

Transients with IceCube

Anna Franckowiak for the IceCube
Collaboration
Asterics Workshop, Amsterdam
Sept. 28, 2017

Outline

- > Neutrino detection with IceCube
- > Transient neutrino sources
- > IceCube realtime streams and some first results
- > Outlook





ICECUBE

SOUTH POLE NEUTRINO OBSERVATORY

50 m

IceTop

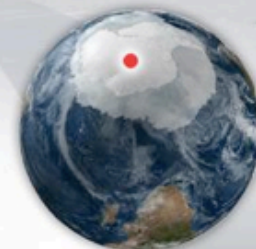


IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW-Madison

1450 m

86 strings of DOMs,
set 125 meters apart



Amundsen-Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility



Digital Optical Module (DOM)

5,160 DOMs
deployed in the ice

2450 m

IceCube
detector

DeepCore

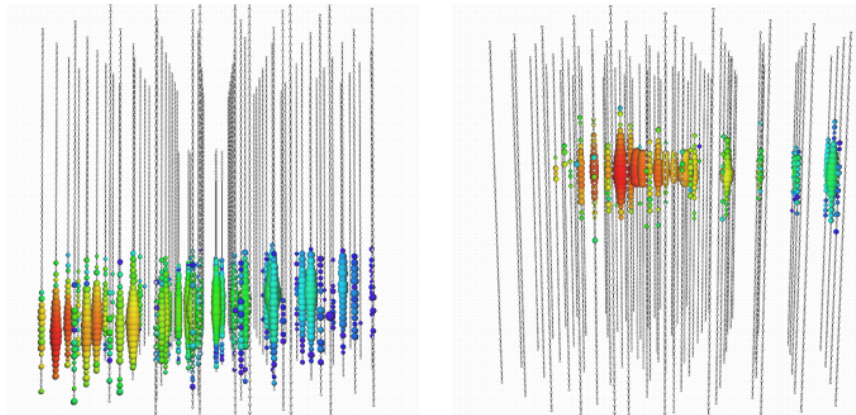
DOMs
are 17
meters
apart

60 DOMs
on each
string



Antarctic bedrock

Event Signatures

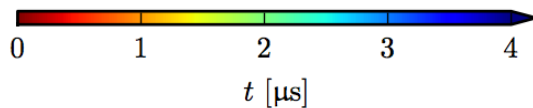
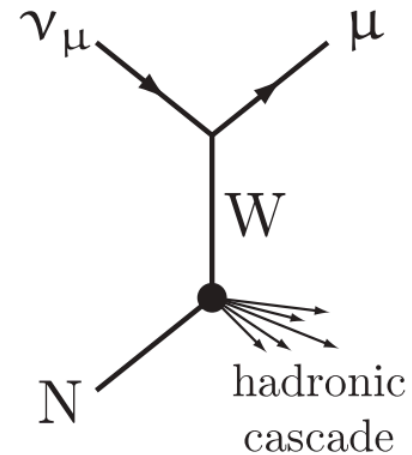


(a)

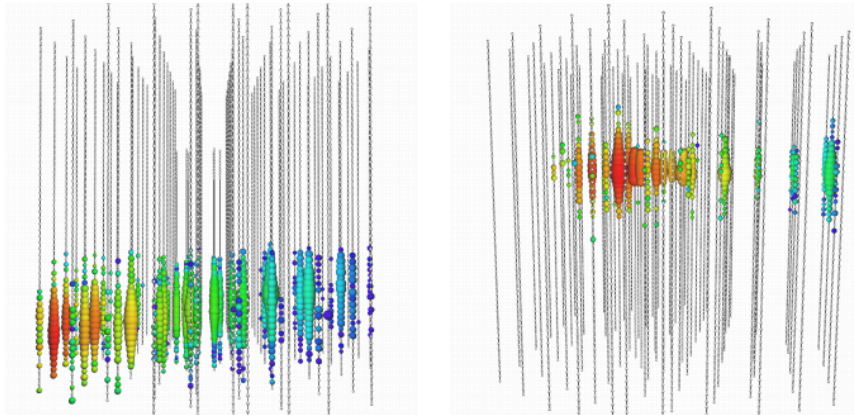
(b)

- a) through-going muon track $E \sim 140$ TeV
- b) Starting muon track $E \sim 70$ TeV

Charged current interaction of muon neutrino
outside / inside the detector volume



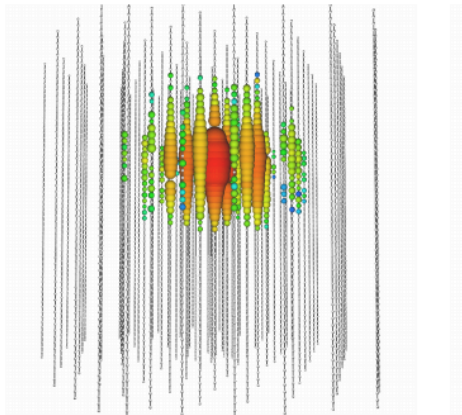
Event Signatures



(a)

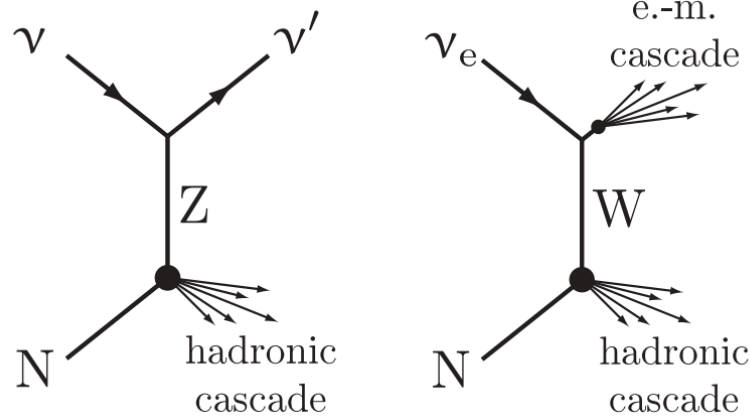
(b)

- a) through-going muon track $E \sim 140$ TeV
- b) Starting muon track $E \sim 70$ TeV
- c) **Shower event $E \sim 1$ PeV**

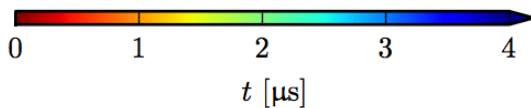


(c)

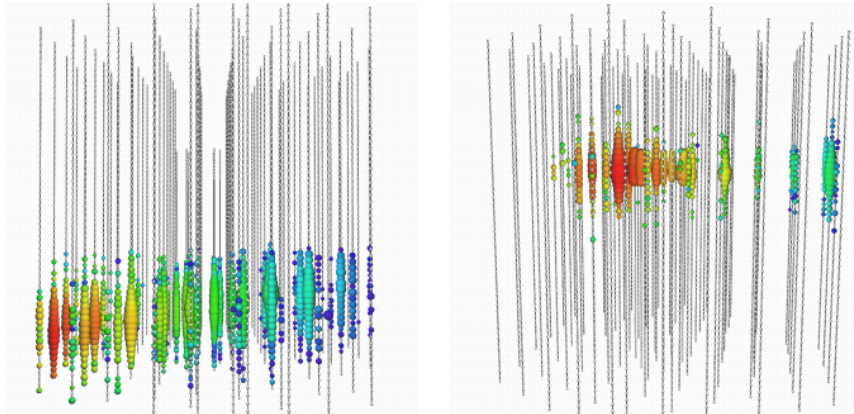
Neutral current or electron neutrino charged current interaction



Cannot distinguish between showers (size few meters)



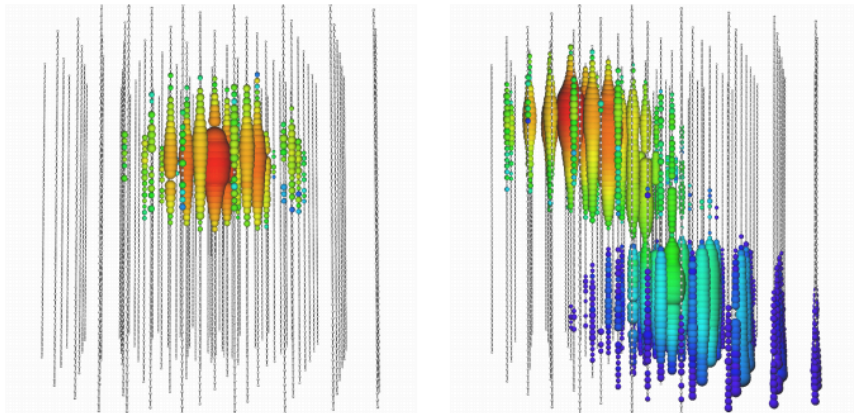
Event Signatures



(a)

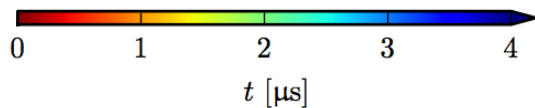
(b)

- a) through-going muon track $E \sim 140$ TeV
- b) Starting muon track $E \sim 70$ TeV
- c) Shower event $E \sim 1$ PeV
- d) **“double bang” event $E \sim 200$ PeV (not measured yet)**

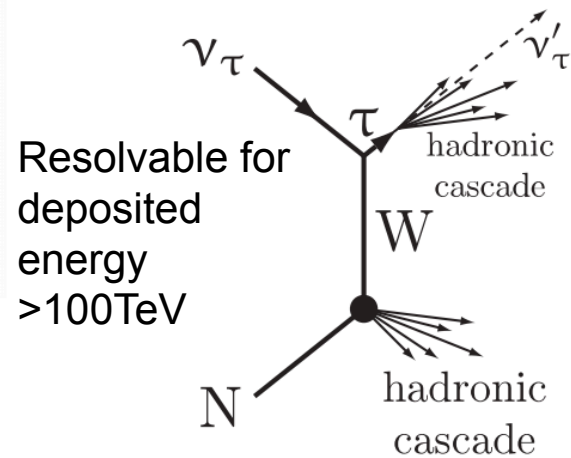


(c)

