Low Latency Transient Searches

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Outline

1. **Motivation**
   - Initiating electromagnetic followup observations
   - Detector and data characterization
2. **The Low-latency Analysis Pipeline**
   - Low-latency data calibration and distribution
   - Event trigger generation
   - Event followup
3. **Looking Ahead**

Motivation

Initiating electromagnetic followup observations

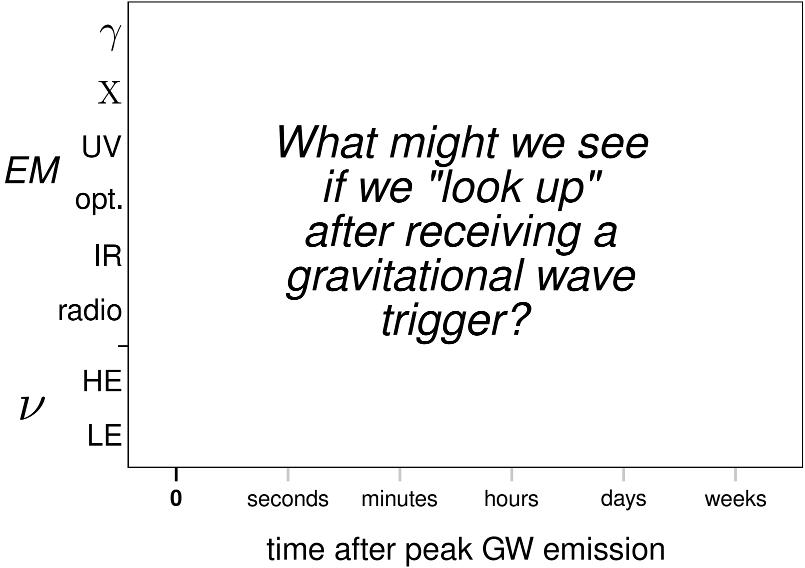
Very strong scientific motivation for promptly identifying gravitational wave event candidates:

observe non-GW counterparts to GW events

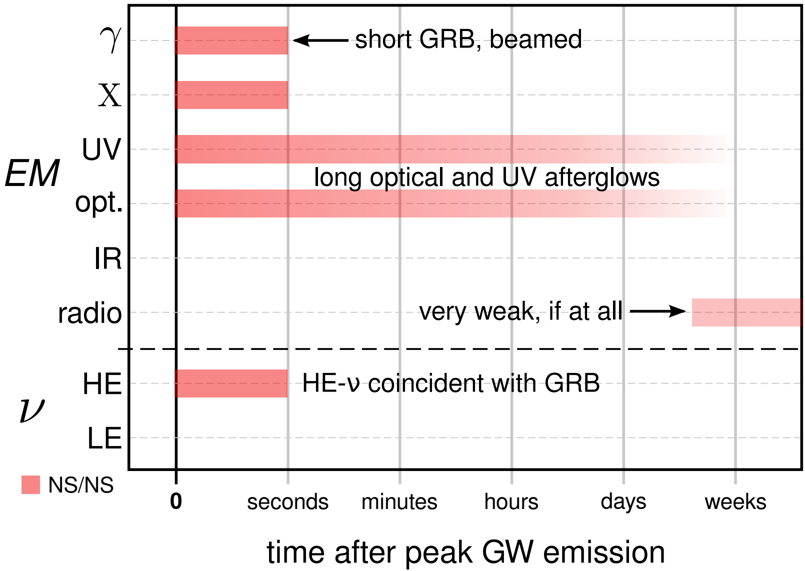
- increase sensitivity of searches (can accept higher FAR)
- increase detection confidence (coincident astronomical observation may even be *necessary* for convincing detection?)
- dramatically increase information about the source (position, distance, composition, etc.)
- catch what non-GW observatories might usually miss (observations of off-axis GRB afterglows, for instance)

See the original LOOC UP paper (CQG/25/184034).

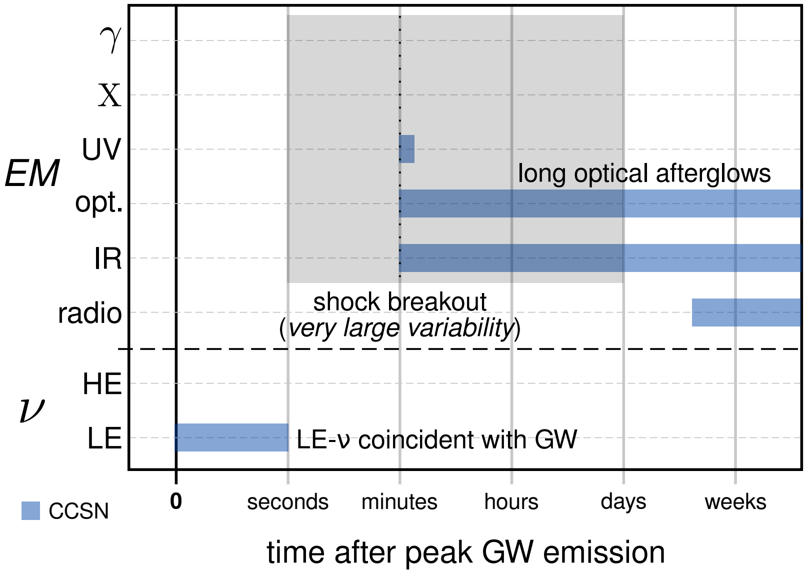
Relative times of gravitational and other emissions



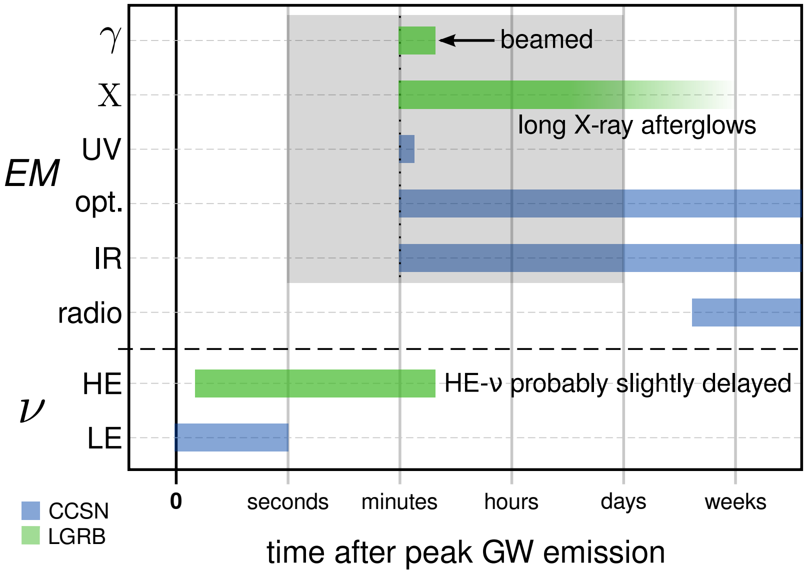
NS,BH/NS binary coalescence (short GRBs)



