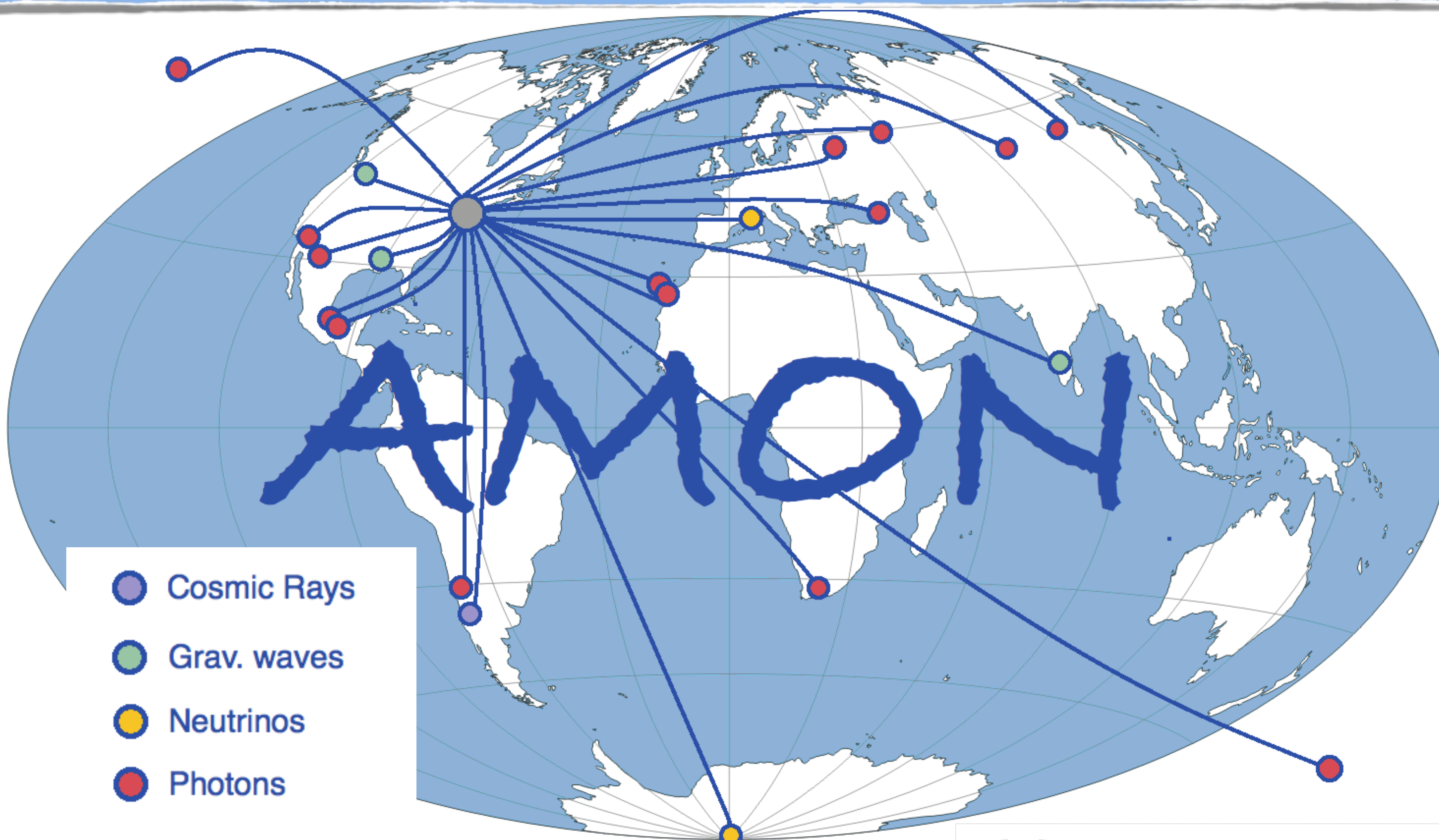
The Astrophysical Multi-Messenger Observatory Network & Neutral UHECRs



PennState
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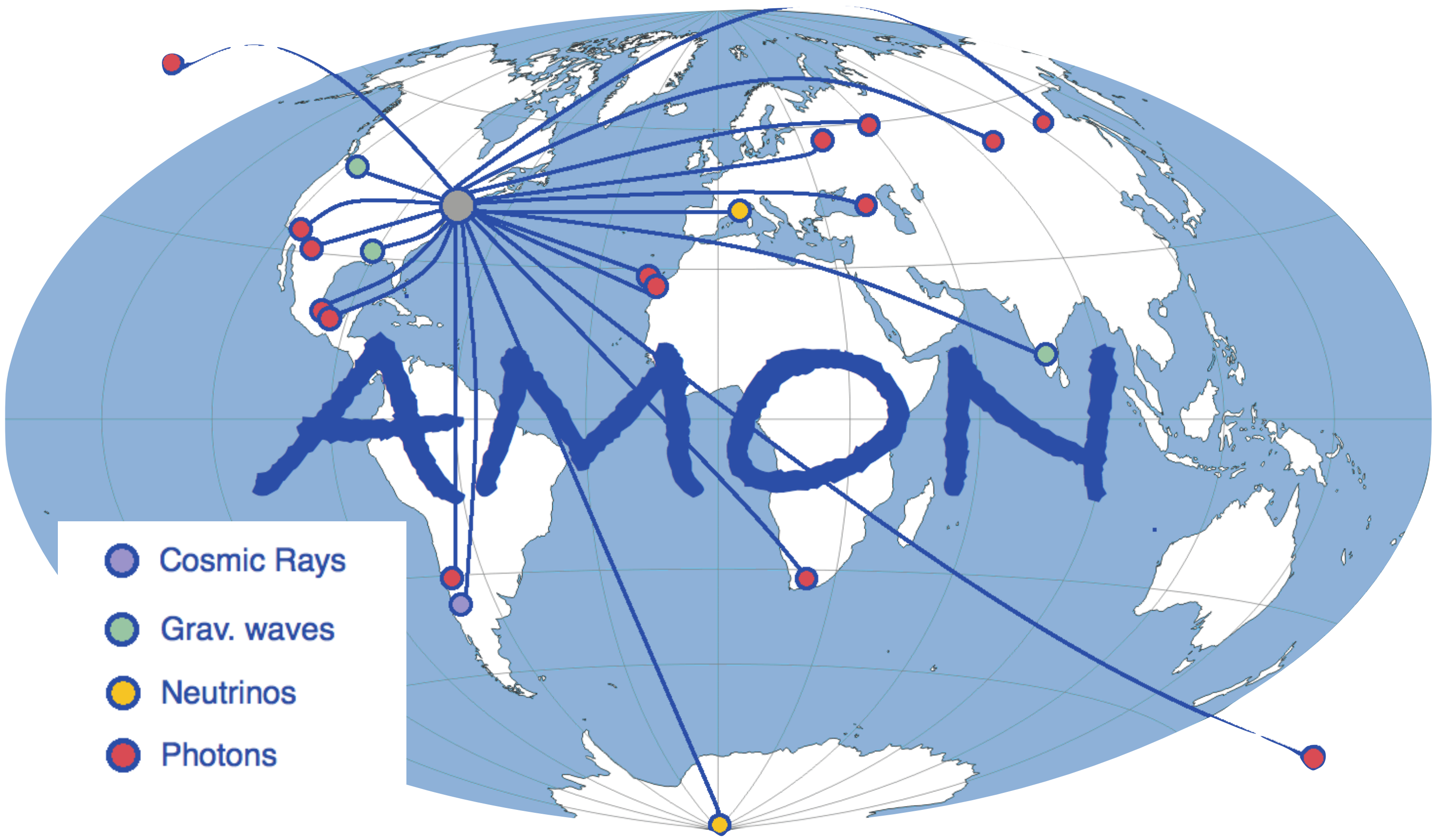
PIERRE AUGER OBSERVATORY

Foteini Oikonomou (for the AMON team)

