

Modeling the Annualized Rate of Public Mass Shootings with Gaussian Processes

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Legendary Entertainment

Legendary Entertainment: Applied Analytics

- Unprecedented unit in a major Hollywood studio



- Integrating data and evidence in executive decision
- 80 Analytics staff in Boston, LA, and Beijing



Motivating Question

How has the rate of
mass public shootings
in the US evolved
over time?

Two decades of unresolved controversy

Mother Jones Database of Mass Shootings

Mother Jones

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US Mass Shootings, 1982-2017: Data From Mother Jones' Investigation

The full data set from our in-depth investigation into mass shootings. Plus:
additional cases from 2013-17.

MARK FOLLMAN, GAVIN ARONSEN, AND DEANNA PAN UPDATED: JAN. 8, 2017, 9:30 A.M. PDT



Editor's note: This dataset originally covered 1982-2012 and has since been expanded through 2017. For more context and analysis, see our [Guide to Mass Shootings in America](#). You can also download this data in [CSV](#), [XLS](#), or [TXT](#) formats, or [click here for the full Google spreadsheet view](#). (The embedded version below does not support expanding the cells to see the full text in some places, but you can access it these other ways.)

Mother Jones' Investigation: US Mass Shootings, 1982-2016

[US mass shootings](#) [Pivot Table 1](#) [Weapon categories](#)

Case	Location	Date	Year	Summary	Fatalities	Injured	Total
Fort Lauderdale airport shooting	Fort Lauderdale, Florida	1/6/2017	2017	Esteban Santiago, 26, flew from Alaska	5	6	11 (d
Cascade Mall shooting	Burlington, WA	9/23/2016	2016	Arcan Cetin, 20, killed a teen girl and th	5	0	

Definition of Public Mass Shooting

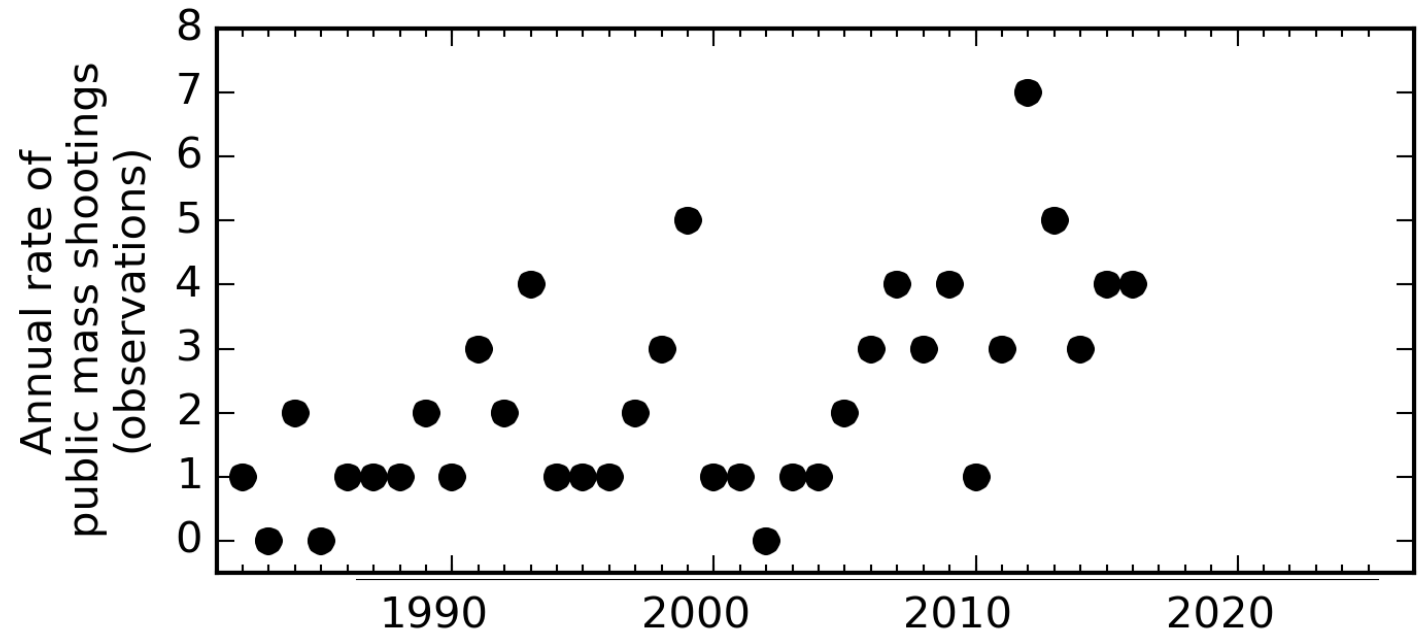
Definition: *“attacks in public places with **four or more victims** killed... [excluding] mass murders in private homes related to domestic violence, as well as shootings tied to gang or other criminal activity.*

