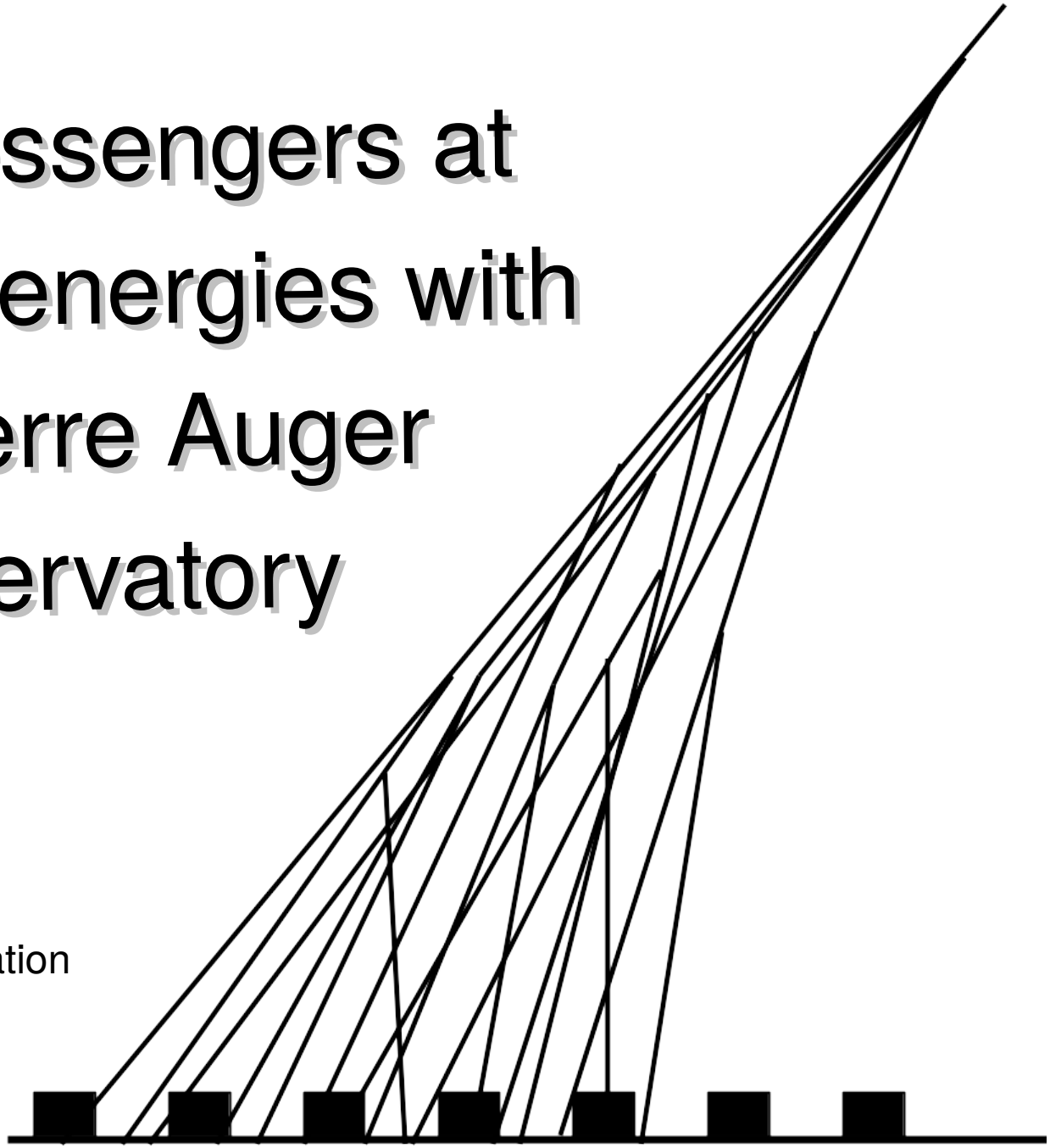
Multi-messengers at ultra-high energies with the Pierre Auger Observatory

Julien Souchard,
on behalf of the
Pierre Auger Collaboration



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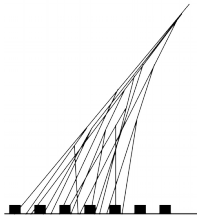
PIERRE AUGER OBSERVATORY

Outline



- Ultra High Energy Cosmic Rays & The Pierre Auger Observatory
- Neutral Particle Searches
- Follow-up Searches

Ultra High Energy Cosmic Rays - Spectrum

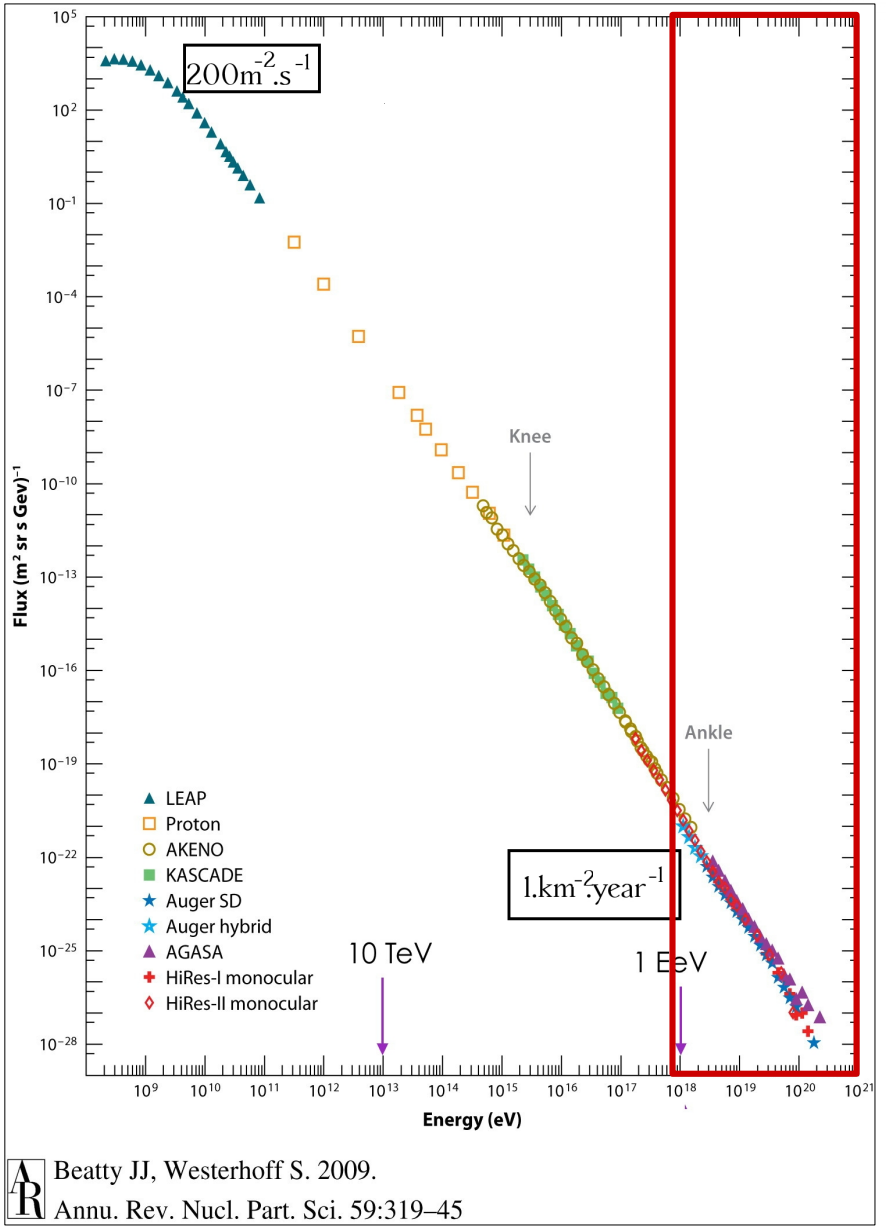
Ultra **H**igh **E**nergy **C**osmic **Ray**s (**UHECRs**) :

- ultra high energies : $E > 10^{18}$ eV
- very limited flux : $< 1.km^{-2}.year^{-1}$
- nucleus from H to Fe & neutrals ($n/\gamma/\nu$) (?)

