

MULTI-MESSENGER PROGRAMS IN ICECUBE

THOMAS KINTSCHER (DESY)
FOR THE ICECUBE COLLABORATION

5TH AMON WORKSHOP
2016/12/10, COCHEM

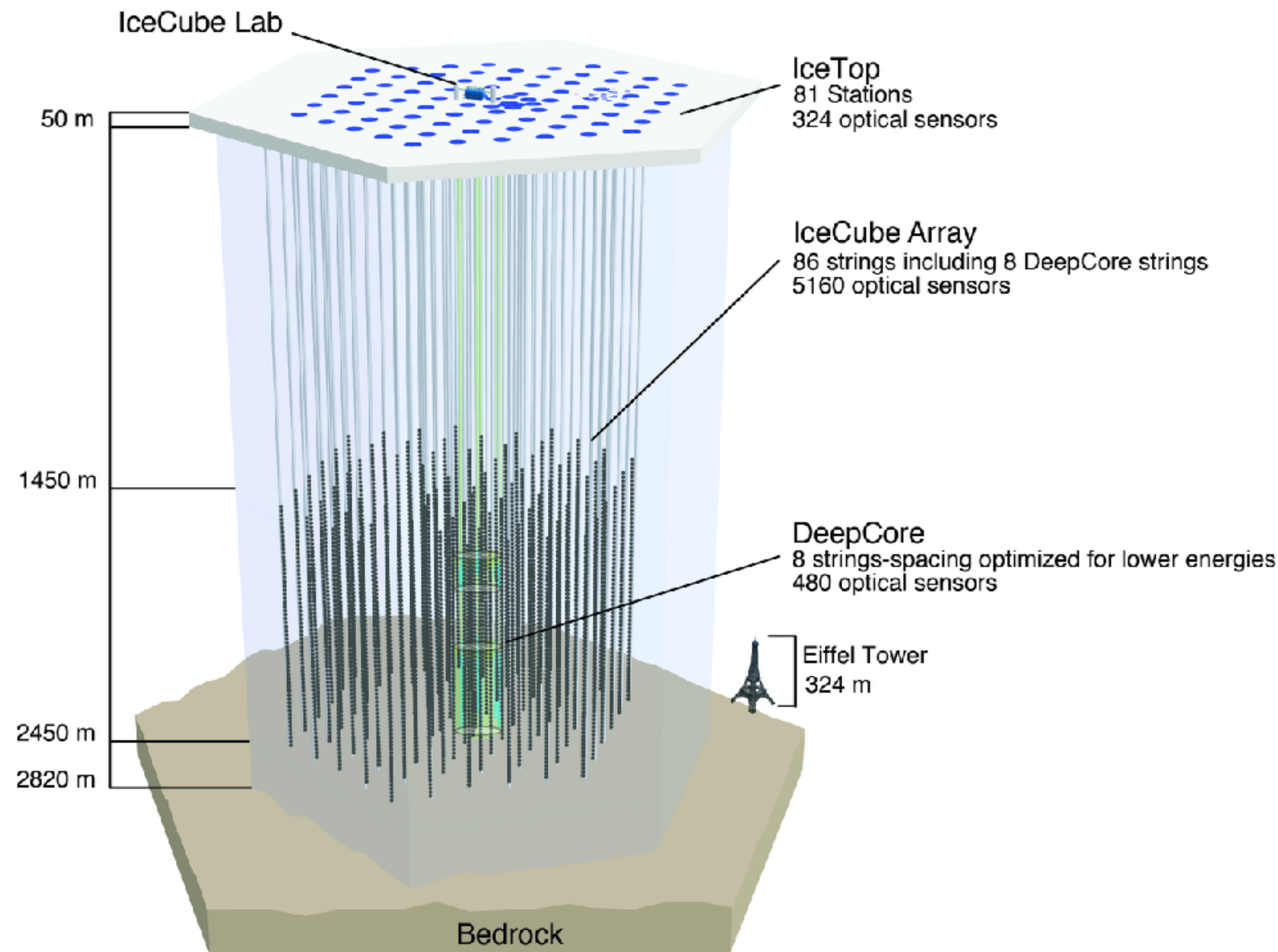


OUTLINE

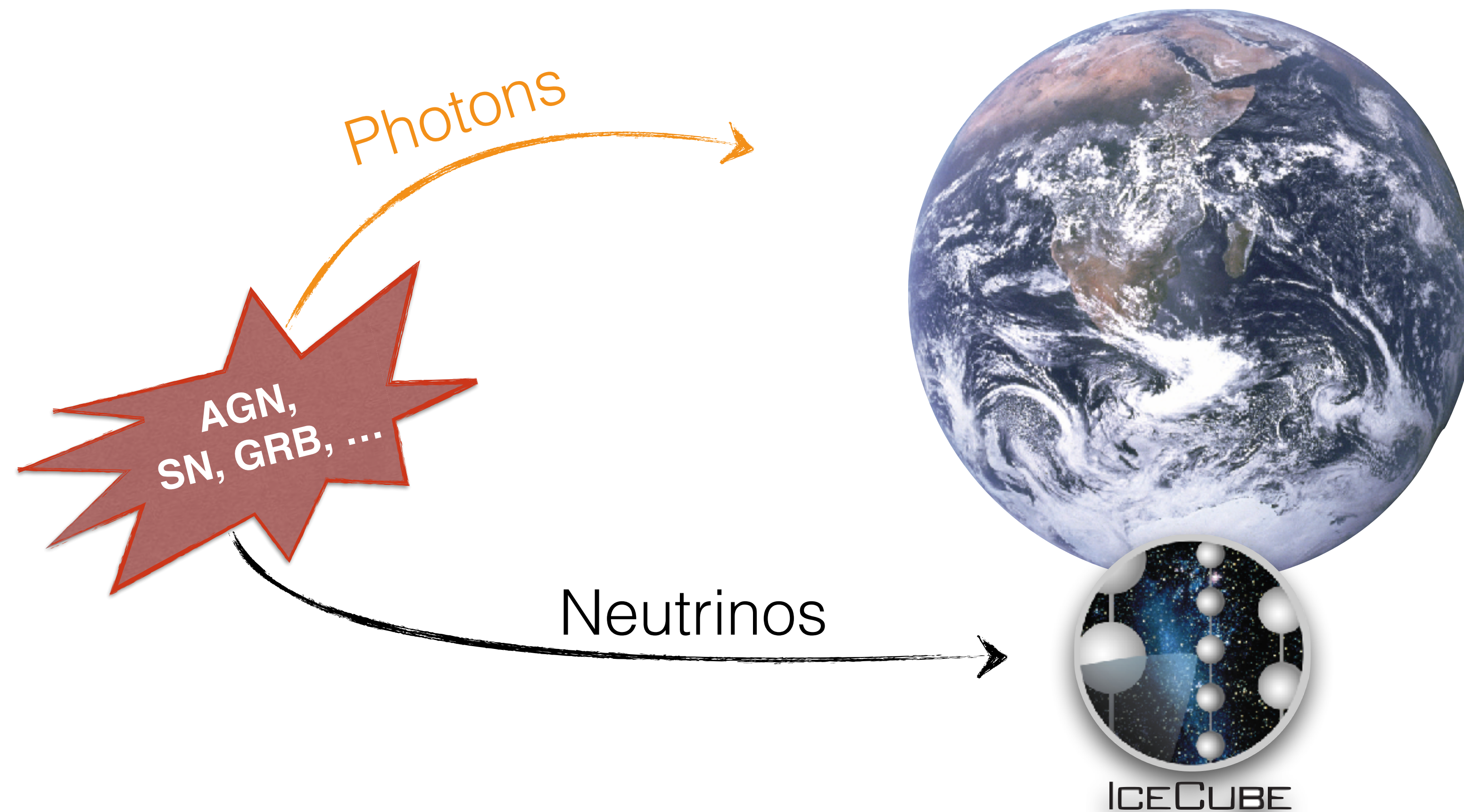
- IceCube Detector
- Real-Time Infrastructure
- Follow-Up / Alert Programs
 - Gamma-Ray Follow-Up, Optical Follow-Up
 - HESE and EHE Alerts
- Summary

