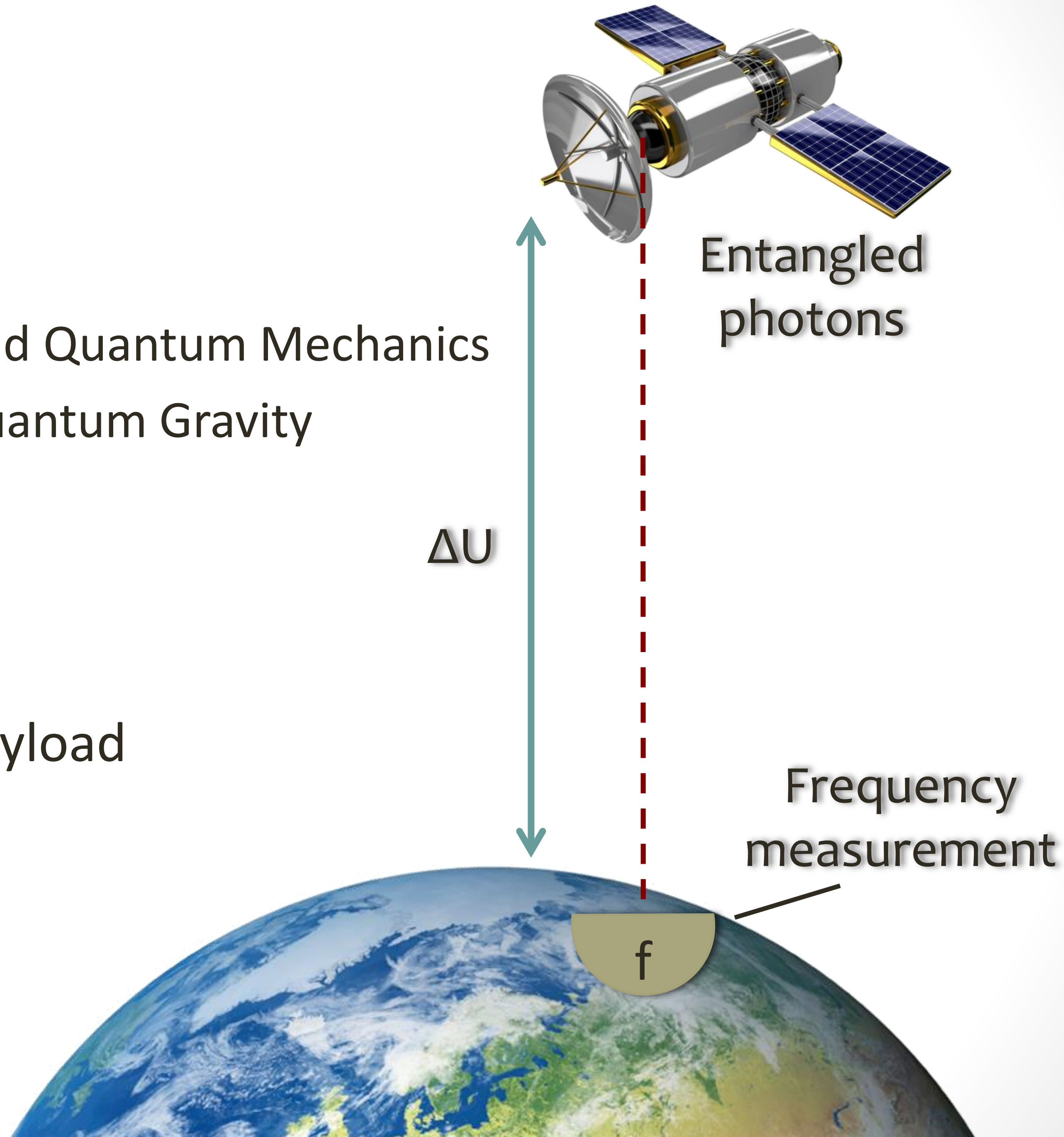
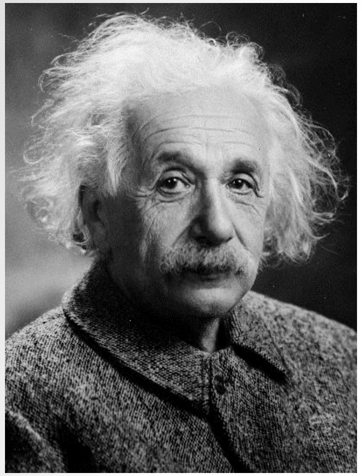
G.R.E.EN.

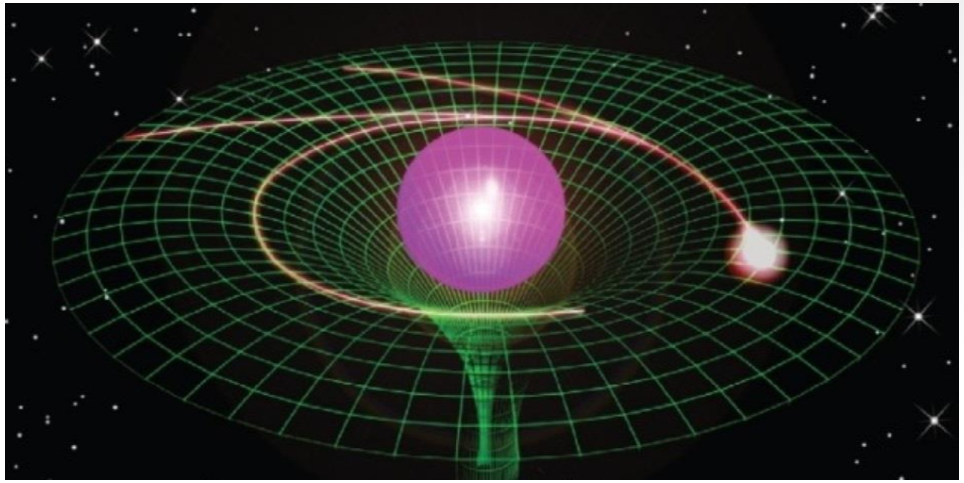
(General Relativistic Effects on ENtanglement)

Contents





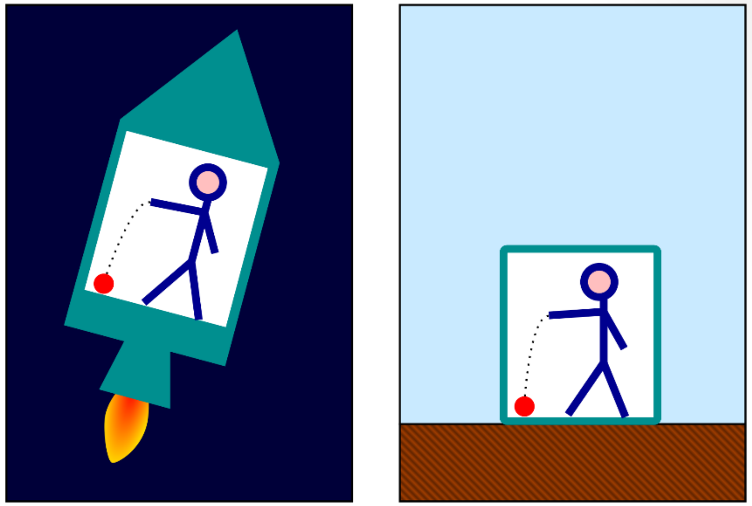
Science background 1: General Relativity



- Einstein's famous 1915 theory of general relativity revolutionized our understanding of gravity
- Gravitation is described by the curvature of space-time induced by the presence of mass
- Gravity describes planets, galaxies, and beyond
- A number of experiments have confirmed the predictions [1,2]

[1] Dyson, F. W.; Eddington, A. S.; *et al* (1920) *Philosophical Transactions of the Royal Society* **220A**: 291–333.
[2] Pound, R. V.; Rebka Jr. G. A. (April 1, 1960). *Physical Review Letters* **4** (7): 337–341.

Equivalence Principle



Equivalence Principle – all objects are affected by gravity in the same way
(Independent of composition, electric charge, flavour, etc…)

Experimentally – Equivalence Principle holds for objects living in the realm of classical physics.

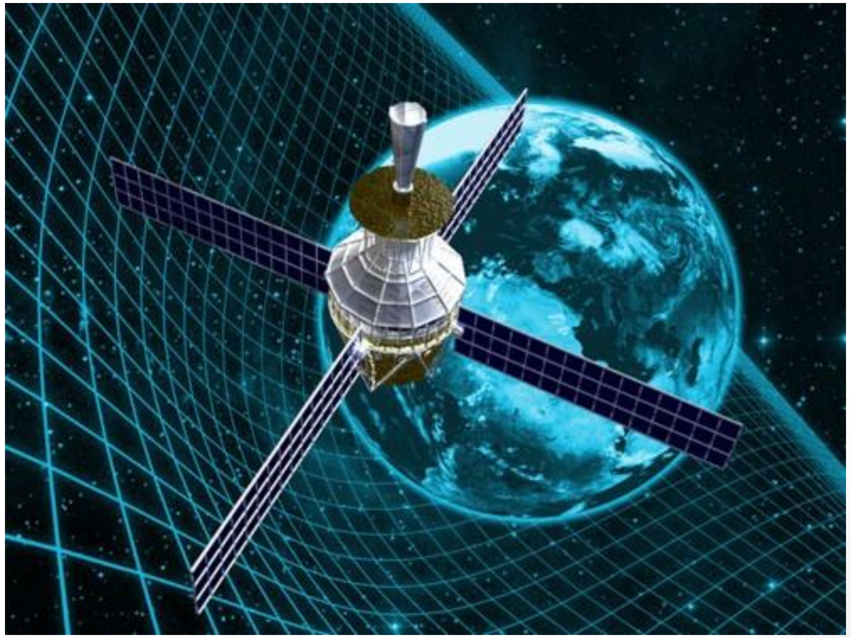
Therefore natural to check whether it breaks in the quantum regime.

The Equivalence Principle leads to gravitational redshift…

Gravitational Redshift

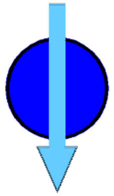
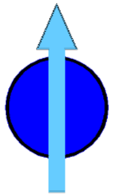
- As light escapes a region of high gravitational potential it loses energy
- The frequency is shifted towards the red end of the electromagnetic spectrum
- This was experimentally confirmed [1]
- GPS relies on redshift of classical

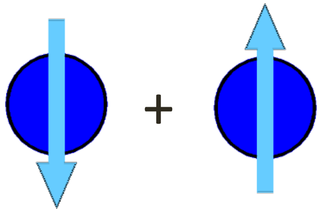
  electromagnetic waves



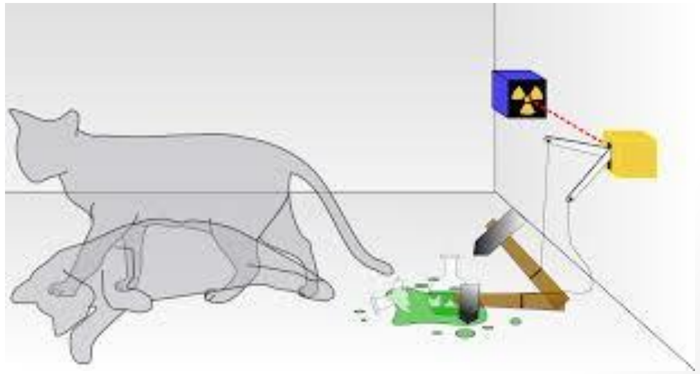
[1] "Fundamental Physics of Space - Technical Details - Gravity Probe A". Nasa JPL. May 2, 2009

Science background 2: Quantum Mechanics

- Successful theory of atoms, photons, electrons…
- Strange features: superposition and entanglement
- Classically:  or 
- Quantum superposition:

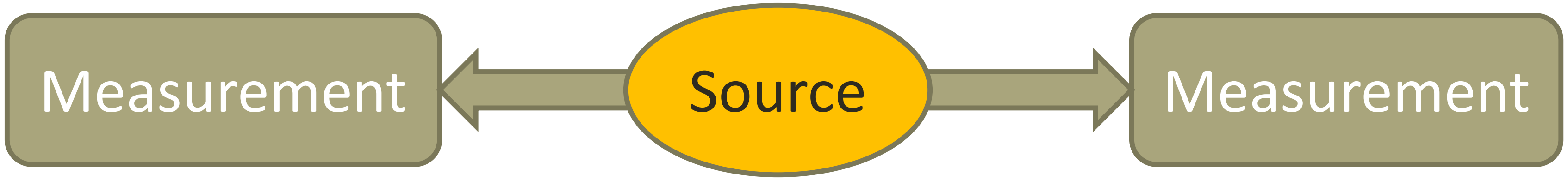


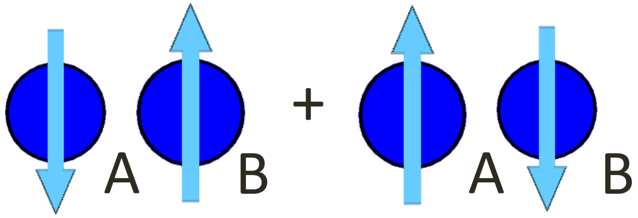
- What about measurement?



Entanglement

Picture: Dmytro Vasylyev





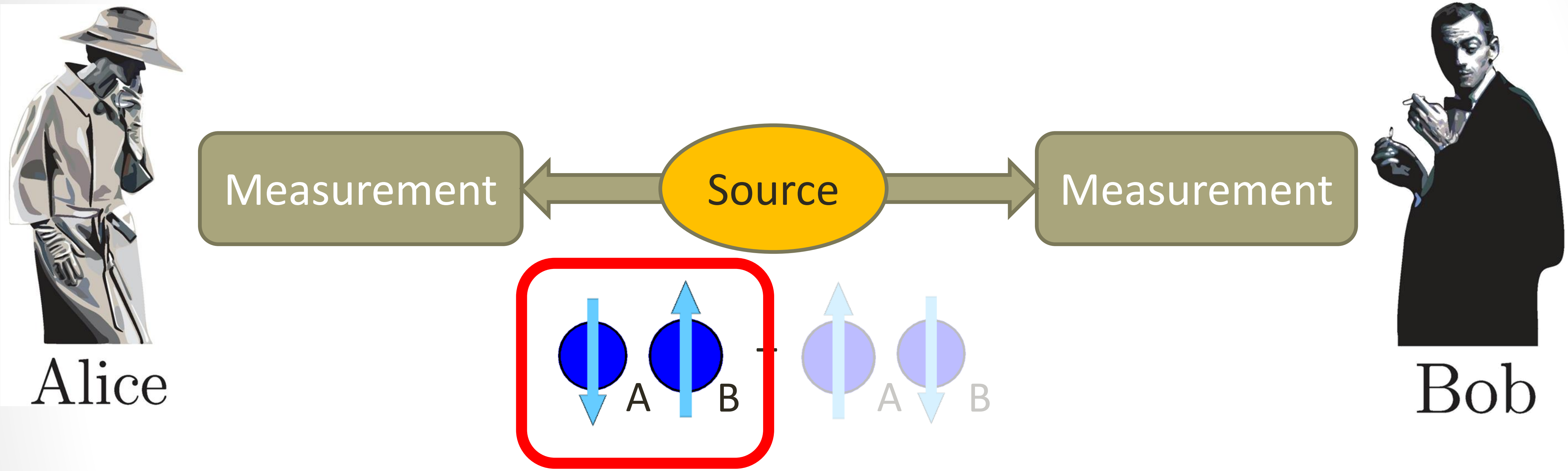
Measurement results:

Result of Alice	Result of Bob

Measurement causes “collapse” as we never measure a superposition!

What if Alice and Bob are separated by a great distance?

Entanglement



Measurement results:

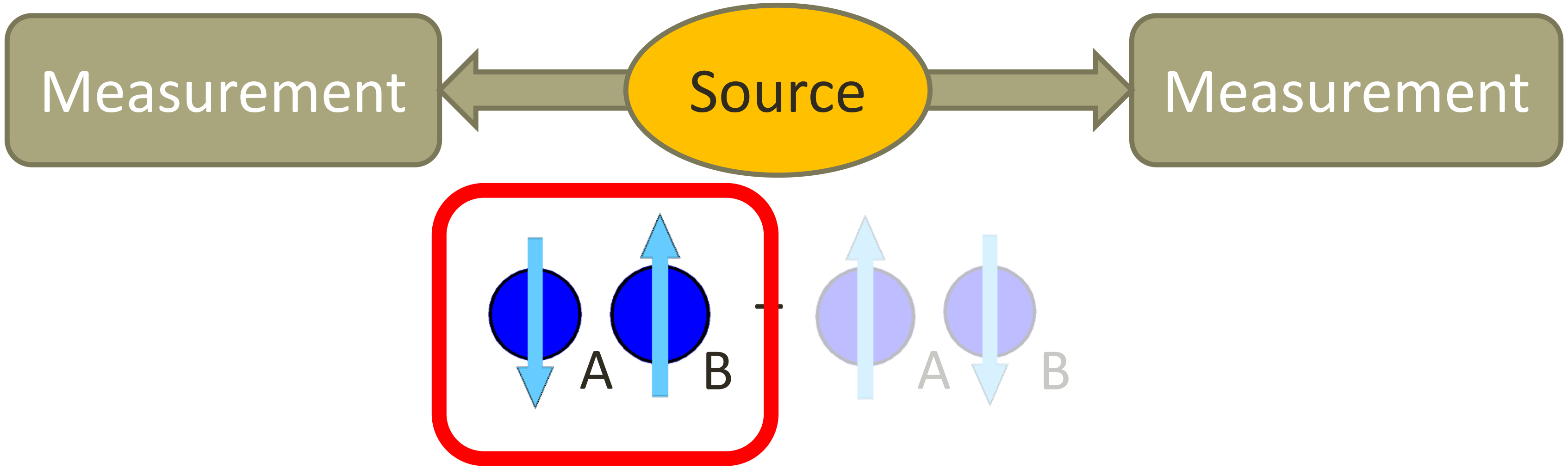
Result of Alice	Result of Bob
Down	

Measurement causes “collapse” as we never measure a superposition!

What if Alice and Bob are separated by a great distance?

Entanglement

Alice



Bob

Measurement results:

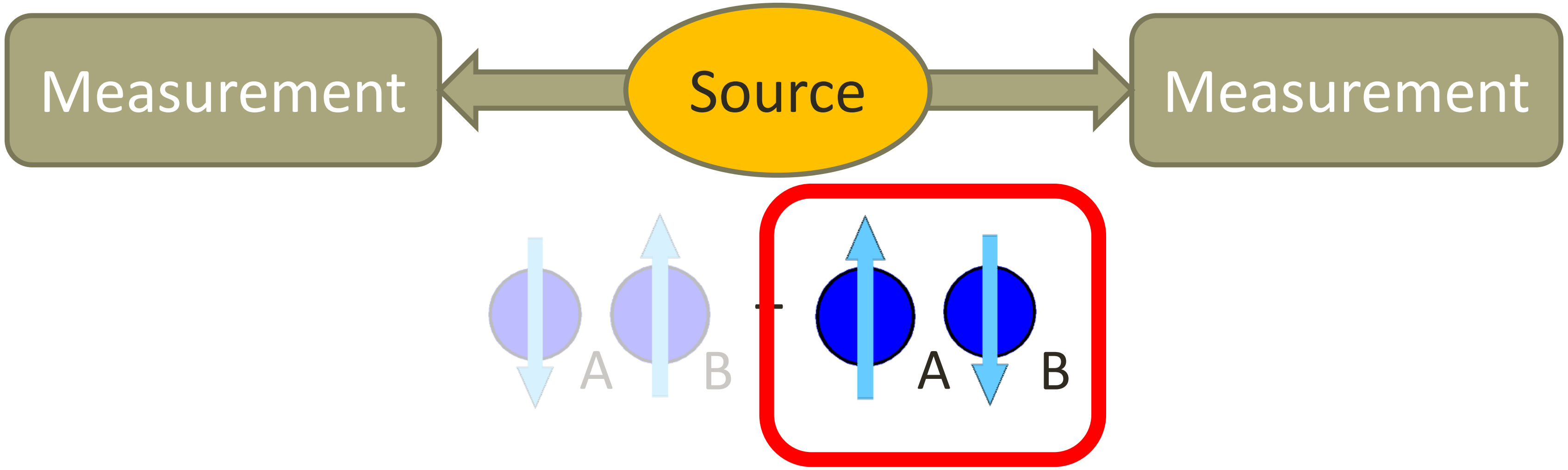
Result of Alice	Result of Bob
Down	Up

Measurement causes "collapse" as we never measure a superposition!

