Simulation and analysis of time-evolutional gamma-ray sources

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Gamma-ray transients

Many transient classes have emerged as gamma-ray observational targets for example:

- Gamma-ray bursts (GRBs)
- Active galactic nuclei (AGNs)
- Short gamma-ray repeaters (SGRs)/Fast radio bursts (FRBs)
- Primordial blackholes (PBHs)

Catastrophic physical state variation

Extreme change in physical state enables us to probe the behavior of observational targets under various conditions

Multiple processes with different nature

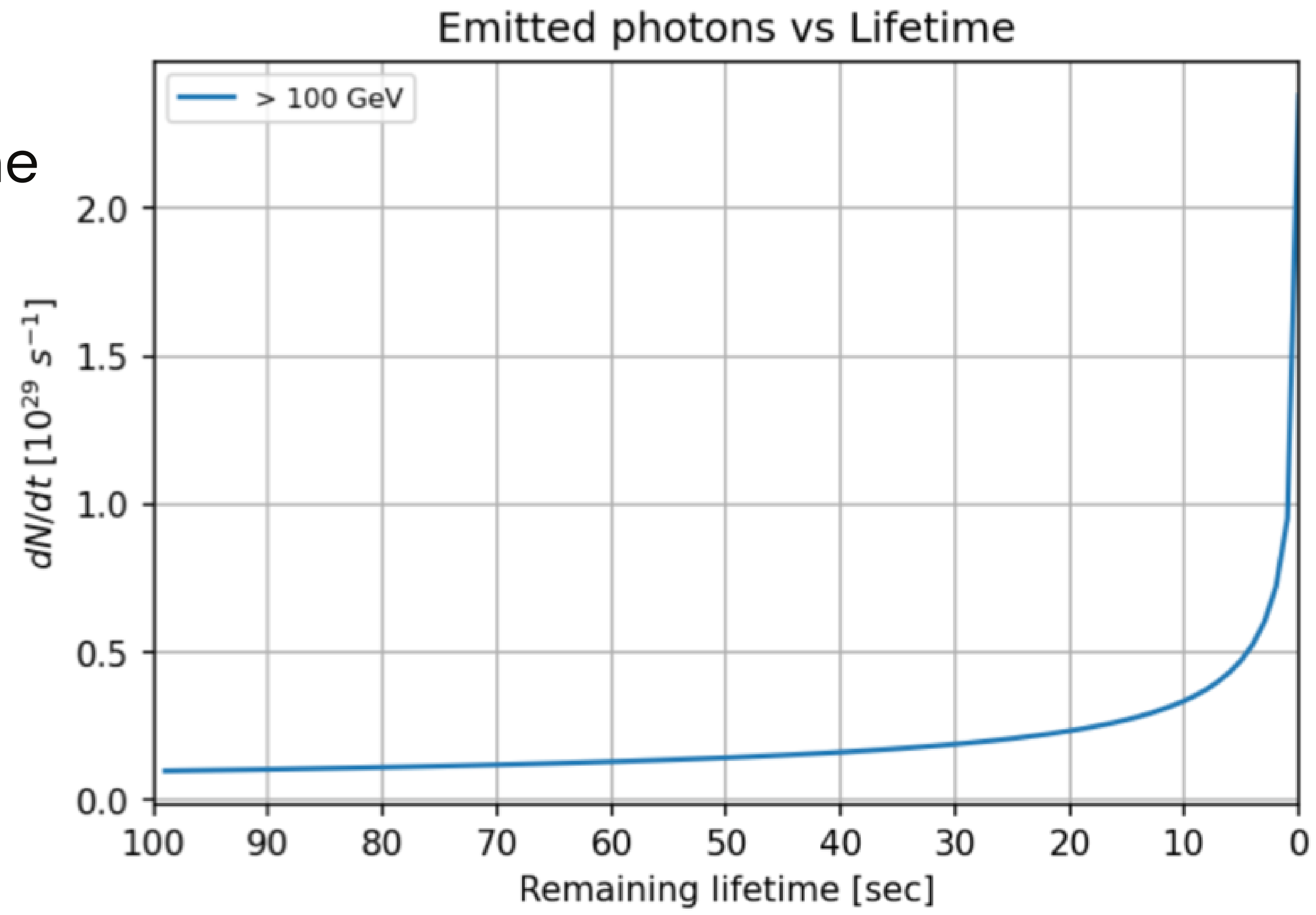
Drastic state changes of astronomical objects may trigger other astrophysical/particle physical processes affecting the observables

Serendipitous for observers in many cases

Because of the nature of the variability, the transient sources are often unknown to observers. We should not miss a chance of discovery!

Primordial Blackhole

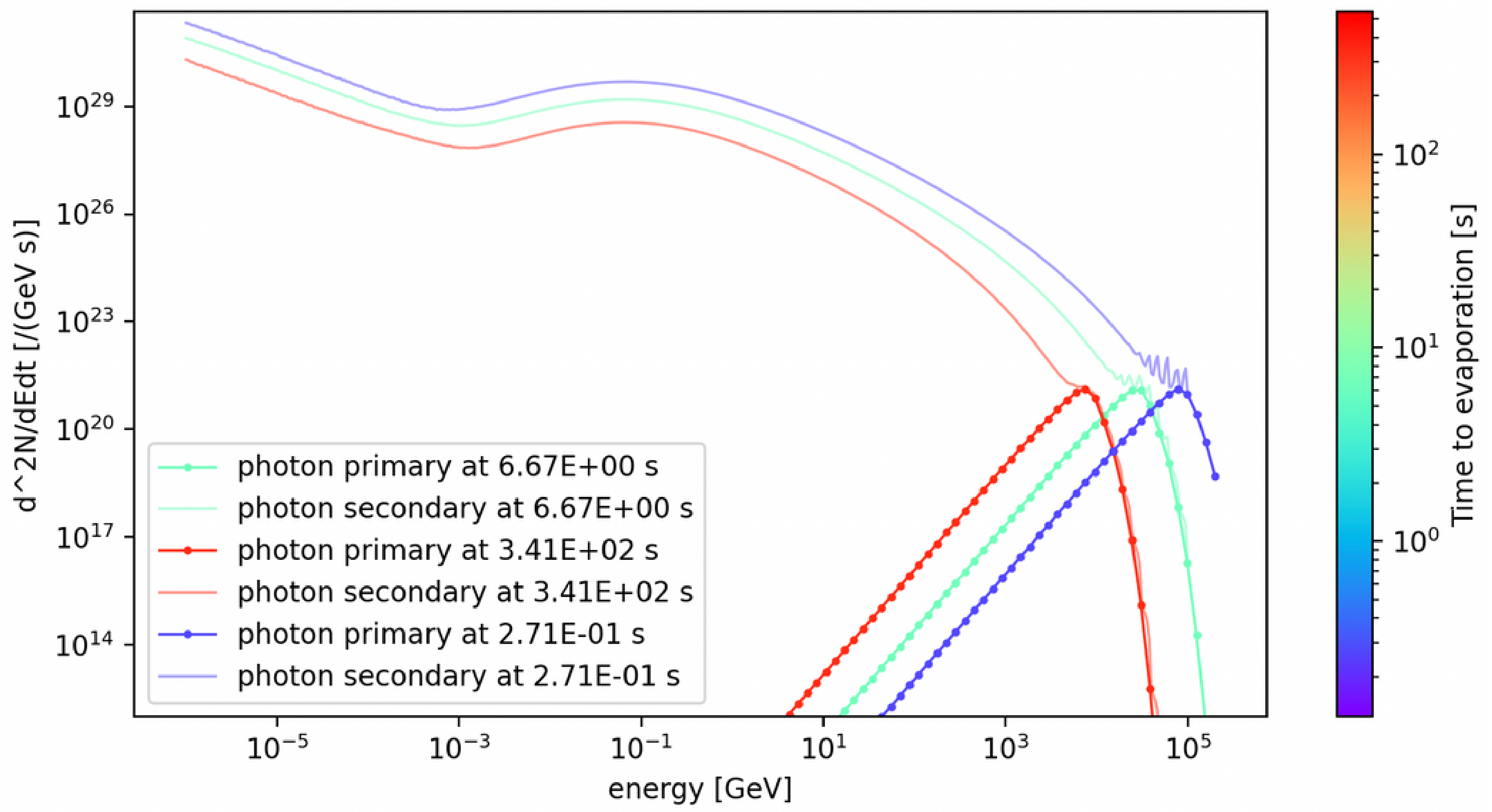
- PBHs were possibly produced by the collapse of over-density regions in the early Universe
  - One of the dark matter candidates
- If their mass is ~10^15 g at birth, they are expected to be evaporating by Hawking radiation at present
  - Emit a bunch of photons
- Temperature becomes higher at the later phase of the lifetime
  - Energy and flux of photons increase rapidly
- PBH discovery enables us
  - Confirmation of Hawking radiation
  - Constraints on density fluctuation in the early Universe
  - Search for particles heavier than the accelerator reach
  - Test QED and QCD physics



