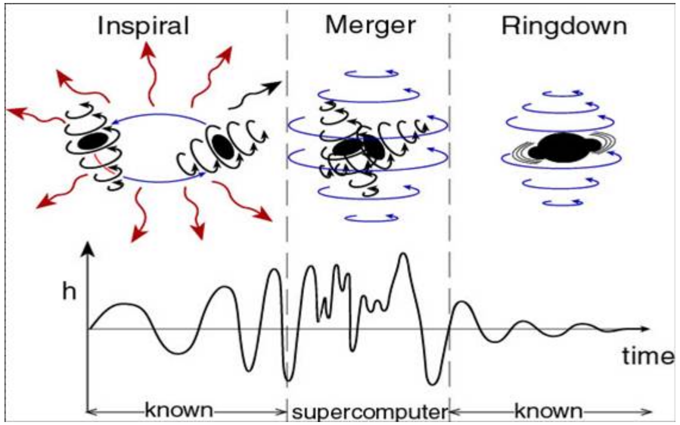
Pi of the Sky telescope contribution to the LSC-Virgo Electromagnetic Follow-up project

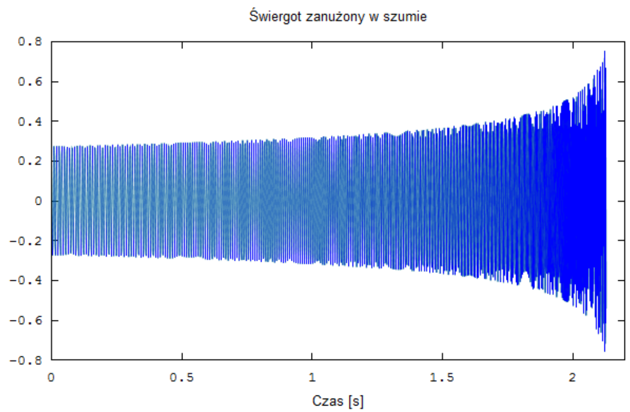
Adam Zadrożny

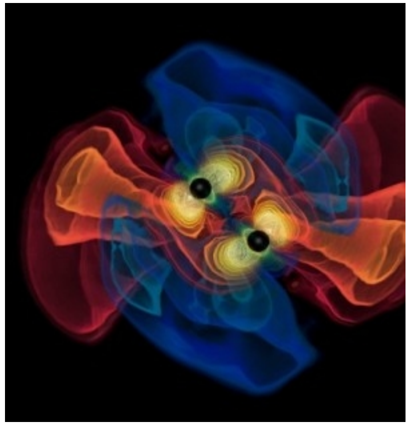
Spała 2014

Possible sources of joint EM-GW signal

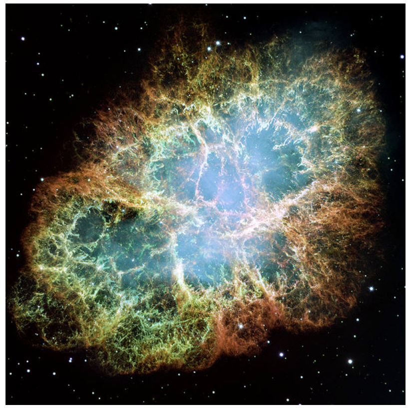
- NS-NS and NS-BH binaries, Kilonovae (Inspiral)







- Supernovae, Stellar Core-Collapse



- ???

Information carried by EM and GW observations

- EM observations gives an information about outcome of the event
  - distance (through redshift)
  - exact position
  - raises confidence about GW candidate

- GW signal
  - an information about motion of mass inside process

EM FOLLOW-UP PROJECT 2009-2010

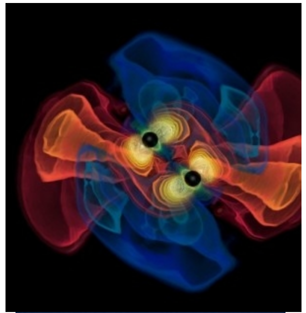
The Astrophysical Journal Supplement Series, 211:7 (25pp), 2014 March doi:10.1088/0067-0049/211/1/7

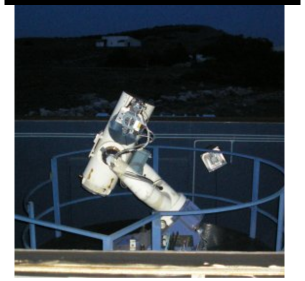
FIRST SEARCHES FOR OPTICAL COUNTERPARTS TO GRAVITATIONAL-WAVE CANDIDATE EVENTS

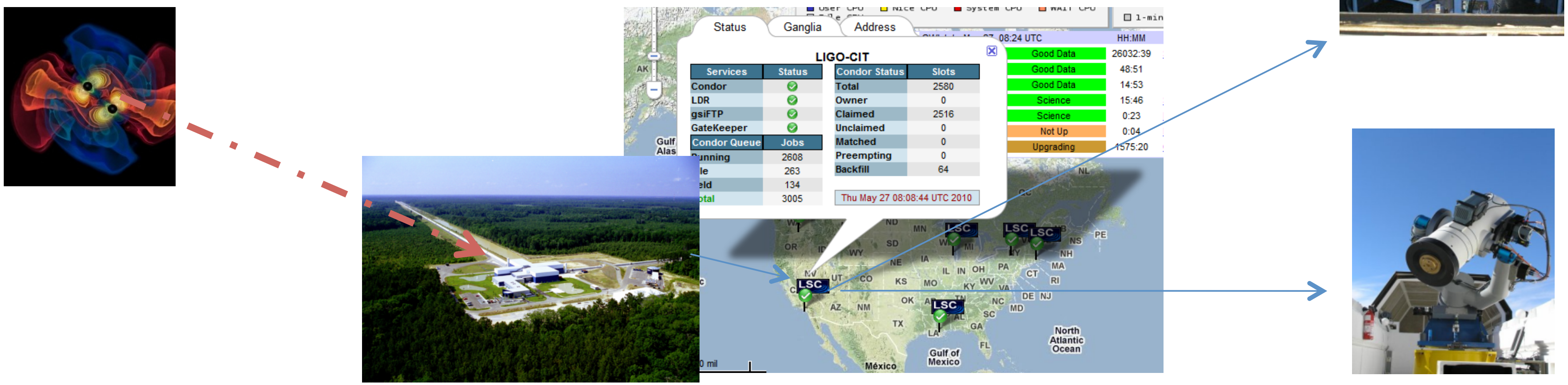
J. Aasi[1], J. Abadie[1], B. P. Abbott[1], R. Abbott[1], T. Abbott[2], M. R. Abernathy[1], T. Accadia[3], F. Acernese[4,5], C. Adams[6], T. Adams[7], R. X. Adhikari[1], C. Affeldt[8], M. Agathos[9], N. Aggarwal[10], O. D. Aguiar[11], P. Ajith[1], B. Allen[8,12,13], A. Allocca[14,15], E. Amador Ceron[12], D. Amariutei[16], R. A. Anderson[1], S. B. Anderson[1], W. G. Anderson[12], K. Arai[1], M. C. Araya[1], C. Arceneaux[17], J. Areeda[18], S. Ast[13], S. M. Aston[6], P. Astone[19], P. Aufmuth[13], C. Aulbert[8], L. Austin[1], B. E. Aylott[20], S. Babak[21], P. T. Baker[22], G. Ballardin[23], S. W. Ballmer[24], J. C. Barayoga[1], D. Barker[25], S. H. Barnum[10], F. Barone[4,5], B. Barr[26], L. Barsotti[10], M. Barsuglia[27], M. A. Barton[25], I. Bartos[28], R. Bassiri[26,29], A. Basti[14,30], J. Batch[25], J. Bauchrowitz[8], Th. S. Bauer[9], M. Bebronne[3], B. Behnke[21], M. Bejger[31], M. G. Beker[9], A. S. Bell[26], C. Bell[26], I. Belopolski[28], G. Bergmann[8], J. M. Berliner[25], A. Bertolini[9], D. Bessis[32], J. Betzwieser[6], P. T. Beyersdorf[33], T. Bhadbhade[29], I. A. Bilenko[34], G. Billingsley[1], J. Birch[6], M. Bitossi[14], M. A. Bizouard[35], E. Black[1], J. K. Blackburn[1], L. Blackburn[36], D. Blair[37], M. Blom[9], O. Bock[8], T. P. Bodiya[10], M. Boer[38,39], C. Bogan[8], C. Bond[20], F. Bondu[40], L. Bonelli[14,30], R. Bonnand[41], R. Bork[1], M. Born[8], S. Bose[42], L. Bosi[43], J. Bowers[2], C. Bradaschia[14], P. R. Brady[12], V. B. Braginsky[34], M. Branchesi[44,45], C. A. Brannen[42], J. E. Brau[46], J. Breyer[8], T. Briant[47], D. O. Bridges[6], A. Brillet[38], M. Brinkmann[8], V. Brisson[35], M. Britzger[8], A. F. Brooks[1], D. A. Brown[24], D. D. Brown[20], F. Brückner[20], T. Bulik[48], H. J. Bulten[9,49], A. Buonanno[50], D. Buskulic[3], C. Buy[27], R. L. Byer[29], L. Cadonati[51], G. Cagnoli[41], J. Calderón Bustillo[52], E. Calloni[4,53], J. B. Camp[36], P. Campsie[26], K. C. Cannon[54], B. Canuel[23], J. Cao[55], C. D. Capano[50], F. Carbognani[23], L. Carbone[20], S. Caride[56], A. Castiglia[57], S. Caudill[12], M. Cavaglià[17], F. Cavalier[35], R. Cavalieri[23], G. Cella[14], C. Cepeda[1], E. Cesarini[58], R. Chakraborty[1], T. Chalermsongsak[1], S. Chao[59], P. Charlton[60], E. Chassande-Mottin[27], X. Chen[37], Y. Chen[61], A. Chincarini[62], A. Chiummo[23], H. S. Cho[63], J. Chow[64], N. Christensen[65], Q. Chu[37], S. S. Y. Chua[64], S. Chung[37], G. Ciani[16], F. Clara[25], D. E. Clark[29], J. A. Clark[51], F. Cleva[38], E. Coccia[58,66],

