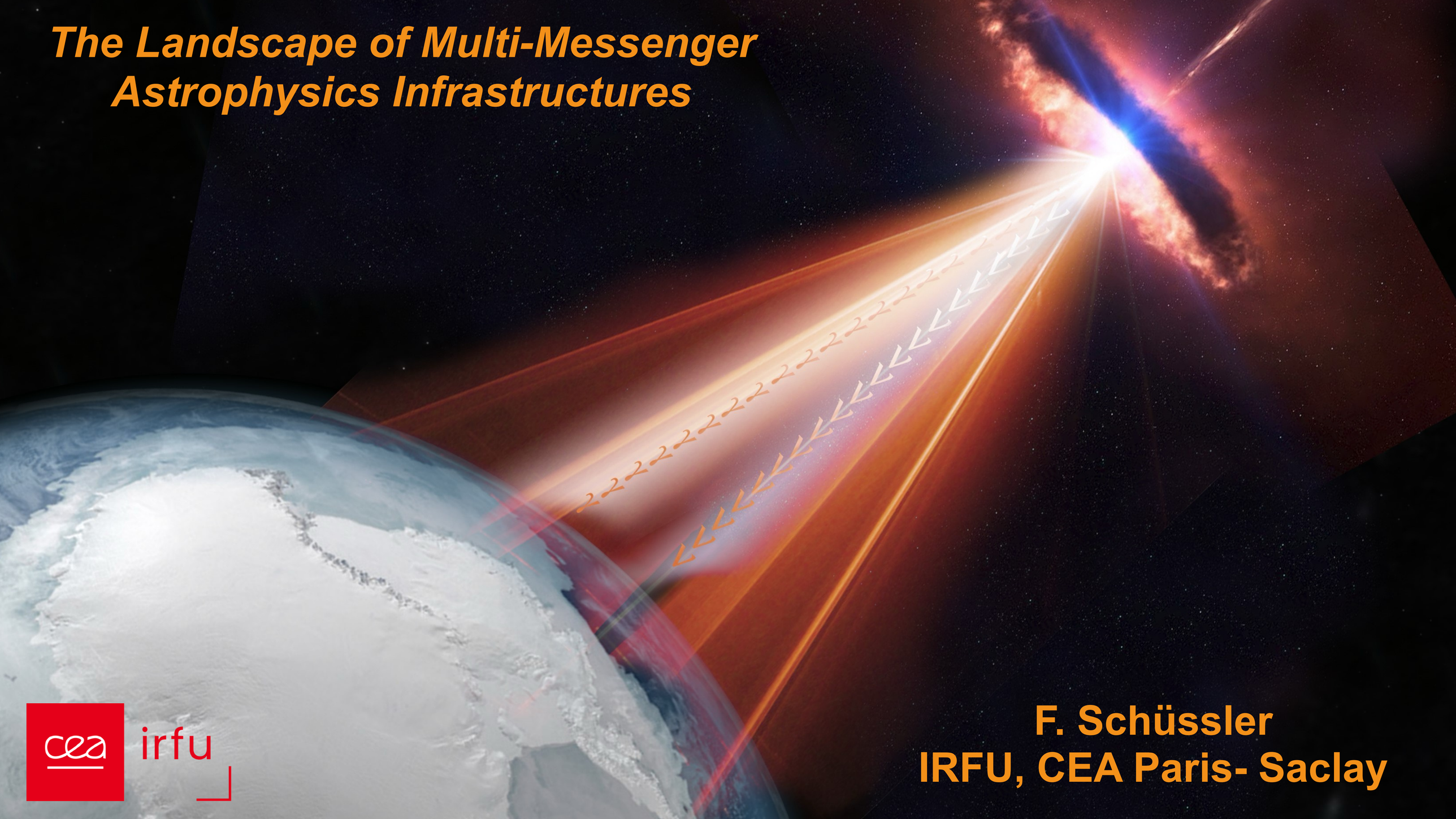
The Landscape of Multi-Messenger Astrophysics Infrastructures



F. Schüssler
IRFU, CEA Paris- Saclay

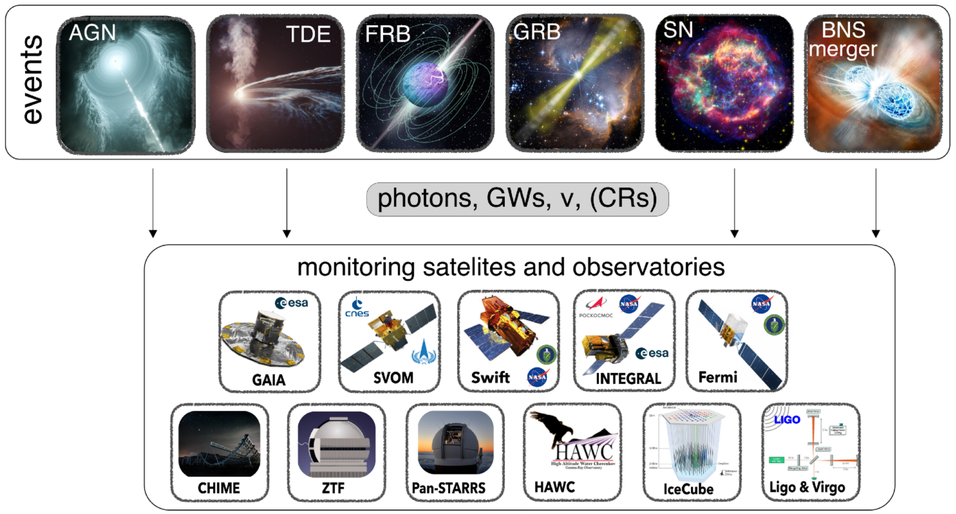

LSST
Skafka
LIGO
Virgo
KAGRA
IceCube
Fermi
KM3NeT
VERITAS
CTAO
Swift
SCiMMA
Newton
Astro
ATLAS
Matplotlib
API
Map
Docker
TOM
TNS
Firebase
COLIBRI
GRANDMA
Treasure
Jupyter
H
JWST
STARRS
Apache
GitHub
DS9
VO
MeerKAT
ElasticSearch
PostgreSQL
net
ZTF
NICER
Pan
MongoDB
Kubernetes
XMM
tilepy
LAST
MAGIC
fermipy
AWS
GOTO
Astrometry
VOEvent
Aladin
Astropy
astroquery
FastAPI
HEASoft
TOPCAT
AMON
INTEGRAL
SciPy
Gammapy
NumPy
Streams
GraphQL
Cloud
GCN
Google
Gaia
LCOGT
GraceDB
REST
SKA
SkyPortal

How can we improve multi-messenger astrophysics ?

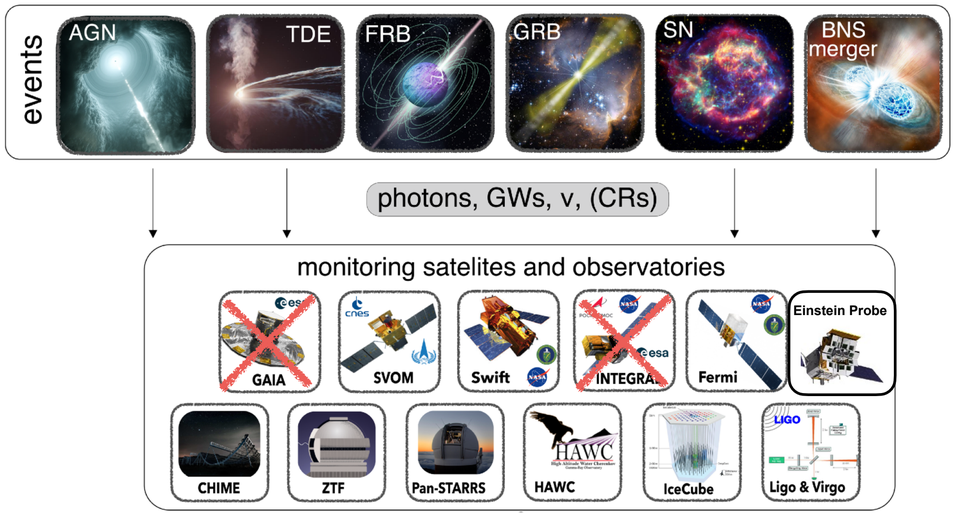
- **Efficient and rapid detections**
  - Including MM/MWL correlations
  - Including (real-time) sharing of information/data
- **Efficient and rapid follow-up observations**
  - Including sharing of information/data
- **Efficient and rapid interpretation**
  - Guiding further observations
  - Detailed, joint analyses

- Requirements
  - Full adoption of open data principles
  - Integration and interconnection of tools and platforms

