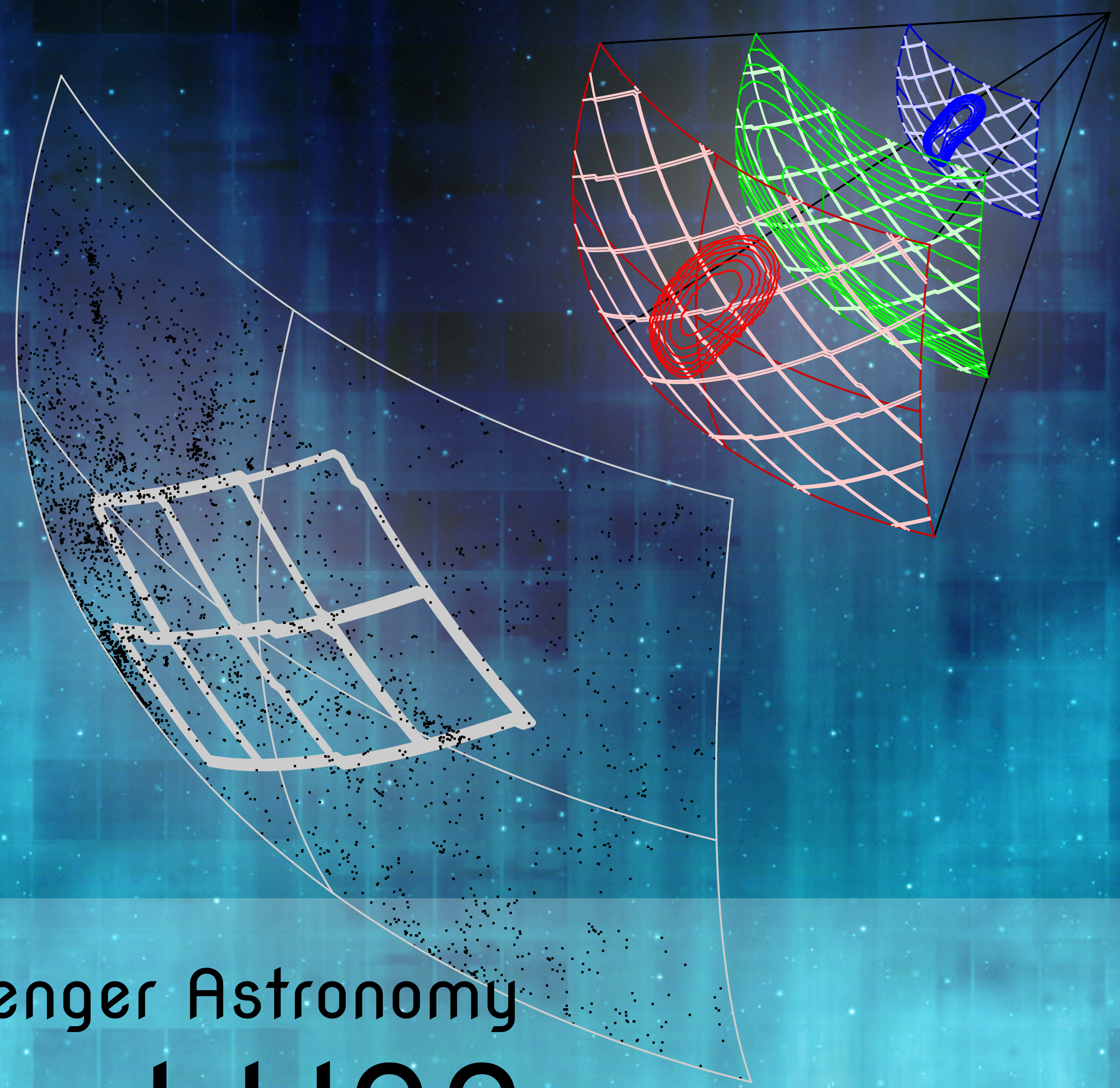


The Road to Multimessenger Astronomy with Advanced LIGO

Leo Singer • LIGO Laboratory, Caltech
lsinger@caltech.edu • Document LIGO-G1300492-v5

The story so far

- Global network of 3 multi-km interferometric observatories: LIGO–Hanford, LIGO–Livingston, Virgo
- During joint LIGO–Virgo science run in Summer—Fall 2010, sent alerts to astronomers to point telescopes see Abadie et al. 2012, A&A 541, A155
- Detectors off-line while they are reconfigured as advanced detectors → eventually 10x greater range for binary neutron stars
- More detectors planned: KAGRA, LIGO–India

http://www.ligo.org/multimedia/gallery/llo-images/Aerial%201%20small.jpg

http://www18.i2u2.org/elab/ligo/home/project.jsp

http://www.phys.ufl.edu/~bernard/IREU2008/images/largeimages/Virgo0.jpg

Possible electromagnetic counterparts

- 2 neutron stars merge, form compact object and accretion disk
- Accretion feeds pair of jets
- Internal shocks in jet produce prompt ɣ-ray burst
- Shock between jet and ISM produces optical and radio afterglow

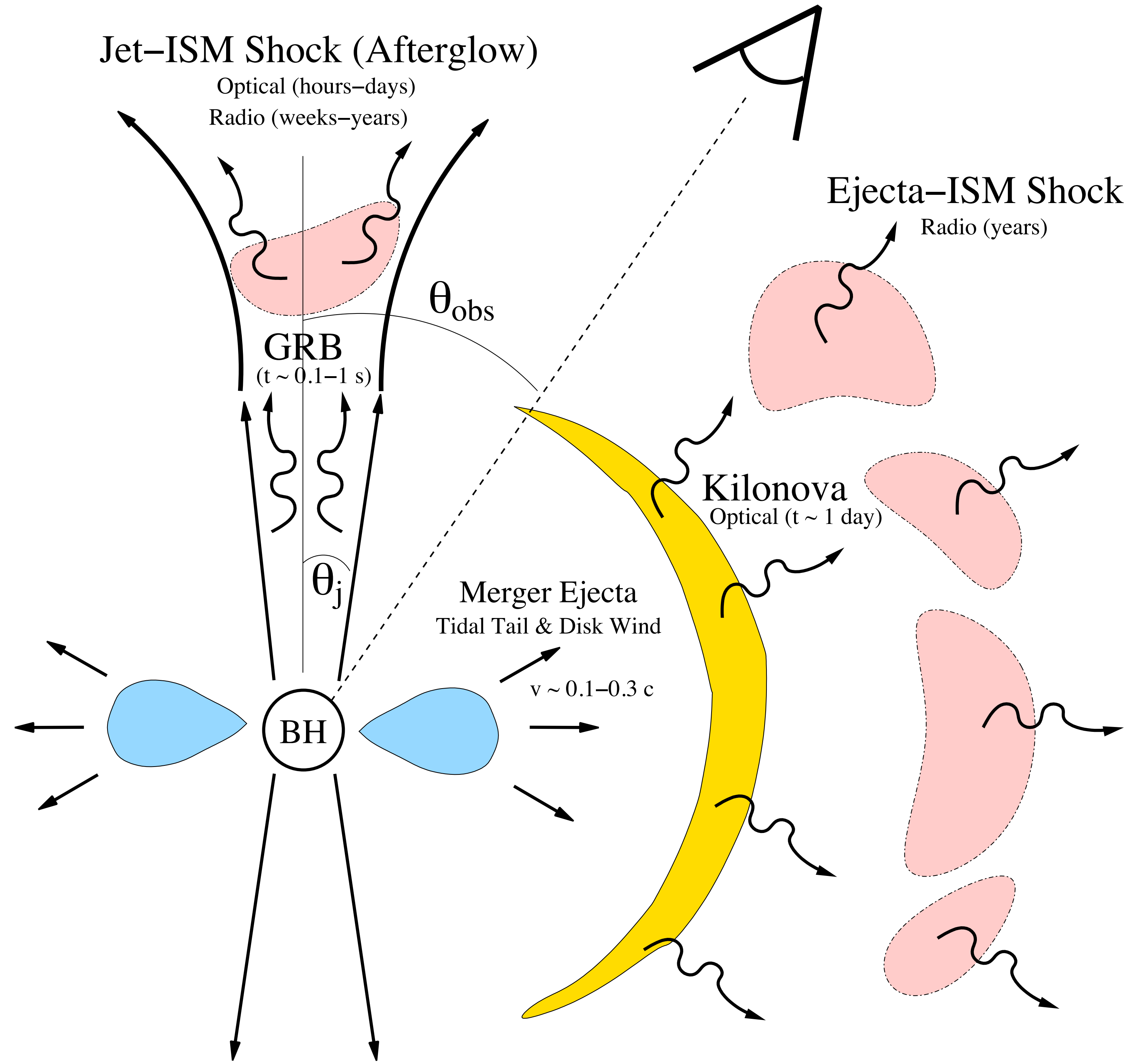
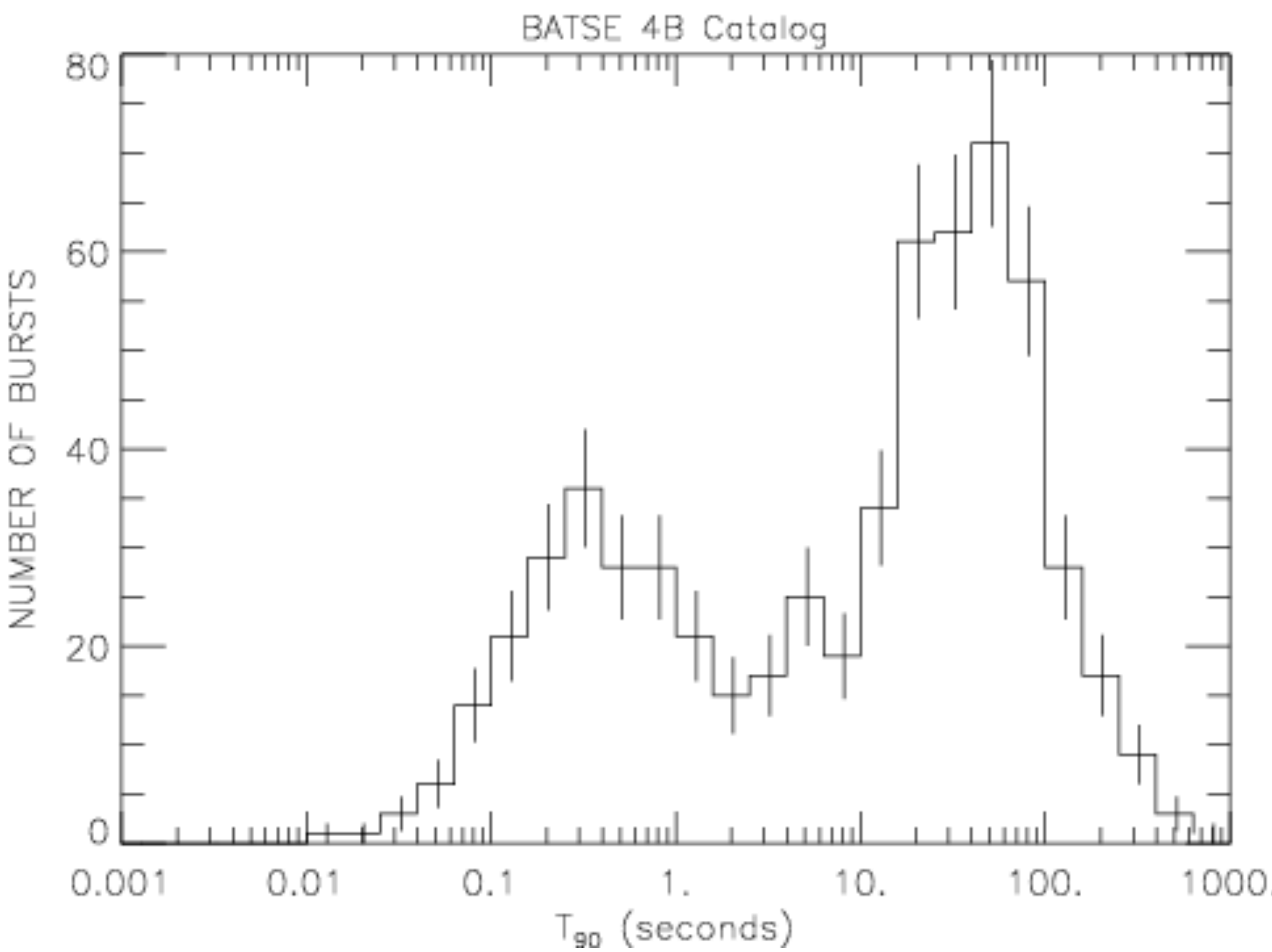
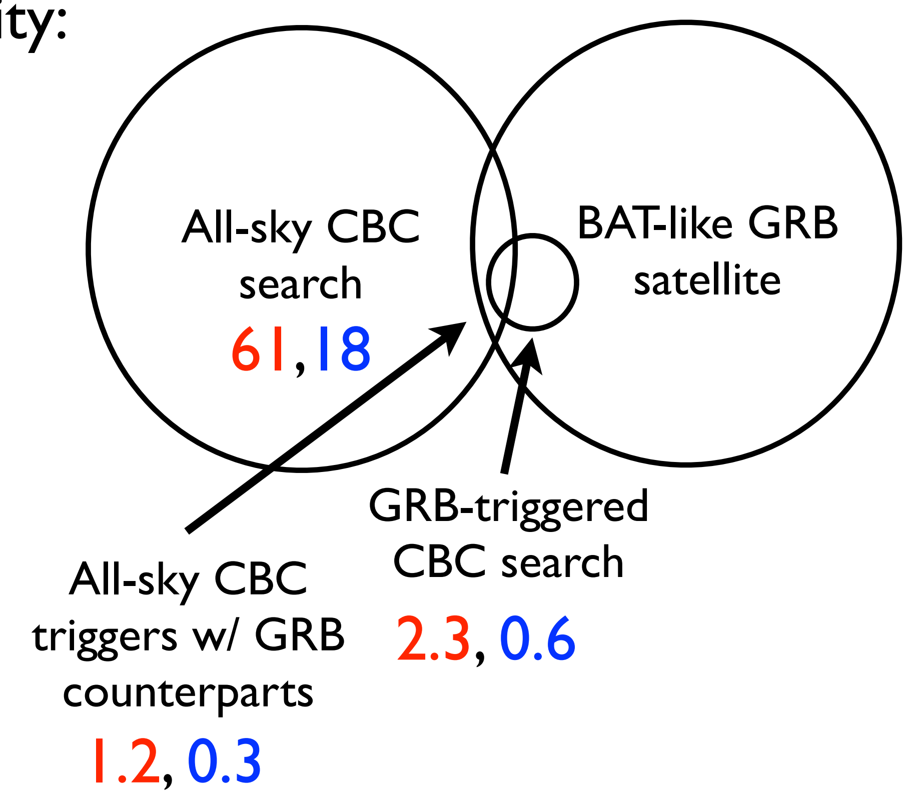


Figure 1 of Meztger & Berger 2012, ApJ, 746, 48

GRBs



Number of BNS, NSBH sources per year at aLIGO/Virgo design sensitivity:



- High-energy sky is relatively clean; temporal coincidence with GW trigger is enough

- But what GRB satellites will be up in 2018?...
  IPN, *Swift*, *Fermi*, *Lobster*, *SVOM*, anything at all?

Outlook for detection of GW inspirals by GRB-triggered searches in the advanced detector era

Deitz, Fotopolous, **Singer**, and Cutler (2013, PRD 87:064033)

http://dx.doi.org/10.1103/PhysRevD.87.064033

Optical afterglows

- Often faint
  (16-22 mag)
- Fade rapidly
  (~several mag/night)
- Optical sky is crowded
  (rocks, quasars, variable stars, supernovae)
- Orphan afterglows!
  (PTF11agg, http://arxiv.org/abs/1304.4236)

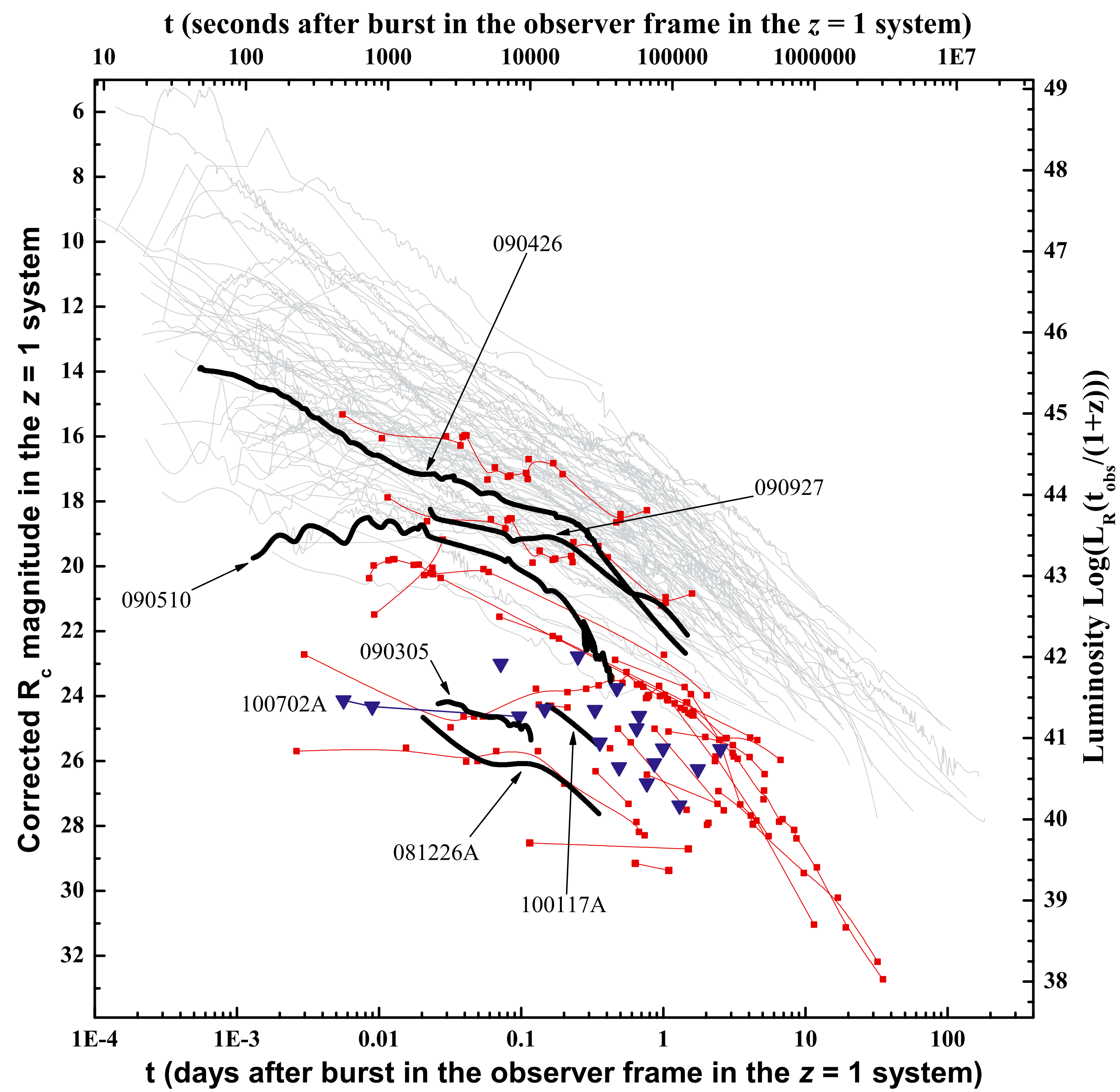


Fig. 15 of Guelbenzu et al. (2012)
A&A 548, A101 (2012)

How do we get there?

low-latency event detection

K. Cannon, C. Hanna, D. Keppel + many others + me

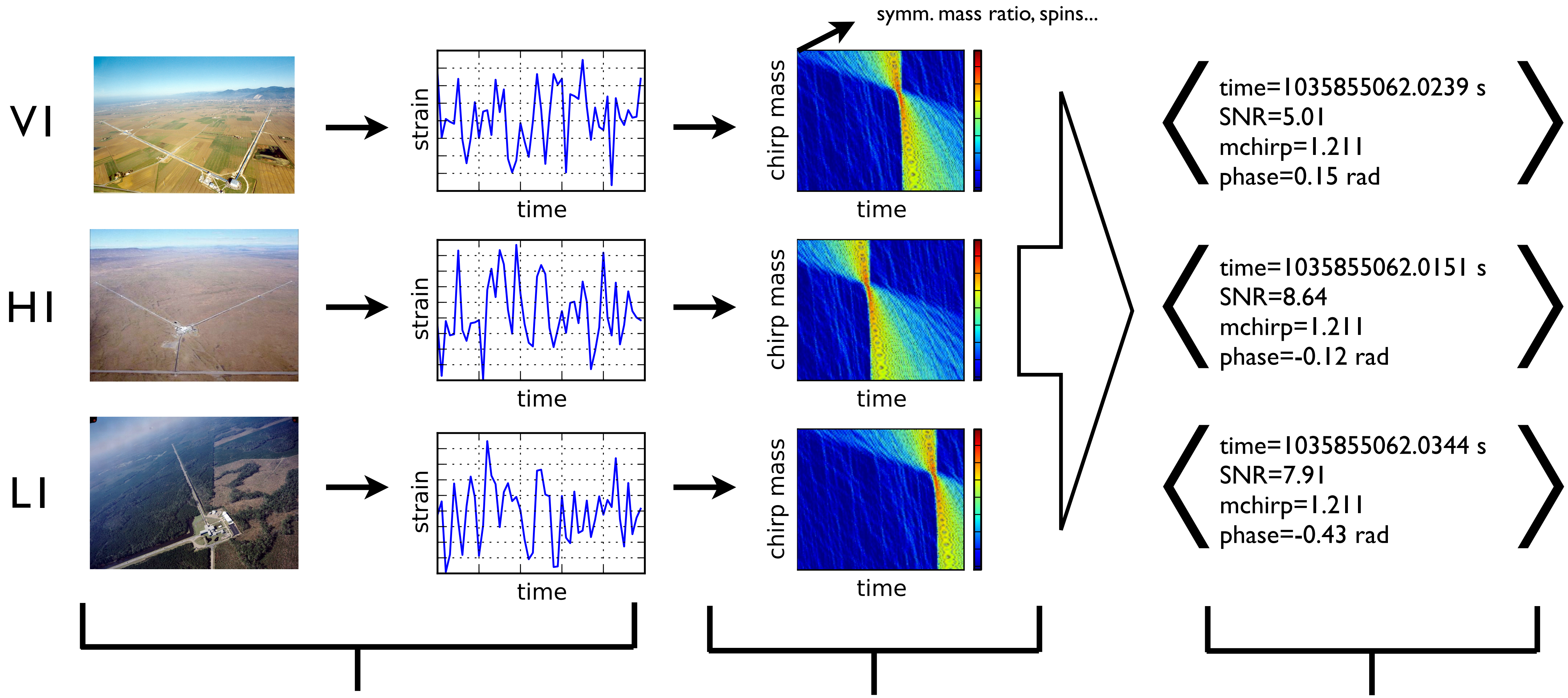
rapid sky localization

L. Price + me + many others

timely optical transient detection

Palomar Transient Factory + S. B. Cenko + D. Brown + M. Kasliwal+ myself

Detection



Strain transduced by detectors

also: data quality, vetoes, aggregate data to analysis clusters

Matched filter

sliding dot product of strain data w/ sampling of all possible inspiral signals

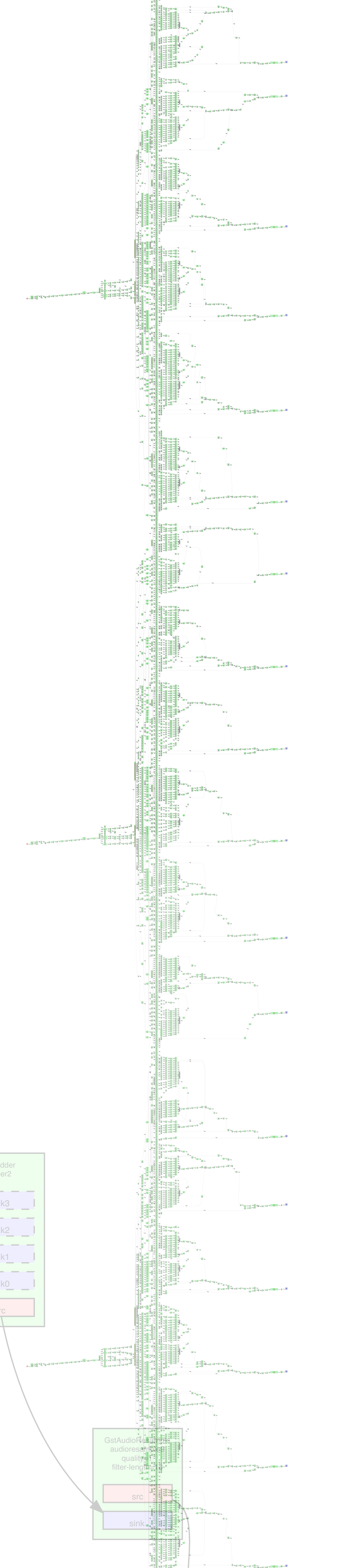
Triggering, coincidence

excursion in matched filter *signal-to-noise ratio (SNR)* at similar times in all detectors

GstLAL:

online inspiral detection engine powered by

gstreamer



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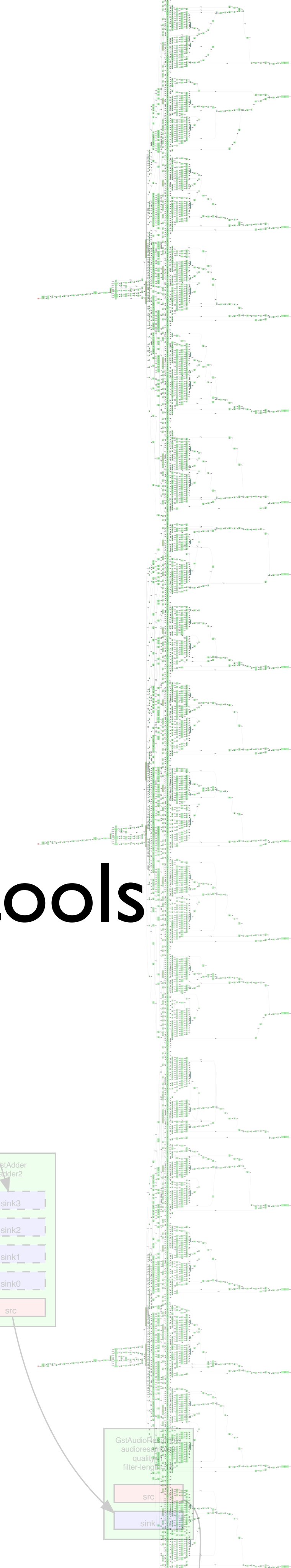

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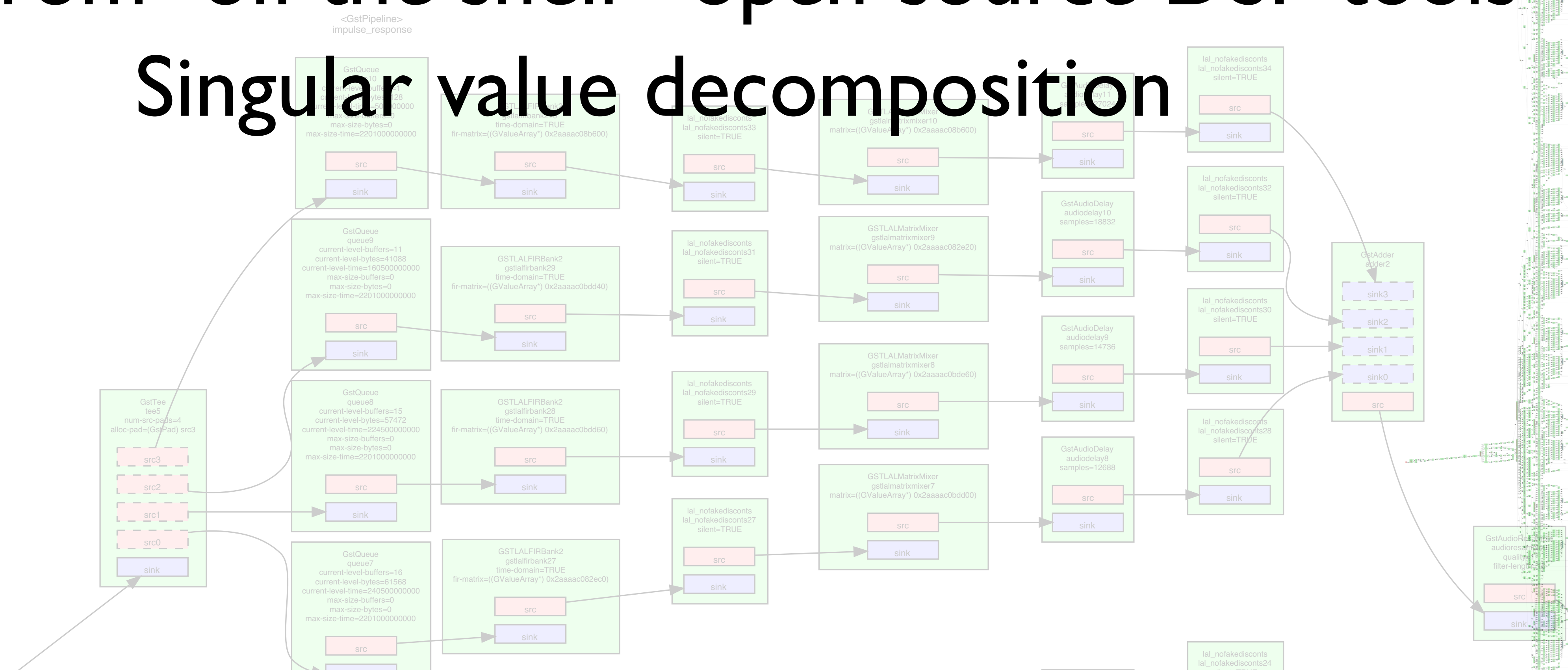

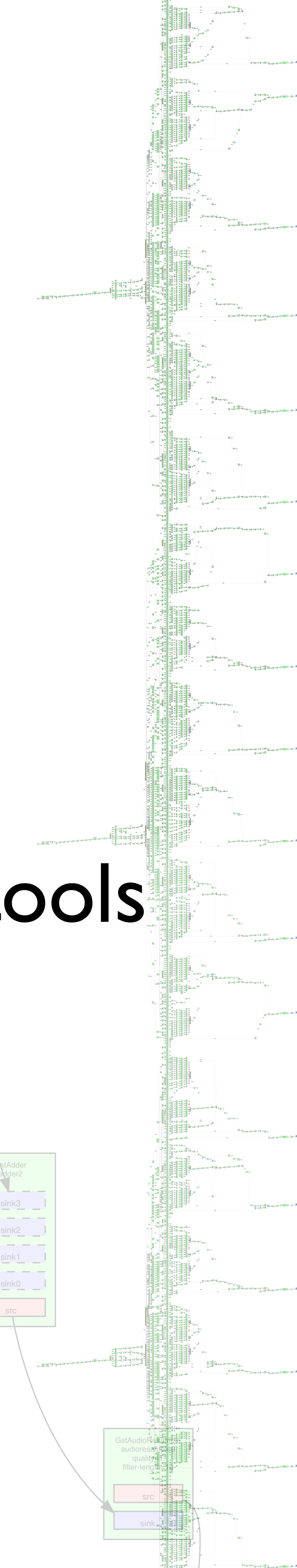

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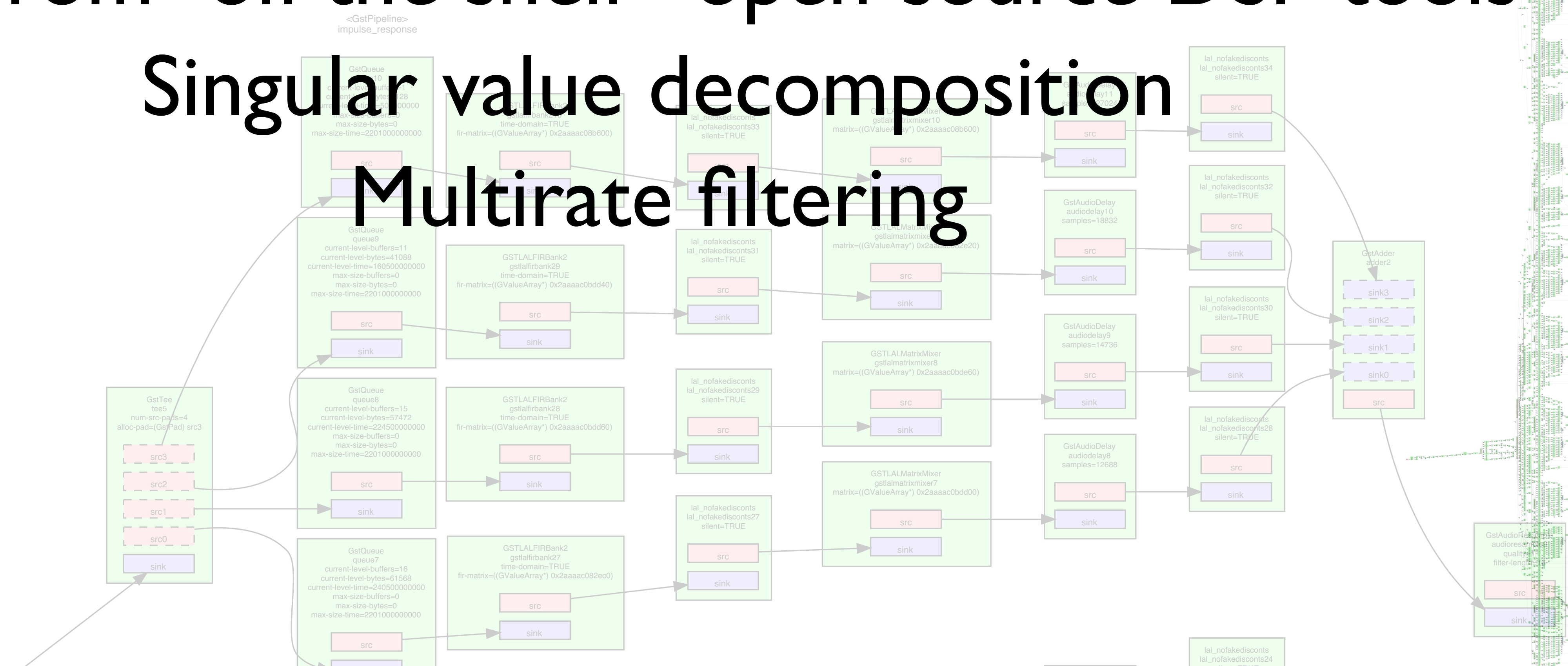

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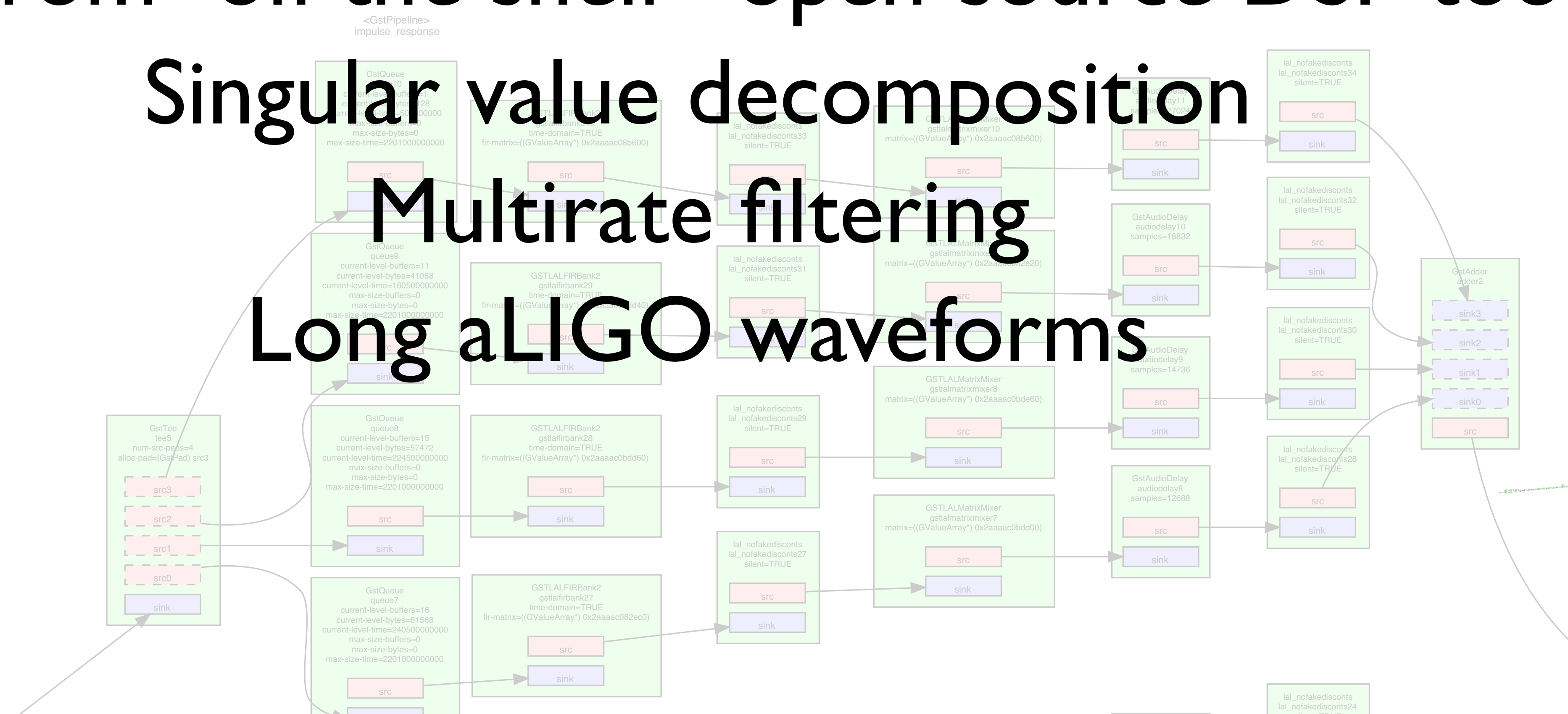
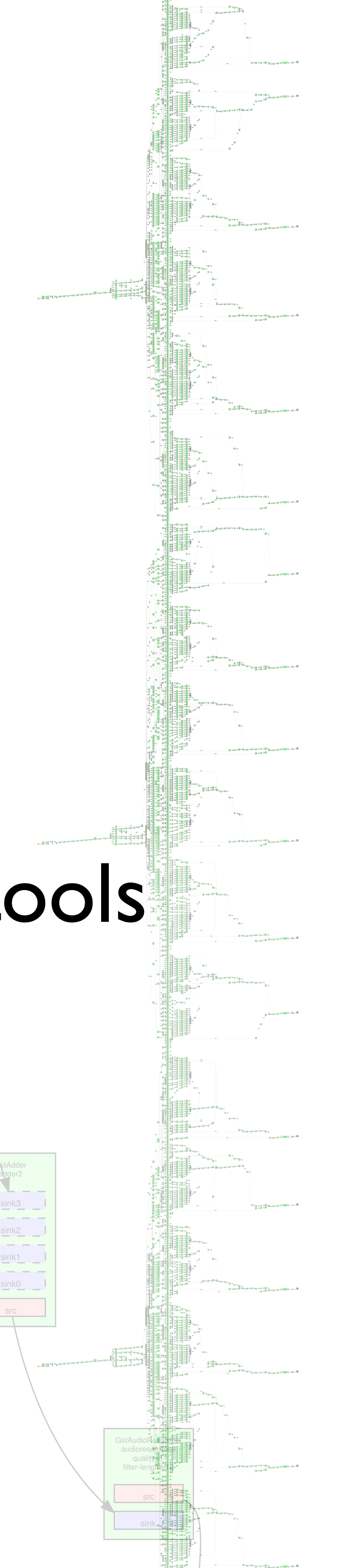
Long aLIGO waveforms





