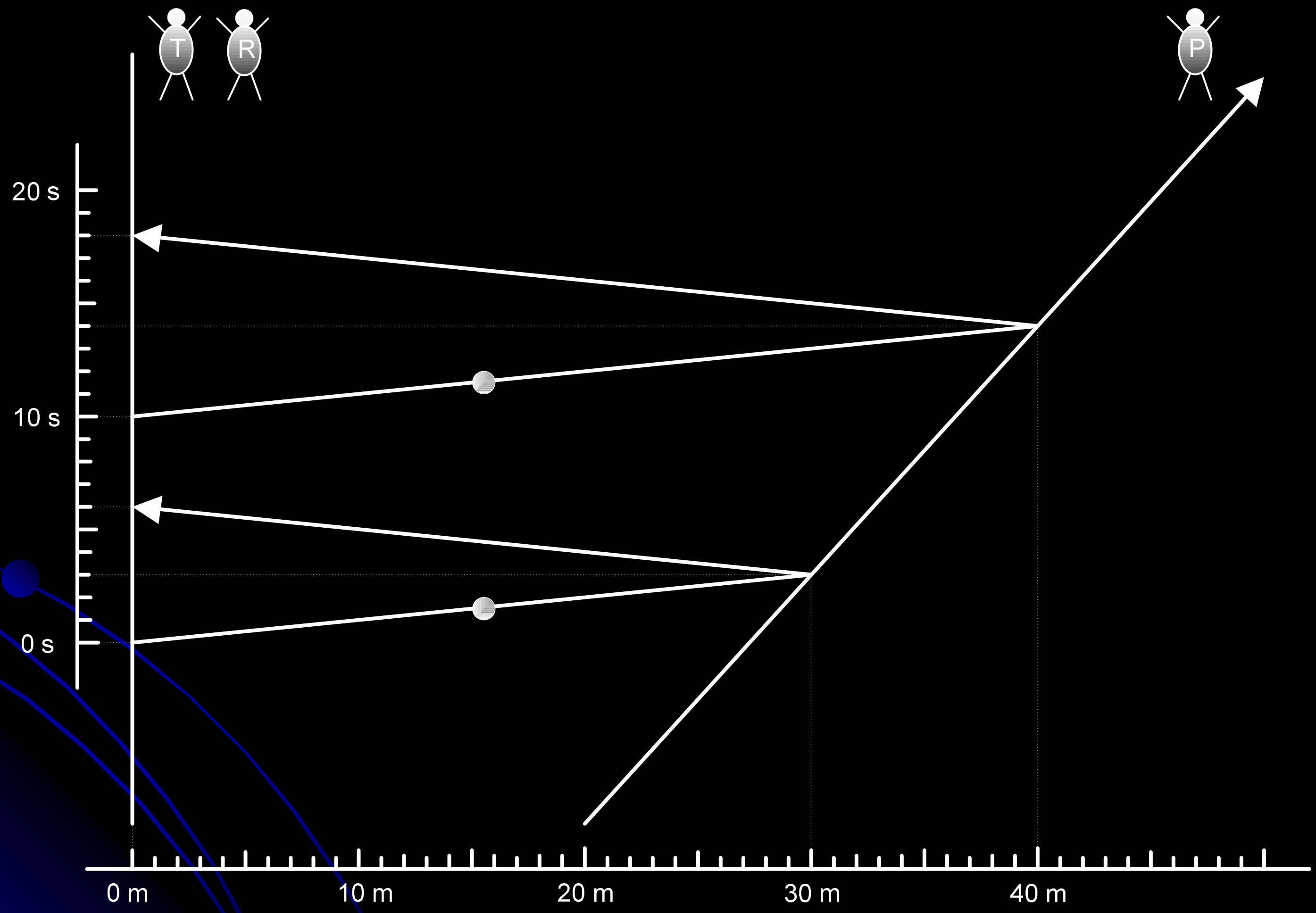
- All observations are two-way or three-way Doppler
- Doppler analysis is about counting cycles

Doppler measurements

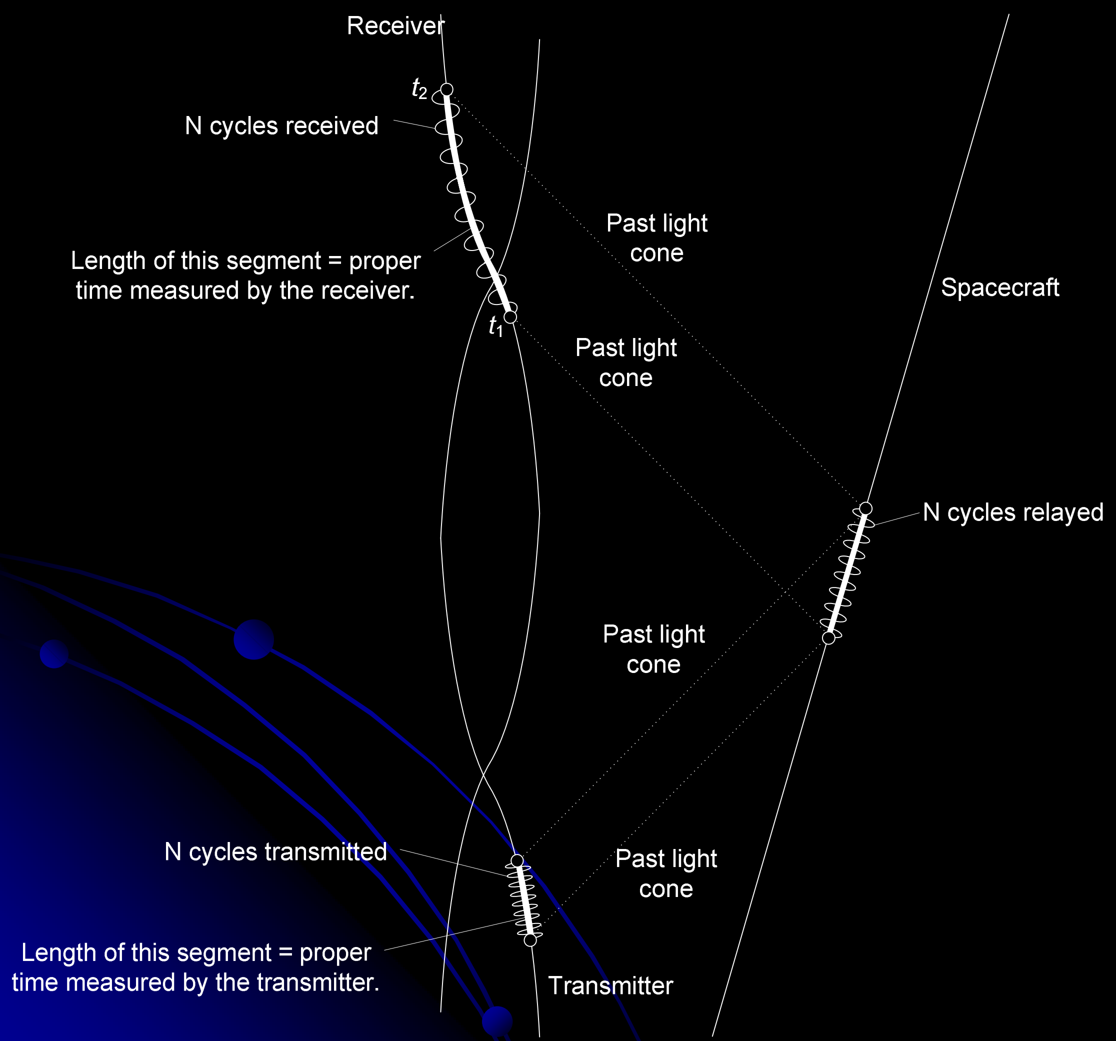
- One-way Doppler
- Two-way Doppler
- Three-way Doppler



Two-way (or three-way) Doppler



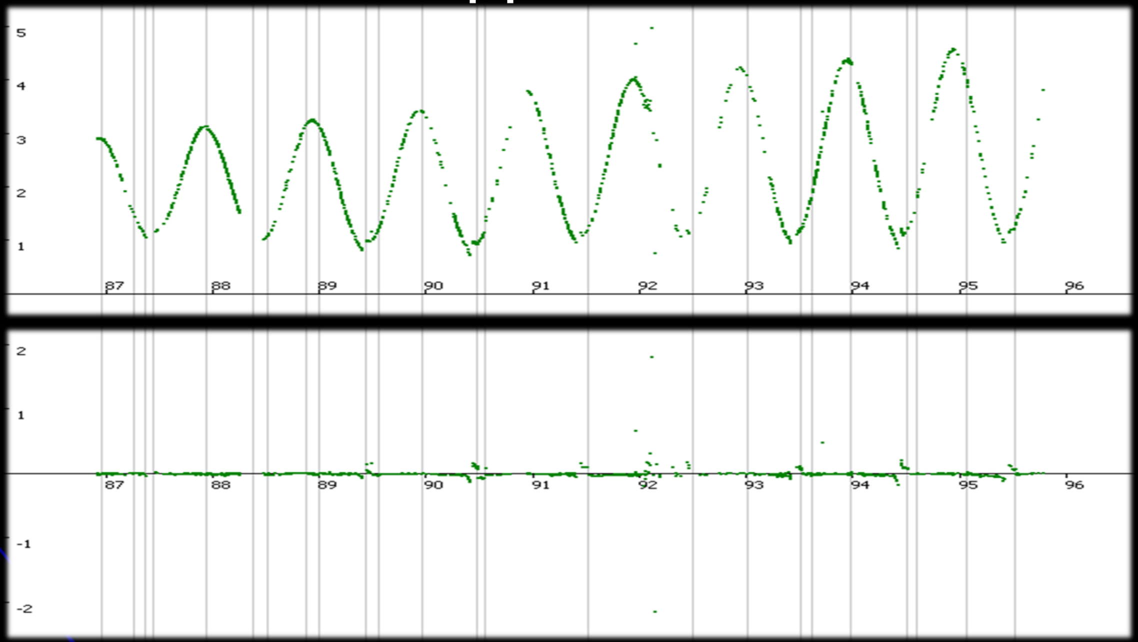
Doppler measurements



- A measurement at the receiver is made between t_1 and t_2
- These two instances of time are projected back onto the spacecraft's and then the transmitter's modeled world line; model accounts for
  - Post-Newtonian gravity of major solar system bodies
  - Maneuvers
  - Small non-gravitational forces (e.g., propellant leaks)
  - Shapiro delay
  - Effects of interplanetary medium (solar plasma)
  - Effects of the atmosphere
  - Motion of ground stations (tides, continental drift)
- The number of cycles transmitted is computed from the transmitter's known frequency
- This is then compared to the actual cycle count observed at the receiver
- Model is iteratively refined to reduce the residual difference.

