

COSMIC BELL: TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH ASTROPHYSICAL OBSERVATIONS



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SSP 2011 - NEW MEXICO TECH



11/14/15

Summer Science Program Alumni Dinner, MIT Media Lab

COSMIC BELL TEAM



**Prof. David
Kaiser** ^{1,2}



**Dr. Andrew
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**Prof. Alan
Guth** ¹



**Prof. Brian
Keating** ⁴



**Prof. Anton
Zeilinger** ⁵



**Dr. Jason
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Other Collaborators

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Marissa Giustina ⁵

Isabella Sanders ¹,
Anthony Mark ¹



1:MIT Physics/CTP, 2:MIT STS, 3:U. Chicago
KICP / Harvey Mudd, 4: UCSD, 5: Vienna IQOQI,
6: Max Planck, 7: JPL/Caltech

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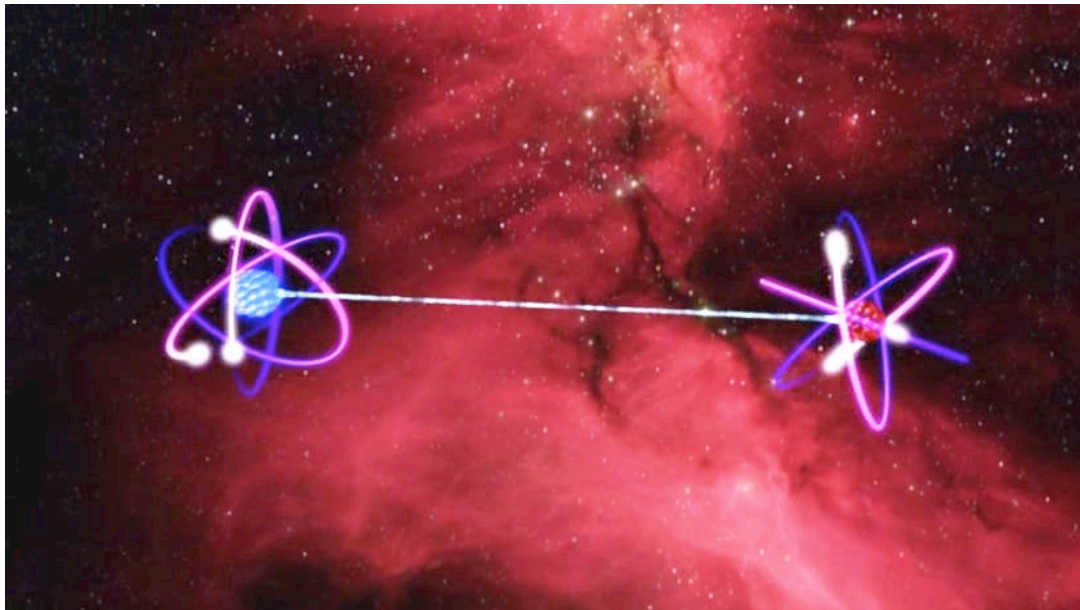


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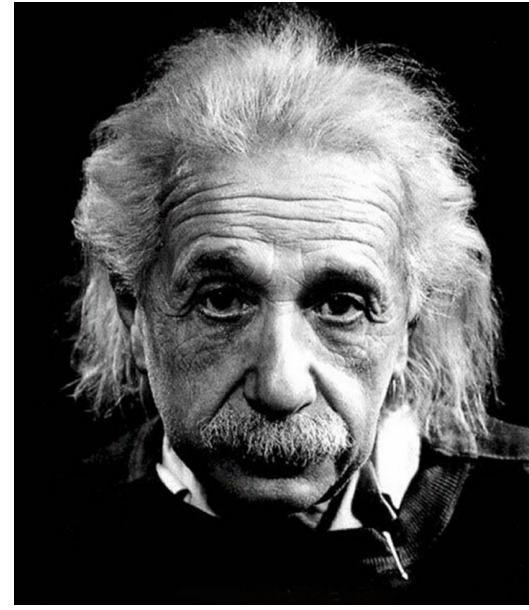
QUANTUM ENTANGLEMENT 101

Entanglement: Paired systems with correlated (or anti-correlated) properties

Measure #1, instantly know something about #2



<https://kuleuvenblogt.files.wordpress.com/2014/06/entangled-atoms.jpg>



<http://xeon24.com/data/wallpapers/2/508769-albert-einstein.jpg>

Is quantum mechanics complete or just spooky?