THE ICECUBE DETECTOR

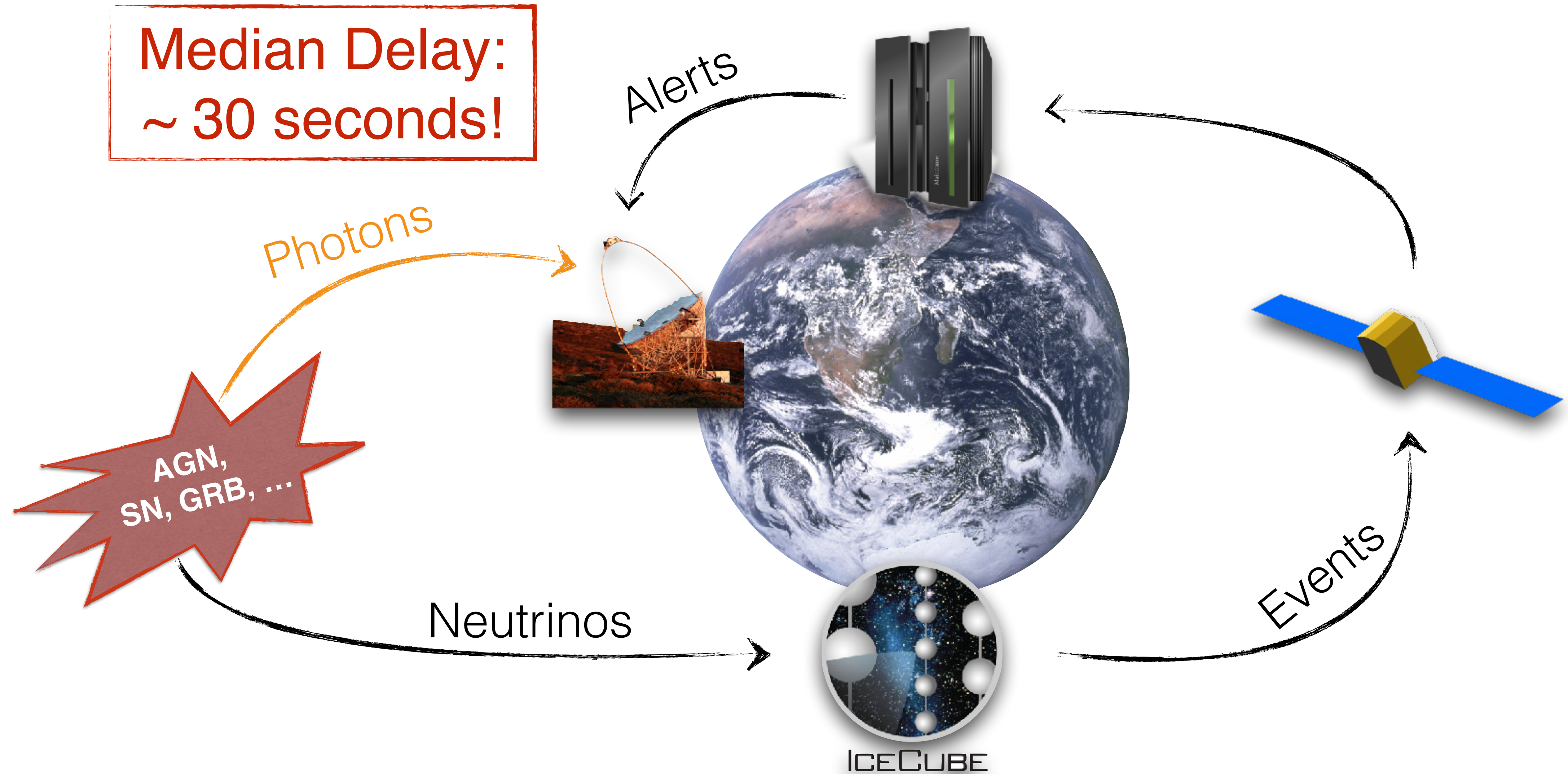
- ▶ 1 km³ detector for Cherenkov light at the South Pole
- ▶ 5160 optical modules on 86 strings
- ▶ Scope of this talk:
Muons from CC ν_μ interaction
- ▶ Angular resolution:
typically better than 1 deg



REAL-TIME ALERT SYSTEM



REAL-TIME ALERT SYSTEM



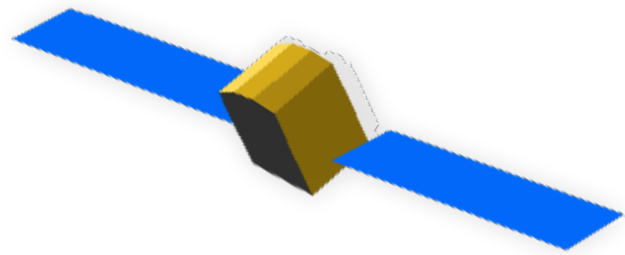
REAL-TIME OPERATIONS



- ▶ Limited computing resources
at the South Pole

- ▶ Limited connectivity
Iridium: low latency, low bandwidth
TDRSS: high latency, high bandwidth

- ▶ Limited detector monitoring
(i.e. no „Good Run List“)



- ▶ Fast/specialized event selections
- ▶ Basic event information first
for quick generation of alerts
- ▶ Full event later
for improved reconstruction
- ▶ Conservative online monitoring

REAL-TIME ANALYSES IN ICECUBE

Clustering
Searches

2008: Optical Follow-Up (OFU)

2012: Gamma-Ray Follow-Up (GFU)

