Binary Neutron Star rate predictions from observations of dwarf galaxies

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Motivation

Binary Neutron Stars (BNS) mergers are expected to produce:
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- Gravitational Wave (GW) signals, detectable with GW interferometers (e.g. LIGO)
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- Electromagnetic signatures, observable with telescopes (e.g. DECam at Blanco Telescope).
What is a Binary Neutron Star (BNS)?

- Gravitationally bound system of two neutron stars.
- A neutron star is the remnant of a core-collapse supernova for $M_{\text{ZAMS}} < 25 \, M_\odot$. 

NASA/Goddard Space Flight Center/Dana Berry
Binary Neutron Star Merger

Merger is the result of the shrinking of the distance between the neutron stars due to emission of gravitational waves.

They are rare events (not detected yet).
Electromagnetic signatures of BNS

- Short Gamma Ray Burst (SGRB)
- Kilonova
- Afterglow

Metzger and Berger 2012.
Rapid neutron capture (r-process) is the process by which heavy radioactive elements are formed (Metzger et al 2010).

Borg and Brennecka 2014.
Reticulum II

- Dwarf galaxy in the local group.
- High-resolution spectra analysis of the nine brightest members of Ret II done by Li et al 2016.
- A promising mechanism to explain metal abundance in Ret II is a binary neutron star merger.

Bechtol et al 2015
High Resolution Spectroscopy on Reticulum II

Seven of the stars have high \textit{neutron-capture} element abundances, consistent with \textit{r-process} pattern.

\textit{Ji et al 2016}
Goal

To calculate a lower limit to the astrophysical rate of Binary Neutron Star Mergers from the event in the dwarf galaxy Reticulum II.

+ 

To analyze the observational selection effects of LIGO.

= 

Predict number of observable events with LIGO
Lower limit approximation for rate of BNS

Based on the event in Reticulum II: At least 1 event observed in 13 dwarf galaxies (galaxies with high-resolution spectroscopy analysis) in the timescale of a few Gyr.

\[
\frac{1\text{event}}{(\sum_{n=1}^{13} M_*) \times (T_{universe} - T_{event})} \approx 10^{-15} M_{\odot}^{-1} \text{yr}^{-1}
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Assumption: Number of BNS mergers scales up with stellar mass!
Two methods to approximate galactic stellar mass / luminosity

• Schechter Mass Function:

Yields spatial density of galaxies as a function of their stellar mass.

• Galaxy catalog of nearby universe (<200 Mpc):

To estimate luminosity (proxy for stellar mass) at different distances.
Schechter Mass Function

\[ \phi(M) = b \times \phi^* \ln(10) [10^{b(M - M^*)}]^{1+\alpha} \exp[-10^{b(M - M^*)}] \]

- \( M^* \) determines where the mass function changes slope
- \( M \) is the mass
- \( \phi^* \) is the normalization
- \( \alpha \) is the slope for fainter, lower mass galaxies.

Multiplying the function by \( 10^M \) and integrating for the limits \( 10^6 \text{–} 10^{12} \, M_\odot \) yields an estimate of the stellar mass in 1 Mpc\(^3\).
Building galaxy catalog to estimate stellar mass

• Initial catalog put together by Jim Annis.
  – i-Band < 15.9 catalog of galaxies over the whole sky.
  – 4 catalogs used to update the distances:
    • EDD
    • NED-D
    • NED
    • SDSS DR12
  – The catalog has
    • RA, Dec, redshift
    • Distance
    • i-magnitude, g-i color
    • Absolute magnitude
    • Stellar mass

\[
mass = \frac{M}{L} - 0.4(M - 4.58)
\]

\[
M/L = -0.68 + 0.7(g - i)
\]

Taylor et al (2011)
Annis (2016)
Building galaxy catalog to estimate stellar mass

Artificial features around galactic plane and SDSS footprint due to difference in catalog source for redshift and color.

Annis 2016
I worked on rebuilding the catalog (<200 Mpc) to eliminate artificial features:
I used 2MASS Extended Source Catalog as the base catalog and added distances from other surveys in the following preferential order:

1) Distances from NED and EDD

2) Spectroscopic redshifts from NEDZ and SDSS

3) Photometric redshifts from 2MPZ catalog
Results from New Galaxy Catalog

Integrated J-band absolute magnitude per pixel

J-Band Magnitude
Results from New Galaxy Catalog

Integrated number of BNS merger event rates per year per pixel

BNS event rates (yr\(^{-1}\)pixel\(^{-1}\))
Comparison with literature values

- Rate with Schechter Function approach = $286 \text{ Gpc}^{-3} \text{yr}^{-1}$
- Rate with Galaxy catalog approach = $135 \text{ Gpc}^{-3} \text{yr}^{-1}$
LIGO observational selection effects

LIGO has observational selection effects for certain regions of the sky (Chen et al 2016): more sensitive to some regions of the celestial sphere than others.

This depends on:

- Declination (latitude) due to location of interferometers
- Right Ascension (longitude) due to nonuniform daily and annual cycle.
LIGO observational selection effects

LIGO Hanford & Livingston network antenna pattern for 09/14/2015

Chen et al. 2016

Probability per deg$^2$

5.01461e-09 1.64807e-05
LIGO observational selection effects

May 2017 preferred regions for GW detections on the celestial sphere

Chen et al. 2016
Predicting observable rates of BNS with LIGO

Multiply LIGO sensitivity map (for every month and rates map.)
Predicting observable rates of BNS with LIGO

We get an expected number of observable events with LIGO of \ (~2.4 \text{ yr}^{-1}).
Literature comparison

Rate of BNS merger events

- O1 (2015)
- O2 (2016-2017)
- 2017-2018
- 2019

- This work (Schechter Mass Function approach)
- This work (Galaxy catalog approach)

Expected number of observed events per year for a radius of 200 Mpc

- Fong et al. 2015
- Coward et al. 2012
Future steps

• Build LIGO sensitivity maps for sources at different distances in order to make a better prediction of the number of observable BNS merger events.

• Consider DECam footprint and use this work to inform future EM follow-up.
References

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