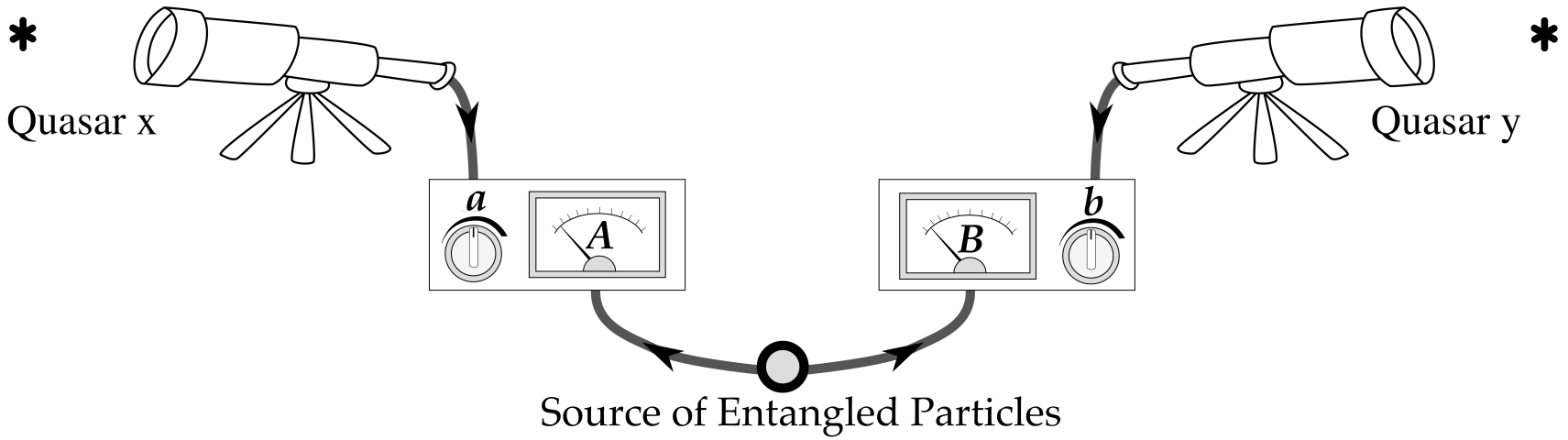

TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH COSMOLOGICAL OBSERVATIONS

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+***MIT UROP Students***
Isabella Sanders
Anthony Mark

"*Testing Bell's Inequality with Cosmic Photons: Closing the Setting-Independence Loophole*"

Gallicchio, Friedman, & Kaiser 2014 = GFK14

***Phys. Rev. Lett. accepted*, arXiv:1310.3288**

"*The Shared Causal Pasts and Futures of Cosmological Events*"

Friedman, Kaiser & Gallicchio 2013 = F13a

Phys. Rev. D. Vol. 88, Iss. 4, 044038, arXiv:1305.3943

1:MIT Physics, 2:MIT CTP, 3:MIT STS, 4:U. Chicago KICP, 5:South Pole Telescope

OUTLINE

1. Bell's Theorem

2. *Cosmic Bell* Experiment

Gallicchio, Friedman, & Kaiser 2014 (GFK14)

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4. Causally Disconnected Quasars

Friedman+2014b *in prep*. (F14b)

5. Actually Doing the Experiment?

COSMIC BELL IN THE NEWS

massachusetts institute of technology

MITnews

Closing the 'free will' loophole

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

Jennifer Chu, MIT News Office

February 20, 2014

Share

Artist's interpretation of ULAS J1120+0641, a very distant quasar.
IMAGE: ESO/M. KORNMESSER

In a paper published this week in the journal *Physical Review Letters*, MIT researchers propose an experiment that may close the last major loophole of Bell's inequality — a 50-year-old theorem that, if violated by experiments, would mean that our universe is based not on the textbook laws of classical physics, but on the less-tangible probabilities of quantum mechanics.

nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio &

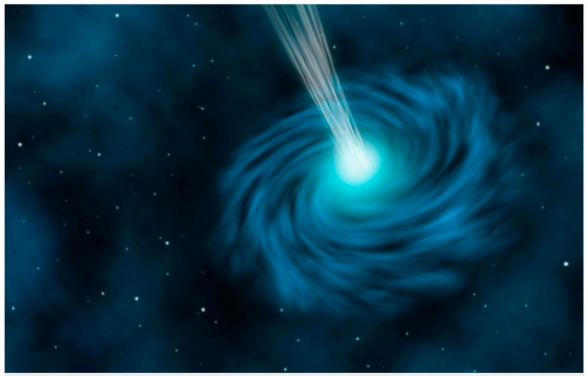
News & Comment > News > 2014 > February > Article

NATURE | NEWS

Cosmic light could close quantum-weirdness loophole

Distant quasars would decide whether quantum entanglement is an illusion.

Zeeya Merali 25 February 2014

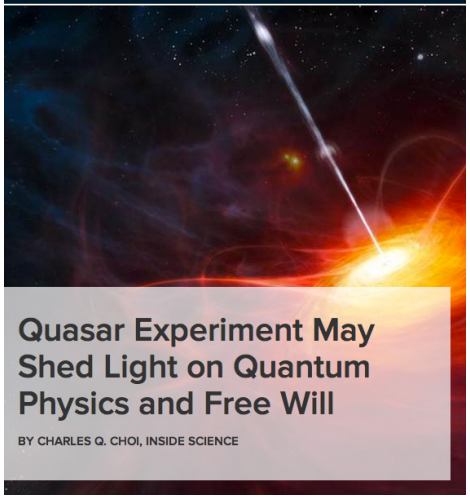


Artist's impression by J.R. Bale / Alamy

Distant quasars at opposite ends of the sky belong to regions of the observable Universe that have not been in contact since the first instants after the Big Bang — so that the quantum states of their light would be essentially unrelated.

menu NBC NEWS

SCIENCE / SPACE



Quasar Experiment May Shed Light on Quantum Physics and Free Will

BY CHARLES Q. CHOI, INSIDE SCIENCE

ars technica THE HEAD TO TOE GUIDE OF THE SEASON

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SCIENTIFIC METHOD / SCIENCE & EXPLORATION

Is entanglement real or is there a super-deterministic cosmic conspiracy?

Researchers use quasars to kill off the last of the quantum hidden variables.

by Matthew Francis - Feb 21 2014, 12:05pm EST

PHYSICAL SCIENCES | SPACE | 125

Composite optical and X-ray image of quasar 3C 186, one of the most distant yet observed. Two such quasars on opposite sides of the sky could close a loophole in interpreting quantum entanglement experiments.

media links on last slide

QM AND HIDDEN VARIABLES

1927 Copenhagen interpretation of QM (Bohr, Heisenberg)

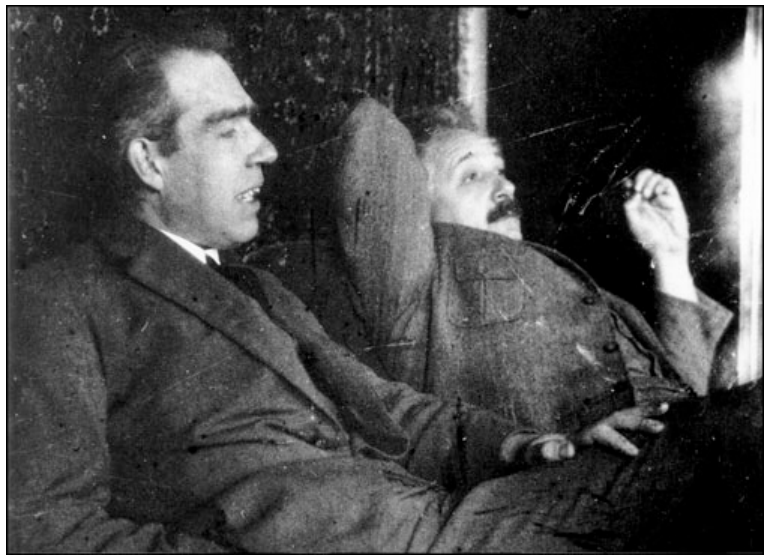
1935 Einstein-Podolsky-Rosen (EPR) paradox paper

1952 De Broglie-Bohm nonlocal hidden variable theory (Bohmian Mechanics)

1964 Bell's Theorem on local hidden variables

1972 First experimental Bell test (Freedman & Clauser 1972)

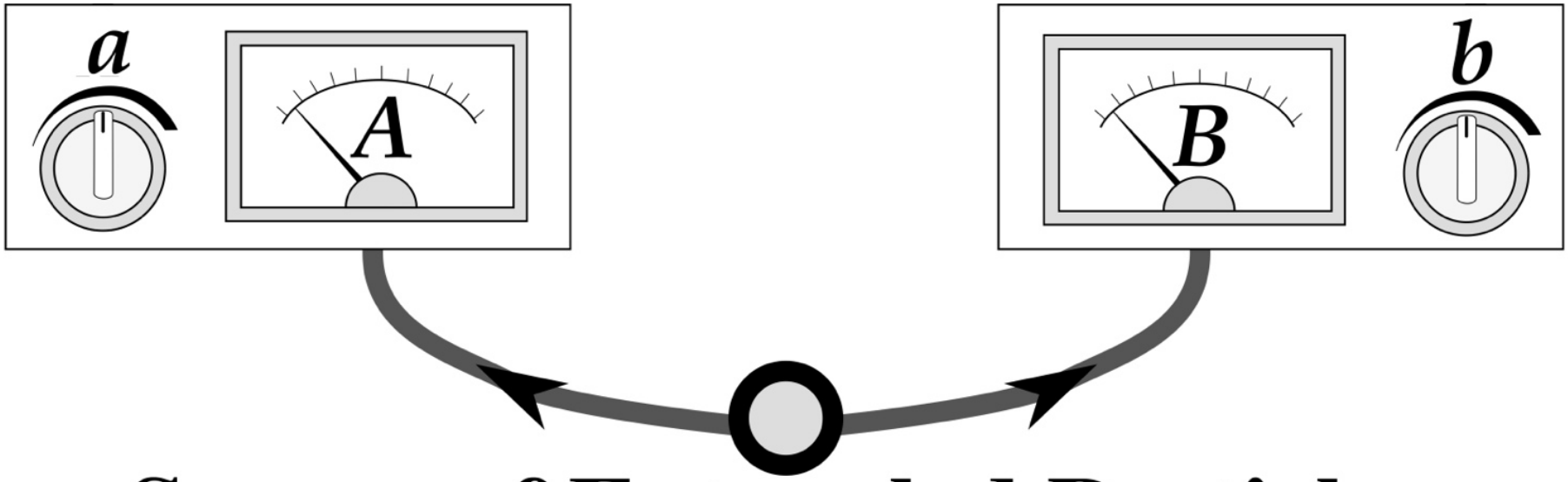
History Credit: Johannes Kofler http://www.qi.ubc.ca/Talks/TalkKofler.pdf



Bohr and Einstein, 1925

Bohr and Einstein, 1925
(in parallel universe where they agree)

EPR OR BELL EXPERIMENTS



a, b = *Settings*

A, B = *Outcomes*

Big question: ***Is the world local or non-local?***

If local, QM incomplete →Hidden variables.

BELL'S THEOREM ASSUMPTIONS

1. Realism

External reality exists and has definite properties, whether or not they are observed.

2. Locality

If distant systems no longer interact, nothing done to system 1 can affect system 2.

3. Setting Independence / "Free Will"

Detector settings choices independent and random.

Observers can choose experimental settings freely.

1,2,3 → Bell's Inequality

CHSH form: $S = E(a_1,b_1) + E(a_1,b_2) + E(a_2,b_1) - E(a_2,b_2) \leq 2$

QM Predictions + Actual Bell Experiments: $2 < S_{max} \leq 2\sqrt{2}$

$S_{max} > 2$ → At least one of 1,2,3 are false!

Einstein, Podolsky, & Rosen (EPR) 1935; Bell 1964; Clauser, Horne, Shimony, & Holt (CHSH) 1969

LOCAL HIDDEN VARIABLES

THEOREM

$S_{max} > 2 \rightarrow$ At least one of 1,2,3 are false!

1. **Realism**
2. **Locality**
3. **Settings Independence**

Experimental Fact ($S_{max} > 2$)

All previous EPR experiments violate Bell's inequality

The Usual Story:

QM incompatible with "local realism" (2 or 1 or both)

Local "hidden variable" (HV) theories ruled out by experiment ...

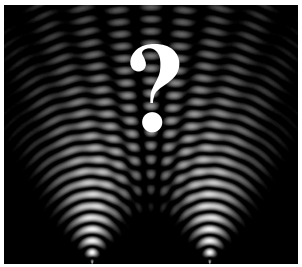
...Equally Logically Consistent Story:

QM incomplete. Local realism OK. Local HVs describe missing degrees of freedom (e.g. EPR 1935)

Possible loophole: Just relax setting independence! (3 false)

BELL'S THEOREM LOOPHOLES

Loopholes: Local Realism still tenable despite $S_{max} > 2$



Why Does it Matter?

Quantum foundations!

Security of quantum cryptography

A. Locality Loophole

Hidden communication between parties

for photons: **Aspect+1982, Weihs+1998**

Closing Method?

