THE EHE EVENT 170922 AND PROSPECTS FROM THE ICECUBE NEUTRINO OBSERVATORY

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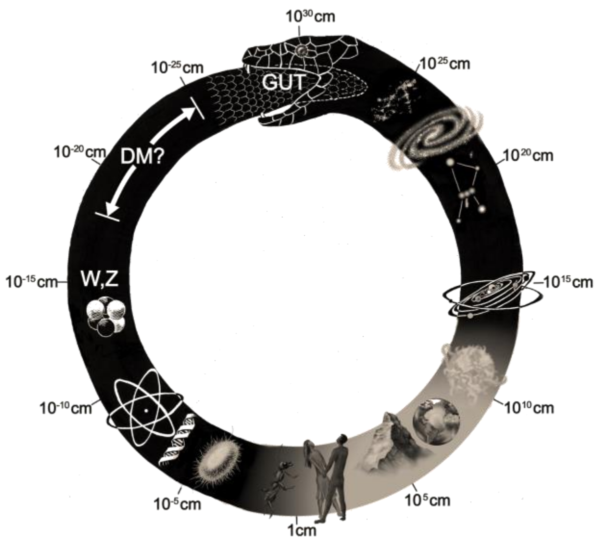
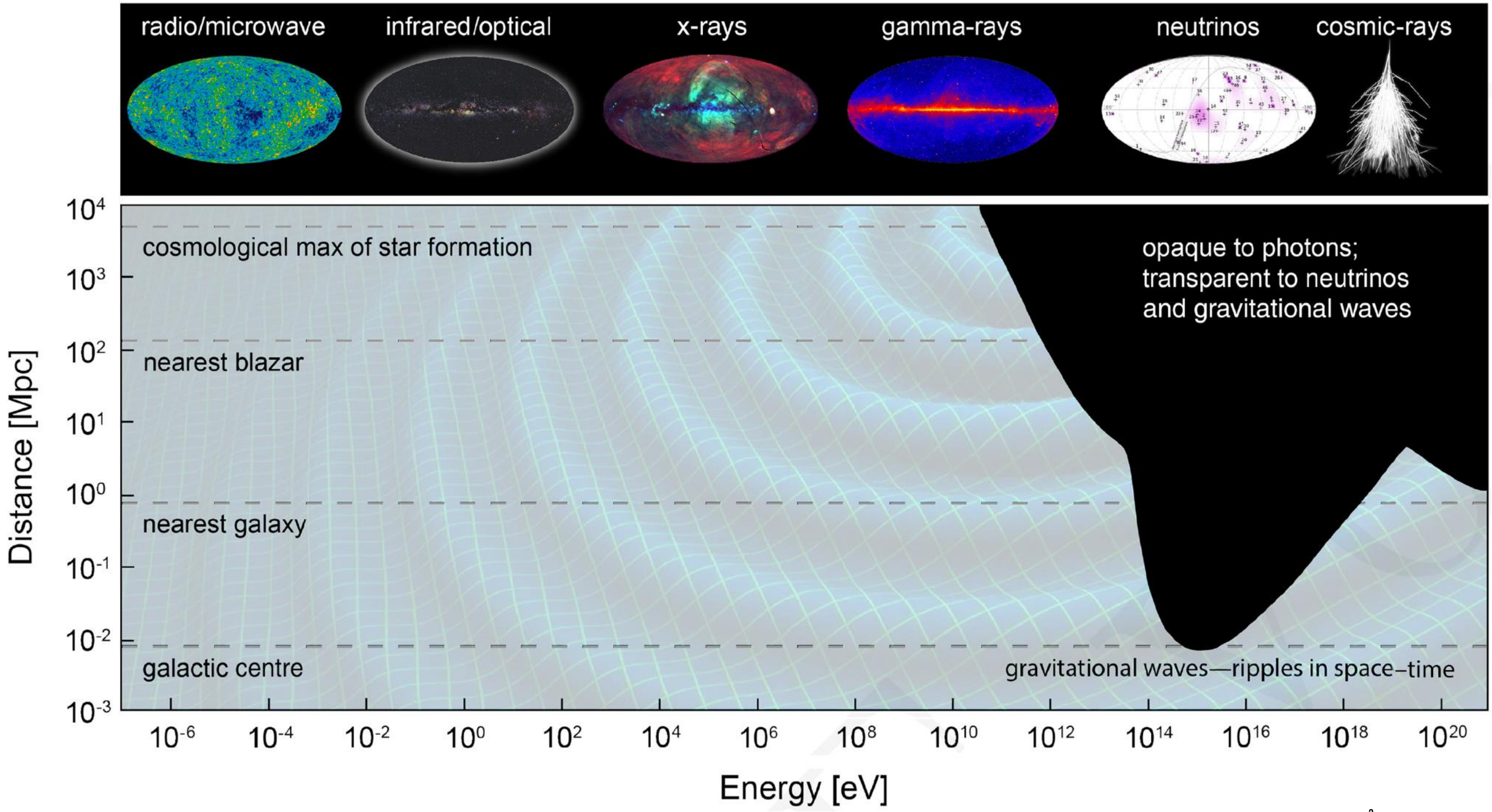
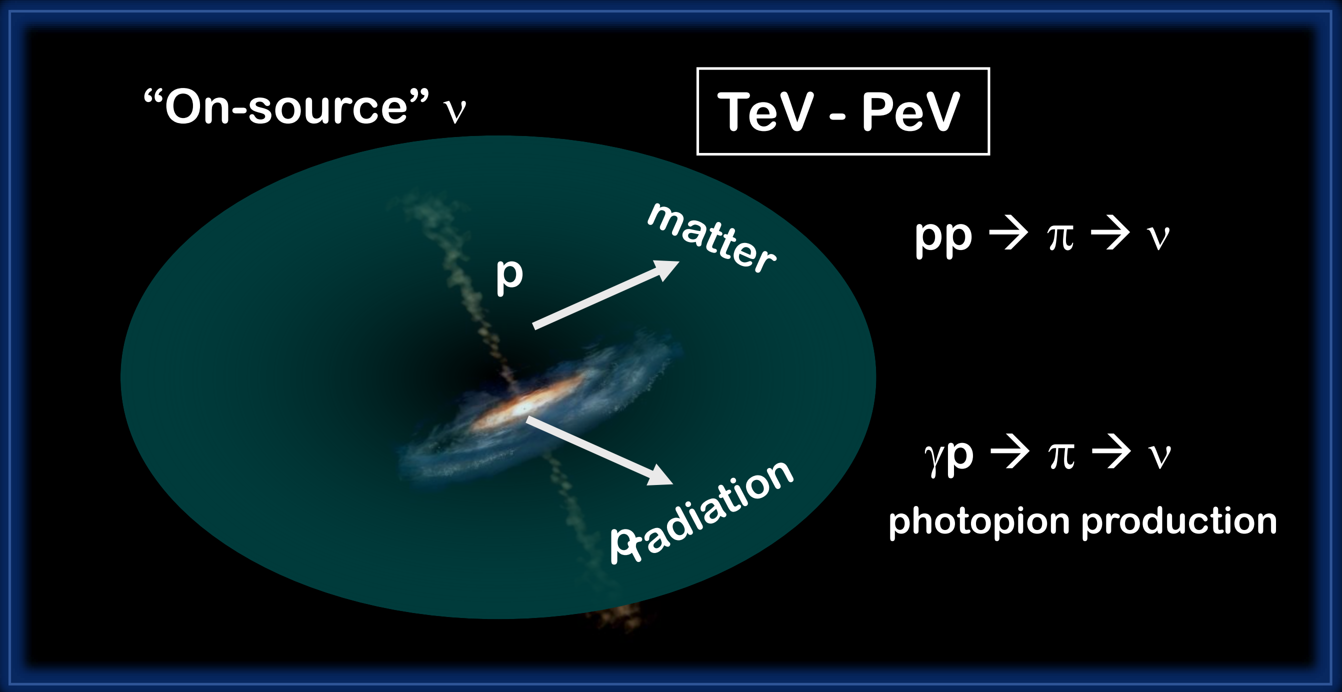
ニュートリノは極小の素粒子の世界と極大の宇宙を結ぶ掛け橋

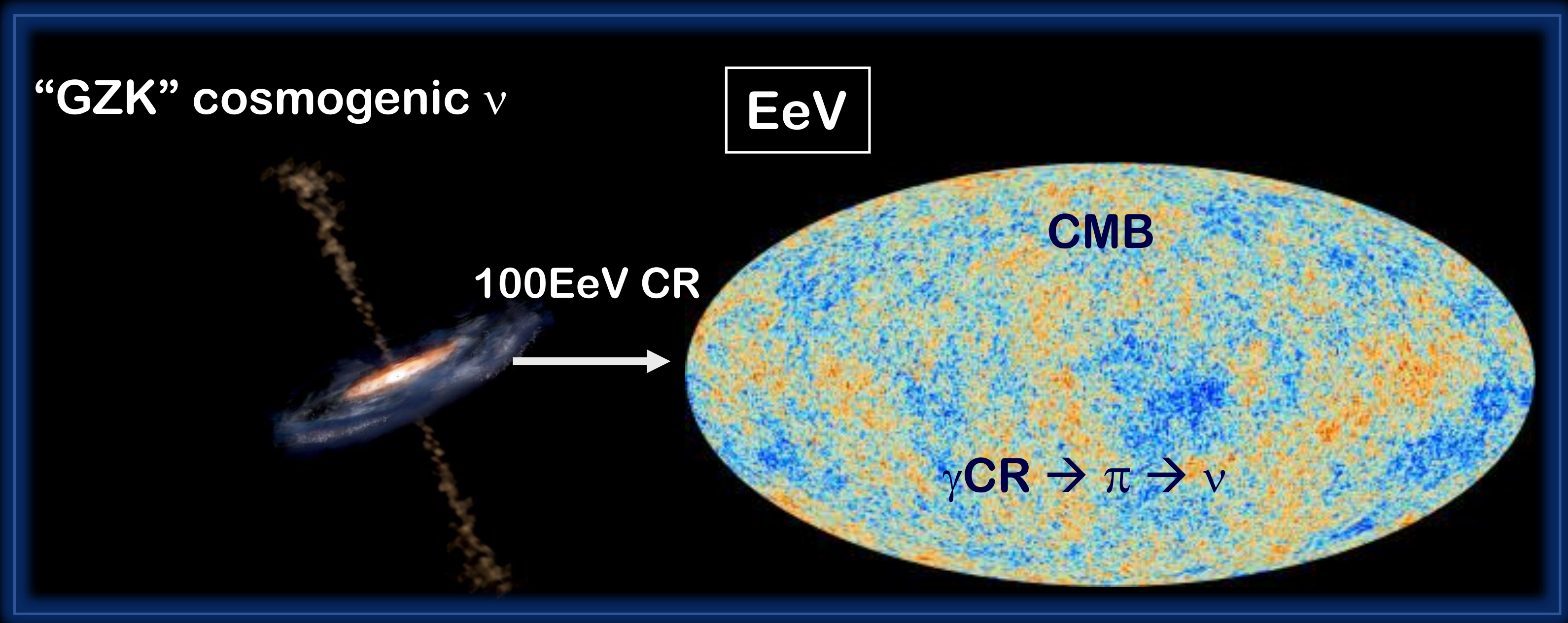


梶田 隆章


radio/microwave
infrared/optical
x-rays
gamma-rays
neutrinos
cosmic-rays
cosmological max of star formation
opaque to photons;
transparent to neutrinos
and gravitational waves
nearest blazar
nearest galaxy
galactic centre
gravitational waves—ripples in space–time
Distance [Mpc]
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-6}
10^{-4}
10^{-2}
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{18}
10^{20}
Energy [eV]

The Cosmic Neutrinos TeV->EeV





Neutrinos as smoking-gun for hadronic sources

$p\,\gamma \longrightarrow (p,n)\,\pi$

$\pi \longrightarrow 2\gamma$

$\pi \longrightarrow \mu\,\nu$

$\mu \longrightarrow e\,\nu\,\nu$

γ-ray observations

Cosmic Ray observations

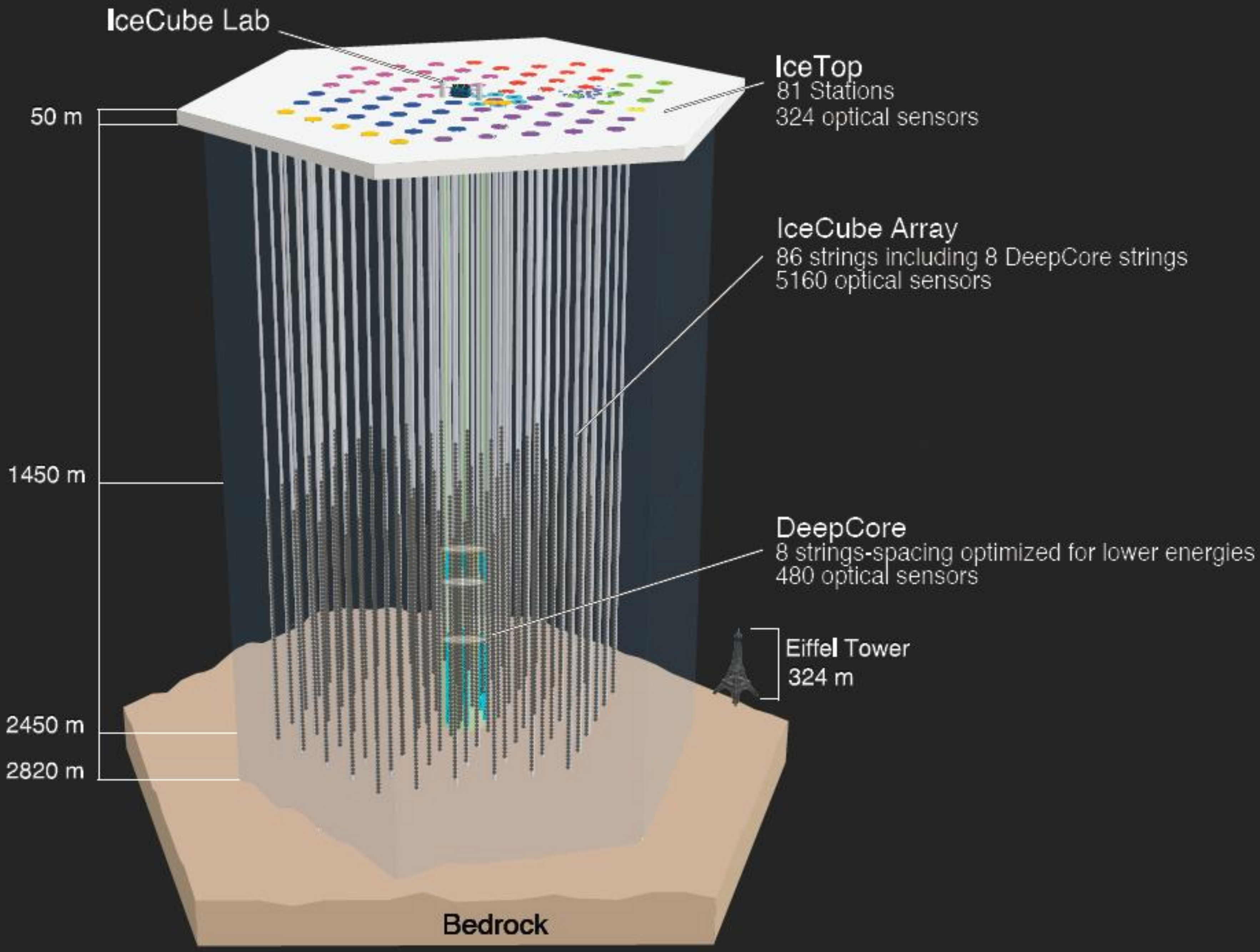
But $eZ \rightarrow e\gamma Z$ (Bremsstrahlung)
$e\gamma \rightarrow e\gamma$ (inverse Compton)

could produce γ-ray

ν observations

||

The smoking gun



5160 PMTs

1 km^3 volume

86 strings

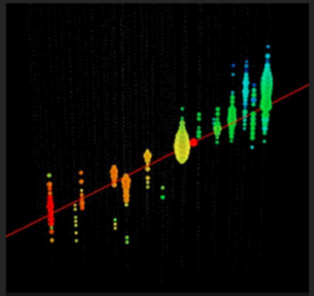
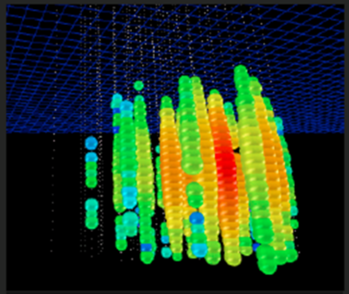
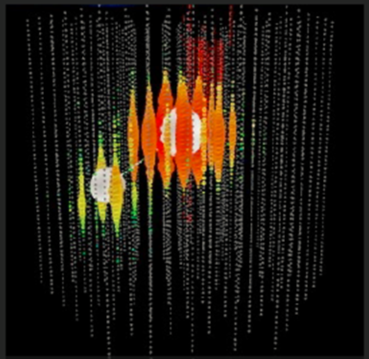
17 m vertical spacing