What if Alice and Bob are separated by a great distance?

Entanglement

Alice



Bob

Measurement results:

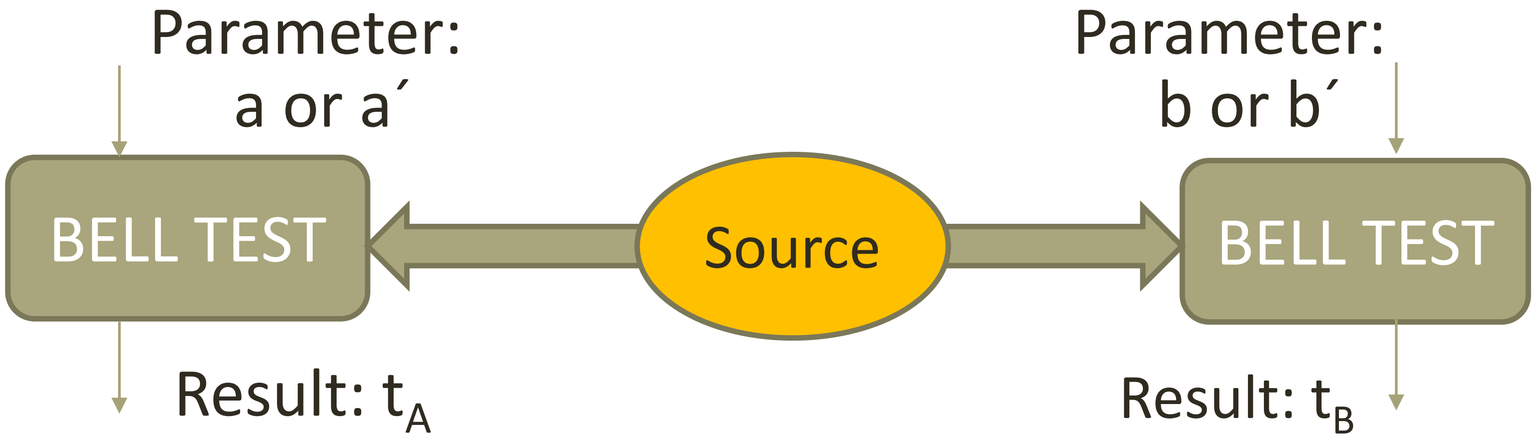
Result of Alice	Result of Bob
Down	Up
Up	Down

Measurement causes "collapse" as we never measure a superposition!

What if Alice and Bob are separated by a great distance?

Confirming entanglement: Bell test

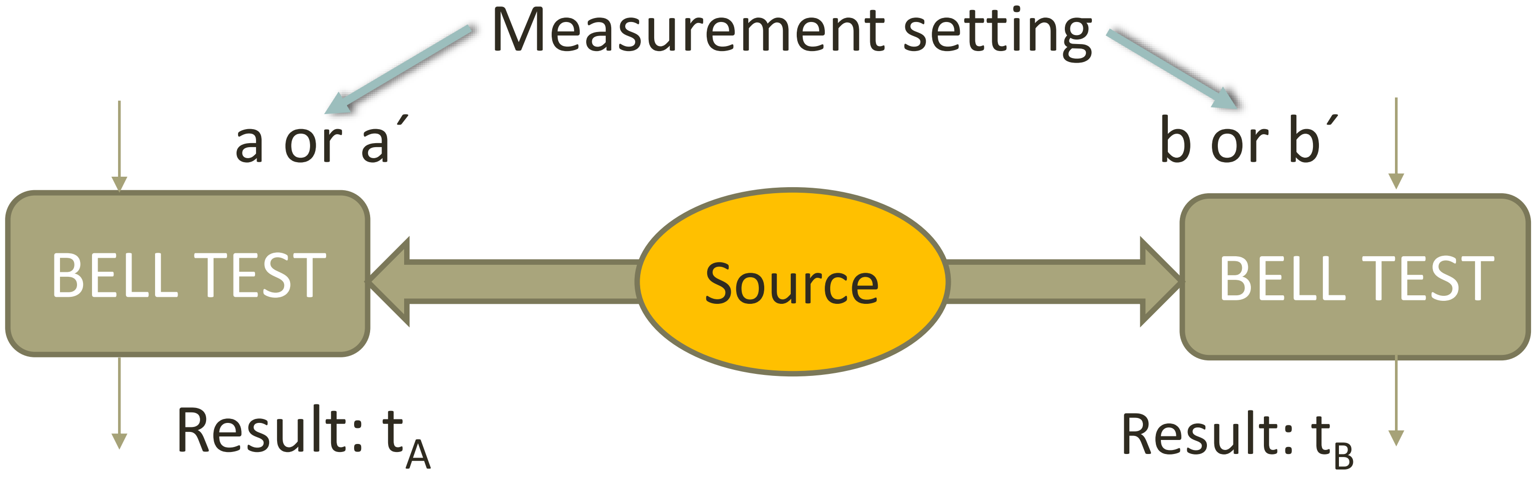
Alice



Bob

Confirming entanglement: Bell test

Alice



Bob

$$S = E(a, b) - E(a, b') + E(a', b) + E(a', b').$$

Unentangled states have S < 2

Entangled states can have S ≥ 2

- Alice & Bob need > 1500 successful measurements to confirm the Bell test to 3σ

Confirming entanglement: Bell test

Alice

Measurement setting

a or a´

b or b´

BELL TEST

Source

BELL TEST

Result: t_A

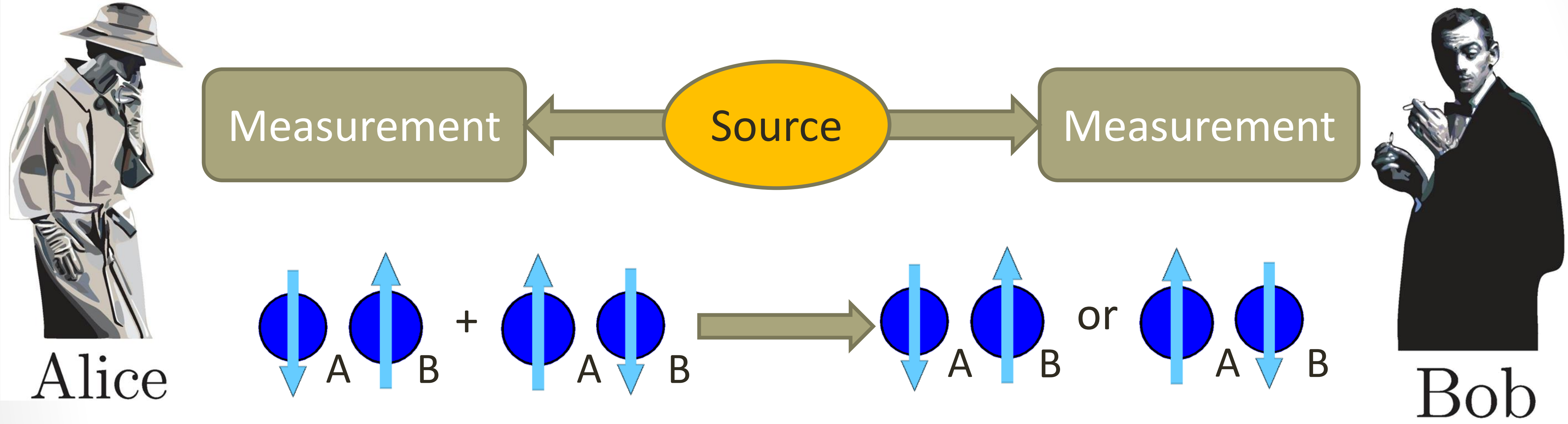
Result: t_B

Bob

Experiment steps:

1. Set apparatus
2. Measure time of arrival t
3. Calculate S
4. Entangled if S ≥ 2

Decoherence



- An entangled state can lose entanglement: decoherence
- Caused by interactions with the environment

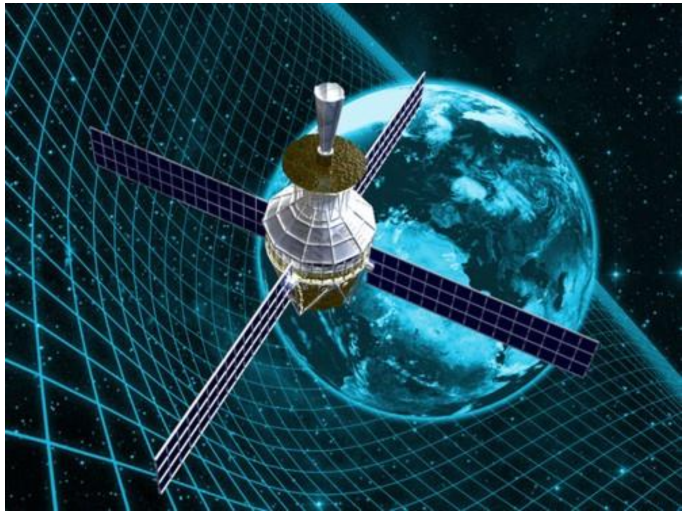
Long distance bell test experiments

- Free space Bell test: 144km [1] → > WORLD RECORD! <
  - Limited due to curvature of Earth and atmospheric attenuation and turbulence
- From satellite to ground [2]: feasibility has been demonstrated – single polarized photons

[1] Ursin, R. et al. (2007). *Nature Physics* 3: 7. 481-486 07
[2] Giuseppe Vallone *et al* Phys. Rev. Lett. 115, 040502 (2015)

Science background 3: Quantum Gravity

Gravity	Quantum Mechanics
Deterministic	Probabilistic
Local	Nonlocal
Time as a dimension	Time as a parameter

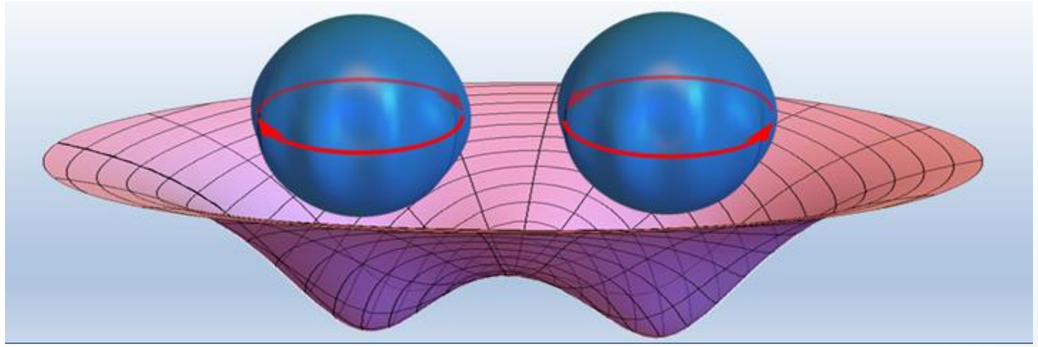


Quantum Gravity

- Not renormalizable:
  - Inconsistent probabilities

- E.g:
  - Probability that it will rain today = 30%
  - Probability that it won´t rain today = 70%

- What is the gravitational field of a particle in a superposition?

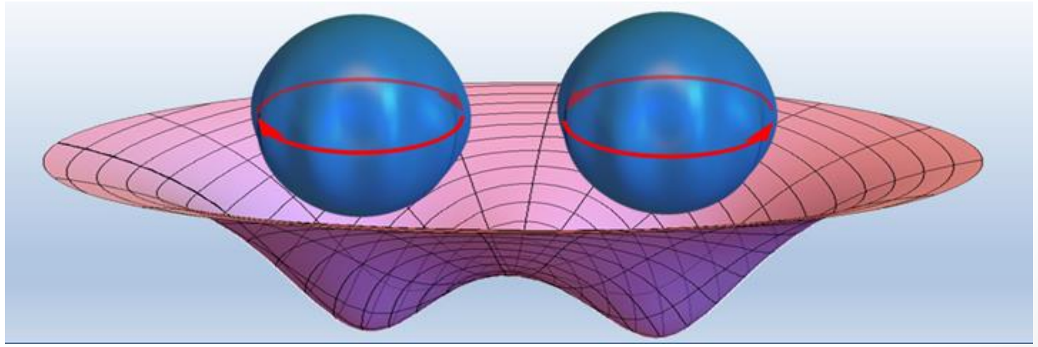


Quantum Gravity

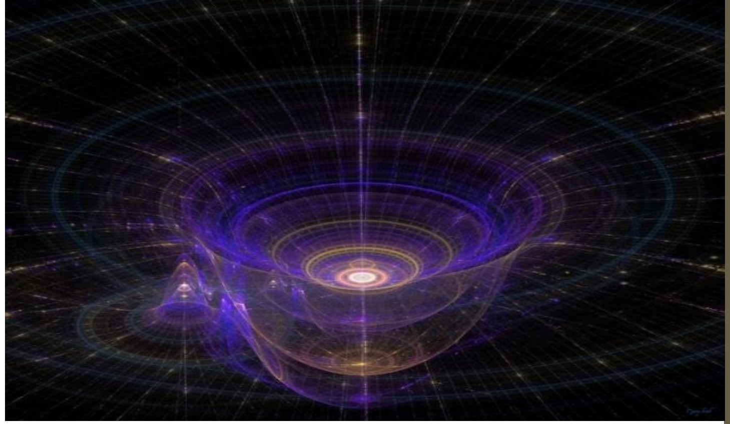
- Not renormalizable:
  - Inconsistent probabilities

Quantum gravity:
- Probability that it will rain today = 40%
- Probability that it won´t rain today = 80%

- What is the gravitational field of a particle in a superposition?



Theories

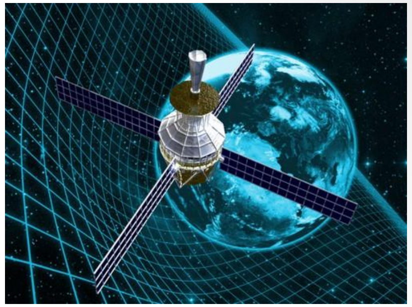


- String theory [1]: tests need energies for higher than the LHC
- Penrose [2]: how quantum physics and gravity interact
- Ralph [3]: gravitational fields reduce entanglement
  - (This won´t effect our experiment)

! Unified theory – Equivalence Principle is predicted to break down by most quantum gravity models !

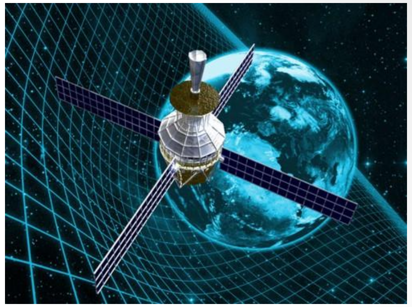
[1] Green, Michael B., John H. Schwarz, and Edward Witten. Cambridge university press, 2012.
[2] Penrose, Roger. "Quantum computation, entanglement and state reduction." (1998): 1927-1937.
[3] Ralph, T. C., and J. Pienaar. "Entanglement decoherence in a gravitational well according to the event formalism." *New Journal of Physics* 16.8 (2014): 085008.

Motivation for the experiment



- There is very little theory on the effect of entangled states interacting with gravity
- There are no experimental studies of this regime
- More experiments are needed:

Motivation for the experiment



- There is very little theory on the effect of entangled states interacting with gravity
- There are no experimental studies of this regime
- More experiments are needed:

We propose to directly test an entangled state in order to understand how quantum mechanics and gravity can be unified

