

Quantum networks for space-based distributed quantum sensing: Perspectives on planetary science applications

NASA Quantum Sensing Workshop 2022

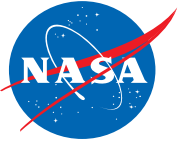
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NASA Glenn Research Center

September 27th, 2022

Some planetary science in the next decade



Origins, Worlds, and Life: Decadal survey

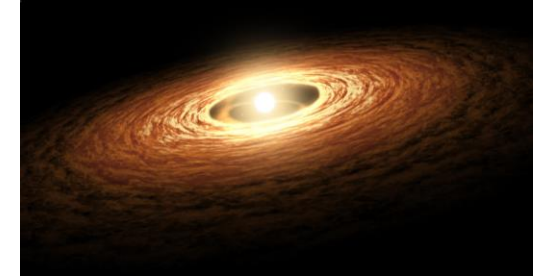
- The National Academies published a decadal survey “Origins, Worlds, and Life: A Decadal Strategy for Planetary Science and Astrobiology 2023-2032”
- The survey identifies 12 priority questions for planetary science:
 - Q1: Evolution of the protoplanetary disk
 - ...
 - Q5: Solid body interiors and surfaces
 - ...
 - Q7: Giant planet structure and evolution
 - ...
 - Q10: Dynamic Habitability
 - ...
 - Q12: Exoplanets

} **Origins**

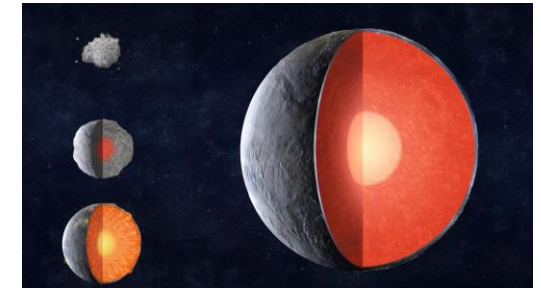
} **Worlds**

} **Life**

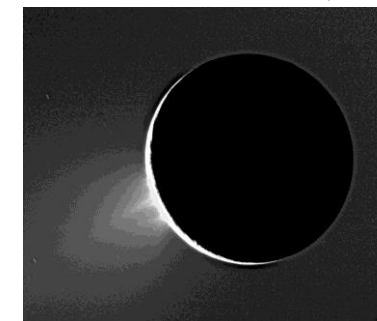
} **All themes**



Artist conception of a planet-forming disk of gas and dust surrounding a young star. Credit: NASA/JPL-Caltech



Artist conception of how a rocky planet forms. Credit: NASA/JPL-Caltech



Cassini image of Enceladus plume. Credit: NASA/JPL/Space Science Institute

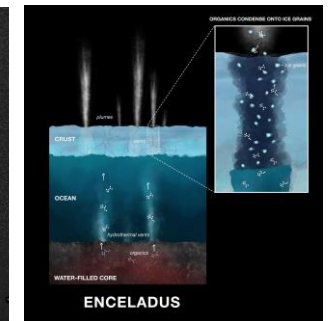


Illustration of Cassini detection of organic compounds in Enceladus' plumes. Credit: NASA/JPL-Caltech

Quantum technologies for planetary science



Planetary Sciences Division summary of quantum technology investments

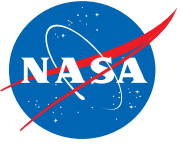
PI name	Org	Specific measurement/Science Application	Solicitation yr
Todd Ely	JPL	“Deep Space Atomic Clock: Veritas TDO” DSAC uses two types of cold traps to isolate mercury ions from wall collisions and excites quantized energy state transitions to create a clock that is significantly less sensitive to variations in environmental radiation, temperature, and magnetic fields. This ultra-stable operation will improve the accuracy of on-board navigation, and gravity and radio science measurements.	STMD
Nan Yu	JPL	“Atomic Drag-Free Accelerometer for Non-Gravitational Forces in Radiometric Orbit Determination and Planetary Science” Uses free-fall atomic particles as proof masses and quantum wave interference for inertial force measurements to measure planetary gravity measurements through radiometric orbit determination.	MatISSE-20
Hannes Kraus	JPL	“Optically Pumped Solid-State Quantum Magnetometer (OPUS-MAGNM)” Optically active, spin-carrying quantum centers in wide-bandgap semiconductors are used to measure external magnetic fields to provide a low-SWAP means to map planetary fields.	PICASSO-20
Michael Cheng	JPL	“Hybrid Radio Frequency and Magneto-Inductive Transceiver for Europa Sub-Ice Communications” Uses SQUID receiver to detect weak magnetic fields for communication through thick ice.	COLDTech-20
Ho Jun Paik	U. MD	“Superconducting Gravity Gradiometer for Planetary Dynamics” Motion of floating test masses measured using SQUID detectors to increase sensitivity; Objective is to probe planetary interiors from crust to core.	MatISSE-18
Nan Yu	JPL	“Lunar Super Low-Frequency Atomic Seismometer” Employs atomic test masses as the inertial reference frame and atom interferometry for displacement measurements. The application is an orbiter atomic drag-free reference instrument for planetary gravity measurements.	DALI-18
Boris Karasik	JPL	“Terahertz heterodyne spectral imager of planets and comets” Development of a tunable antenna-coupled terahertz mixer by exploring the inter-subband transition in a 40nm GaAs/AlGaAs quantum well heterostructure.	PICASSO-18

Part II:

SPACE-BASED QUANTUM NETWORKS FOR HIGH RESOLUTION GEODESY AND VLBI

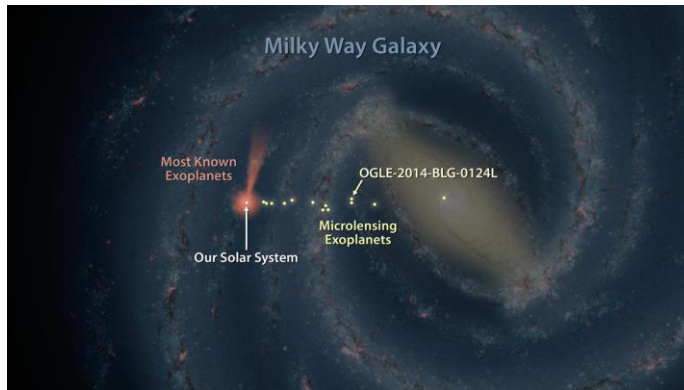
Space-based quantum networks

Potential applications for planetary science



Long Baseline Interferometry

Benefits: High resolution exo-solar imaging of celestial bodies and surfaces

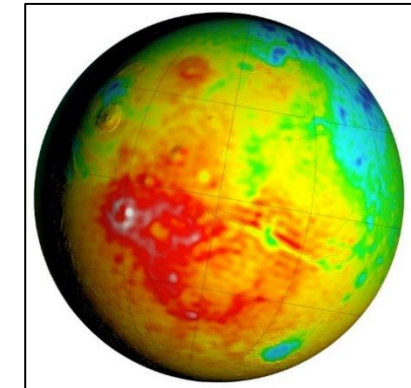


Map of Exoplanets found in our galaxy – artist concept.
Credit: NASA/JPL-Caltech



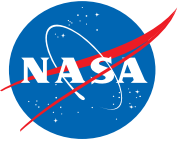
Atomic Clocks

Benefits: High accuracy global timing system. High resolution imaging of celestial gravitation fields. Location of gravimetric sources, such as underground caverns.



Variations in thickness of Mars Crust from gravitational pull on orbiters.
Credit: NASA/GSFC/Scientific Visualization Studio

Gravity field mapping and geodesy



GRACE and GRAIL

- Gravity field measured via distance between two polar-orbiting satellites.

GRACE:

- Altitude 500 km / Separation 220 km
 - Resolution 300 km**
- K-band ranging $\sim 1 \mu\text{m}$
 - Sensitivity $\sim 1 \text{ mGal}$ ($10^{-6} \cdot g$)**

GRAIL:

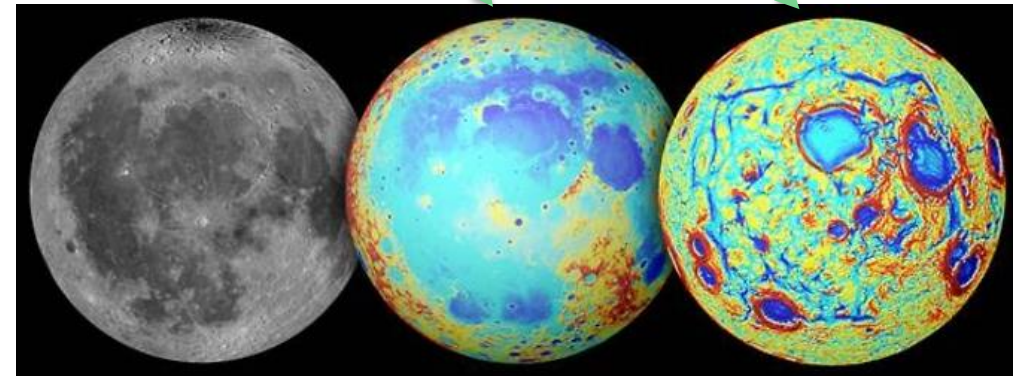
- Altitude 22-55 km / Separation 175-220 km
 - Resolution 4.5 km - 13 km**
- Ka-band ranging to $0.1 \mu\text{m}$
 - Sensitivity $< 1 \text{ mGal}$**

GRACE-FO Laser Ranging $\Rightarrow$ Higher sensitivity

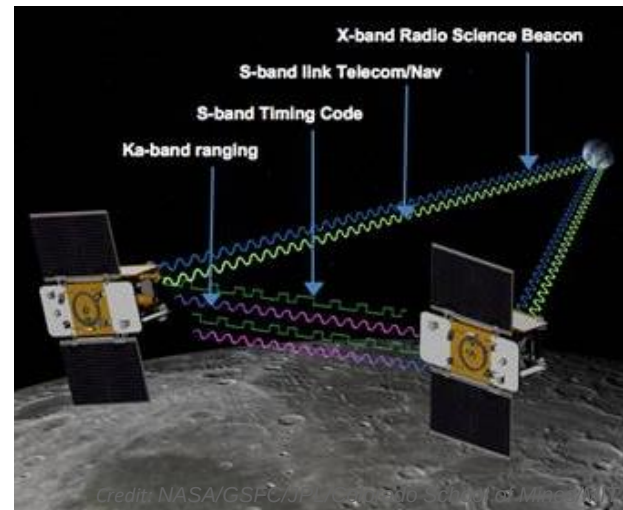
Better accelerometers $\Rightarrow$ Higher resolution