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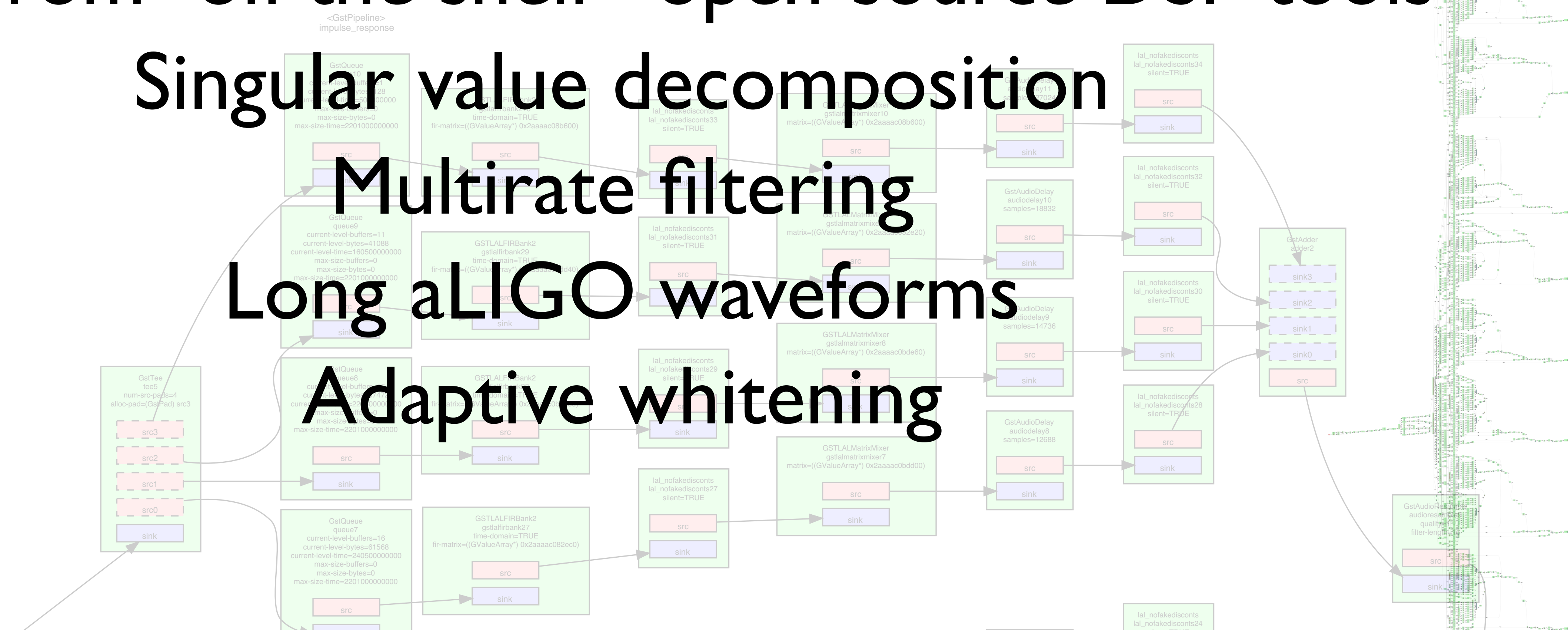

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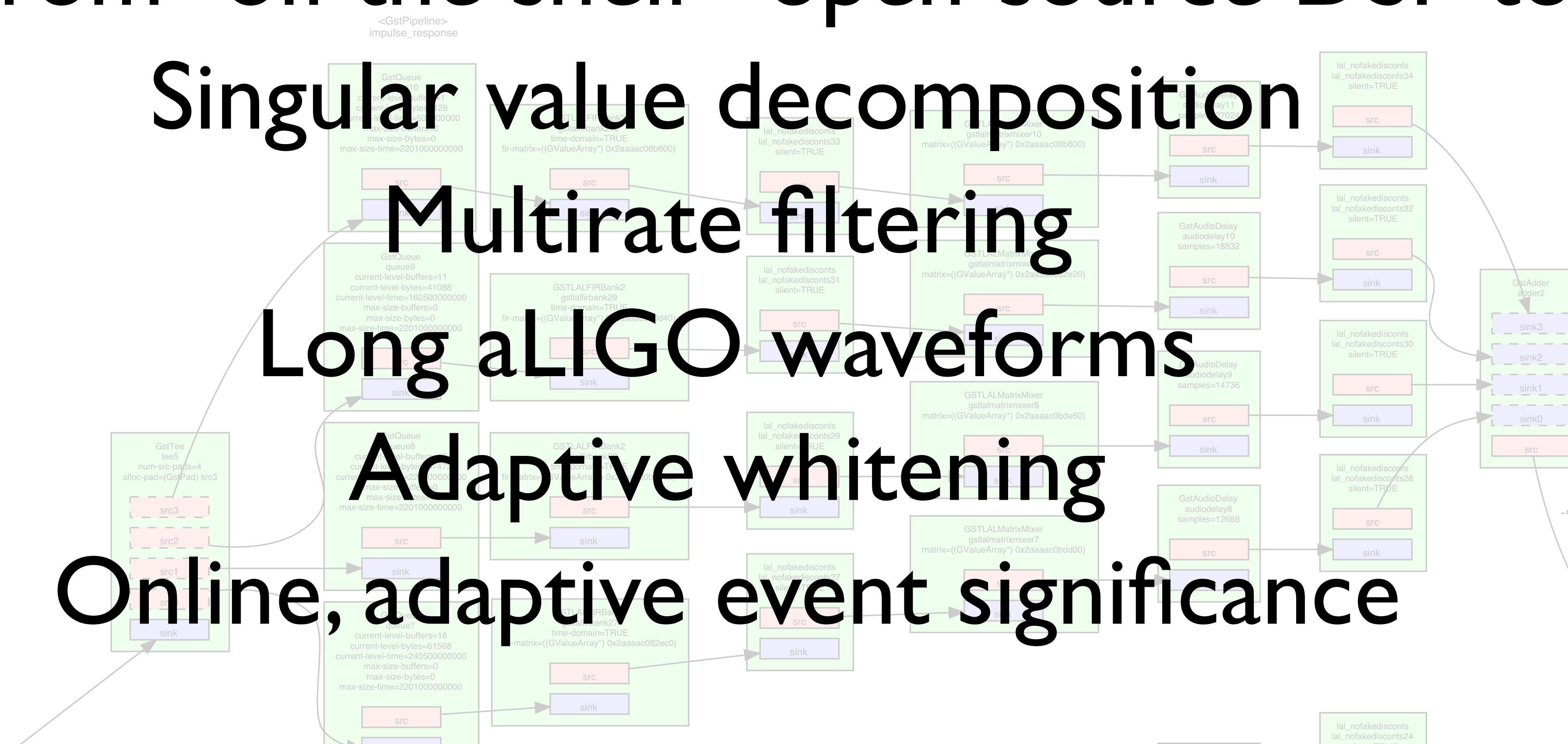
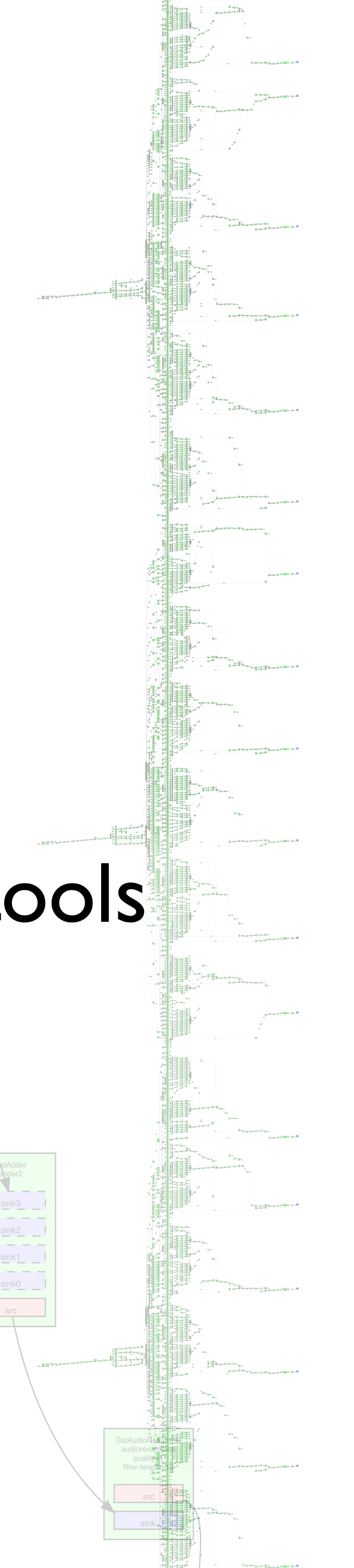
Online, adaptive event significance

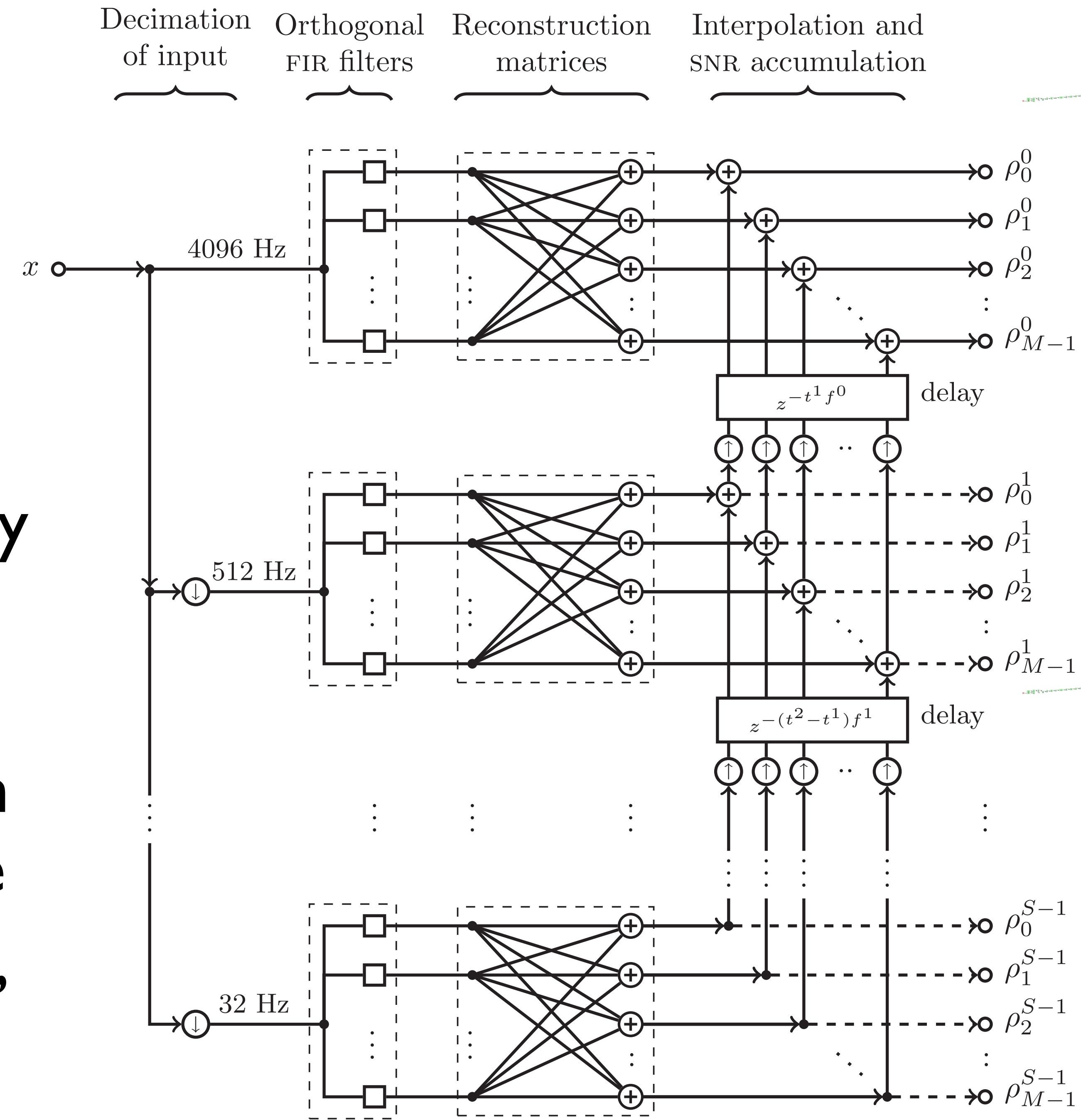




GstLAL:

my contributions

- handle data gaps efficiently (particularly resampling)
- computational budget
- first complete description of algorithm for literature
- improve accuracy of time, SNR of triggers

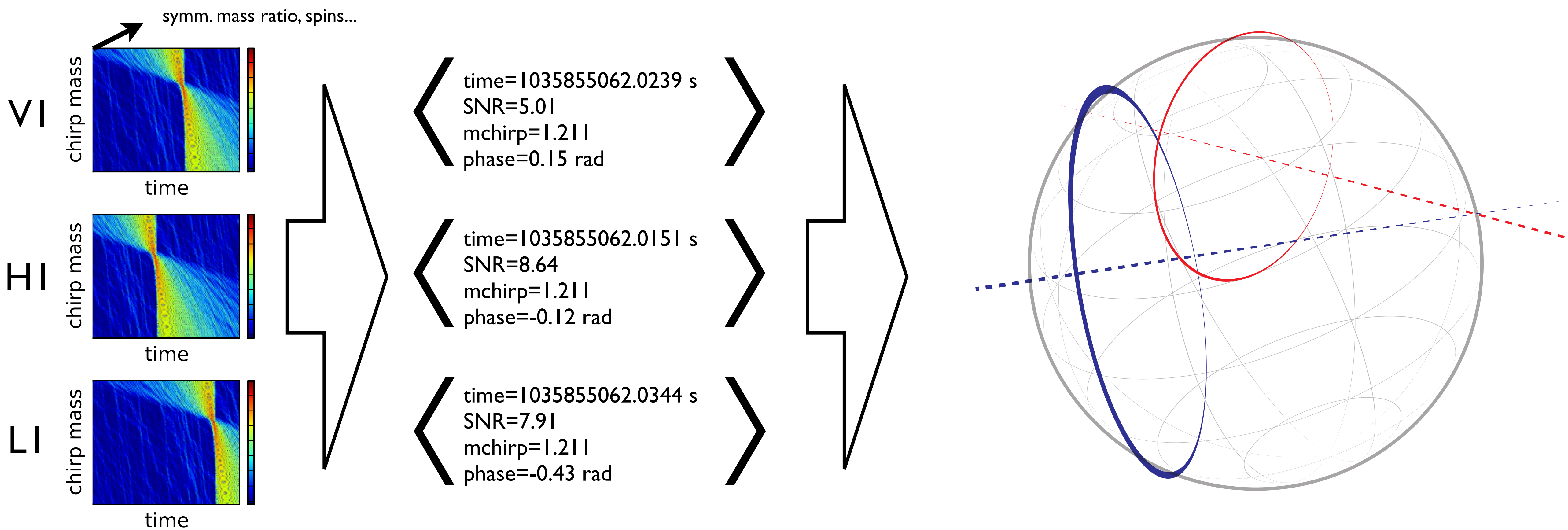


Toward early-warning detection of gravitational waves from compact binary coalescence

Cannon et al. (2012, ApJ 748:136)

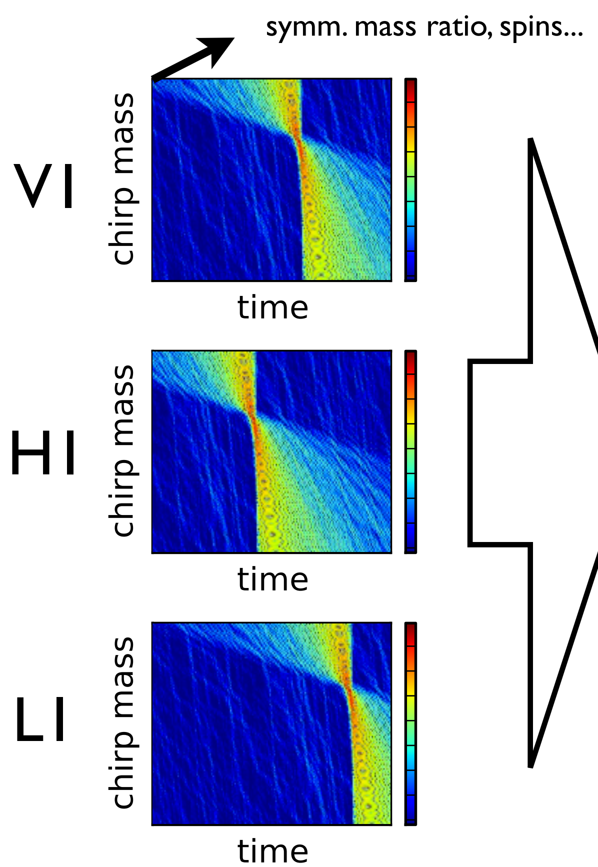
http://dx.doi.org/10.1088/0004-637X/748/2/136

Triangulation



See also: Fairhurst, 2009, New J. Phys., 11, 123006),
Fairhurst, 2011, Class. Quantum Grav., 28, 105021

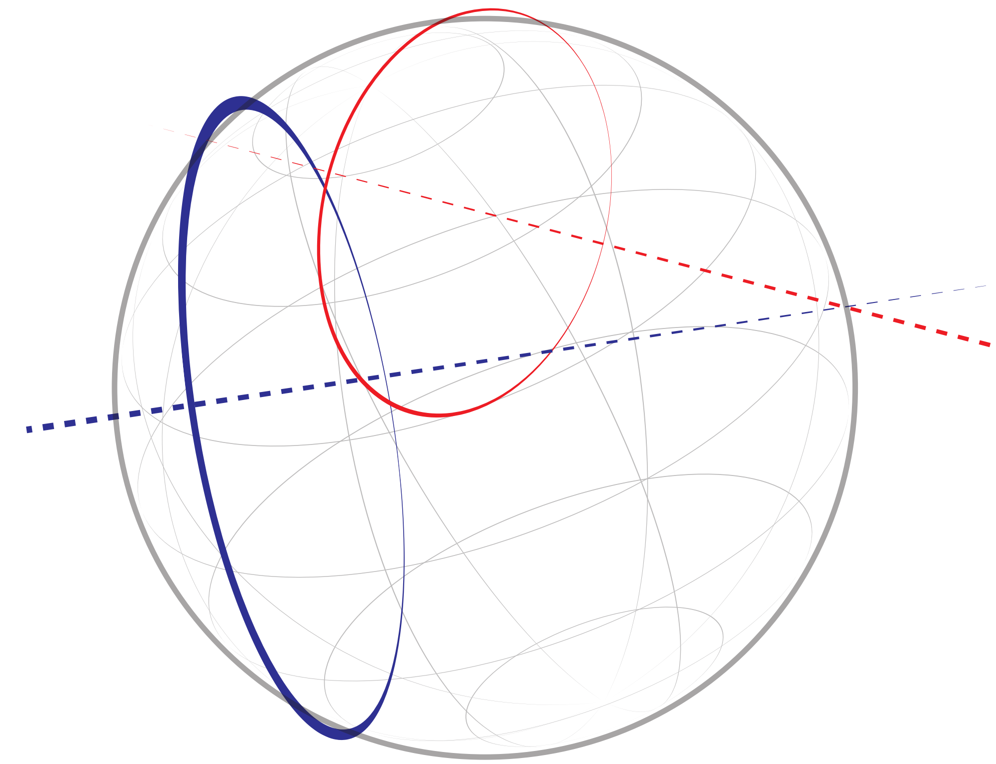
Triangulation

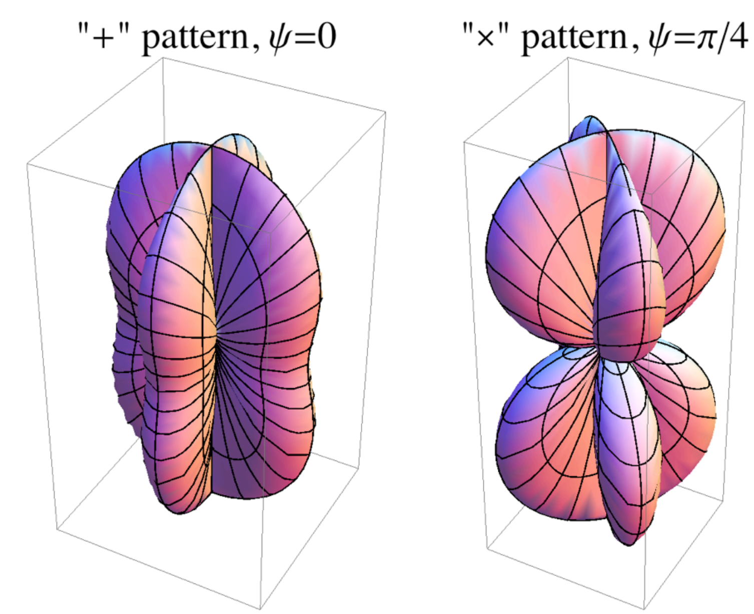


time=1035855062.0239 s
SNR=5.01
mchirp=1.211
phase=0.15 rad

time=1035855062.0151 s
SNR=8.64
mchirp=1.211
phase=-0.12 rad

time=1035855062.0344 s
SNR=7.91
mchirp=1.211
phase=-0.43 rad





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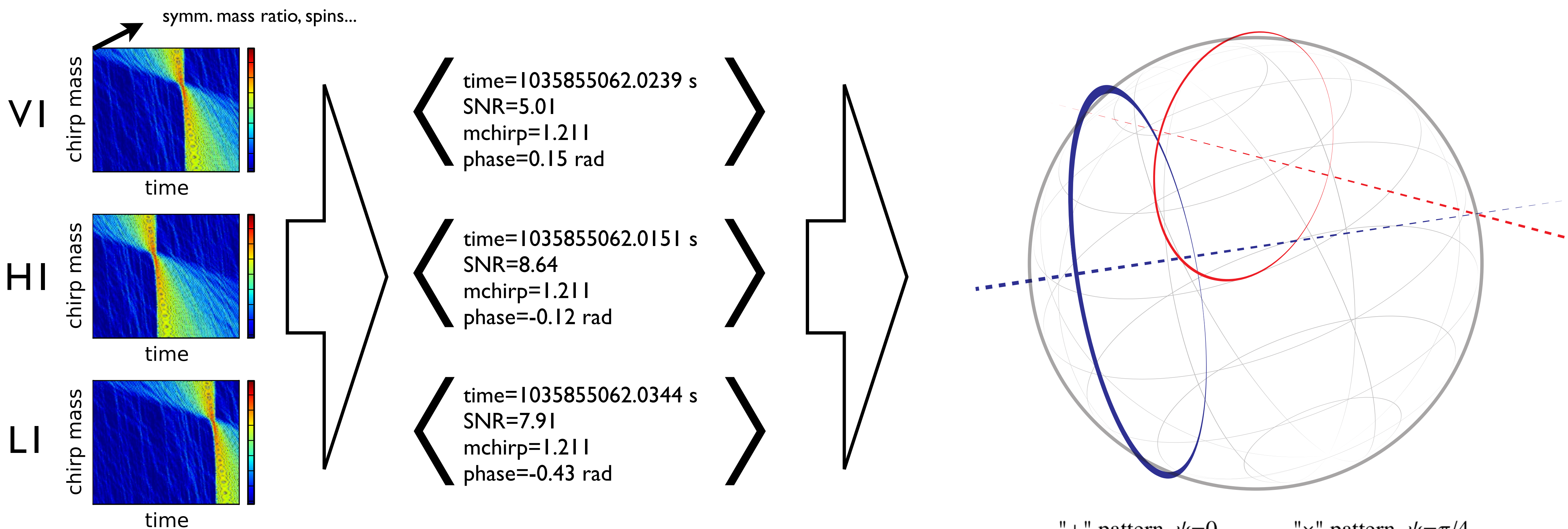

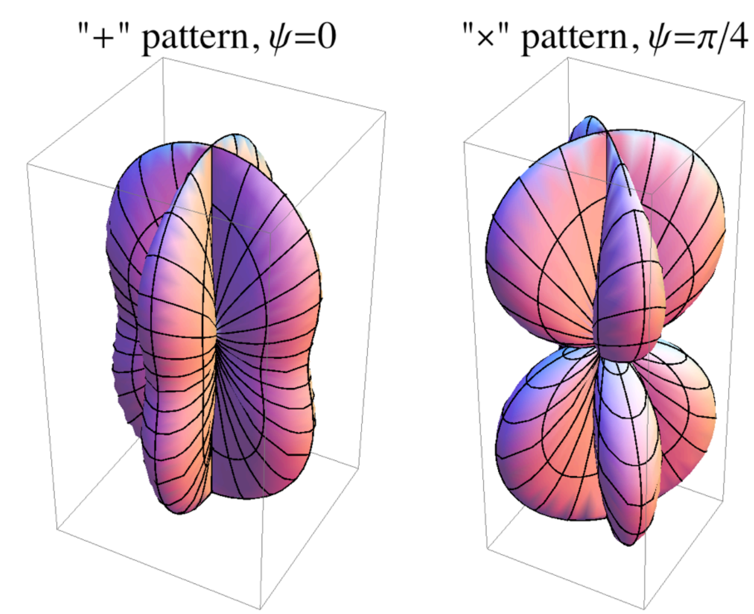

- Time delays & relative amplitudes ⟹inform sky location
- Triggers = point estimates
- Statistics of estimation error
- Very fast!

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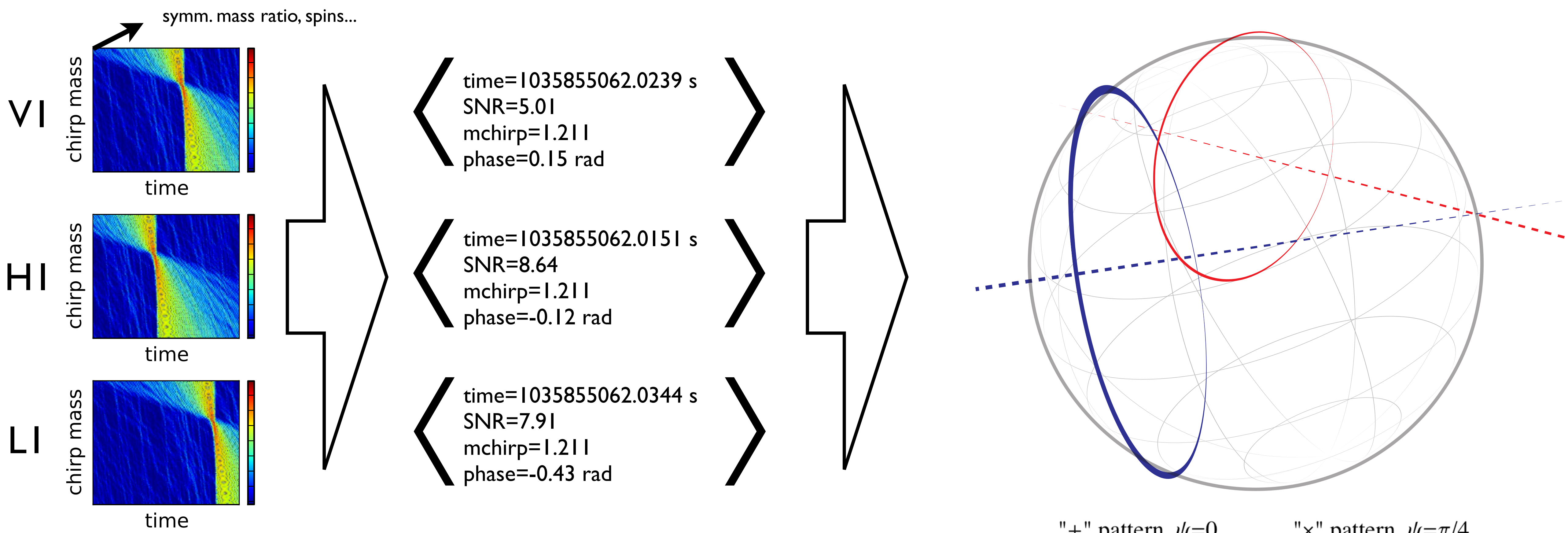

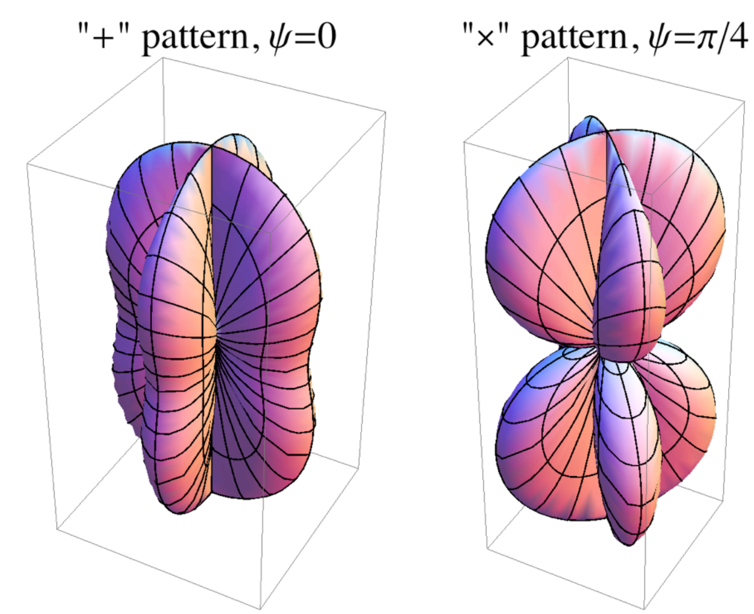

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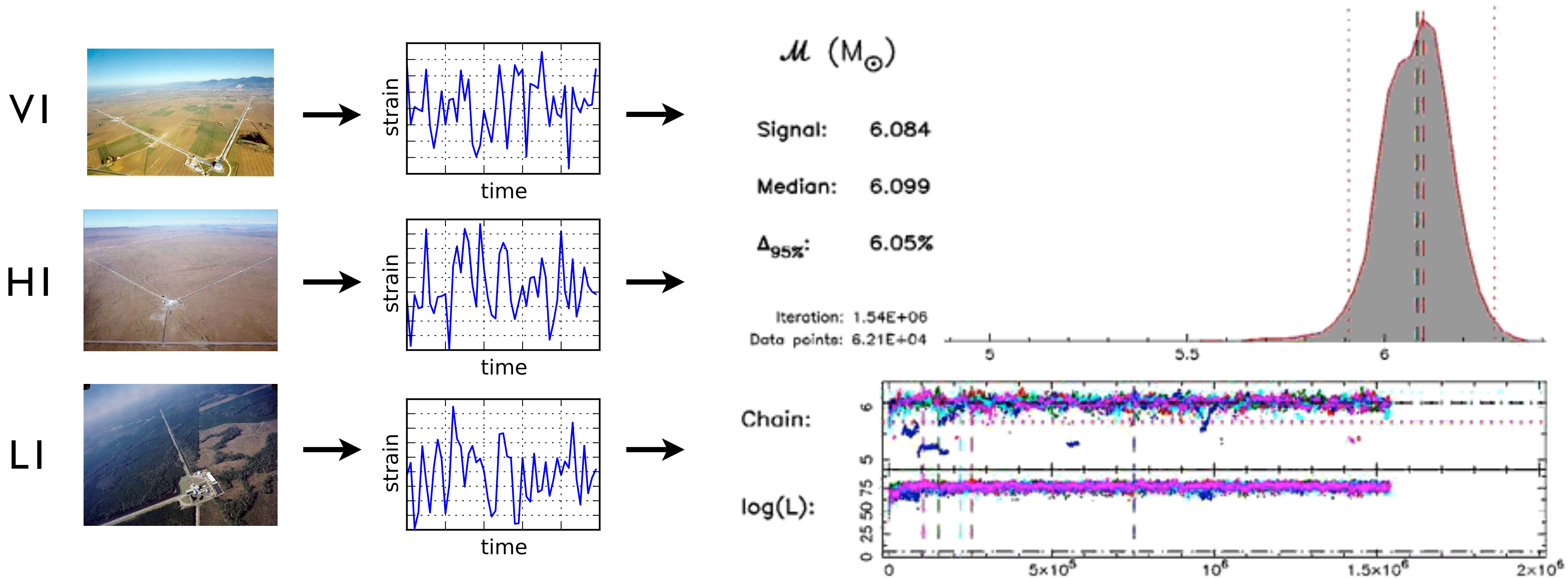
Bayesian Markov-chain Monte Carlo



Vivien Raymond, <http://www.ligo.caltech.edu/~vraymond/>

- Input: strain time series from all detectors
- Stochastically sample from parameter space, compute overlap of signal with data in each detector
- Sample distribution converges to posterior
- Can be computationally expensive
- Takes hours to days, currently

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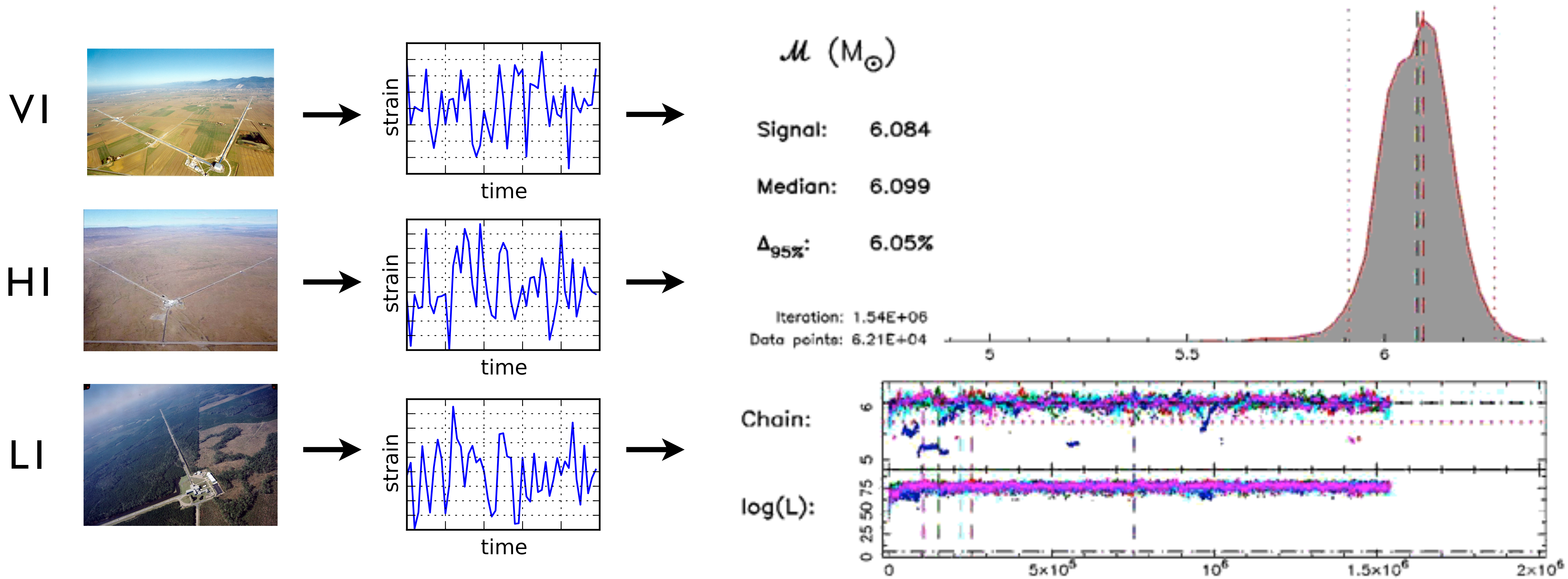