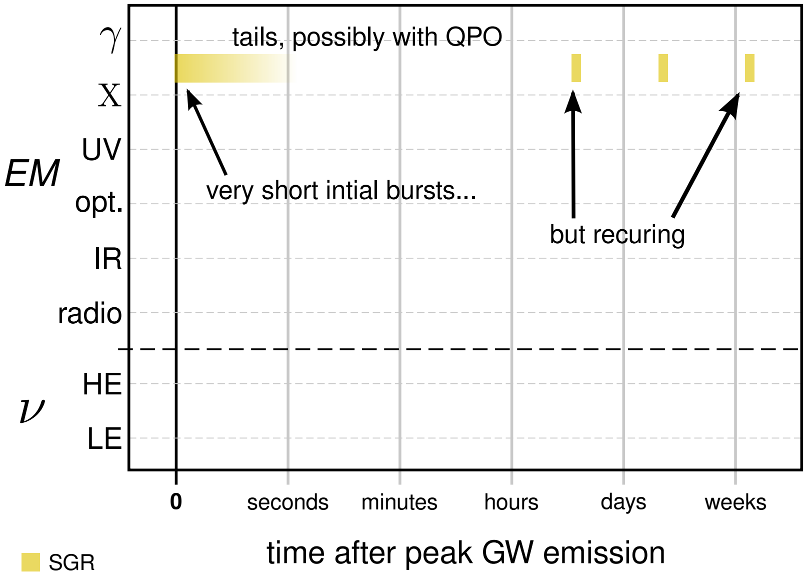
Core-collapse supernovae



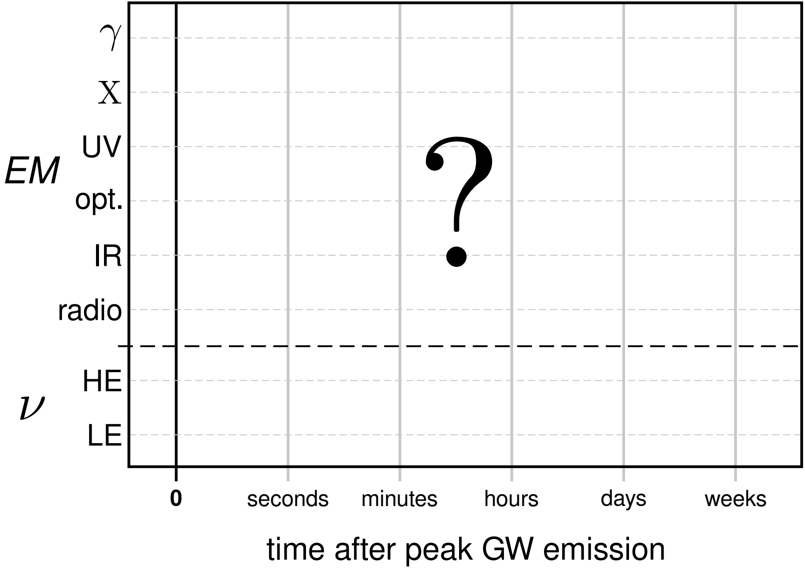
Long gamma-ray bursts (supernovae??)



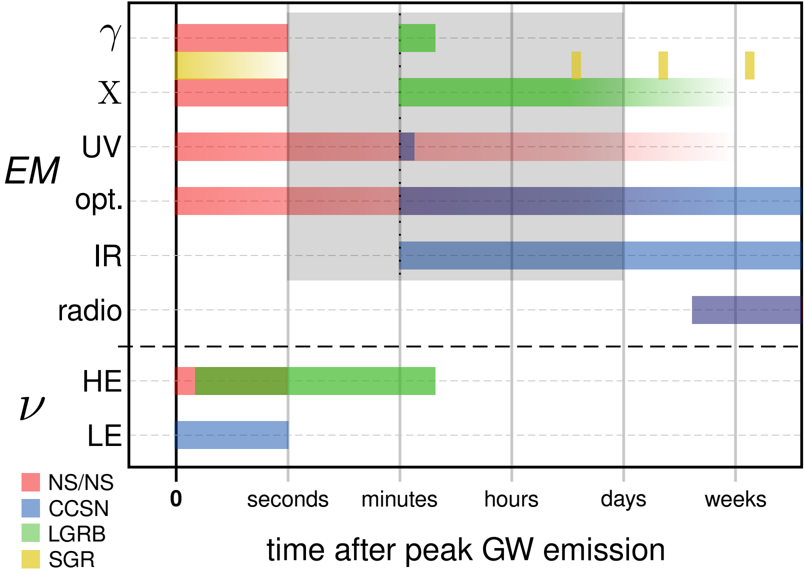
Neutron star disruptions (soft gamma repeaters)



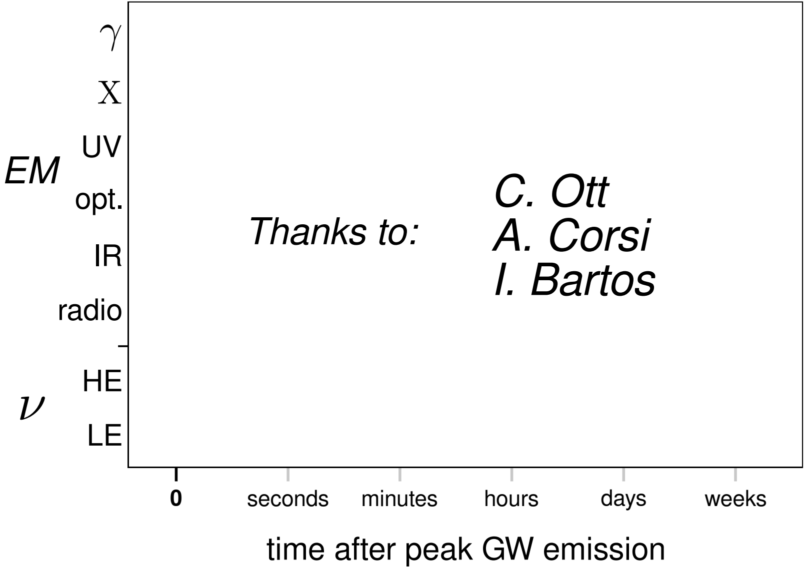
Unknowns


γ
X
UV
EM
opt.
IR
radio
HE
ν
LE
?
0
seconds
minutes
hours
days
weeks
time after peak GW emission