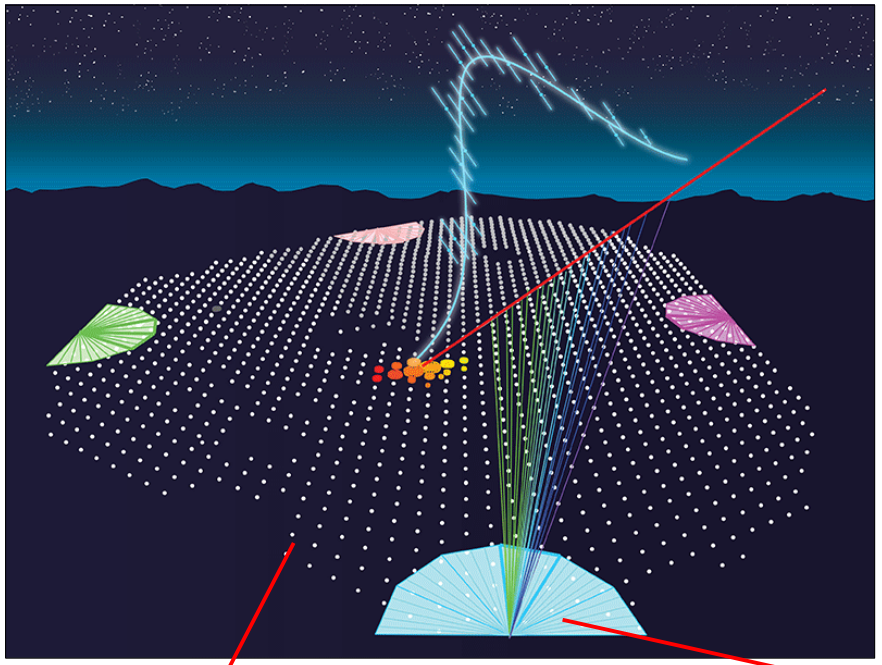
UHECRs interact with Earth's atmosphere :
generate an **E**xtensive **A**ir **S**hower (**EAS**)

At ground : ~5.10^{10} particles (mostly $e^{\pm}, \mu, \gamma$)

(estimation for a 10^{19}eV p-shower)



The Pierre Auger Observatory



The Pierre Auger Observatory (PAO) :

- Completed in 2008
- 400 scientists from 18 countries
- Location : Argentinian pampa
- **Surface (SD) : 3000 km²**

Surface Detector (SD) :

- 1660 Water Cherenkov Detectors
- Duty-Cycle : ~100%
- Measure timing and signal to reconstruct shower energy and arrival direction

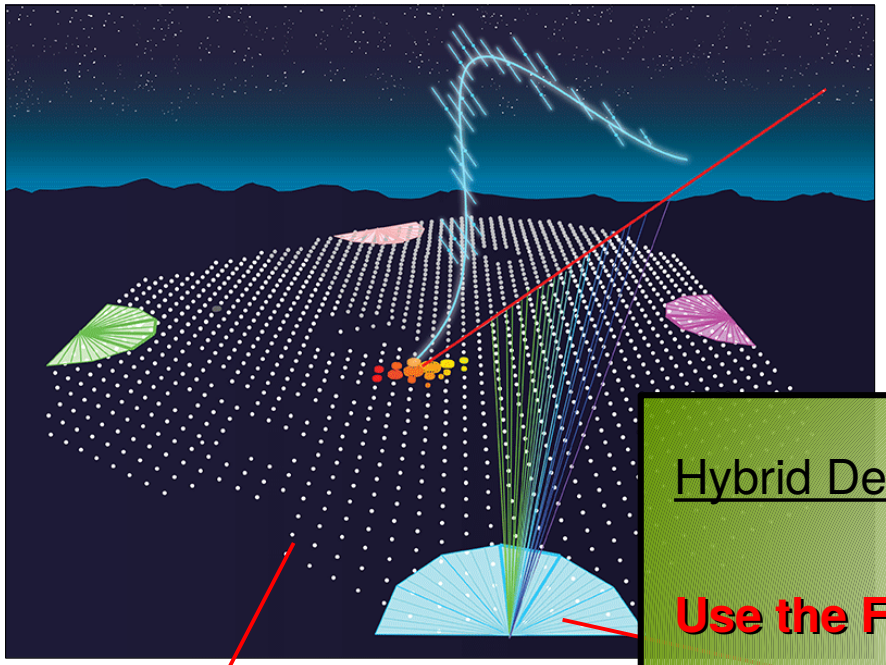
Detects secondary particles on ground

Fluorescence Detector (FD) :

- 27 telescopes in 4 locations
- Overlooking the atmosphere above the array
- Duty-Cycle : ~14%
- Direct measurement of the shower energy and depth

Detects fluorescence light emitted by nitrogen, excited by the cascade

The Pierre Auger Observatory



The Pierre Auger Observatory (PAO) :

- Completed in 2008
- 400 scientists from 18 countries
- Location : Argentinian pampa
- Surface (SD) : 3000 km^2

Hybrid Detection :

Use the FD to calibrate the SD's energy reconstruction

Other detectors at the observatory…

Surface Detector (SD)

- 1660 Water Cherenkov Detectors
- Duty-Cycle : ~100%
- Measure…

Detects secondary par…

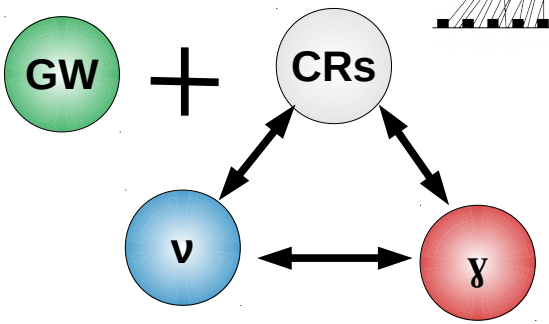
Detector (FD) :

24 telescopes in 4 locations
Overlooking the atmosphere above the array
Direct measurement of the shower energy and depth

…light emitted by …e cascade

A wealth of results from the PAO but focus on neutral particles in the rest of this presentation

Multi-Messenger Astrophysics



Multi-Messenger era of astrophysics :

- combine cosmic rays, gamma, neutrino and gravitational wave observations
- interplay between all these messengers

Complementarity between the observations

- Cosmic-Rays :

⊕ : direct accelerator probe
⊖ : deflected in magn. fields (space and time)

