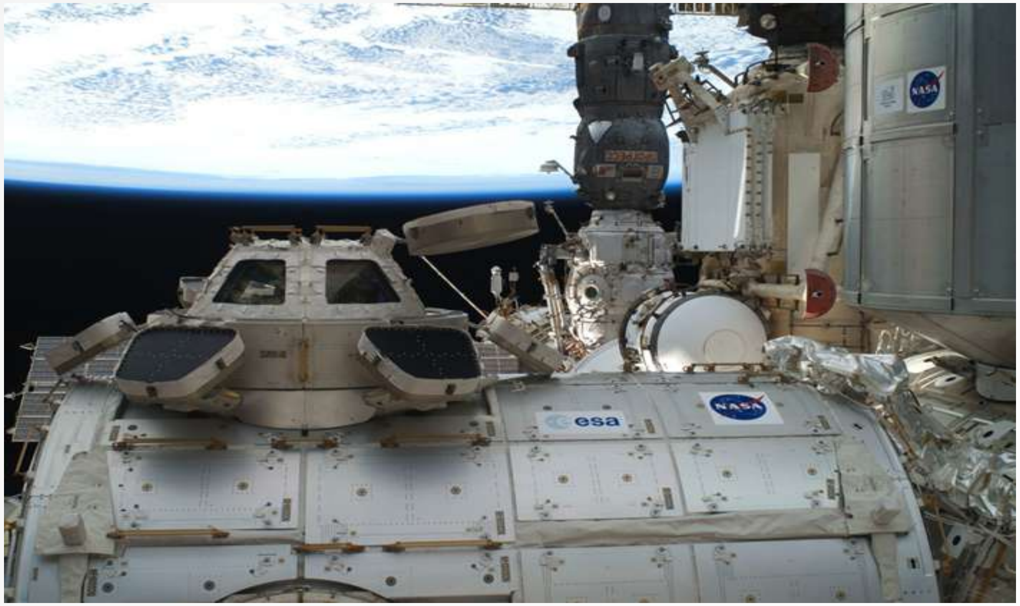
Space-QUEST: Feasibility and Implementation

<u>Siddarth K Joshi</u>, Rupert Ursin, Timothy Ralph, Jacques Pienaar, Gerard Milburn, Eleni Diamanti, Valerio Pruneri, Hugo Zbinden, Giuseppe Bianco, Paolo Villoresi, Giuseppe Vallone, John Rarity and other members of the ESA topical team



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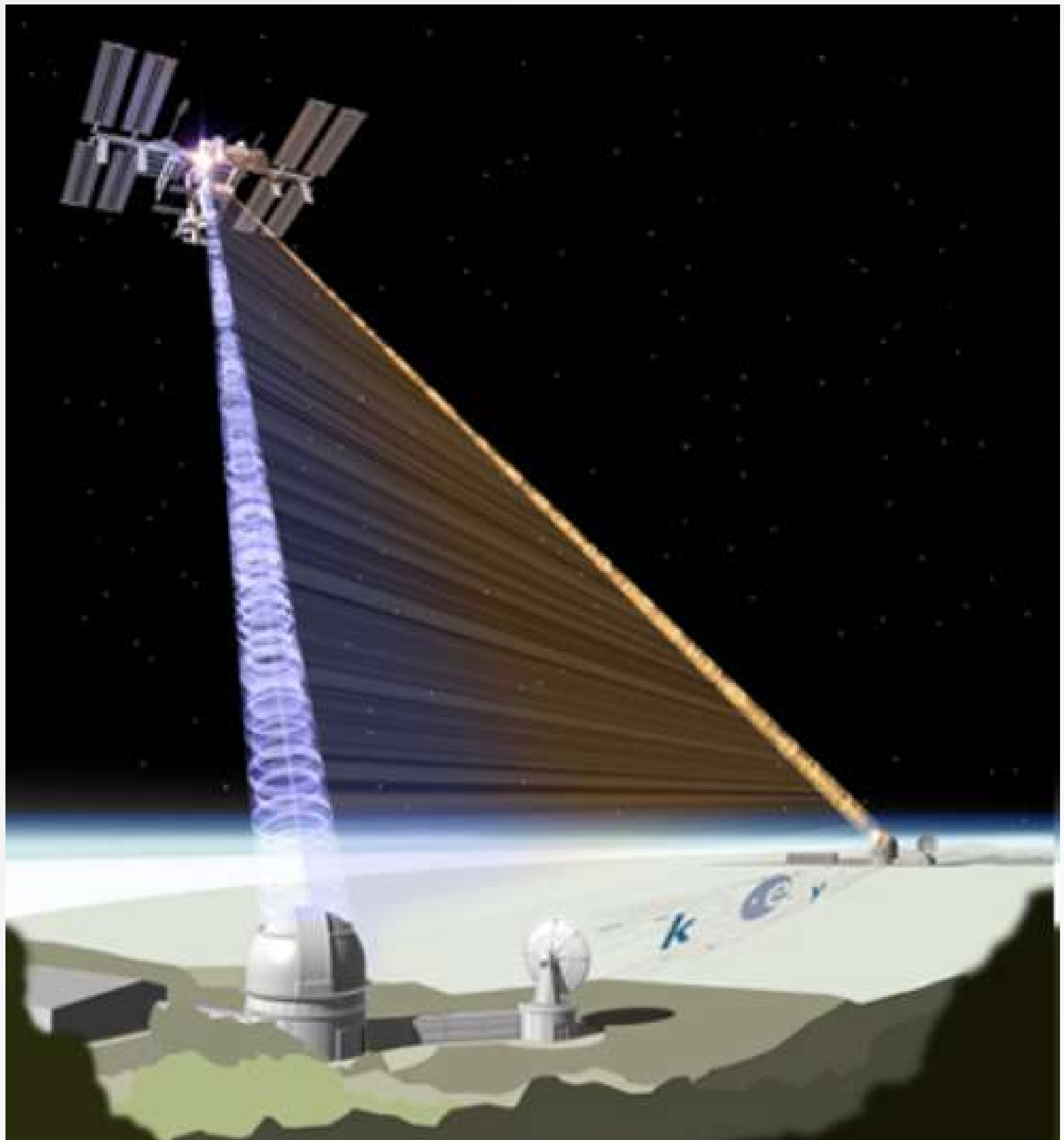
VCQ Vienna Center for Quantum Science and Technology

ÖAW AUSTRIAN ACADEMY OF SCIENCES

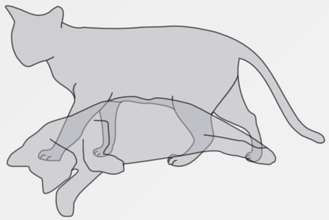
FWF Der Wissenschaftsfonds.

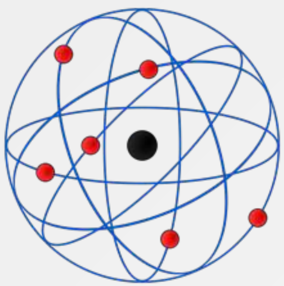
FFG

Background

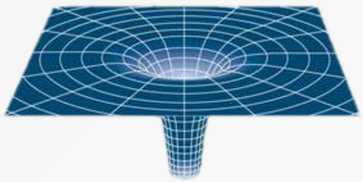


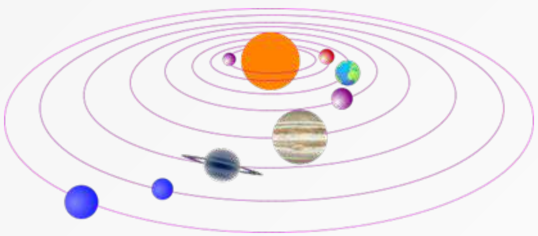
Introduction





Vs





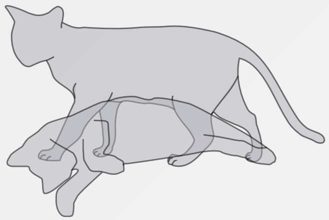
Relativistic Quantum mechanics:

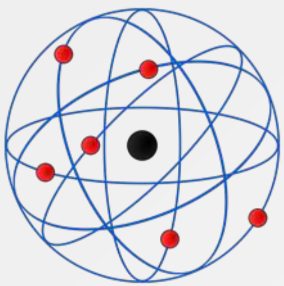
Approximation to a fully self-consistent theory.

enigmass.in2p3.fr/
math-frolic.blogspot.co.at/
www.i2clipart.com/

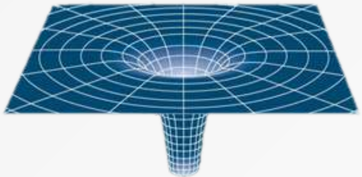
www.tenovuscancercare.org.uk/schools/
upload.wikimedia.org

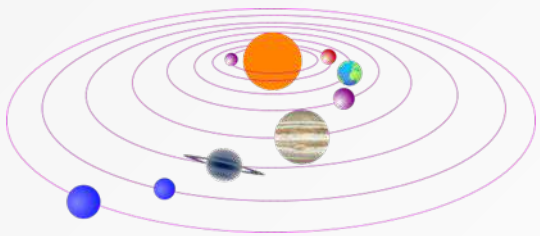
Introduction





Vs

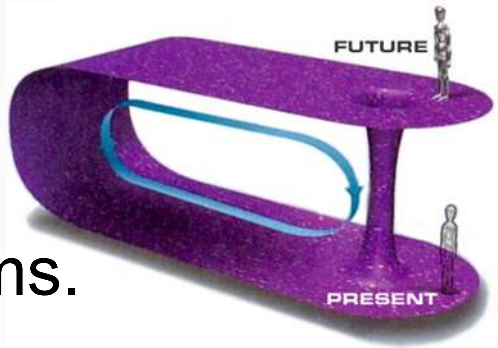




~~Relativistic Quantum mechanics:~~

The Deutsch model:

- Perfect approximation of Q.M. in <u>flat</u> space-time.
- Posits *"Closed Time-like Curves"*.
- Non-linear Q.M. in curved space time



Some effects seen <u>only</u> by entangled systems.

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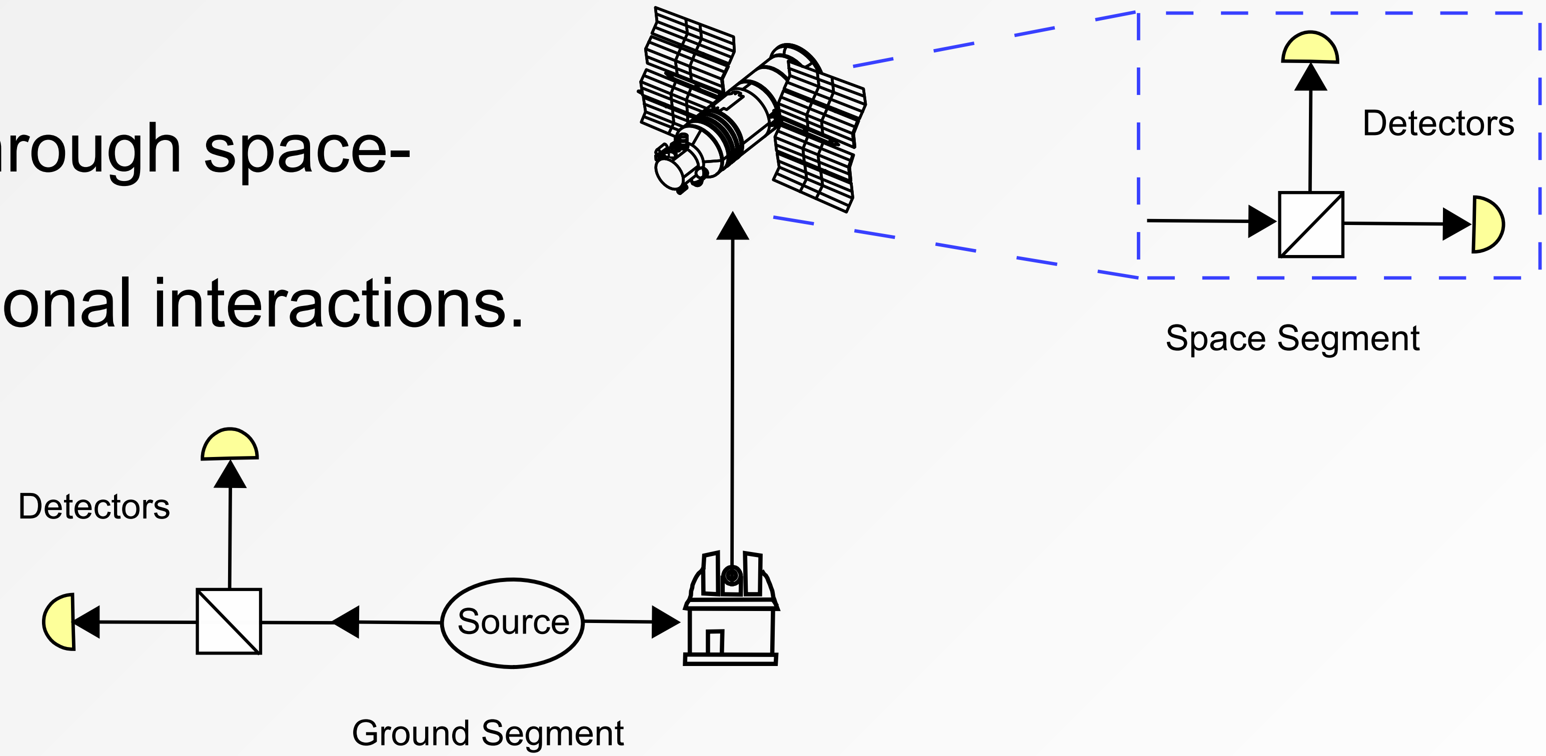
Gravitational Decoherence

Consider a Time-energy entangled system (photon pairs)

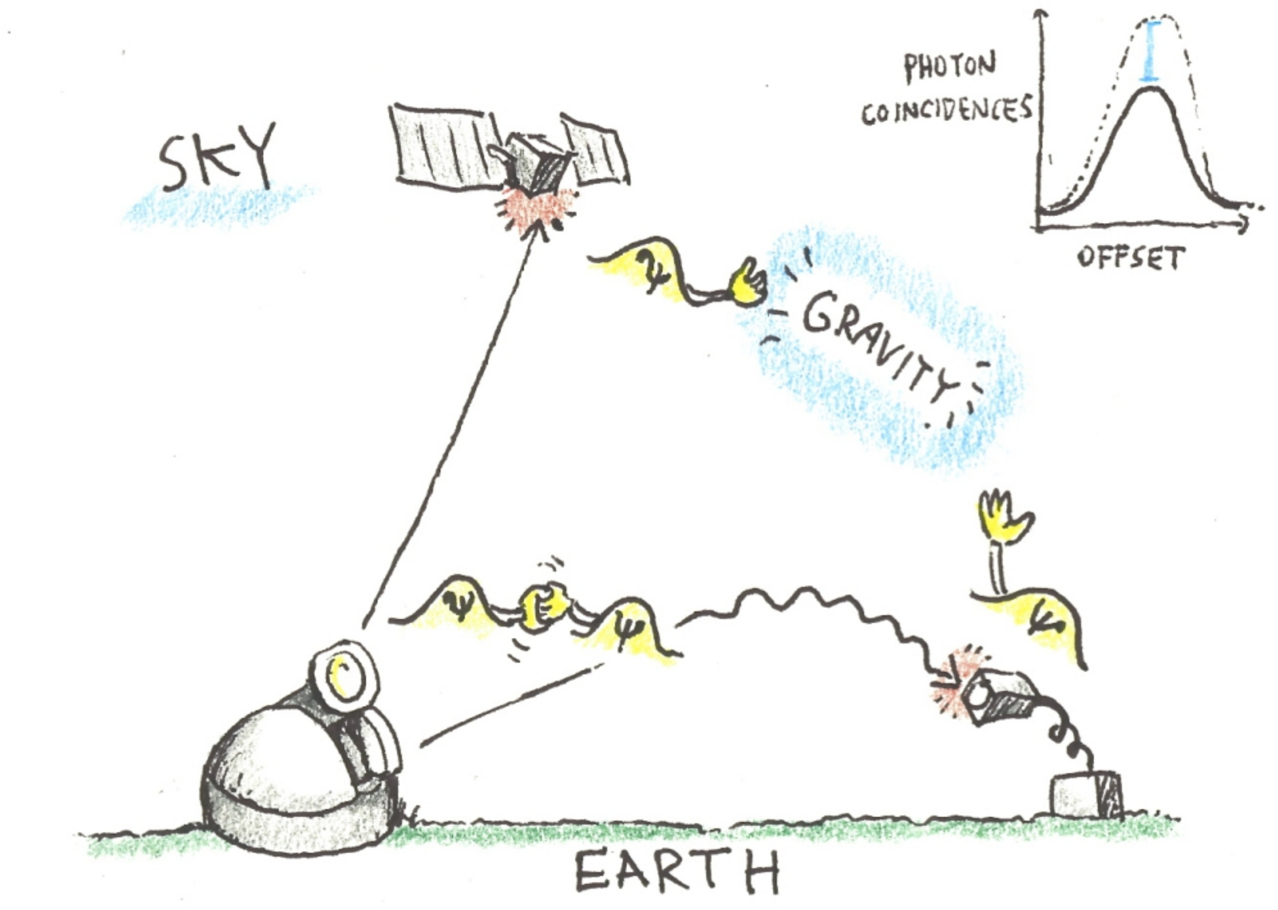
Different paths through space-time.
Different gravitational interactions.