Individual
Events

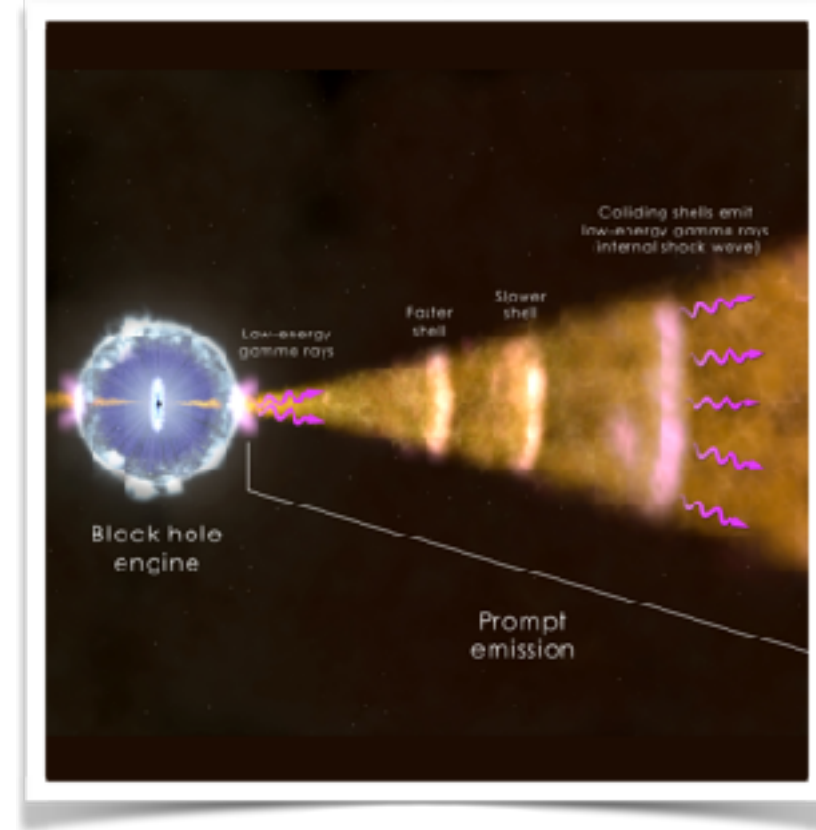
2016: High-Energy Starting Events (HESE)

2016: Extreme High Energy Events (EHE)

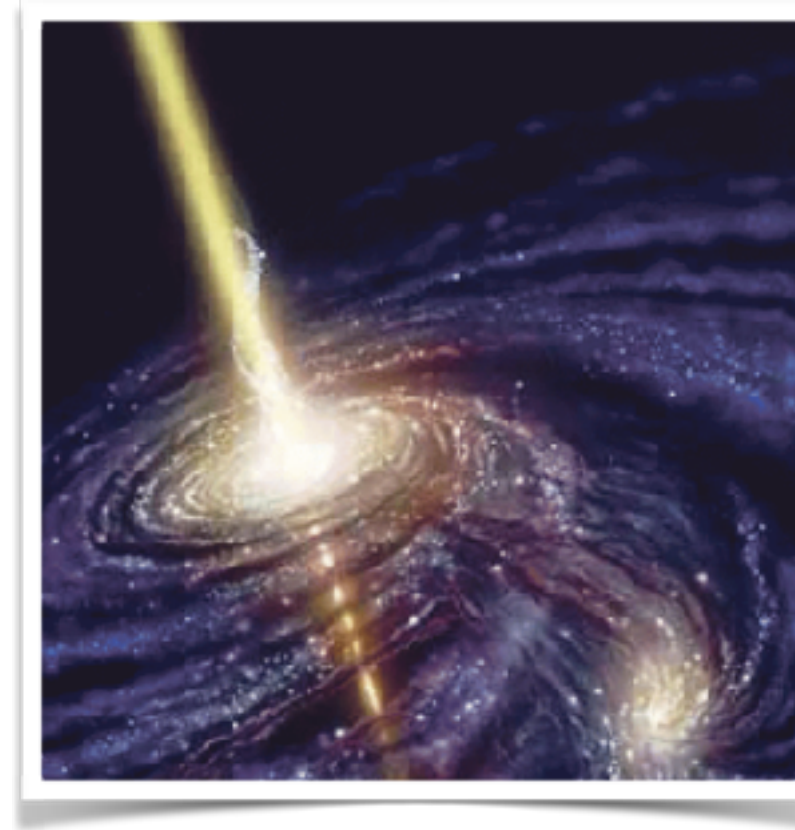
GAMMA, OPTICAL AND X-RAY FOLLOW-UP

Target:

transient and
variable sources



GRB: 10–100 s



AGN: ~ 10 d



SN: ~ 100 d

Time-dependent analyses:

- Optical/X-ray Follow-Up: Multiplets within 100 seconds
- Gamma-Ray Follow-Up: Cluster search for up to 21 days

GAMMA-RAY FOLLOW-UP

Event Selection

Sending to the North

Clustering Analysis

Alerts

- ▶ Fast, BDT-based event selection
- ▶ Picking well-reconstructed, through-going muon tracks
- ▶ Event rate: 4 mHz
- ▶ Typical angular resolution: < 1 deg

GAMMA-RAY FOLLOW-UP

Event Selection

Sending to the North

Clustering Analysis

Alerts

- ▶ Transmit brief summary of each event:
 - Direction
 - Angular Uncertainty
 - Energy Estimate
 - Event shape (track length)
- ▶ For future use:
 - Full event information (i.e. all pulses)

GAMMA-RAY FOLLOW-UP

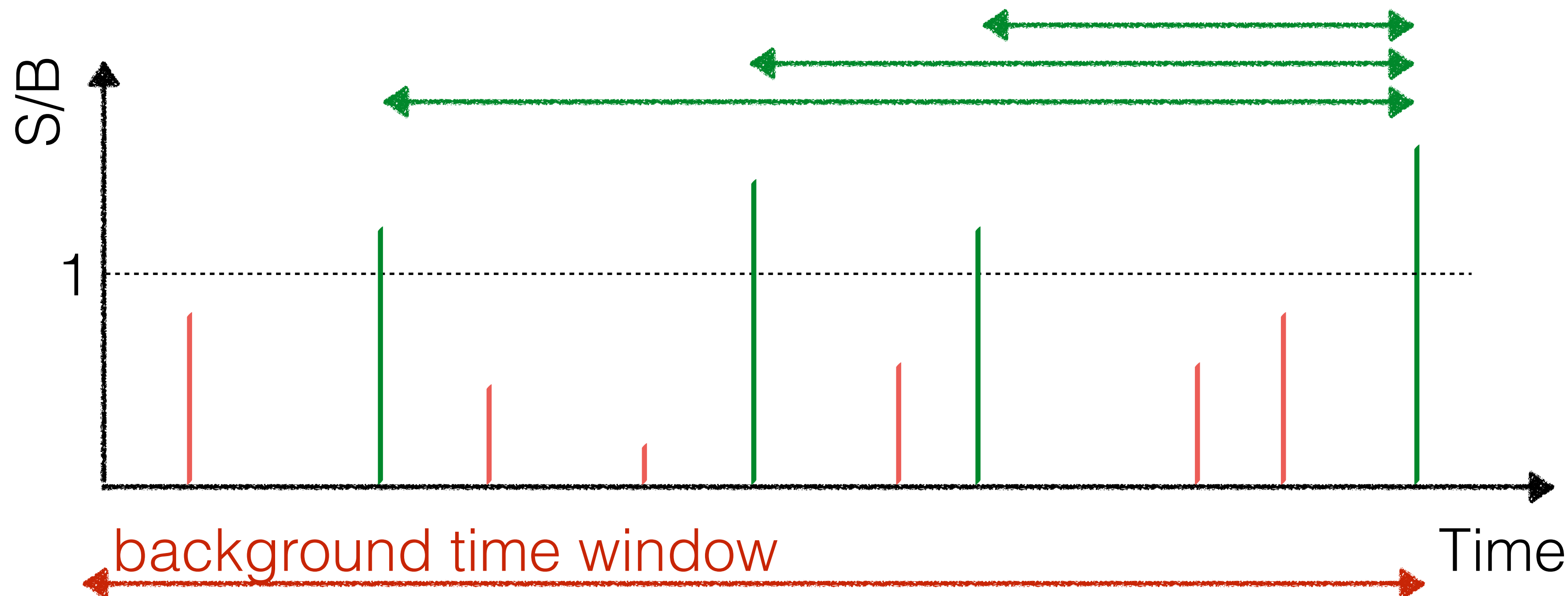
Event Selection

Sending to the North

Clustering Analysis

Alerts

Use signal/bkg PDFs in Likelihood: $\mathcal{L} = \prod_i^{\text{events}} \left[\frac{n}{N} S_i + \left(1 - \frac{n}{N} \right) B_i \right]$



