

**PIERRE
AUGER**
OBSERVATORY

GEFÖRDERT VOM



Bundesministerium
für Bildung
und Forschung

Follow-up searches for ultra-high energy neutrinos from transient astrophysical sources with the Pierre Auger Observatory

Michael Schimp
for the Pierre Auger Collaboration

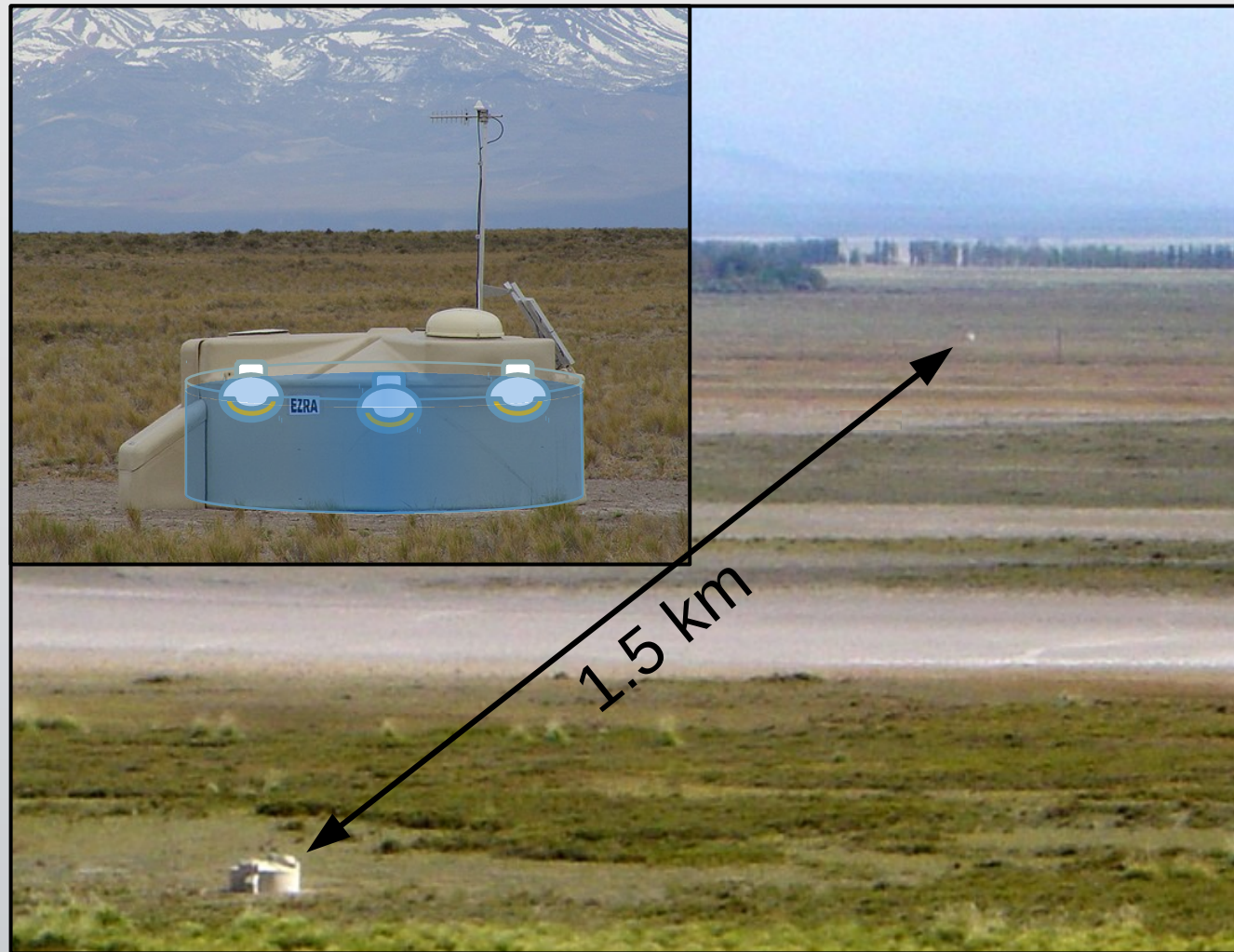
[PoS\(ICRC2019\)415](#)

July 29, 2019



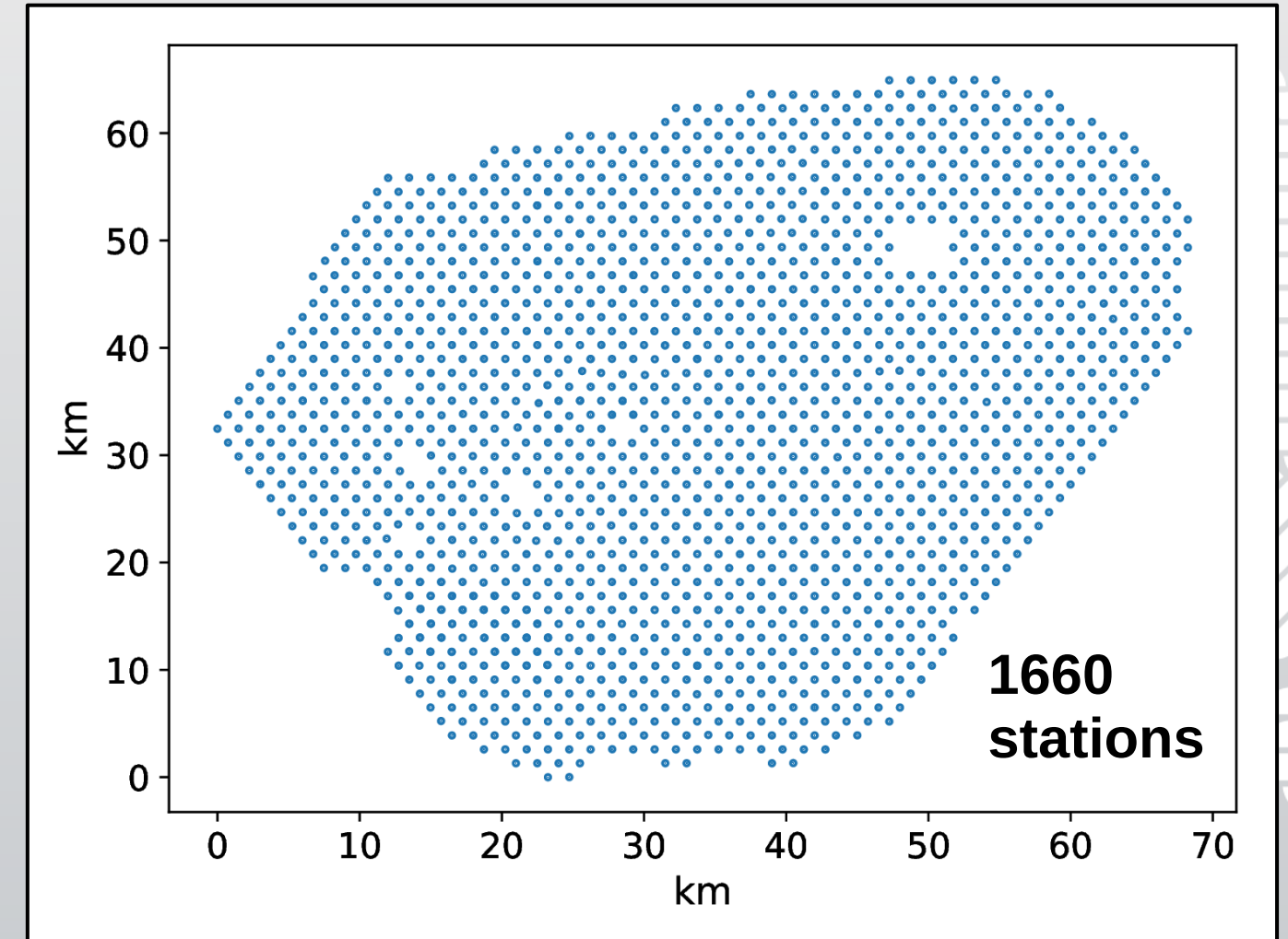
BERGISCHE
UNIVERSITÄT
WUPPERTAL

The Pierre Auger Observatory Surface Detector (SD)



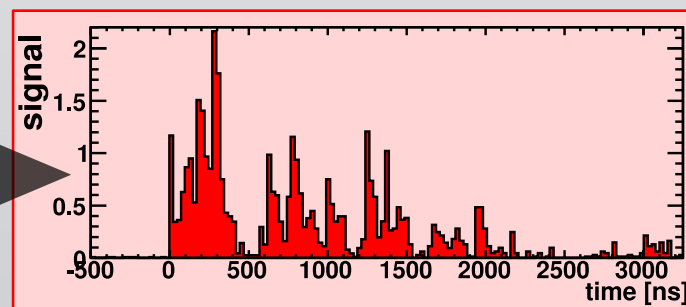
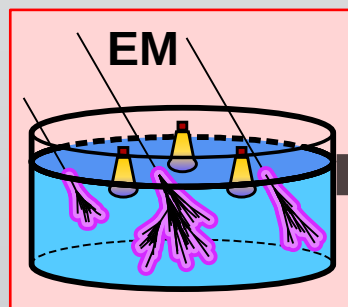
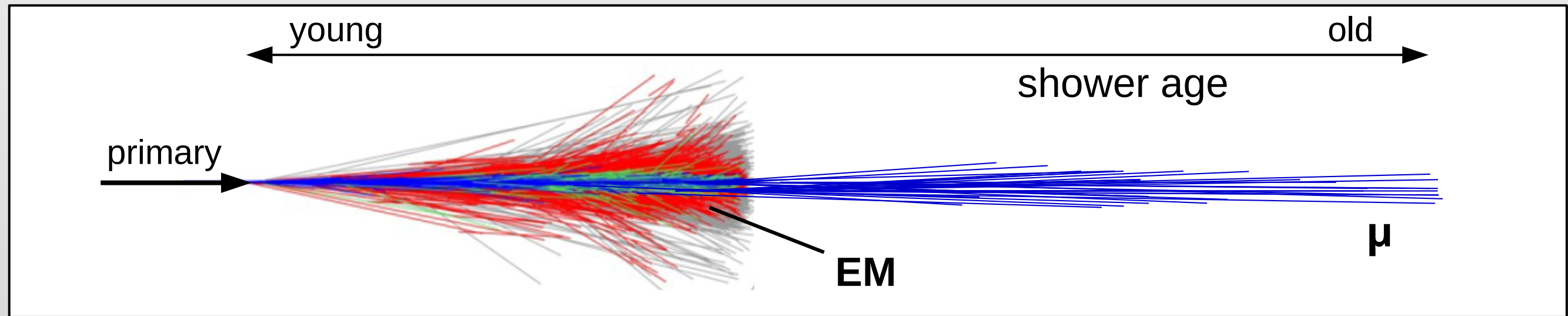
1.5 km spacing

→ Sensitive to EeV air showers

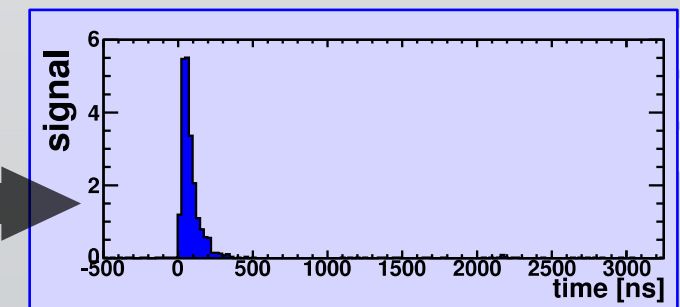
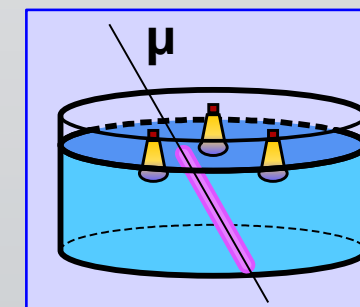


3000 km²

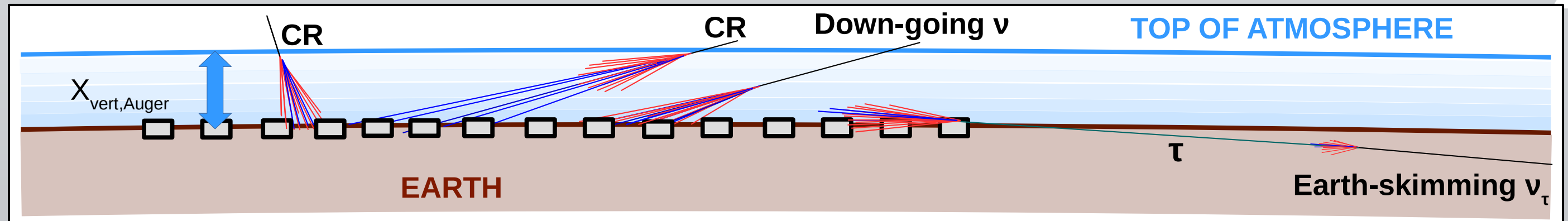
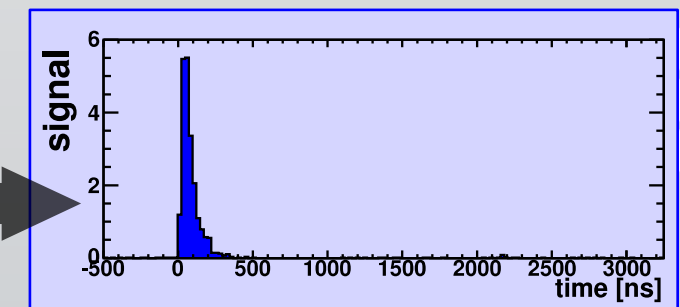
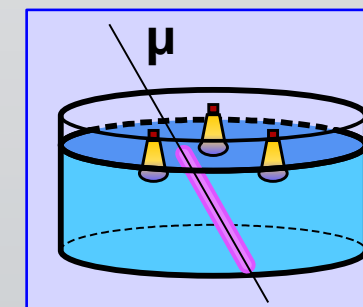
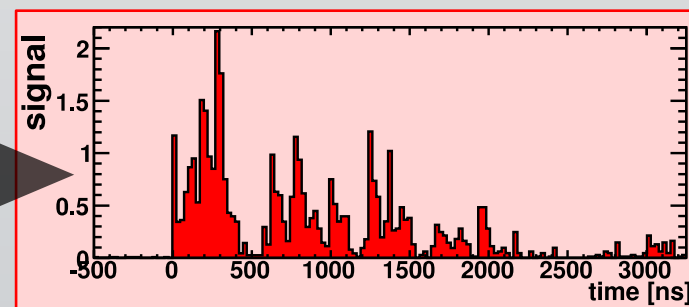
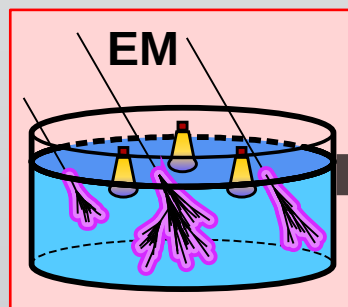
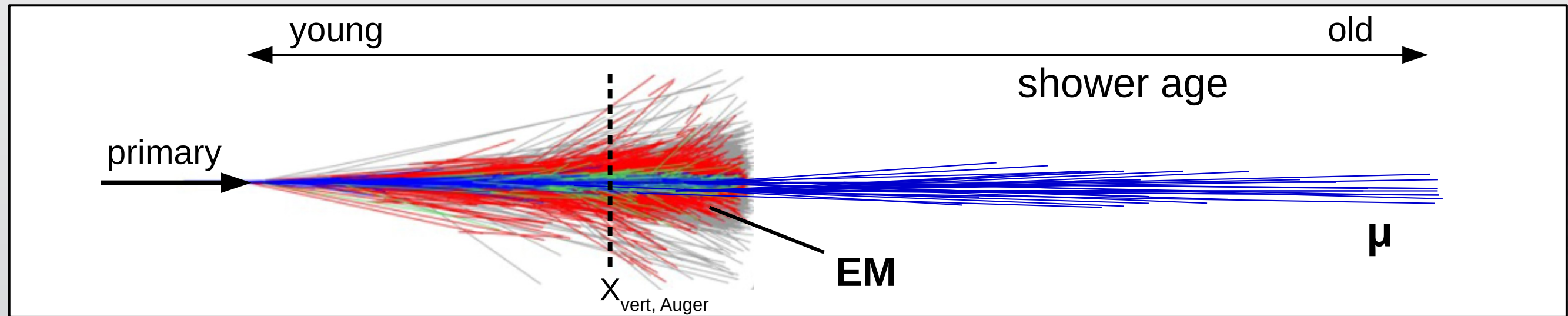
→ Large acceptance

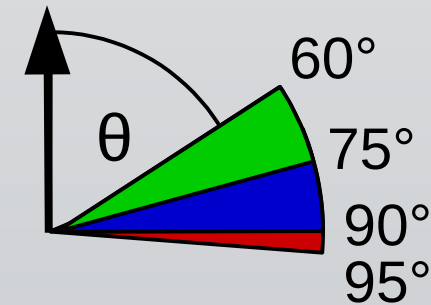


Multiple cascades, i.e. many particles
→ **broad** traces (signal vs. time)

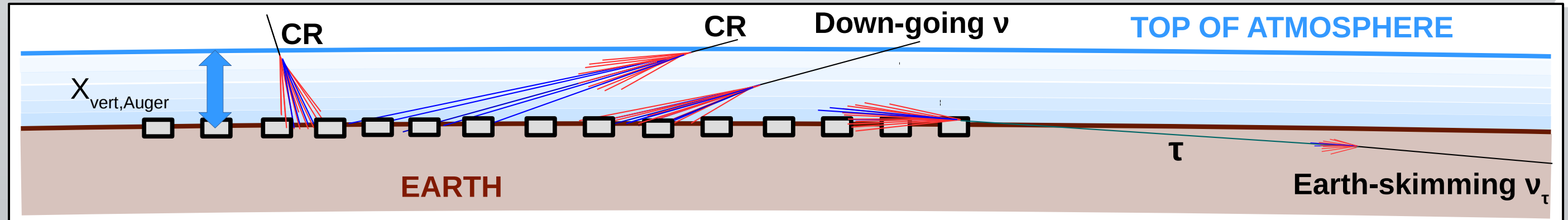


Single particles
→ **narrow** traces





Down-going Low (DGL)
Down-going High (DGH)
Earth-skimming (ES)



Followed up transient sources

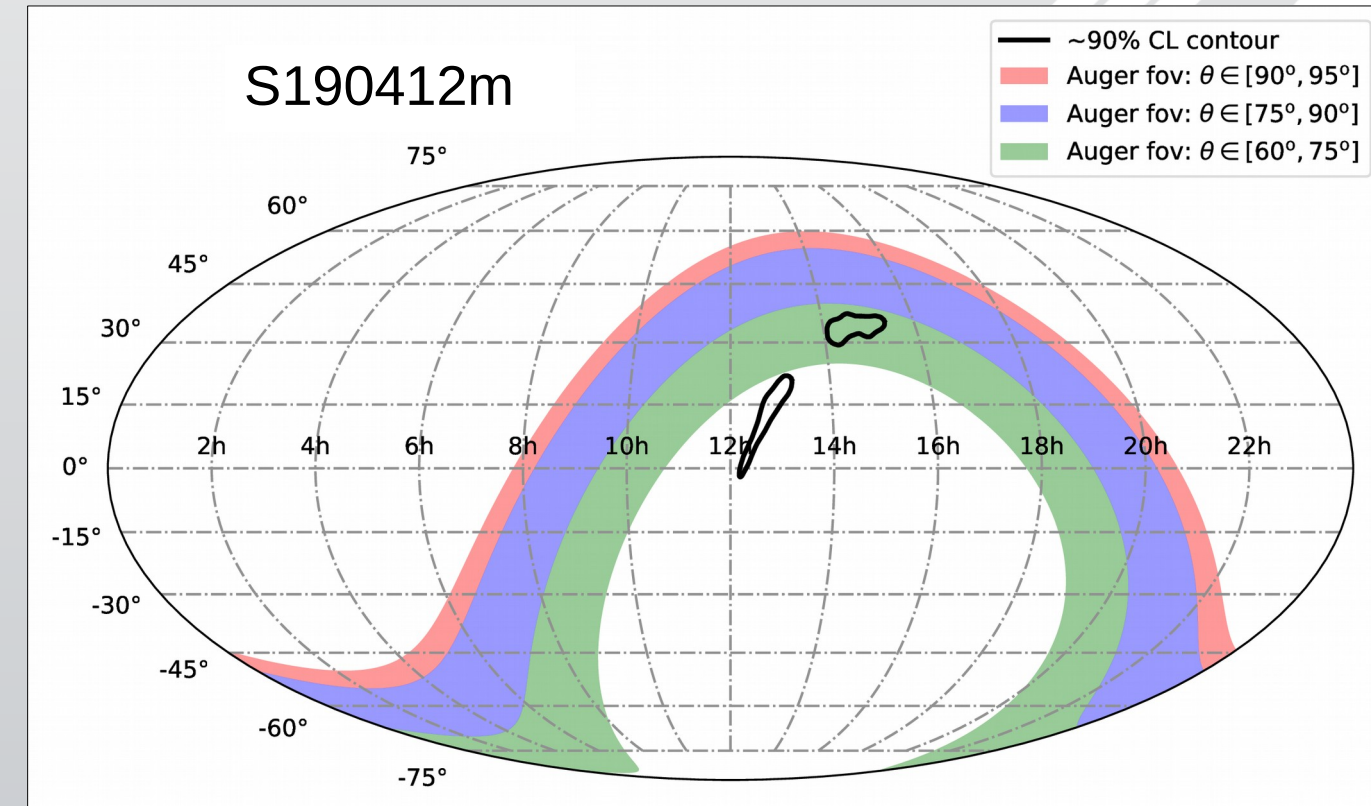
1) LIGO/Virgo Binary black hole (BBH) mergers

- All runs (O1 – O3), until 2019-06-02
→ **21 sources**
- Followed up automatically
 - Until **24 hours** after the merger
 - Most probable source localization (**90% CL**)
- Sources combined by stacking

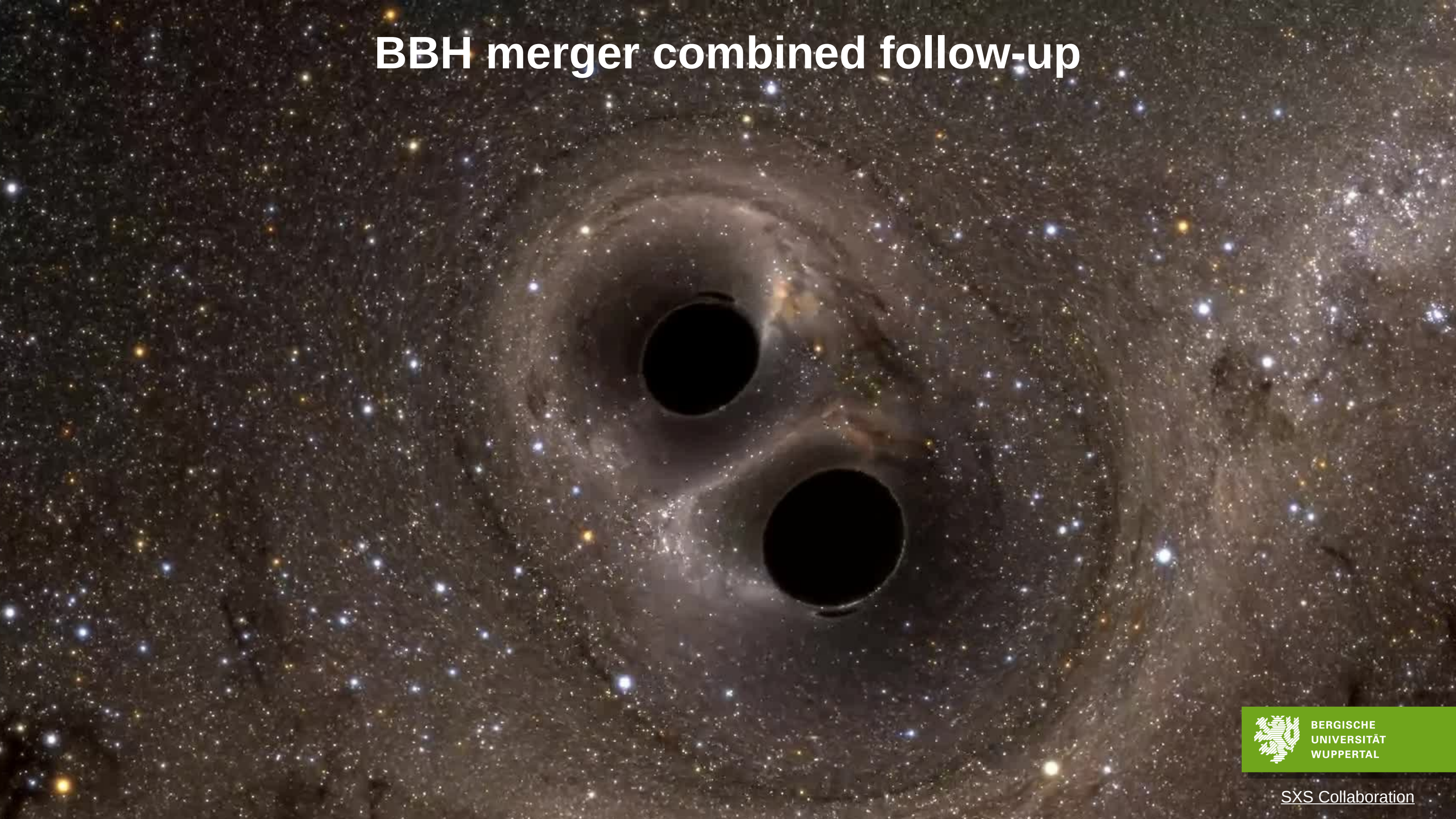
2) Blazar TXS 0506+056

Search motivated by two interesting periods

- IceCube neutrino excess 2014/2015
- IceCube high-energy neutrino during γ -ray flare 2017



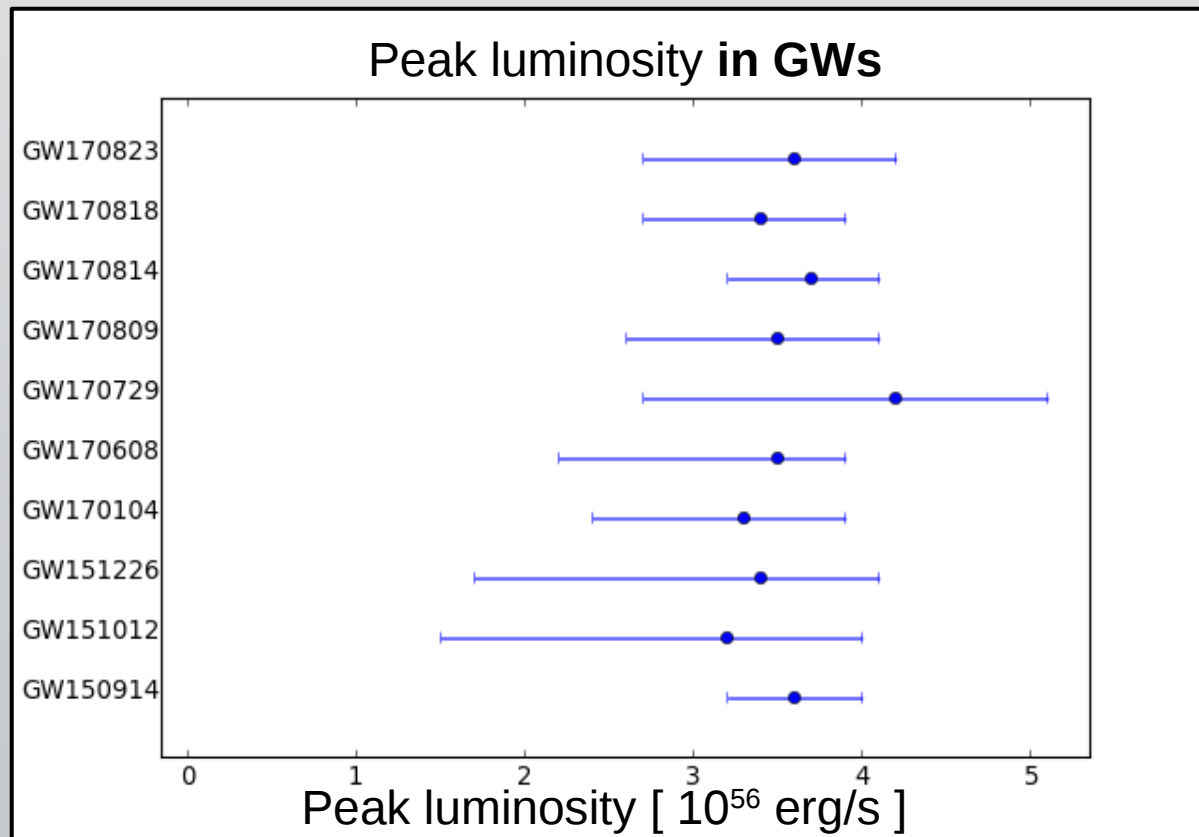
BBH merger combined follow-up



Combining BBH mergers—Assumptions & GW info

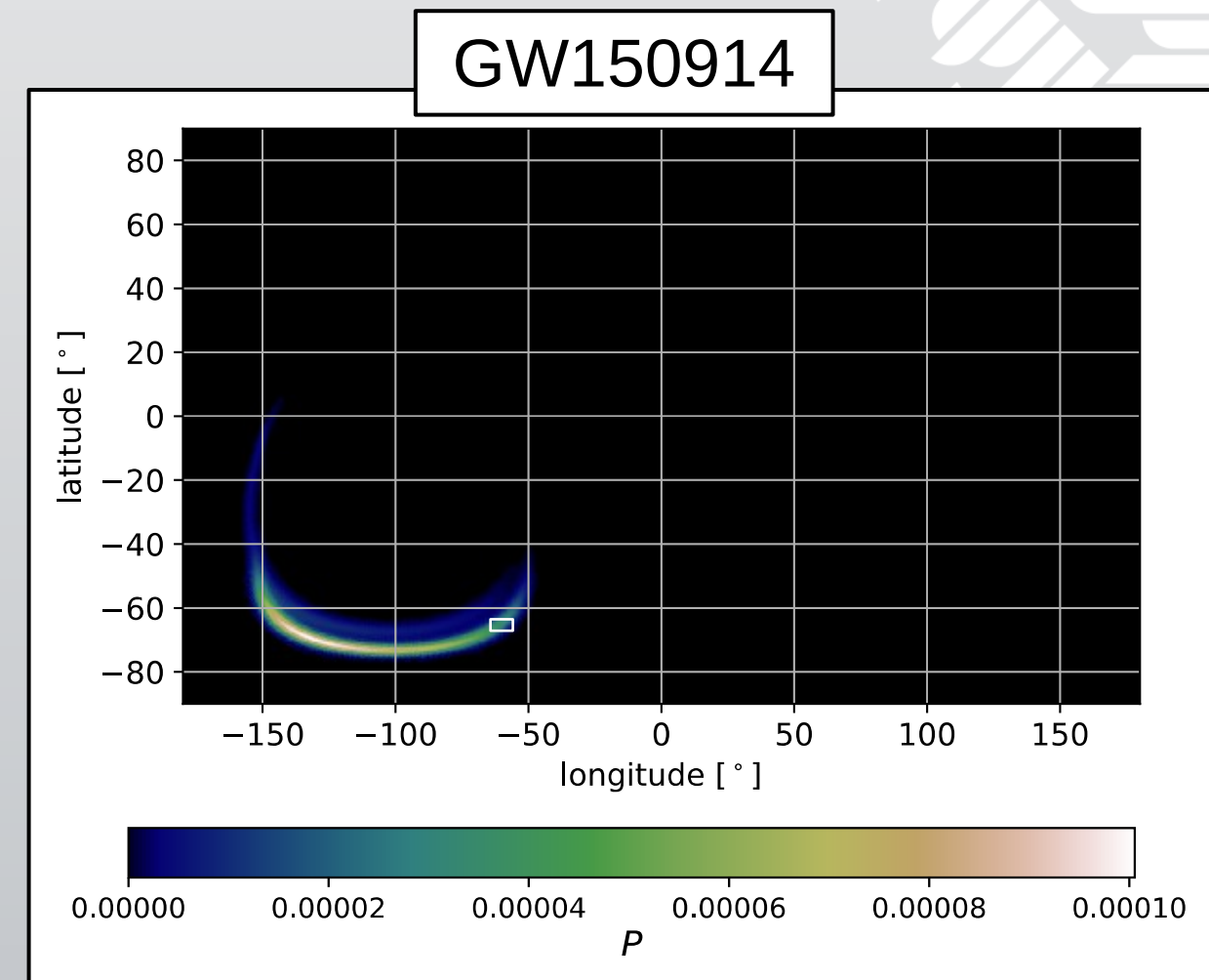
Source property assumptions:

- E^{-2} spectrum
- Universal (all the same) isotropic UHE neutrino emission with luminosity $L(t-t_0)$



time after merger

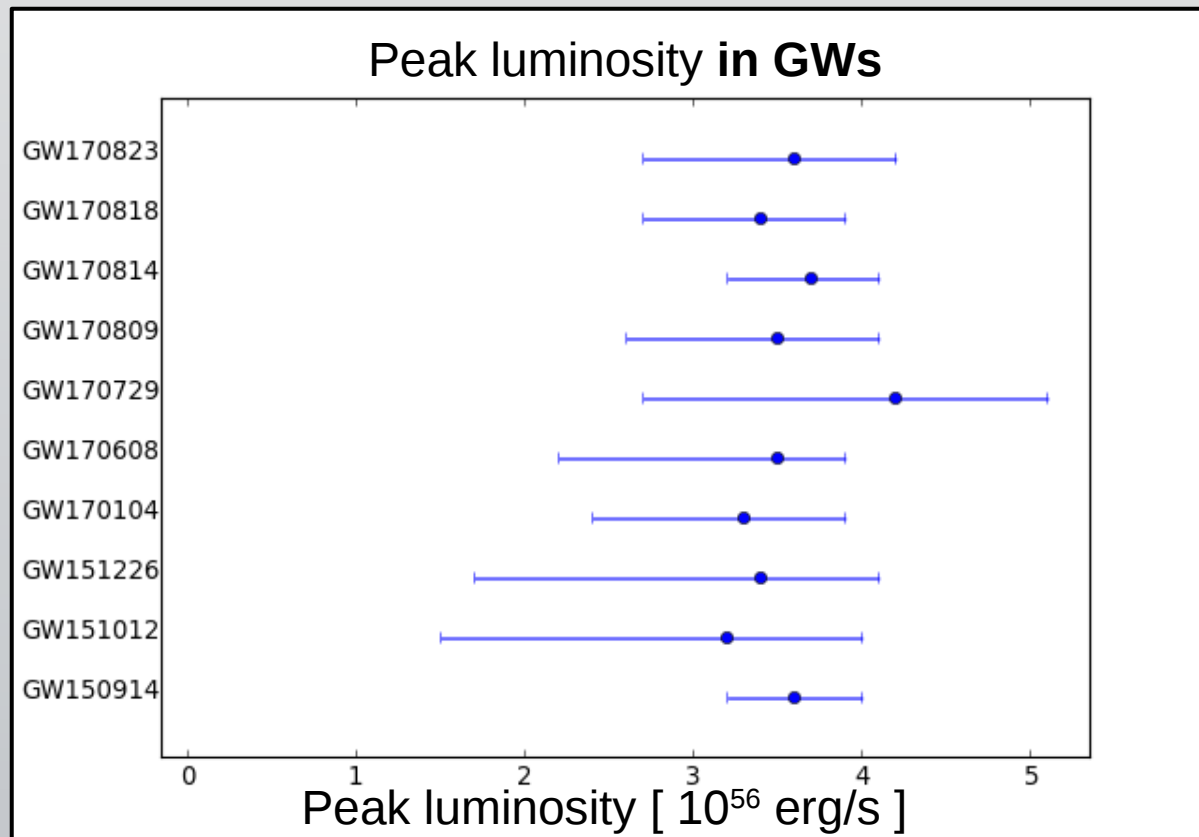
Source localization given as pixel-wise probability P



Combining BBH mergers—Assumptions & GW info

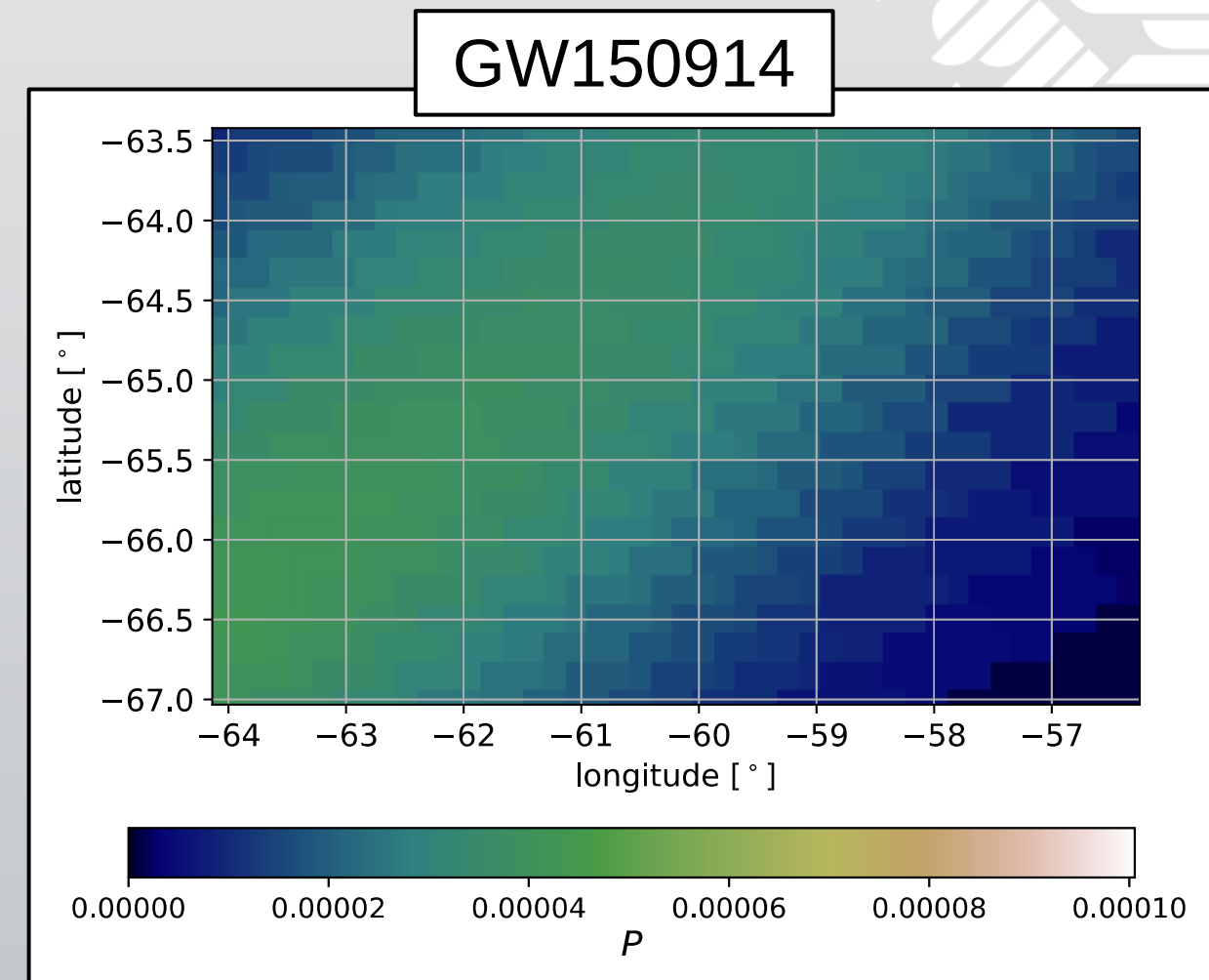
Source property assumptions:

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time after merger

Source localization given as pixel-wise probability P



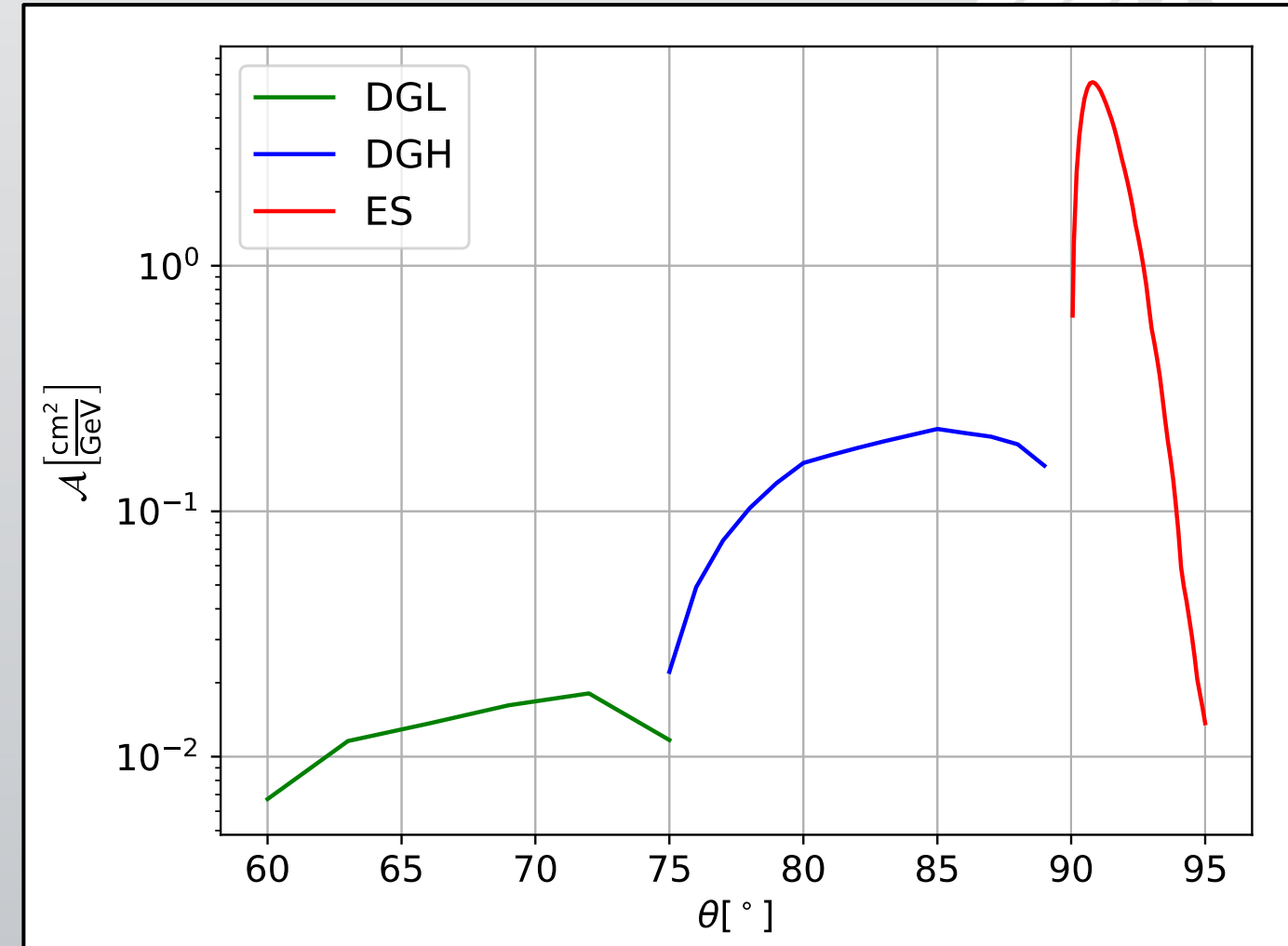
Combining BBH mergers—Time-dependent stacking

Time after the merger is discretized in bins i of $\Delta t = 1$ s

- Obtain UHE neutrino sensitivity to each source s for each time bin i
- Number of detected and identified neutrinos in time bin i , **from all sources s combined**:

$$N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2}$$

Summation over pixels
↔ “solid angle integration”



Combining BBH mergers—Visibility of sources

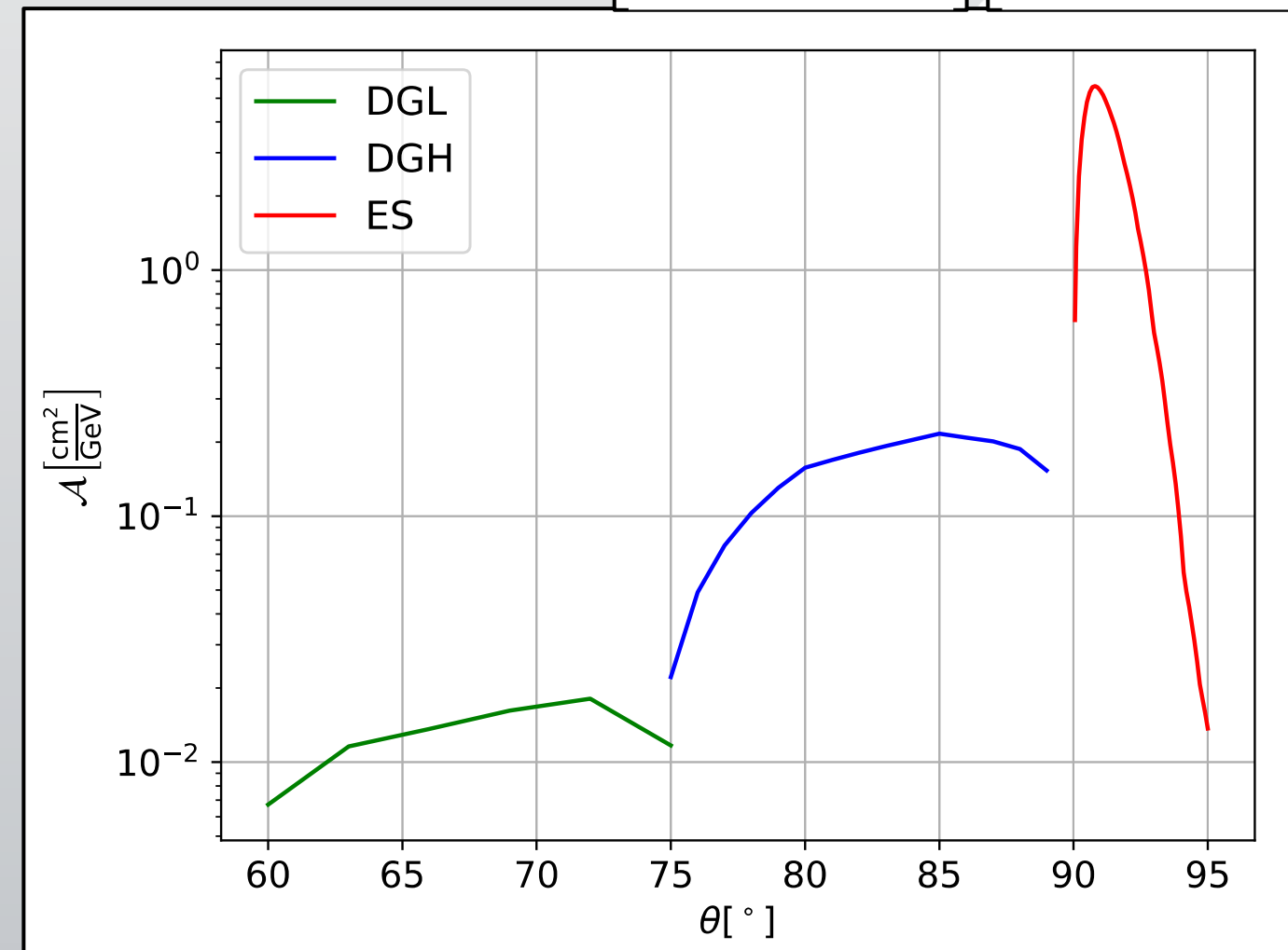
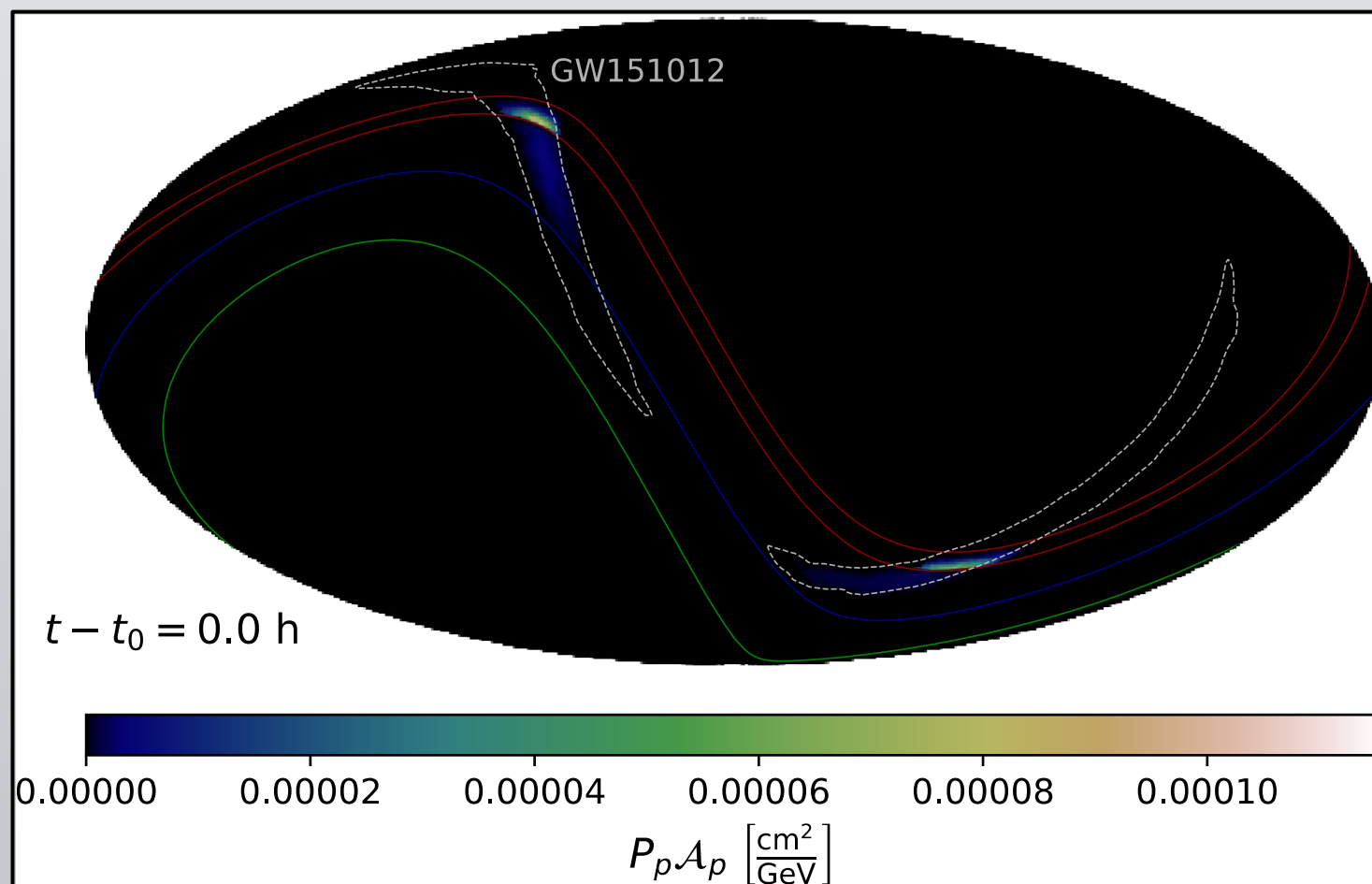
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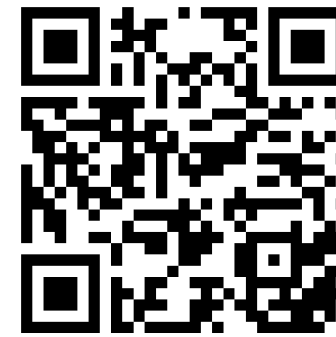


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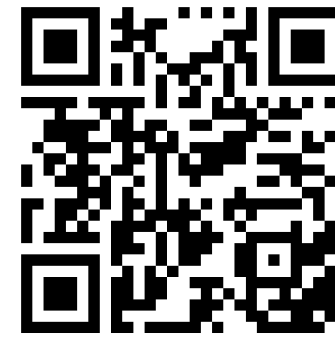


Combining BBH mergers—Visibility of sources

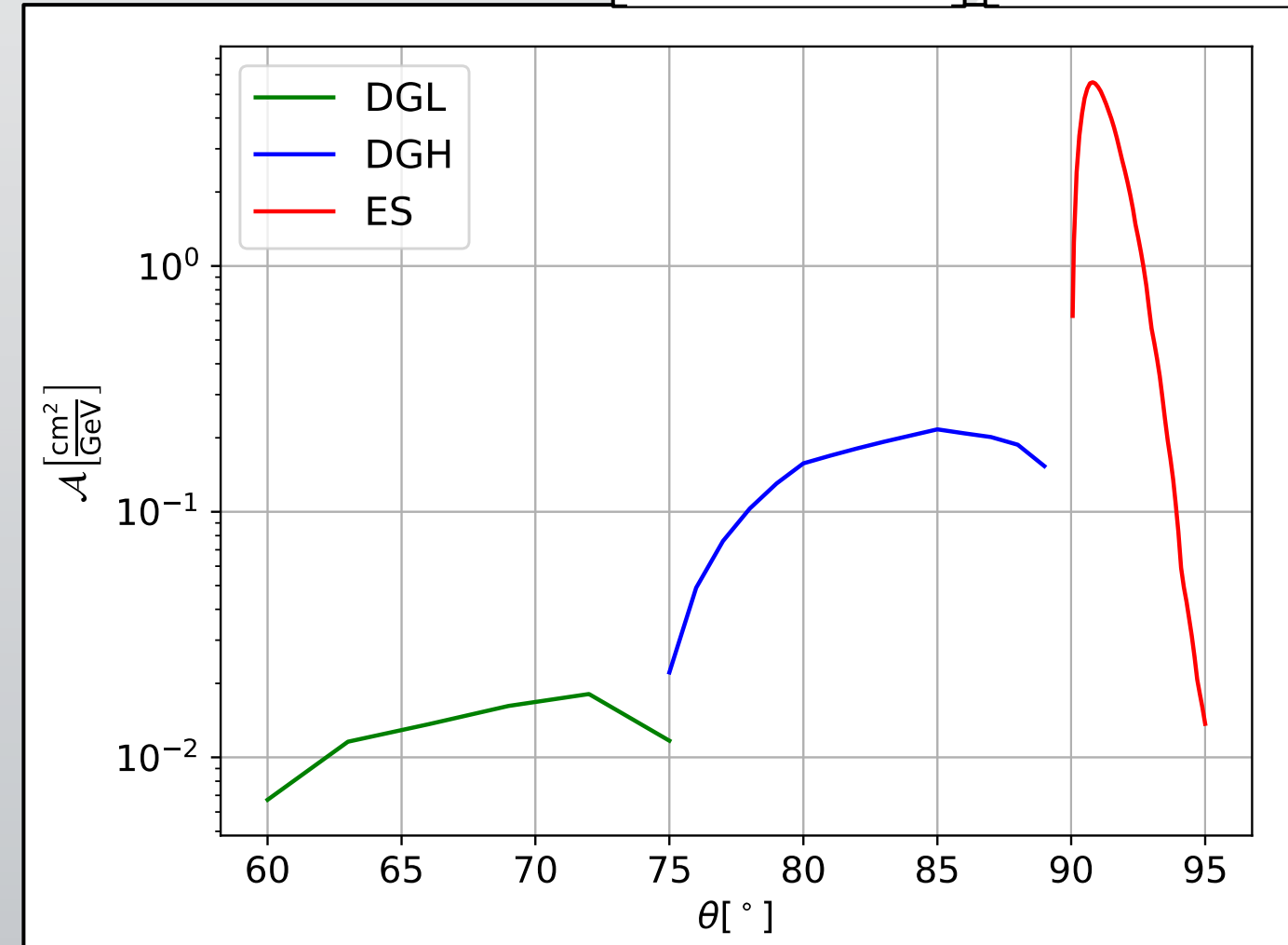
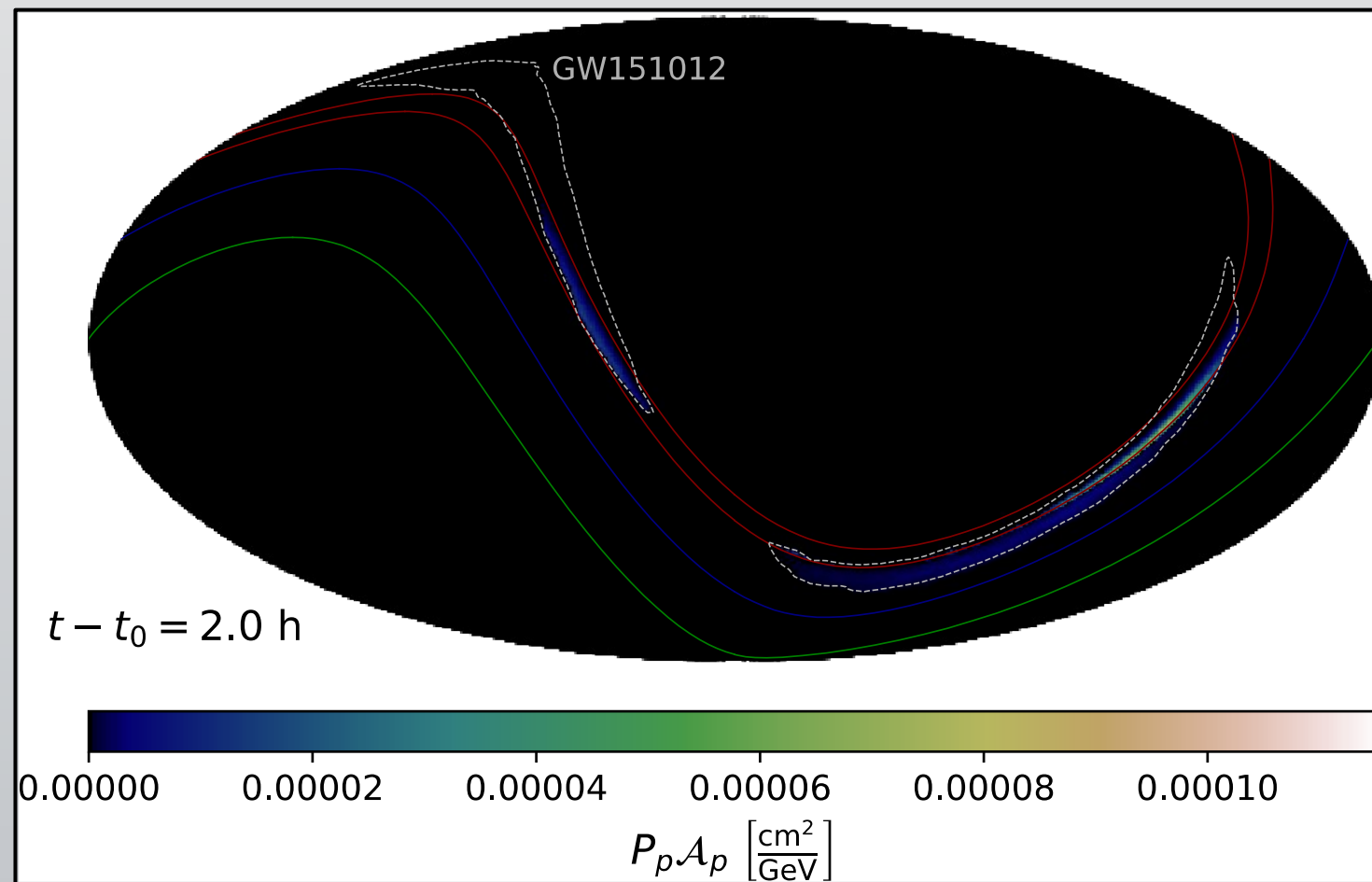
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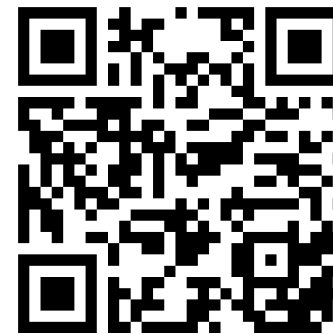


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Combining BBH mergers—Visibility of sources