Spacelike separated measurements

B. Fair sampling / Detection Efficiency Loophole

Measured sub-sample not representative

for atoms: **Rowe+2001**, superconducting qubits: **Ansmann+2009**, photons: **Giustina+2013**, **Christensen+2013**

High efficiency detectors

C. Setting Independence / "Free Will" Loophole

Settings correlated with local hidden variables

partially? for photons: **Scheidl+2010**

Spacelike separated settings (QRNGs)

RELAXING SETTINGS INDEPENDENCE

3. Setting Independence / "Free Will"

Detector settings choices independent and random.
Observers can choose experimental settings freely.

- Can events in past LC of source & detector → correlated settings?
- Trivially YES: deterministic local HV theory (e.g. **Brans 1986**)
- Local deterministic, model can mimic QM with ≤ 1/22 bits of mutual information between settings choices (**Hall 2011**)
- Settings independence = most fragile loophole quantitatively. Communication or indeterministic models need ≥ 1 bit (e.g. **Toner & Bacon 2001**, **Hall 2010, 2011**)

Implausible "cosmic conspiracy" or quantitative, testable model?

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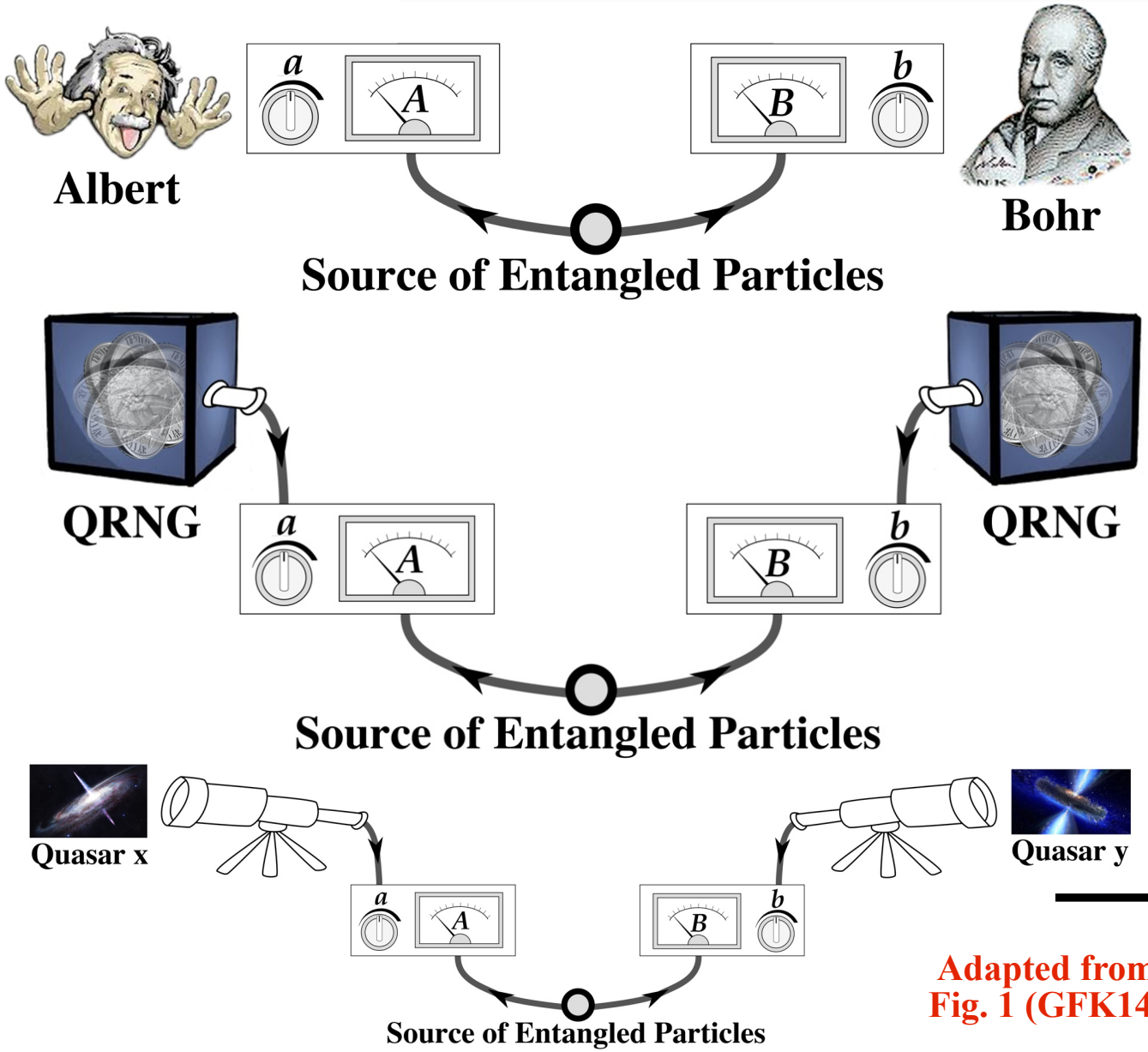
Friedman+2014 *in prep*. (F14b)

5. Actually Doing the Experiment?

CHOOSING SETTINGS *a, b*

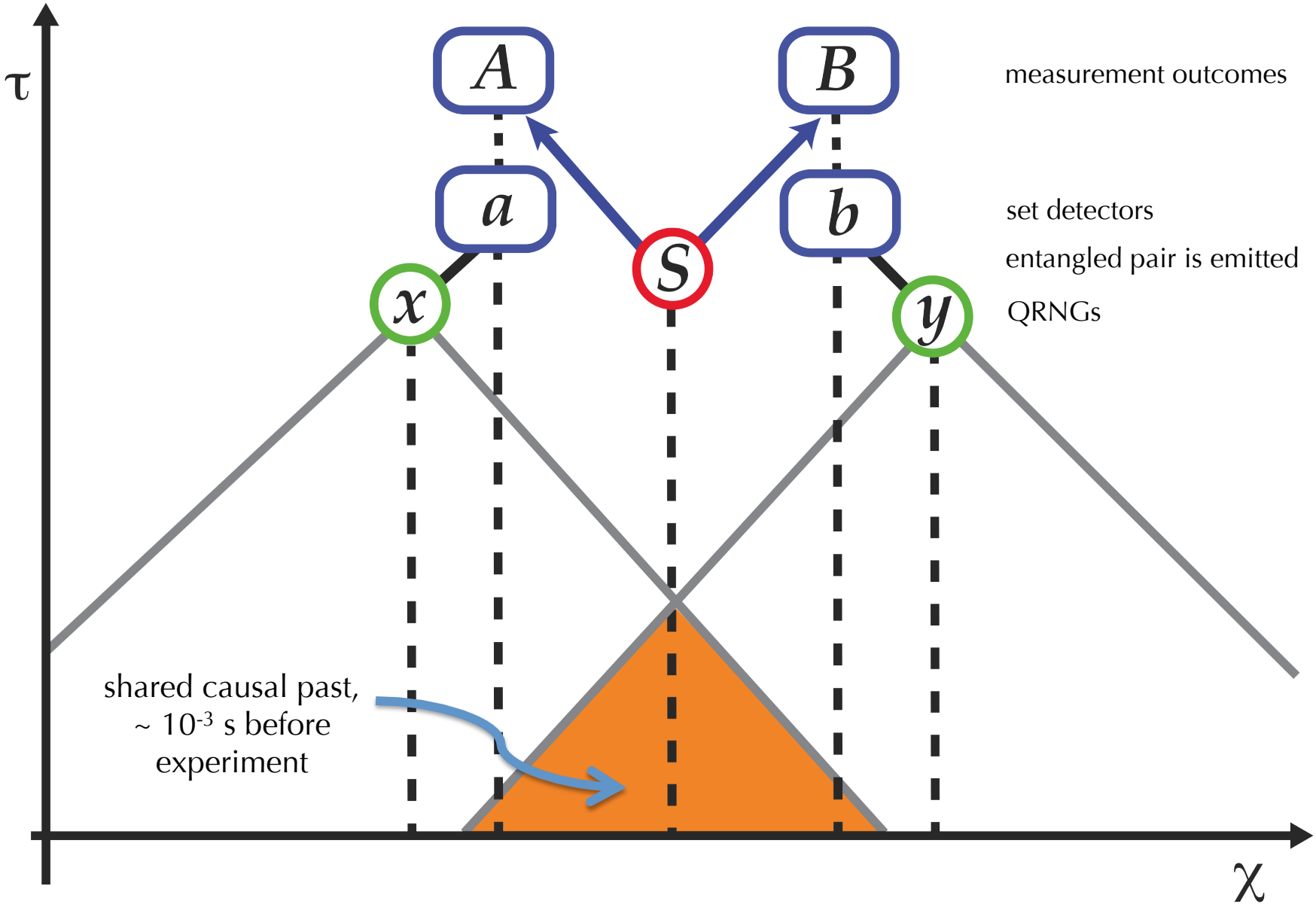


Choose detector settings with real-time observations of causally disconnected cosmic sources

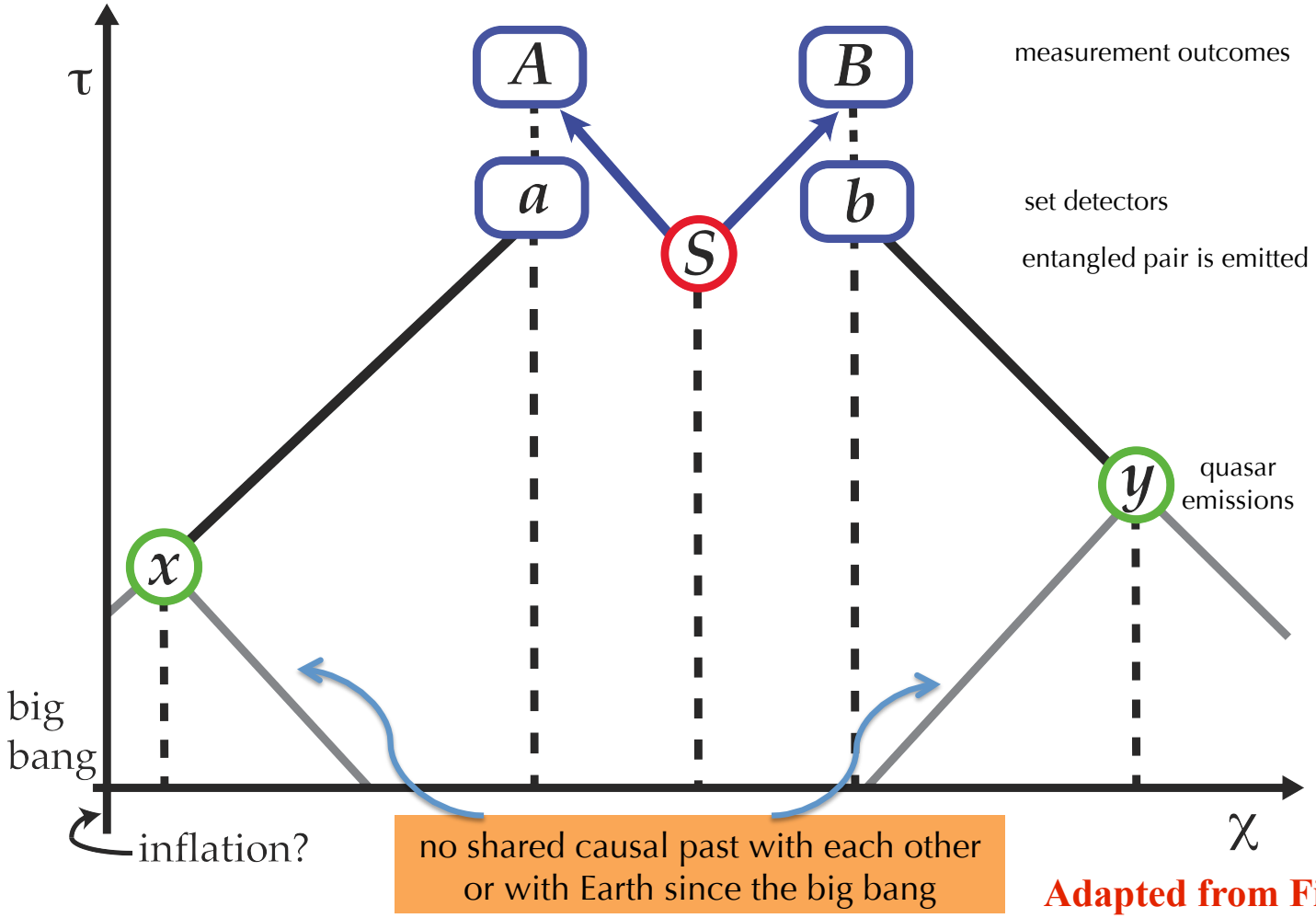
Ensures setting independence as much as is physically possible in our universe!

Adapted from Fig. 1 (GFK14)

BELL TEST CONFORMAL DIAGRAM



COSMIC BELL CONFORMAL DIAGRAM



Adapted from Fig. 2 (GFK14)

***x, y* need z >3.65 (at 180º) for no shared causal past with each other, source, detectors since end of inflation 13.8 Gyr ago**

COSMIC BELL ADVANTAGES

- Same basic idea: e.g. **Maudlin 1994, Scheidl+2010, Zeilinger 2010**
  We're the first to look at real cosmological sources, feasible experimental setups

- No experiment has closed settings independence with **cosmic sources**.

- **No single experiment** has closed all 3 loopholes simultaneously
  photons: separate experiments closed locality & detection loopholes.
  Settings independence only closed with strong assumptions **(Scheidl+2010)**

- Decisive novel part of future "**Loophole free**" Bell test
  Simultaneously Close Locality, Detection, & Settings Independence
  Space-like separate ALL events of interest, use high efficiency detectors.

