Testing exotic cosmological models with future gravitational wave siren data

Maxence Corman
Supervised by M. Hendry
Institute for Gravitational Research

February 14, 2020

Accelerating expansion of the Universe

Evidence

Explanation

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]

Explanation

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]
- Baryon acoustic oscillations (BAO) [3]

Explanation

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]
- Baryon acoustic oscillations (BAO) [3]
- Cosmic Microwave Background (CMB) data [4]

Explanation

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]
- Baryon acoustic oscillations (BAO) [3]
- Cosmic Microwave Background (CMB) data [4]

Explanation

- Lambda-Cold-Dark-Matter model (ΛCDM) [5]

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]
- Baryon acoustic oscillations (BAO) [3]
- Cosmic Microwave Background (CMB) data [4]

Explanation

- Lambda-Cold-Dark-Matter model (ΛCDM) [5]
  - Limitations: Physical origin cold dark matter (CDM) and the cosmological constant (Λ) [6]

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]
- Baryon acoustic oscillations (BAO) [3]
- Cosmic Microwave Background (CMB) data [4]

Explanation

- Lambda-Cold-Dark-Matter model (ΛCDM) [5]
  - Limitations: Physical origin cold dark matter (CDM) and the cosmological constant (Λ) [6]
- Alternative explanations? Several!

Accelerating expansion of the Universe

Evidence

- Cosmologically distant Type 1a supernovae (SNIa) [1, 2]
- Baryon acoustic oscillations (BAO) [3]
- Cosmic Microwave Background (CMB) data [4]

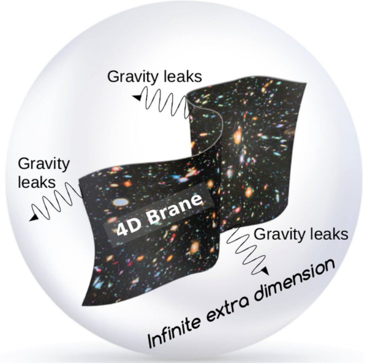
Explanation

- Lambda-Cold-Dark-Matter model (ΛCDM) [5]
  - Limitations: Physical origin cold dark matter (CDM) and the cosmological constant (Λ) [6]
- Alternative explanations? Several!
  - Braneworld models
  - Quintessence models
  - ...

Explaining accelerating expansion of the Universe

Braneworld model of gravity proposed by Dvali, Gabadadze and Porrati (DGP) [7]

$$S_{(5)} = -\frac{1}{16\pi} M^3 \int d^5x \sqrt{-g} R - \frac{1}{16\pi} M_P^3 \int d^4x \sqrt{-g^{(4)}} R^{(4)} + \int d^4x \sqrt{-g(4)} \mathcal{L}_m + S_{GH} \quad (1)$$



Crossover length scale r_0

- $r < r_0$: 4D gravity
- $r > r_0$: 5D modified gravity
  - Brane self-inflationary solution

Testing modified theories of gravity

Supernova (SN) observations

Most sensitive probe of the late-time expansion history of the universe up to redshift $z \sim 1$

Gravitational Wave (GW) observations

- "Standard sirens"

Testing modified theories of gravity

Supernova (SN) observations

Most sensitive probe of the late-time expansion history of the universe up to redshift $z \sim 1$

Gravitational Wave (GW) observations

- "Standard sirens"
- Disadvantage: Redshift needs to be measured independently

Testing modified theories of gravity

Supernova (SN) observations

Most sensitive probe of the late-time expansion history of the universe up to redshift $z \sim 1$

Gravitational Wave (GW) observations

- "Standard sirens"
- Disadvantage: Redshift needs to be measured independently
- New opportunities to test modified theories of gravity

Testing modified theories of gravity

Supernova (SN) observations
Most sensitive probe of the late-time expansion history of the universe up to redshift $z \sim 1$
Gravitational Wave (GW) observations

- "Standard sirens"
- Disadvantage: Redshift needs to be measured independently
- New opportunities to test modified theories of gravity
- *Do large-wavelength gravitational waves and short-frequency photons experience the same number of spacetime dimensions? [8]*

Limits on the number of spacetime dimensions

GW damping in higher dimensional theories: Theory

- In **General relativity** (GR) the strain goes as

$$h_{GR} \propto \frac{1}{d_L^{GW}} \tag{2}$$

where d_L^{GW} is the luminosity distance of GW source, here also the "true" EM distance d_L^{EM}.

- In **General relativity** (GR) the strain goes as

$$h_{GR} \propto \frac{1}{d_L^{GW}} \tag{2}$$

where d_L^{GW} is the luminosity distance of GW source, here also the "true" EM distance d_L^{EM}.

