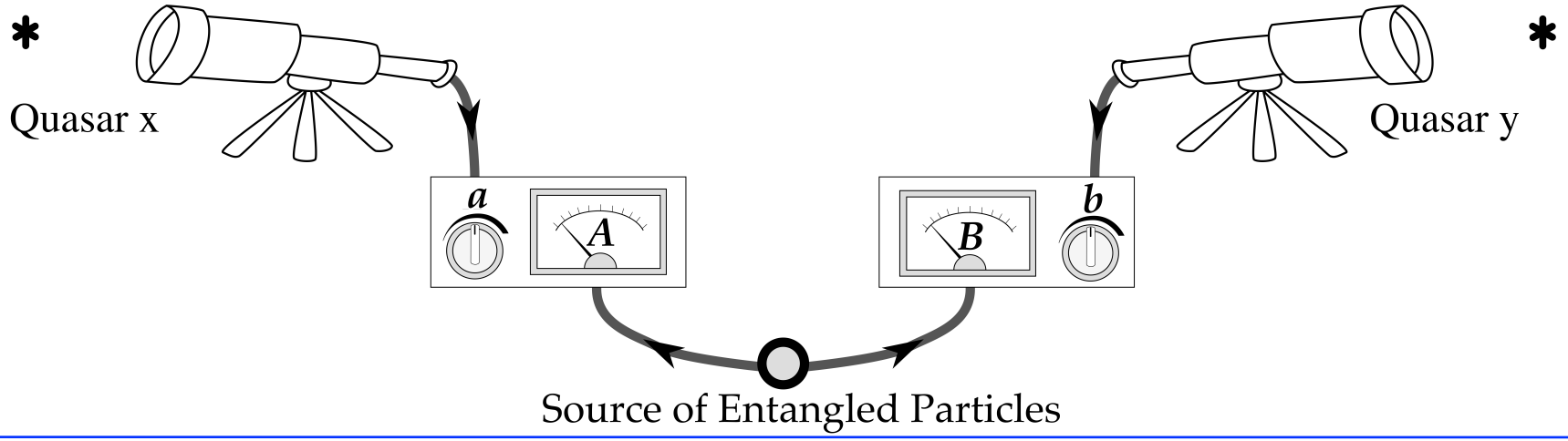

COSMIC BELL: TESTING QUANTUM MECHANICS AND BELL'S INEQUALITY WITH ASTROPHYSICAL OBSERVATIONS

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4: UCSD, 5: Vienna IQOQI,
6: Max Planck

COSMIC BELL PUBLICATIONS

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

Gallicchio, Friedman, & Kaiser 2014 = GFK14

***Phys. Rev. Lett., Vol. 112, 11, 110405,* arXiv:1310.3288**

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

Friedman, Kaiser & Gallicchio 2013 = F13a

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

"*Can the Cosmos Test Quantum Entanglement?*"

Friedman 2014d

***Astronomy, Vol. 42, 10, October 2014, pg. 28-33,* [PDF]**

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

Friedman 2014a

***NOVA, The Nature of Reality. March 9 2014,* [PDF]**

OUTLINE

1. Bell's Theorem

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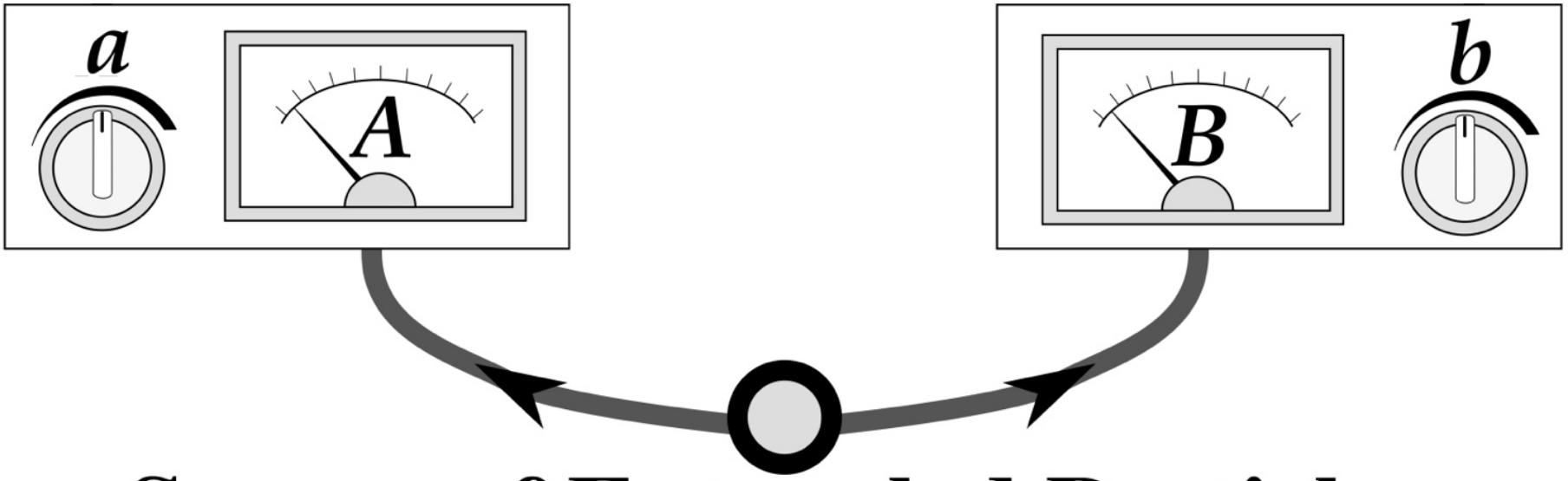
5. Testing Alternative Models

Friedman+2015e *in prep.*

EPR / BELL TESTS



Source of Entangled Particles

a, b = *Settings*

A, B = *Outcomes*

Big question: ***Is local realism true?***

If yes, 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. Fair Sampling

Probability of detector click uncorrelated with events in past light cone of experiment.

4. Freedom (Setting Independence / Free Will)

Detector settings choices independent of any events in their shared past light cones.
Observers can choose settings "freely". Choices only correlated with future LCs.

1,2,3,4 → Bell's Inequality

CHSH form: $S = | \langle AB \rangle + \langle AB' \rangle + \langle A'B \rangle - \langle A'B' \rangle | \leq 2$

QM Prediction (Singlet State): $S_{max} = 2\sqrt{2}$

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

BELL TEST RESULTS

1. Realism 2. Locality 3. Fair Sampling 4. Freedom

Bell/CHSH Inequality: $S = |\langle AB\rangle + \langle AB'\rangle + \langle A'B\rangle - \langle A'B'\rangle| \leq 2$

Real Experiments:

$S_{max} > 2 \rightarrow$ **At least one of 1,2,3,4 are false!**

Usual Story:

Experiments falsify "local realism" (2 or 1 or both).
Local HV theories ruled out. QM non-local, and/or non-realist.

Another Story:

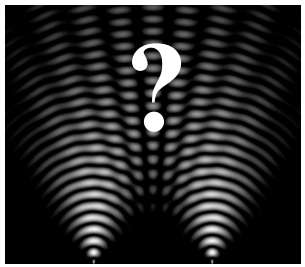
QM incomplete. Local realistic HVs describe missing degrees of freedom (e.g. EPR 1935)

Loopholes: Relax fair sampling or freedom! (3 and/or 4 false)

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

BELL'S THEOREM LOOPHOLES

Loopholes: Local Realism 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. Freedom of Choice / Setting Independence / Free Will Loophole

Settings correlated with local hidden variables

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

Spacelike separated settings (QRNGs)

RELAXING FREEDOM

4. Freedom / Setting Independence

Detector settings choices independent of any events in their shared past light cones. Observers can choose settings "freely". Choices only correlated with future LCs.

- Can events in past LC of source & detector → correlated settings?

  Trivially YES: deterministic local HV theory (e.g. **Brans 1986**)

- Deterministic, LHV model can mimic QM with ~ 1/15 bits of mutual information between settings choices & HVs (**Hall 2011**)

- Freedom = most fragile loophole quantitatively.

  Communication models relaxing locality need ≥ 1 bit

  (e.g. **Toner & Bacon 2001**, **Hall 2010, 2011**)

Quantitative models! Relaxing Freedom does not imply "superdeterministic cosmic conspiracy"

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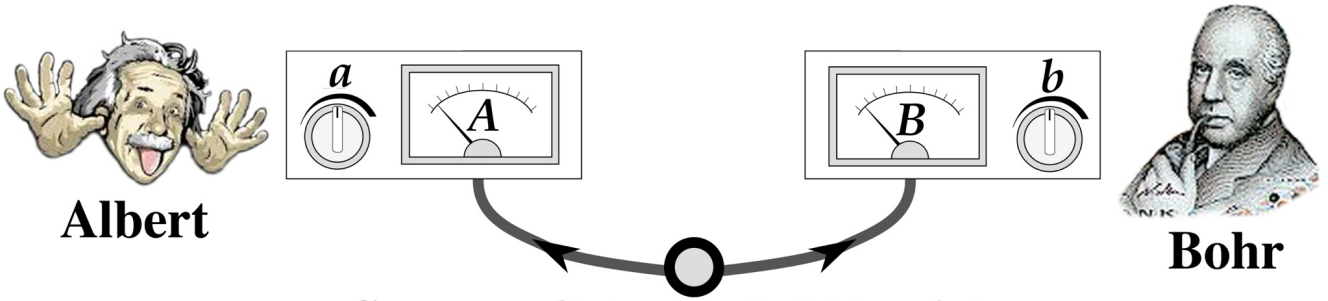
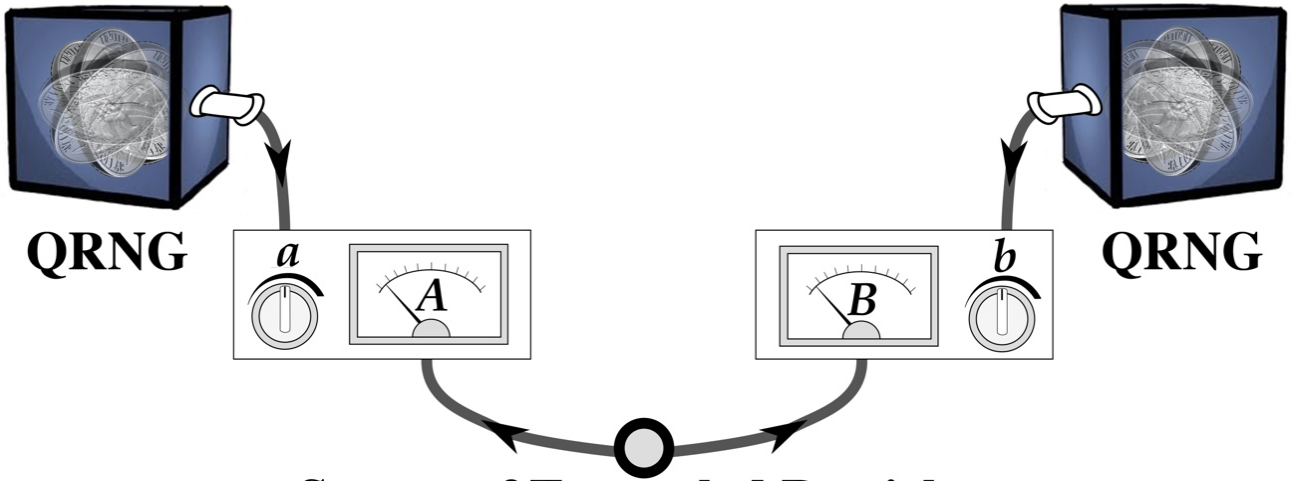
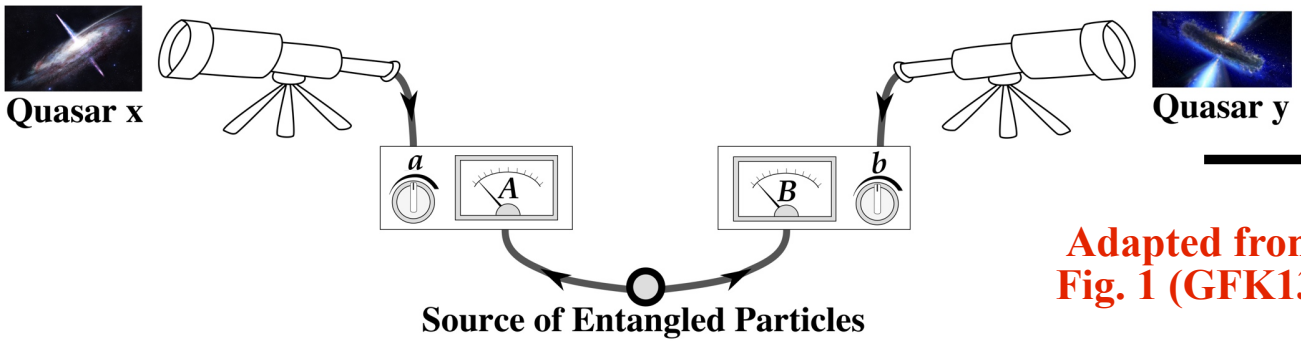
CHOOSING SETTINGS *a, b*





