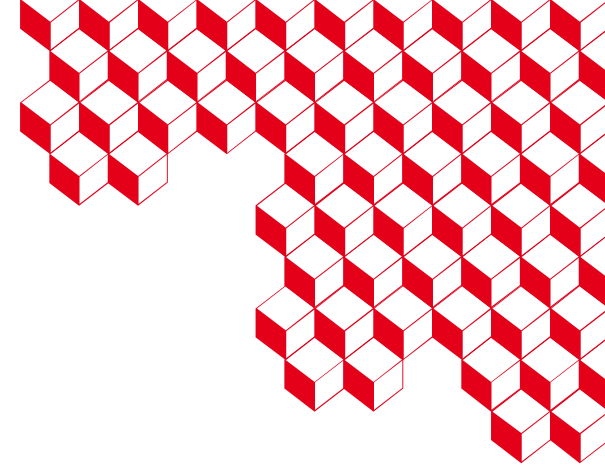




irfu



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)

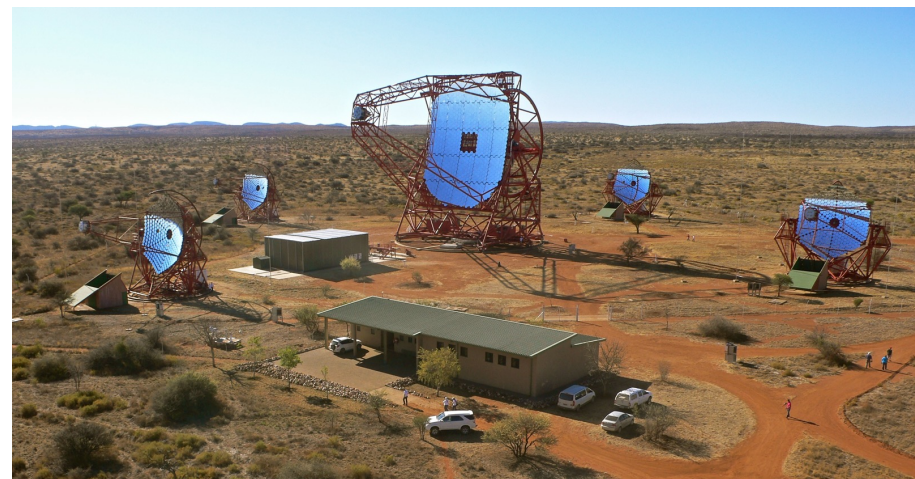


MAGIC

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

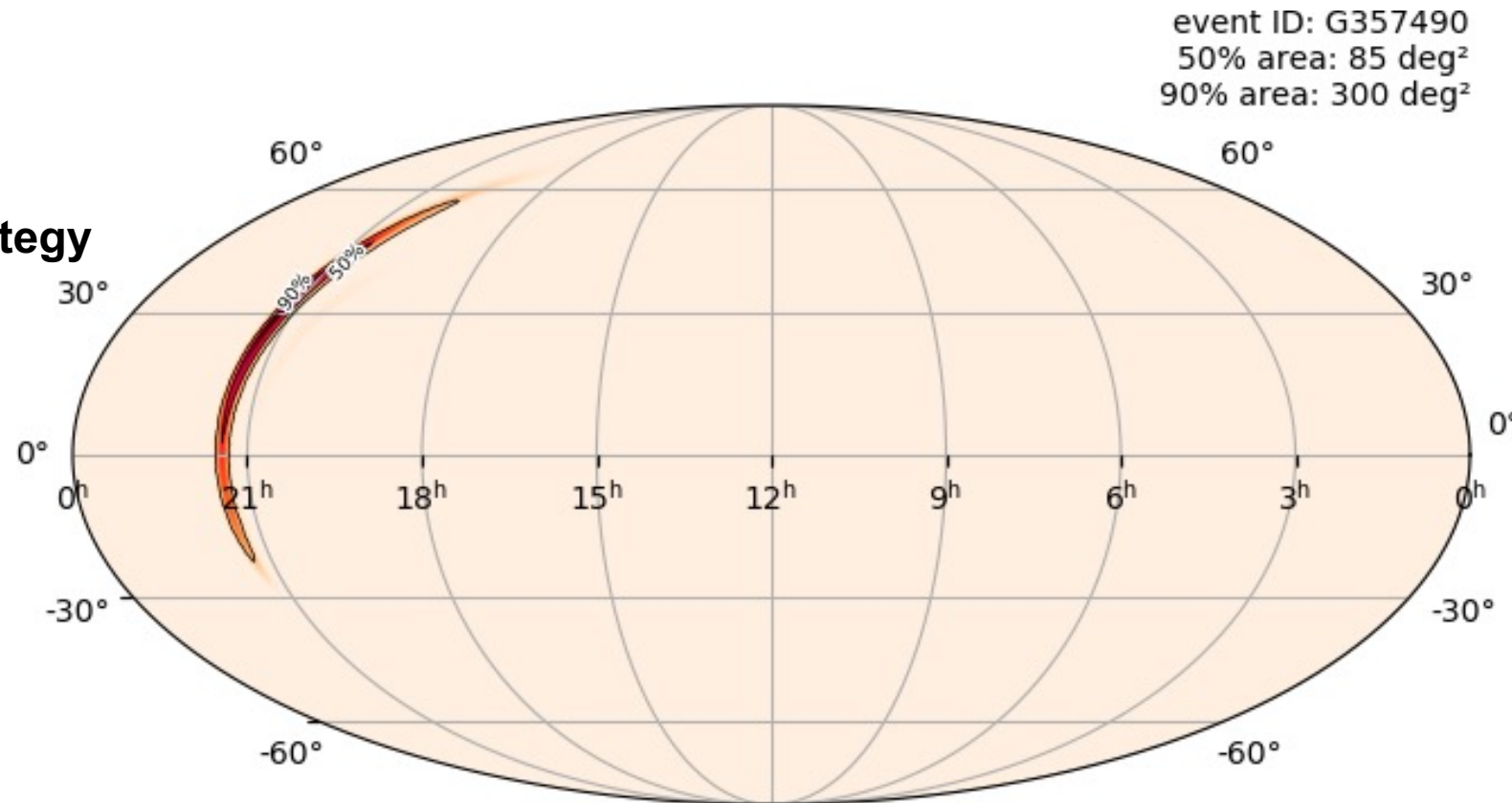
CTA

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



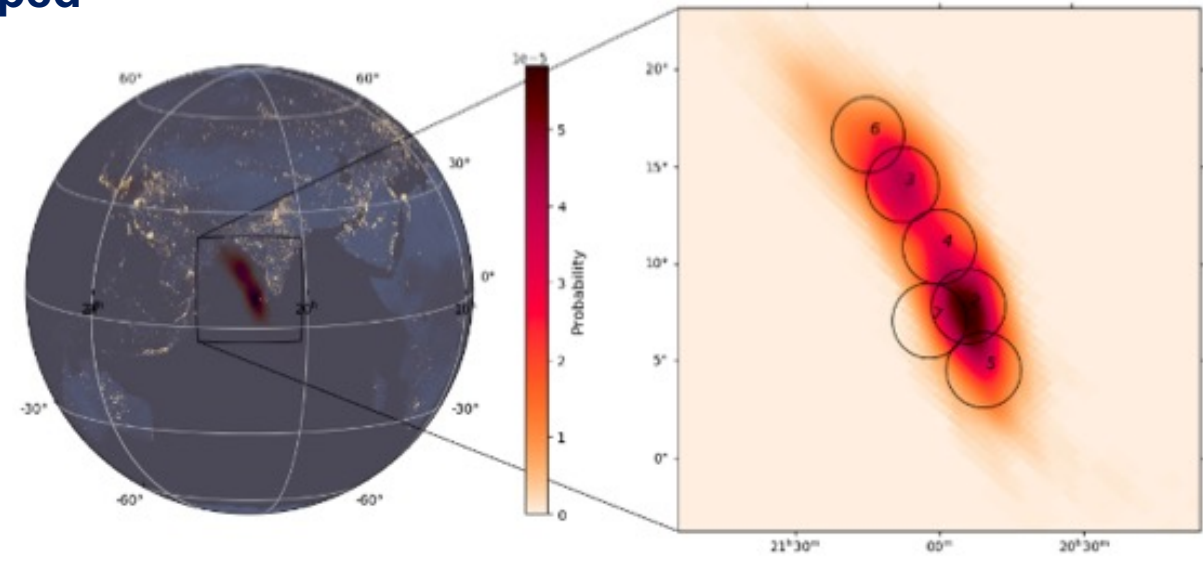
Challenge of GW follow-up

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

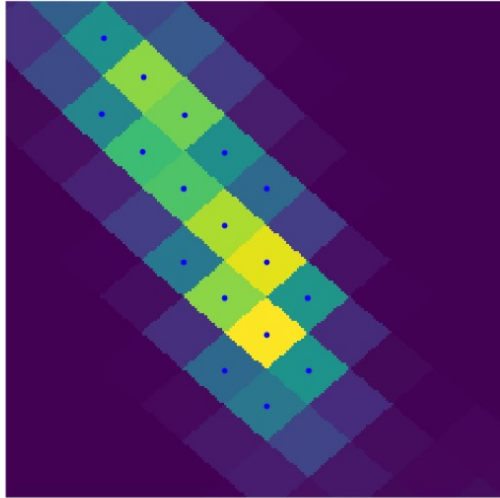
(M. Seglar-Arroyo, 2022)

