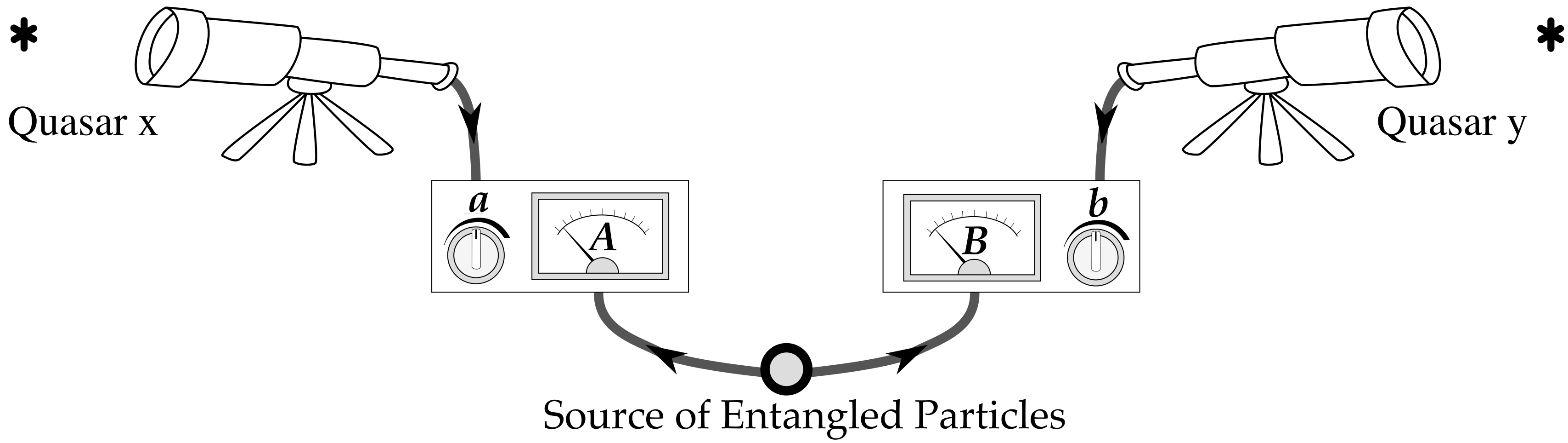

TESTING QUANTUM MECHANICS AND BELLL'S INEQUALITY WITH OBSERVATIONS OF CAUSALLY DISCONNECTED COSMOLOGICAL EVENTS

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

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

Gallicchio, Friedman, & Kaiser 2013 = GFK13
Phys. Rev. Lett. submitted **(arXiv:1310.3288)**

"The Shared Causal Pasts and Futures of Cosmological Events"

Friedman, Kaiser & Gallicchio 2013 = F13a
Phys. Rev. D. Vol. 88, Issue 4, Id. 044038 **(arXiv:1305.3943)**

OUTLINE

1. The Big Picture: Bell's Theorem

2. *Cosmic Bell - Gedankenexperiment*

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4. Causally Disconnected Quasars

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

5. Actually Doing the Experiment?

QM AND HIDDEN VARIABLES

1927 Copenhagen interpretation of QM (Bohr, Heisenberg)

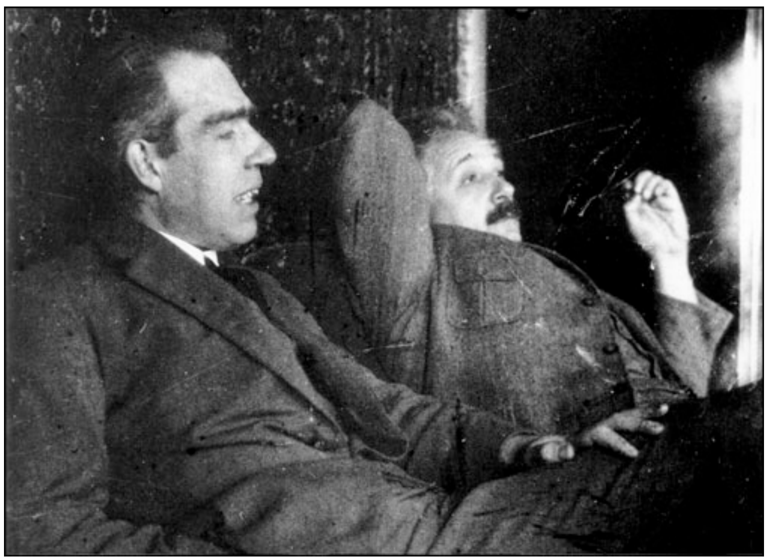
1935 Einstein-Podolsky-Rosen (EPR) paradox paper

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)

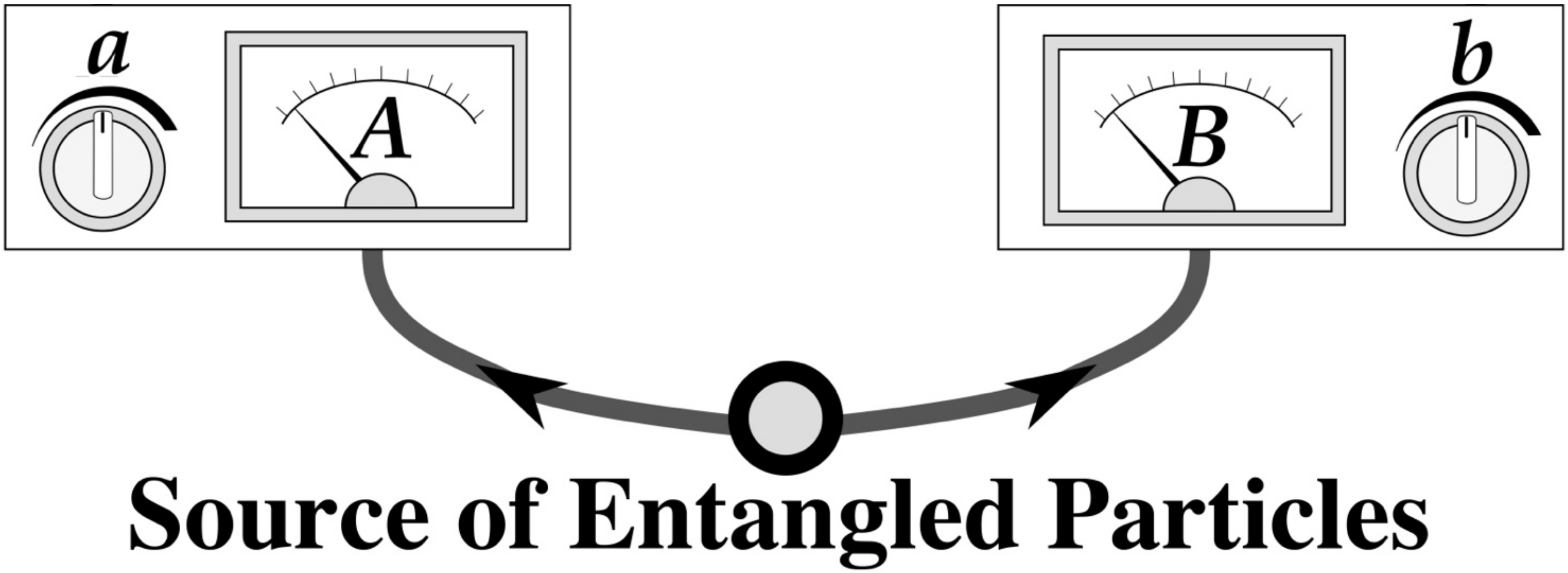
History Credit: Johannes Kofler http://www.qi.ubc.ca/Talks/TalkKofler.pdf



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. Settings Independence / Freedom of Choice

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 ...

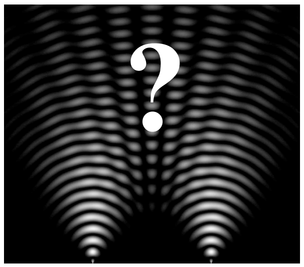
...Equally Logically Consistent Story:

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

Possible loophole: Just relax settings 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

Closing Method?

Hidden communication between parties

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

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. Settings Independence / Freedom of Choice Loophole

Settings correlated with local hidden variables

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

Spacelike separated settings (QRNGs)

RELAXING SETTINGS INDEPENDENCE

3. Settings Independence / Freedom of Choice

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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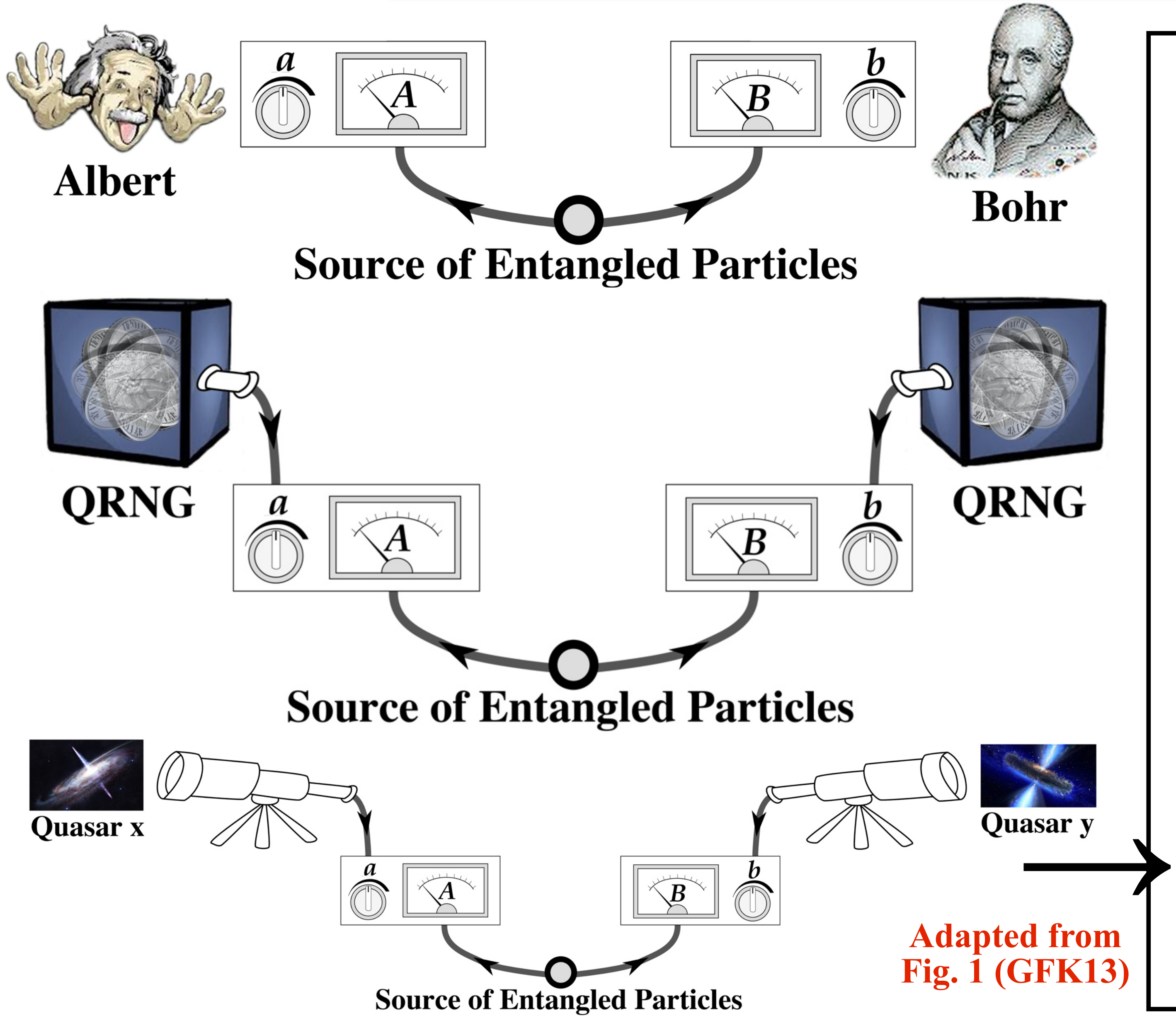
Friedman+2014 *in prep*. (F14b)

