IceCube Realtime Analyses.

Realtime environment and analyses overview

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for the IceCube Collaboration

4th AMON Workshop
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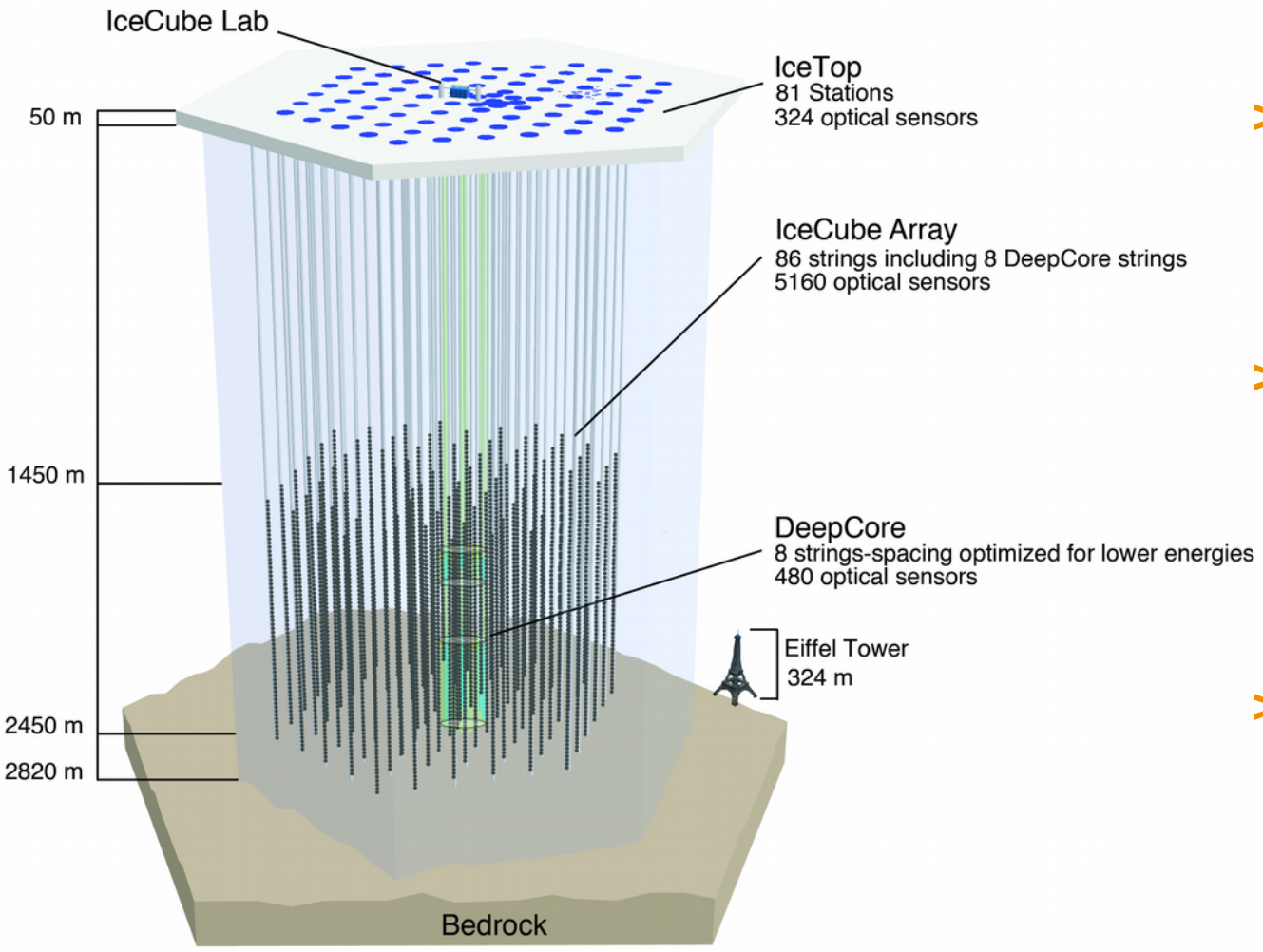
HELMHOLTZ ASSOCIATION

DESY

Outline

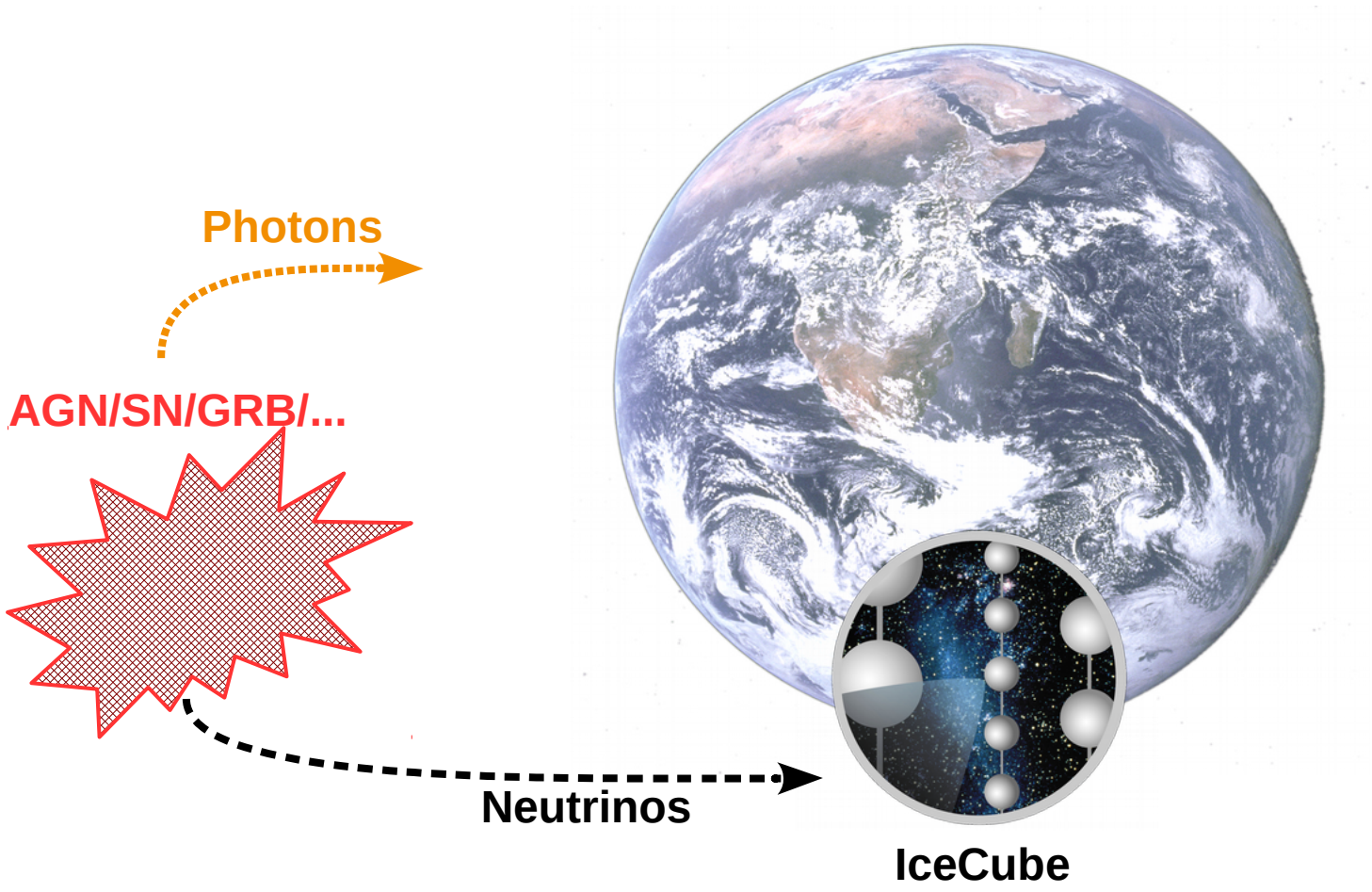
- IceCube Detector
- Real-Time Infrastructure
- Follow-up / Alert Programs:
  - Optical Follow-Up
  - Gamma-Ray Follow-Up
  - HESE Alerts
  - EHE Alerts
- Summary

