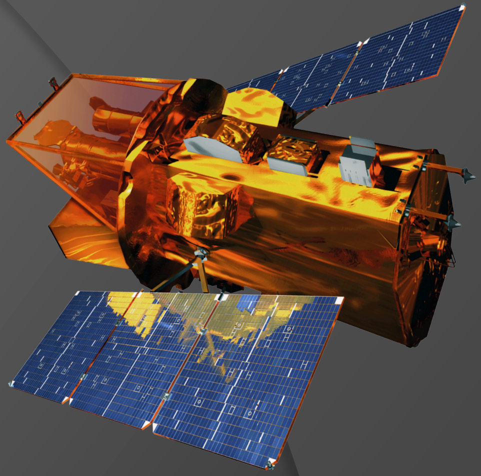


SWIFT TILING: SIMULATIONS, OPTIMIZATION, AND PROBABILITY OF GRAVITATIONAL WAVE COUNTERPART DETECTION

Judy Racusin (NASA/GSFC)

Fermi-LIGO Workshop, March 15-16, 2015, Caltech

Swift's Evolving Capabilities

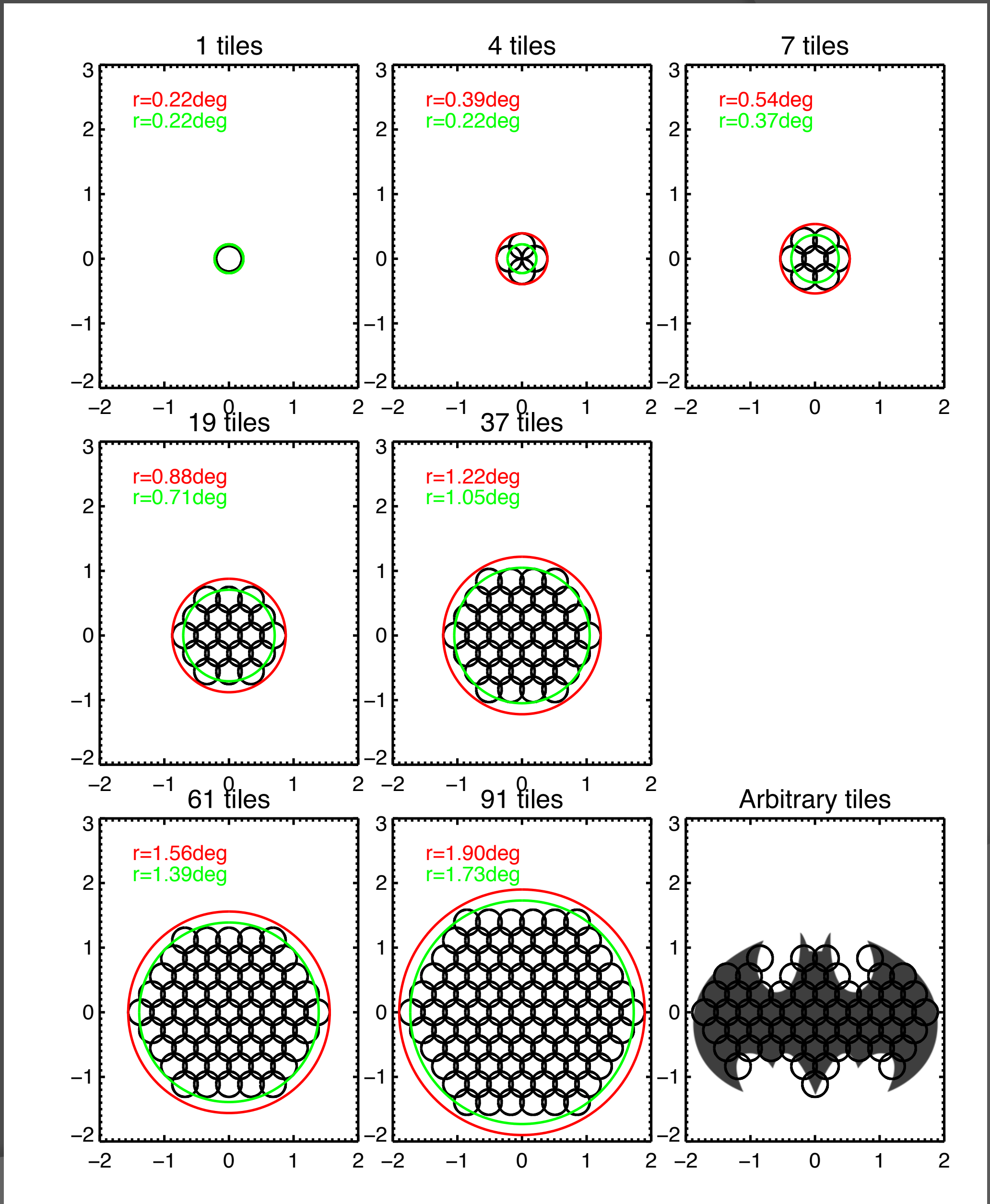
- XRT is good at localizing BAT GRBs – done ~900+ times
- Swift can be used to chase rare, poorly localized GRBs and other transients
  - Fermi LAT/GBM, IPN GRBs
  - LIGO/Virgo Triggers
  - Neutrino Triggers
- On-board Tiling capability added in 2012
  - Some manual (single tile per orbit) prior to that
  - Details on XRT processing: http://www.swift.ac.uk/xrt_products/tiling.php
  - See Jamie's talk yesterday

Swift Tiling

Existing and commonly used patterns

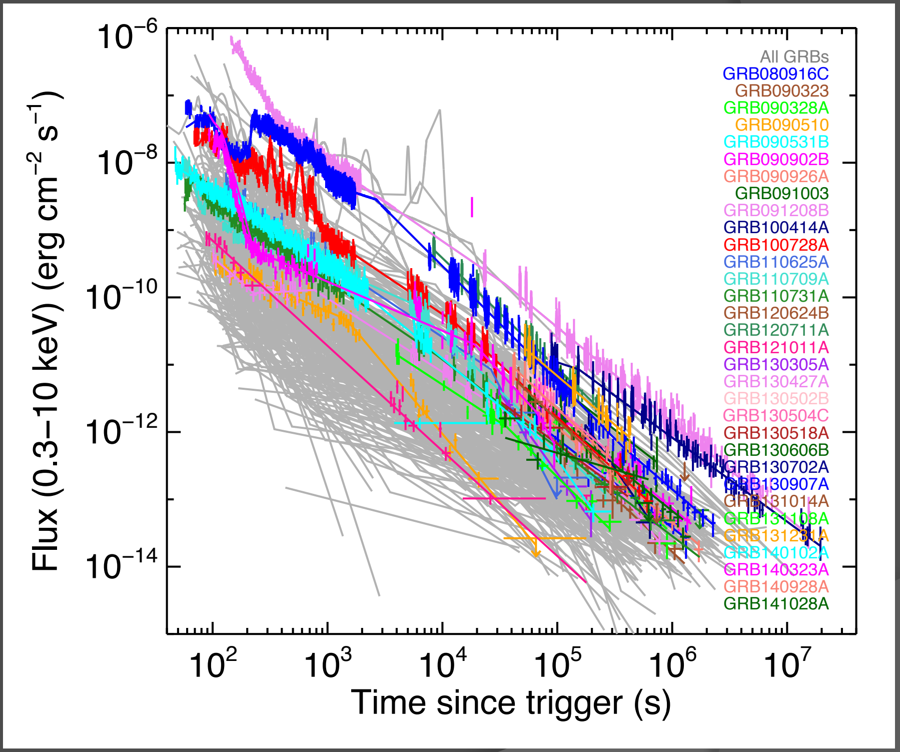
Existing but never tested patterns

Potential Expansions of Tiling Capability *(may be limited by spacecraft resources)*



XRT Observations of LAT GRBs: Follow-up Success Rate

- 93 LAT detections
- 15 BAT/LAT/GBM/XRT co-detections
- 36 detected by XRT
- 45 followed-up by XRT
  - 16 tiled (4 detected)
    - 7 w/ 7 tile pattern (3 det)
    - 8 w/ 4 tile pattern (1 det)
    - 3 w/ other patterns (mainly older bursts) (0 det)
  - 27 single pointing (18 detected)



Tiling Simulations

- Use XRT afterglow light curves to predict flux in realistic tiling windows (including observing constraints, slewing overhead, etc.)
- Strongly depends on start time of observations (ToO upload time)
- Single orbit detection or cumulative detection over several orbits
- Depends on parents sample (all XRT light curves, LAT detections, GBM detections, short/long, fluence cuts)
- Guide for observing strategies and studying intrinsic GRB afterglow distributions

Tiling Simulation Results: LAT GRBs

# Tiles	Simulations (% Detected in 1 day of observations)					Reality
	T_{start}=100s	1 hr	6 hrs	12 hrs	24 hrs	
1	100%	100%	90%	92%	90%	67%
4	100%	100%	93%	88%	53%	25%
7	100%	95%	92%	75%	45%	43%
19	97%	92%	60%	47%	27%	--
37	92%	85%	45%	22%	11%	--
61	92%	65%	25%	12%	5%	--
91	73%	54%	18%	5%	0%	--

Drawn from XRT detections of LAT GRBs
Does not include those not detected

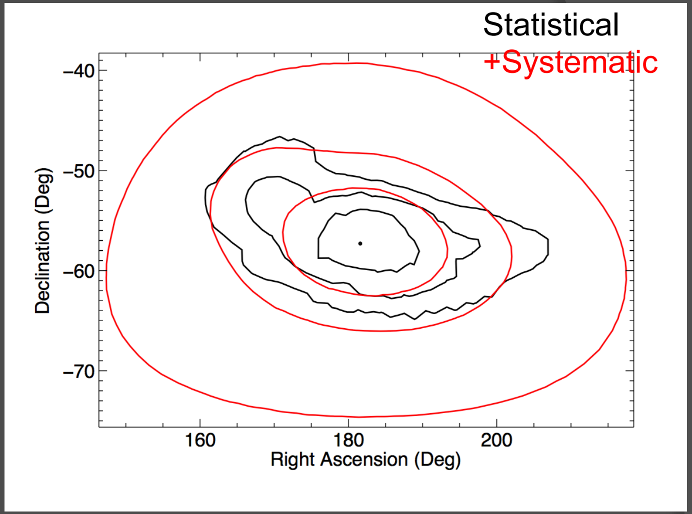
Tiling Simulation Results: High Fluence GRBs (proxy for LAT detection)

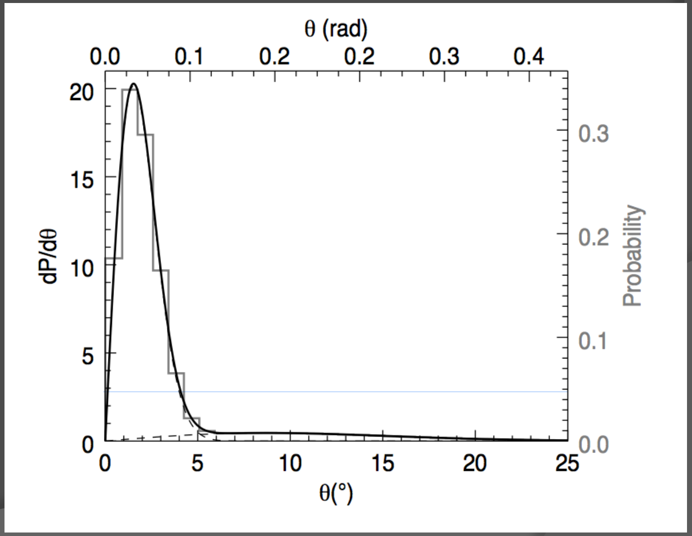
# Tiles	Simulations (% Detected in 1 day of observations)					Reality
	T_{start}=100s	1 hr	6 hrs	12 hrs	24 hrs	
1	100%	100%	98%	95%	87%	67%
4	100%	100%	92%	62%	30%	25%
7	98%	92%	83%	64%	30%	43%
19	98%	92%	55%	25%	10%	--
37	92%	77%	25%	8%	2%	--
61	80%	50%	8%	0%	0%	--
91	47%	17%	3%	1%	0%	--

Drawn from XRT detections of BAT GRBs with Fluence > 5e-6
Does not include those not detected

Fermi-GBM Localizations

- GBM detects ~240 GRBs per year (~40 short + ~40-60 from new ground event data CTTE pipeline)
- Connaughton et al. arXiv: 1411.2685 - New study of systematic errors with large sample with known positions
  - Best fit systematic for 68% localization error ~3.7° Gaussian + 14° tail
  - Some addition dependence on relative orientation of GRB to spacecraft (detector shadowing)
  - No significant difference between short and long burst localizations other than those related to sGRB lower fluence
- Can Swift tile GBM localizations?

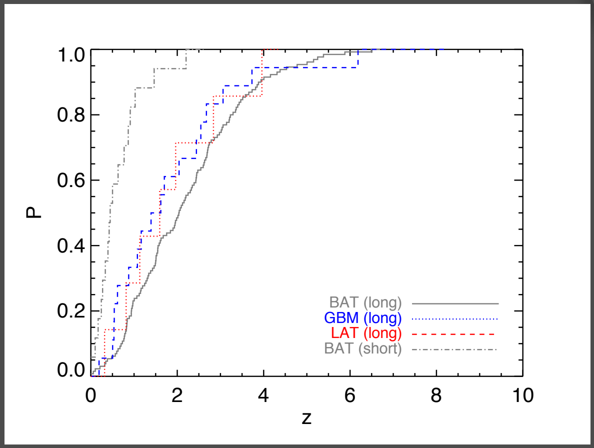




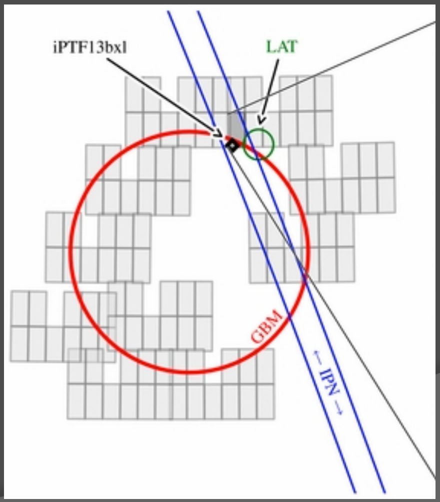
Connaughton et al. 2014

GBM Co-detection and Follow-up

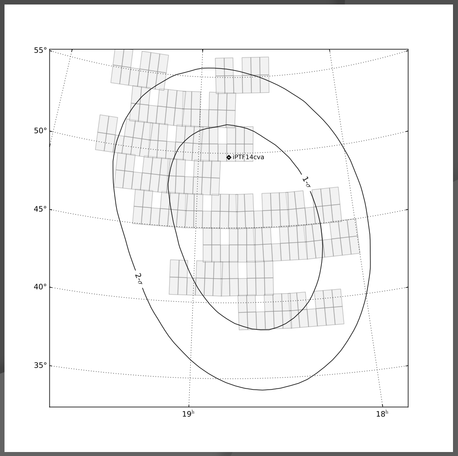
- ~24% co-triggered with BAT
  - Typically GBM bursts have higher fluence than BAT bursts
  - Redshift distributions are similar (but GBM a subset of BAT)
- LAT detections all seeded by GBM
  - ~36 detected by XRT (2/3 during follow-up)
- iPTF & Master (wide FoV robotic optical) tile GBM error contours
  - ~8 detections (of ~40 observed)
- Detections are possible, but it's a statistics game
  - Never detected short burst this way
- See Leo's talk