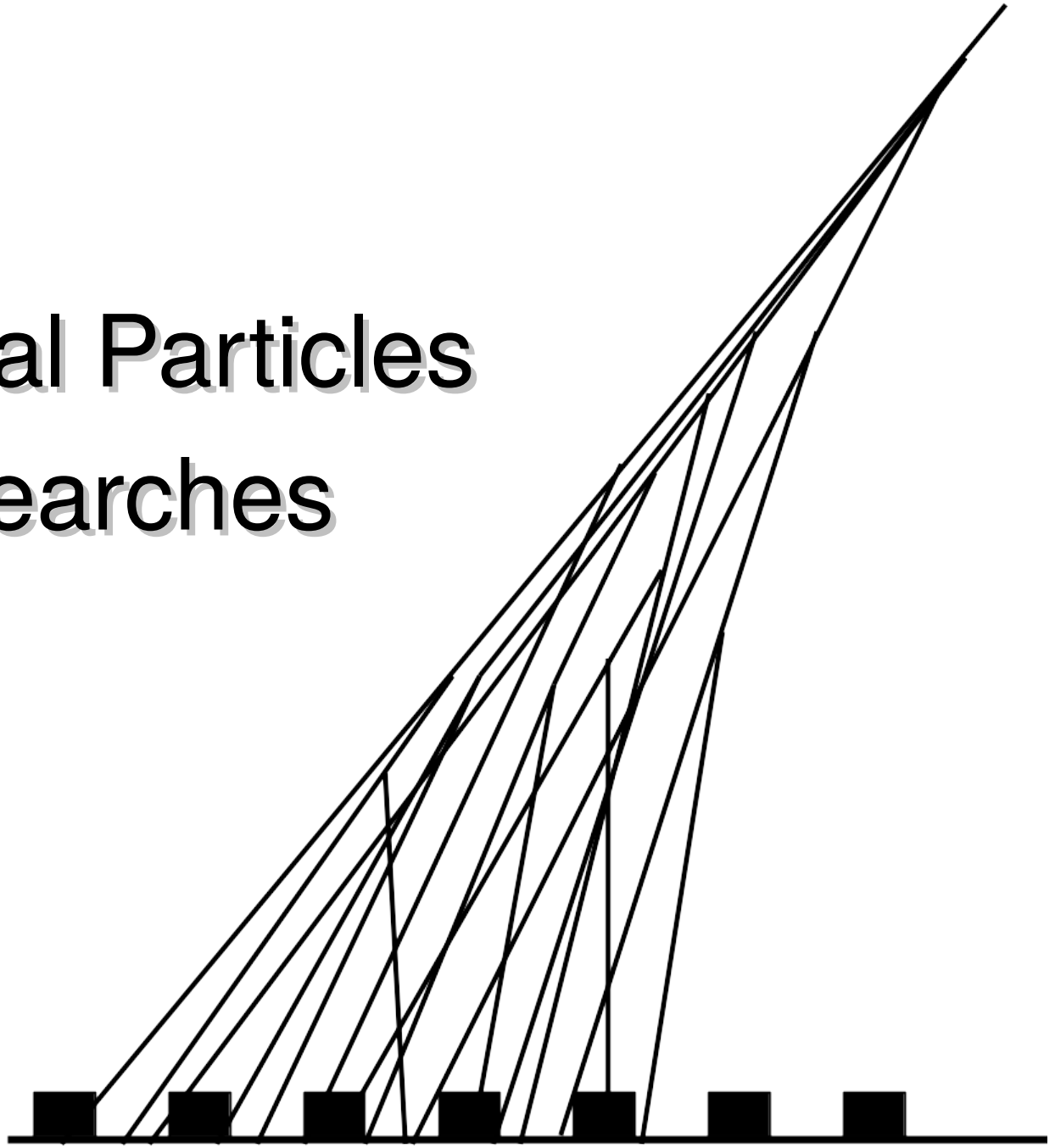
- Gamma-rays :

⊕ : straight line
⊖ : UHE horizon < 10 Mpc

- Neutrinos :

⊕ : straight line, no interaction
⊖ : isotropic diffuse background

Neutral Particles Searches



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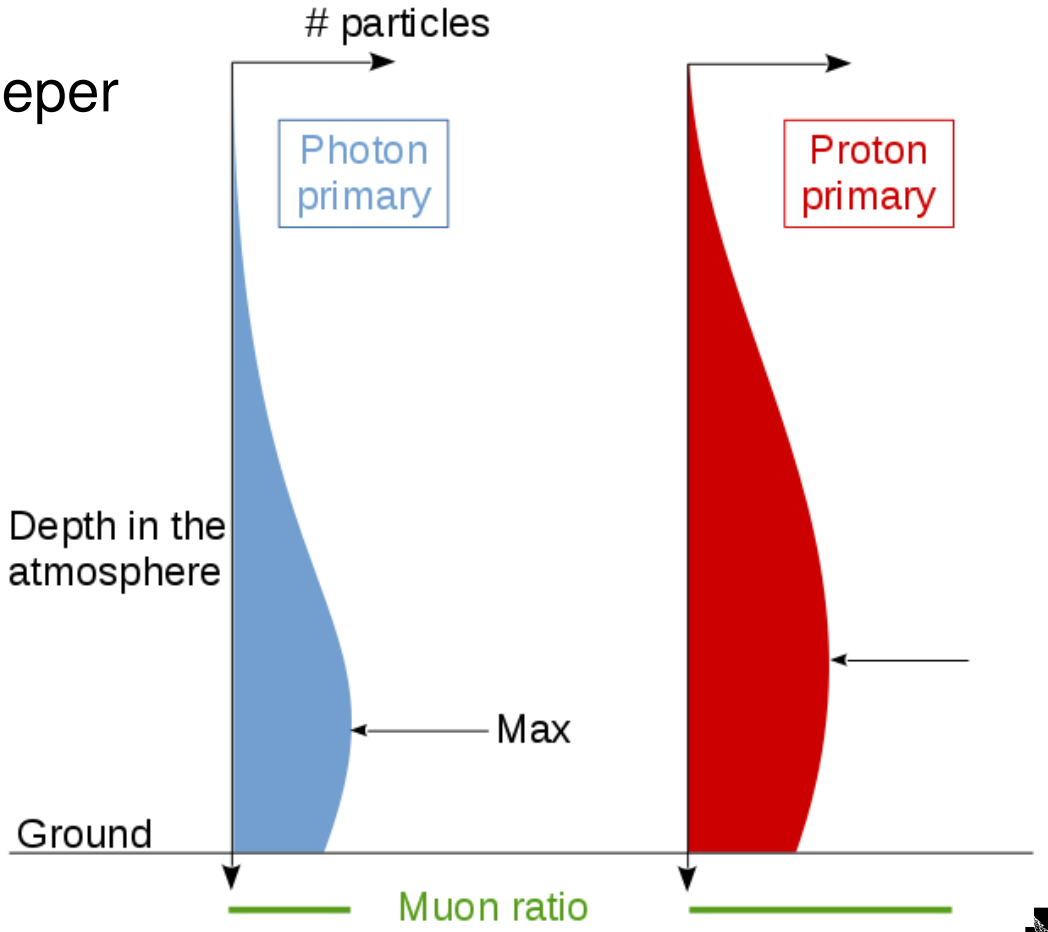
Photon searches

- Neutral particles : arrival directions not smeared through magnetic fields
- Detecting photons : interesting to study transients and steady sources but also to constrain physical scenarios (GZK cut-off, LIV…)

- Less hadrons : showers develop deeper
- Less muons on ground

- So far no UHE photons found : put limits on the flux

- Selection efficiency >50%

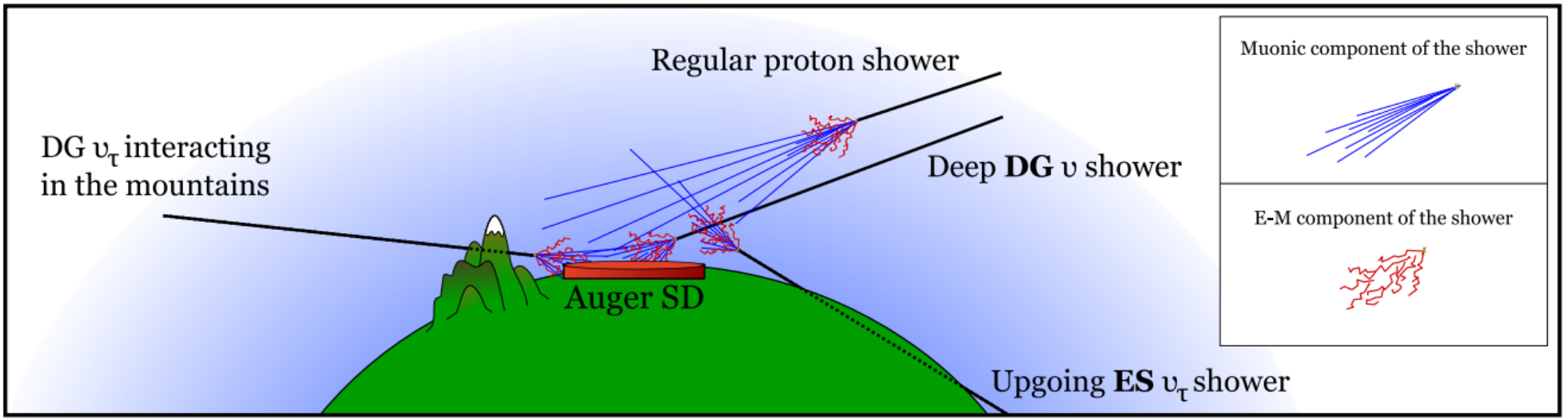


Neutrino searches

- Neutrinos : neutral + almost no interactions → from further away (but harder to detect)
- Very good astrophysical messenger, can combine with other observatories

