Cosmology With Bright Standard Sirens

Josiel Mendonça Soares de Souza
Universidade Federal do Rio Grande do Norte, Brazil

Cosmo 22, Rio de Janeiro, Brazil
August, 2022

Bright Standard Sirens

Spacetime interval

$$dS^2 = -dt^2 + 2h_\times dxdt + (1+h_+)dx^2 + (1-h_+)dy^2 + dz^2$$

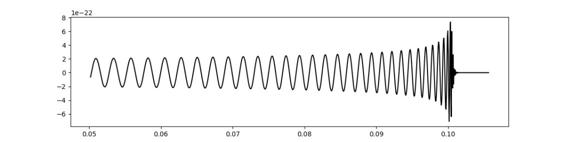
Polarizations

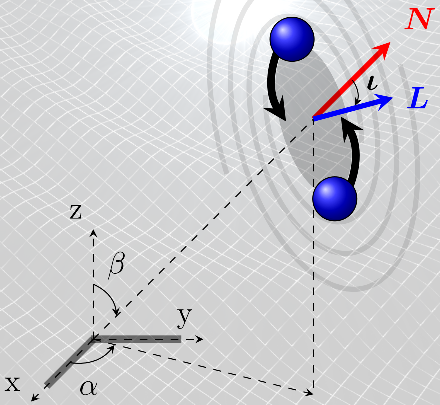
$$h_+ \propto \frac{1}{d_L}\left(\frac{1+\cos^2\iota}{2}\right)$$

$$h_\times \propto \frac{1}{d_L}\cos\iota$$

$$h(t) = F_+ h_+(t) + F_\times h_\times(t) : \textbf{Signal}$$

$$h \propto \frac{1}{d_L} \qquad \Delta L \approx hL_0$$





First Measurement of H_0 with GW170817

Source Properties:

Total Mass $2.74^{+0.04}_{-0.01}\ M_{\odot}$;

Luminosity Distance: $d_L = 40^{+8}_{-14}\ Mpc$;

Inclination: $\iota \leq 55^o$;

From EM-Counterpart

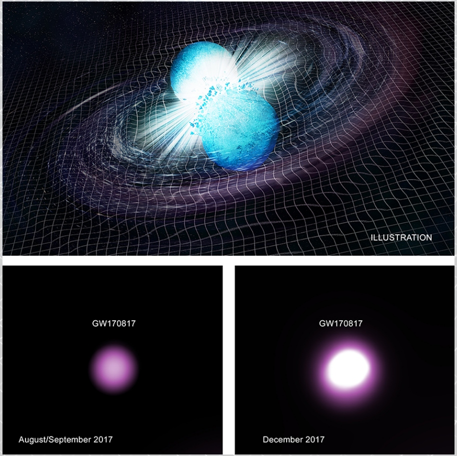
Host Galaxy: NGC 4993;

Redshift: $z = 0.00973$ (host galaxy);

H_0 **Measurement:** $H_0 = 70^{+12}_{-8}\ km/s/Mpc$.

Abbott, B. P., et al., PhysRevLett.119.161101

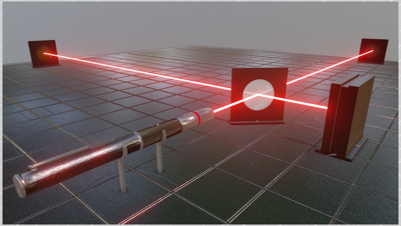
Uncertainty of 12% with respect to the measurement.



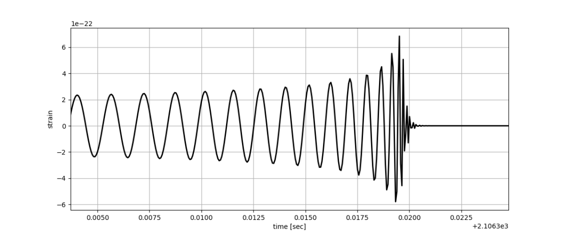
Credit: [https://chandra.harvard.edu/photo/2018/gw170817/]

Gravitational Waves Detectors (Second Generation)

Interferometers



Credit: Author.



$L_{LIGO} = 4km, \quad L_{Virgo} = 3km, \quad L_{KAGRA} = 3km$

Credit: [https://www.virgo-gw.eu/], [https://www.ligo.caltech.edu/], [https://gwcenter.icrr.u-tokyo.ac.jp/en/].