Relative times of gravitational and other emissions

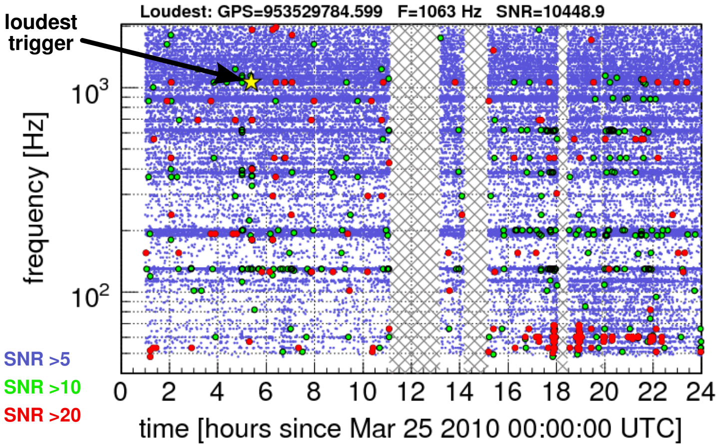


Relative times of gravitational and other emissions



Detector and data characterization

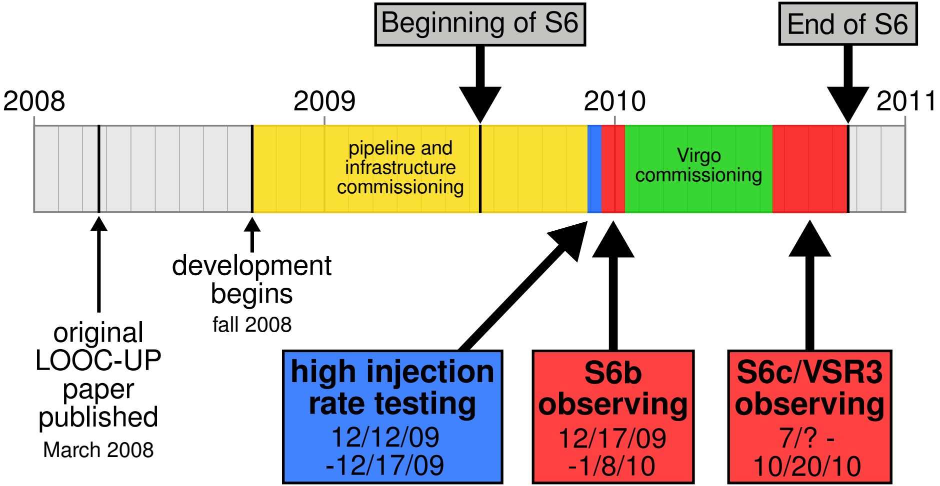
The S5 analyses clearly indicated that excessive non-Gaussian noise and glitches adversely affect the searches, compromising sensitivity.



Low-latency analysis = faster feedback to commissioners

The Low-latency Analysis Pipeline

Development history



Development of low-latency infrastructure

Much new infrastructure needed to be built:

- low-latency data calibration
- low-latency segment generation (IE. DQ/vetos)
- distribution of above to analysis sites
- notification distribution system

And it all got done!

Massive kudos to DASWG for making all of this happen:

Jordi Burguet-Castell, John Zweizig, Xavier Siemens, Ping Wei, Duncan Brown, Larne Pekowsky, Greg Mendell, Igor Yakushin, Dan Kozak, Adam Mercer, Scott Koranda, Patrick Brady, Xavier Amador, Josh Smith, Carsten Aulbert, Stuart Anderson, Brian Moe, Larry Price, et. al.

Modification of the event generators

In addition, the existing event generators (Omega Pipeline and Coherent WaveBurst) had to be modified as well:

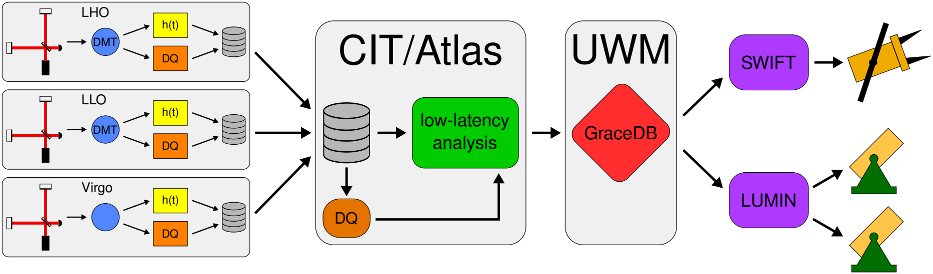
- Position reconstruction code had to be developed and integrated.

Accurate and precise position reconstruction is critical for doing any followup science.

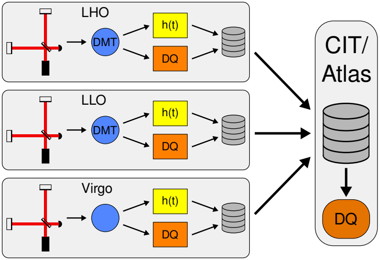
- Pipelines had to be modified/expanded to run in a low-latency mode.

Not to mention **review**!

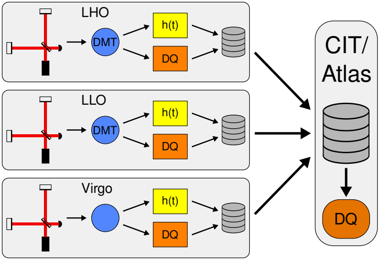
The S6 low-latency pipeline



Low-latency data calibration and distribution

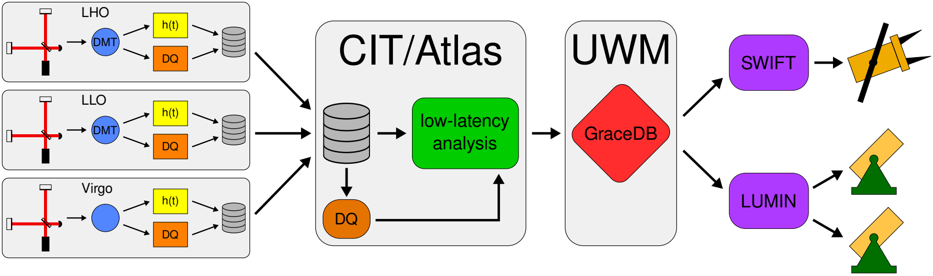


Low-latency data calibration and distribution

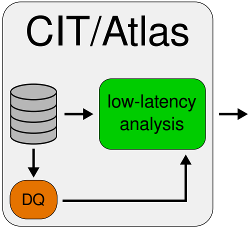


- new LIGO DMT/LAL low-latency calibrated frame generation
  - 16 second frames
  - ~50 second latency
  - include state vector
- new low-latency DQ/veto system
  - stored in XML files for faster processing
- frames and DQ XML distributed to analysis sites via `rsync`

