

Follow-up of gravitational waves alerts with IACTs using Astro-COLIBRI

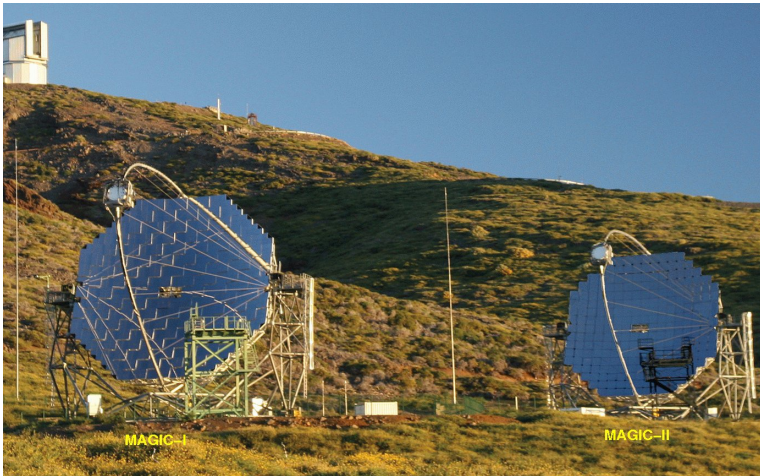
Mathieu de Bony

on behalf of the Astro-COLIBRI team (Fabian Schüssler, Patrick Reichherzer, Atilla Alkan, Jayson Mourier)
and on behalf of the tilepy team (Fabian Schüssler, Monica Seglar Arroy, Halim Ashkar, Jayson Mourier)



IACTs

Observe Very High Energy gamma-rays (> few tens of GeV)

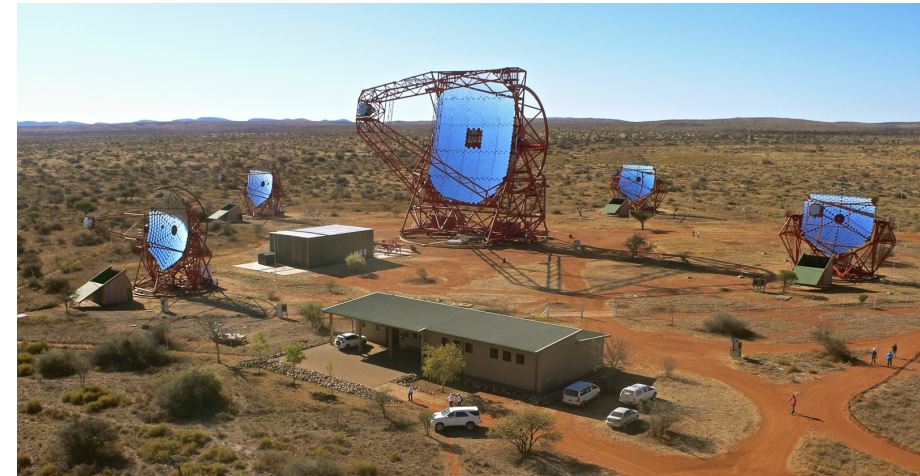


MAGIC

2 x 18m telescopes
FoV ~ 2.5 deg

H.E.S.S.