Racusin et al. 2011

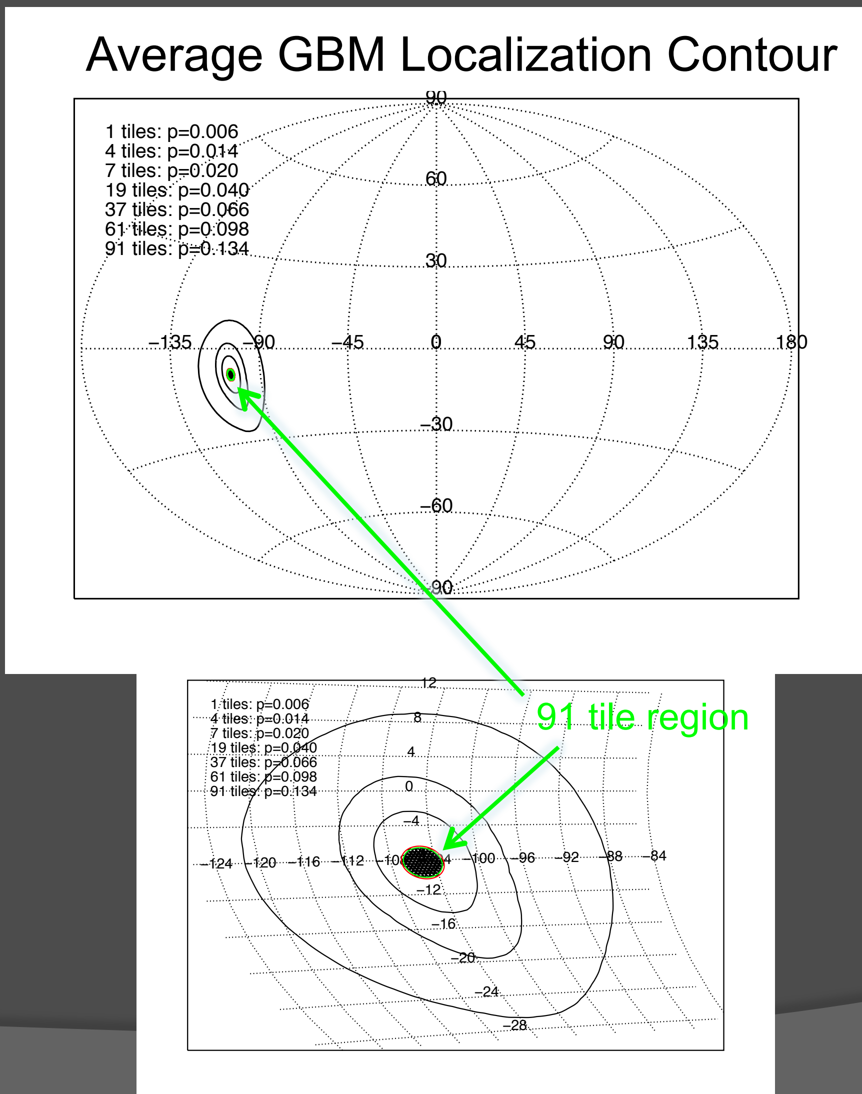


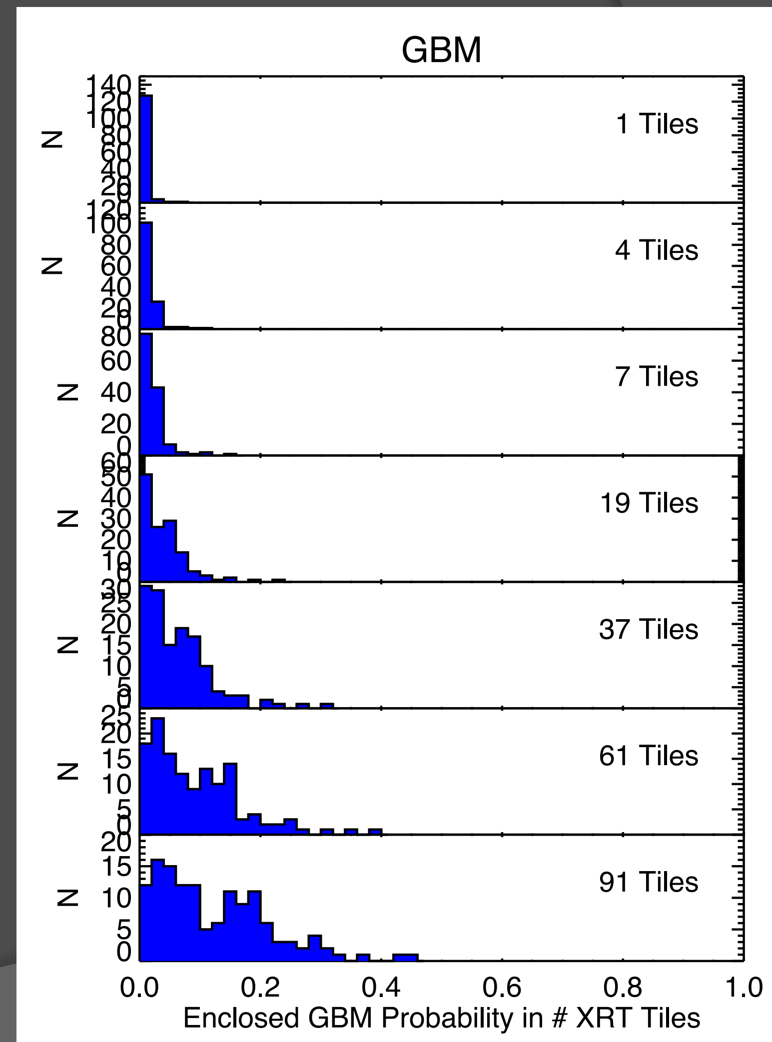
GRB 130702A:
Singer et al. 2013, ApJ



GRB 140620A:
Kasliwal, GCN 16425

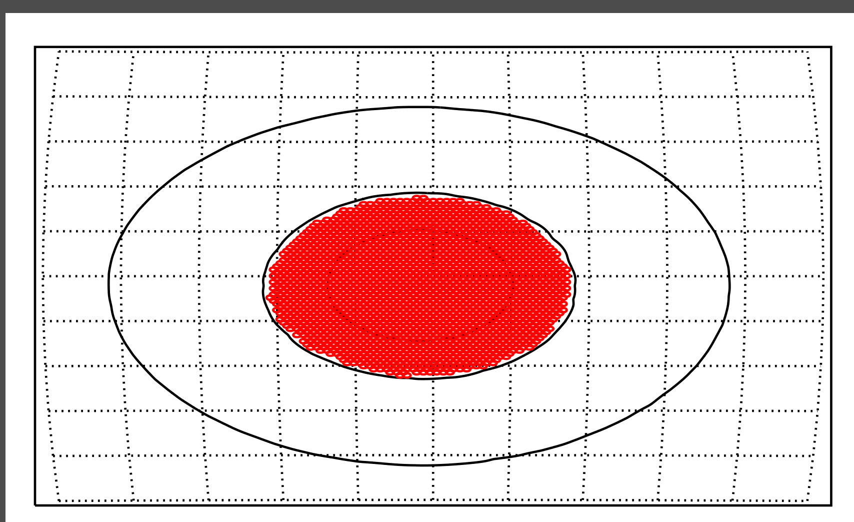
Overlaying XRT Tiles on GBM Probability Contours

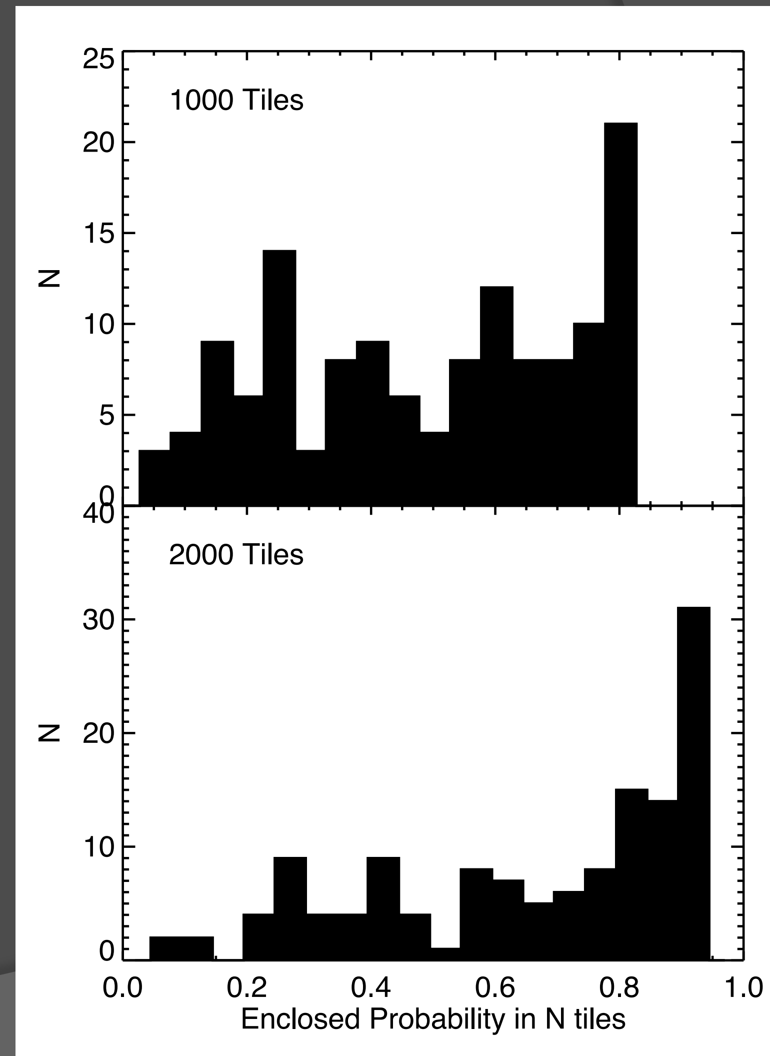




Overlaying XRT Tiles on GBM Probability Contours

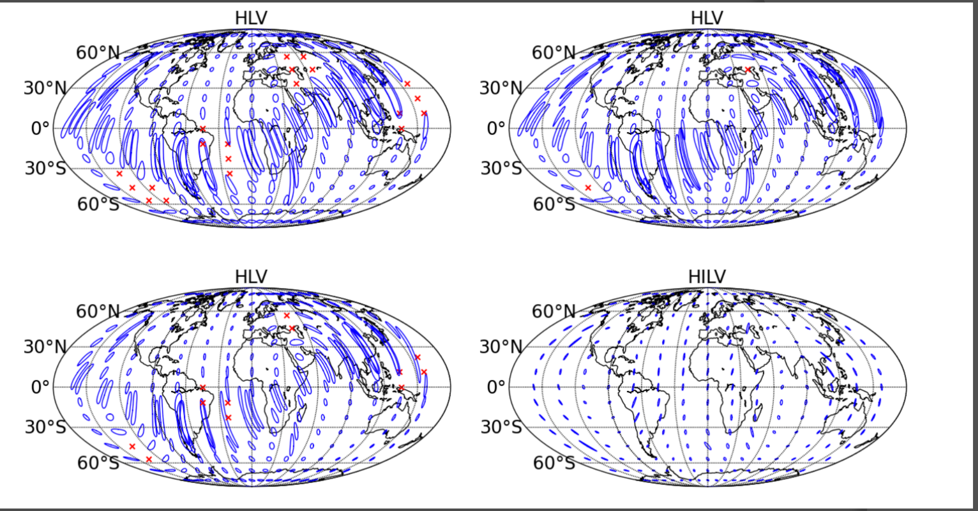
- Enclosed probability within 1000, 2000 tiles
- If 50 s exposures (+slewing, viewing windows, etc.) would take ~2.6 days (1000 tiles) and ~5.2 days (2000 tiles)

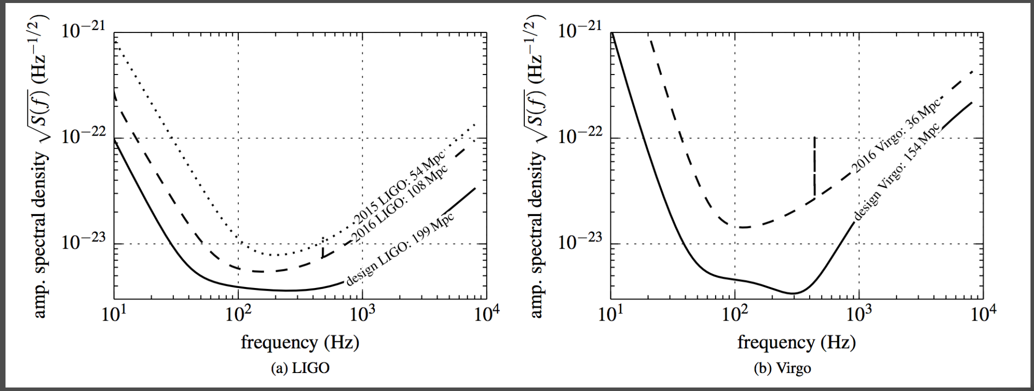




LIGO Localization Probability Contours

- Singer et al. 2014 “The First Two Years of Electromagnetic Follow-up with Advanced LIGO and Virgo”
  - http://www.ligo.org/scientists/first2years/
  - Using bayestar maps
  - 475 in 2016 sample
  - 120 for 2 detectors (HL, HV, LV)
  - 355 for 3 detectors (HLV)





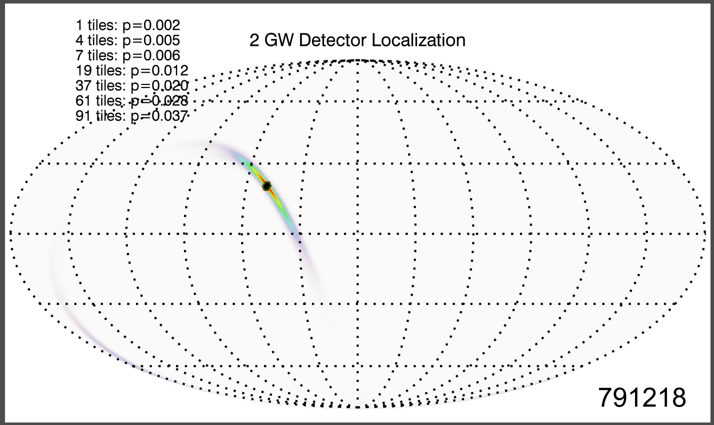
Singer et al. 2014

Epoch	Estimated Run Duration	$E_{GW} = 10^{-2} M_{\odot} c^2$ Burst Range (Mpc) LIGO	Virgo	BNS Range (Mpc) LIGO	Virgo	Number of BNS Detections	% BNS Localized within 5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	2	5 – 12
2017–18	9 months	75 – 90	40 – 50	120 – 170	60 – 85	0.04 – 100	1 – 2	10 – 12
2019+	(per year)	105	40 – 80	200	65 – 130	0.2 – 200	3 – 8	8 – 28
2022+ (India)	(per year)	105	80	200	130	0.4 – 400	17	48

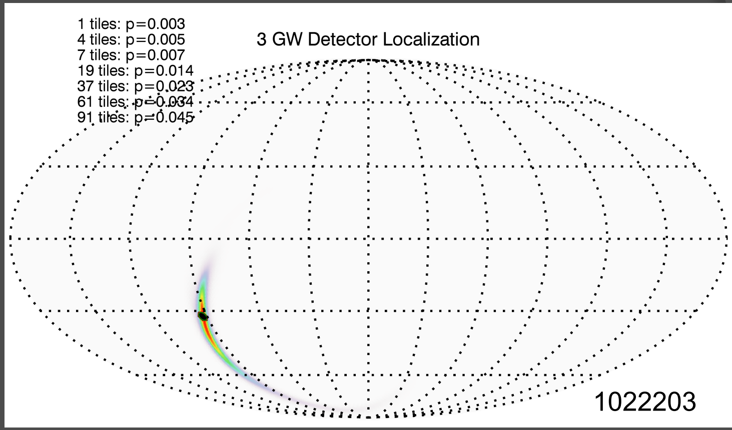
LIGO/Virgo 2013, arXiv:1304.0670

Overlaying XRT Tiles on LIGO Probability Contours

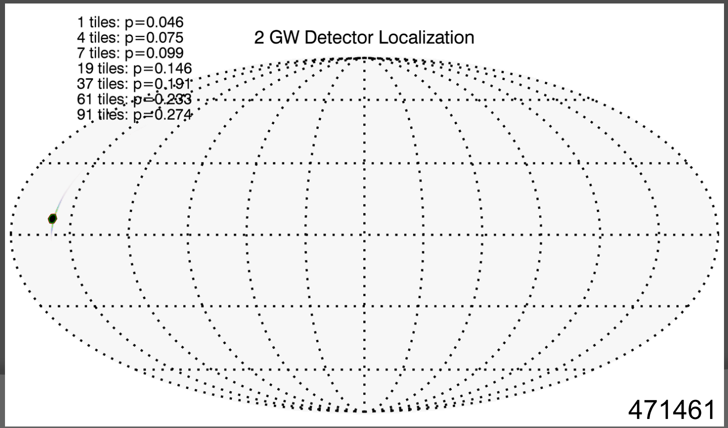
Average (2016) 2 detector LIGO Localization Contour SNR = 14.1



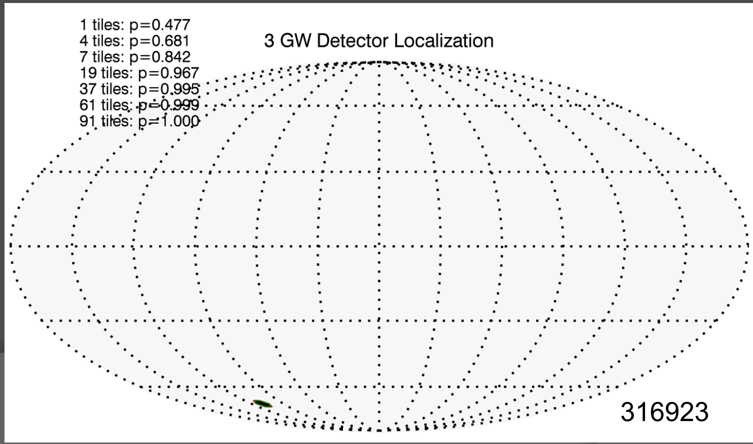
Average (2016) 3 detector LIGO Localization Contour SNR =14.7



