Testing star formation models with Einstein Telescope

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Overview

- Star formation rate (SFR) models and their impact on compact binary coalescence rates
- Binary neutron star coalescences as trackers of SFR
- Simulations
- Results

Star formation models and compact binary coalescence

- Coalescence rate at redshift z, per unit time and unit volume, as observed at z=0:

$$\dot{\rho}_c^0(z) = \dot{\rho}_c^0(0)\frac{\dot{\rho}_{*,c}(z)}{\dot{\rho}_{*,c}(0)}$$

where: $\dot{\rho}_c^0(0)$ coalescence rate at current epoch (Mpc^{-3} Myr^{-1})
$\dot{\rho}_{*,c}^0(z)$ relates past SFR to rate of coalescence

- Relationship with underlying SFR $\dot{\rho}_*(z)$:

$$\dot{\rho}_{*,c}^0(z) = \int \frac{\dot{\rho}_*(z_f)}{(1+z_f)}P(t_d)dt_d$$

with z_f redshift at which progenitor binary formed
t_d delay time between formation of progenitor and coalescence
$P(t_d)$ probability distribution for delay time

- For $t_d > \tau_0$ (minimum delay time), $P(t_d) \propto 1/t_d$

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Star formation models and compact binary coalescence

- $\dot{\rho}_c^0(z)$ coalescence rate per unit time and per unit (comoving) volume
- The coalescence rate per unit time and per unit redshift is then

$$\frac{dR_c^0}{dz}(z) = \dot{\rho}_c^0(z)\frac{dV_c}{dz}(z)$$

- This depends on:

  - Model for the formation of progenitor binaries $\dot{\rho}_*(z)$
  - Rate of coalescence at current epoch $\dot{\rho}_c^0(0)$
  - Minimum delay time τ_0 between formation and coalescence

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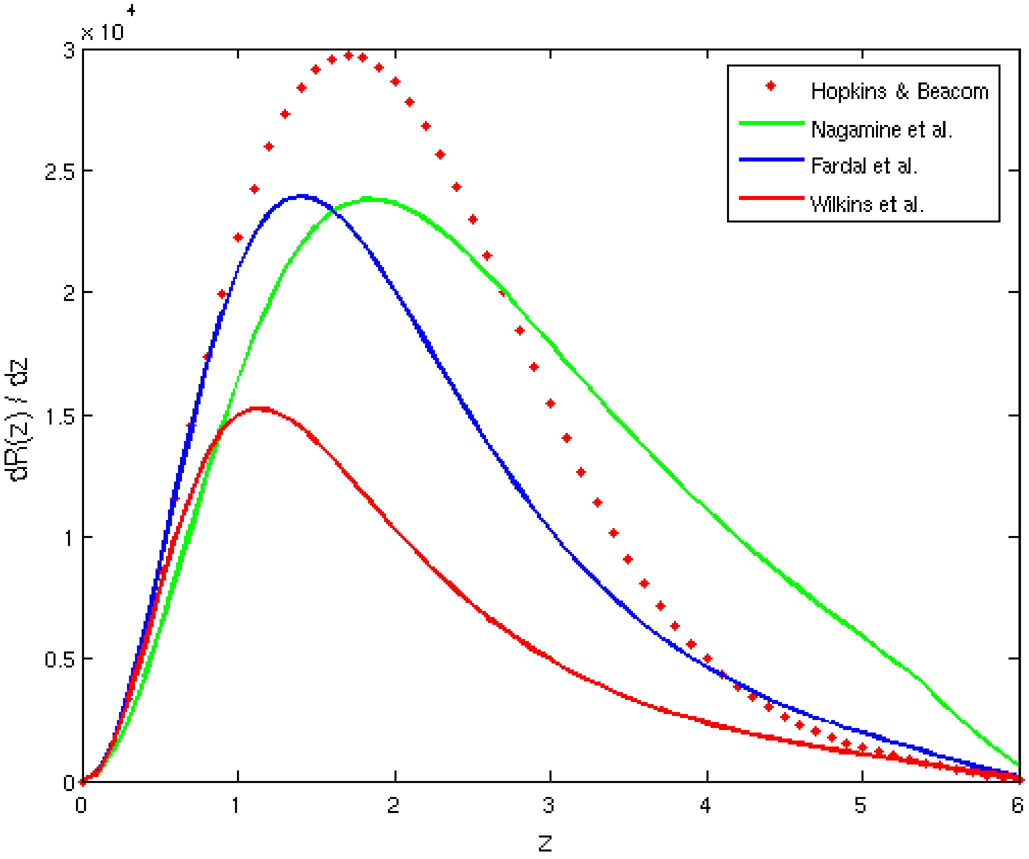
Different SFR models

