

Low-latency LIGO-Virgo Alerts

Reed Essick
on behalf of the LVC

4th AMON Workshop
December 4, 2015

LIGO low-latency alerts

Why low-latency?

What does LIGO mean by “low-latency”?

What challenges are associated with low-latency?

LIGO low-latency alerts

Why low-latency?

- Directed follow-up and multi-messenger astronomy

What does LIGO mean by “low-latency”?

What challenges are associated with low-latency?

LIGO low-latency alerts

Why low-latency?

- Directed follow-up and multi-messenger astronomy

What does LIGO mean by “low-latency”?

- $O(\text{sec-min})$ rather than $O(\text{days-weeks})$

What challenges are associated with low-latency?

LIGO low-latency alerts

Why low-latency?

- Directed follow-up and multi-messenger astronomy

What does LIGO mean by “low-latency”?

- $O(\text{sec-min})$ rather than $O(\text{days-weeks})$

What challenges are associated with low-latency?

- non-stationary, non-Gaussian noise background (“glitches”)
- wide parameter space

What all-sky low-latency searches are running?

Compact Binary Coalescence (CBC)

“Everything else” (Bursts)

What all-sky low-latency searches are running?

Compact Binary Coalescence (CBC)

gstlal (lowmass)

Multi-Band Transit Analysis (MBTA)

Both perform decompositions of
large template banks and
matched-filter data
Templates → assumed morphology

“Everything else” (Bursts)

What all-sky low-latency searches are running?

Compact Binary Coalescence (CBC)

gstlal (lowmass)

Multi-Band Transit Analysis (MBTA)

“Everything else” (Bursts)

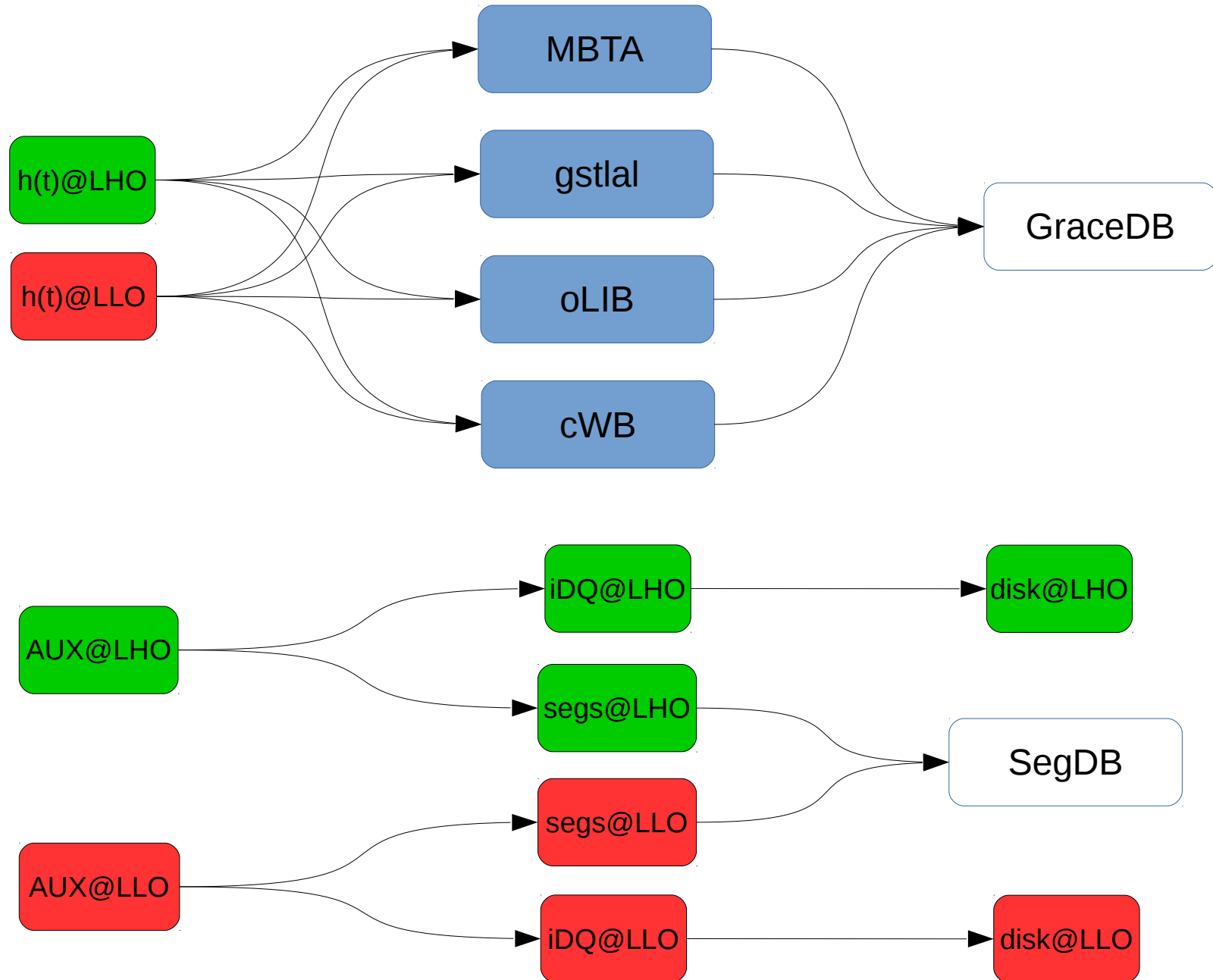
Coherent WaveBurst (cWB)

cWB maximizes a “constrained” likelihood to reconstruct the waveform.
Makes minimal assumptions about polarization (when possible).

Omicron+LALInferenceBurst (oLIB)

oLIB performs incoherent coincidence with sineGaussian template (Omicron) before Computing fully coherent Bayes Factors (LIB) using a single sineGaussian template.

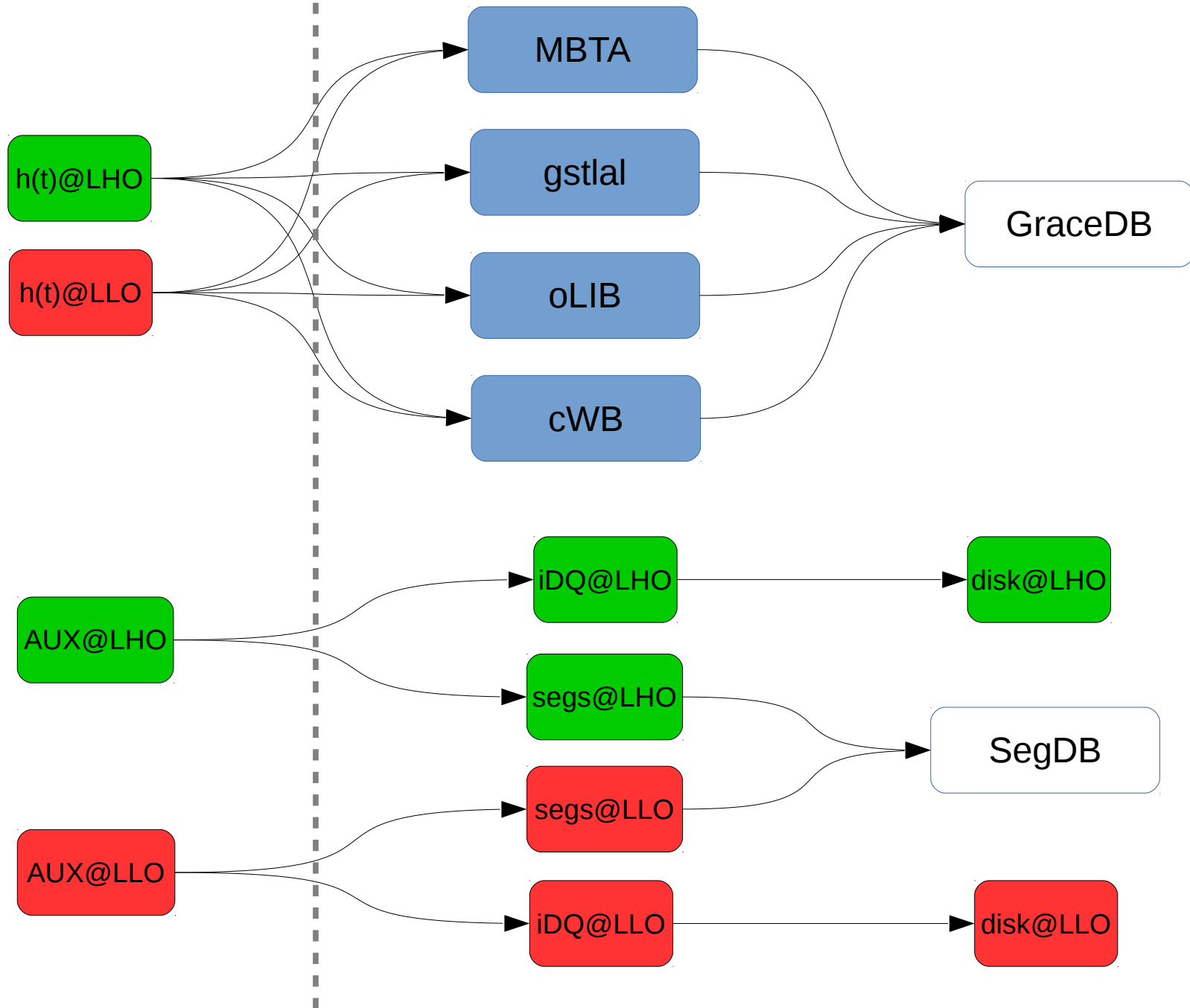
How are candidates reported internally?



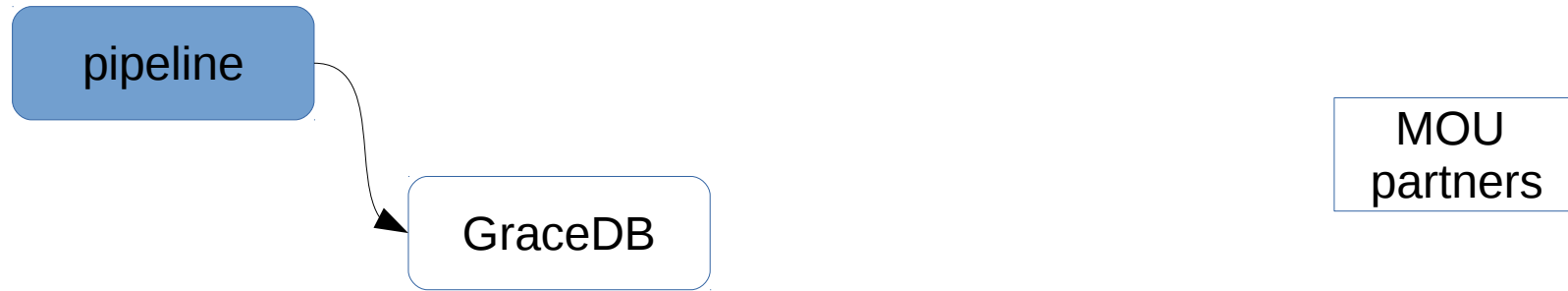
How are candidates reported internally?

synchronous

asynchronous



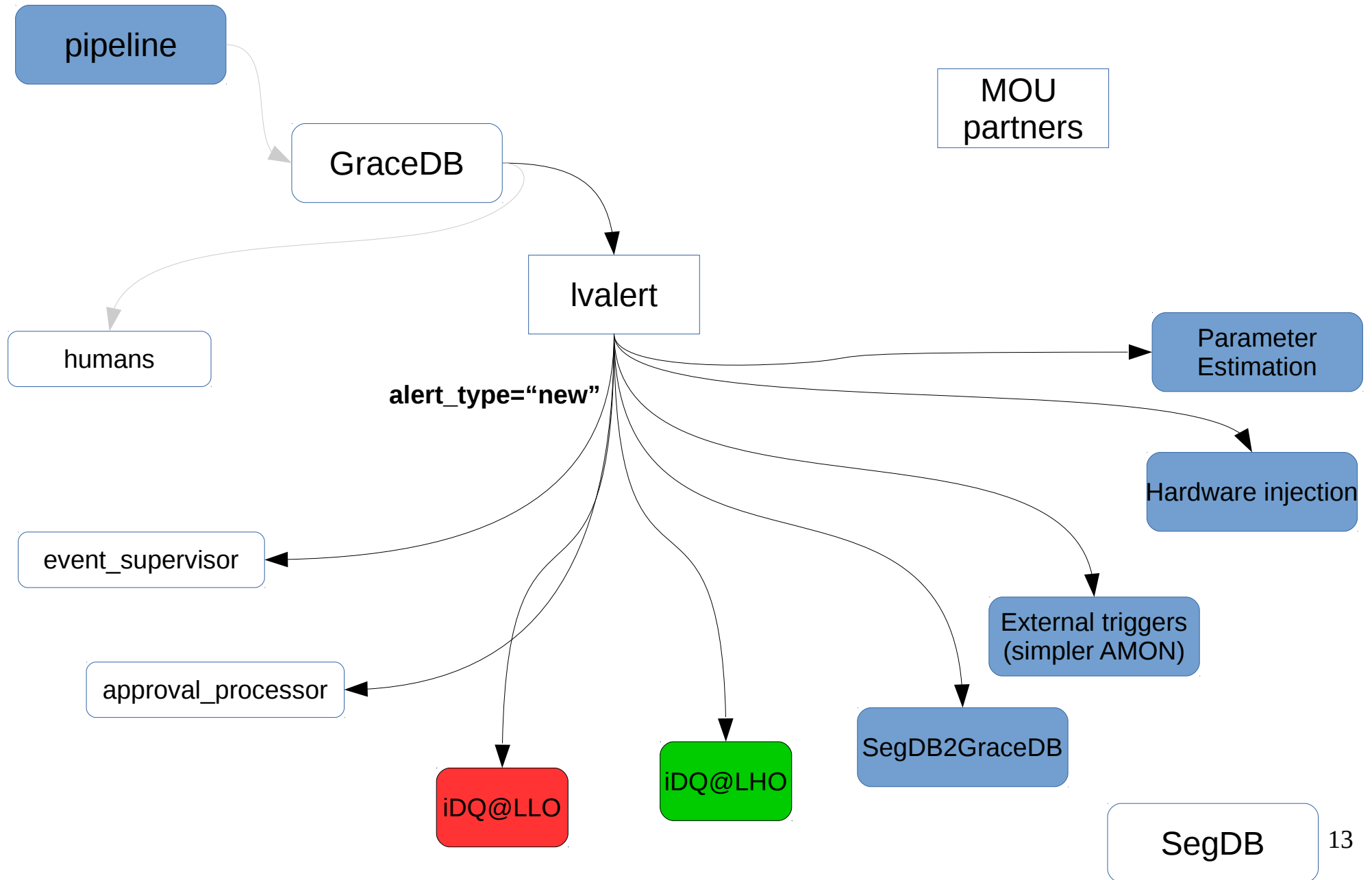
What follow-up is conducted internally?