Reduced time correlations.

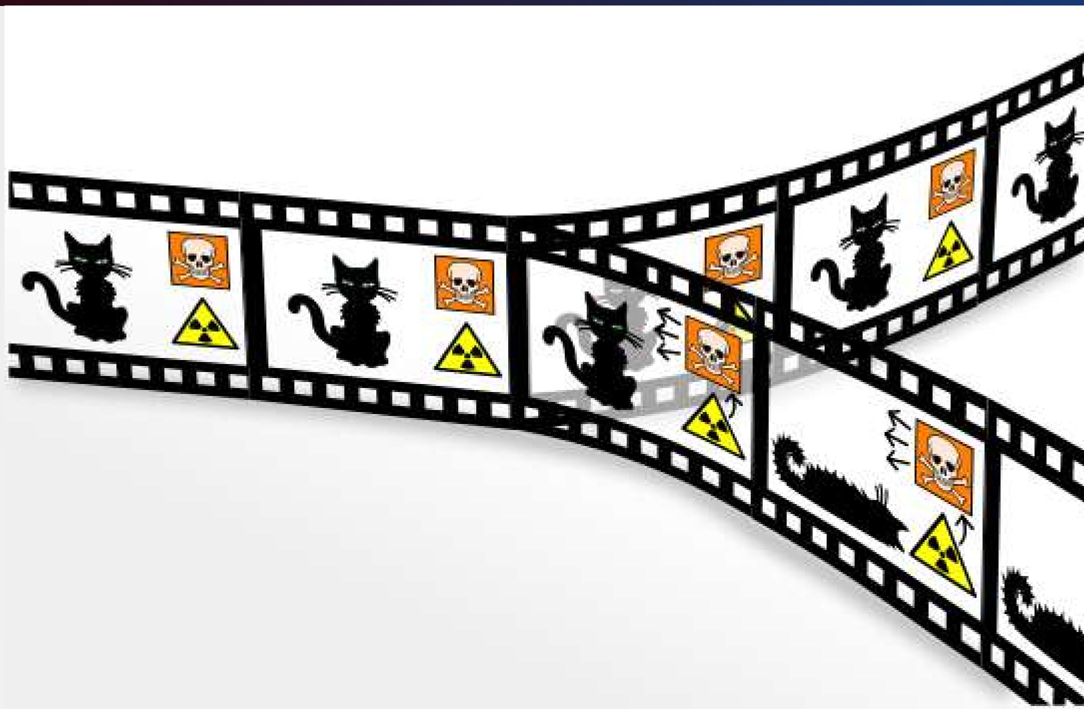


Ralph, T. C. & Pienaar, J. New J. Phys. 16, 085008 (2014).

Alternative Interpretations



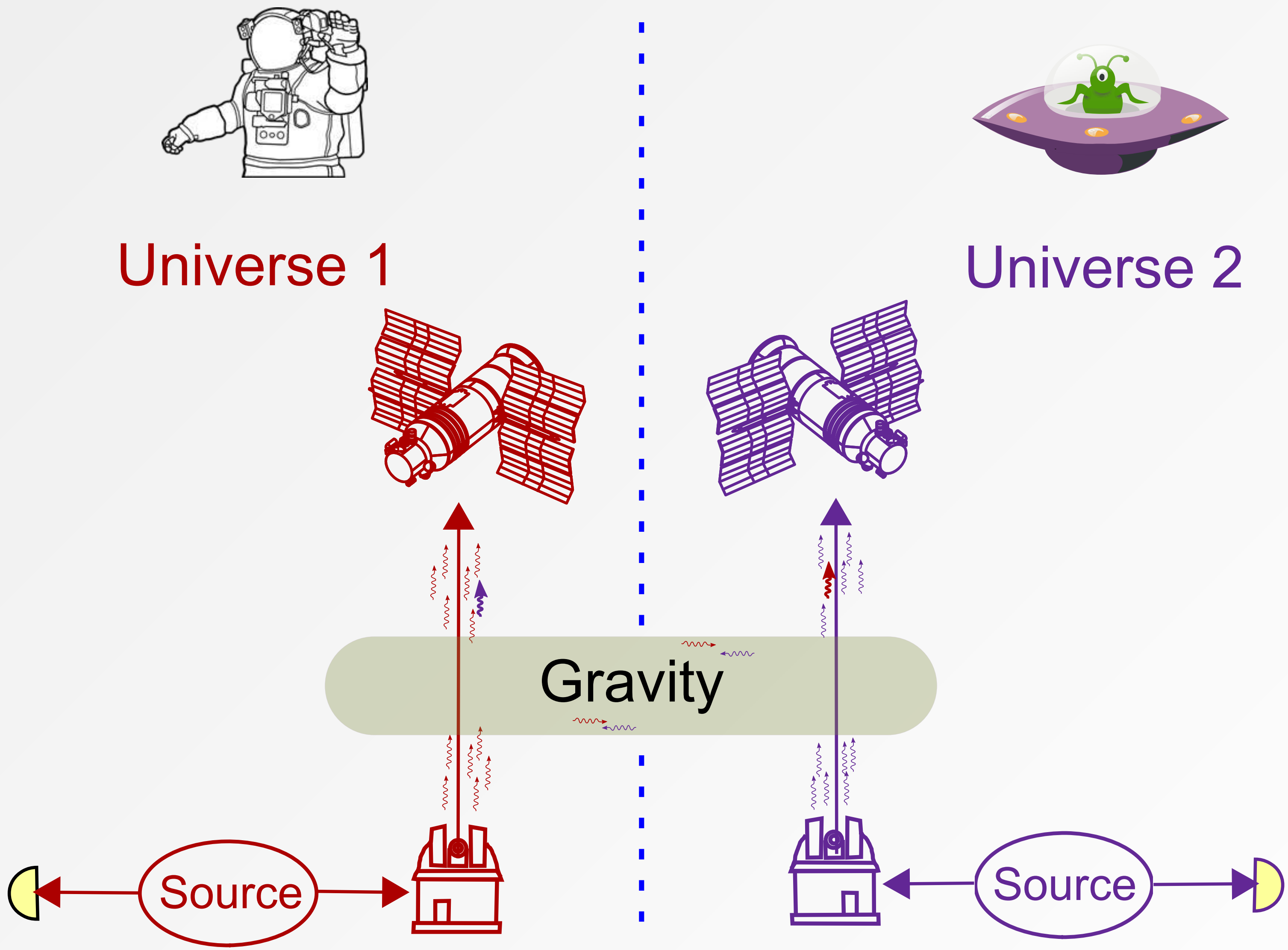
Alternative Interpretations



Multiple Universes

Many worlds

Alternative Interpretations

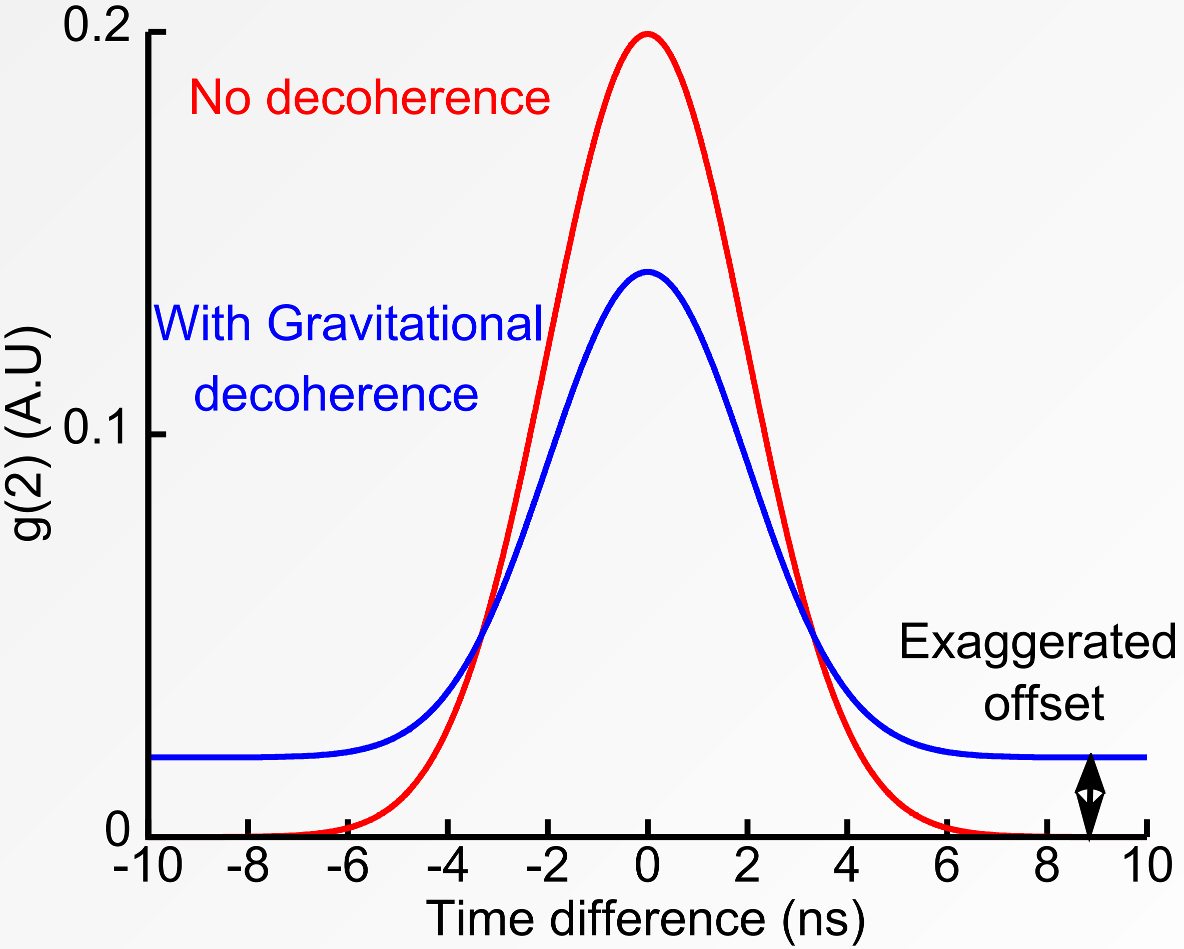


The effect

$$\eta = \frac{p}{\sqrt{s_1 s_2}}$$

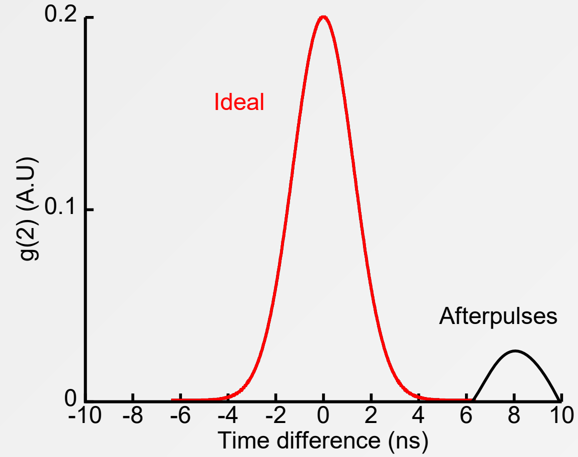
Decrease in Heralding efficiency η given by:

$$\eta_{new} = D_f \,.\, \eta_{old}$$

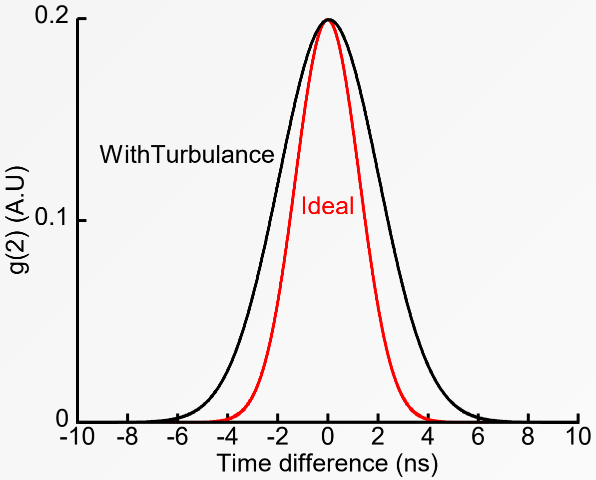


Not the only effect

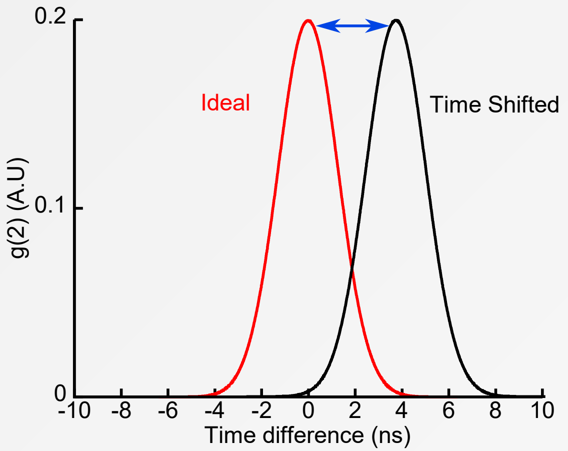
Correlation noise:



Turbulence

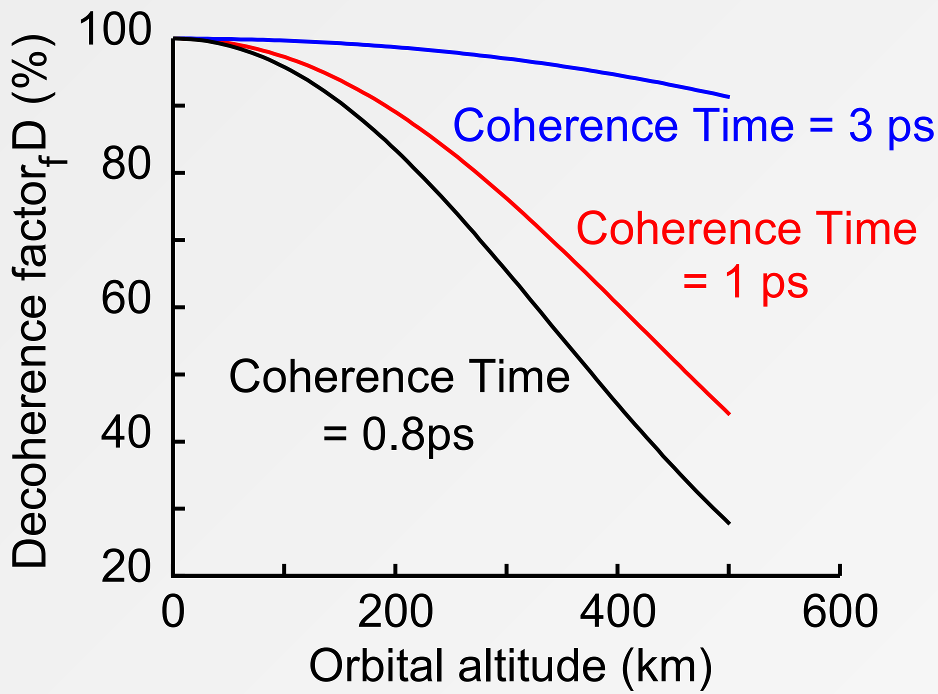


Time shifted

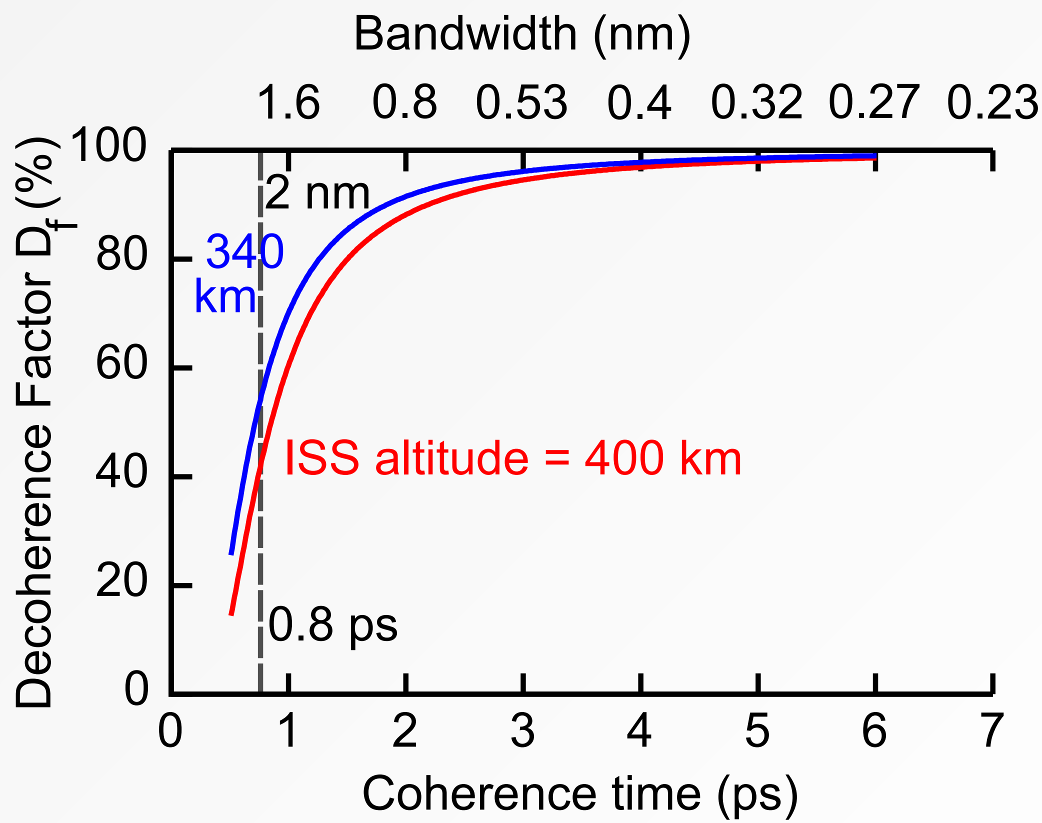


Doppler shift $\approx$ 0.02nm

The effect



Decoherence factor D_f (%)
100
80
60
40
20
0
200
400
600
Orbital altitude (km)
Coherence Time = 3 ps
Coherence Time = 1 ps
Coherence Time = 0.8ps



Bandwidth (nm)
1.6 0.8 0.53 0.4 0.32 0.27 0.23
Decoherence Factor D_f (%)
100
80
60
40
20
0
2 nm
340 km
ISS altitude = 400 km
0.8 ps
0 1 2 3 4 5 6 7
Coherence time (ps)

Measuring the Effect

Gravitational decoherence is:

Strongest for time-energy entanglement.

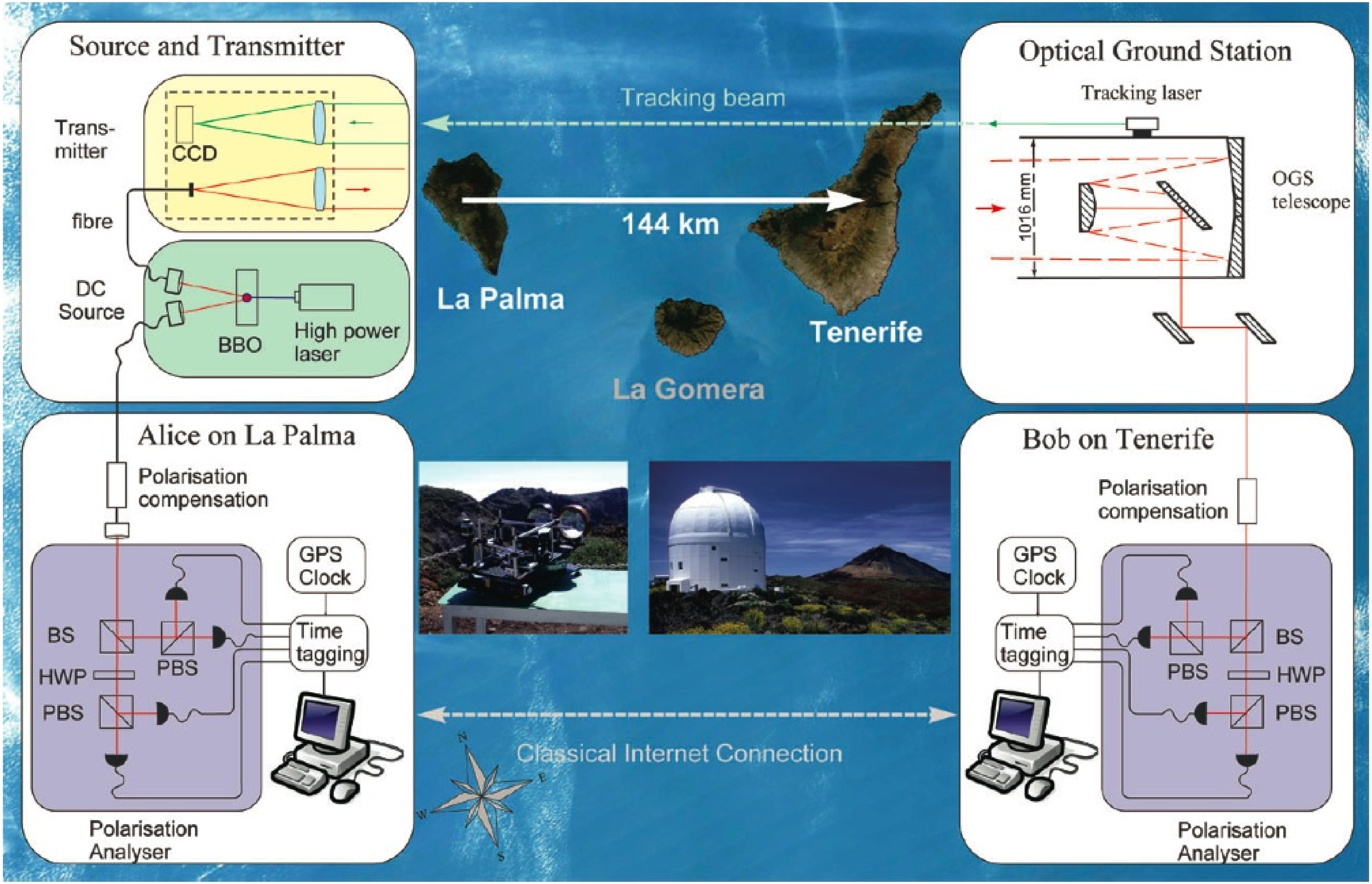
Weakest for polarization entanglement (≈ 10^{-8} smaller).

Polarization correlations → QKD

Time correlations → Detect gravitational decoherence

Most likely: Null result

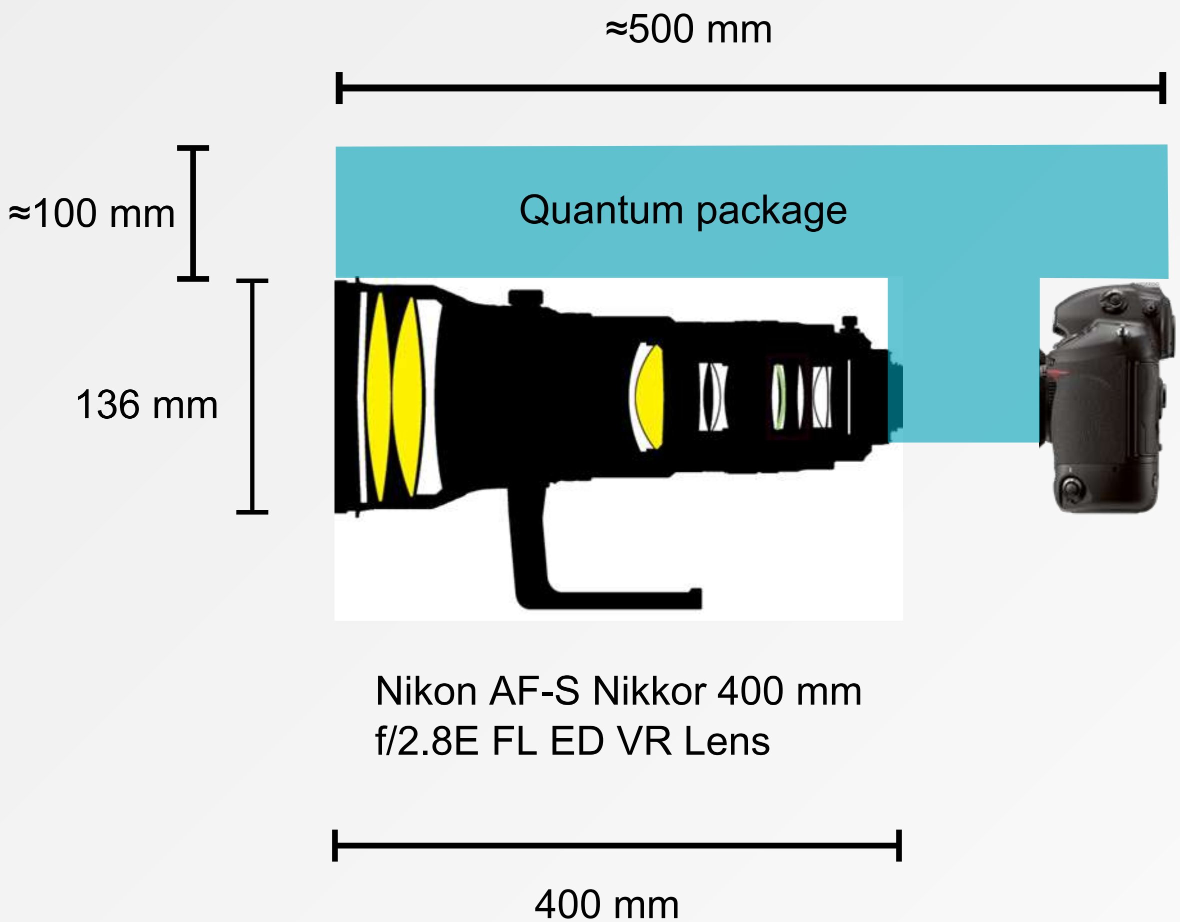
Proof of principle



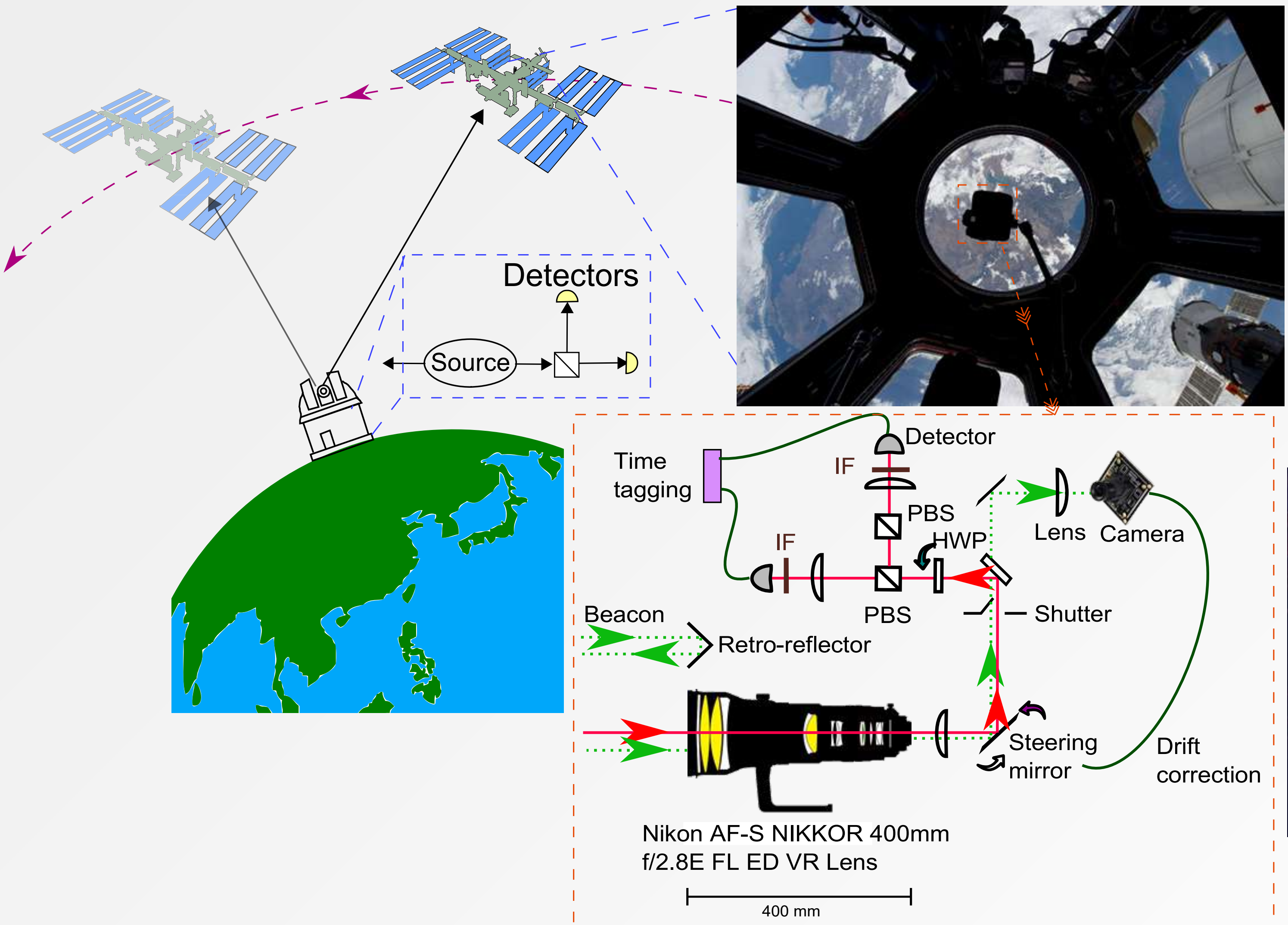
Nature physics 3.7: 481-486 (2007)