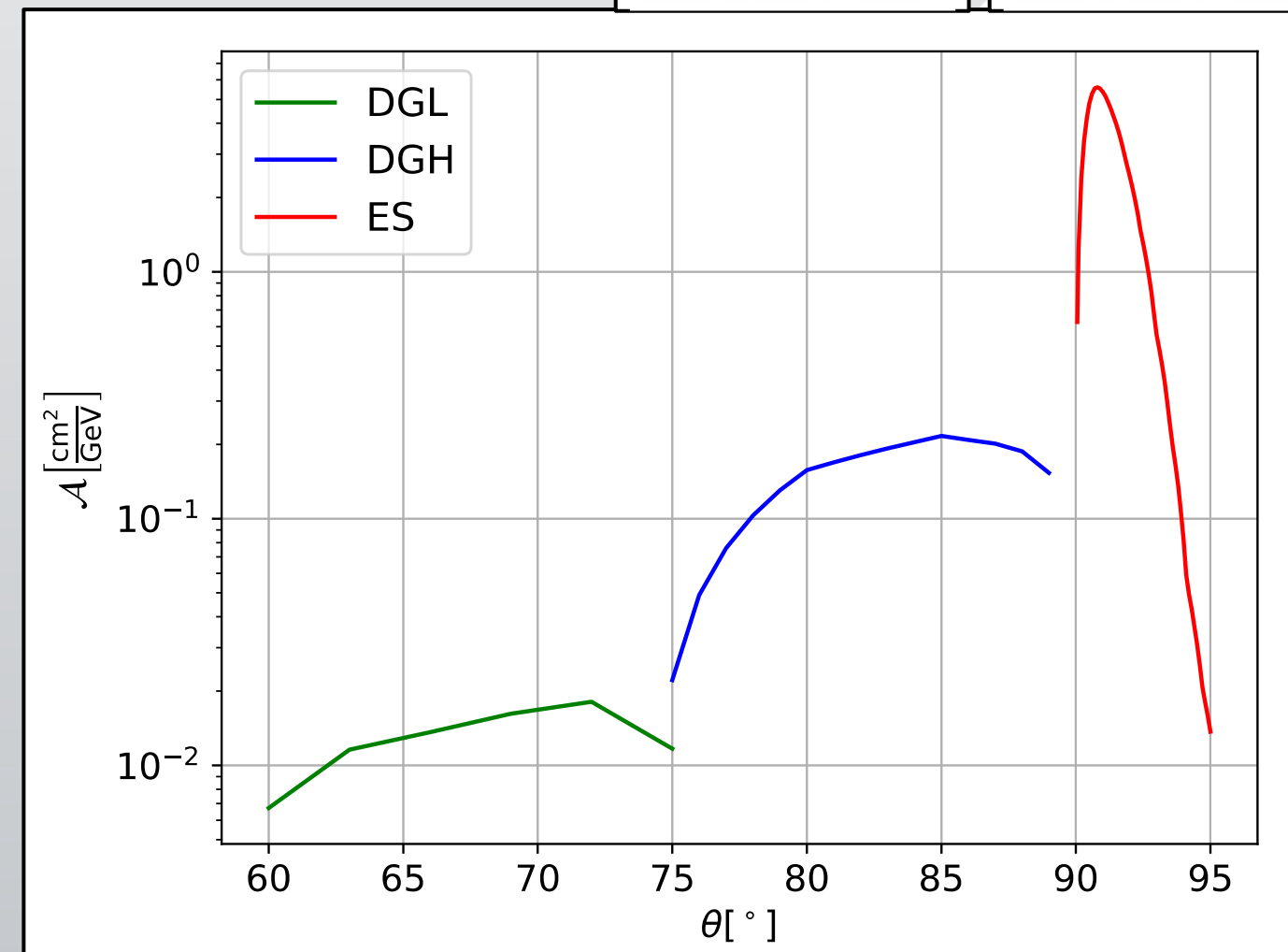
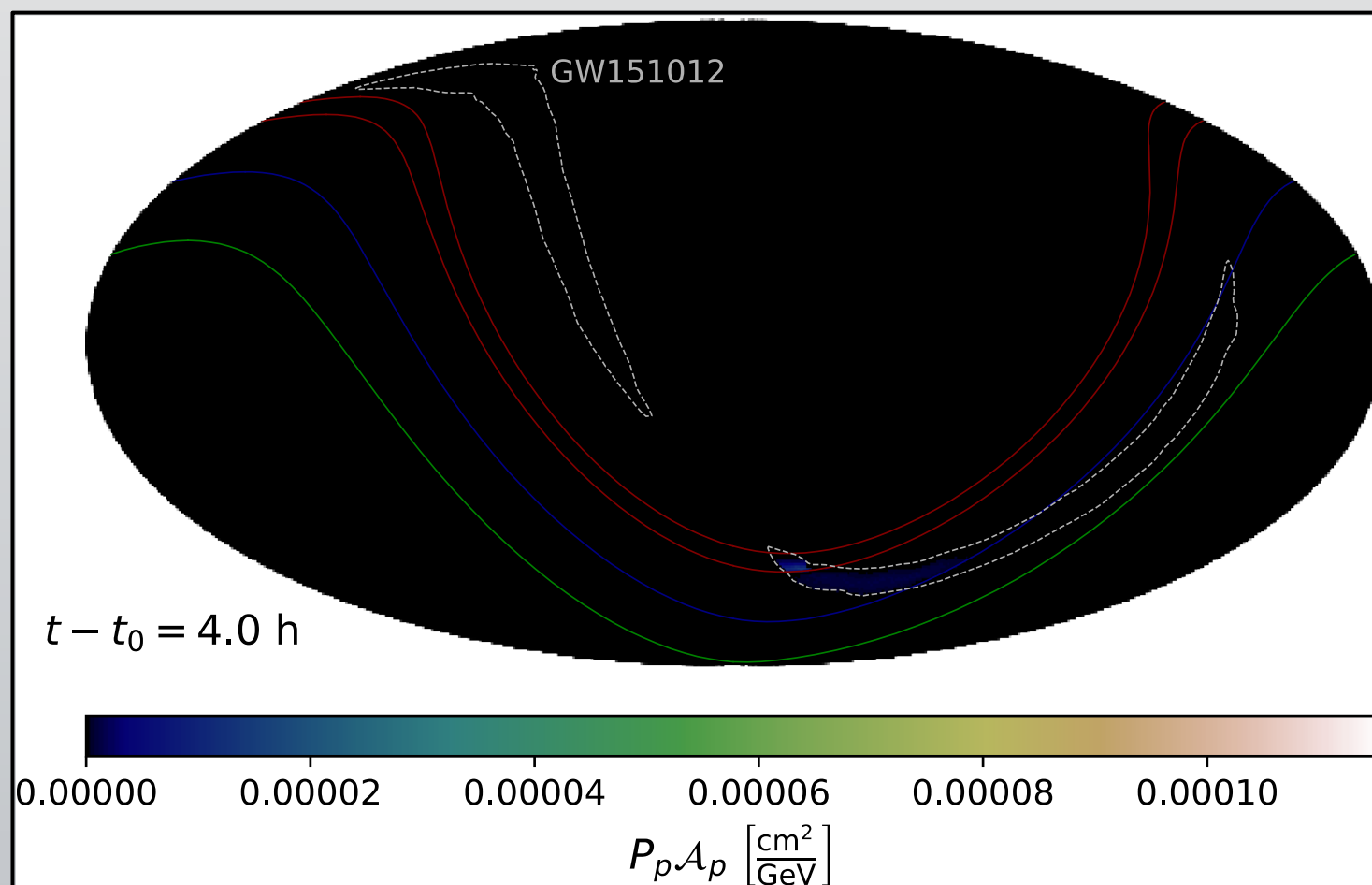
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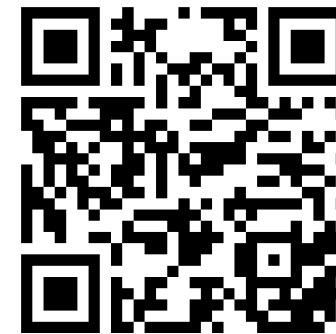


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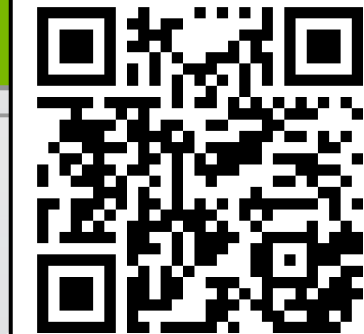


Combining BBH mergers—Visibility of sources

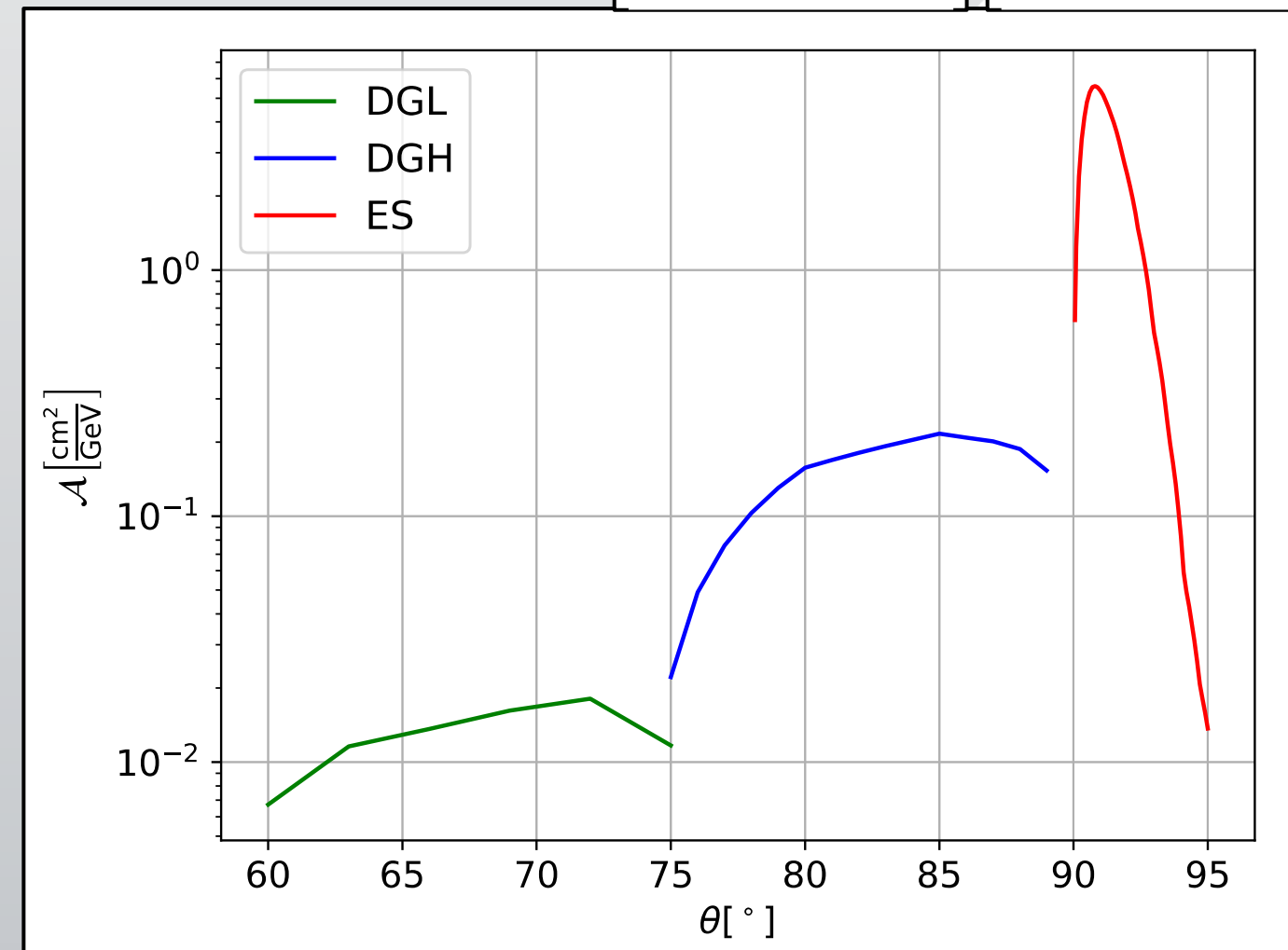
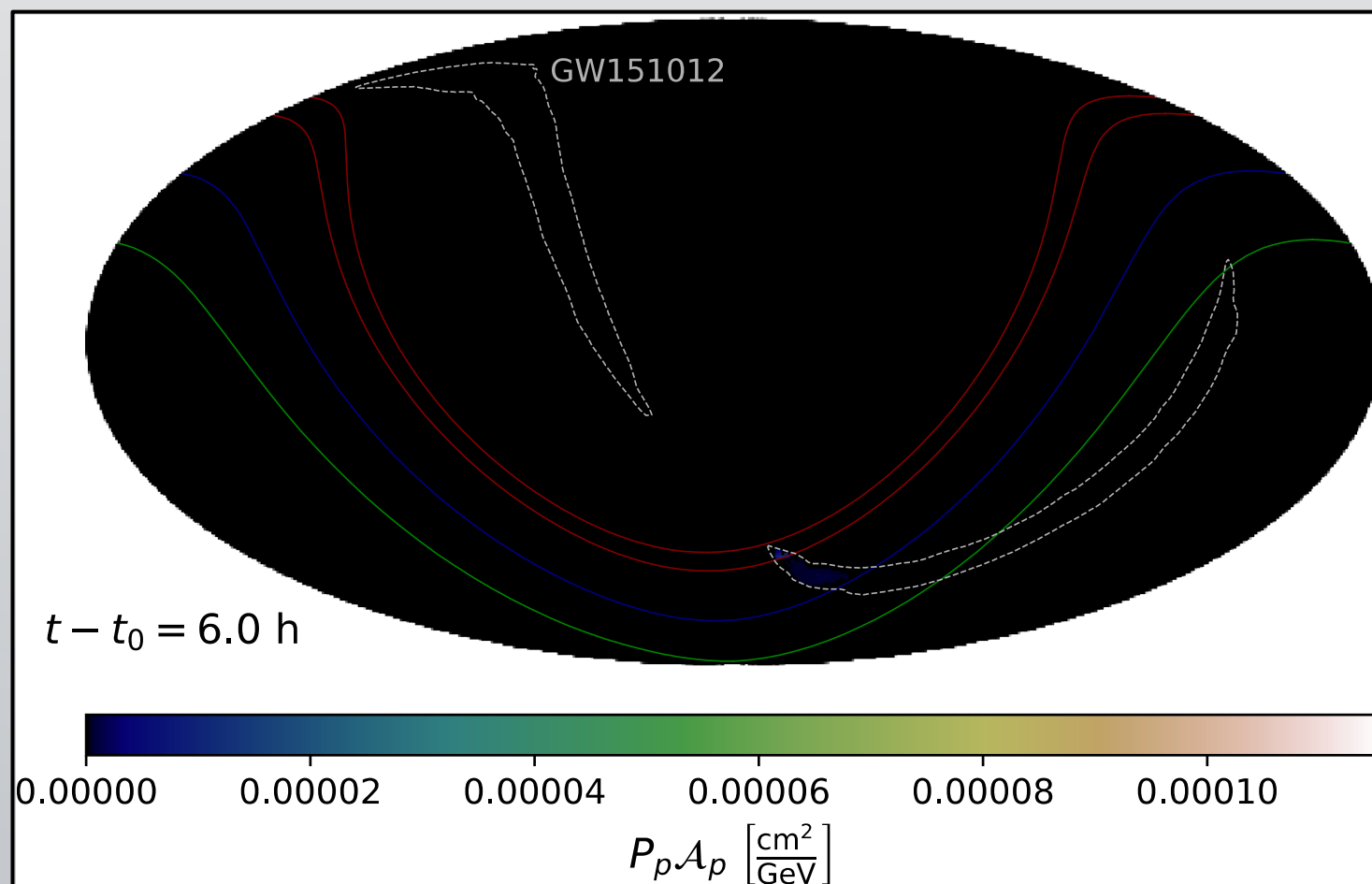
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Combining BBH mergers—Visibility of sources

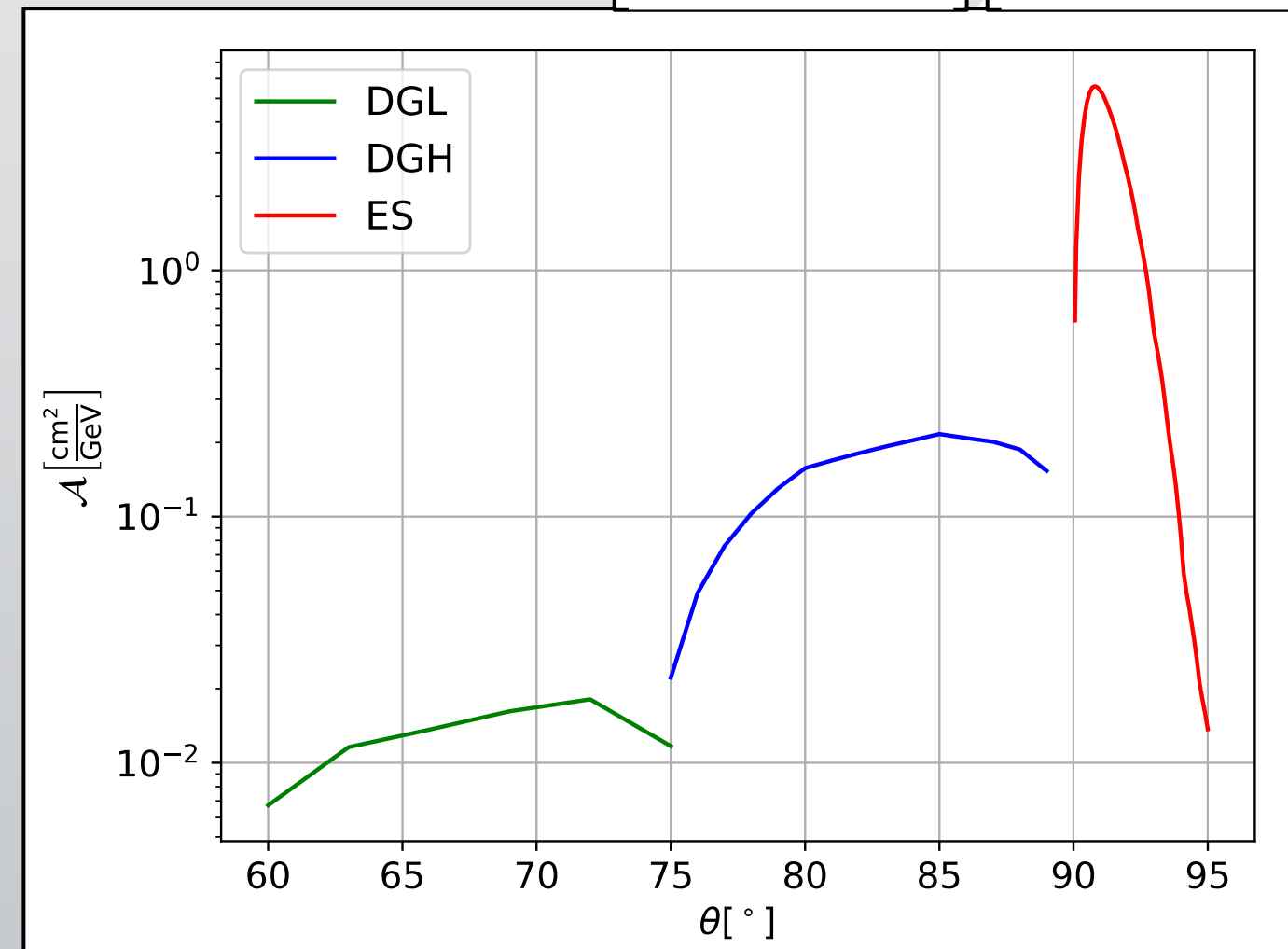
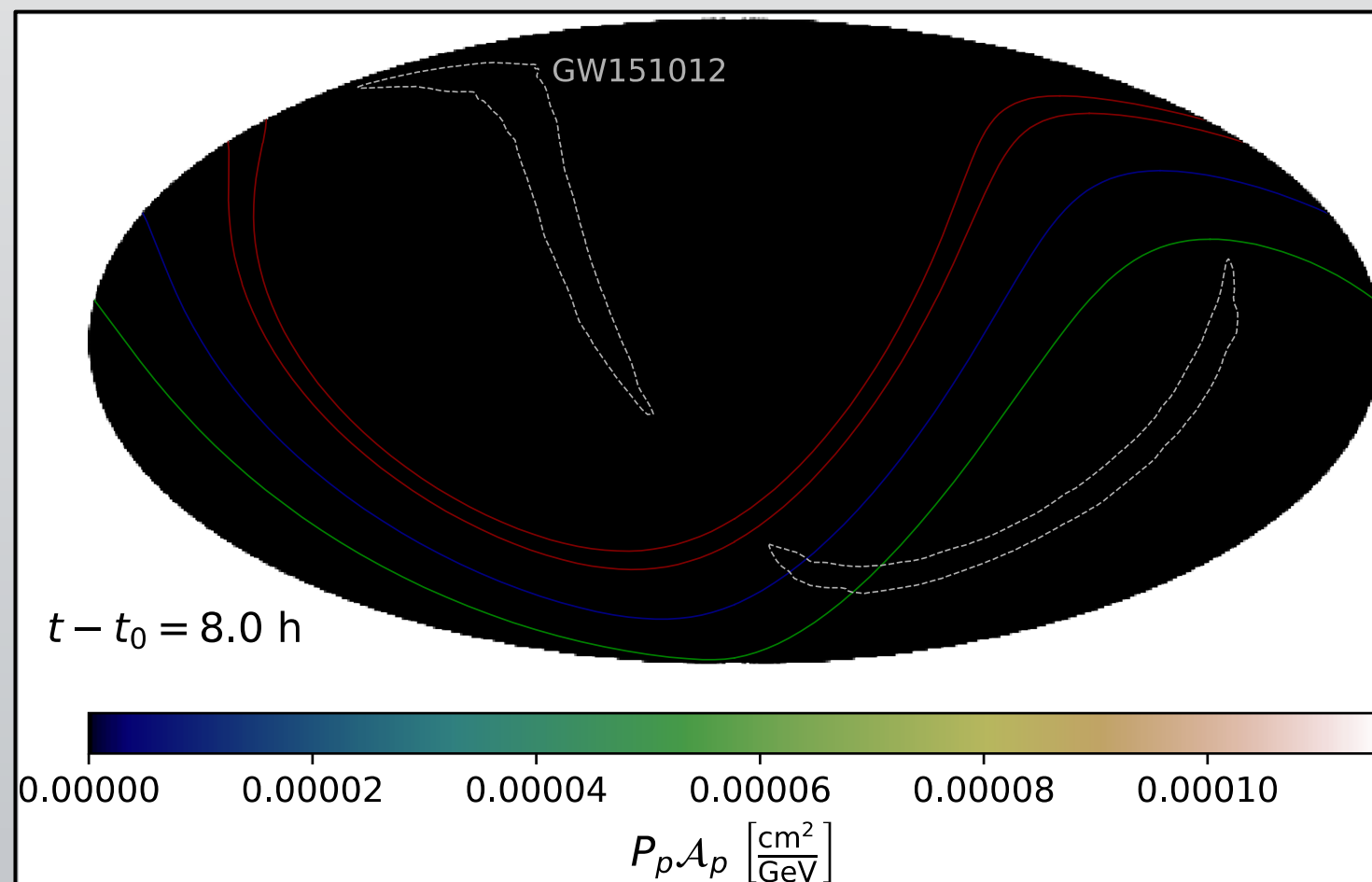
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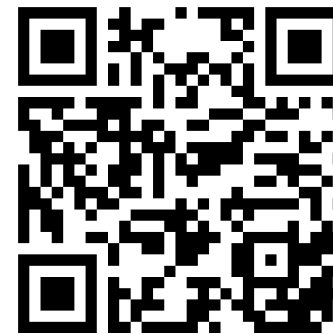


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Combining BBH mergers—Visibility of sources

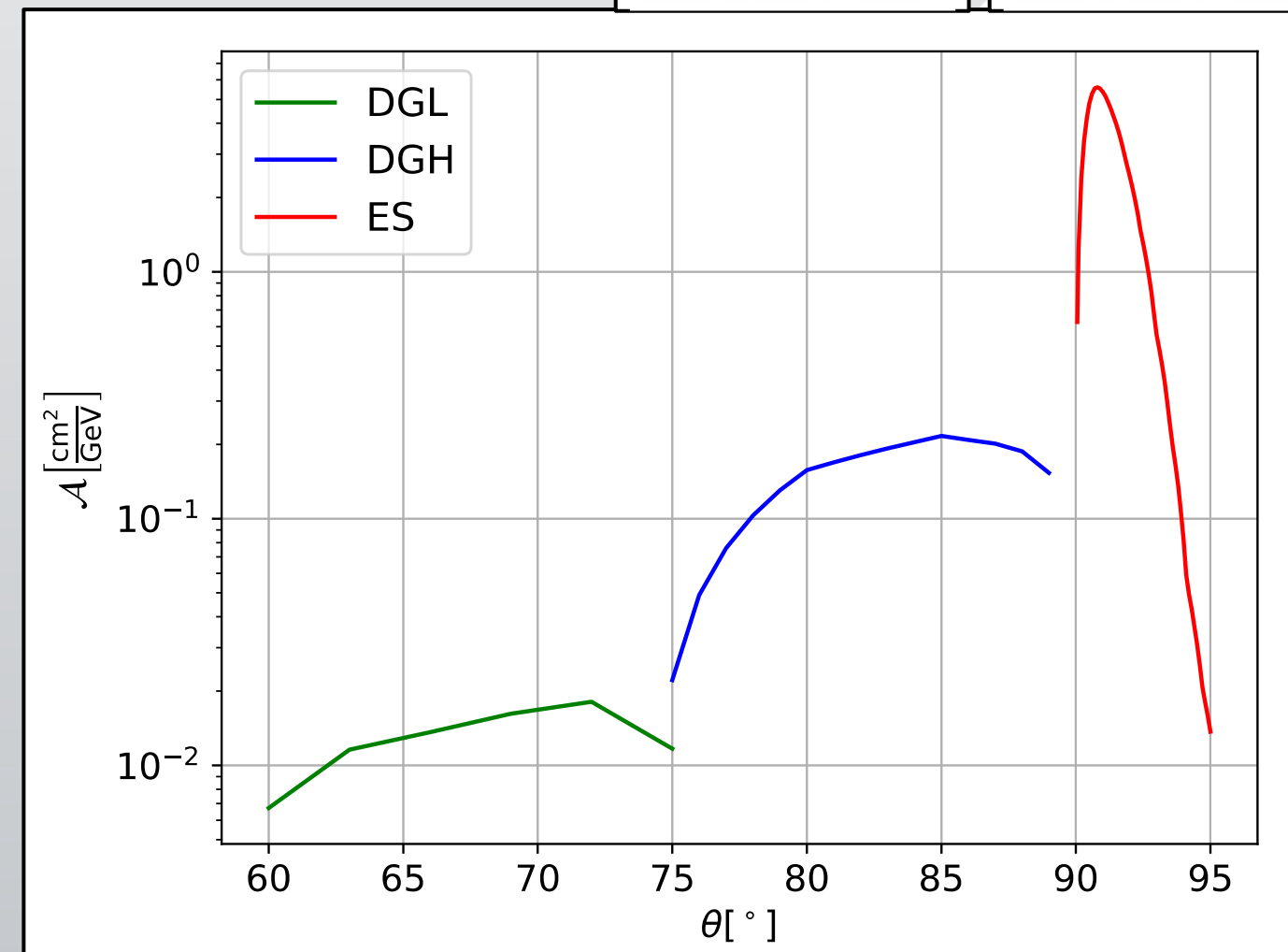
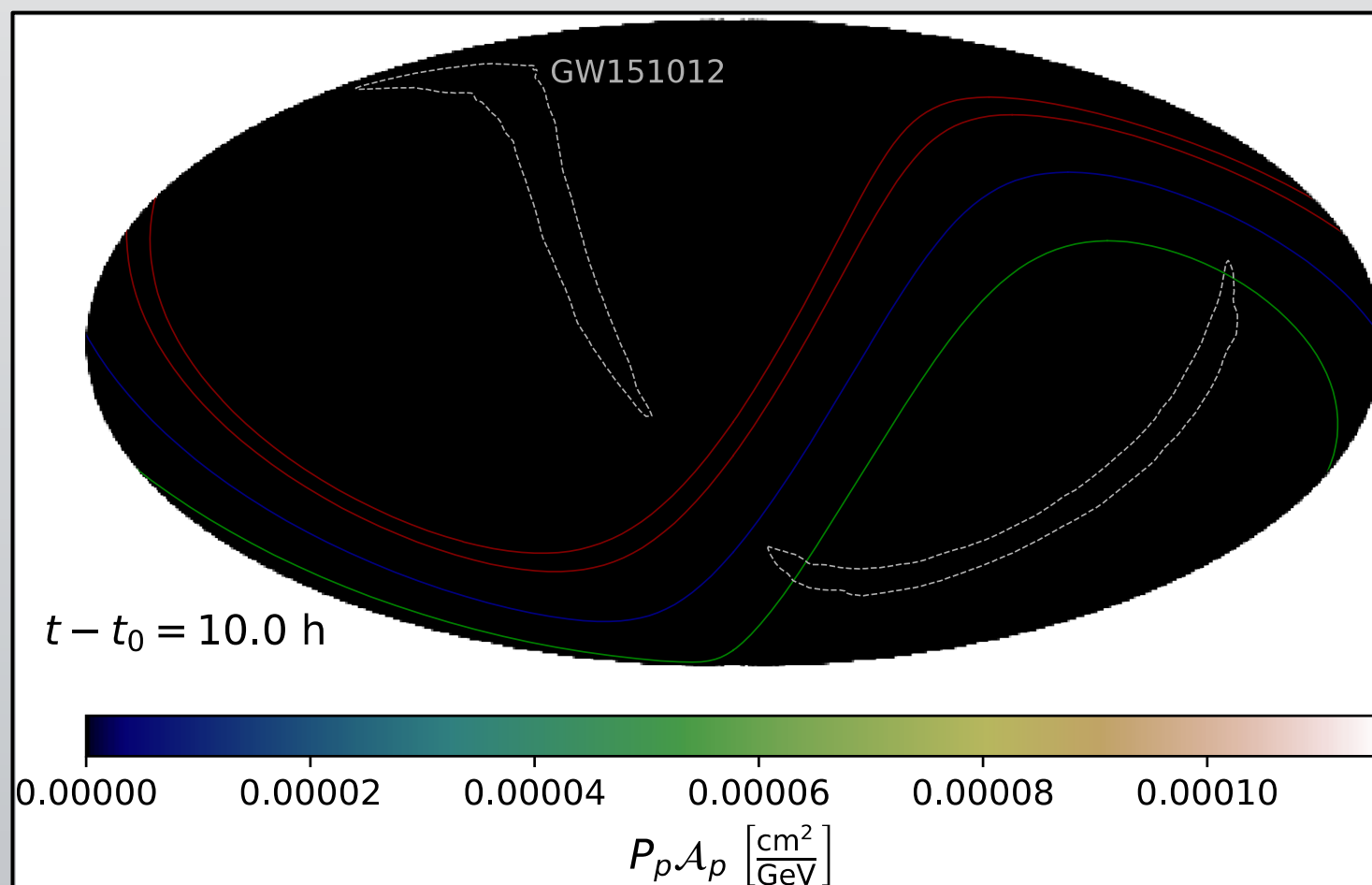
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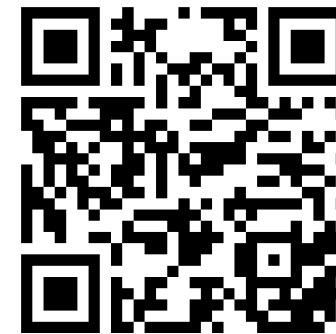