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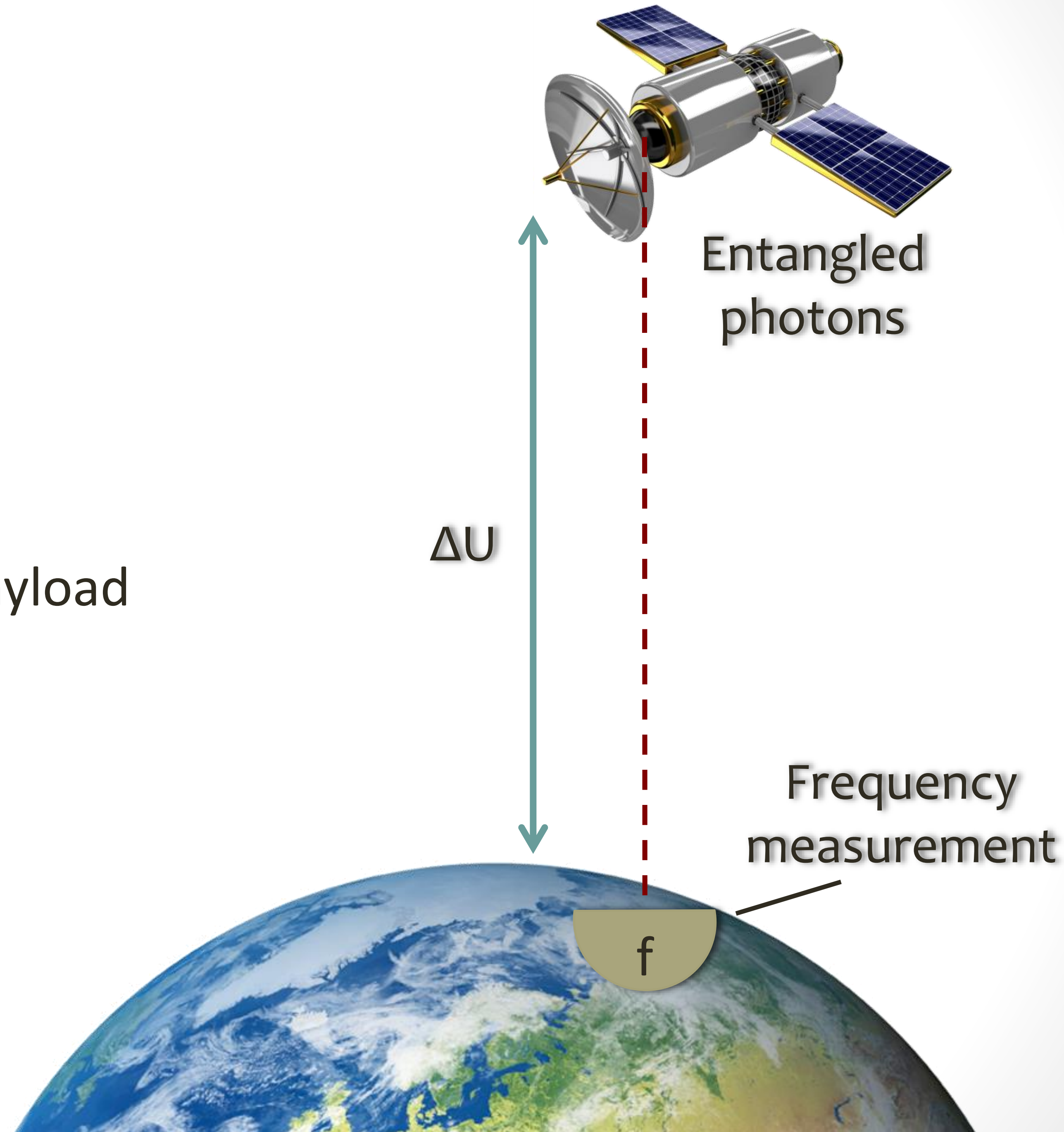
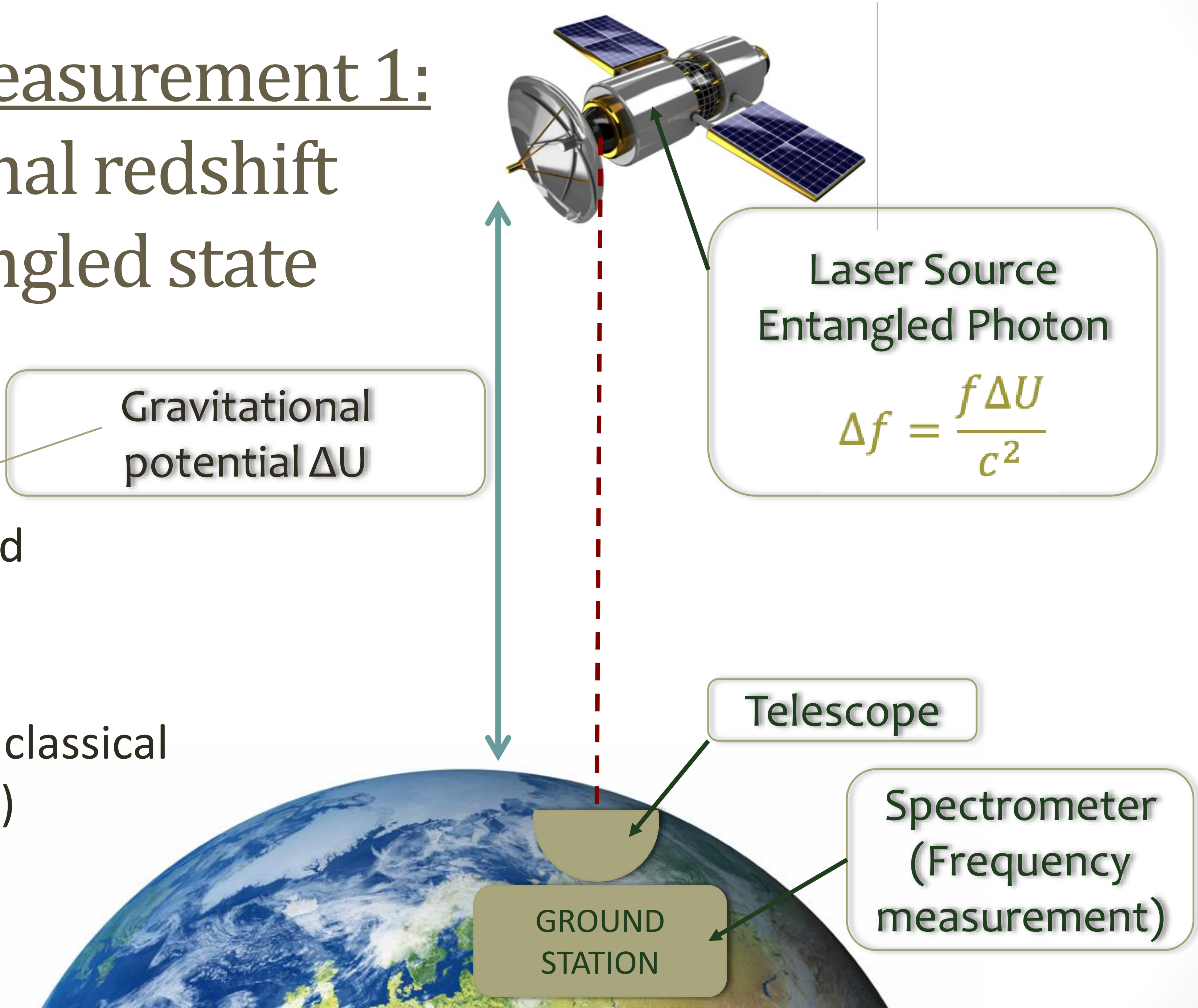


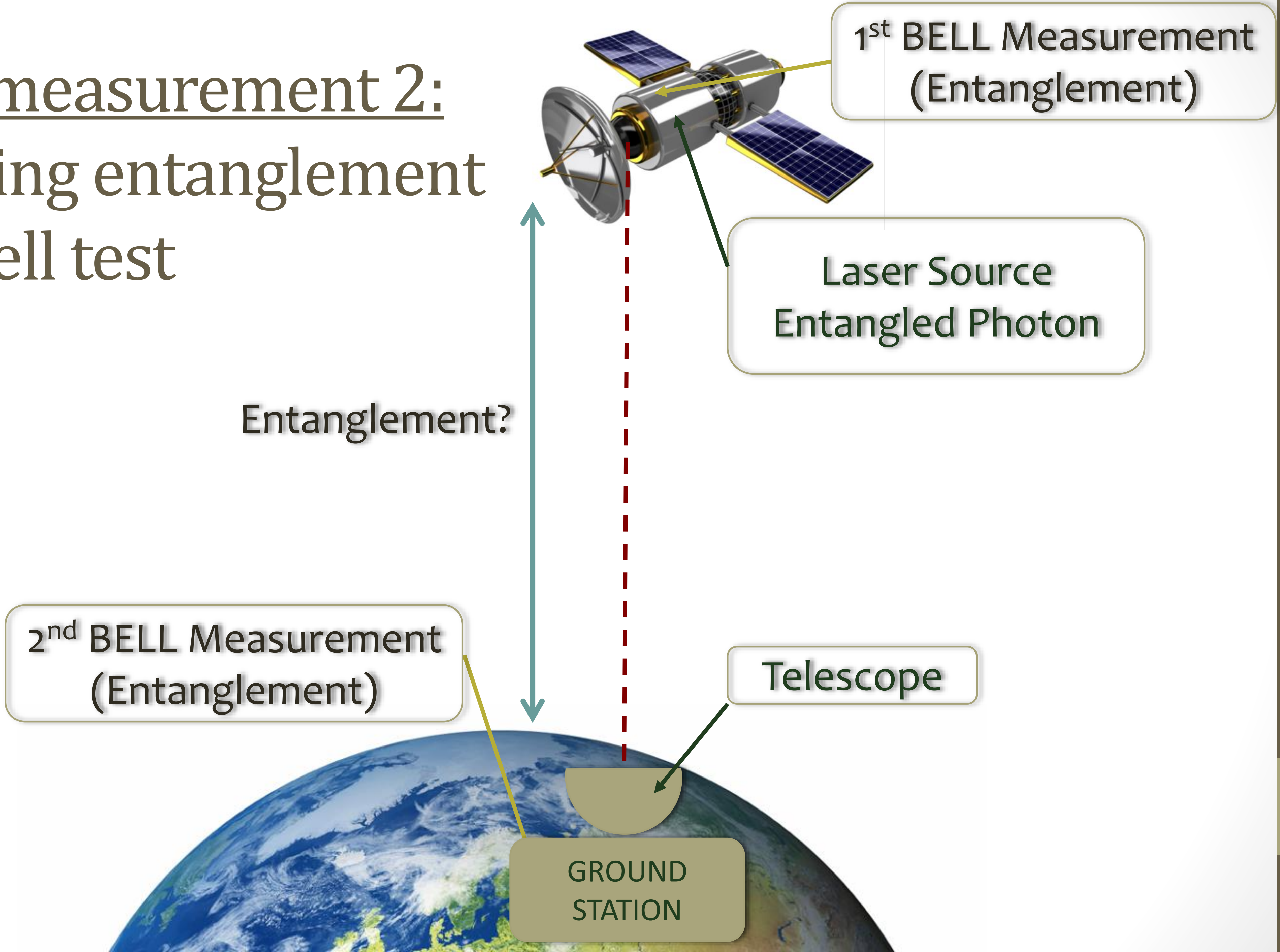
Science measurement 1:
Gravitational redshift of an entangled state



Large value needed for effective test

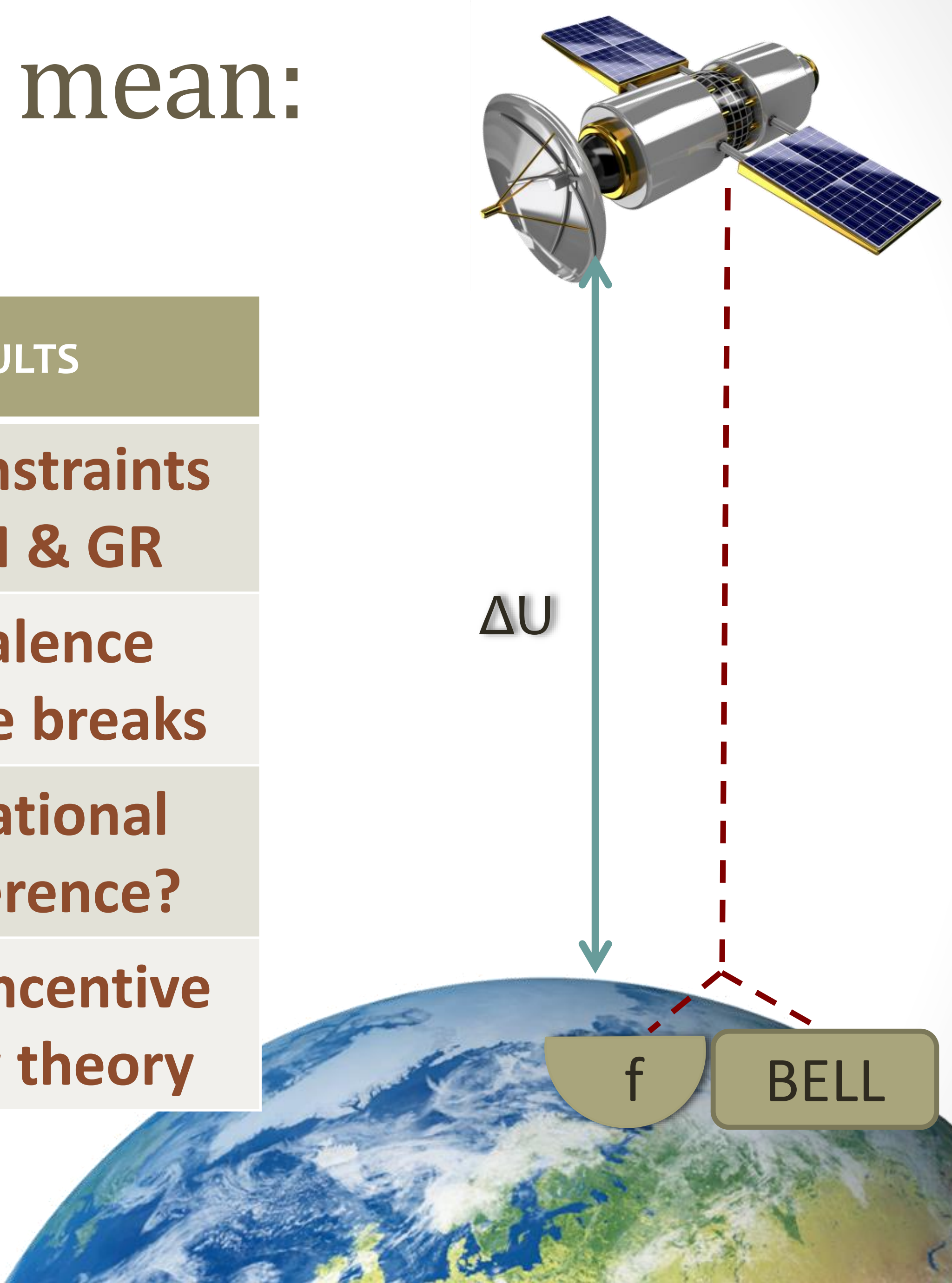
(We account for classical Doppler redshift)

Science measurement 2:
Confirming entanglement with a Bell test



What our results would mean:

ENTANGLEMENT	EXPECTED RED SHIFT	RESULTS
✓	✓	New constraints on QM & GR
✓	✗	Equivalence principle breaks
✗	✓	Gravitational decoherence?
✗	✗	Strong incentive for new theory



Science Objectives	Science Requirements
SO1: Explore the role of gravity on quantum entanglement.	**SR1.1:** Separate entangled photons over a gravitational potential of 10^7 J/kg **SR1.2:** Determine if entanglement still is present after photon has experienced a gravitational potential change. This needs to be confirmed with 99.7% confidence by testing Bell´s inequality.
SO2: Investigate the effect of large spatial separations on quantum entanglement.	**SR2:** In addition to SR1.2, provide distances from 500 km to 10 000 km between the entangled photons.
SO3: Search for discrepancies between Quantum Mechanics and General Relativity by comparing the gravitational redshift of entangled photons with the expected red shift from classical photons.	**SR3:** Determine the gravitational red shift of the entangled photons with precision of 1% of the classical prediction.

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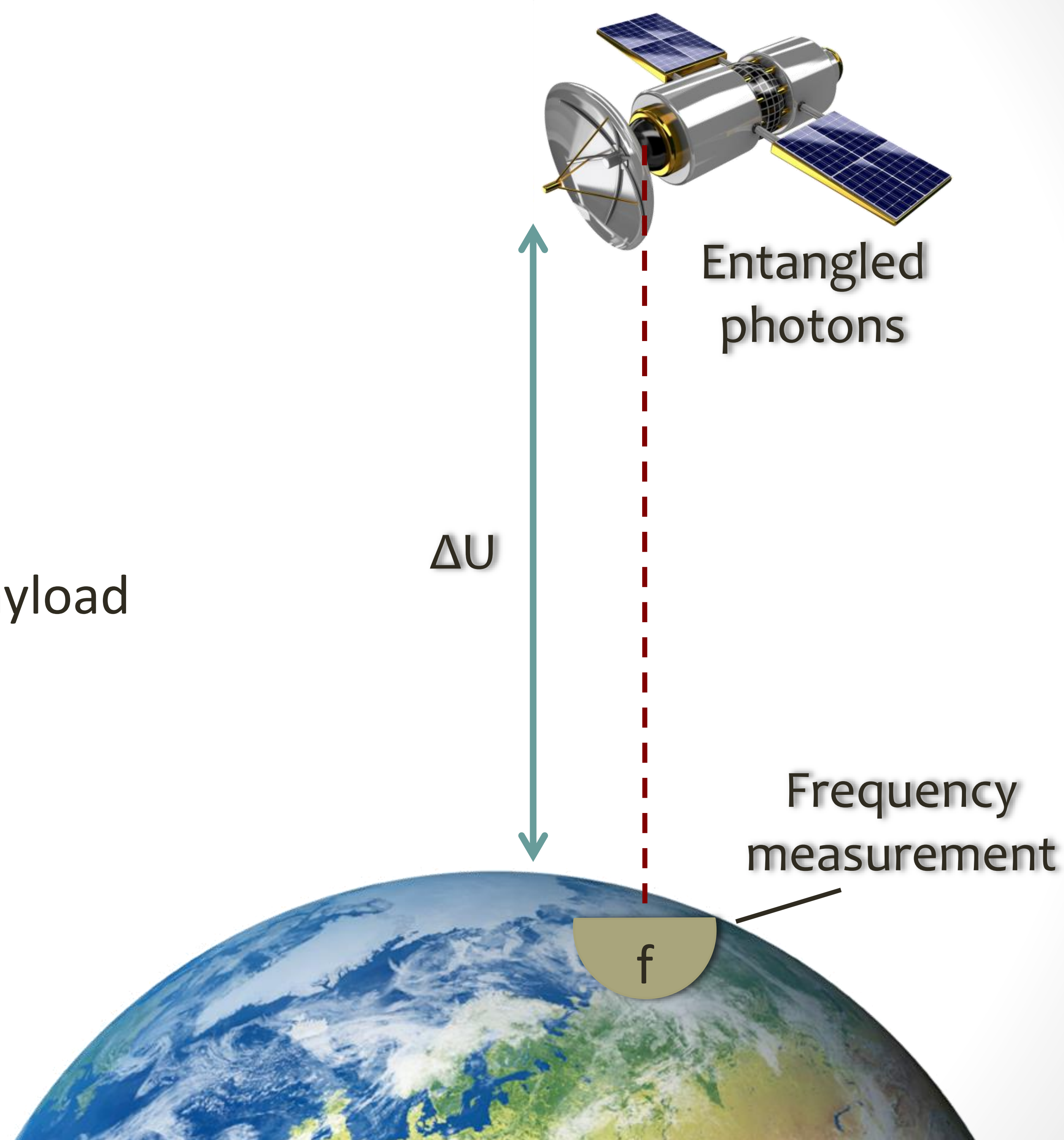
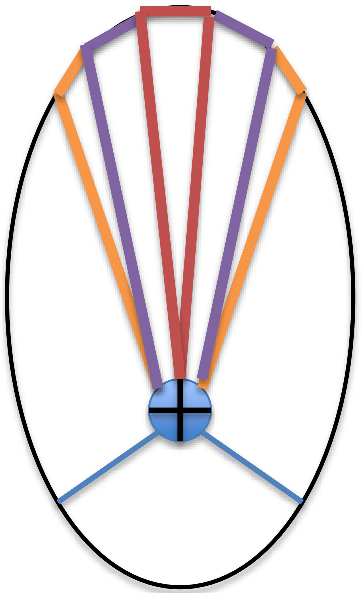


Orbits for Measurement Overview

- To have a variation in gravitational redshift, the orbit has to be elliptical
- Measurements on perigee and apogee
- Data taken at different gravitational potentials are grouped into 25 separate orbit parts (represented by different colors)

GR redshift: $\Delta f = f \frac{\Delta U}{c^2}$

	apogee	perigee
Distance to Earth	10 000 km	500 km
GR redshift	80 KHz	20 KHz



Requirements for red shift measurements

- Single photon bandwith 30 MHz – lower bound on the accuracy of a single measurement

