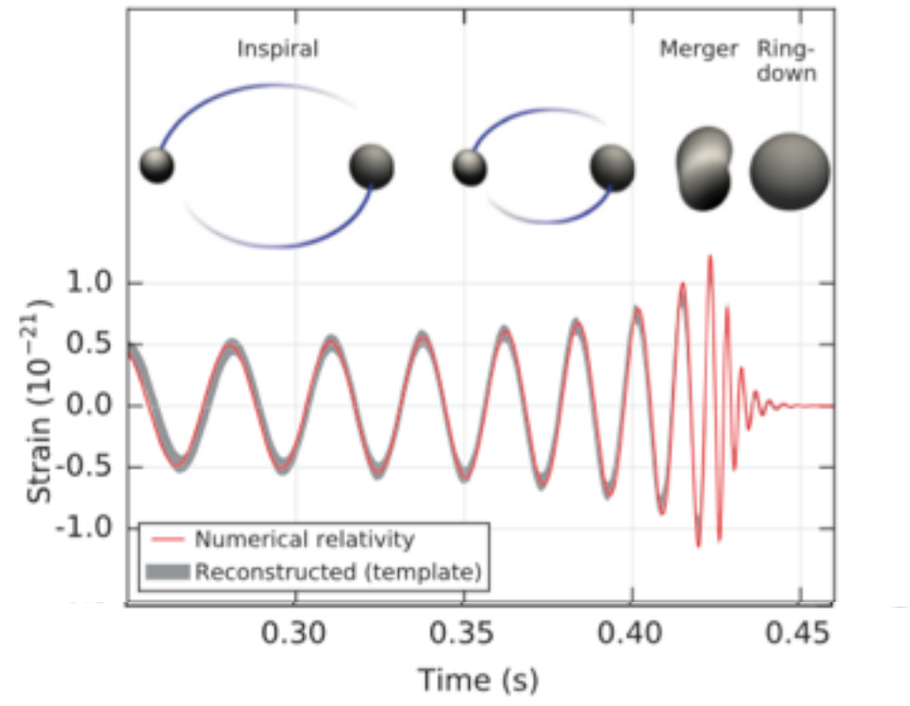
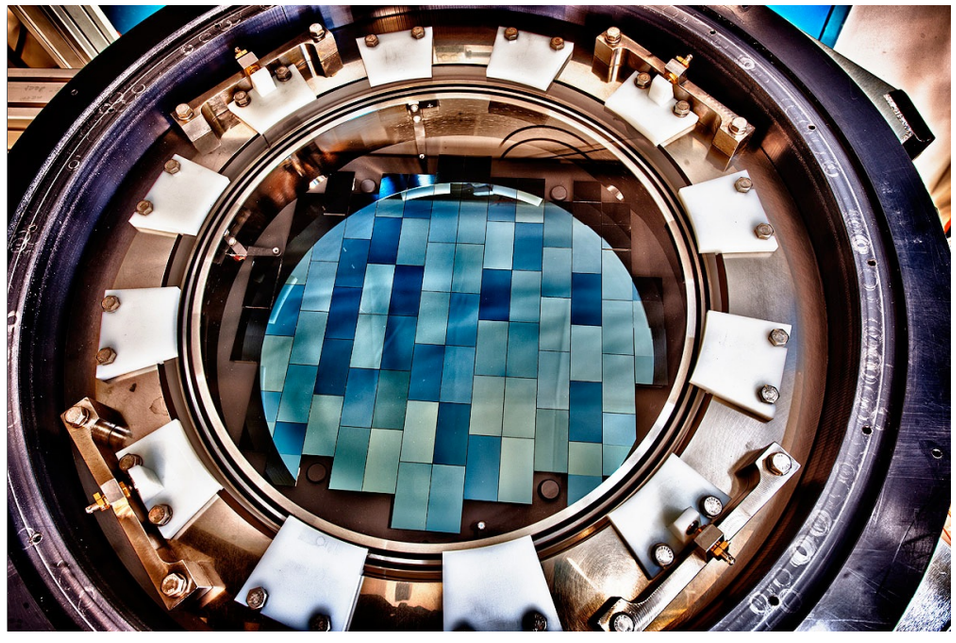
The DECam Gravitational Wave Follow-up Program:

DESGW & BLISS





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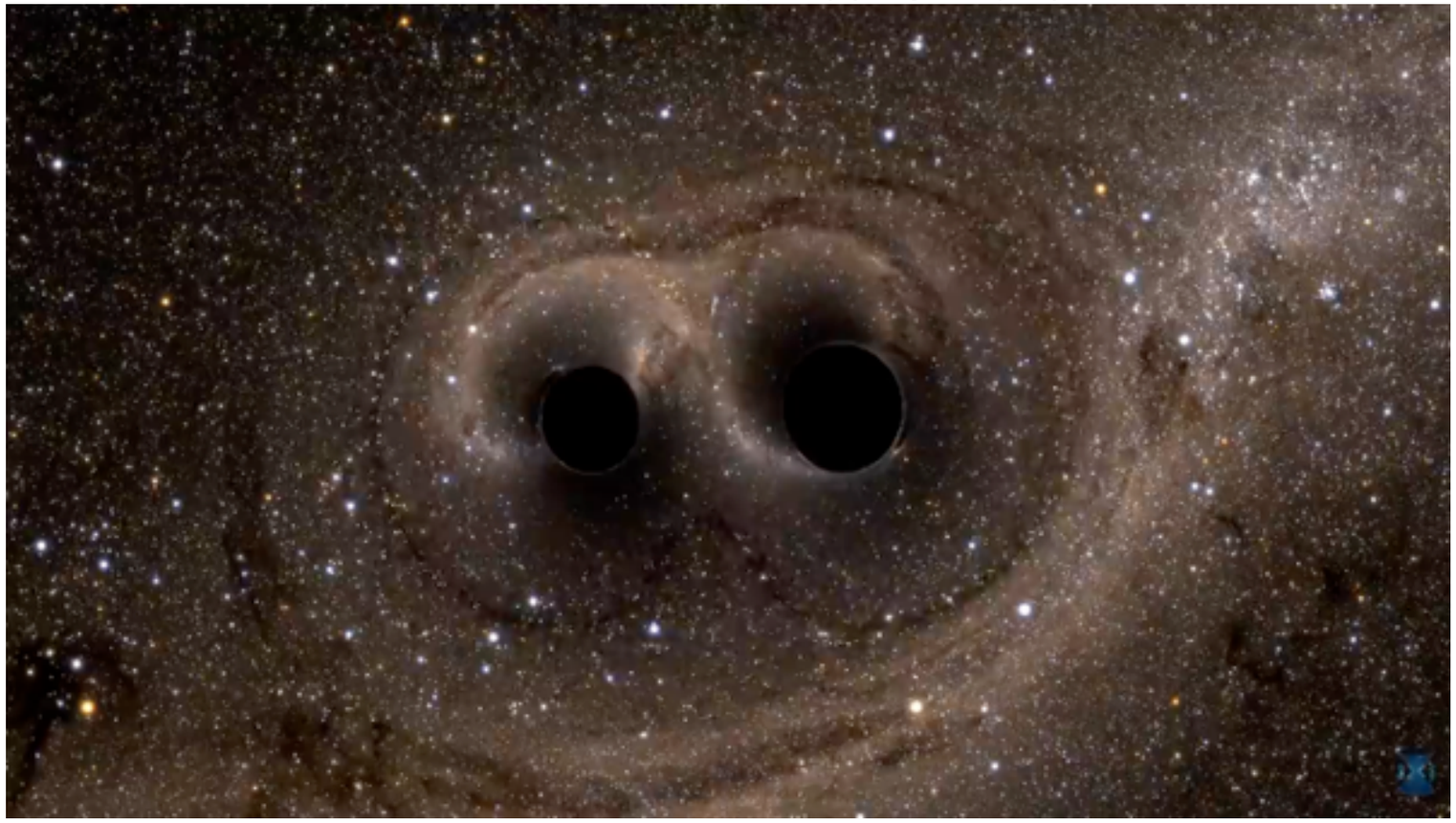
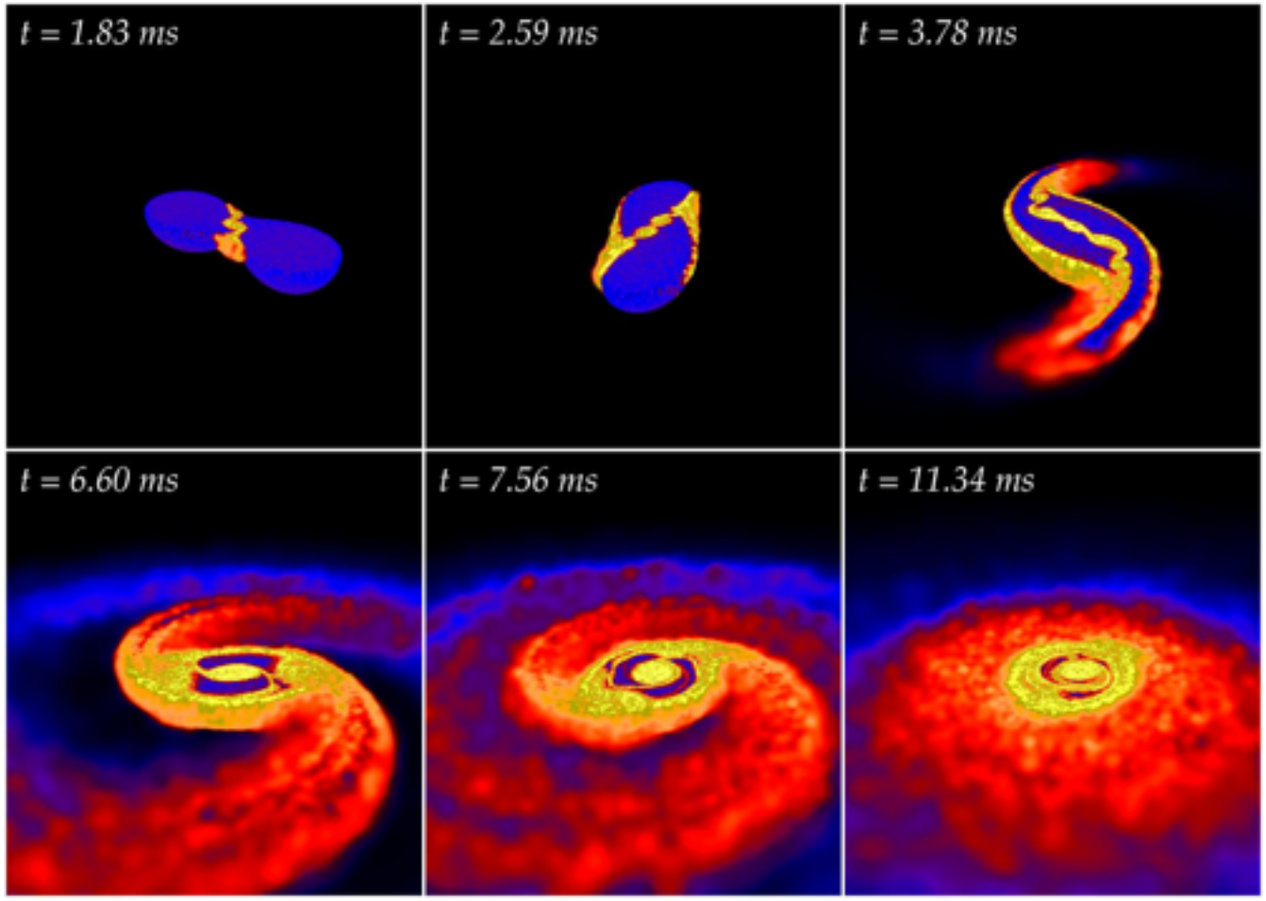
We expect to see more black hole merger events. We don't know if there are counterparts; maybe.

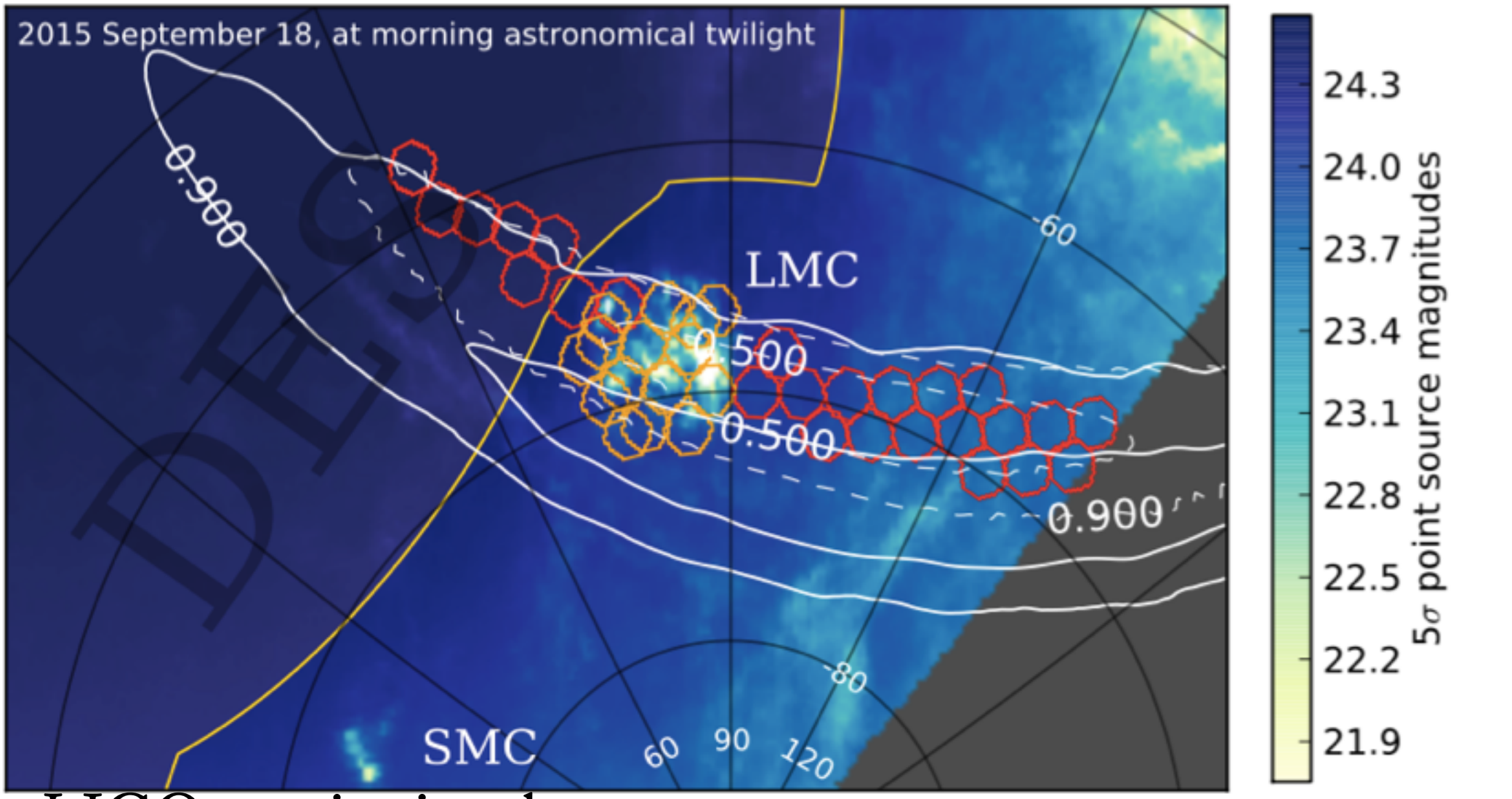
Credit: SXS, the Simulating eXtreme Spacetimes (SXS) project (http://www.black-holes



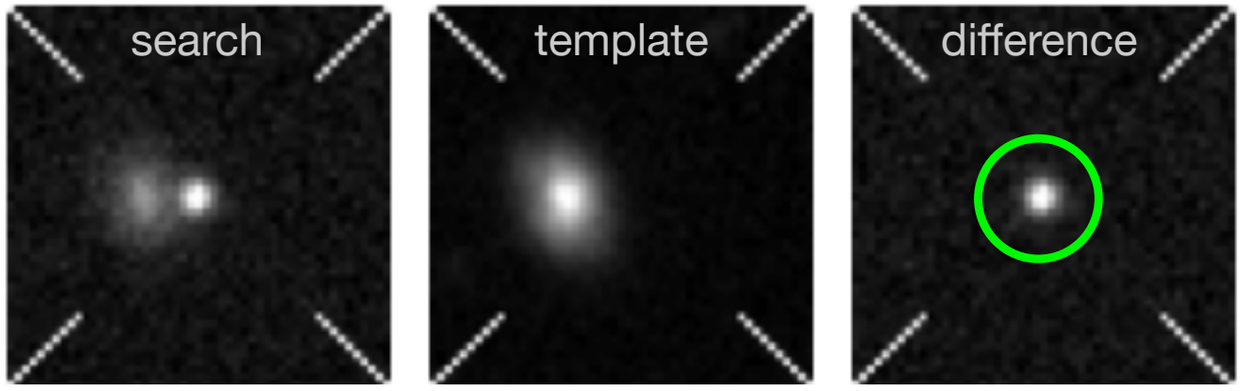
If there is a merger containing a neutron star, we expect to see the explosion of the decompressing neutron star matter, a "kilonova".



Credit: Daniel Price (U/Exeter) and Stephan Rosswog (Int. U/Bremen)



We followup LIGO gravitational wave sources. This is the map of GW150914; the hexes are what we imaged we DECam.



We use difference imaging to find transients, then timescales, colors, and other astrophysics to reject false associations to the event.

The Neutron Star Sources

DESGW is designed as a kilonova machine but there are two classes of merger to followup

- *Mergers involving a neutron star:*
  - Dim red glowing lanthanide opacity dominated neutron star decompression
  - M_i ~ -12

- *Binary black hole mergers*
  - Strong theory prior on no observable optical emission
  - e.g., a bare black hole moving through the galactic disk at 100 pc is i~22, LIGO events are at ~400Mpc

Kilonova are high-opacity explosions, but there can be a blue flash from decaying N

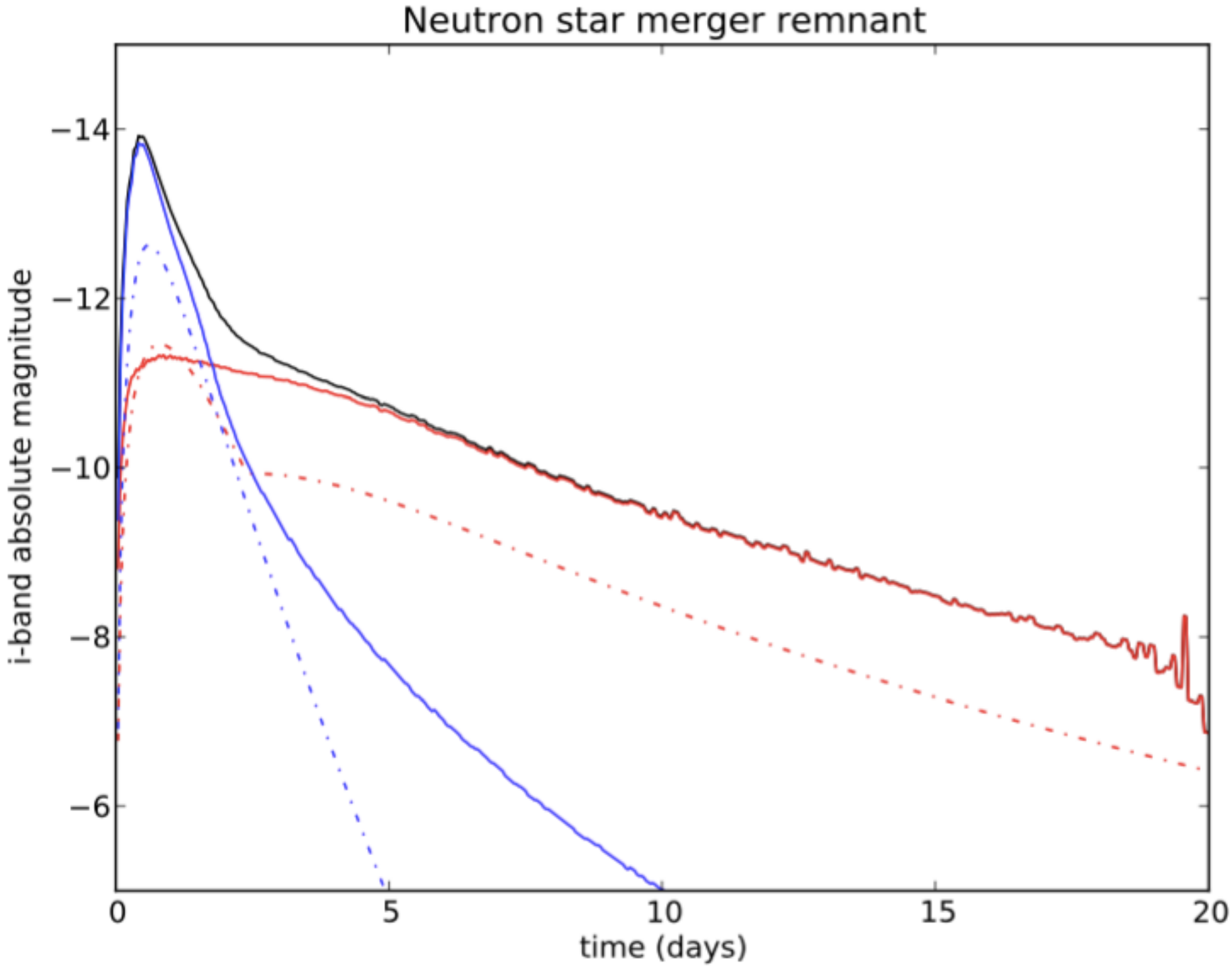
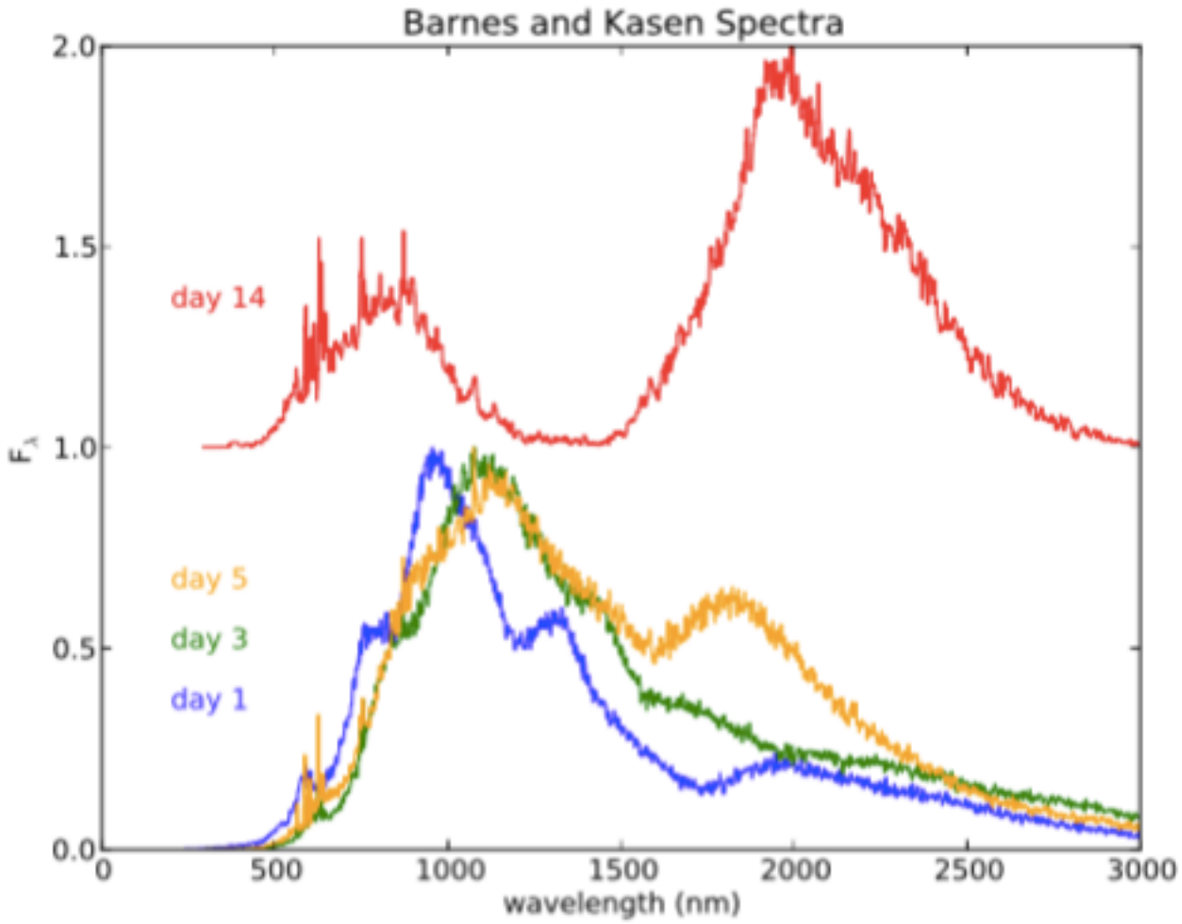
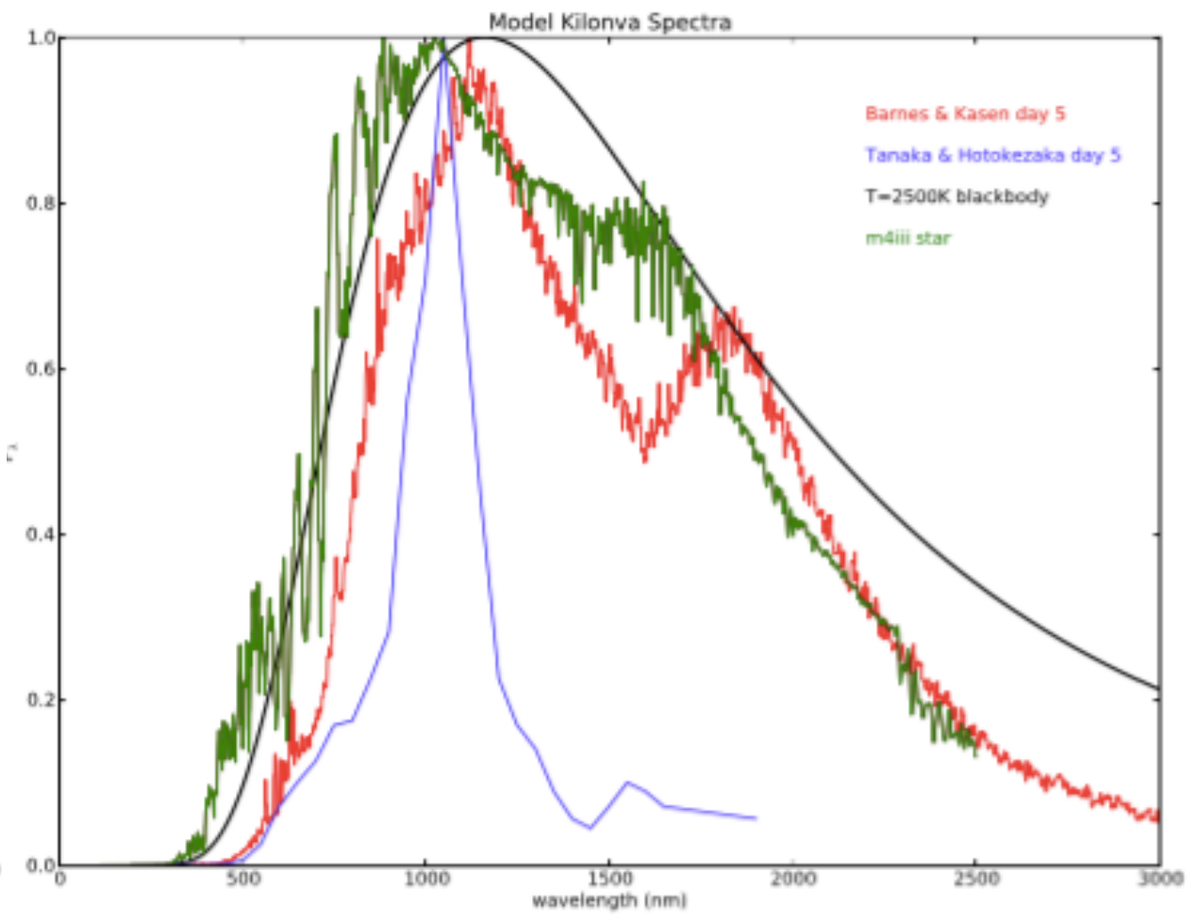


Figure 5: The i-band light curve. The black line is the sum of the disk+wind model.

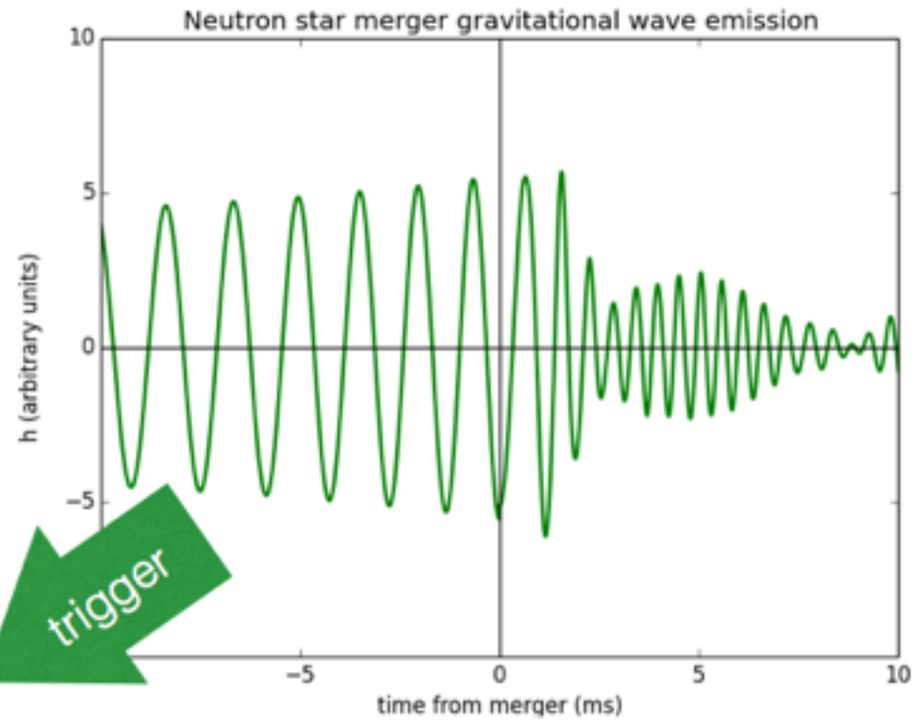
DESGW as a kilonova machine





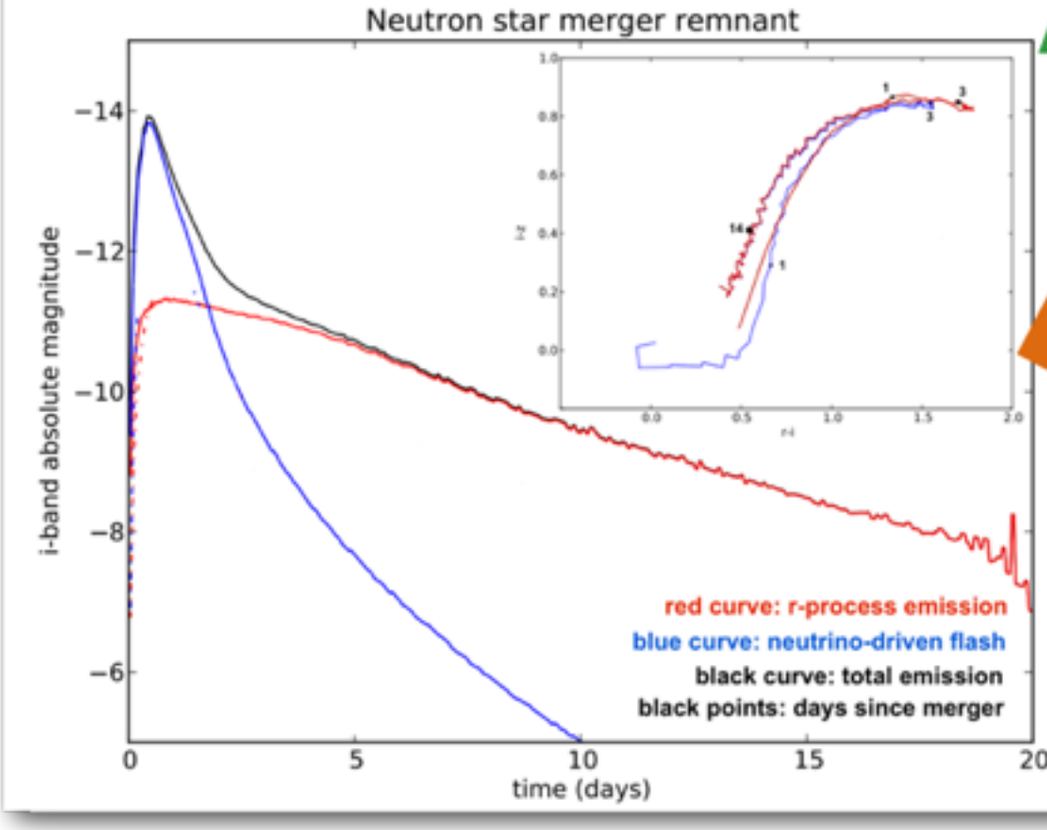
Kilonova change on 7 day scales, from G-star like on day 1 to M-star like on day 5.

LIGO/Virgo

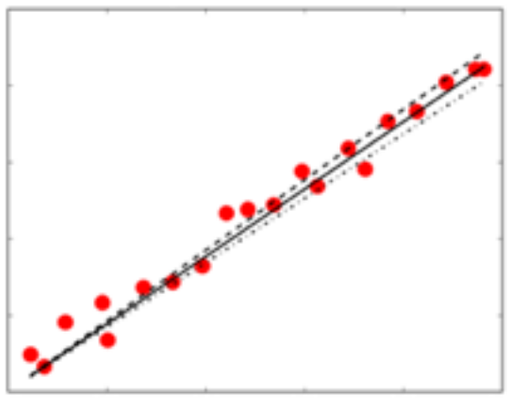


trigger

DES/DECaM



cosmology

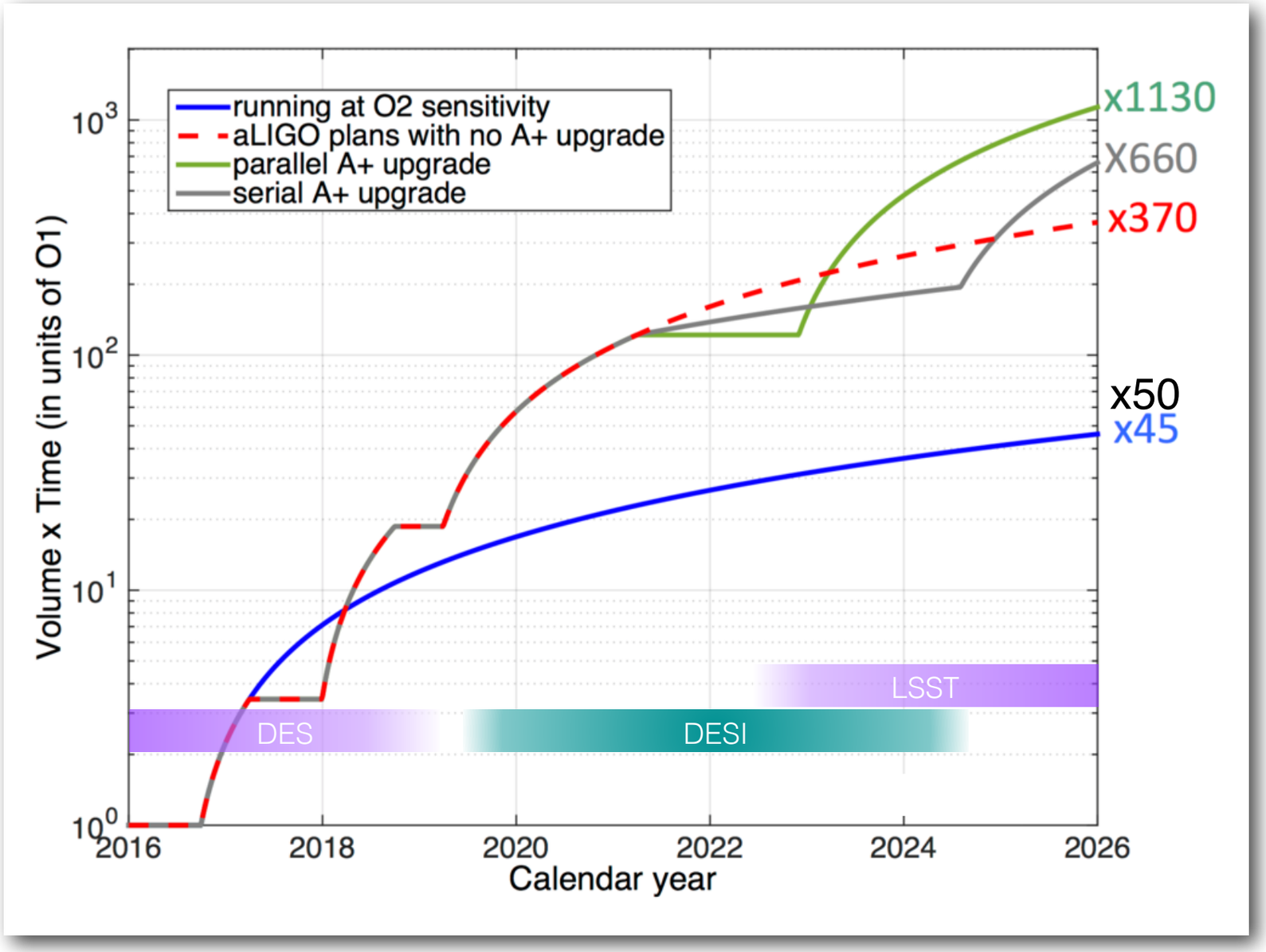


distance

redshift

The Future: LIGO and BLISS

The gravitational wave machines are ramping up. Between now and LSST it is DECam/DES/BLISS that covers the southern skies to the depths we need.

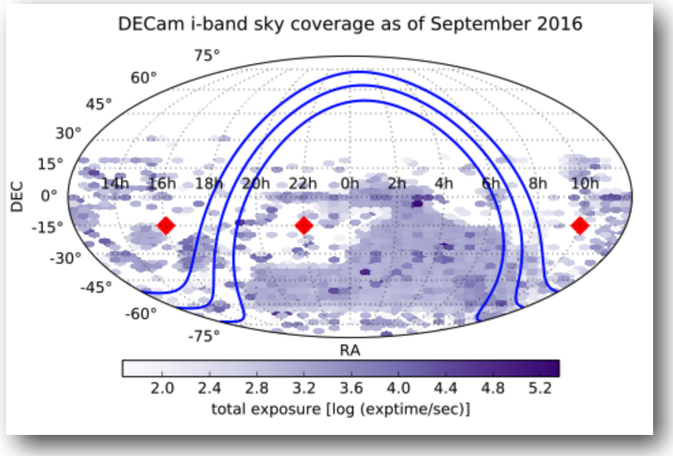


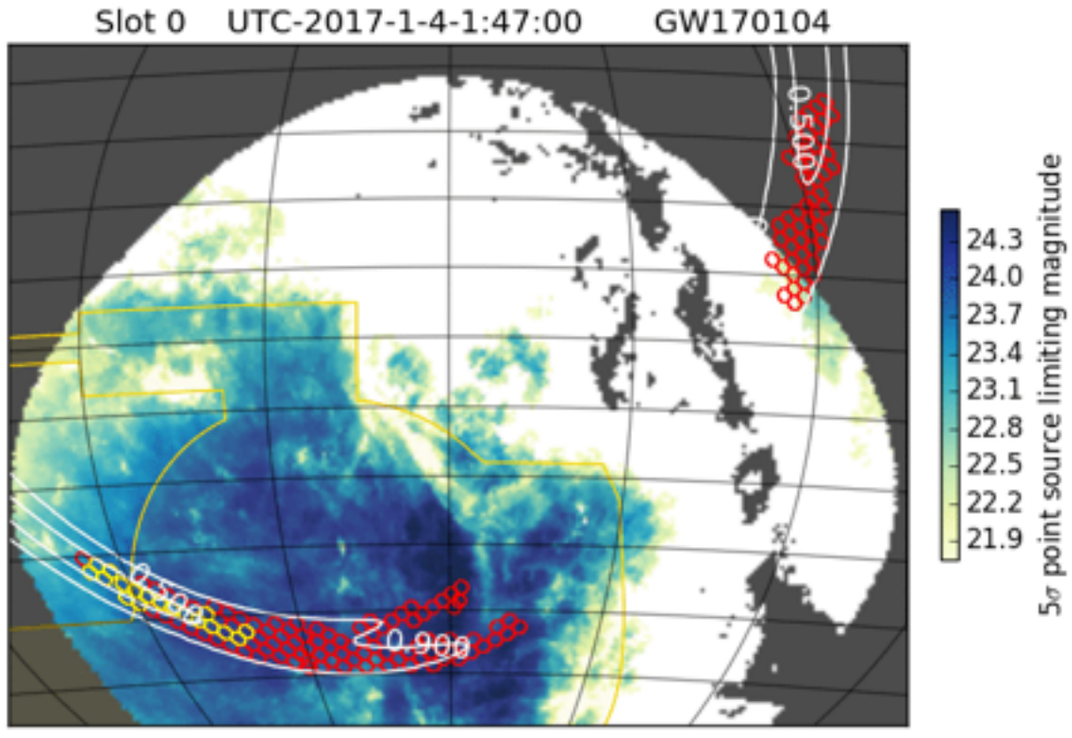
Plot from the DAWN-2016 workshop report.

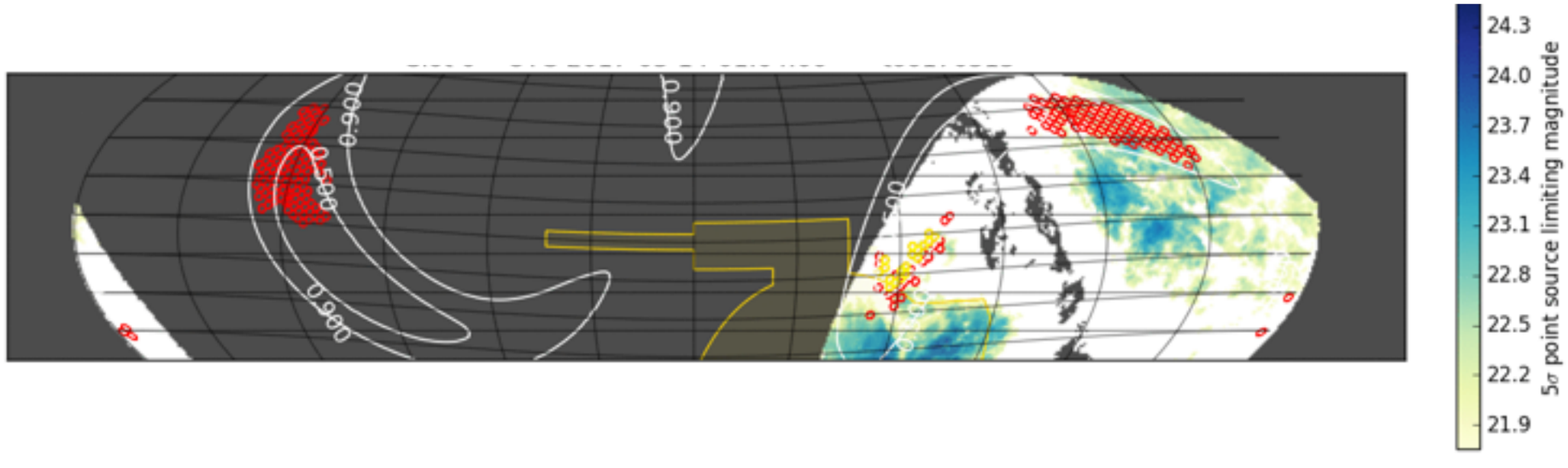
The issue is that the DES doesn't cover the entire southern sky.

These two gifs show plausible events. If we're lucky large fractions of the event are inside the DES footprint. Outside we have to rely on community data, which are spotty.

Bliss's goal of a uniform S/N map at Dec < 30 would solve this.







The potential GW+EM physics payoff

- *Neutron star* decompression events are very interesting (e.g., EOS)
- *Kilonova physics* is fabulously interesting (e.g., r-process element fission powered, lanthanide opacity dominated, possible bare neutron decay signature…)

    r-process nucleosynthesis in the universe likely comes from these events

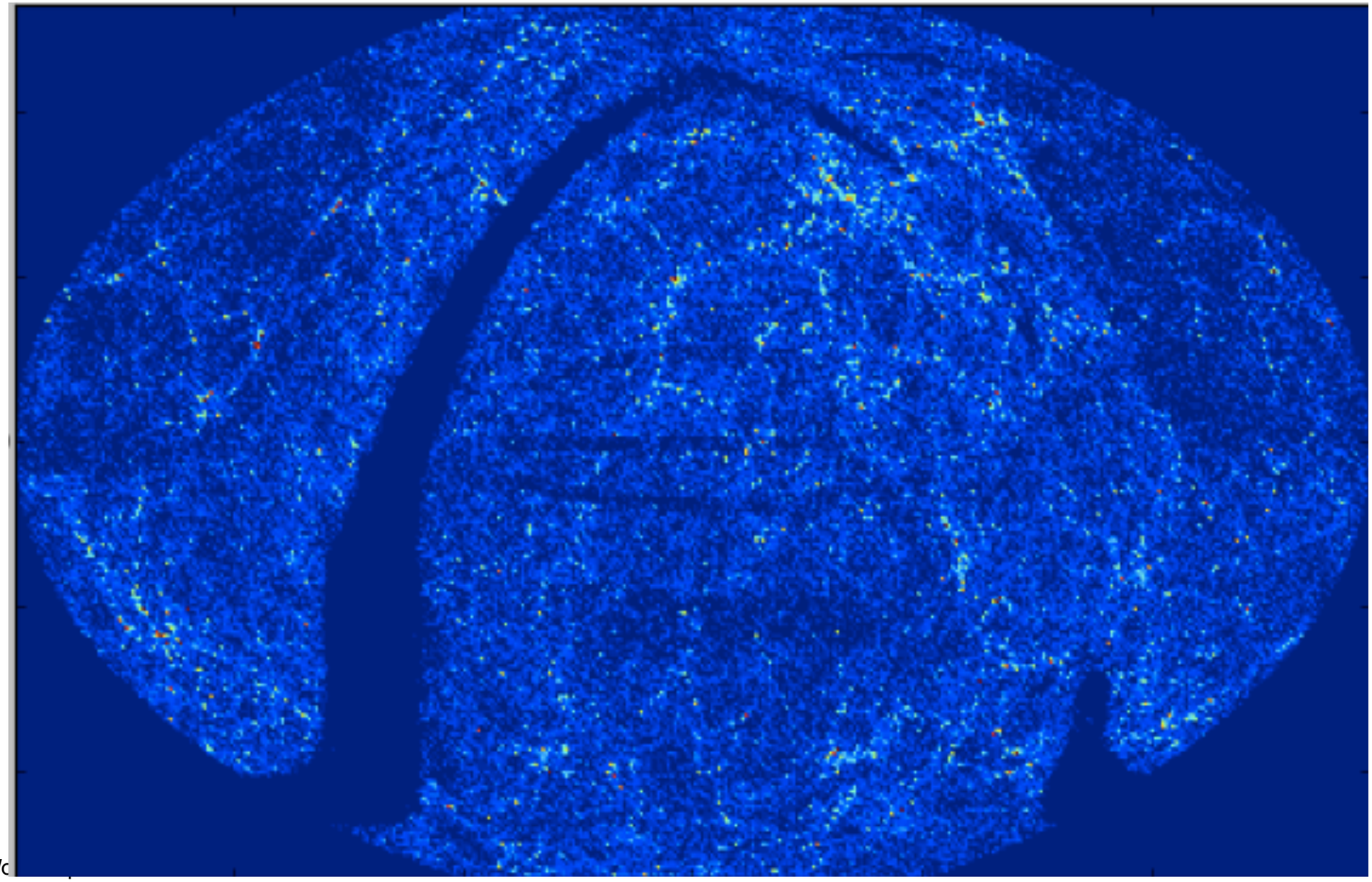
- *Cosmology from black holes and kilonova: Standard Sirens*
    - Distance from gravity wave modeling, redshift from the optical
    - Each event about half as good (in a sqrt(N) metric) as a single maser distance measurement
    - Bypasses both the local universe outward distance ladder and the CMB inward distance ladder
    - ALIGO and VIRGO get more sensitive: counts only go up with time

Galaxy Catalogs for NS sirens

Catalogs for black hole cross correlation cosmology are more standard photo-z catalogs

A 200Mpc galaxy catalog

The range of the LIGO NS events is on order of 200 Mpc.
One goal is to create a all-sky stellar mass calibrated catalog of galaxies with significant probability support at d < 200 Mpc.



The base distance catalog

Start with 2MPZ photometric redshift catalog of Bilicki et al (2014)
Each galaxy has photometric-z, with an uncertainty of 0.015
Some galaxies have spectroscopic z, tiny measurement error.

Will tabulate distance, need uncertainty in distance
$d = cz/H_o$, H_o= 70 kms/s/Mpc
$\sigma_d = c\sigma_z/H$ for photometric redshift $\sigma_z = 0.015$, σ_d = 64 Mpc
$\sigma_d = c\sigma_z/H$ for spectroscopic redshift, $c\sigma_z$ = 600 km/s, σ_d = 9 Mpc
600 km/s is ~Virgo cluster velocity dispersion

Retain all galaxies which do contribute probability at < 200 Mpc => z= 0.0467
$z_{spec} < 0.0467 + 3\sigma_z = z\sim0.053$ or, if there is no z_{spec} :
$z_{phot} < 0.0467 + 3\sigma_z = z\sim0.09$

Update the distances

There are 4 catalogs we will use to update the distances in this catalog:

EDD: The 8162 galaxies of the Extragalactic Distance Database (aka Cosmicflows) have real distances, known by a variety of methods but most often Tully- Fisher measurements (Tully et al., 2009, 2013, 2105).

NED-D: The "Master List of Redshift-Independent Extragalactic Distances" may be more up to date than EDD, though we believe EDD distances are to be preferred. Our NED-D list is all objects on NED-D that are galaxies, have d<250 Mpc, and not in Cosmicflows.

NED: The spectroscopic redshifts in NED will be the most up to date repository of the world's redshifts, modulo large data releases from surveys like SDSS and Oz-DES. Unfortunately, NED is a mess. We match all galaxies from NED at z <0.092 to the 2MASS XSC catalog for J < 15.1, removing matches against NED-D and Cosmicflows.

SDSS DR12 : We then use the SDSS DR12 z <0.1 . catalog. Our SDSS catalog removed matches against NED, NED-D, and Cosmicflows.

Fix 2MPZ incompleteness

The 2MPZ catalog systematically misses low redshift bright galaxies.
For example, the central galaxy of the Coma Cluster is not in 2MPZ.
This is due to image processing problems on the optical data underlying the 2MPZ and the conservative approach to it Bilick et al took.

Our approach is to use the objects from Cosmicflows, NED-D, NED-z and SDSS that are not matched to the 2MPZ catalog.

We will add these into the catalog, using optical data from the SDSS and the COSMOS SSA and infrared data from the 2MASS XSC.

In the next version we will use data from SDSS, DES, DECals both here and to replace the optical data in the 2MPZ catalog.

Work to be done:

- *Change pipeline to handle post-date templates*
  - This allows the writing of a paper based on a O2 event
  - Better- a reanalysis of all events we followed up in O1-O2

- *Merge current strategy code with the main injector*
  - Handles BH, NS, and burst event types
  - Make animated gif all-sky by default in main injector

- *Think about BLISS photo-z catalog and BLISS stellar mass catalog*
  - In the long run, we want to do forced photometry on WISE and VHS data given BLISS measurements of all-southern sky galaxies