5. Actually Doing the Experiment?

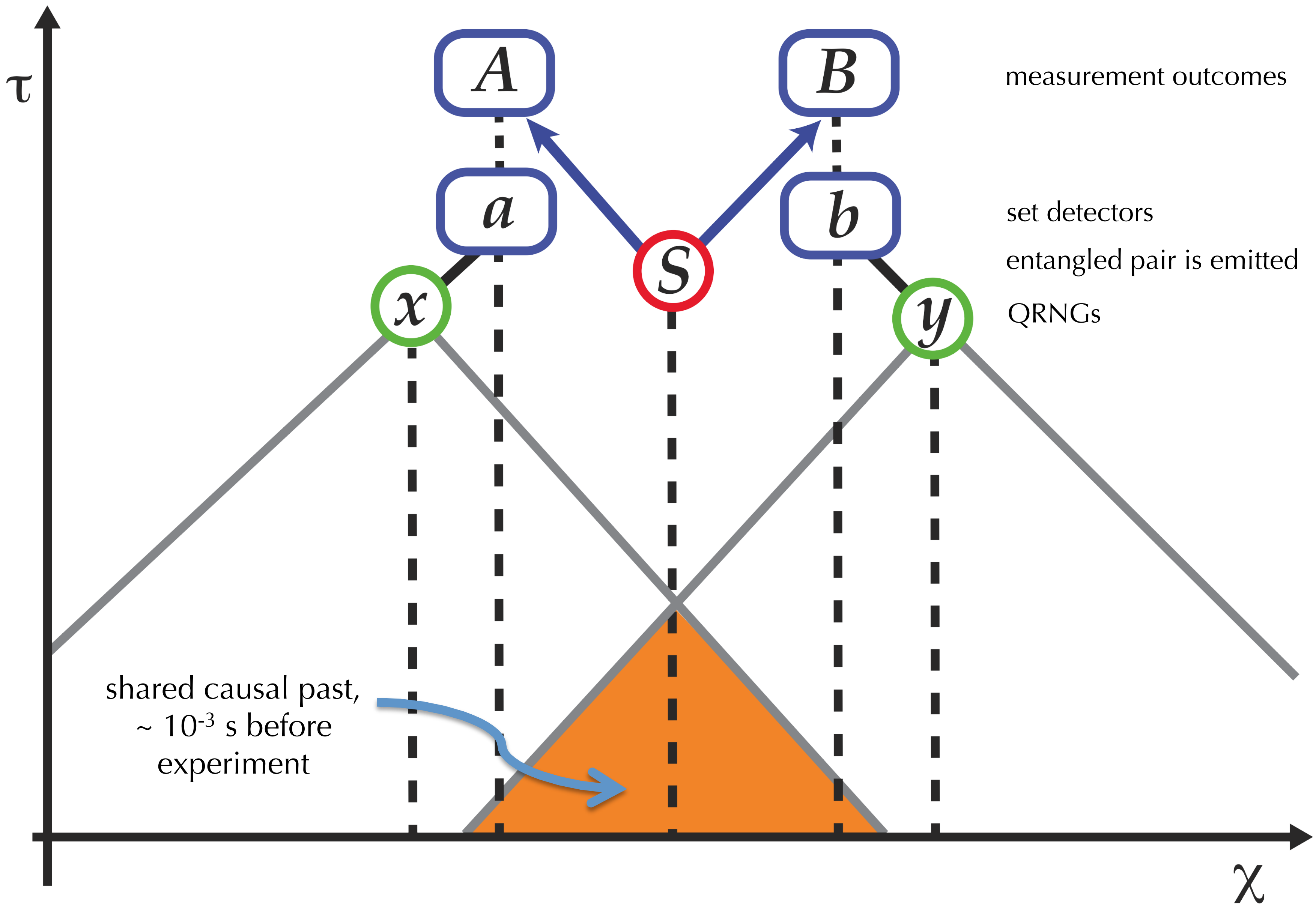
CHOOSING SETTINGS *a, b*



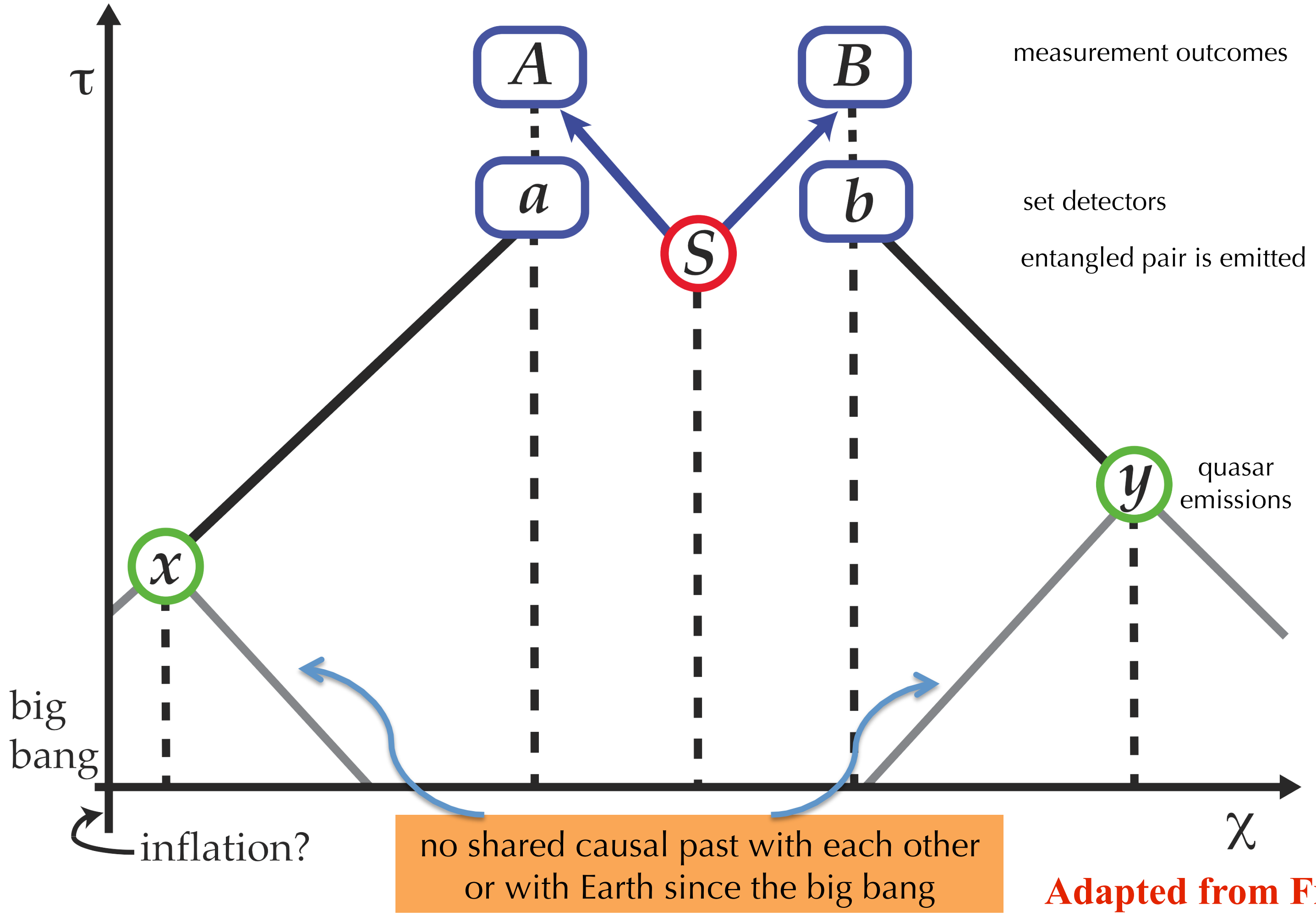
Choose detector settings with real-time observations of causally disconnected cosmic sources

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

BELL TEST CONFORMAL DIAGRAM



COSMIC BELL CONFORMAL DIAGRAM



Adapted from Fig. 2 (GFK13)

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

Cosmic Bell Advantages

- Others had 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**.

- 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.

- **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)**

- **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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5. Actually Doing the Experiment?

COSMOLOGY QUESTION

Cosmological 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 deg): no shared causal past w/ each other or Earth since end of inflation (FLAT univ.)

Constraints complex for angles < 180 deg

General results for curved space (F13a)

DO TWO COSMOLOGICAL EVENTS HAVE A SHARED PAST?

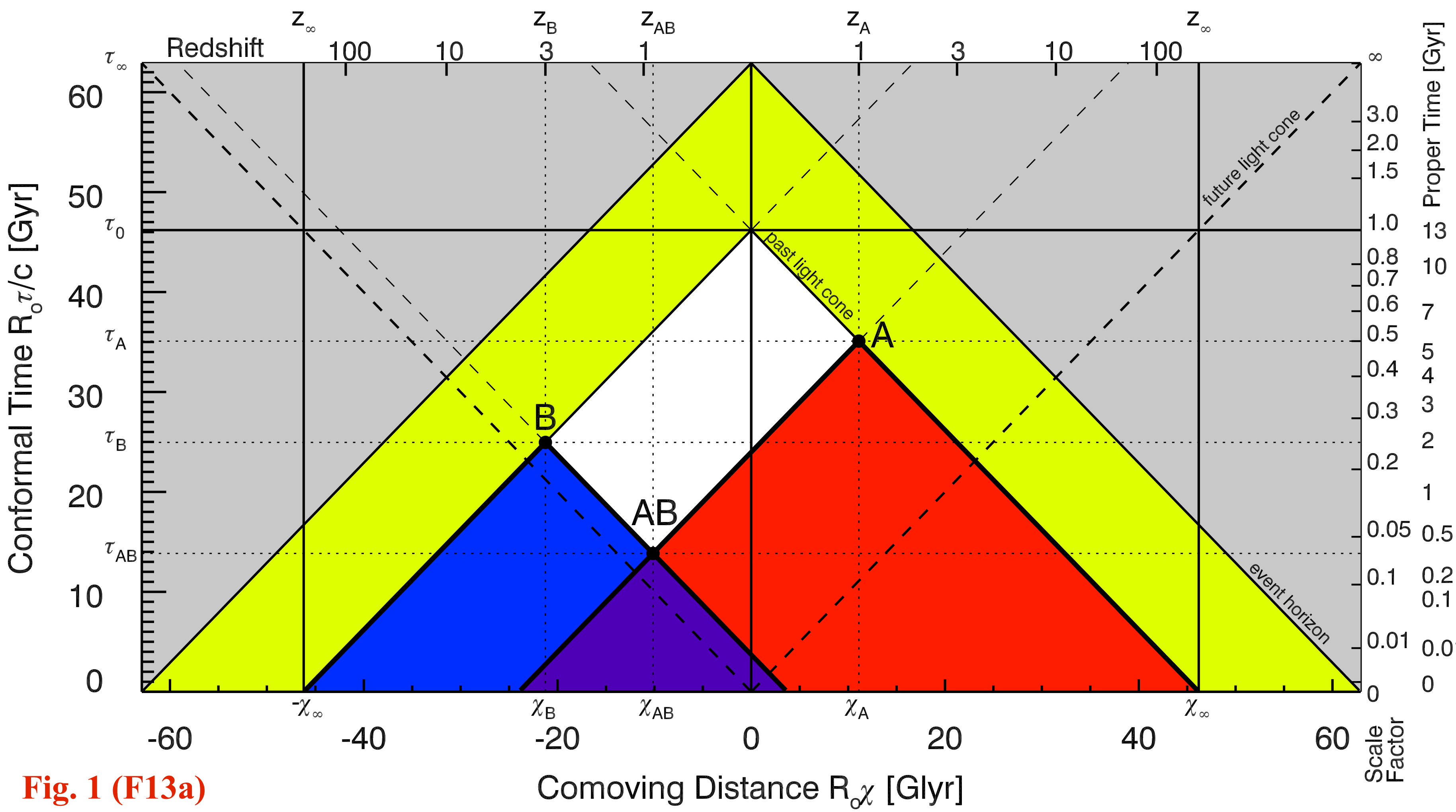


Fig. 1 (F13a)