Based on the FBI's own baseline definition

Dataset & Modeling Goals

1. Interpretable inferences on long term evolution (parametric model)
2. Discover short term deviations (non-parametric model)

Mother Jones Dataset



Gaussian Process Model

Mean Function



Interpretable parameters

$$\mu(x) = \mu_0 + \mu_b x$$

Gaussian Process Model

Mean Function

$$\mu(x) = \mu_0 + \mu_b x$$

→ *Interpretable parameters*

Covariance Function

$$k(x)_{ij} = \eta^2 \exp\left(-\rho^2 \sum_{d=1}^D (x_{i,d} - x_{j,d})^2\right) + \delta_{ij} \sigma^2$$

→ *Non-parametric function*

```
// Calculate covariance matrix using new optimized function
Sigma1 = cov_exp_quad(rx1, sqrt(eta_sq), sqrt(0.5) *
inv_rho);
for (n in 1:N1) Sigma1[n,n] = Sigma1[n,n] + sigma_sq;
```


Gaussian Process Model

Mean Function

$$\mu(x) = \mu_0 + \mu_b x$$

 *Interpretable parameters*

Covariance Function

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```

Likelihood

$$y(x) \sim N(\mu(x), k(x)^2)$$
$$z(x) \sim \text{NB}(\exp(y(x)), \phi)$$

```
// Negative-binomial prior
// For neg_binomial_2, phi^-1 controls the overdispersion.
// phi^-1 ~ 0 reduces to the poisson.
NB_phi_inv ~ cauchy(0, 5);

// Likelihood
z1 ~ neg_binomial_2_log(y1, inv(NB_phi_inv));
```