Gravitational Waves Detectors (Second Generation)

Detector Output:

$$\mathcal{O}(t) = \underset{\text{Signal}}{\underset{\uparrow}{h(t)}} + \underset{\text{Noise}}{\underset{\uparrow}{n(t)}}$$

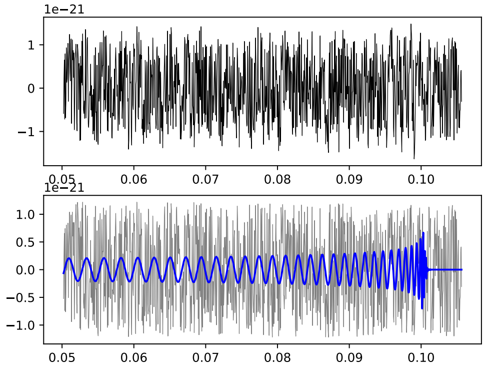
Signal to Noise Ratio [Matched Filtering]:

$$SNR = 2\left[Re\int_0^{\infty}\frac{\tilde{\mathcal{O}}^*(f)\tilde{h}(f)}{S_n(f)}df\right]^{1/2}$$

$$\langle \tilde{n}(f)\tilde{n}^*(f')\rangle = \frac{1}{2}\overset{\text{Noise Power Spectrum Density}}{\overset{\downarrow}{S_n(f)}}\delta(f-f')$$

Adimentional Quantities

$$h_c = 2f|\tilde{h}(f)| \quad , \quad S_c = \sqrt{f\cdot S_n(f)}$$



Gravitational Waves Detectors (Second Generation)

Detector Output:

$$\mathcal{O}(t) = \underset{\substack{\uparrow \\ \text{Signal}}}{h(t)} + \underset{\substack{\uparrow \\ \text{Noise}}}{n(t)}$$

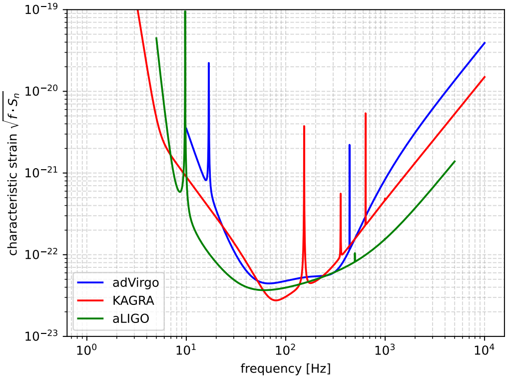
Signal to Noise Ratio [Matched Filtering]:

$$SNR = 2\left[Re\int_0^\infty \frac{\tilde{\mathcal{O}}^*(f)\tilde{h}(f)}{S_n(f)}df\right]^{1/2}$$

$$\langle \tilde{n}(f)\tilde{n}^*(f')\rangle = \frac{1}{2}\overset{\substack{\text{Noise Power Spectrum Density} \\ \downarrow}}{S_n(f)}\delta(f-f')$$

Adimentional Quantities

$$h_c = 2f|\tilde{h}(f)| \quad , \quad S_c = \sqrt{f \cdot S_n(f)}$$



Gravitational Waves Detectors (Second Generation)

Detector Output:

$$\mathcal{O}(t) = \underset{\substack{\uparrow \\ \text{Signal}}}{h(t)} + \underset{\substack{\uparrow \\ \text{Noise}}}{n(t)}$$

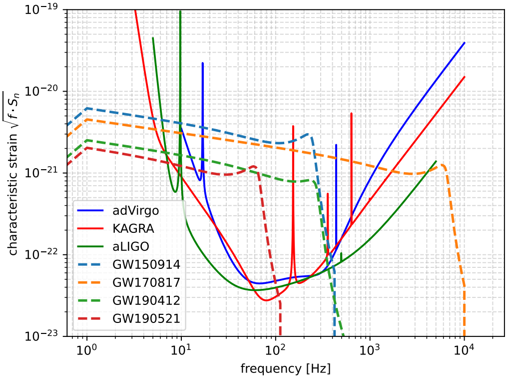
Signal to Noise Ratio [Matched Filtering]:

$$SNR = 2\left[Re\int_0^{\infty}\frac{\tilde{\mathcal{O}}^*(f)\tilde{h}(f)}{S_n(f)}df\right]^{1/2}$$

$$\langle \tilde{n}(f)\tilde{n}^*(f')\rangle = \frac{1}{2}\overset{\substack{\text{Noise Power Spectrum Density} \\ \downarrow}}{S_n(f)}\delta(f-f')$$

Adimentional Quantities

$$h_c = 2f|\tilde{h}(f)| \quad , \quad S_c = \sqrt{f\cdot S_n(f)}$$



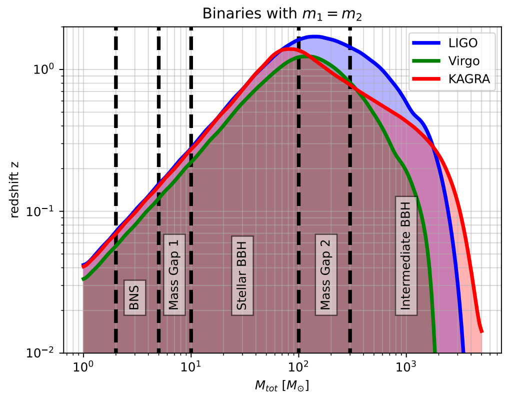
Gravitational Waves Detectors (Second Generation)

For which redshift/distance range can we detect binaries of neutron stars and black holes?