Topographic map

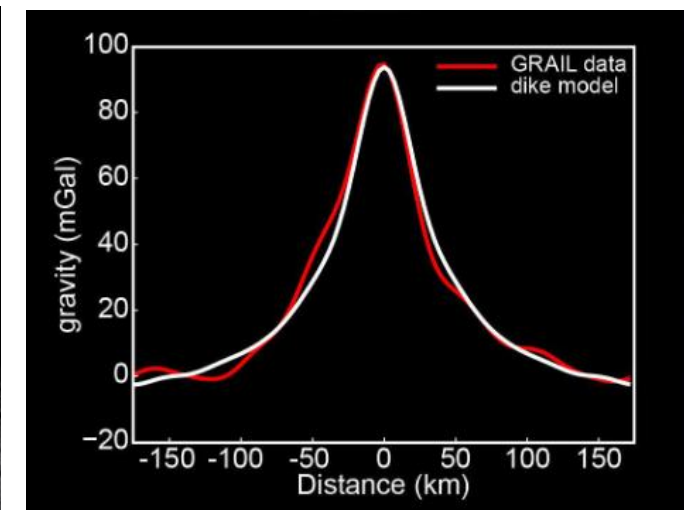
Gravimetric map



Credit:
NASA/GSFC/JPL/
Colorado School of
Mines/MIT

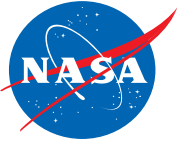


Credit: NASA/JPL

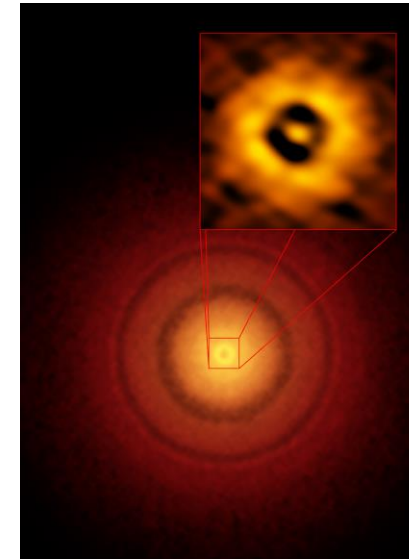


Credit: NASA/JPL-Caltech/CSM

Exoplanetary systems via optical interferometry



- Long-baseline optical interferometers are just reaching minimum resolution required for study of exoplanetary systems
- The Navy Precision Optical Interferometer (NPOI) has outlined a plan for 2020-2030 to achieve multi-km baselines capable of imaging protoplanetary disks
- The European Southern Observatory's Very Large Telescope (VLT) array reported the first direct detection of an exoplanet by optical interferometry, **separating light from the exoplanet from that of its central star** for spectroscopic analysis



Radio interferometer image of protoplanetary disk. An optical array of the same size could yield 600x the resolution. Credit: S. Andrews (Harvard-Smithsonian CfA), ALMA (ESO/NAOJ/NRAO)

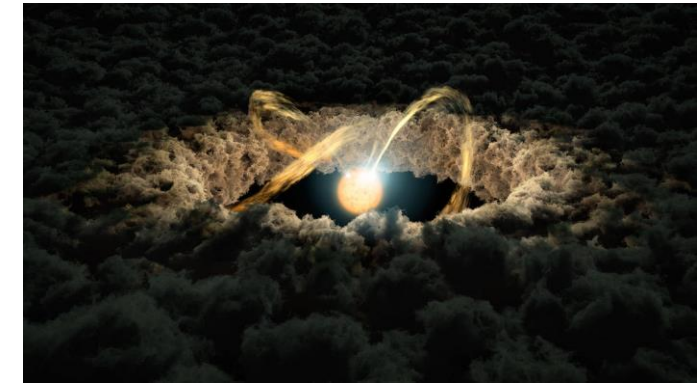
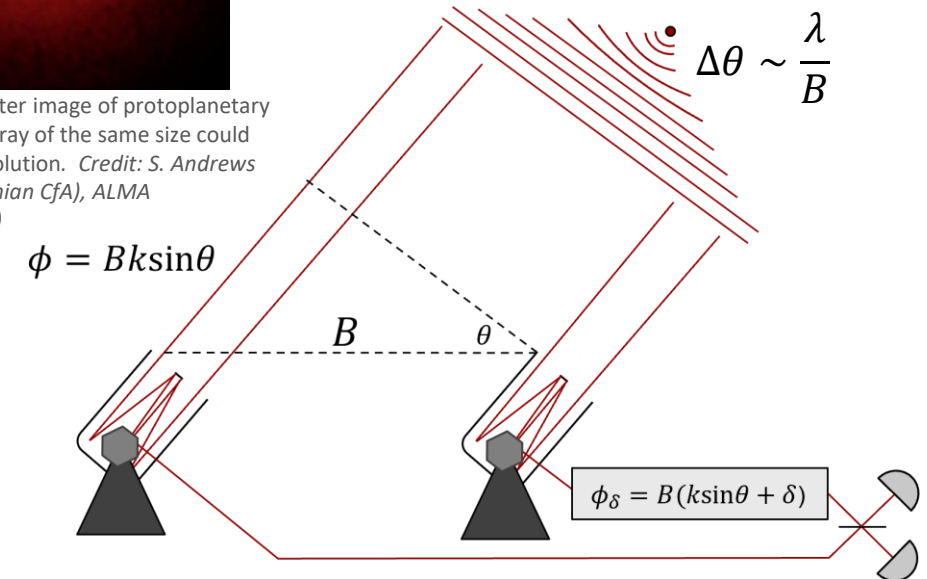
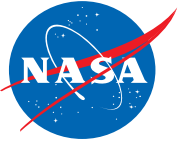


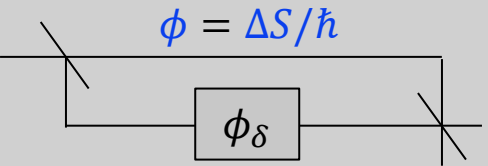
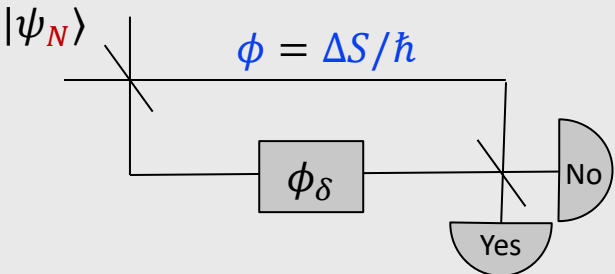
Illustration of a protoplanetary disk surrounding a central star. Credit: NASA/JPL-Caltech



Space-based quantum networks

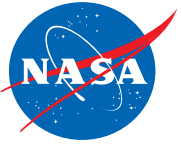
Fundamental resources for quantum metrology



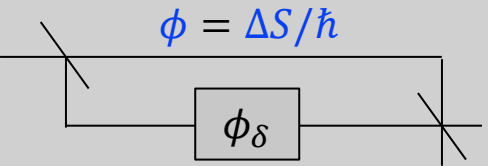
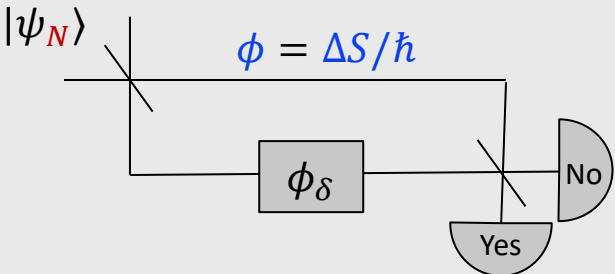
Resource	Constraint
The total action ΔS of the process $\Delta S = \Delta E \cdot \Delta t = \Delta p \cdot \Delta x$ 	Sensitivity $\phi = \frac{\Delta S}{\hbar} \in [0, 2\pi]$ Governs how sensitive the system is to $\Delta E, \Delta t, \Delta p$, or Δx.
The total number of quanta N  limits # bits locating $\phi \in [0, 2\pi]$.	Precision $\Delta\phi \sim \frac{\sqrt{\# \text{ indep. probes}}}{N}$ ↑ "Shot noise" "Quantum Projection Noise"

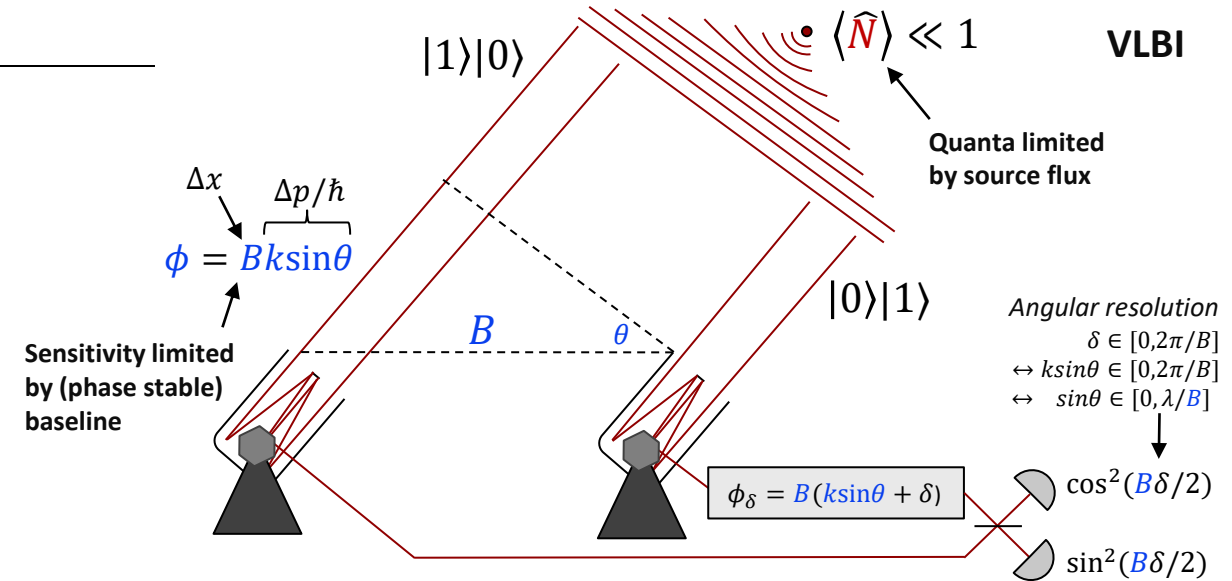
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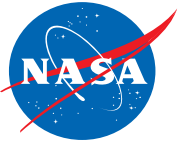
VLBI

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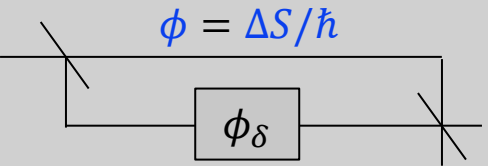
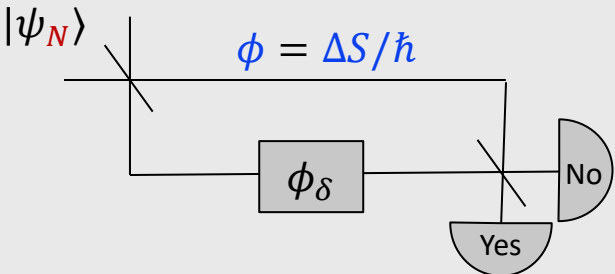