Calculation based on Ukwatta et al. (2016)

PBH as archetype of transient search

- We are developing simulation and analysis of transient gamma-ray sources
    - Plan to apply first for PBHs
        - with several features shared by transient classes
            - rapid flux change
            - spectral variation
            - primary/secondary radiation
            - serendipitous nature
    - Once good PBH software is developed, it can be an archetype to extend to other transients



Calculation based on BlackHawk

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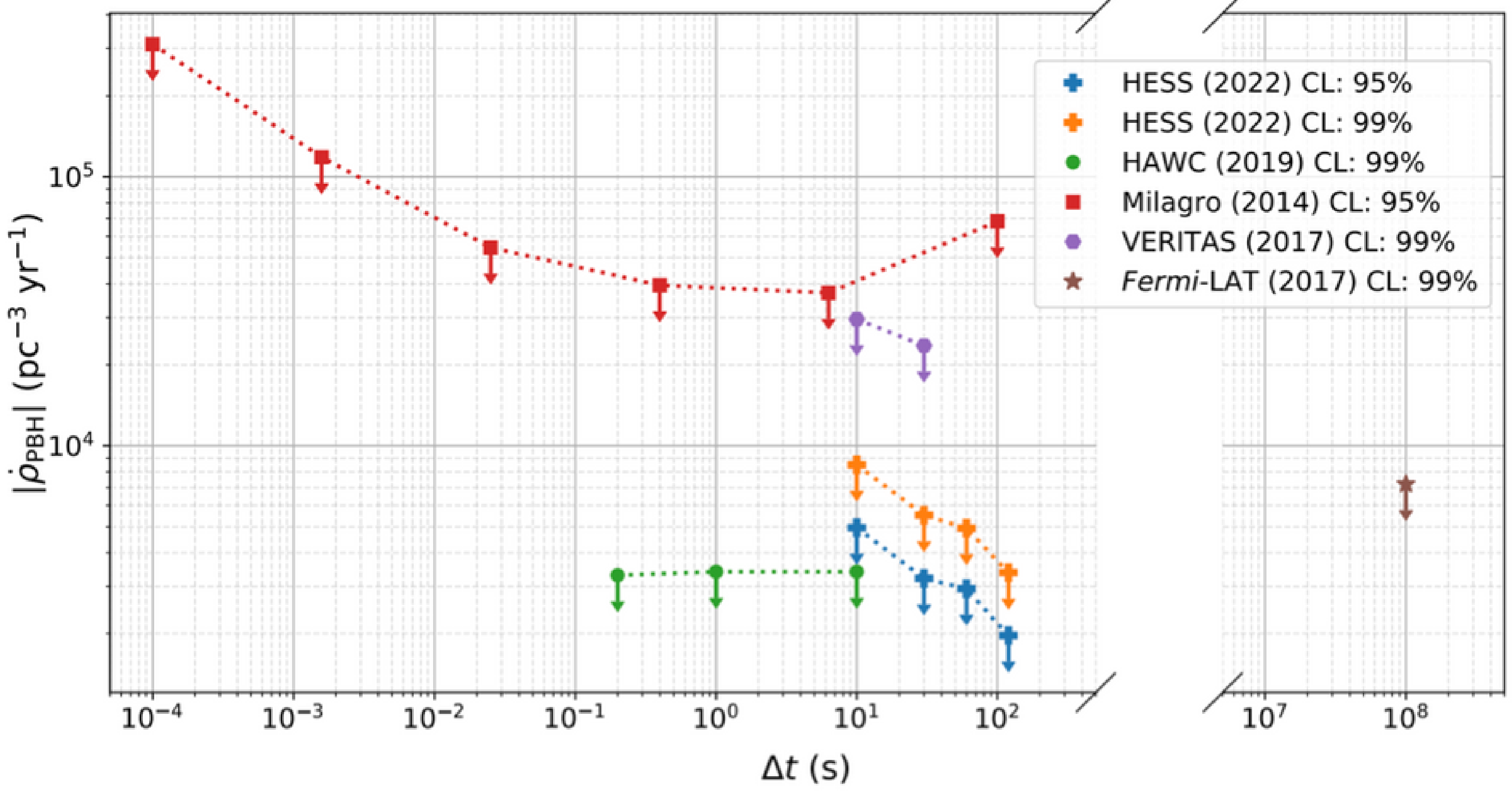
Constraints on PBH evaporation rate

- PBHs are possibly observed in any available data from gamma-ray telescopes
- Milagro, VERITAS, *Fermi*-LAT, HAWC, and H.E.S.S. published upper limits on the evaporation rate
  - H.E.S.S. (2022) is competitive with wide field-of-view telescopes such as HAWC and *Fermi*-LAT
  - Pfrang (2023) applied deep learning technique to the PBH search with VERITAS