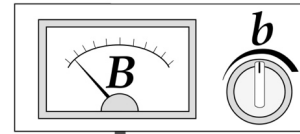
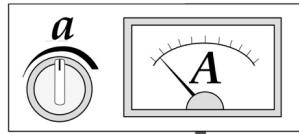
CHOOSING DETECTOR SETTINGS



Anthony



Albert



Source of Entangled Particles

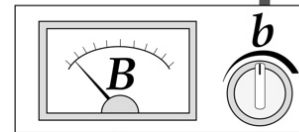
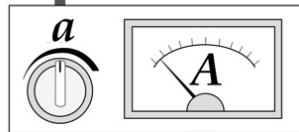


Bohr

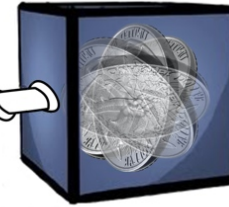


IsaBella

Random
Number
Generator



Source of Entangled Particles



Random
Number
Generator



Quasar x



Source of Entangled Particles

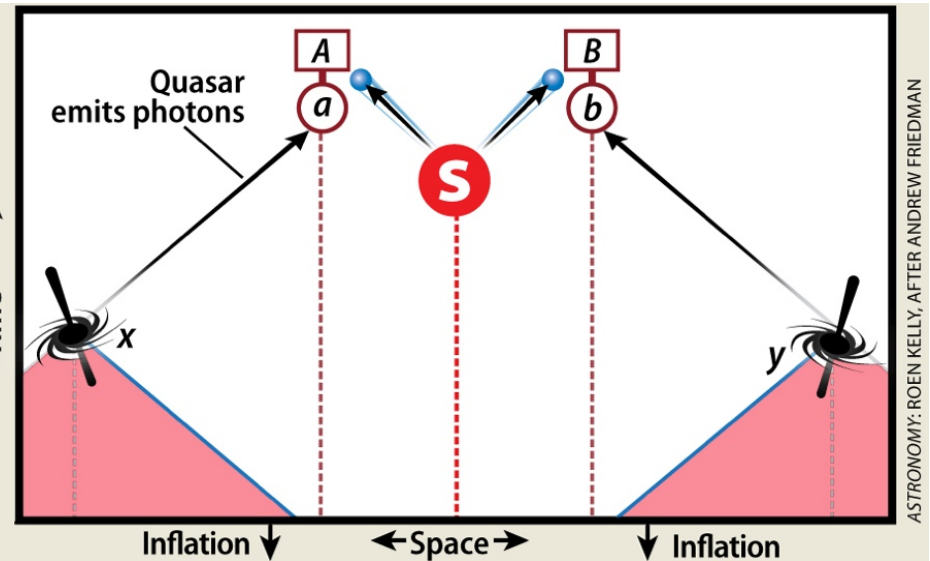
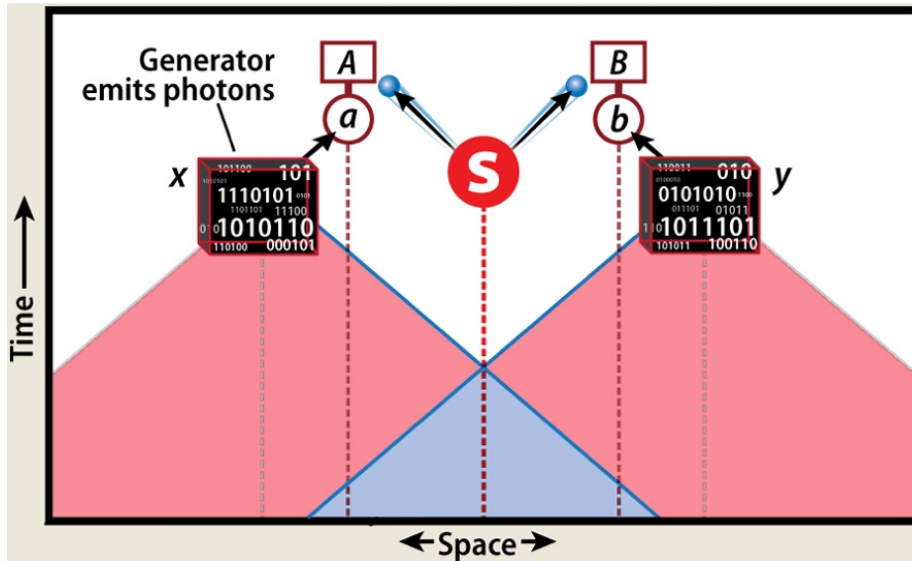