EM Follow-up Project

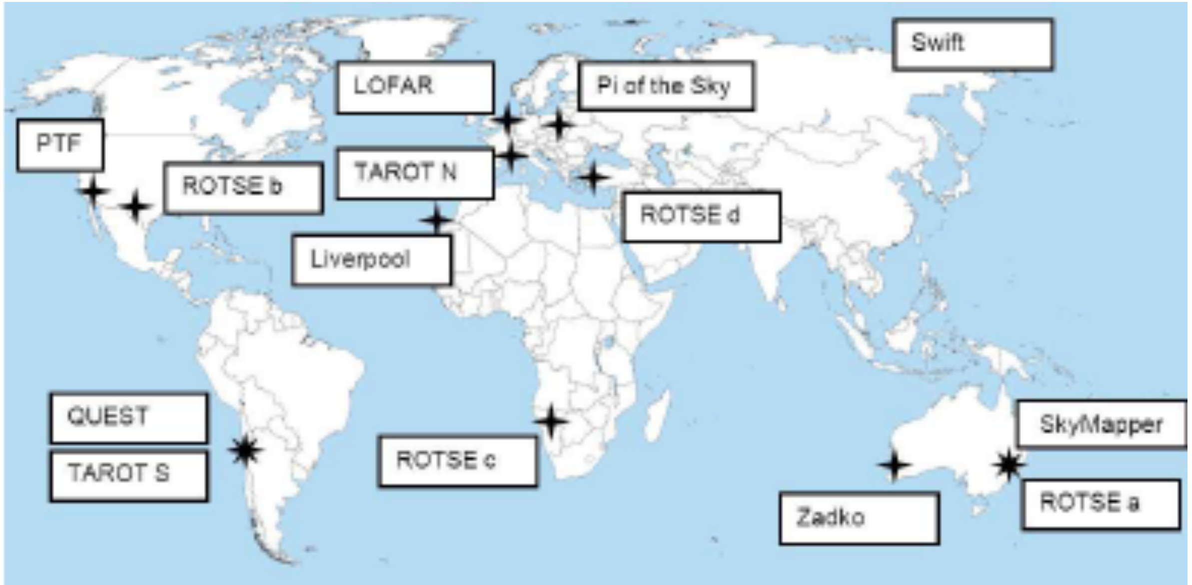
- Search for an optical counterpart to a gravitational waves event
  - to confirm an event
  - to gather more information
- Two past science runs in 2009-2010

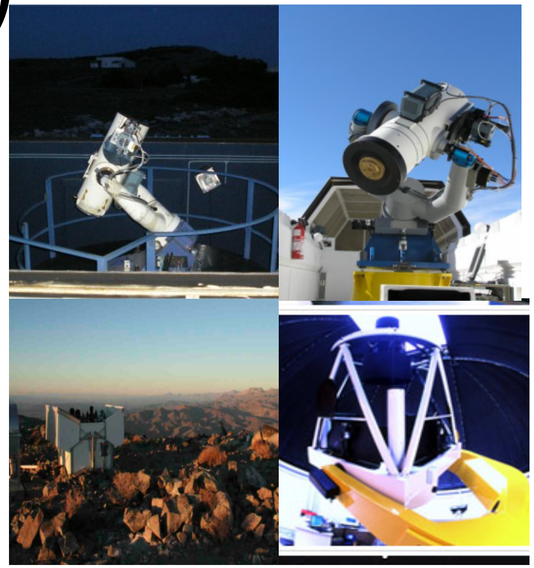






Telescopes Involved in EM Follow-up Project (2009-2010)





Name	Band	FOV (square degrees)	Aperture (m)	Exposure Time (s)	Limiting Magnitude
Palomar Transient Factory	Optical	7.3	1.2	60	20.5
Pi of the Sky	Optical	400	0.072	10	11.5
QUEST	Optical	9.4	1	60	20
ROTSE III	Optical	3.4	0.45	20	17.5
SkyMapper	Optical	5.7	1.35	110	21
TAROT	Optical	3.4	0.25	180	17.5
Zadko Telescope	Optical	0.15	1	180	20
Liverpool Telescope	Optical	0.0058	2	3600	21
LOFAR	Radio	~25	N/A	14400	N/A
Swift	X-ray	0.15	N/A	200-5000	N/A
Swift	UV, Optical	0.078	0.3	200-5000	24

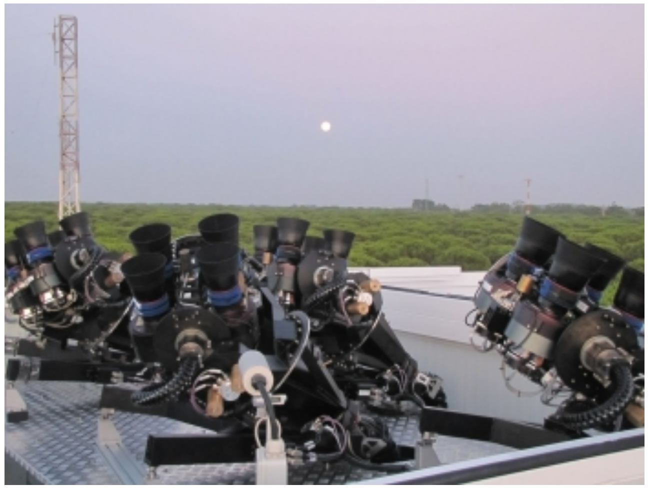
Pi of the Sky - Scopes

INTA (Spain)

- 4 mounts with 4 cameras that might work in coincidence or not
- Each camera
  - FOV: 20 [deg] x 20 [deg]
  - Limiting brightness: 12 mag
  - Exposition time: 10 s

San Pedro de Atacama (Chile)

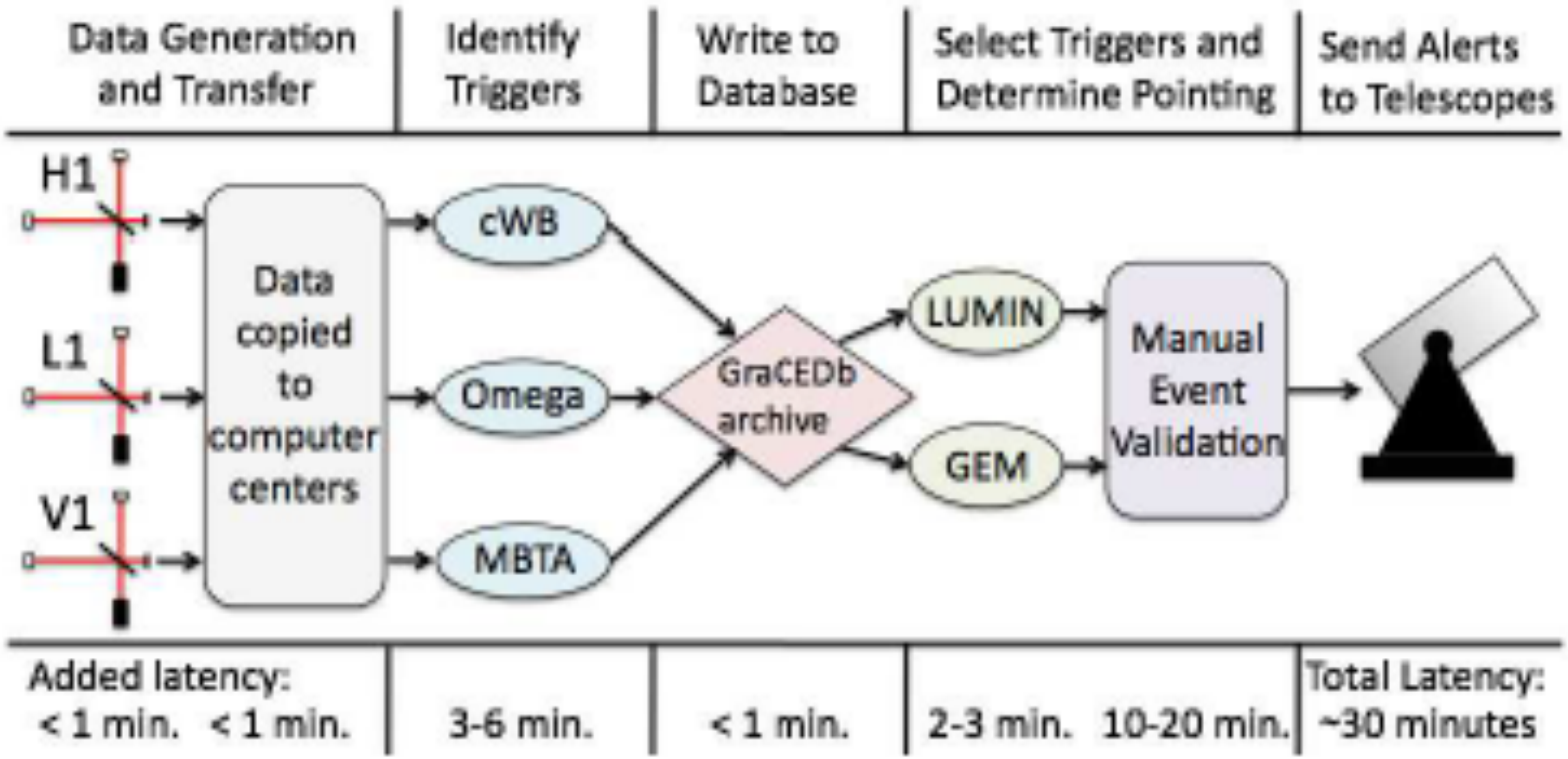
- 2 cameras working in coincidence
- Each camera
  - FOV: 20 [deg] x 20 [deg]
  - Limiting brightness: 12 mag
  - Exposition time: 10 s