Doppler Fits

- Model predicts spacecraft motion and Doppler
- Antenna measures actual Doppler
- Difference is called the "Doppler Residual"
- "Bad" fit:
- "Good" fit:



- Accuracy is measured in mHz!

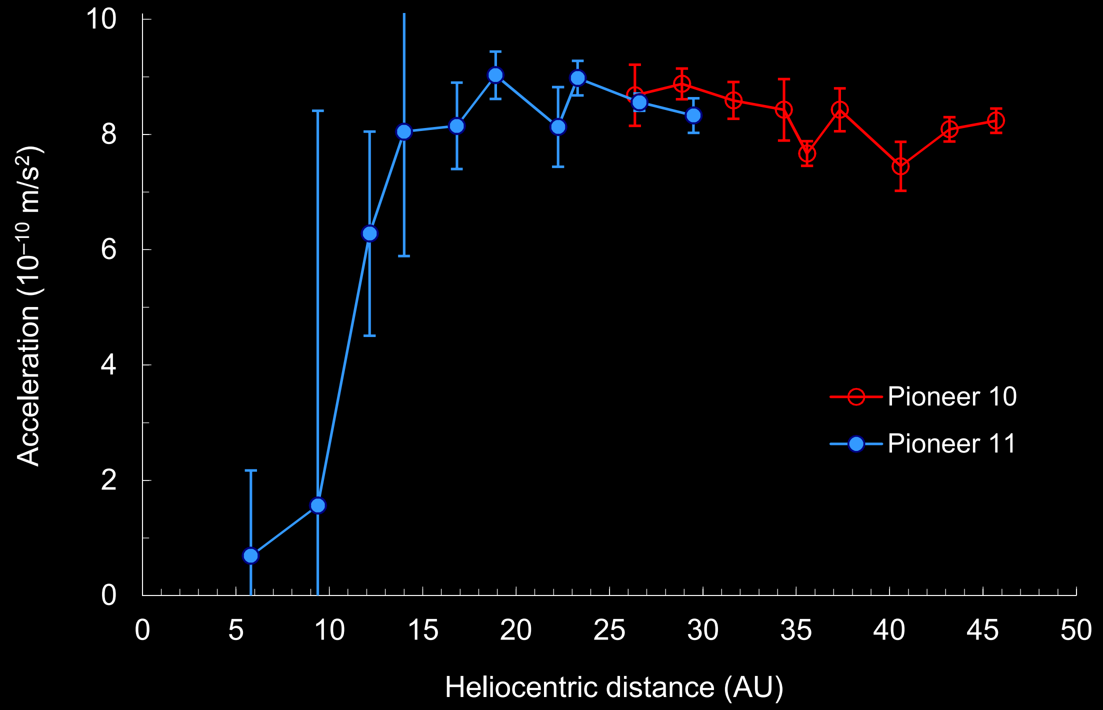
Interpreting the residual

- Frequency drift: $(5.99 \pm 0.01)\times10^{-9}$ Hz/s (@ ~2 GHz)
- Velocity change: $(8.74 \pm 1.33)\times10^{-10}$ m/s^2
- Clock acceleration: $(2.92 \pm 0.44)\times10^{-18}$ s/s^2
- Velocity change (acceleration) is the “conventional” interpretation
- Effect small by engineering standards, but huge by the standards of gravity physics