Will consider 4 different models
[see Regimbau & Hughes, arXiv:0901.2958 for references]:

- Hopkins & Beacom '06: Lower bounds using evolution of stellar mass density, metal mass density, SN rate density; upper bound from Super-Kamiokande results on neutrino flux from core collapse SN
- Nagamine et al. '06: Combining results from (i) direct observations, (ii) a model using local fossil evidence at z ~ 0, (iii) theoretical *ab initio* models
- Fardal et al. '07: New proposal for initial mass function with a view on reconciling SFR predictions with total extragalactic background radiation
- Wilkins et al. '08: Based on stellar mass density measurements, new ansatz for initial mass function

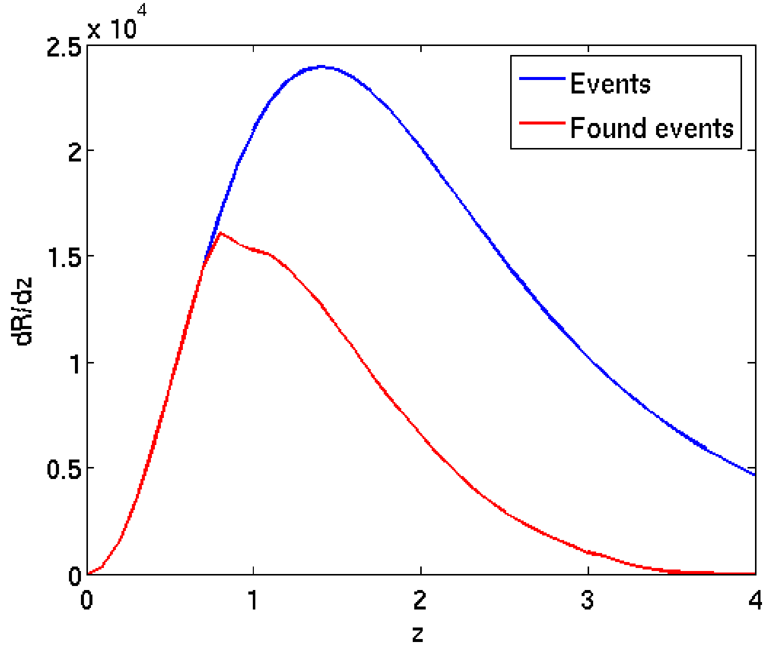
Different SFR models

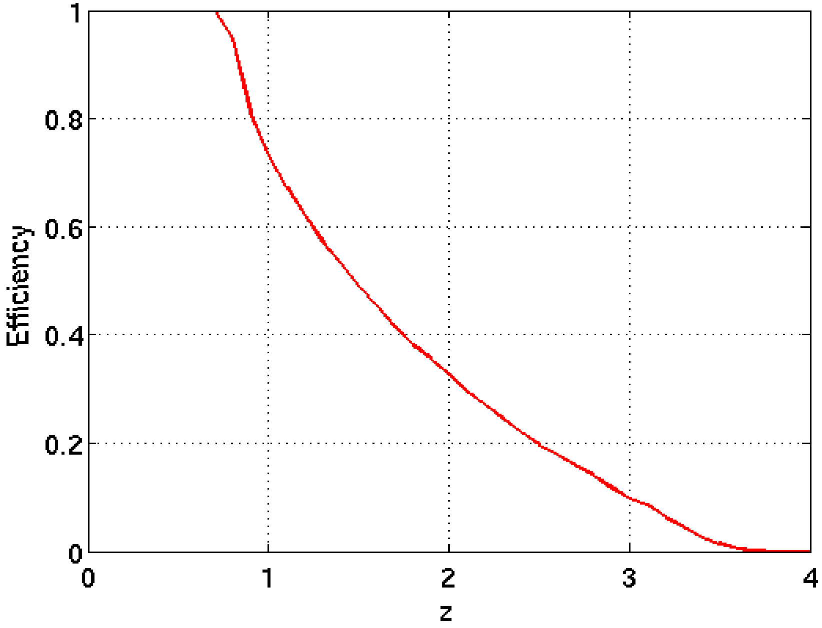
- Tania's code rate.m (available in WG4 work area):
  Specify model, minimum delay time τ_0 (e.g., 20 Myr for BNS),
  local coalescence rate $\dot{\rho}_c^0(0)$ (e.g., 0.03 Mpc^{-3} Myr^{-1})