Quasar y

SPACE-TIME DIAGRAM

Standard Bell Test

Cosmic Bell Test



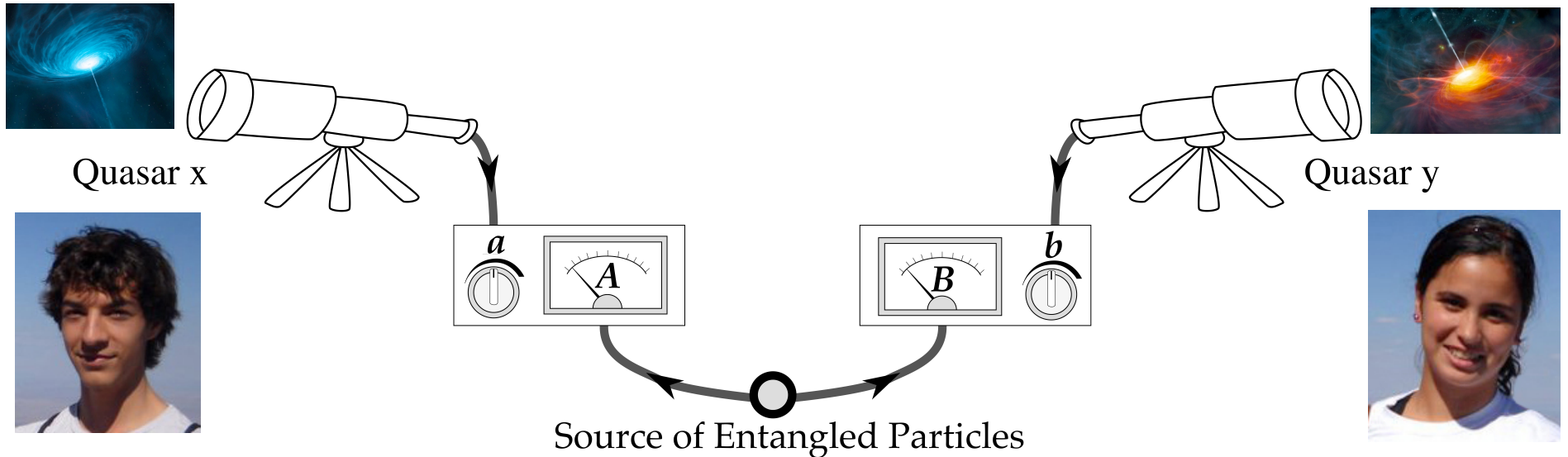
ASTRONOMY: ROEN KELLY, AFTER ANDREW FRIEDMAN

Past light cones from random number generators overlap milliseconds before test.

Past light cones from quasars don't overlap since big bang, 13.8 billion years ago.

	Source of entangled particles			Measurement outcomes
	Quasar			Random-number generator
				Detectors set