Since the hot big bang or the end of inflation

INFLATION & THE HORIZON PROBLEM

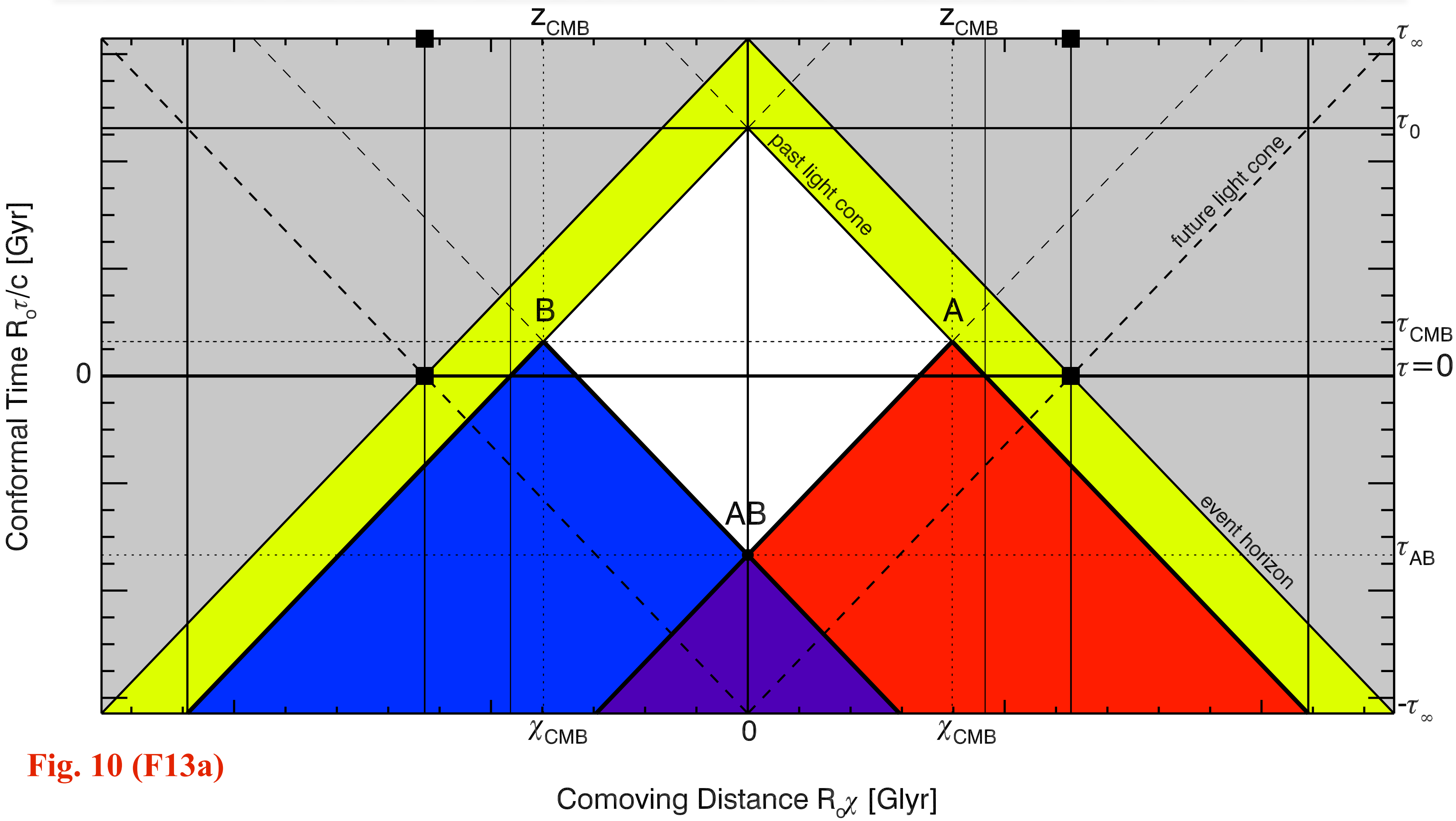


Fig. 10 (F13a)

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

PAST LIGHT CONE INTERSECTION

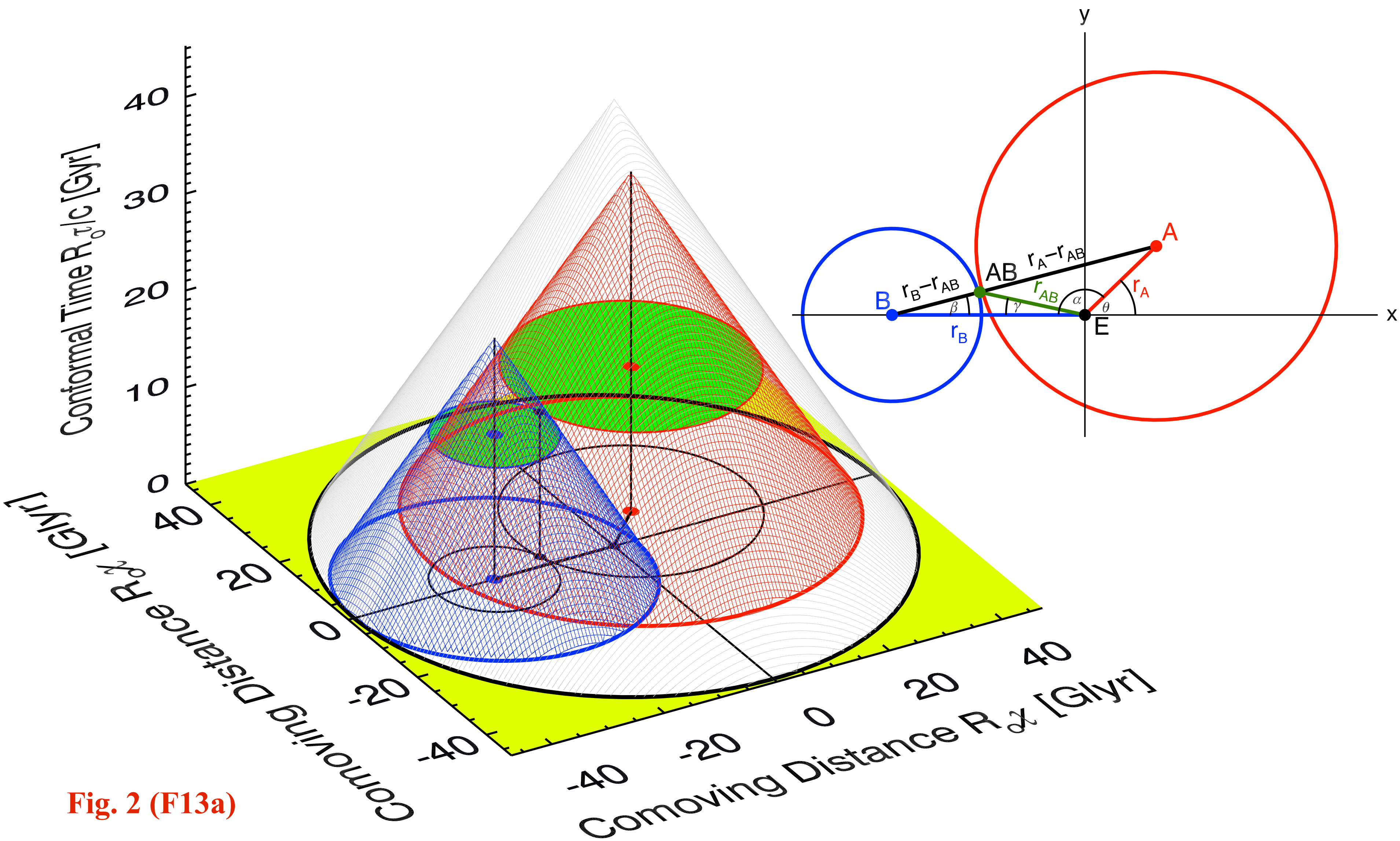
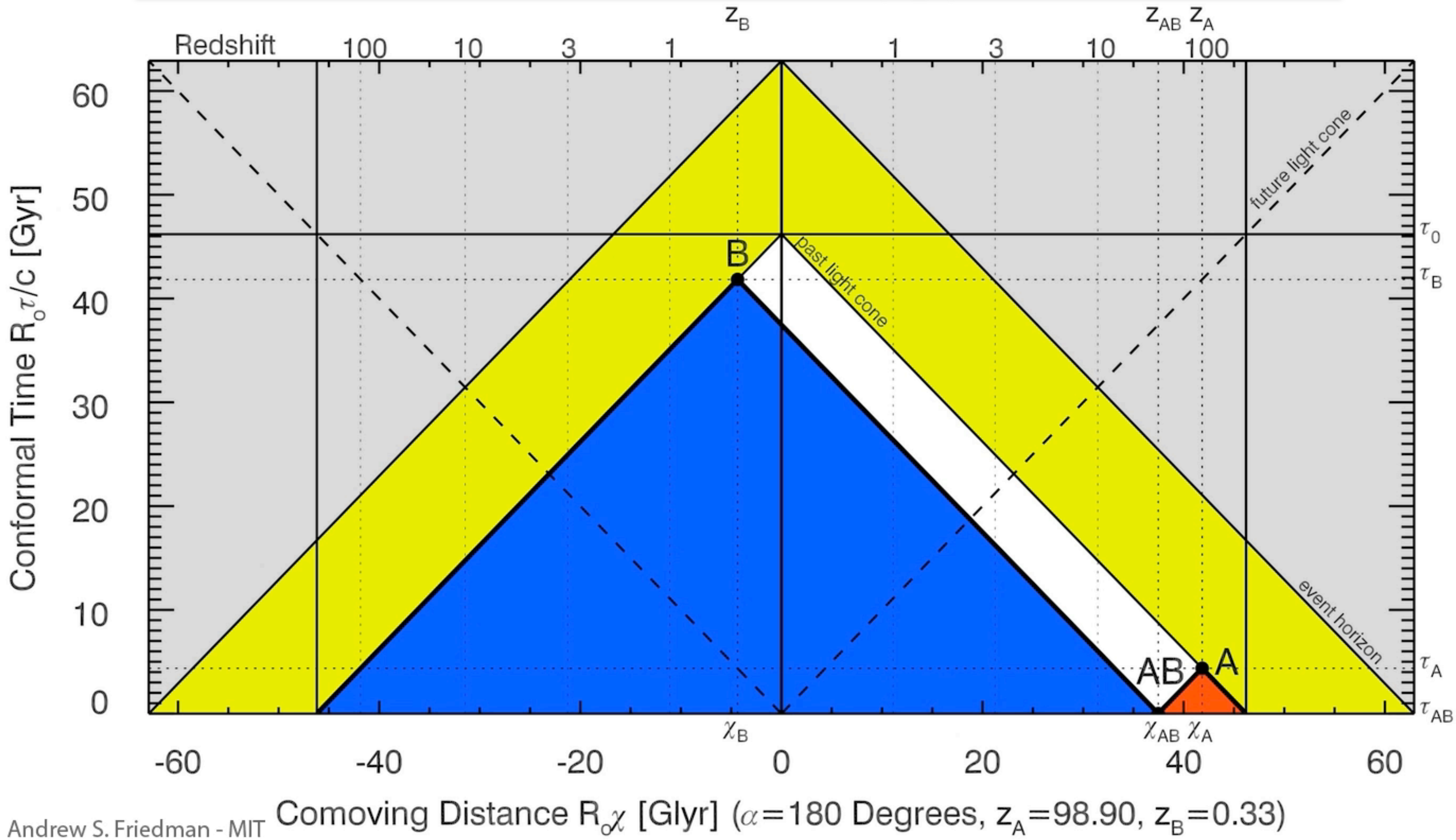


