Cosmological tests on non-metricity based theories of gravity

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[PhysRevD.105.123531]
[arXiv:2306.10176]
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1. Introduction

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

\[ \Omega_m, \Omega_r, \Omega_\Lambda \]

\[ ds^2 = -c^2 dt^2 + a^2(t) (dx^2 + dy^2 + dz^2) \]
1. Introduction
1. Introduction

ACDM
1. Introduction
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2. Gravity as Geometry

2.1. Decomposing the Affine Connection

\[ \Gamma^\lambda_{\mu\nu} = \{^\lambda_{\mu\nu}\} + K^\lambda_{\mu\nu} + L^\lambda_{\mu\nu} \]

- **Levi-Civita connection**

\[ \{^\lambda_{\mu\nu}\} \equiv \frac{1}{2} g^{\lambda\beta} (\partial_\mu g_{\beta\nu} + \partial_\nu g_{\beta\mu} - \partial_\beta g_{\mu\nu}) \]

- **The Contorsion**

\[ K^\lambda_{\mu\nu} \equiv \frac{1}{2} g^{\lambda\beta} (T_{\mu\beta\nu} + T_{\nu\beta\mu} + T_{\beta\mu\nu}) \quad T^\lambda_{\mu\nu} \equiv \Gamma^\lambda_{\mu\nu} - \Gamma^\lambda_{\nu\mu} \]

- **The Disformation**

\[ L^\lambda_{\mu\nu} \equiv \frac{1}{2} g^{\lambda\beta} (-Q_{\mu\beta\nu} - Q_{\nu\beta\mu} + Q_{\beta\mu\nu}) \quad Q_{\alpha\mu\nu} \equiv \nabla_\alpha g_{\mu\nu} \]

[arXiv:1802.00492]
2. Gravity as Geometry

2.2. Decomposing the Curvature

\[ R^\sigma_{\rho\mu\nu} \equiv \partial_\mu \Gamma^\sigma_{\nu\rho} - \partial_\nu \Gamma^\sigma_{\mu\rho} + \Gamma^\alpha_{\nu\rho} \Gamma^\sigma_{\mu\alpha} - \Gamma^\alpha_{\mu\rho} \Gamma^\sigma_{\nu\alpha} \]

\[ R^\sigma_{\rho\mu\nu} = \mathcal{R}^\sigma_{\rho\mu\nu} + \mathcal{C}^\sigma_{\mu\nu} \]

\[ M^\lambda_{\mu\nu} \equiv K^\lambda_{\mu\nu} + L^\lambda_{\mu\nu} \]

Contorsion  Disformation

[arXiv:1802.00492]
2. Gravity as Geometry
2.3. Geometrical Trinity of Gravity

\[ \int \sqrt{-g} \frac{1}{2k} d^4x \quad f(R) \]

[arXiv:1903.06830]
2. Gravity as Geometry

2.4. Gravity in $f(Q)$

\[ \int \sqrt{-g} \left( -\frac{c^4}{16\pi G} f(Q) + \mathcal{L}_m \right) d^4x \]

[PhysRevD.101.103507]

\[ \delta g_{\mu\nu} \]

\[ \frac{2}{\sqrt{-g}} \nabla_\alpha \left( \sqrt{-g} f_Q P^{\alpha\mu}_{\ \nu} \right) + \frac{1}{2} \delta^\mu_\nu f + f_Q P^{\mu\alpha\beta}_{\ \ \nu\alpha\beta} = \frac{8\pi G}{c^4} T^\mu_\nu , \]

Non-Metricity Conjugate: \( P^\alpha_{\mu\nu} \equiv -\frac{1}{2} L^\alpha_{\mu\nu} + \frac{1}{4} (Q^\alpha - \tilde{Q}^\alpha) - \frac{1}{4} \delta^\alpha_{(\mu} Q_{\nu)} \)

Coincident Gauge: \( \Gamma^\alpha_{\mu\nu} = 0 \)

Conservation of the Stress-Energy Tensor: \( \nabla_\nu T^{\mu\nu} = 0 \)

