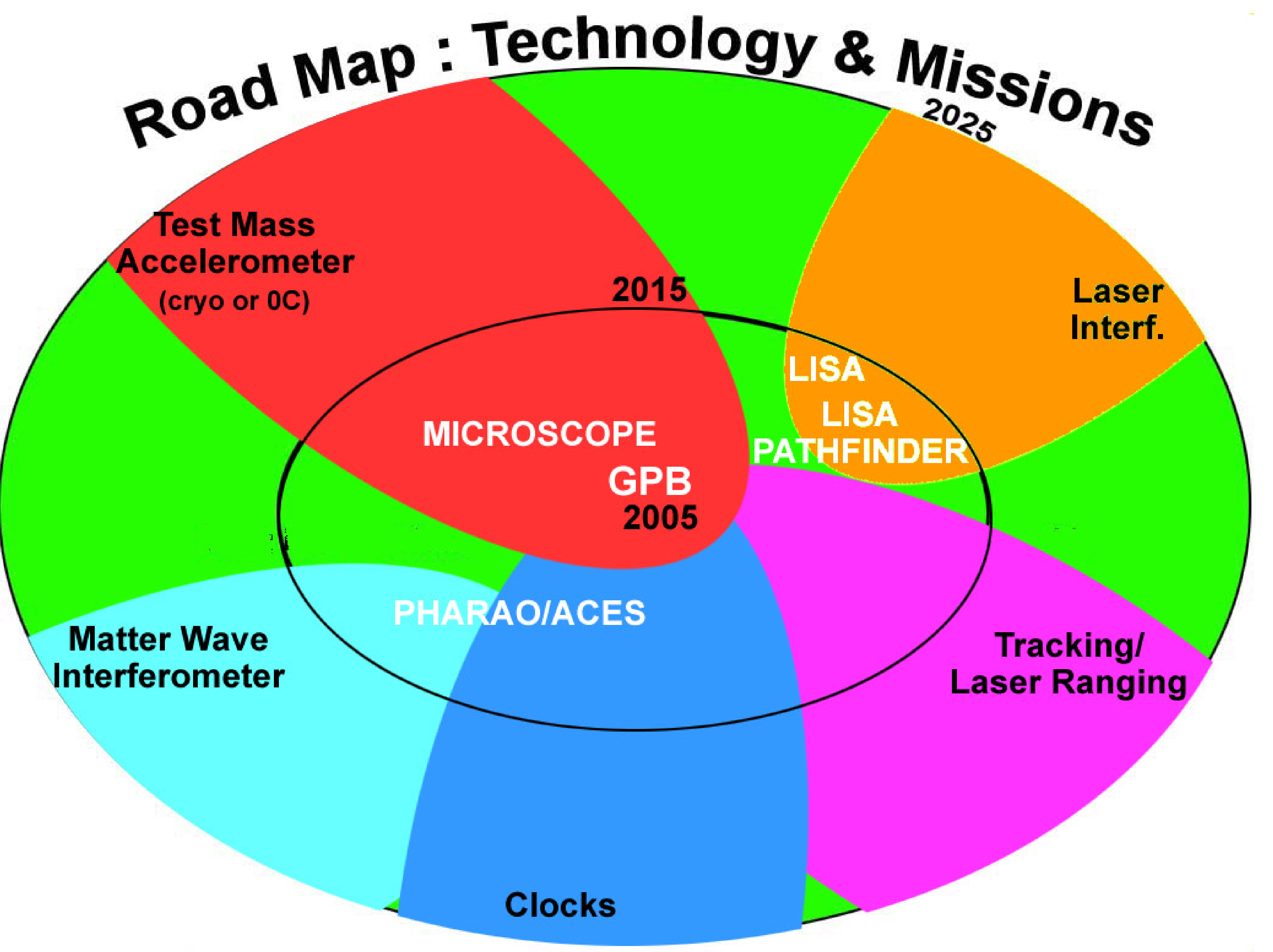
ROAD MAP

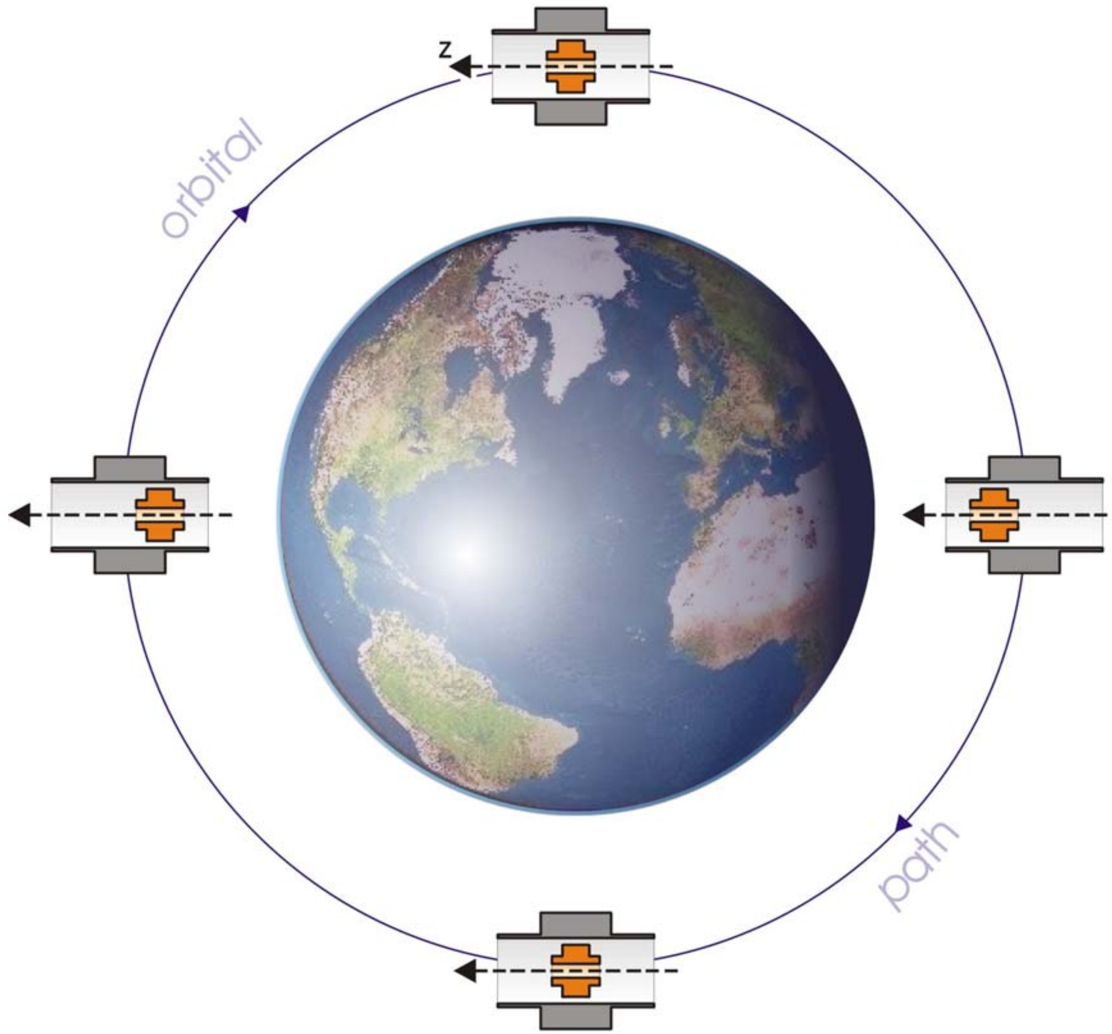
Beyond General Relativity
Towards Quantum Gravity