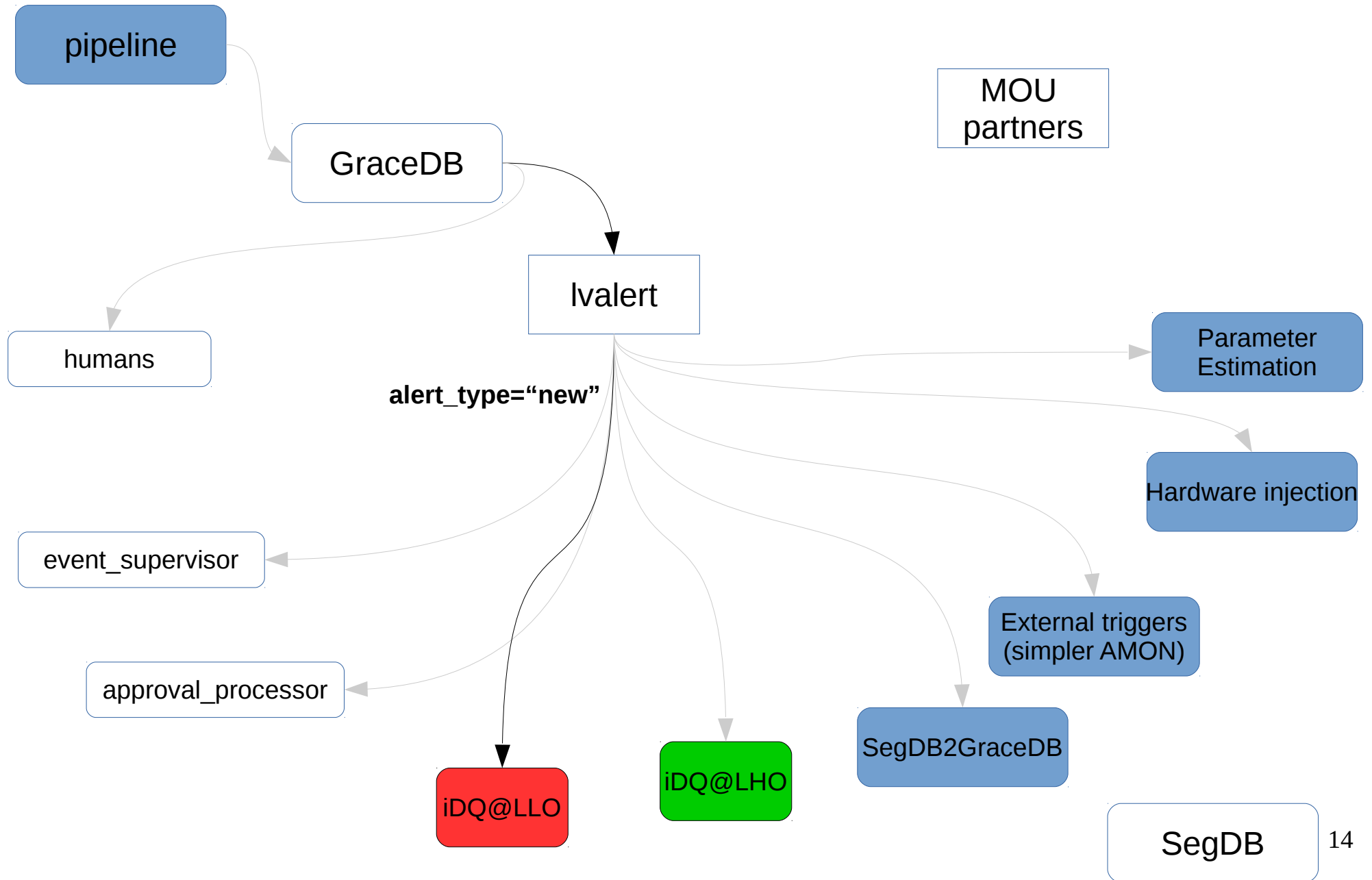
What follow-up is conducted internally?



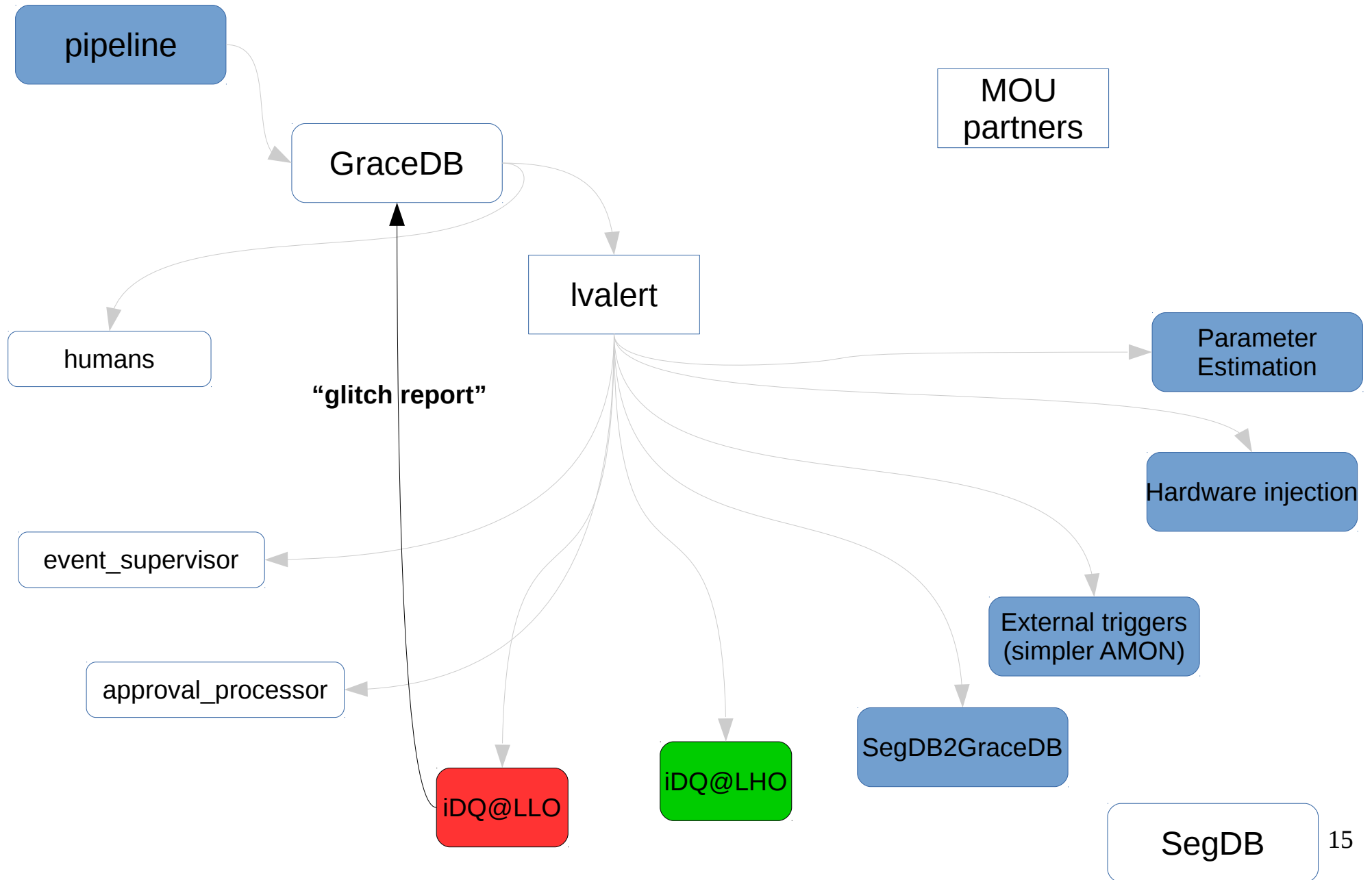
What follow-up is conducted internally?



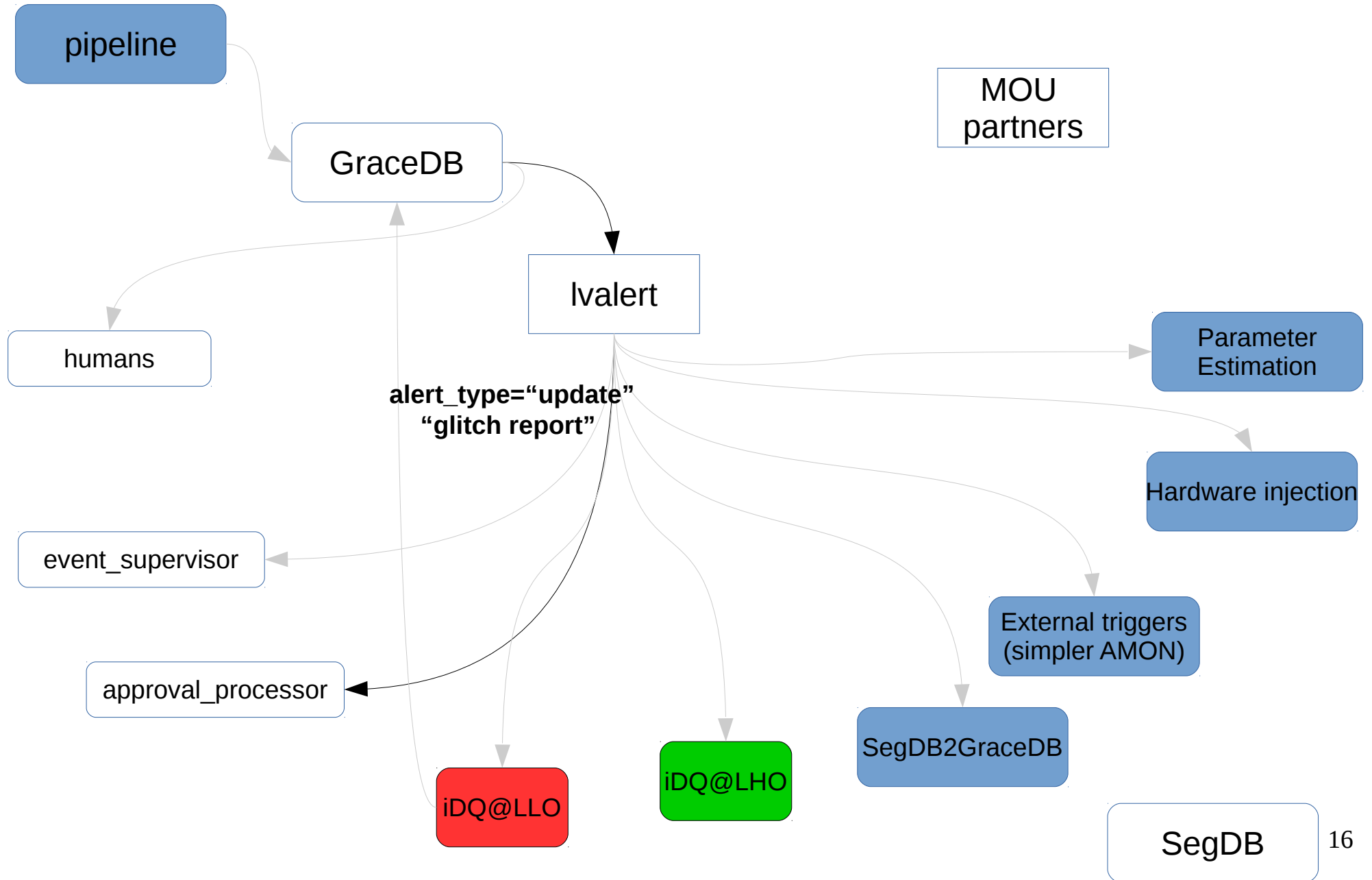
What follow-up is conducted internally?