[arXiv:1710.03116]
[arXiv:gr-qc/0505128]
2. Gravity as Geometry

2.5. Geometrical Representation

Curvature

$R_{\mu \nu \rho \sigma}^\mu$

Torsion

$T_{\mu \nu \rho}^\mu$

Non-metricity

[arXiv:2106.13793]
3. Cosmology in $f(Q)$

3.1. Metric and Matter

**Flat FLRW Metric**

$$ds^2 = -c^2 dt^2 + a^2(t) (dx^2 + dy^2 + dz^2)$$

**Perfect Fluid**

$$\mathcal{T}^{\mu}_{\nu} = -(\rho c^2 + P) \delta^{\mu}_{0} \delta^{0}_{\nu} + P \delta^\mu_{\nu}$$

$$w \equiv \frac{P}{\rho c^2}$$

$$\dot{\rho} + 3\frac{\dot{a}}{a} \left( \rho + \frac{P}{c^2} \right) = 0$$

$$w = \begin{cases} 
1/3, & \text{radiation} \\
0, & \text{matter} \\
-1, & \text{dark energy}
\end{cases}$$
3. Cosmology in f(Q)

3.2. Background

**ΛCDM**

\[ R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \]

**f(Q)**

\[ \frac{2}{\sqrt{-g}} \nabla_\alpha (\sqrt{-g} f_Q P^{\alpha\mu}_{\nu}) + \frac{1}{2} \delta^\mu_\nu f + f_Q P^{\mu\alpha\beta}_{\nu} Q_{\nu\alpha\beta} = \frac{8\pi G}{c^4} T^\mu_\nu \]

Flat FLRW Metric + Perfect Fluid

\[ H^2 = \frac{8\pi G}{3} \rho \]

In flat FLRW f(Q) and f(T) have the same field equations

[PhysRevD.104.02401]
3. Cosmology in $f(Q)$

3.3. Gravitational Waves

\[ g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu} \]
\[ \eta_{\mu\nu} = \text{diag}(-1, 1, 1, 1) \]
\[ |h_{\mu\nu}| \ll 1 \]

\[ \Lambda CDM \quad \ddot{h} + 2\mathcal{H}\dot{h} + k^2 h = 0 \]
\[ d_{L}^{(GW)}(z) = d_L(z) = (1 + z)c \int_0^z \frac{1}{H(z)} dz \]

\[ f(Q) \quad \ddot{h} + 2\mathcal{H}(1 + 2\delta(z))\dot{h} + k^2 h = 0 \]
\[ \delta(z) = \frac{d \ln f_Q}{2Hd\eta} \]
\[ d_{L}^{(GW)}(z) = \sqrt{\frac{f_Q^{(0)}}{f_Q}} d_L(z) \]

Redshift

\[ z \equiv \frac{\lambda_{\text{obs}} - \lambda_{\text{src}}}{\lambda_{\text{src}}} = \frac{1}{a} - 1 \]
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7. Final Remarks
4. Datasets

4.1. Type la Supernova

\[
m^{\text{(obs)}} = M + 5 \log (d_L(z)) + 25
\]

\[
\mathcal{L} = \prod_{i=0}^{N} \frac{1}{\sigma(z_i)\sqrt{2\pi}} e^{-\frac{1}{2} \left( \frac{m^{\text{(obs)}}(z_i) - m(z_i)}{\sigma(z_i)} \right)^2}
\]

Marginalize $M, H_0$

\[
\mathcal{L} = e^{\frac{1}{2}(-A+B^2/C)}
\]

\[
A \equiv \sum_{i=1}^{N} \frac{\Delta^2(z_i)}{\sigma^2(z_i)} \quad B \equiv \sum_{i=1}^{N} \frac{\Delta(z_i)}{\sigma^2(z_i)} \quad C \equiv \sum_{i=1}^{N} \frac{1}{\sigma^2(z_i)}
\]

\[
\Delta(z) \equiv m^{\text{(obs)}} - 5 \log \frac{H_0}{c} d_L(z)
\]