MCW Sandford - FPAG


Road Map : Technology & Missions
2025
Test Mass
Accelerometer
(cryo or 0C)
2015
Laser
Interf.
LISA
LISA
PATHFINDER
MICROSCOPE
GPB
2005
PHARAO/ACES
Matter Wave
Interferometer
Tracking/
Laser Ranging
Clocks

STEP – Satellite Test of the Equivalence Principle

- Pairs of concentric test masses are in free-fall in a polar orbit...
- within a drag-free spacecraft—an ultra-quiet environment
- Full acceleration due to gravity of Earth is used
- Any differential acceleration along the sensitive (z-) axis between a pair of masses is sensed using a SQUID detector
- Test masses are kept in UHV at a temperature of 2K, so…
- exceptionally high degree of magnetic shielding (> 10^{10}), and mechanical stability
- Persistent supercurrents create an exceptionally stable detection system
- EP signal is at orbital frequency ± spacecraft rotation-frequency

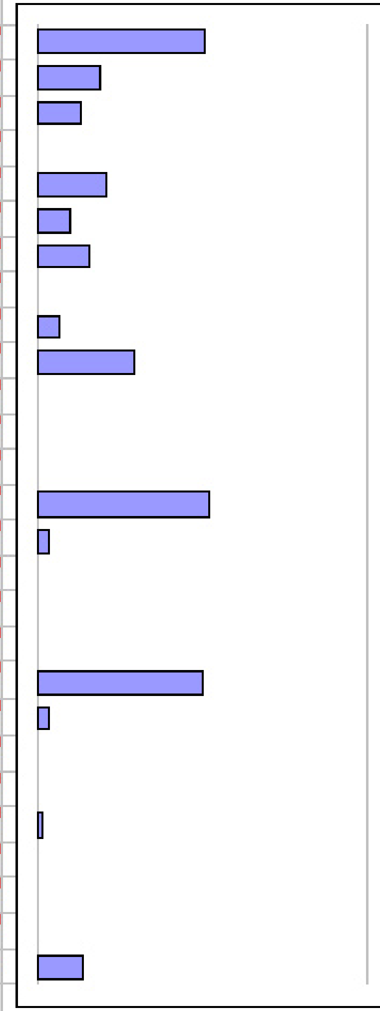


$$\frac{\Delta a_z}{a} = 10^{-18}$$

Mission Design Overview

Main Mission Design Features

- Sun synchronous Orbit (I=97^{o})
- Altitute: 550 Km
- Eccentricity < 2%
- Mass: 819 kg
- Power: 301 W
- Rockot Launch Vehicle; from Plesetsk, Russia
- Operational life: 6 months
- Data Analysis: 6 months concurrent with operation, 12 months after completion.



DFC Reference accelerometer Disturbance	Systematic component at signal frequency m/sec^2			Comment
SQUID noise	2.73E-18			acceleration equivalent to intrinsic noise
SQUID temp. drift	1.03E-18			regulation of SQUID carriers
Thermal expansion	6.79E-19			gradient along DAC structure
Differential Thermal expansion	3.95E-23			Radial gradient in DAC structure
Nyquist Noise	1.12E-18			RMS acceleration equivalent
Gas Streaming	5.05E-19			decaying Gas flow, outgassing
Radiometer Effect	8.64E-19			gradient along DAC structure
Thermal radiation on mass	1.58E-22			Radiation pressure, gradient
Var. Discharge uv light	3.34E-19			unstable source, opposite angles on masses
Earth field leakage to SQUID	1.57E-18			estimate for signal frequency component
Earth Field force	9.60E-22			estimate for signal frequency component
Penetration depth change	3.50E-20			longitudinal gradient
Electric Charge	8.56E-21			Assumptions about rate
Electric Potential	2.78E-18			variations in measurement voltage
Sense voltage offset	1.59E-19			bias offset
Drag free residual in diff. Mode	1.08E-21			estimated from squid noise
Viscous coupling	3.83E-25			gas drag + damping
Cosmic ray momentum	3.20E-21			mostly directed downward
Proton radiation momentum	2.70E-18			unidirectional, downward
dynamic CM offset	1.83E-19			vibration about setpoint, converted
static CM offset limit	4.36E-22			A/D saturation by 2nd harmonic gg
Trapped flux drift acceleration	7.08E-23			actual force from Internal field stability
Trapped flux changes in squid	7.65E-20			apparent motion from internal field stability
S/C gradient + CM offset	7.67E-36			gravity gradient coupling to DFC residual of S/C
rotation stability	4.01E-23			centrifugal force variation + offset from axis
Eccentricity subharmonic.	4.19E-20			real part at signal frequency
Helium Tide	7.00E-19			placeholder
position sensor gap, mm	1.00		550000	Orbit height
common mode period	1398		0.0086	Sensor current, A
differential mode period	1091		4.1E-12	CM distance, m
S/C rotation per orbit	-2.30E+00	**RMS error**	5.38E-18	m/sec^2
Total error	1.48E-17	m/sec^2	**5.48E-19**	η