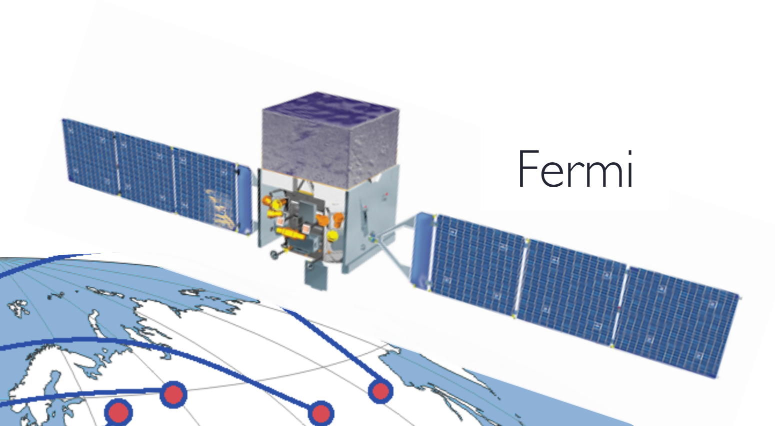
NeuCos DESY - May 31, 2017

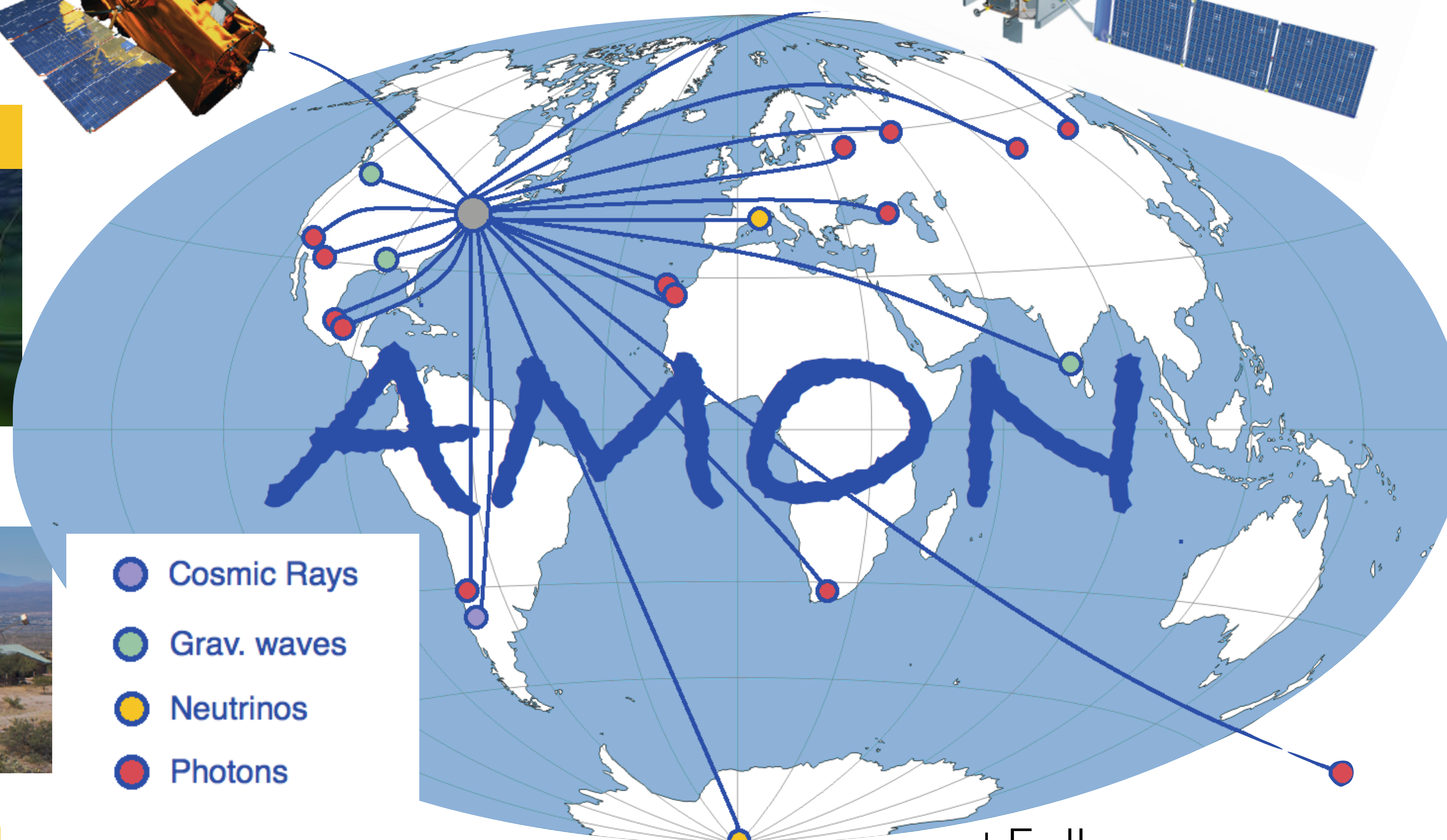
Outline

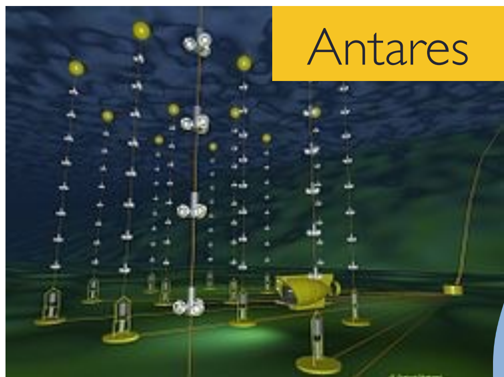
- AMON - status of operations
- IceCube real-time streams
- Auger - Neutral UHECRs
- **Discuss** - How can theory help optimise multi-messenger searches?

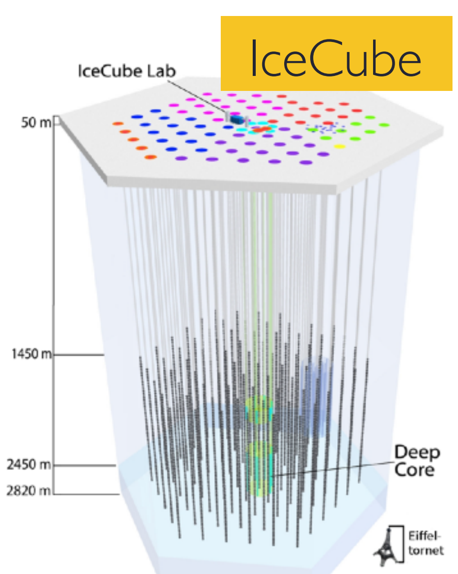


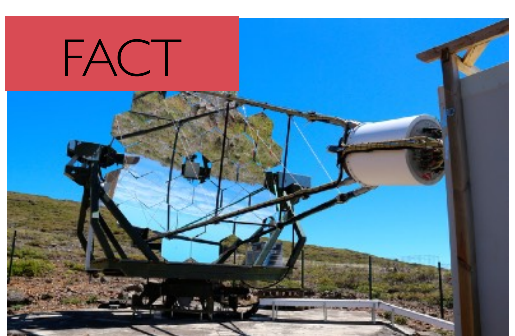
The Astrophysical Multi-messenger Observatory Network (AMON)











+Follow-up:

Swift XRT&UVOT

VERITAS MASTER

FACT LCOGT

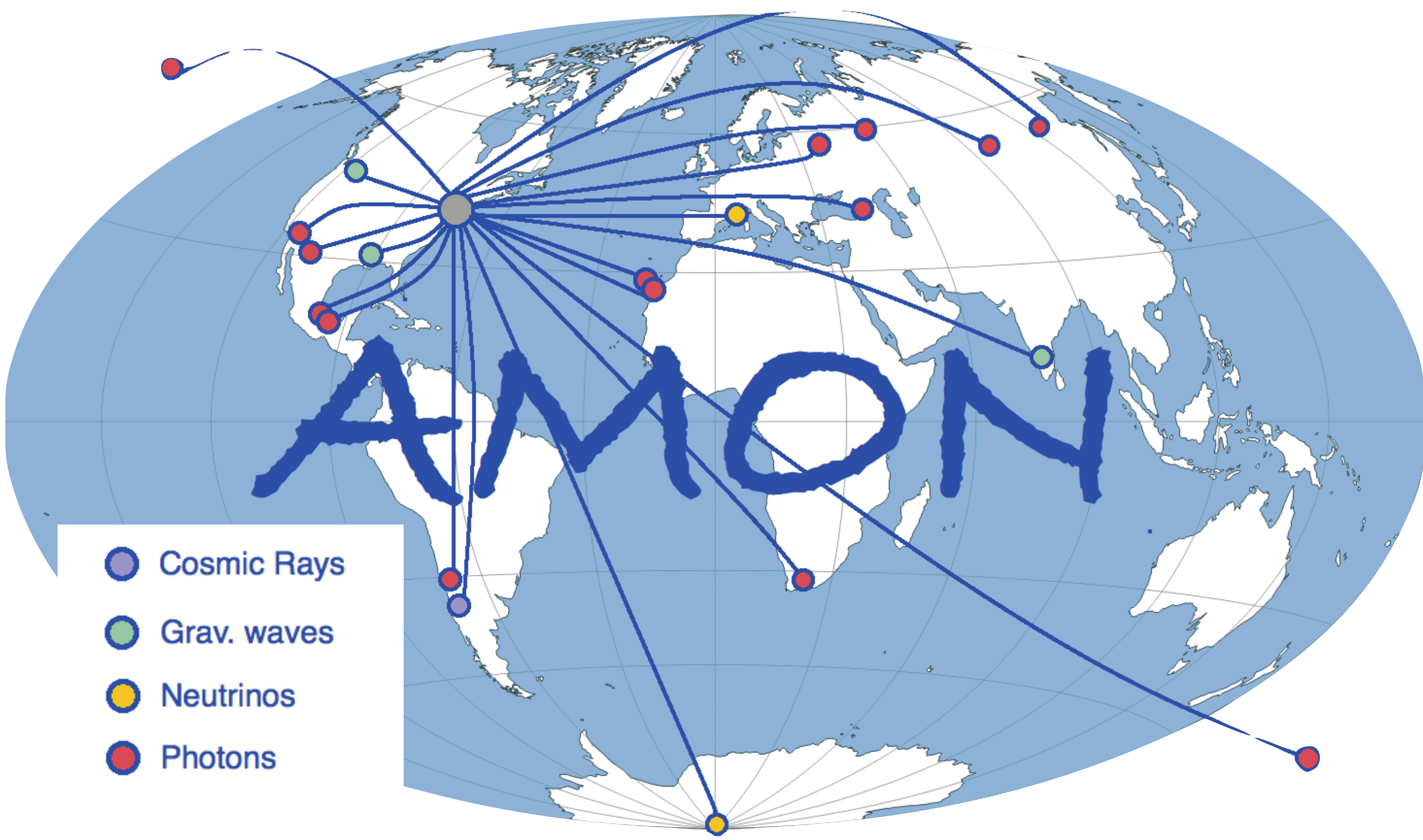
http://amon.gravity.psu.edu

+Pending: LIGO, MAGIC, H.E.S.S., PTF, TA

The Astrophysical Multi-messenger Observatory Network (AMON)

Triggering observatories:

- Transmit data/alerts to AMON in real-time



AMON:

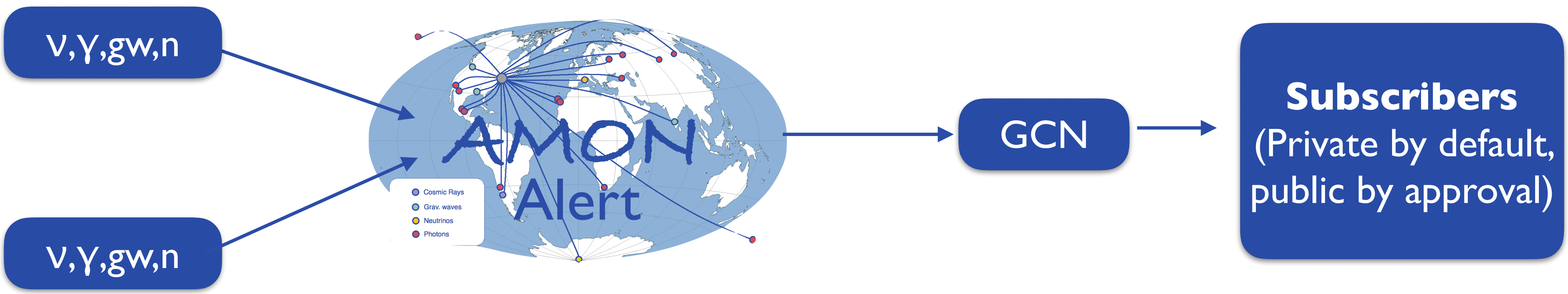
- *Real-time coincidence searches* in direction & time.
- *Real-time alerts* (via VOEvent & GCN).

Follow-up observatories:

- Respond to AMON alerts
- Optical feedback on potential multi-messenger transients.

AMON network status

Data streams: time, arrival direction, energy, false positive rate (false positive rate may dominate data rate)



AMON real-time alert system active as of May 2015

Real time streams as of April 2016 (IceCube HESE - 50+ subscribers/IceCube EHE - 45+ subscribers/Fermi LAT/Swift BAT)

AMON status (participation)

	Stream content	Test Stream (Scrambled data)	Real Data Stream
ANTARES	✓	in progress	in progress
Auger	✓	✓	in progress
FACT	✓	✓	in progress
Fermi LAT	✓	n/a	✓
HAWC	in progress	in progress	in progress
IceCube EHE	✓	✓	✓
IceCube HESE	✓	✓	✓
IceCube OFU	✓	✓	✓
IceCube singlet	✓	✓	in progress
Swift BAT		n/a	✓
VERITAS	in progress	in progress	in progress

AMON Analyses

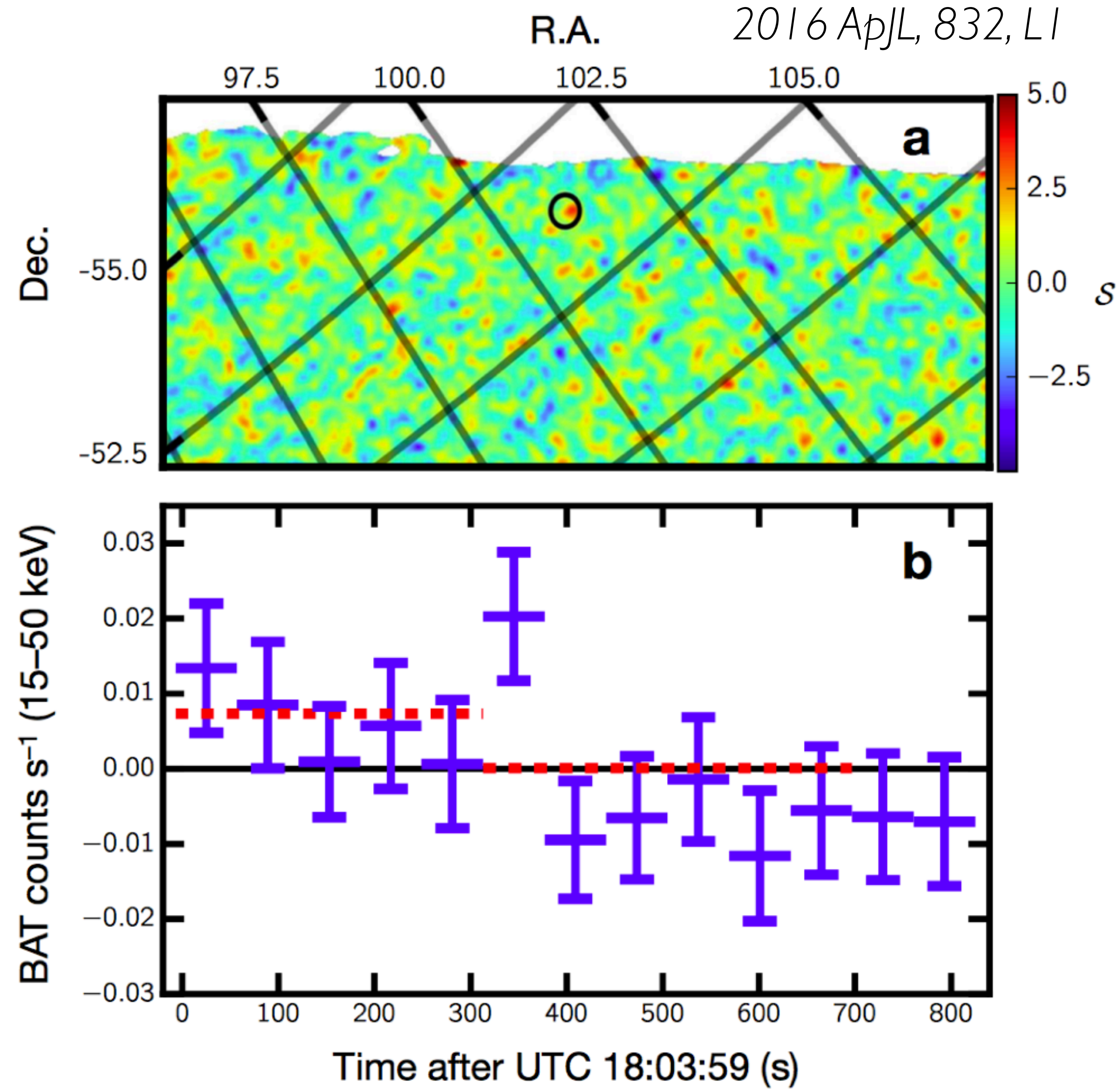
Archival analyses:

- Gamma-rays from FRB 131104 (*Delauney et al, 2016 ApJL, 832, L1*)
- Fermi LAT – IC40/59 *(Keivani et al. ICRC 2015, Turley et al. in prep)*
- Primordial black holes *(Tešić, ICRC 2015)*
- VERITAS blazars – IC40 *(Turley et al, APJ 833, 117 (2016))*

Realtime analyses:

- IceCube triplet follow-up *(led by DESY group, submitted to A&A)*
- Swift XRT/UVOT – IceCube HESE
- SwiftBAT–IceCube subthresh.
- HAWC – IceCube subthresh.
- Auger–IceCube subthresh.

