Primordial black hole evaporation searches with very-high-energy gamma-ray telescopes

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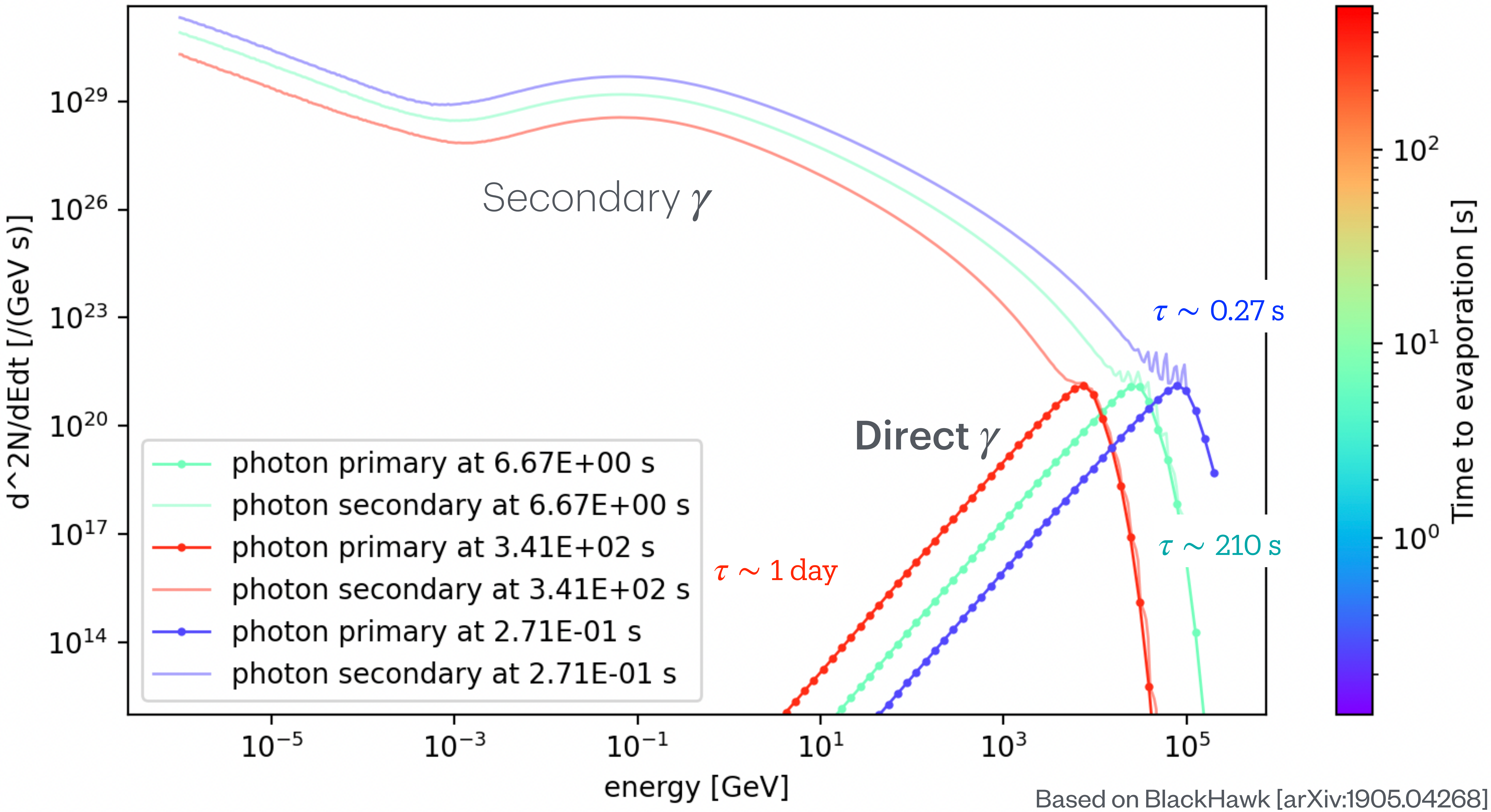
Final Phase of PBH evaporation

Temperature and flux burst

- ✦ For a PBH with mass $\sim 5 \times 10^{14}\mathrm{g}$ at birth, the lifetime is similar to the age of Universe
  - Evaporation is reaching explosion now!
- ✦ Temperature $k_B T_{BH} = 7.8 \left(\frac{\tau}{1\mathrm{s}}\right)^{-1/3} \mathrm{TeV}$ for the remaining lifetime τ
  - Exceeds 100 GeV at $\tau \sim 5.6\,\mathrm{days}$
  - Suitable target for very-high-energy (VHE; >100 GeV) gamma-ray telescopes
- ✦ Smoking-gun evidence of PBH and Hawking radiation

Temporal evolution of gamma-ray spectrum



Based on BlackHawk [arXiv:1905.04268]

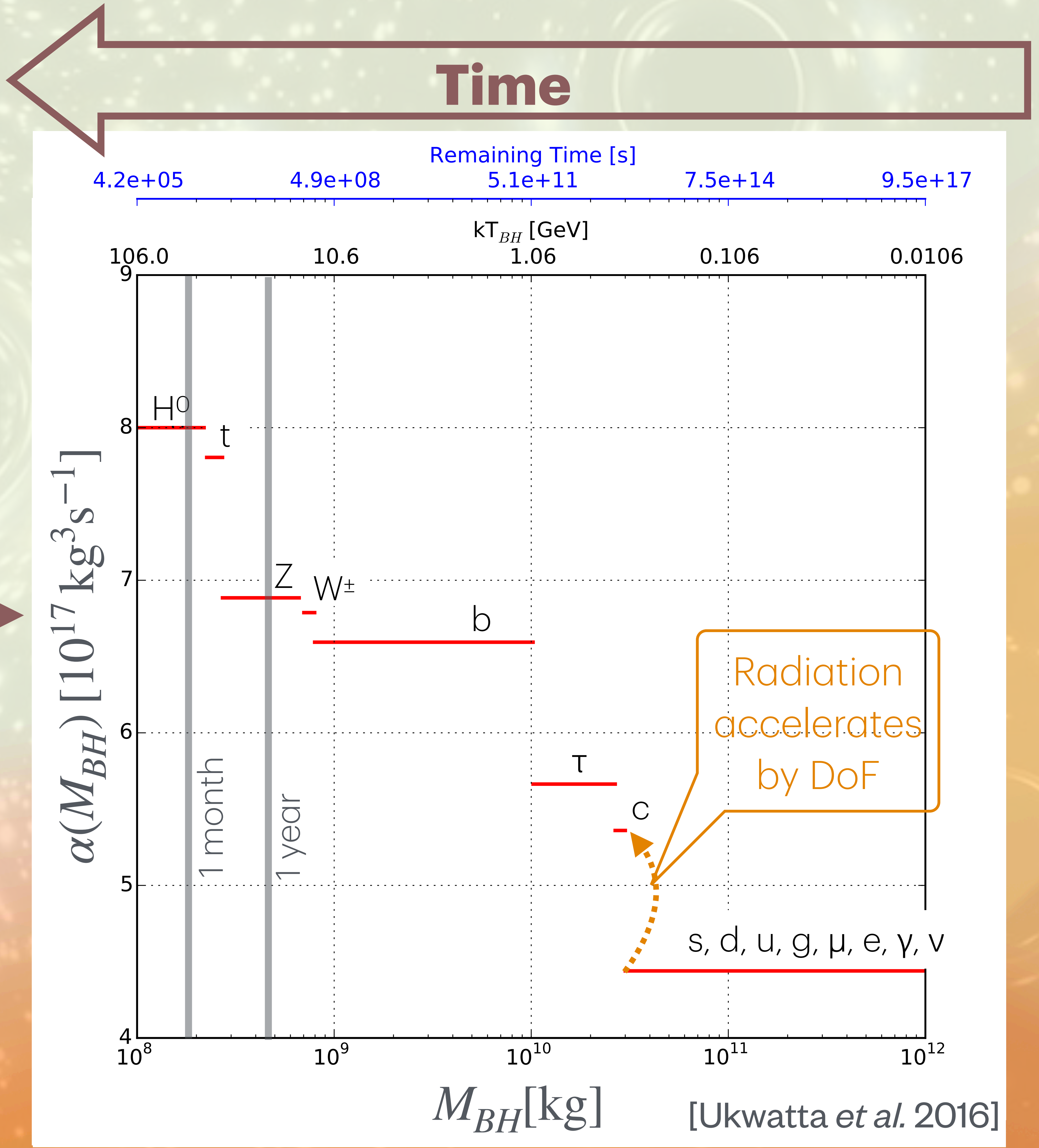
Radiation of various elementary particles