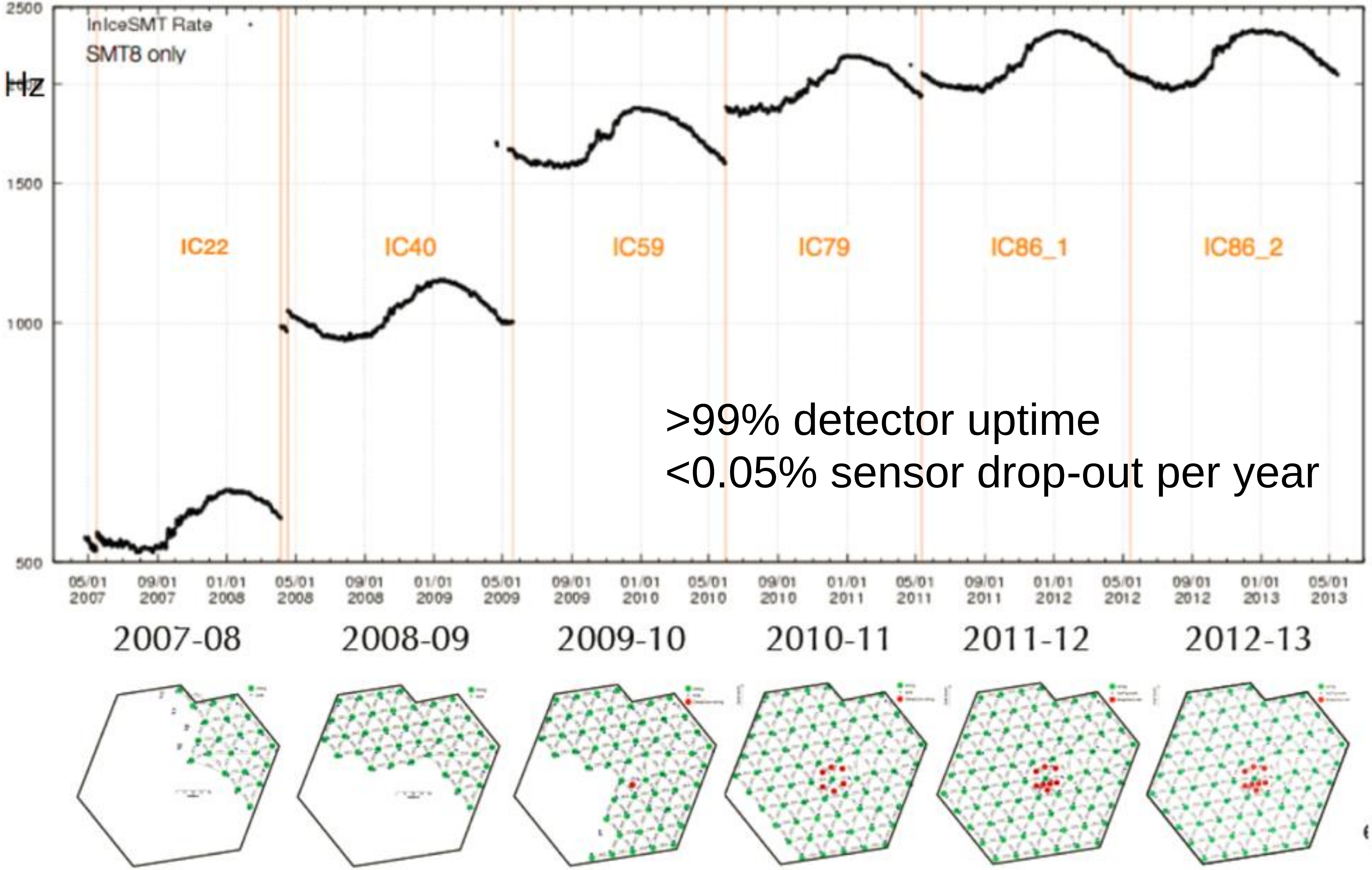
125 m string spacing

Completed **2010**

movie

EVENT SIGNATURE

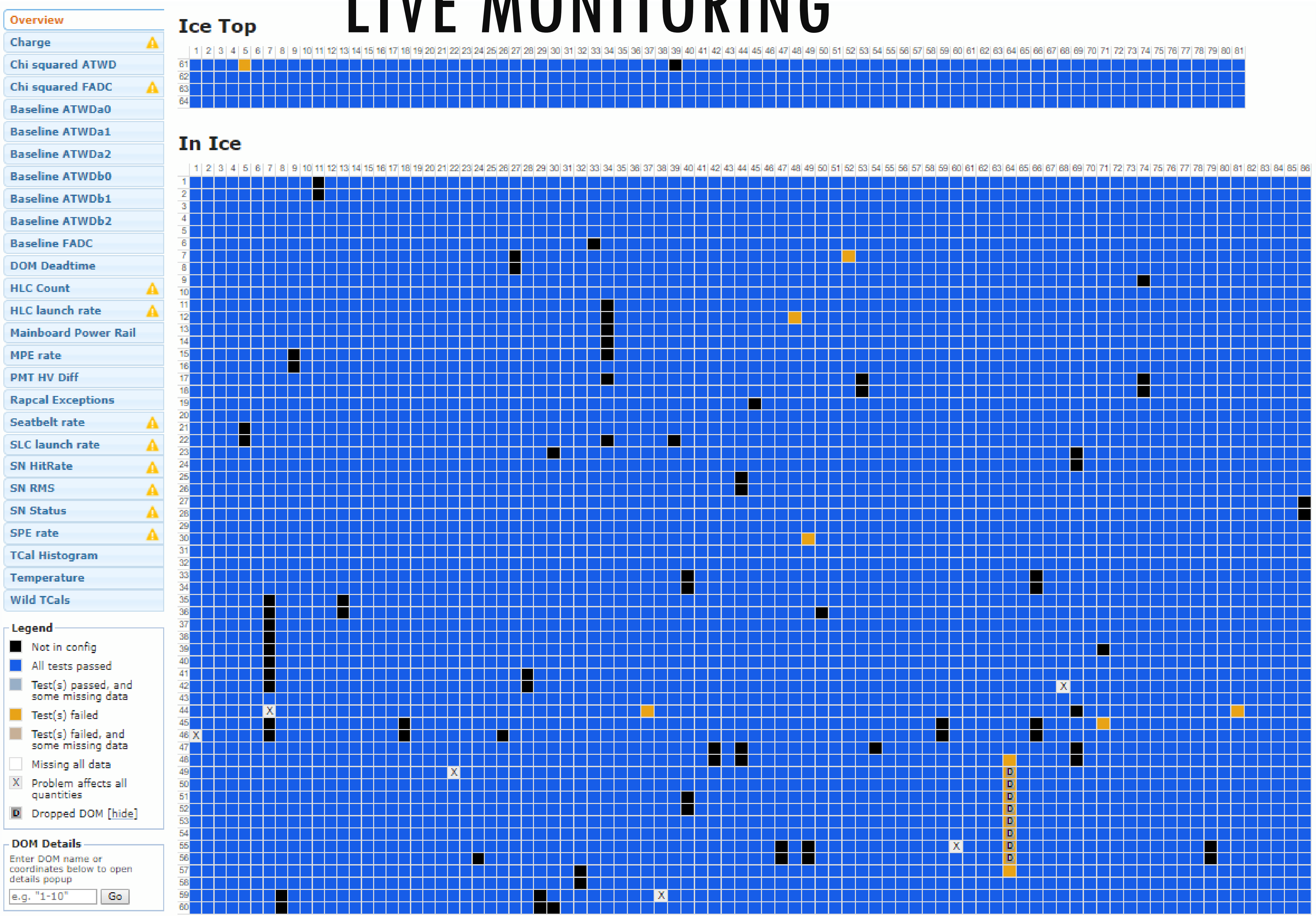
CC Muon Neutrino	Neutral Current / Electron Neutrino	CC Tau Neutrino
		
$\nu_\mu + N \to \mu + X$	$\nu_e + N \to e + X$ $\nu_x + N \to \nu_x + X$	$\nu_\tau + N \to \tau + X$
track (data)	cascade (data)	"double-bang" (≳10PeV) and other signatures (simulation)
factor of ≈ 2 energy resolution < 1° angular resolution at high energies	≈ ±15% deposited energy resolution ≈ 10° angular resolution (in IceCube) (at energies ≳ 100 TeV)	(not observed yet: τ decay length is 50 m/PeV)



