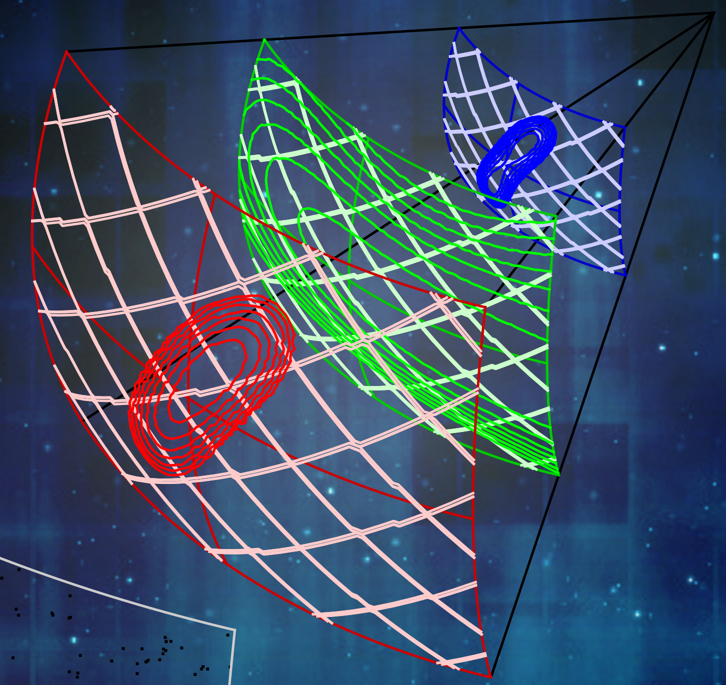
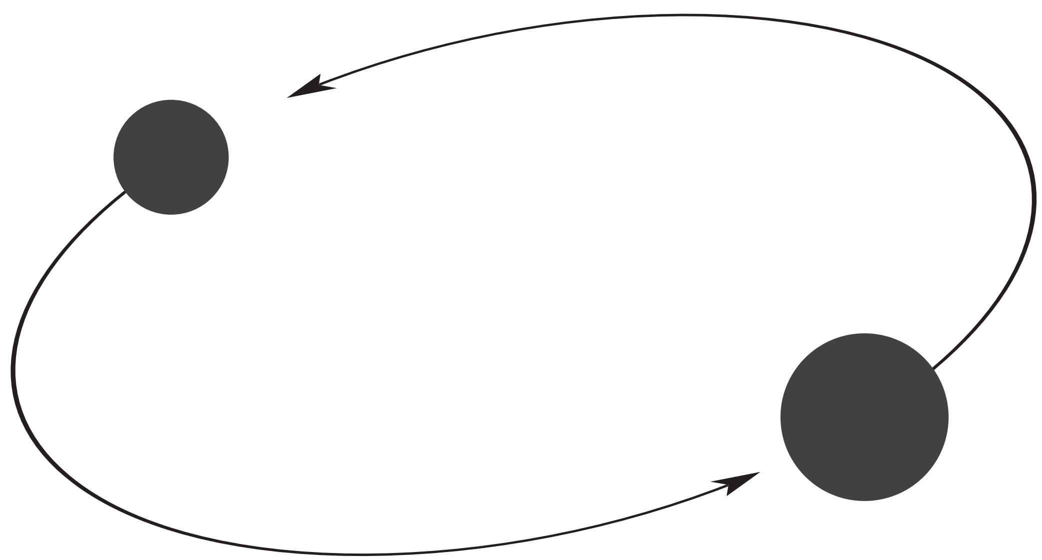


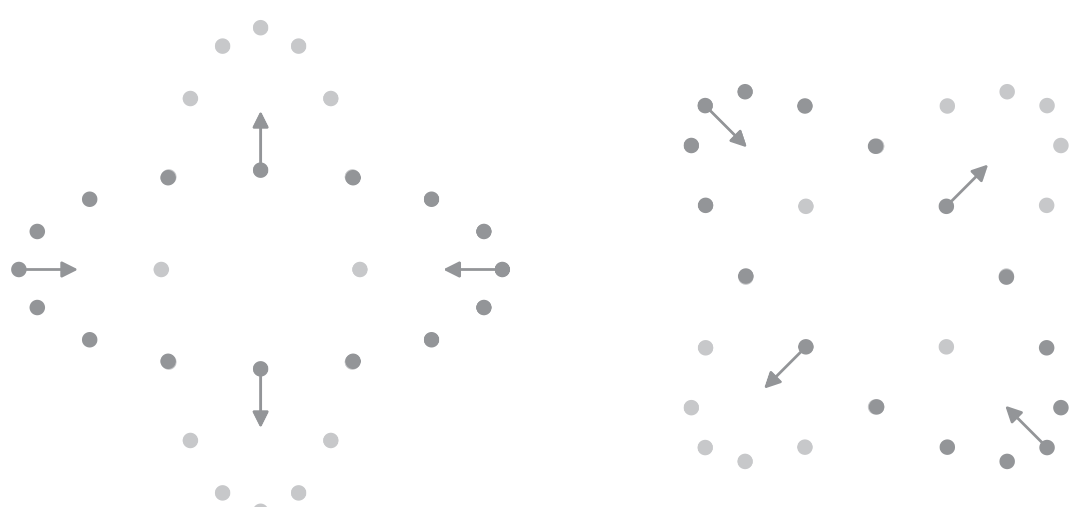
FROM FERMI GRBS TO LIGO DISCOVERIES:

THE NEEDLE IN THE 100 DEG^2 HAYSTACK

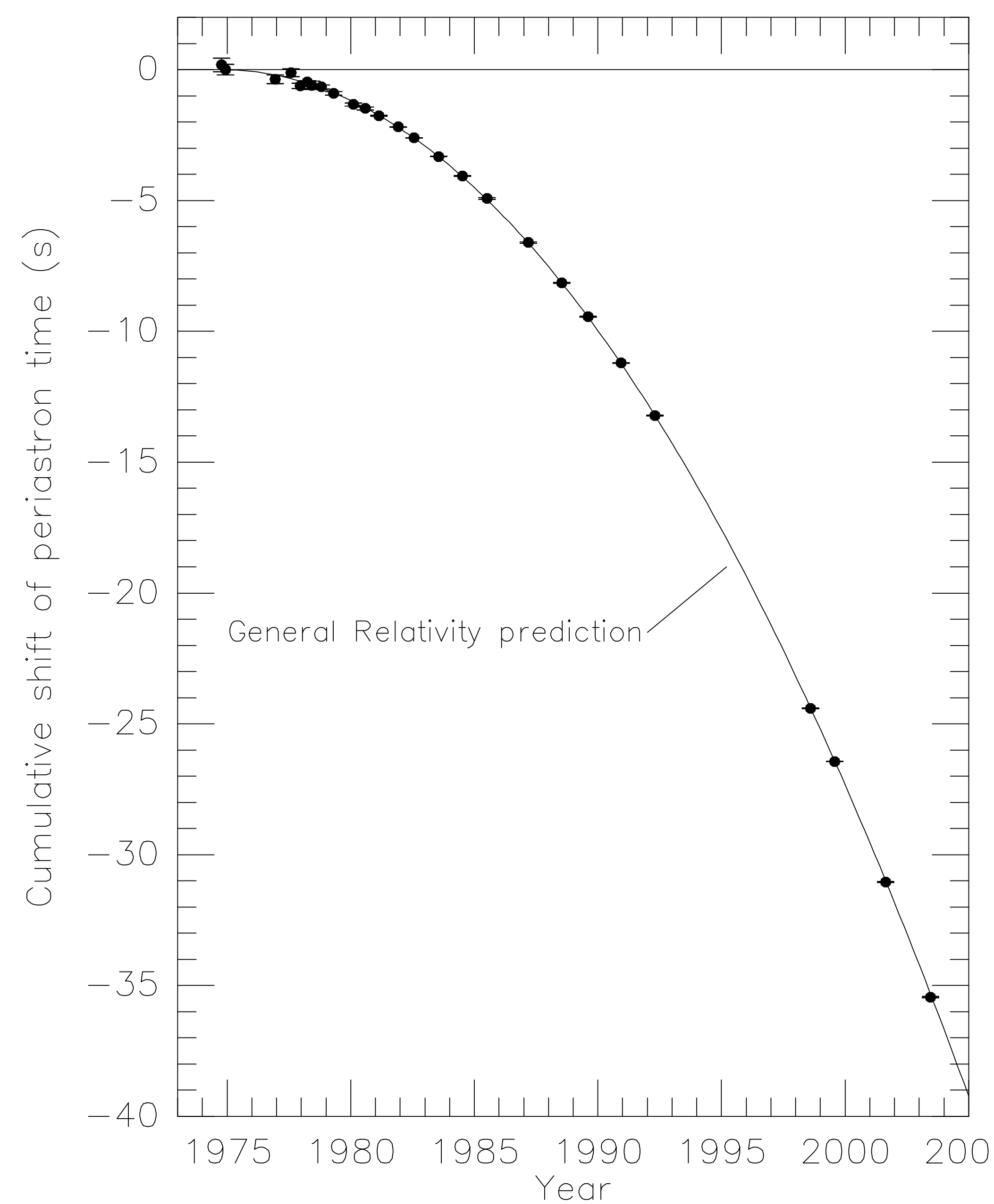
Leo Singer • LIGO Laboratory,
lsinger@caltech.edu

Gravitational waves

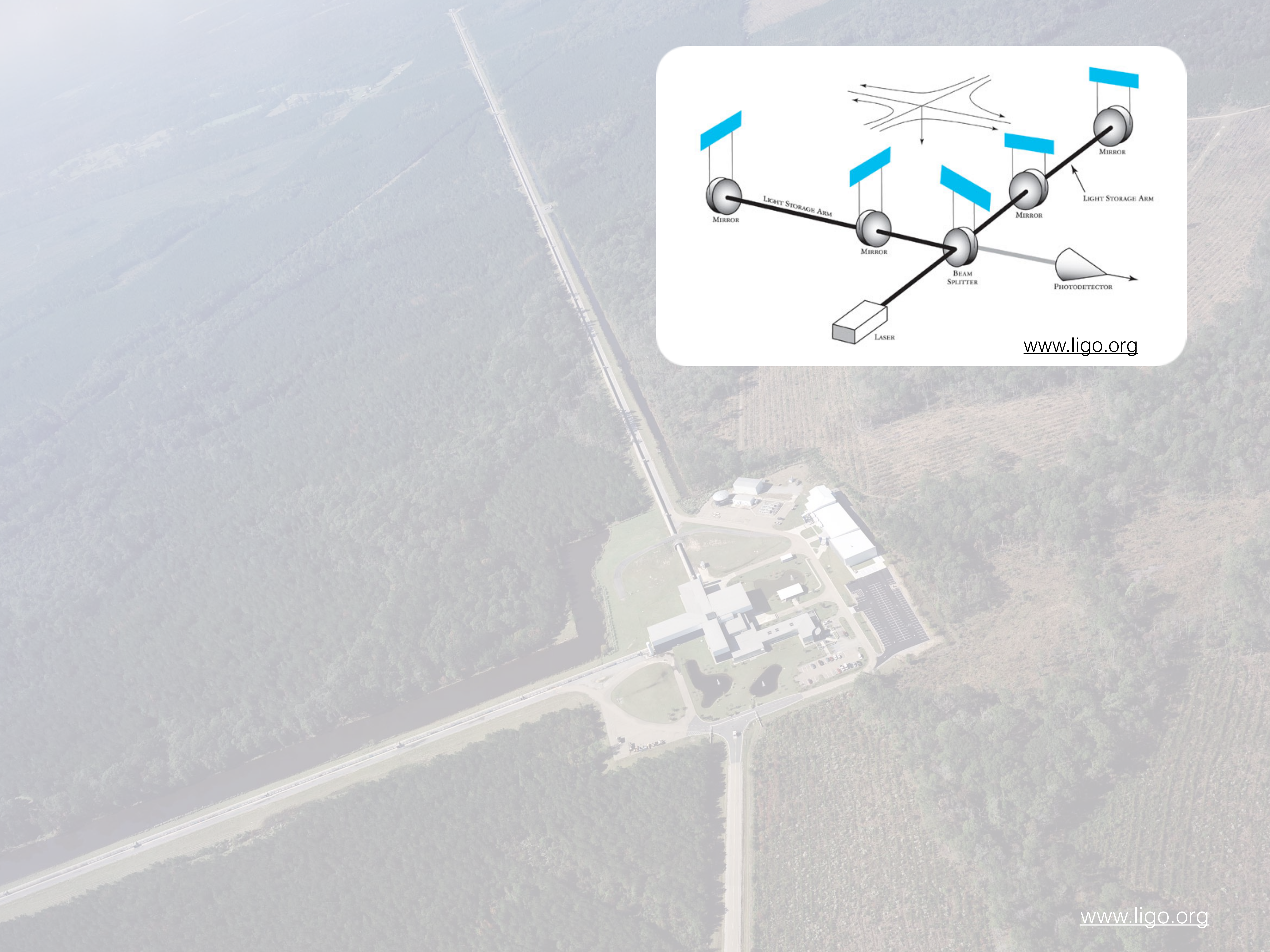




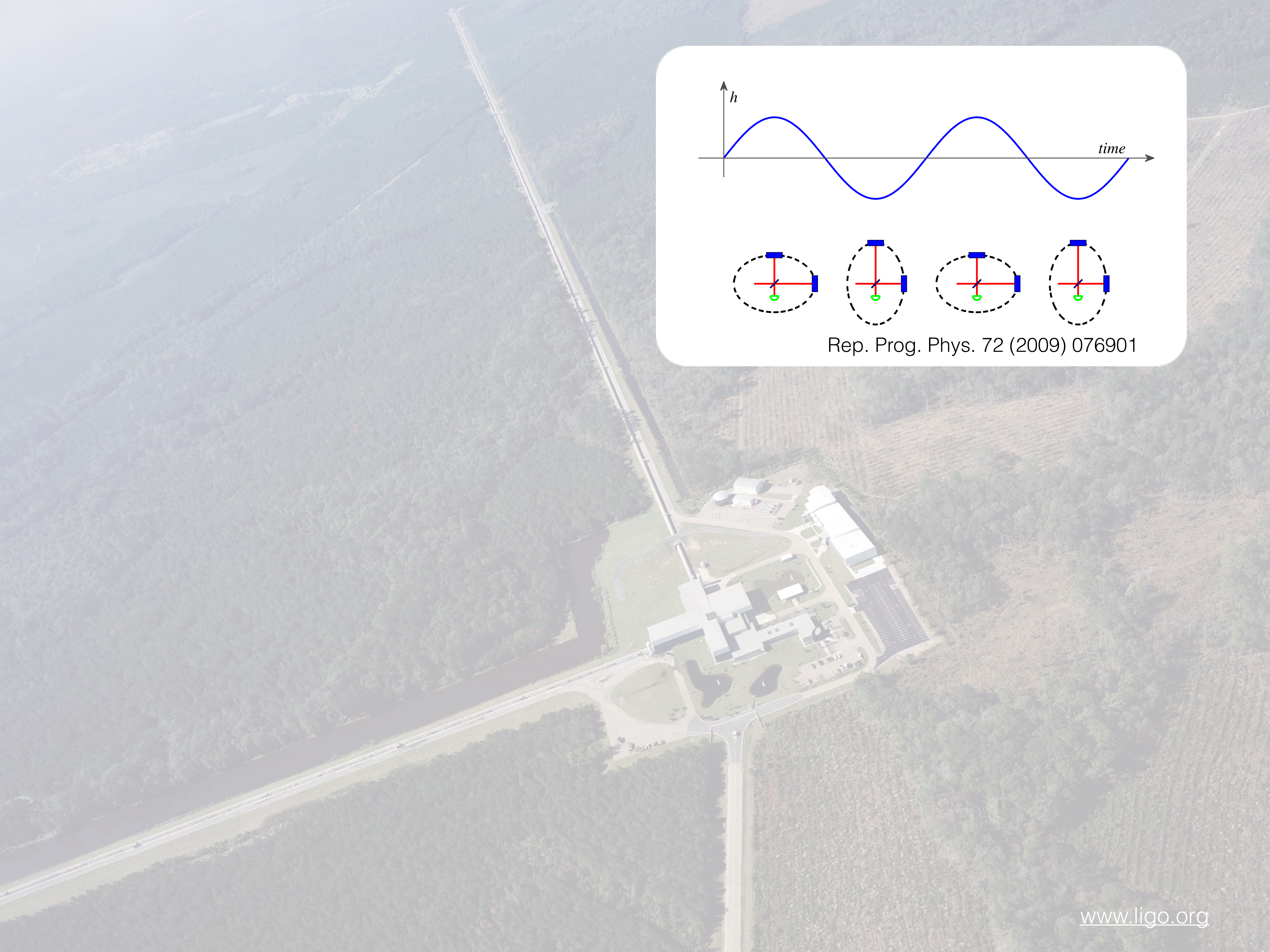
Weisberg & Taylor (2005)




ADVANCED LIGO + VIRGO
www.ligo.org


Mirror
Light Storage Arm
Mirror
Beam Splitter
Mirror
Mirror
Light Storage Arm
Photodetector
Laser
www.ligo.org

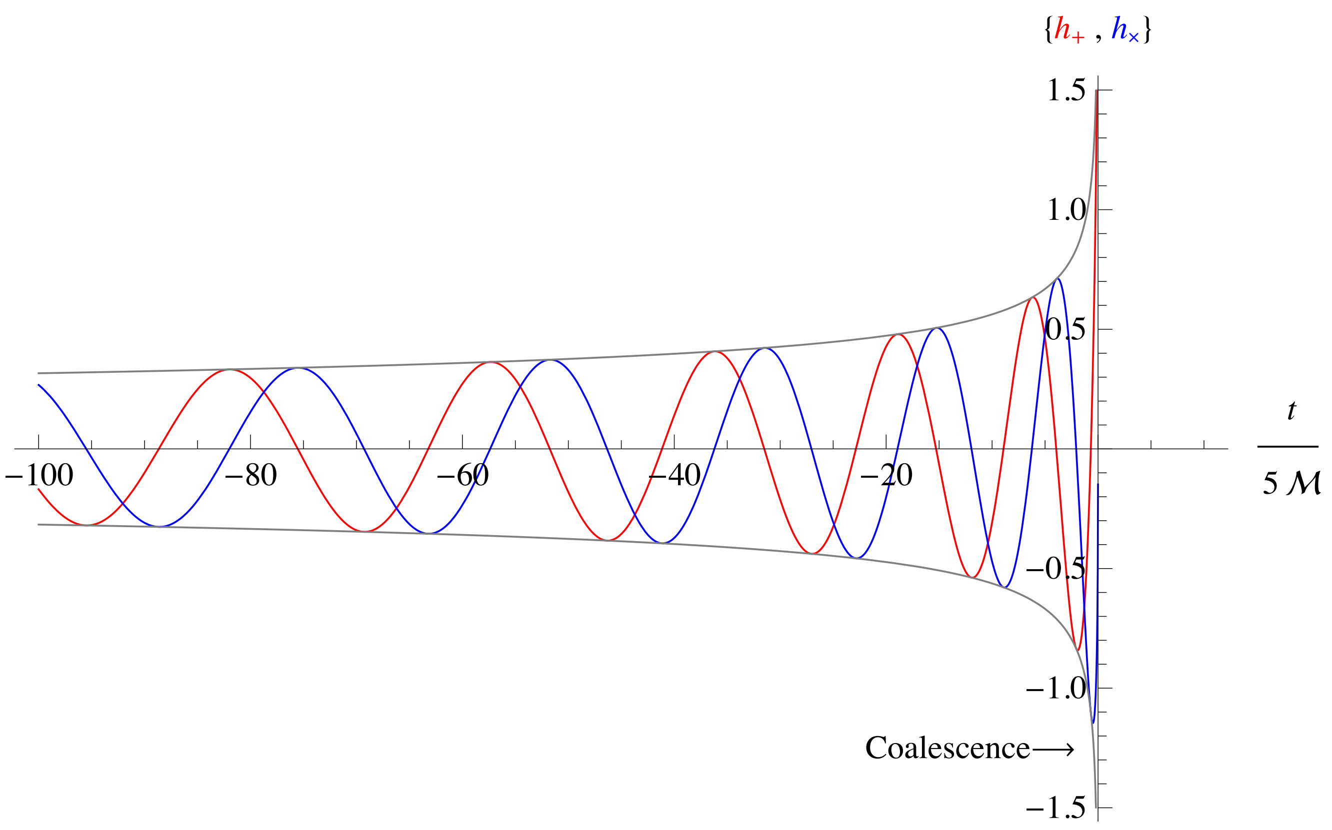
www.ligo.org



Rep. Prog. Phys. 72 (2009) 076901

www.ligo.org

GW and EM signatures of BNS mergers



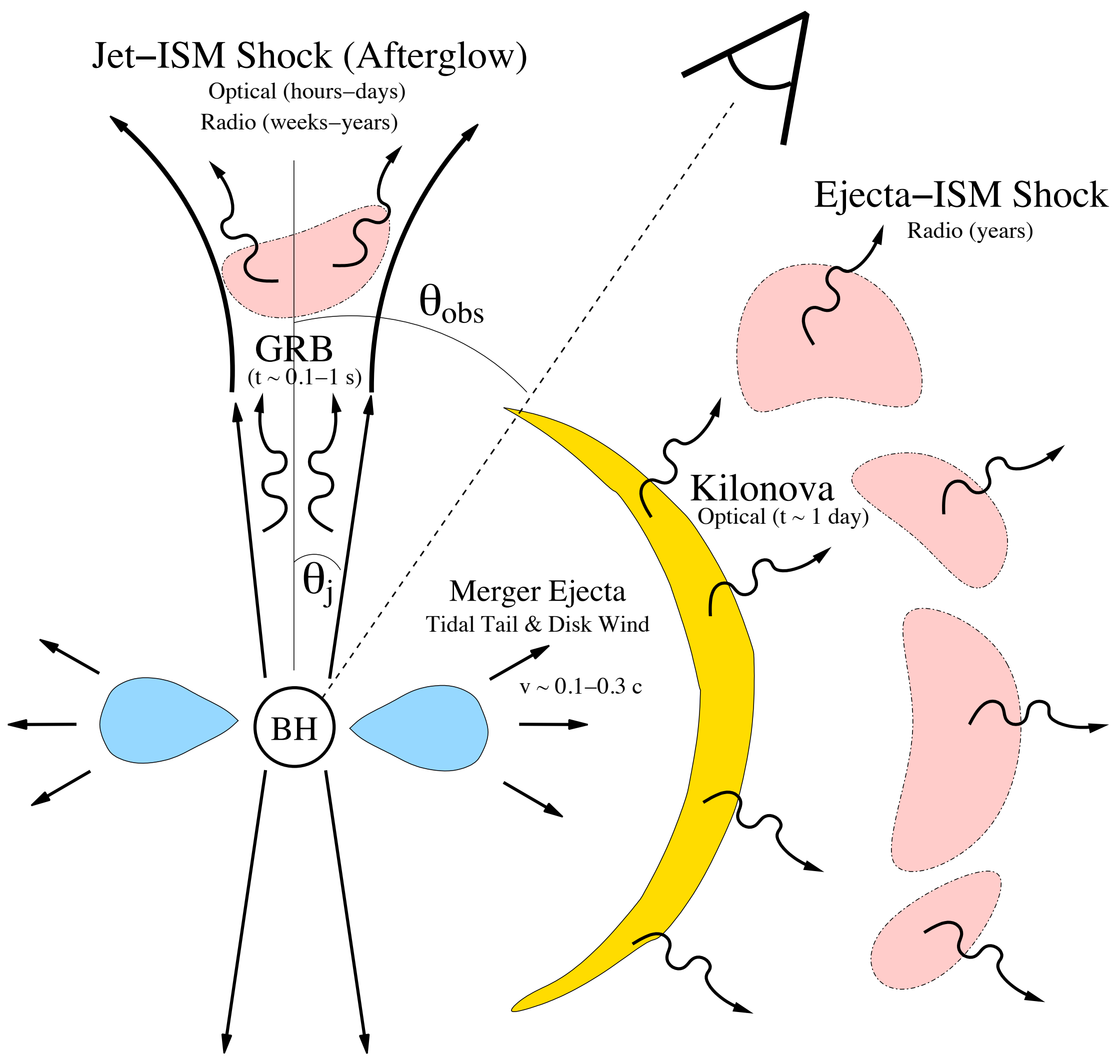
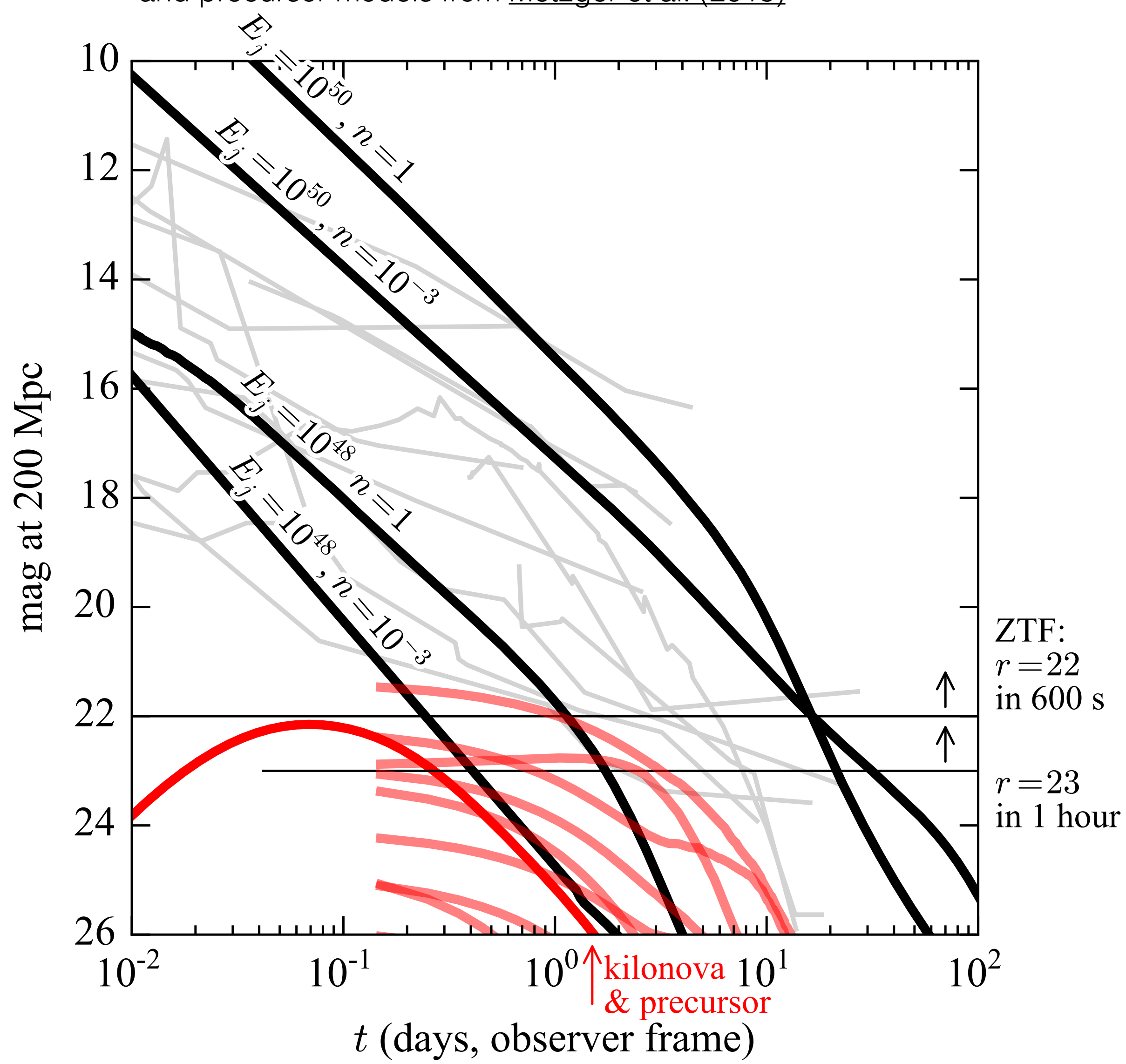


Figure 1 of Meztger & Berger 2012

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

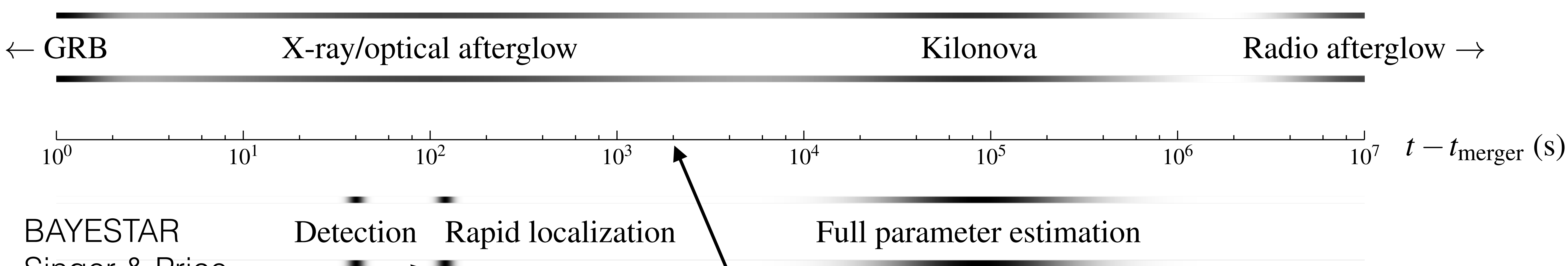
Singer et al. (2014, in prep.)
with afterglows from Kann et al. (2011),
afterglow models from van Eerten & MacFadyen (2011),
kilonova models from Barnes & Kasen (2013),
and precursor models from Metzger et al. (2015)



Challenge 1:

Optical counterparts of GW events are expected to be *faint* (R >(>) 22 mag) and *fast* (peaking at an hour–day time scale).

Singer et al. (2014)

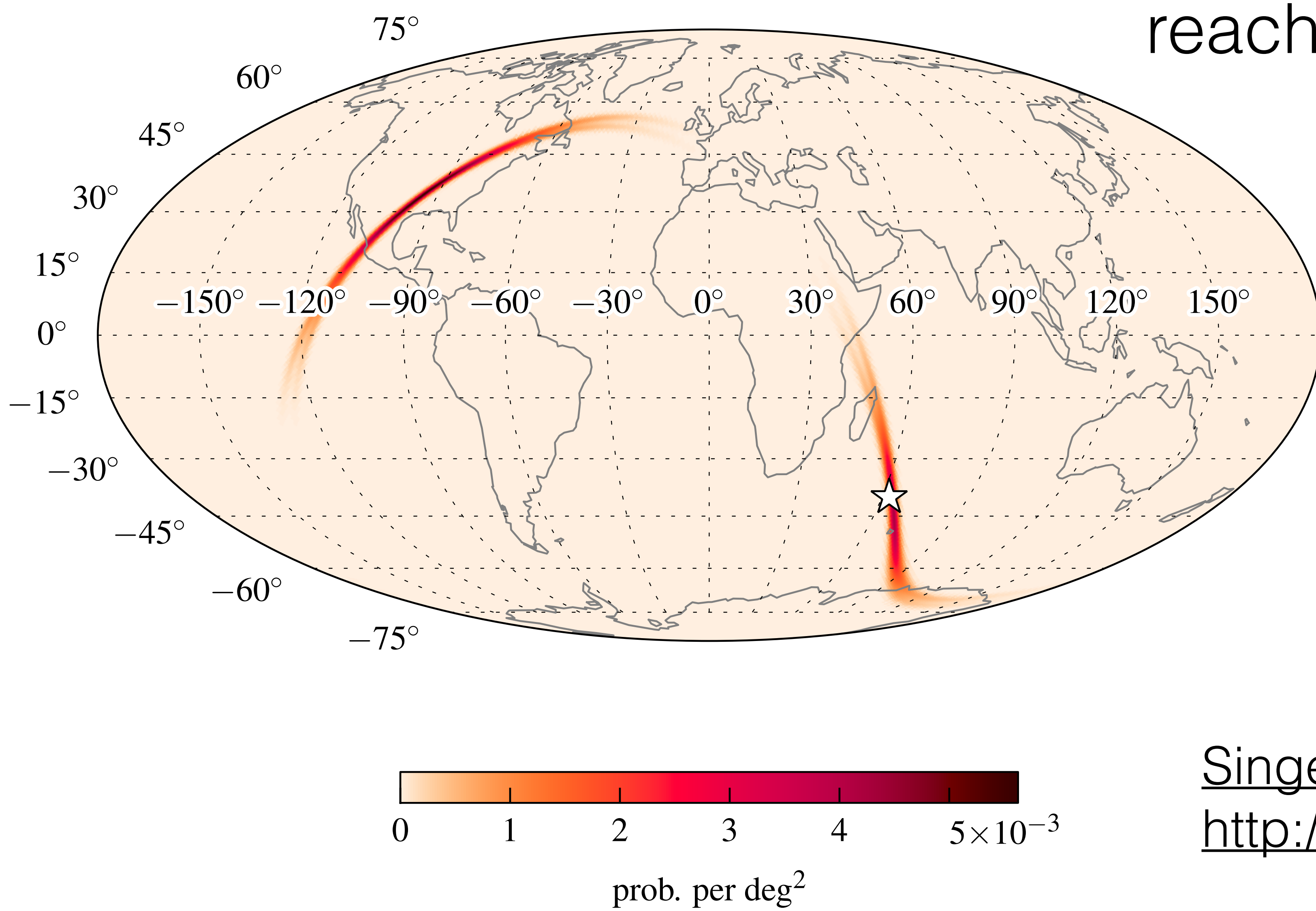


BAYESTAR Singer & Price (in prep.)

Achieved in last science run, Abadie et al. 2012, A&A

Challenge 2:

GW events are expected to be poorly localized, starting at ≈600 deg^2 in 2015 and reaching ~10 deg^2 late in the decade.



Singer et al. (2014), *ApJ*
http://www.ligo.org/scientists/first2years

My thesis:

The major pieces of a search for optical counterparts of LIGO/Virgo compact binary mergers, including detection, rapid parameter estimation, and the search for optical counterparts with the Palomar Transient Factory.

My thesis:

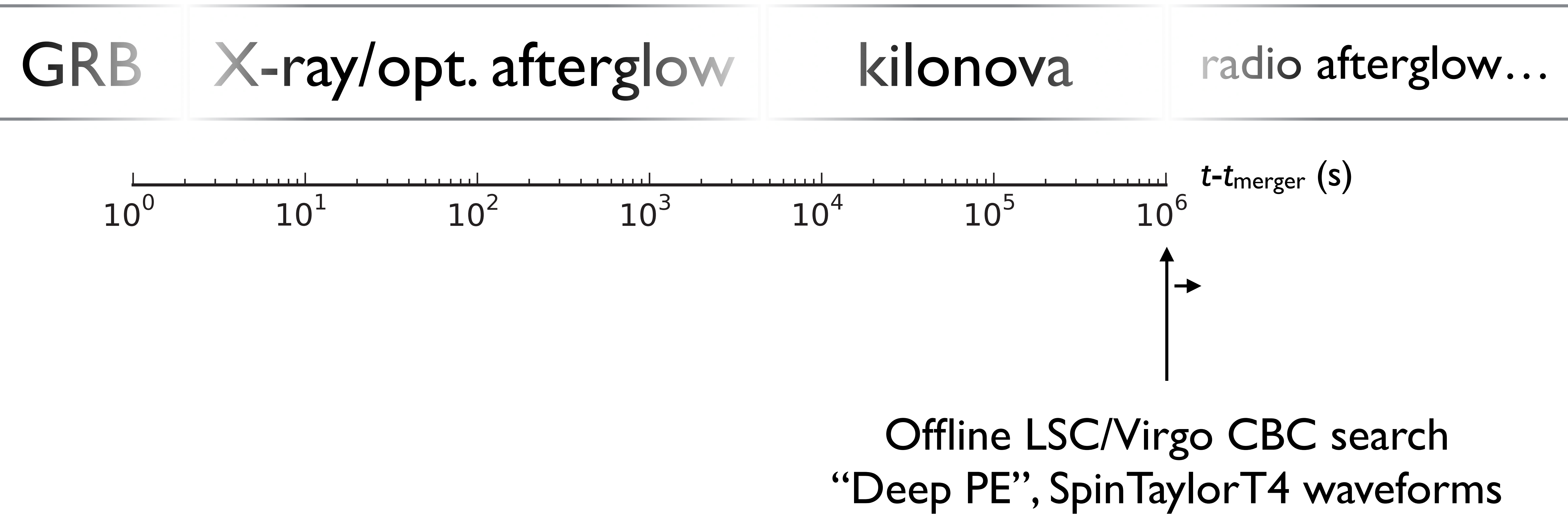
The major pieces of a search for optical counterparts of LIGO/Virgo compact binary mergers, including **detection**, rapid parameter estimation, and the search for optical counterparts with the Palomar Transient Factory.