✦ **Heavier particles are radiated when the temperature becomes higher**

- Mass loss accelerates as degree of freedom increases
  - Temperature dependence of mass-loss rate

$$\alpha(M_{BH}) \equiv -M_{BH}^2 \frac{dM_{BH}}{dt}$$

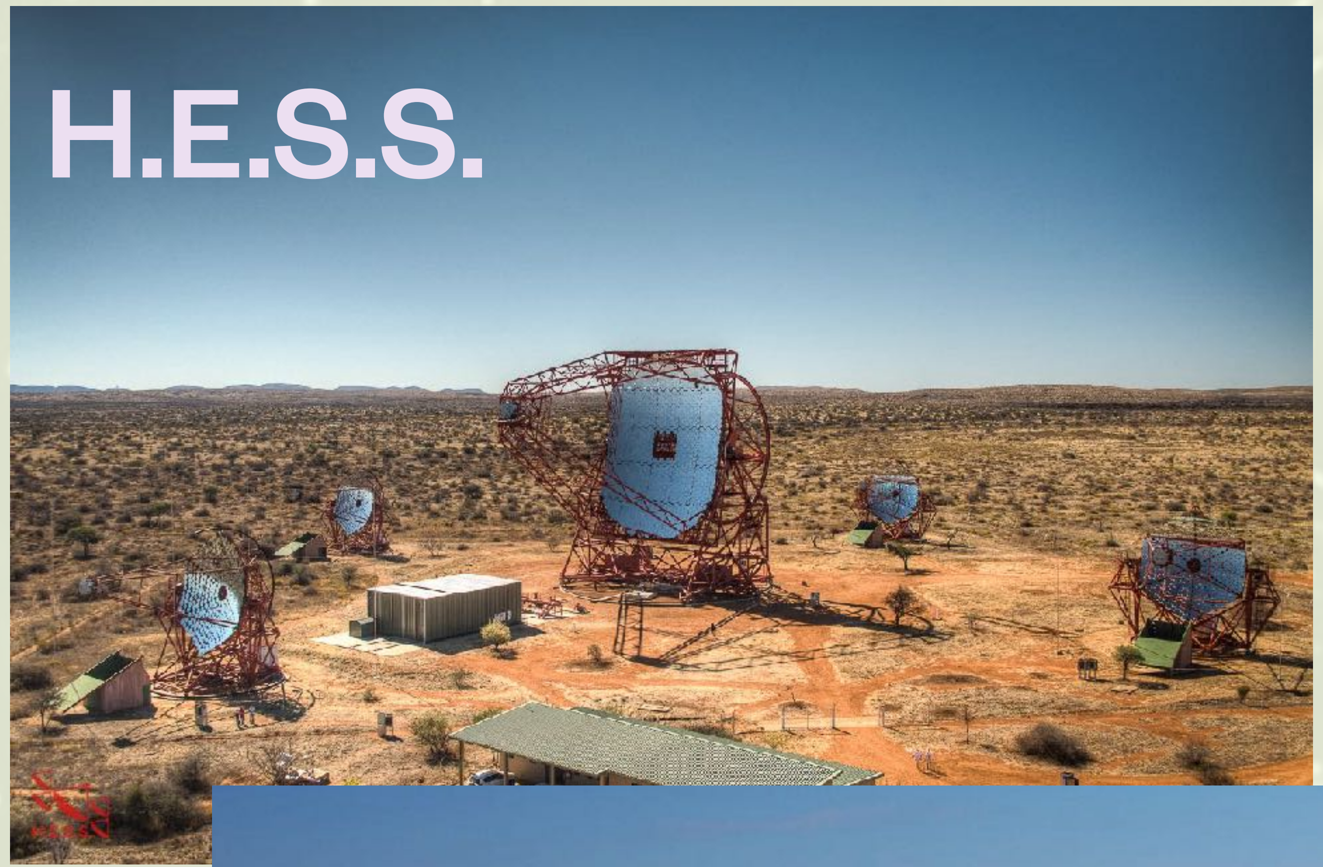
✦ **Possible signature of unknown particles heavier than accelerator coverage observable**



[Ukwatta *et al.* 2016]

Very-high-energy gamma-ray telescopes

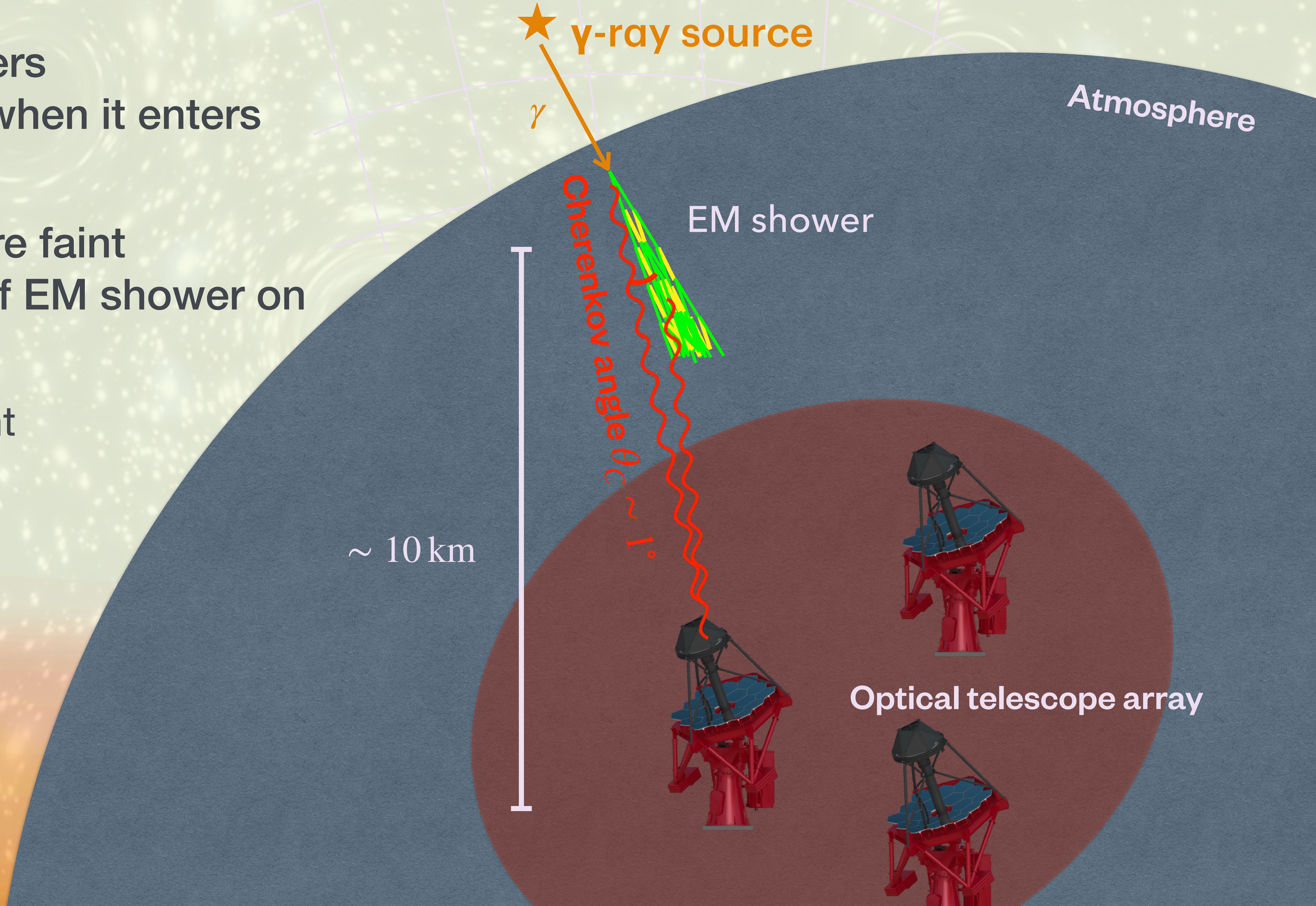
Imaging Atmospheric Cherenkov Telescope (IACT)