4 x 12 m telescopes
+ 28 m telescope
FoV ~ 5 deg

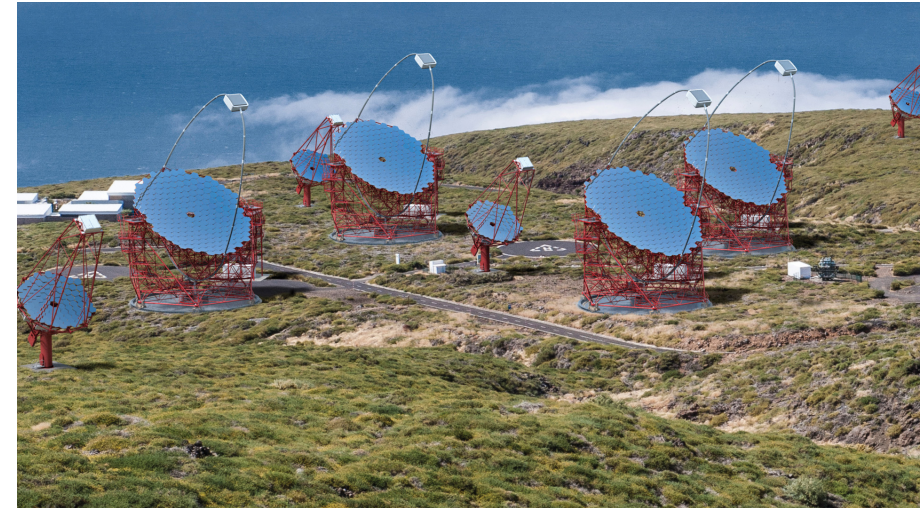


VERITAS

4 x 12m telescopes
FoV ~ 3.5 deg

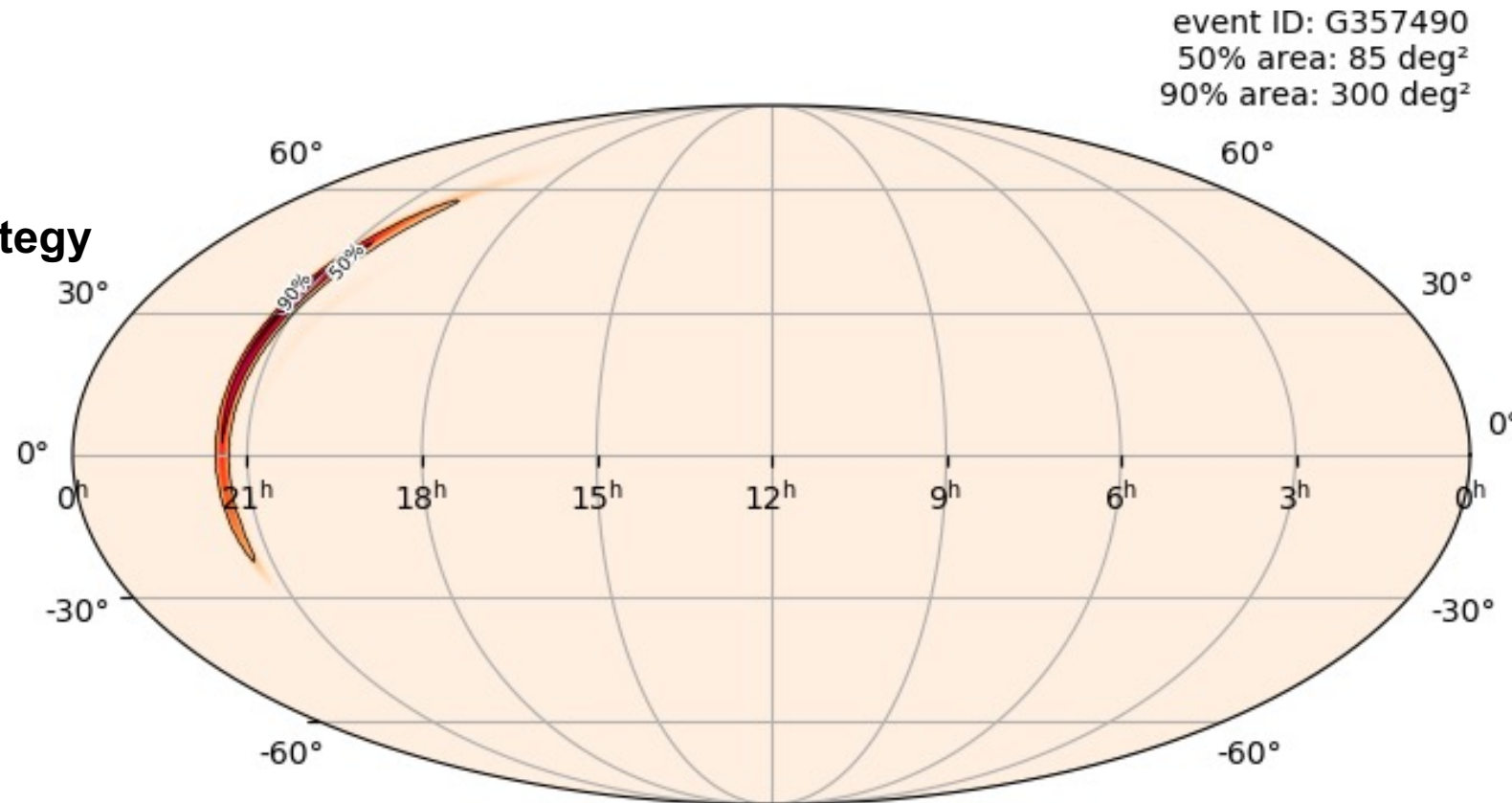
CTA

2 sites
> 64 telescopes
3 size of telescopes
FoV ~ 5 to 10 deg



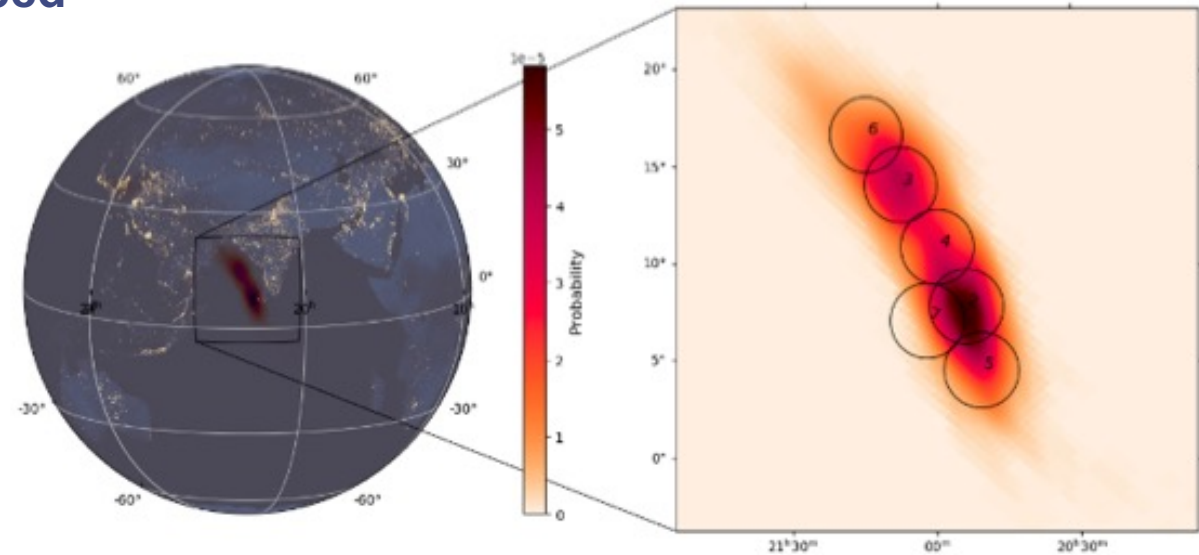
Challenge of GW follow-up

- Large localisation uncertainty
- Small FoV
- Covering the uncertainty region requires a smart observation strategy



Tiling

- Observation of multiple tiles to cover the uncertainty region
- A python software called tilepy has been developed at IRFU / CEA Paris-Saclay since 2016
 - Currently used by H.E.S.S. and LST-1



GW190915_235702 ($R_{\text{FoV}}=2^\circ$)

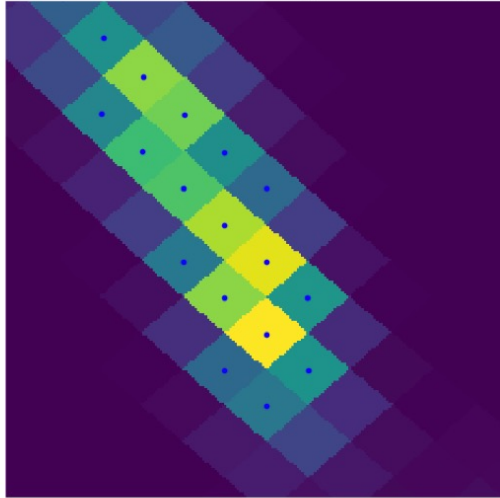
(M. Seglar-Arroyo, 2022)

2D algorithm



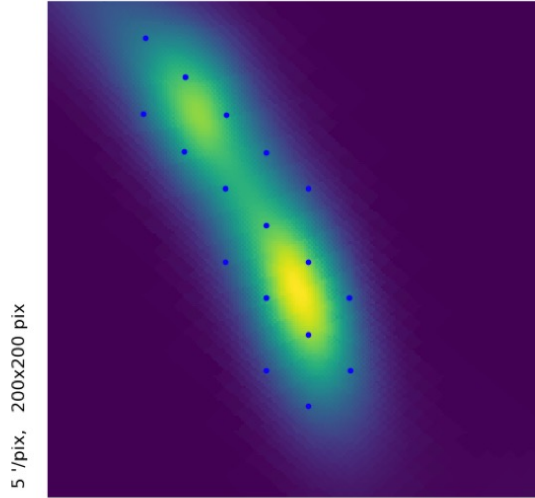
■ Iterative algorithm based on spatial information

1: Coordinate grid using low res maps



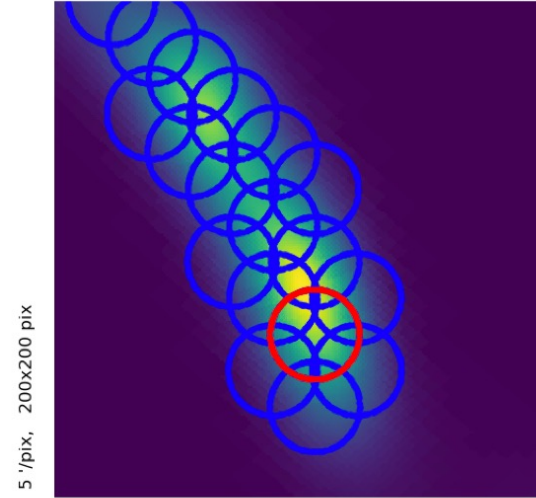
1.55e-10 0.0457 ρ_i

2: Grid used as FoV pointing centers



1.51e-13 5.81e-05 ρ_i

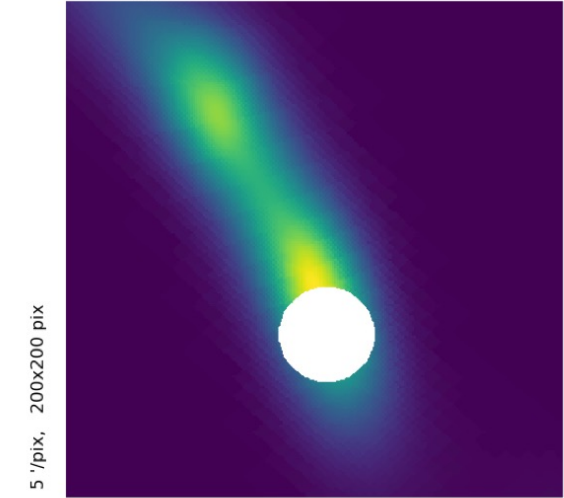
3: P_{GW}^{FoV} computation with high res maps



1.51e-13 5.81e-05 ρ_i

Ashkar et al., ICRC 2021

4: $P_{GW}^{FoV, MAX}$ FoV selected then masked



1.51e-13 5.81e-05 ρ_i



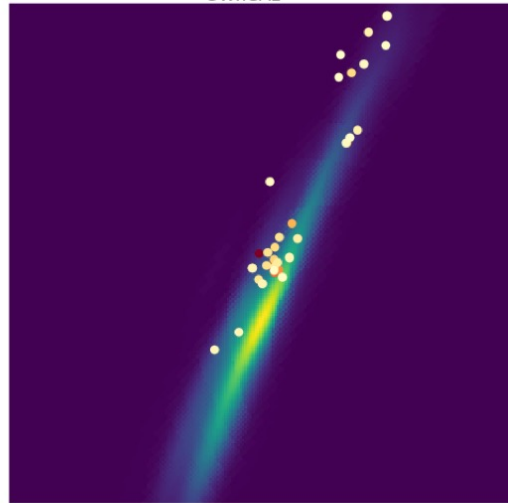
3D algorithm

- Correlation of the spatial and distance information with Glade+ galaxy catalog
 - Compute probabilities for each galaxy
- Iterative process based on galaxy position

