Open Issues in Joint Analysis of Gravitational-Wave and Electromagnetic Data.

Ruslan Vaulin[1],
Brennan Hughey[2] and Erik Katsavounidis[1]

[1] Massachusetts Institute of Technology
[2] University of Wisconsin-Milwaukee.

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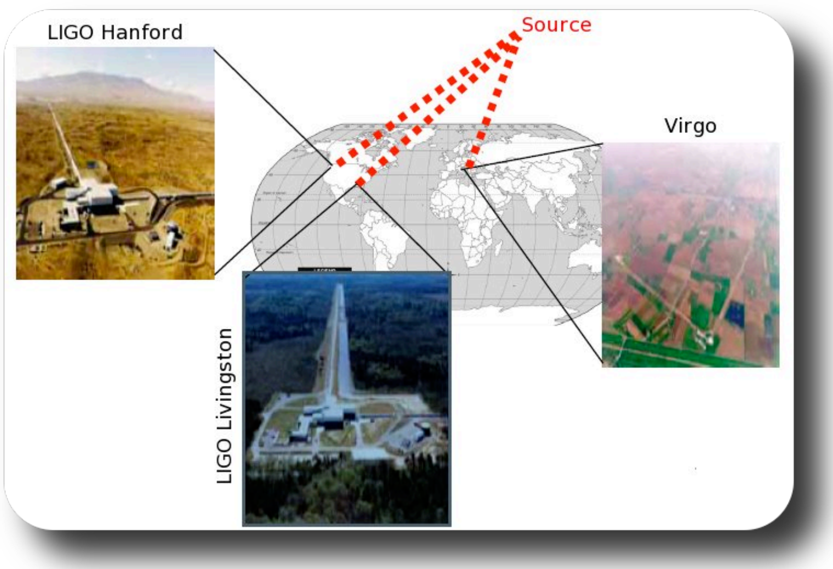
Massachusetts Institute of Technology
Kavli Institute for Astrophysics and Space Research

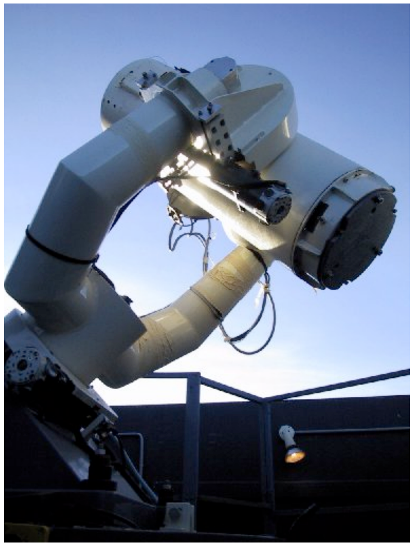
Outline

- Joint GW-EM data analysis.
- Example: Swift follow-up of GW transients during 2009-2010 LIGO-Virgo science run.
- Key factors in a joint analysis and their contribution to efficiency.
- Prospects for joint GW-EM observations in the era of advanced GW detectors.

Joint GW-EM observations and analysis

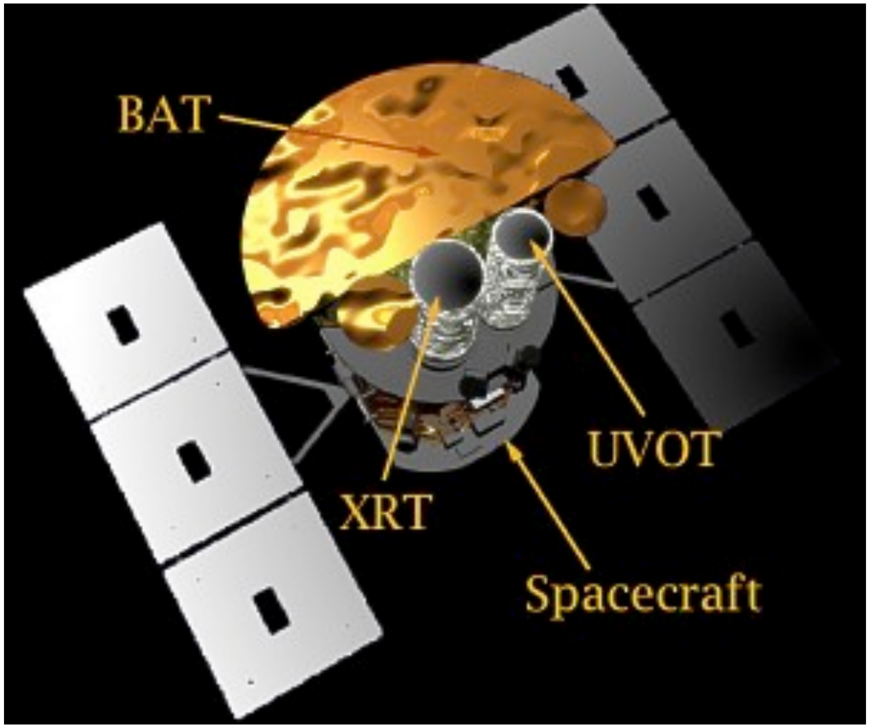
- Perform coordinated observations with GW detectors and EM telescopes.
- Identify significant GW and EM candidates.
- Optimally combine GW and EM data and assign significance to the joint (GW, EM) events.
- Detection only statement.