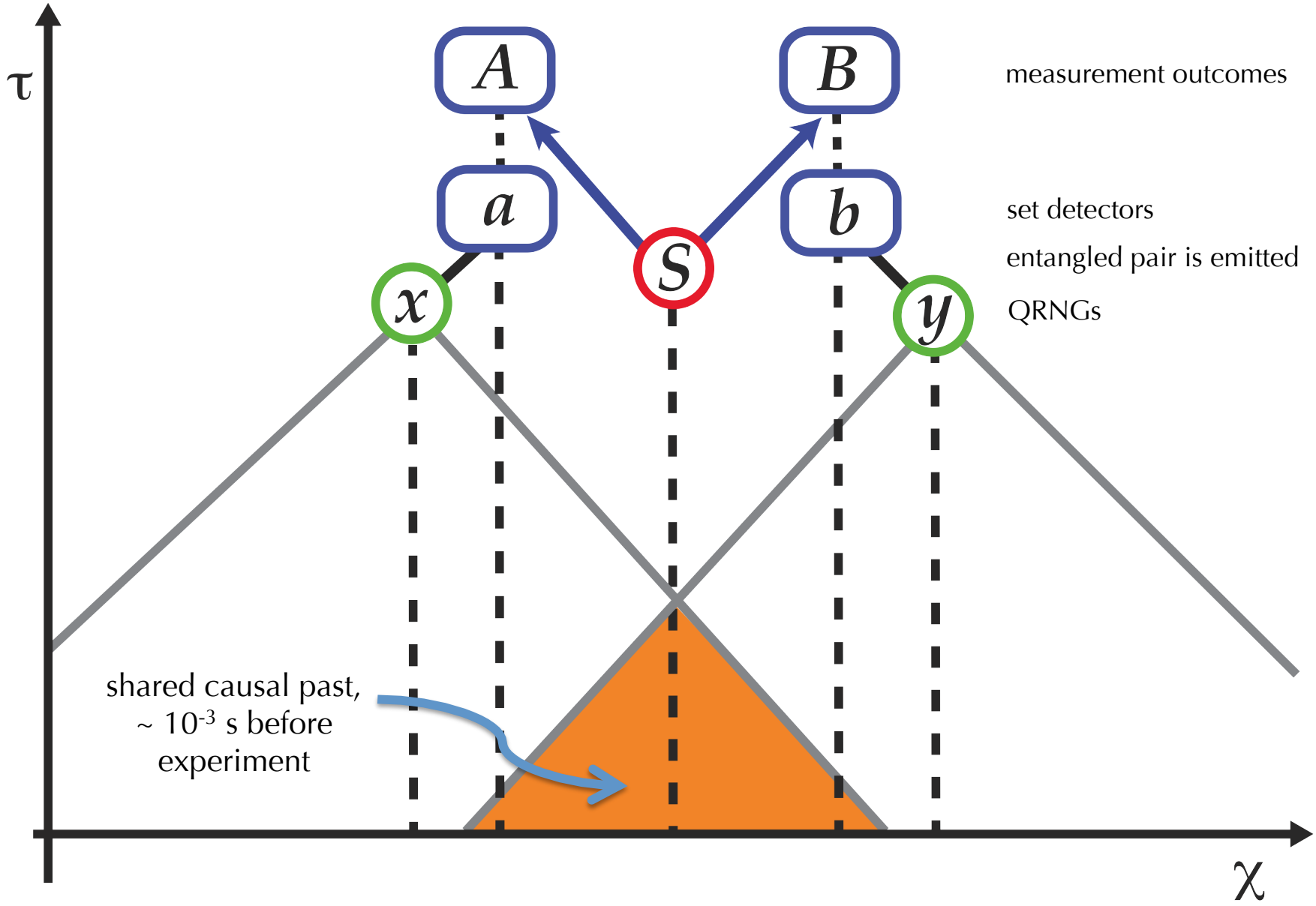


Adapted from Fig. 1 (GFK13)

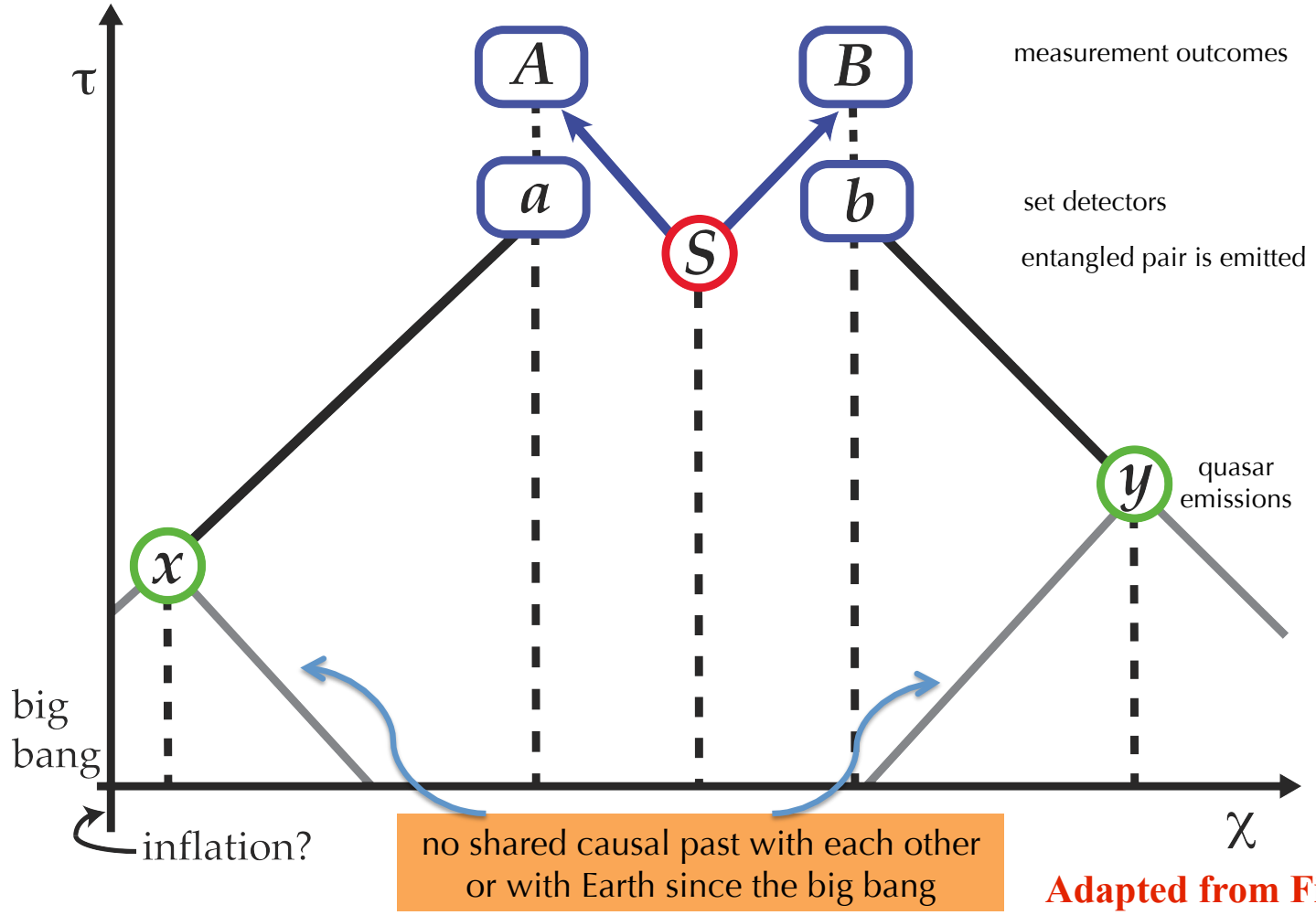
Choose detector settings with real-time observations of causally disconnected cosmic sources

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

BELL TEST CONFORMAL DIAGRAM



COSMIC BELL CONFORMAL DIAGRAM



Adapted from Fig. 2 (GFK13)

***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**

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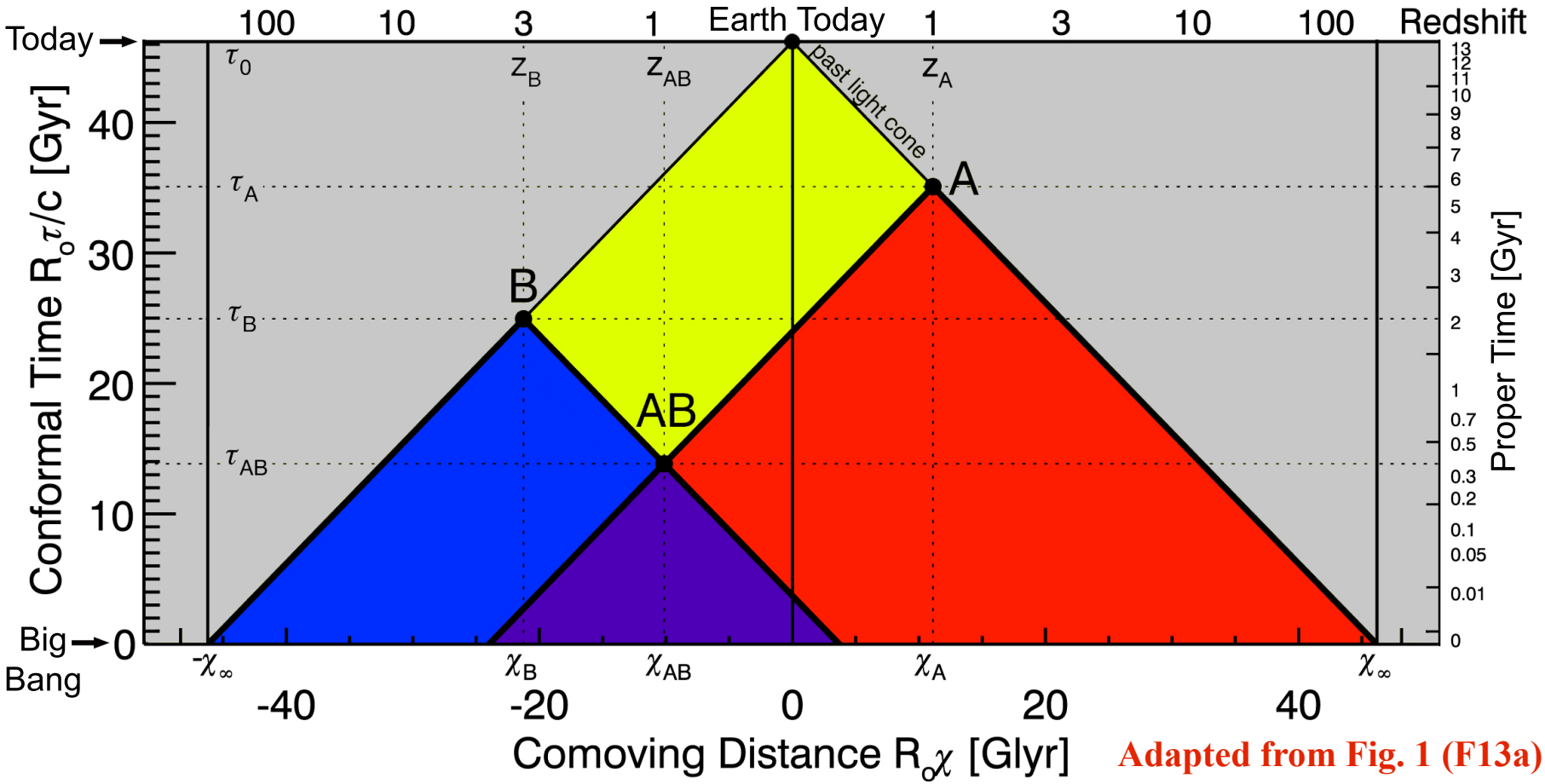
DO TWO COSMOLOGICAL EVENTS HAVE A SHARED PAST?