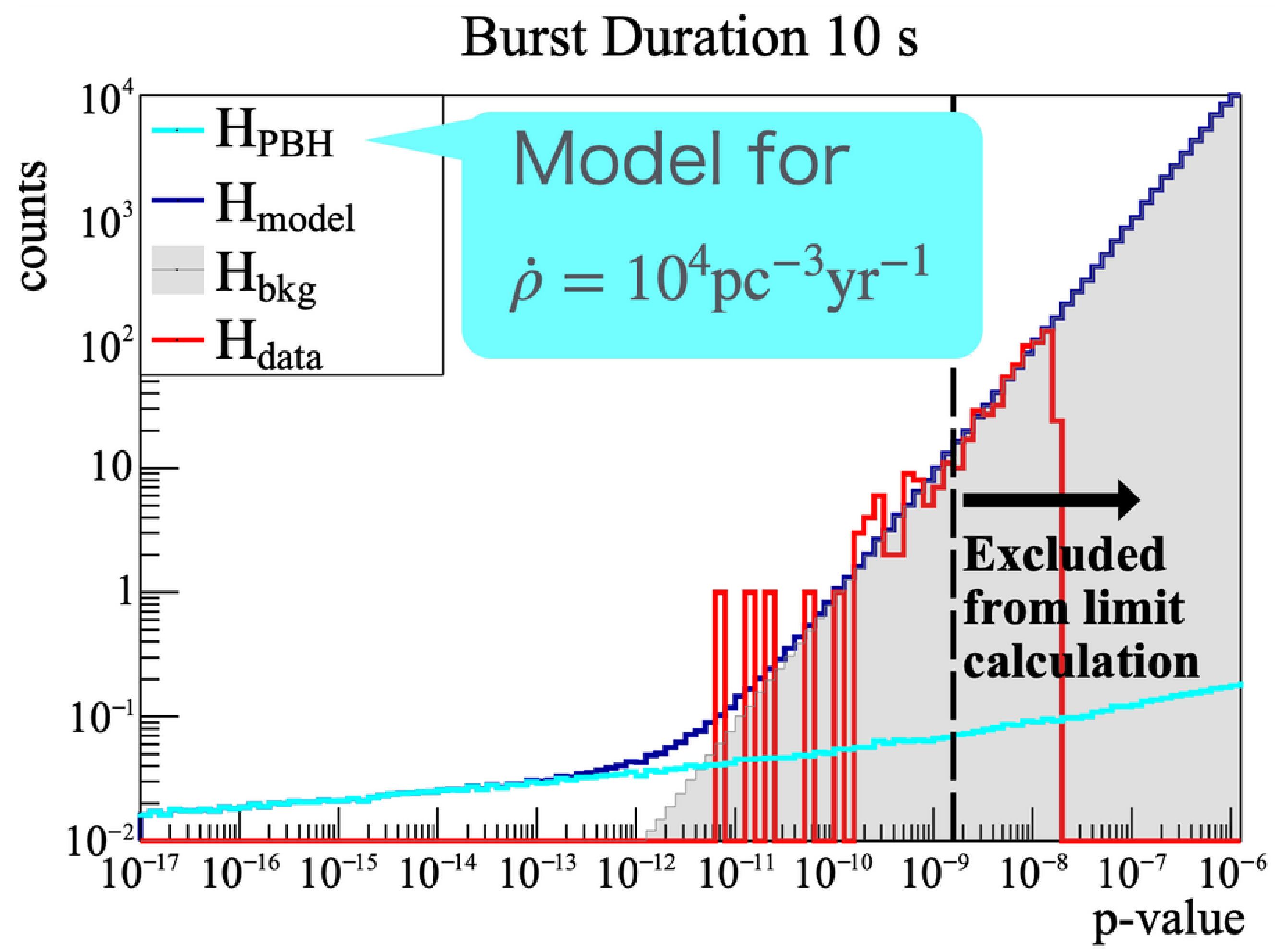
Burst rate vs time until evaporation



H.E.S.S. Collaboration et al., JCAP04(2023)040

HAWC (A. Albert et al. 2019)

- Data: 959 days in 2015–2018
- **Sliding time-window** method
  - Originally used for GRB detection
  - Divides data into 2.1°×2.1° spatial bins and 0.2-s/1-s/10-s temporal bins
  - Searches gamma-like event rate peak
- For each found cluster, p-value under background-only hypothesis is tagged
- Test statistics is calculated scanning the PBH explosion rate



H.E.S.S. (F. Aharonian et al. 2022)

- Data: 4816 hours in 2004–2013
- **Cluster search**
  - Define both angular (spatial) and temporal distance between gamma-ray events
  - Find event clustering using the OPTICS (Ordering Points To Identify the Clustering Structure) algorithm
- Maximal time duration: 120 s
- Combine the likelihood of all clusters

Poisson

PBH signal model

PBH explosion rate (Single parameter)

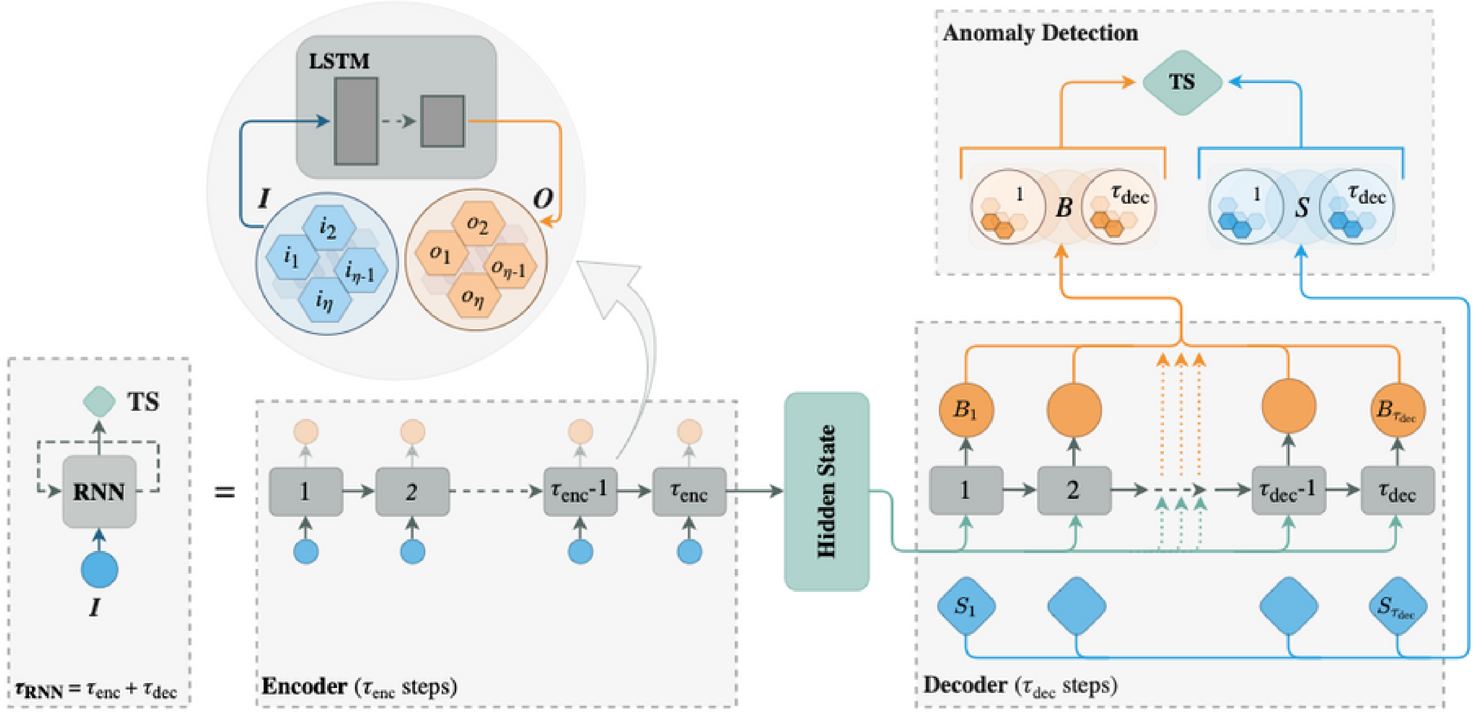
$$\frac{\mathcal{L}_{H_1}}{\mathcal{L}_{H_0}} = \prod_i \frac{\mathcal{P}(n^i_{\mathrm{ON}} | \lambda = n^i_{\mathrm{OFF}} + n^i_{sig}(b, \Delta t, \dot{\rho}_{\mathrm{PBH}}))}{\mathcal{P}(n^i_{\mathrm{ON}} | \lambda = n^i_{\mathrm{OFF}})}$$

Product for every found cluster i

Background model

VERITAS (K. J. Pfrang 2022)

- Data: 4222 hours in 2012–2021
- Search transients using **Recurrent Neural Networks (RNN)**
  - Trains RNN so that it predicts background
    - Able to take complicated instrumental responses into account flexibly
  - Evaluates the difference from real data
    - Usable for transient phenomena other than PBHs
  - Input the data of the previous time period
    - Enable to take time evolution of PBH signal into account
- Upper limit is weaker than VERITAS (2017)