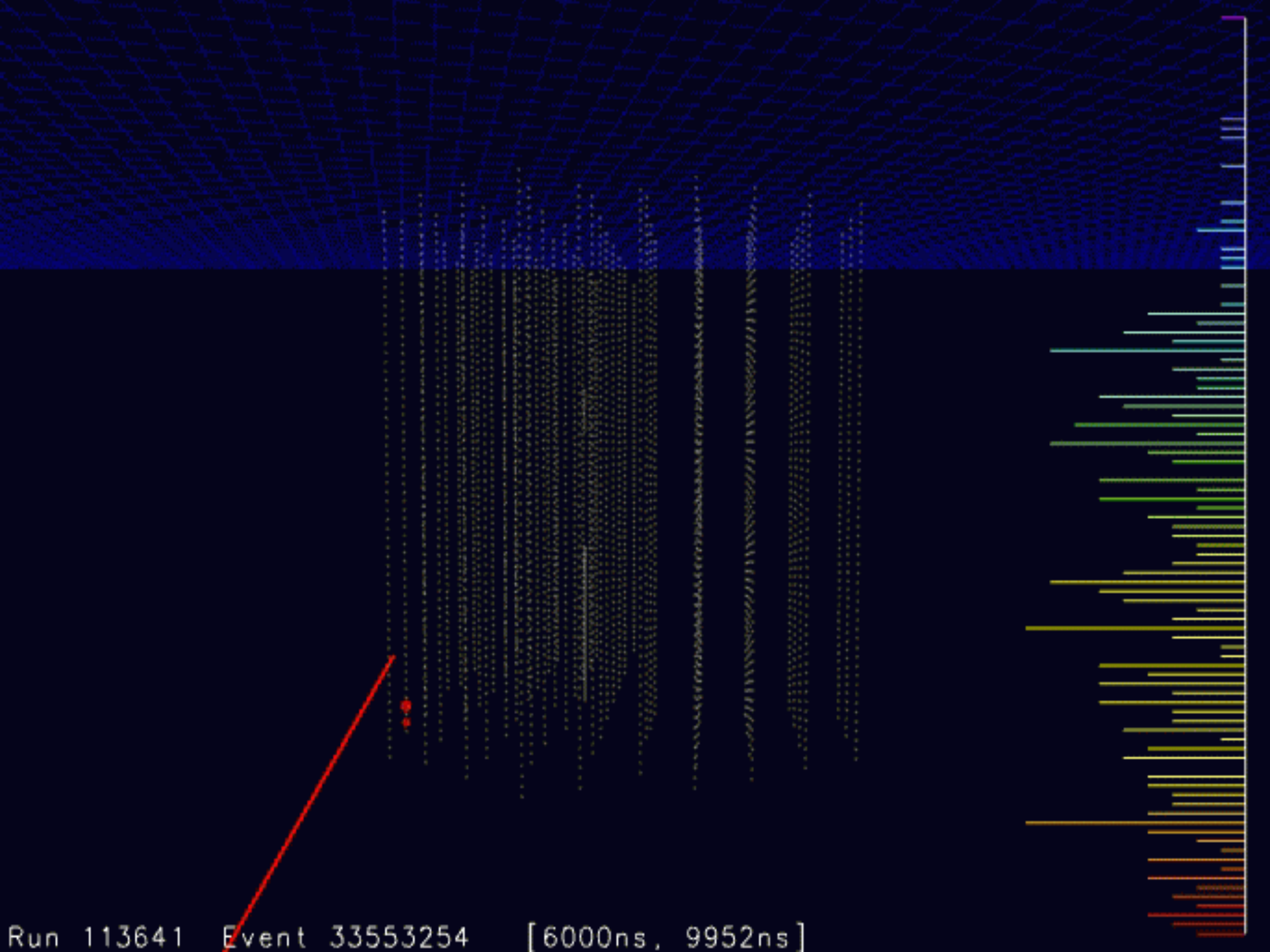
(d)



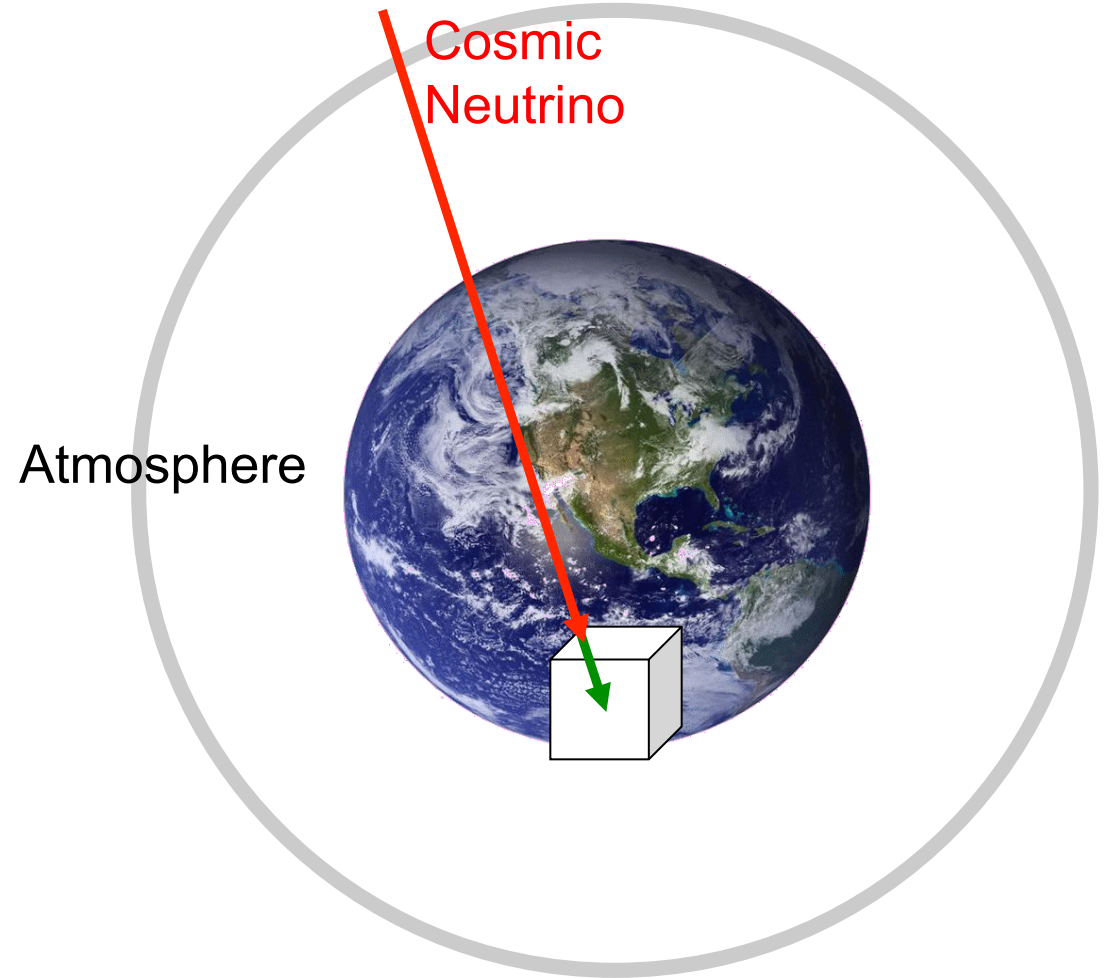
Tau neutrino charged current interaction



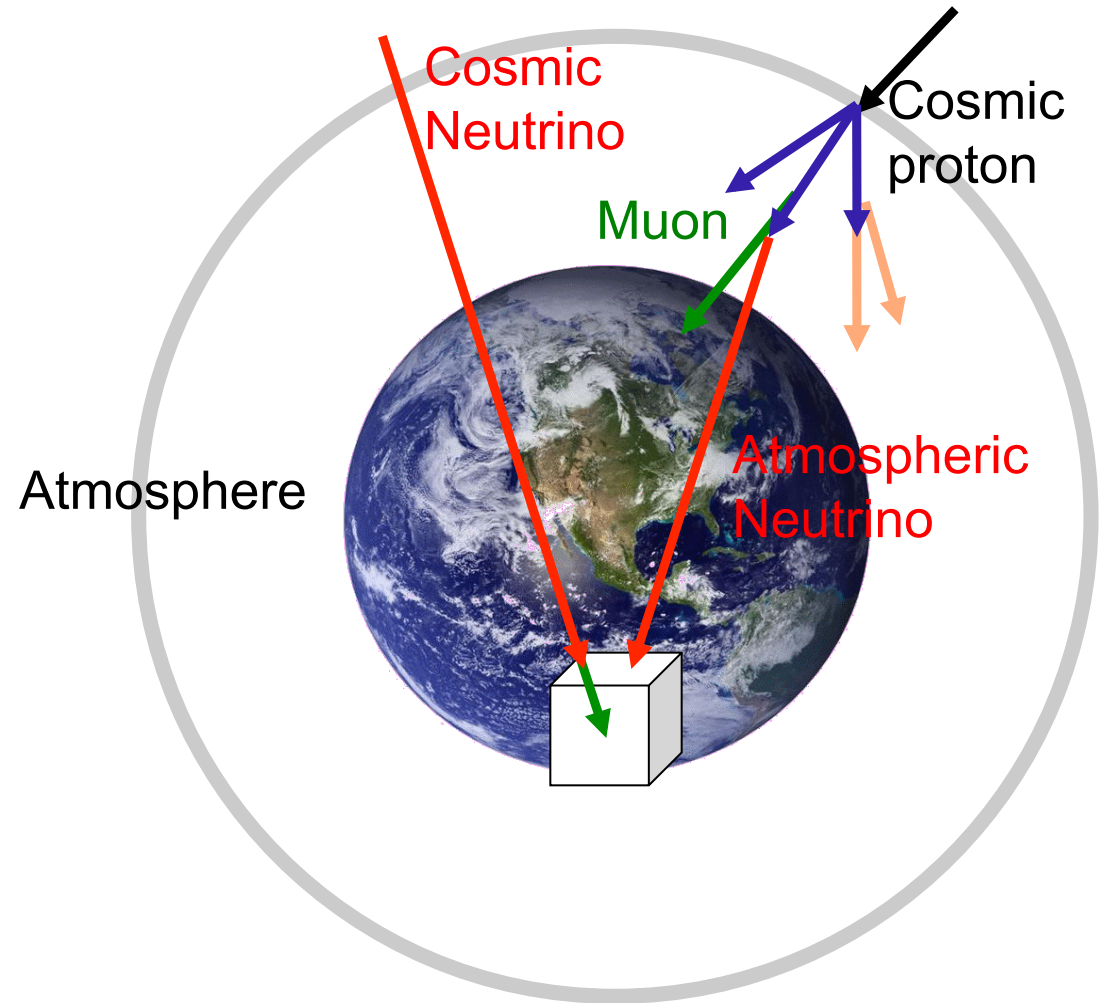
Only for very large energies the two showers can be separated (otherwise signature c)



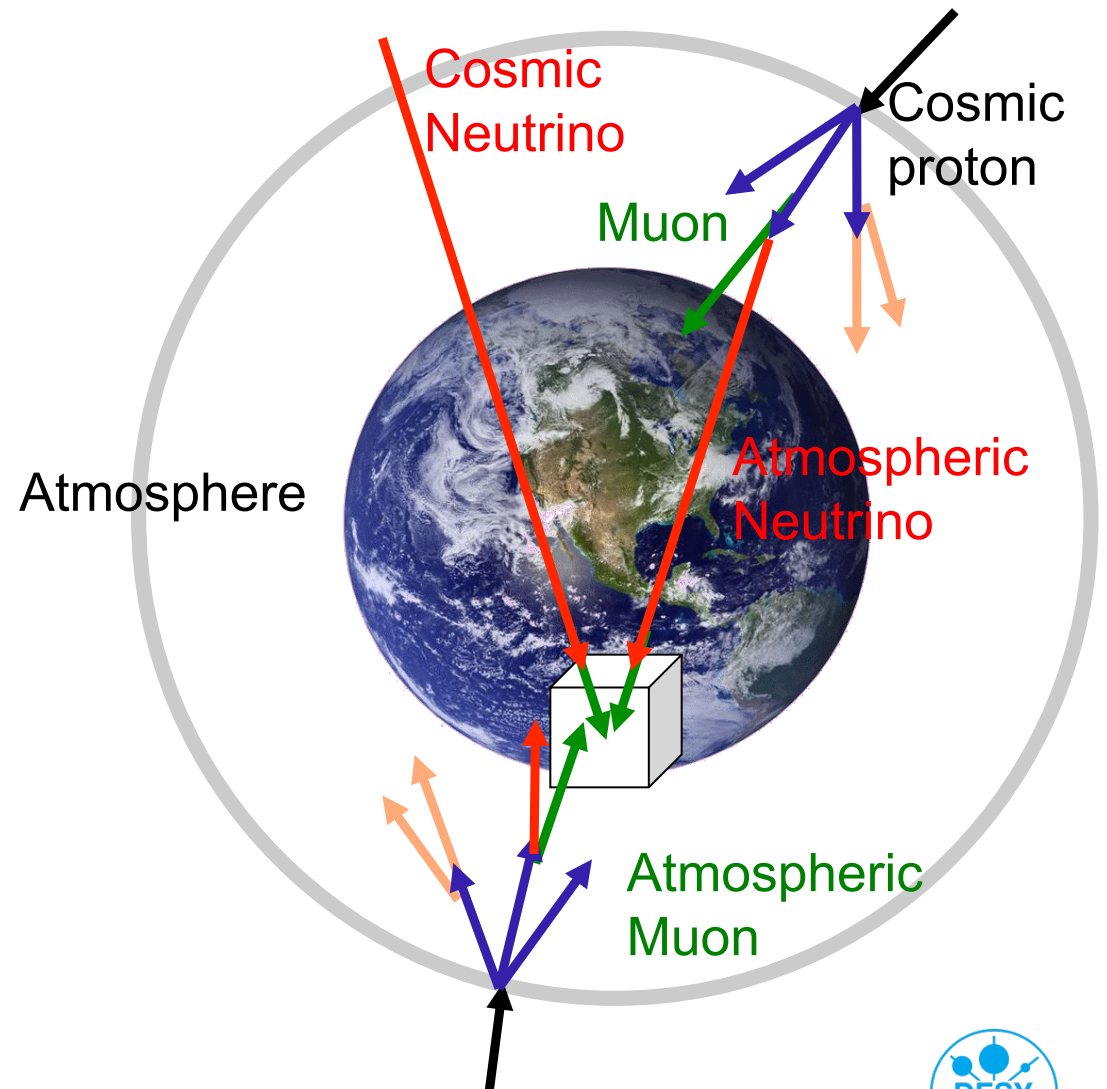
Background in Search for Cosmic Neutrinos