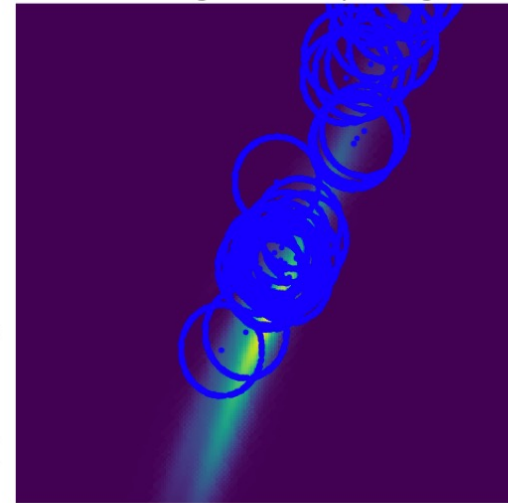


Ashkar et al., ICRC 2021

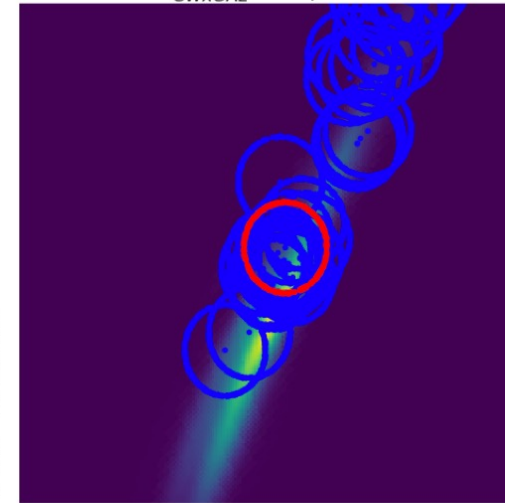
1: Calculate P_{GWxGAL}^i for each galaxy



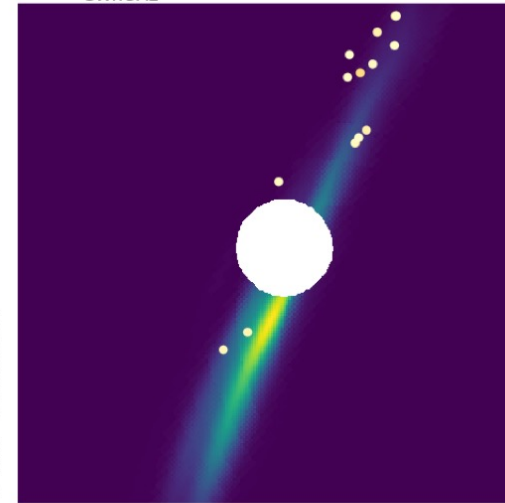
2: Choose the galaxies as pointing seeds



3: P_{GWxGAL}^{FoV} computation

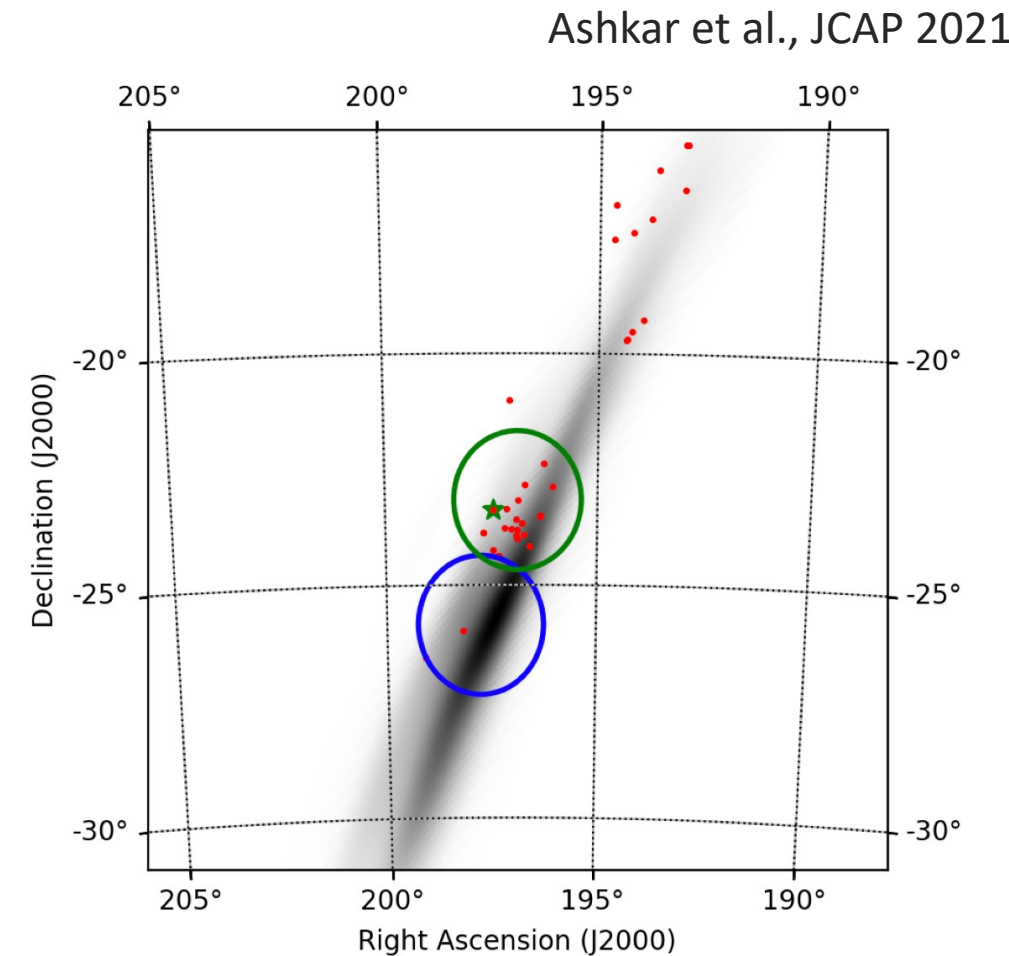


4: $P_{GWxGAL}^{FoV, MAX}$ FoV selected then masked



GW 170817

- **Coincidence EM/GW**
 - BNS merger detected by LIGO/Virgo
 - Short GRB detected by Fermi/GBM
- **Poor localisation from both instruments**
- **With the help of tilepy, H.E.S.S. was the first ground based instrument to point in the direction of the true position of the merger**



Tilepy



- **Publication in 2021**
The H.E.S.S. gravitational wave rapid follow-up program, Ashkar et al., JCAP 2021
DOI : [10.1088/1475-7516/2021/03/045](https://doi.org/10.1088/1475-7516/2021/03/045)
- **Proceeding at ICRC 2023**
tilepy: rapid tiling strategies in mid/small FoV observatories, Schüssler et al., ICRC 2021
DOI : [10.22323/1.444.1590](https://doi.org/10.22323/1.444.1590)
- **Preliminary code release on github** : <https://github.com/astro-transients/tilepy>
 - Documentation ongoing
 - Refactoring of the code is starting



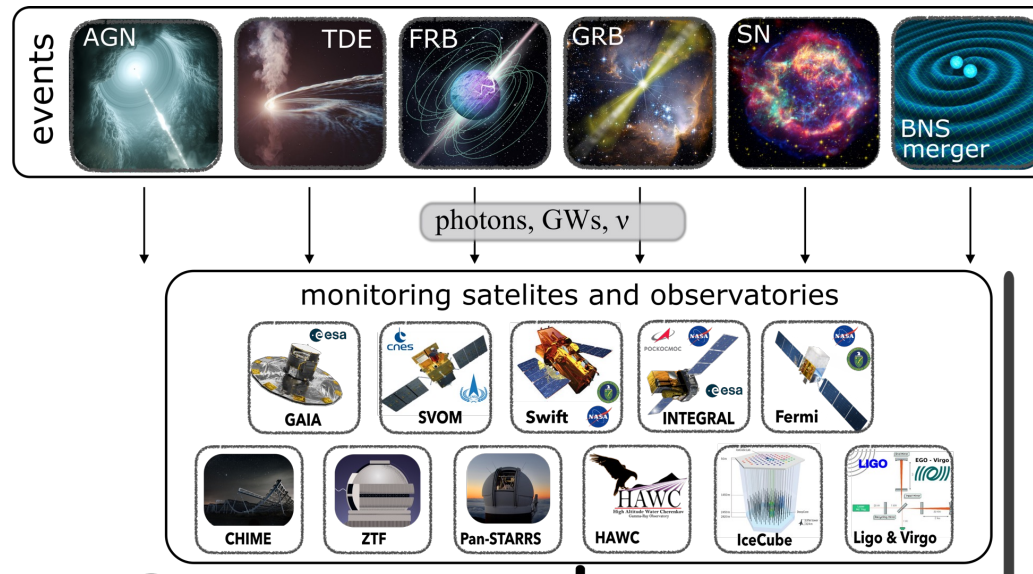
Tilepy in the cloud

- Tilepy is now running in the cloud
 - No need for local installation
 - No need to download the GW localisation map
 - Should work with slow internet connection