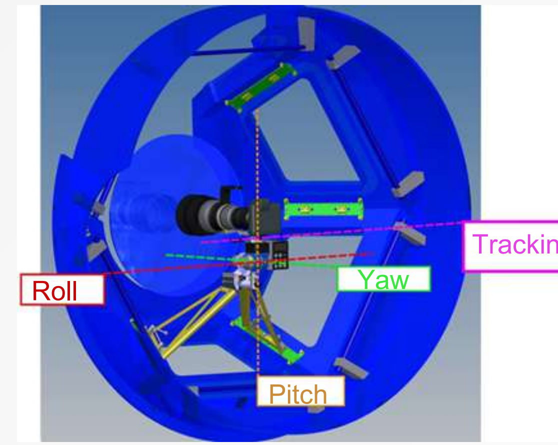
Pay load constraints

As small and <u>light</u> as possible...



Instrumentation





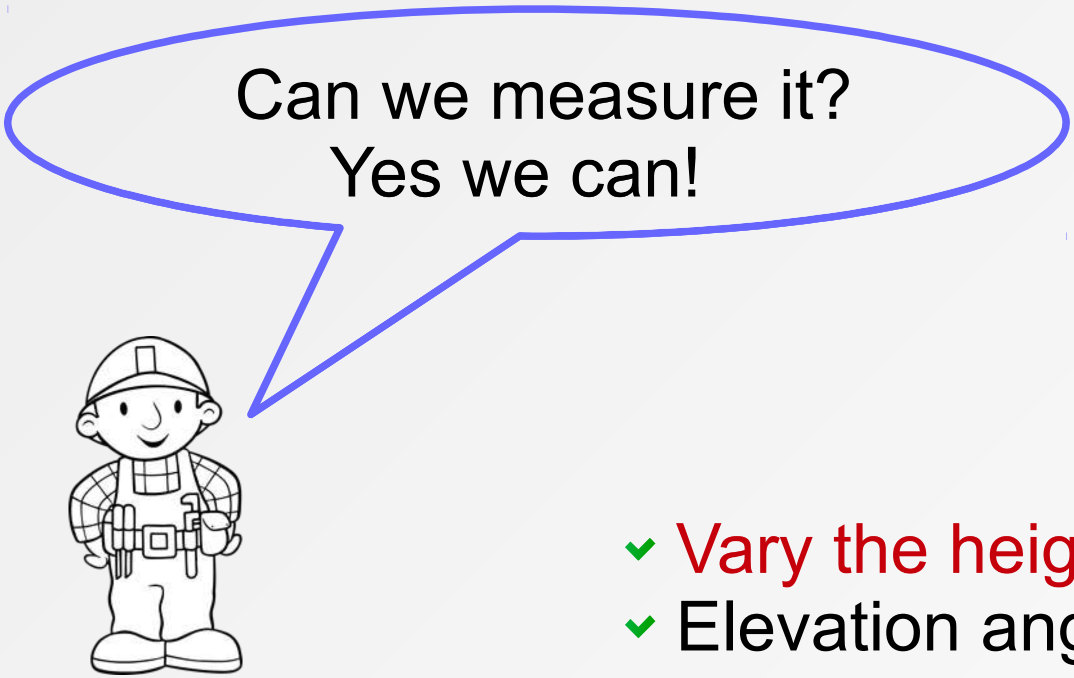
www.e-geos.it

www.nasa.gov

But…

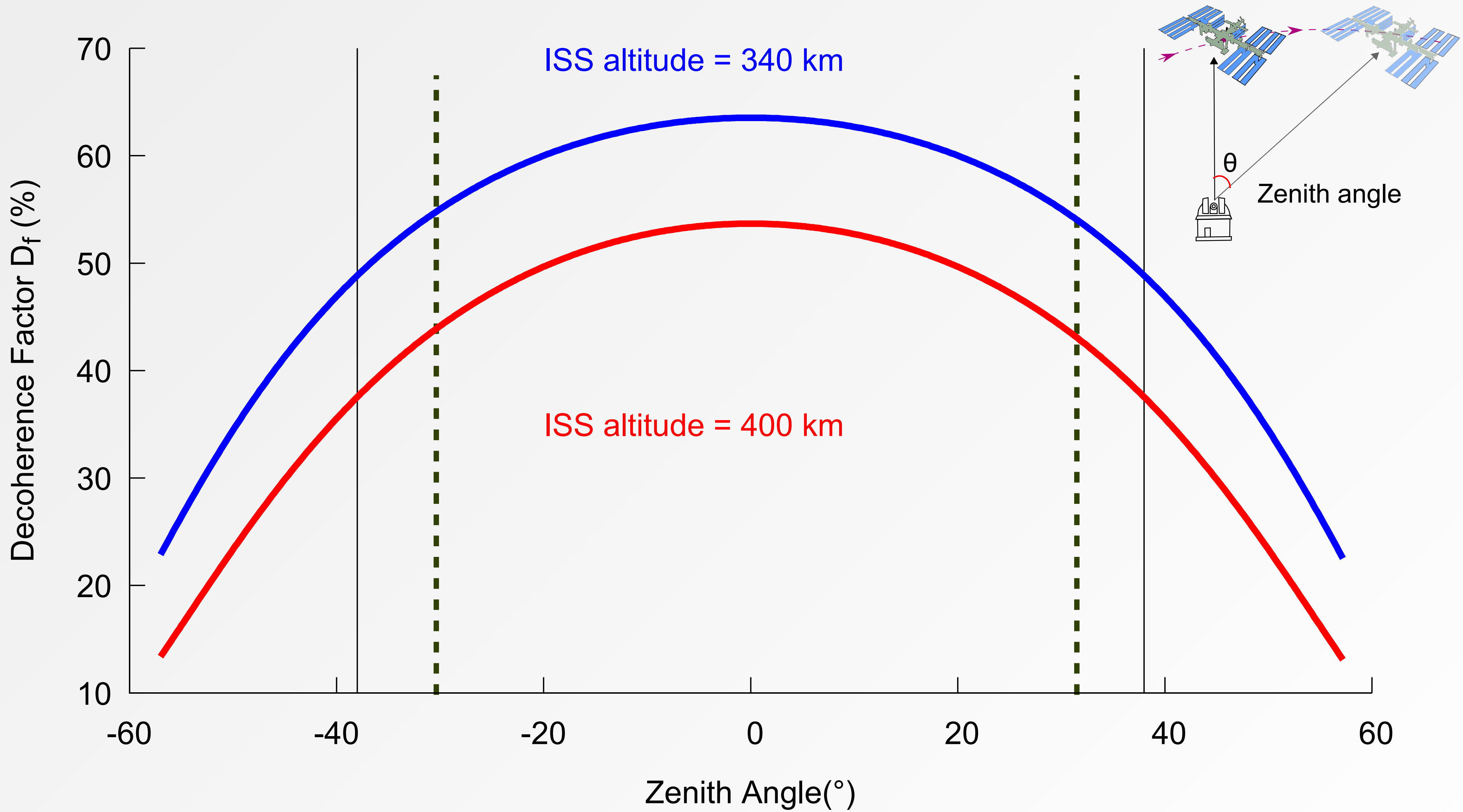

WORFから撮影する宇宙飛行士
軌道上でのWORFとWORFラック
Destiny構体壁（Nadir側）に
設けられたWORF用穴。

Can we measure it?

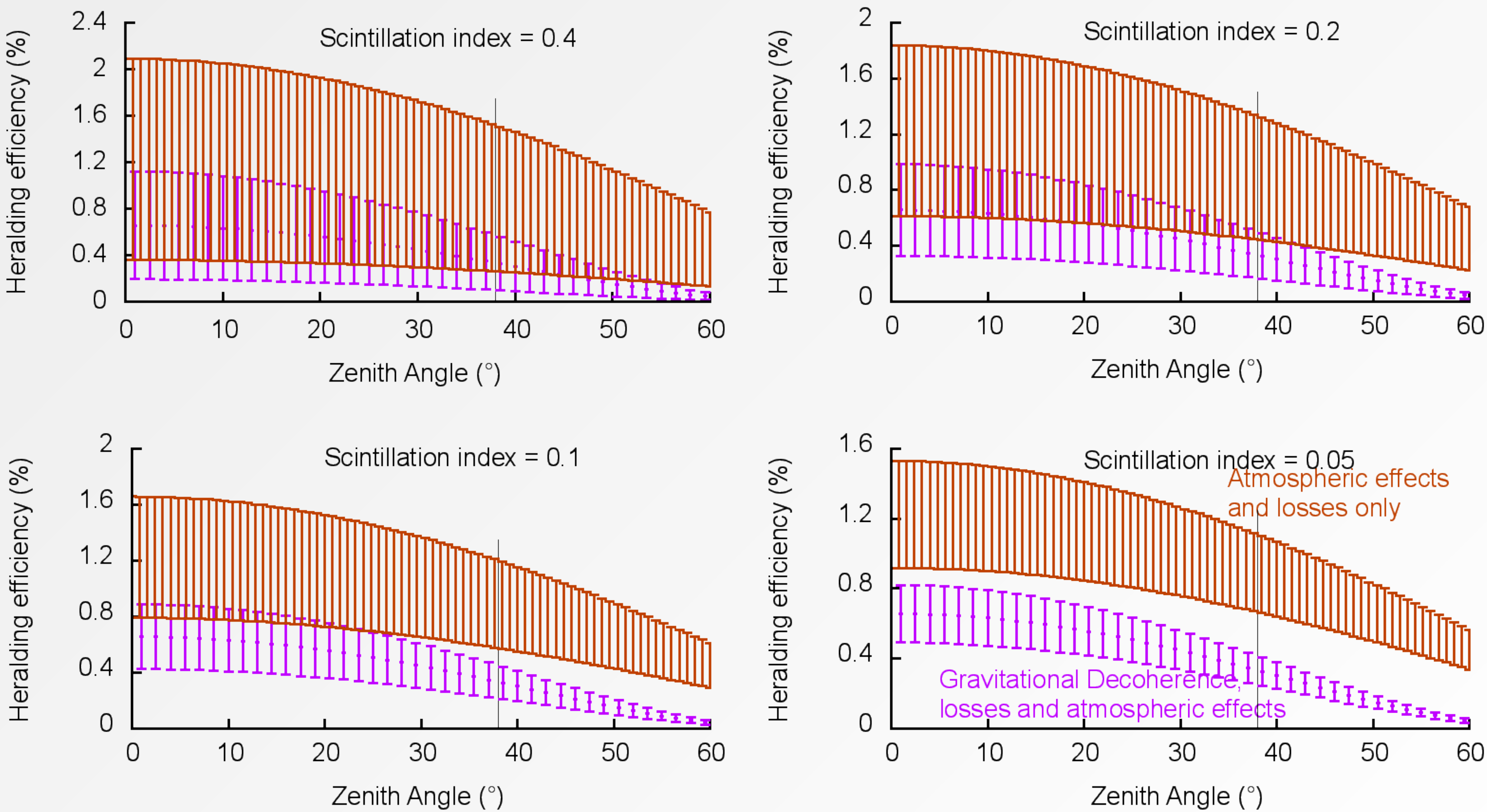


- Vary the height of the ISS
- Elevation angle dependence
- Entangled Vs classical
- Coherence time dependence

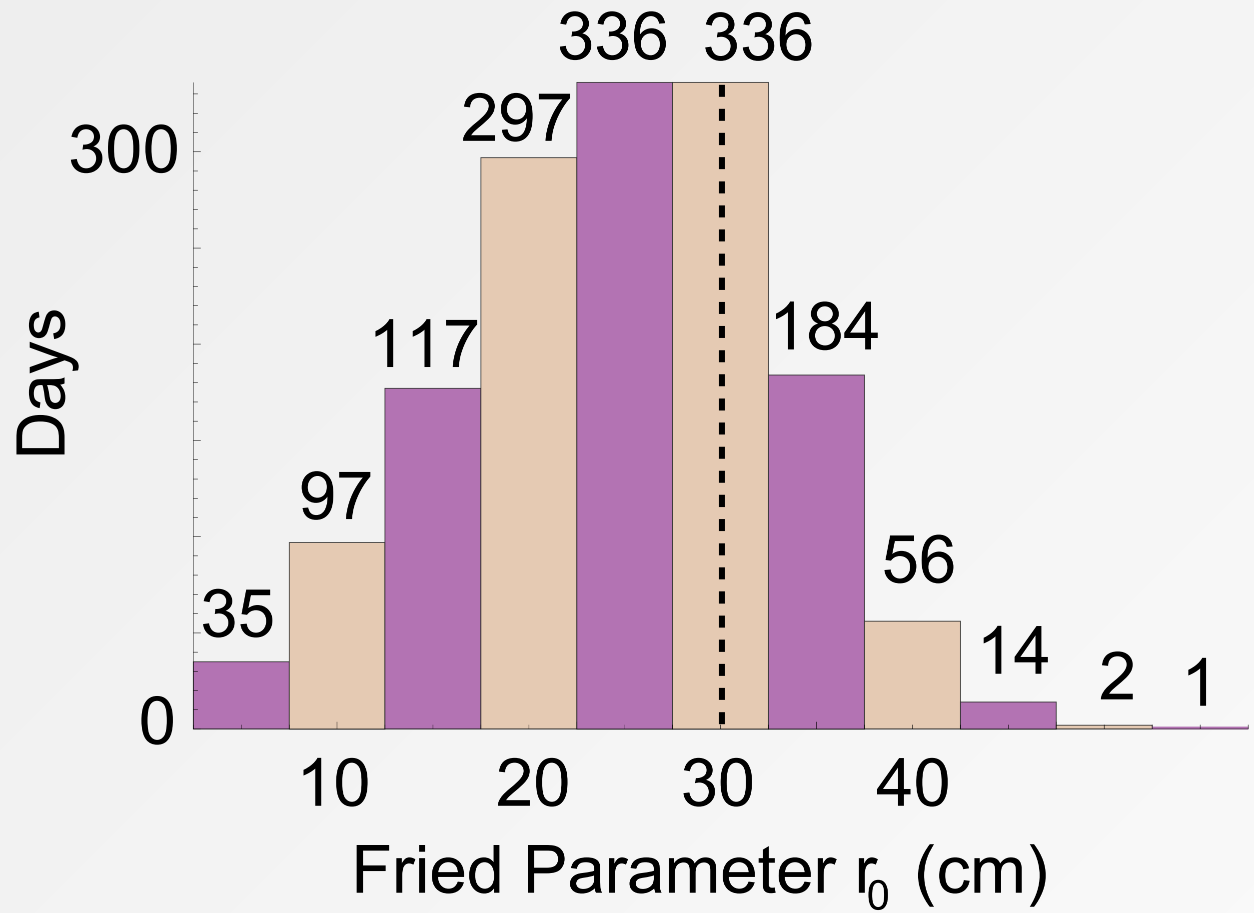
Motion of the ISS



Wait for a clear night



Turbulence



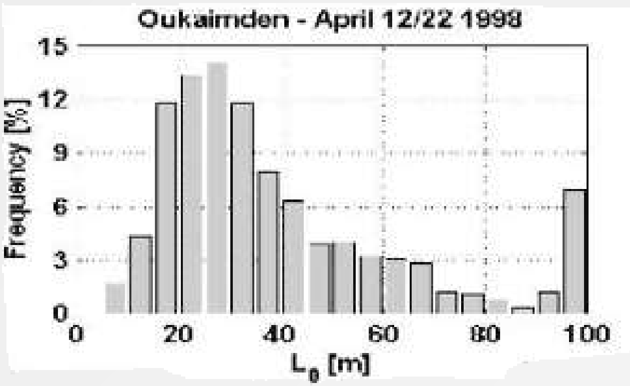
Fried Parameter for the OGS at Tenerife (4 years)