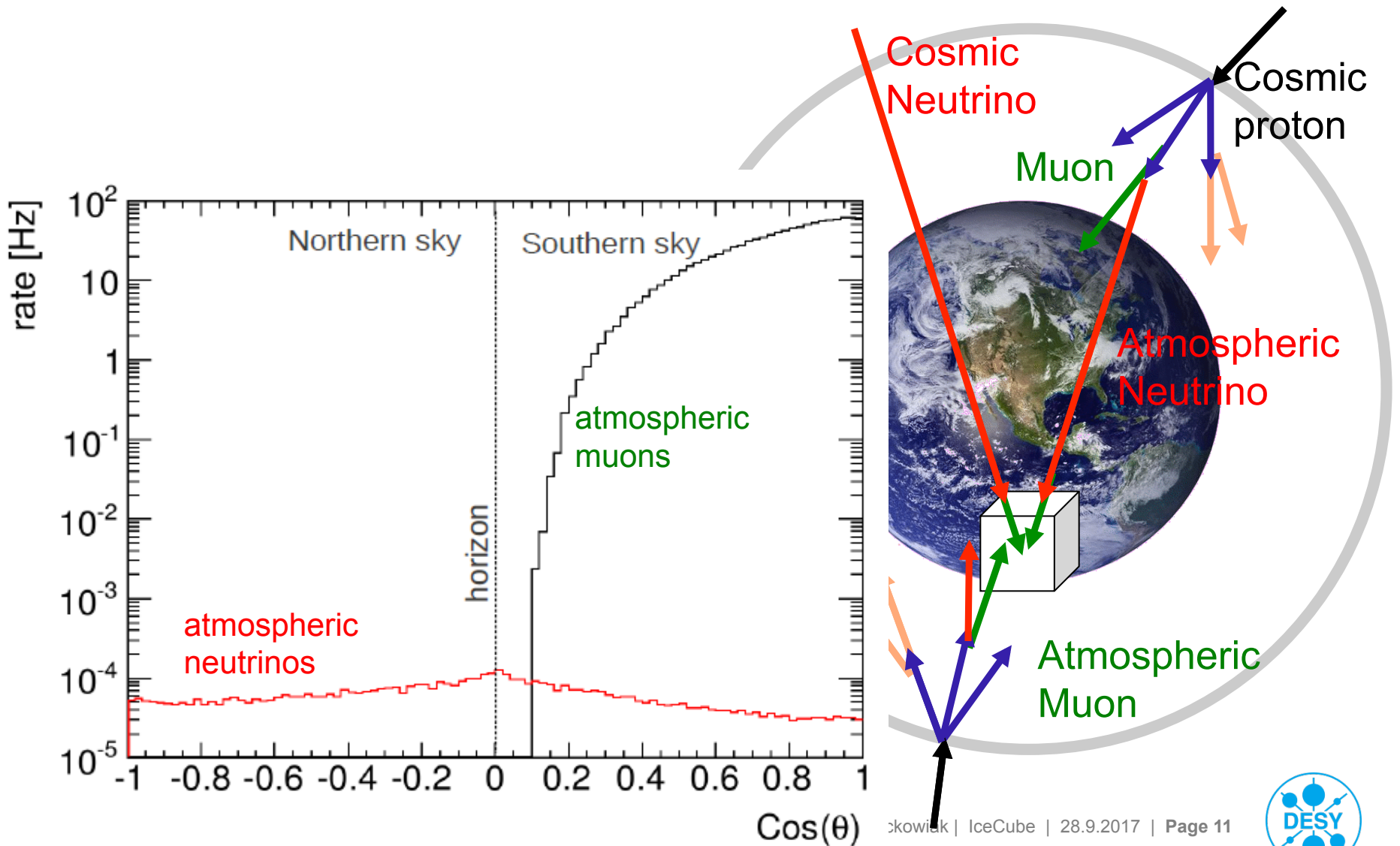
Background in Search for Cosmic Neutrinos



Background in Search for Cosmic Neutrinos

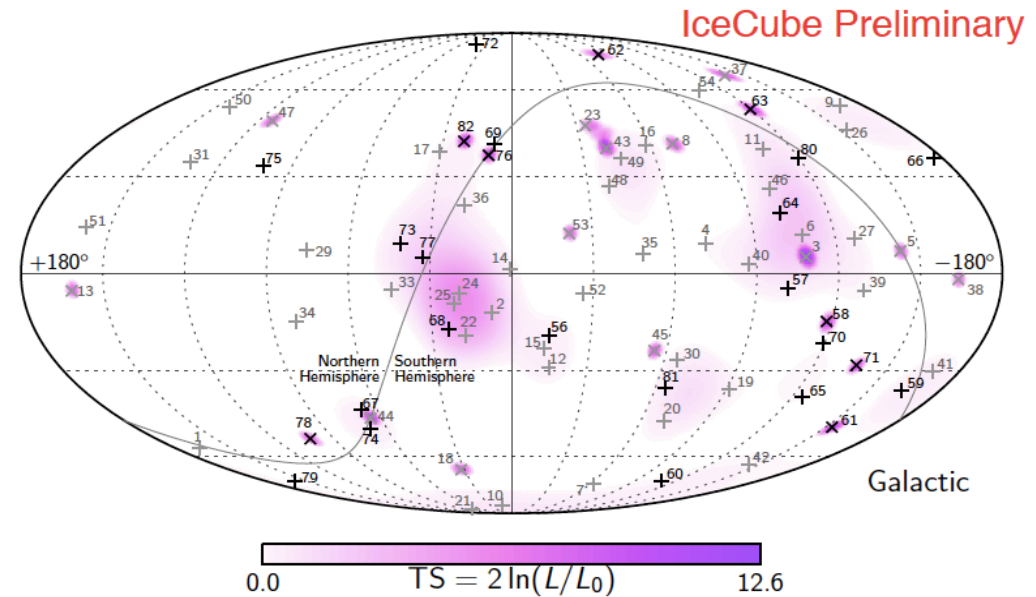
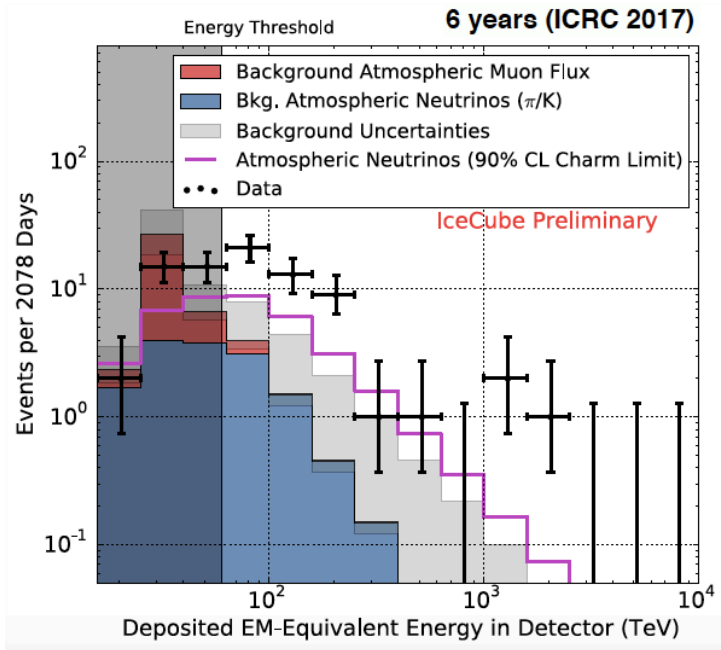


Background in Search for Cosmic Neutrinos



Discovery of High-Energy Astrophysical Neutrinos

physicsworld
**BREAKTHROUGH
OF THE YEAR
2013**



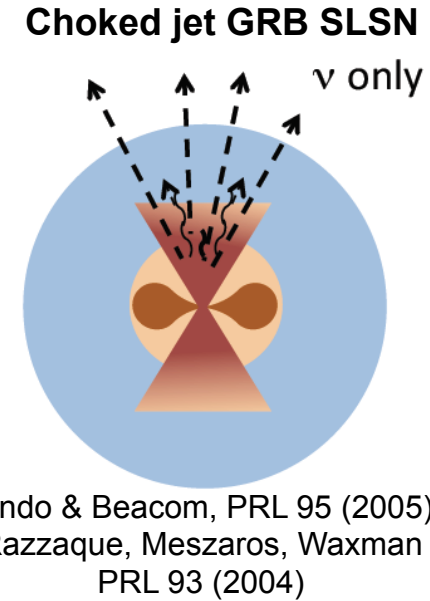
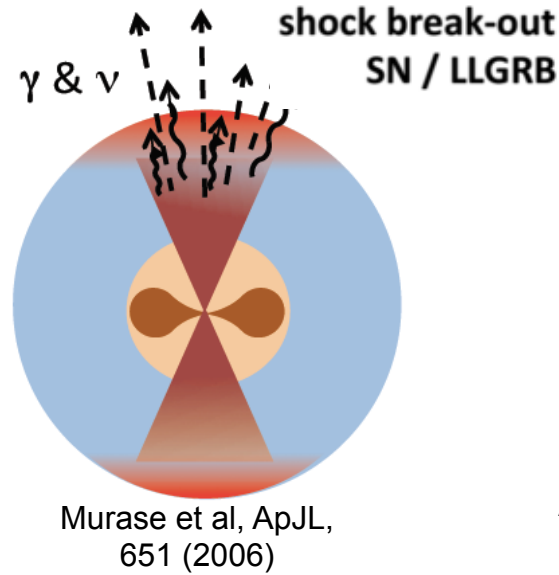
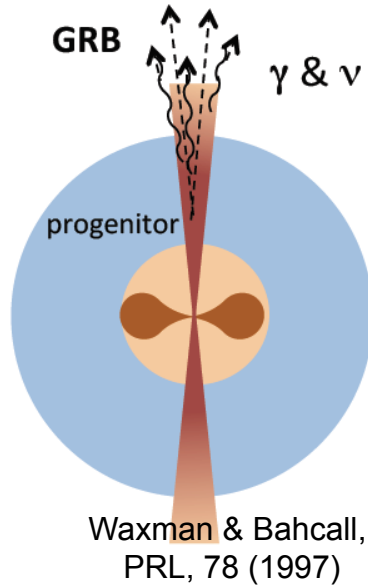
Origin still unknown