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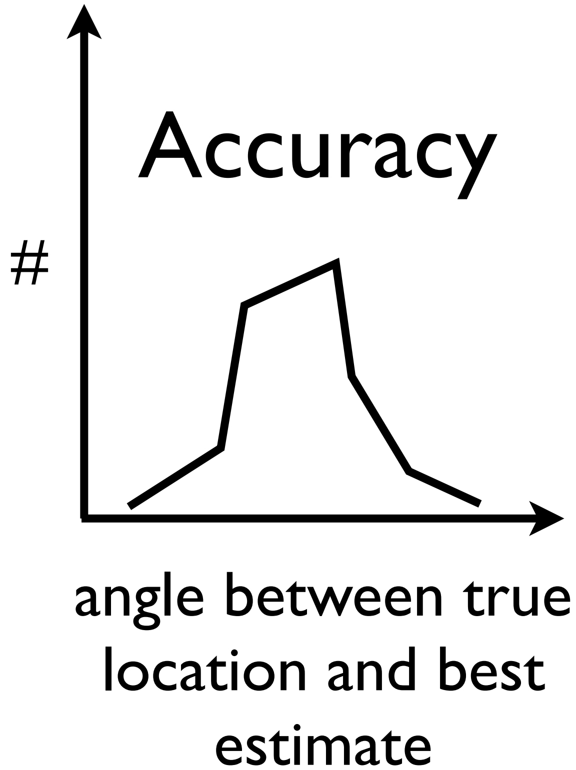
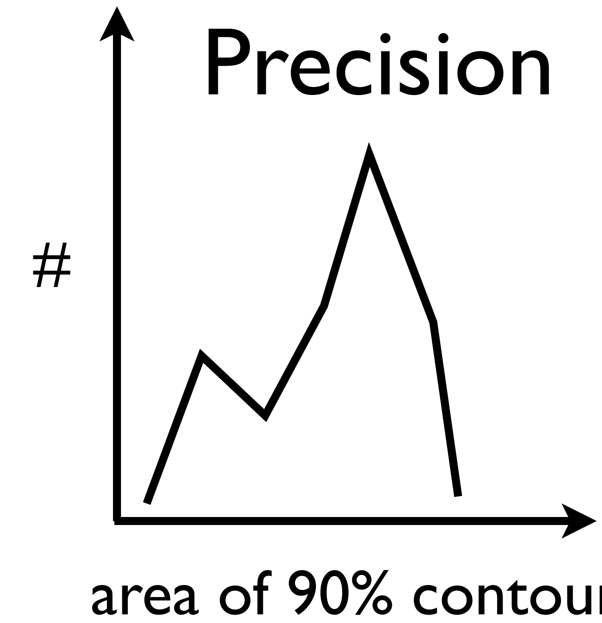
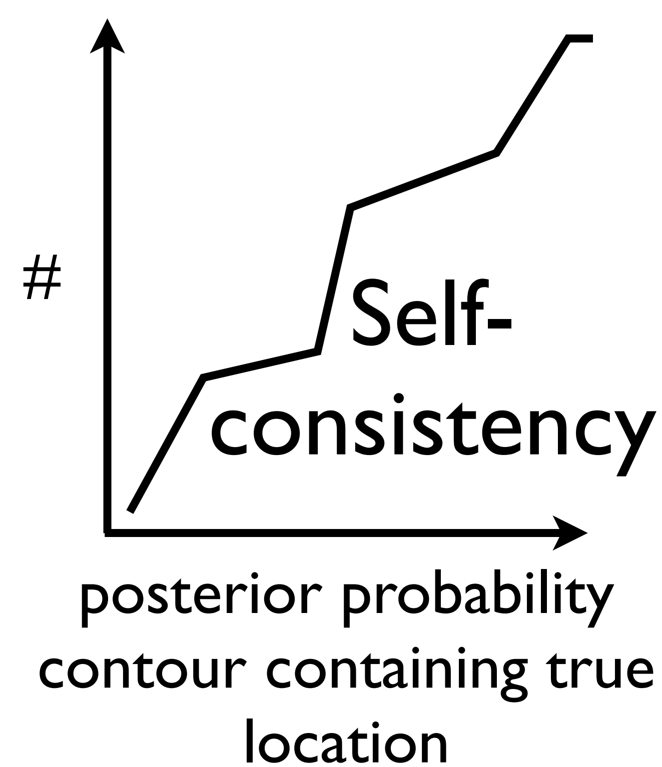


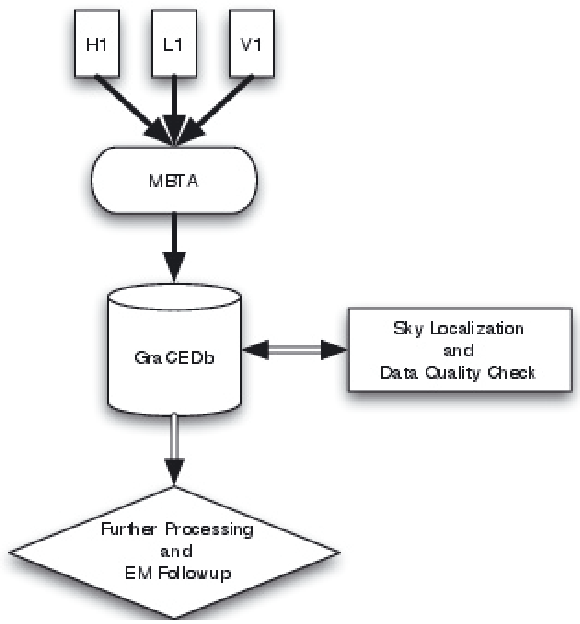


Parameter estimation:

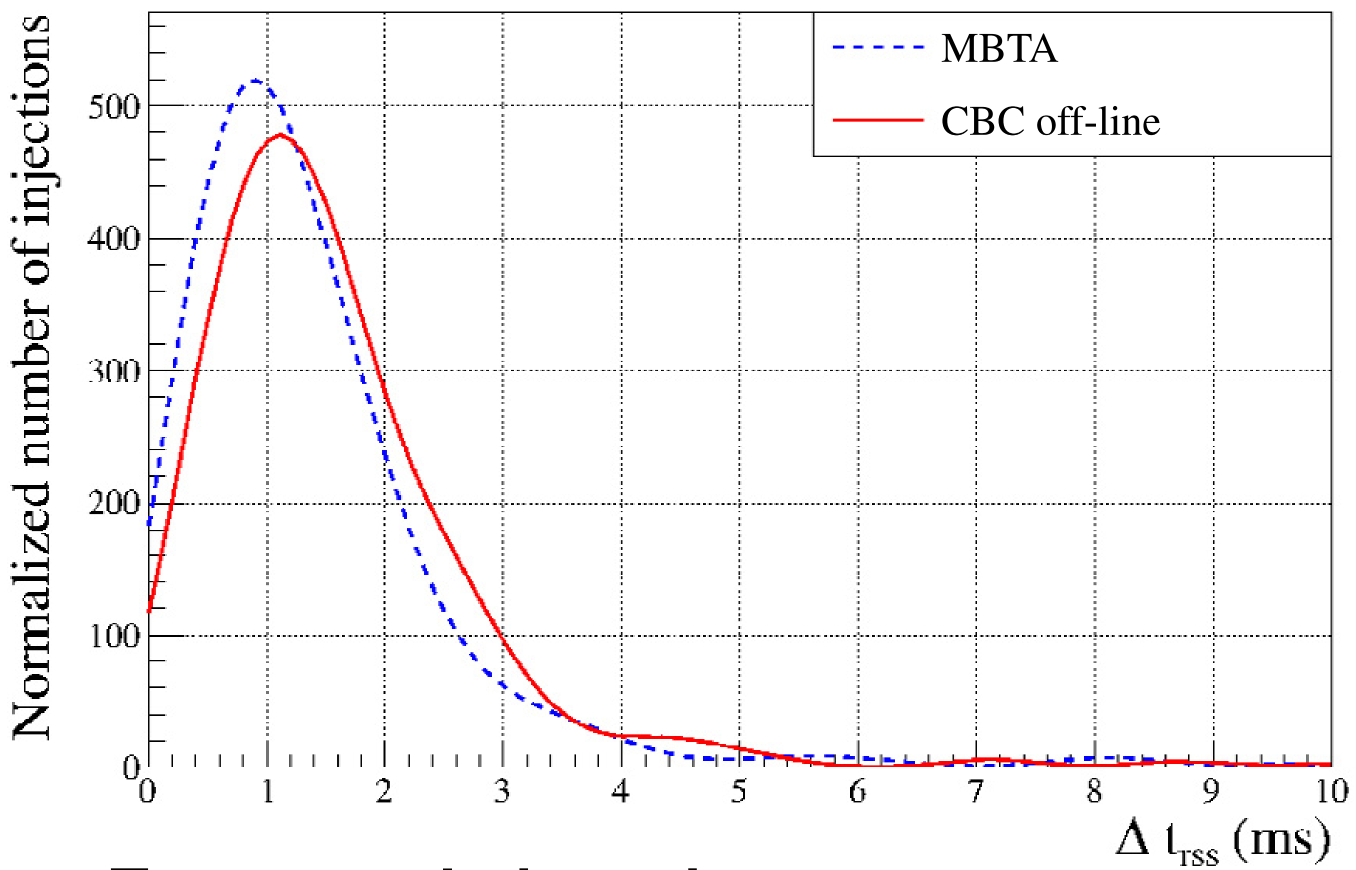
The 3 figures of merit



Rapid sky localization in last science run: S6/VSR3

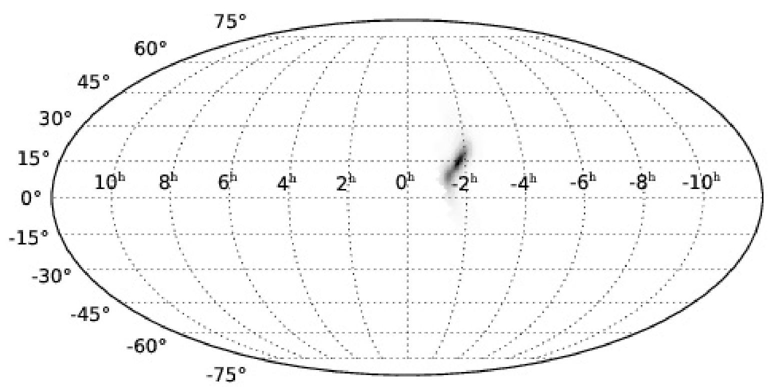


Low latency detection candidates from MBTA

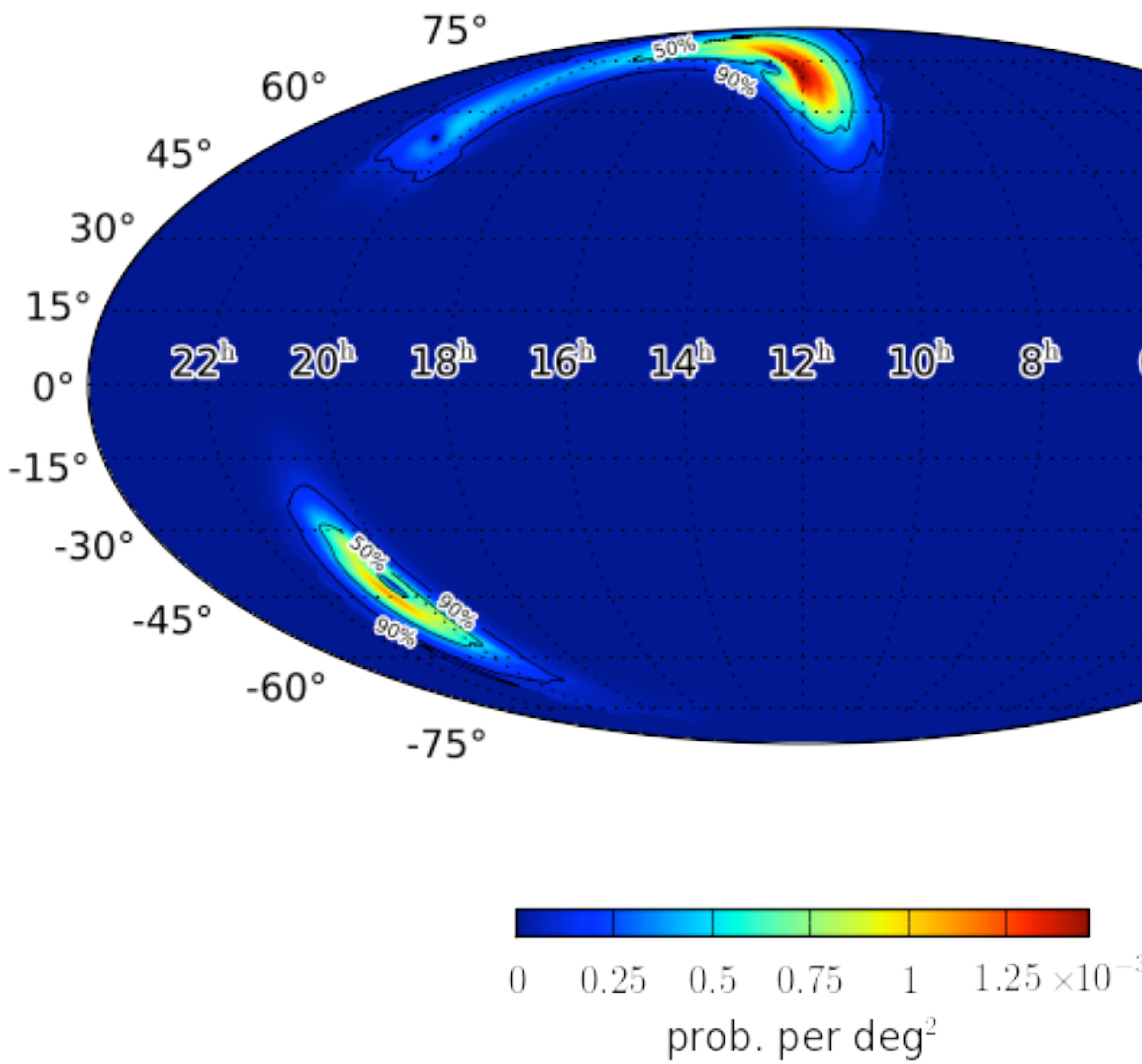


Empirical distribution of timing accuracy from pipeline

Alerts sent to astronomers!



G71031: ER3 gstlal event, ***before***



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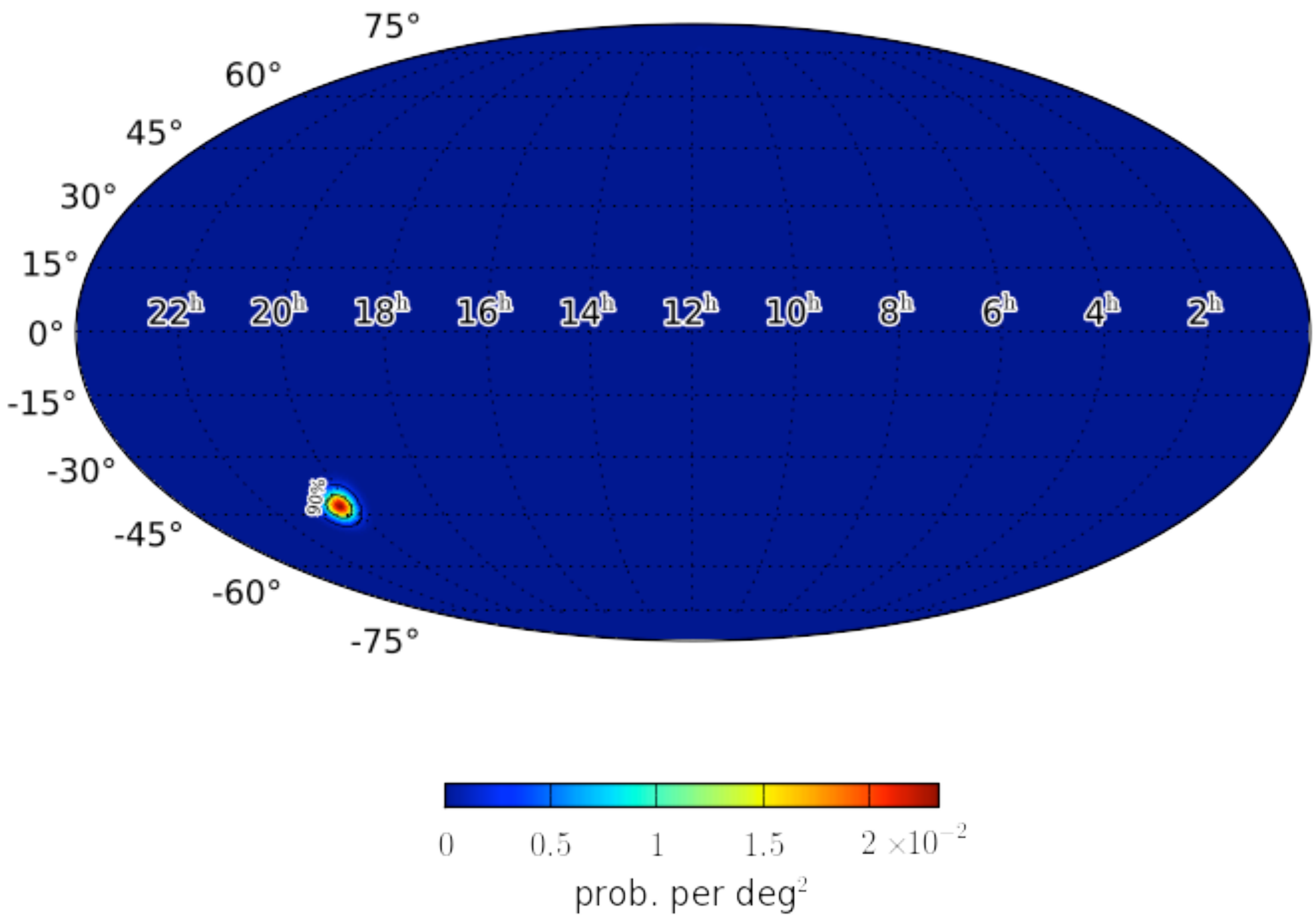

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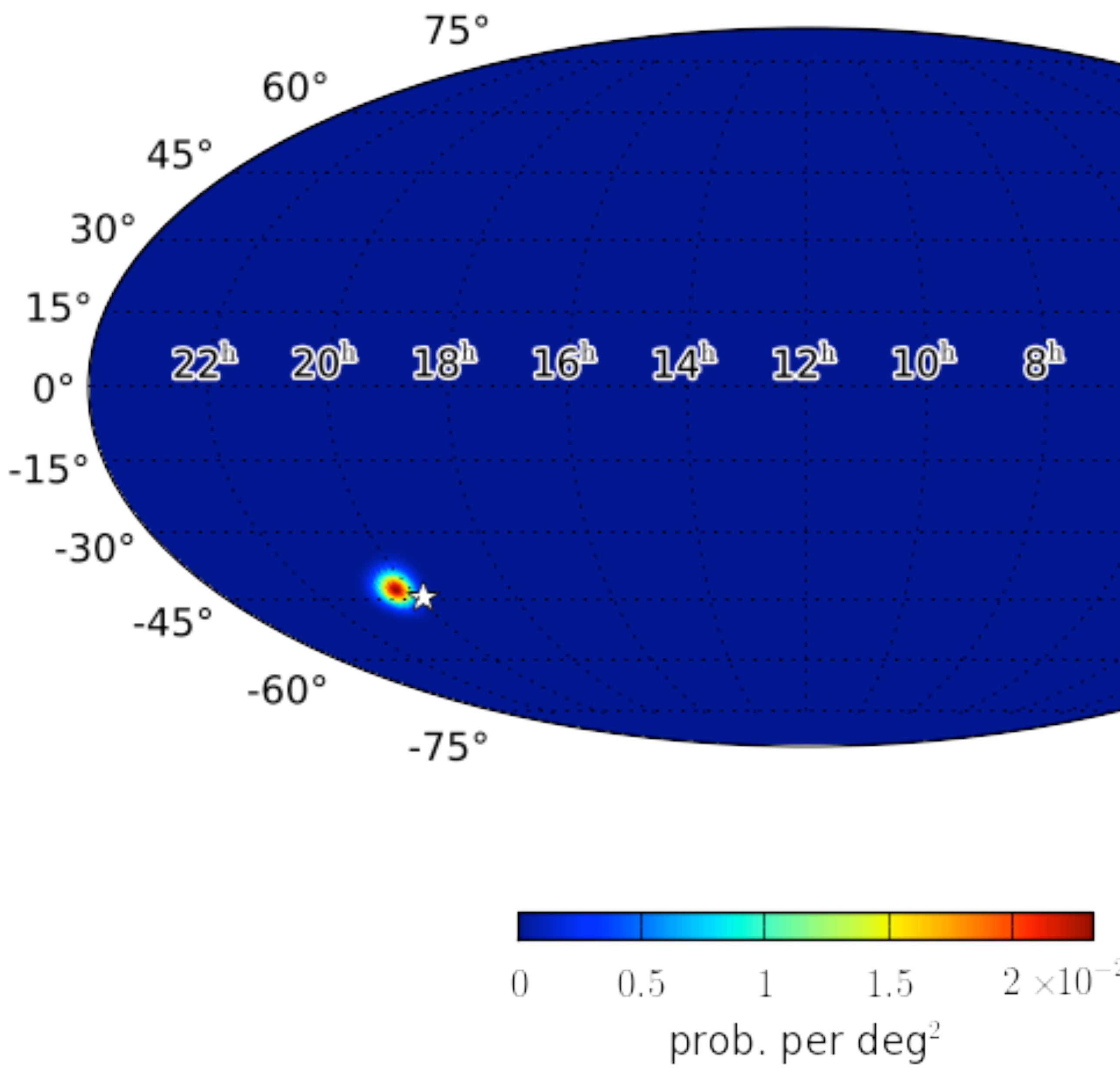

Idea: Use point estimates triggers, but *start from Bayes' theorem*

Then hold to same *self-consistency standards as full MCMC*

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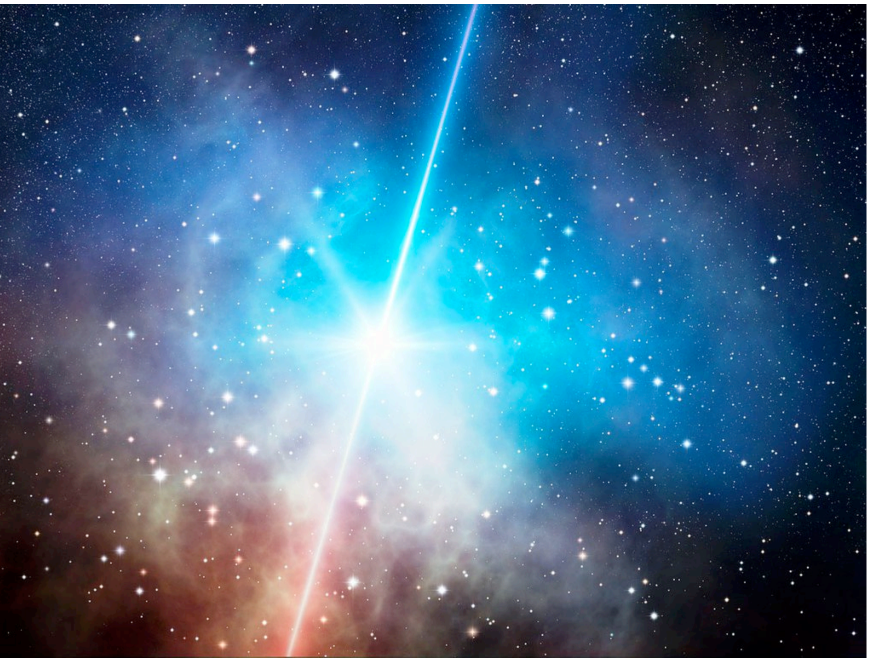

image credit:
http://www.scenicreflections.com/files/GRB%20Wallpaper__yvt2.jpg

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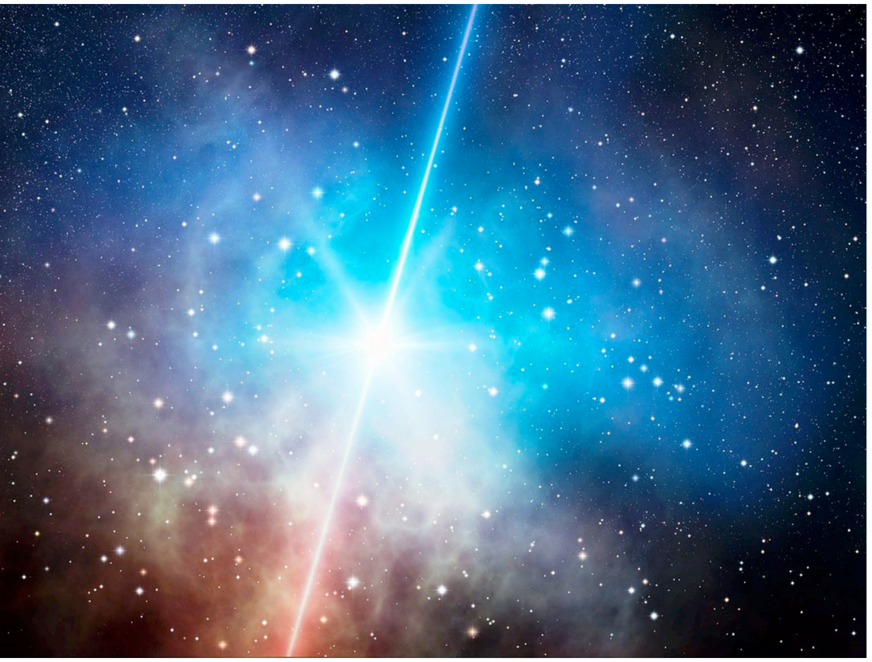

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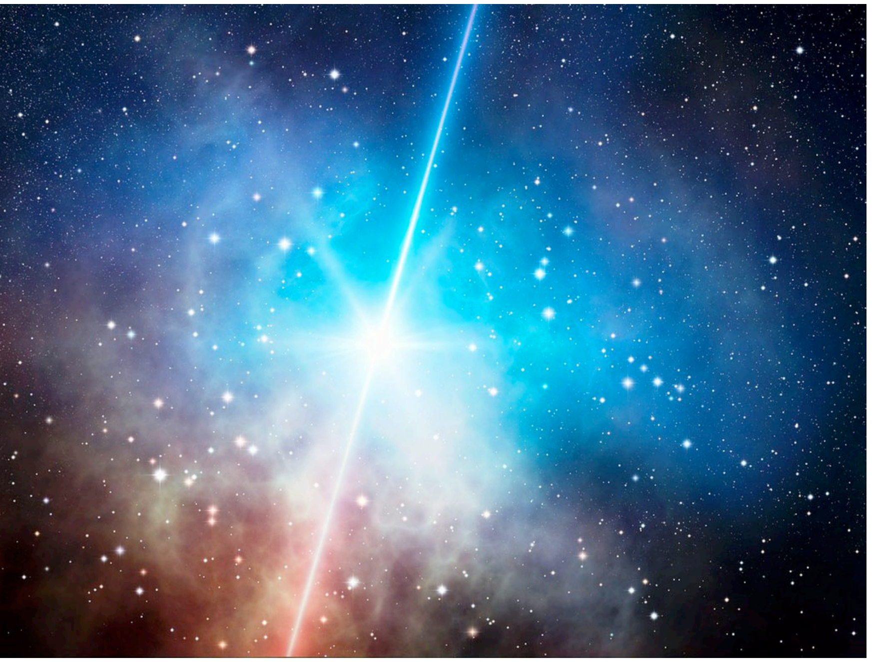

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image credit: http://www.fanpop.com/clubs/battlestar-galactica/images/10655496/title/battlestar-galactica-cylon-centurion-photo

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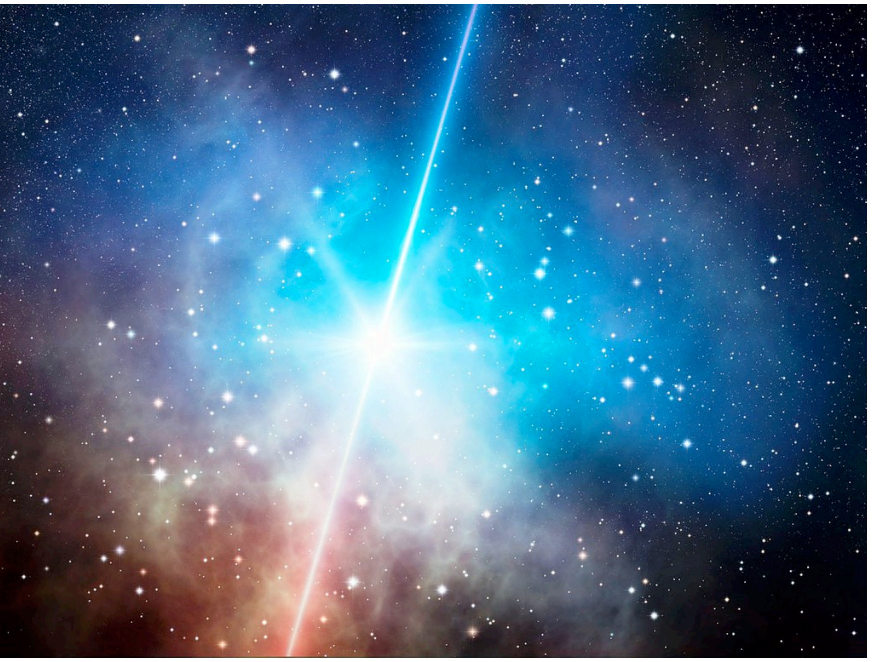

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image credit: http://www.fanpop.com/clubs/battlestar-galactica/images/10655496/title/battlestar-galactica-cylon-centurion-photo

thus was born...

BAYESTAR

Bayes' Rule

- Take some data, X, and form a hypothesis, Θ. How probable is your hypothesis, given the data?

"likelihood" "prior"

"posterior"

$$P(\Theta|X) = \frac{P(X|\Theta) \times P(\Theta)}{P(X)}$$

"evidence"

- Marginalize to get rid of nuisance parameters

$$P(\Theta, \lambda|X) = \frac{\sum_\lambda P(X|\Theta, \lambda) P(\Theta, \lambda)}{P(X)}$$

- Or, if hypothesis is continuously parameterized,

$$p(\theta|x) = \frac{\int p(x|\theta, \lambda) p(\theta, \lambda) \mathrm{d}\lambda}{p(x)}$$

REV. T. BAYES

Problem setup: data, parameters

Data/observation

strain time series

$$\left.x_i(t_j)\right\}_{ij} \quad \begin{array}{l} N \text{ detectors} \\ M \text{ samples} \end{array}$$

amplitude, SNR; phase

$$\left.\rho_i, \tau_i, \gamma_i\right\}_i \quad N \text{ detectors}$$

TOA

note: not using phase right now

Nuisance variables

component masses

$$m_1, m_2, \mathbf{S}_1, \mathbf{S}_2$$

spins

intrinsic variables (fixed at maximum-likelihood estimates for triangulation)

luminosity distance; polarization angle

$$\tau_\oplus, D_\mathrm{L}, \iota, \psi, \phi_c$$

TOA at geocenter; inclination; coalescence phase

extrinsic variables

Parameters of interest

direction of source $\mathbf{n}$

e.g.,

right ascension, declination α, δ

Outline of calculation

Likelihood: factor into a time of arrival (TOA)-only contribution and an SNR-only contribution, both Gaussian

$$\mathcal{L} \propto \mathcal{L}_{\mathrm{SNR}} \times \mathcal{L}_{\mathrm{TOA}}$$

Prior: uniform in

$$\tau_{\oplus}, \phi_c, \psi, \cos\iota, {D_L}^3$$

Posterior: factor into an TOA-only contribution and an SNR-only contribution

$$p(\mathbf{n}|\hat{\tau}_1, \ldots, \hat{\tau}_N, \hat{\rho}_1, \ldots, \hat{\rho}_N)$$
$$= f_{\mathrm{TOA}}(\mathbf{n}|\hat{\tau}_1, \ldots, \hat{\tau}_N) \times f_{\mathrm{SNR}}(\mathbf{n}|\hat{\rho}_1, \ldots, \hat{\rho}_N)$$

Adaptive resolution

Evaluate **TOA** posterior **first**, then evaluate **SNR** posterior for those points that comprise the **99.99th percentile** of the TOA posterior.

