Detectability of Fast Radio Burst (FRB) Optical Counterparts in Future Follow-Up Observations

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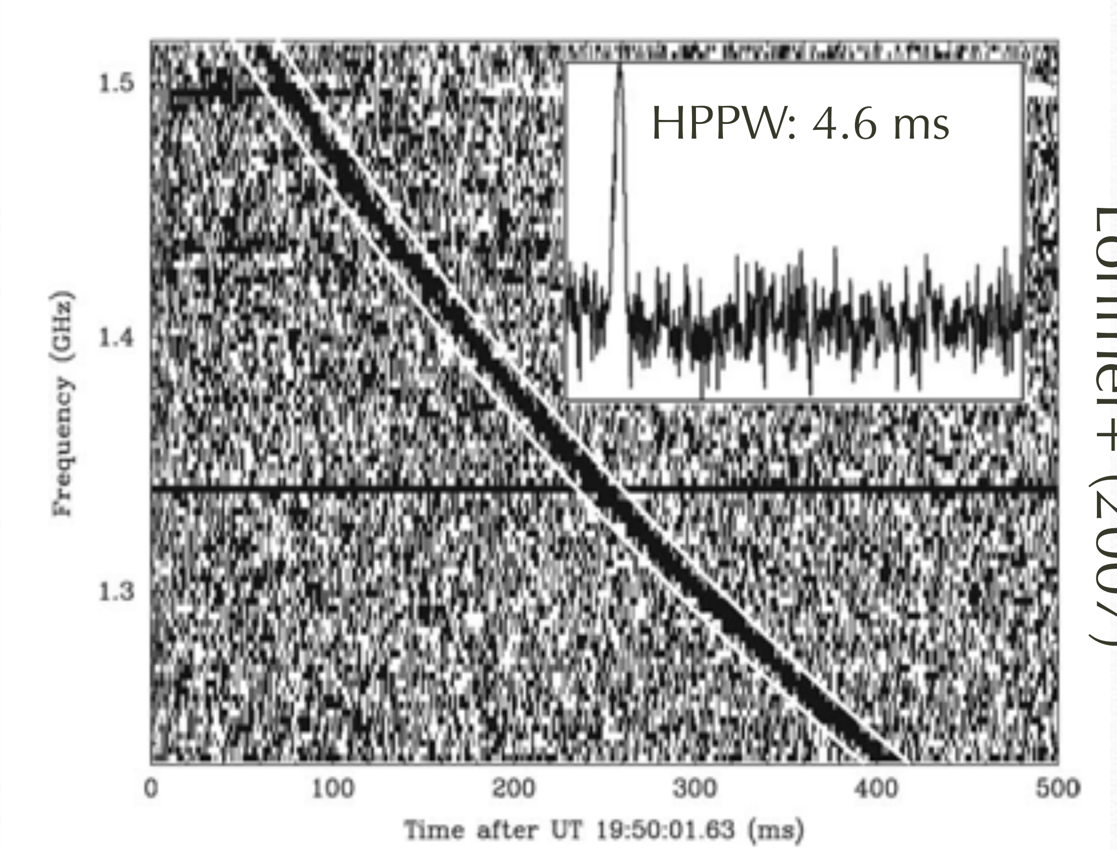
What's FRB?

- Fast Radio Burst (FRB)
  - a radio transient event with a duration of several milliseconds.
  - For now, 8 events are known (Lorimer+ 2007; Keane+ 2012; Thornton+ 2013; Spitler+ 2014; Burke-Spolaor+ 2014).
    - 7 were detected by the Parkes radio telescope, 1 was detected by the Arecibo telescope.