- **QRNGs** (or any Earthbound devices) have shared pasts milliseconds before experiment. Not causally independent!
  Our setup: ~13-20 orders of magnitude better than previous tests

- Even with **local stars**, can push conspiracy before recorded history!

- **Rule out local HV cosmic conspiracies** as much as is physically possible in our universe (except "superdeterminism", e.g. **t'Hooft 2007**)

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4. Causally Disconnected Quasars

Friedman+2014 *in prep*. (F14b)

5. Actually Doing the Experiment?

COSMOLOGY QUESTION

Cosmic event pairs with arbitrary redshifts, angular separations

1. Do they have a shared causal past since the hot big bang (end of inflation)?

2. Could any other events (post inflation) have jointly influenced both. Are the events indep.?

$z > 3.65$ pairs (180^o): no shared causal past w/ each other or Earth since end of inflation (flat FLRW)

Complex constraints for angles < 180 deg

+general results for curved space (F13a)

DO TWO COSMOLOGICAL EVENTS HAVE A SHARED PAST?

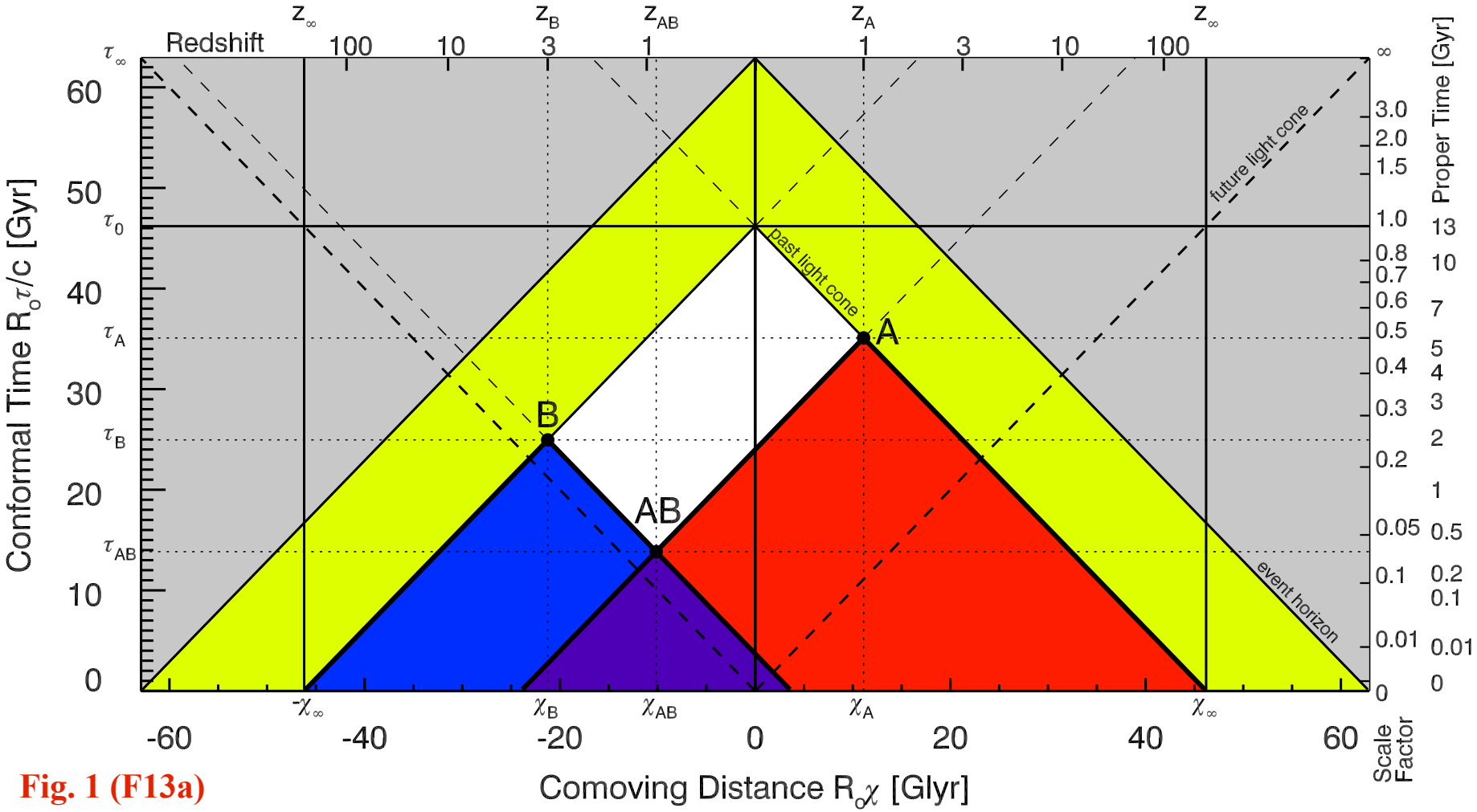


Fig. 1 (F13a)

Since the hot big bang (end of inflation)

INFLATION & THE HORIZON PROBLEM

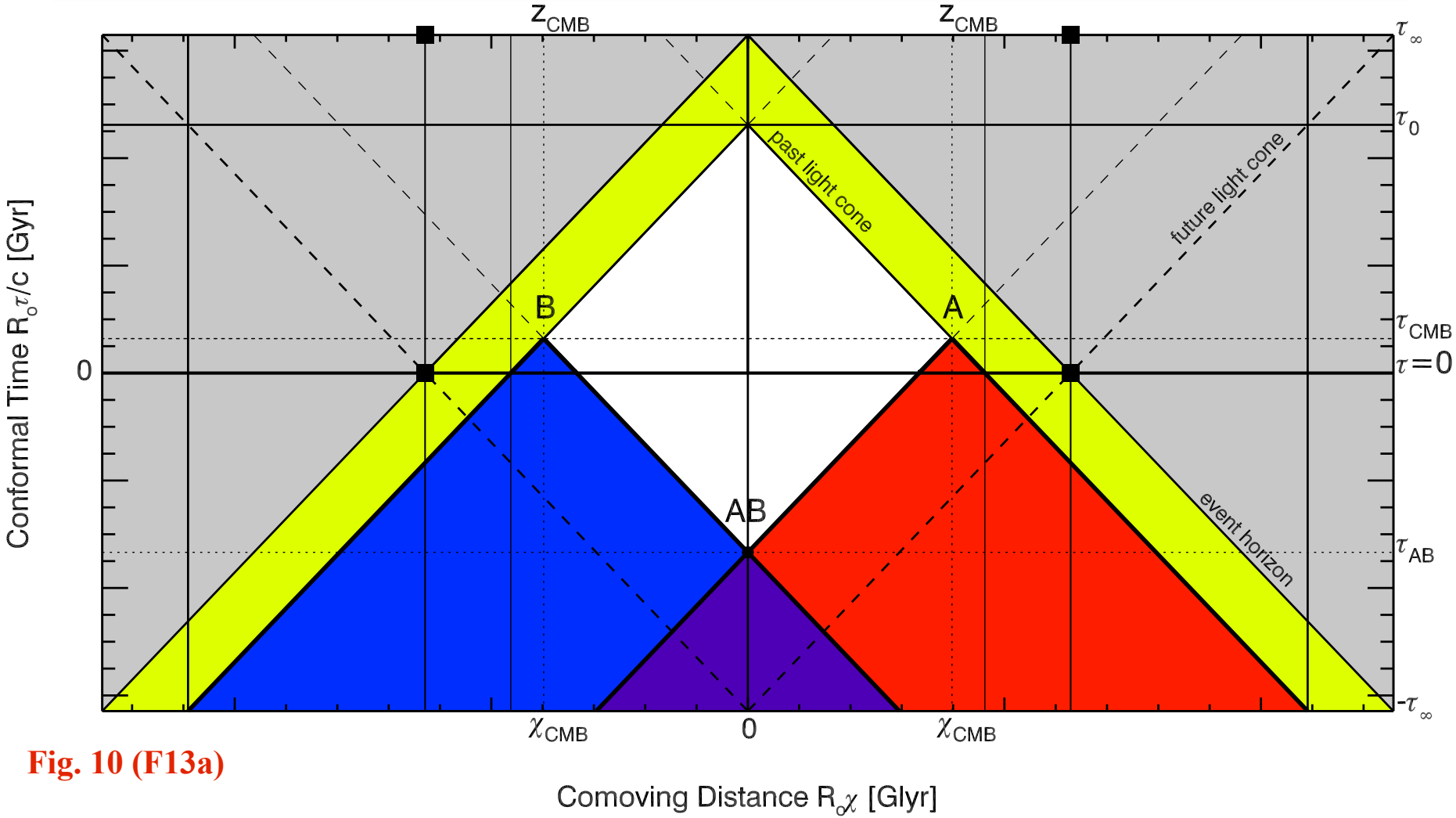


Fig. 10 (F13a)

If enough inflation happened to solve horizon problem, ALL events in our past LC have shared pasts

PAST LIGHT CONE INTERSECTION

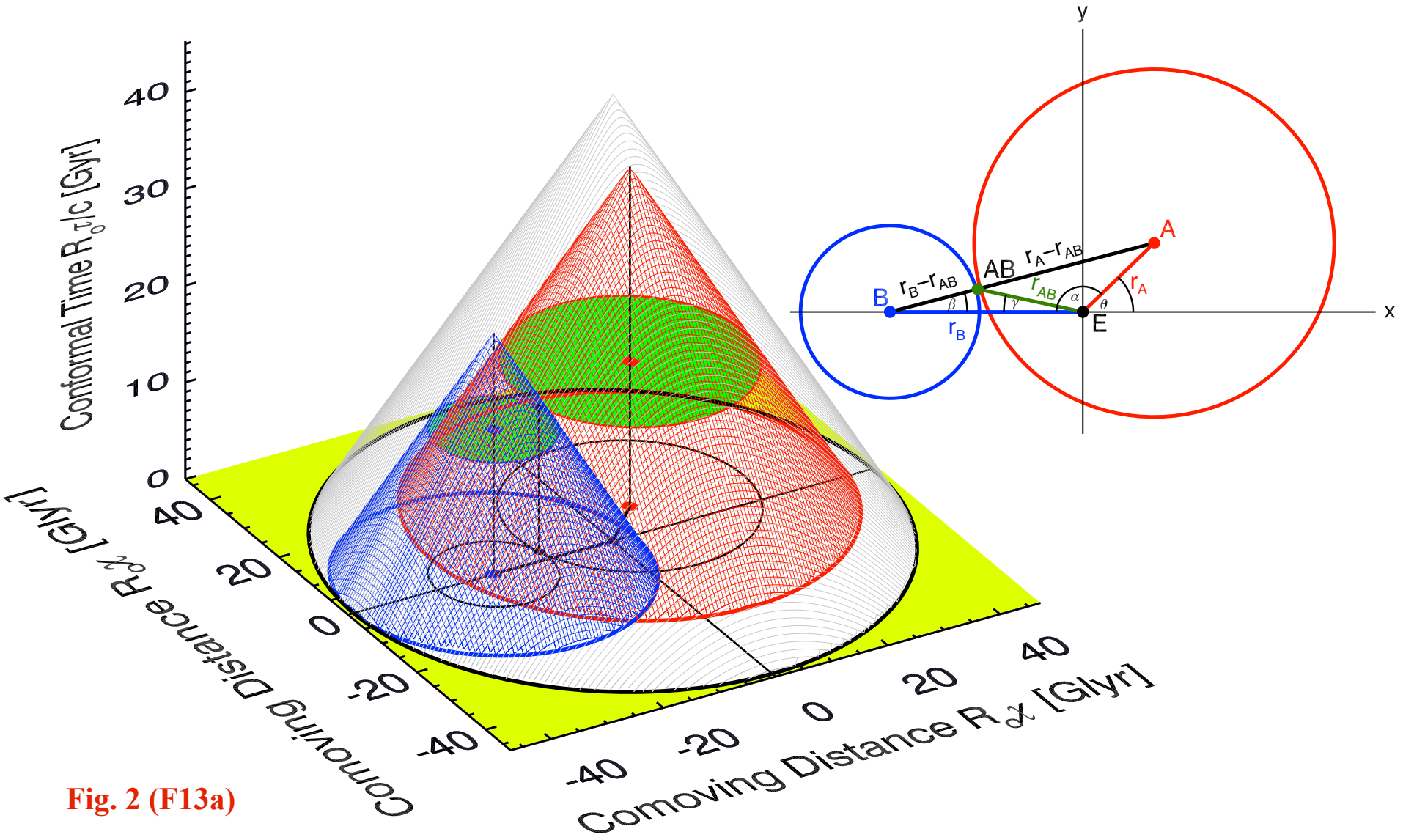
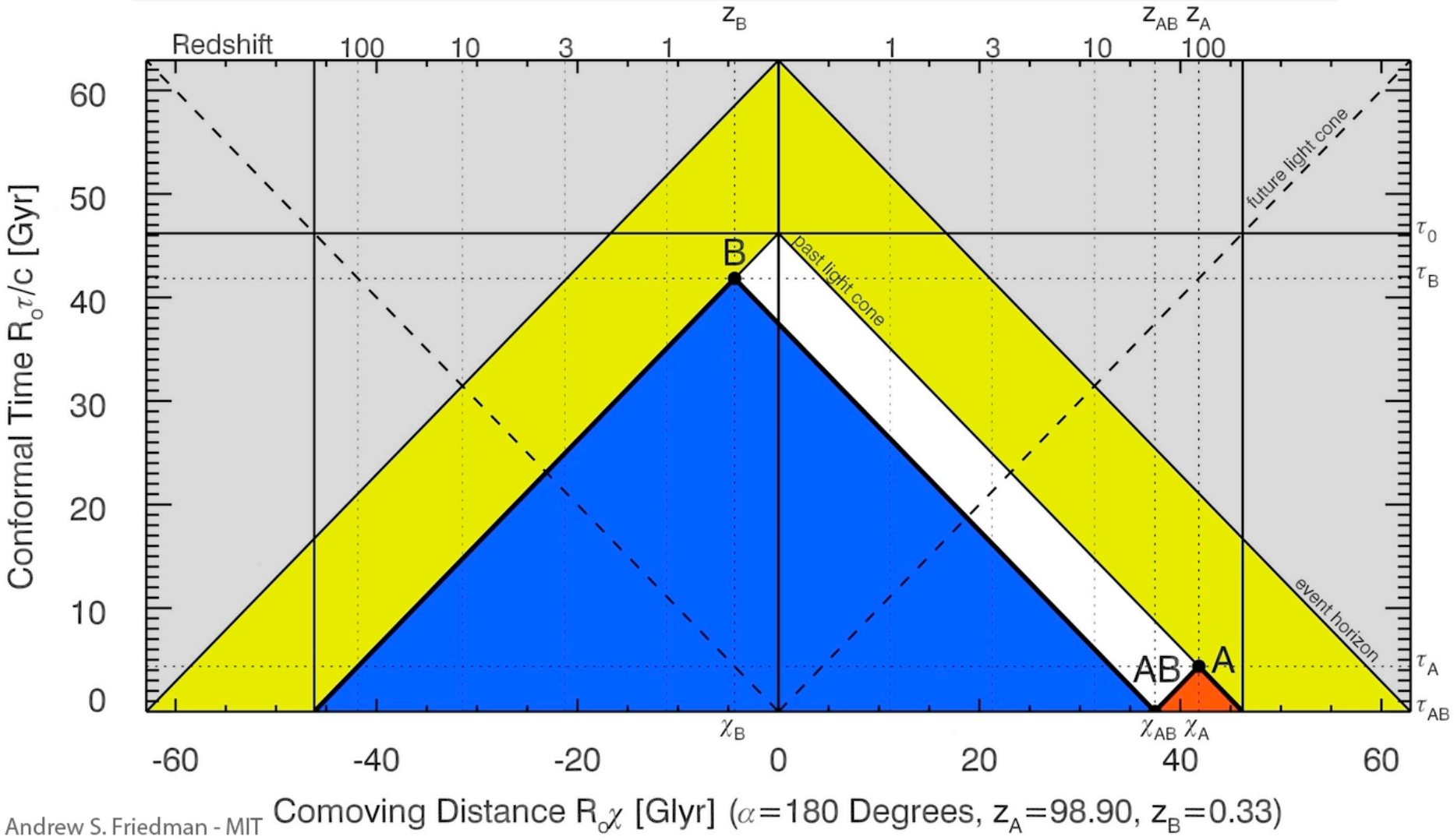