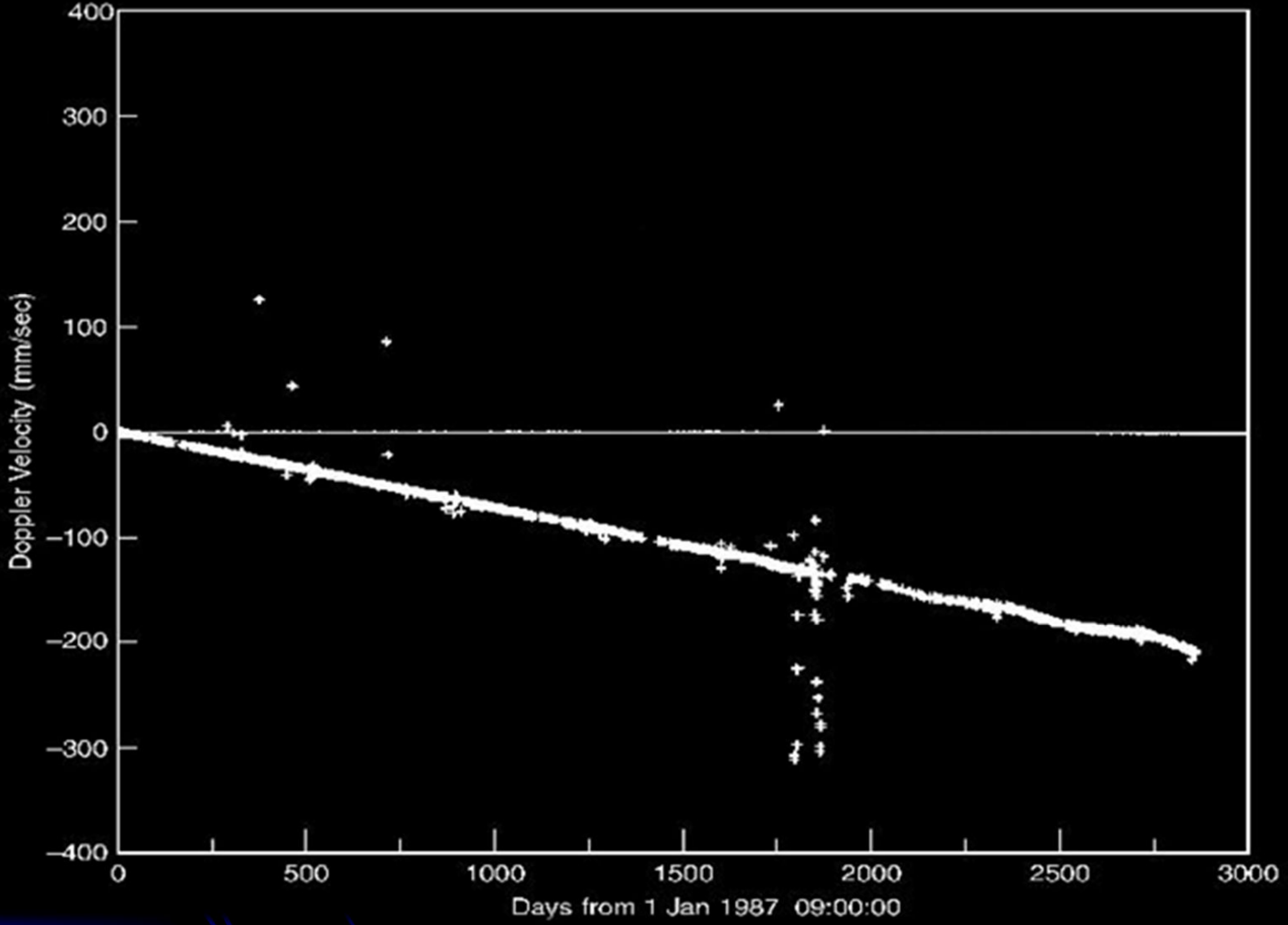
The Pioneer Anomaly is NOT

$$a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$$

The Pioneer Anomaly is NOT



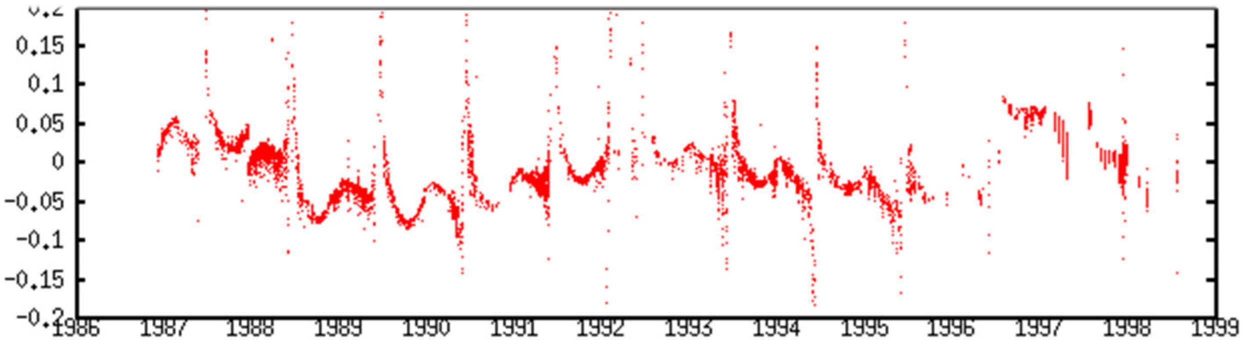
The Pioneer Anomaly is NOT



The Pioneer Anomaly IS

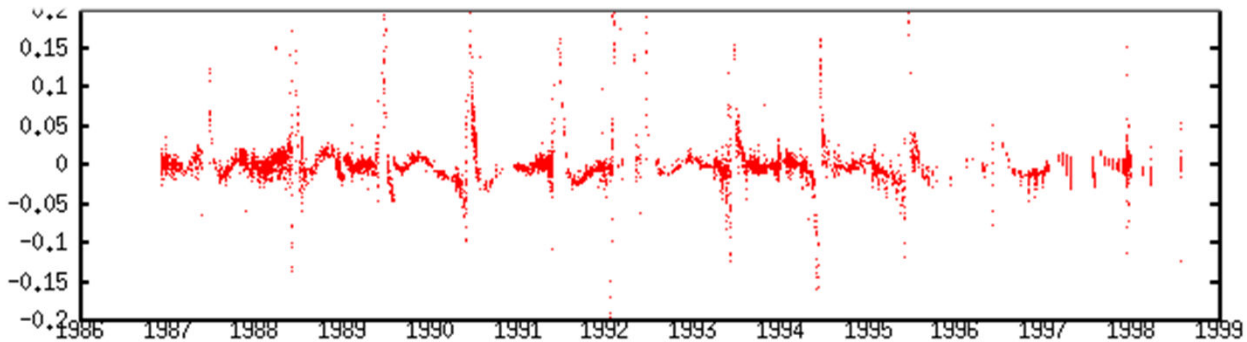
The Pioneer Anomaly IS

this:



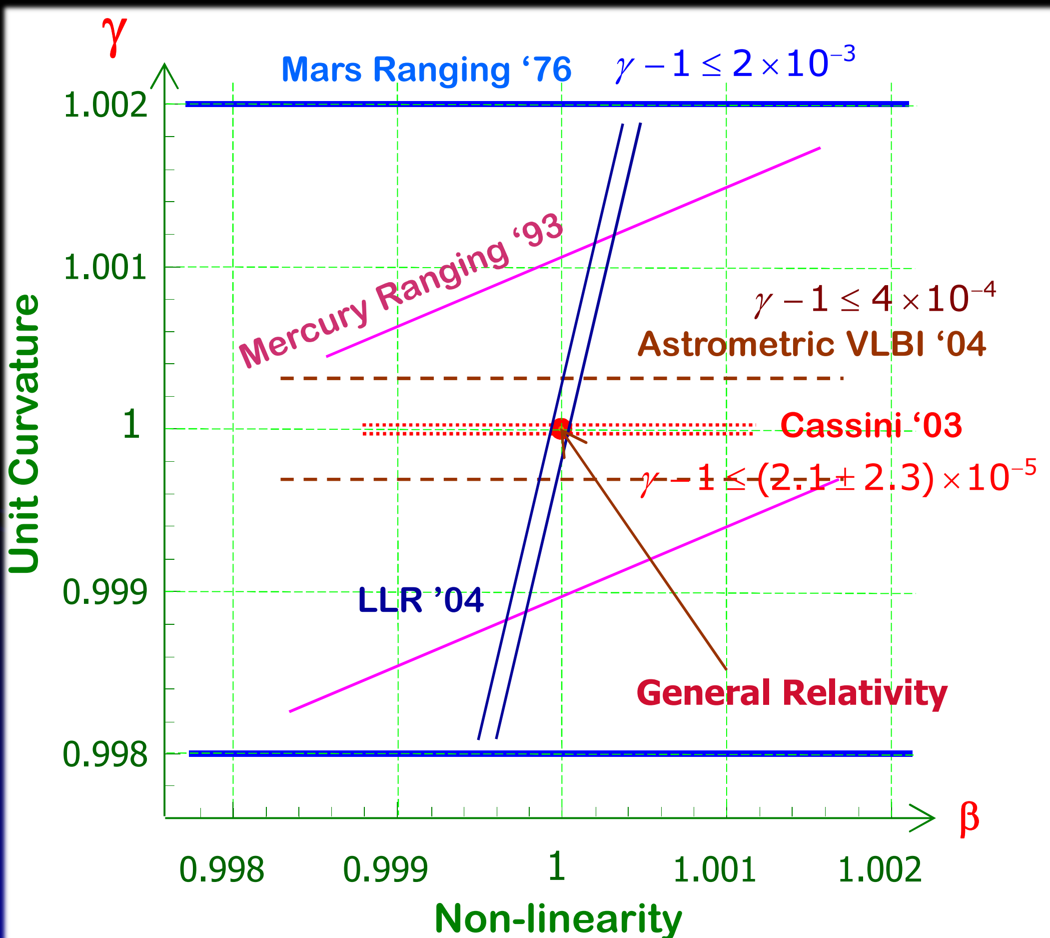
The Pioneer Anomaly IS

instead of this:



THE PIONEER ANOMALY IS OUR *INABILITY TO MODEL THE DOPPLER RESIDUAL AT THE EXPECTED LEVEL OF ACCURACY* USING ONLY KNOWN CONVENTIONAL PHYSICS.

Experimental General Relativity



$$g_{11} = g_{22} = g_{33} = -\left(1 + \frac{2\gamma}{c^2}\sum_{j \ne i}\frac{\mu_j}{r_{ij}}\right)$$

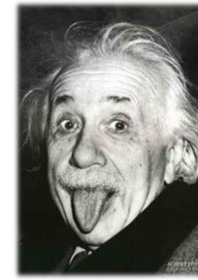
$$g_{pq} = 0 \quad (p, q = 1,2,3;\ p \ne q)$$

$$g_{14} = g_{41} = \frac{2 + 2\gamma}{c^3}\sum_{j \ne i}\frac{\mu_j \dot{x}_j}{r_{ij}}$$

$$g_{24} = g_{42} = \frac{2 + 2\gamma}{c^3}\sum_{j \ne i}\frac{\mu_j \dot{y}_j}{r_{ij}}$$

$$g_{34} = g_{43} = \frac{2 + 2\gamma}{c^3}\sum_{j \ne i}\frac{\mu_j \dot{z}_j}{r_{ij}}$$

$$g_{44} = 1 - \frac{2}{c^2}\sum_{j \ne i}\frac{\mu_j}{r_{ij}} + \frac{2\beta}{c^4}\left(\sum_{j \ne i}\frac{\mu_j}{r_{ij}}\right)^2 - \frac{1 + 2\gamma}{c^4}\sum_{j \ne i}\frac{\mu_j \dot{s}_j{}^2}{r_{ij}} + \frac{2(2\beta - 1)}{c^4}\sum_{j \ne i}\frac{\mu_j}{r_{ij}}\sum_{k \ne j}\frac{\mu_k}{r_{jk}} - \frac{1}{c^4}\sum_{j \ne i}\mu_j\frac{\partial^2 r_{ij}}{\partial t^2}$$

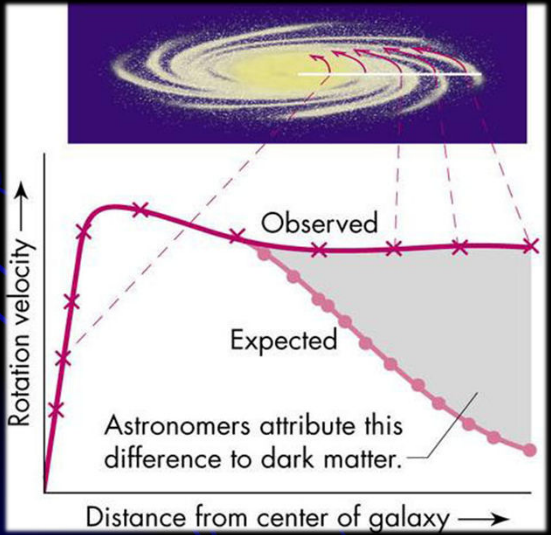


Albert Einstein
(1879-1955)

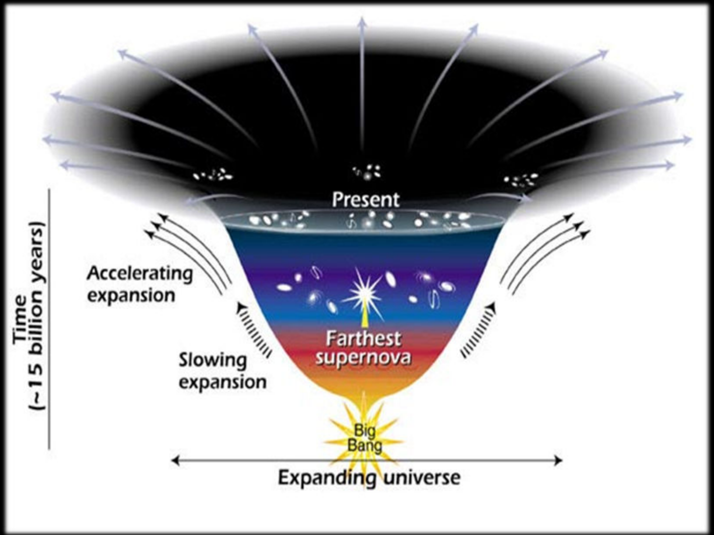
Parameterized Post-Newtonian (PPN) formalism
From Moyer (JPL Publication 00-7)

May not work at large distances

- Galaxies do not rotate as expected
- Supernovae, microwave background show accelerated expansion



Dark matter?