Delauney et al., 2016 ApJL, 832, L1



IceCube real-time alert system

Astropart. Phys., 92, 30 (2017)

HESE

- 4 alerts/year ~ 1 signal event
- 3 track-like highest p_{cosmic} events followed up by Swift *(NASA1215235 award)*

EHE

6 events /year ~ 3 signal events

Alerts pass-through AMON

Singlet stream

AMON only

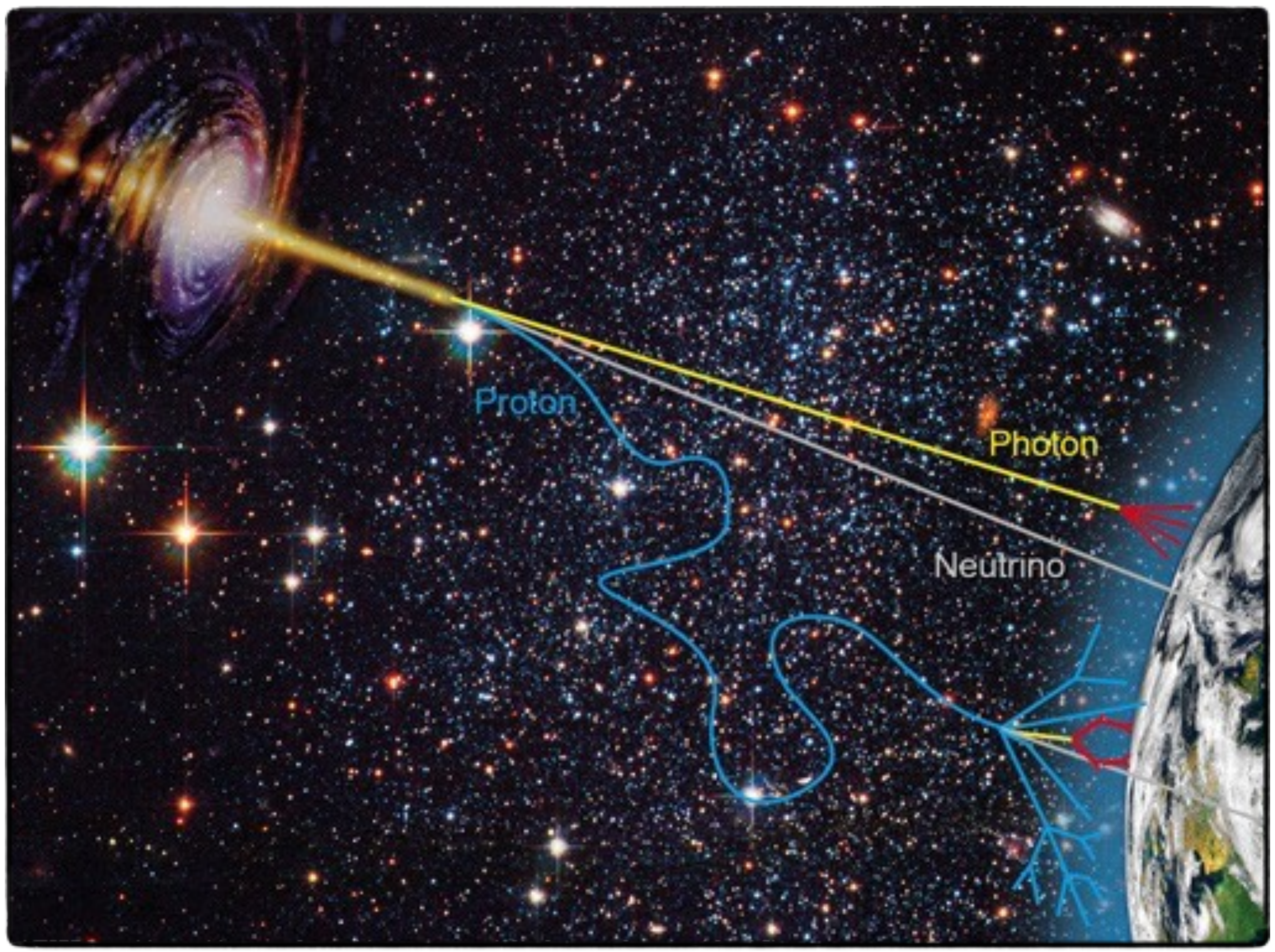
OFU (optical/x-ray follow-up)

2 or more northern tracks, < 100s, < 3.5°

GFU (gamma-ray follow-up)

Excess of events from monitored (e.g. LAT) sources, 3 week window

Auger data of interest to multi-messenger monitoring



UHE neutrals guaranteed by UHECR observations (through GZK process):

$p+\gamma_{CMB/source} \longrightarrow n+\pi^{+}$

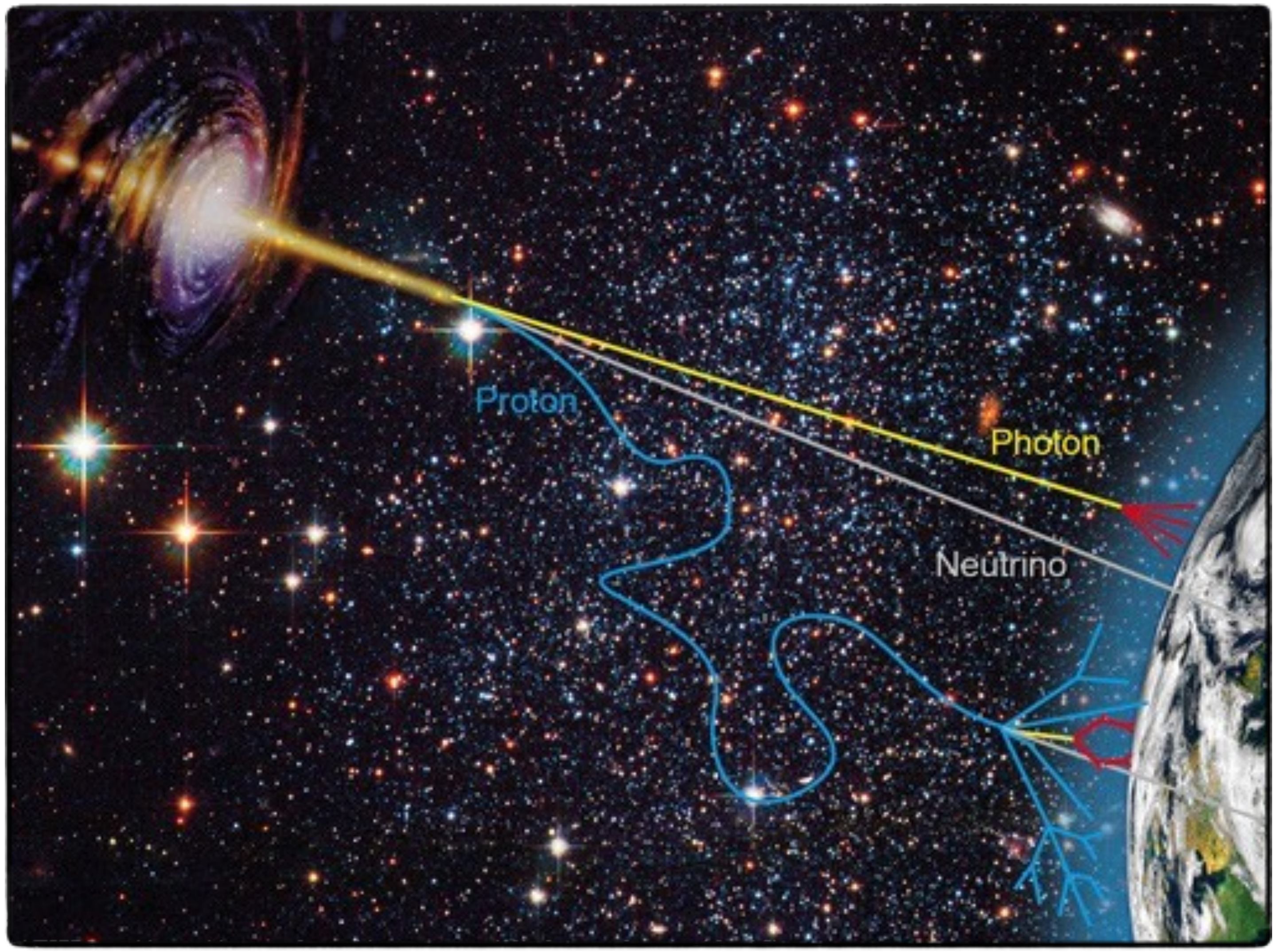
$n+\gamma_{CMB/source} \longrightarrow p+\pi^{0}$

$\hookrightarrow \gamma\gamma$

$n+\gamma_{CMB/source} \longrightarrow p+\pi^{+/-}$

$\hookrightarrow e^{+}+e^{-}+\nu\nu$

Auger data of interest to multi-messenger monitoring



- ☒ UHE charged hadrons
  (magnetic deflections/delays)
- ☑ UHE neutrons
- ☑ UHE photons
- ☑ UHE neutrinos