Overview of Pi of the Sky system used for EM Follow-up Project 2009-2010

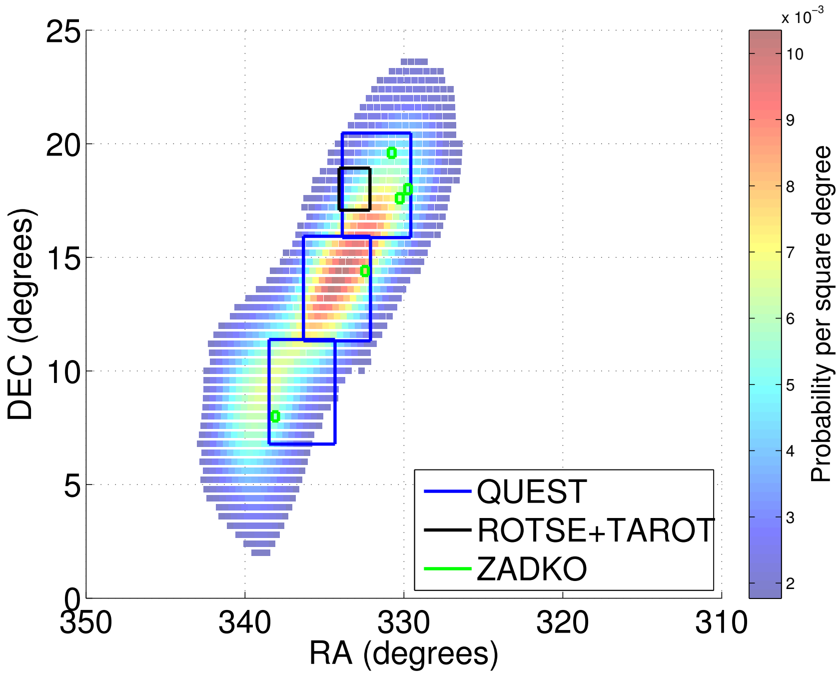
- Camera:
  - FOV: 20 deg x 20 deg
  - Exposure time: 10 s
  - Limiting magnitude : 12 mag
  - CCD: 2 K x 2 K
- Observation site:
  - Koczargi Stare near Warsaw, Poland

A Simplified Flowachart of the Online Analysis [1.]

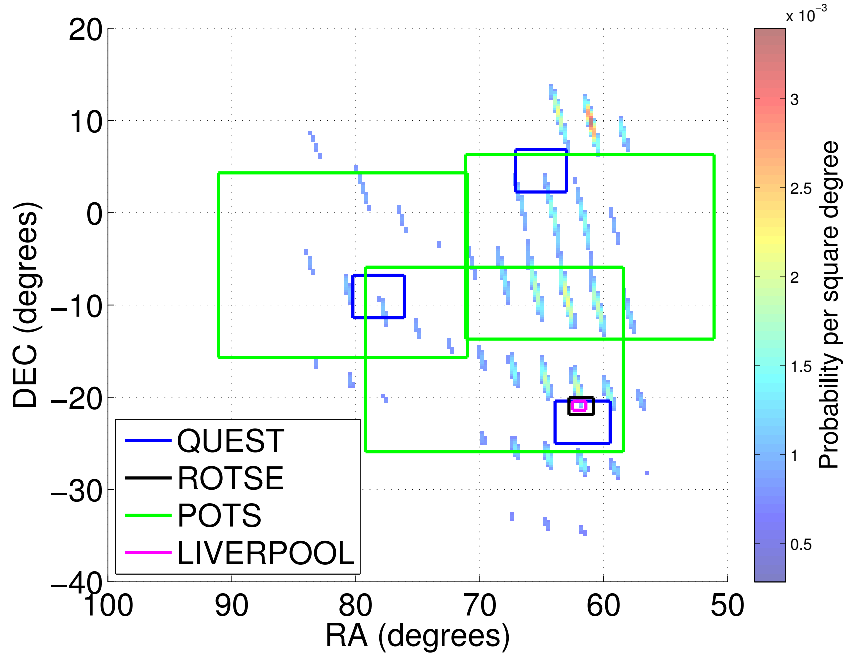


Examples of localization of inspiral and burst signals

Inspiral Signals – G20190

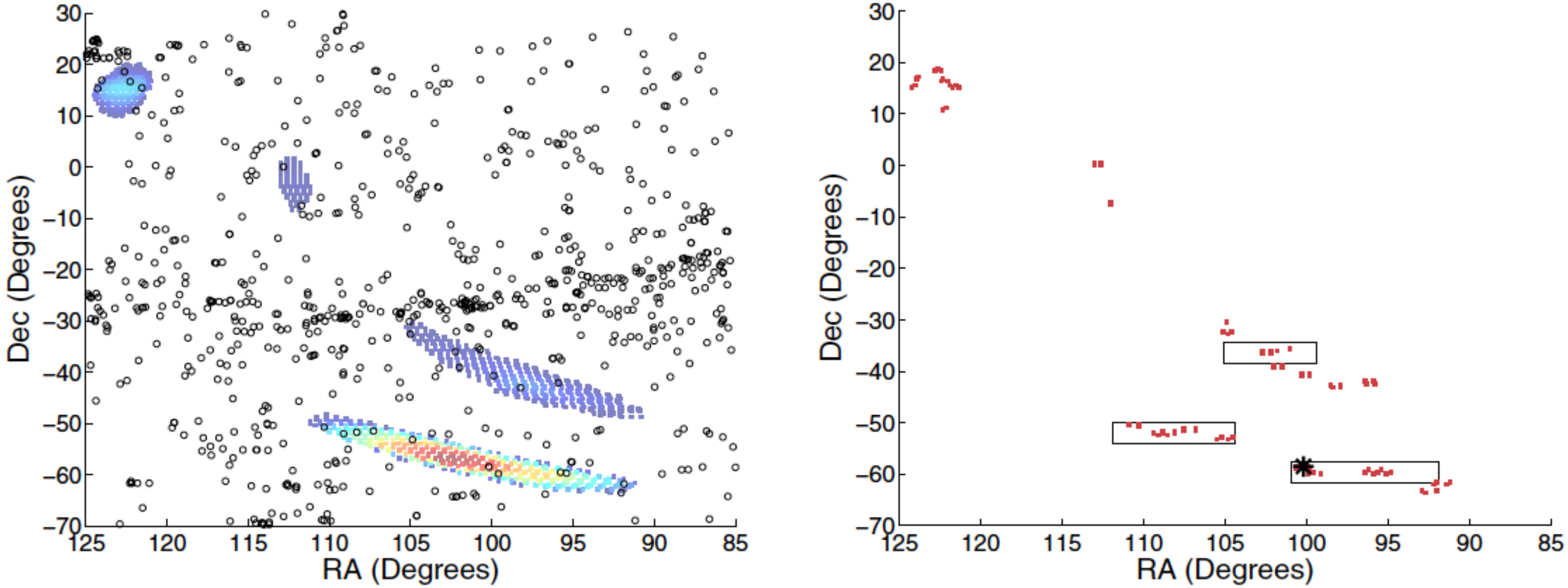


Burst Signals – G23004



Sky localization

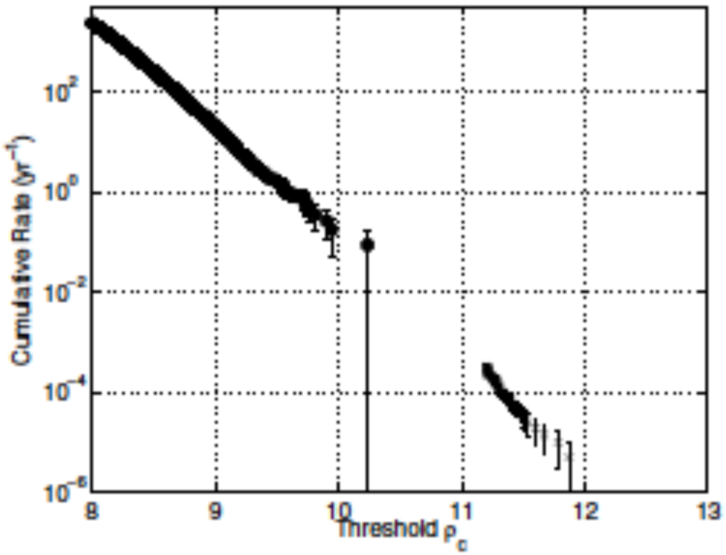
- the search area could be reduced by assuming that GW transient are most likely originate form nearby galaxy or globular cluster



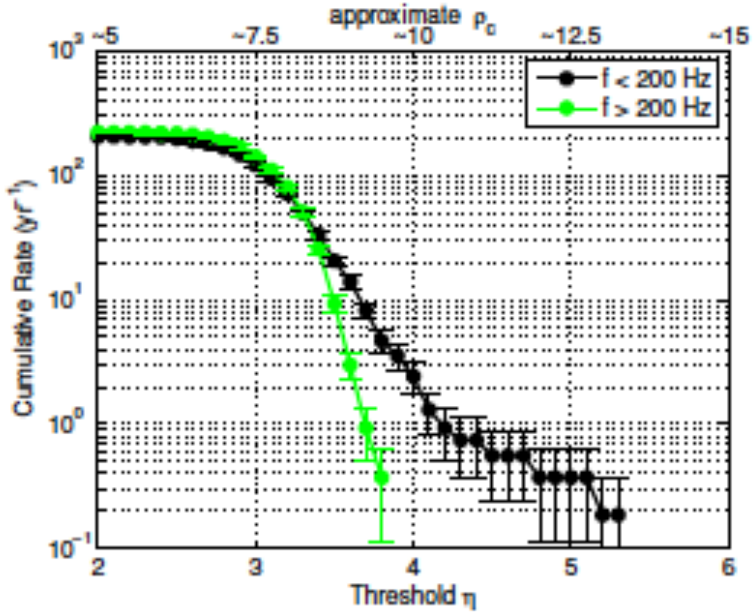
False Alarm Rate

- additional conformation might be need for low frequency burst signals
(plots based on LSC-Virgo data 2009-2010)