Detection: monitoring instruments

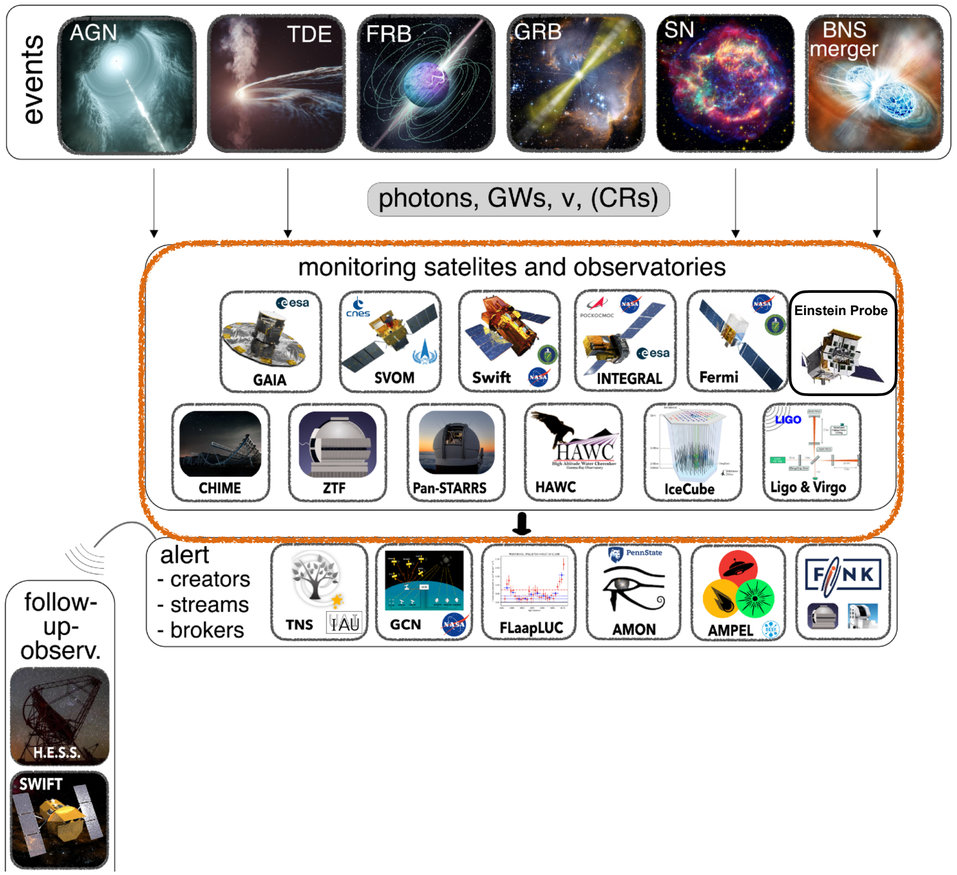


Detection: monitoring instruments

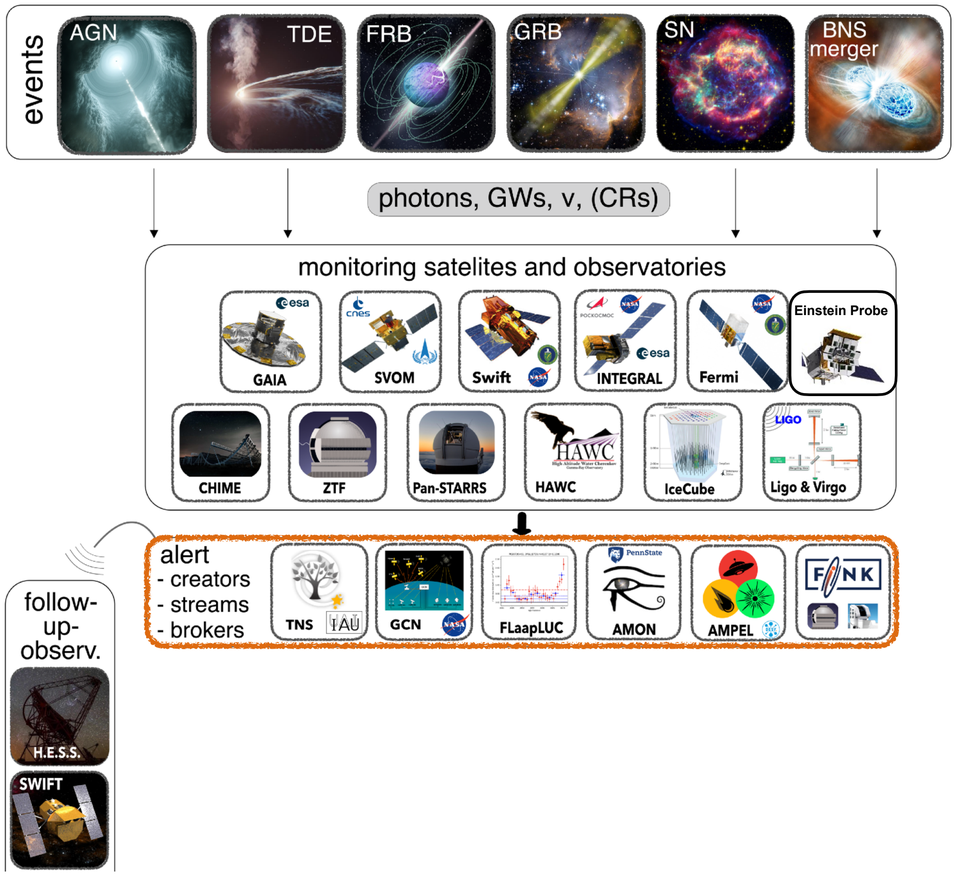


	Large FoV	Small FoV
Monitoring (+ duty cycle)	✓	✗
Sensitivity	✗	✓
Resolution	✗	✓

Real-time information sharing + alerts



- Requires real-time data analysis and alert publication
  - Examples:
    - LVK public alerts (incl. early warnings)
    - IceCube public alerts
    - Fermi/Swift/SVOM/EP/etc.
    - CHIME FRB alerts
    - Rubin/LSST 😱
    - …

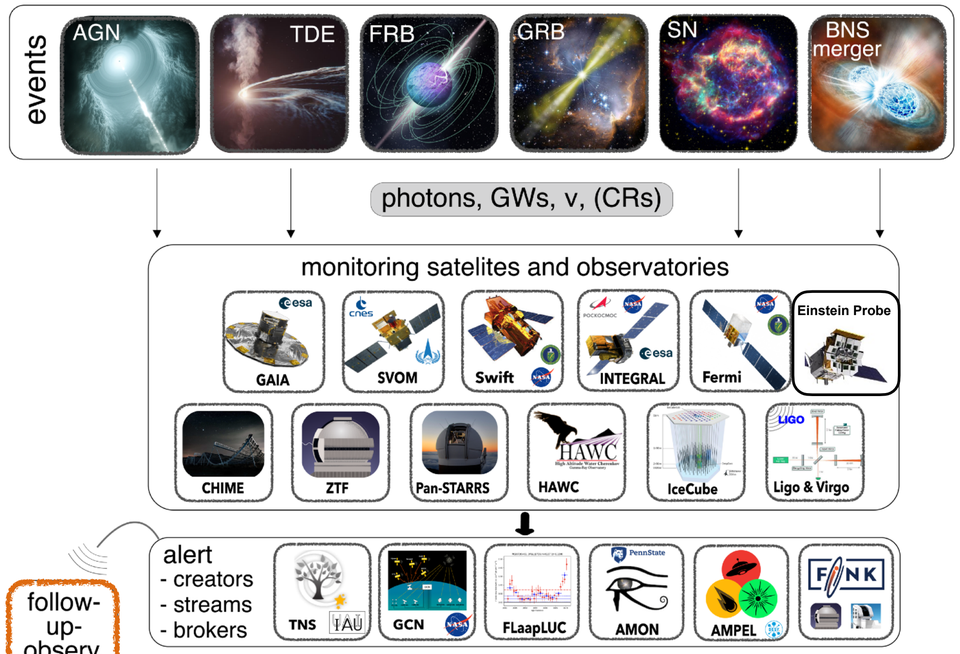


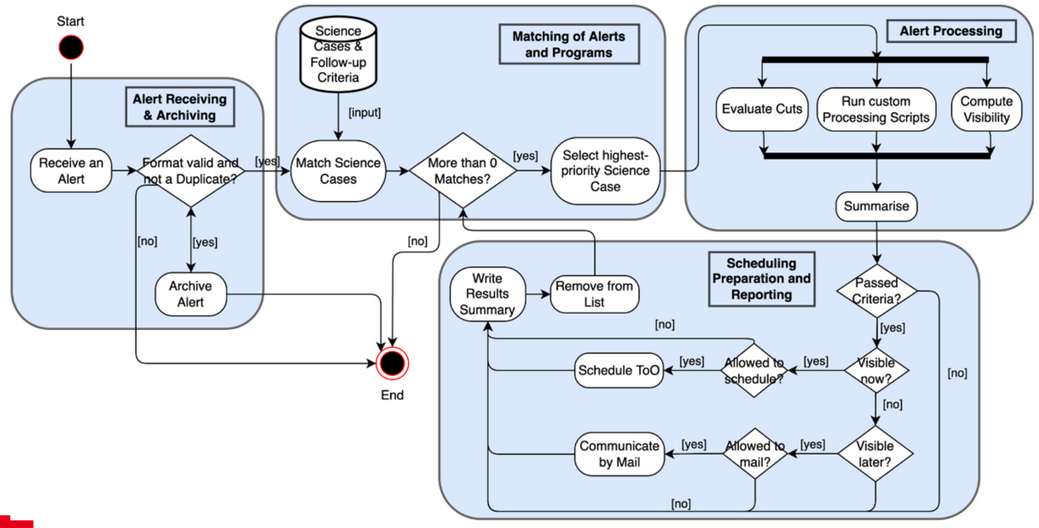
Information/alert distribution

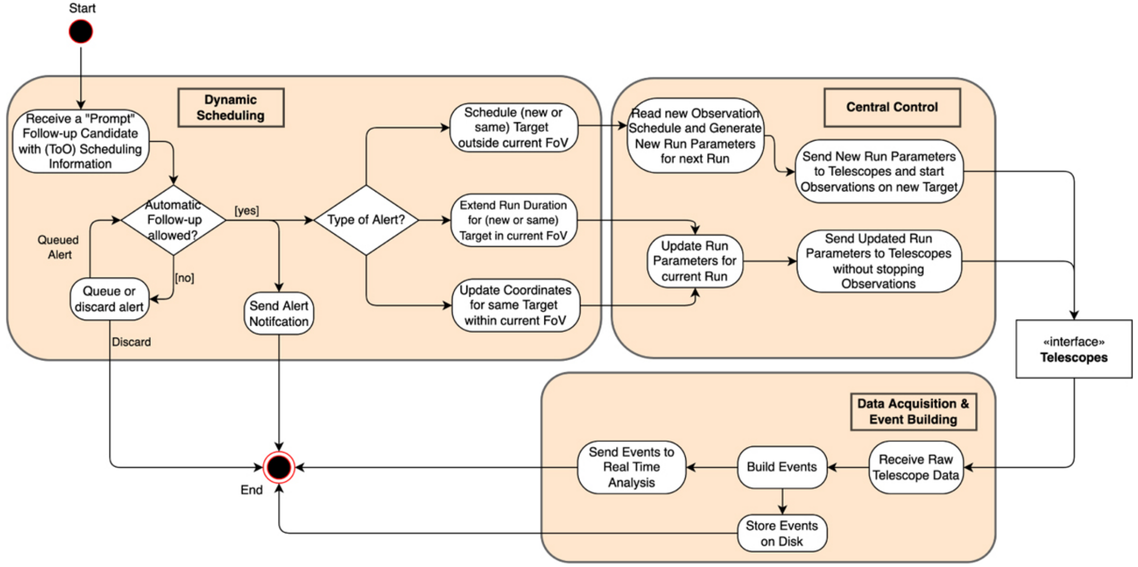
- Increasing number of distribution channels + brokers
  - Multiple classification + characterization of the same data
  - => European Broker Initiative ACME
- Increasing number of data transmission protocols (VoEvent, Kafka, emails, websites, etc.)
- Increasing number of data schema and serializations (VoEvent vs. GCN; XML vs. JSON vs. Avro, etc.)

Automatic follow-up observations

- Proposal preparation/submission/etc.
- Automatic alert filtering + selection
  - Caveat: you'll typically only trigger on known phenomena/features
- Triggering of follow-up observations
  - Integration with observatory/telescope software

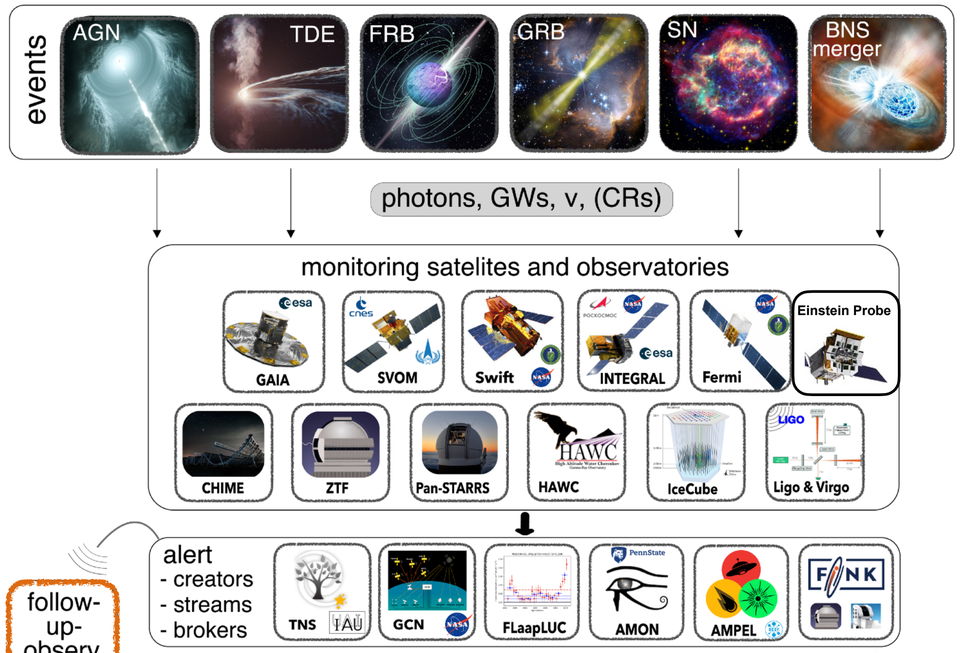




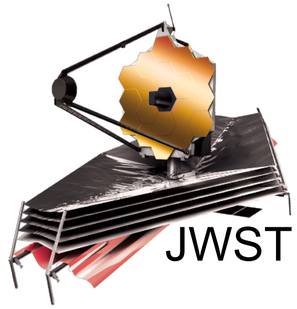


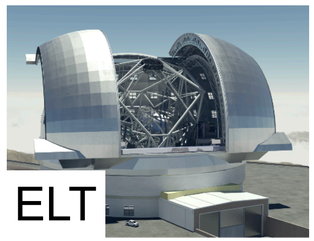
C. Hoischen et al., A&A 666, A119 (2022)