The IceCube Neutrino Observatory



- 1km³ detector for Cherenkov light
- In this talk: μ-tracks from CC ν_μ-int.
- Angular resolution of ≤ 1 deg

The Follow-Up Procedure



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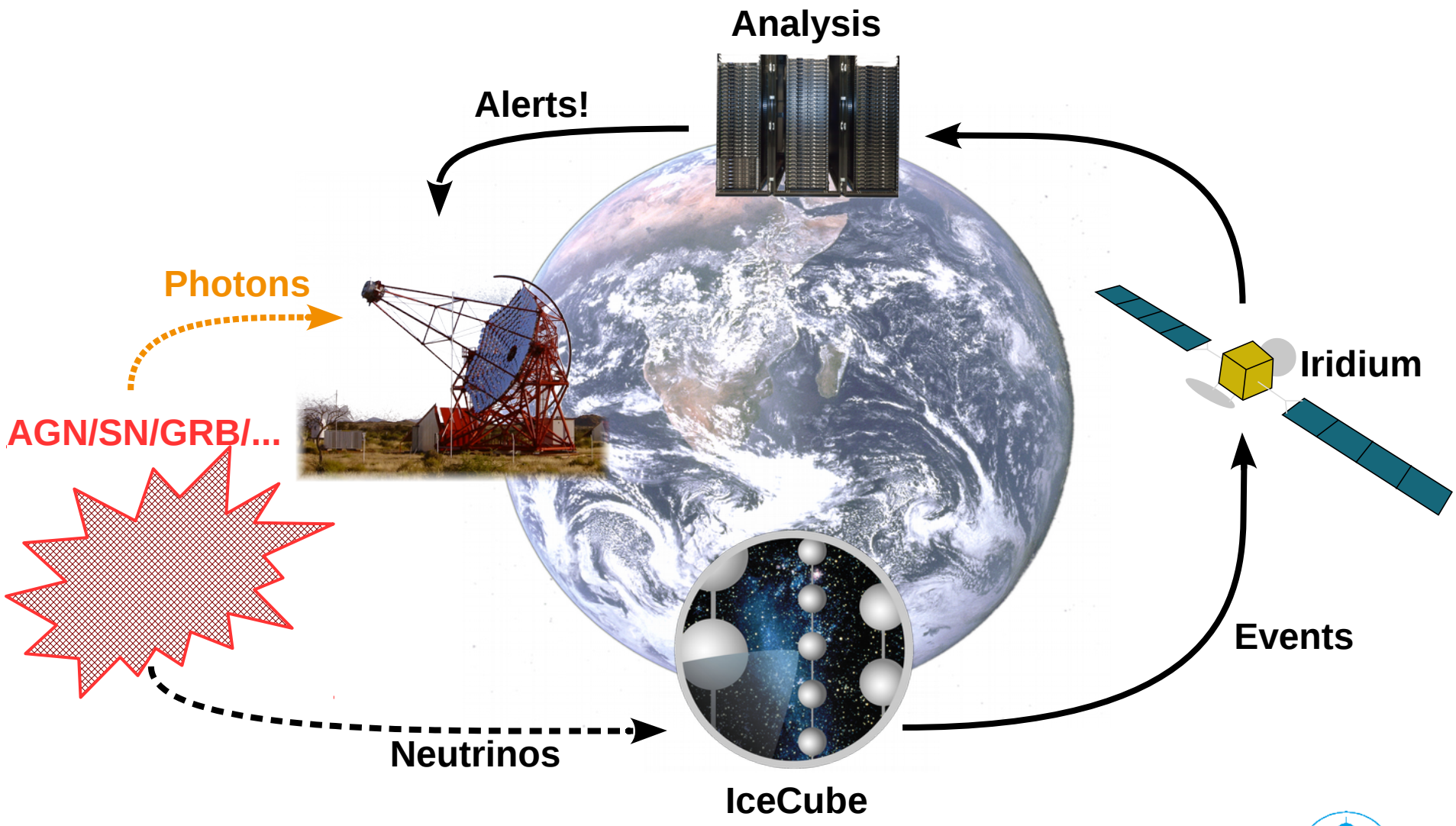

Challenges (not just) for Realtime Operations

- Limited computing resources at the South Pole

- Limited connectivity
  - Iridium:
    Low-latency and low-bandwidth
  - TDRSS:
    High-bandwidth and high-latency