Extensive Air Shower (EAS) Array

IACT technique

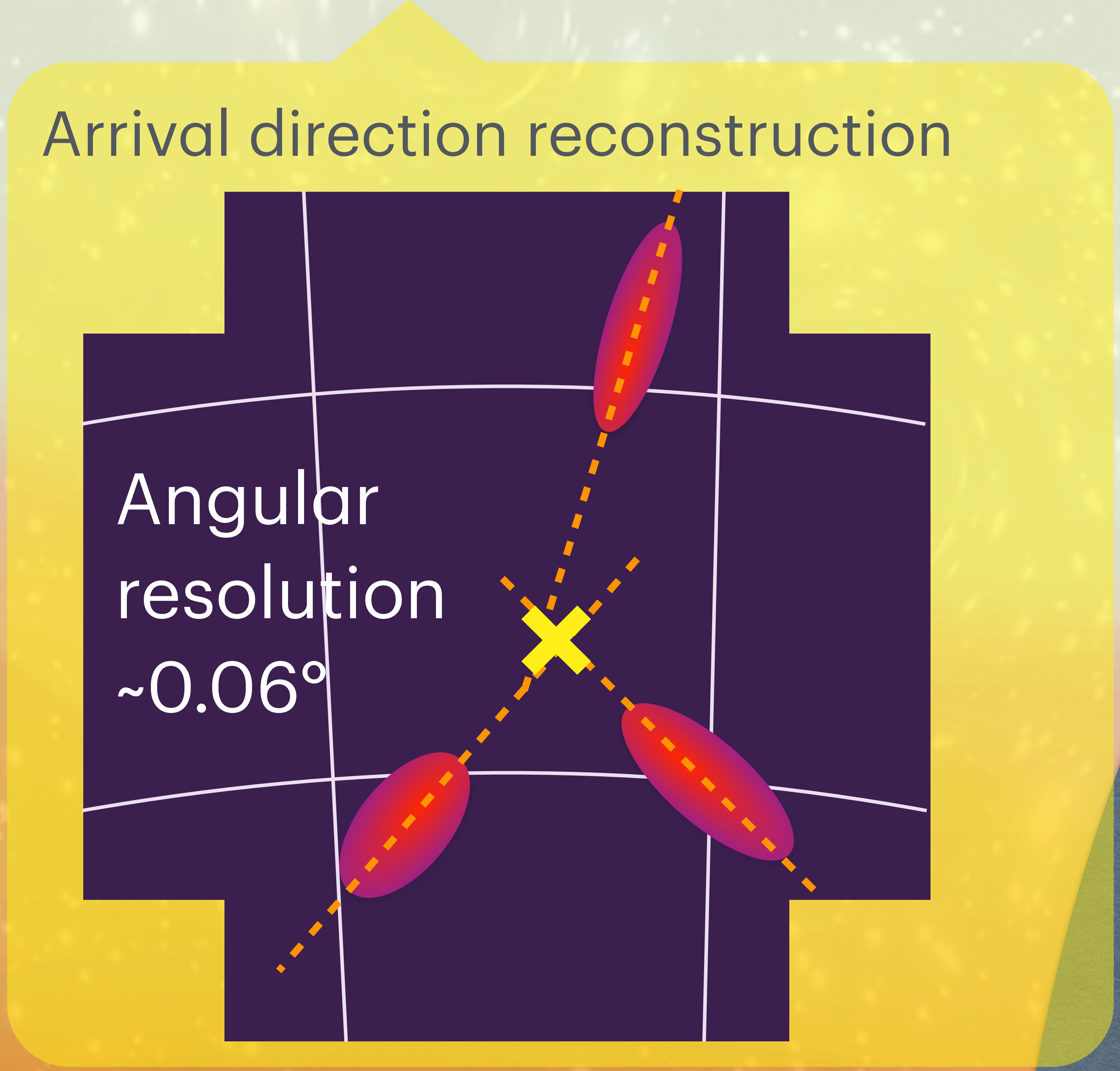
- ✦Cosmic gamma-ray triggers electromagnetic shower when it enters atmosphere
- ✦Optical telescopes capture faint Cherenkov light from $e^{\pm}$ of EM shower on ground
    - Operable only during night