Follow-up observatories



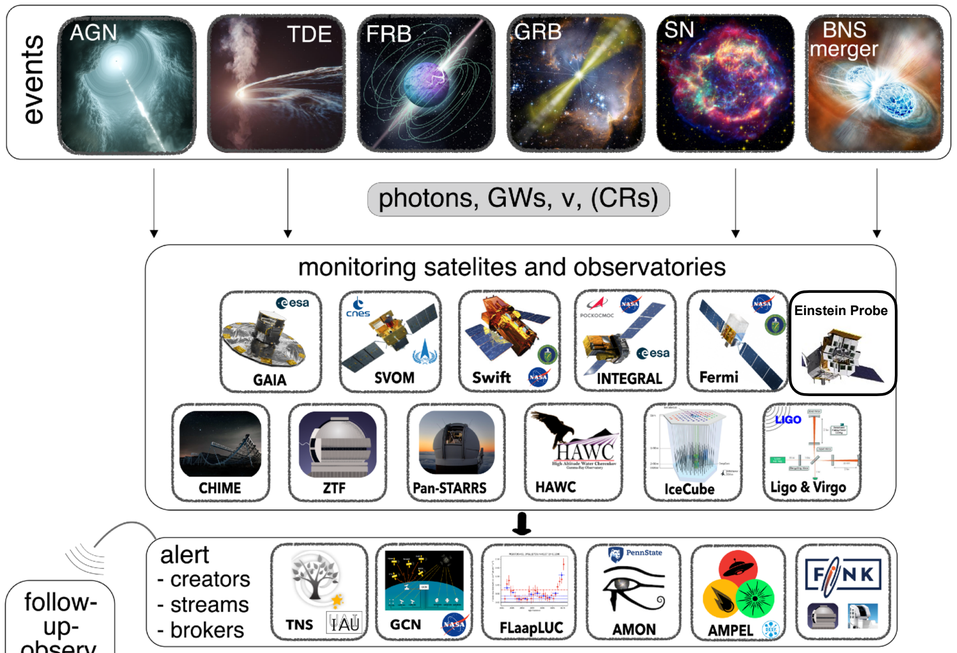
	Large FoV	Small FoV
Monitoring (+ duty cycle)	✓	✗
Sensitivity	✗	✓
Resolution	✗	✓

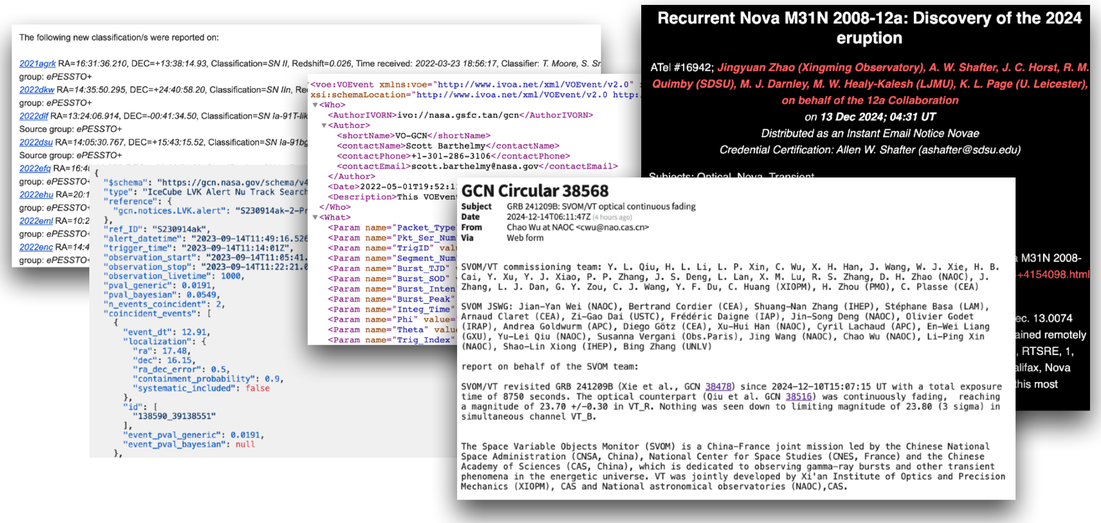




- Localisation (e.g. GRB afterglows, kilonovae, …)
- Classification + characterization
  - Spectroscopy + Polarimetry + …
- Strong competition for time at major facilities
  - Increasing fraction of non-classified transients

Manual follow-up observations

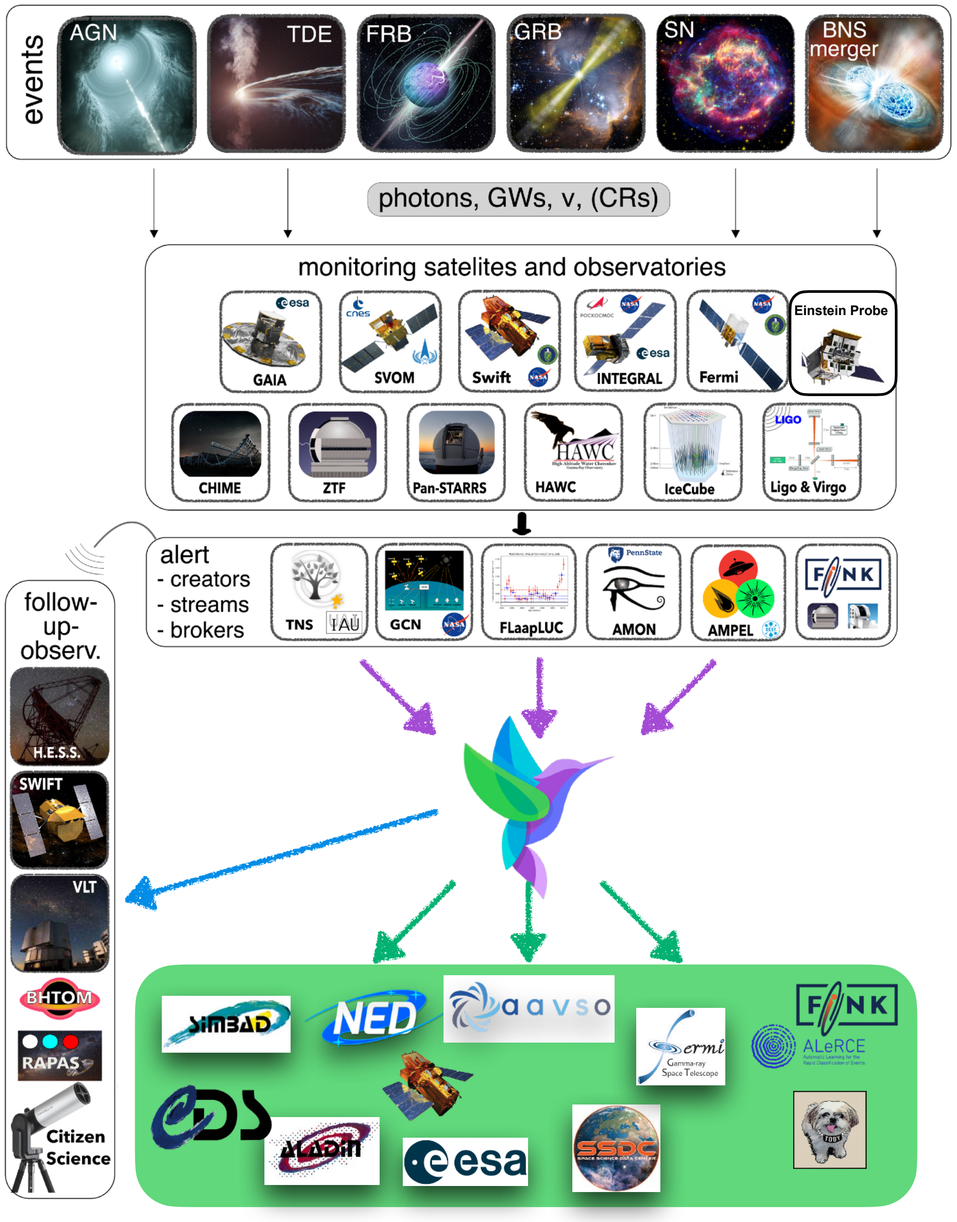


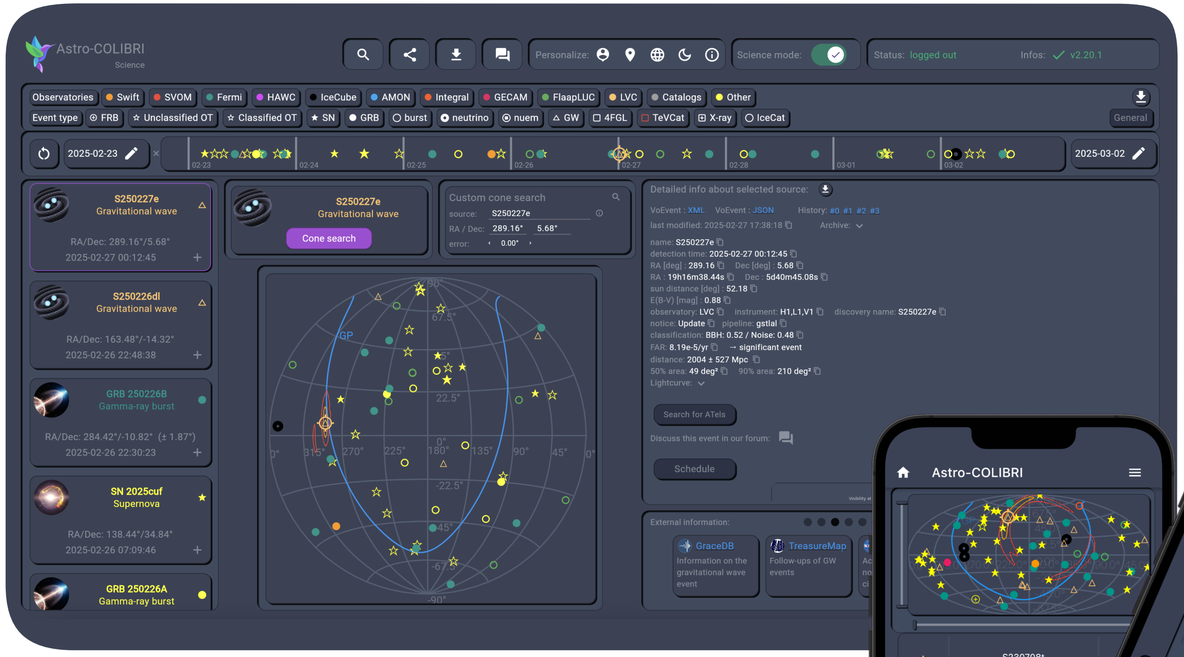


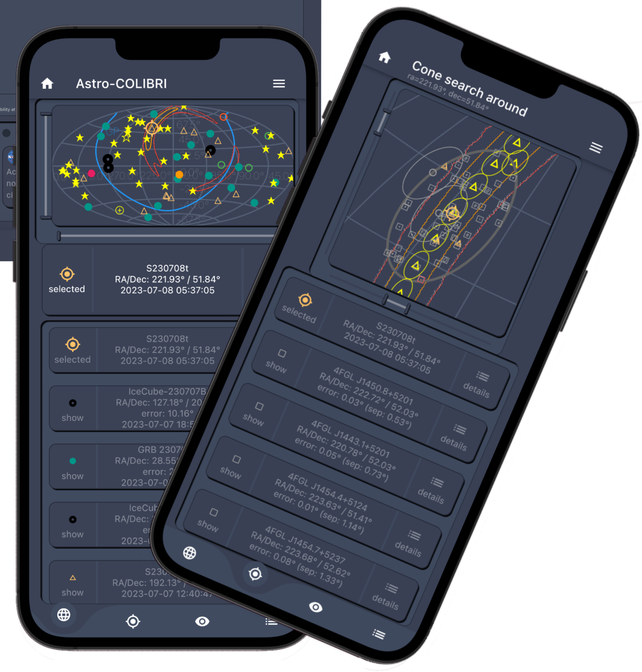
- Proposal preparation/submission/etc.