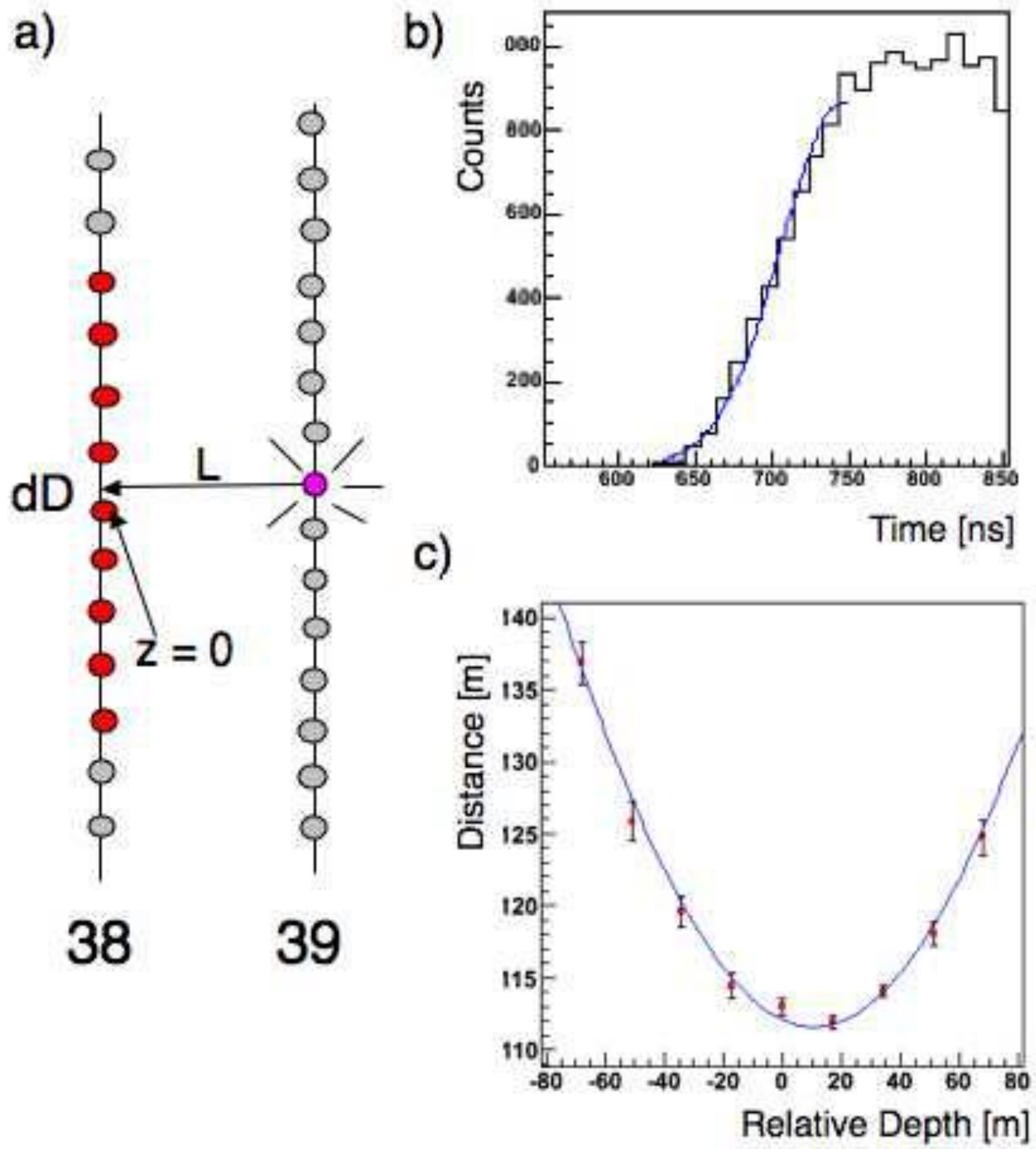
>99% detector uptime

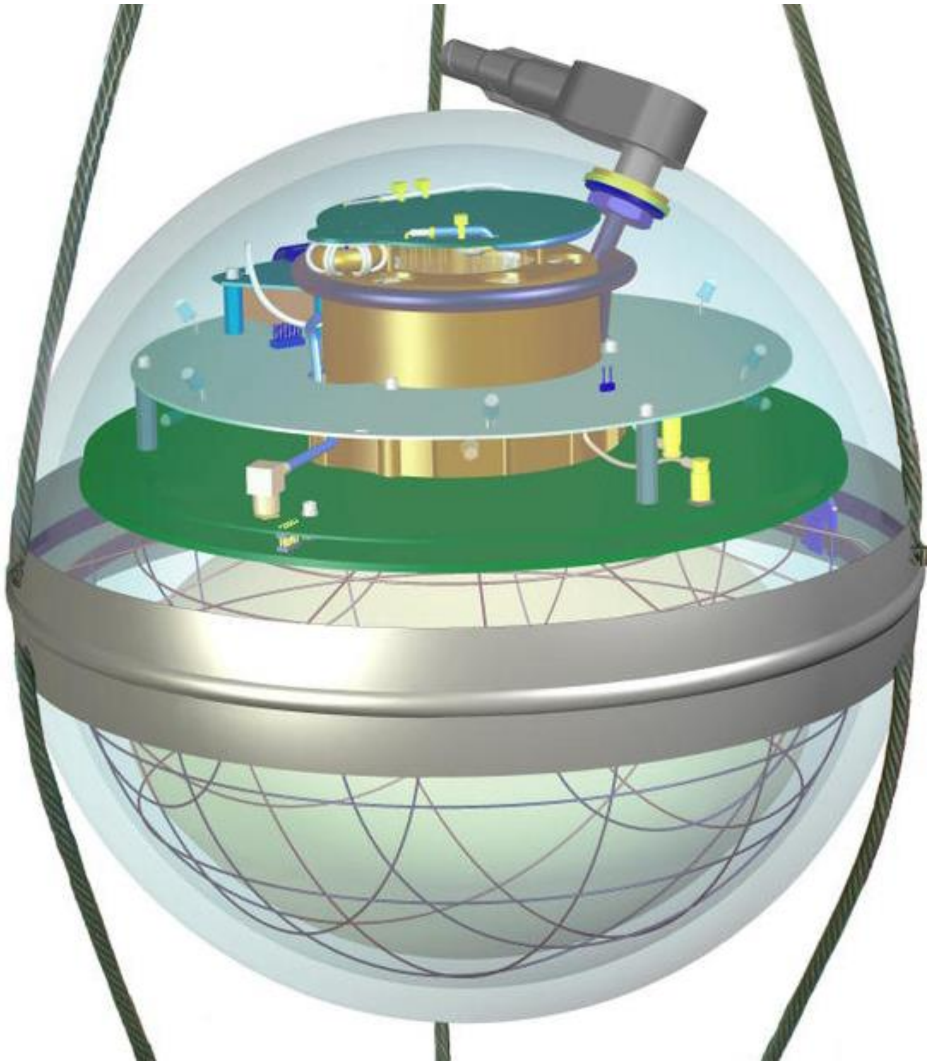
<0.05% sensor drop-out per year

LIVE MONITORING



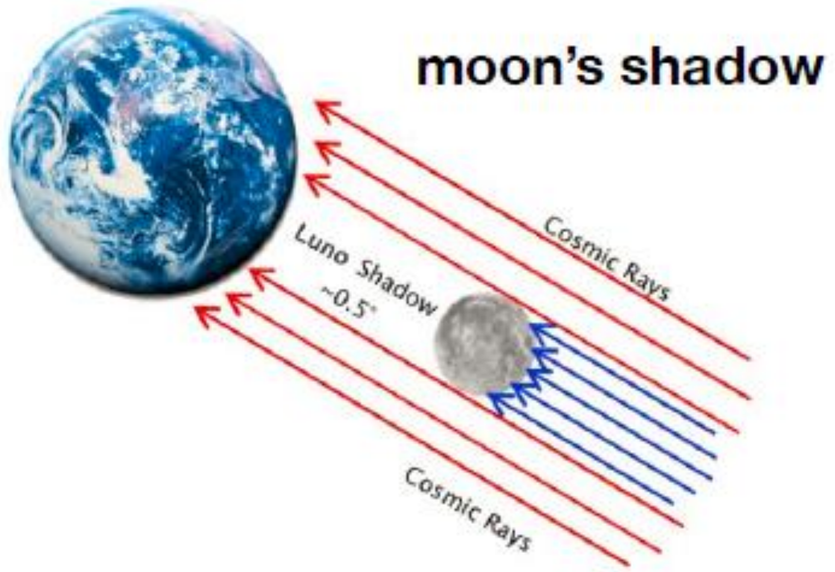
ON-BOARD LEDS





Position and timing calibrations

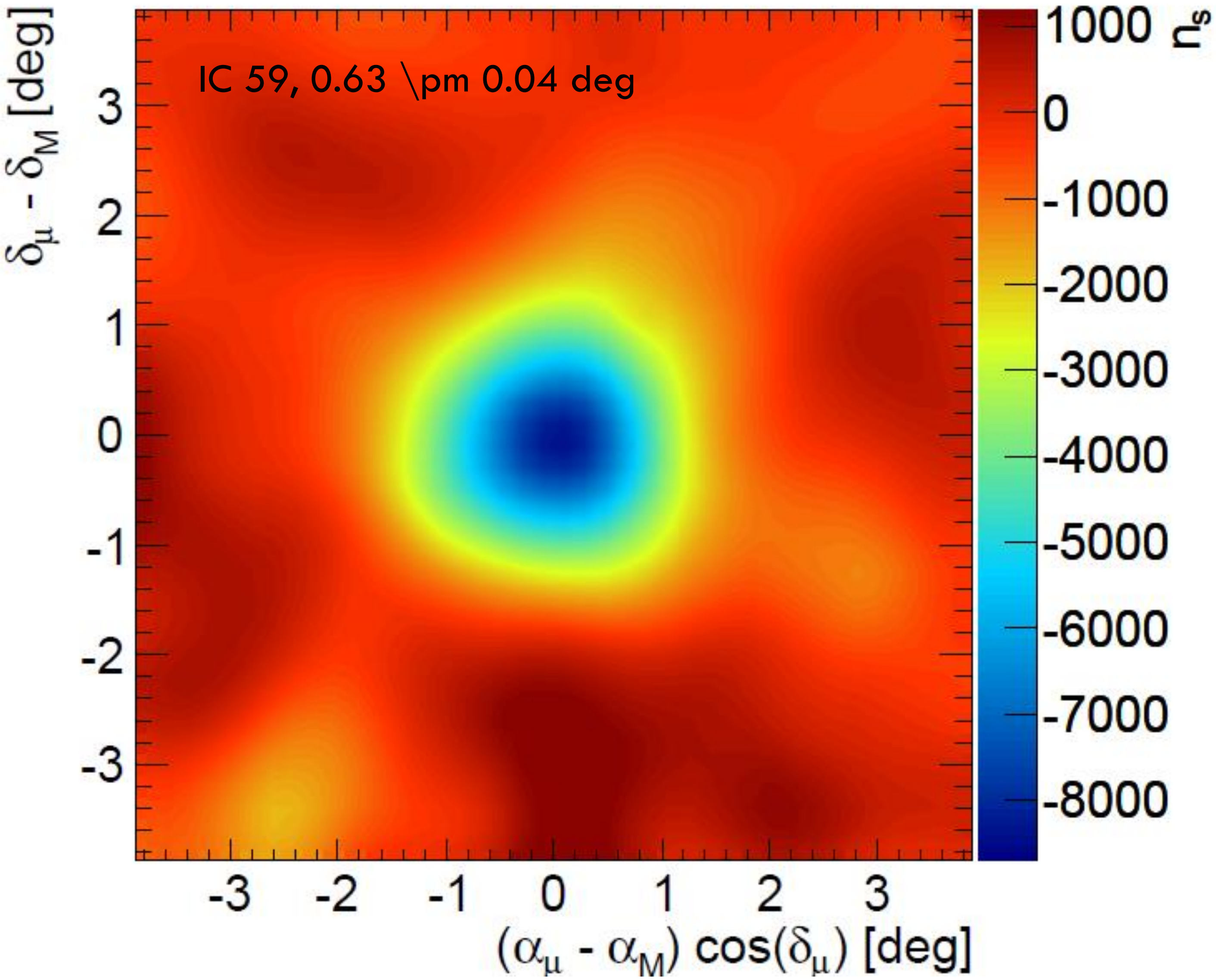
MOON SHADOW



< 0.5 degree online

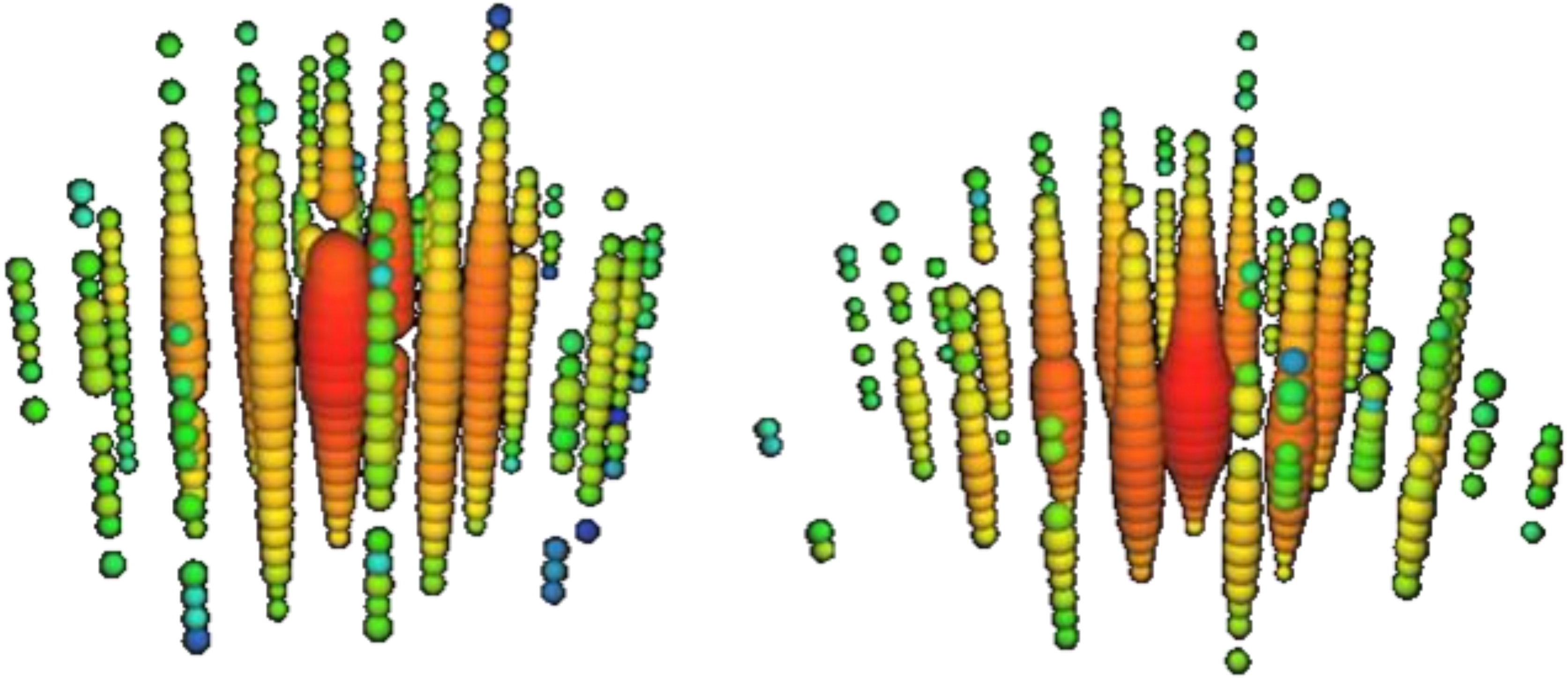
< 0.3 degree offline for muon tracks

10~15 degrees for showers

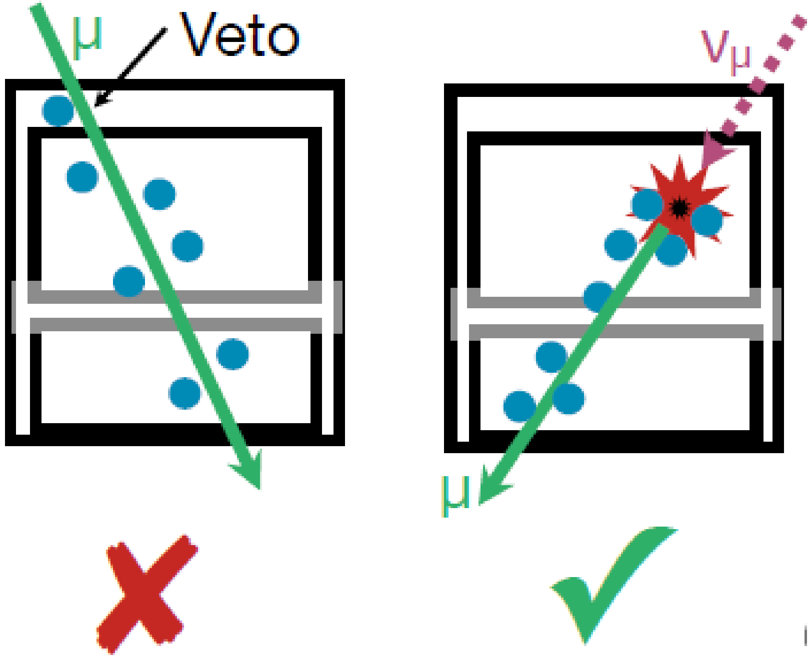


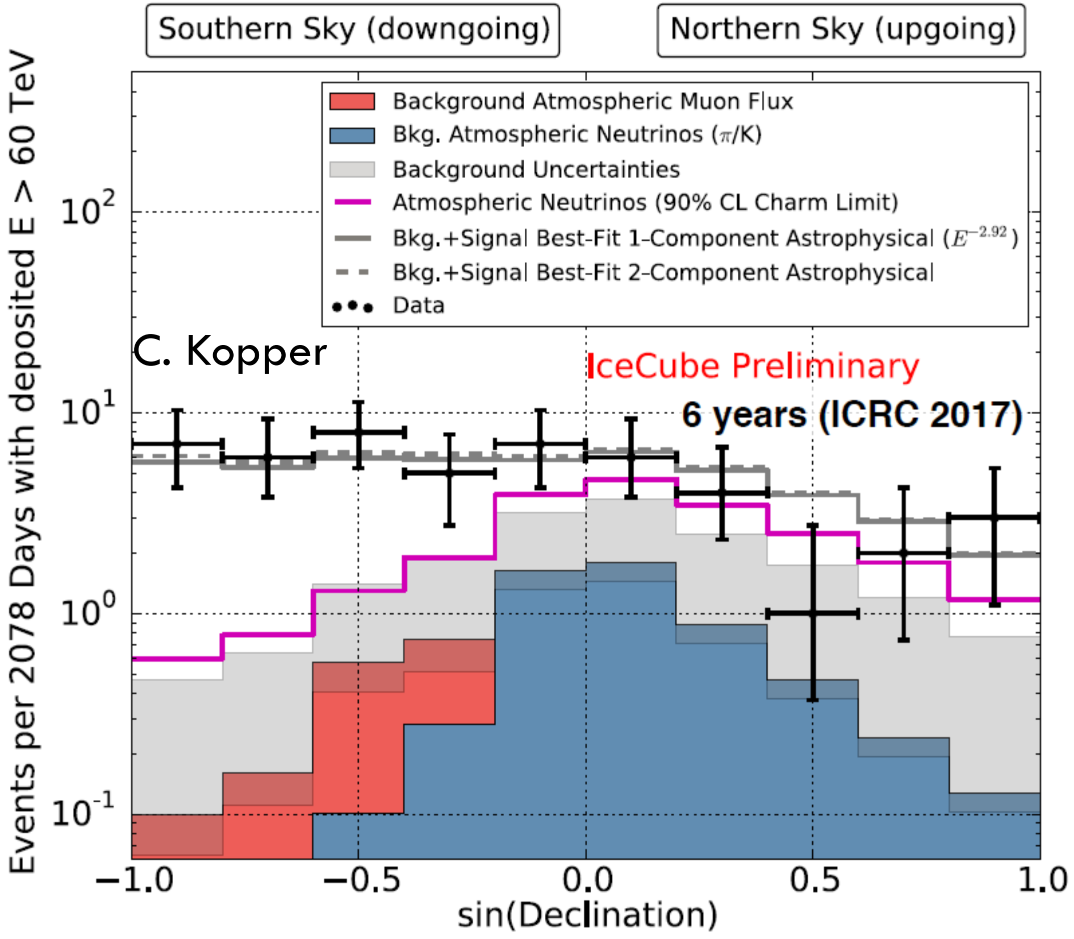
DISCOVERY OF ASTROPHYSICAL NEUTRINO

PeV neutrinos!



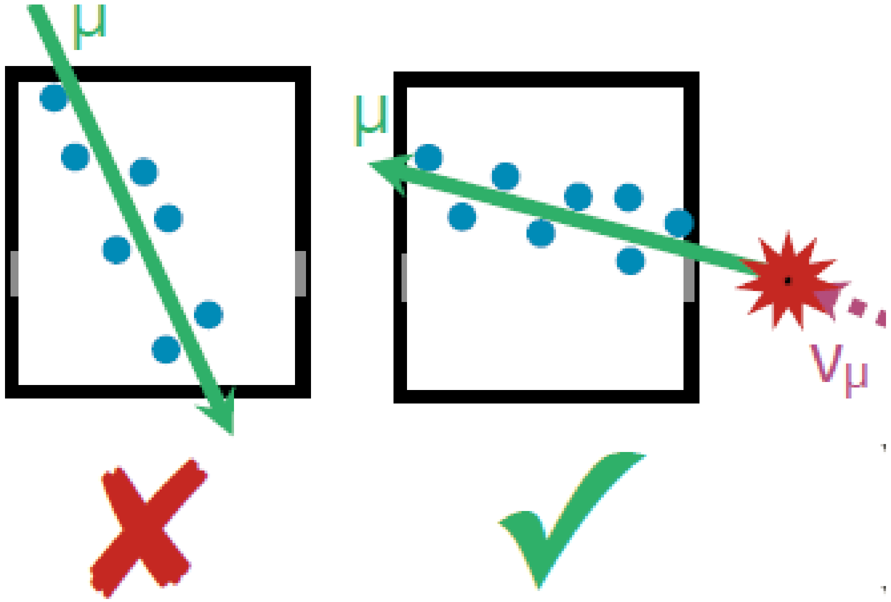
EVIDENCE OF ASTROPHYSICAL NEUTRINO

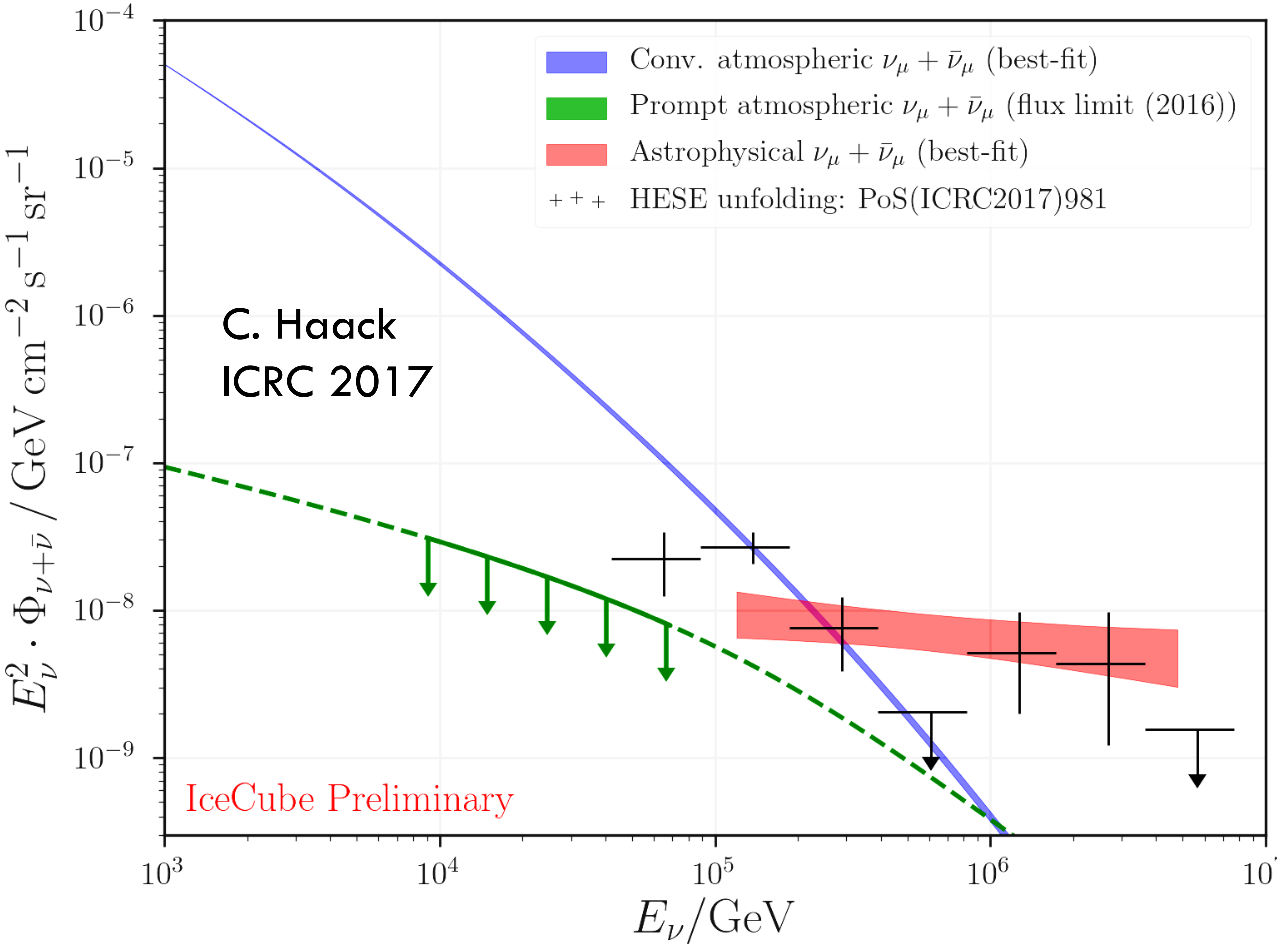


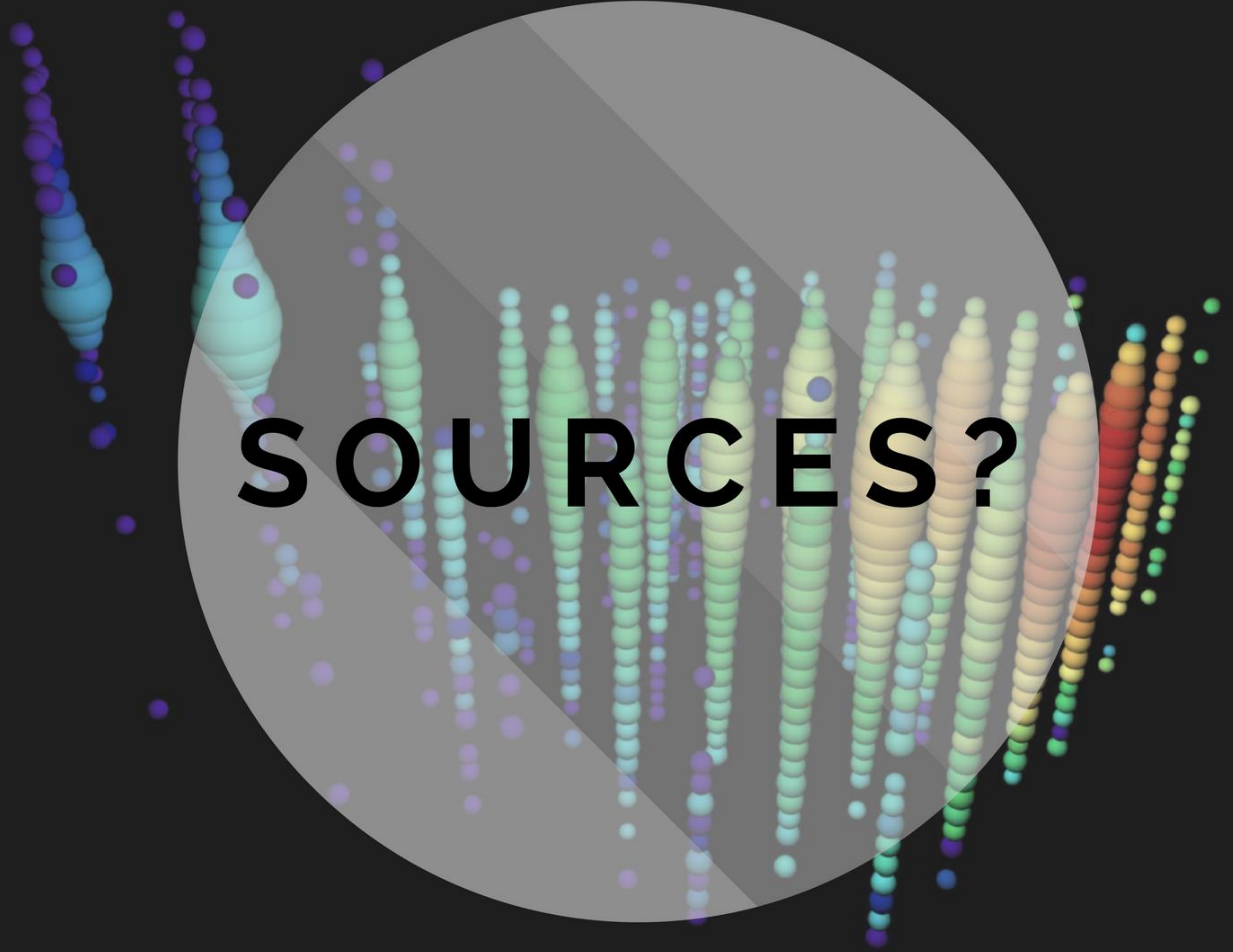


82 events in 6 years

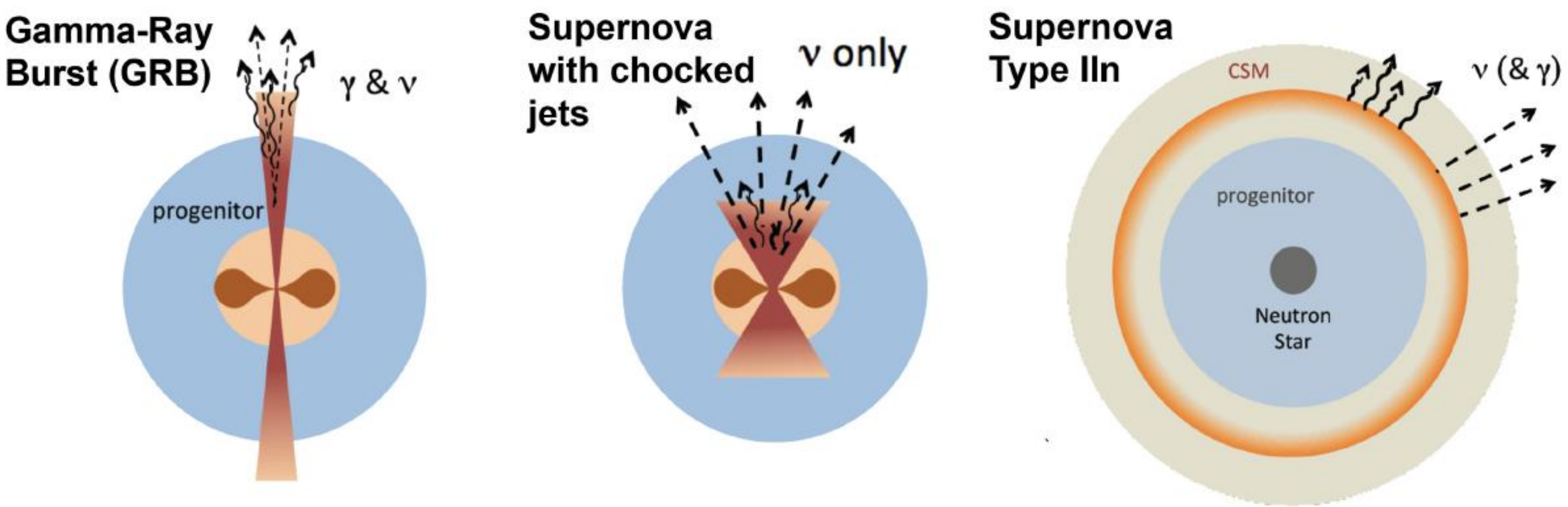
EVIDENCE OF ASTROPHYSICAL NEUTRINO

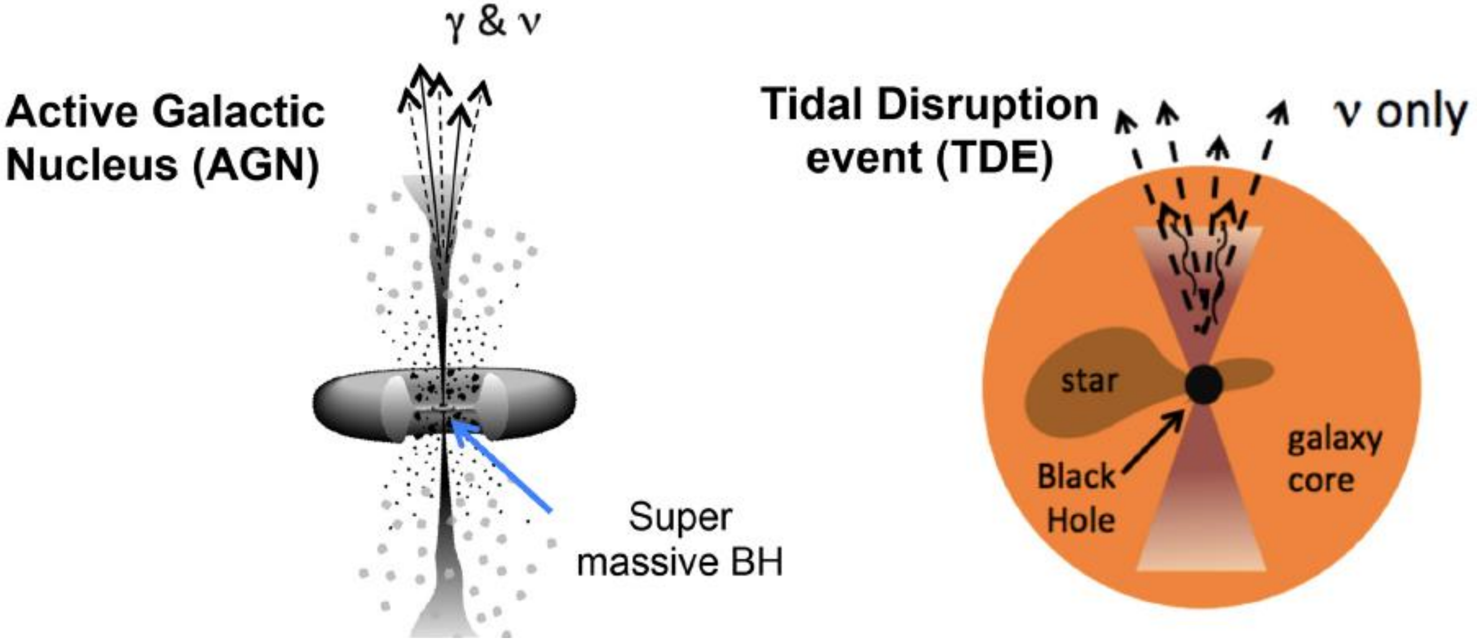






SOURCES?