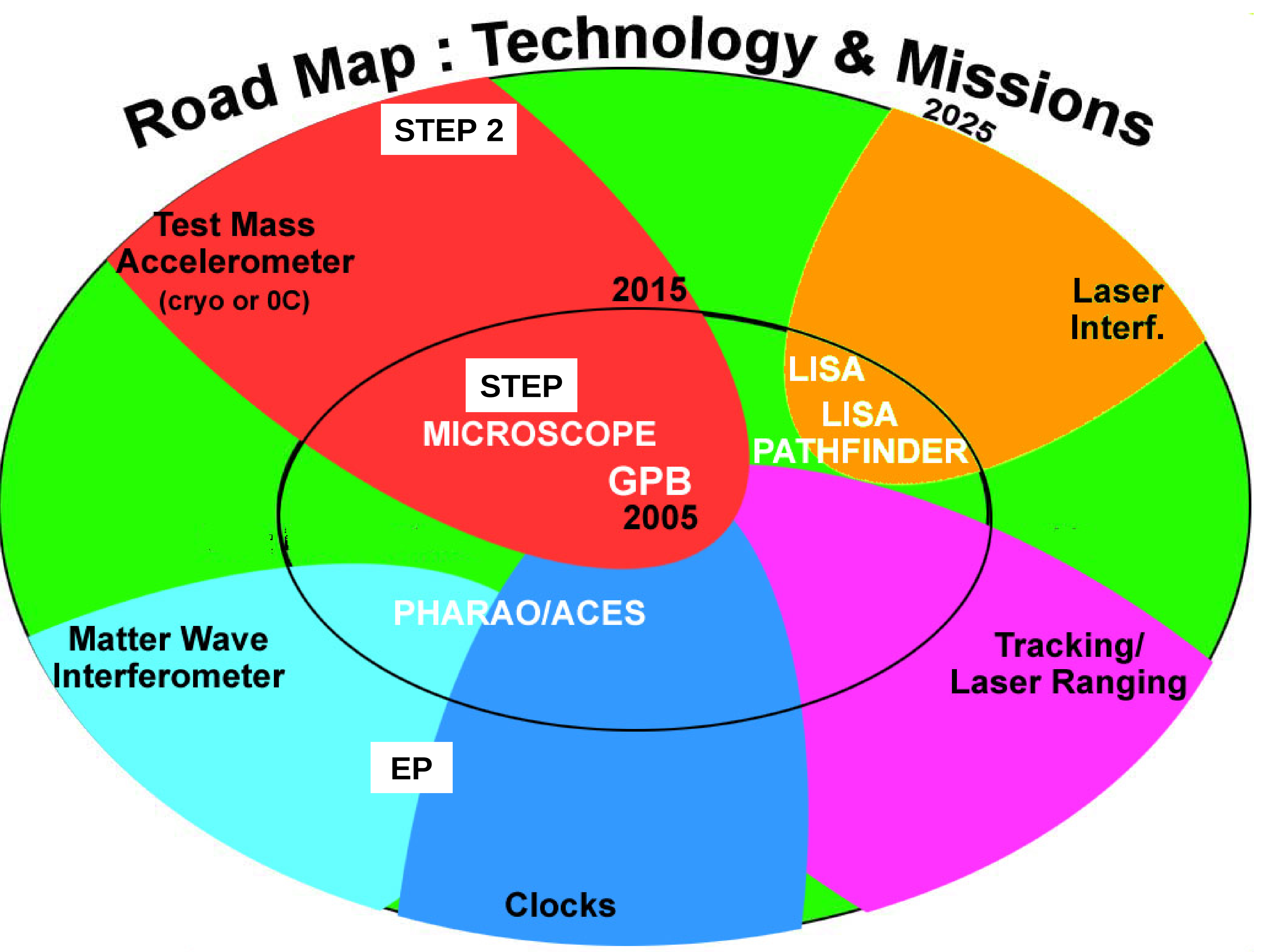
Equivalence Principle Proposals

- Breakthrough in FP
  - Follow on to Microscope
- Ultra High Precision EP
  - Follow on to STEP – aims at < 1 in 10^{21}

STEP 2

- Test of Gravity Matter Coupling….
  - Clocks
- Exploring Gravity in the Quantum Domain…
  - atom interferometer

Add to Atom Interferometer Mission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Atom Interferometers and Quantum Gravity

Diffusion of the wave function.

- How can an atom interferometer measure physics on the Planck scale?
- Einstein's (1905) Brownian motion work of inferred properties of atoms by observing stochastic motion of macrostructure's
- Space time fluctuations on the Planck scale produce stochastic phase shifts.

$\Rightarrow$ **Produces decoherence in an atom interferometer**

- **Possible to measure space-time fluctuation Amplitude A_{planck}**

$$A_{planck} \approx \Gamma\left(\frac{\Delta_{decoherence}}{M_{atom}^{2}T}\right)^{\frac{1}{7}}$$

(Powers & Percival 1999, Ellis 1990))

Physics of Decoherence

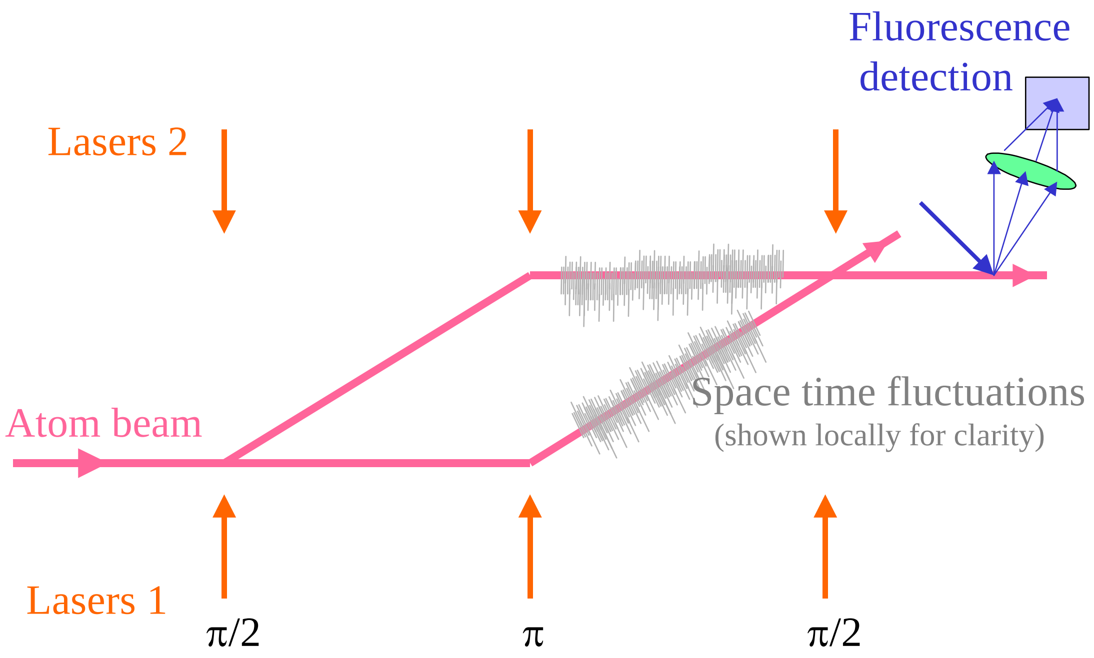
- **Difficult to avoid interaction with environment.**

Natural Vibrations of the system.

Collisions with ambient particles.

Interaction with its own components.

Black body radiation.



Spacetime time quantum fluctuations.

Atom Interferometers and Quantum Gravity

- **Granulation of space-time - Universe no longer four dimensional,
  higher number of dimensions are required.
  e.g. Superstring theory - 10 dimensions**

- **Length scale below which granulation is important** $\ell_{cut-off} = \lambda \ell_{planck}$

- **This is an effective cut-off for Quantum gravity theories determined by the amplitude of zero point gravitational fluctuations**

$$A_o \approx \omega_M^2 t_{planck}^2 \approx \lambda^{-2}$$

where ω_M **is the cut-off frequency, and**

$$\lambda = \left(\sqrt{\frac{1}{2}} \pi \frac{M^2 c^4 t_{planck} T}{\hbar^2 (\delta\rho / \rho(0))} \right)^{\frac{1}{7}}$$

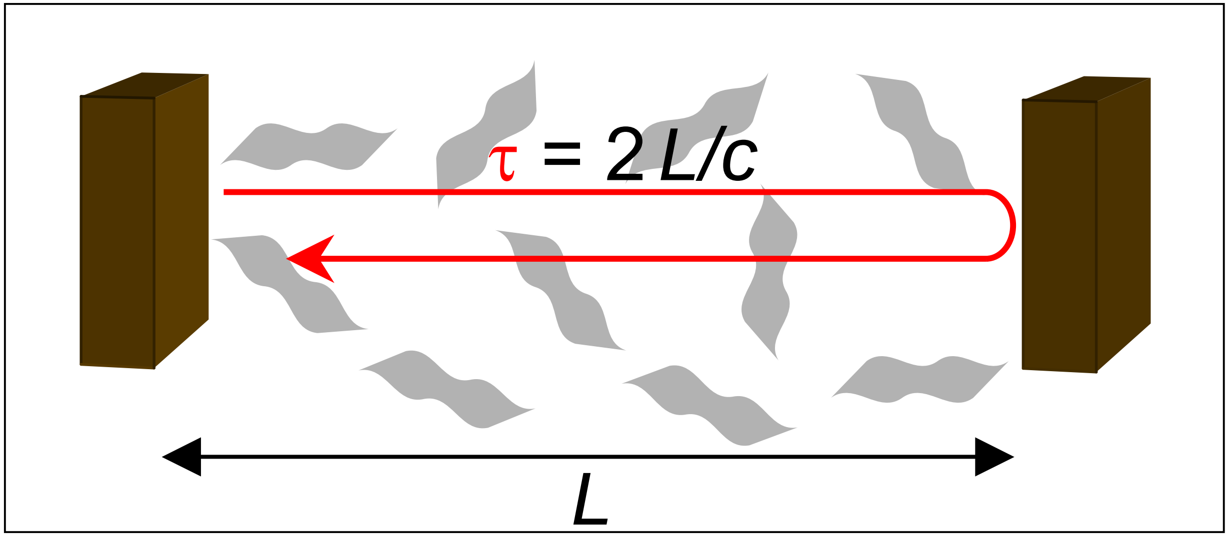
- **From theoretical considerations λ is in range 10^2 - 10^6**