- Limited realtime detector monitoring
  - No Good Run List

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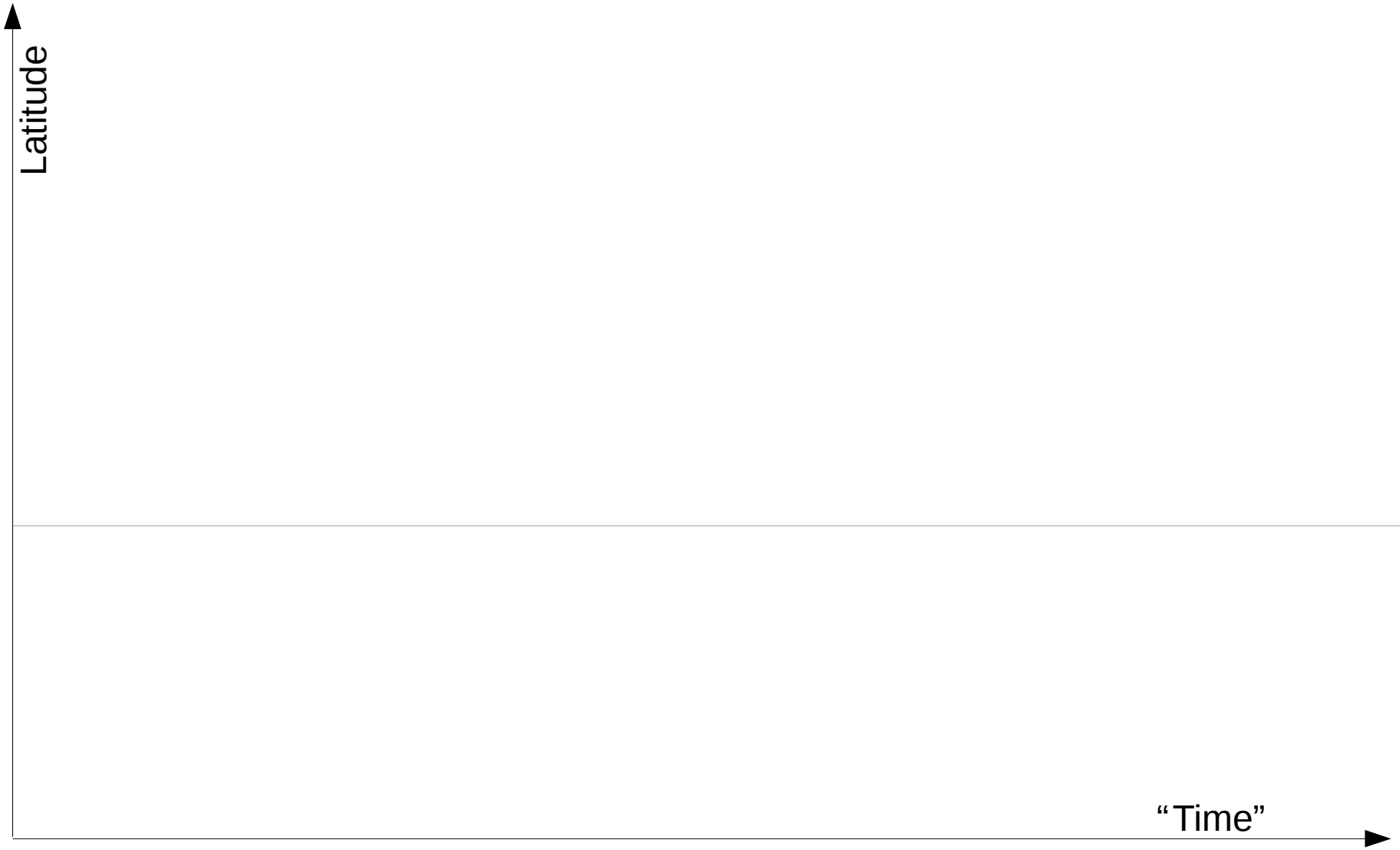
- Limited realtime detector monitoring
  - No Good Run List

- Fast/specialized event selections

  Structure of this talk
- Basic event information first via low-latency channel
- Full event transferred later for improved recos
- Solutions available

Realtime Analyses in IceCube



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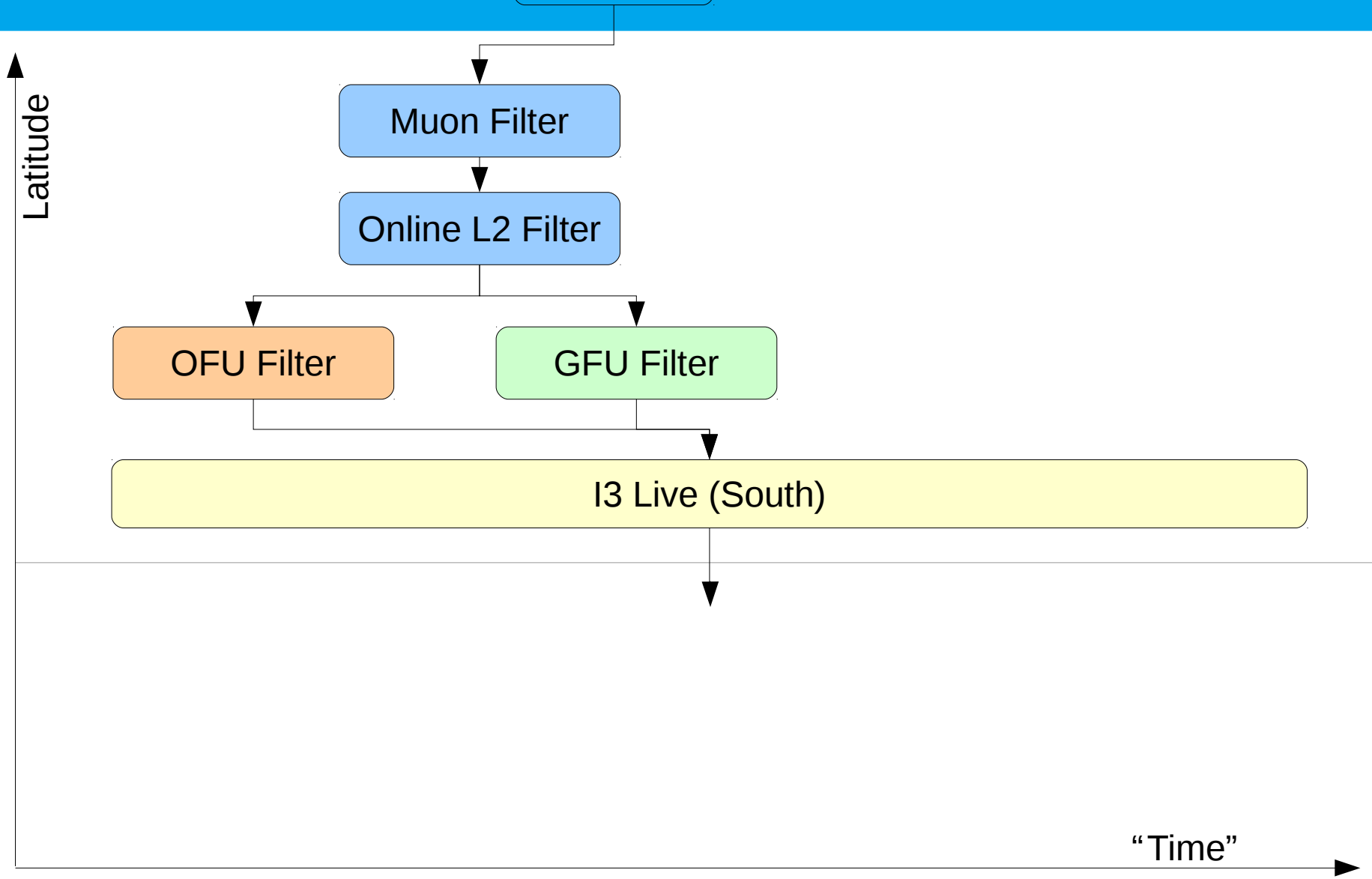