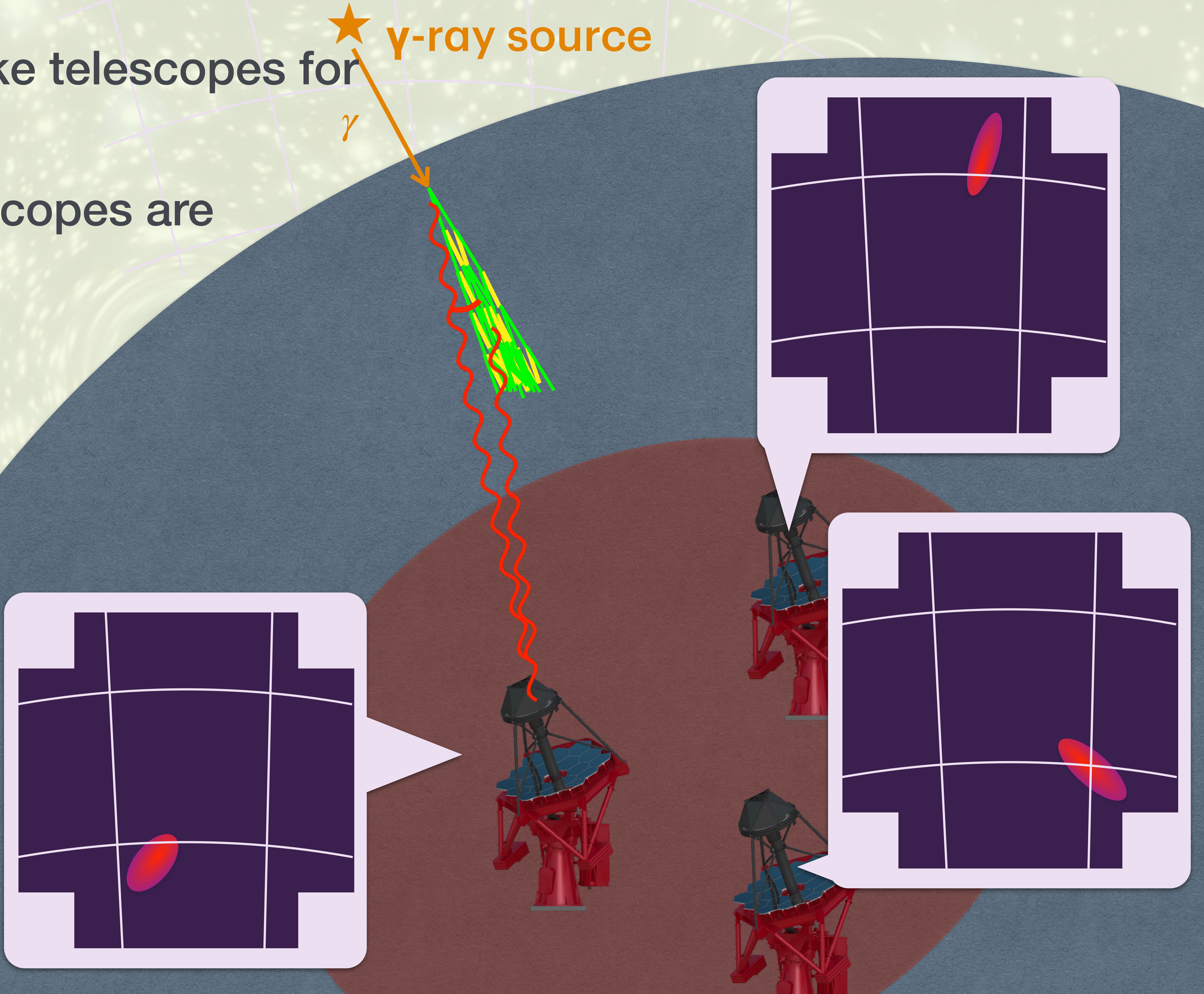


Reconstruction of cosmic gamma rays

✦Cherenkov photons (UV–optical) strike telescopes for ~3 ns

✦Cherenkov images captured by telescopes are elongated along the shower axis



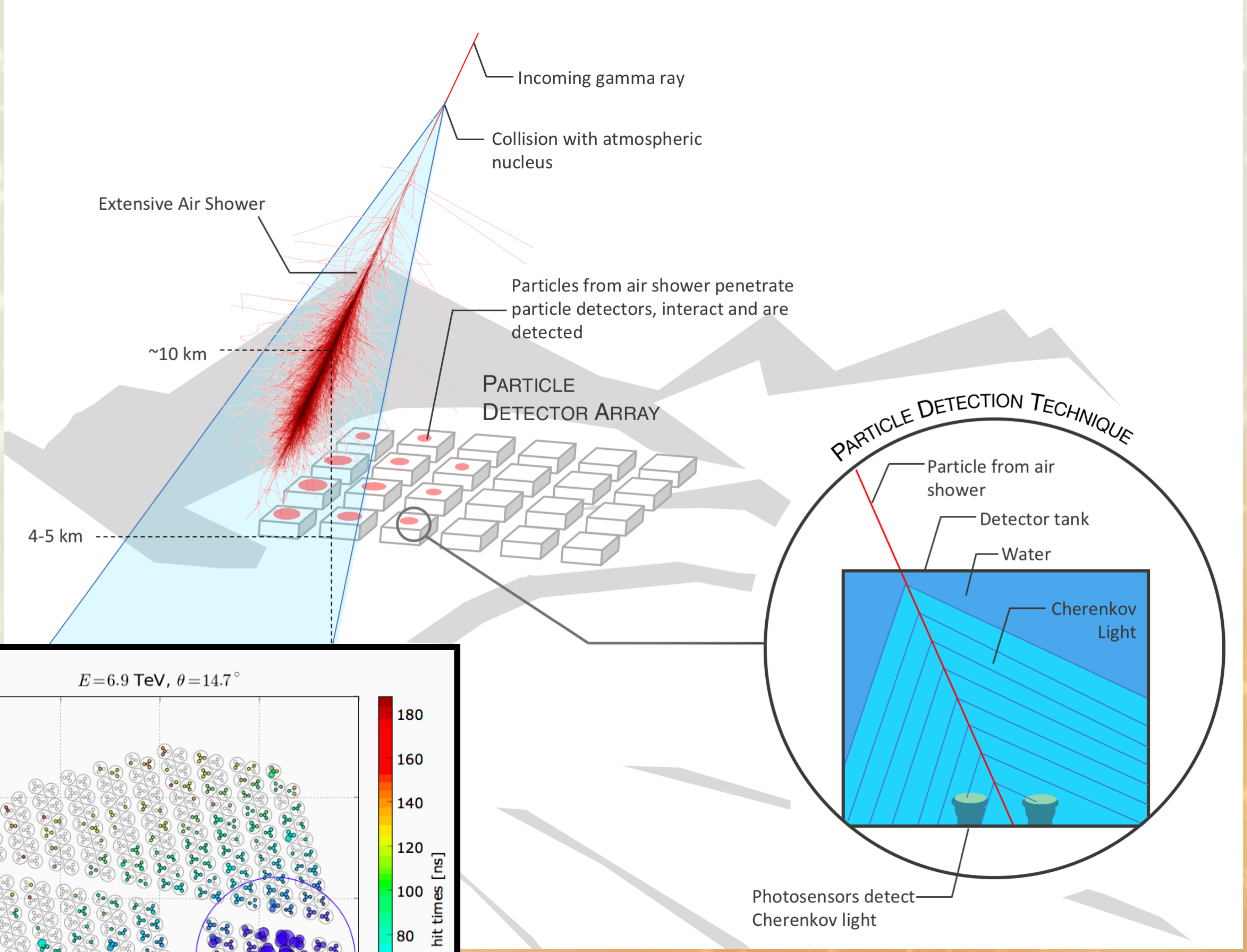


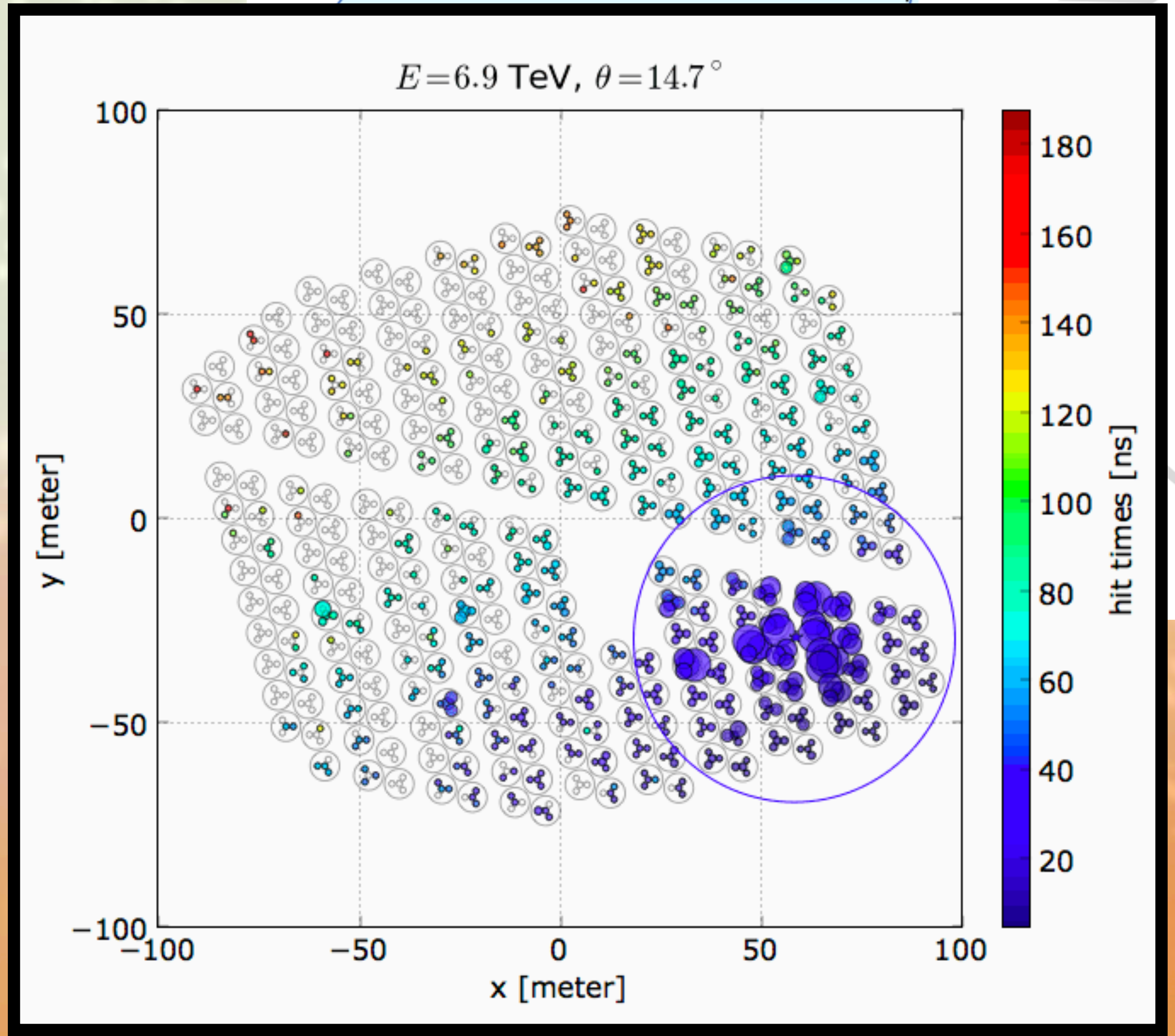
EAS technique

- ✦ **Particle detectors (e.g. water Cherenkov) directly capture secondary charged particles on ground**
  - Operable regardless of sunlight and weather

Source direction of a gamma ray can be reconstructed from the arrival time distribution

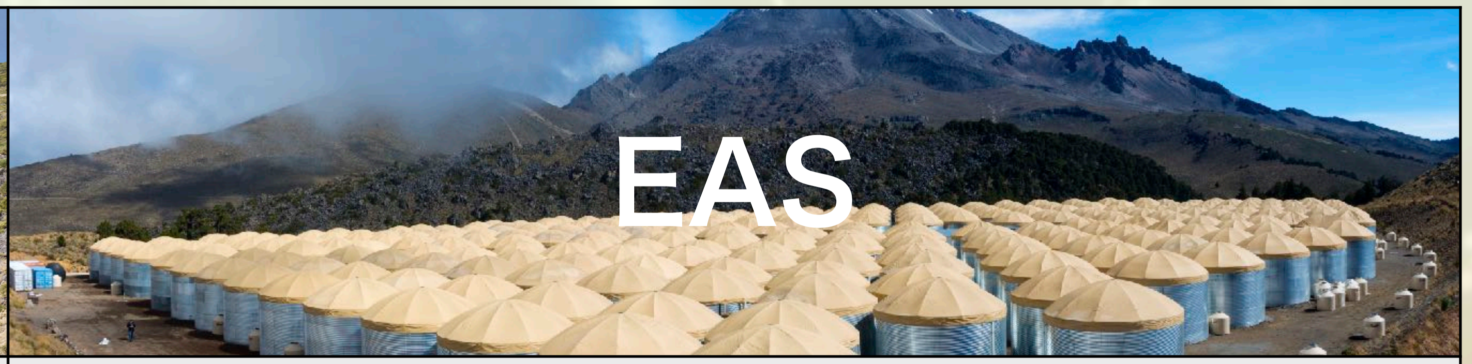
Angular resolution ~0.2°





[H. Schoorlemmer]

IACT v.s. EAS Array

	 IACT	 EAS
Observable energies	Tens of GeV–Tens of TeV	Hundreds of GeV –100 TeV
PBH search range	~1 pc	~0.25 pc
Field of view	~5°	~2 sr
Duty cycle	A few tens of %	≳95%