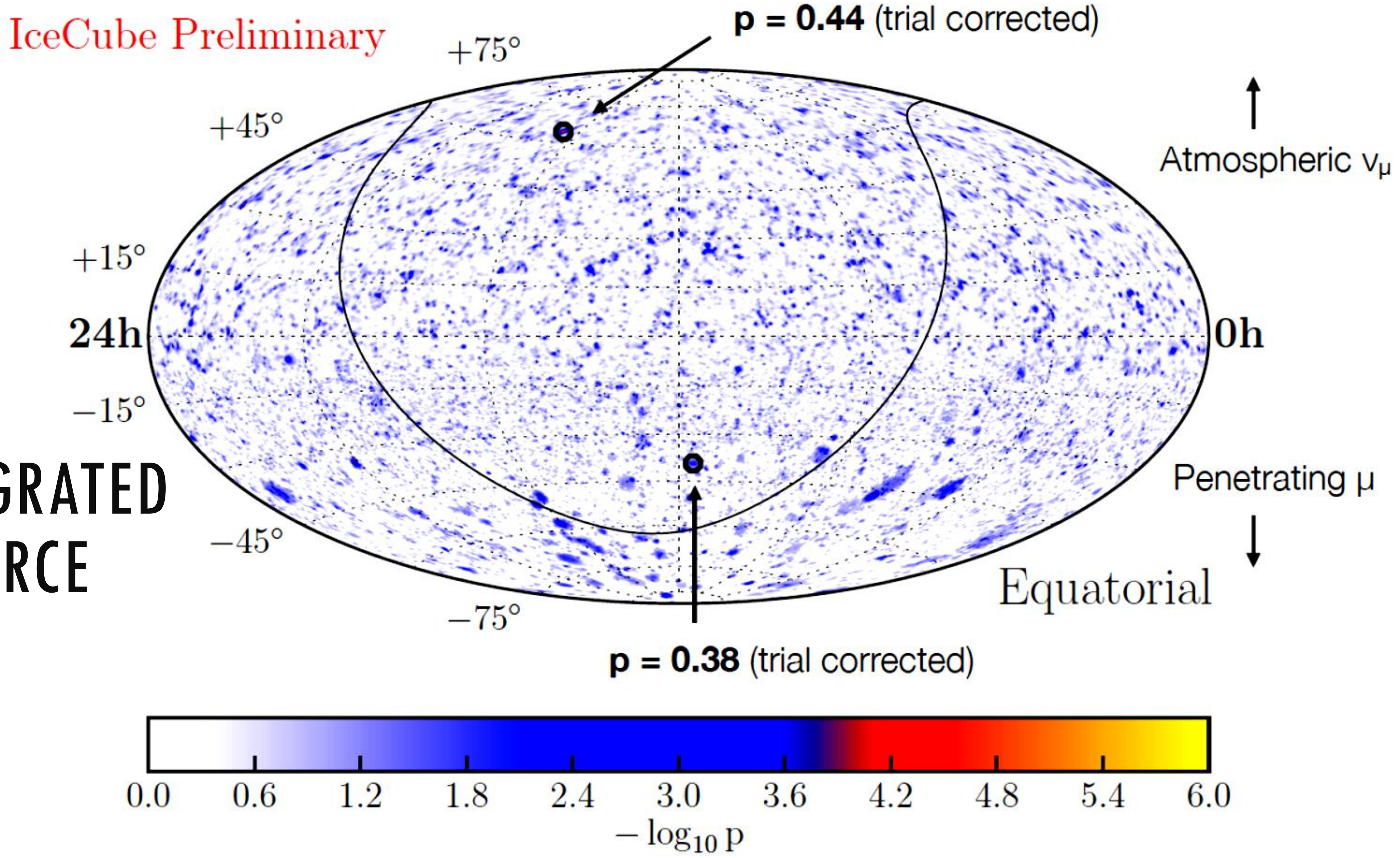




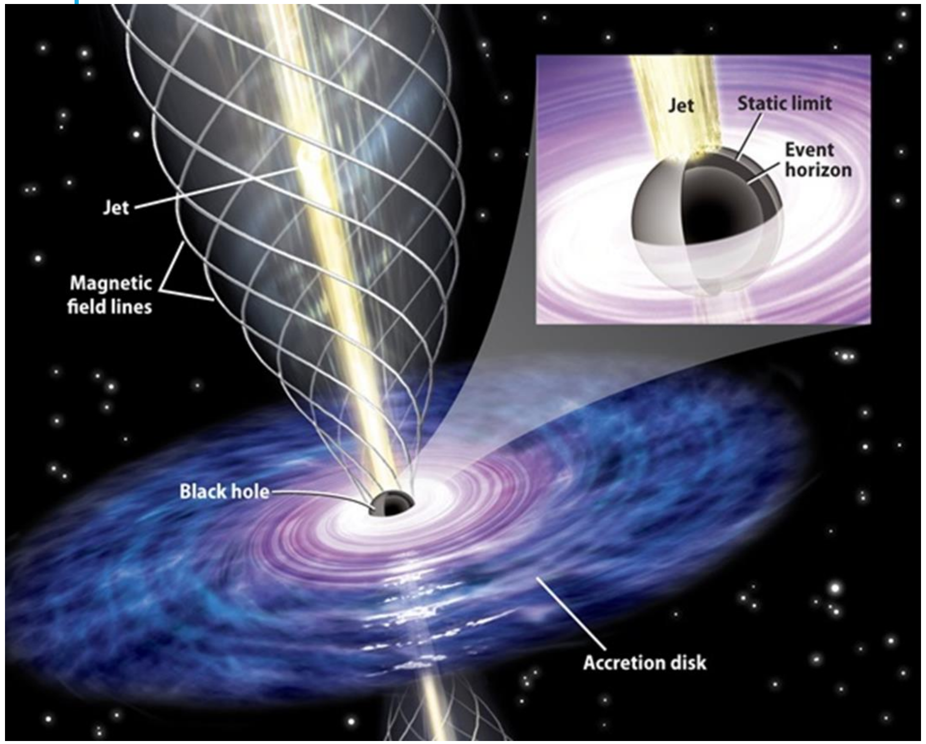
- All-sky stacking
- Catalogue stacking
- Time integrated and dependent

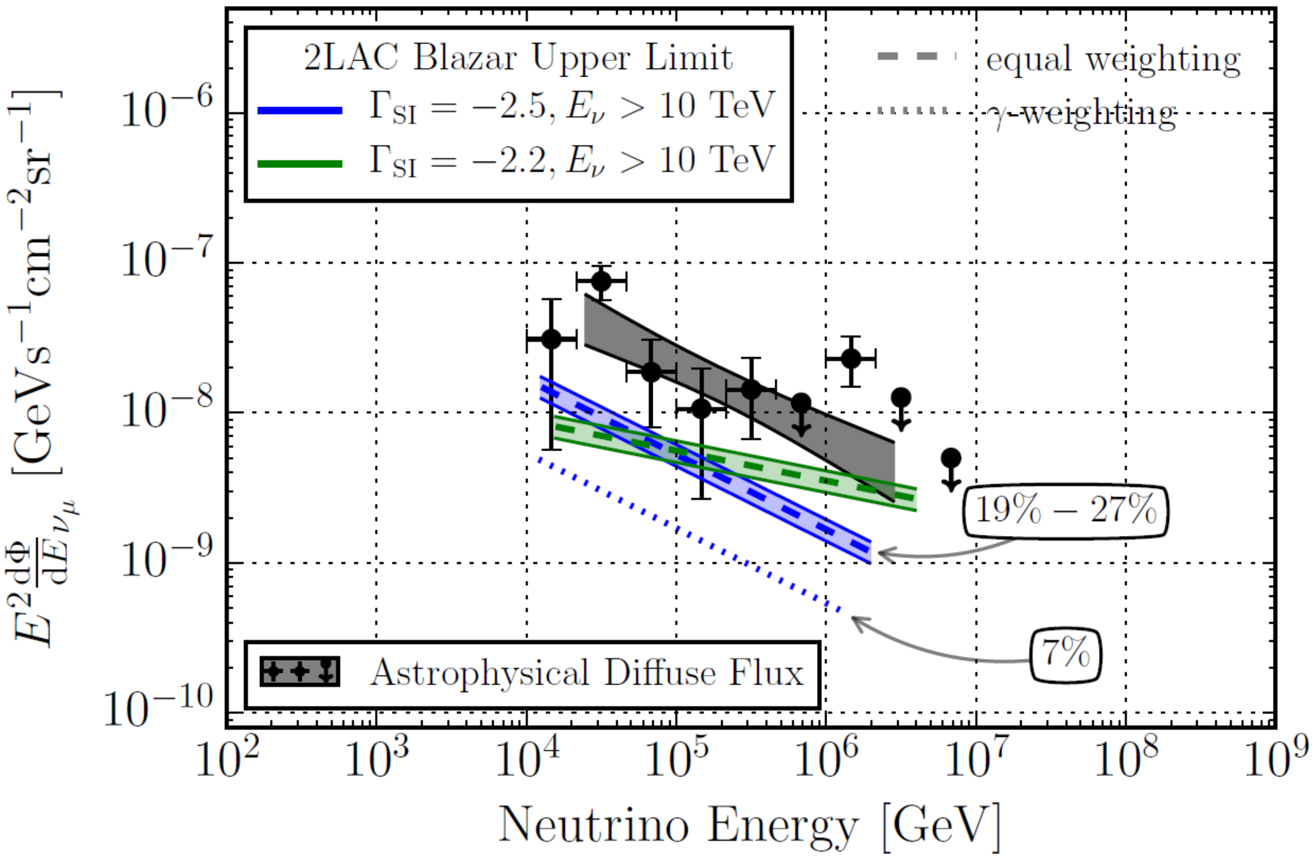
No significant clustering

ALL-SKY TIME-INTEGRATED POINT-SOURCE SEARCH



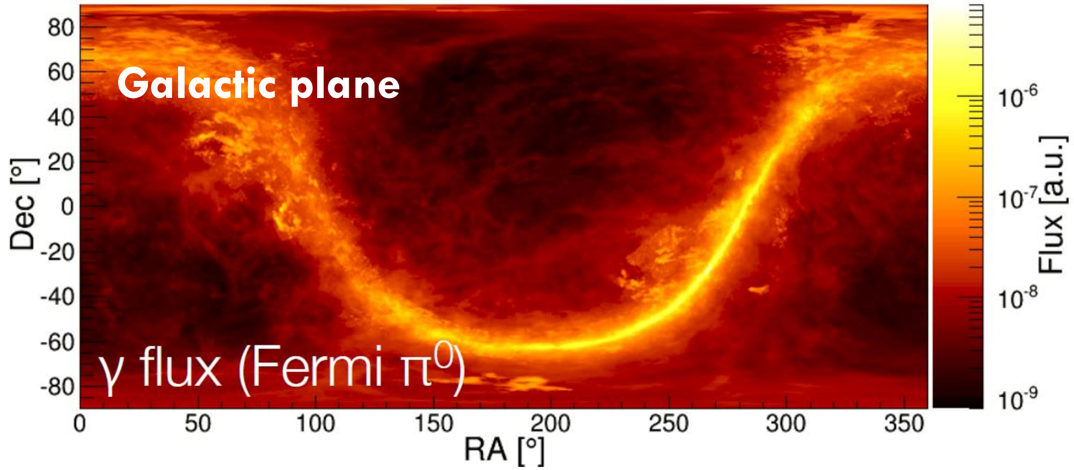
CORRELATIONS WITH BLAZARS



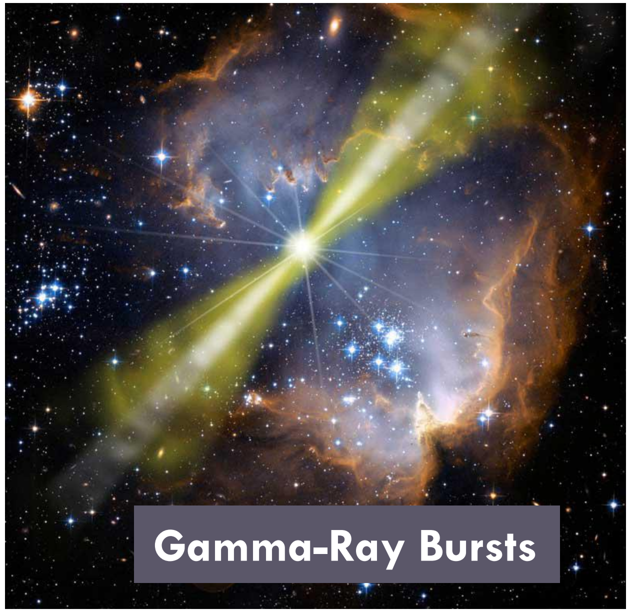


86% Fermi diffuse photons are from blazars
highly variable EM emission
IceCube time-integrated stacking analysis

IceCube, ApJ vol. 835, no. 1, p. 45 (2017)
862 gamma-ray blazars with 3 years of IceCube neutrino data found that **< 30%** (6-27%) of the neutrino flux originates in blazars



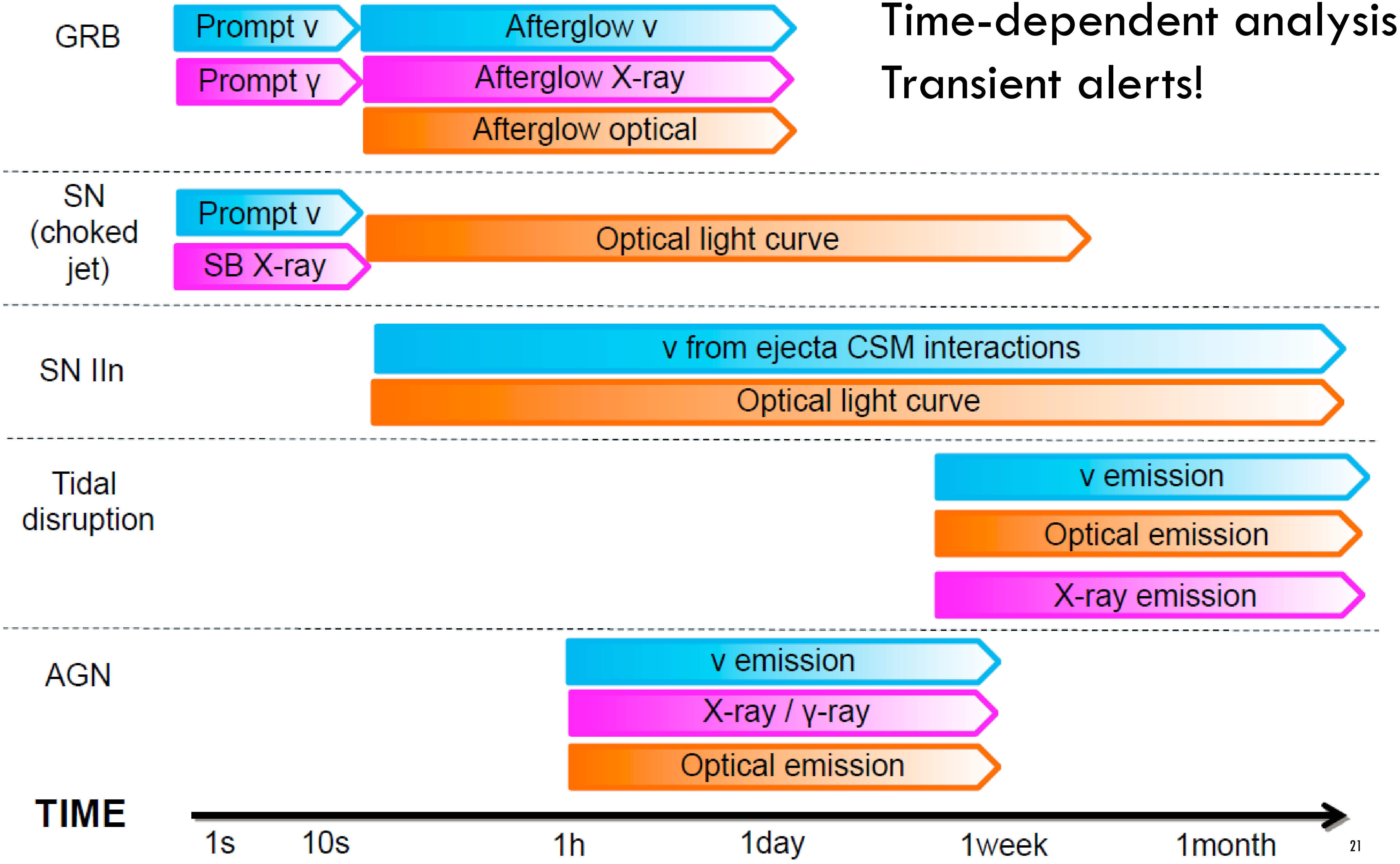
IceCube, Astrophys.J. 849 (2017) 67
<16% of $E^{-2.5}$ flux above 1 TeV



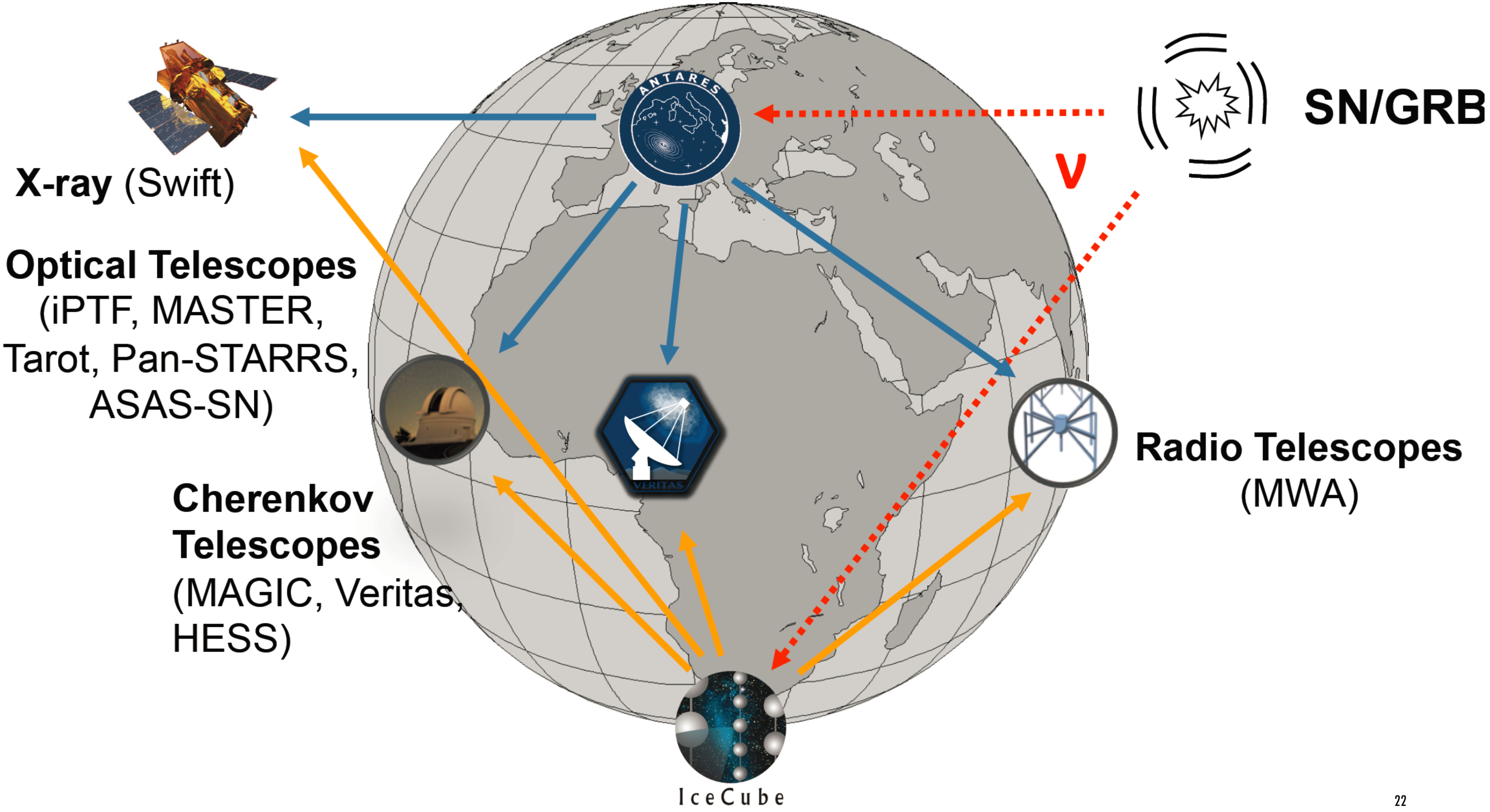
Icecube, Astrophys.J. 824 (2016) no.2, 115
Short duration -> low background
No neutrinos observed in coincidence with GRBs
Prompt emission from GRBs can produce **<1%** of observed neutrino flux

Bechtol K et al. 2017 Astrophys. J. 836 47
86% Fermi diffuse photons are from blazars
<30% (at 100 TeV) diffuse nu flux
Applies to pp optical thin sources

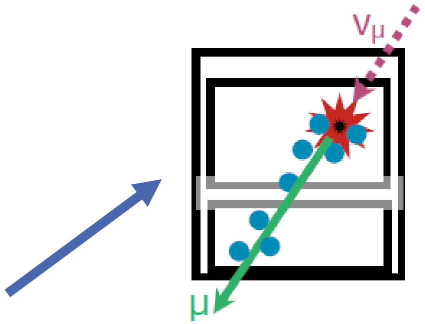
Time-dependent analysis
Transient alerts!