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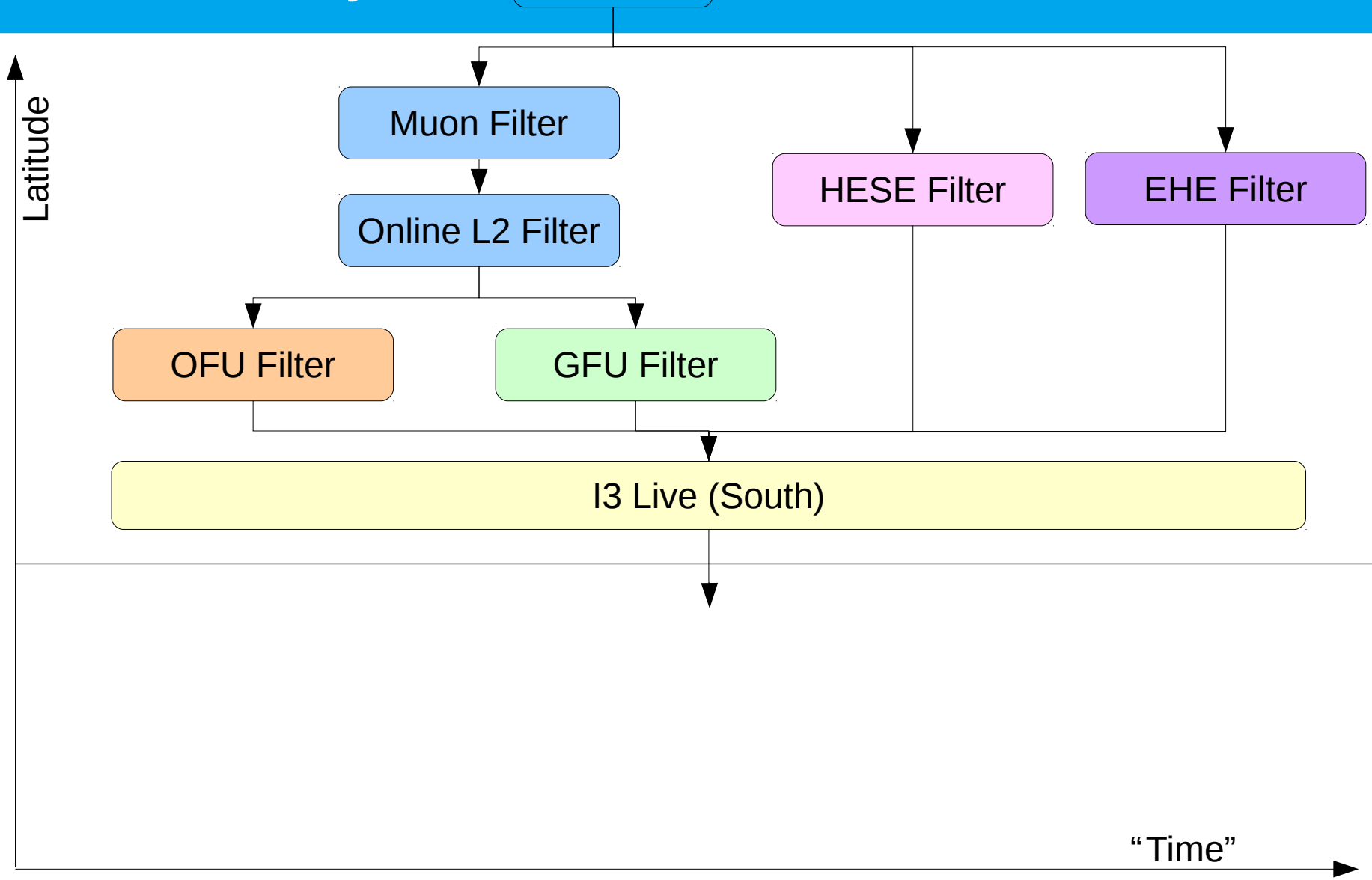