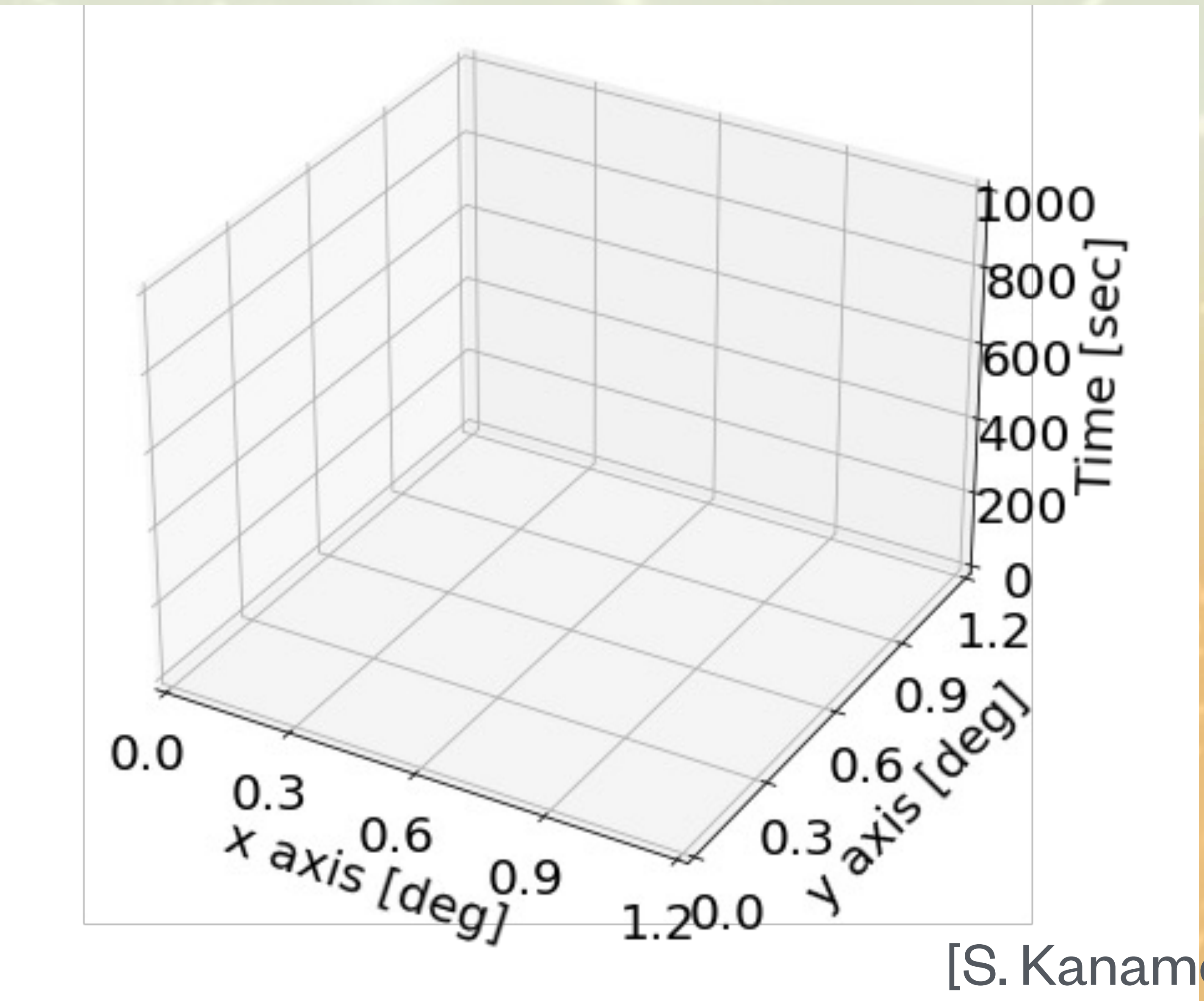
Basic method of PBH search

✦**PBH direction is unknown**

- Telescope cannot point to them
- **Basically all data are usable**

✦Simple analysis idea

- Bin observed data spatially and temporally
- **Evaluate deviation of the gamma-ray counts from Poison distribution**

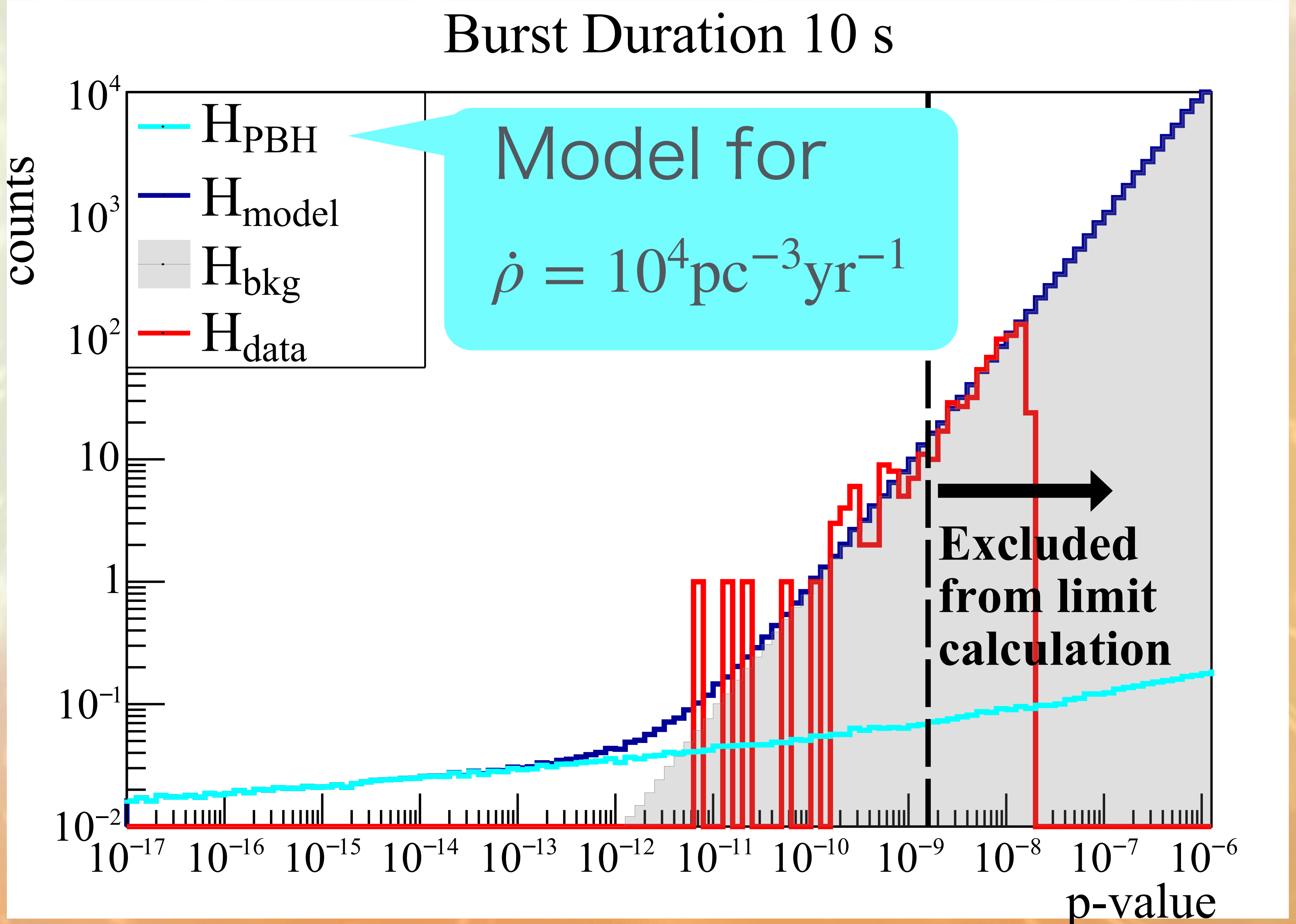


[S. Kanamori]

Previous studies

HAWC (A. Albert *et al.* 2019)

- ✦Data: 959 days in 2015–2018
- ✦Sliding time-window method
  - Originally used for gamma-ray burst detection
  - Divide data into 2.1°×2.1° spatial bins and 0.2-s/1-s/10-s temporal bins
  - Continuously search gamma-like event rate peak
- ✦For each found cluster, p-value under background-only hypothesis is tagged
- ✦TS is calculated scanning single parameter $\dot{\rho}$, 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 likelihood of all clusters**

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

Poisson

PBH signal model

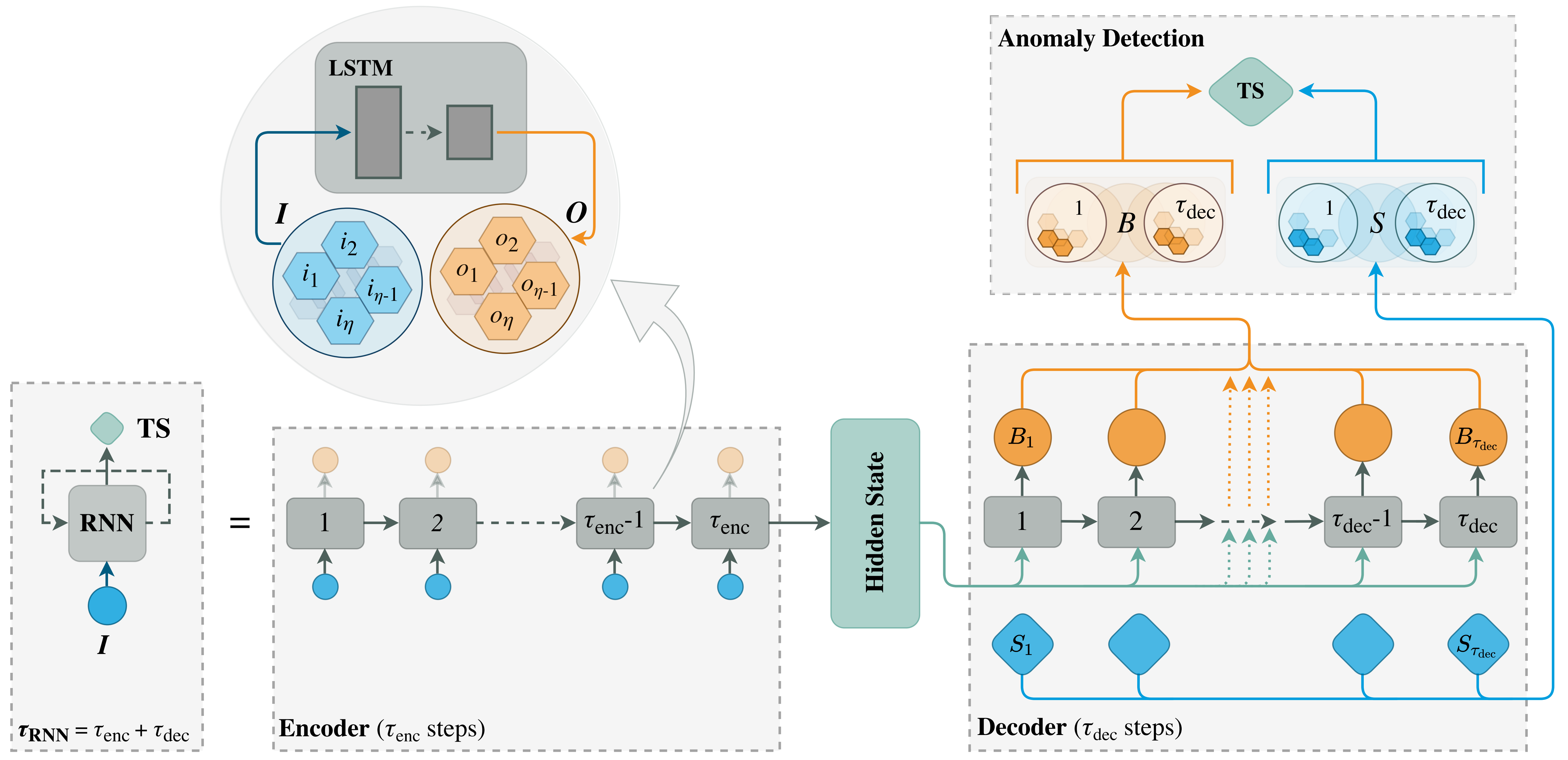
PBH explosion rate (Single parameter)