Adapted from Fig. 1 (F13a)

Since the hot big bang at the end of inflation

PAST LIGHT CONE INTERSECTION

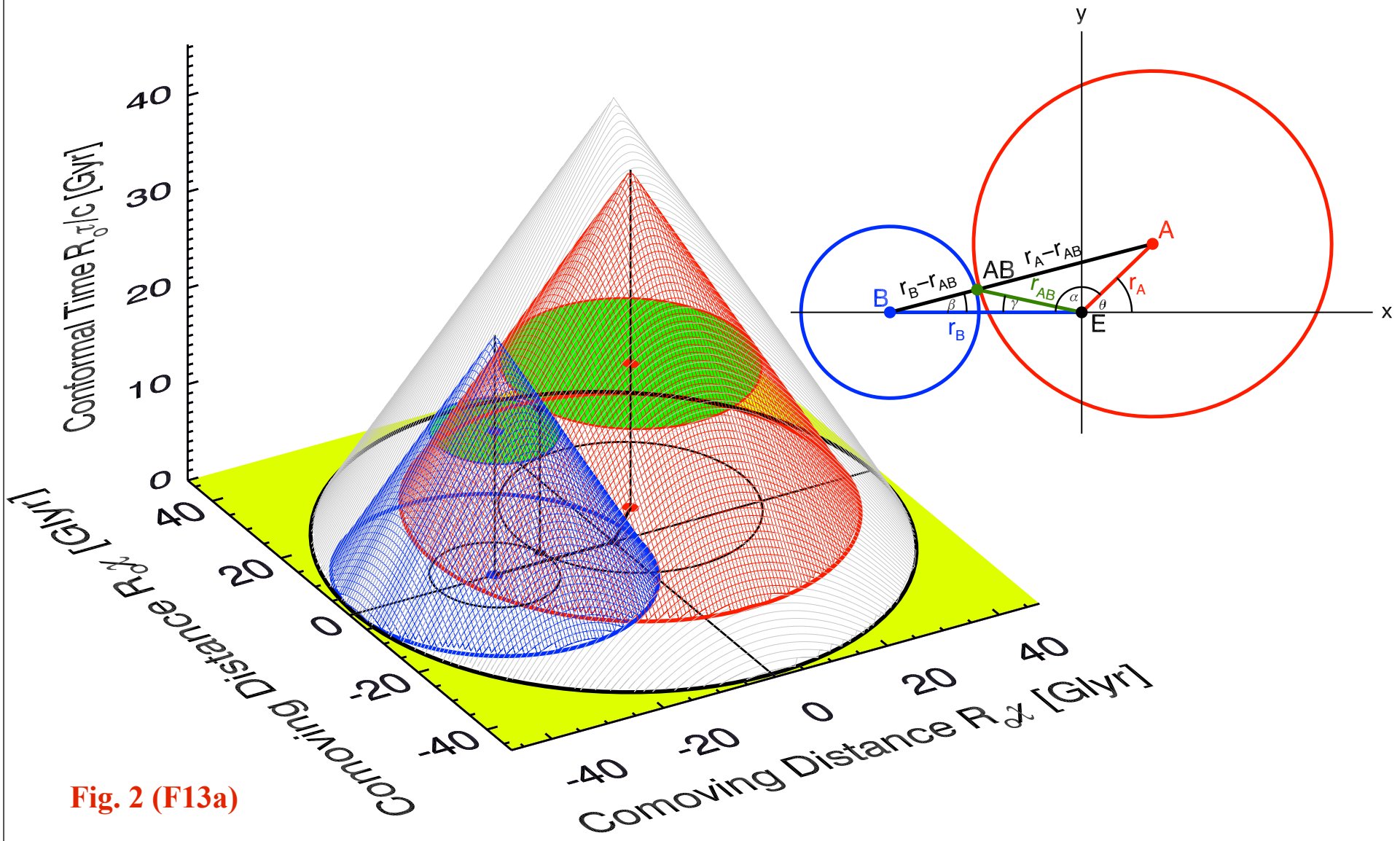


Fig. 2 (F13a)

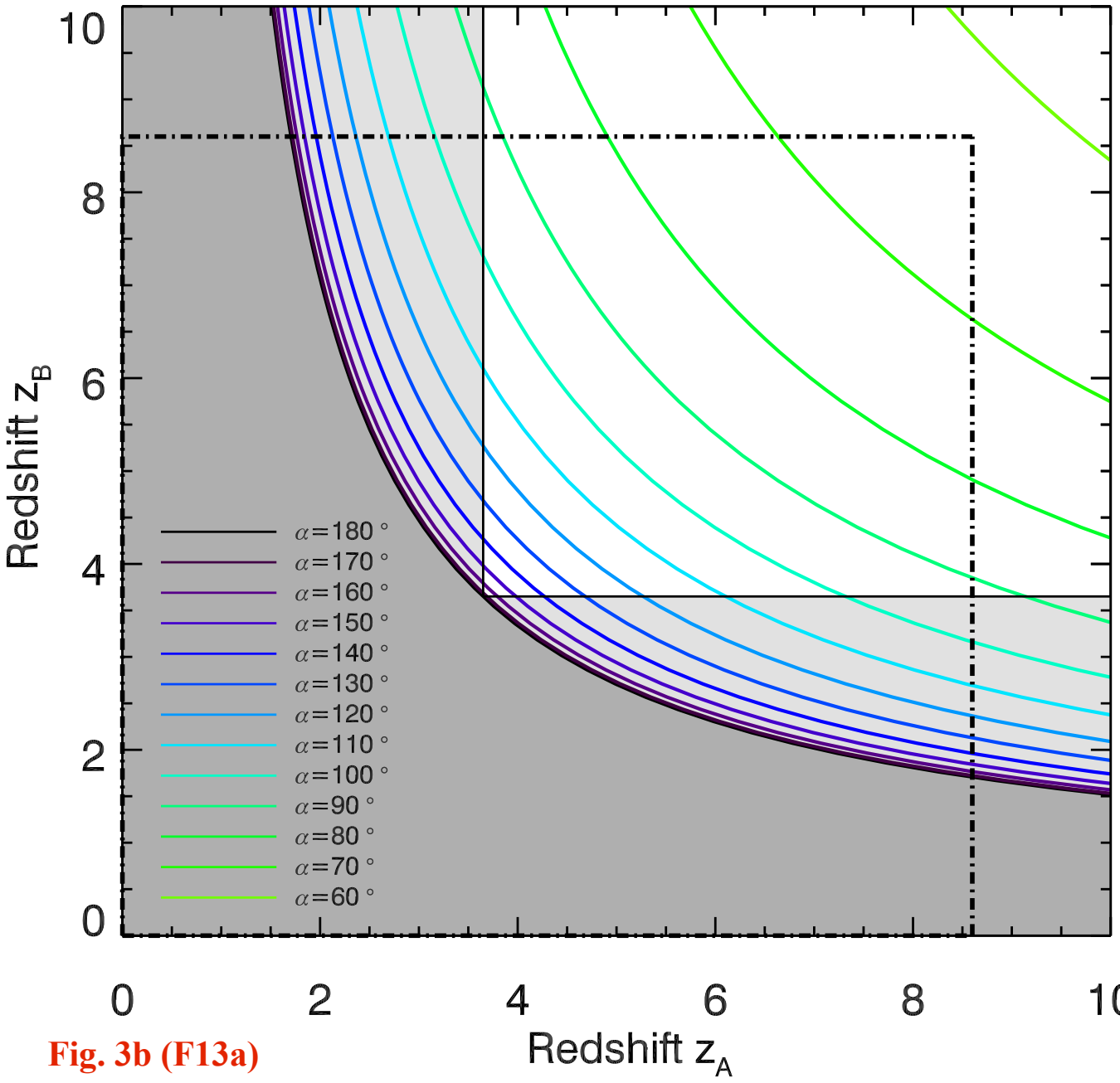


Fig. 3b (F13a)

Do A,B have a shared past?

Dark Gray
YES: any angle

Light Gray / White
NO: large angles

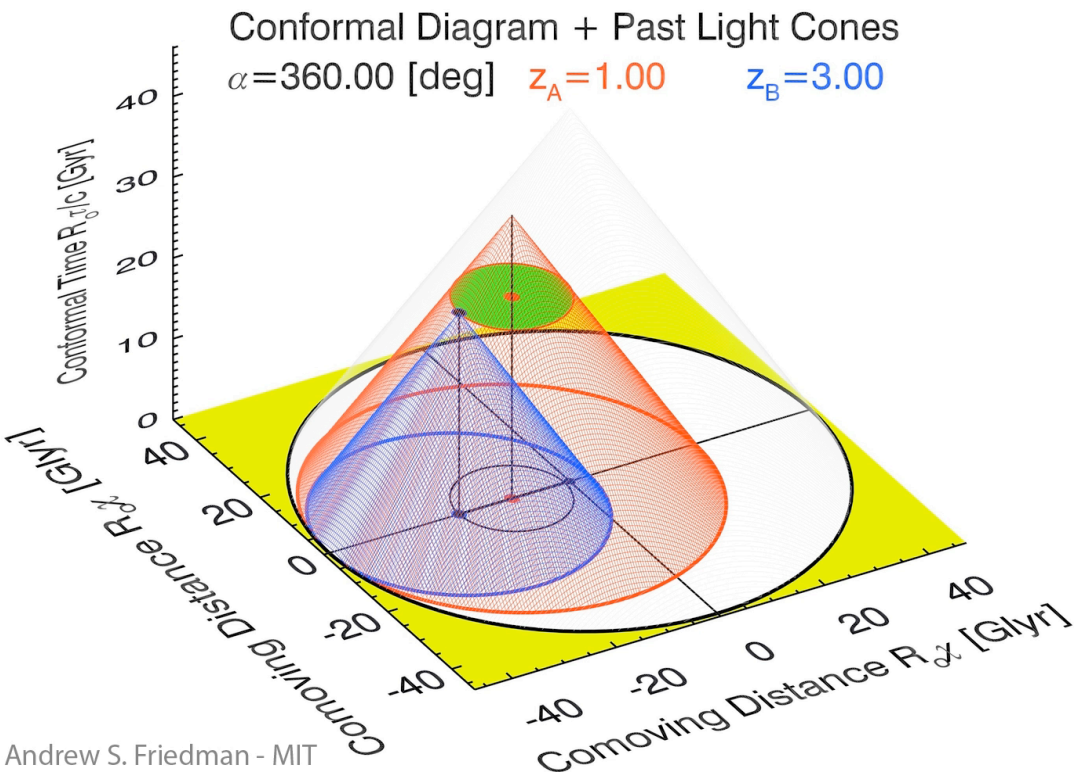
...with Earth?

