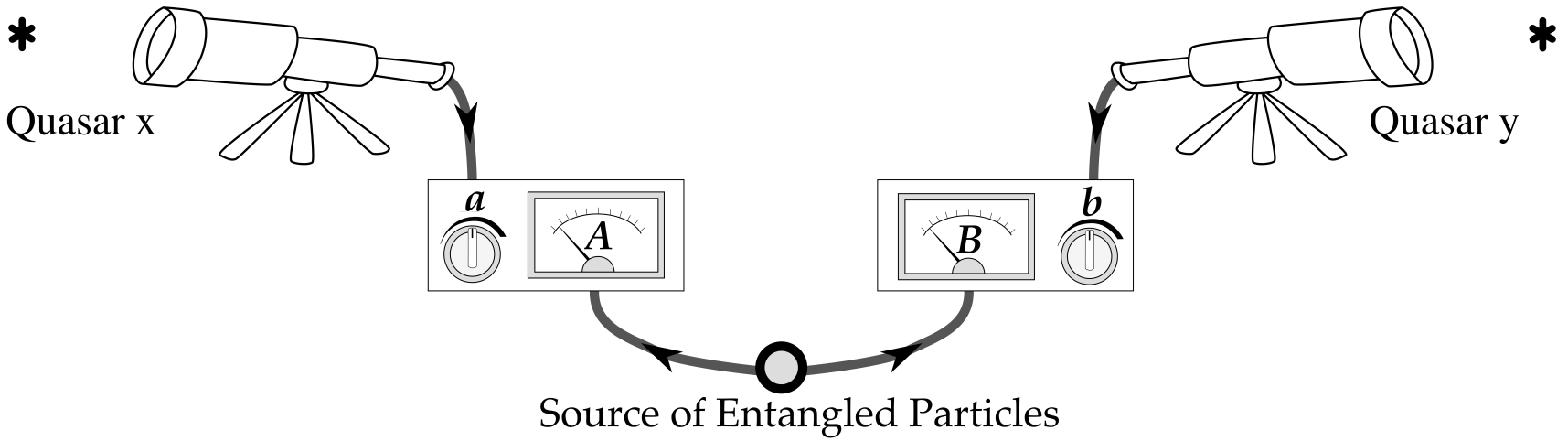

TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH OBSERVATIONS OF CAUSALLY DISCONNECTED COSMOLOGICAL EVENTS

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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*

Gallicchio, Friedman, & Kaiser 2013 (GFK13)
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3. Shared Causal Pasts of Cosmic Events

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4. Causally Disconnected Quasars

Friedman+2013 *in prep*. (F13c)

5. Actually Doing the Experiment?

QM AND HIDDEN VARIABLES

1927 Copenhagen interpretation of QM (Bohr, Heisenberg)

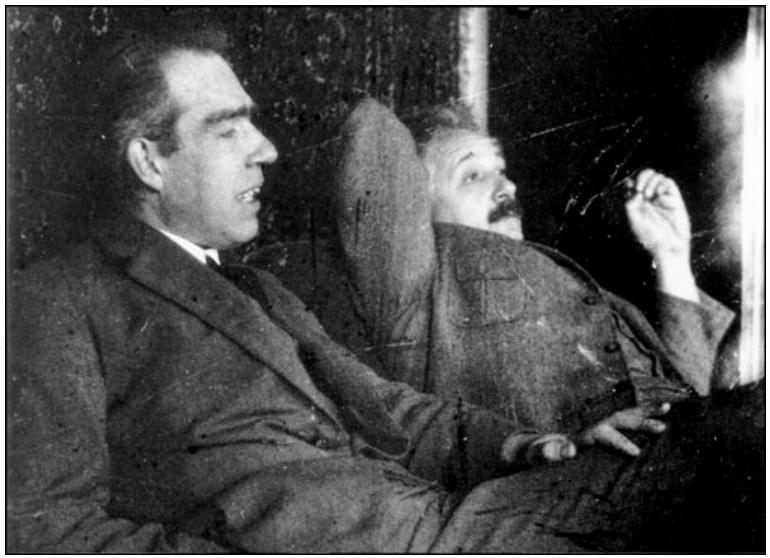
1935 Einstein-Podolsky-Rosen (EPR) paradox paper

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

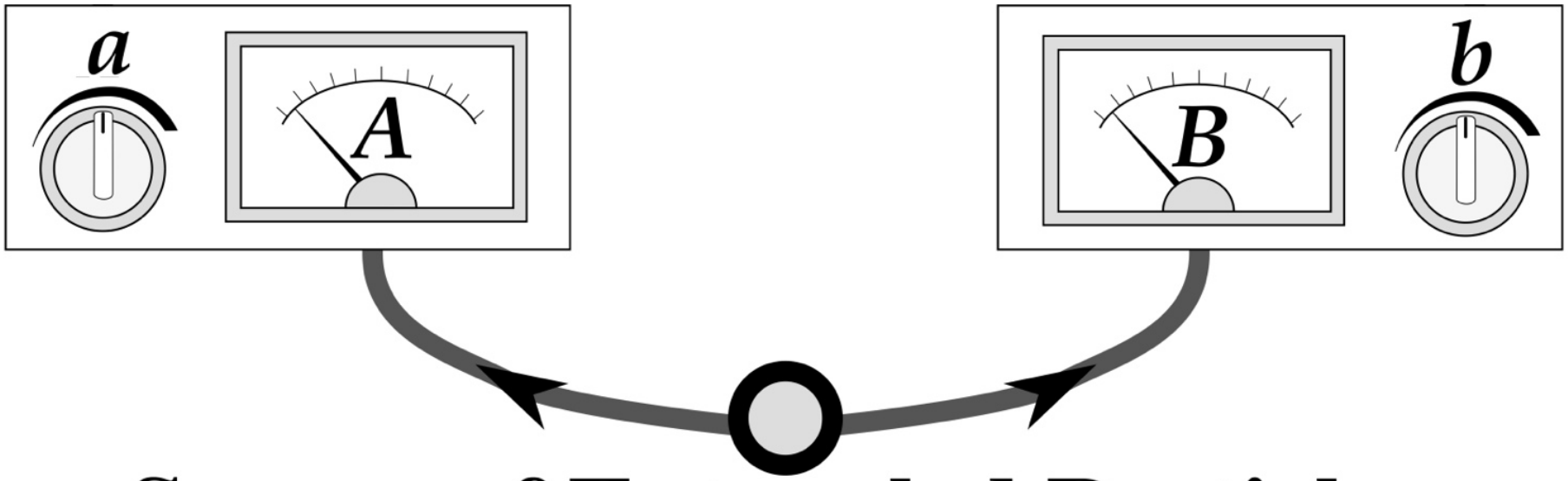


Bohr and Einstein, 1925

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

EPR EXPERIMENTS

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



a, b = *Settings*

A, B = *Outcomes*

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 ...

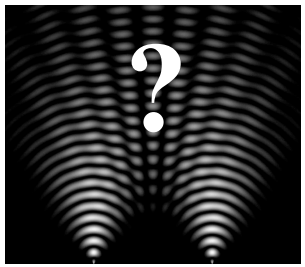
...Equally Logically Consistent Story:

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

Hidden communication between parties

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

Closing Method?

Space-like separate outcomes!

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**

QRNGs + Space-like separate settings choices & outcomes!

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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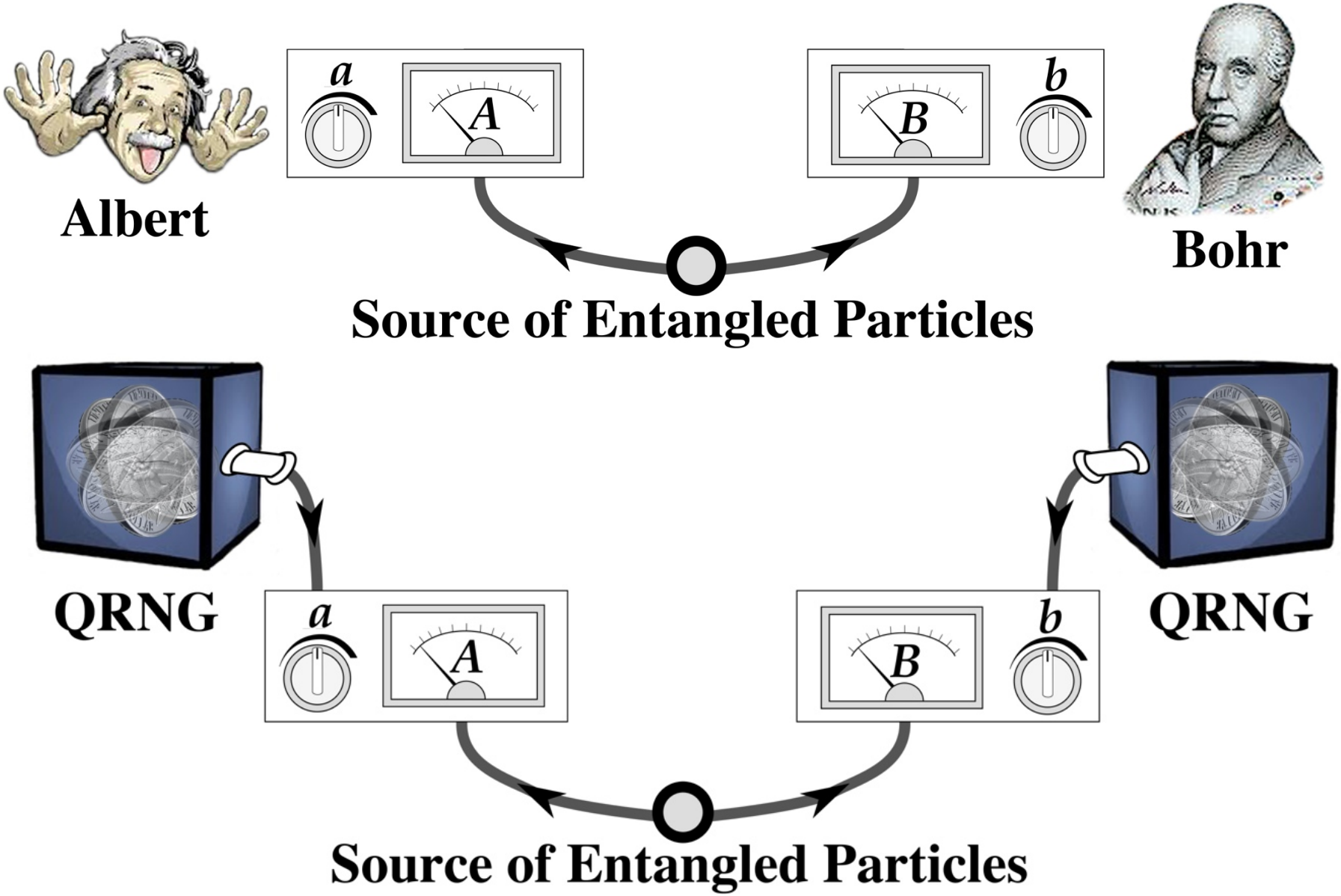
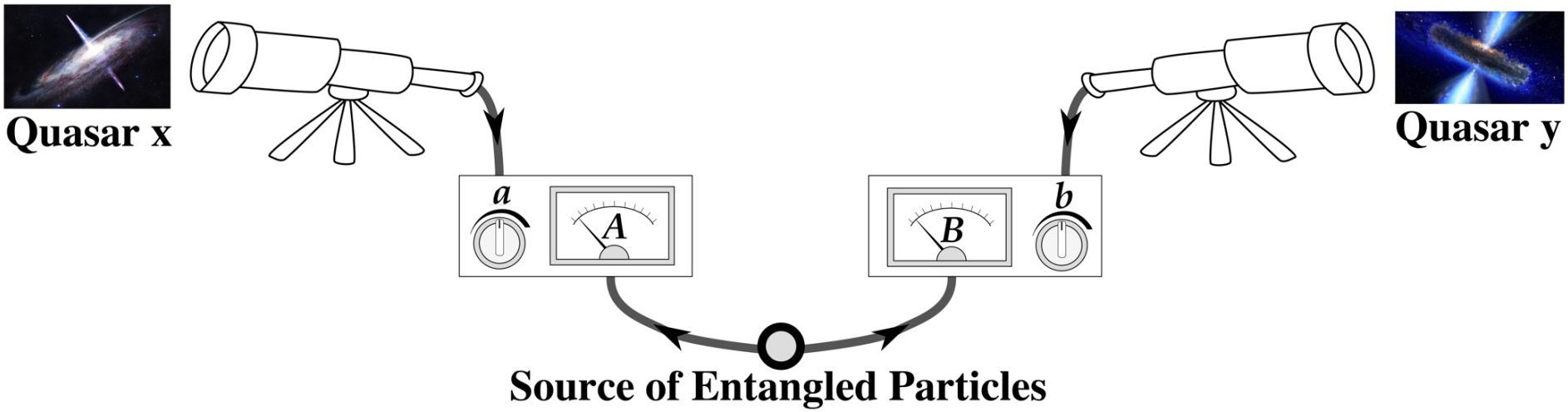
CHOOSING SETTINGS *a, b*



COSMIC BELL GEDANKENEXPERIMENT



Adapted from Fig. 1 (GFK13)

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

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

COSMIC BELL IN THE BLOGOSPHERE

Credit: Dr. Warren Huelsnitz, Fermilab
http://www.thefunisreal.com

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« The Many Worlds Interpretation of Quantum Mechanics and the Emperor's New Clothes

Hydrodynamic Quantum Analogs »

Closing Loopholes in Quantum Mechanics

By Warren Huelsnitz | October 16, 2013 | double slit experiment, entanglement, EPR paradox, quantum nonlocality, quantum physics

Violations of Bell's Inequalities and Loopholes in Quantum Mechanics

Recall that, in 1935, Einstein, Podolsky, and Rosen wrote their famous paper that became known as the EPR paradox. In it, they pointed out the bizarre consequences of the mathematics of quantum mechanics. If two particles were in an entangled state, then measurement on one of the particles would immediately affect the results of a measurement on the other particle, even if the two particles were arbitrarily far apart at the time of the measurements. This non-locality was later called "spooky action a distance" by Einstein.