Binary neutron star coalescences as trackers of SFR

- BNS events most abundant compact binary coalescences
- ET should see ~10^6 yr^{-1}
- But: detection efficiency? (Demanding, e.g., inspiral SNR>8)





Inferring coalescence rates from observed BNS events

- From BNS inspiral signal: measure luminosity distance D_L
- Relationship between D_L and redshift z depends on dynamics and geometry of the Universe
- Assume a cosmological model, e.g., spatially flat Friedman-Robertson-Walker with H_0 = 70 km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_\Lambda = 0.73$, $w = -1$
- Use cosmological model to infer z from measured D_L
- Bin "measured" redshifts to measure dR/dz
- Recovered distribution will be imperfect because of:
    - Loss of efficiency above $z \sim 0.7$
    - Uncertainties in measuring D_L

Measuring D_L

- Uncertainty in D_L :

  - Uncertainty due to ET's noise; can be modeled roughly as

    $$[\Delta D_L/D_L]_{ET} \sim 1/SNR$$

  - Uncertainty due to weak lensing, which we model as

    $$[\Delta D_L/D_L]_{WL} = 0.05\ z$$

- Add in quadrature:

$$\Delta(\ D_L/D_L)^2 = (\ [\Delta D_L/D_L]_{ET}\ )^2 + (\ [\Delta D_L/D_L]_{WL}\ )^2$$

Simulations

- Simulate a “catalog” of coalescence events, distributed
  - Randomly in sky position, drawn from uniform distribution
  - Randomly in orientation, drawn from uniform distribution
  - Randomly in (m_1, m_2), drawn from Gaussian $(1.35\pm0.04)\ M_{sun}$
  - Randomly in redshift, drawn from coalescence rate model dR/dz
- Demand SNR>8 for detectability
- To each event, assign “measured” distance

$$D_L'(z) = D_L^0(z) + \delta D_L(z)$$

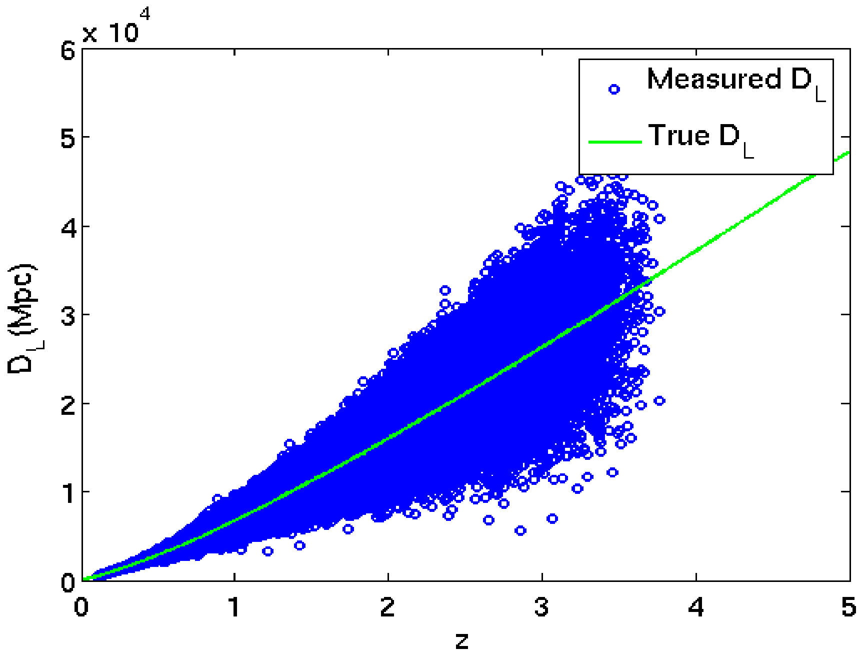
where $D_L^0(z)$ computed using cosmological model,