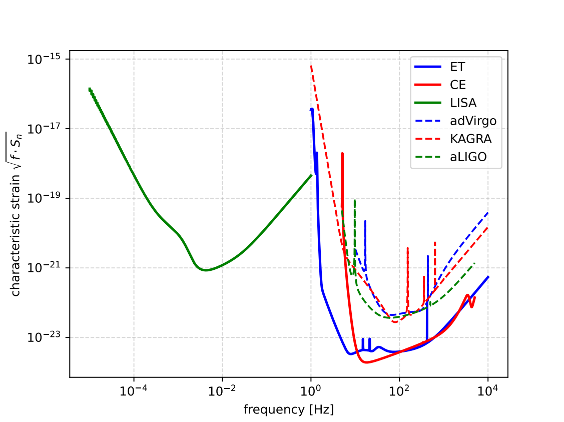
Aside we show the sensibility region of detectors in mass/redshift space of detections with **SNR bigger than 8**.

$$SNR(M_{tot}, z) = 2\left[\int_0^\infty \frac{|\tilde{h}(f, M_{tot}, z)|^2}{S_n(f)} df\right]^{1/2}$$

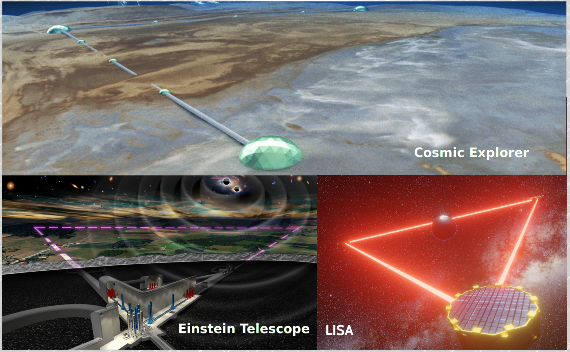
$$\langle \tilde{n}(f)\tilde{n}^*(f')\rangle = \frac{1}{2}S_n(f)\delta(f - f')$$



Gravitational Waves Detectors (Ground 3G and Space 1G)



$L_{ET} = 10km,\ L_{CE} = 40km,\ L_{LISA} = 2.500.000km$

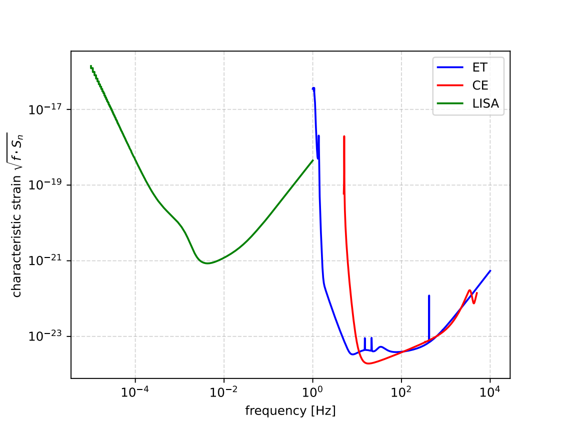


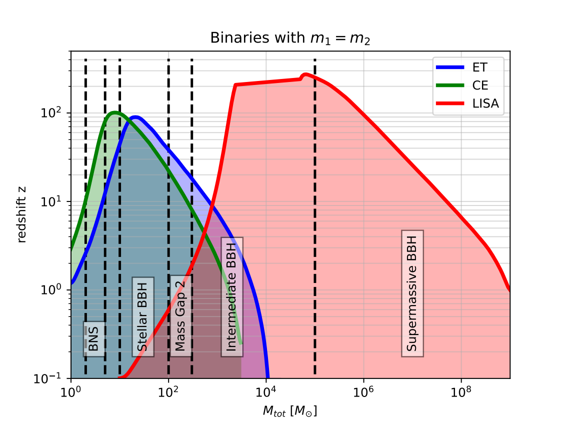
Curves of ET and CE retrived from [https://dcc.ligo.org/LIGO-T1500293/public]

Credits: [https://gwic.ligo.org/3Gsubcomm/], [http://www.et-gw.eu/] e Author (figura do LISA).