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Requirements from PBH nature

- For simulation
  - Theoretical predictions have large uncertainty

    → Should be feasible to modify the emission model
  - Some primary particles produces secondary photons

    → Should separate the evolution of radiated particles from astronomical objects
- For analysis
  - Observation is (almost totally) serendipitous

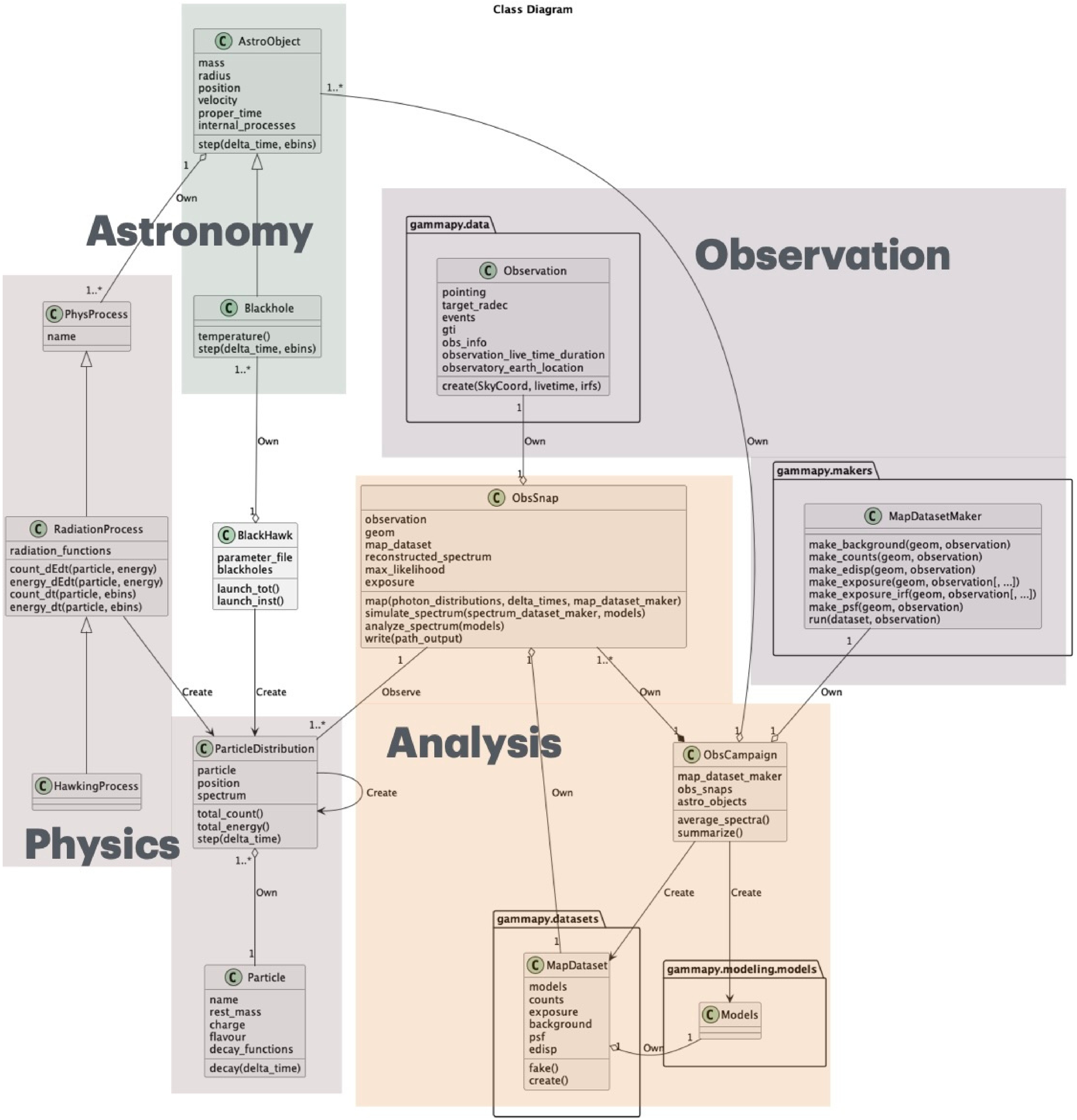
    → Should be able to process large amounts of data without spatial/temporal reduction
  - Flux in a certain energy band rapidly increases over time

    → Should be sensitive to time variation of the flux
  - Increase in the temperature (gamma-ray energy) is a decisive feature

    → Should be sensitive to spectral evolution

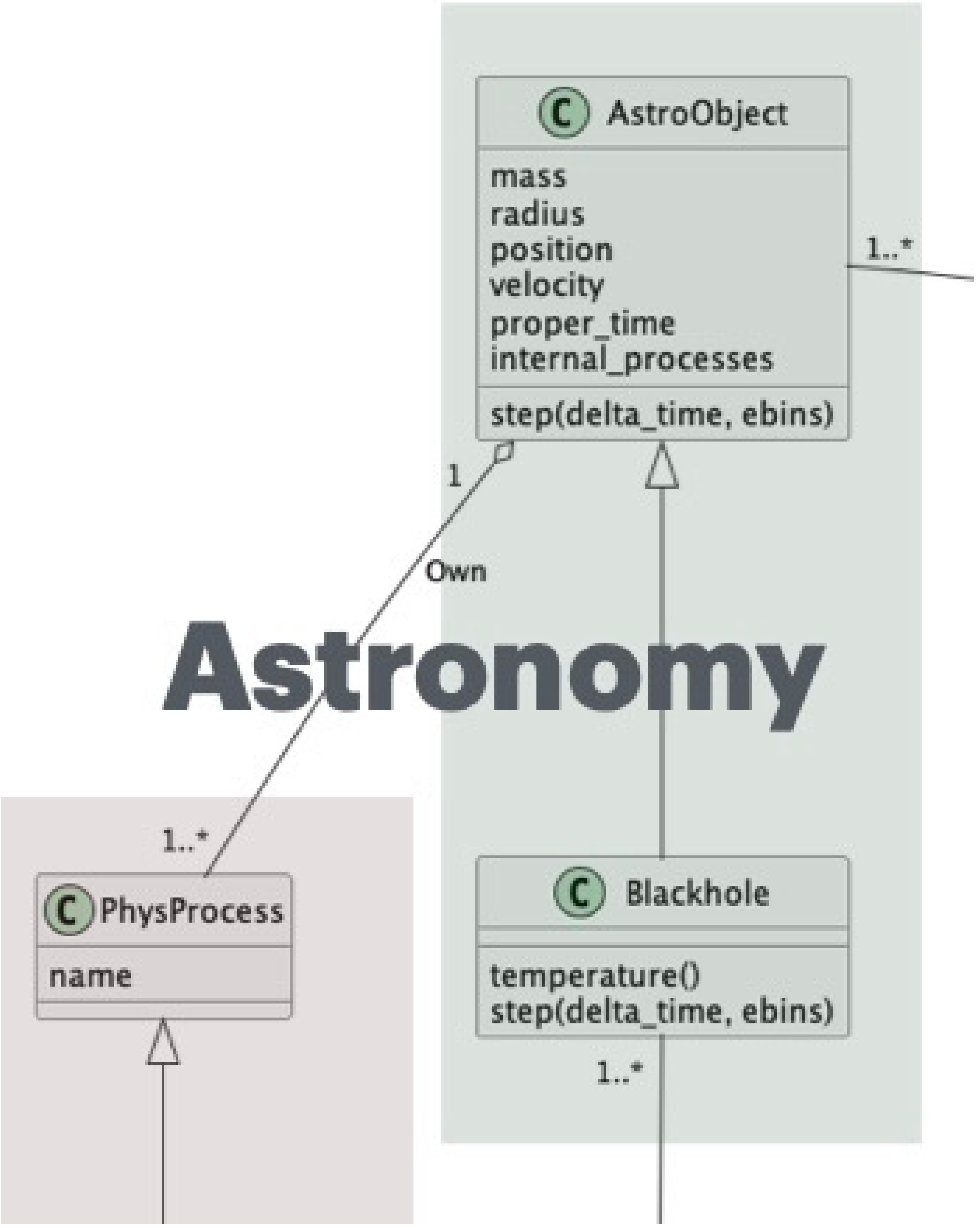
Software design

- Our software is formed by classes categorized into four segments:
  - astronomy
  - physics
  - observation
  - analysis
- This scheme ensures flexibility and expandability