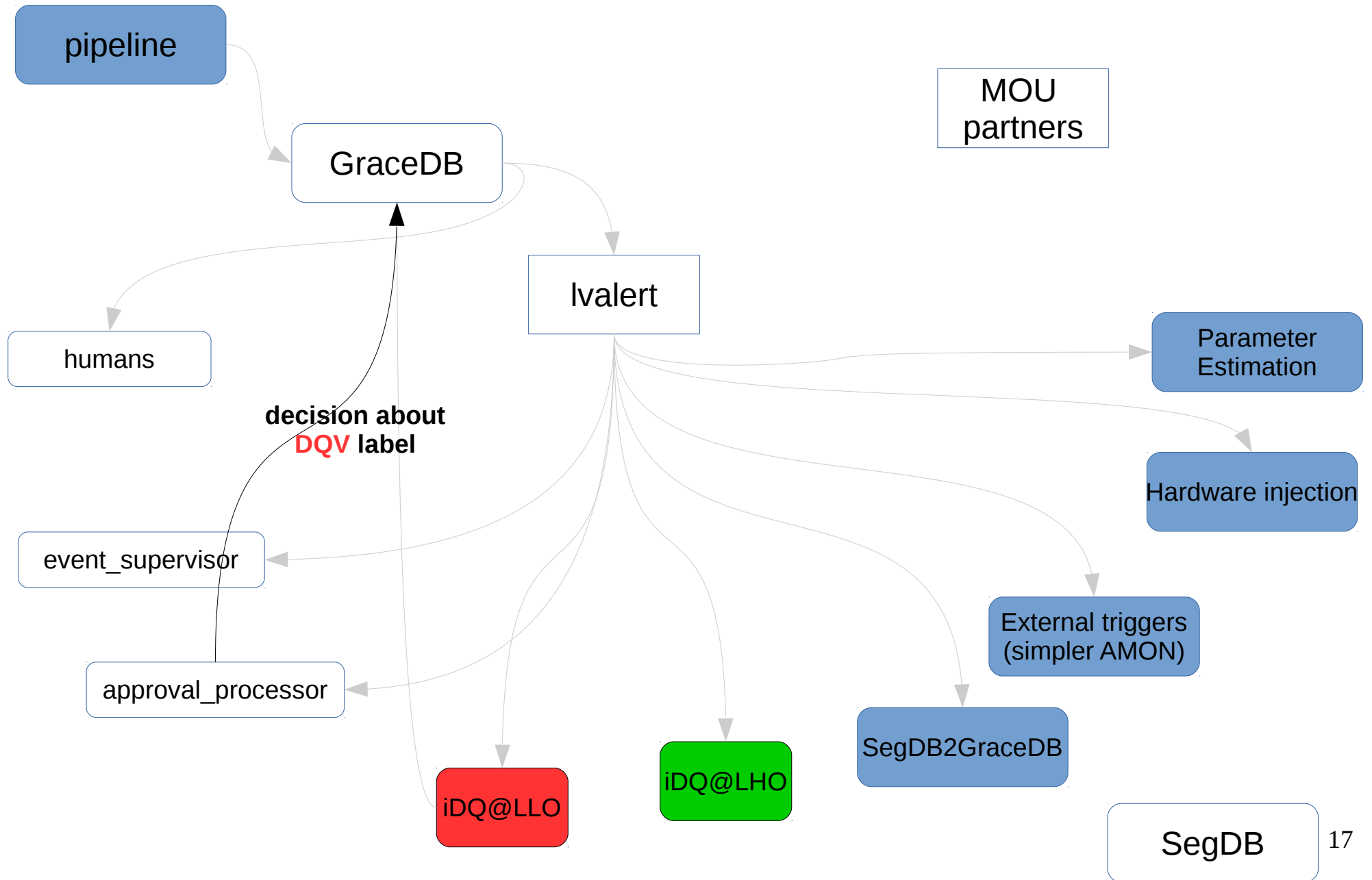
What follow-up is conducted internally?



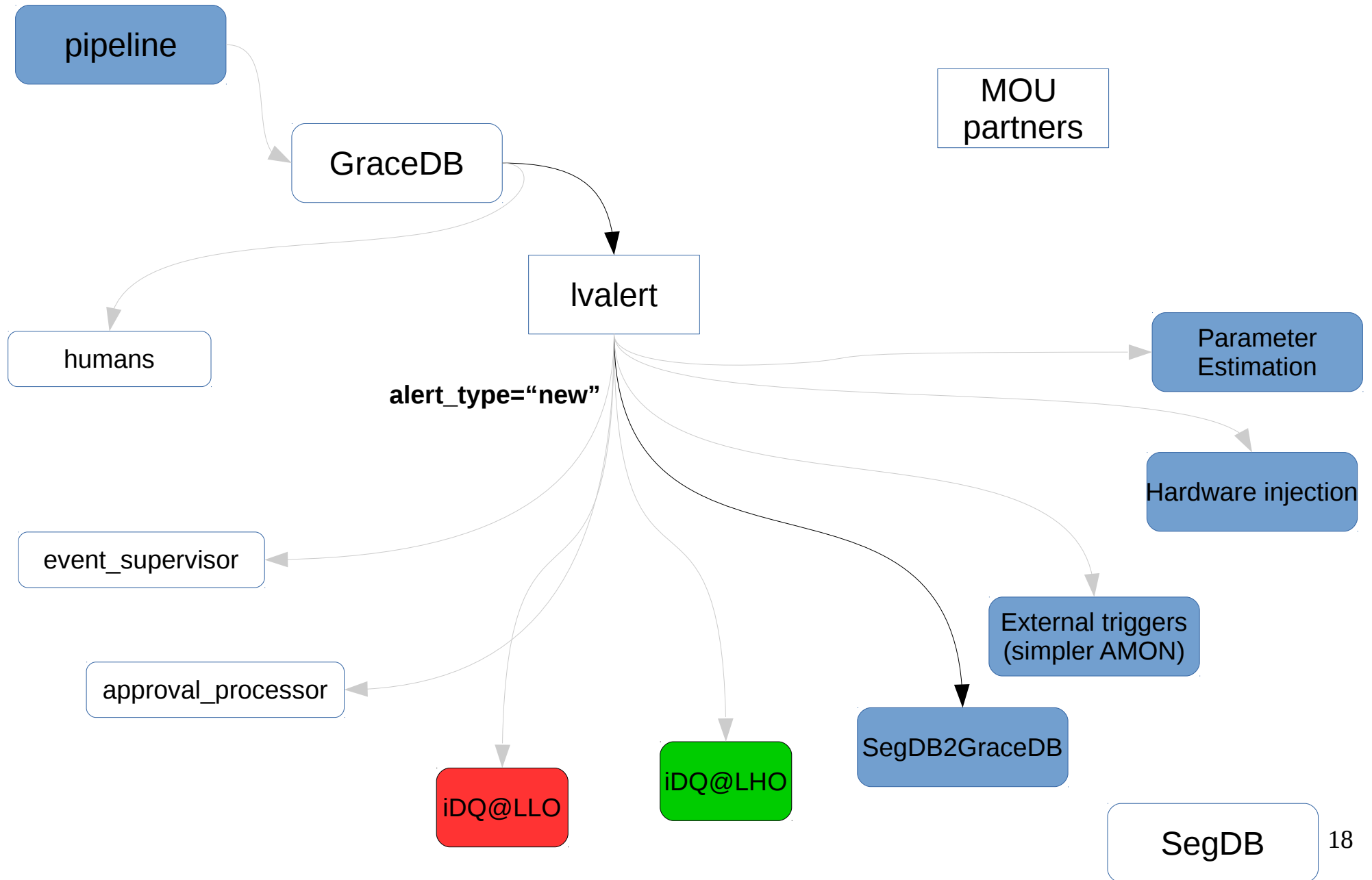
What follow-up is conducted internally?



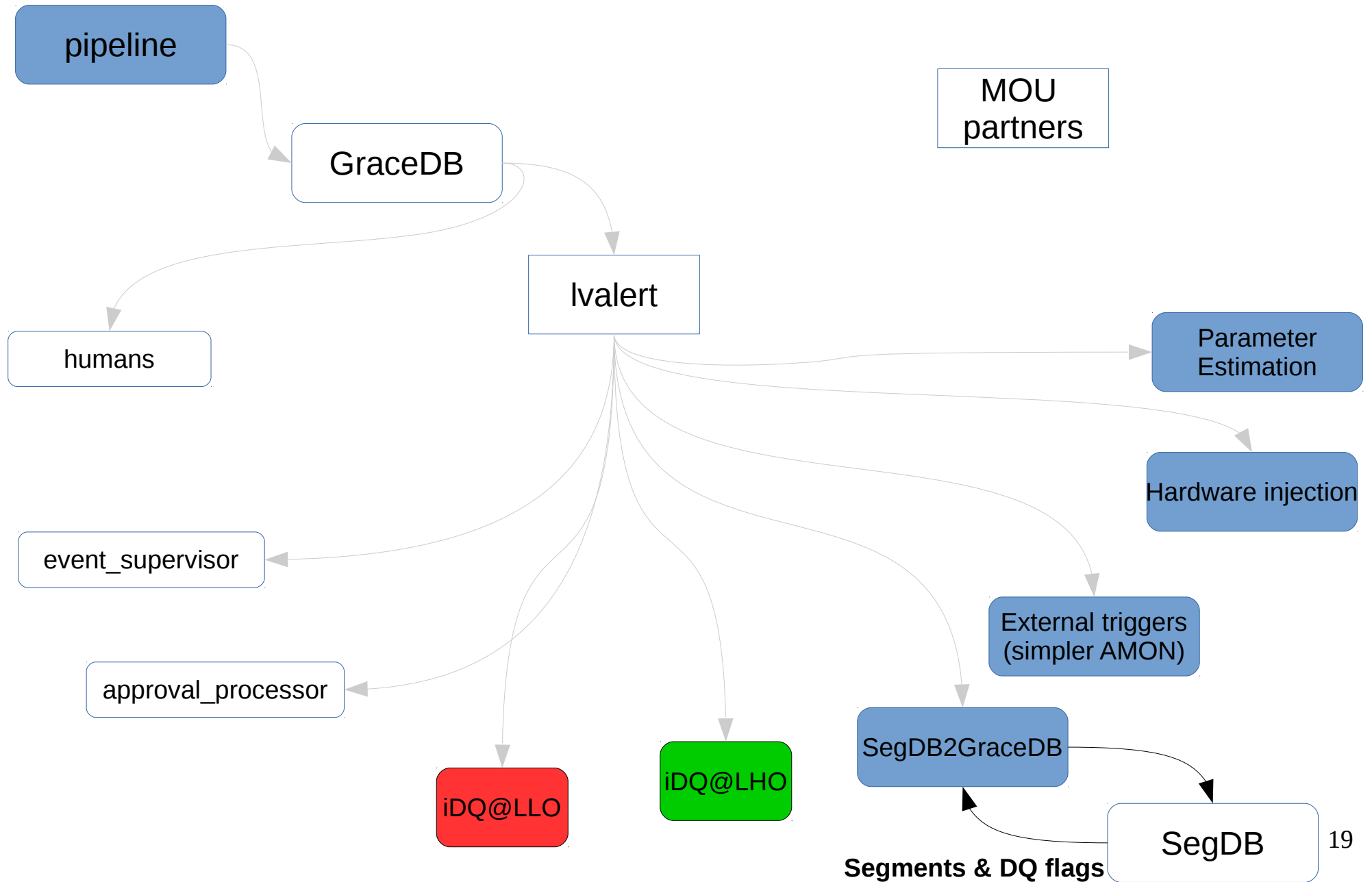
What follow-up is conducted internally?



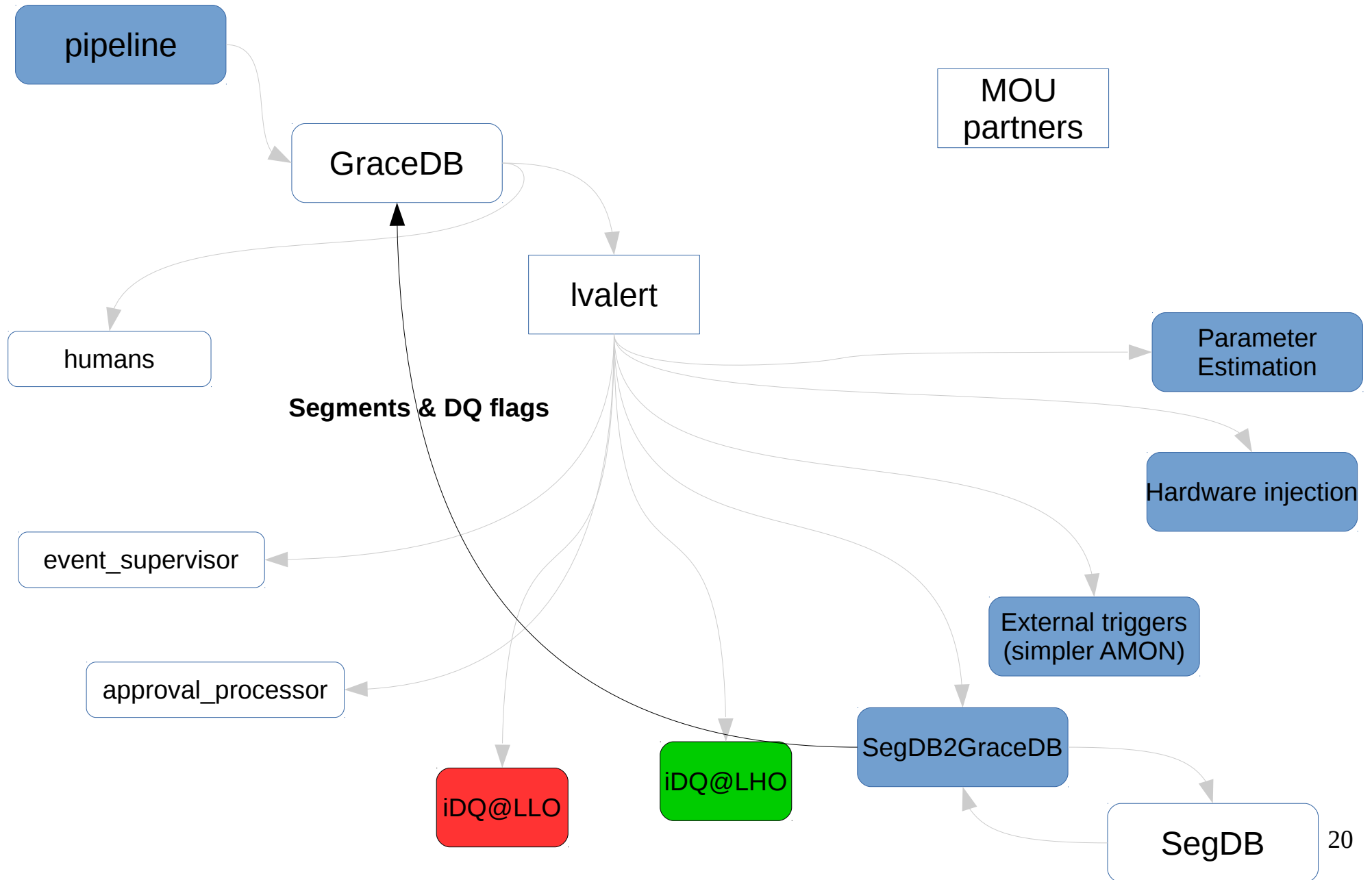
What follow-up is conducted internally?