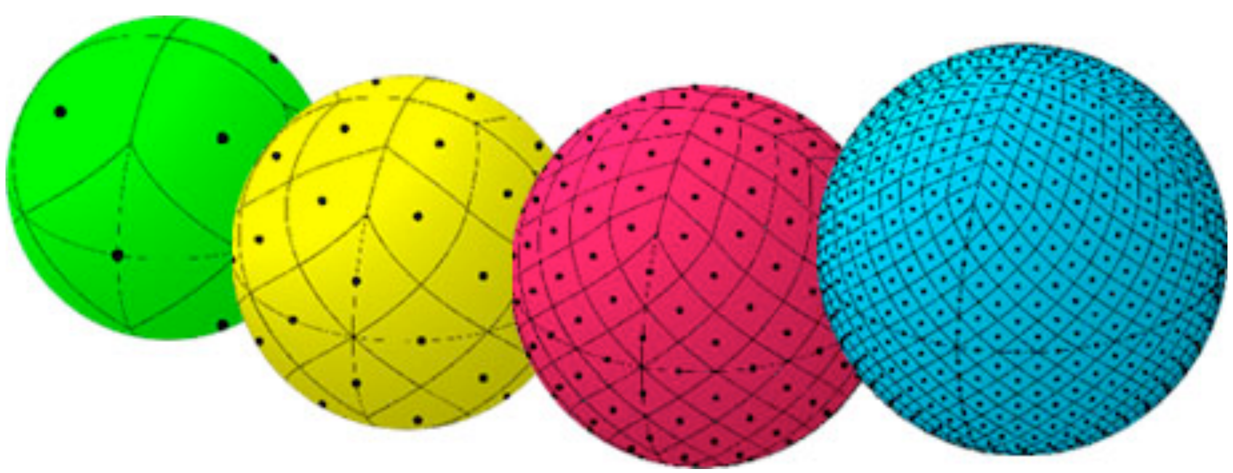

image: http://healpix.jpl.nasa.gov

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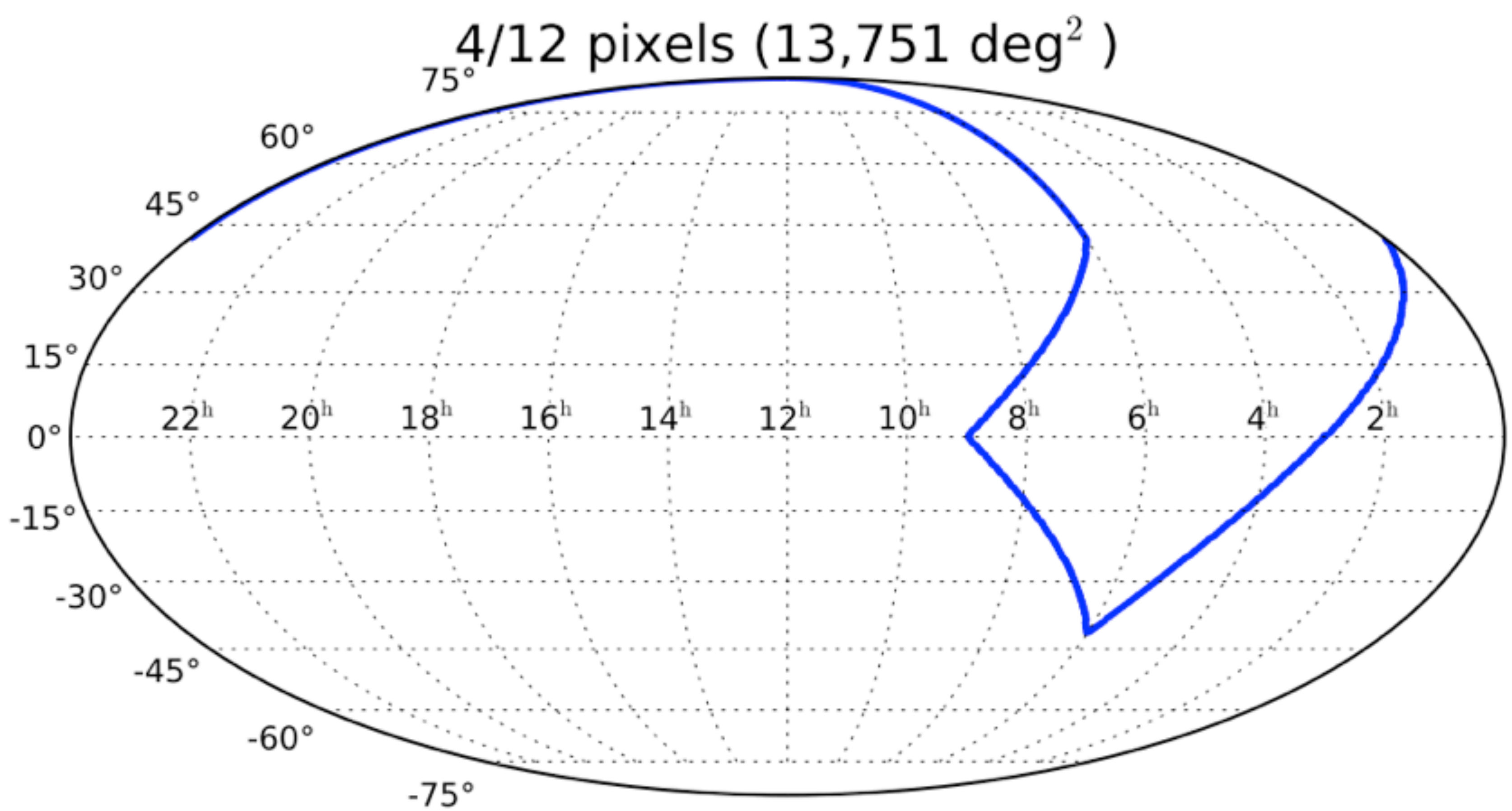

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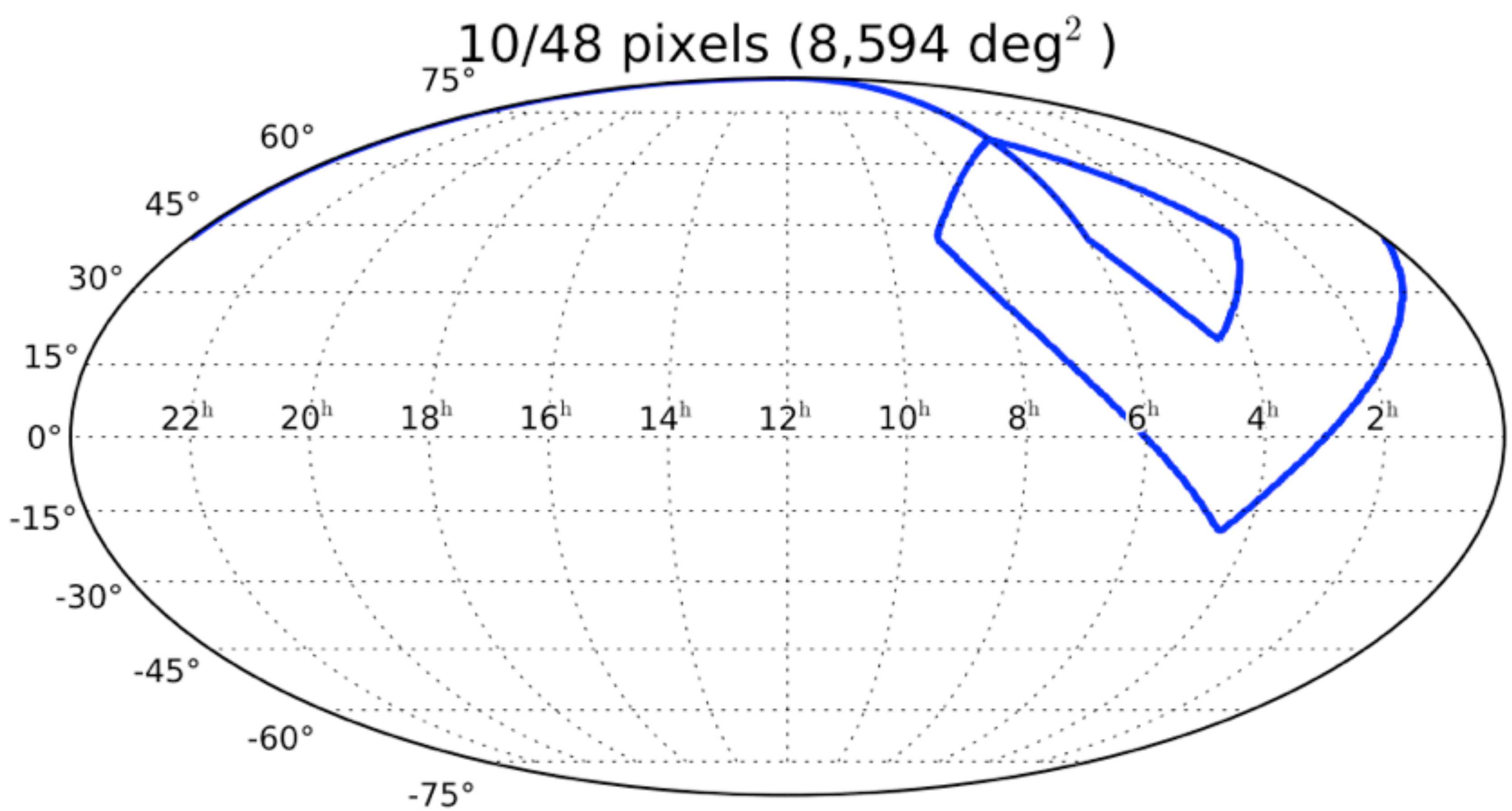

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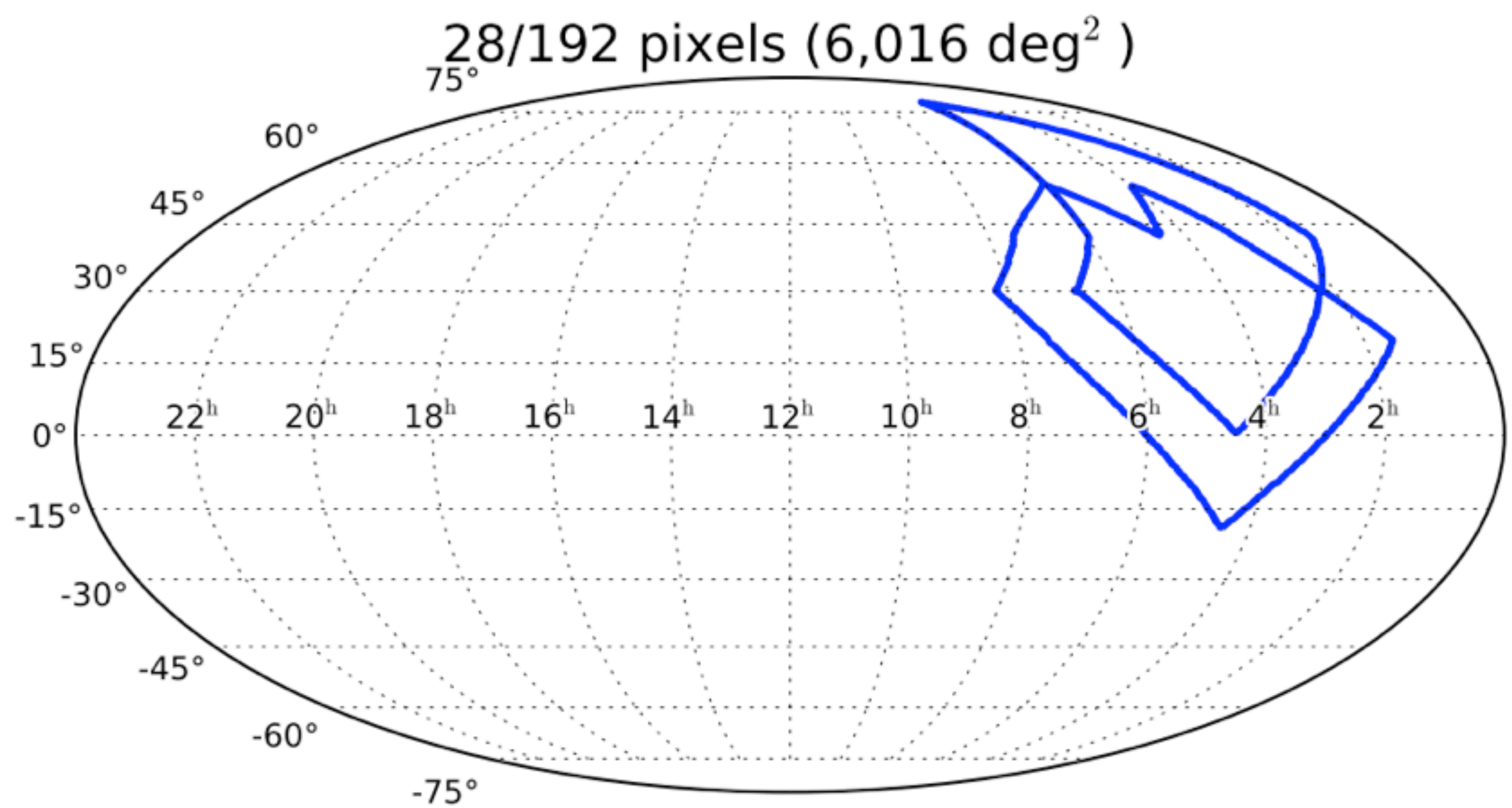

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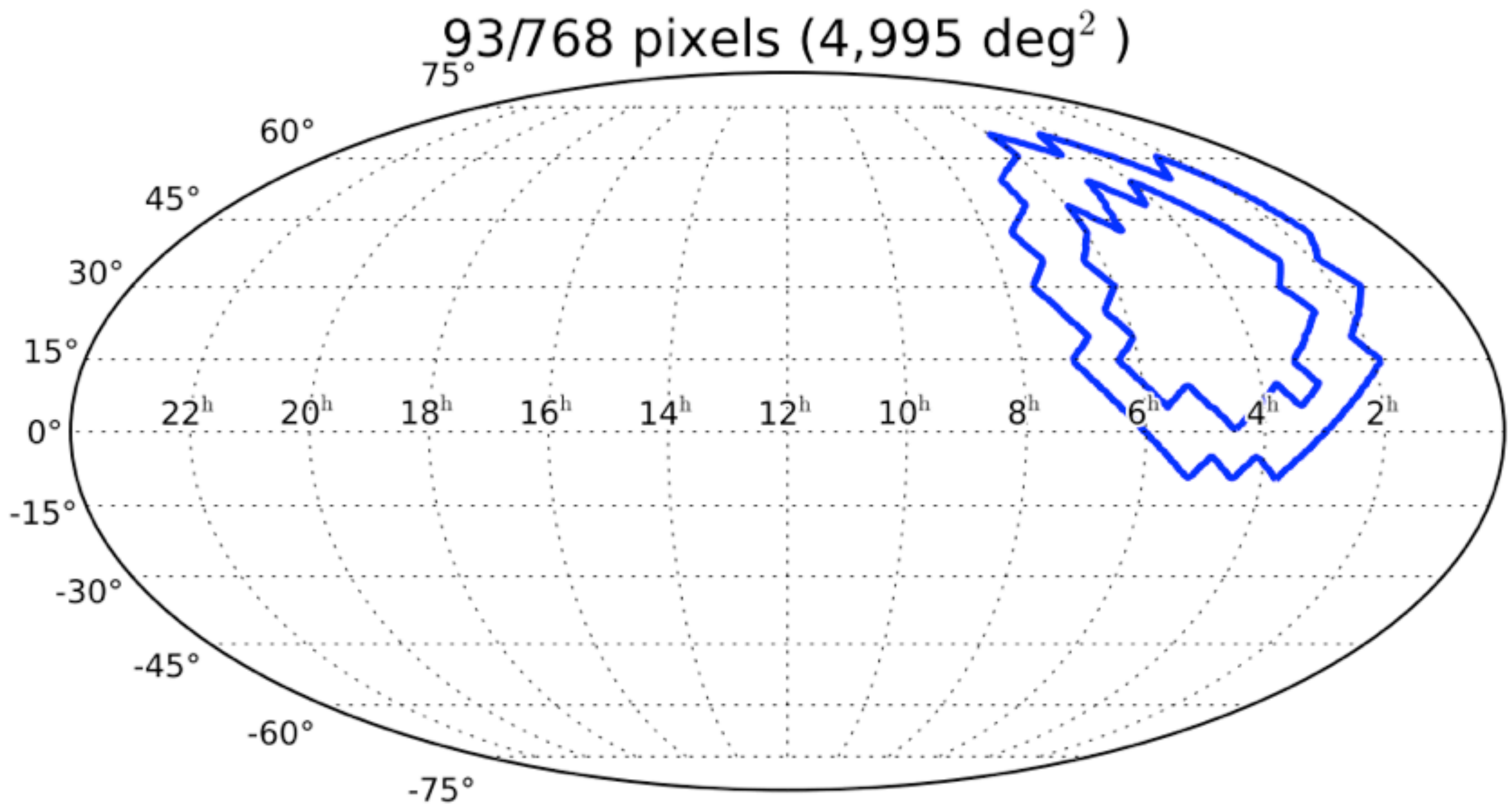

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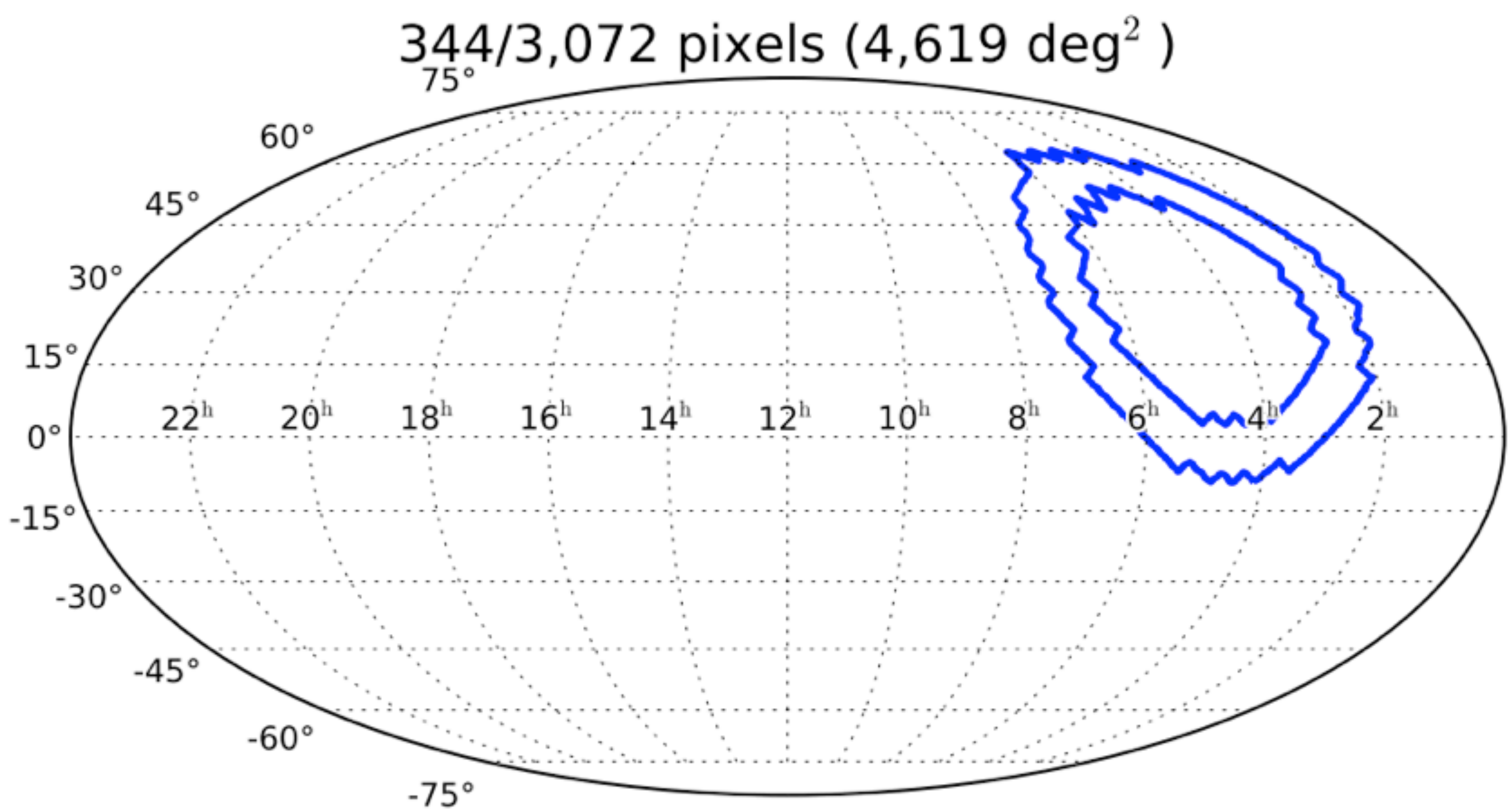

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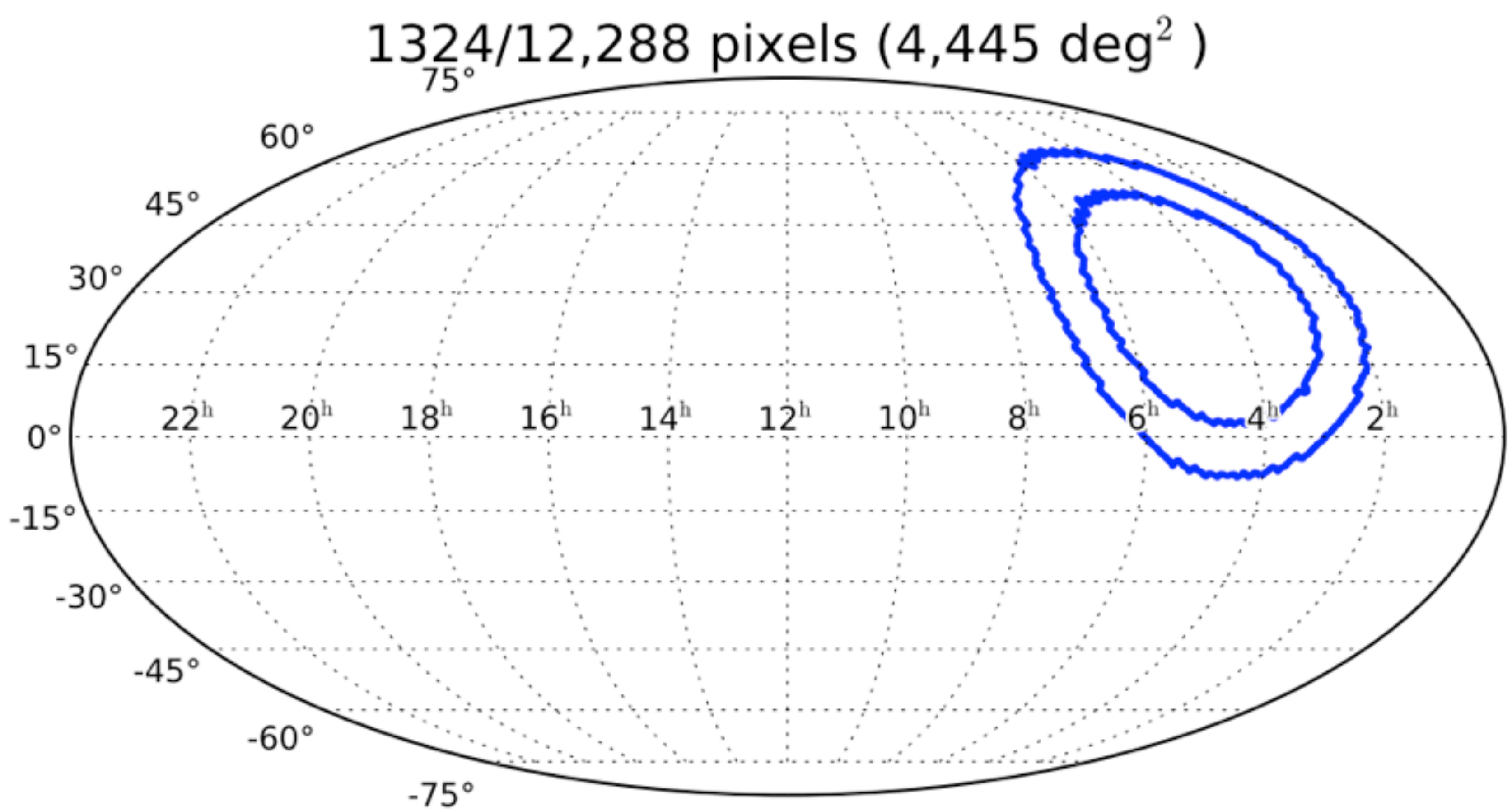

Adaptive resolution

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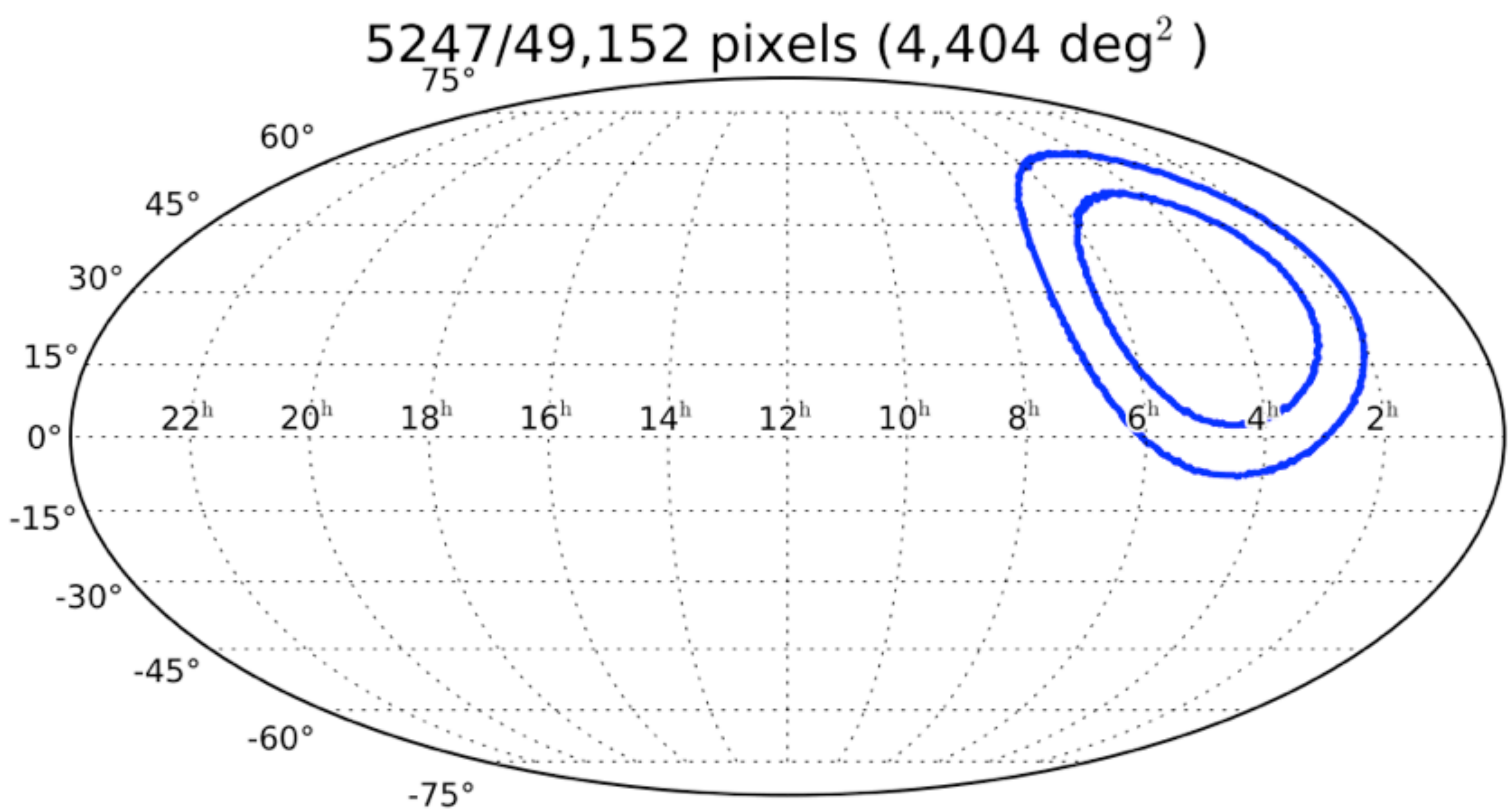
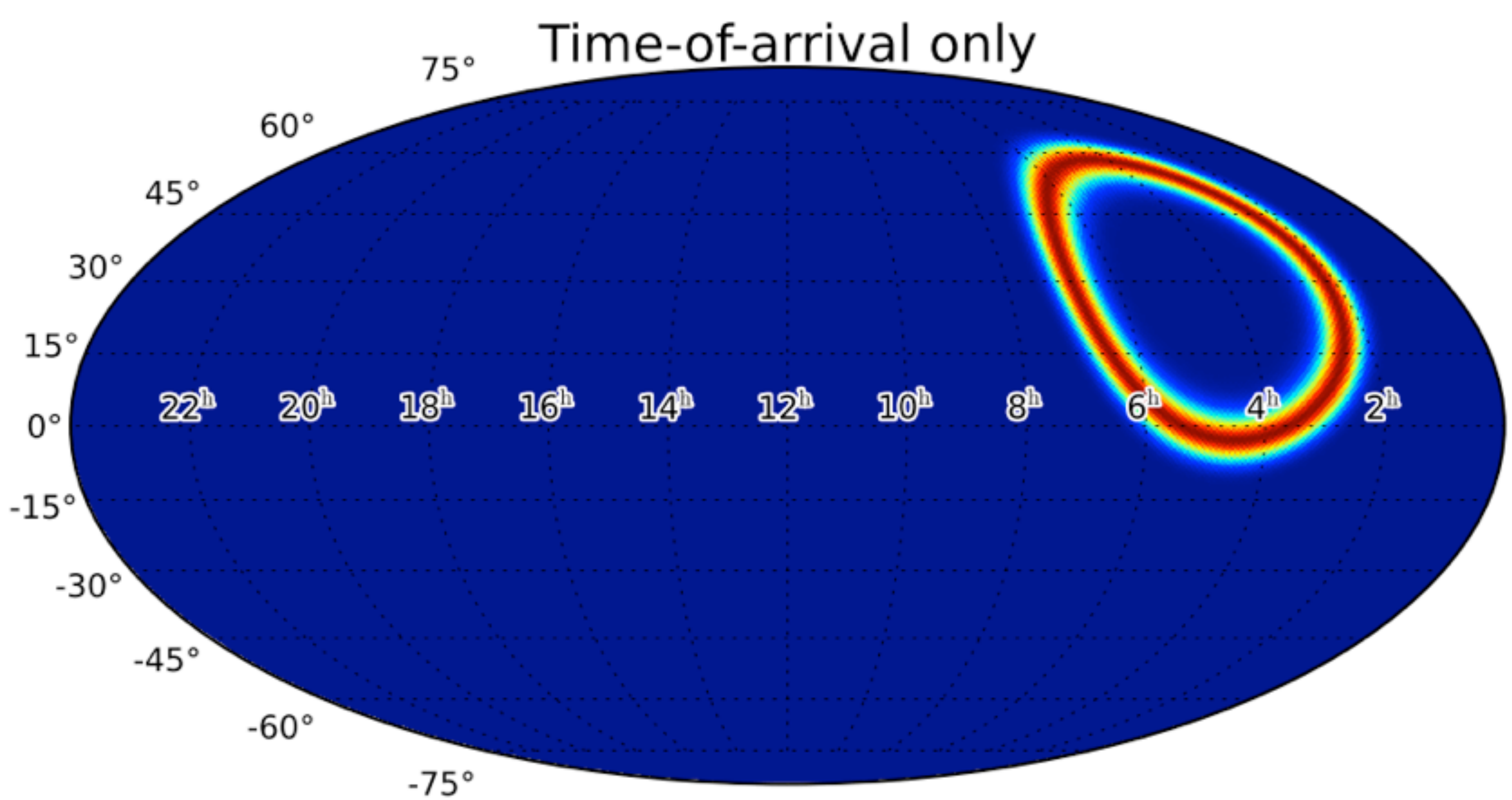


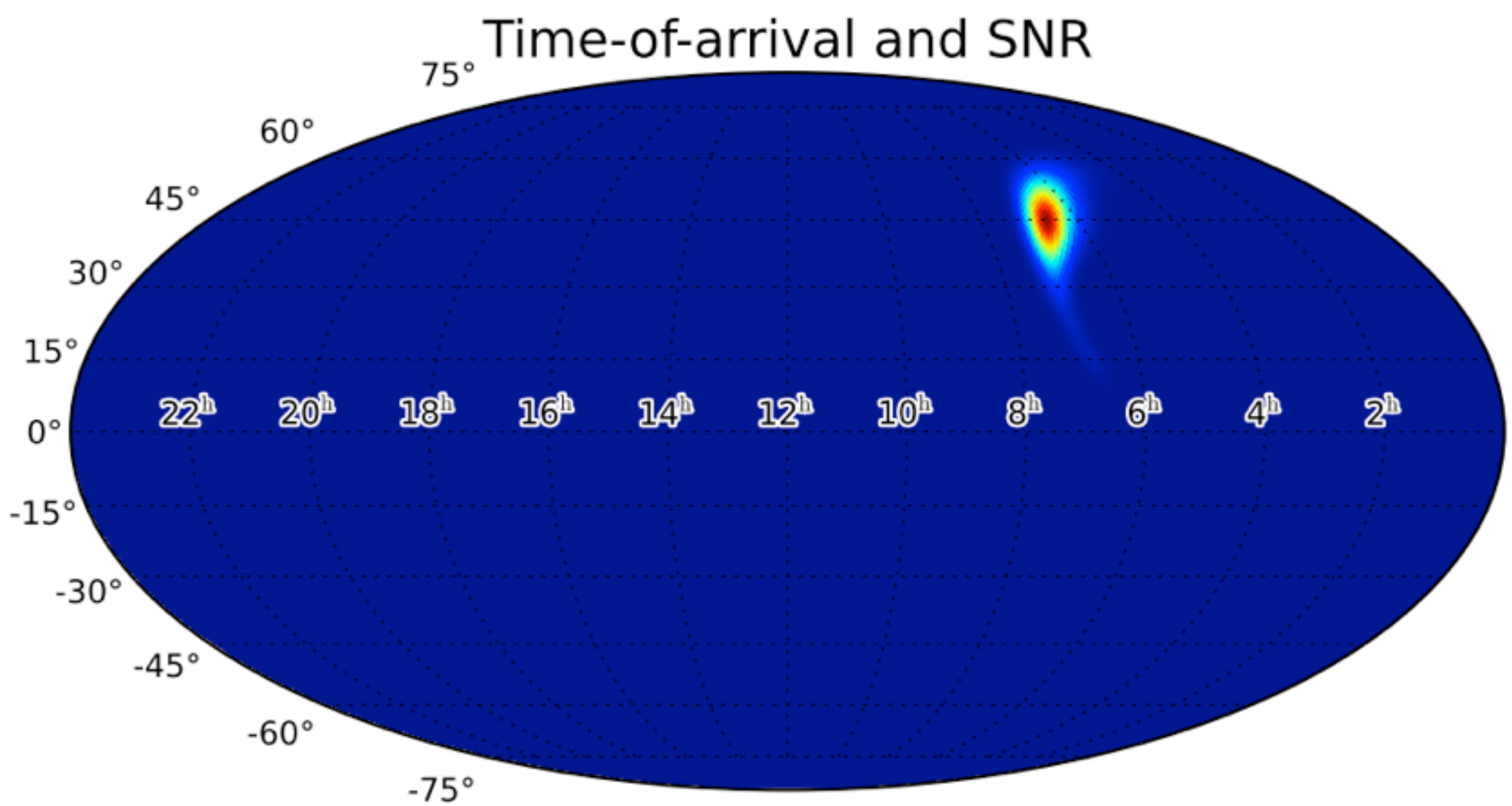
Adaptive resolution

Evaluate **TOA** posterior **first**, then evaluate **SNR** posterior for those points that comprise the **99.99th percentile** of the TOA posterior.



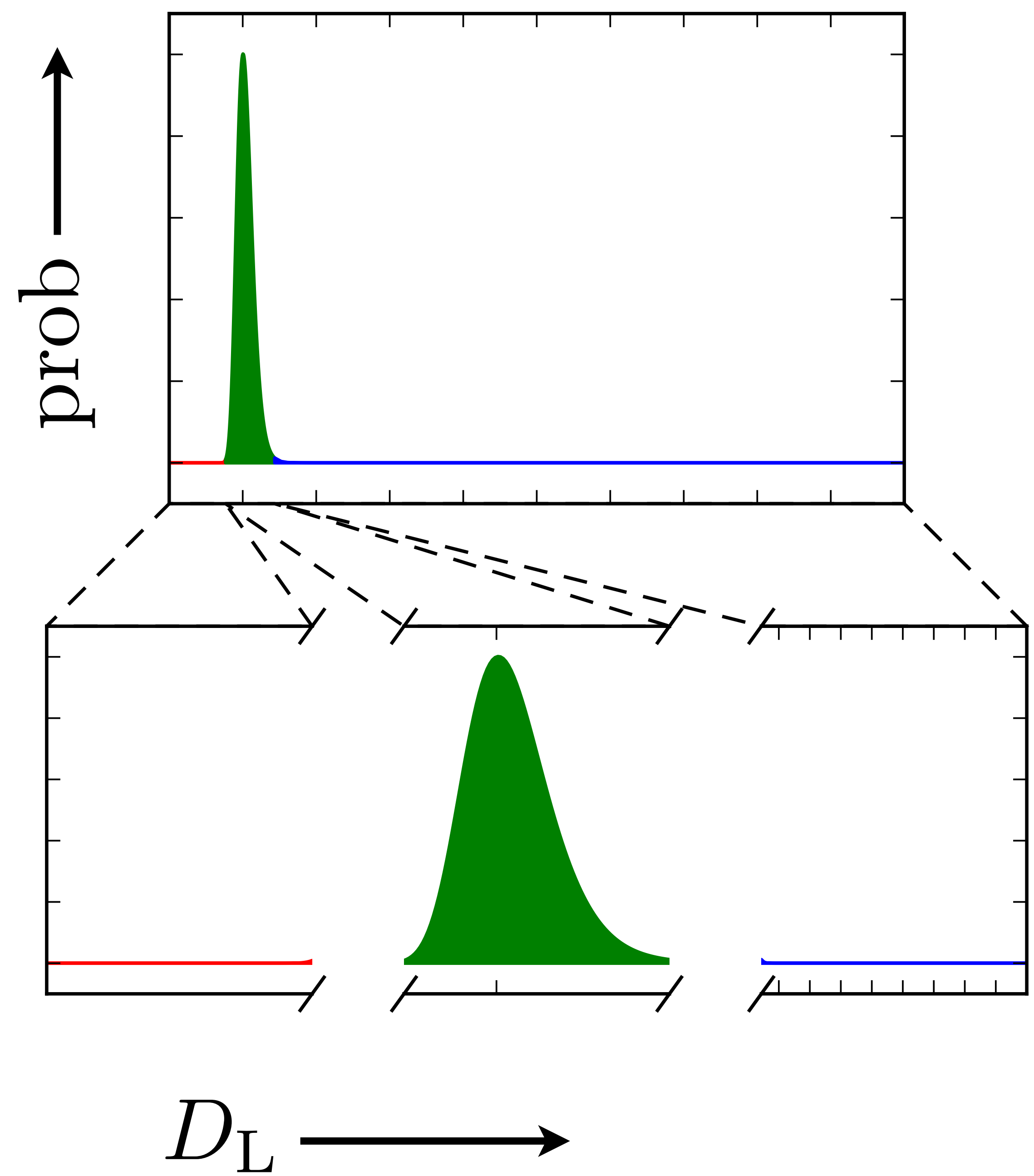
Adaptive resolution

Evaluate **TOA** posterior **first**, then evaluate **SNR** posterior for those points that comprise the **99.99th percentile** of the TOA posterior.