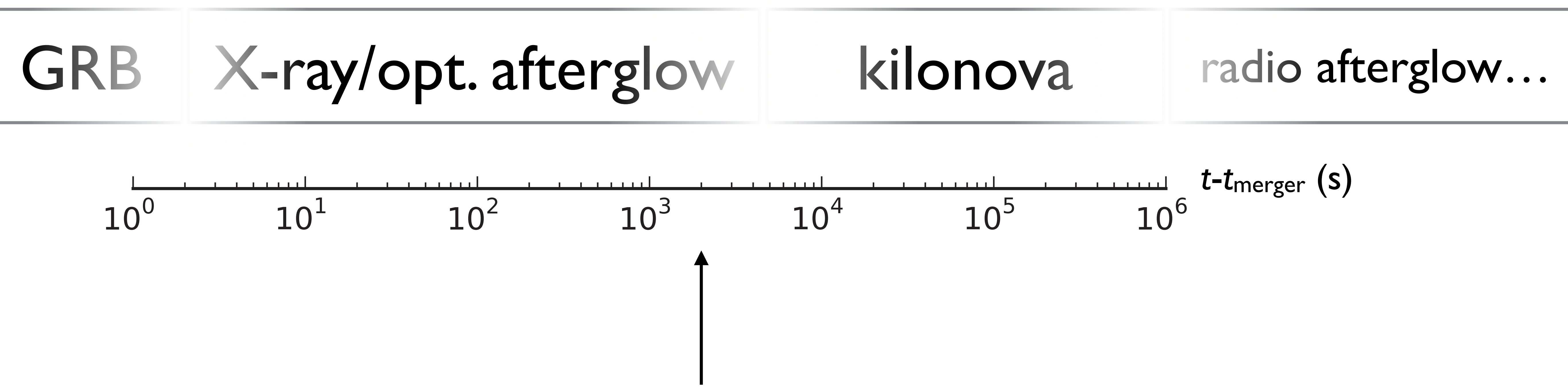
My thesis:

The major pieces of a search for optical counterparts of LIGO/Virgo compact binary mergers, including detection, **rapid parameter estimation**, and the search for optical counterparts with the Palomar Transient Factory.

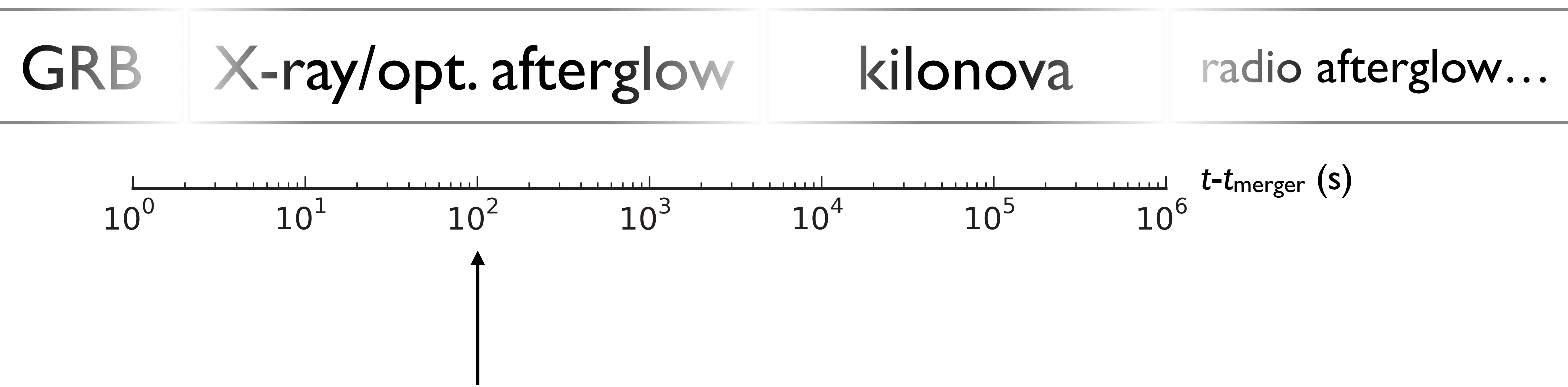
My thesis:

The major pieces of a search for optical counterparts of LIGO/Virgo compact binary mergers, including detection, rapid parameter estimation, and the **search for optical counterparts** with the Palomar Transient Factory.

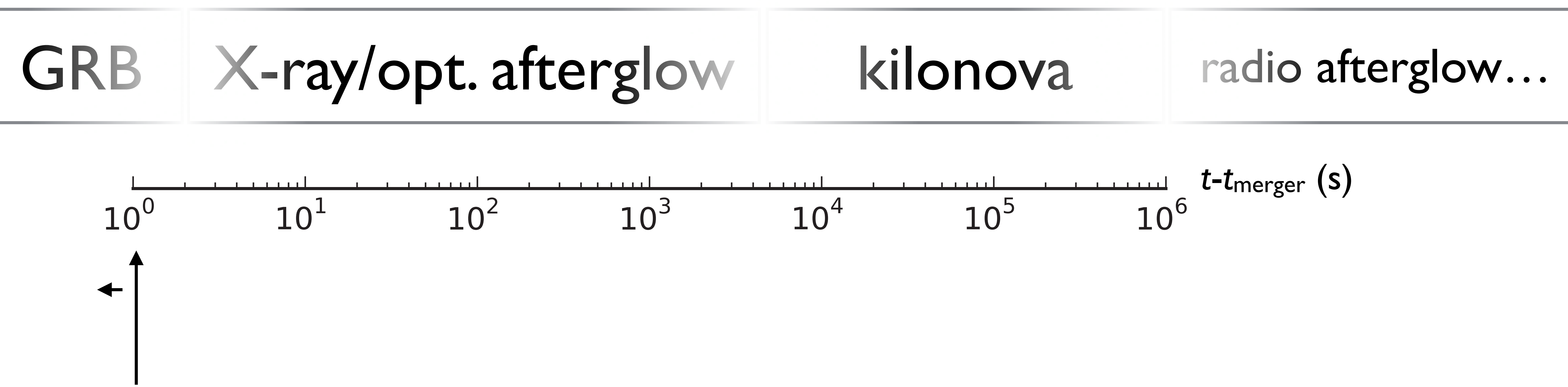

GRB
X-ray/opt. afterglow
kilonova
radio afterglow…
t-t_merger (s)
10^0
10^1
10^2
10^3
10^4
10^5
10^6
Offline LSC/Virgo CBC search
“Deep PE”, SpinTaylorT4 waveforms



First online LSC/Virgo search (S6/VSR2/3)
MBTA, rapid sky localization (“Timing++”)
Abadie et al. (2012)



My thesis!
GSTLAL, BAYESTAR
demonstrated in LSC/Virgo
engineering runs



Possible due to my thesis work

(though requires modifications to LSC/ Virgo data acquisition infrastructure)

GRB | X-ray/opt. afterglow | kilonova | radio afterglow…

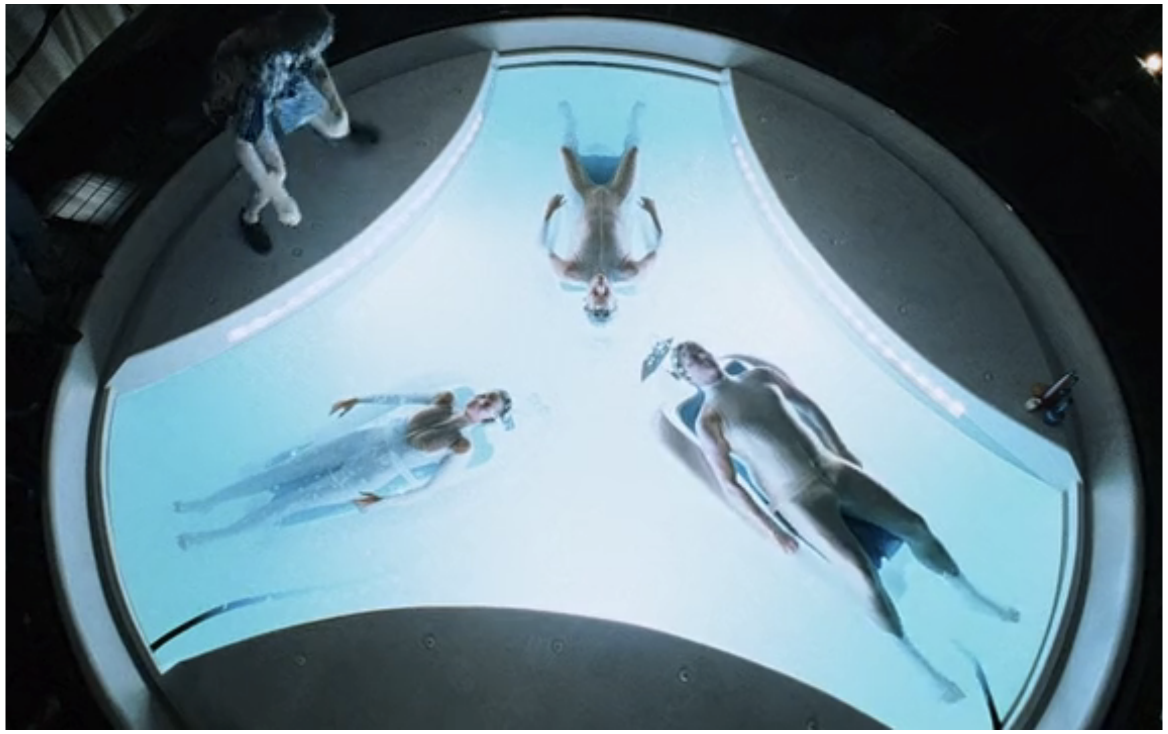
t-t_{merger} (s)

10^0 10^1 10^2 10^3 10^4 10^5 10^6

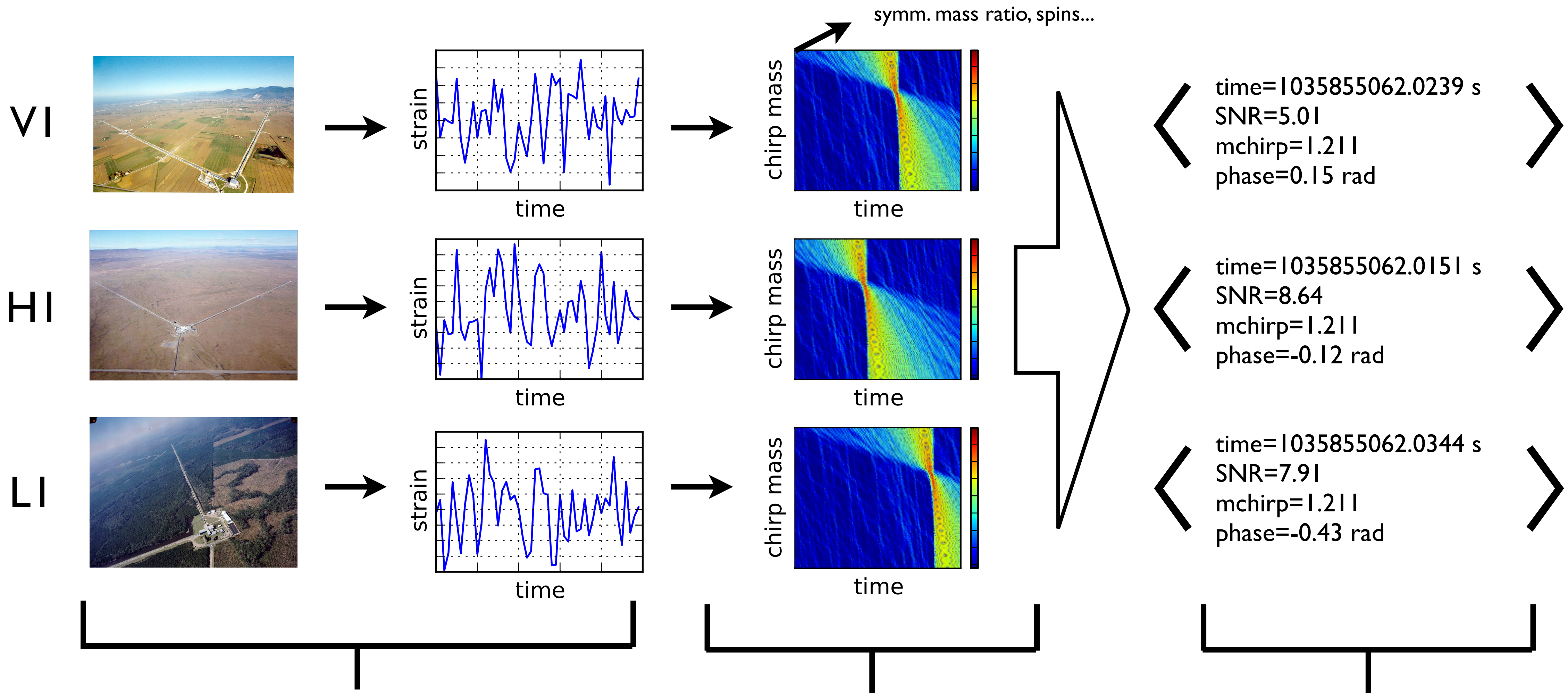
Possible due to my thesis work

(though requires modifications to LSC/ Virgo data acquisition infrastructure)

Image: *Minority Report*



Detection



Strain transduced by detectors

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

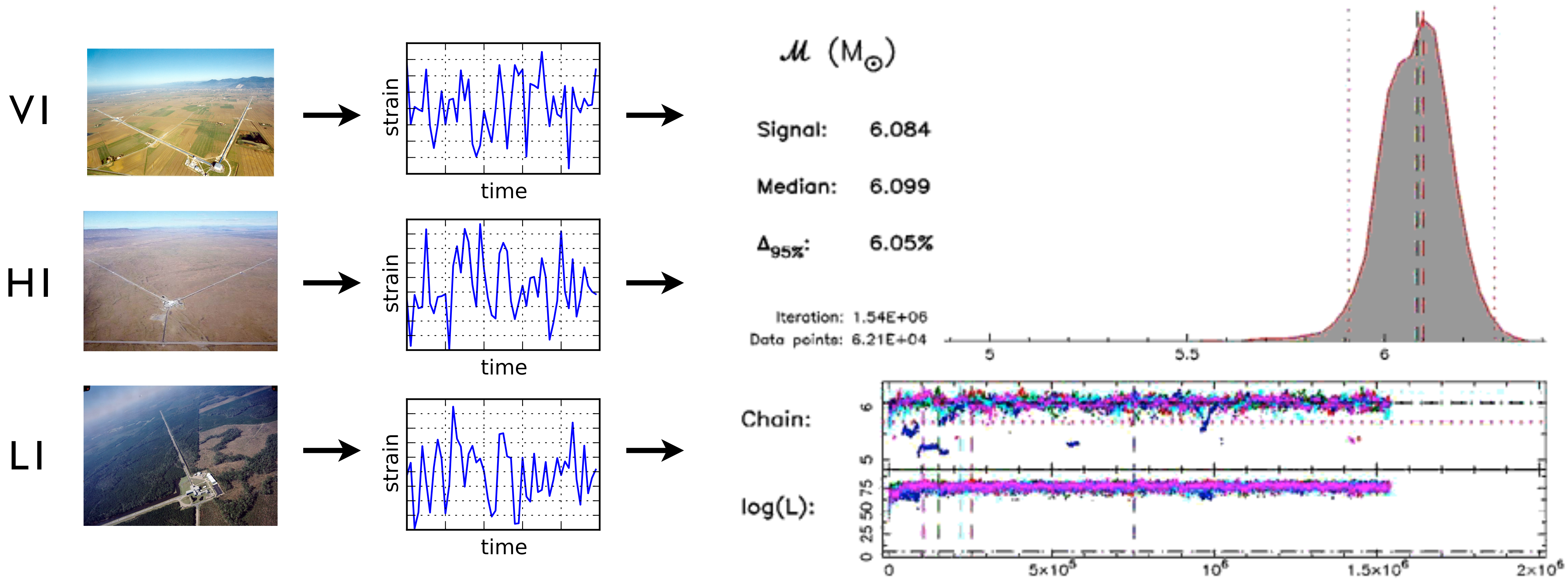
Matched filter

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

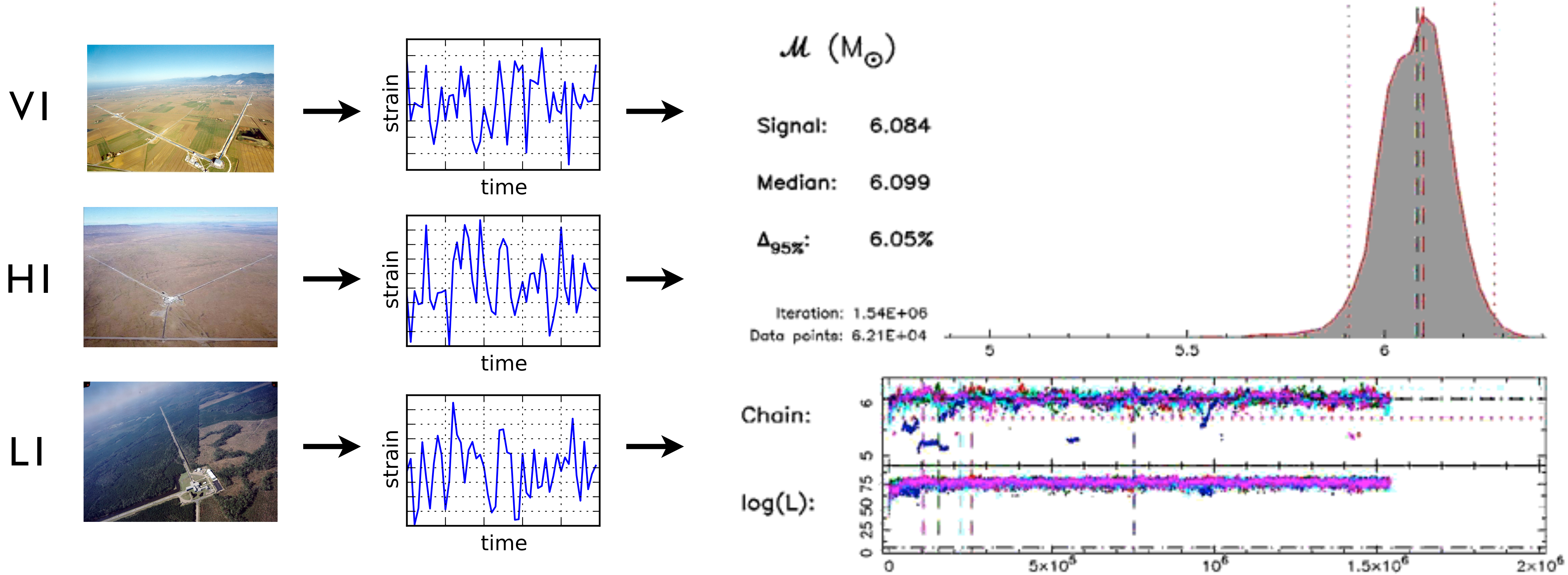
Bayesian Markov-chain Monte Carlo



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

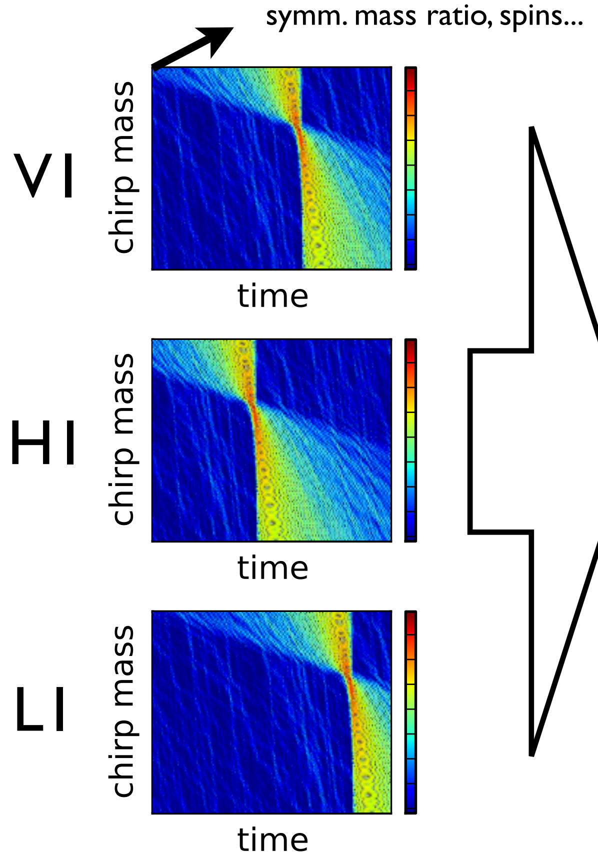
Bayesian Markov-chain Monte Carlo



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

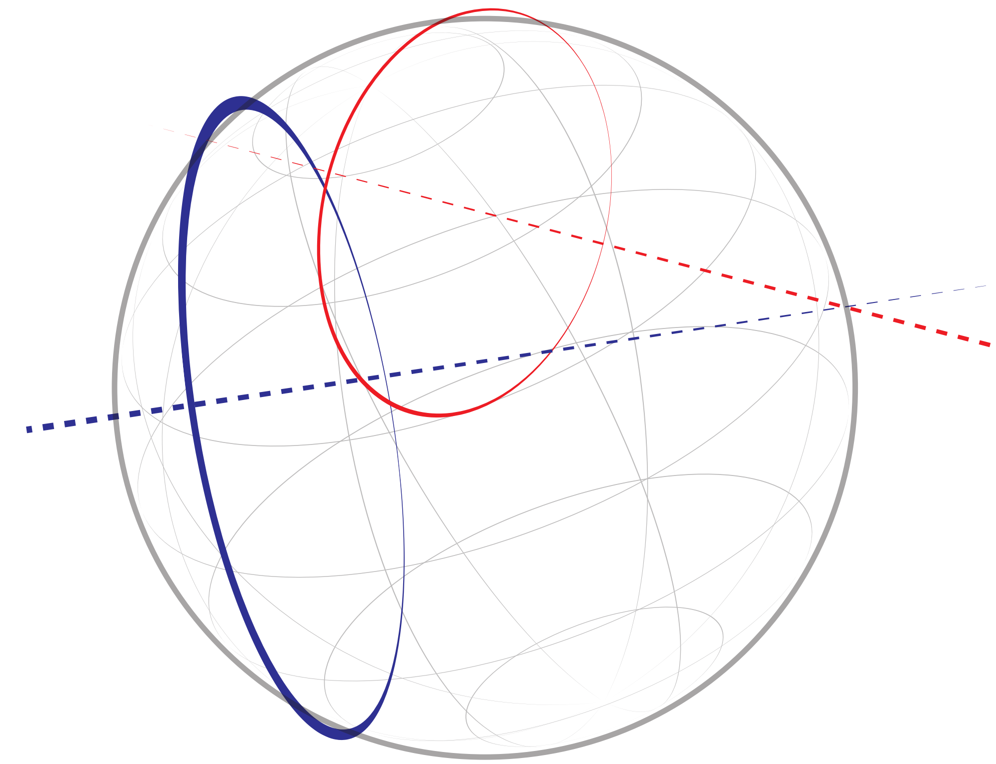
Triangulation



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

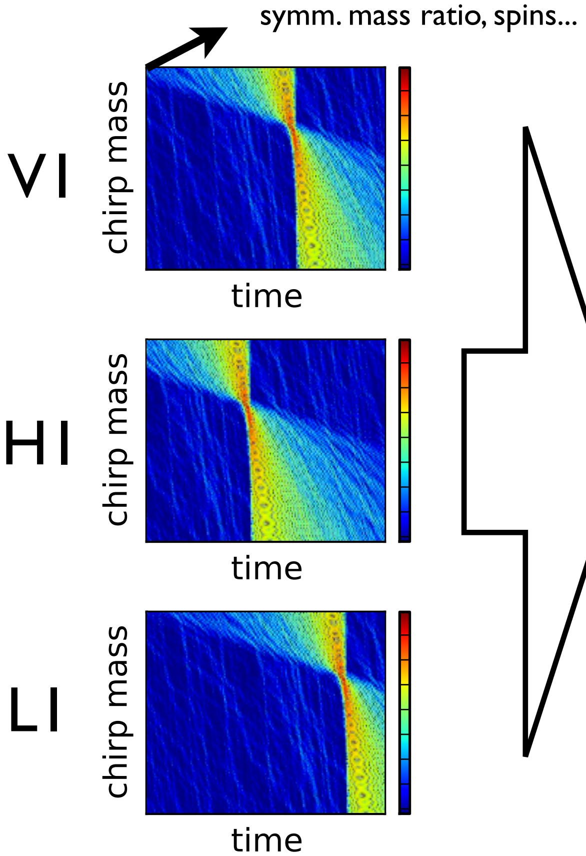
time=1035855062.0151 s
SNR=8.64
mchirp=1.211
phase=-0.12 rad

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



See also: Fairhurst (2009), Fairhurst (2011)

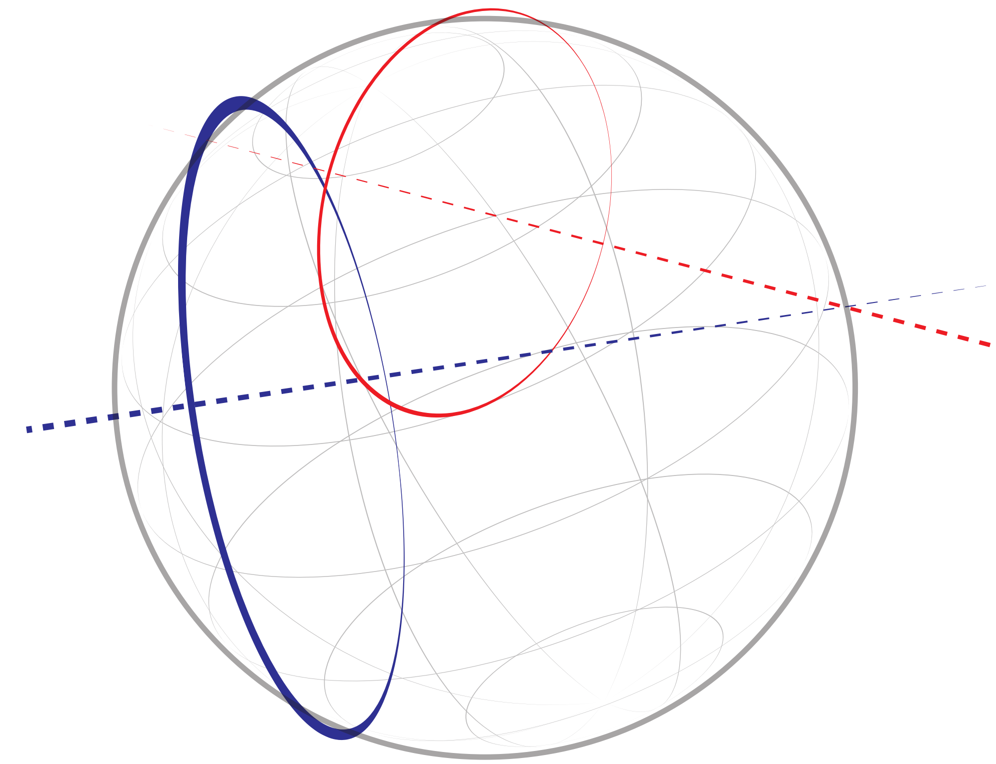
Triangulation

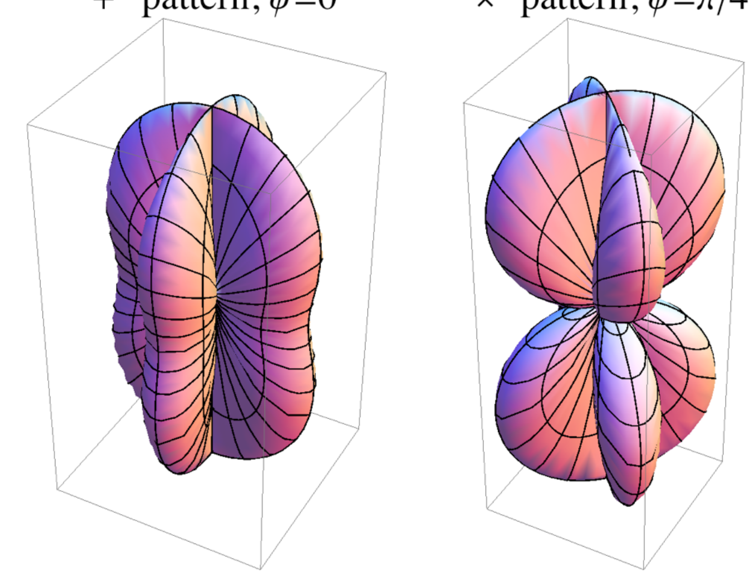


⟨ time=1035855062.0239 s
SNR=5.01
mchirp=1.211
phase=0.15 rad ⟩

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

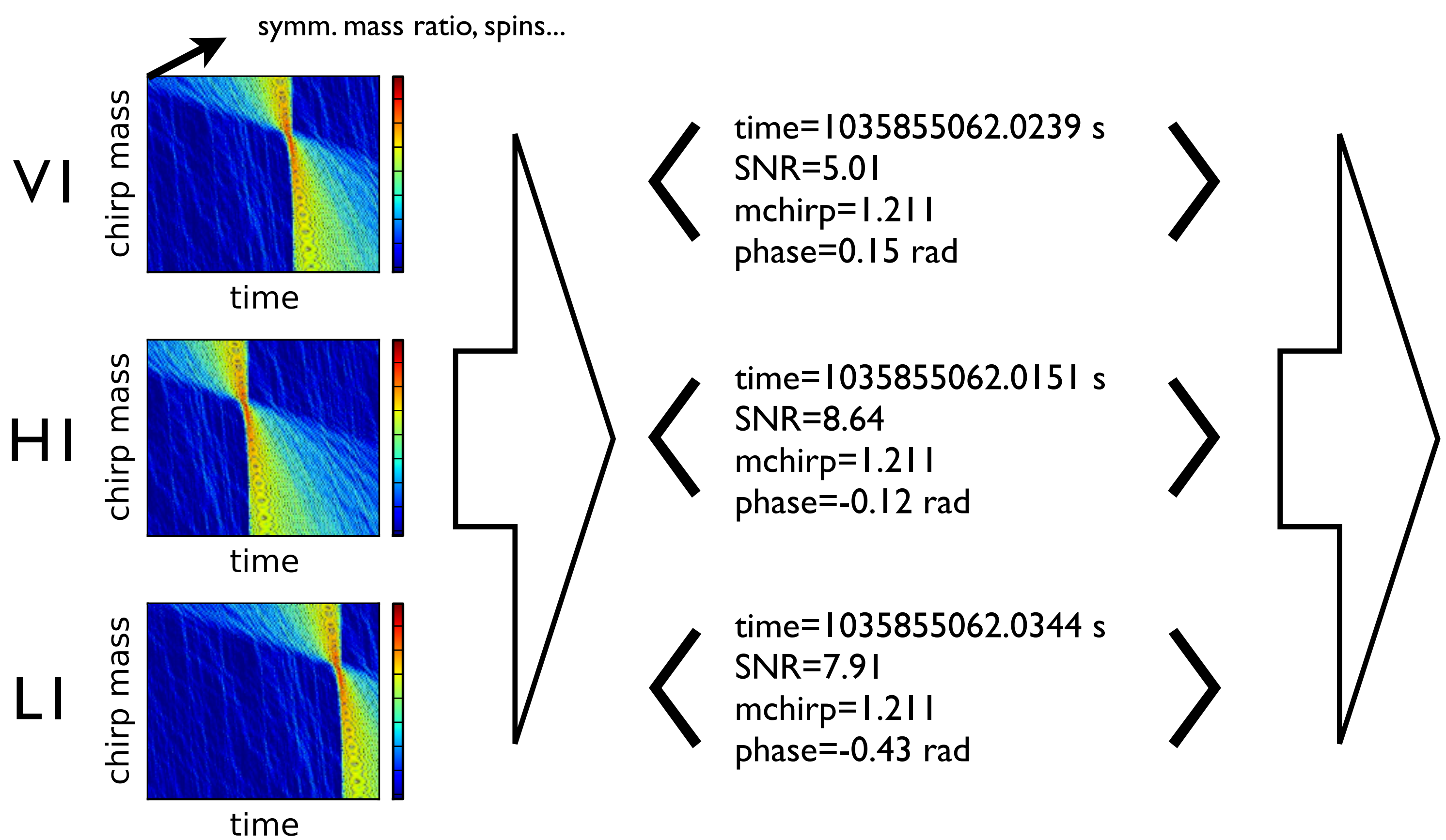
⟨ time=1035855062.0344 s
SNR=7.91
mchirp=1.211
phase=-0.43 rad ⟩

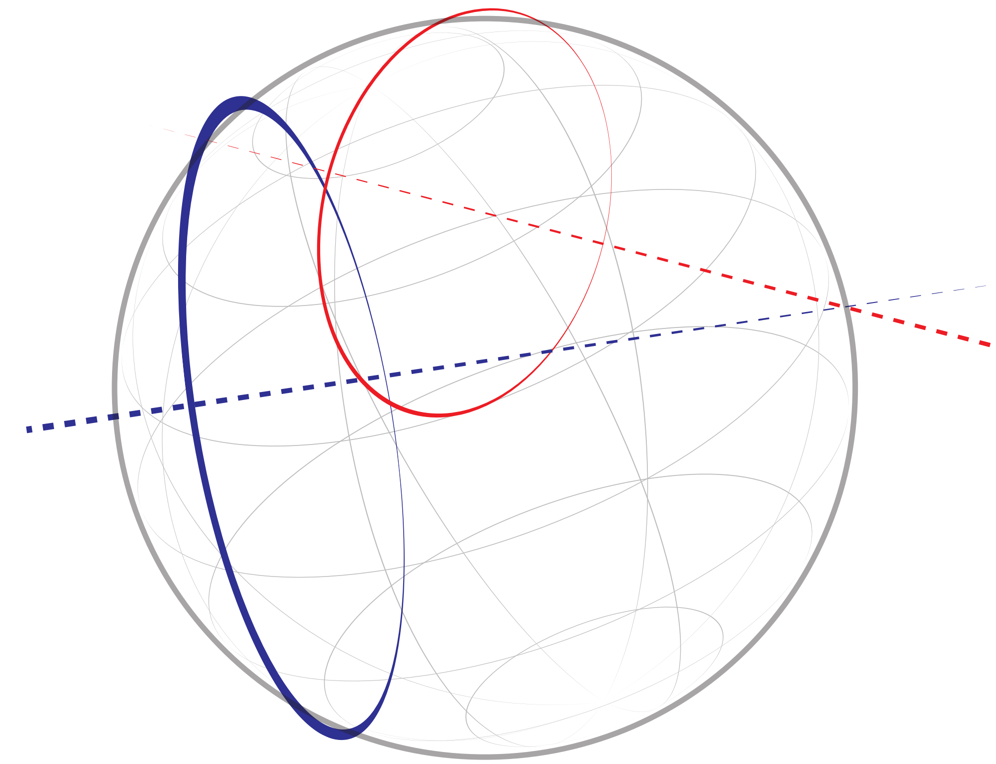


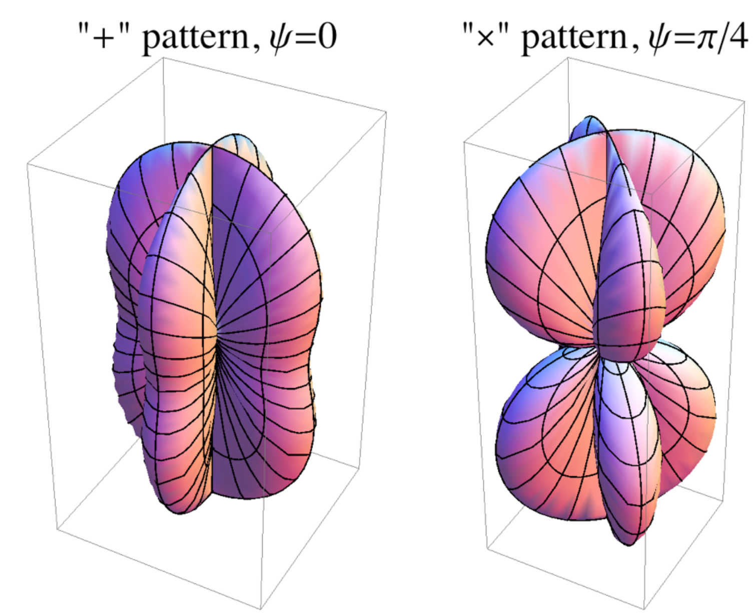


See also: Fairhurst (2009), Fairhurst (2011)

Triangulation



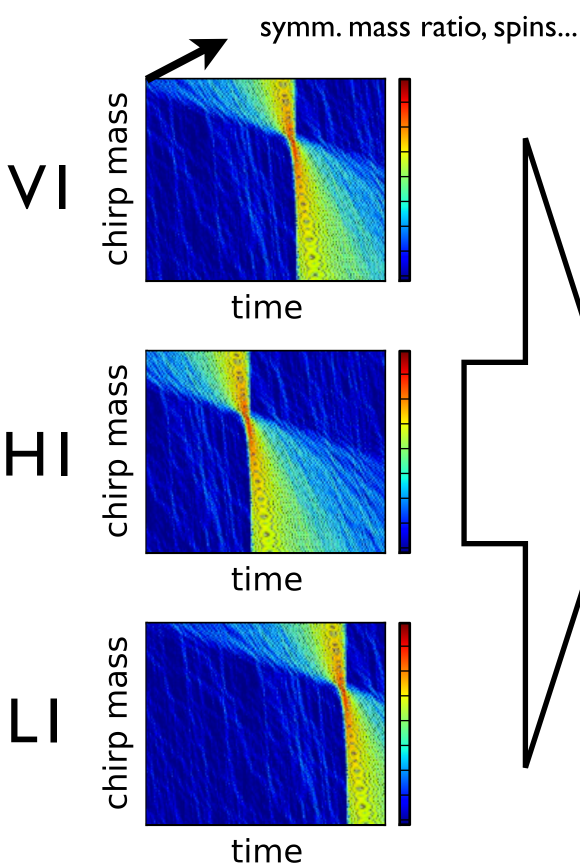




- Time delays & relative amplitudes ⟹inform sky location
- Triggers = point estimates
- Statistics of estimation error
- Very fast!