Fig. 2 (F13a)

LC INTERSECTION @BIG BANG



Andrew S. Friedman - MIT

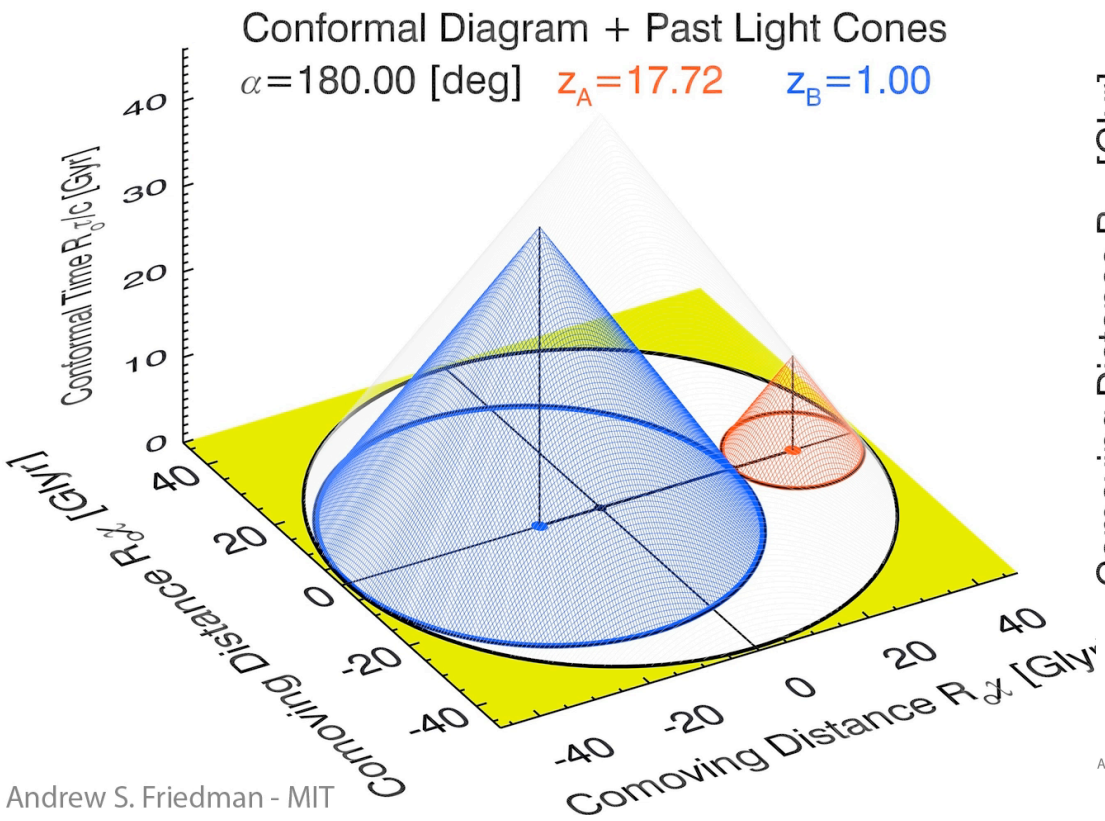
Animation 1 (F13a supplementary material)

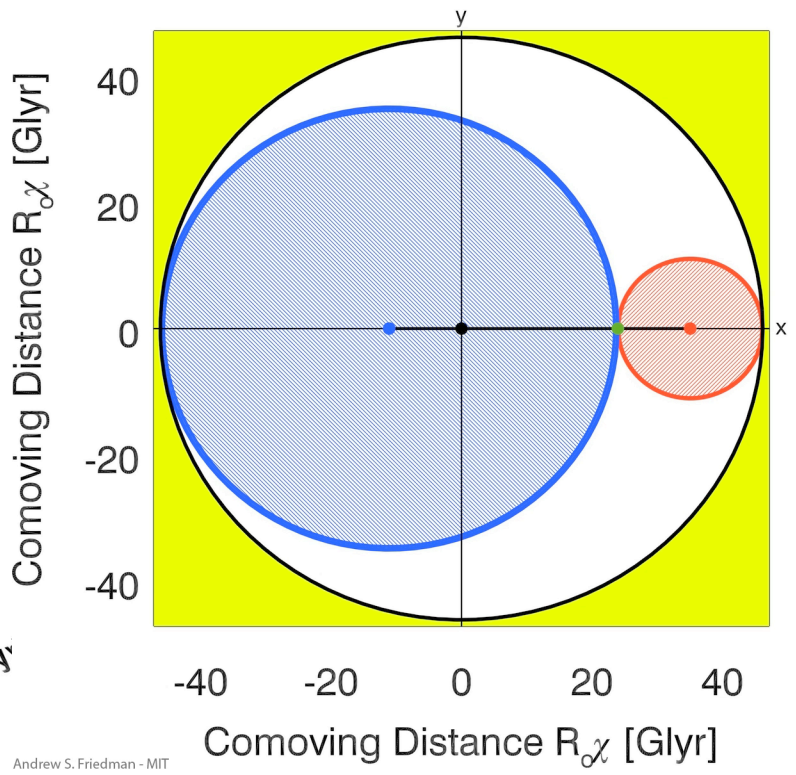
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

http://web.mit.edu/asf/www/causal_past.shtml

http://web.mit.edu/asf/www/01_conformal_movie.shtml

LC INTERSECTION @BIG BANG

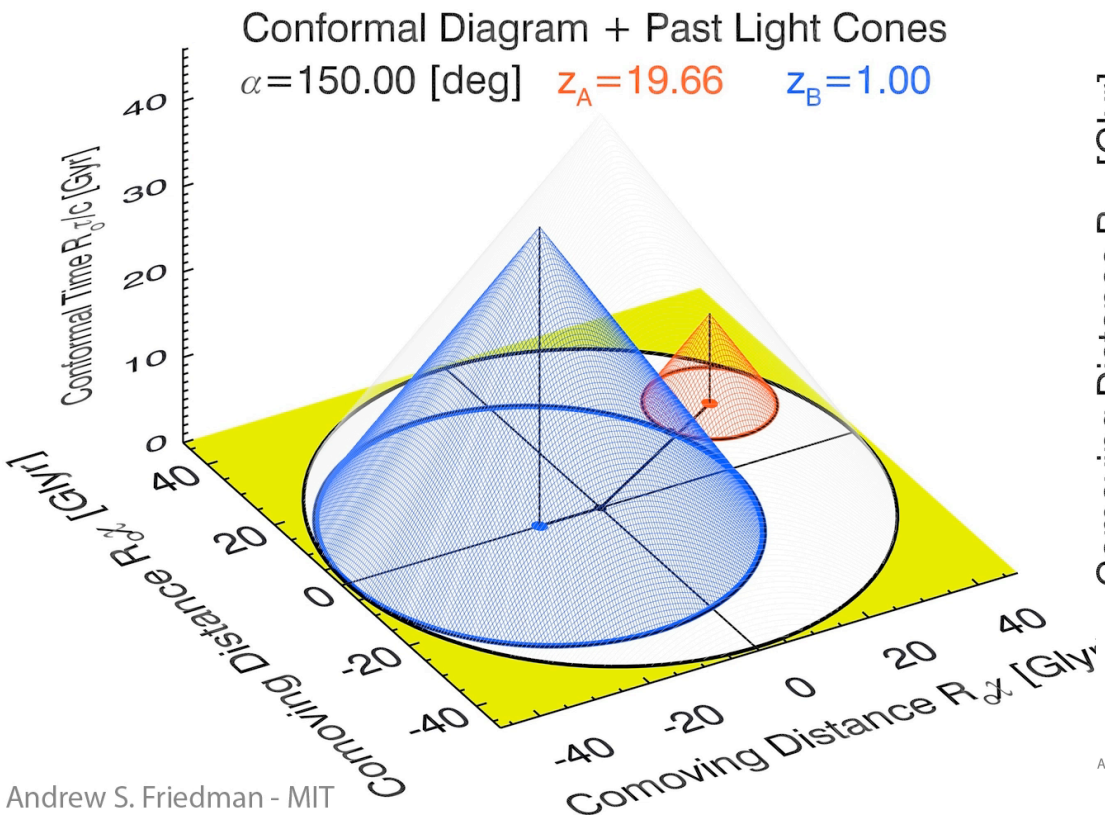


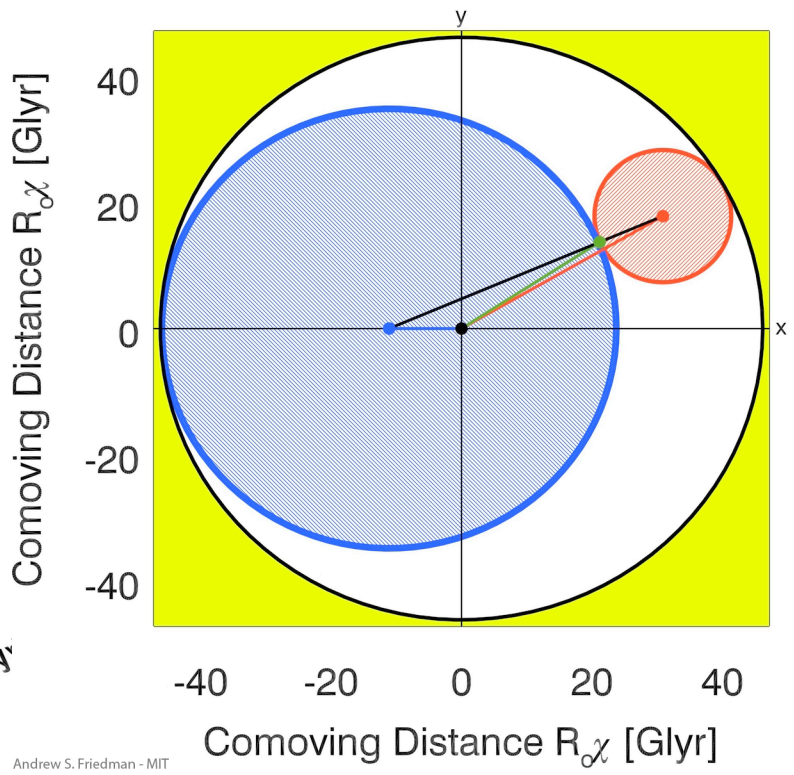


Animations 2-3 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

http://web.mit.edu/asf/www/causal_past.shtml
http://web.mit.edu/asf/www/02_BB_180.shtml