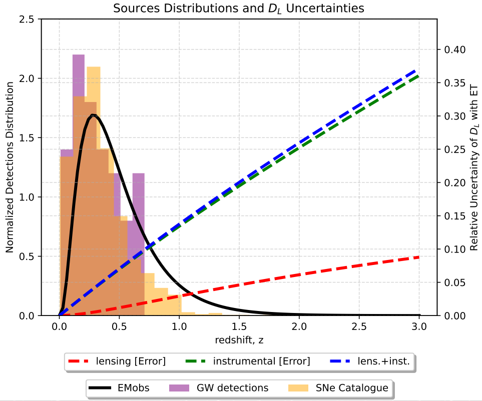
Gravitational Waves Detectors (Third Generation)

Range Power of Detectors (SNR > 8): $SNR(z,\ M_{tot})$

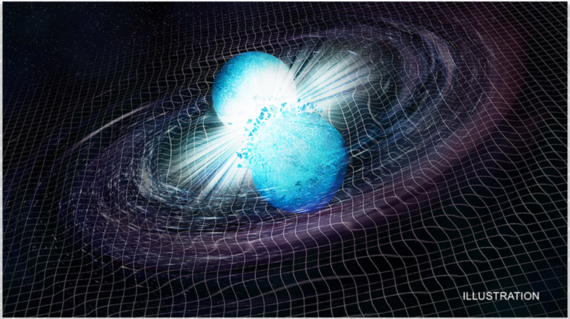




GW+shGRBs with Einstein Telescope

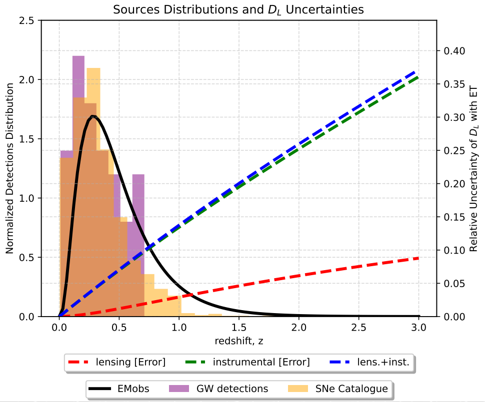


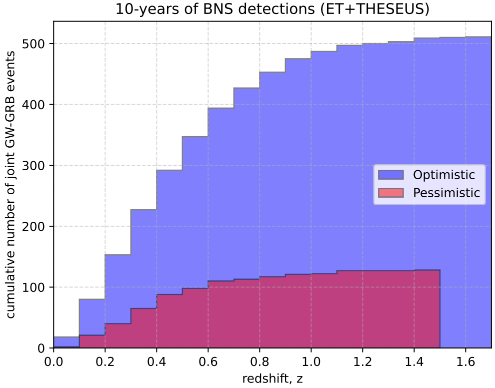
Distributions and Uncertainties in d_L:
Belgacem, E., et al. *JCAP*, 2019(08), 015.
Zhao, W., et al. *Physical Review D*, 83(2), 023005.
Tamanini, N., et al. *JCAP* 2016.04 (2016): 002.



Credit: [https://chandra.harvard.edu/photo/2018/gw170817/]

GW+shGRBs with Einstein Telescope

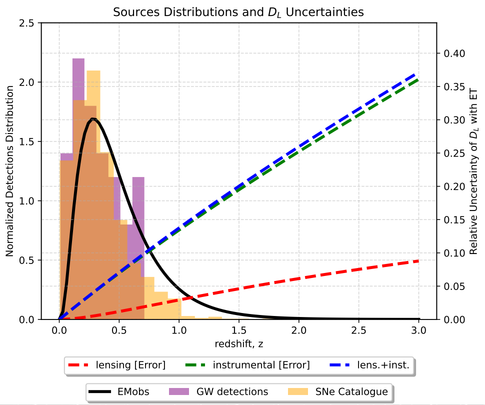


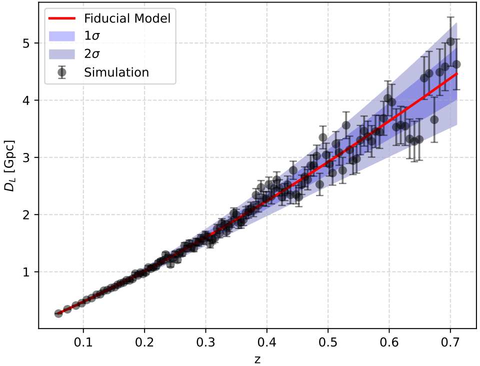


Distributions and Uncertainties in d_L:
Belgacem, E., et al. *JCAP*, 2019(08), 015.
Zhao, W., et al. *Physical Review D*, 83(2), 023005.
Tamanini, N., et al. *JCAP* 2016.04 (2016): 002.

Belgacem, E., et al. JCAP, 2019(08), 015.