See also: Fairhurst (2009), Fairhurst (2011)

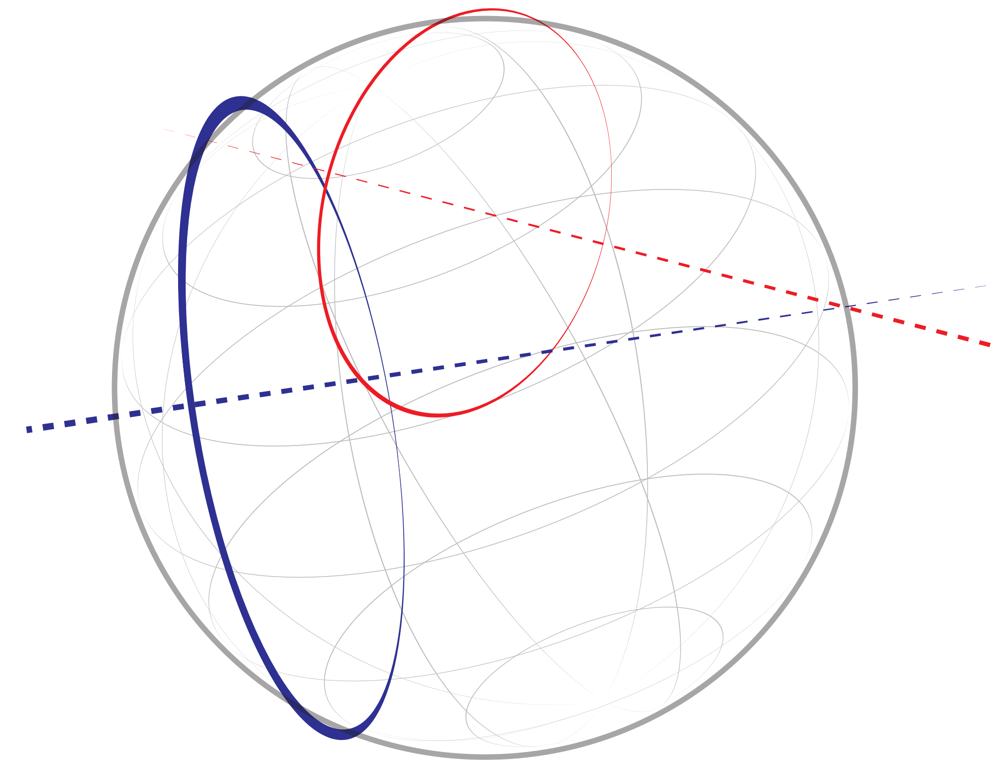
Triangulation

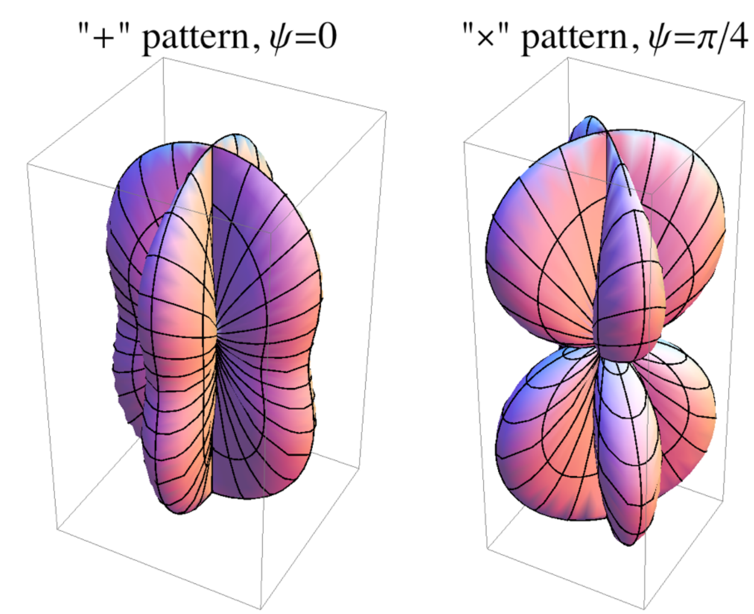


time=1035855062.0239 s
SNR=5.01
mchirp=1.211
phase=0.15 rad

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





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

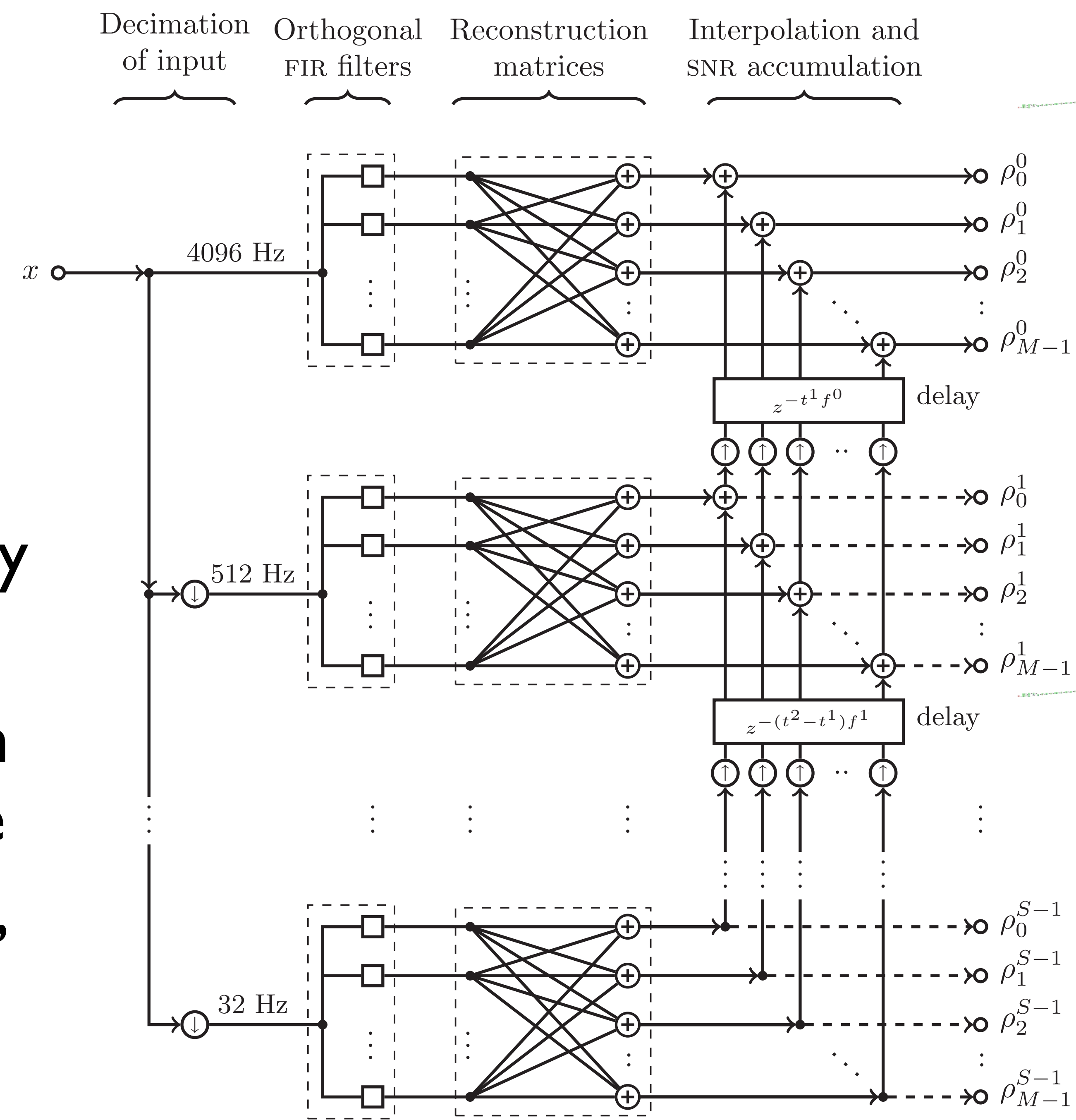
See also: Fairhurst (2009), Fairhurst (2011)

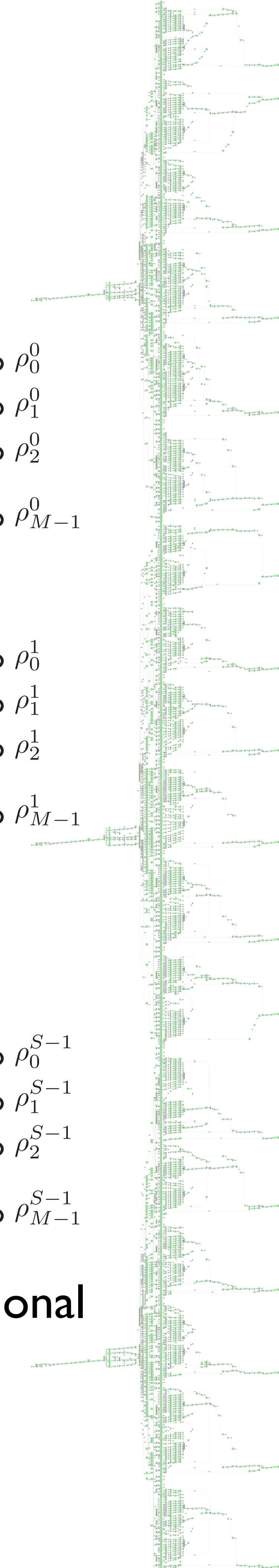
Real-time detection pipeline:

GSTLAL

my contributions

- drive latency down
- handle data gaps efficiently
- computational budget
- first complete description of algorithm for literature
- improve accuracy of time, SNR of triggers



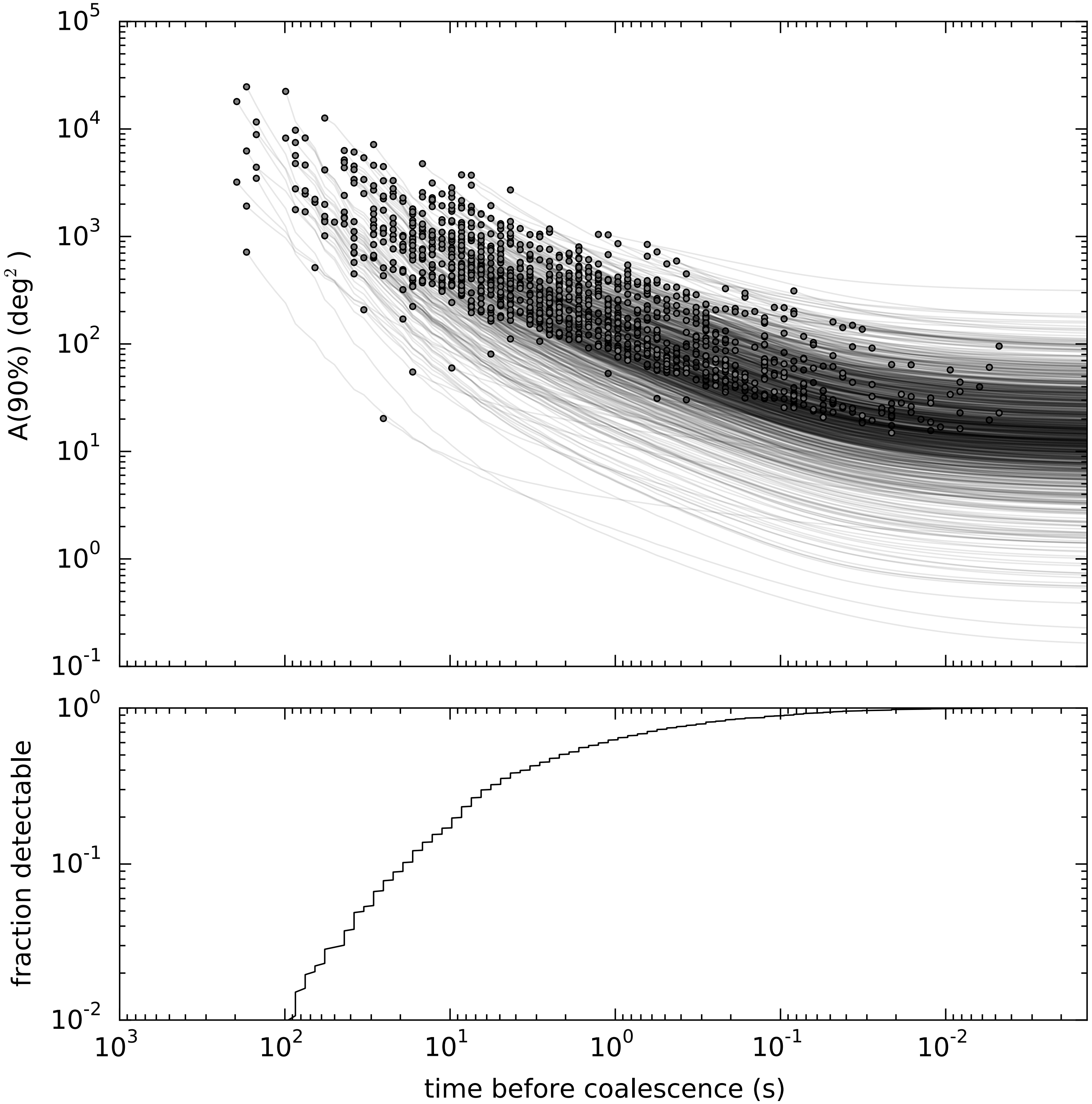


gstreamer

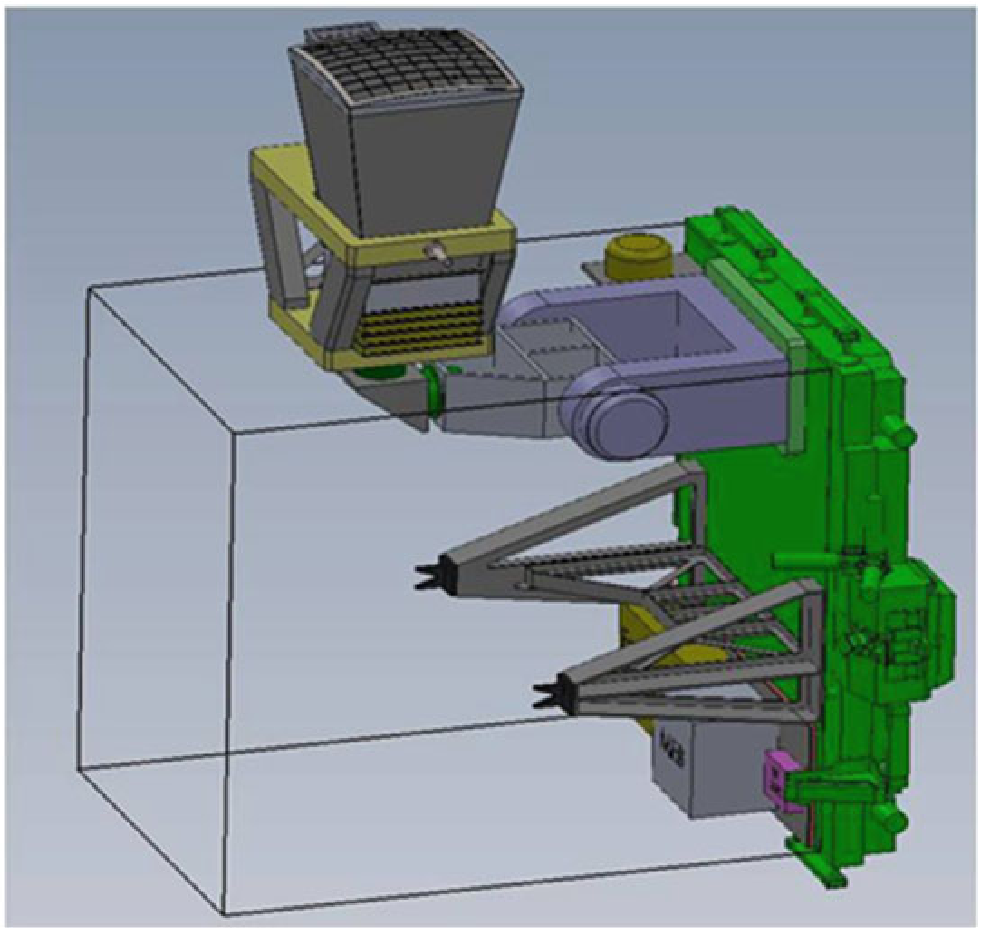
Toward early-warning detection of gravitational waves from compact binary coalescence

Cannon et al. (2012)

(note: corresponding author)



Bonus:
Pick off SNR from different sub-bands to create BNS merger early warning system



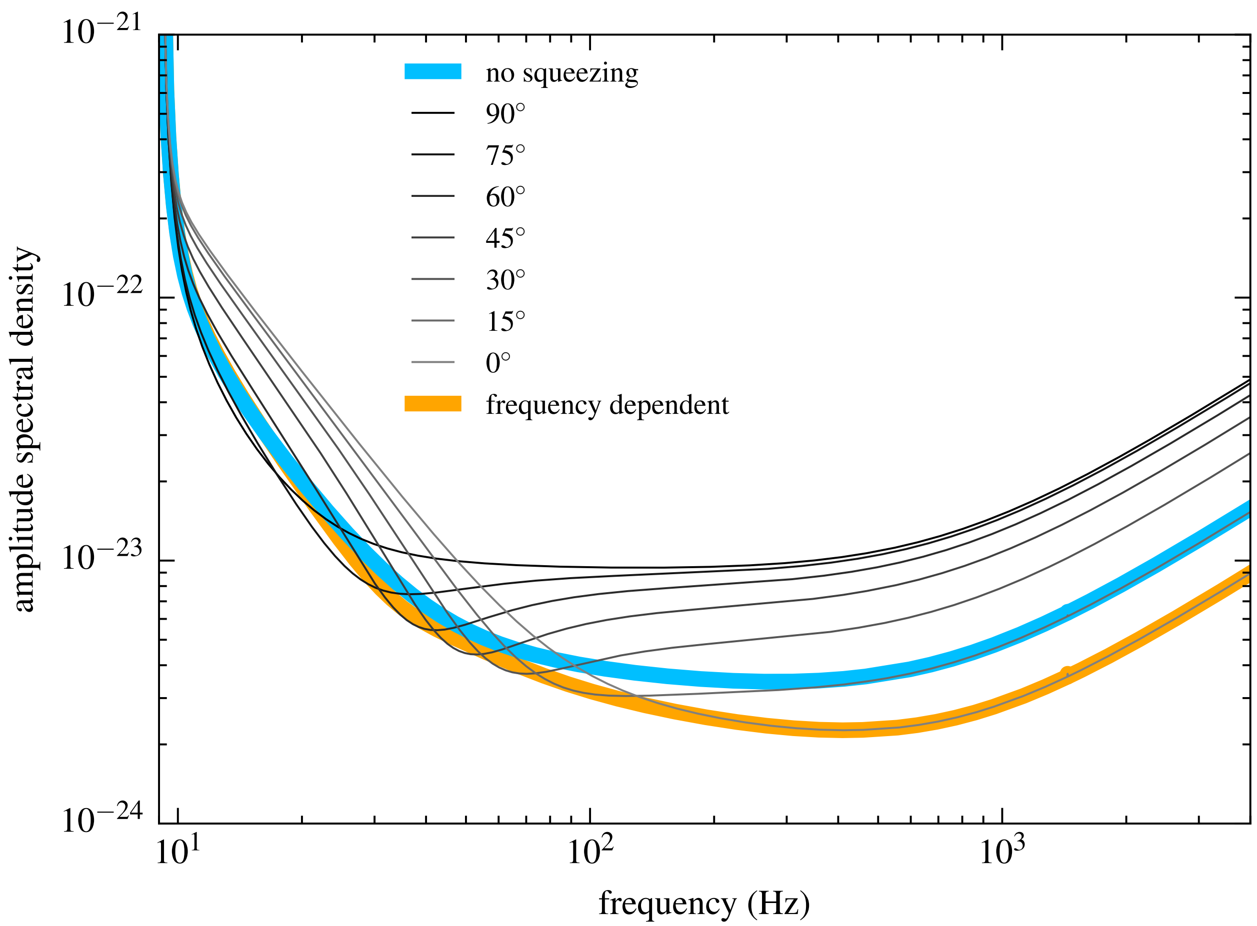
Camp et al. (2014)

ISS-Lobster:
Proposed 820 deg^2 X-ray imager on International Space Station.

Sensitivity:
0.3–5 keV (similar to *Swift* XRT band)
1.3×10^{-11} erg cm^{-2} s^{-1} in 2 ks

Slew time: ~25 s
Start looking for X-ray afterglow within 15 seconds after a BNS merger detected by LIGO

Sensitivity curves generated with GWINC by Nic Smith



See also:
Kimble et al. (2002)
LSC (2011), *Nature Physics*
LSC (2013), *Nature Photonics*

Time-dependent squeezing:

Inject squeezed vacuum states into the interferometer to get sensitivity below the standard quantum limit in a narrow band.

Sweep squeezing angle so that narrowband sensitivity follows the chirp signal.

Increase LIGO's sensitivity by 30% → detection rate doubled.

Can be slightly more sensitive than frequency depend squeezing because it does not involve a lossy filter cavity.

Real-time parameter estimation:

BAYESTAR

- *Bayesian* position reconstruction for binary neutron star mergers
- *Not* Markov-chain Monte Carlo (MCMC), but has excellent agreement with MCMC so far
- *Coherent* analysis based on time, phase, and amplitude on arrival in all detectors
- ***Response time < 1 minute!***

REV. T. BAYES

Real-time parameter estimation:

BAYESTAR

- *Bayesian* position reconstruction for binary neutron star mergers
- *Not* Markov-chain Monte Carlo (MCMC), but has excellent agreement with MCMC so far
- *Coherent* analysis based on time, phase, and amplitude on arrival in all detectors
- ***Response time < 1 minute!***

REV. T. BAYES

Real-time parameter estimation:

BAYESTAR

stay tuned for:
Singer & Price, "WHOOMP! (There It Is): Rapid Bayesian Position Reconstruction for Gravitational-Wave Transients"

- *Bayesian* position reconstruction for binary neutron star mergers
- *Not* Markov-chain Monte Carlo (MCMC), but has excellent agreement with MCMC so far
- *Coherent* analysis based on time, phase, and amplitude on arrival in all detectors
- ***Response time < 1 minute!***

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; TOA

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

Nuisance variables

component masses; spins

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

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

luminosity distance; polarization angle; TOA at geocenter; inclination; coalescence phase

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

extrinsic variables

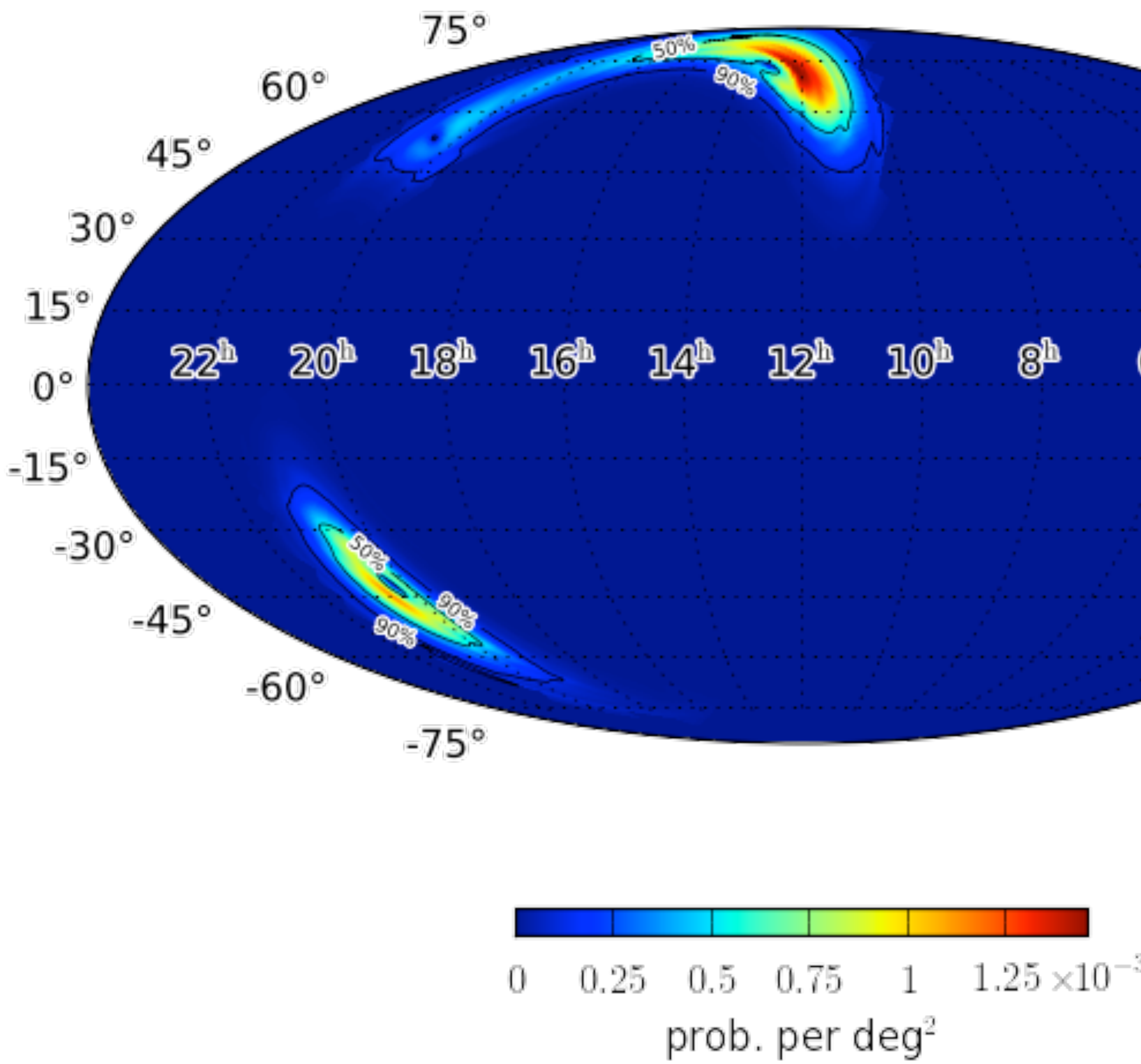
Parameters of interest

direction of source $\mathbf{n}$

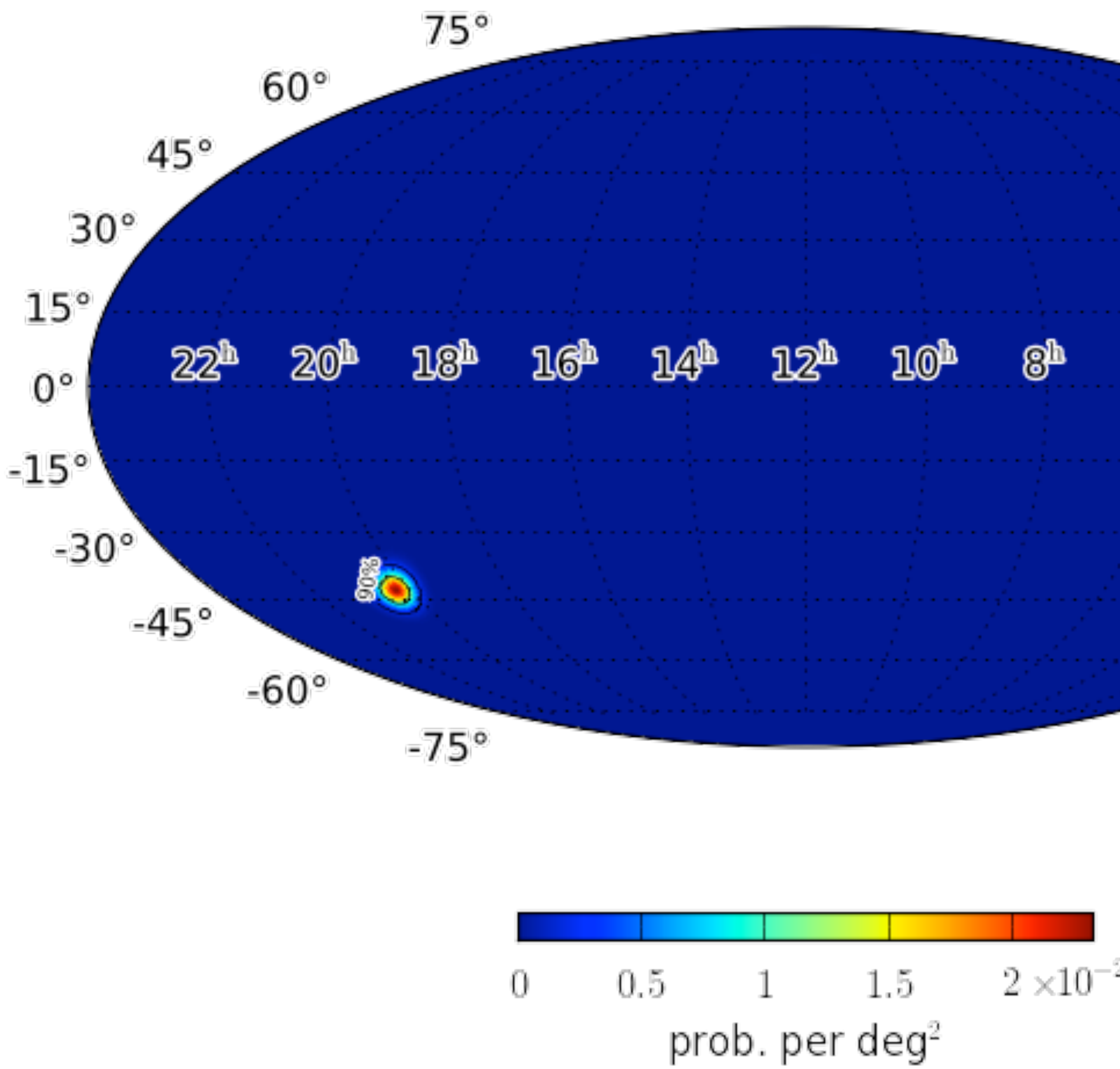
e.g.,

right ascension, declination α, δ

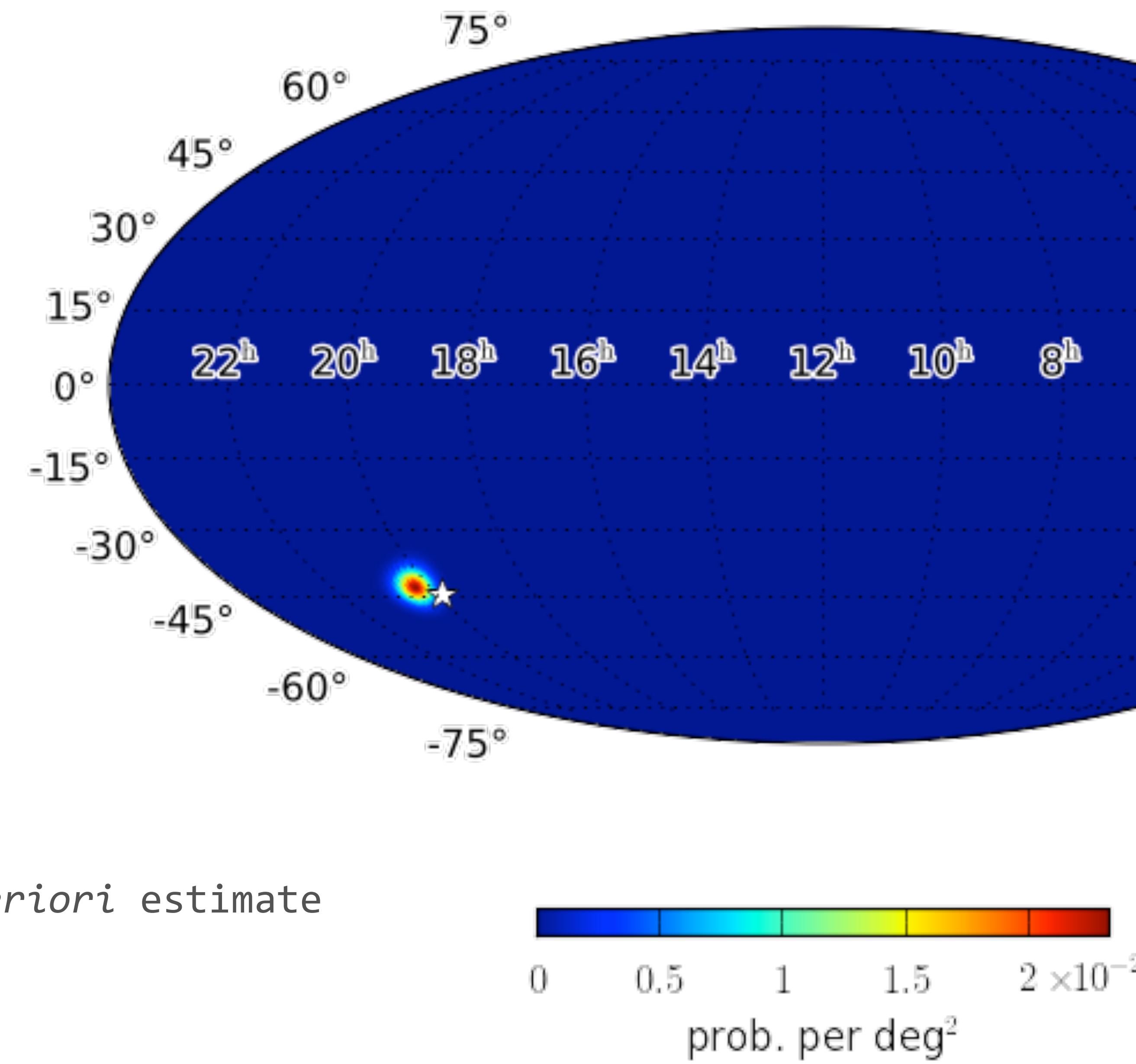
Localization by original S6/VSR2/3 code



BAYESTAR localization



BAYESTAR localization



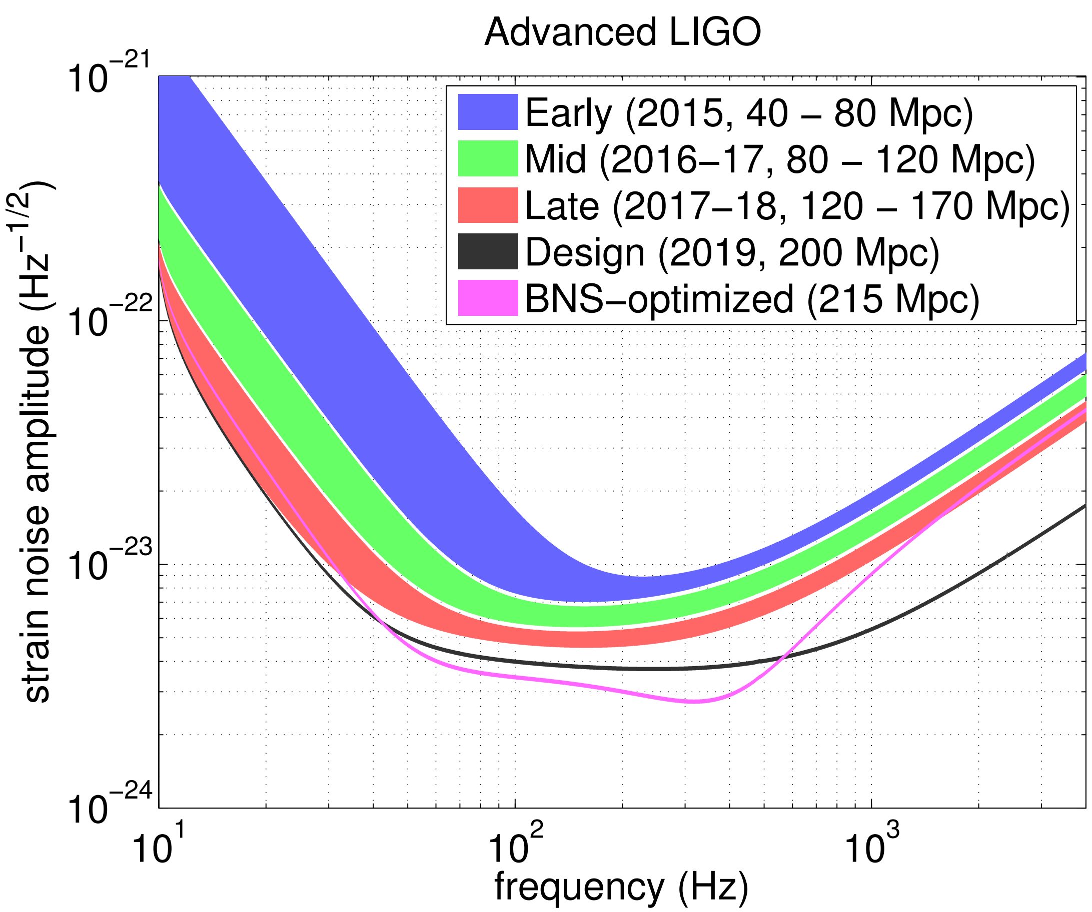
true location
19h51m58.39s
-44°36'10.2"