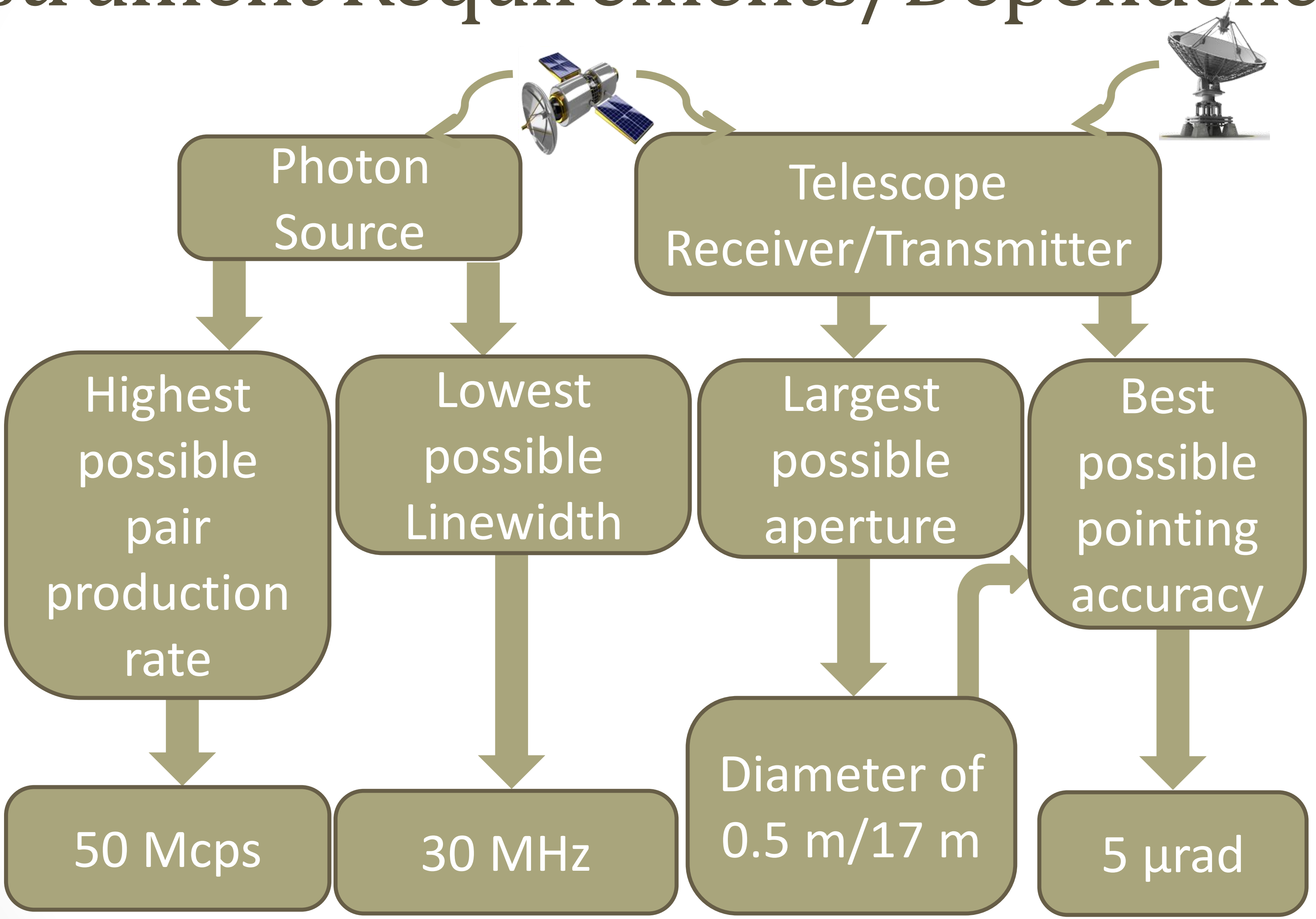
- Spectrometer design: impose apparatus accuracy of 10 MHz – challenging but technically feasible

$$\sqrt{(30\ MHz)^2 + (10\ MHz)^2} \approx 32\ MHz$$

$$32\ MHz/1\ kHz = \sqrt{N}$$

$$\therefore N \approx 10^9$$

Instrument Requirements/Dependencies



Entangled photon source

- CW pumped SiN microring resonator*
- Bandwidth: 30 MHz
- Pair production rate: 50 Mcps
- Wavelength: 1.55 µm

*Performance demonstrated in a laboratory [1], operation principle described in [2]

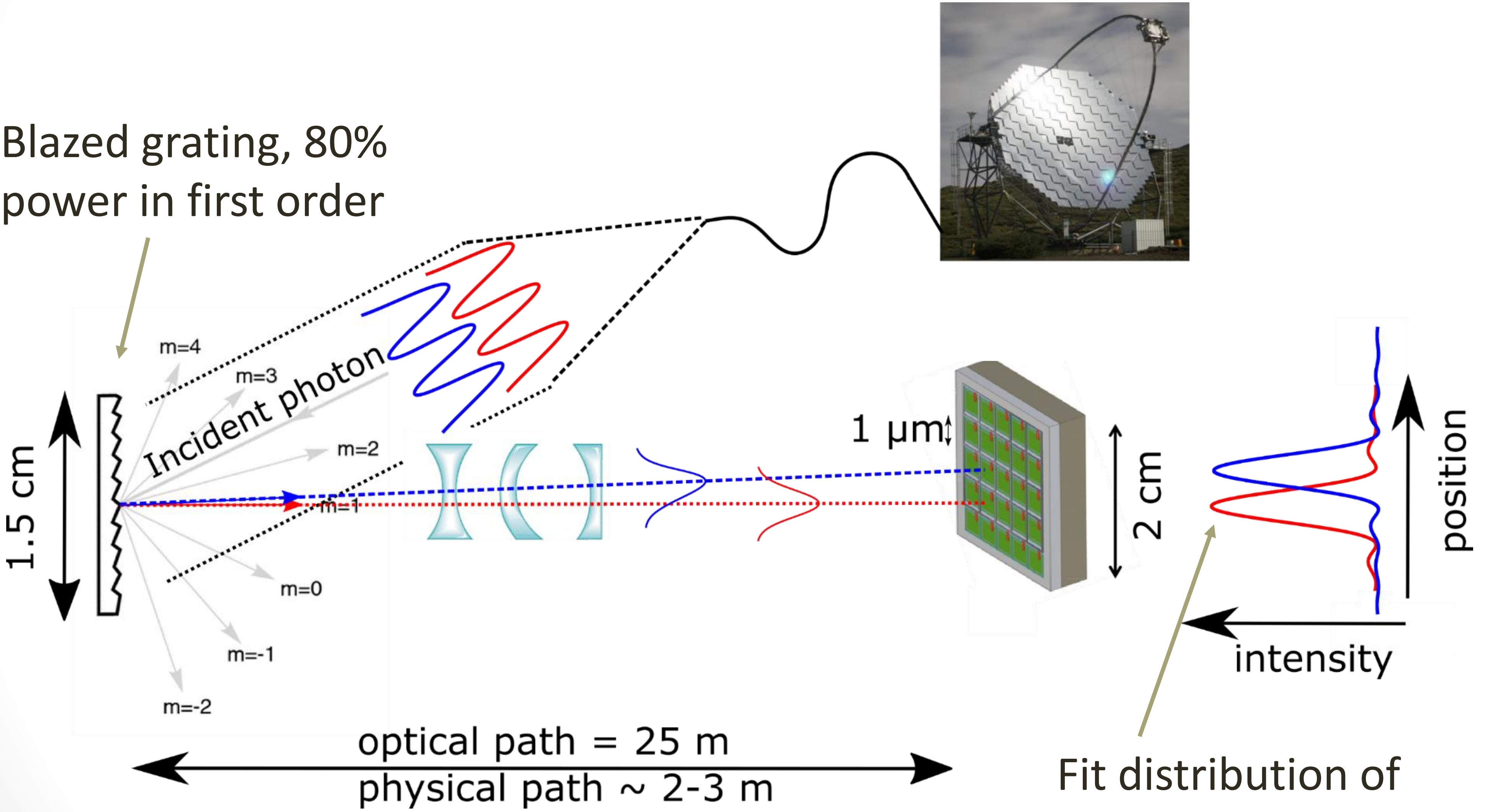
[1] Personal communication with Dr. Rupert Ursin
[2] Helt, L. G. et al., Opt. Lett. 35, 3006 (2010)

Ground-Based Spectrometer

- We require a spectrometer of 10 MHz to detect the gravitational redshift;
- To measure the frequency of light it is sufficient to look on the first order maximum in the diffraction pattern;
- Use blazed grating - 80% of the total incident power is in the first order maximum.

Ground-Based Spectrometer

Blazed grating, 80% power in first order



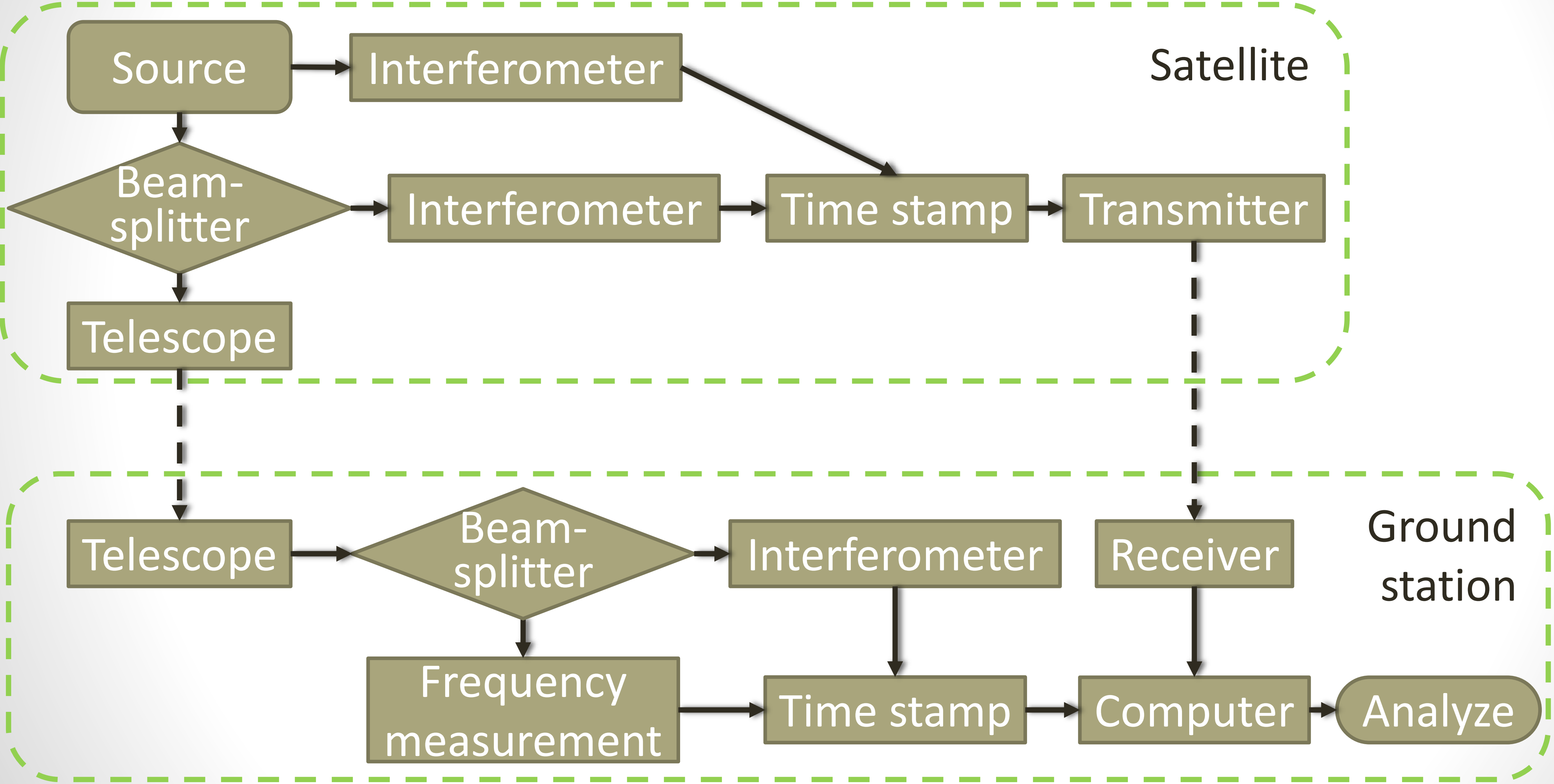
Fit distribution of many measurements

Spectrometer Specifications

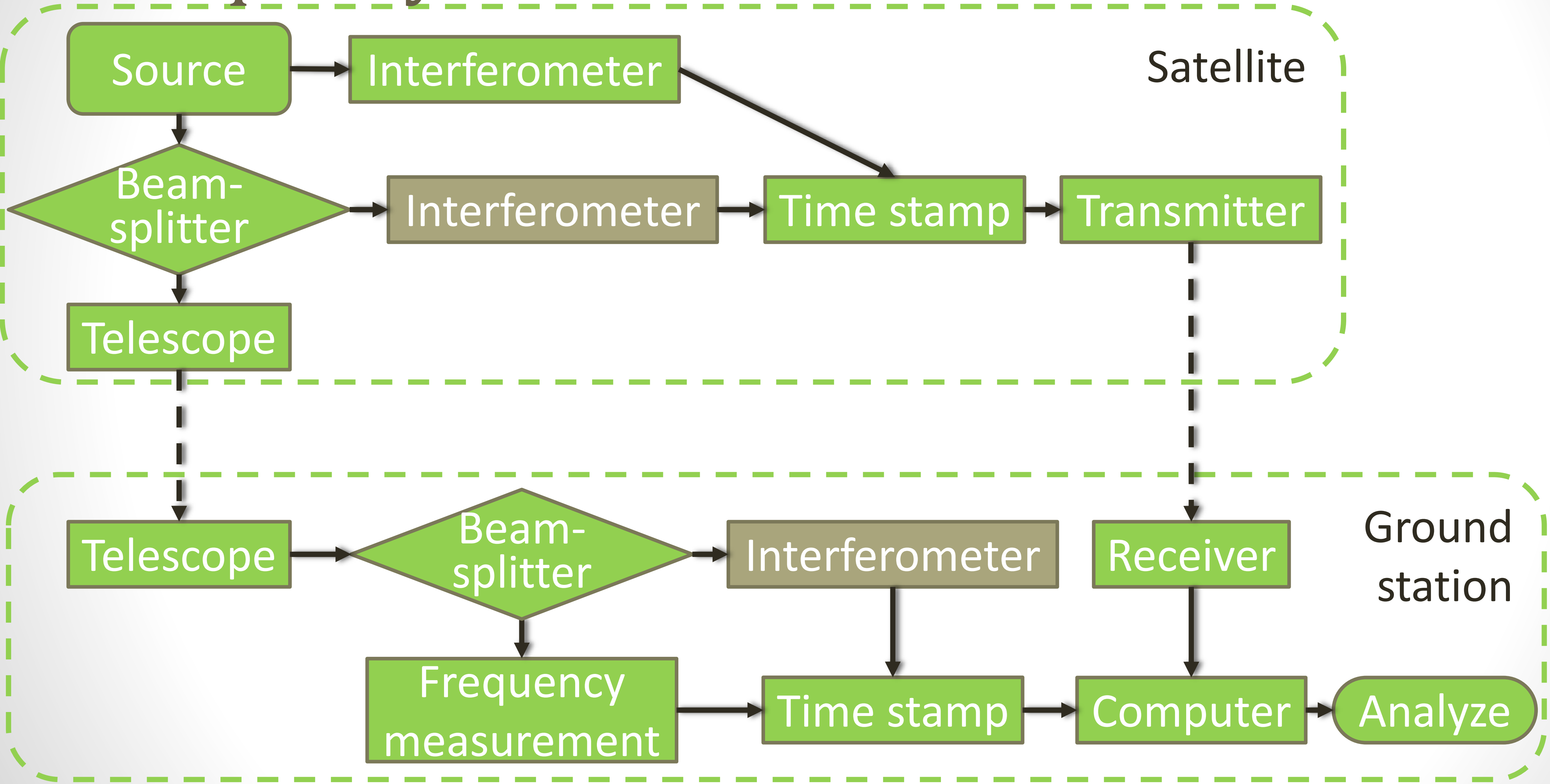
Number of lines	Line width	Line separation	Pixel size on screen
5000	2 µm	3 µm	1 µm

Grating to detector optical path	Width of the detector	Width of the grating	Apparatus frequency resolution
25 m (using adaptive optics: 2-3 m physical path)	2 cm	1.5 cm	10 MHz

Measurement overview

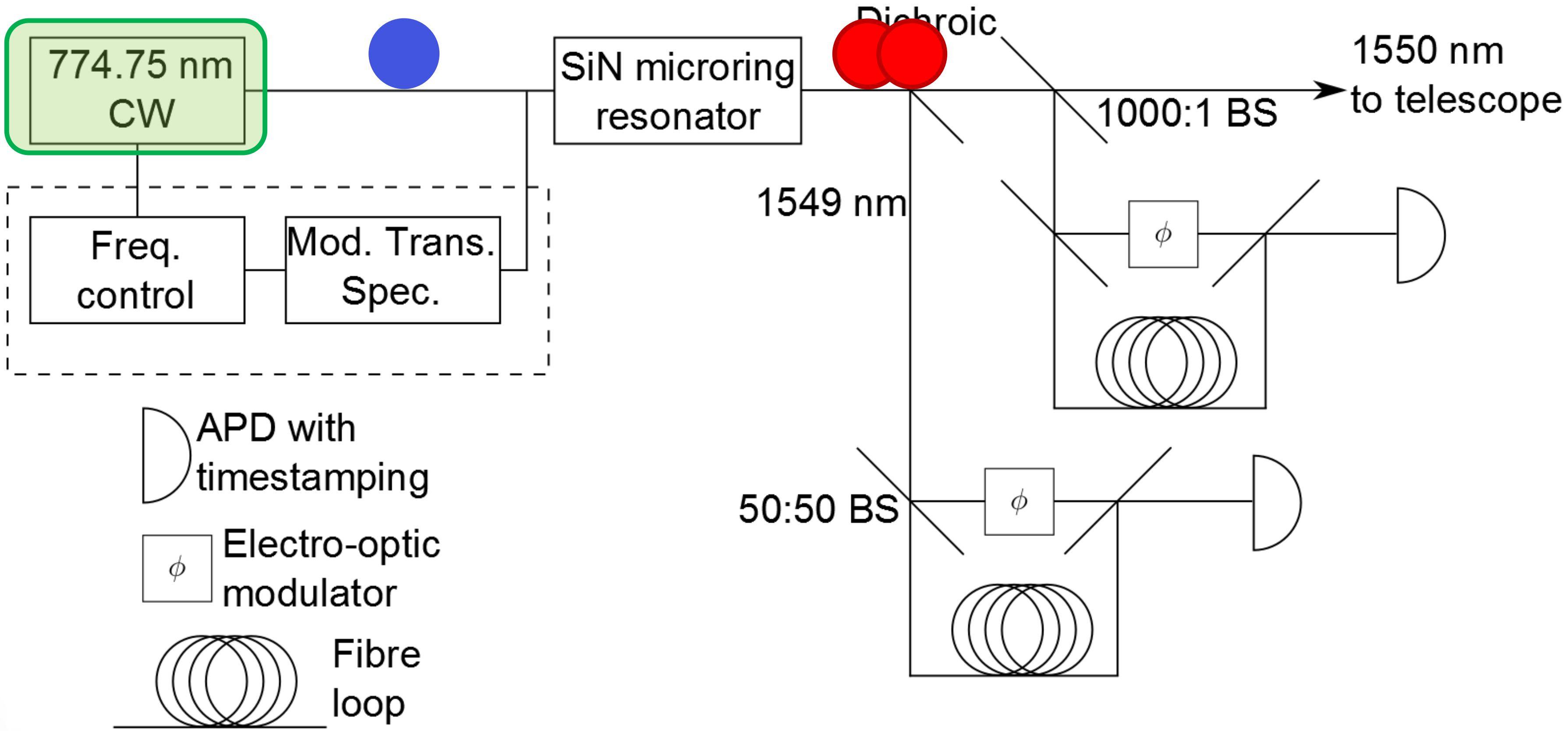


Frequency measurement



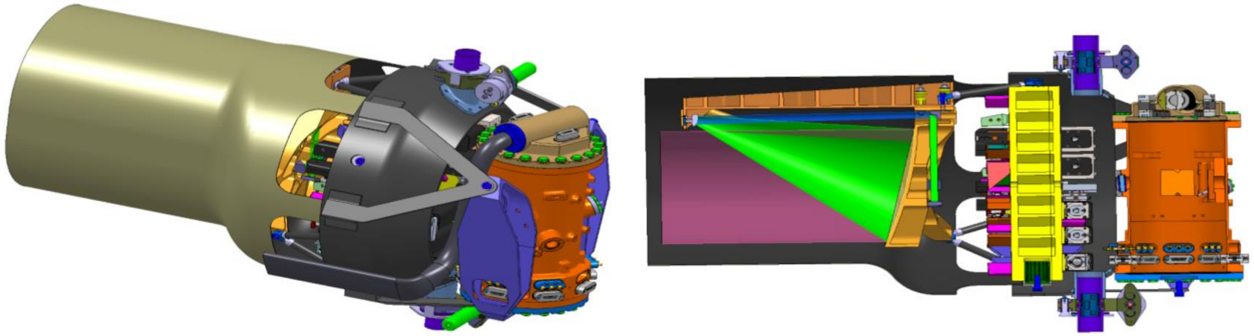
Frequency measurement

Measure the redshift of this photon on the GS



Telescope on Spacecraft

- The physical dimensions of our telescope is 0,5m of diameter and 0,6m of length
- The beam magnification is 100
- The estimated mass for our telescope is about 20kg
- We will use an equipment very similar to the LISA's Program:

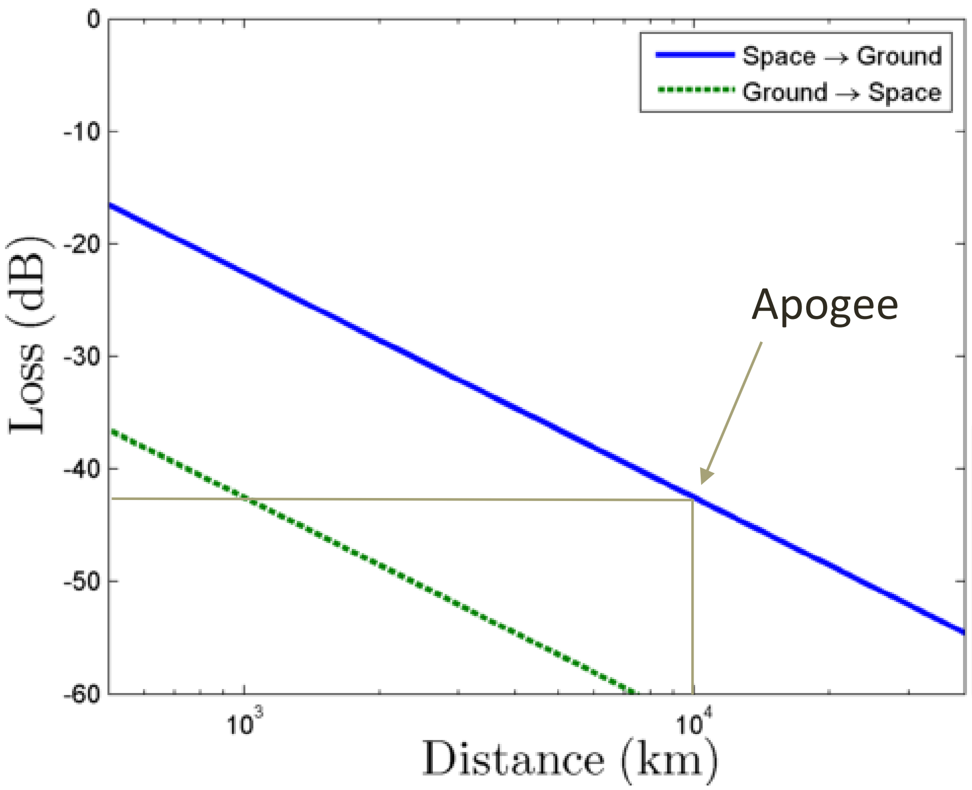


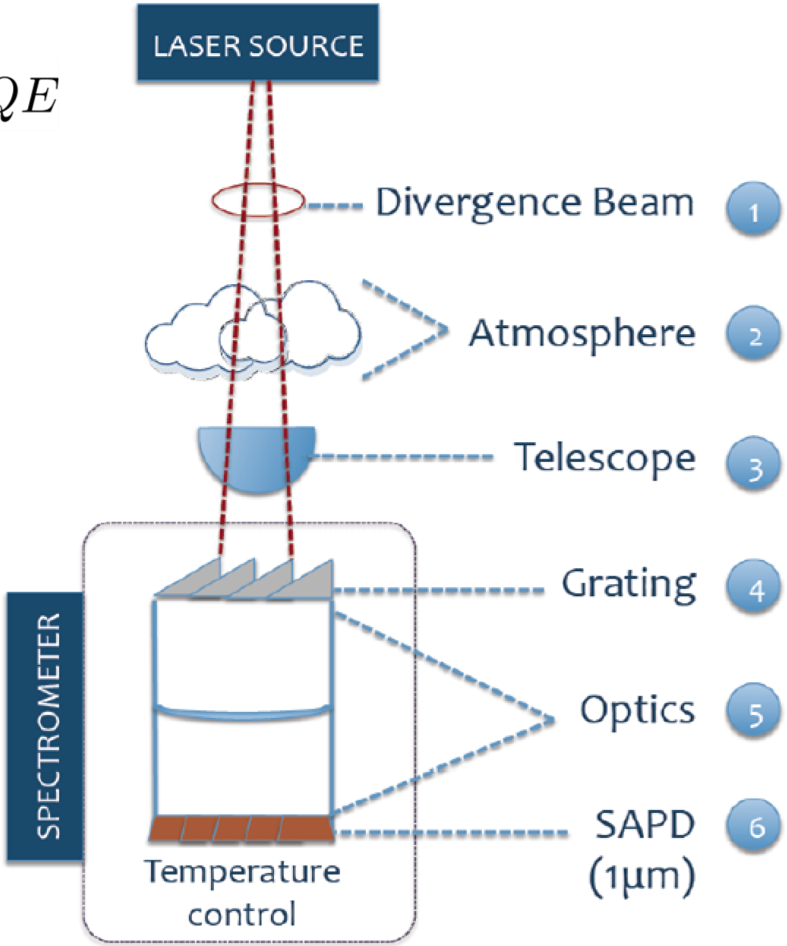
Ground Telescope

- MAGIC telescope as a receiver station, 17 m diameter
- Can point to any direction in the sky within 40 s
- Adaptive optics for aberration compensation

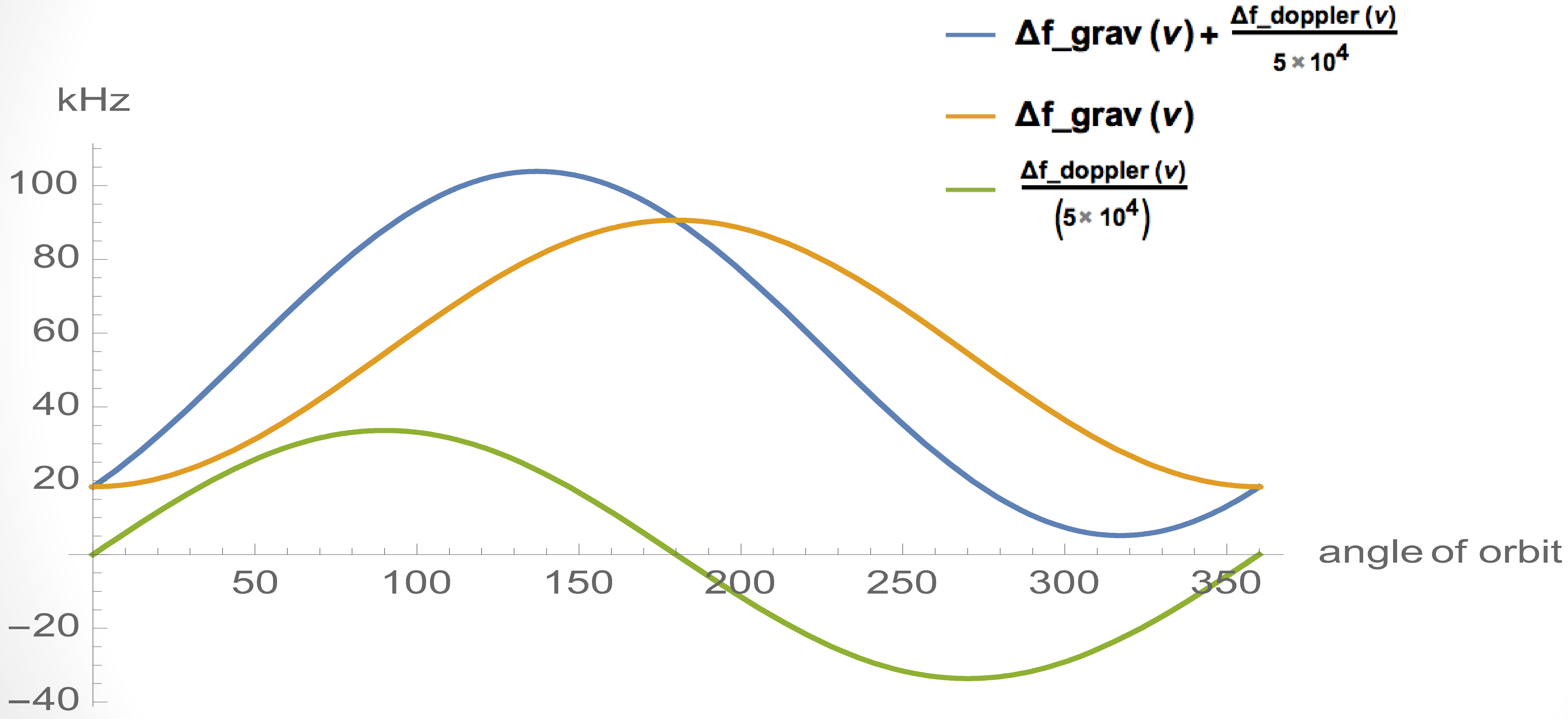
Optical link budget

$$L = \left(\frac{D_t D_r}{2\lambda R}\right)^2 \cdot L_t \cdot L_r \cdot L_{atm} \cdot L_{pt} \cdot L_{spec} \cdot QE$$





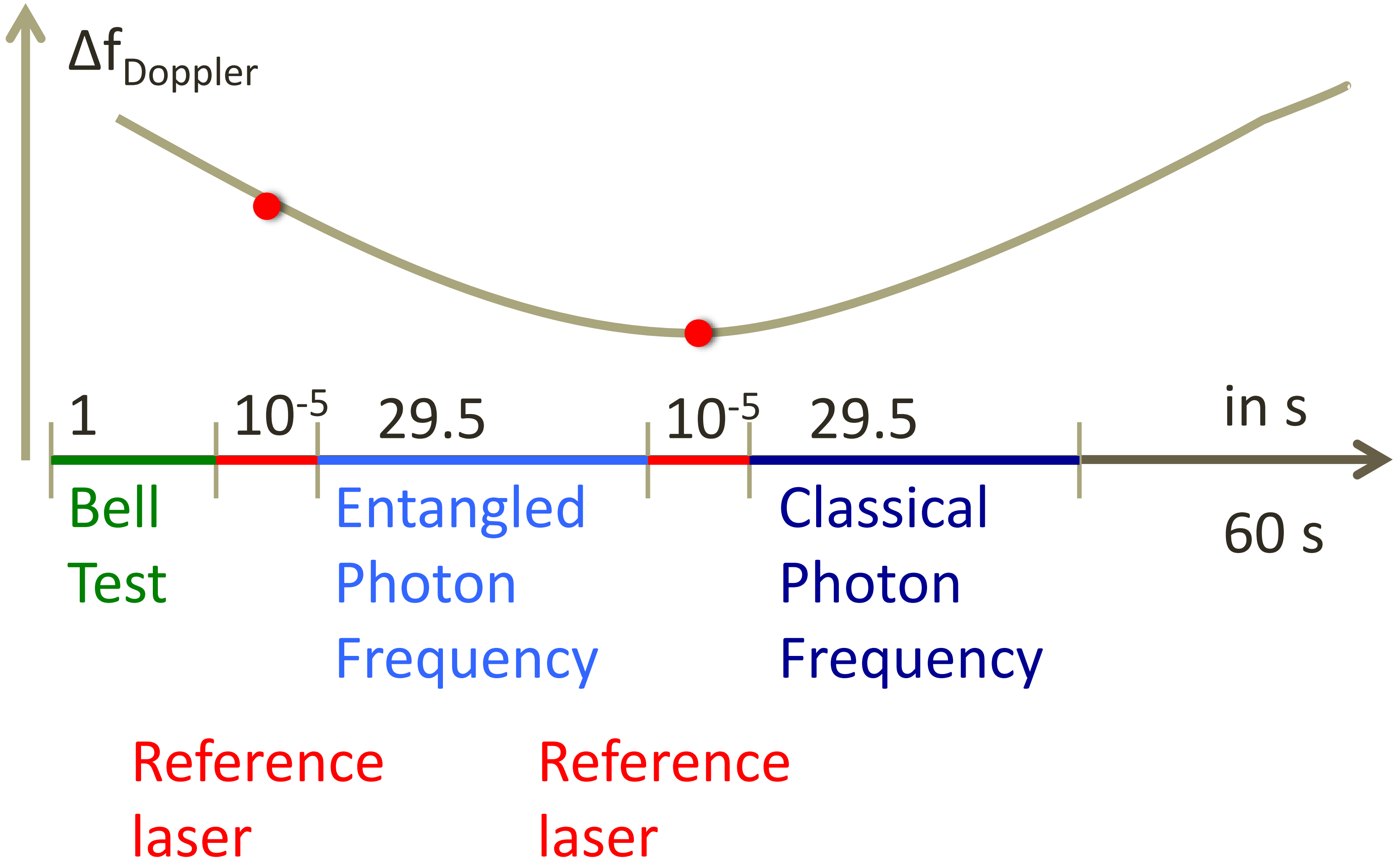
Expected results



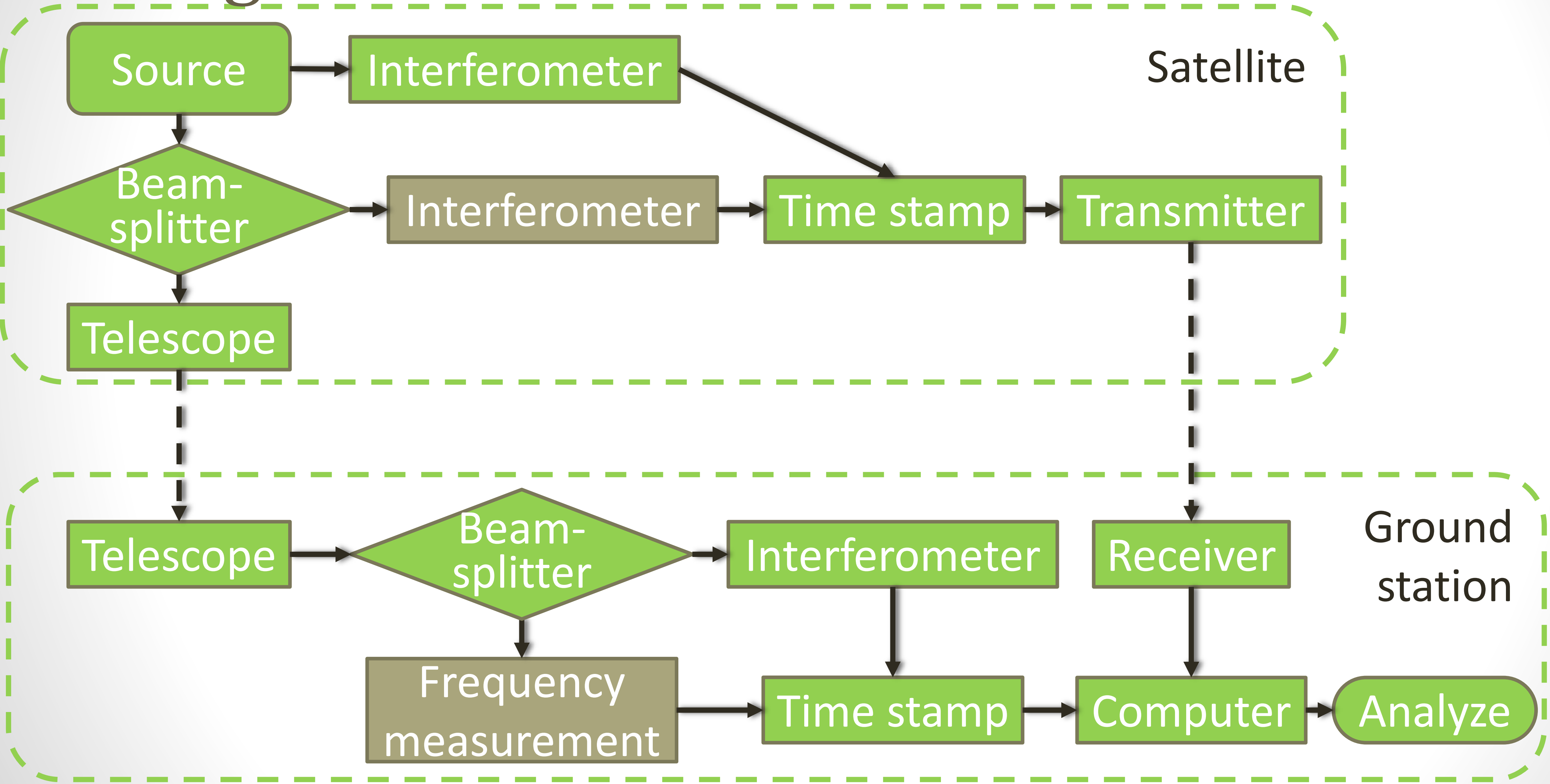
Noise and Uncertainty

Source	Size of Error	Remedy	After remedy
Doppler shift	10^5 bigger than original signal	Laser ranging	< 1% on each data point
Stability of pump laser		Active frequency stabilization	1 kHz
Spectrometer, APD dark counts,		Cooling and Temperature Stability	100cps
Satellite Black Body Radiation		T < 320 K	Negligible
Non-constant gravitational potential	TBD	TBD	TBD