In the 1960's, John Bell came up with a set of equations, inequalities, that quantified the disagreement between the predictions of quantum mechanics and that of a purely local theory (i.e. one that assumed the distant measurement could not affect the local measurement). Since then, violations of these inequalities have been experimentally verified on numerous occasions. Thus, the inescapable conclusion is that nature *does* make use of non-locality, some how. However, this conclusion is based on the assumption that *nothing else unusual or unexpected* is happening during the experiment.

Scrutinizing Loopholes in Observed Violations of Bell's Inequalities

Many different variations of the experiments have been done. See, for example, my discussion at *Quantum Weirdness: The unbridled ability of quantum physics to shock us.* Many more, different types of experiments have also been done. In some of these experiments, the violation is more dramatic – not just a matter of the frequency of apparently correlated outcomes. These experiments are go or no-go; they are designed to look for an event that would not happen under a purely local theory. See *Do We Really Understand Quantum Mechanics?* or *Do we really understand quantum mechanics? Strange correlations, paradoxes, and theorems* for more in-depth discussions.

Given that the implication of these experiments is so profound, scientists have gone to great lengths to ensure that there is not some more benign, classical, local, or deterministic explanation that has been missed. One possibility is that, since we do not detect every photon due to limitations in detector efficiency, we are detecting a special subset of events. Another possibility is that the detector settings are not actually independent or random. Typically, detector settings are chosen randomly; for example, by a quantum random number generator. But if there were even some slight correlations between the choice of detector settings and some

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- Hydrodynamic Quantum Analogs
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great article by Sean Carrroll - clears up errors in the way dark energy and the accelerating expansion of the universe are often explained:
http://www.preposterousuniverse.com/blog/2013/11/16/why-does-dark-energy-make-the-universe-accelerate/

Why Does Dark Energy Make the Universe Accelerate?

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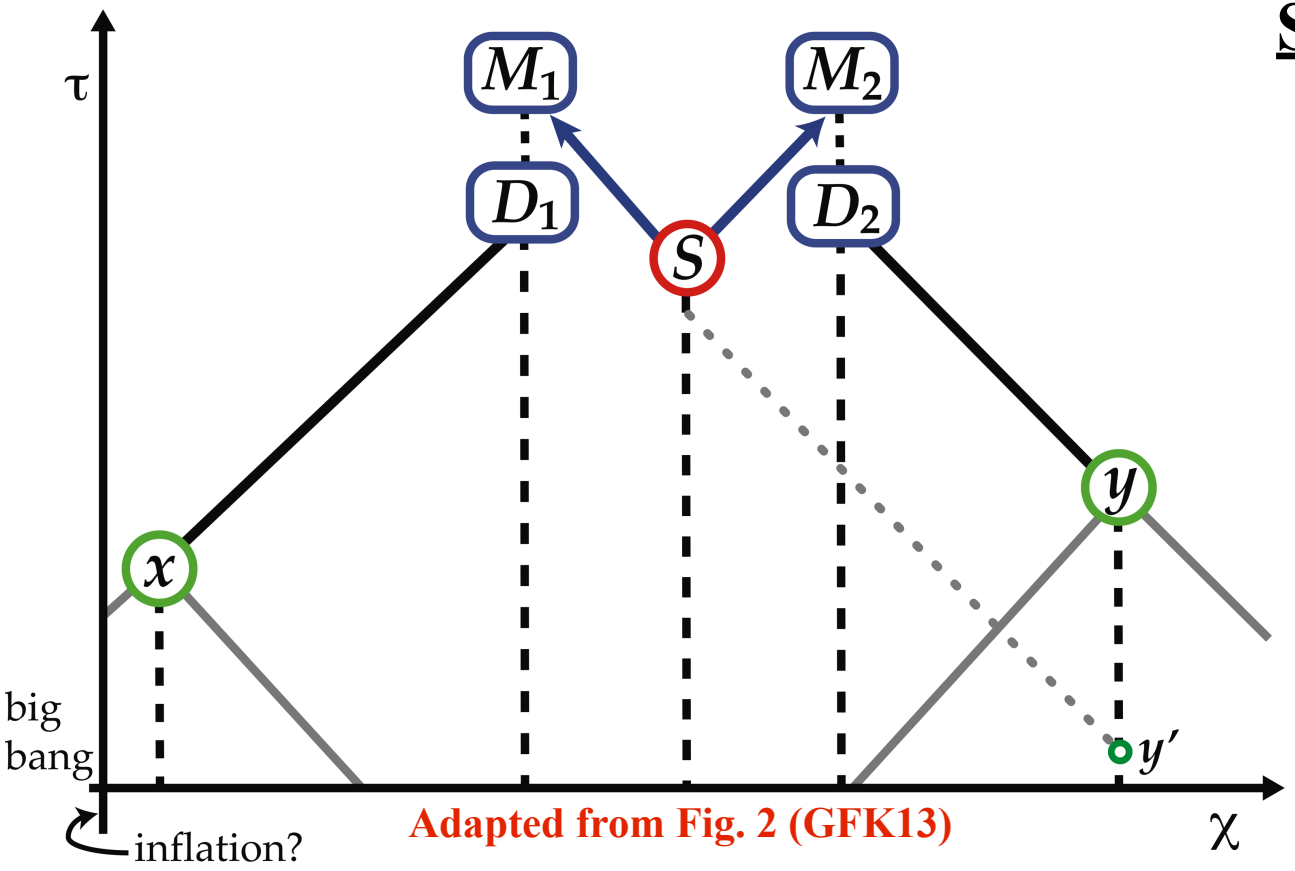
COSMIC BELL CONFORMAL DIAGRAM



Adapted from Fig. 2 (GFK13)

Space-time events

x , y : cosmic sources emit light

D_1, D_2: settings choices

S: source emits EPR particles

M_1, M_2: EPR particles measured

***x, y* need z >3.65 (at 180º) to have no shared causal past with each other, source, or detectors since hot big bang (end of inflation)**

y' : event in past LC of y and S

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

For pairs of cosmological events with arbitrary redshifts and angular separation on the sky:

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?

3. Are the events independent or correlated (since inflation)?

COSMOLOGICAL CONSTRAINTS

MAIN RESULT: CAUSAL PAST CONDITION

Event pairs on opposite sides of sky with $z > 3.65$ have no shared causal past with each other or Earth since hot big bang (end of inflation)

Constraints on causal independence redshift more complex for angles < 180 deg

Flat, FLRW cosmological parameters: *Planck*

General results for curved space (F13a)

DO TWO COSMOLOGICAL EVENTS HAVE A SHARED PAST?

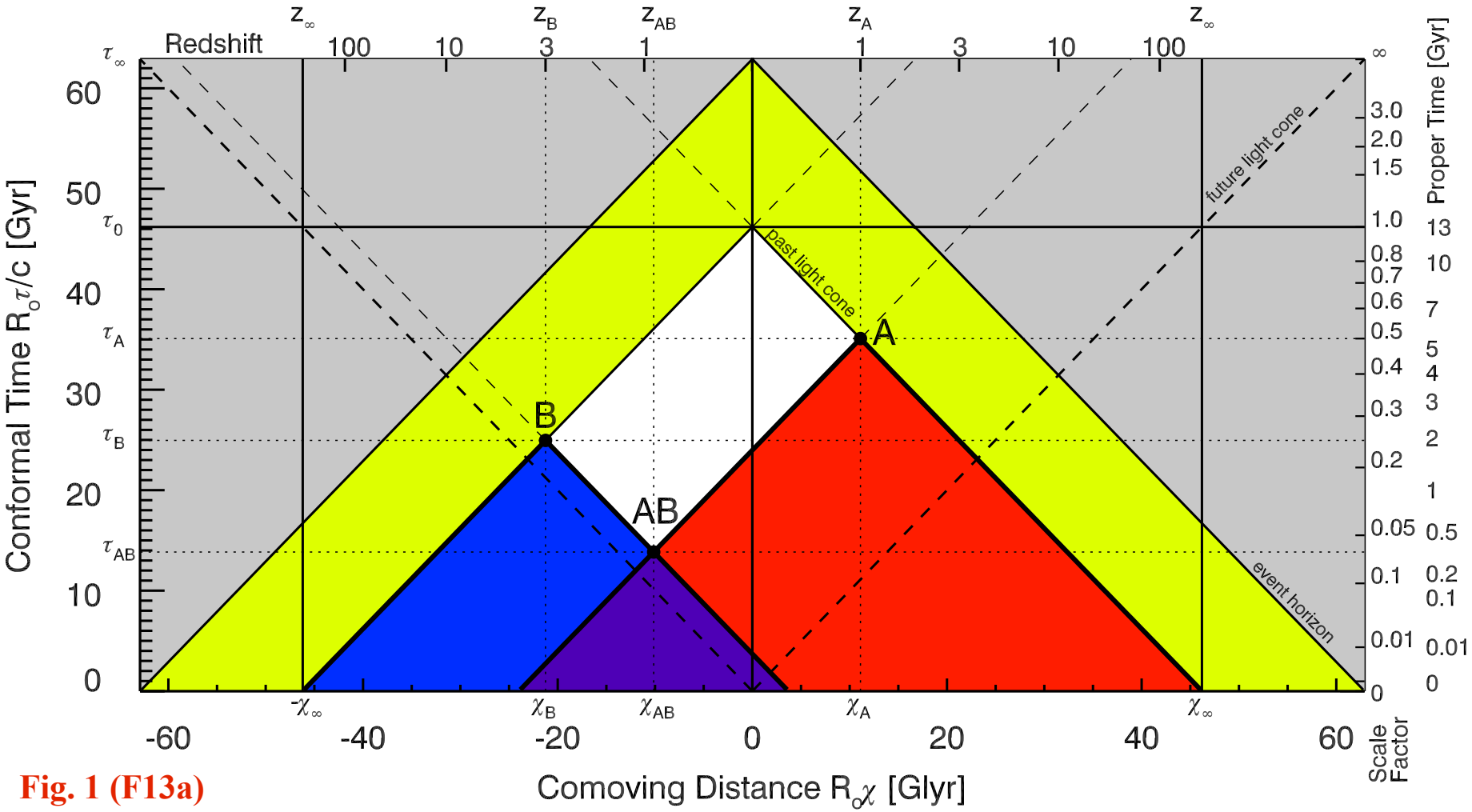


Fig. 1 (F13a)

Since the hot big bang or the end of inflation

INFLATION & THE HORIZON PROBLEM

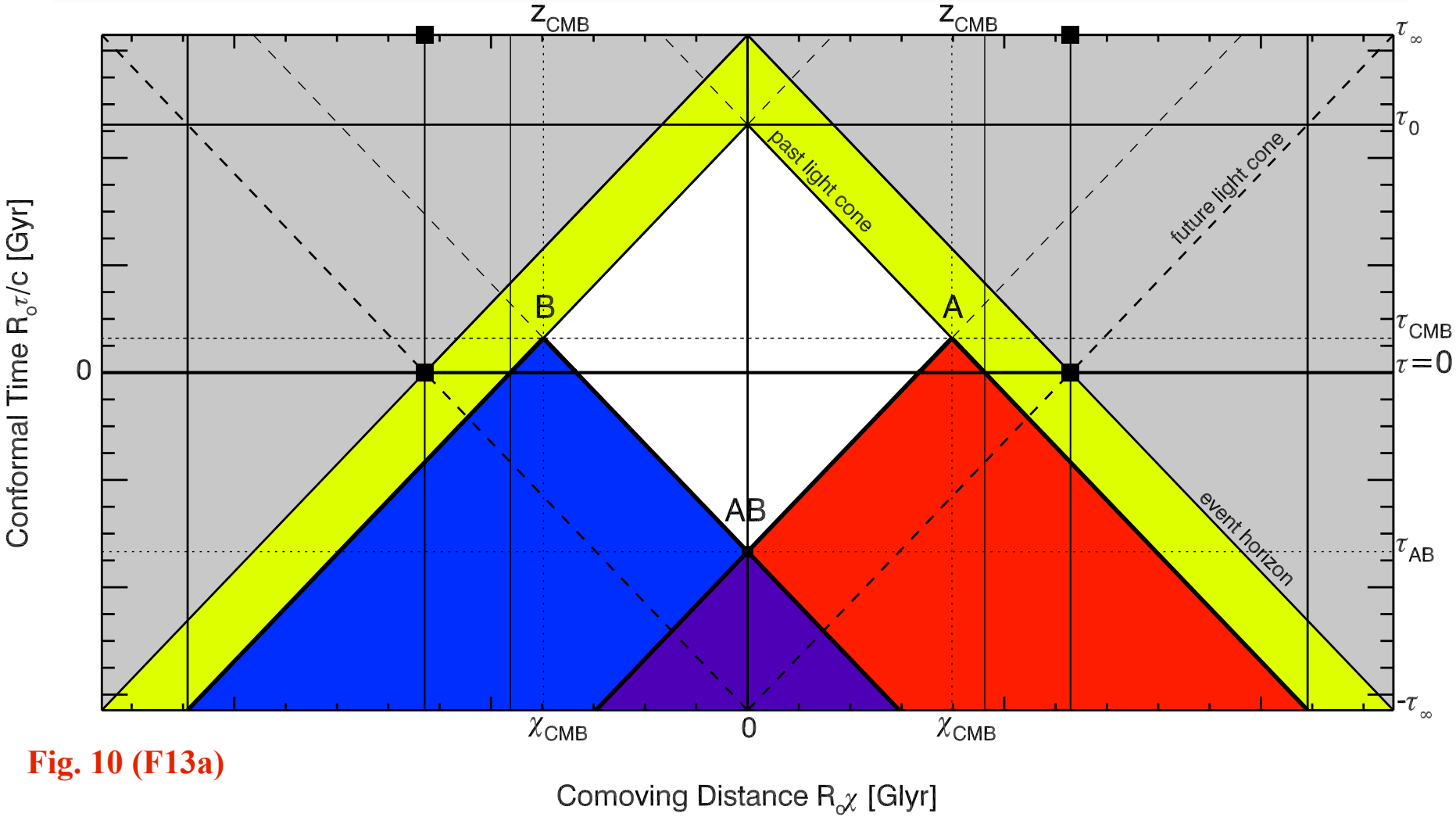


Fig. 10 (F13a)