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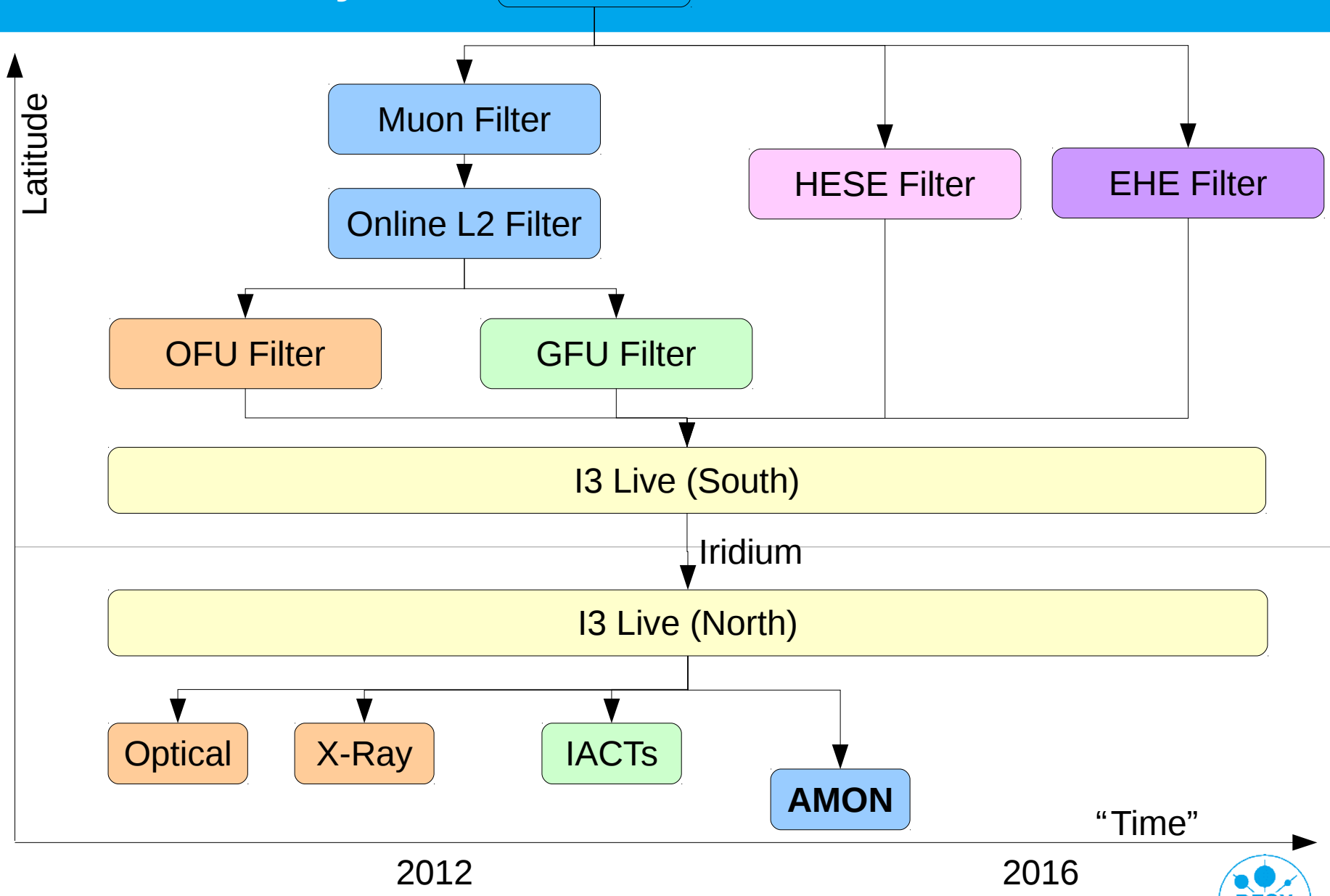

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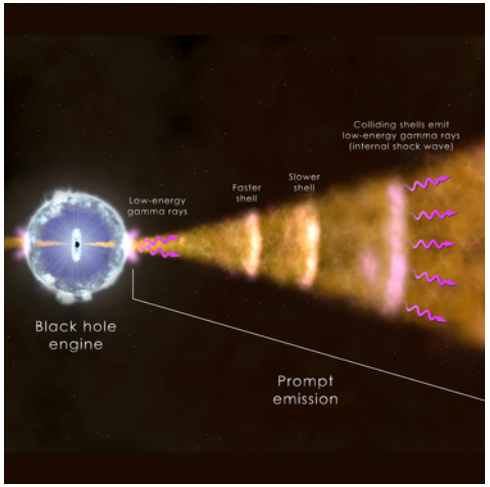
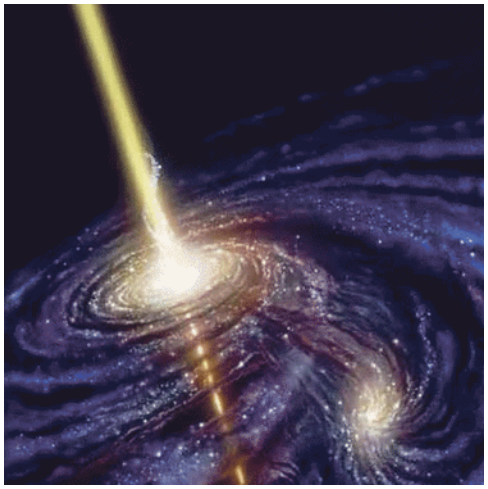
Gamma-Ray, Optical and X-ray Follow-Up

> Targeted at transient and variable sources





GRB: 10 – 100 s

AGN flare: ~ 10 d

SN: ~ 100 d

> Wide variety of time-scales for evolution

> Time-dependent analyses:

Optical/X-ray Follow-Up: Multiplets within 100 seconds

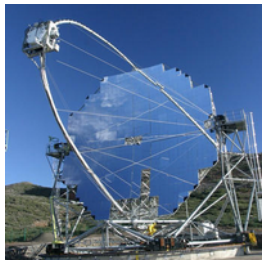
Gamma-Ray Follow-Up: Point Source search

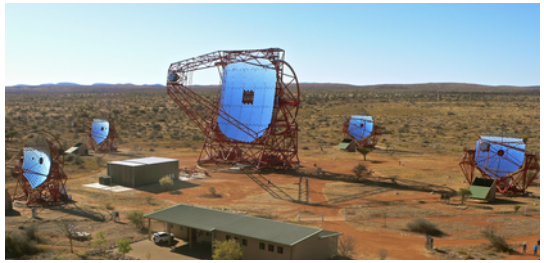
DESY

(Current) Follow-Up Observatories

> Gamma-rays

- MAGIC (1 alert / year)
- VERITAS (3 alerts / year)
- HESS (t.b.d.)
- Energy ranges: ~ 50 GeV – 50 TeV
- FoV: ~ 3.5 deg.