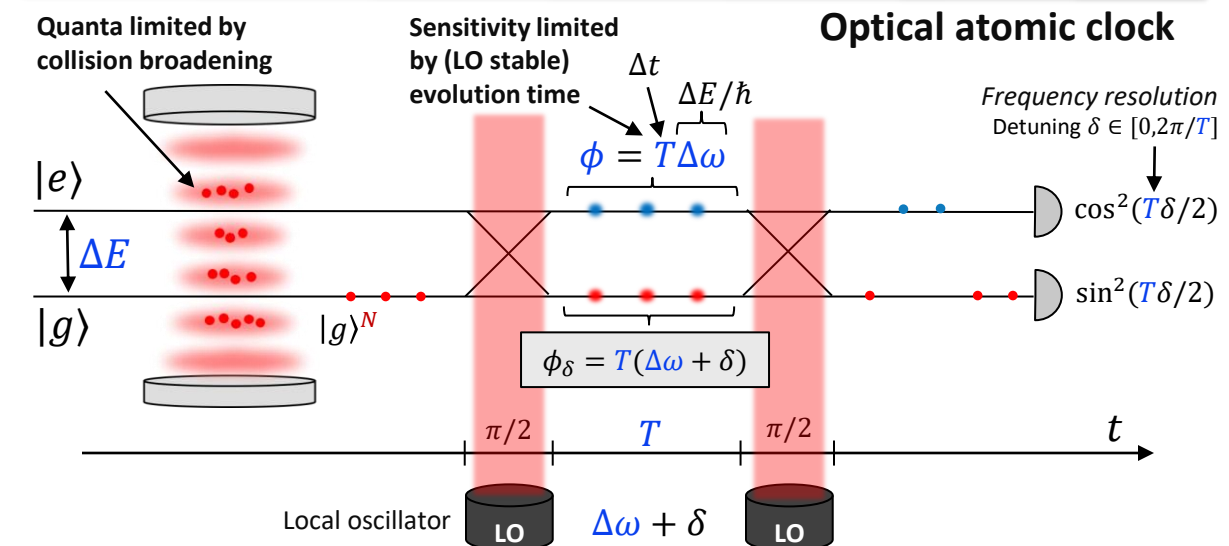
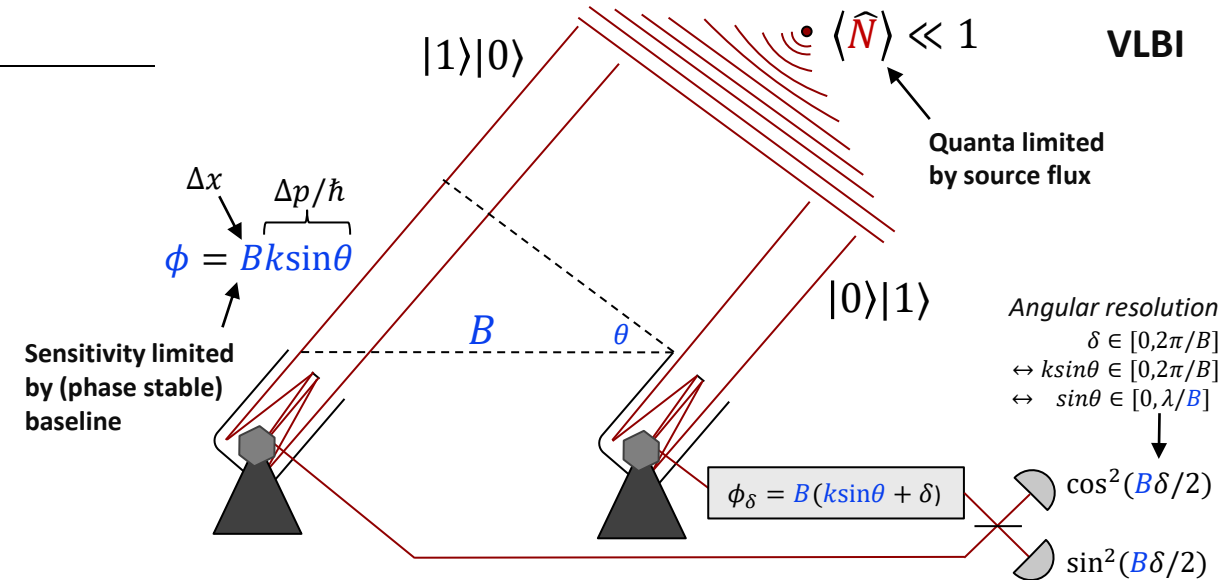
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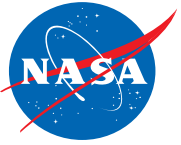
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Part III:

GEODESY USING QUANTUM NETWORKS OF CLOCKS



Geodesy using quantum networks of clocks

Comparison to satellite ranging

Satellite Ranging-Based Gravimetry

ρ = inter-satellite range vector

$$\ddot{\rho} = \hat{\rho} \cdot \overbrace{(g_2 - g_1)}^{\text{Gravitational accelerations}} + \hat{\rho} \cdot \overbrace{(a_2 - a_1)}^{\text{Non-gravitational accelerations (on-board accelerometers)}} + \frac{1}{\rho} \underbrace{(|\dot{\rho}|^2 - \dot{\rho}^2)}_{\text{Centrifugal term (requires orbital positions, e.g. GNSS)}}$$

Ranging Measurement $\rightarrow \ddot{\rho}$

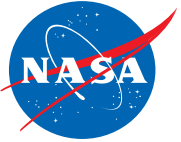
GRACE Resolution: **300 km** to **~1 mGal**

GRAIL Resolution: **5 km** to **~1 mGal**

Standard Quantum Limit: **~70 $\mu\text{m} \cdot \text{nGal}$**
(for 220 kg at 1 km/s via $\Delta g \geq (\hbar/m\tau^3)^{1/2}$)

Practical limit is **isolation of non-gravitational accelerations** $\Rightarrow$ 1-10 second integration time

Geodesy using quantum networks of clocks



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Relativistic Gravimetry

IAU metric: $g_{\mu\nu} = \eta_{\mu\nu} + (2\Phi/c^2)\delta_{\mu\nu} + O(c^{-3})$

$$d\tau^2 = \left(-1 + \frac{2\Phi}{c^2} + \frac{v^2}{c^2} \right) dt^2$$

Satellite clock $\rightarrow d\tau$

Gravitational potential $\rightarrow \Phi$

3-velocity in coordinate time (requires orbital positions, e.g. GNSS) $\rightarrow v$

$$\frac{f}{f_0} = \frac{d\tau_0}{d\tau} + \text{doppler}$$

Reference clock (e.g. geostationary orbit) $\rightarrow f_0$

Requires two-way frequency transfer $\leftarrow$

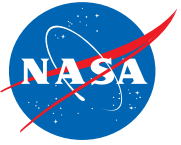
Direct recovery of gravitational potential Φ (instead of gravitational acceleration g) relegates non-gravitational accelerations to smaller order error $d^2\tau/dt^2$.

Comparison to highly stable 'master' clock f_0 is needed

Needs velocity determination $< 10^{-6}$ m/s and **clock stability $< 10^{-18}$ s** (Mayrhofer and Pail, 2012)

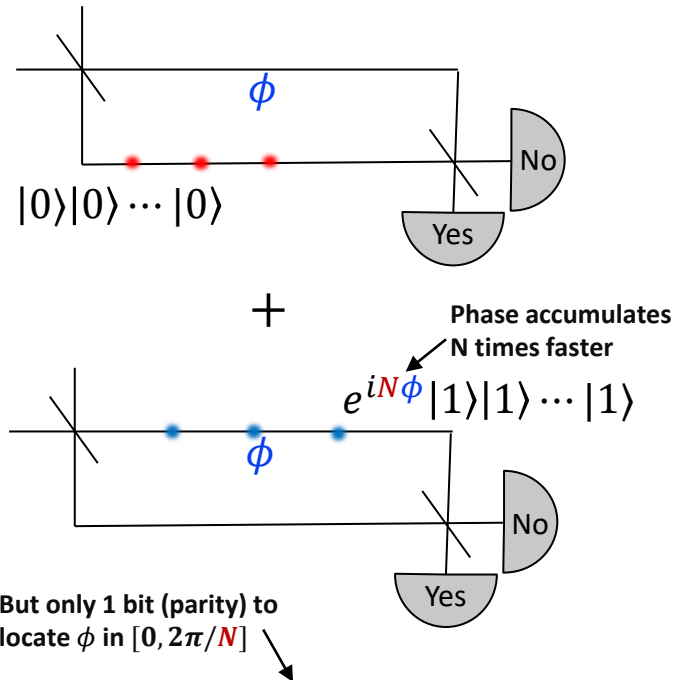
Geodesy using quantum networks of clocks

Enhanced interferometry with GHZ states

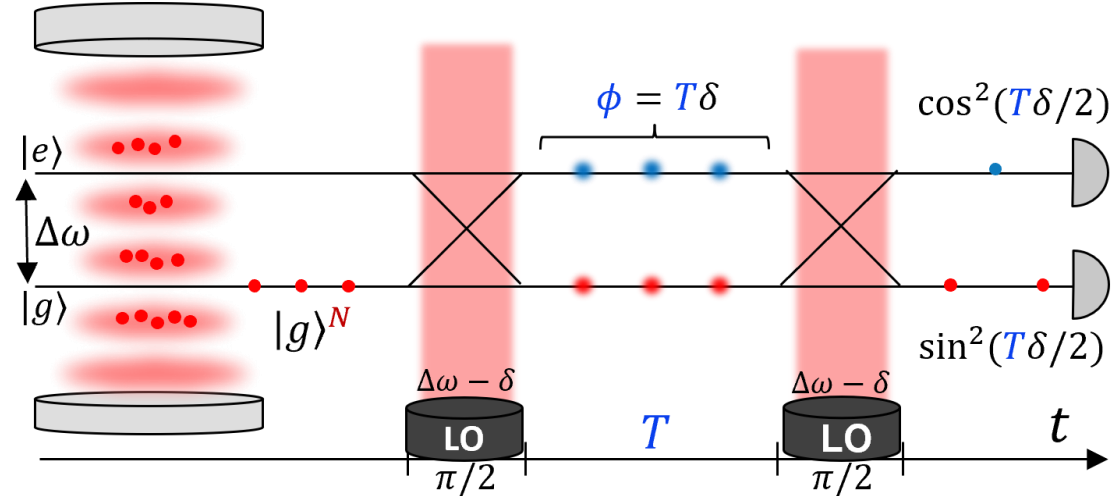


Local Quantum Correlations

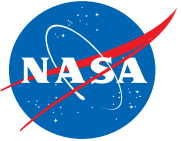
$$\begin{aligned} & |\underbrace{\bullet \bullet \dots \bullet}_N\rangle + |\underbrace{\bullet \bullet \dots \bullet}_N\rangle \\ & |0\rangle|0\rangle \dots |0\rangle + |1\rangle|1\rangle \dots |1\rangle \end{aligned}$$