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

PAST LIGHT CONE INTERSECTION

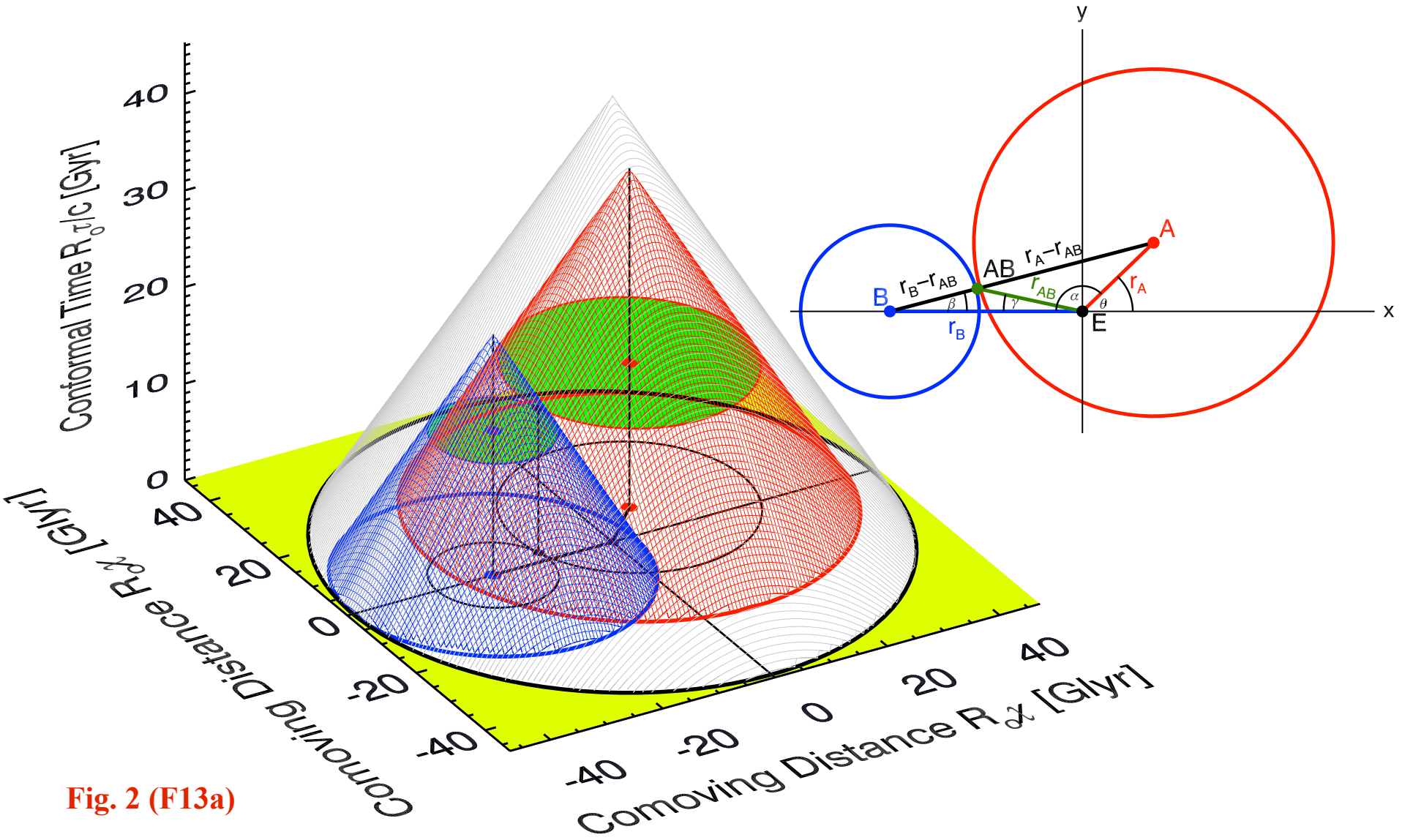
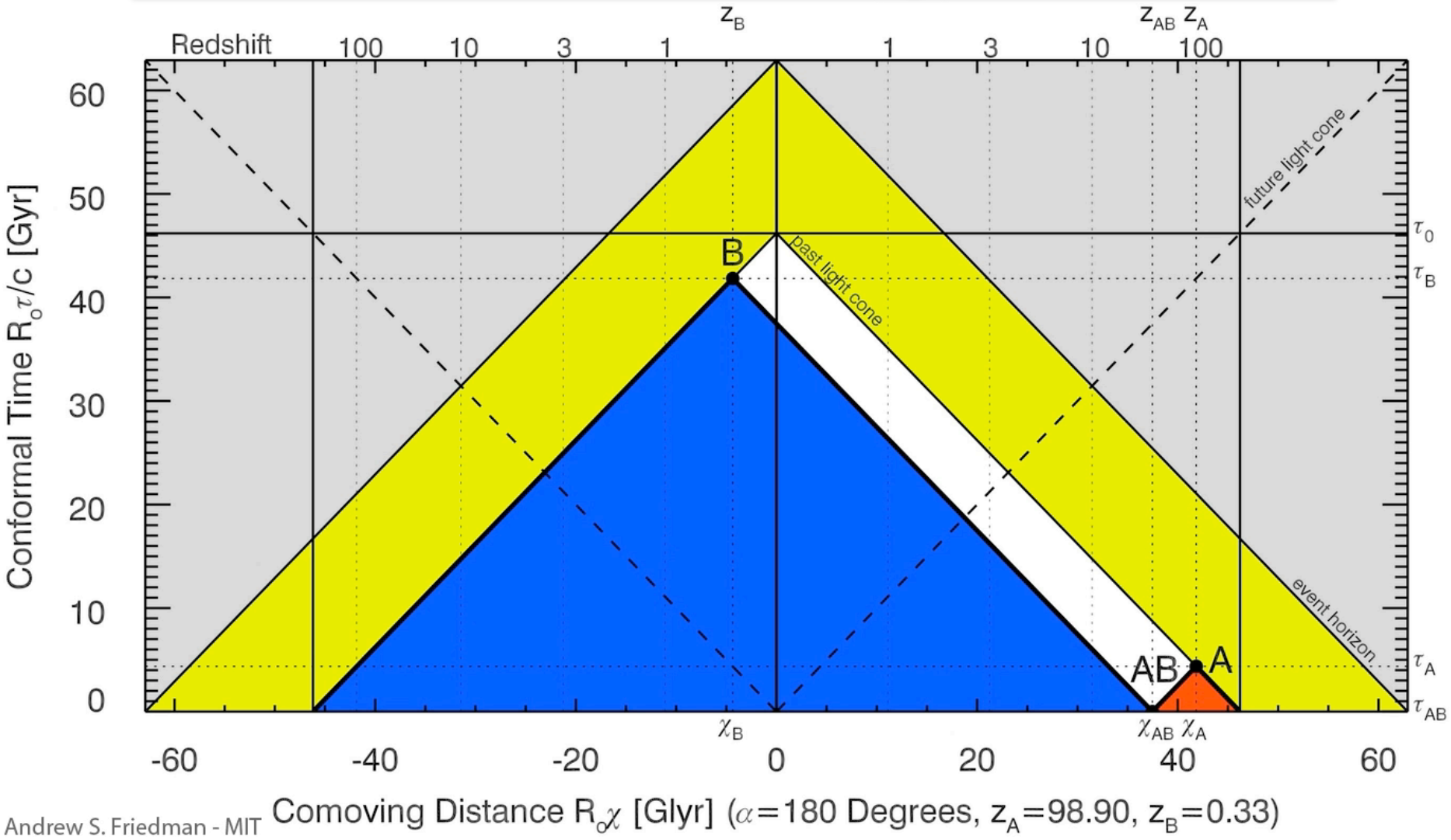


Fig. 2 (F13a)

LC INTERSECTION @BIG BANG

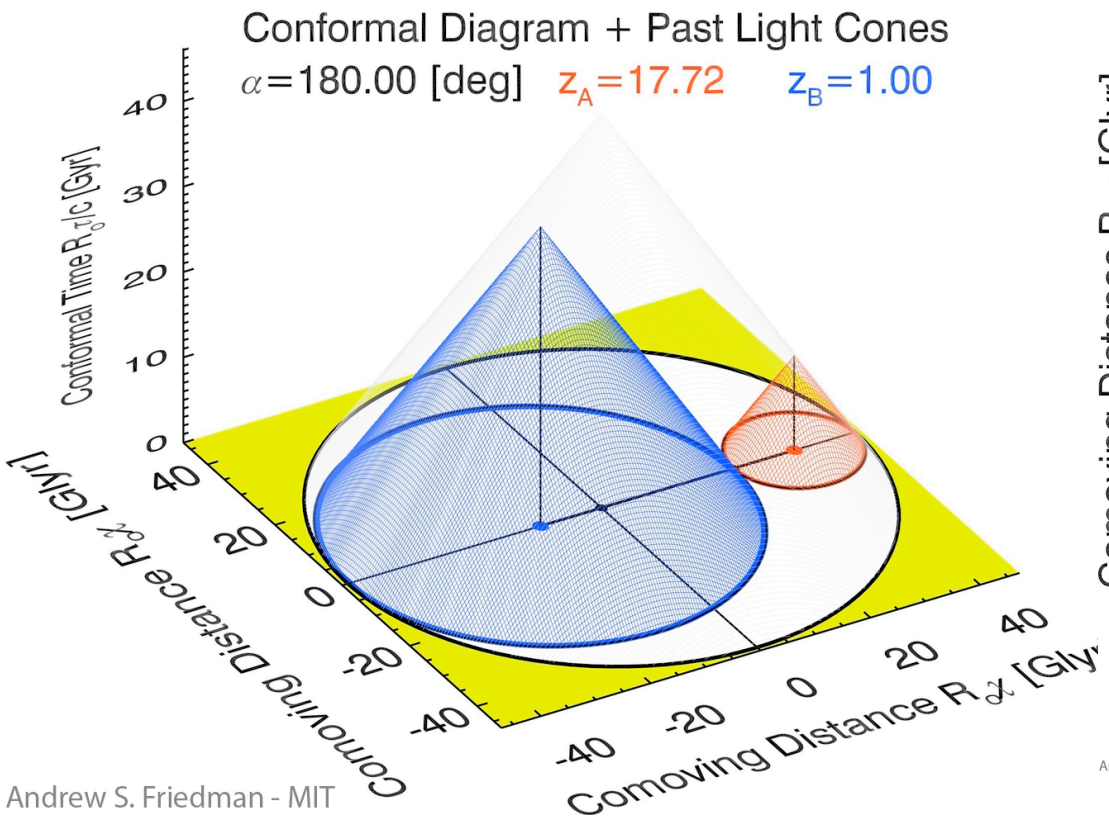


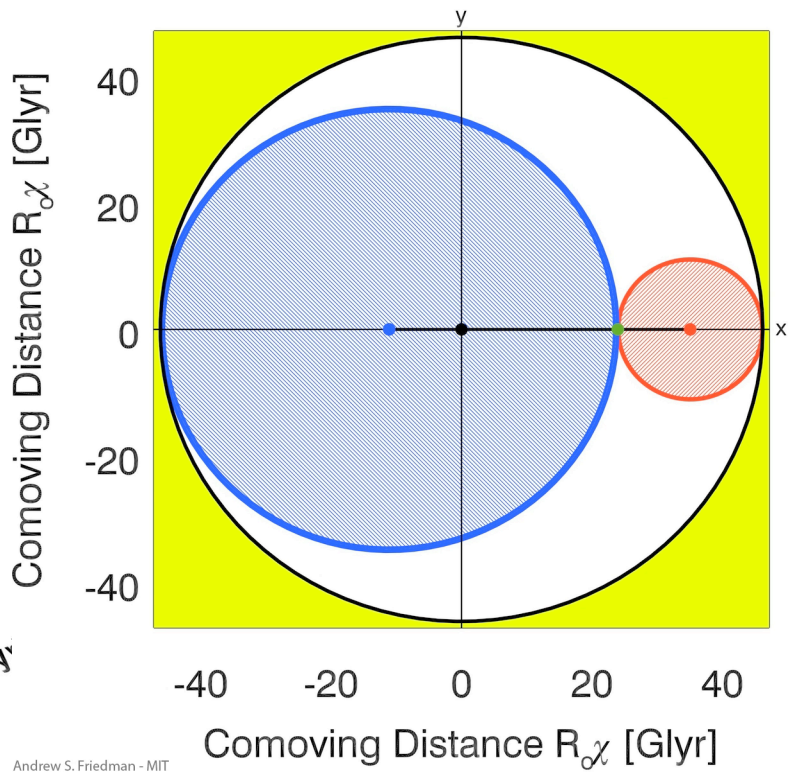
Andrew S. Friedman - MIT

Animation 1 (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/01_conformal_movie.shtml