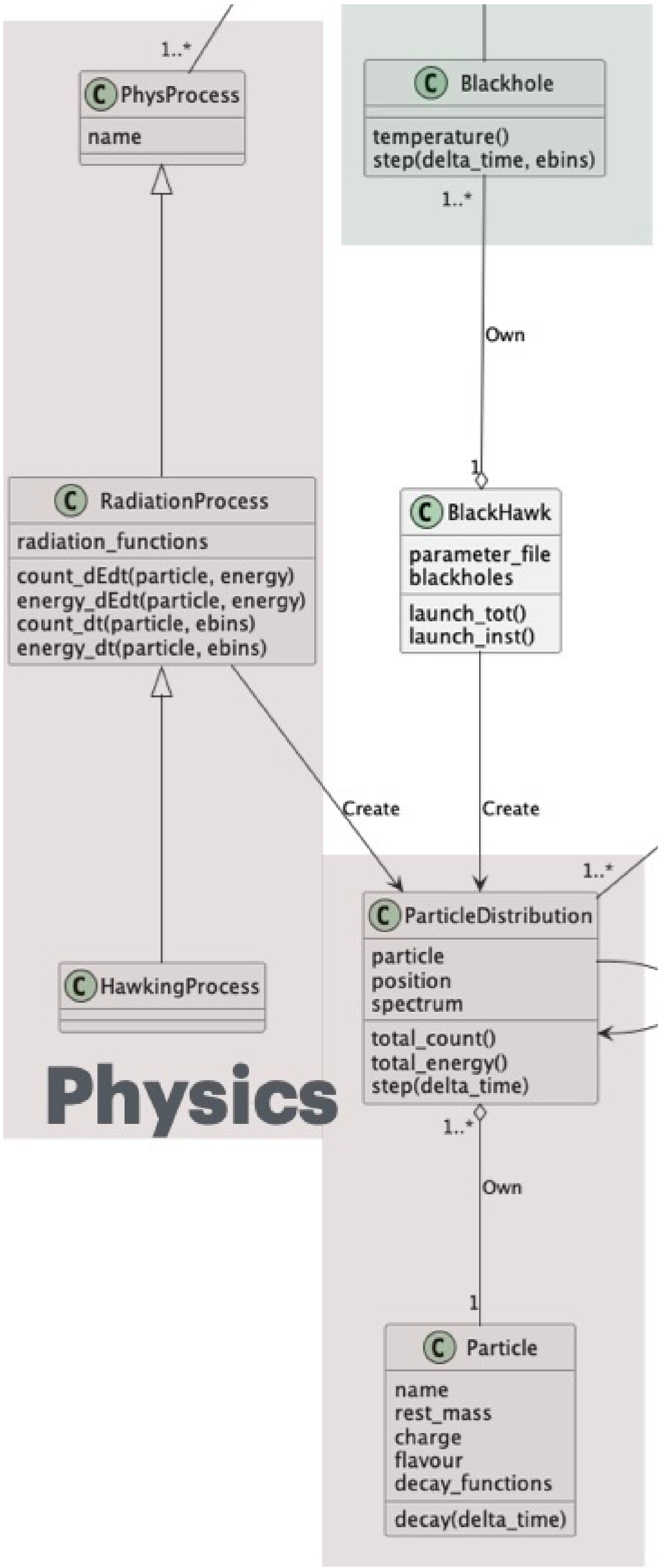
Astronomy segment

- In the astronomy segment, the class of **AstroObject** stores the astronomical characteristics such as the mass and position as a member variable.
  - Value of the member variables is changed by PhysProcess → Physics segement
- Each specific astronomical-object class is inherited as a subclass of **AstroObject**
  - <u>**Blackhole** has a variable of temperature</u>
- New class of astronomical object with additional features can be defined flexibly