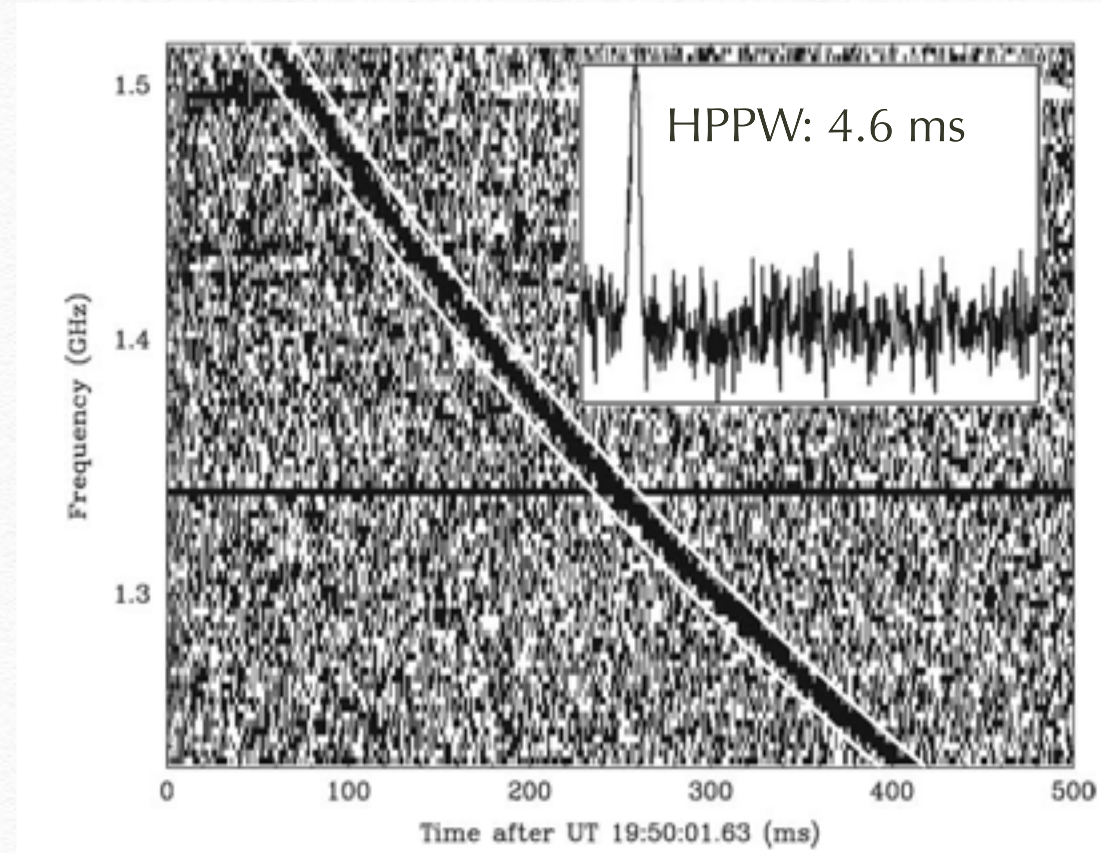


Lorimer+ (2007)

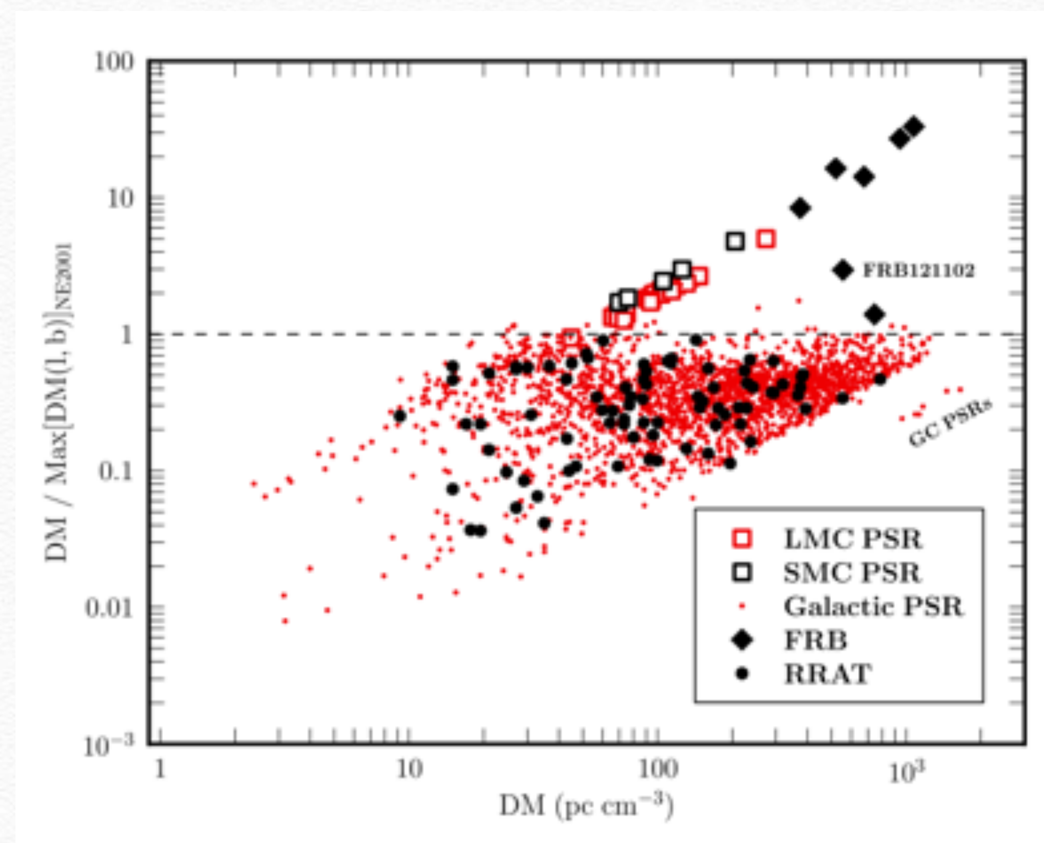
Caption: CSIRO's Parkes radio telescope. Credit: David McClenaghan, CSIRO