Fig. 2 (F13a)

LC INTERSECTION @BIG BANG



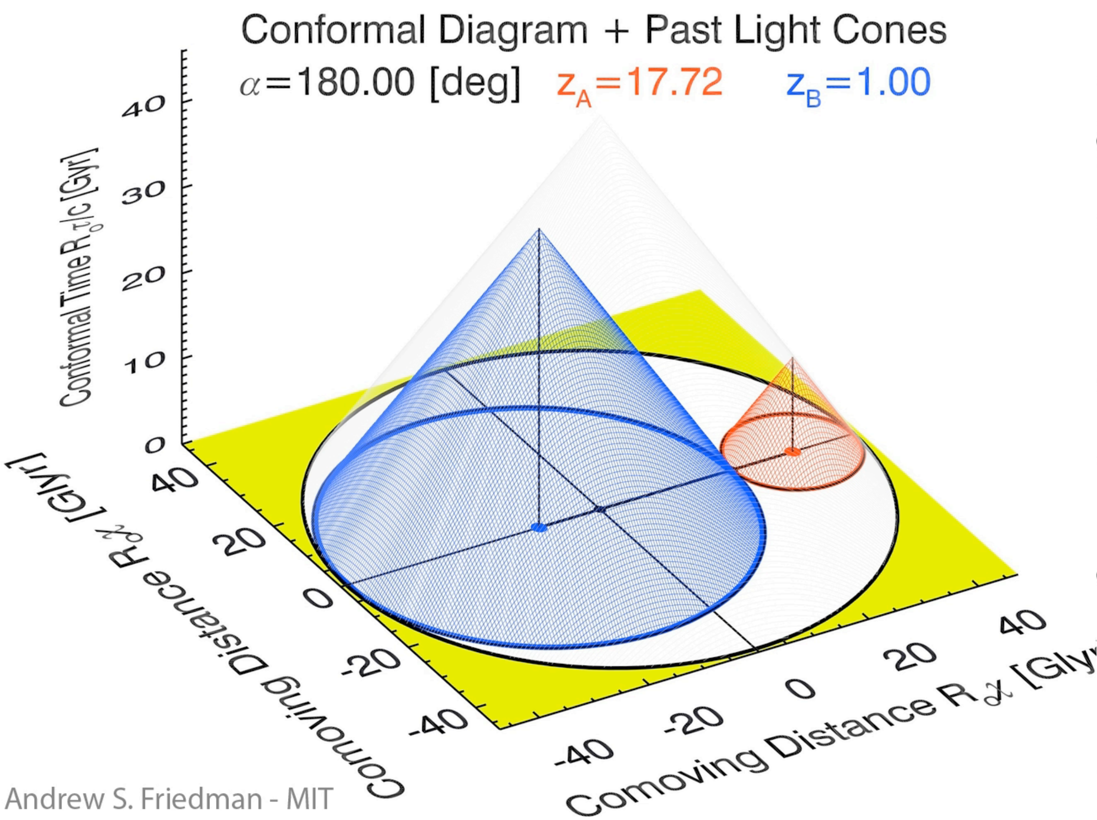
Animation 1 (F13a supplementary material)

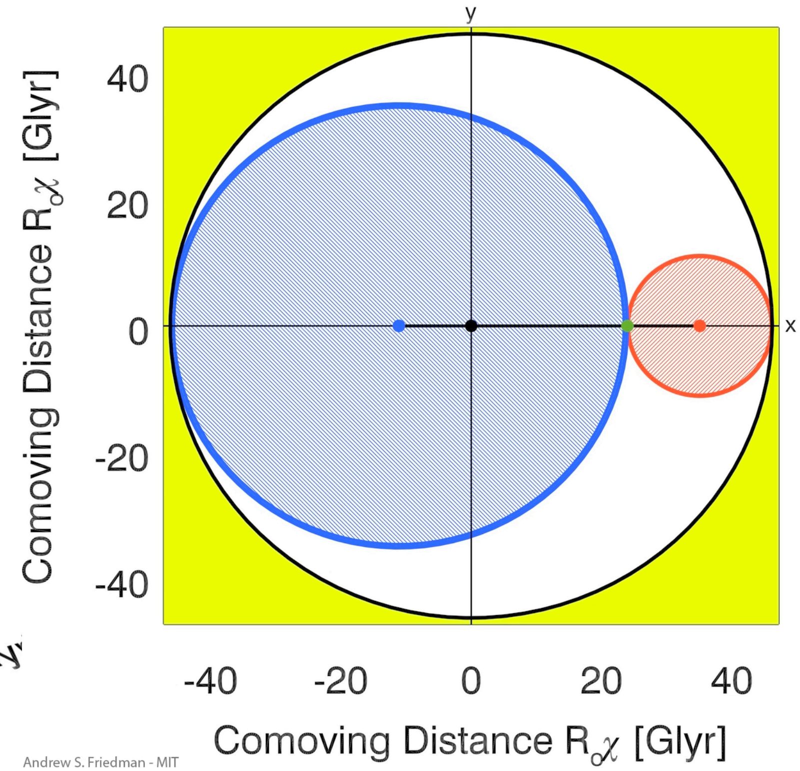
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

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

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

LC INTERSECTION @BIG BANG

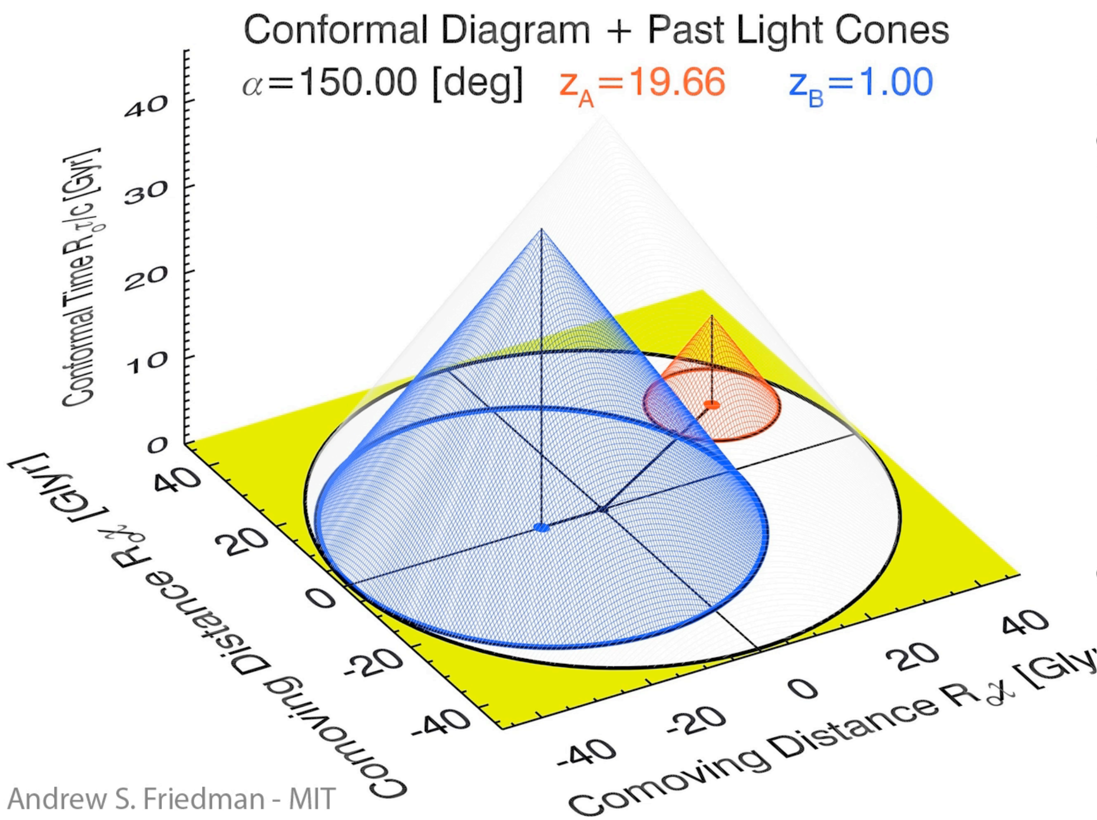


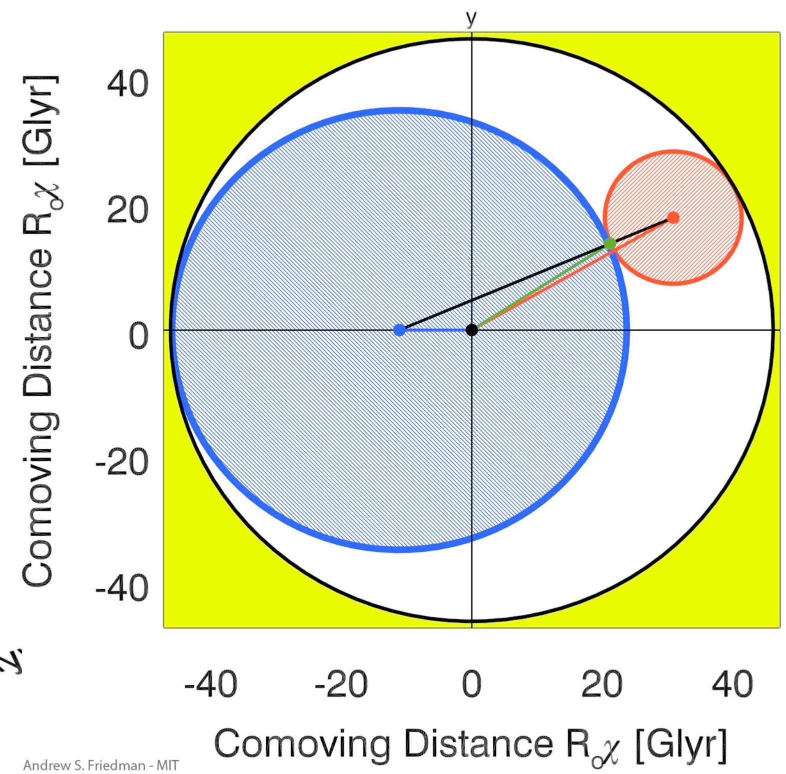


Animations 2-3 (F13a supplementary material) **http://web.mit.edu/asf/www/causal_past.shtml**