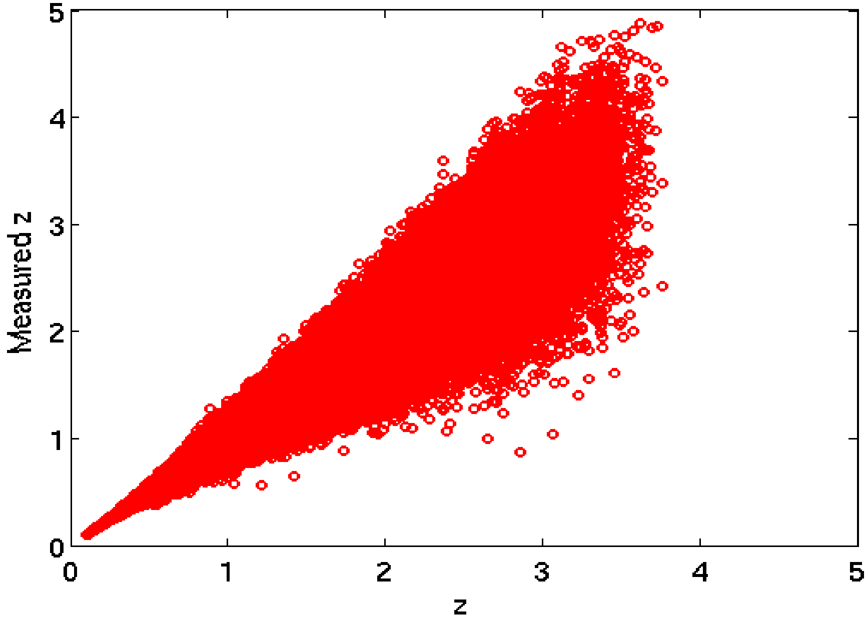
$\delta D_L(z)$ drawn from Gaussian distribution, width ΔD_L

- Invert $D_L'(z)$ to get inferred redshift z'
- Perform binning in z' → recover rate distribution dR'/dz
- Do this many times (many different catalogs) to get a 1-sigma spread for dR'/dz

Simulations (cont'd)

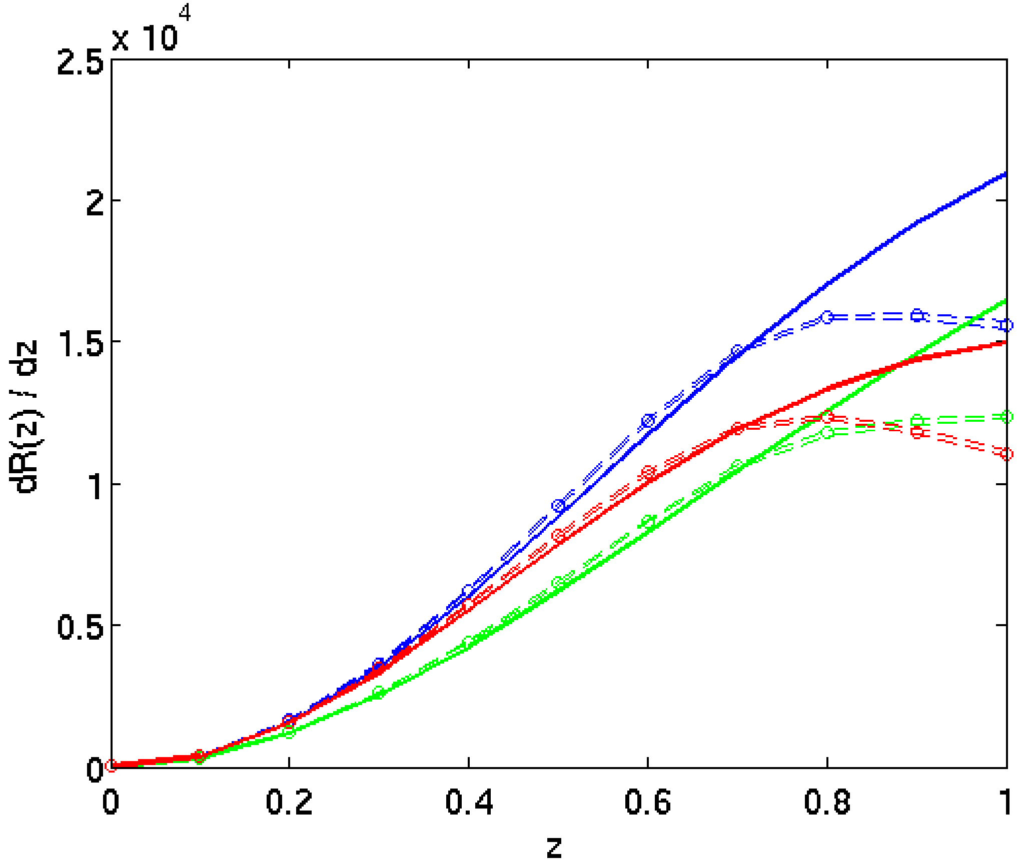
- “Measured” luminosity distances, “measured” redshifts in a catalog:





Results

- Assume minimum delay time τ_0 = 20 Myr, local coalescence rate $\dot{\rho}_c^0(0)$ = 0.03 Mpc^{-3} Myr^{-1}



- Blue: Fardal et al.
- Red: Wilkins et al.
- Green: Nagamine et al.

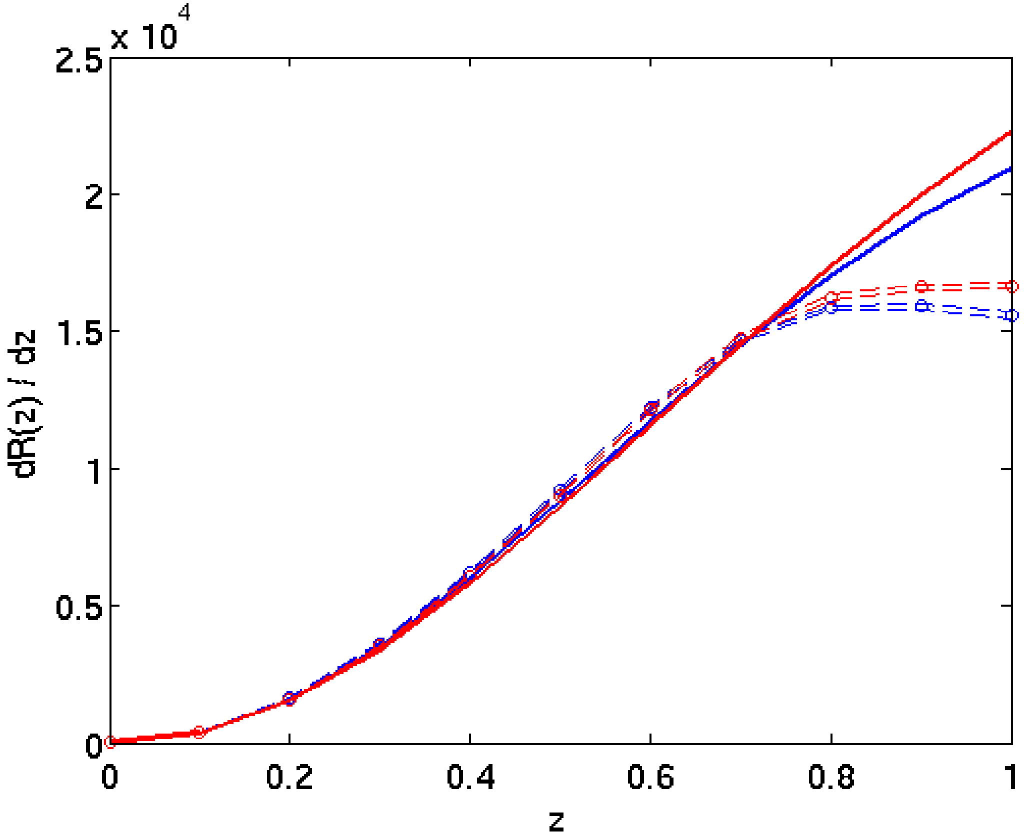
Solid lines: predicted rates

Circles: recovered rates

Dashed: 1-sigma spreads

Results (cont'd)

- For the given $\dot{\rho}_c^0(0)$ and τ_0, ET cannot distinguish between Hopkins & Beacom and Fardal et al.