Snla cannot constrain $H_0$!
4. Datasets
4.2. Cosmic Microwave Background

\[ R = \sqrt{\Omega_b + \Omega_c} \frac{H_0}{c} r(z_*) \]
\[ l_a = \pi \frac{r(z_*)}{r_s(z_*)} \]
\[ \omega_b = \Omega_b h^2 \]

Comoving Distance

\[ r(z) = \int_0^z \frac{c}{H(z)} dz \]

Comoving Sound Horizon

\[ r_s(z) = \int_z^\infty \frac{c_s(z)}{H(z)} dz \]
\[ c_s(z) = \frac{c}{\sqrt{3(1 + \hat{R}_b/(1 + z))}} \]

4. Datasets
4.3. Standard Sirens

\[ d_L^{GW}(z) \]
4. Datasets

4.3. Standard Sirens

\( \Lambda \)CDM

GWCatalog

github.com/jpmvferreira/gwcatalog
4. Datasets

4.3. Standard Sirens

2002 - Present

2030 – 2034/2040

2035
Datasets

4.4. Catalog Selection Criteria

• We generated 15 different catalogs for LISA, each with 15 events, and picked the best, median and worst catalogs.

\[ \Delta_{\text{tot}} \equiv \prod_{i=1}^{N} \sigma_{\theta_i} \]

• For the ET we generated 5 different catalogs, each with 1000 events, which all showed to be similar, so we only considered 1 catalog.

• For LIGO we generated 15 catalogs, each with 50 events.

• However, it was unable to set proper forecasts on our model, so we considered the best, median and worst catalogs based on how well it would complement the worst LISA catalog.
4. Datasets
4.5. Model Selection Criteria

Leave-one-out Cross Validation

Pareto Smoothed Importance Sampling

 Estimate fit of N-1 knowing fit of N

\[ \text{elpd}_{\text{PSIS-LOO-CV}} \rightarrow \text{elpd} \]

[arXiv:1507.04544]
4. Datasets

4.6. Bayesian Inference Methodology

Bayes’ Theorem

\[ P(\theta|X) \propto P(X|\theta) \times P(\theta) \]

Posterior Distribution

\[ P(\theta|X) \]
4. Datasets
4.6. Bayesian Inference Methodology

mc-stan.org
python.arviz.org
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5. f(Q) Cosmology with a $\Lambda$CDM Background

5.1. The Model

The Model

$$f(Q) = Q + \alpha \sqrt{Q}$$

Energy-Matter content

$$\Omega_r \ll 1$$

$$\Omega_m + \Omega_\Lambda = 1$$

Propagation of GWs

$$d_{L}^{(GW)}(z) = \sqrt{\frac{2\sqrt{6} + \alpha}{2\sqrt{6} + \alpha/E(z)}} d_L(z)$$

Degeneracy between $\alpha$ and $\Omega_m$

Use SNIa to fix $\Omega_m$
5. \( f(Q) \) Cosmology with a \( \Lambda \)CDM Background

5.2. Forecasts using Standard Sirens
5. $f(Q)$ Cosmology with a $\Lambda$CDM Background

5.2. Forecasts using Standard Sirens
5. *f*(Q) Cosmology with a $\Lambda$CDM Background

5.2. Forecasts using Standard Sirens

---

![Graph showing $d_\text{L}$ vs $z$](image)

![Plot of forecasts using Standard Sirens](image)
5. \( f(Q) \) Cosmology with a \( \Lambda \)CDM Background

5.2. Forecasts using Standard Sirens

![Graph showing forecasts using Standard Sirens]
5. $f(Q)$ Cosmology with a $\Lambda$CDM Background

5.2. Forecasts using Standard Sirens
### 5. f(Q) Cosmology with a $\Lambda$CDM Background

#### 5.2. Forecasts using Standard Sirens

<table>
<thead>
<tr>
<th>Catalog</th>
<th>$\sigma_\alpha$</th>
<th>Relative Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>ET</td>
<td>0.25</td>
<td>1</td>
</tr>
<tr>
<td>LISA (best)</td>
<td>0.37</td>
<td>1.5</td>
</tr>
<tr>
<td>LISA (worst) + LIGO (best)</td>
<td>0.44</td>
<td>1.8</td>
</tr>
<tr>
<td>LISA (median)</td>
<td>0.49</td>
<td>2</td>
</tr>
<tr>
<td>LISA (worst)</td>
<td>1.70</td>
<td>6.8</td>
</tr>
</tbody>
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6. f(Q) as Dark Energy