LC INTERSECTION @BIG BANG





Animations 4-5 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

http://web.mit.edu/asf/www/causal_past.shtml
http://web.mit.edu/asf/www/03_BB_150.shtml

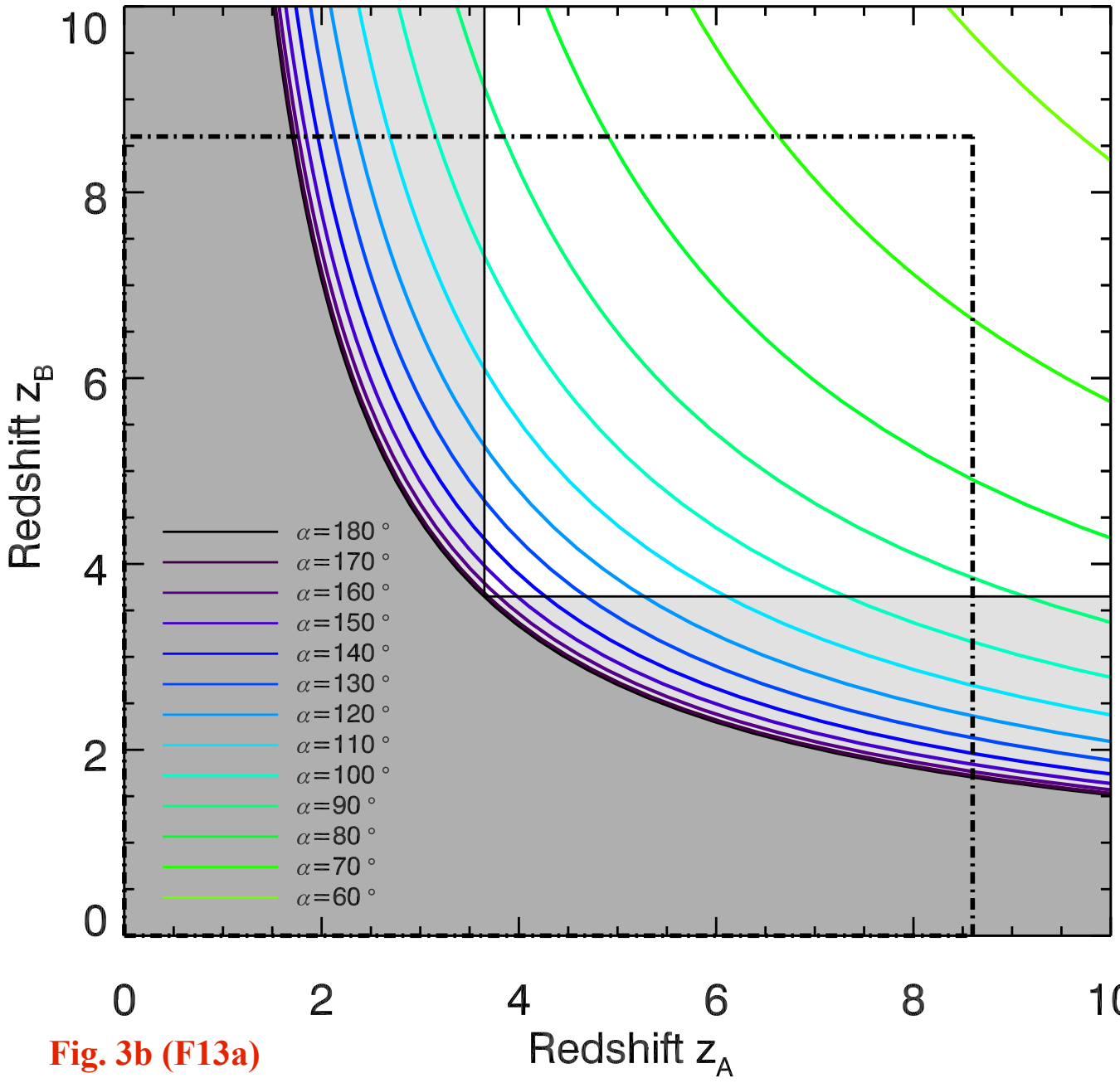


Fig. 3b (F13a)

Do A,B have a shared past?

Dark Gray
YES: any angle

Light Gray / White
NO: large angles

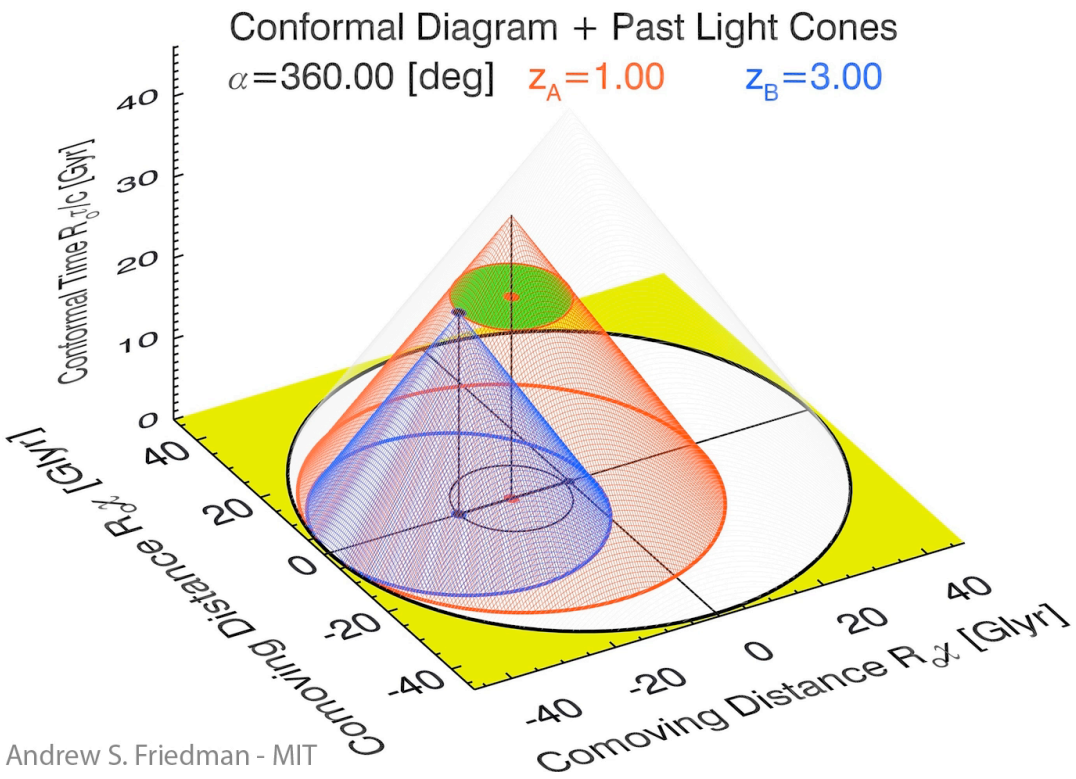
...with Earth?