- Initiate showers close to ground
- More EM component

- Horizontal or even upward-going showers



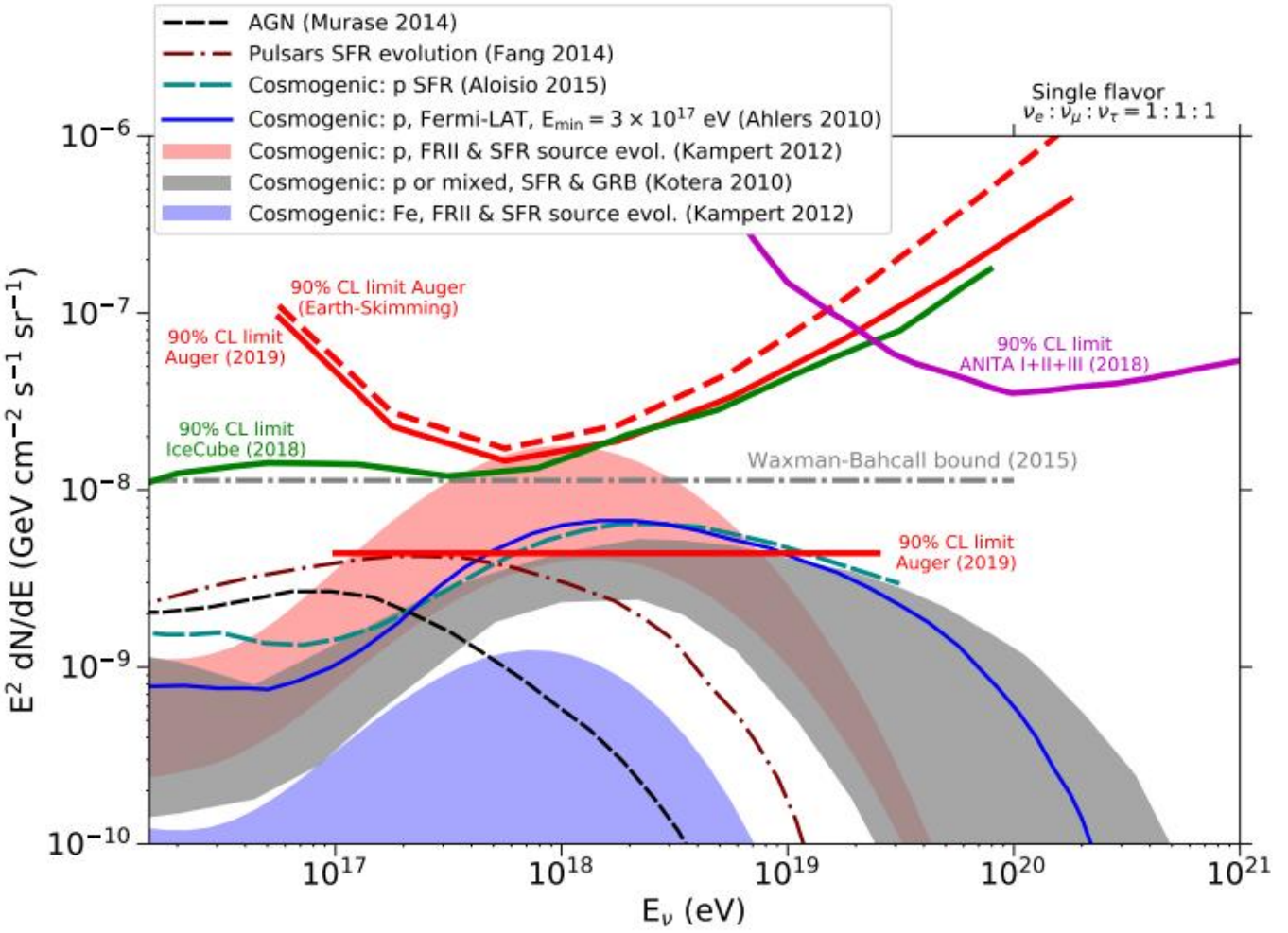
Neutrino searches

Very good selection efficiency :

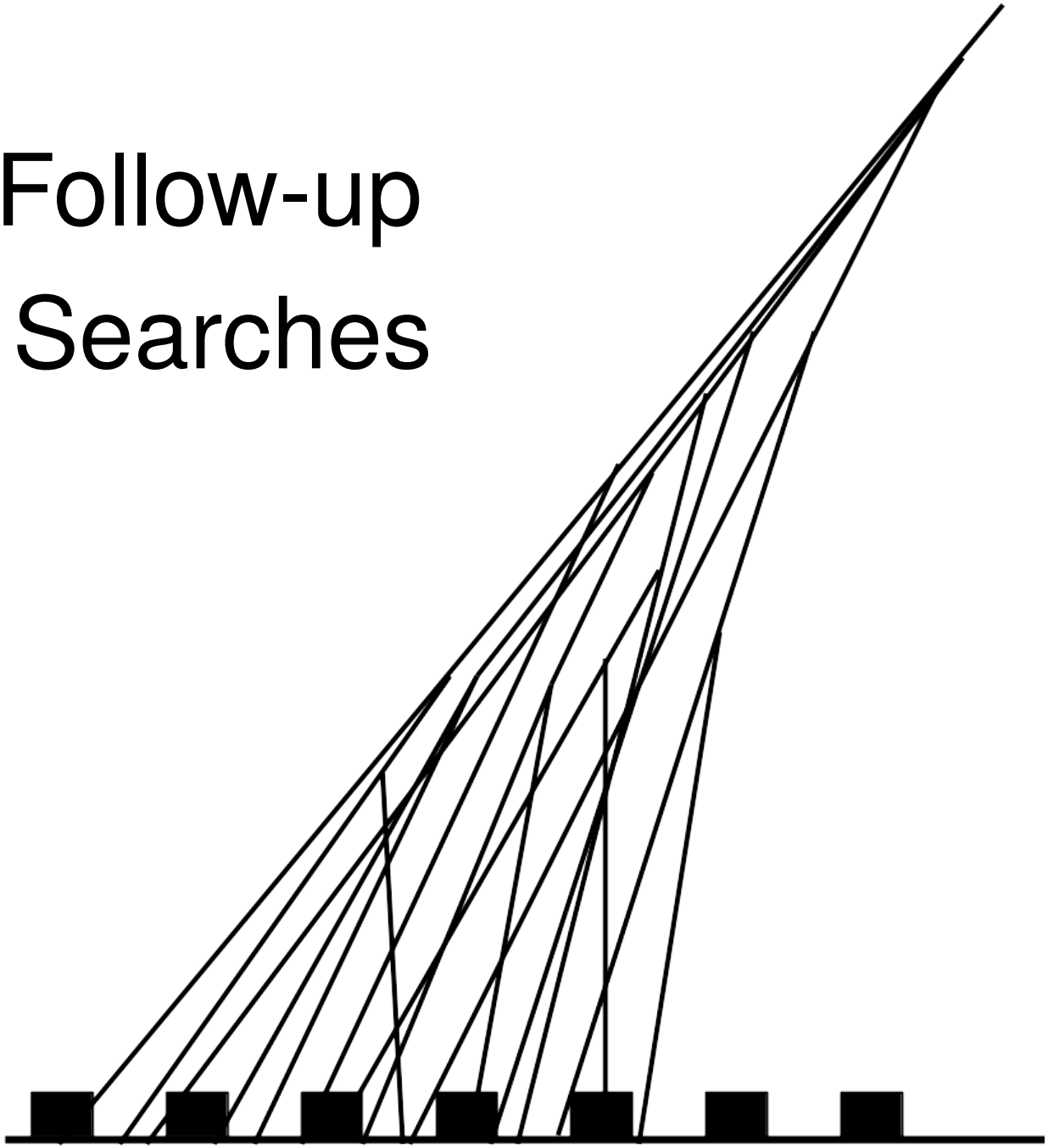
- Downward-Going ~ 85%
- Earth-Skimming ~ 95%