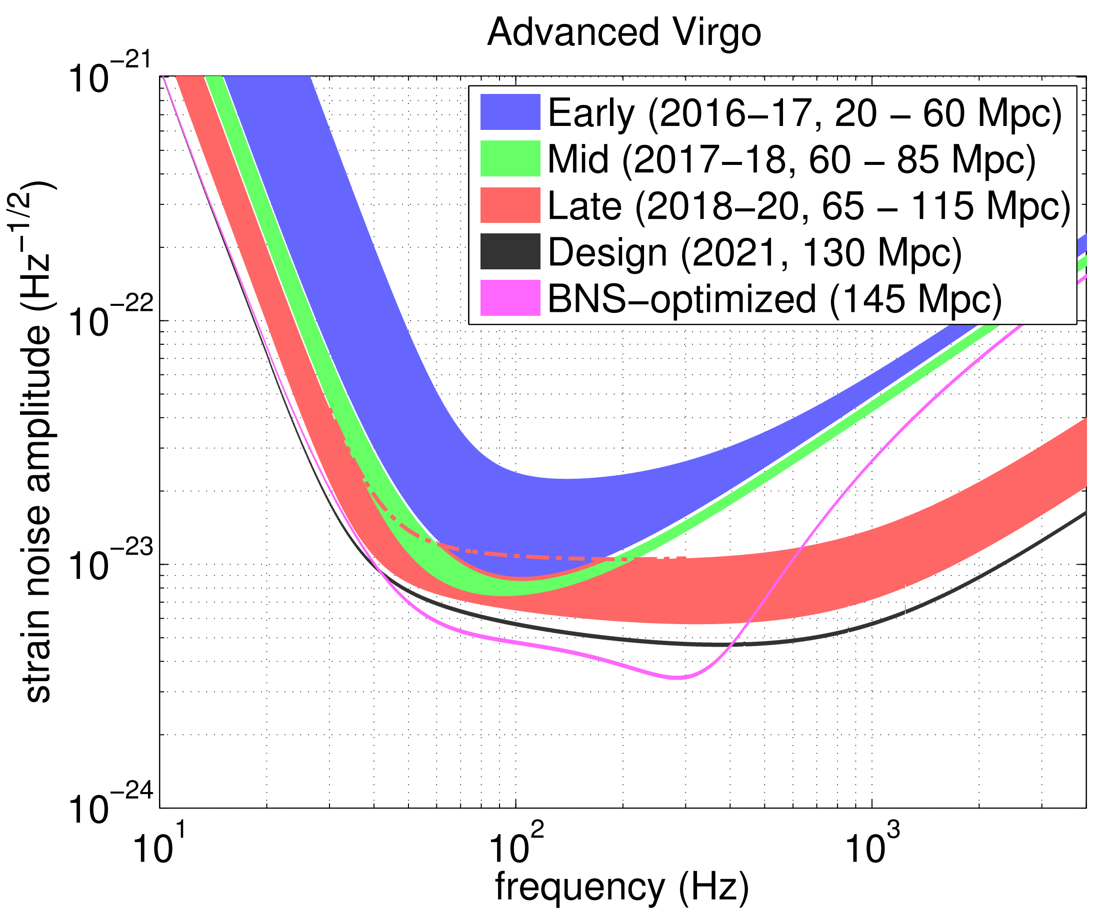
maximum *a posteriori* estimate
20h18m34.29s
-42°36'35.3"

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

Observing scenarios

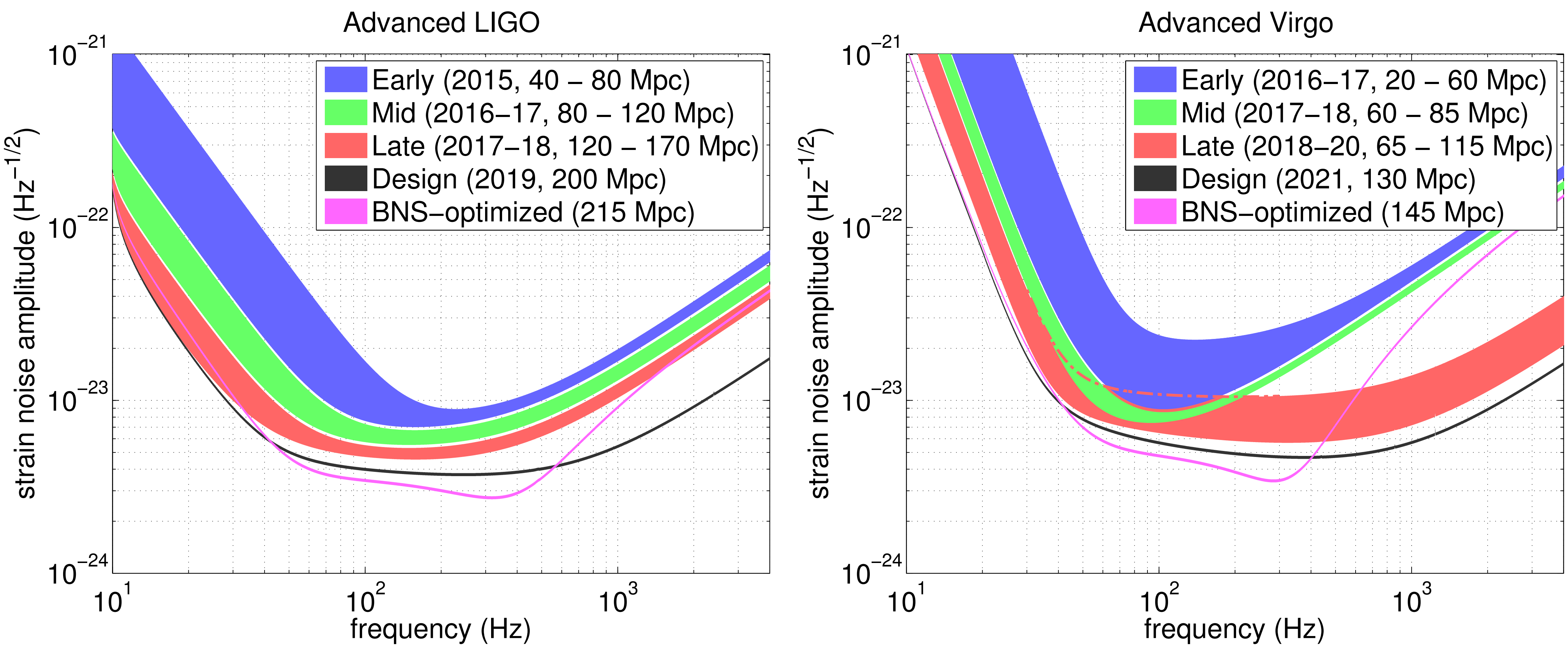




Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20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

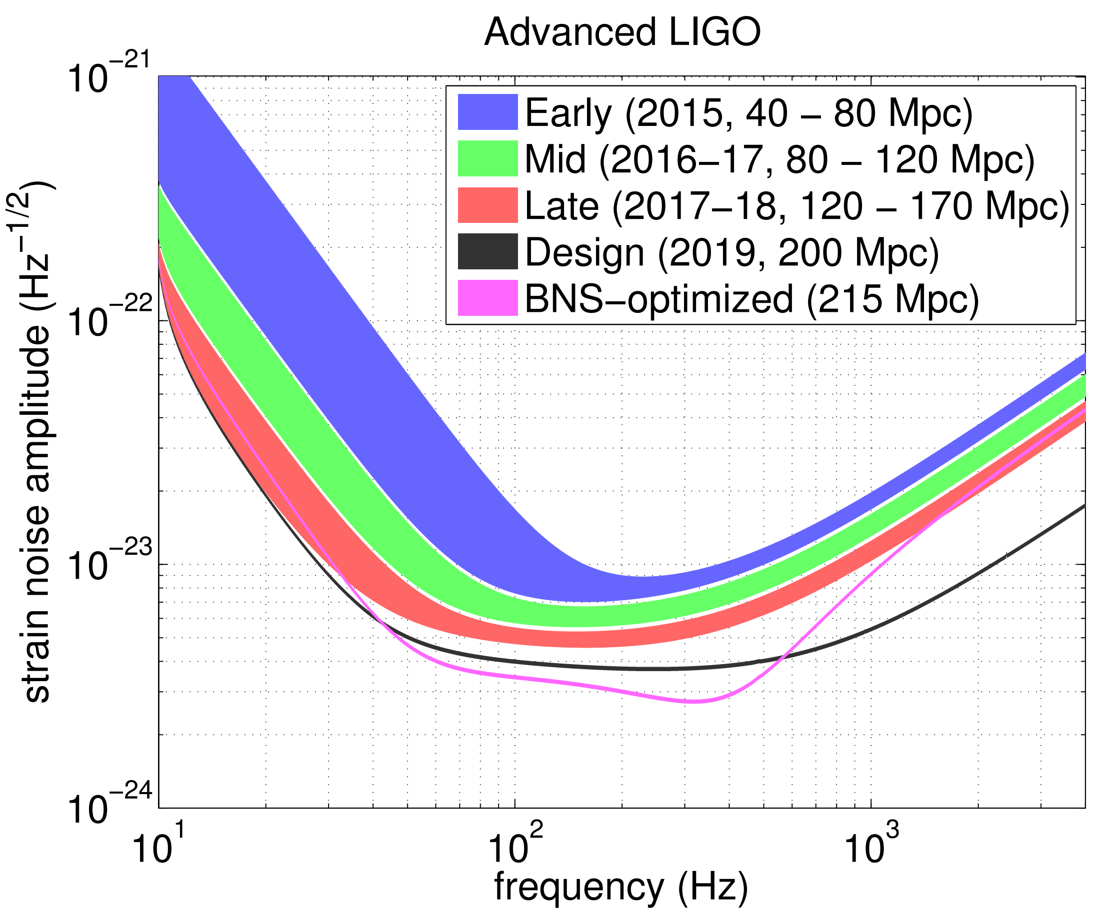
Observing scenarios

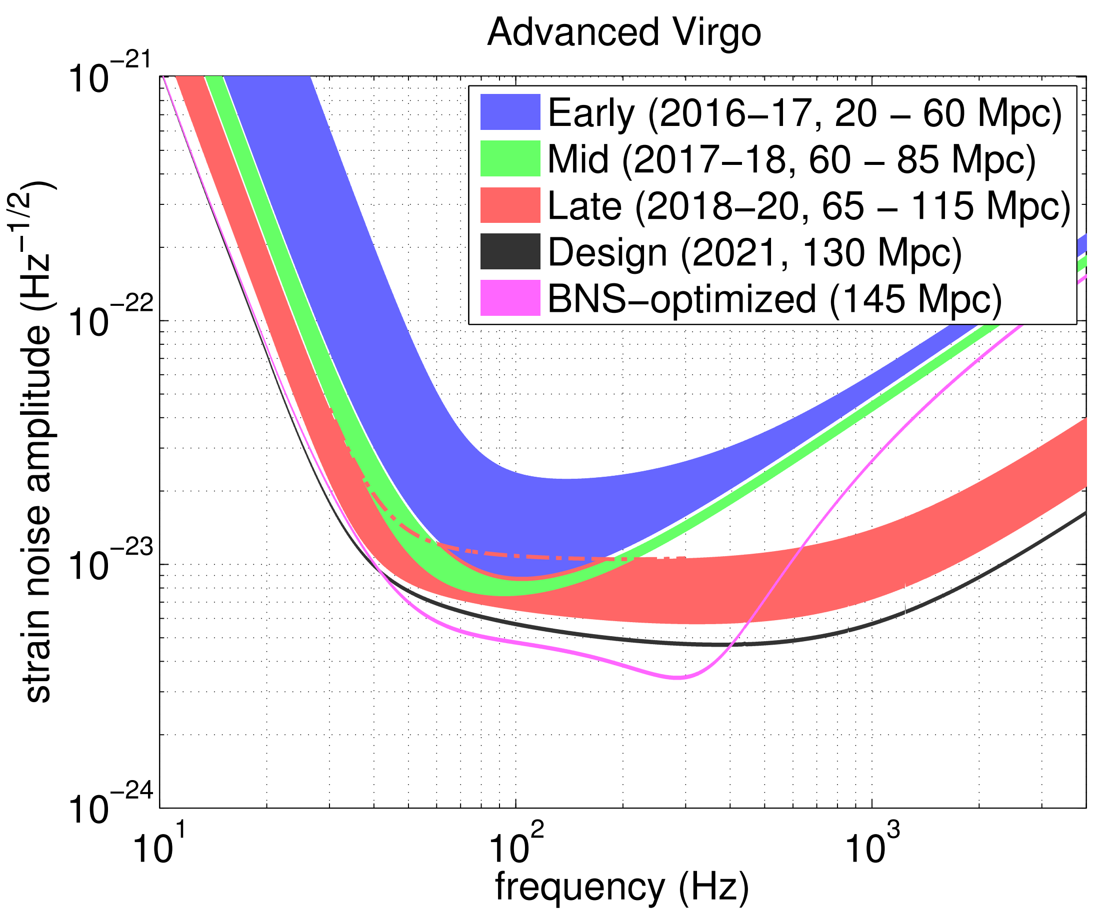


Epoch	Estimated Run Duration	$E_{\rm GW} = 10^{-2} M_\odot c^2$ Burst Range (Mpc)		BNS Range (Mpc)		Number of BNS Detections	% BNS Localized within	
		LIGO	Virgo	LIGO	Virgo		5 deg^2	20 deg^2
2015	3 months	40 – 60	–	40 – 80	–	0.0004 – 3	–	–
2016–17	6 months	60 – 75	20 – 40	80 – 120	20 – 60	0.006 – 20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

Binary Neutron Star Mock Data Challenge

100k injections, 4 months of data

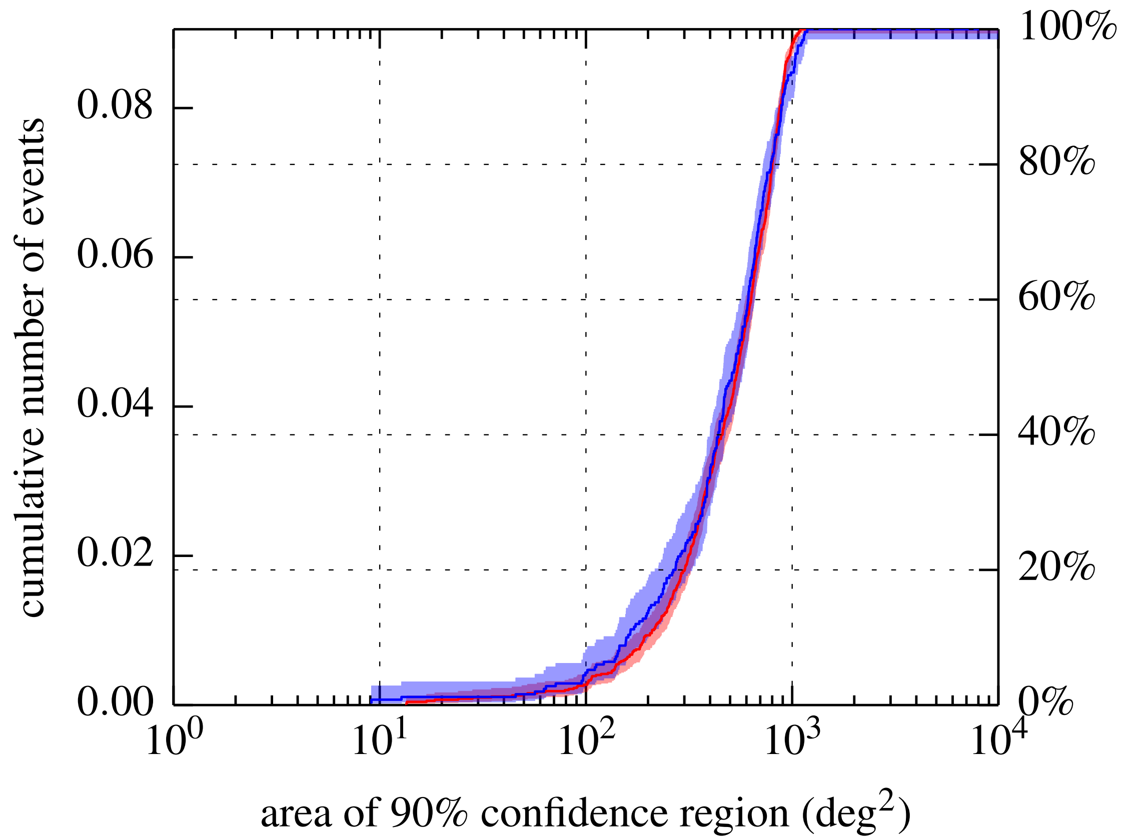
GW localizations for ≈1k events

HL, 2015 & HLV, 2016 configurations

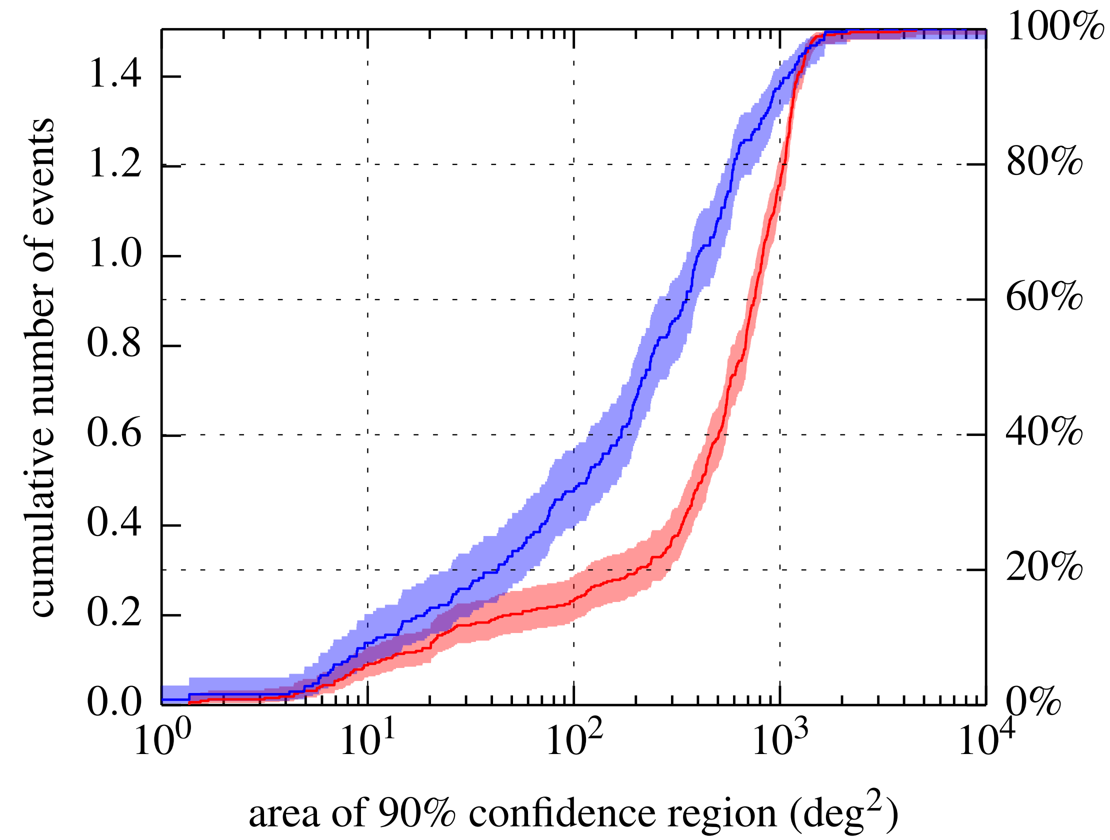
Uniformly distributed component masses

$1.2\ M_\odot \leq m_{1,2} \leq 1.6\ M$

Singer et al. (2014), *ApJ*
http://www.ligo.org/scientists/first2years



2015



2016

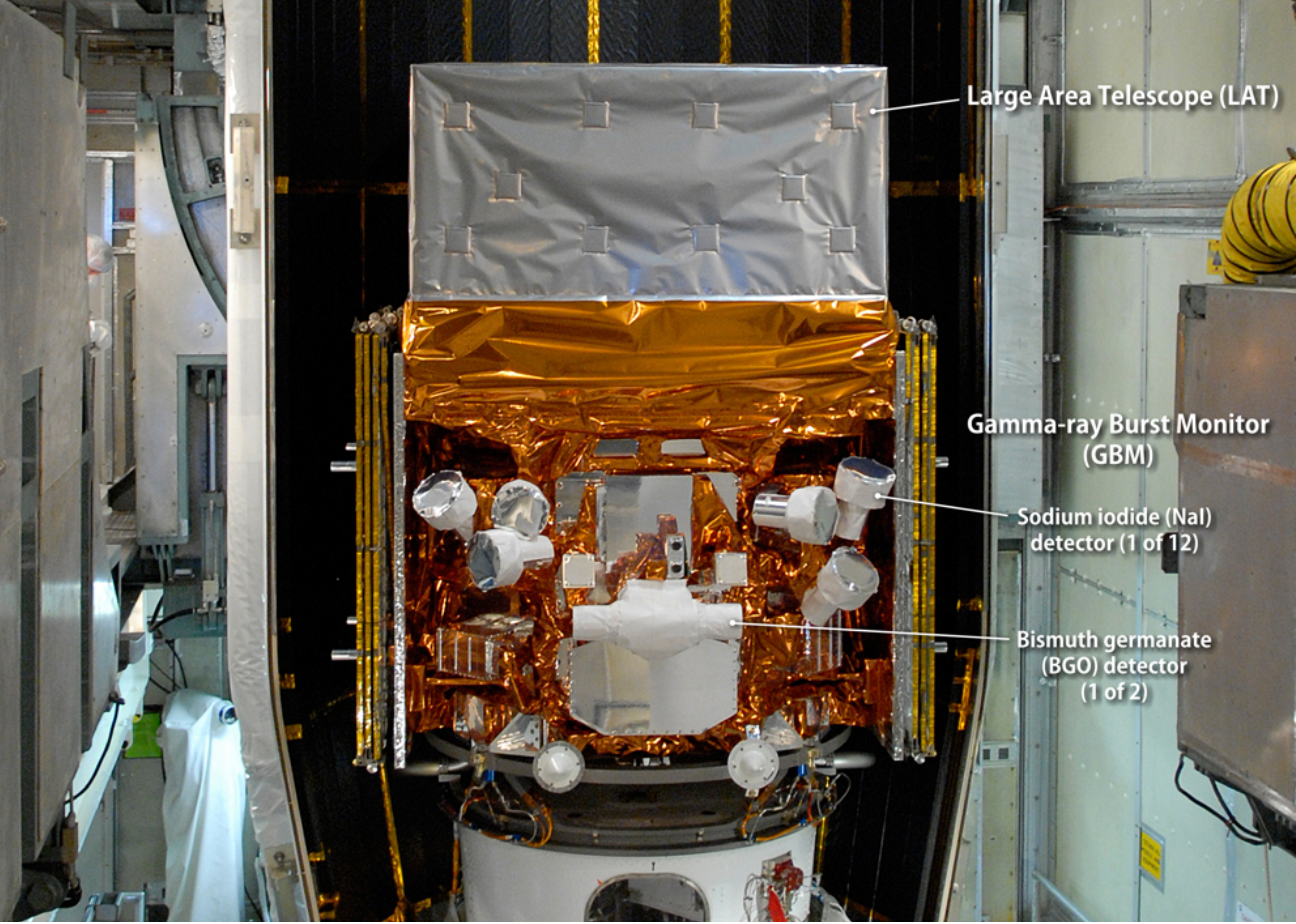
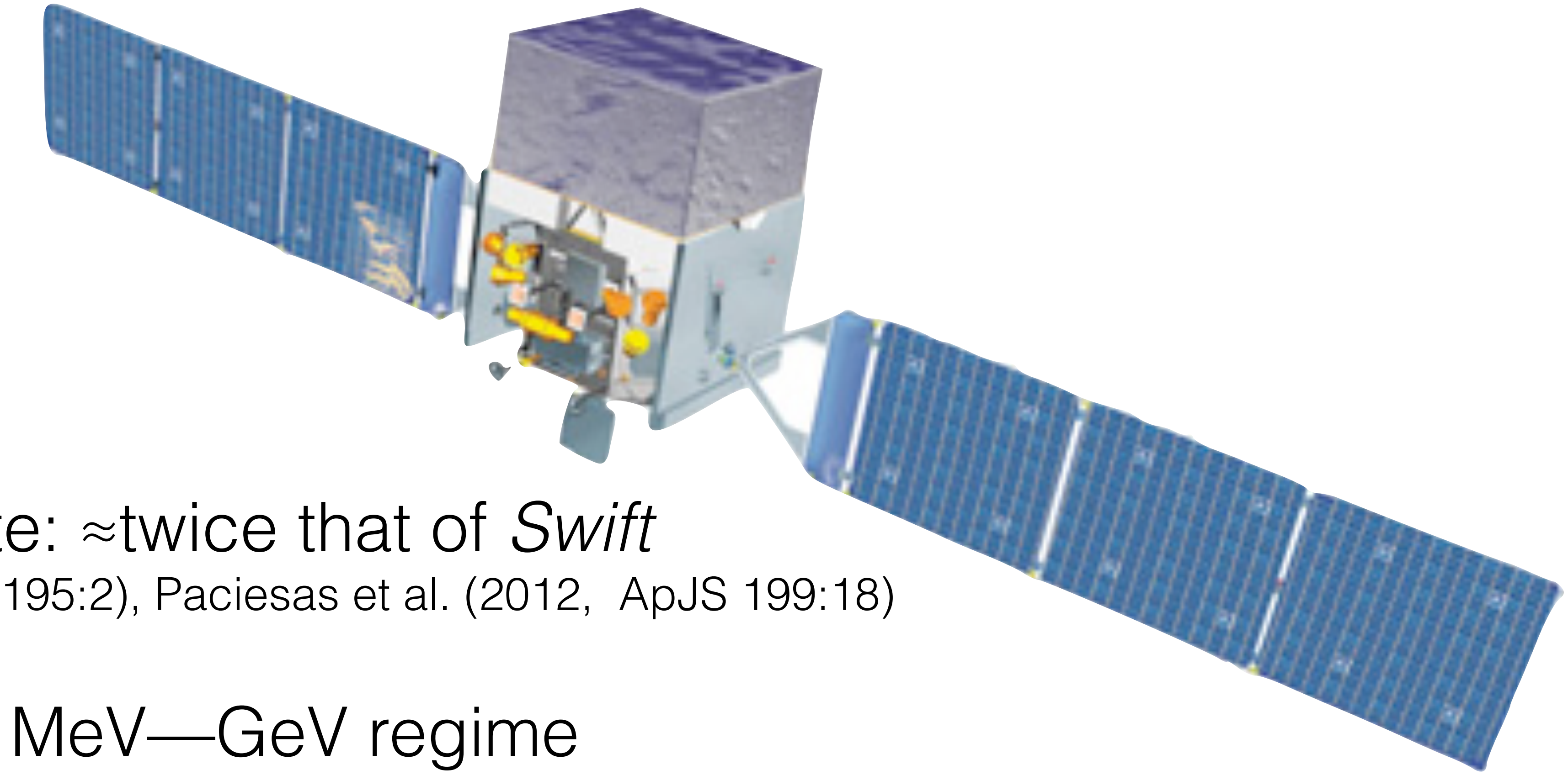


Image credit: NASA/Jim Grossmann
http://www.nasa.gov/mission_pages/GLAST/news/vision-improve.html

Fermi



- Prolific detection rate: ≈twice that of *Swift*
  Sakamoto et al. (2011, ApJS 195:2), Paciesas et al. (2012, ApJS 199:18)

- With LAT, access to MeV—GeV regime
  →delayed onset of GeV emission Abdo et al. (2009, Science 323:1688)

- Hyper-energetic bursts; strain budget of collapsar model
  Cenko et al. (2011, ApJ 732:29)

- GBM: all-sky monitor (~70% of sky)

- Strengths for detecting short-hard bursts
  - Coarse localization, ~10–100 deg^2, w/o LAT (~16% of sky)

- Vast majority **not observed outside gamma-rays!**

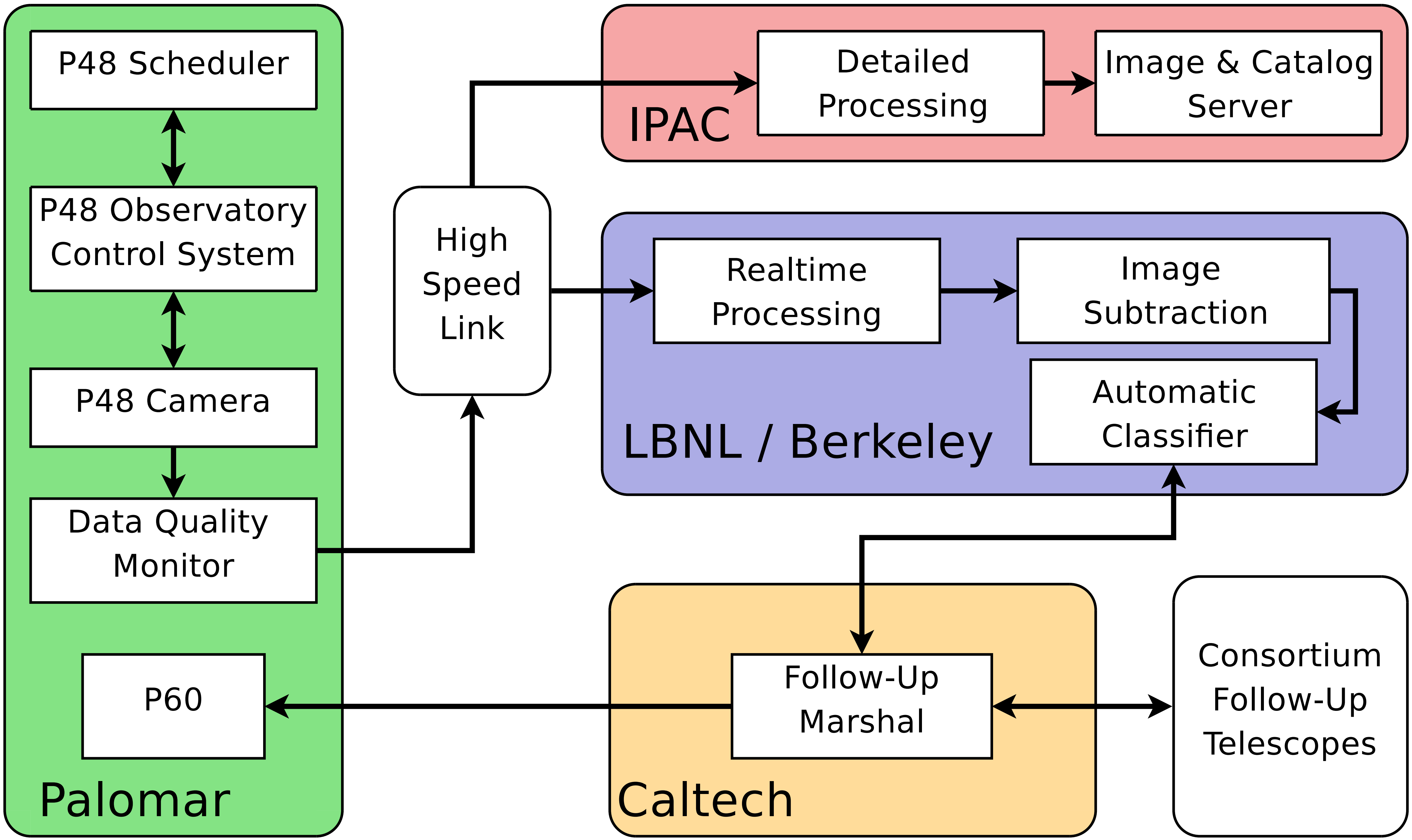
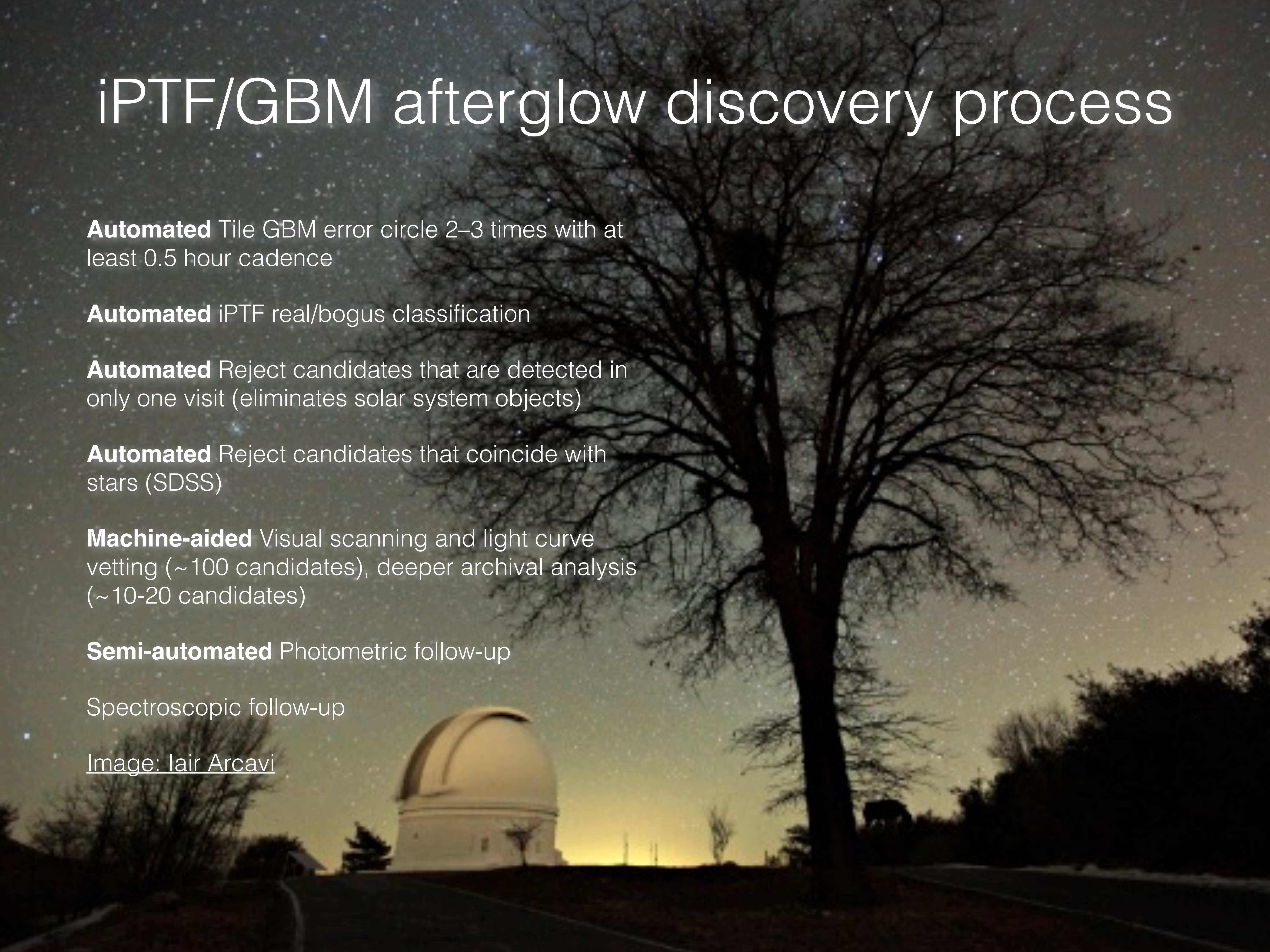


image credit: Law et al. (2009, PASP 121, 1395)



iPTF/GBM afterglow discovery process

Automated Tile GBM error circle 2–3 times with at least 0.5 hour cadence

Automated iPTF real/bogus classification

Automated Reject candidates that are detected in only one visit (eliminates solar system objects)

Automated Reject candidates that coincide with stars (SDSS)

Machine-aided Visual scanning and light curve vetting (~100 candidates), deeper archival analysis (~10-20 candidates)

Semi-automated Photometric follow-up

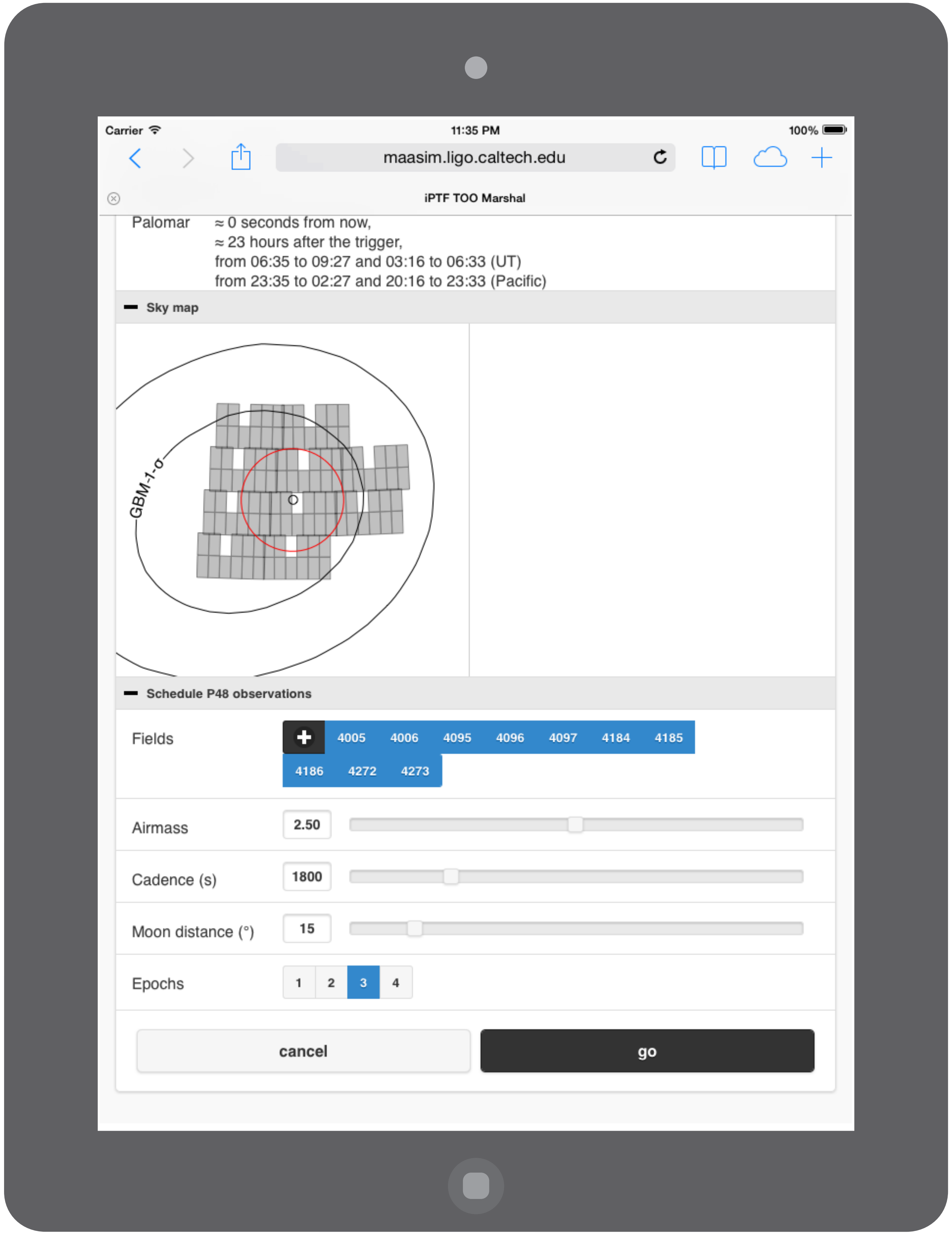
Spectroscopic follow-up

Image: Iair Arcavi

The iPTF TOO Marshal

Listens for GCN notices, plans P48 tiling, monitors progress of observations and real-time analysis.