6.1. Dynamical System Analysis

\[ f(Q) = Q e^{\lambda Q_0/Q} \]

\[ 6f_Q H^2 - \frac{1}{2} f = 8\pi G \rho \quad \Omega_m, \Omega_r \]

\[ x_1 + x_2 + x_3 = 1 \]

\[ x_1 = \frac{\Omega_m}{E^2 e^{\lambda/E^2} a^3} \quad x_2 = \frac{\Omega_r}{E^2 e^{\lambda/E^2} a^4} \quad x_3 = \frac{2\lambda}{E^2} \]

\[ \lambda = 0 \implies \Lambda CDM \]
6. f(Q) as Dark Energy

6.1. Dynamical System Analysis

Equations of Motion

\[ x'_1 = -x_1 \left( -\left(1 + x_1 + x_2 \right) \frac{E'}{E} + 3 \right) \]
\[ x'_2 = -x_2 \left( -\left(1 + x_1 + x_2 \right) \frac{E'}{E} + 4 \right) \]

\[ \frac{E'}{E} \equiv \frac{3x_1 + 4x_2}{2 - \left( x_1 + x_2 \right) + \left( x_1 + x_2 \right)^2} \]

\[ ', \equiv \frac{d}{dN} \equiv \frac{d}{d \ln a} \]
6. f(Q) as Dark Energy
6.1. Dynamical System Analysis

Fixed Points

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>(0, 0)</td>
<td>(0, 1)</td>
<td>(1, 1)</td>
</tr>
<tr>
<td>Stable</td>
<td>Saddle</td>
<td>Unstable</td>
</tr>
<tr>
<td>λ dominated</td>
<td>Matter dominated</td>
<td>Radiation dominated</td>
</tr>
</tbody>
</table>

Regions

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>λ &gt; 0</td>
<td>λ = 0</td>
<td>λ &lt; 0</td>
</tr>
</tbody>
</table>
6. **f(Q) as Dark Energy**
6.2. **Model Selection using Standard Sirens**

\[
d_{L}^{\text{(GW)}}(z) = \sqrt{\frac{1 - \lambda}{1 - \lambda/E^2}} e^{\frac{\lambda}{2} (1 - 1/E^2)} d_L(z)
\]

<table>
<thead>
<tr>
<th>Model</th>
<th>elpd</th>
</tr>
</thead>
<tbody>
<tr>
<td>LISA (best)</td>
<td>-19.58 ± 7.17</td>
</tr>
<tr>
<td>ET</td>
<td>-1720.99 ± 36.50</td>
</tr>
<tr>
<td>f(Q) as Dark Energy</td>
<td>-19.76 ± 7.19</td>
</tr>
<tr>
<td>ΛCDM</td>
<td>-1721.00 ± 36.52</td>
</tr>
</tbody>
</table>
6. f(Q) as Dark Energy

6.2. Model Selection using Standard Sirens

![Graphs showing model selection using Standard Sirens](image)
6. f(Q) as Dark Energy

6.3. Model Selection using Supernovae

<table>
<thead>
<tr>
<th>Model</th>
<th>elpd</th>
</tr>
</thead>
<tbody>
<tr>
<td>f(Q) as Dark Energy</td>
<td>$-24.47 \pm 6.21$</td>
</tr>
<tr>
<td>$\Lambda$CDM</td>
<td>$-25.83 \pm 6.22$</td>
</tr>
</tbody>
</table>
6. f(Q) as Dark Energy
6.4. Standard Sirens vs Supernovae