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



IceCube real-time stream



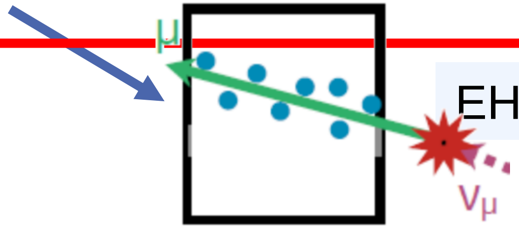
veto-based
HESE

all neutrino flavor sensitive

High cosmic ν purity samples.
Launched in 2016!

high chance of real cosmic neutrino signals

angular resolutions so-so



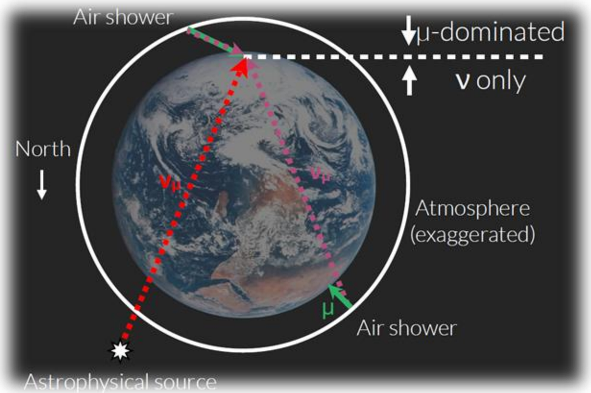
EHE (Ultra-High Energies)

all neutrino flavor sensitive

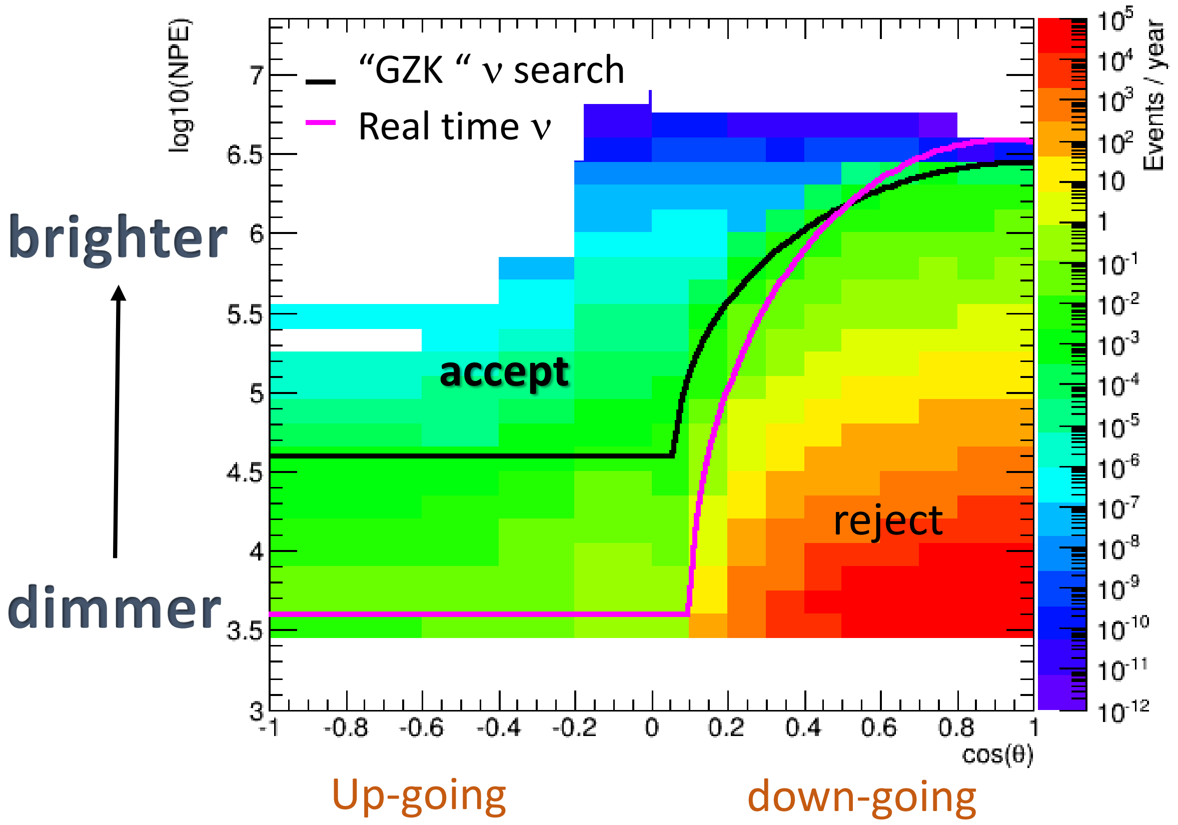
The breakthrough event
detected in this channel

high chance of real cosmic neutrino signals
good angular resolutions
signal flux highly uncertain

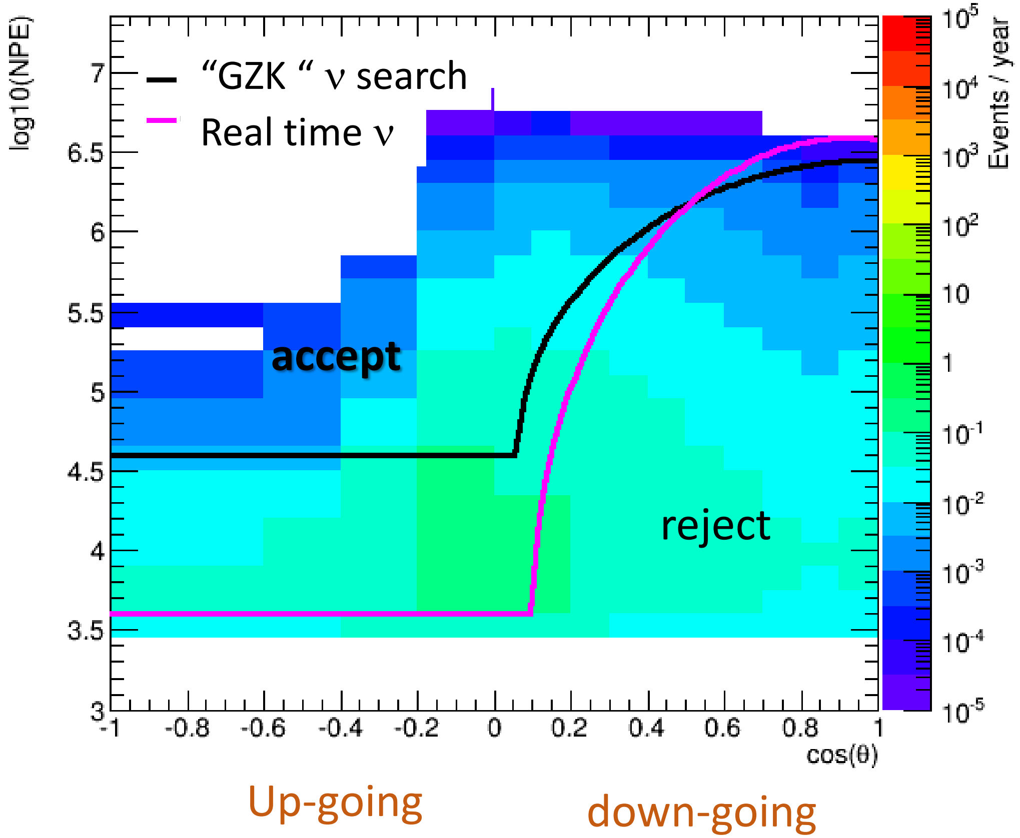
Event selection for EHE alerts



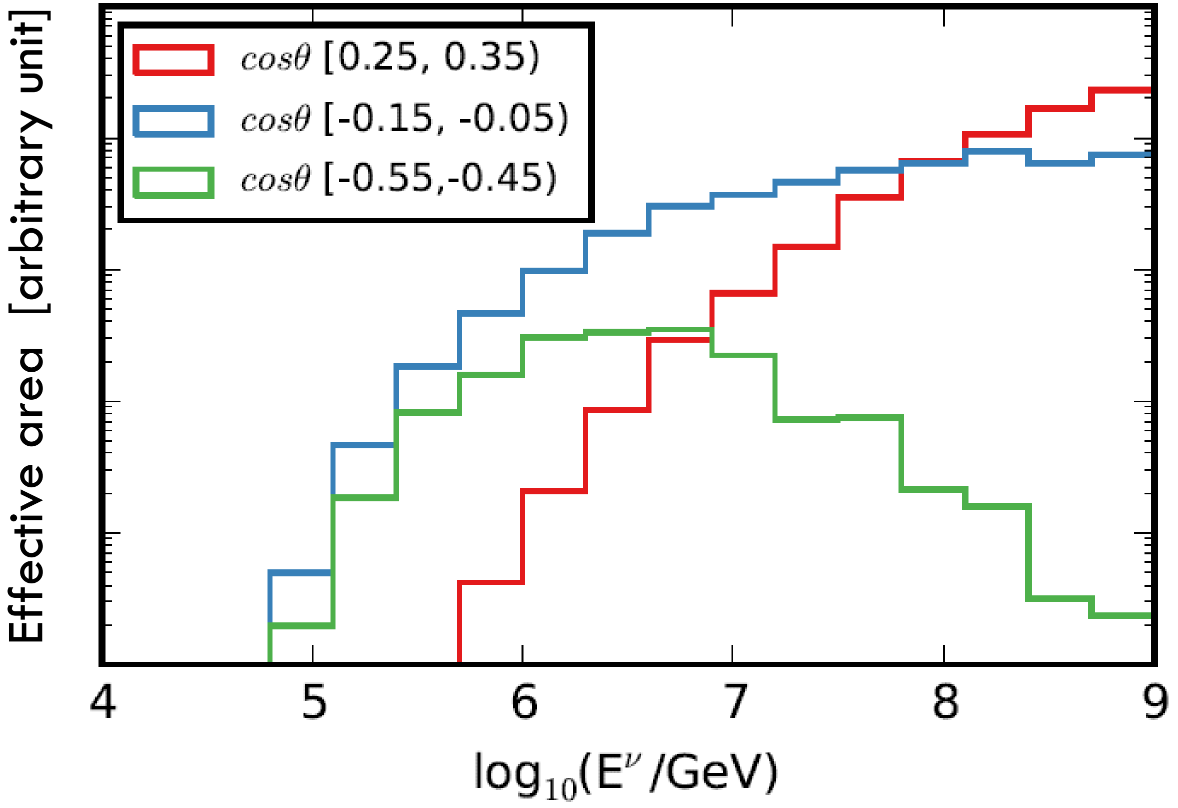
Atmospheric BG



E^{-2} signal

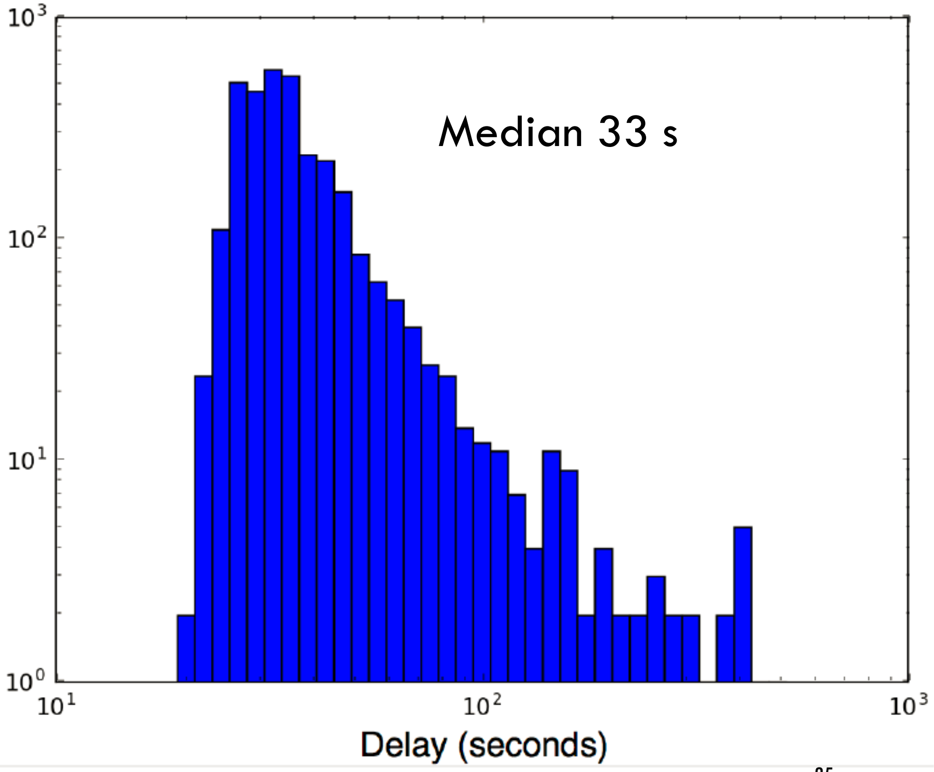


EHE ALERT EVENT RATES

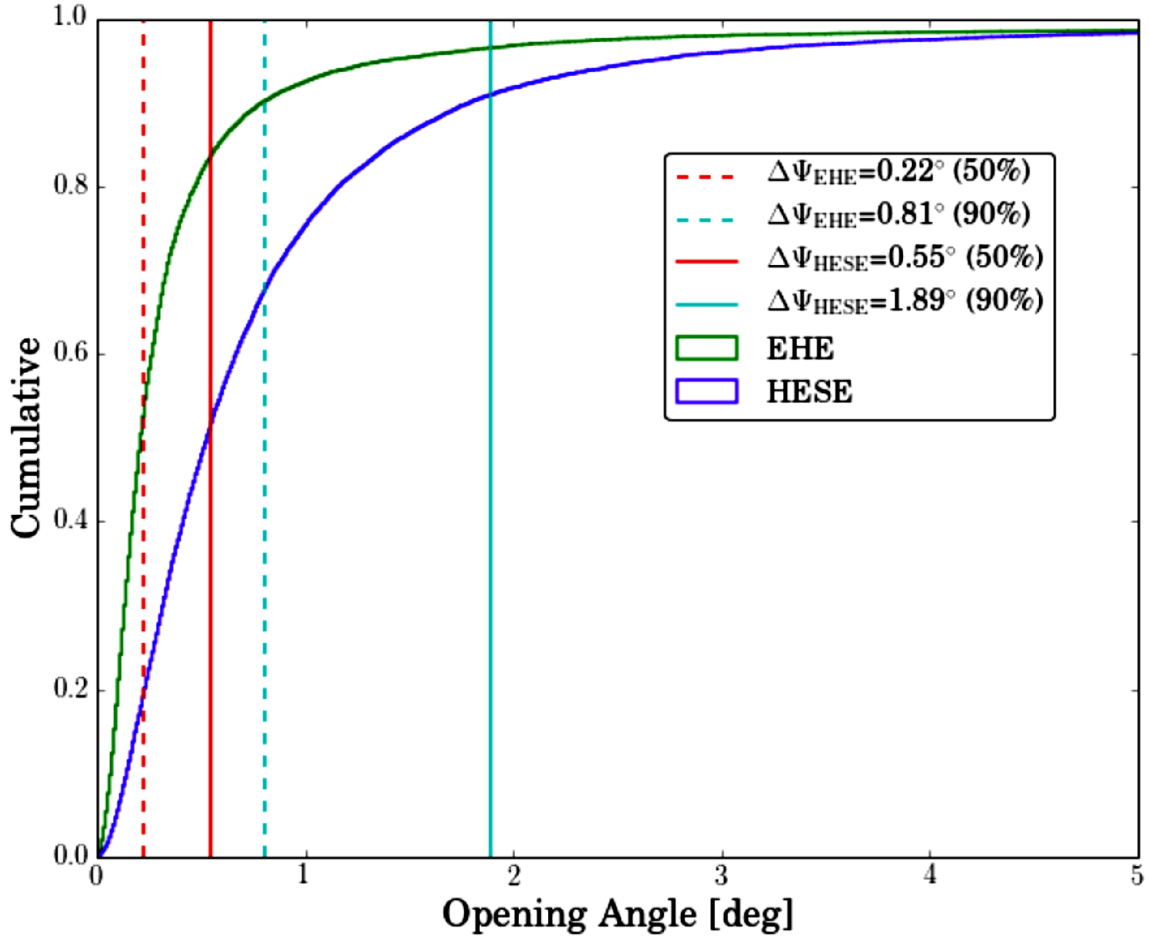


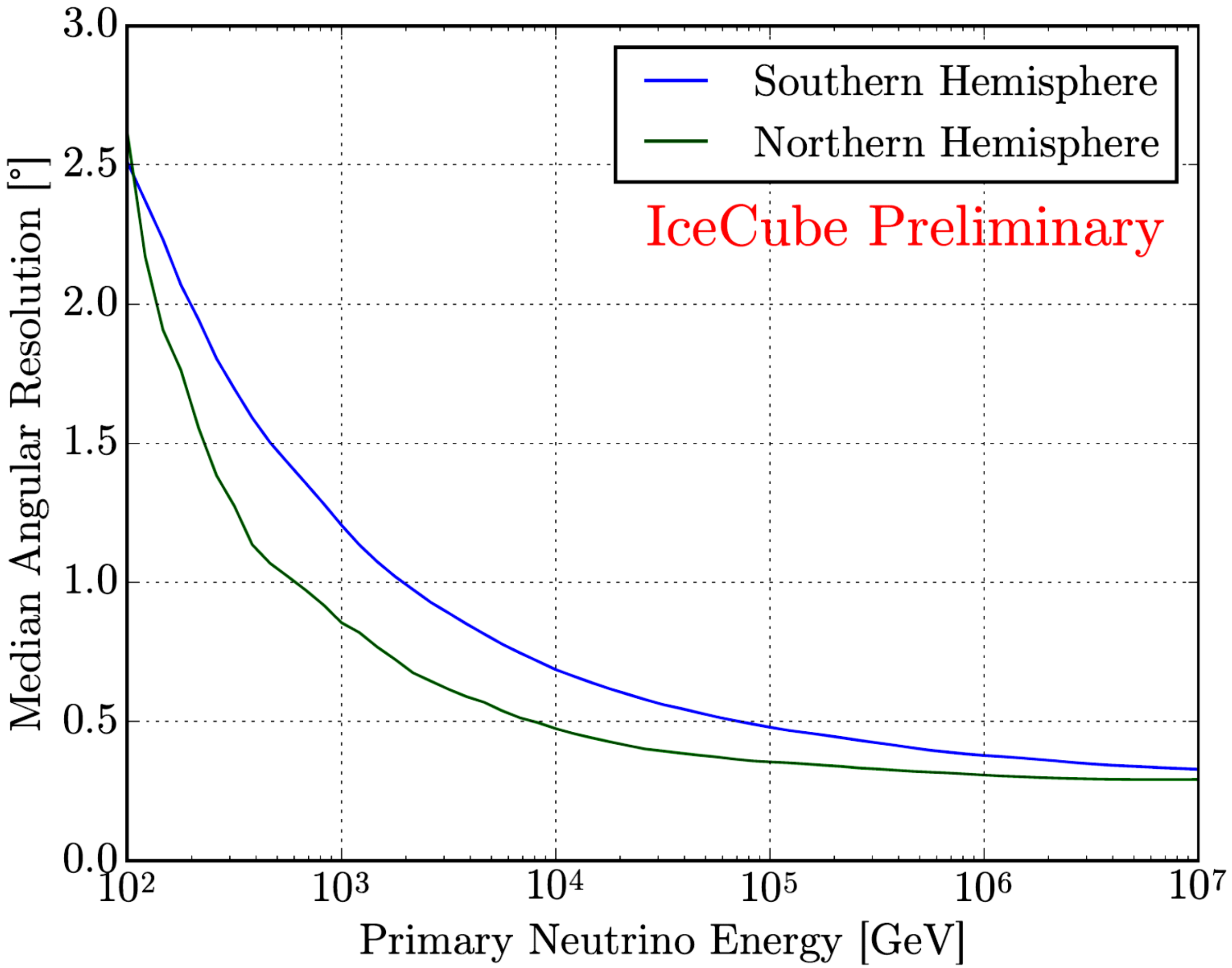
$$N = T \int d\Omega \int dE_\nu \phi_\nu(E_\nu)\, A_\nu(E_\nu)$$

