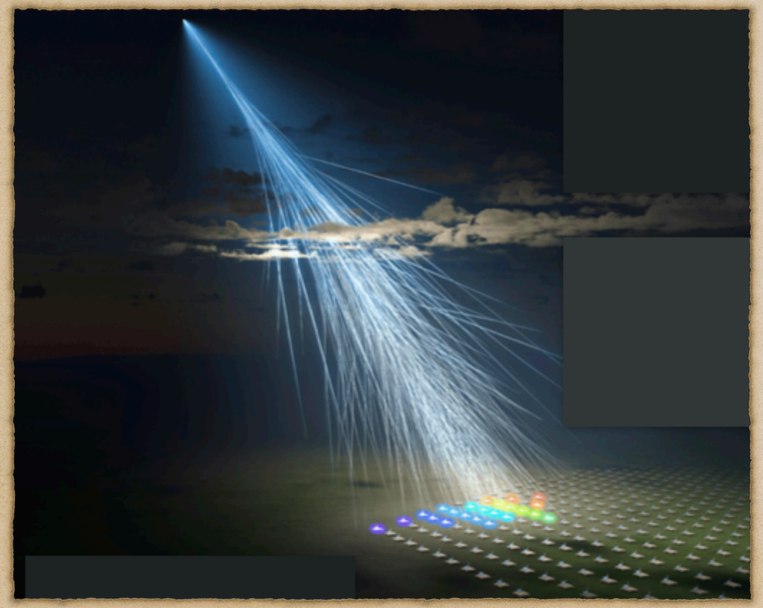
Ultrahigh Energy Cosmic Rays and Binary Neutron Star Mergers



Glennys R. Farrar, New York University

APC Workshop, Paris, Dec. 13, 2024

arXiv: 2405.112004 [astro-ph.HE]

Plan of talk

Observations & status of UHECRs:

- Modern data is very constraining; no GZK violation; "usual suspects" sources — AGNs, long Gamma Ray Bursts (collapse of massive star) — all have problems

NEW PROPOSAL: UHECRs are produced in jets of binary neutron star mergers.

- This is first scenario which potentially satisfies all requirements
- Can account for all UHECRs with a single mechanism.
- Fascinating prediction: Highest energy UHECRs are r-process nuclei.

Key conditions on UHECR sources

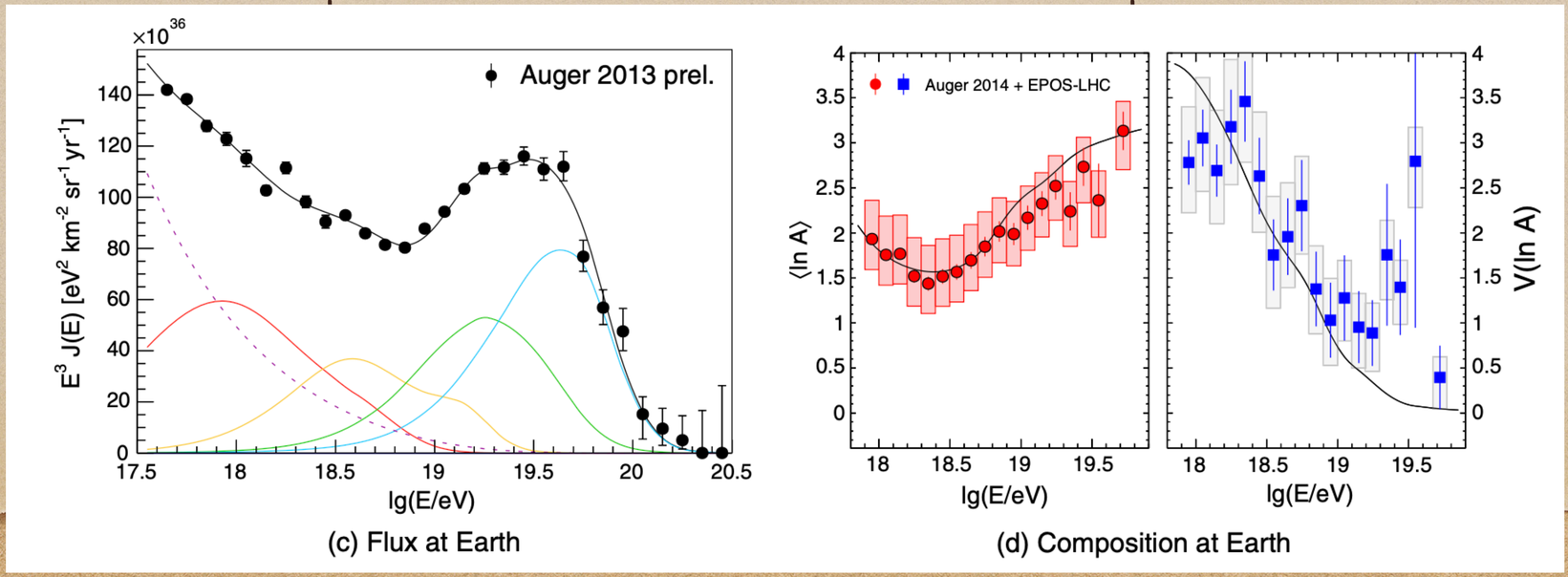
- Hillas criterion: CR escapes unless its Larmor radius is < source size Larmor radius controlled by rigidity, R=E/Q; ⇒ $R_{max,EV} \approx 3 \times 10^{-6}\ L_{cm}\ B_G$
- Source number density and energy injection rate:
  - $n_S \gtrsim 10^{-3.5}$ Mpc^{-3} and $dQ/dt = 6 \times 10^{44}$ erg Mpc^{-3} yr^{-1} for $E_{CR} > 10$ EeV
- Highest energy UHECRs are produced in TRANSIENTS (Amaterasu, OMG)
- Universal maximum rigidity (little source-to-source variation)
- Anomalously high energy of "OMG" & Amaterasu (250 EeV & 220 EeV)

Constraints from Spectrum and Composition, I.

- Unger, GF, Anchordoqui 2015: Take into account interactions in the environment surrounding the accelerator, not just with the CMB.
- Energy injection in UHECRs > 10 EeV: 6×10^{44} erg Mpc^{-3} yr^{-1}
- Mixed composition; hard spectrum, depends on Rigidity: $R \equiv E/(Z\,e)$

Spectrum

Composition



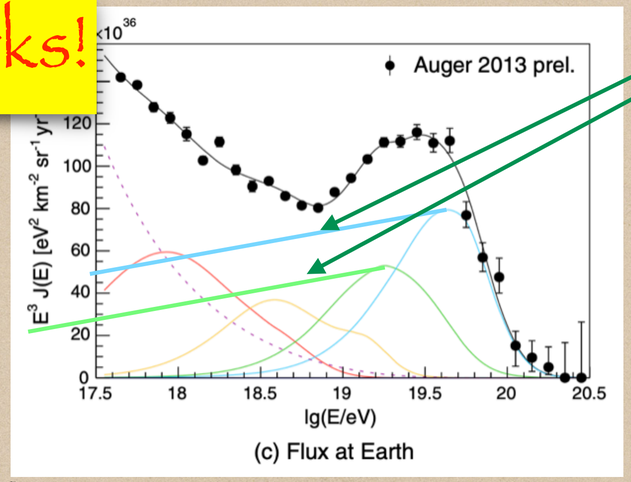
(c) Flux at Earth

(d) Composition at Earth

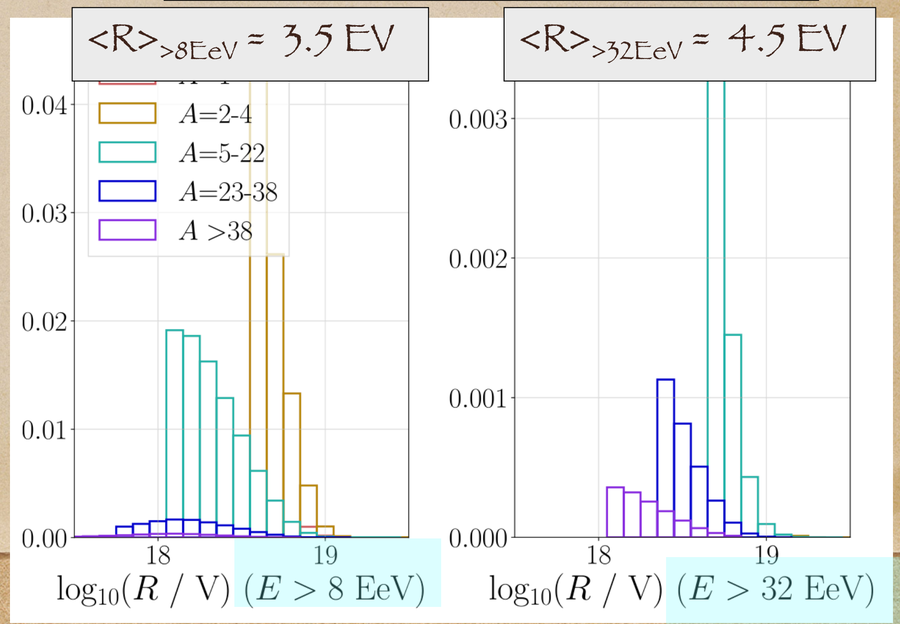
Constraints from Spectrum and Composition, II.

- But UFA did not allow for source-to-source variation…
- Ehlert, Oikonomou, Unger 23: Where are the expected low-rigidity tails?

No known source class works!



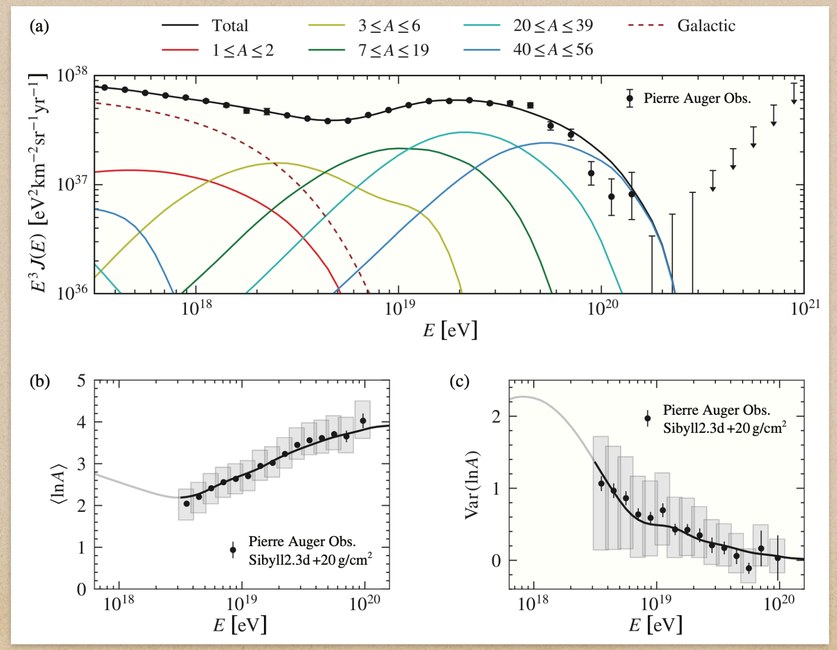
Rigidity spectrum with Auger composition Bister, GF 23

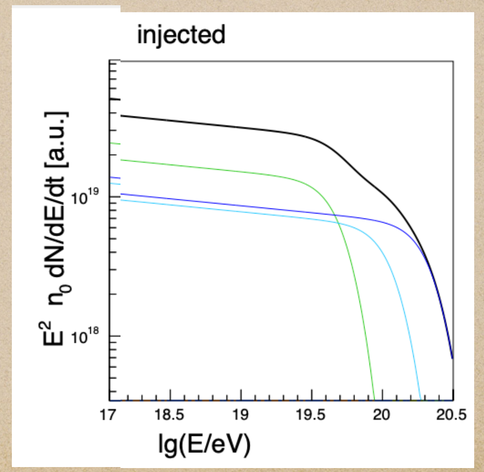


- Rigidity ranges only a factor 2.5 around mean value of ~4 EV!

Constraints from Spectrum and Composition, III.

- Fitting Auger data using the magnetized turbulence spectral cutoff ⇒ good fit with source spectrum $E^{-2.1}\,\mathrm{sech}[(E/E_{cut})^2]$ (M. Muzio for Comisso, GF, MM 24)





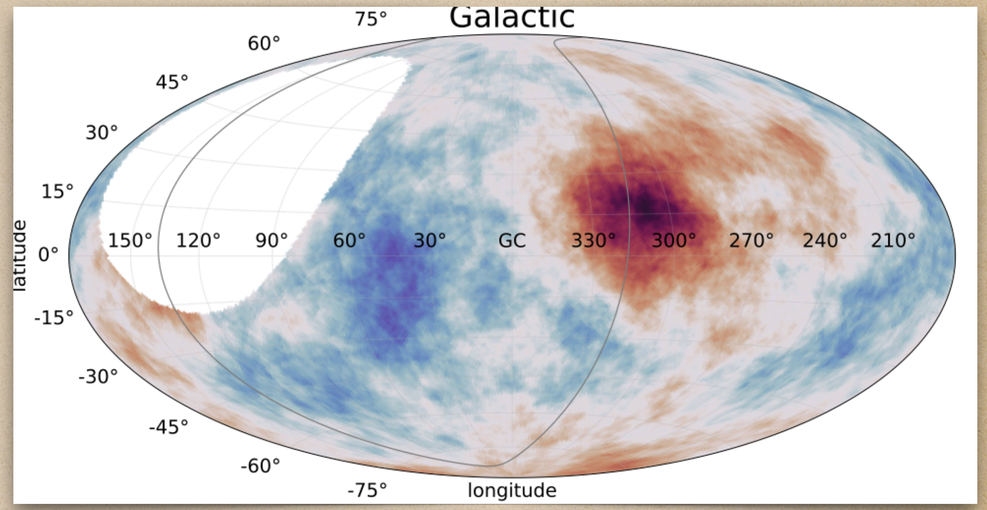
Constraints from Arrival Directions

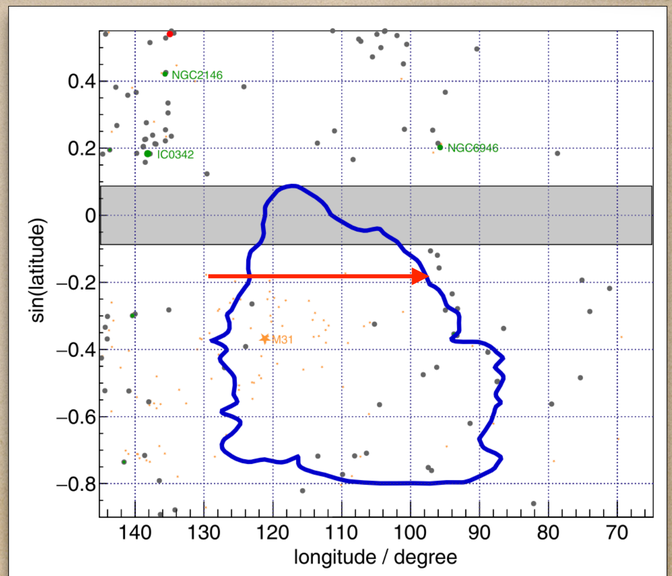
- Sources fairly abundant

  T. Bister and GRF, ApJ 2024

- HIGHEST ENERGY UHECRs are produced in TRANSIENTS (TA's Amaterasu, Fly's Eye OMG)

  M. Unger and GRF, ApJL 2024





(d) $E_{\rm low}$, $D_{0.1} = 25$ Mpc

Key conditions on UHECR sources

- Hillas criterion: CR escapes unless its Larmor radius is < source size
  - ➜ $R_{max,EV} \approx 3 \times 10^{-11}\ \Gamma_{jet}\ L_{km}\ B_G$
- Source number density and energy injection rate:
  - $n_S \gtrsim 10^{-3.5}\ Mpc^{-3}$ and $dQ/dt = 6 \times 10^{44}\ erg\ Mpc^{-3}\ yr^{-1}$ for $E_{CR} > 10$ EeV
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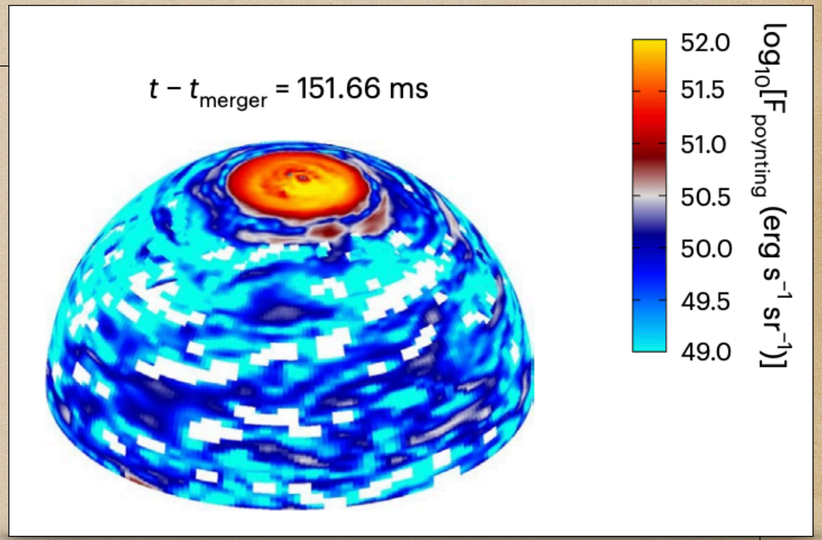
Binary Neutron Star Mergers

- Universal Maximum Rigidity is natural
  - $M_{BNS} = (2.64 \pm 0.14) M_\odot$
  - Gravitationally-driven dynamo
  - strong magnetic fields

Kiuchi+ NatureAstron23



- Energy injection rate: (obs = 6×10^{44} erg Mpc^{-3} yr^{-1})
  - BNS rate $\Gamma_{NSmerg} = 10\text{-}1700$ Gpc^{-3} yr^{-1}
  - Energy in jet alone $E_j \approx 10^{51.5}$ erg (Kiuchi+23)

✔ if $\Gamma_{NSmerg} \gtrsim 100$ Gpc^{-3} yr^{-1}

- Effective source density:

✔ as long as magnetic smearing $\beta_{EGMF} > 0.04$

$$\beta_{\rm EGMF} \equiv B_{\rm EGMF}/{\rm nG}\sqrt{L_c/{\rm Mpc}}$$

(expected range 0.1-1)

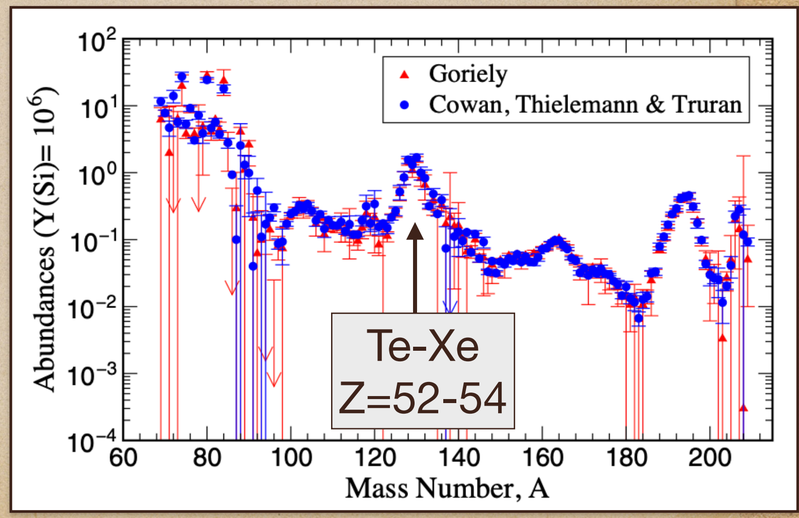
arXiv: 2405.112004 [astro-ph.HE]

Very highest energy events explained!

- r-process nucleosynthesis takes place in BNS mergers
- r-nuclei can be accelerated in outflow

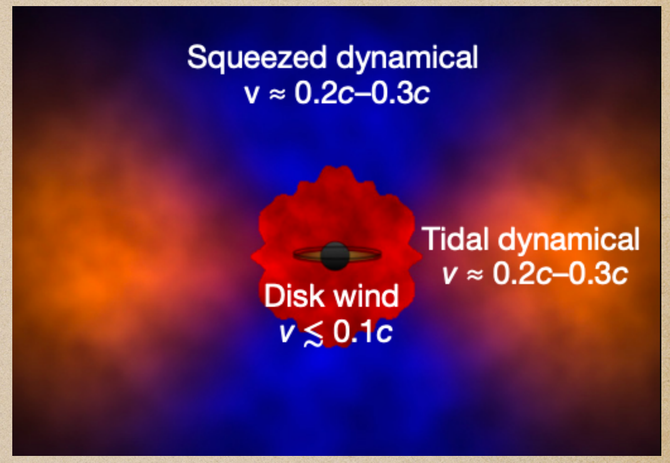
➜ $E = R\,Z_{Te\text{-}Xe} \approx 4.5\ EV \times (52\text{-}54) = 240\ EeV$

- Excellent agreement with OMG and Amaterasu!
- $E_{OMG} \approx 250 \pm 70\ EeV^{*}$, $E_{Amaterasu} \approx 212 \pm 25\ EeV^{**}$



*with modern air fluorescence yield **higher if a proton

Where are the UHECRs accelerated?

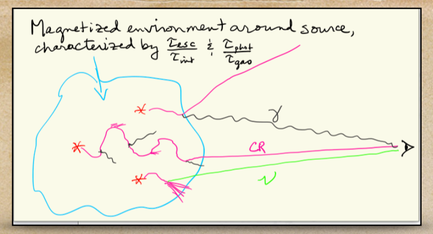


- Highly magnetized turbulent flow:
  - $B \sim r^{-3/2}$ or slower using magnetic energy conservation (n.b., CR feedback increases B) .
  - $dE_{accel}/dt \sim E/\tau_{accel} \sim 0.016\ Z\ B$ (CFM 24)
  - $dE_{synch}/dt \sim 4/9\ (\gamma\ \beta)^2\ B^2\ c\ Z^4/A^2$
- Simple Mathematica estimate of r such that $dE_{accel}/dt > dE_{synch}/dt$:
  - For initial $B=10^{15.5}$G at r = 10 km, R_{max} = 3.5 EV (reached at $r = 10^{16}$ cm)

Summary: Source candidates & key constraints

	Powerful AGN	long GRBs	TDEs	Accretion Shocks	BNS mergers
$n_S \gtrsim 10^{-3.5}$ Mpc^{-3}	[✘]	[✘]	?	?	✔
UHECR energy injection	✔	✘	?	?	[✔]
Ordinary galaxy	✘	✘	✔	[✘]	✔
Universal R_{max}	✘	✘	✘	✘	✔
Highest energy events?	✘	✘	✘	✘	✔

All can satisfy Hillas size > Larmor radius



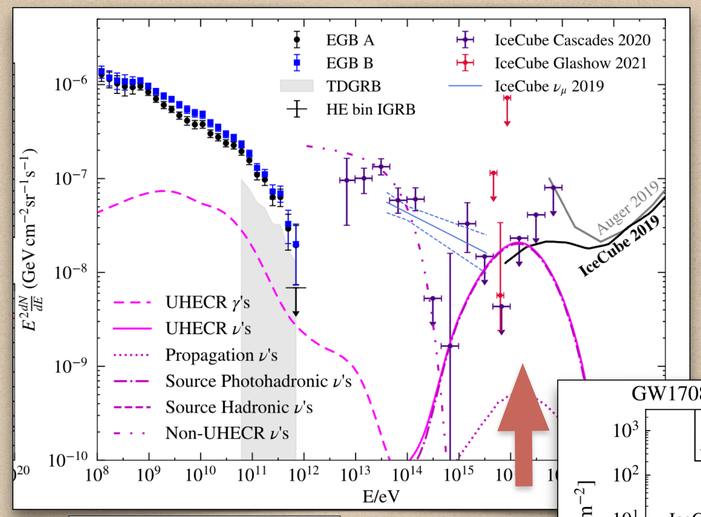
Future test of BNS-merger origin:

≈20 PeV neutrinos coincident with GW from BNS mergers

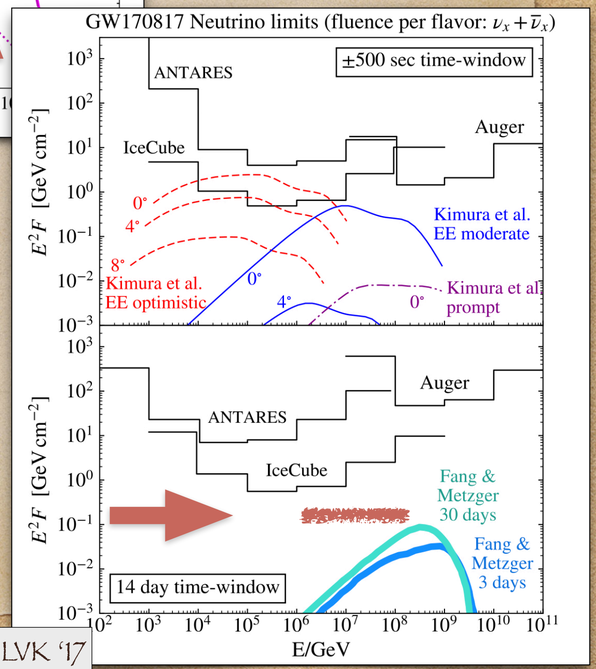
- UHECRs interact while escaping the source producing ν's with $E_\nu \approx 20$ PeV

⇒ Every ≈ 20 PeV ν should be accompanied by a gravitational wave from a NS merger.
CE+ET+IC-Gen2 x few yrs: very promising.

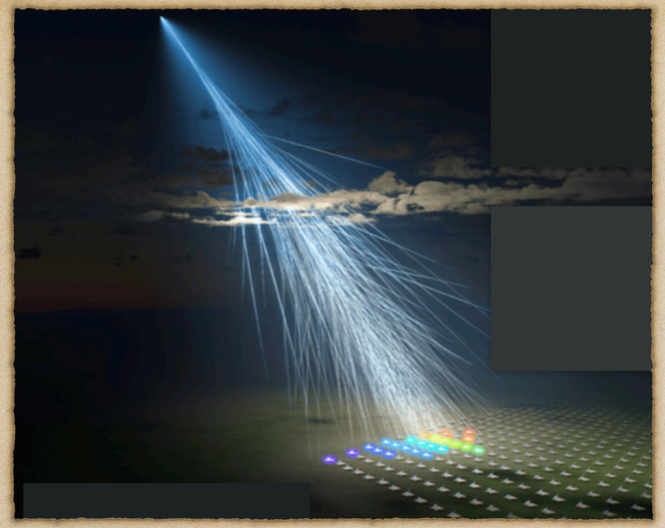
- GW170817 should have been accompanied by 20 PeV neutrinos. Estimated fluence for aligned jet ≈ 0.15 GeV cm^{-2} per flavor (preliminary).
Detector sensitivity not adequate.



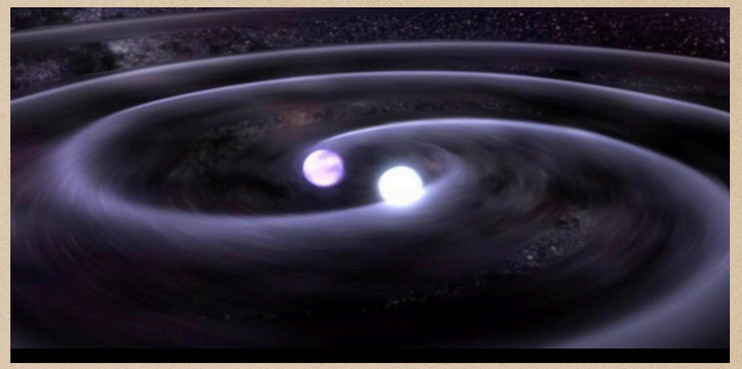
Muzio, GF, Unger '22



Antares, IceCube, Auger, LVK '17



Summary



New suggestion: UHECRs are produced in binary NS mergers.

- Uniquely, so far, BNS-merger mechanism can satisfy all basic requirements:
  - Universal Maximum Rigidity potentially explained.
  - Can account for all CRs (dependent on BNS merger rate & power in CRs)
- Highest energy events are r-process nuclei
- Should see coincidences between ≈20 PeV neutrinos and GWs from BNS-merger

Qualitatively it works well — next must look harder at details…