2D algorithm

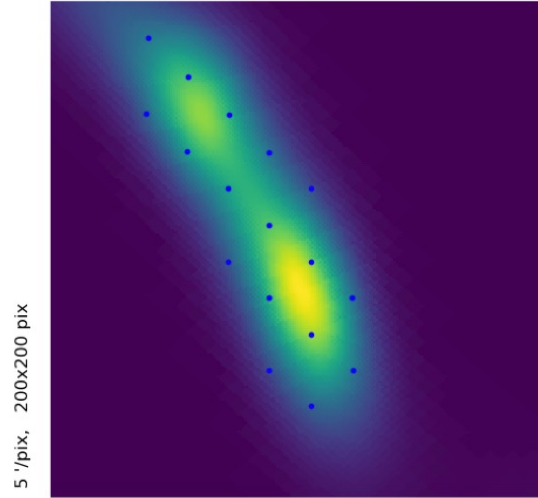


■ Iterative algorithm based on spatial information

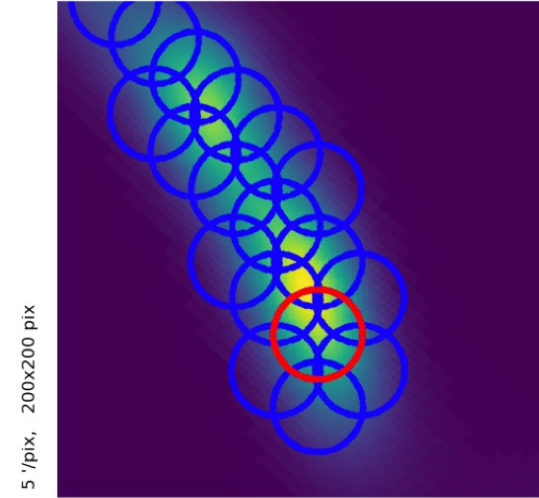
1: Coordinate grid using low res maps



2: Grid used as FoV pointing centers

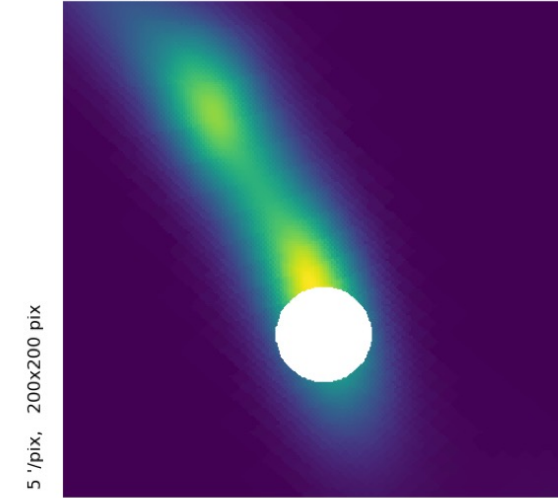


3: P_{GW}^{FoV} computation with high res maps



Ashkar et al., ICRC 2021

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



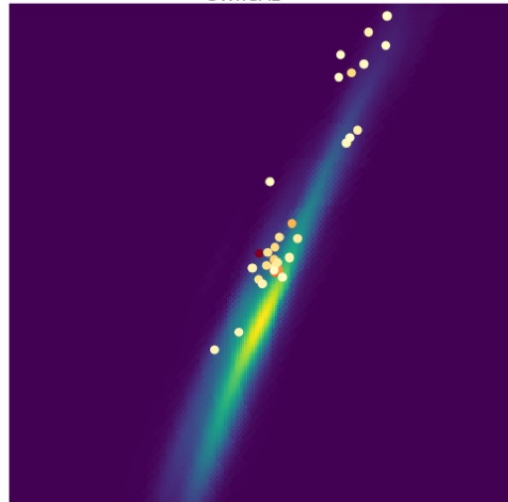
3D algorithm

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

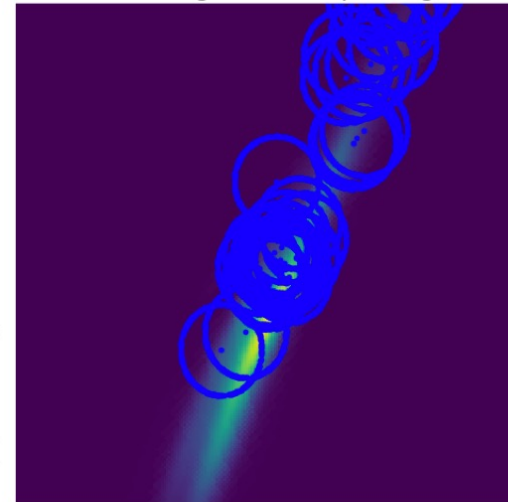


Ashkar et al., ICRC 2021

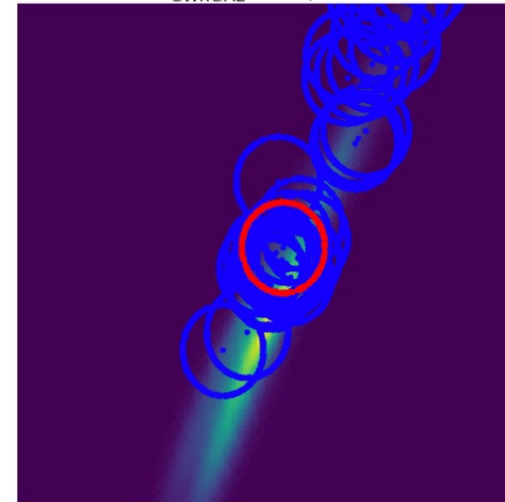
1: Calculate P_{GWxGAL}^i for each galaxy



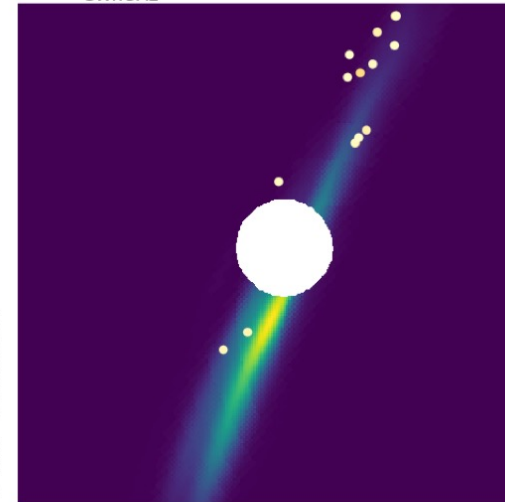
2: Choose the galaxies as pointing seeds



3: P_{GWxGAL}^{FoV} computation

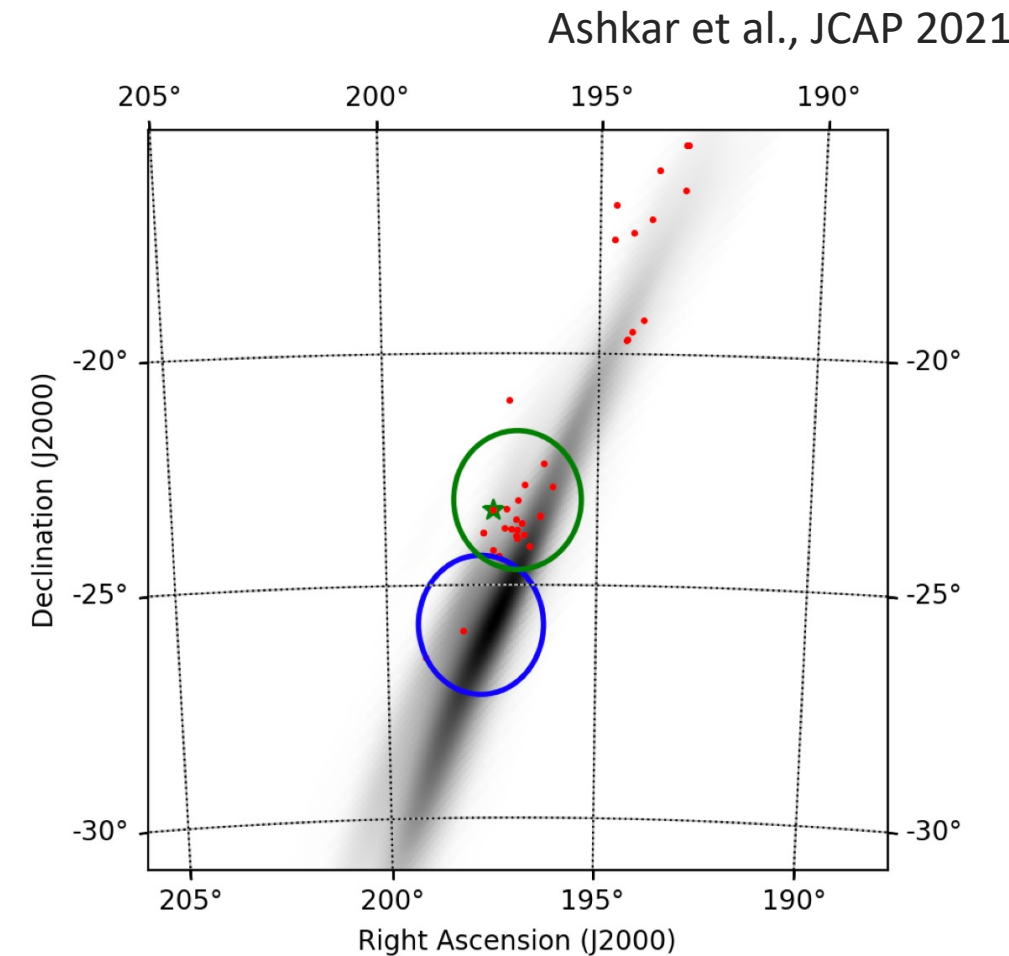


4: $P_{GWxGAL}^{FoV, MAX}$ FoV selected then masked



GW 180817

- **Coincidence EM/GW**
 - BNS merger detected by Ligo/Virgo
 - Short GRB detected by Fermi
- **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 event**



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)
- **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 map
 - Should work with small connection
 - Stable interface