LC INTERSECTION @BIG BANG

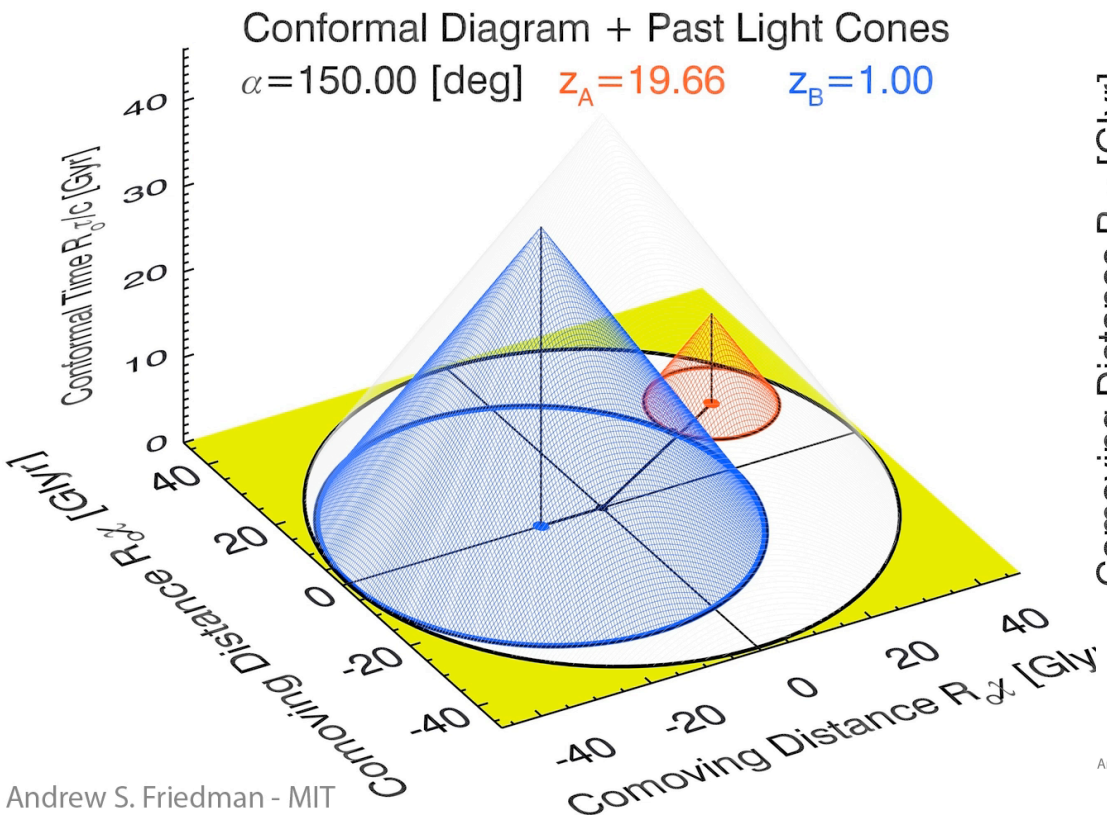


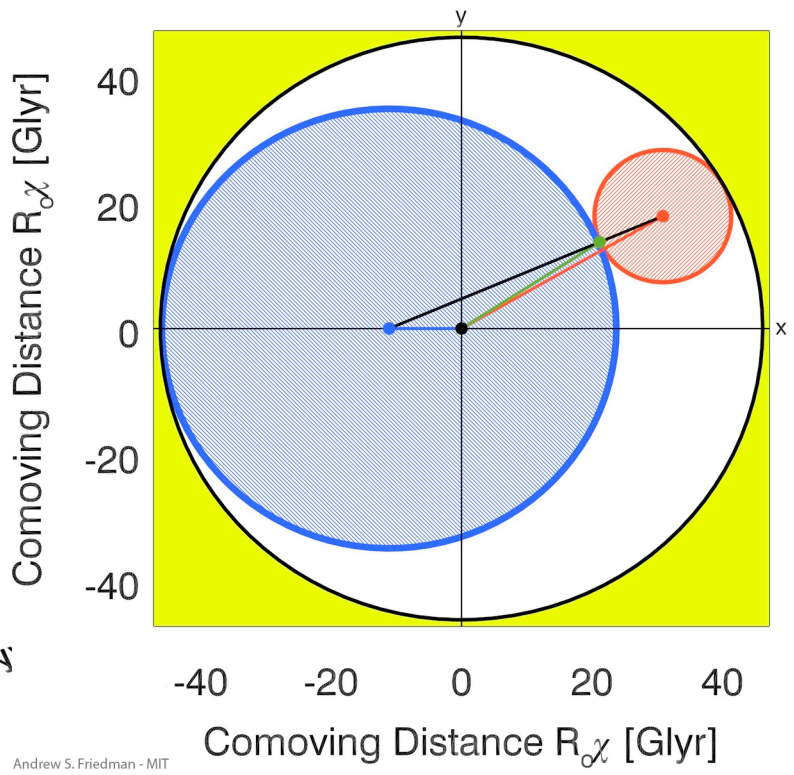


Animations 2-3 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

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

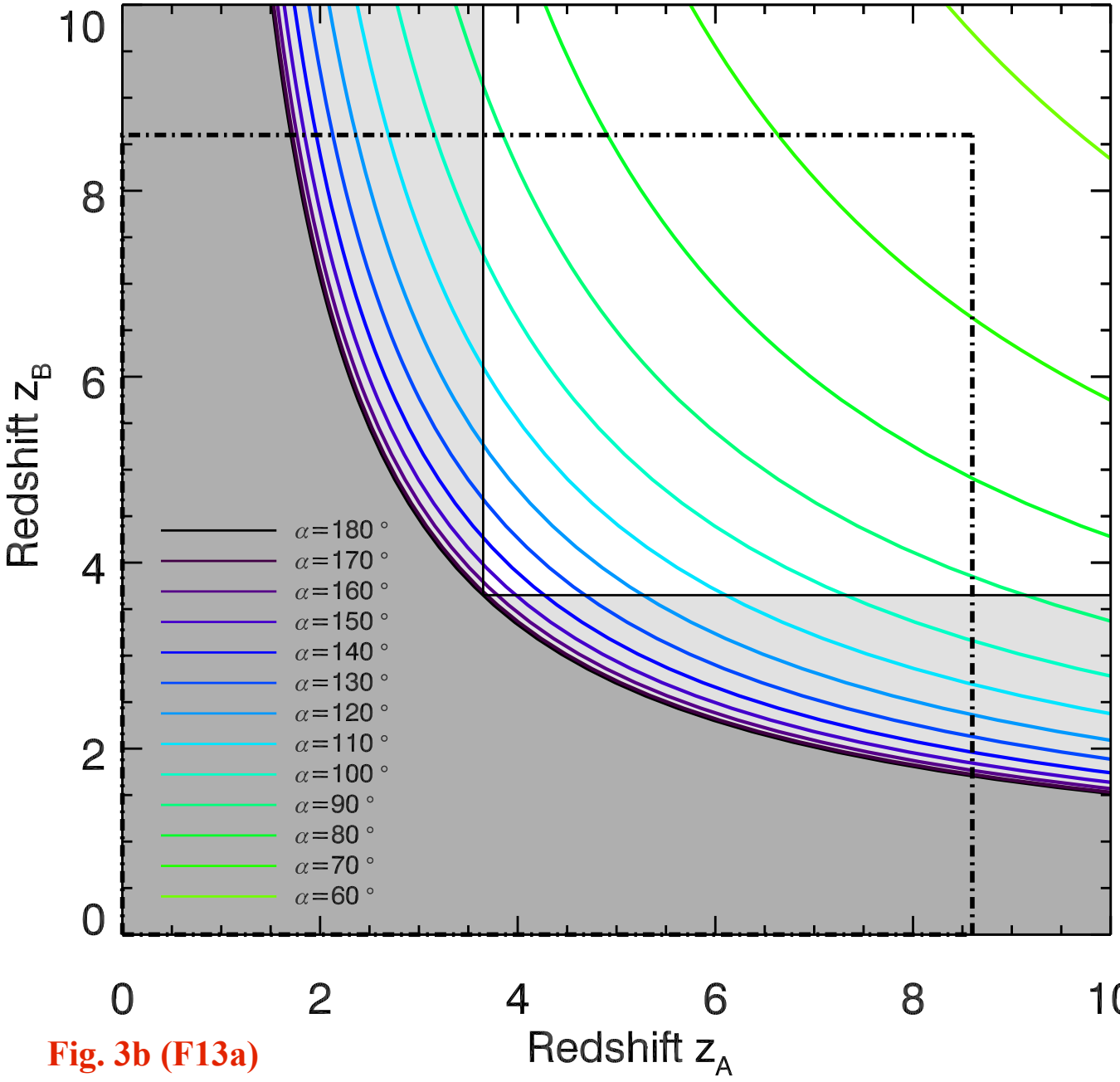


Fig. 3b (F13a)

Do A,B have a shared past?

Dark Gray
YES: any angle

Light Gray / White
NO: large angles

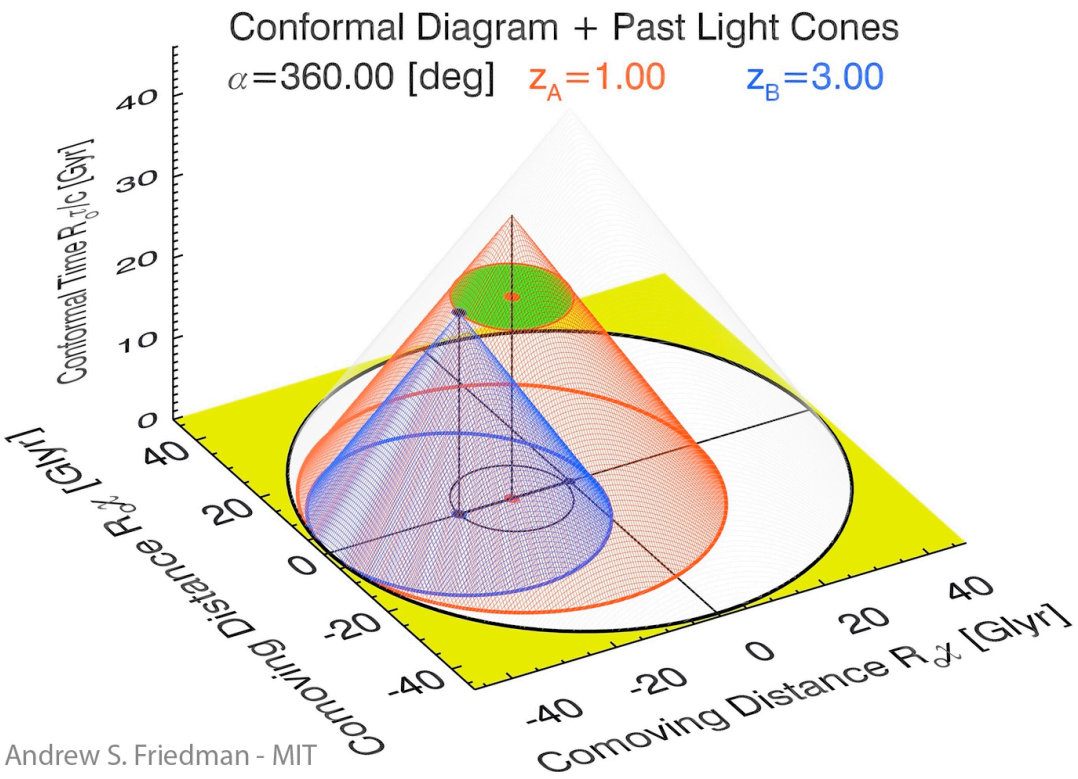
...with Earth?