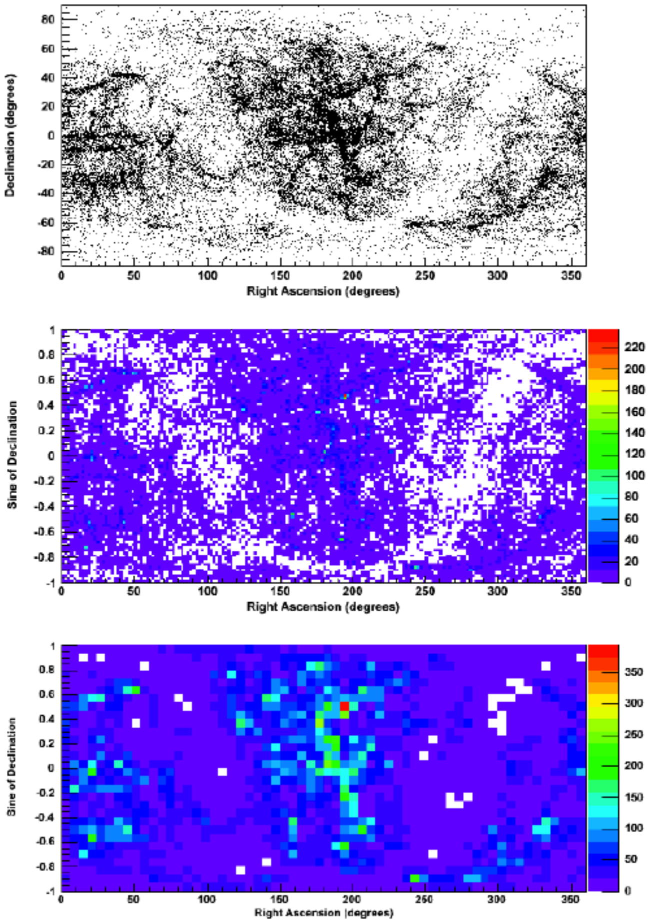
Inspiral signals

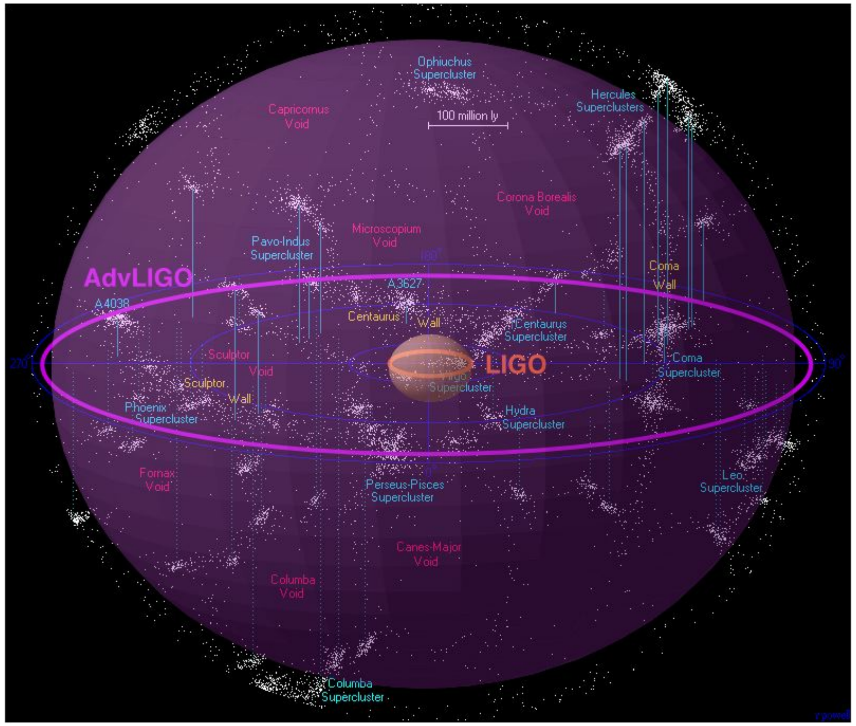


Burst signals



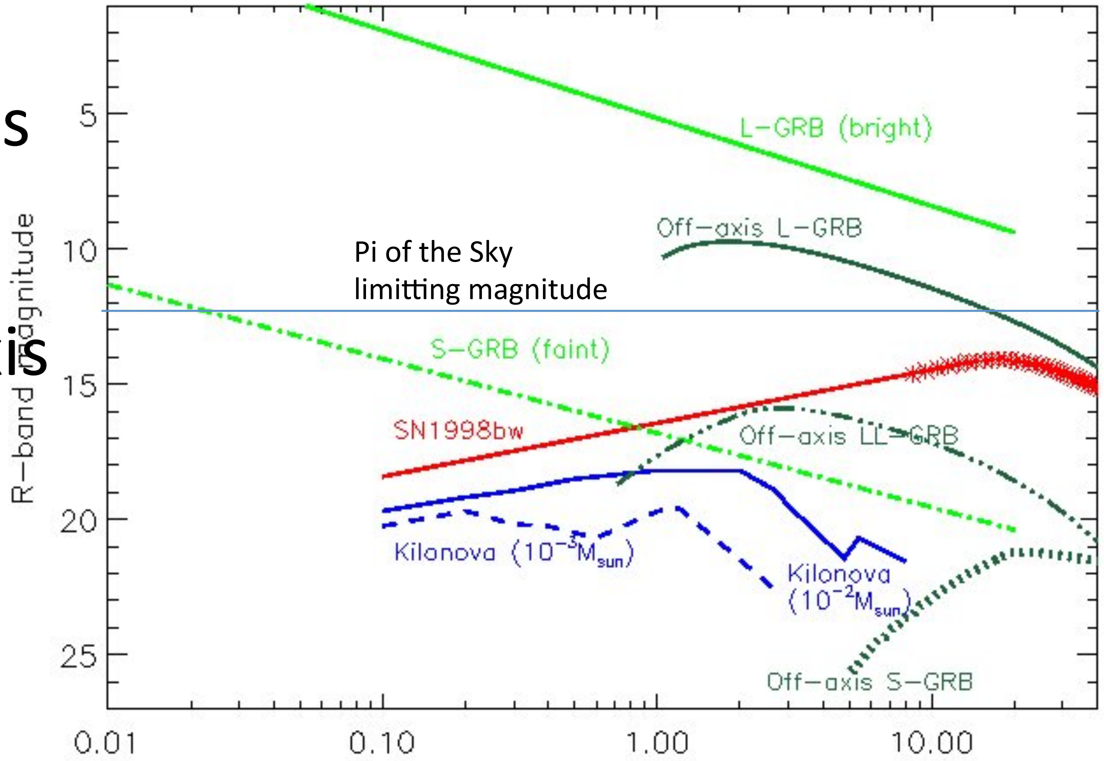
Gravitational Wave Galaxy Catalogue





Models of possible sources

- Long GRB
  - Long GRB off-axis
- Short GRB
  - Short GRB off-axis
- Supernovae
- Kilonovae
- *Other …*



Science Runs

- Winter Science Run (Dec 09 – Jan 10)

GRAVITATIONAL WAVE TRIGGERS IN THE WINTER RUN

ID	Date	UTC	Pipeline	FAR (day^{-1})	Follow-up
G3821	Dec 29, 2009	15:16:33	Ω	0.66	QUEST collected 12 images
CWB1	Jan 03, 2010	20:37:22	cWB	1.3	Alert sent Jan 7; TAROT collected 6 images
G4202	Jan 06, 2010	06:49:45	Ω	4.5	QUEST collected 9 images
CWB2	Jan 07, 2010	08:46:37	cWB	1.6	QUEST collected 12 images

- Autumn Science Run (Sep 10 – Oct 10)

GRAVITATIONAL WAVE TRIGGERS IN THE AUTUMN RUN

ID	Date	UTC	Pipeline	FAR (day^{-1})	Follow-up
G19377	Sep 16, 2010	06:42:23	cWB (unmodeled)	< 0.01	ROTSE collected 117 images, TAROT collected 20, Zadko 129, and SkyMapper 21. Blind injection
G20190	Sep 19, 2010	12:02:25	MBTA	0.16	ROTSE collected 257 images, QUEST 23, Zadko 159, and TAROT 3
G21852	Sep 26, 2010	20:24:32	cWB (linear)	0.02	ROTSE collected 130 images, PTF 149, CAT 3 DQ
G23004	Oct 3, 2010	16:48:23	Ω	0.21	ROTSE collected 153 images, QUEST 40, Liverpool - RATCam 22, Liverpool - SkyCamZ 121, and POTS 444

Results

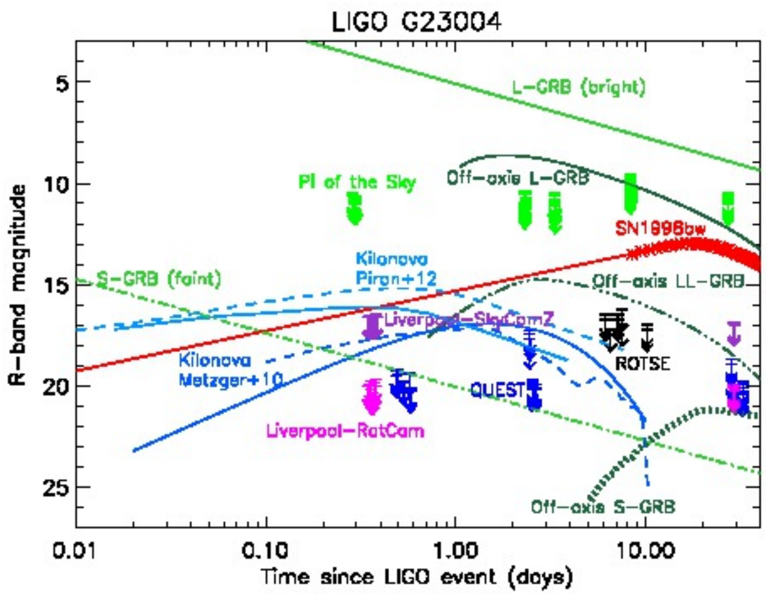
- Winter Science Run
  - Observation were conducted only during single night, so the only results were the number of unknown objects
  - It helped to prepare for autumn science run
- Autumn Science Run
  - Three real candidates had EM follow-up
  - Although for each trigger there were candidates for EM transient all of them were rejected after careful analysis