IceCube Coll. ICRC 2017
IceCube Coll., Science 342, 2013
PRL 113, 101101 (2014)

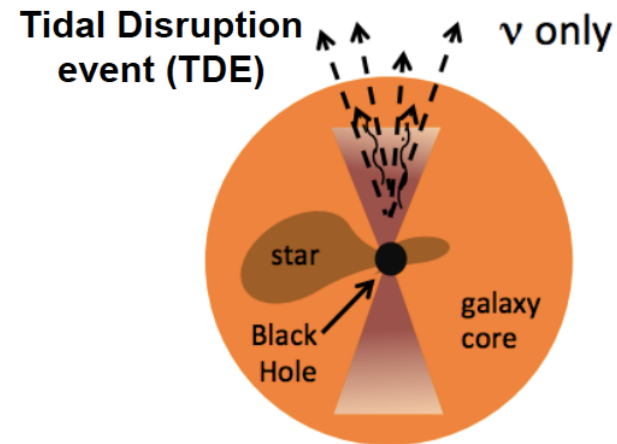
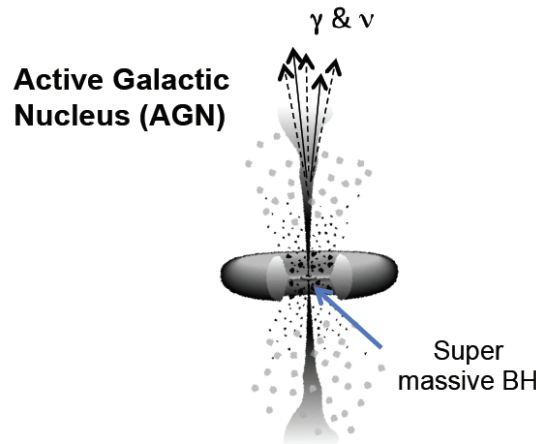