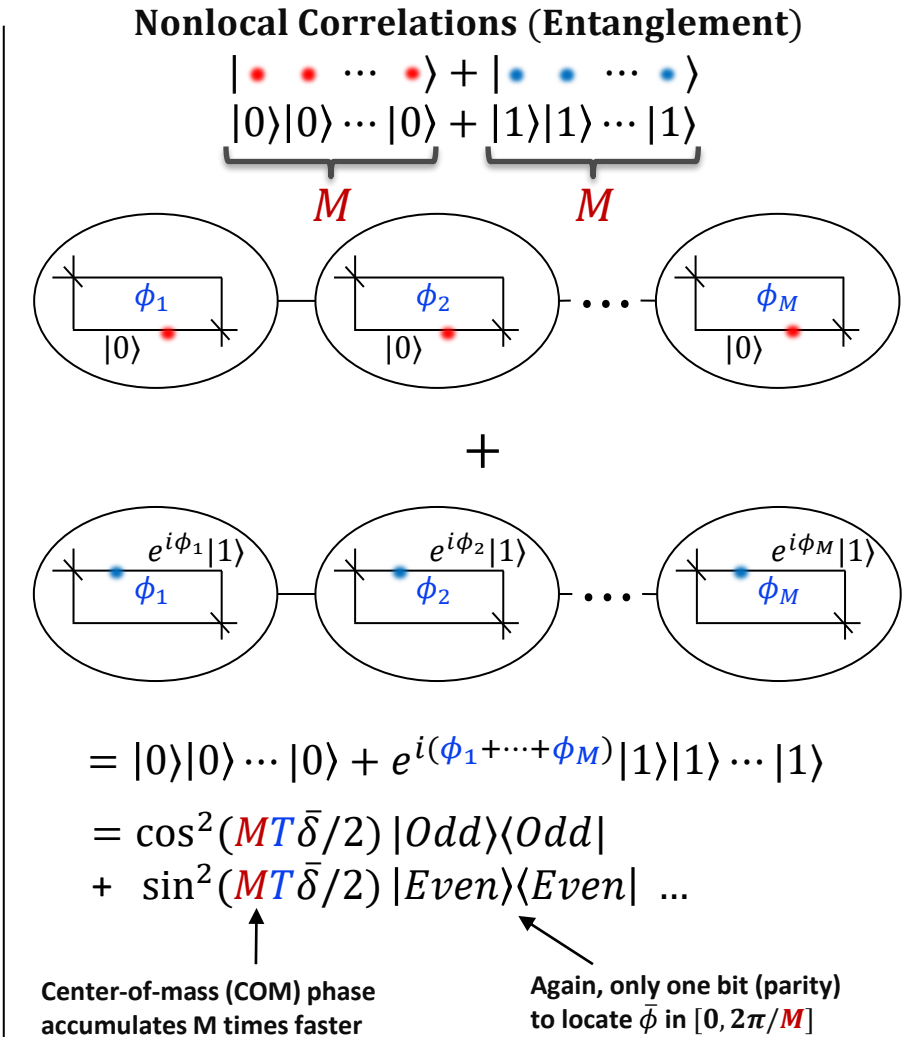
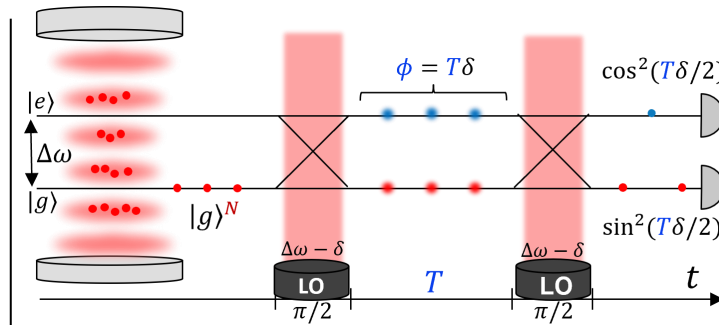
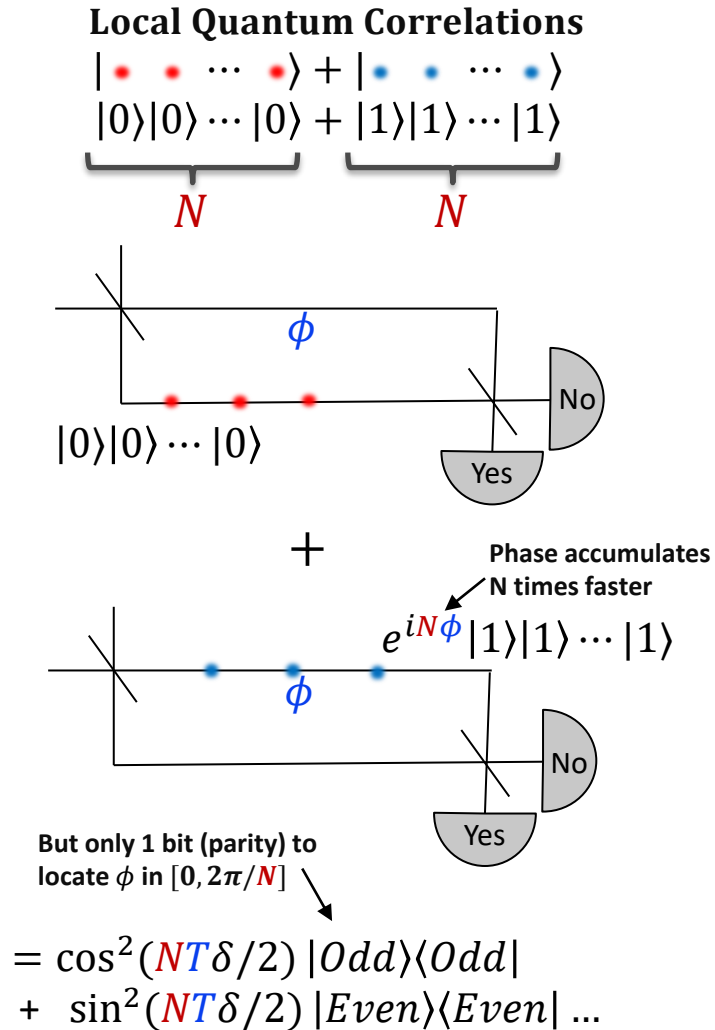
$$\begin{aligned} &= \cos^2(N\phi/2) |Odd\rangle\langle Odd| \\ &+ \sin^2(N\phi/2) |Even\rangle\langle Even| \dots \end{aligned}$$



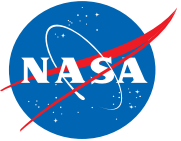
Geodesy using quantum networks of clocks



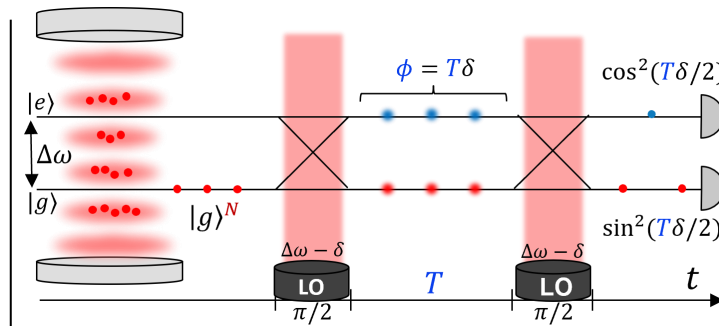
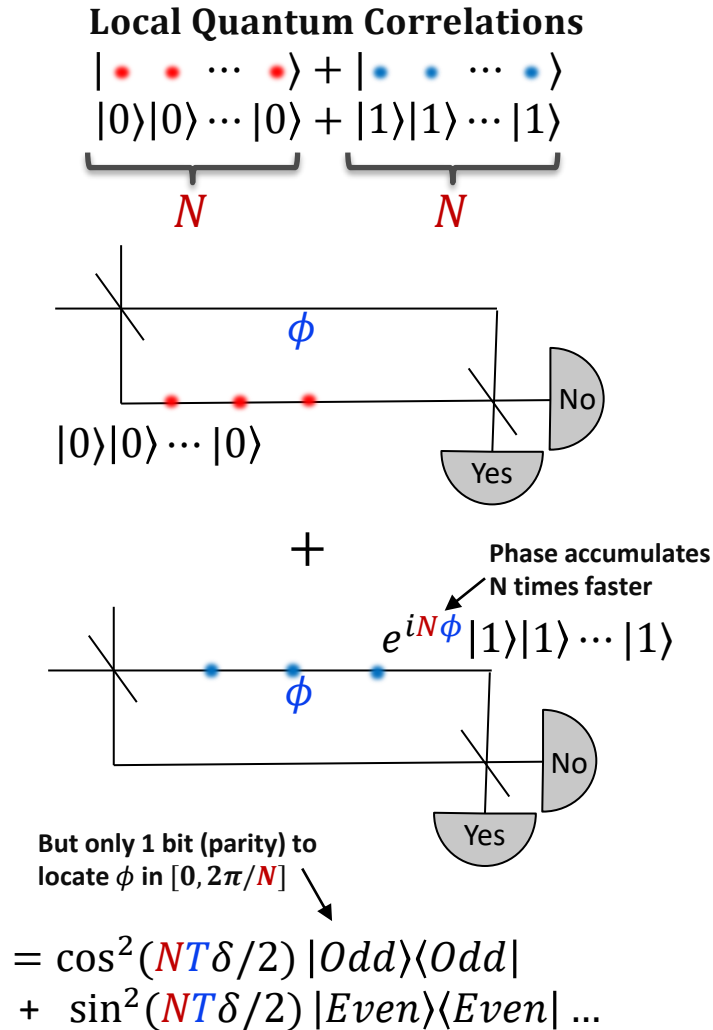
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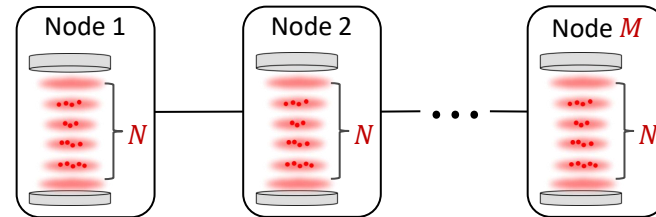
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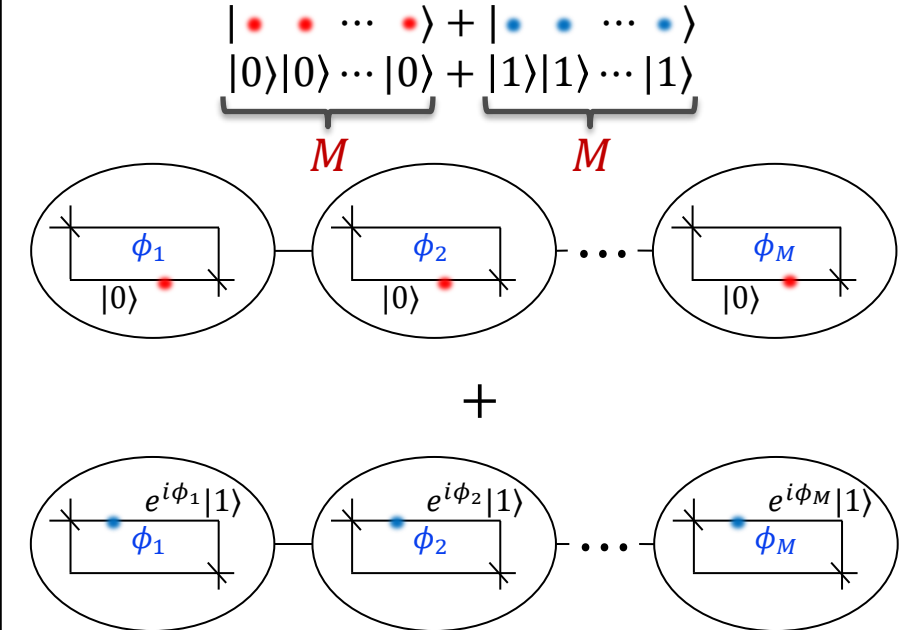