Swift observations during 2009-2010 EM follow-up campaign.

- Joint effort between LIGO-Virgo collaborations and Swift analysts.
- 2 ToO transient gravitational-wave (GW) candidates from low-latency search were promptly followed-up with Swift XRT (0.4x0.4 deg) and UVOT (0.28x0.28 deg) telescopes in search of EM counterpart.
- One of the GW candidates was a weak trigger consistent with expected instrumental noise (exercise).
- Another was a blind GW injection ("Big Dog" CBC).
- EM observations found no EM counterpart (consistent with GW data).
- Paper: arXiv:1205.1124.



XRT - X-Ray Telescope
UVOT - Ultra-Violet and Optical Telescope

Observations with Swift

- Two independent analyses of XRT data were performed by teams from U. of Leicester and MIT.
- Two candidates were followed up 2 hours after the GW triggers were generated.
- Nominally five 0.4x0.4 fields are observed.
- Typical exposures 30 minutes. Fields were observed again a month after original observations.
- January GW trigger was found to be consistent with instrumental background in LIGO and Virgo.
- September GW trigger was a "blind" simulated CBC signal injected in the data.

Joint GW-EM statistic

- $\mathbf{g}$ - GW data, $\mathbf{I}$ - EM data.
- Optimal joint detection statistic is the likelihood ratio:

$$\Lambda_{\rm joint}(\mathbf{g},\mathbf{I}) = \Lambda_{\rm GW}(\mathbf{g})\Lambda_{\rm EM}(\mathbf{I})\Lambda_{\rm corr}(\mathbf{g},\mathbf{I})$$

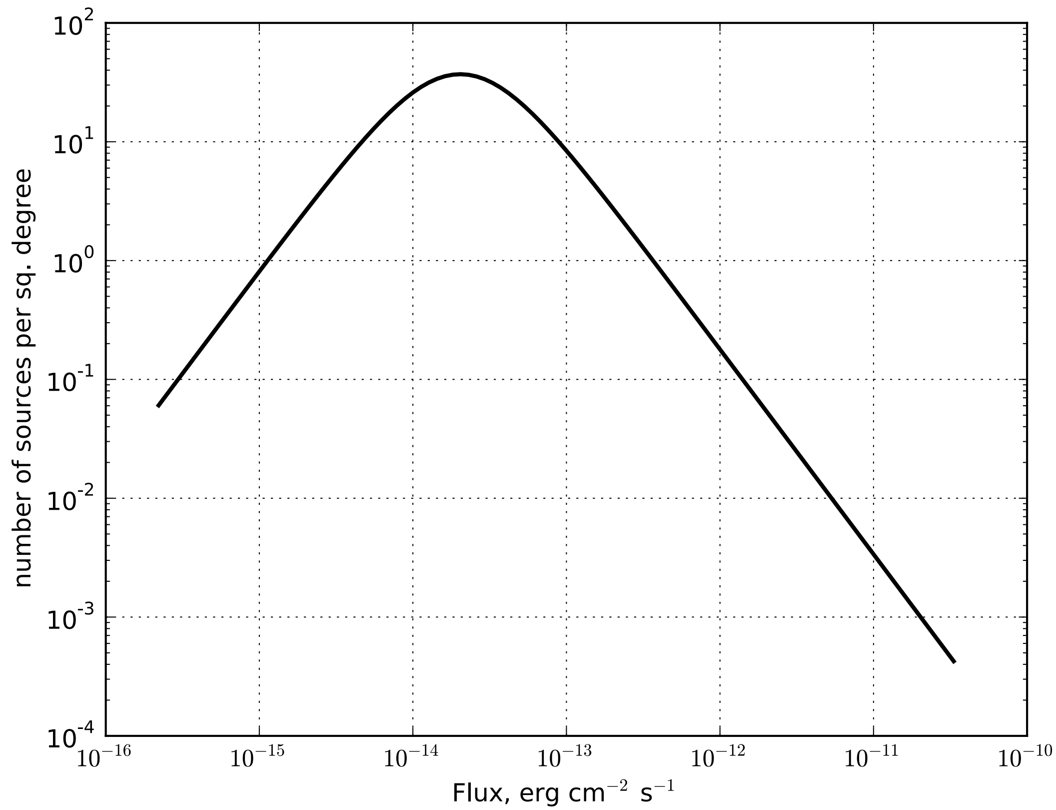
Significance of GW trigger

Significance of EM transient

Position correlation: sky-map

- Significance of EM transient is primarily probability of observing accidental EM transient(s) and is determined by distribution of serendipitous sources
- Position correlation is convolution of EM and GW sky-maps, $\Lambda_{\rm corr} \approx p_{\rm m}(\Omega_0)$

Background of serendipitous X-ray sources.