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

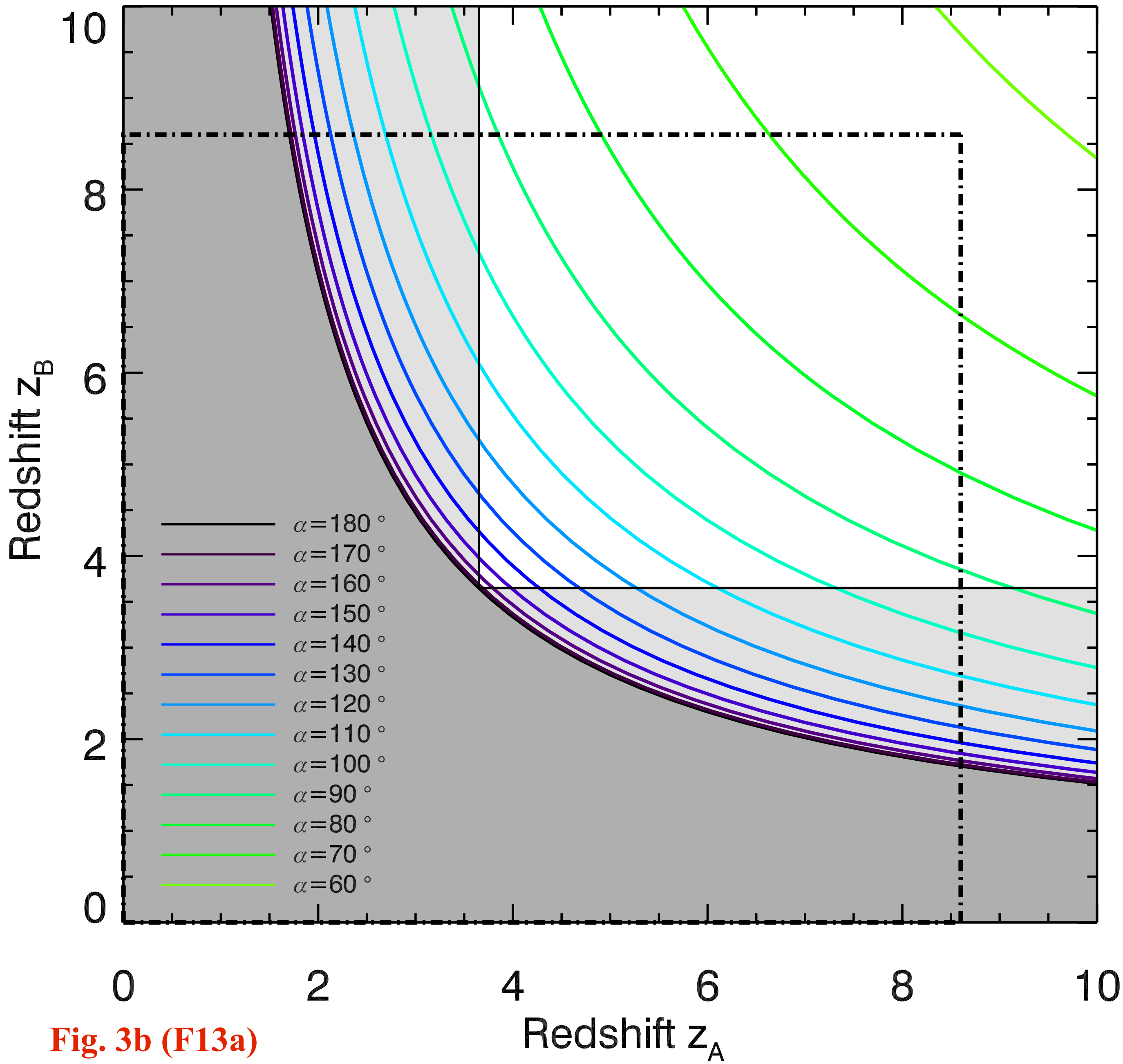


Fig. 3b (F13a)

Do A,B have a shared past?

Dark Gray

YES: any angle

Light Gray / White

NO: large angles

...with Earth?