GW+shGRBs with Einstein Telescope





Distributions and Uncertainties in d_L:
Belgacem, E., et al. *JCAP*, 2019(08), 015.
Zhao, W., et al. *Physical Review D*, 83(2), 023005.
Tamanini, N., et al. *JCAP* 2016.04 (2016): 002.

Bayesian Model Selection [ET]

Bayes Theorem:

$$\overbrace{P(\{\theta_i\}|data,\ M)}^{\text{Posterior}} = \frac{\overbrace{P(data|\{\theta_i\}, M)}^{\text{Likelihood}}\ \overbrace{P(\{\theta_i\}, M)}^{\text{Prior}}}{\underbrace{P(data)}_{\text{Evidence}}}$$

Bayesian Evidence:

$$\mathcal{Z} = P(data) \equiv \int P(data|\{\theta_i\}, M) P(\{\theta_i\}, M) d\theta_1 ... d\theta_N$$

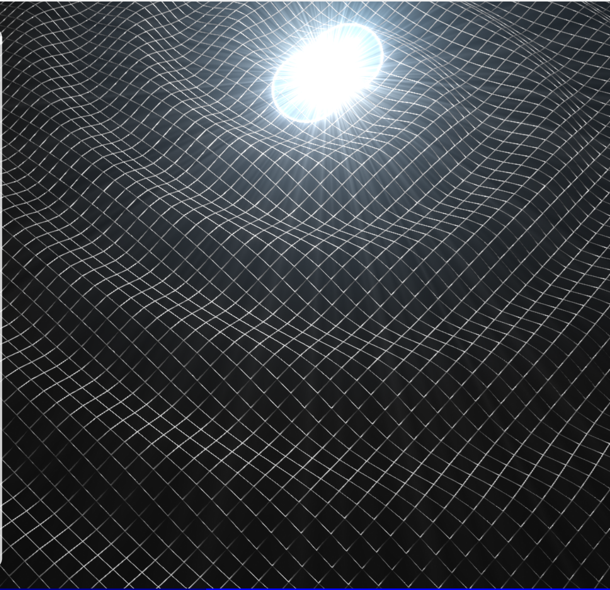
Bayes Factor:

$$B_{0,1} \equiv \frac{\mathcal{Z}_0 \leftarrow \text{ Evidence for the model } M_0}{\mathcal{Z}_1 \leftarrow \text{ Evidence for the model } M_1}$$

Jeffrey's Scale

$log\ B_{0,1}$	Conclusion
< 1	Inconclusive
$> 1, < 2.5$	Weak Evidence
$> 2.5, < 5.0$	Moderate Evidence
> 5.0	Strong Evidence

Trotta, R. *Contemporary Physics*, 49(2), 71-104.



Bayesian Model Selection [ET]

Bayes Theorem:

$$\overbrace{P(\{\theta_i\}|data,\ M)}^{\text{Posterior}} = \frac{\overbrace{P(data|\{\theta_i\},M)}^{\text{Likelihood}}\ \overbrace{P(\{\theta_i\},M)}^{\text{Prior}}}{\underbrace{P(data)}_{\text{Evidence}}}$$

Bayesian Evidence:

$$\mathcal{Z} = P(data) \equiv \int P(data|\{\theta_i\},M)P(\{\theta_i\},M)d\theta_1 ... d\theta_N$$

Bayes Factor:

$$B_{0,1} \equiv \frac{\mathcal{Z}_0 \leftarrow \text{ Evidence for the model } M_0}{\mathcal{Z}_1 \leftarrow \text{ Evidence for the model } M_1}$$

Jeffrey's Scale

$log\ B_{0,1}$	Conclusion
< 1	Inconclusive
$> 1, < 2.5$	Weak Evidence
$> 2.5, < 5.0$	Moderate Evidence
> 5.0	Strong Evidence

Trotta, R. *Contemporary Physics*, 49(2), 71-104.

Dark Energy Equation of State Parametrizations

$$P_{DE} = \omega_{DE}\rho_{DE}$$

$$\begin{aligned} \Lambda CDM \text{ Model} \quad & \omega_{DE} = -1; \\ \omega_0 CDM \text{ Model} \quad & \omega_{DE} = \omega_0; \\ \omega_0\omega_a CDM \text{ Model} \quad & \omega_{DE} = \omega_0 + \omega_a z/(1+z); \end{aligned}$$

$$\Omega_{DE}(z) = \Omega_{DE_0} exp\left[-3\int_0^z \frac{1+\omega_{DE}(z')}{1+z'}dz'\right]$$

Bayesian Model Selection [ET]

Bayes Theorem:

$$\overbrace{P(\{\theta_i\}|data,\ M)}^{\text{Posterior}} = \frac{\overbrace{P(data|\{\theta_i\},M)}^{\text{Likelihood}}\ \overbrace{P(\{\theta_i\},M)}^{\text{Prior}}}{\underbrace{P(data)}_{\text{Evidence}}}$$