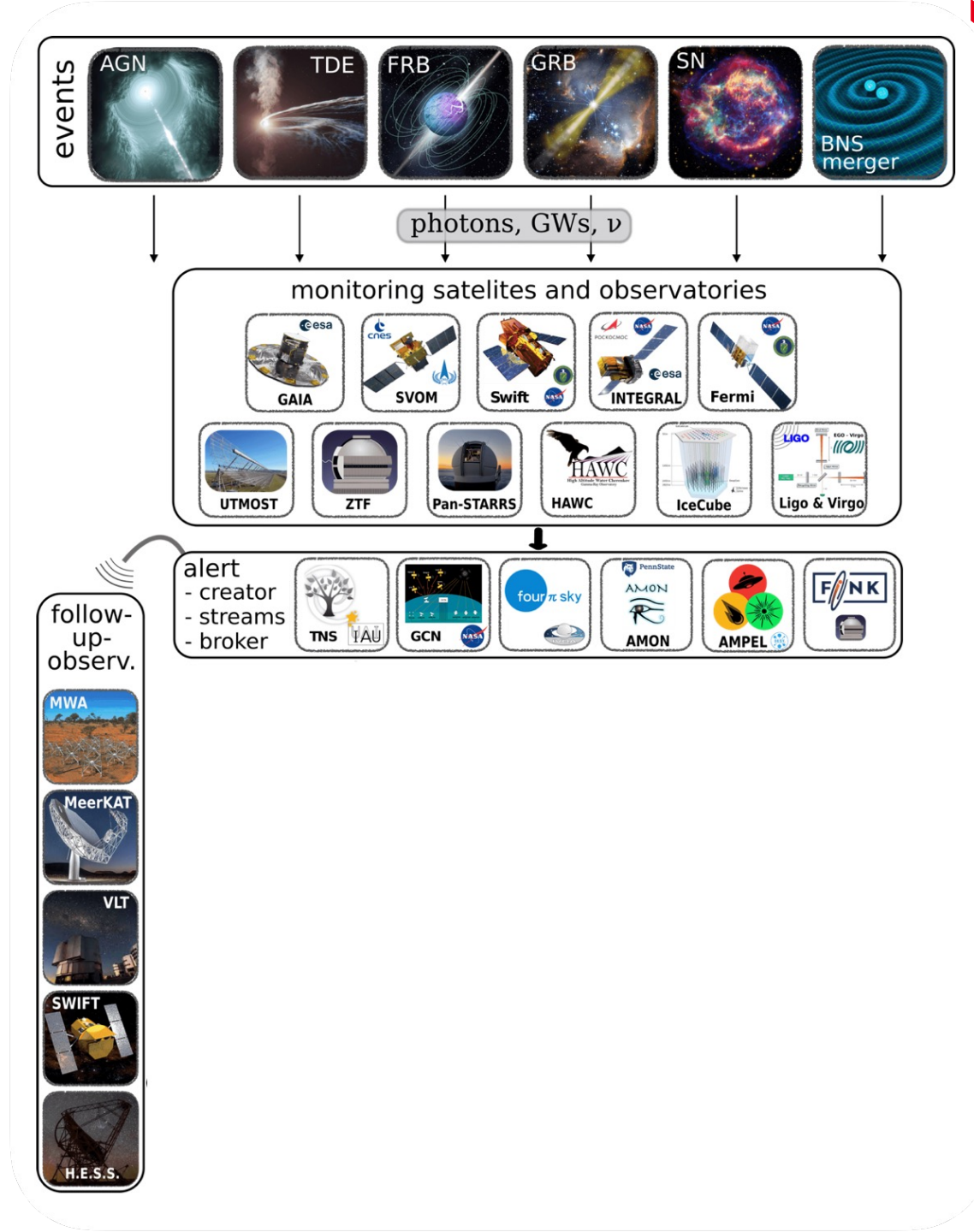
Astro-COLIBRI

A tool for transient astronomy



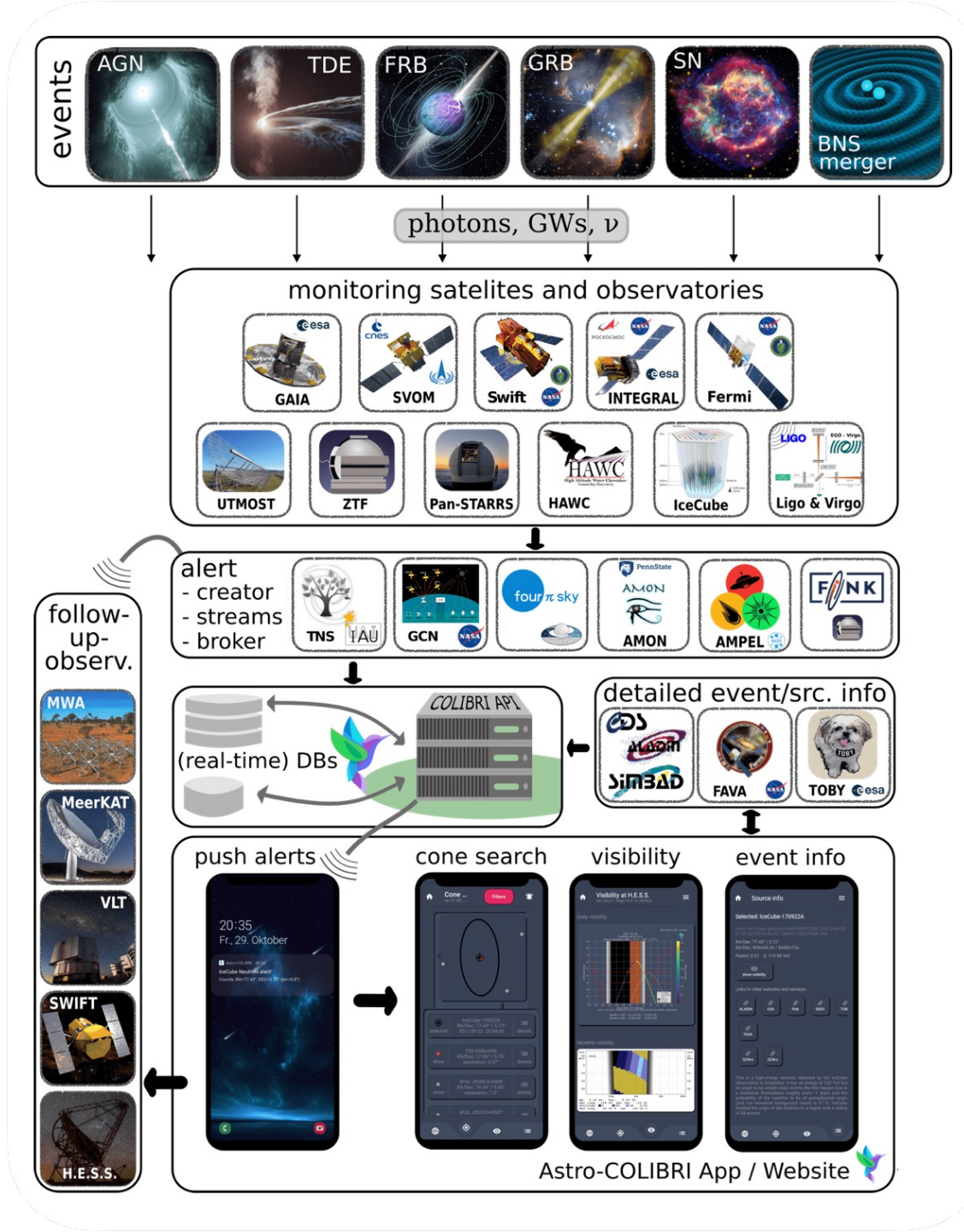
Astro-COLIBRI

A tool for transient astronomy



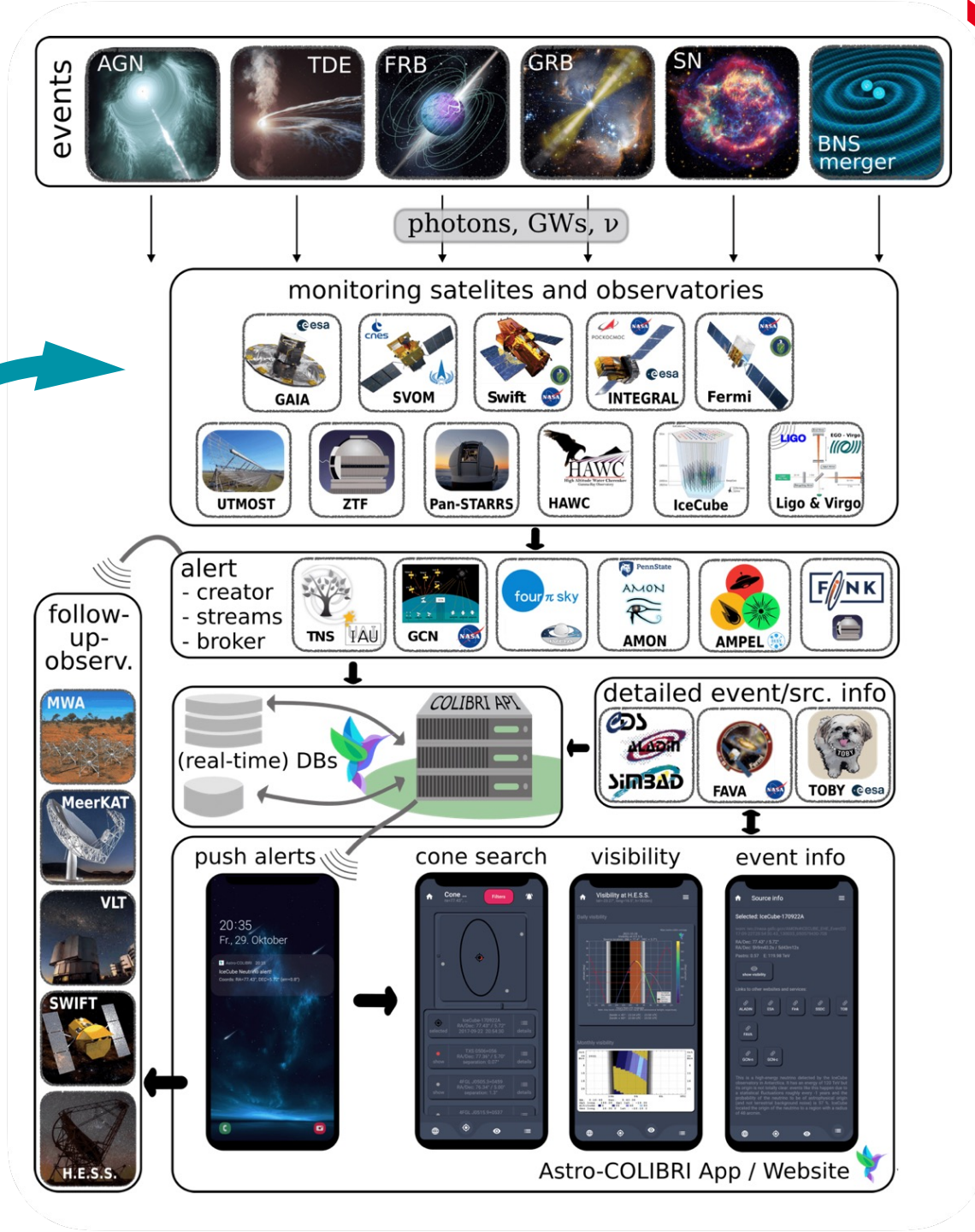
Astro-COLIBRI

A tool for transient astronomy



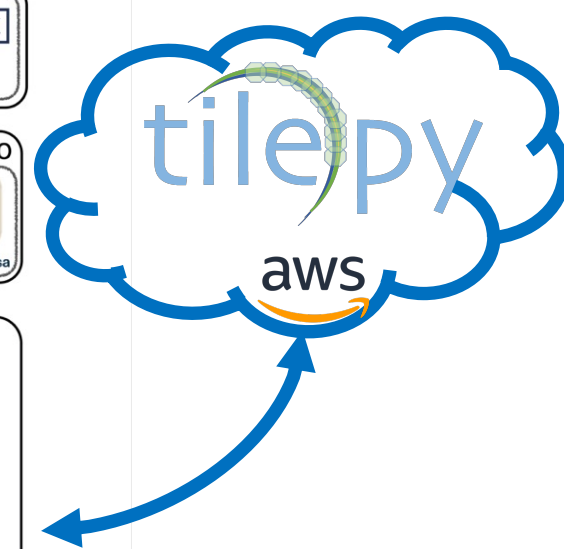
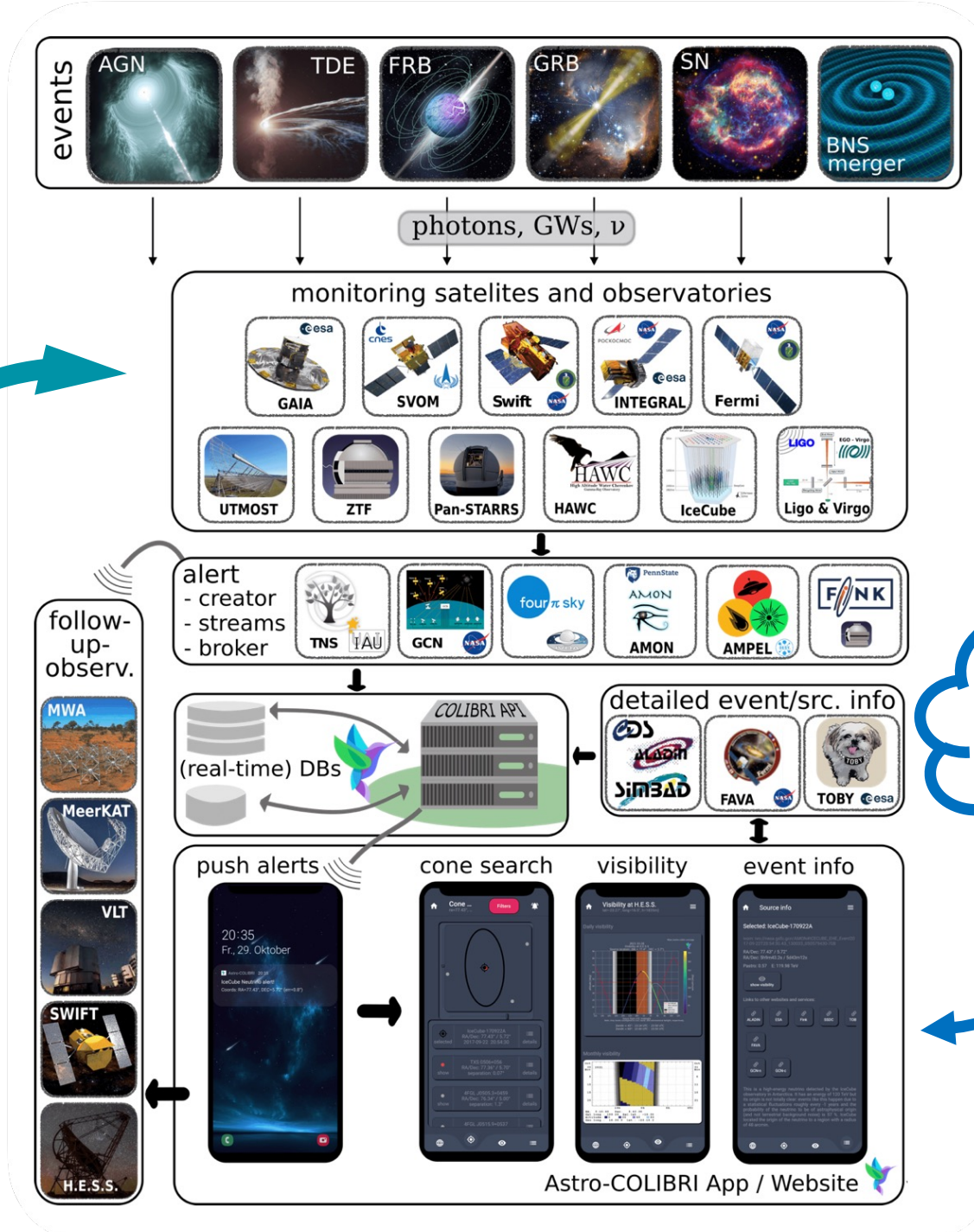
Astro-COLIBRI

A tool for transient astronomy



Astro-COLIBRI

A tool for transient astronomy



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), 'Personalize' (user, location, globe, info), '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 three columns. The left column lists recent events: GRB 230405B (Gamma-ray burst), SN 2023eod (Supernovae optical), GRB 230405A (Gamma-ray burst), IceCube-230405A (Neutrino), and SN 2023eoa (Supernovae optical). The middle column features a 'Custom cone search' for IceCube-230405A, showing RA/Dec: 120.85° 9.75°, source: IceCube-230405A, and radius: 2.97°. Below this is a star map with a blue cone search region. The right column provides 'Detailed info about selected source' for IceCube-230405A, including 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. At the bottom right, there are links for further details from ALADIN, ESASky, Fink, ASAS-SN, and AAVSO.