Wakes up humans to do visual scanning and follow-up target selection.



Visual scanning

Limit query (boolean):

Young Only [0] & Local Universe Only [0] & Co-add Only [0] & New Only [0] & Hide Rocks [1] & Field [3486]

Change query parameters:

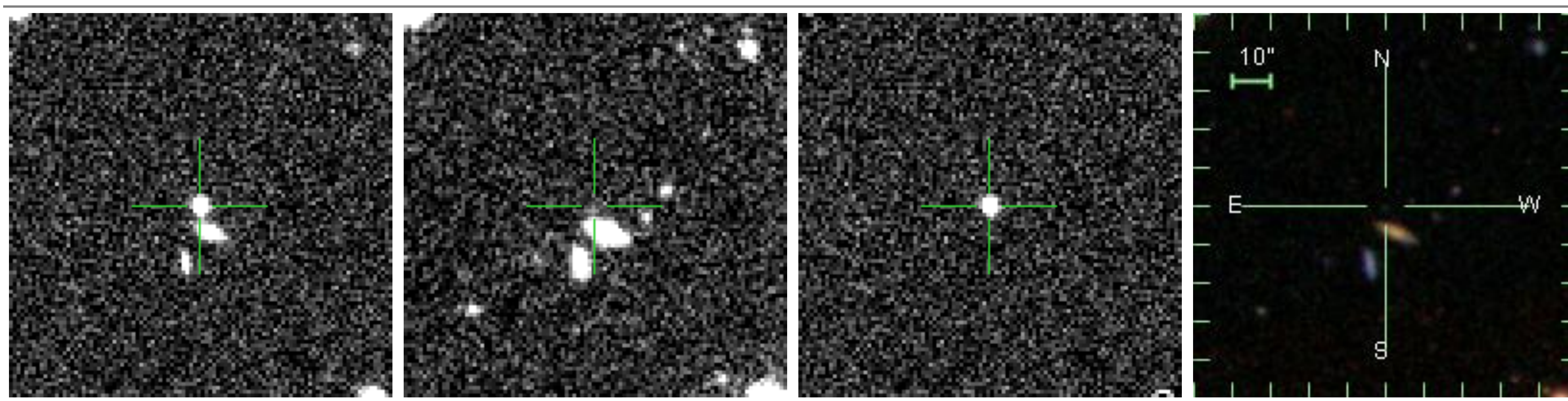
Observation date > [20130701] & Realbogus > [0.2] & Match radius (deg) < [0.000277] & Match time (days) > [0.020833] & Number of Candidates < [200] & Fraction of best candidates < [0.03] &

Reload Page

SELECT acnd.id, acnd.rb2, acnd.mag, acnd.ra, acnd.dec, acnd.x_sub, acnd.y_sub, acnd.lu_match_id, bcnd.id as bid, acnd.sub_id as subid FROM candidate as acnd, candidate as bcnd, subtraction a
q3c_join(acnd.ra, acnd.dec, bcnd.ra, bcnd.dec,0.000278) AND acnd.sub_id=asub.id and bcnd.sub_id=bsub.id AND acnd.rb2 > 0.2 and bcnd.rb2 > 0.2 AND asub.id >= 232052 and bsub.id >= 2320
acnd.is_star='f' and bcnd.is_star='f' AND asub.ptffield != 120001 AND bsub.ptffield != 120001 AND asub.ptffield != 4138 AND bsub.ptffield != 4138 AND asub.image_id != -1 and bsub.image_id !=
bsub.ptffield = 3486 GROUP BY acnd.id,bid ORDER BY acnd.rb2 desc, acnd.ra desc LIMIT 200;

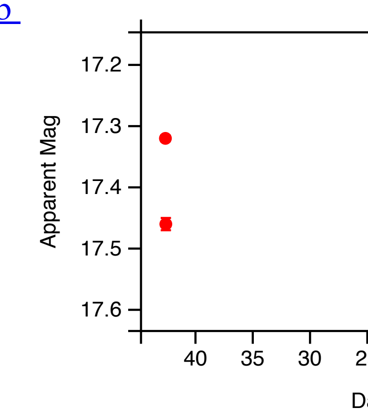
20130701 - Found 2 candidates with RB2 >= 0.2:
Only showing unique candidates

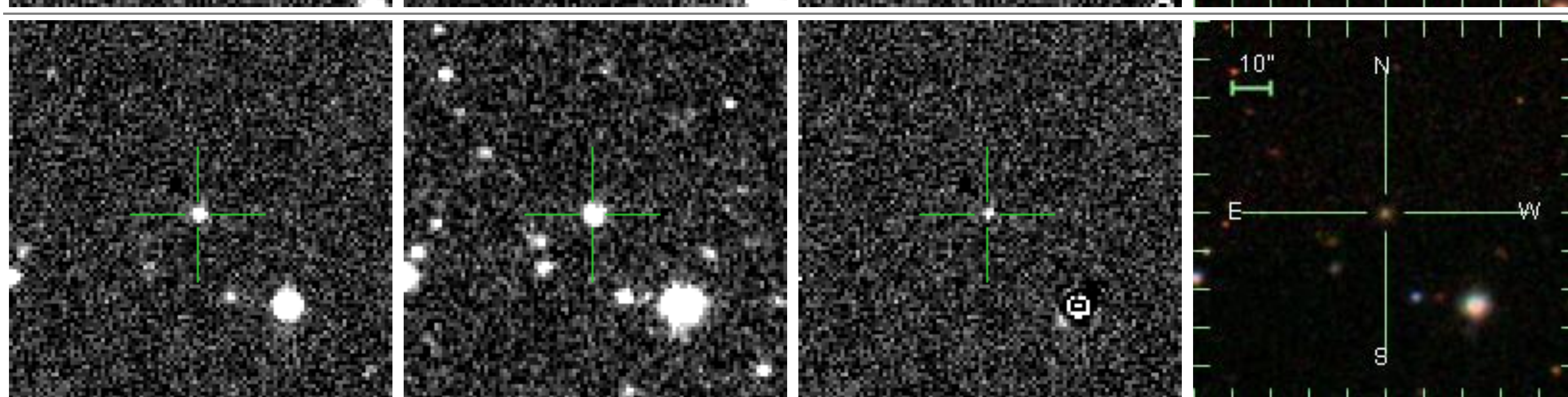
New	Ref	Sub	SDSS



ID: 68144320 Examine , 232606 Zoom-Sub
RB2: 0.83
Mag: 17.46
iPTF 13bxl
0 Matches in iPTF DB before tonight
0 Matches in PTF/best DB
Not a bad sub. 0.007, 0.138, 0.495

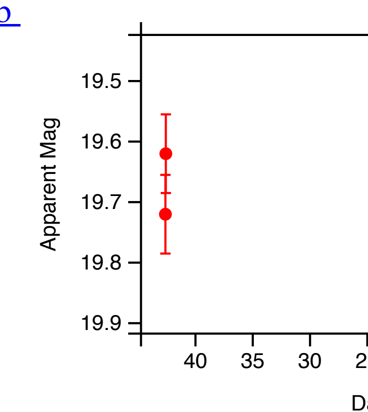
Transient   Save





ID: 68144281 Examine , 232606 Zoom-Sub
RB2: 0.49
Mag: 19.62
iPTF 13bxk
0 Matches in iPTF DB before tonight
0 Matches in PTF/best DB
Not a bad sub. 0.007, 0.138, 0.495

Transient   Save

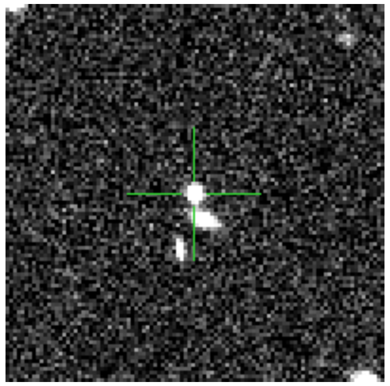


13bxl

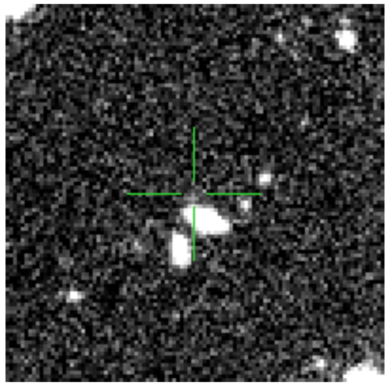
14:29:14.78 +15:46:26.4
217.311582 +15.774013

View another

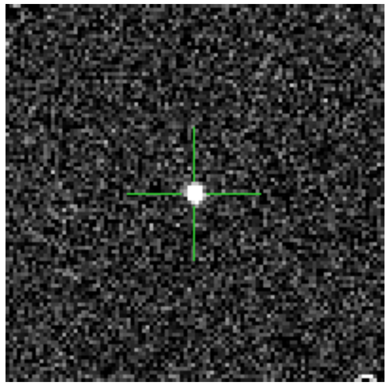
NEW



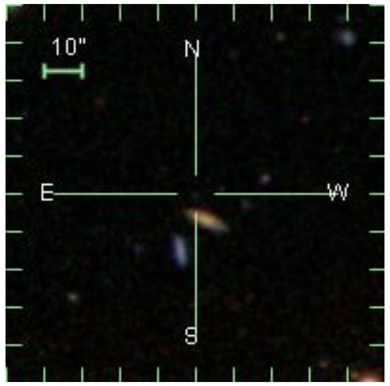
REF

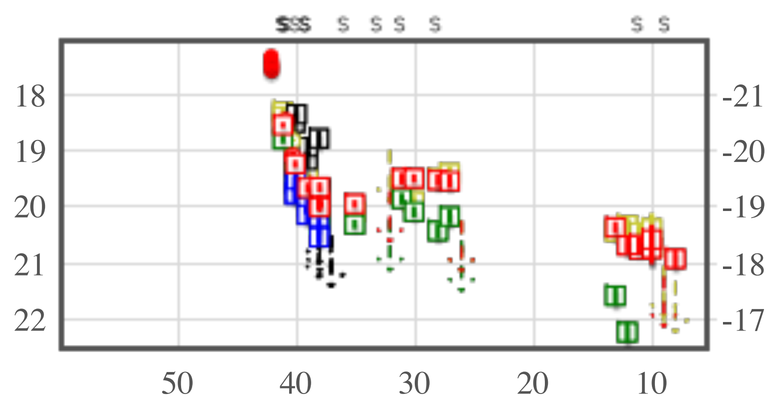


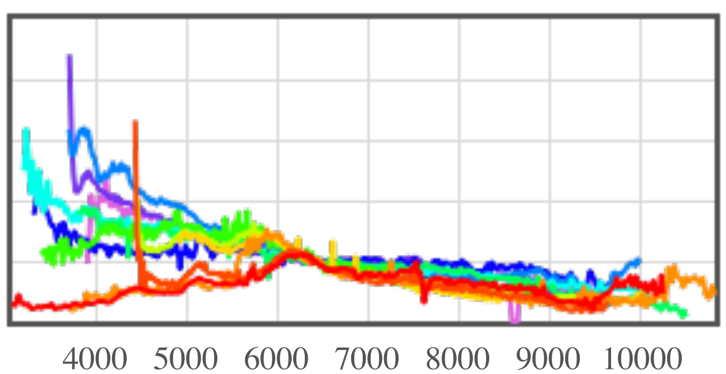
SUB



SDSS







r = 17.6 (42.2 d) | Upload New Photometry

z = 0.145 | Upload New Spectroscopy
DM (approximate) = 39.19

ADDITIONAL INFO

NED | SIMBAD | VizieR | HEASARC | SkyView | PyMP | Extinction
IPAC | DSS | WISE | Subaru | VLT | Variable Marshal (Search) | ADS

Add to Cart

FOLLOW UP

PROGRAMS

COMMENTS

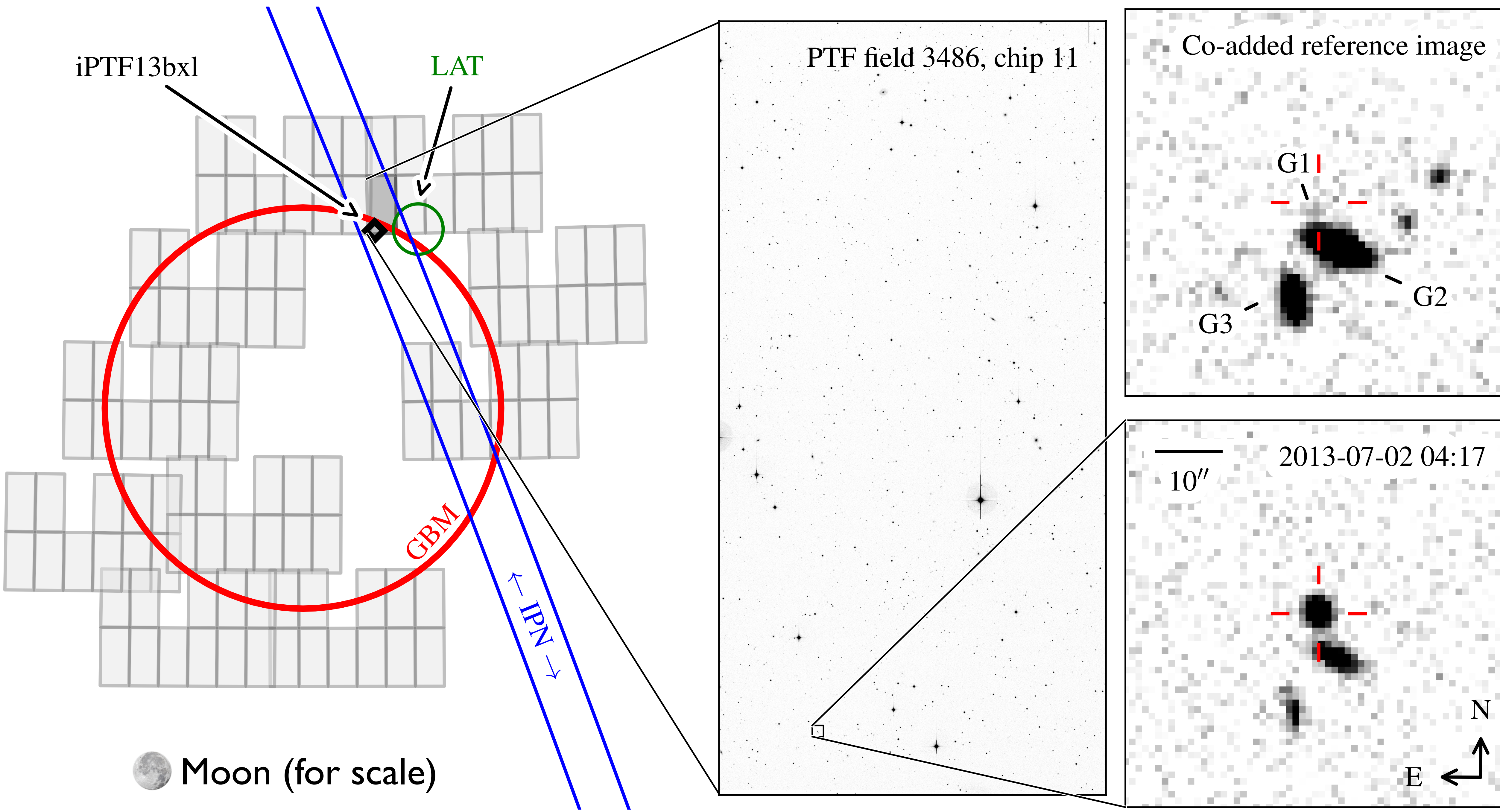
2013 Aug 04 sumin [info]: observed with LRIS
2013 Jul 15 iair [info]: Observed at P200+DBSP (PA 166.1)
2013 Jul 14 jesper [info]: Latest Keck spectrum (July 11) looks like 2006aj close to Max. The fit with 98bw is less good.
2013 Jul 11 sumin [info]: observed with lick 3-m kast, g-band and R-band images
2013 Jul 11 sumin [info]: observed with Lick Kast g-band image, 130711
2013 Jul 09 brad [info]: Broad features identified in NOT spectrum (GCN 14994) are clearly visible. But it doesn't look like an exact match to 98bw to me (see attached). [view attachment]
2013 Jul 08 robert [info]: Light curve is still fading as a powerlaw (see attached plot). Could have been a break in the LC before 10^5 seconds. [view attachment]
2013 Jul 06 jesper [info]: interesting features, and about right timing. Although some structure also in earlier spectra. SNID attached. /jesper [view attachment]
2013 Jul 06 avishay [info]: SN signatures seem to be already emerging, as light curve decline slows down. Comparison with SN 1998bw and SN 2006aj attached. [view attachment]
2013 Jul 05 ofer [comment]: Quick reduction (to be compared with final one)
2013 Jul 04 mansi [redshift]: 0.145
2013 Jul 04 iair [info]: Observed with P200+DBSP
2013 Jul 03 iair [redshift]: 0.145
2013 Jul 03 iair [comment]: possible redshift based on narrow H, O I, O III
2013 Jul 03 eric [info]: Observed with P200-DBSP 130703
2013 Jul 03 duncan [info]: There is a Fermi/LAT detection (GRB130702A). The best LAT on-ground location is found to be: RA, DEC = 216.4, 15.8 (J2000), with an error radius of 0.5 deg (90% containment, statistical error only) This position is 4 deg from the best GBM position (RA, Dec = 218.81, +12.25 with a 4 deg radius), and 0.8 deg from the position of the optical afterglow.
2013 Jul 02 eric [info]: Observed with P200-DBSP 130702
2013 Jul 02 duncan [info]: Final Fermi GBM position: +14h 35m 14s, +12d 15' 00" (218.810d, +12.250d) (J2000) Error 3.99 [deg radius, statistical only]

Finding the afterglow among tens or hundreds of thousands of candidates

Number of optical transient candidates surviving each vetting stage

GRB	SNR > 5	RB2 > 0.1	not stellar	not known asteroid	detected twice	saved for follow-up
130702A	14 629	2 388	1 346	1 323	98	11
131011A	21 308	8 652	4 344	4 197	102	23
131231A	9 843	2 503	1 776	1 543	11	10
140508A	48 747	22 673	9 970	9 969	272	42
140606B	68 628	26 070	11 063	11 063	256	28
140620A	152 224	50 930	17 872	17 872	[?]	34
140623A	71 219	29 434	26 279	26 279	[?]	23
140808A	19 853	4 804	2 349	2 349	127	12
median	reduction	36%	17%	16%	[?%]	0.068%

Discovery & redshift of a GBM GRB in 71 deg²



=SN2013dx

Singer et al.(2013, 2013, ApJL 776:34)

http://dx.doi.org/10.1088/2041-8205/776/2/L34

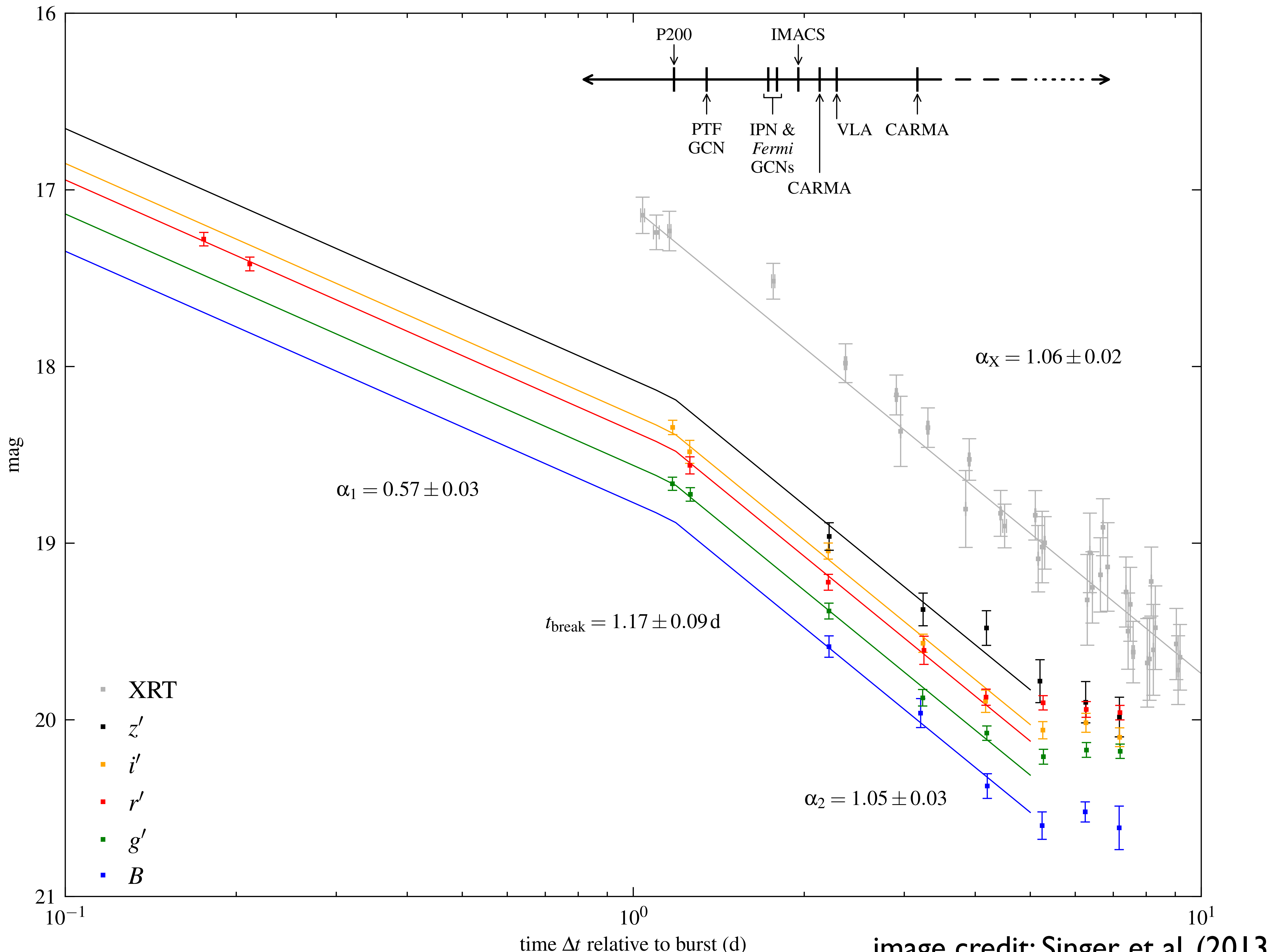


image credit: Singer et al. (2013)

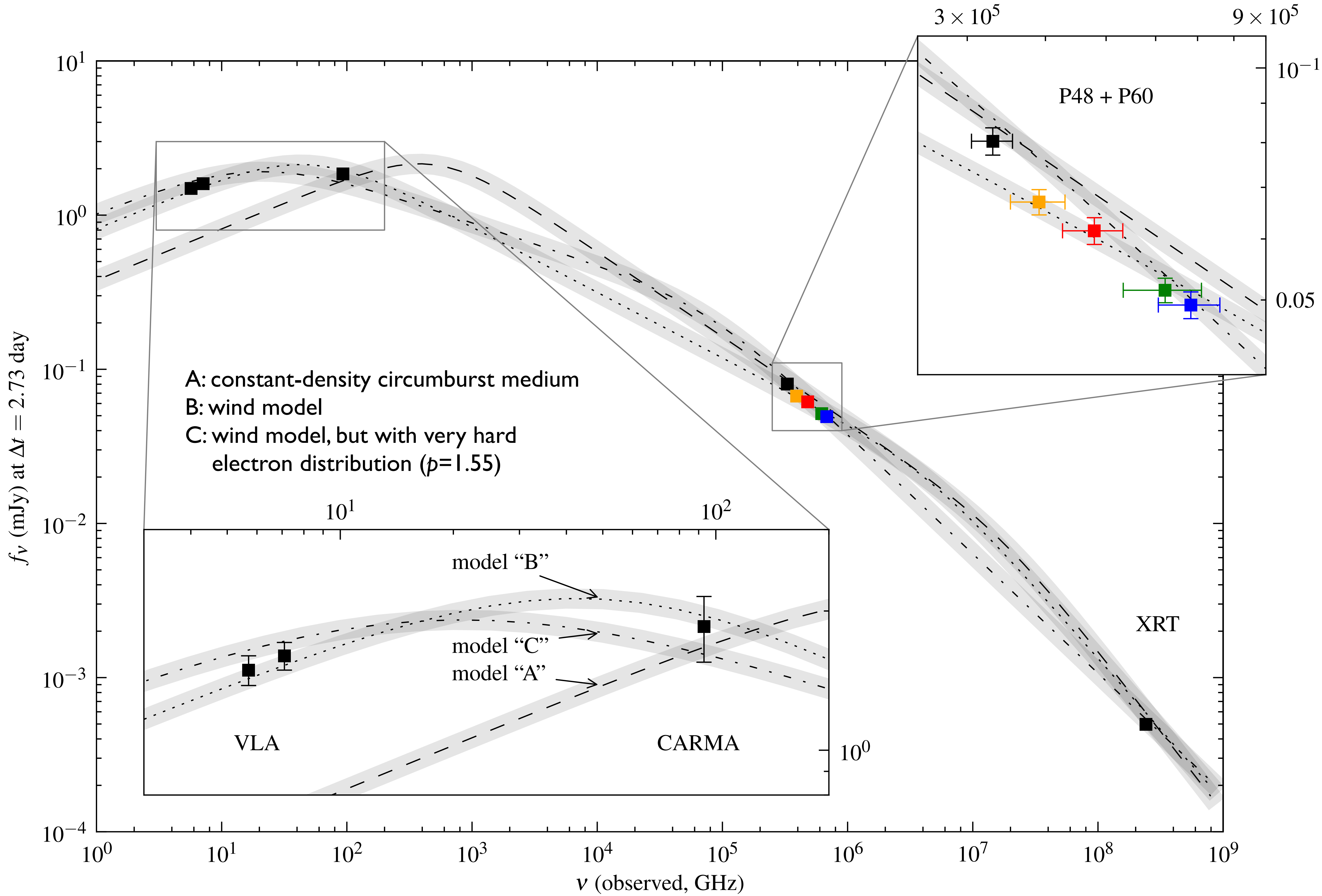
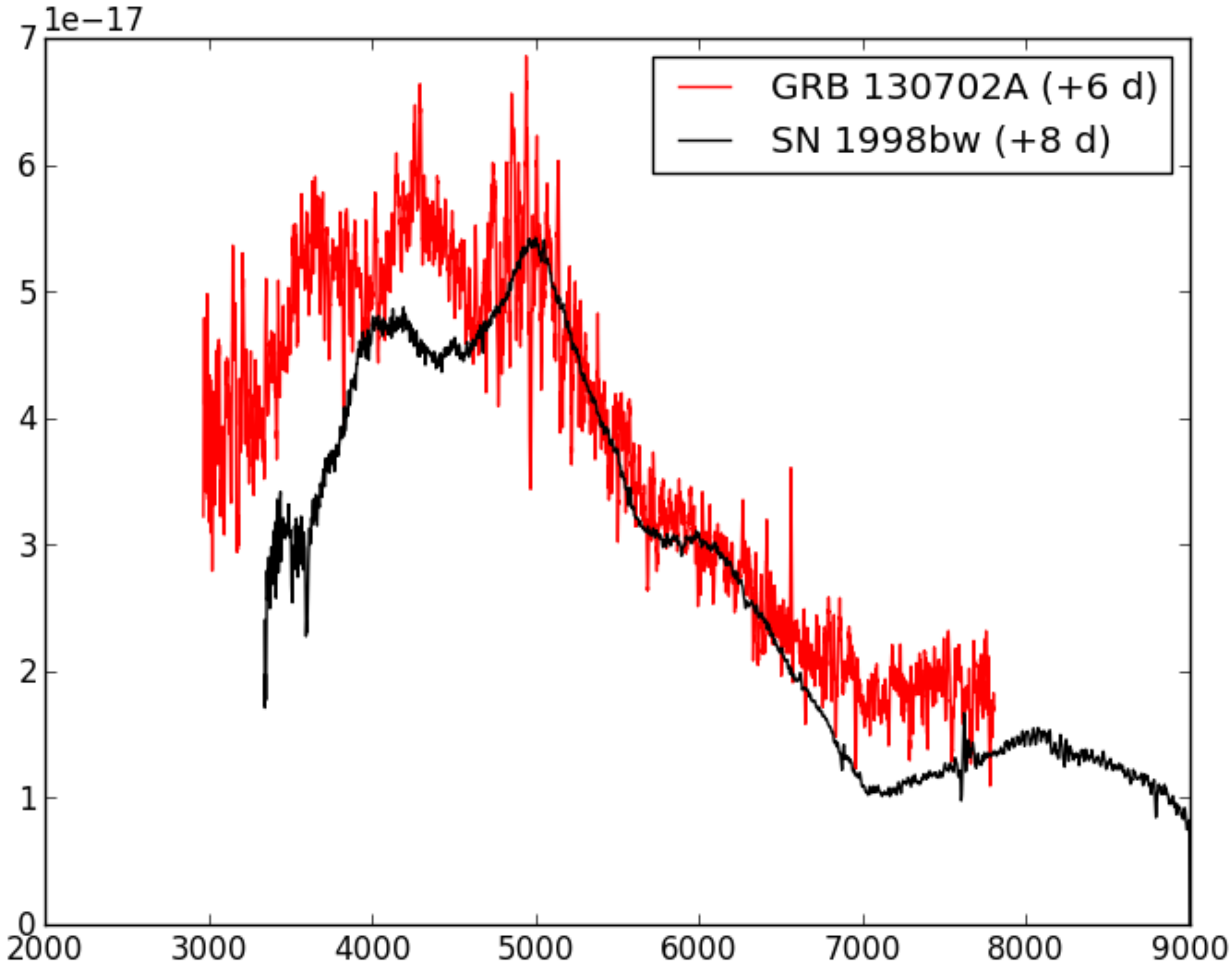
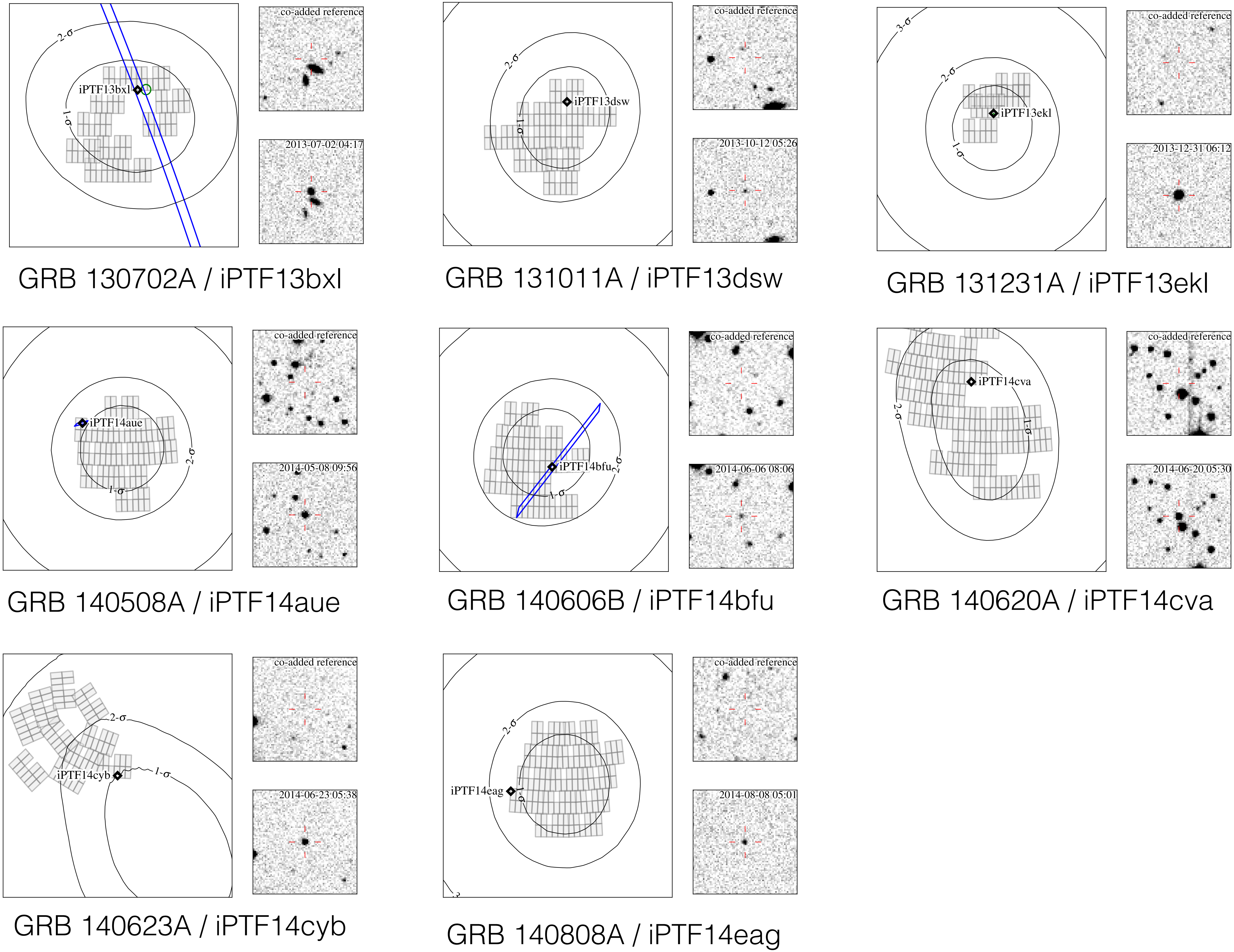


image credit: Singer et al. (2013)

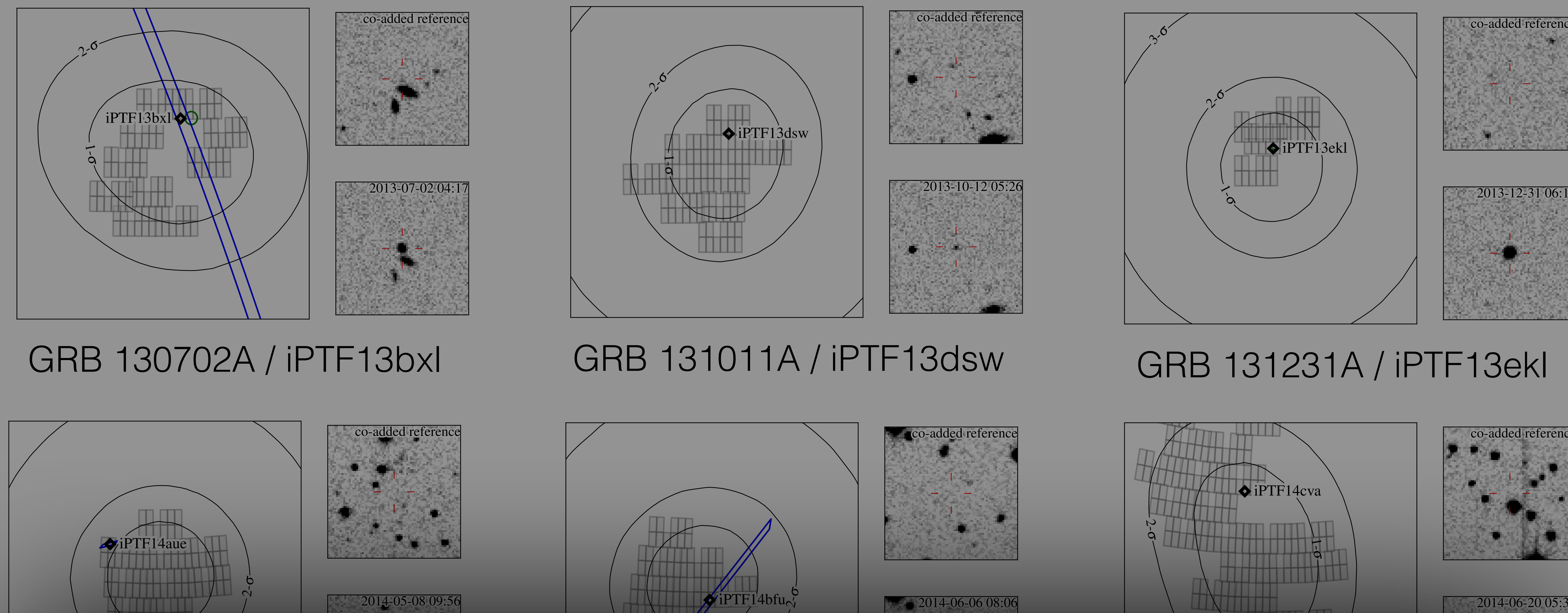
iPTF13bxl = SN2013dx



NOT spectrum (Schulze et al. 2013, GCN 14994)
plot by S. B. Cenko



iPTF13bxl
2-σ
1-σ
co-added reference
2013-07-02 04:17
GRB 130702A / iPTF13bxl
iPTF13dsw
2-σ
1-σ
co-added reference
2013-10-12 05:26
GRB 131011A / iPTF13dsw
iPTF13ekl
3-σ
2-σ
1-σ
co-added reference
2013-12-31 06:12
GRB 131231A / iPTF13ekl
iPTF14aue
2-σ
1-σ
co-added reference
2014-05-08 09:56
GRB 140508A / iPTF14aue
iPTF14bfu
2-σ
1-σ
co-added reference
2014-06-06 08:06
GRB 140606B / iPTF14bfu
iPTF14cva
2-σ
1-σ
co-added reference
2014-06-20 05:30
GRB 140620A / iPTF14cva
iPTF14cyb
2-σ
1-σ
co-added reference
2014-06-23 05:38
GRB 140623A / iPTF14cyb
iPTF14eag
2-σ
1-σ
co-added reference
2014-08-08 05:01
GRB 140808A / iPTF14eag



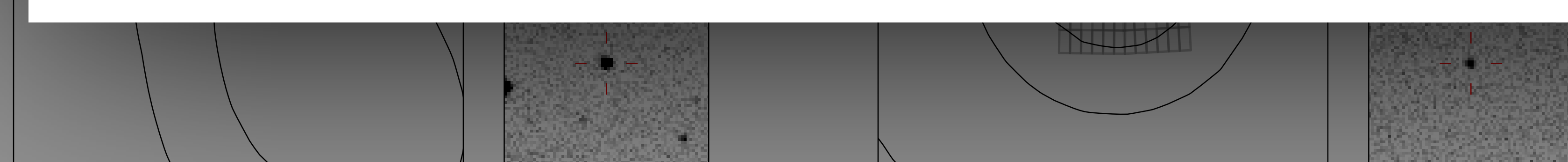
GRB 130702A / iPTF13bxl

GRB 131011A / iPTF13dsw

GRB 131231A / iPTF13ekl

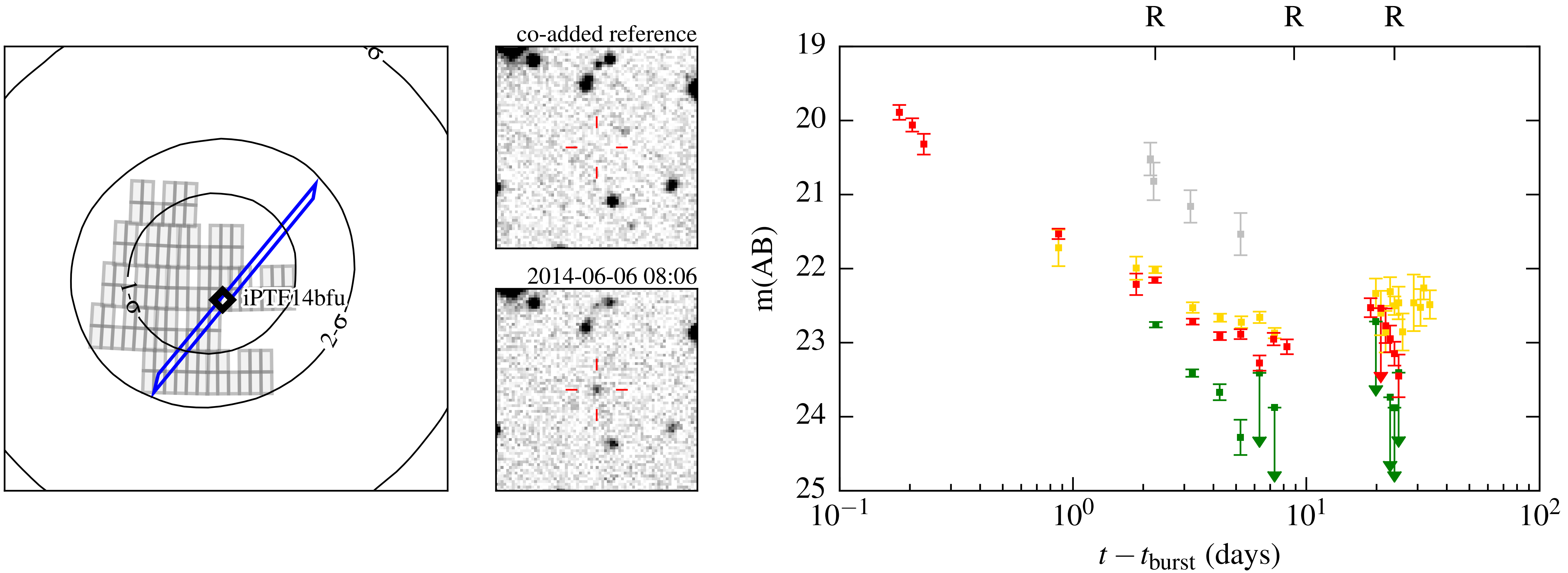
Table 1
iPTF/GBM detections.