UHE neutrons in Auger

- $L_n \sim c \cdot \tau_n \cdot \gamma_n \sim 9\ (E_n/1\ \text{EeV})$ kpc [c.f. Milky Way radius ~ 8 kpc]
- Neutron showers indistinguishable from proton showers
- Identify from excess of CRs from source direction at E > 1EeV
- Strong limits on Galactic steady EeV neutron sources (Auger Coll. ApJ 789 (2014) L34)

		Weighted P-value P_w			
Class	No.	≥1 EeV	1-2 EeV	2-3 EeV	≥3 EeV
msec PSRs	68	0.48	0.40	0.22	0.61
γ-ray PSRs	77	0.23	0.13	0.71	0.24
LMXB	87	0.37	0.43	0.81	0.40
HMXB	48	0.014	0.011	0.061	0.27
H.E.S.S. PWN	17	0.083	0.021	0.98	0.21
H.E.S.S. other	16	0.91	0.93	0.94	0.35
H.E.S.S. UNID	15	0.82	0.78	0.98	0.94
Microquasars	13	0.28	0.16	0.85	0.96
Magnetars	16	0.69	0.52	0.60	0.46
Gal. Center	1	-	-	-	-
Gal. Plane	1	-	-	-	-

Auger Coll. ApJ 789 (2014) L34

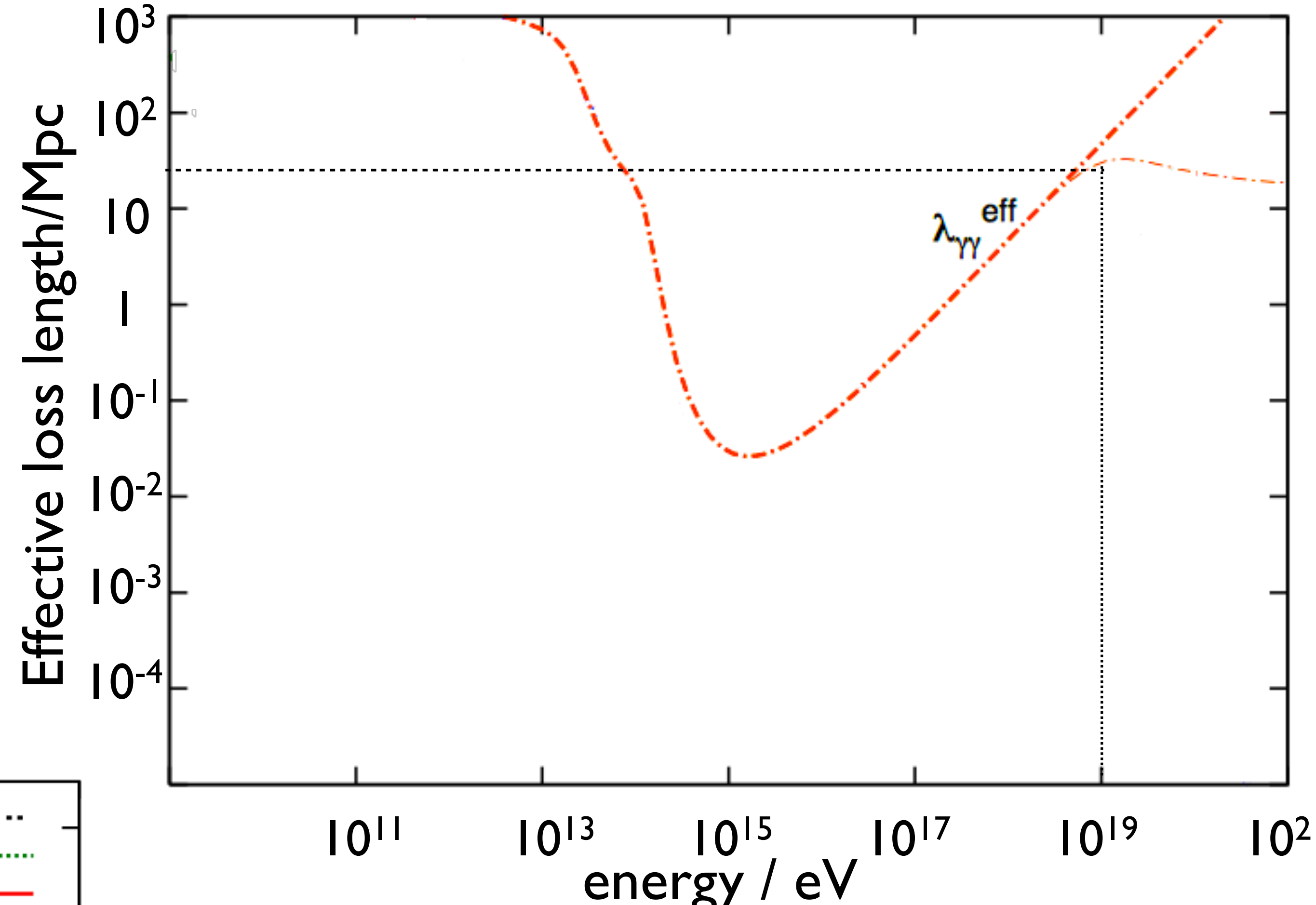
UHE Photons

$\gamma \longrightarrow e \longrightarrow \gamma \ldots$

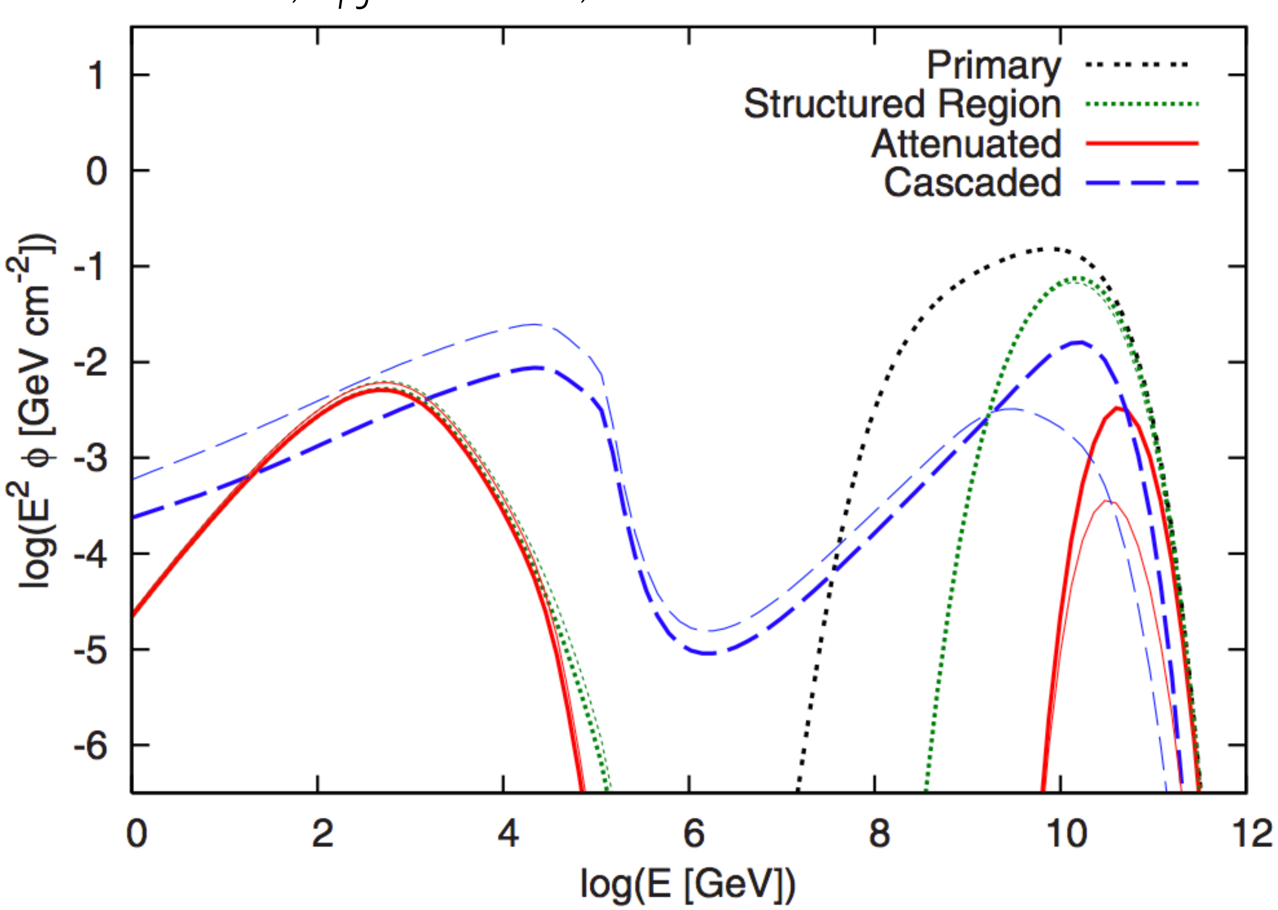
At extreme KN regime cascade propagates ~as single particle