Example: $M=25$ nodes with $N = 1000$ atoms



Network Type	$\Delta\delta$	N=1000 atoms and M=25 nodes
Single Sr Clock	$1/\sqrt{N}$	$\sim 10^{-18}$
Classical network	$1/\sqrt{MN}$	$\sim 2 \cdot 10^{-19}$
Quantum network	$1/MN$	$\sim 10^{-21}$

Nonlocal Correlations (Entanglement)



$$= |0\rangle|0\rangle \dots |0\rangle + e^{i(\phi_1 + \dots + \phi_M)} |1\rangle|1\rangle \dots |1\rangle$$

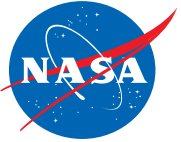
$$= \cos^2(MT\delta/2) |Odd\rangle\langle Odd| + \sin^2(MT\delta/2) |Even\rangle\langle Even| \dots$$

Center-of-mass (COM) phase accumulates M times faster

Again, only one bit (parity) to locate ϕ in $[0, 2\pi/M]$

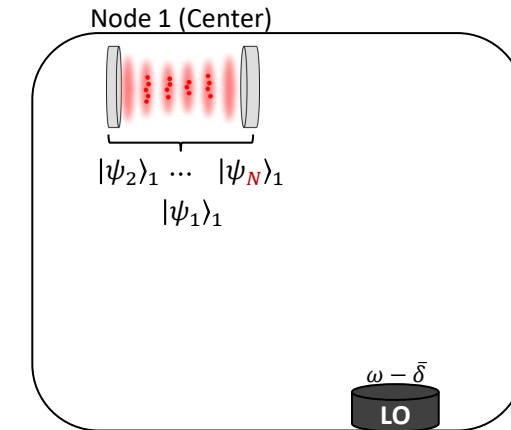
Geodesy using quantum networks of clocks

Quantum processing for entangled clock networks

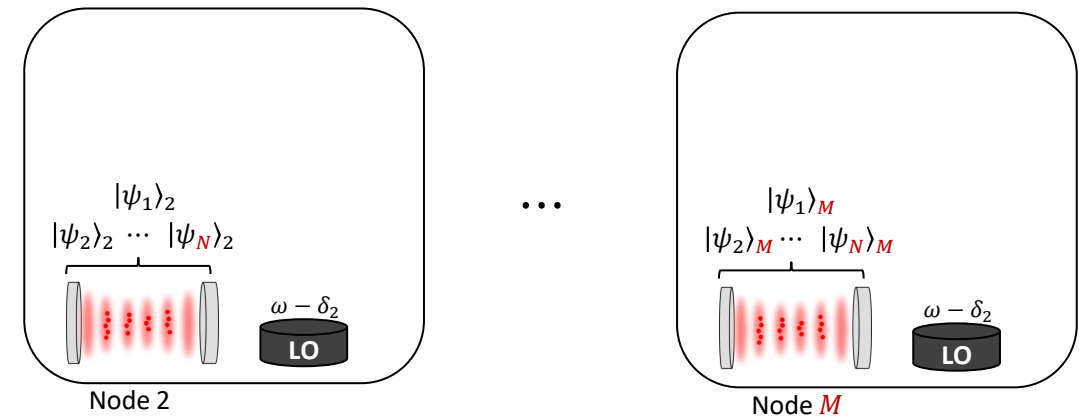


Adapted from: Kómár, P., Kessler, E., Bishof, M. *et al.* A quantum network of clocks. *Nature Phys* **10**, 582–587 (2014)

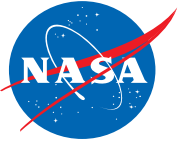
Each satellite contains a local oscillator (LO) and N atomic clock qubits.



Establishing a network of entangled clocks requires both **high-rate entanglement distribution** and **quantum processing**.



Geodesy using quantum networks of clocks



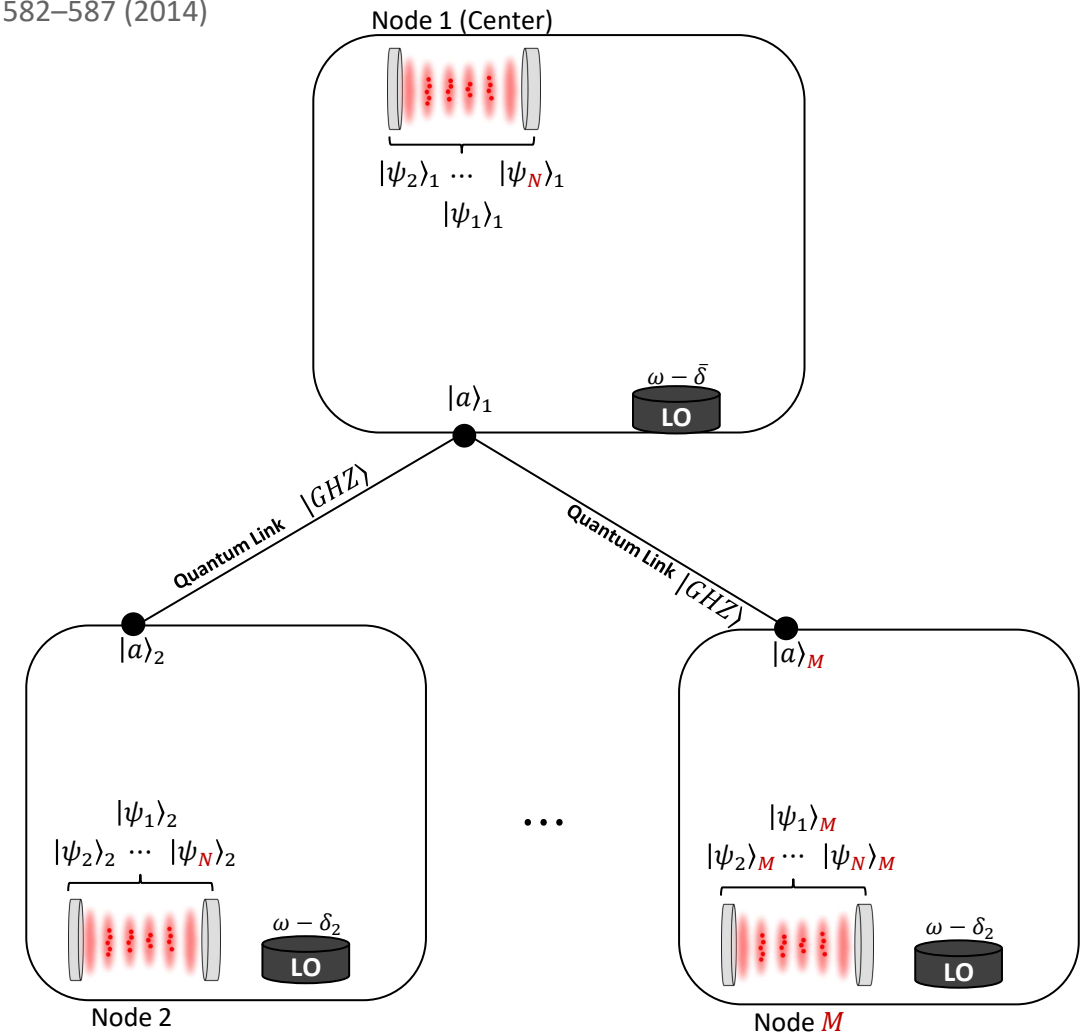
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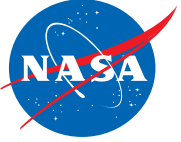
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1. An GHZ state $|\mathbf{0}\rangle_1 \cdots |\mathbf{0}\rangle_M + |\mathbf{1}\rangle_1 \cdots |\mathbf{1}\rangle_M$ of M auxiliary qubits $|a\rangle_j$ is distributed from a central node.

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Geodesy using quantum networks of clocks



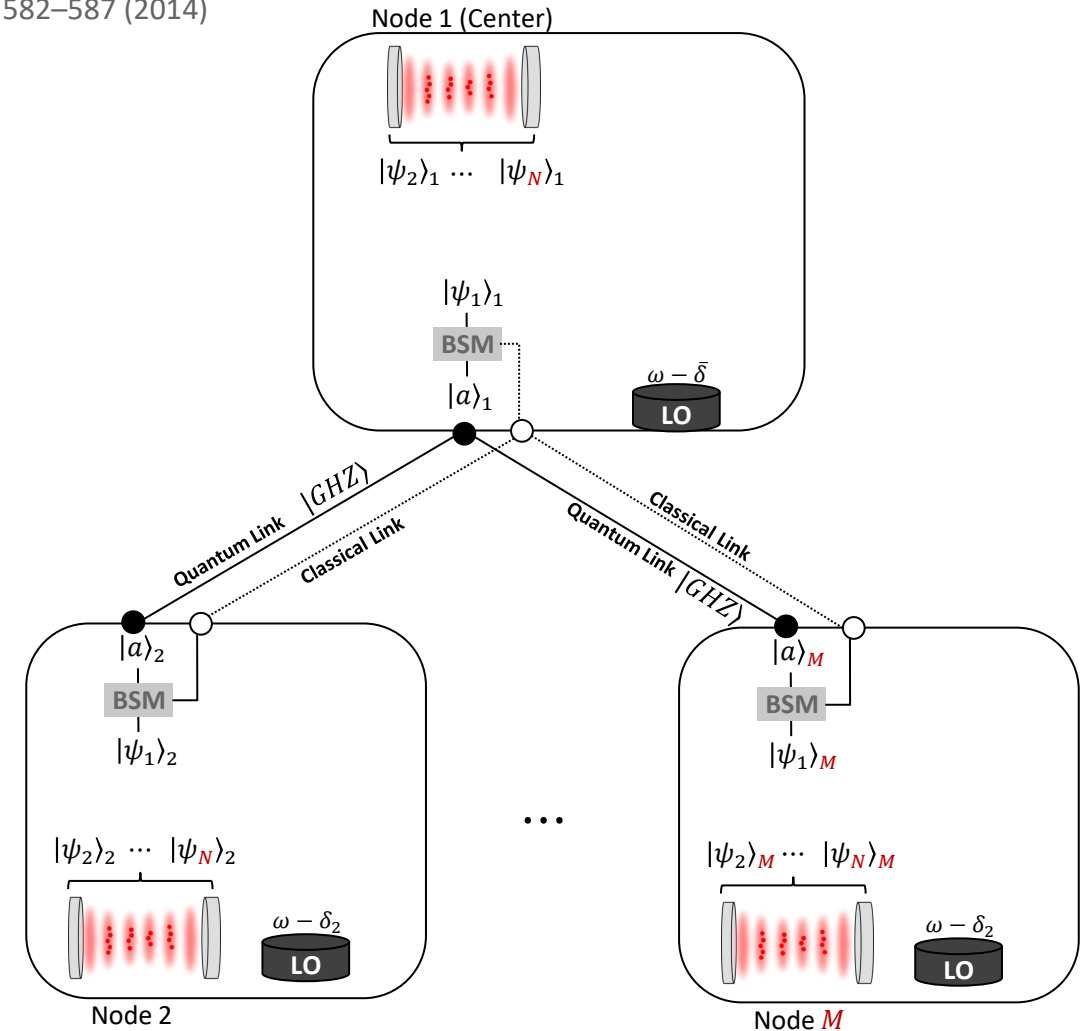
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2. Results of Bell state measurements at each node are exchanged over classical links to transfer the auxiliary GHZ state to a GHZ state consisting of the first clock qubit $|\psi_1\rangle_j$ at each node j .