- In **higher dimensional-theories** with screening scale R_c, GW strain scales as [9]

$$h_{NGR} \propto \frac{1}{d_L^{EM}\left[1+\left(\frac{d_L^{EM}}{R_c}\right)^{n/2}\right]^{2(\gamma-1)/n}} \tag{3}$$

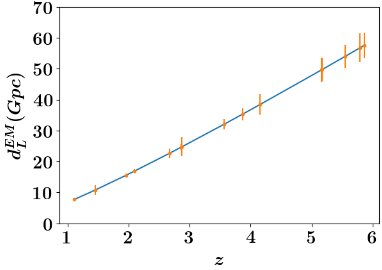
where γ is related to the number of dimensions D by

$$\gamma = \frac{D-2}{2} \tag{4}$$

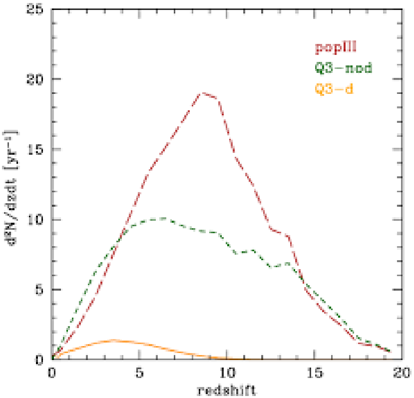
and n gives transition steepness.

Limits on the number of spacetime dimensions

Laser Interferometer Space Antenna (LISA): Redshift distribution of MBHBs [11]

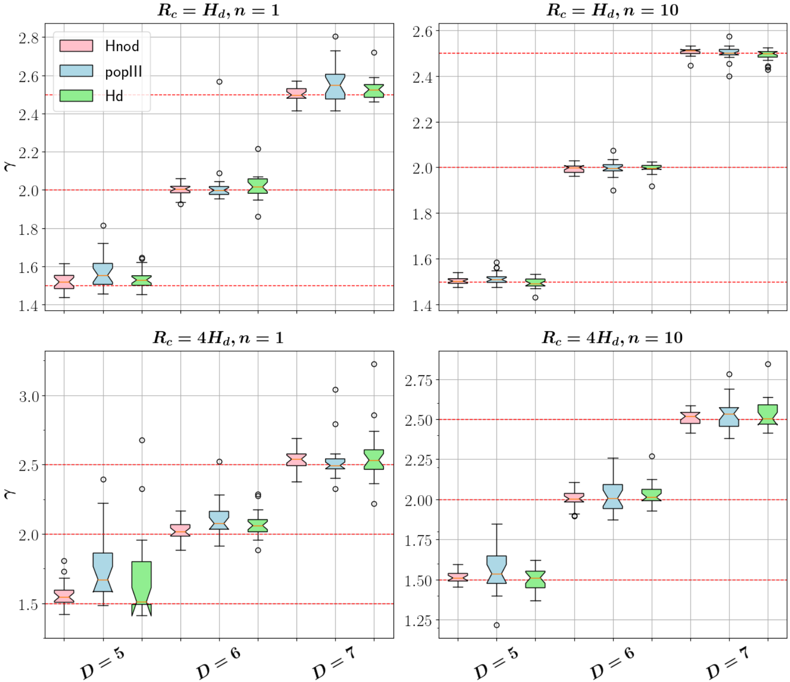


Simulated data points with their error bars for one random catalogue in the model "popIII".