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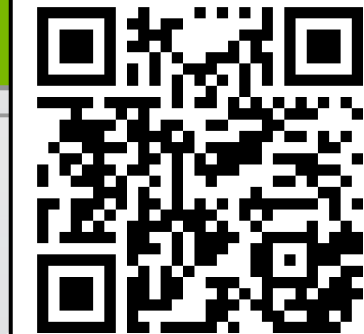


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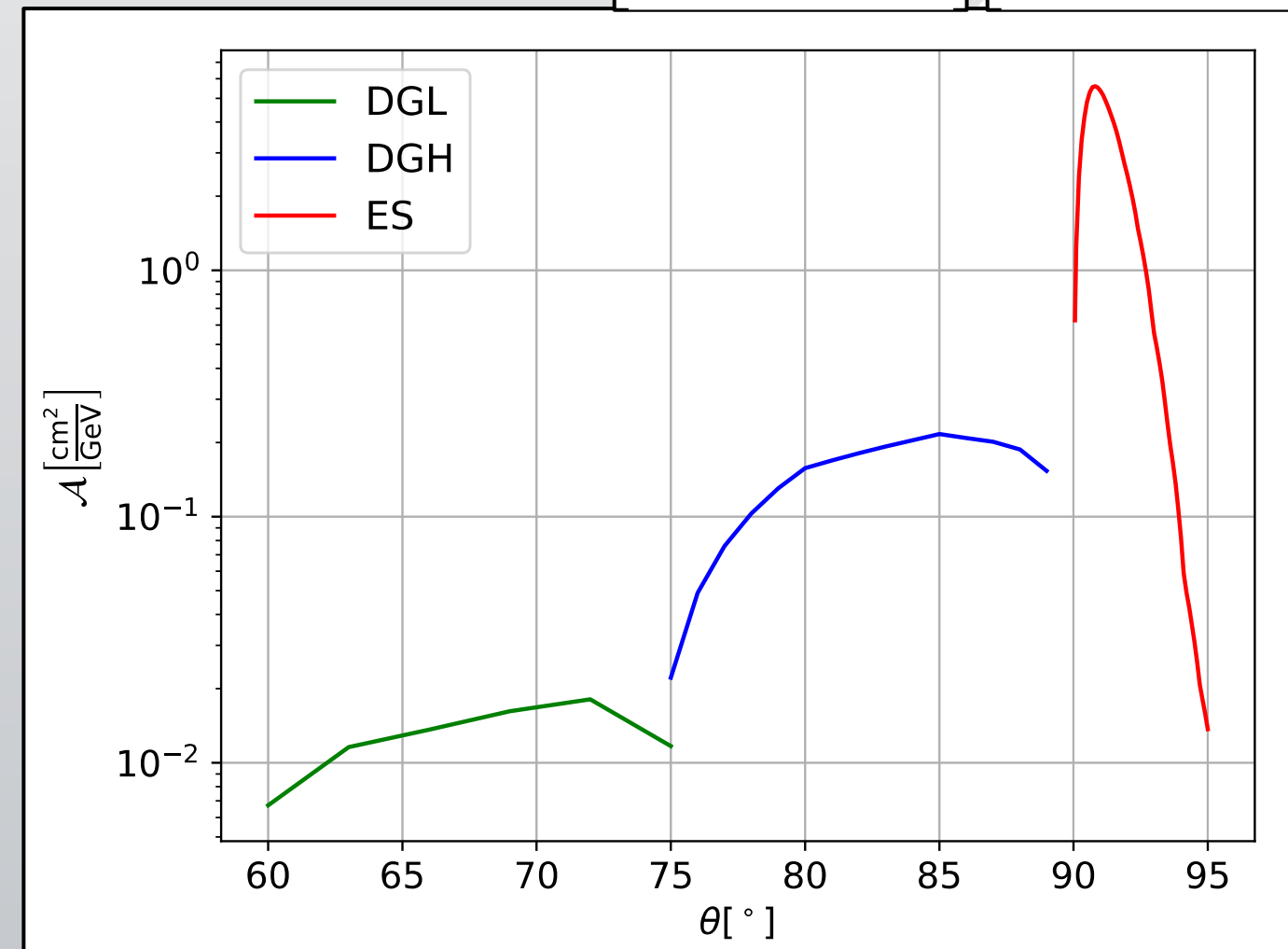
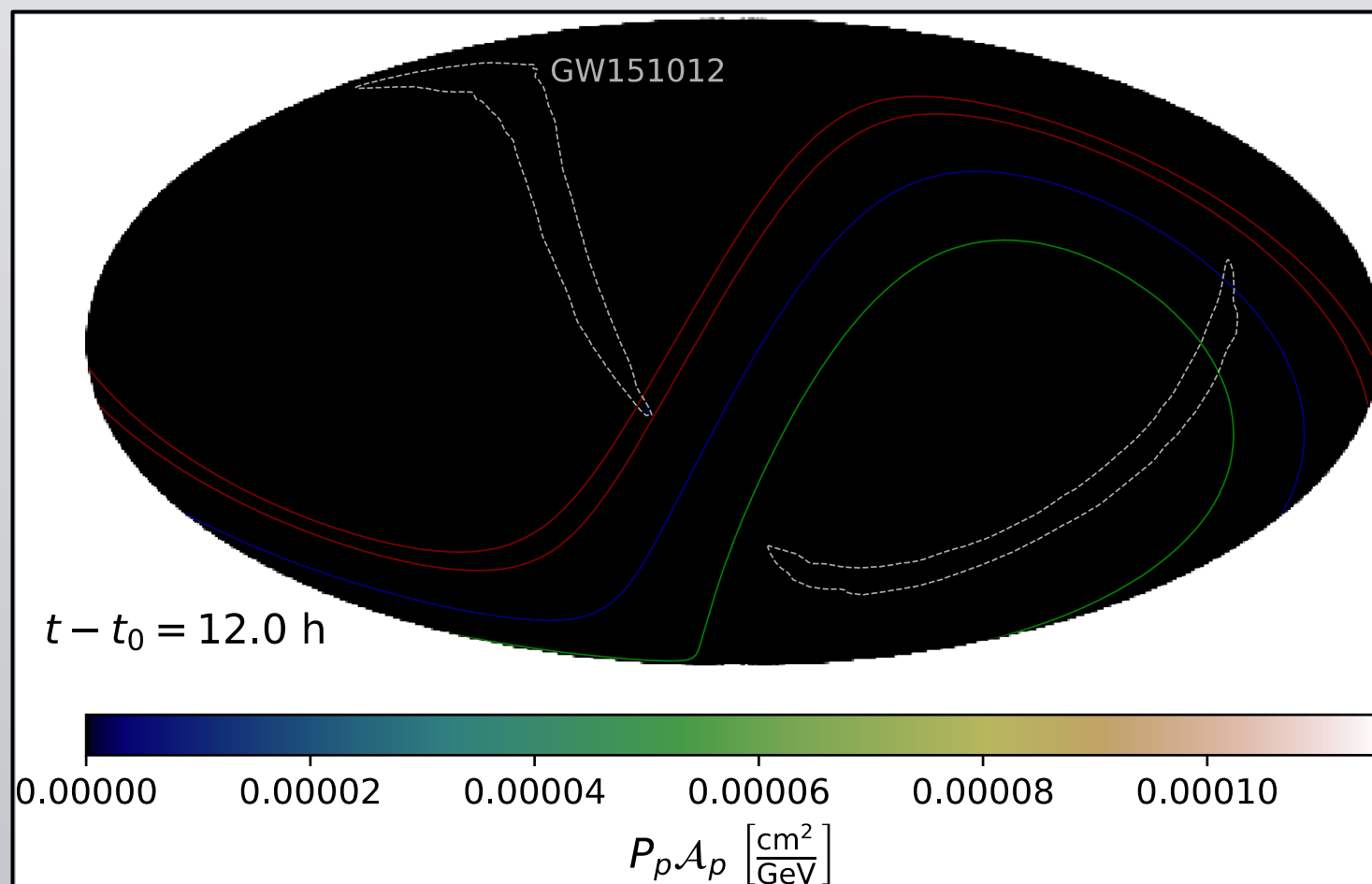
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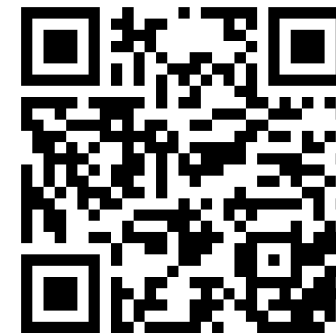


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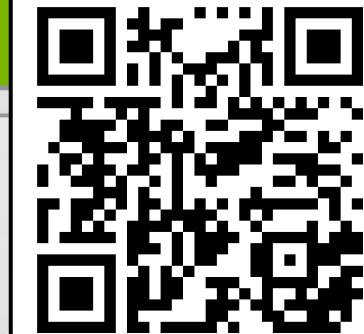


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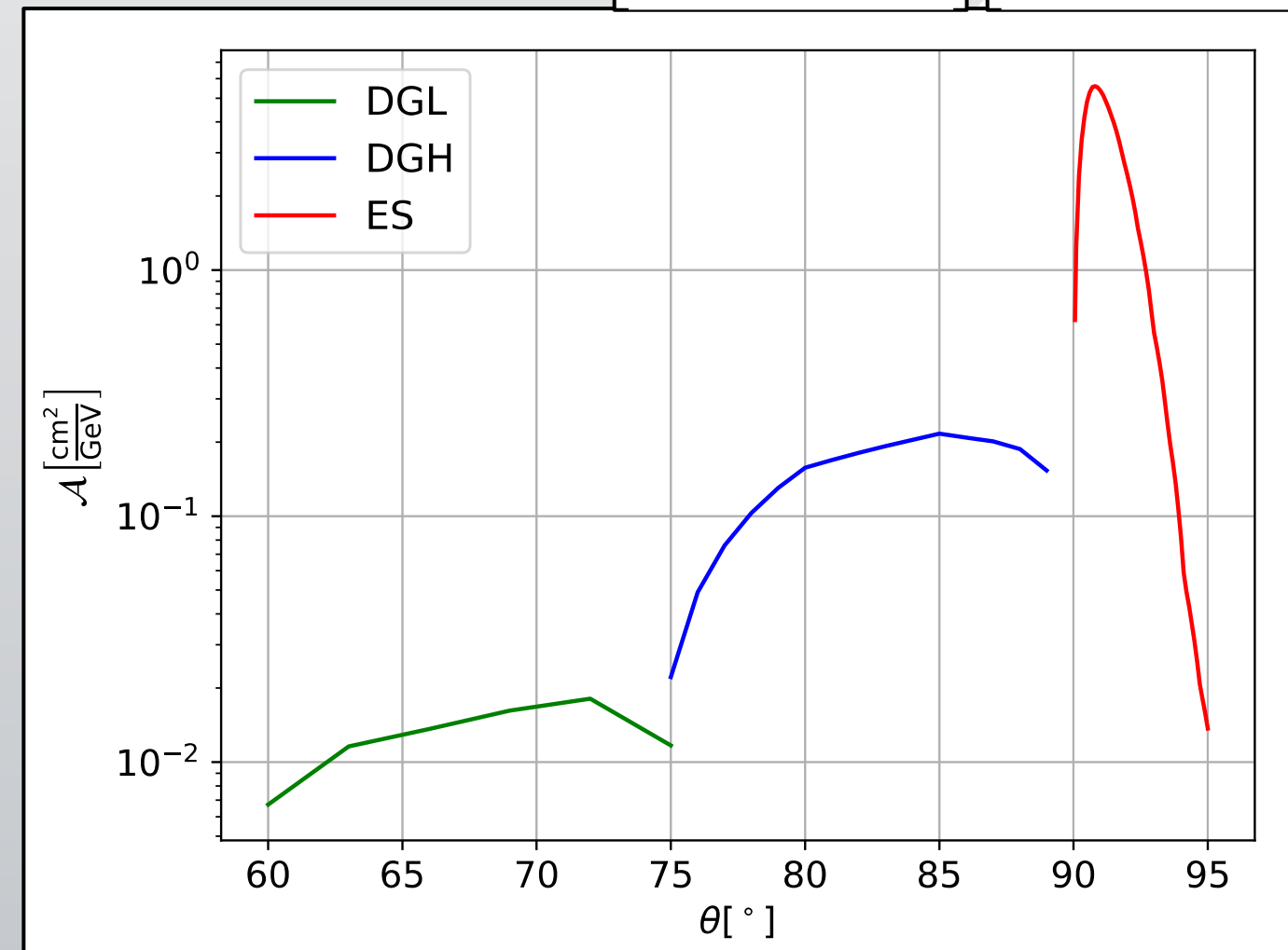
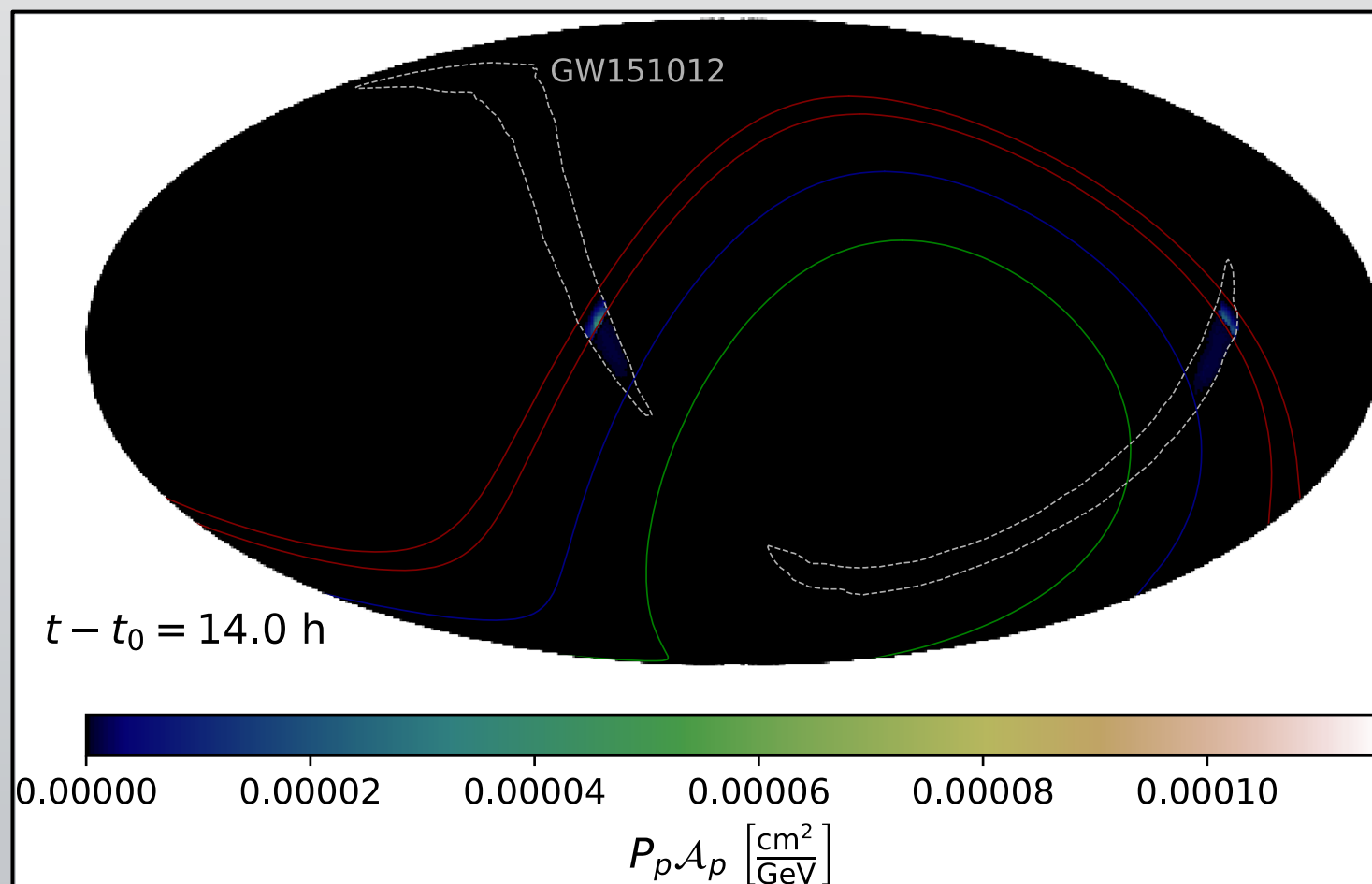
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Combining BBH mergers—Visibility of sources

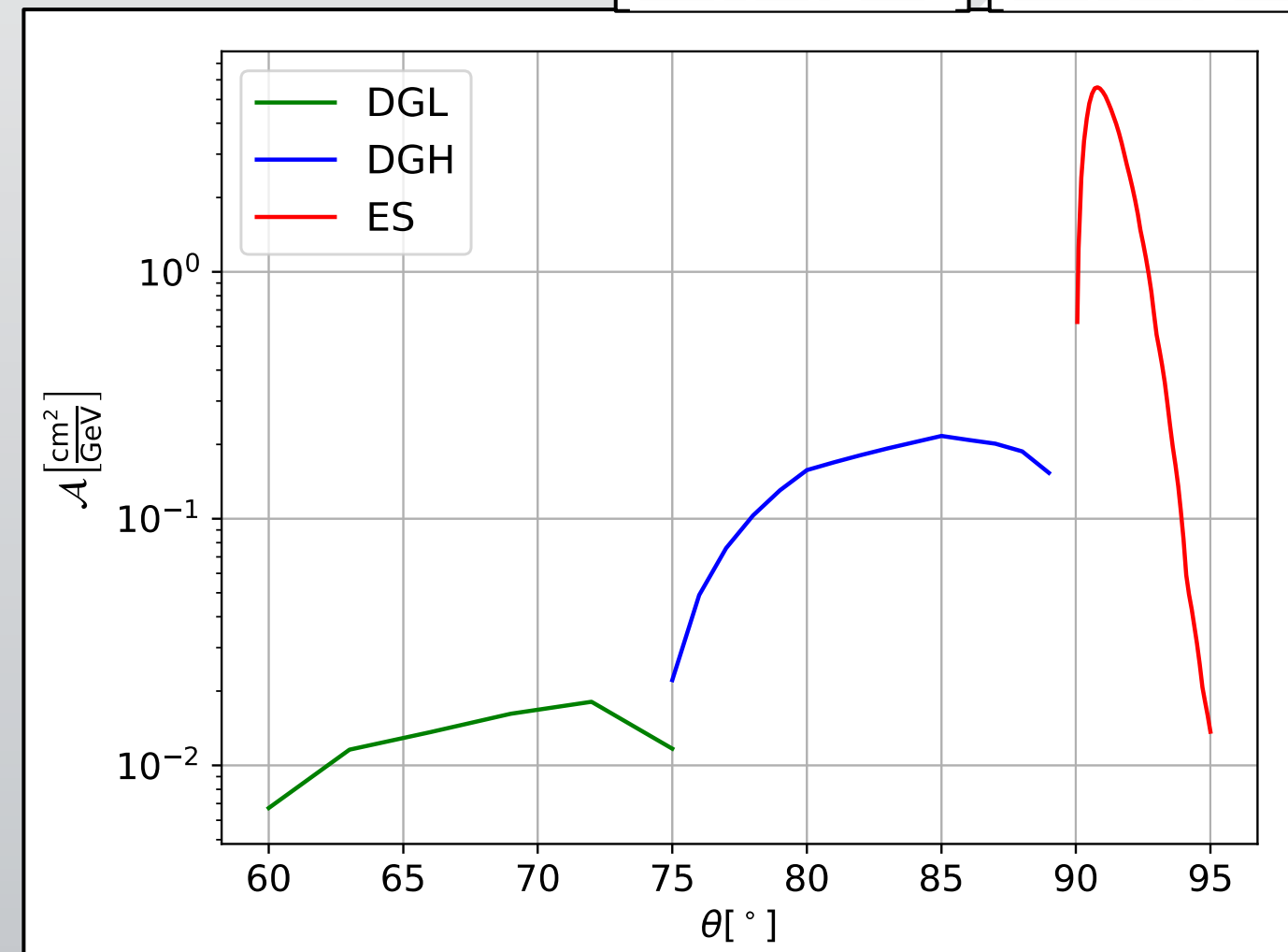
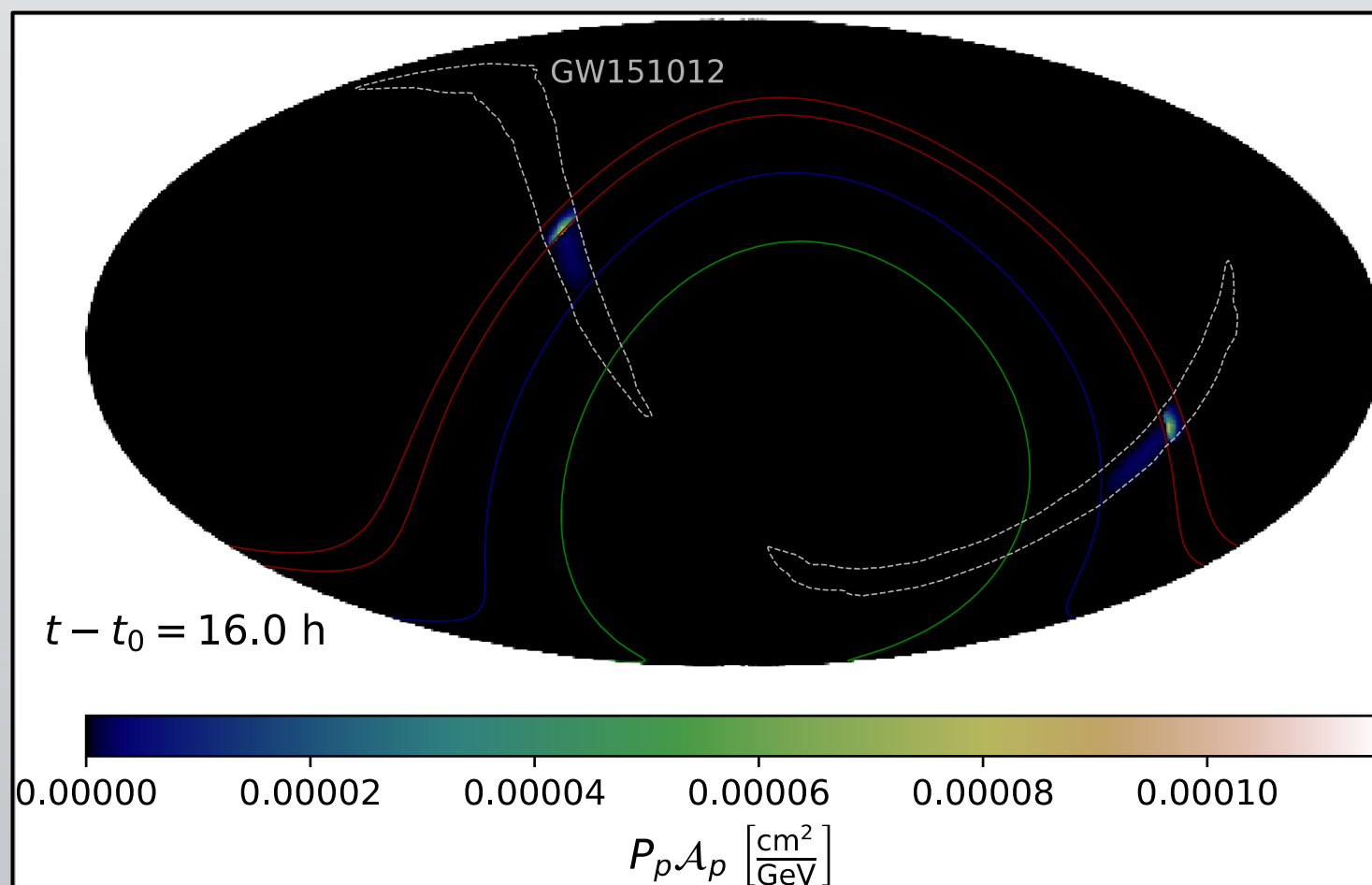
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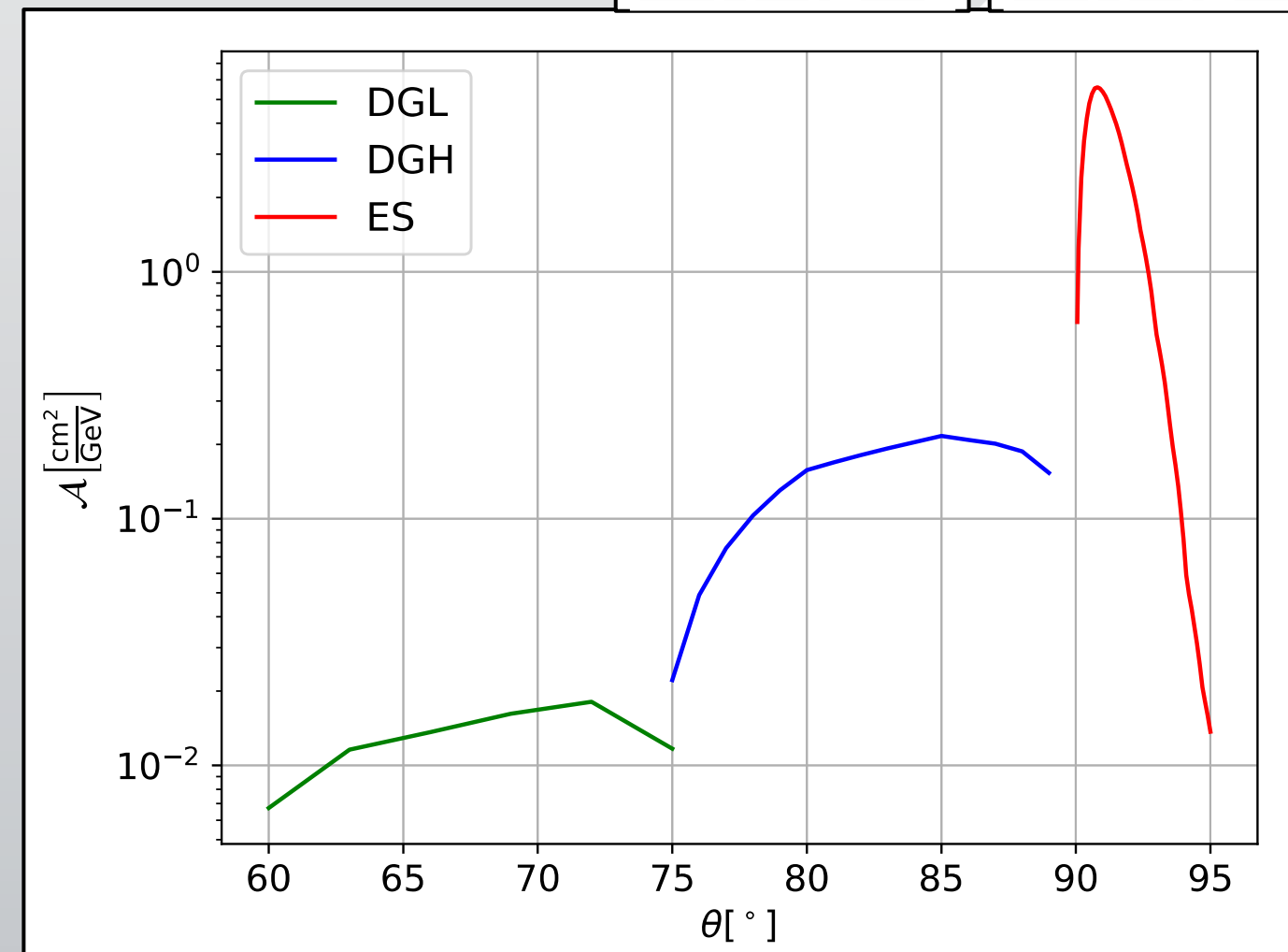
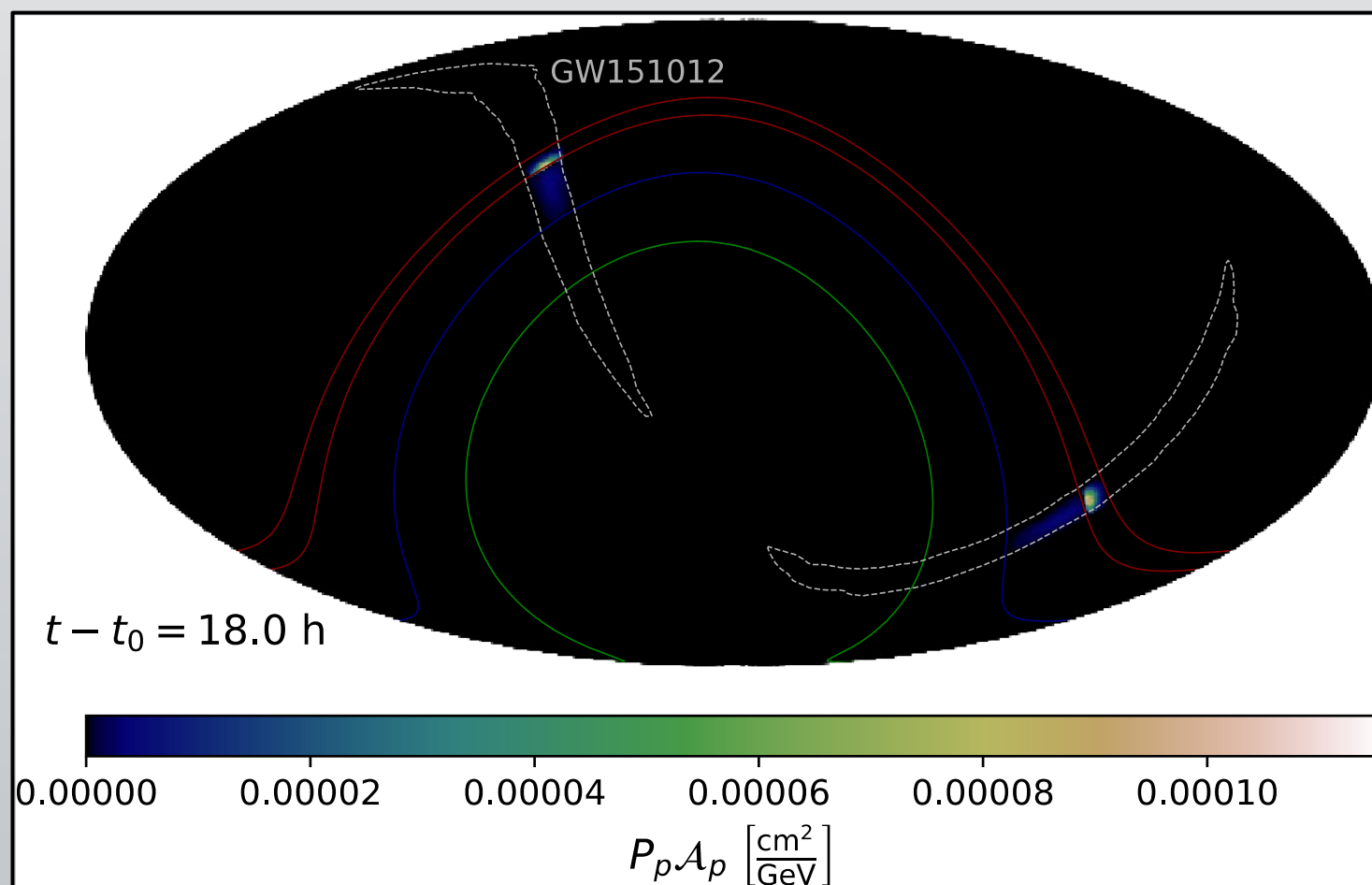
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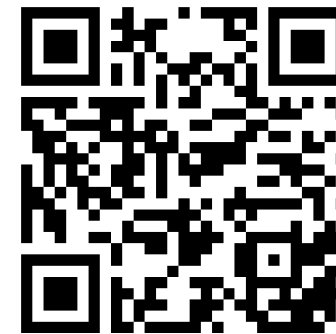