Measurement timing

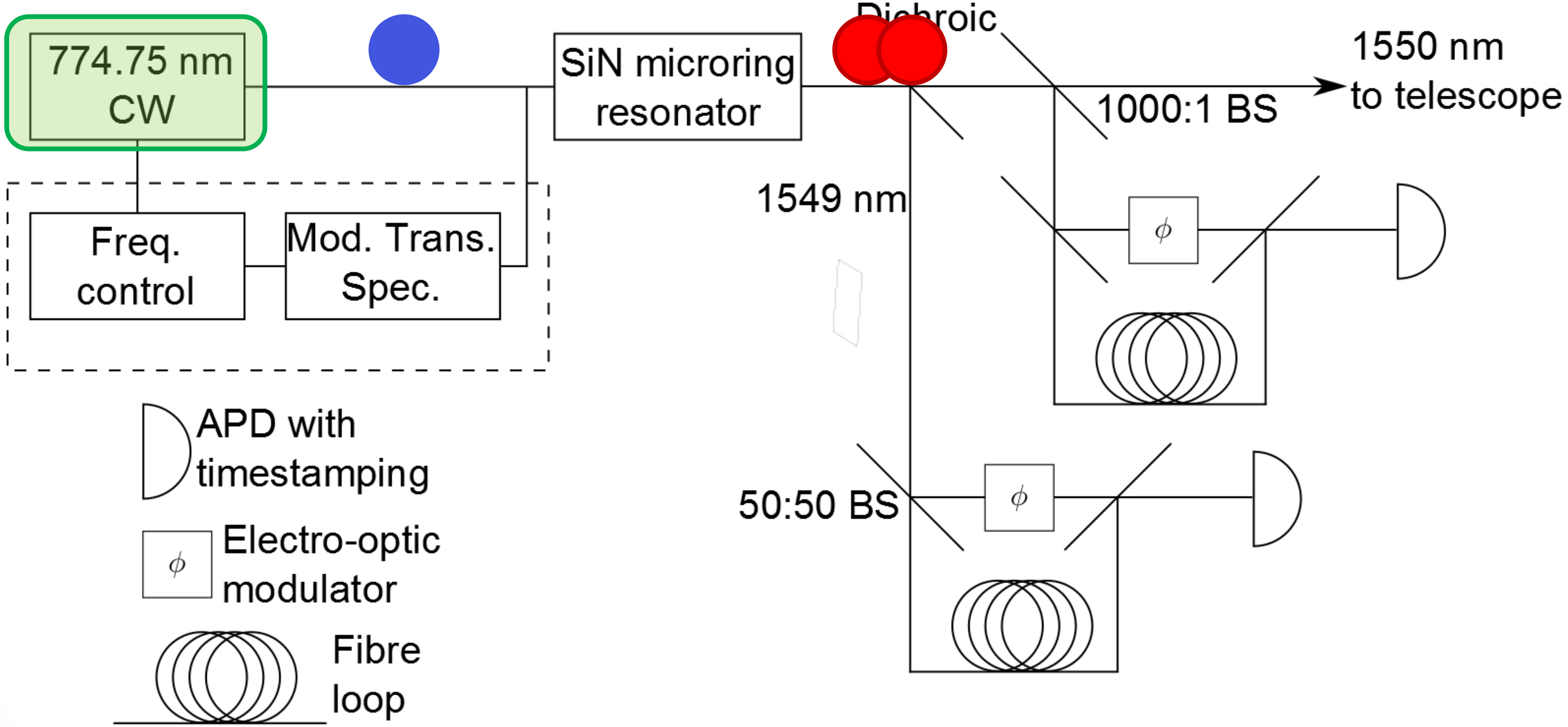


Long-distance Bell test



Bell Test Measurement

Bell test measurement between satellite and GS

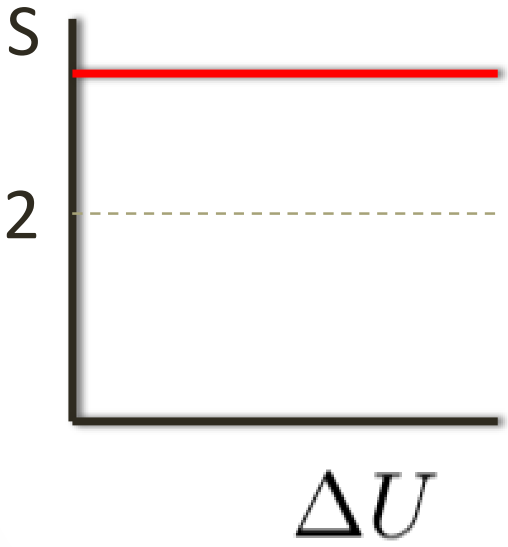


Possible results of Bell Test

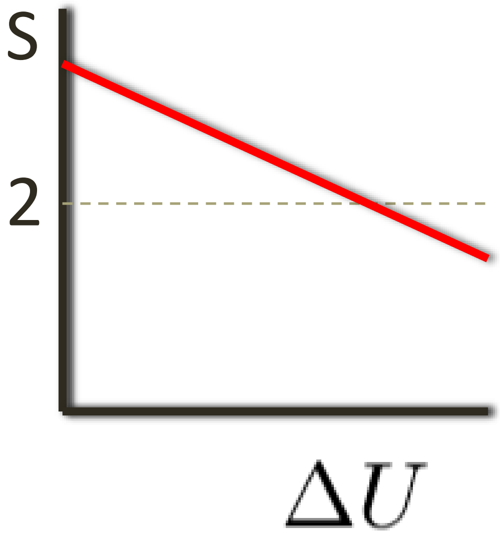
$$S = E(a, b) - E(a, b') + E(a', b) + E(a', b').$$

$S \geq 2$ means that our state is entangled

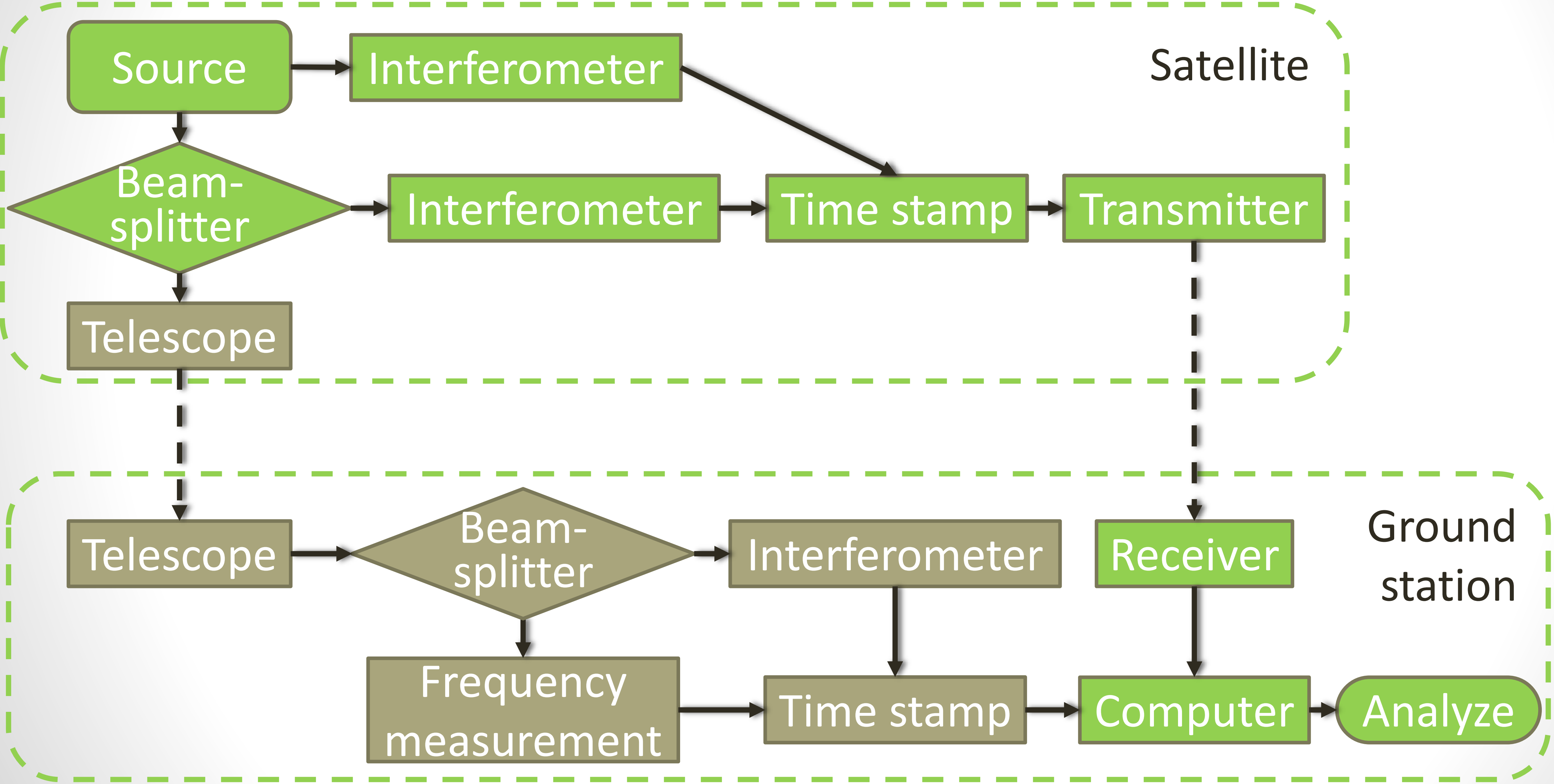
QM Prediction



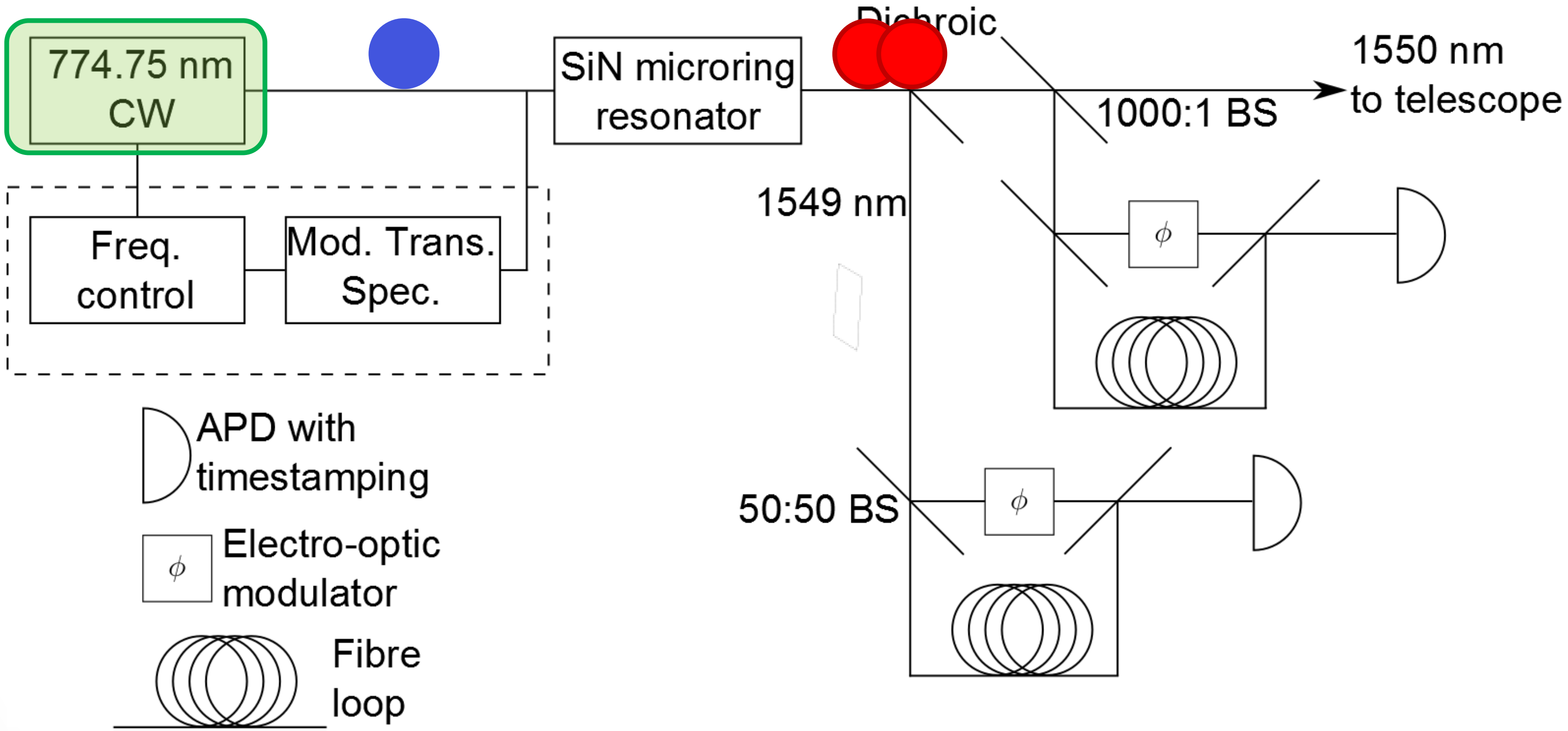
If gravity affects entanglement



Local Bell test



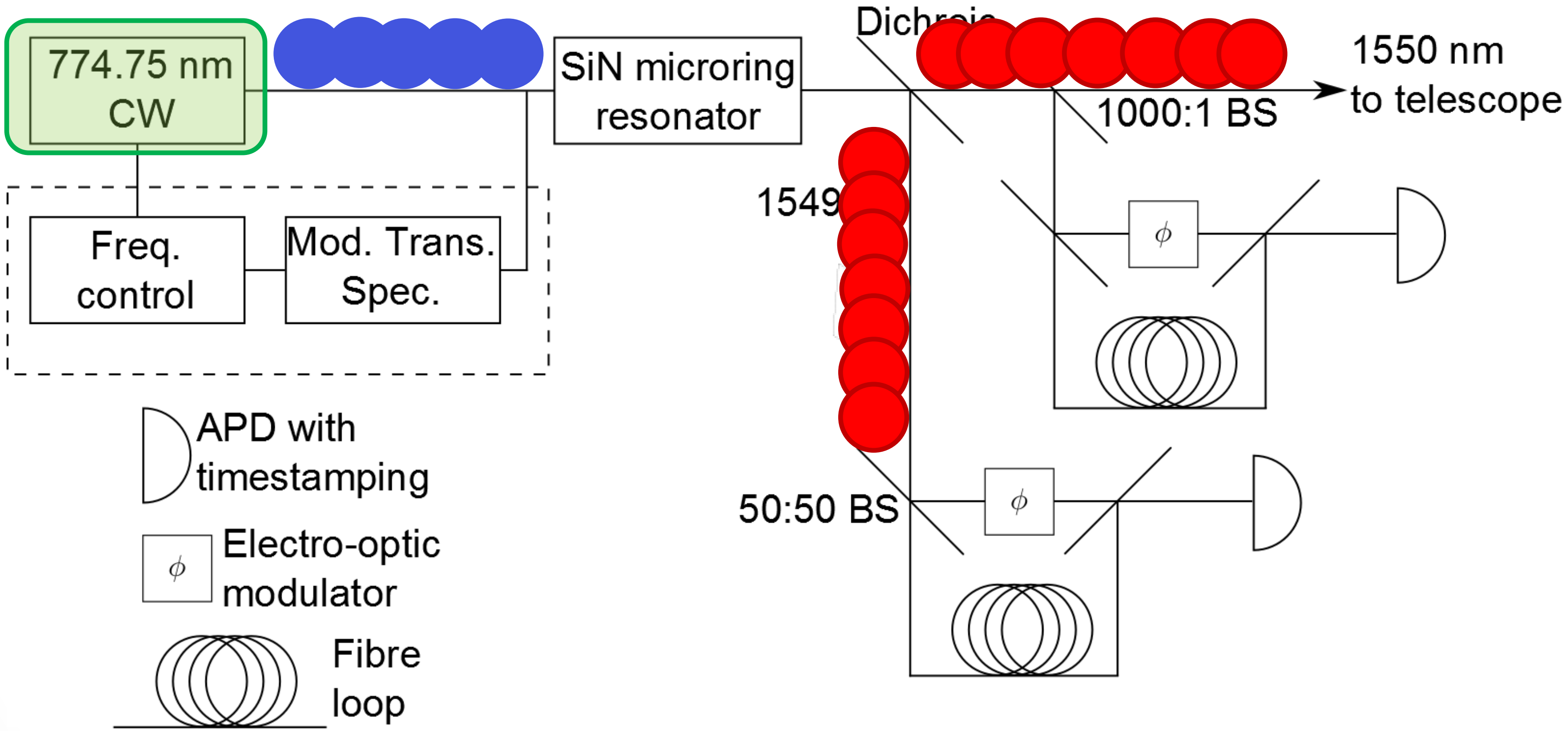
Verification of Entanglement by Bell Test on Satellite



Calibration of the Measurement Setup by Classical Photons

Increase the source power

Classical photons



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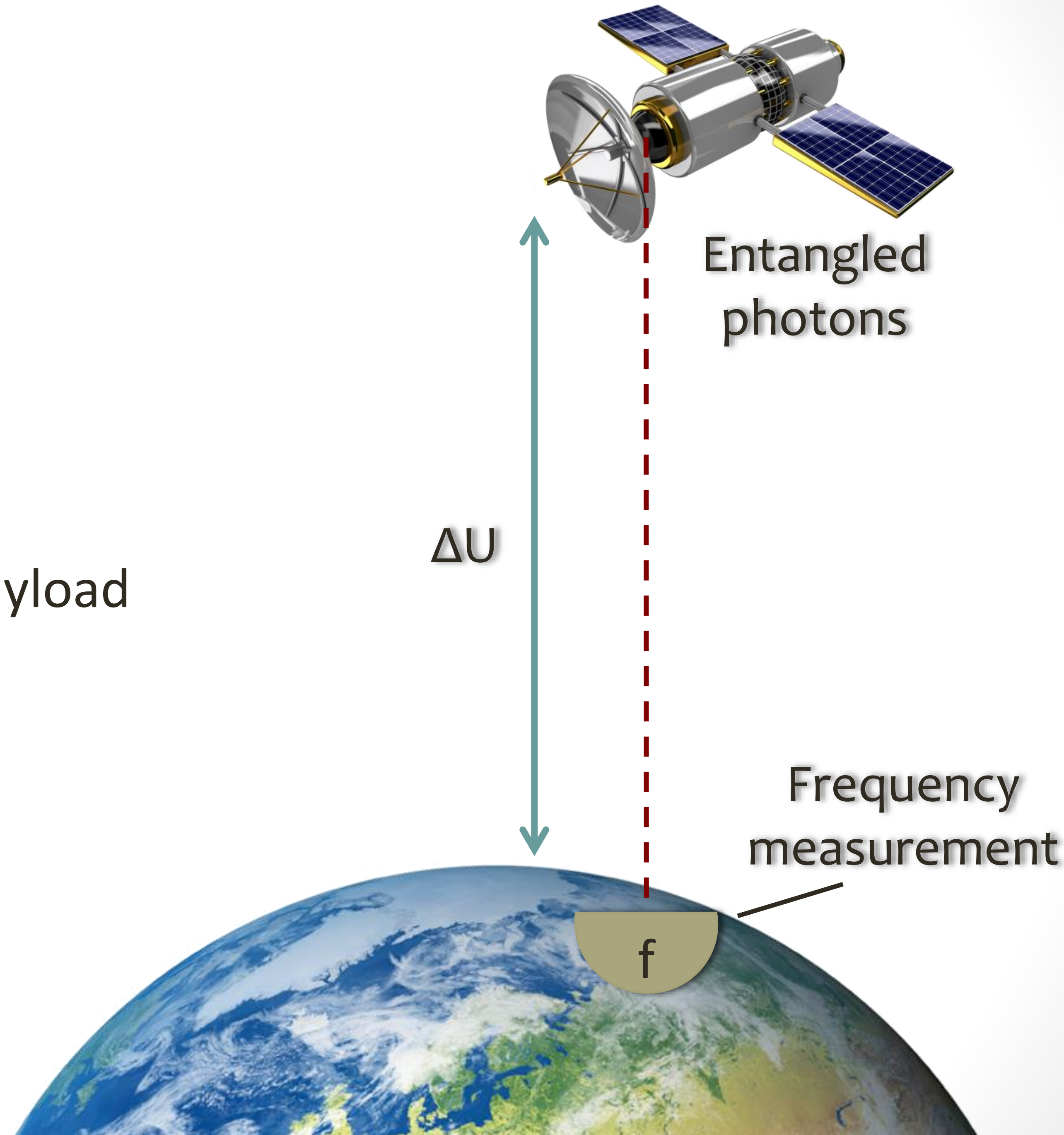


Measurement 1 (Redshift): Description

Description	Value
Number of points (photons) on GS needed	10^9
Signal-to-Noise-Ratio (SNR)	40dB
→ Measurement Duration (continous)	**200000s**
→ Measurement Duration (Apogee)	**~20 days**
→ Measurement Duration (Perigee)	**~85 days**
Only local Bell-Test data on SAT, must be evaluated in realtime, only result to store	
→ Data on GS per measurement	**4GB**

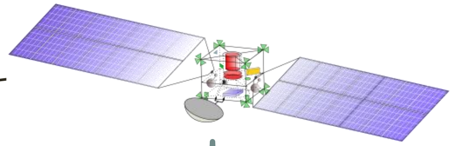
Measurement 2 (Long distance-entanglement): Description

Description	Value
Number of points (photons) on GS needed	1500
Signal-to-Noise-Ratio (SNR)	40dB
[and again additional local Bell-Test]	
→ Measurement Duration	1s
→ Number of points (photons) on SAT	15 000 000
→ Data on SAT per measurement	**75MB**
→ Data on GS per measurement	**50kB**

Implementation

- Mission overview
- Spacecraft
- Orbit and launcher
- Ground segment
- Development schedule
- Mission development cost
- Risks
- Descoping
- Outreach program