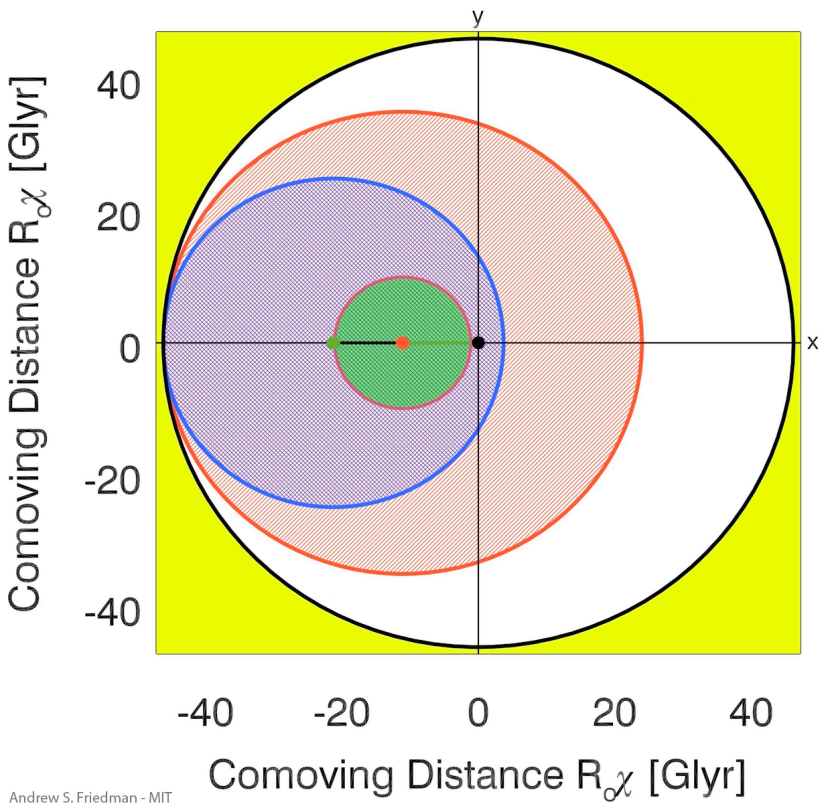
Dark Gray
YES

White
NO: A and B

Light Gray
YES: Either A or B

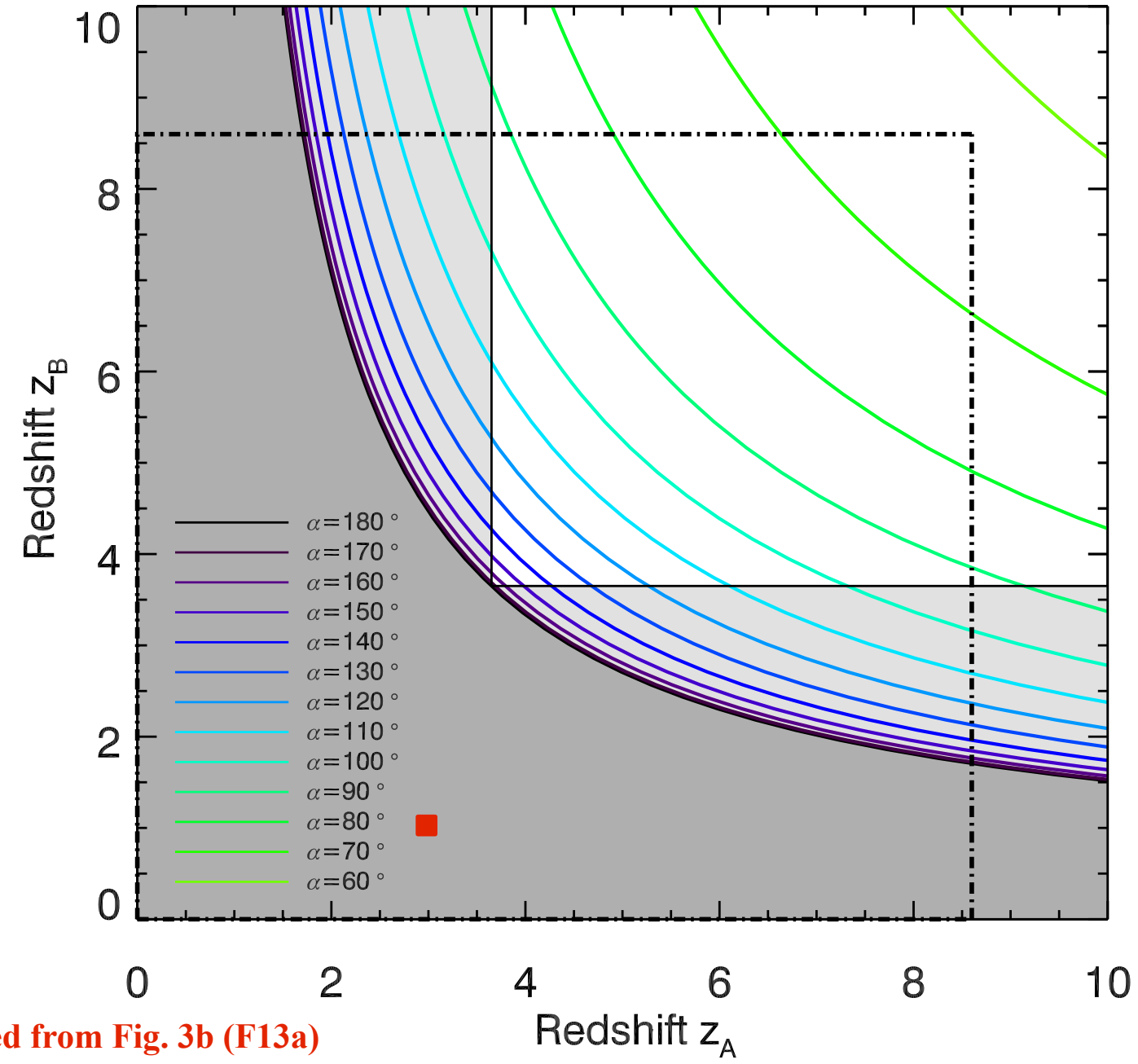
FIX REDSHIFTS, CHANGE ANGLE





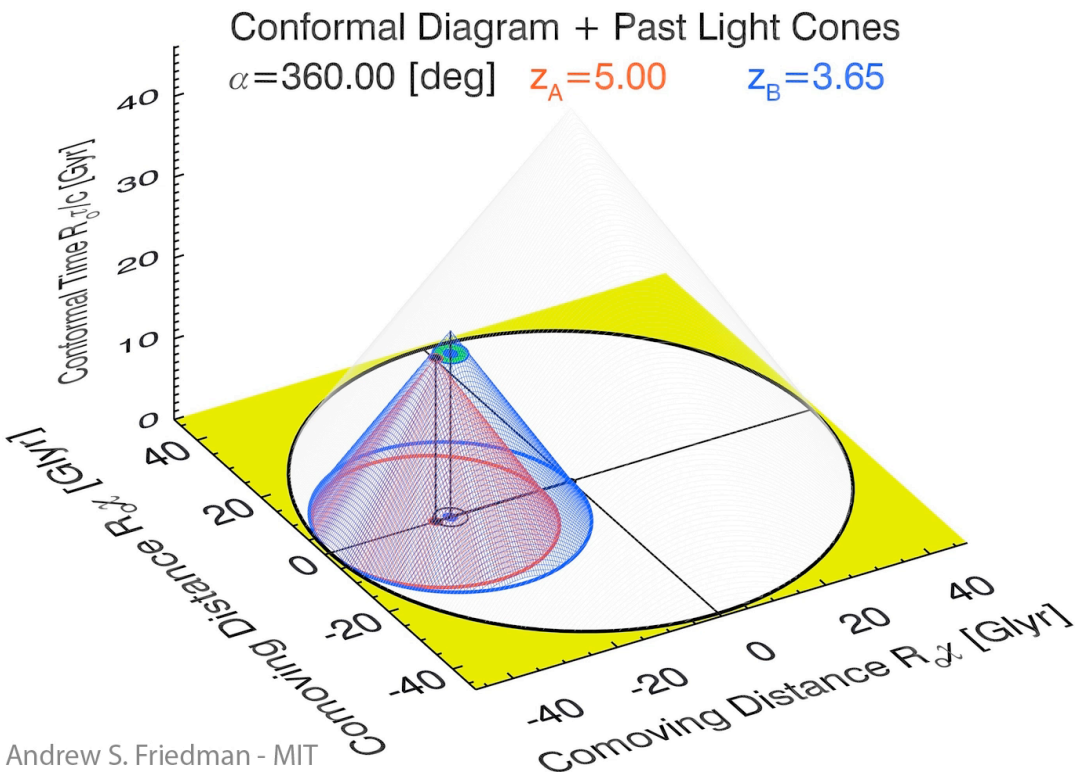
Animations 6-7 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

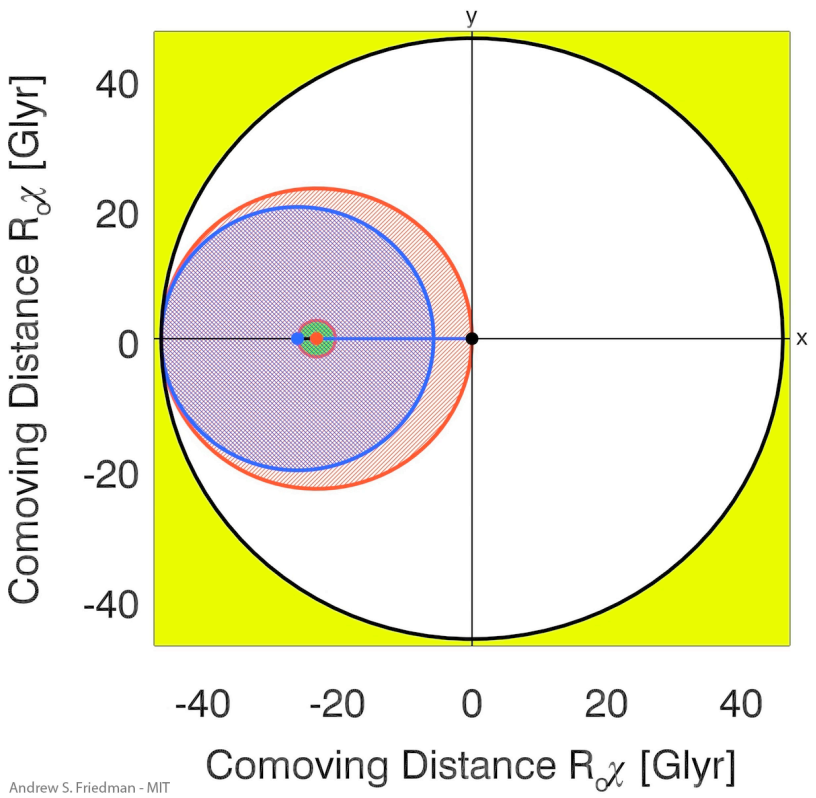
http://web.mit.edu/asf/www/causal_past.shtml
http://web.mit.edu/asf/www/04_alpha_1_3.shtml



Adapted from Fig. 3b (F13a)

FIX REDSHIFTS, CHANGE ANGLE



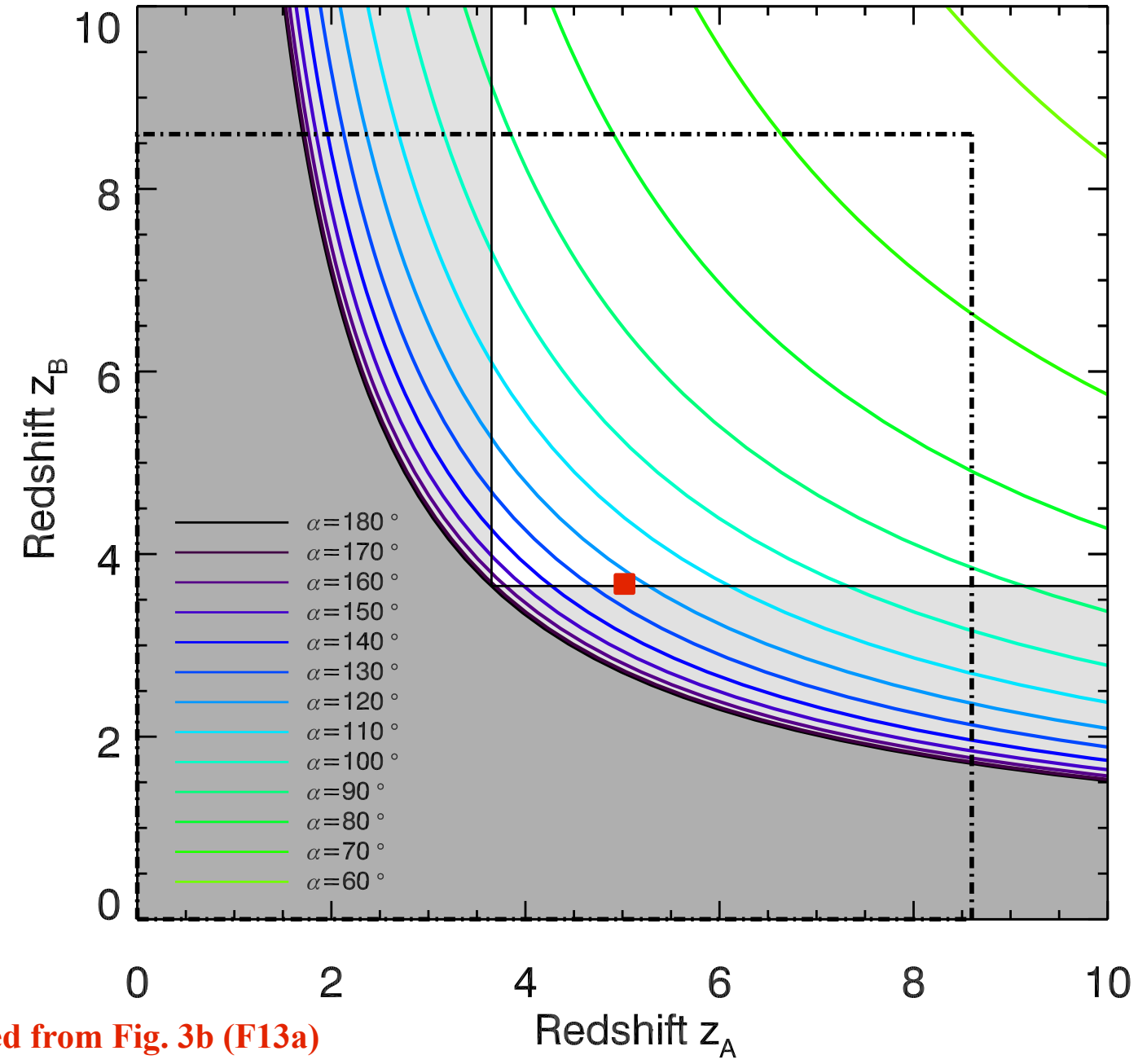


Animations 8-9 (F13a supplementary material)