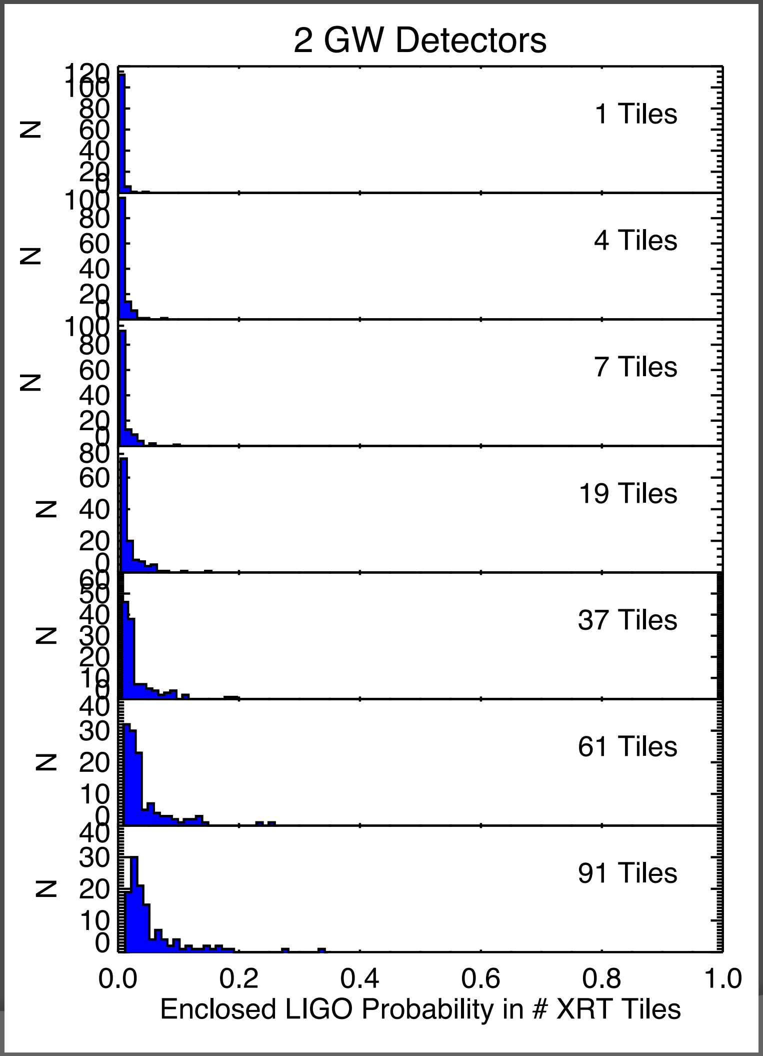
Best Case (2016) 2 detector LIGO Localization Contour SNR = 69.2

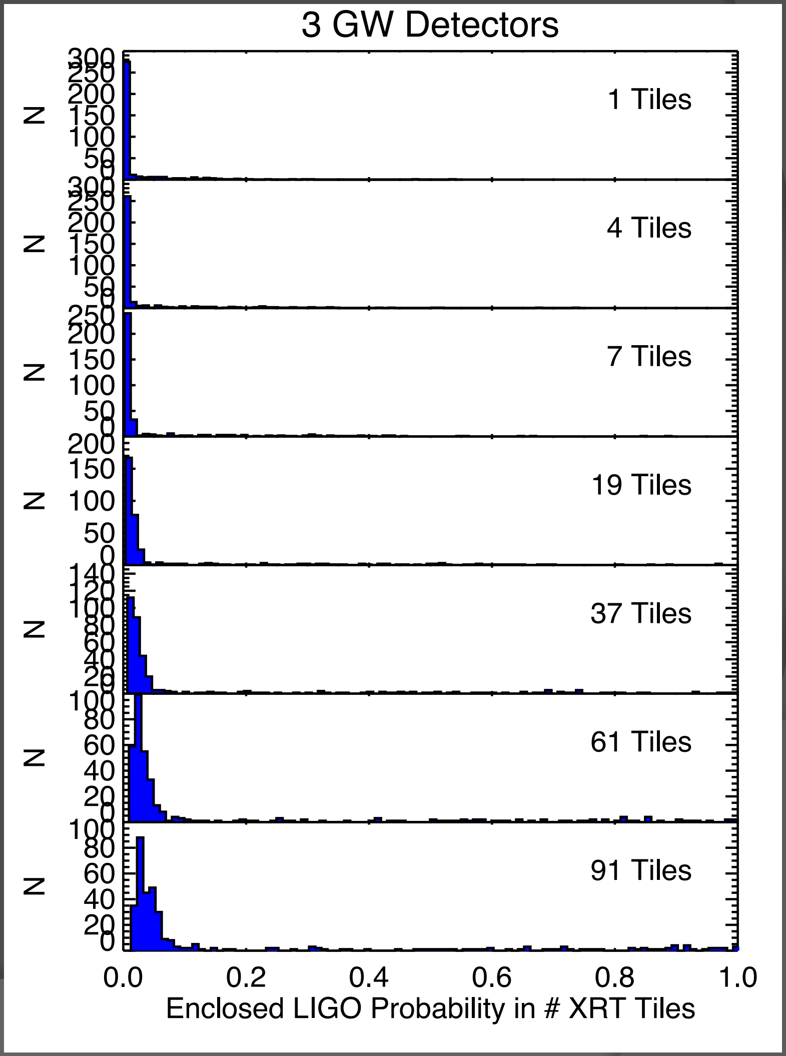


Best Case (2016) 3 detector LIGO Localization Contour SNR = 52.2



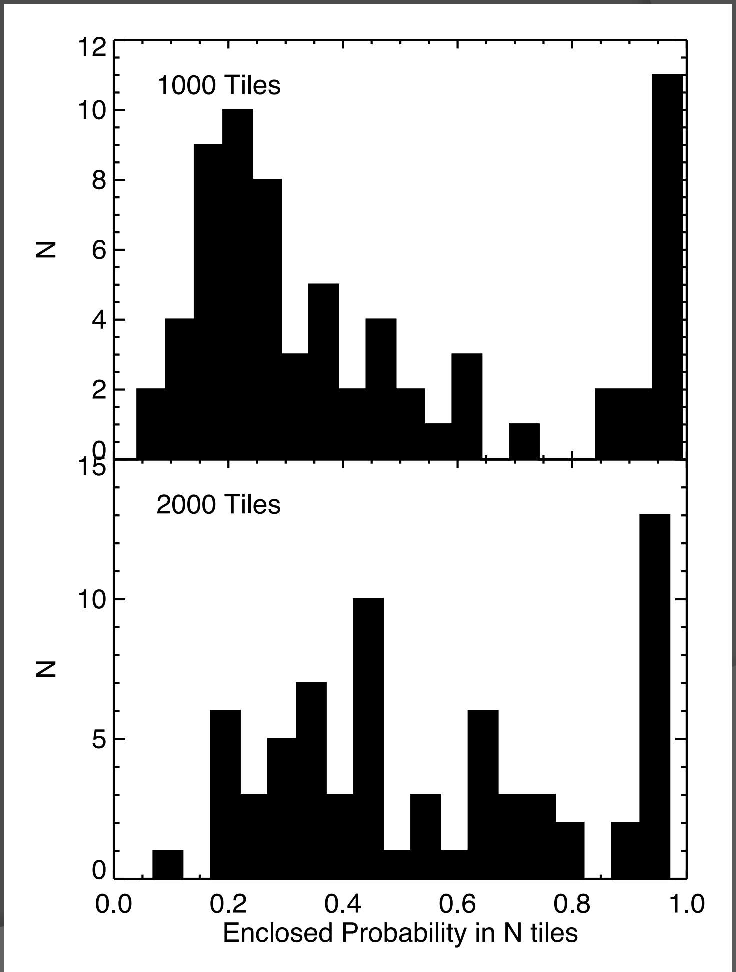
Overlaying XRT Tiles on LIGO Probability Contours



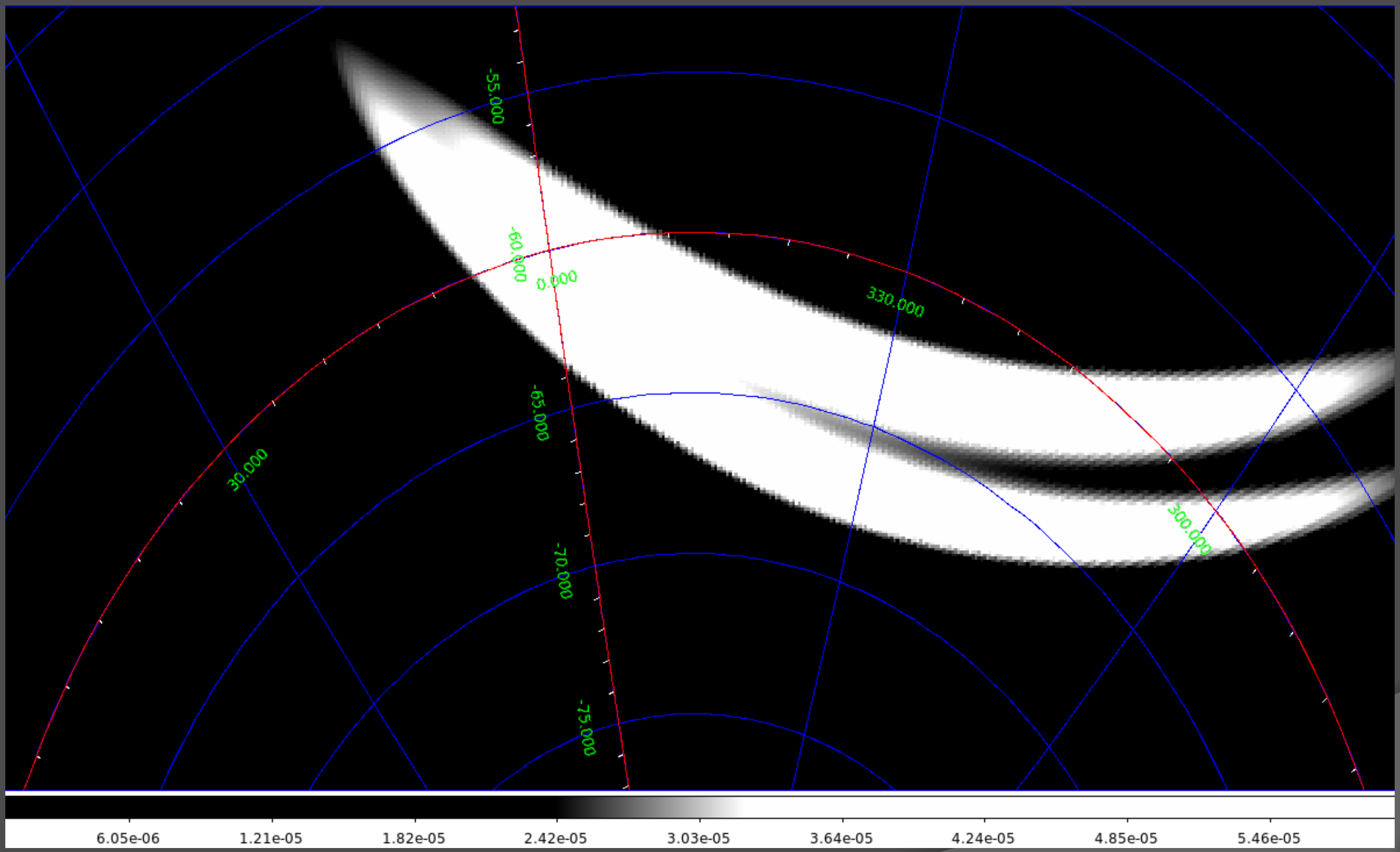


Overlaying XRT Tiles on LIGO/ Virgo Probability Contours

- Enclosed probability within 1000, 2000 tiles
- Would still take days to cover regions, while most short GRB afterglows fade much faster