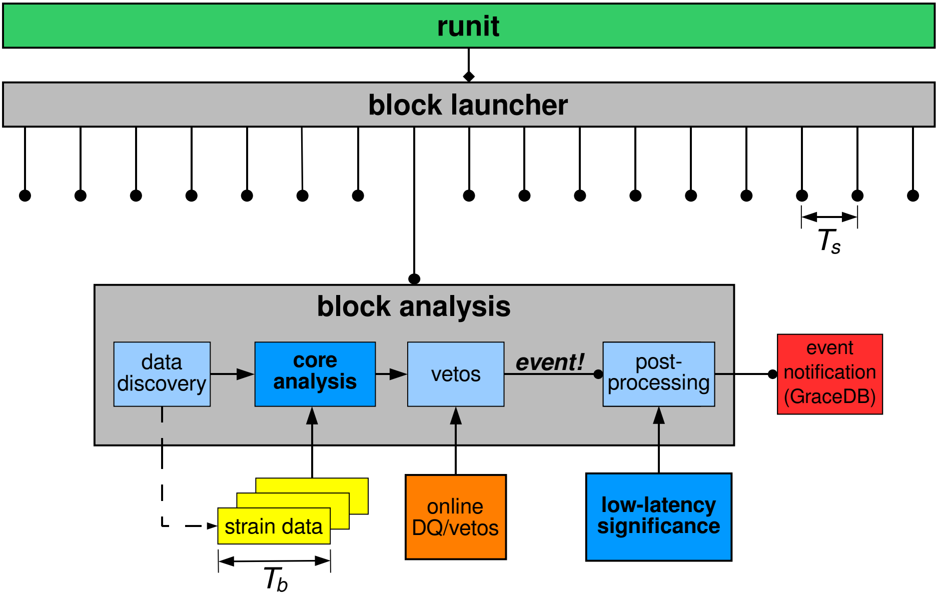
Next stage of pipeline...



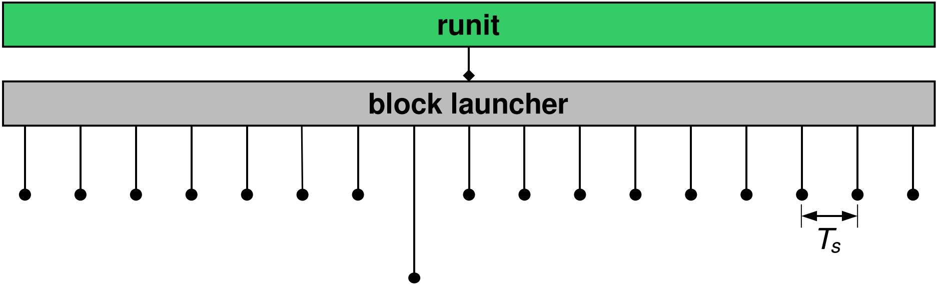
Event trigger generation



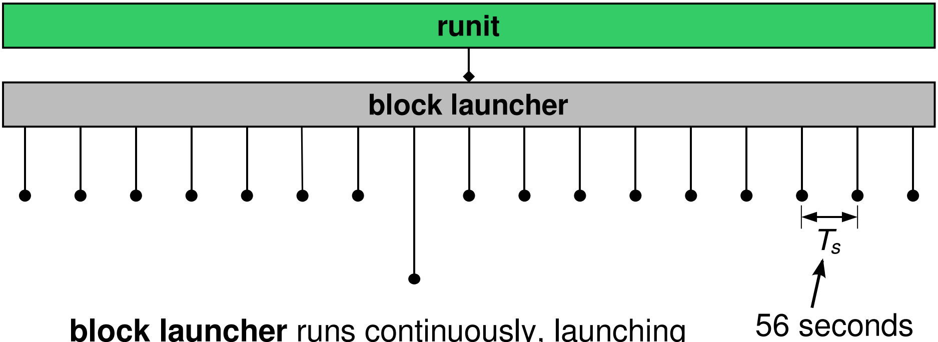
Omega Rapid Online Analysis



OROA: block launcher



OROA: block launcher

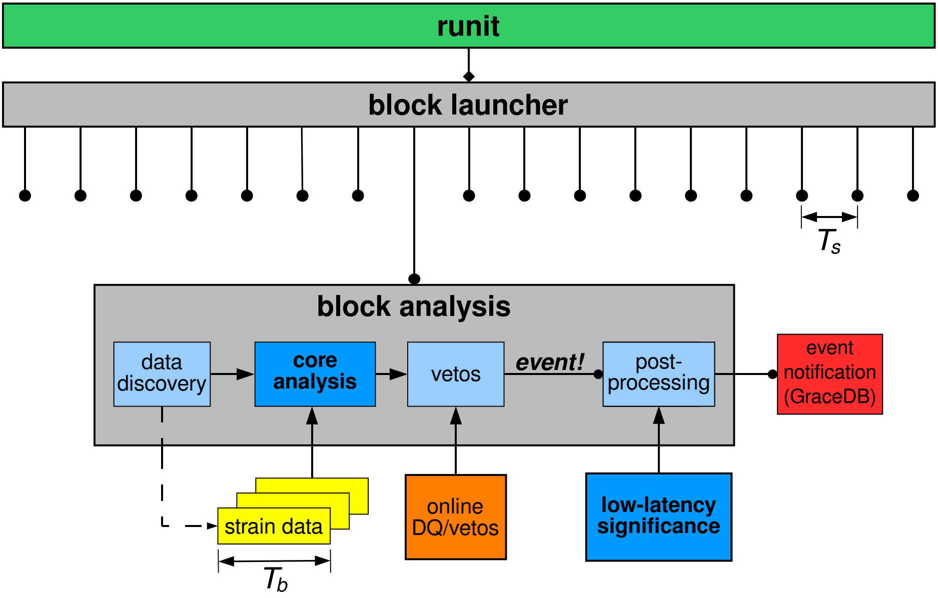


block launcher runs continuously, launching block analyses in the background

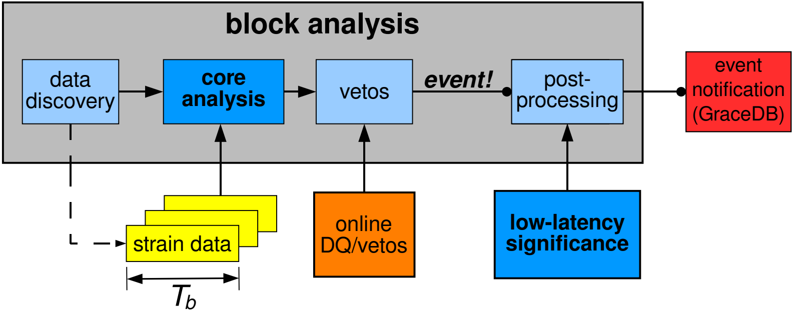
- each block completely independent
- each block analysed as fast as data for that block becomes available
- blocks monitored for problems