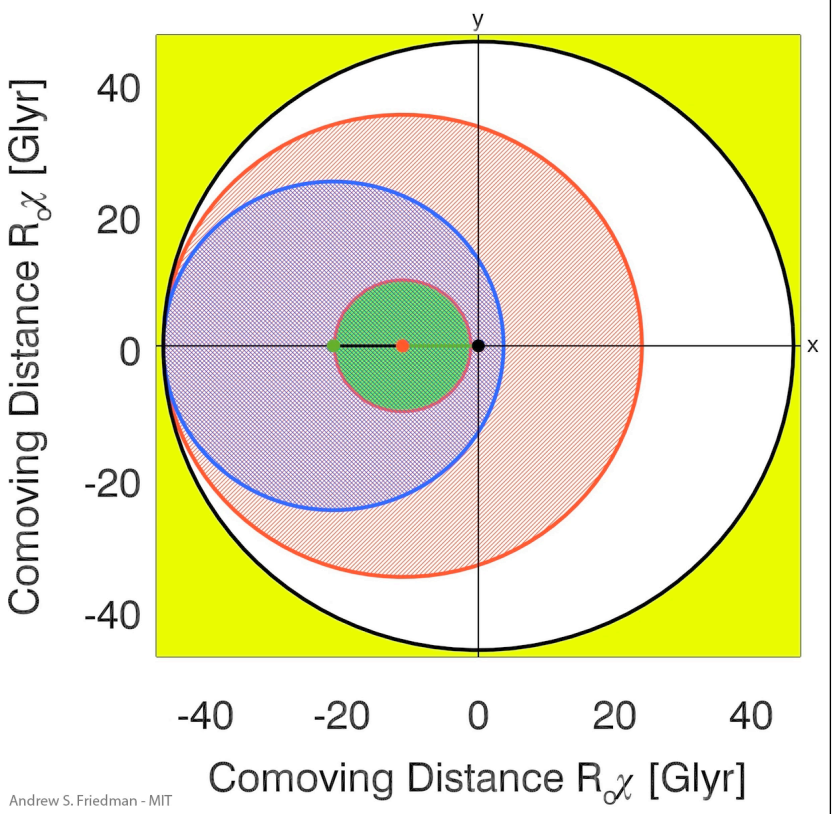
Dark Gray
YES

White
NO: A and B

Light Gray
YES: Either A or B

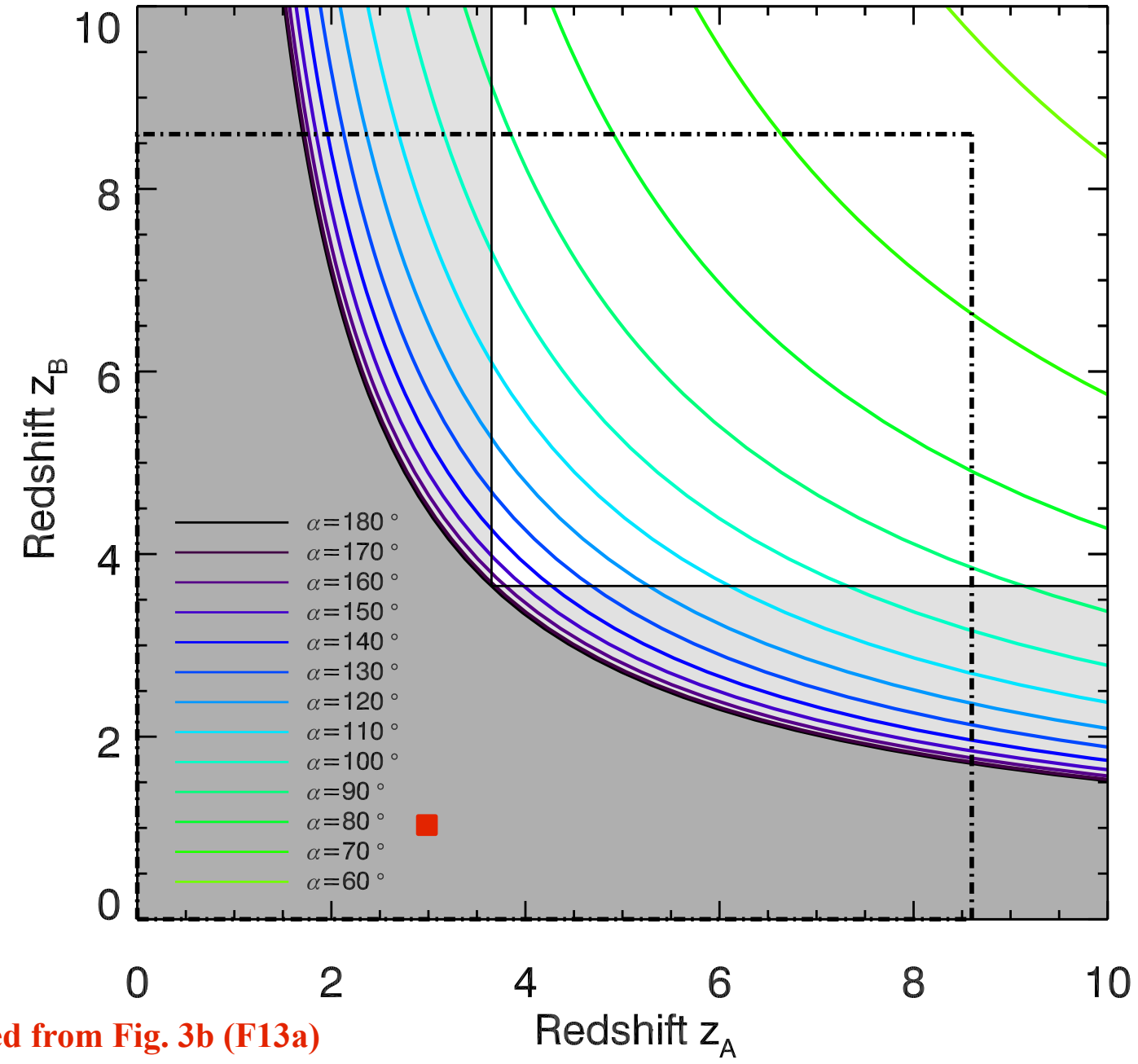
FIX REDSHIFTS, CHANGE ANGLE





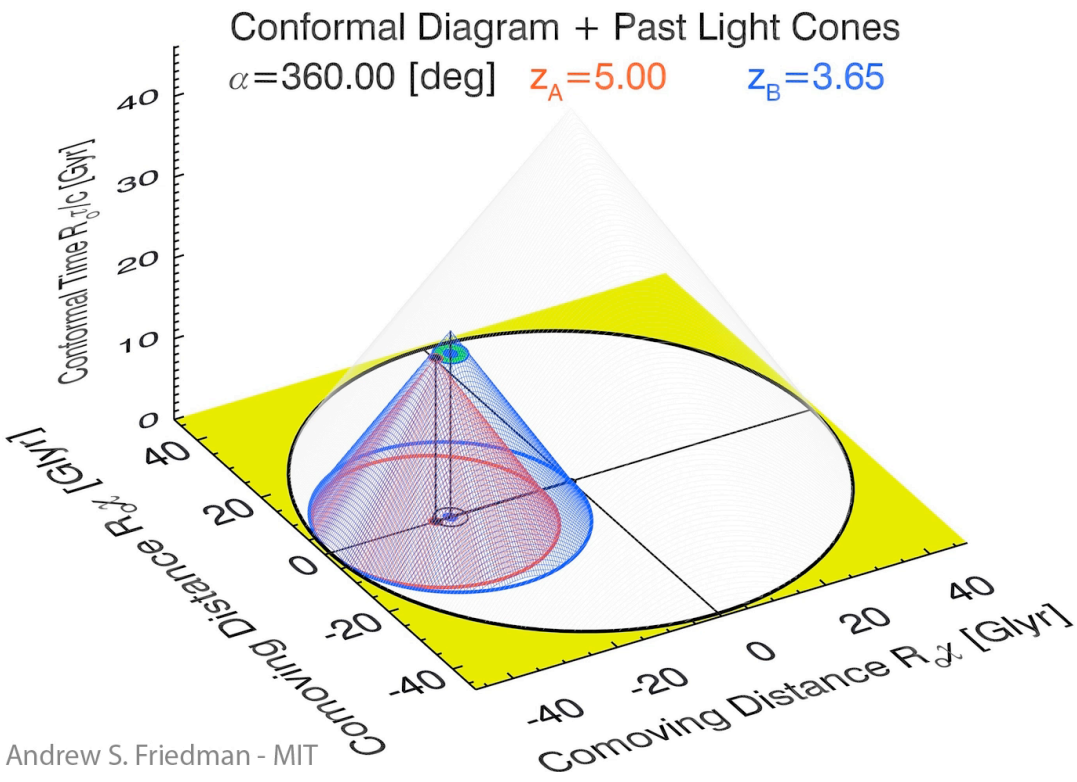
Animations 6-7 (F13a supplementary material)
http://prd.aps.org/supplemental/PRD/v88/i4/e044038

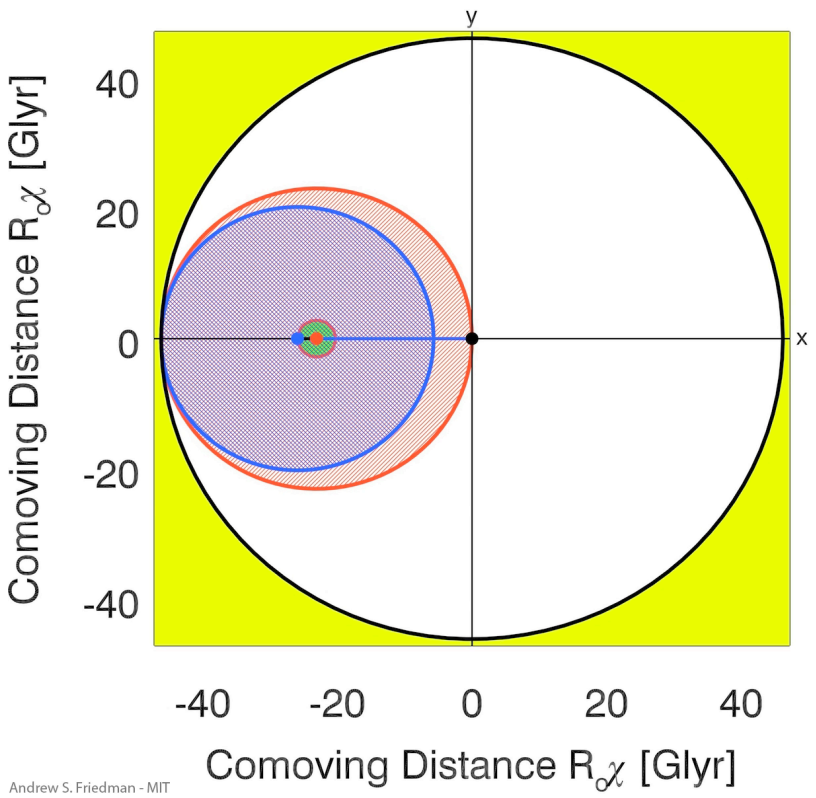
http://web.mit.edu/asf/www/causal_past.shtml
http://web.mit.edu/asf/www/04_alpha_1_3.shtml



Adapted from Fig. 3b (F13a)