- **Current experiments using atom Interferometers by Peters *et al.*, 1997 set a lower bound of λ > 18.**

- **Improvements on experimental sensitivity can raise this value.**

Quantum fluctuations of space

- Believed to exist at some level
- Possible evidence: round-trip time τ of a light pulse exhibits shot-to-shot fluctuations $\delta\tau$



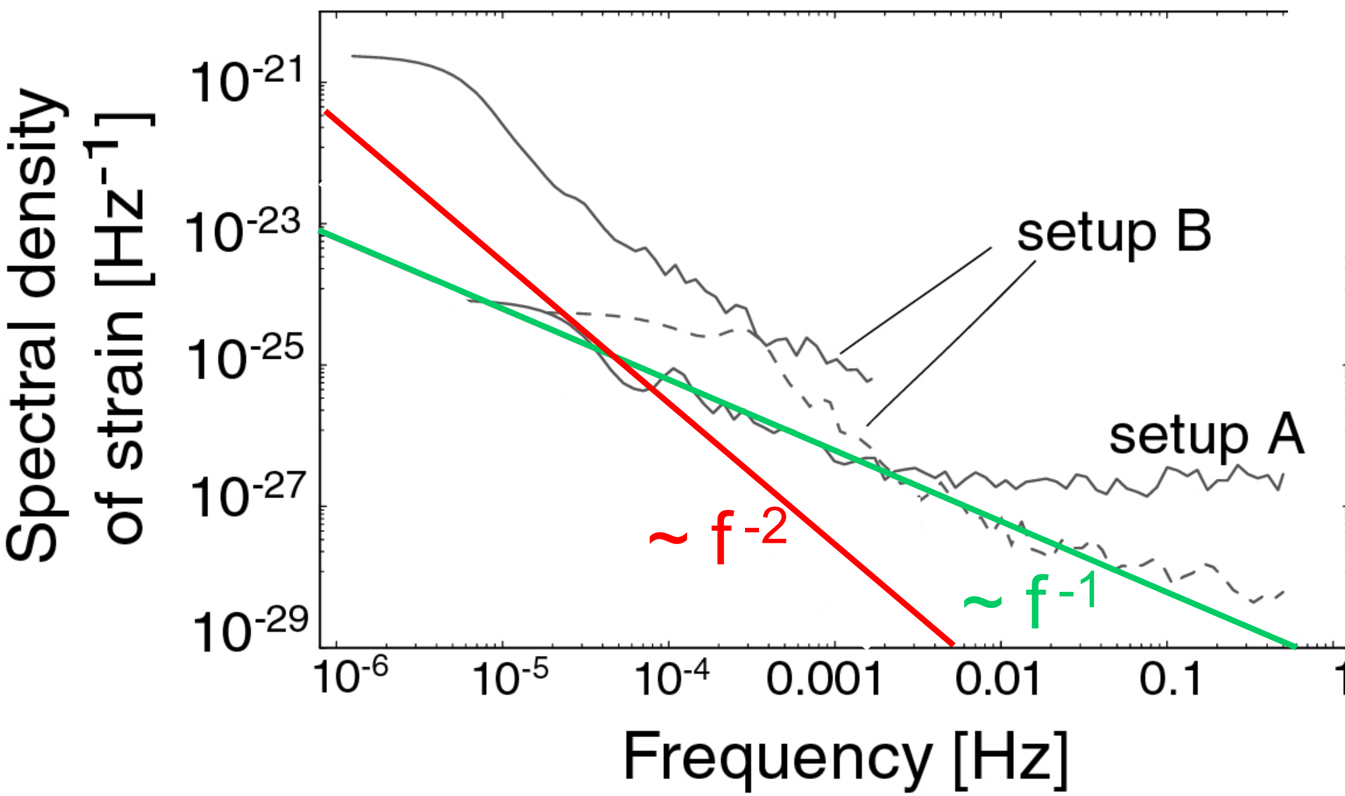
- Magnitude unknown; models proposed e.g. by Amelino-Camelia (2001), Ng, ...

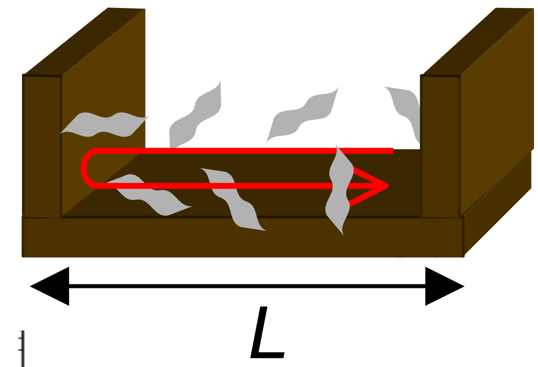
- Earth-based searches:
  – with gravitational-wave interferometers (but seismics imposes f > 100 Hz)
  – with rigid optical cavities (f < 1 mHz possible, but masses are not free)

Spectral density of differential length fluctuations

Schiller et al., Phys. Rev. D 69, 027504 (2004)