launcher is monitored by `runit` process supervision

Omega Rapid Online Analysis



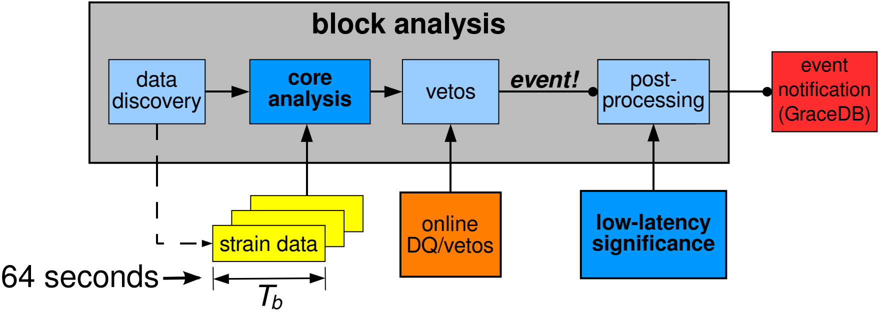
OROA: block analysis



OROA: block analysis

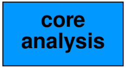
block analysis handles all processing of single block of data

- data discovery: waits for data from all IFOs, or timeout
- core analysis: Omega Pipeline identifies most significant event in block
- apply vetos: full IFO, fixed threshold, Cat2 DQ
- post-processing:
  - significance calculations
  - event notification → GraceDB



OROA core

- core analysis: Omega Pipeline identifies most significant event in block

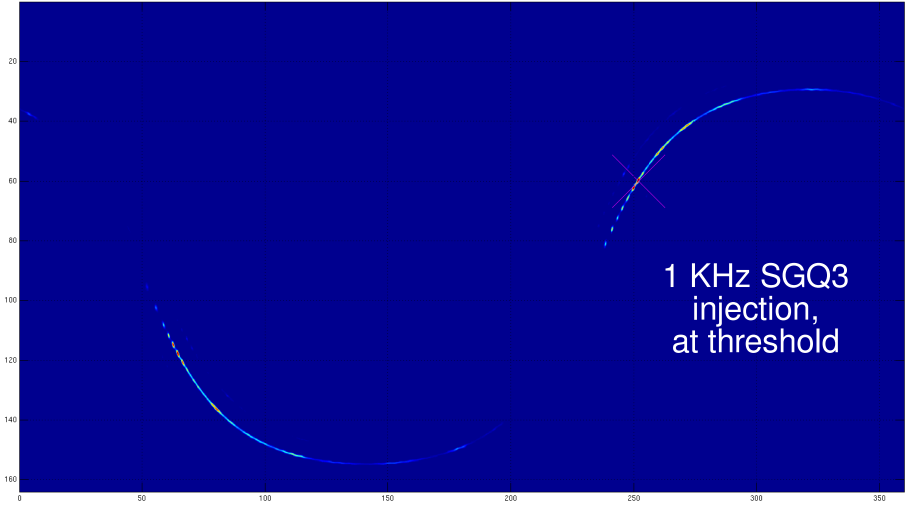


OROA core: Omega Pipeline

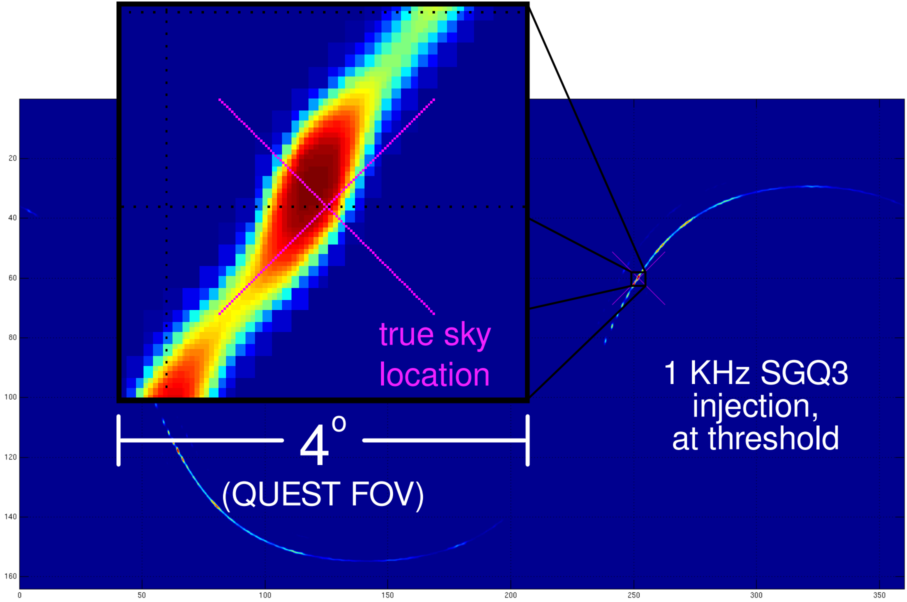
Omega Pipeline: hierarchical, coherent, transient search pipeline, built on Q-Pipeline, written mostly in MATLAB and Python.

- initially, each data stream (IFO) is analyzed independently:
  - each block is convolved with multiple sine-gaussian templates of different Qs
  - significant time/frequency/Q tiles are clustered
- clusters from each IFO are tested for time and frequency coincidence
- the loudest coincident cluster is passed to internal followup analyses:
  - **Bayesian**: calculates direction posterior
  - **xCoherent**: computes X-Pipeline-like coherent statistics based on sky location determined from Bayesian analysis