FIX REDSHIFTS, CHANGE ANGLE



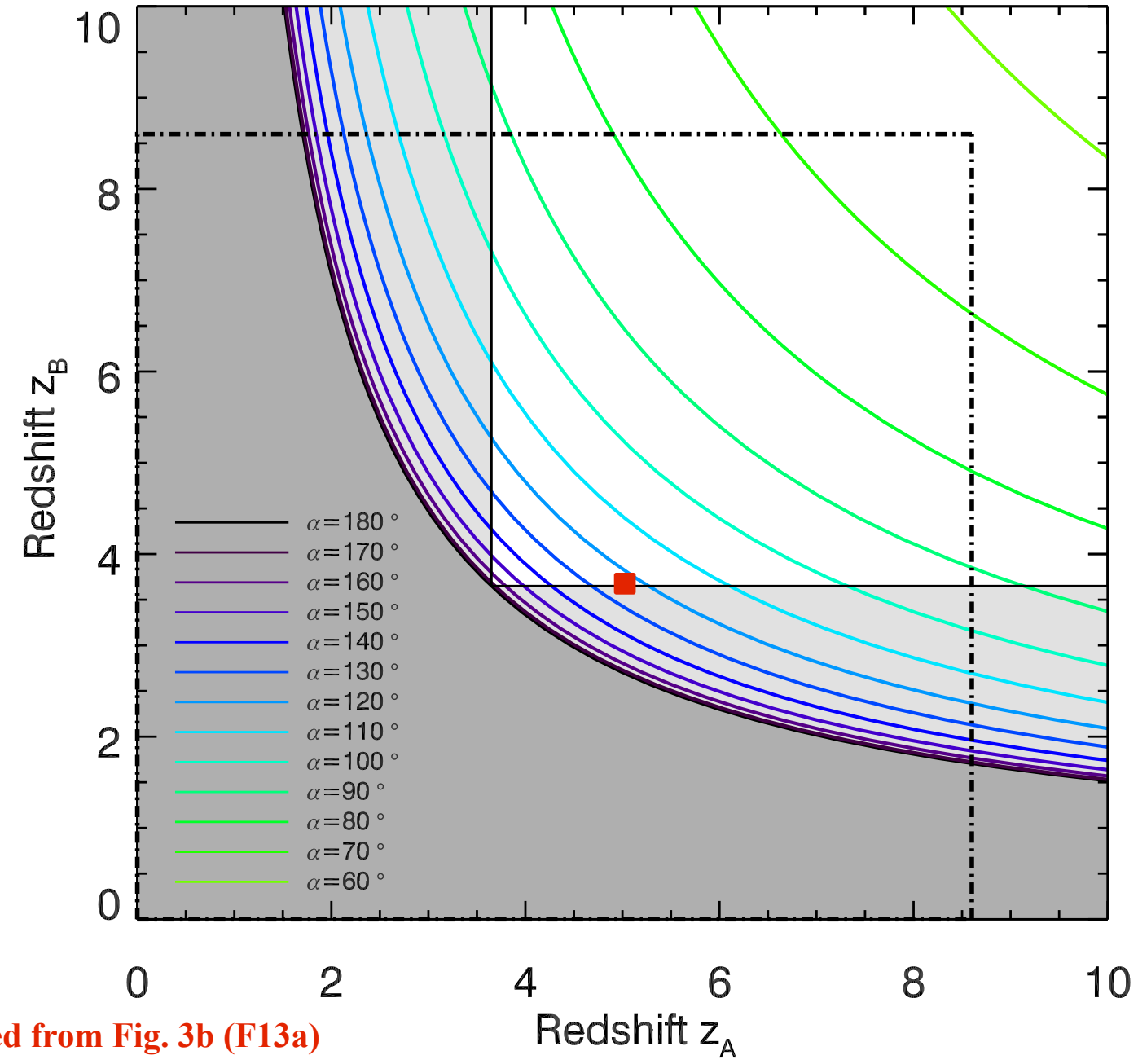


Animations 8-9 (F13a supplementary material)

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)

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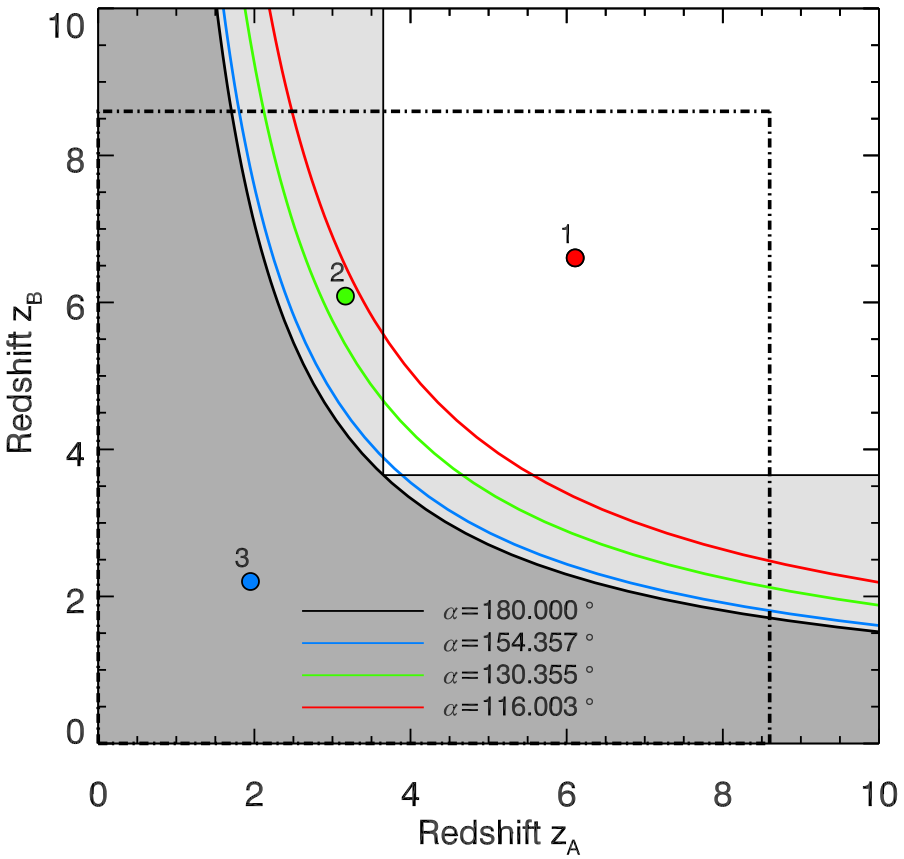


EXAMPLE QUASAR PAIRS

pair 3 - YES shared past with each other & Earth

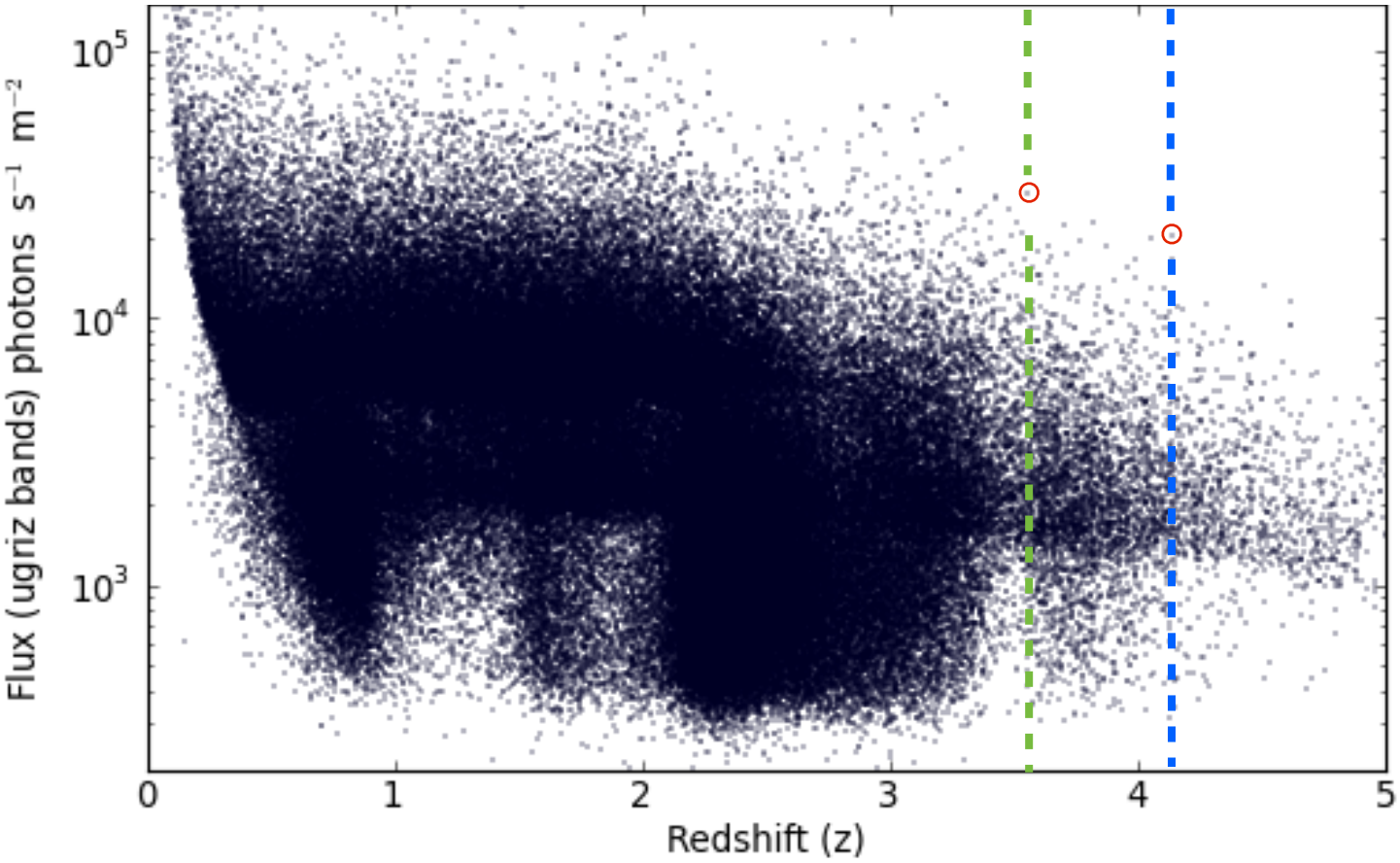
pair 2 - NO shared past with each other, but A_2 has shared past with Earth

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?

Freedom of Choice / Setting Independence

Choose settings with cosmic sources.

Locality

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

Fair Sampling / Detection Efficiency

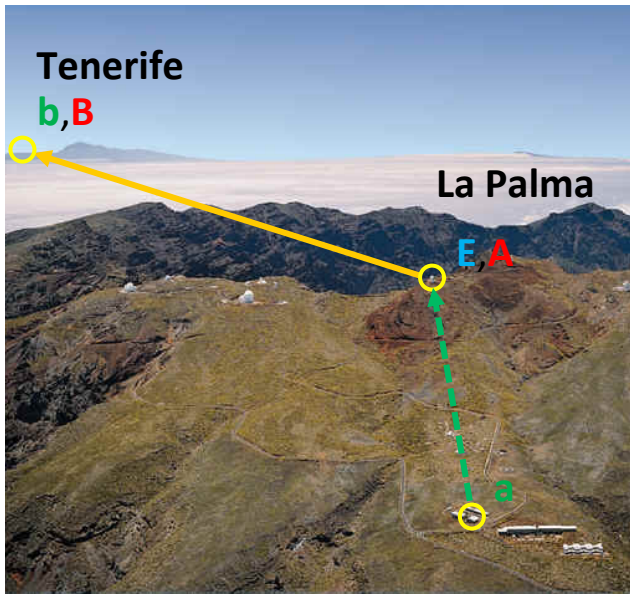
Use existing detector technology: efficiency & time resolution

With feasible experimental parameters, can close first two loopholes simultaneously! (GFK13)

~1-meter	**Telescope mirror diameters**
~100km	**Baseline between 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)**