- Find **interesting** targets
  - Increasing number of transient detections
  - MWL/MM context scattered across multiple platforms
  - …

Astro-COLIBRI

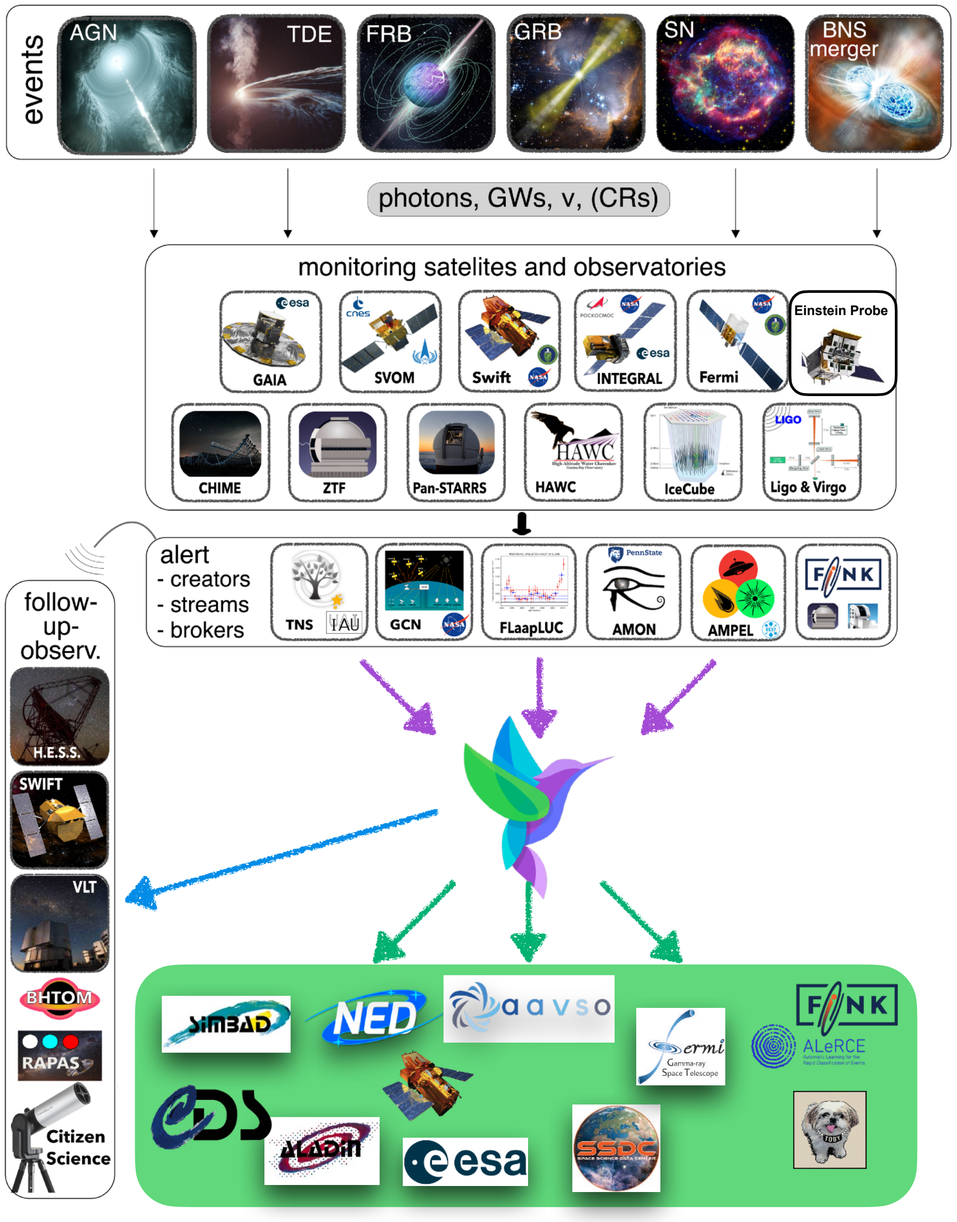






https://astro-colibri.science

MWL/MM context

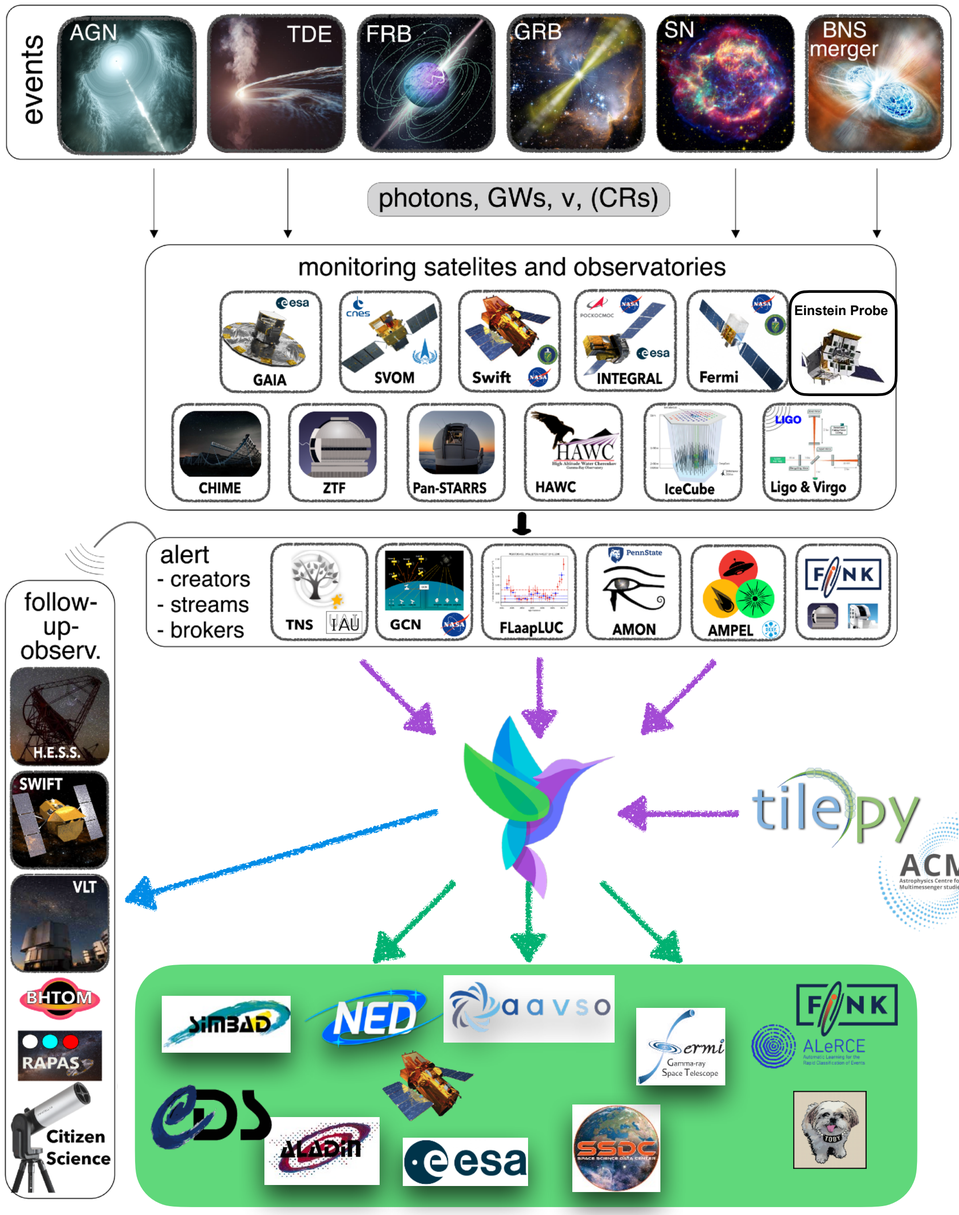


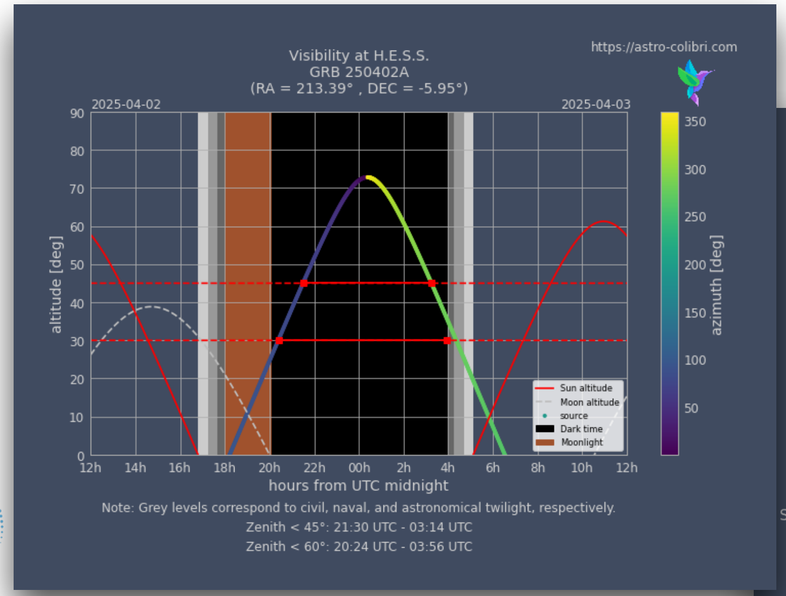
- Additional information
  - MWL context, archival information + related MWL/MM transients
    - Aggregated information and direct links to MWL/MM platforms
      - Lightcurves (ASAS-SN + ATLAS + ZTF; Swift-XRT; Fermi LCR, …)
      - Realtime context: GraceDB, brokers, TNS, LSXPS, …
      - Archival context (IceCat-1, 4FGL, TeVCat, …)
      - Simbad, Aladin, ESASky, NED, SSDC, …
      - …
- Coordination with colleagues and the community
  - Sharing of events
  - Discussion forum
  - …

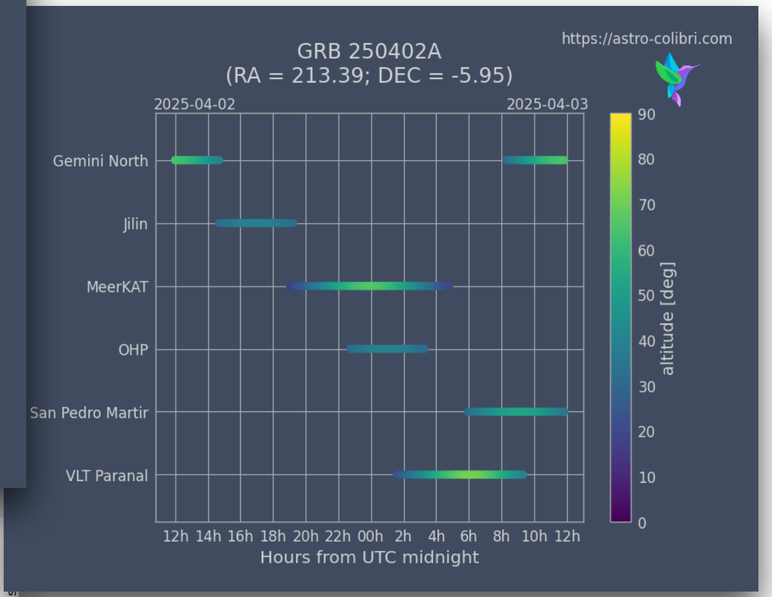
https://astro-colibri.science

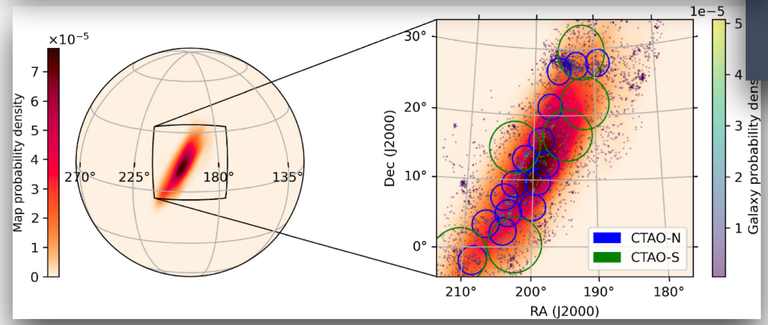
Observation planning

- Observation planning
  - (Multi-observatory) observability assessment
  - Optimized observation plans (e.g. Tilepy integration)