Dark energy?

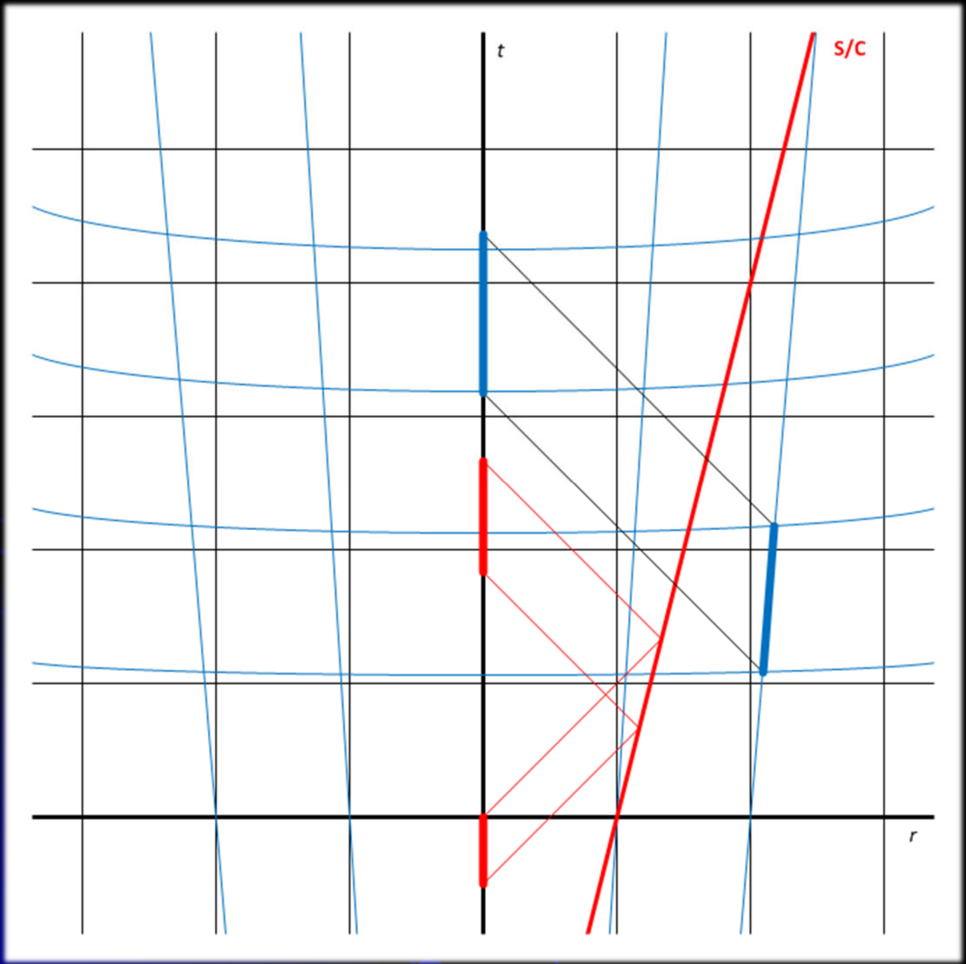
Analysis of the Anomaly

- May be systematic or “new physics”
- Another independent confirmation by Markwardt (2002)
- Also confirmed independently by Olsen (2005), Toth (2009)
- Only limited stretches of data were studied; no telemetry, no formal thermal model.

Consensus as of 2006

- The Pioneer Anomaly is real
- Conventional physics *fails* to explain it
- Alternatives proposed include
  - Gravity modification (MOND, MSTG, Yukawa potential)
  - Dark matter
  - Cosmological origin
- $|a_P| \approx cH_0$: coincidence?

The sign of a_P vs. cH_0



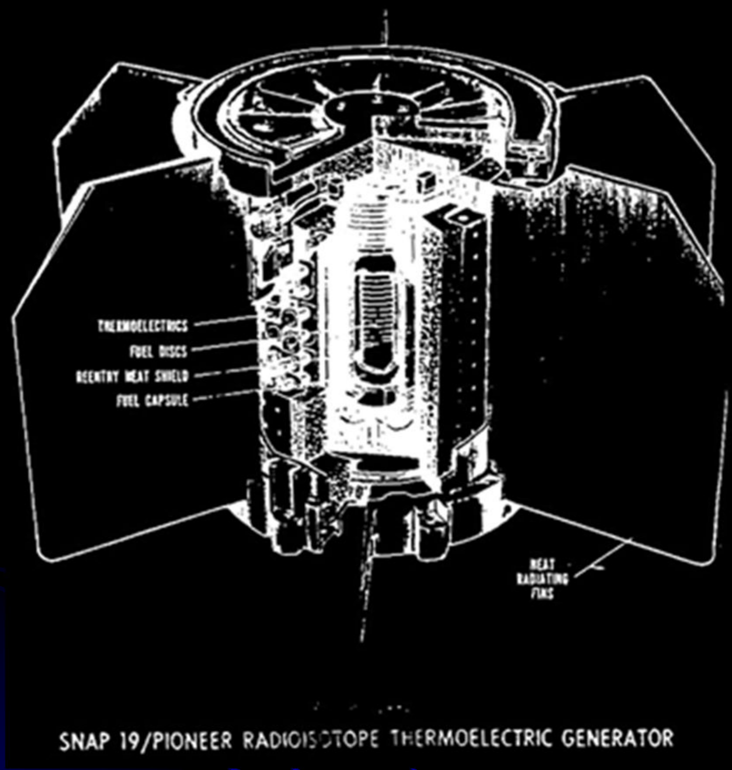
- Much has been said about a_P having the wrong sign for a cosmological origin
- This argument is not universally valid: an example is a conformal metric
  - The light of a distant star (blue) appears redshifted in accordance with Hubble's law
  - A radio signal of unit duration (half unit, actually, for drawing convenience) sent to a receding spacecraft S/C will be returned with a redshift. However, in the conformally transformed coordinate system, less time will appear to have elapsed, resulting in an apparent, small, additional blue shift. Ref: Hill, Phys. Rev. (68) 232 (1945).

The case for thermal recoil

- It's not a question of either-or, but a question of how much
- Let me establish the case for the thermal recoil force:

The case for thermal recoil

Pioneer power source

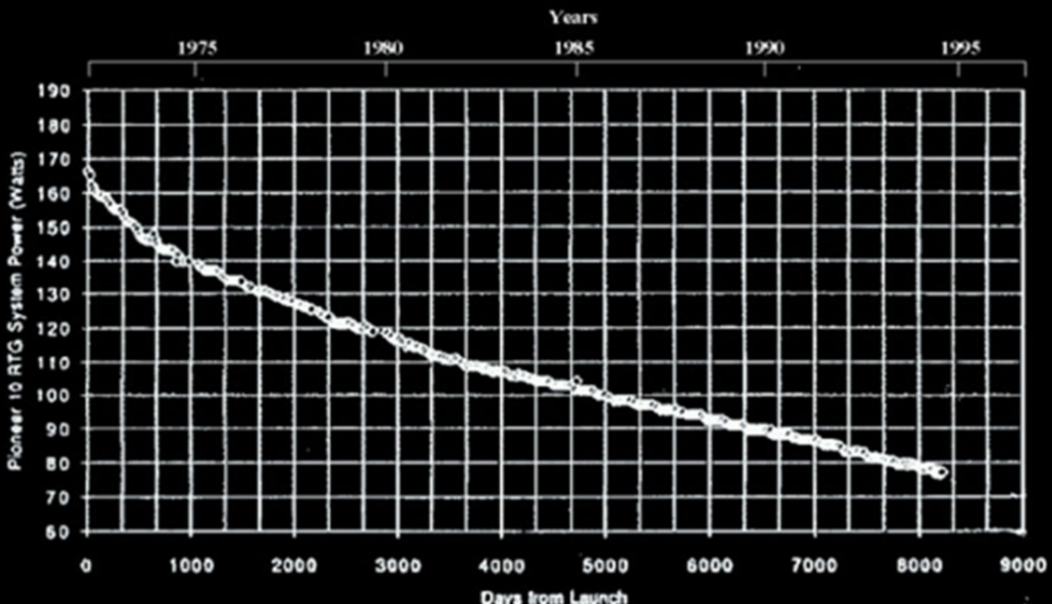


RTG Thermal Power: ~650W

Electrical Power: ~40W

4 RTGs per spacecraft

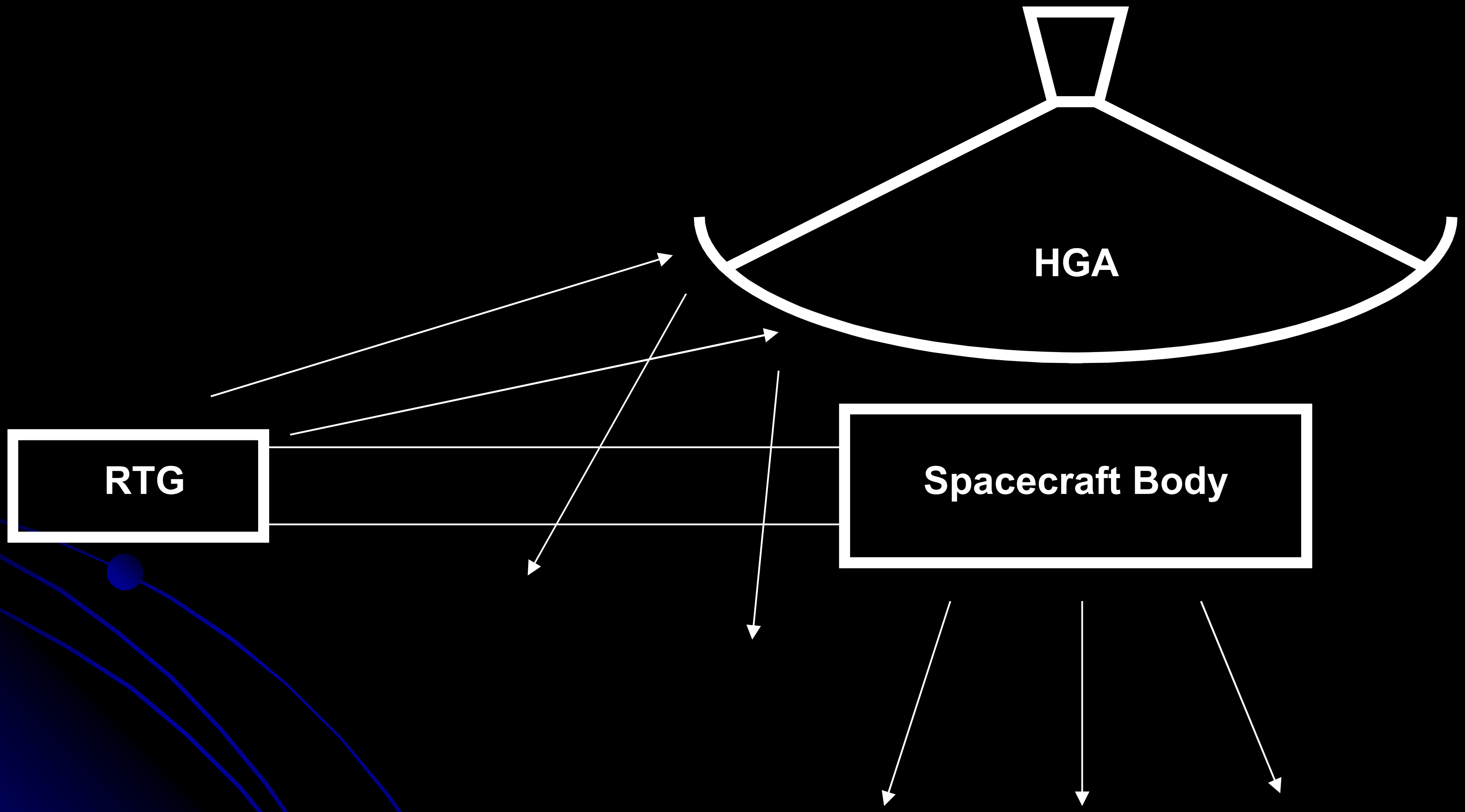
~4.6 kg ^{238}Pu on board



Thermal analysis

- The question: What recoil force is generated by on-board heat?
- Heat sources are easily enumerated:
  - RTG waste heat (~2.5 kW)
  - Electrical heat (~100 W)
  - RHUs (~10 W)
  - Propulsion system (transient)

Thermal recoil geometry



The thermal hypothesis

- Total thermal output: 2.5 kW
- Small anisotropy: −2.5% on one side, +2.5% on the other, sufficient to explain acceleration
- Thermal models are approximations
- The anisotropy is a difference that is almost 2 orders of magnitude smaller than the estimated quantities

ACCURACY IS ESSENTIAL!

But difficult...

- Spacecraft were built 40 years ago
- Documentation is incomplete, some saved from dumpster

The ideas are not new...

- They have been around for some time:
  - Murphy (1999): Electrical heat accounts for much of the acceleration
  - Katz (1999): Electrical heat and reflected RTG heat account for the acceleration
  - Scheffer (2003): Combination of conventional forces (including paint degradation) explains acceleration

...but dismissed prematurely?

- Dismissed using "back-of-the-envelope" estimates
- "Back of the envelope" models are a dime a dozen:
  $$P_{1\to 2} = \iint P_1 \cos\chi_1 \cos\chi_2 / \pi r^2 \, dA_1 dA_2$$
- Doing it the right way is hard.

New effort

- Recovered all telemetry from both craft
- Recovered twice the Doppler data
- Recovered project documentation
- New Doppler analysis
- Comprehensive thermal analysis
- New ways to integrate thermal model and trajectory reconstruction

Constancy and direction

- Isn't the acceleration a) constant, b) sunward?
- Short answer: No
- Long(er) answer: Acceleration is not the observable.
- Long answer: ...

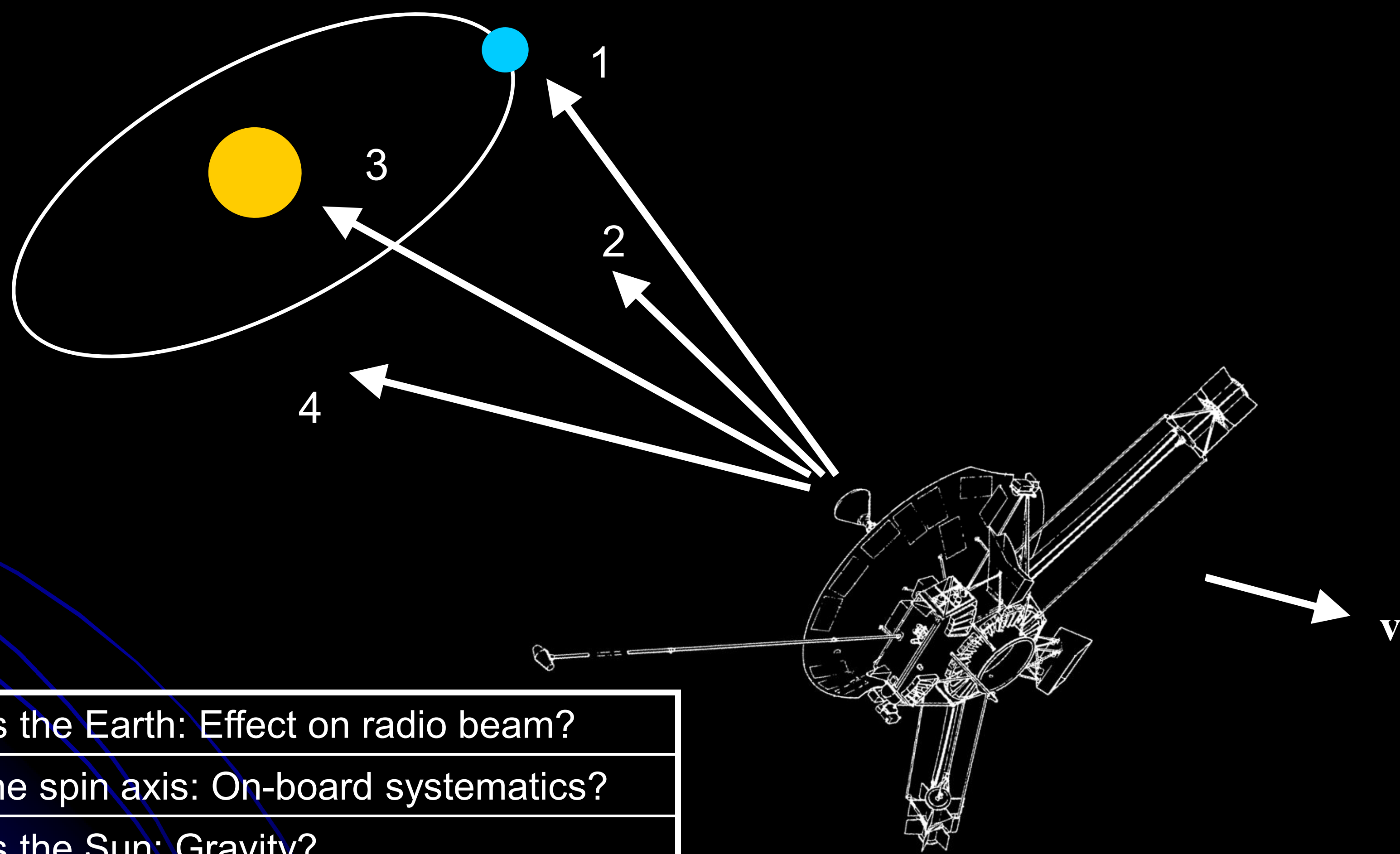
The navigational solution

- Navigators aren't doing fundamental physics. They fix the *navigational problem* by introducing fictitious forces.
- A constant sunward acceleration ($a_P = (8.74 \pm 1.33) \times 10^{-10}\ \mathrm{m/s^2}$) fixes the problem. It does NOT mean that the Pioneer spacecraft necessarily experience a constant sunward acceleration.

Other solutions

- A temporally decaying acceleration fixes the problem and it is slightly better (no statistically significant difference.)
- Earthward acceleration fixes the problem.
- Earthward, temporally decaying acceleration fixes the problem.
- Other, equally valid solutions also exist.