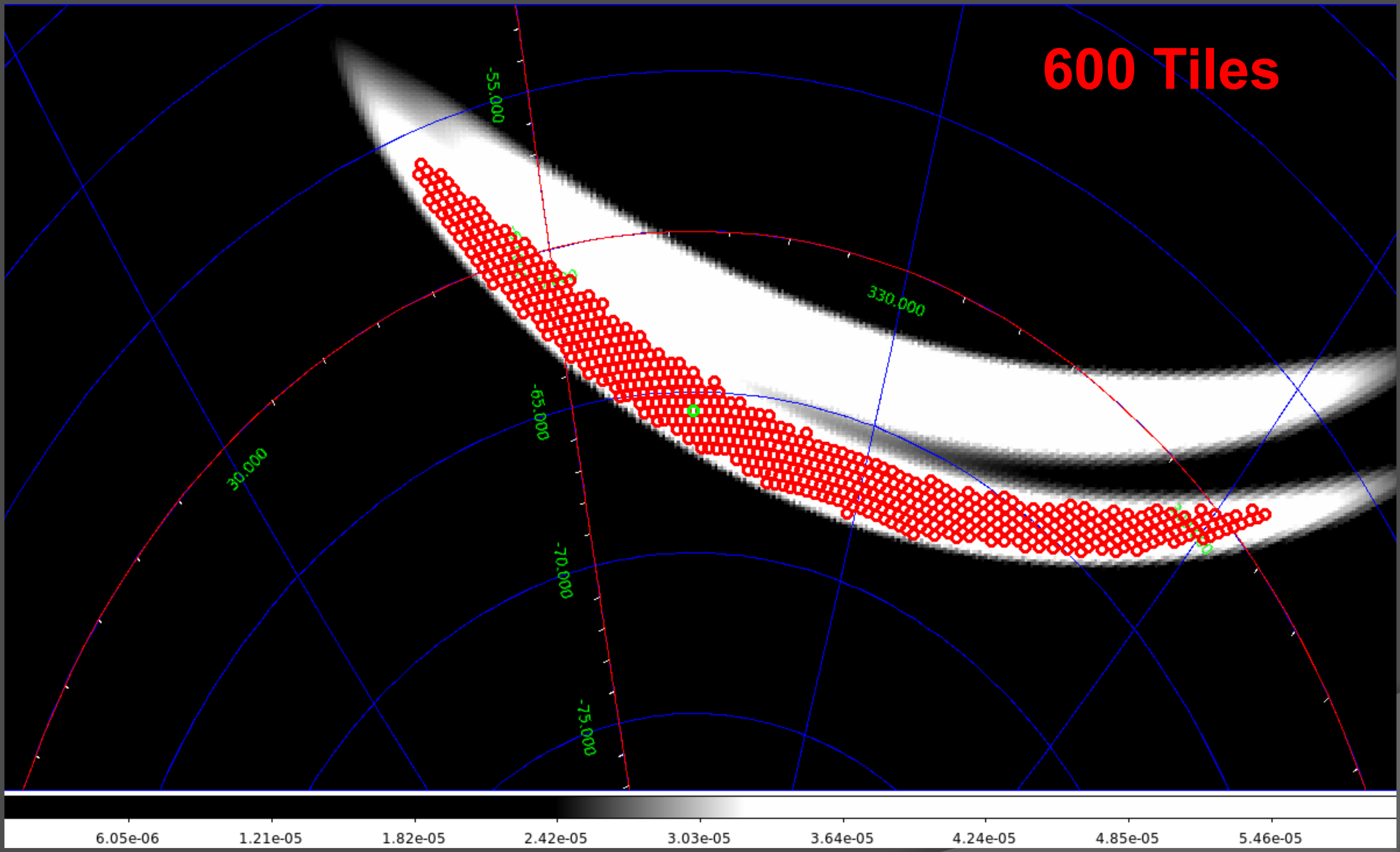


Arbitrary Swift Tile Patterns Applied to LIGO Error Contours



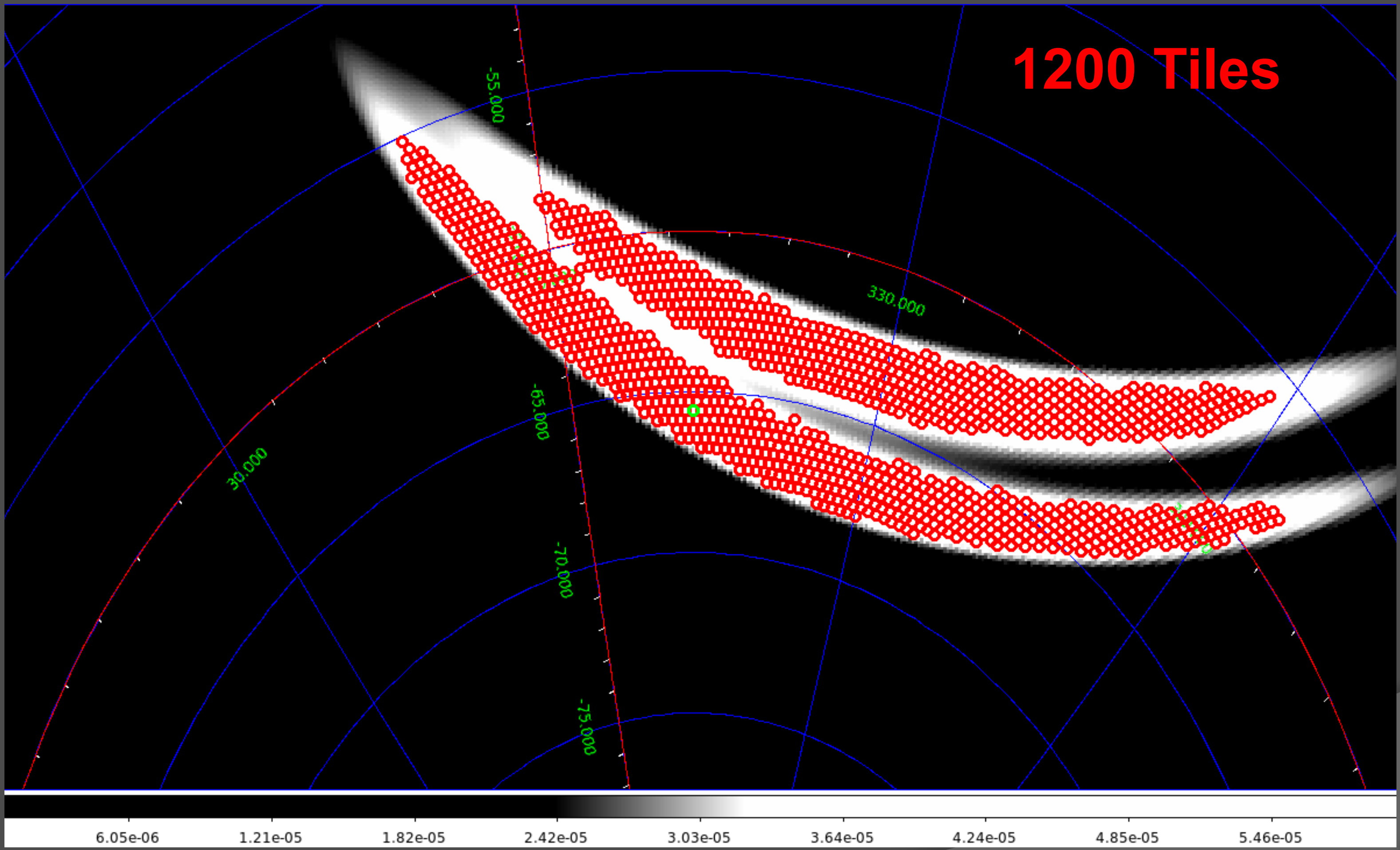
Simulations by Phil Evans

Arbitrary Swift Tile Patterns Applied to LIGO Error Contours



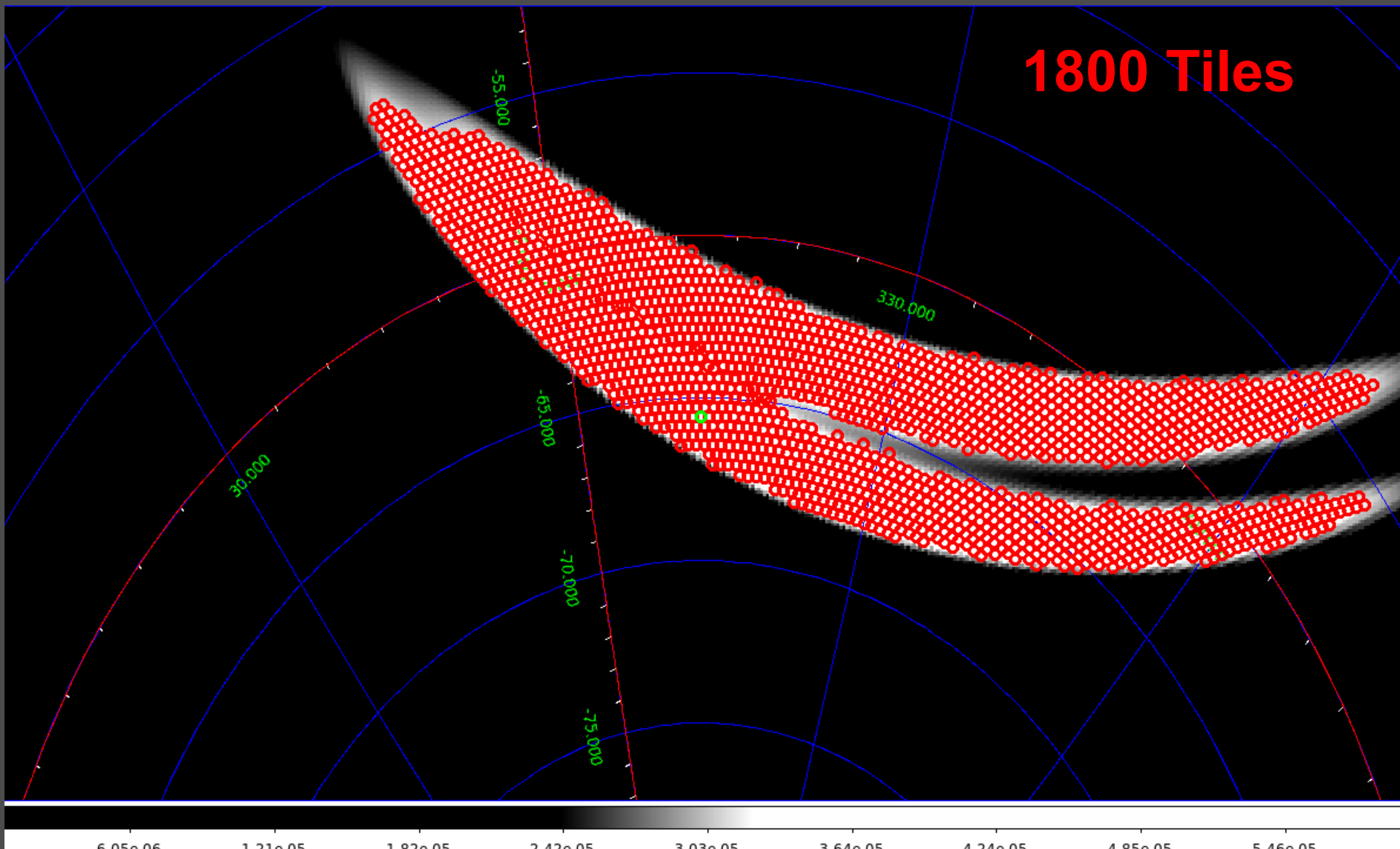
Simulations by Phil Evans

Arbitrary Swift Tile Patterns Applied to LIGO Error Contours



Simulations by Phil Evans

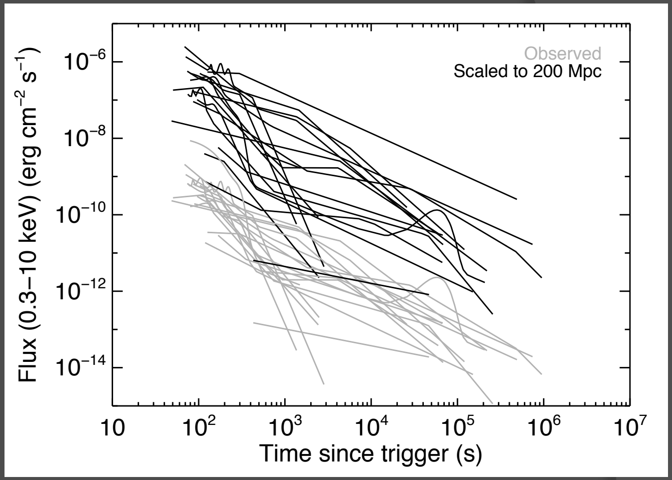
Arbitrary Swift Tile Patterns Applied to LIGO Error Contours

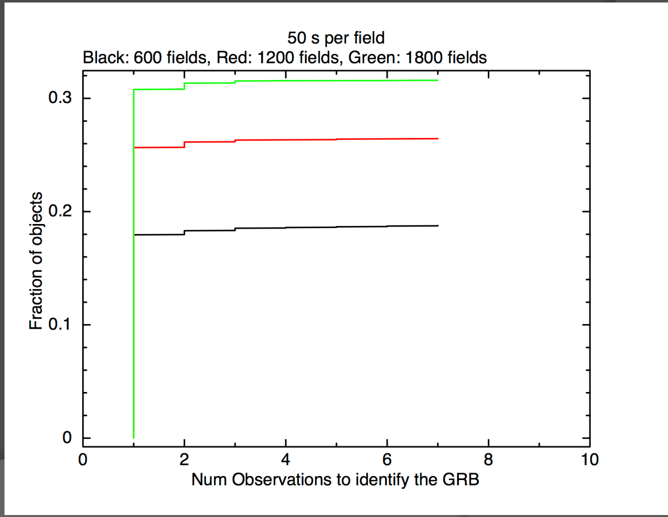


Simulations by Phil Evans

Arbitrary Swift Tile Patterns Applied to LIGO Error Contours

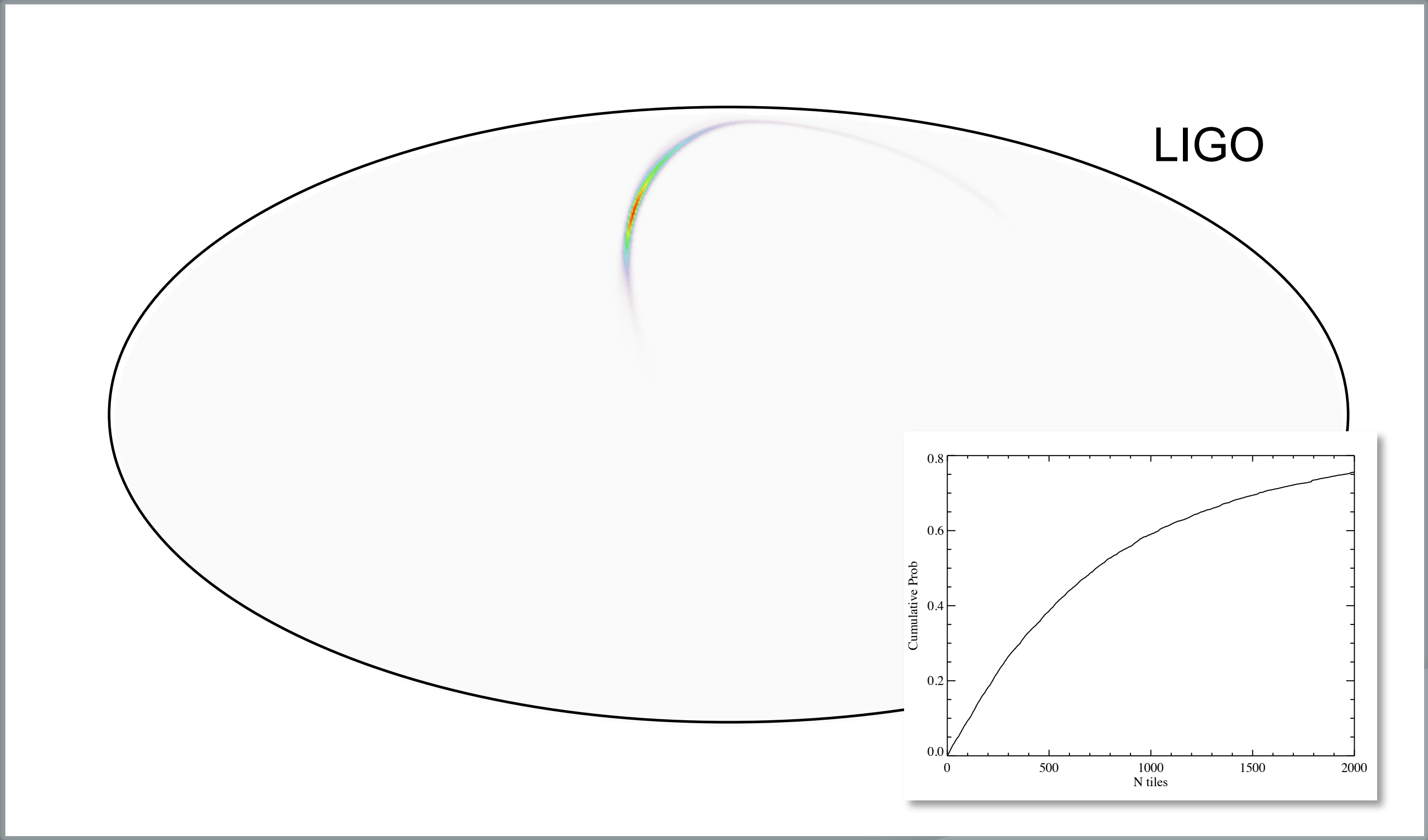
- Simulations
  - Detect a new source and identify it as non-background source
  - Observations start 1-2 hours after burst
  - Swift short GRBs scaled to 200 Mpc (x4000)
  - Best case is 30% chance of afterglow detection
- Many short exposures (~50-100 s) while afterglow is bright are best to maximize detection fraction
- Searching around nearby galaxies cuts down the area substantially, but biases observations (catalogs incomplete)
- Whether Swift can safely conduct such observations is under evaluation