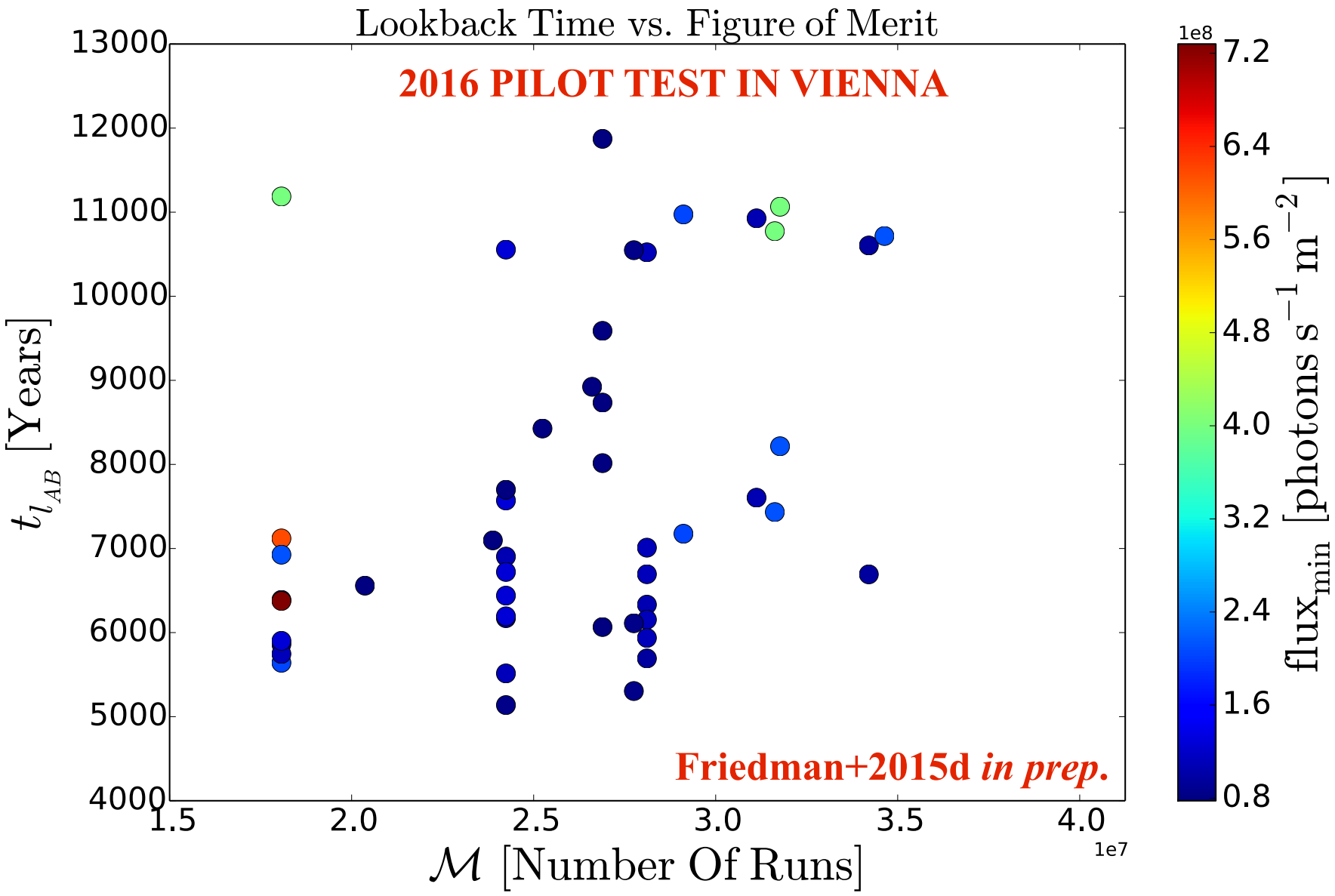
ZEILINGER GROUP EXPERIMENTS

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

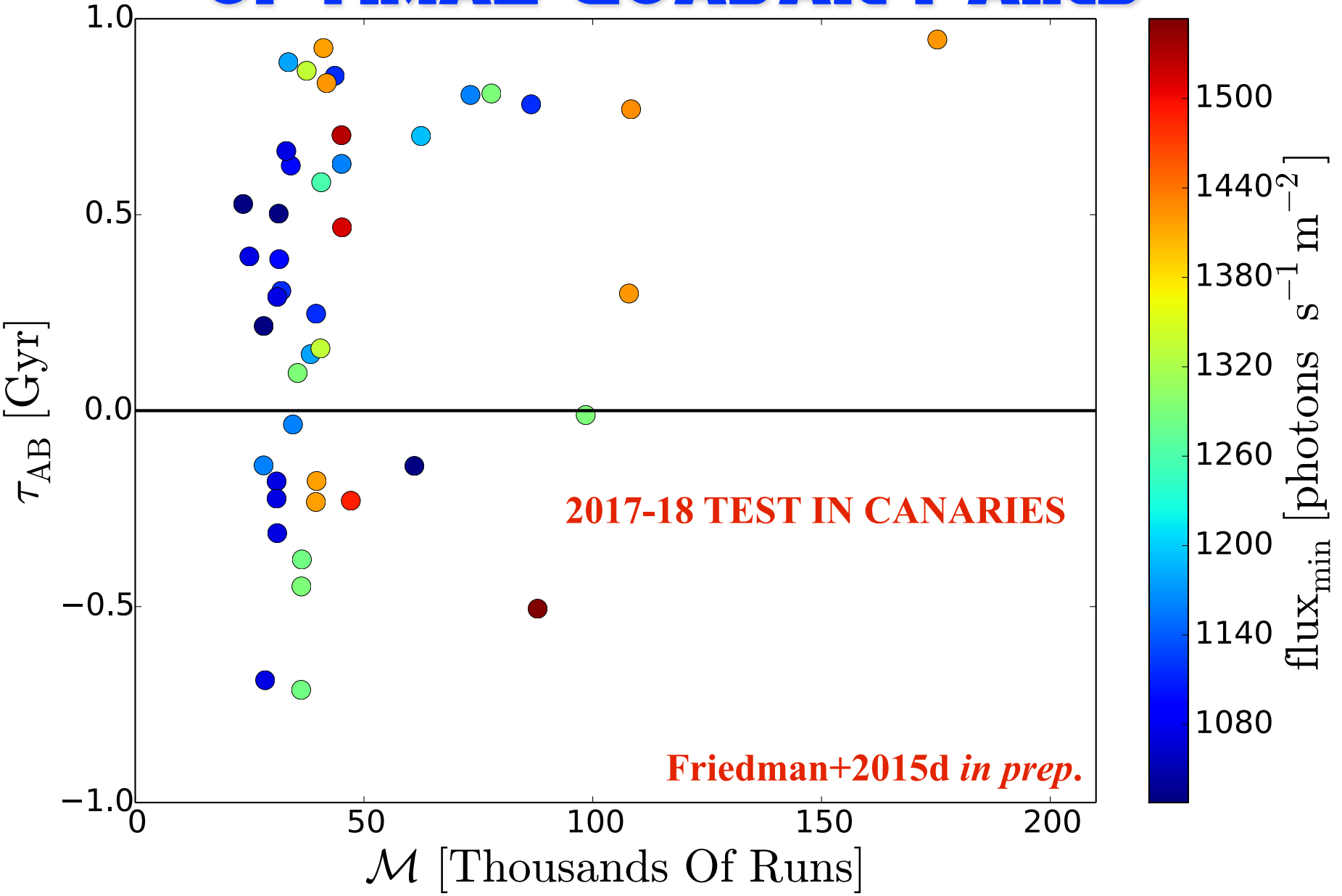


Scheidl+2010, *PNAS*, 107, 46, p. 19708-19713

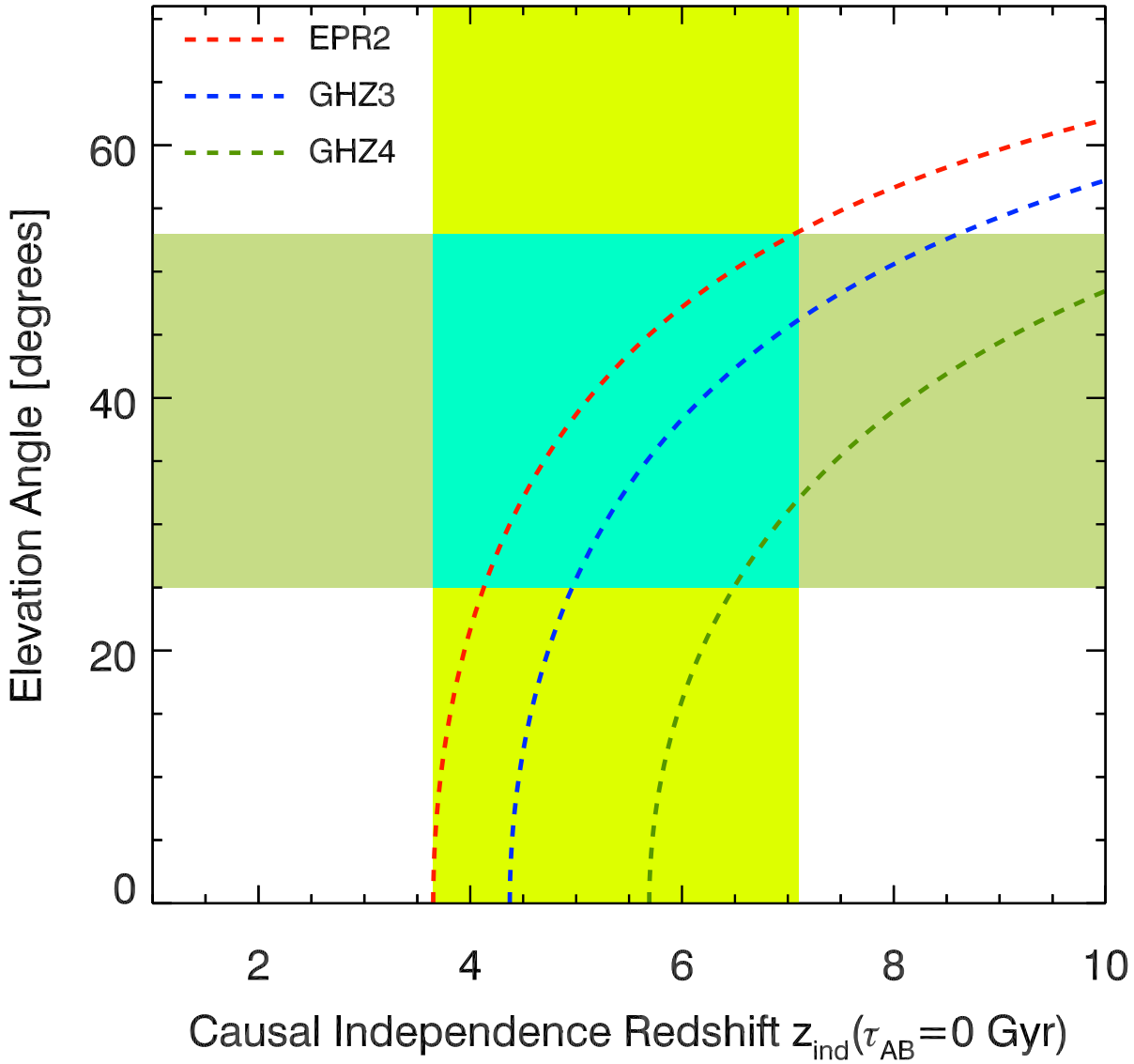
OPTIMAL HIPPARCOS STARS



OPTIMAL QUASAR PAIRS



GHZ: 3 OR 4 QUASARS?



Push past LC intersection to inflationary epoch 13.8 Gyr ago.