FRB properties

- Dispersion Measures (DM [cm^{-3}pc], free electron column density)
  - frequency dependent delay $\propto \nu^{-2}$DM
  - DM of FRBs: 300-1000 cm^{-3}pc
    - larger than MW model
  - Assuming dominant contribution from IGM, redshifts are ~ 0.3-1.0.
- Rates: $1.0 \pm 0.6 \times 10^4$ $sky^{-1} day^{-1}$
- If cosmological…
  - energy release: 10^{38-40} erg
  - rate density at z < 1:
    - $2.3 \pm 1.4 \times 10^4$ $yr^{-1} Gpc^{-3}$



Lorimer+ (2007)



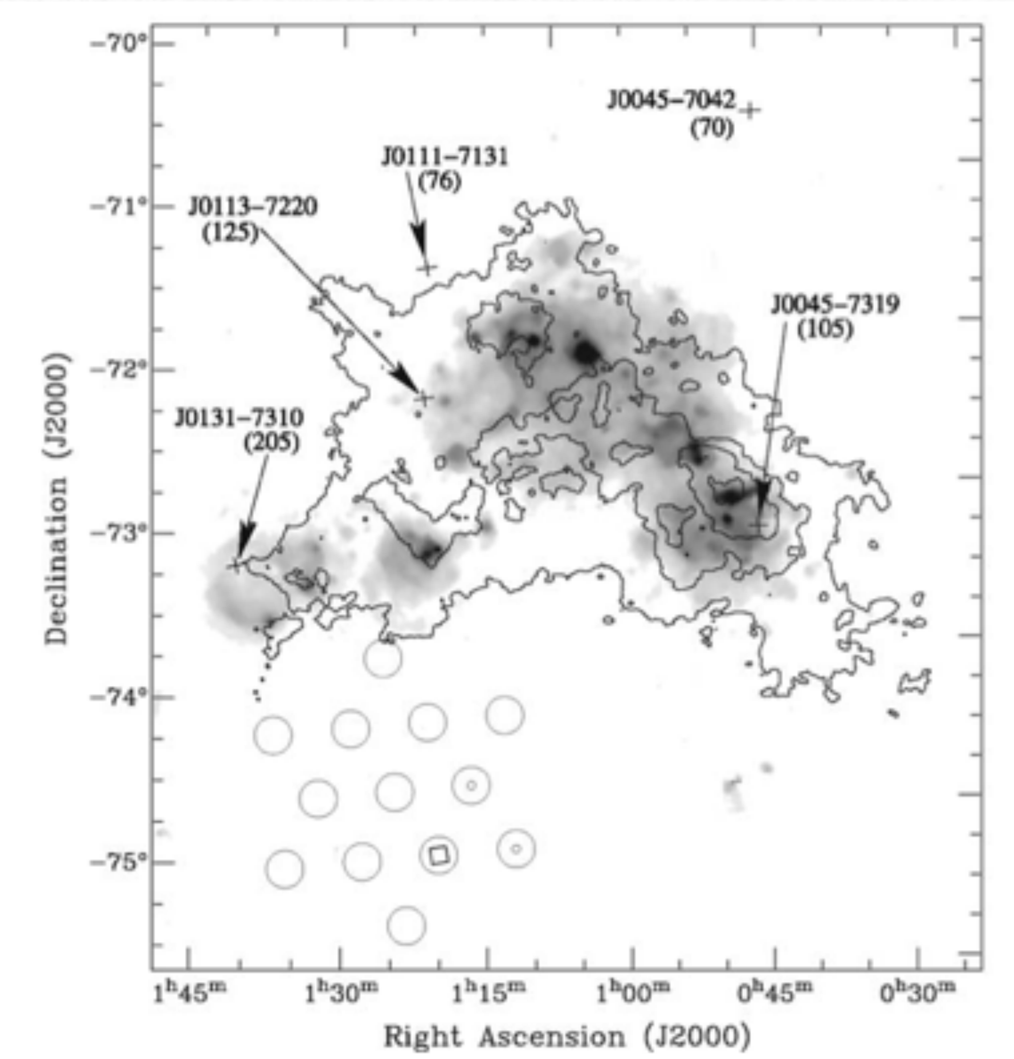
Spitler+ (2014)