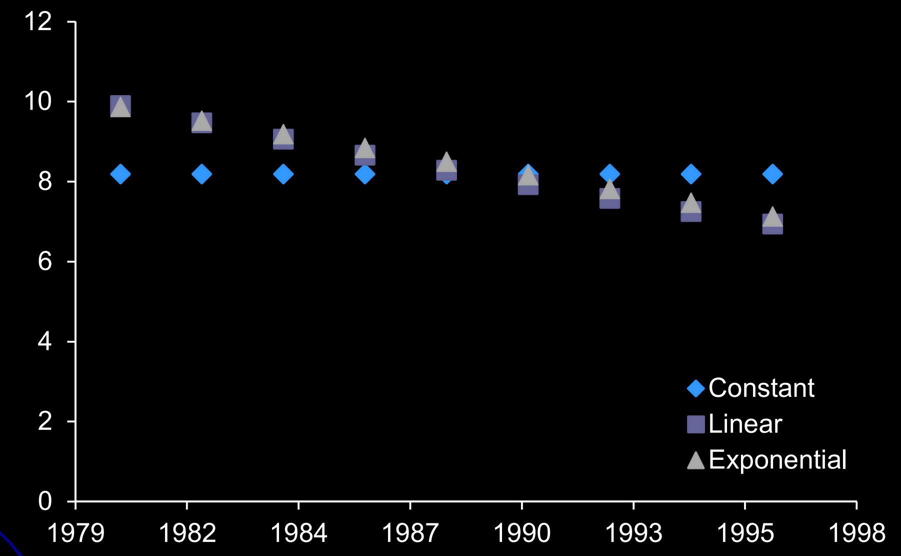
The question of direction



1.	Towards the Earth: Effect on radio beam?
2.	Along the spin axis: On-board systematics?
3.	Towards the Sun: Gravity?
~~4.~~	~~Opposite the direction of motion: Drag force?~~

Temporal behavior

- Is the acceleration constant or variable?



The goodness of fit

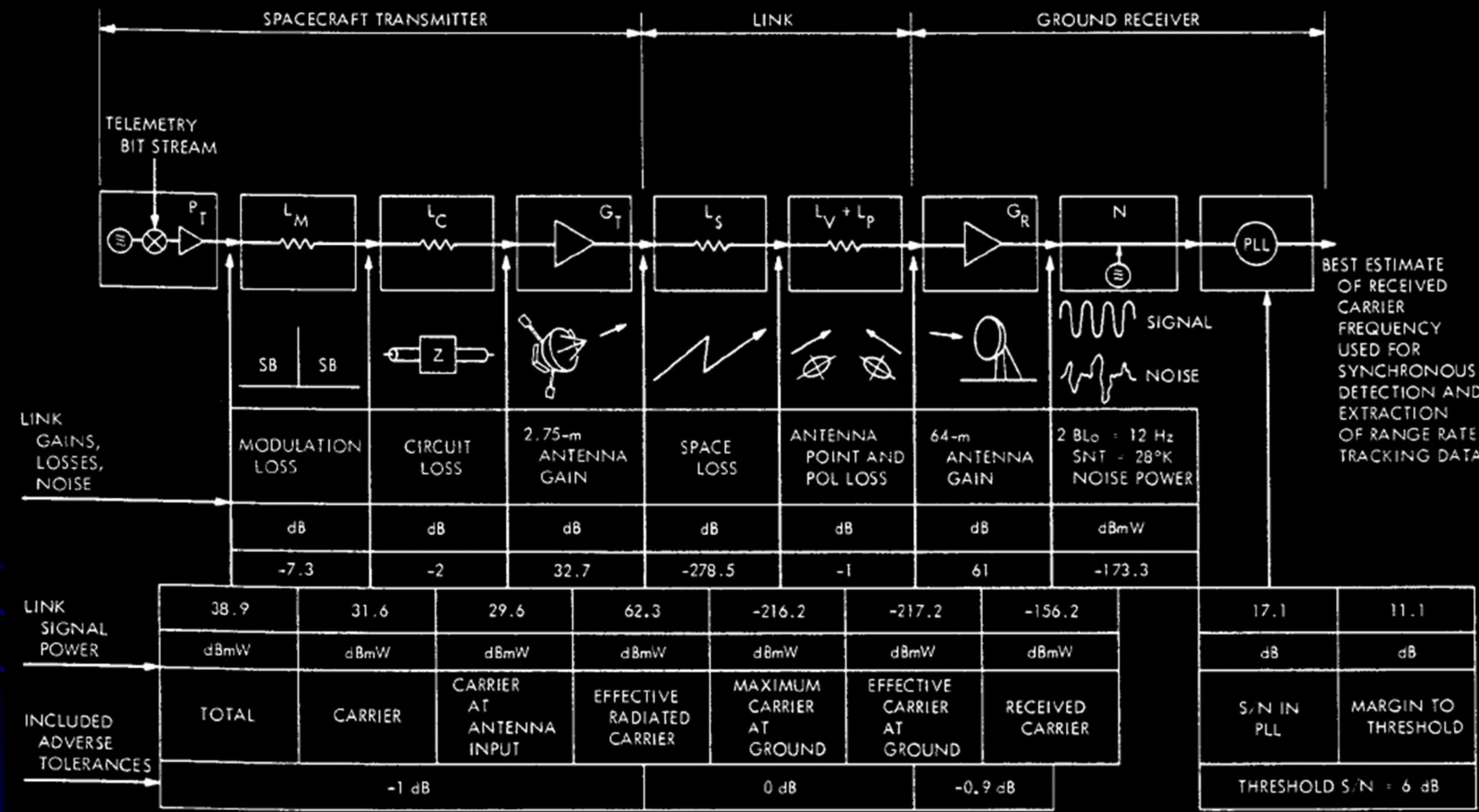
- To compare solutions, we compare residuals
- Even the best residual contains plenty of noise:
  - Mismodeling of the solar system
  - Unknowns: solar plasma, troposphere, other effects
  - Unmodeled forces: small leaks
  - Measurement noise, clock stability, etc.
  - Numerical accuracy

THE PIONEER SIGNAL IS MODELED WITH AN ERROR AS LOW AS ~2 mHz OVER 20 YEARS IN A 2.29 GHz RADIO SIGNAL!

Accuracy

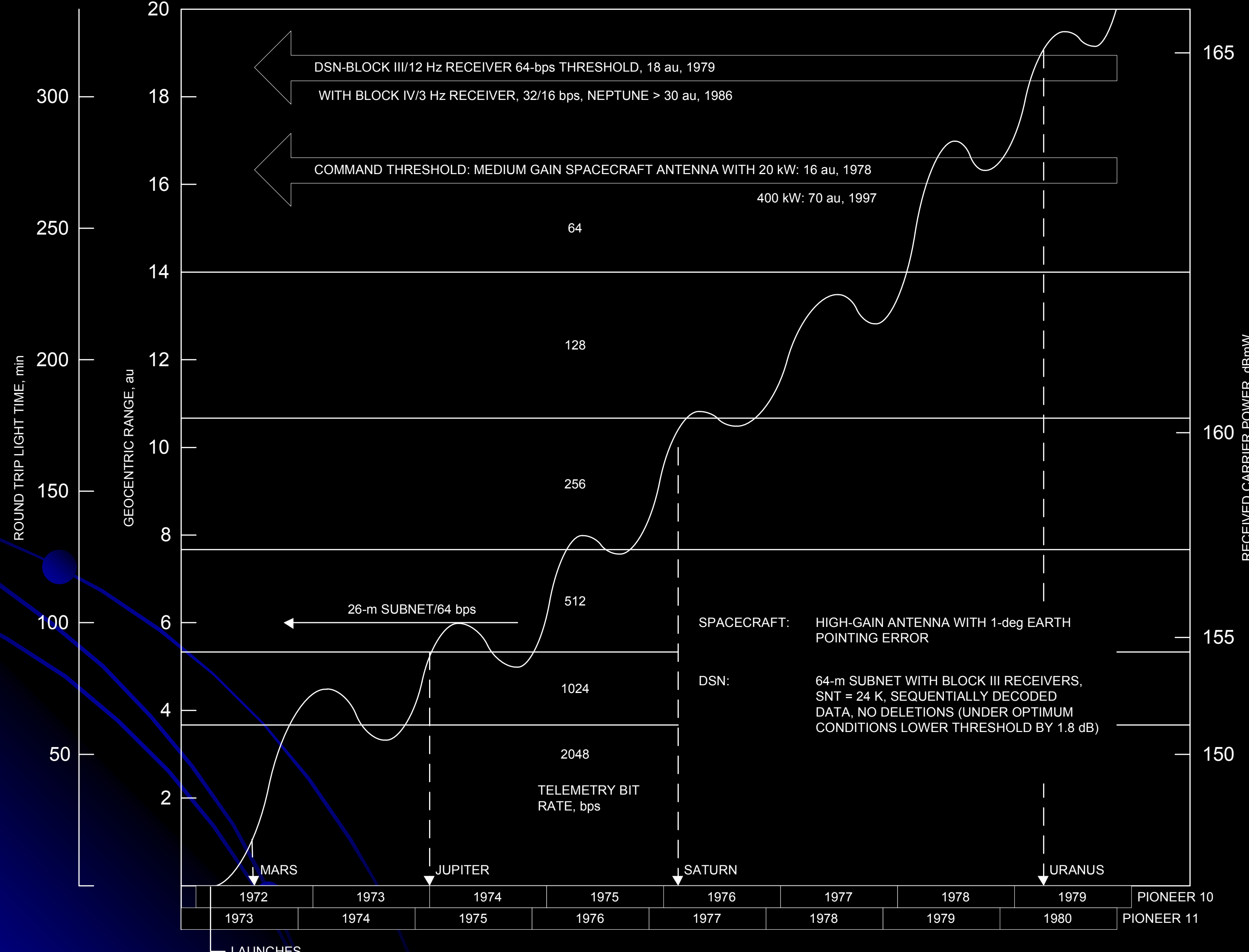
- Measurement and models must be accurate to better than 1 part in 10^{14} over 20 years.
- (IEEE 64-bit double precision floating point accuracy: about 1 part in 10^{16}.)