Smaller angles Larger redshifts z~3.65-7.1

Quasars too faint, too few for ground-based test with 3 or 4 objects ~1-3 m telescopes

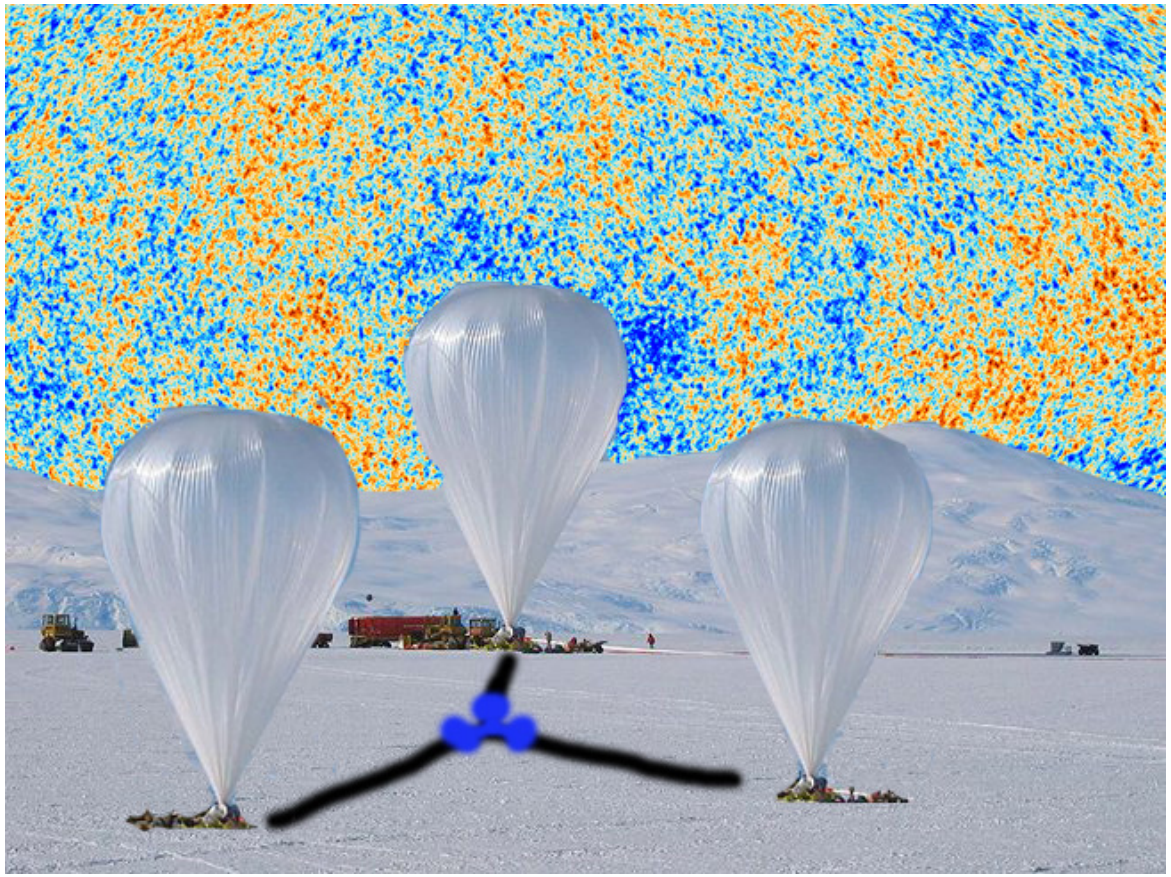
Friedman+2015d *in prep.*

GHZ WITH CMB?

3+ particles, Bell's theorem without inequalities

QM, Local realism give opposite answers to yes/no questions

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



Balloon based test in Antarctica?

Easy! Pick 3 CMB patches, each separated by 2.3°

Hard! Local noise dominates from ground (GFK14)

Noise loophole limits better than 2-particle Bell test (Hall 2011)

Friedman+2015d *in prep*.

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POSSIBLE OUTCOMES

Expected

Bell inequalities always violated. Rule out ("implausify") local HV theories as much as possible, modulo inflation.

Unexpected

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

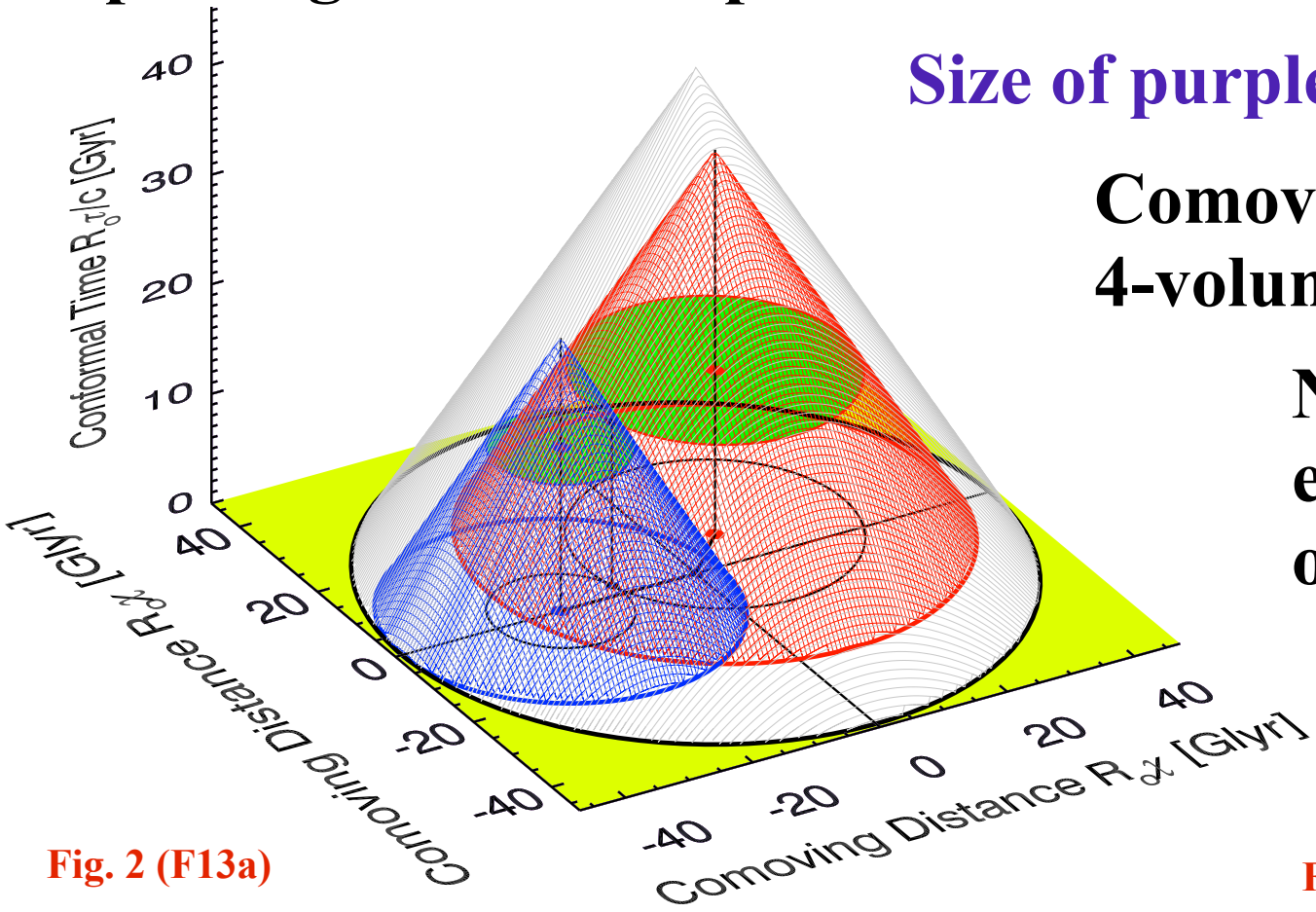
Strangest

Bell inequality not violated for very distant cosmic sources.

Perhaps freedom / setting independence assumption is false!
Maybe universe actually exploits free will loophole.
Implications for inflation? Quantum gravity?

CAUSAL OVERLAP REGION

What if Bell test correlations depended on extent of causal overlap region? Causal origin for entanglement exploiting free will loophole?



Size of purple region.

Comoving spacetime 4-volume

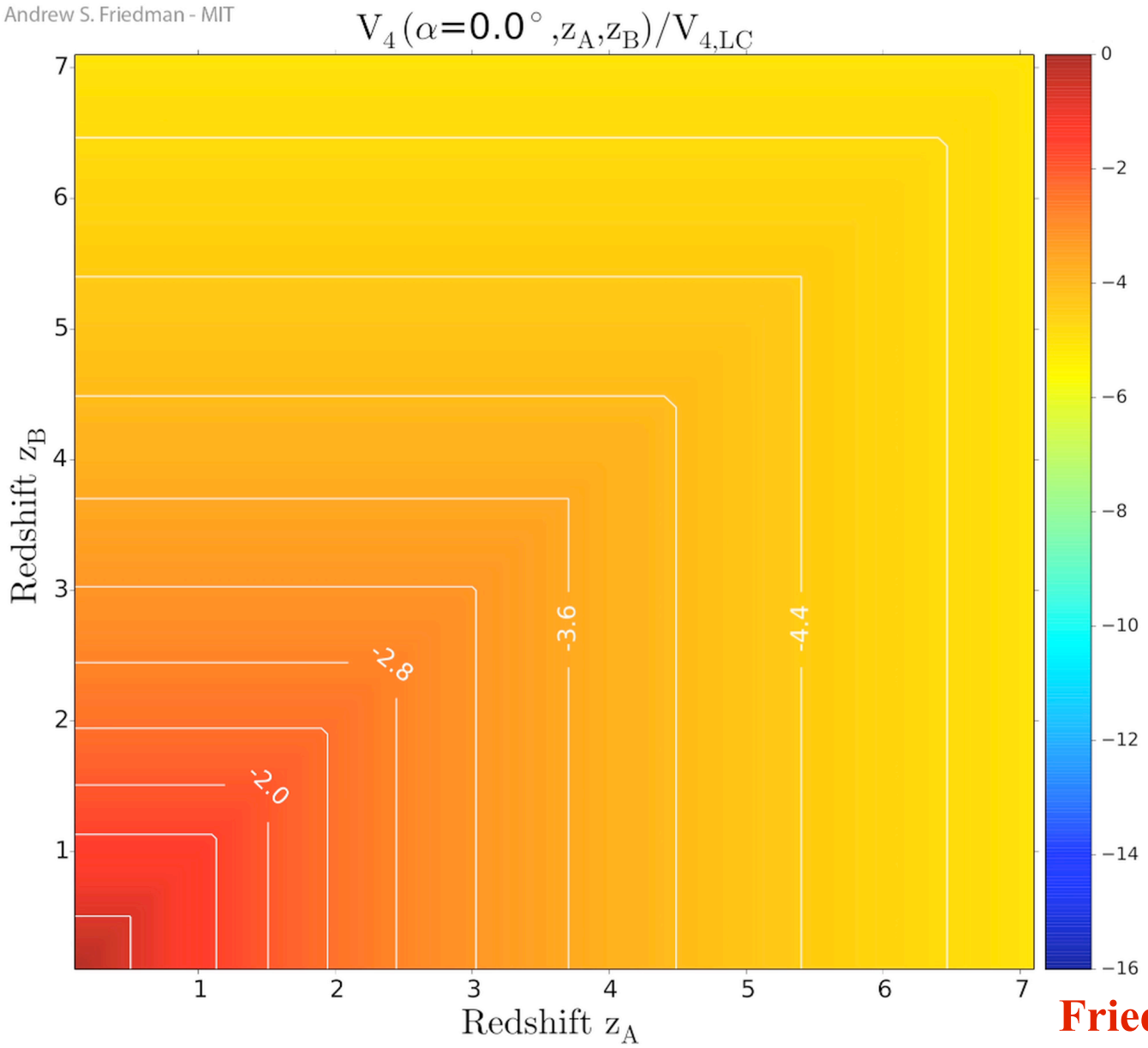
Normalize to extent of our past LC

→ physical coordinates

Fig. 2 (F13a)