ΛCDM

f(Q) as Dark Energy

20/11/2023
José Ferreira
6. f(Q) as Dark Energy

6.4. Supernovae vs Cosmic Microwave Background

Modified First Friedmann Equation

\[(E^2 - 2\lambda)e^{\lambda/E^2} = \Omega_m(1 + z)^3 + \Omega_r(1 + z)^4\]

\[\begin{align*}
  z & \gg 1 \\
  E^2 & \approx \Omega_m(1 + z)^3 + \Omega_r(1 + z)^4 + \lambda \\
  z & \ll 1 \\
  E^2 & \approx e^{-\lambda}\Omega_m(1 + z)^3 + e^{-\lambda}\Omega_r(1 + z)^4 + 2\lambda
\end{align*}\]
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7. Final Remarks
7. Final Remarks

- Constructed SS mock catalogs for LIGO, LISA and the ET;

- Studied the most general f(Q) model that replicates a $\Lambda$CDM background
  - Introduces an additional free parameter $\alpha$
  - The ET will outperform LISA and LIGO alone will not be able to constrain this model
  - LISA and LIGO are subject to non-negligible statistical fluctuations in their catalogs, ET is not
  - LIGO will be able to improve the quality of the constrains set by LISA

- Studied an f(Q) model which replicates late-time expansion without dark energy
  - It introduces no additional free parameters
  - Neither SS events nor SnIa are expected to be able to distinguish between this model and $\Lambda$CDM
  - There is a tension between SnIa and the CMB, effectively ruling out the model

Questions?
A. GWCatalog

GWCatalog

```
gwc.save(redshifts, distances, errors, "catalog.csv")
gwc.load("catalog.csv")
gwc.plot(redshifts, distances, errors, "catalog1")
gwc --cosmology mycosmology.py generate ET --events 1000
```

Save and Load Catalogs

Plot Catalogs

Generate events with custom cosmological model

Not Available

$ gwc save catalog.csv
$ gwc load catalog.csv
$ gwc plot --input catalog1.csv --legend "catalog 1"
$ gwc --cosmology mycosmology.py generate ET --events 1000
A. GWCatalog

```
>> redshifts, distances, errors = gwc.LIGO(events=50)

$ gwc generate LIGO --events 50
```

```
>> redshifts, distances, errors = gwc.LISA(population="Pop III", events=15)

$ gwc generate LISA --population "Pop III" --events 15
```

```
>> redshifts, distances, errors = gwc.ET(events=1000)

$ gwc generate ET --events 1000
```
B. Observatories

B.1. LIGO

[arXiv:1901.03321]
B. Observatories

B.2. LISA

[arXiv:1607.08755]

[arXiv:2010.09049]
B. Observatories

B.3. ET

[arXiv:1805.08731]
C. Model Selection Criteria

Utility

\[
elpd = \sum_{i=1}^{N} \int p_t(\bar{y}_i) \ln p(\bar{y}_i | y) d\bar{y}_i
\]

Unknown

\[
p(\bar{y}|y) = \int p(\bar{y}_i | \theta)p(\theta | y) d\theta
\]

\[y_{-i} = \text{dataset } y \text{ without the } i\text{-th event}\]

Leave-one-out

\[
elpd_{\text{LOO-CV}} = \sum_{i=1}^{N} \ln p(y_i | y_{-i})
\]

[arXiv:1507.04544]

Pareto Smoothed Importance Sampling

\[
elpd_{\text{PSIS-LOO-CV}} = \sum_{i=1}^{N} \ln \left( \frac{\sum_{s=1}^{S} w_i^s p(y_i | \theta^s)}{\sum_{s=1}^{S} w_i^s} \right)
\]