Transient Search for EM Follow-up

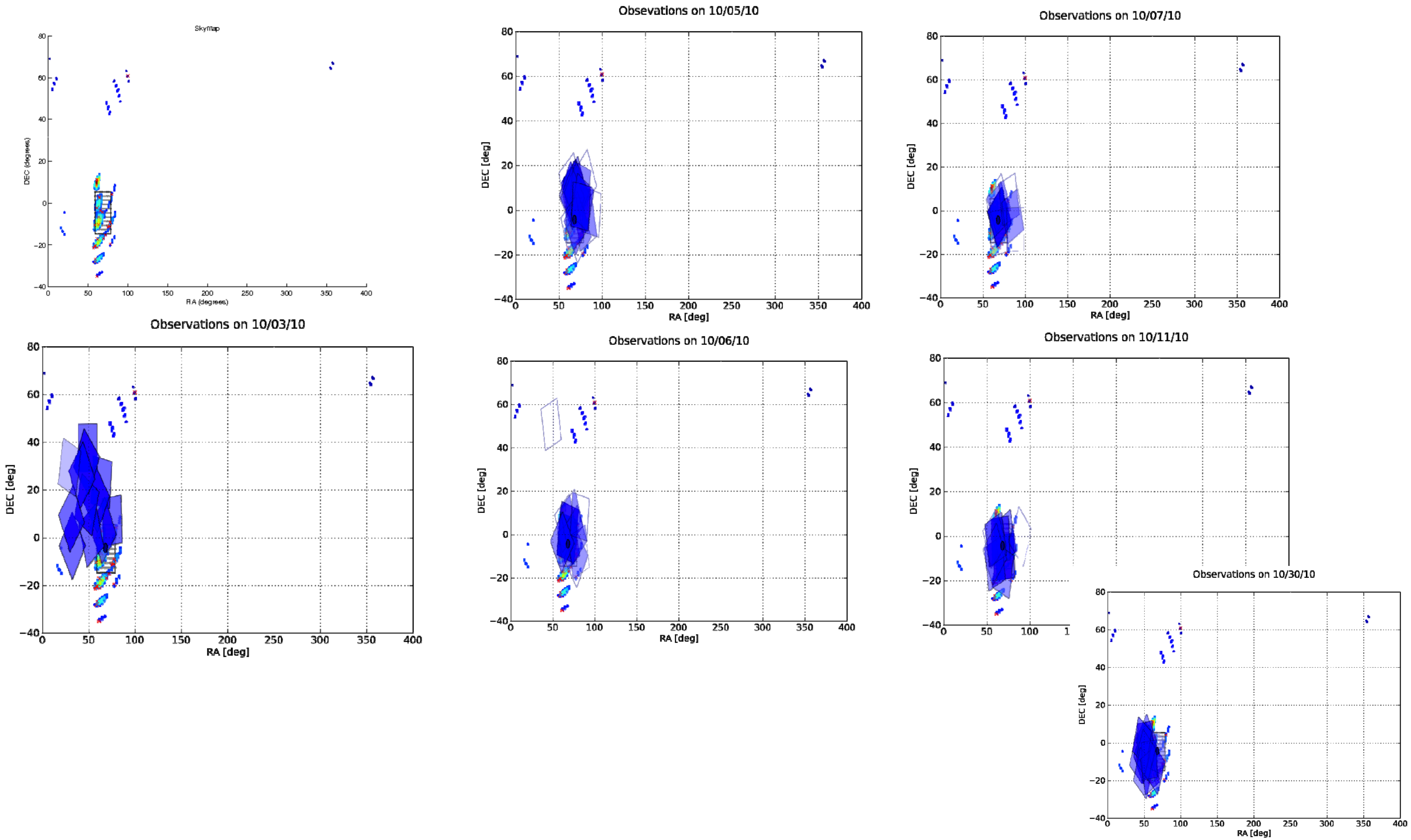
- Transient search using PotS off-line algorithm:
  - Looking for new objects that fulfill quality constrains
  - Looking for objects that suddenly increase their brightness more than 2 mag
  - All transients are undergoing human inspection
- Objects that are suspected to be transients were cross-correlated with INTA images taken few months later

G23004 - Results

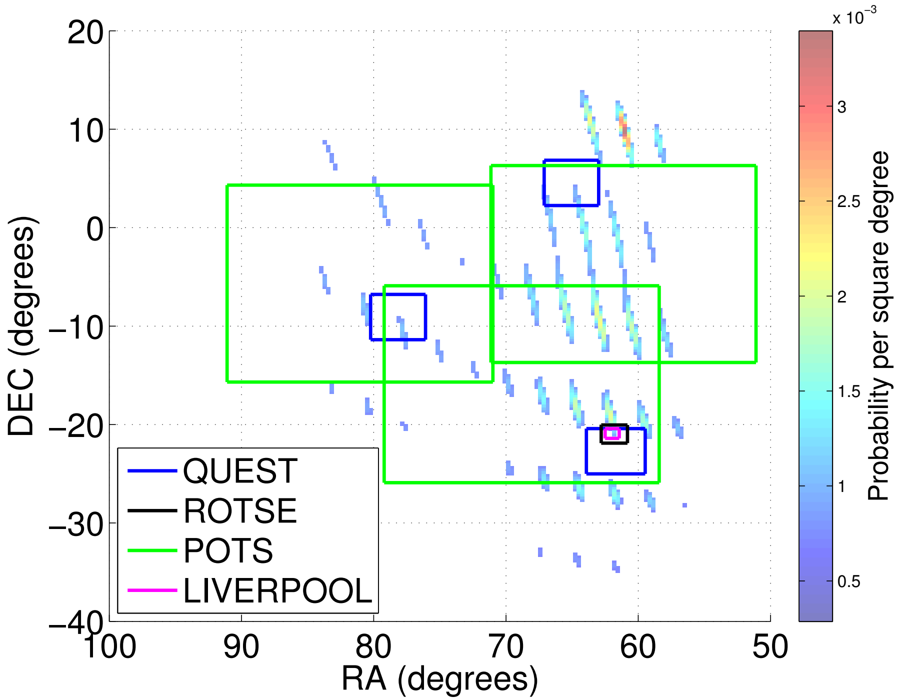
- Pi of the Sky
  - Found around 700 objects at the first night that might be transient candidates but all of them were discarded
  - About 40 objects visible on multiple nights were classified as transient candidates, but none of them survived human inspection
  - About 40 % of alert area was covered in 10 minutes