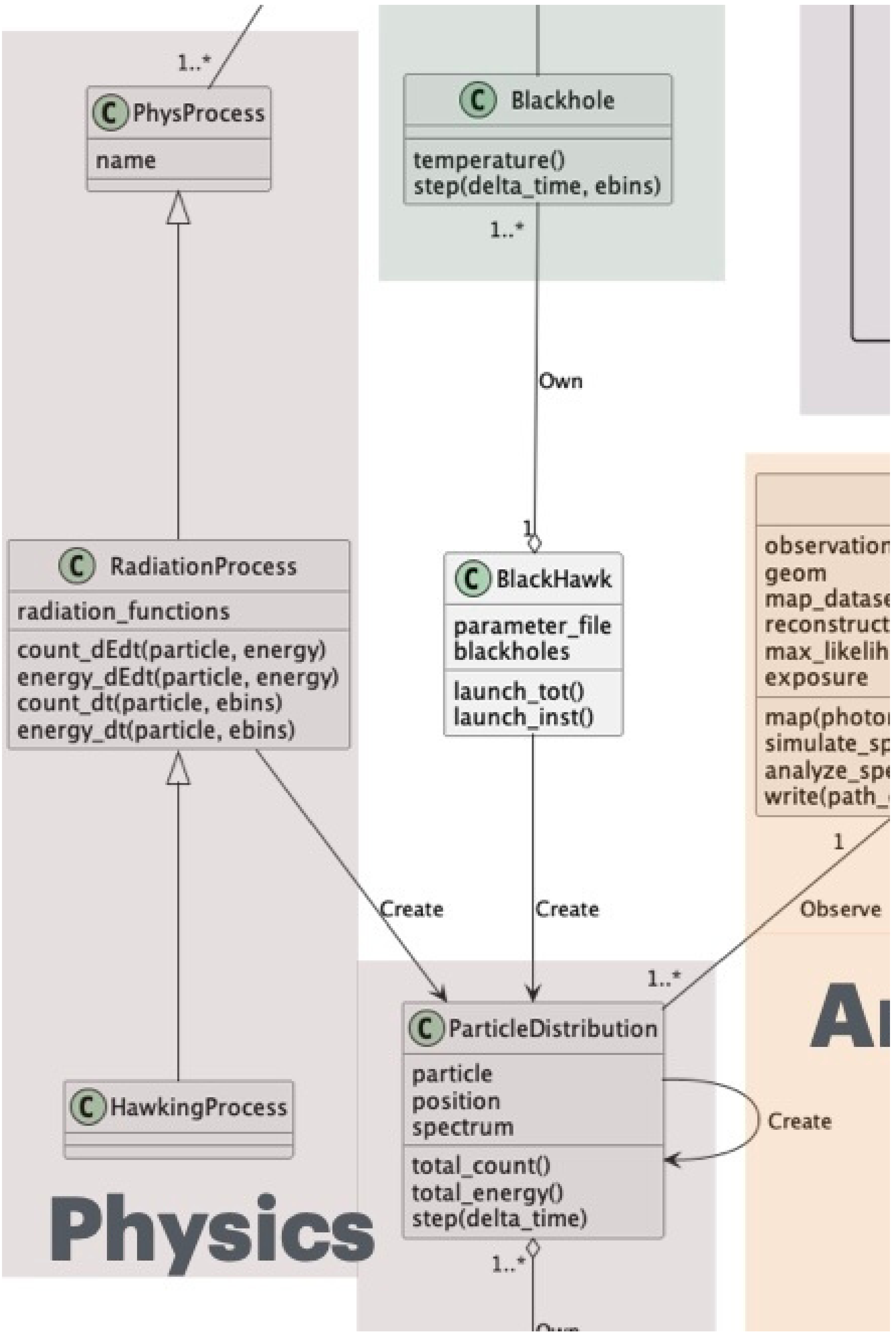
Physics segment

- As a subclass of **PhysProcess**, **RadiationProcess** is introduced
  - RadiationProcess can create **ParticleDistribution**
  - **HawkingProcess** is defined as a subclass of **RadiationProcess**
- **ParticleDistribution** is associated with a specific **Particle** (e.g. photon, u-quark, e-neutrino, etc.)
  - **ParticleDistribution** is created by **RadiationProcess** or another **ParticleDistribution** (→ secondary particles)
  - State of **ParticleDistribution** evolves due to decaying, energy loss, and so on
    - Can be modeled independently from the astronomy part



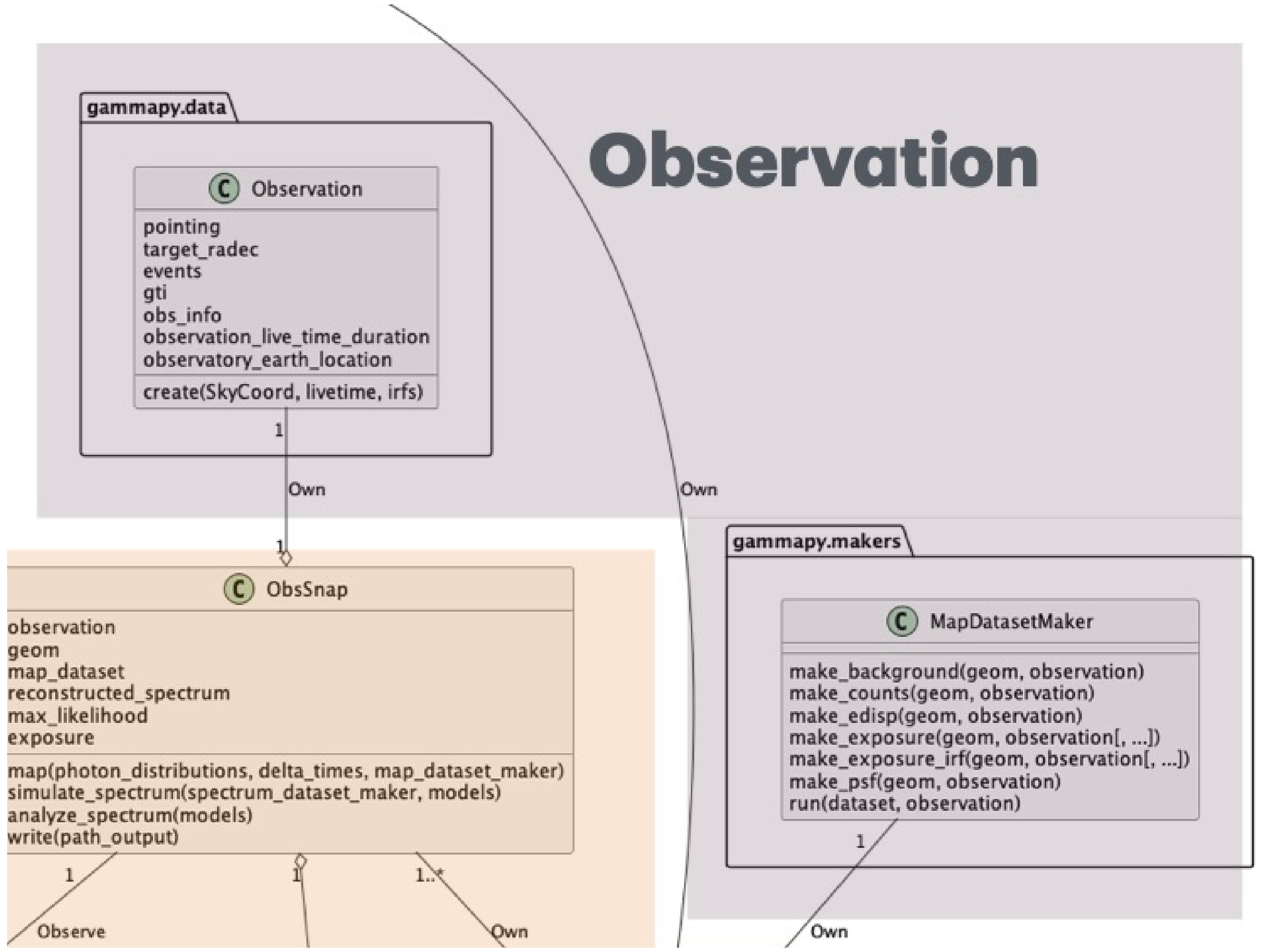
Third-party PBH simulator

- Third-party simulators (e.g. **BlackHawk**, a public program for calculating the Hawking evaporation spectra) can be used via a wrapper
  - It provides **ParticleDistribution** directly, bypassing **PhysProcess**