- ▶ test expanding signal time windows
- ▶ boundaries defined by S/B llh ratio
- ▶ find time window with best TS

GAMMA-RAY FOLLOW-UP

IceCube, MAGIC, VERITAS:
JINST 11 P11009 (2016)

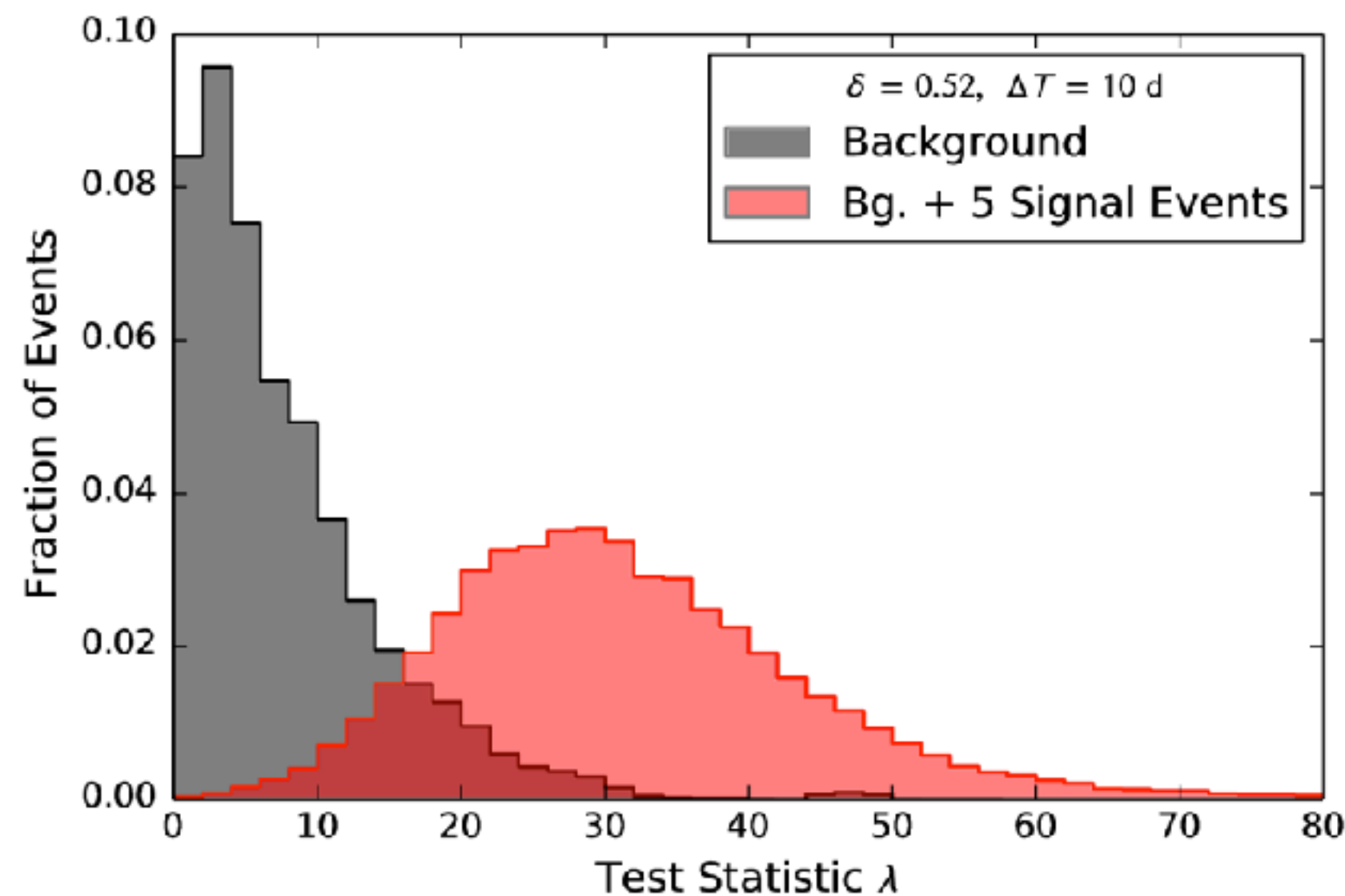
Event Selection

Sending to the North

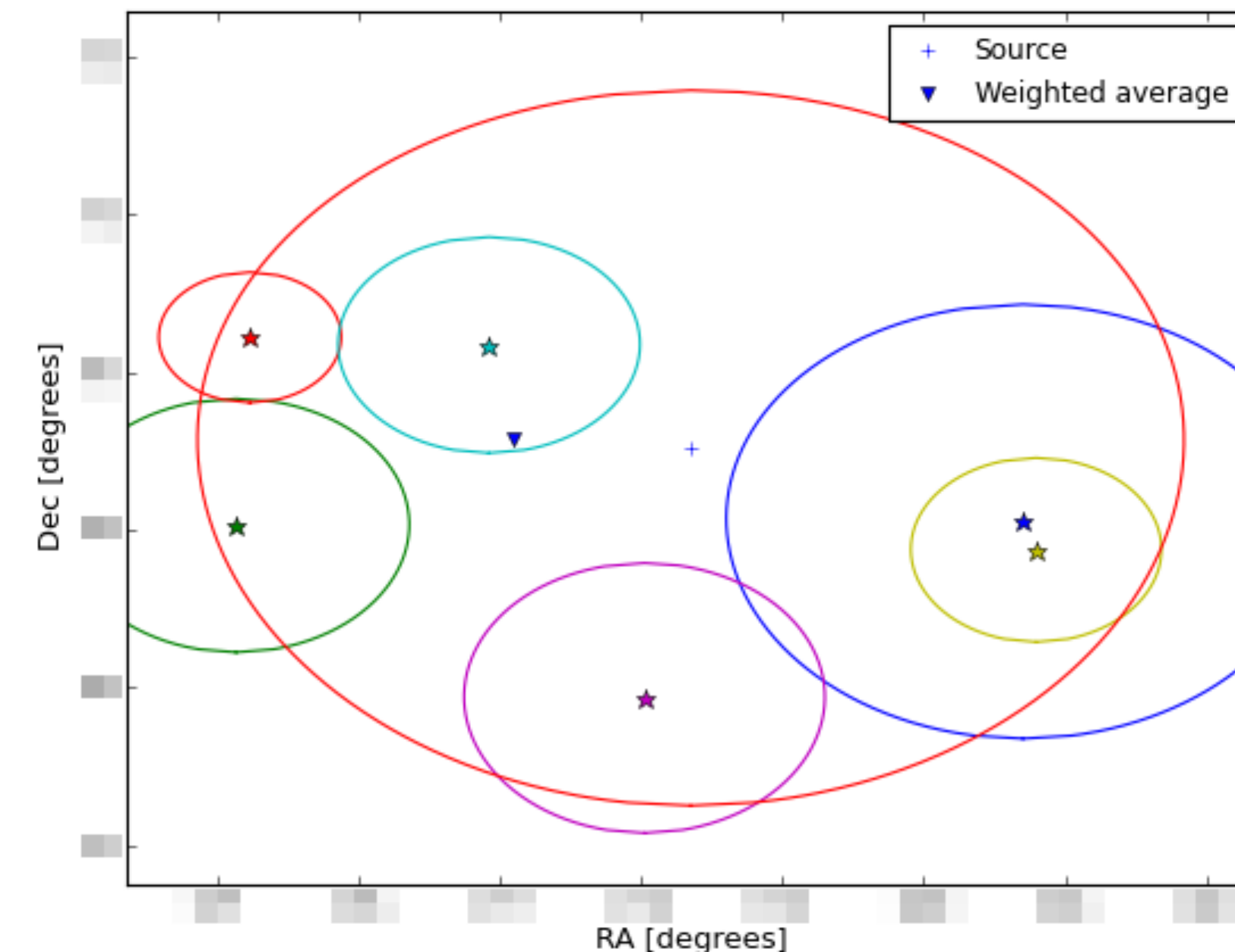
Clustering Analysis

Alerts

- ▶ Likelihood ratio test (vs. bkg-only hypothesis)
- ▶ Pre-agreed list of monitored sources
- ▶ Test statistic cut yields ~ 2 alerts/year



- ▶ Most significant alert: 2012/11/09
 - 6 events in 4.2 days ($p=0.002\%$)
- ▶ VERITAS: no significant excess seen



OPTICAL FOLLOW-UP

- Similar, but on shorter time-scales and whole sky
- **Straight cuts for multiplets**
