PROBING THE INHOMOGENEOUS UNIVERSE WITH GW COSMOLOGY

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§1 Introduction
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1-1 Acceleration of our Universe

- Cosmological observations
  \[ \Rightarrow \text{accelerating expansion of our Universe!} \]

- homogeneous & isotropic
  \[ G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

① G.R.+ Dark Energy
② Modified Gravity

③ Inhomogeneous: G.R., no Dark Energy needed.

TypeIa SN observation

Alnes et al. (2006)
1–2 Inhomogeneous Universe

- Spherically symmetric, dust, inhomogeneous (LTB model)

(The simplest example of the inhomogeneous universe model)

- We live at the center of **void**
  (less dense region).

Density gradient

- **Apparent accelerating expansion** of the Universe!
• This model can also explain the peaks of CMB & BAO

Garcia-Bellido & Haugboelle (2008)

• We need observables that can probe the LTB void model more clearly!

  z-drift
Time evolution of the redshift $z$ reflects the accelerating expansion more directly!

- **FLRW**
  \[
  \Delta t z = H_0 \Delta t_0 \left( 1 + z - \frac{H(z)}{H_0} \right)
  \]
  \[
  \sim \frac{\text{obs. time}}{\text{cosmic age}} \sim 10^{-10}
  \]
  (1yr obs.)

- **LTB**

\[
\frac{d}{dz} \left( \frac{\Delta t z}{1 + z} \right) = \frac{1}{(1 + z)^2} \frac{\partial_t^2 \partial_r R}{\partial_t \partial_r R} \Delta t_0
\]

LTB with monotonically increasing density profile:

\[
\Rightarrow \Delta t z < 0 \text{ for } \forall z > 0
\]

(Kai, Nakao & Yoo 2010)
1–4 Measuring z-drift with E-ELT

Quartin & Amendola (2010)

- Use absorption lines of quasars (Ly $\alpha$ forest)
  (only for high $z$ observation)
- If $\Lambda$CDM is correct
  $\Rightarrow$ can reject typical void models with 10yr obs.
- To probe $\Delta z > 0$ $\Rightarrow$ We need low $z$ obs.

GW observation!!
§2 Constraining Inhomogeneous Universe with GW Observations
§ 2-1 Effect of accelerated expansion in GW waveform

(Seto, Kawamura & Nakamura 2001)

**NS/NS**

Accelerated Expansion

![Diagram of NS/NS system with acceleration parameters](image)

\[ \Delta t_o = \Delta T (1 + X(z) \Delta T) \]

**Obs. time**

\[ \Delta T \equiv (1 + z) \Delta t_e \]

- **correction in GW phase:**
  \[ \delta \Psi_{acc} = -2\pi \int f X(z) \Delta t^2 \]
  \[ \Delta t: \text{time to coalescence} \]

- **Accelerating parameter**
  \[ X(z) = \frac{H_0}{2} \left( 1 - \frac{H(z)}{(1+z)H_0} \right) \]

- **Advantages of using DECIGO/BBO over ground-based detectors:**
  (i) Longer observation time
  (ii) Larger numbers of GW cycles: \(0.1\text{Hz} \times 5\text{yr} \approx 10^7\)
  (iii) Larger NS/NS binary detection rate: \(10^6 / \text{yr}\)
§ 2-2  Correction in waveform

How accurately can we measure this difference?
§ 2-3 Numerical Calculations

K.Y. & A. Nishizawa & C. Yoo (in prep.)

Determining z-drift with DECIGO/BBO using Fisher analysis

- circular NS/NS binaries at
  - $z=0\sim 4$
- Divide $z$ bin with $\delta z=0.1$
- Randomly distributing binaries at each $z$ bin
  (Directions and orientations)

**Monte Carlo simulation**

- spins
- **WD/WD confusion noise**
- **merger rate evolution** based on **star formation galaxy** obs.
  - Event rate: $10^6$/yr
- Motion of Detectors
- Fiducial: $\Lambda$CDM

![Graph showing event rate $\Delta N(z)$ vs. $z$]
$10^{10} \Delta_t z$

§ 2-4 Results

5yr $\Lambda$CDM

Void

10yr

5~10yr obs. with DECIGO/BBO
⇒ we can test $\Delta_t z > 0$
⇒ we can kill all of the monotonic LTB void model!!
(z determined from EM obs.)
We can test $\Delta_t z - D_L$ with GW observations alone!
§3 Discussions & Summary
**Discussions**

Can we probe LTB with **arbitrary density profile**?

General LTB Void model ⇒ $\frac{d}{dz} \Delta_t z < 0$ at $z=0$

(Kai, Nakao & Yoo 2010)

Probing $\Delta_t z > 0$ at sufficiently low $z$

⇒ It seems we can rule out any LTB model!

**Summary**

- **Direct detection of the acceleration of the Universe**
  with DECIGO/BBO
  ⇒ 5-10yr obs. can **rule out monotonic LTB void models or even general ones!**

  **Ground-Based Detectors** ⇒ **GW Astronomy**

  **Space-borne Detectors** ⇒ **GW Cosmology!!!**