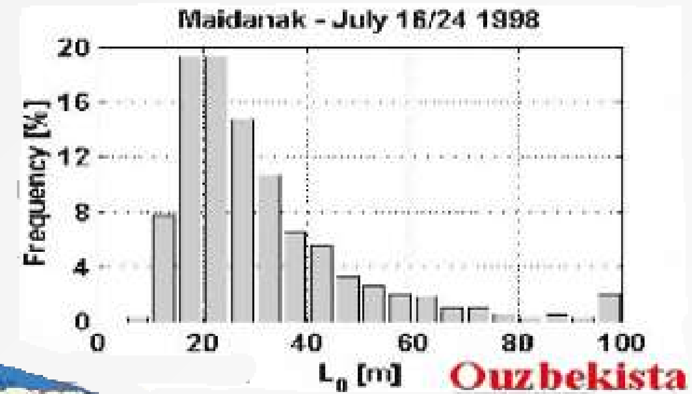
$r_0 \approx 28\,\mathrm{cm}$

Scintillation index

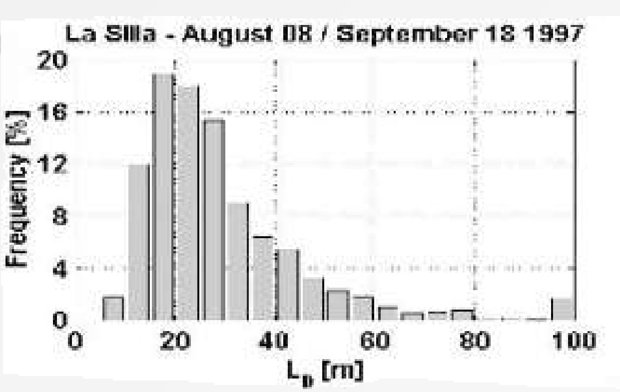
$s_i = 0.05$

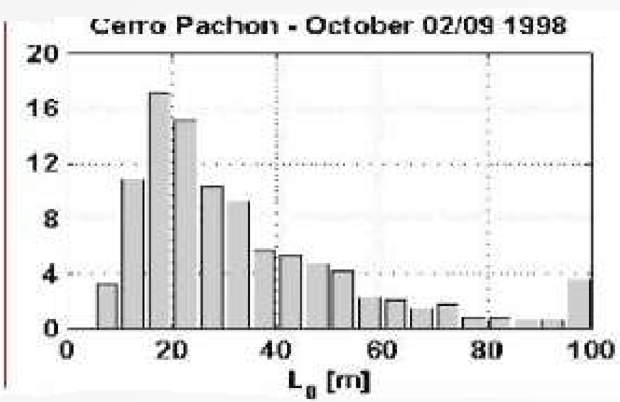
Turbulence

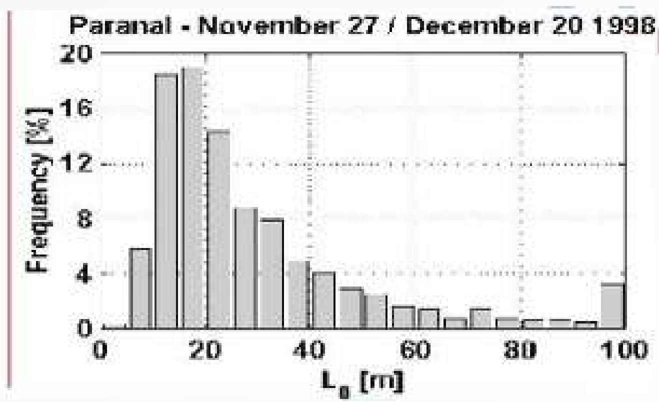

Oukaimden - April 12/22 1998
Frequency [%]
L_0 [m]


Maidanak - July 16/24 1998
Frequency [%]
L_0 [m]
Ouzbekista


North America
Europe
Russia
ASIA
China
Middle East
Africa
South America
Australia/ Oceania
Antarctica


La Silla - August 08 / September 18 1997
Frequency [%]
L_0 [m]

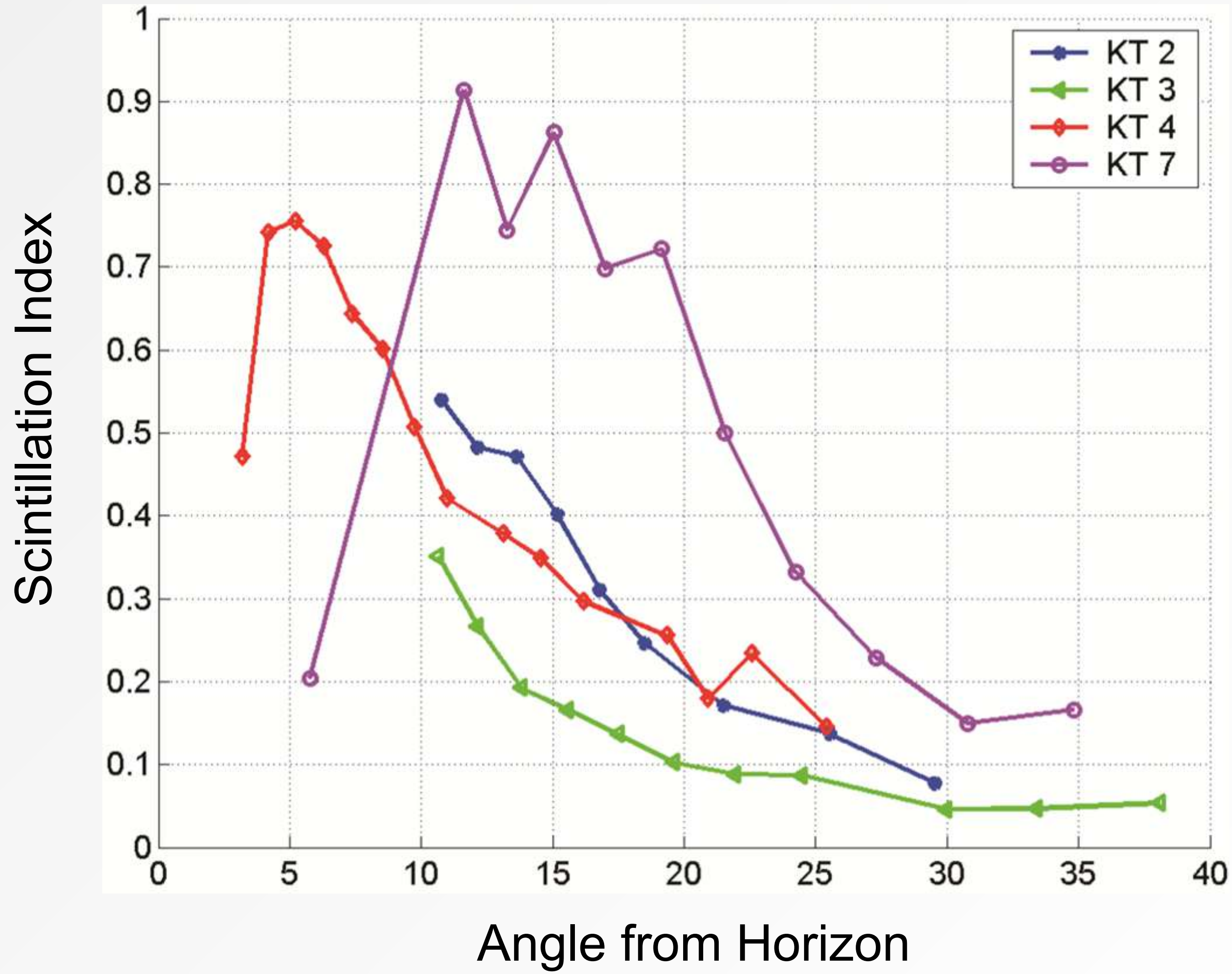

Cerro Pachon - October 02/09 1998
L_0 [m]


Paranal - November 27 / December 20 1998
Frequency [%]
L_0 [m]

Atmospheric Scintillation

OICETS with 2 uplink transmitters:

Scintillation Index = 0.05

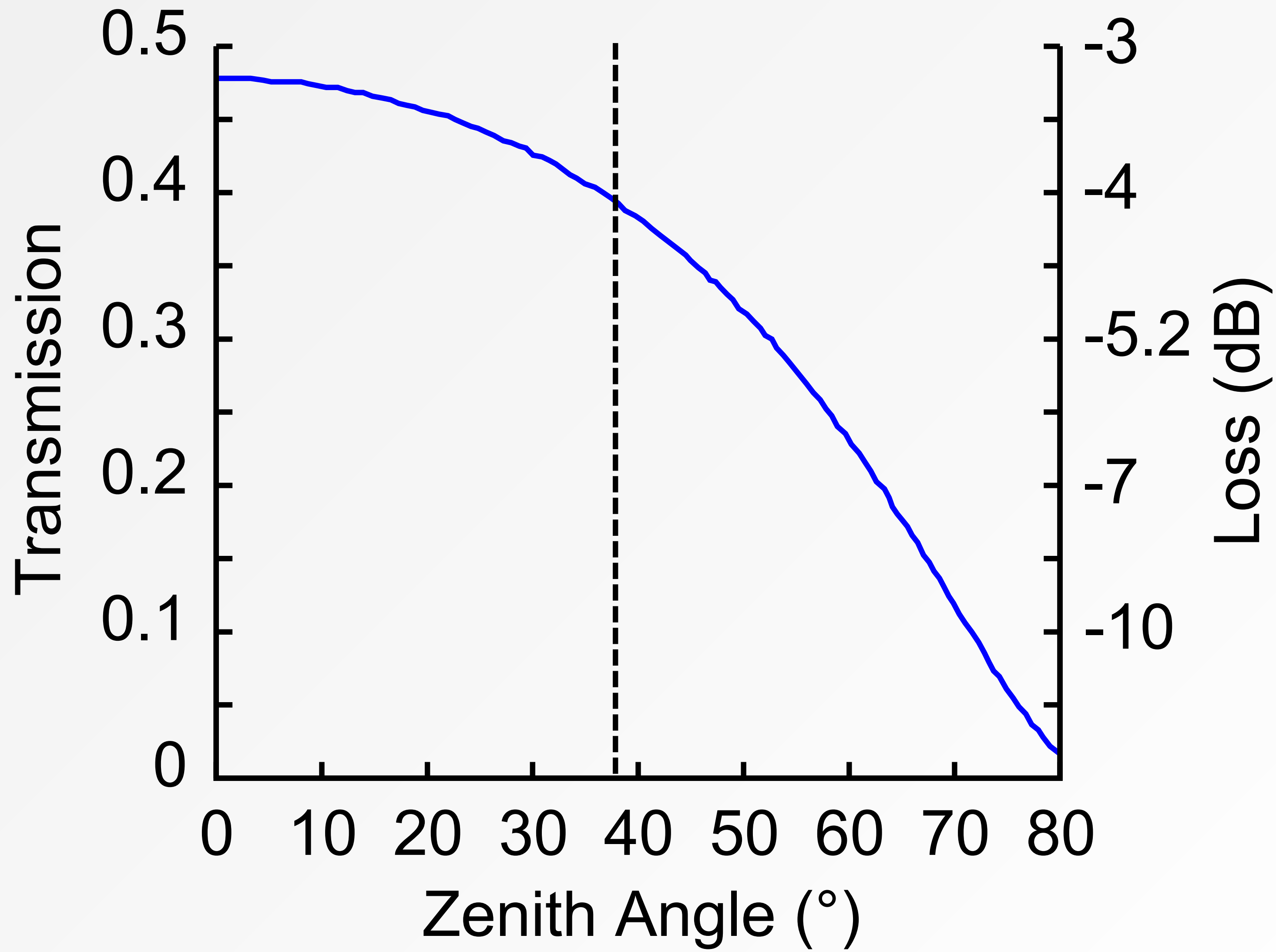


Losses: Atmospheric

MODTRAN 5 model of losses:

Absorption
&
Scattering

(20°C,
50% humidity,
clear night,
above sea)



New J.Phys.15, 023006 (2013).

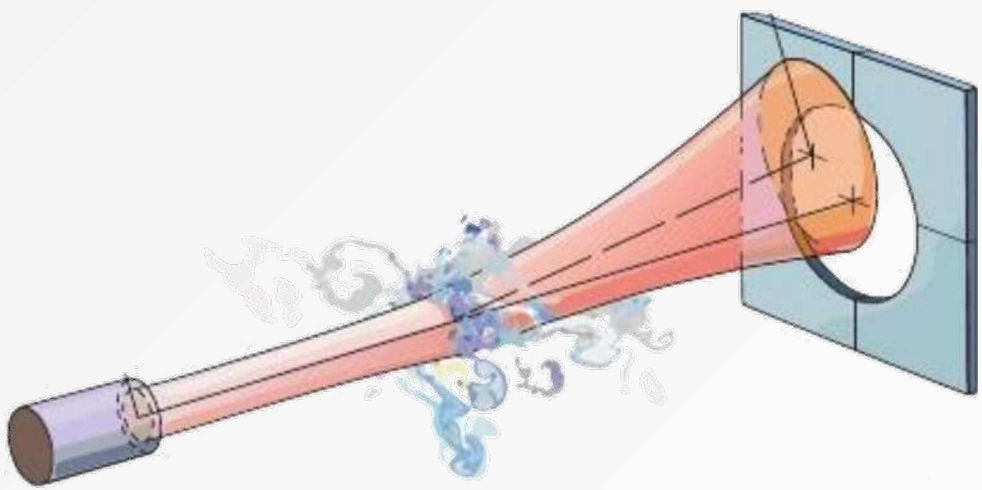
Losses: Clipping

Distance: 400 to **522 km**
Final beam diameter (max): ≈ **6 m**, (min: 2.1m)
Receiving telescope aperture: 0.23 m
Clipping loss: ≈ -22 to -27 **dB (Worst case)**

Losses: Beam wander

Pointing accuracy: ≈10 +5 µrad (Closed Loop)

Beam wander loss: ≈ -5 **dB**



Phys. Rev. A 81, 023835 (2010).