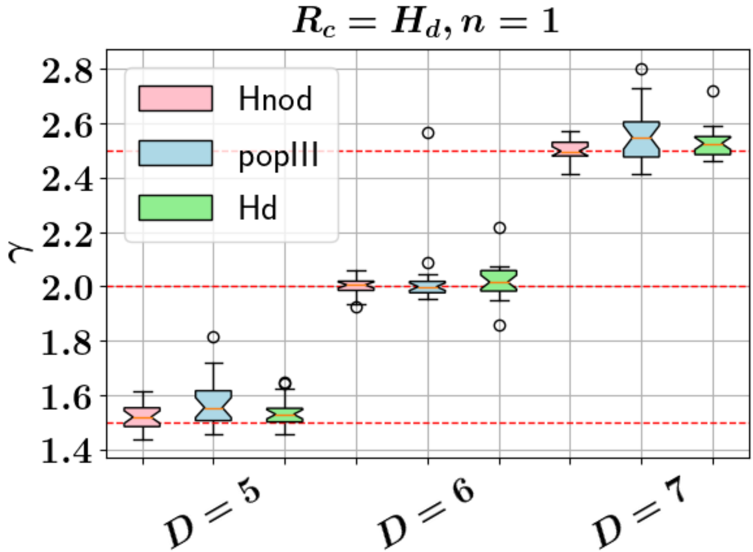


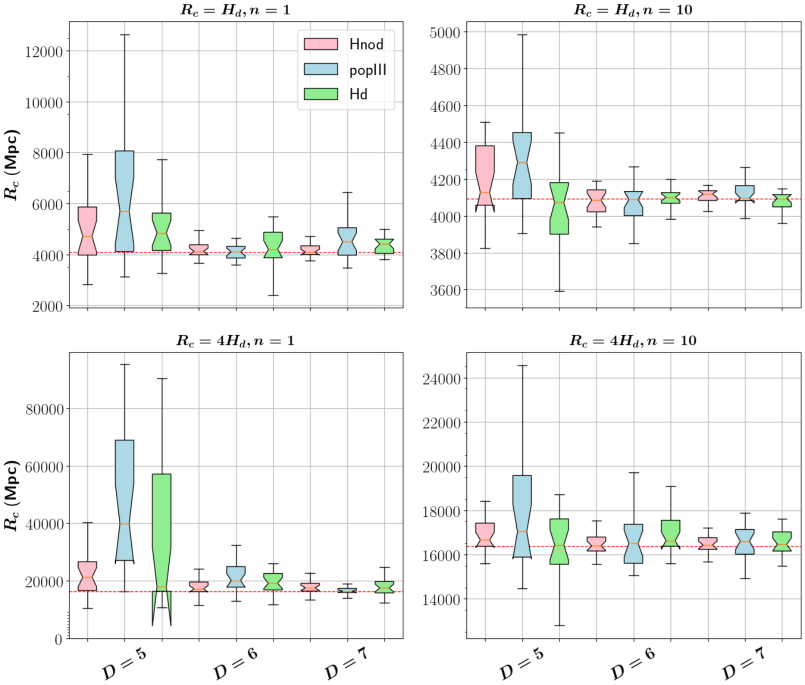
Predicted merger rates per unit redshift taken from [10].

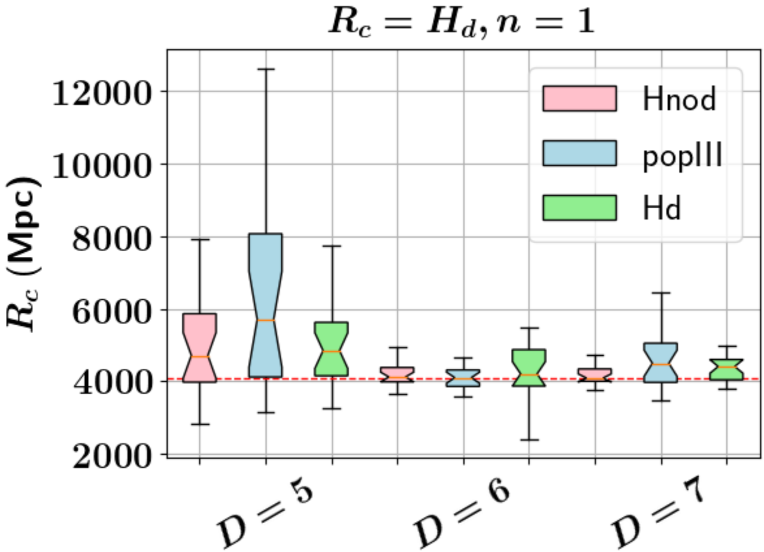
Results Bayesian parameter estimation



$R_c = H_d, n = 1$
$R_c = H_d, n = 10$
$R_c = 4H_d, n = 1$
$R_c = 4H_d, n = 10$
Hnod
popIII
Hd
γ
$D = 5$
$D = 6$
$D = 7$


$R_c = H_d, n = 1$
Hnod
popIII
Hd
γ
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
$D = 5$
$D = 6$
$D = 7$


$R_c = H_d, n = 1$
$R_c = H_d, n = 10$
$R_c = 4H_d, n = 1$
$R_c = 4H_d, n = 10$
R_c (Mpc)
R_c (Mpc)
Hnod
popIII
Hd
$D = 5$
$D = 6$
$D = 7$
$D = 5$
$D = 6$
$D = 7$



$R_c = H_d, n = 1$
12000
10000
8000
6000
4000
2000
R_c (Mpc)
Hnod
popIII
Hd
$D = 5$
$D = 6$
$D = 7$

Conclusions

- GWs are a powerful probe of the universe

Conclusions

- GWs are a powerful probe of the universe
- LISA has the potential to probe the expansion of the universe in the redshift range $1 \leq z \leq 8$

Conclusions

- GWs are a powerful probe of the universe
- LISA has the potential to probe the expansion of the universe in the redshift range $1 \leq z \leq 8$
- LISA's ability to place limits on the number of spacetime dimensions will depend on:

Conclusions

- GWs are a powerful probe of the universe
- LISA has the potential to probe the expansion of the universe in the redshift range $1 \leq z \leq 8$
- LISA's ability to place limits on the number of spacetime dimensions will depend on:
  - Redshift distribution of MBHBs and the corresponding efficiency of host galaxy identifications
- Our analysis is a phenomenological one

References I

N. Suzuki et al.
The Hubble Space Telescope Cluster Supernova Survey: V. Improving the Dark Energy Constraints Above z¿1 and Building an Early-Type-Hosted Supernova Sample.
Astrophys. J., 746:85, 2012.