\(\text{elpd}_{\text{PSIS-LOO-CV}} \rightarrow \text{elpd}\)
D. Example Stan Program

```stan
data {
  real N;
  array[N] real x;
  array[N] real yobs;
  array[N] real error;
}

parameters {
  real m;
  real b;
}
transformed parameters {
  array[N] real y;
  for (i in 1:N) {
    y[i] = m * x[i] + b; // indices range from 1 to N!
  }
}
model {
  // priors
  m ~ normal(0, 4);
  b ~ normal(0, 3);
  // likelihood
  y ~ normal(yobs, error);
}
```

```python
# imports
from cmdstanpy import CmdStanModel
import matplotlib.pyplot as plt
import arviz as az

# compile the model into an executable
cmdstanmodel = CmdStanModel(stan_file="model.stan")

# constrain the model with the dataset provided
fit = cmdstanmodel.sample(data="data.json")

# use Stan's pre-built tools to check for problems
print(fit.diagnose())

# convert fit to something that arviz can understand
azfit = az.from_cmdstanpy(posterior=fit)

# traceplot
az.plot_trace(azfit, var_names=('m', 'b'), compact=False)
plt.tight_layout()
plt.show()
plt.close()

# corner plot
az.plot_pair(azfit, var_names=('m', 'b'), kind='kde')
plt.show()
```
E. References and Source Code

Forecasting $F(Q)$ cosmology with ΛCDM background using standard sirens

José Ferreira, Tiago Barreiro, José Mimoso, and Nelson J. Nunes

1 Instituto de Astrofísica e Ciências do Espaço, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Edifício C8, P-1749-016, Lisboa, Portugal
2 Departamento de Física, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Edifício C8, P-1749-016, Lisboa, Portugal
3 ECEO, Universidade Lusófona de Humanidades e Tecnologias, Campo Grande, 376, 1749-024 Lisboa, Portugal

(Dated: October 20, 2022)

Forecast constraints for a Symmetric Teleparallel Gravity model with a ΛCDM background are made using forthcoming ground and space based gravitational waves observatories. A Bayesian analysis resorting to generated mock catalogs shows that LIGO-Virgo is not expected to be able to distinguish this model from ΛCDM, while both LISA and the ET will, with the ET outperforming LISA. We also show that low redshift events are favored in order to improve the quality of the constrains.

Testing Λ-Free $f(Q)$ Cosmology

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2 Departamento de Física, Faculdade de Ciências da Universidade de Lisboa, Campo Grande, Edifício C8, P-1749-016, Lisboa, Portugal
3 ECEO, Universidade Lusófona de Humanidades e Tecnologias, Campo Grande, 376, 1749-024 Lisboa, Portugal

(Dated: June 21, 2023)

We study a model of Symmetric Teleparallel gravity that is able to account for the current accelerated expansion of the universe without the need for dark energy component. We investigate this model by making use of dynamical system analysis techniques to identify the regions of the parameter space with viable cosmologies and constrain it using type Ia supernova (SNIa), cosmic microwave background (CMB) data and make forecasts using standard siren (SS) events. We conclude that this model is disfavored with respect to ΛCDM and forthcoming standard siren events can be decisive in testing the viability of the model.
Credits
Riess, A.G. The expansion of the Universe is faster than expected. *Nat Rev Phys* 2, 10–12 (2020). https://doi.org/10.1038/s42254-019-0137-0

https://www.nature.com/articles/nature.2013.13379

https://www.esa.int/ESA_Multimedia/Images/2013/03/Planck_Power_Spectrum

https://pages.uoregon.edu/imamura/SCS123/SCS.123.html

https://www.nature.com/articles/nature.2013.13379

https://www.ligo.org/detections/GW170817.php

By NASA/ESA, CC BY 3.0, https://commons.wikimedia.org/w/index.php?curid=407520

Credit: P. K. Blanchard / E. Berger / P. Edmonds
https://astrobites.org/2015/04/07/super-bright-supernovae-are-single-degenerate/

https://indico.cern.ch/event/688110/contributions/2853781/attachments/1638652/2627583/7_Renk_MGCodes.pdf

By Janina Renk, adapted from the original of Tessa Baker

https://ned.ipac.caltech.edu/level5/Sept11/Norman/Norman2.html

https://physicsworld.com/a/planck-perspectives/

https://www.researchgate.net/figure/Illustration-of-Markov-Chain-Monte-Carlo-method_fig1_334001505
Bayes' Theorem

\[ P(\theta | X) = \frac{P(X | \theta) \times P(\theta)}{P(X)} \]