Transient Neutrino Sources

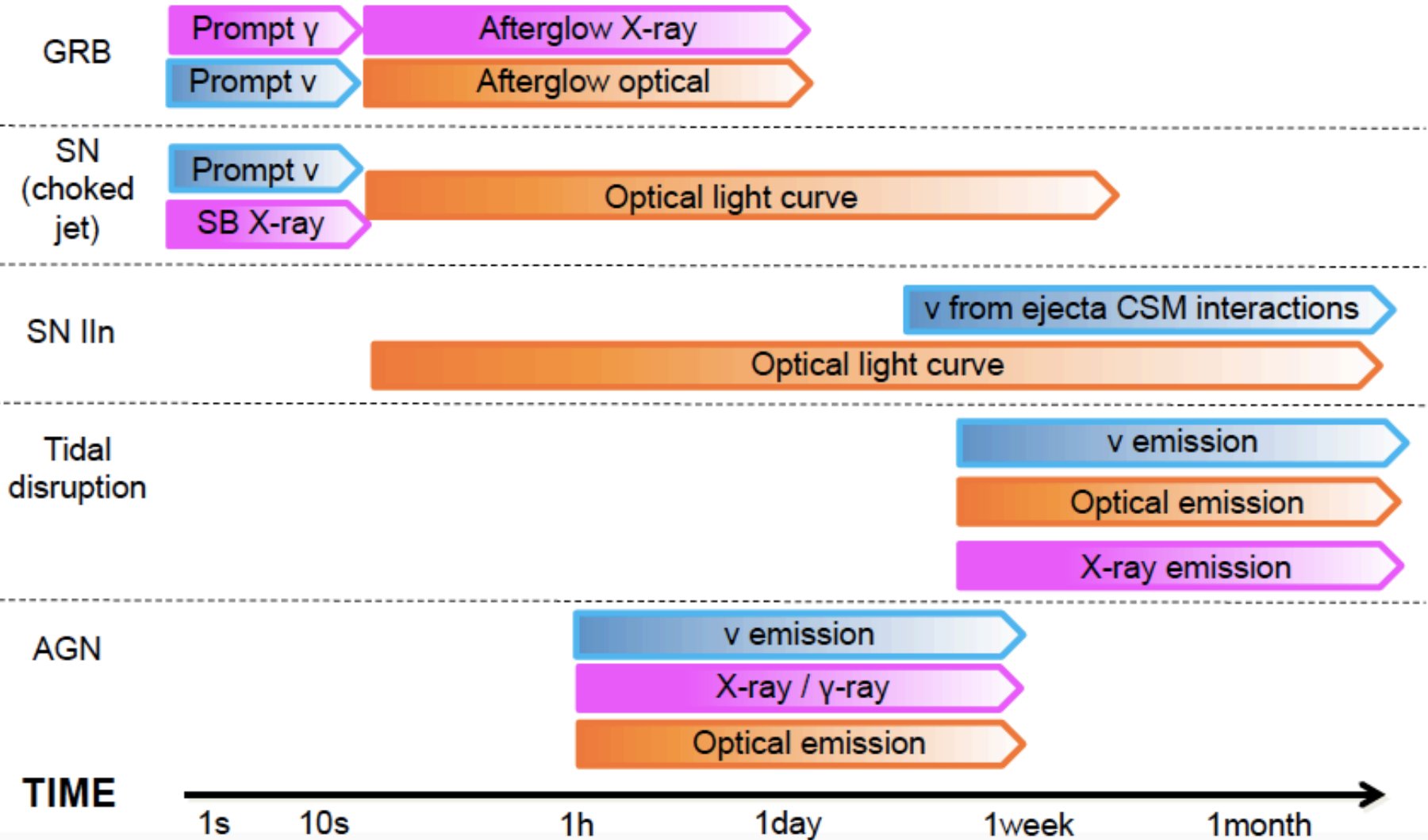
> Stellar collapses



> Galaxy core activity

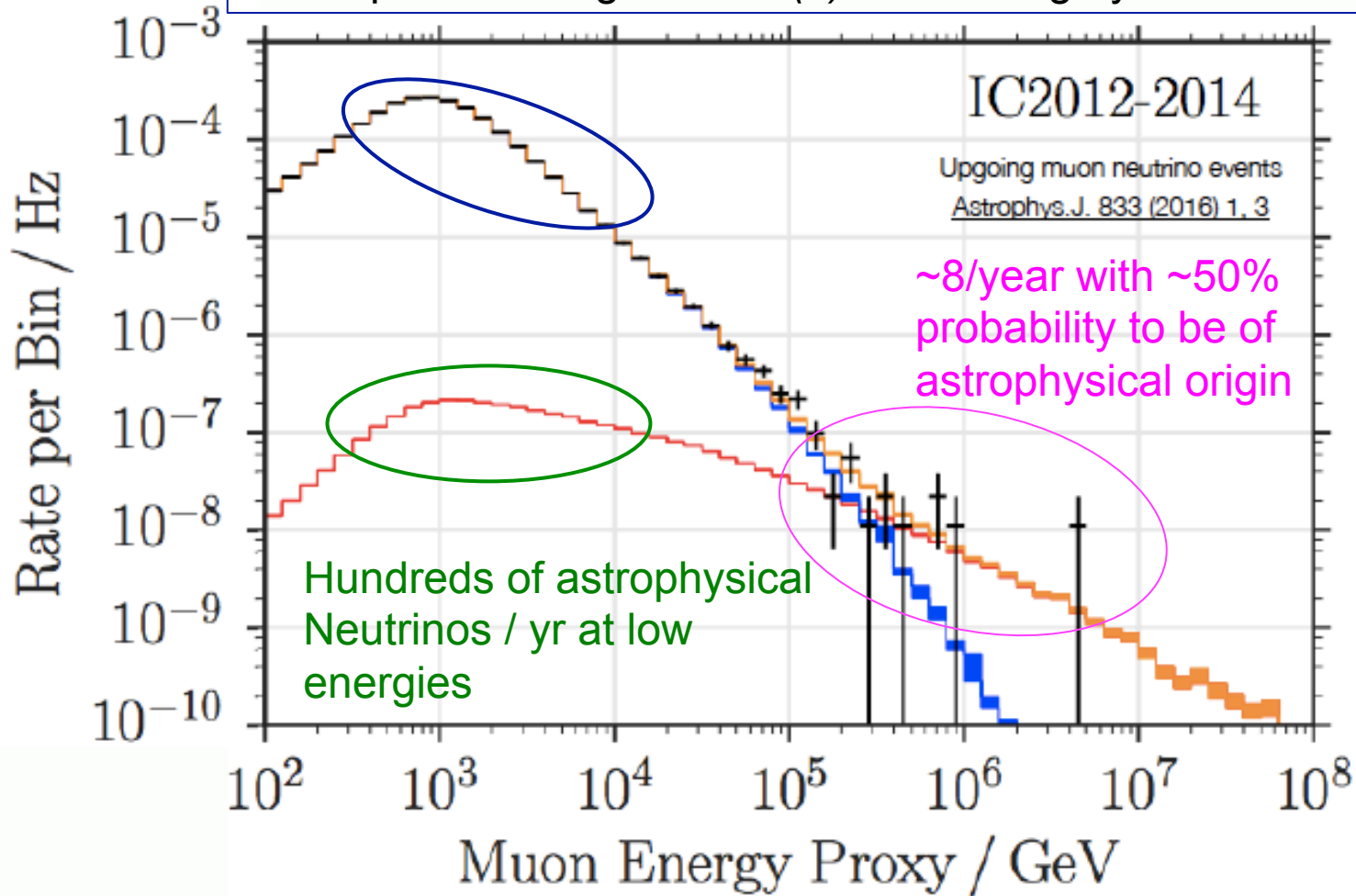


Counterpart of Transient / Variable Sources



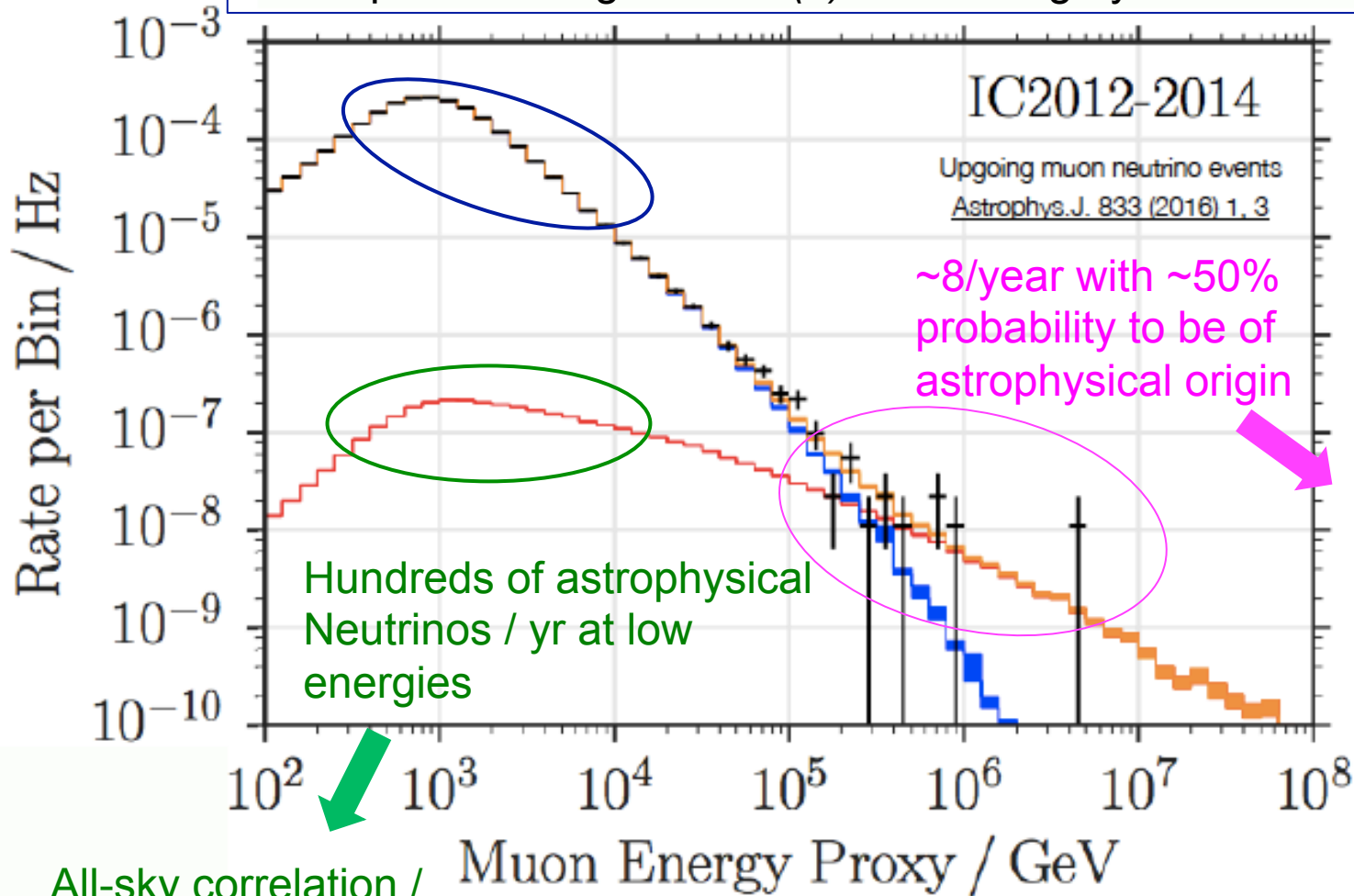
Astrophysical High-Energy Neutrinos

Atmospheric background: $O(1)$ events/deg²/year \sim 100/day



Astrophysical High-Energy Neutrinos

Atmospheric background: $O(1)$ events/deg²/year \sim 100/day



All-sky correlation / stacking program

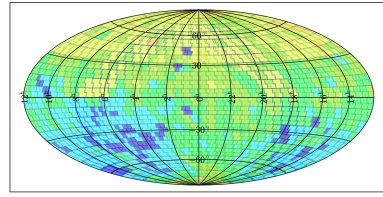


Two Approaches To Correlate Neutrinos

> All-sky correlation / stacking

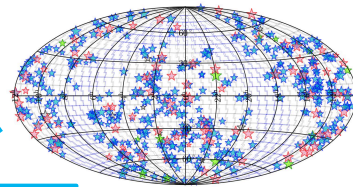


telescope scans
entire sky

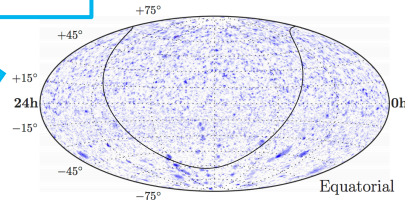


0 39 79 119 158 198 238 277 317 357 397
Times Observed

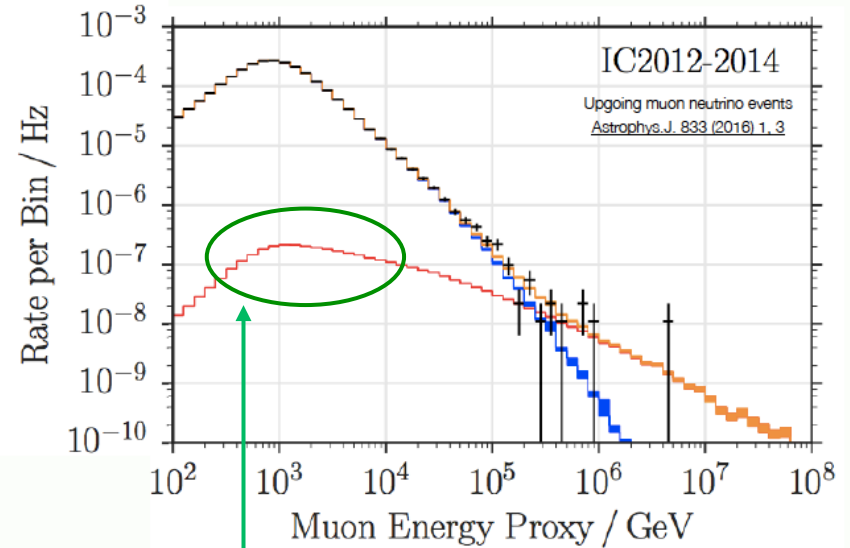
many transients found
and identified



Cross-correlate neutrinos with
transients → search for statistically
significant excess of transients from
neutrino directions



IceCube detects ~100
neutrinos per day



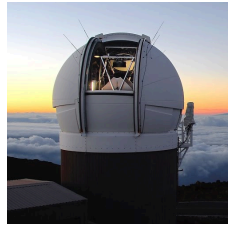
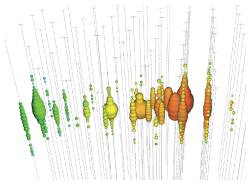
Hundreds of astrophysical
Neutrinos / yr at low energies



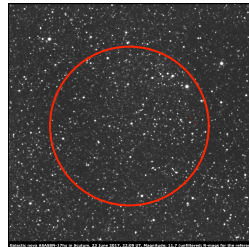
Two Approaches To Correlate Neutrinos

> Target of Opportunity (ToO)

neutrino arrives



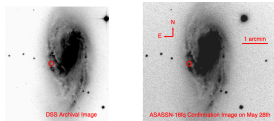
telescope observes
neutrino error circle



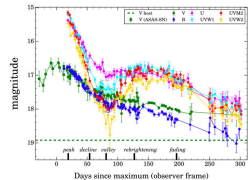
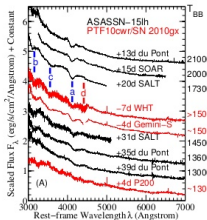
calculate p-value
(how significant is
detection?)



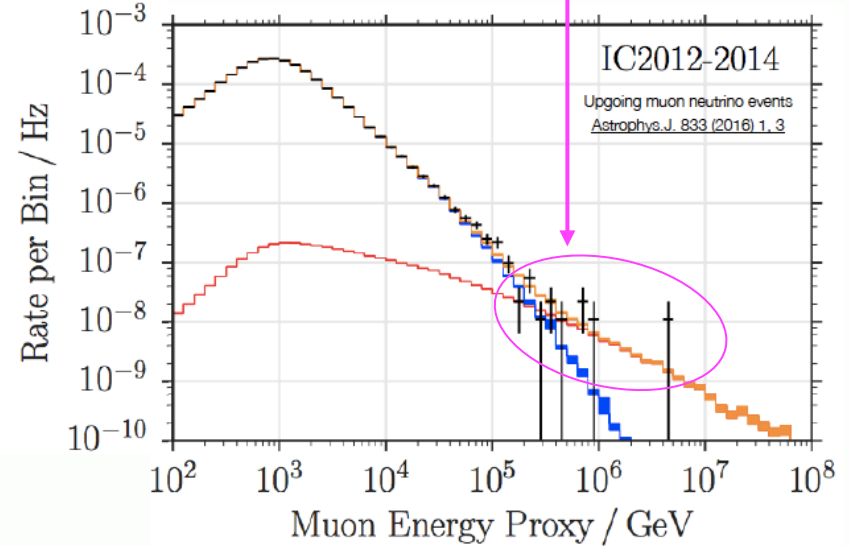
discovery of
transient



identification
of transient



~8/year with ~50%
probability to be of
astrophysical origin



Clusters

- > Several events from same direction in given time window → suppress isotropic atmospheric background
- > Optical follow-up stream (OFU)
- > Gamma-ray follow-up stream (GFU)

GFU online stream used by OFU and GFU:

- ~2 events / 5 min
- Well-reconstructed track-like events
- atm. neutrinos in Northern Sky, muons in Southern Sky

High-energy events

- > Single high-energy events → suppress atmospheric events which follow a softer energy spectrum
- > High Energy Starting Events (HESE)
- > Extremely High Energy Events (EHE)

IceCube Optical Follow-up Program (OFU)

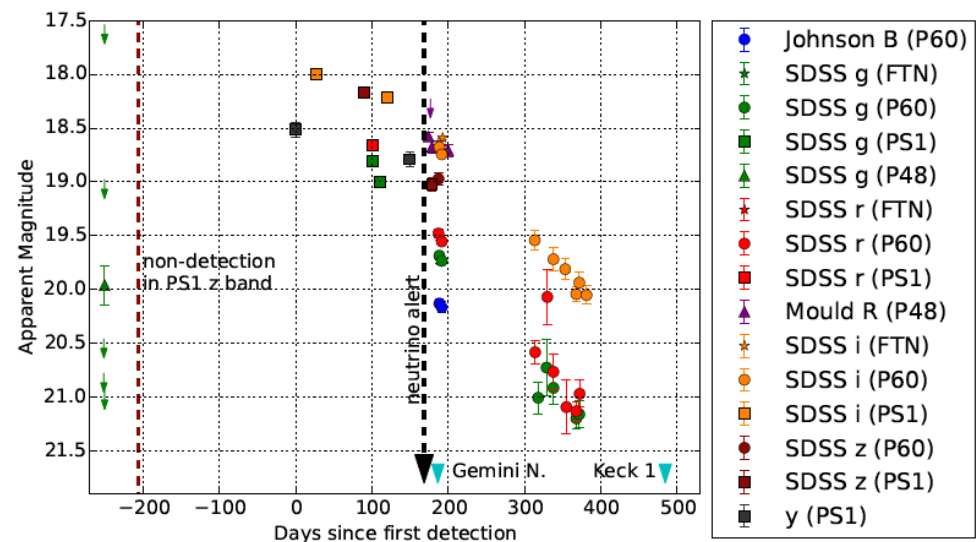
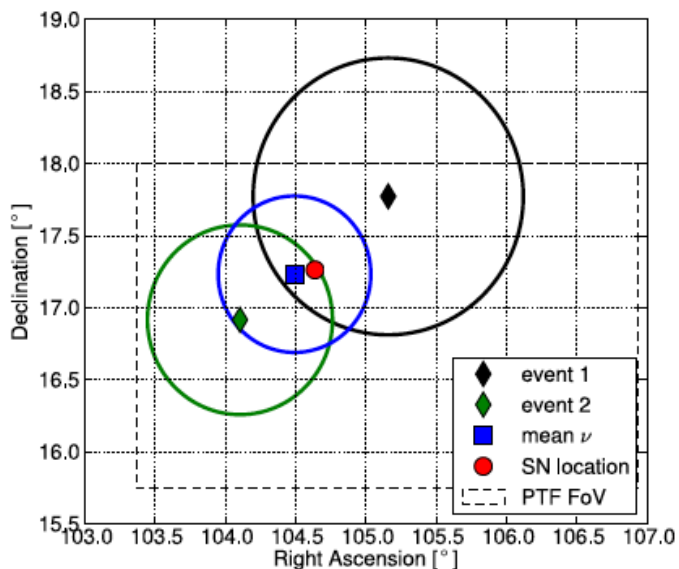
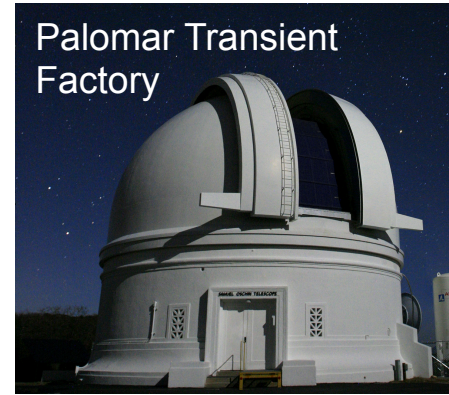
- > GFU event selection, Northern sky only
- > Clusters of ≥ 2 neutrinos
 - From the same direction ($\Delta\psi \leq 3.5^\circ$)
 - Within 100 seconds ($\Delta T \leq 100$ sec)
 - Likelihood term selects most significant doublets
- > Forwarded as private GCN via AMON to
 - Optical telescopes (PTF, MASTERS, ASAS-SN) ~ 6 / year
 - X-ray satellite (Swift-XRT) ~ 2 / year

