Prospects for kilonova signals in the gravitational wave era

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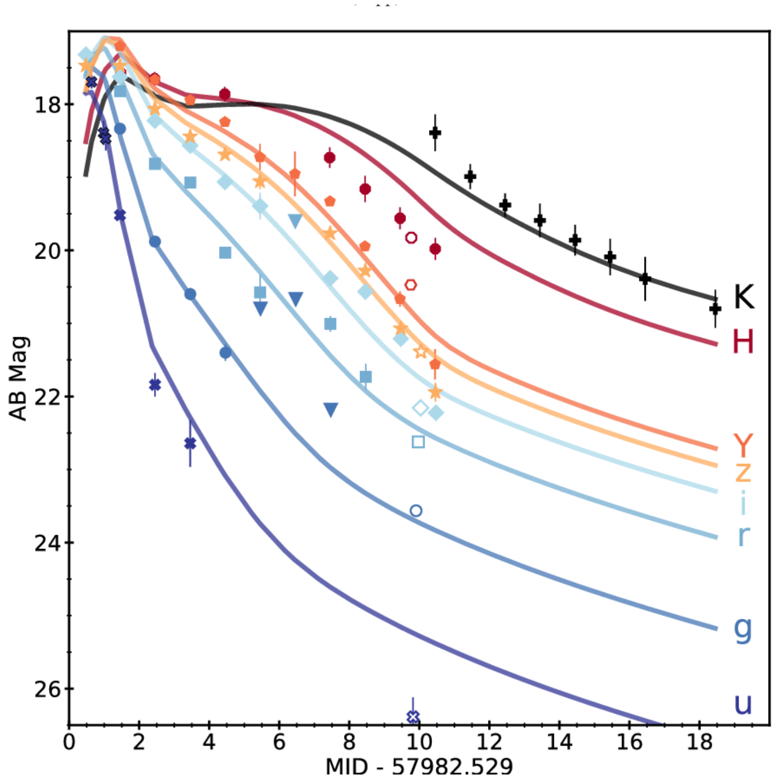


What to expect for the future: O3 and beyond ?

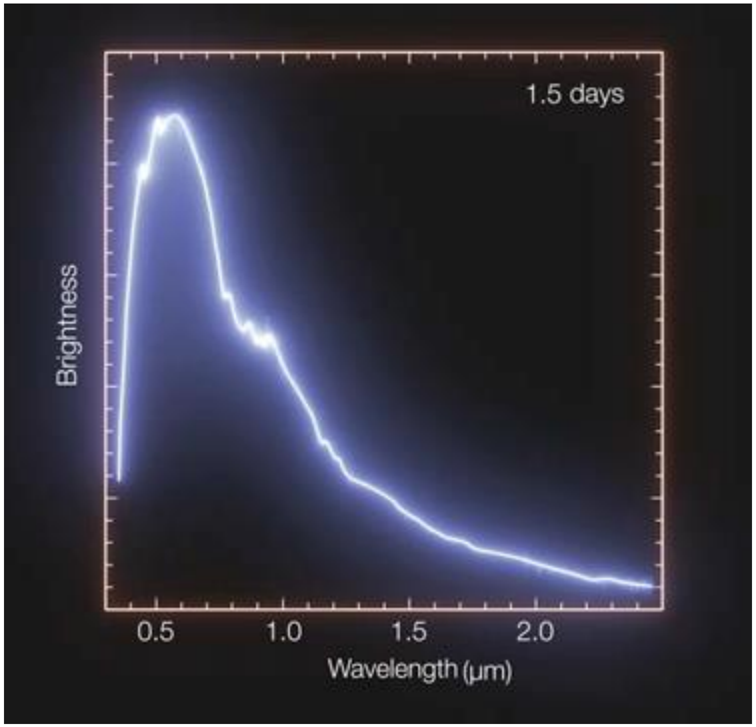
The kilonova: $10^{-2} - 10^{-1}\ M_\odot$ escaping the system when two NS merge; $v_{exp} \sim 0.1 - 0.3$ c

Expanding ejecta heated by radioactivity of r-process elements

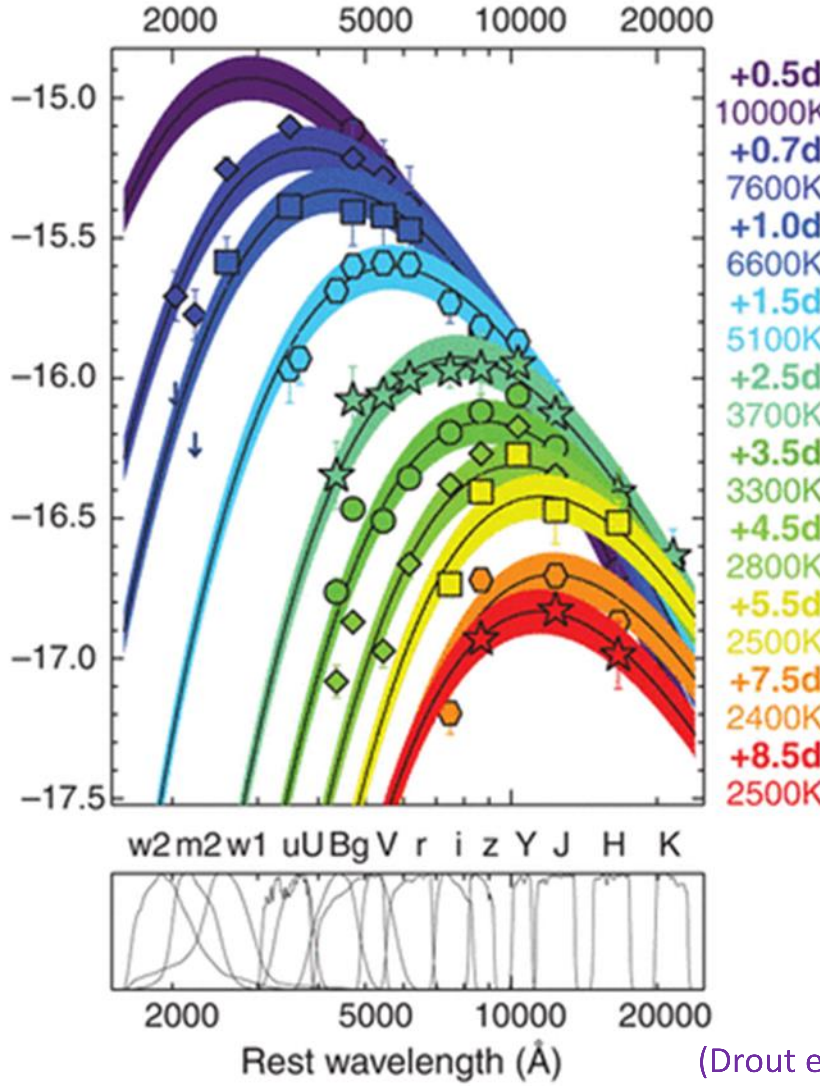
Equatorial/polar ejecta: lanthanide rich/poor

Rapid evolution from blue to red

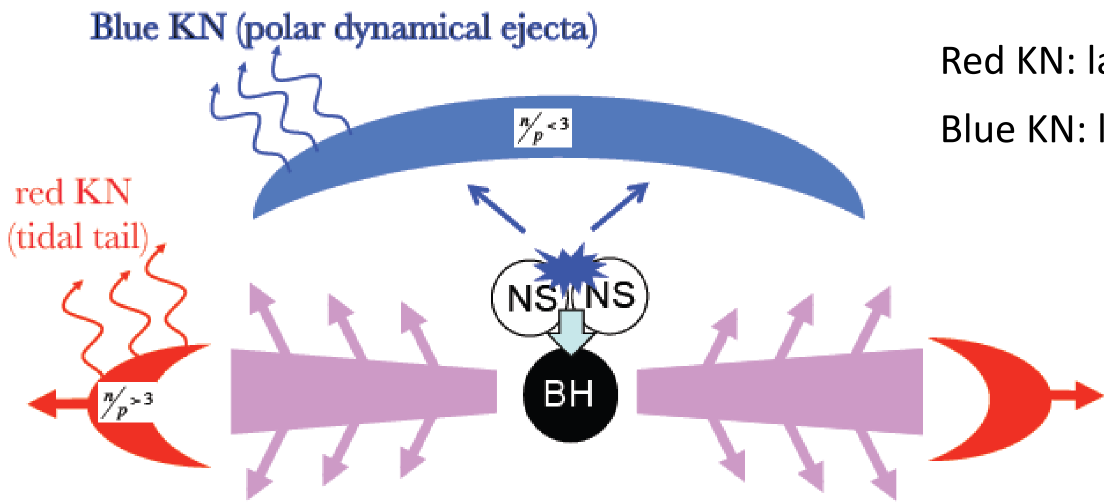
Quasi-blackbody spectrum



ESO/E. Pian et al./S. Smartt & ePESSTO/L. Calçada



(Drout et al, 2017)



Red KN: lanthanide opacity: $\kappa \sim 5$ -10 cm^{2}g^{-1}

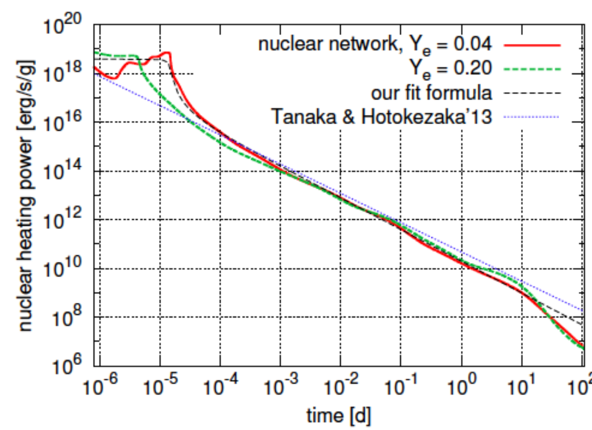
Blue KN: lanthanide free: $\kappa \sim 0.5$ -1 cm^{2}g^{-1}

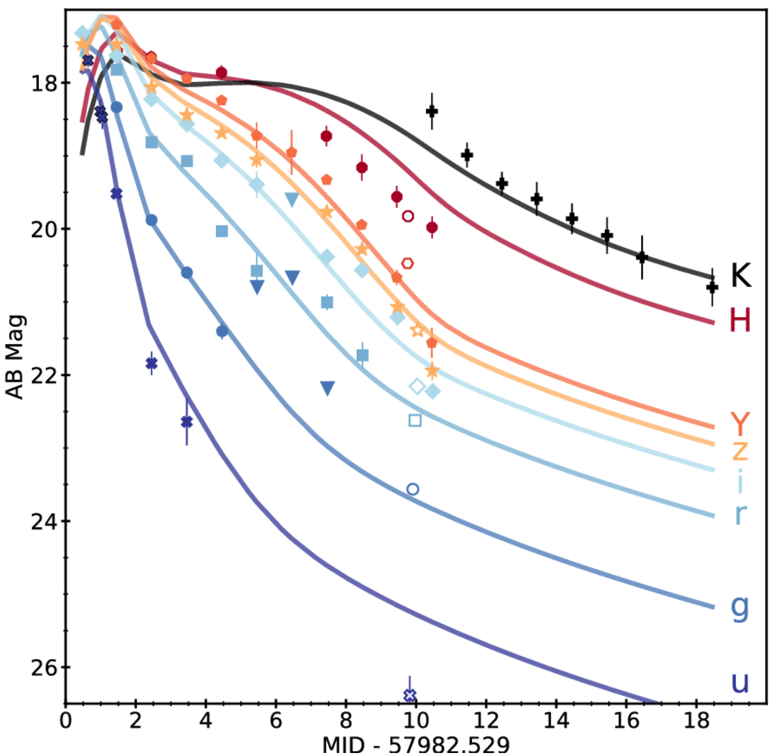
Simple model:

$$\frac{dL}{du} = -L + L_* \qquad \text{with } u = \left(\frac{t}{t_0}\right)^2 \quad \text{and } \; t_0 \; = \left(\frac{3\kappa M}{4\pi c v_{exp}}\right)^{1/2} = 2\left(\frac{\kappa_1 M_{-2}}{v_{.1c}}\right)^{1/2} \text{ days}$$

Radioactive heating: $L_* = M \times \epsilon_*$

$$\varepsilon_* \propto t^{-1.3}$$





Composite model to fit the data:

Red component: $M=0.036\ M_{\odot}$; $v_{exp}=0.12c$; $\kappa= 3.5\ cm^2g^{-1}$

Blue component: $M=0.014\ M_{\odot}$; $v_{exp}=0.27c$; $\kappa= 0.5\ cm^2g^{-1}$

$\rightarrow$ t_0 (red)=6.5 days ; t_0 (blue)=1.3 days

(Cowperthwaite et al, 2017)

What to expect now?

O2 → O3: Horizon distance D_{H} increases from about 140 to 230 Mpc (429 Mpc for design)

Key issue for EM counterpart searches as the sources are at larger distance: LOCALIZATION !

- finding the GRB? (Swift, SVOM: ~ 10 arcmin): strong limits on distance and viewing angle
- finding the kilonova

  GW 170817: error box of 28 square degrees + distance from GW → localization in 12 hours

  m_{KN} ~17.5

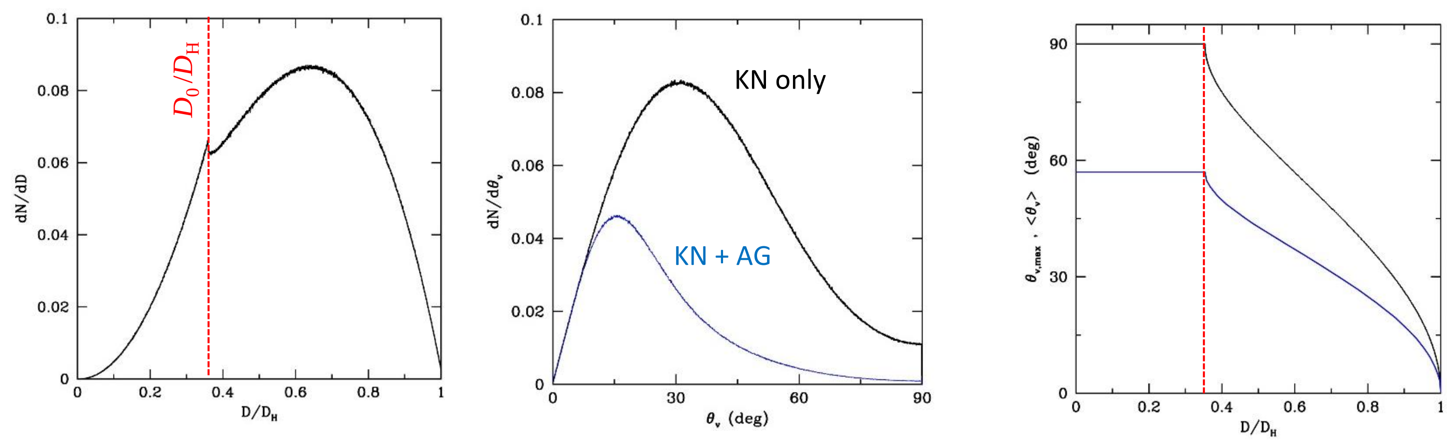
Since O3 started three BNS candidates:

- S190425z: D=155 ± 45 Mpc → m_{KN} ~ 20.5 ±1.5 mag but huge error box (L1, V1 only)
- S190426c: D=377 ± 100 Mpc → m_{KN} ~ 22.5 ±2 mag (possible BH+NS ?)
- S190510g: D=269 ± 108 Mpc → m_{KN} ~ 21.7 ±2 mag

When distance increases: larger error box, larger volume to explore, fainter kilonova

→ no kilonova found in the three cases above

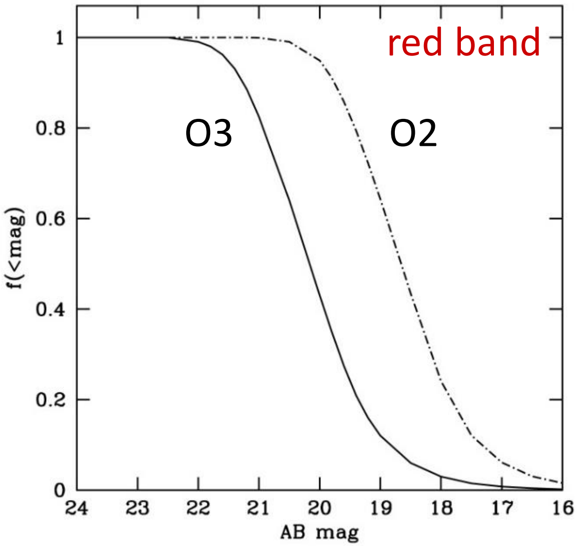
Population model: distribution in distance and viewing angle:



GW detection for all viewing angle up to:

D_0/D_{H}=0.36

Kilonova magnitude distribution



$$M_{\theta_v} \approx M_{\theta_v=0} + \Delta M(1 - cos\theta_v) + \delta M$$

$M_{\theta_v=0}$: value on-axis ; ΔM: amplitude of angular effect (Wollaeger et al, 2018)

δM (intrinsic variability: e.g. mass, velocity, opacity)

In red band: $\Delta M_r \approx 4$ mag ; $\delta M_r \approx \pm 1$ mag

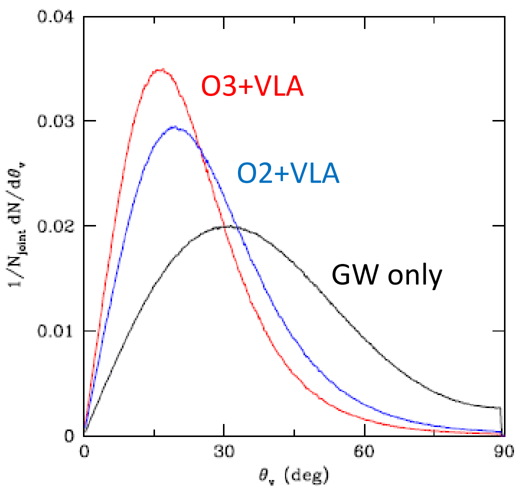
Calibrated with KN 170817: $M_{\theta_v=20°} = -15.6$

Using the distribution in distance and viewing angle →

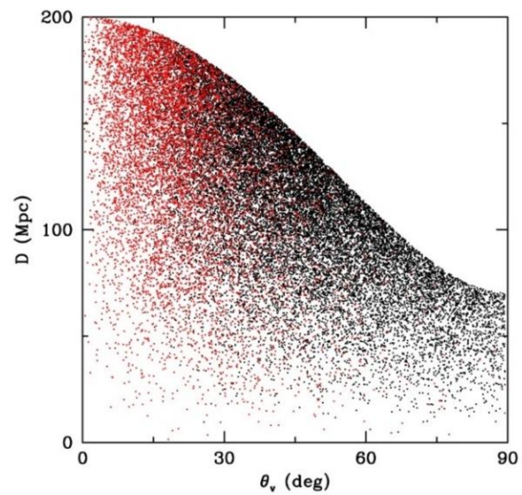
O2: half of the events expected brighter than $m = 18.5$

O3: half of the events fainter than $m = 20$

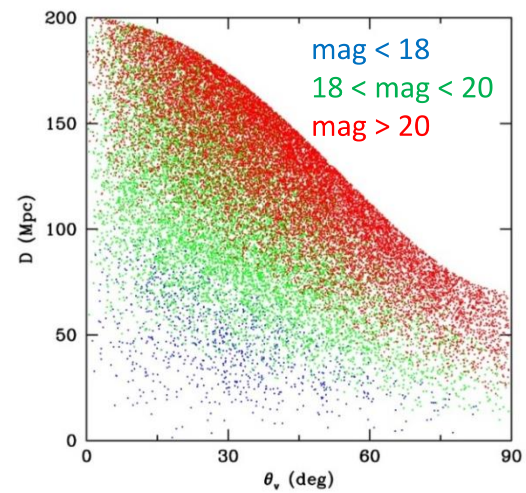
Distribution in viewing angle



Two-parameter plots (O3)



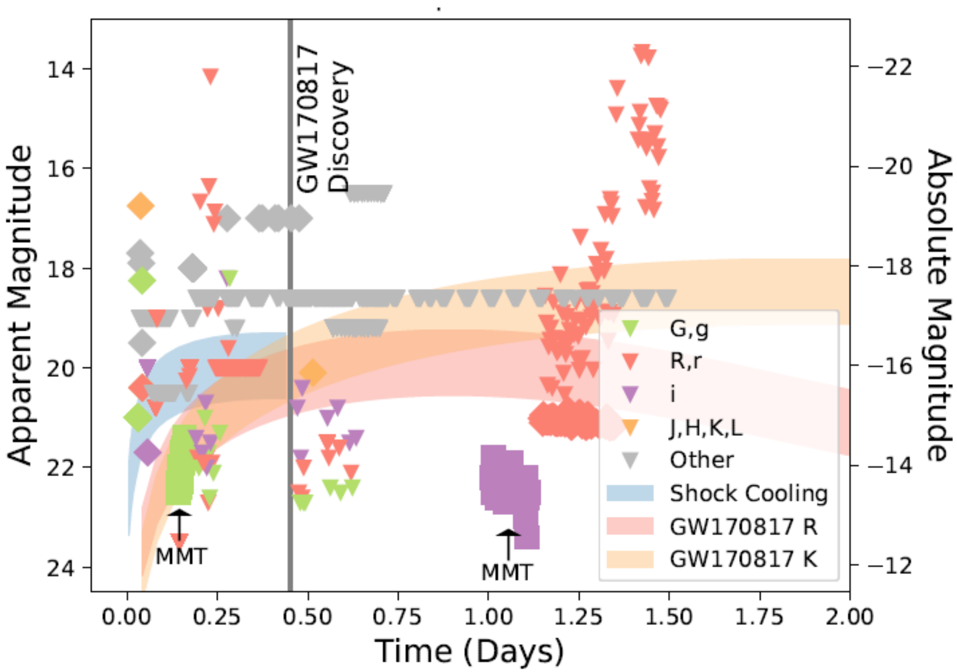
red: AG detected in radio
black: all detected GW events



KN magnitudes (red band)

Example of S190425z: D=155 ± 45 Mpc

Putting KN 170817 at the distance of S190425z

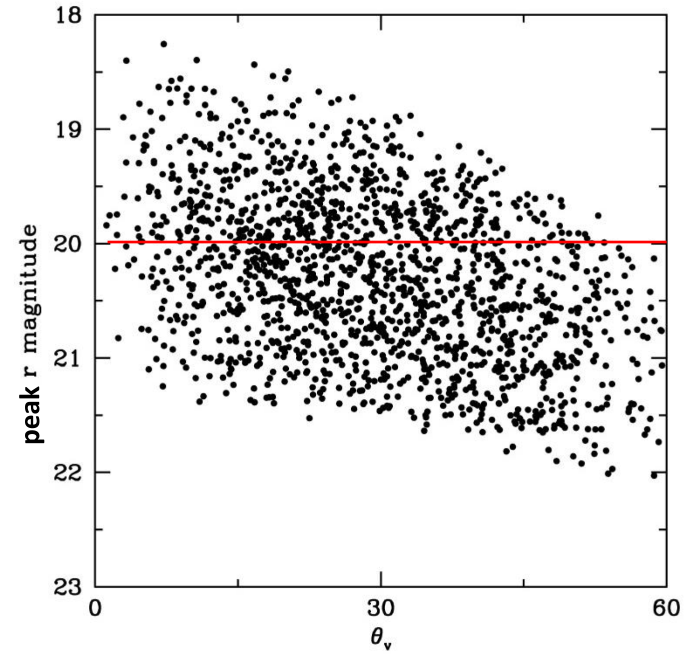


(Hosseinzadeh et al, 2019)

Viewing angle-magnitude diagram

Population model

m_r brighter than:	22	20	19.5	19
%:	100	36	14	0.3



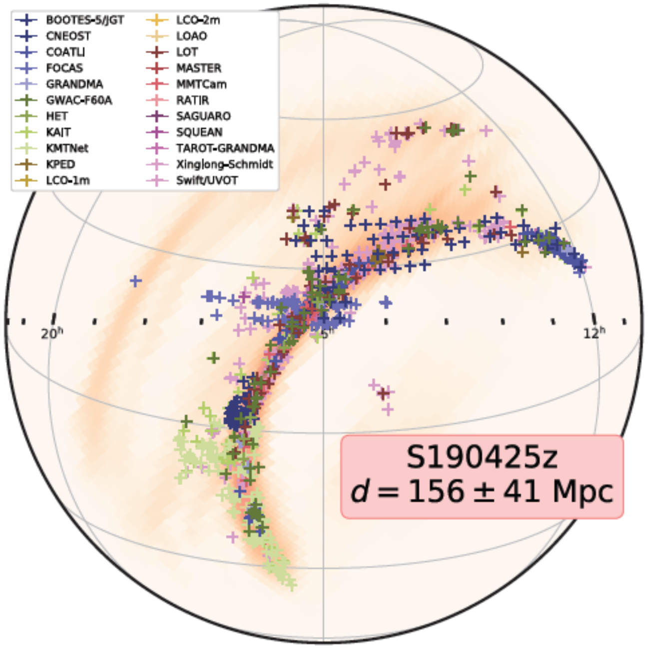
KN accessible to COLIBRI but…

… must be first localized ?

Observational strategy

The recent examples: S190425z and S190426c

Both pointed (400+ galaxy-targeted) and wide-field searches (thousands of deg^2)



Large error box 7500 deg^2 (Livingstone + Virgo only)
but reasonable coverage by ZTF (40%)
~ 70 reported candidates but no KN found
→ not in the searched area or fainter than mag 20.5

S190426c: smaller error box ~ 1200 deg^2
but larger distance (expected KN mag ~ 22.5)

Discovery and follow-up

Discovery:

- coordination to avoid multiple observations of the same galaxies
  sufficiently deep reference images?
- smaller error boxes when KAGRA (2020+) and LIGO India (2024+) join the network
  5% (2020+) to 25% (2024+) of error boxes smaller than 5 deg^2
- Wide-field searches: ZTF efficient down to mag $\sim$ 20.5
- LSST: deep searches in large fields "an amazing machine for discovery" (Cowperthwaite, 2019)

Follow-up:

When a kilonova is found:

- multi-wavelength follow-up possible with medium telescopes (in H or K band after a few days)
- search for the afterglow (time to rise to peak $\propto \theta_v{}^{8/3}$ ~ 150 days for 170817 with $\theta_v \sim 20°$)
- redshift of the host galaxy $\rightarrow H_0$

Conclusions

For viewing angle less favorable than in the case of GW 170817
and/or as the typical distance of GW detected sources increases in O3 and beyond

→ the kilonova will often remain the only accessible EM counterpart
but finding it will require deep searches in extended areas

When the kilonova is the only counterpart, $\theta_v > 45°$ in one third of the cases

→ viewing angle diversity → angular structure of the KN ejecta

→ also exploration of the intrinsic diversity: M_{KN} , v_{ej} , κ

Avidly waiting for the first kilonovae of O3
also waiting for the first kilonova from a BH+NS merger (if any ?)
(but distance larger in average → kilonova fainter for same M_{KN}, v_{ej}, κ)

Ready to bet when it comes ?