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Losses: Optics

Detection efficiency: ≈60 % (in space)

Transmission through sending optics: ≈70 %

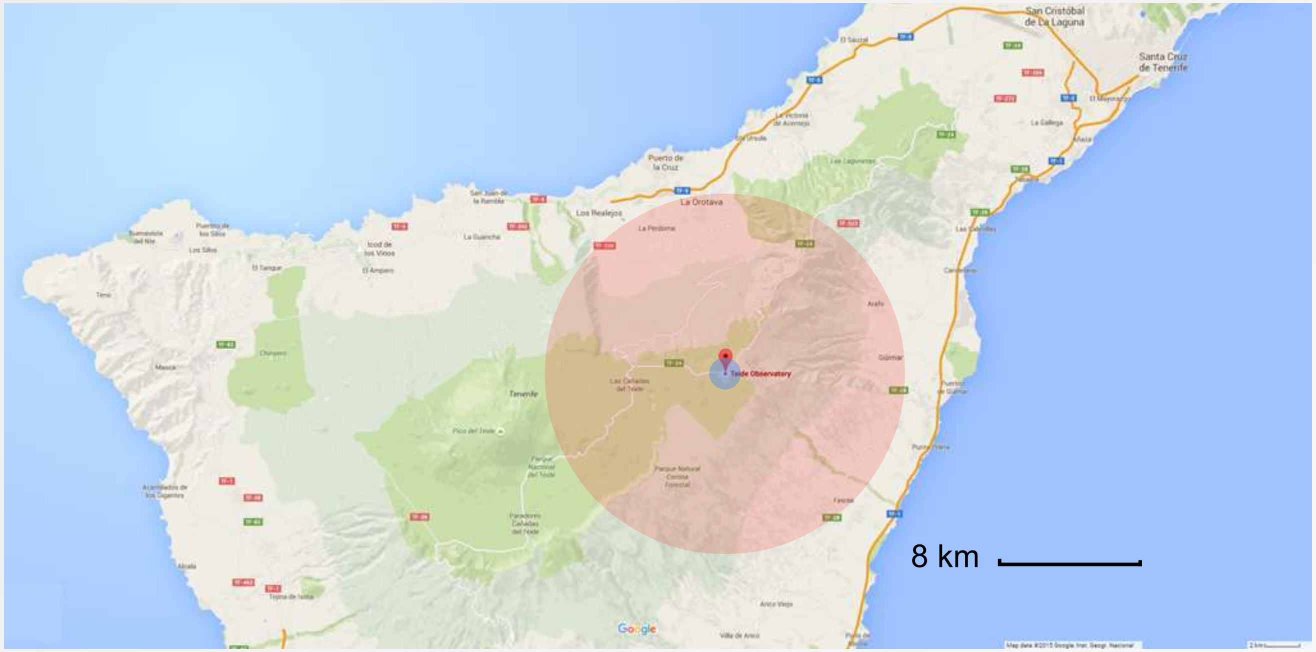
Transmission through receiving optics: ≈70 %

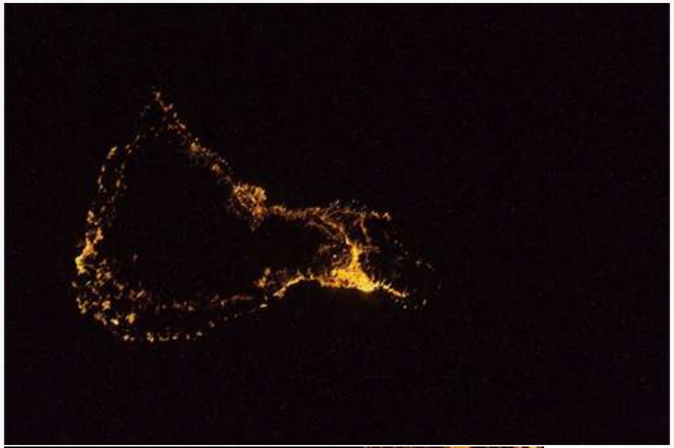
Losses in optics: **-7 dB**

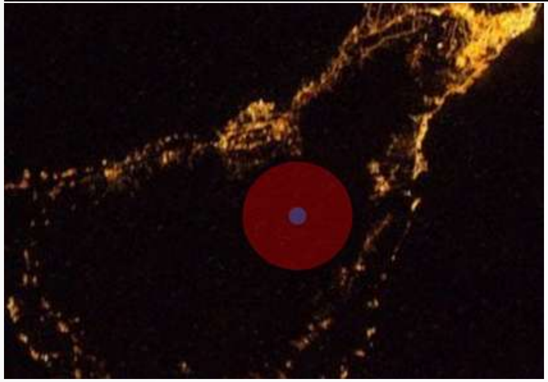
Losses

Total losses: $\ll$**-46 dB**

Requirements: Tracking



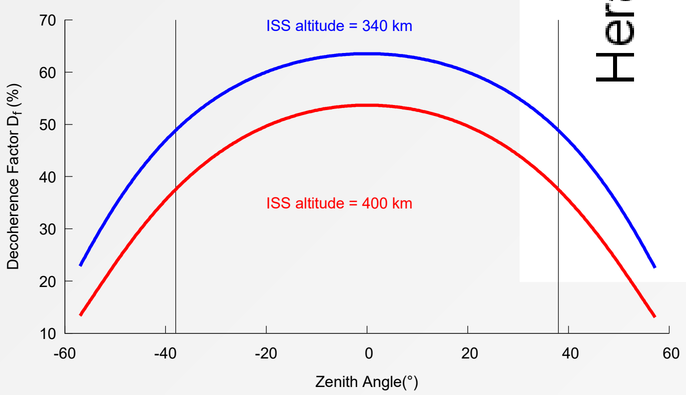


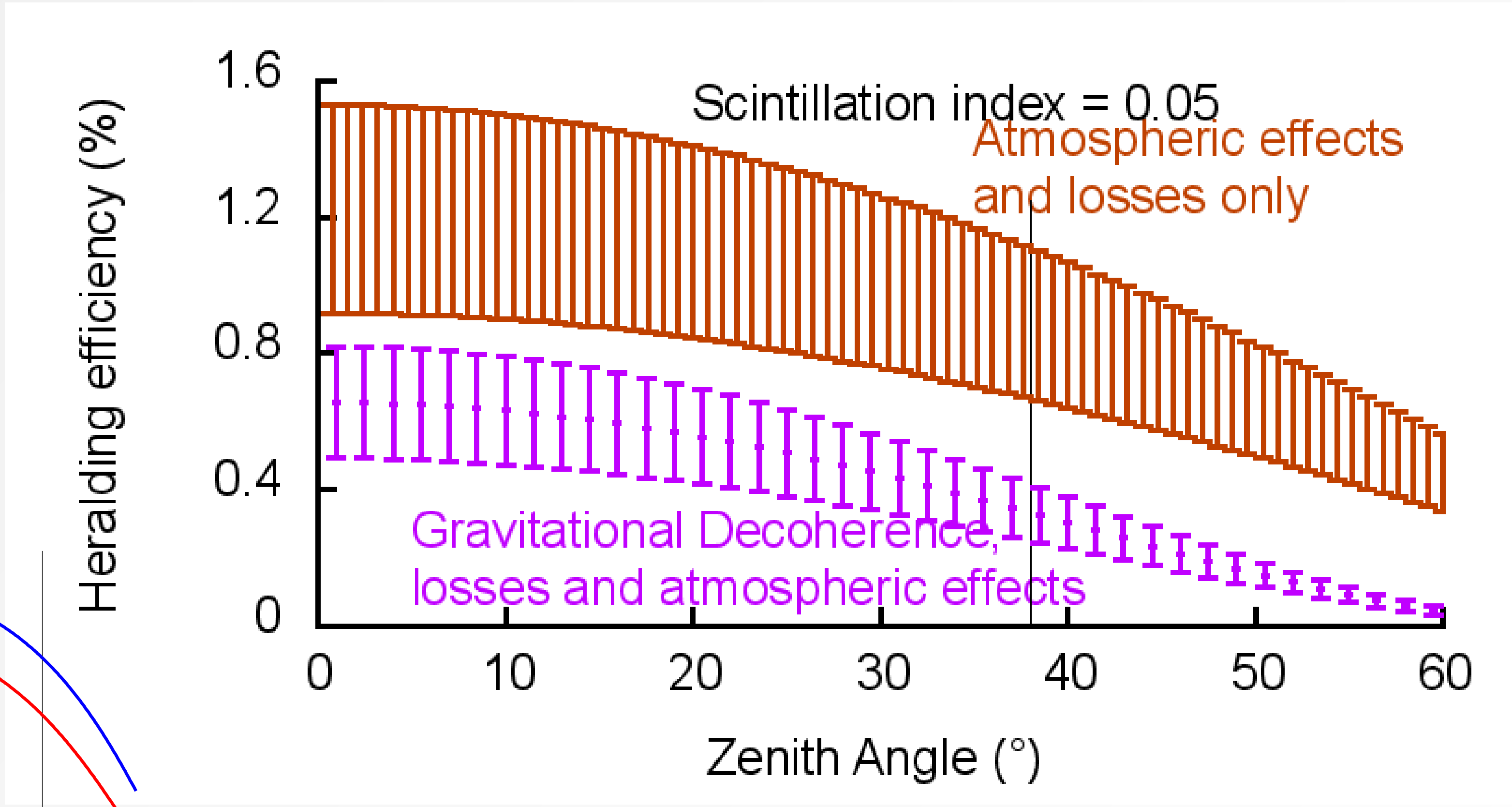


Ground to ISS: ≈ 10 to 15 arc sec

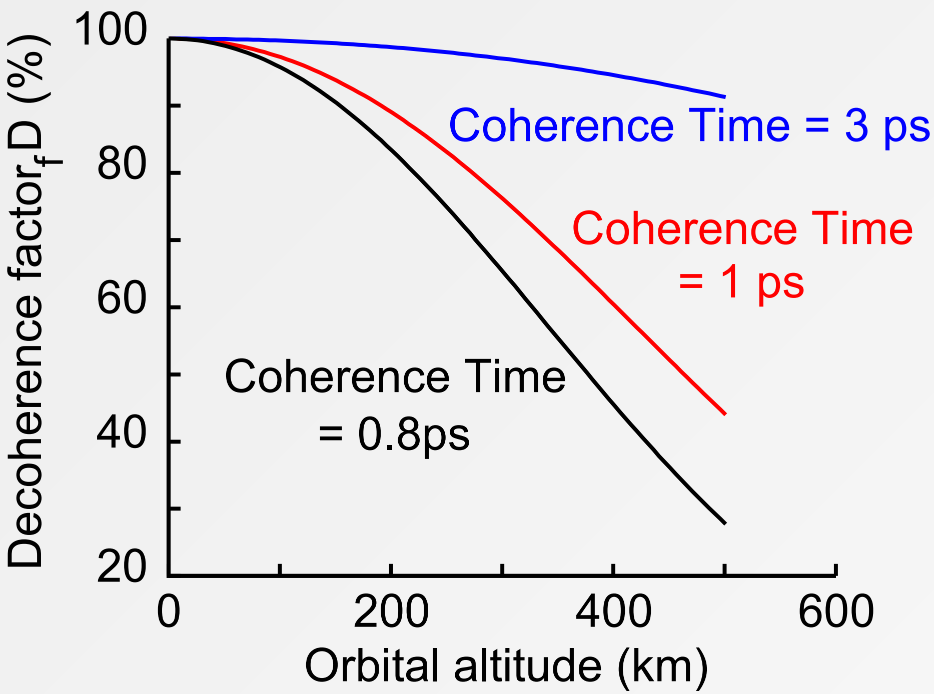
ISS to ground: Constant tracking of ground station's beacon