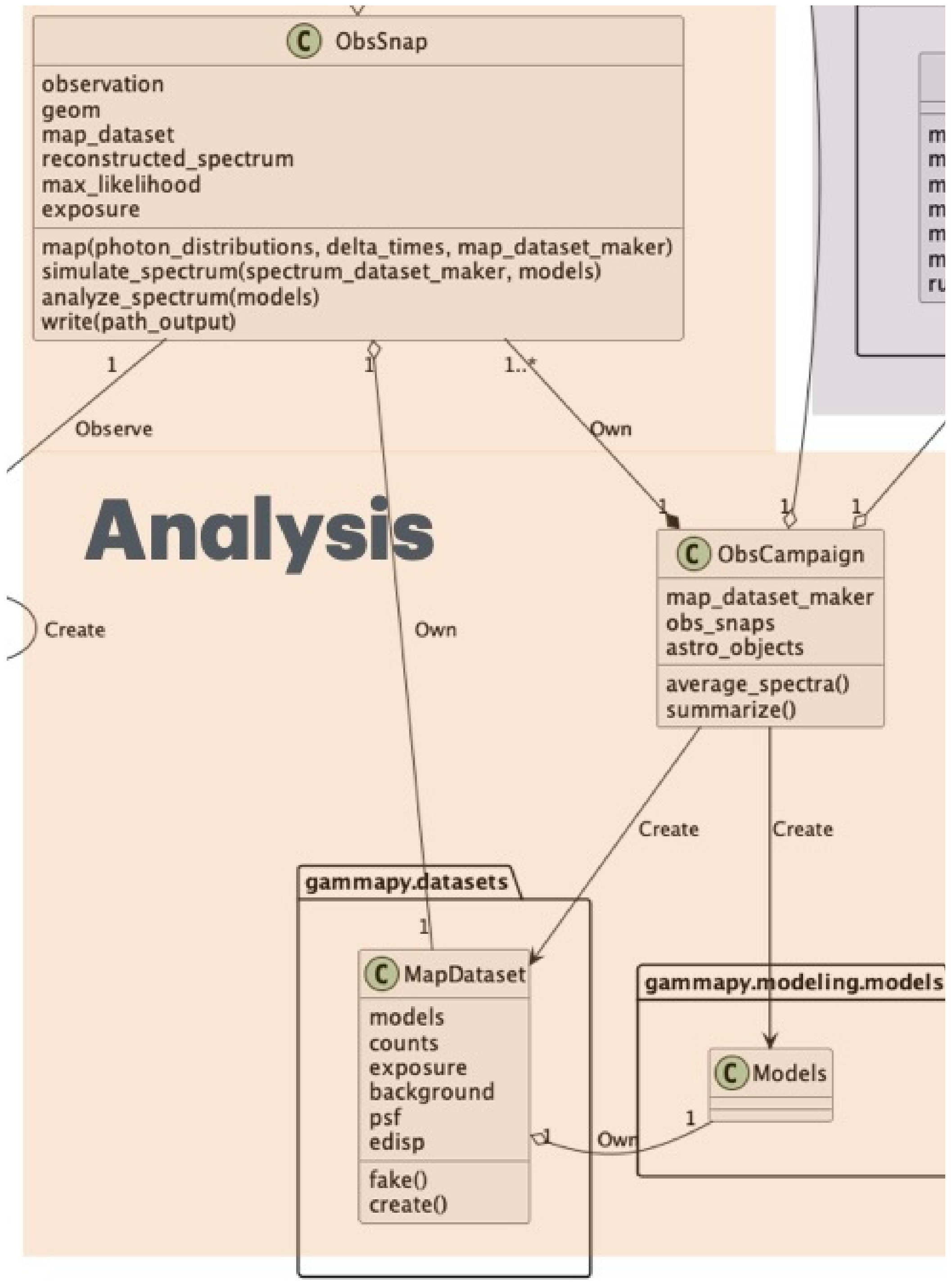
Observation segment

- For the observation segment, some **Gammapy** (a public Python package for gamma-ray analysis) classes are imported
- One instance of **gammapy.data.observation** models an observation
  - Gamma-ray flux and the instrumental response functions (IRFs) should be considered constant



Analysis segment

- The analysis focuses on time variation via two steps:
  a. Time-independent step for relatively short time data
    - Class of **ObsSnap**, which is associated with one **gammapy.data.observation**
    - Duration: <1 night for PBHs
  b. Time-dependent step by combining multiple results of a.
    - Class of **ObsCampaign**, which holds multiple **ObsSnaps**
    - Total duration: 1 night–1 season in a case of PBHs

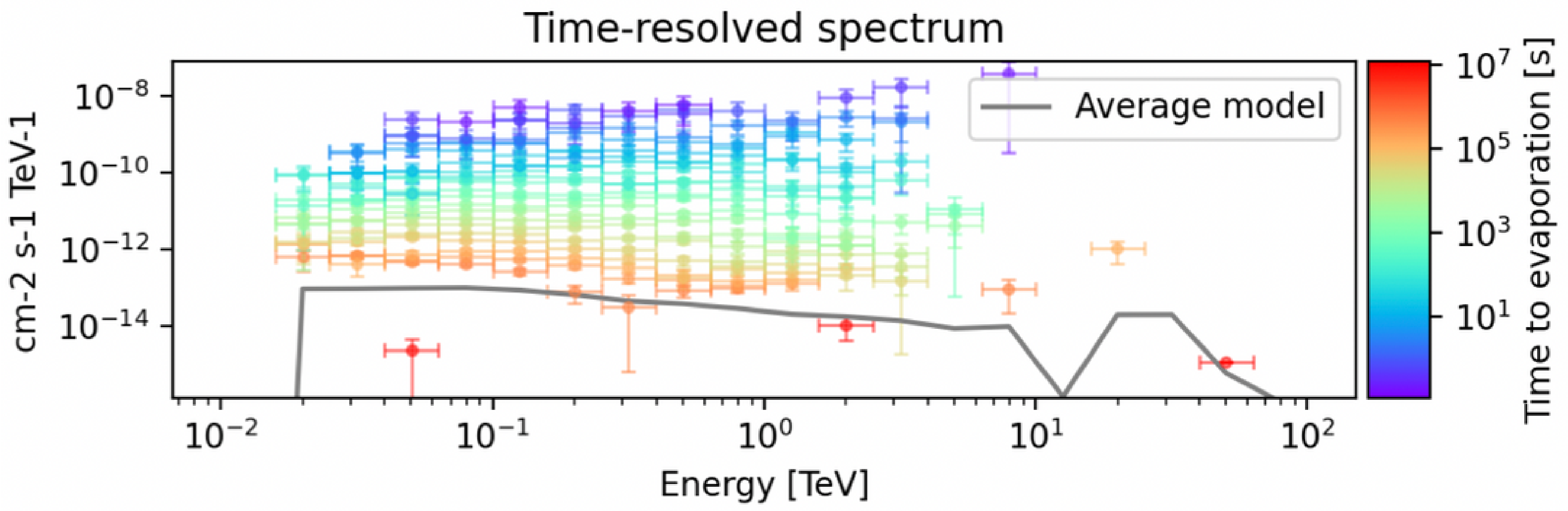


Time-independent analysis

- In this stage, **ObsSnap** performs a 1D-spectral analysis for every region of interest, which the sky is divided to
  - Reconstructs <u>the flux spectrum</u>
    - stored to use later
  - Calculates <u>the possible maximum likelihood</u>
    - Likelihood of the observed count spectrum against itself
      - $L\_max = L(Observed; Observed)$
      - No model yields a larger likelihood value by definition
- ObsSnap is the smallest unit of the analysis
- Result is stored as a file

Time-dependent analysis

- In this stage, **ObsCampaign** summarizes the result of all ObsSnaps and tests the time variability
  - Average flux spectrum is derived from the reconstructed spectrum of all **ObsSnap**s
    - Time-average is used as a null hypothesis of the time variation
    - Likelihood of the observed count spectrum against the average model *L_ave* is calculated
- Test statistics of the time variation is calculated for each ObsSnap by taking $\Delta \log L = \log L_{max} - \log L_{ave}$
- This approach is independent from the spectral model
- When new observation is done, **ObsSnap** is added to **ObsCampaign**
  - Existing **ObsSnaps** are reused to save computational resources