 - ... in space (3.5 deg)
 - ... and time (100 s)
- **Most significant doublet: 2012/03/30**
 - two neutrinos within 1.7 s
 - 0.14 deg away from CCSN PTF12csy
 - p-Value: 0.014
 - neutrinos likely unrelated to SN
- **Growing list of follow-up observatories:**

~~ROTSE~~, PTF, MASTER, SWIFT, (ASAS-SN, LCOGT)

RESULTS FROM THE OFU PROGRAM

- Similar, but on shorter time-scales and whole sky

- **Straight cuts for multiplets**

- ... in space (3.5 deg)
- ... and time (100 s)

- **Most significant doublet: 2012/03/30**

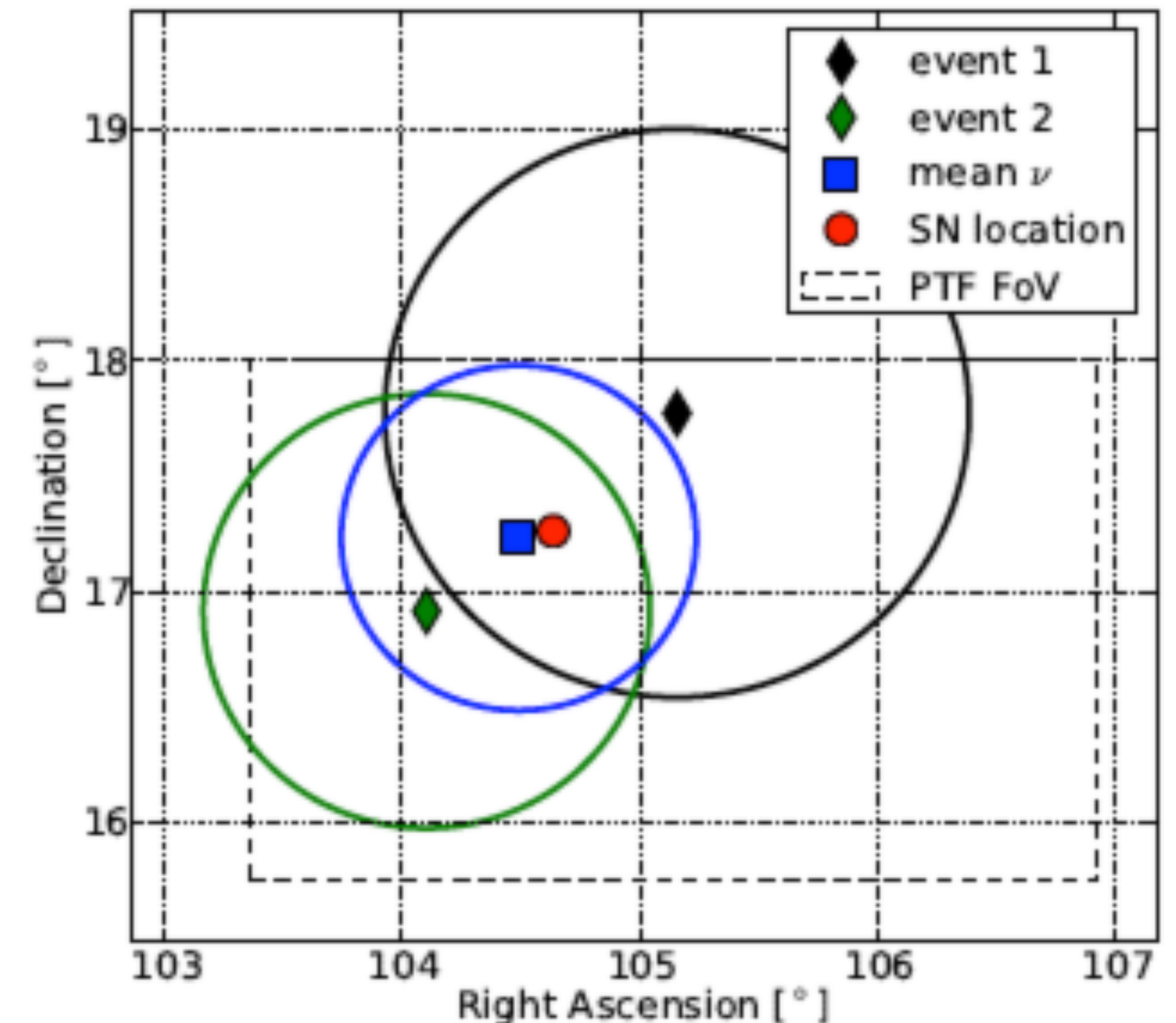
- two neutrinos within 1.7 s
- 0.14 deg away from CCSN PTF12csy
- p-Value: 0.014
- neutrinos likely unrelated to SN