M. Betoule et al.
Improved cosmological constraints from a joint analysis of the SDSS-II and SNLS supernova samples.
Astron. Astrophys., 568:A22, 2014.

Daniel J. Eisenstein et al.
Detection of the Baryon Acoustic Peak in the Large-Scale Correlation Function of SDSS Luminous Red Galaxies.
Astrophys. J., 633:560–574, 2005.

References II

P. A. R. Ade et al.
Planck 2015 results. XIII. Cosmological parameters.
Astron. Astrophys., 594:A13, 2016.

P.J.E. Peebles and Bharat Ratra.
The cosmological constant and dark energy.
Rev.Mod.Phys., 75:559–606, Apr 2003.

Philip Bull et al.
Beyond ΛCDM: Problems, solutions, and the road ahead.
Phys. Dark Univ., 12:56–99, 2016.

G. R. Dvali, Gregory Gabadadze, and Massimo Porrati.
4-D gravity on a brane in 5-D Minkowski space.
Phys. Lett., B485:208–214, 2000.

References III

Kris Pardo, Maya Fishbach, Daniel E. Holz, and David N. Spergel.
Limits on the number of spacetime dimensions from GW170817.
JCAP, 1807(07):048, 2018.

Cedric Deffayet and Kristen Menou.
Probing Gravity with Spacetime Sirens.
Astrophys. J., 668:L143–L146, 2007.

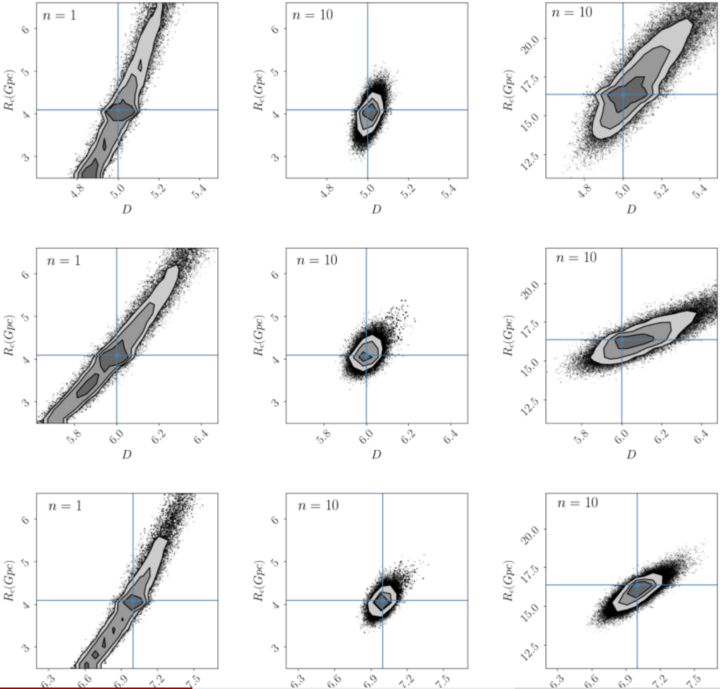
Antoine Klein et al.
Science with the space-based interferometer eLISA: Supermassive black hole binaries.
Phys. Rev., D93(2):024003, 2016.

References IV

Nicola Tamanini, Chiara Caprini, Enrico Barausse, Alberto Sesana, Antoine Klein, and Antoine Petiteau.
Science with the space-based interferometer eLISA. III: Probing the expansion of the Universe using gravitational wave standard sirens.
JCAP, 1604(04):002, 2016.

Cedric Deffayet, G. R. Dvali, and Gregory Gabadadze.
Accelerated universe from gravity leaking to extra dimensions.
Phys. Rev., D65:044023, 2002.

David W. Hogg.
Distance measures in cosmology.
1999.


$n = 1$
$n = 10$
$n = 10$
$R_c(Gpc)$
D
4.8
5.0
5.2
5.4
5.8
6.0
6.2
6.4
6.3
6.6
6.9
7.2
7.5
3
4
5
6
12.5
15.0
17.5
20.0