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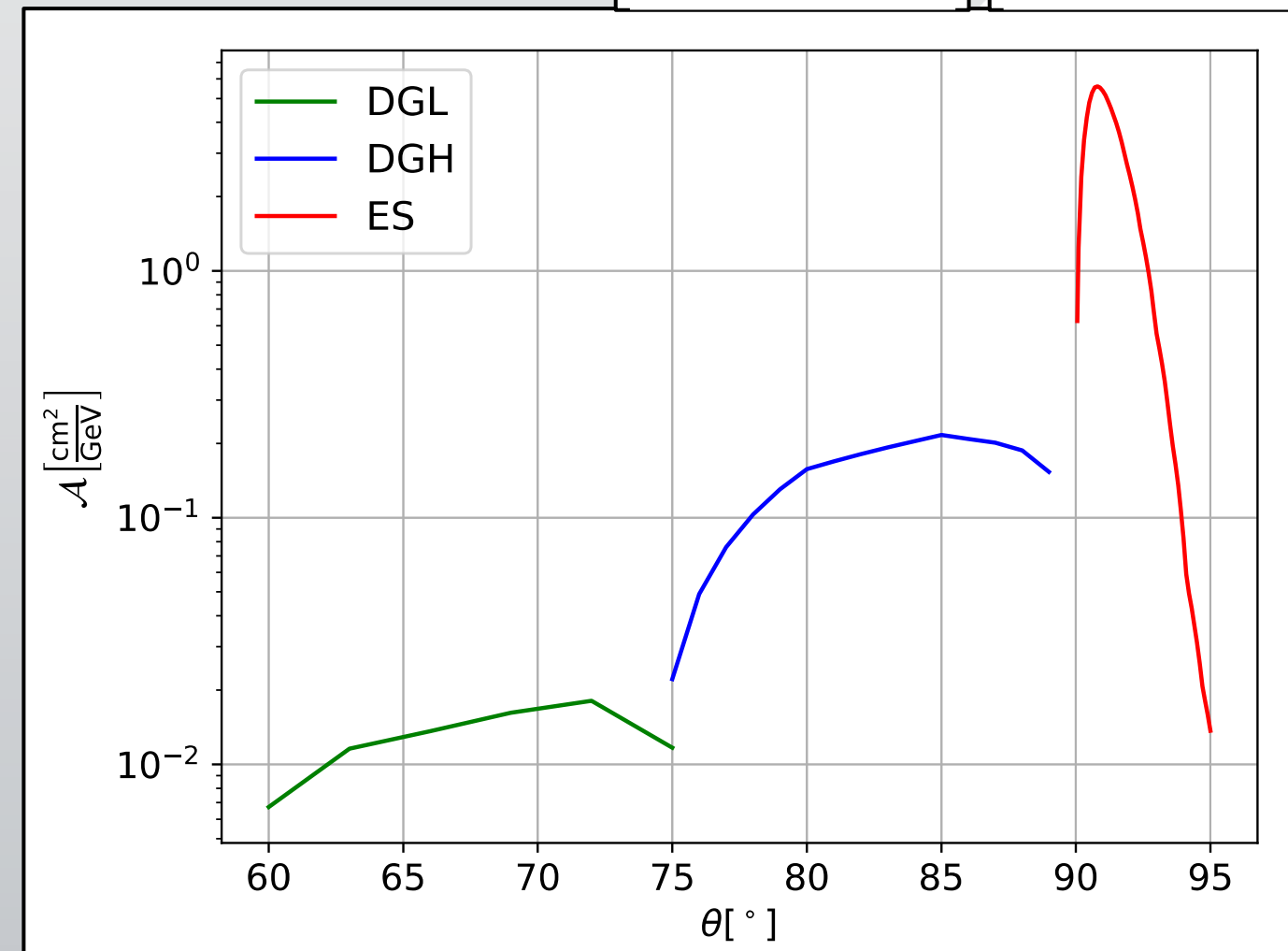
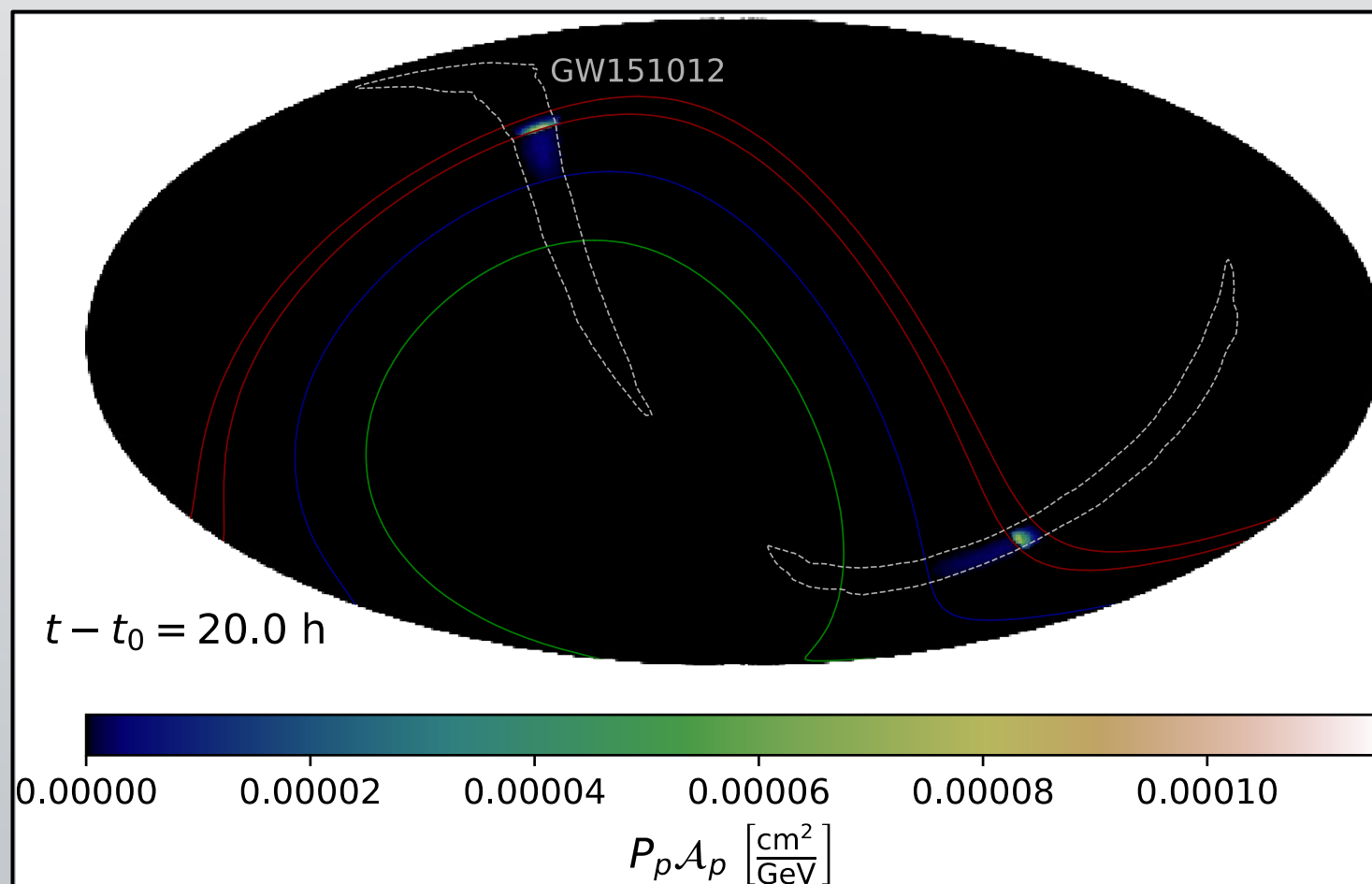
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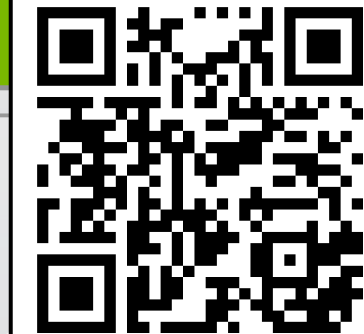


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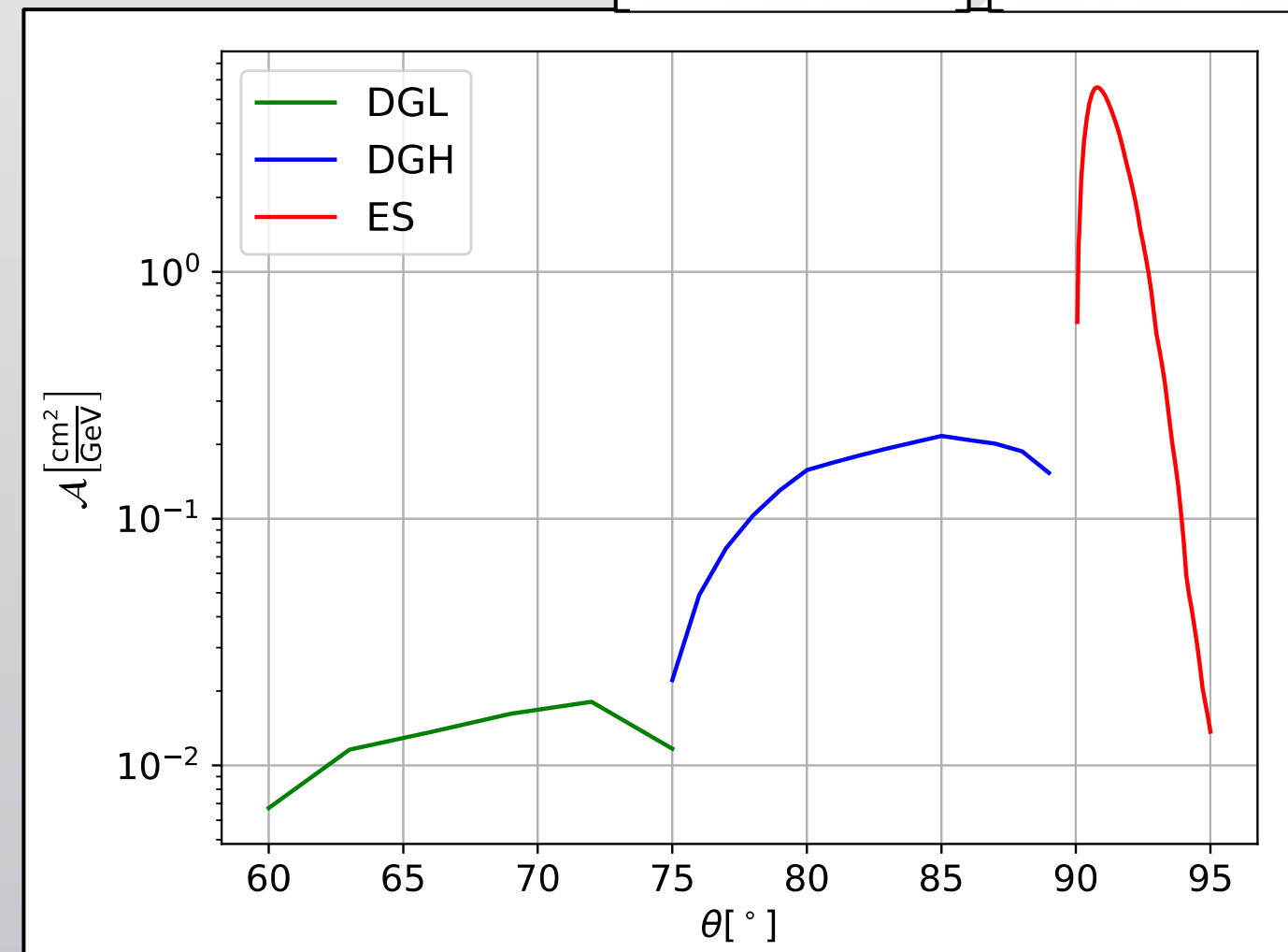
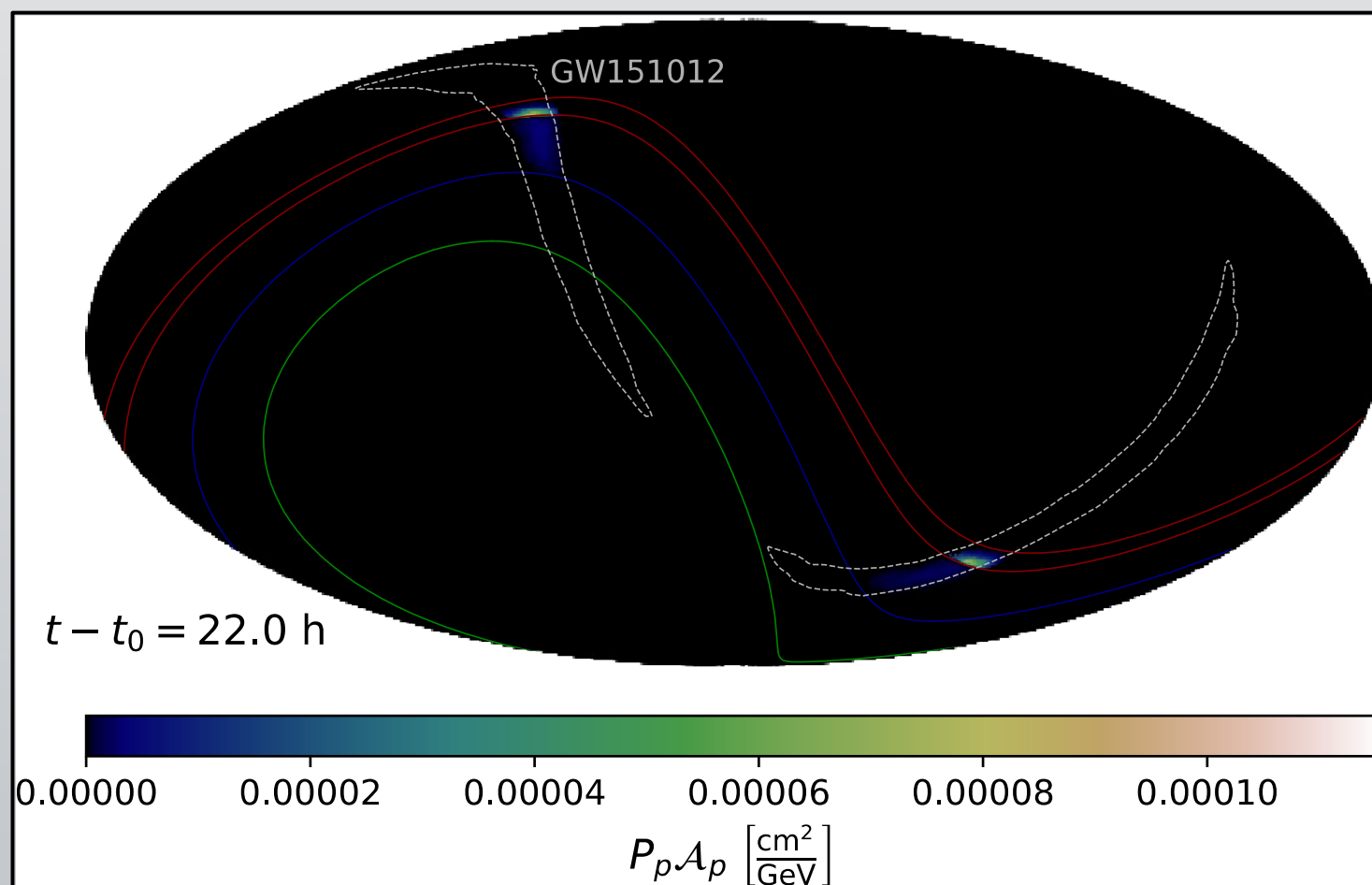
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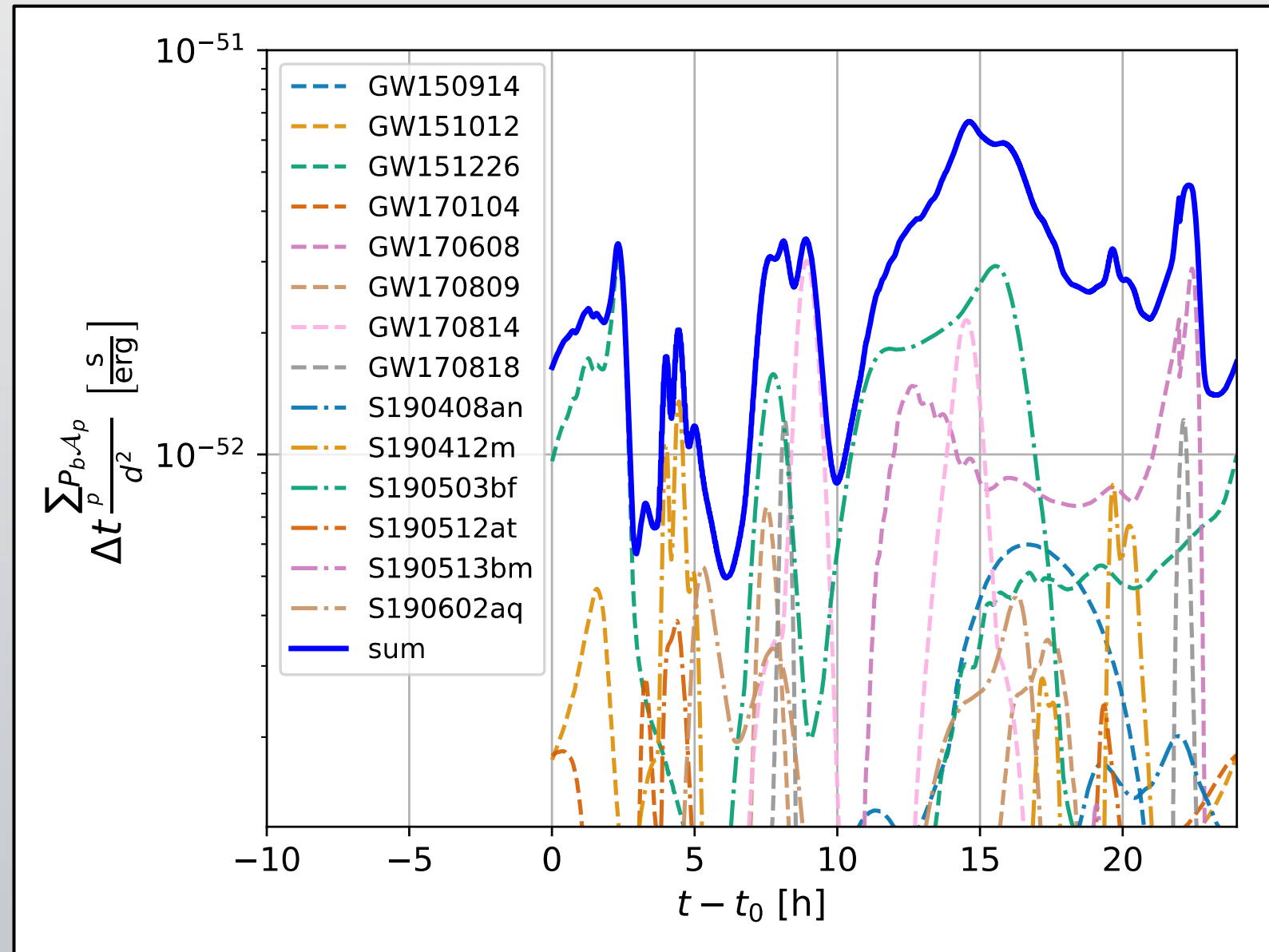


Combining BBH mergers—Visibility of sources

$$N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2}$$

“Number of neutrinos per time bin per luminosity”

Alternating domination by different sources



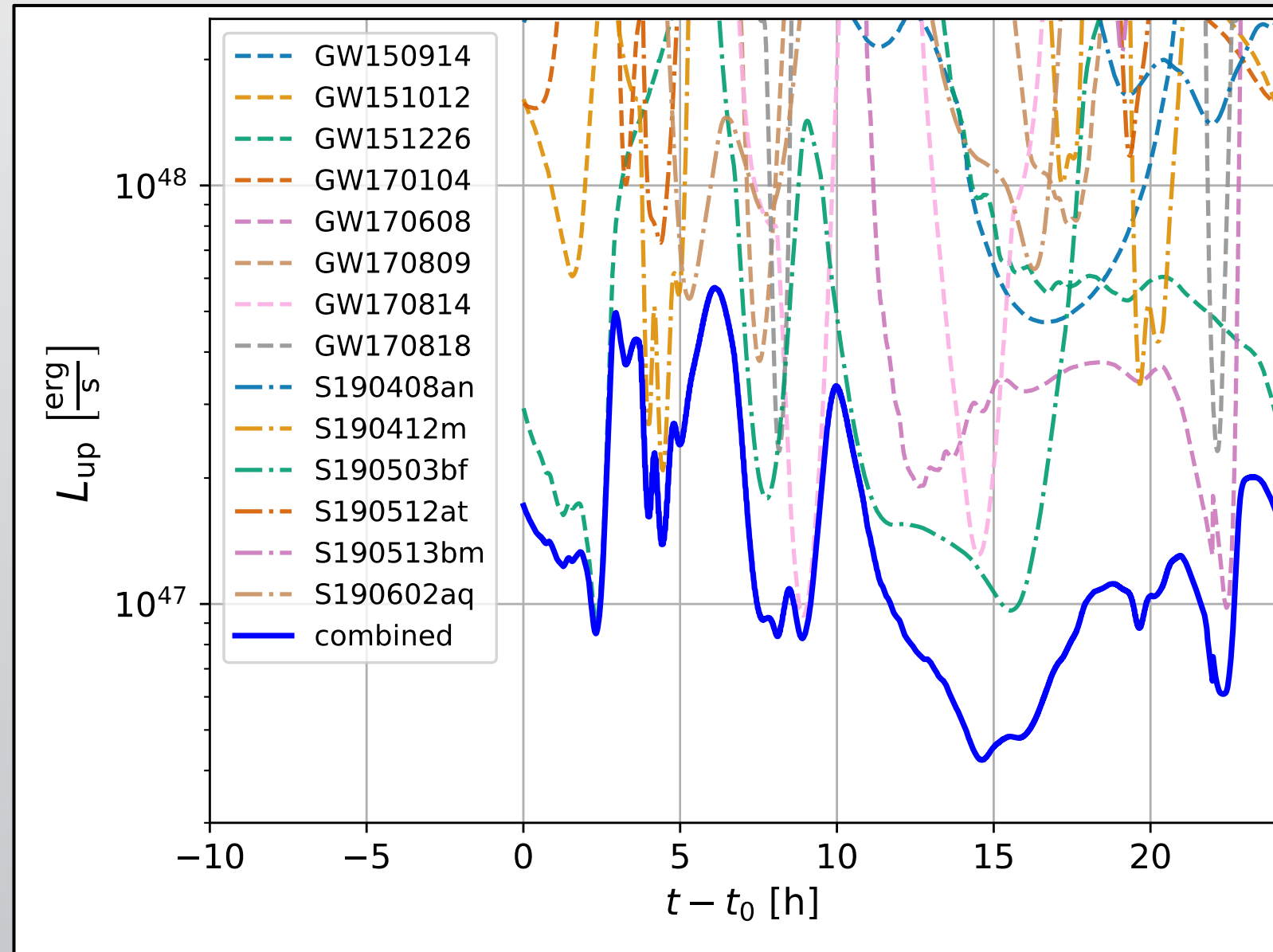
Combining BBH mergers—Upper limit on luminosity

$$N_{\nu,i} = L_i \Delta t \sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2}$$

No neutrinos observed during 24 h after any merger: **upper limit on L_i**

$$N_{\text{up},\nu,i} = \frac{N_{\text{up},\nu,\text{tot}}}{N_{\text{bins}}} = \frac{2.44}{\frac{24 \text{ h}}{\Delta t}} = \frac{2.44}{86400}$$

$$\Rightarrow \boxed{L_{\text{up},i}} = \frac{2.44}{86400 \text{ s}} \left(\sum_s \frac{\sum_p P_{p,s} \mathcal{A}_{p,s,i}}{d_s^2} \right)^{-1}$$