Bayesian Evidence:

$$\mathcal{Z} = P(data) \equiv \int P(data|\{\theta_i\},M)P(\{\theta_i\},M)d\theta_1 \ldots d\theta_N$$

Bayes Factor:

$$B_{0,1} \equiv \frac{\mathcal{Z}_0 \leftarrow \text{ Evidence for the model } M_0}{\mathcal{Z}_1 \leftarrow \text{ Evidence for the model } M_1}$$

Jeffrey's Scale

$log\ B_{0,1}$	Conclusion
< 1	Inconclusive
$> 1, < 2.5$	Weak Evidence
$> 2.5, < 5.0$	Moderate Evidence
> 5.0	Strong Evidence

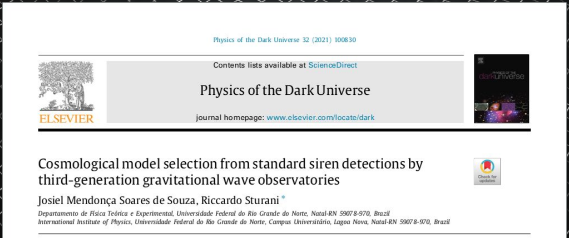
Trotta, R. *Contemporary Physics*, 49(2), 71-104.

Dark Energy Equation of State Parametrizations

$$P_{DE} = \omega_{DE}\rho_{DE}$$

$$\begin{aligned} \Lambda CDM \text{ Model} &\quad \omega_{DE} = -1; \\ \omega_0 CDM \text{ Model} &\quad \omega_{DE} = \omega_0; \\ \omega_0\omega_a CDM \text{ Model} &\quad \omega_{DE} = \omega_0 + \omega_a z/(1+z); \end{aligned}$$

$$\Omega_{DE}(z) = \Omega_{DE_0} exp\left[-3\int_0^z \frac{1+\omega_{DE}(z')}{1+z'}dz'\right]$$


Physics of the Dark Universe 32 (2021) 100830

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark

Cosmological model selection from standard siren detections by third-generation gravitational wave observatories

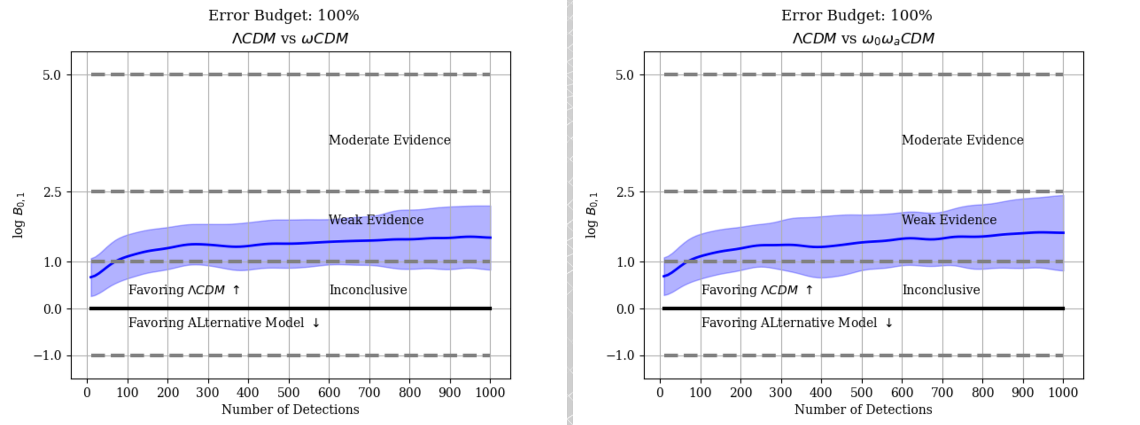
Josiel Mendonça Soares de Souza, Riccardo Sturani *

Departamento de Física Teórica e Experimental, Universidade Federal do Rio Grande do Norte, Natal-RN 59078-970, Brazil

International Institute of Physics, Universidade Federal do Rio Grande do Norte, Campus Universitário, Lagoa Nova, Natal-RN 59078-970, Brazil

Bayesian Model Selection [ET]

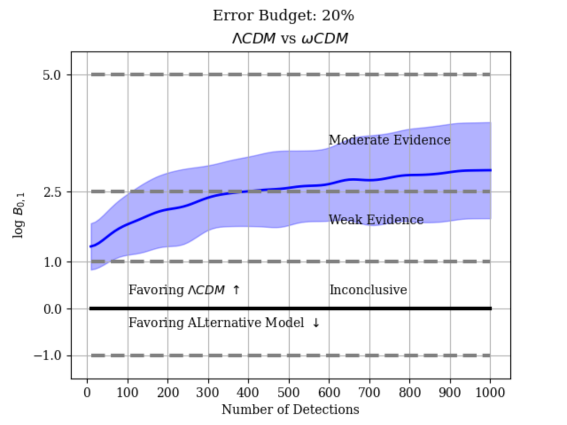
The simulations where performed 50 times. The plots show the averages over 50 realizations of the Bayes factor computations.