- Used cryogenic optical resonators

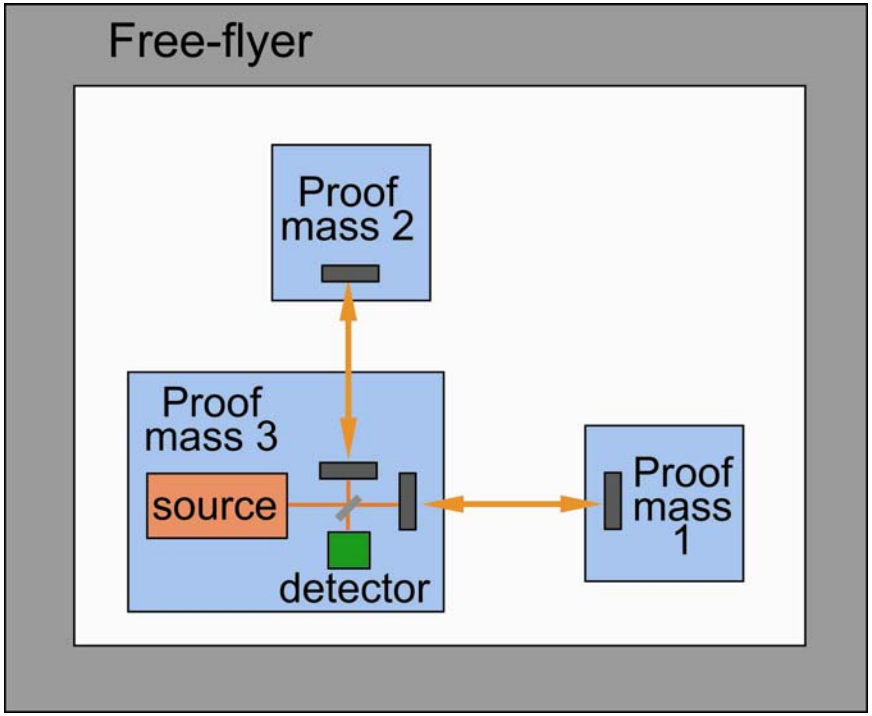


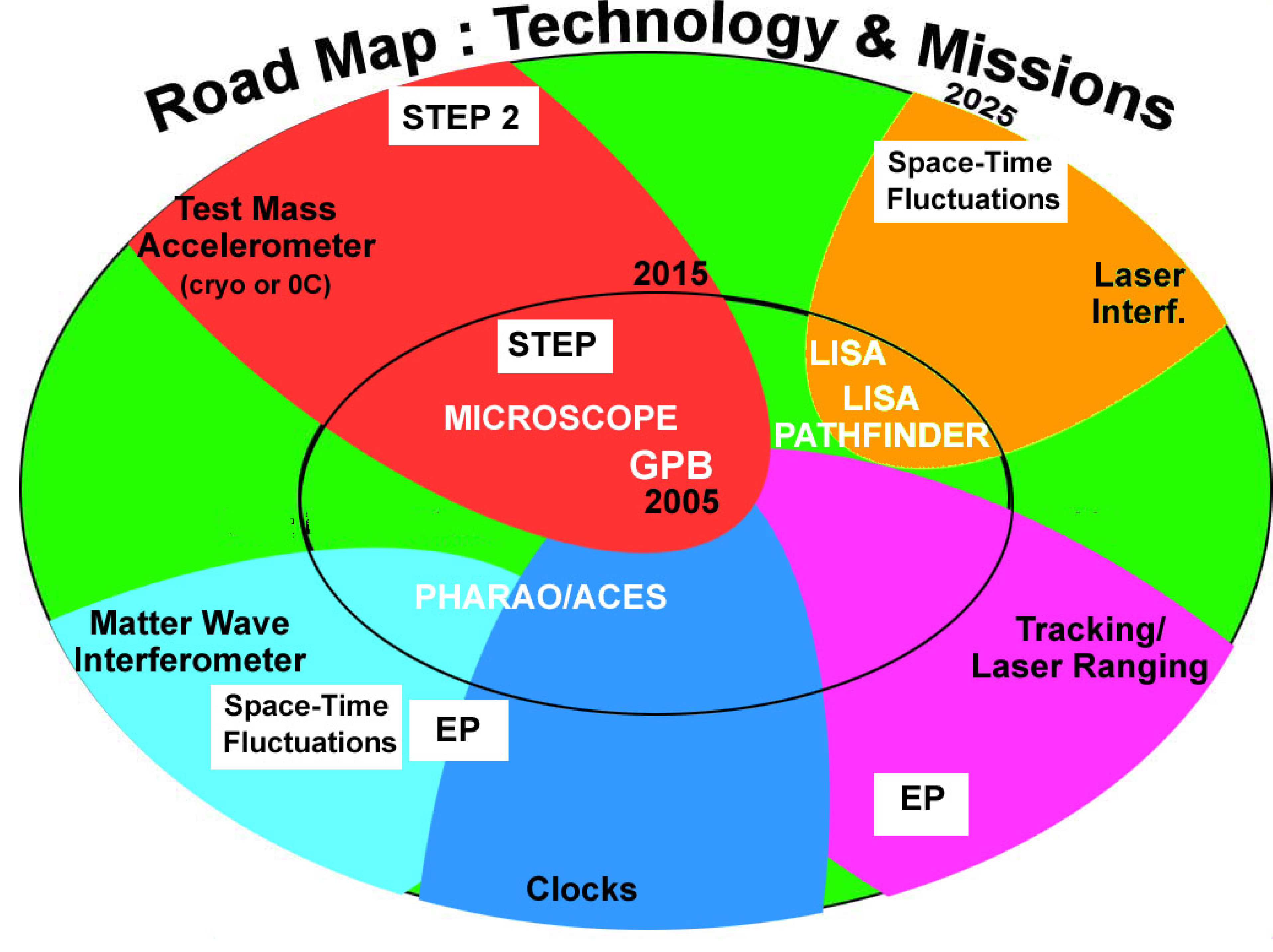


- First limits in the sub-Hz regime: $S < 6 \cdot 10^{-30}\ f^{-1}, \quad S < 3 \cdot 10^{-35}\,\mathrm{Hz}\ f^{-2}$

Implementation in space

- Michelson-type interferometer measures differential fluctuations in orthogonal space directions
- Free - flying proof masses inside drag-free satellite
  → Measurements at very low frequency possible
- Low noise → high sensitivity
- Interferometer can use matter waves (cold atoms) or optical (laser) waves, or both (for differential measurement)





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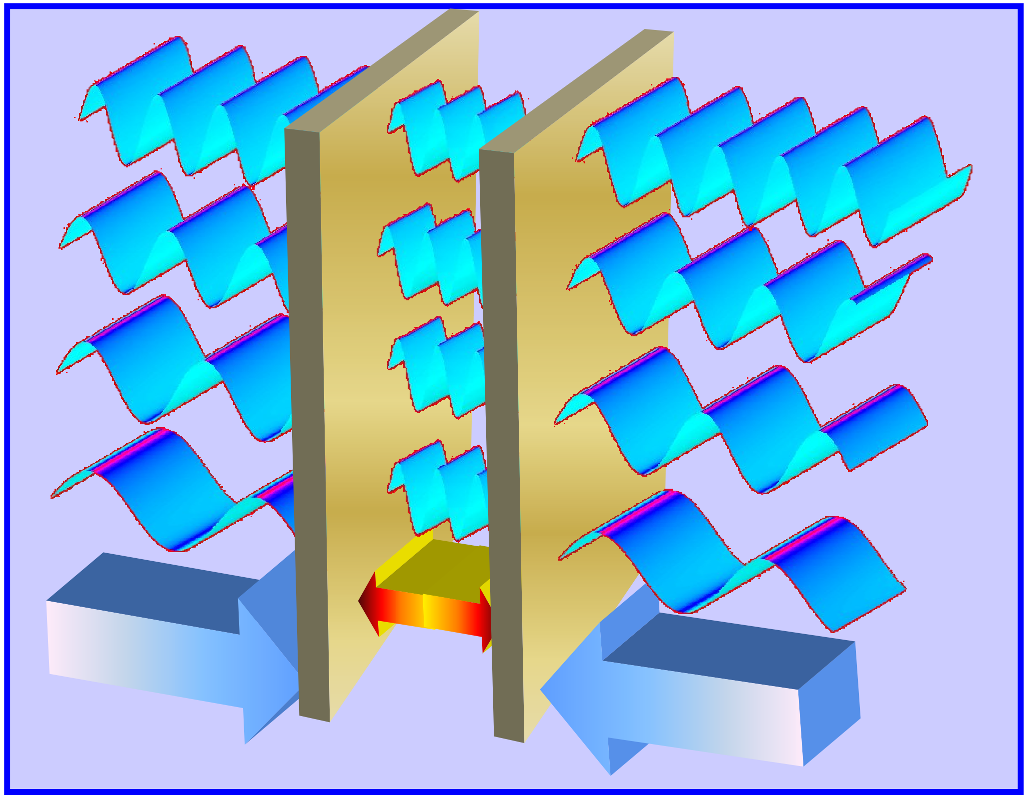
Vacuum Fluctuations of EM Field
Casimir Force