- Blue: Fardal et al.
- Red: Hopkins & Beacom

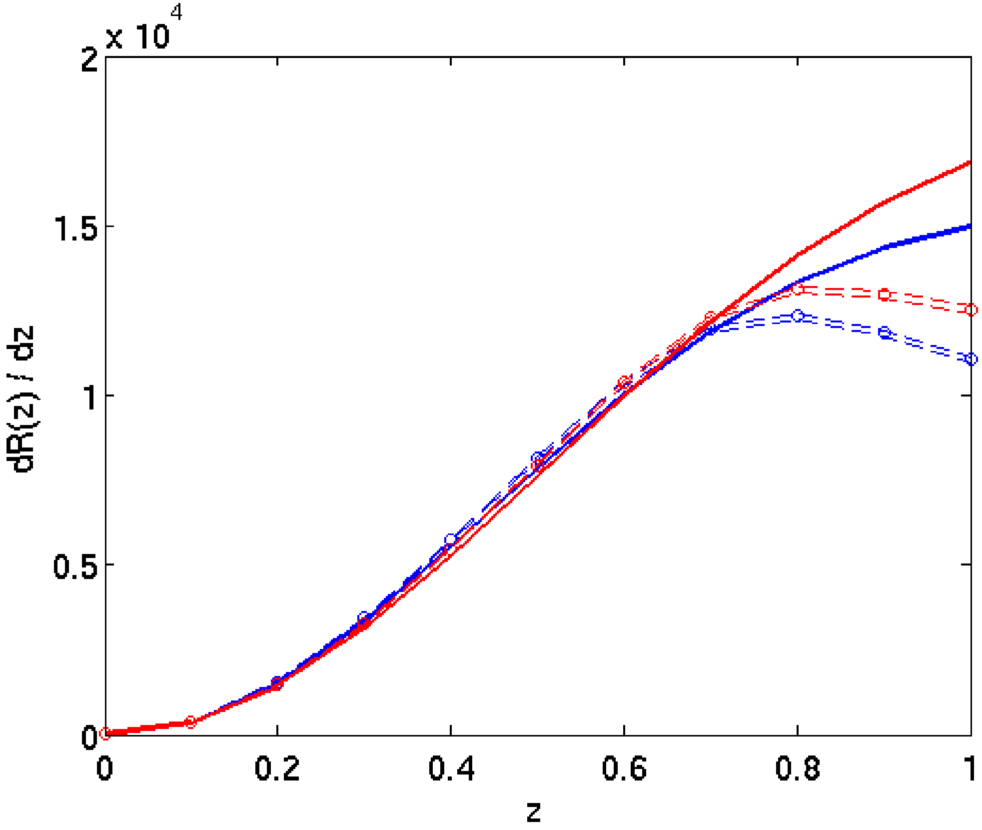
Solid lines: predicted rates

Circles: recovered rates

Dashed: 1-sigma spreads

Results (cont'd)

- Effect of minimum delay time?



- Blue: Wilkins et al., $\tau_0 = 20$ Myr
- Red: Fardal et al., $\tau_0 = 100$ Myr

Solid lines: predicted rates

Circles: recovered rates

Dashed: 1-sigma spreads

Conclusions

- Can use BNS coalescences as trackers of SFR
- Given an SFR model, free parameters are:

  - Coalescence rate at current epoch $\dot{\rho}_c^0(0)$

    (Can be assumed known from 2nd generation detectors.)

  - Minimum delay time τ_0

- For same minimum delay time, ET can distinguish between 3 SFR models in recent literature
- But: Differences in minimum delay time can easily lead to confusion between models

General statement: ET can measure coalescence rate up to z ~ 0.7 with uncertainty of a few percent