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 central panel features a sky map with a custom cone search for IceCube-230405A Neutrino, showing RA/Dec: 120.85° / 9.75° and a radius of 2.97°. The right panel provides detailed information about the source, including its name, detection time, localisation, and a description of the high-energy neutrino event. 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's a navigation bar with '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°, and a 'Detailed info about selected source' panel for IceCube-230405A. The detailed info panel includes event name, detection time, localisation (RA: 8h3m23.98s, Dec: 9d45m0s, error: 2.9700), observatory (IceCube), notice (Bronze), FAR (2.84/yr), P_astro (0.30), and 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 its origin is not clear, with a 30% probability of being of astrophysical origin. Below this are links for ATels, ALADIN, ESASky, Fink, ASAS-SN, and AAVSO. A central map shows the sky with a blue cone search region and various colored stars representing different observatories.

Tiling with Astro-COLIBRI

The web interface

Activate the GW filter

The screenshot shows the Astro-COLIBRI web interface. At the top, there's a navigation bar with 'Select action', 'Latest transients', 'Cone search', and user status 'logged out'. Below this is a filter bar with 'Observatories' (Swift, Fermi, HAWC, IceCube, AMON, LIGO, Virgo, KAGRA, LVC, other) and 'Event type' (FRB, OT, SN, GRB, burst, neutrino, **GW**, 4FGL, TeVCAT, SGR/AXP, IceCat). A red circle highlights the 'GW' filter, with a red arrow pointing to it from the text 'Activate the GW filter'. The main area shows 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 event details include: name: S230601bf, Detection time: 2023-06-01 22:41:34, RA [deg]: 307.97, Dec [deg]: -40.82, RA: 20h31m52.5s, Dec: -40d49m1.38s, observatory: LVC, instrument: H1,L1, discovery name: S230601bf, notice: Update, pipeline: spsir, classification: BBH: 1.00, FAR: 5.41e-8/yr, distance: 3565 ± 1260 Mpc, 50% area: 907 deg², 90% area: 2497 deg². A visibility graph is shown at the bottom right, plotting altitude (deg) against azimuth (deg) for the event at H.E.S.S. (RA = 308.0°, DEC = -40.8°).

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', and 'Cone search'. The status bar shows 'logged out' and 'Infos: v2.4.2'. Below this, there are filters for 'Observatories' (Swift, Fermi, HAWC, IceCube, AMON, Integral, GECAM, LVC, other) and 'Event type' (FRB, OT, SN, GRB, burst, neutrino, nuem, GW, TeVCAT, SGR/AXP, IceCat). 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, source name, radius, and a visibility plot for H.E.S.S. at the event location. The visibility plot shows altitude and azimuth over time, with a color scale for azimuth. At the bottom, there are links for further details, including GraceDB, TreasureMap, GCN Viewer, GCN-n, and ALADIN.

Tiling with Astro-COLIBRI

The web interface

Compute the schedule

The screenshot displays the Astro-COLIBRI web interface. At the top, there are navigation buttons for 'Select action', 'Latest transients', and 'Cone search', along with user status 'logged out' and version '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 dates from 2023-05-31 to 2023-06-15. The main content area is divided into several sections: a list of gravitational wave events (S230615an, S230615ak, S230615af, S230615t, S230615k) on the left; a central sky map showing a search cone and various sources; a 'Detailed info about selected source' panel for S230601bf on the right, which includes detection time, coordinates, and classification; and a 'Visibility at H.E.S.S.' plot at the bottom right showing altitude and azimuth over time. A red arrow points from the text 'Compute the schedule' to the 'Schedule' button in the visibility plot section.

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 panels:

- Left Panel:** A list of tiling regions for the event S230601bf. Each region is represented by a small image and text: S230601bf_tile_015, S230601bf_tile_014, S230601bf_tile_013, S230601bf_tile_012, and S230601bf_tile_011. Each entry includes RA/Dec coordinates and a timestamp.
- Center Panel:** A map of the sky showing the localization region for the gravitational wave event S230601bf. The map includes a 'Cone search' button and a 'Custom cone search' section with RA/Dec coordinates (307.97°, -40.82°) and a radius of 1°.
- Right Panel:** Detailed information about the selected source S230601bf. It includes detection time (2023-06-01 22:41:34), RA/Dec coordinates, distance (3565 ± 1260 Mpc), and a proposed observation schedule. A red arrow points to the 'Schedule' section, which is circled in red. The schedule table is as follows:

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

Below the schedule table, there are links for further details and a section for external resources: GraceDB, TreasureMap, GCN Viewer, GCN-n, and ALADIN.

Tiling with Astro-COLIBRI

The web interface



Observation Plan

Observation Plan

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

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

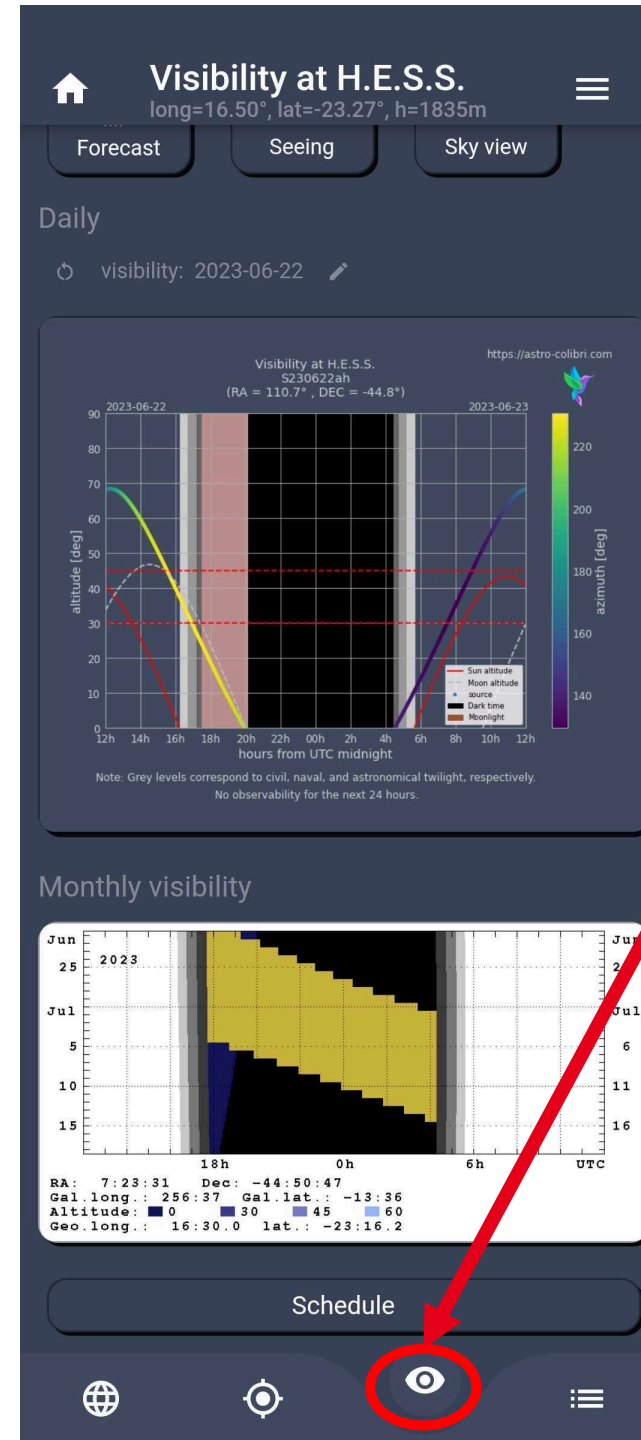
Tiling with Astro-COLIBRI

The mobile interface

Android Play Store



Apple iOS App Store



Visibility panel

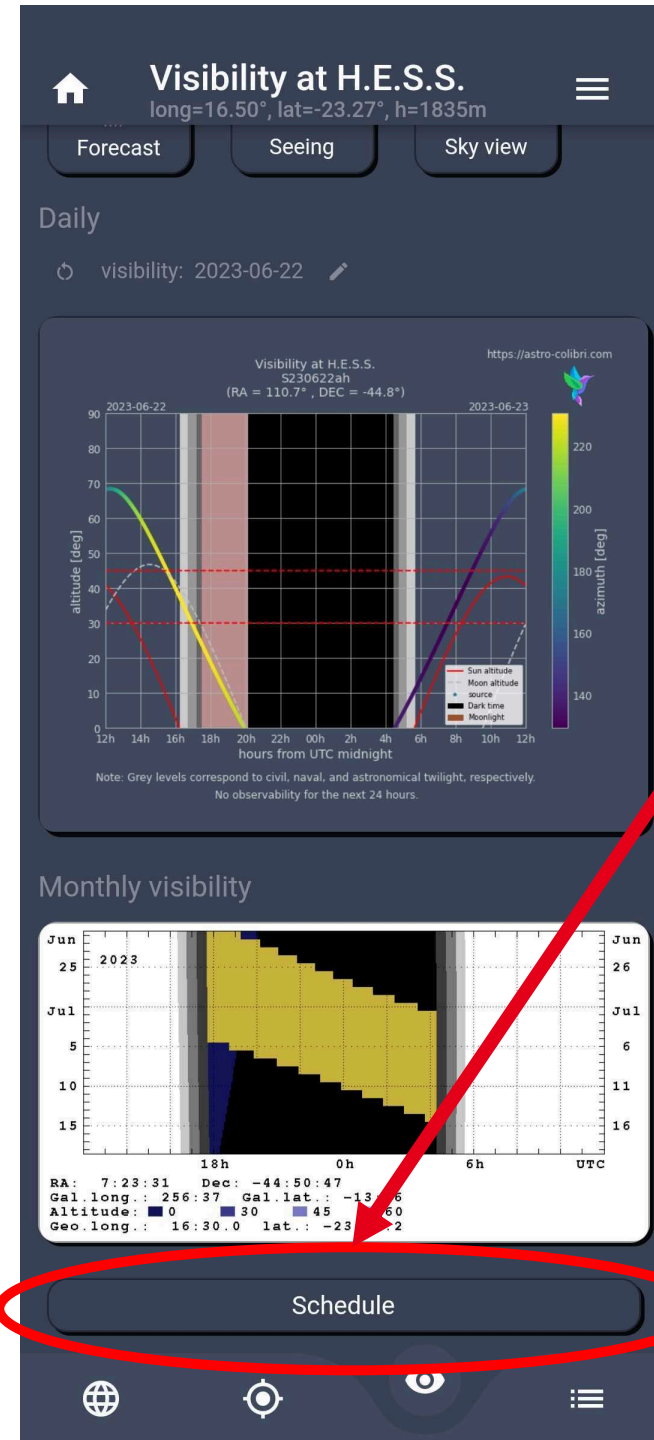
Tiling with Astro-COLIBRI

The mobile interface

Android Play Store



Apple iOS App Store



Compute the schedule

Schedule

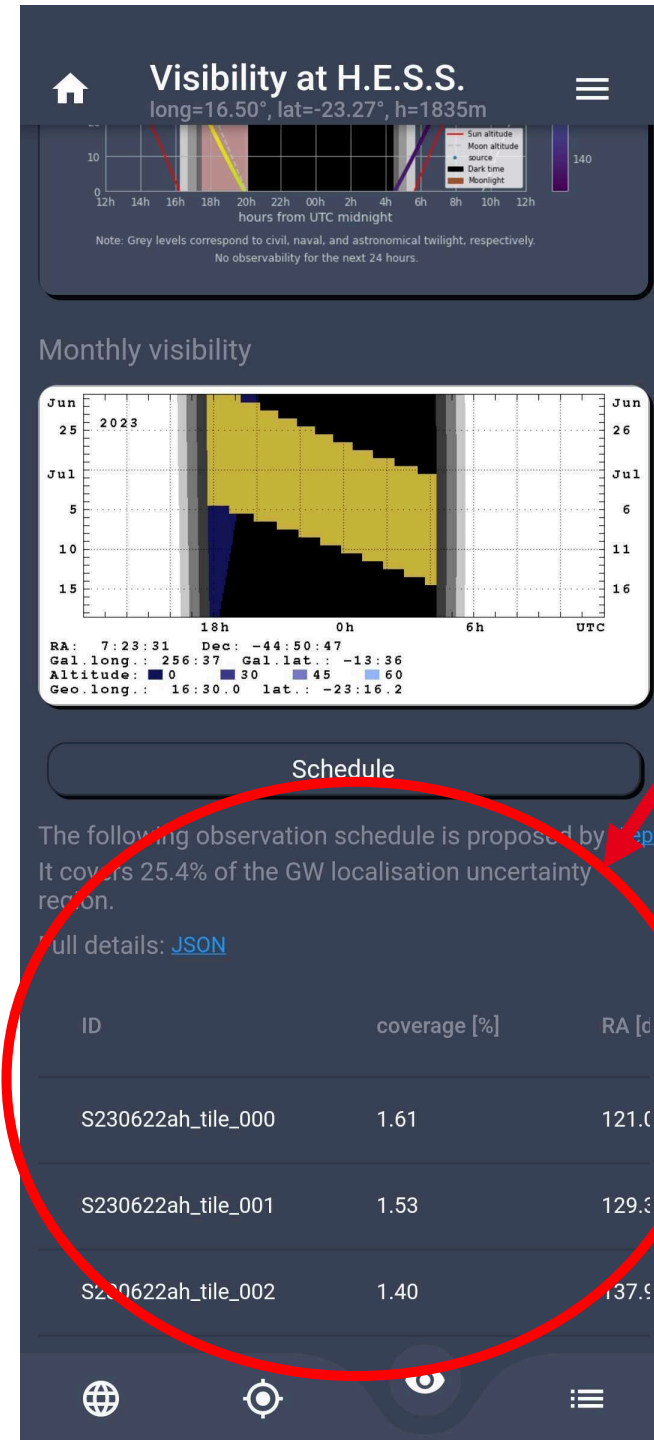
Tiling with Astro-COLIBRI

The mobile interface