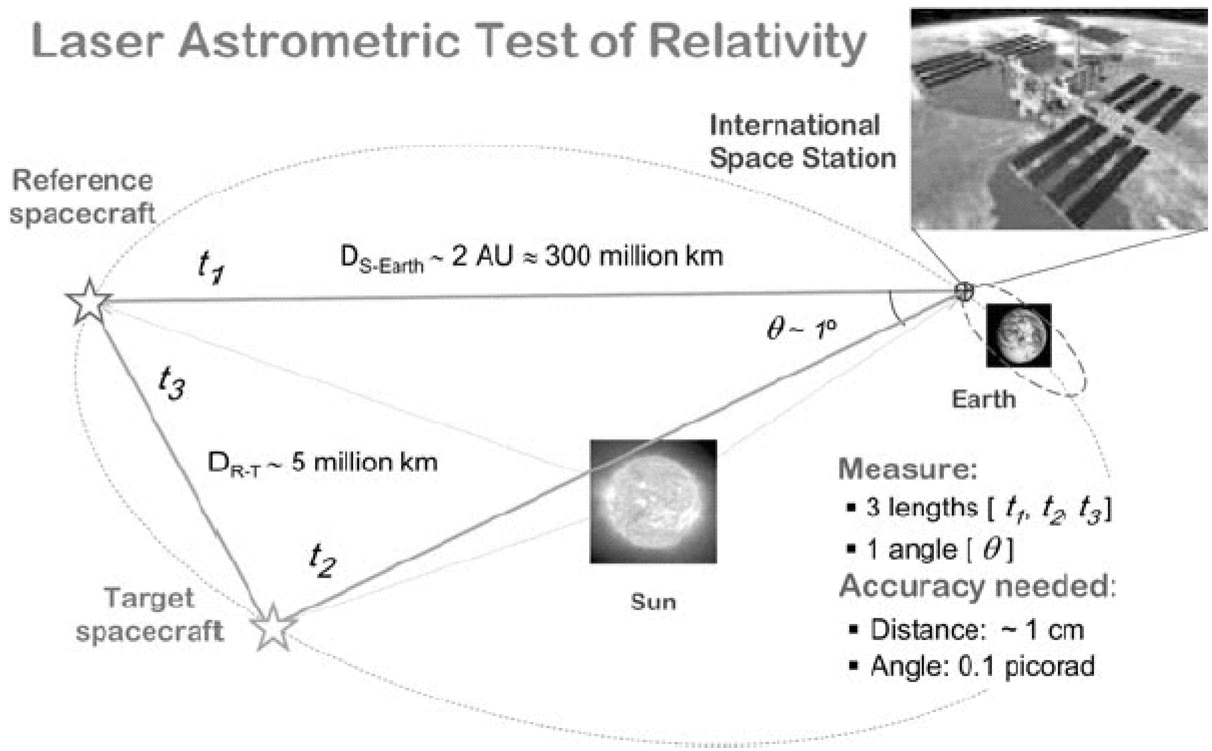
$$F = -\frac{\pi^2 \hbar c}{240 a^4} S$$

The Casimir effect was introduced in the middle of the past century by H. B. G. Casimir who showed that neutral perfectly conducting parallel plates placed in the vacuum attract each other. The attractive force was then considered as a manifestation of the zero-point energy of the quantized electromagnetic field.

Casimir Force Measurements

- CASIMIR force measured by torsion pendulum and Atomic Force Microscope (1997-2000)
- 1% accuracy at 1 micron separation
- Limitation is accuracy of surfaces and disturbances in laboratory
- Studies for STEP have shown that 10^5 improvement can be obtained in a gravitationally quiet drag-free satellite

Laser Interferometric Test of Relativity



Determine λ to 1 in 10^8

Observation of the Gravitomagnetic Clock-Effect

Compare clocks in counter rotating orbits to 10^{-7} s

Add to satellite to GPS/Galileo constellations

Testing General Relativity by Mapping the Latitudinal Dependence of the Lense-Thirring effect

Studied in the Hyper Mission

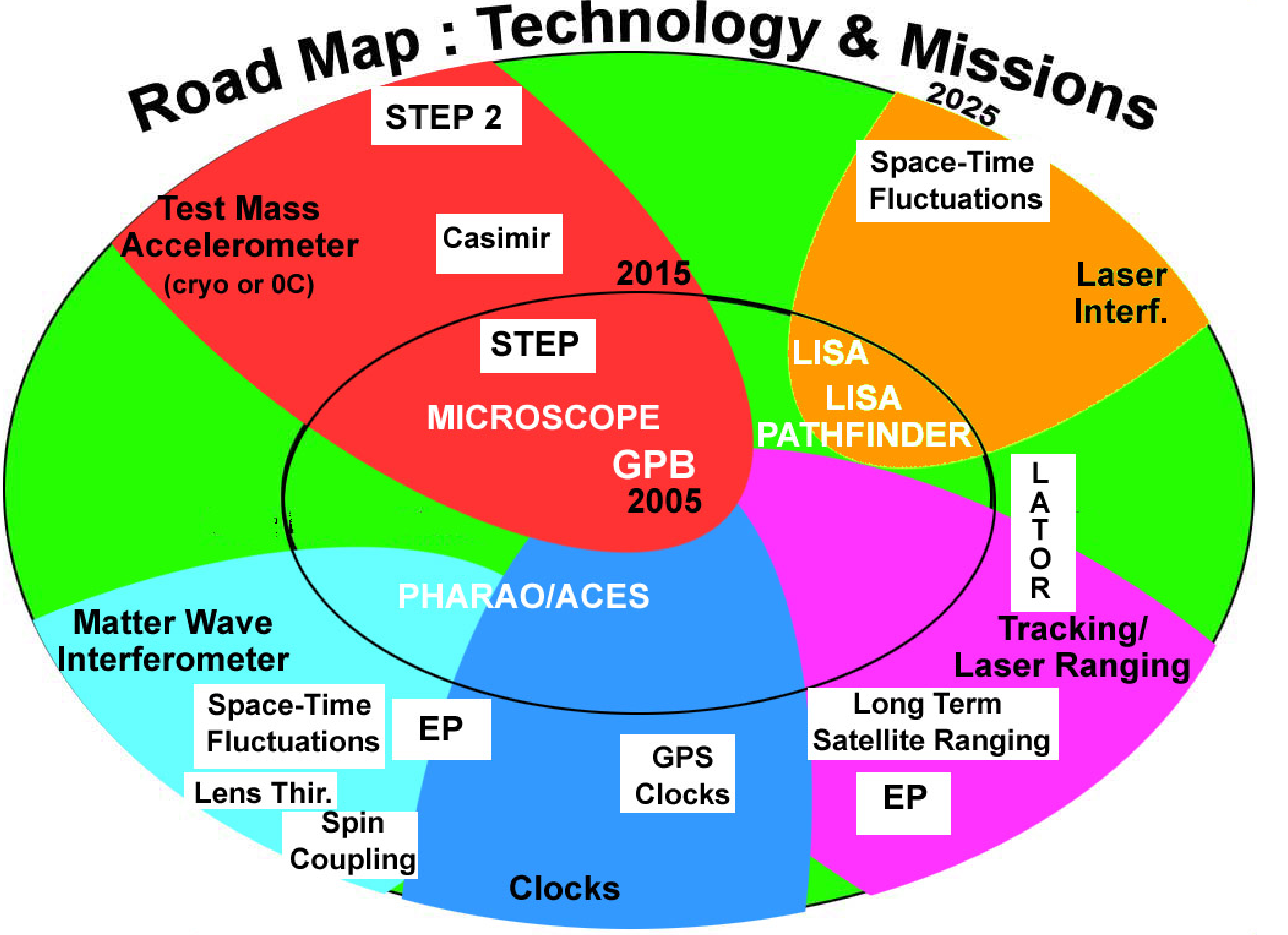
Sagnac Atom Interfometeters and reference startracker