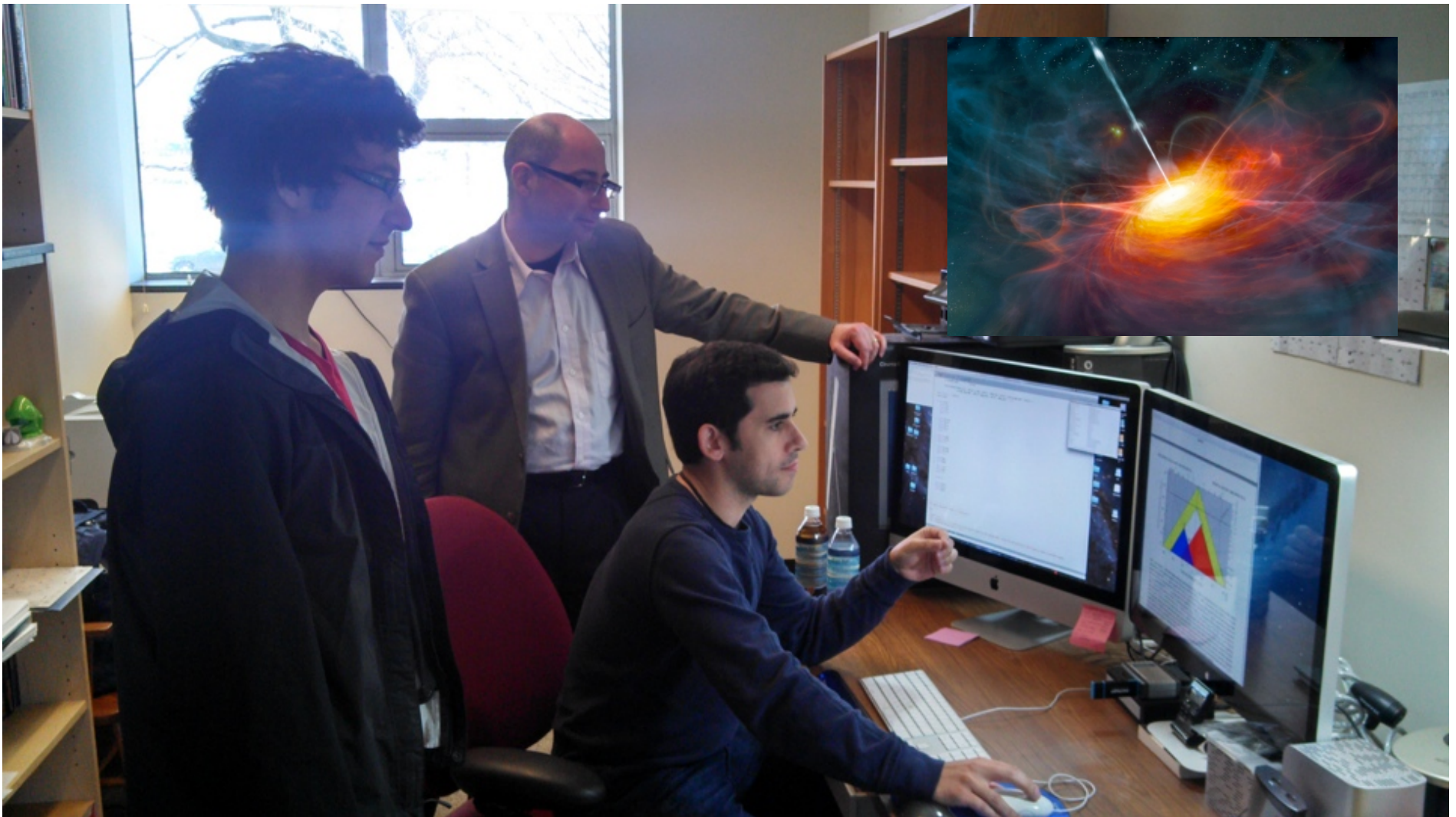
COSMIC BELL TEST



Let the Universe decide how
to set up experiment!

Use quasars as cosmic random
number generators

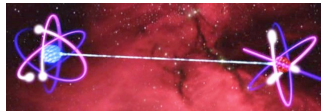
MILLIONS OF QUASARS



Isabella and Anthony helped Prof. Kaiser and I search the world database of over 1 million quasars for optimal candidate pairs!

COSMIC BELL IN THE NEWS

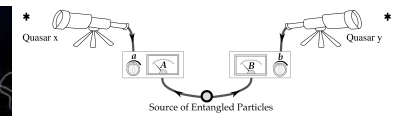
MIT News
ON CAMPUS AND AROUND THE WORLD



Cosmic conundrum

Can the cosmos test quantum entanglement?

Albert Einstein hated the idea he called "spooky actions at a distance," but astronomers now are hoping to illuminate some of these tricky quantum puzzles. *by Andrew Friedman*



Closing the 'free will' loophole

MIT researchers propose using distant quasars to test Bell's theorem.