**Aiming for short transient such as
GRBs or choked-jet supernovae**



IceCube Optical Follow-up Program: Supernova Detection

- 2 neutrinos, 1.6 sec apart (most significant doublet)
- PTF12csy, a very bright supernova type II_n at 300 Mpc
- Chance probability 1.6%
- Supernova 150 days old at time of neutrino detection

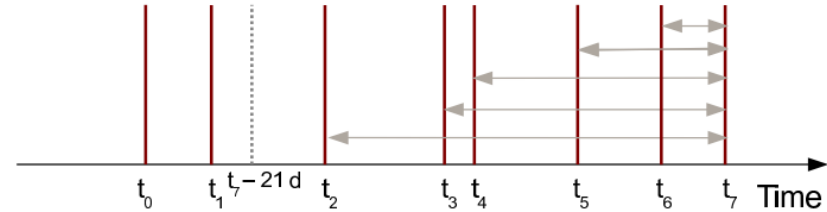


Gamma-Ray Follow-up (GFU)

> GFU event selection, all-sky

> Clusters from predefined source list

- Bright, hard and variable GeV γ -ray sources
- 180 sources: mostly blazars
- Clusters on all time scales up to 3 weeks
- p-value calculated for clusters, if threshold is reached alert is sent



> Forwarded as

- Email alert to MAGIC and VERITAS ~2/yr
- VOEvent to HESS in preparation
- Private GCN via AMON to Fermi, HAWC in preparation

Aiming for flaring gamma-ray sources such as blazars

Planned Extensions to GFU

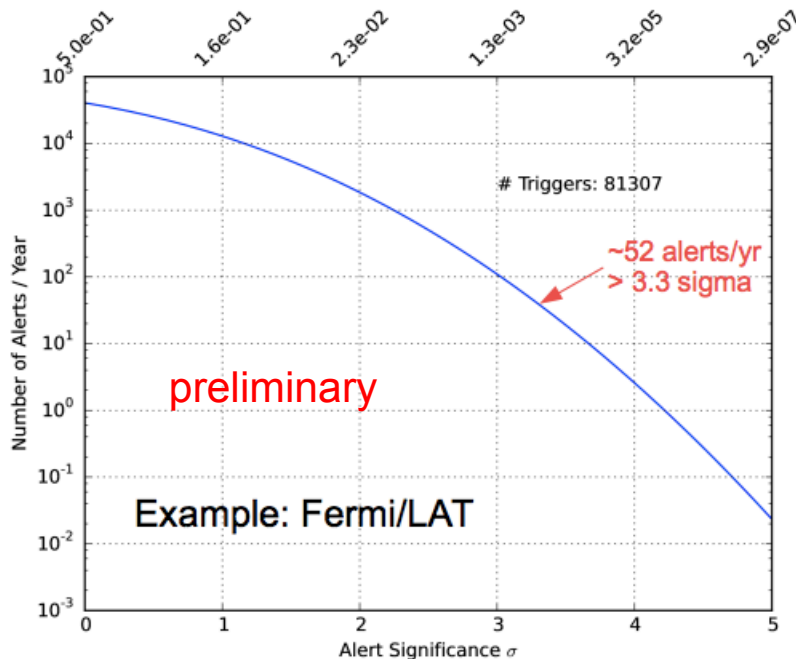
➤ Update GFU source list to target follow-up with Fermi/HAWC/HESS

➤ New source list criteria (preliminary, 575 sources)

- 3FGL: $z > 0$, var index > 77.42 (430 sources)
- 3FHL: $z > 0$, bayesian block variability > 1 (+20 sources)
- Plus additional FAVA sources (+125 sources)

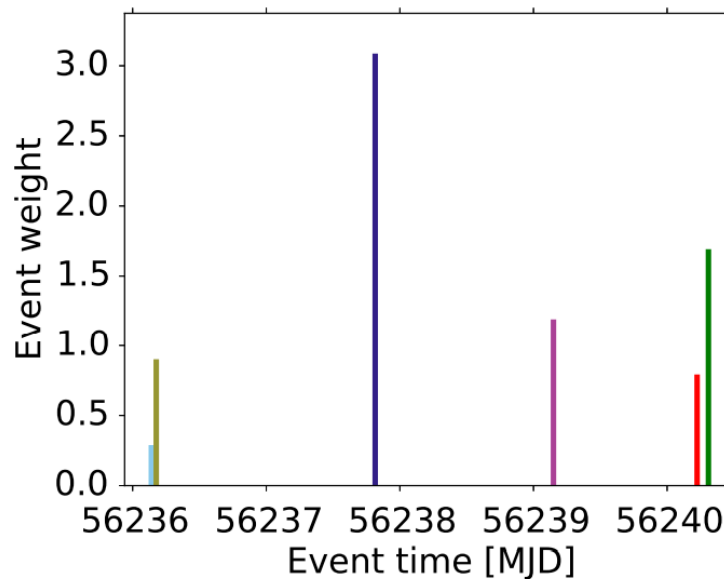
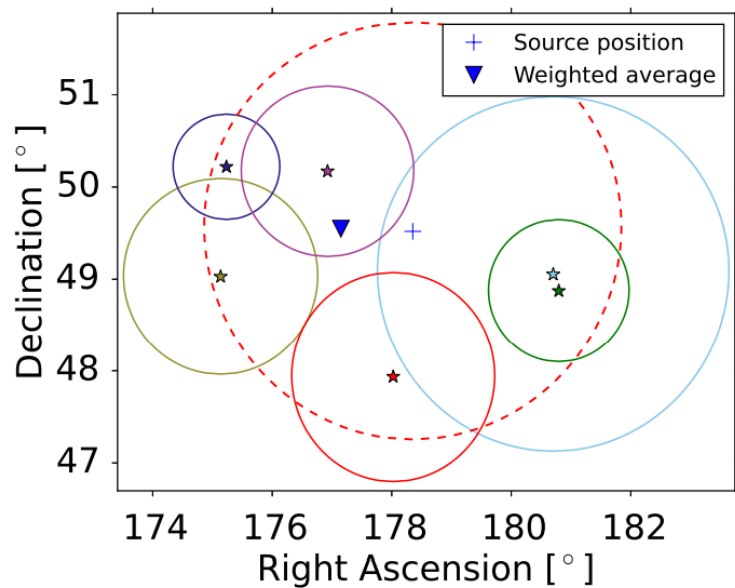
Fermi source list,
IACT source lists
are subsets +
variable TeV
emitters

➤ Implement an all-sky clustering algorithm



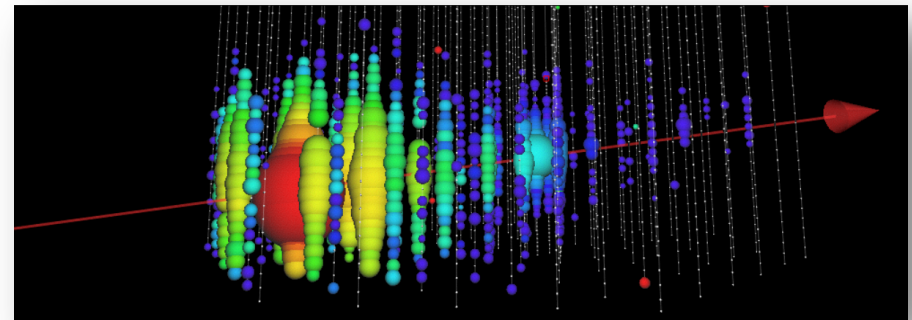
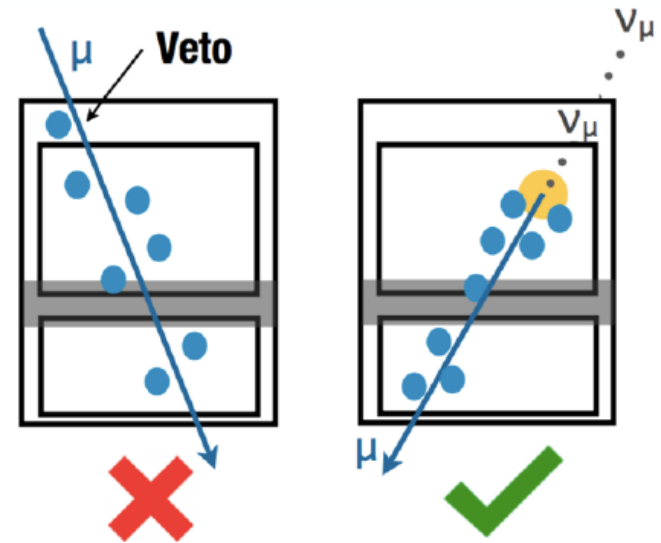
Real-time Search for Neutrinos and TeV flare Correlation

- **Most significant alert:** Nov. 9th 2012
- 6 events in 4.2 days, followed up by VERITAS, no counterpart found
- $\text{Log}_{10}(\text{p-value}) = -4.64$ (0.2% after trials correction)



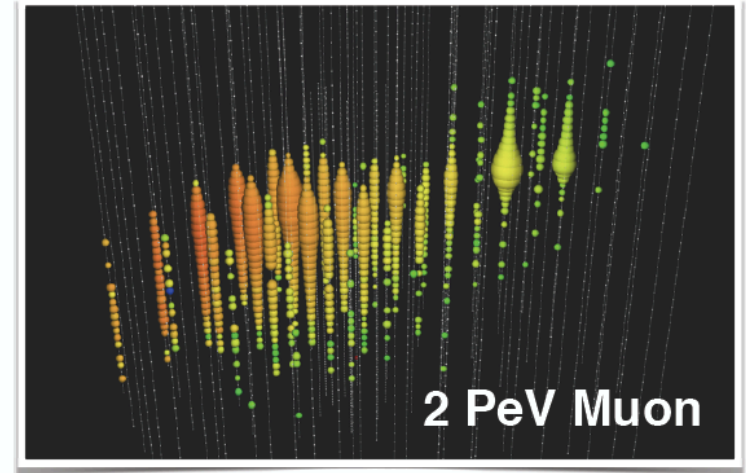
High-Energy Starting Events (HESE)

- > Veto against atmospheric muons by outer detector layer
- > Starting tracks with $Q > 6000$ pe
- > Sensitive to $E_\nu > 60$ TeV
- > Expensive reconstruction (\rightarrow revised alerts after few h)
- > 4 events / year (1 signal/y)
- > Angular resolution:
 - > 0.4 deg (50% confidence)
 - ~ 1.4 deg (90% confidence)