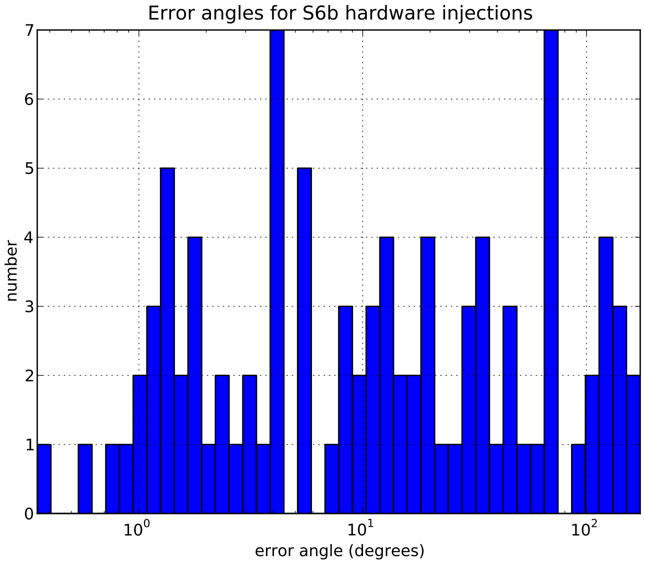
Bayesian position reconstruction



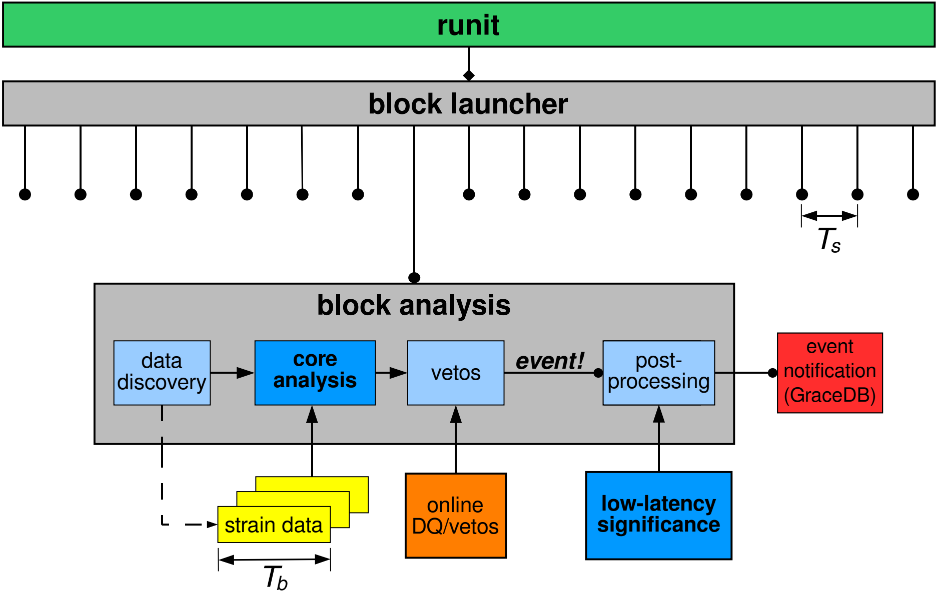
Bayesian position reconstruction



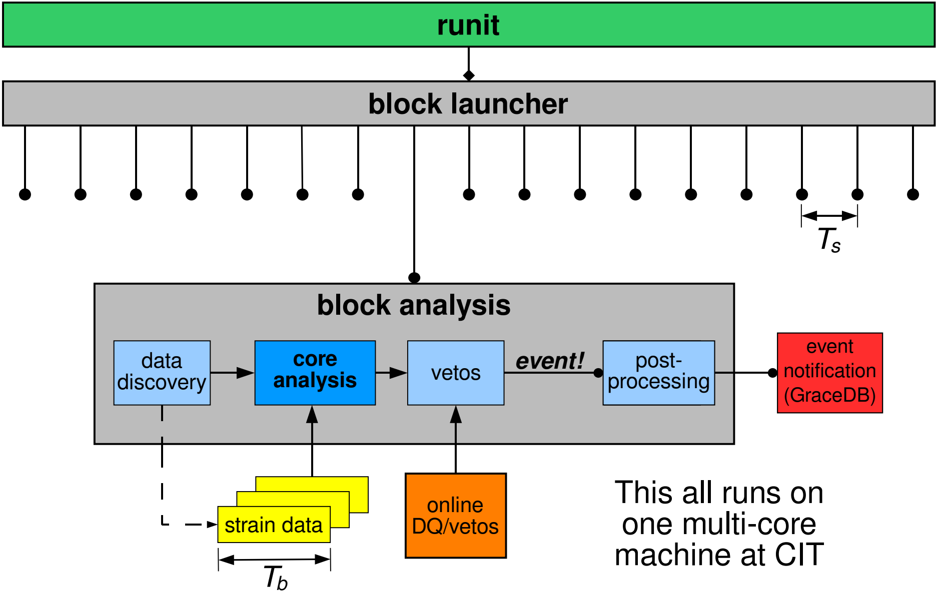
Error angles for S6b hardware injections



OROA: resource requirements

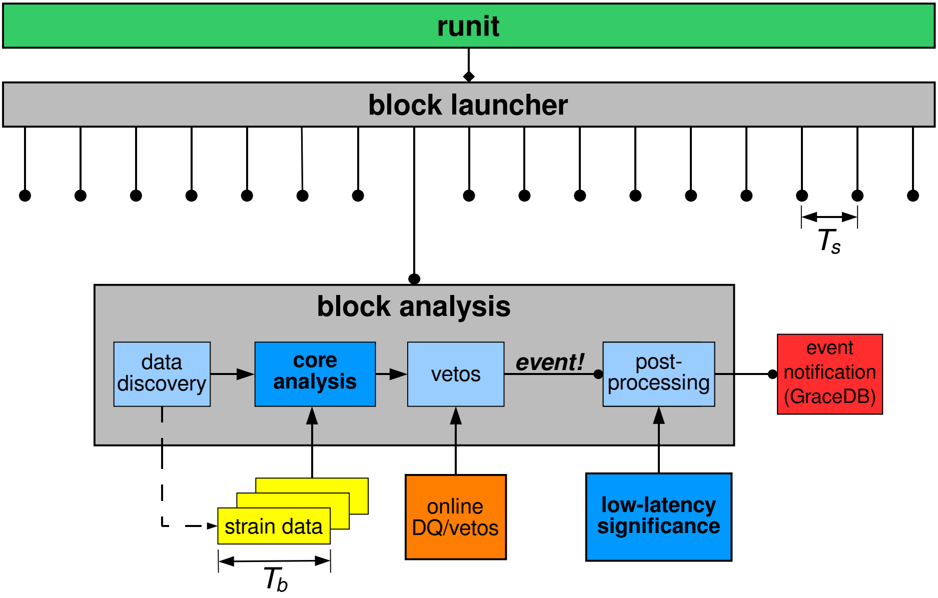


OROA: resource requirements



This all runs on one multi-core machine at CIT

OROA: but...


runit
block launcher
T_s
block analysis
data discovery
core analysis
vetos
event!
post-processing
event notification (GraceDB)
strain data
T_b
online DQ/vetos
low-latency significance

