Testing star formation models with Einstein Telescope

Chris Van Den Broeck

NIKHEF

2nd ET Annual Workshop, Erice, Italy, October 14-16, 2009

Overview

- Star formation rate (SFR) models and their impact on compact binary coalescence rates
- Coalescence rates predictions from qualitatively different SFR models: Will ET distinguish them?
- Reconstructing coalescence rates with ET
- Simulations and 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 ($\mathrm{Mpc}^{-3}\,\mathrm{Myr}^{-1}$)

- 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), $P(t_d) \propto 1/t_d$

NIKHEF

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

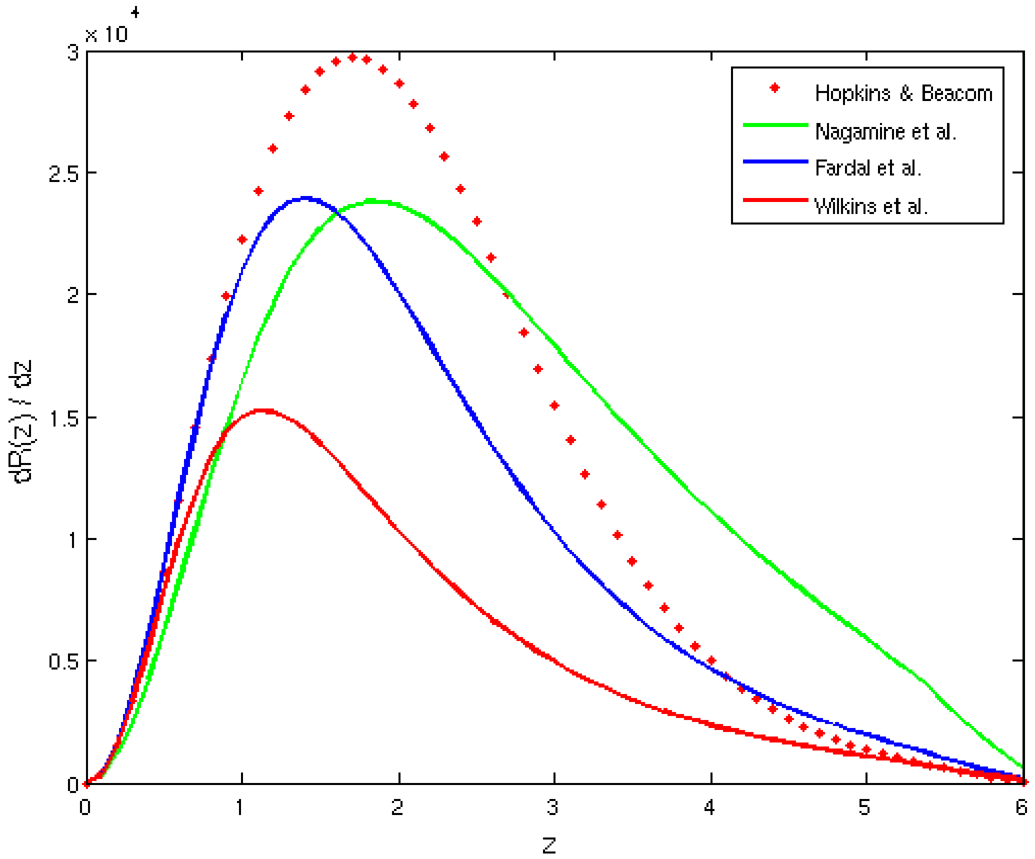
Different SFR models

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 $z \sim 0$, (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