Extreme High-Energy Events (EHE)

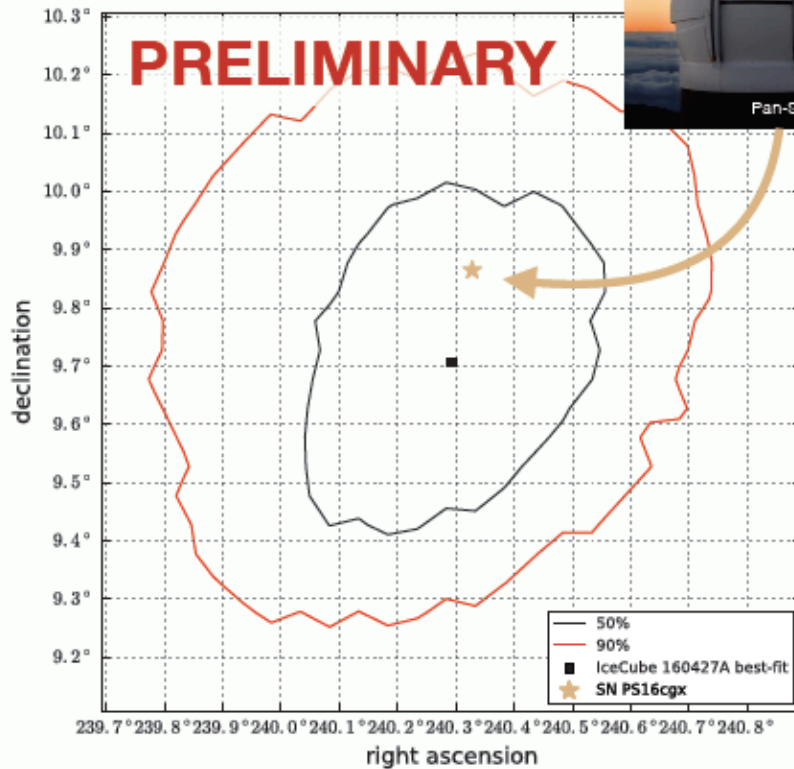
- Through-going muon tracks
- Combination of charge and zenith cut
- Sensitive to $E_\nu > 500 \text{ TeV}$
- 4 events / year (2 signal/y)
- Angular resolution
 - $> 0.2 \text{ deg}$ (50% confidence)
 - $\sim 0.8 \text{ deg}$ (90% confidence)



Supernova found by Pan-STARRS in public IC Alert

IceCube, ICRC 2017

Pan-STARRS followed up IceCube HESE alert on 2016-04-27 and found a recent supernova at $z=0.3$:



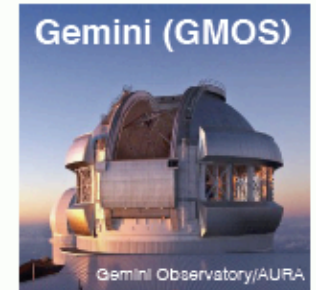
Light curve consistent with explosion days before neutrino alert



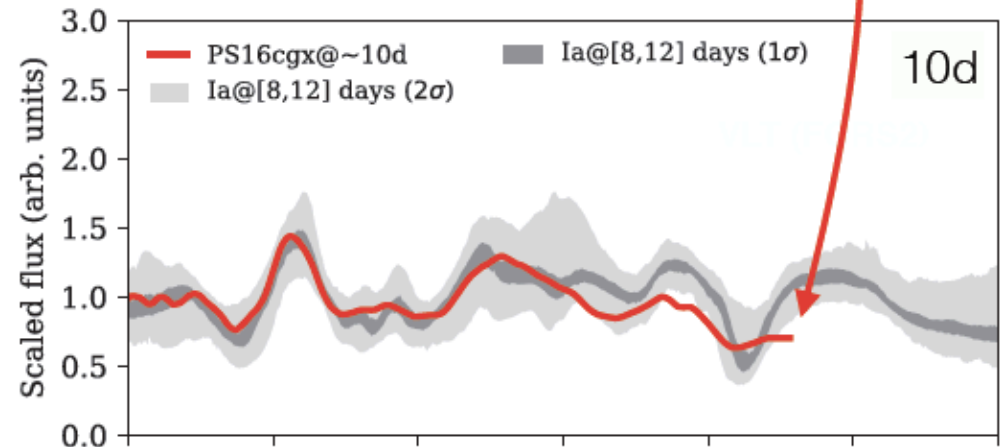
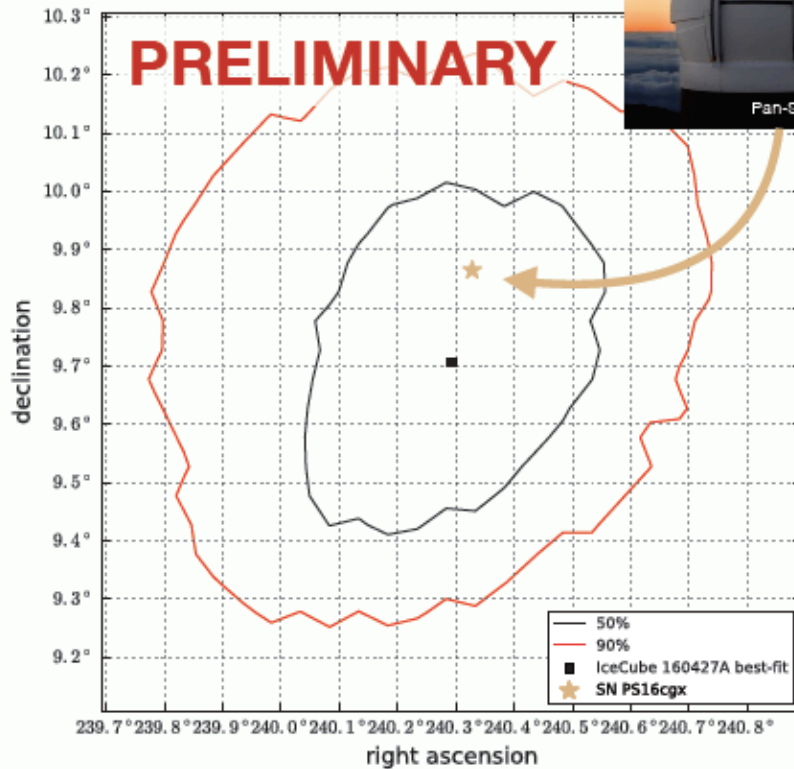
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Optical spectroscopy taken 10, 20 days post peak



Features atypical for SNIa but not sufficient to exclude

Light curve consistent with explosion days before neutrino alert



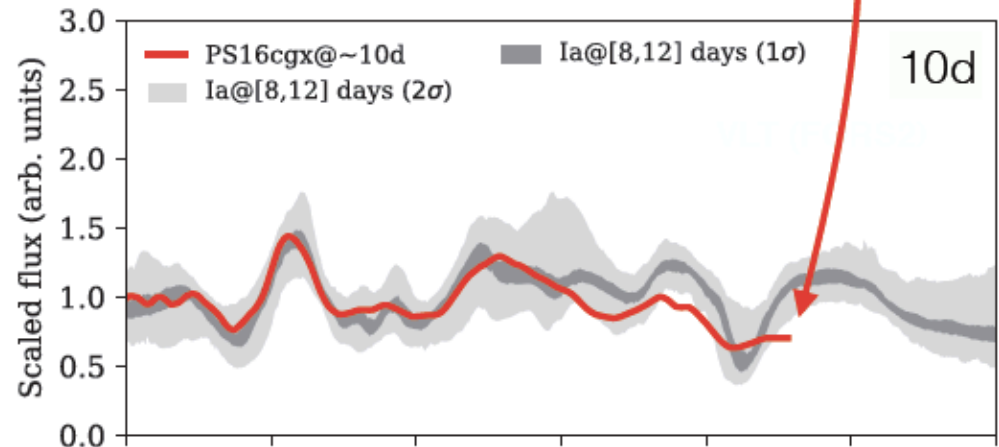
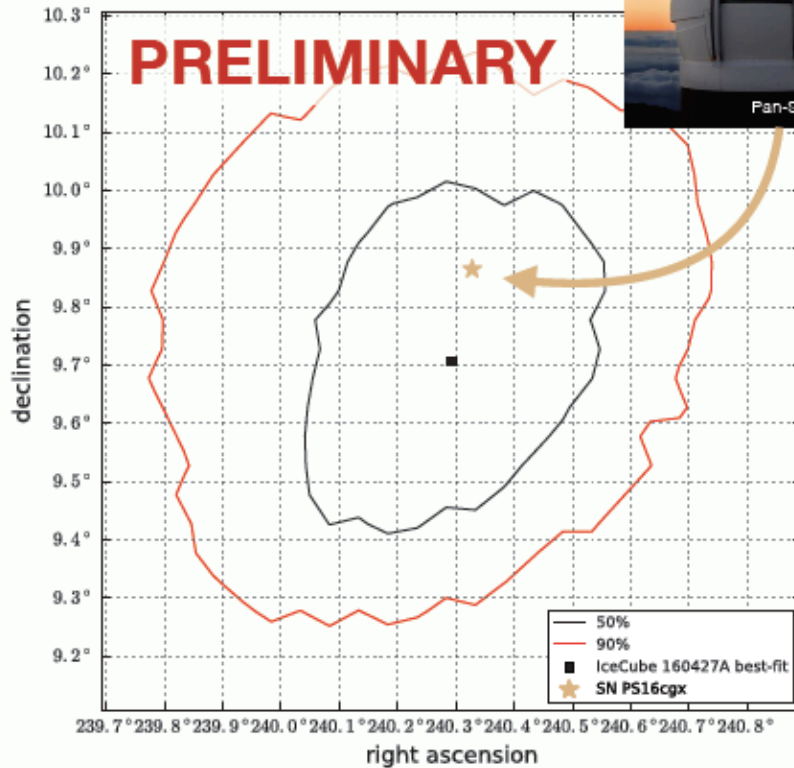
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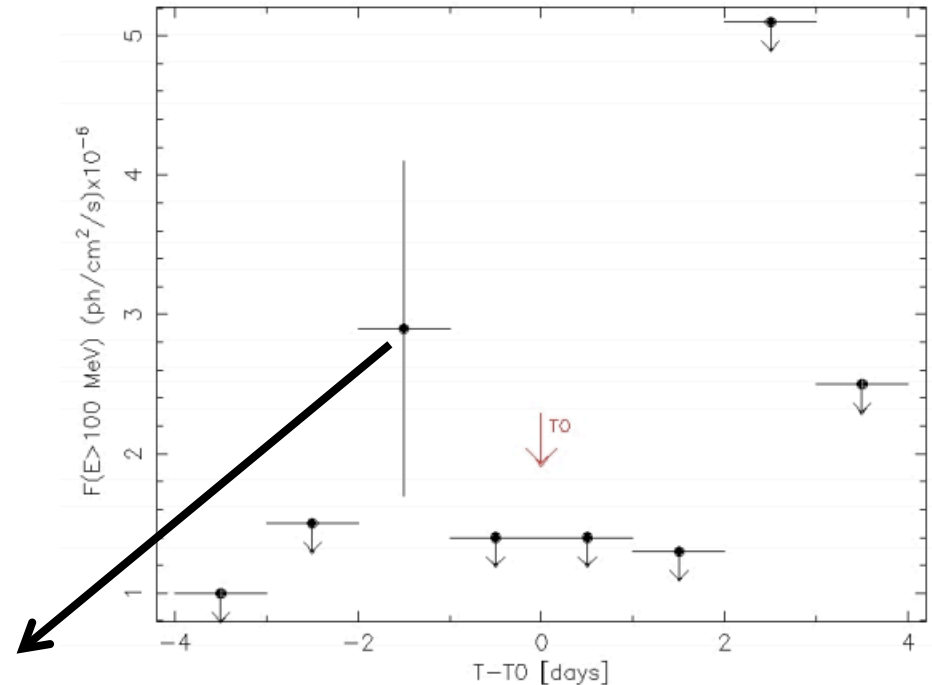
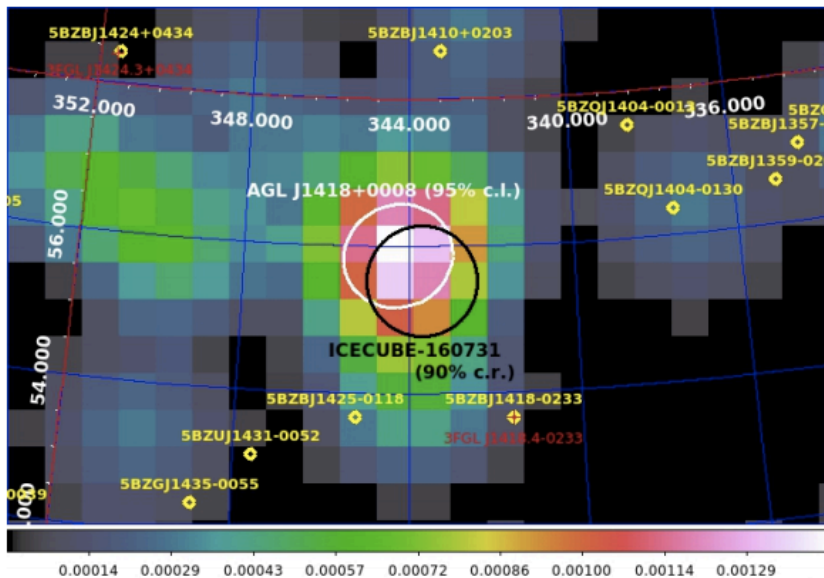
Chance probability { if Ic (associated with GRBs): $<1\%$
if Ia (no HE neutrinos exp.): $<10\%$