Jennifer Chu, MIT News Office
February 20, 2014

Forbes / Tech

JUN 18, 2014 @ 07:00 AM 16,356 VIEWS

Cosmic Test For Quantum Physics' Last Major Loophole



Quasar Experiment May Shed Light on Quantum Physics and Free Will

BY CHARLES Q. CHOI, INSIDE SCIENCE

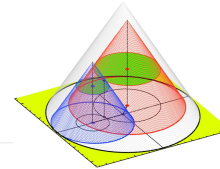
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MAR

QUANTUM PHYSICS

The Universe Made Me Do It? Testing "Free Will" With Distant Quasars

By Andrew Friedman on Wed, 19 Mar 2014



Sunday Review

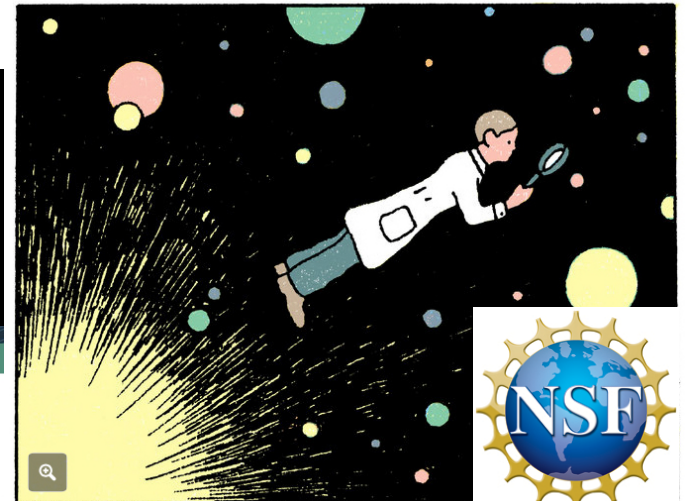
The New York Times

Is Quantum Entanglement Real?

Gray Matter

NOV. 14, 2014

By DAVID KAISER



11/14/15

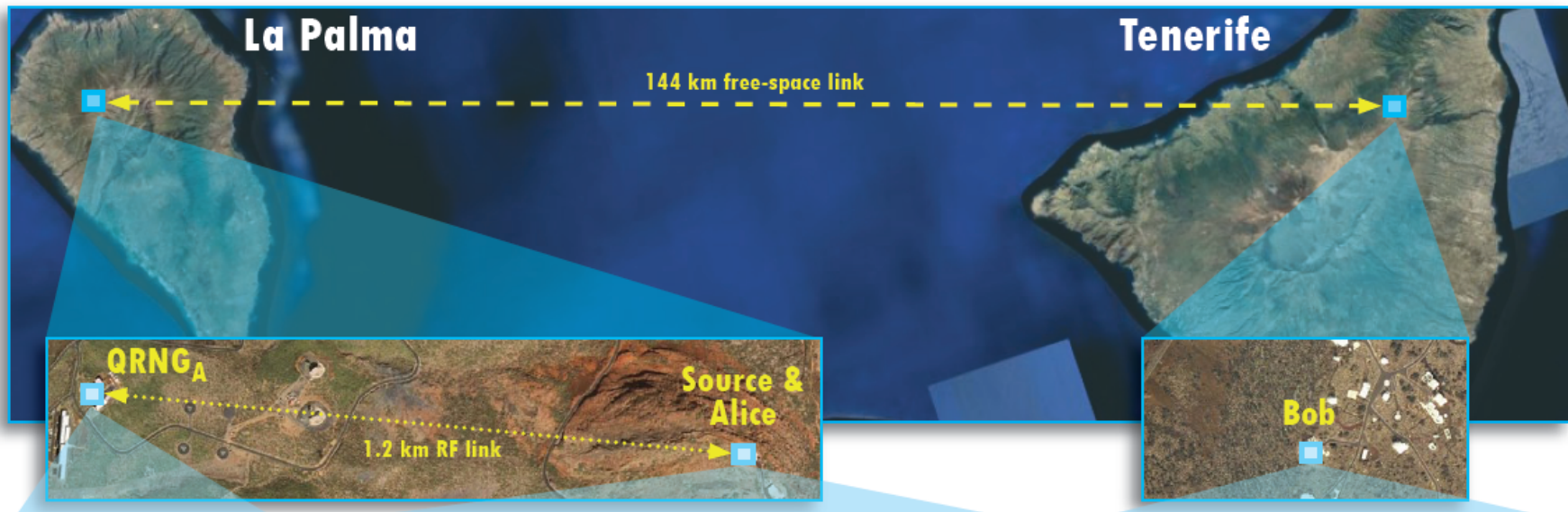
Summer Science Program Alumni Dinner, MIT Media Lab