Effective photon loss length @10^{20}eV~10-100 Mpc

Murase, ApJL 745:L16, 2012



Murase, ApJL 745:L16, 2012

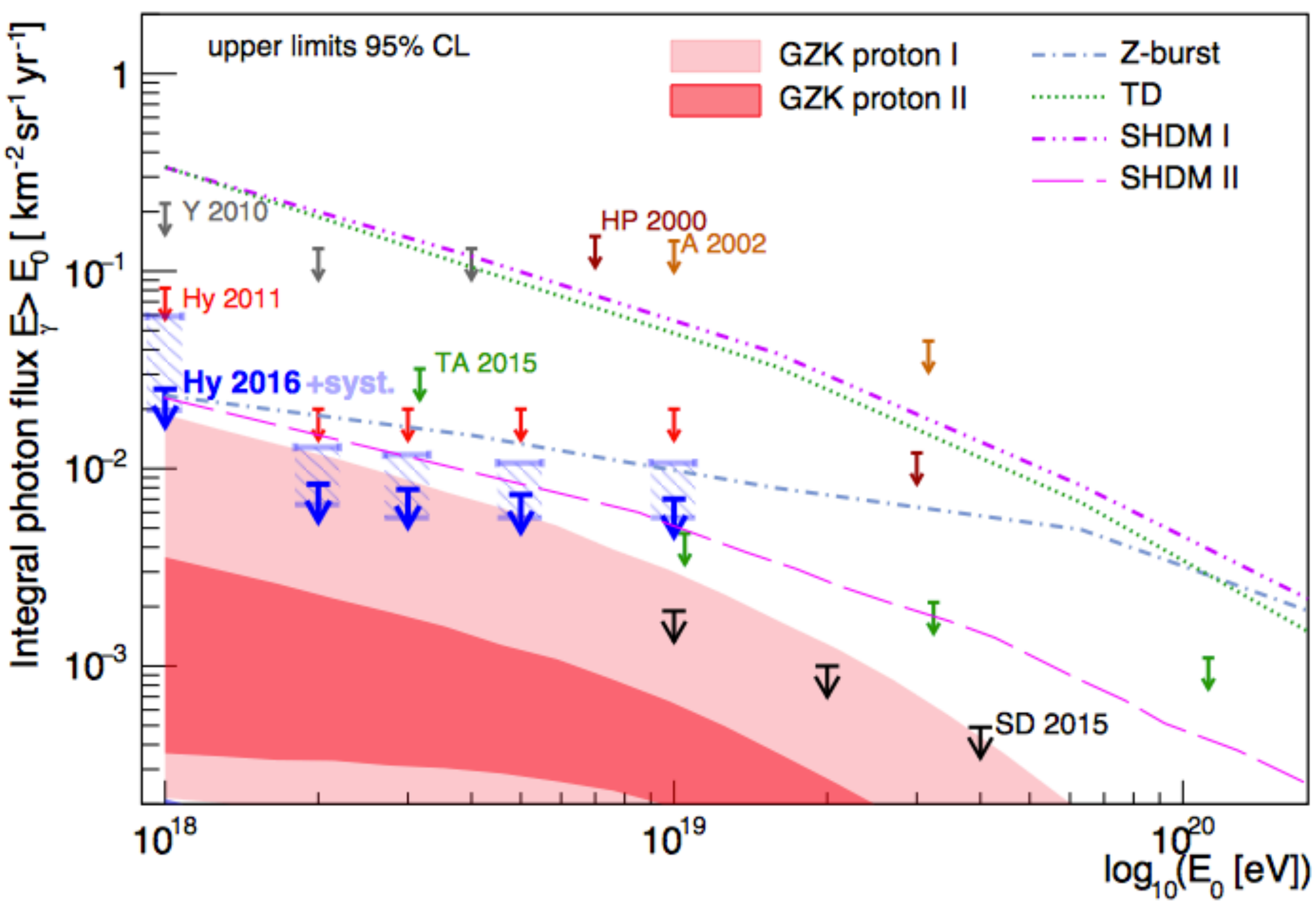


Observe GeV/TeV counterpart with small delay:

$$\delta t \sim \frac{2\theta^2 d}{2c} \sim 5\ \mathrm{min} \cdot \left(\frac{B}{10^{-9}\ \mathrm{G}}\right) \cdot \left(\frac{d}{100\ \mathrm{Mpc}}\right) \cdot \left(\frac{E_e}{10^{18}\ \mathrm{eV}}\right)^{-2}$$