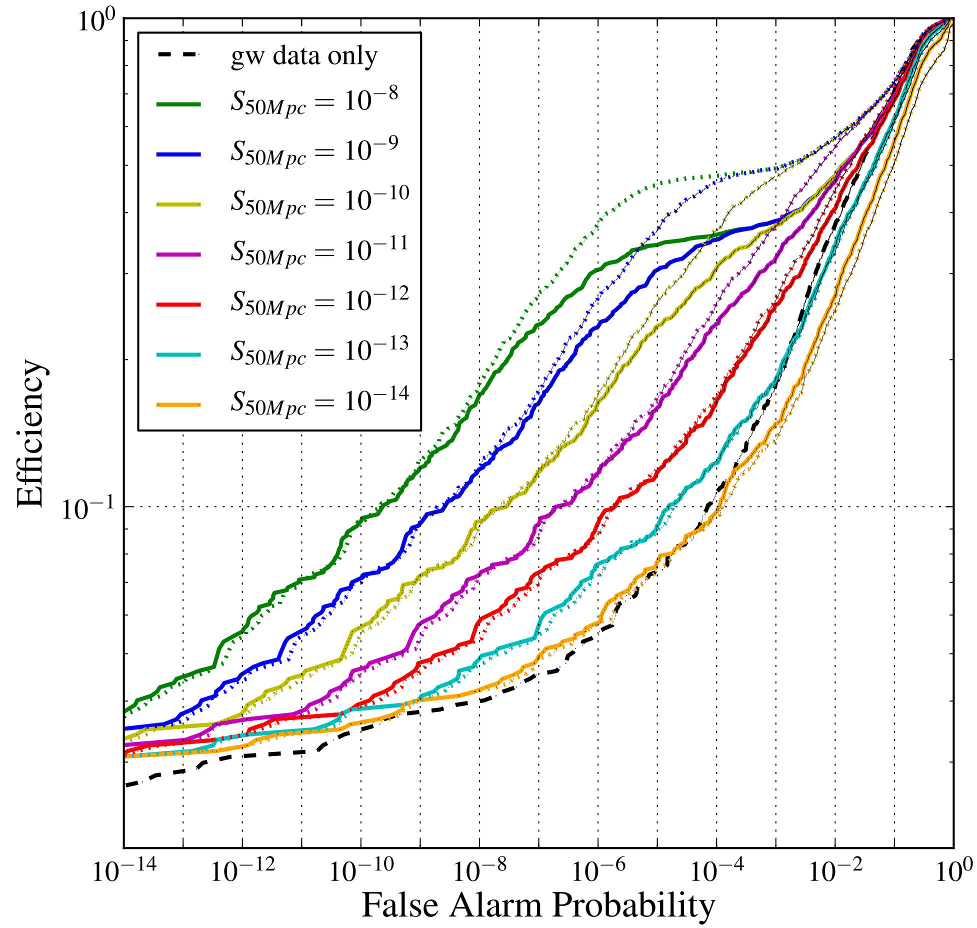


arXiv:1205.1124

LogN-LogS of X-ray serendipitous sources as a function of flux estimated using XMM-Newton catalog. The turn in the curve reflects limited sensitivity of the instrument to low flux sources.

Efficiency of the joint LIGO-Virgo/Swift search

- Simulated population of GW+EM signals and performed joint analysis.
- Efficiency as a function of false alarm probability for the joint LIGO-Virgo and Swift search.
- The solid (dotted) curves represent performance of the joint search with five (ten) pixels observed by Swift for various models of X-ray counterpart defined by the value of flux for a source 50 Mpc away, S_{50MPC} .
- The dashed line is the curve for the GW only search.