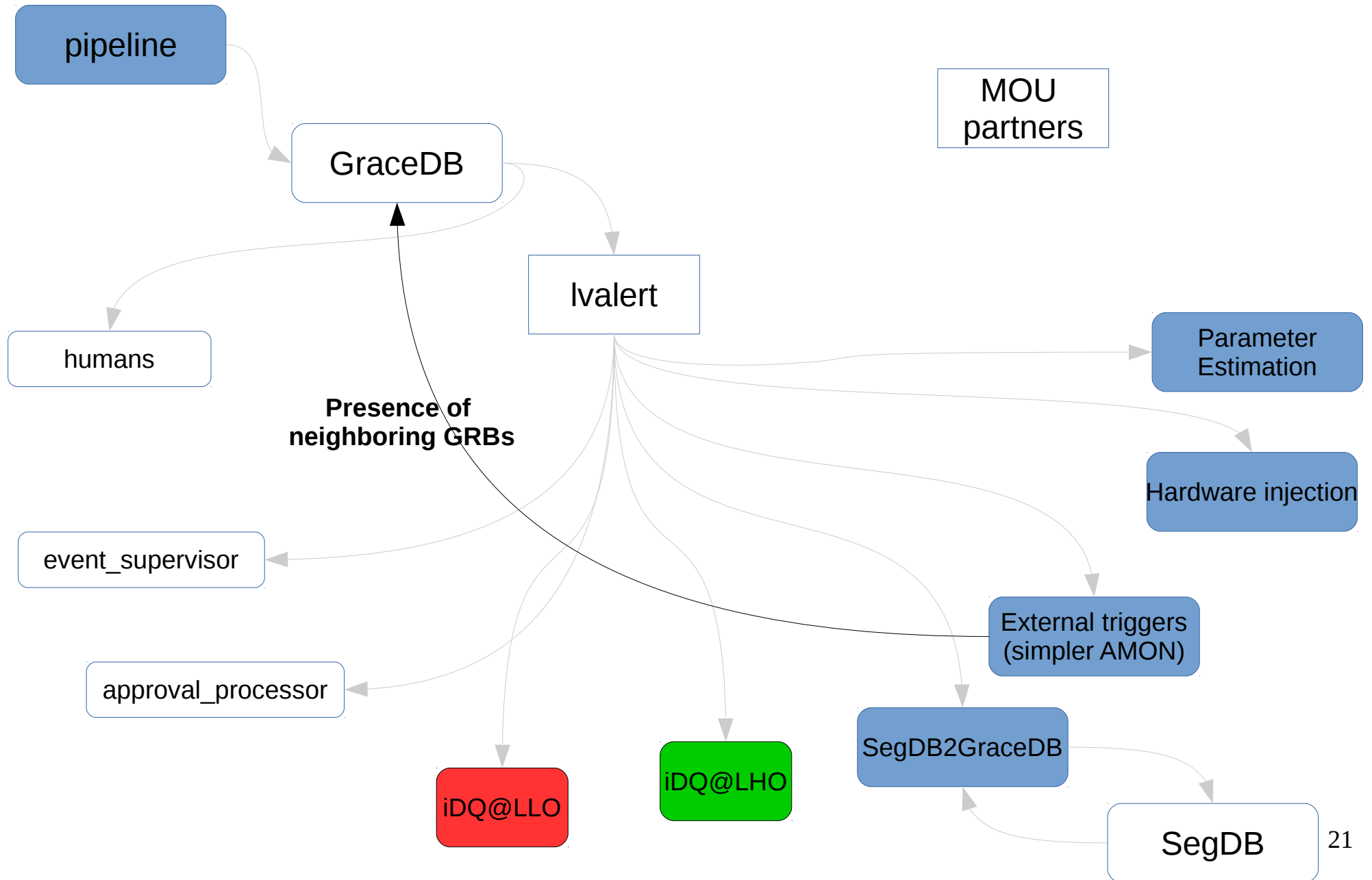
What follow-up is conducted internally?



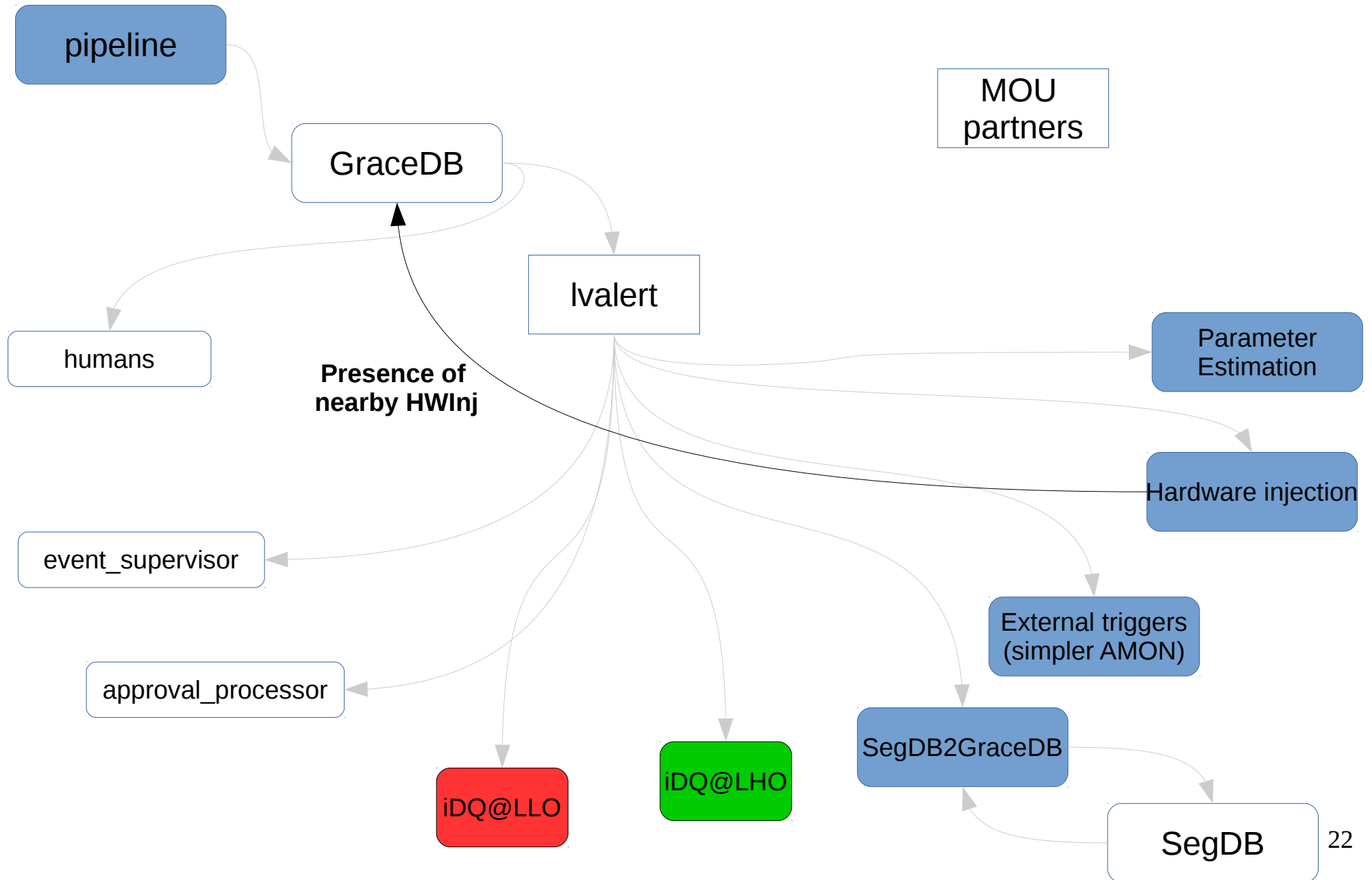
What follow-up is conducted internally?



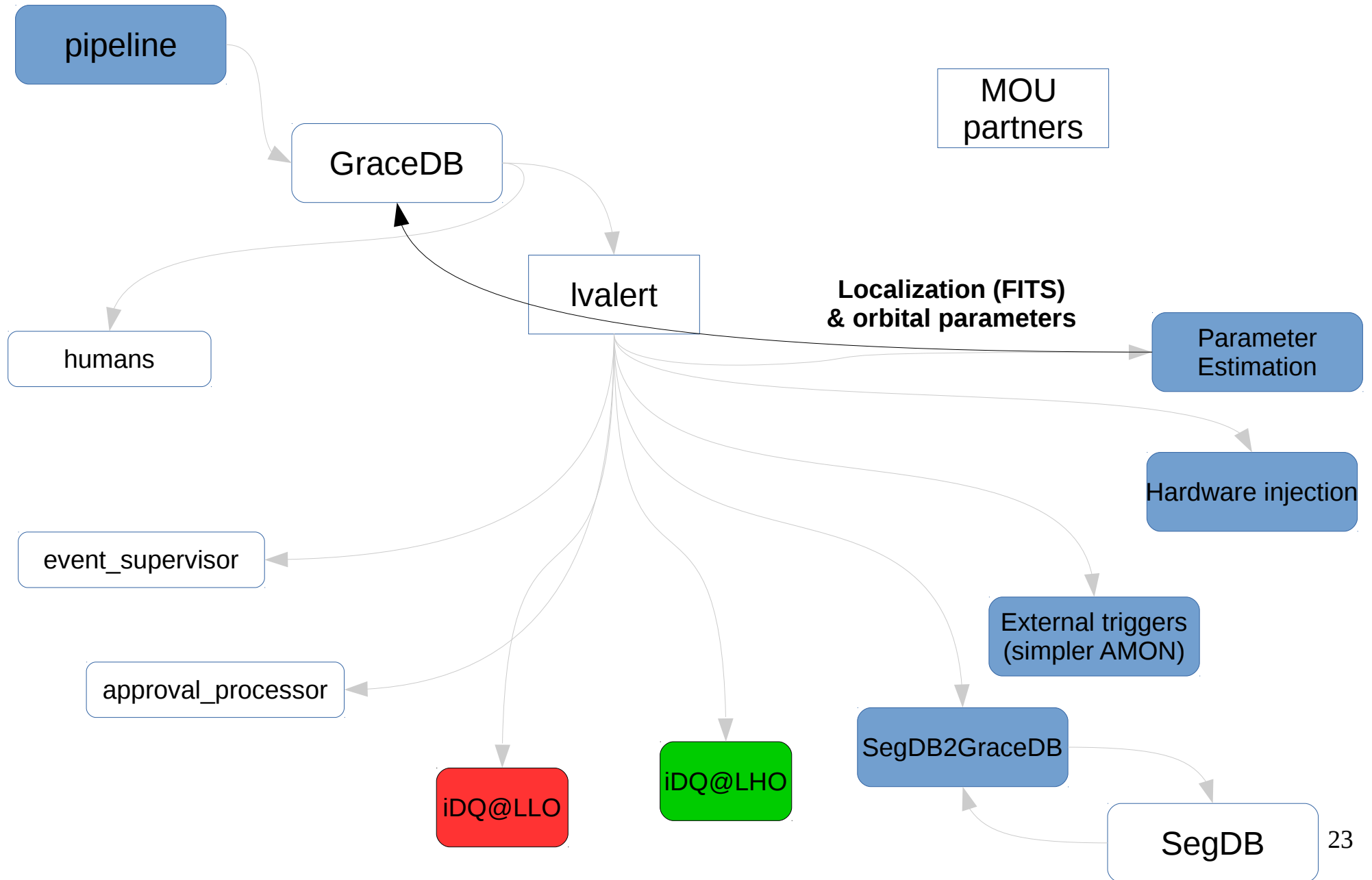
What follow-up is conducted internally?



What follow-up is conducted internally?