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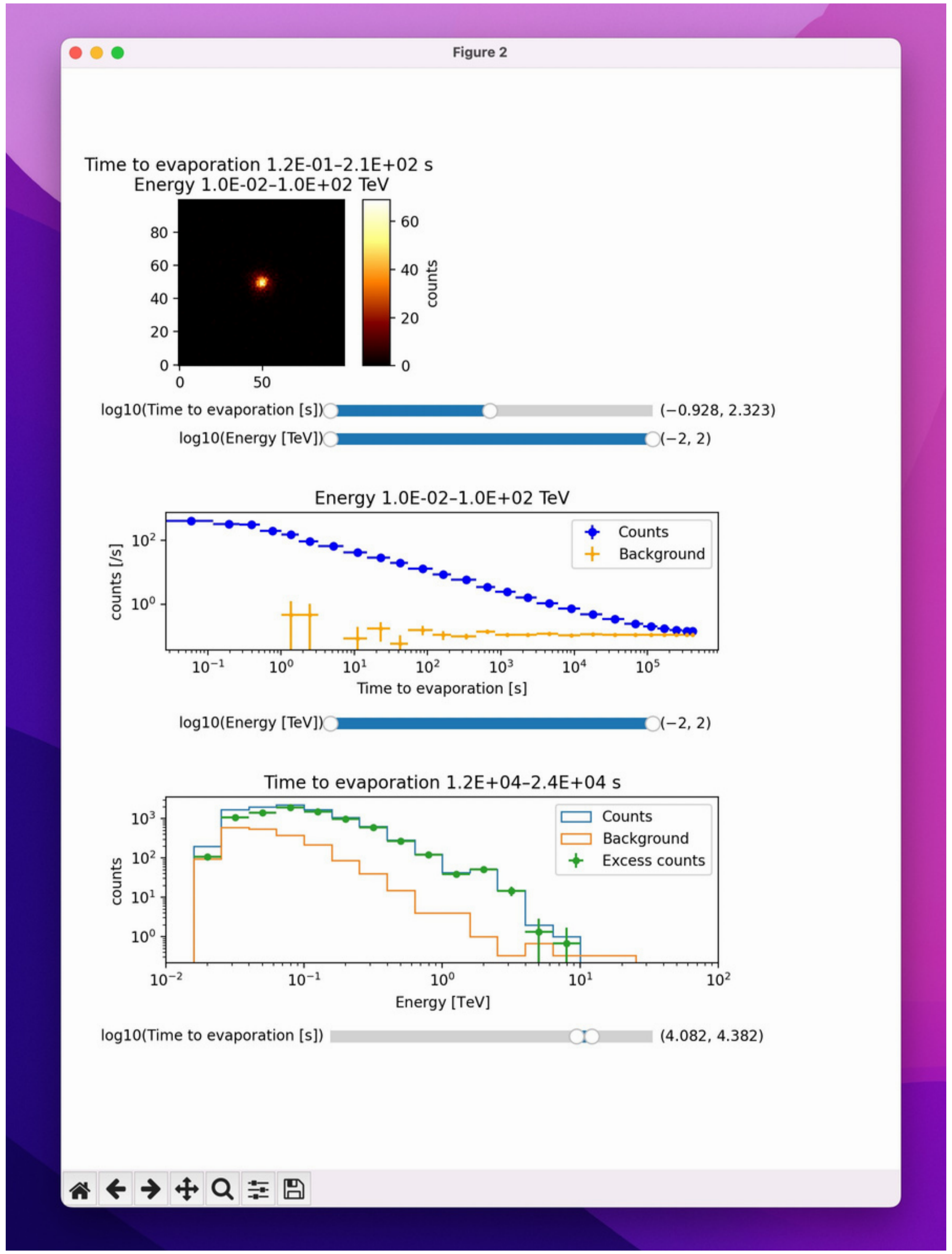
Simulation of PBH observations

- We plan to simulate PBH observations with gamma-ray telescopes by the following two setups
  a. Purely serendipitous search
     - PBH with the remaining lifetime of <hours radiates gamma-rays above TeV
  b. Precursory hint search
     - PBH with the remaining lifetime of days–months radiates gamma-rays below hundreds of GeV
       - Possible to raise an alert before the final phases?
  - Evaluate the performance
  - Optimize the observational/analysis strategies



PBH search in real data

After the optimization, we apply the analysis to the real data from gamma-ray telescopes, e.g. CTA, Fermi-LAT sophisticating the arforithm

01

Search in existing data

We will establish software to analyze existing data from gamma-ray telescopes

02

Continuous update

We deploy a pipeline to update the result every day by adding newly taken data

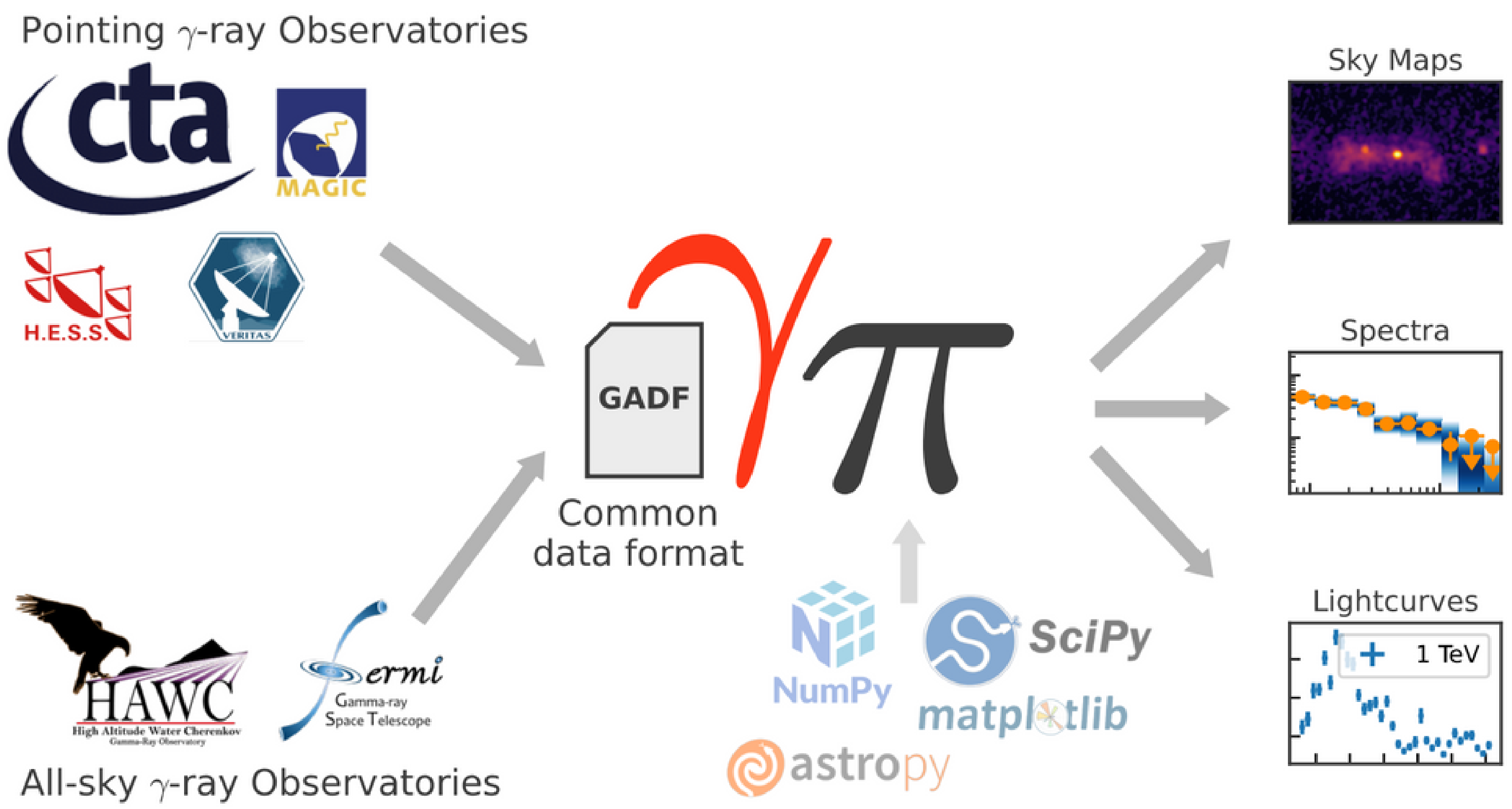
03

Online analysis

We plan to develop an online analysis pipeline to raise an alert as early as possible but still under discussion

Integration with Gammapy

- We will integrate our project with gammapy
  - Visibility in the community
  - Multi-instruments analysis
  - Maintenance feasibility
- We started discussion with the Gammapy developers



[Donath et al. (2023), arXiv:2308.13584](https://arxiv.org/abs/2308.13584)

Summary

- Transient source classes are most interesting targets for gamma-ray observatories
  - GRBs, AGNs, SGRs/FRBs, and PBHs
- We are developing simulation and analysis
  - Not to miss important discoveries!
- PBH can be an archetype of transient classes
- Our Software design
  - sensitive for the time evolution
  - flexible for the emission model
  - expandable to other sources and multiple instruments
  - sensitive also for totally unanticipated sources!