GW, cosmic rays and neutrinos

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UHECRs – the evidence

- Spectrum must extend to 100s EeV
- Composition – no protons, heavy nuclei
- Luminosity- ~6×10^{44} erg/Mpc^3/yr
- Anisotropy - dipole
- Small scale anisotropy – sources? Centaurus cluster?

Possible origin – the guilty

- Black holes
  - Big – accretion in all flavours
  - Small – Long GRBs, hypernovae
- Neutron stars:
  - Single - magnetars
  - **Binary – mergers,** short GRBs
- Shocks in large outflows

The merger rate densities

- BBH estimate $R = 17.9 - 44 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BNS estimate $R = 10 - 1700 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- BHNS estimate $R = 7.8 - 140 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The local supernova rate ~ $10^5 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$
- The BH formation rate is ~ $10^4 \mathrm{Gpc}^{-3}\mathrm{yr}^{-1}$

Properties of GW sources

Luminosities:

- GW: Each BNS merger emits $0.1Mc^2 \approx 2 \times 10^{54}\mathrm{erg}$

$$Q_{inj}^{GW} \approx 2 \times 10^{45} - 4 \times 10^{47}\mathrm{erg\ yr^{-1}Mpc^{-3}}$$

- Kinetic energy only $10^{51-52}\mathrm{erg}$

$$Q_{inj}^{kinetic} \approx 2 \times 10^{43} - 4 \times 10^{45}\mathrm{erg\ yr^{-1}Mpc^{-3}}$$

BNS - energetics

- Energy injection in CRs from BNS mergers – 10% of jet energy

$$Q_{inj}^{kinetic} \approx 2 \times 10^{42} - 4 \times 10^{44} \mathrm{erg\ yr^{-1} Mpc^{-3}}$$