- **Growing list of follow-up observatories:**

in preparation

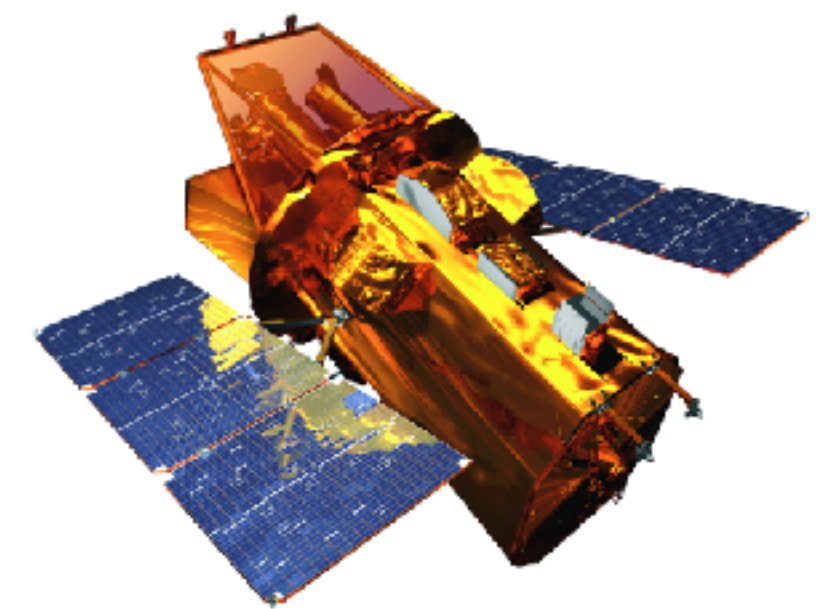
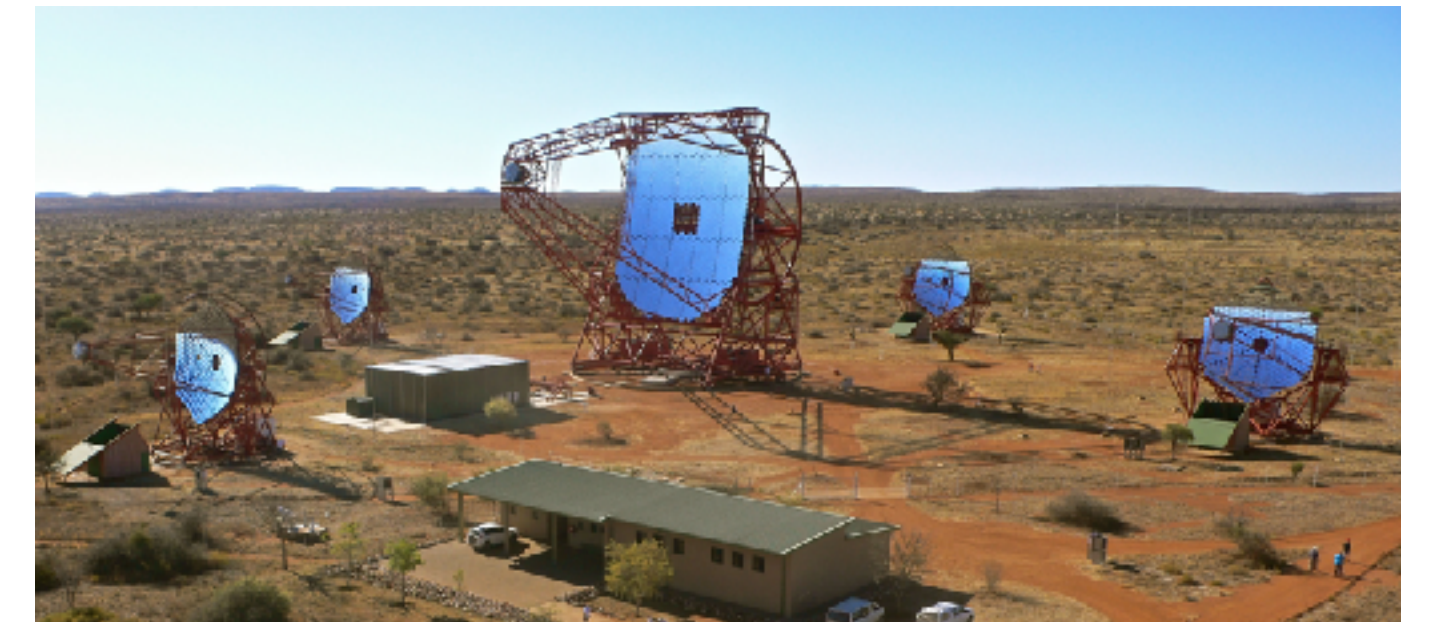
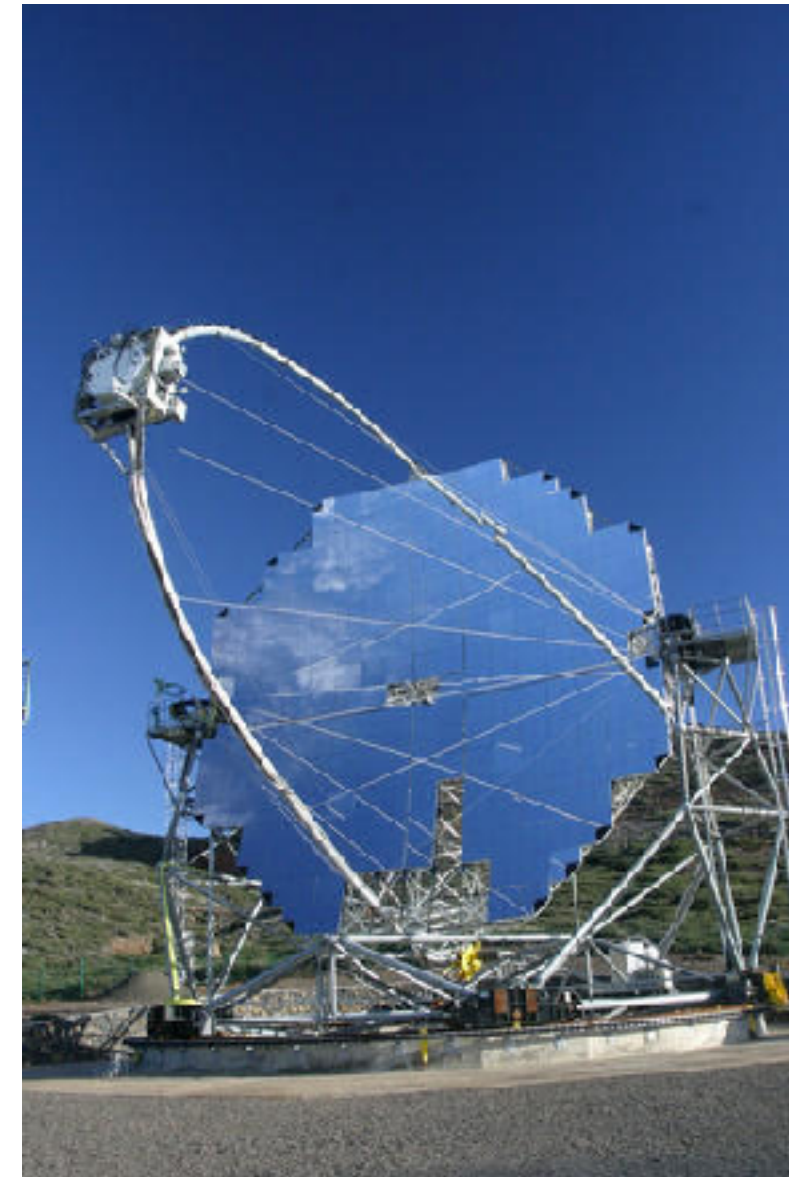
~~ROTSE~~, PTF, MASTER, SWIFT, (ASAS-SN, LCOGT)