Sample	Events / year
Atmospheric muon	0.52
Conv. Atmos. ν_μ	1.20
Prompt Atmos. ν_μ	0.19
Total Background	1.91
Astro. ν_μ (E^{-2})	4.09
Astro. ν_μ ($E^{-2.49}$)	2.48



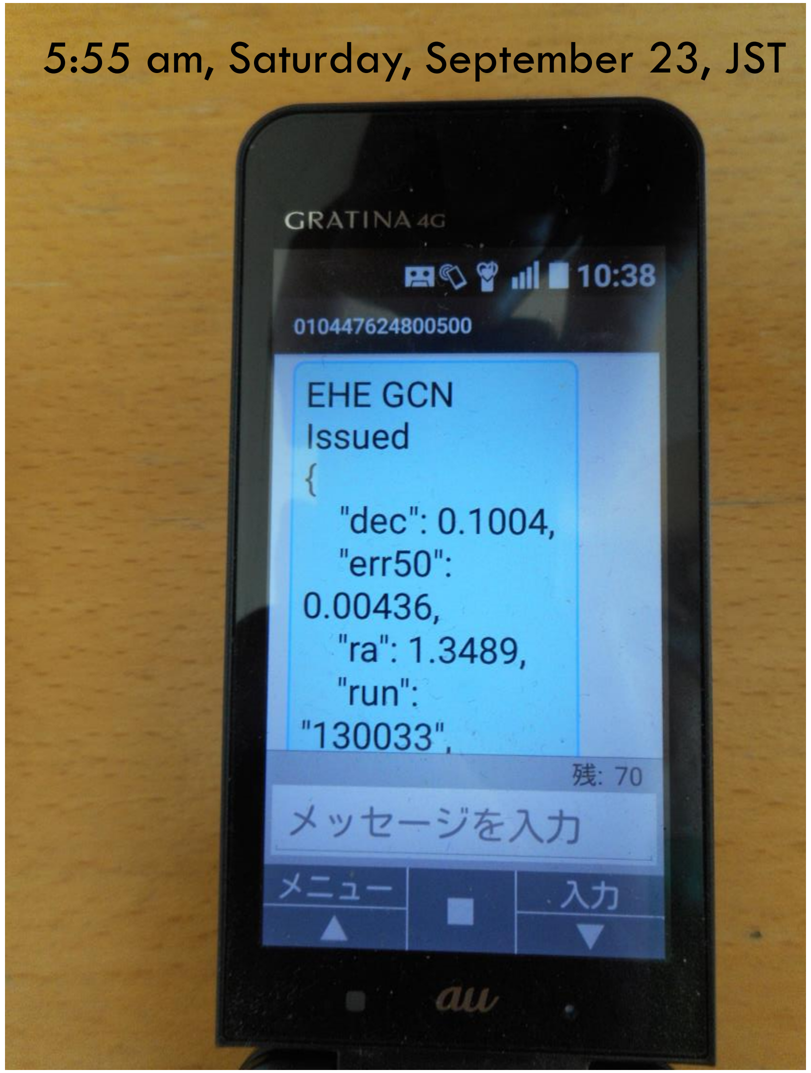
ANGULAR RESOLUTION

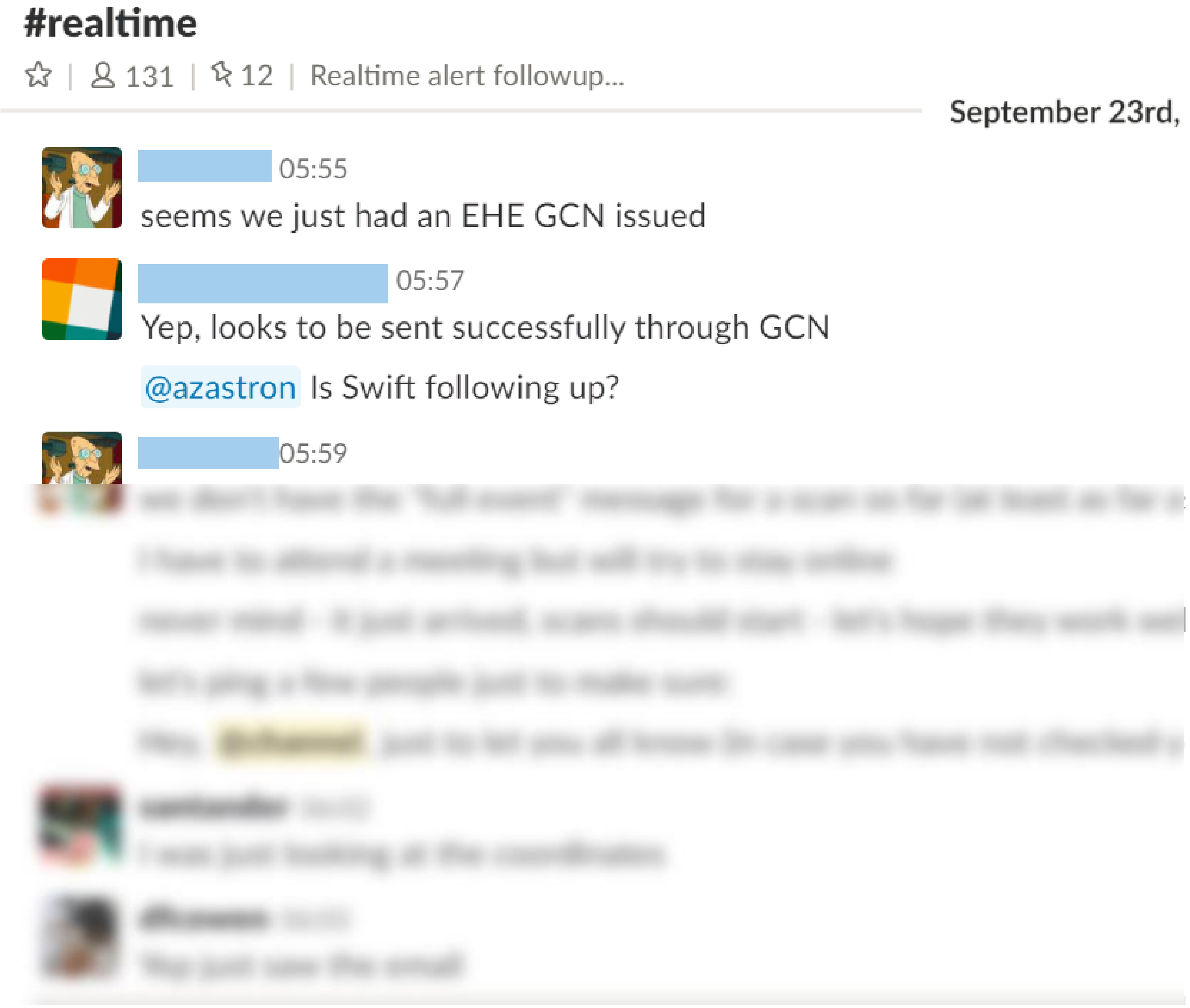




A story about EHE alert
IC170922A

ON A QUIET SATURDAY MORNING IN LATE SEPTEMBER 2017





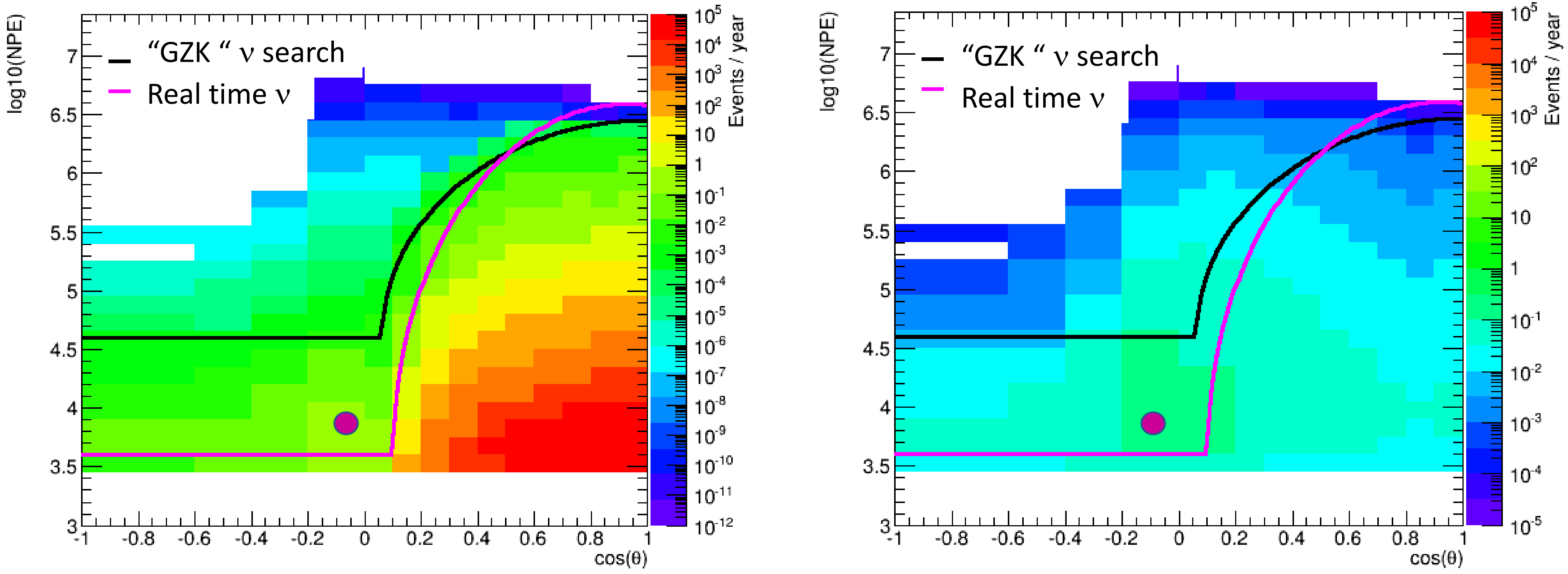

movie

IceCube 170922A

NPE 5,786 cos(zenith) -0.13

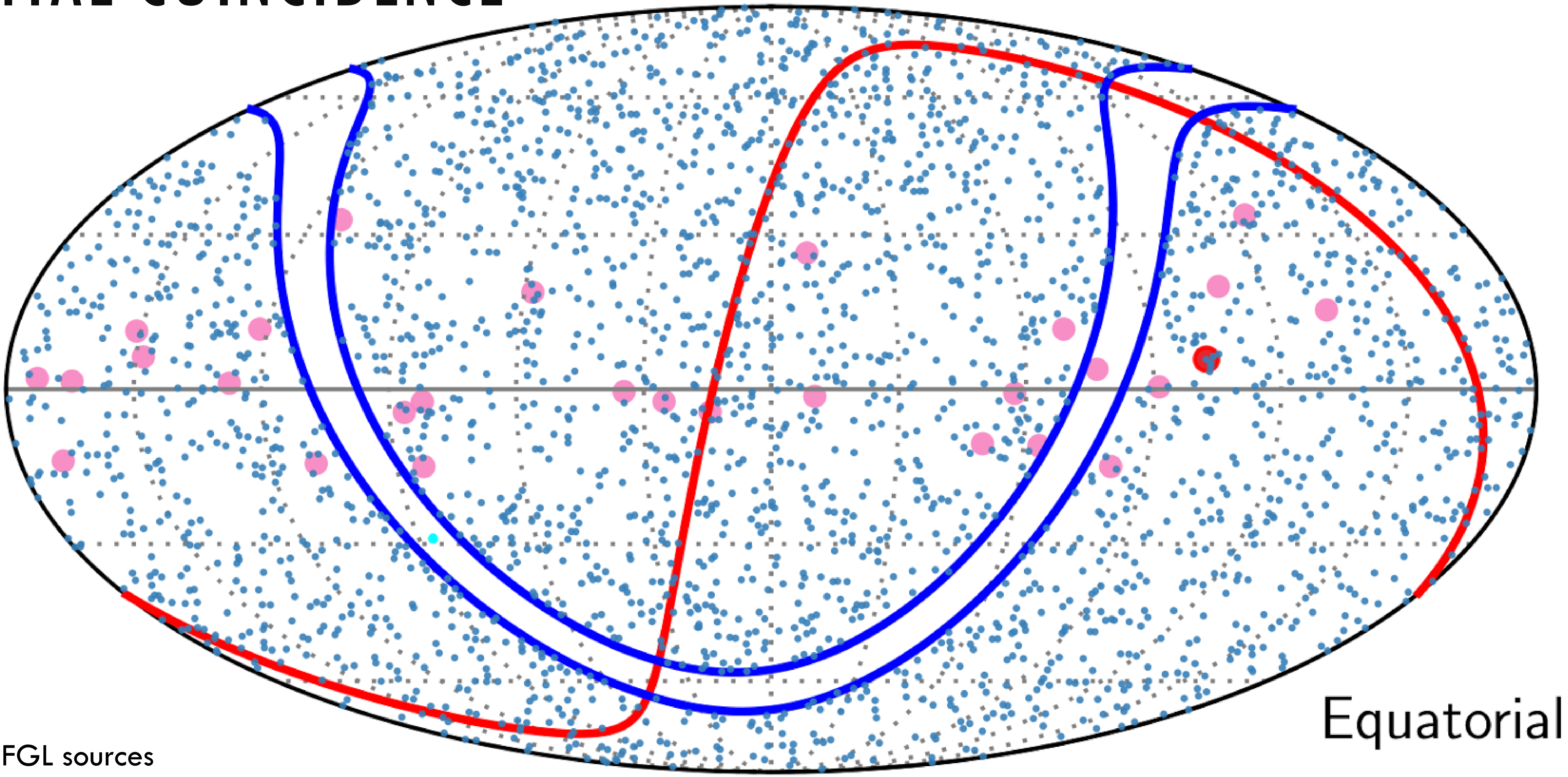
right on the “sweet spot” signalness : 56.5 %

Atmospheric BG E^{-2} signal



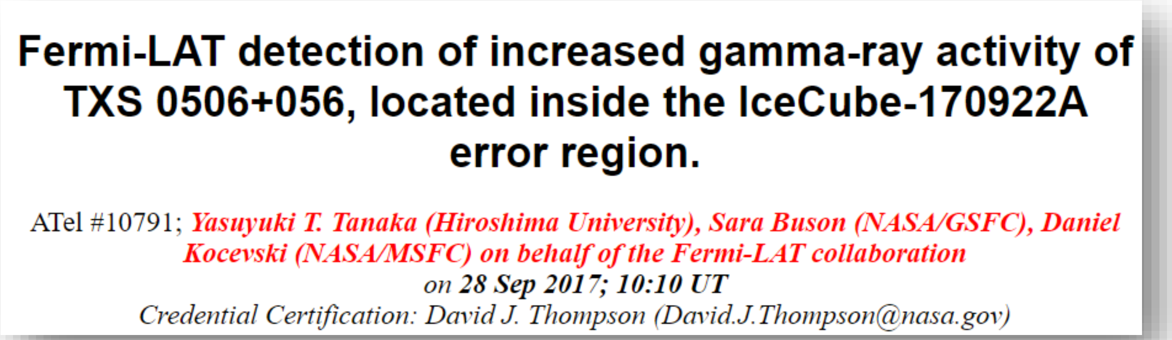
Observatory	Observation Time	Detection	Source	Comments
Fermi-LAT	Sept 15-27	✓	TXS 0506+056 / 3FGL J0509.4+0541 / 3FHL J0509.4+0542	Flaring >800 MeV
Swift-XRT	Sept 23 00:09-22:42 UT Sept 27 18:52 UT, 5 ks Sept 30 – Oct 7, 2 ks	✓	1SXPS J050925.9+054134	Spectral softening/evolution
Liverpool	Sept 28, 900 s	✓	TXS 0506+056 (PMN J0509+0541)	Typical BL Lac spectrum "Bluer when brighter"
ASAS-SN	-50 days	✓	TXS 0506+056	~0.5 mag in V-band
AGILE	Sept 18 12:00 UT + 3 days ±6 days	✓	< 1° from 3FGL J0509.4+0541	Excess > 100 MeV
H.E.S.S.	Sept 23 01:05 UT, 1 hr Sept 24 03:10 UT, 1 hr	×		Set 90% CL UL on ν fluence
HAWC	Sept 15 09:04 UT - Sept 19 14:41 UT Sept 21 08:41 UT to Sept 27 14:10 UT	×		At T0, this location was not in HAWC's fov
ANTARES	±1 hr and ±1 day of T0	×		Set 90% CL UL on ν fluence
INTEGRAL	±300 s of T0	×		Set 3σ UL
IC multi-day	Sept 15 00:00 UT – Sept 29 00:00 UT	×		
VERITRAS	Sept 23, 1 hr + Sept 28-39, 5.5 hrs	×		~200 GeV

‘SPATIAL COINCIDENCE’



3 FGL sources
Historical EHE events

‘TIME COINCIDENCE’

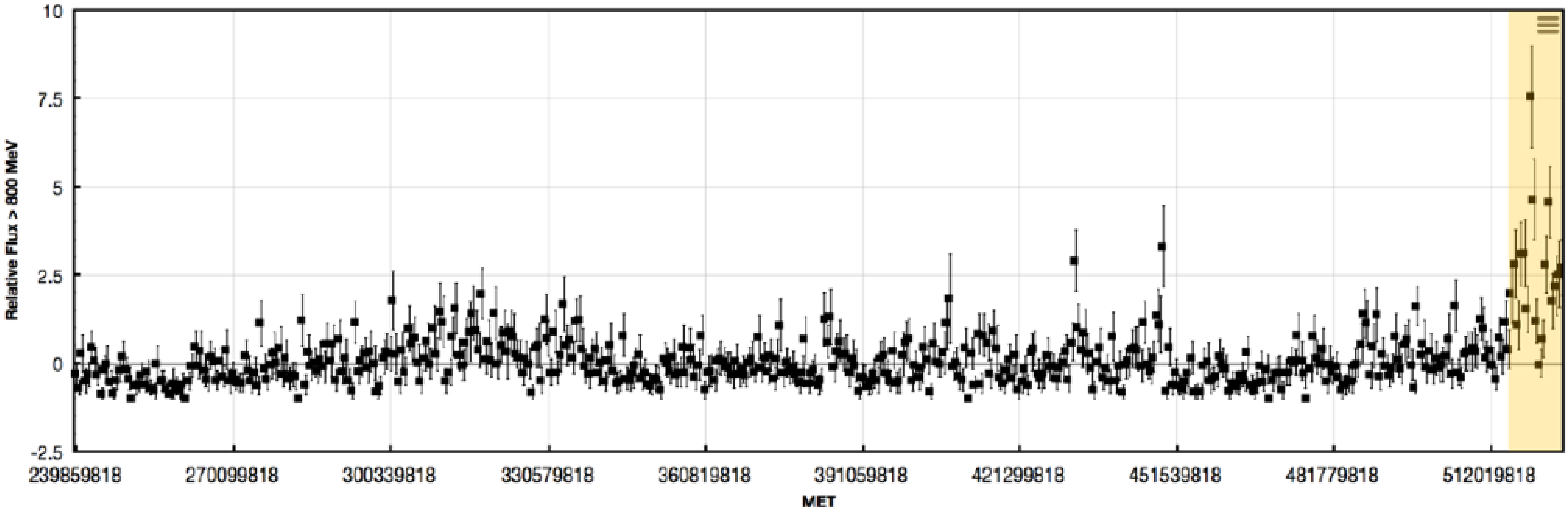


Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on ***28 Sep 2017; 10:10 UT***
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Fermi All-sky Variability Analysis (FAVA)

https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27



P-VALUE CALCULATION

Testing nu->gamma correlations

Is there a **spatial-timing** correlation between the EHE alert event with Fermi flare?