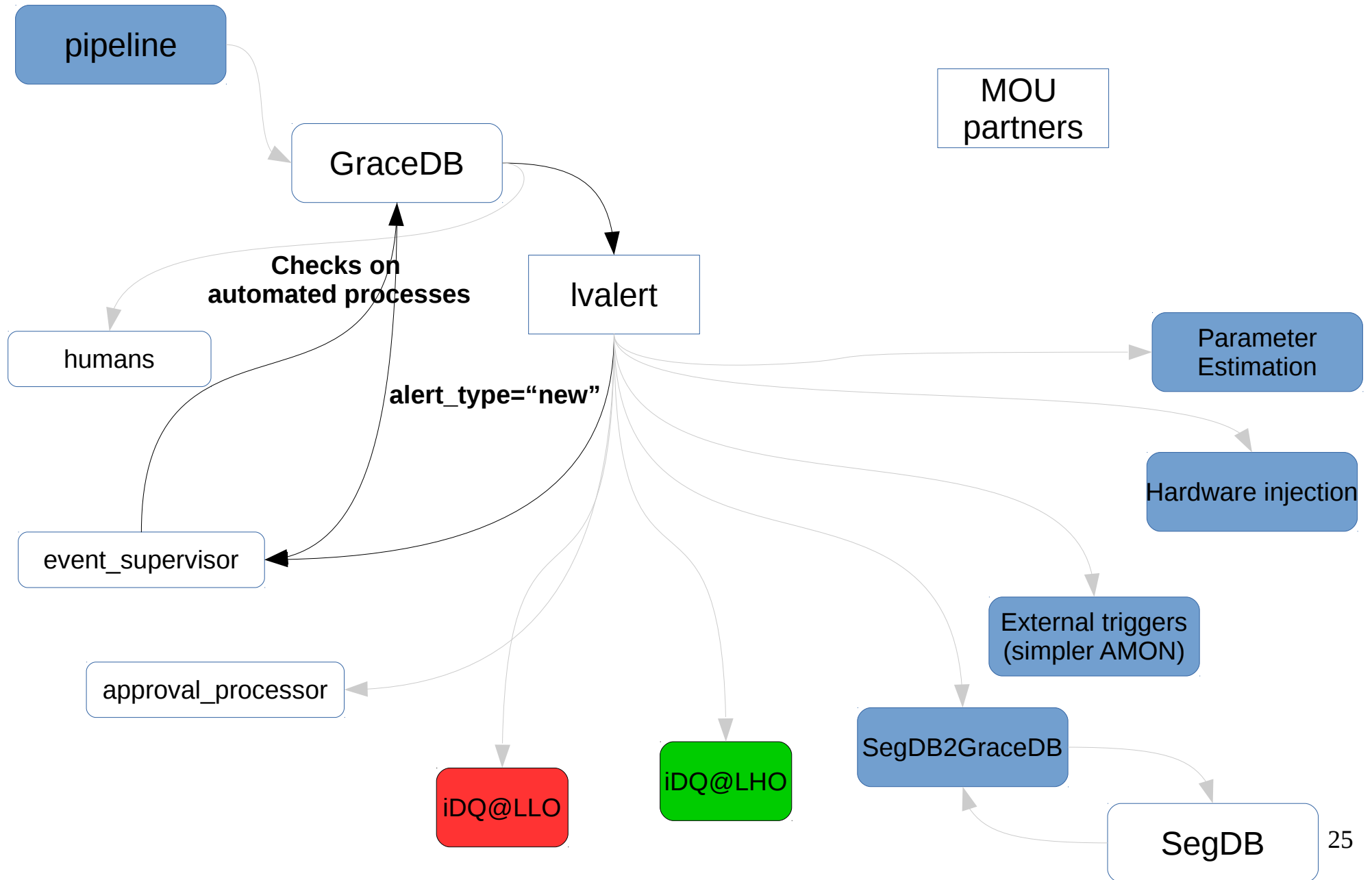


What follow-up is conducted internally?

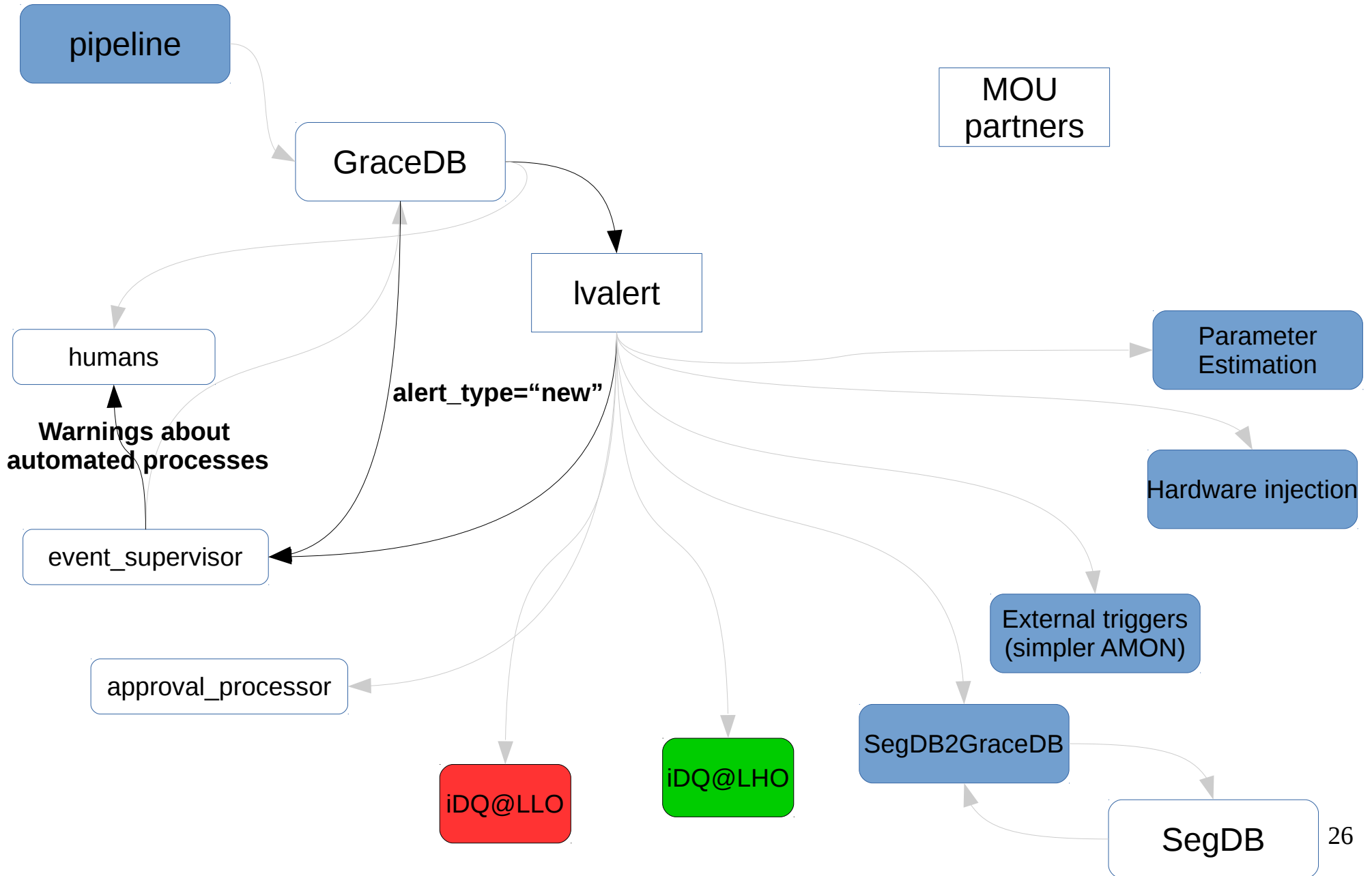




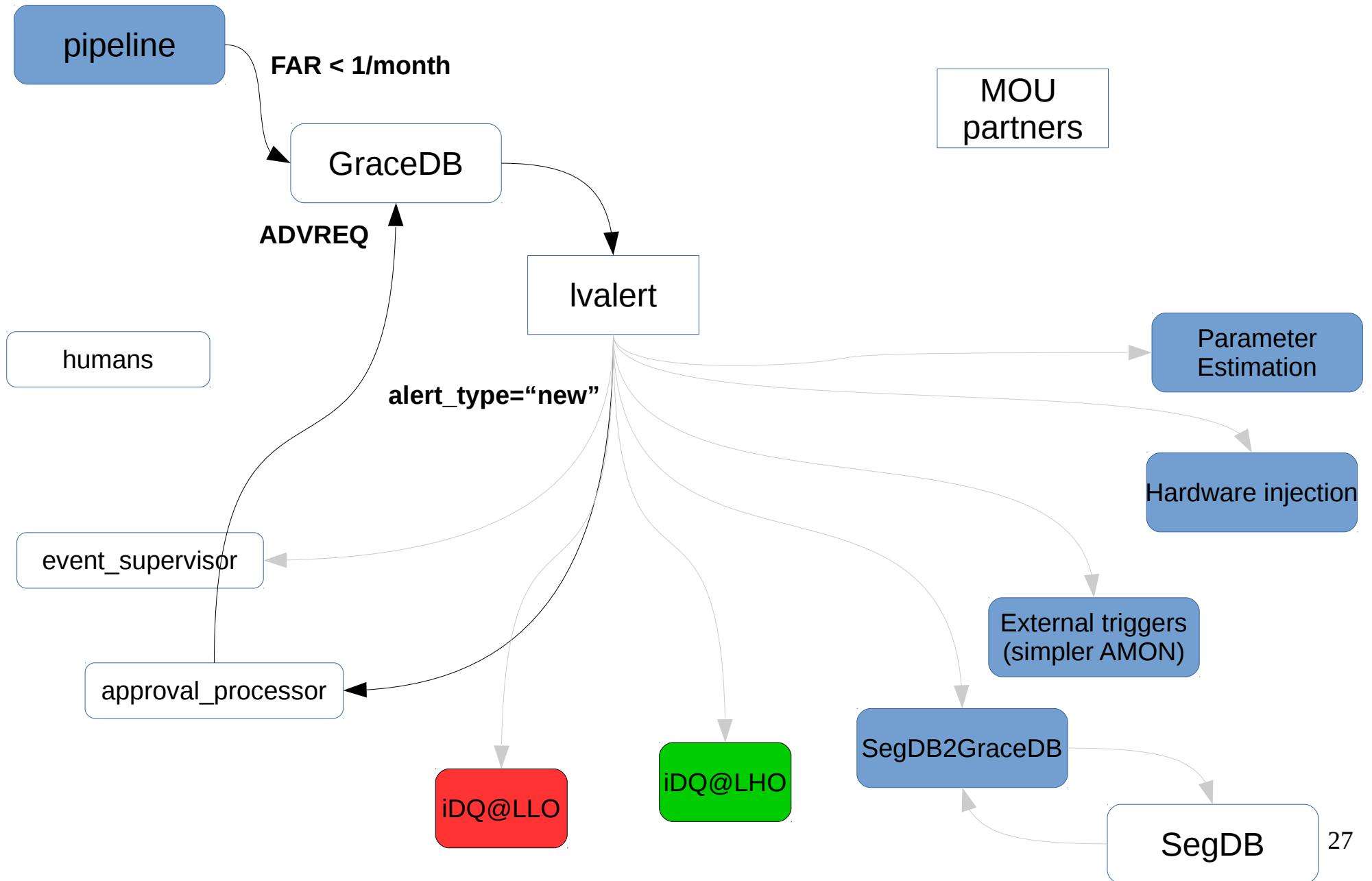
What follow-up is conducted internally?



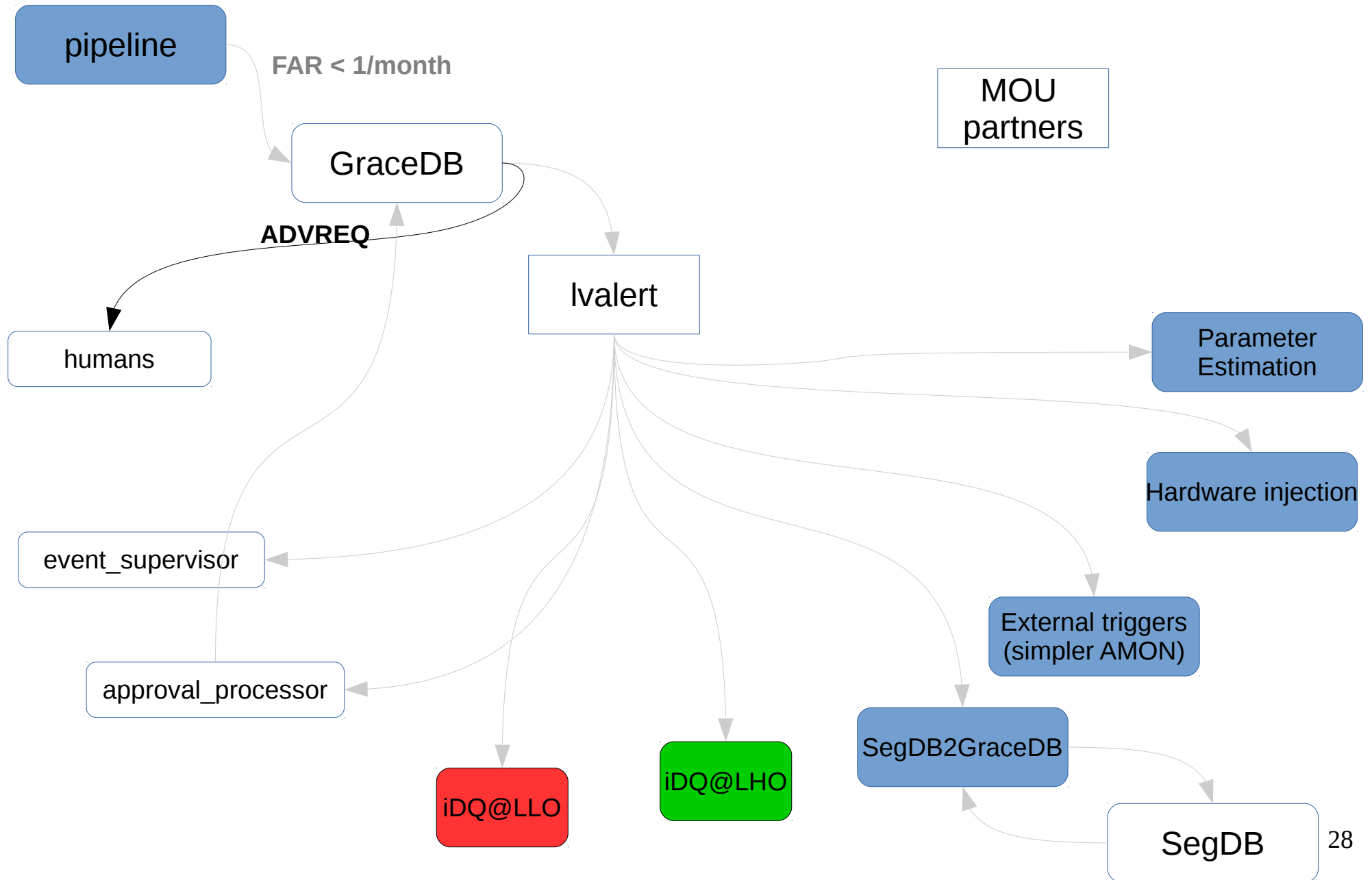
What follow-up is conducted internally?



