UHECR from GW sources?

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UHECRs – the evidence

- Spectrum must extend to 100s EeV

- Composition – no protons, heavy nuclei

- Luminosity- ~6x1044 erg/Mpc3/yr

- Anisotropy - dipole

- Small scale anisotropy – sources? Centaurus cluster?
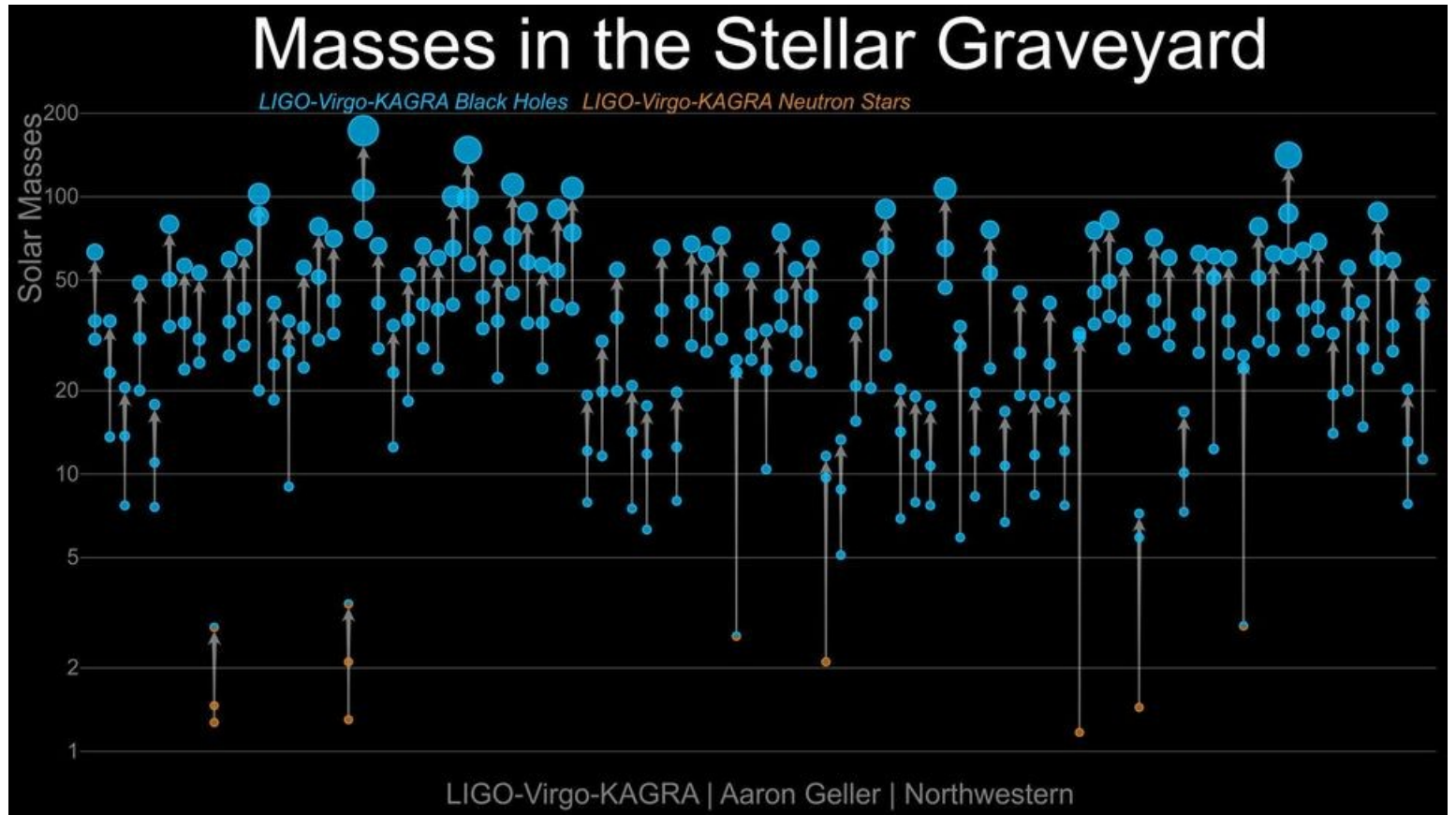
Possible origin – the guilty