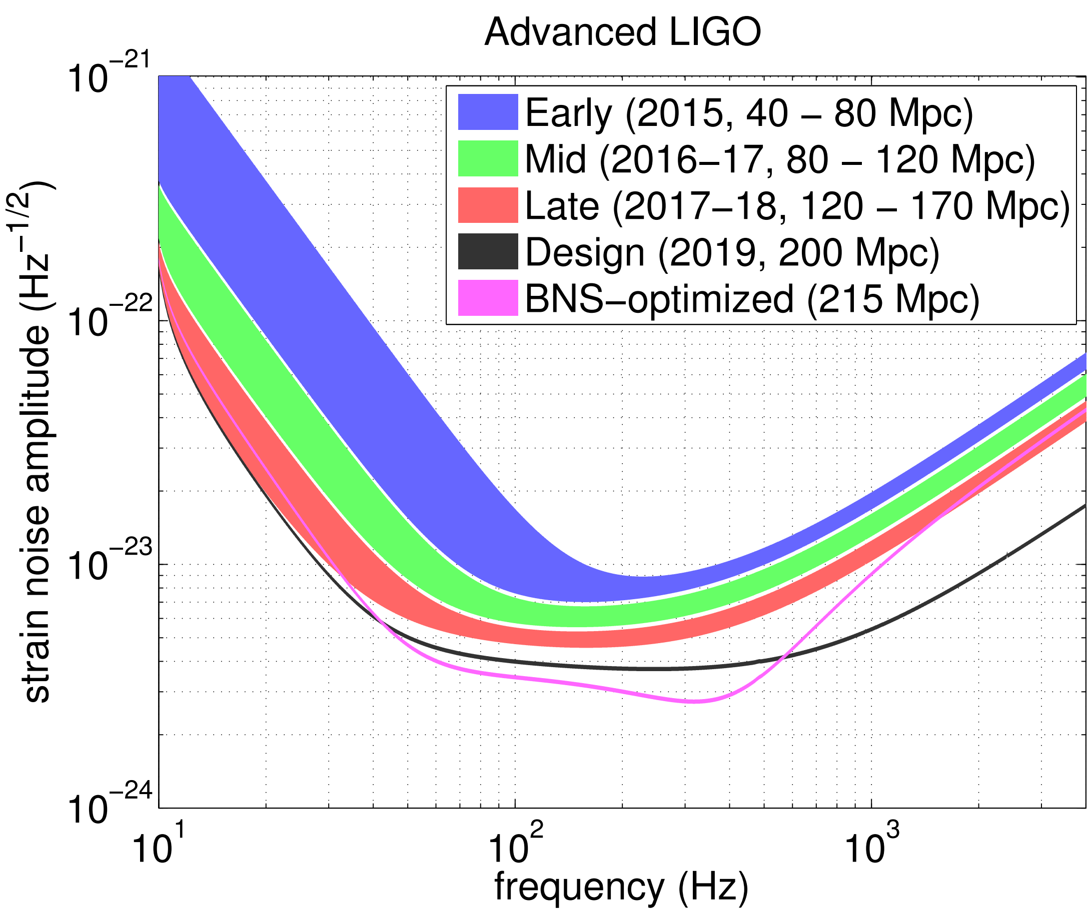
Distance marginalization

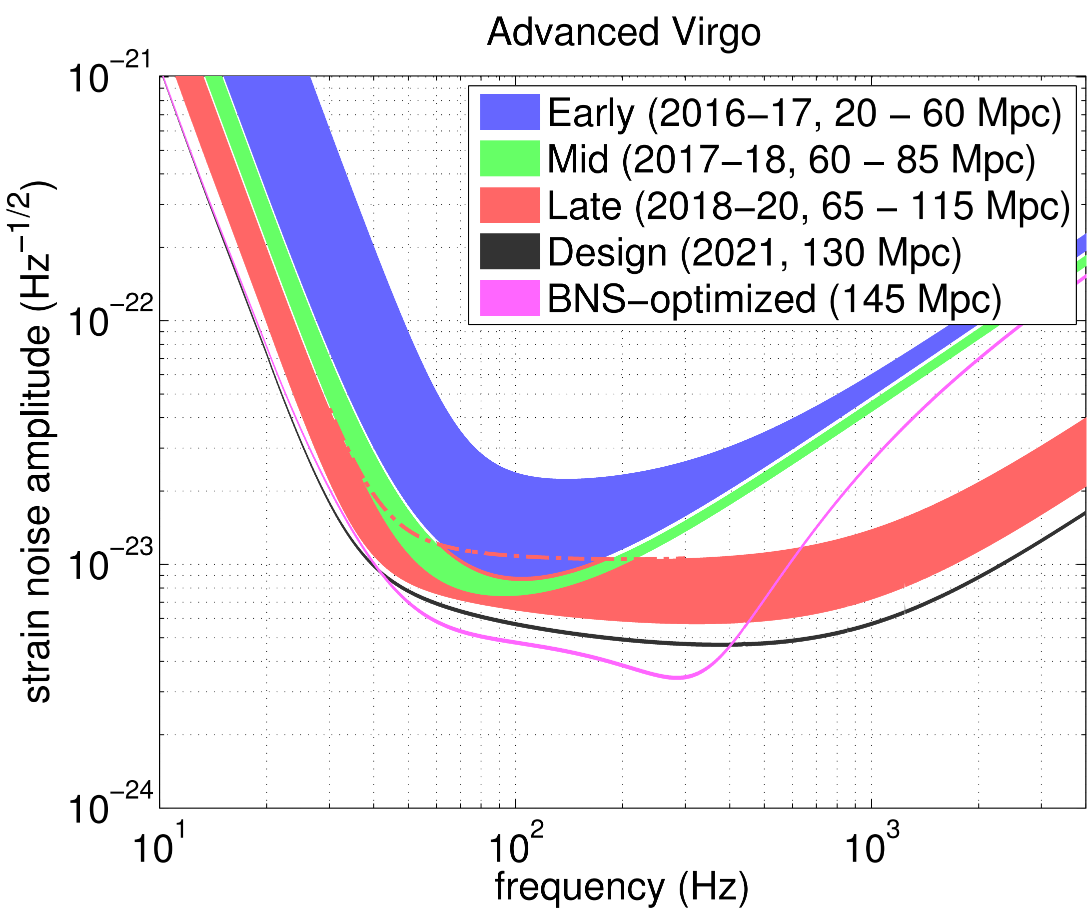
- Radial integrand peaks sharply at distance that is best supported by data
- Divide integration domain into 3 sub-domains that enclose maximum likelihood peak, small-distance tail, and large-distance tail
- Use adaptive Gaussian quadrature to discover which region dominates (gsl_integration_qagp)



CBC Mock Data Challenge

Observing scenarios

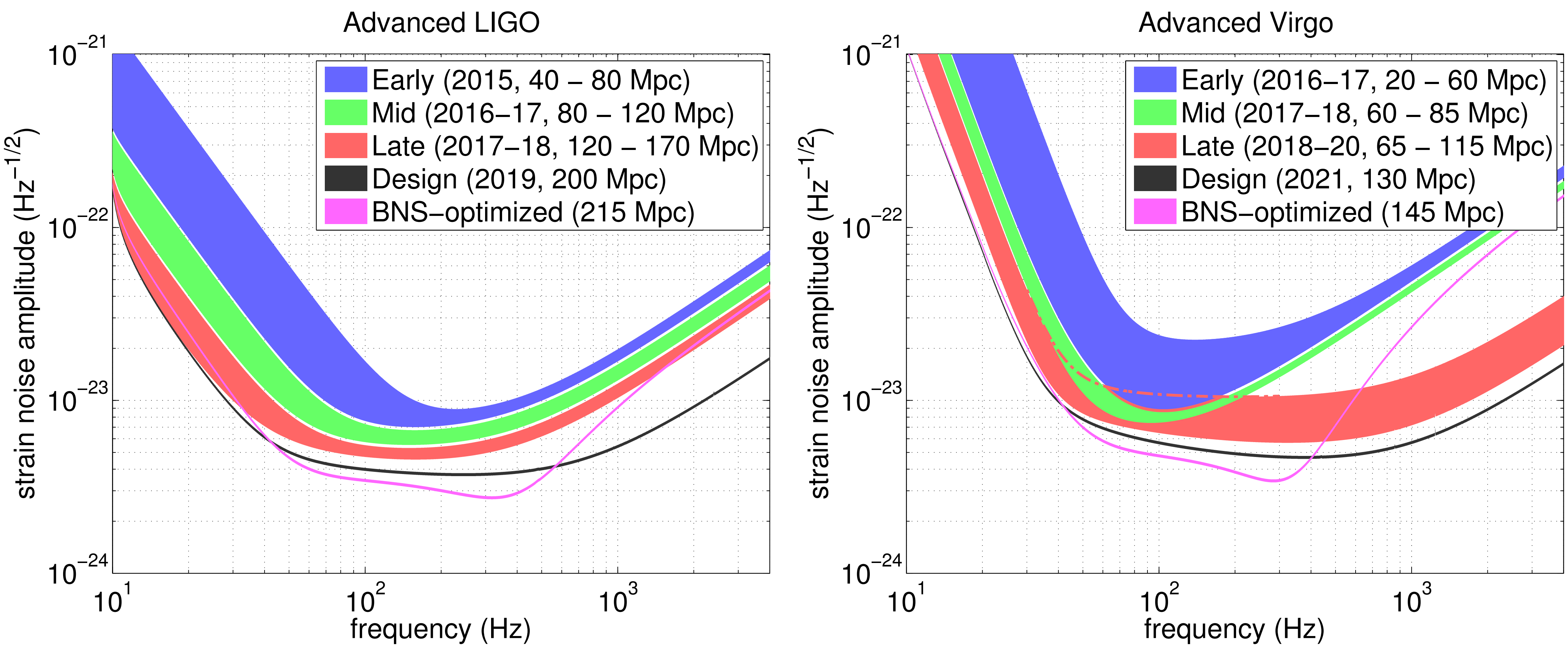




Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20	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

LSC & Virgo 2013, arXiv:1304.0670

Observing scenarios



Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ 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
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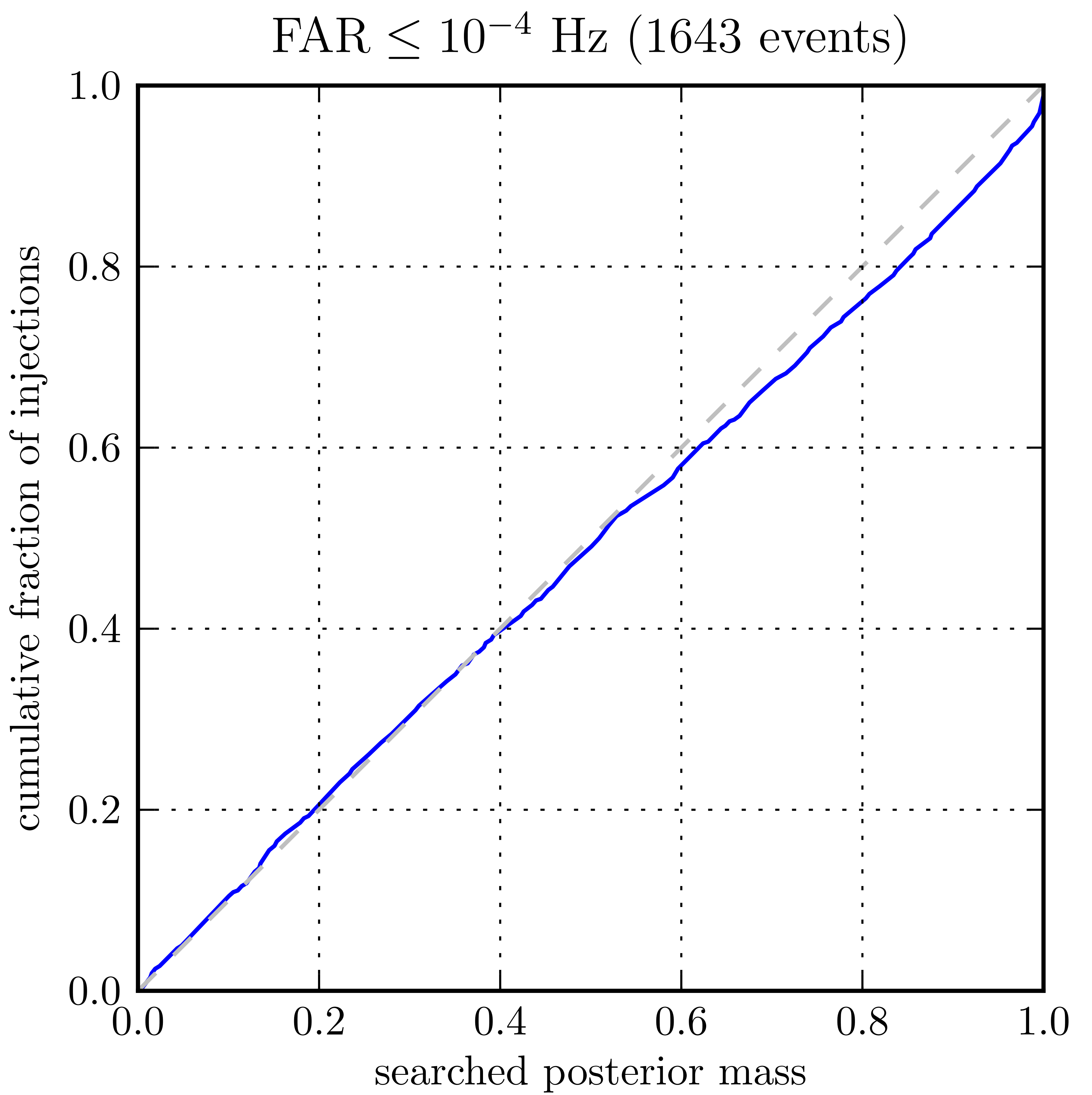
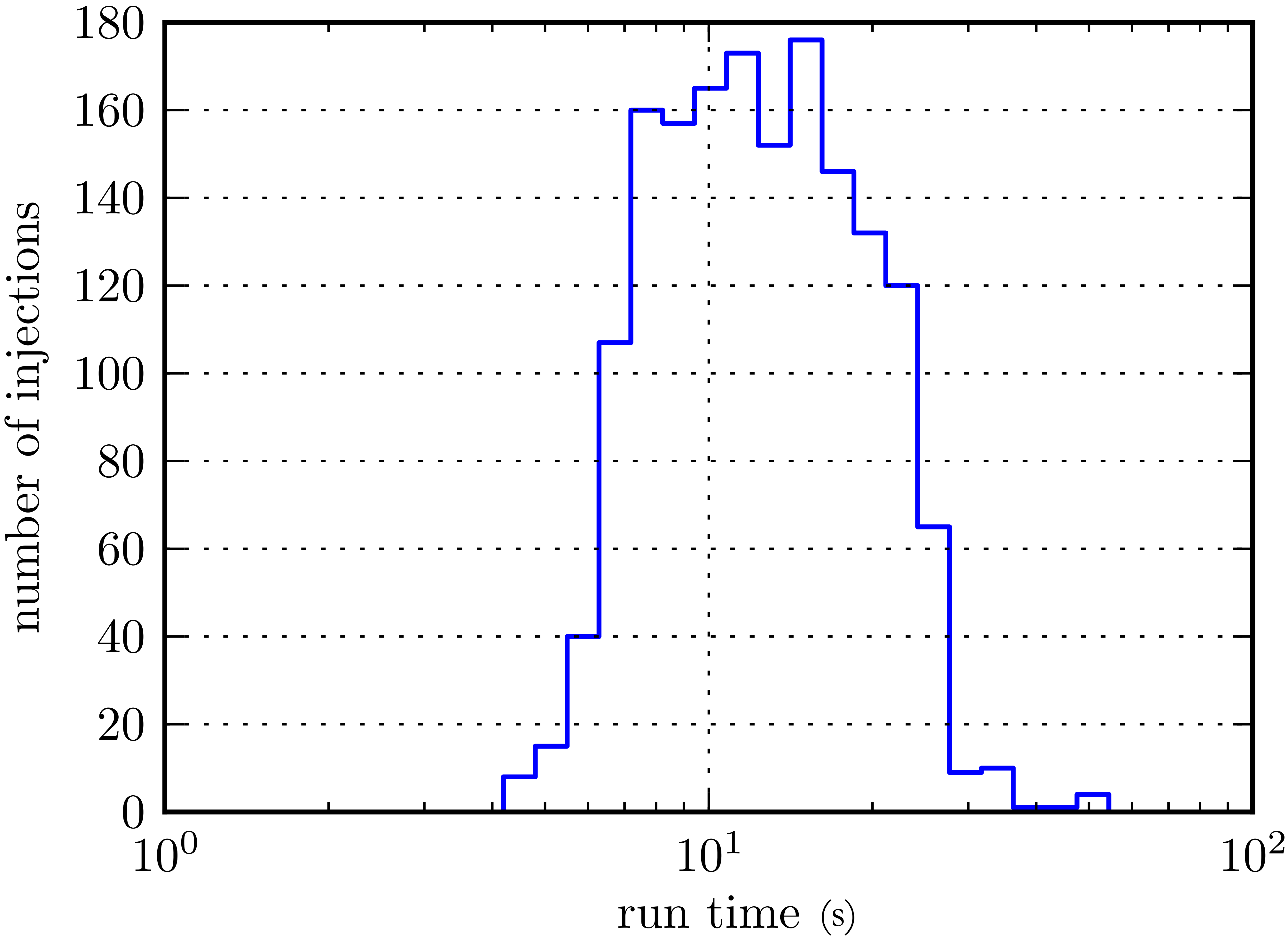
LSC & Virgo 2013, arXiv:1304.0670

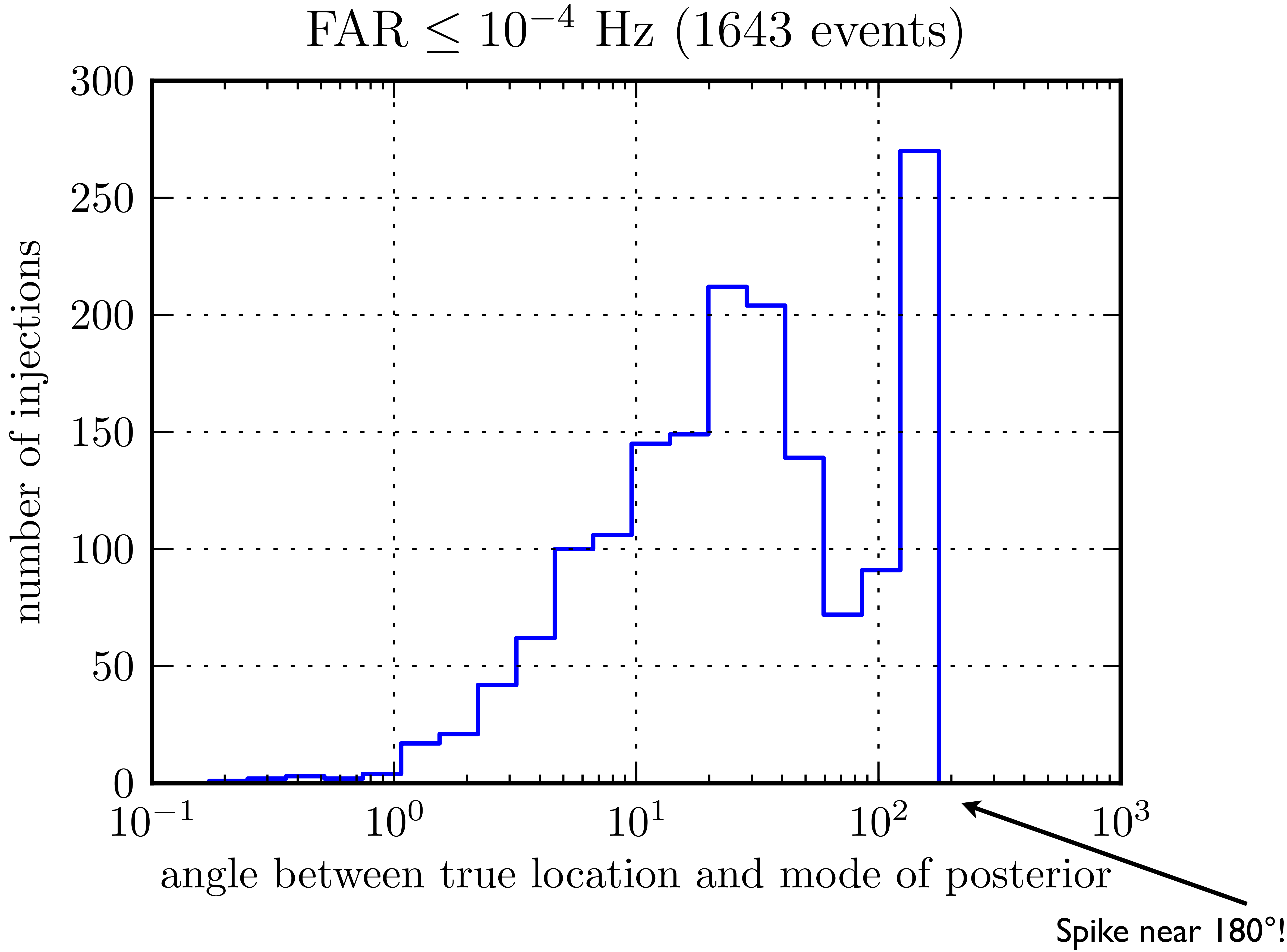
BNS Mock Data Challenge

5k injections
H1-L1 network
early aLIGO configuration
Uniformly distributed component masses
$1.2\ M_\odot \leq m_{1,2} \leq 1.6\ M$
TaylorT4threePointFivePN waveforms
Gaussian noise (recolored noise simulations exist too)


FAR ≤ 10^{-4} Hz (1643 events)
1.0
0.8
0.6
0.4
0.2
0.0
cumulative fraction of injections
0.0
0.2
0.4
0.6
0.8
1.0
searched posterior mass

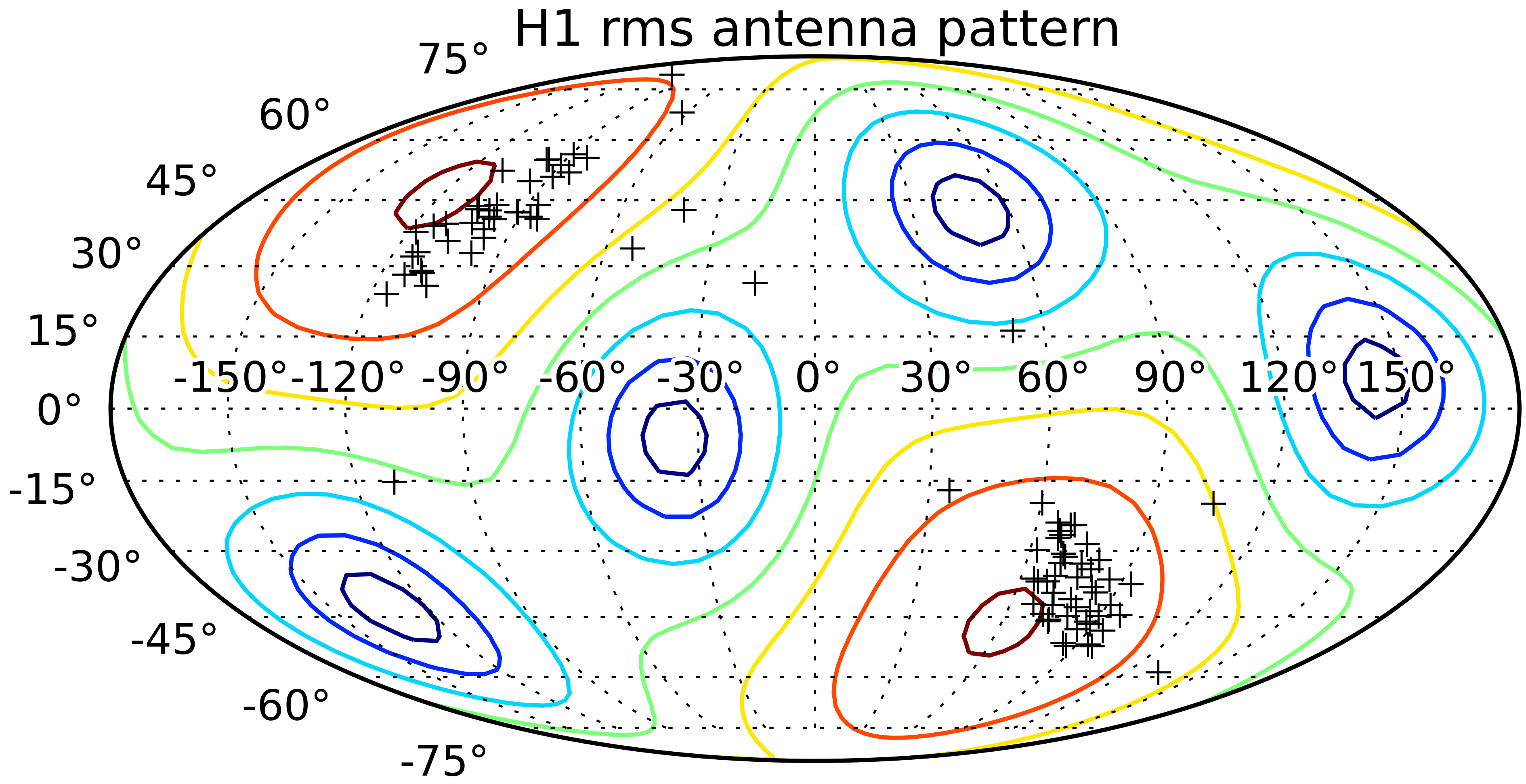


(single threaded; parallelized with OpenMP)

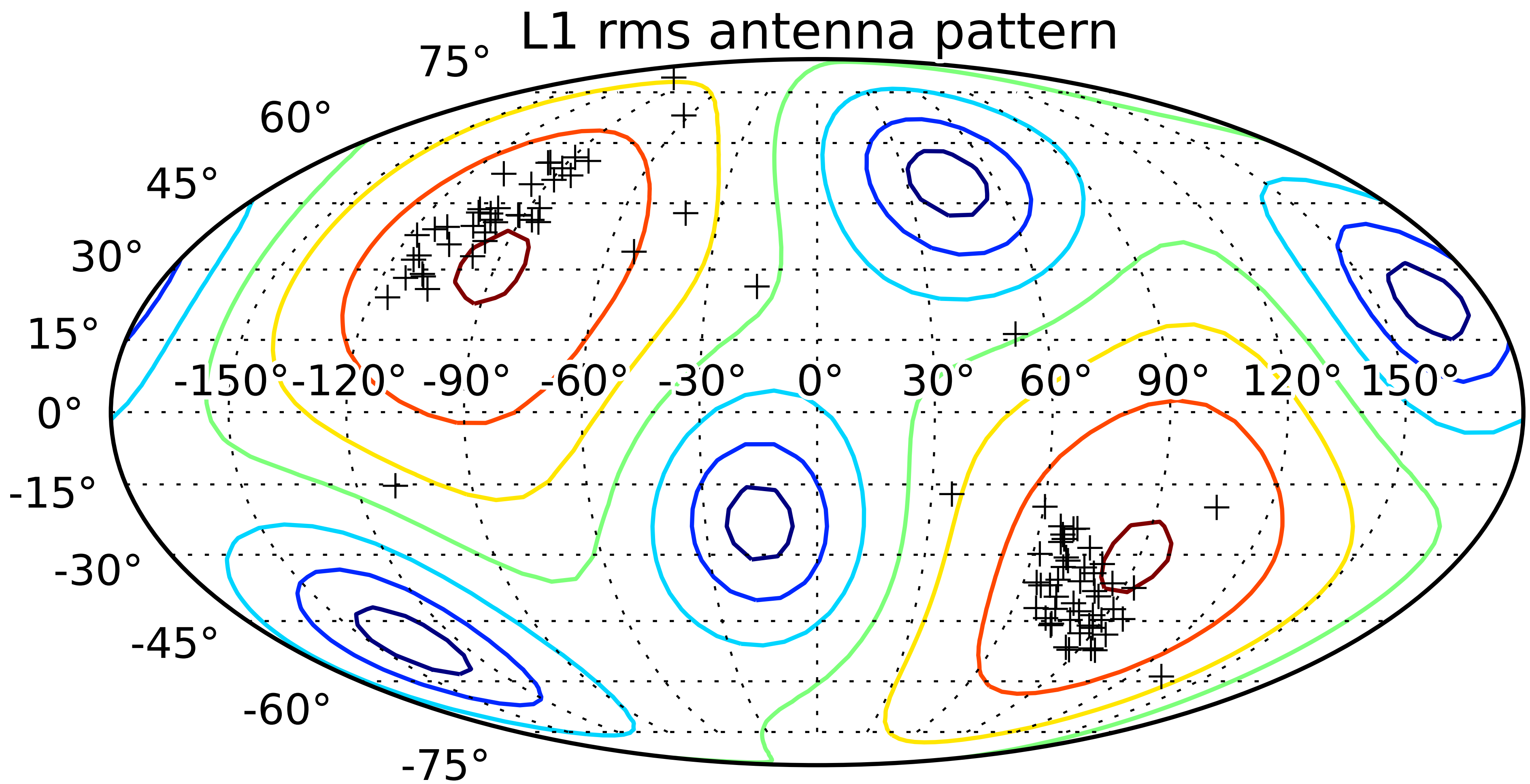


FAR ≤ 10^{-4} Hz (1643 events)
number of injections
300
250
200
150
100
50
0
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
angle between true location and mode of posterior
Spike near 180°!

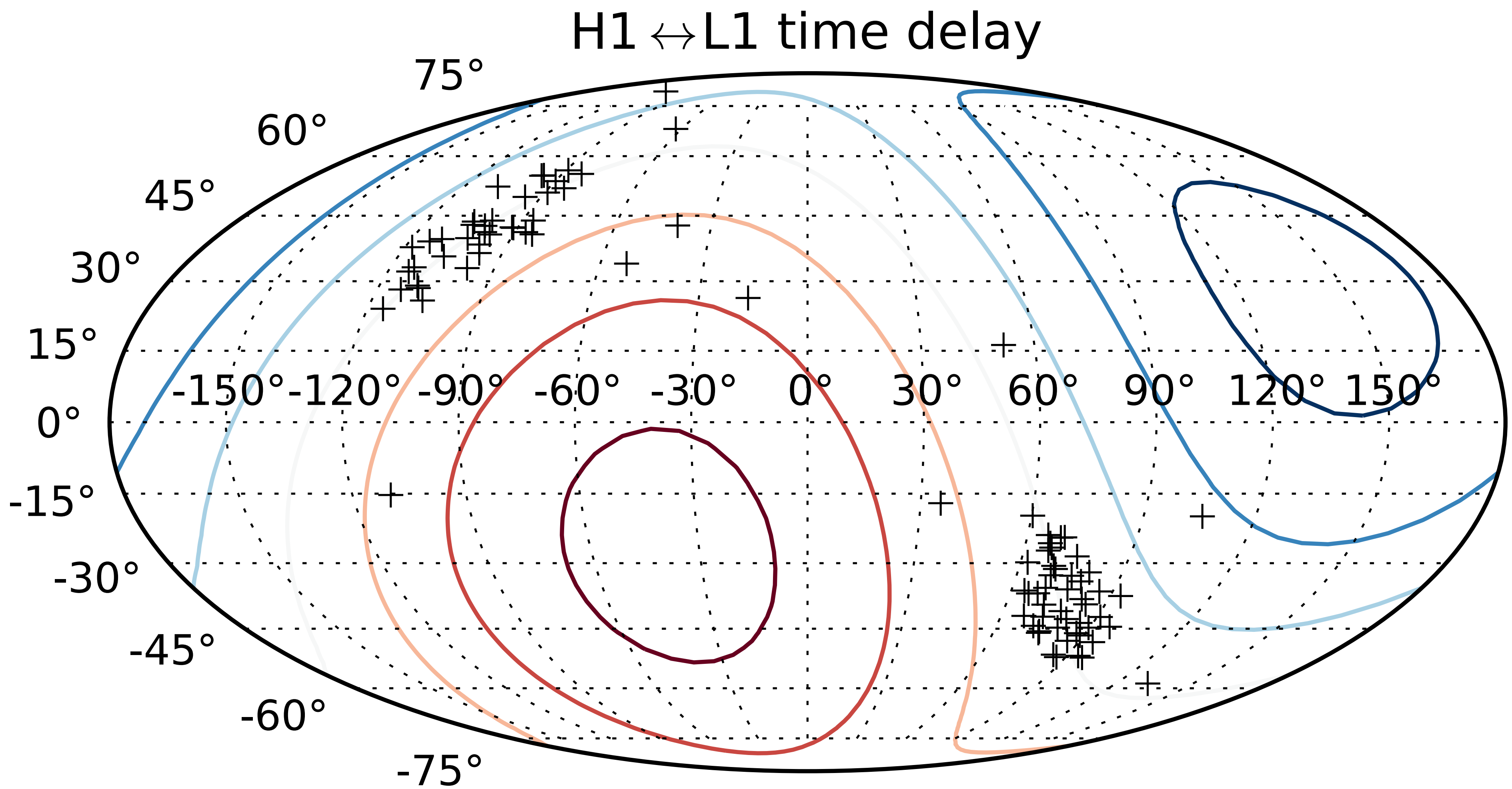
Why the bump at 180°?

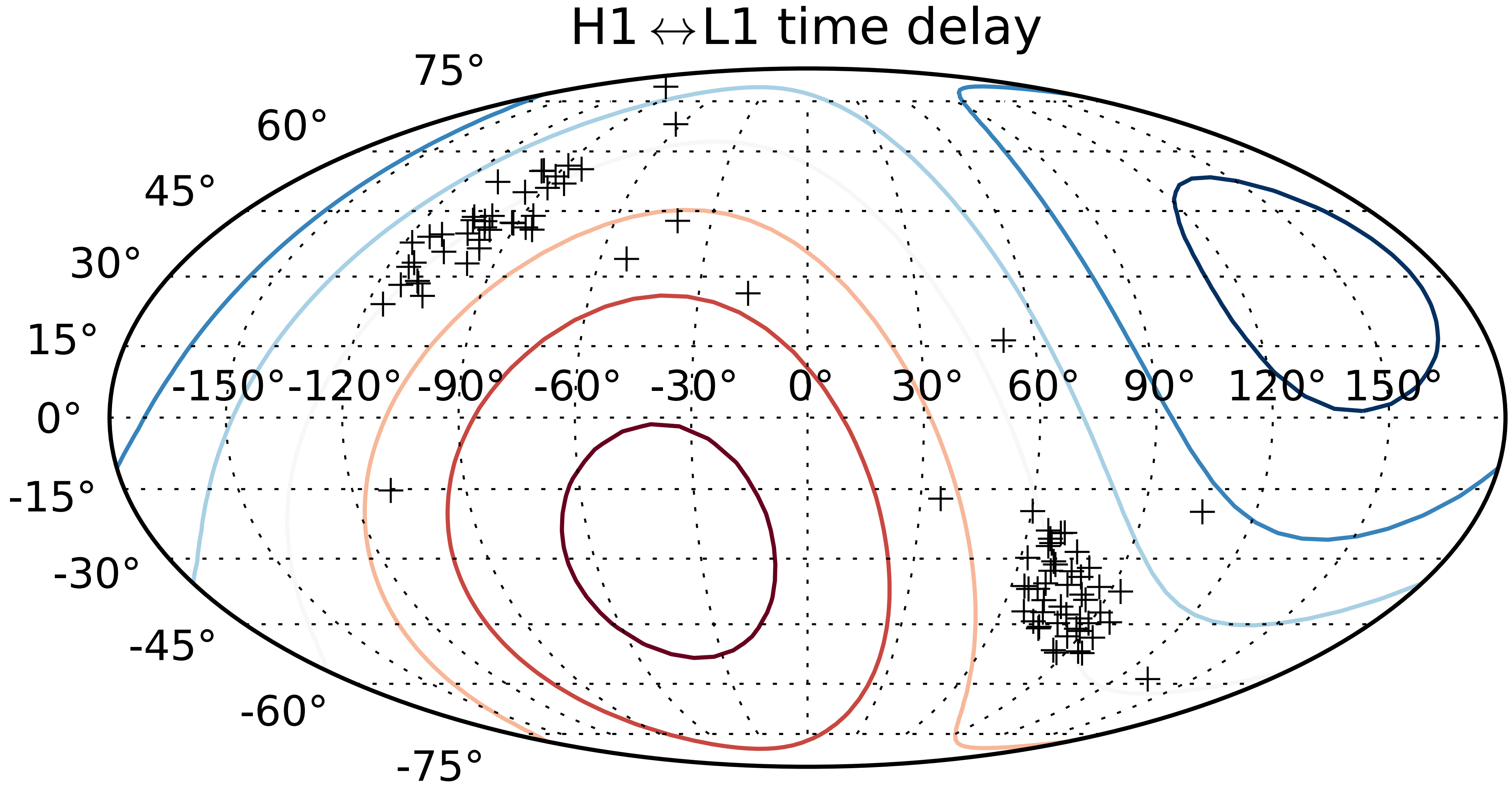


Why the bump at 180°?

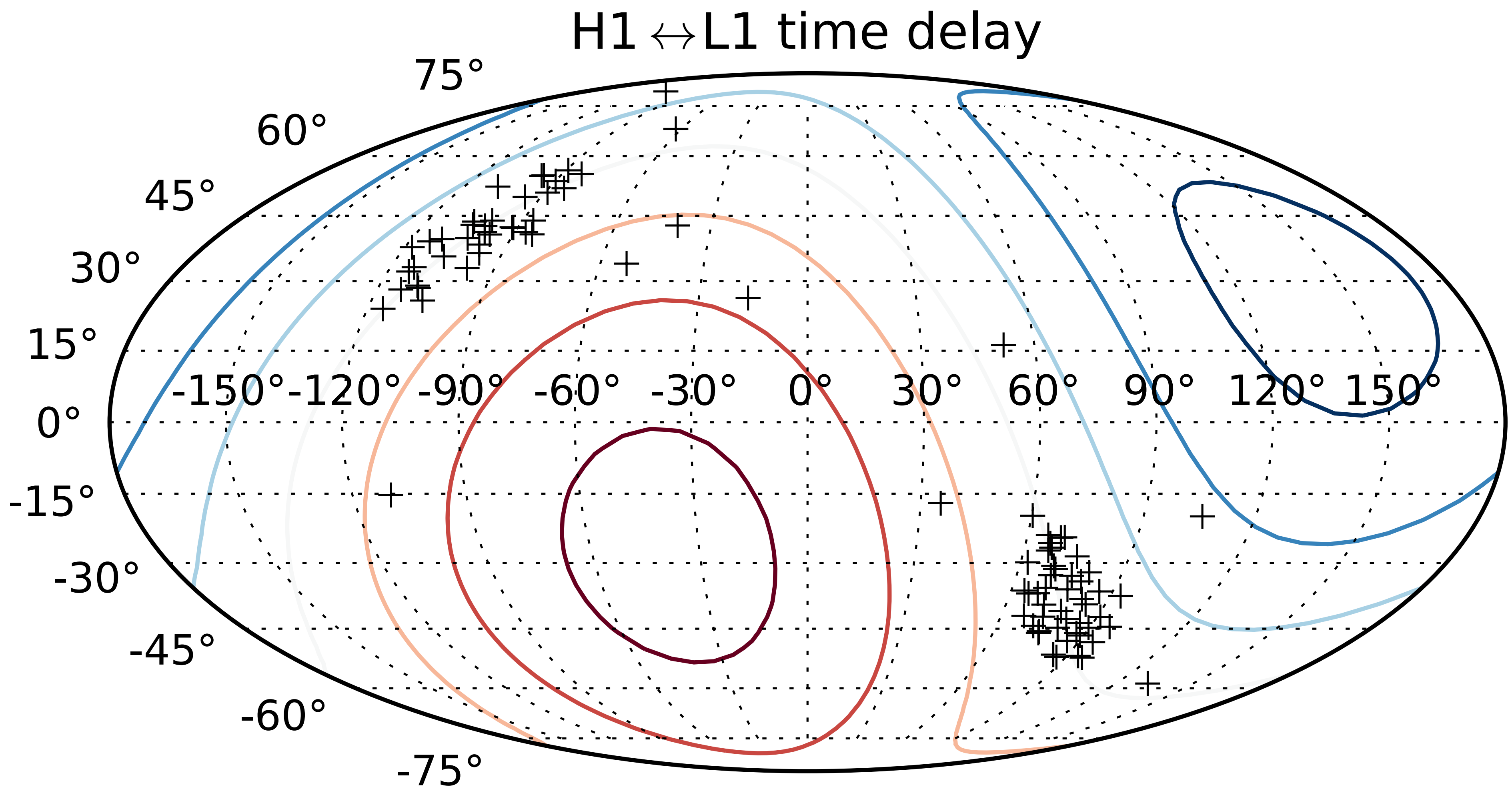


Why the bump at 180°?