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)
  - Pros
    - Able to take complicated instrumental response into account flexibly
    - Usable for transient phenomena other than PBHs
  - Train RNN as it predicts background
    - Evaluate difference from real data
  - Input data of previous time period
    - Enable to take time evolution of PBH signal into account



Results

- ✦No significant detection
- ✦H.E.S.S.(2022) obtained upper limit as strong as HAWC
  - Despite HAWC has much wider FoV
- ✦Machine learning by VERITAS (2022) needs improvement

Instrument	Observation time	Upper limit (99%) on explosion rate (pc^{-3} yr^{-1})
VERITAS (2017)	747 hours	2.2×10^4
VERITAS (2022)	4222 hours	1.1×10^5
H.E.S.S. (2022)	4816 hours	3.4×10^3
HAWC (2019)	2.6 years	3.4×10^3

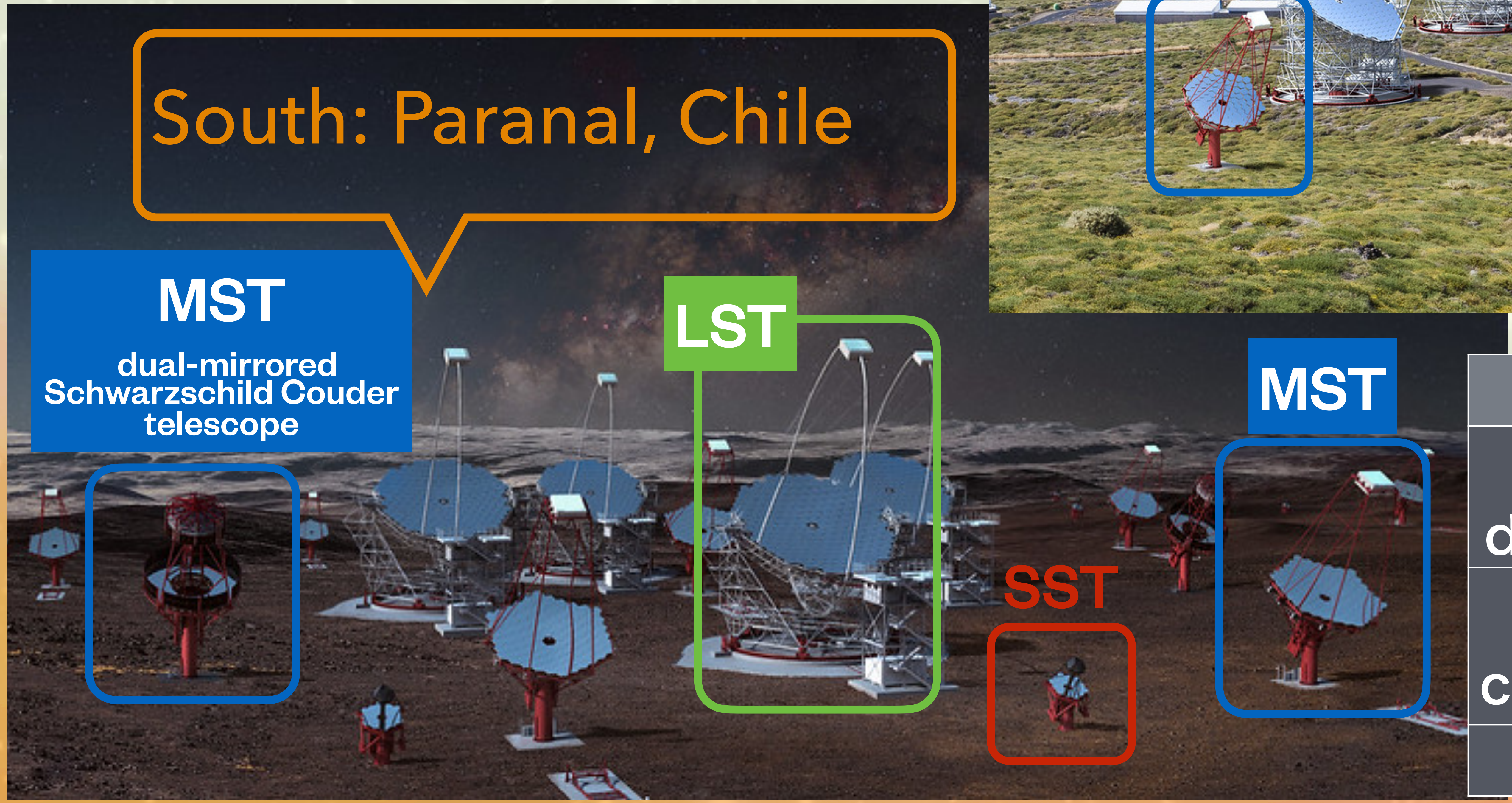
Cherenkov Telescope Array (CTA)

Cherenkov Telescope Array (CTA)

✦ **Next-generation VHE observatory**

- First LST is in operation now

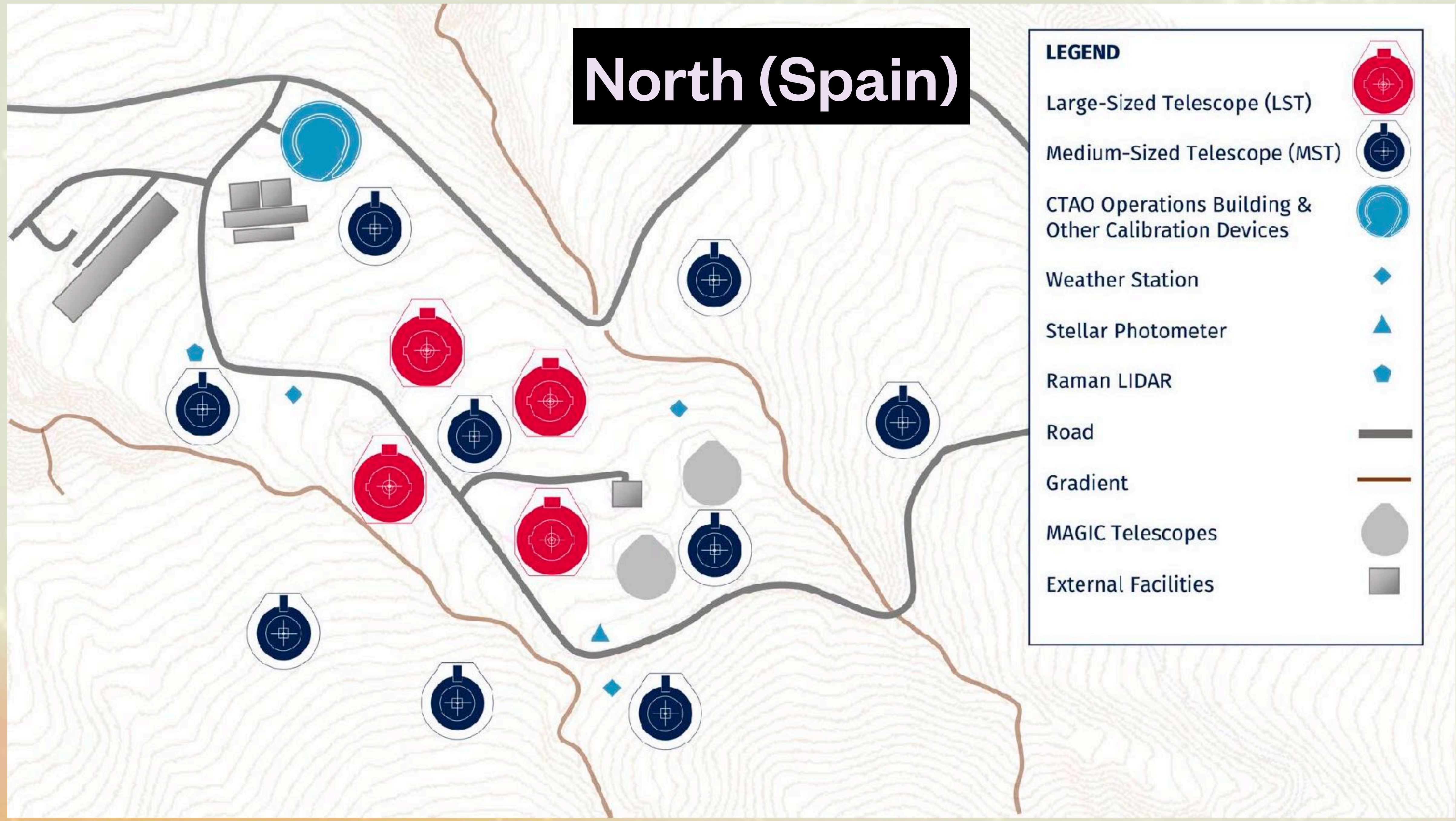
North: La Palma, Spain



	LST	MST	SST
Mirror diameter	23 m	11.5 m/9.7 m	4.3 m
Energy coverage	20 GeV–3 TeV	80 GeV–50 TeV	1 TeV–300 TeV
FoV	4.5°	7.5–7.7°	10.5°