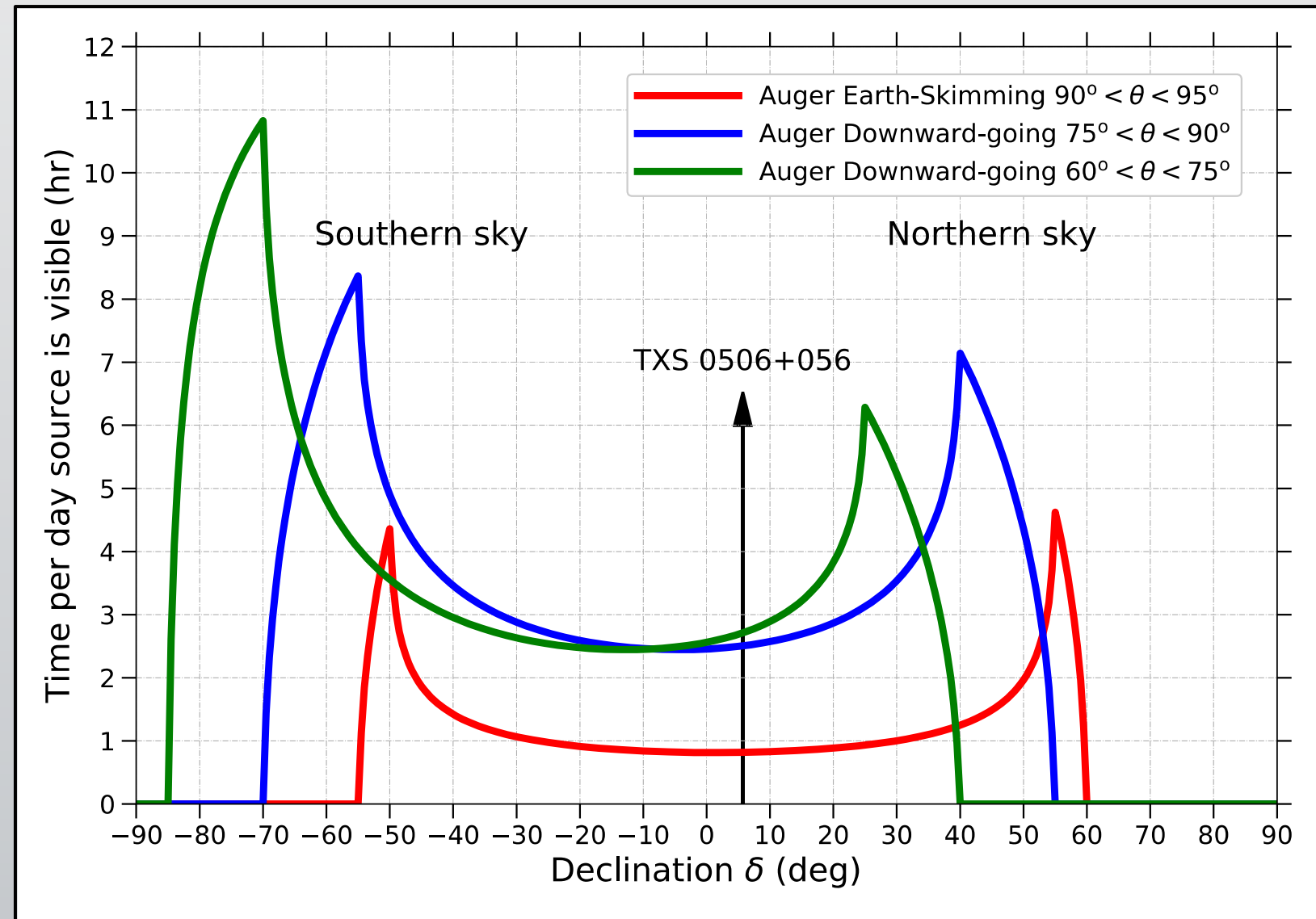
TXS 0506+056 follow-up



TXS 0506+056 follow-up

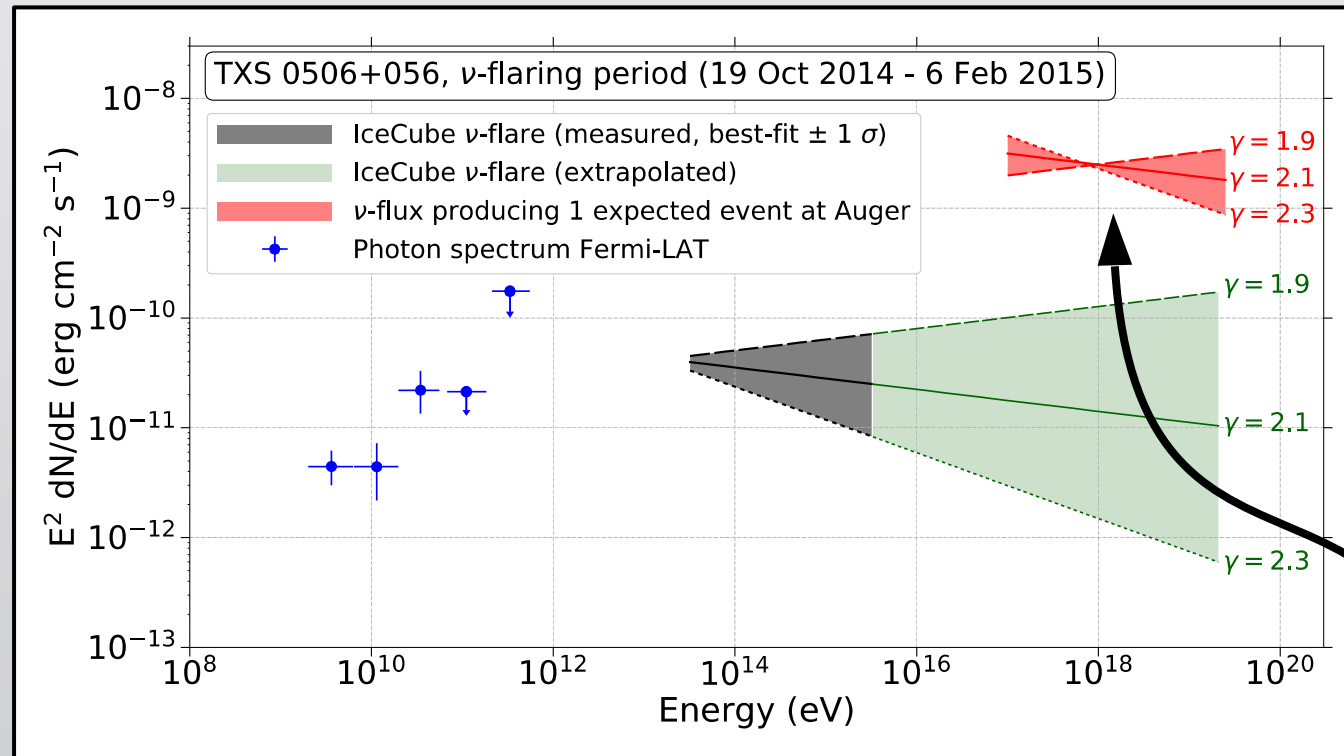
Blazar, $z \approx 0.34$

- 2014-10-19 – 2015-02-06
→ IceCube **neutrino excess**
- 2017-03-22 – 2017-09-22
→ IceCube high energy neutrino during **gamma-ray flare**
- Whole days of follow-up observation
→ sensitivity depends only on source declination



TXS 0506+056 follow-up

IceCube neutrino excess



$$\gamma = 1.9$$

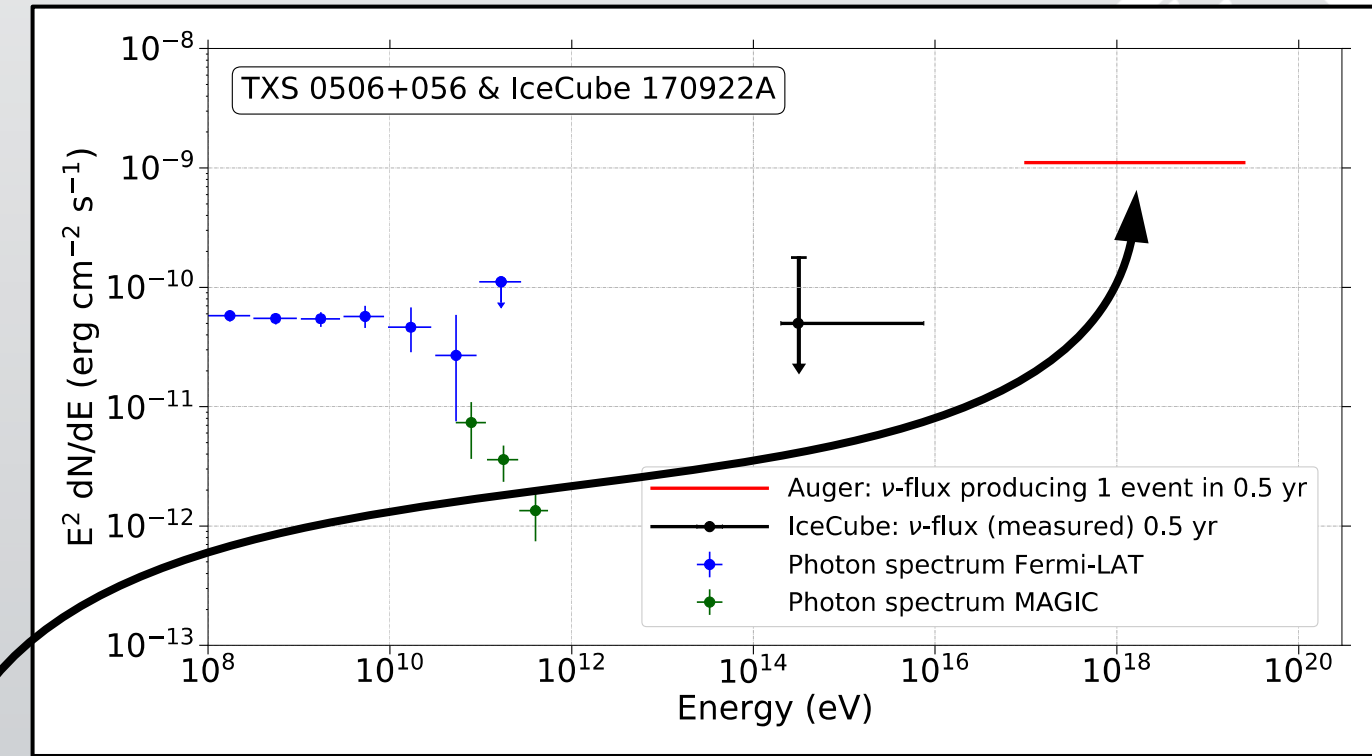
→ ~ 20 x IC extrapolation

$$\gamma = 2.3$$

→ ~ 2000 x IC extrapolation

Flux such that
1 event expected
with Auger

γ ray flare with IceCube HE neutrino



~ 20 x IC extrapolation

Conclusions



Conclusions

UHE neutrino follow-up searches performed for

- LIGO/Virgo BBH mergers
 - Method for **combining all sources** making simple assumptions
 - Sensitive to neutrino luminosities below **5×10^{46} erg/s** for certain periods during 1-day follow-up searches
- TXS 0506+056
 - Follow-up searches during **2 periods of several months**
 - Periodic visibility, **only a few hours per day**
 - Benchmark flux that would produce one neutrino in Auger:
~ 20 times IceCube extrapolated flux
 - Energy range complementary to IceCube

proceedings



The End

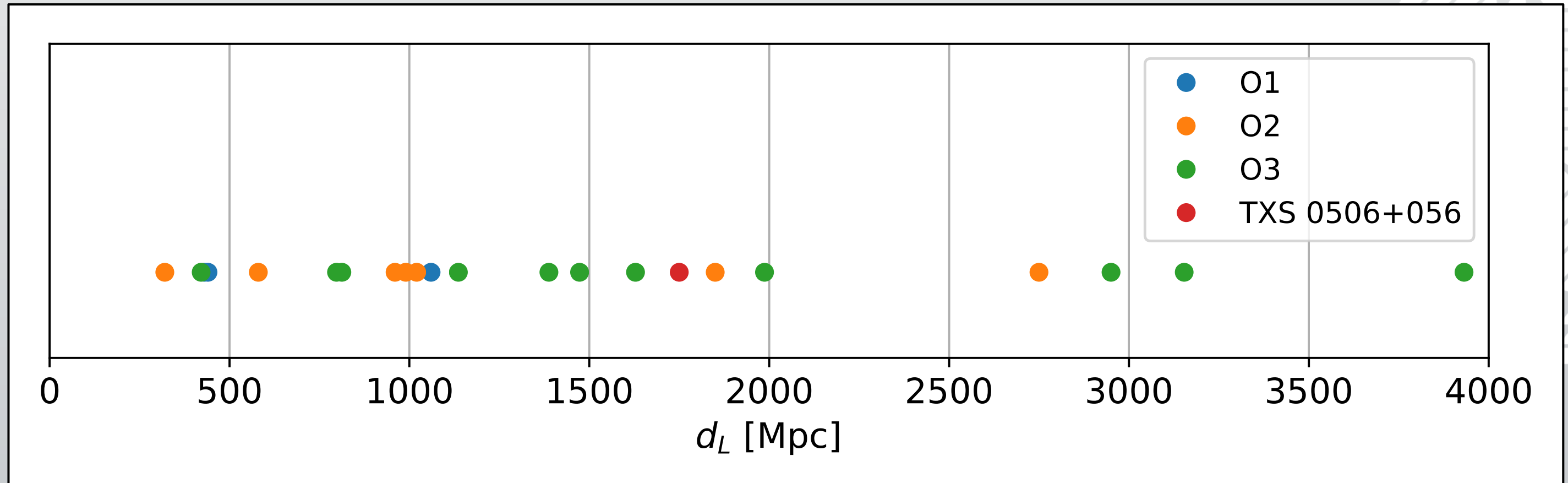


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- LIGO/Virgo switched to **open public alerts (OPAs)**, communicated via GCN
- Previously: MoU to share data with LIGO/Virgo, now we **automatically** follow-up the OPAs
- O3 runs since April 2019 with increased sensitivity
 - Increased rates / horizon / source volume
 - + possibly NS-BH mergers

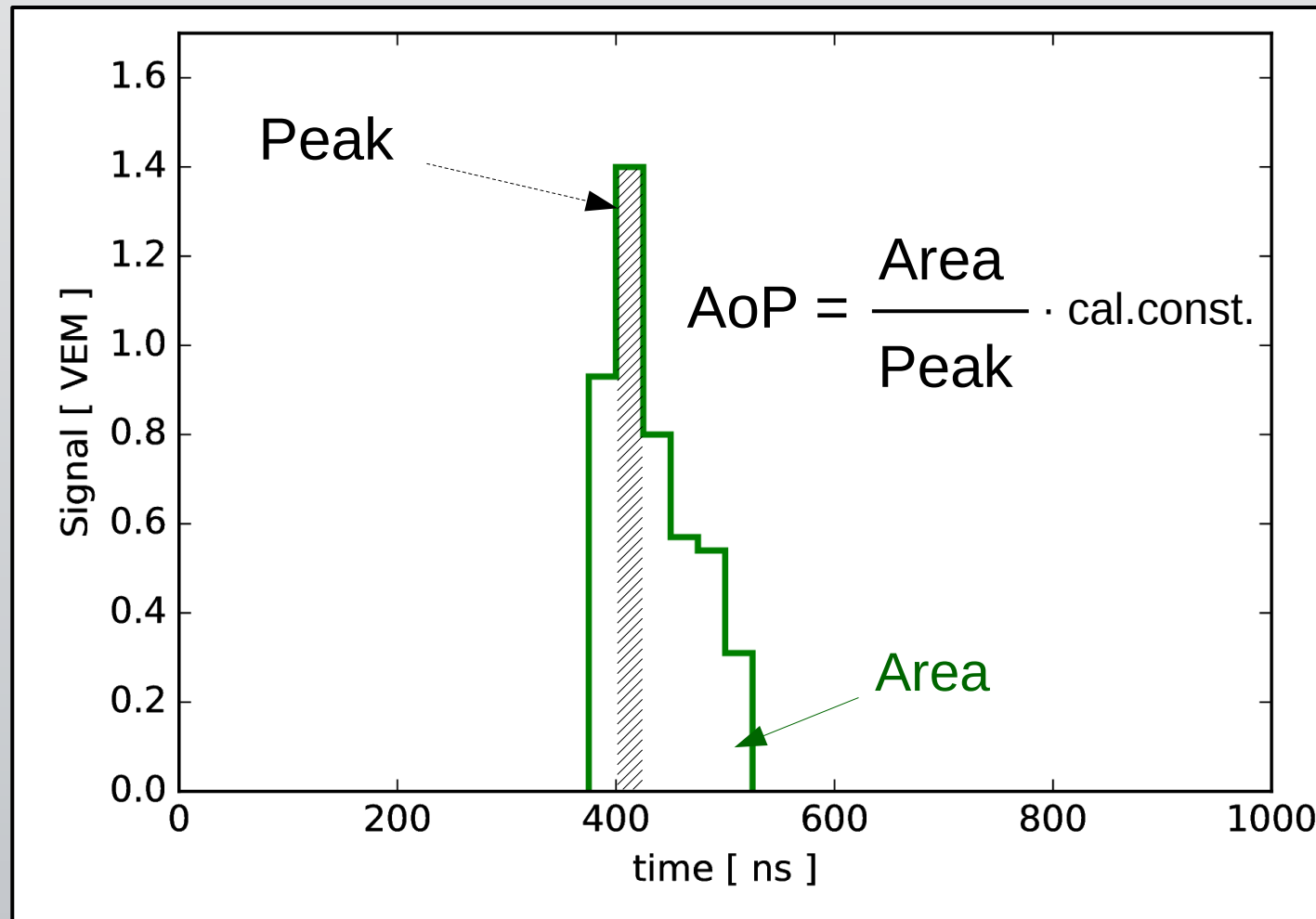


Source Distances



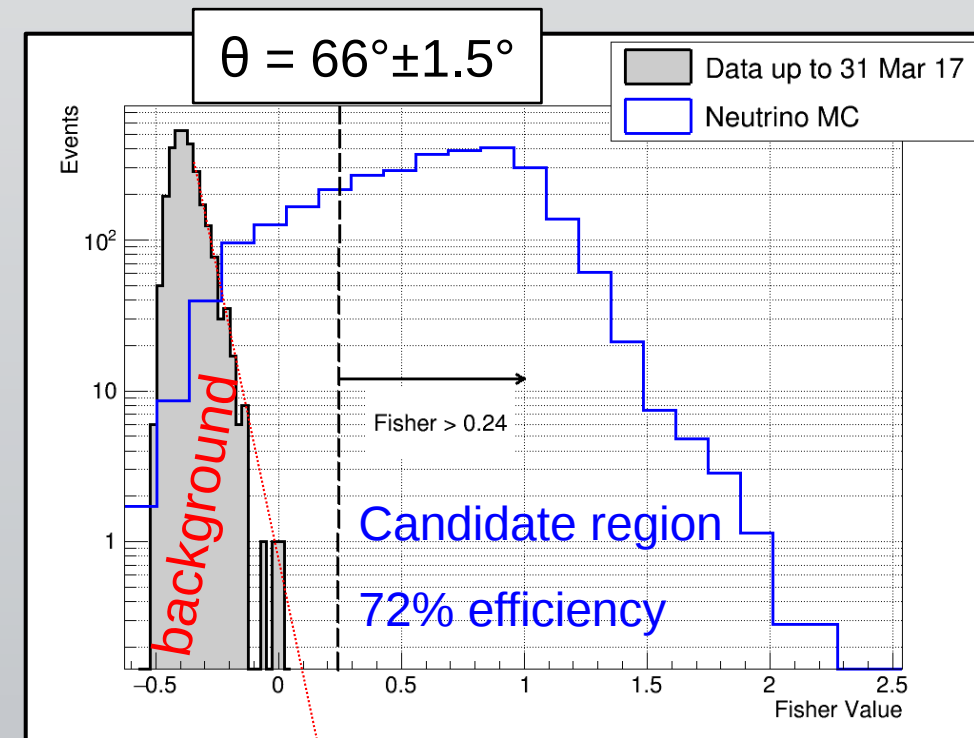
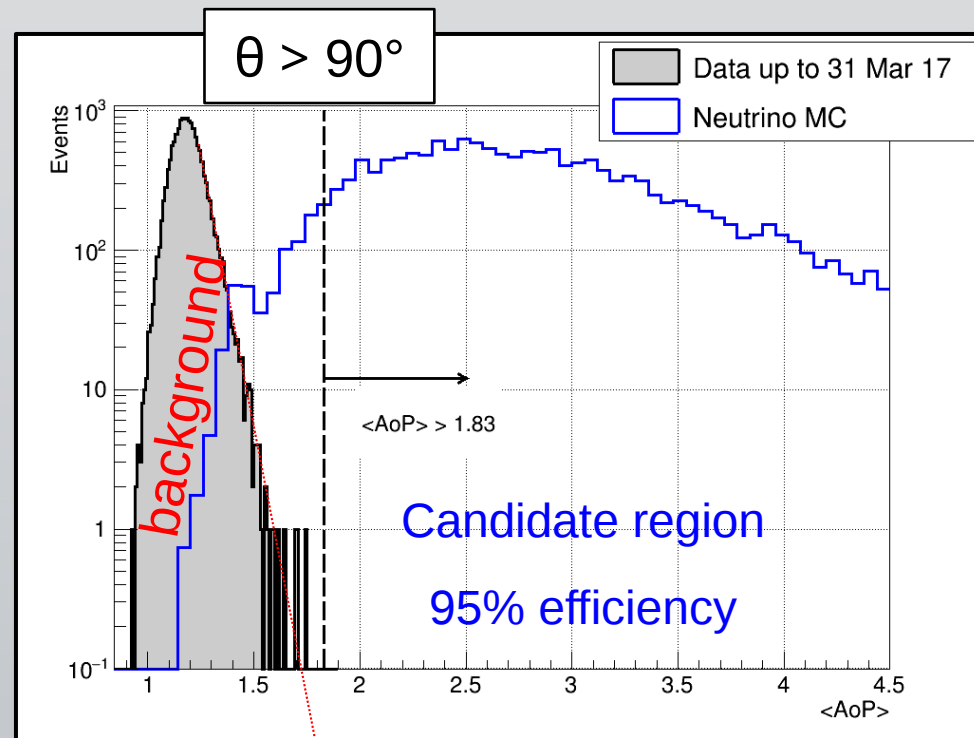
Neutrino search and identification

- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
- Crucial variable: **Area over Peak (AoP)**



Neutrino search and identification

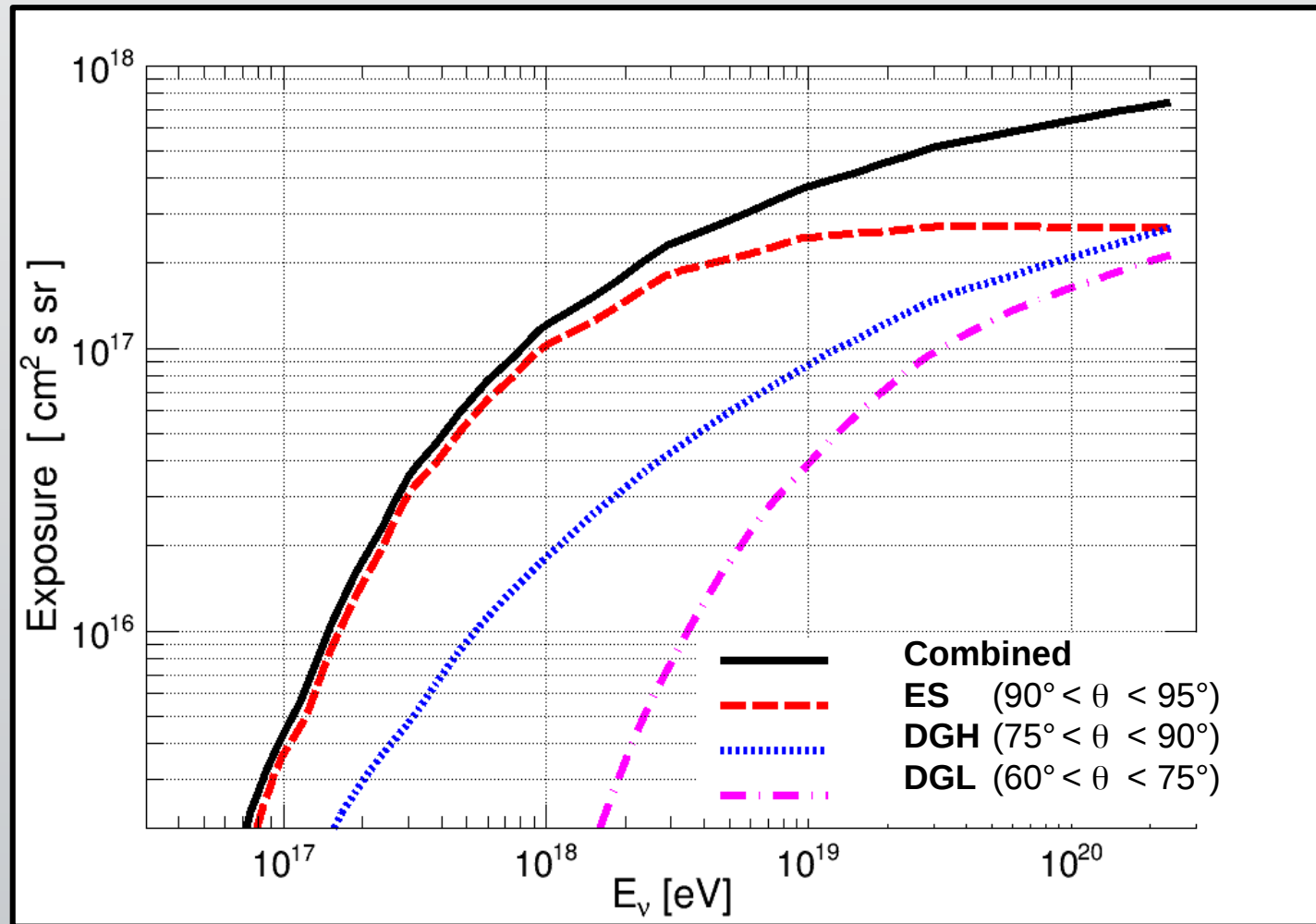
- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
 - Earth-skimming: **<AoP>** of all stations in event
 - Down-going: Optimized linear discriminant
 - **Combination of AoPs** of certain stations (esp. early and late ones)
 - “Fisher value”



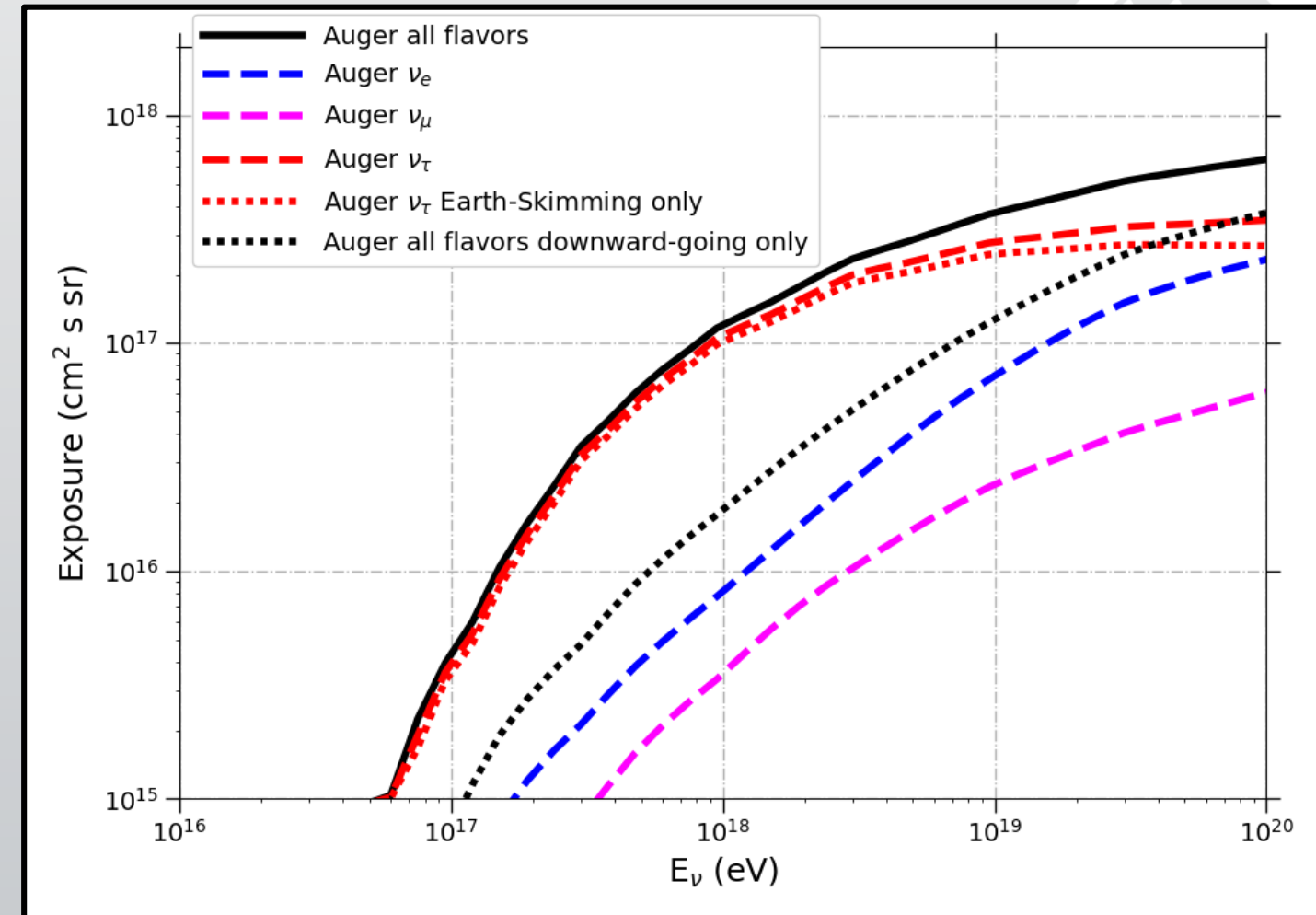
No
candidates
so far

Neutrino exposure

By direction

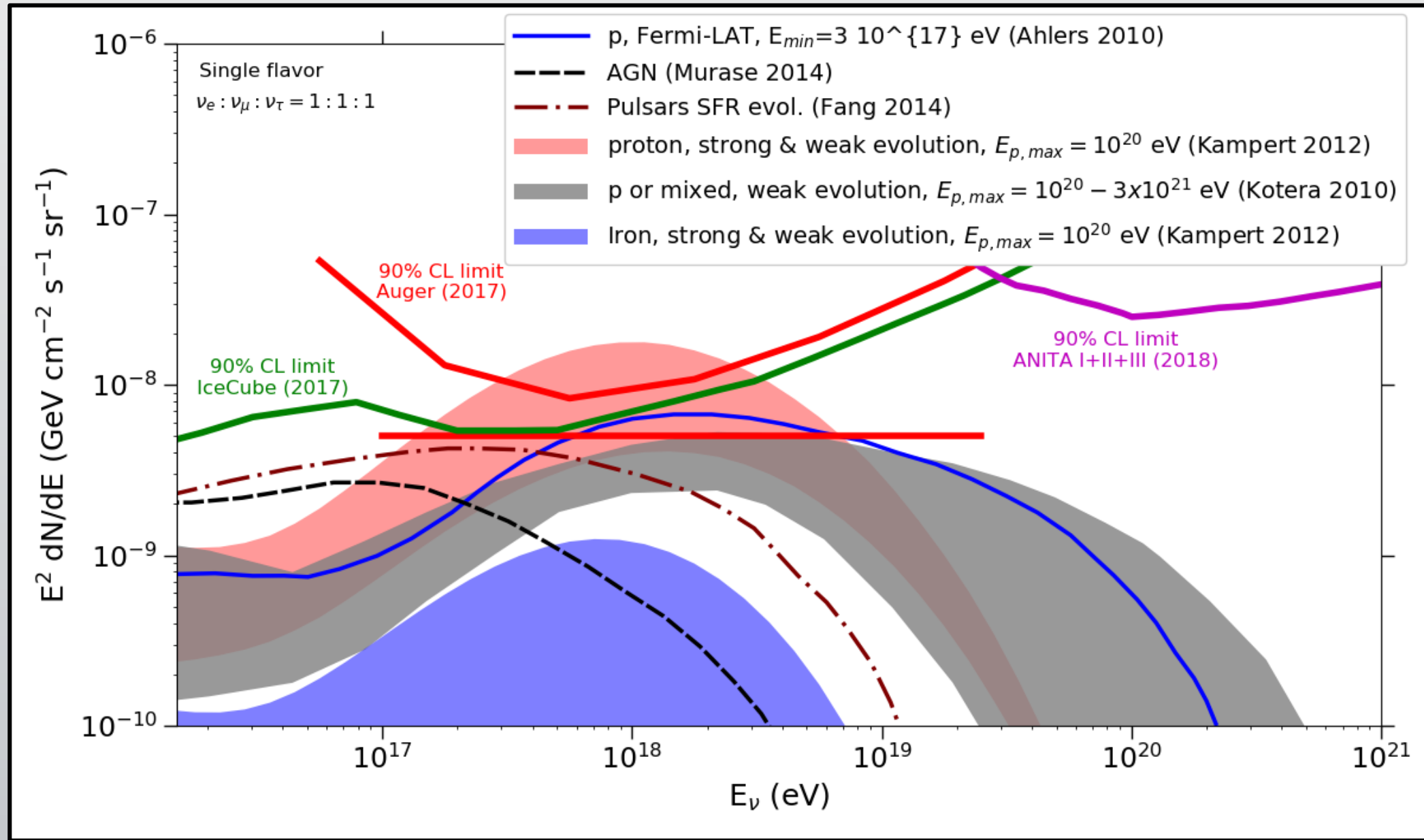


By flavor

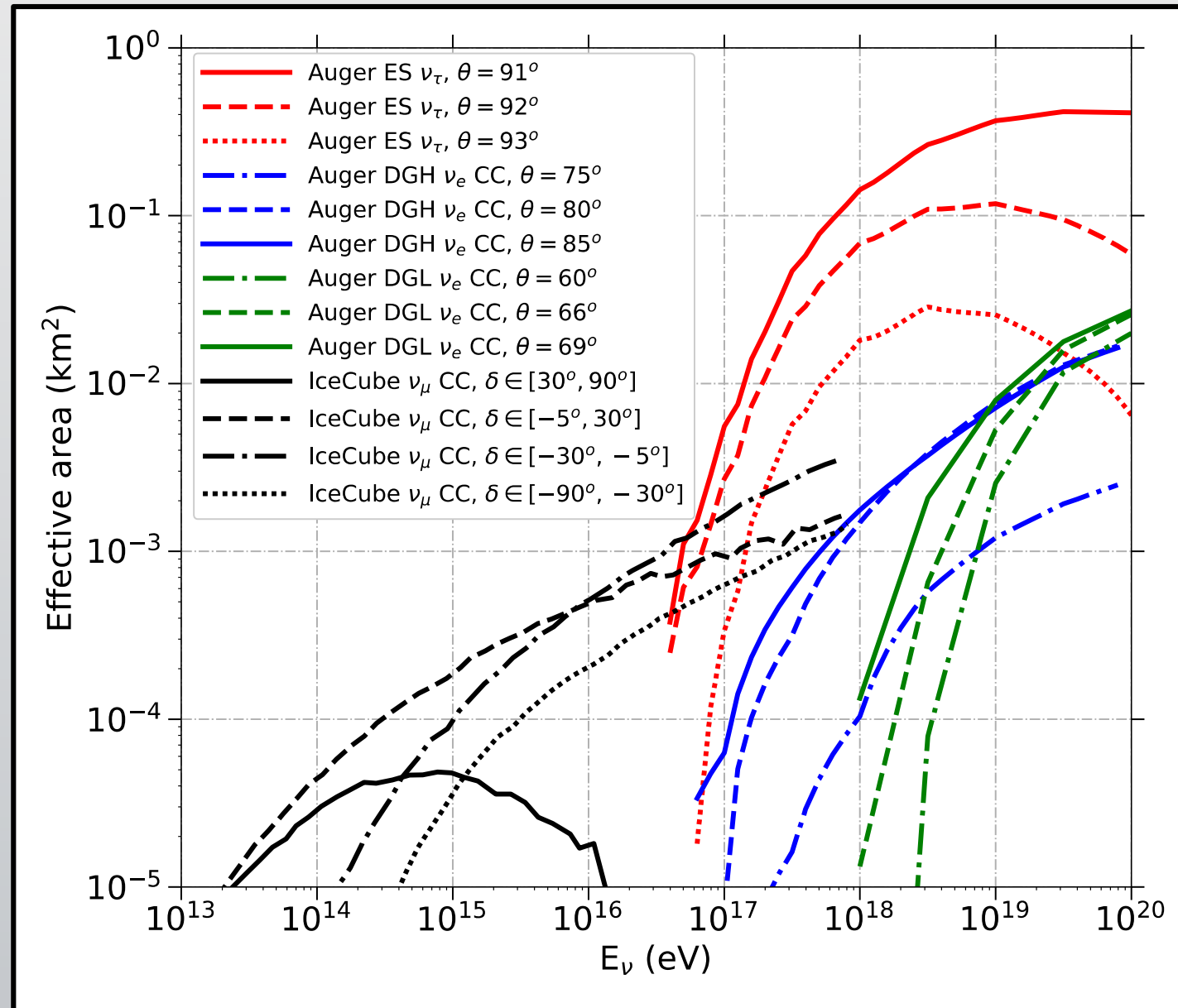


Enrique Zas, ICRC 2017

Limits on diffuse neutrino flux



Effective area



Follow-ups of O1+O2 GW events

LIGO/Virgo O1+O2: MoU between Auger and LVC:

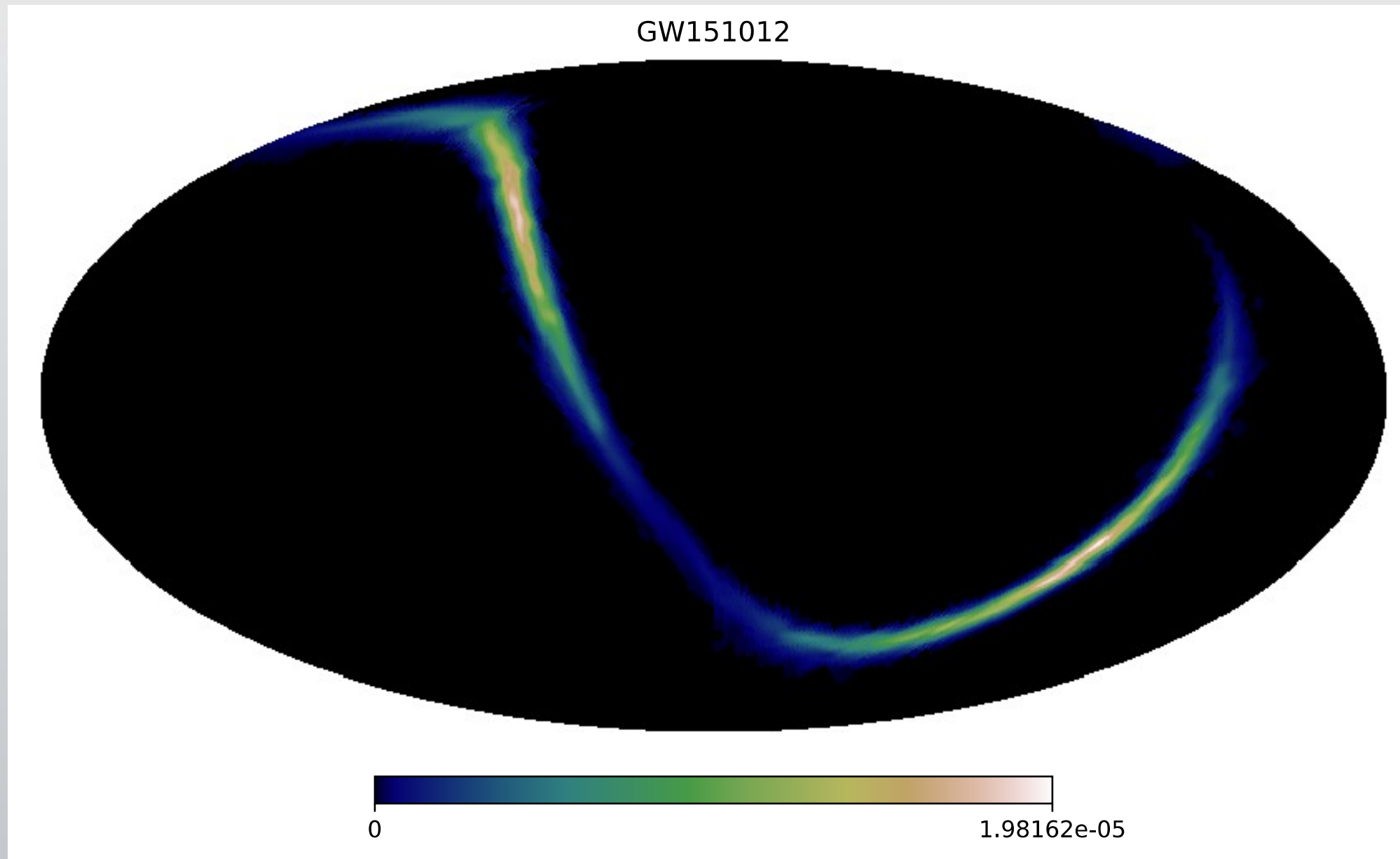
Default neutrino search, considering only

- ± 500 s around & +1 day after GW event
- Times at which location of the GW event is visible

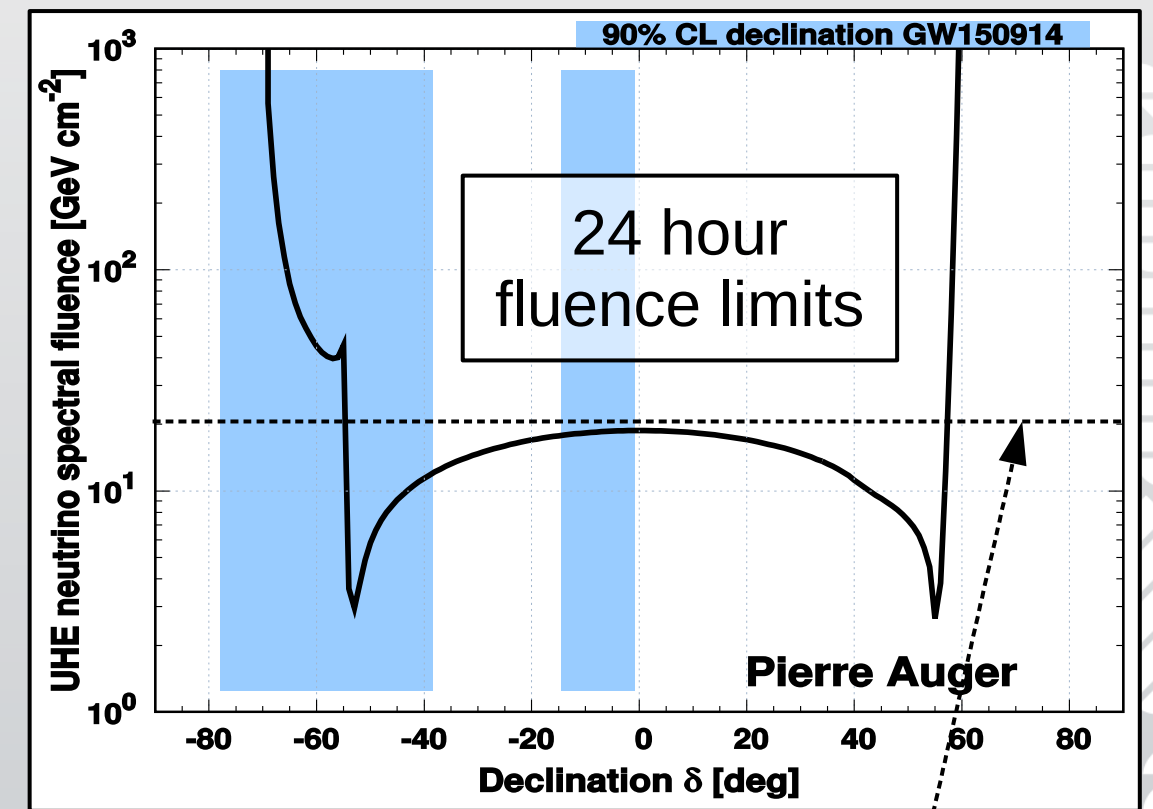
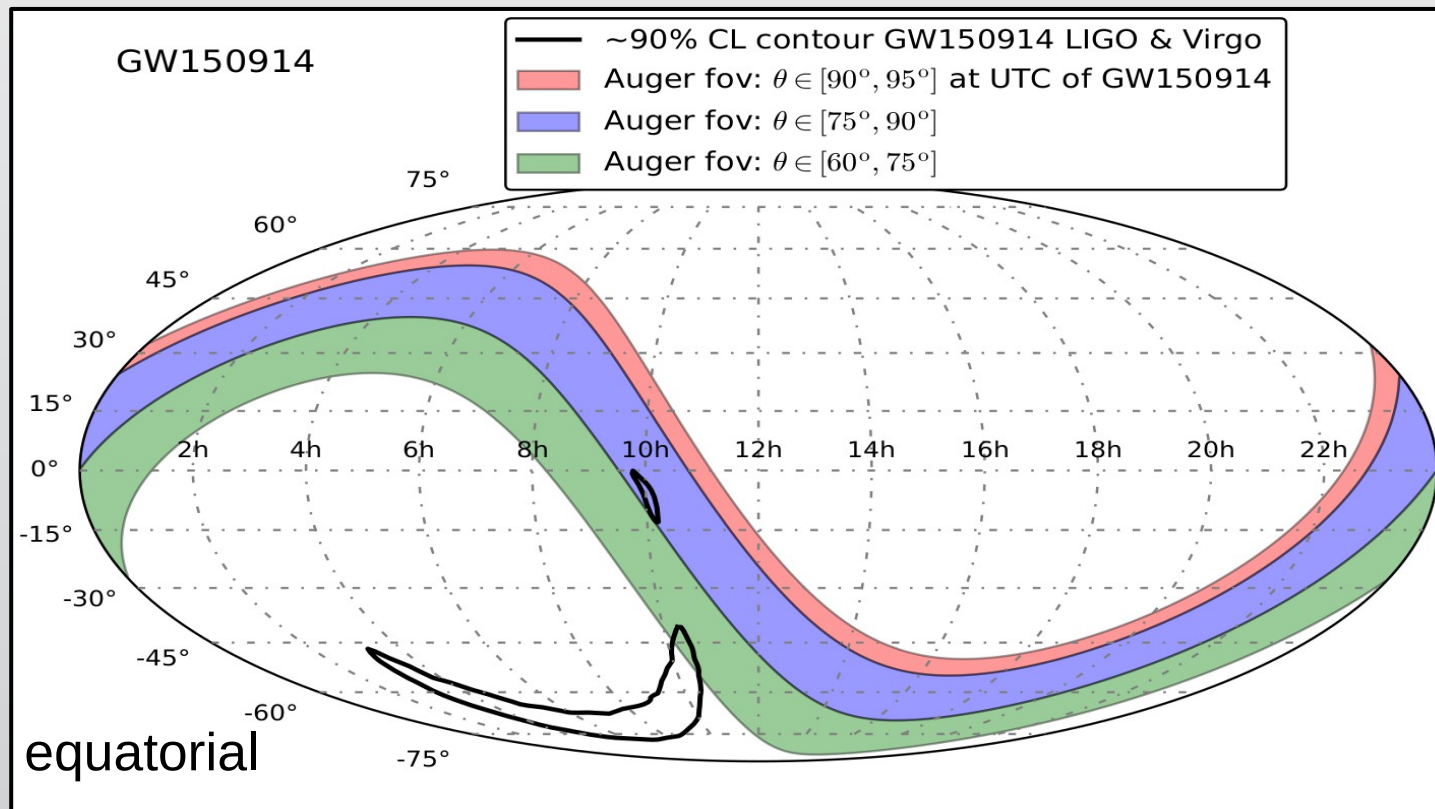
BNS merger GW170817: ± 500 s & 14 day period after the event



Follow-ups of O1+O2 GW events



Follow-Up of BBH merger GW150914



UHE neutrino sensitivity declination dependent

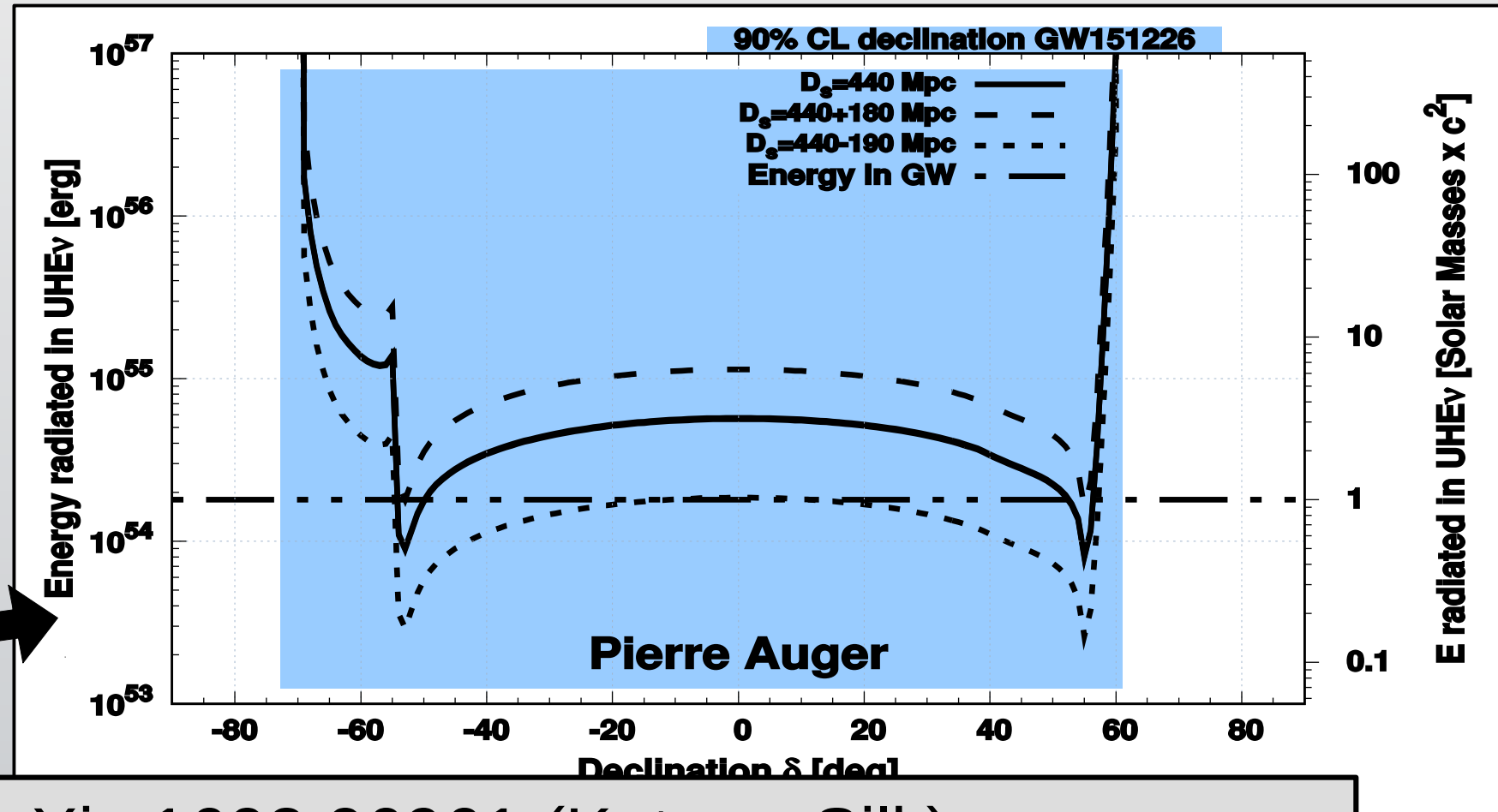
Newer events: More GW detectors

→ improved localization by triangulation

total neutrino energy =
emitted GW energy

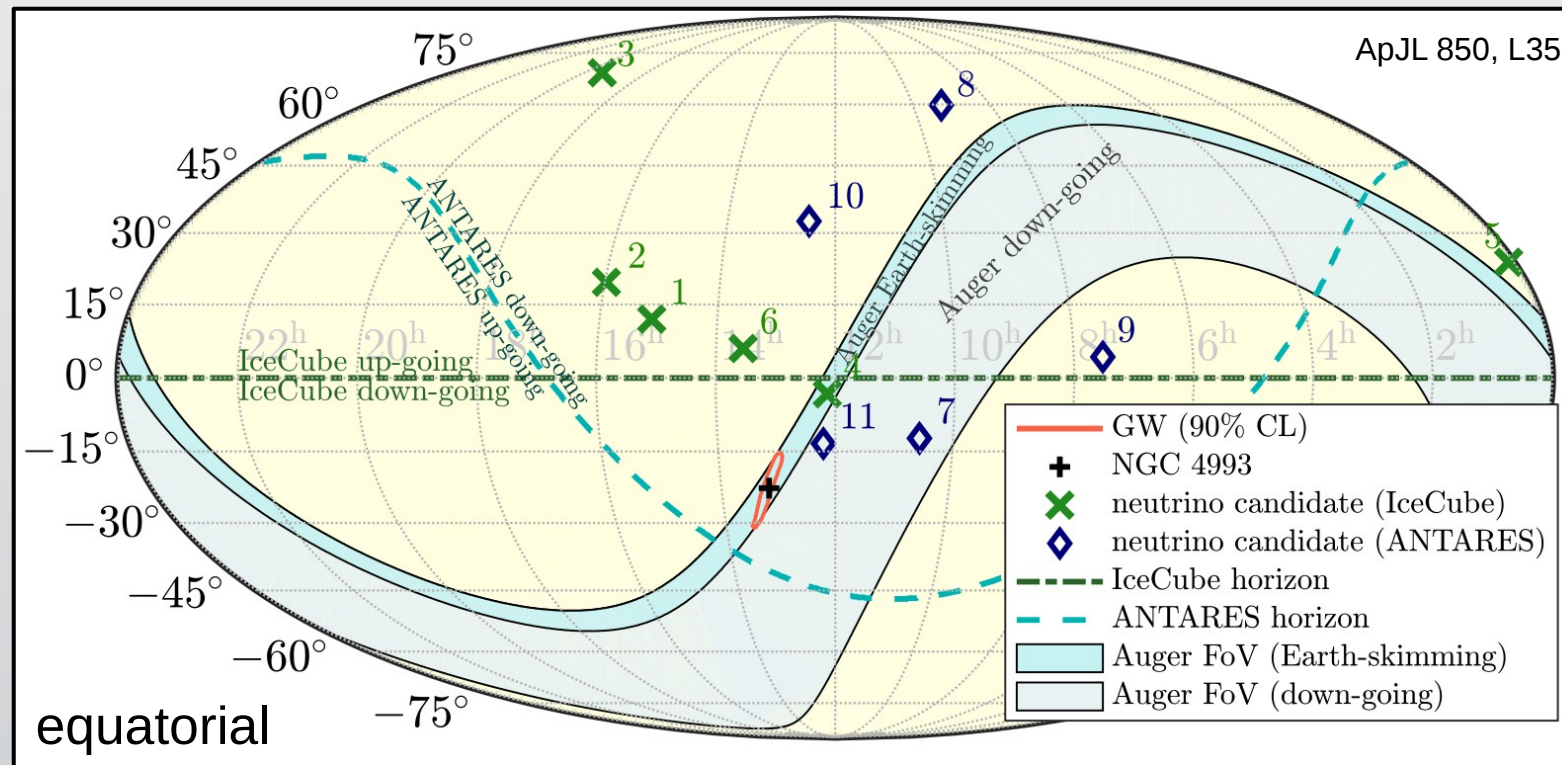
GW151226 Follow-Up—Results

No candidates
→ Flux limit
→ Limit on total emitted UHE ν energy

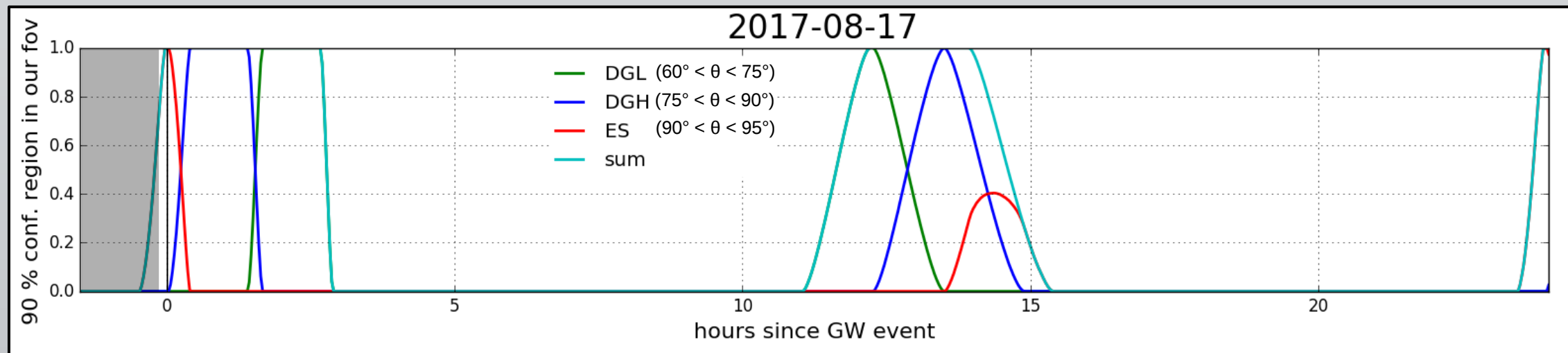


arXiv:1602.06961 (Kotera, Silk):
Binary BHs could produce the measured UHECR flux!
→ Needs $\sim 3\%$ “efficiency” ($E_{\text{UHECR}}/E_{\text{GW}}$)

Visibility of GW170817



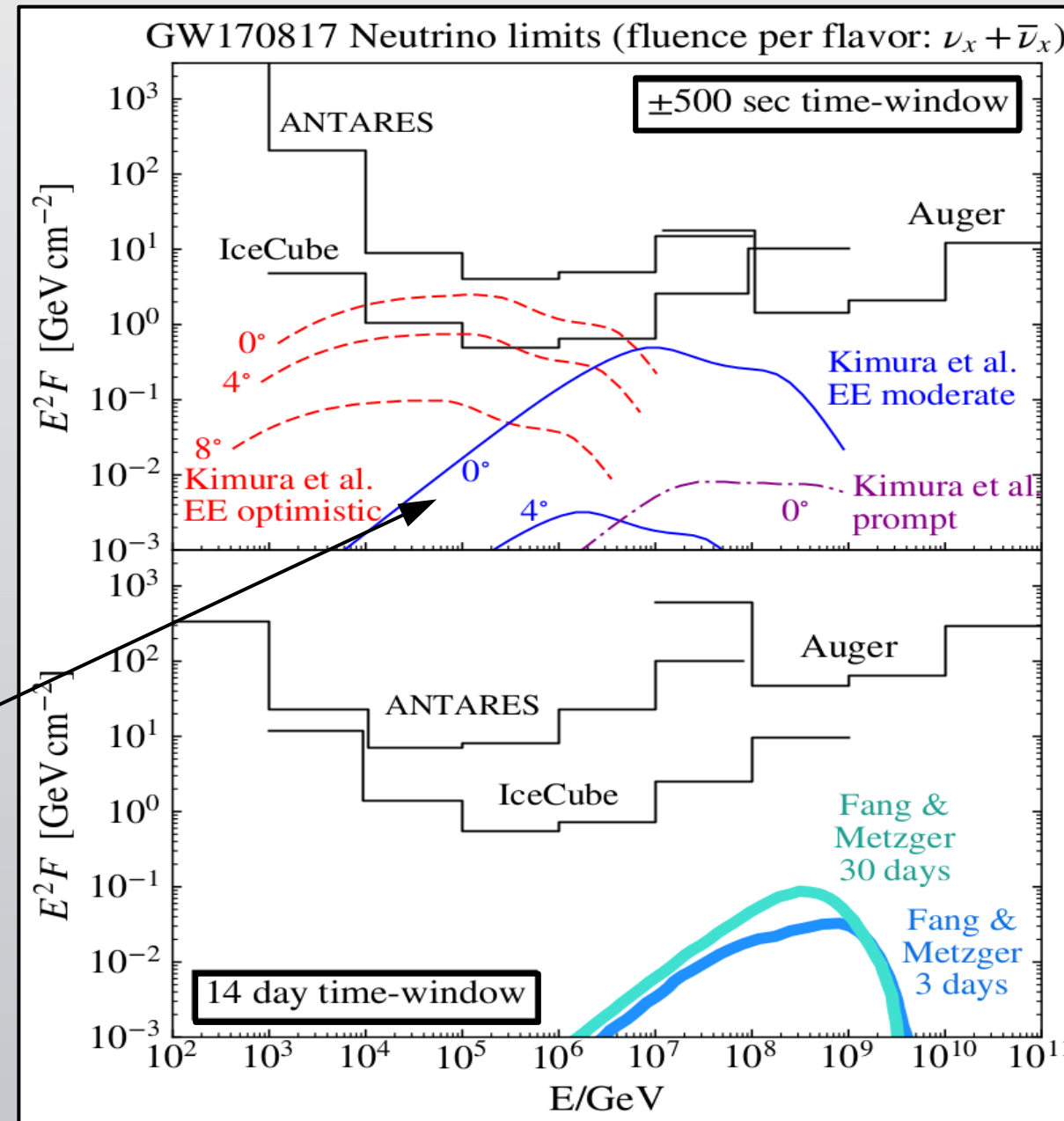
Good visibility at
time of merger



Neutrino limits for GW170817

- **No related neutrinos** detected by ANTARES, IceCube and Auger
- Sensitivity high for ± 500 s but reduced for 14 days
→ Good vs. periodic visibility

Viewing angle,
constrained to $< 36^\circ$
(at time of publication)

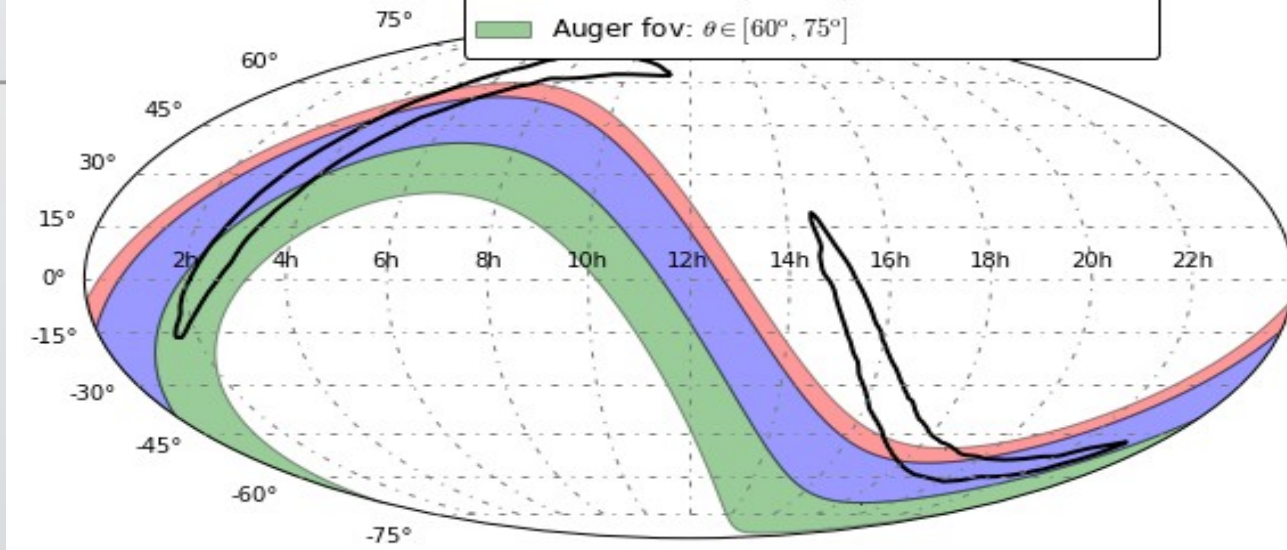


Systematic uncertainties (PRD 91 092008)