The Origin of FRBs

- Collapse of rotating super-massive neutron stars to black holes (Falcke & Rezzolla 2014).
- Merger of double neutron star binaries (NS-NS, Totani 2013).
- Merger of double white dwarf binaries (WD-WD, Kashiyama + 2013).
- Flaring stars in the milky way (Loeb+ 2014).
  - Large DM may result from corona.
    - But $\Delta t \propto \nu^{-2}$DM law breaks down at high density (e.g. Tuntsov 2014).
- Pulsars with unusual amplitude distribution, or annihilation of 10^{13} kg BHs (Burke-Spolaor+ 2011; Keane+ 2012).
  - relies on uncertainties of the MW ISM model
- Perytons (Kulkarni+ 2014)

Localizing FRBs

- Beam diameter of the beams: 14 arcmin.
  - Host galaxy ID is unavailable.
  - Multi wavelength follow up is desirable.
- The currently known FRBs are discovered in post analyses.
  - Real time follow up has never been performed yet.



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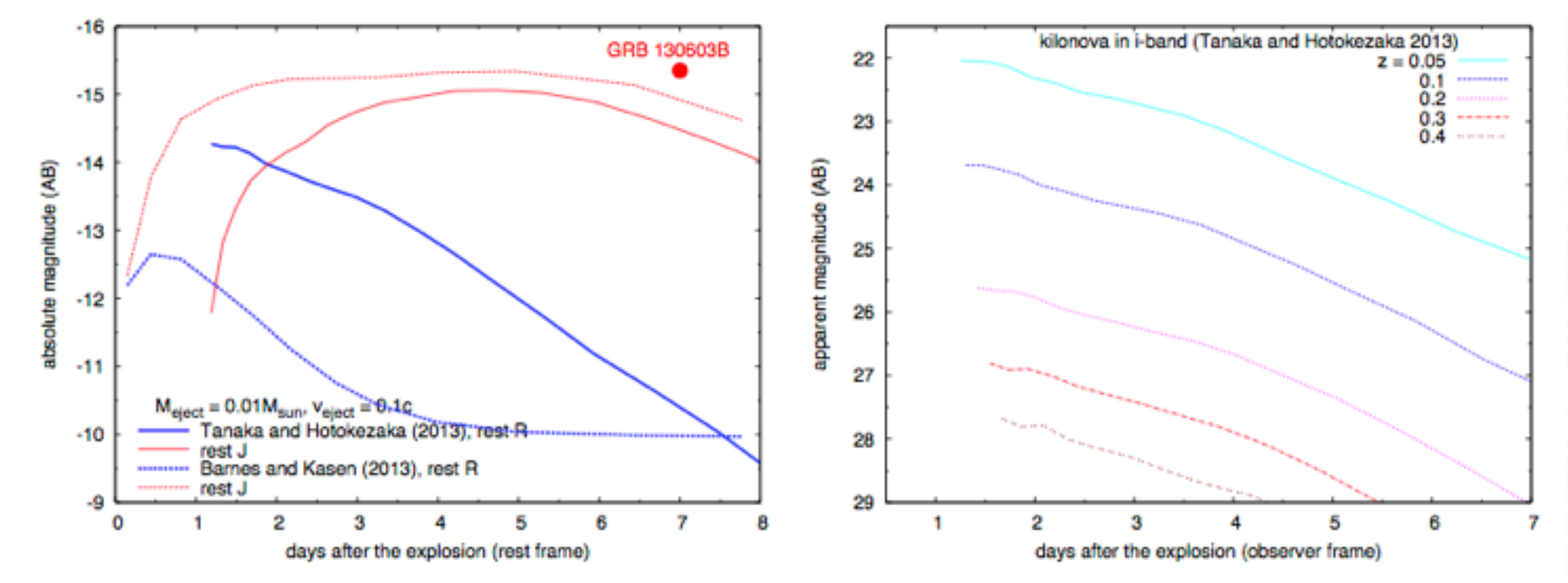
Kilonovae as the Counterparts