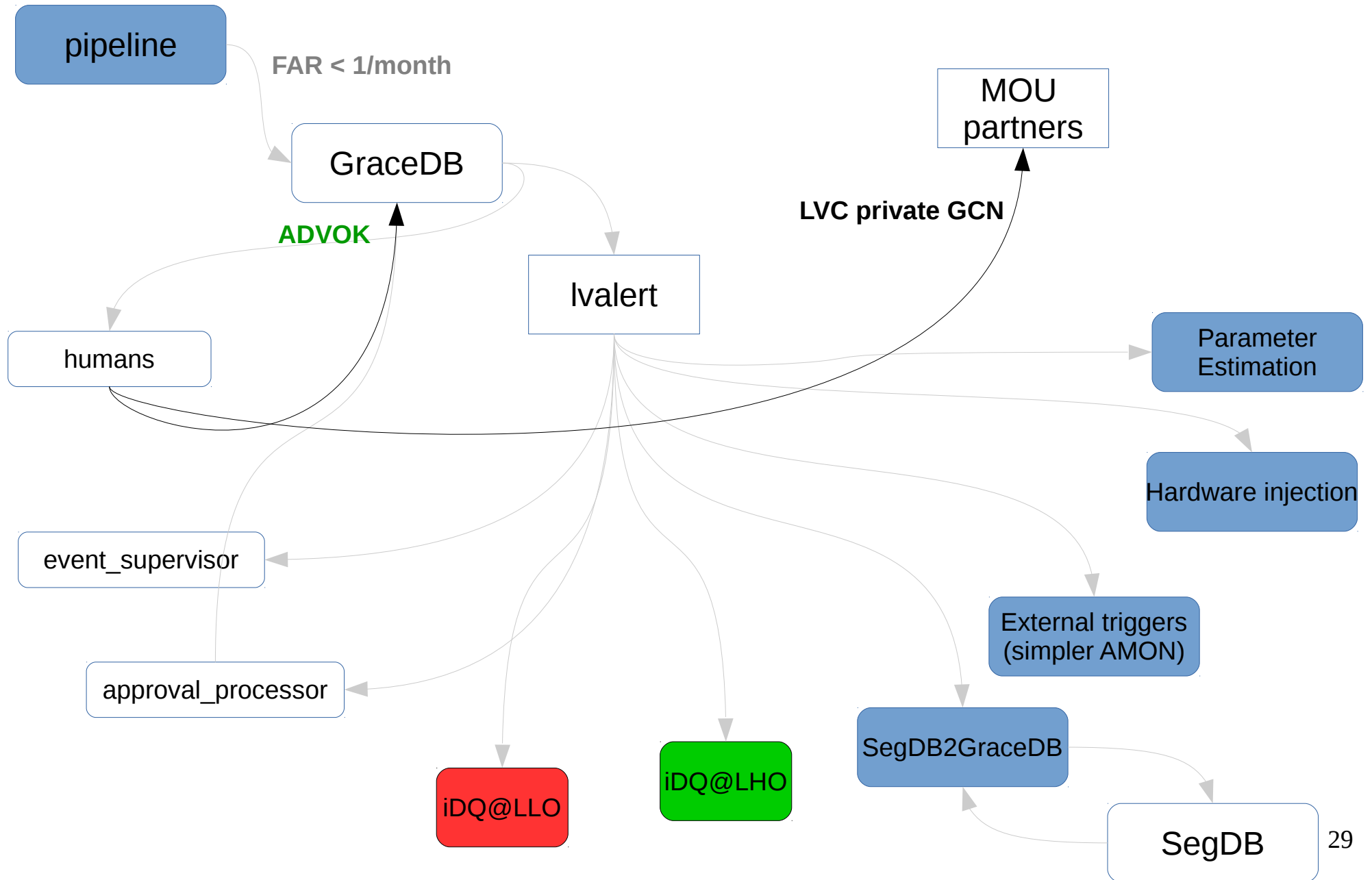
What follow-up is conducted internally?



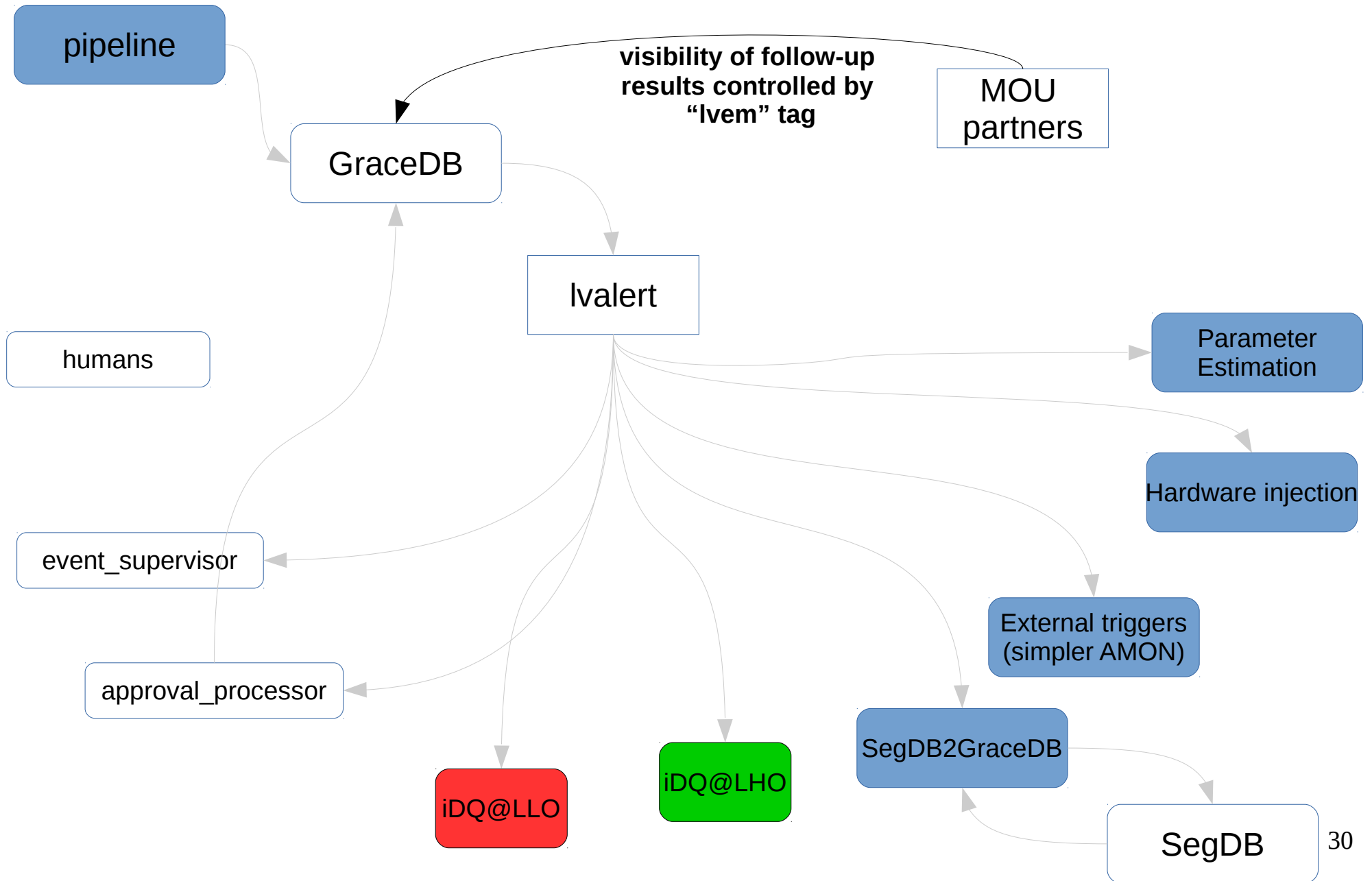
What follow-up is conducted internally?



What follow-up is conducted internally?



What follow-up is conducted internally?



What follow-up is conducted internally?

Basic information about the event

More detailed information
(parameters reported by search)

Neighboring events
(internal and external)

Comments and analysis input by hand

Localizations (HEALPix FITS files)
Follow-up footprints and EM
observations reported below

GraceDB — Gravitational Wave Candidate Event Database

| | | | | | | | | | |
|------|--------|--------|---------|-----|--------|---------|---------------|-------------------------------|--|
| HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION | AUTHENTICATED AS: REED ESSICK | |
|------|--------|--------|---------|-----|--------|---------|---------------|-------------------------------|--|

Basic Info

| UID | Labels | Group | Pipeline | Search | Instruments | GPS Time Event Time | FAR (Hz) | Links | UTC Submitted |
|----------|----------|-------|----------|--------|-------------|------------------------|-----------|----------------------|-------------------------|
| M2009014 | EM_READY | CBC | gstlal | MDC | H1,L1 | 968260901.3157 | 3.772e-14 | Data | 2015-12-04 16:00:09 UTC |

Coinc Tables

| | |
|-------------------------|--------------------|
| End Time (GPS) | 968260901.3157 s |
| Total Mass | 2.8543 M_{\odot} |
| Chirp Mass | 1.2059 M_{\odot} |
| SNR | 12.4075 |
| False Alarm Probability | 3.655e-08 |
| Log Likelihood Ratio | 1177125393310000 |

Single Inspirals Tables

| IFO | H1 | L1 |
|--------------------|-----------------------|-----------------------|
| Channel | GAUSSIAN | GAUSSIAN |
| End Time (GPS) | 968260901.315715717 s | 968260901.311128484 s |
| Template Duration | 25.8786291615 s | 25.8786291615 s |
| Effective Distance | 114.28889 Mpc | 140.0869 Mpc |
| COA Phase | 2.2572782 rad | -0.21591516 rad |
| Mass 1 | 1.7415119 M_{\odot} | 1.7415119 M_{\odot} |
| Mass 2 | 1.112743 M_{\odot} | 1.112743 M_{\odot} |
| η | 0.23786788 | 0.23786788 |
| F Final | 2047.0 Hz | 2047.0 Hz |
| SNR | 9.6287241 | 7.8252397 |
| χ^2 | 0.87733775 | 0.89437026 |
| χ^2 DOF | 1 | 1 |
| spin1z | 0.0 | 0.0 |
| spin2z | 0.0 | 0.0 |

Neighbors [-5,+5]

No neighbors in range.

Event Log Messages [add](#)

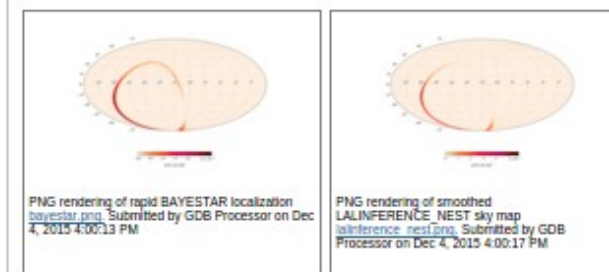
Analyst Comments

| LLO Local | Submitter | Comment |
|--|---------------|--|
| Log Entry Created Dec 4, 2015 10:00:11 AM | GDB Processor | This simulated detection candidate is a copy of event 19892 from the 2015 scenario of the "First Two Years" paper. |

Noise Curves

| LLO Local | Submitter | Comment |
|--|---------------|--|
| Log Entry Created Dec 4, 2015 10:00:11 AM | GDB Processor | strain spectral densities psd.xml.gz |

Sky Localization



| LLO Local | Submitter | Comment | |
|--|---------------|---|---------------------------------------|
| Log Entry Created Dec 4, 2015 10:00:32 AM | SkymapViewer | lal inference_nest.json | View in SkymapViewer! |
| Dec 4, 2015 10:00:22 AM | SkymapViewer | bayestar.json | View in SkymapViewer! |
| Dec 4, 2015 10:00:16 AM | GDB Processor | smoothed LALINFERENCE_NEST sky map lal inference_nest.fits.gz | |
| Dec 4, 2015 10:00:13 AM | GDB Processor | rapid BAYESTAR localization bayestar.fits.gz | |

EM Observations

How are candidates circulated externally?

Private GCN notices

- currently written by hand.

- contain at least one FITS file and brief description of event.

- an “initial” alert rather than a “preliminary” alert.

What is in the MOU?

- Privacy rules:

 - who owns what data and with whom can it be shared?

- Publication rules:

 - possible counterparts embargoed until GW event published.

 - LVC will provide “detailed information” prior to publication.

What follow-up is conducted internally?

Basic information about the event

More detailed information
parameters reported by search

Neighboring events
(internal and external)

Comments and analysis input by hand

Localizations (HEALPix FITS files)
Follow-up footprints and EM
observations reported below

GraceDB — Gravitational Wave Candidate Event Database

| | | | | | | | | | |
|------|--------|--------|---------|-----|--------|---------|---------------|-------------------------------|--|
| HOME | SEARCH | CREATE | REPORTS | RSS | LATEST | OPTIONS | DOCUMENTATION | AUTHENTICATED AS: REED ESSICK | |
|------|--------|--------|---------|-----|--------|---------|---------------|-------------------------------|--|

Basic Info

| UID | Labels | Group | Pipeline | Search | Instruments | GPS Time Event Time | FAR (Hz) | Links | UTC Submitted |
|----------|----------|-------|----------|--------|-------------|------------------------|-----------|----------------------|-------------------------|
| M2009014 | EM_READY | CBC | gstlal | MDC | H1,L1 | 968260901.3157 | 3.772e-14 | Data | 2015-12-04 16:00:09 UTC |

Coinc Tables

| | |
|-------------------------|--------------------|
| End Time (GPS) | 968260901.3157 s |
| Total Mass | 2.8543 M_{\odot} |
| Chirp Mass | 1.2059 M_{\odot} |
| SNR | 12.4075 |
| False Alarm Probability | 3.655e-08 |
| Log Likelihood Ratio | 1177125393310000 |

Single Inspirals Tables

| IFO | H1 | L1 |
|--------------------|-----------------------|-----------------------|
| Channel | GAUSSIAN | GAUSSIAN |
| End Time (GPS) | 968260901.315715717 s | 968260901.311128484 s |
| Template Duration | 25.8786291615 s | 25.8786291615 s |
| Effective Distance | 114.28889 Mpc | 140.0869 Mpc |
| COA Phase | 2.2572782 rad | -0.21591516 rad |
| Mass 1 | 1.7415119 M_{\odot} | 1.7415119 M_{\odot} |
| Mass 2 | 1.112743 M_{\odot} | 1.112743 M_{\odot} |
| η | 0.23786788 | 0.23786788 |
| F Final | 2047.0 Hz | 2047.0 Hz |
| SNR | 9.6287241 | 7.8252397 |
| χ^2 | 0.87733775 | 0.89437026 |
| χ^2 DOF | 1 | 1 |
| spin1z | 0.0 | 0.0 |
| spin2z | 0.0 | 0.0 |

Neighbors [-5,+5]

No neighbors in range.