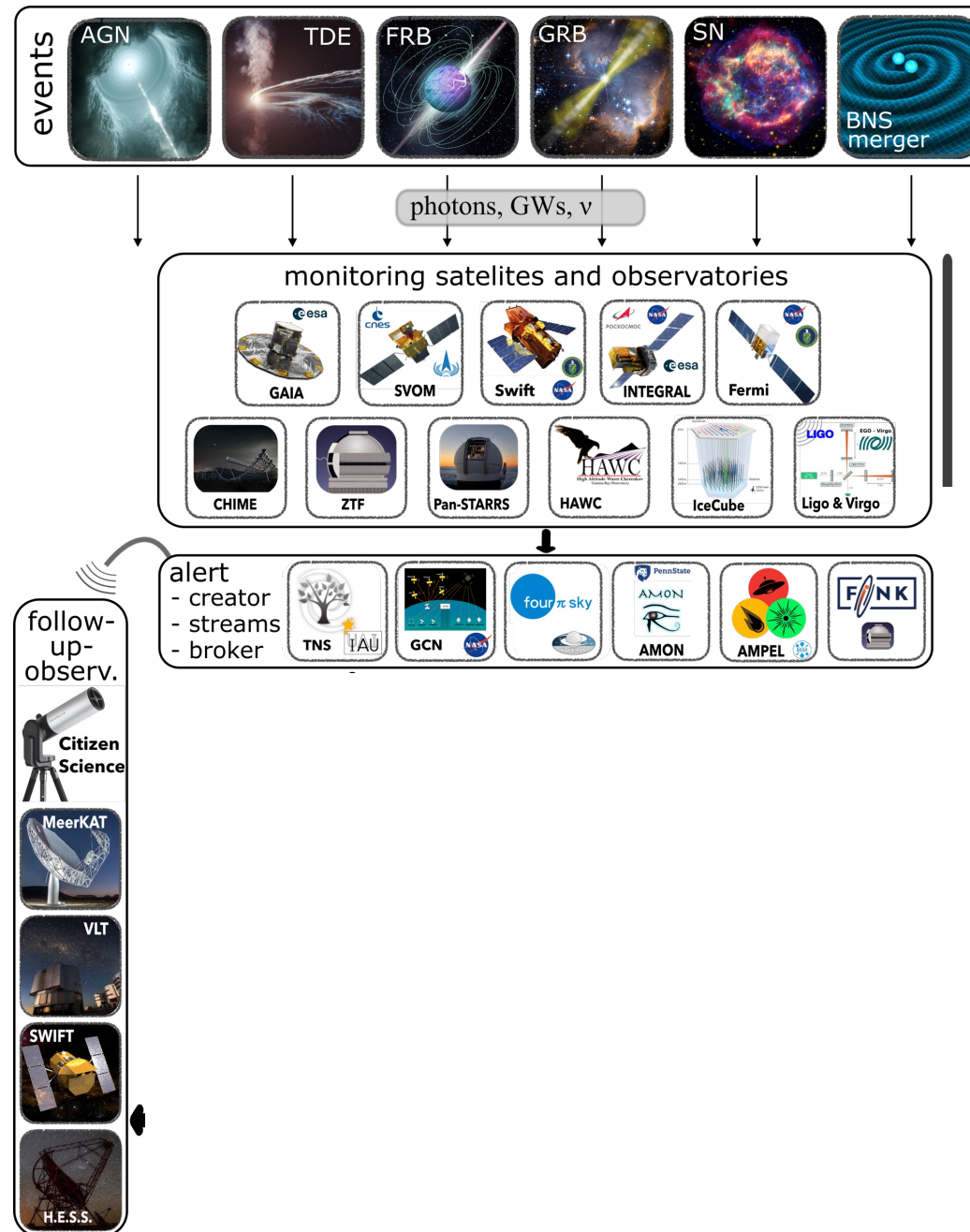
Astro-COLIBRI

A tool for transient astronomy



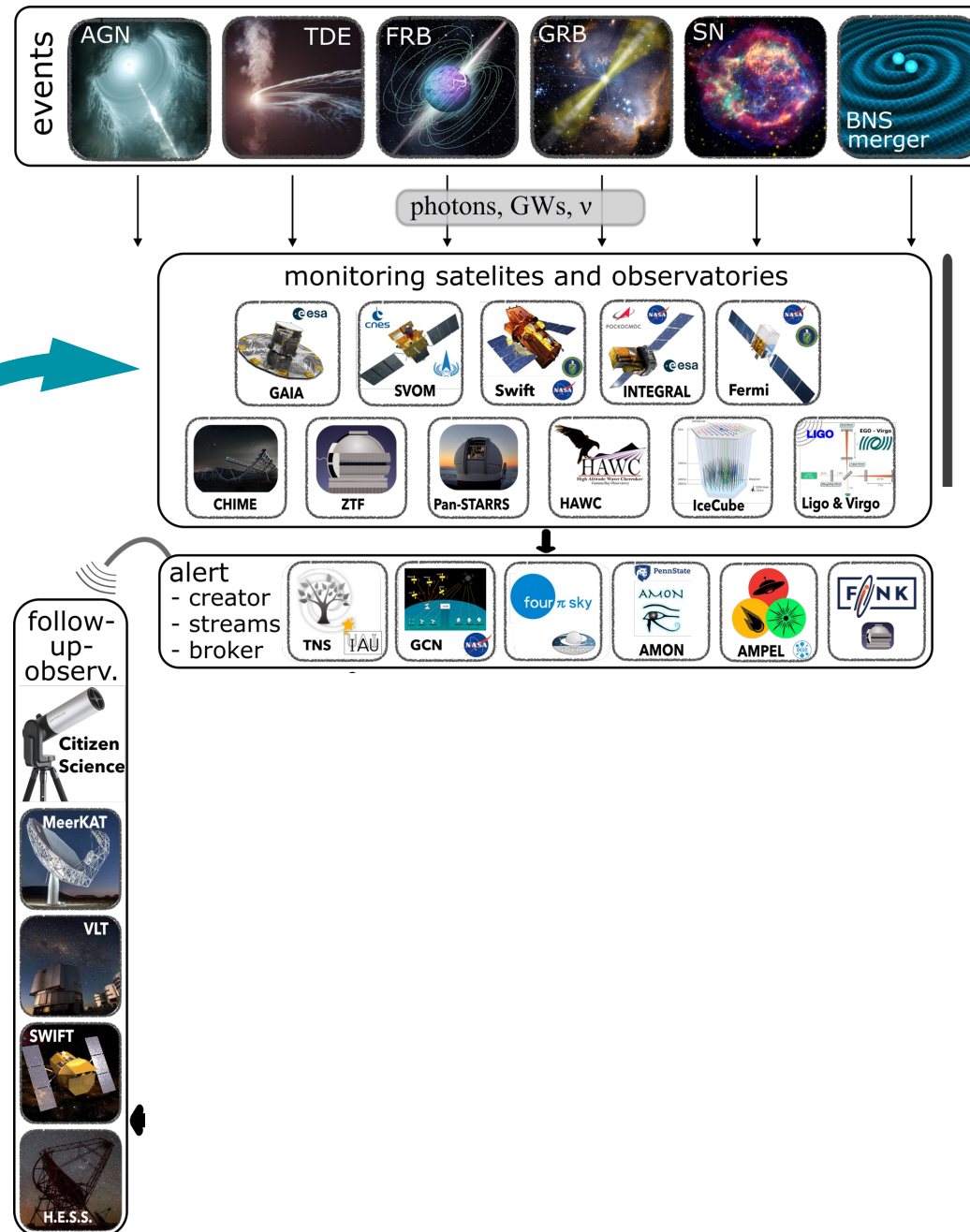
Astro-COLIBRI

A tool for transient astronomy



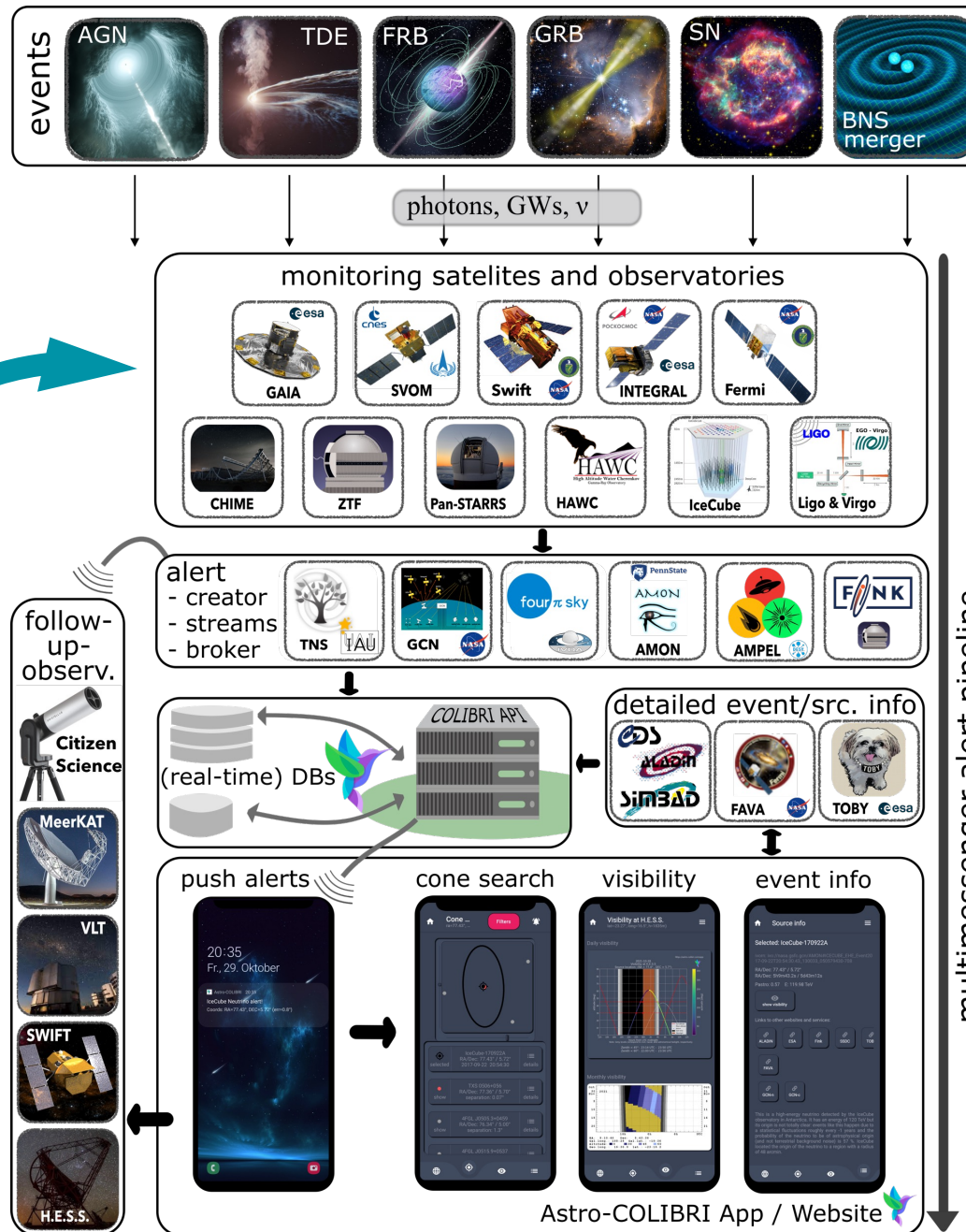
Astro-COLIBRI

A tool for transient astronomy



Astro-COLIBRI

A tool for transient astronomy



multimesenger alert pipeline

Astro-COLIBRI functionality

- Website and mobile application