arXiv:1205.1124

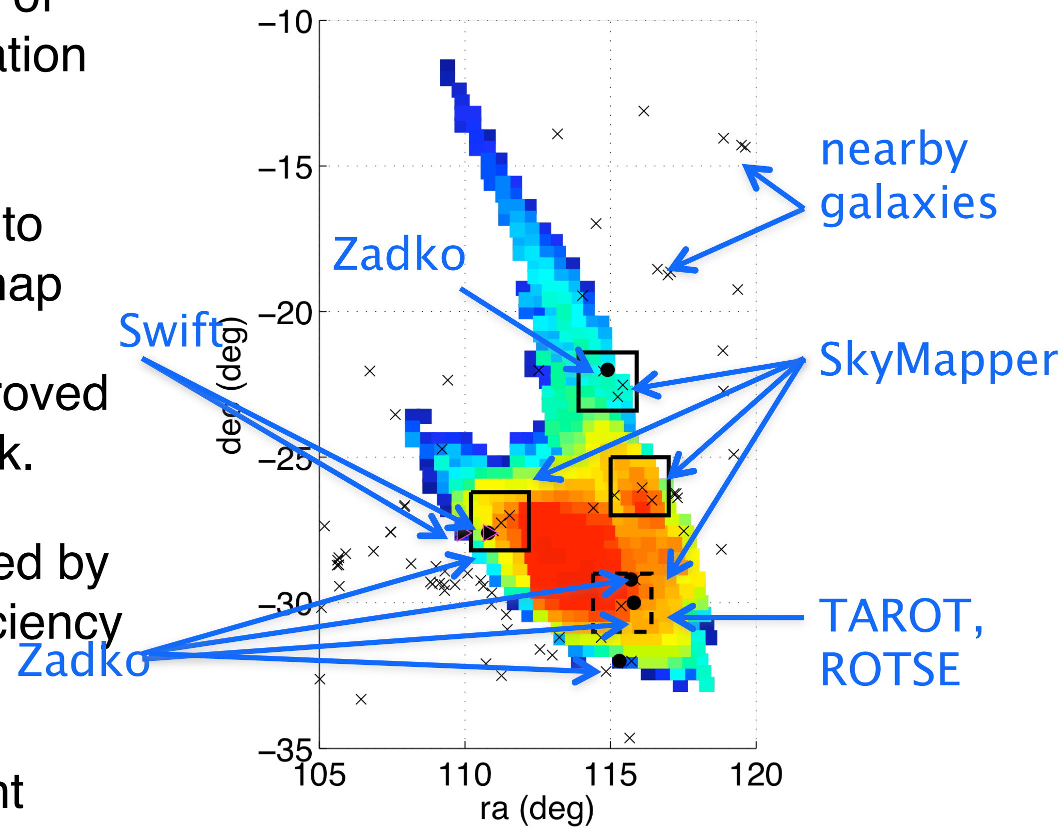
LIGO

LSC VIRGO

Sky-map contribution

arXiv:1205.1124

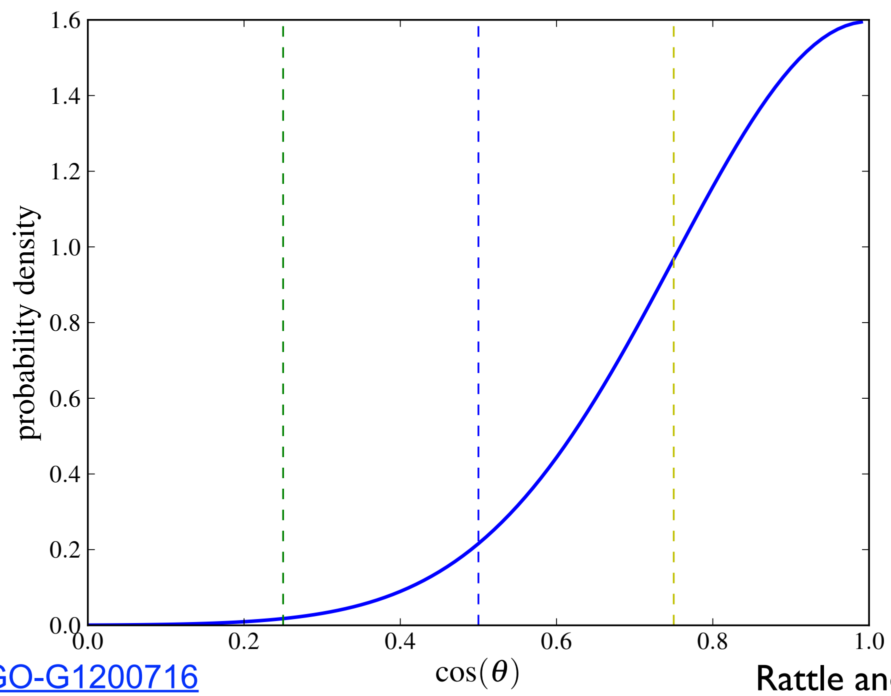
- With Swift we observed very small part of the GW sky-map and neglected correlation term.
- Telescopes with wide FOV will be able to observe significant portion of the sky-map
- In addition, sky-localization will be improved for the advanced GW detectors network.
- Optimal inclusion of information provided by sky-map may significantly improve efficiency of the joint search
- According to correlation term of the joint likelihood ratio, significance of EM counterpart is proportional to the probability density sky-map at its location.