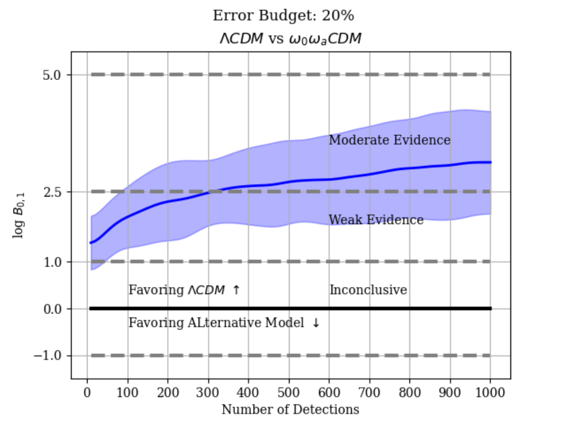


[Souza, J. M. S., & Sturani, R. *Physics of the Dark Universe*, 32, 100830.]

Bayesian Model Selection [ET]

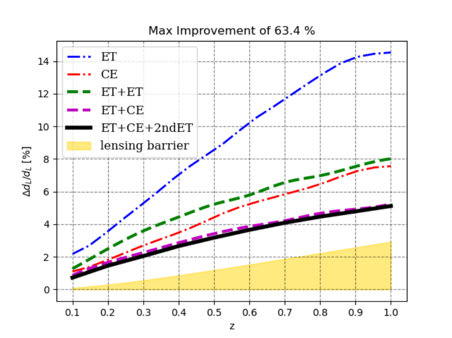
The simulations where performed 50 times. The plots show the averages over 50 realizations of the Bayes factor computations.

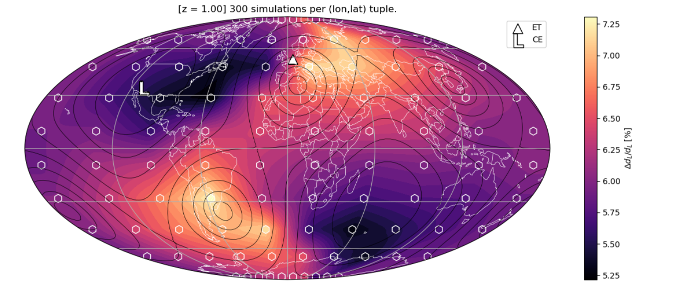




[Souza, J. M. S., & Sturani, R. *Physics of the Dark Universe*, 32, 100830.]

Improving $D_L(z)$ Measurements With Multiple 3G Ground Detectors





Estimations from Fisher Matrix Approach.

Cosmography with Standard Sirens [ET]

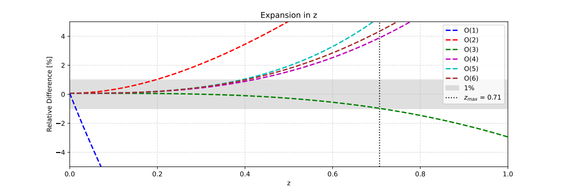
Cosmographic Expansion:

$$d_L(z) = \frac{1}{H_0}\left[z + \frac{1}{2}(1-q_0)z^2 + \frac{1}{6}(q_0 + 3q_0^2 - j_0 - 1)z^3 + O(z^4)\right]$$

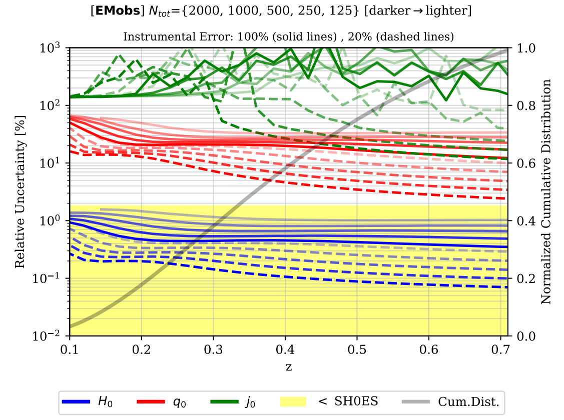
onde,

$$H_0 = \frac{1}{a}\frac{da}{dt}\Big|_{t=t_0}, \quad q_0 = -\frac{1}{(aH_0)^2}\frac{d^2a}{dt^2}\Big|_{t=t_0}, \quad j_0 = \frac{1}{(aH_0)^3}\frac{d^3a}{dt^3}\Big|_{t=t_0}$$

Convergence of the Series:



The simulations where performed up to $z = 0.71$ with 125, 250, 500, 1000 e 2000 bright standerd sirens detections.