So far, no UHE neutrinos found :

- Set limit to UHE neutrino flux



Follow-up Searches



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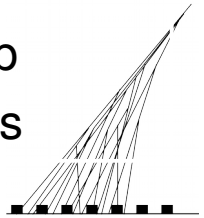
Response to an alert



What happens when Auger receives an alert? :

- What do we look for?
  - Neutrals and in particular neutrinos, in physically motivated time-windows around the event and after it
- For now the analysis is done “manually”
- Infrastructure for automatic response is being built (+ our own alerts)

Binary Black Hole mergers (GW150914 & GW151226)

With the first detections of gravitational waves (BBH mergers) :

- Search for UHE neutrinos
- Around the time of the events
  - ±500s
- After the event
  - 1 day

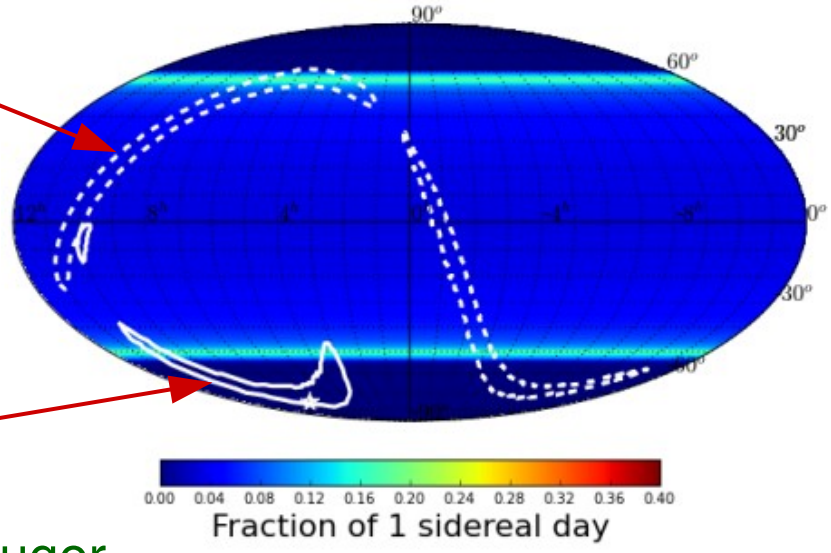
No UHE neutrino found :

- Set limits on UHE neutrino flux
- Constrain the fraction of the total energy of the GW radiated as neutrinos

GW151226

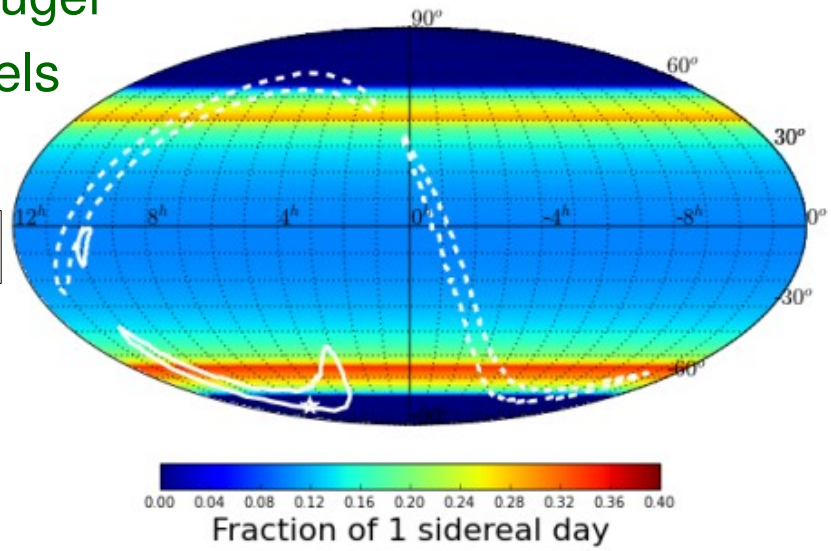
ES channel

GW150914



Sky visible by Auger in both channels

DGH channel



Binary Neutron Star merger (GW170817)

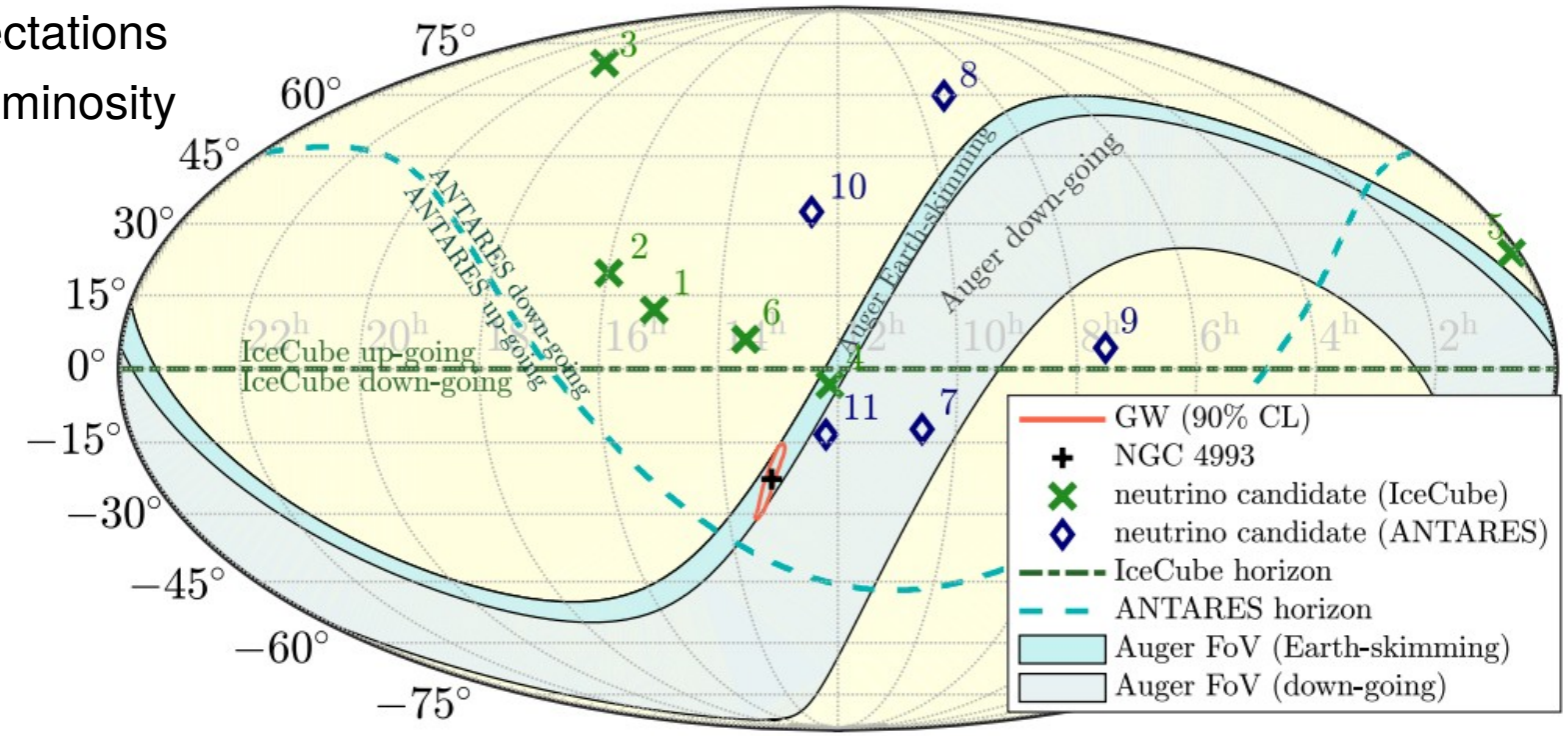
Remarkably, NGC 4993 was right on Auger's sweetspot at the time of the merger

Combined search for HE neutrinos and UHE neutrinos with IceCube and Antares:

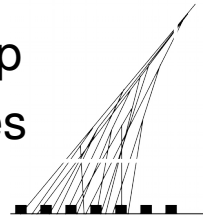
- No neutrino candidate found in coincidence

Non-observation is consistent with expectations for off-axis, or low luminosity GRBs

Complementarity between the 3 experiments (≠ energy range)



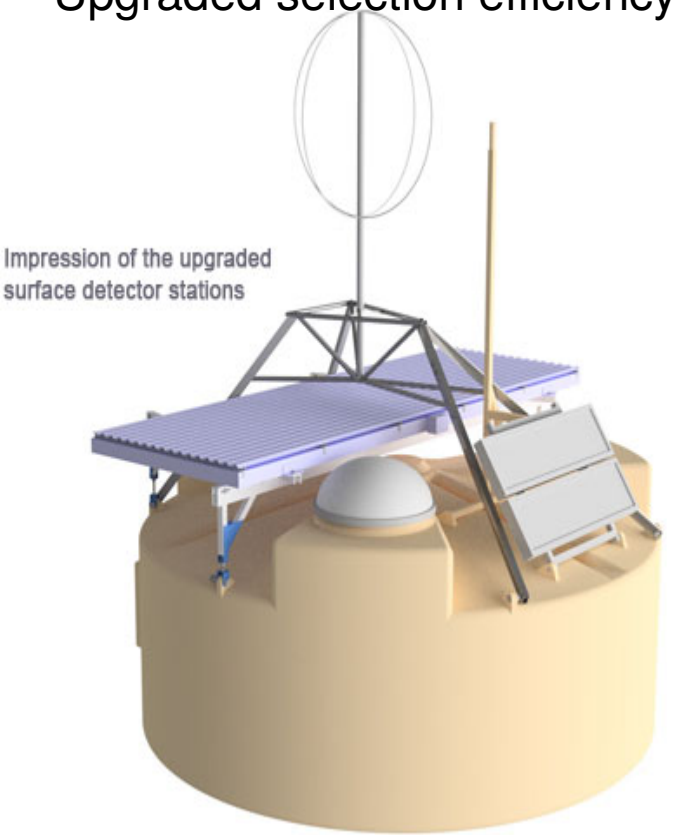
AMON & AugerPrime



In coming years, for the Pierre Auger Observatory...

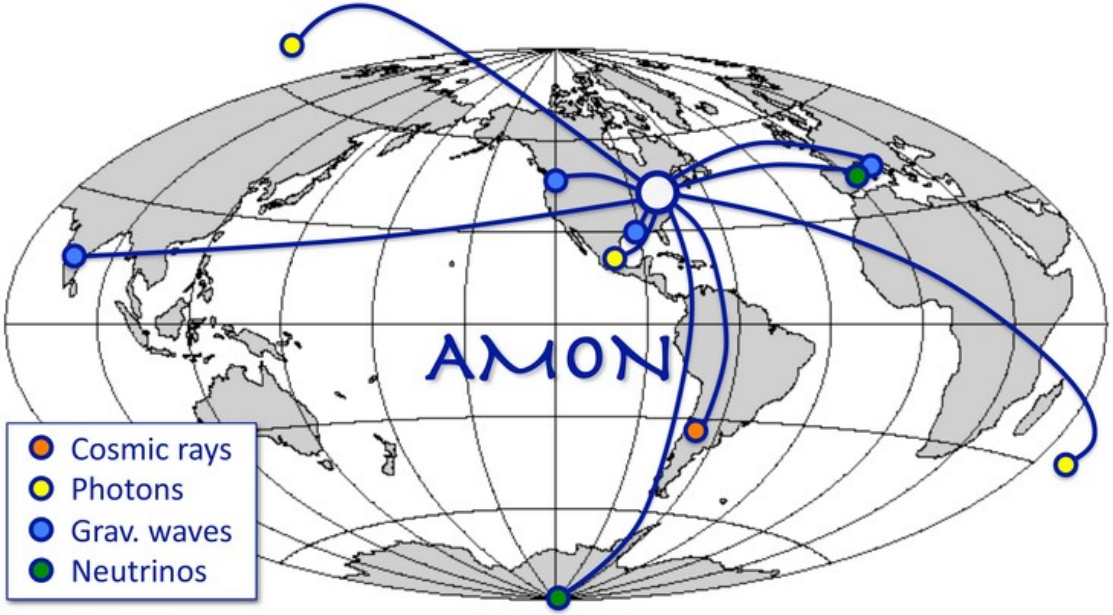
AugerPrime Upgrade :

- Better reconstruction and identification of the primaries on a shower-to-shower basis
- Upgraded selection efficiency

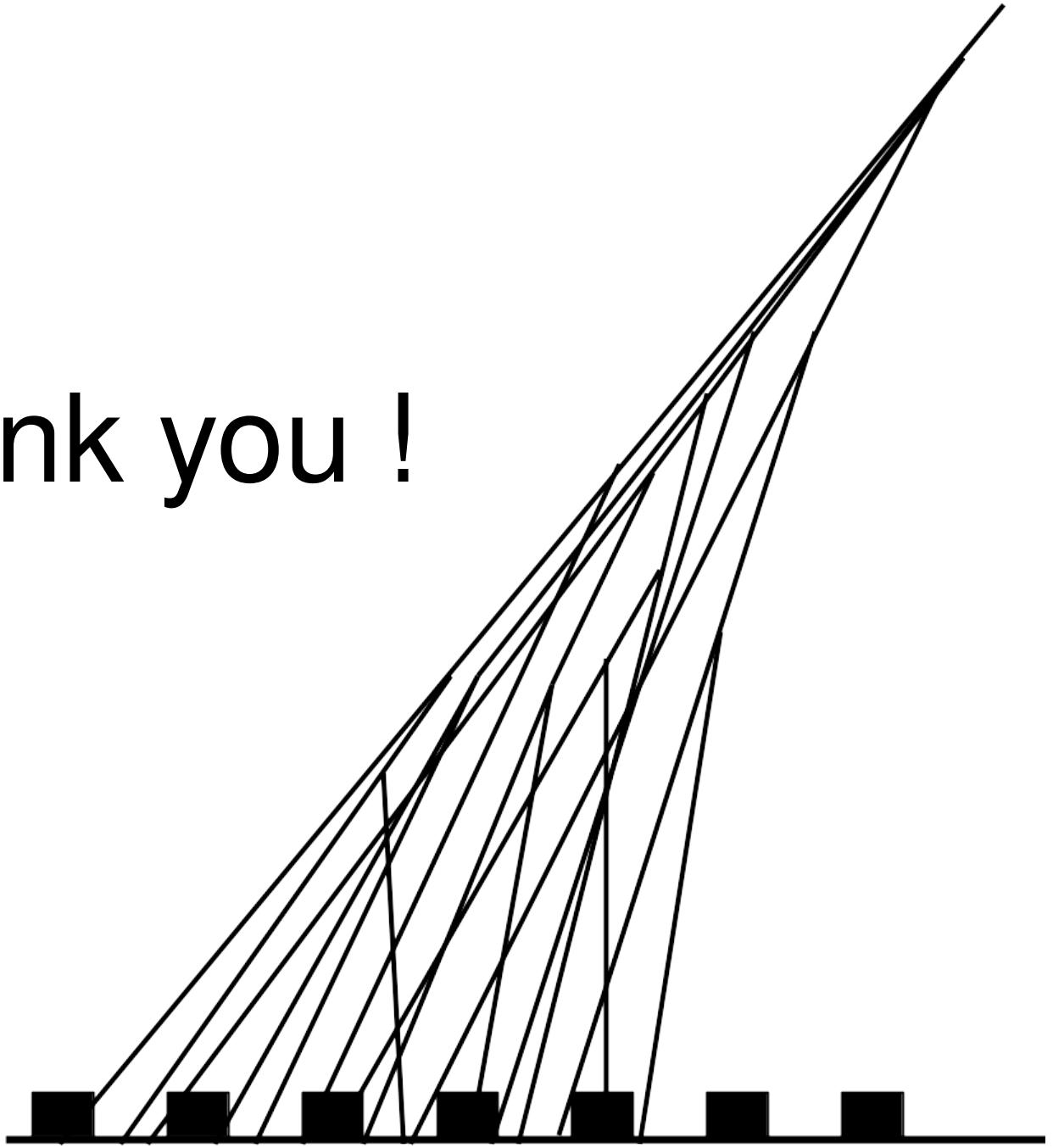


Share data with AMON (Astrophysical Multimessenger Observatory Network)

Hope to get real-time coincidence with other experiments (IceCube, HAWK,…) and send alerts



Thank you !