Event Log Messages [add](#)

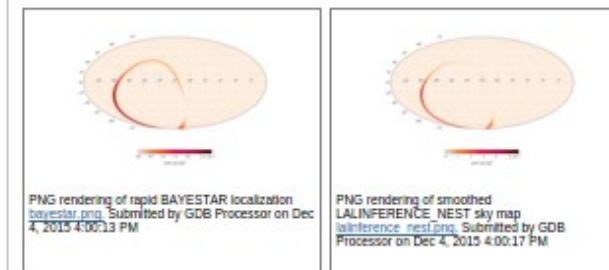
Analyst Comments

| | | |
|---|----------------------------|---|
| LLO Local Log Entry Created Dec 4, 2015 10:00:11 AM | Submitter GDB Processor | Comment This simulated detection candidate is a copy of event 19892 from the 2015 scenario of the "First Two Years" paper. |
|---|----------------------------|---|

Noise Curves

| | | |
|---|----------------------------|---|
| LLO Local Log Entry Created Dec 4, 2015 10:00:11 AM | Submitter GDB Processor | Comment strain spectral densities psd.xml.gz |
|---|----------------------------|---|

Sky Localization





| | | |
|---|---------------------------|--|
| LLO Local Log Entry Created Dec 4, 2015 10:00:32 AM | Submitter SkymapViewer | Comment lalinference_nest.json |
| Dec 4, 2015 10:00:22 AM | SkymapViewer | bayestar.json |
| Dec 4, 2015 10:00:16 AM | GDB Processor | smoothed LALINFERENCE_NEST sky map lalinference_nest.fits.gz |
| Dec 4, 2015 10:00:13 AM | GDB Processor | rapid BAYESTAR localization bayestar.fits.gz |

EM Observations

[View in SkymapViewer!](#)
[View in SkymapViewer!](#)

How is follow-up coordinated externally?


Skymap Viewer

A sky atlas for understanding LIGO-Virgo skymaps. Help [here](#), and skymaps [here](#). If you do not see the big dark sky map, look below and widen your browser. Zoom with the + and - at the right of the sky.

LIGO-Virgo Skymaps

This skymap is from GraceDB candidate **M205793**.
 50% area = 276.2 sq deg
 90% area = 954.0 sq deg



South North



☐ Show Weighted Galaxies (or [table](#)).

Time and Place


Universal time
 2010-10-12T17:59:47 Now

E Longitude East ID Latitude Latitude ID


Show Sky

Sun =  and  = Moon



Catalog Sources



Click the Layers icon  to switch on catalogs. If you click on the sources on the sky, information will appear here with links to Simbad and NED.

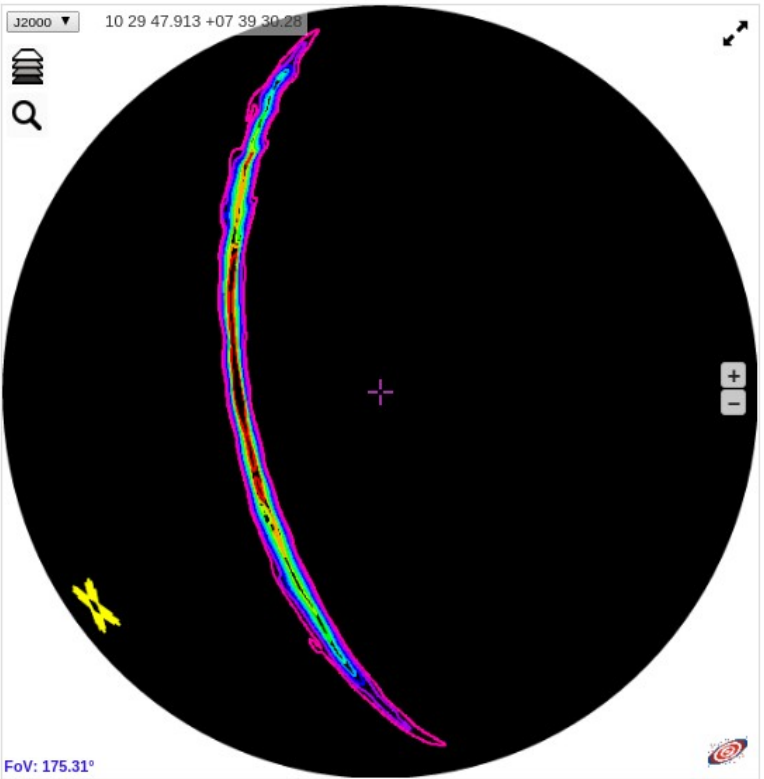
Zoomable Multiwavelength Sky

Zoom in on the sky with the mouse or the +/- icons on the right of the sky. To change the image layer, click the Layers icon  and select on Base image layer. Select the DSS rather than Mellinger to get better fine detail.


J2000 10 29 47.913 +07 39 30.26



FoV: 175.31°



34

How is follow-up coordinated externally?

Skymap Viewer

A sky atlas for understanding LIGO-Virgo skymaps. Help [here](#), and skymaps [here](#). If you do not see the big dark sky map, look below and widen your browser. Zoom with the + and - at the right of the sky.

LIGO-Virgo Skymaps

This skymap is from GraceDB candidate **M205793**.
 50% area = 276.2 sq deg
 90% area = 954.0 sq deg



South North

☐ Show Weighted Galaxies (or [table](#)).


Time and Place

Universal time
 2010-10-12T17:59:47


E Longitude East Id Latitude

Sun =  and  = Moon

Catalog Sources

Click the Layers icon  to switch on catalogs. If you click on the sources on the sky, information will appear here with links to Simbad and NED.

Zoomable Multiwavelength Sky

Zoom in on the sky with the mouse or the +/- icons on the right of the sky. To change the image layer, click the Layers icon  and select on Base image layer. Select the DSS rather than Mellinger to get better fine detail.

Skymap Viewer Interface:

Top: J2000 10 29 47.913 +07 39 30.26

Left: Search icon

Right: Zoom in (+) and Zoom out (-) icons

Bottom Left: FoV: 175.31°

Bottom Right: LIGO and Virgo logos

Electro-Magnetic
Bulletin Board (EMBB)
part of GraceDB accessible
by MOU partners.

EMBB Event Log (EEL)
Standardized format for
reporting observation
footprints to EMBB.

What to expect from LVC alerts

CBC alerts

Burst alerts

What to expect from LVC alerts

CBC alerts

Initial

- search's point estimates
- Bayestar localization

Updates

- LALInference posterior distributions
- LALInference localization

Burst alerts

What to expect from LVC alerts

CBC alerts

Initial

- search's point estimates
- Bayestar localization

Updates

- LALInference posterior distributions
- LALInference localization

Burst alerts

Initial

- search's point estimates
- cWB (or LIB PE) localization

Updates

- LIB PE localization
- BayesWave waveform reconstruction
- BayesWave localization

Public Data

Technical documentation, tutorials, and instructions for registering for LV-EM services

https://gw-astronomy.org/wiki/LV_EM/TechInfo

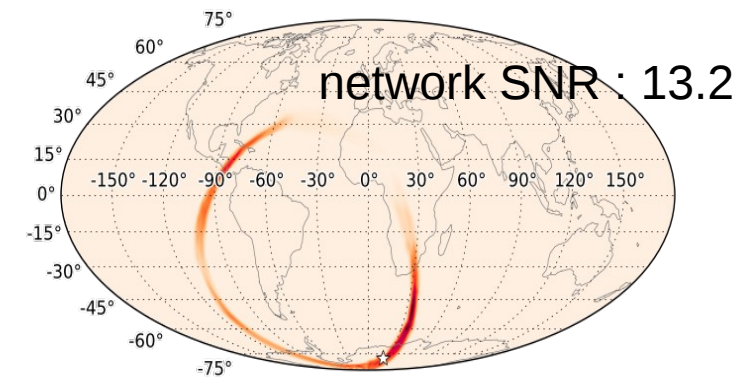
LIGO Open Science Center (LOSC) provides instructions on how to access and manipulate archival LIGO data. A variety of formats are provided as well data quality information.

S5 data : 2005 - 2007

S6 data : 2009 - 2010

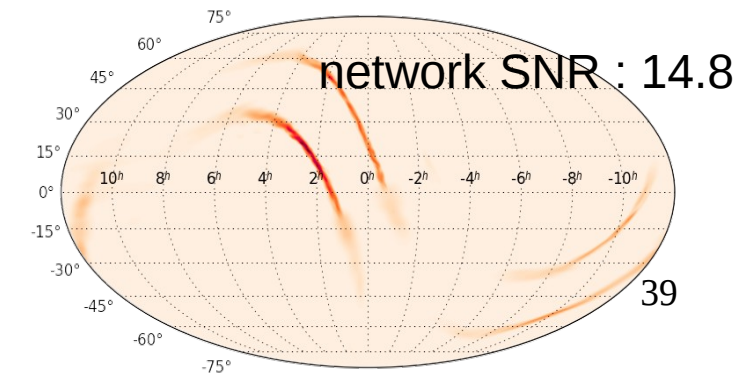
BNS F2Y OpenData : arXiv:1404.5623

A large-scale MDC study of detectability of BNS signals in both Gaussian and re-colored noise. Provides estimates on the expected detection rate as well as a large catalog of Bayestar and LALInference localizations.