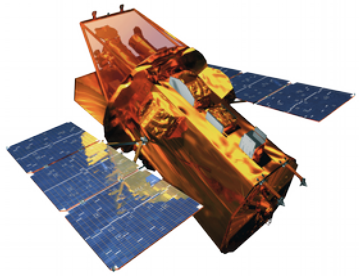
> Optical

- PTF (9 alerts / year)
  - > FoV: 7.3 sq. deg.
- ZTF (under construction)
  - > FoV: 47 deg.

now also in AMON

> X-rays: SWIFT-XRT (7 alerts / year)

- FoV: 0.4 deg. (→1.1 deg.)
- Energy: 0.2 – 10 keV



DESY

Single Event Stream(s)

Old design:

> Event selection, analyses and alert generation at the South Pole
> Only alerts sent north

New design:

> Event selection at the South Pole
> Basic event information sent north
> Analyses and alert generation in the North

→ more flexible and easily upgradable

Single Event Stream(s)

> Fast event selection at the South Pole using BDTs

> Pick well-reconstructed, **through-going** muon **tracks**

	OFU	GFU
Precuts	same	
BDT Variables	10	10+2
Trained spectrum	equally weighted E^{-1}, E^{-2}, E^{-3} spectra	E^{-2} spectrum
Cover	Northern sky	Full sky
Event rate	5 mHz	4 mHz

- Merging effort underway (scheduled for the new season)

> Basic event information sent north:

Direction, Energy, Directional uncertainty estimate, BDT score

> **Median delay so far: 22 seconds!**

DESY

Follow-Up with Gamma-Ray Observation

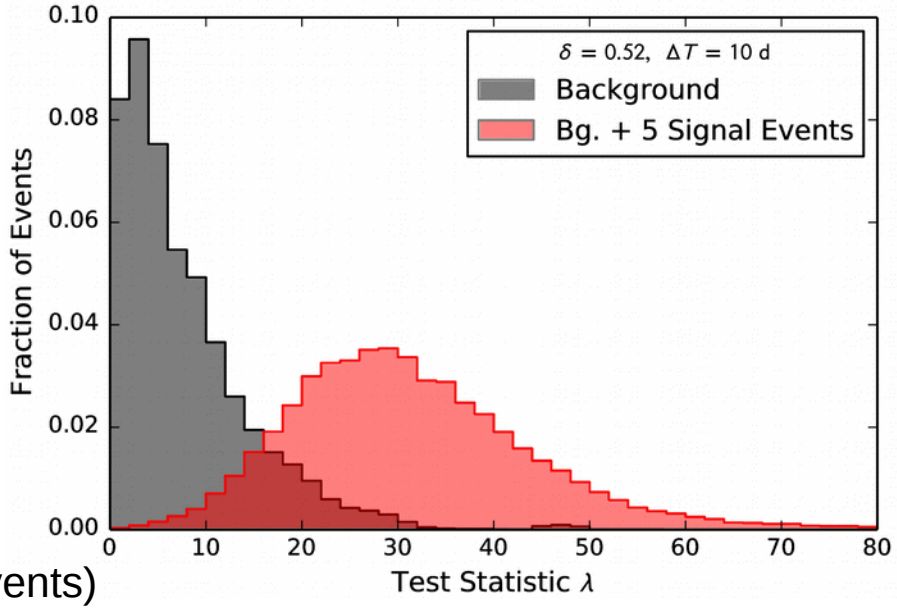
- Receive tracks from (GFU) single event stream
- Marginalized likelihood: $\mathcal{L}(x_i, t_i, E_i | n_{sig}, \gamma) = \prod_{i=0}^{N} \left(\frac{n_{sig}}{N} S_i + \left(1 - \frac{n_{sig}}{N}\right) B_i \right)$

  S_i/B_i: PDFs containing spatial, energy and timing information

- Test statistic:

$$\lambda = -2 \ln \left(\frac{U(T_s^{sig}, T_e)}{U(T_s, T_e)} \frac{\mathcal{L}(n_{sig} = 0)}{\mathcal{L}(\gamma, n_{sig})} \right)$$

  Maximum-Likelihood fit of
  - Spectral index
  - “Signalness” (~amount of signal in events)



- Determination of most likely extent of time window (starting with last received event, looking back up to 21 days)

DESY

Follow-Up with Gamma-Ray Observation

- Current setup: pre-agreed upon list of sources

Considerations:

- Source visibility to follow-up observatory (~40% of time)

(zenith at the telescope, moon phase and proxmity…)

- Duty cycle of follow-up telescope
- Test statistic cut → e.g. 2 alerts / year to MAGIC (automated email)

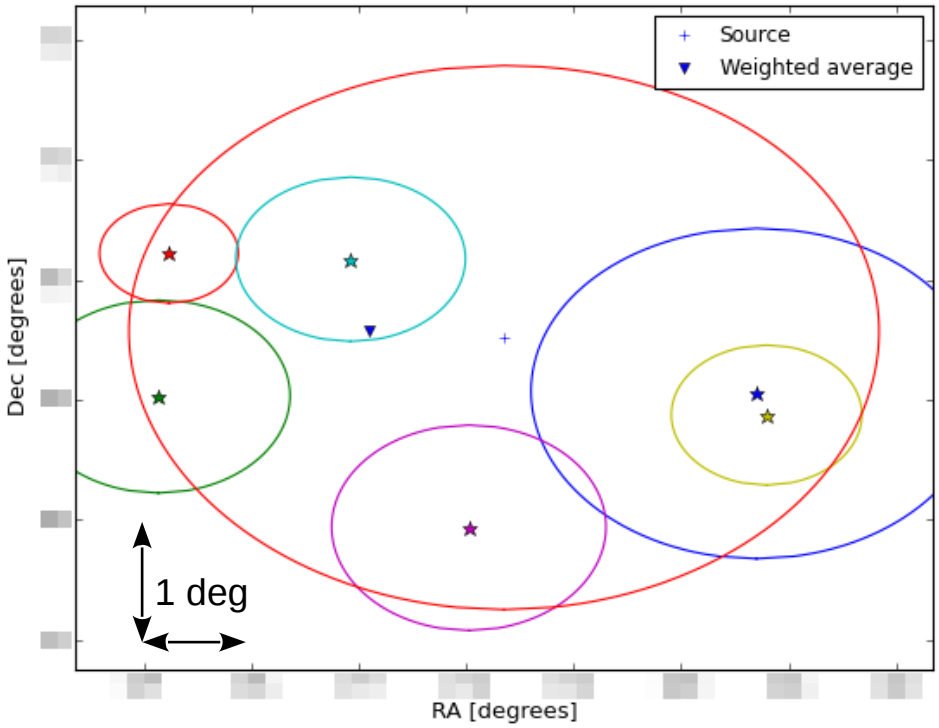
Future plans:

- Develop unbiased (i.e. self-triggering, w/o source list) clustering search
- High(est)-energy single neutrino events among GFU events