GRB	OT	z	E_{peak} (keV)	$E_{\gamma,\mathrm{iso}}$ (10^{52} erg)	T_{90} (s)	$t_{\mathrm{discovery}}$ $-t_{\mathrm{burst}}$ (h)	m_R (discovery)	P48 area (deg^2)	Containment probability
GRB 130702A	iPTF13bxl	0.145	18±3	<0.065±0.001	58.9±6.2	4.21	17.38	74	38%
GRB 131011A	iPTF13dsw	1.874	632±86	85.083±4.451	77.1±3	11.64	19.83	73	54%
GRB 131231A	iPTF13ekl	0.644	270±10	17 ±1	31.2±0.6	1.45	15.85	30	32%
GRB 140508A	iPTF14aue	1.03	430±100	21 ±1	44.3±0.2	6.88	17.89	73	67%
GRB 140606B	iPTF14bfu	0.384	352±40	0.15 ±0.04	22.8±2.1	4.33	19.89	74	56%
GRB 140620A	iPTF14cva	2.04	234±15	6.392±0.347	45.8±12.1	0.25	17.60	147	59%
GRB 140623A	iPTF14cyb	1.92	1022±467	7.832±0.848	114.7±9.2	0.28	18.04	74	4%
GRB 140808A	iPTF14eag	3.29	494±33	8.063±0.536	4.5±0.4	3.36	19.01	95	69%



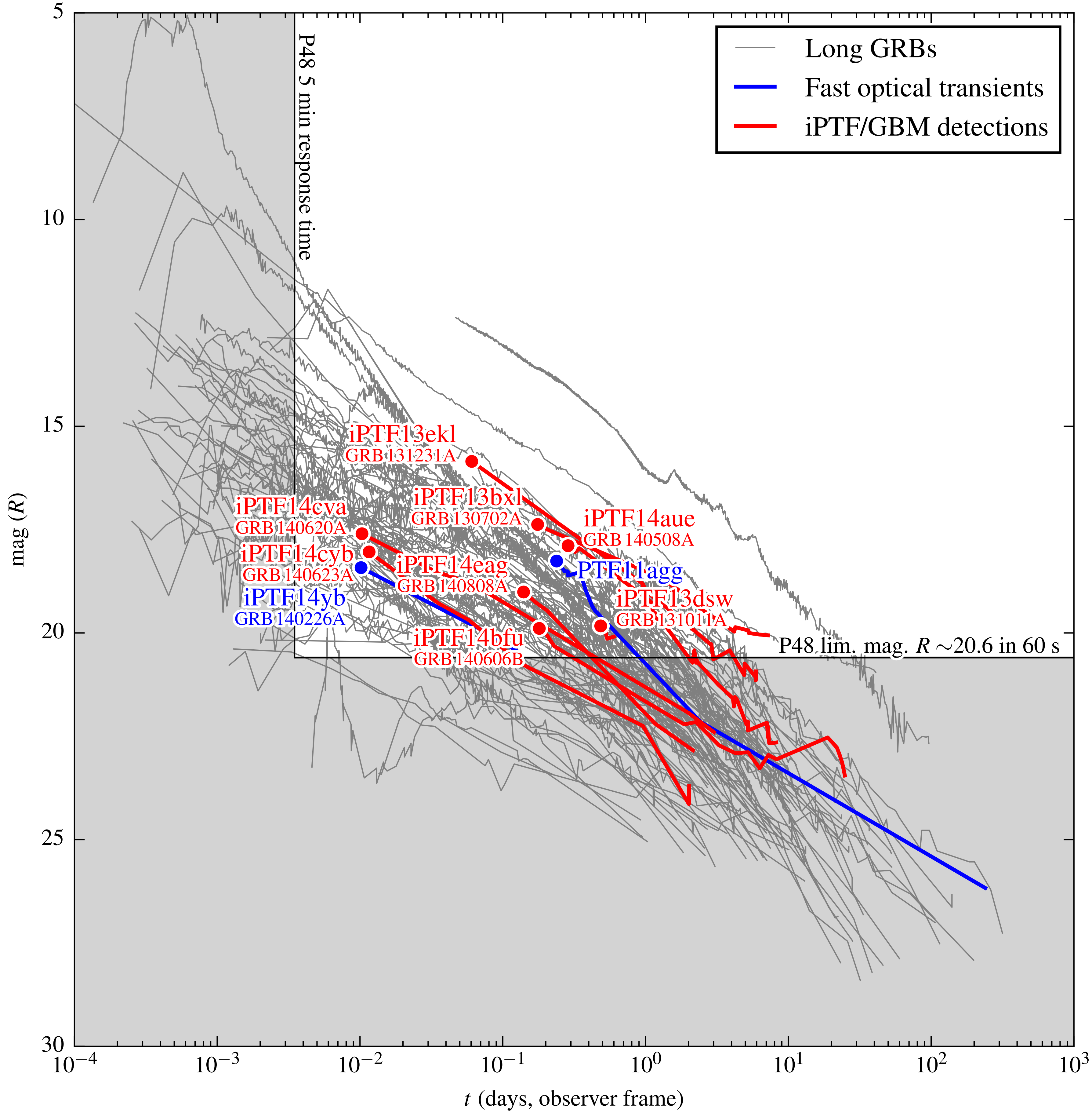
GRB 140623A / iPTF14cyb

GRB 140808A / iPTF14eag

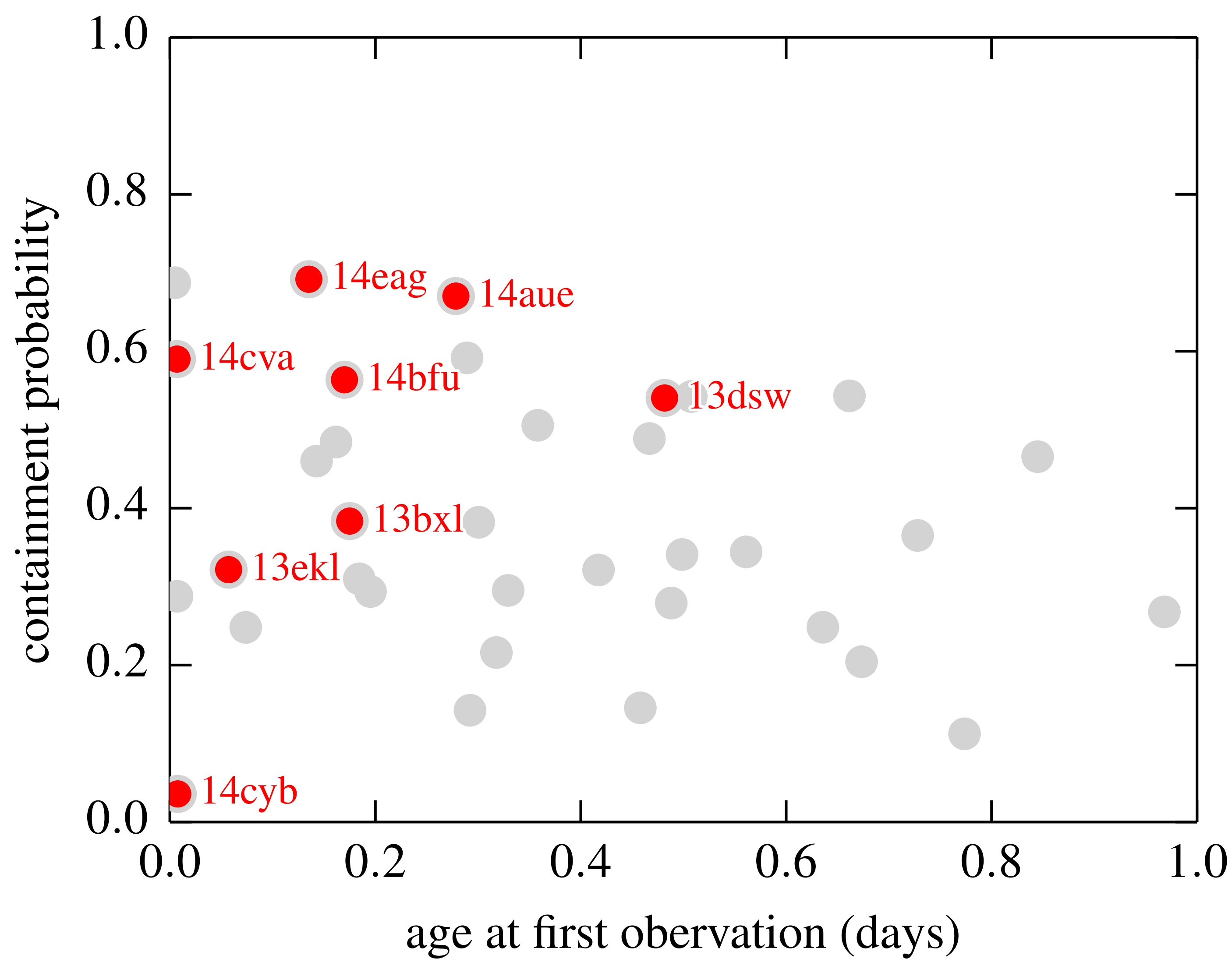


GRB 140606B / iPTF14bfu

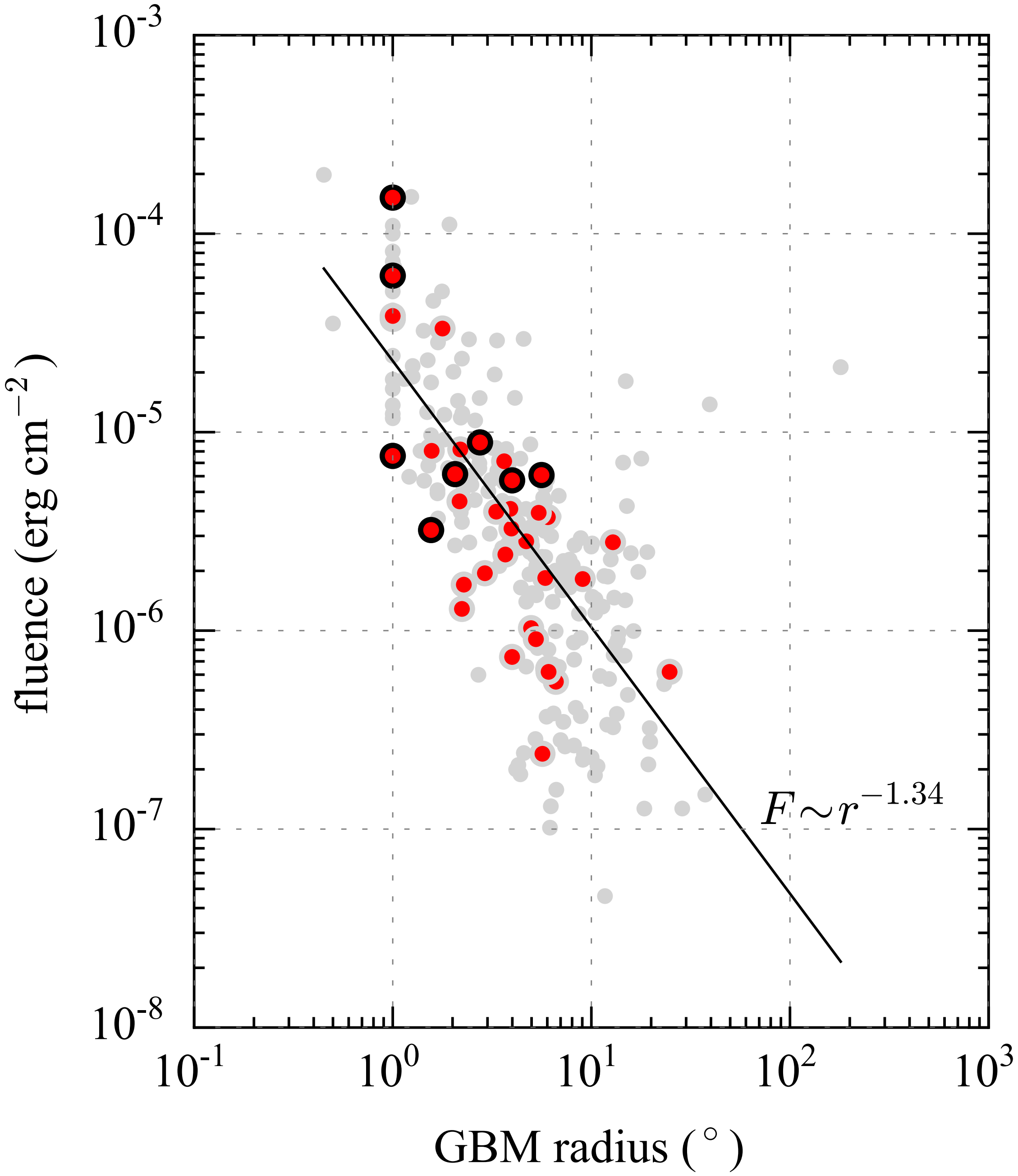
GRB + spectroscopic SN at z=0.384


Long GRBs
Fast optical transients
iPTF/GBM detections
P48 5 min response time
P48 lim. mag. R ~20.6 in 60 s
iPTF13ekl
GRB 131231A
iPTF13bxl
GRB 130702A
iPTF14aue
GRB 140508A
iPTF14cva
GRB 140620A
iPTF14cyb
GRB 140623A
iPTF14eag
GRB 140808A
PTF11agg
iPTF13dsw
GRB 131011A
iPTF14yb
GRB 140226A
iPTF14bfu
GRB 140606B
mag (R)
t (days, observer frame)

Detection efficiency



- Dominated by coverage of GRB localization and LF of optical afterglows at age of P48 observations.
- Can predict expected number of detections to date using historical optical afterglow sample.
- Expected: 6–8. Observed: 8 ✓

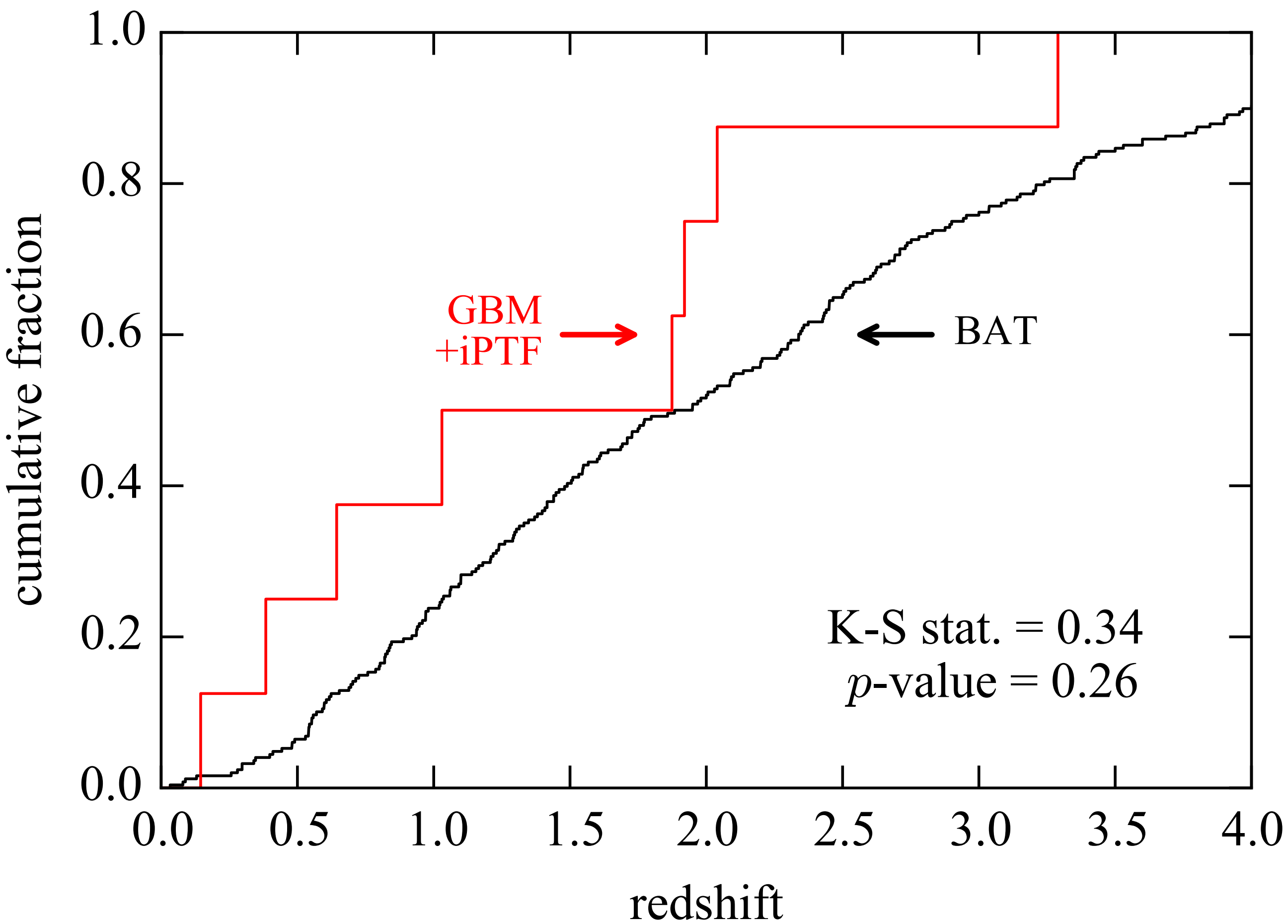


Preference for well localized GRBs

→ slight bias toward high-fluence events

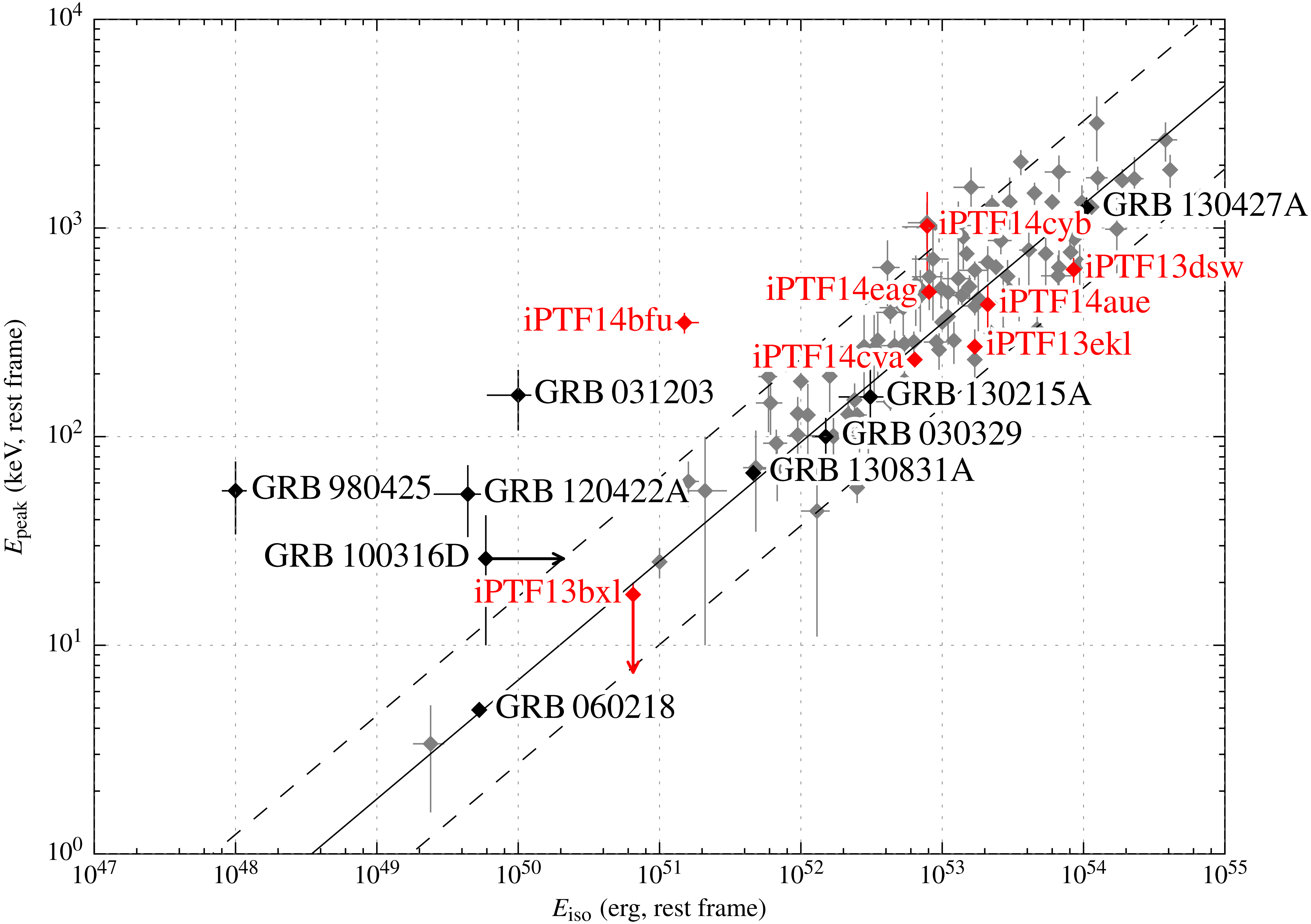
→ very weak preference for bright optical afterglows

(due to very weak correlation between gamma and optical brightness, Nyswander et al. 2009)



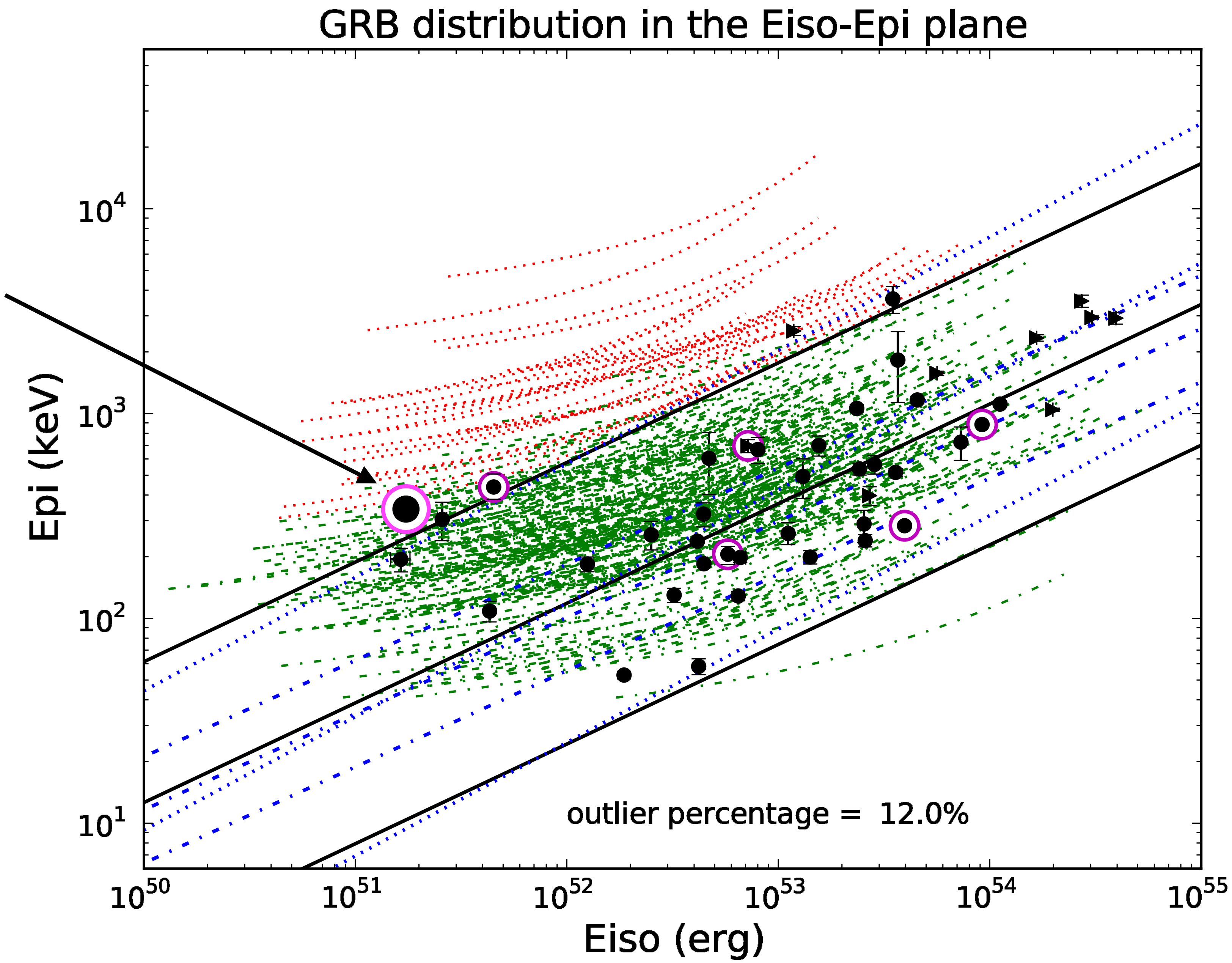
Slight preference for lower redshifts compared to *Swift* BAT (median of z=1.5 versus z=1.9), but not statistically significant with small sample size

Energetics in context



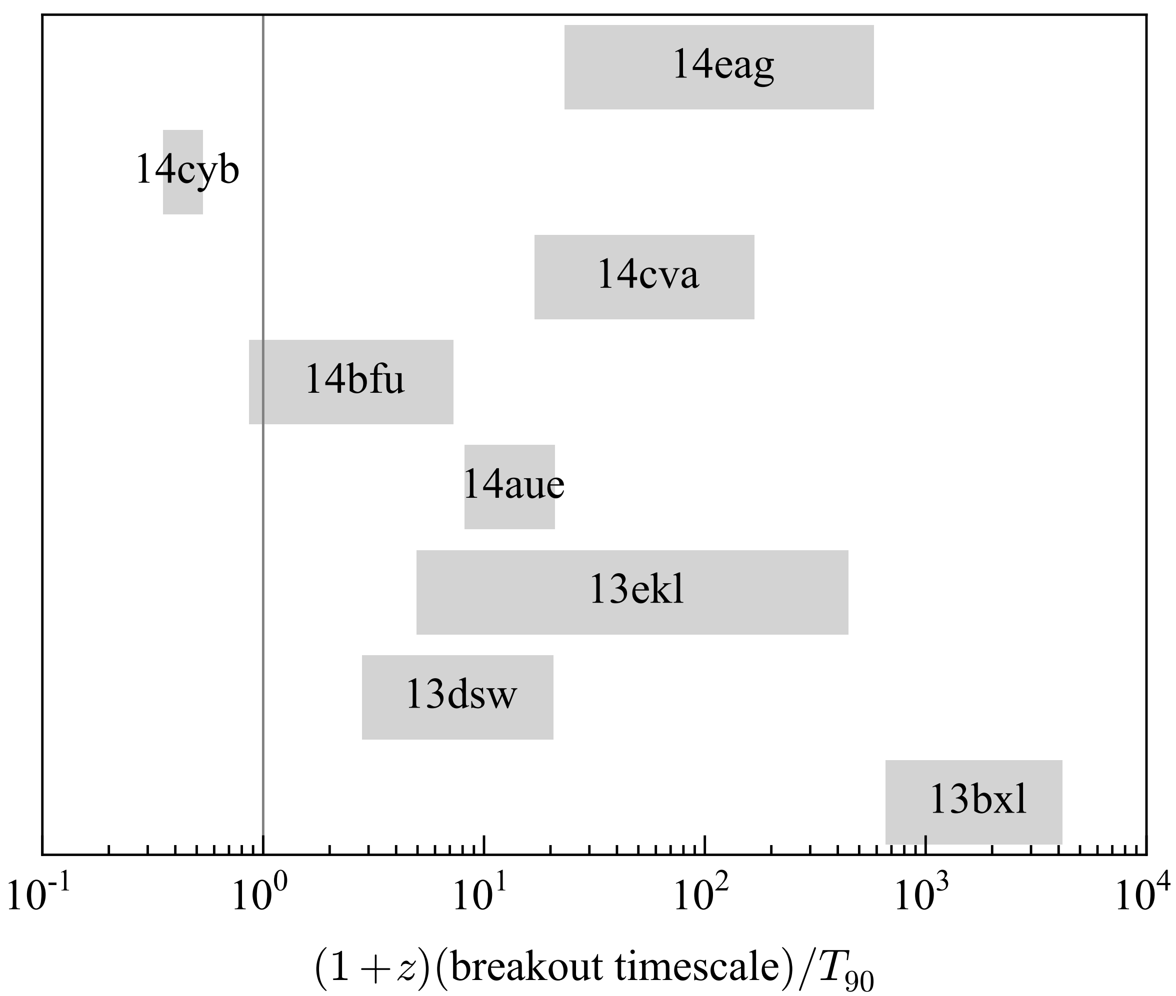
Heussaff, Atteia, & Zolnierowski 2013
http://dx.doi.org/10.1051/0004-6361/201321528

GRB140606B
iPTF14bfu



GRBs as standard candles:
Amati relation cannot be the whole story.

Ultra-relativistic jet or mildly relativistic shock breakout?