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

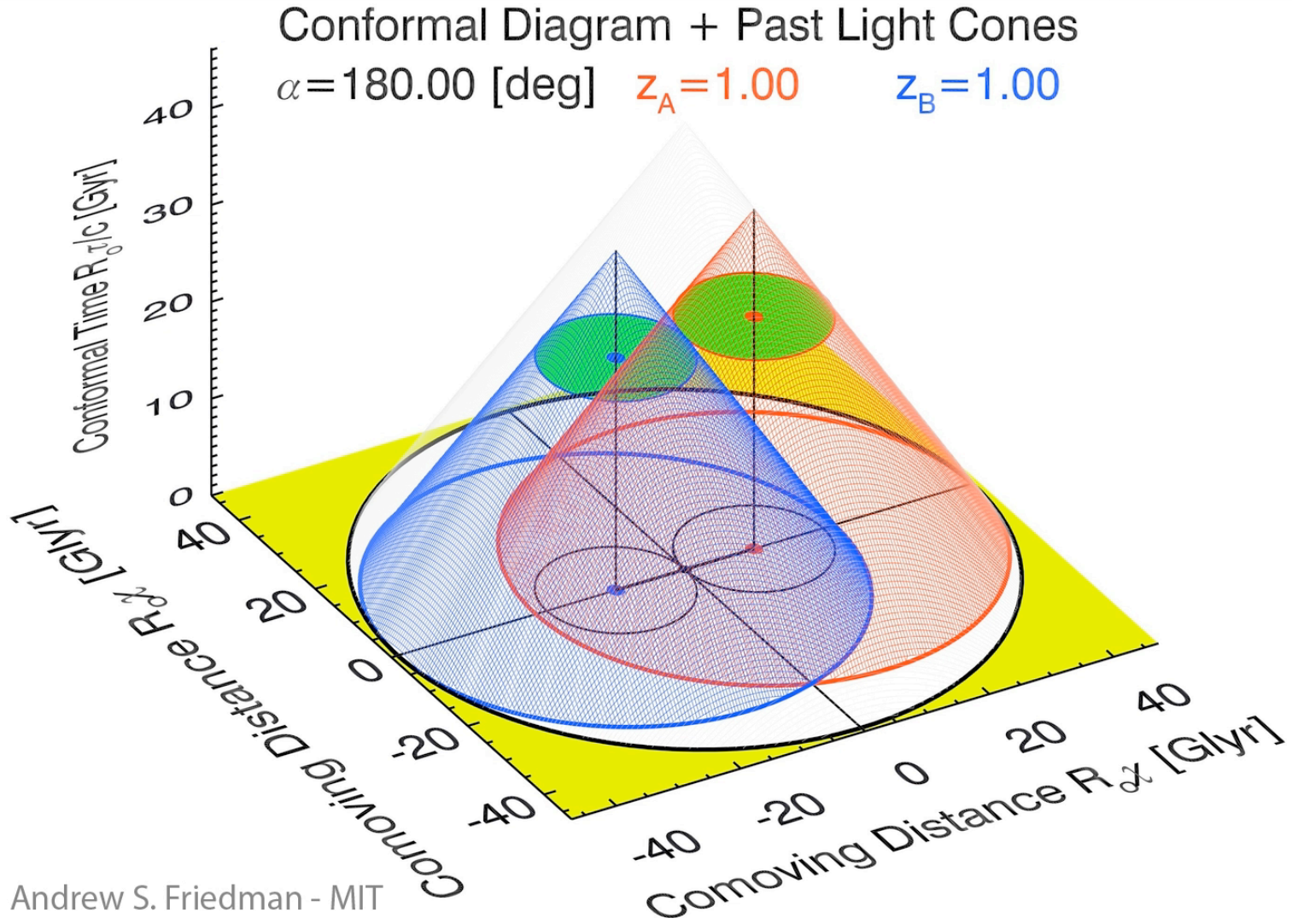
http://web.mit.edu/asf/www/causal_past.shtml

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://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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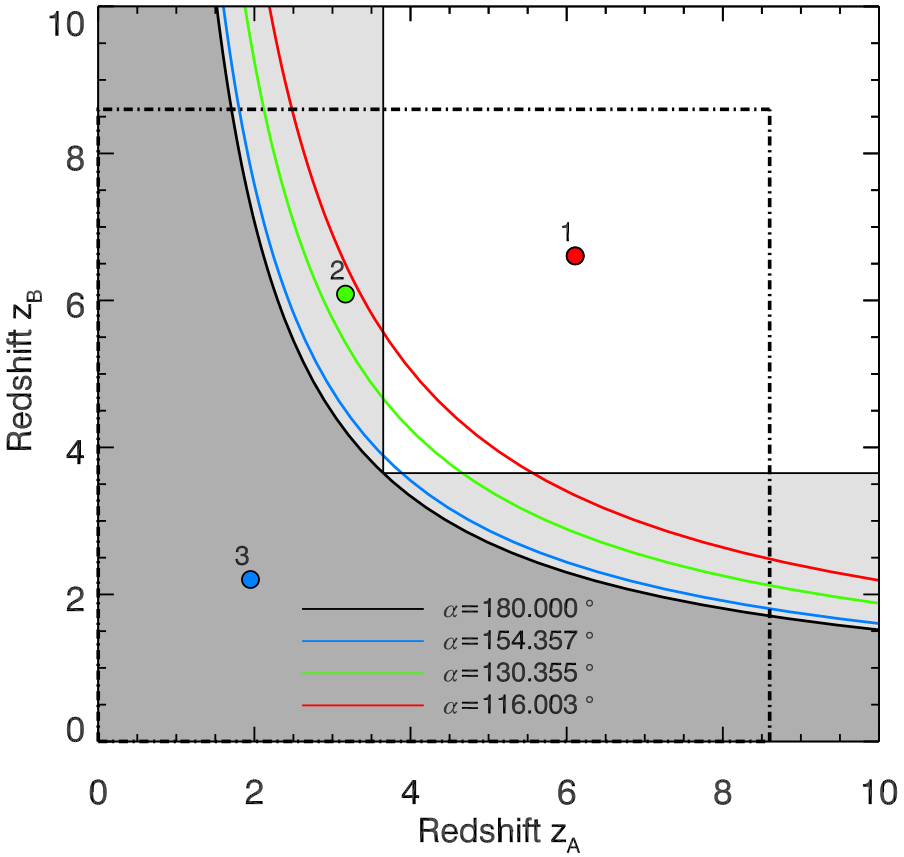


EXAMPLE QUASAR PAIRS

pair 3 - YES shared past with each other & Earth

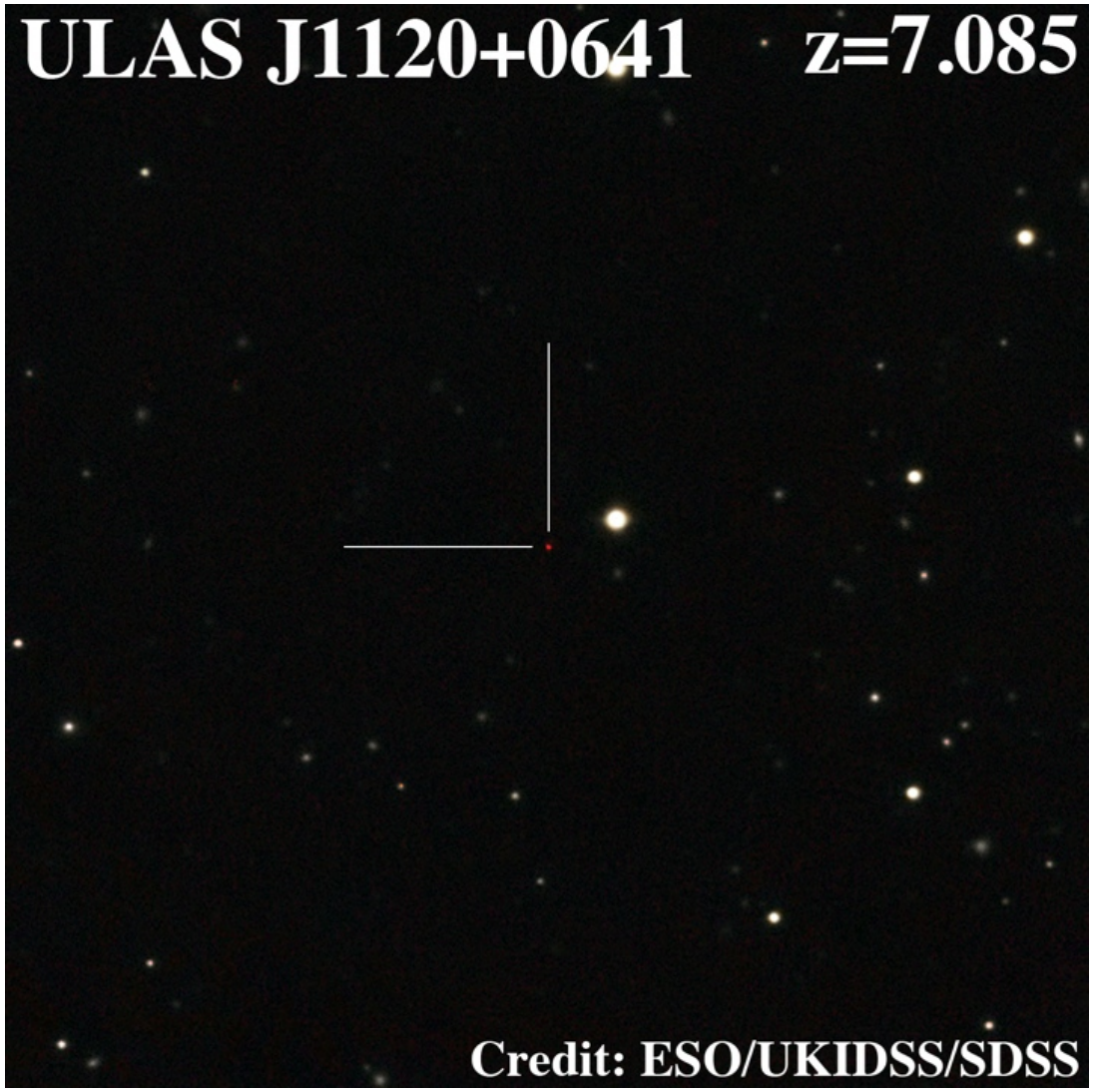
pair 2 - NO shared past with each other, but A_2 has shared past with Earth

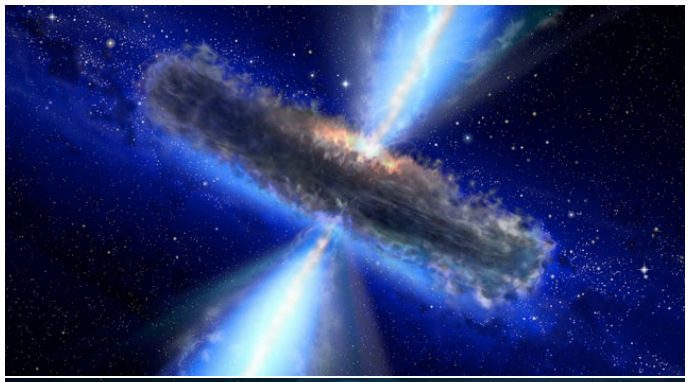
pair 1 - NO shared past with each other or Earth

Fig. 5, Table I (F13a)

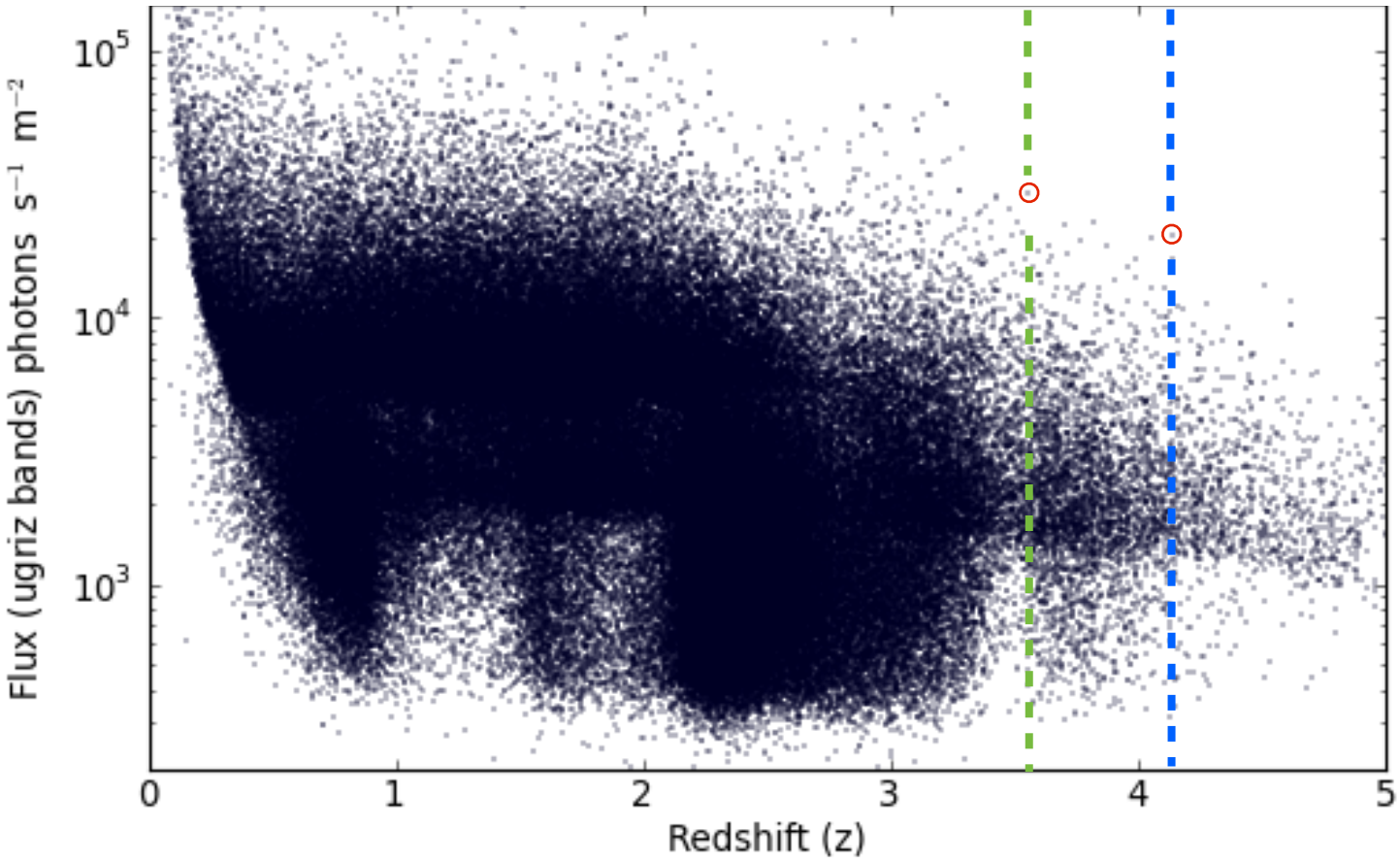
Pair	Separation Angle α_i [deg]	Event Labels	Redshifts z_{Ai}, z_{Bi}	Object Names	RA [deg]	DEC [deg]	R [mag]	B [mag]
1	116.003	A_1	6.109	SDSS_J031405.36-010403.8	48.5221	-1.0675	16.9	20.1
		B_1	6.606	SDSS_J171919.54+602241.0	259.8313	60.3781	18.6	16.9
2	130.355	A_2	3.167	KX_257	24.1229	15.0481	16.7	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

MOST DISTANT QUASAR





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}

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

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**
~ 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

- **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 suitable observing site (? Canary Islands)**

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

Friedman+2013c *in prep*.