Dark Gray

YES

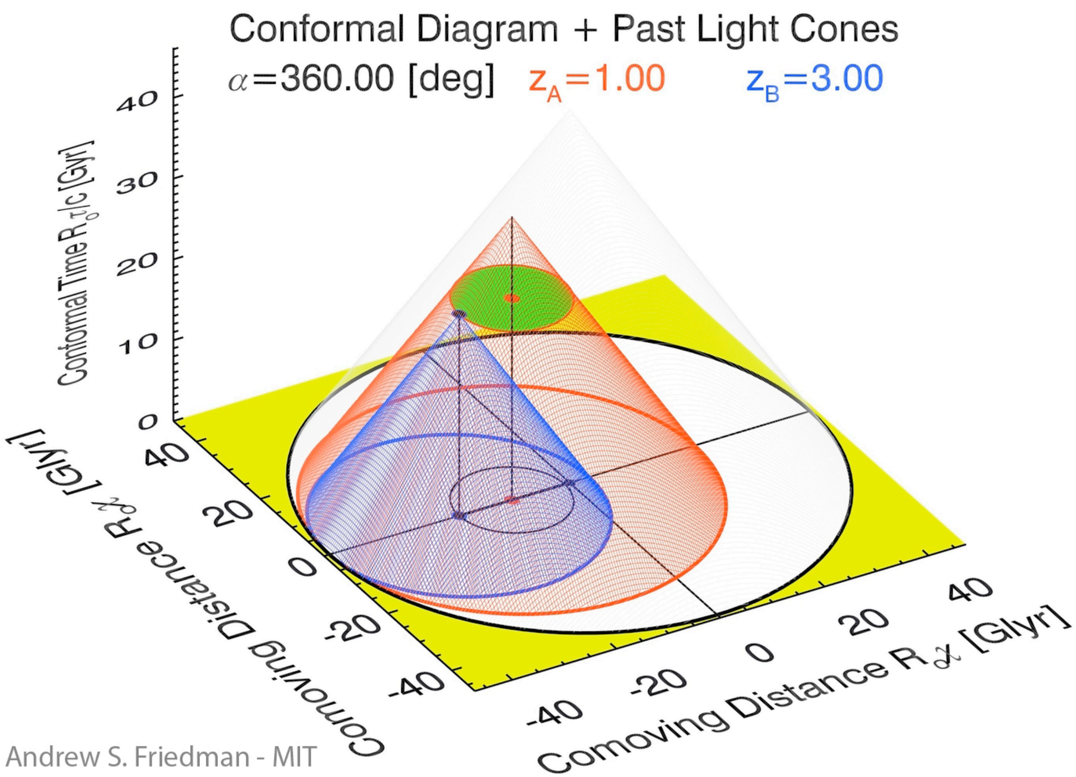
White

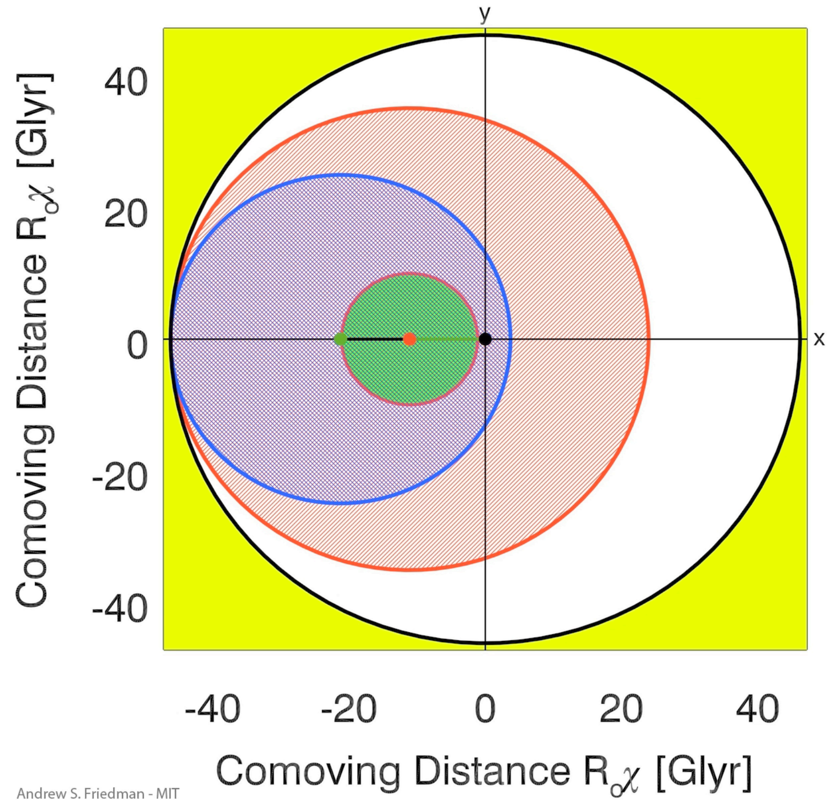
NO: A and B

Light Gray

YES: Either A or B

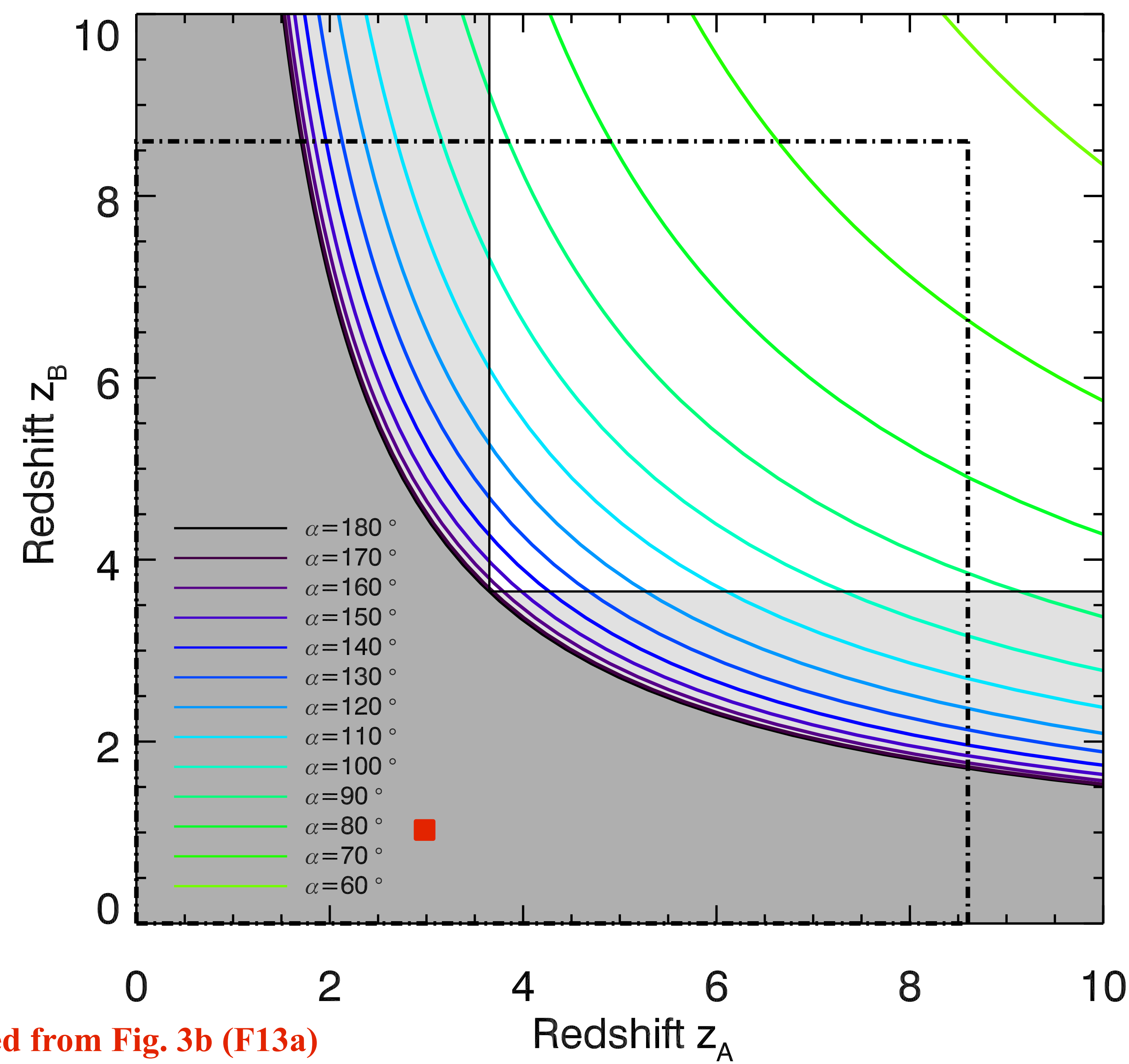
FIX REDSHIFTS, CHANGE ANGLE





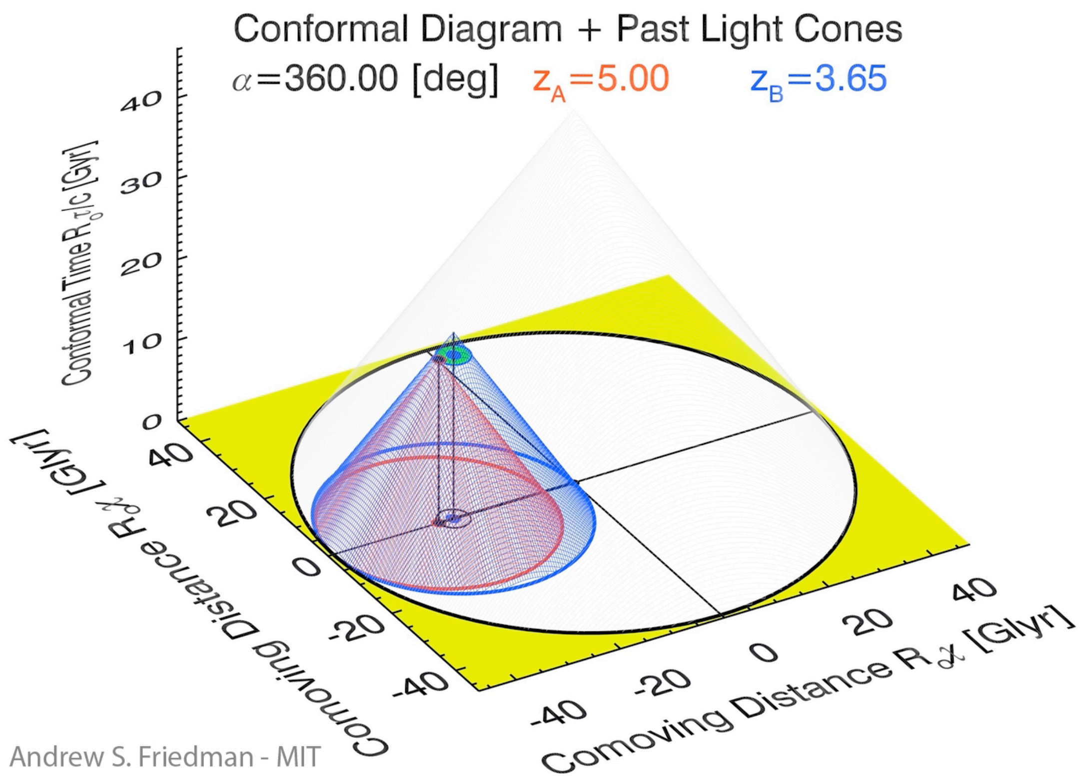
Animations 6-7 (F13a supplementary material) http://web.mit.edu/asf/www/causal_past.shtml

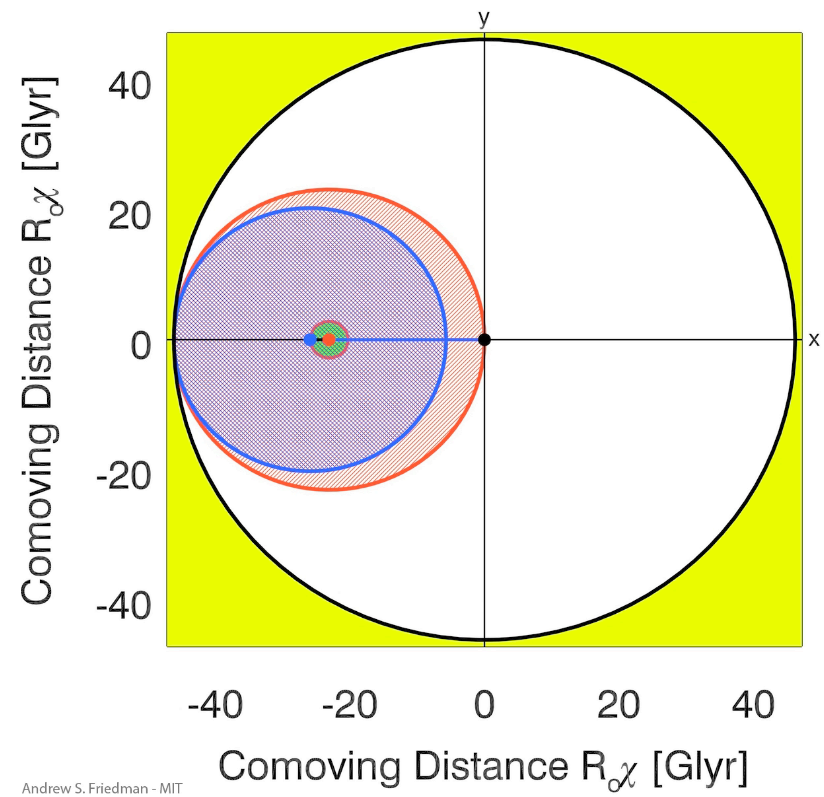
http://prd.aps.org/supplemental/PRD/v88/i4/e044038 http://web.mit.edu/asf/www/04_alpha_1_3.shtml



Adapted from Fig. 3b (F13a)