Nakar & Sari (2012) closure relation:

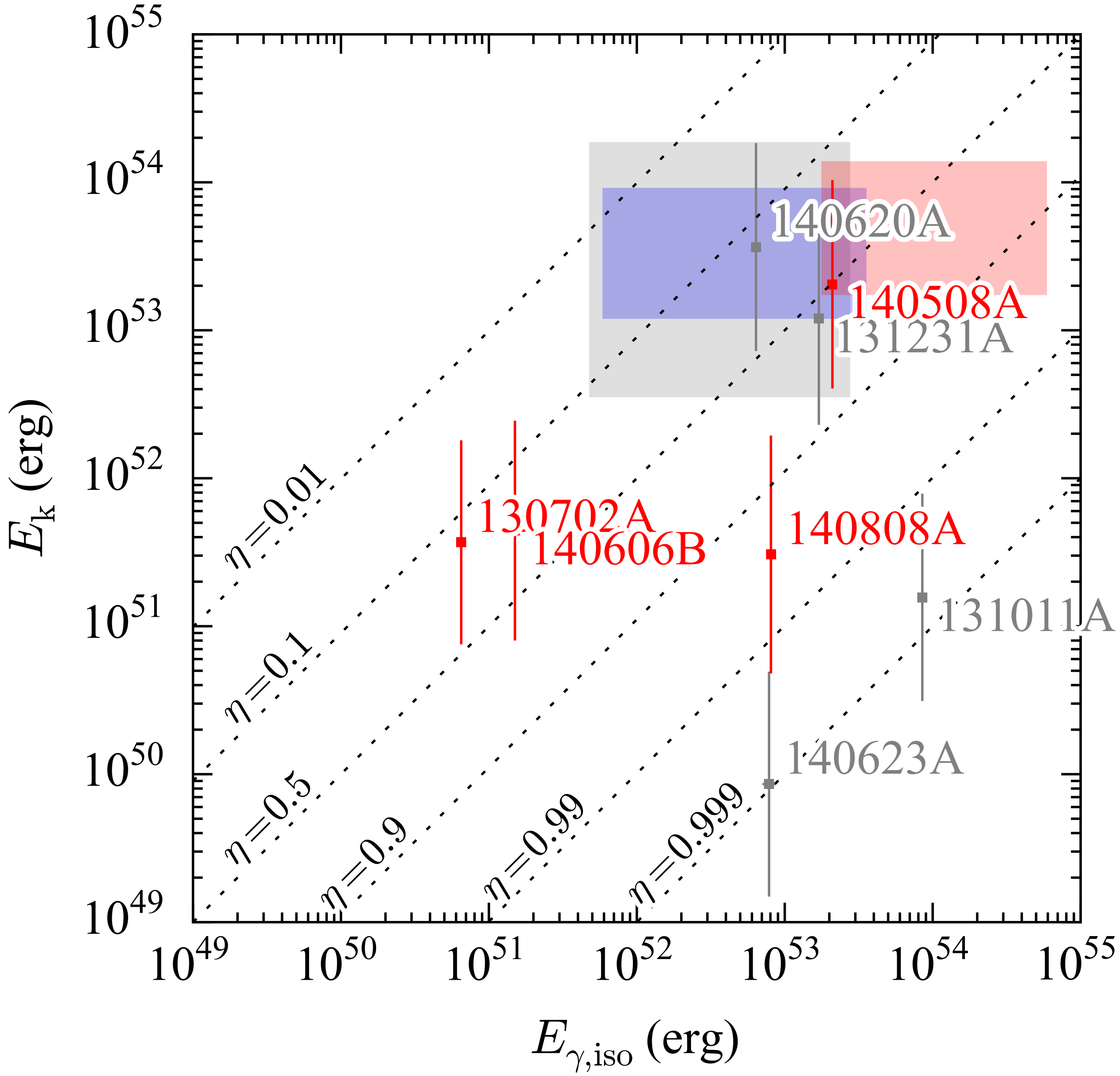
$$t_{\rm bo}^{\rm obs} \sim 20\,{\rm s} \left(\frac{E_{\rm bo}}{10^{46}\,{\rm erg}}\right)^{\frac{1}{2}} \left(\frac{T_{\rm bo}}{50\,keV}\right)^{-\frac{9+\sqrt{3}}{4}}$$

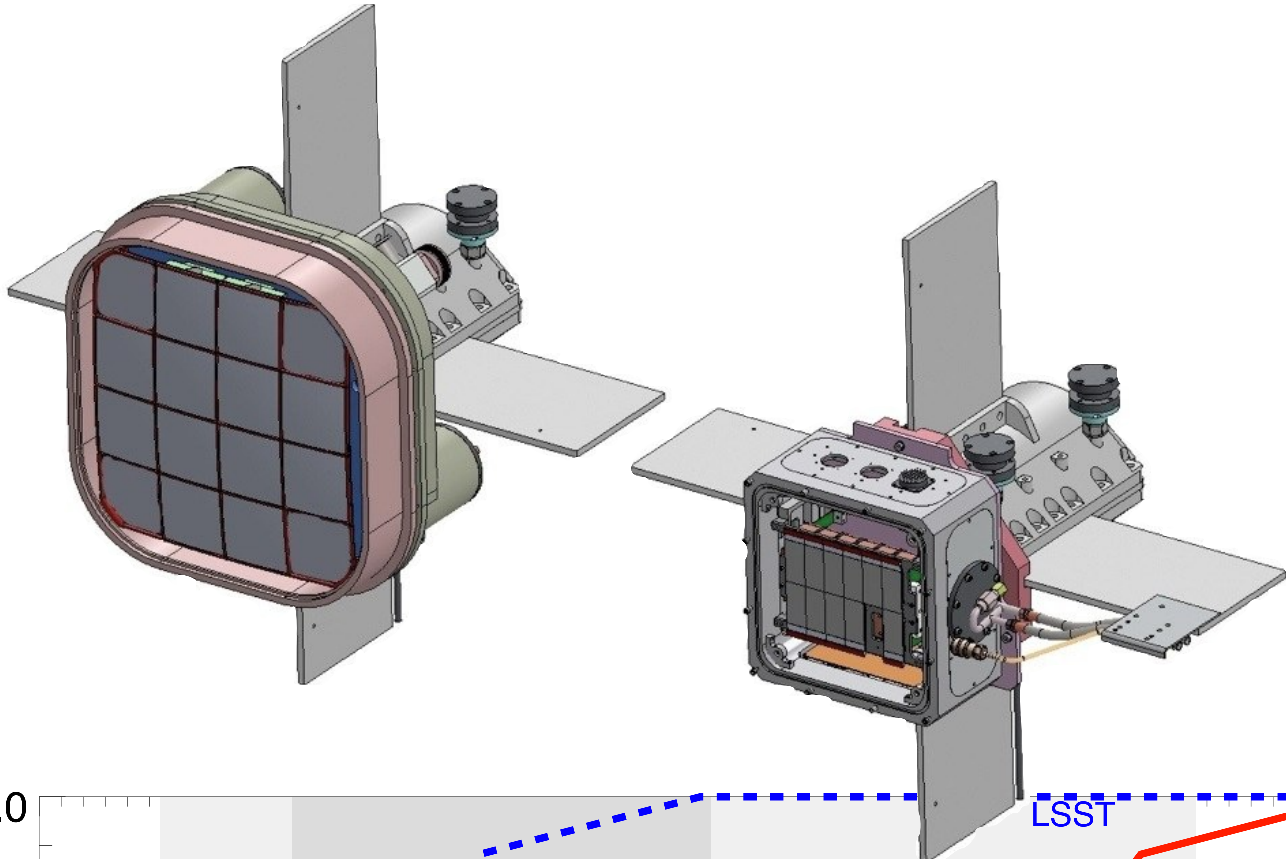
Least-squares estimate of shock breakout parameters for GRB 140606B / iPTF14bfu:

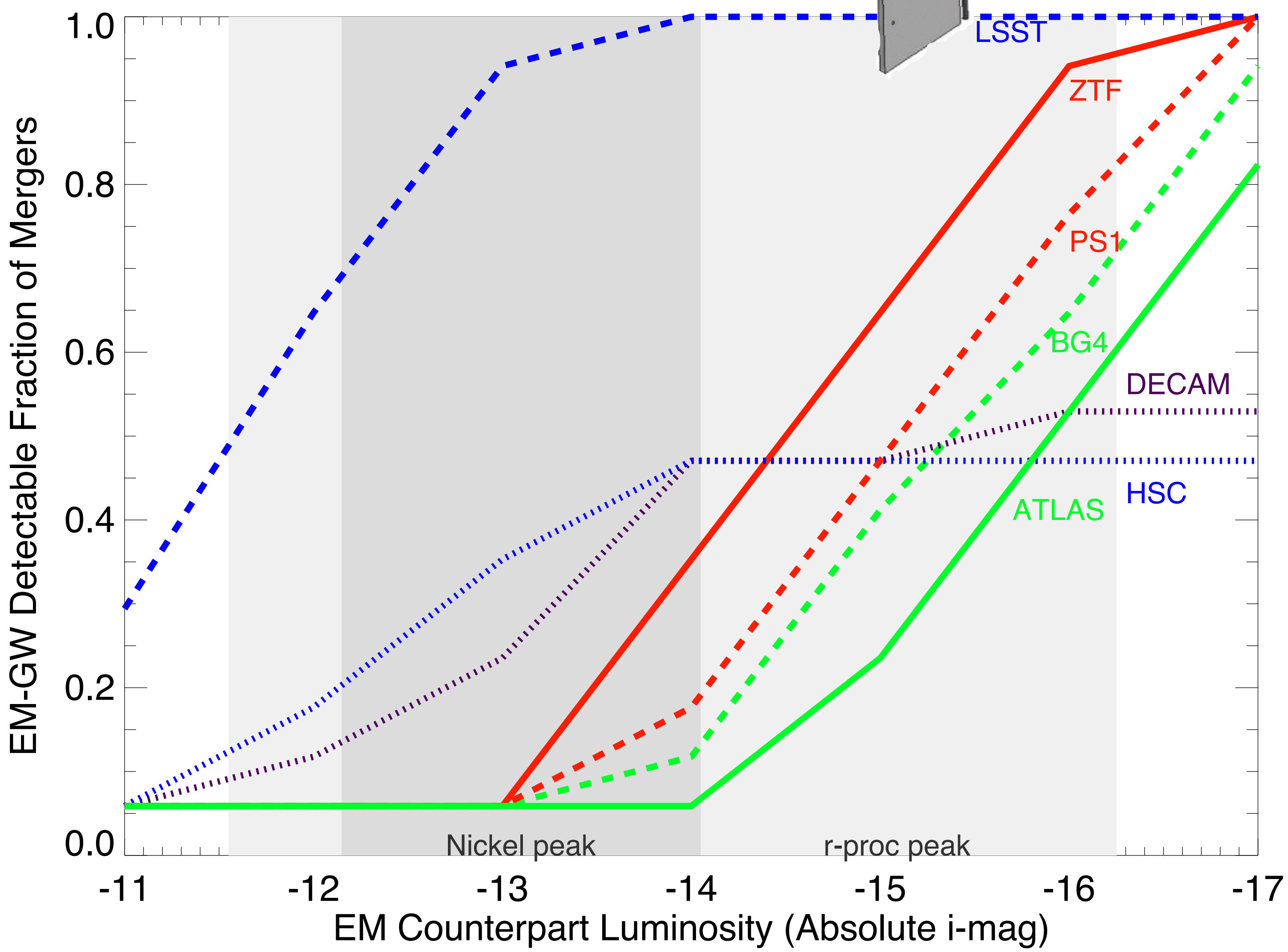
$$R_{\rm bo} = (917 \pm 106)\,R_{\odot}$$
$$\gamma_{f,0} = 9.6 \pm 1.4$$

Radiative efficiency

- X-ray afterglow is (usually) a clean diagnostic of the explosion's kinetic energy (Freedman & Waxman 2001)
- GRBs 130702A and 140606B are both subluminous *and* subenergetic
- Similar in radiative efficiencies to "normal" GRBs (Racusin et al. 2011)







Kilonovae+ZTF

Kasliwal & Nissanke (2014)
http://dx.doi.org/10.1088/2041-8205/789/1/L5

- See also Metzger, Bauswein, Goriely, & Kasen (2014, http://arxiv.org/abs/1409.0544)

  bluer, faster-rising kilonova precursor

Conclusions

- Rapid detection and sky localization pipeline ready for Advanced LIGO now
- Broadband follow-up outside of the well-studied *Swift* GRB sample
- Sample of challenges to come with searching for optical counterparts of Advanced LIGO events with ZTF
- Next step is challenging: automated target selection to feed photometric and spectroscopic follow-up!

THANK YOU

Alan Weinstein, Shri Kulkarni,
Christian Ott, & David Reitze

Brad Cenko & Mansi Kasliwal

Dan Perley, Eran Ofek, Peter Nugent, Alessandra Corsi, Dale Frail, Eric Bellm, John Mulchaey, Iair Arcavi, Tom Barlow, Josh Bloom, Yi Cao, Neil Gehrels, Assaf Horesh, Frank Masci, Julie McEnery, Arne Rau, Jason Surace, Ofer Yaron, Varun Bhalerao

Larry Price, Alex Urban, Chris Pankow, Salvatore Vitale, Ruslan Vaulin, Chad Hanna, Kipp Cannon, Duncan Brown, Patrick Brady

Astropy

HEALPix

NSF Graduate Research Fellowship

Extra slides

Bayes' Rule

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

"posterior" "likelihood" "prior" "evidence"

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

- Marginalize to get rid of nuisance parameters

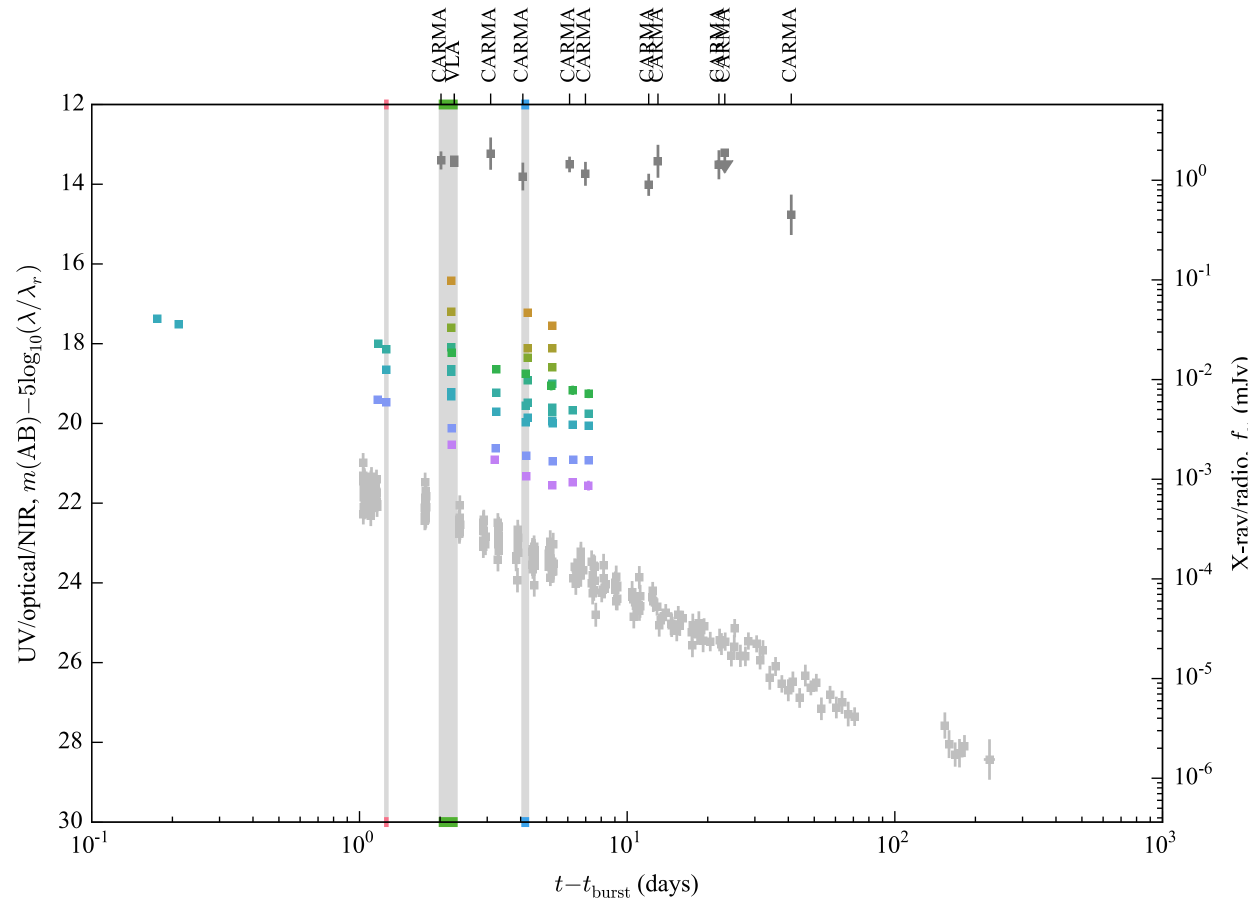
$$P(\Theta, \lambda|X) = \frac{\sum_\lambda P(X|\Theta, \lambda)P(\Theta, \lambda)}{P(X)}$$

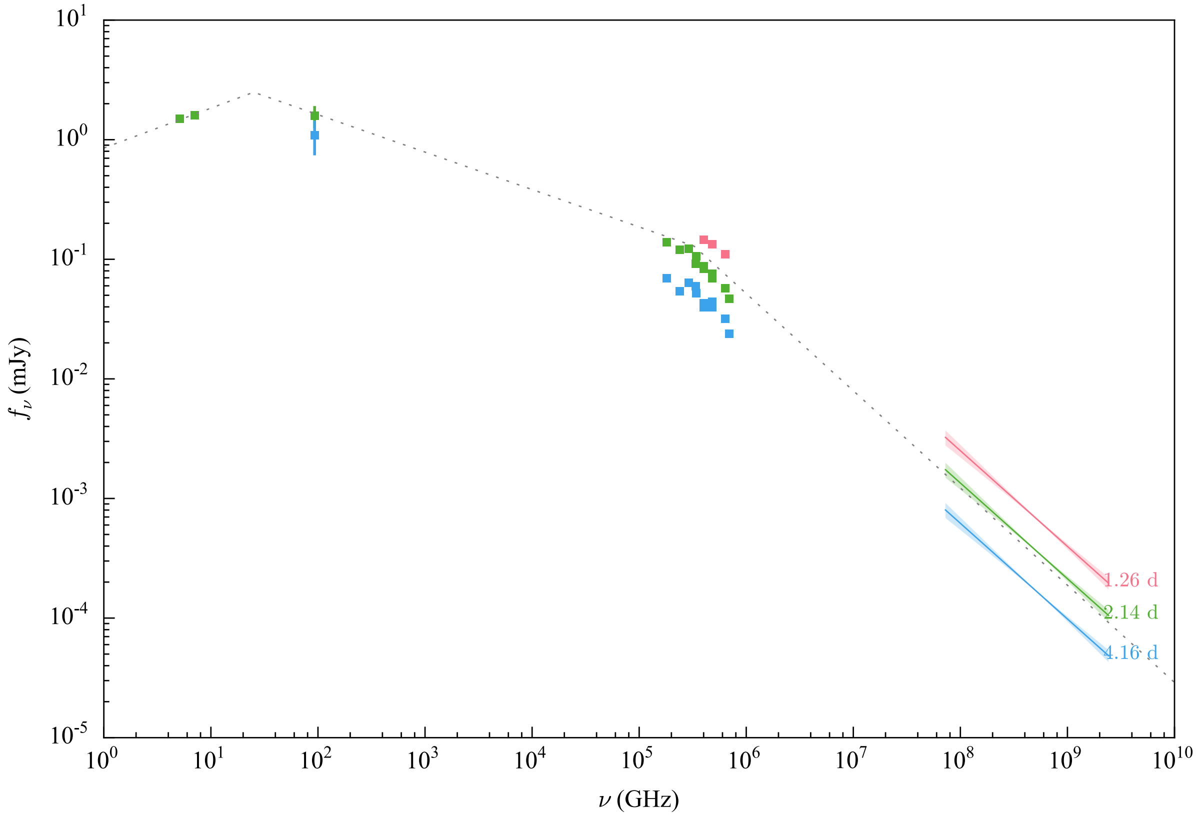
- Or, if hypothesis is continuously parameterized,