"Alpha" Array Configuration

✦Financially conservative 1st phase

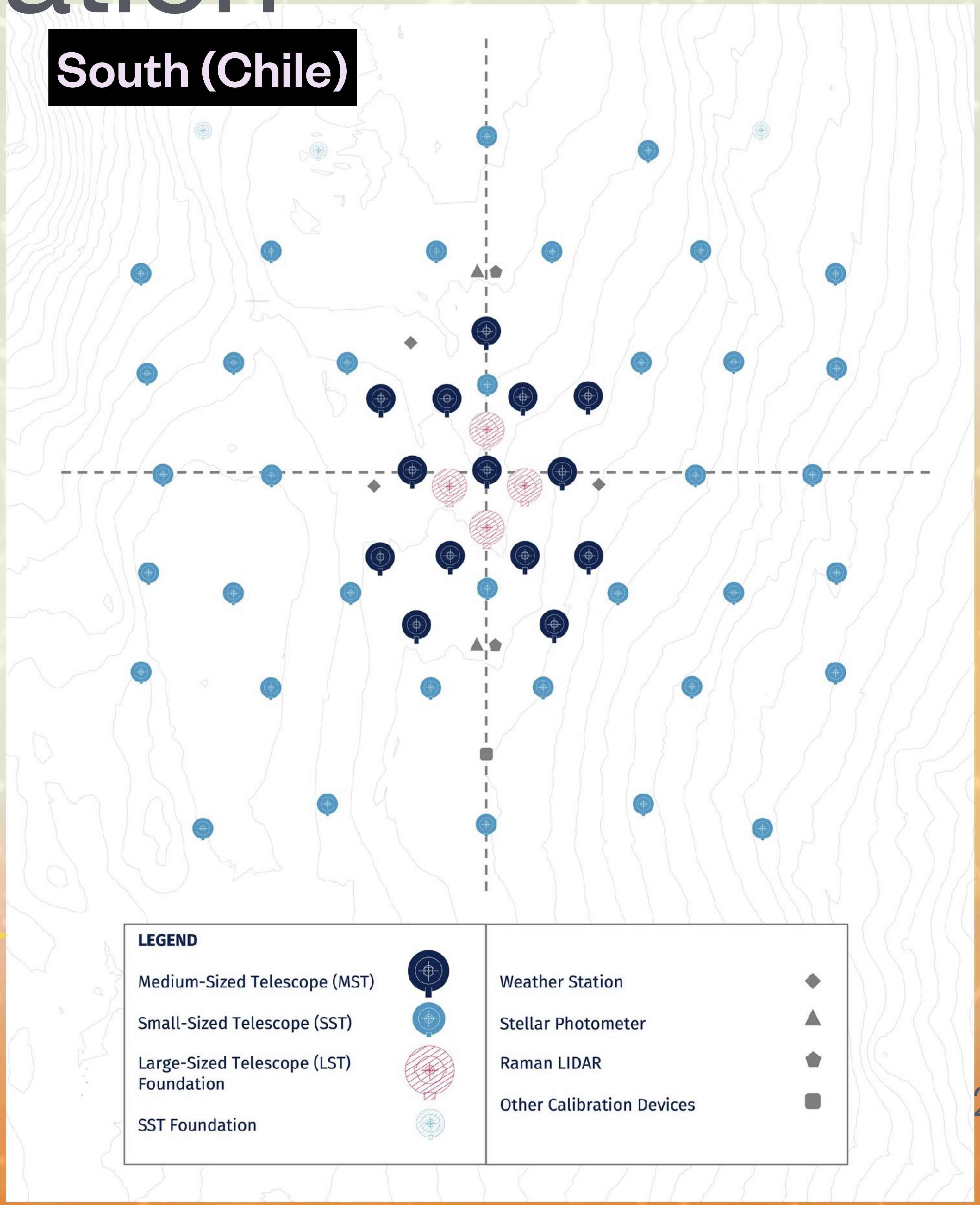


$\sim 0.5\,\mathrm{km}^2$

- LST: 4
- MST: 9 (→15)

$\sim 3\,\mathrm{km}^2$

- LST: 0→2 (→4)
- MST: 14 (→25)
- SST: 37→42 (→70)



Construction status

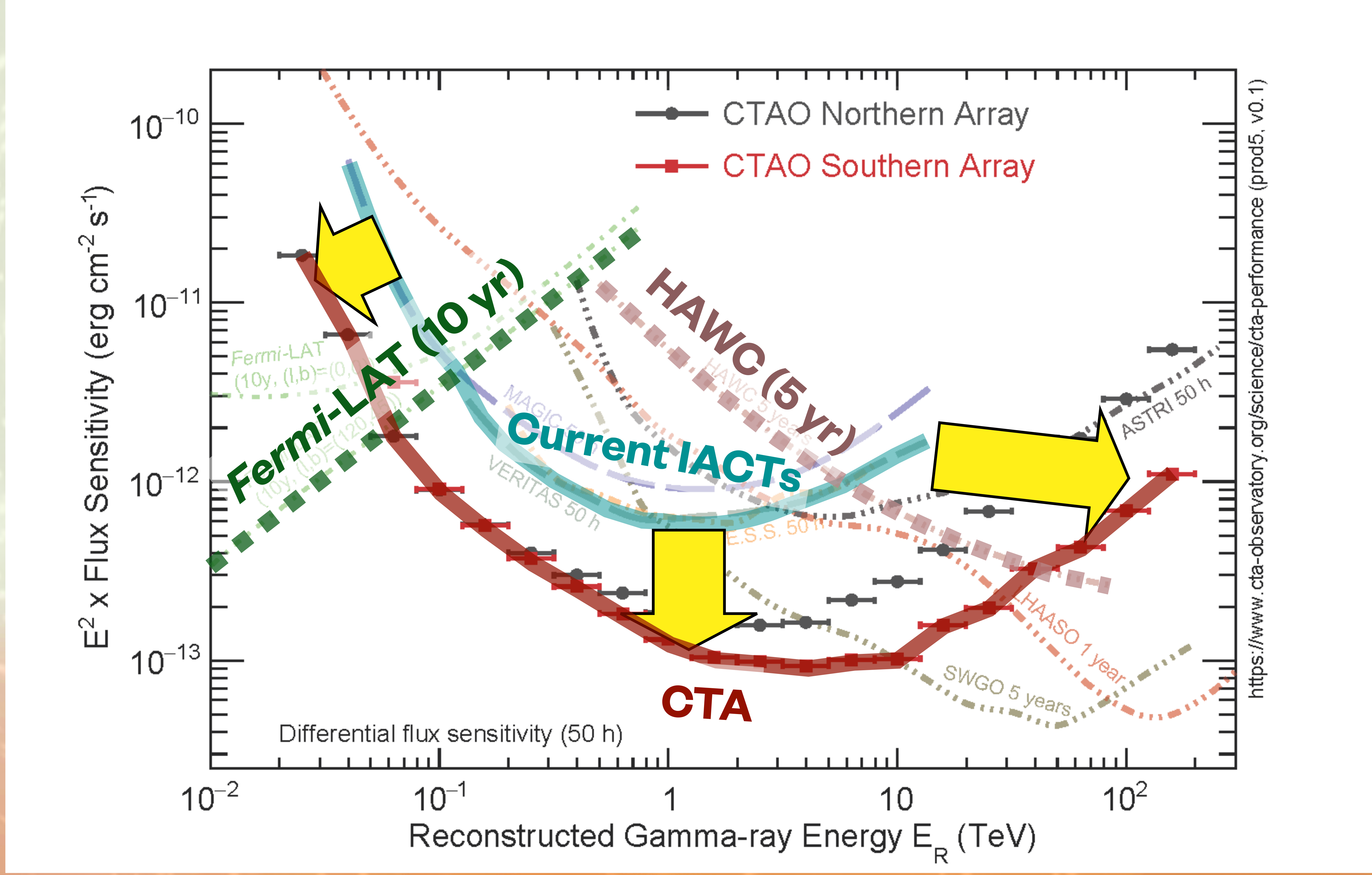
- ✦**CTA-North**
  - LST-1 is in operation
  - LST-2–4 will be built by 2025
  - MST-1 will be built in 2024
    - Construction is permitted
    - LST-2–4 cameras have been already integrated and are being tested in lab
- ✦**CTA-South**
  - Infrastructure is being constructed
  - Budget for 2 LSTs is obtained from Italy
  - First full camera (engineering model) of SST is being developed now