Friedman+2015e *in prep.*

SPACETIME 4-VOLUME MOVIES



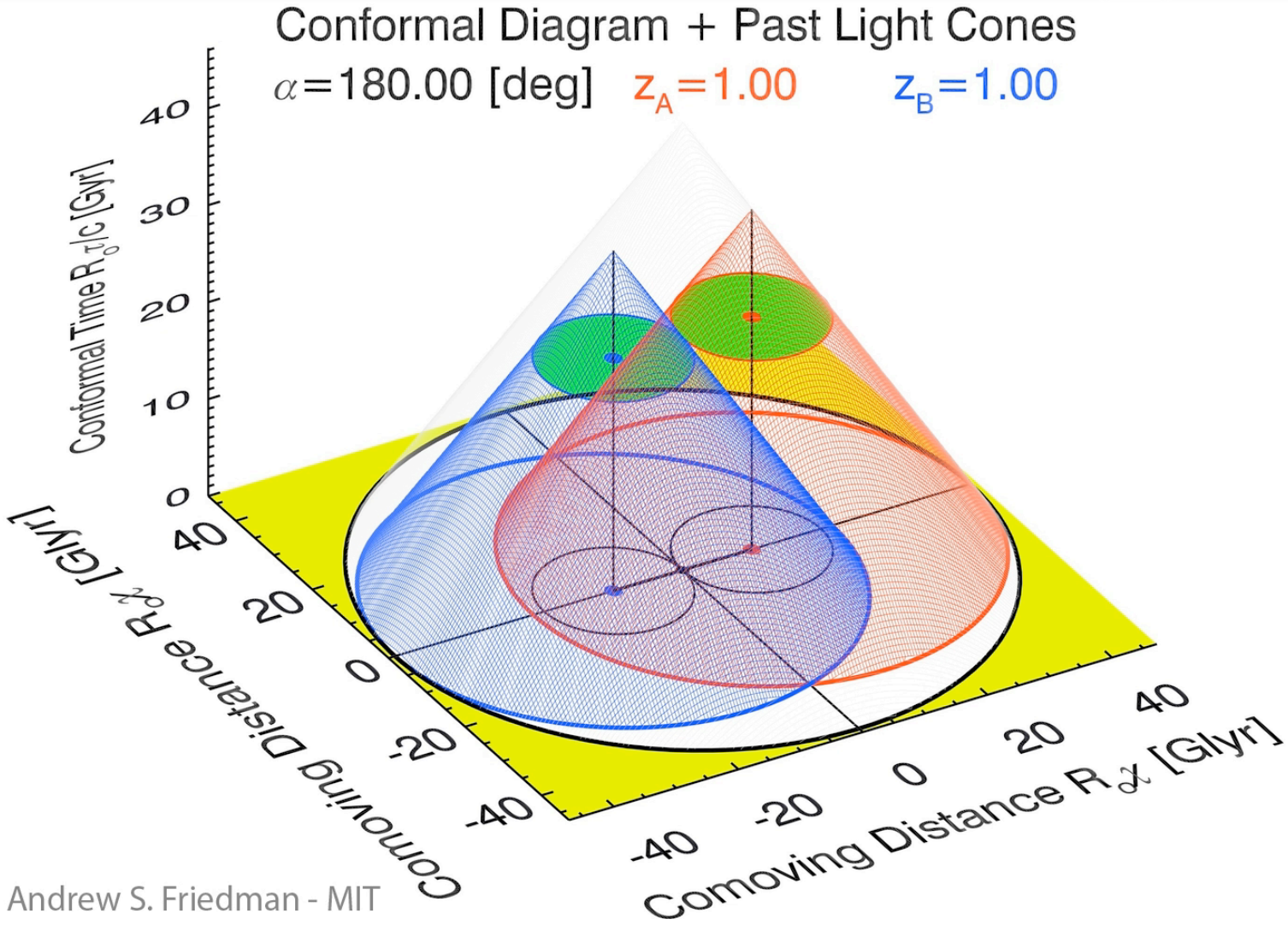
Log scale

Red:
Entire past LC

White:
No causal overlap after inflation

Friedman+2015e *in prep.*

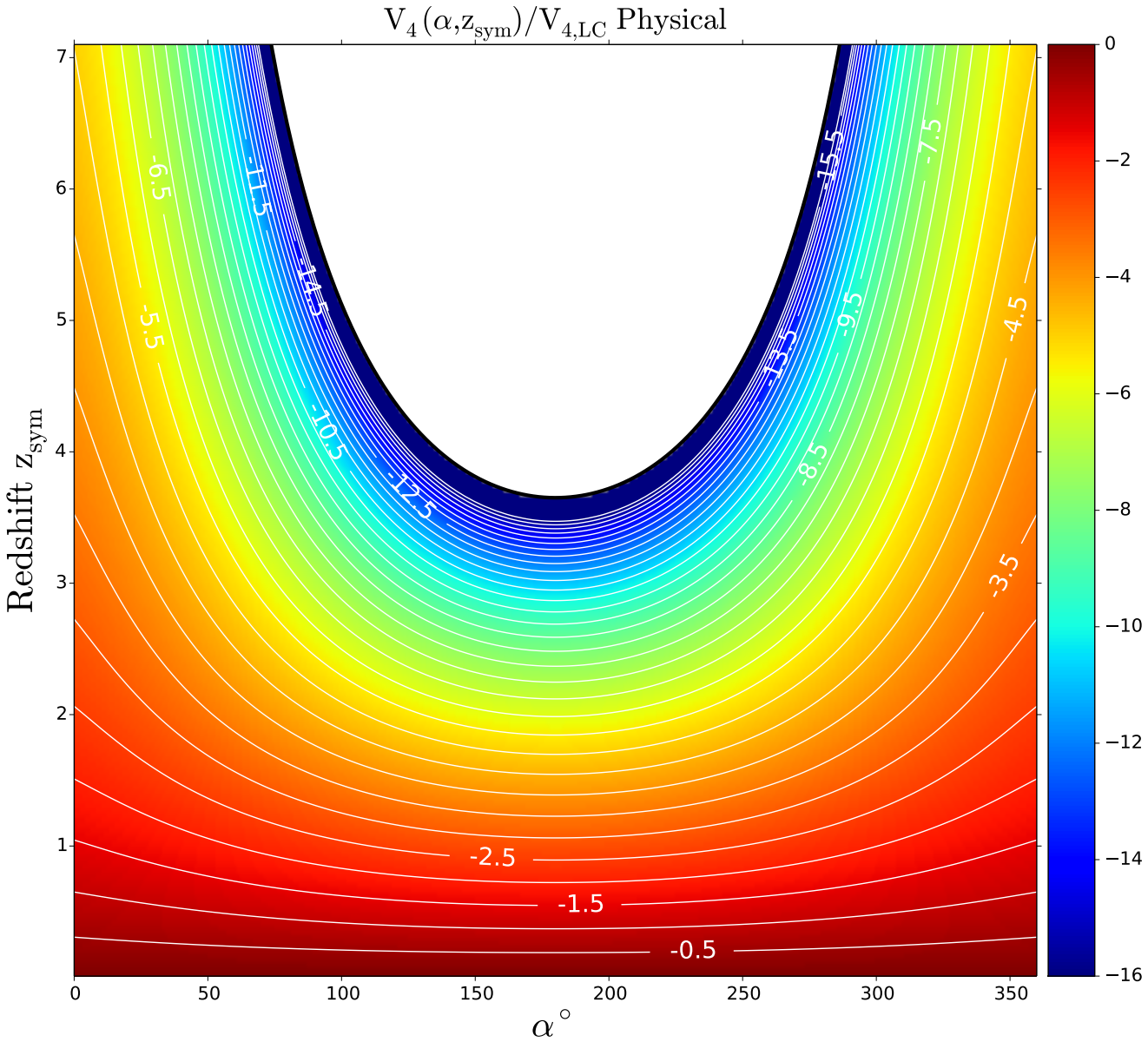
FIX ANGLE, CHANGE Z = Z_A = Z_B



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

SPACETIME 4-VOLUME



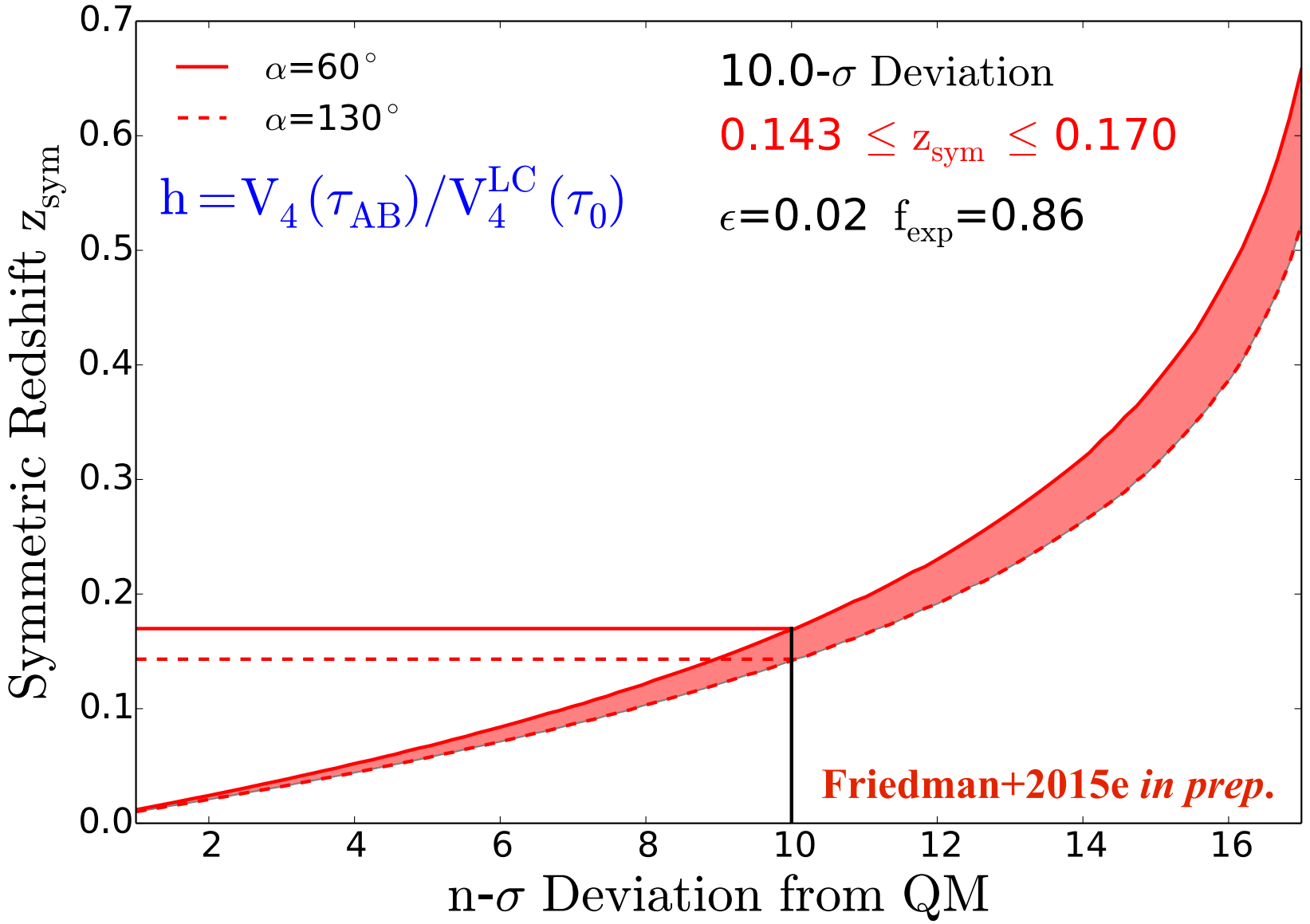
Symmetric redshift: $z_A = z_B = z_{sym}$ VS. angular separation

Normalized to 4-volume of past LC

Physical units

Friedman+2015e ***in prep.***

TESTING ALTERNATIVE MODELS



FUTURE WORK

Optimal candidate stars, quasars, observing plan.

Quasars vs CMB? EPR2 vs GHZ3, GHZ4.

Ground, baloon, space-based tests.

Quantifying alternative models

GFK14, Friedman+2015d *in prep*, Friedman+2015e *in prep*.

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.

"Inflation Loophole" Shared past during inflation

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