  or more if more kinetic energy…

- Compatible with UHECR needs energetic requirement

BNS – kilonovae

Lots of heavy material

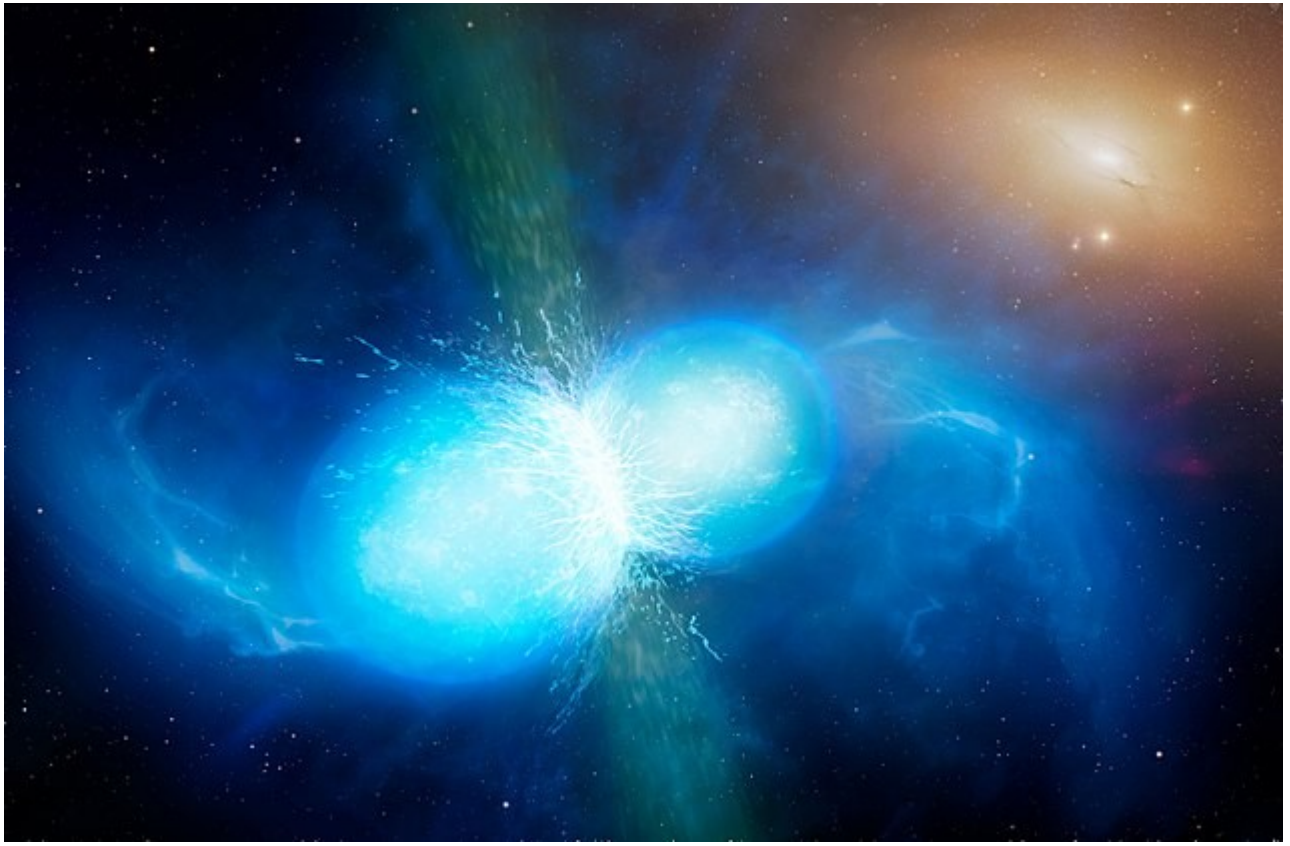
Ample source of heavy nuclei

Likely little or no hydrogen

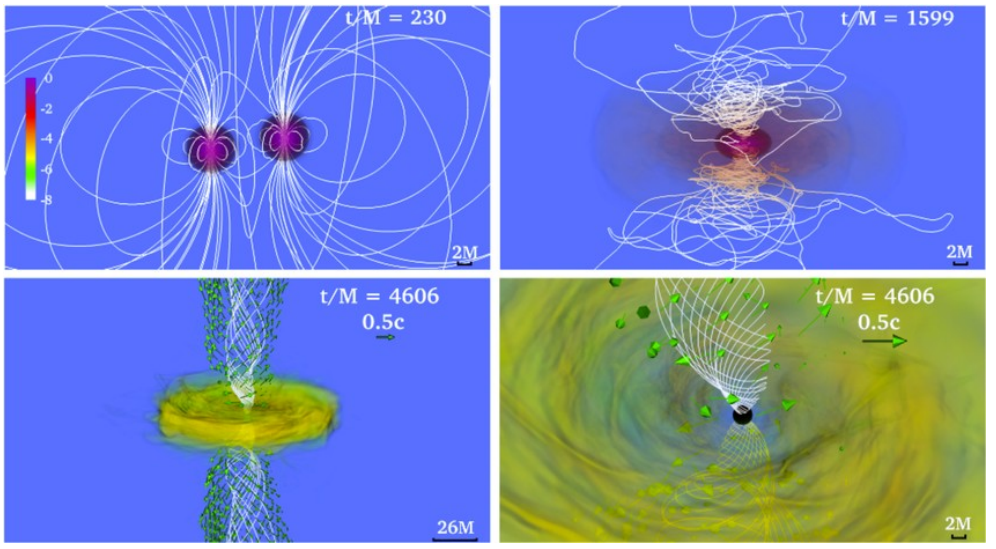
Relativistic outflows

Particle acceleration in jets

Mus also make neutrinos if making UHE CRs

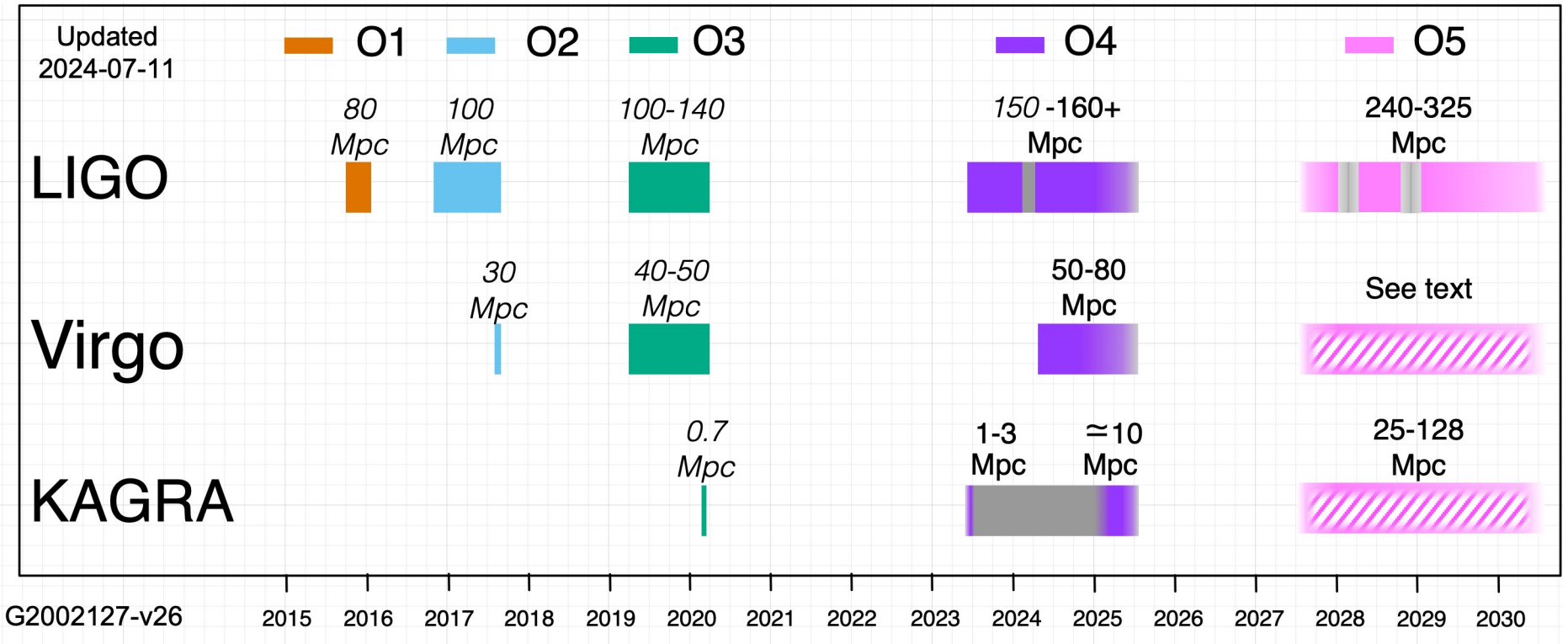


Some circumstantial evidence points towards the suspect



Ciolfi 2020

GW observations past and future



Expect more than 4 years of data taking with BNS range ~200Mpc

Number of BNS expected

Time Volume to be probed: 0.4-0.5 Gpc^3

Number of sources: 4 – 680 given the rate uncertainty in the rate

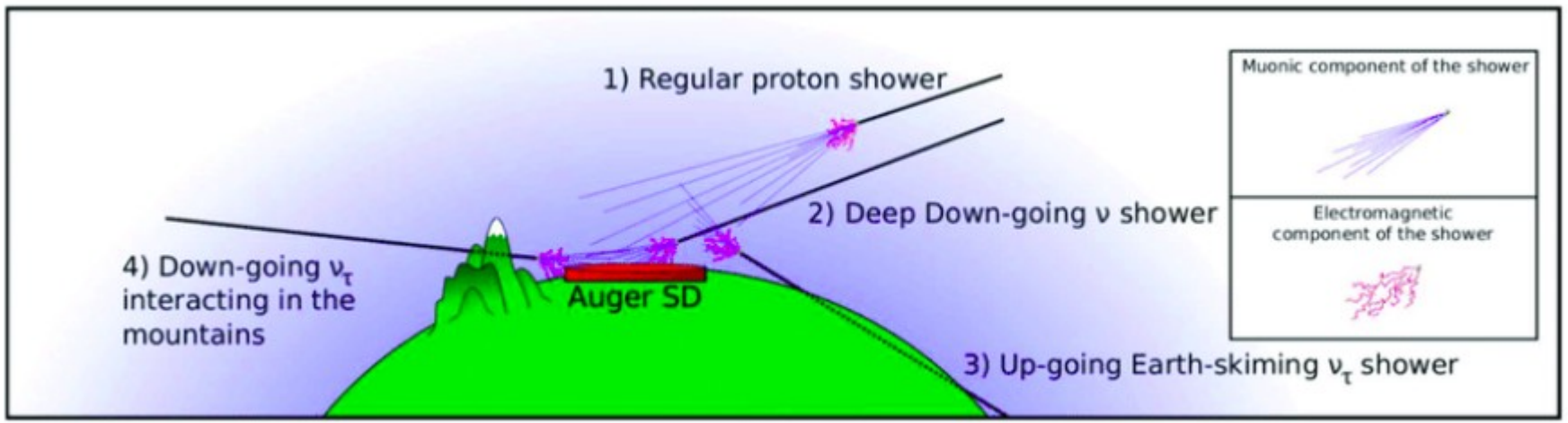
Typical distance: 140 Mpc, but if rate is large one may expect a close BNS down to 20Mpc

Still too far for UHECR! Delay too long…

BUT…...

Detecting neutrinos associated with CR

- Acceleration of cosmic rays in jets should be accompanied by neutrino production
- Neutrinos will move like photons, and exchange flavors
- PAO – can see neutrinos, FOV~ 0.6 sr
- Expected # BNS mergers in the FOV: 0.2 -34 over O4 and O5.



Eijk, 2019

Required neutrino luminosity

- Assume optimistically 20 Mpc
- Energy in neutrinos to detect one neutrino

$$E^{\nu} \approx 10^{47}\mathrm{erg}$$

- Efficiency of conversion to neutrinos needed

$$\frac{E^{\nu}}{E^{\mathrm{jet}}} > 10^{-4}$$

Summary – can we solve the case?

- Mild arguments for BNS origin of UHECR:
  - Energetics, star forming galaxies, composition, physical mechanism
- Observational verification
  - Direct CR impossible
  - Neutrinos coincident with BHS mergers- viable in the next 10 years, but require neutrino production in jets
  - ET will help if more sensitive neutrino detectors are available: GRAND, RNG,
- Require converting more than 10^{-4} of jet energy to neutrinos, and some luck.