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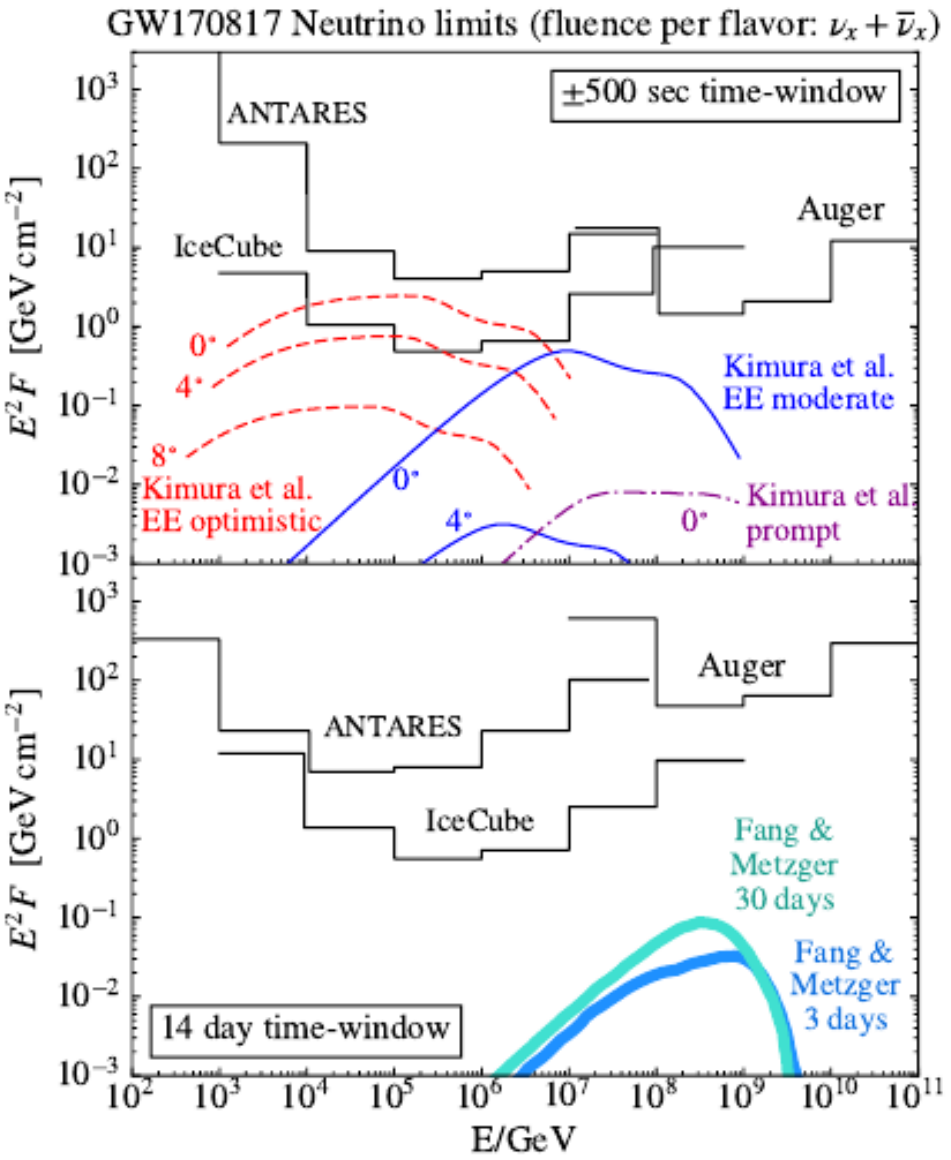
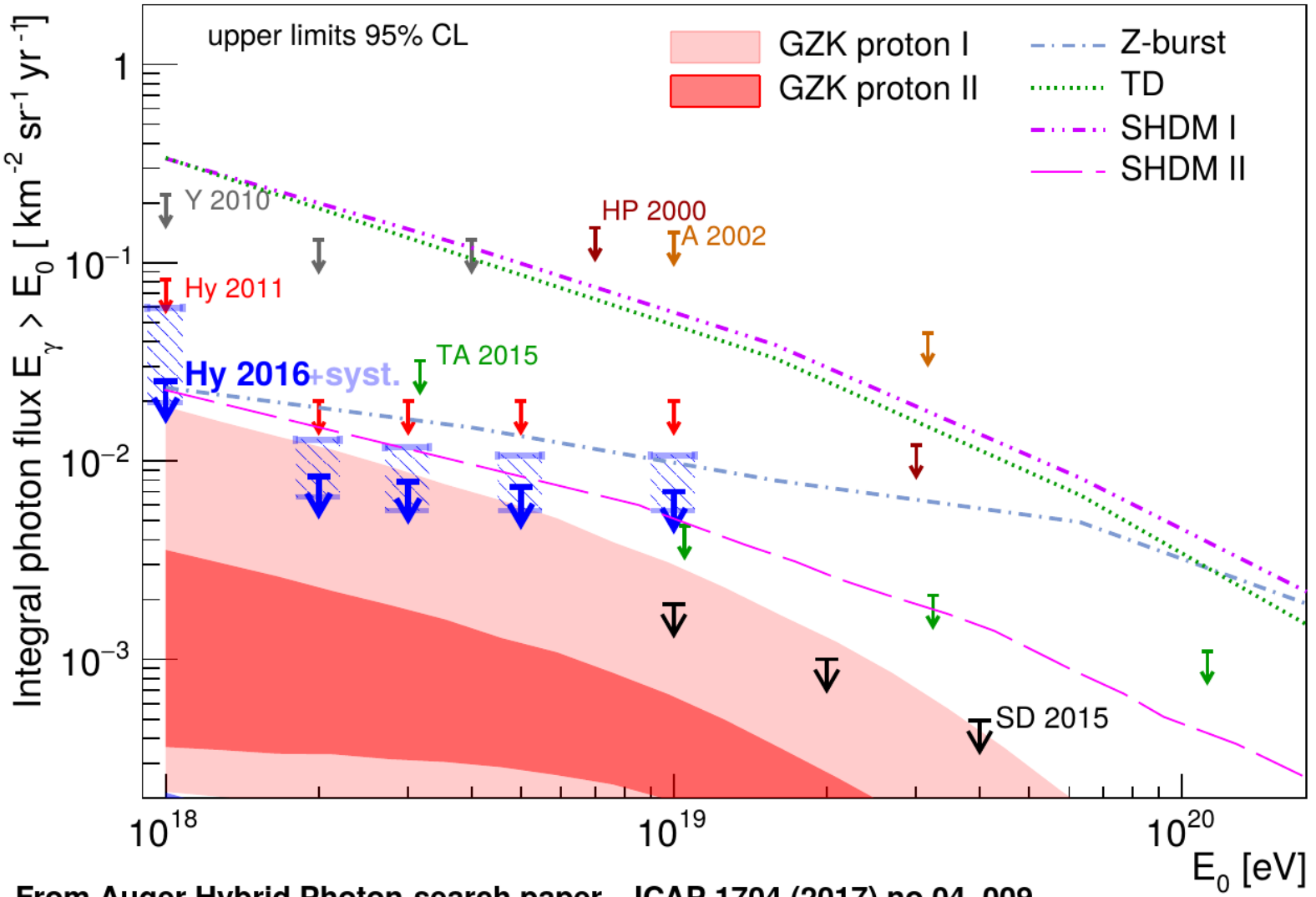
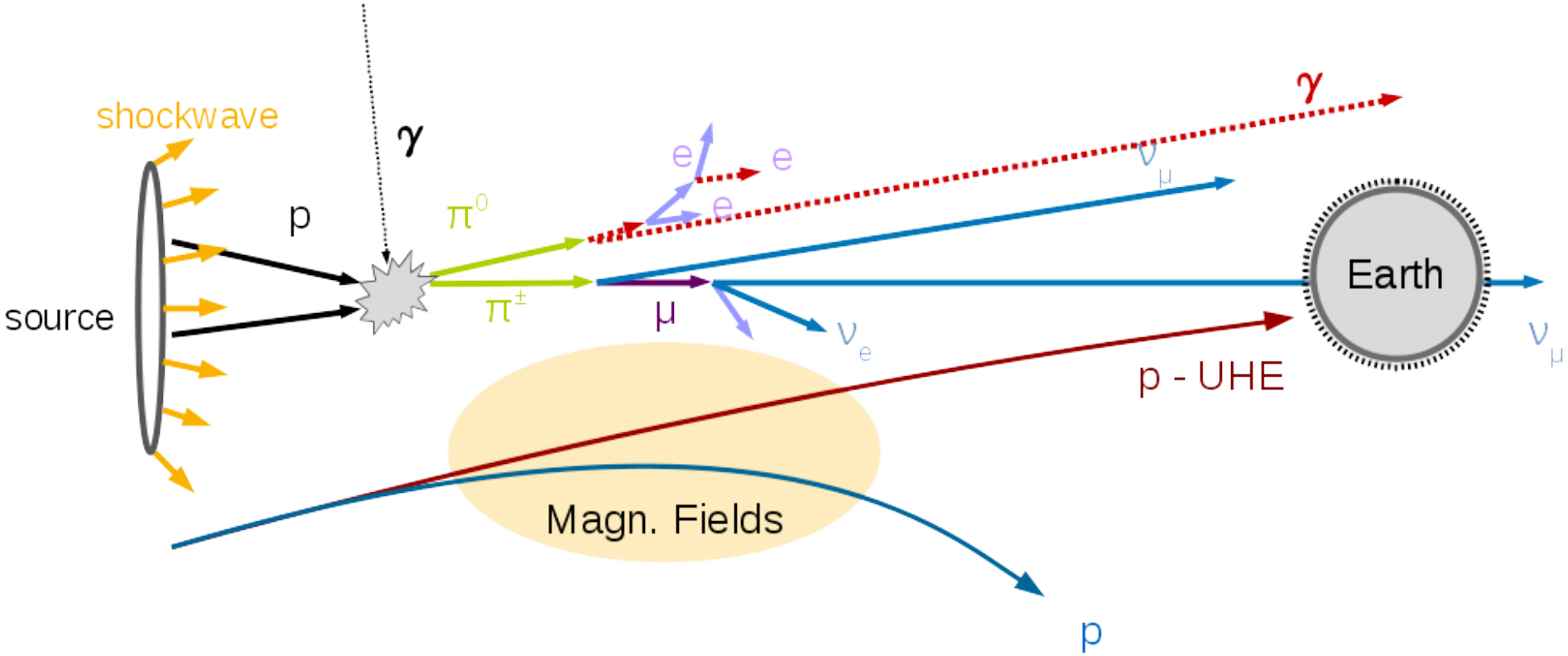
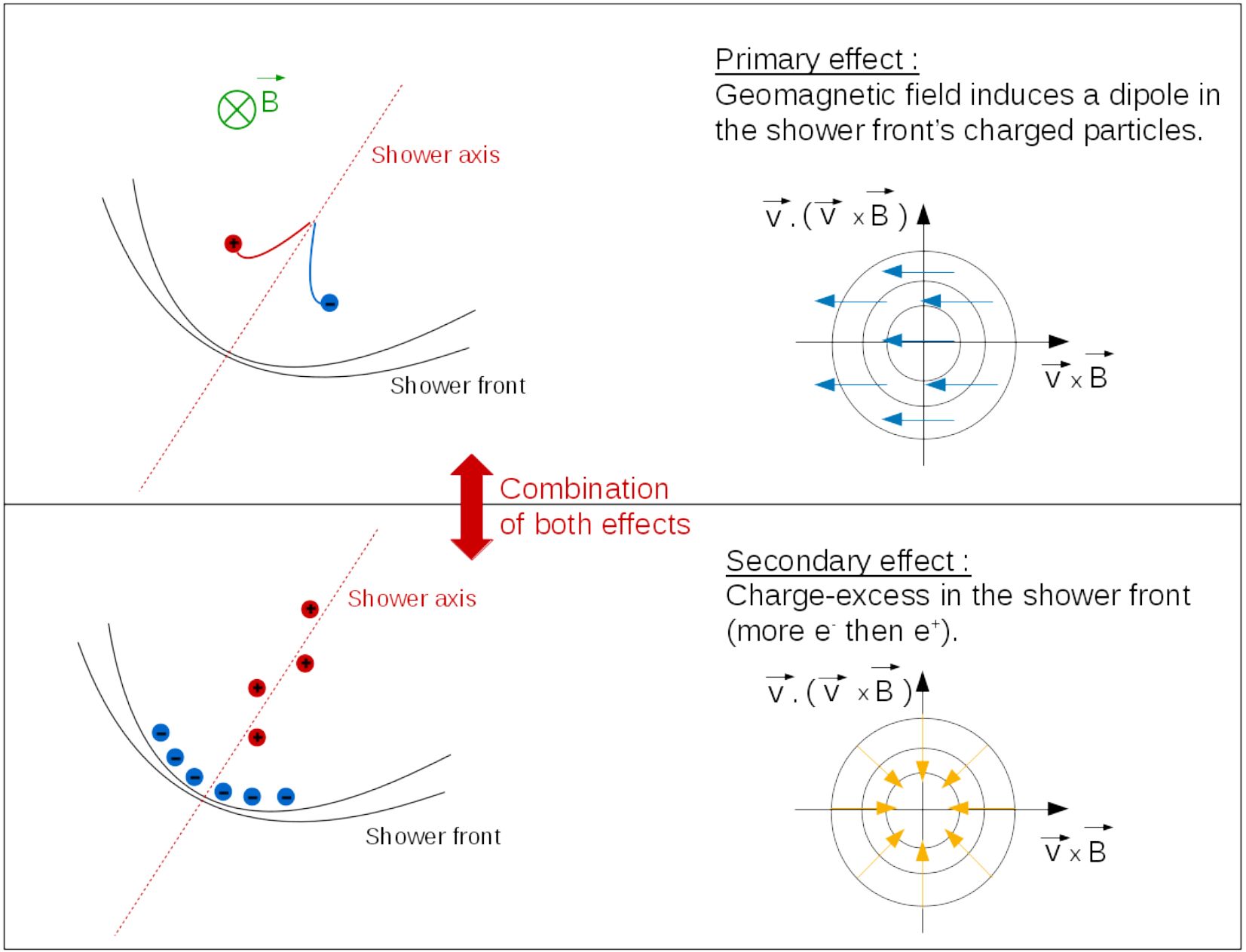

GW170817 Neutrino limits (fluence per flavor: $\nu_x + \bar{\nu}_x$)
±500 sec time-window
ANTARES
IceCube
Auger
0°
4°
8°
Kimura et al.
EE optimistic
Kimura et al.
EE moderate
0°
4°
Kimura et al.
prompt
0°
E^2F [GeV cm^{-2}]
Auger
ANTARES
IceCube
Fang &
Metzger
30 days
Fang &
Metzger
3 days
14 day time-window
E/GeV



From Auger Hybrid Photon-search paper, JCAP 1704 (2017) no.04, 009


shockwave
γ
p
source
π0
π±
e
e
e
μ
νe
νμ
γ
Earth
νμ
p - UHE
Magn. Fields
p


B
Shower axis
Shower front
Primary effect :
Geomagnetic field induces a dipole in the shower front's charged particles.
$\vec{v}.(\vec{v}\times\vec{B})$
$\vec{v}\times\vec{B}$
Combination of both effects
Shower axis
Shower front
Secondary effect :
Charge-excess in the shower front (more e^- then e^+).
$\vec{v}.(\vec{v}\times\vec{B})$
$\vec{v}\times\vec{B}$