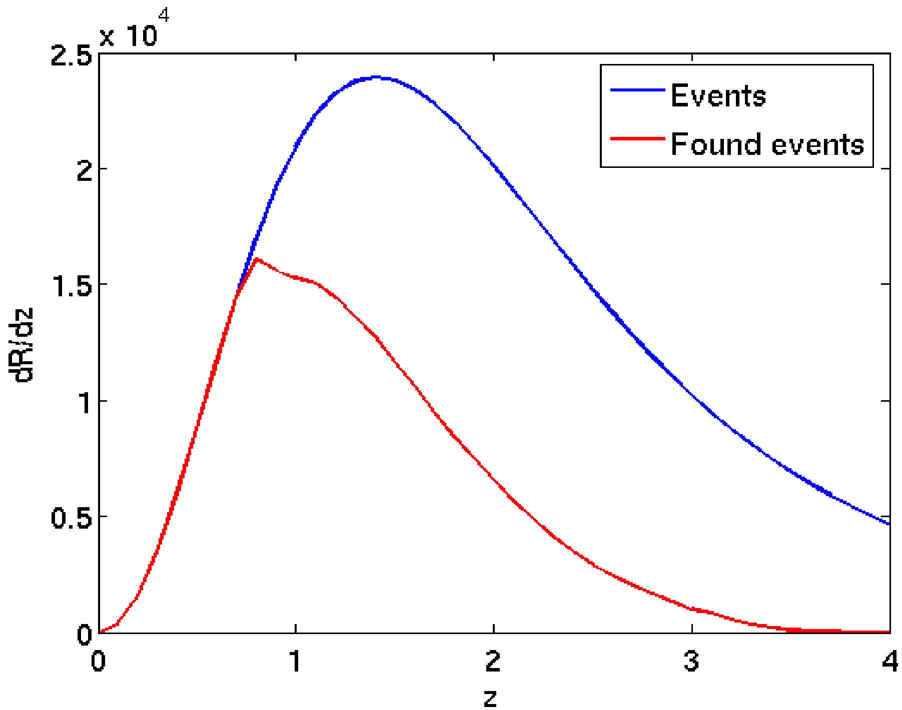
- Tania's code rate.m (available in WG4 work area):
  Specify model, minimum delay time τ_0 (e.g., 20 Myr for BNS),
  local coalescence rate $\dot{\rho}_c^0(0)$ (e.g., 0.03 Mpc^{-3} Myr^{-1})



Inferring coalescence rates from observed BNS events

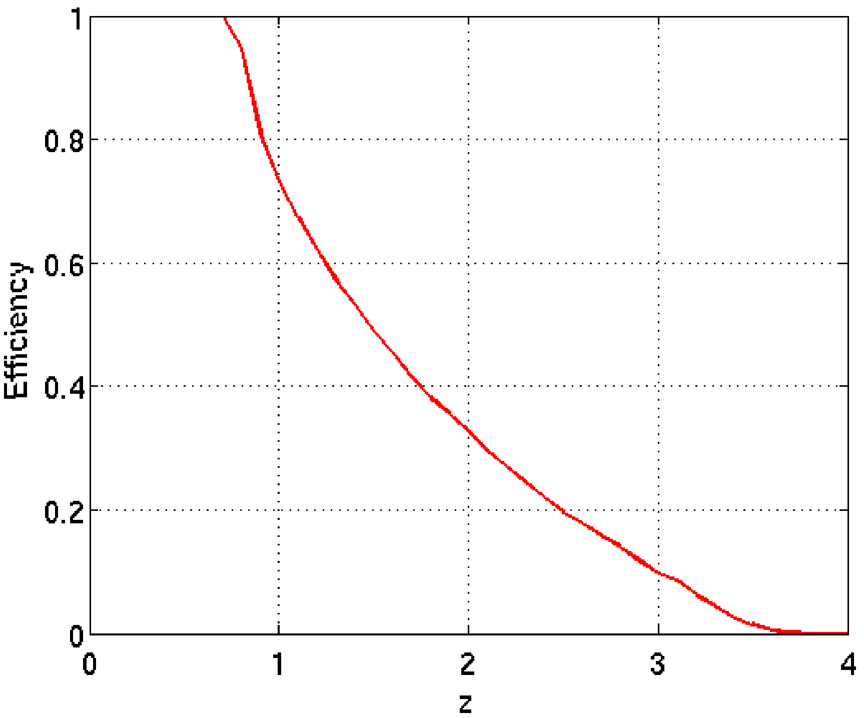
- From BNS inspiral signal: measure luminosity distance D_L
- Assuming a cosmological model, from D_L calculate z
- Do this for all observed sources → list of redshifts z
- Bin events in redshift to get measured coalescence rate dR_m/dz
- Affected by