Downlink power budget



Received power was –181 dBm (<10^{-21} W) at EOM

Downlink power budget



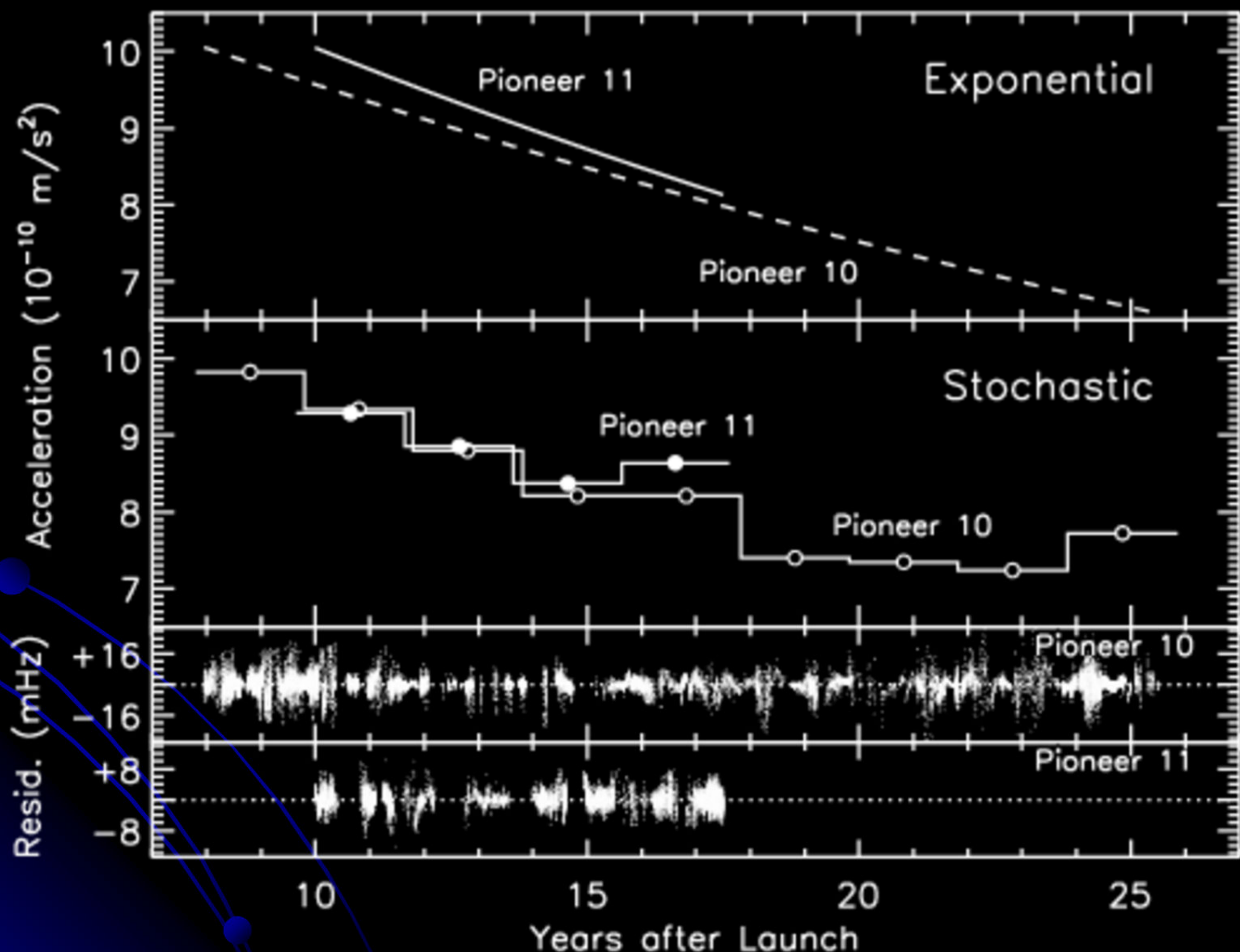
Noise is inevitable

- Some of it is random, some not
- Residuals have visible structure

Doppler analysis results

- The anomaly is confirmed with all available Doppler data
- Temporal decay is possible
- Earth direction is possible

Stochastic and exponential models

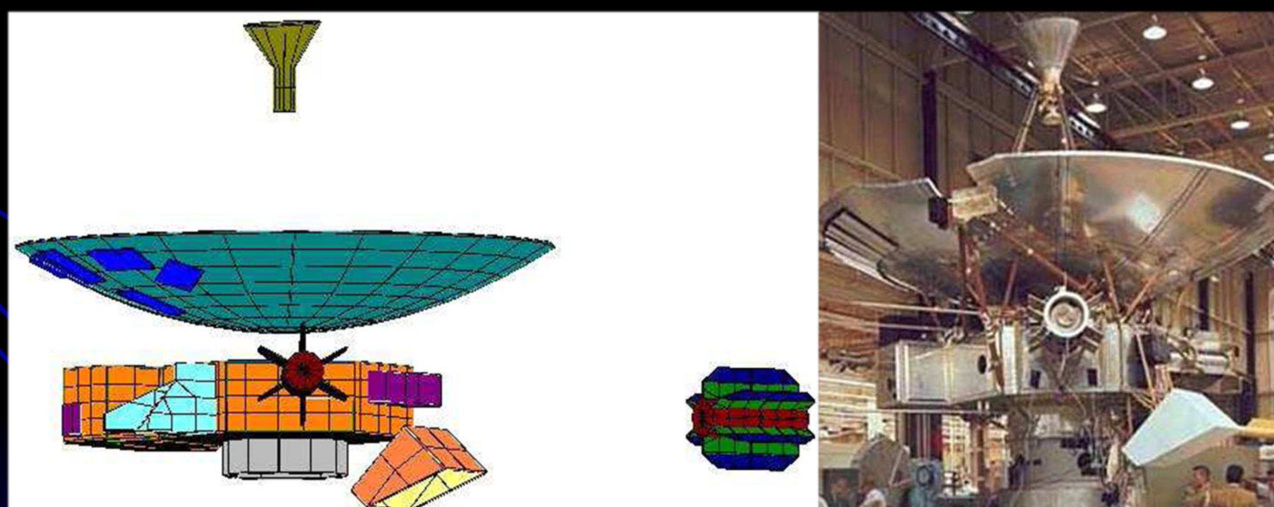


New thermal analysis

- Build a comprehensive thermal model
- Use all available data: Validate the model using redundant telemetry
- Incorporate the model into the orbit determination code to model the actual observable (Doppler)

A comprehensive model

- Constructed by JPL engineers using "industry standard" tools and expertise



Significance of spin

- Thermal forces are slowly changing. Rate of change much smaller than angular velocity: $\dot{F}/F \ll \omega/\pi$
- To first order, force components perpendicular to spin axis average to zero
- Hence only spin axis component of thermal forces needs to be computed

Linear behavior

- The two significant non-transient heat sources are electrical and RTG:

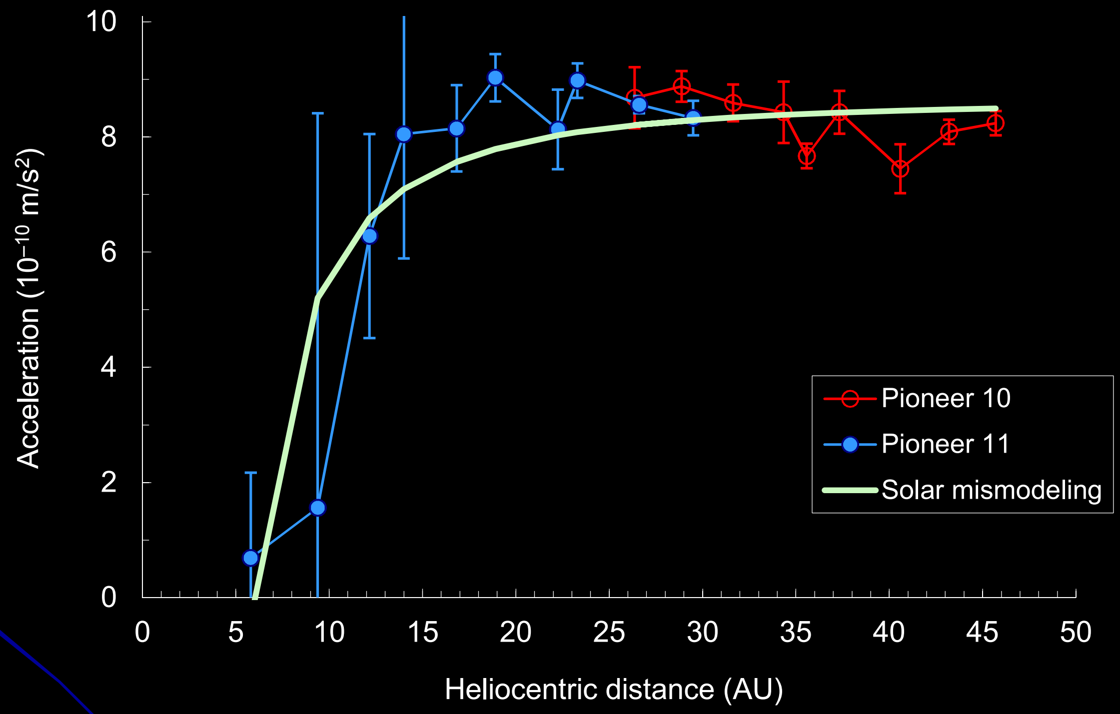
$$F \approx c^{-1}\Sigma\eta_i Q_i \qquad (Q_i = Q_{\rm rtg}, Q_{\rm elec})$$