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

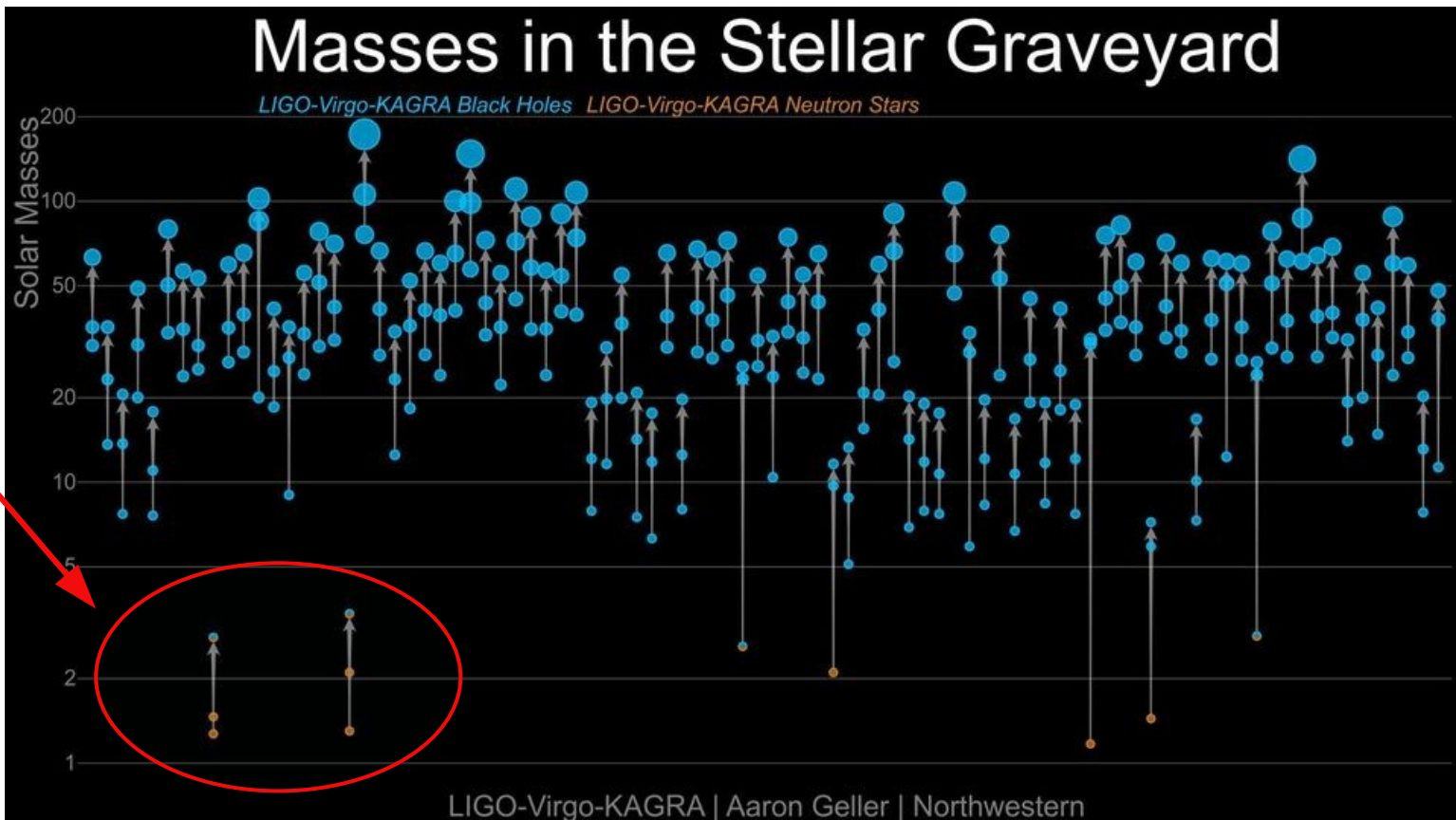# GW sources – a suspect?

- What do we know?

  – BBH

  – BNS

  – BHNS

Masses in the Stellar Graveyard

LIGO-Virgo-KAGRA Black Holes   LIGO-Virgo-KAGRA Neutron Stars

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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Solar Masses

LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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 $0.1 Mc^2 \approx 2 \times 10^{54} \mathrm{erg}$

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

- 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

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

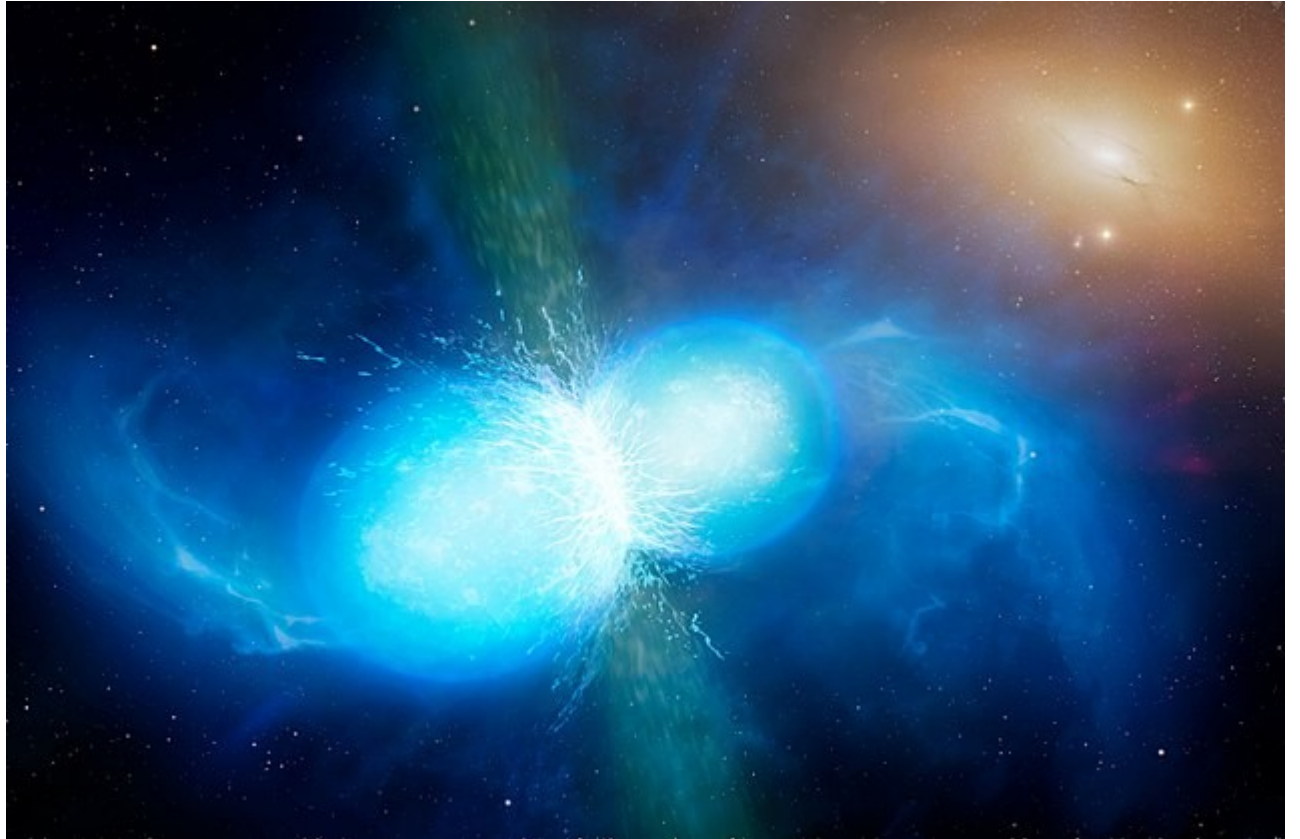 or more if more kinetic energy…

- Marginally compatible with UHECR needs energetic requirement

BNS – kilonovae

Lots of heavy material

Ample source of heavy nuclei

Likely little or no hydrogen

BNS mergers

- Known to make GRBs

- Relativistic outflows

  Many models of particle acceleration in jets
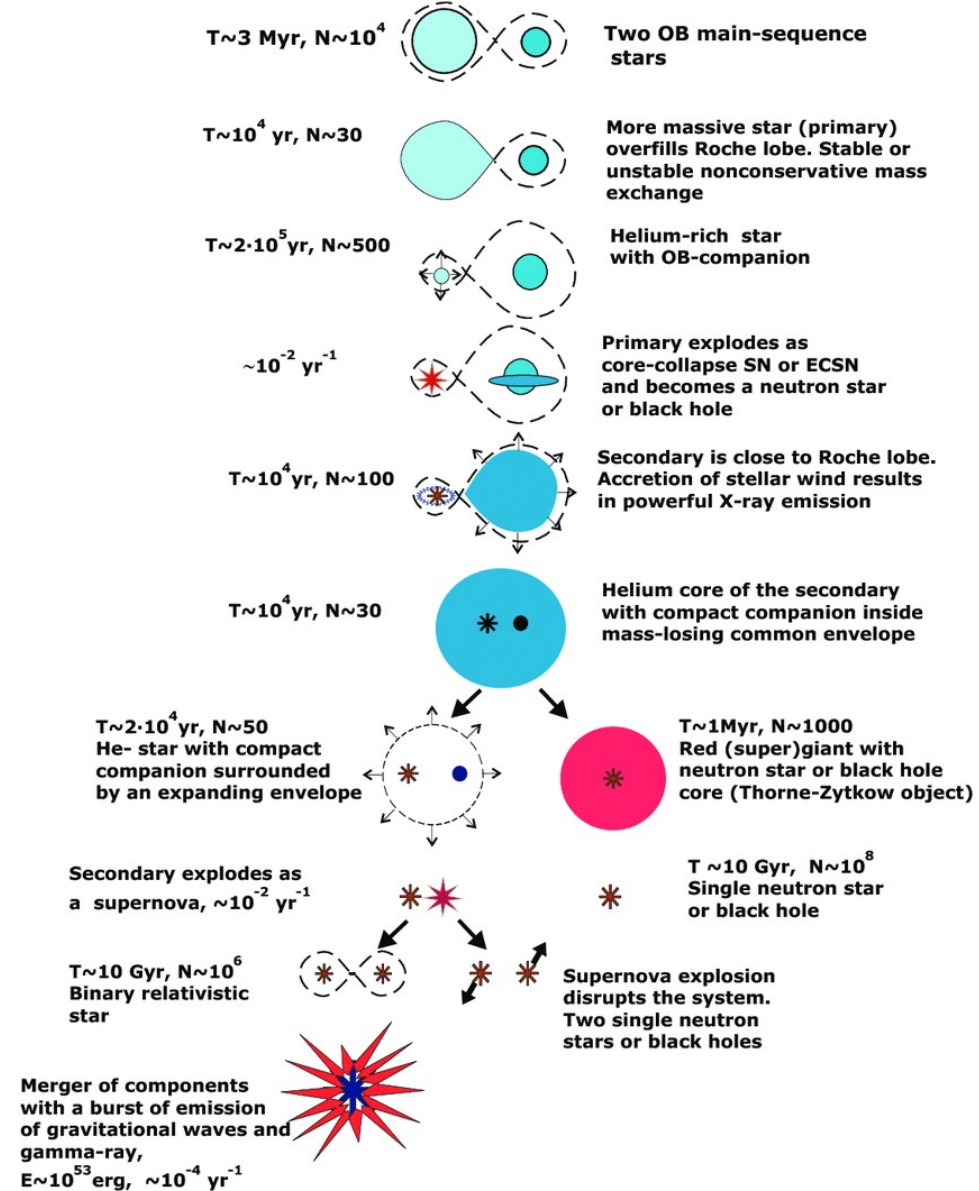
- Collision of magnetospheres

Merging BNS – how to make them?
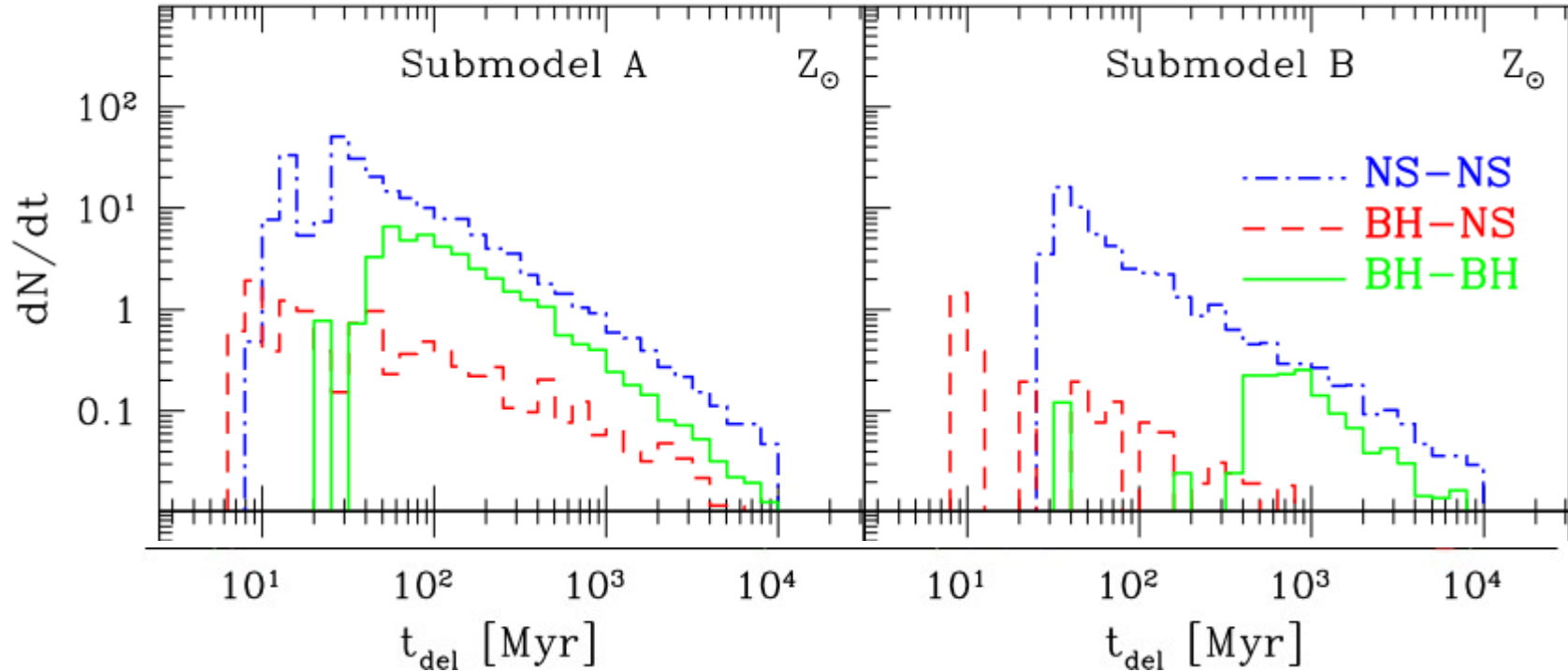
Binary evolution in field
- population compatible with Galactic binary pulsars

Globular clusters
- more freedom
- less mass higher efficiency
- simiar propoerties

$T{\sim}3$ Myr, $N{\sim}10^4$ — Two OB main-sequence stars

$T{\sim}10^4$ yr, $N{\sim}30$ — More massive star (primary) overfills Roche lobe. Stable or unstable nonconservative mass exchange

$T{\sim}2{\cdot}10^5$ yr, $N{\sim}500$ — Helium-rich star with OB-companion

$\sim 10^{-2}$ yr^{-1} — Primary explodes as core-collapse SN or ECSN and becomes a neutron star or black hole

$T{\sim}10^4$ yr, $N{\sim}100$ — Secondary is close to Roche lobe. Accretion of stellar wind results in powerful X-ray emission

$T{\sim}10^4$ yr, $N{\sim}30$ — Helium core of the secondary with compact companion inside mass-losing common envelope

$T{\sim}2{\cdot}10^4$ yr, $N{\sim}50$ He- star with compact companion surrounded by an expanding envelope

$T{\sim}1$ Myr, $N{\sim}1000$ Red (super)giant with neutron star or black hole core (Thorne-Zytkow object)

Secondary explodes as a supernova, $\sim 10^{-2}$ yr^{-1}

$T{\sim}10$ Gyr, $N{\sim}10^8$ Single neutron star or black hole

$T{\sim}10$ Gyr, $N{\sim}10^6$ Binary relativistic star

Supernova explosion disrupts the system. Two single neutron stars or black holes

Merger of components with a burst of emission of gravitational waves and gamma-ray, $E{\sim}10^{53}$ erg, $\sim 10^{-4}$ yr^{-1}
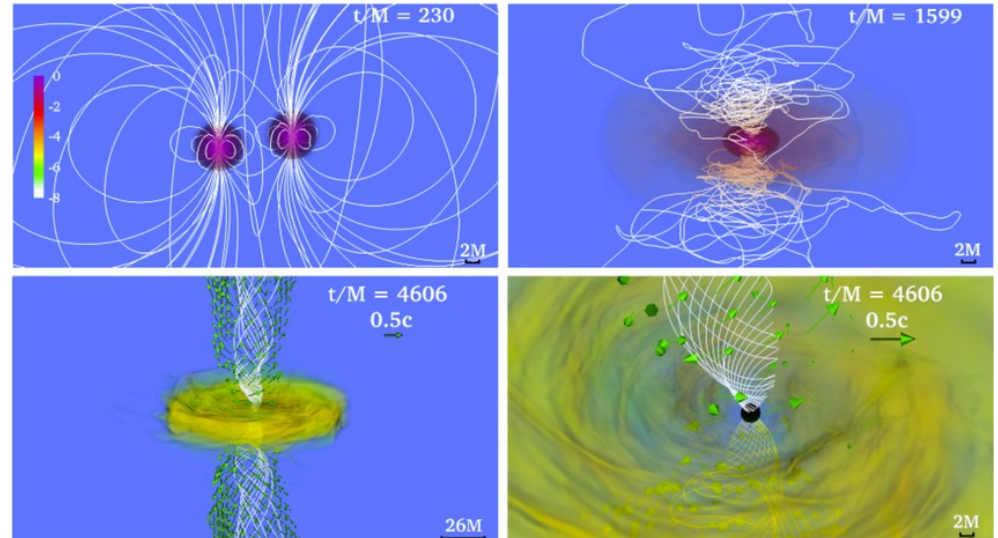
BNS delay to merger

Merger time peak 10-30Myrs after star formation – connection with starburst galaxies
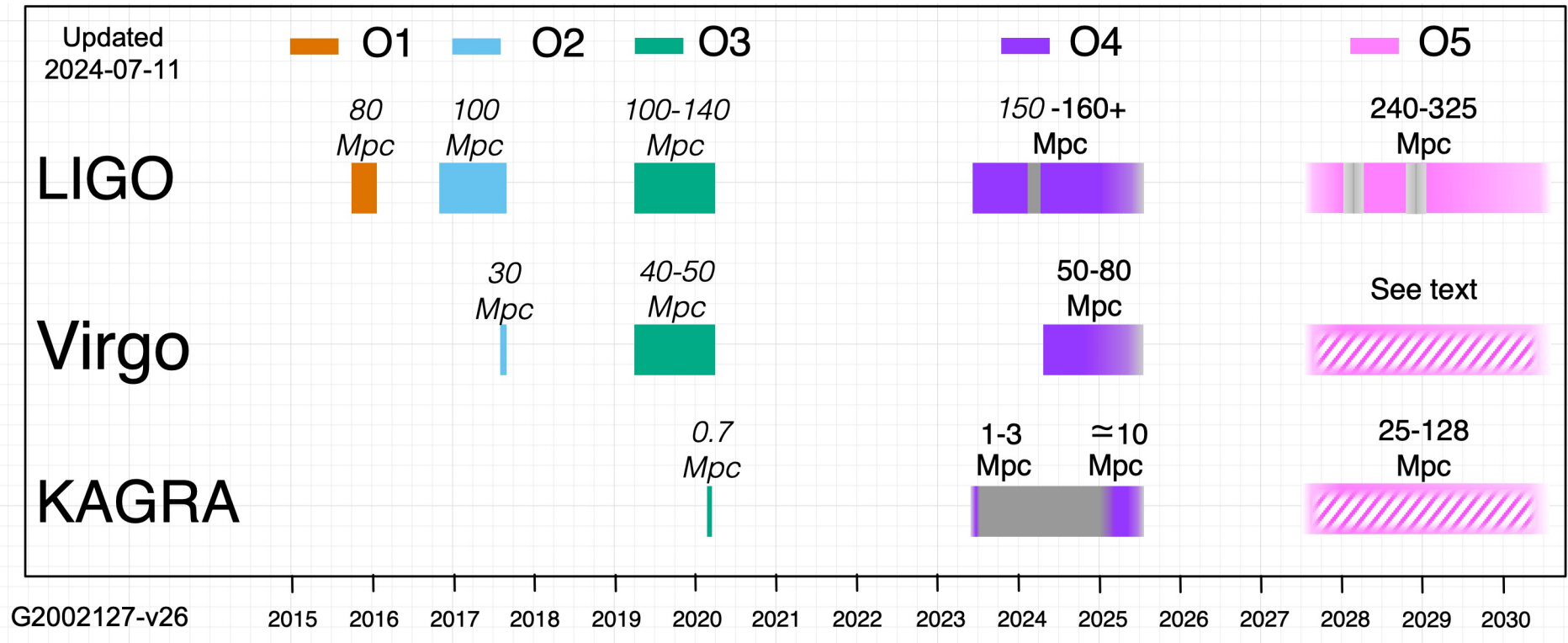
However, GW170817...

Host is an old elliptical alaxy with almost no star formation….
Short GRBs – in and out of galaxies – because of the delay tails

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…...

Another possibility - neutrinos

- 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
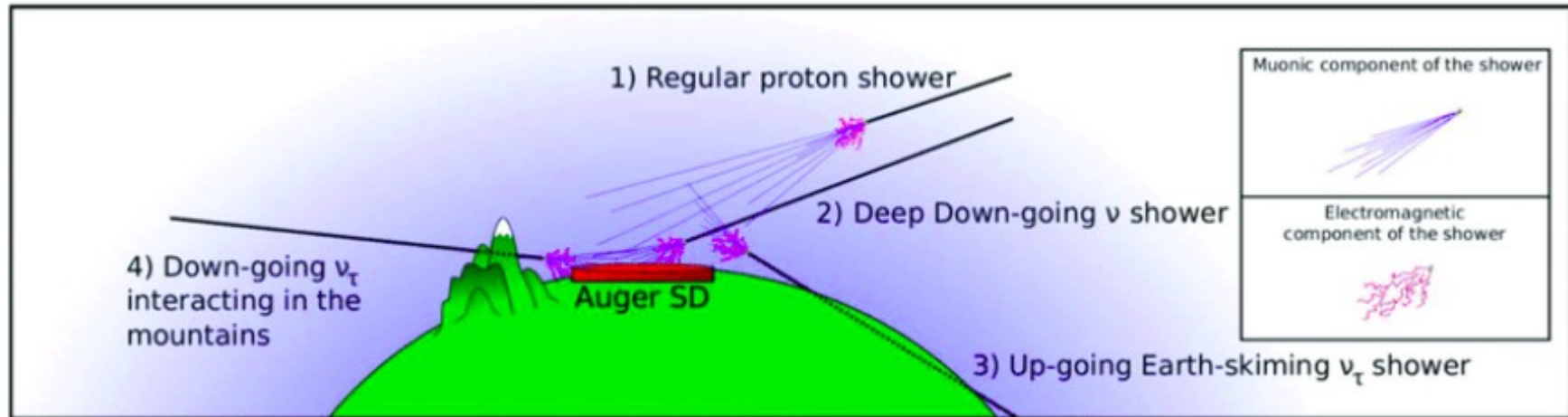
Required neutrino luminosity

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

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

- Efficiency of conversion to neutrinos needed

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

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
- Require converting more than 10^{-4} of jet energy to neutrinos, and some luck.