  detection efficiency which needs to be corrected for



Estimating detection efficiency

- Consider large number of software injections
  - arbitrary sky positions
  - arbitrary orientations
  - sprinkled uniformly in co-moving volume
- Impose detection SNR > 8
- Using sufficiently small redshift bins, calculate efficiency
  $\varepsilon(z)$ = (# found in bin)/(# total in bin)
- Use this to correct the directly measured coalescence rate:
  $dR_{rec}/dz = \varepsilon(z)^{-1}\ dR_m/dz$



NIKHEF

Uncertainties in measuring D_L

Recovered distribution will be affected by
uncertainties in measured D_L → errors in redshift binning

- Contributions to 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

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

- Total uncertainty:

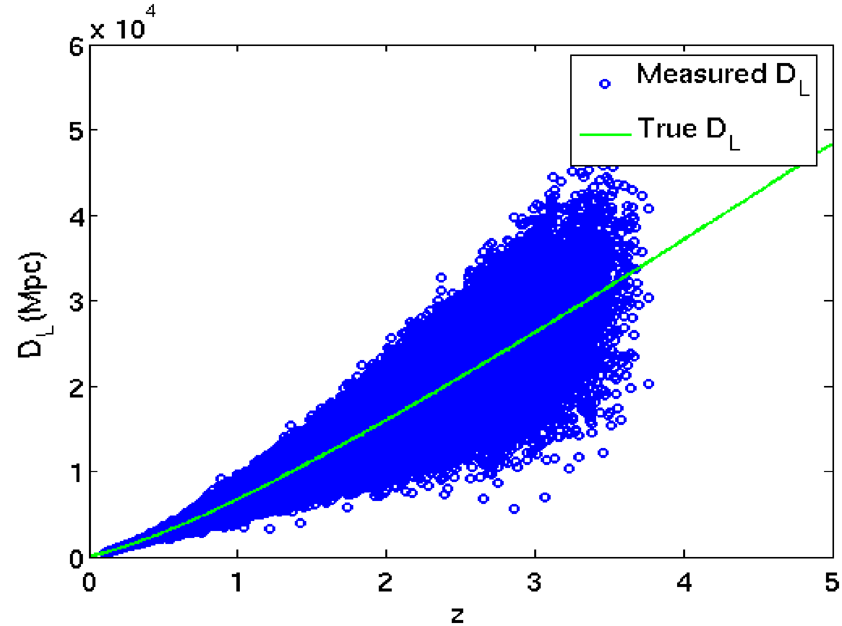
$$(\Delta D_L / D_L)^2 = ([\Delta D_L / D_L]_{ET})^2 + ([\Delta D_L / D_L]_{WL})^2$$