- Observability assessments for predefined and custom observatory
- Link to external services for each event (FAVA, Fink, TNS,)
- Filtering of the events
(new update with more functionality will arrive soon)
- Notification of new events on your smartphone
- Sharing events with other people
-



Website : astro-colibri.science

Android Play Store

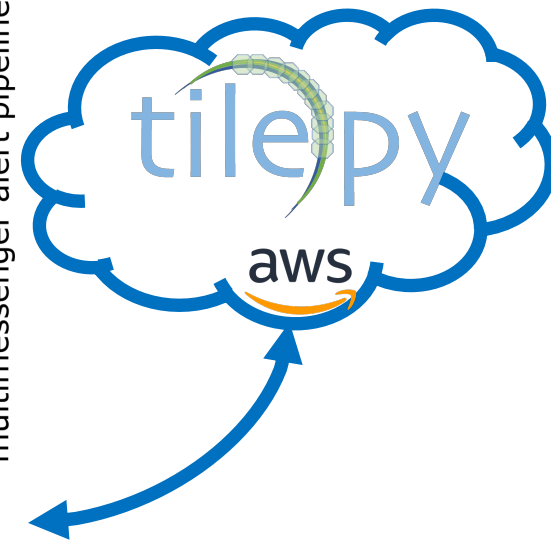
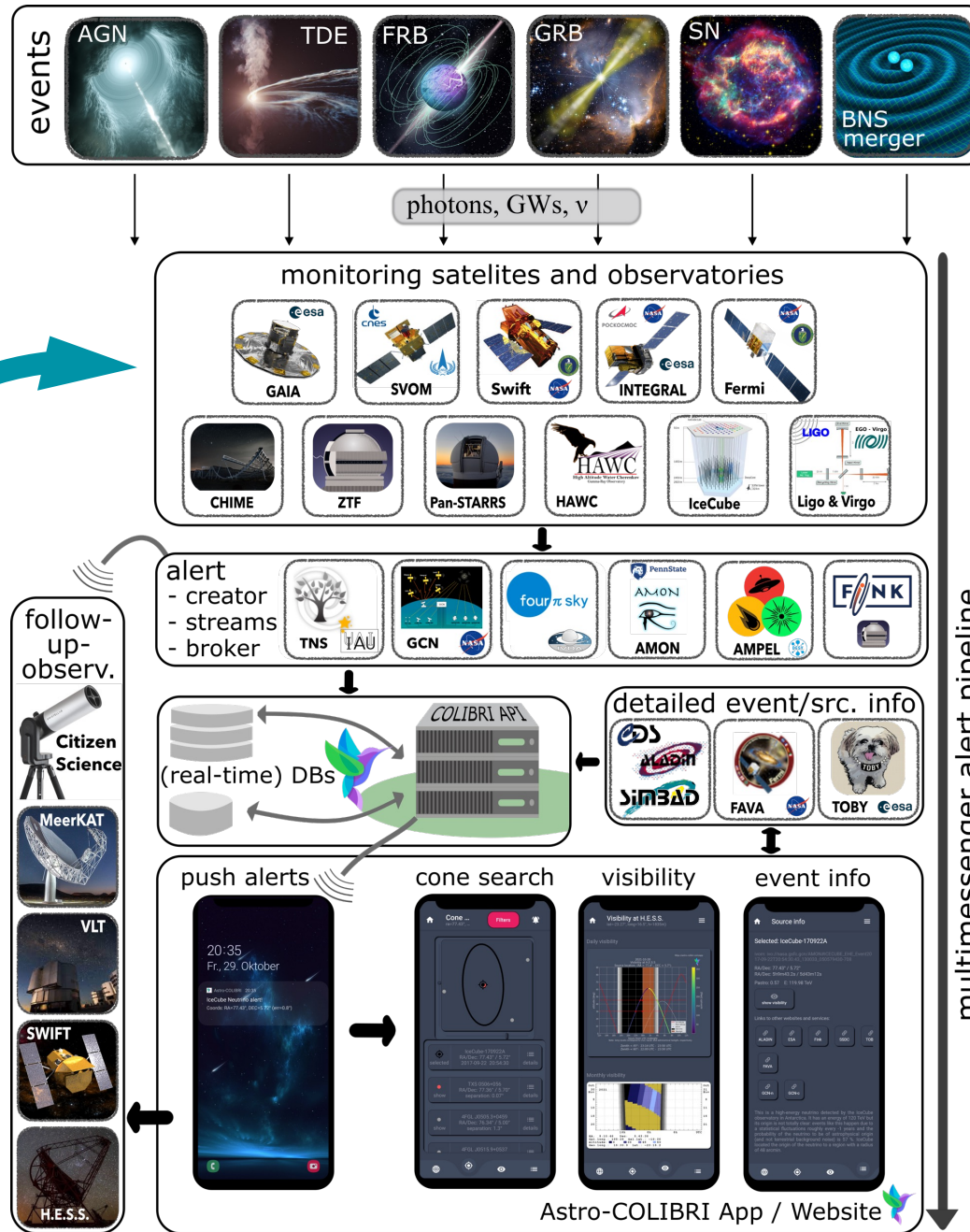