IceCube: ApJ, 811, 52 (2015)



FOLLOW-UP OBSERVATORIES

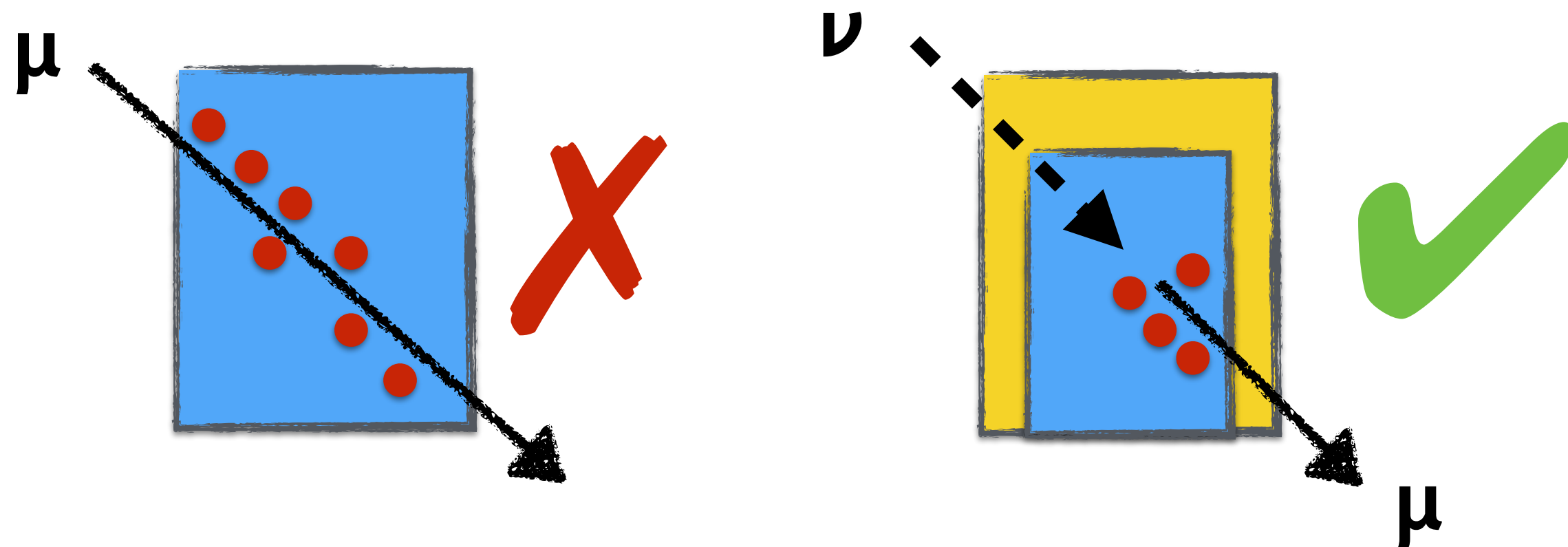
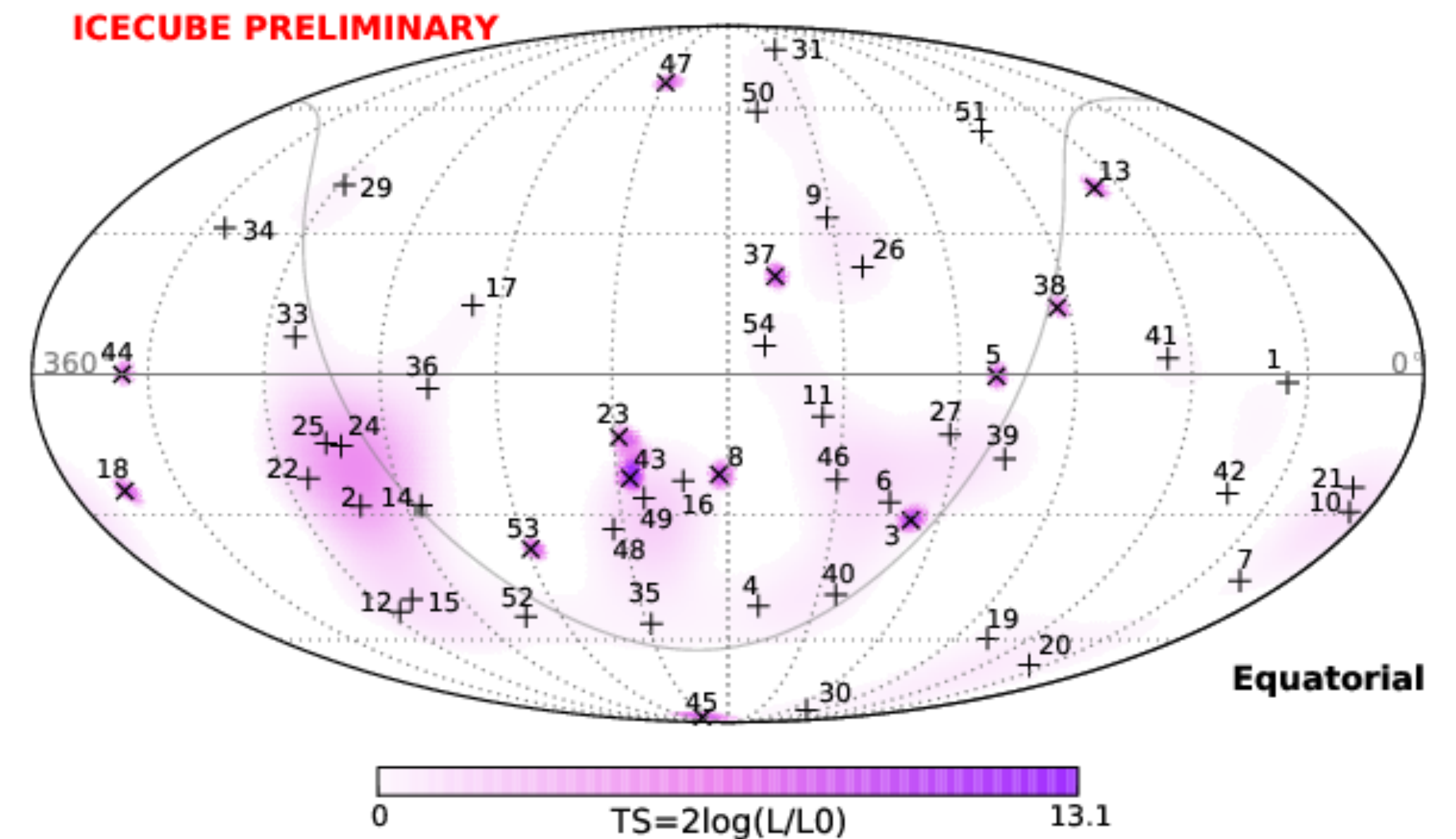
- ▶ Gamma-Rays:
 - **HESS, VERITAS, MAGIC**
 - Energy ranges: ~ 50 GeV – 50 TeV
 - FoV: ~ 3.5 deg
- ▶ Optical:
 - **PTF** (FoV: 7.3 sq. deg)
 - **ZTF** (FoV: 47 deg)
- ▶ X-rays:
 - **SWIFT-XRT** (FoV: 0.4/1.1 deg)
 - Energy range: 0.2 – 10 keV