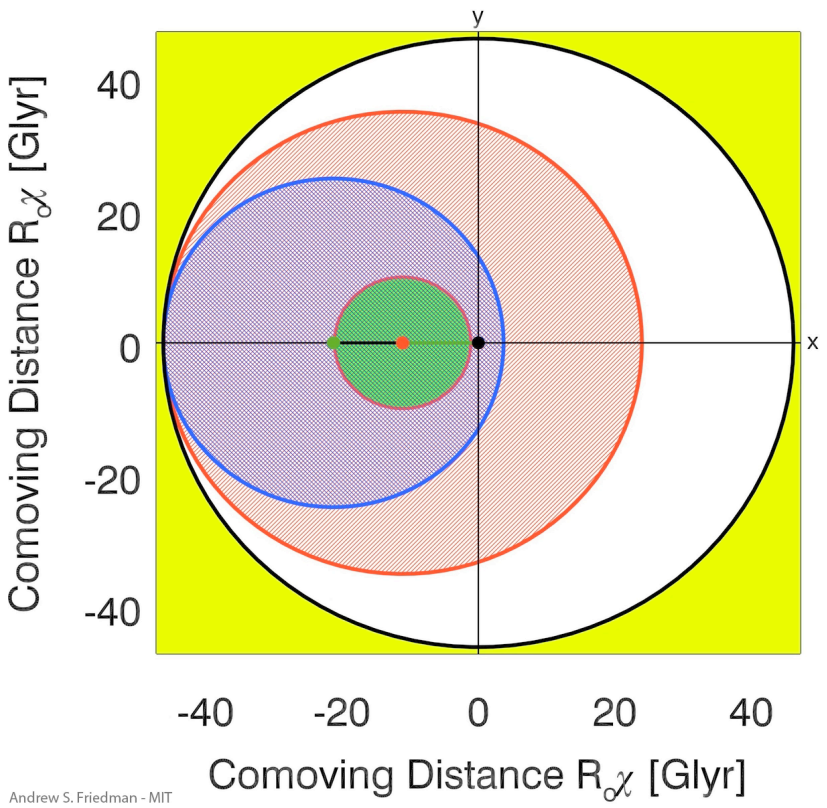
Dark Gray
YES

White
NO: A and B

Light Gray
YES: Either A or B

FIX REDSHIFTS, CHANGE ANGLE





Animations 6-7 (F13a supplementary material)
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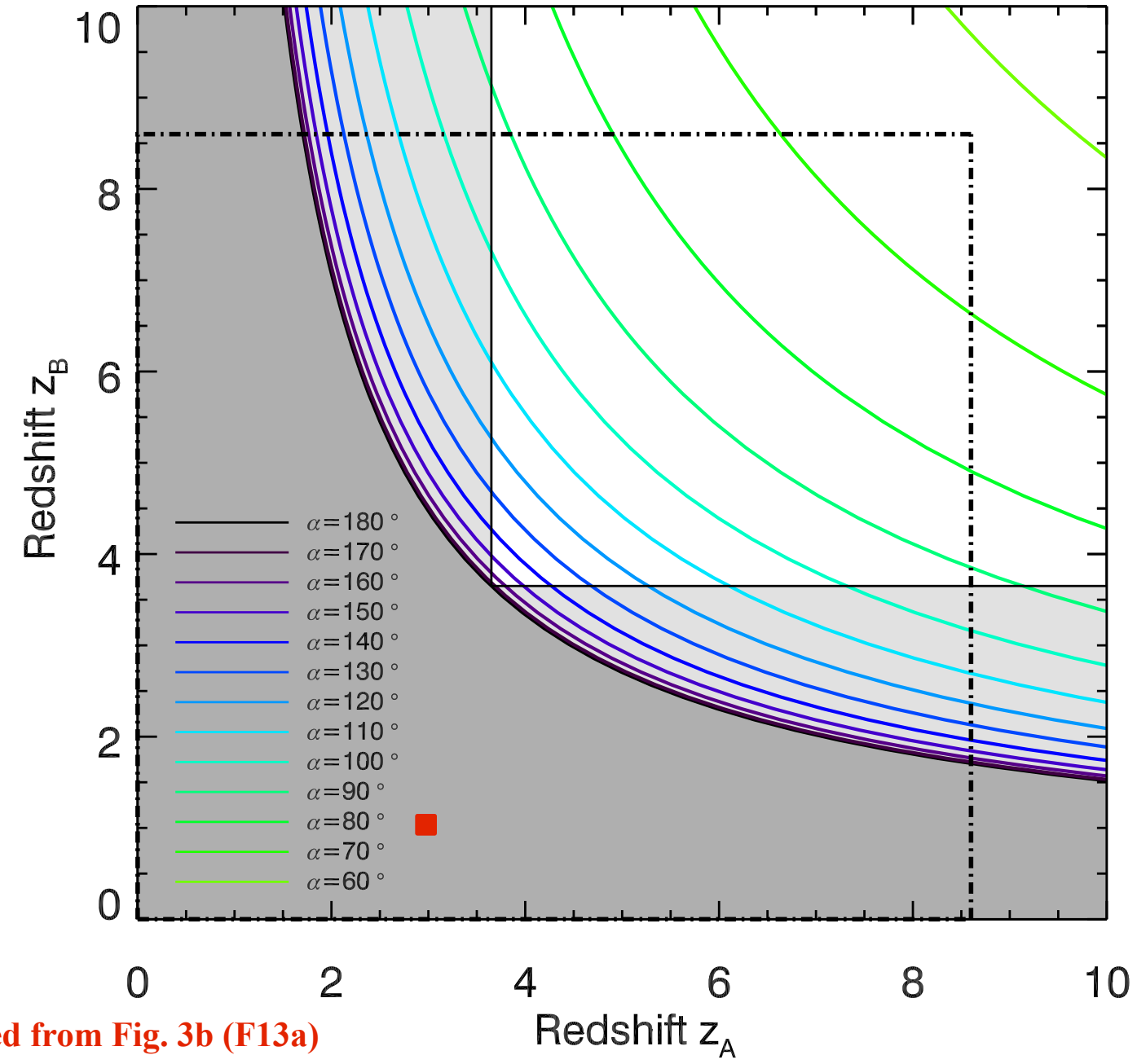
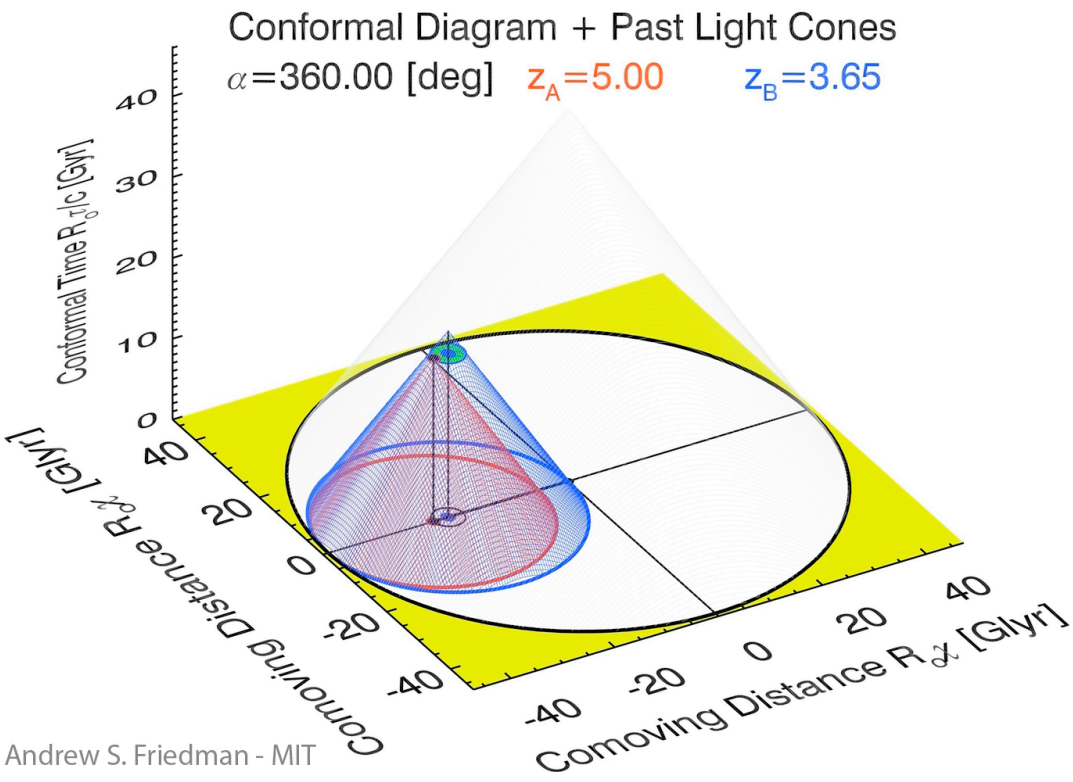
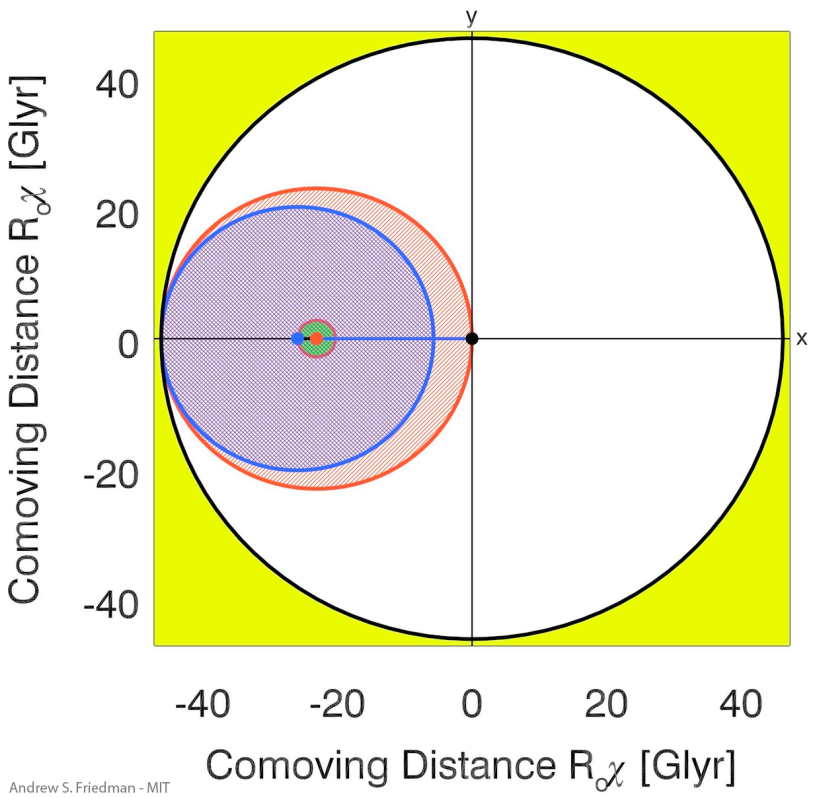


Adapted from Fig. 3b (F13a)

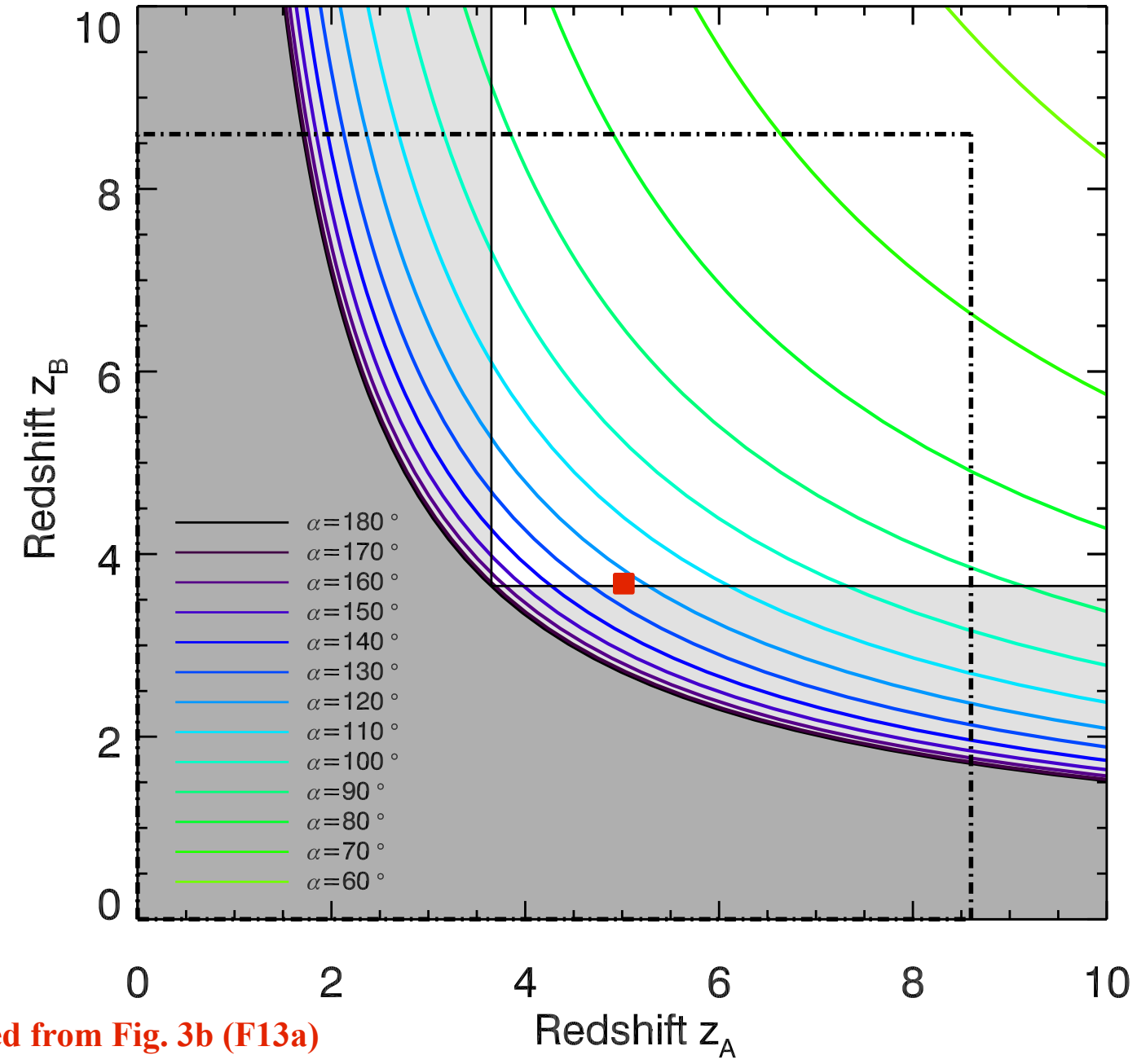
FIX REDSHIFTS, CHANGE ANGLE





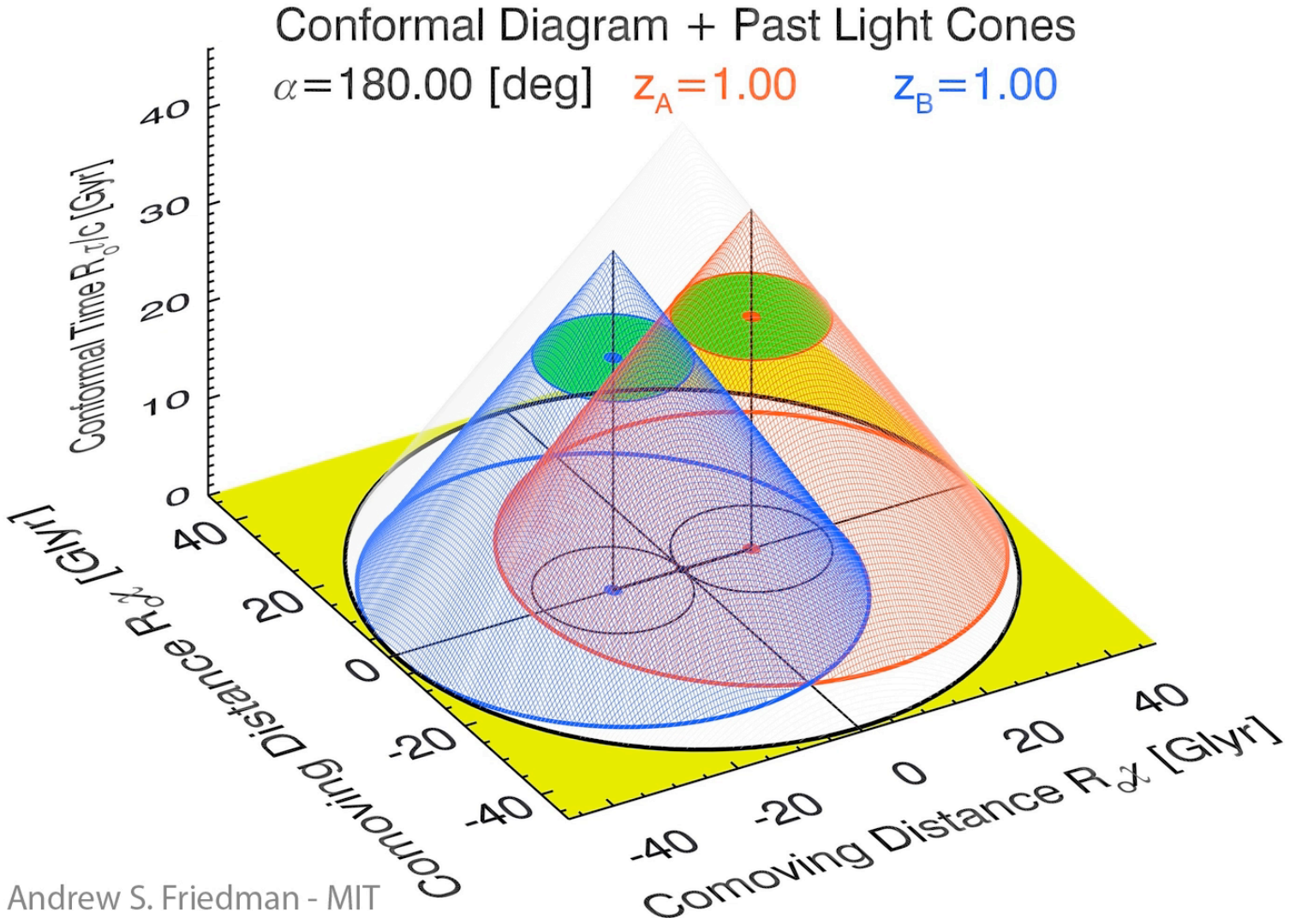
Animations 8-9 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

http://web.mit.edu/asf/www/causal_past.shtml
http://web.mit.edu/asf/www/05_alpha_5_3p65.shtml



Adapted from Fig. 3b (F13a)

FIX ANGLE, CHANGE Z = Z_A = Z_B



Animation 11 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

http://web.mit.edu/asf/www/causal_past.shtml
http://web.mit.edu/asf/www/06_zcrit.shtml