Sensitivity and energy coverage of CTA

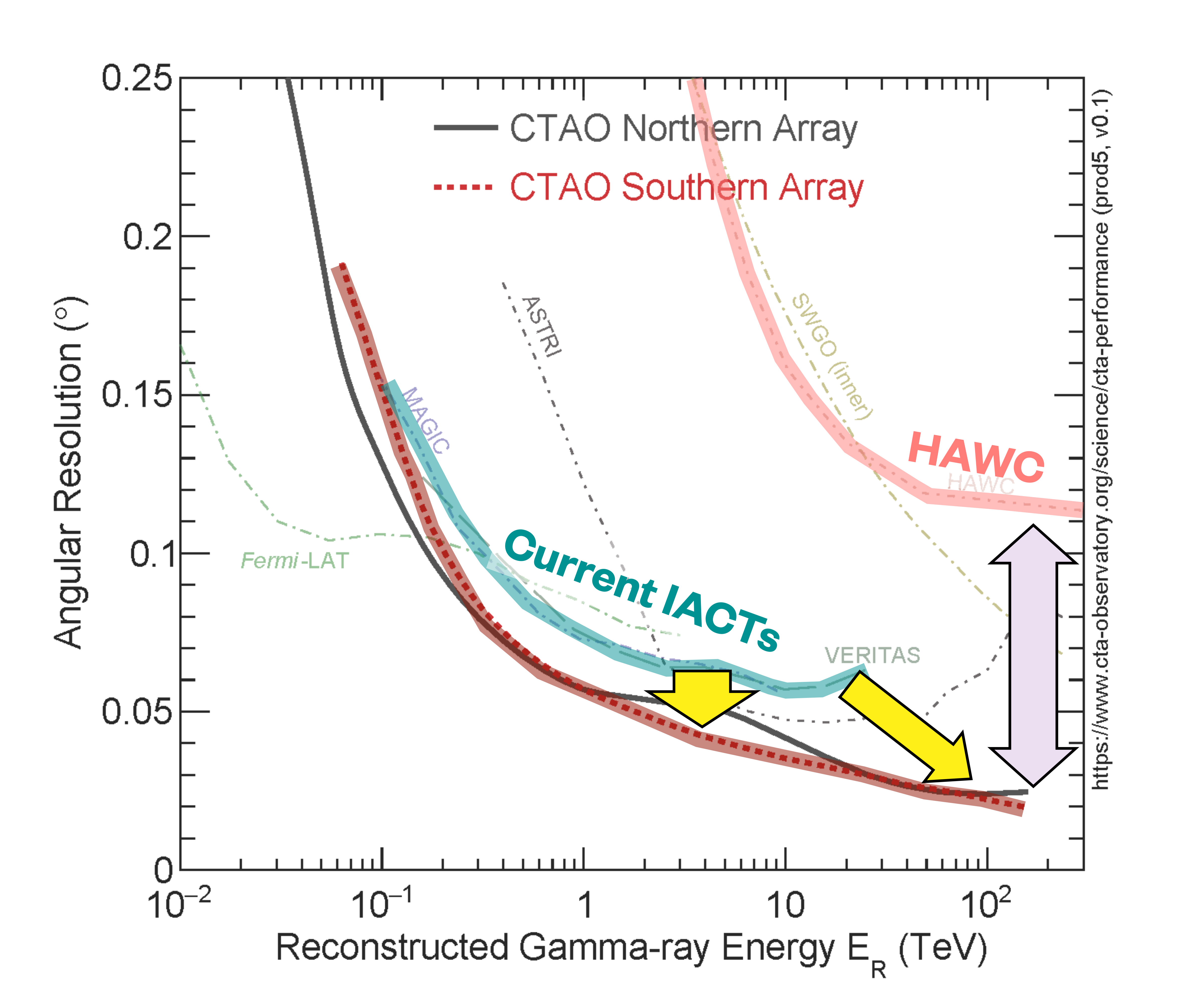
✦5–10 times more sensitive at TeV than current IACTs

✦Energies for 4 decades in scope

- Lower energy threshold : ~ 50 GeV→20 GeV
- Covers energy range corresponding to the PBH lifetime of ~days–months
  - Observational strategy can be optimized?



Angular resolution of CTA



✦**Resolution: ~arcmin at 100 TeV**

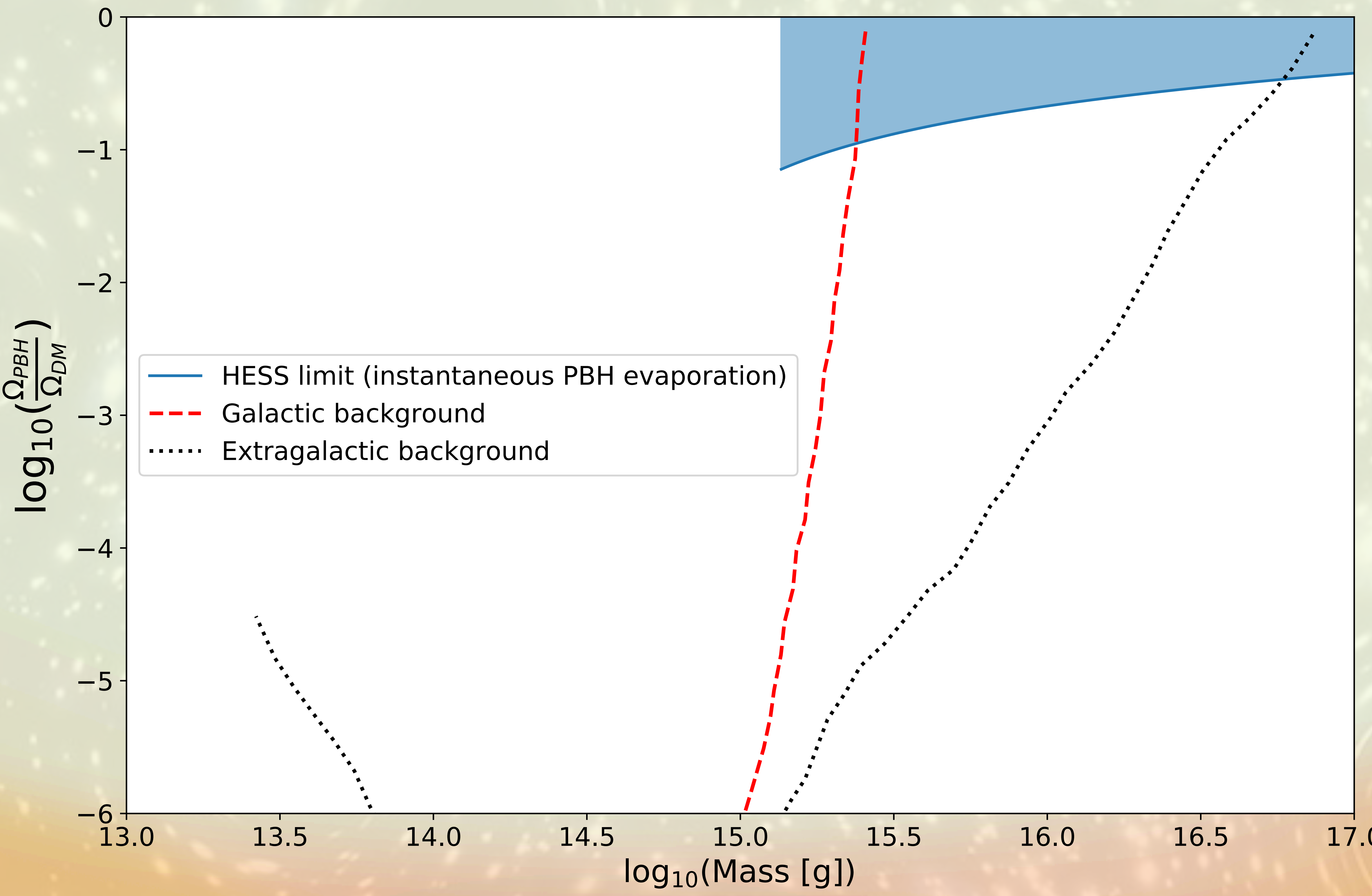
- A few times better than current IACTs
- works complementarily to air-shower arrays

Summary

- ✦PBH explosions are expected to be ongoing now for the initial mass $\sim 5 \times 10^{14}\mathrm{g}$
- ✦Ground-based VHE gamma-ray telescopes search for burst-like signals
- ✦Best upper limit is $\dot{\rho} < 3.4 \times 10^{3}\mathrm{pc}^{-3}\mathrm{yr}^{-1}$
- ✦CTA, the next-generation observatory, will be an order of magnitude more sensitive than current IACTs
- ✦Various analysis techniques are employed including machine learning, and still there is room for improvement
- ✦Analysis technique and observational strategy should be optimized more

Appendix

Upper limits on PBH dark-matter



[F. Aharonian *et al.* 2022]

Figure 6: Upper limits on the present mass fraction of PBH as a function of the effective PBH mass. The initial mass distribution index β is varied between 2 and 3, giving the blue exclusion region. The limit is compared to monochromatic gamma-ray limits compiled in [37].