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ZEILINGER GROUP EXPERIMENTS



Prof. Anton Zeilinger



CANARY ISLANDS TELESCOPES



**Roque de los Muchachos
Observatory on La Palma**

**Teide Observatory
on Tenerife**



PROF. MEREDITH HUGHES

Wesleyan University, Department of Astronomy



“Planet Formation Through Radio Eyes”



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POPULAR ARTICLES

[Can the Cosmos Test Quantum Entanglement?](#), Friedman, A.S., *Astronomy*, Vol. 42, Issue 10, October 2014, pg. 28-33
[The Universe Made Me Do It? Testing "Free Will" With Distant Quasars](#), Friedman, A.S., *NOVA Physics Blog: The Nature of Reality*, Mar 9 2014

ACADEMIC PAPERS

[Testing Bell's Inequality with Cosmic Photons: Closing the Setting-Independence Loophole](#), Gallicchio, J., Friedman, A.S., Kaiser, D.I., *Physical Review Letters*, Vol. 112, Issue 11, id. 110405, 5 pp. 2014 ([arXiv:1310.3288](#)) ([DOI](#))
[The Shared Causal Pasts and Futures of Cosmological Events](#), Friedman, A.S., Kaiser, D.I., & Gallicchio, J. *Physical Review D*, Vol. 88, Issue 4, id. 044038, 18 pp. 2013 ([arXiv:1305.3943](#)) ([DOI](#))

MEDIA COVERAGE

[Is Quantum Entanglement Real?](#), David Kaiser, *New York Times*, *Sunday Review*, 11/14/14
[Cosmic Test For Quantum Physics' Last Major Loophole](#), Bruce Dorminey, *Forbes*, 6/18/14
[Bell's Theorem: Closing the Loopholes](#), Iulia Georgescu, *Nature Physics*, *News & Views*, 4/1/14
[Cosmic Experiment Aims To Close Loophole In Quantum Theory: Distant quasars could help confirm 'spooky action' between particles](#), Charles Q. Choi, *Inside Science*, *NBC News*, 3/5/14
[Cosmic light could close quantum-weirdness loophole: Distant quasars would decide whether quantum entanglement is an illusion](#), Zeeya Merali, *Nature*, *News & Comment*, 2/25/14
[Is entanglement real or is there a super-deterministic cosmic conspiracy? Researchers use quasars to kill off the last of the quantum hidden variables](#), Matthew Francis, *Ars Technica*, 2/21/14
[Closing the 'free will' loophole: MIT researchers propose using distant quasars to test Bell's theorem](#), Jennifer Chu, *MIT News Office*, 2/20/14

FREE WILL REFERENCES

[The Quantum Physics of Free Will](#), George Musser, *Scientific American* blog, 2012
[Do Electrons Have Free Will? The Conway-Kochen Free Will Theorem - Closing the Free Will Loophole, Cracking the Nutshell](#), Dolors, 2015
[The Ghost in the Quantum Turing Machine](#), Scott Aaronson, ([arXiv:1306.0159](#)), 2013, To appear in "The Once and Future Turing: Computing the World," a collection edited by S. Barry Cooper and Andrew Hodges.
[Programming the Universe](#), Seth Lloyd, *Vintage*, 2007
[A Turing Test for Free Will](#), Seth Lloyd, *Phil. Trans. Roy. Soc. A* 28, 3597-3610 (2012) ([arXiv:1310.3225](#))
[Violation of Local Realism With Freedom of Choice](#), Sheidl, Thomas S. et al., *Proceedings of the National Academy of Sciences, USA*, 107, 46, p. 19708-19713, 2010
[Dance of the Photons](#), Anton Zeilinger, Farrar, Straus & Giroux; 1st Ed., 2010