Apple iOS App Store



Astro-COLIBRI

A tool for transient astronomy



multimessenger alert pipeline

Tiling with Astro-COLIBRI

The web interface

The screenshot displays the Astro-COLIBRI web interface. At the top, there's a navigation bar with the logo, 'Select action' (Latest transients, Cone search), and user status (logged out, v2.4.2). Below this are filter bars for Observatories (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, FLAapLUC, LVC, other) and Event type (FRB, OT, SN, GRB, burst, neutrino, nuem, GW, 4FGL, TeVCAT, SGR/AXP, IceCat). A timeline shows dates from 2023-03-01 to 2023-04-07. The main content area is divided into several panels:

- Left Panel:** A vertical list of event cards. The top card is for GRB 230405B (Gamma-ray burst) with RA/Dec: 276.86°/-50.27° (± 1.58°) and time 2023-04-05 19:58:03. Below it are SN 2023eod (Supernovae optical), GRB 230405A (Gamma-ray burst), IceCube-230405A (Neutrino), and SN 2023eoa (Supernovae optical).
- Center Panel:** A star map showing a custom cone search around RA 120.85° and Dec 9.75°. The map includes a 'Cone search' button and a radius of 2.97°.
- Right Panel:** Detailed information for the selected source, IceCube-230405A. It includes detection time (2023-04-05 13:20:20), localisation (RA: 8h3m23.98s, Dec: 9d45m0s, error: 2.9700), and energy (E: 110.43 TeV). A text block explains that this is a high-energy neutrino detected by IceCube in Antarctica, with an energy of 110 TeV and a 30% probability of being of astrophysical origin. It also provides links for ATels, Twitter (@AstroColibri), and further details.
- Bottom Panel:** A row of links for further details, including ALADIN (interactive sky atlas), ESASky (interactive sky atlas), Fink (real-time transient classification), ASAS-SN (photometric lightcurves), and AAVSO (lightcurves collected by amateur astronomers).

Tiling with Astro-COLIBRI

The web interface

Activate science mode

The screenshot displays the Astro-COLIBRI web interface. At the top, there is a navigation bar with the logo, 'Select action' (Latest transients, Cone search), and user status (logged out, v2.4.2). Below this is a filter bar for observatories (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, FLaapLUC, LVC, other) and event types (FRB, OT, SN, GRB, burst, neutrino, nuem, GW, 4FGL, TeVCAT, SGR/AXP, IceCat). A timeline shows events from 2023-03-01 to 2023-04-07. The main content area is divided into three sections: a left sidebar with event cards (GRB 230405B, SN 2023eod, GRB 230405A, IceCube-230405A Neutrino, SN 2023eoa), a central sky map showing a search cone around RA 120.85°, Dec 9.75°, and a right panel with detailed information for IceCube-230405A. A red arrow points to a 'science mode' button in the top right corner of the interface.

Tiling with Astro-COLIBRI

The web interface

Select your observatory

The screenshot displays the Astro-COLIBRI web interface. At the top, there is a navigation bar with the logo, 'Select action' (Latest transients, Cone search), 'Personalize' (with a location pin icon circled in red and an arrow pointing to the text 'Select your observatory'), and 'Status: logged out' and 'Infos: v2.4.2'. Below this is a filter bar for 'Observatories' (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, FLaapLUC, LVC, other) and 'Event type' (FRB, OT, SN, GRB, burst, neutrino, nuem, GW, 4FGL, TeVCAT, SGR/AXP, IceCat). A timeline shows dates from 2023-03-01 to 2023-04-07. The main content area is divided into several panels: a list of recent events (GRB 230405B, SN 2023eod, GRB 230405A, IceCube-230405A Neutrino, SN 2023eoa), a 'Custom cone search' panel for IceCube-230405A with RA/Dec: 120.85° 9.75°, source: IceCube-230405A, and radius: 2.97°, a central sky map showing a search cone, and a 'Detailed info about selected source' panel for IceCube-230405A, including detection time (2023-04-05 13:20:20), localisation (RA: 8h3m23.98s, Dec: 9d45m0s, error: 2.9700), and observatory (IceCube). The detailed info panel also includes a notice (Bronze), FAR (2.84/yr), P_astro (0.30), and E (110.43 TeV). At the bottom, there are links for further details from ALADIN, ESASky, Fink, ASAS-SN, and AAVSO.

Tiling with Astro-COLIBRI

The web interface

Activate the GW filter

The screenshot shows the Astro-COLIBRI web interface. At the top, there are navigation buttons for 'Select action', 'Latest transients', and 'Cone search'. Below this is a filter bar with various observatories (Swift, Fermi, HAWC, IceCube, AMON, LIGO, LVC, etc.) and event types (FRB, OT, SN, GRB, burst, neutrino, GW, 4FGL, TeVCAT, SGR/AXP, IceCat). The 'GW' filter is highlighted with a red circle and an arrow pointing to it from the text 'Activate the GW filter'. Below the filter bar is a timeline showing dates from 2023-05-31 to 2023-06-15. The main content area is divided into three sections: a list of gravitational wave events on the left, a central sky map with a search cone, and detailed information for the selected event S230601bf on the right. The sky map shows a search cone centered on the event location, with various stars and galaxies visible. The detailed information section includes fields for name, detection time, RA/Dec, distance, and FAR, along with a visibility graph for the event.

Tiling with Astro-COLIBRI

The web interface

Select your event

The screenshot displays the Astro-COLIBRI web interface. At the top, there are navigation buttons for 'Select action', 'Latest transients', 'Cone search', and user status 'logged out'. Below this is a filter bar for observatories (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, LVC, etc.) and event types (FRB, OT, SN, GRB, burst, neutrino, GW, etc.). A timeline at the top shows dates from 2023-05-31 to 2023-06-15. On the left, a list of gravitational wave events is shown, with the first event, S230615an, circled in red. The central part of the interface features a sky map with various colored markers and a 'Cone search' button. On the right, detailed information for the selected event S230601bf is displayed, including its RA/Dec coordinates, detection time, and a visibility plot for H.E.S.S. at the bottom right.

Tiling with Astro-COLIBRI

The web interface



Compute the schedule

The screenshot displays the Astro-COLIBRI web interface. At the top, there's a navigation bar with 'Select action' (Latest transients, Cone search), 'Personalize' (user icons), and 'Status: logged out' (Infos: v2.4.2). Below this are filter buttons for 'Observatories' (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, FLAapLUC, LVC, other) and 'Event type' (FRB, OT, SN, GRB, burst, neutrino, nuem, GW, 4FGL, TeVCAT, SGR/AXP, IceCat). A timeline shows dates from 2023-05-31 to 2023-06-15. On the left, a list of gravitational wave events is shown, including S230615an, S230615ak, S230615af, S230615t, and S230615k. The central part features a sky map with a custom cone search for S230601bf, showing RA/Dec: 307.97° -40.82° and a radius of 1°. The right panel provides detailed information for S230601bf, including detection time (2023-06-01 22:41:34), RA/Dec (307.97, -40.82), distance (3565 ± 1260 Mpc), and a 'Schedule' button. A red arrow points to this button, and a red circle highlights the 'visibility' section of the detailed view, which includes a graph of altitude vs. azimuth and buttons for 'Daily' and 'Monthly' views.