Mission overview



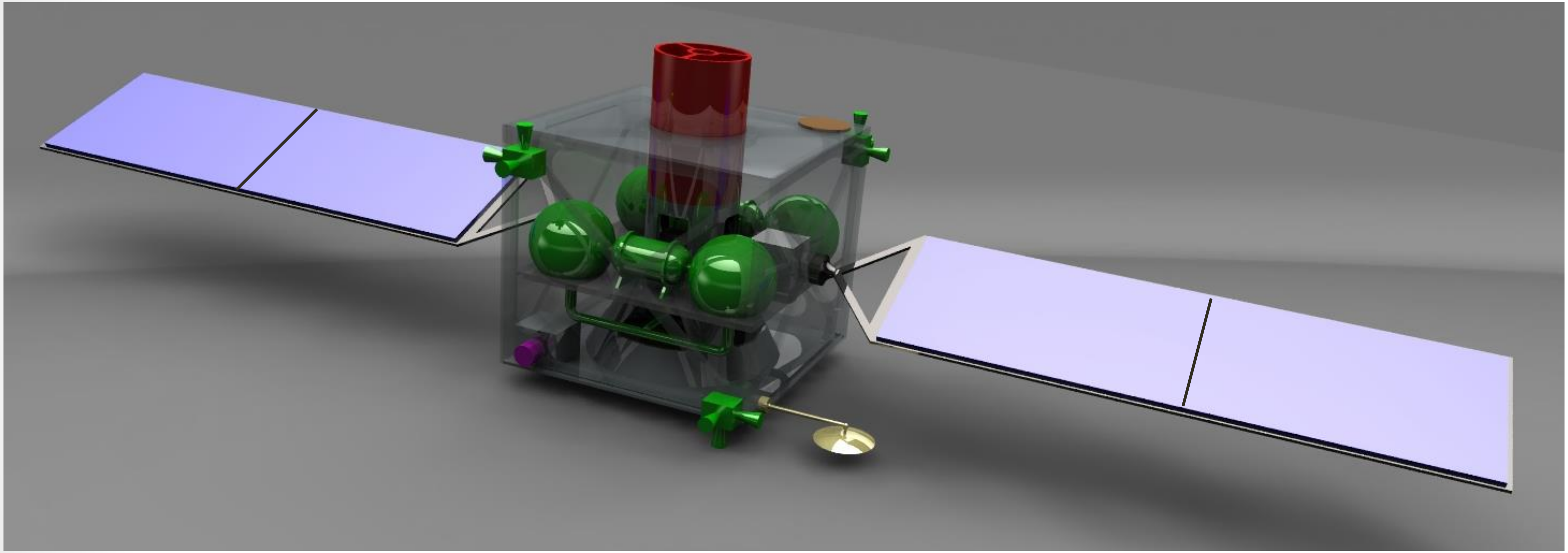
Mission

Launch:
Kourou (French
Guiana)

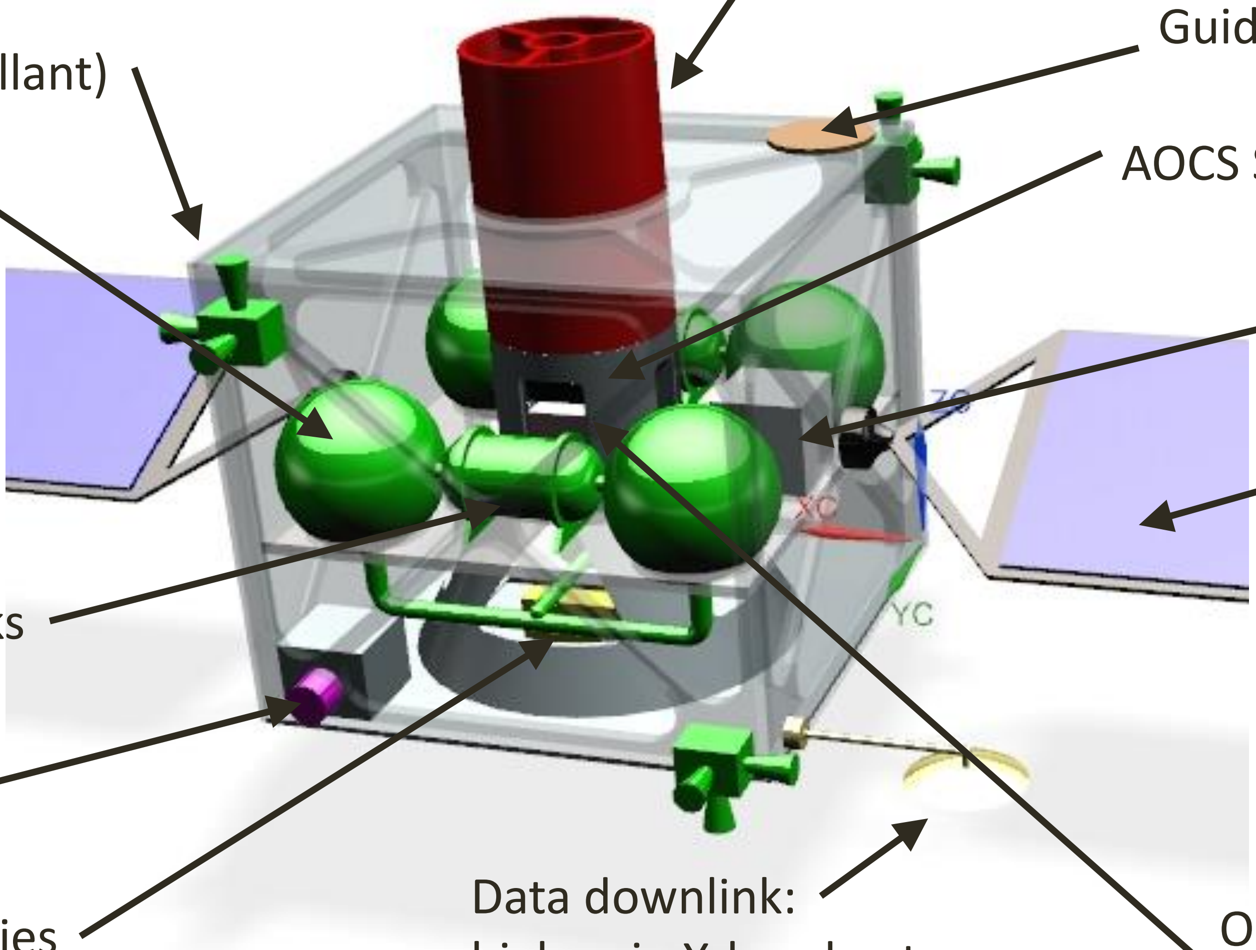
Ground Station
Gran Canarias

EOL controlled
deorbiting
(< 25 years)

Spacecraft

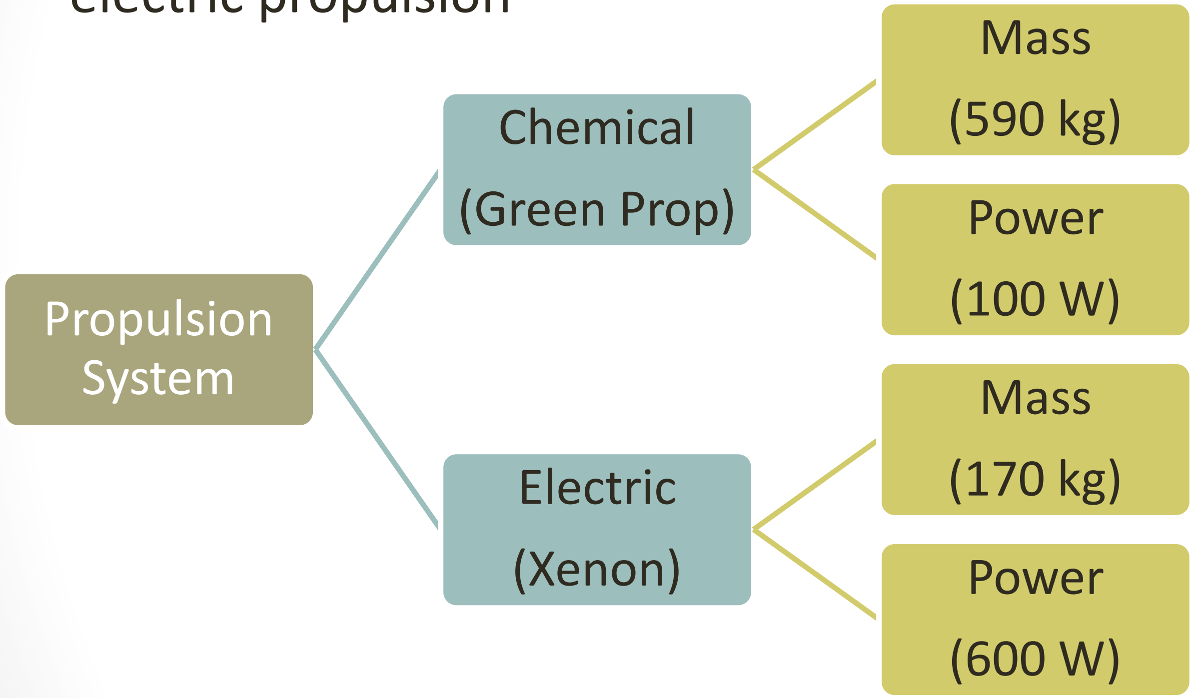


Spacecraft Subsystems



RCS System

- Propulsion system: tradeoff between chemical and electric propulsion



Delta V Budget (* 3 Years)	
Orbit corrections*	225 m/s
East-West stationkeeping*	18 m/s
North-South stationkeeping*	165 m/s
Survivability (incl. Ev. maneuvers)	200 m/s
Drag-makeup	200 m/s
Controlled reentry	150 m/s
Total delta V:	958 m/s

Amount of RCS Thrusters (Isp = 255 s): 12

RCS System

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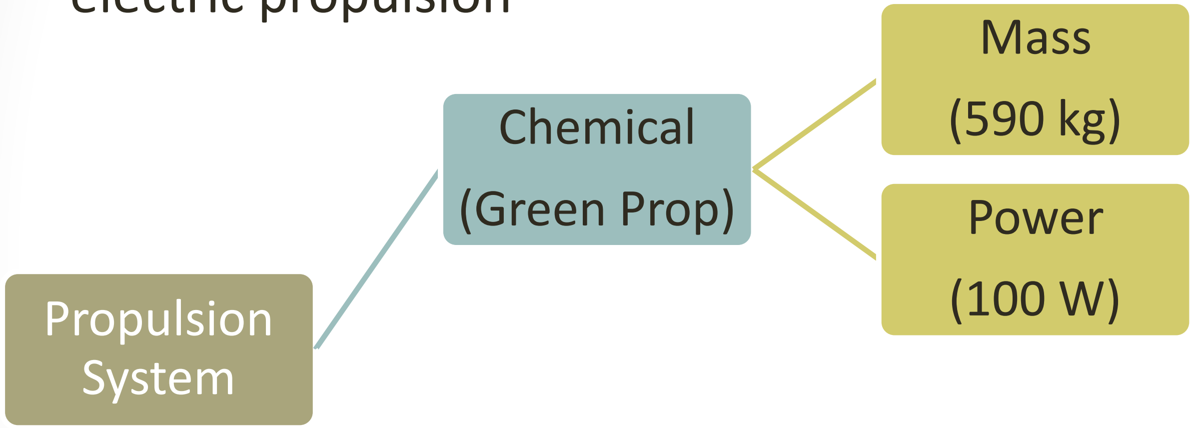

High performance chemical propulsion (green propellant: ammonium dinitramide, ADN) system has been selected

- Power limitation in eclipse
- Chemical propulsion suitable for the low Δv requirements

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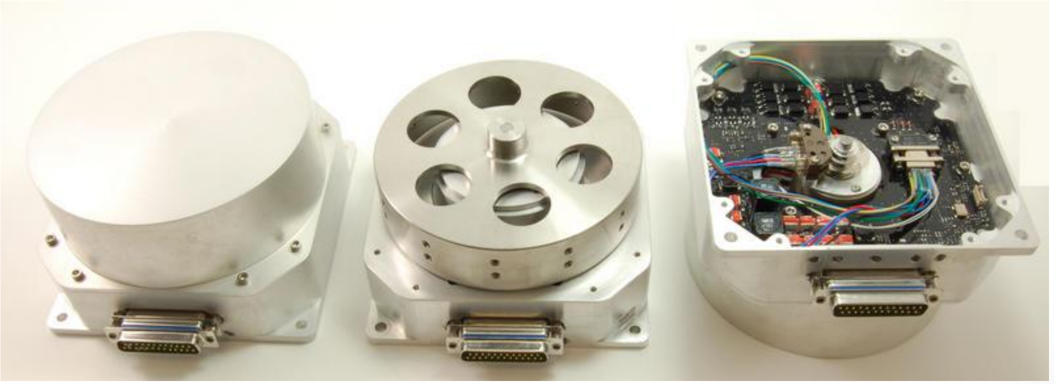
Attitude and Orbit Control System

- Requirement:
  - High pointing accuracy of 5 µradians required → see requirements
- Technical Solutions:
  - 3-Axis-stabilized satellite
  - Use of star trackers and circular laser gyroscopes for attitude determination
  - Use of guidance laser to improve accuracy
  - Actuator system similar to Hubble Space Telescope (reaction wheels)



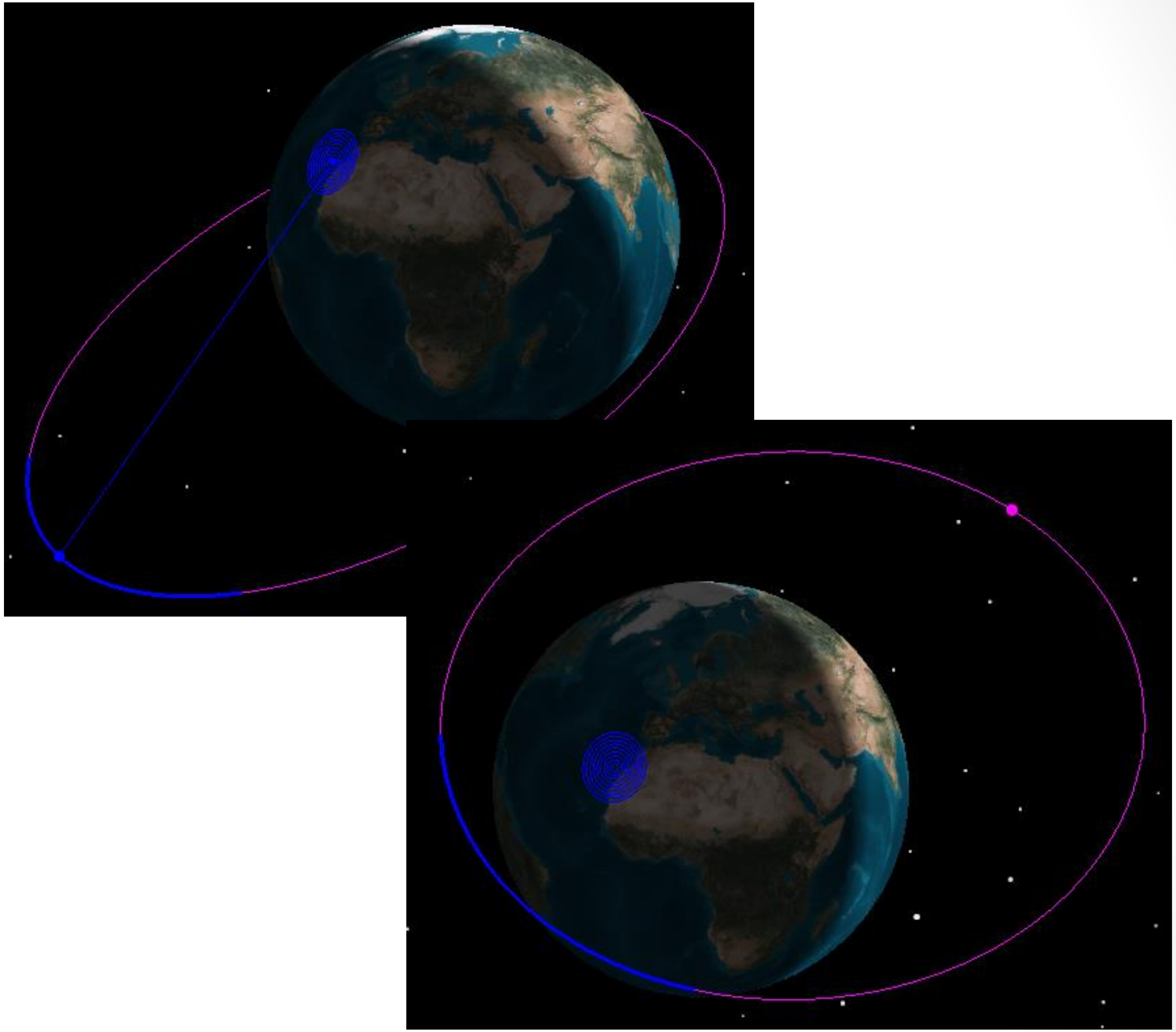
Mass and Power Budgets

Subsystem	Power consumption	Mass (w/o margin)	Mass (w/ margin)
Propulsion system	100.0 W	75.2 kg	94.0 kg
AOCS	100.0 W	63.0 kg	78.8 kg
TCS	200.0 W	53.6 kg	67.0 kg
OBDH	25.0 W	21.0 kg	26.3 kg
TT&C	25.0 W	35.0 kg	43.8 kg
Structure and mech.	50.0 W	168.8 kg	211.0 kg
EPS	100.0 W	165.0 kg	206.3 kg
Payload	300.0 W	150.0 kg	187.5 kg
Launch adapter		150.0 kg	150.0 kg
Satellite (dry mass)	800.0 W	881.6 kg	1064.5 kg
Propellant (ADN)		512.0 kg	640.0 kg
Satellite (wet mass)	800.0 W	1393.6 kg	1704.5 kg
Margin (+40%)	1120.0 W	1951.1 kg	2386.3 kg

- Electrical power generation:
  - approx. 1.12 kW @ EOL
  - Solar array area: 7 m^2
  - Solar array mass: 35 kg
- Required battery capacity and mass:
  - 1.9 kWh (65 kg)

Target Orbit

- Highly elliptical orbit
  - 500 km x 10000 km
  - i = 27.7° inclination
- Eclipse time at apogee:
  - ~60 minutes
- Eclipse time at perigee:
  - < 30 minutes
- Total eclipse time:
  - Approx. 4 hours/day
- Orbit period: 3.5 hours



Communication

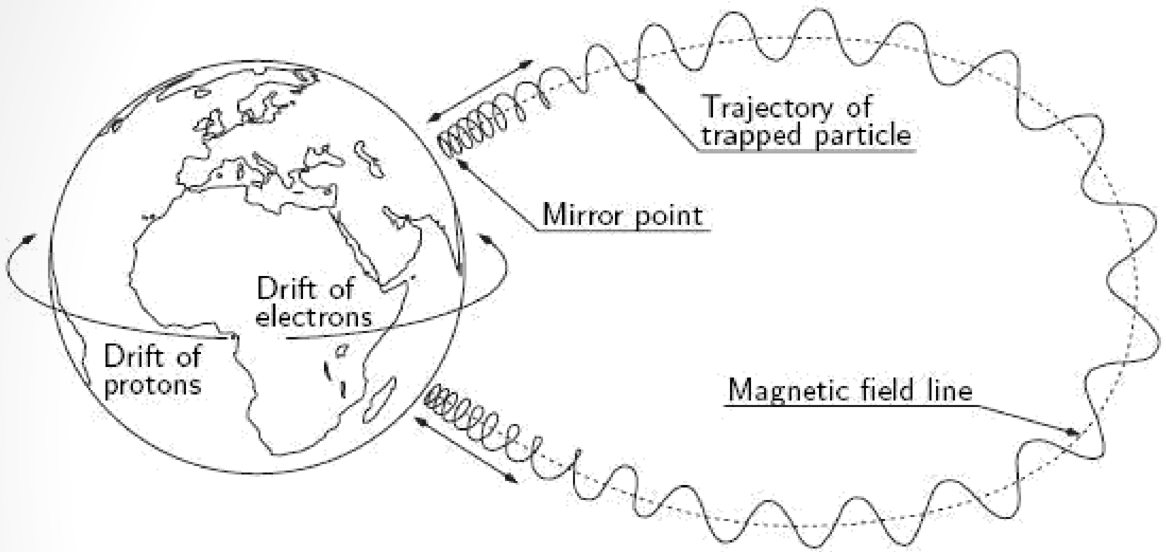
	S-Band (Apogee)	S-Band (Perigee)	X-Band (Perigee)
Distance	10 000 km	500 km	500 km
Power	5 W	5 W	20 W
Antenna diameter on SAT	13 cm	13 cm	13 cm
Dish diameter on GS	50 cm	50 cm	50 cm
Frequency	2 GHz	2 GHz	10 GHz
Transmission loss (LS+La)	-180.7 dB	-154.7dB	-168.6 dB
EIRP	12.6 dB	12.6 dB	32.6 dB
Rx G/T	-6.4 dB	-6.4 dB	7.5 dB
EB/EN	20.8 dB	46.8 dB	30.1 dB
Data rate	2 kbps	2 kbps	10 Mbps