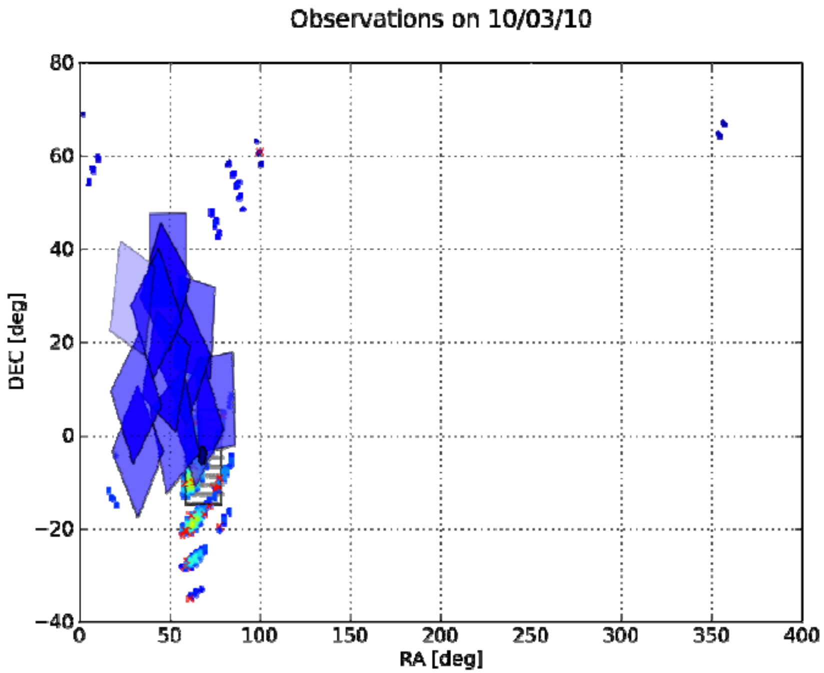


G23004 – observations Pi of the Sky

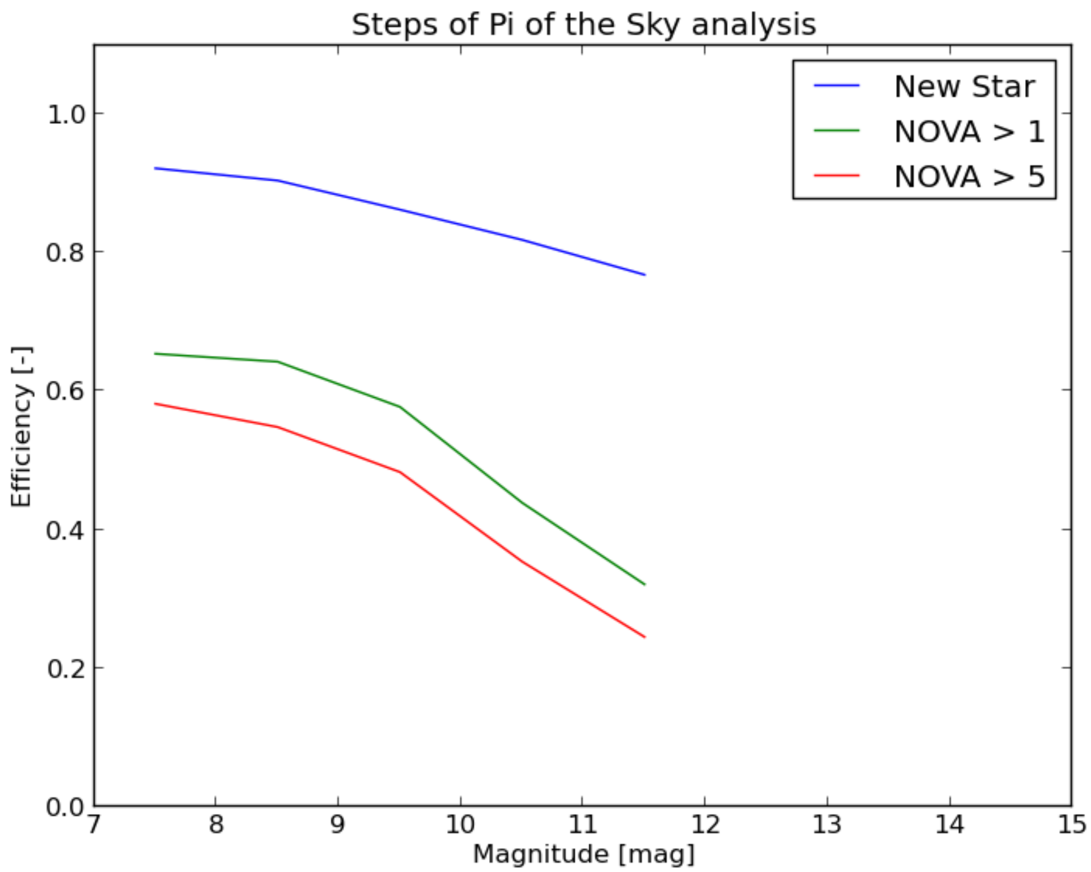


Pi of the Sky comparison to other telescopes





Pipeline Efficiency



Lesson Learned

- With Pi of the Sky system it is possible to image huge part (1200 deg^2) of the sky within less than an 15 minutes taking multiple images of each field

- On-line transient recognition might be helpful in next run for effective transients observation and recognition
  - And possibly to provide transient for other scopes

Improving efficiency for possible events

- Lowering constrains for events that are in most probable regions of a sky maps of gravitational event candidate

- Inspecting all objects that are near to galaxies that might be a source of gravitational waves (closer than 100 MPc)

EM FOLLOW-UP PROJECT IN ADVANCED DETECTOR ERA

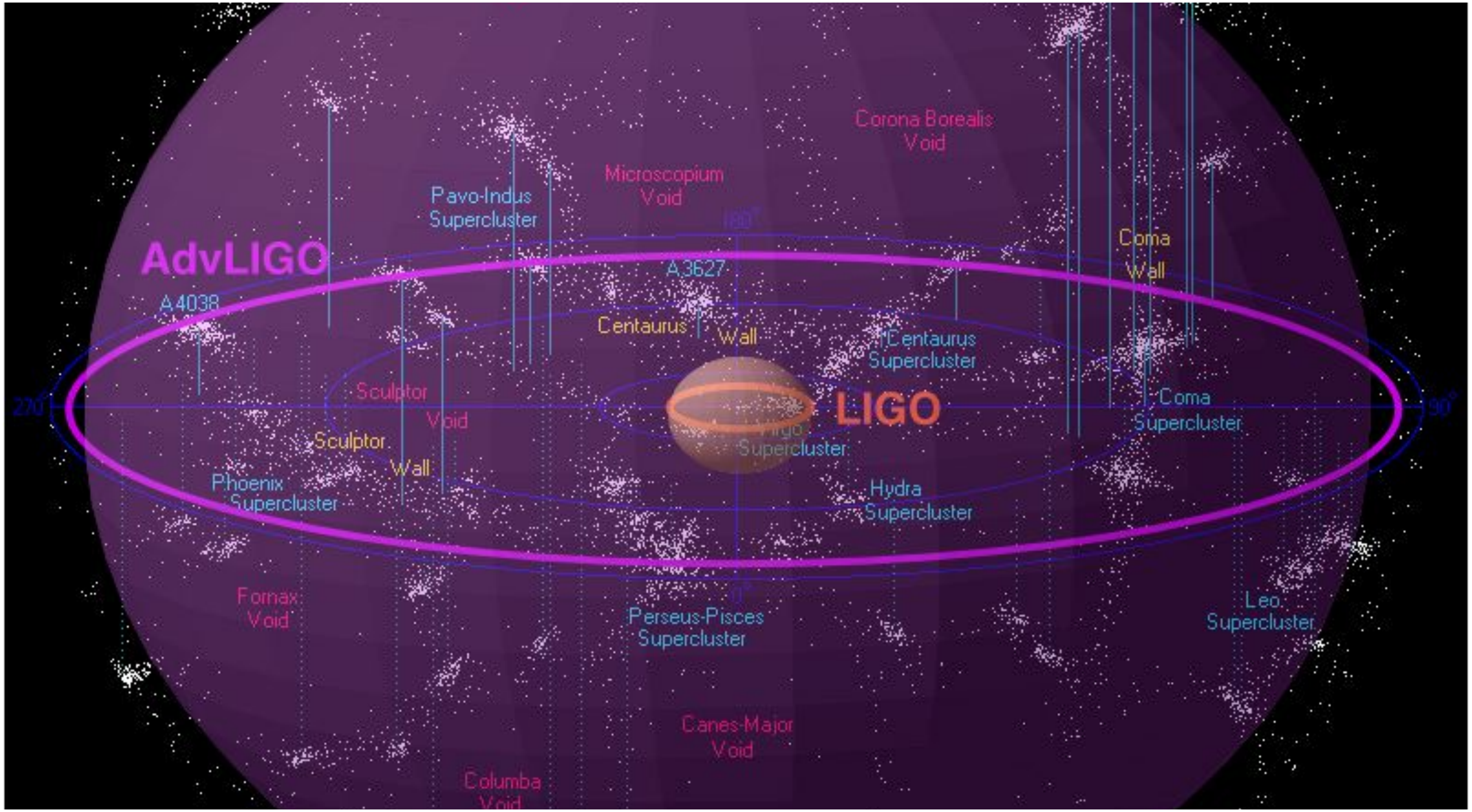
Advanced Detector Era

- Currently Virgo and LIGO detectors are being upgraded and they should become operational in 2015 (2016)

- For the upcoming years, till the end of decade, detector's sensitivity curve are planned to be improved

- Continuous observation of sky in gravitational wave band are planned to start from 2019+