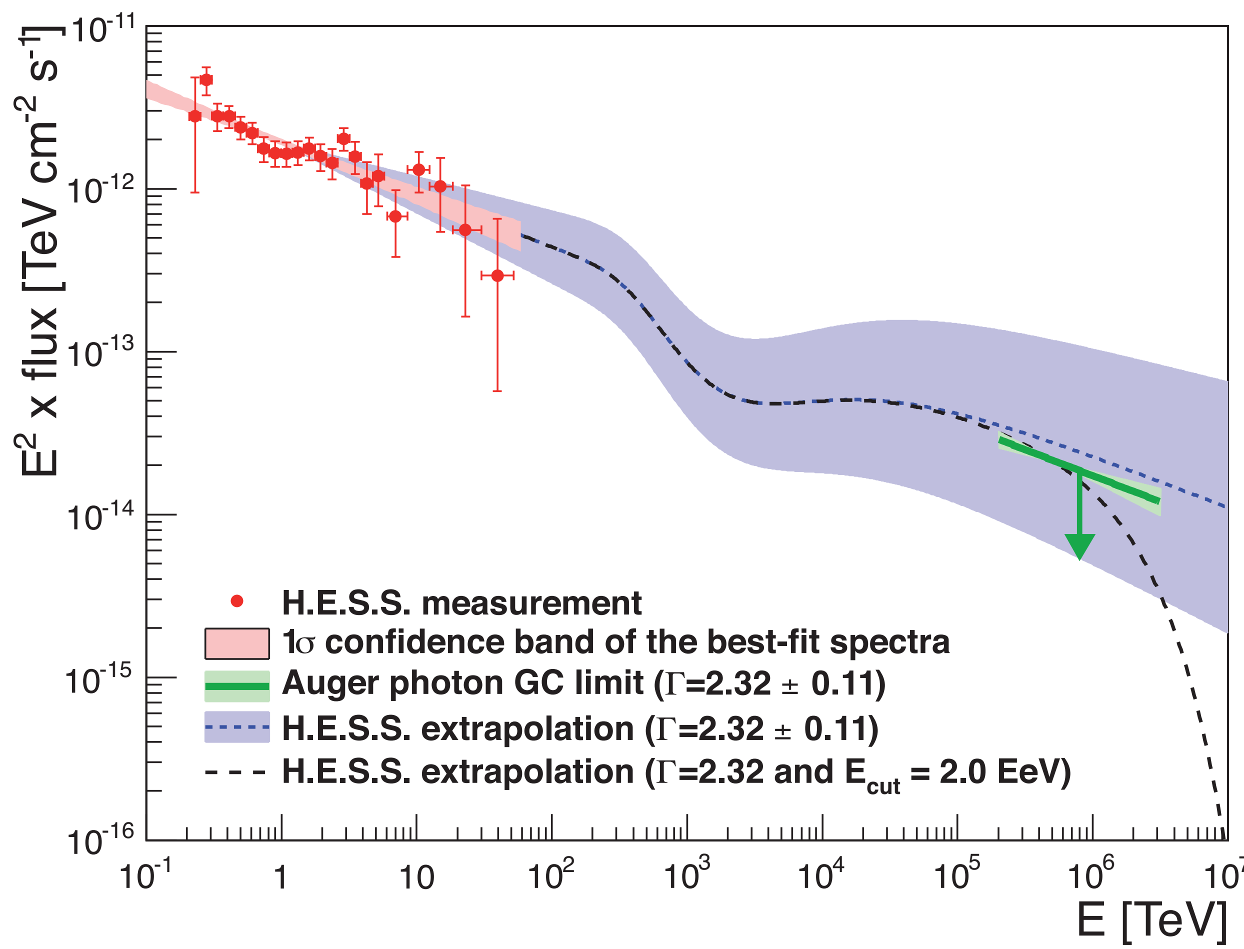
UHE photon search results

Auger Coll., JCAP04(2017)009



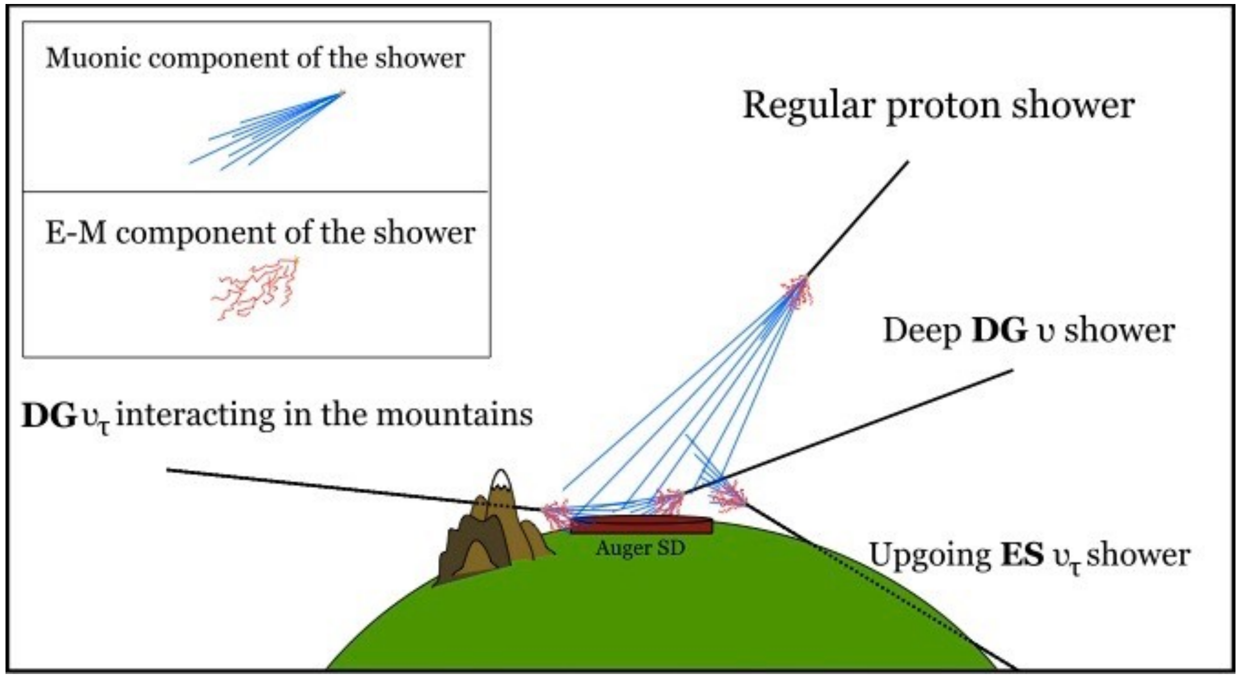
Photons < 0.1% (1 EeV) - 2.7% (10 EeV) of total CR flux at 95% CL

Auger Coll., ApJL 837:L25, 2017

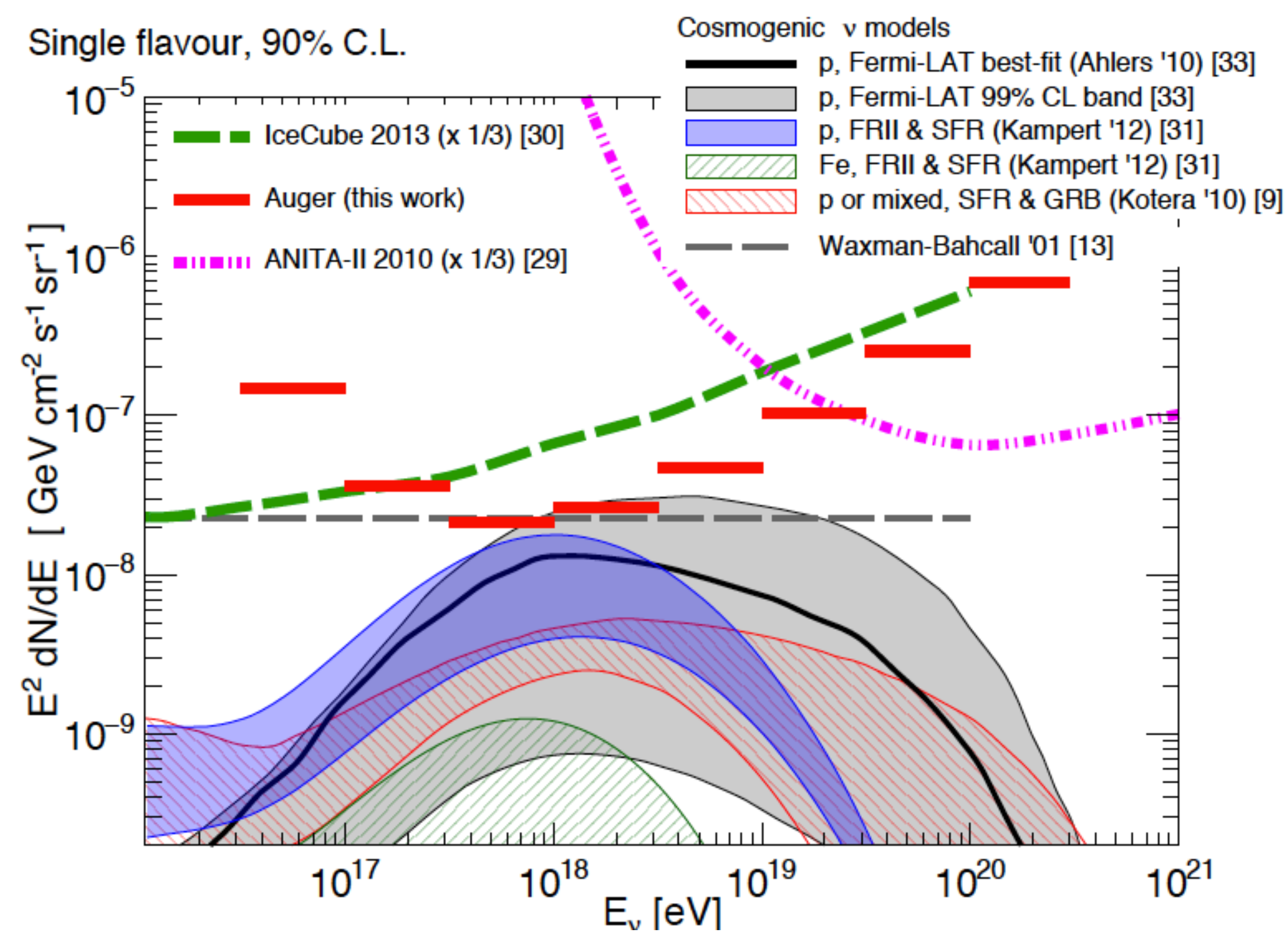


Strict upper limits on steady Galactic sources from targeted search

UHE neutrinos



- Auger SD sensitive to earth-skimming tau neutrinos and highly inclined neutrinos of all flavours
- Present limits (data to July 2013) below Waxman-Bahcall bound
- Null results from follow-up of GW150914 and GW151226, limit UHE nu output of these sources *(Auger Coll. PRD 94, 122007 (2016))*



Auger Coll. PRD 91, 092008 (2015)

Auger contribution to AMON

Neutron trigger:

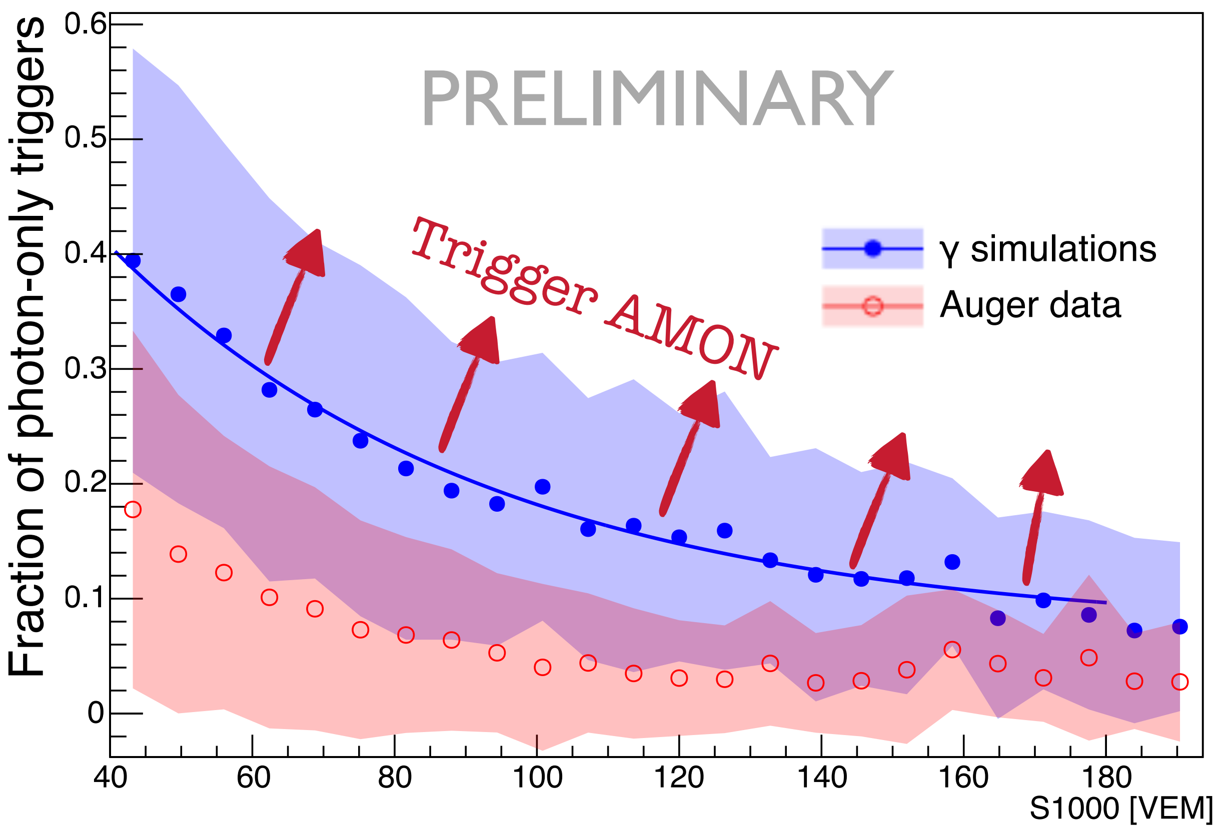
- Each Auger shower is a neutron candidate (cf. IceCube singlet stream)
- Background doublet rate ~1/yr, threefold coincidences ~0.05/yr* (100s/3°)