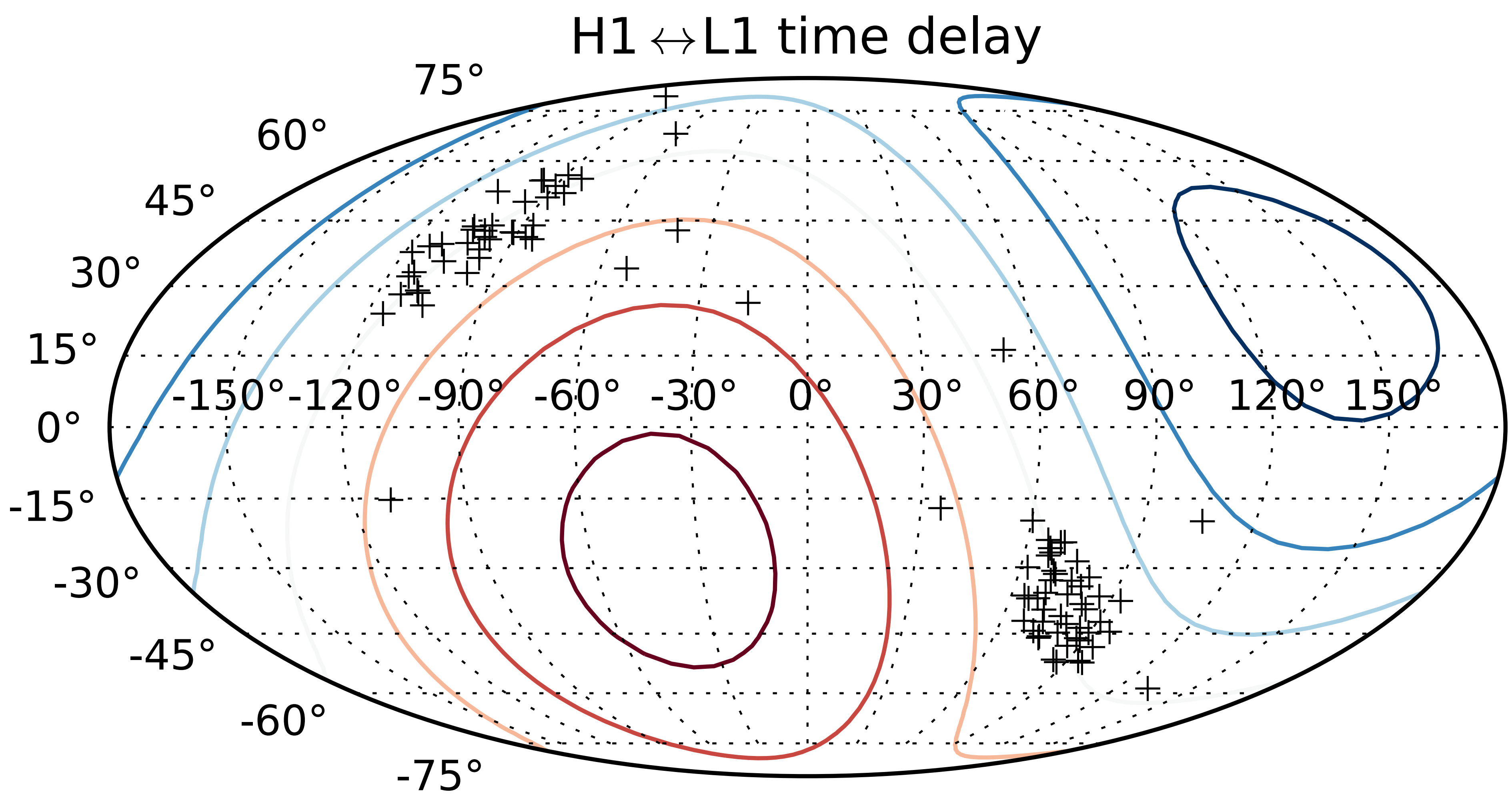



H1↔L1 time delay
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
-150°
-120°
-90°
-60°
-30°
0°
30°
60°
90°
120°
150°

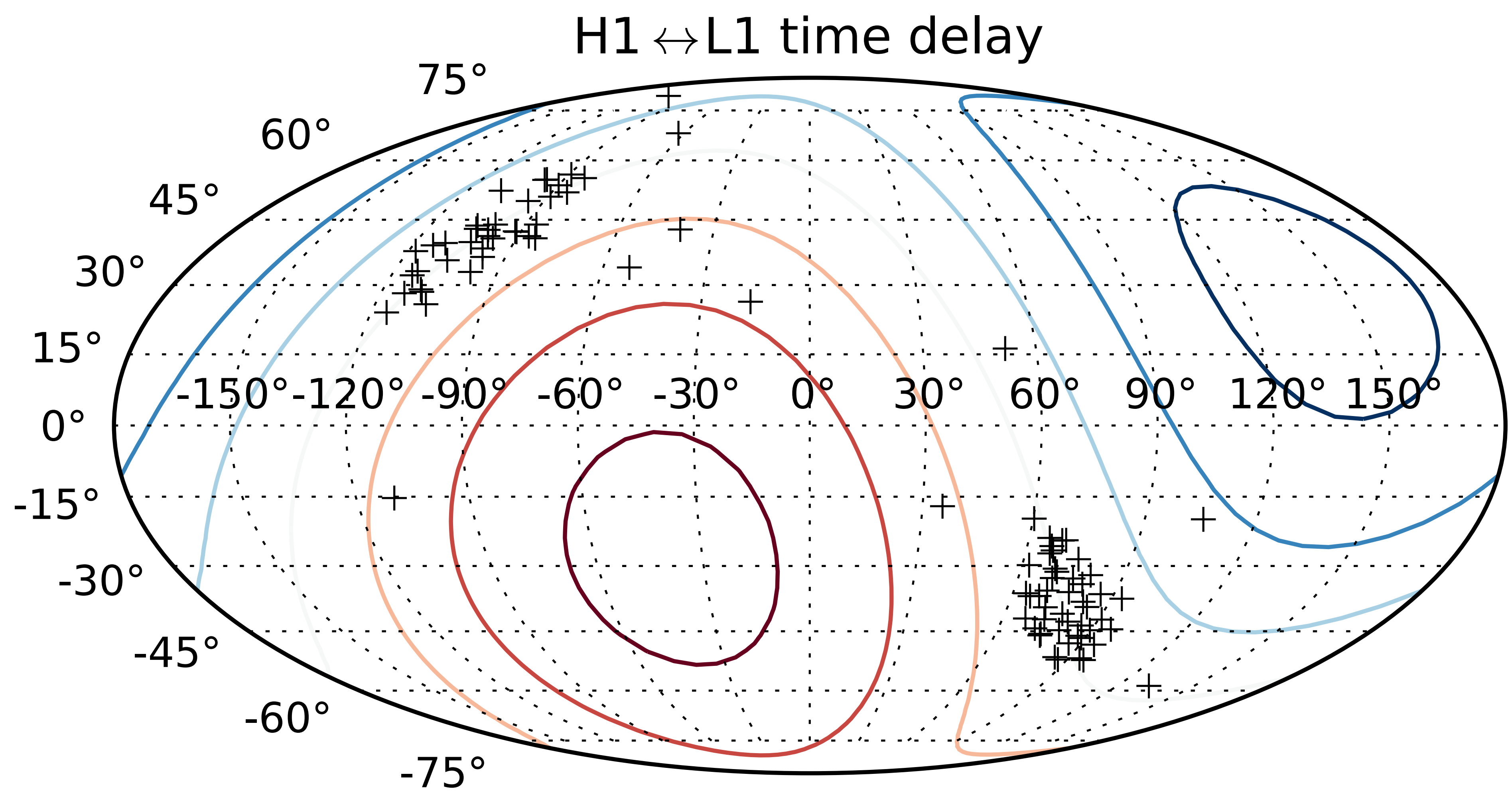
Crosshairs cluster at time delay=0 and maxima in H1, L1 antenna pattern



Crosshairs cluster at time delay=0 and maxima in H1, L1 antenna pattern ⟷ 2 locations, 180° apart, nearly indistinguishable by TOAs or SNR

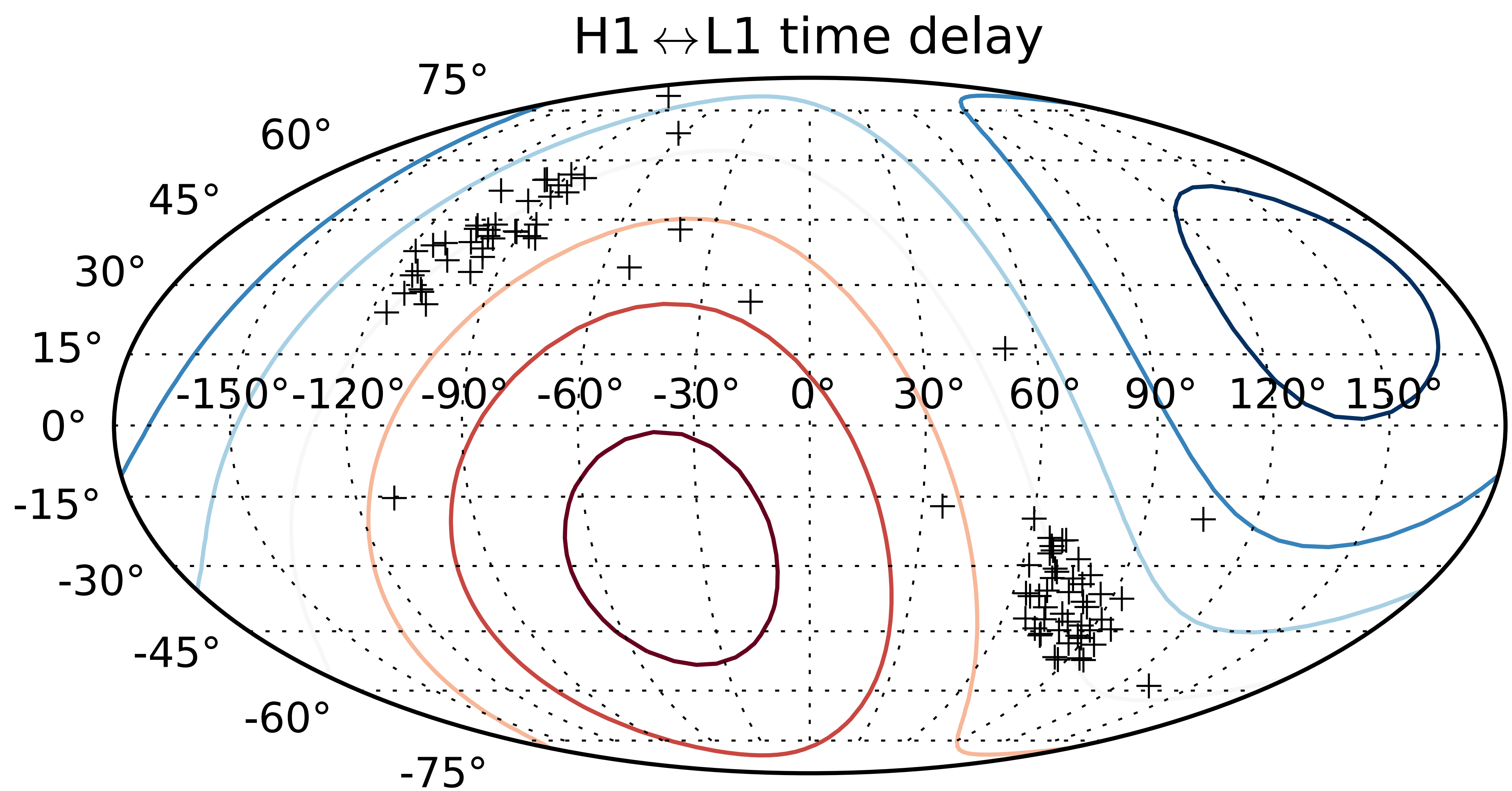


Crosshairs cluster at time delay=0 and maxima in H1, L1 antenna pattern ⟷ 2 locations, 180° apart, nearly indistinguishable by TOAs or SNR



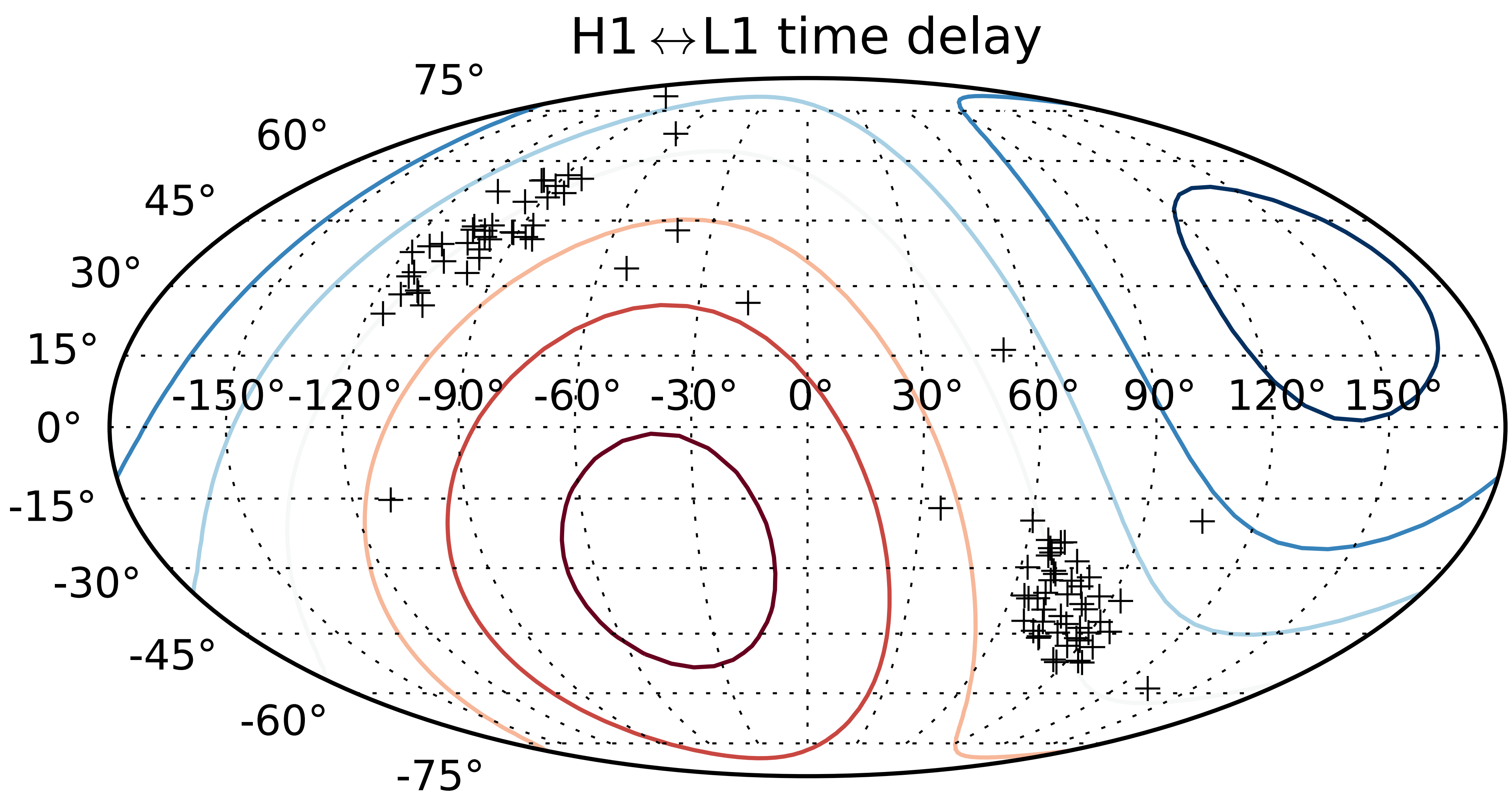
Bump near 180° is inevitable, given H1,L1 configuration.

Crosshairs cluster at time delay=0 and maxima in H1, L1 antenna pattern ⟷ 2 locations, 180° apart, nearly indistinguishable by TOAs or SNR



Bump near 180° is inevitable, given H1,L1 configuration. Worse: these degenerate points are almost 12h apart in RA.

Crosshairs cluster at time delay=0 and maxima in H1, L1 antenna pattern ⟷ 2 locations, 180° apart, nearly indistinguishable by TOAs or SNR



Bump near 180° is inevitable, given H1,L1 configuration.
Worse: these degenerate points are almost 12h apart in RA.

Multiple ***nights*** and multiple ***optical facilities required*** to follow up many GW events!

Observing scenarios

Observing scenarios

Epoch
2015
2016–17
2017–18
2019+
2022+ (India)

Observing scenarios

Epoch	Number of BNS Detections	% BNS Localized within	
		5 deg^2	20 deg^2
2015	0.0004 – 3	–	–
2016–17	0.006 – 20	2	5 – 12
2017–18	0.04 – 100	1 – 2	10 – 12
2019+	0.2 – 200	3 – 8	8 – 28
2022+ (India)	0.4 – 400	17	48

Observing scenarios document doesn't even bother to put a number for % localized in 2015 run...

Observing scenarios

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2019+	0.2 – 200	3 – 8	8 – 28
2022+ (India)	0.4 – 400	17	48

Observing scenarios document doesn't even bother to put a number for % localized in 2015 run...

Statistically, in "2015 epoch" MDC:

	% BNS localized within 5 deg^2	% BNS localized within 20 deg^2
with $\rho_c \geq 12$	2.2 ± 0.6%	9.8 ± 1.2%

...for good reason, considering the sky maps for the H1L1 events in the MDC.

Observing scenarios

Epoch	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
2015	0.0004 – 3	–	–
2016–17	0.006 – 20	2	5 – 12
2017–18	0.04 – 100	1 – 2	10 – 12
2019+	0.2 – 200	3 – 8	8 – 28
2022+ (India)	0.4 – 400	17	48

These numbers will be more interesting to fill in as MDCs progress through detector configurations...

Observing scenarios

Epoch	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
2015	0.0004 – 3	–	–
2016–17	0.006 – 20	2	5 – 12
2017–18	0.04 – 100	1 – 2	10 – 12
2019+	0.2 – 200	3 – 8	8 – 28
2022+ (India)	0.4 – 400	17	48

Team assembled to produce MDCs for all of the observing scenarios: Chad Hanna, Chris Pankow, Branson Stephens, Alex Urban, Sarah Caudill, Ruslan Vaulin, Salvatore Vitale, Larry Price, Leo Singer

Observing scenarios

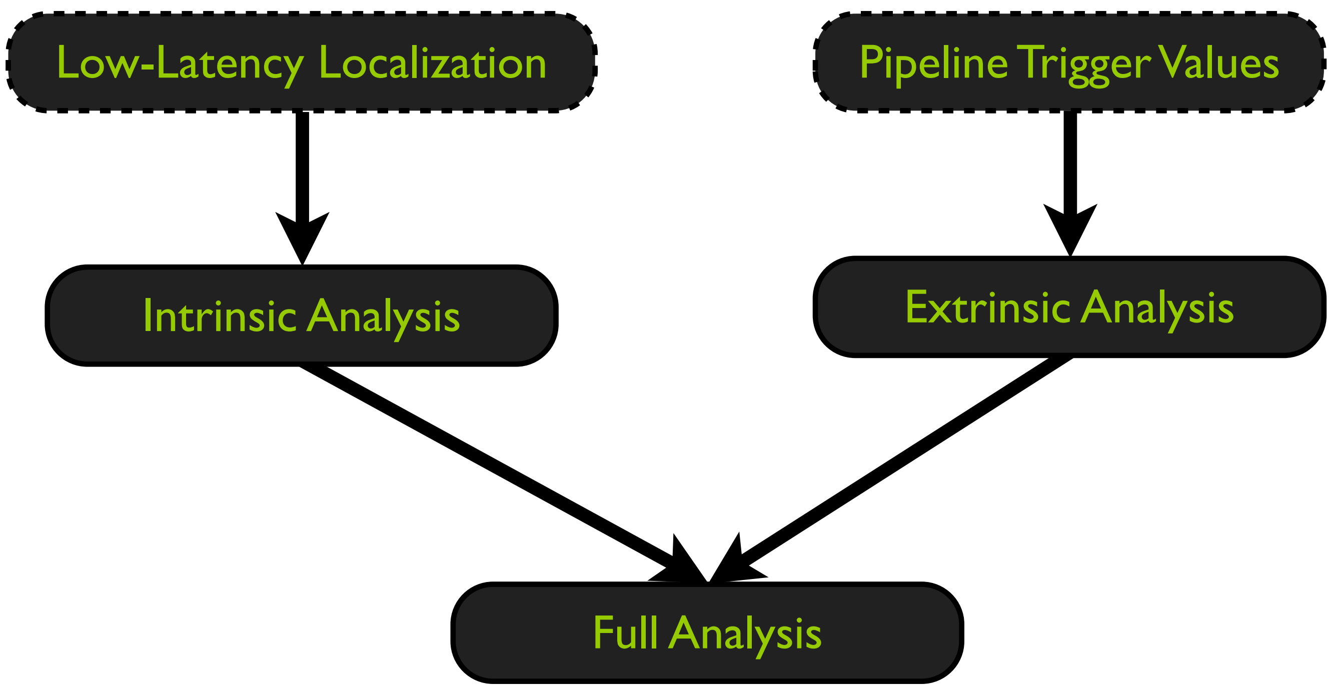
Epoch	Number of BNS Detections	% BNS Localized within 5 deg^2	% BNS Localized within 20 deg^2
2015	0.0004 – 3	–	–
2016–17	0.006 – 20	2	5 – 12
2017–18	0.04 – 100	1 – 2	10 – 12
2019+	0.2 – 200	3 – 8	8 – 28
2022+ (India)	0.4 – 400	17	48

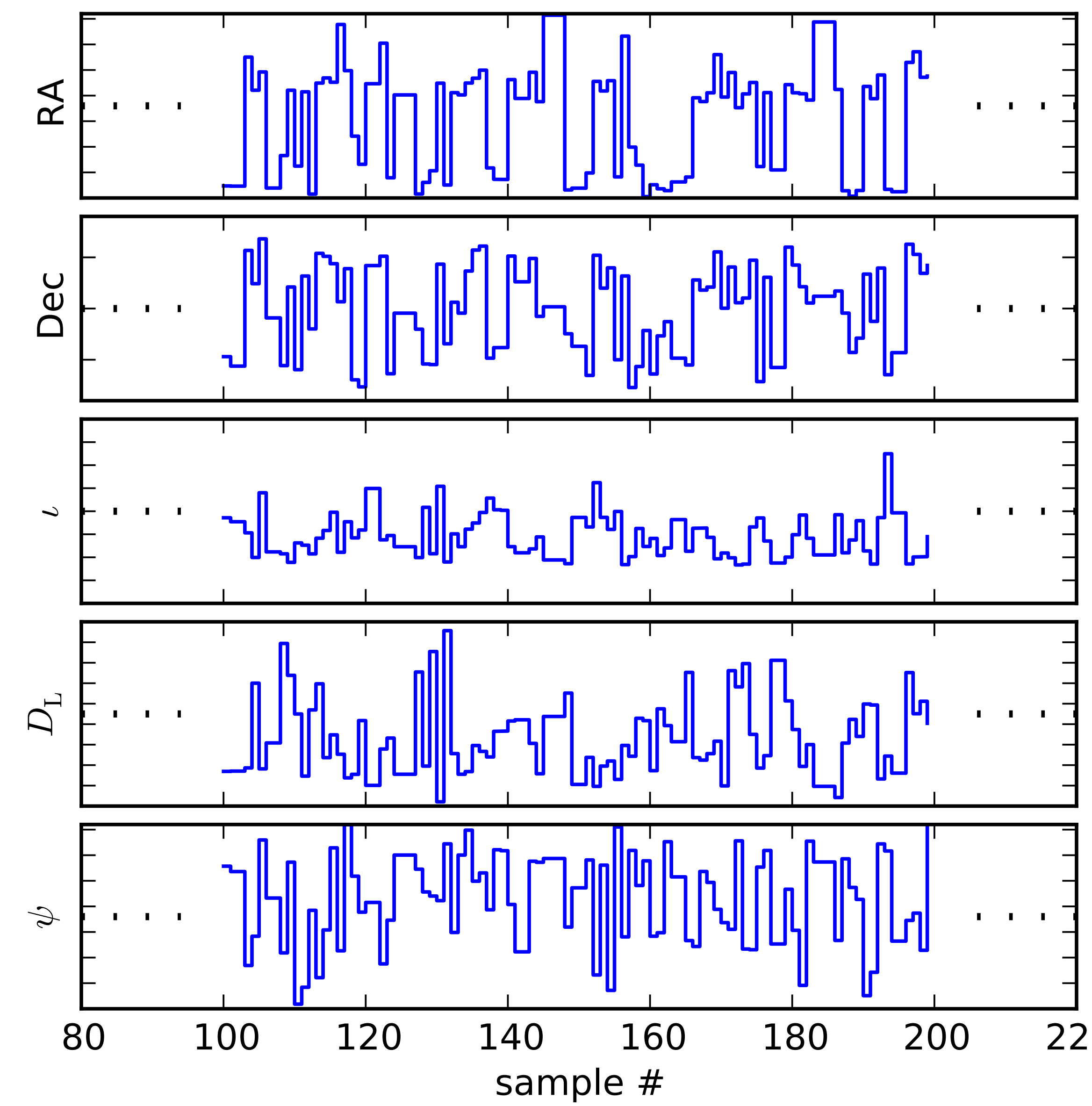
Which detector network is *likely* to produce the first well-localized CBCs?

Team assembled to produce MDCs for all of the observing scenarios: Chad Hanna, Chris Pankow, Branson Stephens, Alex Urban, Sarah Caudill, Ruslan Vaulin, Salvatore Vitale, Larry Price, Leo Singer

Future work

- Feed rapid localization into full parameter estimation
- MCMC implementation of BAYESTAR developed w/ Ben Farr





see https://dcc.ligo.org/LIGO-G1300015-v3
Ben Farr, Northwestern U.

Searching for optical counterparts of GBM events with PTF

TITLE: GCN CIRCULAR
NUMBER: 13489
SUBJECT: GRB 120716A: Candidate Optical Afterglow from PTF
DATE: 12/07/19 00:01:37 GMT
FROM: **S. Bradley Cenko** at Caltech <cenko@srl.caltech.edu>

S. B. Cenko (UC Berkeley), E. O. Ofek (Weizmann Institute of Science), and P. E. Nugent (Lawrence Berkeley National Laboratory / UC Berkeley) report on behalf of a larger collaboration:

We have imaged the location of the IPN GRB 120716A (Hurley et al., GCN 13487) with the Palomar 48 inch Oschin Schmidt telescope as part of the Palomar Transient Factory (PTF). Images were obtained in the r' filter beginning at 4:25 UT on 18 July 2012 (~ 1.5 d after the IPN trigger).

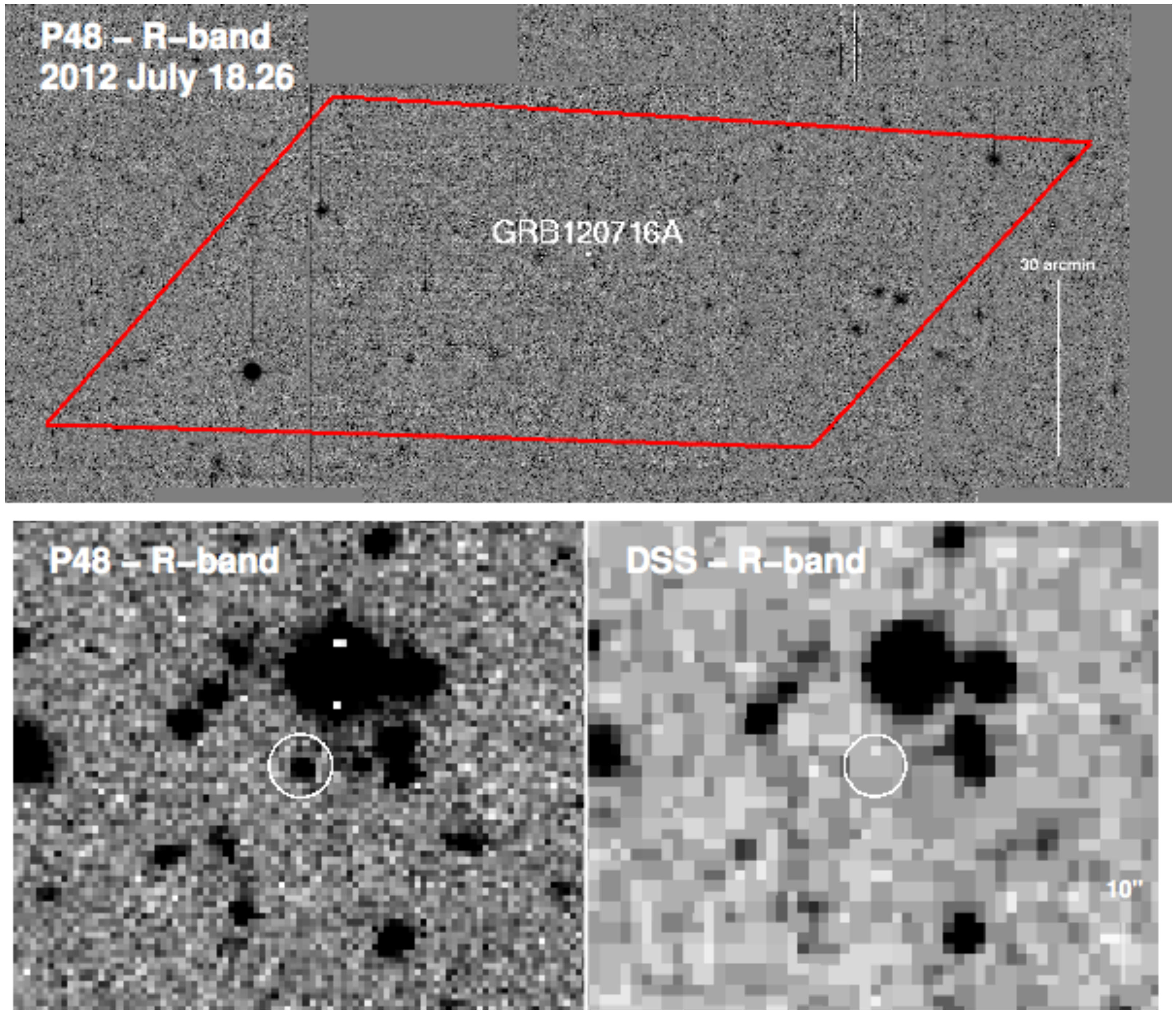
Within the IPN localization, **we identify a new point source** with coordinates:

RA: 20:52:12.10   Dec: +09:35:53.7 (J2000.0)

Using several nearby stars from the Sloan Digital Sky Survey for reference, we measure a **magnitude of r' ~ 20.4** at this time.

Nothing is detected at this location in previous PTF imaging of this field, with images beginning in June 2011. Furthermore, no source is detected in archival SDSS imaging of this location (a faint nearby object in the SDSS database, SDSS J205212.01+093551.9, appears to be of very low significance). However, our most recent epoch of PTF imaging was obtained in March 2012, so we cannot currently rule out the chance alignment of an unassociated foreground or background transient.

Further observations of this candidate optical afterglow are planned.