Tiling with Astro-COLIBRI

The web interface

Observation Plan

The screenshot displays the Astro-COLIBRI web interface. At the top, there are navigation buttons for 'Select action', 'Latest transients', and 'Cone search'. The user is logged in, and the version is v2.4.2. Below this, there are filters for observatories (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, FLapLUC, LVC, other) and event types (FRB, OT, SN, GRB, burst, neutrino, nuem, GW, 4FGL, TeVCAT, SGR/AXP, IceCat). A timeline shows dates from 2023-05-31 to 2023-06-15. The main content area is divided into several sections: a list of tiling regions on the left, a central map showing the localization region with various markers and a 'Cone search' button, and a detailed information panel on the right. The detailed panel includes 'Detailed info about selected source' for S230601bf, a 'Schedule' section with a table of observation plans, and links for further details.

Observation Plan Table:

ID	coverage [%]	RA [deg]	Dec [deg]
S230601bf_tile_000	0.14	285.82	-17.74
S230601bf_tile_001	0.64	288.81	-8.69

Tiling with Astro-COLIBRI

The web interface



Observation Plan

S230601bf
Gravitational wave

Custom cone search
RA / Dec: 307.97° -40.82°
source: S230601bf
radius: < 1°

Detailed info about selected source:
VoEvent: XML VoEvent: JSON History: #0 #1 #2 #3
name: S230601bf
Detection time: 2023-06-01 22:41:34
RA [deg]: 307.97 Dec [deg]: -40.82
RA [m]: 31m52.5s Dec [m]: -40d49m1.38s
Observatory: LVC instrument: H1,L1 discovery name: S230601bf
notice: Update pipeline: spsir
classification: BBH: 1.00
FAR: 5.41e-8/yr → significant event
distance: 3565 ± 1260 Mpc
50% area: 907 deg² 90% area: 2497 deg²
Search for ATels!

The following observation schedule is proposed by tilepy.
It covers 11.8% of the GW localisation uncertainty region.
Full details: JSON

ID	coverage [%]	RA [deg]	Dec [deg]
S230601bf_tile_000	0.14	285.82	-17.74
S230601bf_tile_001	0.64	288.81	-8.69