Realtime photon tagging:

- (in progress) use info from triggers installed in 2013 in SD array

Neutrino trigger:

- Easy to implement, based on SD observables
- Follow-up LIGO alerts within 12 hours



*sensitive to other experiments' data stream rate Smith et al. 2013, Astroparticle Physics, 45, 56-70

Summary/Discussion

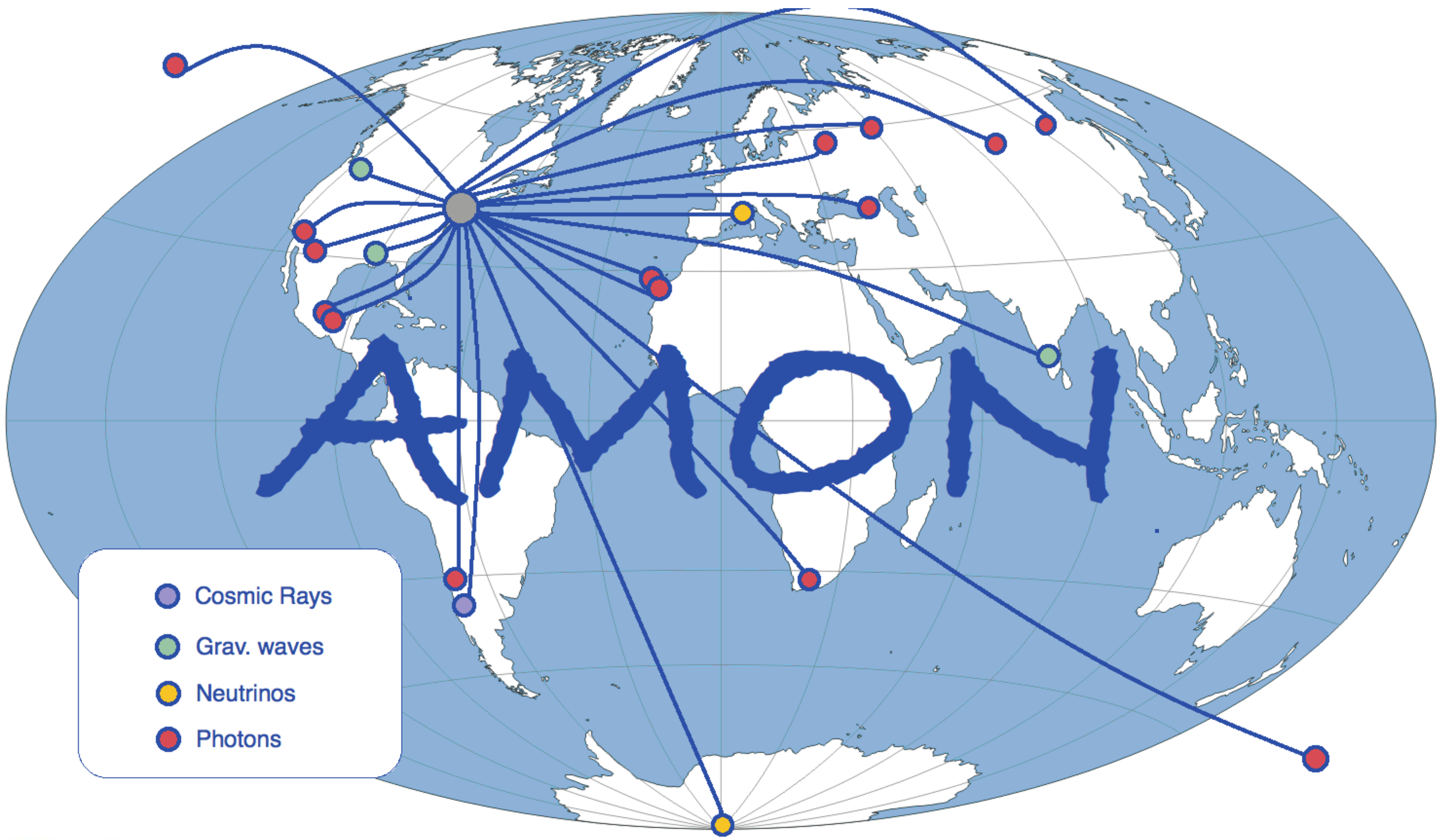
- AMON expands multi-messenger discovery space
- Real-time operation since 2015 with IceCube
- Antares, Auger, HAWC to join real-time phase in next months

- How can we use theory to improve multi-messenger strategies? (When should a telescope interrupt observations?)
- What directions/objects should we target/monitor?

Back-up slides

The AMON development and advisory team

A. Ashtekar[1,3], Sydney Chamberlin[1,2,3], S. Coutu[1,2,3], D. Cowen[1,2,3], J. DeLaunay[1], A. Falcone[2,3], G. Fillipatos [2,3], D. Fox[2,3], A. Keivani[1,3], P. Mészáros[1,2,3], C. Messick[1], M. Mostafá[1,3], K. Murase[1,3], C. Hanna[1,3], F. Oikonomou[1,3], B. S. Sathyaprakash, G. Tešić[1,3], M. Toomey[1,2], C. Turley[2]



http://sites.psu.edu/amon/

[1]Department of Physics, [2]Department of Astronomy and Astrophysics

[3]Insitute for Gravitation and the Cosmos, [4]Computer Science and Engineering,

[5]Insitute for CyberScience

Background rates (slightly outdated - for illustration)

		IceCube	ANTARES	LIGO-Virgo	Auger	BAT	GBM	LAT	HAWC
(a) Single streams	Above thresh.	~0	~0	~0	~0	~100	~250	~10	~10
	Subthreshold	8.8×10^4	2.9×10^4	3.2×10^3	2.4×10^5	1.4×10^5	3.1×10^2	3.9×10^4	2.6×10^4
(b) Pair-wise FPR	IceCube	30	1.5	35	1.8	11	10	24	6.5
	ANTARES	1.5	0.5	12	1.1	0.7	3.5	7.1	0.6
	LIGO-Virgo	35	12	N/A	8.4	53	0.6	16	10
	Auger#	1.8	1.1	8.4	20	2.9	2.5	5.9	1.5
	BAT	11	0.7	53	2.9	N/A	16	32	3.3
	GBM	10	3.5	0.6	2.5	16	N/A	5.0	3.2
	LAT	24	7.1	16	5.9	32	5.0	N/A	6.8
	HAWC	6.5	0.6	10	1.5	3.3	3.2	6.8	N/A
(c) High significance	GRB lt. curve†	0.071	0.003	0.16	-	0.0004	0.08	0.13	0.019
	SNe lt. curve†	1.5	0.07	3.4	-	0.009	1.6	2.7	0.4
	3-fold coinc.	0.15	0.03	0.31	0.64	0.12	0.09	0.40	0.08
	3-fold coinc#	0.10	0.02	0.15	0.06	0.08	0.04	0.23	0.04
	High-sig. EM*	0.015	0.002	0.045	0.044	0.010	0.014	0.039	0.005
	PBH search‡	0.13	0.01	-	0.21	-	-	-	0.35

Auger events for the pairwise (and optionally threefold) analysis are selected with galactic latitude within ±5° and energy ≥ 1 EeV.
† Coincidence rate of event pairs with serendipitous follow-up detection of a GRB or SNe light curve (not including galactic searches).
* Event pairs with above threshold EM detection. GBM not included as the high significance partner, due to poor spatial localization.
‡ An additional temporal cut of $\Delta T = 1$ s is applied to the pairwise analysis for TeV and higher observatories, to search for primordial black holes and other exotic phenomena. Shown here are the FPRs for pairwise coincidences with HAWC.

Expected AUGER background doublets/yr

Expected threefold AMON coincidences inc. AUGER/yr

AugerPrime: Photon & Neutrino reach

Auger Coll, PoS(ICRC2015)1103

Increased exposure
Improved low-energy trigger (low-energy threshold)
Improved mass discrimination power