Alerts from Gamma-Ray Follow-Up

- Running stable since March 2012
- Number of physics alerts sent so far: 14

- Most significant: 2012/11/09
  - $N_{observed}$: 6
  - Duration: 4.169 d
  - $-\log_{10}$(pre-trial p-value): 4.637



- Alert forwarded to VERITAS
- No significant evidence for gamma-ray emission seen

Intermission: Real-time Monitoring

> 'Good Run List' not available online,
but need for detector stability and event quality in real-time

  - Clustering of events recorded during stable running conditions
  - Detector live time influences likelihood

Alternative demonstrated with GFU at the South Pole:

> Selection of trigger and filter rates

> Sliding window averages: $S_i = \alpha x_i + (1-\alpha) S_{i-1} \qquad \alpha = 0.01$

$$\sigma_i = \sqrt{\langle x^2 \rangle - S_i S_i}$$

> **Stability score:** $\xi_i = \sum_j \frac{|x_i^j - S_{i-1}^j|}{\sigma_{i-1}^j}$

> (will be) available in the North too

> Cut on stability score by analyses

Follow-Up with Optical/X-ray Observations

- Receive tracks from (OFU) single event stream
- Closely clustered events on very short timescales
  → (almost) no background
  - Angular distance: < 3.5°
  - Temporal distance: < 100 s
- Test quantity: $\lambda = -2 \log \mathcal{L}$

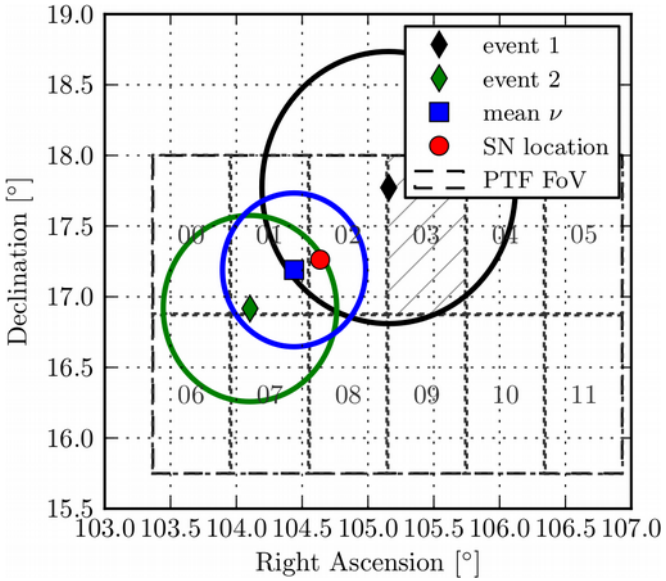
$$= \frac{\Delta\Psi^2}{\sigma_q^2} + 2\log(2\pi\sigma_q^2) - 2\log\left(1 - \exp\left(-\frac{\theta_A^2}{2\sigma_w^2}\right)\right) + 2\log\left(\frac{\Delta T}{100\,\mathrm{s}}\right)$$

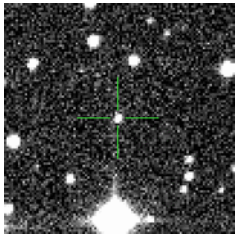
  - angular separation, reconstruction quality, events in telescope's FoV, small time intervals
- Forwarding to
  - PTF: 9 alerts / year
  - SWIFT: 7 alerts / year

DESY

Alerts from Optical/X-ray Follow-Up

- 2012/03/30: Most significant OFU alert to PTF
  - Two neutrinos within 1.7 s
- Detection of core-collapse supernova PTF12csy within 0.14 deg
  - Distance: 300 Mpc
  - Age: > 169 days
- p-Value: 0.014 (2.6σ)
- Chance detection, neutrinos likely unrelated to SN
- [arXiv:1506.03115], accepted by ApJ

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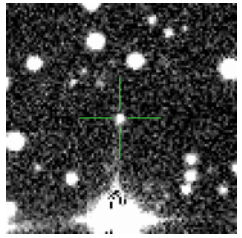
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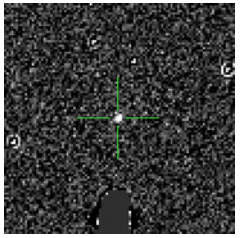
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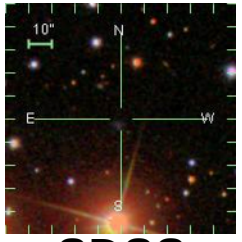
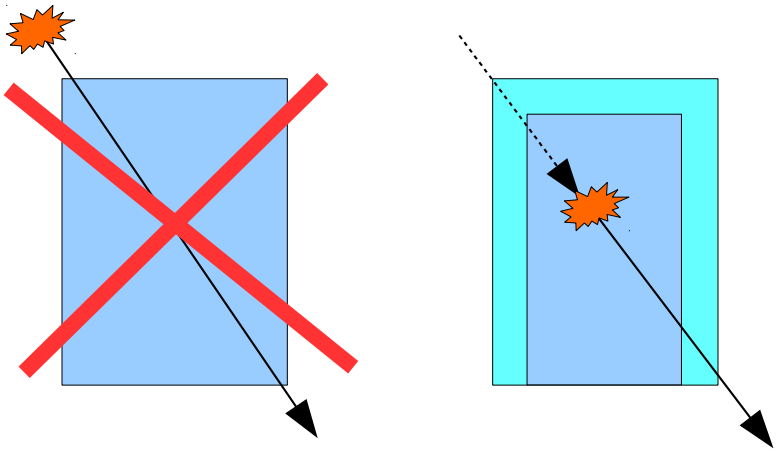