P48 – R-band
2012 July 18.26
GRB120716A
30 arcmin
P48 – R-band
DSS – R-band
10"

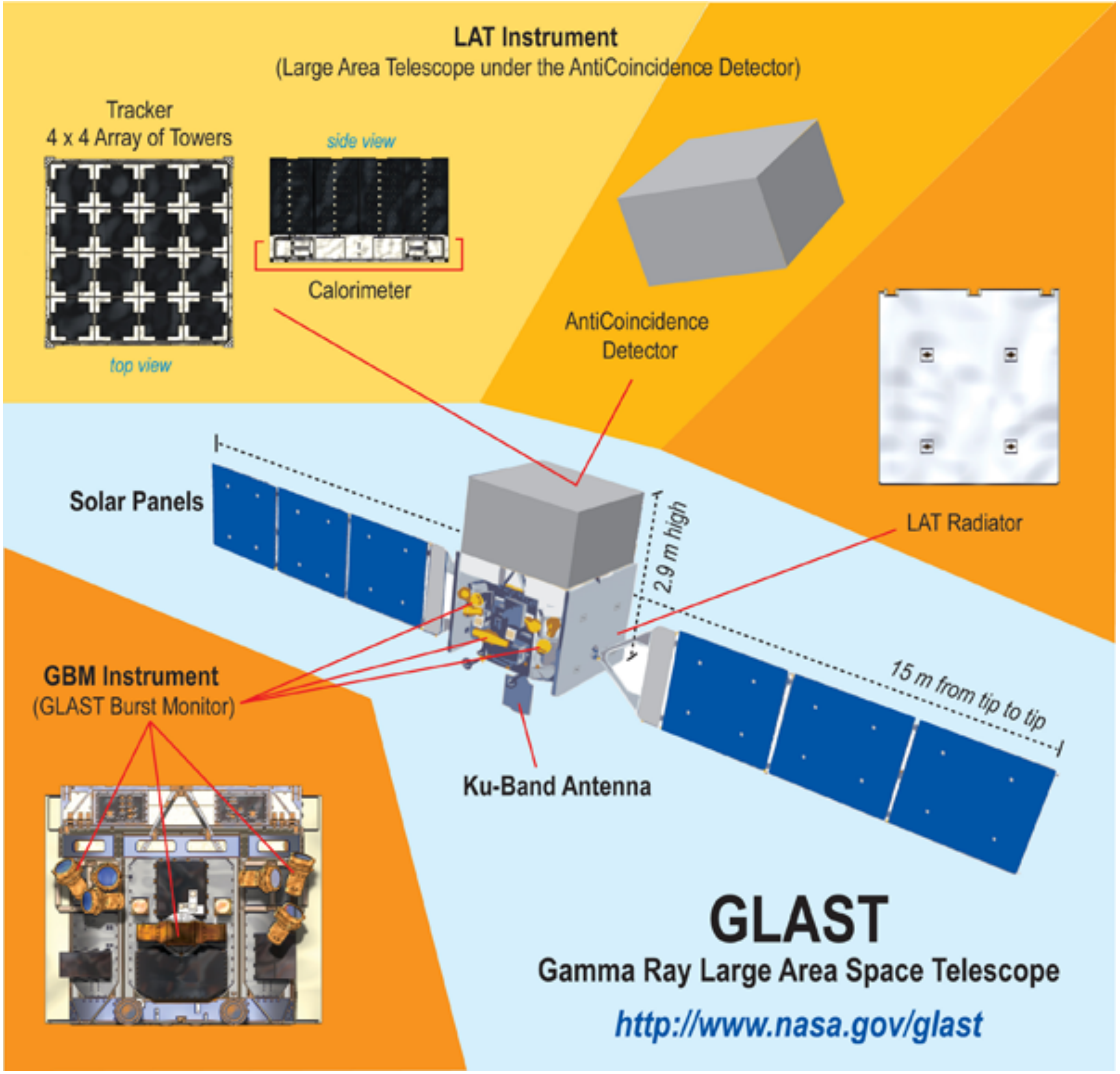


Illustration: NASA/Sonoma State University/Aurore Simonnet
http://physics.aps.org/articles/v2/37

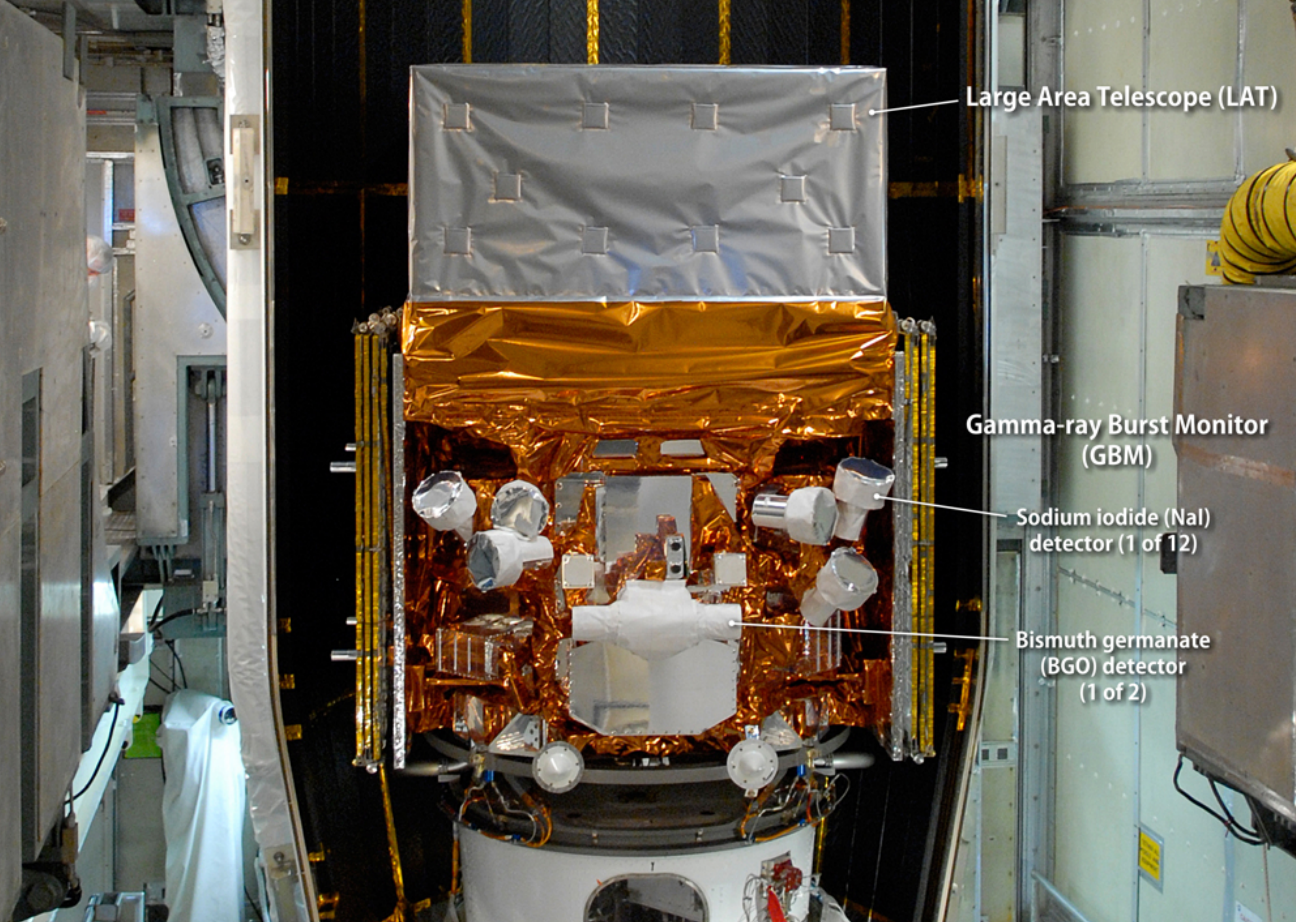
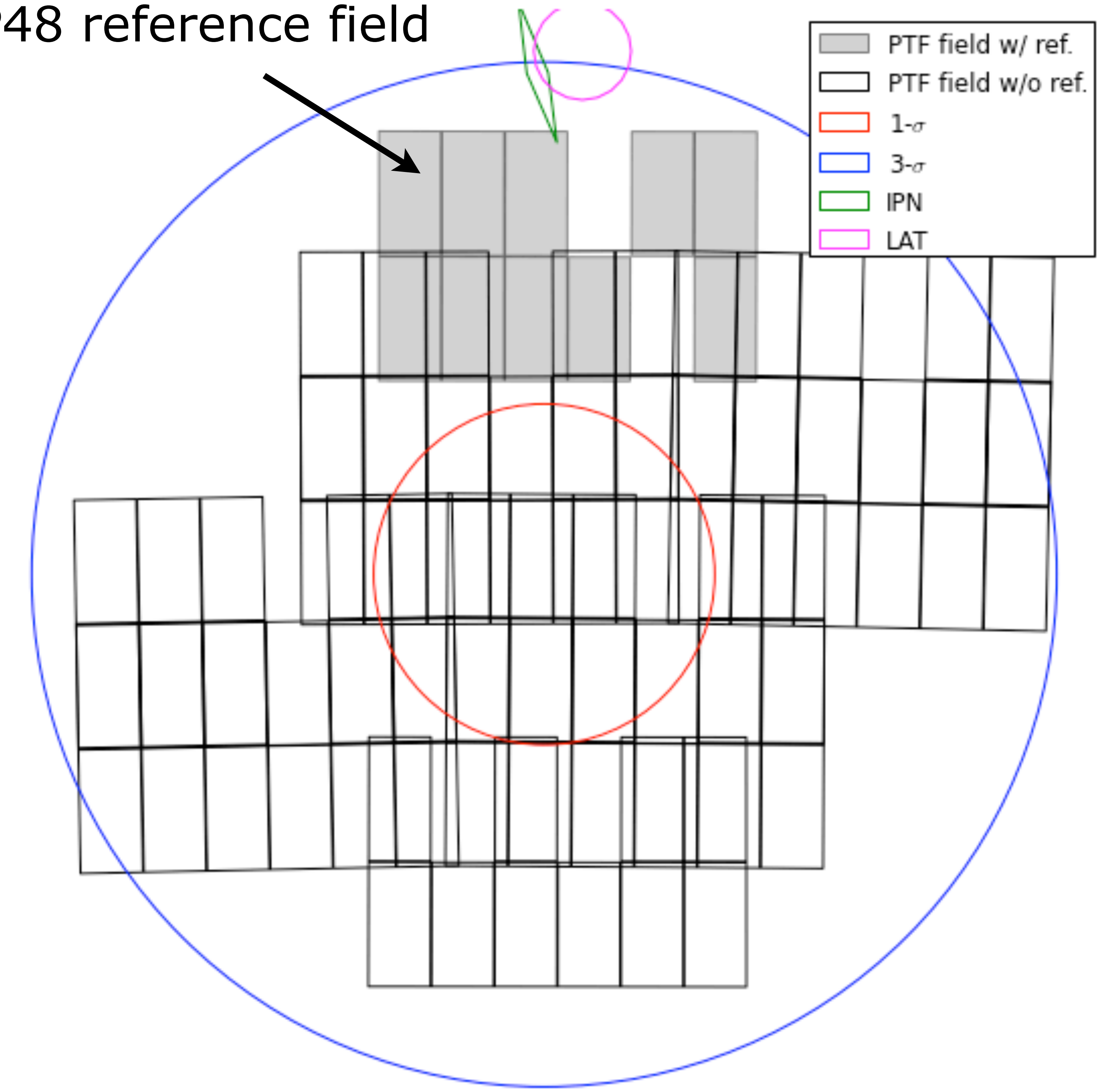
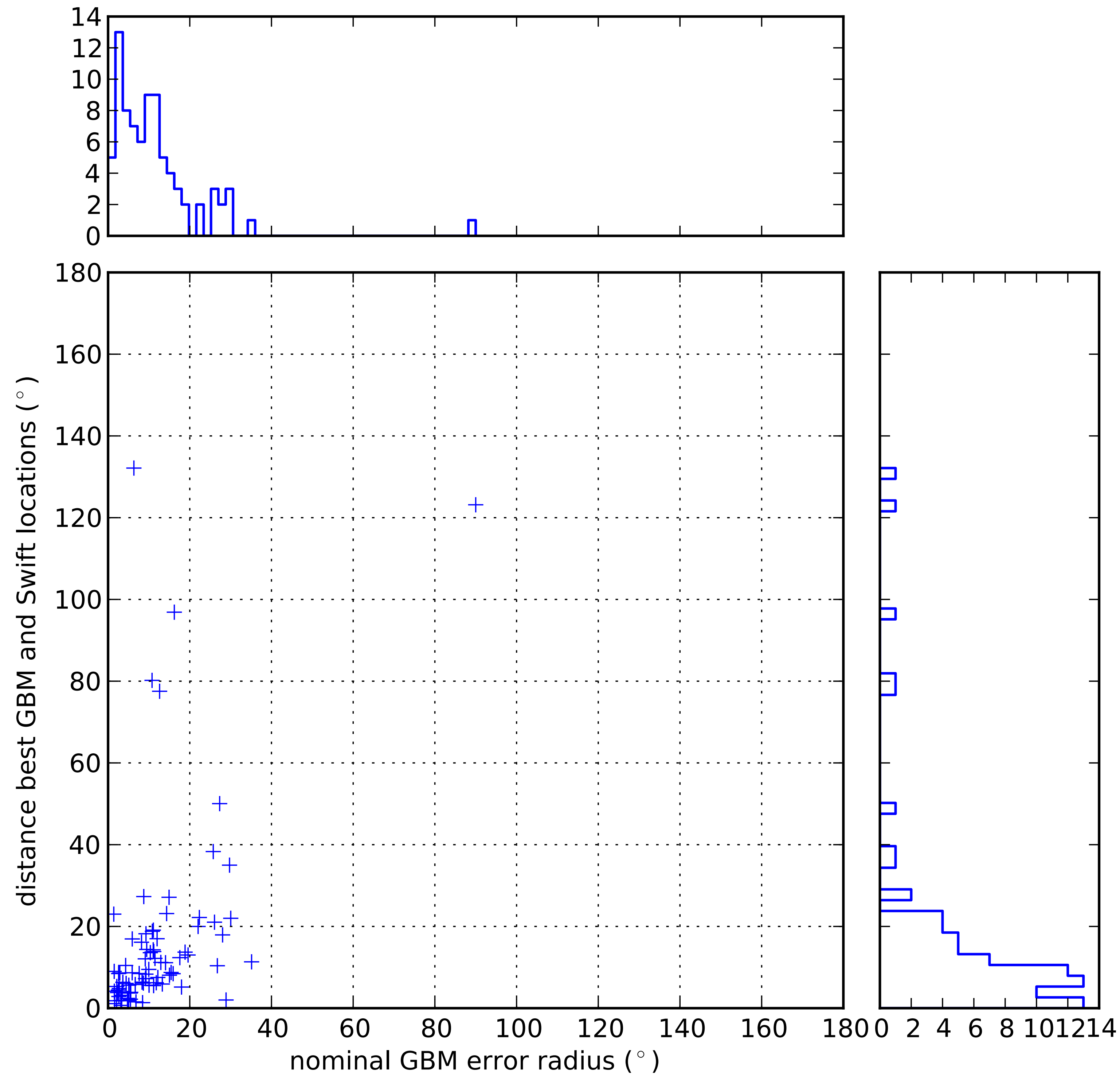


Image credit: NASA/Jim Grossmann
http://www.nasa.gov/mission_pages/GLAST/news/vision-improve.html

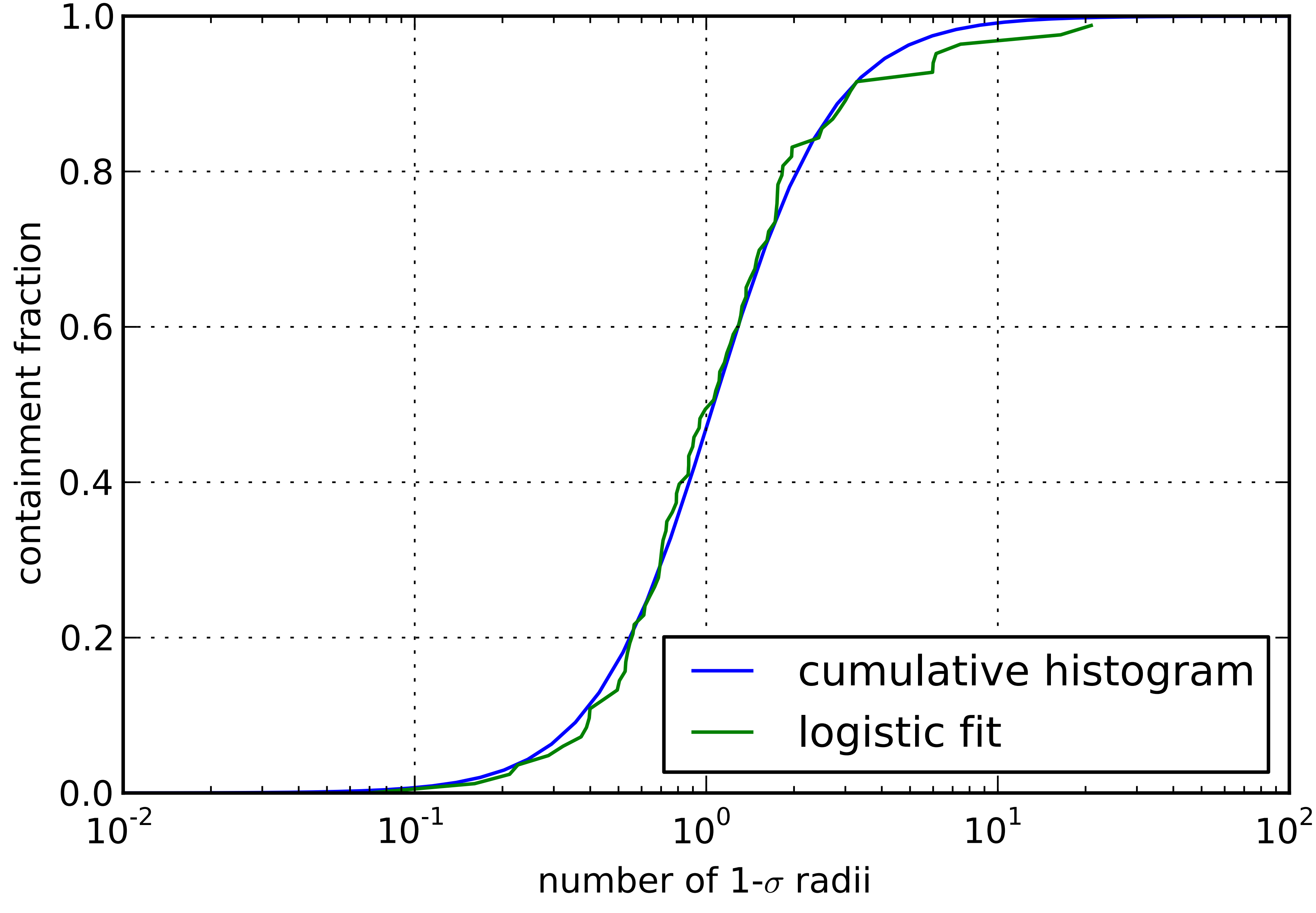
one 7.25 deg^2 P48 reference field

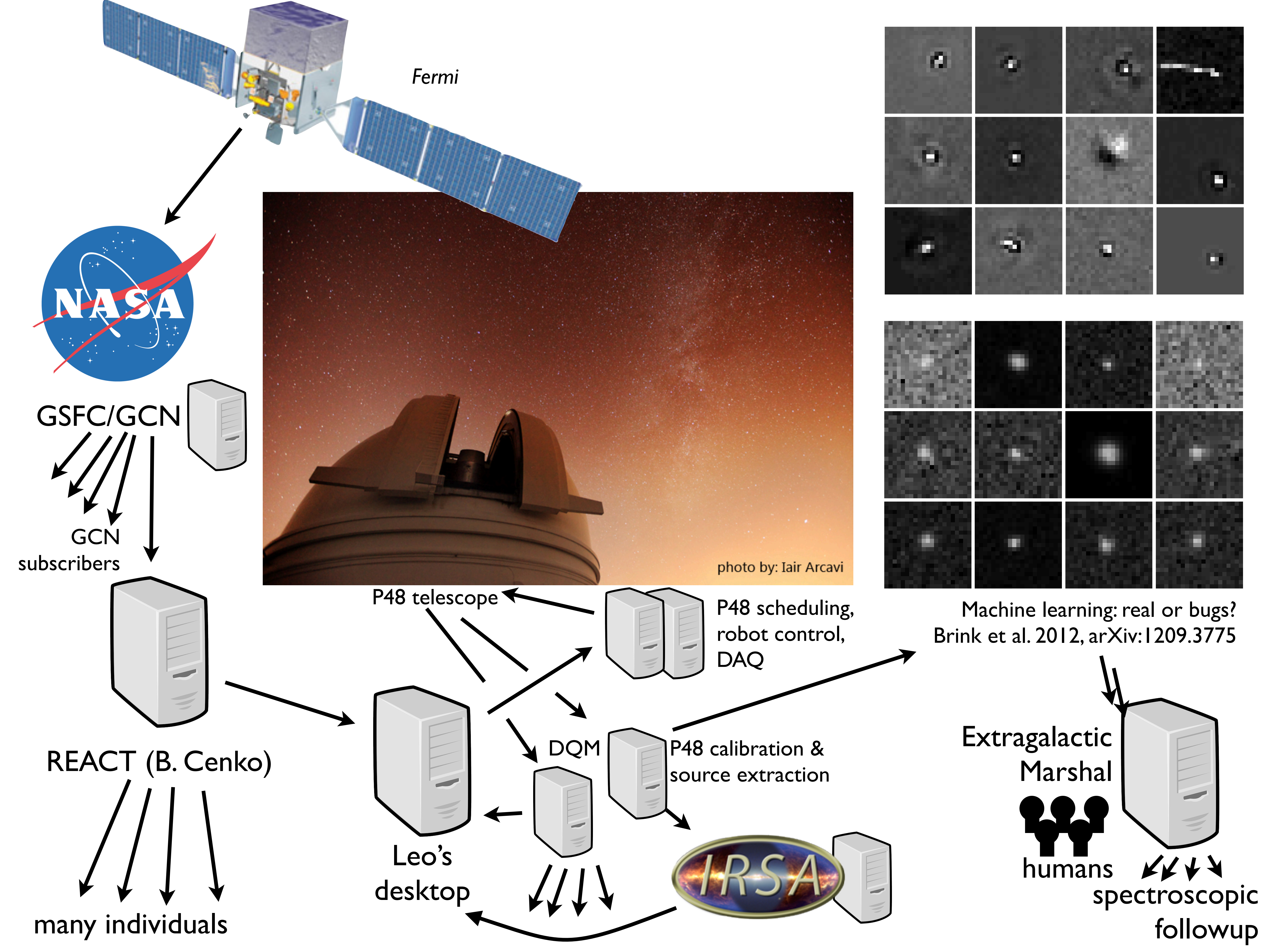


Fermi GBM triggers: localization accuracy compared with *Swift*

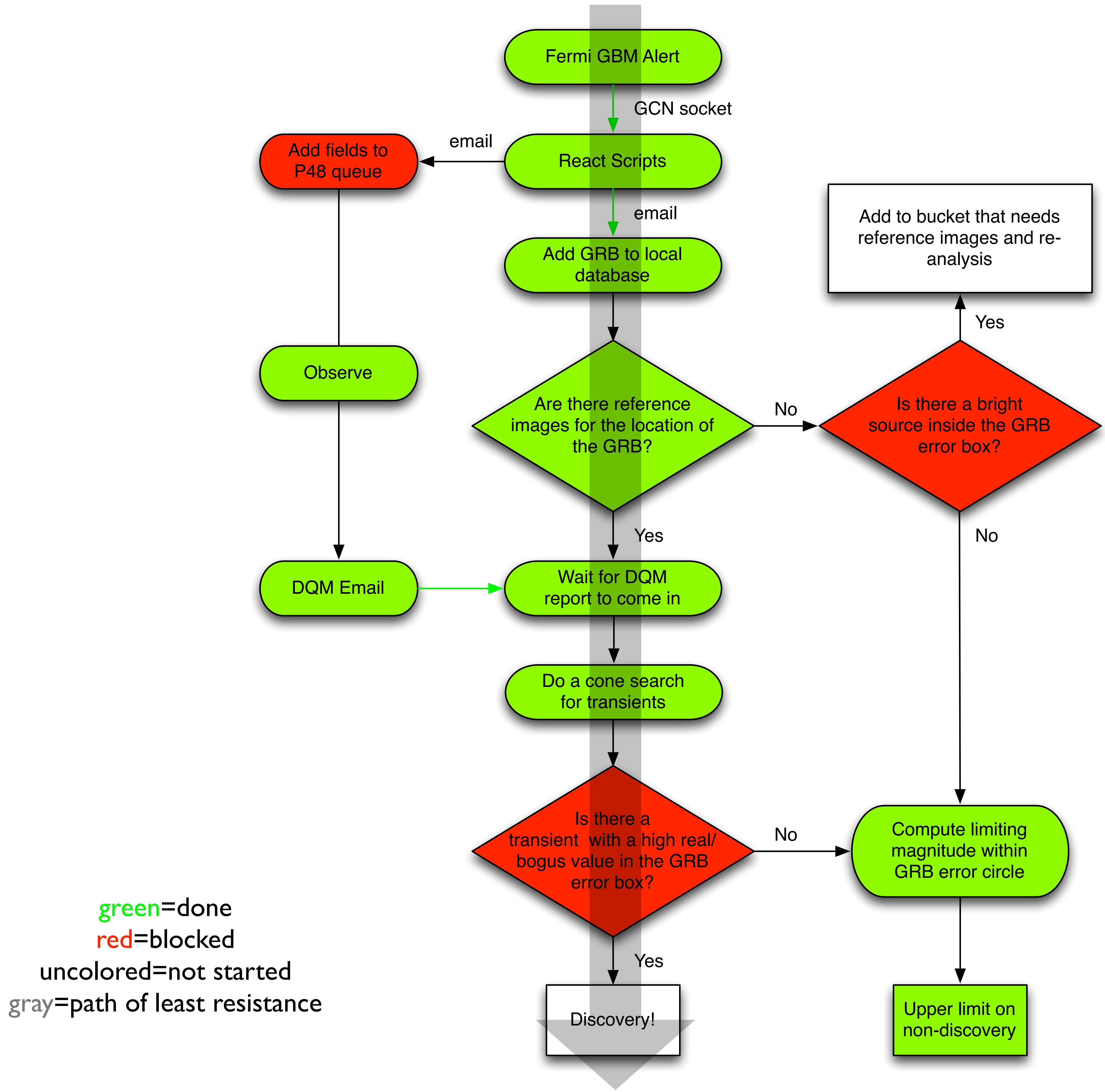


Estimated radial profile of *Fermi* GBM localization errors



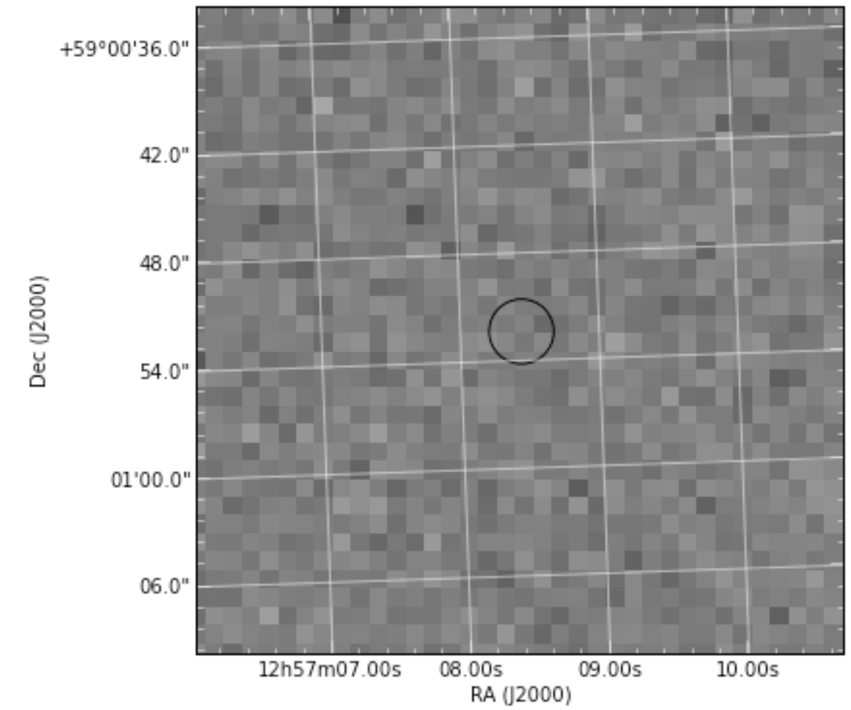


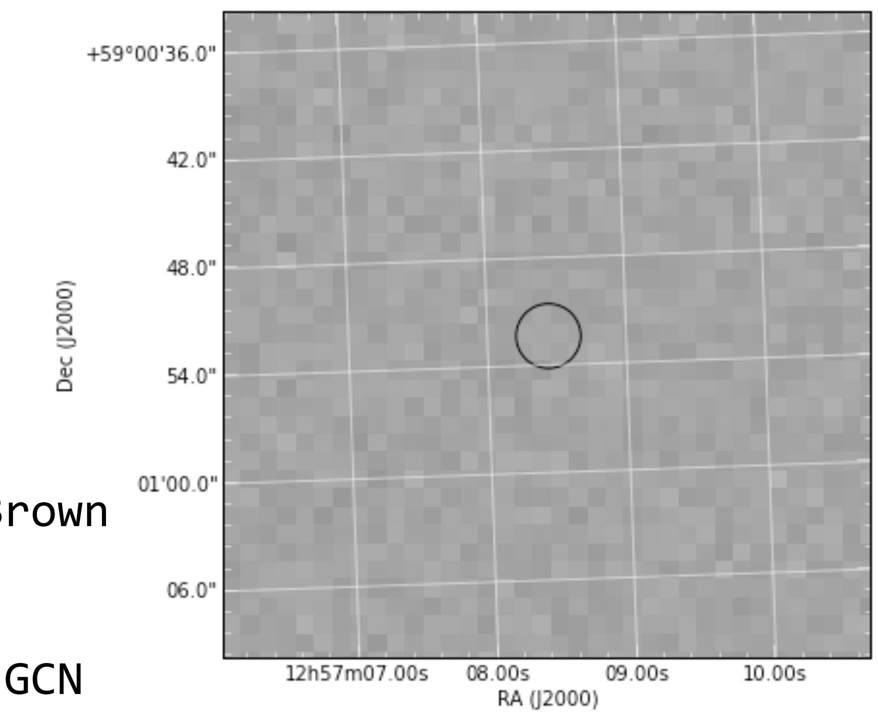
Fermi
NASA
GSFC/GCN
GCN
subscribers
REACT (B. Cenko)
many individuals
photo by: Iair Arcavi
P48 telescope
P48 scheduling,
robot control,
DAQ
Leo's
desktop
DQM
P48 calibration &
source extraction
IRSA
Machine learning: real or bugs?
Brink et al. 2012, arXiv:1209.3775
Extragalactic
Marshal
humans
spectroscopic
followup


Fermi GBM Alert
GCN socket
React Scripts
email
Add fields to P48 queue
email
Add GRB to local database
Observe
Are there reference images for the location of the GRB?
No
Is there a bright source inside the GRB error box?
Yes
Add to bucket that needs reference images and re-analysis
No
Yes
DQM Email
Wait for DQM report to come in
Do a cone search for transients
Is there a transient with a high real/bogus value in the GRB error box?
No
Compute limiting magnitude within GRB error circle
Yes
Discovery!
Upper limit on non-discovery
green=done
red=blocked
uncolored=not started
gray=path of least resistance

Photometric upper limits for UVOT event

aperture photometry using P48 calibration





TITLE: GCN CIRCULAR
NUMBER: 14192
SUBJECT: GRB 130122A: **PTF P48 optical upper limits**
DATE: 13/02/09 15:33:37 GMT
FROM: **Leo Singer** at CIT/PTF <lsinger@caltech.edu>

L. P. Singer (Caltech), S. B. Cenko (UC Berkeley), and D. A. Brown (Syracuse) report on behalf of a larger collaboration:

We have imaged the **3-sigma Swift UVOT error circle** (P. Evans, GCN 14143) of GRB130122A (Swift546731, S. Barthelmy, GCN 14140) with the Palomar 48 inch Oschin telescope (P48) as part of the Palomar Transient Factory (PTF). Images were obtained in the Mould R filter at 2013-01-23 at 06:27:39 and 07:11:25 UTC, 6.7 and 7.5 hours after the trigger.

With sporadic cloud cover and a bright moon, **we find no point source, fading or otherwise, to 5-sigma limiting magnitudes of 19.1 and 18.4.**

Pipeline composes GCN circulars

```
Content-Type: text/plain; charset="us-ascii"
MIME-Version: 1.0
Content-Transfer-Encoding: 7bit
Subject: GRB 130122A: PTF P48 optical upper limits

Dear humans,

Would you please review and submit this GCN circular?

Thanks,
react@localhost
```

```
TITLE:   GCN CIRCULAR
NUMBER:  14192
SUBJECT: GRB 130122A: PTF P48 optical upper limits
DATE:    13/02/09 15:33:37 GMT
FROM:    Leo Singer at CIT/PTF  <lsinger@caltech.edu>

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the trigger.

With sporadic cloud cover and a bright moon, we find no point source,
fading or otherwise, to 5-sigma limiting magnitudes of 19.1 and 18.4.
```
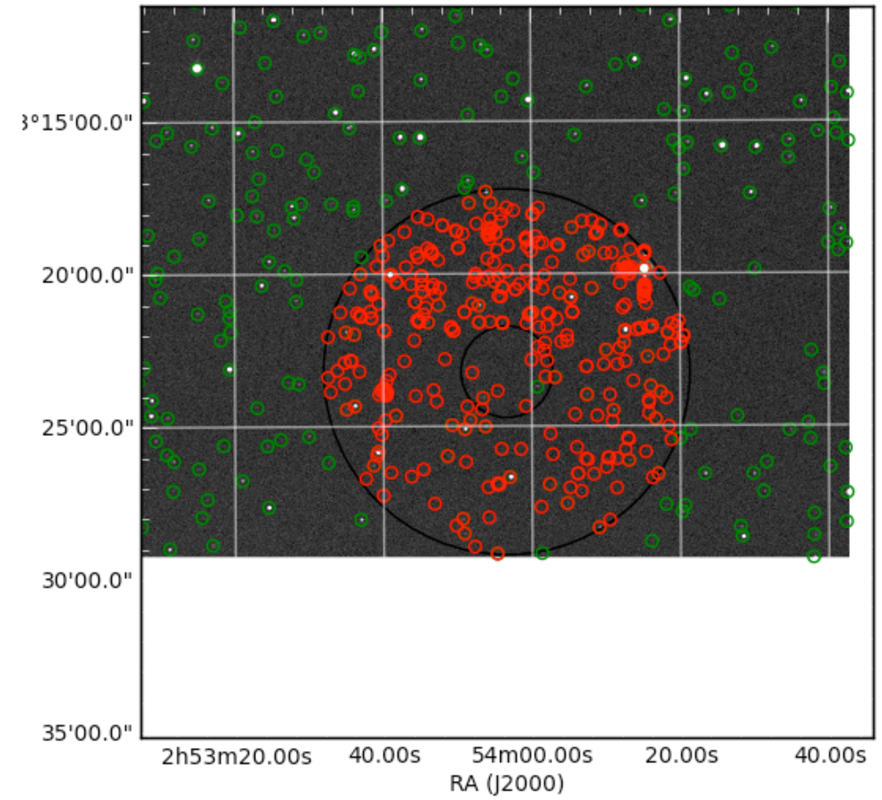

Multiple detection of BAT event in catalog search

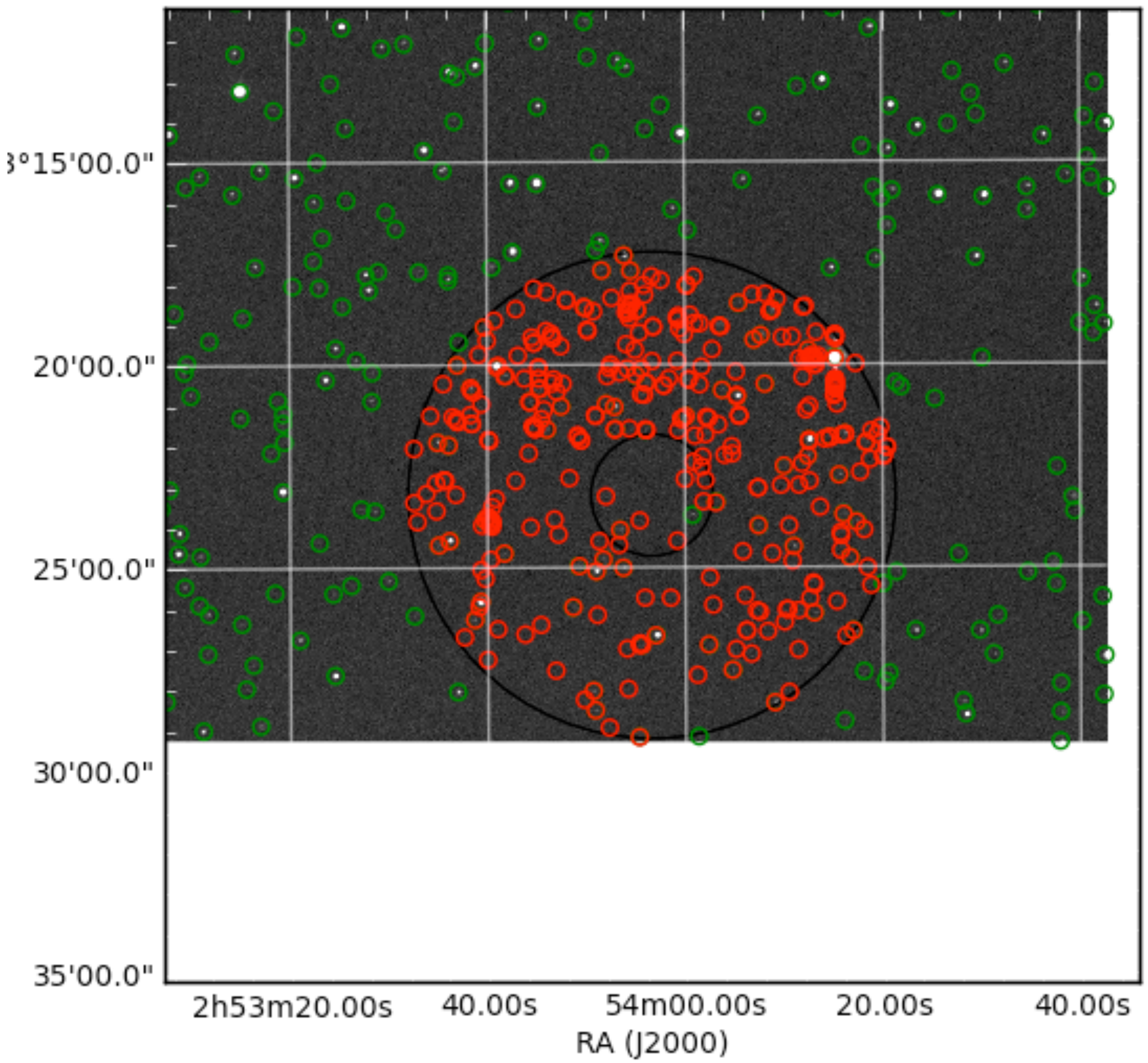
light curve power law index measured




```
TITLE:   GCN CIRCULAR
NUMBER:  14244
SUBJECT: GRB 130215A: PTF P48 optical detection
DATE:    13/02/21 06:08:29 GMT
FROM:    Leo Singer at CIT/PTF  <lsinger@caltech.edu>

L. P. Singer (Caltech), S. B. Cenko (UC Berkeley), and D. A. Brown
(Syracuse) report on behalf of a larger collaboration:

We have imaged the 3-sigma Swift BAT error circle (S. Barthelmy, GCN
14214) of GRB130215A (Swift548760, S. Barthelmy, GCN 14204) with the
Palomar 48 inch Oschin telescope (P48) as part of the Palomar
Transient Factory (PTF).

Images were obtained in the Mould R filter on 2013-02-15 at 02:35:05
and 04:05:52 UTC, 1.1 and 2.6 hours after the trigger. We detect a
fading point source that is absent in the USNO B-1 catalog at
magnitudes of 16.38 and 17.59 at
    RA(J2000)   =   2h 54m 00.73s
    DEC(J2000) = +13d 23' 43.0"
, matching the ROTSE-IIIb position (GCN 14205, Zheng & Flewelling).

Assuming a power-law decay, these two P48 observations give us an index
alpha=-1.25, consistent with the index of alpha=-1.24 reported by ROTSE
analysis (GCN 14208, Zheng et al.).
```

Multiple detection of BAT event in catalog search

light curve power law index measured



Deeper photometric limit in good observing conditions

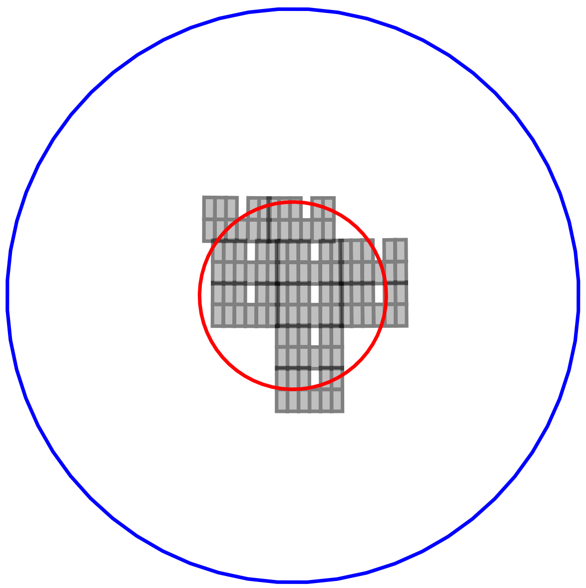
aperture photometry using P48 calibration

```
TITLE:   GCN CIRCULAR
NUMBER:  14313
SUBJECT: GRB 130305A: PTF P48 optical upper limits
DATE:    13/03/15 19:28:32 GMT
FROM:    Leo Singer at CIT/PTF  <lsinger@caltech.edu>
```

L. P. Singer (Caltech), S. B. Cenko (UC Berkeley), and D. A. Brown (Syracuse) report on behalf of a larger collaboration:

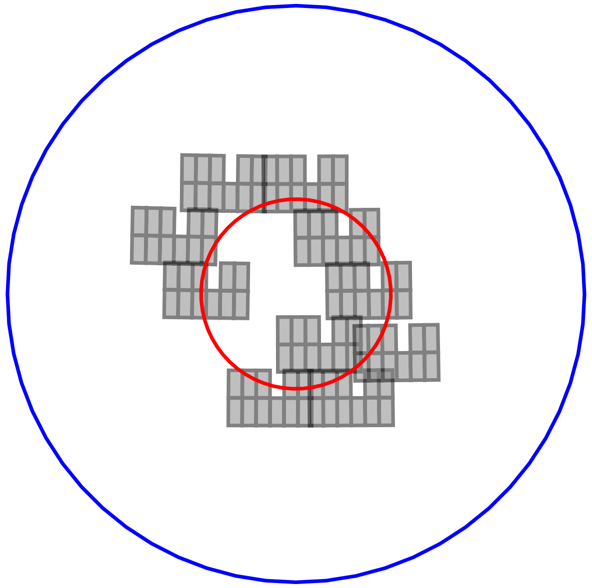
We have imaged the 3-sigma Swift XRT error circle (D. Malesani, GCN 14263) of GRB130305A (Fermi384176354, J. R. Cummings, GCN 14257) with the Palomar 48 inch Oschin telescope (P48) as part of the Palomar Transient Factory (PTF). Images were obtained in the Mould R filter at 2013-03-06 at 05:13:35 and 05:56:17 UTC, 17.6 and 18.3 hours after the trigger.