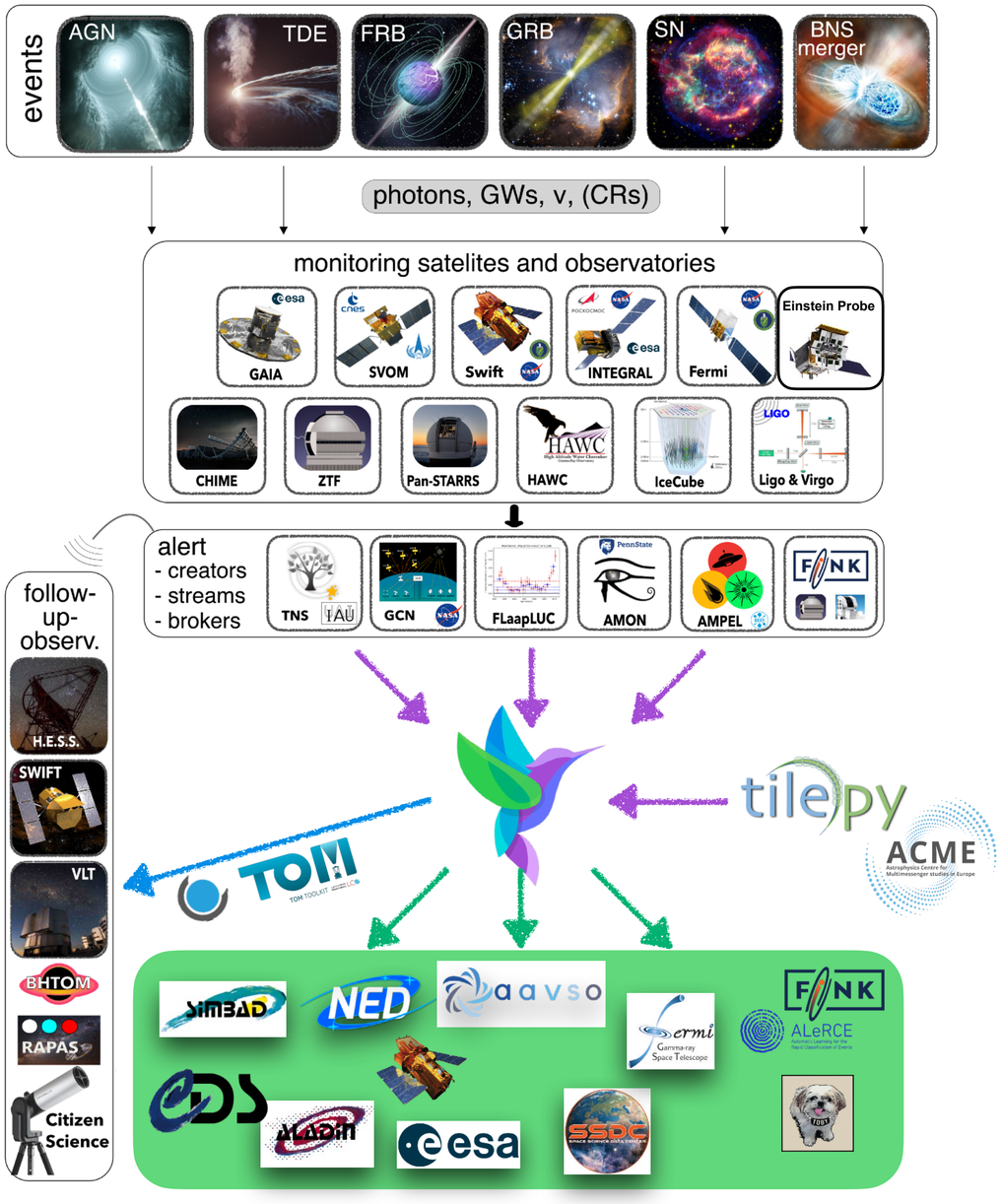




M. Seglar-Arroyo et al., ApJS 274 (2024) 1

Follow-up observations

- Triggering of follow-up observations
  - Dedicated tools: TOM toolkit + SkyPortal
  - Connection with amateur astronomers + citizen scientists

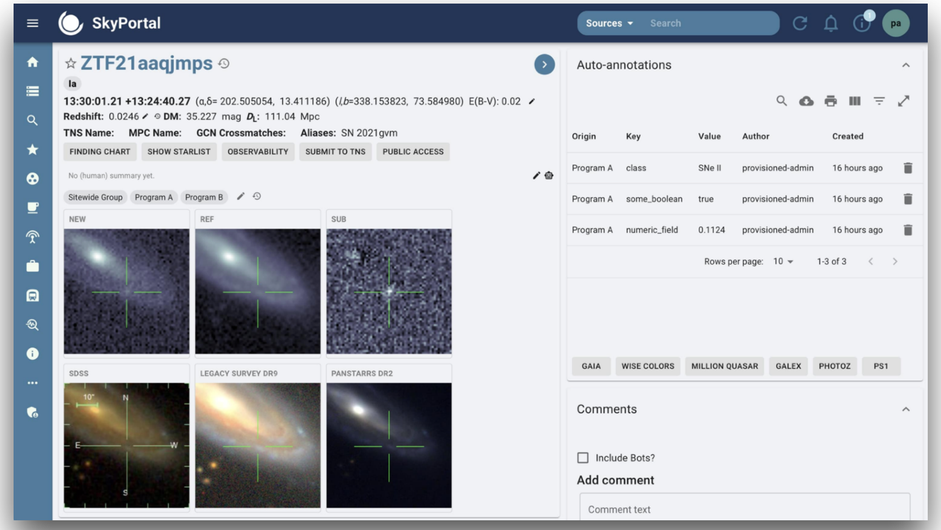


TOM TOOLKIT

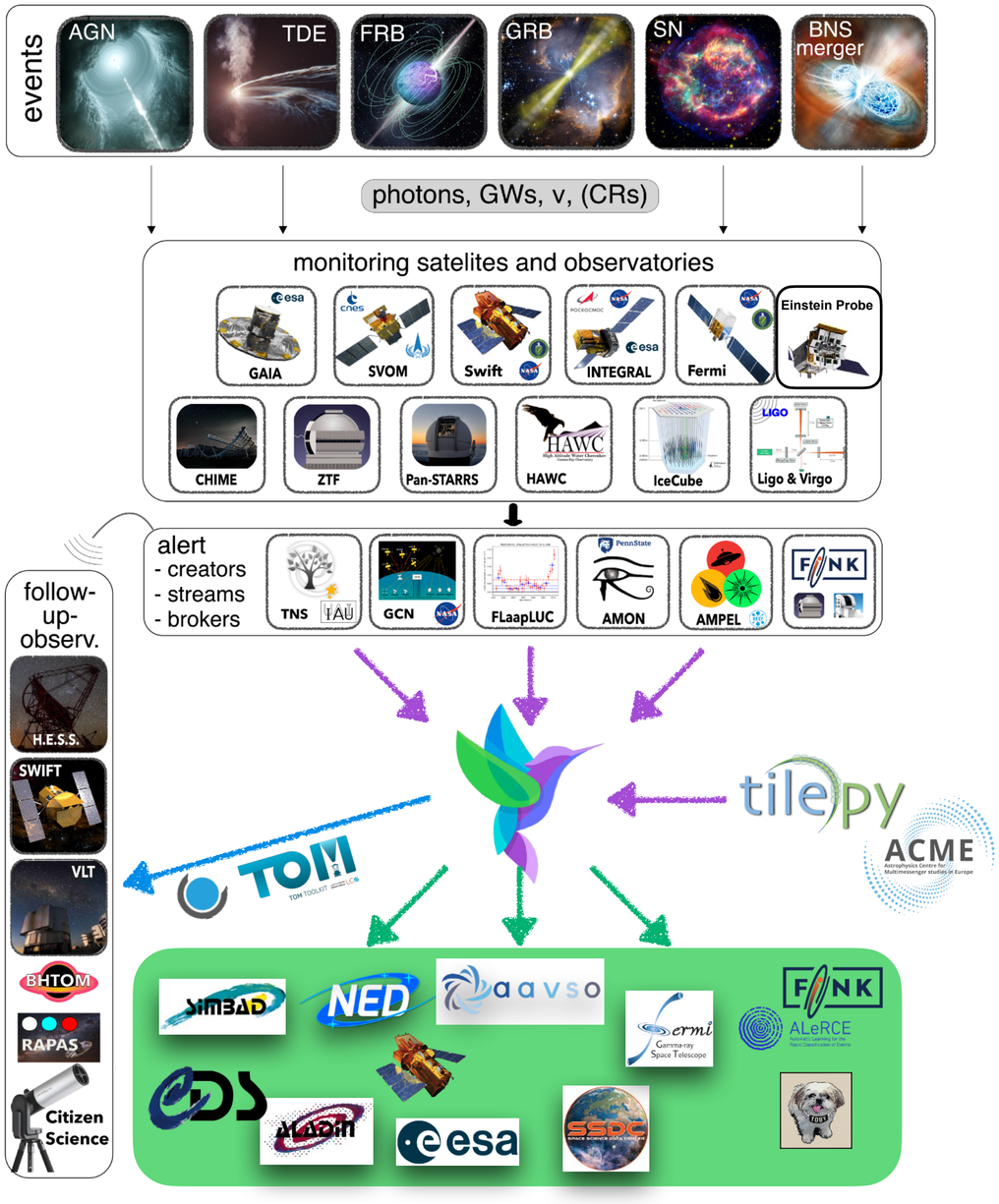
AEON
Astronomical Event Observatory Network

ACME
Astrophysics Centre for Multimessenger studies in Europe

SkyPortal
An Astronomical Data Platform



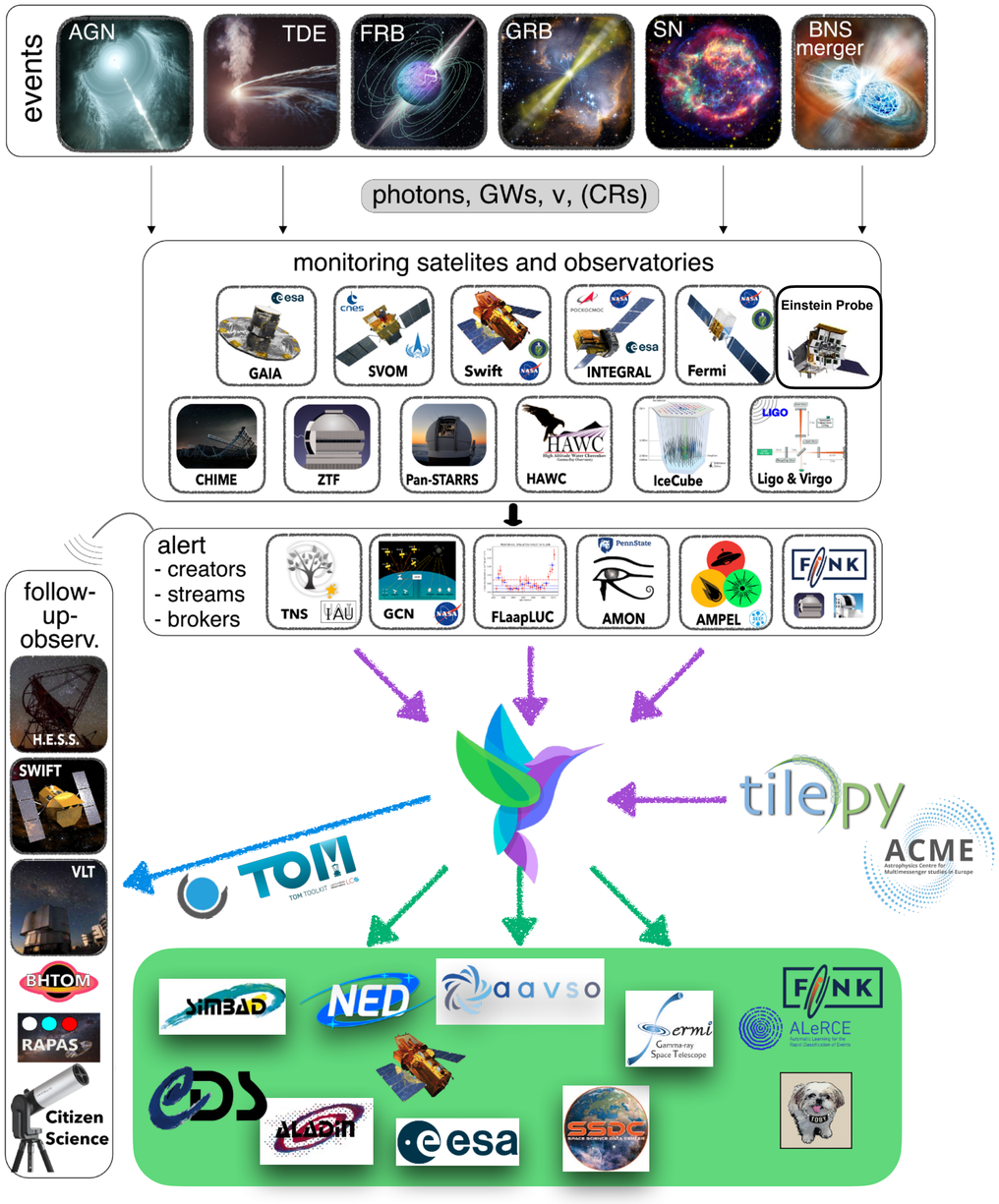
Coordinated follow-up observations



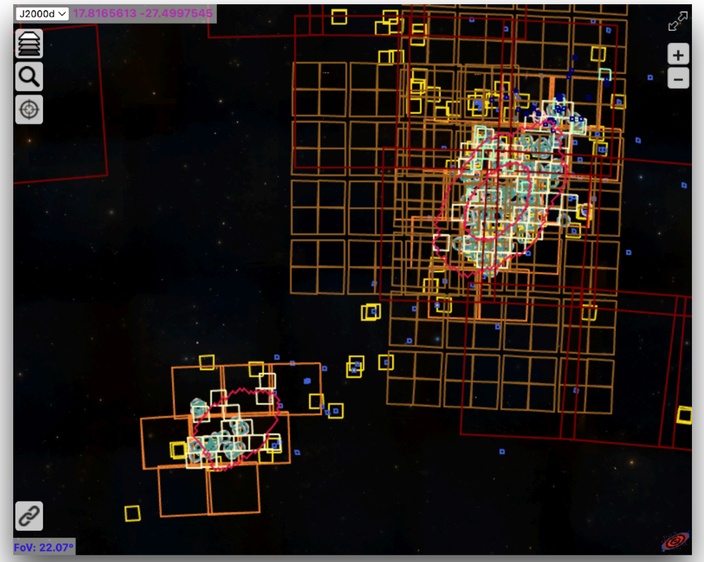
- Gravitational waves: TreasureMap.space

S190814bv
Well-localized NS-BH merger

Coordinated follow-up observations

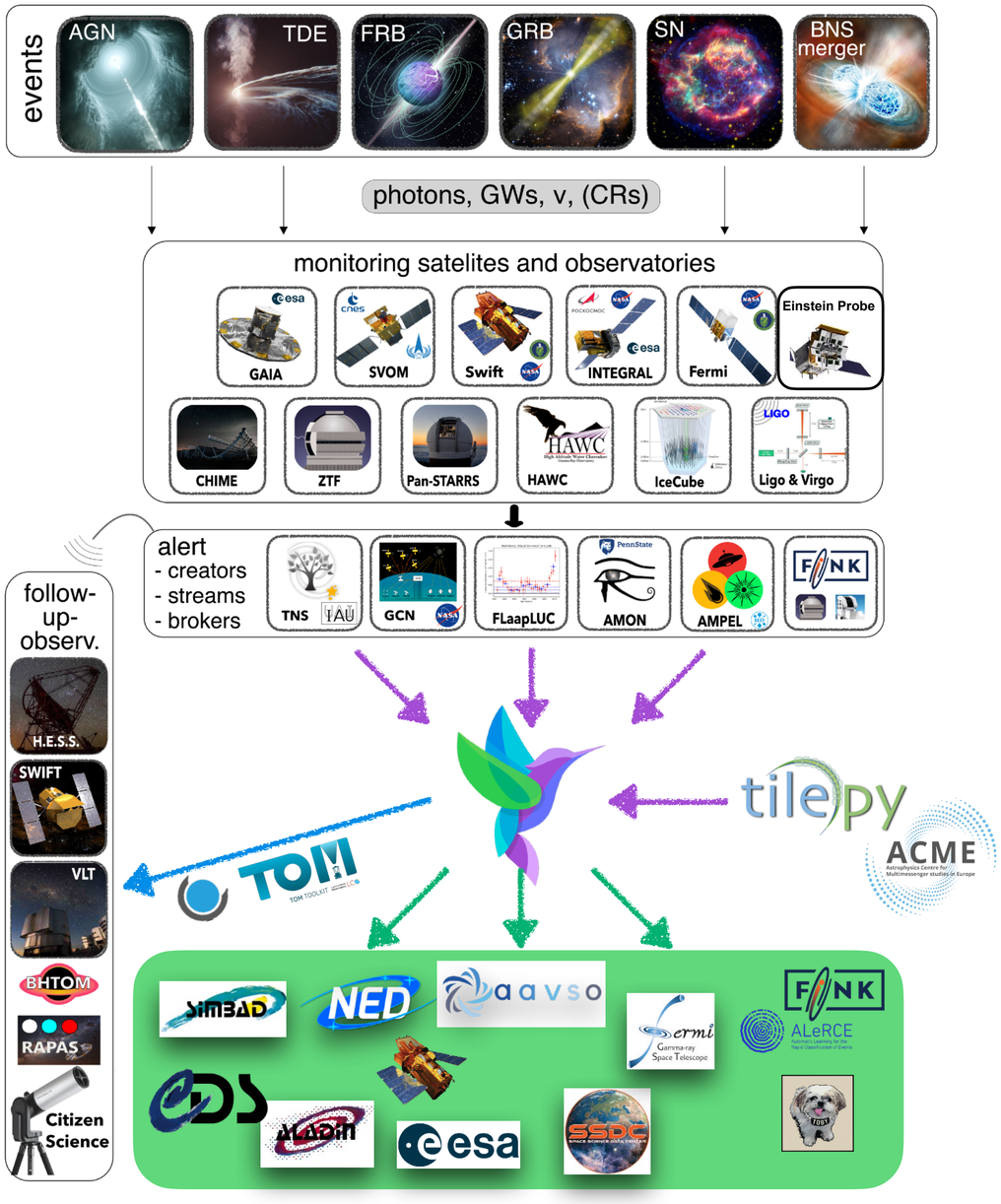


- Gravitational waves: TreasureMap.space

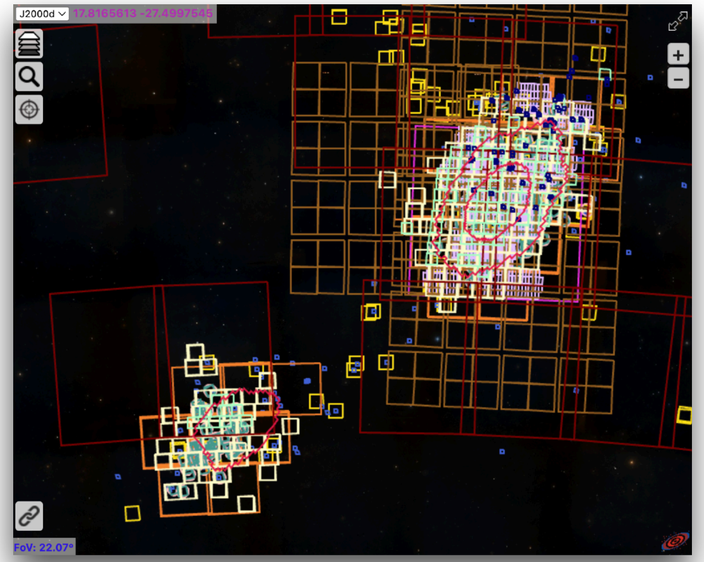


S190814bv
Well-localized NS-BH merger

Coordinated follow-up observations

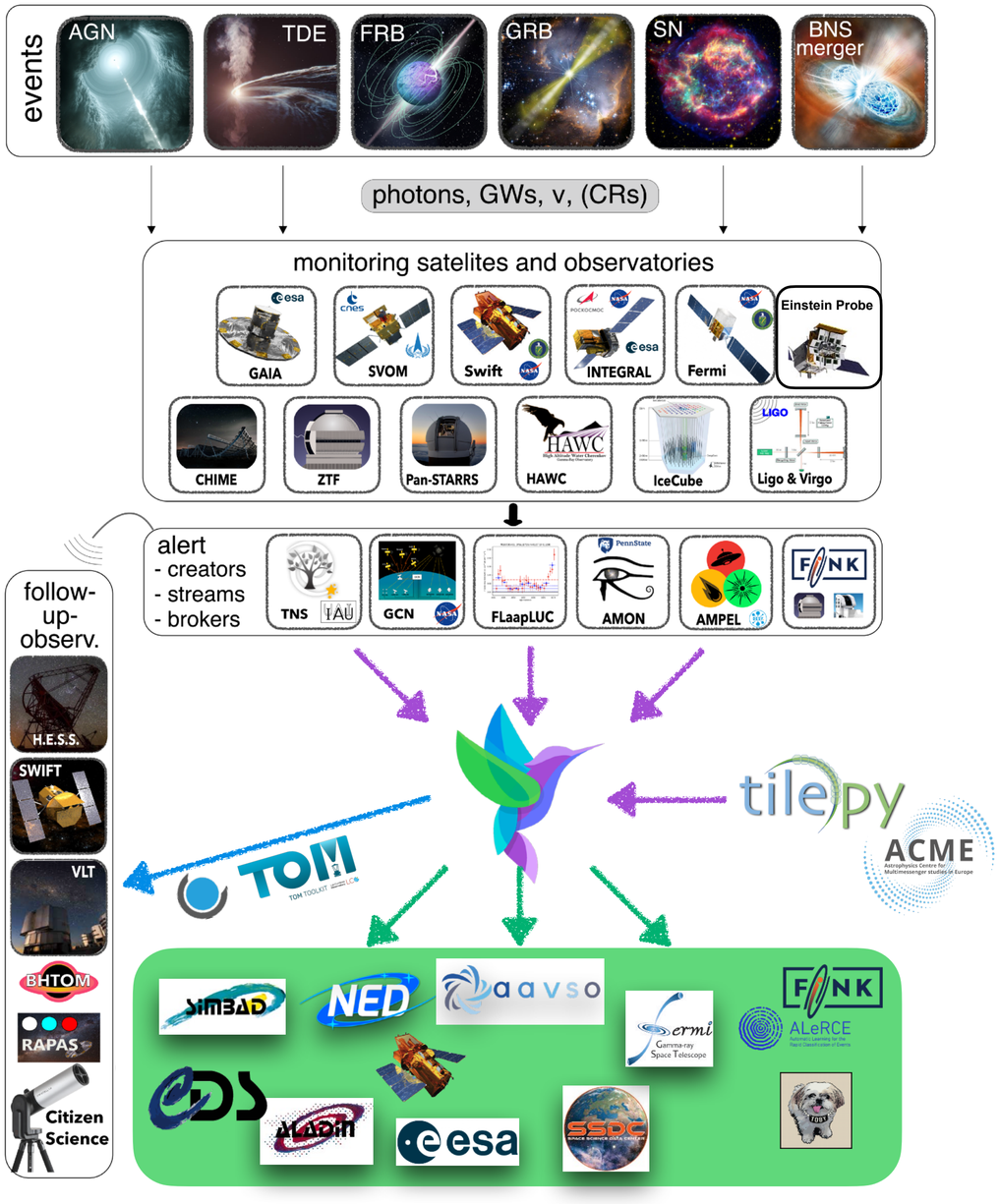


- Gravitational waves: TreasureMap.space

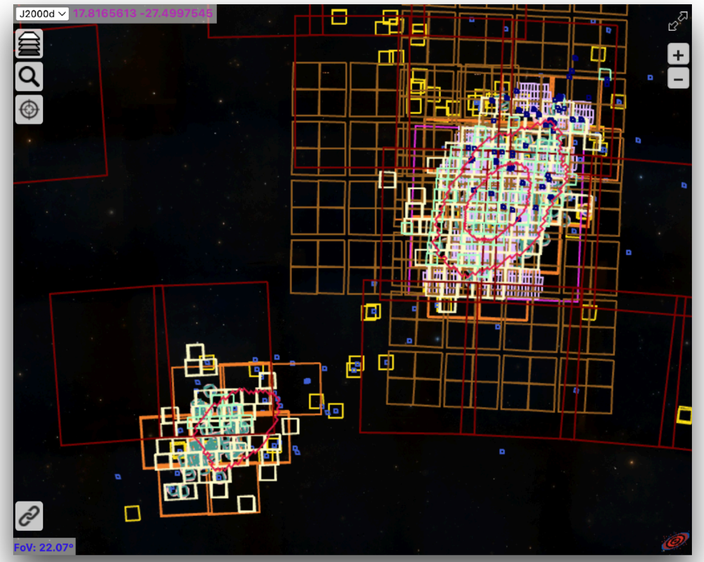


S190814bv
Well-localized NS-BH merger

Coordinated follow-up observations



- Gravitational waves: TreasureMap.space

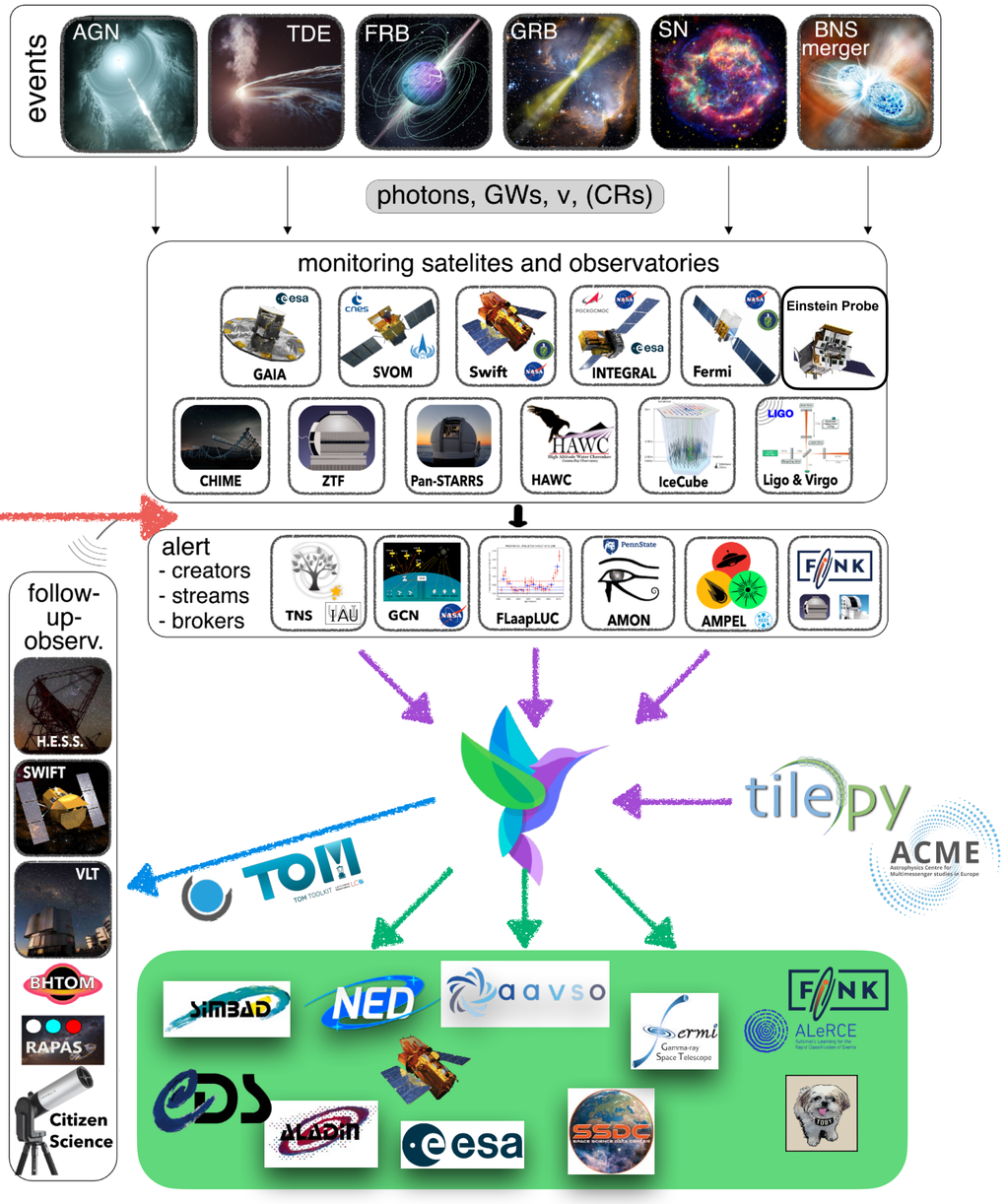


S190814bv
Well-localized NS-BH merger

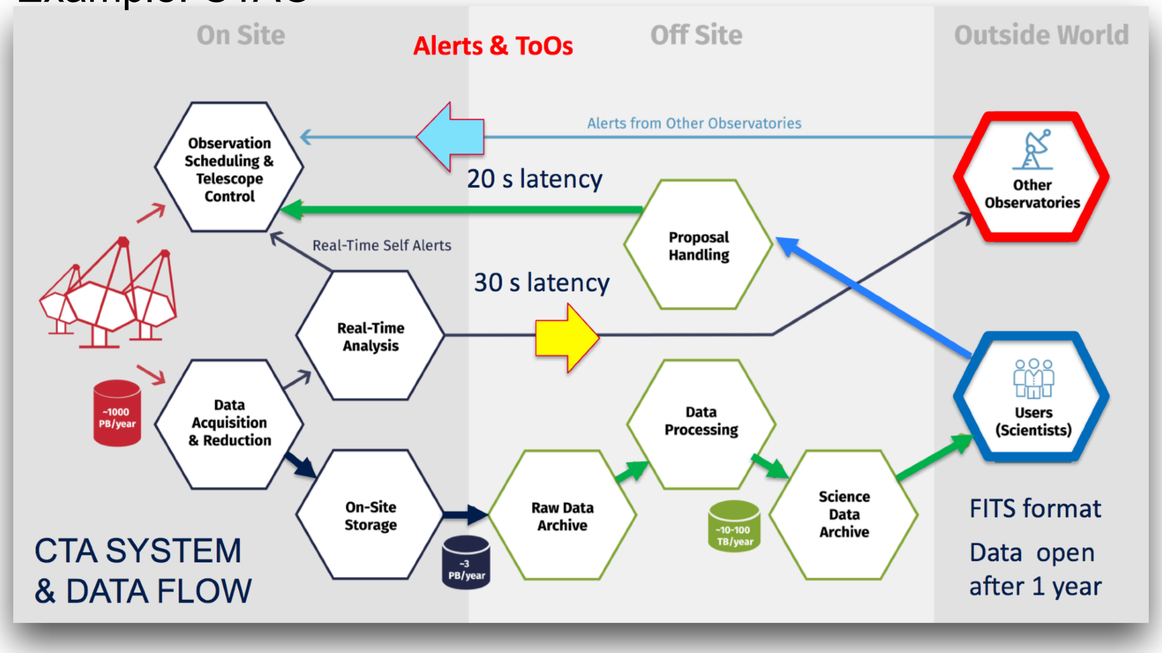
- Public schedules
  - ObsLocTAP services (e.g. TOBY)
  - Individual observatories
    - Example: H.E.S.S. GRB follow-up schedule (https://grbhess.github.io/)

Rapid data analysis + dissemination

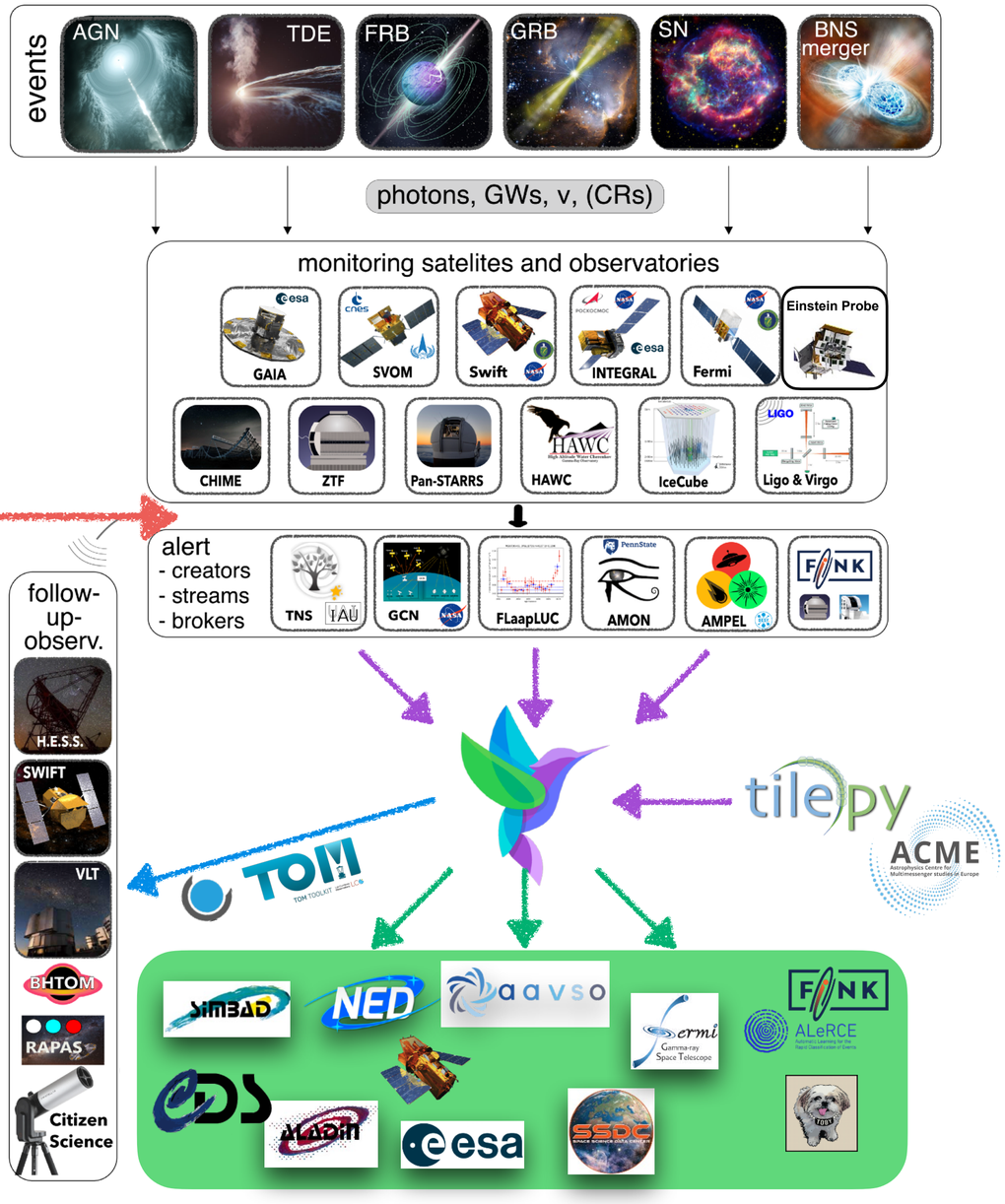
- (realtime) data analyses => guide further observations