Range of LIGO and Advanced LIGO interferometer

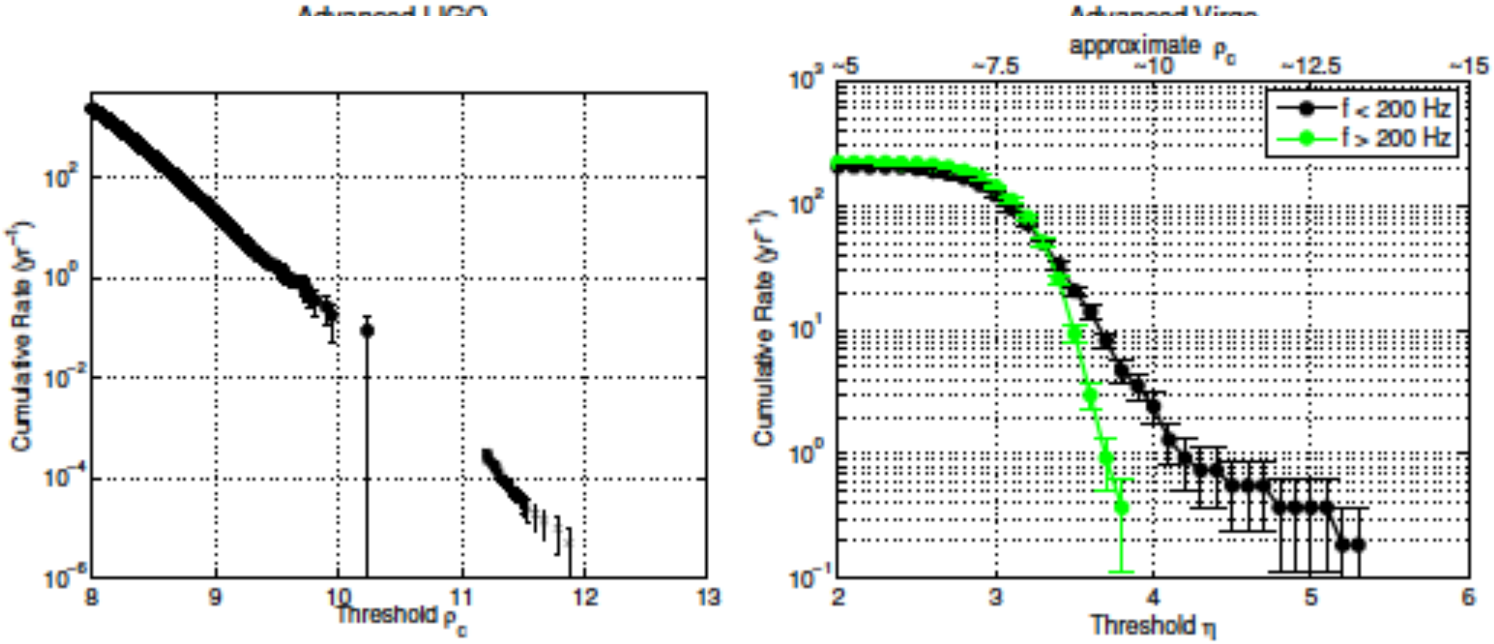


Outline of planned science runs

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

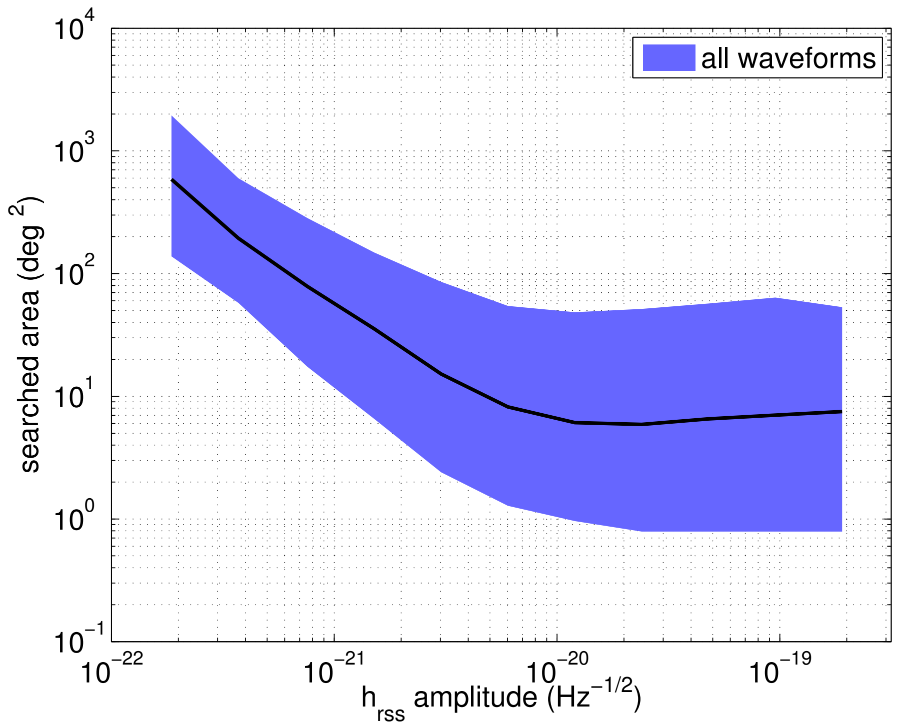
Advanced Detector Era

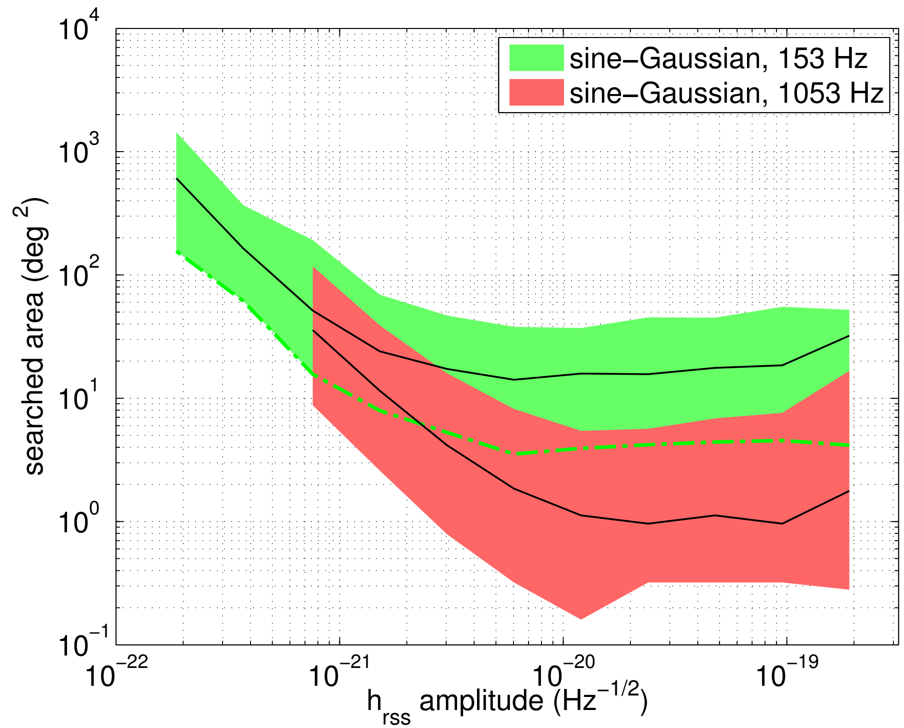
- planned sensitivity improvement over years



Search Area

-


all waveforms
searched area (deg 2)
h rss amplitude (Hz −1/2)


sine−Gaussian, 153 Hz
sine−Gaussian, 1053 Hz
searched area (deg 2)
h rss amplitude (Hz −1/2)

EM Follow-up

- EM Follow-up of GW triggers would be carried out by LSC-Virgo and astronomical partners
- MOUs are already been signed and about 60 teams were interested. Next call for MOU is planned in 2015. (Pi of the Sky signed MOU in 2014)
- After four successful detections of gravitational waves, all triggers are going to be publicly available

PI OF THE SKY PREPARATION FOR ADVANCED DETECTOR ERA

New Photometry and Astrometry

- Pi of the Sky have recently developed next version of its photometry and astrometry algorithms
- New astrometry allows to localize optical transient with accuracy of ~6 arcsec compering to previously ~36 arcsec
- Photometry have better accuracy for faint stars so it allowseasier outburst detection

Pi of the Sky in Advance Detector Era

- Two sites
  - San Pedro de Atacama, Chile
  - Inta, Spain
- Luiza framework new data processing pipeline including more accurate
  - Photometry
  - Astrometry

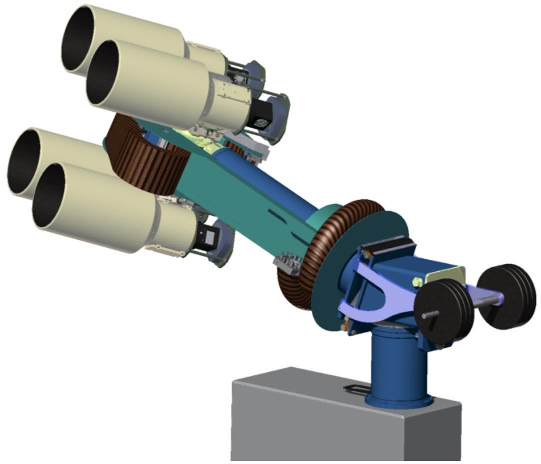
Pi of the Sky in Advance Detector Era

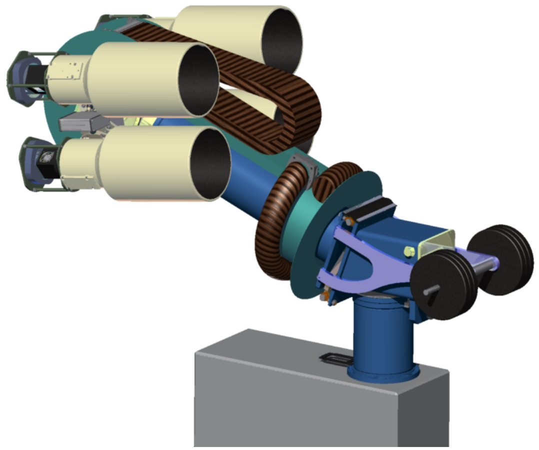
- planned improvements

- Providing fast cross-correlation of observed flashes with GWGC
  - to shifter and providing other telescopes information about possible correlation
- Enhancing off-line and on-line algorithm
  - to be less restrictive for suspected flashes connected to GWGC objects
- Observation of objects from GWGC to estimate their brightness or limiting magnitude visible for the scopes
  - To make them more sensitive for brightness changes