H0: No spatial or time correlation between IceCube EHE alert event with Fermi 3FGL+3FHL catalogue

Use Fermi light curves collected from the past 9 years

Results soon to be published, now in iterations with reviewers

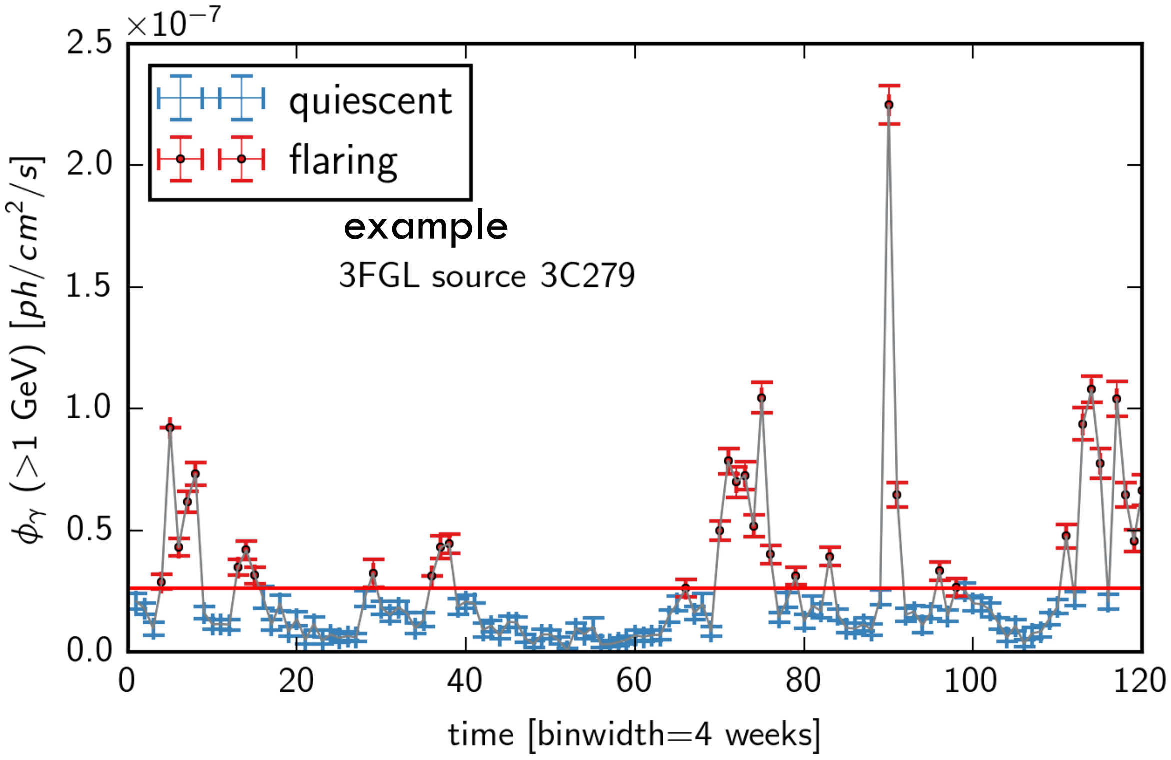
P-VALUE CALCULATION

How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

$$\mathcal{L}_{\text{flux}} \propto I_\gamma(t) / \langle I_\gamma \rangle$$

Hypo 1: ν detection scales to ***variations*** in γ flux of the source, regardless of γ luminosity



P-VALUE CALCULATION

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$$\mathcal{L}_{\text{flux}} \propto I_\gamma(t) / \langle I_\gamma \rangle$$

$$\mathcal{L}_{\text{flux}} \propto \frac{\phi_E(t)}{\sum_s^{N_s} \sum_i^{N_t} \phi_E(t_i)}$$

Hypo 1: ν detection scales to ***variations*** in γ flux of the source, regardless of γ luminosity

Hypo 2: ν detection scales linearly to γ energy flux. Brighter γ source more likely

P-VALUE CALCULATION

How often do we see a 3FGL source in the error window of EHE event

$$TS \propto \mathcal{L}_{\text{spatial}} \cdot \mathcal{L}_{\text{flux}} \cdot \mathcal{A}_{eff}(\theta)$$

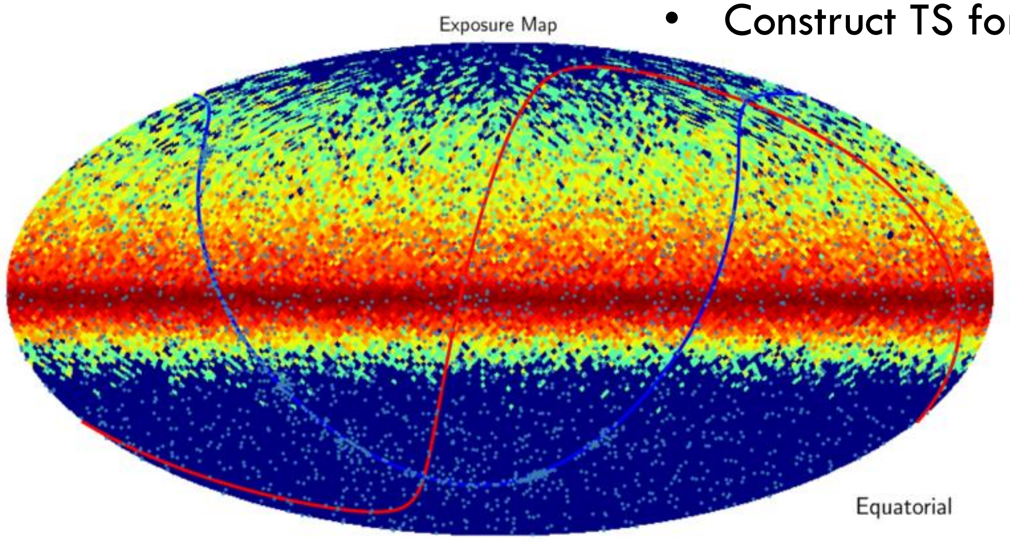
Scales with variations of γ flux of the source

Or

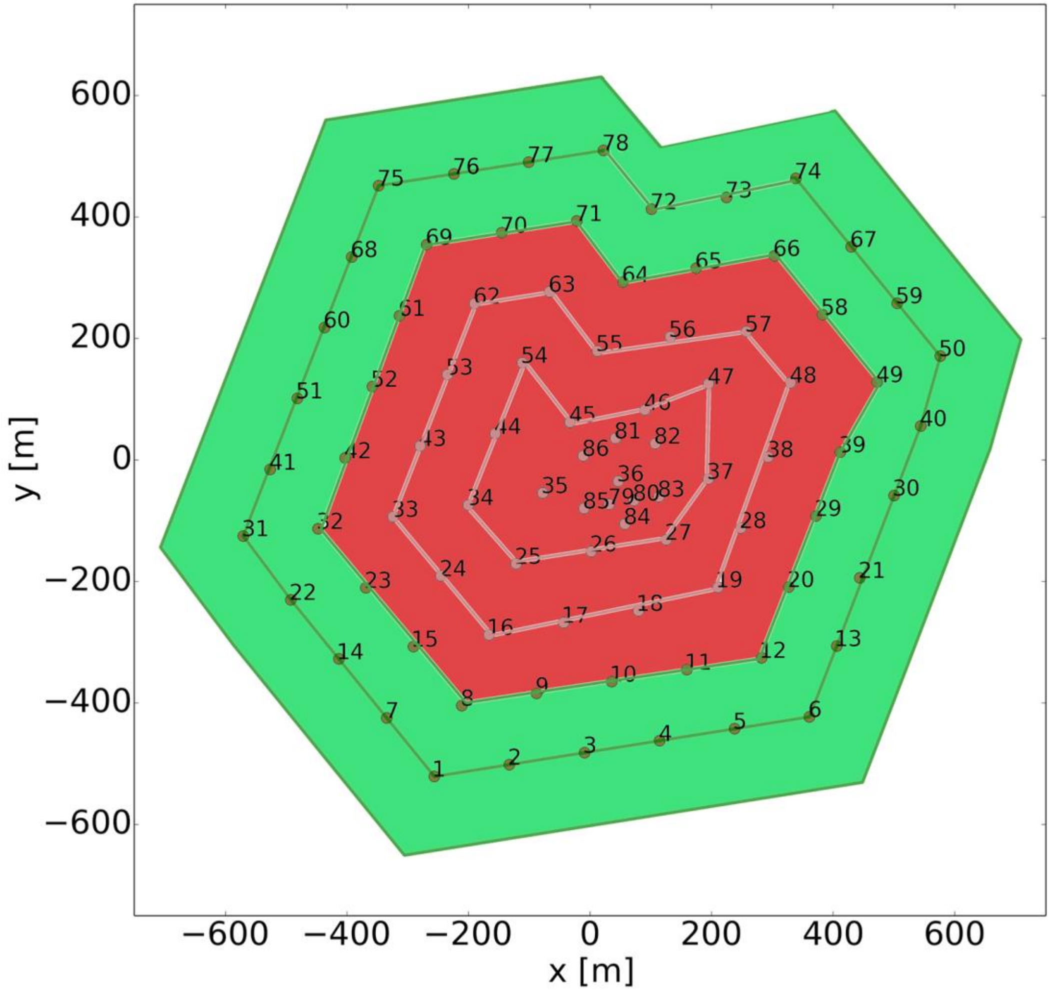
Scales with γ energy flux, the brightness of the source

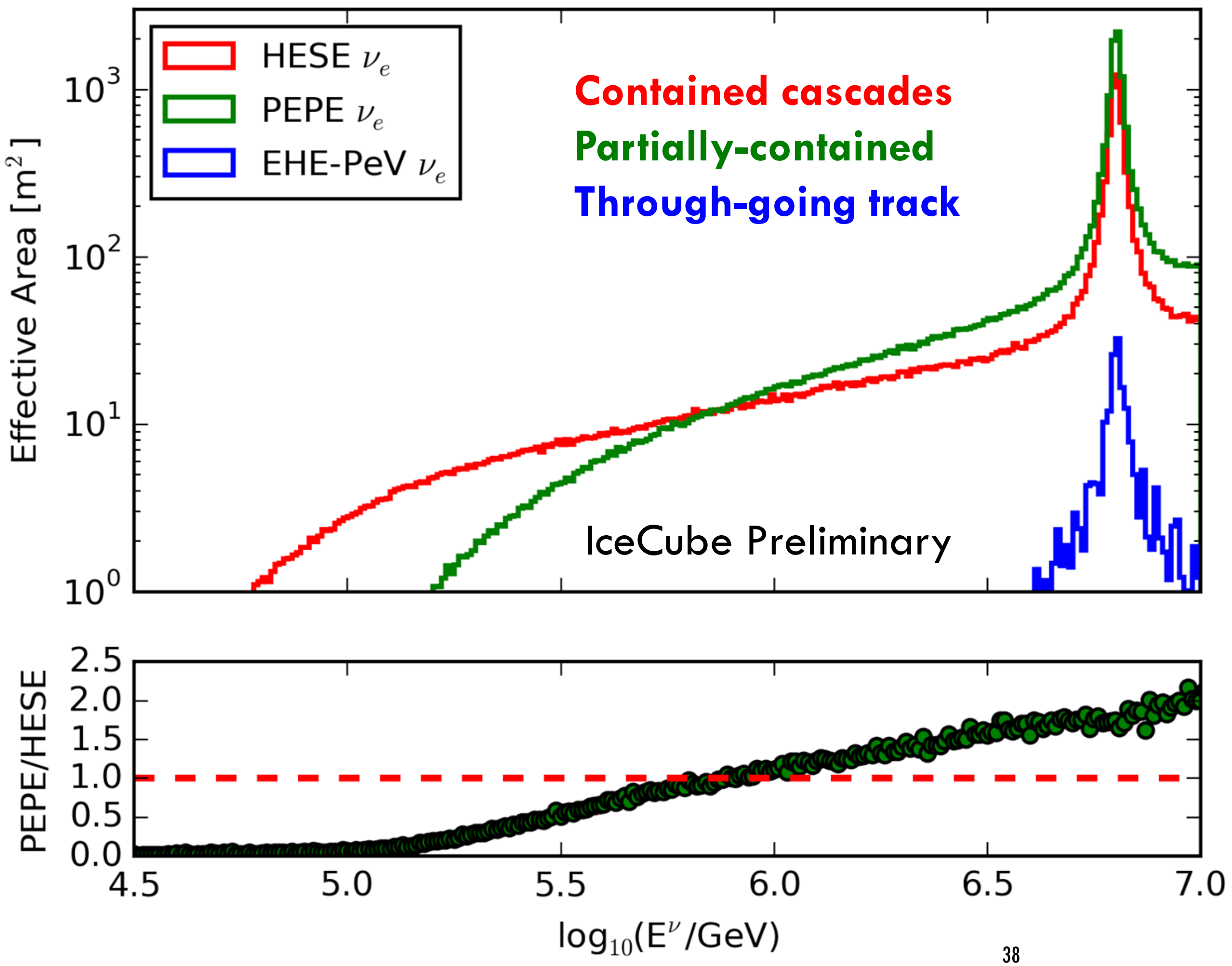
Pseudo experiments

- Randomly sample time t (flat pdf)
- Randomly sample DEC according to event selection pdf
- Randomly sample RA
- Construct TS for H0

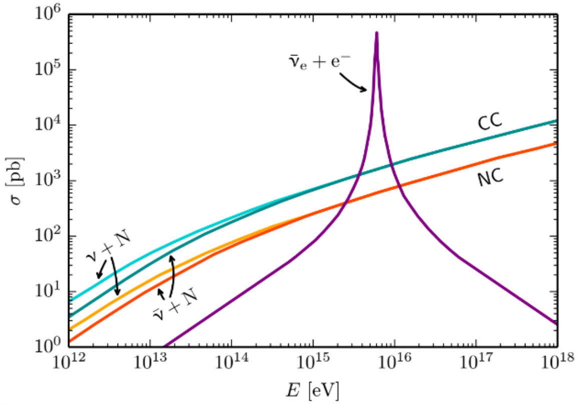


NEW ANALYSIS FOR PEV EVENT SEARCHES

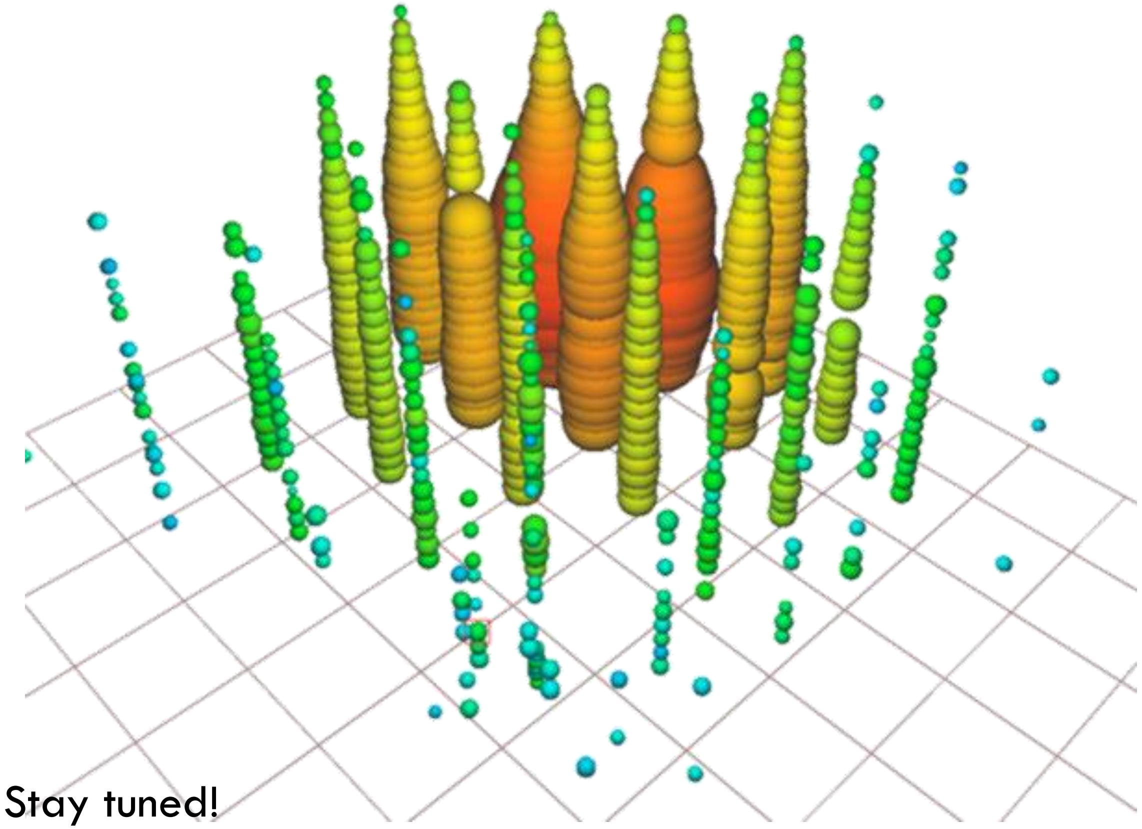


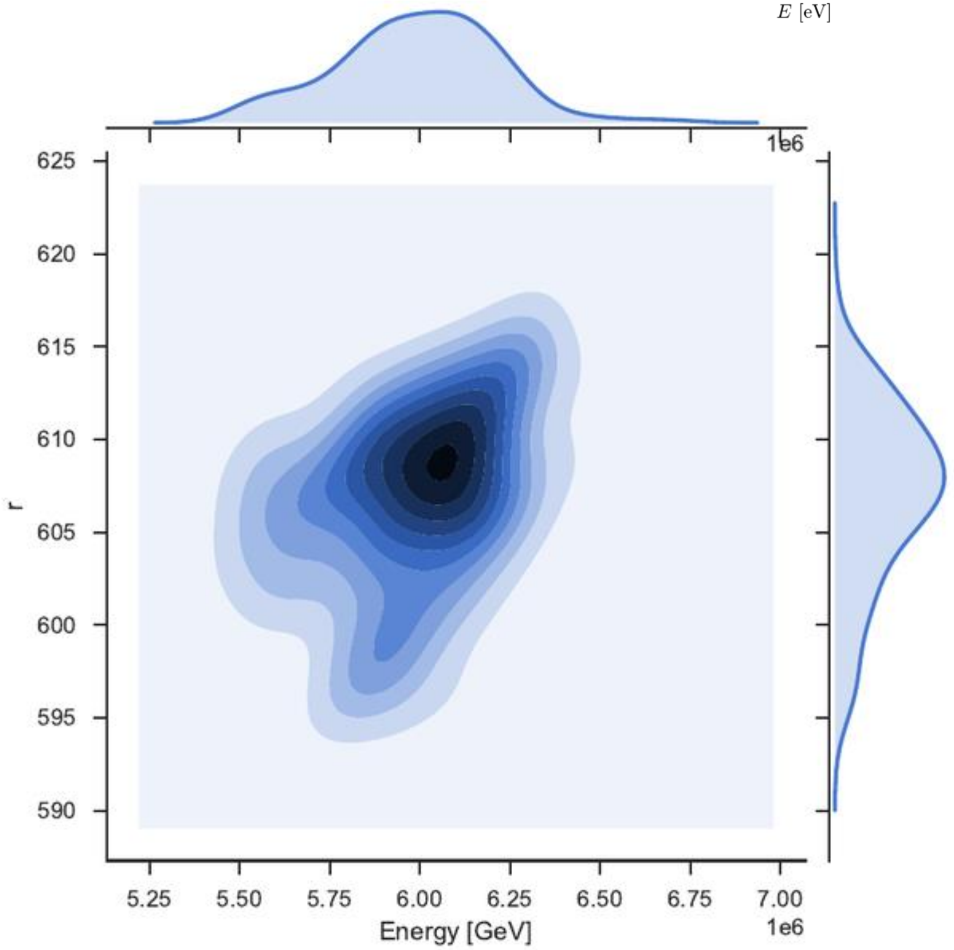


NEW: A NEW 6 PEV NEUTRINO CANDIDATE



Hadronic cascade with good angular resolution
Highest deposit energy event
Glashow candidate





Stay tuned!