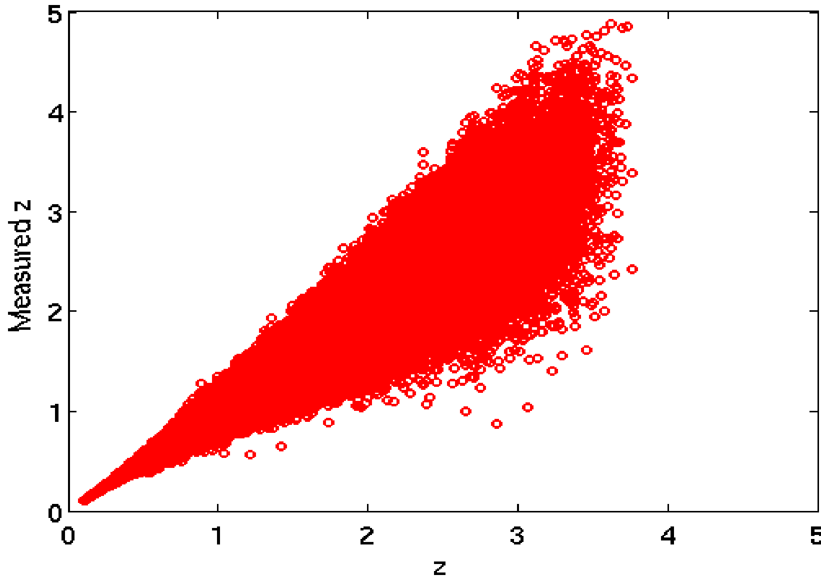
Simulations

- Simulate a "catalog" of coalescence events, distributed
  - Randomly in sky position and orientation, uniform distribution
  - Randomly in (m_1, m_2), 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

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

  - $D_L^0(z)$ "true distance"
  - $\delta D_L(z)$ drawn from Gaussian, spread ΔD_L
- Invert $D_L'(z)$ to get inferred redshift z'





NIKHEF

Simulations (cont'd)

- Perform binning of inferred redshifts z' to get directly measured coalescence rate dR_m/dz
- Recovered coalescence rate: $dR_{rec}/dz = \varepsilon(z)^{-1}\, dR_m/dz$

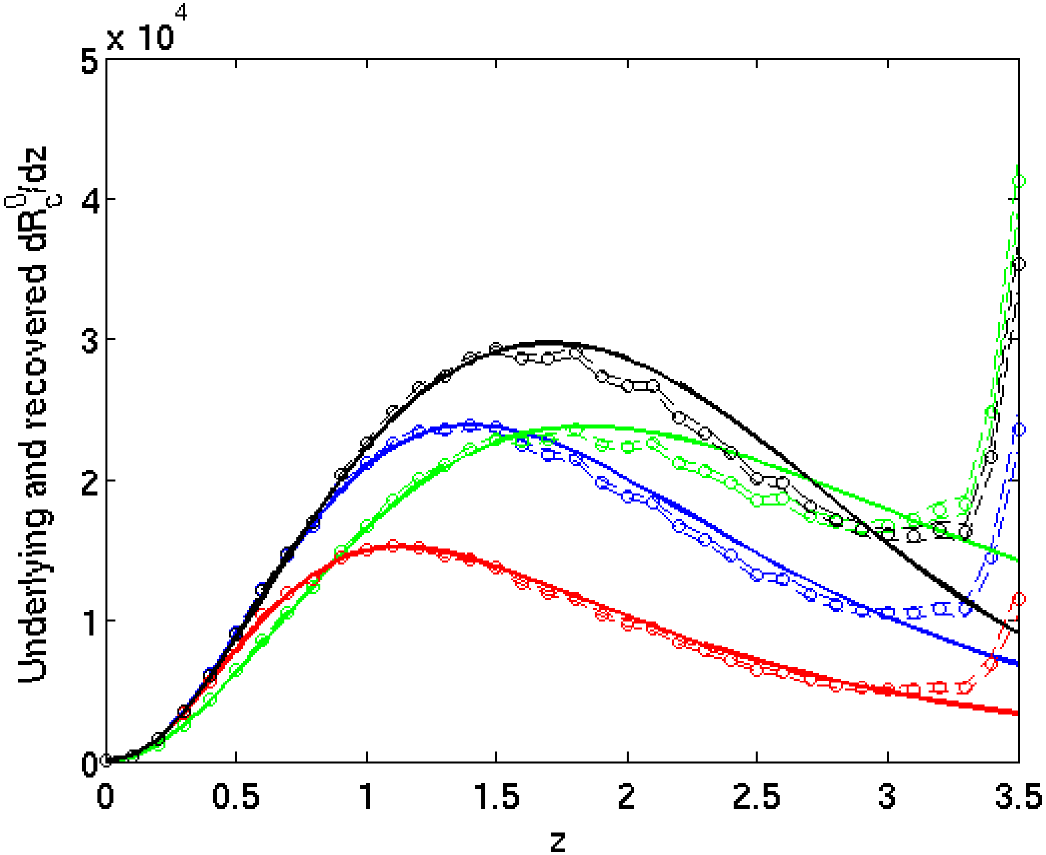
Do this for many different catalogs

- In each redshift bin:
  - compute mean of recovered rate over all catalogs
  - compute $1\text{-}\sigma$ spread in recovered rate over all catalogs

NIKHEF

Results

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



- Black: Hopkins & Beacom
- Blue: Fardal et al.
- Red: Wilkins et al.
- Green: Nagamine et al.