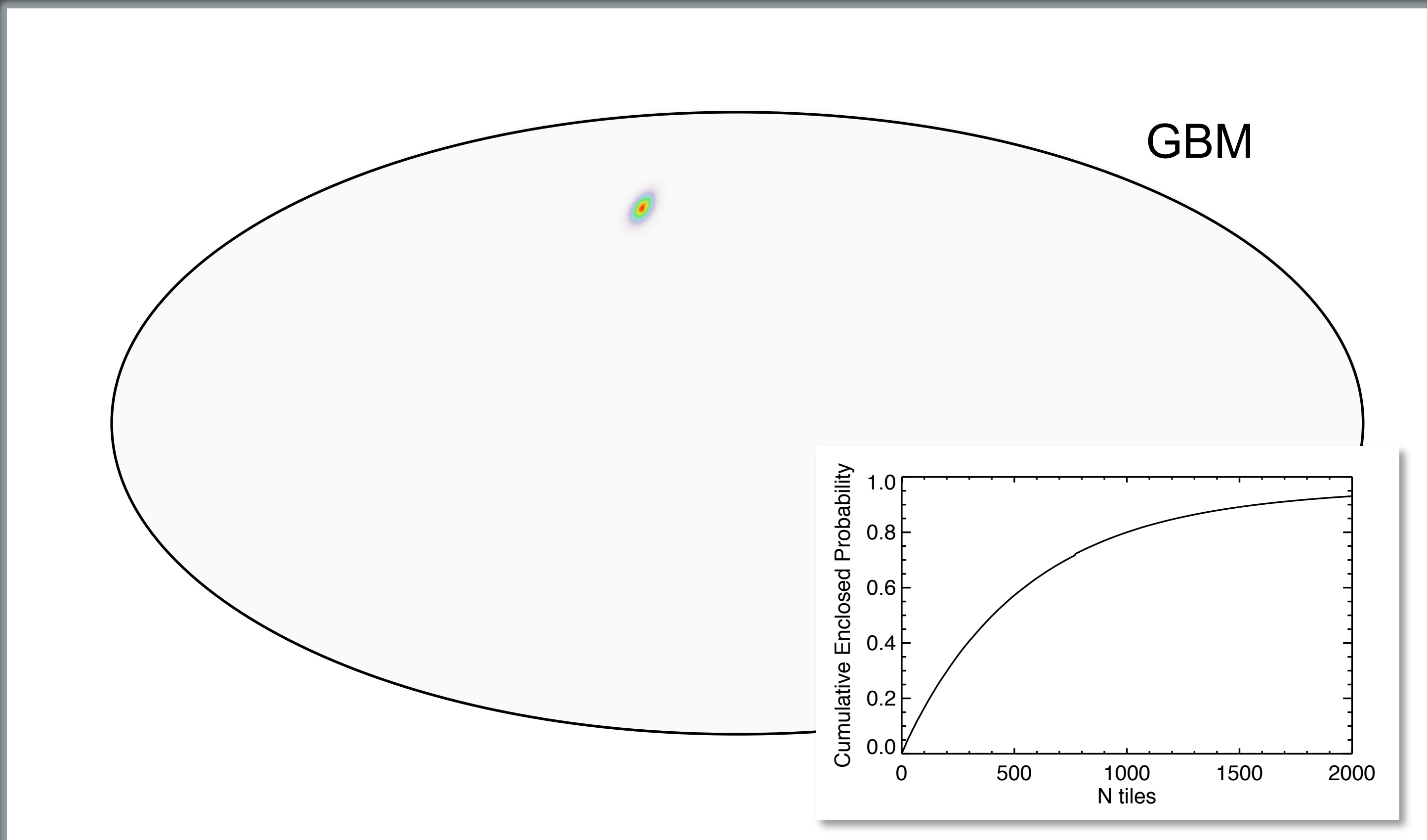


Simulations by Phil Evans

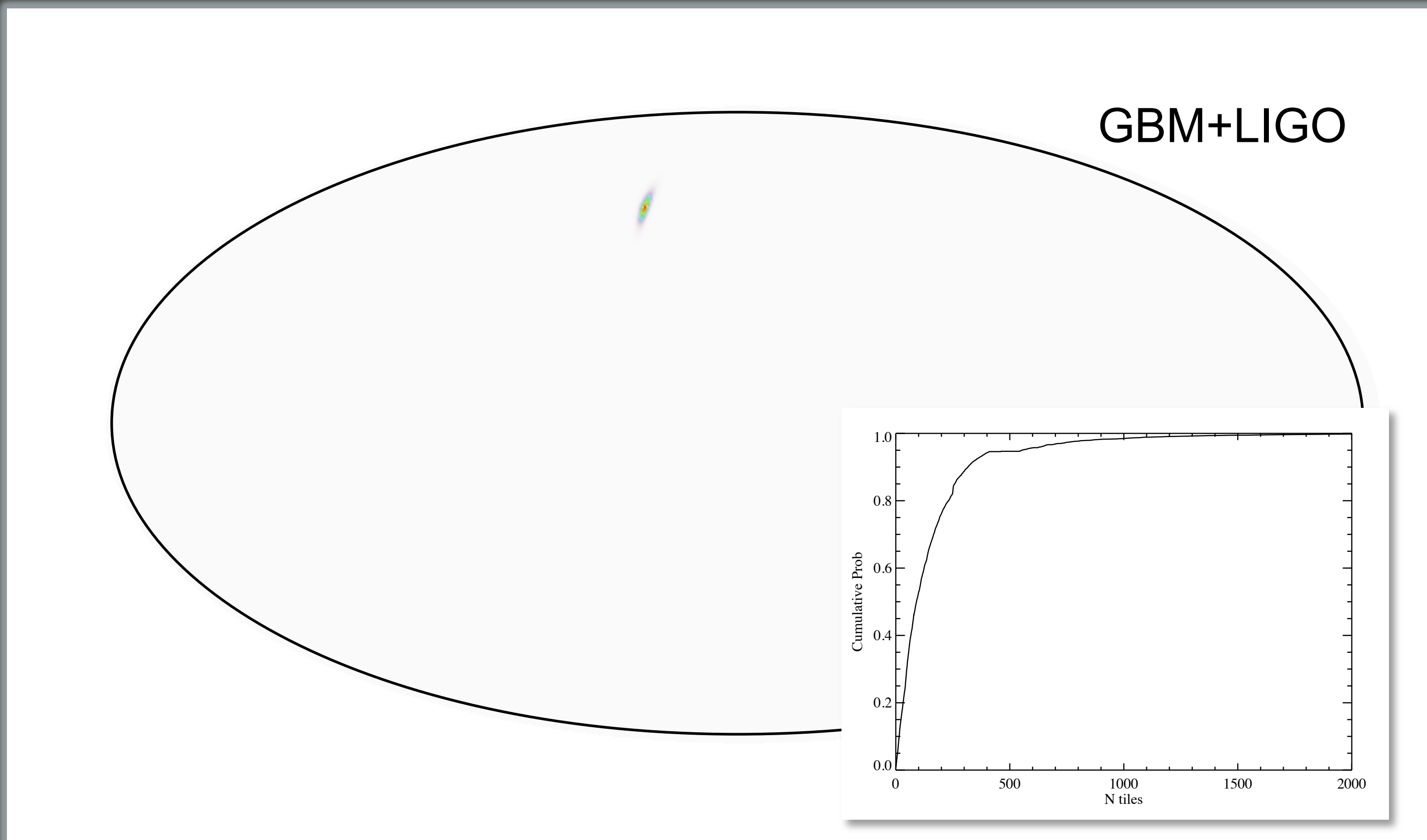
Intersection of GBM + advanced LIGO/Virgo error regions



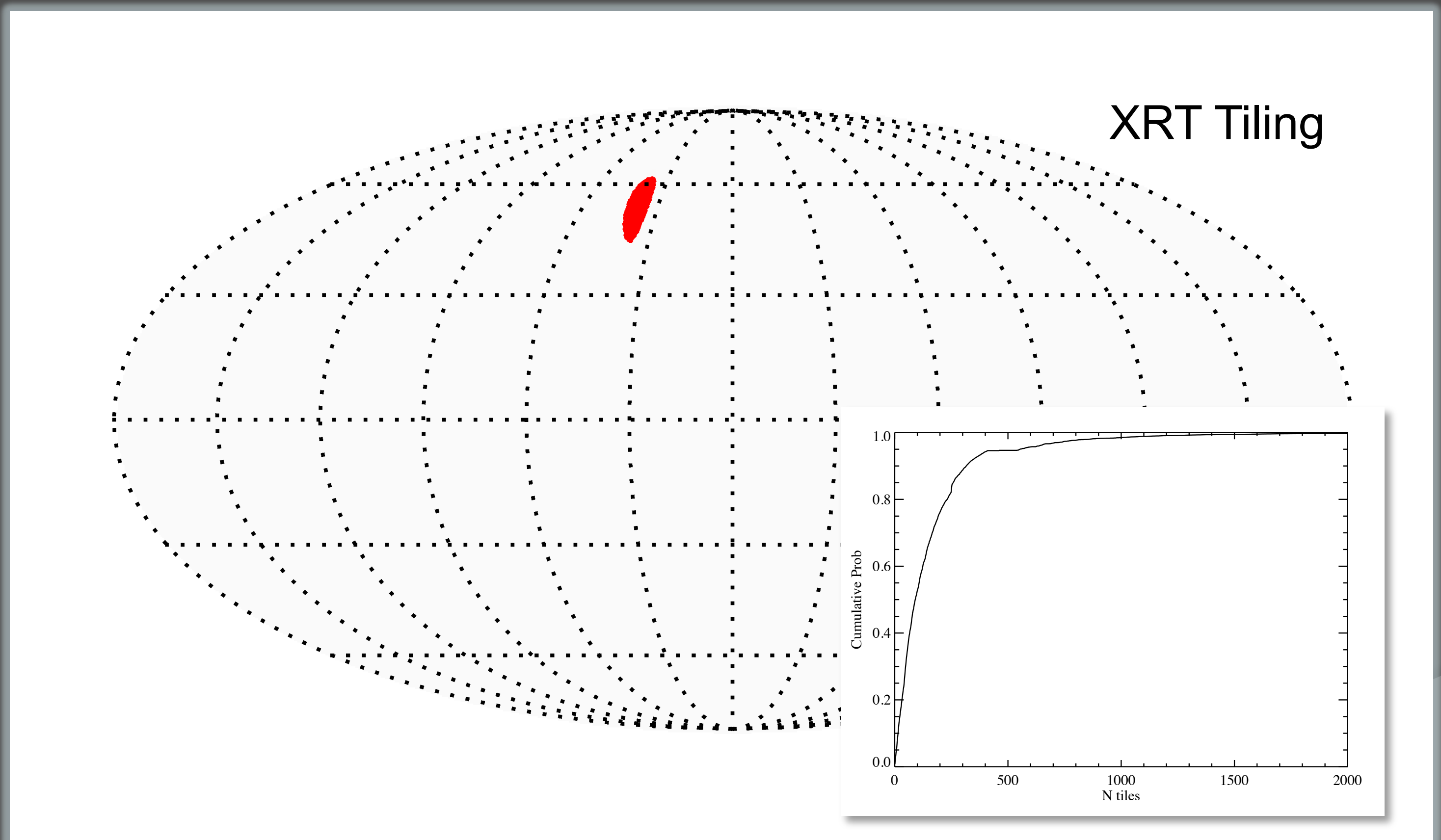
Intersection of GBM + advanced LIGO/Virgo error regions



Intersection of GBM + advanced LIGO/Virgo error regions



Intersection of GBM + advanced LIGO/Virgo error regions



Trade-offs to investigate

- Longer exposures give us greater sensitivity (we can detect fainter afterglows), but means it takes longer to reach the field containing the GRB.
- Targeting only galaxies within the LIGO error, rather than the entire error, dramatically reduces the area we need to cover, but also means that we will miss GRBs in galaxies not in the catalogue.

To understand the impacts of these trade-offs and determine the “best” strategy, we will use simulations.

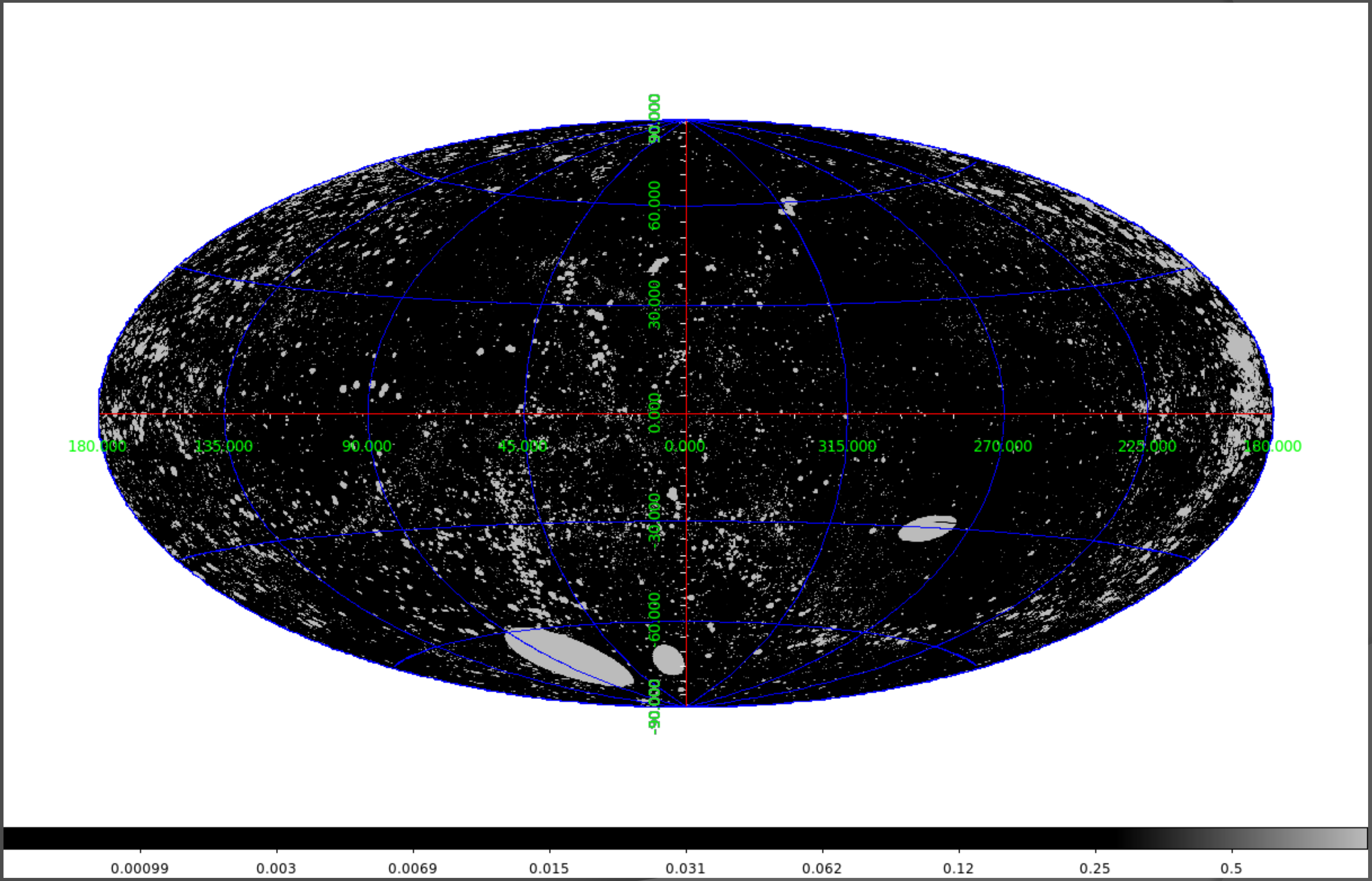
Slides from Phil Evans

Simulation approach

- Use the “LIGO 2 year” simulations from Leo Singer, but correct so that the GRBs may be in known galaxies, based on the completeness of the galaxy catalogue.
- Build a list of XRT fields to cover the most probable parts of the error circle (this may not contain the GRB).
- Choose GRB template, time to observe at random.
- Select random day/time for trigger, and build REAL Swift observing windows (using TAKO settings, not AT)
- Create an observing strategy, and observe.
  - Initially, observe most probable field visible
  - If possible choose an overlapping field next, the most probable one.
  - Otherwise, slew to the most probable field we can observe (or wait until we can observe something, if all fields are in eclipse).

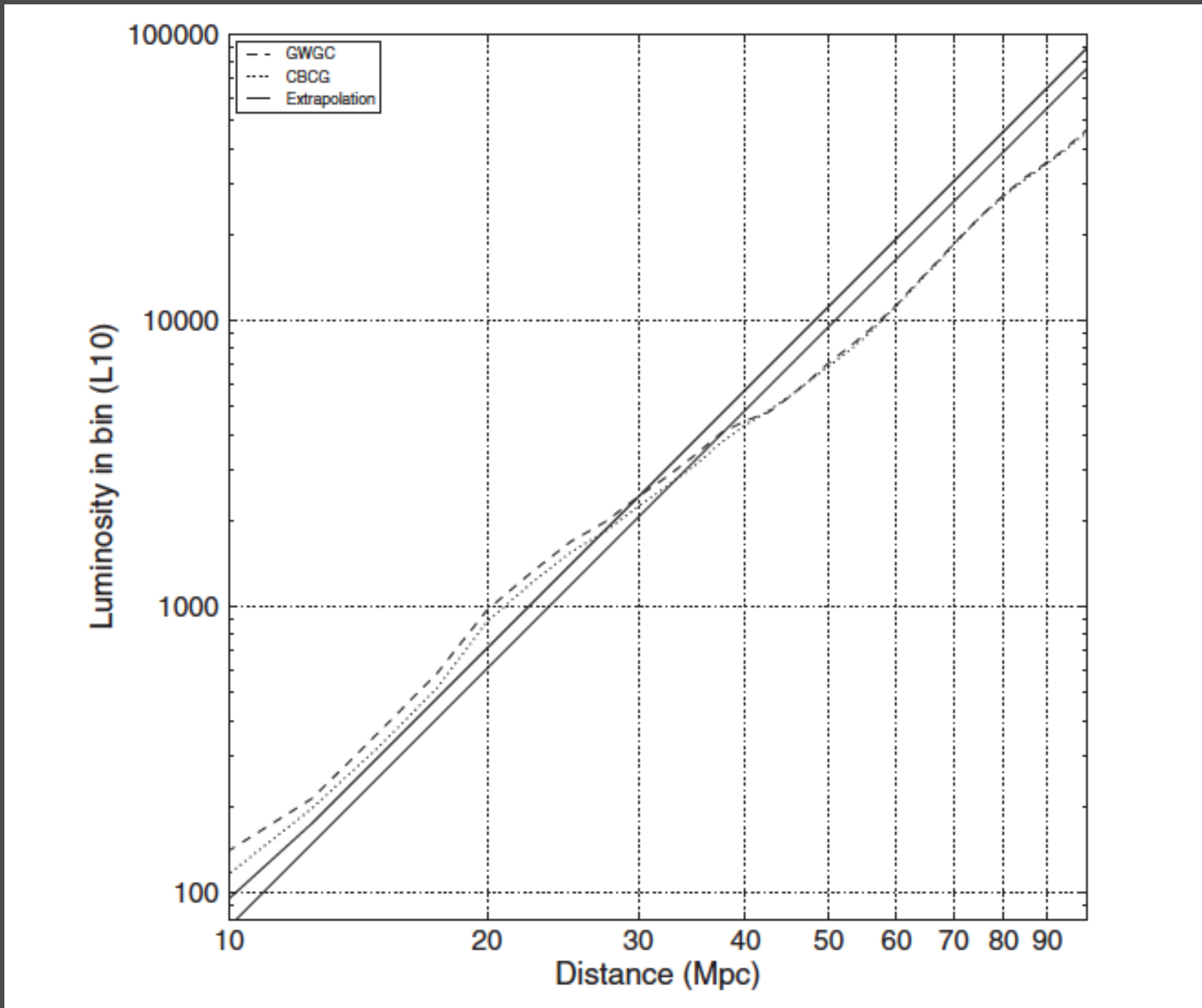
Slides from Phil Evans

Galaxy targeting



Slides from Phil Evans

Galaxy targeting - completeness



40 Mpc = 100% complete

50 Mpc = 70% complete

60 Mpc = 65% complete

70 Mpc = 65% complete

80 Mpc = 60% complete

90 Mpc = 58% complete

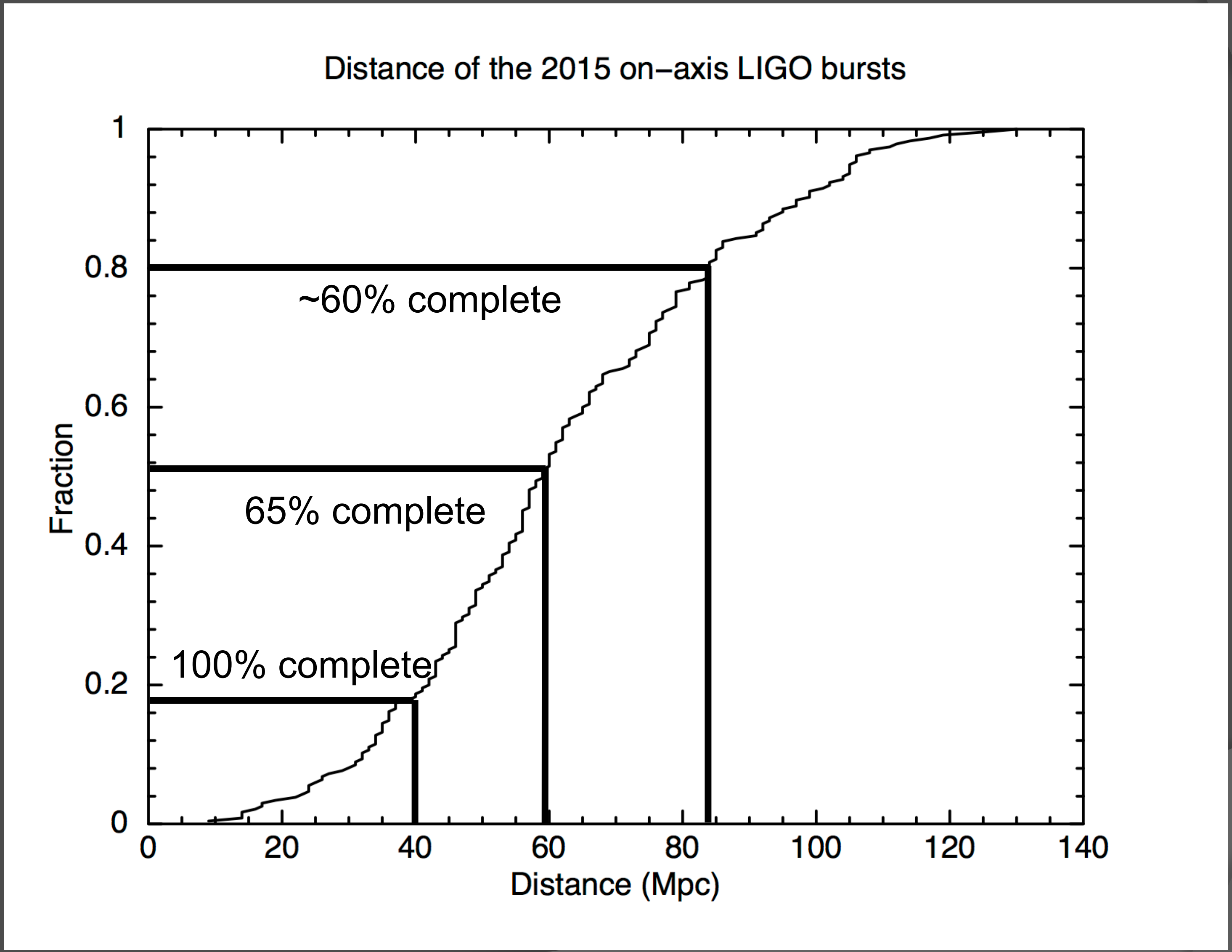
100 Mpc = 55% complete

Based on the BLUE luminosity

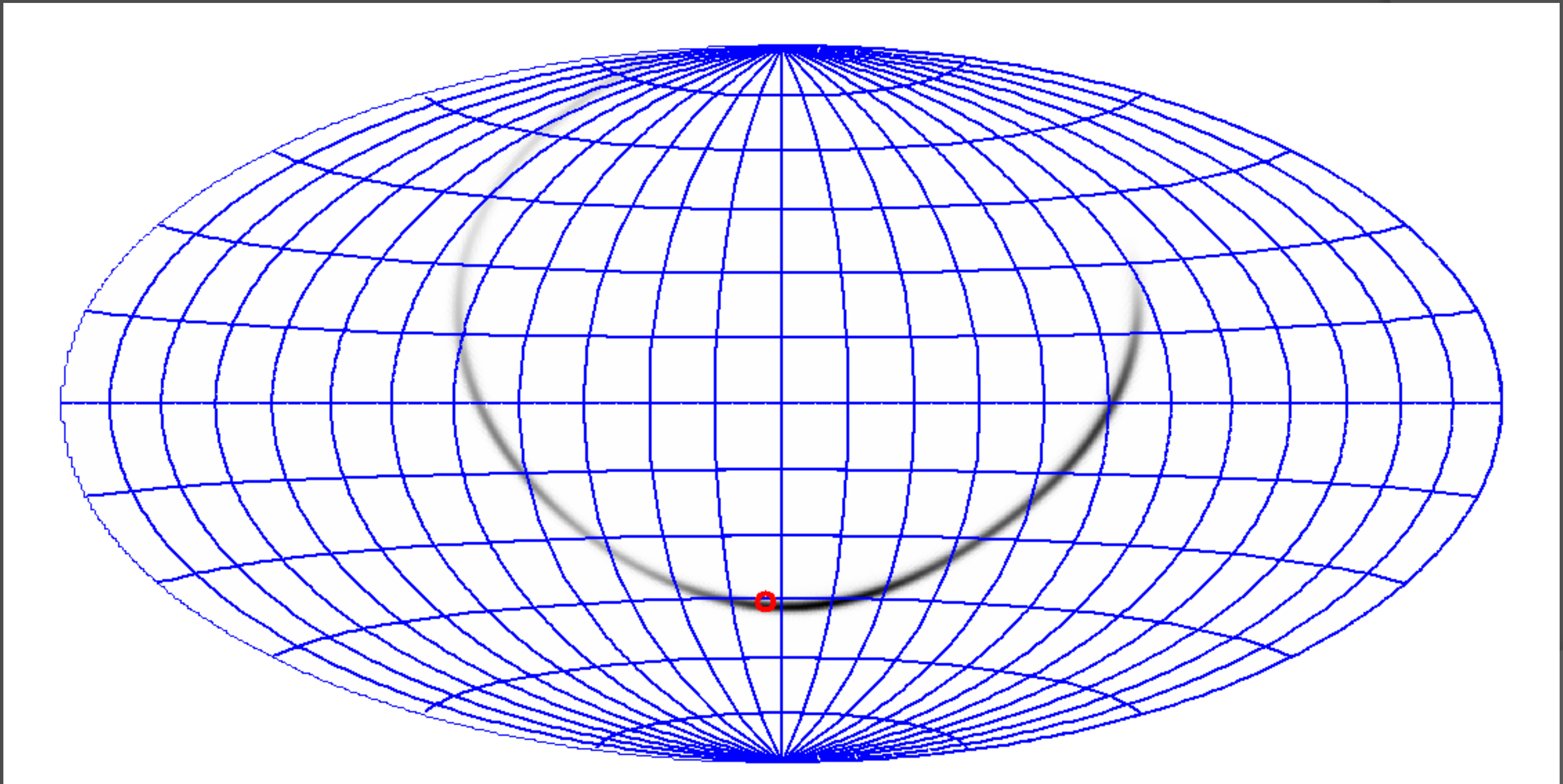
White, Daw & Dhillon, CQGra, 28, 085016

Slides from Phil Evans

Galaxy targeting - caveats

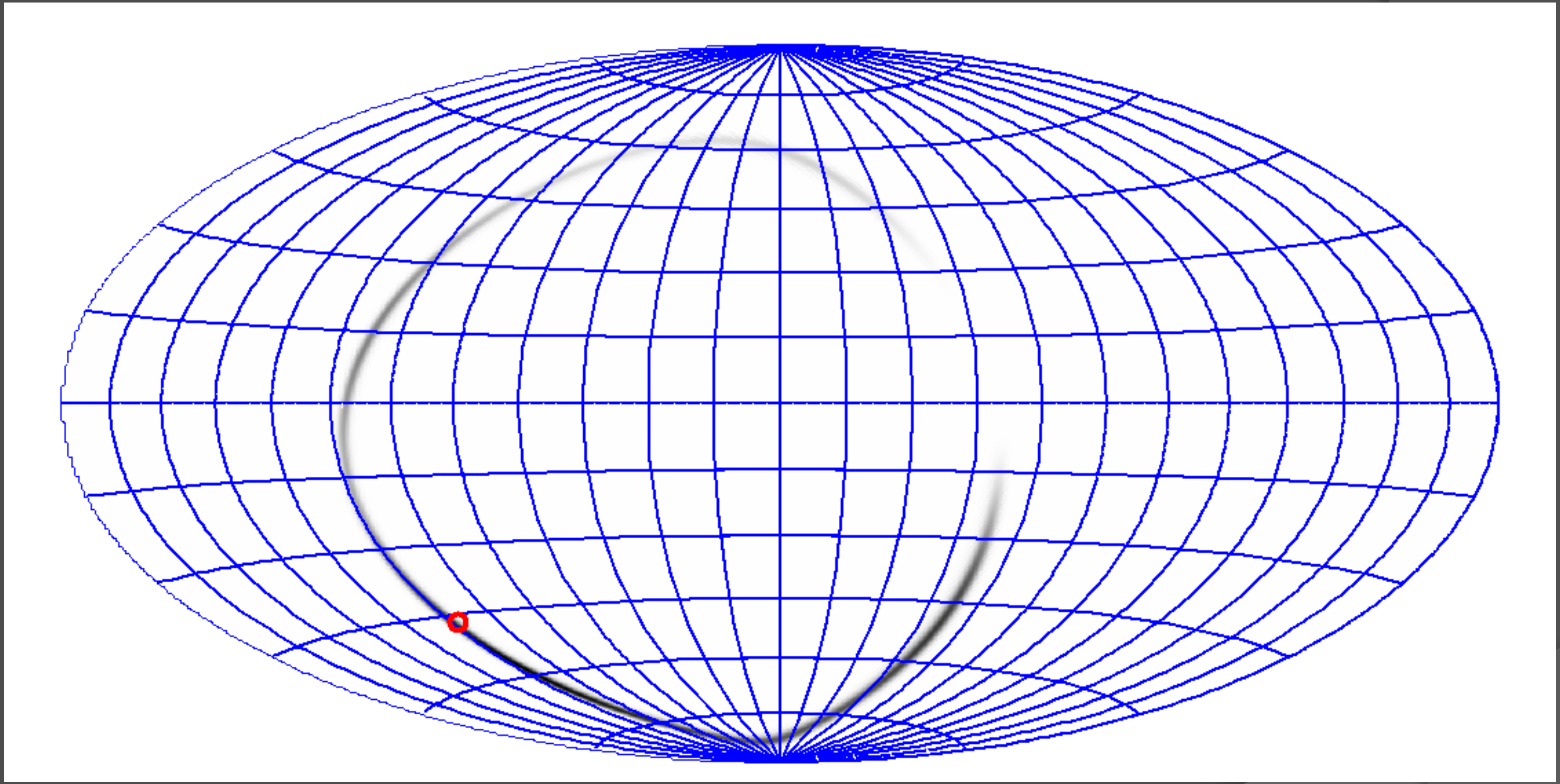


Example simulation



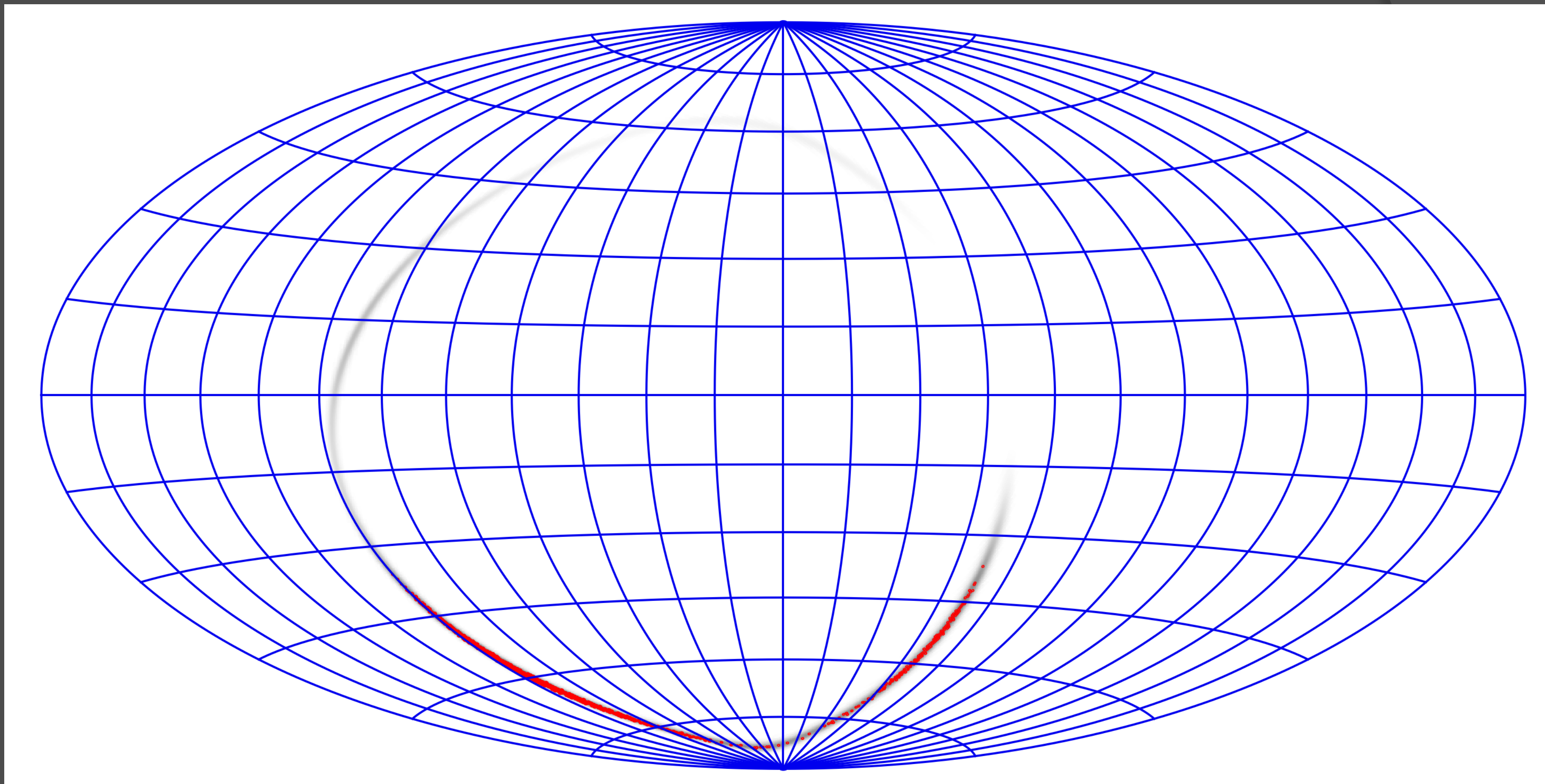
Original simulation

Example simulation



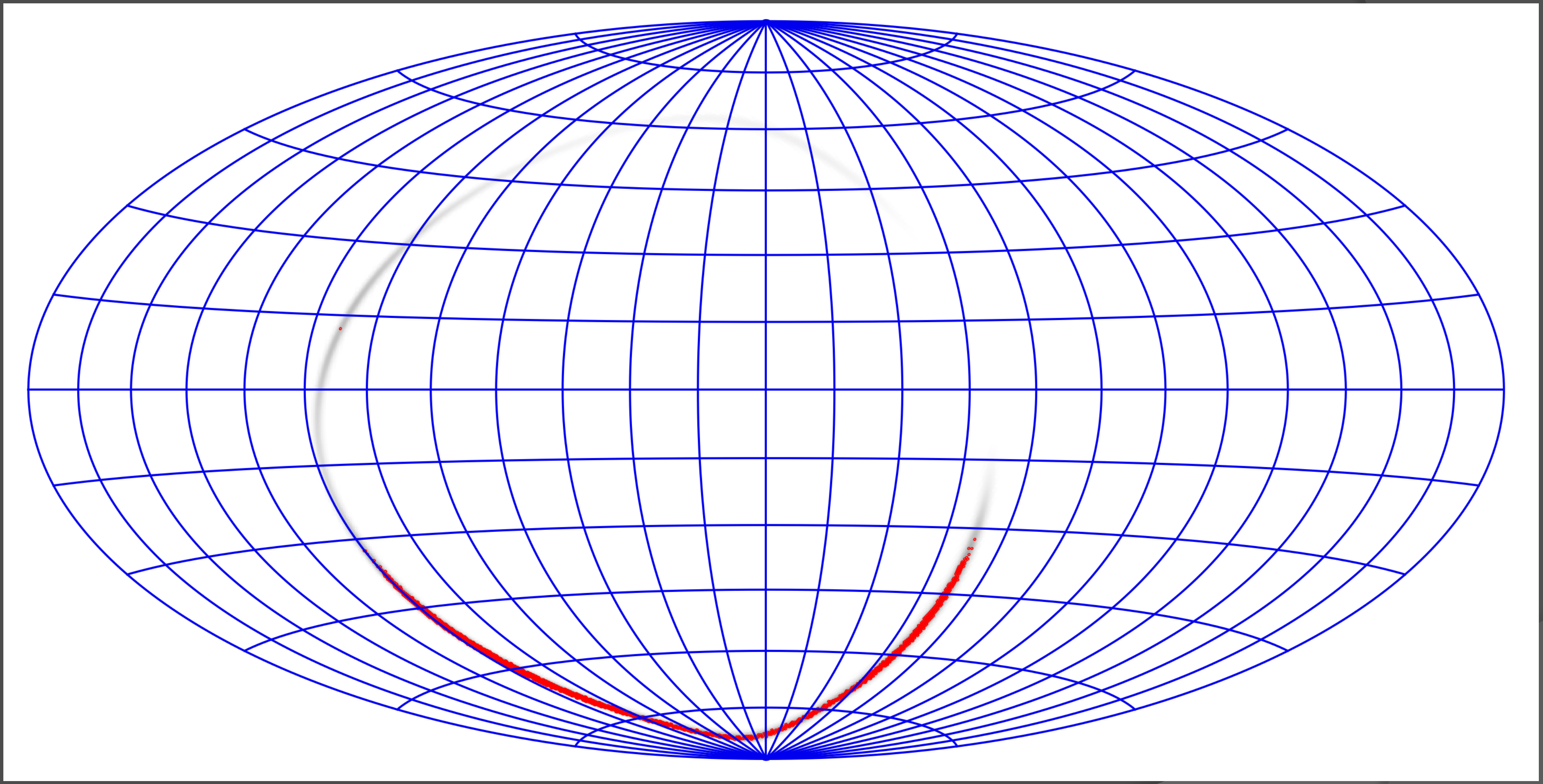
Shifted to a galaxy

Example simulation



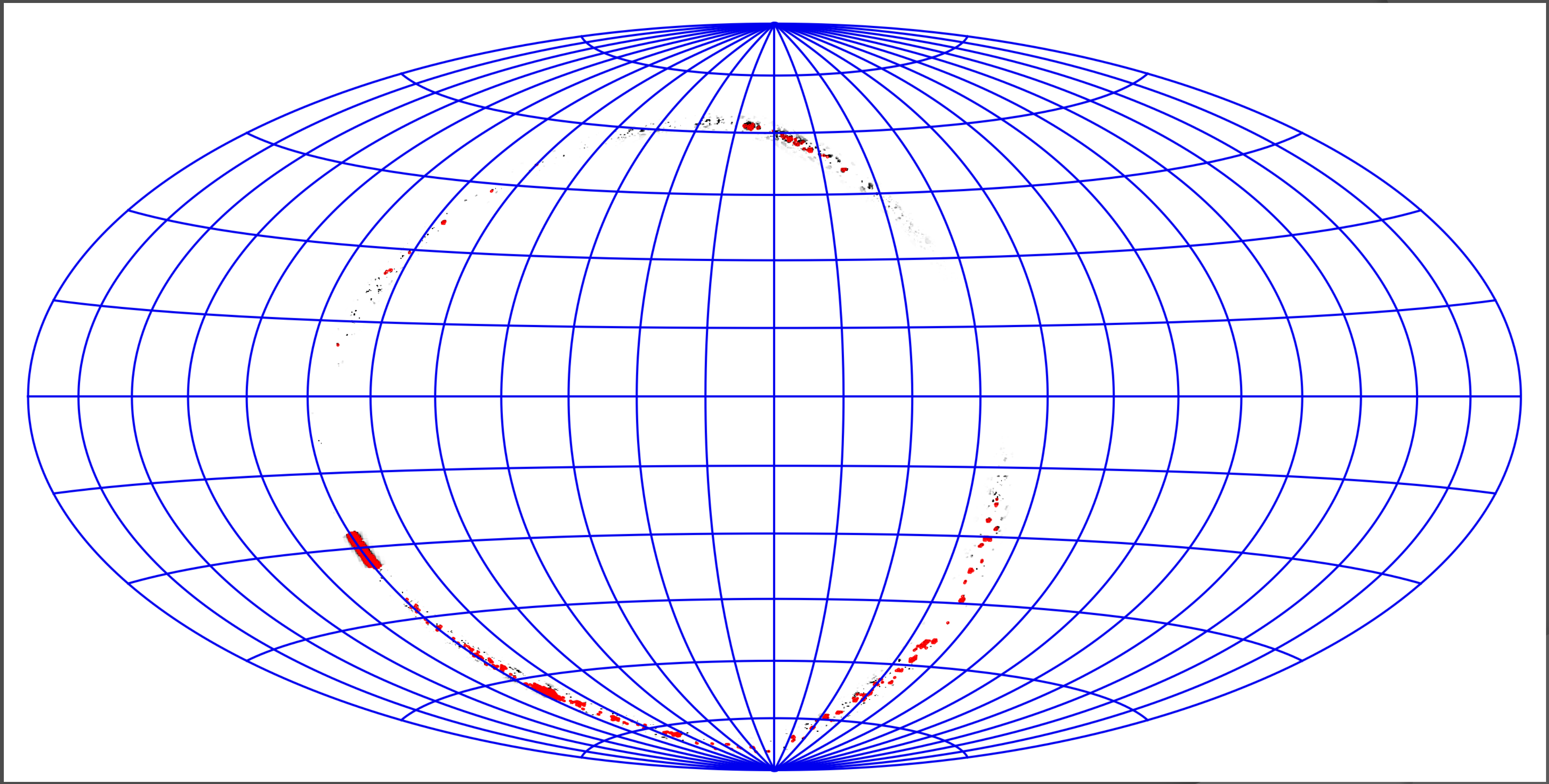
600 XRT fields

Example simulation



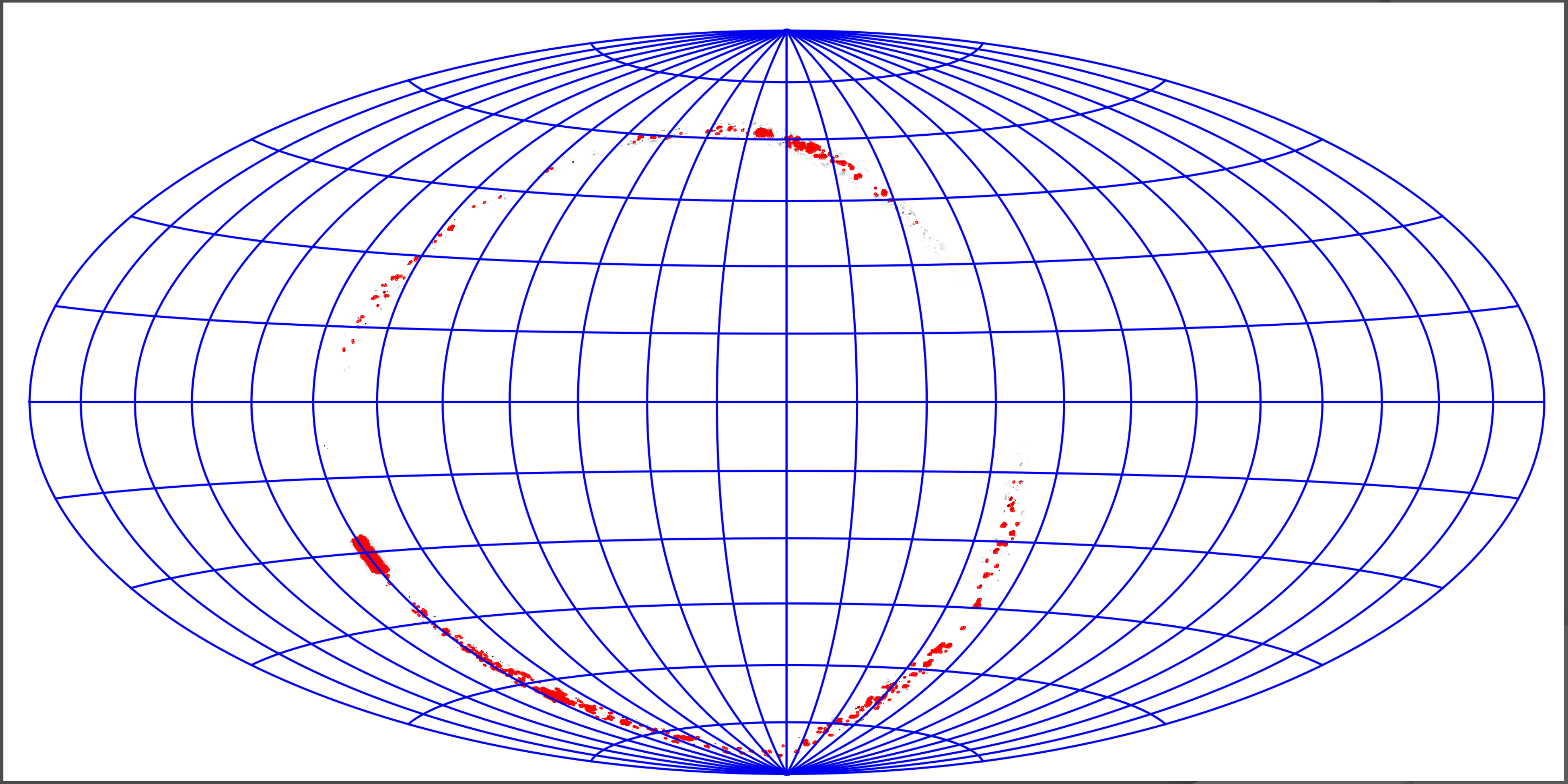
1200 XRT fields

Example simulation



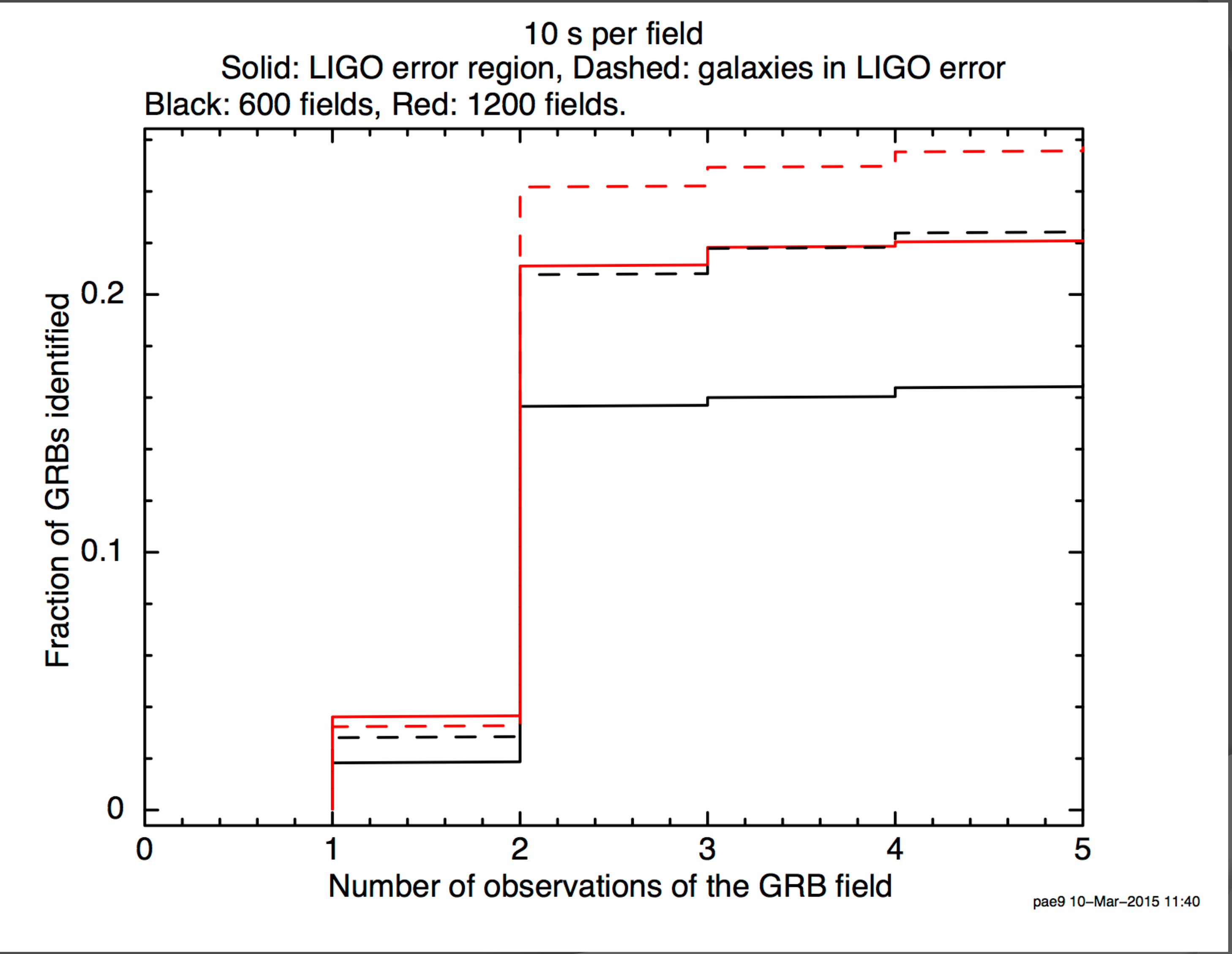
600 XRT fields, targeting galaxies

Example simulation



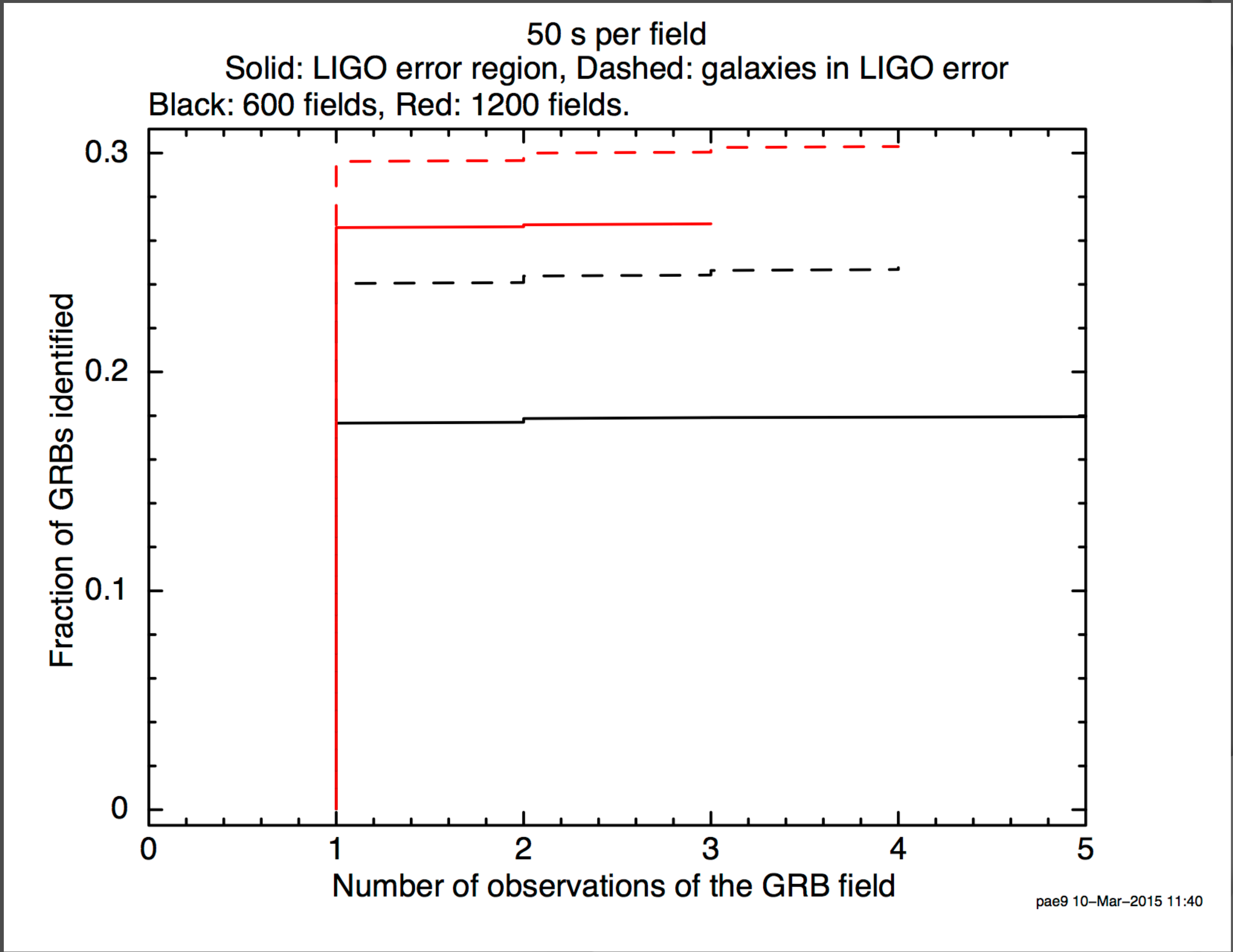
1200 XRT fields, targeting galaxies

Results



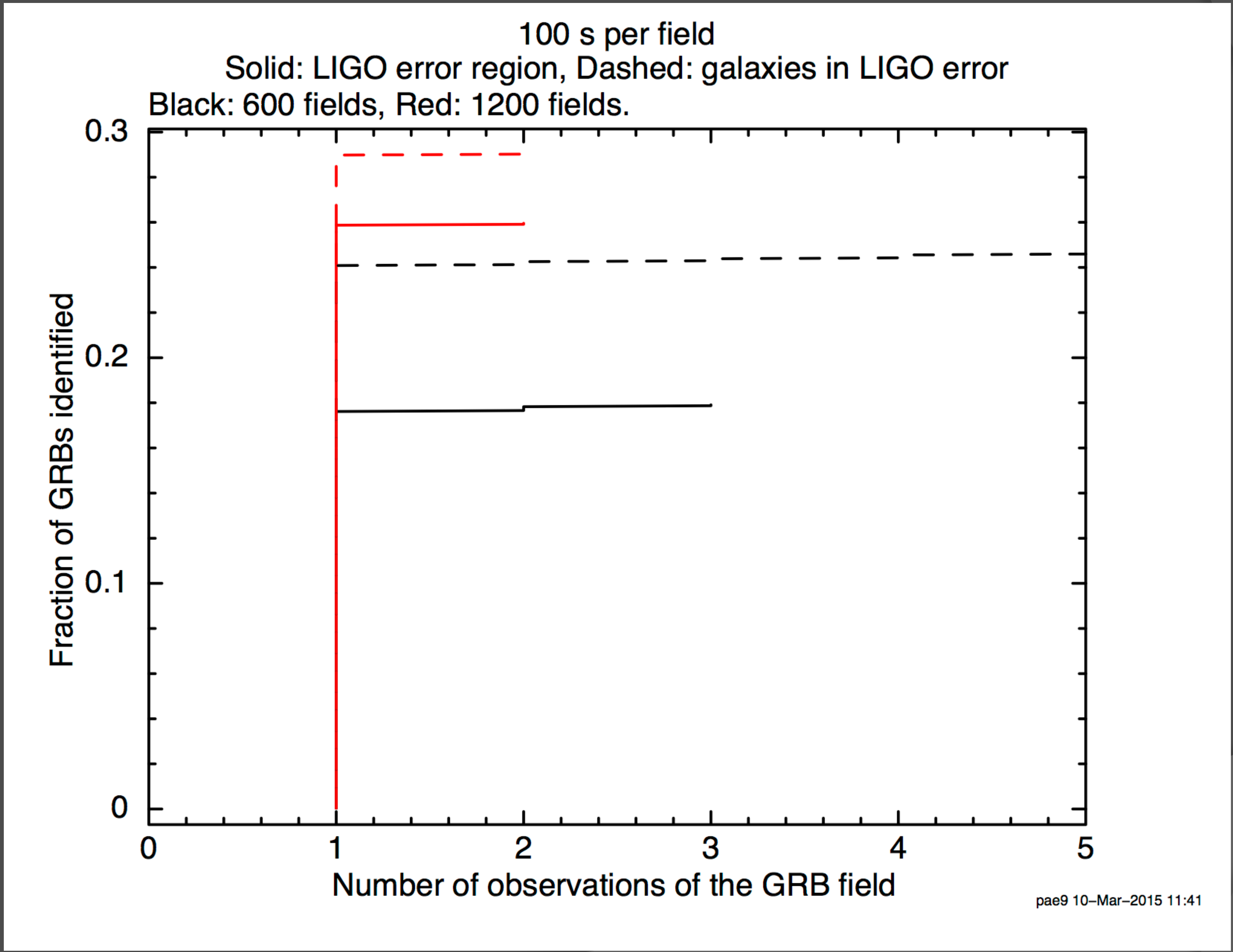
Slides from Phil Evans

Results



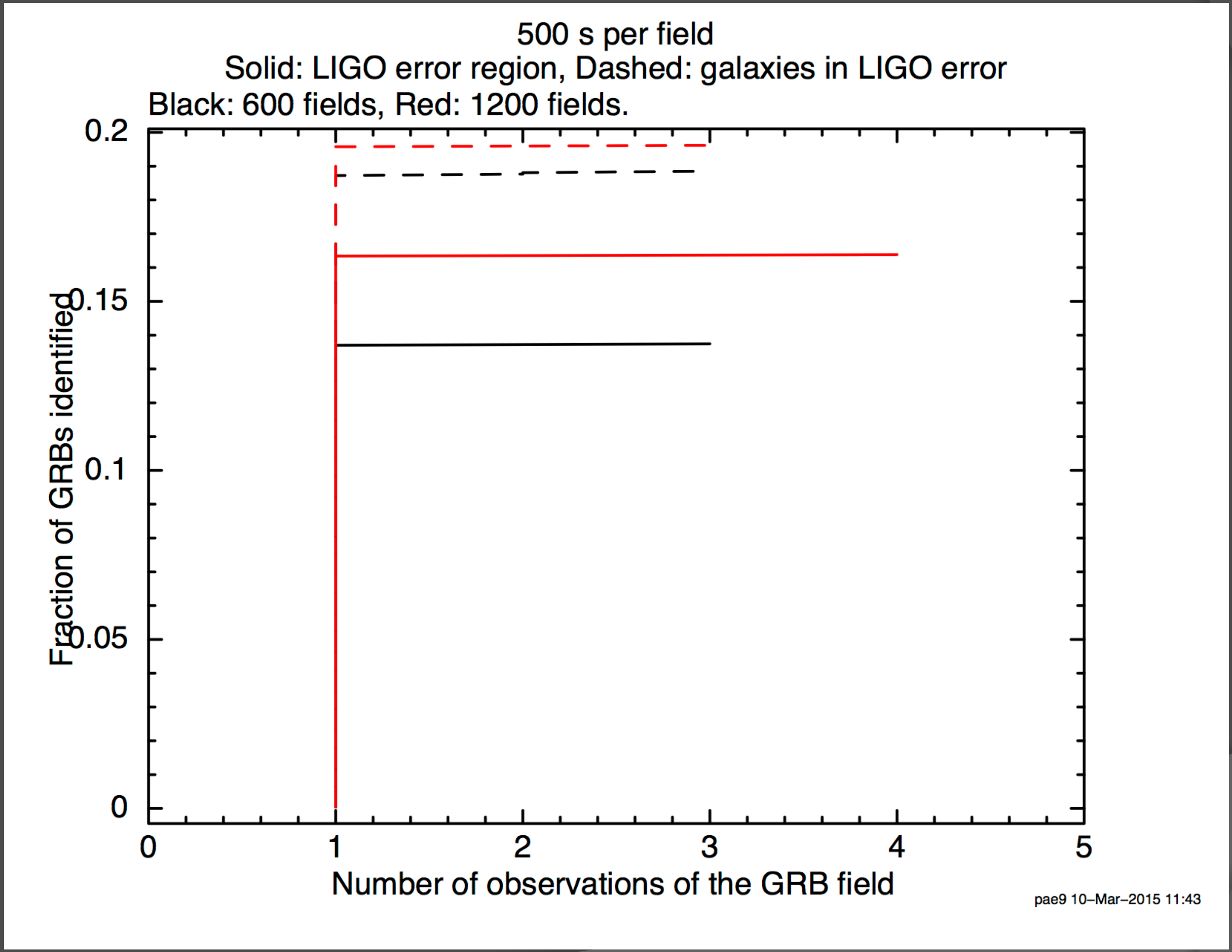
50 s per field
Solid: LIGO error region, Dashed: galaxies in LIGO error
Black: 600 fields, Red: 1200 fields.
Fraction of GRBs identified
0.3
0.2
0.1
0
0
1
2
3
4
5
Number of observations of the GRB field
pae9 10–Mar–2015 11:40

Results

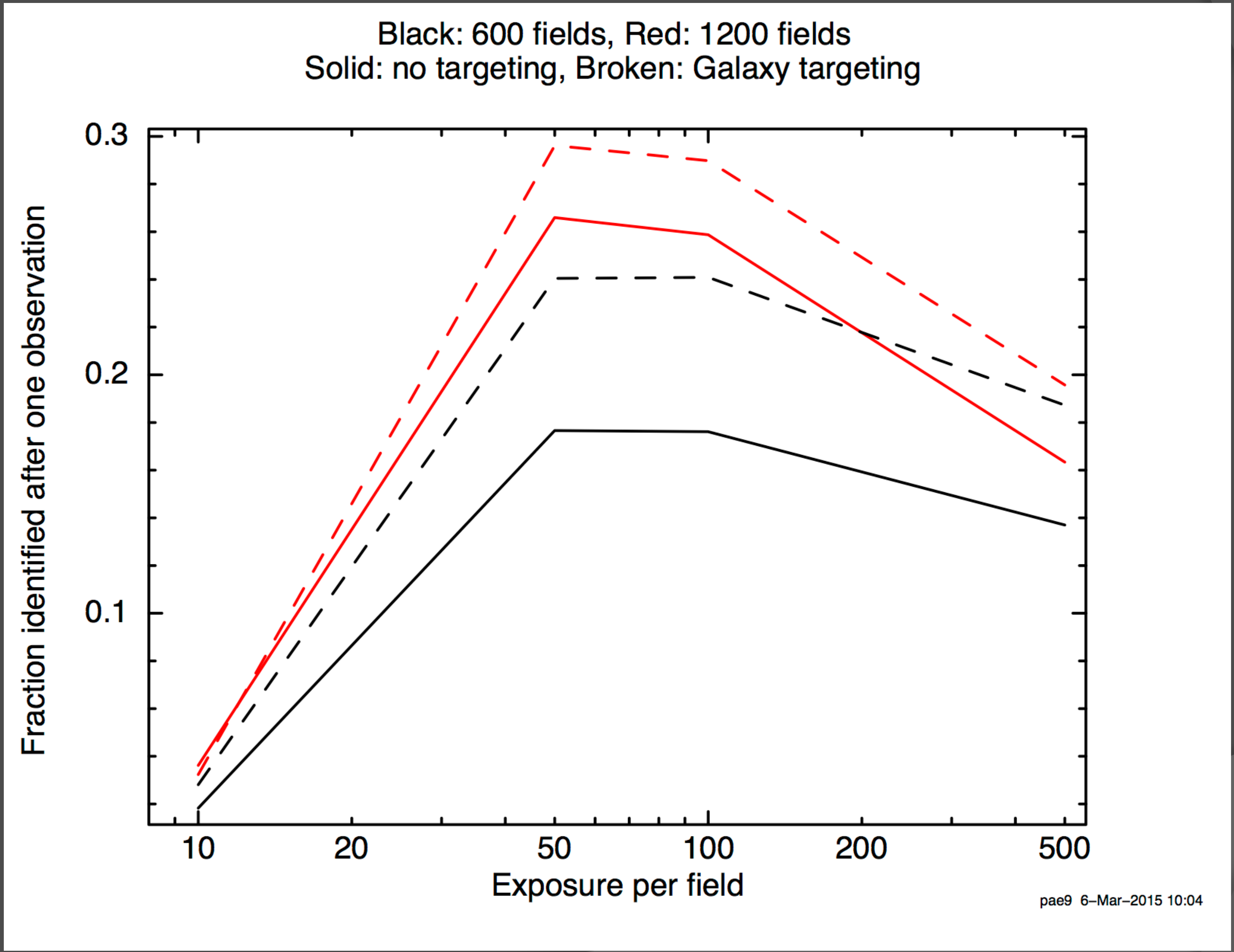


Slides from Phil Evans

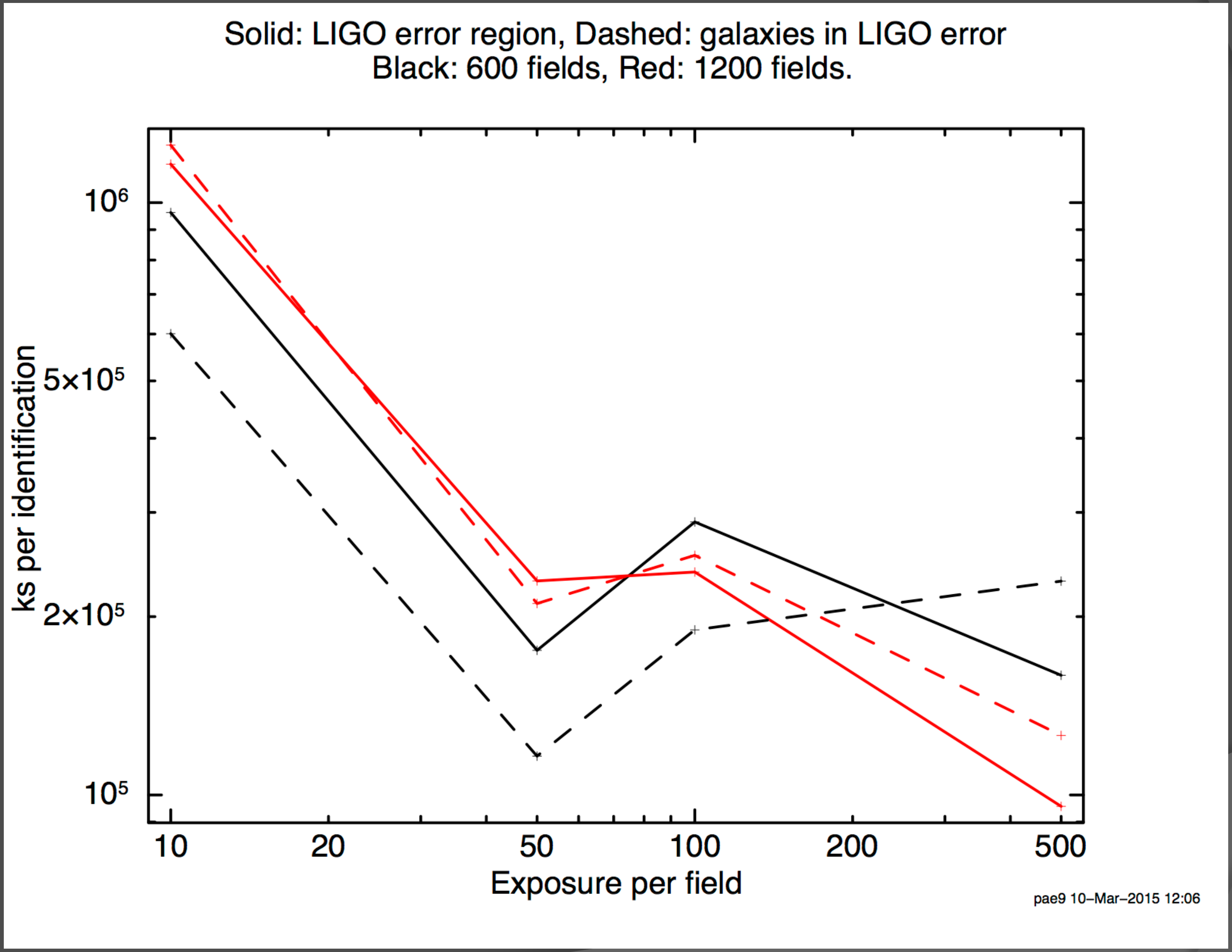
Results


500 s per field
Solid: LIGO error region, Dashed: galaxies in LIGO error
Black: 600 fields, Red: 1200 fields.
0.2
0.15
0.1
0.05
0
Fraction of GRBs identified
0
1
2
3
4
5
Number of observations of the GRB field
pae9 10–Mar–2015 11:43

Results


Black: 600 fields, Red: 1200 fields
Solid: no targeting, Broken: Galaxy targeting
0.3
0.2
0.1
Fraction identified after one observation
10
20
50
100
200
500
Exposure per field
pae9 6–Mar–2015 10:04

A single metric ks per ID



Slides from Phil Evans

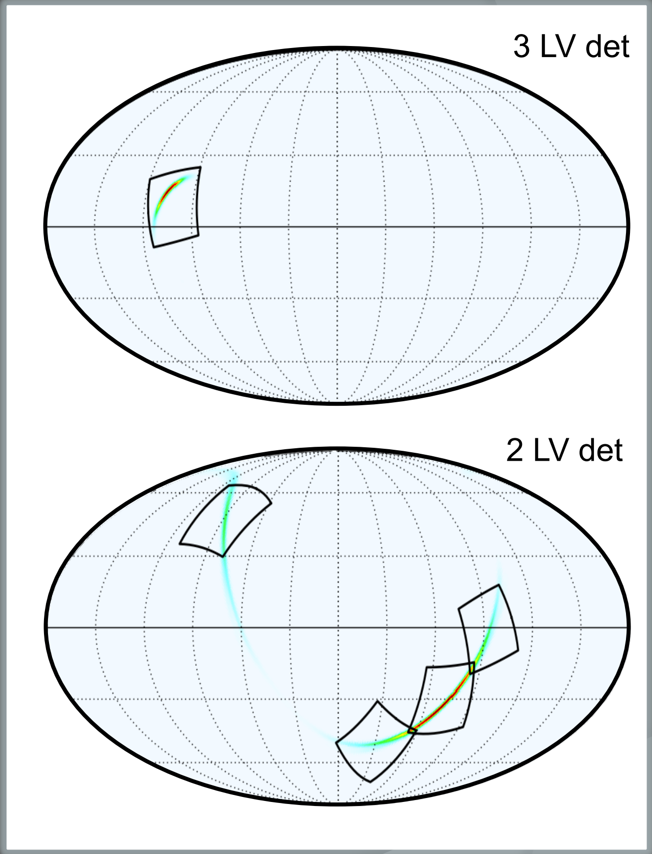
Phil's Conclusions

- If aLIGO detects a short GRB, on-axis, Swift-XRT has a 20-30% chance of finding the afterglow (assuming the afterglow is similar to the short GRBs Swift has seen to date).
- For the 2015-aLIGO configuration, it is preferable to target known galaxies: the gain in this is much much more than the losses due to the GRBs which are in unknown galaxies.
- Observing each XRT field once, for 50-s per, seems to give both the most efficient approach, and maximises the probability of identifying the afterglow.
- Using 1,200 XRT fields (if possible) gets us more GRBs than 600 fields, but not proportionally so: 600 fields is more "efficient"

Judy's Conclusions

- Swift-XRT is currently the most capable X-ray instrument for chasing transients with large localizations regions
- Coincident γ-ray detections are possible, but with low probability
- Finding a firm counterpart is a probability game

- New wide-field soft X-ray focusing instruments (ISS-Lobster, XTiDE, Einstein Probe, etc.) designed for these observations have a much better chance, but are 5+ years off



ISS-Lobster Tiling of LIGO Localization Contours