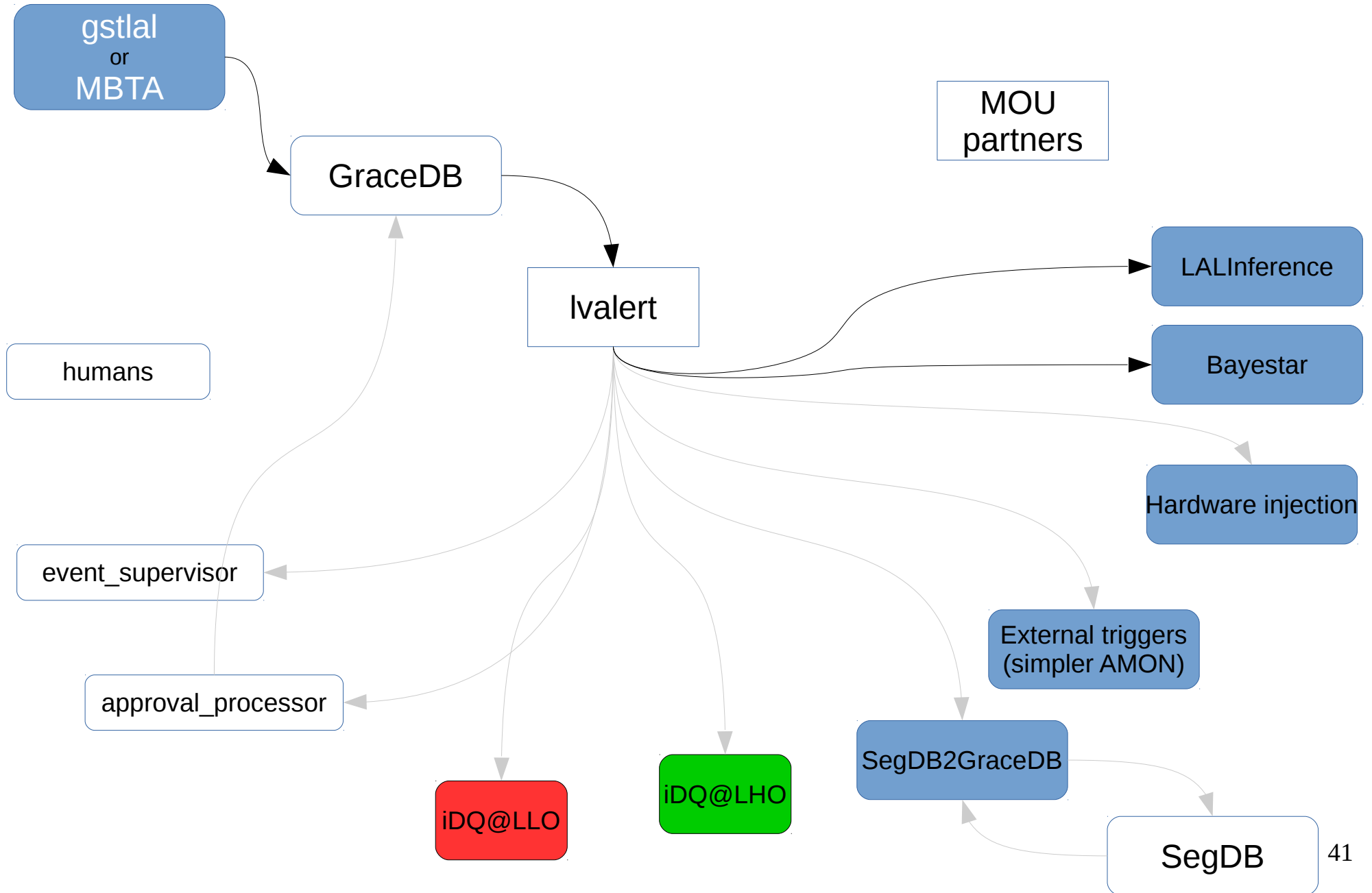


Burst F2Y OpenData arXiv:1409.2435

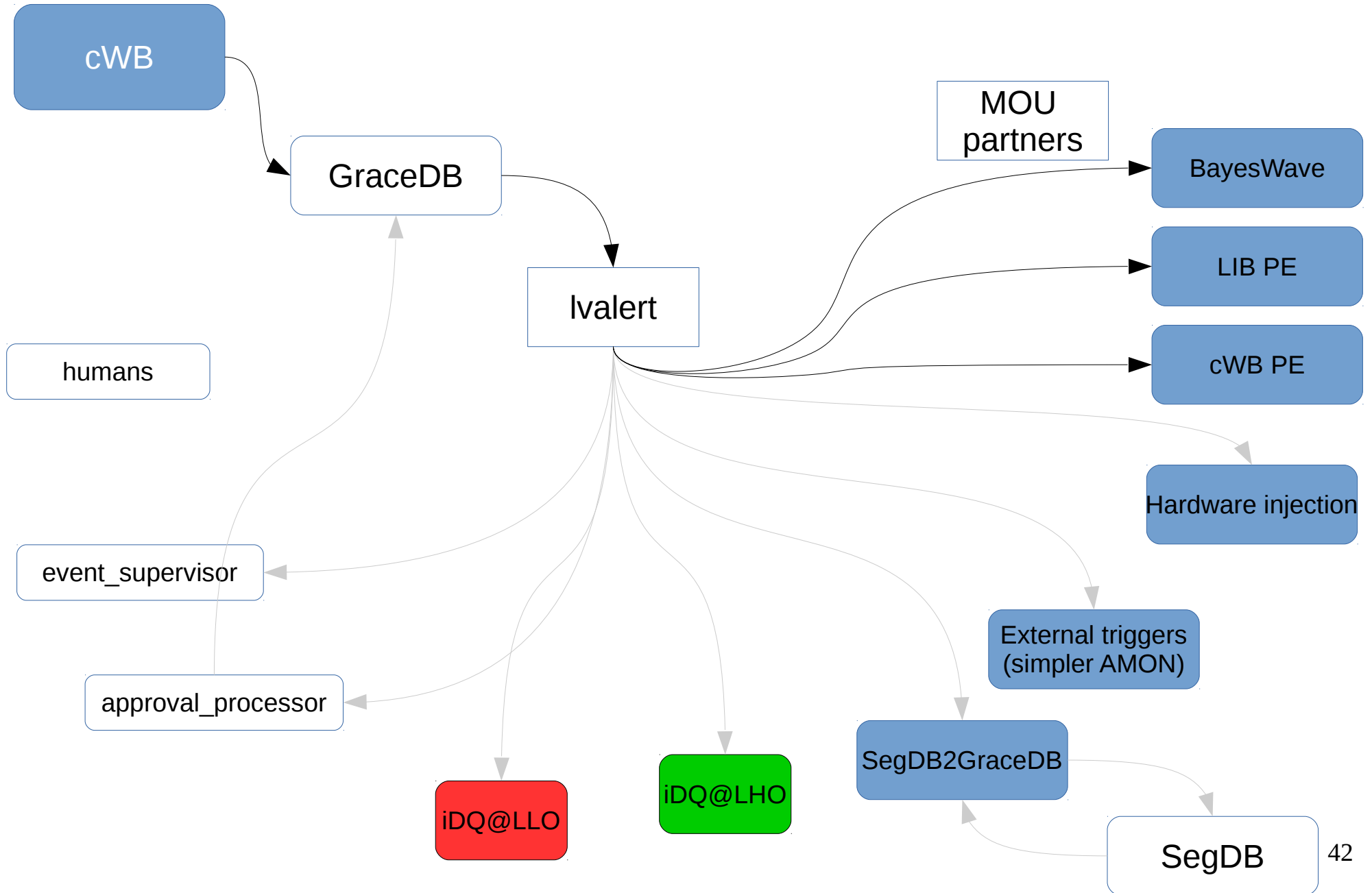
A large-scale MDC study of burst localizations in Gaussian noise. Makes no predictions for detection rate. Provides a large catalog of cWB and LIB localizations.



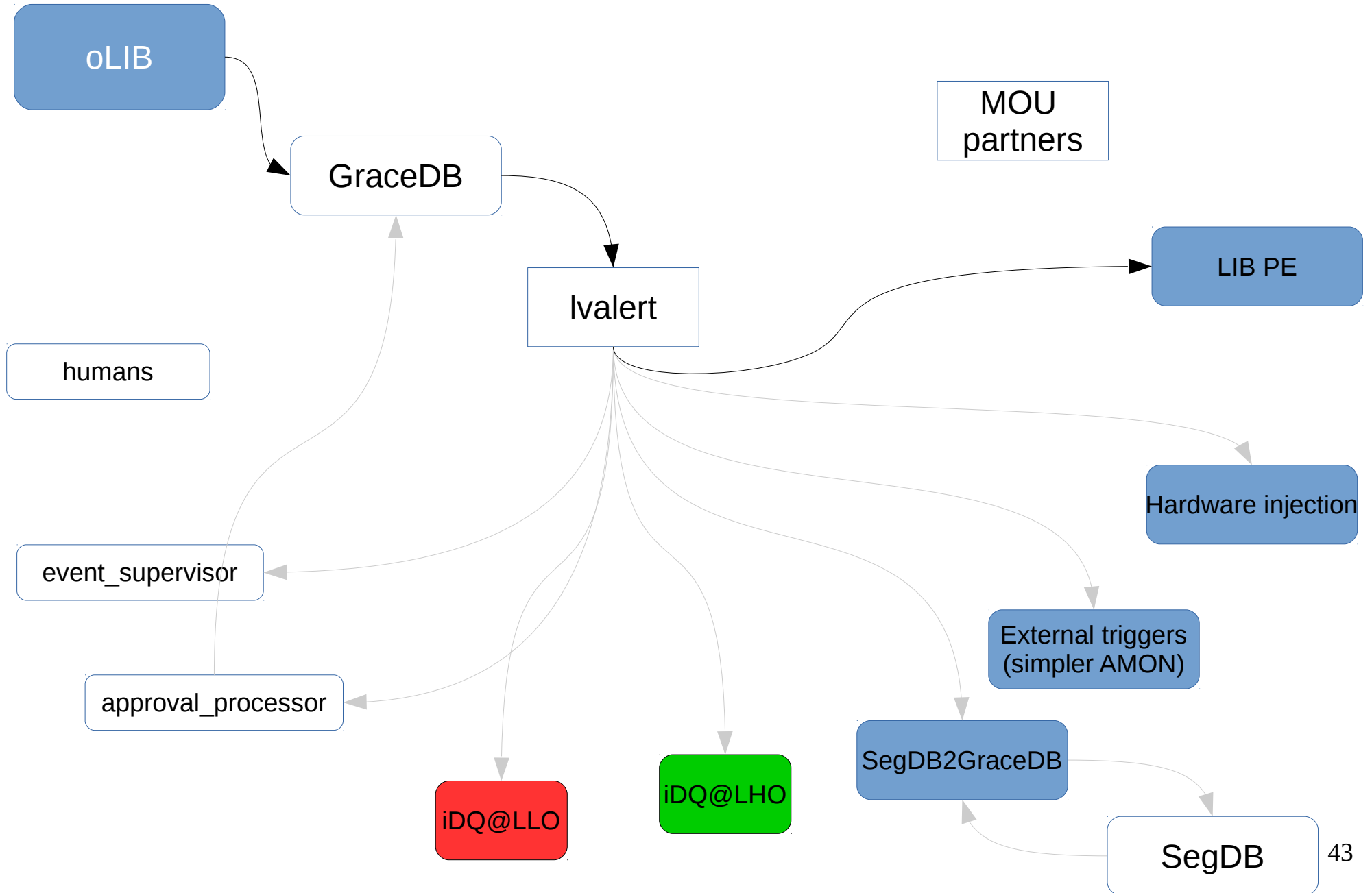
What follow-up is conducted internally?



What follow-up is conducted internally?



What follow-up is conducted internally?



Public Data

Technical documentation, tutorials, and instructions for registering for LV-EM services

https://gw-astronomy.org/wiki/LV_EM/TechInfo

LIGO Open Science Center (LOSC) provides instructions on how to access and manipulate archival LIGO data. A variety of formats are provided as well data quality information.

S5 data : 2005 - 2007

S6 data : 2009 - 2010

BNS F2Y OpenData

A large-scale MDC study of detectability of BNS signals in both Gaussian and re-colored noise. Provides estimates on the expected detection rate as well as a large catalog of Bayestar and LALInference localizations.

[Data release](#)
[2015, HL](#)
[2016, HL](#)
 [2015, recoloured](#)
[Show/hide columns](#)

The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo

 **Singer et al. 2014**
arXiv:1404.5623

 **Berry et al. 2015**
arXiv:1411.6934

This web page provides additional online material related to the paper "[The First Two Years of Electromagnetic Follow-Up with Advanced LIGO and Virgo](#)" and the follow-up paper "[Parameter Estimation for Binary Neutron-Star Coalescences with Realistic Noise During the Advanced LIGO Era.](#)"

These papers predict the detection, sky-localization, and parameter-estimation capabilities of the Advanced LIGO and Virgo gravitational-wave detector network through two early two- and three-detector configurations. The data release comprises a database of simulated signals, recovered detections candidates, and posterior probability maps resulting from Bayesian parameter estimation.



Instructions

You can use the tables in the [2015](#), [2016](#), and [2015, recoloured](#) tabs above to browse through all of the events and sky maps in the study. You can sort on any column by clicking its header, or show and hide columns using the [Show/hide columns](#) button above. You can also use this menu to switch the image previews between equatorial (RA, Dec) and geographic (longitude, latitude) coordinates with continent outlines.

Click any sky map thumbnail to open a larger version with a link to a FITS file representing the posterior in the [HEALPix](#) projection. The FITS files always use equatorial coordinates and the NESTED indexing scheme. For reading these files, the authors recommend the Python package [Healpy](#) or the official [HEALPix C/C++/IDL/Java/Fortran library](#). They can also be displayed by many standard imaging programs such as [DS9](#) and [Aladin](#).

In [WebGL capable browsers](#), there is also an option to show any sky map  [interactively in 3D](#).

Each table is also available in ASCII form in [Machine Readable Table \(CDS/VizieR\)](#) format. For reading these tables, the journal suggests several [Machine Readable Table readers](#), but

Public Data

Technical documentation, tutorials, and instructions for registering for LV-EM services

https://gw-astronomy.org/wiki/LV_EM/TechInfo

LIGO Open Science Center (LOSC) provides instructions on how to access and manipulate archival LIGO data. A variety of formats are provided as well data quality information.

S5 data : 2005 - 2007

S6 data : 2009 - 2010

BNS F2Y OpenData : arXiv:1404.5623

A large-scale MDC study of detectability of BNS signals in both Gaussian and re-colored noise. Provides estimates on the expected detection rate as well as a large catalog of Bayestar and LALInference localizations.

Burst F2Y OpenData arXiv:1409.2435

A large-scale MDC study of burst localization in Gaussian noise. Makes no predictions for detection rate. Provides a large catalog of cWB and LIB localizations.

Burst First2Years 2015 (LHO-LLO) two-detectors network 2016 (LHO-LLO-Virgo) three-detectors network

Localization of Short Duration Gravitational-wave Transients with the Early Advanced LIGO and Virgo Detectors

Read on arXiv
Essick et al, arXiv:1409.2435

Read on IOPscience
Essick et al, ApJ 800, 2

A catalog of HEALPix all-sky maps produced as part of the
[Burst First2Years localization characterization study](#).

This includes both the 2015 (LHO-LLO) two-detector network and the 2016 (LHO-LLO-Virgo) three-detector network, for all four morphologies considered:

sine-Gaussians (SG), Gaussians (G), White-noise Bursts (WNB), and Binary Black Holes (BBH).

We compare two localization algorithms, coherent WaveBurst (cWB) and LALInferenceBurst (LIB) over a set of astrophysically distributed injections detected by cWB. These injections cover a broad range of morphologies and probe very different frequency ranges and content. In particular, we discuss how signal morphology affect localization with examples taken from our data set. We also include typical localization results, focusing in the "searched area" as our main quantitative description.

We provide the full lists of detected injections as well as associated skymaps and injection parameters as part of the catalogs. Please browse through our thumbnail galleries ([2015](#), [2016](#)) or download tarballs below and investigate the FITS files yourself.

2015 G

256 cWB maps
256 LIB maps

[View gallery](#)

[Download catalog](#)

2015 SG

1112 cWB maps
1112 LIB maps

[View gallery](#)

[Download catalog](#)

2015 WNB

769 cWB maps
769 LIB maps

[View gallery](#)

[Download catalog](#)

2015 BBH

2488 cWB maps
500 LIB maps

[View gallery](#)

[Download catalog](#)

Lessons learned during O1

Latencies associated with pipelines and follow-up processes.

What needs to be monitored.

What can be automated.

Glitch background and how it affects searches.

Planned improvements for O2+

Update/improve approval_processor → send alerts without human verification?

Update/improve event_supervisor (mostly internal)

Improve DQ, it's “verbosity” and it's application to searches
(reinstate streaming iDQ to CIT, GraceDB reports, etc)

Improve automated skymap comparison to reject glitches

Misc stuff, else? generic “improve pipelines”

references/pointers