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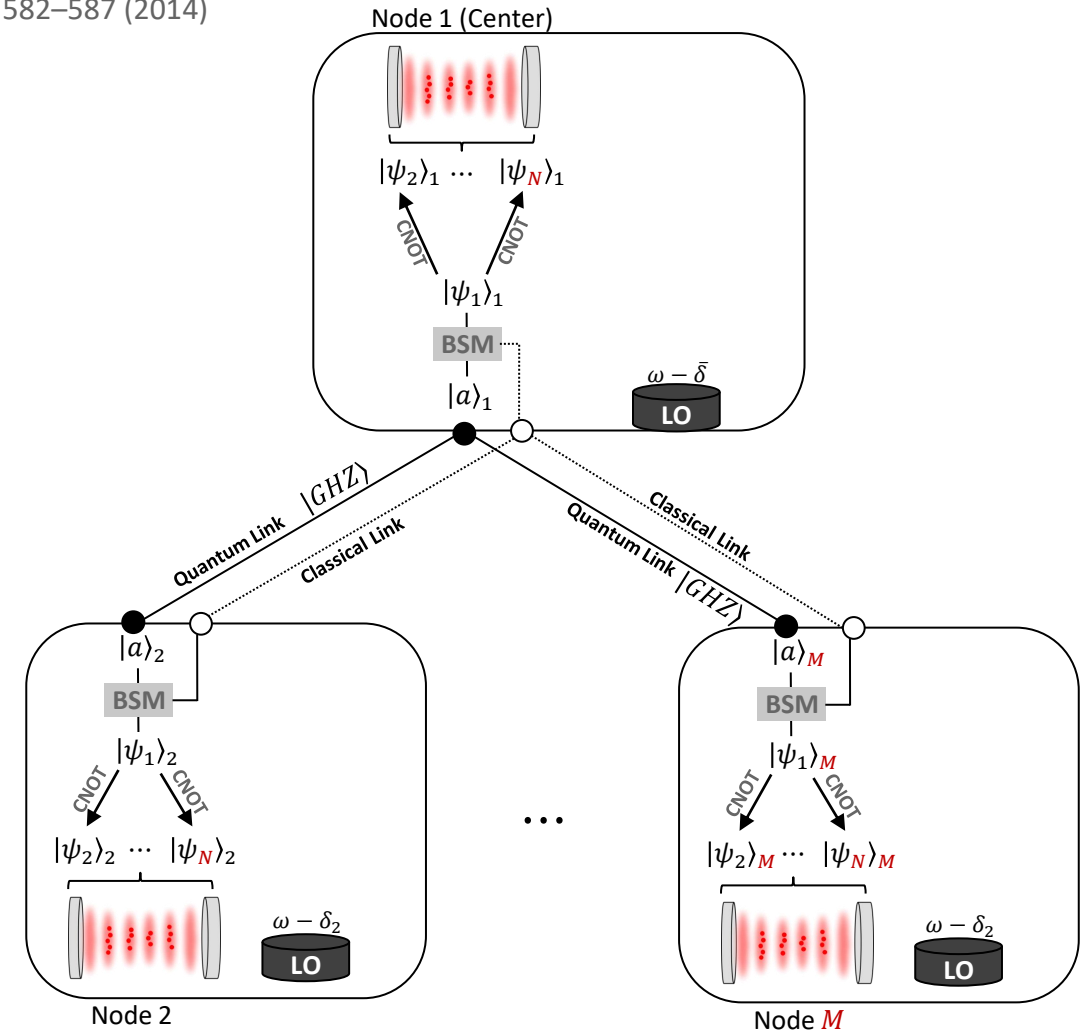
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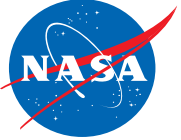
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3. This entanglement is extended to the other clock qubits at each node via CNOT gates with the first clock qubit $|\psi_1\rangle_j$.

Establishing a network of entangled clocks requires both **high-rate entanglement distribution** and **quantum processing**.



Geodesy using quantum networks of clocks



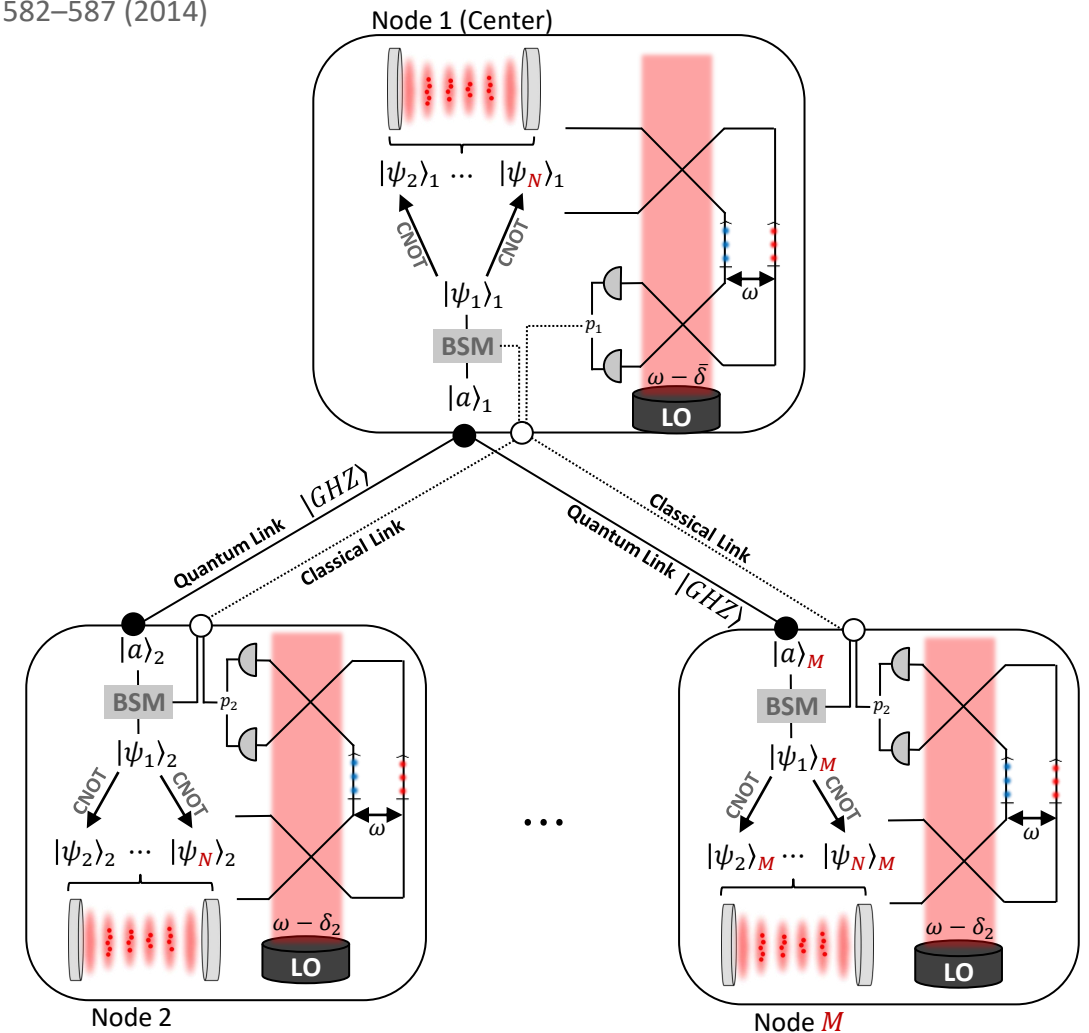
Quantum processing for entangled clock networks

Adapted from: Kómár, P., Kessler, E., Bishof, M. *et al.* A quantum network of clocks. *Nature Phys* **10**, 582–587 (2014)

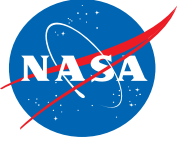
Each satellite contains a local oscillator (LO) and N atomic clock qubits.

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4. The clock qubits are interrogated by each LO yielding a parity measurement p_j at each node sent classically to a center node where the center-of-mass (COM) detuning $\bar{\delta}$ is determined.

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Geodesy using quantum networks of clocks



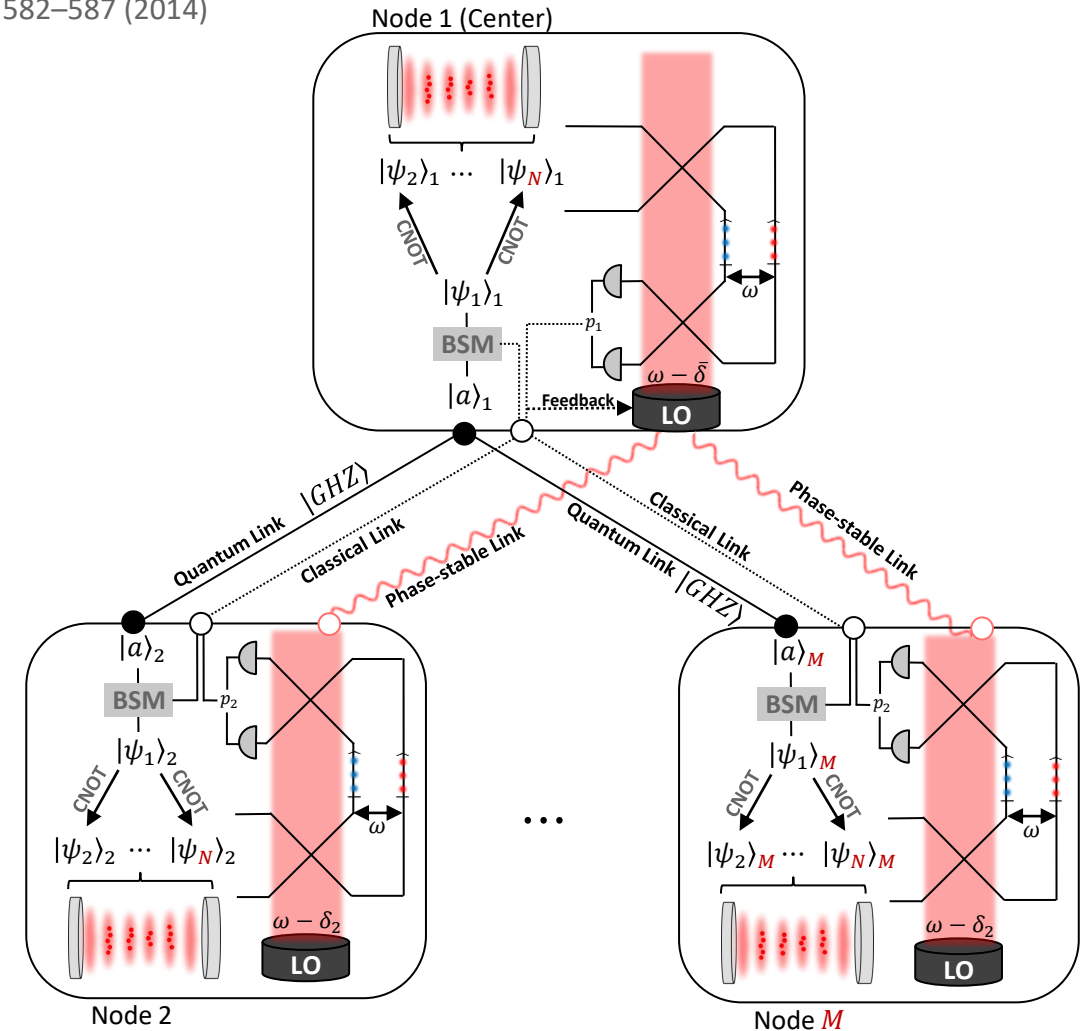
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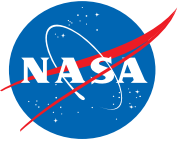
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4. The clock qubits are interrogated by each LO yielding a parity measurement p_j at each node sent classically to a center node where the center-of-mass (COM) detuning $\bar{\delta}$ is determined.
5. Each node sends the LO field to the center via phase-stable links. The center node synthesizes the COM frequency and distributes the stabilized clock signal back to each node via individual error signals $\bar{\delta}_j$.