Example: CTAO

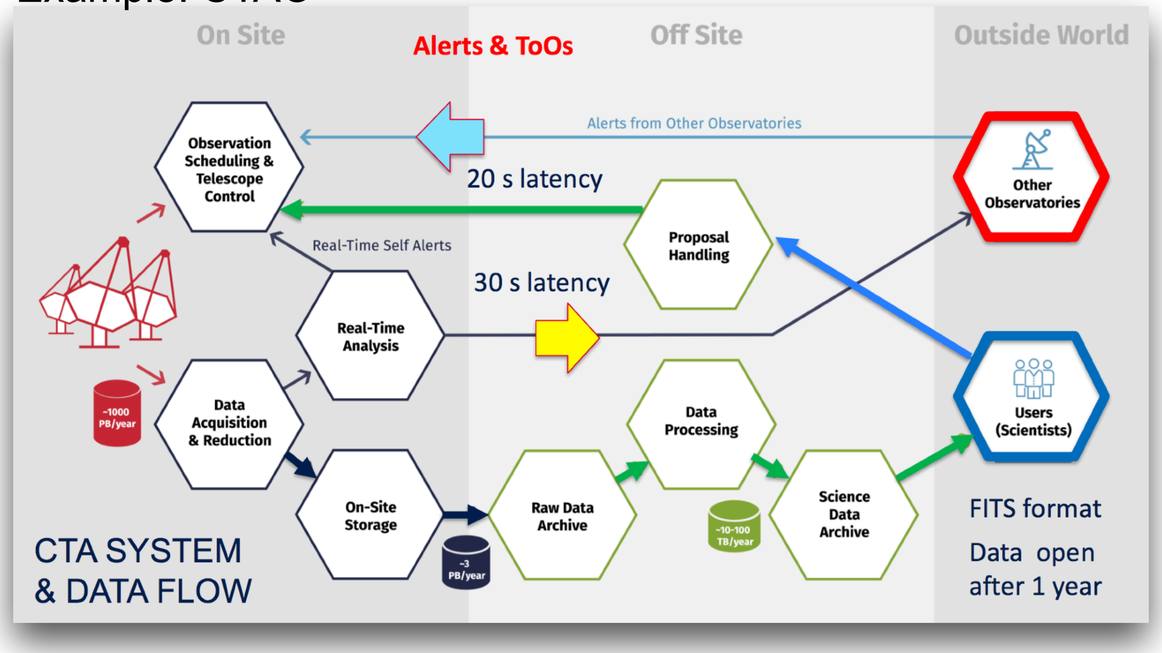


Rapid data analysis + dissemination



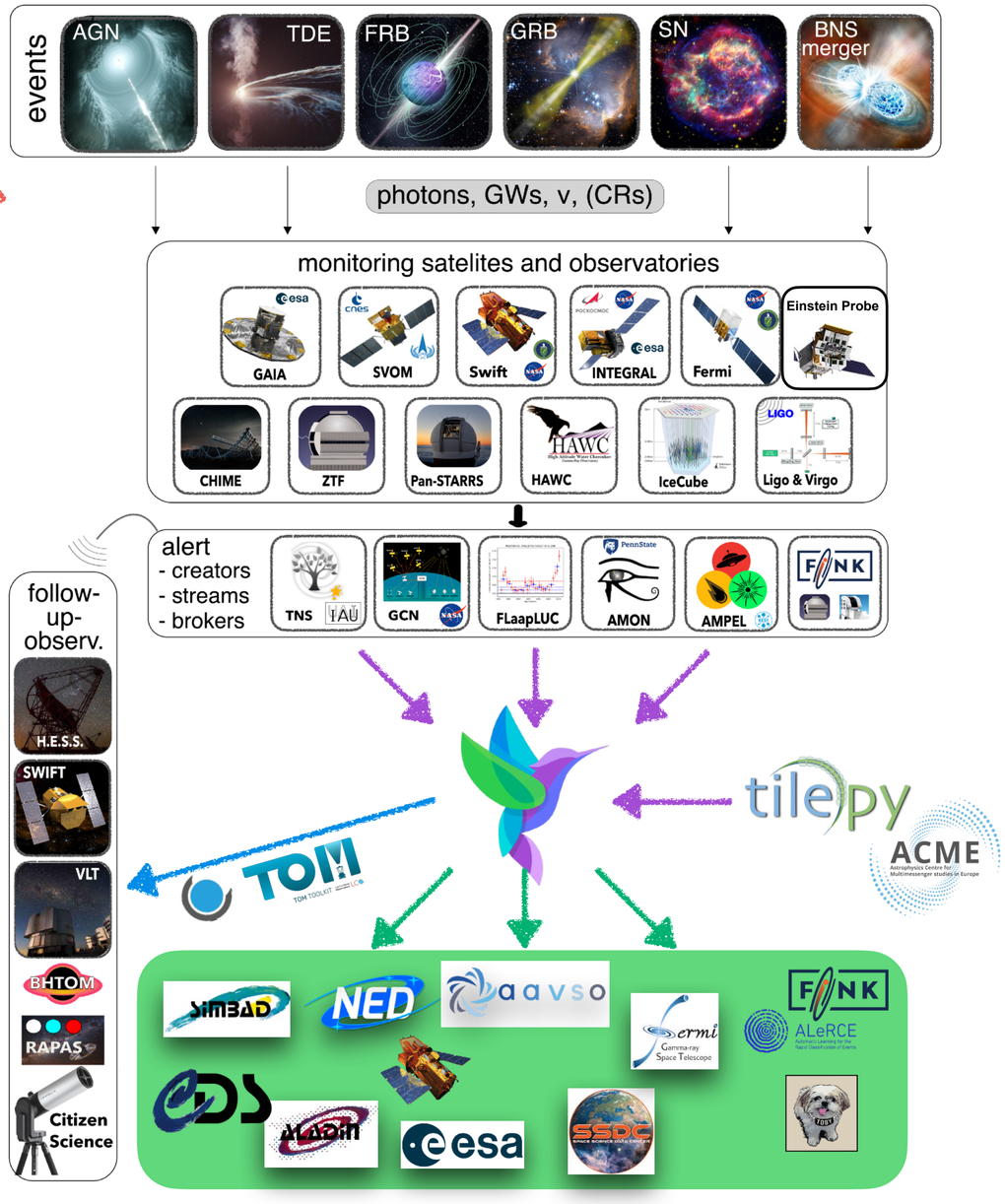
- (realtime) data analyses => guide further observations

Example: CTAO



- Rapid publication of follow-up results
  - Classification + characterization => increased efficiency
  - Comparable results (e.g. BHTOM)

Global, joint MWL/MM analyses

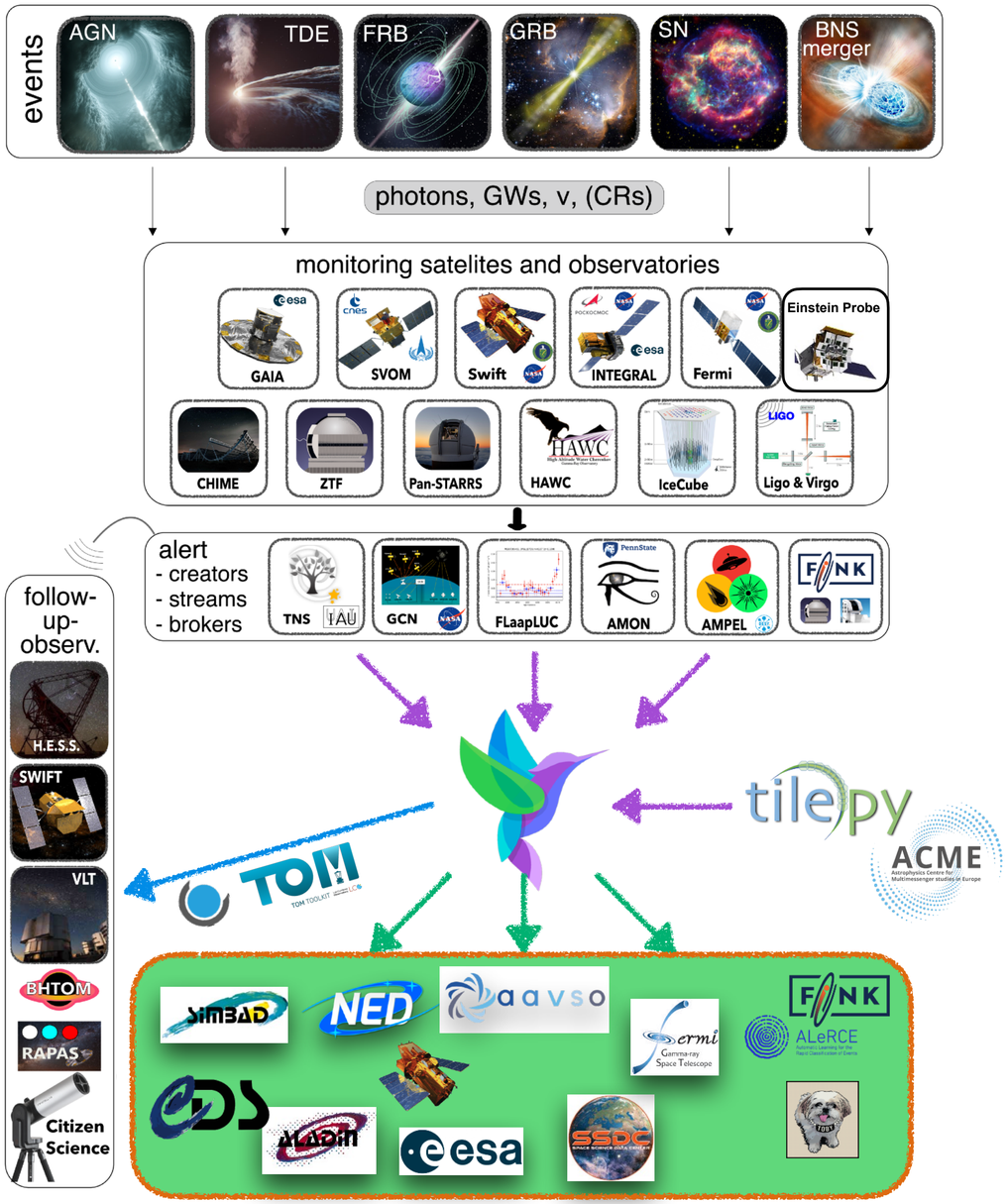


- Complete picture of (transient) phenomena
- Rapid publication + data releases
- Finding data: global information database of available datasets ?
- MWL/MM + multi-instrument data analysis tools

γπ A **Python** package for **gamma-ray** astronomy

...

FAIR data archives



- FAIR data archives
  - Comprehensive archives of MWL/MM data
  - Association with computing resources: facilitate reproducibility of analyses
    - e.g. MMODA
  - Common interfaces to allow for easy integration
    - e.g. connection to realtime decision making processes

Summary

- (Transient) multi-wavelength and multi-messenger observations are challenging
- We already have an enormous set of increasingly sophisticated tools at our disposal
- Further automatization and integration is necessary to cope with the increasing number and complexity of MWL/MM data.

- The Astrophysics Center for Multimessenger studies in Europe aims to advance this process

- Many open questions
  - How sustainable is the current landscape of tools and platforms in the mid/long-term? Single point failures?
  - What role will AI play?
    - Extract information from human written observation reports (e.g. GCN Circulars, ATELs, Astronotes)
    - Decision making processes: event classifiers as first step => agents ingesting all available data and take autonomous decisions on follow-ups ?
  - How can we further leverage contributions from citizen scientists?
  - ...