Android Play Store



Apple iOS App Store



Observation Plan

An API to go further

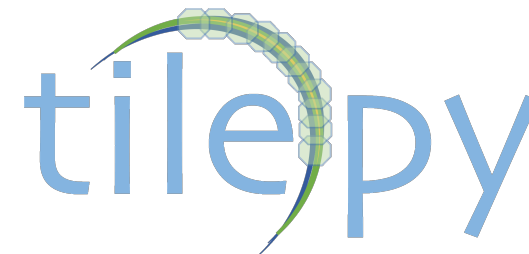
- **Astro-COLIBRI** allows you to set simple observatory parameters (Position, FoV, Zenith limit, Maximum Moon phase)

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>

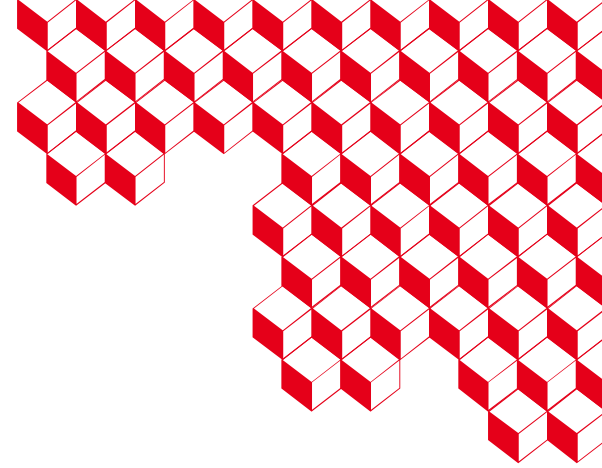
Conclusion

- 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 currently integrated in Astro-COLIBRI
- An HTTP API allows also to send requests with more parametrisation possibilities
- Feedback is welcome





irfu



Thank for your attention

FoV of CTA