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

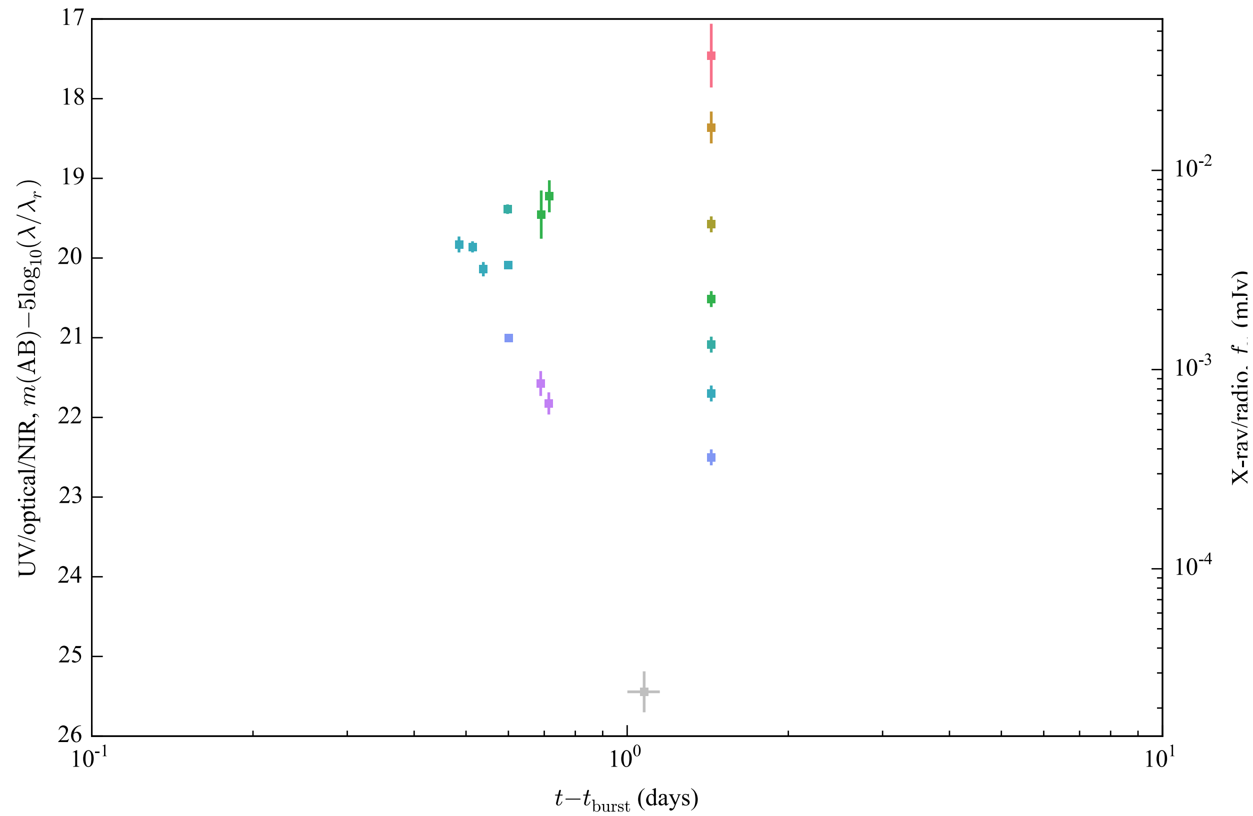
Rev. T. Bayes

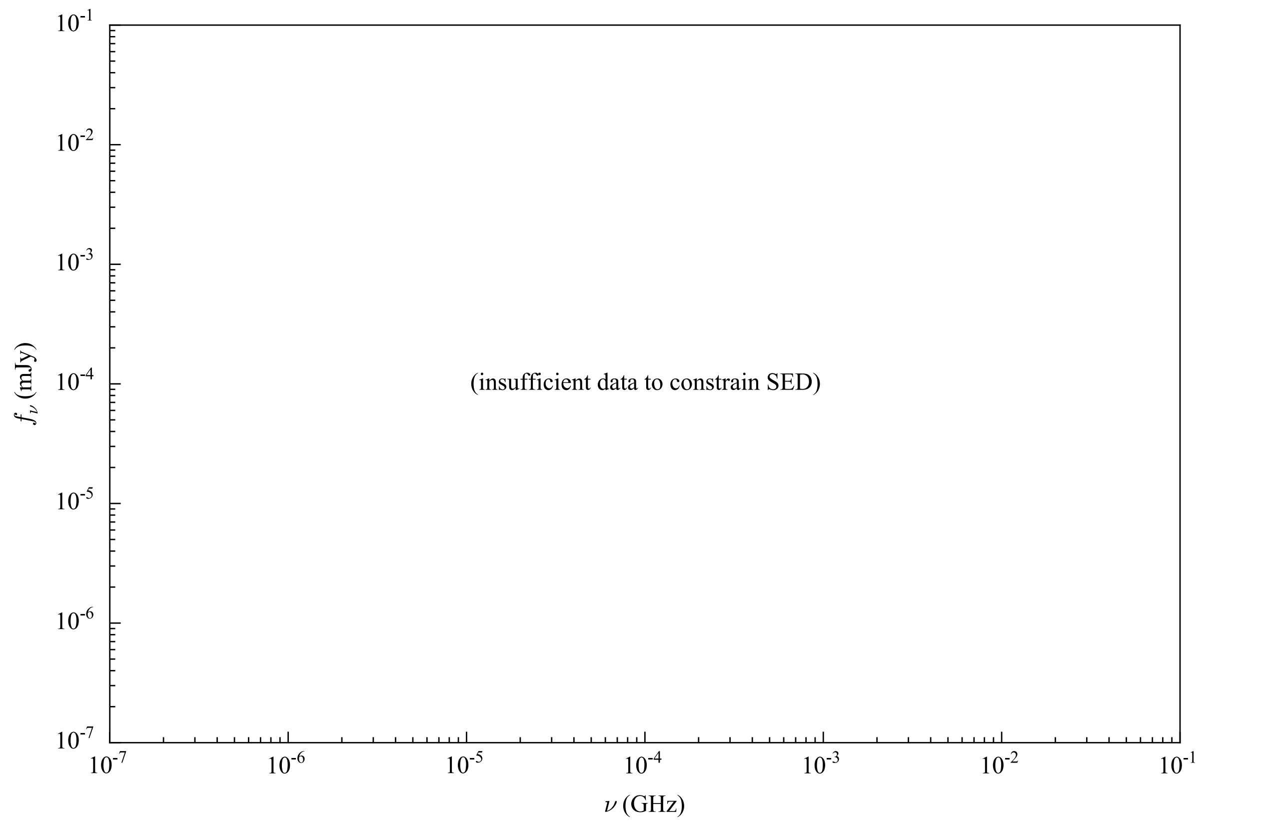
GRB 130702A
iPTF13bxl



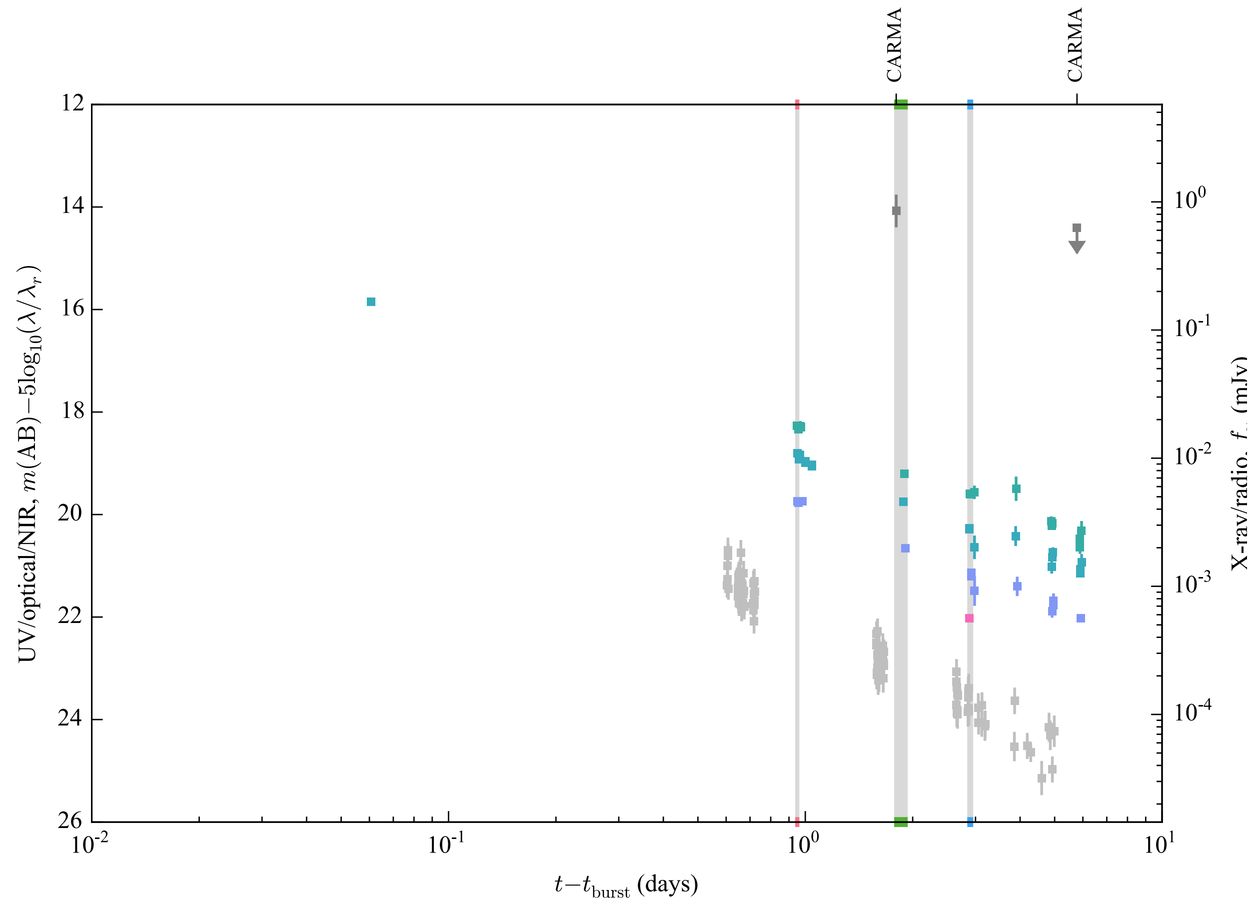


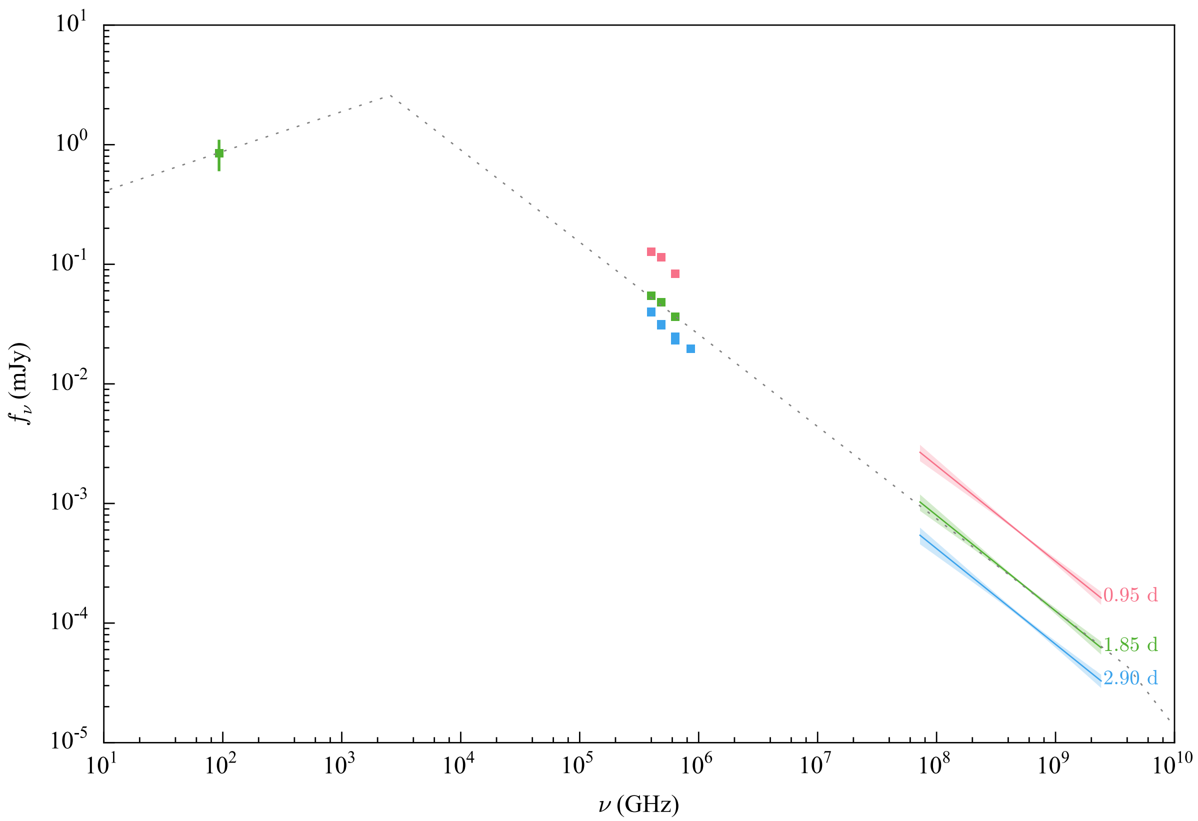
GRB 131011A
iPTF13dsw



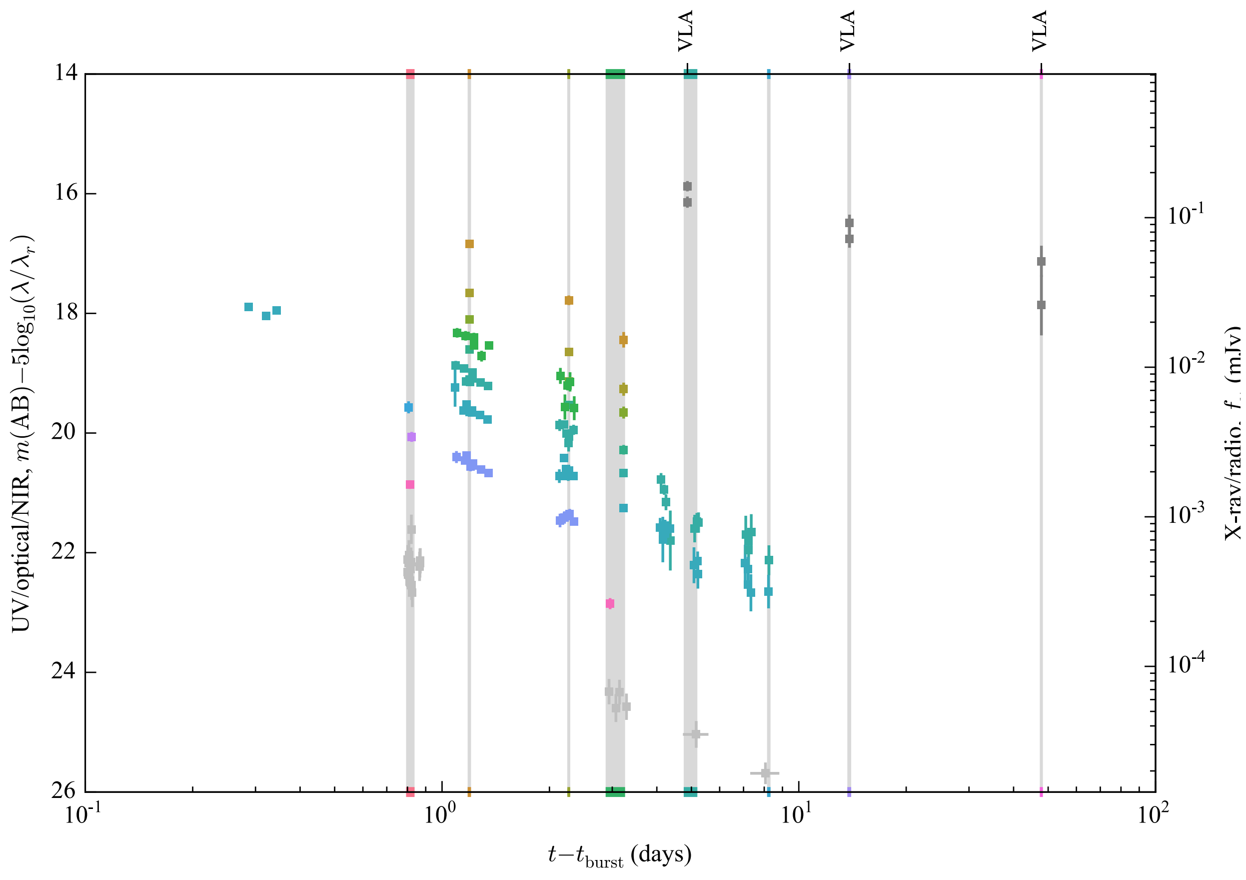


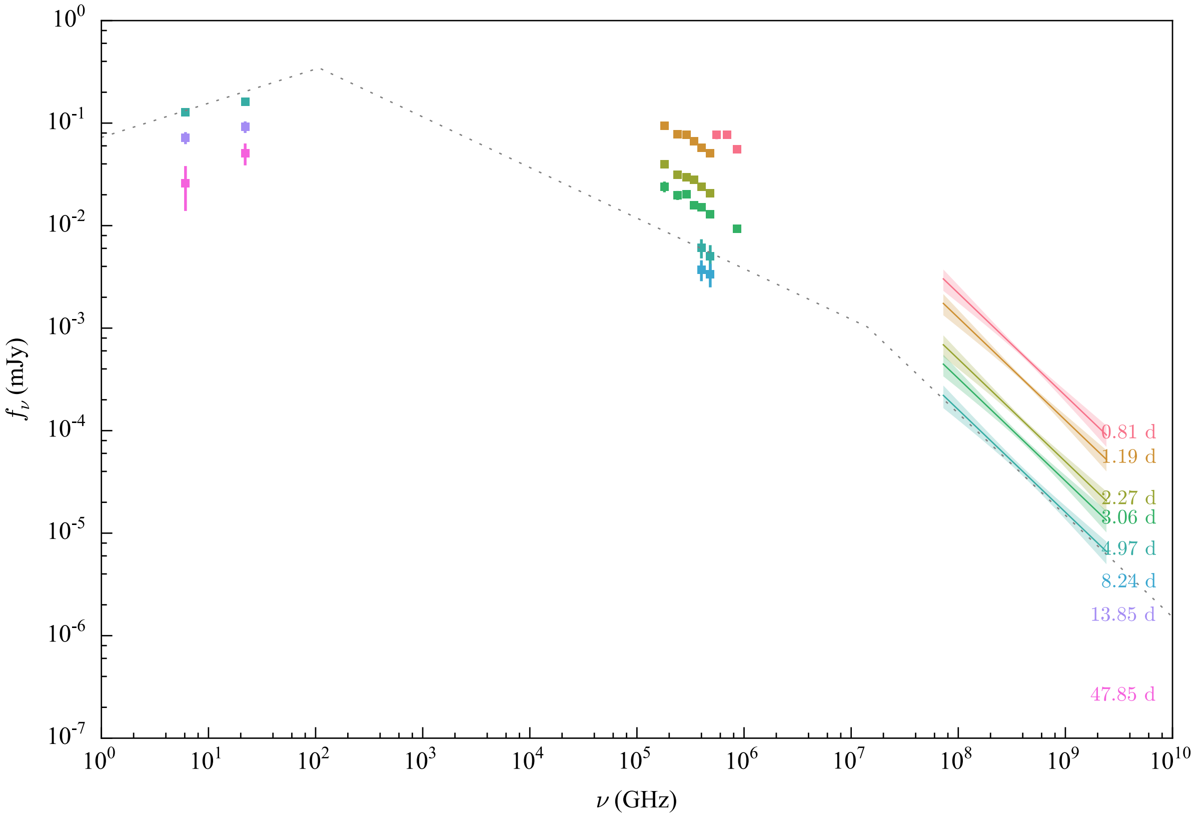
GRB 131231A
iPTF13ekl



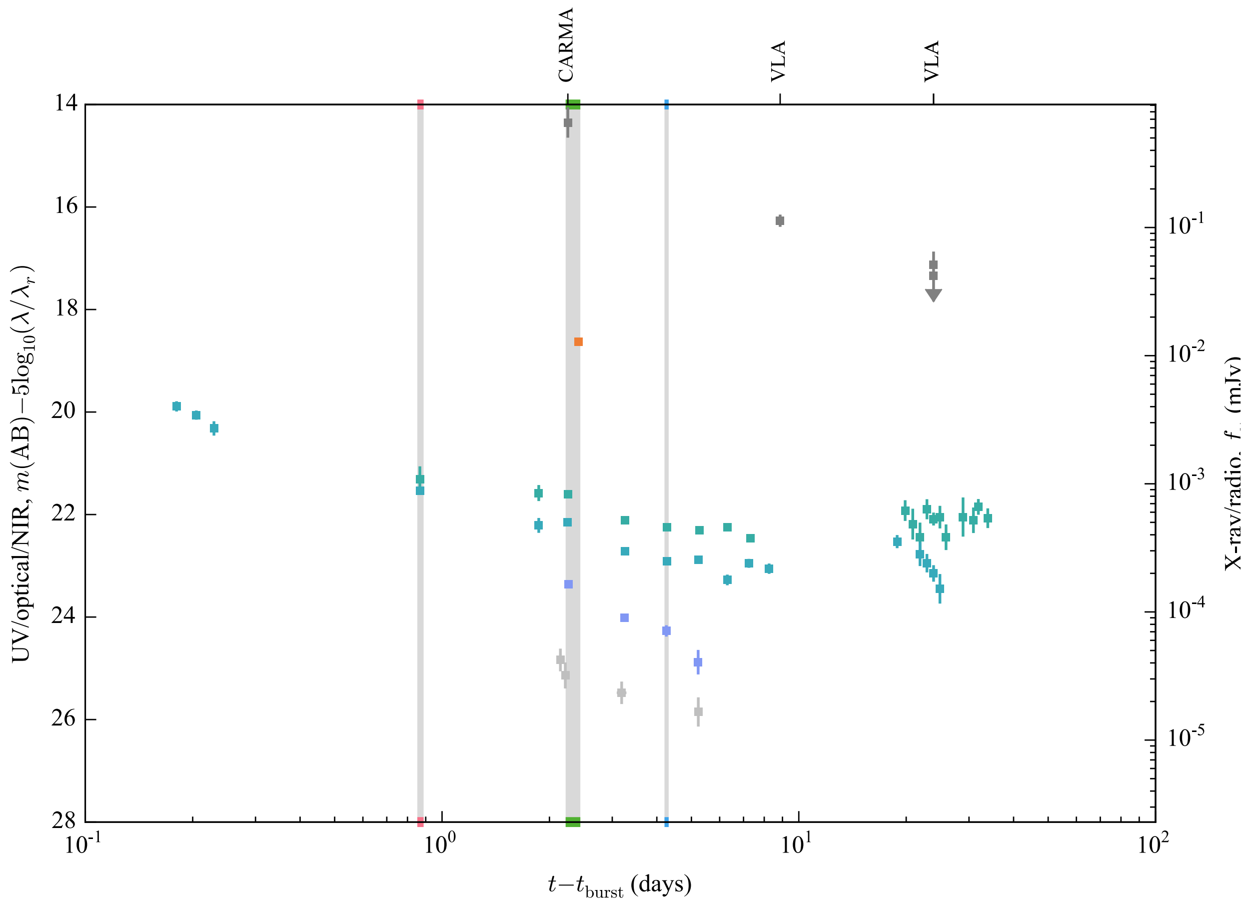


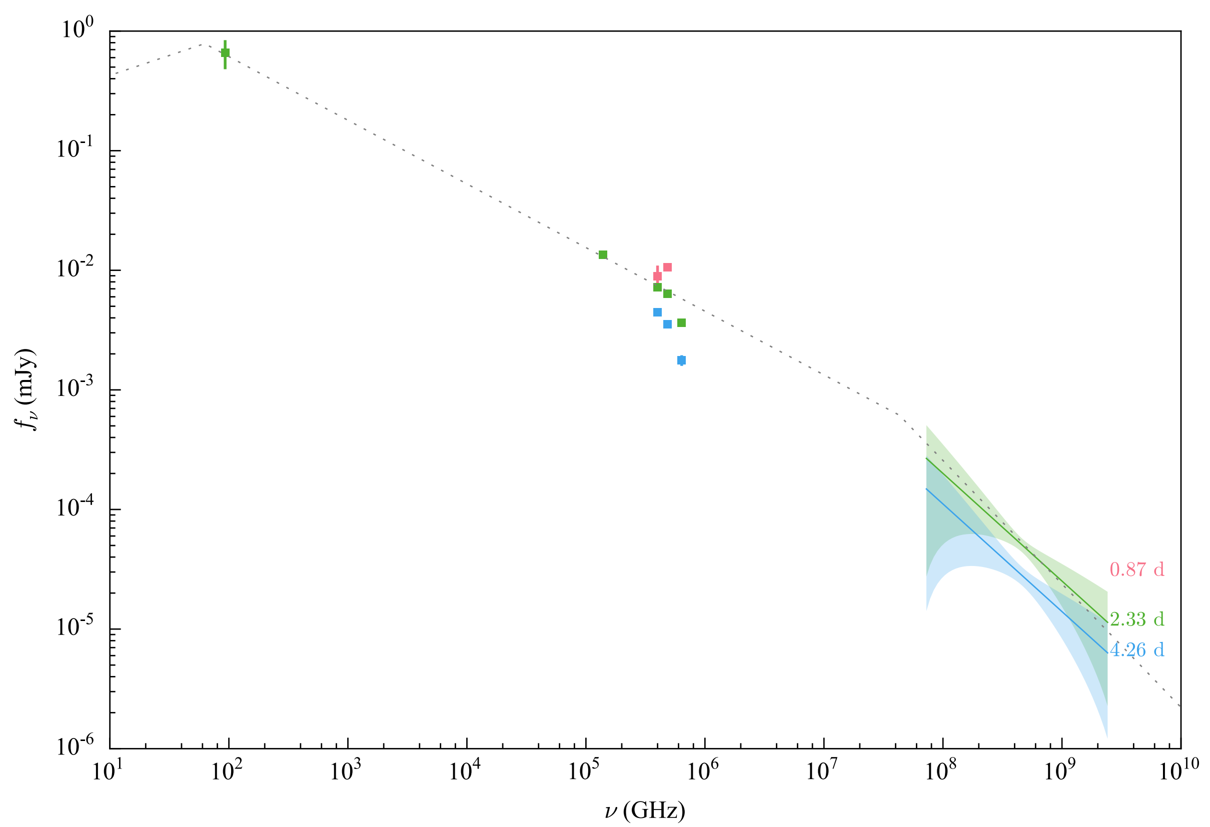
GRB 140508A
iPTF14aue



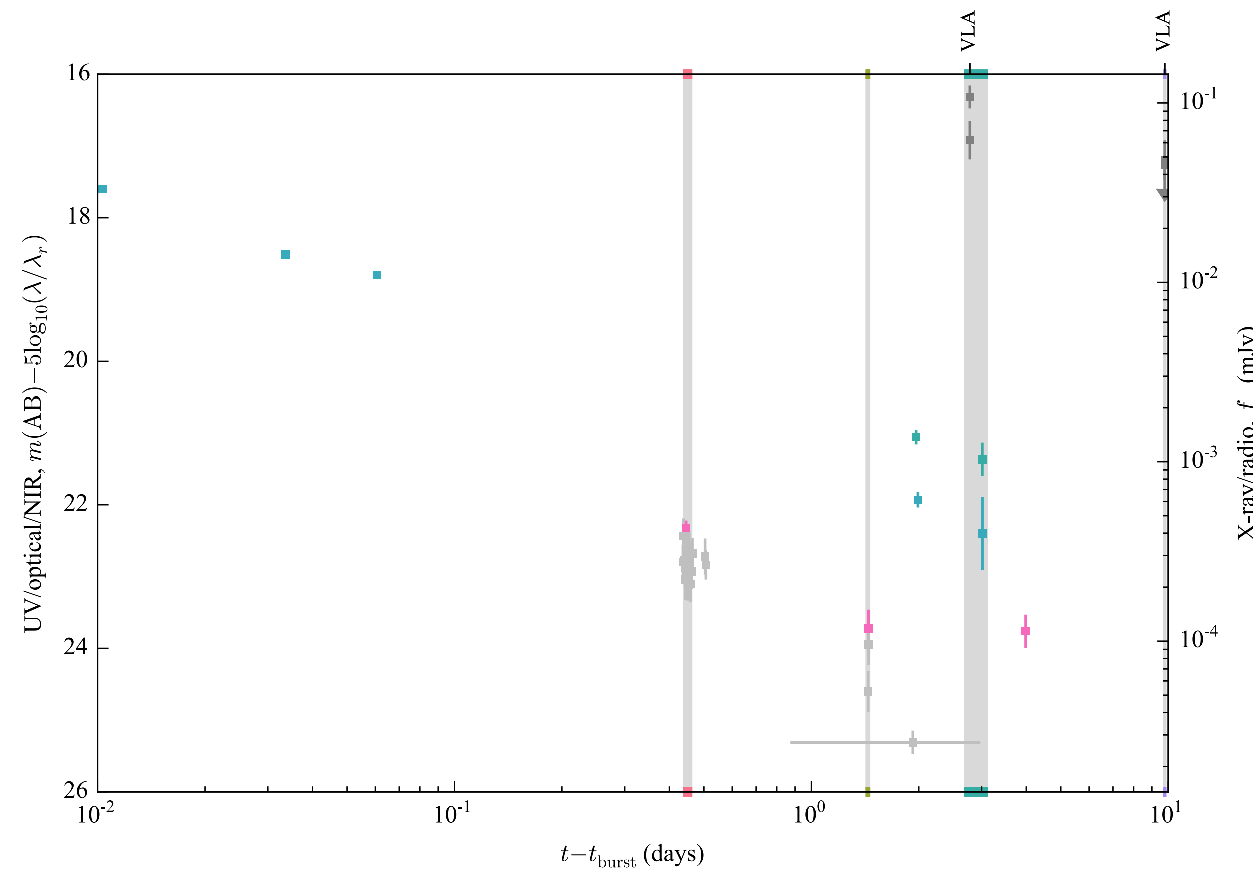


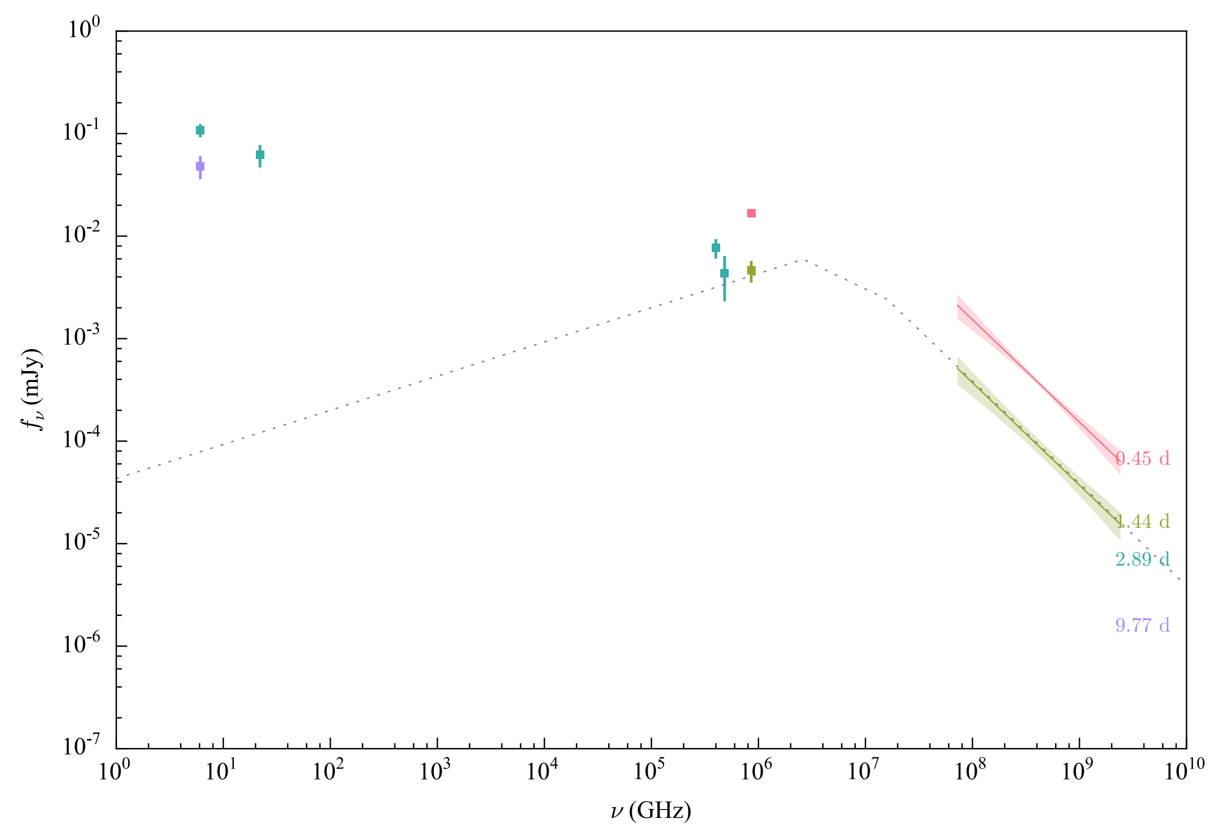
GRB 140606B
iPTF14bfu



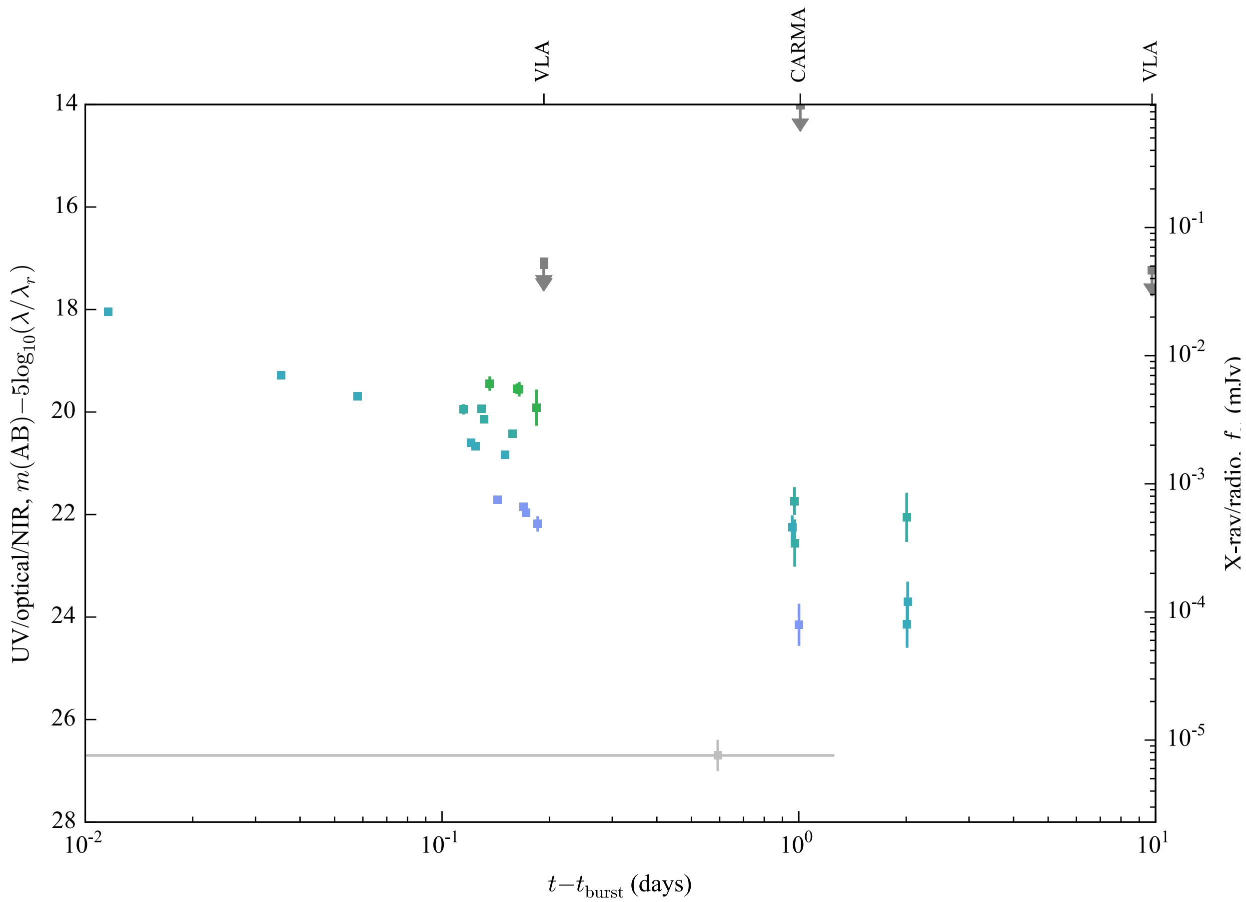


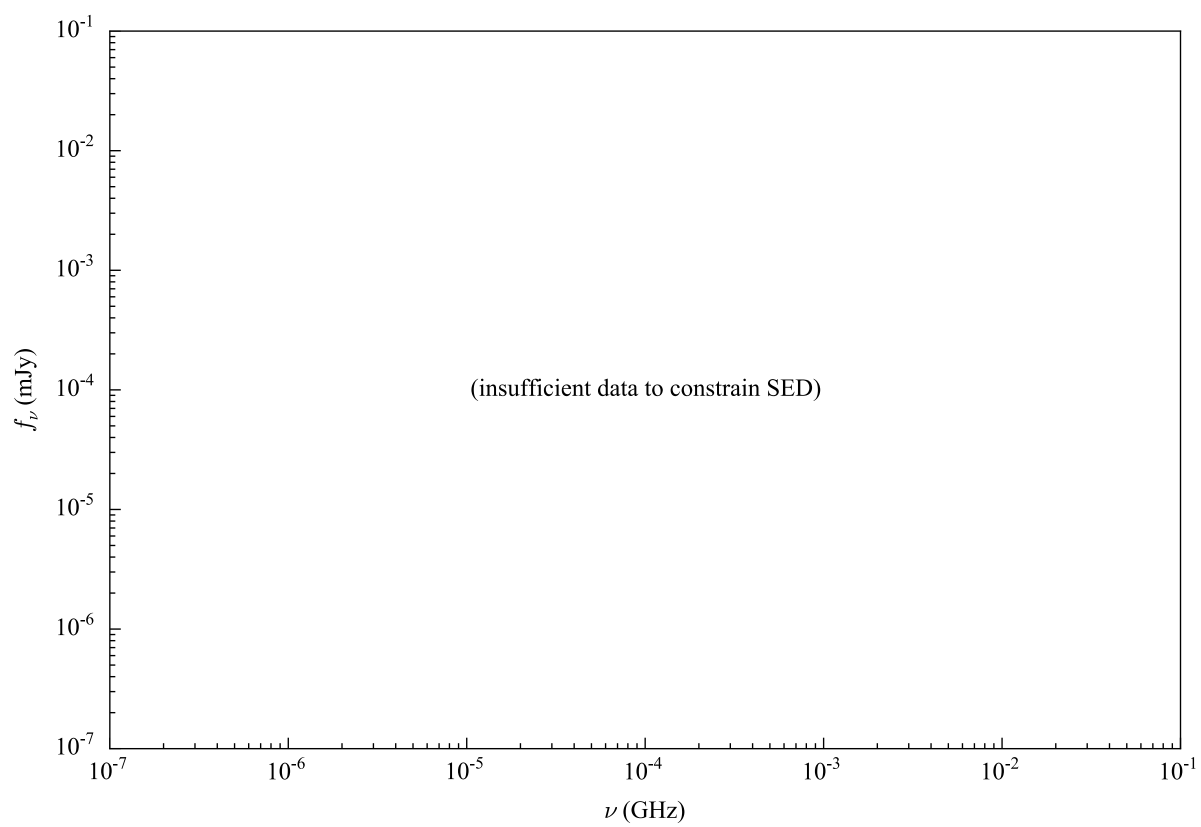
GRB 140620A
iPTF14cva



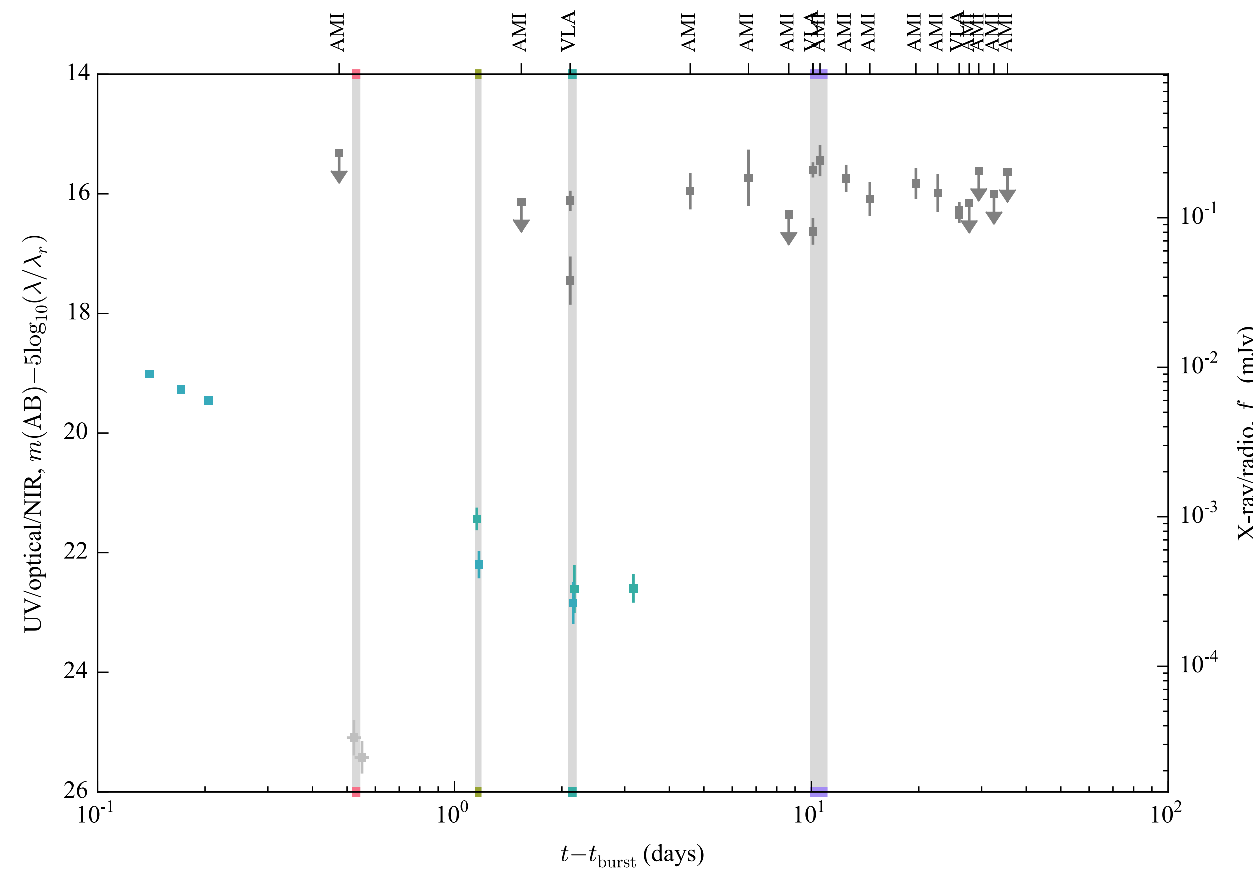


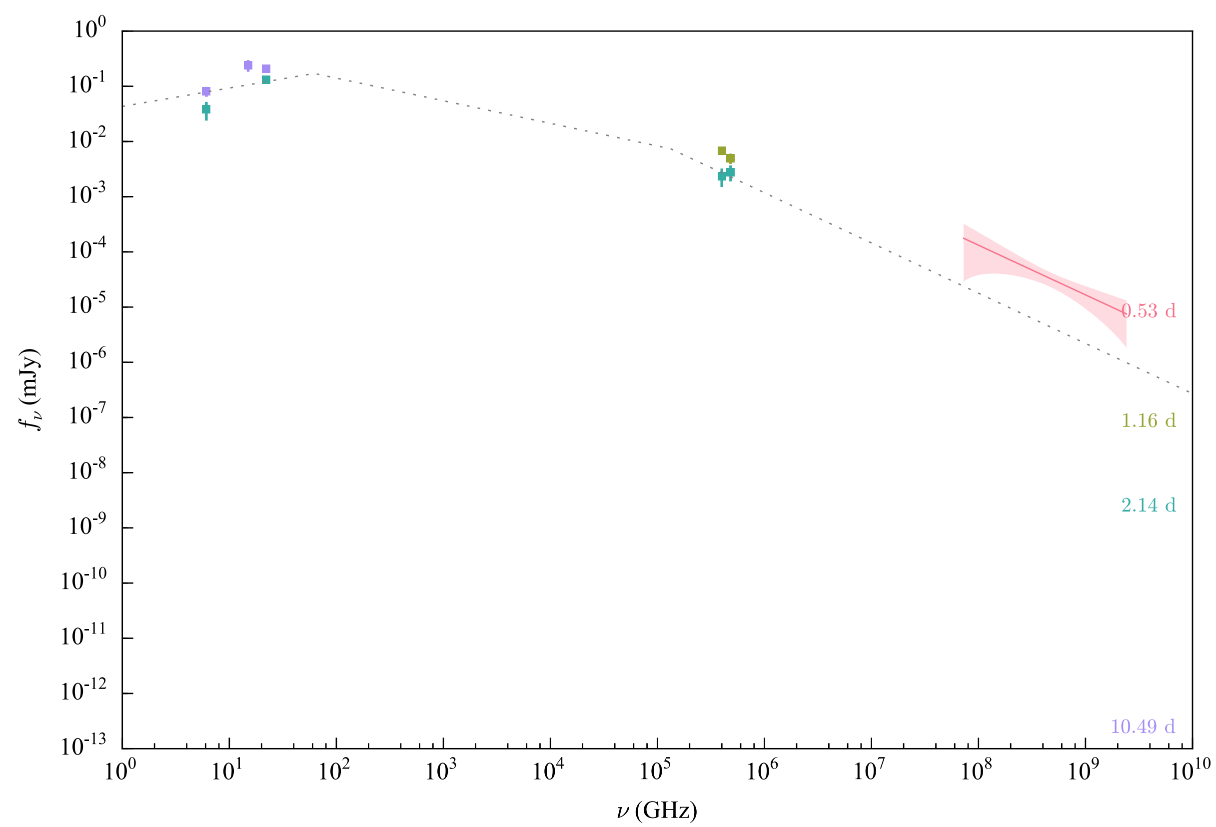
GRB 140623A
iPTF14cyb

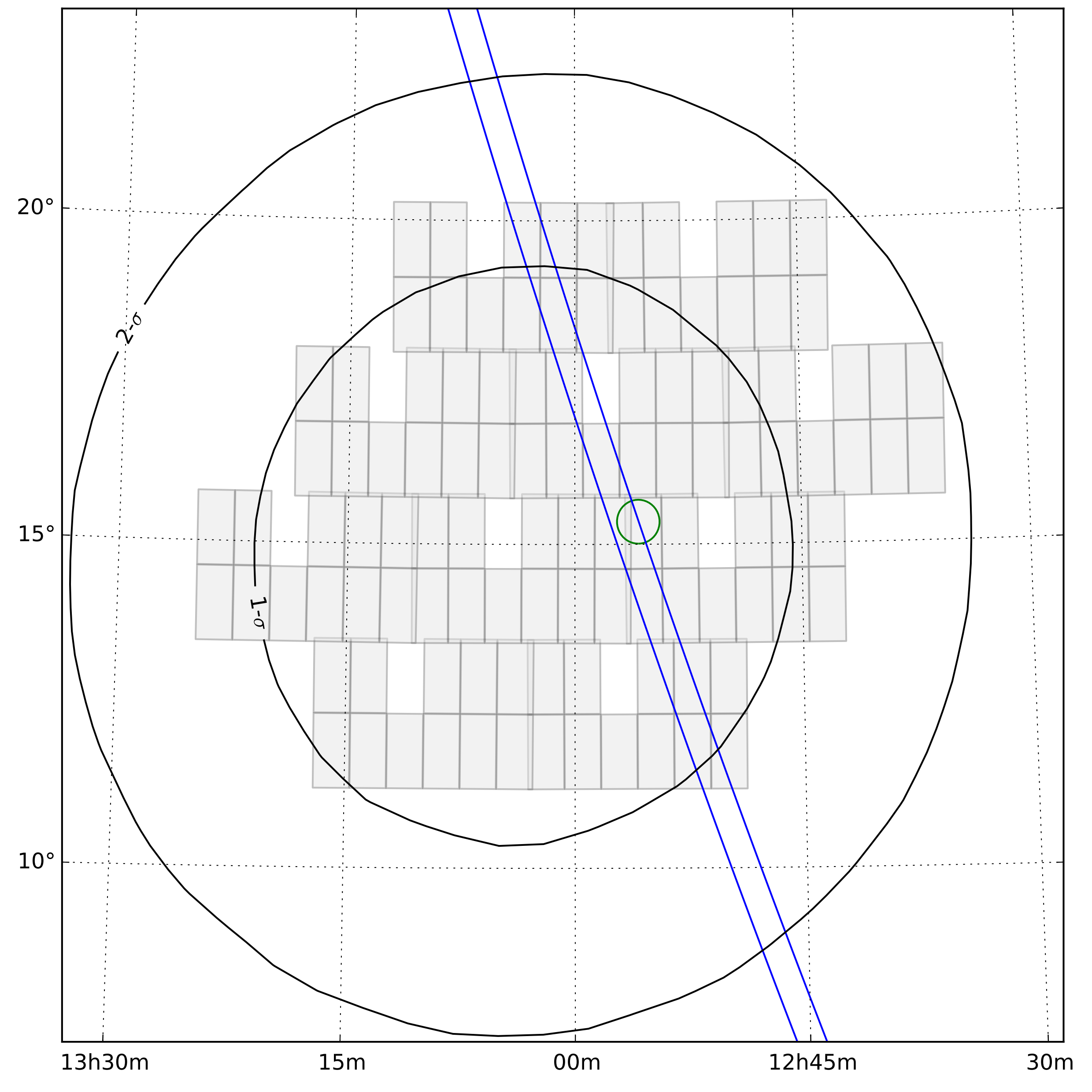




GRB 140808A
iPTF14eag







GRB 140729A: a dark burst?

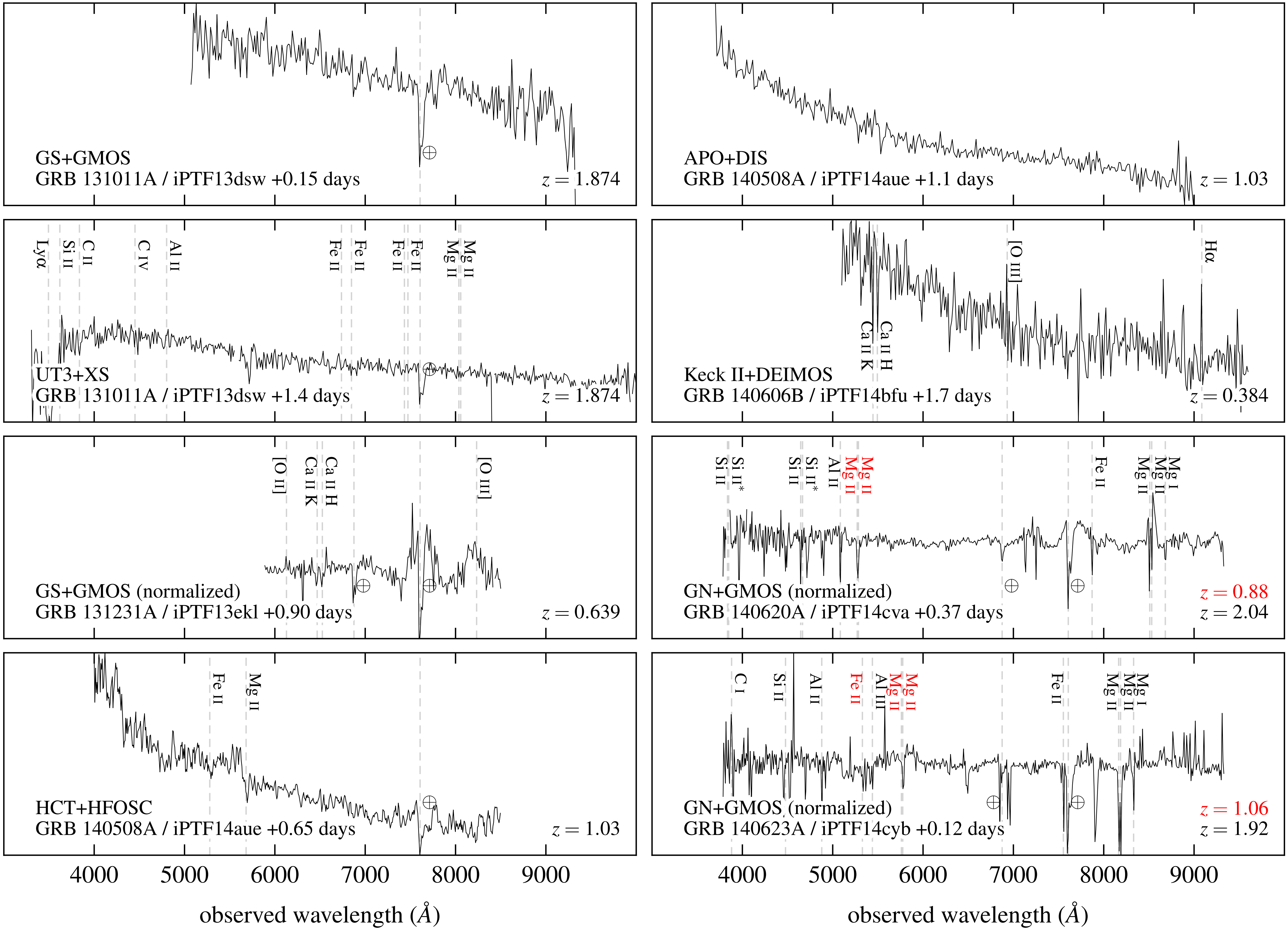

GS+GMOS
GRB 131011A / iPTF13dsw +0.15 days
z = 1.874
APO+DIS
GRB 140508A / iPTF14aue +1.1 days
z = 1.03
UT3+XS
GRB 131011A / iPTF13dsw +1.4 days
z = 1.874
Lyα
Si II
C II
C IV
Al II
Fe II
Fe II
Fe II
Fe II
Mg II
Mg II
Keck II+DEIMOS
GRB 140606B / iPTF14bfu +1.7 days
z = 0.384
Ca II K
Ca II H
[O III]
Hα
GS+GMOS (normalized)
GRB 131231A / iPTF13ekl +0.90 days
z = 0.639
[O II]
Ca II K
Ca II H
[O III]
GN+GMOS (normalized)
GRB 140620A / iPTF14cva +0.37 days
z = 0.88
z = 2.04
Si II
Si II*
Si II
Si II*
Al II
Mg II
Mg II
Fe II
Mg II
Mg II
Mg I
HCT+HFOSC
GRB 140508A / iPTF14aue +0.65 days
z = 1.03
Fe II
Mg II
GN+GMOS (normalized)
GRB 140623A / iPTF14cyb +0.12 days
z = 1.06
z = 1.92
C I
Si II
Al II
Fe II
Al III
Mg II
Mg II
Fe II
Mg II
Mg II
Mg I
4000
5000
6000
7000
8000
9000
observed wavelength (Å)
4000
5000
6000
7000
8000
9000
observed wavelength (Å)

Table 3
Sky positions of GBM–iPTF bursts.

GRB	OT	RA (J2000)	Dec (J2000)	Galactic latitude
GRB 130702A	iPTF13bxl	$14^h29^m15^s$	$+15°46'26''$	65°
GRB 131011A	iPTF13dsw	$02^h10^m06^s$	$-4°24'40''$	-61°
GRB 131231A	iPTF13ekl	$00^h42^m22^s$	$-1°39'11''$	-64°
GRB 140508A	iPTF14aue	$17^h01^m52^s$	$+46°46'50''$	38°
GRB 140606B	iPTF14bfu	$21^h52^m30^s$	$+32°00'51''$	-17°
GRB 140620A	iPTF14cva	$18^h47^m29^s$	$+49°43'52''$	21°
GRB 140623A	iPTF14cyb	$15^h01^m53^s$	$+81°11'29''$	34°
GRB 140808A	iPTF14eag	$14^h44^m53^s$	$+49°12'51''$	59°

Table 4
iPTF/GBM non-detections.

GRB time	$t_{\rm P48} - t_{\rm burst}$ (h)	P48 area (deg^2)	Containment probability
2014-08-07 11:59:33	15.88	73	54%
2014-07-29 00:36:54	3.43	73	65%
2014-07-16 07:20:13	0.17	74	28%
2014-06-28 16:53:19	16.16	76	20%
2014-06-08 17:07:11	11.20	73	49%
2014-05-19 01:01:45	4.42	73	41%
2014-05-17 19:31:18	8.60	95	69%
2014-04-29 23:24:42	10.99	74	15%
2014-04-04 04:06:48	0.11	109	69%
2014-03-19 23:08:30	3.88	74	48%
2014-03-11 14:49:13	12.18	73	54%
2014-02-24 18:55:20	7.90	72	30%
2014-02-19 19:46:32	7.01	71	14%
2014-02-11 02:10:41	1.77	44	19%
2014-01-22 14:19:44	11.97	75	34%
2014-01-05 01:32:57	7.63	74	22%
2014-01-04 17:32:00	18.57	15	11%
2013-12-30 19:24:06	7.22	80	38%
2013-11-27 14:12:14	13.46	60	50%
2013-11-26 03:54:06	6.94	109	59%
2013-11-25 16:32:47	11.72	95	26%
2013-11-10 08:56:58	17.47	73	44%
2013-11-08 00:34:39	4.69	73	37%
2013-10-06 20:09:48	15.26	74	18%
2013-09-24 06:06:45	23.24	74	28%
2013-08-28 07:19:56	20.28	74	64%
2013-06-28 20:37:57	10.02	73	32%

Note. — Columns are time of the burst, age of the burst at the beginning of the P48 observations, area enclosed by the P48 fields, and prior probability for the burst to be located within the P48 fields.