Establishing a network of entangled clocks requires both **high-rate entanglement distribution** and **quantum processing**.

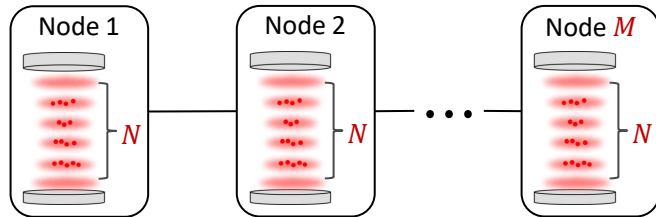


Geodesy using quantum networks of clocks

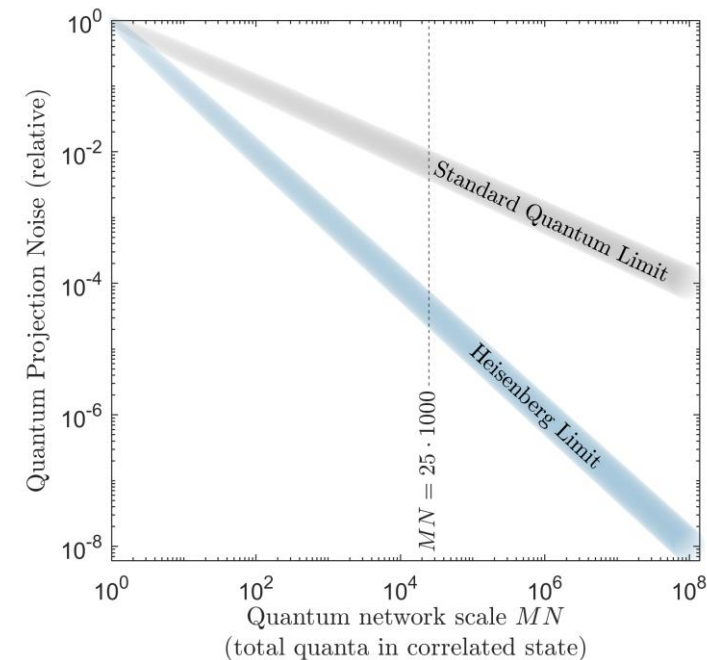
Scaling of quantum networks



Example: $M=25$ nodes with $N = 1000$ atoms



Network Type	$\Delta\delta$	N=1000 atoms and M=25 nodes
Single Sr Clock	$1/\sqrt{N}$	$\sim 10^{-18}$
Classical network	$1/\sqrt{MN}$	$\sim 2 \cdot 10^{-19}$
Quantum network	$1/MN$	$\sim 10^{-21}$



It remains to be seen how real quantum networks will scale

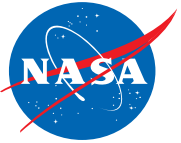
Significant potential gains depending on the governing “Moore’s law” of quantum networks

Part IV:

OPTICAL VLBI USING QUANTUM NETWORKS

Optical VLBI using quantum networks

Optical VLBI for studying exoplanetary systems



Angular resolution

$$\Delta\theta \sim \frac{\lambda}{B}$$

Very Large Telescope Interferometer (VLTI):

$B = 130 \text{ m}$

$\Delta\theta \sim 0.01 \mu\text{rad}$

Center for High Angular Resolution Astronomy (CHARA):

$B = 330 \text{ m}$

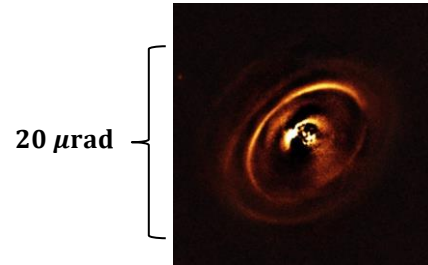
$\Delta\theta \sim 0.001 \mu\text{rad}$

Event Horizon Telescope (EHT):

$\lambda \sim 1.3 \text{ mm}$

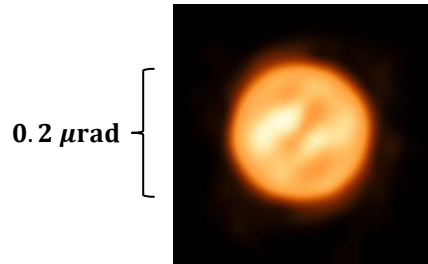
$B \sim 10,000 \text{ km}$

$\Delta\theta \sim 0.0001 \mu\text{rad}$



$20 \mu\text{rad}$

Planetary disk imaged by
VLT SPHERE instrument.
Credit: ESO/J. de Boer et al.

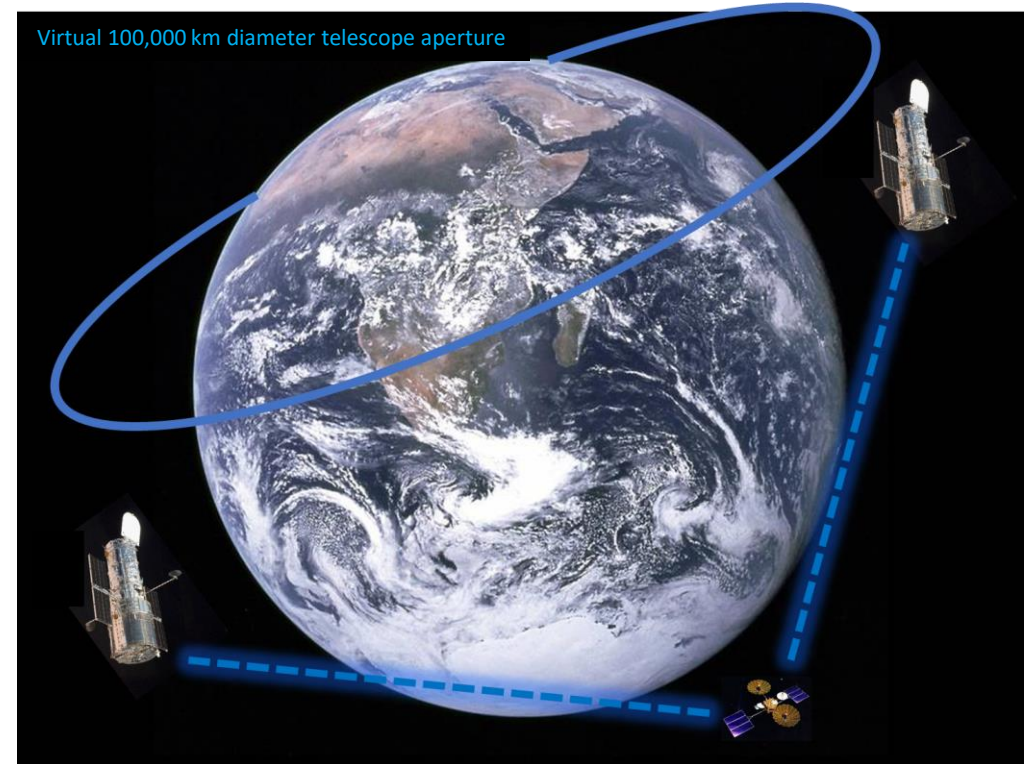


$0.2 \mu\text{rad}$

VLT reconstructed view
of the surface of Antares.
Credit: ESO/K. Ohnaka



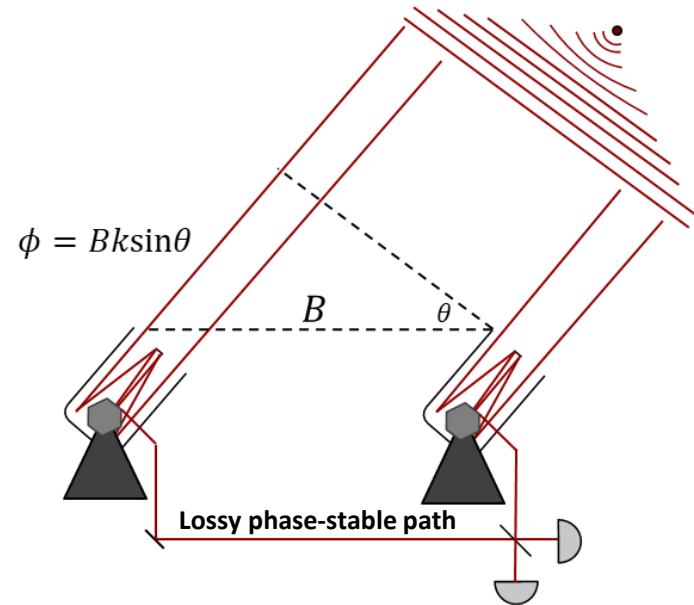
Artist conception of HR8799e, the first
exoplanet directly detected by optical
interferometry. Credit: ESO/L. Calçada



Optical VLBI using quantum networks

Quantum teleportation for extending baselines

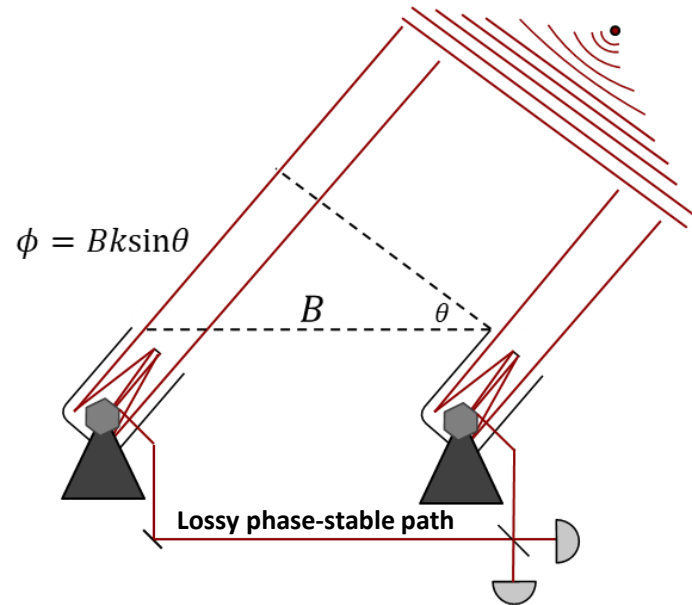
Direct detection optical baselines limited by signal losses