Gaussian Process Model: Priors

Priors

$$\rho^{-1} \sim \Gamma(\alpha_\rho, \beta_\rho)$$

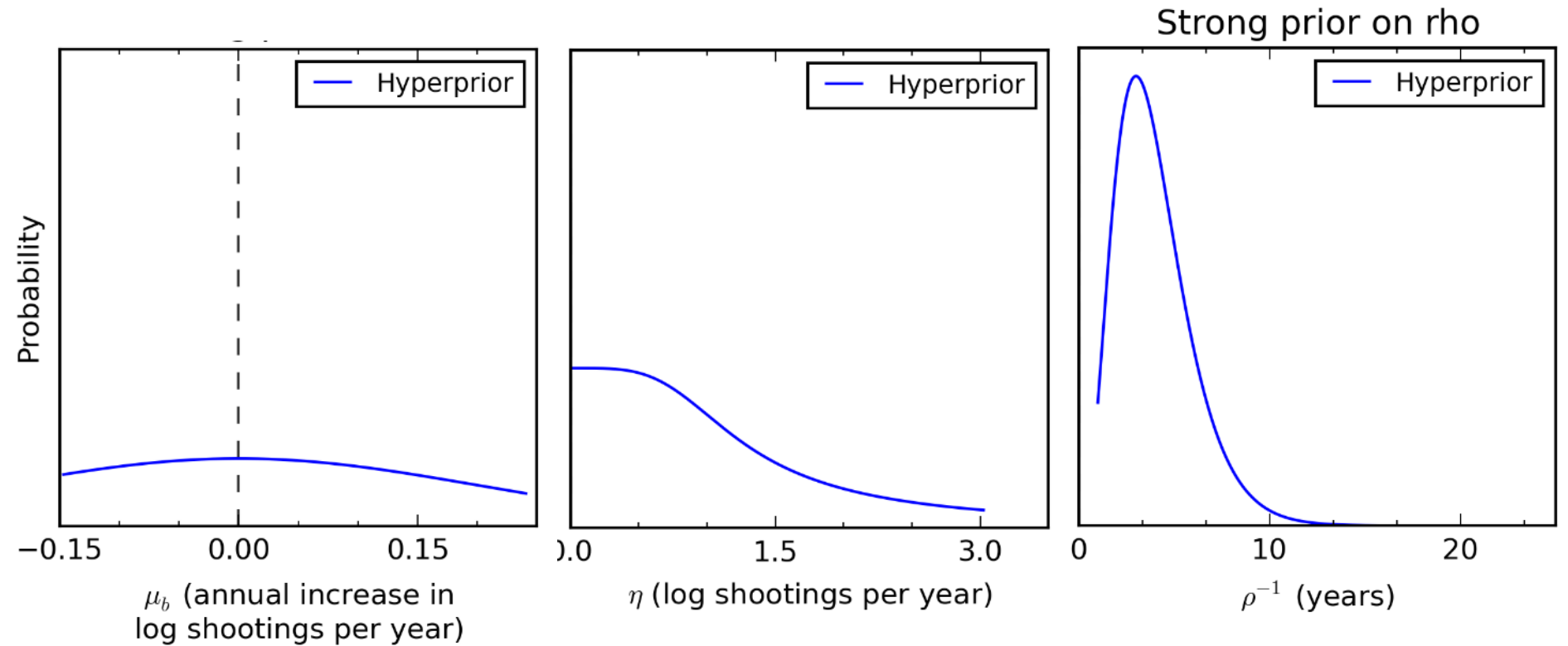
$$\eta^2 \sim C(2.5)$$

$$\sigma^2 \sim C(0, 2.5)$$