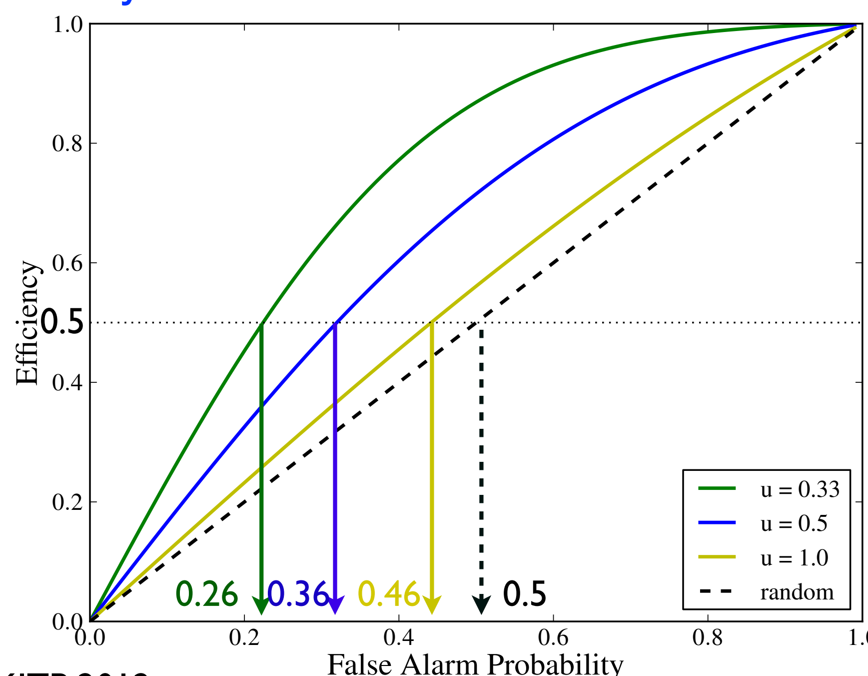


Skymap for September event, Swift maximized probability on NGC2380 and ESO492-010.

Simple model for sky-map

- Consider symmetric Gaussian sky-map for a source at the zenith.
- We compute distribution of $\Lambda_{\rm corr} = p_{\rm m}(\Omega_0)$ for correlated GW-EM events and for random coincidences, and estimate efficiency from this term only.
- We consider FOV of 1, 2 and 3 sigmas, which leads to average FAP = 0.46, 0.36, 0.26 for correlated events (compare it to FAP=0.5 for uncorrelated events)
- For 3 sigmas, on average significance increased by factor of 2 !





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Rattle and Shine, KITP, 2012

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Summary and Future Directions

- Real-life exercise proved to be successful. Simulations demonstrated importance of EM follow-up observations for future searches.

- Main factors contributing to efficiency of a joint search:

  - Maximize probability of observing EM counterpart: Wide FOV telescopes, coordination between instruments, galaxy catalogs etc.

  - Characterizing/reducing background of optical/X-ray/radio serendipitous transients is critical, (logN-logS curves in all bands, surveys for transients, transients classification?)

  - Include sky-map information into statistic if observing >1 sigma ()

- Observational strategy and data analysis techniques combining all available data need to be refined, tested and optimized in simulations of realistic instruments

- Future is exciting! Advanced LIGO and Virgo detectors 10 times more sensitive. Low latency searches will benefit from improved sky-localization (especially with LIGO India)

Joint GW-EM statistic

- **g** - GW data, **I** -data.
- 1 - signal from source of GW and EM counterpart, 0 - noise and/or serendipitous EM source.
- Optimal joint detection statistic is the likelihood ratio:

$$\Lambda_{\rm joint}(\mathbf{g},\mathbf{I}) = \Lambda_{\rm GW}(\mathbf{g})\Lambda_{\rm EM}(\mathbf{I})\Lambda_{\rm corr}(\mathbf{g},\mathbf{I})$$

- $\Lambda_{\rm GW}(\mathbf{g}) = p(\mathbf{g}\,|\,1)/p(\mathbf{g}\,|\,0)$- estimates significance of GW candidate based on GW data
- $\Lambda_{\rm EM}(\mathbf{I}) = p(\mathbf{I}\,|\,1)/p(\mathbf{I}\,|\,0)$ - estimates significance of EM candidate based on expected instrumental noise and background of serendipitous EM sources.
- $\Lambda_{\rm corr}(\mathbf{g},\mathbf{I}) = \int \mu_{\rm GW}(\Omega)p(\Omega\,|\,1)\mu_{\rm EM}(\Omega)\,{\rm d}\Omega$ - measures correlation between inferred positions of GW and EM signals.
- $\mu_{\rm GW}(\Omega)$ and $\mu_{\rm EM}(\Omega)$ are the sky-maps for GW and EM candidates.