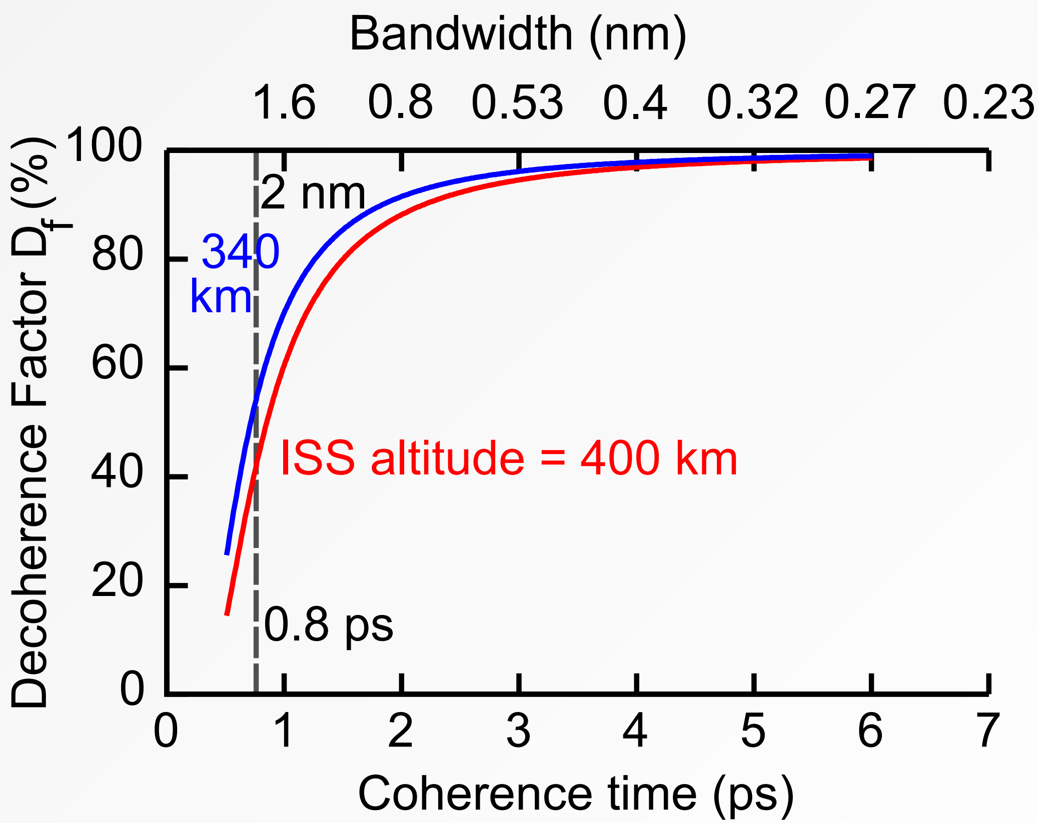
All together





Coherence time





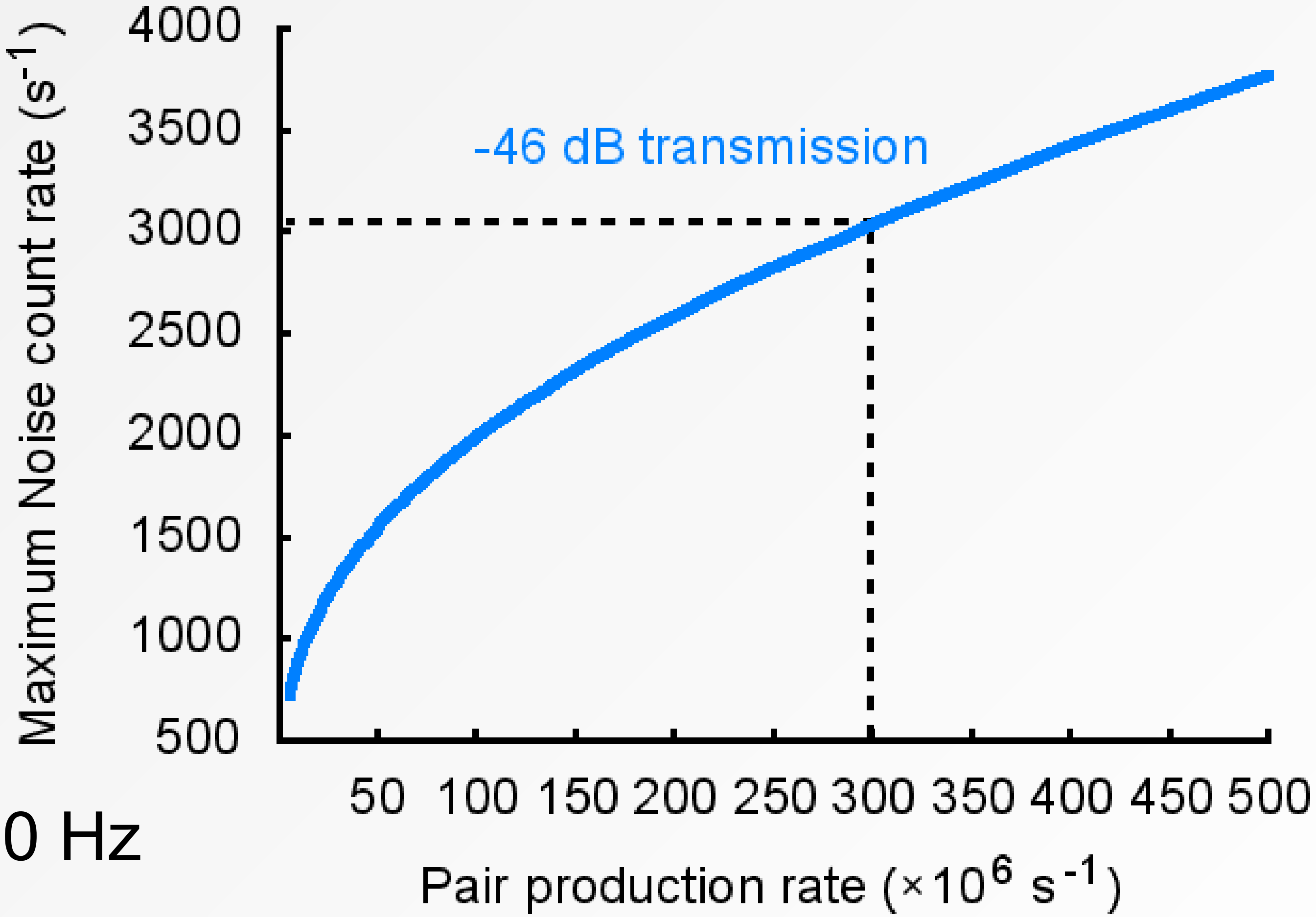
Background light & Errors

Max noise rate per detector to measure a 5% change in D_f

Worst case:

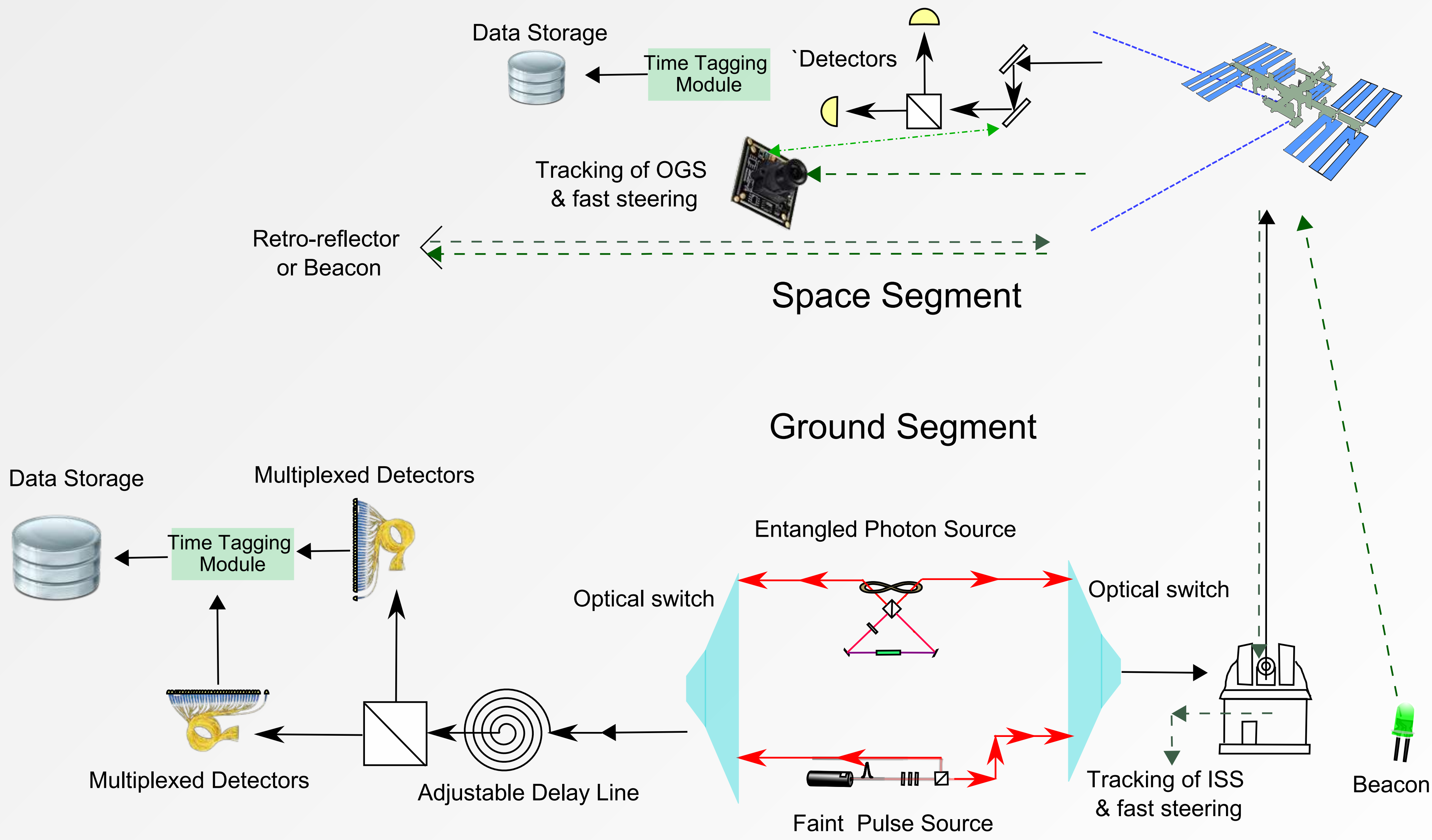
Log normal error distribution.

Scintillation Index = 0.05



We can tolerate > 6000 Hz Background!

Requirements: Ground



Requirements: Ground

> 250 Million pairs/second → 10^7 pairs/s/mW (2 nm)

≈ 200 detectors

> 600 MB/s (compressed)
2.3 GB/s (uncompressed)

Further challenges

Fluctuation of:		Solved by:
Clocks	→	GPS sync (±10ns)
Losses	→	Pulsed laser calibration signal
Background	→	Block transmission & measure
Polarization	→	Ini. calib. & intermittent measurement

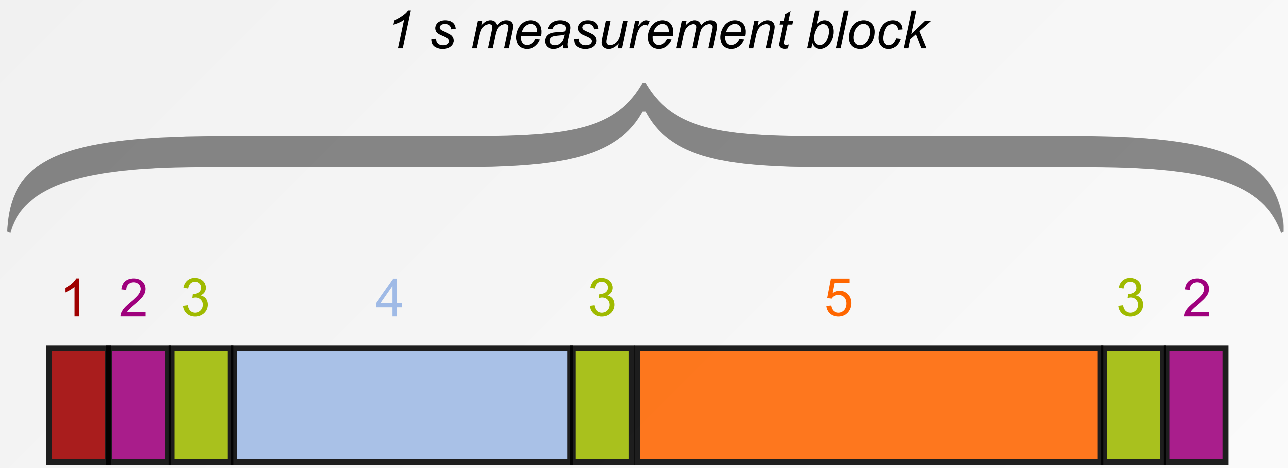
Further challenges

Compare classical (FPS) to quantum entangled.

Discard data with high fluctuations.

Ground based optical Switch ($\ll$100 μs).

Adjust block duration to turbulence



1) Dark count measurement 5%

2) Link loss and polarization calibration 10%

3) Background measurement 15%

4) Faint pulse source experiments 29%

5) Quantum entangled experiments 40%

6) Switching time 1%

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What if we have a negative result?

General Relativity (GR):

Closed Time-like Curves exist ⇒ Decoherence

Local causal structure

Null result:

No Closed Time-like Curves

Non-Local

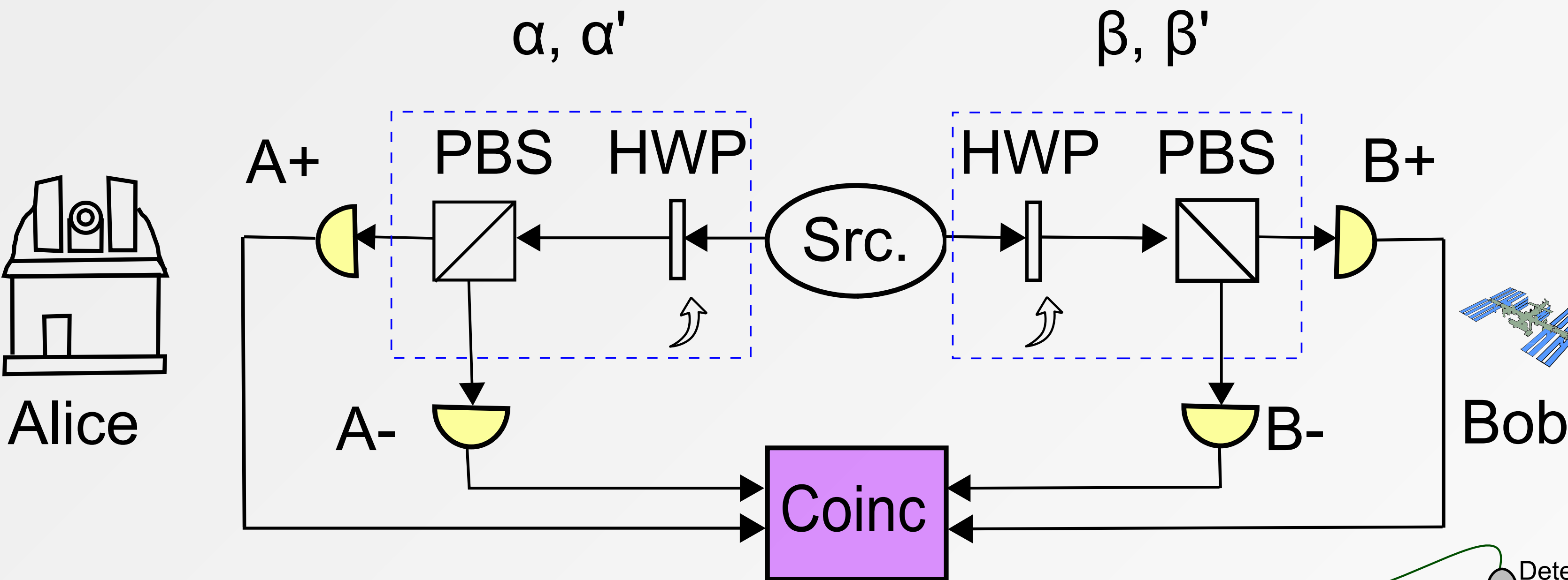
Bound on the maximum curvature of space-time!

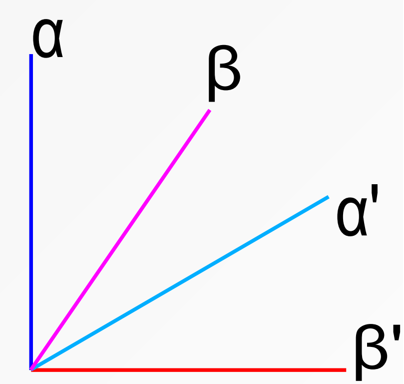
Secondary Objectives

Quantum

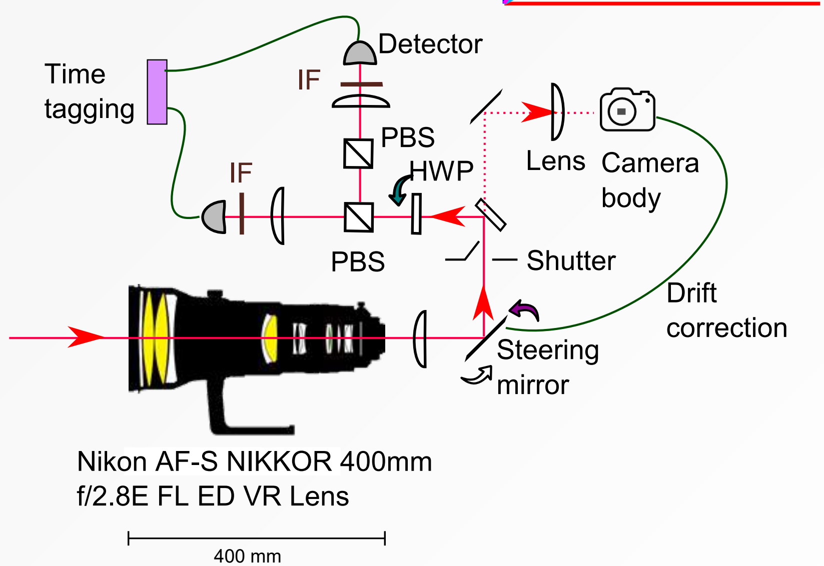
Classical

Bell Tests





The same instrument can be used for Bell tests!



Quantum Communication

Also good for polarization based quantum communication

E91 and BB84

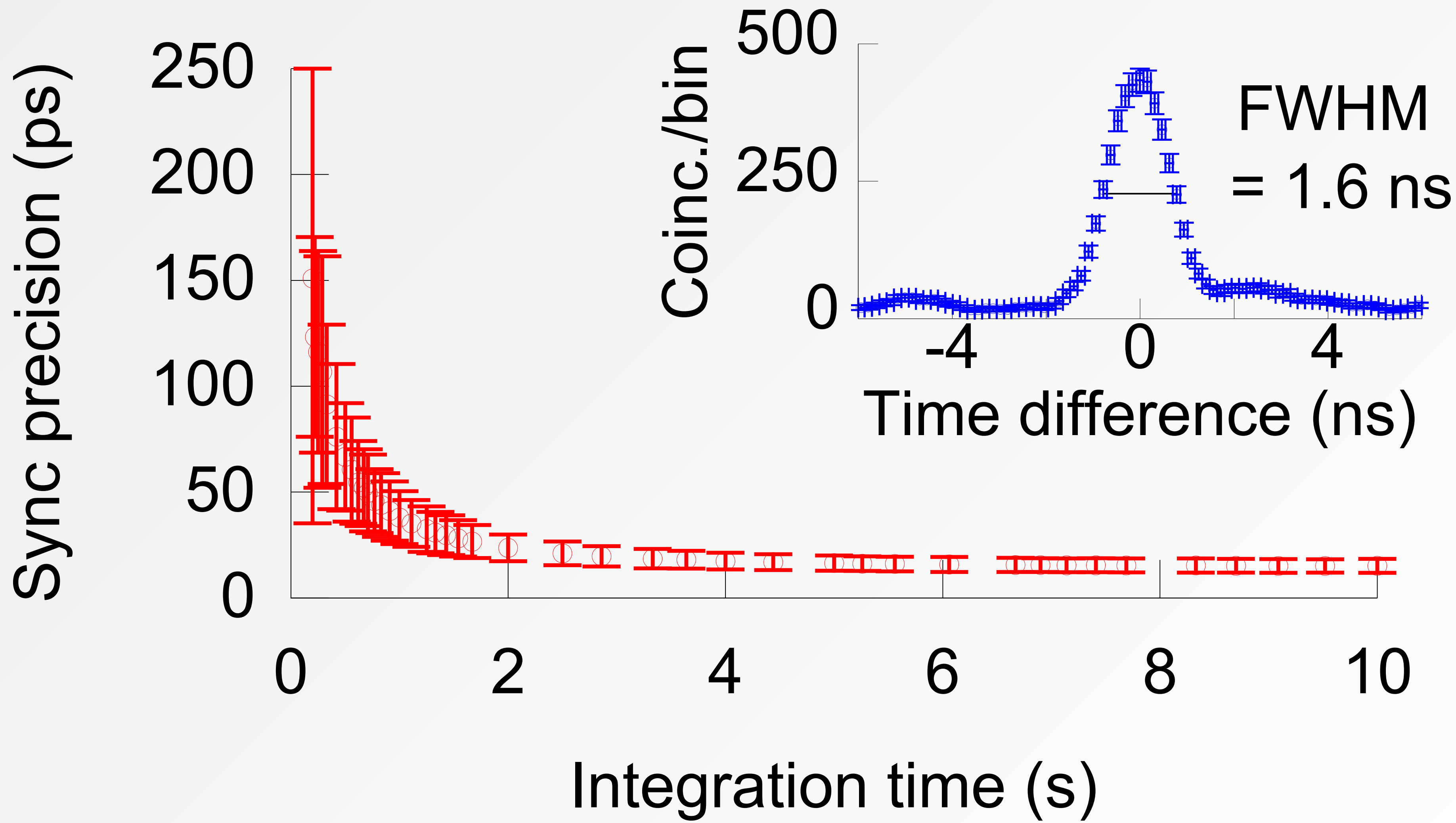
Beam pointing errors at PBS → Variable extinction, lower visibility

→ Use Wire grid PBS
e.g Medowlark or Moxtek, Inc
>0.1% change in extinction ratio for ± 10°

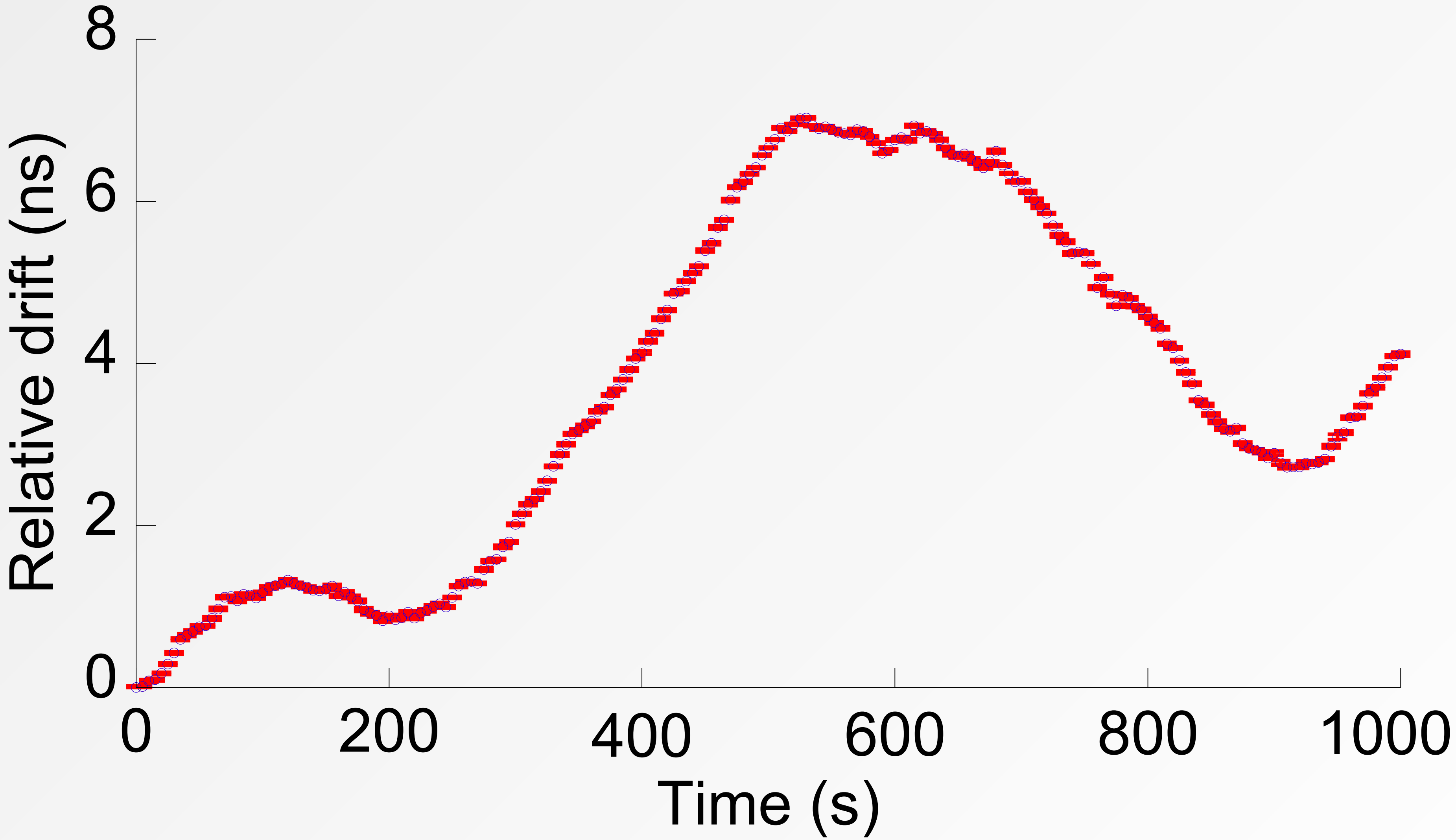
Polarization rotation form window and telescope → Calibrate & compensate or Circular polarization states

http://www.meadowlark.com/store/applicationNotes/Beam%20Splitting%20Polarization%20Cube.pdf

Clock Synchronization



Clock Synchronization



Classical Communication

Pulse Position Modulation:

Proving ground for uplinks to the moon/planets

High orders (PPM2048) because of precise time tags

Multiple input Multiple Output Transmit Diversity:

Encode data in different polarization channels

Alternative modulation formats for turbulent uplinks:

PAM & PolMod

Influence of Ice clouds

Optimal beam shape

& others…...

Conclusion

The experiment is feasible.

Positive result → Non-linear Q.M.

Null result → Bound on curvature of space-time.

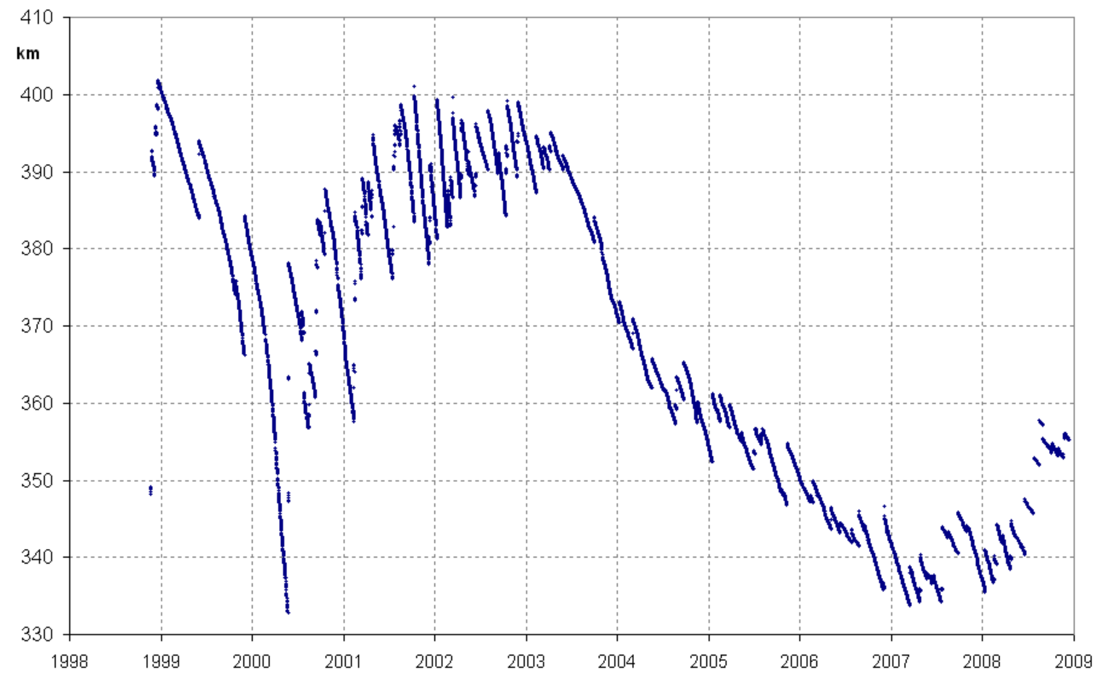
Can also study: Bell tests, BB84, E91, Decoy state, Clock sync., non-Gaussian modes, information encoding in angular momentum, etc.

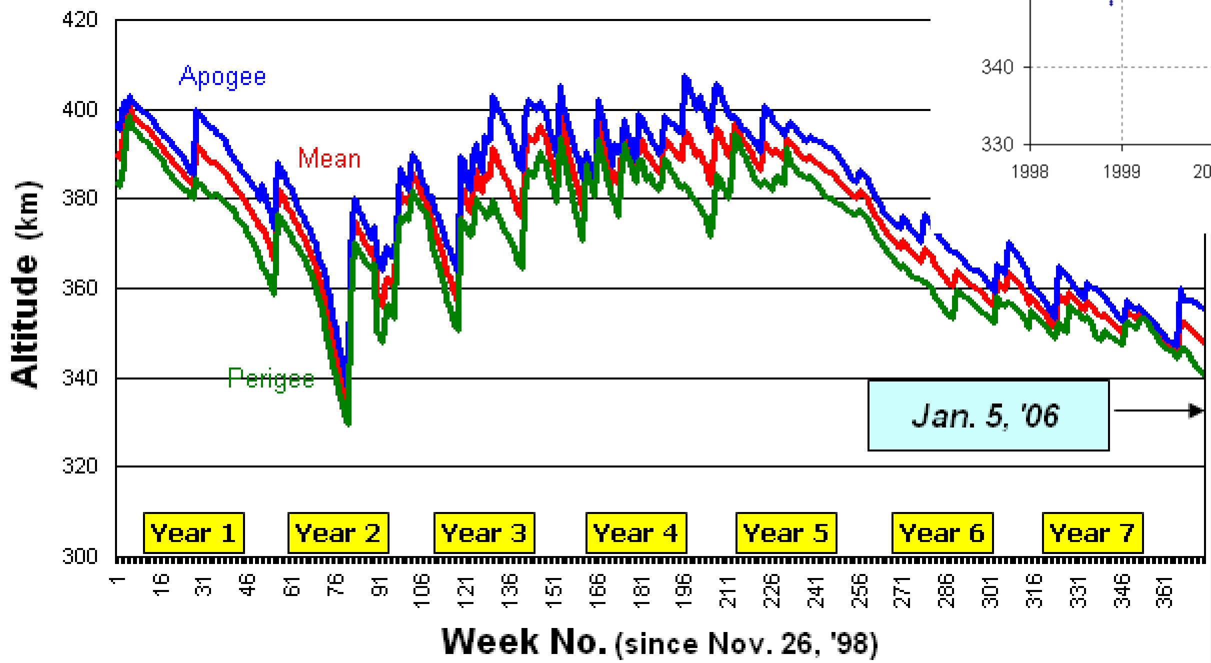
Simple and cheap ISS segment.

ESA Topical Team

<u>Siddarth K Joshi</u>, Rupert Ursin, Anton Zeilinger, Harald Weinfurter, John Rarity, Cesare Barbieri, Etienne Samain, Nicolas Gisin, Hugo Zbinden, Gregor Weihs, Paolo Villoresi, Giuseppe Bianco, Sergio Cova, Dirk Giggenbach, Ian Walmsley, Nikolaos Solomos, Robert H Hadfield, Juan P Torres, Momshil Peev, Christophe Salomon, Marek Zukowski, Renato Renner, Romain Alleaume, Norbert Lütkenhaus, Raymond Laflamme, Timothy Ralph, Gerard Milburn, Wolfgang Tittel, Hiro Ogawa, Jose Capmany, Walter Leeb, Valerio Pruneri, Hoi-Kwong Lo, Wolfgang Ertmer, Romain Alléaume, Morio Toyoshima, Paolo Martaloni, Thomas Jennewein, Miloslav Dušek, Mohamed Bourennane, Carlo Nicola Colacino, Aneas Poppe, Vadim Makarov, Johannes Skaar, Michael A Krainak, et al.

Varying the orbital altitude





William Crochot wikipedia.org
https://jarphys.wordpress.com/2014/06/14/space-station-orbit-reboosts/