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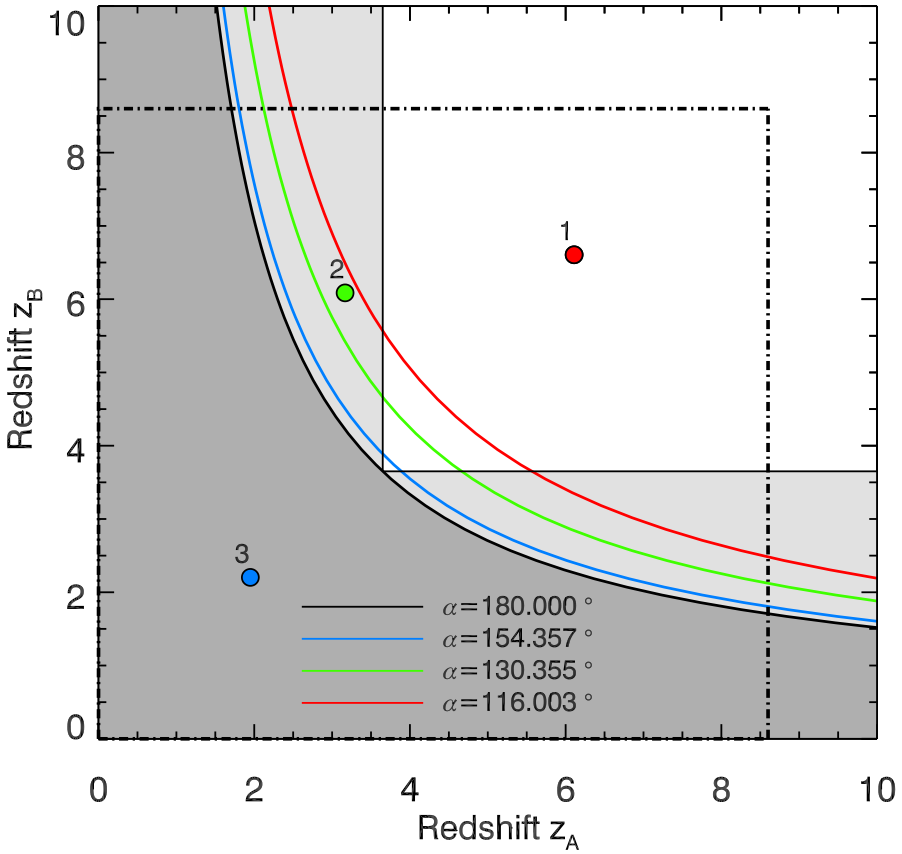


EXAMPLE QUASAR PAIRS

pair 3 - YES shared past with each other & Earth

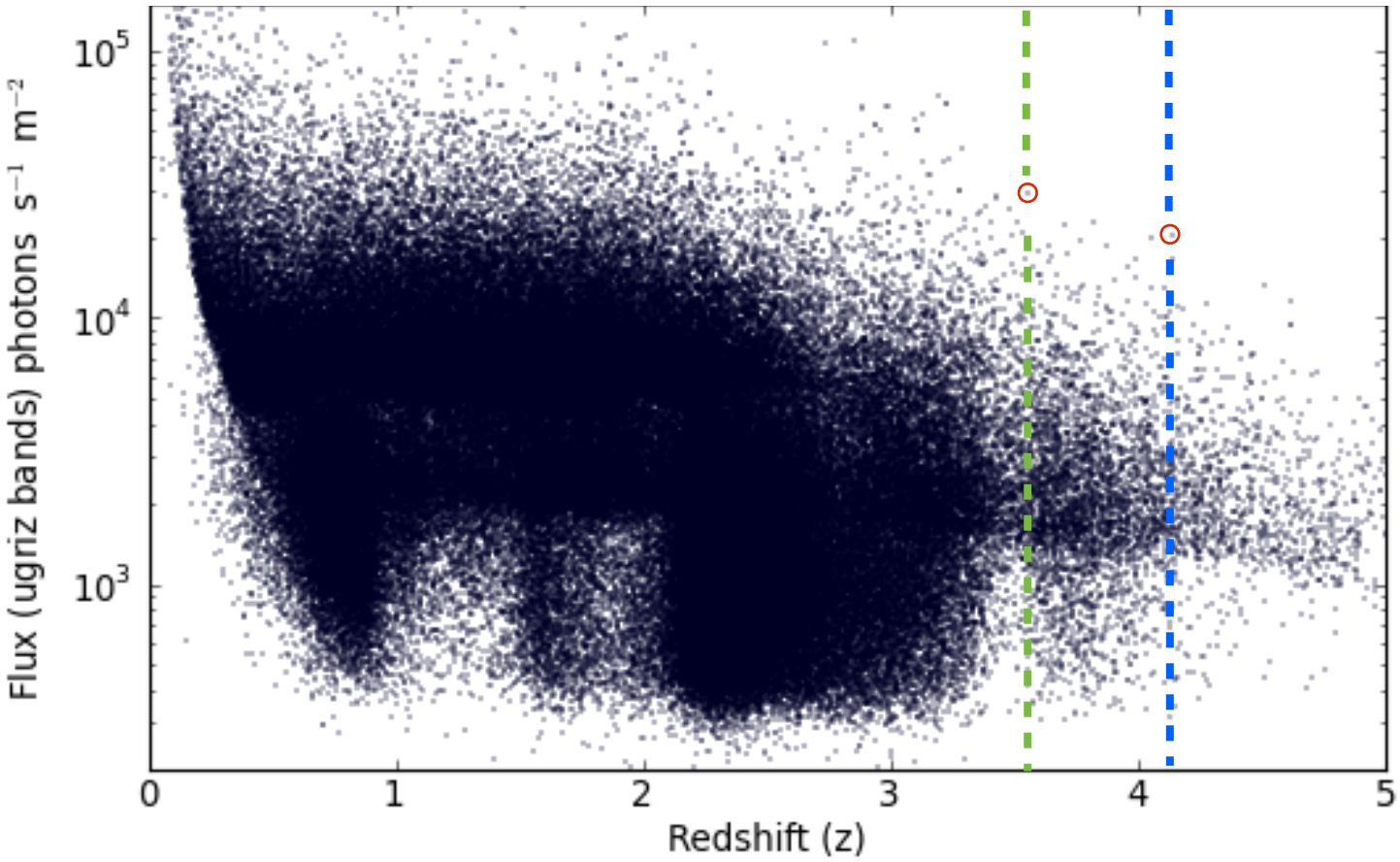
pair 2 - NO shared past with each other, but A_2 has shared past with Earth

pair 1 - NO shared past with each other or Earth

Fig. 5, Table I (F13a)

Pair	Separation Angle α_i [deg]	Event Labels	Redshifts z_{Ai}, z_{Bi}	Object Names	RA [deg]	DEC [deg]	R [mag]	B [mag]
1	116.003	A_1	6.109	SDSS_J031405.36-010403.8	48.5221	-1.0675	16.9	20.1
		B_1	6.606	SDSS_J171919.54+602241.0	259.8313	60.3781	18.6	16.9
2	130.355	A_2	3.167	KX_257	24.1229	15.0481	16.7	17.8
		B_2	6.086	SDSS_J110521.50+174634.1	166.3396	17.7761	16.4	25.1
3	154.357	A_3	1.950	Q_0023-4124	6.5496	-41.1381	14.2	15.4
		B_3	2.203	HS_1103+6416	166.5446	64.0025	14.7	15.4

QUASAR FLUX VS. REDSHIFT



Ground based optical flux.

IR only usable from space

Local Sky noise!

Adapted from Fig. 3 (GFK14)

z~3.65 : $F_{Opt} \sim 3 \times 10^4$ photons s^{-1} m^{-2} **180 degrees**

z~4.13 : $F_{Opt} \sim 2 \times 10^4$ photons s^{-1} m^{-2} **130 degrees**

SDSS quasars - photometric and spectroscopic redshifts

LOOPHOLE FREE COSMIC BELL?

Setting Independence / "Free Will"

Choose settings with cosmic sources.

Locality

Choose settings with cosmic sources ***while EPR pair is in flight****.*

Fair Sampling / Detection Efficiency

Use existing detector technology: efficiency & time resolution

With reasonable experimental parameters, can close all three loopholes simultaneously during quasar visibility window!
~50% experimental runs triggered by cosmic photons. (GFK14)

~1-meter	**Telescope mirror diameters**
~50km	**Baselines between EPR source and telescopes**
~ 2×10^4 photons s^{-1} m^{-2}	**Optical quasar flux at z~4.13, separated by 130°**
~50-98%	**Cosmic photon detector efficiency (APD / TES)**

QUASAR CANDIDATES

- **Which quasar pairs (from > 1 million objects) causally independent for given lookback time?**
- **Choose candidate pairs.**
- **Design observational program.**
- **Find best observing site (? Canary Islands)**

Working with MIT undergrads on UROP project:
Isabella Sanders and Anthony Mark

Friedman+2014b *in prep*.

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Phys. Rev. Lett. accepted, arXiv:1310.3288

3. Shared Causal Pasts of Cosmic Events

Friedman, Kaiser, & Gallicchio 2013 (F13a)

Phys. Rev. D. Vol. 88, Issue 4, Id. 044038, arXiv:1305.3943

4. Causally Disconnected Quasars

Friedman+2014b *in prep*. (F14b)

5. Actually Doing the Experiment?

2 OR MORE COSMIC SOURCES

2, 3, or 4 entangled particle states (EPR or GHZ)

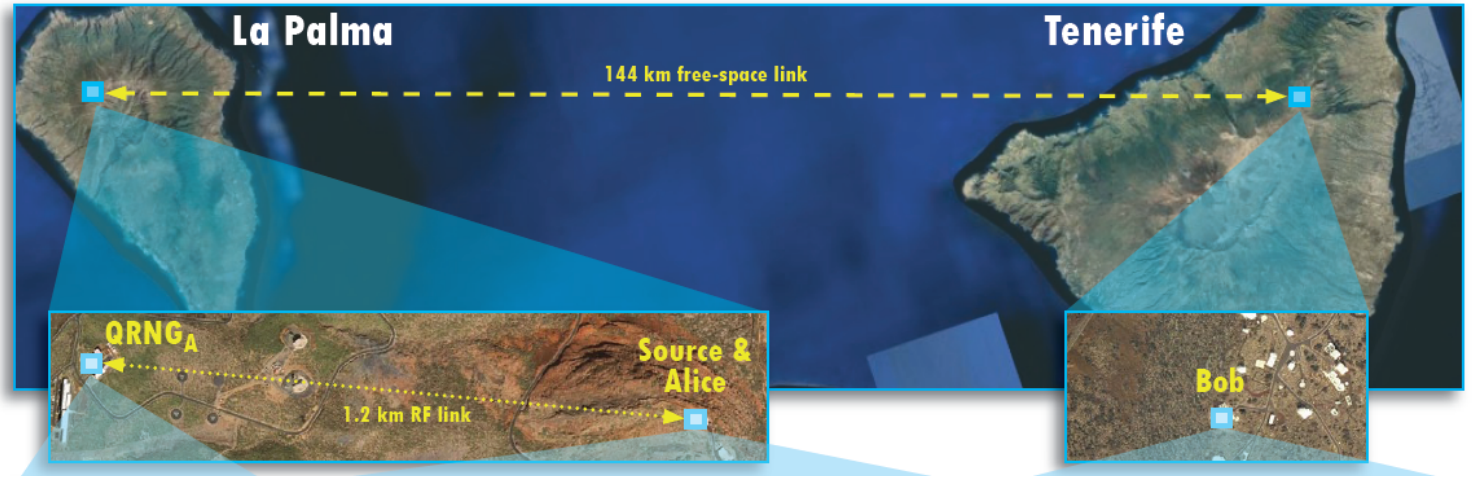
Greenberger, Horne, Zeilinger 1989; Greenberger+1990; Mermin 1990

Each cosmic source pair in set of 2, 3 or 4 satisfies pairwise constraints from F13a

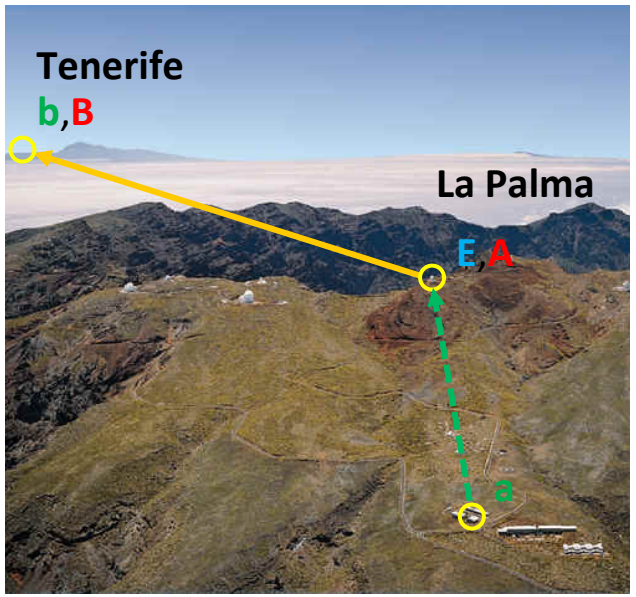
	Optimal space configurations	Redshifts	Feasible Ground-Based Tests	Redshifts
EPR2	180°	> 3.65	≲ 130°	> 4.13
GHZ3	120° Equilateral Triangle	> 4.37	≲ 105° Triangular pyramid	> 4.89
GHZ4	~109.5° Tetrahedron	> 4.69	≲ 75° Square pyramid	≳ 6.5
GHZ4	90° Square in Plane	> 5.69		