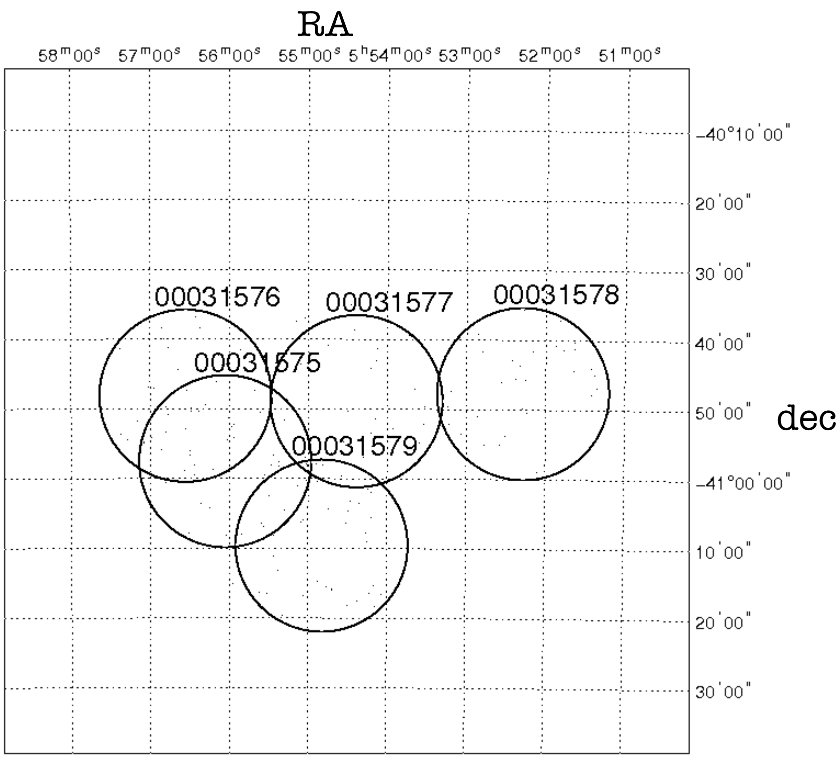
Joint GW-EM statistic for Swift analysis

- **g**: η - GW Burst statistic, $p_m(\Omega)$ - sky-map, where $\Omega \equiv$[RA, DEC].
- **I**: S - X-ray flux observed by Swift, Ω_0 - location of X-ray counterpart, sky-map $\mu_{\mathrm{EM}}(\Omega) = \delta(\Omega - \Omega_0)$.
- $\Lambda_{\mathrm{GW}}(\mathbf{g}) = p(\eta\,|\,1)/p(\eta\,|\,0)$- convert η into likelihood ratio (using η distributions for GW injections and for noise)
- $\Lambda_{\mathrm{EM}}(\mathbf{I}) = 1/p_0(S\,|\,0)$ - estimated from XMM-Newton catalog of serendipitous sources.
- $\Lambda_{\mathrm{corr}} = \mu_{\mathrm{GW}}(\Omega_0)p(\Omega_0\,|\,1) = p_{\mathrm{m}}(\Omega_0)$ - because only very small area ($1\mathrm{deg}^2$) of the GW sky-map was observed, this term was found to have small effect and dropped from the detection statistic of the search.
- Thus, joint detection for Swift:

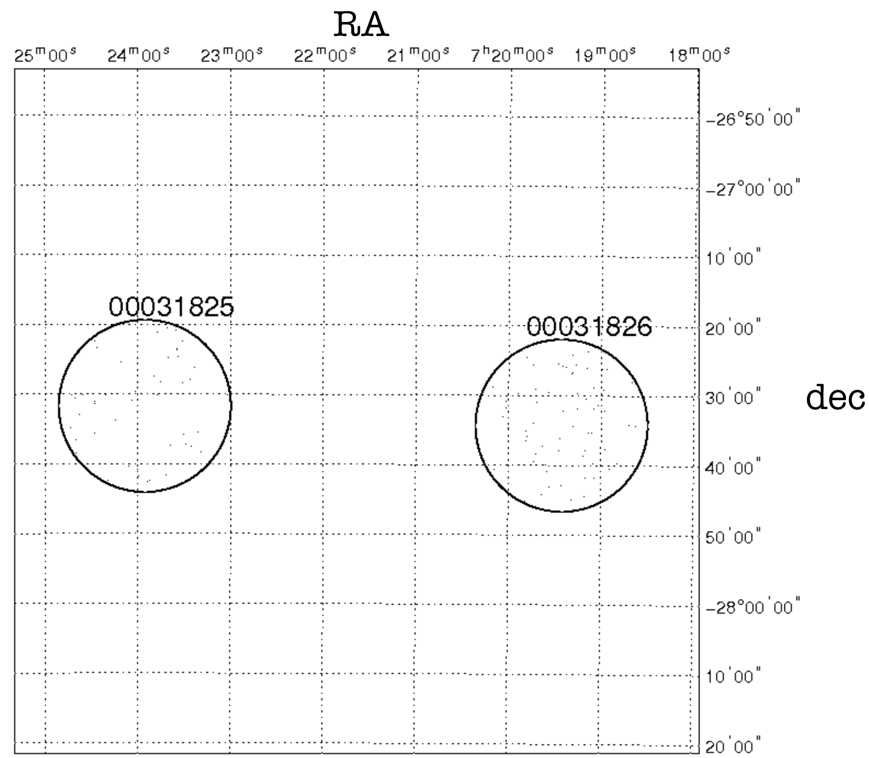
$$\Lambda_{\mathrm{Swift}}(\mathbf{g}, \mathbf{I}) = \Lambda_{\mathrm{GW}}(\eta)\Lambda_{\mathrm{EM}}(S)$$