Links for further details: GraceDB, TreasureMap, GCN Viewer, GCN-n, ALADIN

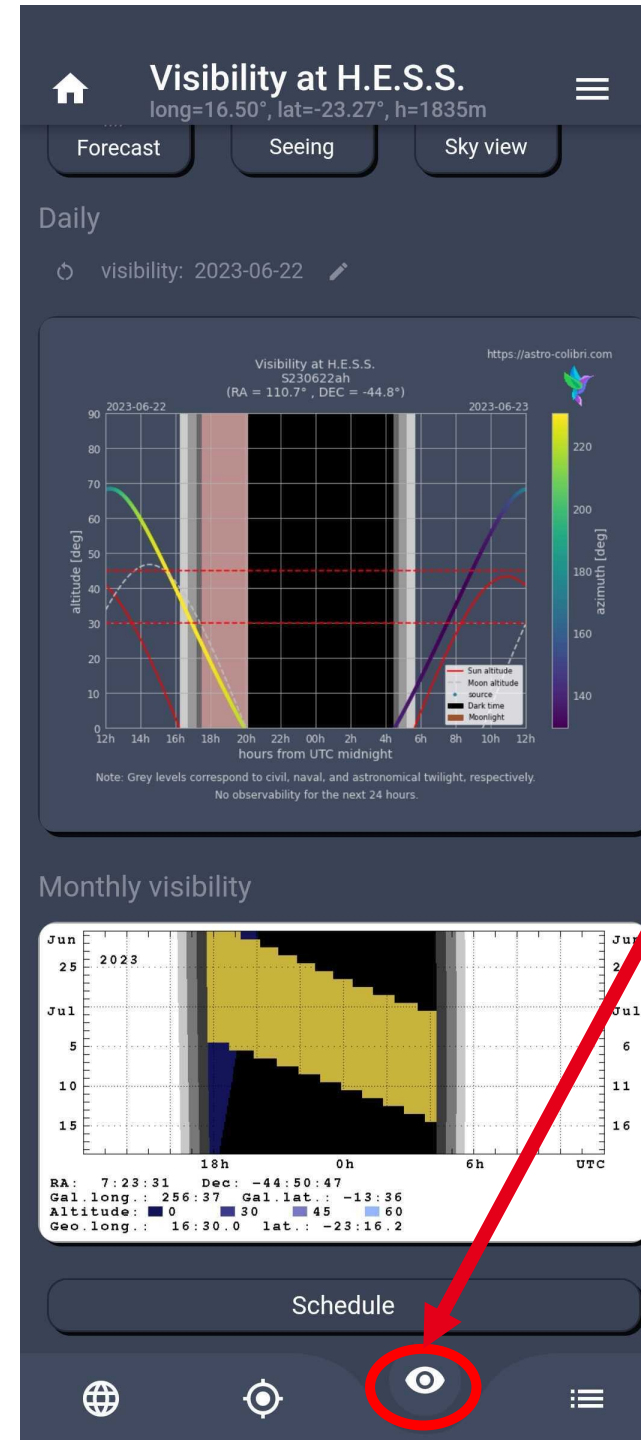
Tiling with Astro-COLIBRI

The mobile interface

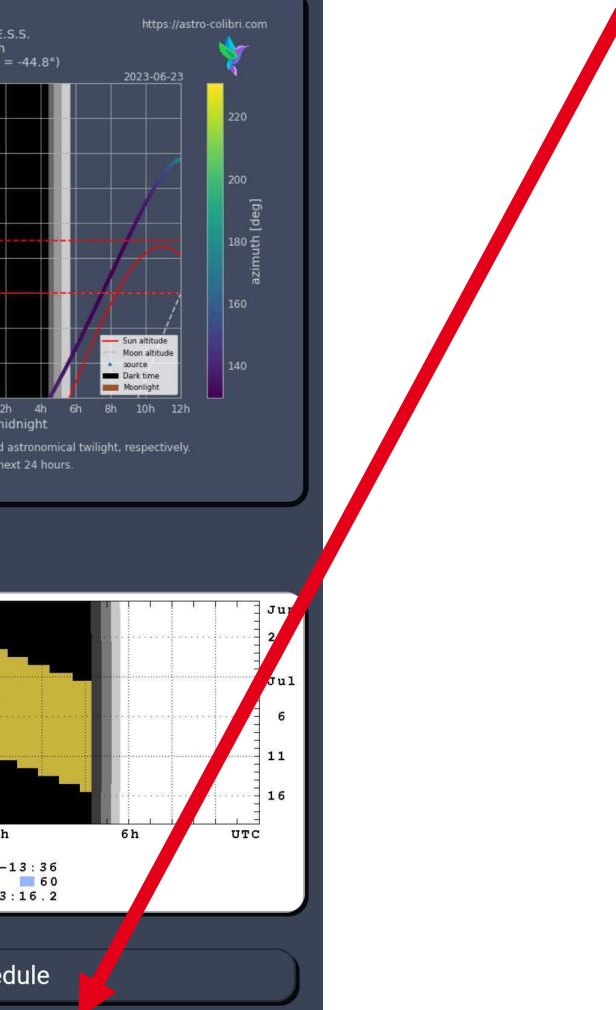
Android Play Store



Apple iOS App Store



Visibility panel



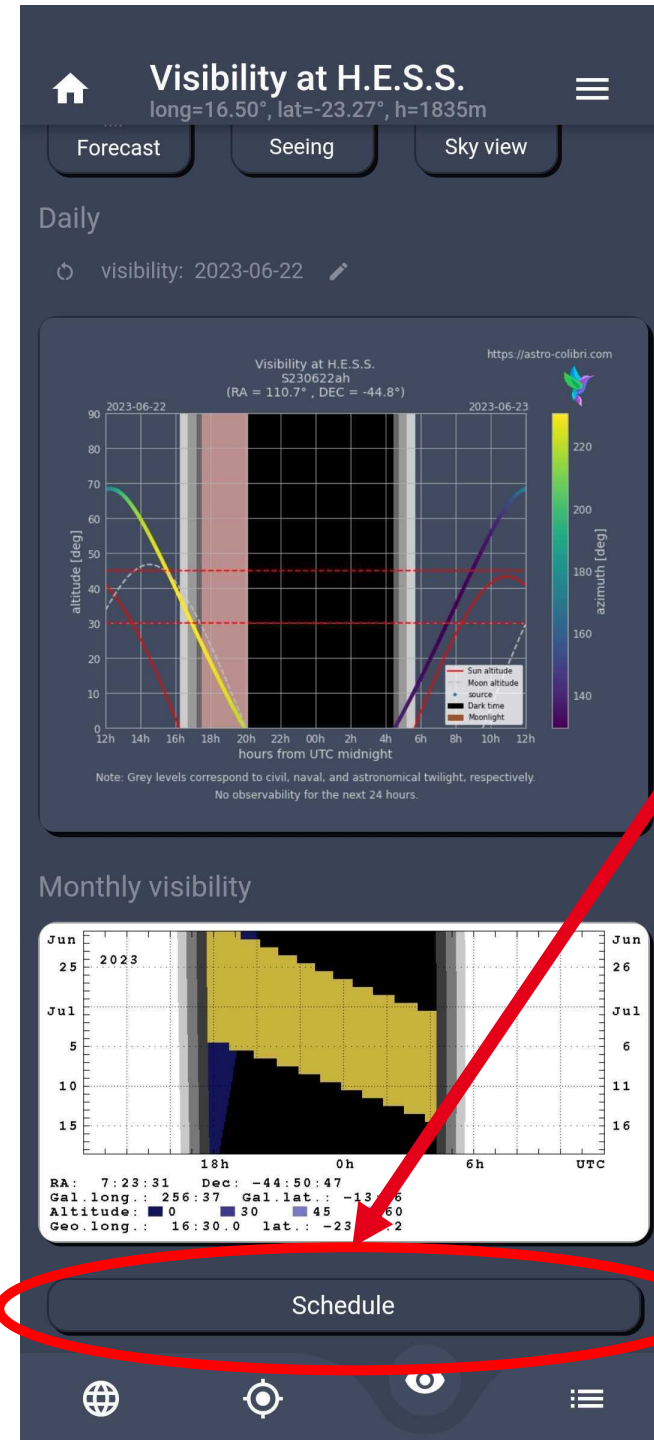
Tiling with Astro-COLIBRI

The mobile interface

Android Play Store



Apple iOS App Store



Compute the schedule

Schedule

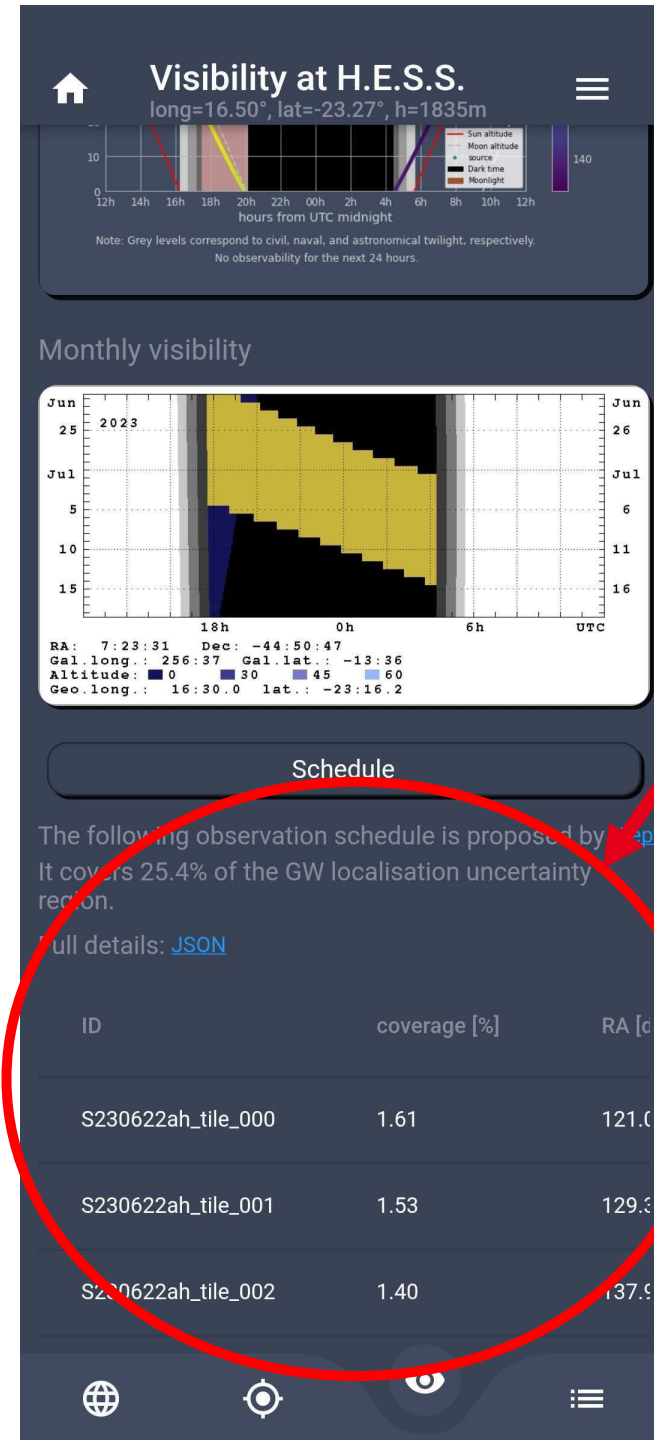
Tiling with Astro-COLIBRI

The mobile interface

Android Play Store



Apple iOS App Store



Observation Plan

An API to go further

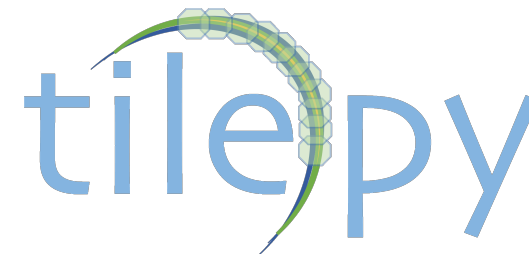
- **Astro-COLIBRI** allows you to set simple observatory parameters (Position, FoV, Zenith limit, Maximum Moon phase)

An API to go further

- **Astro-COLIBRI allows you to set simple observatory parameters**
(Position, FoV, Zenith limit, Maximum Moon phase)
- **The HTTP API allows you to customise much more parameters:**
 - Visibility constraints (Moon, Sun, ...)
 - Number of pointings
 - Number of observation nights
 - Start observation time
 -
- Website : <https://tilepy.com>
API : <https://tilepy.com/tiling>
API documentation : <https://tilepy.com/apidoc>

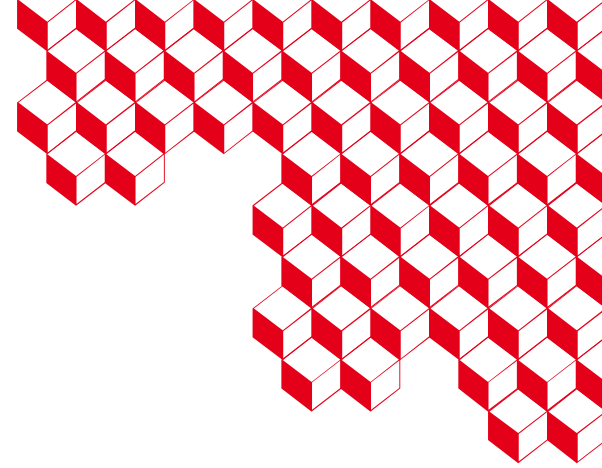
Conclusion

- IACTs use a tiling observation strategy for GW follow-up
- The `tilepy` python software has been developed to compute an optimal observation schedule
 - 2D algorithm for distant alerts
 - 3D algorithm for close-by alerts
- `tilepy` is integrated in Astro-COLIBRI
- An HTTP API allows also to send requests with more parametrisation possibilities
- Feedback is welcome





irfu



Thank you for your attention

FoV of CTA