GFK14; Friedman+2014b *in prep.*

ZEILINGER GROUP EXPERIMENTS

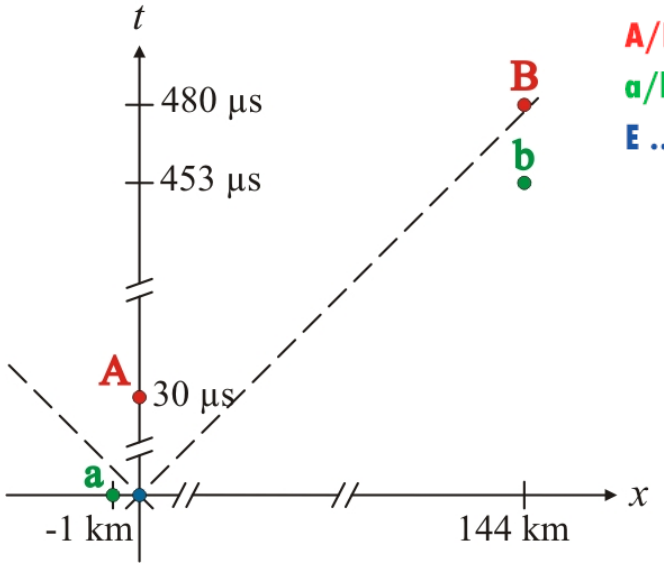


ESA - Optical Ground Station (OGS) 1-m receiver telescope, Laser guide to La Palma

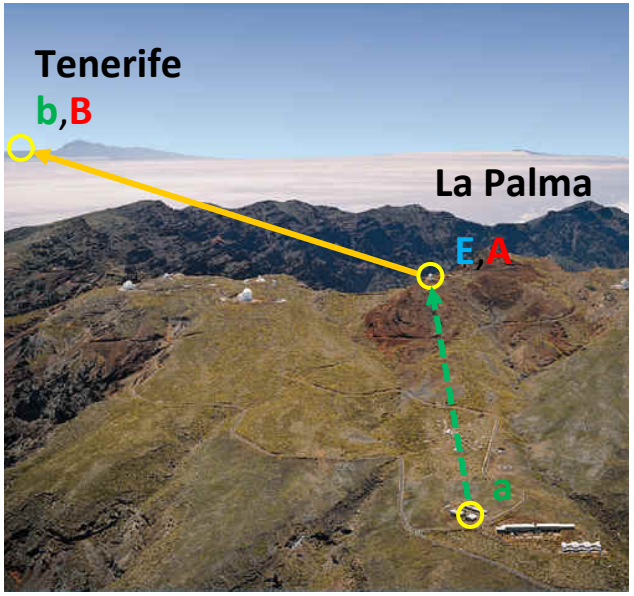


Scheidl+2010, *PNAS*, 107, 46, p. 19708-19713

VIOLATION OF LOCAL REALISM WITH FREEDOM OF CHOICE



A/B ... Alice's/Bob's measurement
a/b ... Alice's/Bob's setting choice
E ..... photon pair emission



Locality: **A** is space-like sep. from **b** and **B**
B is space-like sep. from **a** and **A**

Freedom of choice: *a* and *b* are *random*
a and **b** are space-like sep. from $\mathbf{E}_\lambda$

Credit: Johannes Kofler http://www.qi.ubc.ca/Talks/TalkKofler.pdf

Scheidl+2010, *PNAS*, 107, 46, p. 19708-19713

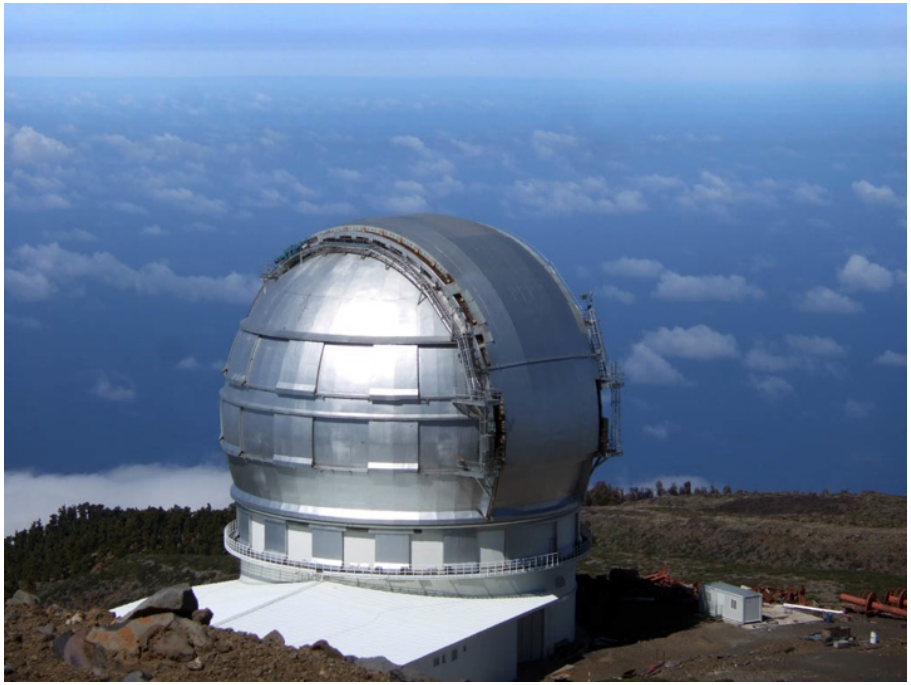
CANARY ISLANDS TELESCOPES

Roque de los Muchachos Observatory on the island of **La Palma** in the **Canary Islands**

Teide Observatory on the island of **Tenerife in the Canary Islands**

Both operated by the Instituto de Astrofísica de Canarias.

GRAN TELESCOPIO CANARIAS



10.4-m reflecting telescope at Roque de los Muchachos Observatory on La Palma in the Canary Islands

World's largest optical telescope!

POSSIBLE OUTCOMES

Expected

Bell inequalities always violated.
Rule out local HV theories as much as possible.

Unexpected

Bell inequality not violated for some cosmic source pairs ???

Strangest

Degree of Bell violation depends on degree of shared causal past of cosmic sources, lookback time to past LC intersection.

Implications for inflation? Quantum gravity?

FUTURE WORK

Find optimal candidate quasars, observing plan.

Friedman+2014b *in prep*.

Advantages of quasars vs CMB (GFK14)

EPR2 vs GHZ3, GHZ4. Ground + space-based tests.

It's Loopholes all the way down...

"Noise Loophole" Need triggers by genuine cosmic photons, not local "noise" photons. Need sufficient signal-to-noise from cosmic sources. (GFK14)

"Inflation Loophole" Shared past during inflation

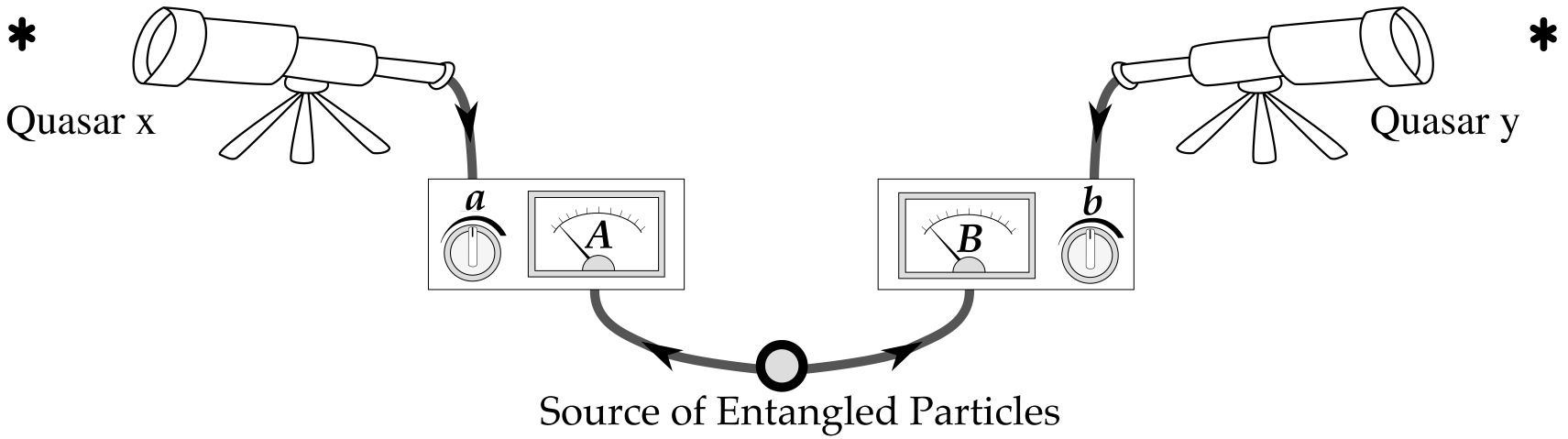
CONCLUSIONS

An actual Cosmic Bell experiment:

Is well motivated

Feasible in the real world.

Lots of fun to think about!



REFERENCES

Ade+2013, *A & A sub.*, (arXiv:1303.5076)
Aspect+1982, *Phys. Rev. Lett.*, Vol. 49, 25, December 20, p. 1804-1807
Barret & Gisin 2011, *Phys. Rev. Lett.*, vol. 106, 10, id. 100406
Bell 1964, *Physics* Vol. 1, No. 3, p. 195-200, *Physics Publishing Co.*
Bell+1989, *Speakable & Unspeakable in Quantum Mechanics*, *American Journal of Phys., Vol. 57, Issue 6, p. 567*
Clauser, Horne, Shimony, & Holt 1969, PRL 23, 880
Clauser & Shimony 1978, Rep. Prog. Phys. 41, 1881
Christensen+2013, Phys. Rev. Lett., 111, 120406
Einstein, Podolsky, & Rosen 1935, *Phys. Rev.*, Vol. 47, 10, p. 777-780
Freedman & Clauser 1972, Phys. Rev. Lett., vol. 28, 14, p. 938-941
Friedman, Kaiser, & Gallicchio 2013a, *Phys. Rev. D,* Vol. 88, Iss. 4, id. 044038, 18 p. (arXiv:1305.3943)
Friedman+2014b, *ApJ in prep.*
Gallicchio, Friedman, & Kaiser 2014=GFK14, *Phys. Rev. Lett. accepted* (arXiv:1310.3288)
Giustina+2013, *Nature*, Vol. 497, 7448, p. 227-230
Greenberger, Horne, & Zeilinger 1989, "*Going Beyond Bell's Theorem*", in Bell's Theorem, Quantum Theory, and Conceptions of the Universe, Ed. M. Kafatos, Kluwer Academic, Dordrecht, The Netherlands, p. 73-76
Greenberger+1990, American Journal of Physics, Volume 58, Issue 12, pp. 1131-1143
Guth 1981, *Phys. Rev. D*, Vol. 23, 2, p. 347-356
Guth & Kaiser 2005, *Science*, Vol. 307, 5711, p. 884-890
Hall 2010, *Phys. Rev. Lett.*, vol. 105, 25, id. 250404
Hall 2011, *Phys. Rev. A*, vol. 84, 2, id. 022102
Maudlin 1994, "*Quantum Non-Locality and Relativity*", Wiley-Blackwell; 1st edition
Mermin 1990, American Journal of Physics, Volume 58, Issue 8, pp. 731-734
t'Hooft 2007, (arXiv:quant-ph/0701097)
Scheidl+2010, *PNAS,* 107, 46, p. 19708-19713
Weihs+1998, *Phys. Rev. Lett.*, Vol. 81, 23, Dec 7, p. 5039-5043
Zeilinger 2010, "*Dance of the Photons*", Farrar, Straus & Giroux; 1st Ed.

MEDIA COVERAGE

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***, Mar 5 2014

Free will, the quantum and the cosmos, Valerio Scarani, ***Spreadquantum*** (National University of Singapore), Mar 4 2014

Free Willy, Brian Koberlein, ***Briankoberlein.com*** (Rochester Institute of Technology), Feb 28 2014

Cosmic test for quantum theory, Rainer Kayser, ***Weltraum Aktuell***, *Germany*, Feb 26 2014

Cosmic light could close quantum-weirdness loophole*: Distant quasars would decide whether quantum entanglement is an illusion*, Zeeya Merali, ***Nature***, *News & Comment*, Feb 25 2014

Does Free Will Exist? *Ancient Quasars May Hold the Clue*, Jason Major, ***Universe Today,*** Feb 25 2014

MIT wants quasars to help put free will to rest: Ringing the Bell on inequality, Richard Chirgwin, ***The Register,*** *UK*, Feb 24 2014

For the last loophole, let there be light!, Vasudevan Munkuth, ***The Hindu,*** *Copernican Blog*, Feb 24 2014

A Test of Bell's Theorems Using Distant Quasars, Andrius T., ***Physics Database,*** Feb 24 2014

Op-Ed: Do quantum or classical physics rule? *MIT wants to find out*, Paul Wallis, ***Digital Journal,*** Feb 22 2014

Distant quasars to fill a loophole of Bell's theorem, Analissa Arci, ***Gaia News***, *Italy*, Feb 21 2014

Closing 'Free Will' Loophole From Bell's Theorem, Lee Rannals, ***redOrbit,*** Feb 21 2014

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***, Feb 21 2014

Bell's Inequality And The Speed Of Light: Quasar Findings Might Close The 'Free Will' Loophole, Staff, ***Science 2.0,*** Feb 20 2014

Closing the 'free will' loophole*: MIT researchers propose using distant quasars to test Bell's theorem*, Jennifer Chu, ***MIT News Office***, Feb 20 2014

Cosmic Bell, Sabine Hossenfelder, ***Backreaction*** (NORDITA), Nov 27 2013

Closing Loopholes in Quantum Mechanics, Warren Huelsnitz, ***The Fun is Real!,*** Oct 16 2013