Search for an Anomalous Coupling of the Elementary Particle Spin to Gravity

Ramsey atom interferometer using spin flips
Needs superconducting magnetic shield

Testing General Relativity with Long-Term Satellite Tracking

Uses laser ranging to calibrate DC drag free satellite over 10 years
- Lens Thirring;
- Gravito electric perigee advance;
- Search for Yukawa part of gravitational potential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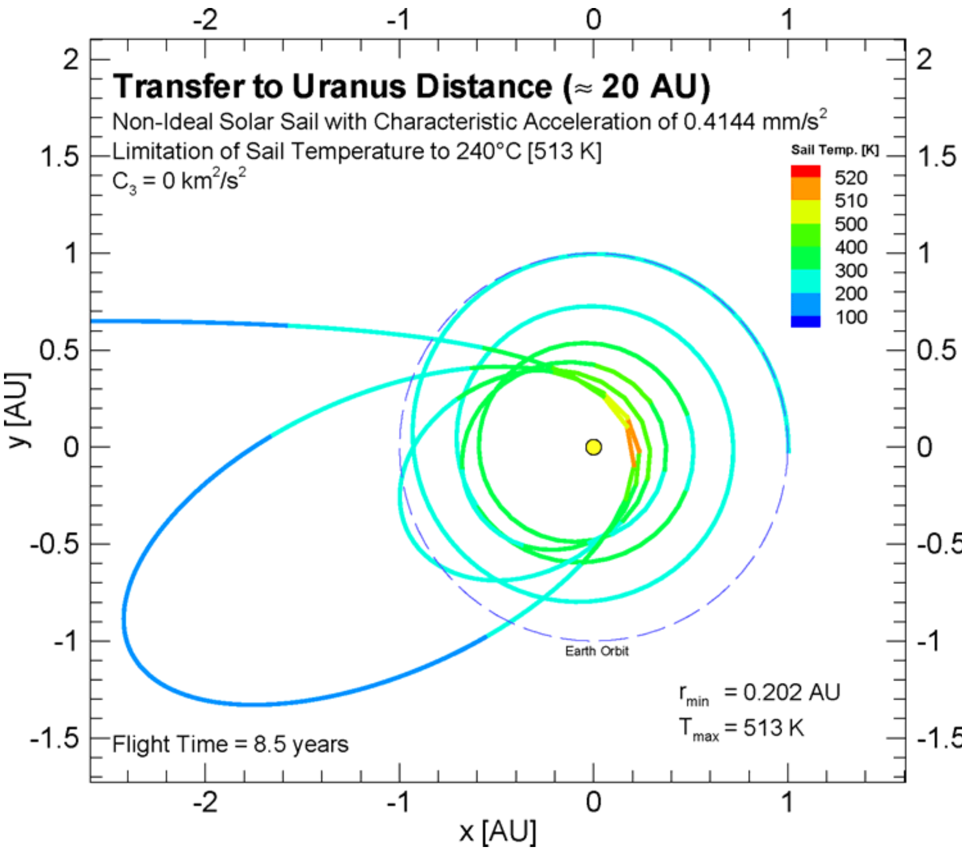
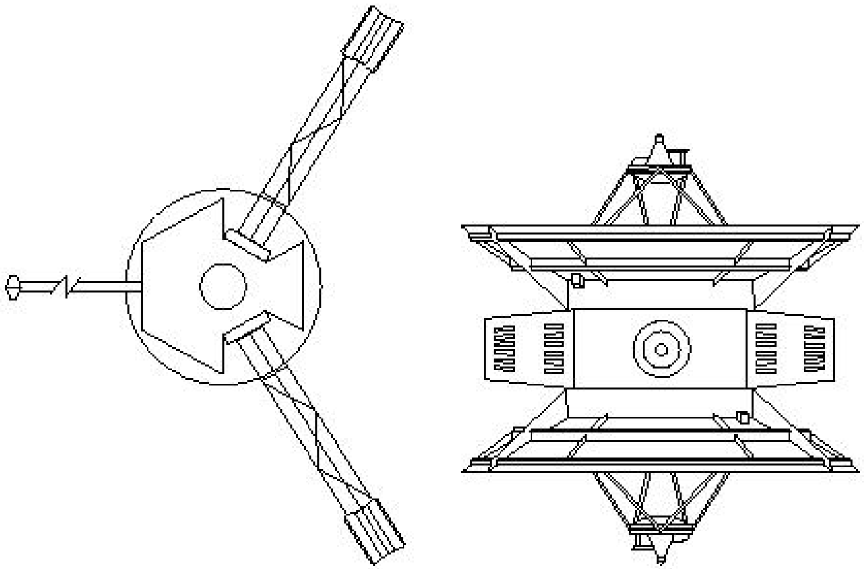
Pioneer Anomaly

Large Effect ~ 10^{-9} ms^{-2} but DC not mHz

5~20 AU & Hyperbolic Orbit

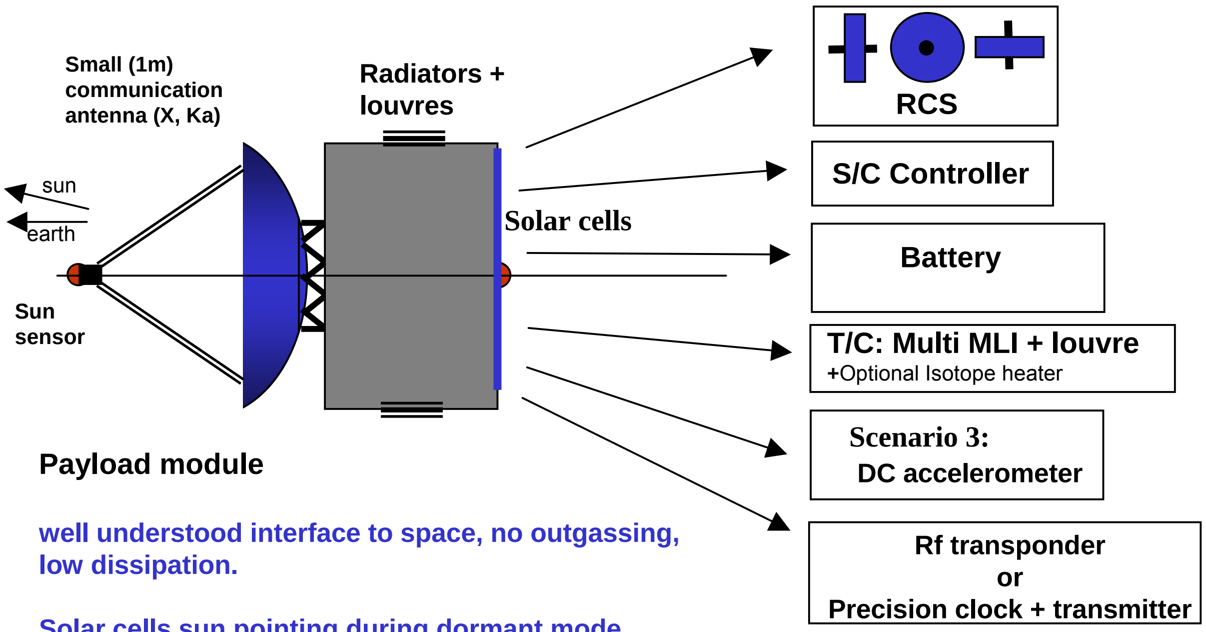
Control Systematics





Fore/Aft Symmetric Spacecraft

Pioneer Anomaly – Small Class Mission

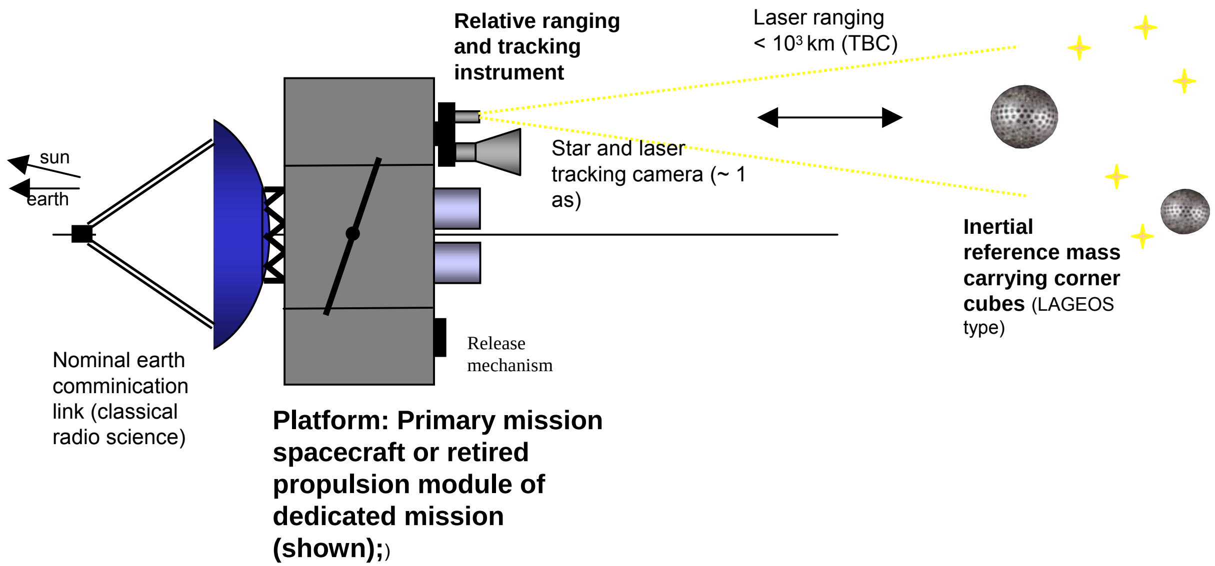


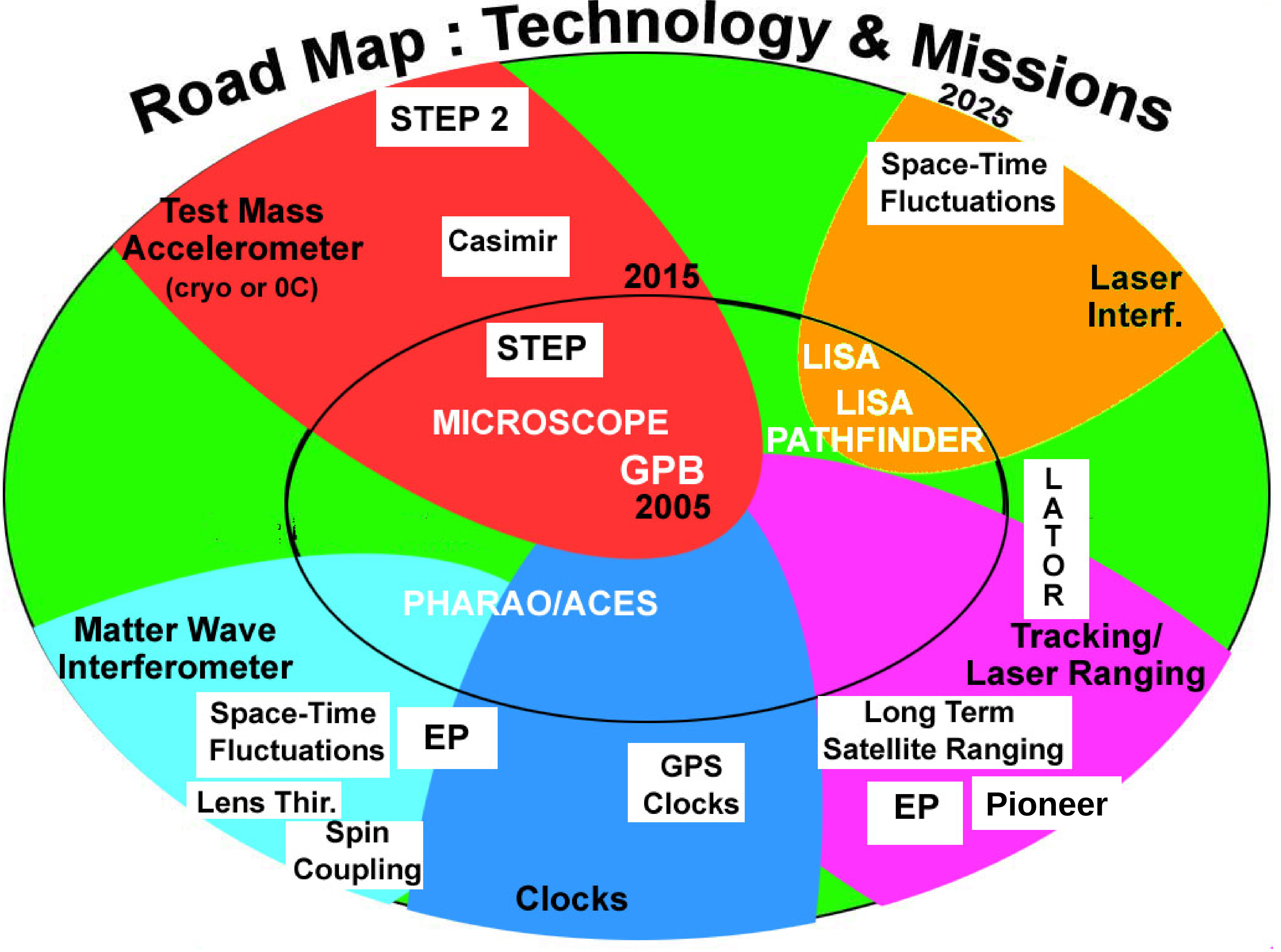
well understood interface to space, no outgassing, low dissipation.

Solar cells sun pointing during dormant mode (month)

Antenna sun/earth pointing during transmit mode (few hours)

Pioneer Anomaly – Formation Flying





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