OROA: low-latency significance

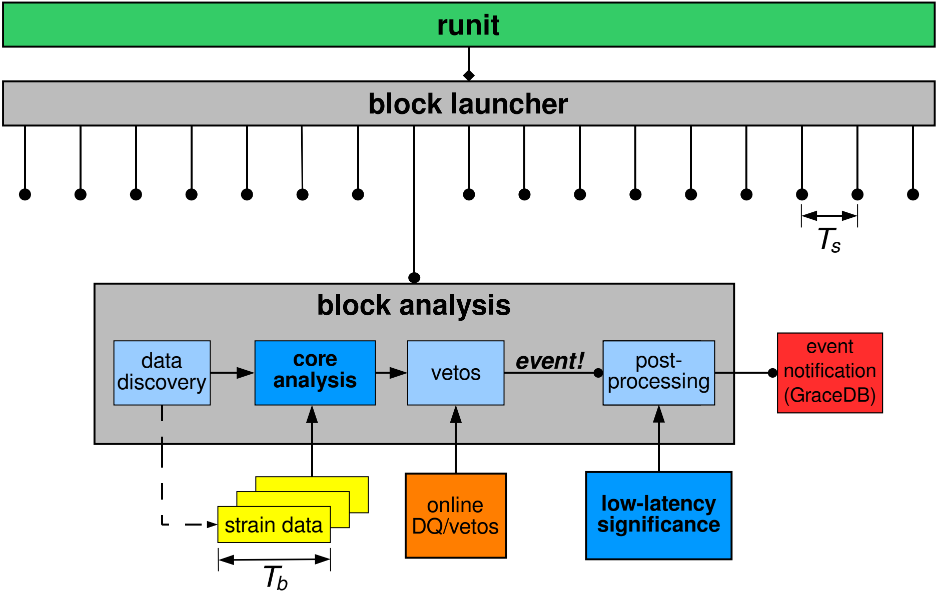
Low-latency significance most computationally intensive part of the pipeline

- 100 time-slide analyses of last 30 minutes every 30 minutes
- significance of every event is measured against background from:
  - most recent run
  - last day of background
  - background from entire run "epoch"

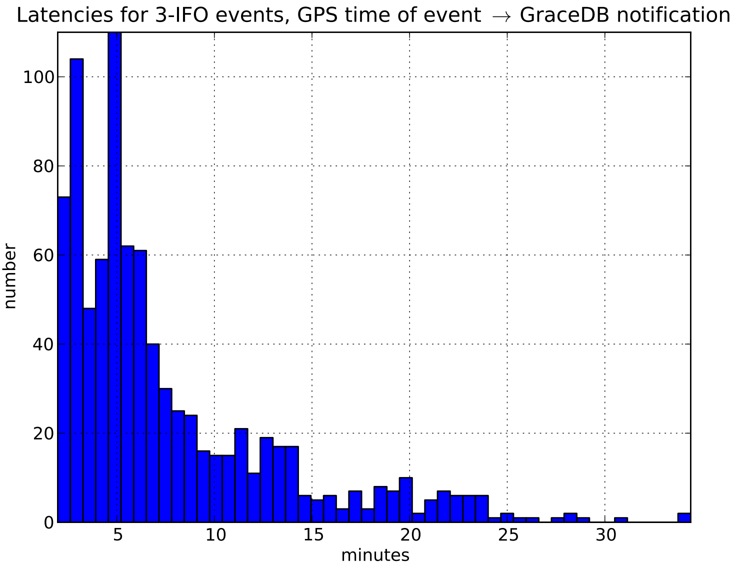
Requires ~100 cores from CIT cluster *continuously*

low-latency significance

OROA: results

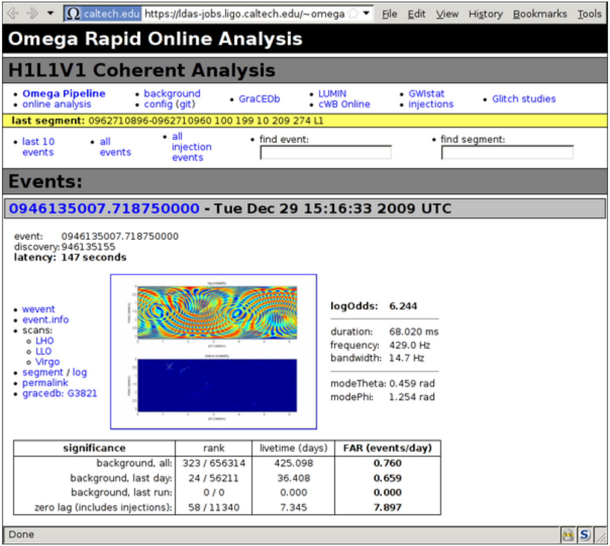


Latencies: event time → GraceDB



OROA: results

main H1L1V1 analysis web page



caltech.edu https://ldas-jobs.ligo.caltech.edu/~omega File Edit View History Bookmarks Tools

Omega Rapid Online Analysis

H1L1V1 Coherent Analysis

- **Omega Pipeline**
- online analysis
- background
- config (git)
- GraCEDb
- LUMIN
- cWB Online
- GWIstat
- injections
- Glitch studies

last segment: 0962710896-0962710960 100 199 10 209 274 L1

- last 10 events
- all events
- all injection events
- find event:
- find segment:

Events:

0946135007.718750000 - Tue Dec 29 15:16:33 2009 UTC

event: 0946135007.718750000
discovery: 946135155
latency: 147 seconds

- wevent
- event.info
- scans:
  - LHO
  - LLO
  - Virgo
- segment / log
- permalink
- gracedb: G3821

logOdds: 6.244

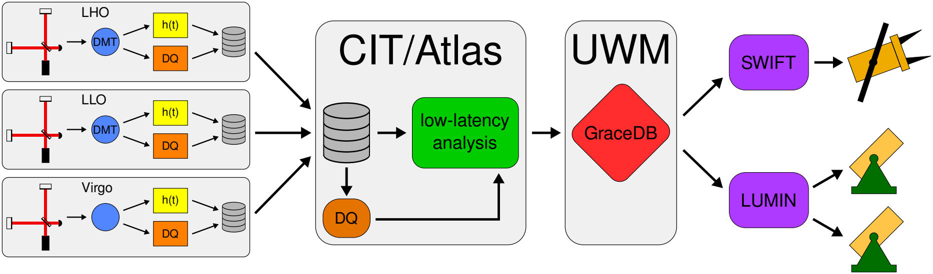
duration: 68.020 ms
frequency: 429.0 Hz
bandwidth: 14.7 Hz

modeTheta: 0.459 rad
modePhi: 1.254 rad

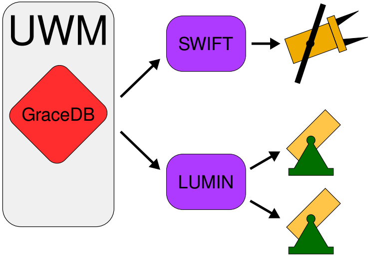
significance	rank	livetime (days)	FAR (events/day)
background, all:	323 / 656314	425.098	**0.760**
background, last day:	24 / 56211	36.408	**0.659**
background, last run:	0 / 0	0.000	**0.000**
zero lag (includes injections):	58 / 11340	7.345	**7.897**

Done

Last stage of pipeline...