- No significant trapped heat relative to the rate of change in temperatures (no latency)
- No significant variability in the emission/absorption spectrum of materials at spacecraft temperatures
- Physical configuration of spacecraft and mass constant during deep space cruise
- Temperatures are high enough
  - it can be shown that the necessary condition is $T^3 \gg k/\sigma\epsilon l$, where k is the conductance, ϵ is the emittance, l is the scale or thickness of the material, and σ is the Stefan-Boltzmann constant

The biggest known unknown

- RTG coating: “three mils of zirconia [ZrO_2] in a sodium silicate binder”
- Some similar paints gained emittance in thermal vacuum chamber tests; other paints lost emittance
- This specific paint was never tested
- RTG exterior temperatures may also play a role
- A 5% decrease in emissivity can result in a 50% increase in the RTG anisotropy; a roughly 25% error in the overall thermal recoil force

Onset

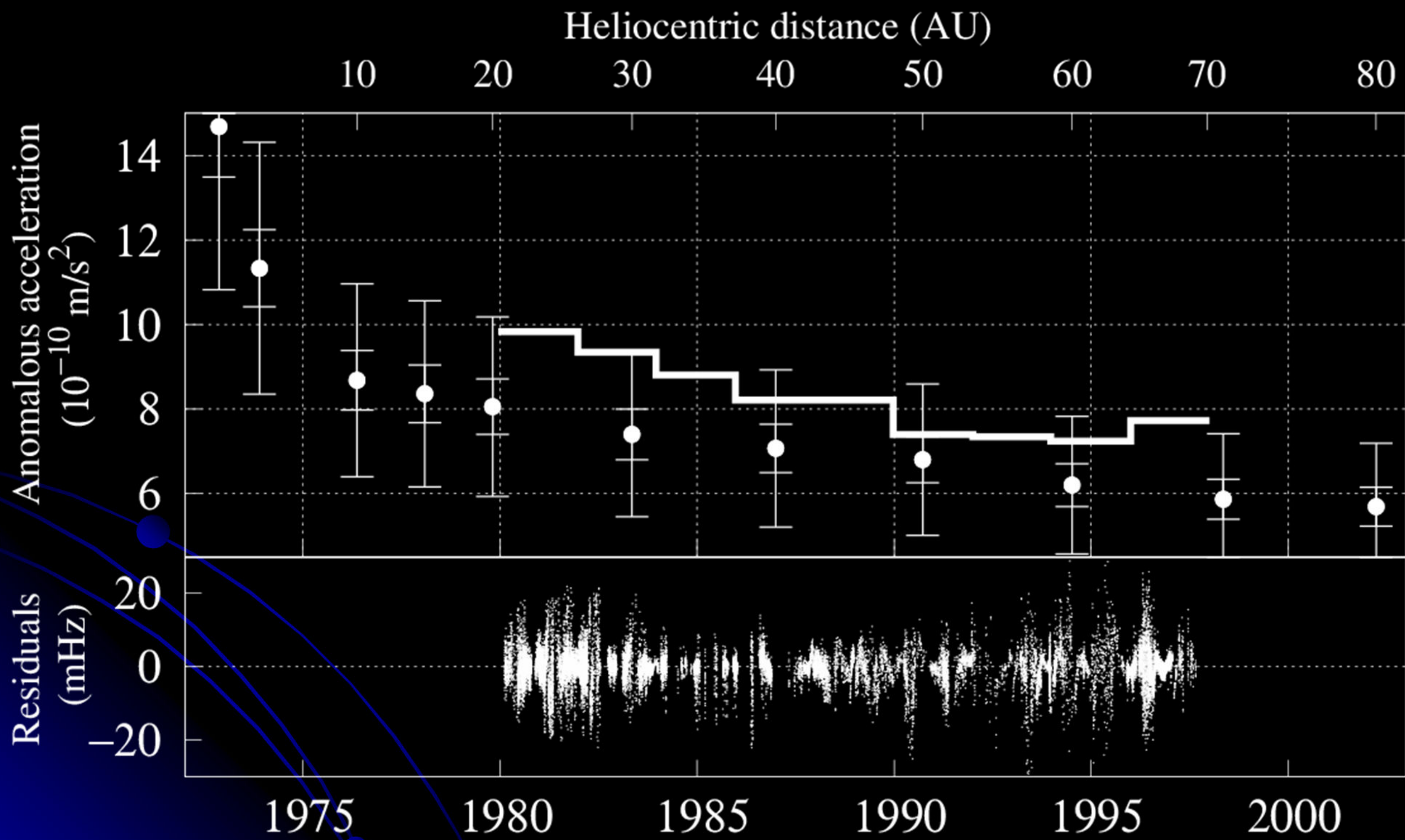


- At 6 AU, spacecraft still receives >225 W of solar heating

Onset

- The onset is almost certainly a model artifact
- Solar mismodeling can lead to apparent onset

Thermal results

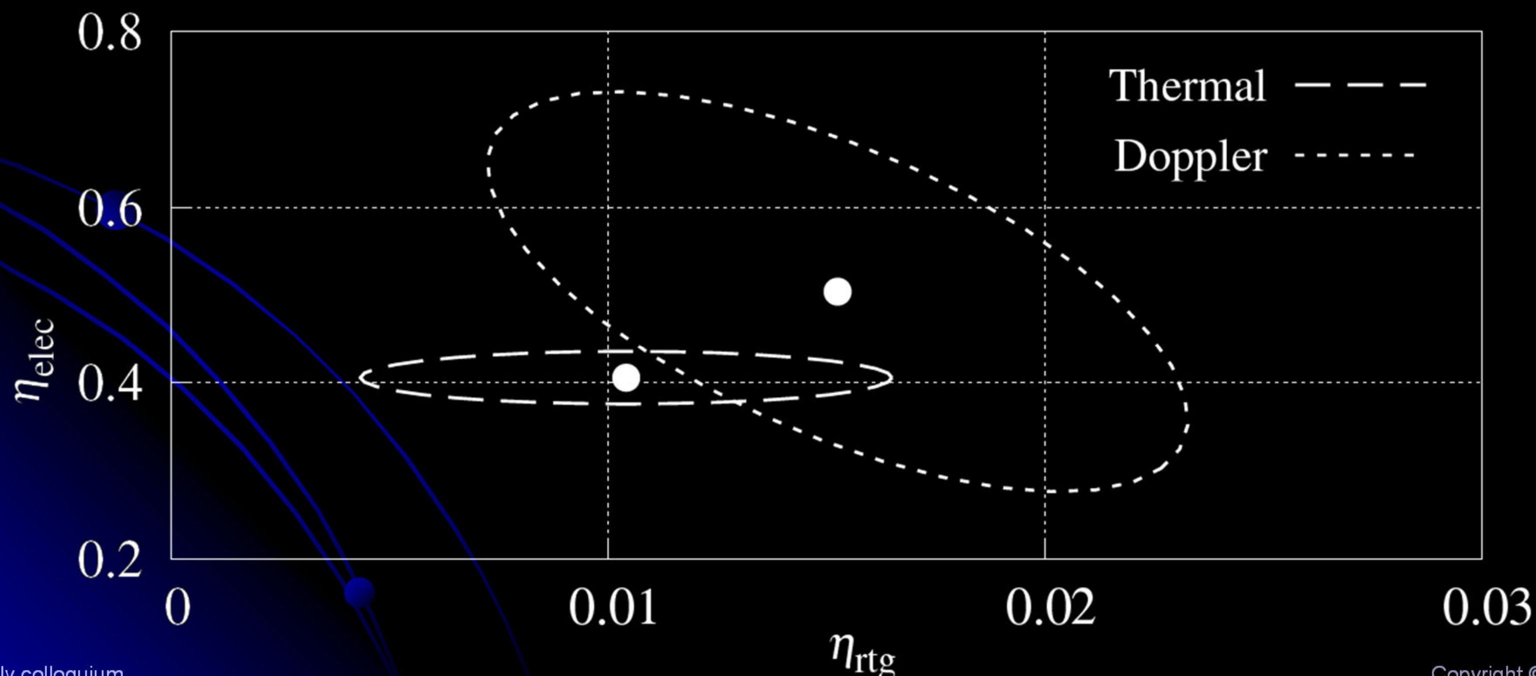


Comparison

- Linear model's validity is confirmed:

$$a_P = \eta_{\rm rtg}(Q_{\rm rtg}/mc) + \eta_{\rm elec}(Q_{\rm elec}/mc).$$

- Parameters can be estimated independently from thermal vs. Doppler data



AT THE PRESENT LEVEL OF OUR KNOWLEDGE OF THE PIONEER 10 SPACECRAFT AND ITS TRAJECTORY, NO STATISTICALLY SIGNIFICANT ACCELERATION ANOMALY EXISTS.

Other spacecraft

- New Horizons: no funding for Doppler tracking; opportunity to confirm “onset” lost
- Voyagers: 3-axis stabilized
- Other spacecraft: wrong orbit, large RTGs, frequent maneuvers, etc.

Pioneer 10/11 are the most precisely navigated deep space craft to date.

Summary

- For the foreseeable future, Pioneer 10 and 11 remain the largest scale precision gravitational experiment ever conducted
- Ability to test post-Einsteinian gravity in the solar system would have been marvelous
- The anomaly was probably a wild goose chase
- Lessons to be learned:
  - Limits on navigational accuracy
  - Importance of preserving raw data and original documents
  - Dangers of "back of the envelope" estimation of small forces

Some open questions

- Behavior of Pioneer 11 (no surprises expected)
- Analysis of spin rate change
- Onset and solar mismodeling
- Outgassing of surface materials
- Autocorrelation analysis
- RTG coating properties
- Using DSN signal strength measurements

Thank you!

- Questions?

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