OUTLINE

1. The Big Picture: Bell's Theorem

2. *Cosmic Bell - Gedankenexperiment*

Gallicchio, Friedman, & Kaiser 2013 (GFK13)
Phys. Rev. Lett. submitted (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+2013 *in prep*. (F13c)

5. Actually Doing the Experiment?

2 OR MORE COSMIC SOURCES

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

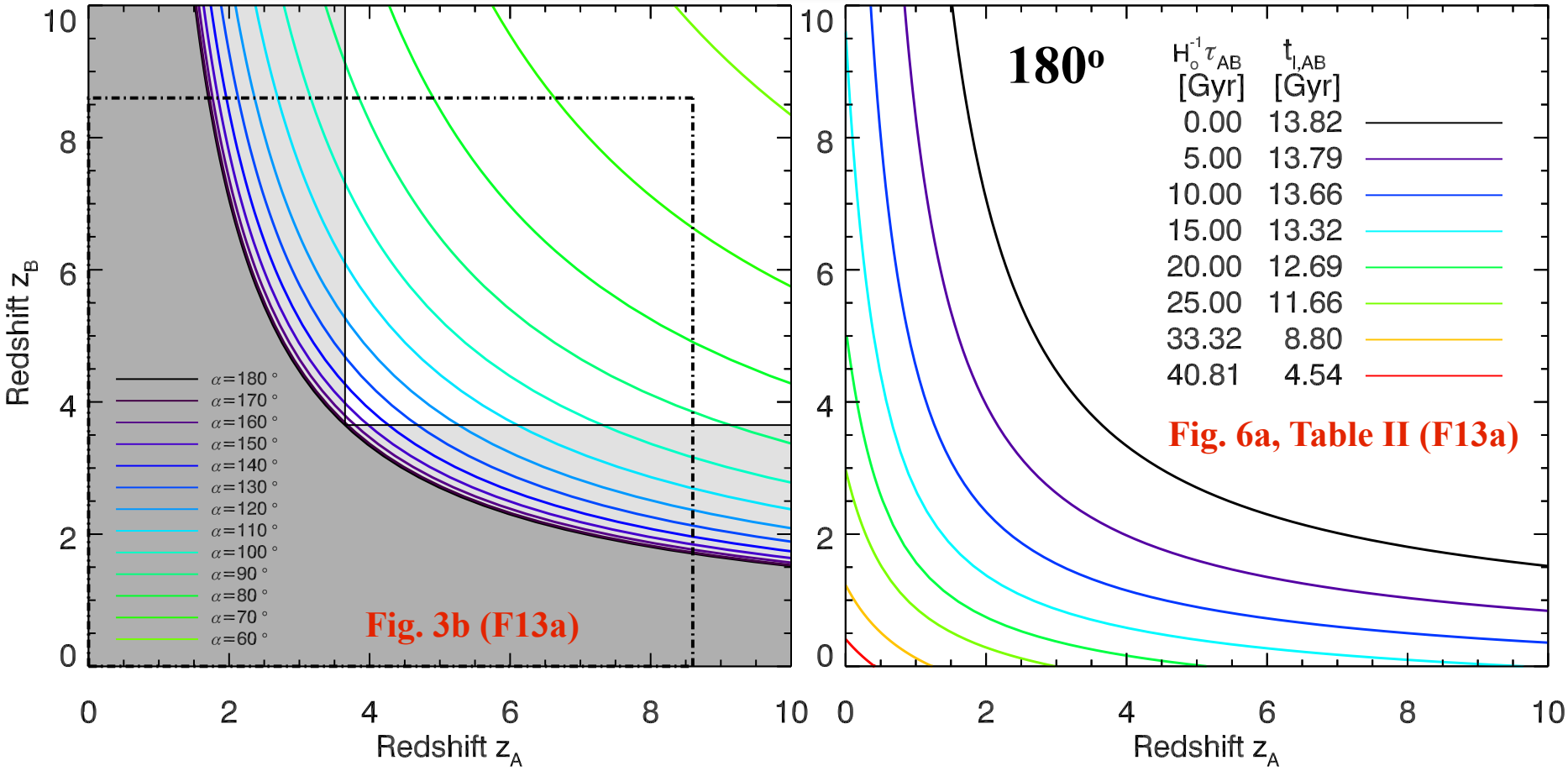
Greenberger, Horne, Zeilinger 1989; Greenberger+1990; Mermin 1990

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		

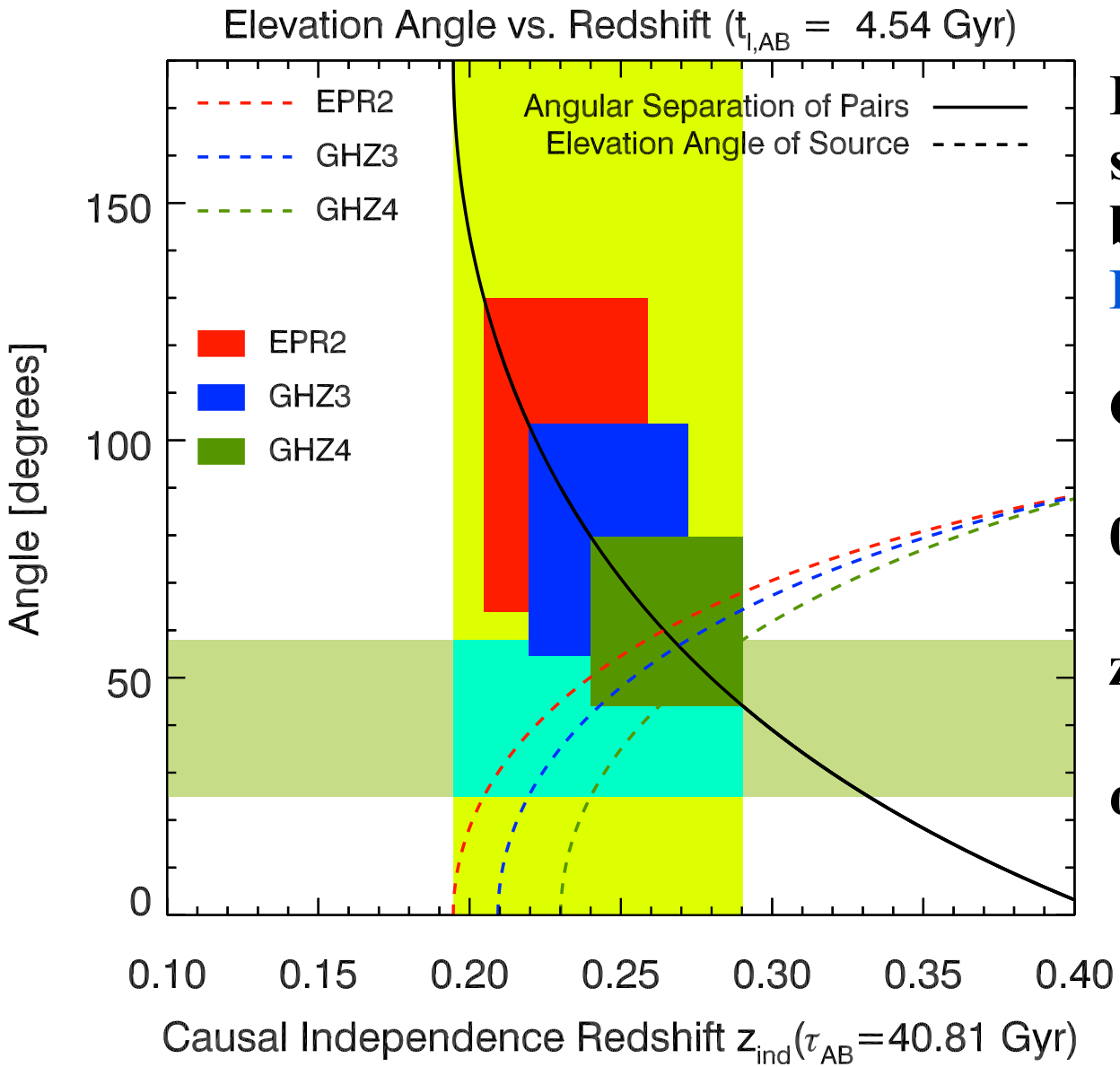
GFK13; Friedman+2013c *in prep.*

SHARED PASTS AFTER BB



Event	Redshift z	Lookback Time $t_{l_{AB}}$ [Gyr]	Proper Time t_{AB} [Gyr]	Conformal Time $H_0{}^{-1}\tau_{AB}$ [Gyr]	causal-independence redshift $\tilde{z}_{\rm ind}(\tau_{AB})$
Big Bang	∞	13.81	0	0	3.65
Galaxy Formed	1.23	8.80	5.01	33.32	0.506
Earth Formed	0.41	4.54	9.27	40.81	0.195
First Eukaryotes	0.124	1.65	12.16	44.45	0.061

PROTOTYPE COSMIC BELL



Push correlated settings conspiracy to before formation of Earth 4.5 Gyr ago.

Ground-based test

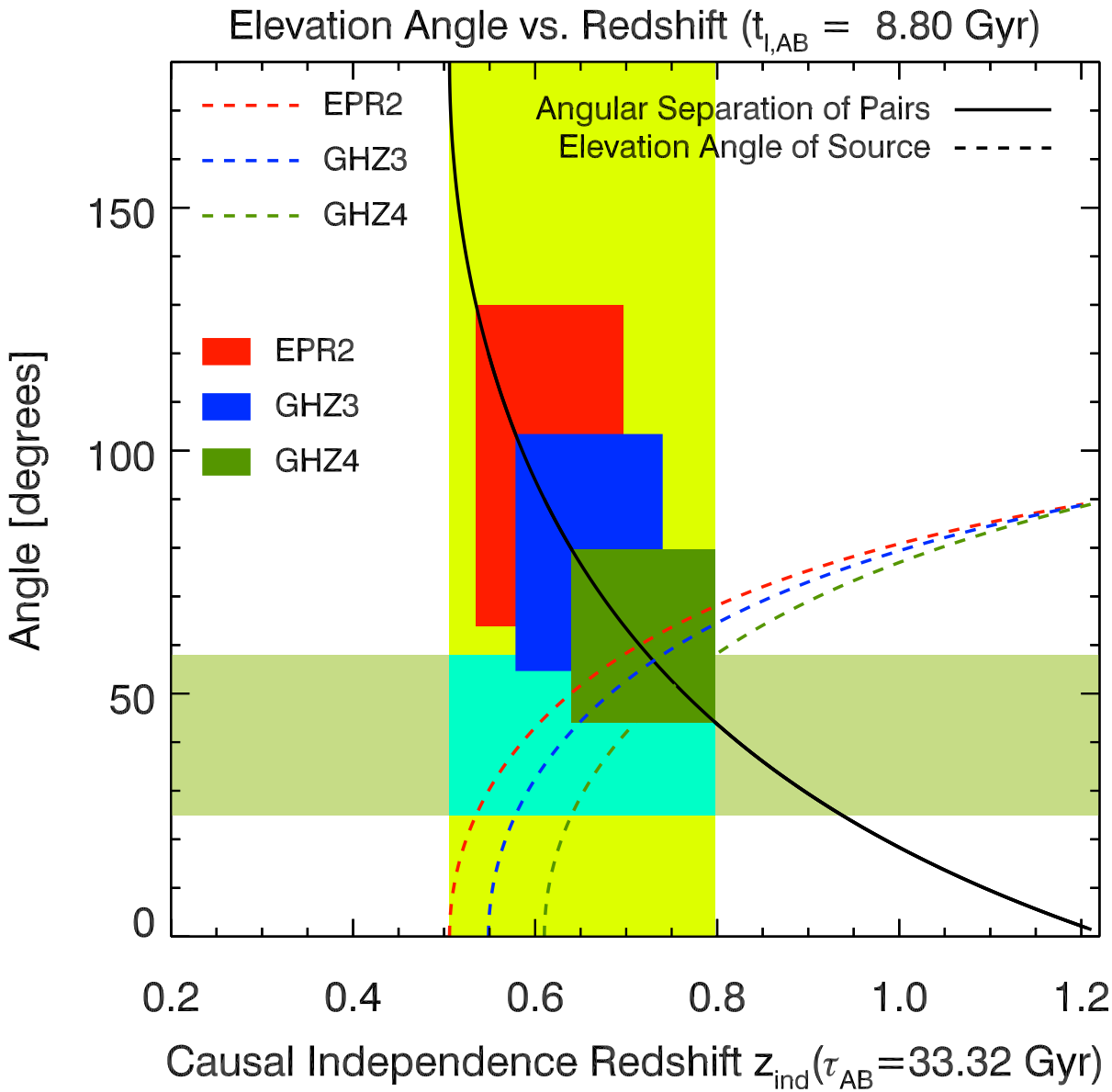
0.25~0.5-m telescopes

z~0.2-0.29

α~40-130°

Friedman+2013c *in prep.*

INTERMEDIATE COSMIC BELL



Push conspiracy to before Milky Way formed 8.8 Gyr ago.