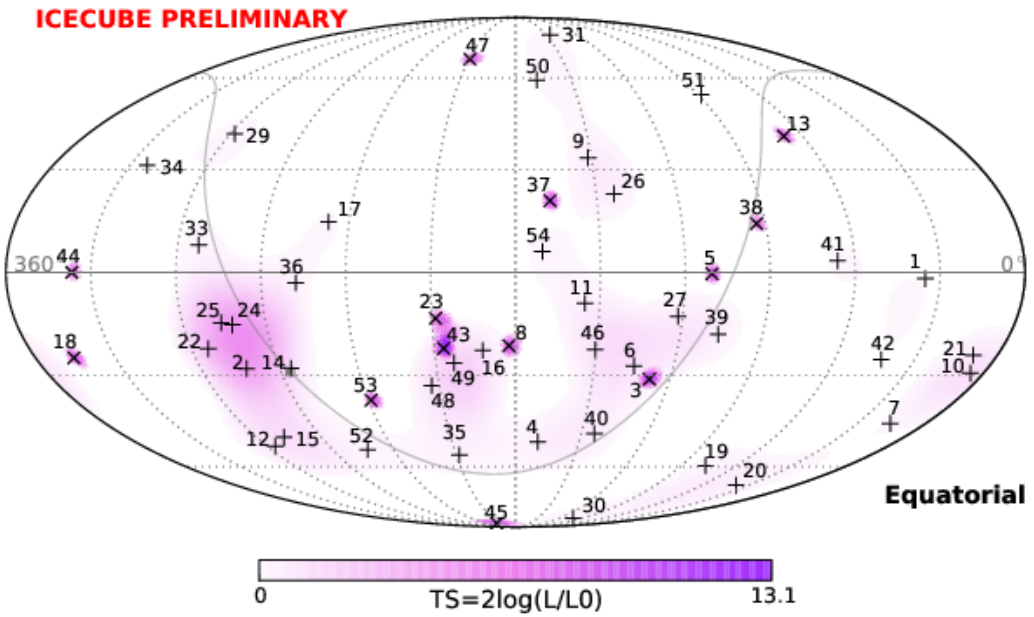
SDSS

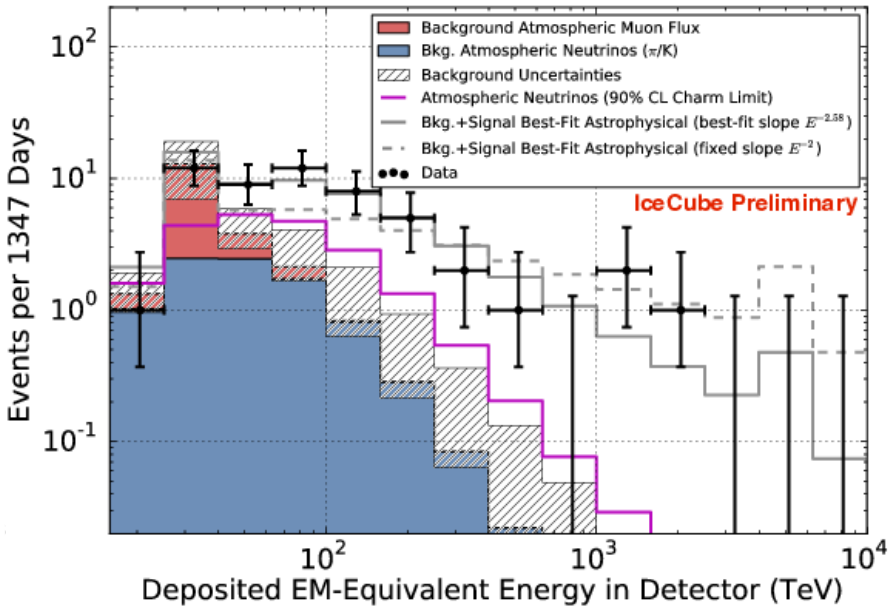
HESE Stream

- High-Energy Starting Events
  - Veto by outer detector layer
  - Q > (1500) 6000 pe
- Starting tracks with lots of charge and short lever arm

→ expensive reconstruction







HESE Stream

Handle in two stages:

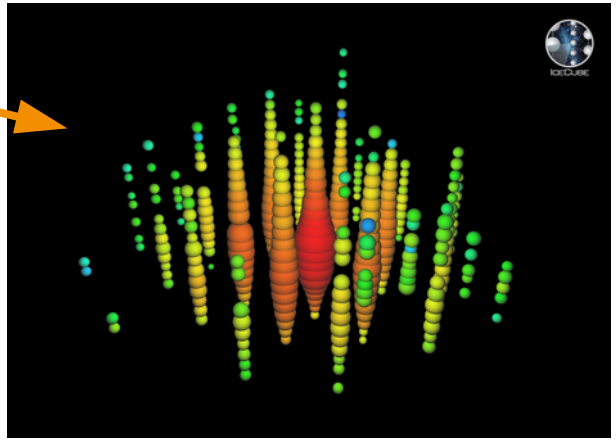
- Basic event reconstruction (cascade and track fit) at the Pole
- Send event summary via high-priority, low-latency messages
  - To the North
  - And to AMON:
    Quick correlation analyses with HAWC, Auger, etc.

Sooner
Later

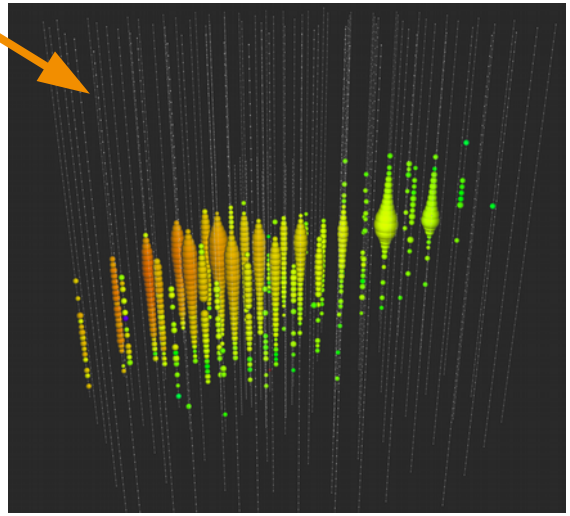
- Send full event information (i.e. pulses) via lower-priority channel
- Run demanding reconstructions in the North
- Update AMON event with latest reco results

EHE (Extreme High Energy) Alert Stream

- Similar to (offline) diffuse EHE analysis
  - Npe > 3000, Nch > 300, fit quality cuts
- Adapted to target astrophysical neutrinos
- Only track-like candidates
  (with Online L2 reconstructions)



- **Expected yield: 6 events / year**
  (2 background + 4 signal)



Intended audience:

- Not generally public
- MoU partners (e.g. MAGIC, HESS)
- AMON partners: VERITAS, Swift, HAWC, ANTARES, ...

Summary and Outlook

- Feasibility of realtime analyses demonstrated with IceCube and partner experiments:
  - Through-going Muon Stream
  - Gamma-Ray Follow-Up (with Realtime Stability Monitoring)
  - Optical/X-ray Follow-Up
- Transition to flexible system
  - more event classes
  - more analyses
- New event selections available soon
  - HESE Stream
  - EHE Alert Stream