We find no point source, fading or otherwise, to **5-sigma limiting magnitudes of 20.8 and 20.8**.



Fermi trigger from Friday, result so far:

dozens of variable stars
some image subtraction muck
two likely background supernovae, awaiting classification



Fermi trigger from last night

more follow-up observations tonight

How do we get there?

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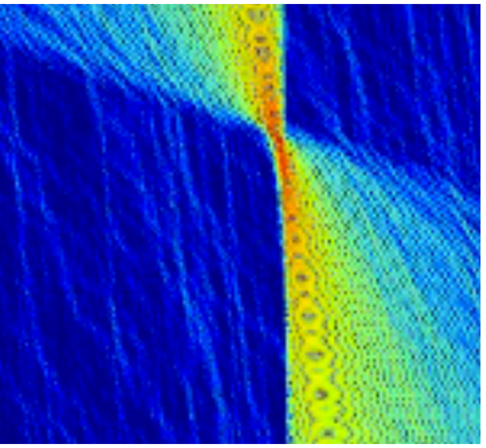

low-latency event detection

seems to be in hand

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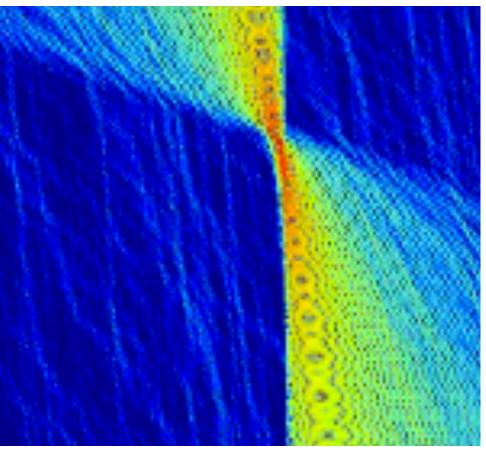

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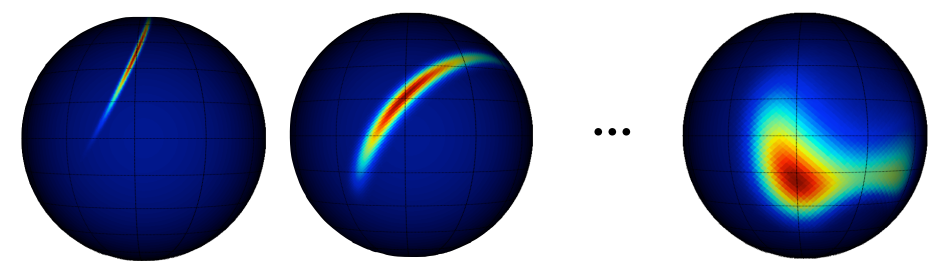

rapid sky localization

as shown by engineering runs and mock data challenges,
demonstrably ready now, but can be improved a little bit

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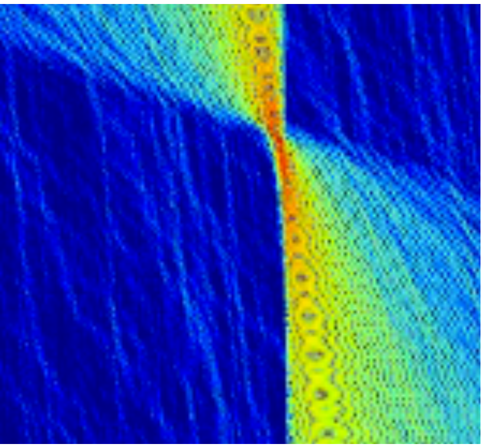

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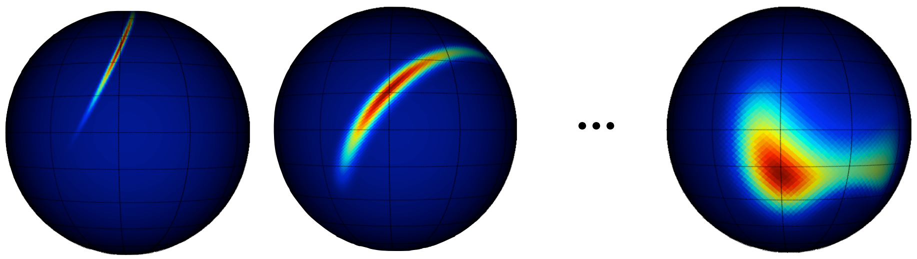


as shown by engineering runs and mock data challenges, demonstrably ready now, but can be improved a little bit

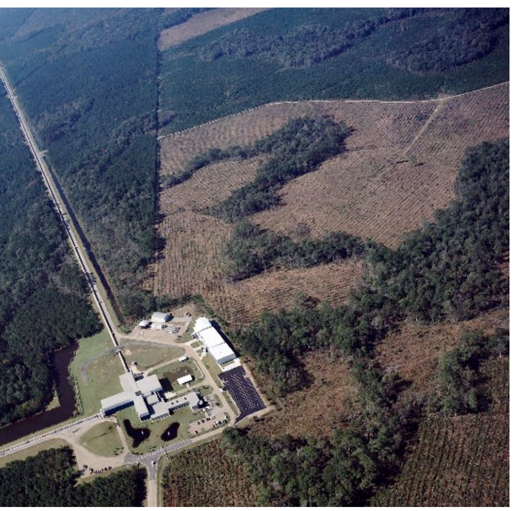
optical follow-up

the hard part: largely uncharted territory,
hic sunt dracones...


photo by: Iair Arcavi

Acknowledgements

My advisor: Alan Weinstein



Larry Price, Chad Hanna, Brad Cenko, Duncan Brown, Ben Farr, and many other collaborators...

LIGO Laboratory

Palomar Transient Factory

HEALPix

astropy
A Community Python Library for Astronomy

NSF Graduate Research Fellowship

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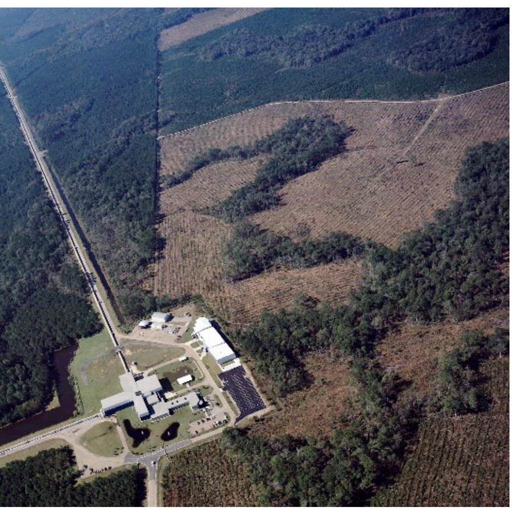

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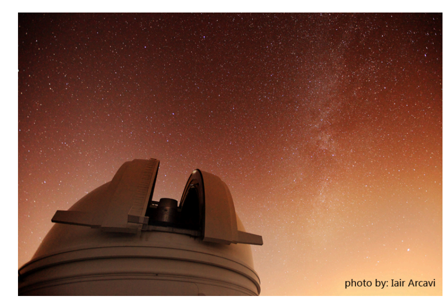

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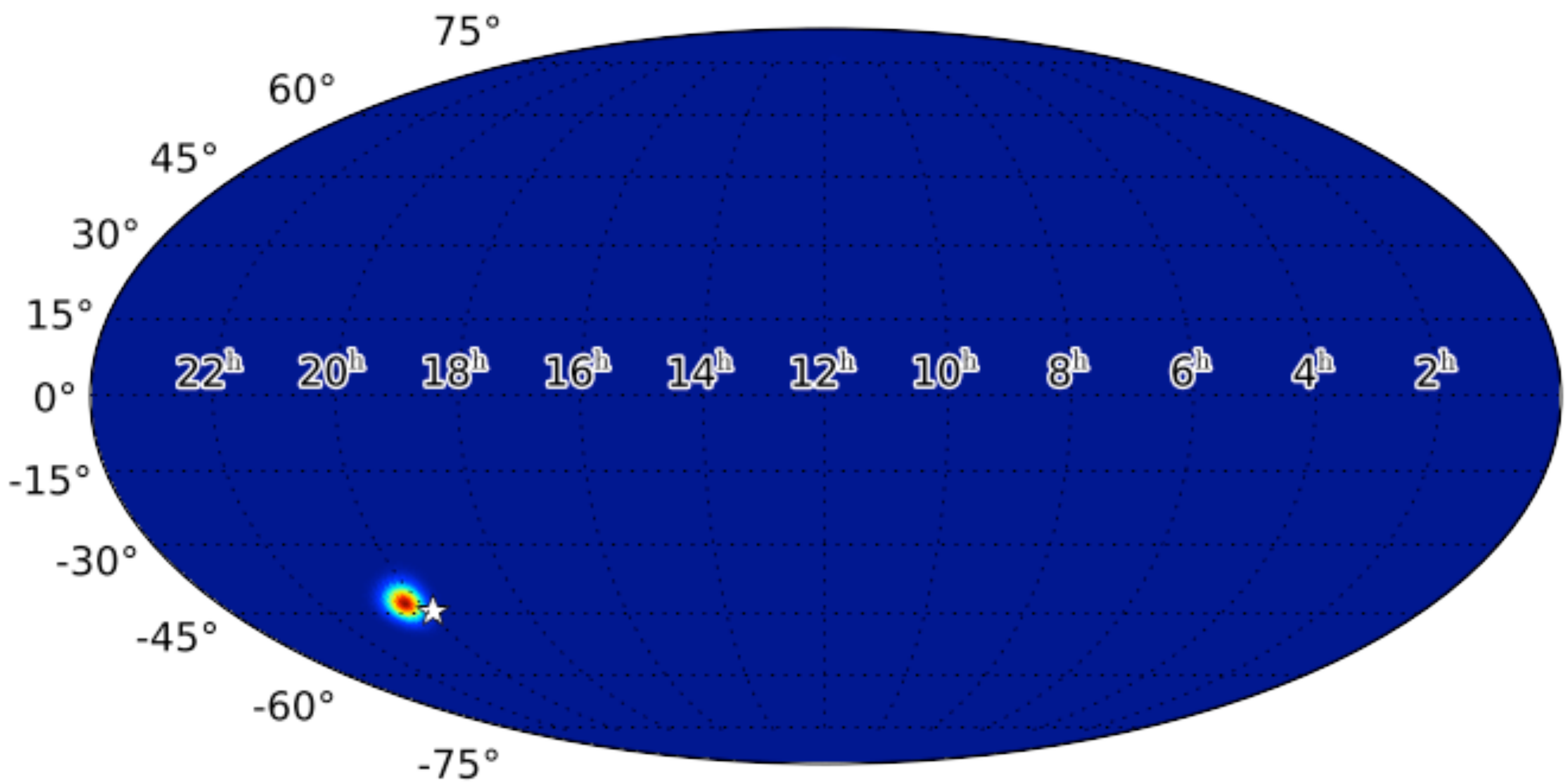
Extra slides

ER3: Injections Found

4 low-mass triggers, all reported by gstlal

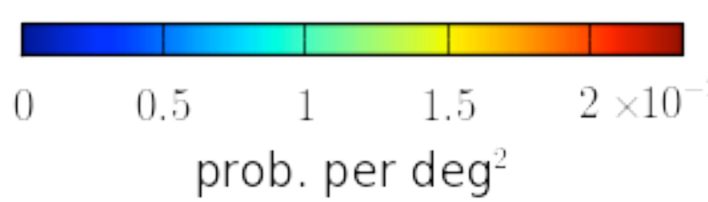
G71031



true location
19h51m58.39s
-44°36'10.2"

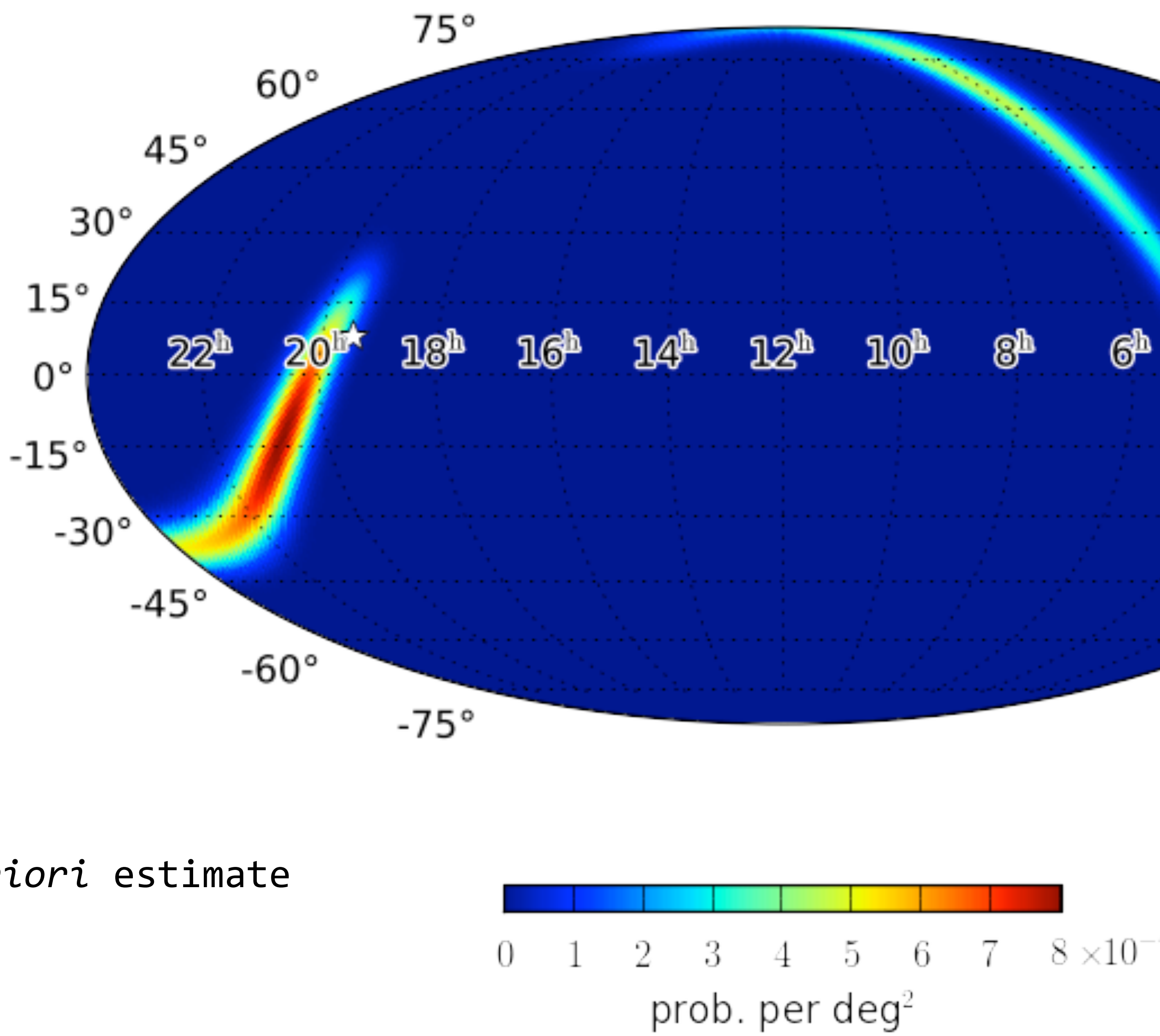
maximum *a posteriori* estimate
20h18m34.29s
-42°36'35.3"

found at confidence level: 96%
enclosing area: 140 deg^2
offset: 5.2°



Event Type: LowMass
MChirp: 1.191
MTot: 2.75351202488
End Time: 1045019974.847648153
SNR: 13.656
IFOs: H1,L1,V1
FAR: 8.053e-11

G71593



true location
19h25m10.65s
+7°53'50.3"

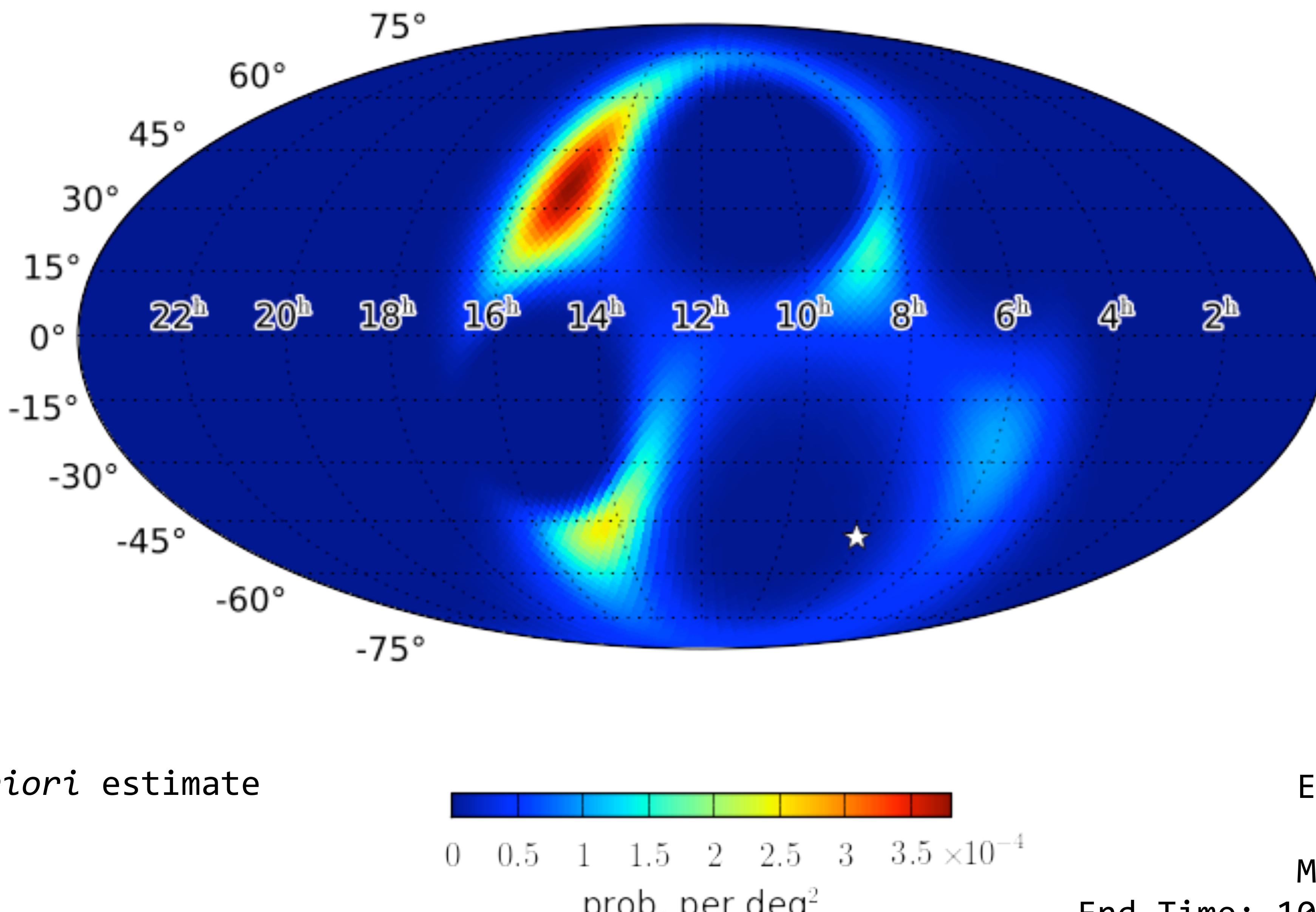
maximum *a posteriori* estimate
20h51m33.75s
-14°28'39.0"

found at confidence level: 92%
enclosing area: 3240 deg^2
offset: 31°

Event Type: LowMass
MChirp: 1.533
MTot: 3.53183591366
End Time: 1045456996.50528038
SNR: 10.271
IFOs: H1,L1
FAR: 1.226e-04

note: "freak" event, with V1 in an artificially sensitive state

G71627



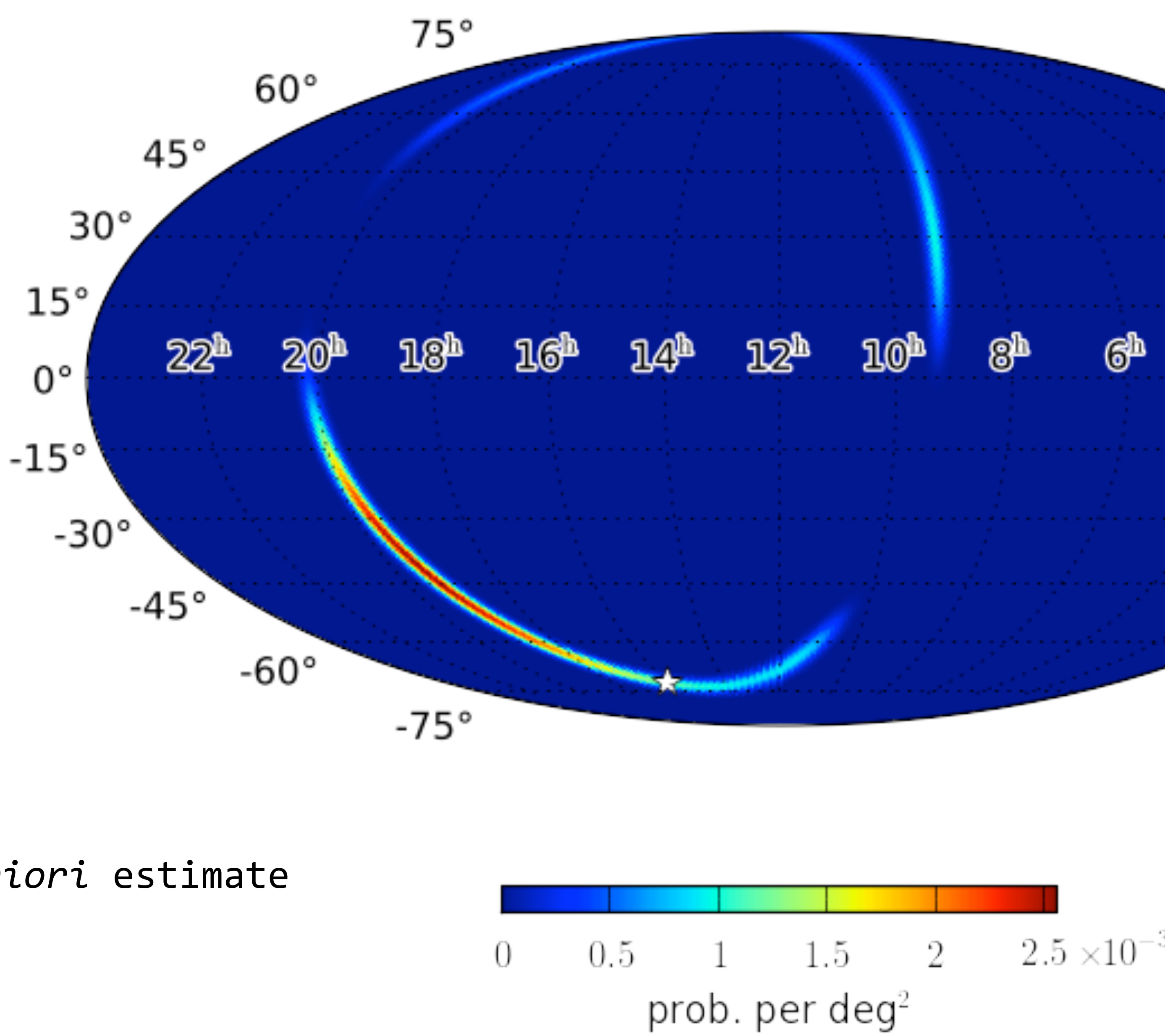
true location
8h04m29.85s
-49°37'08.1"

maximum *a posteriori* estimate
14h54m22.50s
+35°41'07.2"

found at confidence level: 99%
enclosing area: 15725 deg^2
offset: 124°

Event Type: LowMass
MChirp: 4.536
MTot: 17.7093279362
End Time: 1045473314.707031385
SNR: 12.672
IFOs: L1,V1
FAR: 1.367e-10

G71831



true location
 16h06m35.63s
-71°58'40.0"

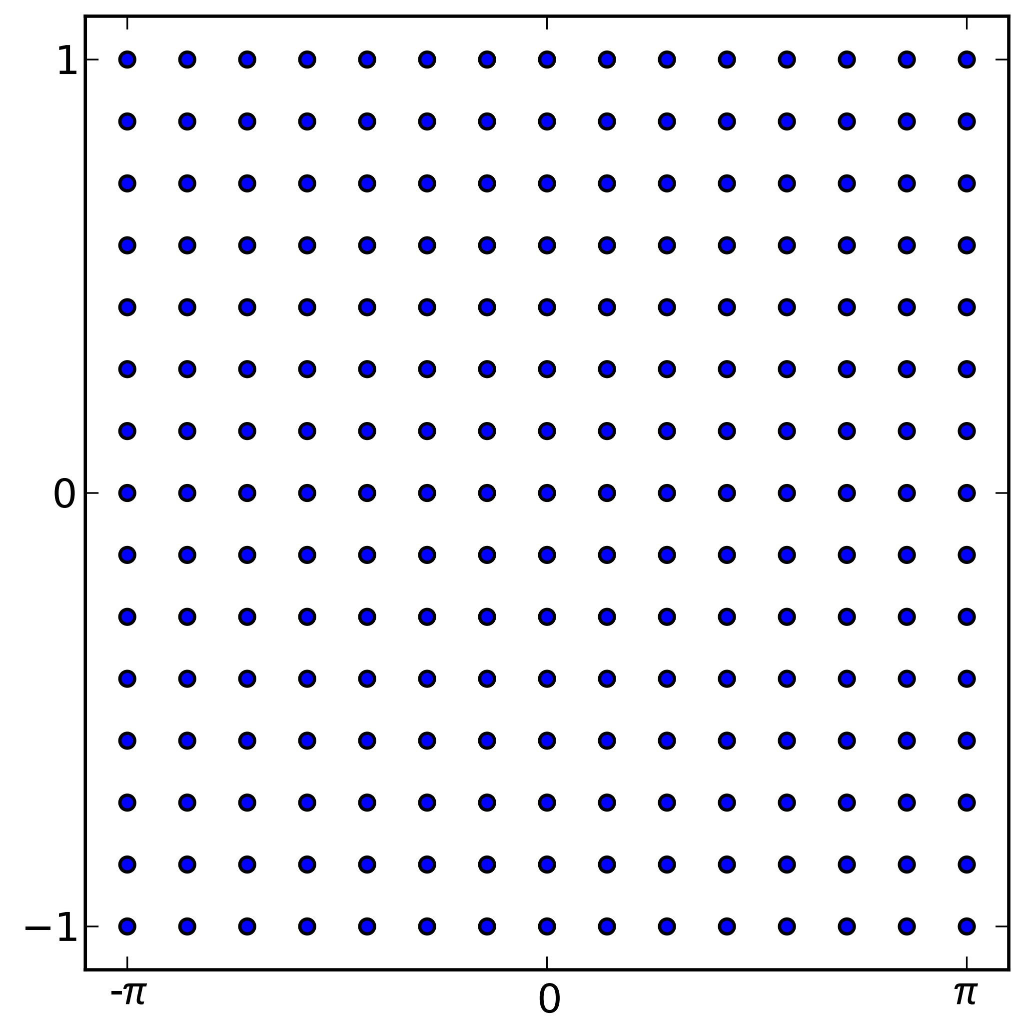
maximum *a posteriori* estimate
 19h30m00.00s
-39°27'03.2"

found at confidence level: 40%
enclosing area: 223 deg^2
offset: 41°

Event Type: LowMass
MChirp: 1.355
MTot: 3.15994691849
End Time: 1045702467.740710217
SNR: 10.954
IFOs: L1,V1
FAR: 1.848e-06

Orientation integral

- Newton-Cotes quadrature in $\psi, \cos\iota$

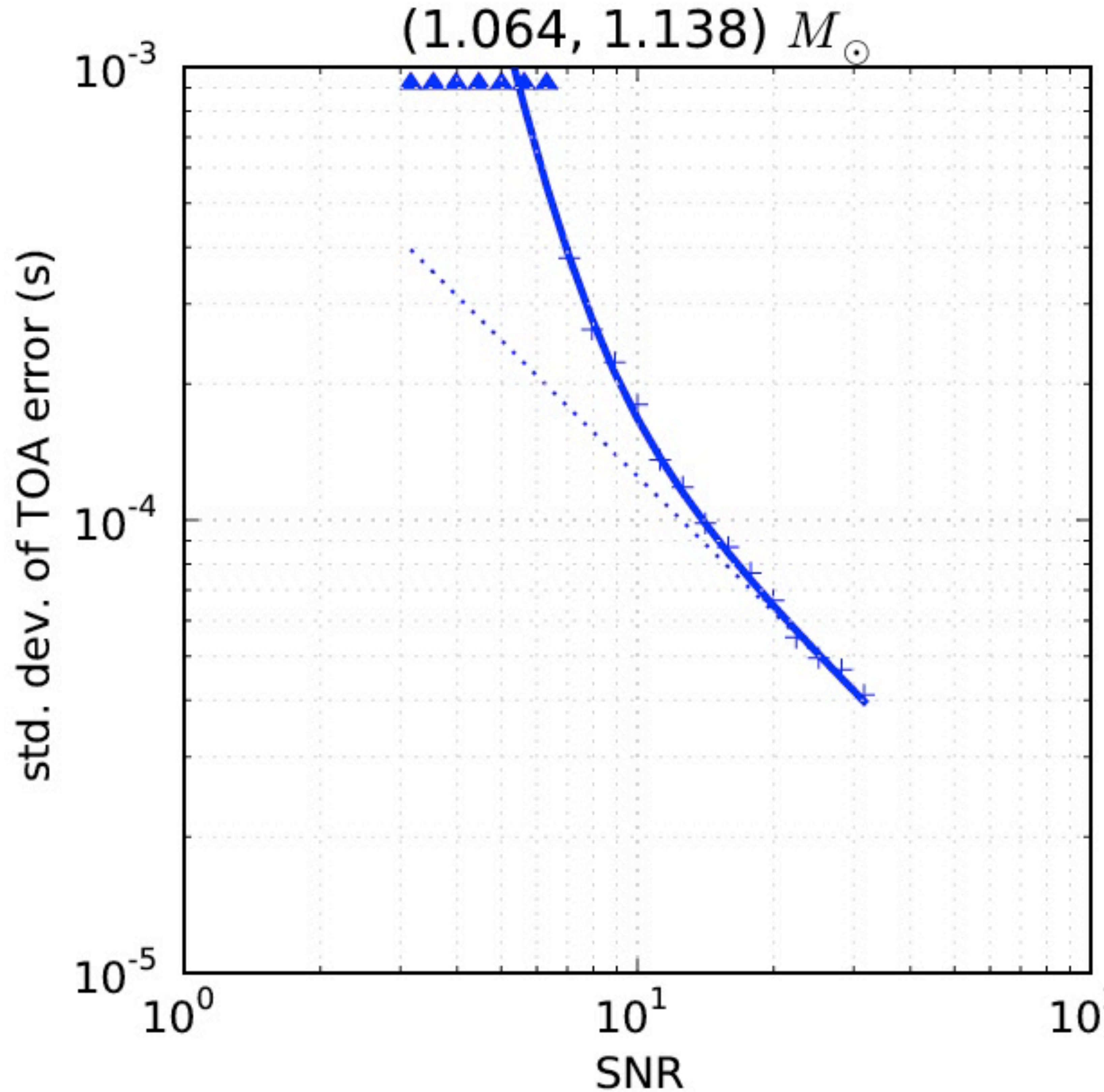


The devil is in the details...

- σ_t veers from $1/\rho$ dependence at ρ~10
- Proper relation of σ_t vs. ρ critical for self-consistency
- Lots of ideas:
  Nicholson & Vecchio 1998, PRD 57, 4588

  'beyond Fisher information' series expansions
  Zanolin et al. 2010, PRD, 81, 124048
  Vitale & Zanolin 2010, PRD 82, 124065

  'effective Fisher information'
  Cho e al. 2013, PRD, 87, 024004



crosses: measurement of timing uncertainty by numerical experimentdashed
line: Cramér-Rao bound
heavy line: Barankin bound
E.W. Barankin, Ann. Math. Stat., 20, 477
w/fudge factor of π (!?)

The devil is in the details...

Barankin bound on s^{th} central moment of function *h*:

test weights

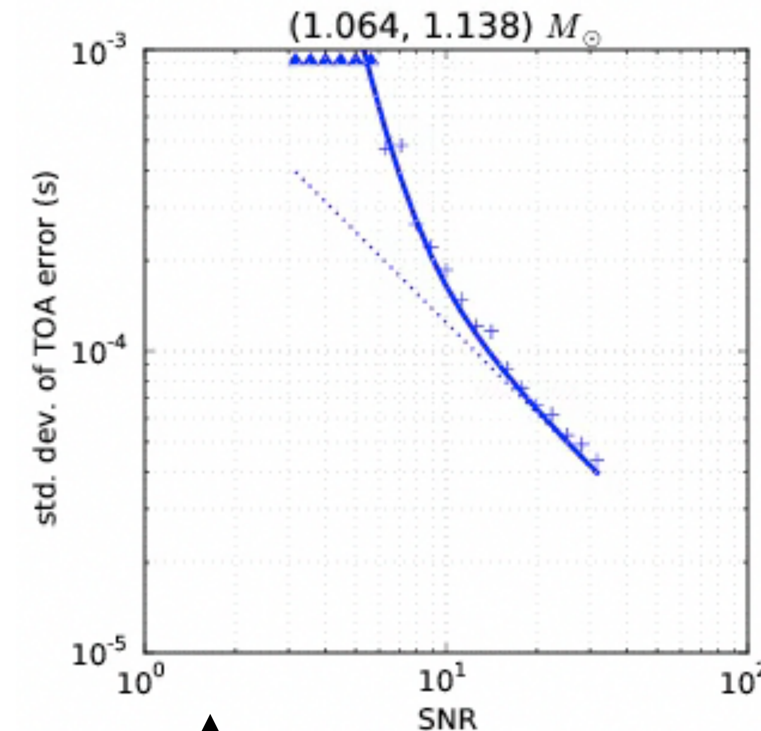
test points

$$\sigma_s \geq \sup_{\substack{\theta_1,\dots,\theta_n\in\Theta\\ a_1,\dots,a_n\in\mathbb{R}\\ n\in\mathbb{Z}^+}} \frac{\left|\sum_{i=1}^{n} a_i h(\theta_i)\right|}{\left\|\sum_{i=1}^{n} a_i \pi_{\theta_i}\right\|_r}$$

r^{th} norm, an integral

likelihood ratio against θ_0

where $r = \dfrac{s}{s-1}$

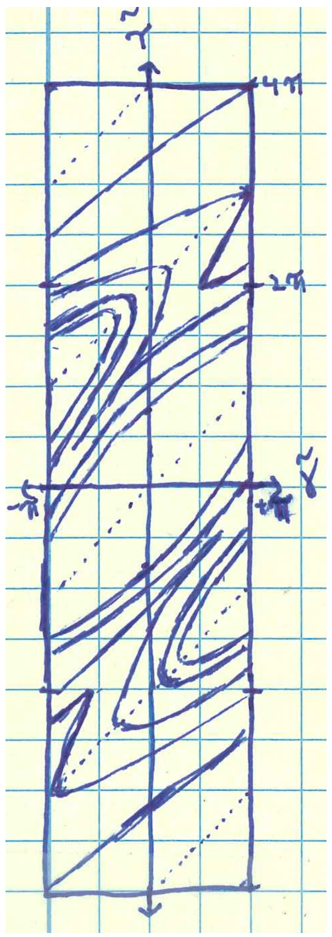


heavy line: Barankin bound

E.W. Barankin, Ann. Math. Stat., 20, 477

w/fudge factor of π (!?)

Enhancement: fold phase measurement into likelihood



- CRB⟹time & phase errors are correlated
- Likelihood looks like Gaussian wrapped on cylinder
- At least two ways to do this: