Ultra-high-energy neutrino searches and gravitational wave Follow-up with the Pierre Auger Observatory

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for the Pierre Auger Collaboration

XIX International Workshop on Neutrino Telescopes

February 23, 2021

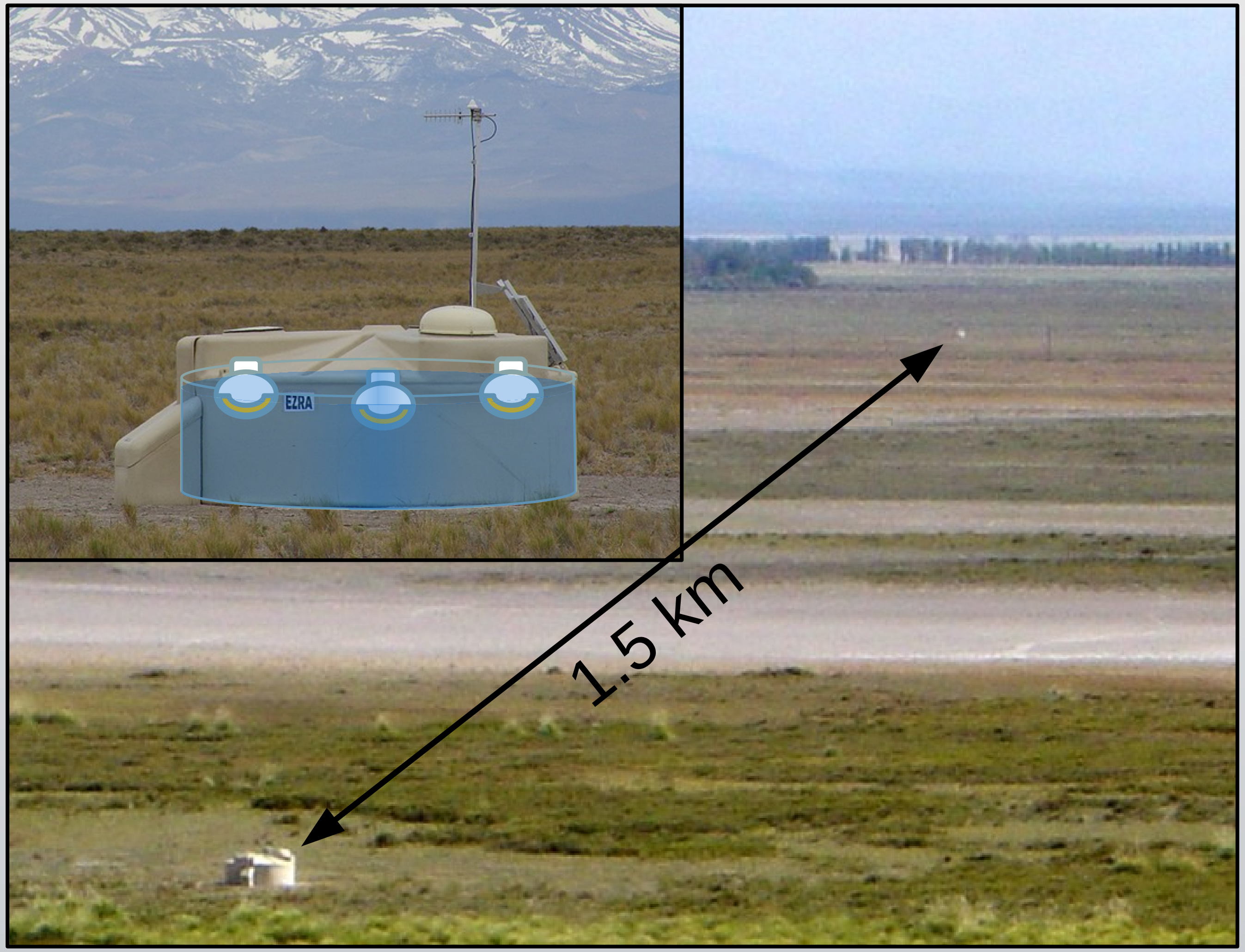
PIERRE AUGER OBSERVATORY

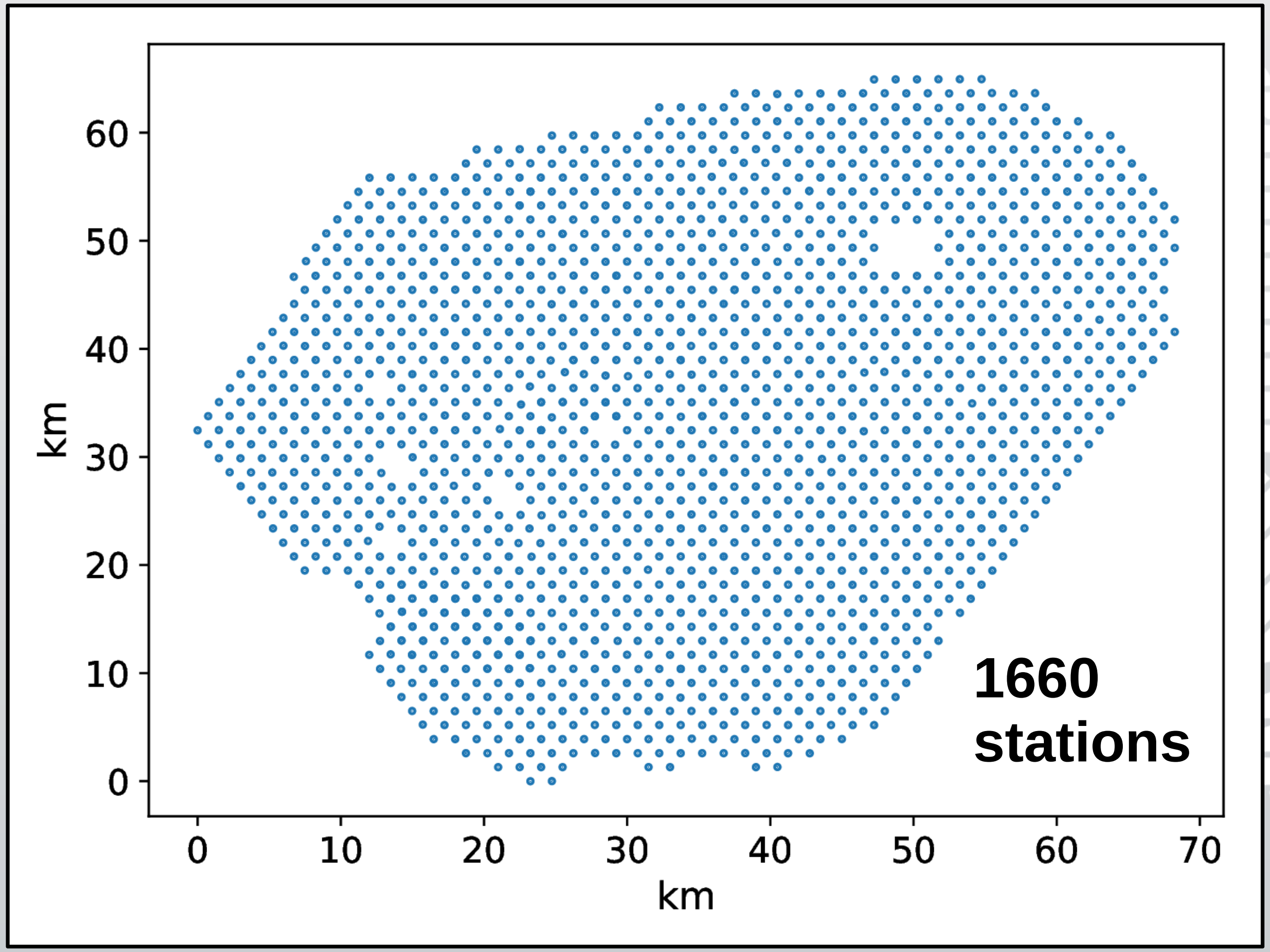
GEFÖRDERT VOM

Bundesministerium für Bildung und Forschung

BERGISCHE UNIVERSITÄT WUPPERTAL

The Pierre Auger Observatory Surface Detector (SD)

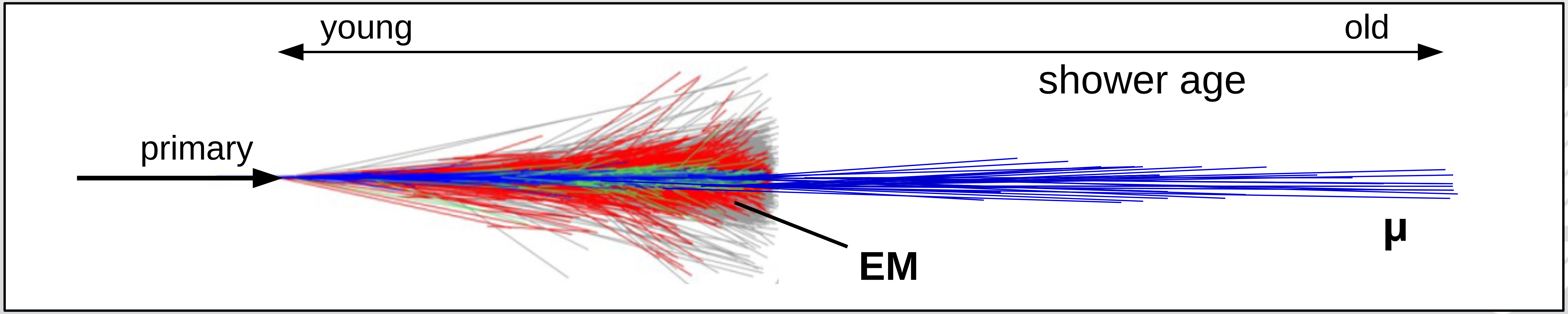


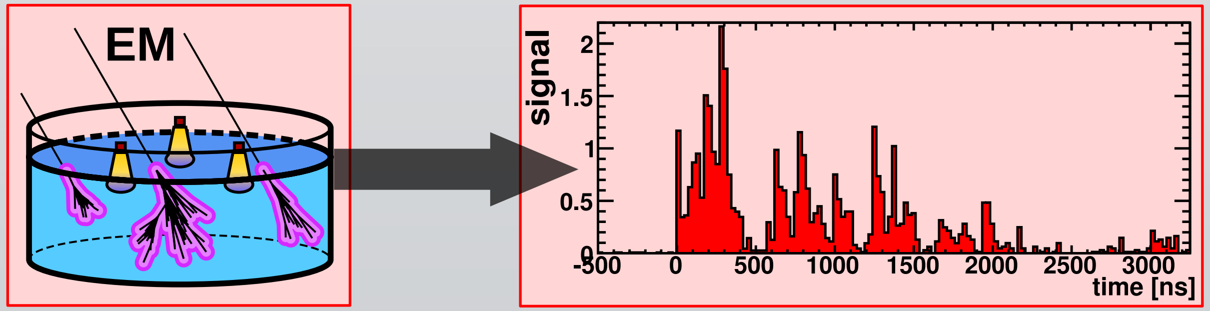


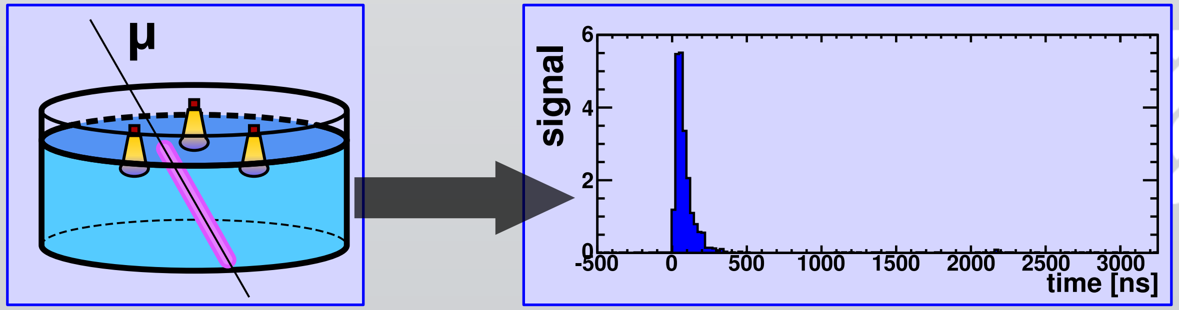
1.5 km spacing
→ Sensitive to EeV air showers

3000 km²
→ Large acceptance

Neutrino detection with the Auger SD



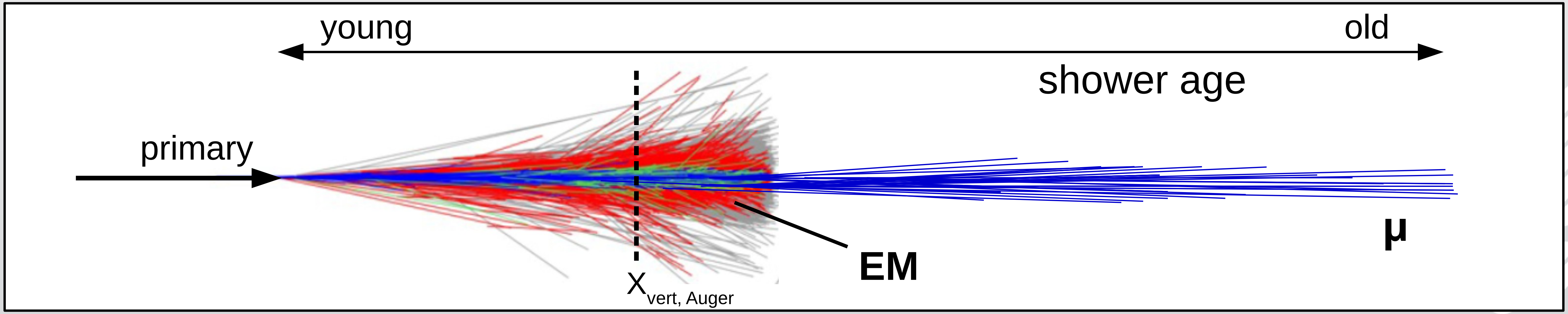


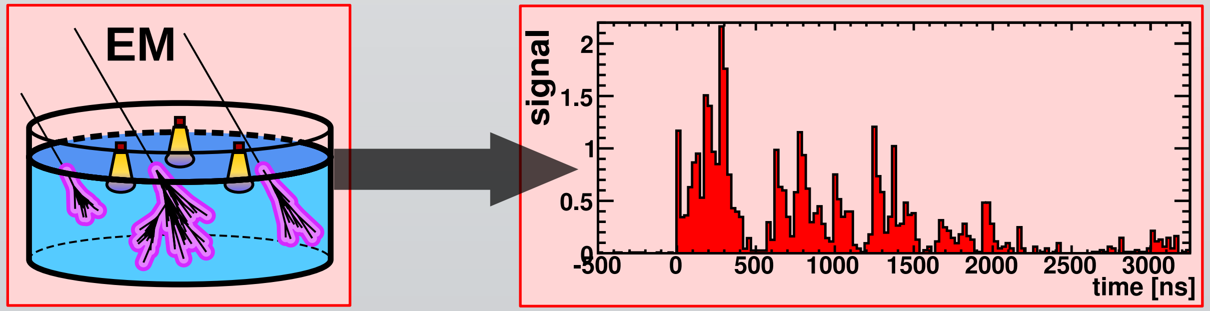


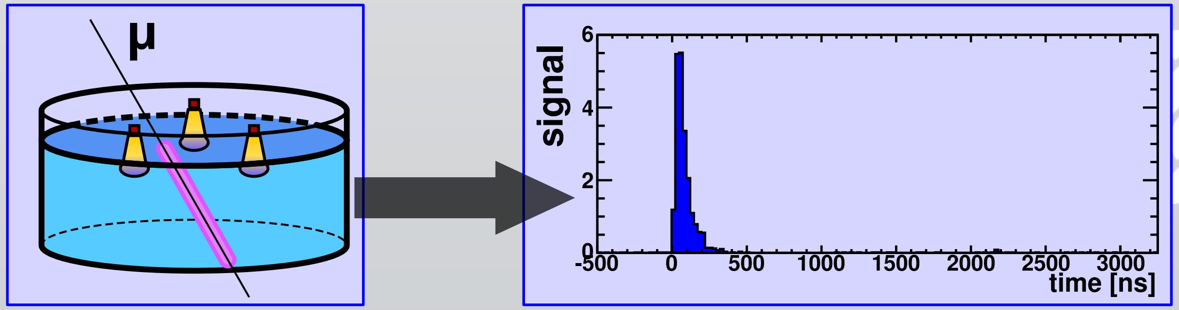
Multiple cascades, i.e. many particles
→ **broad** traces (signal vs. time)

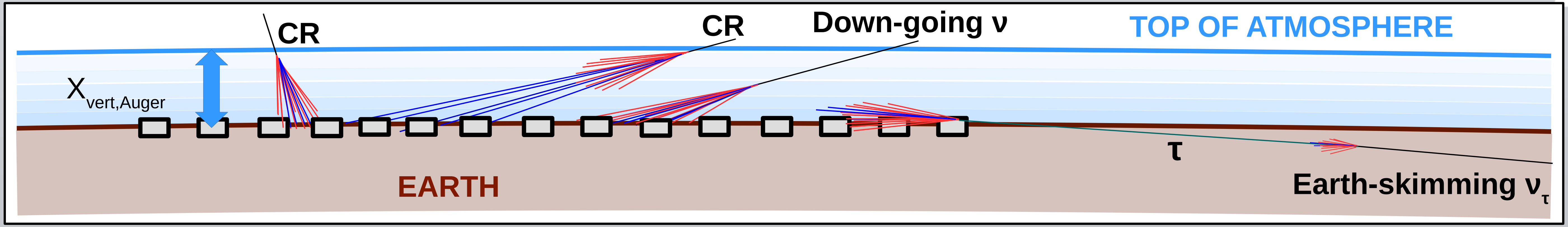
Single particles
→ **narrow** traces

Neutrino detection with the Auger SD









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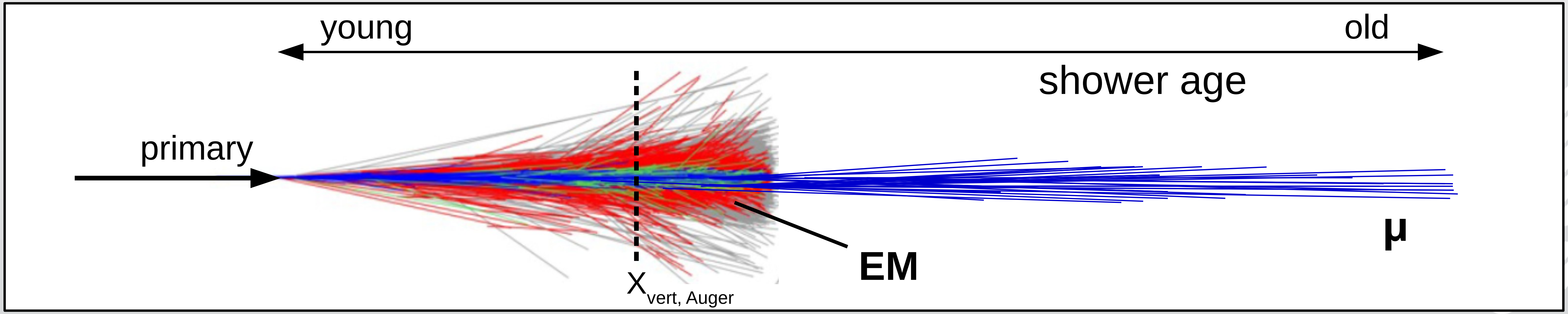
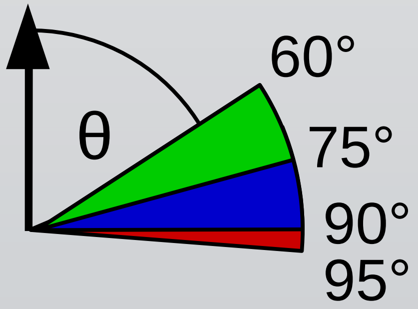
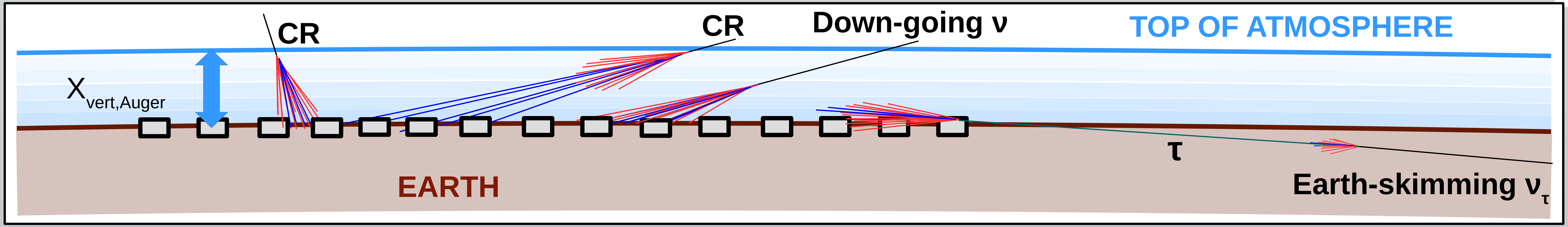




Down-going Low (DGL)
Down-going High (DGH)
Earth-skimming (ES)

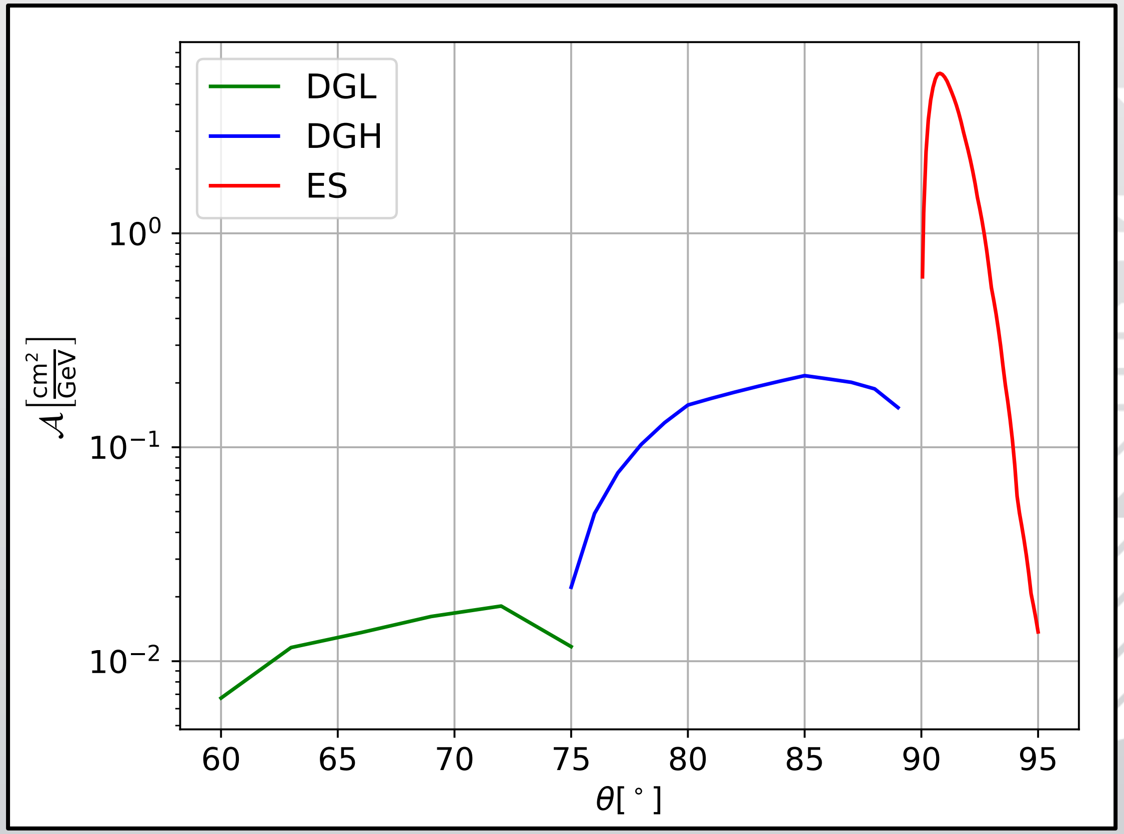


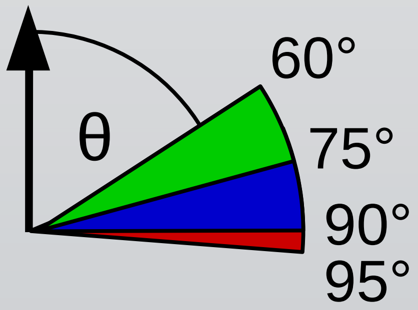
Neutrino detection with the Auger SD

JCAP 11 (2019) 004

$$\mathcal{A}(\theta, t) = \int_0^\infty E_\nu^{-2}\, A_{\mathrm{eff}}(E_\nu, \theta, t)\, \mathrm{d}E_\nu$$

“Effective area per energy”





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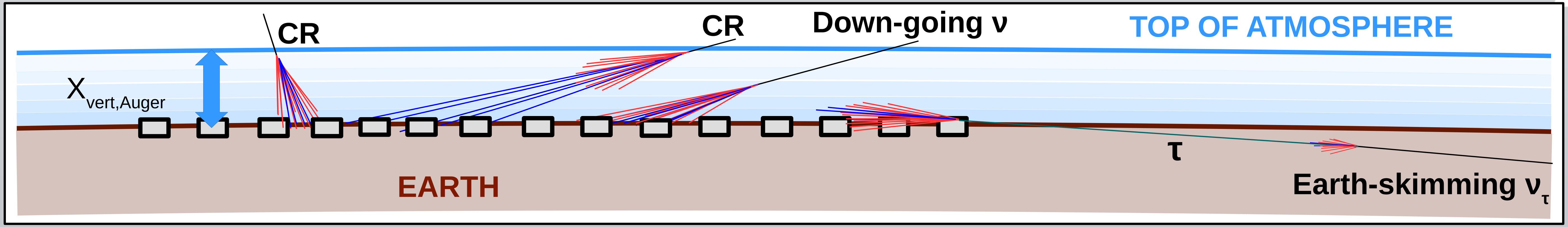
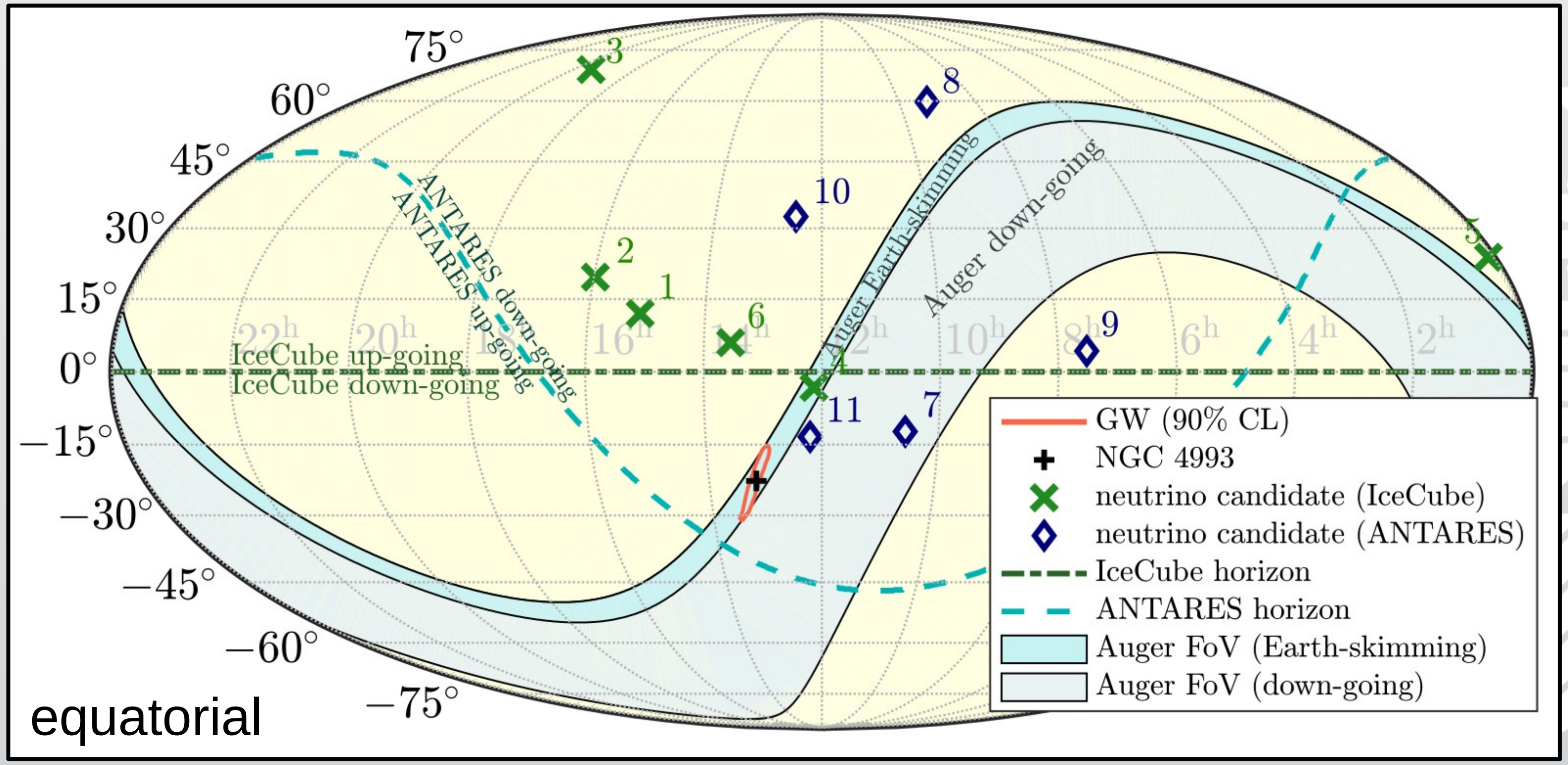
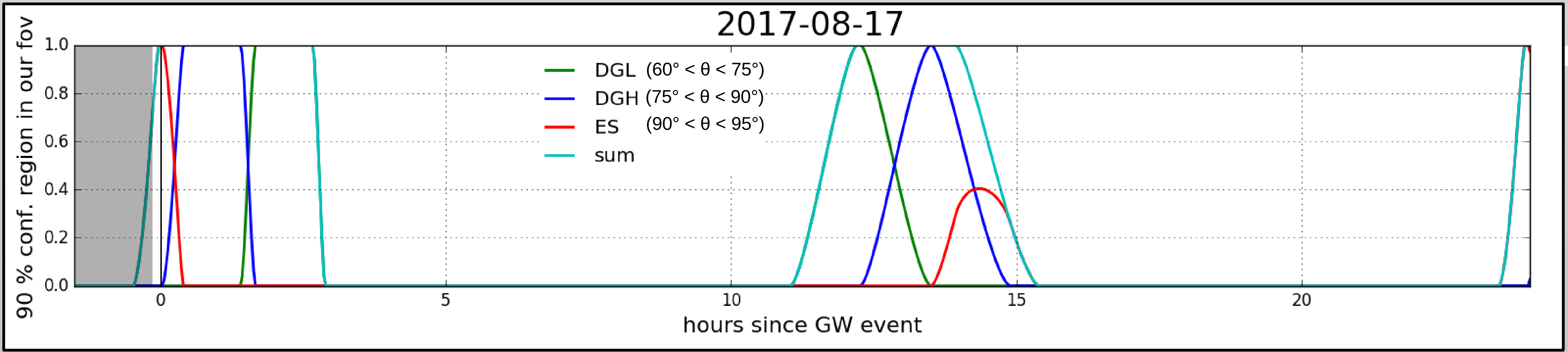


GW170817 visibility

ApJL 850, L35

- Excellent visibility of the merger
- Fast LIGO/Virgo + Fermi GCN circular
- Our follow-up routines were not automatized, manual unblinding was necessary
  - Now: immediate search initiation

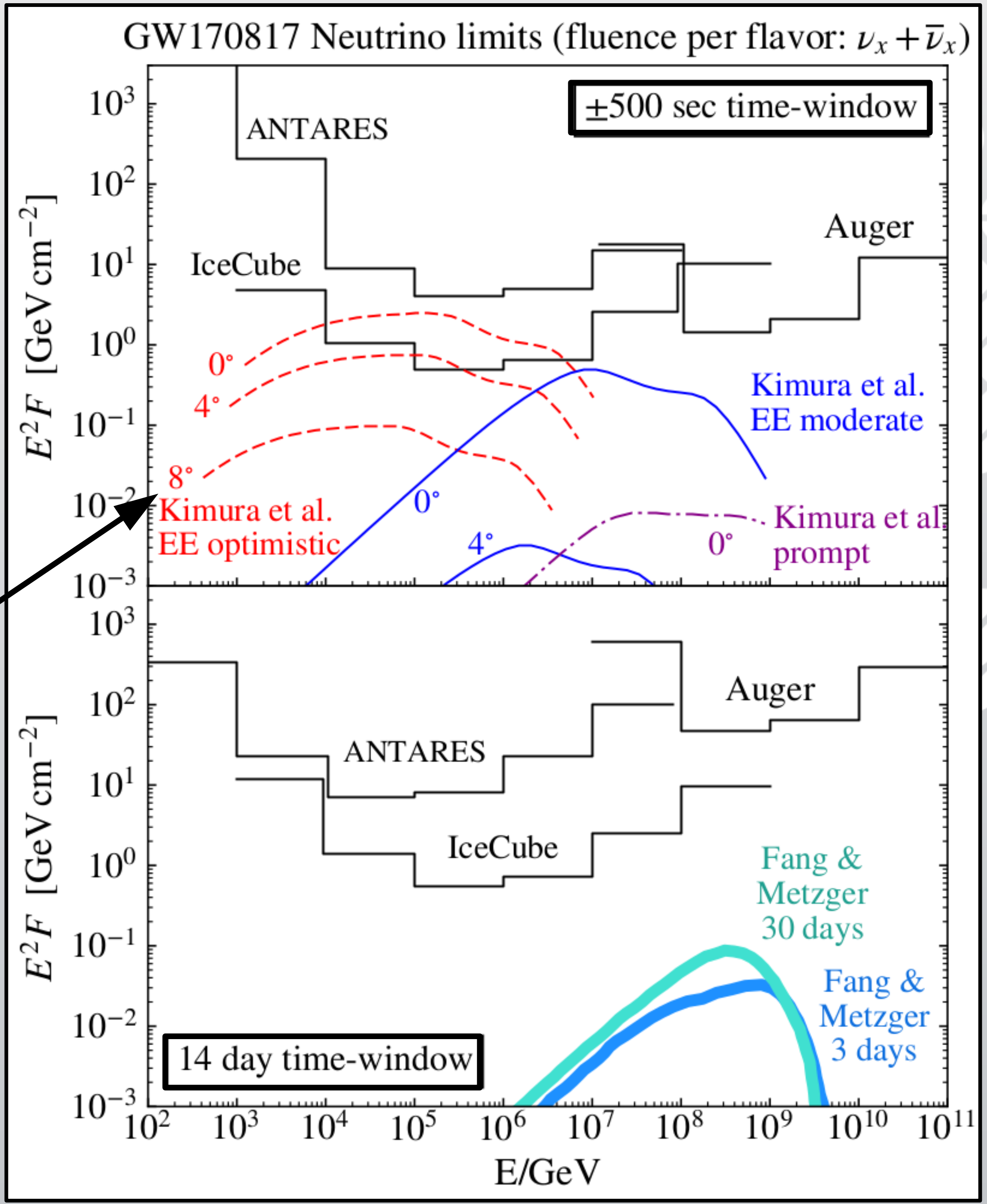




GW170817 neutrino limits

ApJL 850, L35

- **No related neutrinos** detected by ANTARES, IceCube, and Auger
- Sensitivity high for ±500 s but reduced for 14 days
  - Good vs. periodic visibility
  - Lesson: lucky strikes happen, improved preparation (faster follow-up) might pay off in the future



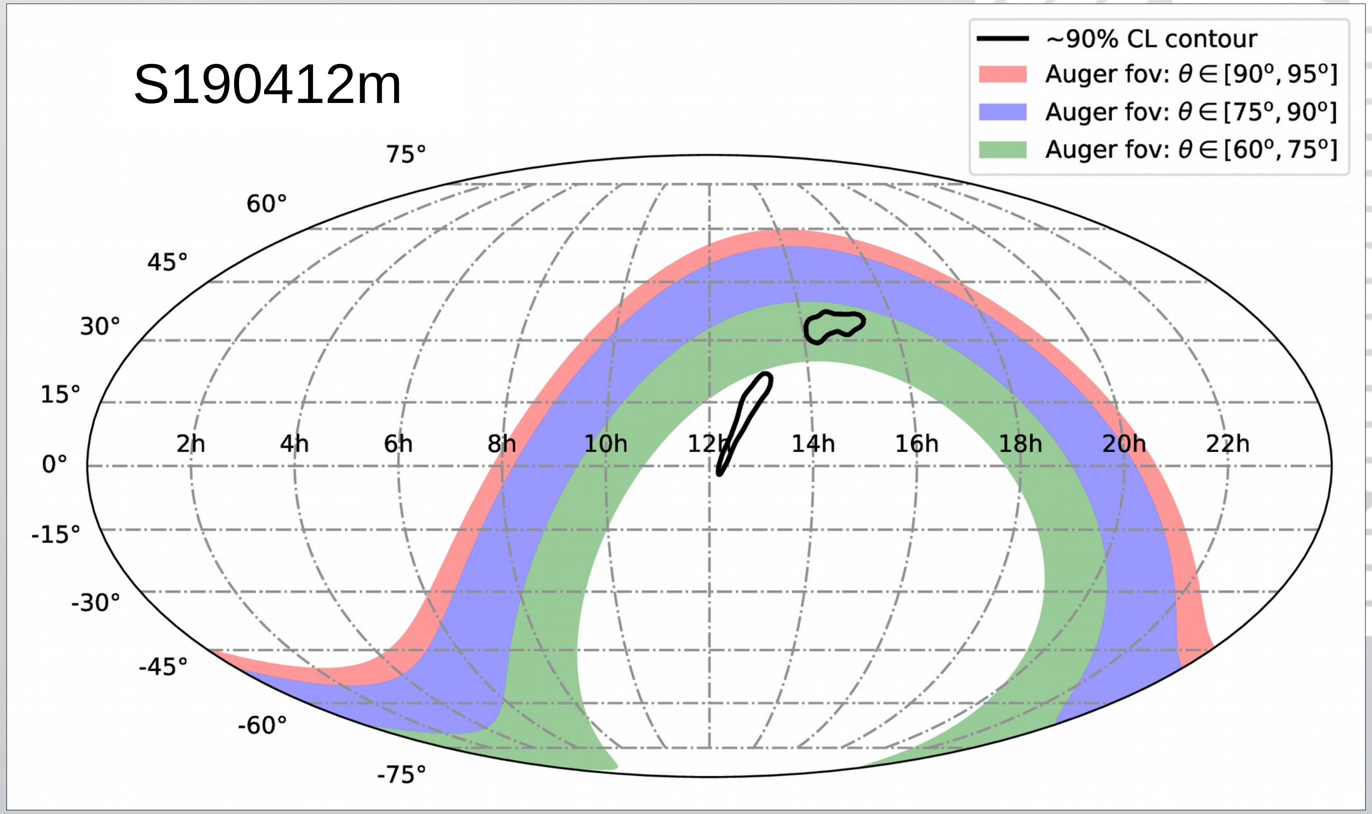
Off-axis viewing angle, constrained to < 36° (at time of publication)

Follow-up searches of binary black hole mergers

- LIGO/Virgo binary black hole (BBH) mergers published until 2019-06-02
  - GWTC-1 + open public alerts
  - ➢ **21 BBH mergers as hypothetical sources**

- Followed up immediately & automatically
  - Regular ultra-high energy (UHE) neutrino searches
  - Until **24 hours** after the merger
  - Most probable source localization (**90%** CL)

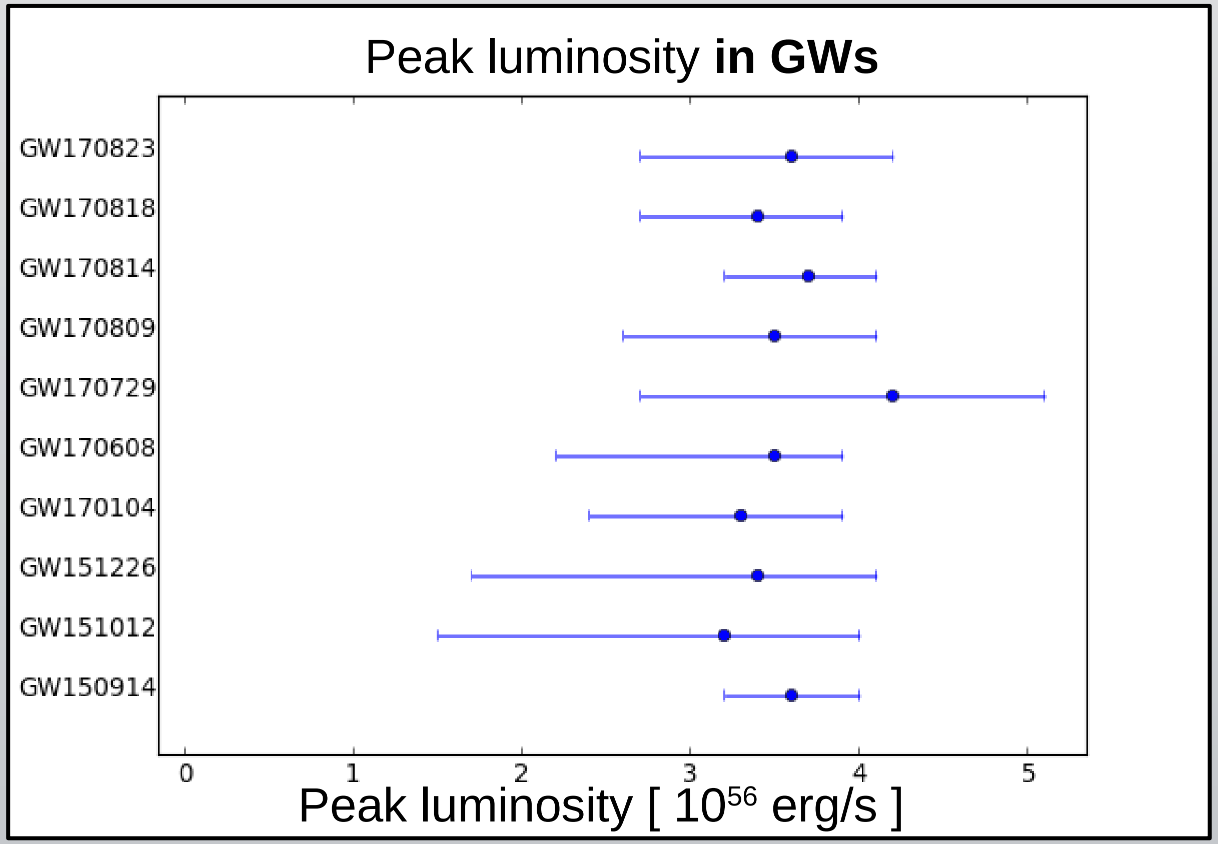
- Sources combined by stacking



Combining BBH mergers—Assumptions & GW info

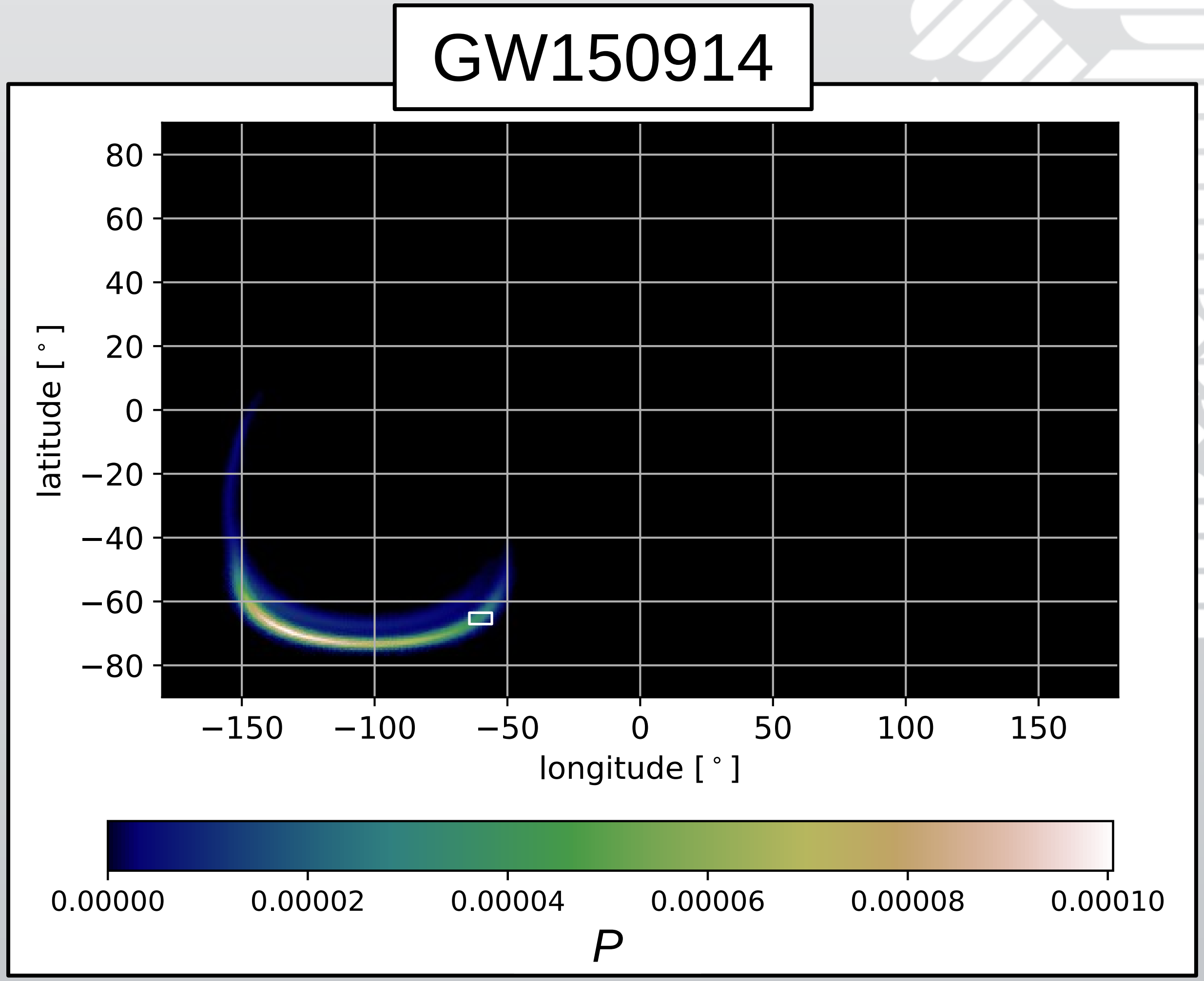
Source property assumptions:

- 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***



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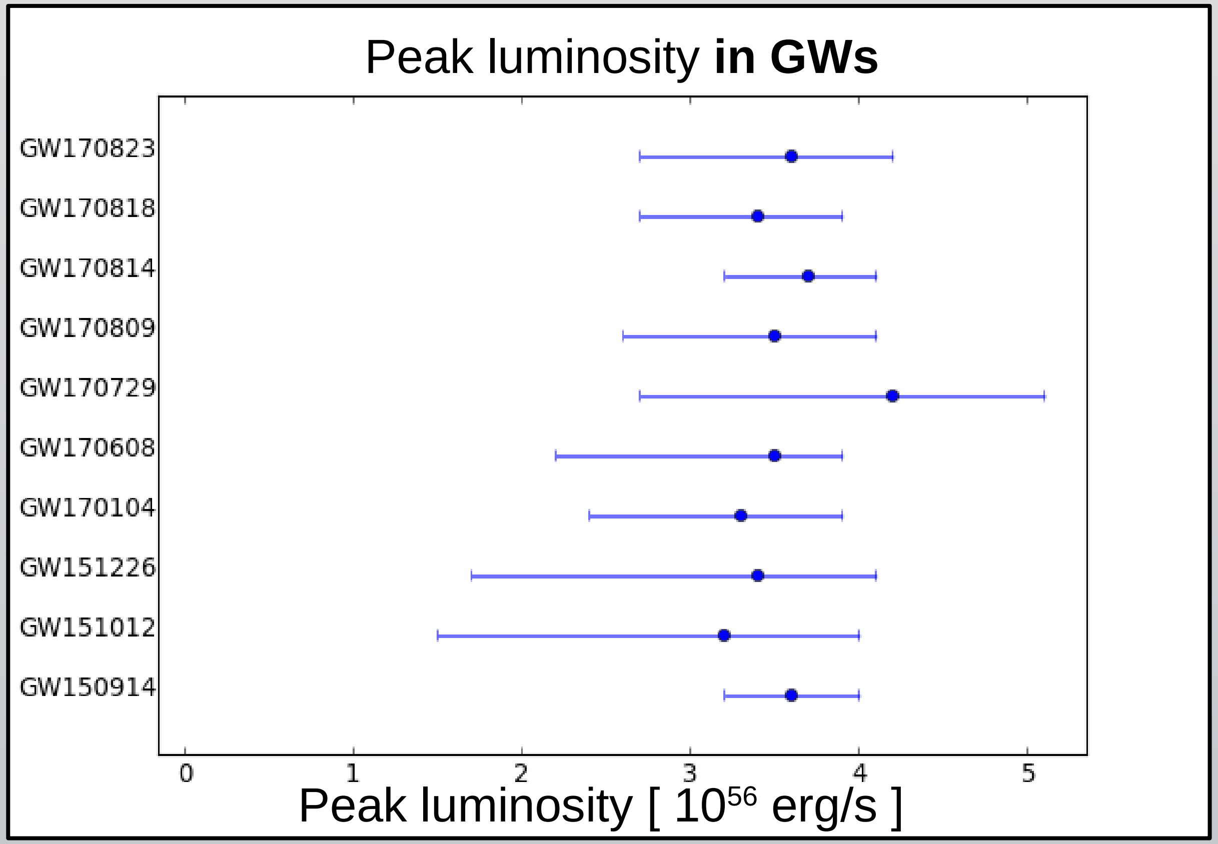
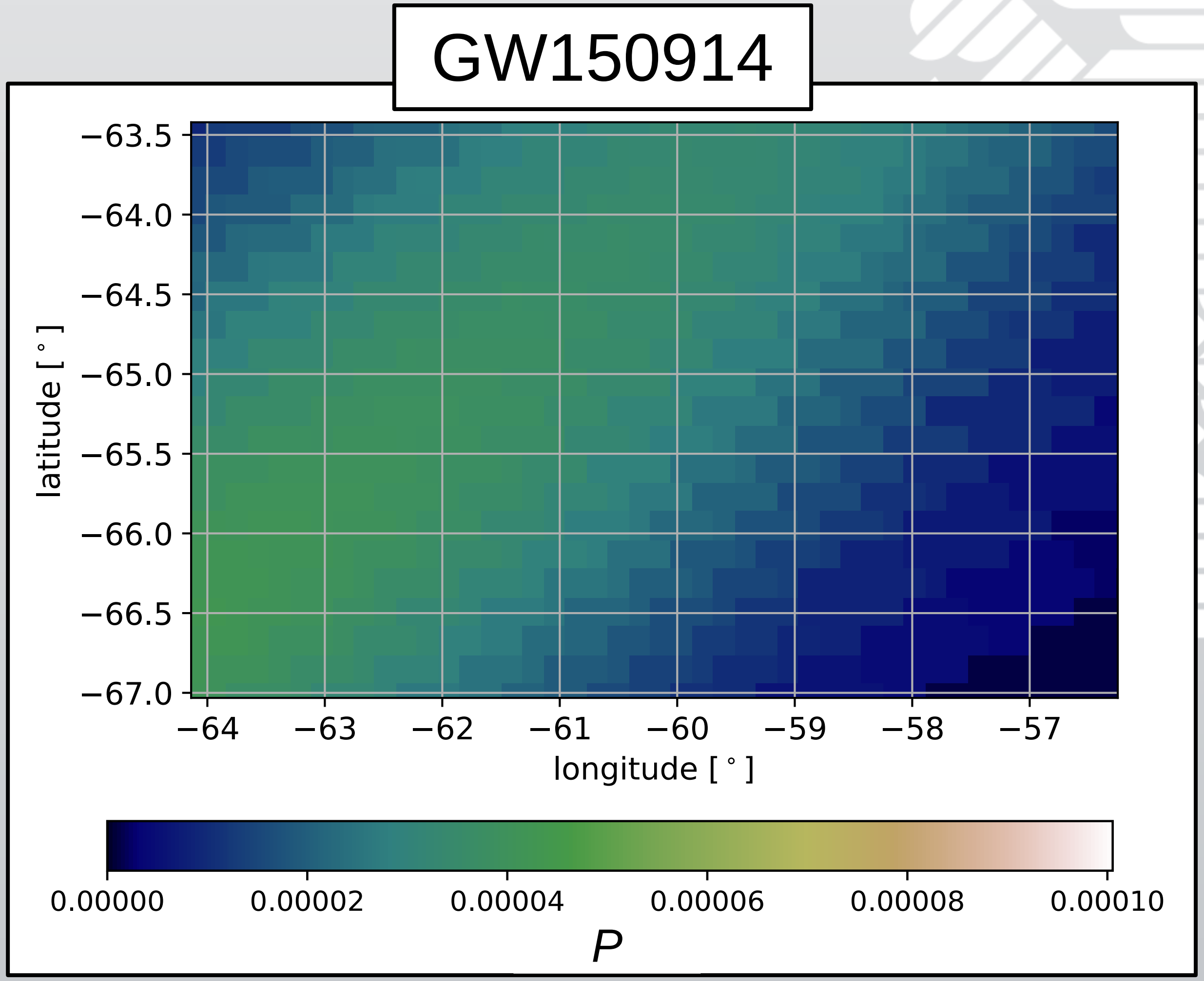




Combining BBH mergers—Time-dependent stacking

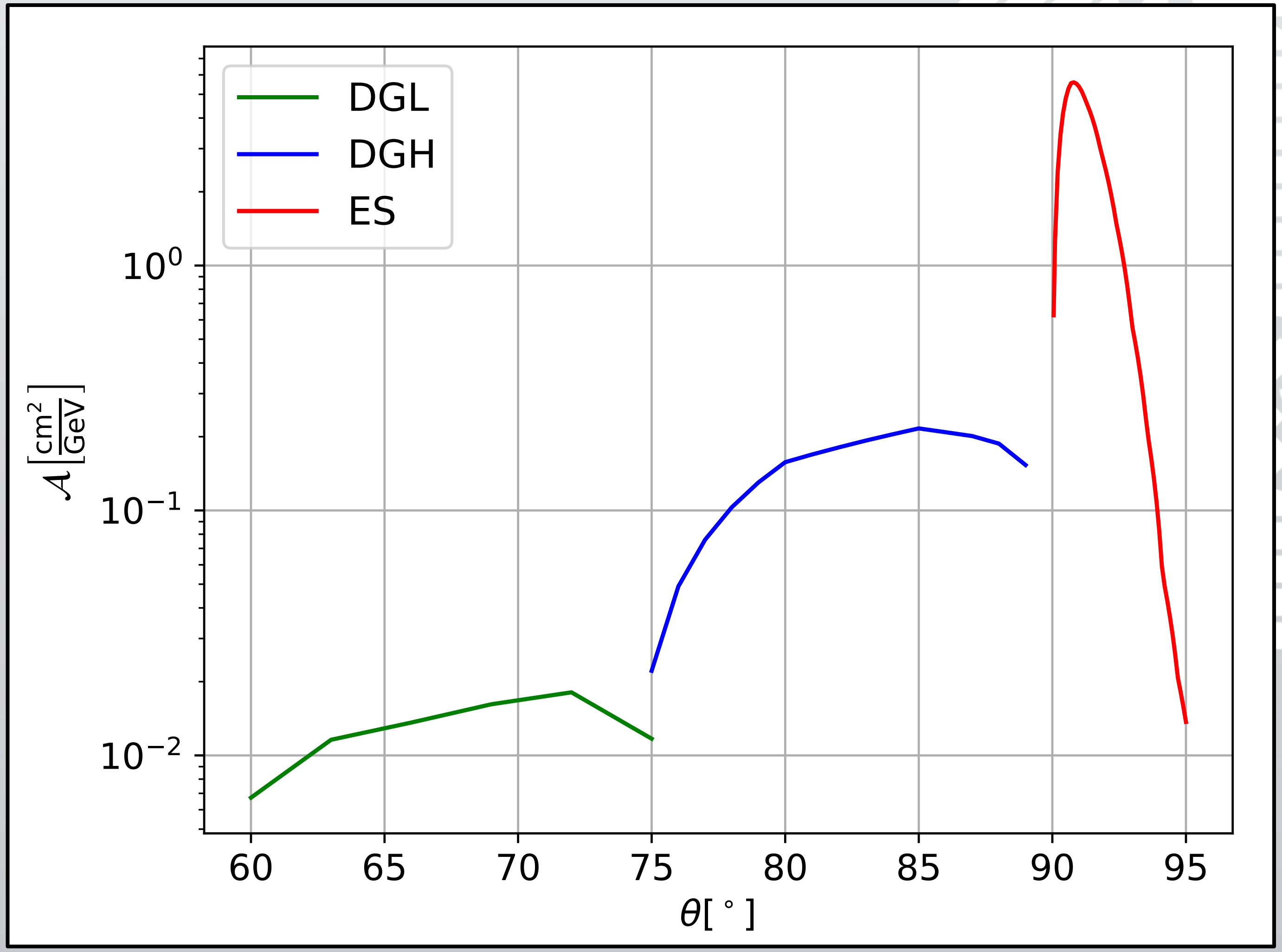
Consider time after the merger in **bins *i* of Δ*t* = 1 s**

- 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 *p***
↔ “solid angle integration”



Combining BBH mergers—Visibility of sources

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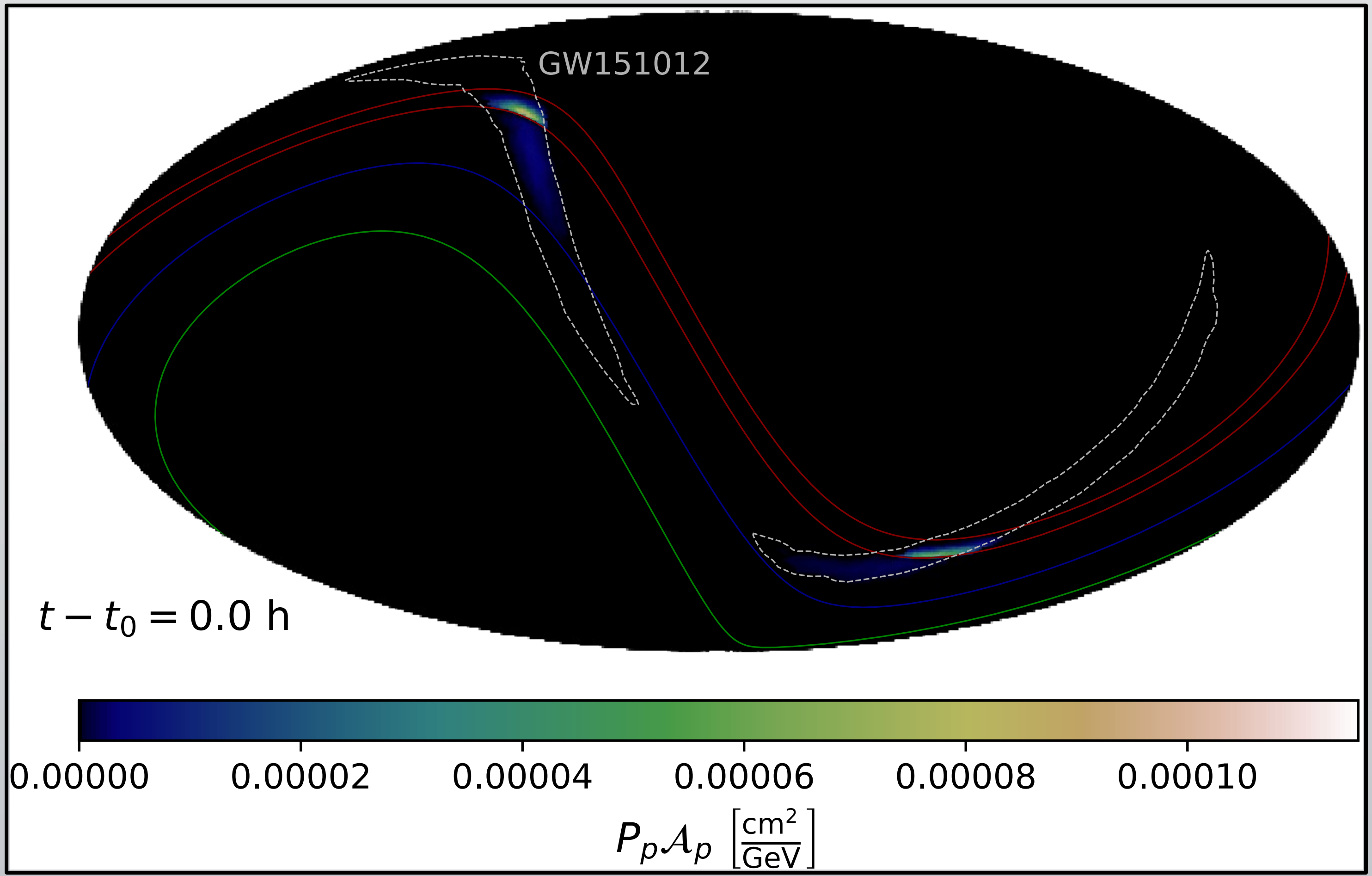

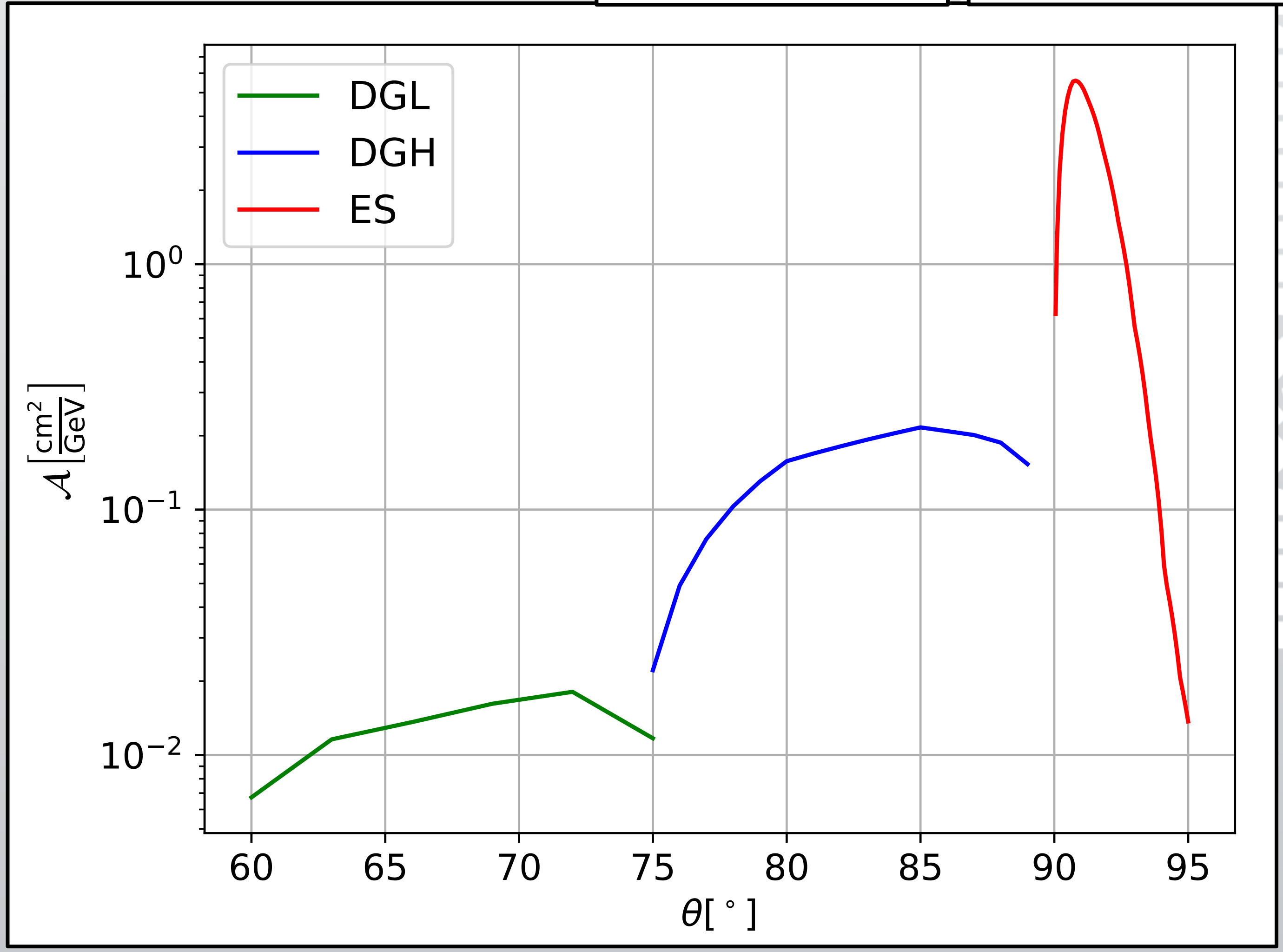

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Combining BBH mergers—Visibility of sources

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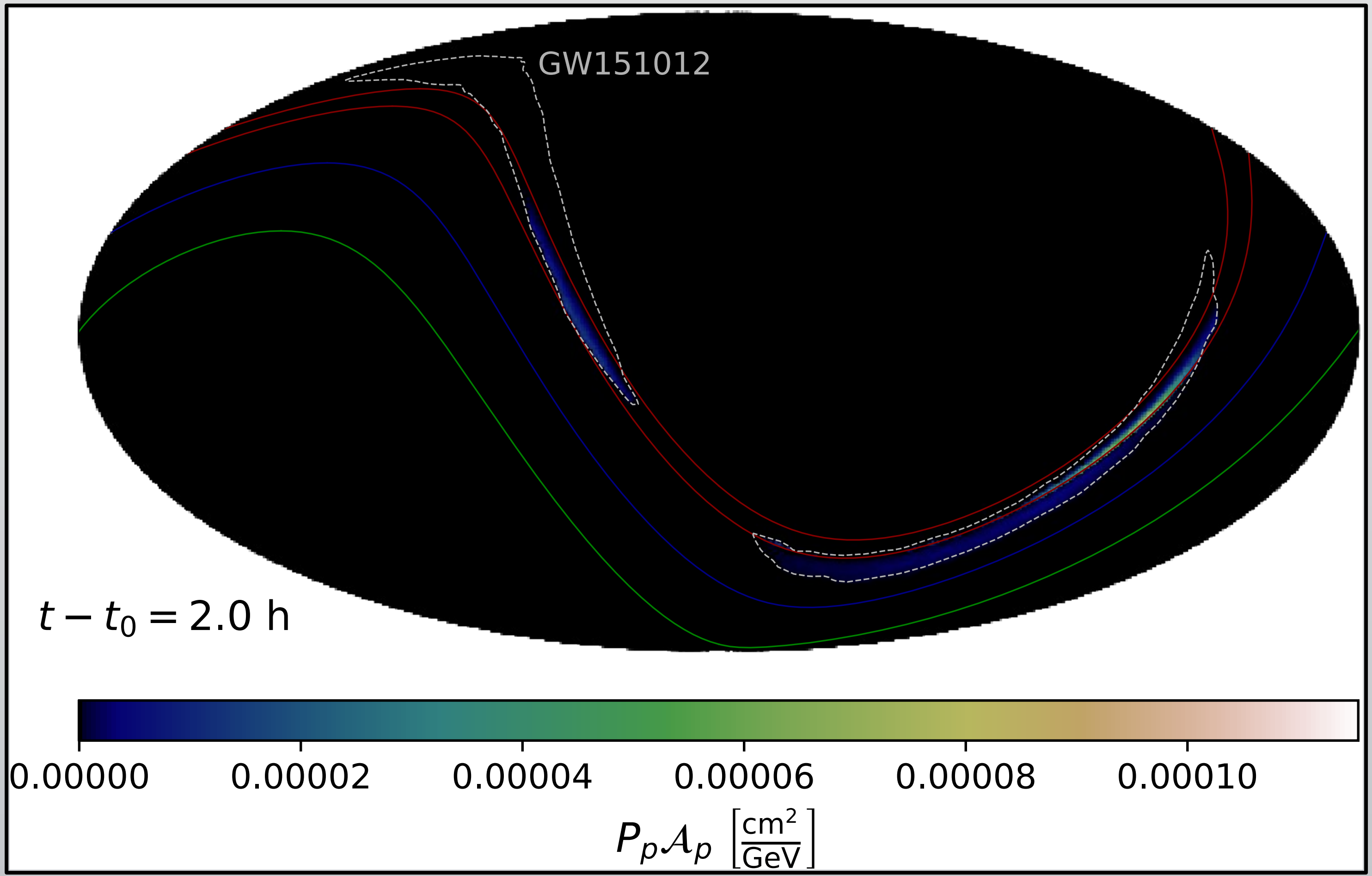

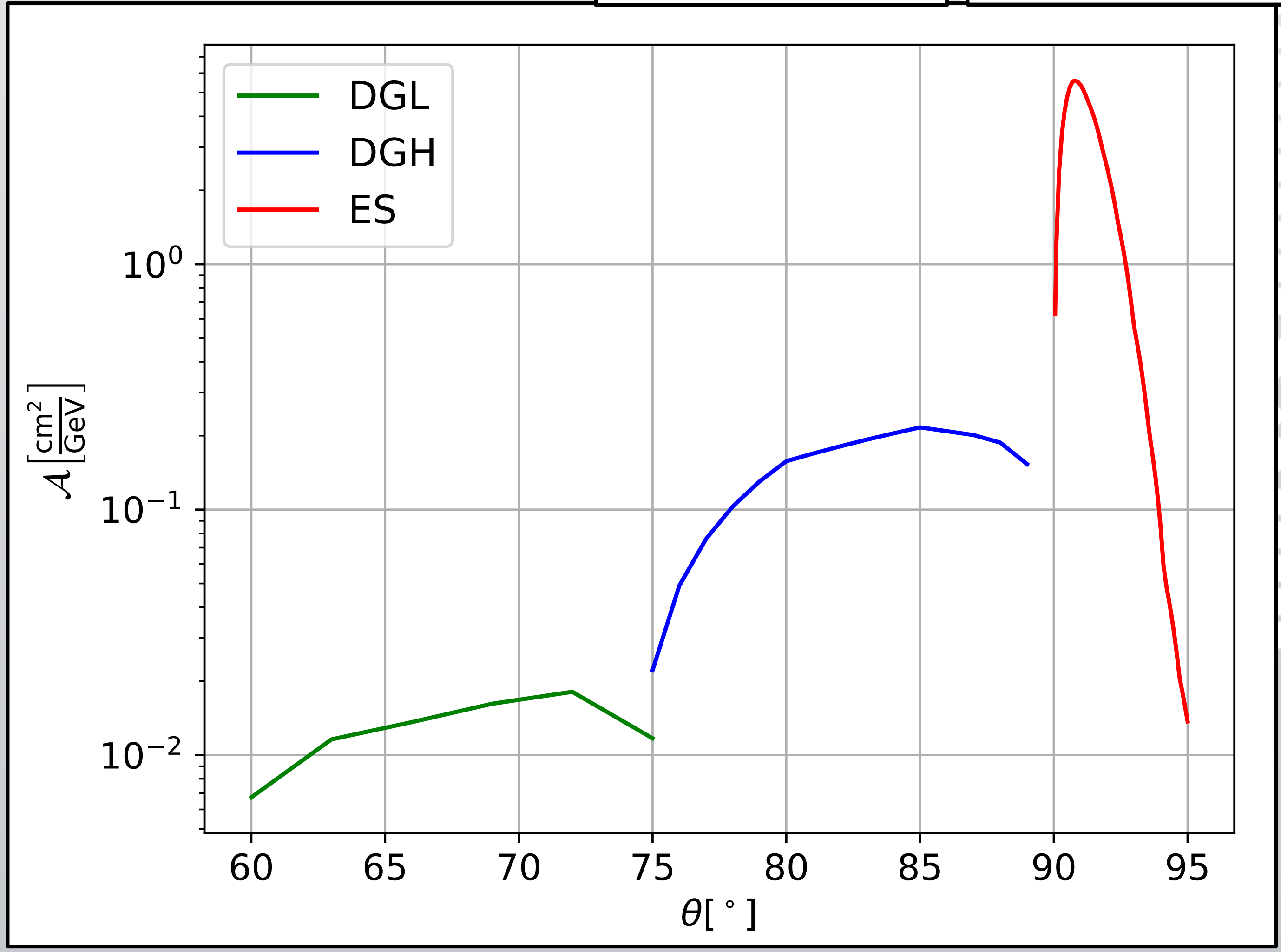

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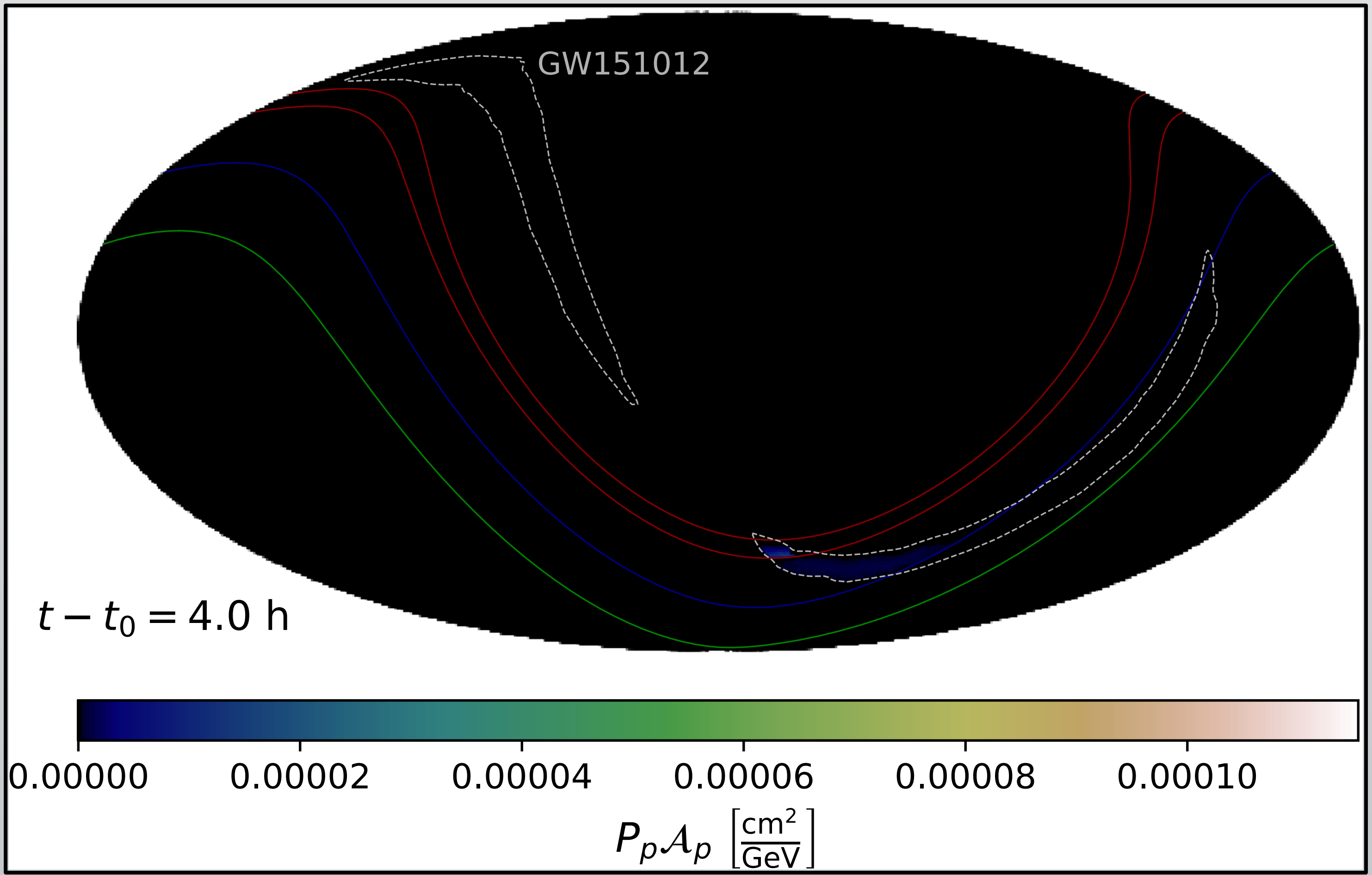

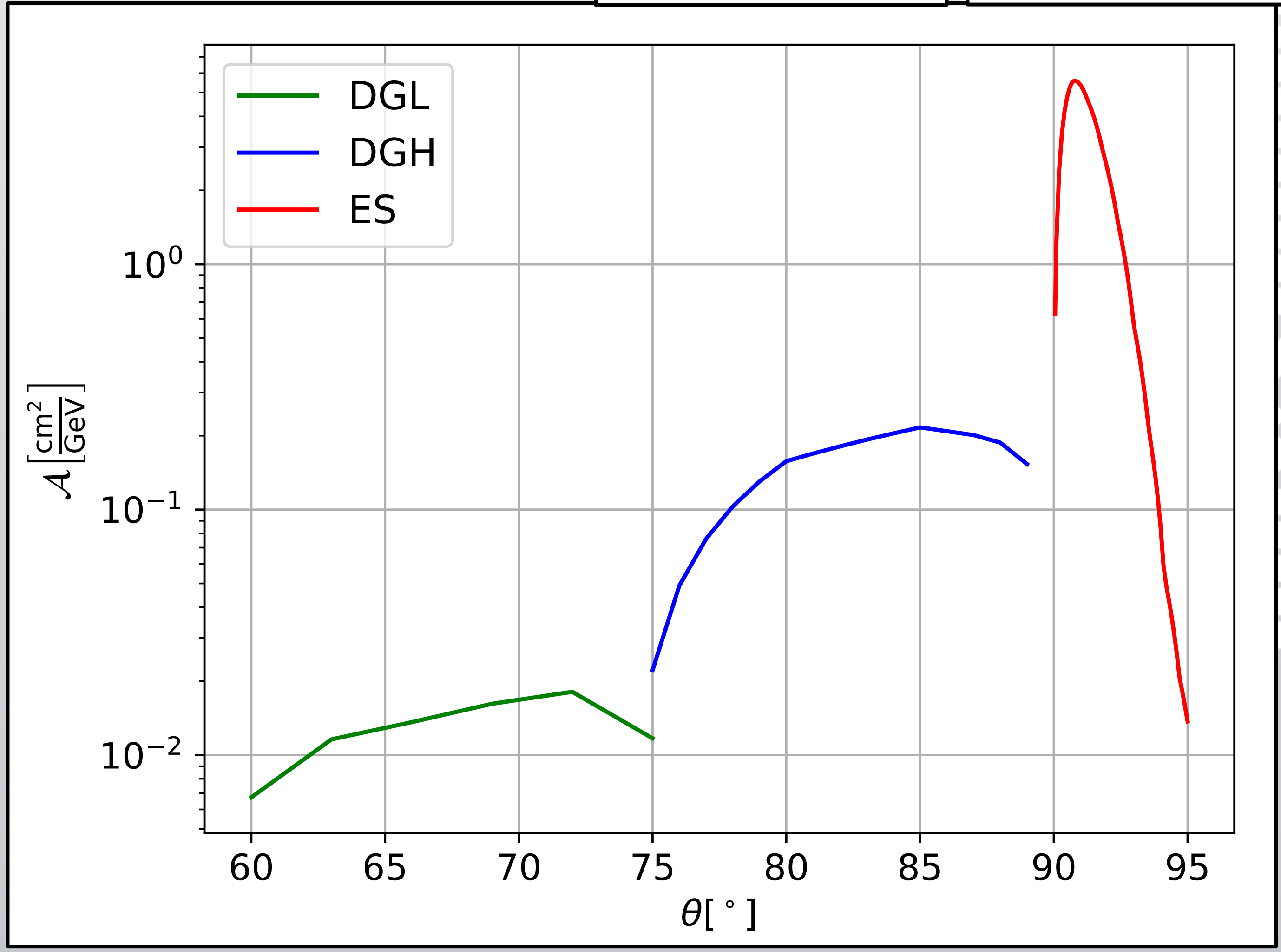

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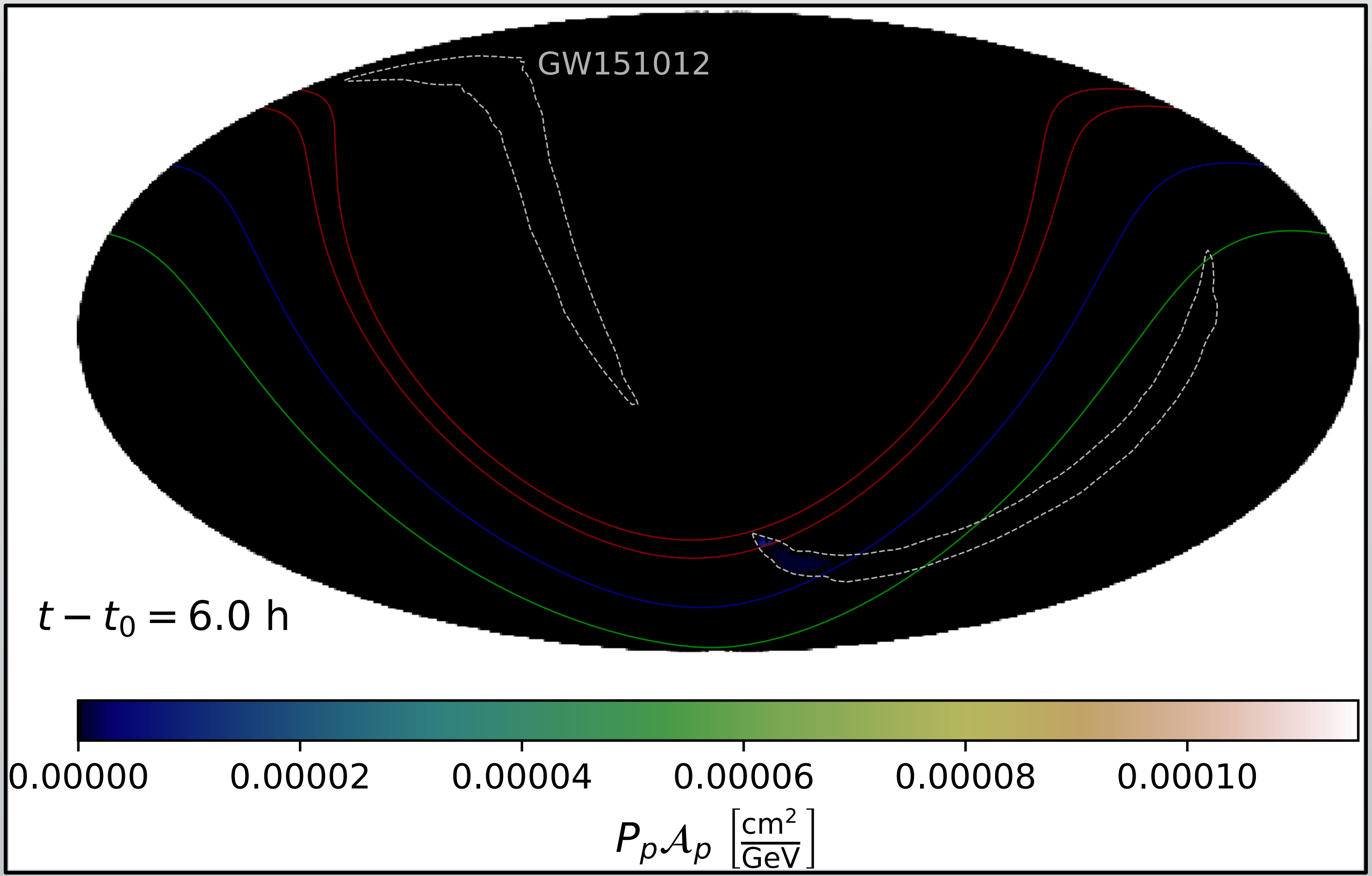

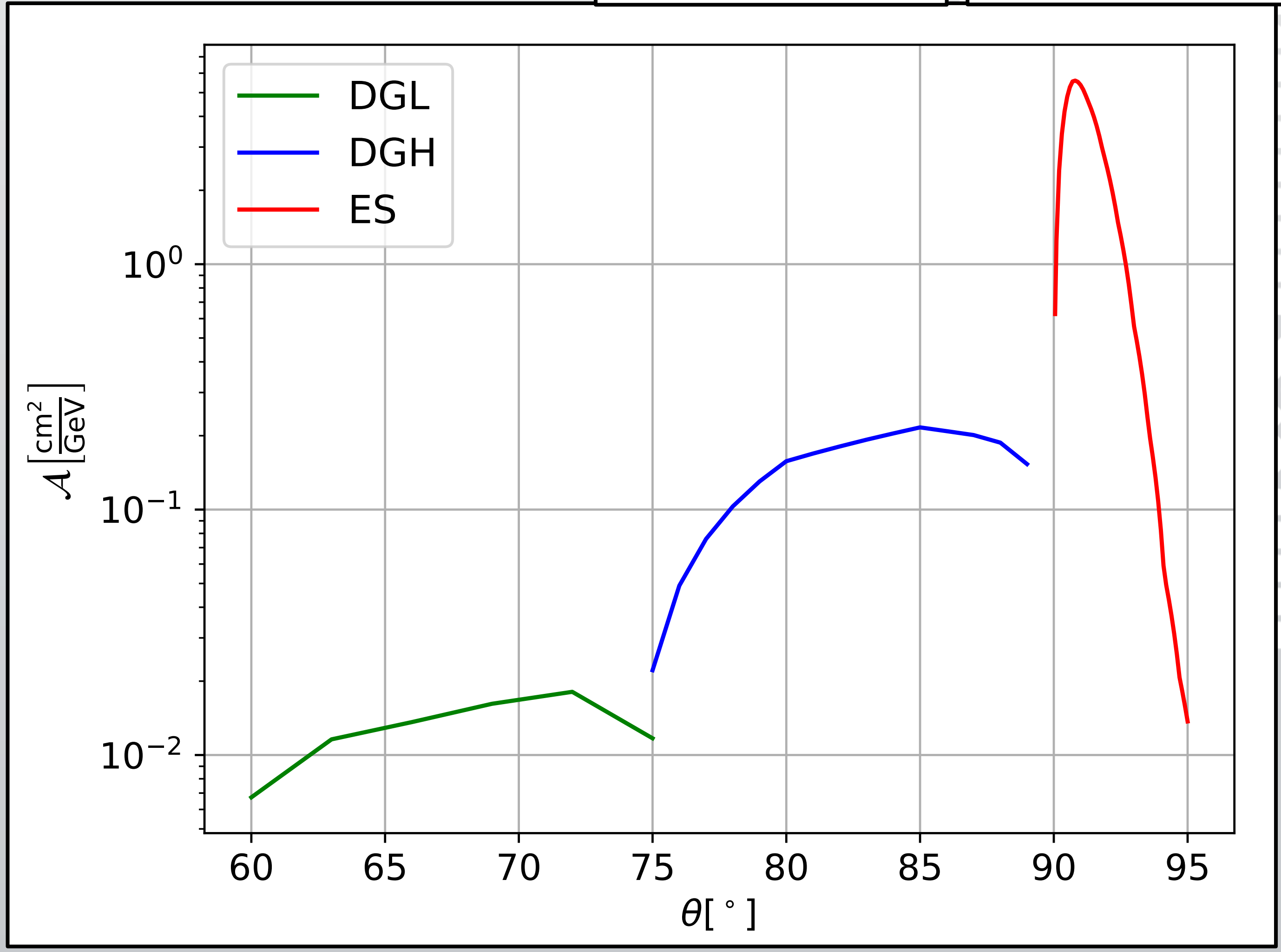

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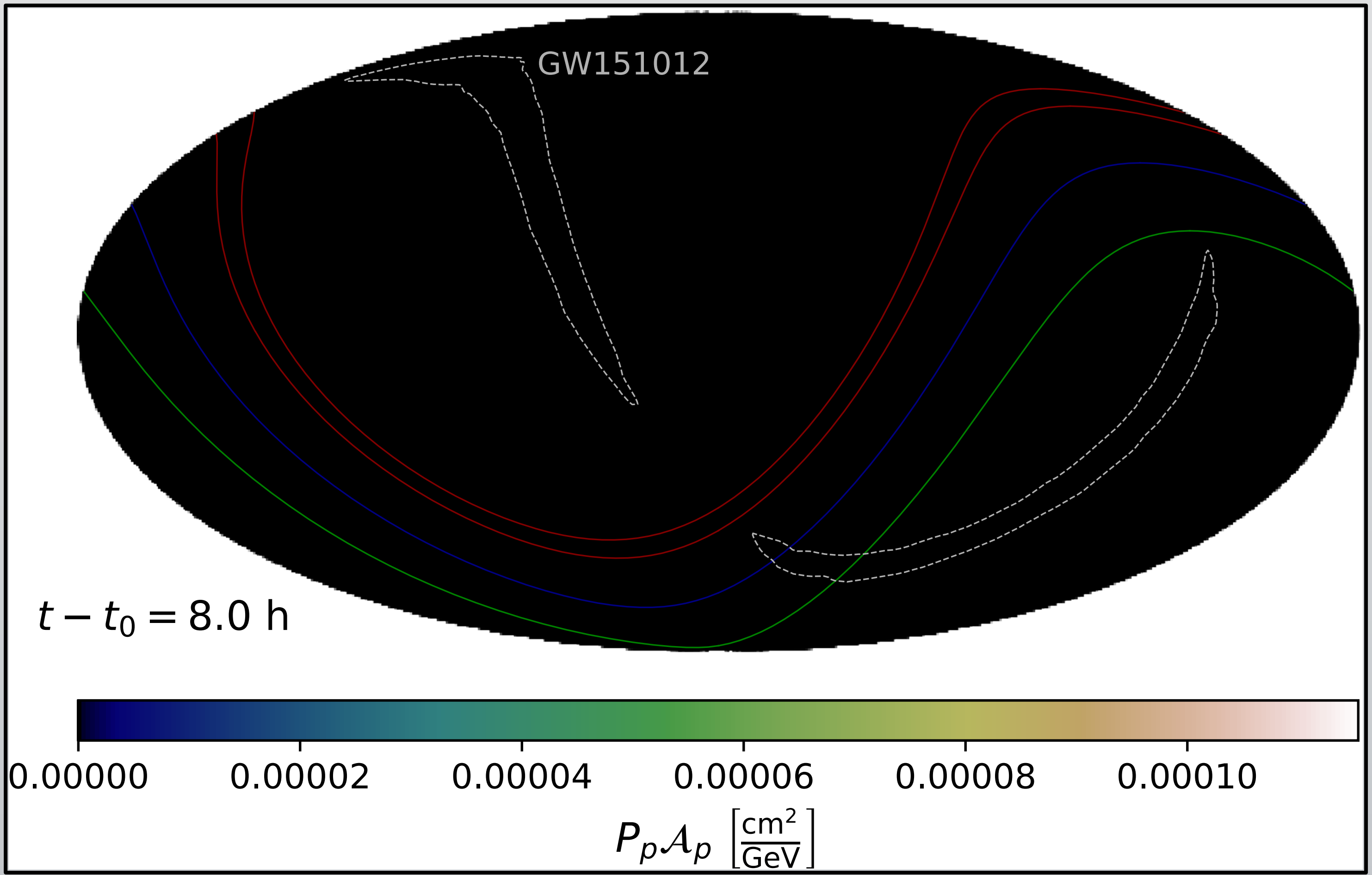

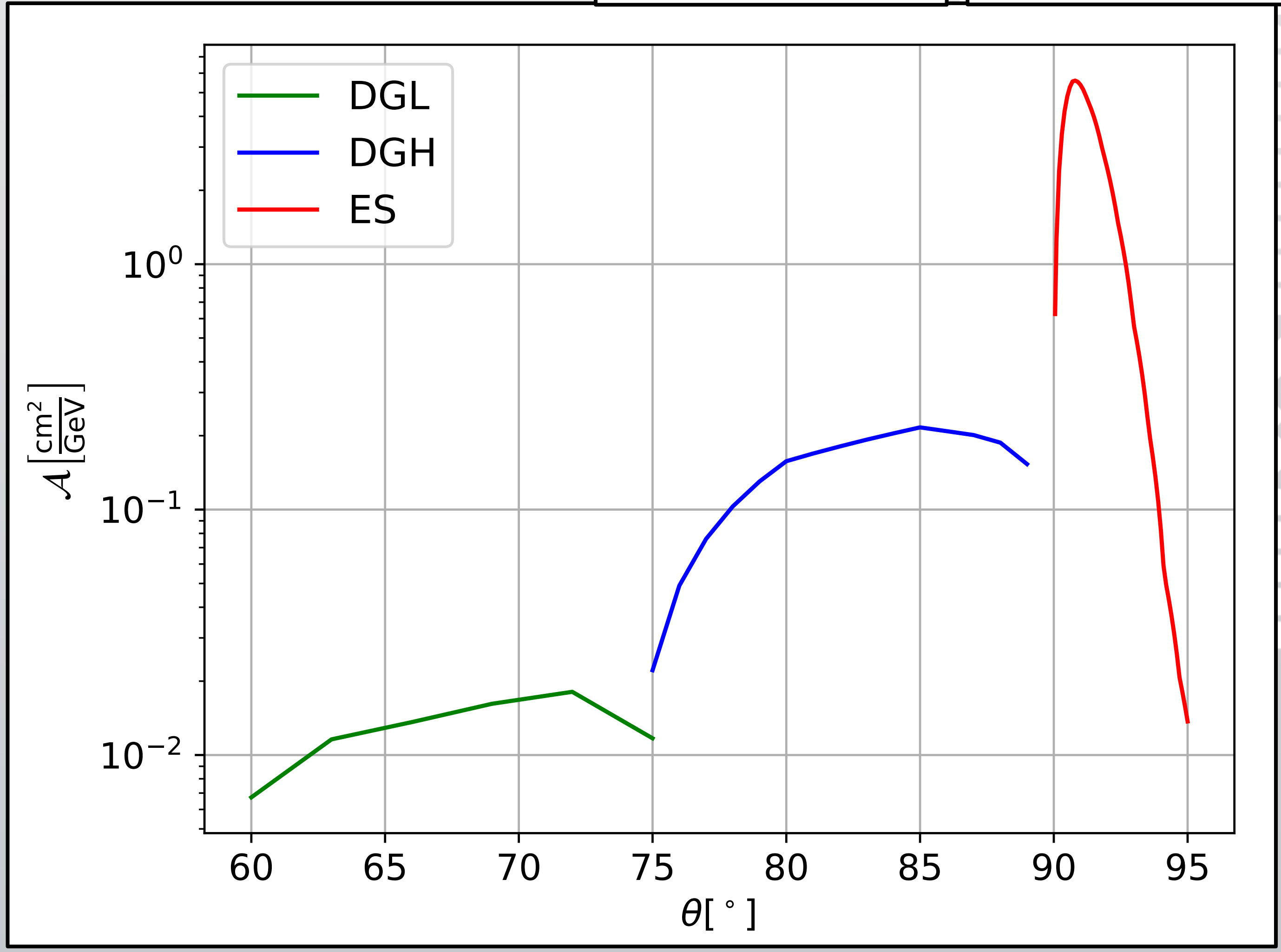

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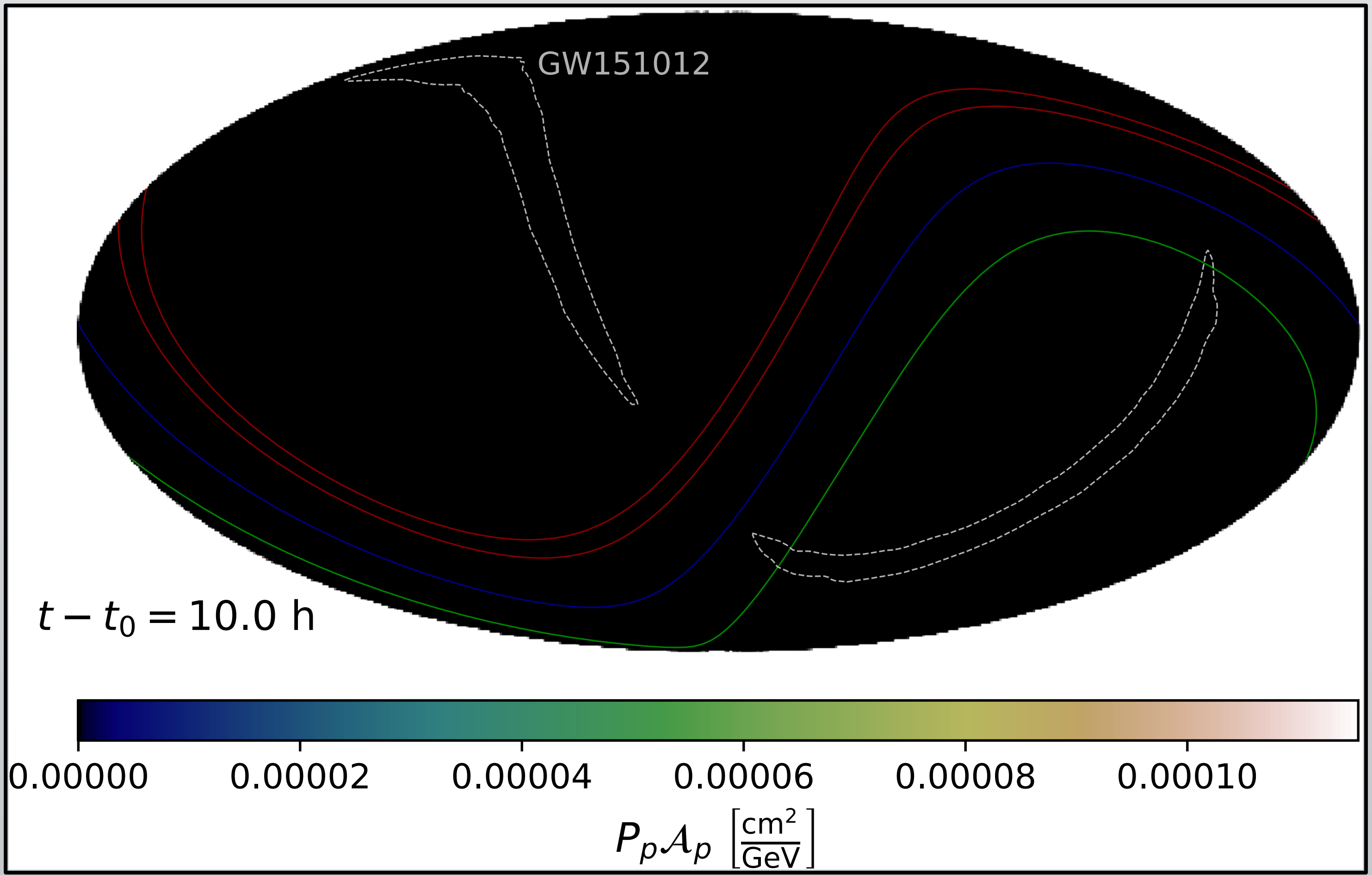

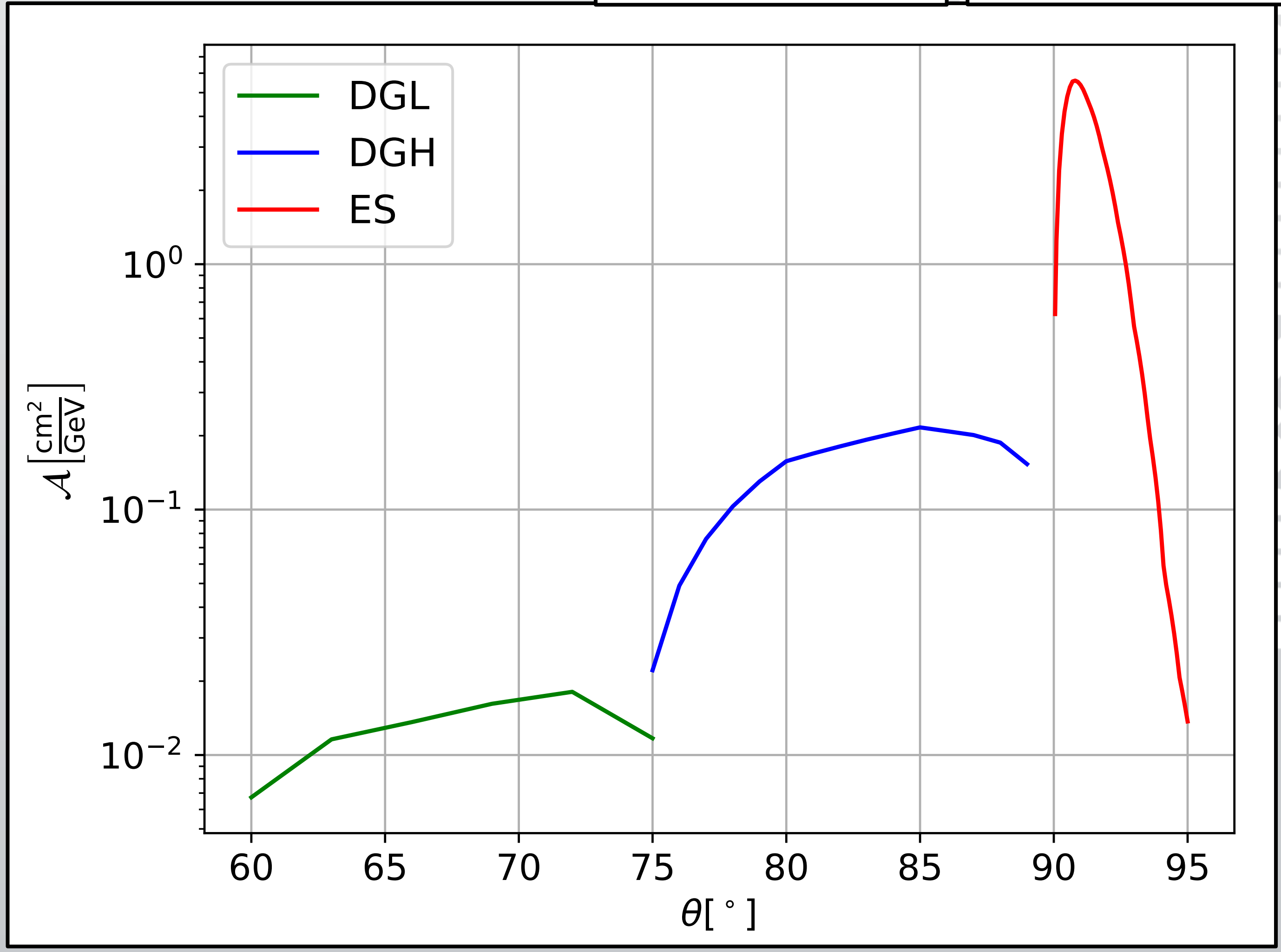

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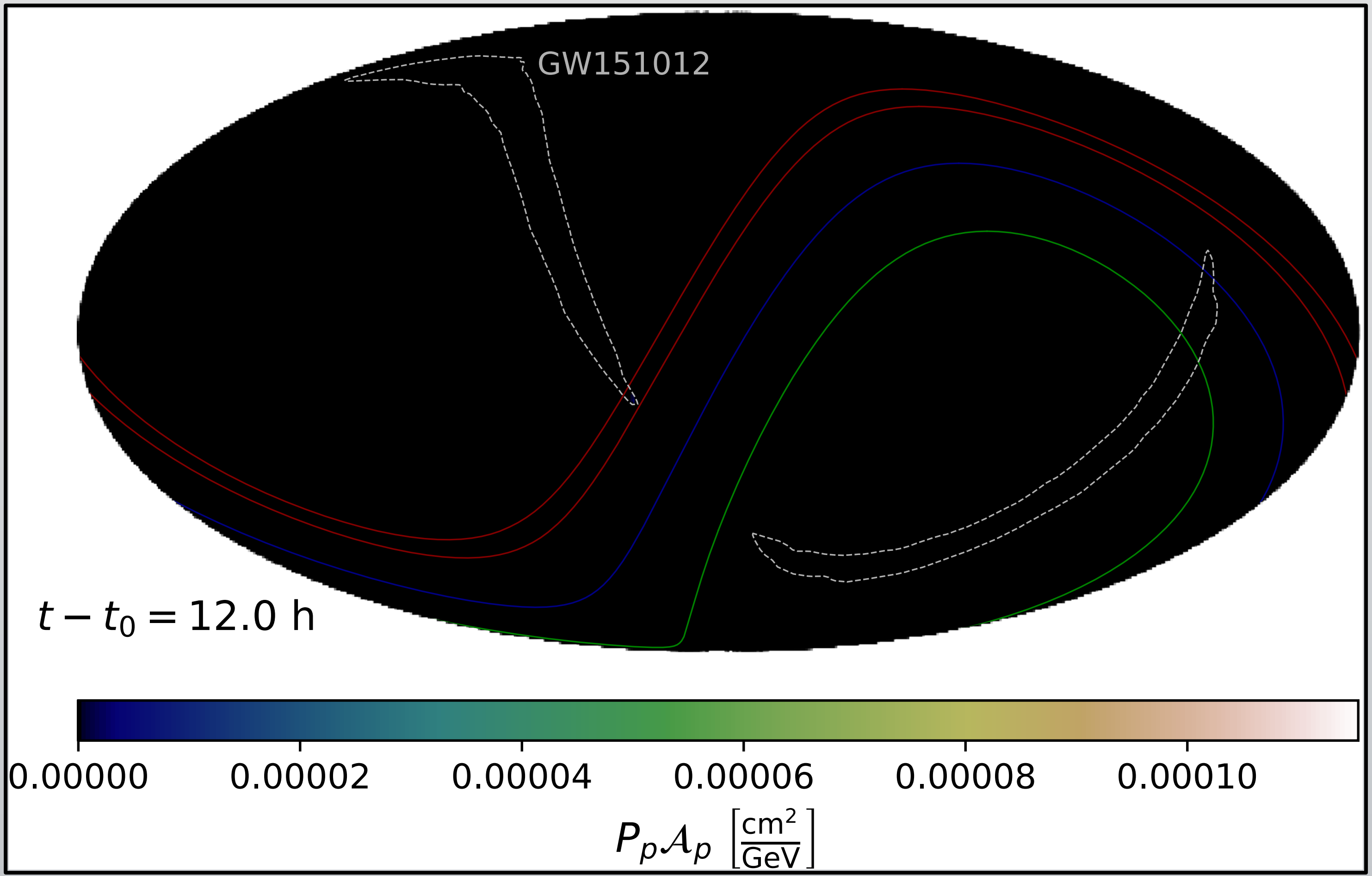

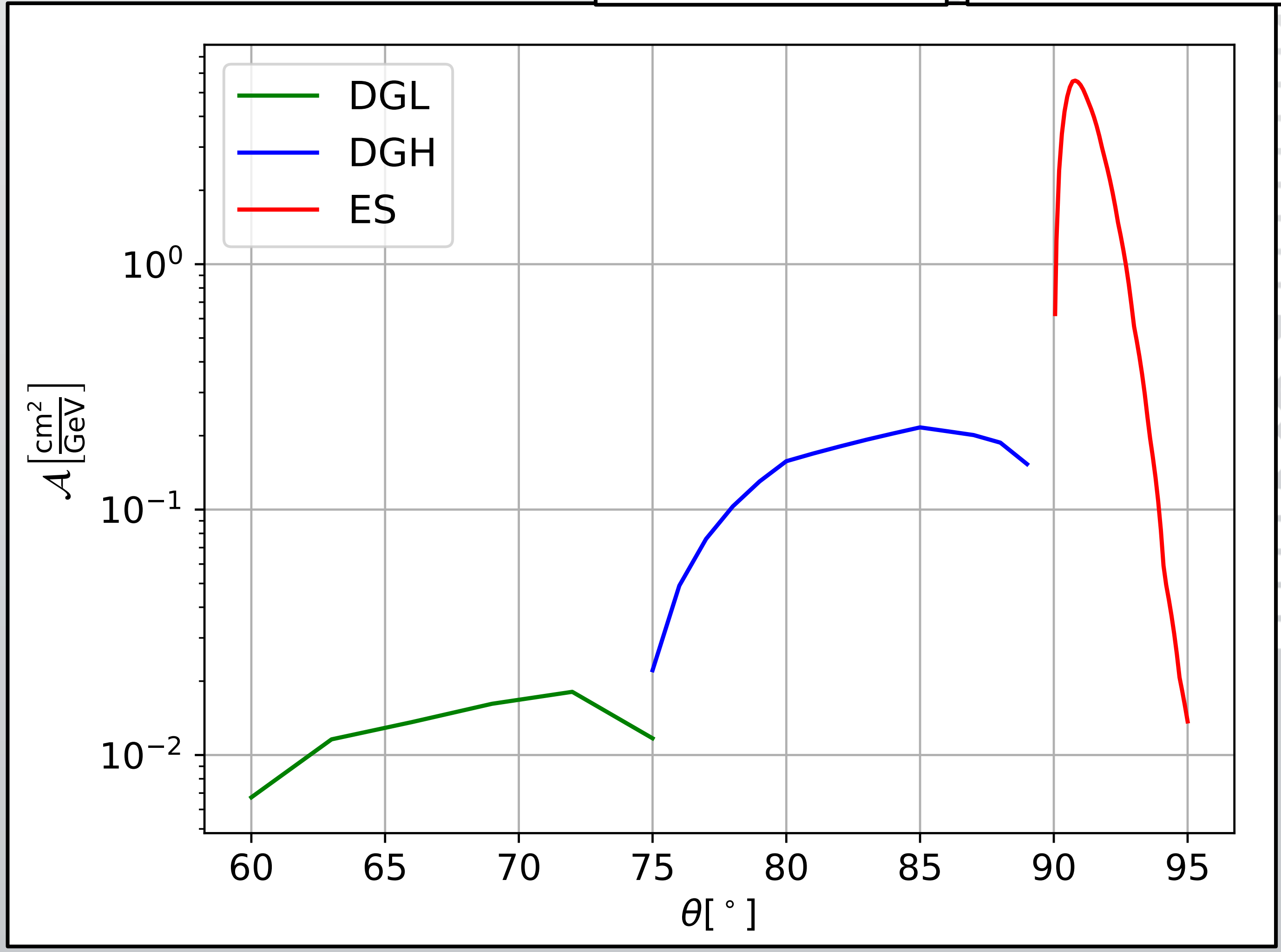

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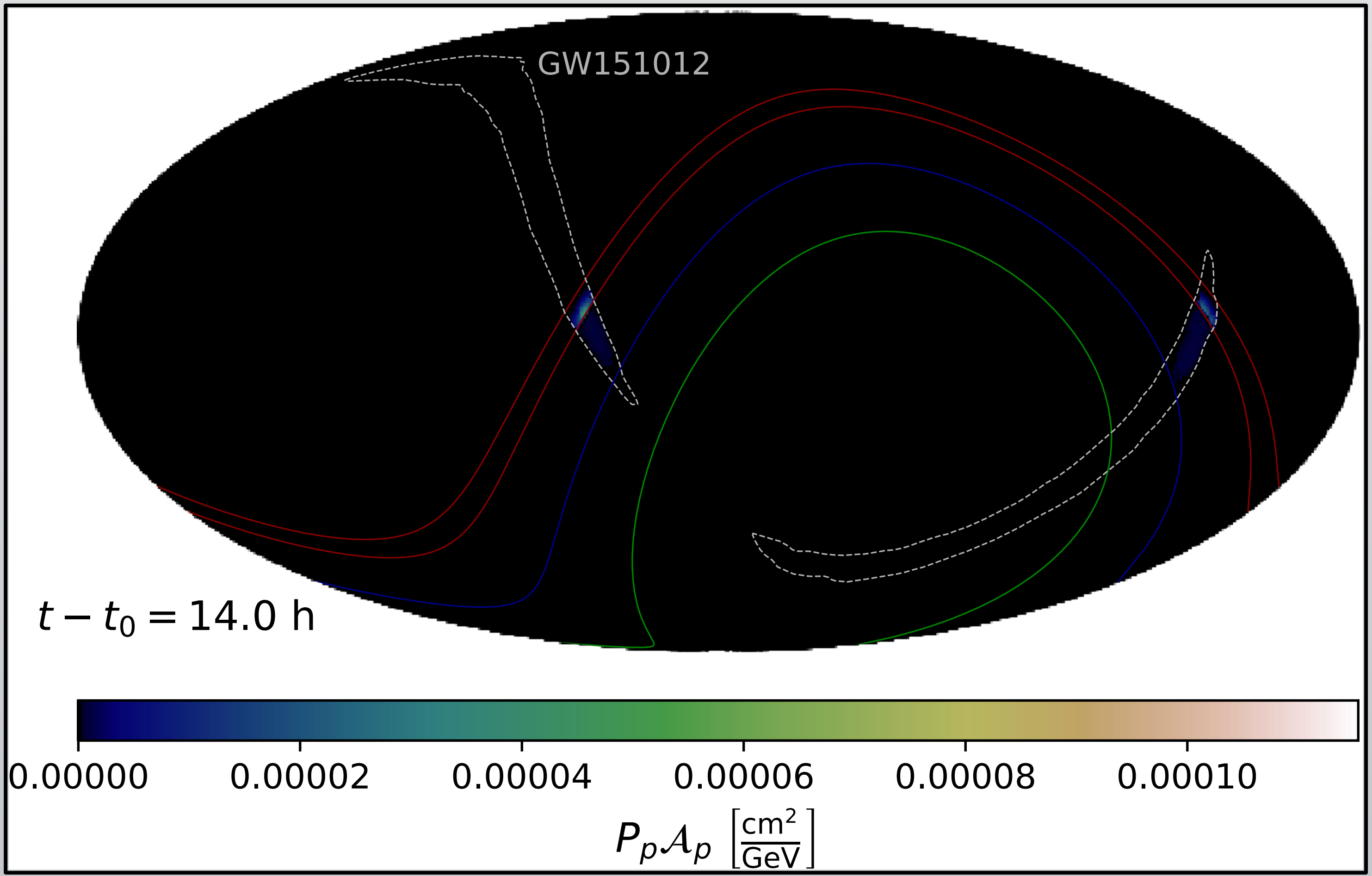

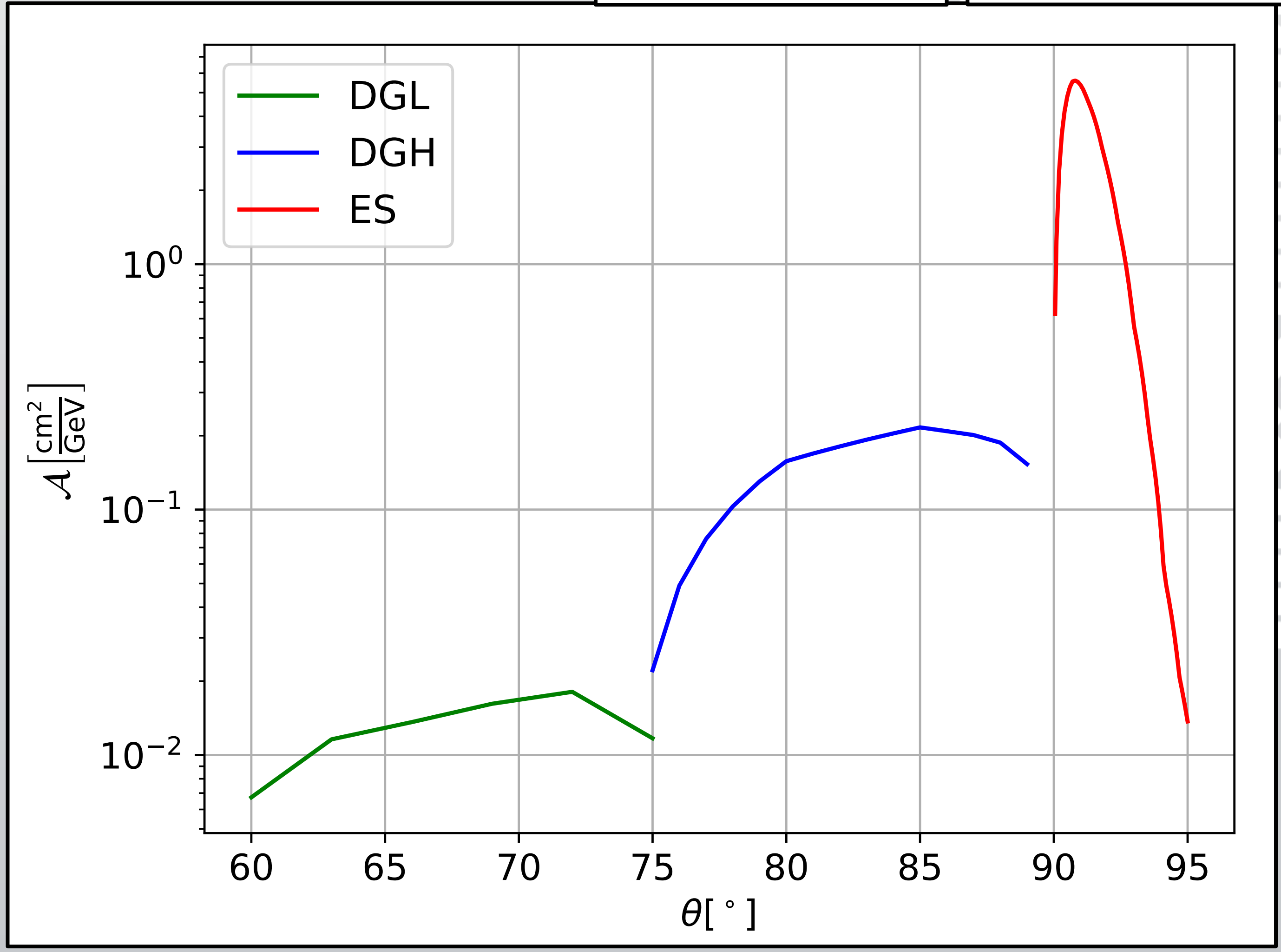

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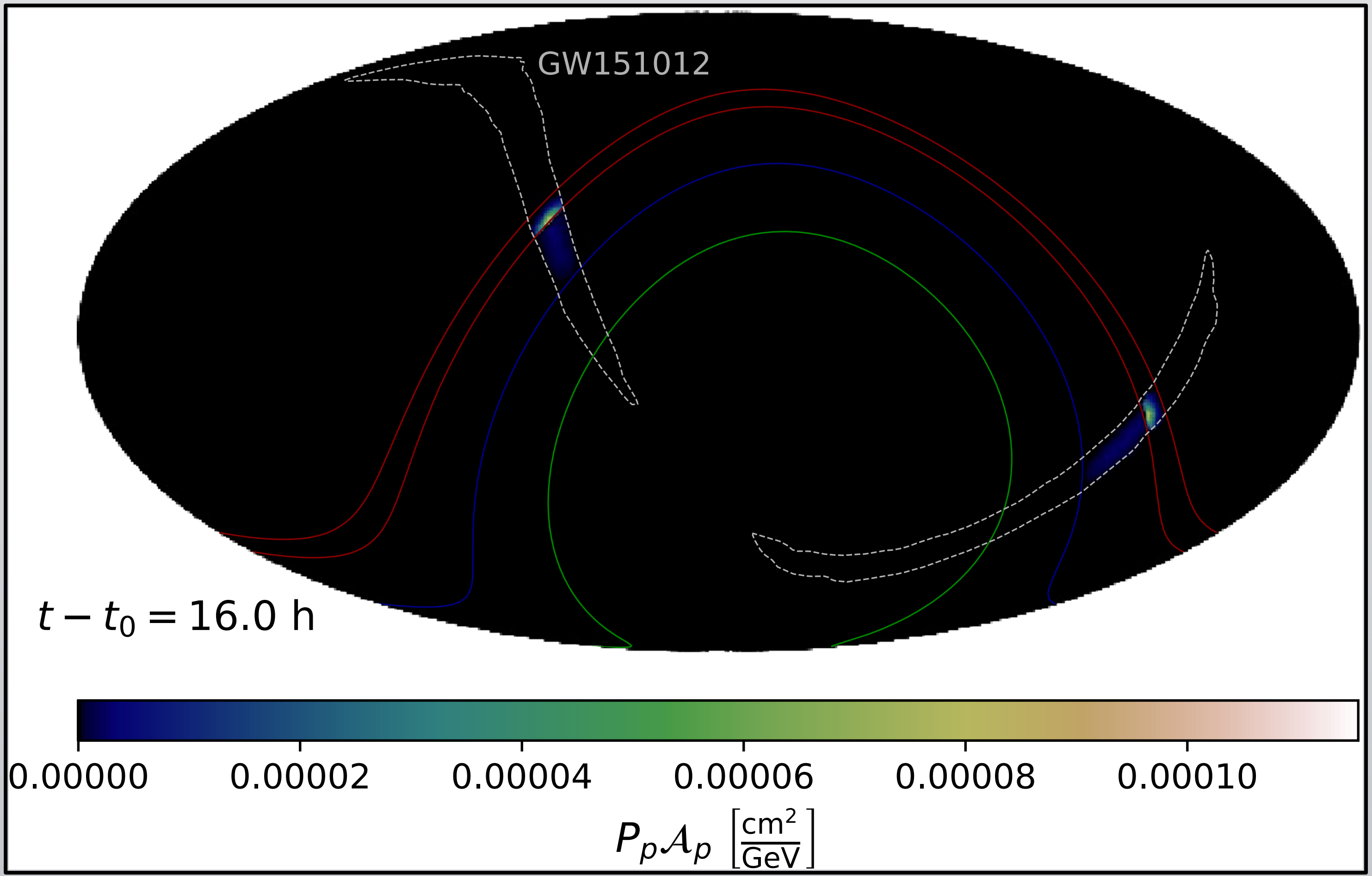

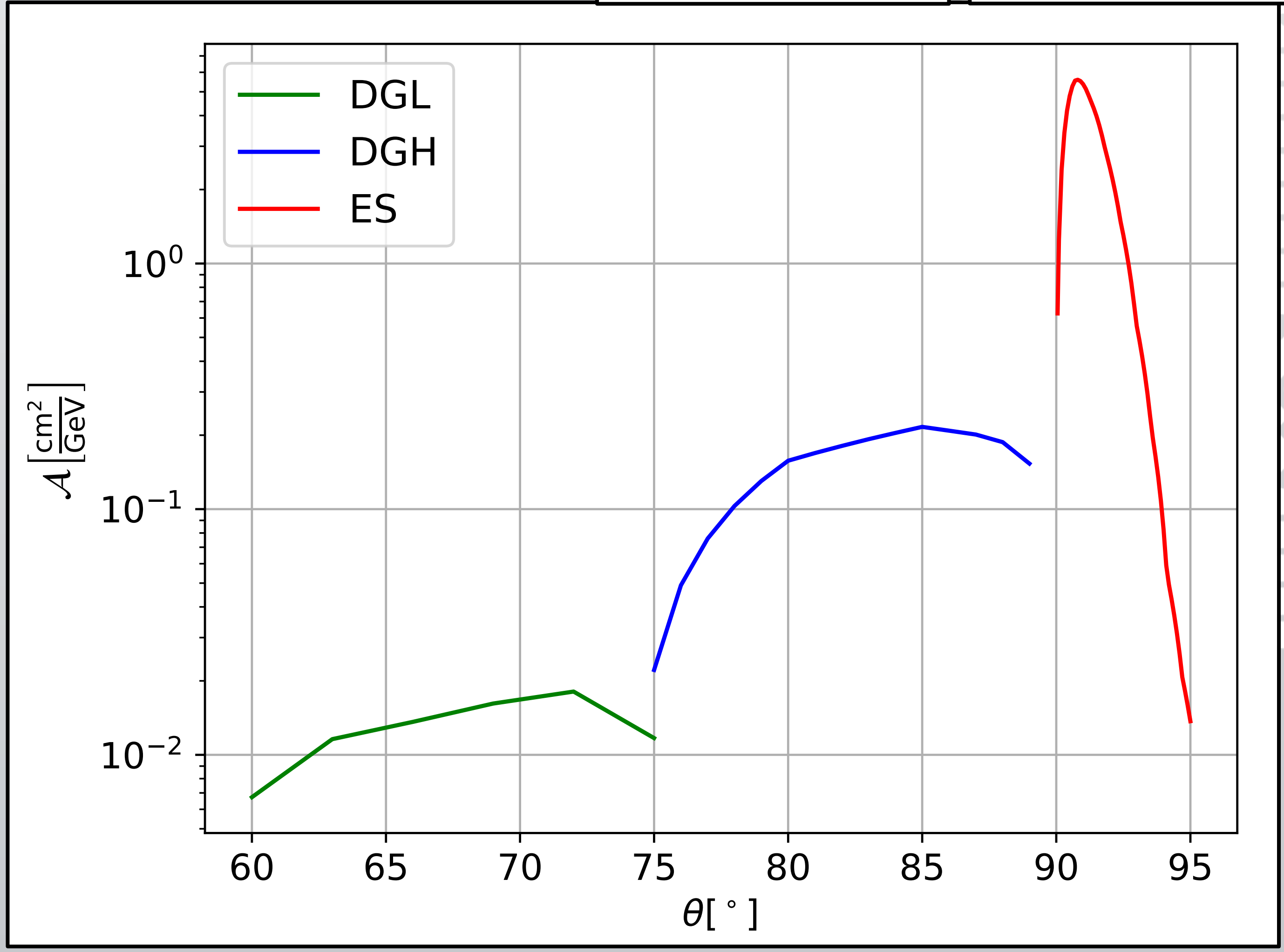

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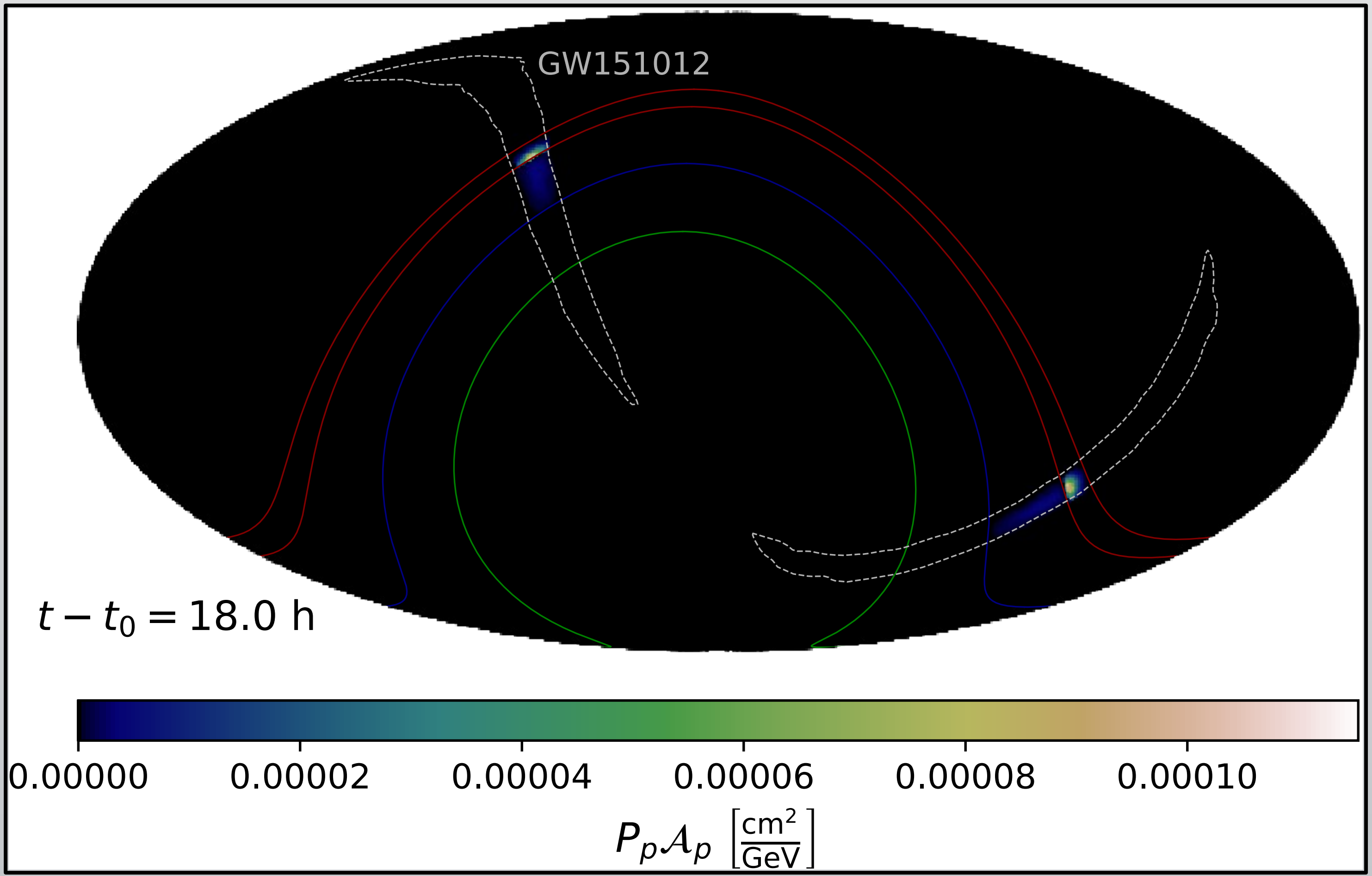

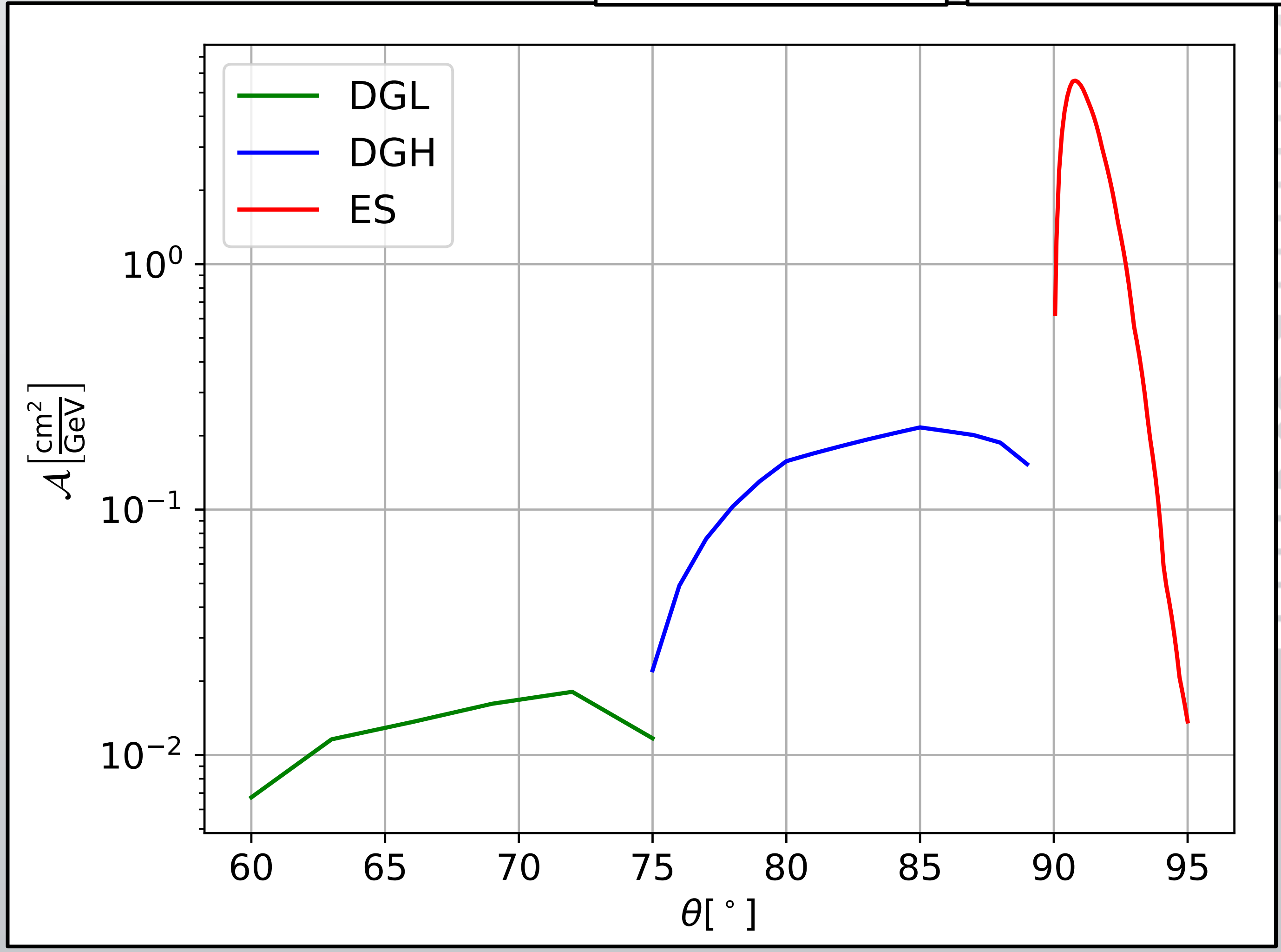

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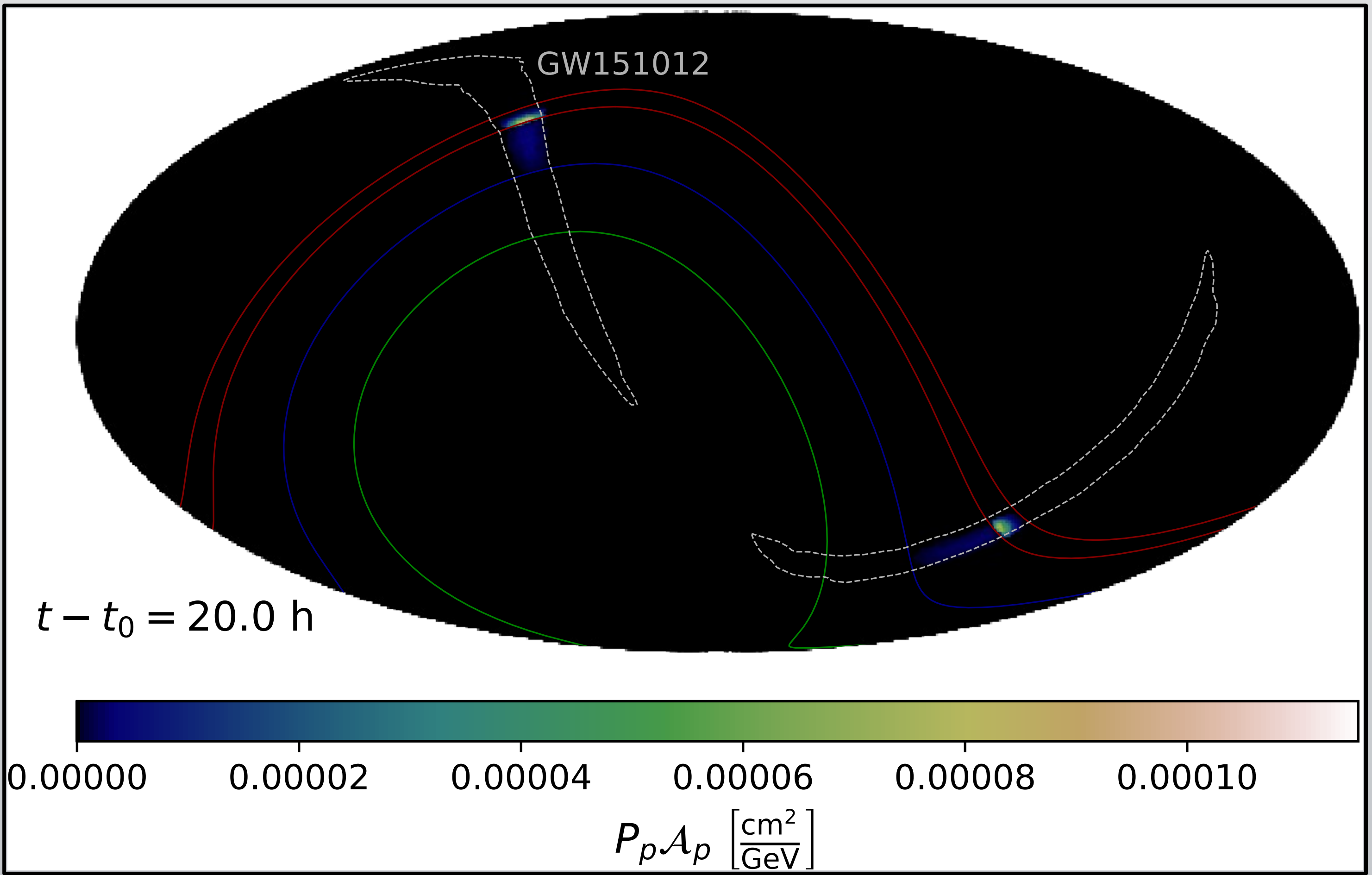

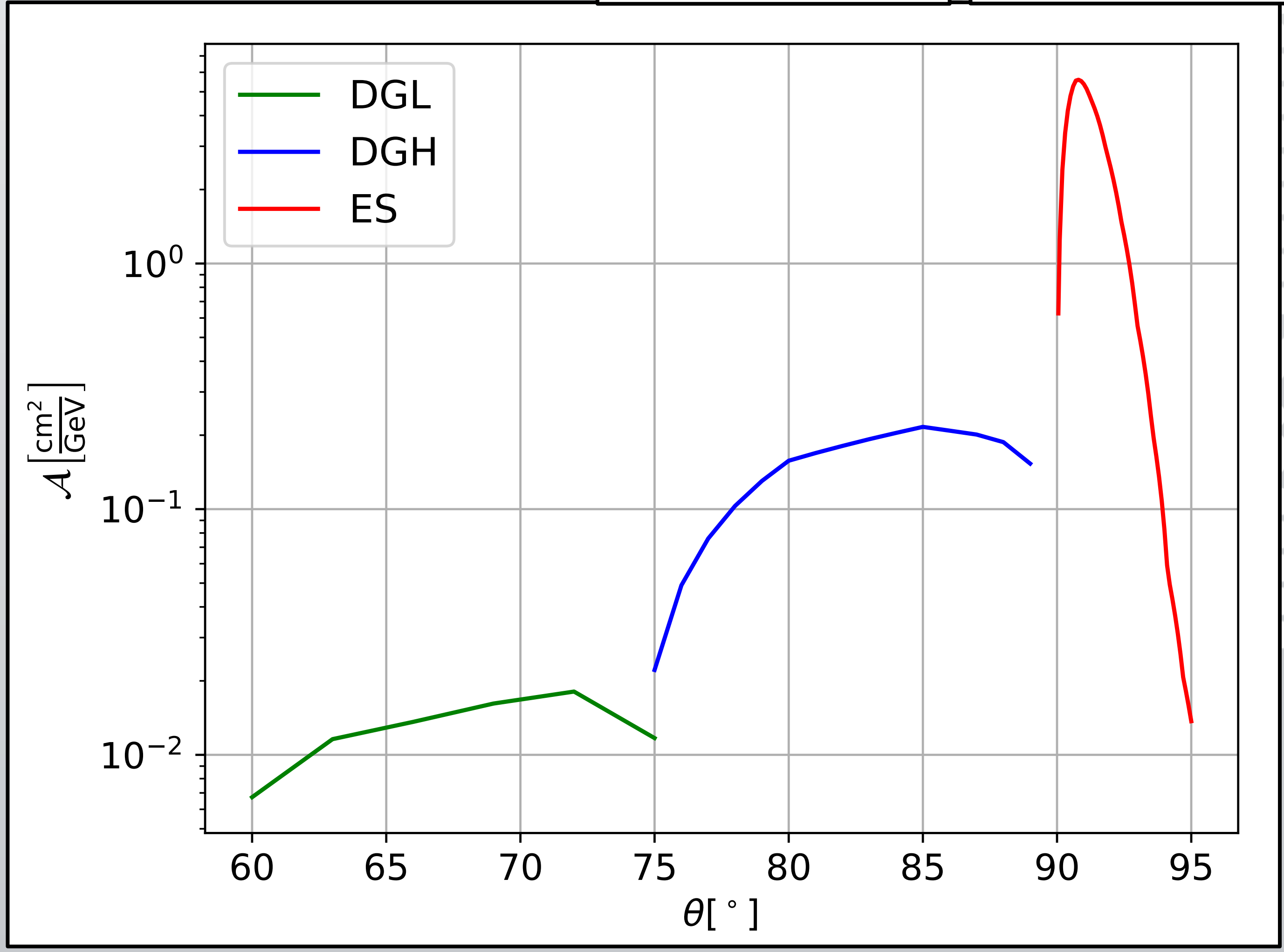

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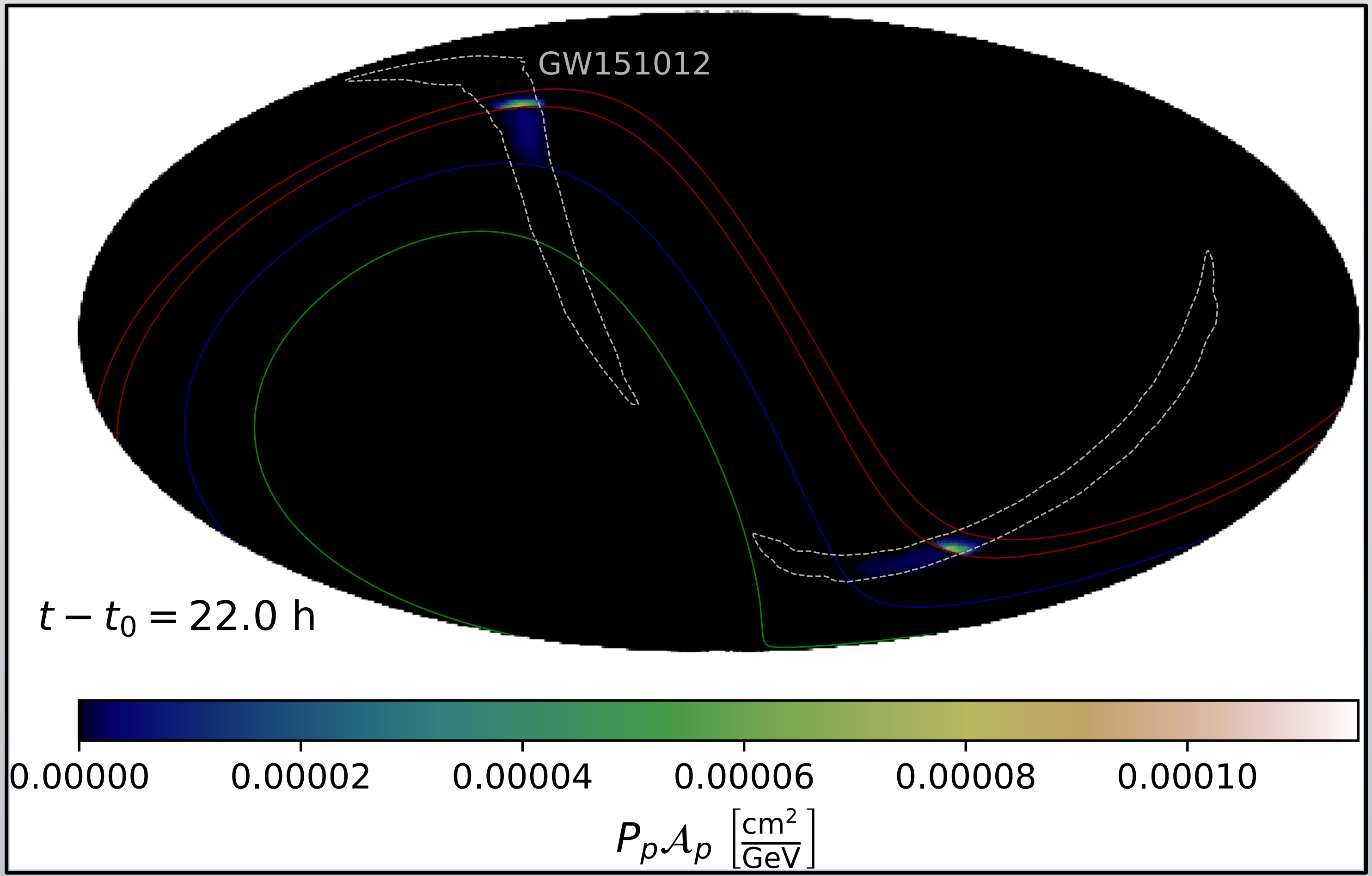

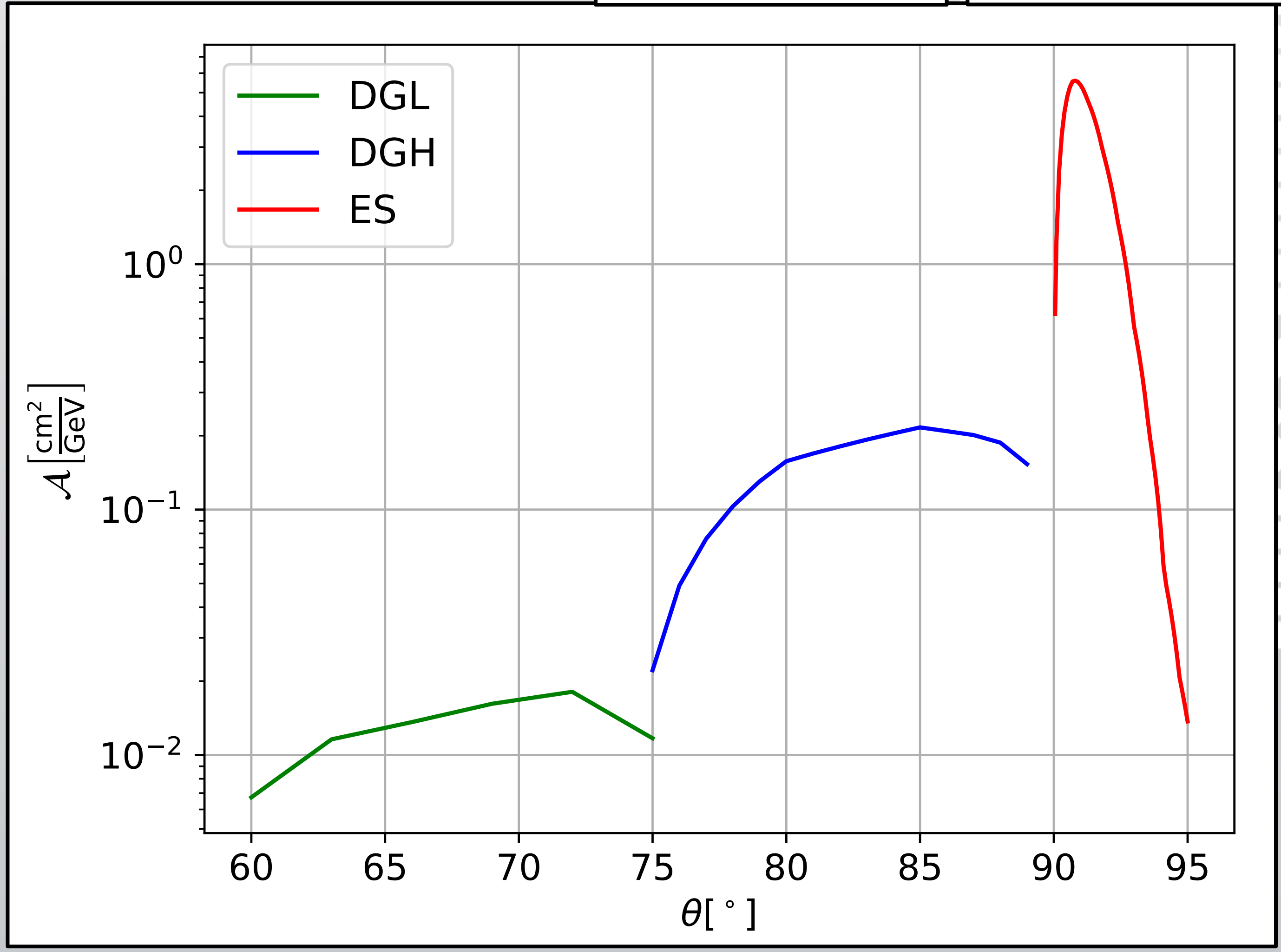

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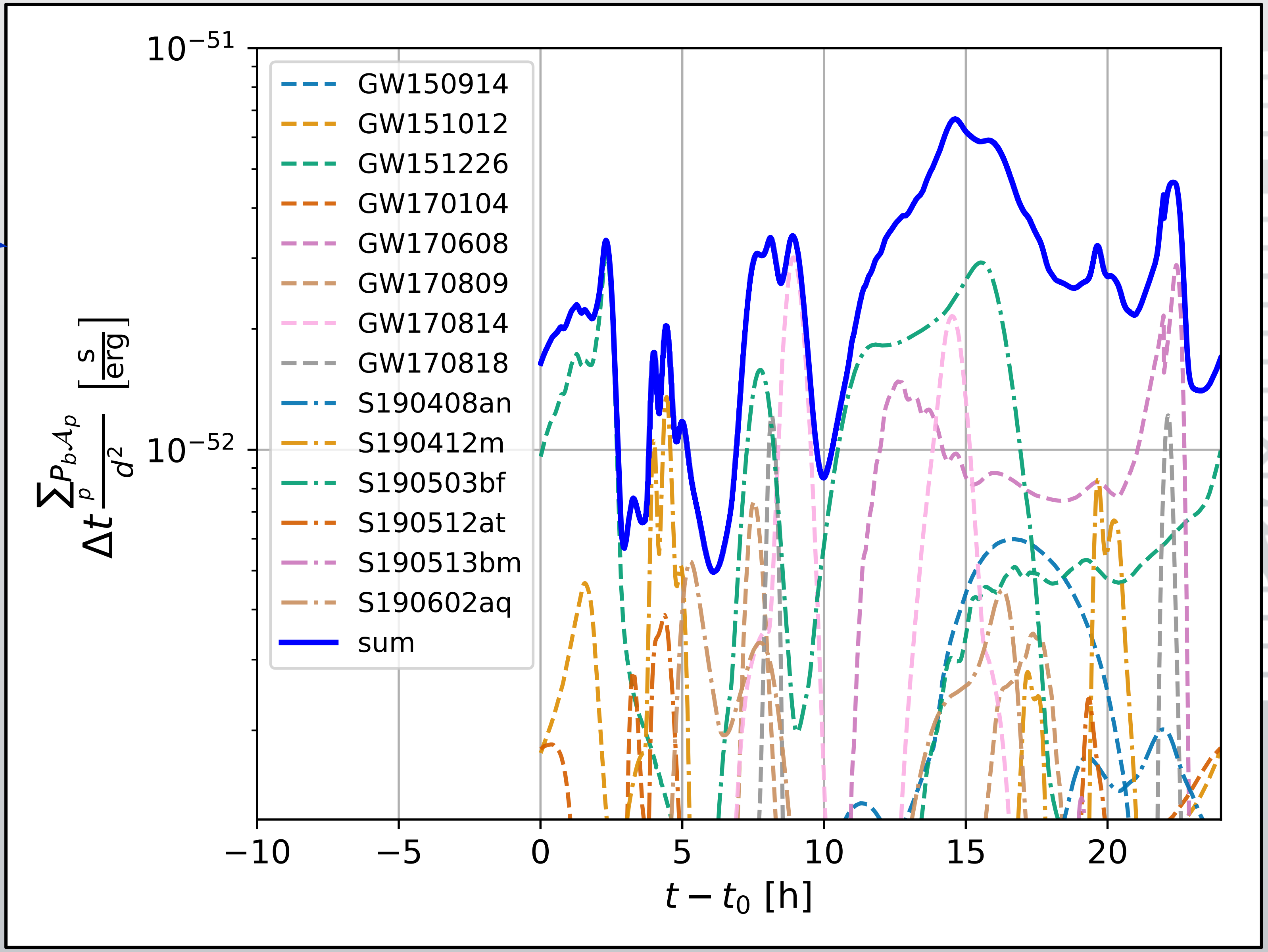


“Number of neutrinos per time bin per luminosity”

Alternating domination by different sources

Combining BBH mergers—Luminosity limit

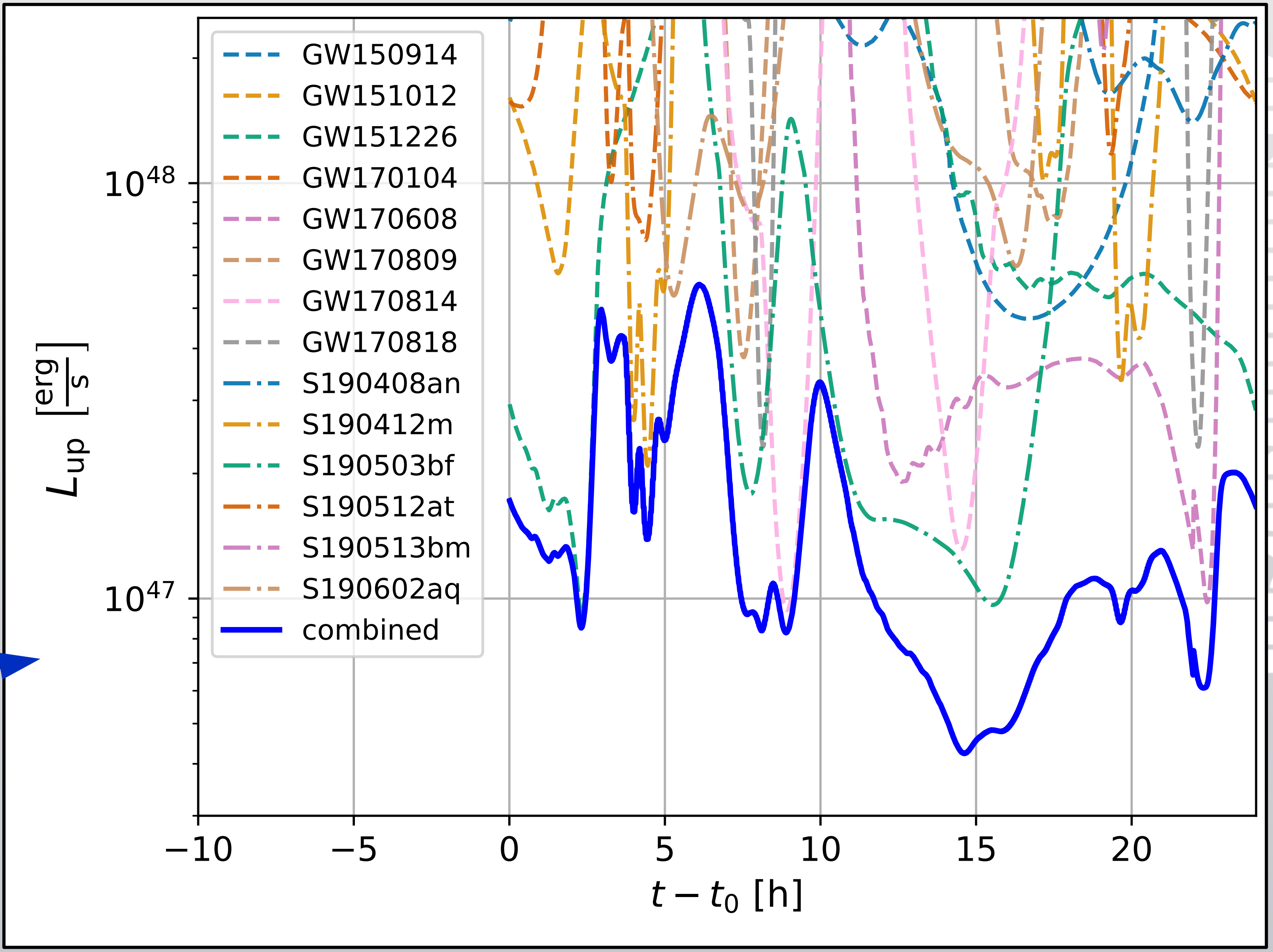
PoS(ICRC2019)415

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

No neutrinos observed during 24 h after any merger: **90 % CL upper limit on L_i**

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

$$\Rightarrow L_{\mathrm{up},i} = \frac{2.44}{86400\ \mathrm{s}} \left(\sum_s \frac{\sum_p P_{p,s} A_{p,s,i}}{d_s^2} \right)^{-1}$$



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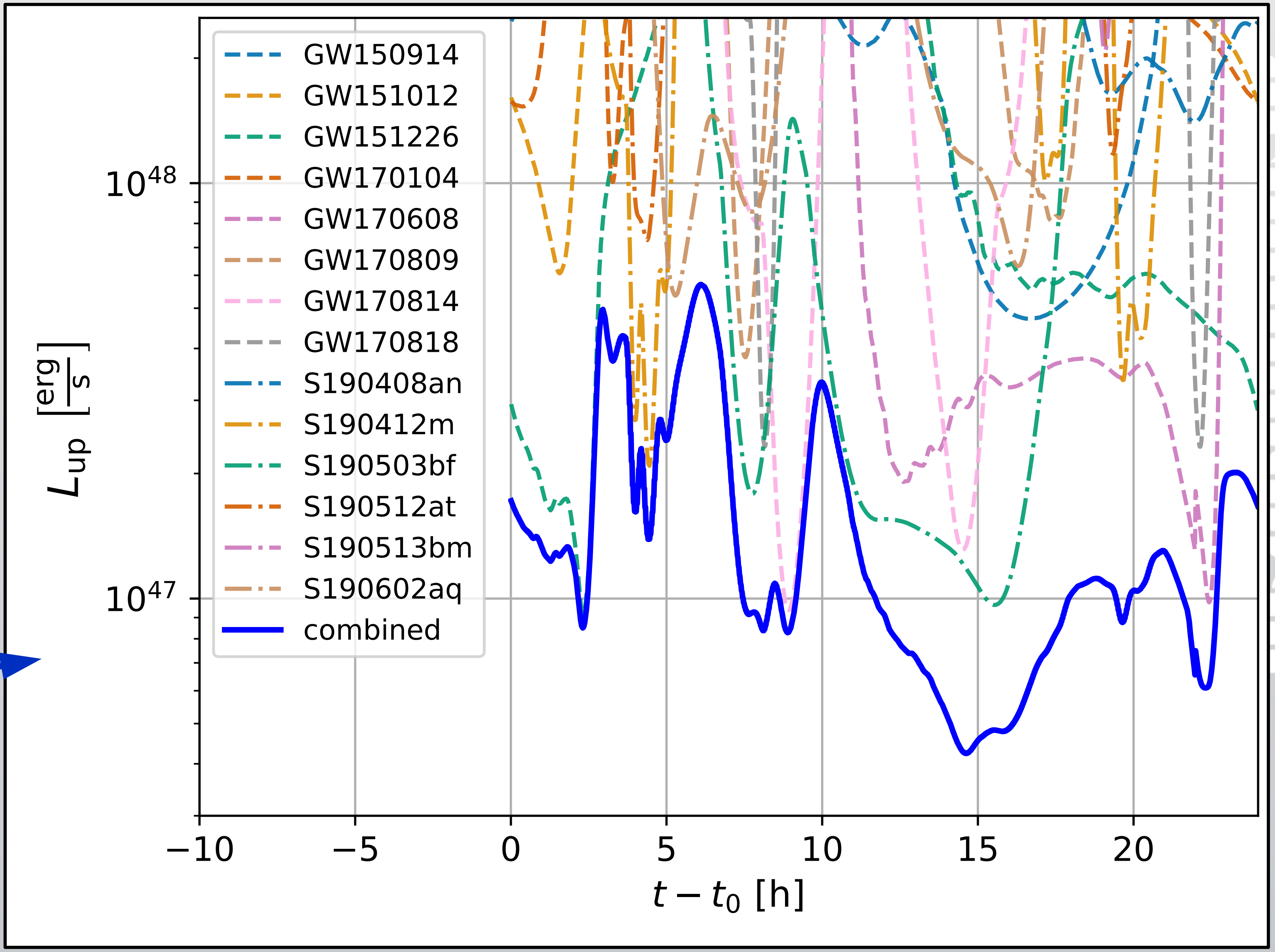
Combining BBH mergers—Luminosity limit

PoS(ICRC2019)415

Sum over all $L_{\mathrm{up},i} \cdot \Delta t$

- $E_{\mathrm{up}} = 1.35 \cdot 10^{52}$ **erg**

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



Conclusions

Conclusions

- Moving field of view of the Pierre Auger Observatory → strong enhancement of UHE neutrino sensitivity in certain directions → Chance for transient follow up

- UHE neutrino follow-up searches performed for LIGO/Virgo BBH mergers
- Method for **combining all sources** making simple assumptions

- Sensitive to neutrino luminosities below $\mathbf{5 \cdot 10^{46}}$ **erg/s** for certain periods during 1-day follow-up searches
- Overall limit on emitted UHE neutrino energy per source: $\mathbf{1.35 \cdot 10^{52}}$ **erg**

- **Stay tuned for new results this year! >60 sources, full "4D" GW information**

The End

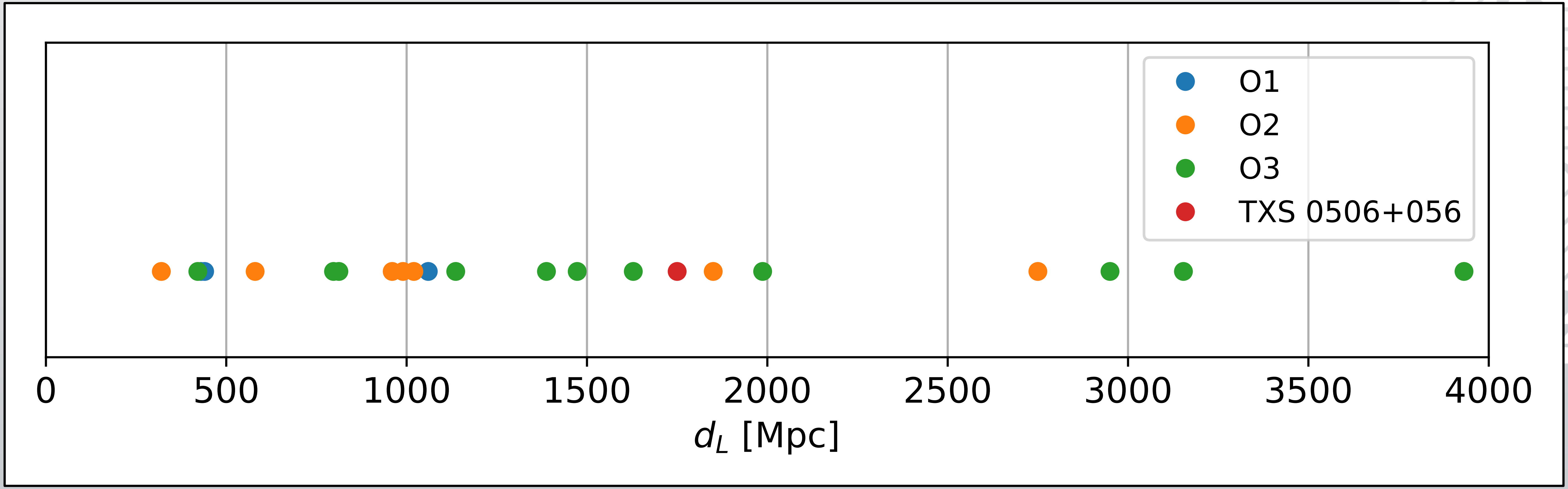
Follow-up of GW events O3

- 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

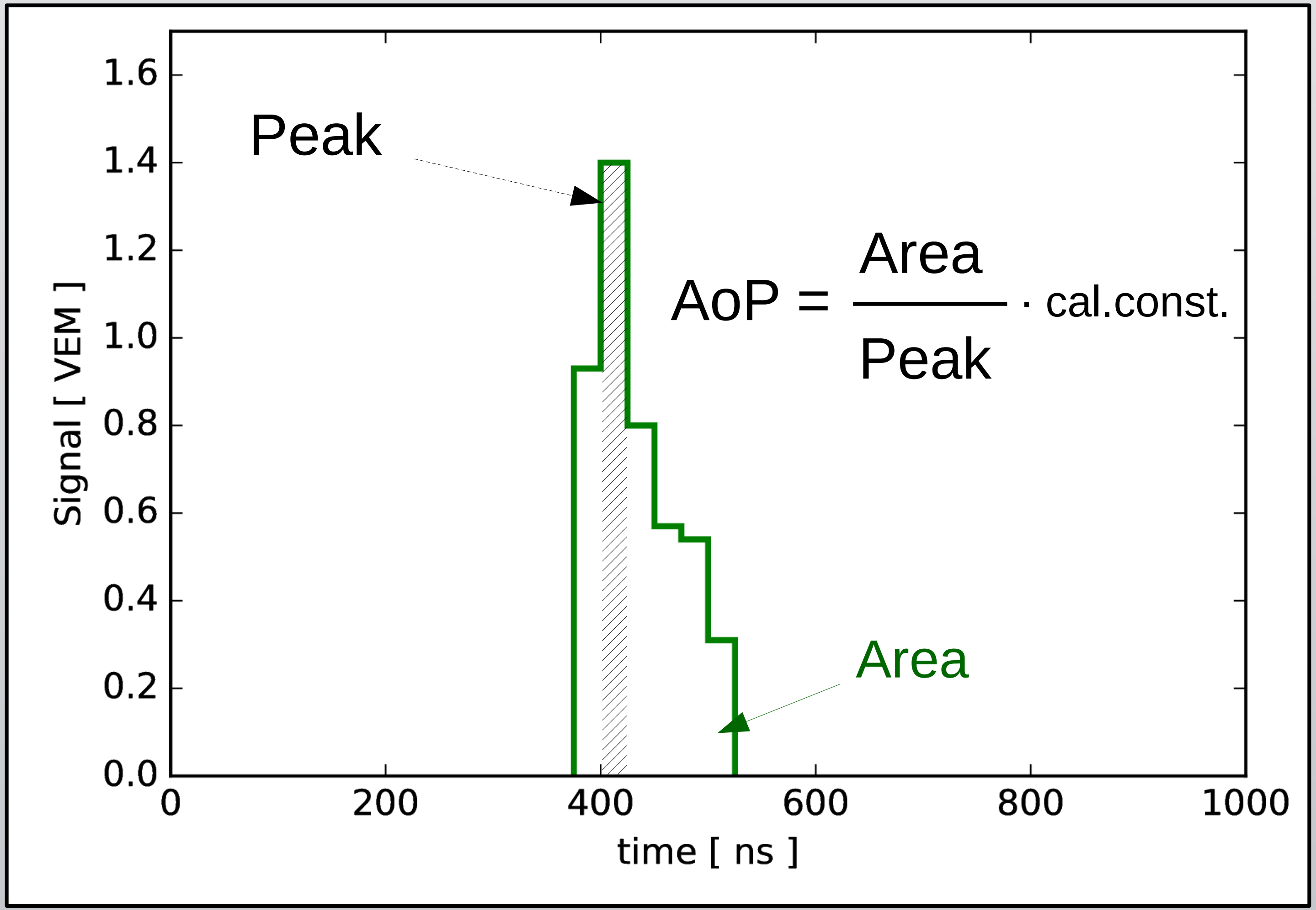
- O3 runs since April 2019 with increased sensitivity
  - Increased rates / horizon / source volume
- + possibly NS-BH mergers

Source Distances



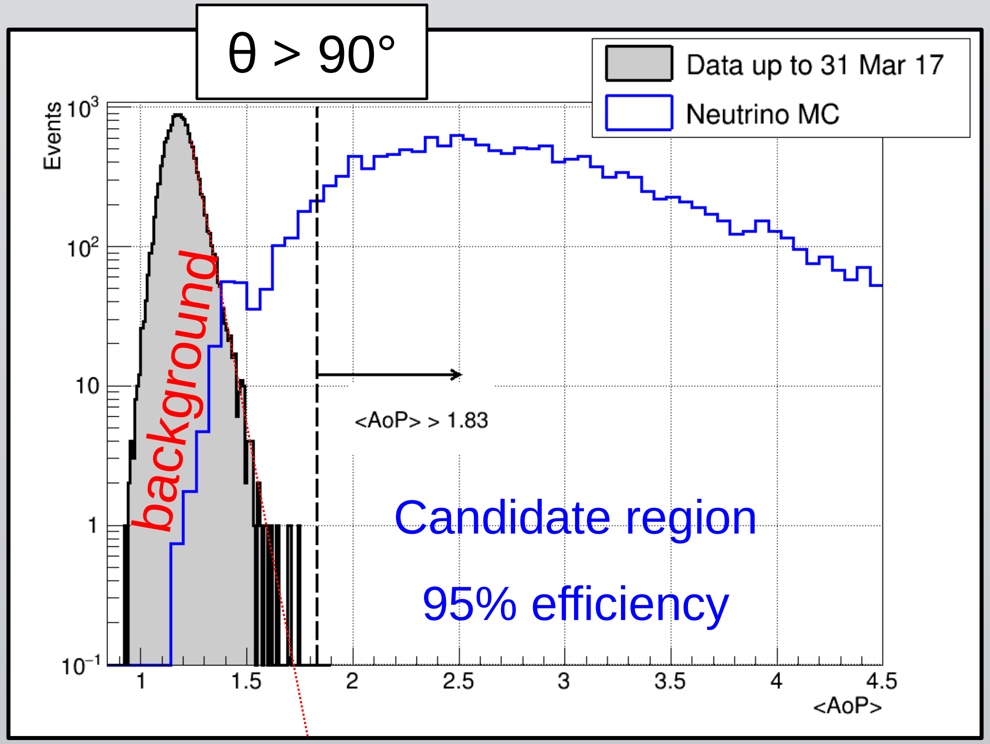
Neutrino search and identification

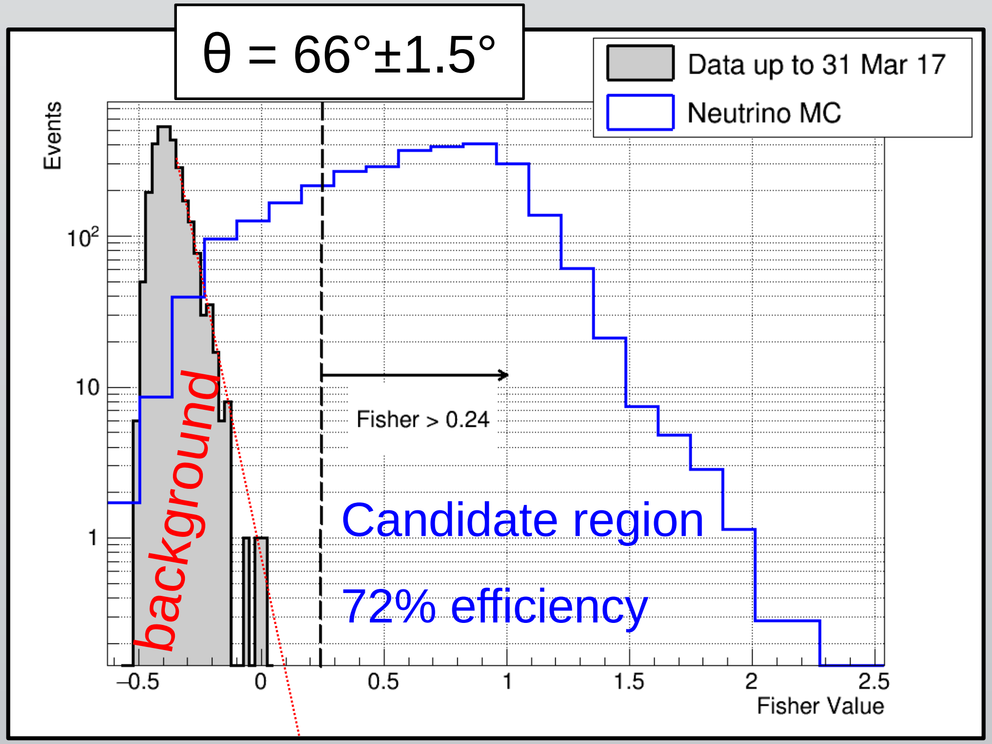
- Pre-select **inclined** and **young** showers
- Neutrino **identification** by zenith-dependent event classification
- Crucial variable: **Area over Peak (AoP)**



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"

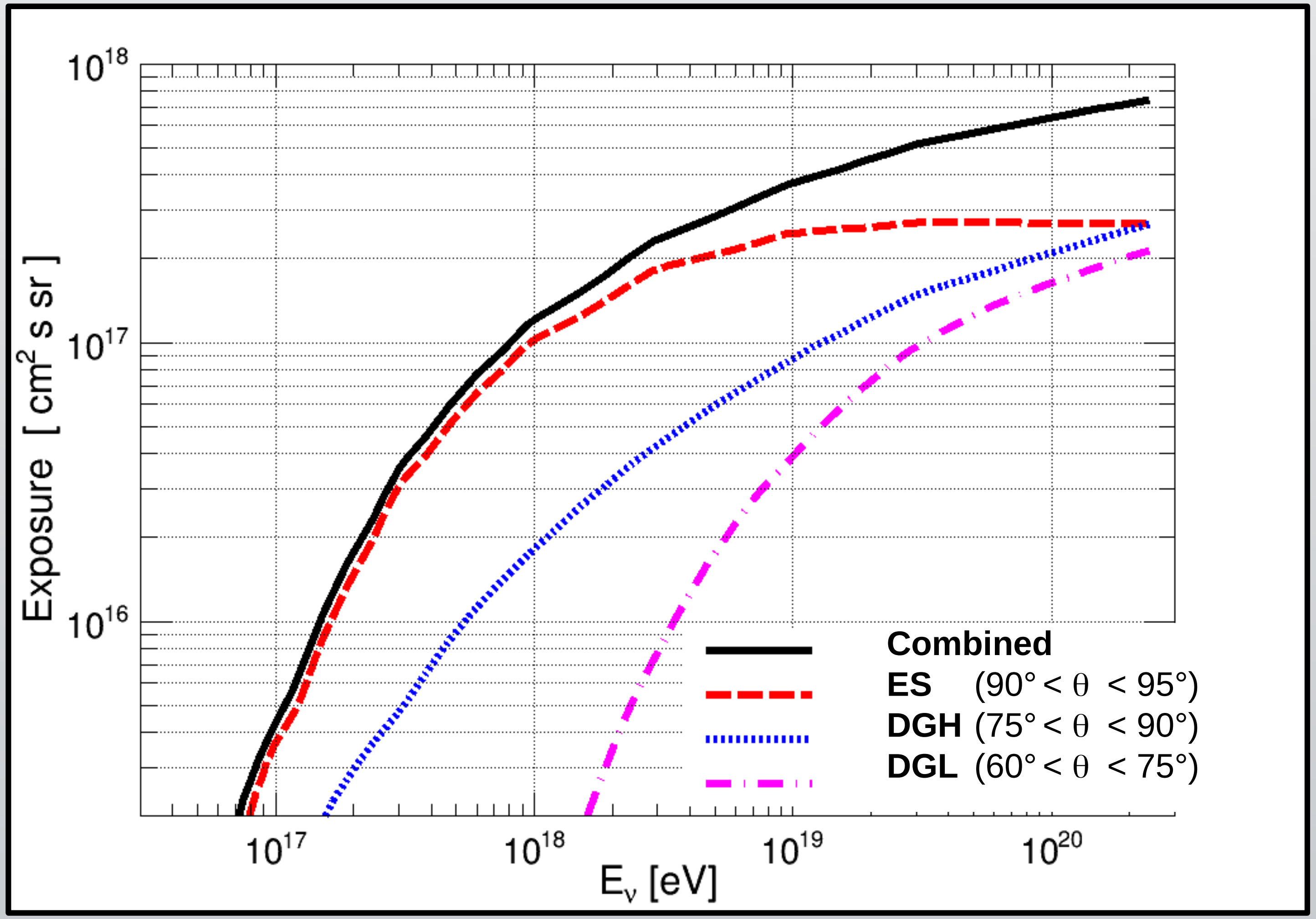




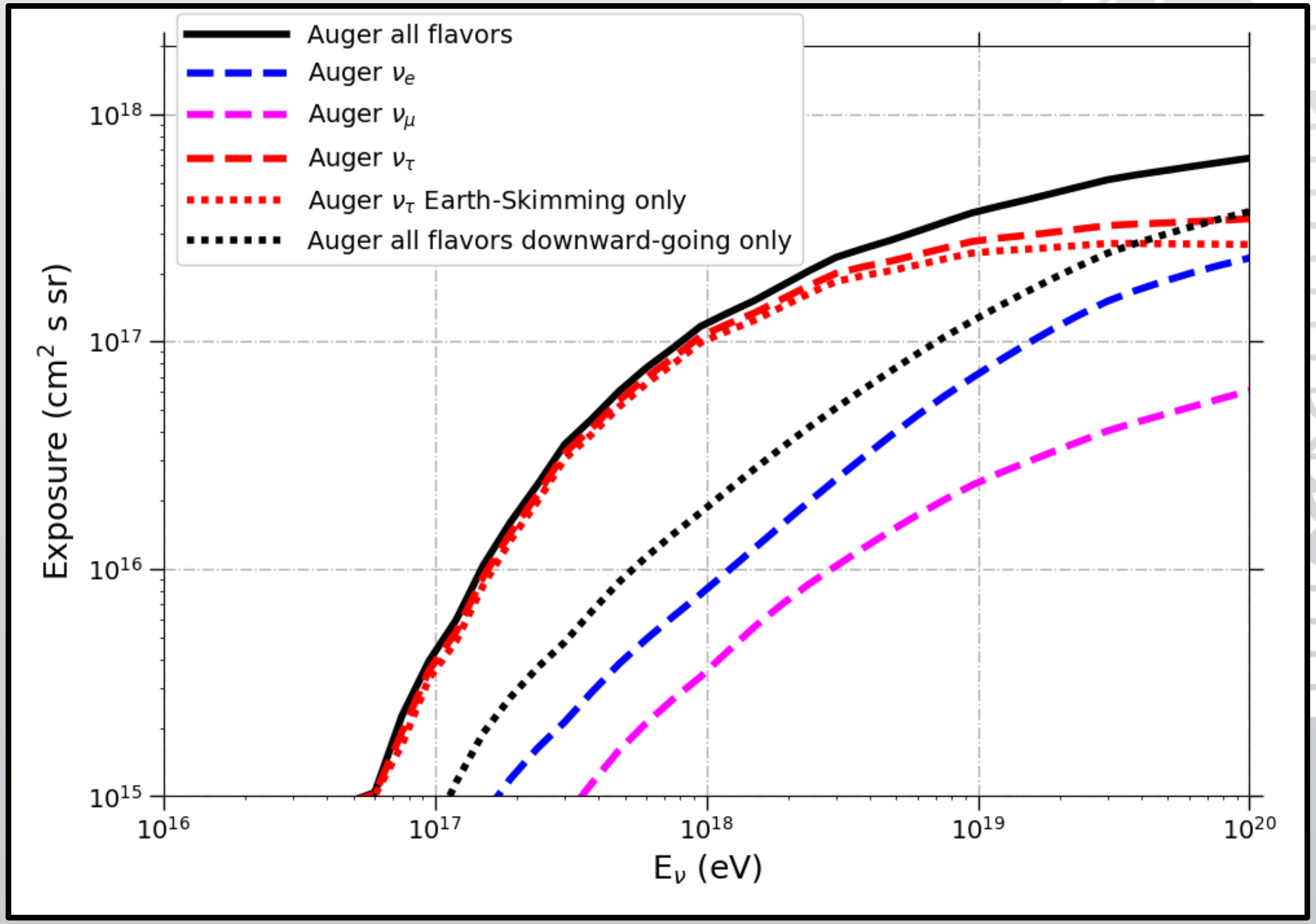
No candidates so far

Neutrino exposure

By direction

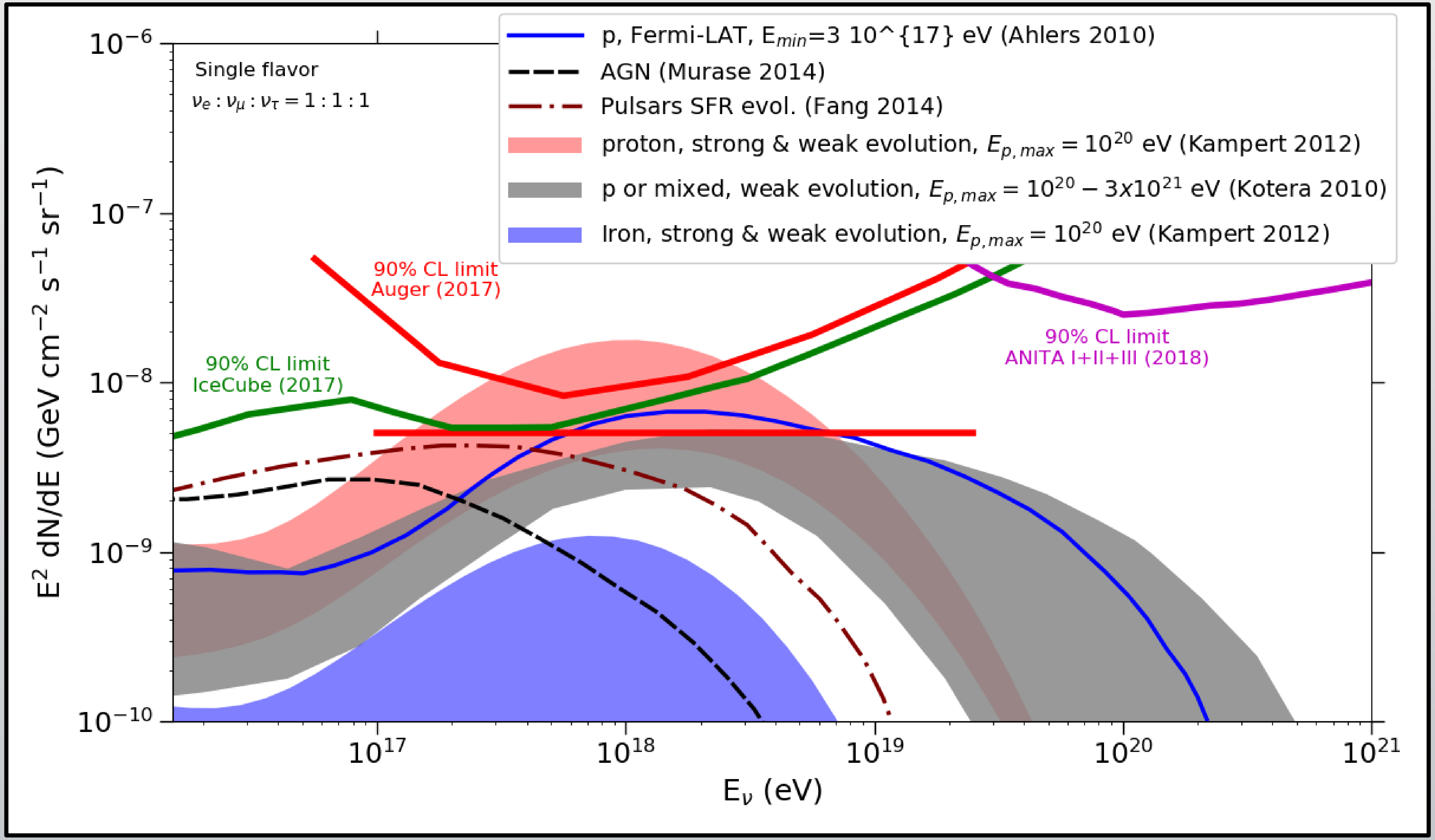


By flavor

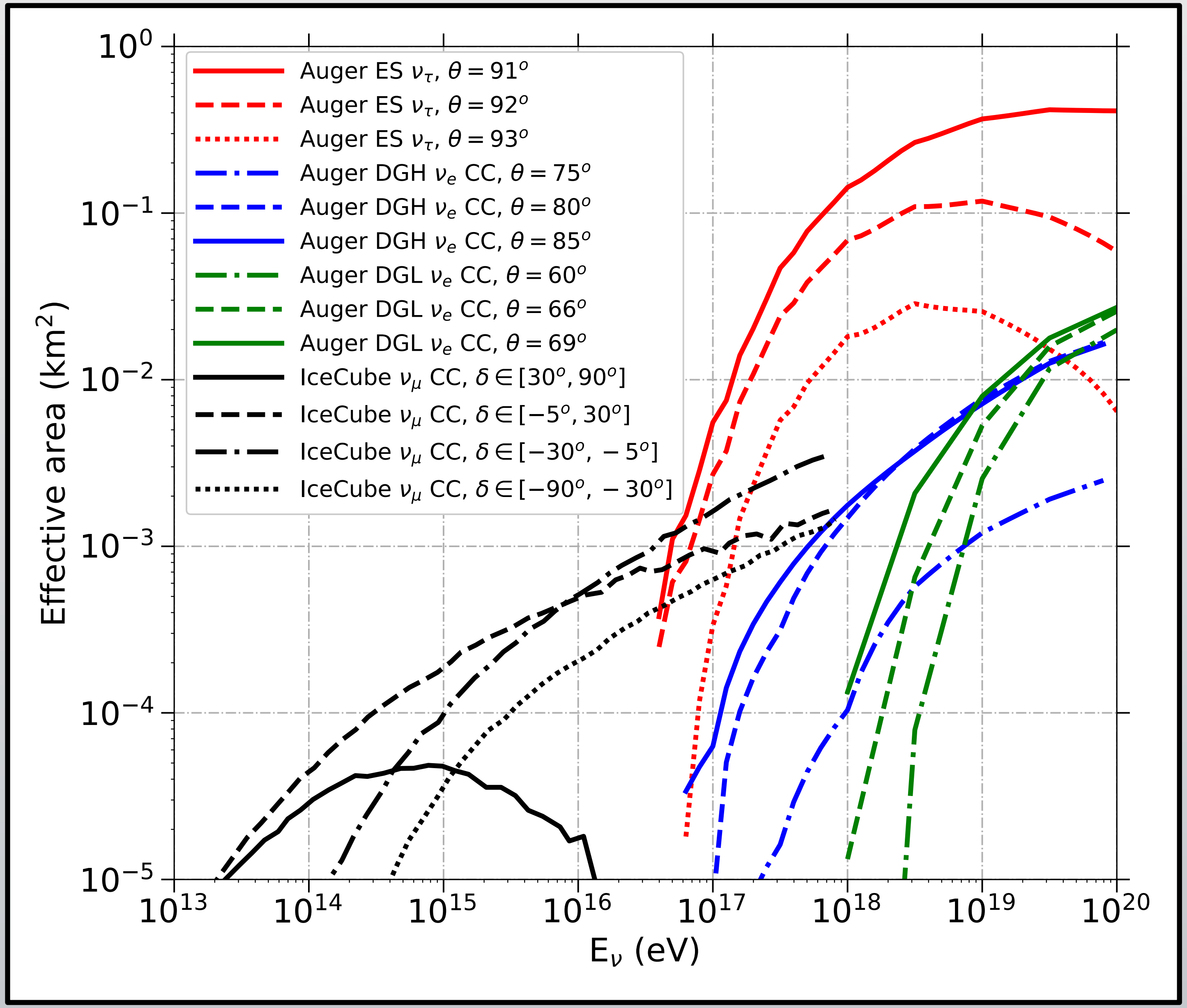


Enrique Zas, ICRC 2017

Limits on diffuse neutrino flux



Effective area



Follow-ups of O1+O2 GW events

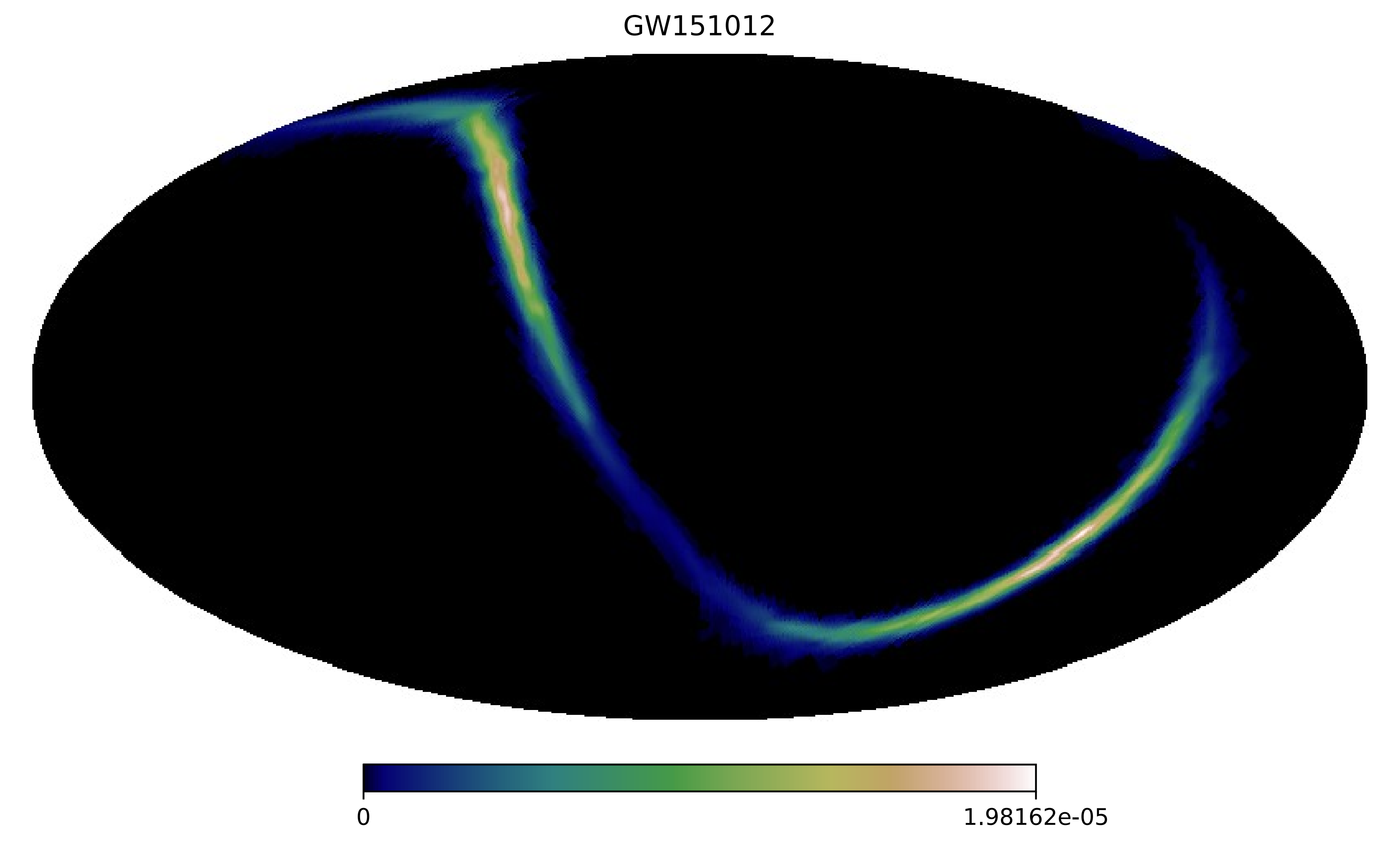
LIGO/Virgo O1+O2: MoU between Auger and LVC:

Default neutrino search, considering only

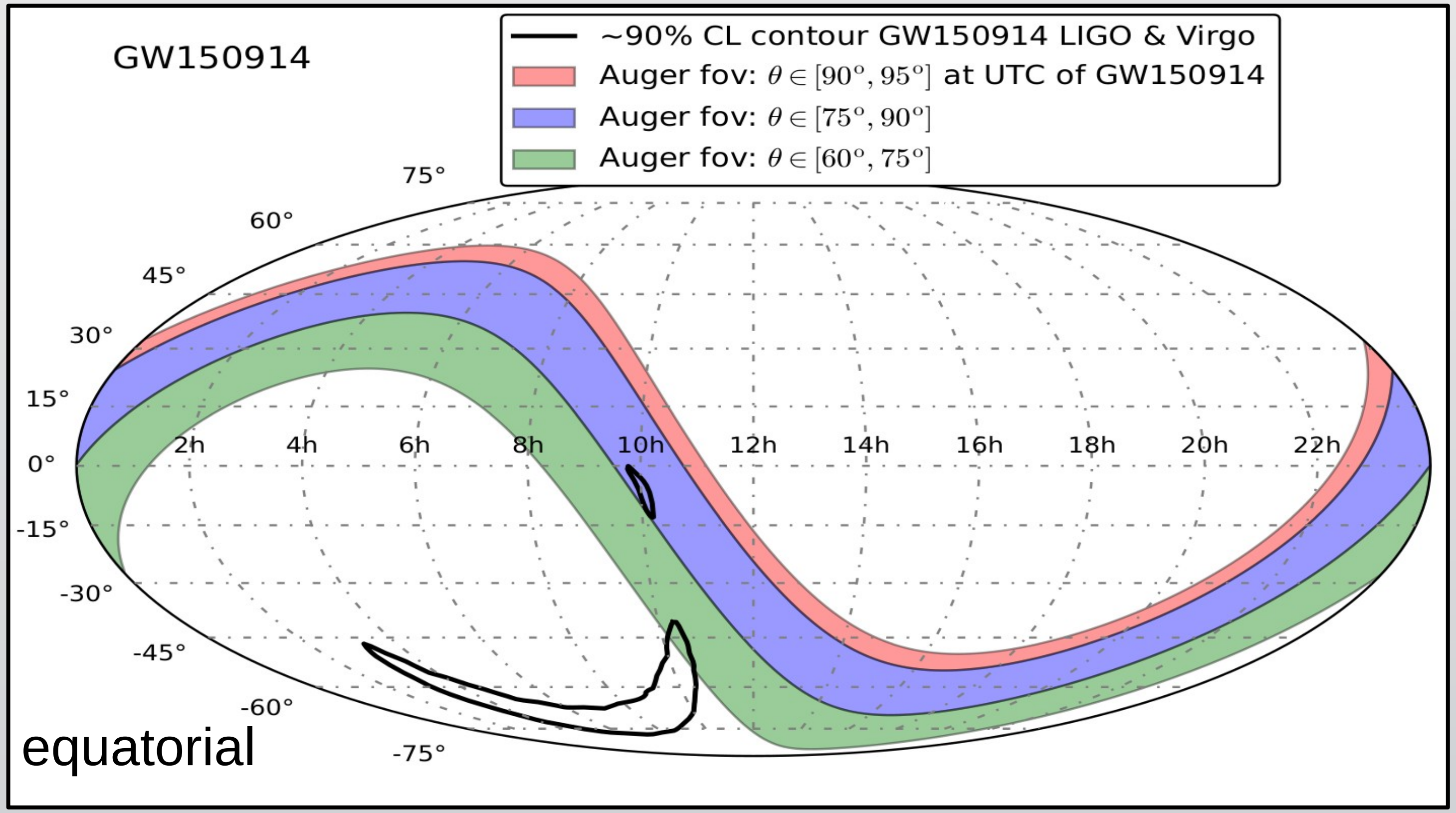
- ±500 s around & +1 day after GW event
- Times at which location of the GW event is visible

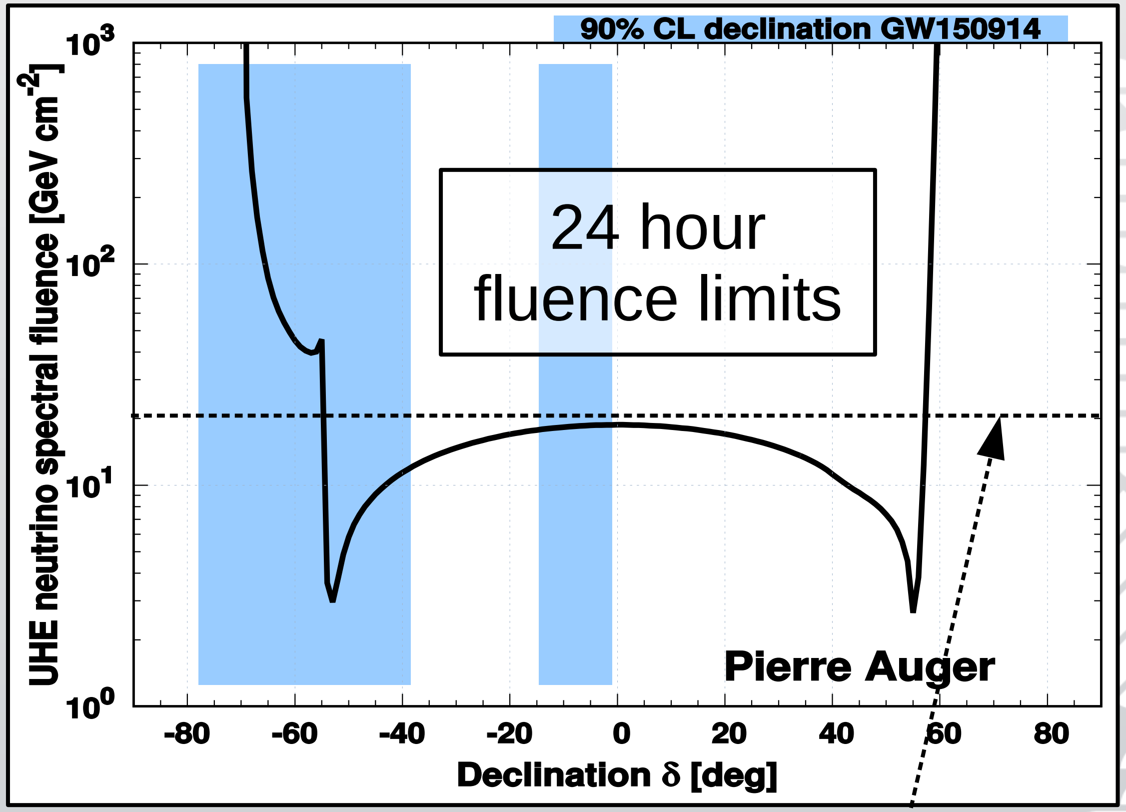
BNS merger GW170817: ±500 s & 14 day period after the event

Follow-ups of O1+O2 GW events



Follow-Up of BBH merger GW150914





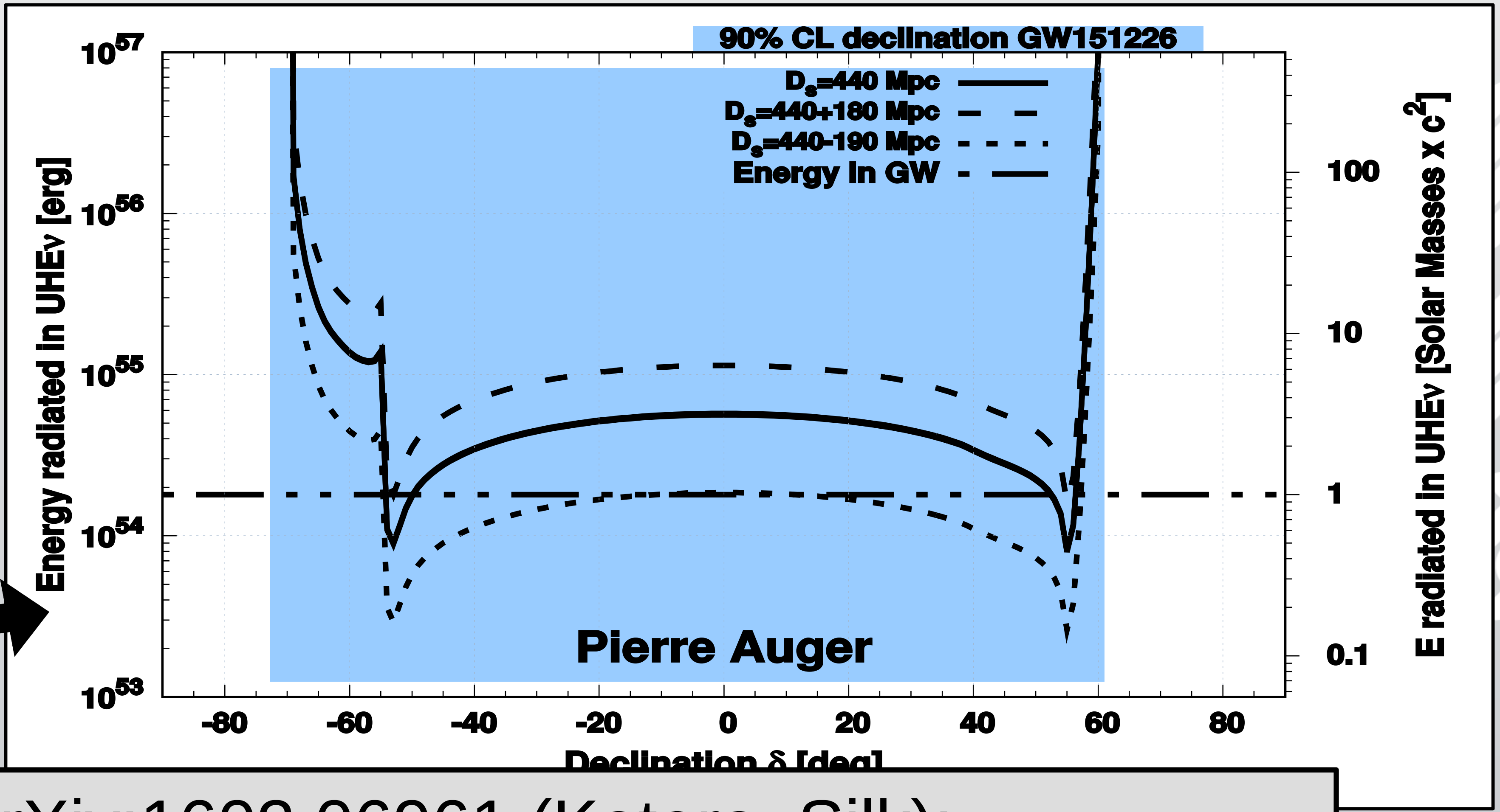
UHE neutrino sensitivity declination dependent

Newer events: More GW detectors
➔ improved localization by triangulation

total neutrino energy =
emitted GW energy

GW151226 Follow-Up—Results

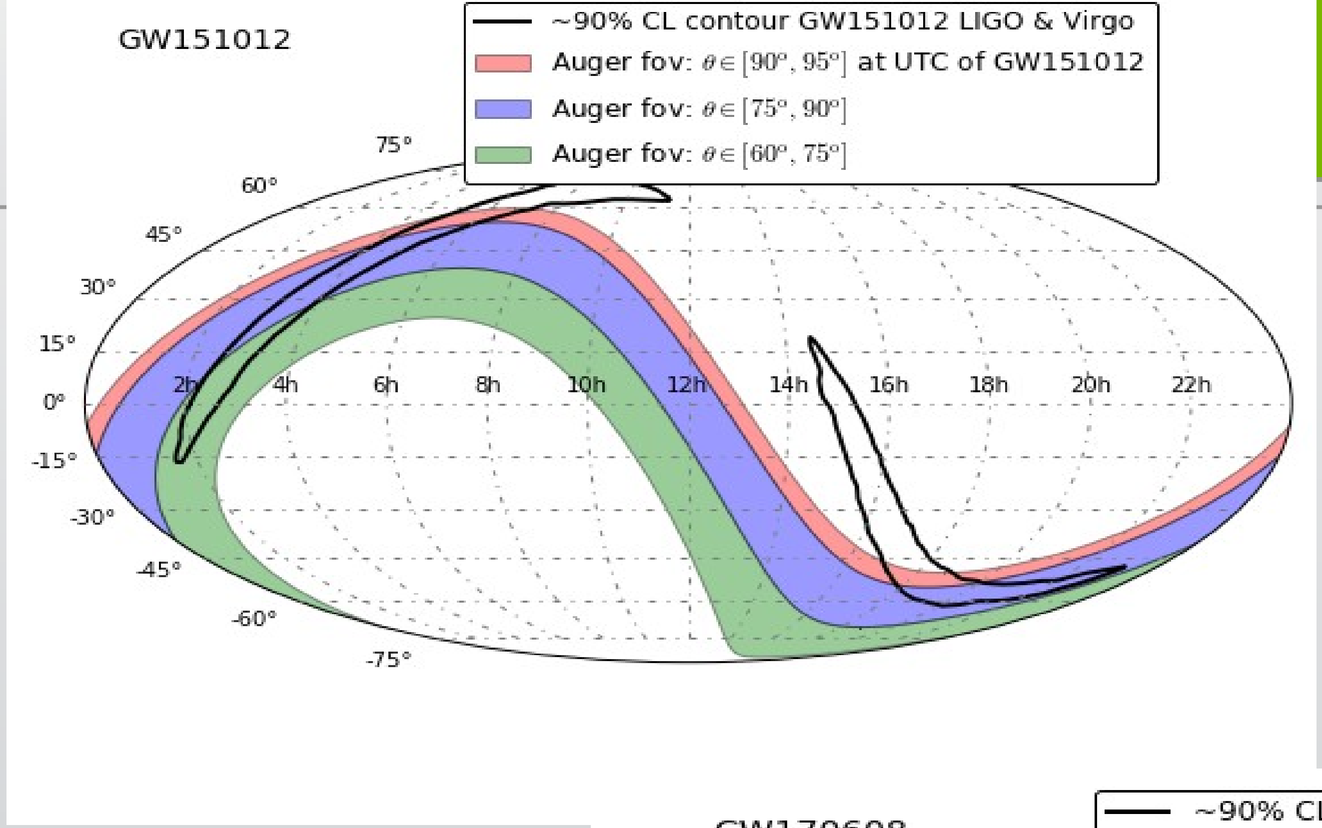
No candidates
→Flux limit
→Limit on total emitted UHE ν energy

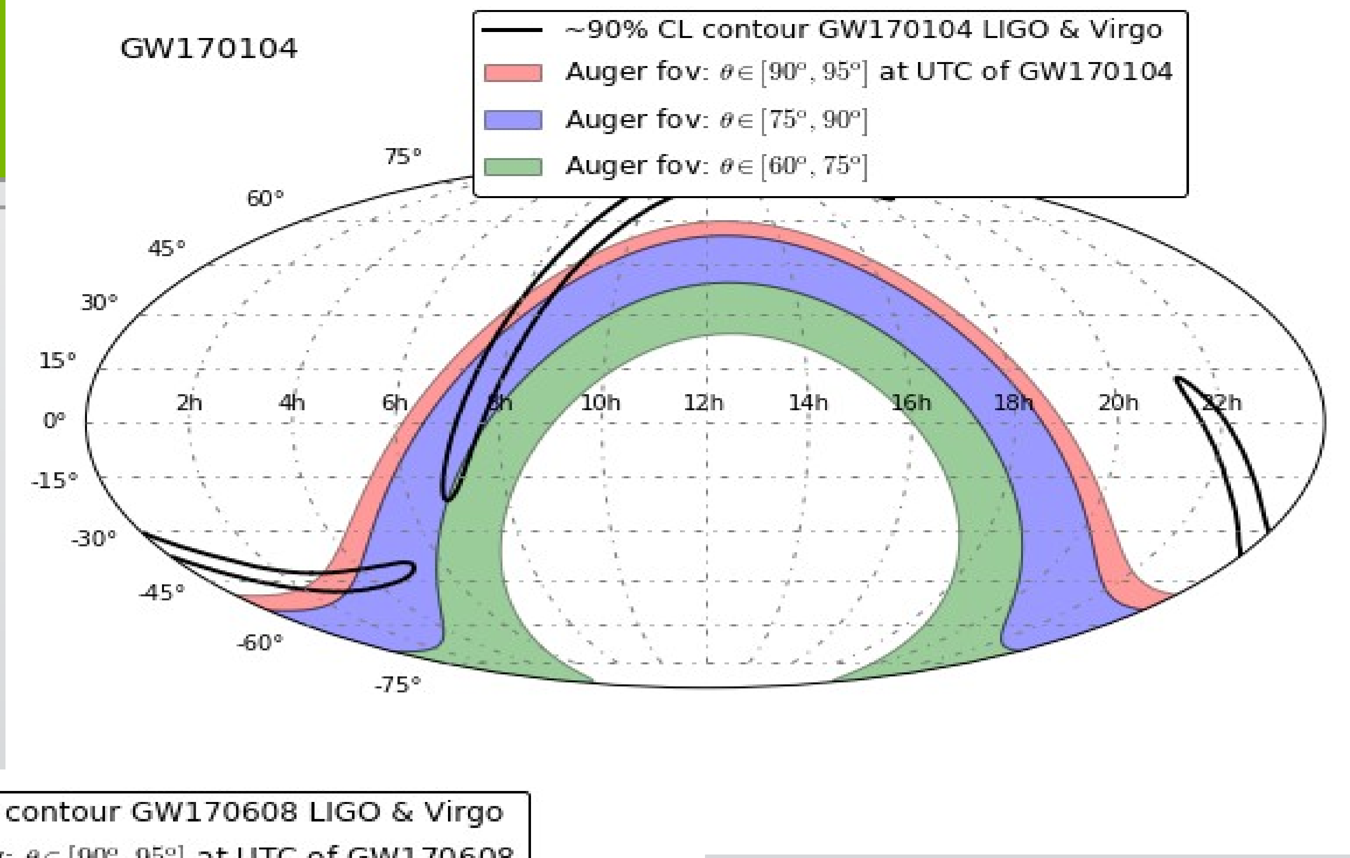


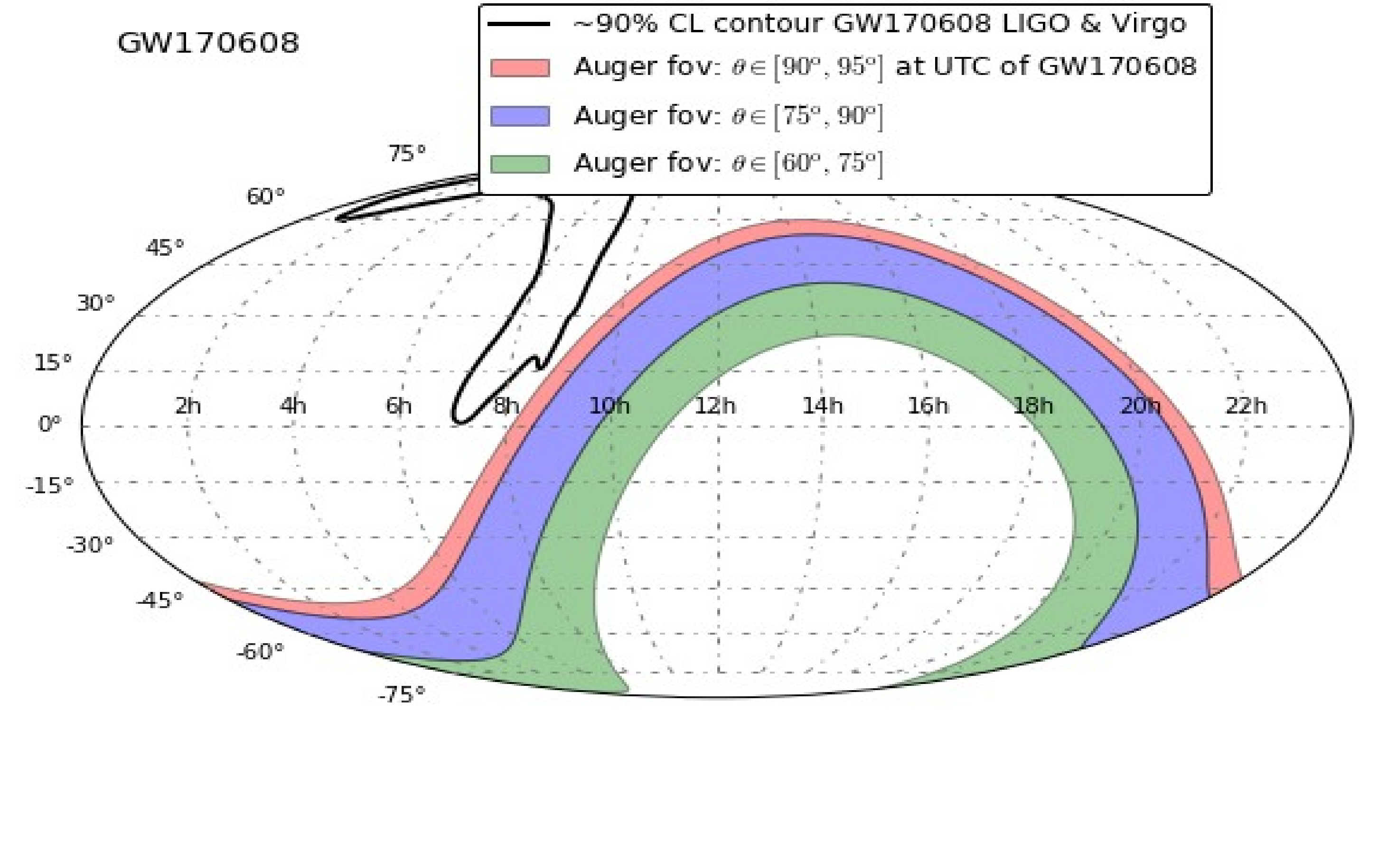
arXiv:1602.06961 (Kotera, Silk):
Binary BHs could produce the measured UHECR flux!
→Needs ~ 3% “efficiency” (E_{UHECR}/E_{GW})

Systematic uncertainties (PRD 91 092008)

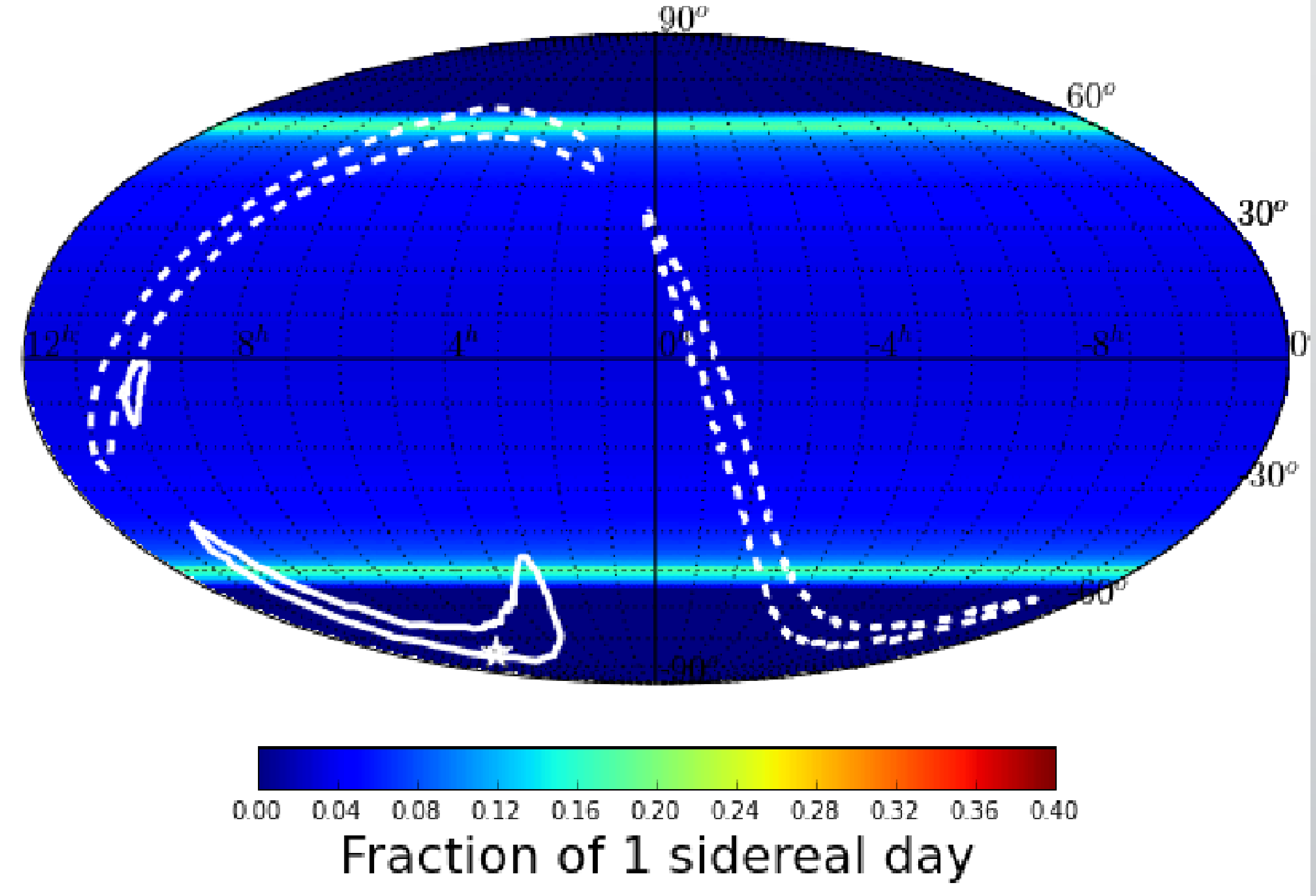
Source of systematic	Combined uncertainty band
Simulations	$\sim +4\%, -3\%$
ν cross section and τ E-loss	$\sim +34\%, -28\%$
Topography	$\sim +15\%, 0\%$
Total	$\sim +37\%, -28\%$

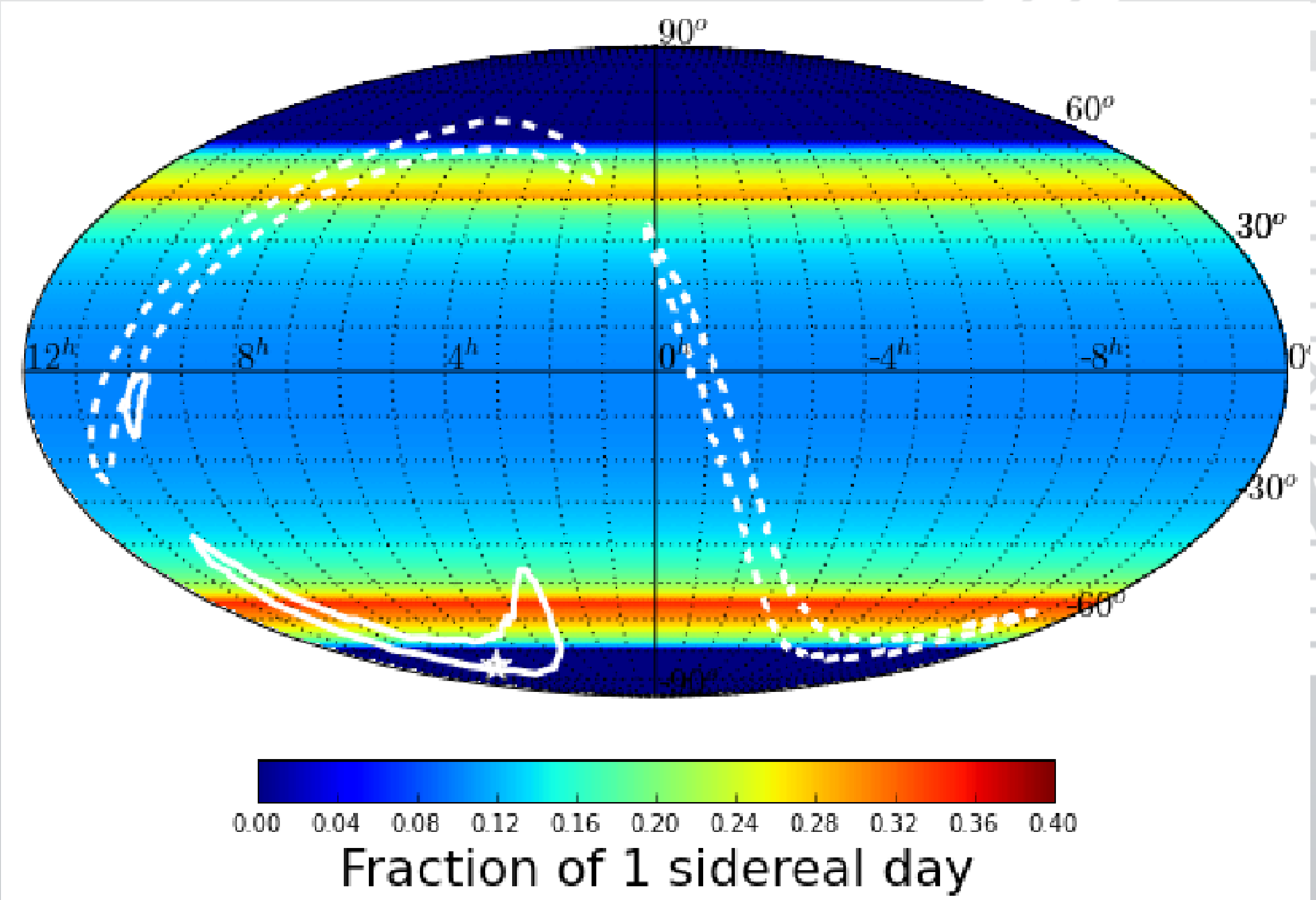

GW151012
~90% CL contour GW151012 LIGO & Virgo
Auger fov: $\theta \in [90^o, 95^o]$ at UTC of GW151012
Auger fov: $\theta \in [75^o, 90^o]$
Auger fov: $\theta \in [60^o, 75^o]$
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h


GW170104
~90% CL contour GW170104 LIGO & Virgo
Auger fov: $\theta \in [90^o, 95^o]$ at UTC of GW170104
Auger fov: $\theta \in [75^o, 90^o]$
Auger fov: $\theta \in [60^o, 75^o]$
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h


GW170608
~90% CL contour GW170608 LIGO & Virgo
Auger fov: $\theta \in [90^o, 95^o]$ at UTC of GW170608
Auger fov: $\theta \in [75^o, 90^o]$
Auger fov: $\theta \in [60^o, 75^o]$
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
2h
4h
6h
8h
10h
12h
14h
16h
18h
20h
22h

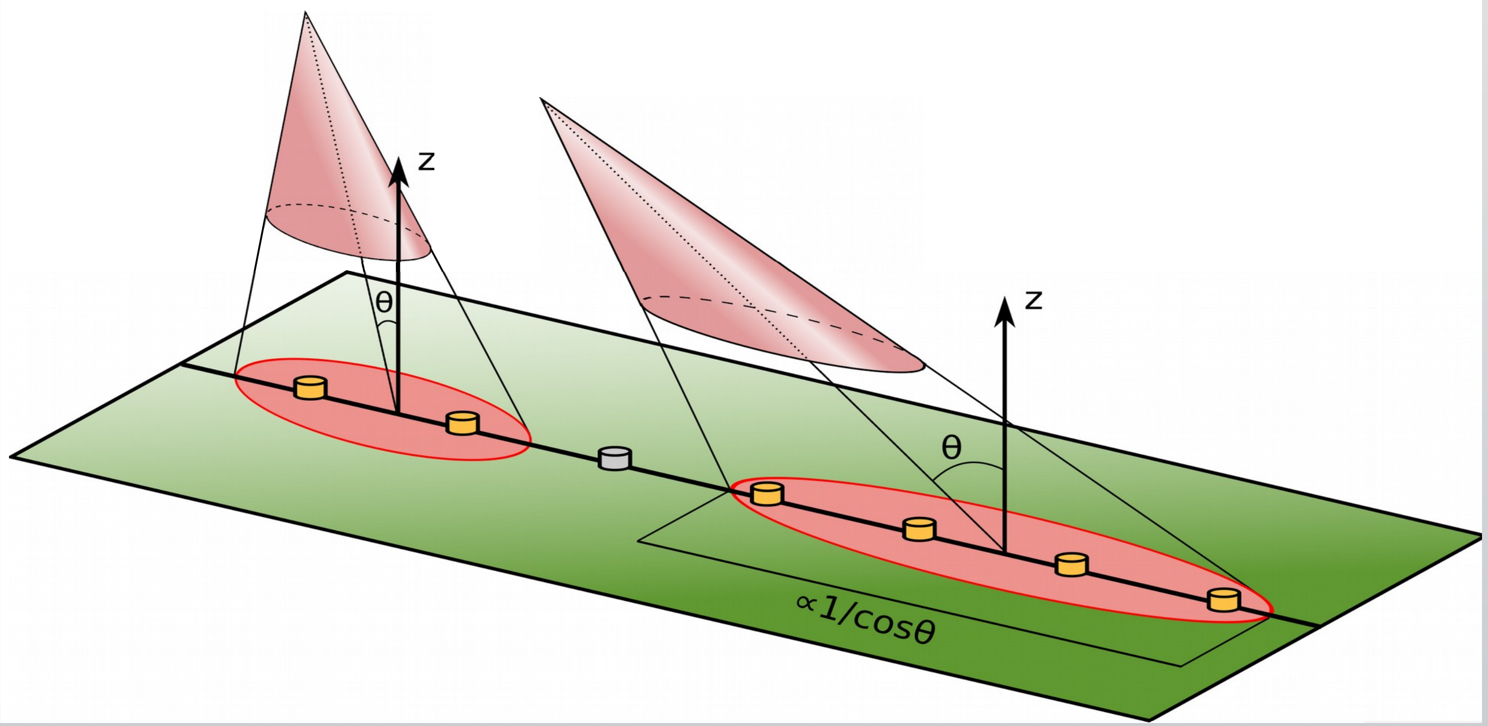
O1 GW Follow-Up



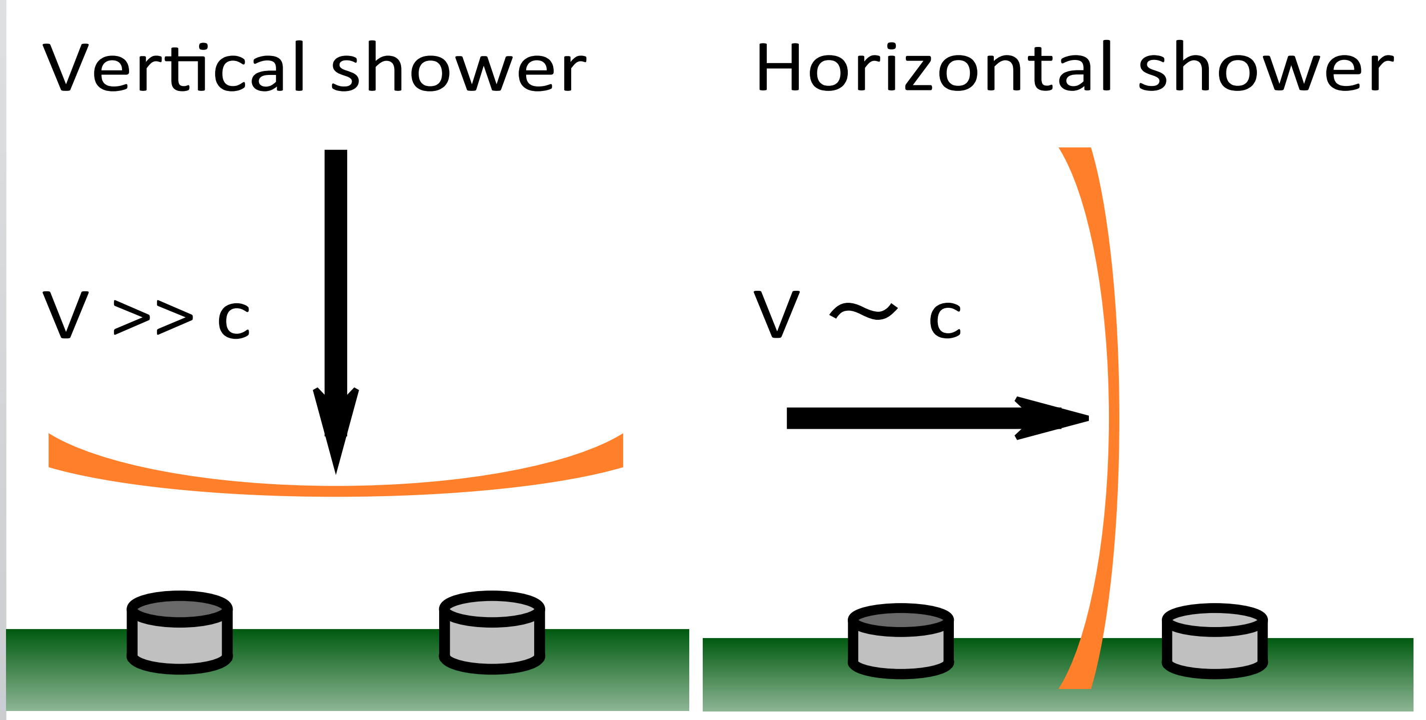


Earth-Skimming ν_τ Selection

Inclination: 90° < θ < 95°
→ elongated footprint

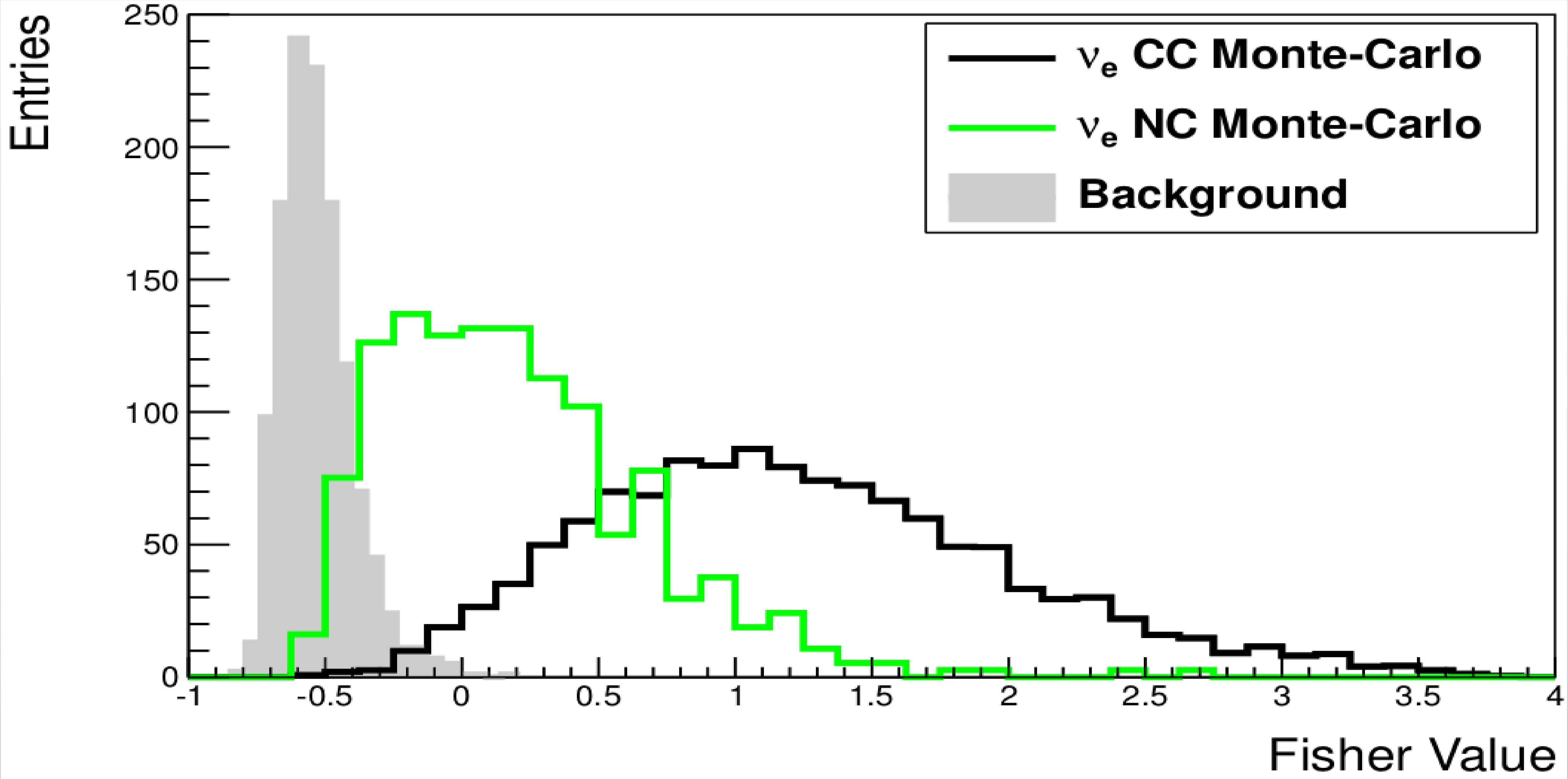


"Ground signal speed" ~ c

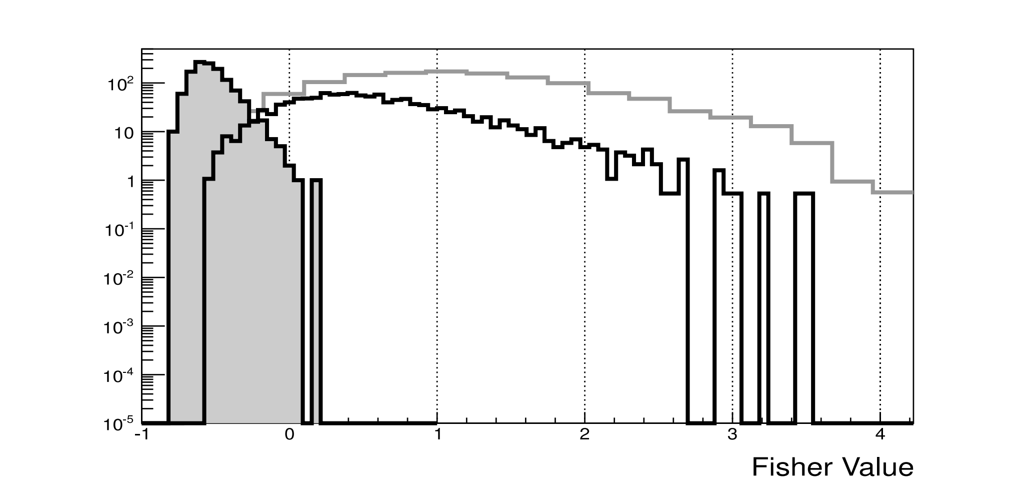


Reject "muonic" events → > 60 % stations ToT triggered

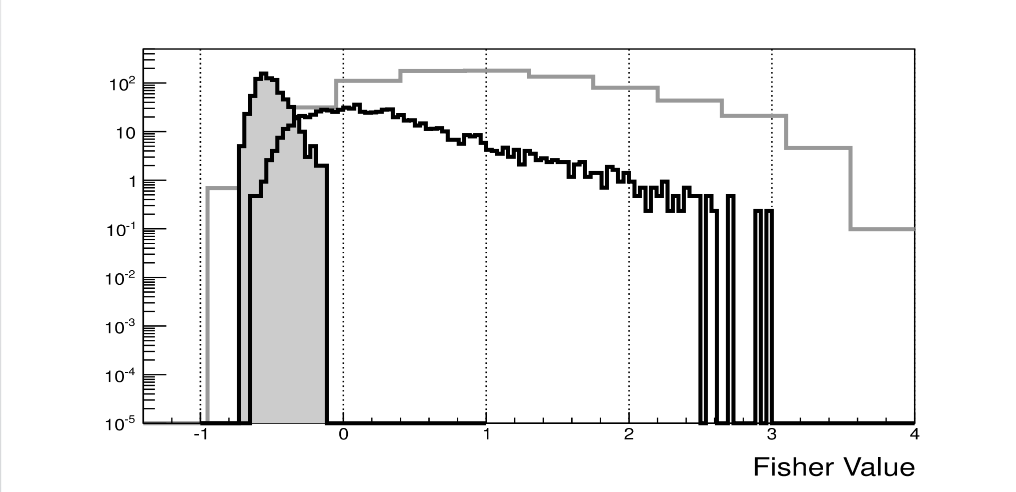
CC vs NC Fisher Values



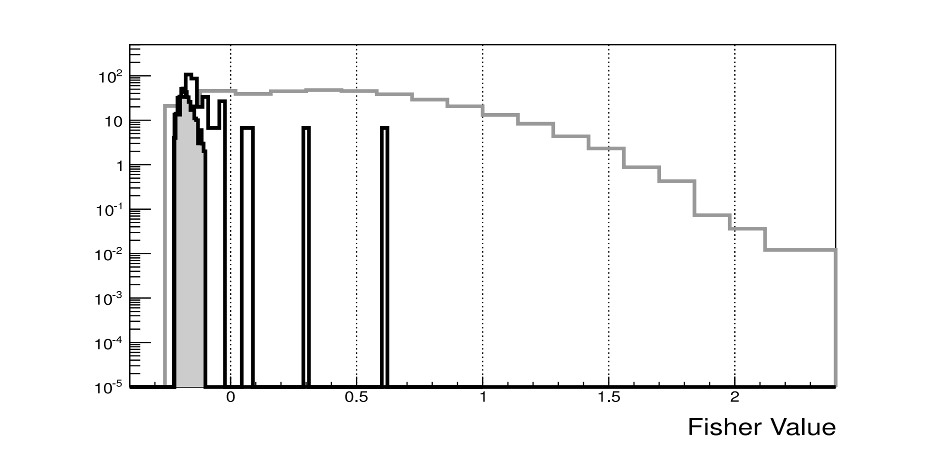
Neutrinos vs. Photons



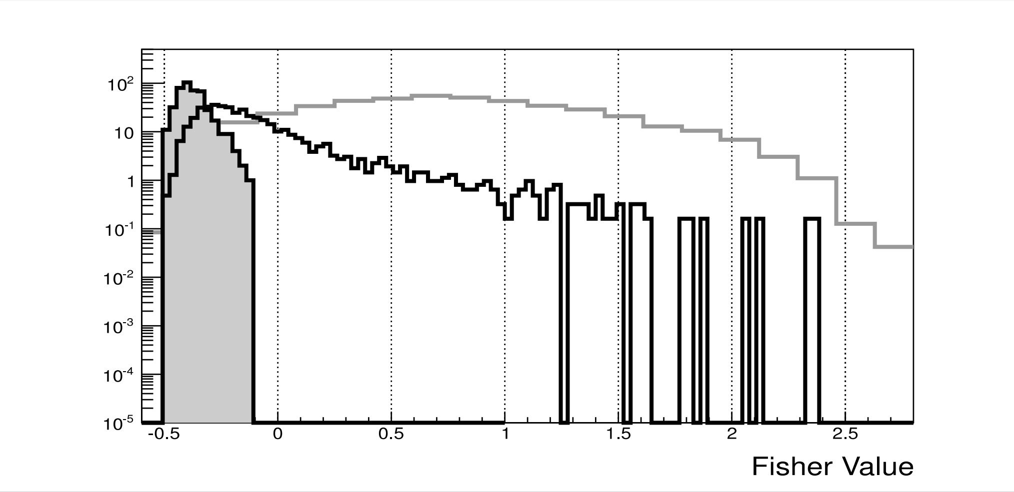
(a) $58.5° < \theta_{\mathrm{Rec}} \leq 61.5°$



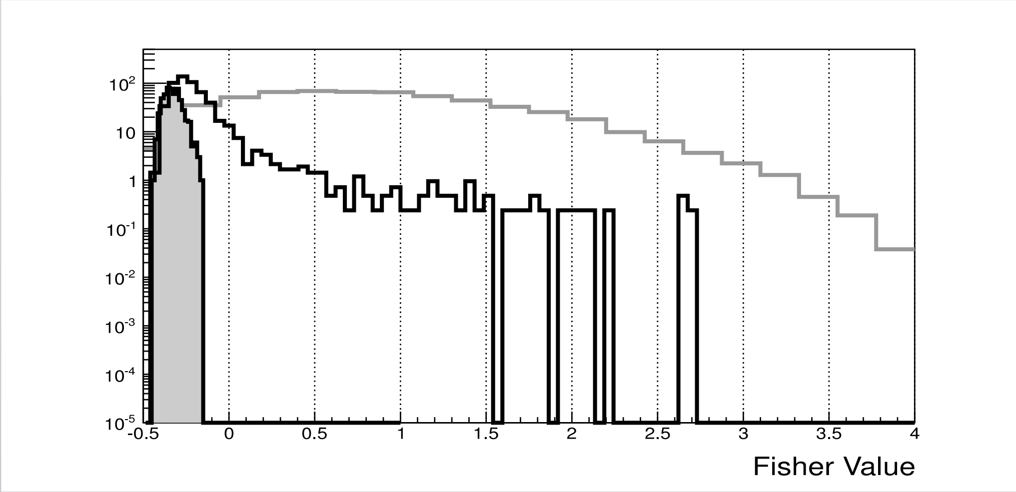
(b) $61.5° < \theta_{\mathrm{Rec}} \leq 64.5°$



(e) $70.5° < \theta_{\mathrm{Rec}} \leq 76.5°$



(c) $64.5° < \theta_{\mathrm{Rec}} \leq 67.5°$



(d) $67.5° < \theta_{\mathrm{Rec}} \leq 70.5°$