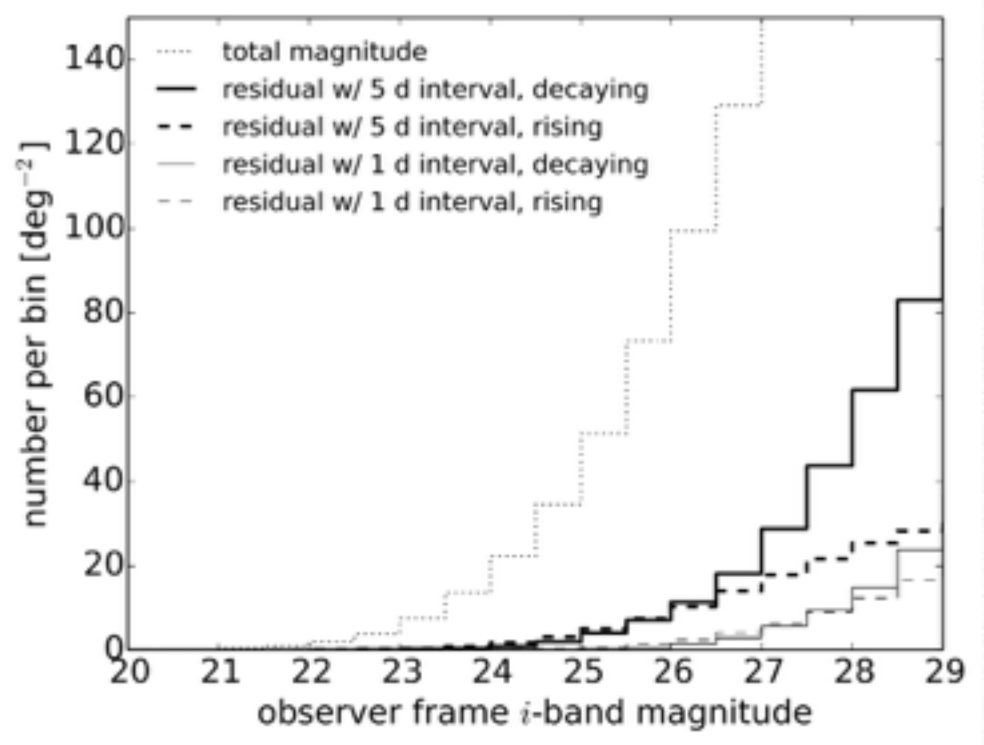
- Optical/NIR transients powered by decay of radioactive elements formed via *r*-process in NS-NS merger ejecta (Li & Paczynski 1998).
  - A candidate was found associated with short GRB 130603B (e.g. Tanvir+ 2013).
- Much fainter than SNe due to opacity of the *r*-process elements (Barnes & Kasen 2013; Tanaka & Hotokezaka 2013).
  - Red optical bands are preferable.
  - detectable up to z ~ 0.3 ⇒ ~ 2 FRB/yr by the Parks receiver.
  - FOV must cover the radio beam (~ 100 $arcmin^2$)

SN Contamination

- Some physically unrelated SNe may be found in the error circle.
- mock catalog of SNe
  - Ia & core-collapse (Ibc, IIP, IIL, IIn) SNe at redshifts $0 < z < 2$ (up to 4 for IIn) are considered.
    - luminosity functions (Barbary+ 2012; Dahlen+ 2012)
    - spectral templates (Hsiao+ 2007; Nugent+ 2002)
    - cosmic SN rate history
      - Ia : Okumura+ (2014)
      - core-collapse: $\propto$ cosmic SFR history (Behroozi+ 2013) with normalization to low-z SN rate of each type (Dahlen+ 2012).

Searching Transients

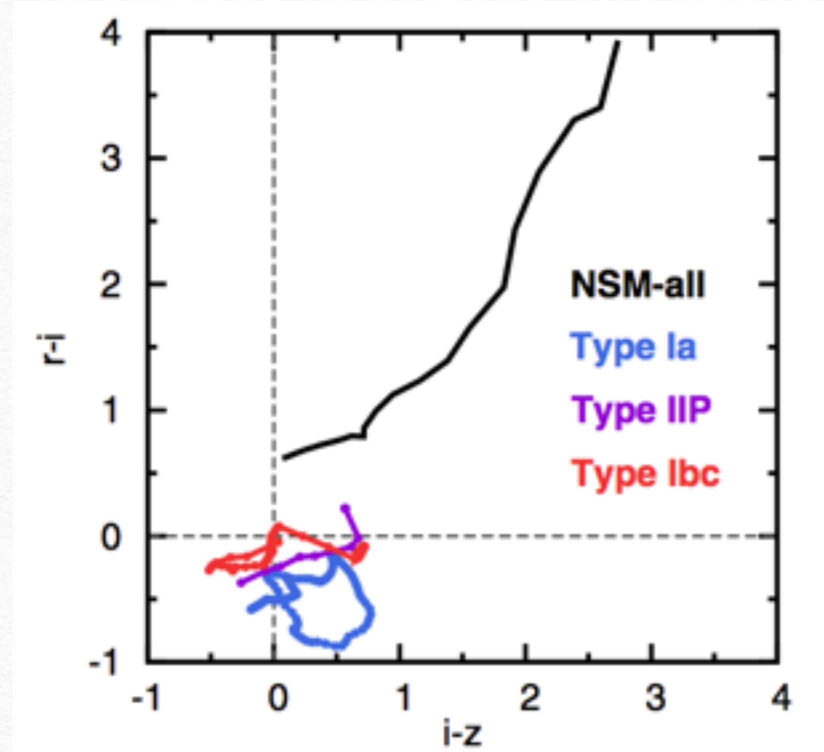
- transient search in a residual image with some time interval
  - The interval of several days is sufficient for kilonovae.
  - in a survey down to $i_{res} = 27.5$, the number density of contaminating SNe is 73.5 deg^{-2} (3.3 in a Perkes beam).

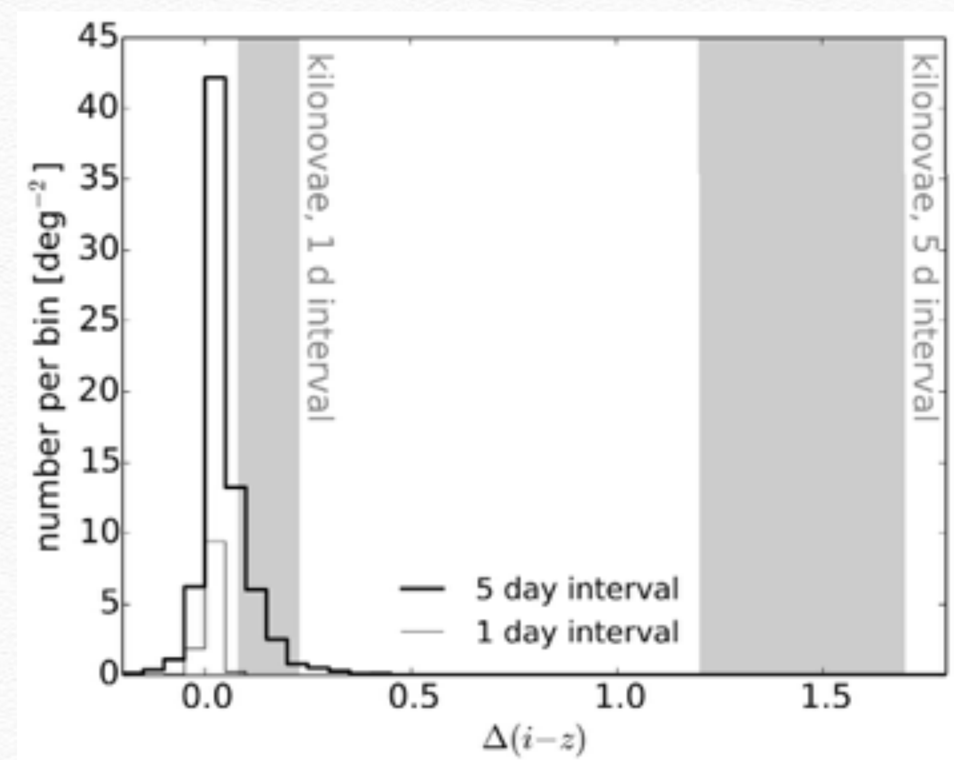


- residual magnitude:
  a magnitude observed in a residual image, $m_{res} = -2.5\log_{10}|f_{\nu,1st} - f_{\nu,2nd}| - 48.6$.
- total magnitude: non residual magnitude

Color of kilonovae

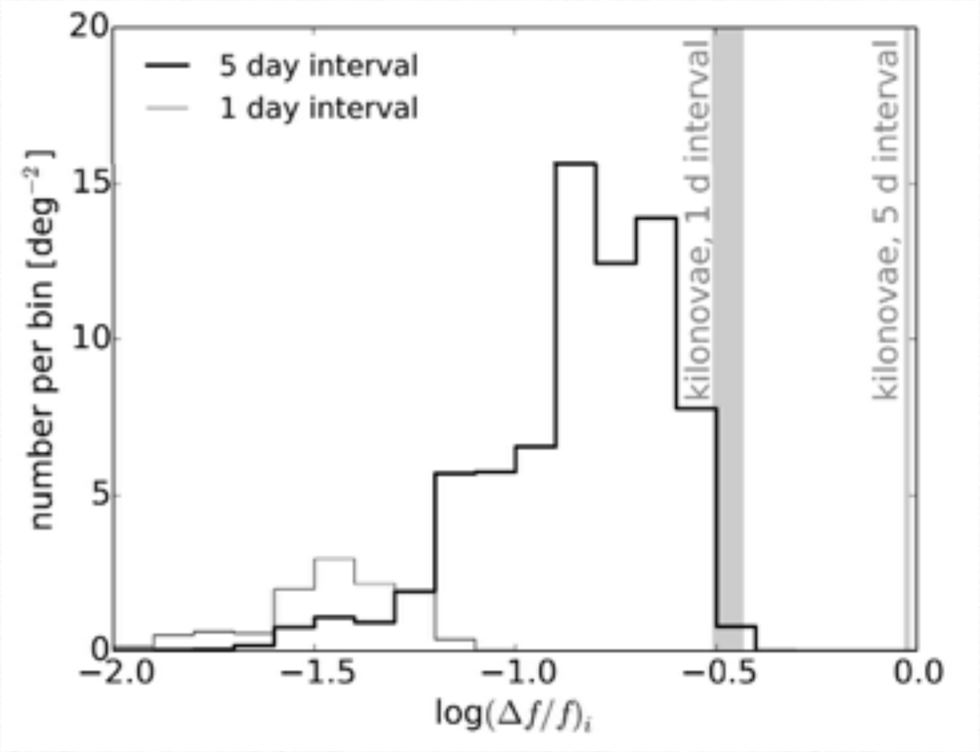
- Kilonovae are redder than SNe.
    - SNe may have similar color with dust/ redshift.
- Kilonovae dramatically evolve redder with time.





Tanaka & Hotokezaka (2013)

How to distinguish a kilonova from SNe



- Kilonovae decay more rapidly than SNe.
  - SNe with similar m_{res} ($-\Delta f$) to that of a kilonova have much larger Δm ($-\Delta f/f$).
- Not necessarily requires 2nd epoch detection.

SNe Ia as the Counterparts

- A WD-WD merger is one of the promising candidates of SN Ia progenitor.
- much brighter than kilonovae
  - How can we distinguish it from contaminants?
- For a SN Ia, the explosion time can be constrained to a day scale precision with spectroscopic classification and some light curve data points.
  - Spectroscopic classification is available when $i \lesssim 24$.
    - redshift $\lesssim 0.6$ for SNe Ia
    - Number of contaminations with $i < 24$ is 1.3 in a Parkes beam, but probability that a contaminant have the same explosion date to the FRB is $\lesssim 0.005$ assuming SN Ia rate density derived by Okumura+ (2014).
  - The FRB associated SN Ia can be verified with significant confidence.

Conclusions

- If FRBs originates from NS-NS mergers, a kilonovae may accompany a FRB.
    - Recent model of kilonova suggests it can be detected at cosmological distances with 8-m class telescope.
    - Kilonovae can be distinguished from SNe with the color evolution [e.g. Δ(i-z)] and/or the variability (Δf/f).
- In the case of WD-WD mergers, the expected counterparts are SNe Ia (brighter than kilonovae).
    - SN Ia association can be verified with the spectroscopic classification and some data points of light curves.