Gamma-ray Counterpart to ICECUBE-160731

➤ AGILE gamma-ray signal:

- No prompt emission in +/-1000 sec
- Gamma-ray signal 2 days before the neutrino event (~4 σ post-trial significance)
- Possibly HBL blazar

AGILE intensity map (>100MeV)



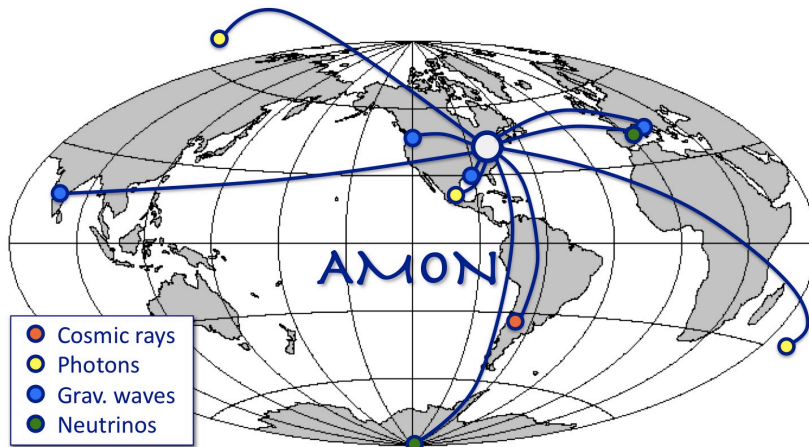
F. Lucarelli et al, ApJ 846, Vol. 2, p. 121 (2017)



Comparison of Streams

Stream	Distribution	Time scale	Median Angular Resolution (90%)	Rate	Signal Fraction
OFU	Private GCN	100 sec	0.5 deg (1.5 deg)	2-6 / yr	0-30%*
GFU	Email (GCN)	< 21 days	predefined source position	2 / yr	
HESE	Public GCN	---	>0.4 deg (~1.3 deg)	4 / yr	25%
EHE	Public GCN	---	>0.2 deg (~0.8 deg)	4 / yr	50%

*depends on assumed source density



talk by Azadeh

Public and some private alerts are sent through GCN via AMON

Median latency 33 sec

IceCube Fast Response Analysis – What did IceCube see?

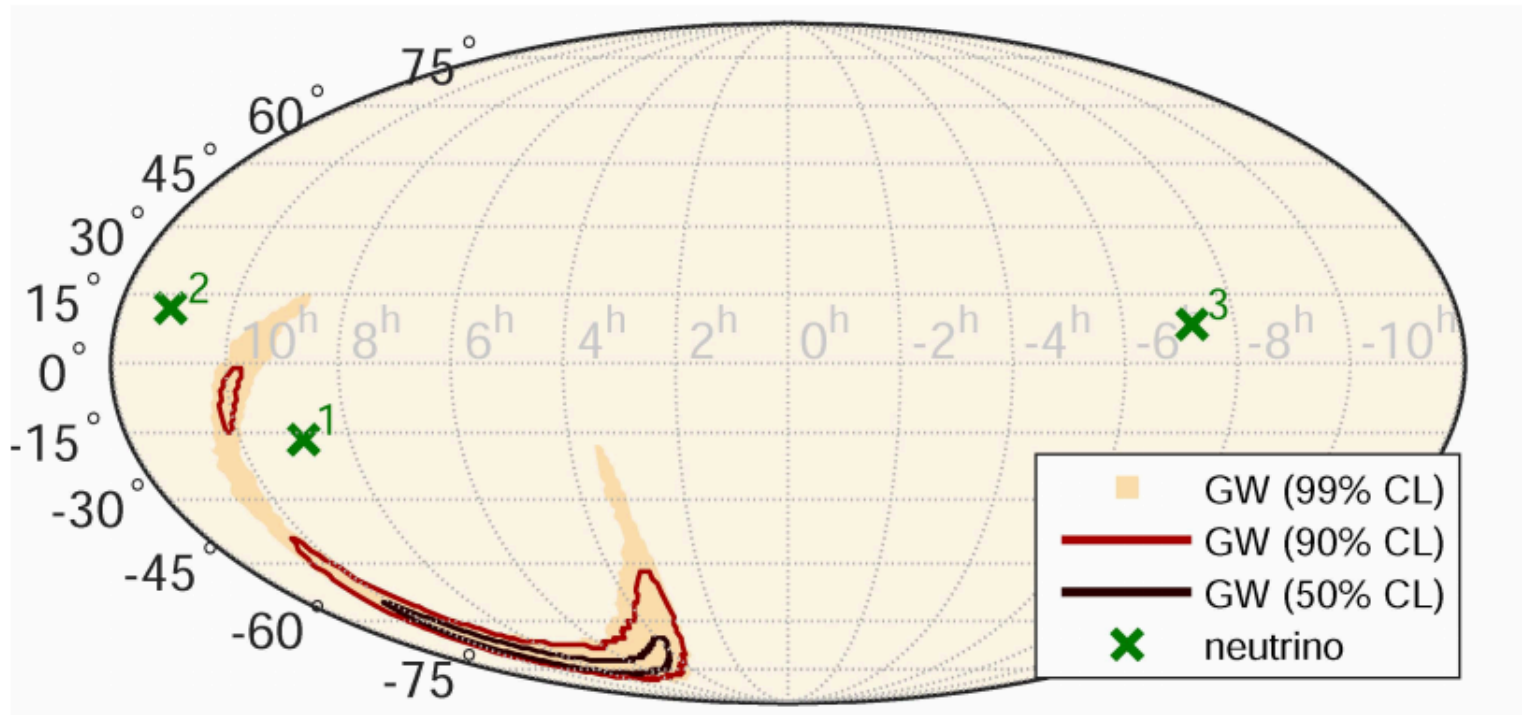
- Based on GFU online stream
- Search for neutrino emission in time window <1 week
- Approval by IceCube Realtime Oversight Committee (ROC)
- Externally triggered

Source	Start Time [UTC]	Duration [D:H:M:S]	RA	Dec	Extension
PS16cgx	2016-04-26 15:59:12	1:03:46:40	240.33°	+09.86°	0.0°
Cygnus X-3	2017-04-03 00:00:00	1:00:00:00	308.11°	+40.96°	0.0°
GRB 170405A	2017-04-05 18:35:49	0:00:20:02	219.83°	-25.24°	0.0°
AGL J0523+0646	2017-04-15 11:50:00	2:00:00:00	080.86°	+06.78°	0.6°
IceCube 170506A	2017-05-06 00:36:55	1:00:00:00	221.80°	-26.00°	1.0°
AT2017eaw	2017-05-10 12:00:00	3:00:00:00	308.68°	+60.19°	0.0°



Gravitational Waves (GW) and Neutrinos

Search for neutrinos from GW150914 in ANTARES and IceCube data
in +/-500 sec → no counterpart found



Neutrino could help to constrain direction and teach us about the GW source environment

Future Streams – Work in Progress

> Enhanced Starting Track Event Selection (ESTRES)

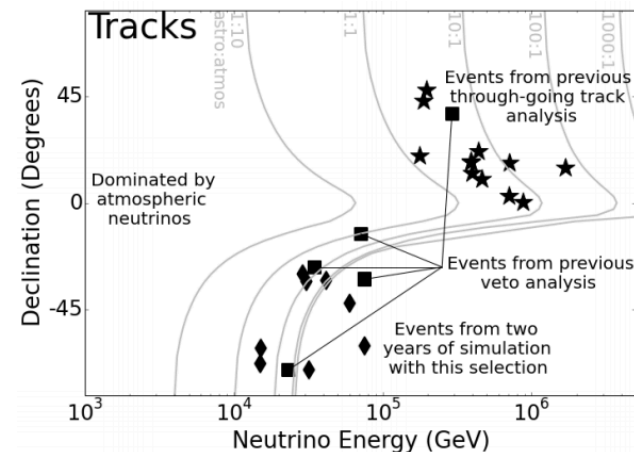
- Improved veto technique compared to HESE
- Lower energy threshold to ~10 TeV

> Through-going muon stream

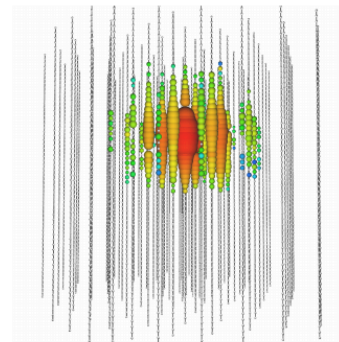
- Like EHE, but with lower energy threshold

> Realtime Cascade stream

- Bad angular resolution 10-20 deg
- High signal purity
- Interesting for search for short transients



K. Jero for the IceCube Coll.,
Neutrino 2016



Possible Future Multi-Messenger Programs

- > Optical ToO with PanSTARRS / DES
 - Supernovae, GRBs
 - TDEs
 - AGN
- > All-sky correlation with ASAS-SN and ZTF
- > Gamma-ray ToO with CTA
 - AGN flares
 - GRBs
- > Time-depend analysis with CTA light curves
 - AGN
- > SKA / eROSITA
 - AGN cores
 - GRBs



Summary

- Neutrinos are unique messengers from the high-energy universe
 - Diffuse flux was discovered
 - Sources still unknown
 - Promising source classes are transient
- IceCube has an established realtime program with several public and private streams and a fast response pipeline
- MoU with several partner observatories in place
- Open for new collaborations!