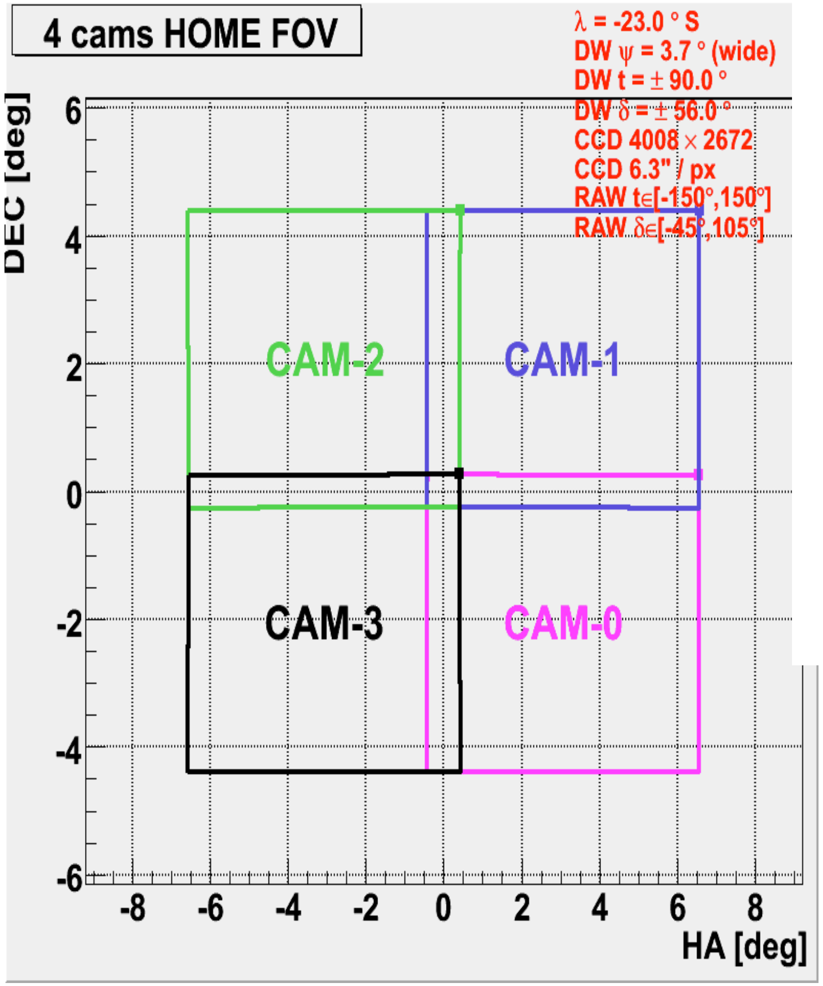
Pi of the Sky+

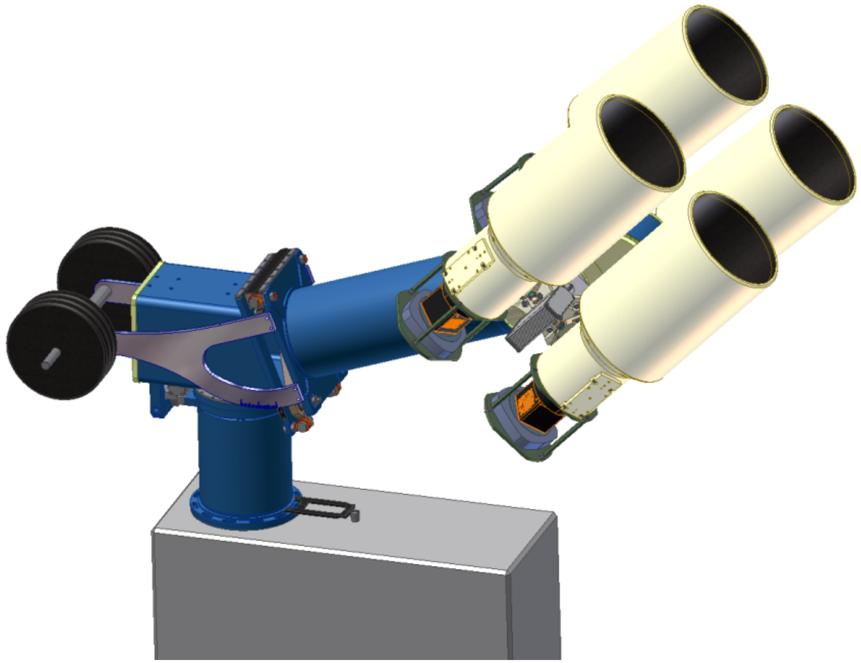
- Main advantages:
  - Very short reaction time
  - Fast positioning
- Currently under construction
  - Expected installation: 2015/2016
- 4 CCD cameras – 3 frames/sec (limiting magnitude: 12 mag)
- FOV
  - (Deep mode) 7 deg x 5 deg
  - (Wide mode) 13 deg x 9 deg
- Pointing speed 30 deg/s
- Planned location: South America



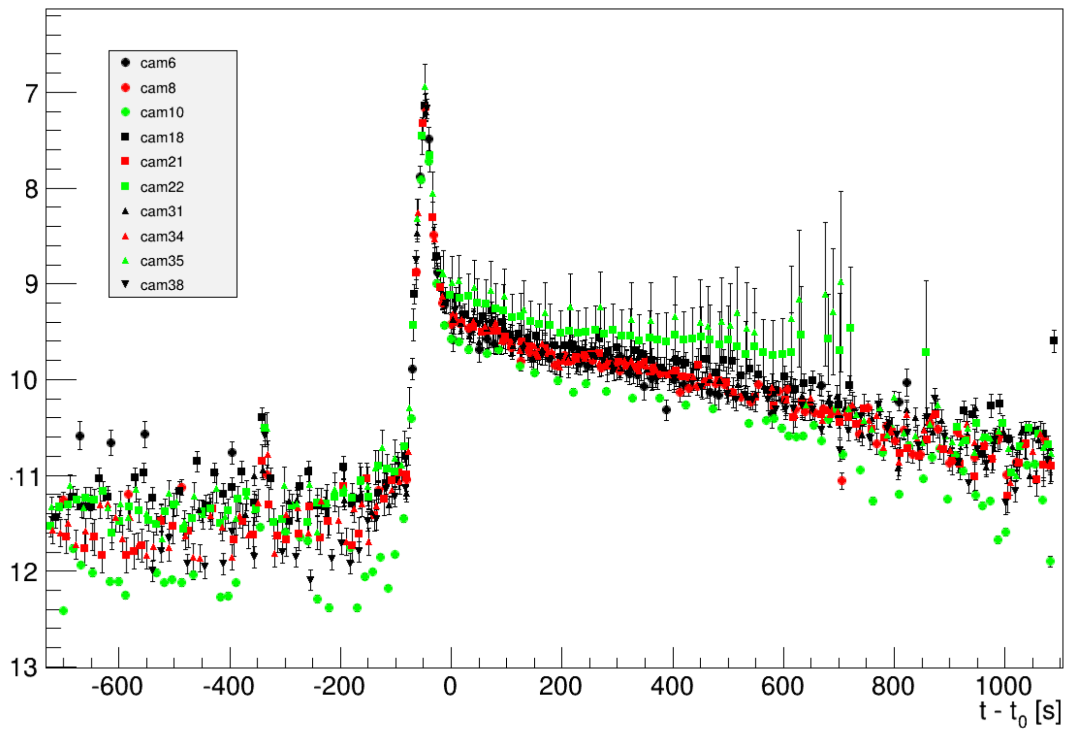


Pi of the Sky+


4 cams HOME FOV
λ = -23.0 ° S
DW ψ = 3.7 ° (wide)
DW t = ± 90.0 °
DW δ = ± 56.0 °
CCD 4008 × 2672
CCD 6.3" / px
RAW t∈[-150°,150°]
RAW δ∈[-45°,105°]
CAM-2
CAM-1
CAM-3
CAM-0
DEC [deg]
6
4
2
0
-2
-4
-6
-8
-6
-4
-2
0
2
4
6
8
HA [deg]



Observing an object using multiple cameras



SUMMARY

Summary

- Pi of the Sky took part in LSC-Virgo EM Follow-up Project 2009-2010 (Results are published in ApJS in 2014) and have signed MOU for AdE time

- The system would be most helpful in the first few runs science runs of EM Follow-up project, when localization uncertainties are going to be big

- Enhanced data analysis algorithms or methodologies might be used as well for other teams

BACKUP

EM Follow-up project

An observation of an astrophysical event in both gravitational and optical band might bring very significant scientific results and could be the first step toward the direct detection of gravitational waves. The main aim of the EM Follow-up project, initiated by LSC and Virgo collaborations and several other electromagnetic (EM) observation teams, was to try to find such a coincidence by doing an electromagnetic follow-up of the most promising GW event candidates selected by the low-latency analysis of LIGO and Virgo detector data.

The first EM Follow-up science run took place in 2009-2010. Nine astronomical teams and the Swift satellite team took part in it. Scopes of those teams were placed all over the world.

The methods paper was published in 2012 in A&A.

The results paper was publish in 2014 in ApJS.

The next EM Follow-up observations are schedule with Advance LIGO and Advance Virgo in 2015+.

Pi of the Sky Data Analysis Pipeline

- For analysis we used catalog based pipeline
- As a seed for star catalog we used Guide Star Catalog with stars up to 11 mag
- For each exposition we add all recognized stars to the databases with their brightness measurements
  - Normalization of brightness to V magnitudes from the TYCHO catalog

Algorithms for fast cross-correlation with GWGC

- The first step towards AdE would be to allow easy correlation of observed transients with GWGC

- All alerts could be cross-correlated with GWGC and shifter could get immediate information about correlation

- For data taken for EM Follow-up 2009-2010 about 80 objects was associated with GWGC for one alert. So this data was easy for human inspection.

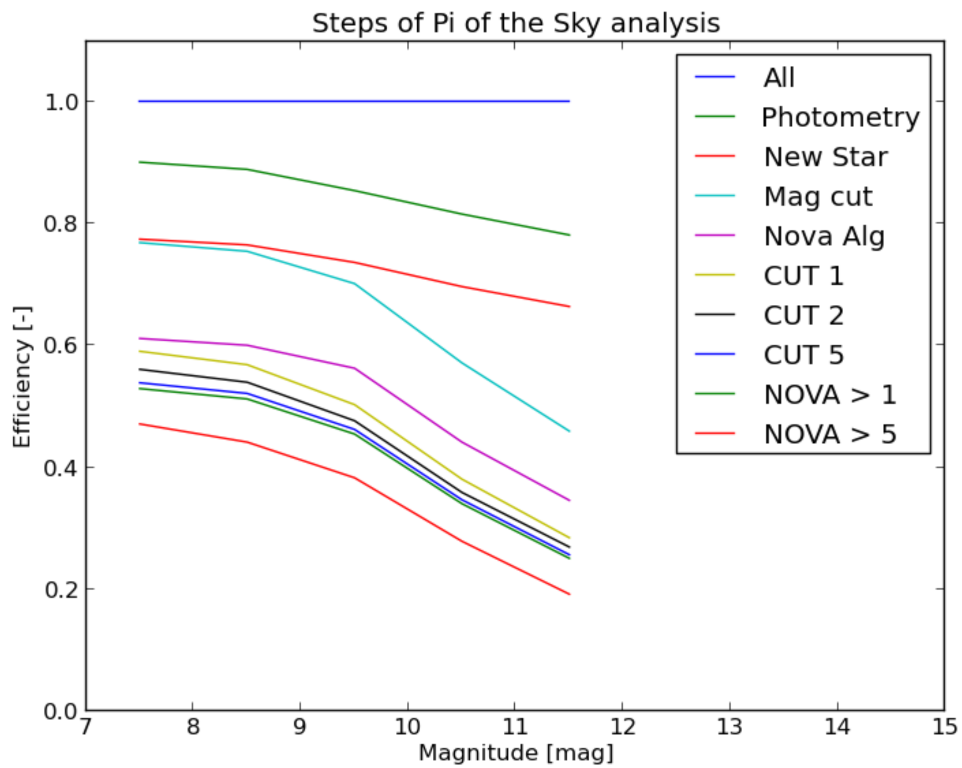
Enhancing On-line Algorithm

- Transient candidates, connected with GWGC objects, that passes very basic cuts would be considered as valid. Information about failed quality cuts would be added do results.

- Implementation of this algorithm is tricky to make it work in low-latency (it requires px,py -> ra,dec)
  - But under the assumption that for every fifth frame astrometry is done it is possible

Enhancing Off-line Algorithm

- Identify transients connected to GWGC objects
- Transients that are linked with GWGC, would be added to results with information about the cuts that their failed, if any.



Object from GWGC catalogue visible for Pi of the Sky

- In order to prepare for Advanced Detector Era, it would be worth to gather information about objects that are visible to PotS and estimate their brightness (min, max, median value)

- Estimation of brightness of GWGC objects would allow to construct better algorithms for online and offline transients search in AdE