THE FUTURE: GEN2

In-ice upgrade:

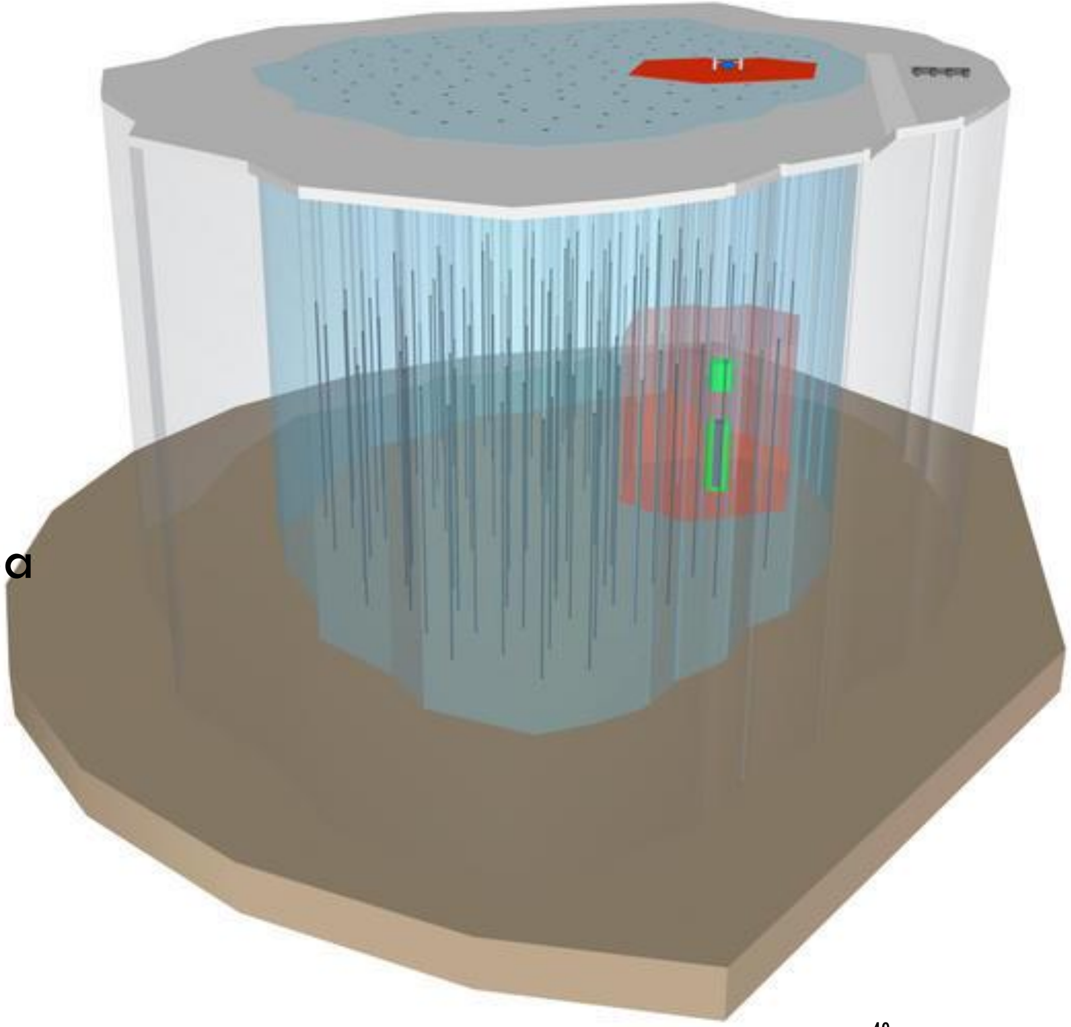
- ~ 10,000 more optical sensors
- 5 – 10 km^3 instrumented volume
- ~ 120 strings

Wish-list:

- **sensors** with directionality and more effective area
- smaller holes to reduce drilling cost
- a **surface array** for veto cosmic-ray background

Challenges:

- -45°C, 10,000 psi, logistics



DESIGNS FOR IN-ICE SENSORS

- More sparse string spacing → sensors need to have **larger effective area** (Cherenkov UV photons)
  - Benefits veto, event reconstruction
- For > **PeV neutrinos** we should have **PMTs looking up** since down-going is favoured due to **earth absorption**

IceCube DOM

35 cm

mDOM

36 cm

36 cm

- Directional information
- More sensitive area per module

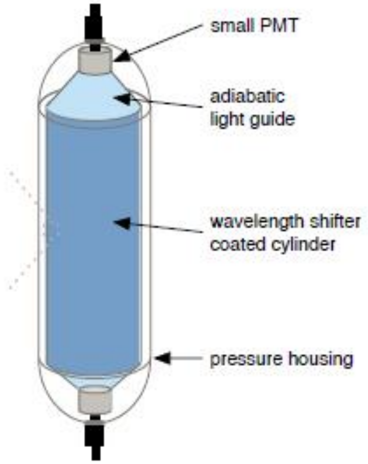
D-Egg

30 cm

30 cm

- Directional information
- More sensitive area per module
- Smaller geometry

WOM



11 cm

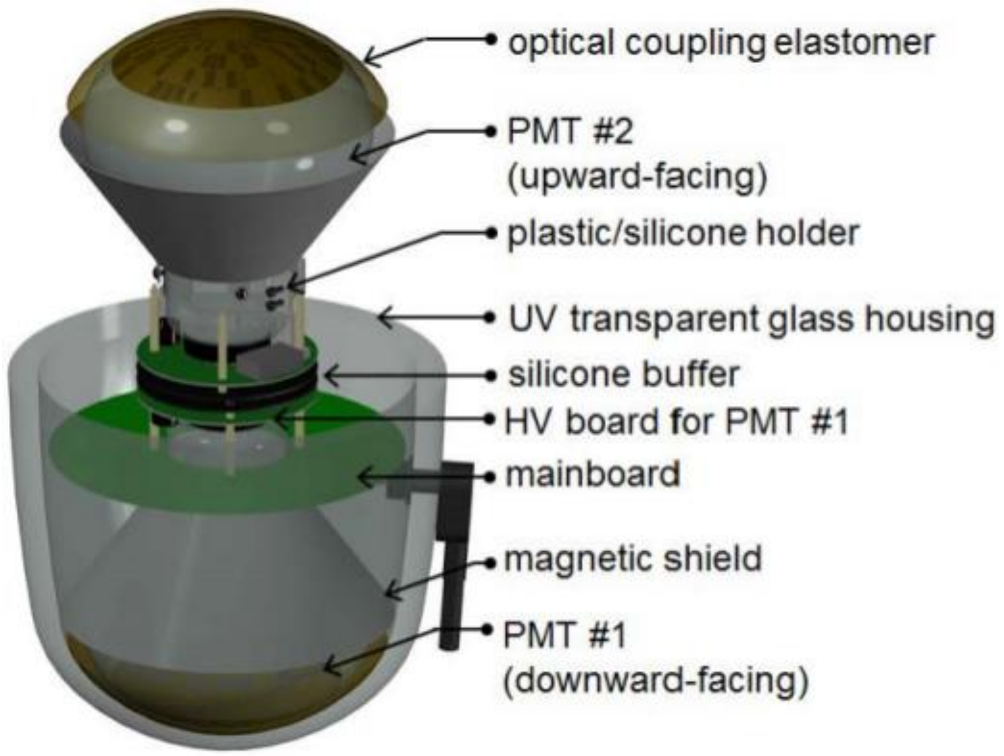
11 cm

- more sensitive area per $
- Small diameter
- Lower noise rate

D-EGG DETECTORS MAP OUT ICE

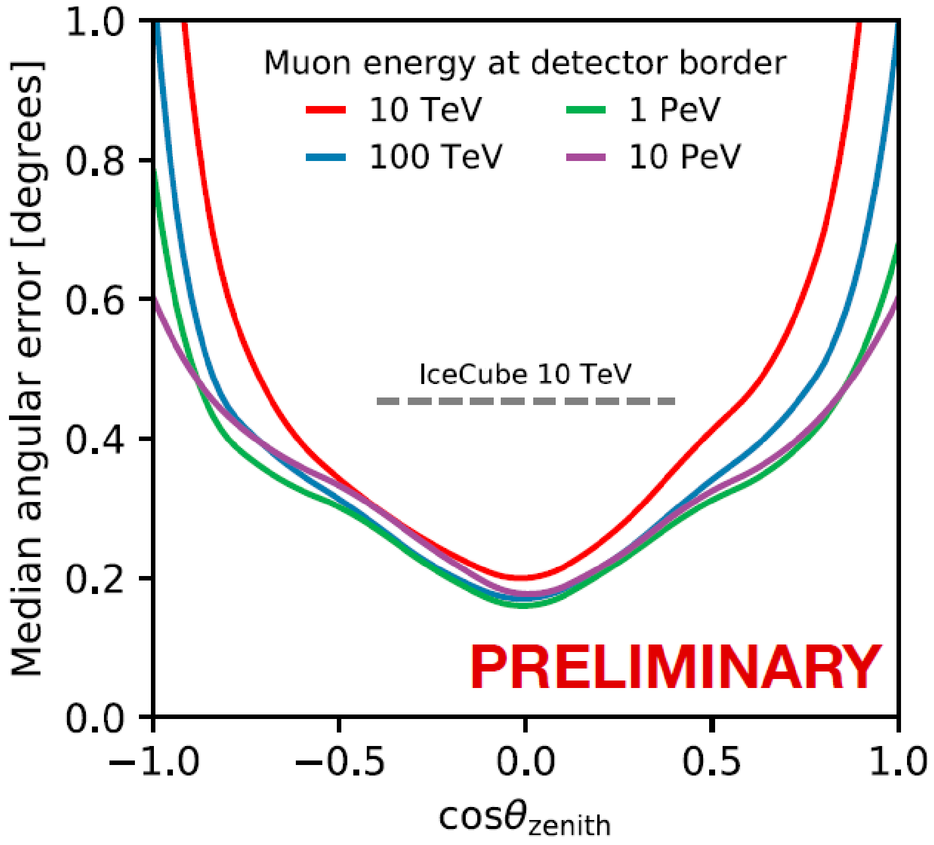
Phase 1 IceCube upgrade: better systematics and improve angular resolution

D-Egg schematics

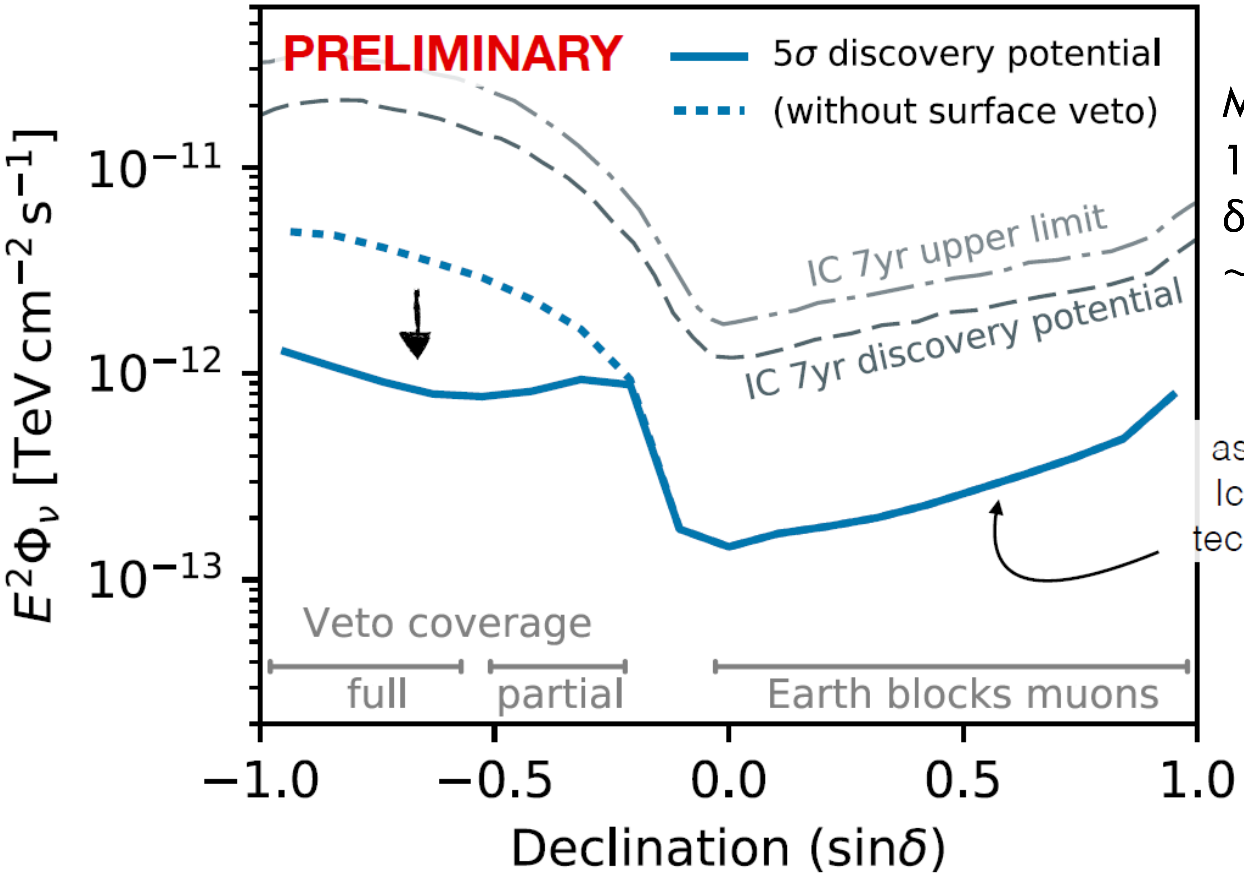


D-Egg prototypes

GEN2 POINT SOURCE SENSITIVITY



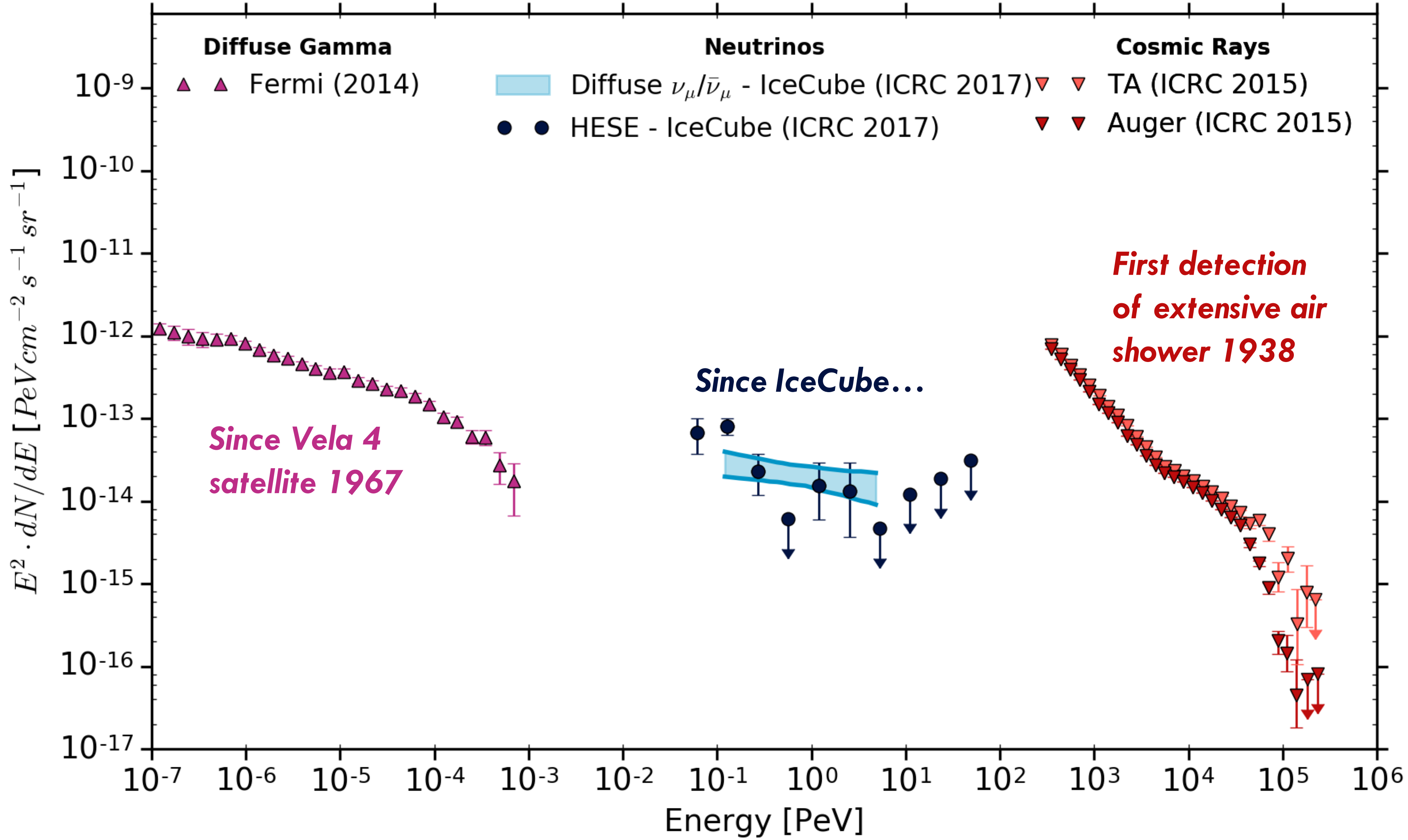
15 years IceCube + 15 years IceCube-Gen2 (7.9 km^3)



Markarian421
122 Mpc
δ=+38.21°
~1e-12

assumes
IceCube
technology

WAY TO GO FOR UHECR SOURCES?



THANK YOU VERY MUCH