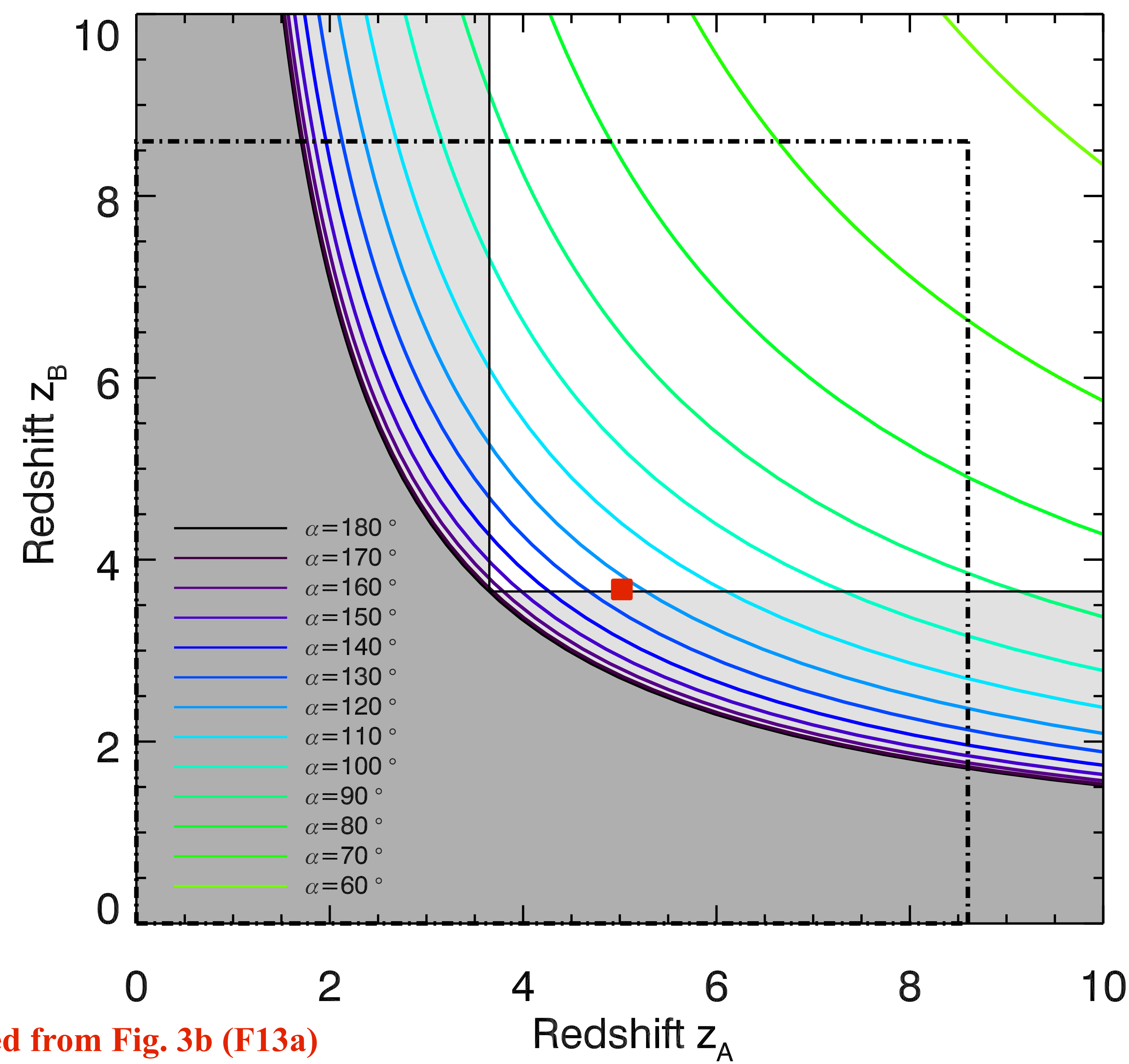
FIX REDSHIFTS, CHANGE ANGLE





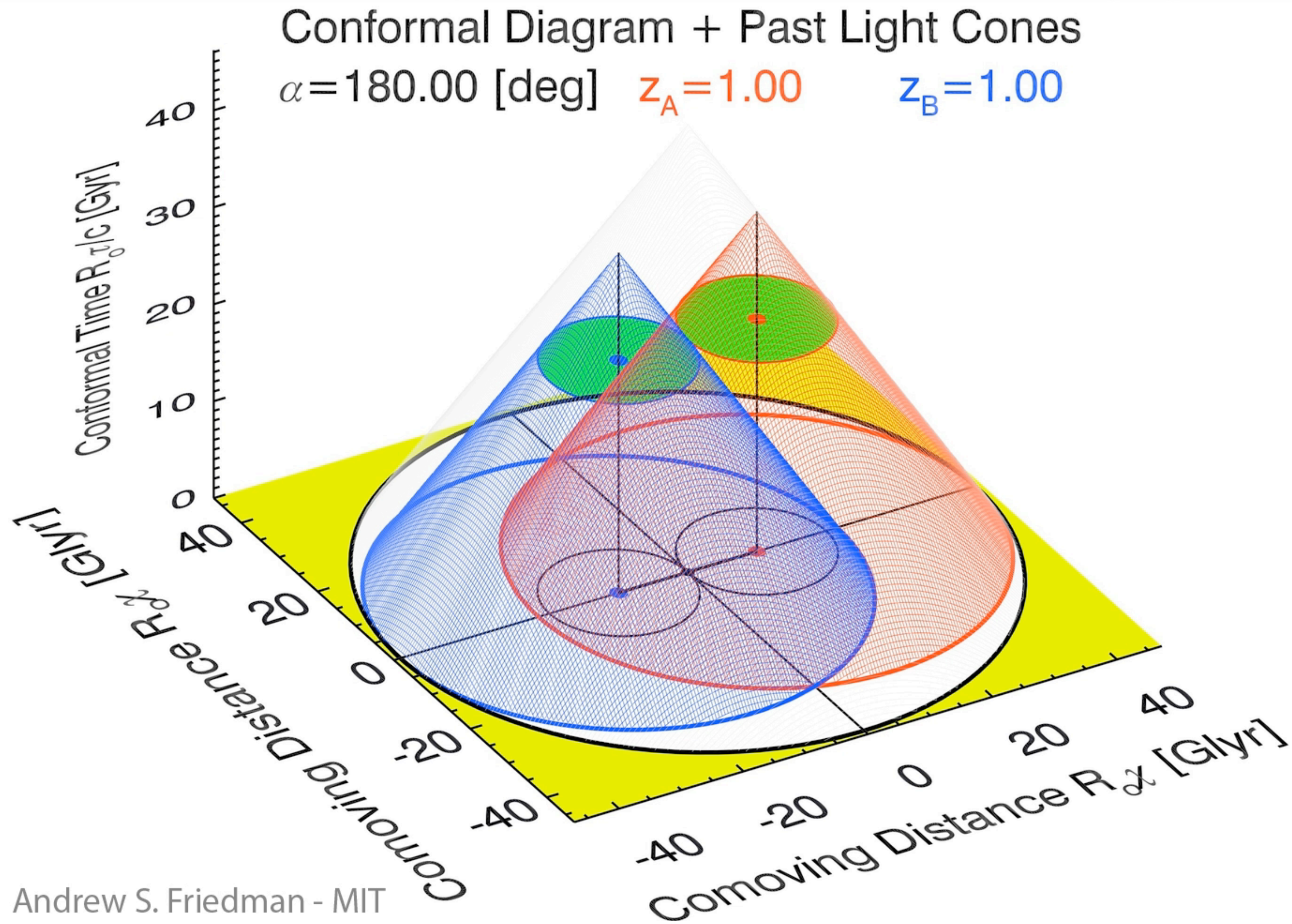
Animations 8-9 (F13a supplementary material) http://web.mit.edu/asf/www/causal_past.shtml

http://prd.aps.org/supplemental/PRD/v88/i4/e044038 http://web.mit.edu/asf/www/05_alpha_5_3p65.shtml



Adapted from Fig. 3b (F13a)

FIX ANGLE, CHANGE Z = ZA = ZB



Animation 11 (F13a supplementary material) **http://web.mit.edu/asf/www/causal_past.shtml**

http://prd.aps.org/supplemental/PRD/v88/i4/e044038 **http://web.mit.edu/asf/www/06_zcrit.shtml**

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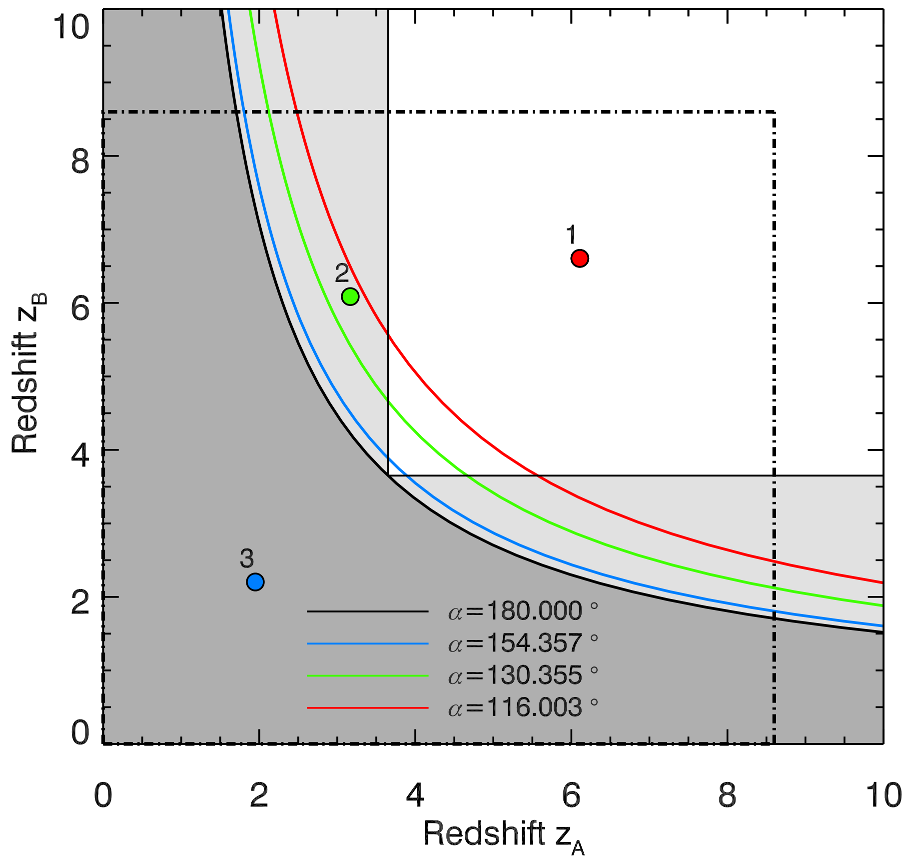


EXAMPLE QUASAR PAIRS

pair 3 - YES shared past with each other & Earth

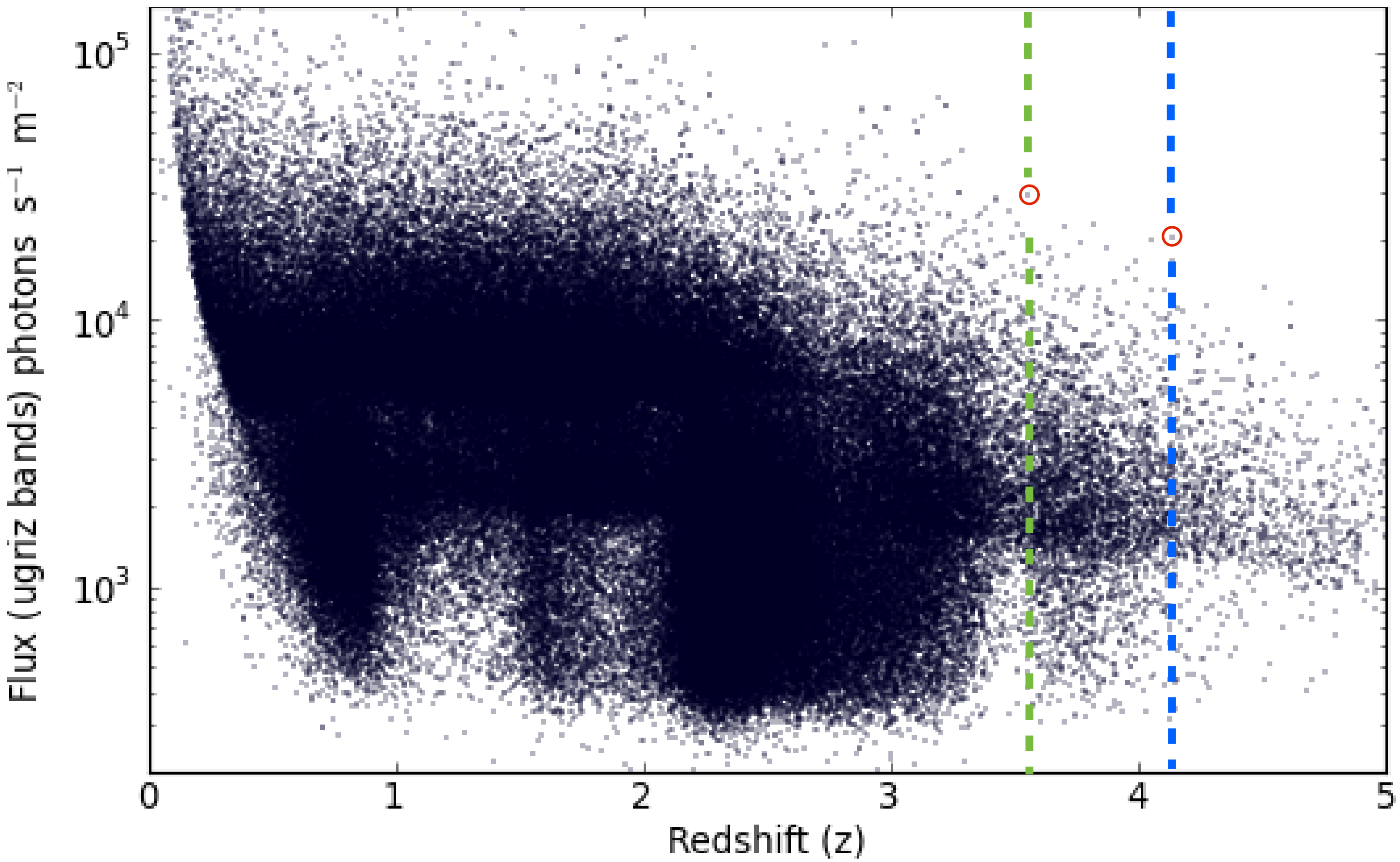
pair 2 - NO shared past with each other, but A_2 has shared past with Earth

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 (GFK13)

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?