Launcher and Orbit Injection

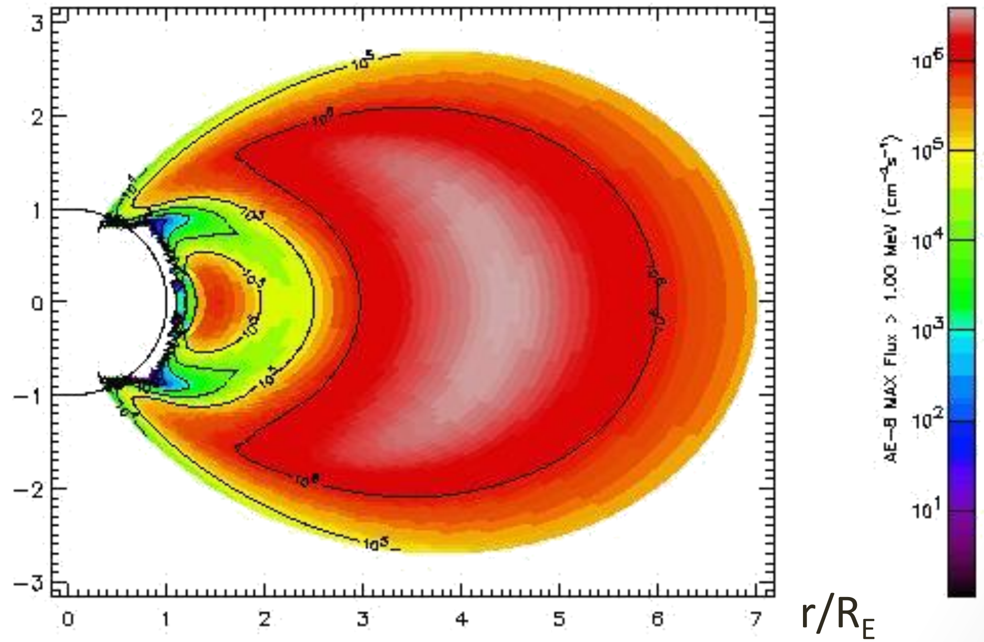
- Start from Kourou into a highly elliptical orbit (HEO)
- Total payload mass: < 2400 kg

- Launchers:
  - VEGA: 1963 kg to 200x1500 km (i=5.4 degree)
  - Soyuz: 3250 kilograms to GTO
  - Ariane 5-ECA: 10500 kg to GTO (tandem satellite launch)

Radiation Effects on the Spacecraft



Damage mostly due to trapped protons and electrons in van Allen radiation belts.

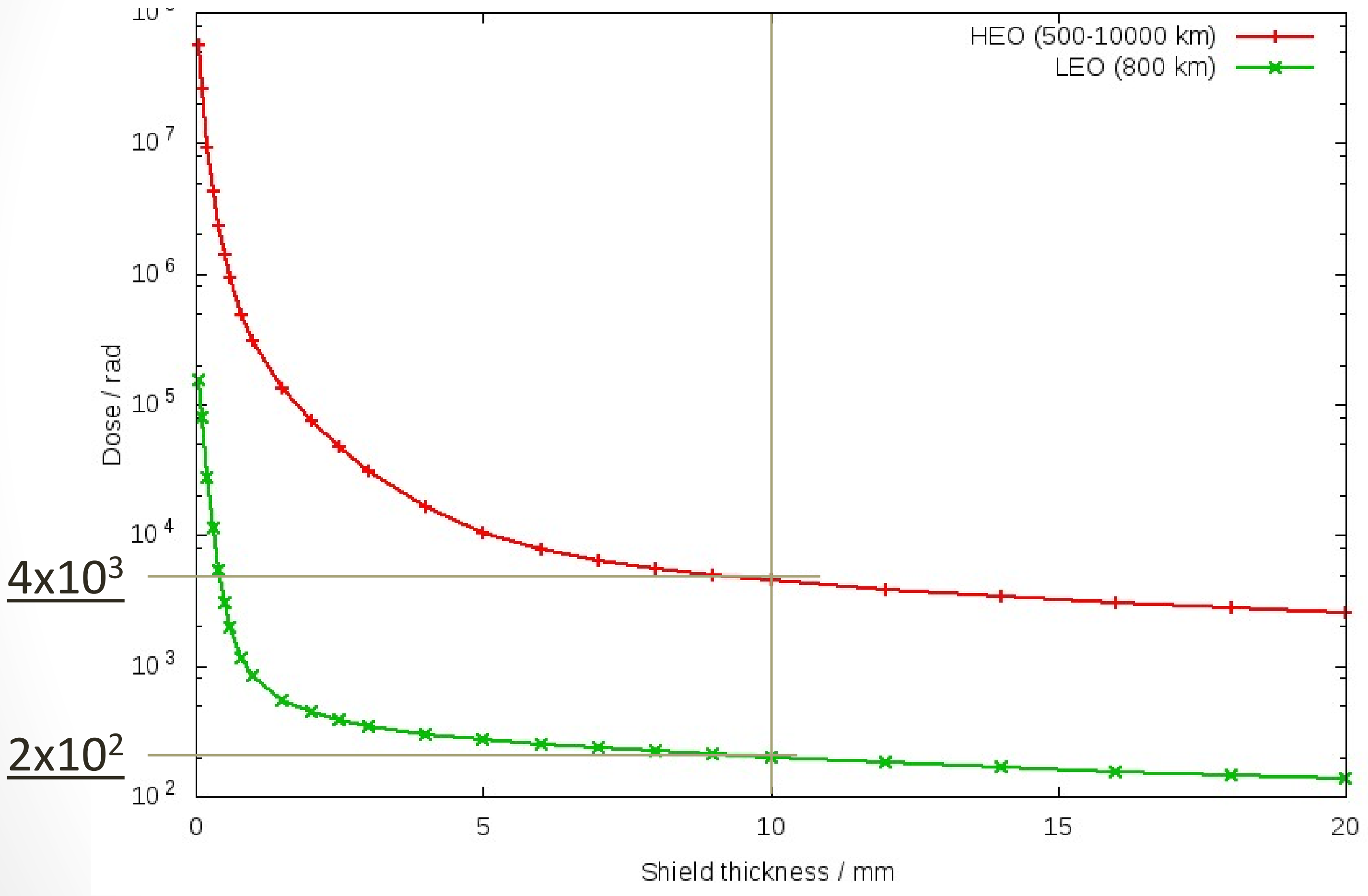


Problems:

- Changes in detector properties
- Surface damage
- False counts

Radiation Effects on the Spacecraft

Total dose in silicon after 1 year (shielding material: aluminum)



Total radiation dose for two types of orbit (HEO and LEO) computed using SPENVIS (SPace ENVironment Information System)

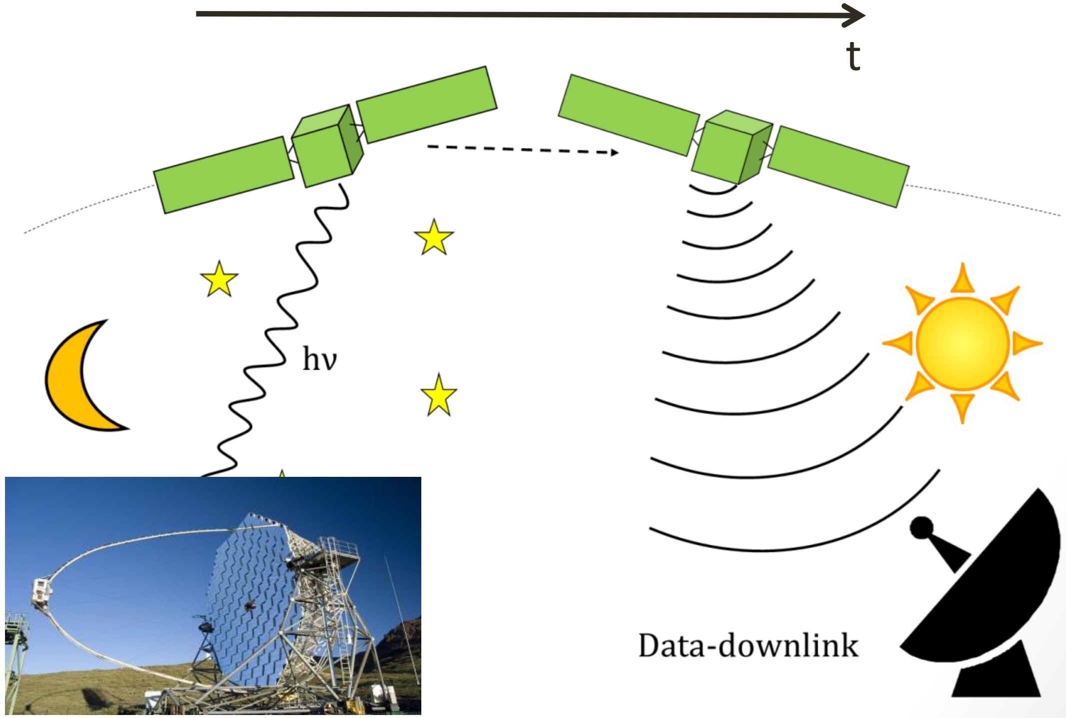
Calculated radiation dose:
10^4 rad/year

Countermeasures:

- Use of rad.-hardened components
- Use sufficient shielding on critical components (10 mm aluminum)
- Redundancies

Operations & Ground Segment

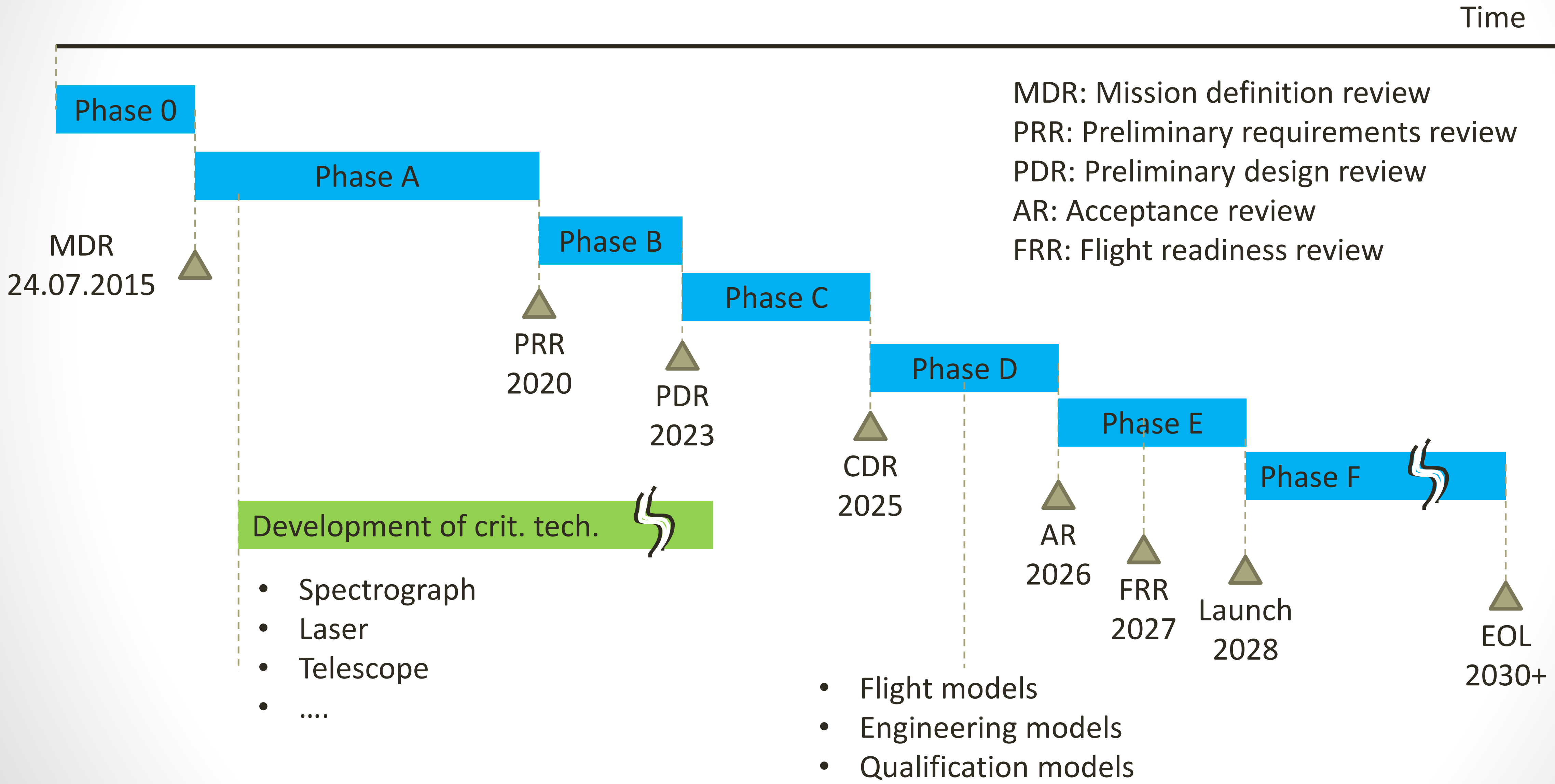
- Measurements performed during eclipse time (apogee and perigee)
- Data downlink during next ground station pass
- Ground segment: Two ESA ground stations
- End of life: controlled reentry of spacecraft (space debris mitigation)



Critical Technology (TRL Overview)

Technology	Readiness Level
Ground-based spectrometer	TRL 1
5-Newton RCS Thrusters (ADN, green propellant, 1-Newton ADN thruster is space qualified TRL 9)	TRL 5
Laser source	TRL 2
LISA telescope	TRL 5
Satellite single photon avalanche diode (SPAD)	TRL 3 – 4
Mach-Zehnder interferometer (satellite)	TRL 3 – 4

Development Schedule



Mission Development Cost

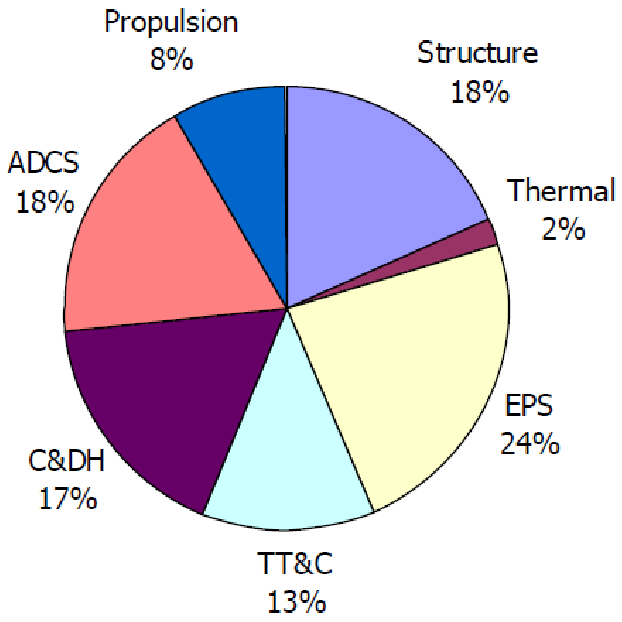
#	Item	Cost (M€)
1	Project Team	45
2	Industrial Cost	350
3	Mission Operations	50
4	Science Operations	40
5	Payload**	300
6	Launcher (Soyuz)	75
7	Contingency	75
	Total:	935

** Includes the Ground Station Equipment

The cost splitting would go as follows:

- 635 M€ from ESA
- 300 M€ from member states

Usually, the cost of the satellite‘s bus can be split as follows:



Development Risks

What?	Consequence	Probability	Severity	Overall Risk
Spectrograph technology not mature enough	Inability to accomplish science objective 3*	4	5	20
Entangled Photon Source (Laser)	Delay in the development schedule	3	3	9
Single Photon Avalanche Source (SAPD)	Delay in the development schedule	3	3	9
Interferometer	Delay in the development schedule	3	3	9

* Science objective SO1 and science objective SO2 can still be achieved

Risk Outcome	
Low	Significant
Moderate	High

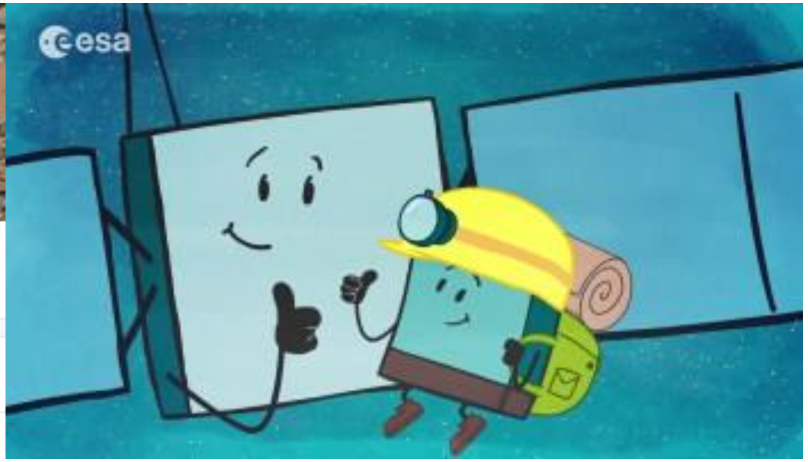
Mission Risks

What?	Consequence	Probability	Severity	Overall Risk
Solar Flares	Damage to critical components (optics & optoelectronics)	2	5	10
Continuity of Funding	Mission Delay	3	4	12
Personnel Unavailability	Mission Delay	3	4	12

Risk Outcome	
Low	Significant
Moderate	High

Outreach Program

- Call for name proposals from the public (e.g. students)
- Use social media to communicate on a regular basis (e.g. photos of the spacecraft)
- Inspire young people to participate in a real space mission (e.g. school programs)
- Examples: NASA's Curiosity and ESA's Rosetta mission



Summary

- The purpose of the GREEN mission is to experimentally test systems at the intersection of the domains of quantum mechanics and general relativity. An insight into the gravitational redshift of entangled photons might either suggest revisions of quantum mechanics or general relativity or restrict predictions of future theories.
- An entangled pair of photons will be established that is separated by a gravitational potential on the order of 10^7 m^2/s^2 provided by a highly elliptical orbit of a satellite around the earth. Bell tests will be performed to determine the correlation of the photons and a frequency measurement done on earth will determine the gravitational redshift.
- Expected launch: Soyuz-Fregat from Kourou on 19/07/2028. The total mass and power with a 40% margin will be approx. 2386 kg and 1120 W EOL, respectively.

Thank you for your attention!

Backup

De-scoping Option

- No spectrometer - the Bell can still be performed → Science objectives SO1 and SO2 (i.e. test over astronomical distances and a significant gravitational potential)
- Smaller receiver telescope - would increase expected measurement time inversely proportional to area of telescope