Ground-based test

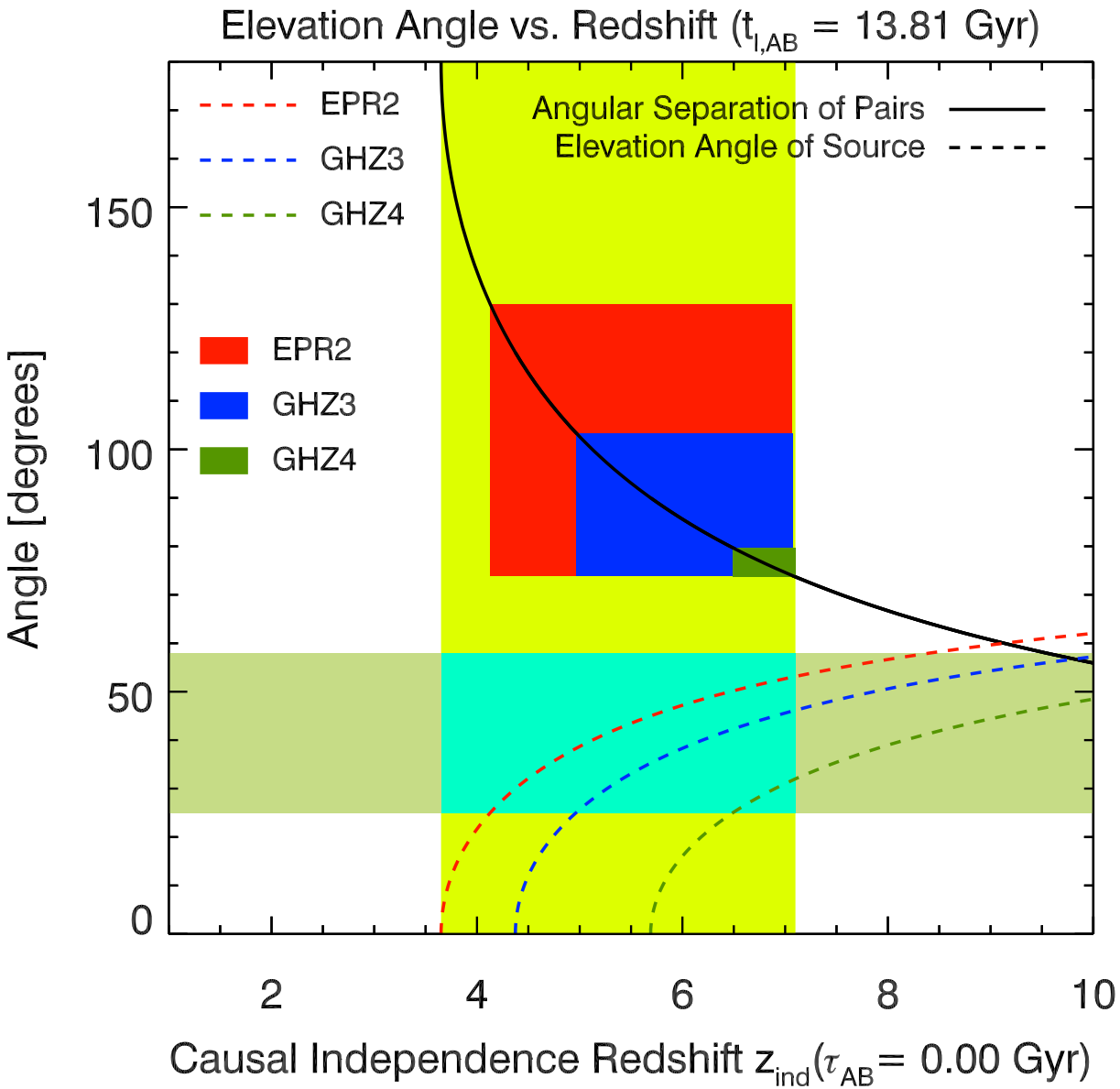
0.25~0.5-m telescopes

z~0.55-0.8

α~40-130°

Friedman+2013c *in prep.*

FULL COSMIC BELL



Push conspiracy to inflationary epoch 13.8 Gyr ago.

Ground-based test

≳1-m telescopes

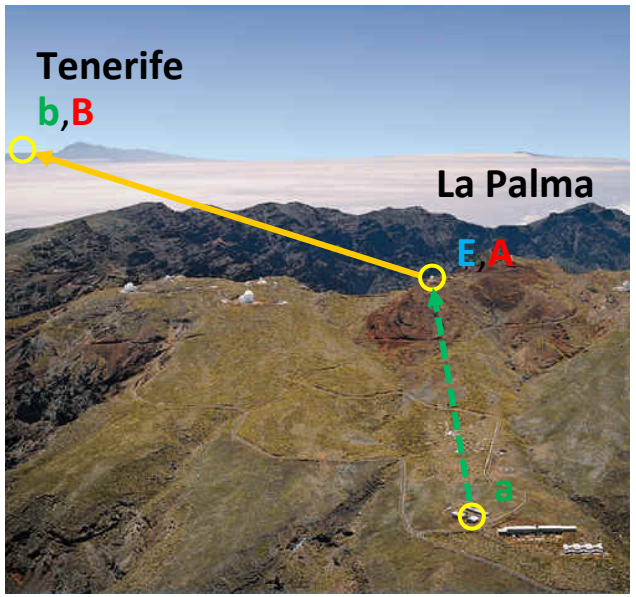
z~3.65-7.1

α~75-130°

Friedman+2013c *in prep.*

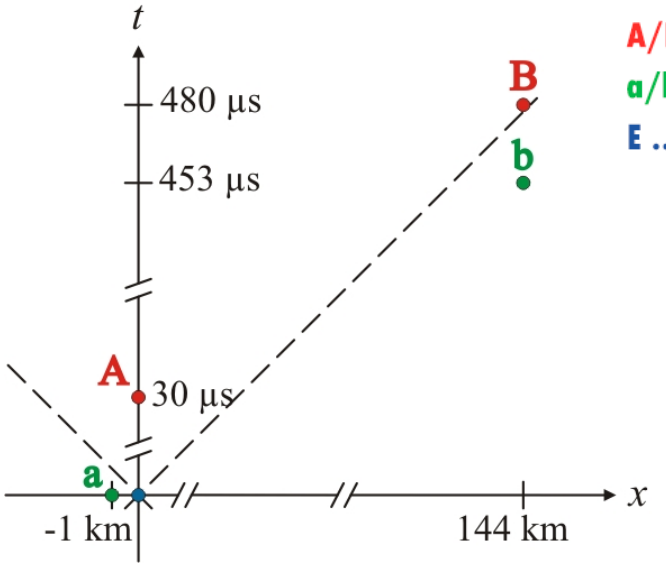
ZEILINGER GROUP EXPERIMENTS

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

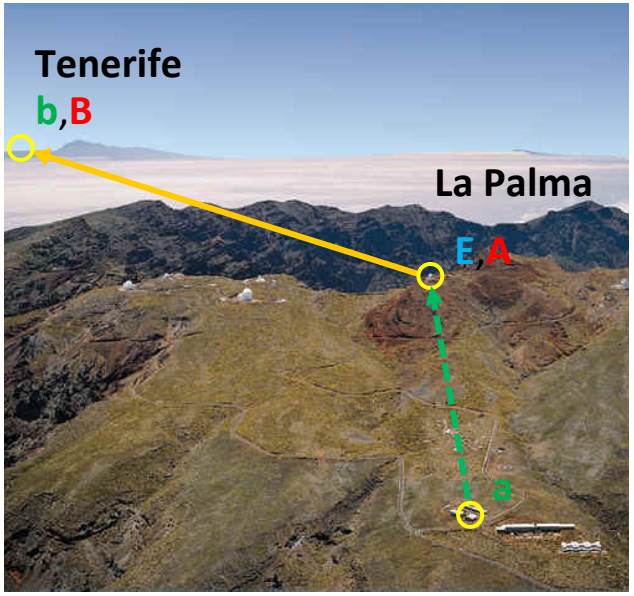


Scheidl+2010, *PNAS*, 107, 46, p. 19708-19713

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

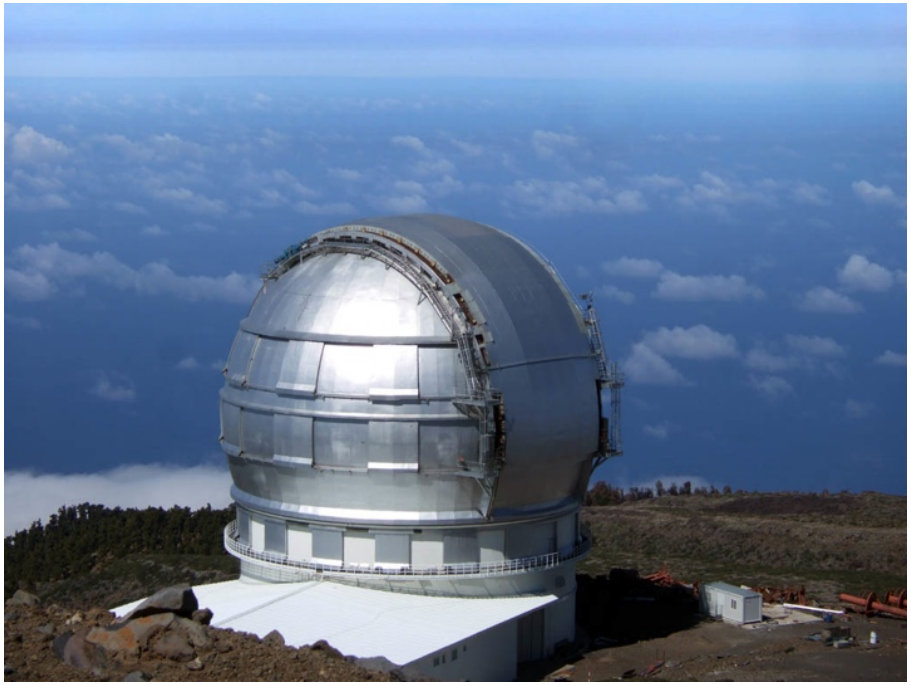
CANARY ISLANDS TELESCOPES

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+2013 *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)

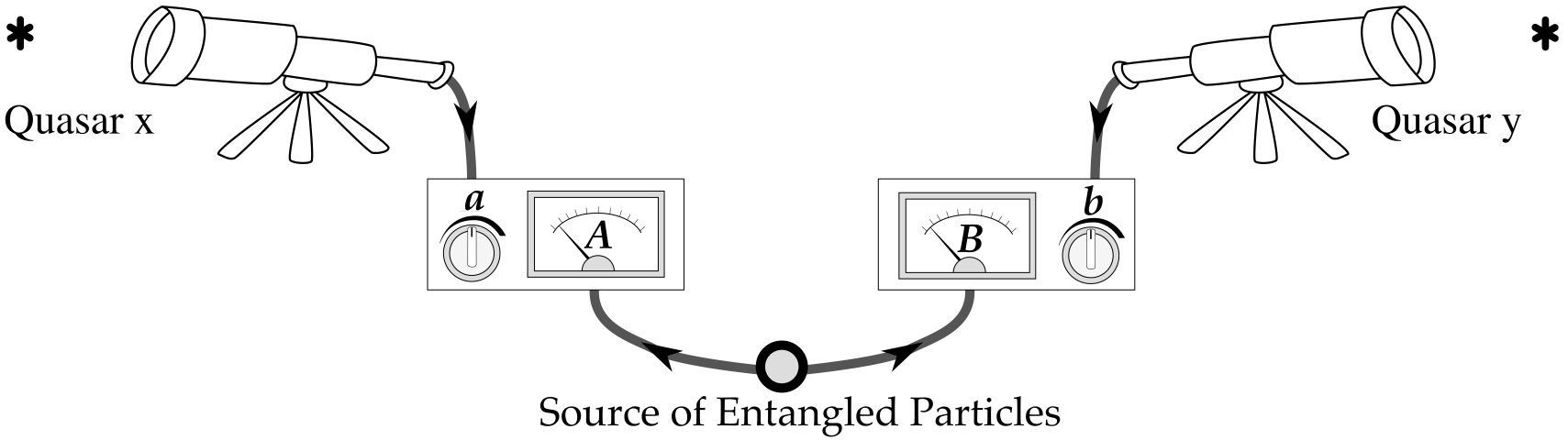
CONCLUSIONS

An actual Cosmic Bell experiment:

Is well motivated

Feasible in the real world.

Lots of fun to think about!



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