Source of systematic	Combined uncertainty band
Simulations	$\sim +4\%, -3\%$
ν cross section and τ E-loss	$\sim +34\%, -28\%$
Topography	$\sim +15\%, 0\%$
Total	$\sim +37\%, -28\%$

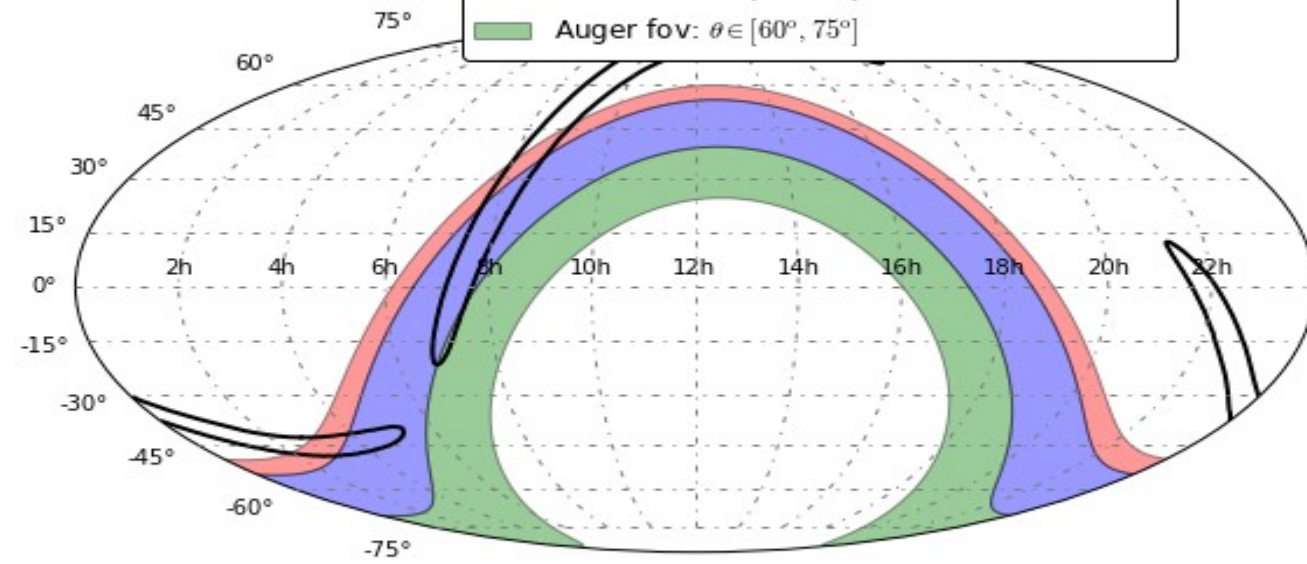
GW151012

- ~90% CL contour GW151012 LIGO & Virgo
- Auger fov: $\theta \in [90^\circ, 95^\circ]$ at UTC of GW151012
- Auger fov: $\theta \in [75^\circ, 90^\circ]$
- Auger fov: $\theta \in [60^\circ, 75^\circ]$



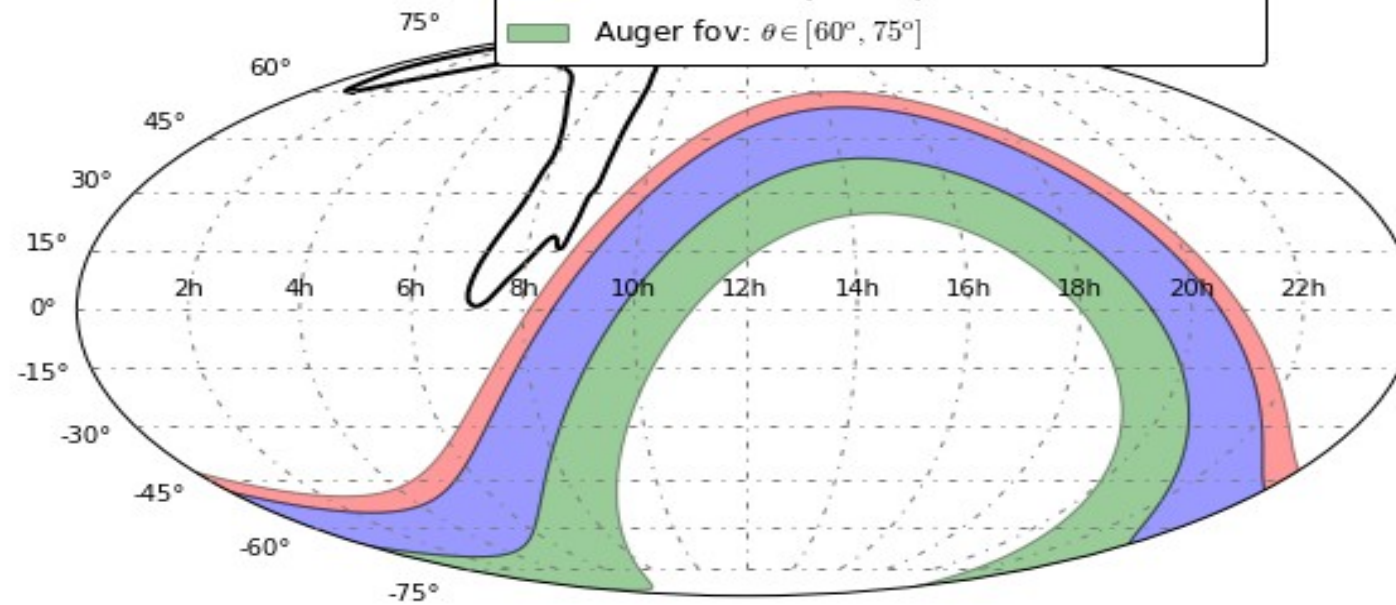
GW170104

- ~90% CL contour GW170104 LIGO & Virgo
- Auger fov: $\theta \in [90^\circ, 95^\circ]$ at UTC of GW170104
- Auger fov: $\theta \in [75^\circ, 90^\circ]$
- Auger fov: $\theta \in [60^\circ, 75^\circ]$

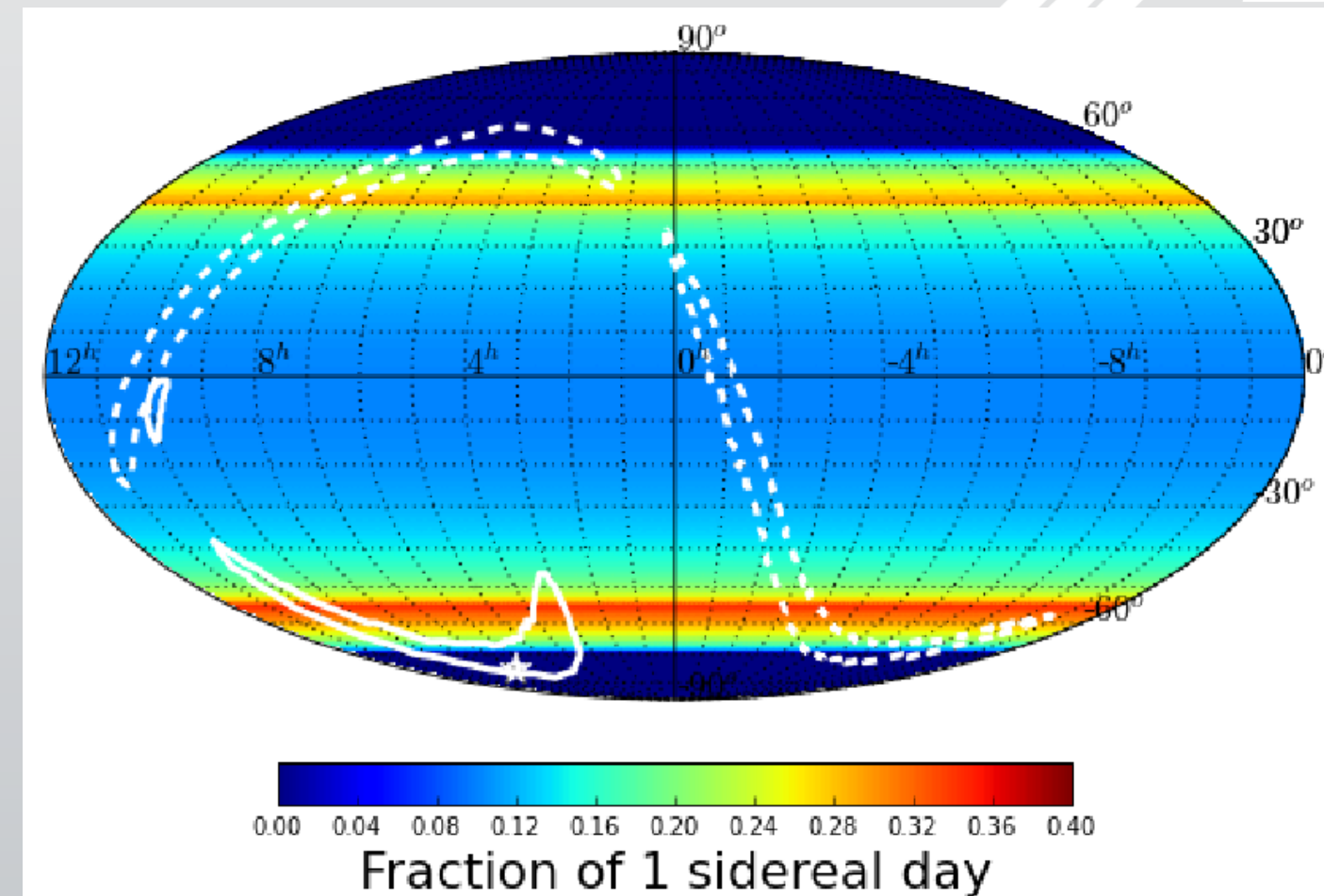
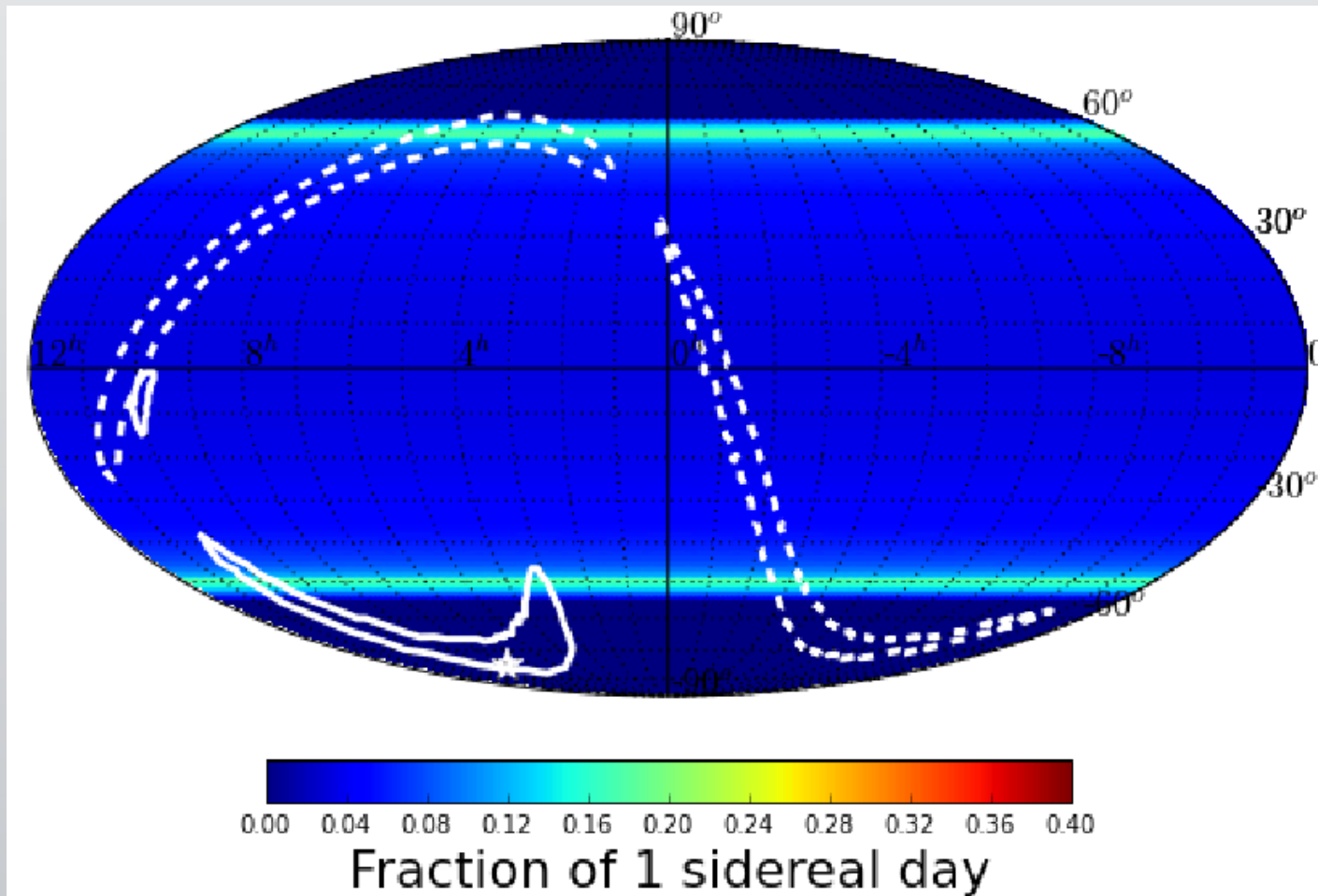


GW170608

- ~90% CL contour GW170608 LIGO & Virgo
- Auger fov: $\theta \in [90^\circ, 95^\circ]$ at UTC of GW170608
- Auger fov: $\theta \in [75^\circ, 90^\circ]$
- Auger fov: $\theta \in [60^\circ, 75^\circ]$

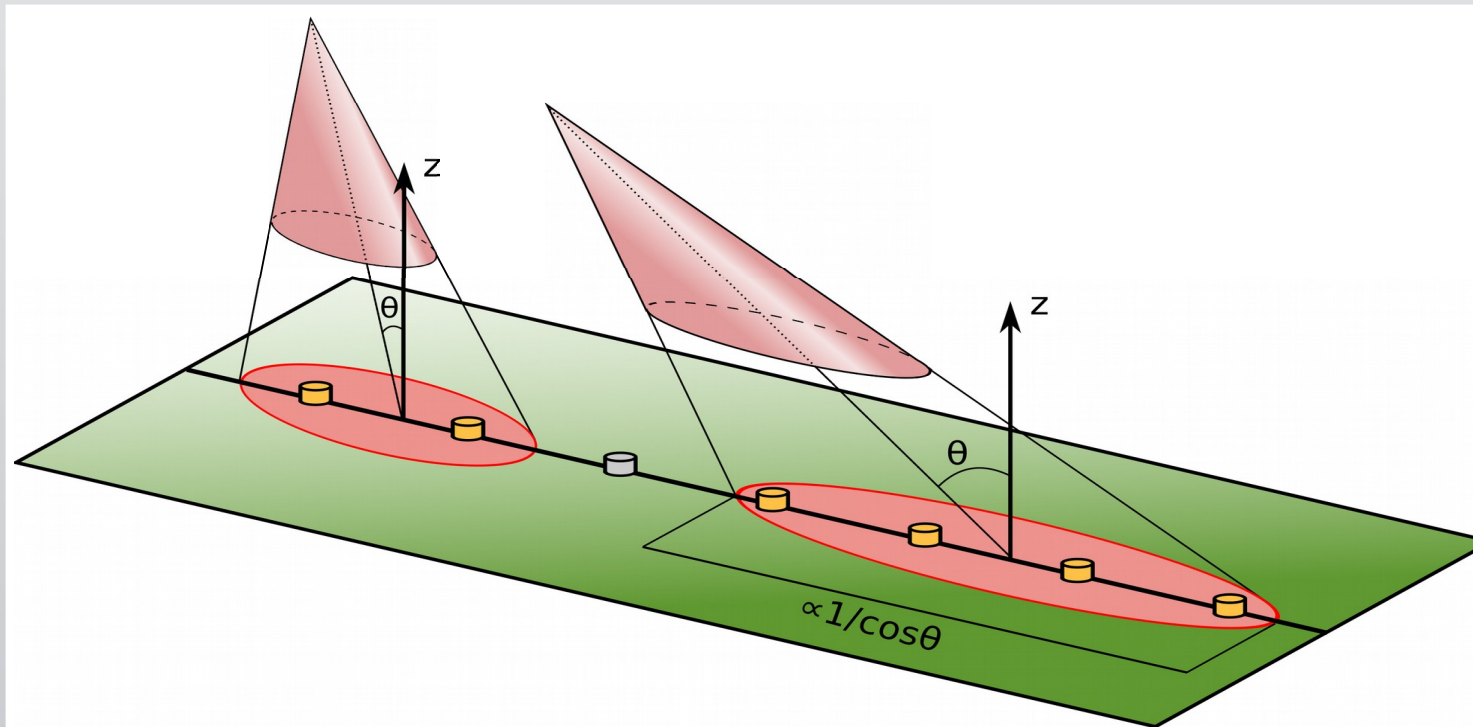


O1 GW Follow-Up



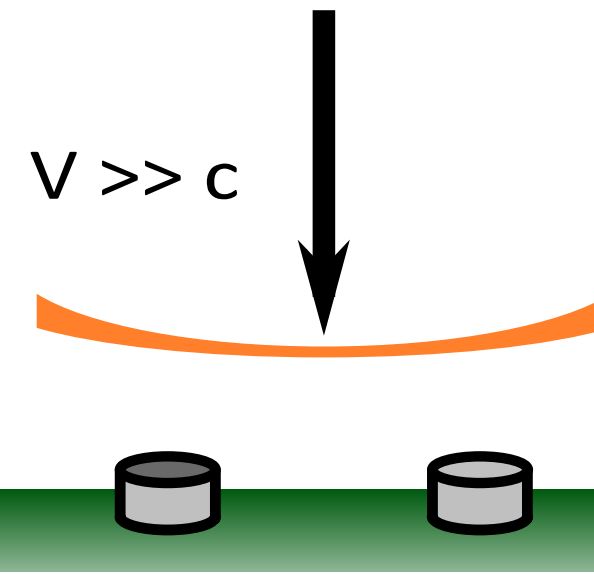
Earth-Skimming ν_τ Selection

Inclination: $90^\circ < \theta < 95^\circ$
→ elongated footprint

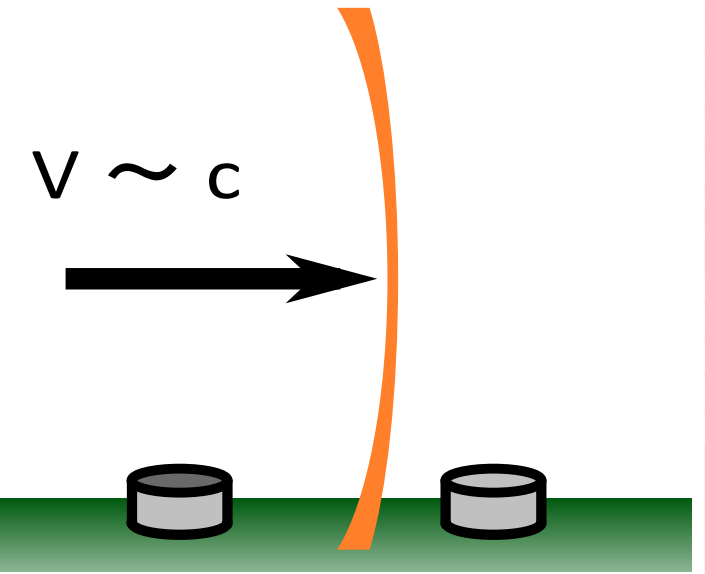


“Ground signal speed” $\sim c$

Vertical shower

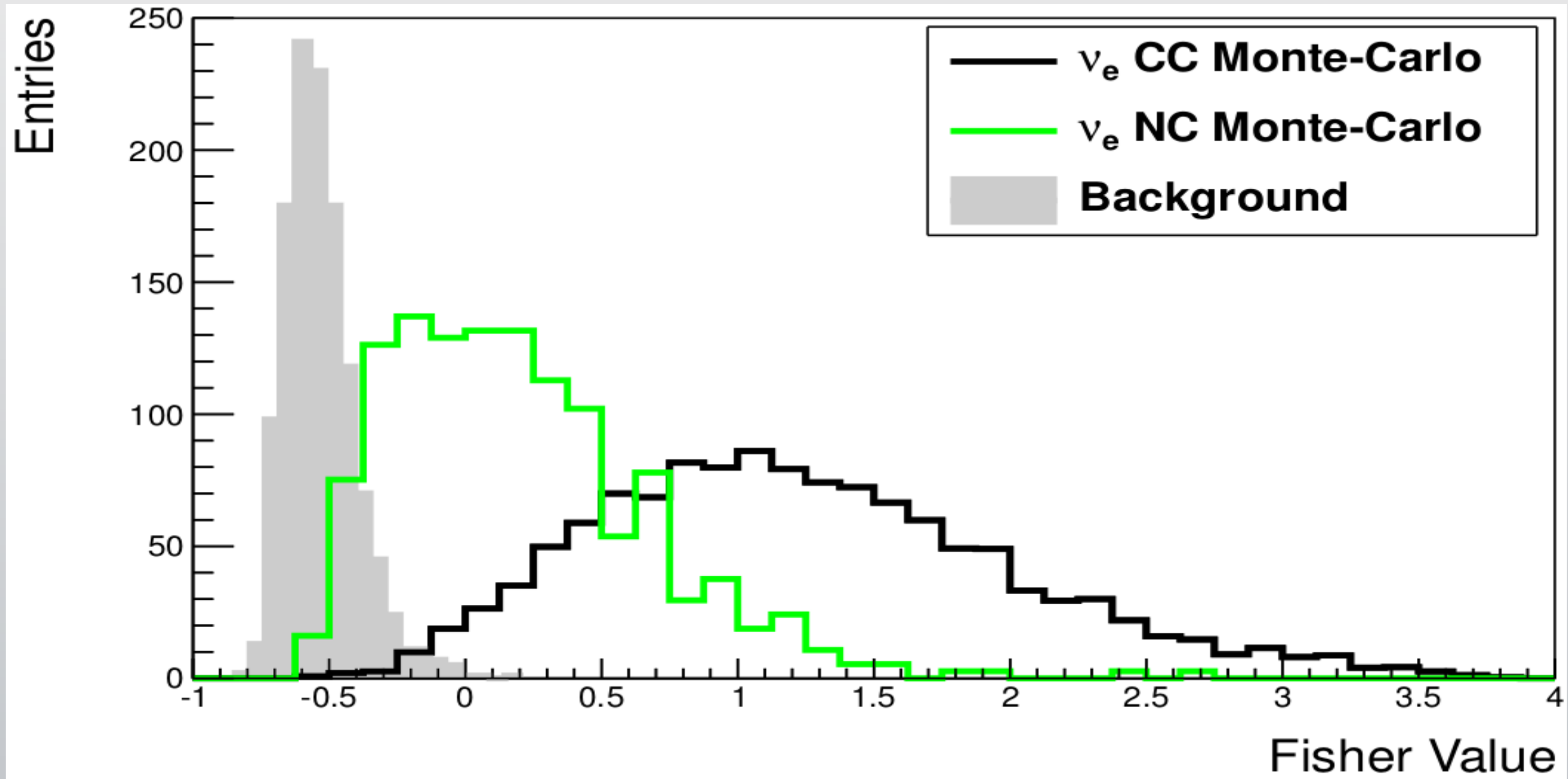


Horizontal shower

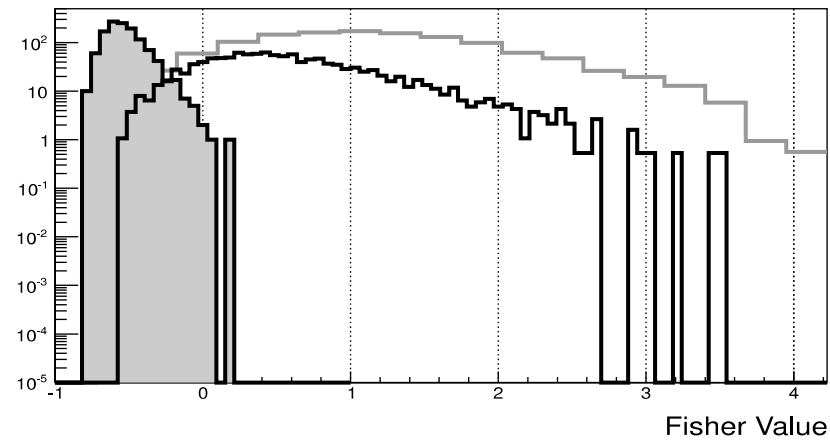


Reject “muonic” events → > 60 % stations ToT triggered

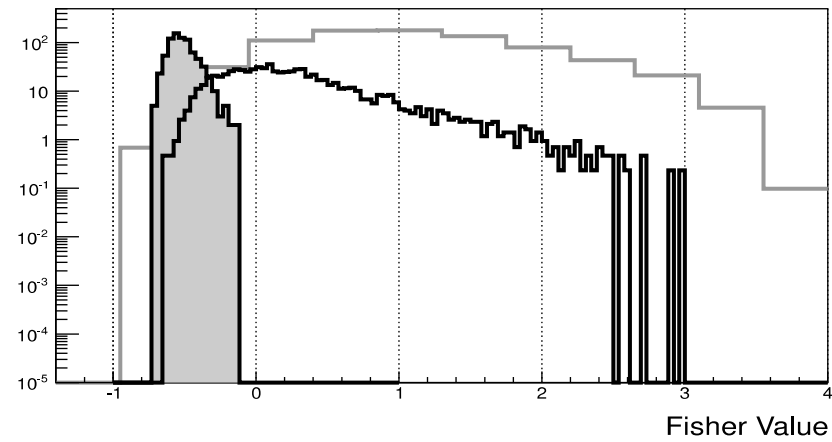
CC vs NC Fisher Values



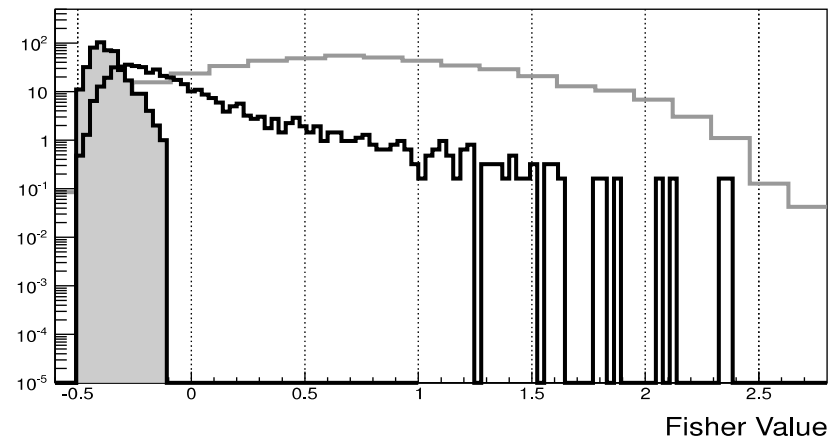
Neutrinos vs. Photons



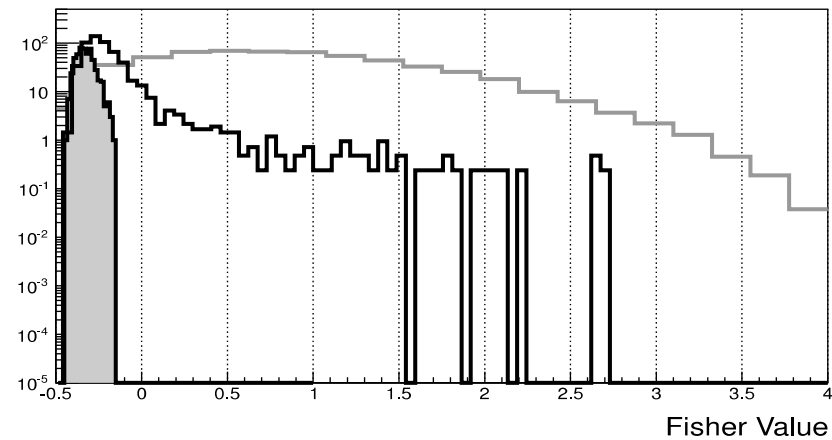
(a) $58.5^\circ < \theta_{\text{Rec}} \leq 61.5^\circ$



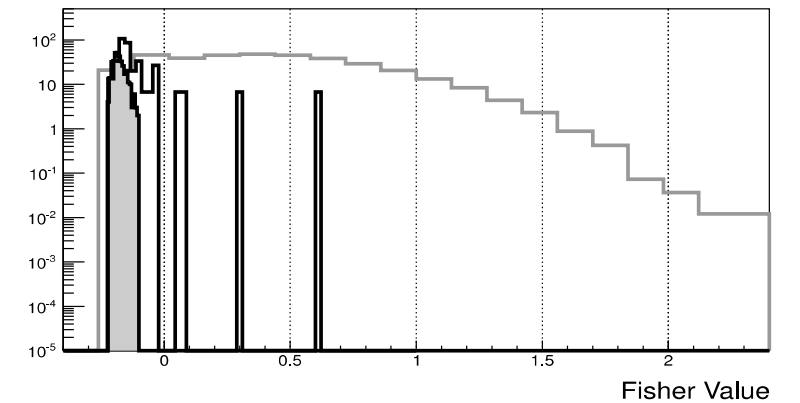
(b) $61.5^\circ < \theta_{\text{Rec}} \leq 64.5^\circ$



(c) $64.5^\circ < \theta_{\text{Rec}} \leq 67.5^\circ$



(d) $67.5^\circ < \theta_{\text{Rec}} \leq 70.5^\circ$



(e) $70.5^\circ < \theta_{\text{Rec}} \leq 76.5^\circ$