Journal of Cosmology and Astroparticle Physics 2022.03 (2022): 025

Cosmography with Standard Sirens [ET]

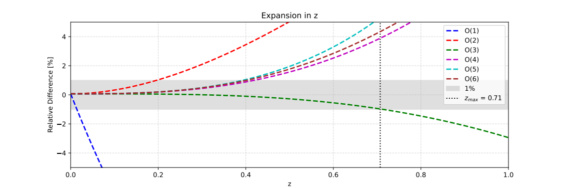
Cosmographic Expansion:

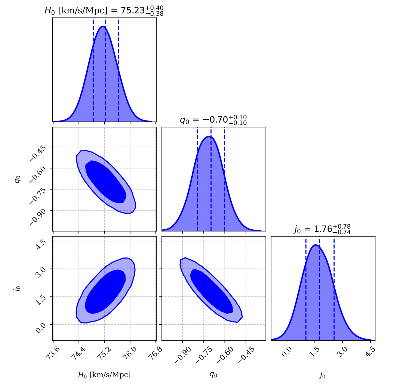
$$d_L(z) = \frac{1}{H_0}\left[z + \frac{1}{2}(1 - q_0)z^2 + \frac{1}{6}(q_0 + 3q_0^2 - j_0 - 1)z^3 + O(z^4)\right]$$

onde,

$$H_0 = \frac{1}{a}\frac{da}{dt}\bigg|_{t=t_0}, \quad q_0 = -\frac{1}{(aH_0)^2}\frac{d^2a}{dt^2}\bigg|_{t=t_0}, \quad j_0 = \frac{1}{(aH_0)^3}\frac{d^3a}{dt^3}\bigg|_{t=t_0}$$

Convergence of the Series:





The simulations where performed up to $z = 0.71$ with 125, 250, 500, 1000 e 2000 bright standerd sirens detections.

Journal of Cosmology and Astroparticle Physics 2022.03 (2022): 025

Cosmography with Standard Sirens [ET]

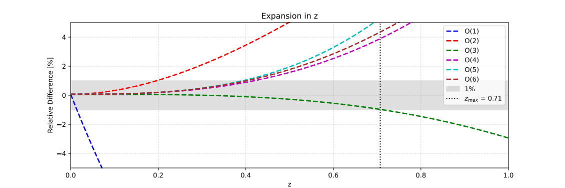
Cosmographic Expansion:

$$d_L(z) = \frac{1}{H_0}\left[z + \frac{1}{2}(1 - q_0)z^2 + \frac{1}{6}(q_0 + 3q_0^2 - j_0 - 1)z^3 + O(z^4)\right]$$

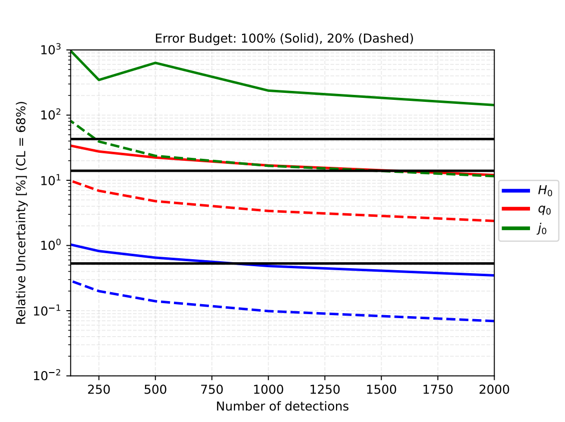
onde,

$$H_0 = \frac{1}{a}\frac{da}{dt}\bigg|_{t=t_0}, \quad q_0 = -\frac{1}{(aH_0)^2}\frac{d^2a}{dt^2}\bigg|_{t=t_0}, \quad j_0 = \frac{1}{(aH_0)^3}\frac{d^3a}{dt^3}\bigg|_{t=t_0}$$

Convergence of the Series:



The simulations where performed up to $z = 0.71$ with 125, 250, 500, 1000 e 2000 bright standerd sirens detections.



Journal of Cosmology and Astroparticle Physics 2022.03 (2022): 025

Thank You

UFRN
UNIVERSIDADE FEDERAL DO RIO GRANDE DO NORTE

DFTE
DEPARTAMENTO de FÍSICA TEÓRICA e EXPERIMENTAL

PPGF
Programa de Pós-Graduação Física
Universidade Federal do Rio Grande do Norte

iip INTERNATIONAL INSTITUTE OF PHYSICS

CAPES