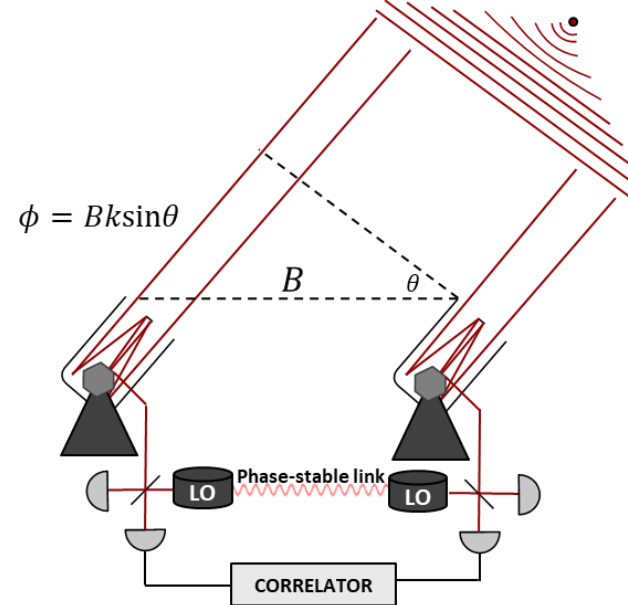
Optical VLBI using quantum networks

Quantum teleportation for extending baselines

Direct detection optical baselines limited by signal losses

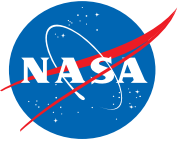


Heterodyne detection limited by *local* shot noise

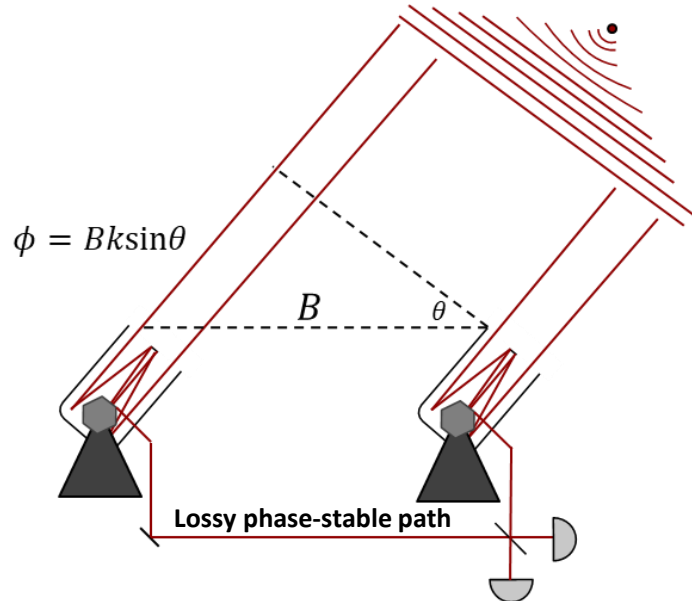


Optical VLBI using quantum networks

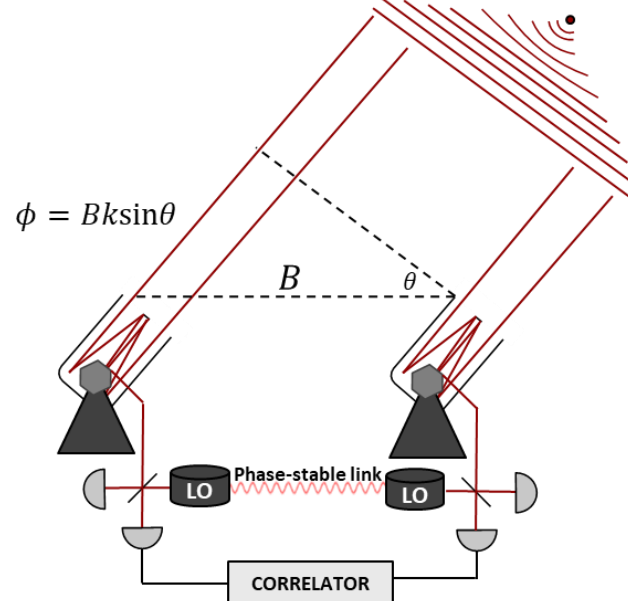
Quantum teleportation for extending baselines



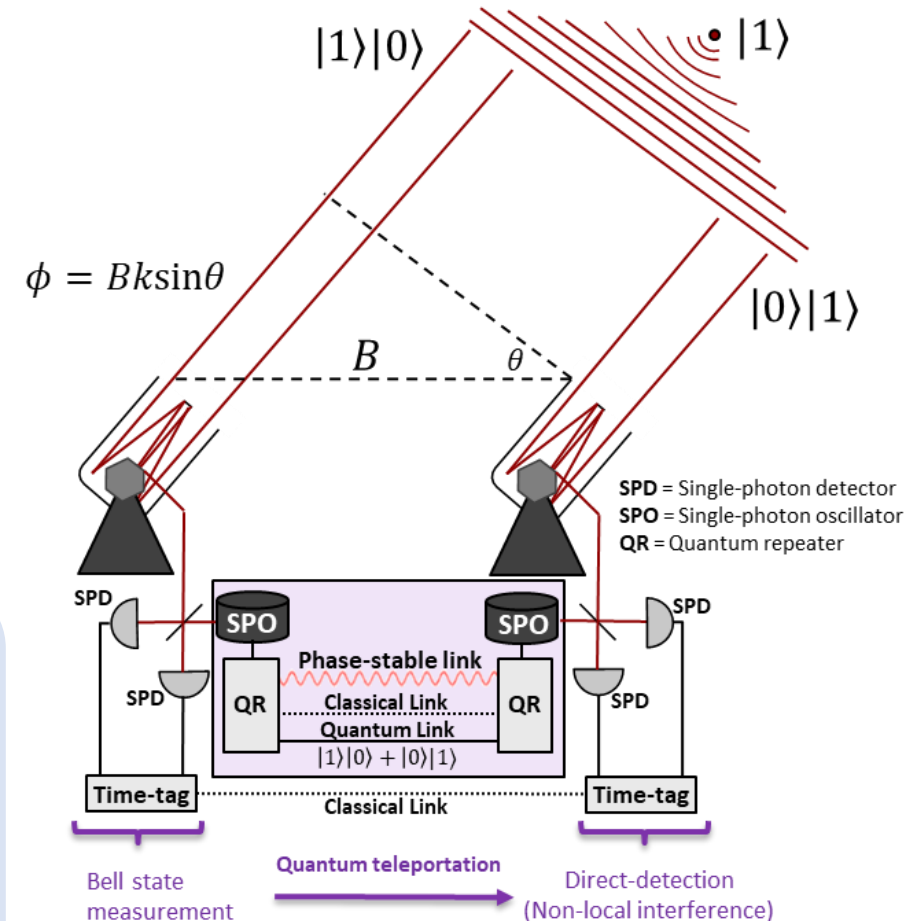
Direct detection optical baselines limited by signal losses



Heterodyne detection limited by *local* shot noise



Non-local interference using quantum repeaters to eliminate baseline losses (Gottesman, Jennewein, and Croke, 2012)



Baseline optical losses and local shot noise can be overcome using quantum repeaters to share entangled states to produce non-local interference.

- Problem:** Requires **very high-rate entanglement distribution**

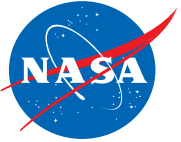
Entangled photon rate $\sim$ Optical system bandwidth

(one photon per time-frequency mode)

Distribution rate can be reduced with more sophisticated **quantum processing/memory**.

Adapted from D. Gottesman, T. Jennewein, and S. Croke Phys. Rev. Lett. **109**, 2012

Summary



- Priorities in planetary science are big questions requiring the most demanding technology which is not limited only to fundamental physics
- Once systems are engineered to hard constraints in quantum resources (i.e. the standard quantum limit), quantum networks enable orders of magnitude improvement
- Like gravitational wave astronomy, high resolution geodesy and optical telescoping provide examples which **may soon reach the limits accessible to classical systems**
- In contrast to metrology with continuous-variable states (e.g. squeezed states, LIGO), the most ambitious applications of discrete-variable quantum networks demand **sophisticated quantum processing**
- Nevertheless, for **resource-limited applications** quantum networks may open new regimes of study throughout Earth science, planetary science, and astrophysics

Other References

- [1] Mayrhofer, R., Pail, R. (2012) Future satellite gravity field missions: feasibility study of post-Newtonian method. In: Kenyon, S., Pacino, M.C., Marti, U. (eds.), Geodesy for Planet Earth, IAG Symp. 136: 231-238, Springer-Verlag, Berlin, Heidelberg
- [2] First direct detection of an exoplanet by optical interferometry - Astrometry and K-band spectroscopy of HR 8799 e. GRAVITY Collaboration, S. Lacour, M. Nowak, J. Wang, O. Pfuhl, F. Eisenhauer, R. Abuter, A. Amorim, N. Anugu, M. Benisty, J. P. Berger, H. Beust, N. Blind, M. Bonnefoy, H. Bonnet, P. Bourget, W. Brandner, A. Buron, C. Collin, B. Charnay, F. Chapron, Y. Clénet, V. Coudé du Foresto, P. T. de Zeeuw, C. Deen, R. Dembet, J. Dexter, G. Duvert, A. Eckart, N. M. Förster Schreiber, P. Fédou, P. Garcia, R. Garcia Lopez, F. Gao, E. Gendron, R. Genzel, S. Gillessen, P. Gordo, A. Greenbaum, M. Habibi, X. Haubois, F. Haußmann, Th. Henning, S. Hippler, M. Horrobin, Z. Hubert, A. Jimenez Rosales, L. Jocou, S. Kendrew, P. Kervella, J. Kolb, A.-M. Lagrange, V. Lapeyrière, J.-B. Le Bouquin, P. Léna, M. Lippa, R. Lenzen, A.-L. Maire, P. Mollière, T. Ott, T. Paumard, K. Perraut, G. Perrin, L. Pueyo, S. Rabien, A. Ramírez, C. Rau, G. Rodríguez-Coira, G. Rousset, J. Sanchez-Bermudez, S. Scheithauer, N. Schuhler, O. Straub, C. Straubeier, E. Sturm, L. J. Tacconi, F. Vincent, E. F. van Dishoeck, S. von Fellenberg, I. Wank, I. Waisberg, F. Widmann, E. Wieprecht, M. Wiest, E. Wieszorek, J. Woillez, S. Yazici, D. Ziegler and G. Zins. A&A, 623 (2019) L11
- [3] van Belle, G., Armstrong, J. T., Baines, E., Llama, J., and Schmitt, H., "The Navy Precision Optical Interferometer", vol. 51, no. 7, 2019.