Solid lines: predicted rates

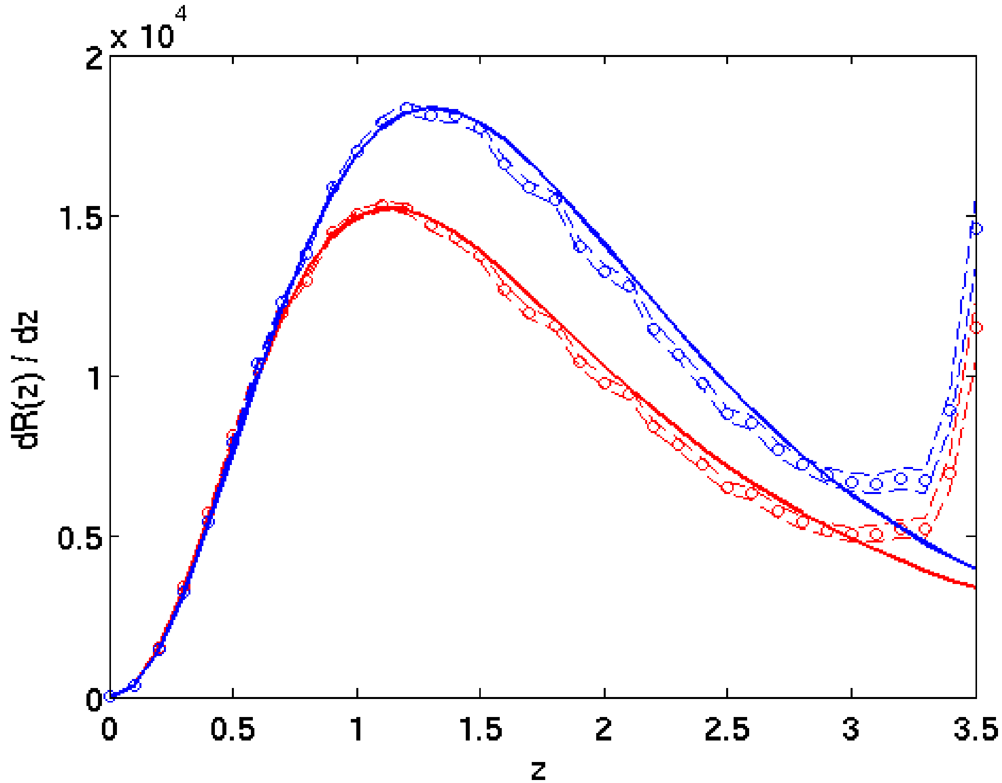
Circles: recovered rates

Dashed: 1-sigma spreads

NIKHEF

Effect of free parameters

- Local coalescence rate $\dot{\rho}_c^0(0)$: constrained by 2nd generation detectors
- Effect of minimum delay time?



- Red: Wilkins et al., τ_0 = 20 Myr
- Blue: Fardal et al., τ_0 = 100 Myr

Solid lines: predicted rates

Circles: recovered rates

Dashed: 1-sigma spreads

NIKHEF

Summary and future work

General conclusion:

ET can reliably reconstruct coalescence rates up to z ~ 1.5 at the 1% level

- In particular, ET can distinguish between the predicted coalescence rates from four different SFR models in recent literature

Remaining issues:

- Beyond z ~ 1.5: systematic effects in dR_{rec}/dz due to large D_L errors, incorrect z binning; can presumably be corrected for
- Is there a way to (partially) correct for weak lensing?
- Only used "restricted" inspiral waveform
- Given *any* coalescence rate, how well can underlying SFR model be reconstructed from ET measurements?

NIKHEF