Bonus slides: Swift observations

January trigger



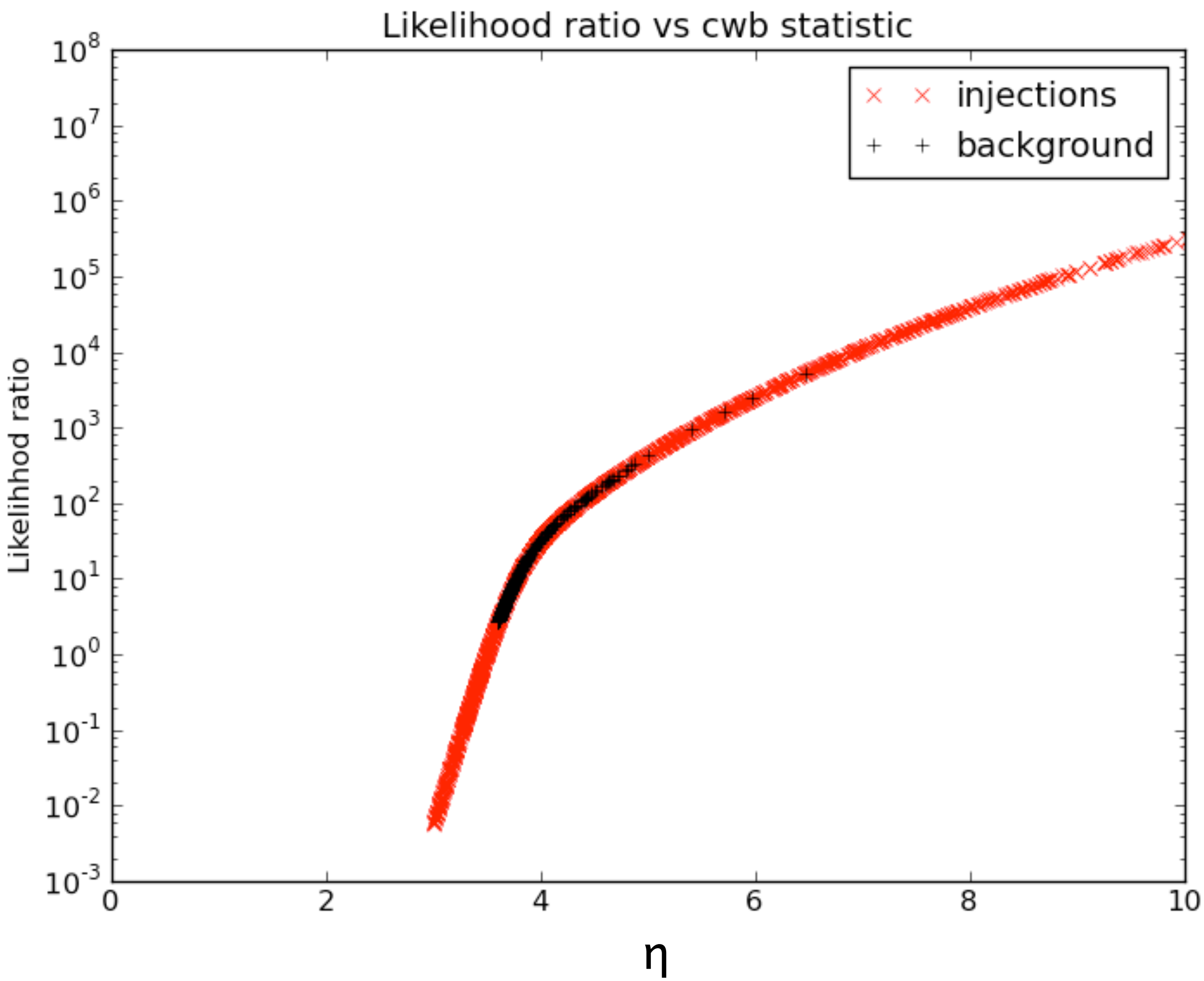
September trigger



Typical exposure 2ks. Swift found 8/12 sources for january/september candidates, all consistent with background of serendepitous X-ray sources. UVOT did not find variable EM countepart. arXiv:1205.1124