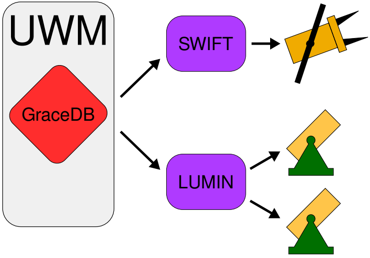


Event followups



Event followups

- new **GraceDB** event database and notification/distribution system
  - events reported via XMPP
  - event info stored in searchable database
  - listeners can subscribe to event notifications (XMPP, email, RSS)
- followup analyses receive event notification via GraceDB



LOOC UP

The LOOC-UP followup analysis uses triggers to point wide-field optical telescopes (QUEST and TAROT).

- events collected from GraceDB
- event position reconstruction information and catalog of local galaxies are used to determine telescope pointings

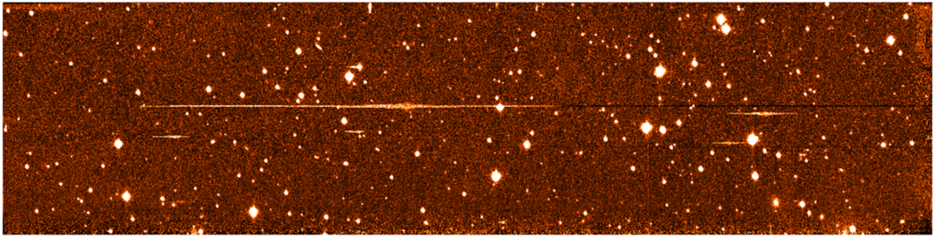
LOOC UP S6b observations

ETG	GPS	Lag	Observed
Omega	945320899	37 minutes	none
Omega	945895177	30 minutes	none
Omega	946135007	20 minutes	QUEST
cWB	946465347	25 minutes	none
cWB	946786257	25 minutes	none
Omega	946795800	20 minutes	QUEST
cWB	946586256	re-visit	TAROT
cWB	946889212	95 minutes	QUEST

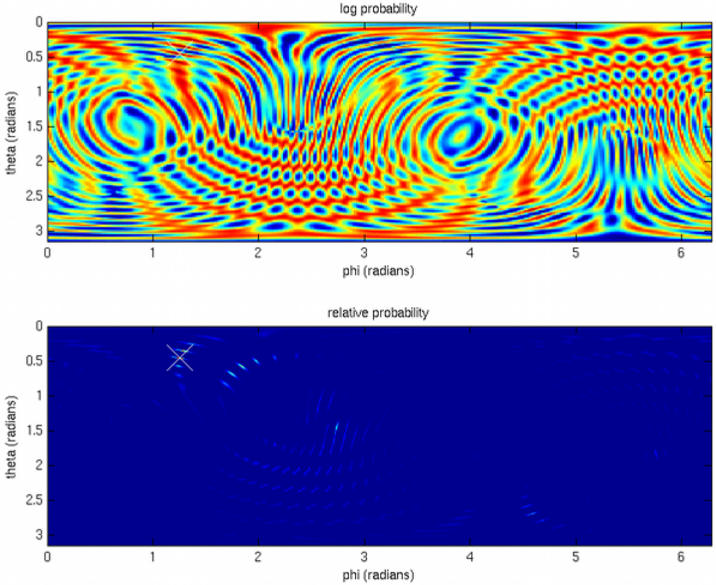
First ever triggered observation!

From Omega!

Event: **946135007**

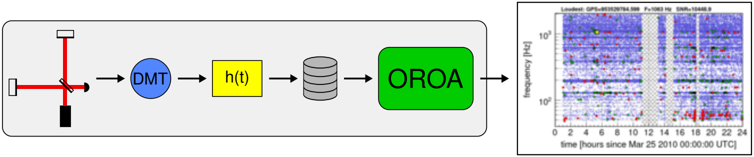


Event 946135007 Bayesian skymap



OROA: single detector

The "OmegaGrams" (shown in slide 13) are created by a single interferometer version of the OROA (first two stages of the full pipeline):



These are running independently on dedicated nodes at the LIGO sites and Virgo.

Looking Ahead

S6d/VSR3

Things are building up for a very productive run this summer (hopefully starting in soon!):

- **analyses have been improved** - bug fixes and better glitch rejection in Omega, and position reconstruction in cWB
- **new online analyses** - MBTAOnline will hopefully be providing triggers for EM followups
- **lots of new EM follows** - The GEM processor will provide pointings for Swift, and LOOC-UP has new telescopes in roster:
  - **Pi of the Sky**
  - **ROTSE**
  - **Liverpool Telescope**
  - **SkyMapper? Zadko?**
- **galaxy targeting** - in both LUMIN and GEM
- **reviewed** - analysis and followup reviews nearing completion

What have we learned so far?

A lot.

- **monitoring is important** - calibration, distribution, ETGs, NFS, etc. all occasionally go down
- **redundancy is good** - for the ETGs themselves, and for data distribution
- **significance estimation can be tricky** - computing requirements were under-appreciated

Resource requirements

There will likely be a lot more low-latency analyses running in Advanced LIGO

- for searches.
- for detector/data characterization.

For searches, it's particularly important to pay attention to requirements for significance estimation.

- example: 10 searches *x* 1000 time-slides = 10,000 cores **continuously**

Need to get more clever about how to determine event significance.

Streaming data

The use of data streams, as opposed to data read off disk, will likely become increasingly important in aLIGO.

$\Longrightarrow$ **NDS2**

Will probably need things like stream proxies at the analysis sites to keep from overburdening the network.

It's good to keep in mind what latencies are really scientifically relevant.

Conclusion

Low-latency burst analysis in S6 has been a great success.

- 4 observations were made with two observatories, based on triggers passed from the low-latency analyses via LOOC UP.
- Hopefully many more will be made this summer.

Low-latency analysis is critical moving into Advanced LIGO.

- We have learned a lot, but there is much work and many challenges still ahead.

Conclusion

Thank you.