HIGH ENERGY STARTING EVENTS

- ▶ Veto against atmospheric muons by outer detector layer
- ▶ Starting tracks with $Q > 6000$ pe, but short lever arm
- ▶ Expensive reconstruction (→revised alerts)

IceCube: Phys. Rev. Lett. 113, 101101 (2014)



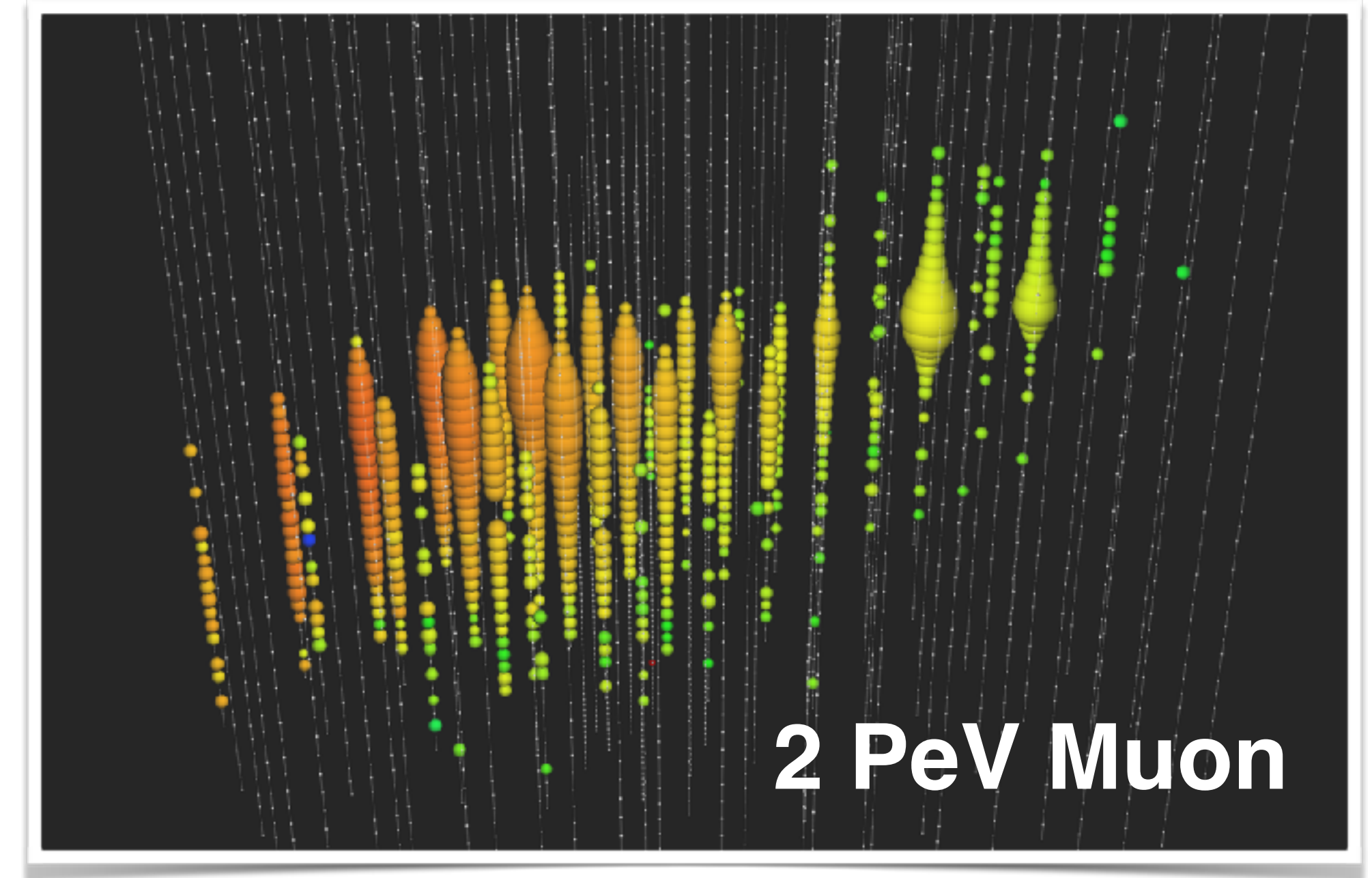
Public events (GCN)
~ 4 alerts / year

EXTREME HIGH ENERGY EVENTS

IceCube: Phys. Rev. Lett. 117, 241101 (2016)

- ▶ High-energy, throughgoing events
- ▶ $N_{pe} > 3000$
- ▶ Very good resolution (< 0.2 deg)
- ▶ Public alerts (GCN)

- ▶ Expected yield (S+B):
 - $4+2$ events/year (E^{-2})
 - $2+2$ events/year ($E^{-2.5}$)



FIRST HESE/EHE ALERTS

Date	Type	RA	Dec	50% Error
2016/04/27	HESE	240.6 deg	9.3 deg	0.6 deg
2016/07/31	EHE + HESE	214.5 deg	- 0.3 deg	0.35 deg
2016/08/06	EHE	122.8 deg	- 0.7 deg	0.11 deg
2016/08/14	HESE	200.3 deg	- 32.4 deg	0.48 deg
2016/11/03	HESE	40.9 deg	12.6 deg	0.42 deg

- all alerts published as GCN (via AMON)
- responses from observers also via GCN

FIRST HESE/EHE ALERTS

Date	Type	RA	Dec	50% Error
2016/04/27	HESE	240.6 deg	9.3 deg	0.6 deg
2016/07/31	EHE + HESE	214.5 deg	- 0.3 deg	0.35 deg
2016/08/06	EHE	122.8 deg	- 0.7 deg	0.11 deg
2016/08/14	HESE	200.3 deg	- 32.4 deg	0
2016/11/03	HESE	40.9 deg	12.6 deg	0

Optical

Observer	Result
iPTF	3 transients, all AGN
MASTER	no detection
PanSTARRS	7 SN candidates

Gamma-Rays

Observer	Result
IPN	no detection
Fermi-LAT	5 unrelated blazars
Fermi-GBM	no detection
FACT	no detection
VERITAS	no detection
HAWC	no detection
MAGIC	no detection

SUMMARY

- ▶ Long-standing experience in realtime analyses
 - Clustering searches
 - Single events
- ▶ Successful exchange of alerts with
MAGIC, VERITAS, HESS, ROTSE, PTF, SWIFT, MASTER, ...
- ▶ Alerts are shared...
 - ... directly through MoU with partners
 - ... through AMON / GCN