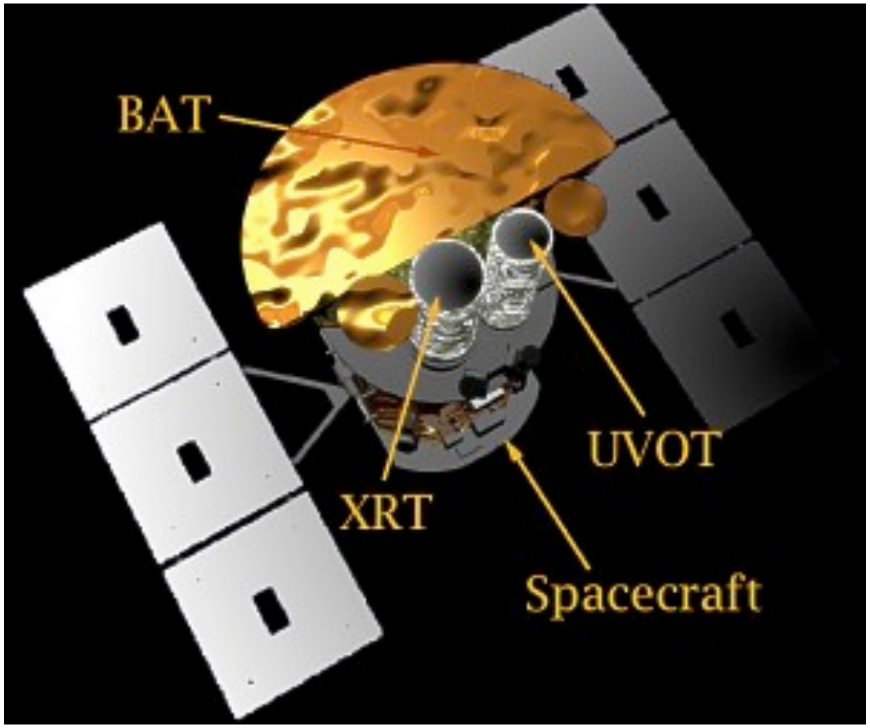
GW likelihood ratio vs CWB statistic

arXiv:1205.1124



Bonus slides: Swift observatory

- Great for follow-up: fast response, flexible operation, three telescopes.
- The Burst Alert Telescope (BAT): wide field, designed to detect GRB.
- The Ultra Violet and Optical Telescope (UVOT):0.28x0.28 deg FOV, follow-up observations in 170 - 600 nm band.
- The X-Ray Telescope (XRT): 0.4x0.4 deg FOV, follow-up observations in 0.3 - 10 keV.
- Target of opportunity (ToO) observations: response is typically < 4 hours, can be < 1 hour.
- ToO performed on 2 GW candidates with XRT and UVOT.



Bonus slides: Selection of GW transients

- Low-latency CBC and Coherent WaveBurst pipelines
- Trigger selection criteria: H1L1V1 trigger, FAR < 1 / 35 days, 20% of sky-map probability in five 0.4x04 deg^2 sky pixels.
- Posterior sky-map weights sky pixels by galaxies' blue light luminosity and inverse of distance:

$$P \propto \sum_i \frac{M_i L}{D_i}$$

- Both triggers were from Coherent WaveBurst low-latency pipeline.
- January candidate event passed lowered thresholds (for purpose of exercise), FAR < 1/day and 10% of sky-map probability in five 0.4x04 deg sky pixels.
- September candidate event (the "Big Dog") passed all nominal criteria.

Bonus slides: Model for X-ray counterpart.

arXiv:1205.1124

Type 1 GRBs: typically short/hard, progenitor is CBC.

GRB	Z of the host galaxy	Luminosty distance, Mpc	Flux (erg sm^-2 s^-1) after 10^3 s	Flux , 10^4 s	Flux, 10^5 s	Flux, 10^6
050724	0.1606	760.5	3x10^-12, (7x10^-10)	4x10^-13, (9x10^-11)	5x10^-12, (1x10^-9)	3x10^-14, (6x10^-12)
060614	0.1250	578.3	1x10^-10, (1x10^-8)	1x10^-11, (1x10^-9)	2x10^-12, (3x10^-10)	1x10^-14, (1x10^-12)
061006	0.4377	2400.5	2x10^-12, (5x10^-9)	3x10^-13, (7x10^-10)	1x10^-13, (2x10^-10)	2x10^-14, (5x10^-11)
061210	0.4095	2221.3	---	---	5x10^-14, (1x10^-10)	3x10^-14, (6x10^-11)
070809	0.2187	1073.3	3x10^-12, (1x10^-9)	1x10^-12, (5x10^-10)	2x10^-13, (9x10^-11)	---
071227	0.3940	2121.7	1x10^-12, (2x10^-9)	1x10^-13, (2x10^-10)	1x10^-14, (2x10^-11)	---
090510	0.9000	5817.2	8x10^-11, (1x10^-6)	5x10^-13, (7x10^-9)	2x10^-14, (3x10^-10)	---

Type 2 GRBs: typically long/soft, progenitor is collapsed star.

GRB	z of the host galaxy	Luminosity distance, Mpc	Flux(erg sm^-2 s^-1) after 10^3 s	Flux, 10^4 s	Flux, 10^5 s	Flux, 10^6 s
050826	0.2970	1523.1	1x10^-11, (9x10^-8)	4x10^-13, (4x10^-10)	7x10^-14, (6x10^-11)	---
060218	0.0330	143.0	2X10^-9, (2x10^-8)	1x10^-12, (8x10^-12)	1x10^-13, (8x10^-13)	7x10^-15, (6x10^-14)
080520	1.5450	11421.8	2x10^-12, (1x10^-7)	3x10^-13, (2x10^-8)	3x10^-14, (2x10^-10)	---
050525a	0.6060	3566.8	---	1x10^-11, (5x10^-8)	2x10^-13, (1x10^-9)	1x10^-14, (5x10^-11)