Settings Independence

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. (GFK13)

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

QUASAR CANDIDATES

- **Determine which quasar pairs (from existing database of > 1 million objects) satisfy causal independence 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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5. **Actually Doing the Experiment?**

2 OR MORE COSMIC SOURCES

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

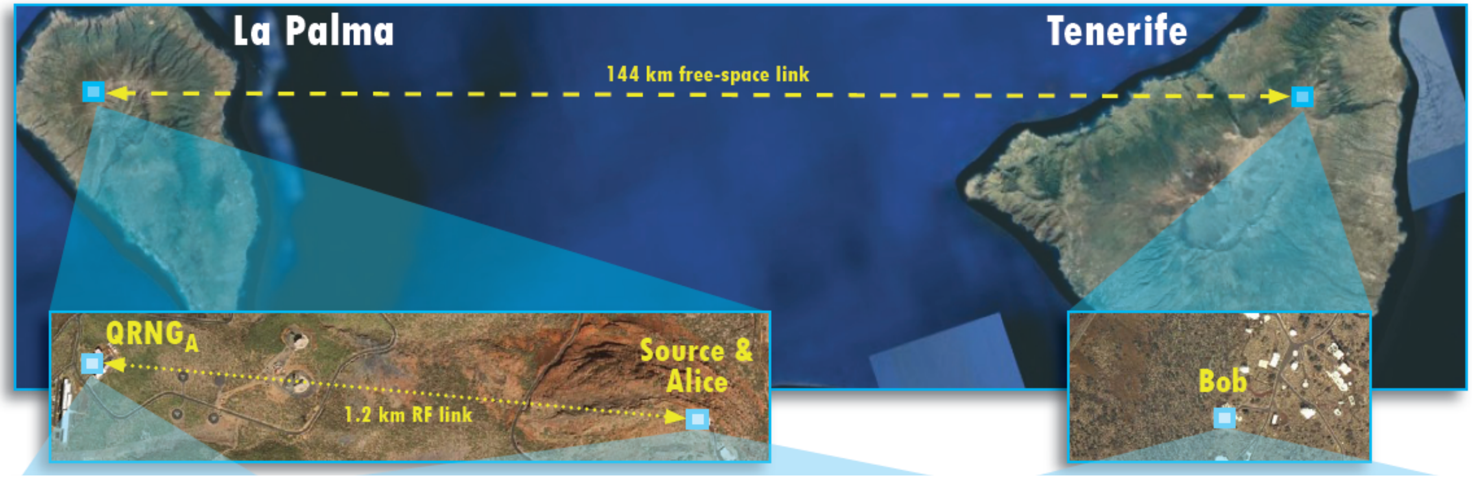
Greenberger, Horne, Zeilinger 1989; Greenberger+1990; Mermin 1990

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

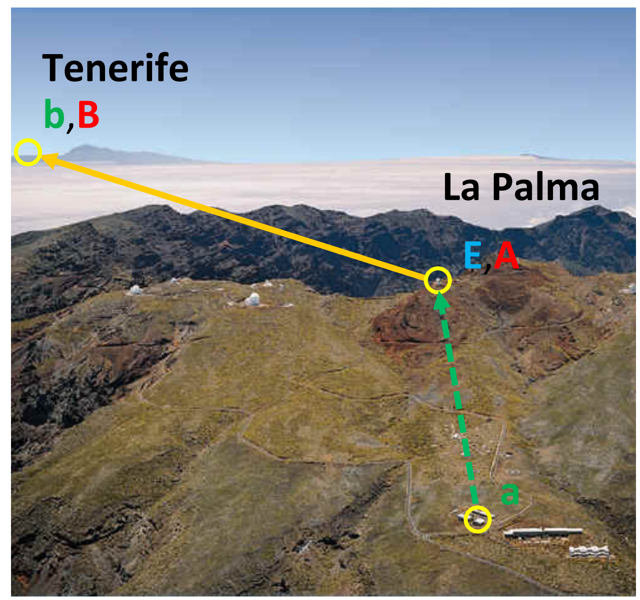
	Optimal space configurations	Redshifts	Feasible Ground-Based Tests	Redshifts
EPR2	180^{o}	> 3.65	≲ 130^{o}	> 4.13
GHZ3	120^{o} Equilateral Triangle	> 4.37	≲ 105^{o} Triangular pyramid	> 4.89
GHZ4	~109.5^{o} Tetrahedron	> 4.69	≲ 75^{o} Square pyramid	≳ 6.5
GHZ4	90^{o} Square in Plane	> 5.69		

GFK13; Friedman+2014b *in prep*.

ZEILINGER GROUP EXPERIMENTS

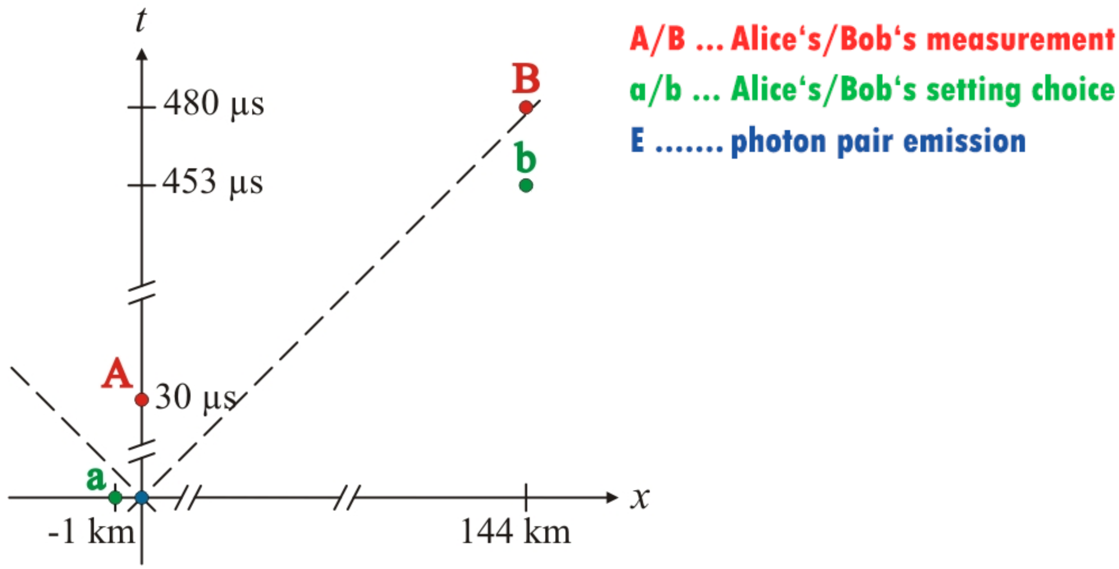


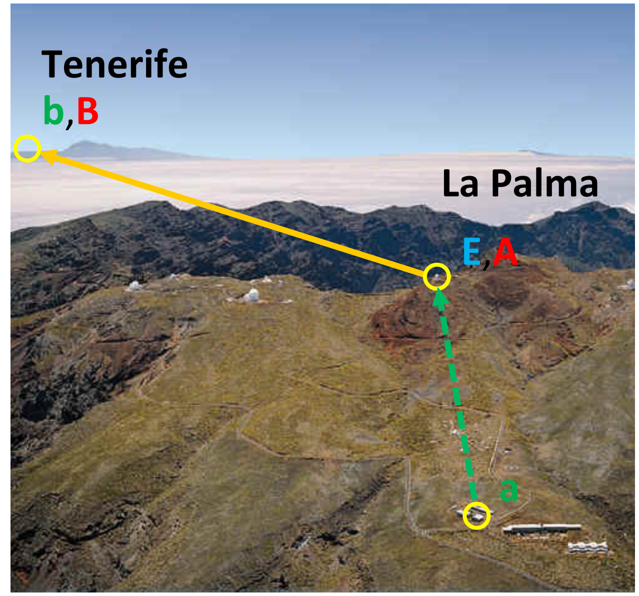
ESA - Optical Ground Station (OGS) 1-m receiver telescope, Laser guide to La Palma



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

VIOLATION OF LOCAL REALISM WITH FREEDOM OF CHOICE





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

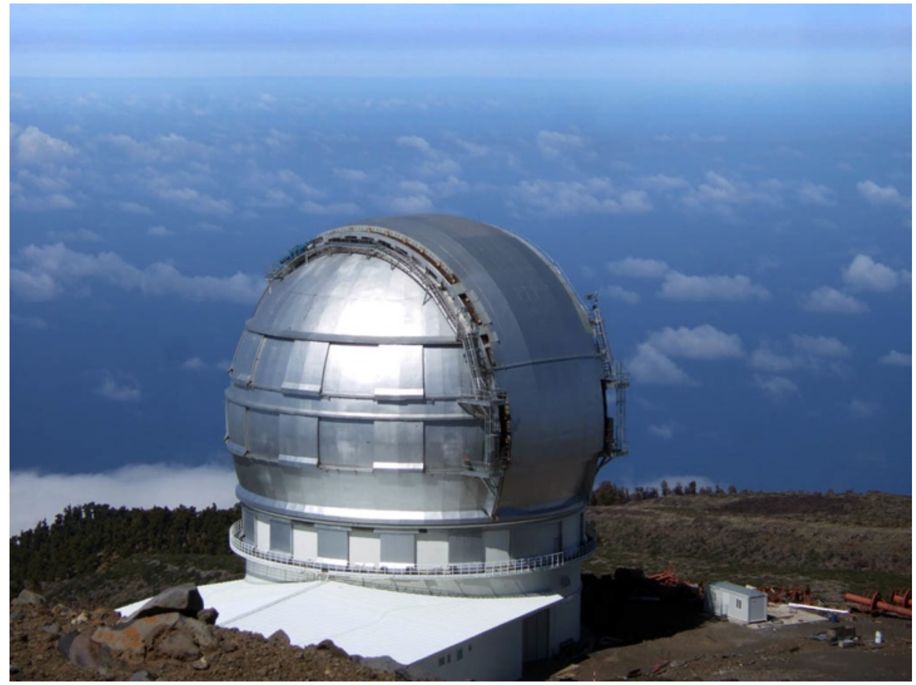
Canary Islands Telescopes

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

Roque de los Muchachos Observatory on the island of **La Palma** 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 (GFK13)

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. (GFK13)

"Inflation Loophole" Shared past during inflation

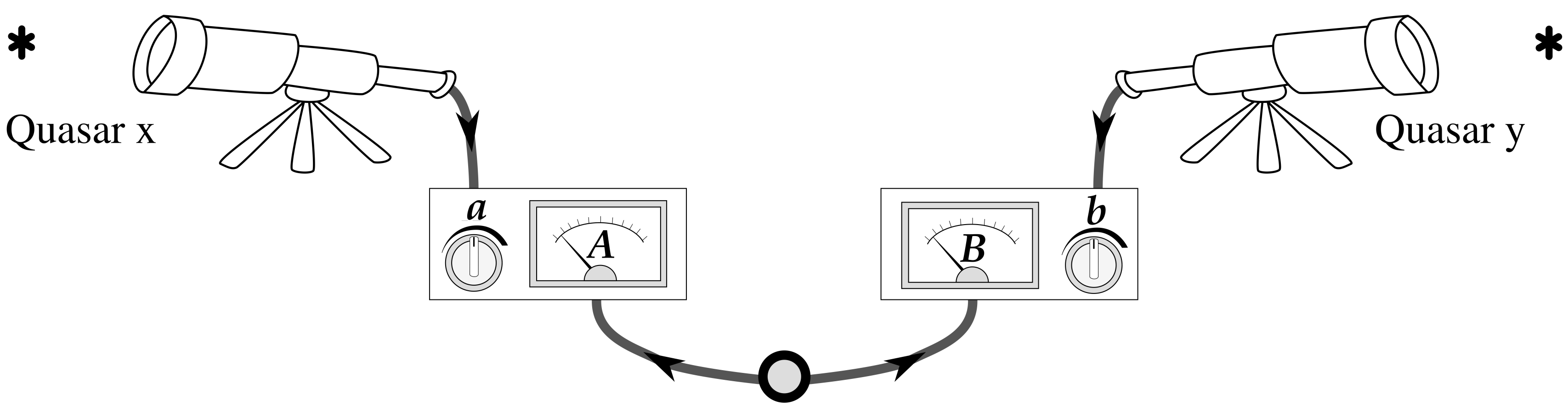
CONCLUSIONS

An actual Cosmic Bell experiment:

Is well motivated

Feasible in the real world.

Lots of fun to think about!



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