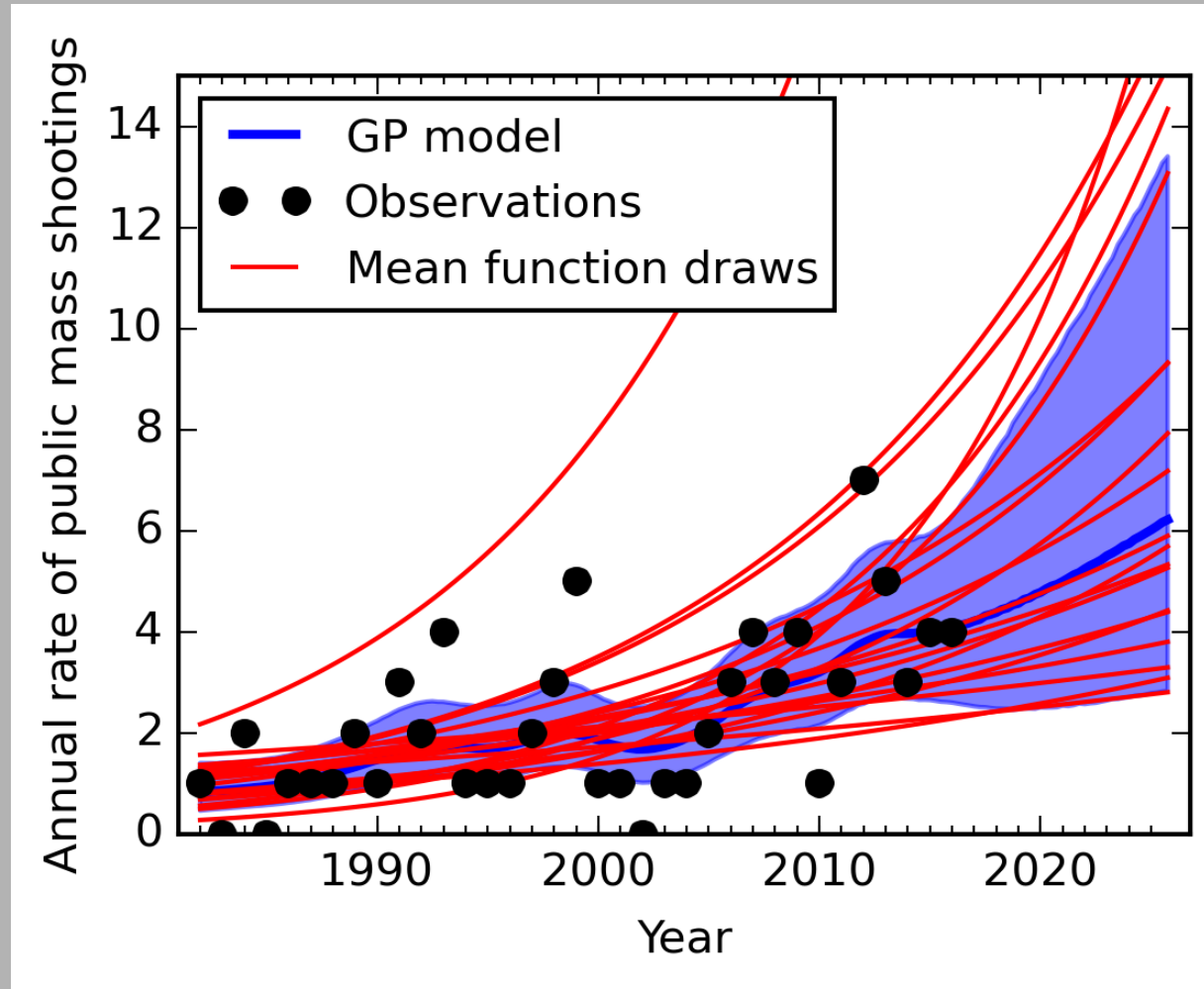
$$\mu_0 \sim N(0, 2)$$

$$\mu_b \sim N(0, 0.2)$$

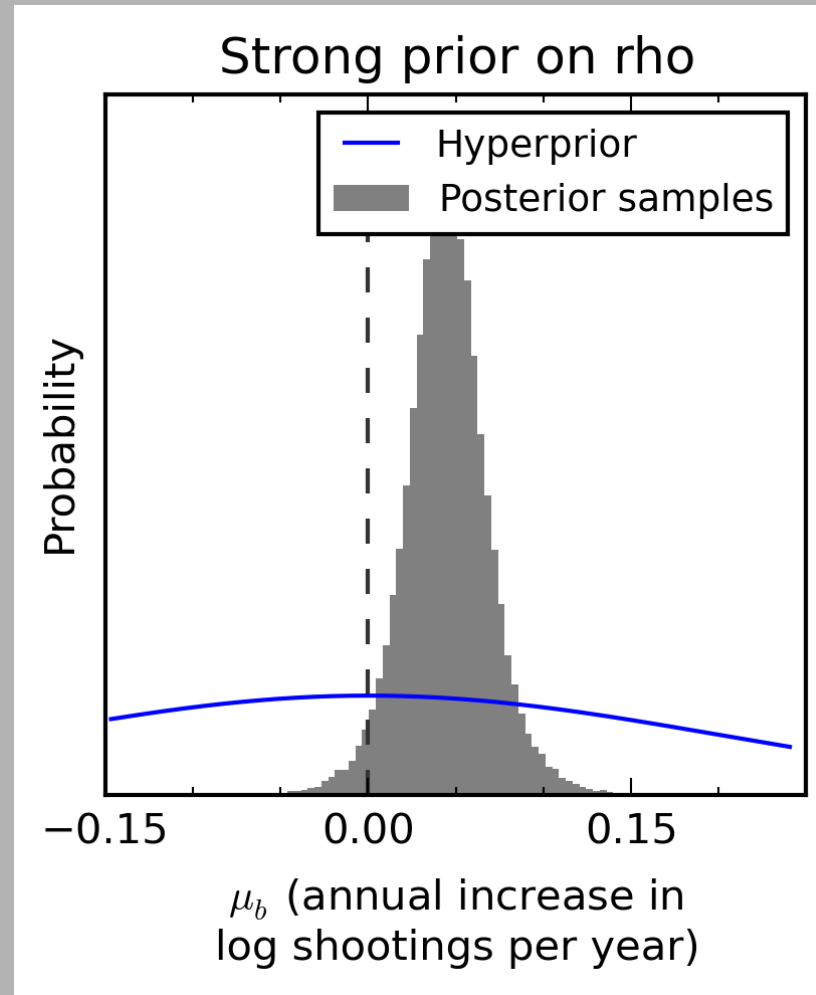
$$\phi^{-1} \sim C(0, 5)$$



Mean Function / Posterior Visualization



Inference on μ_b

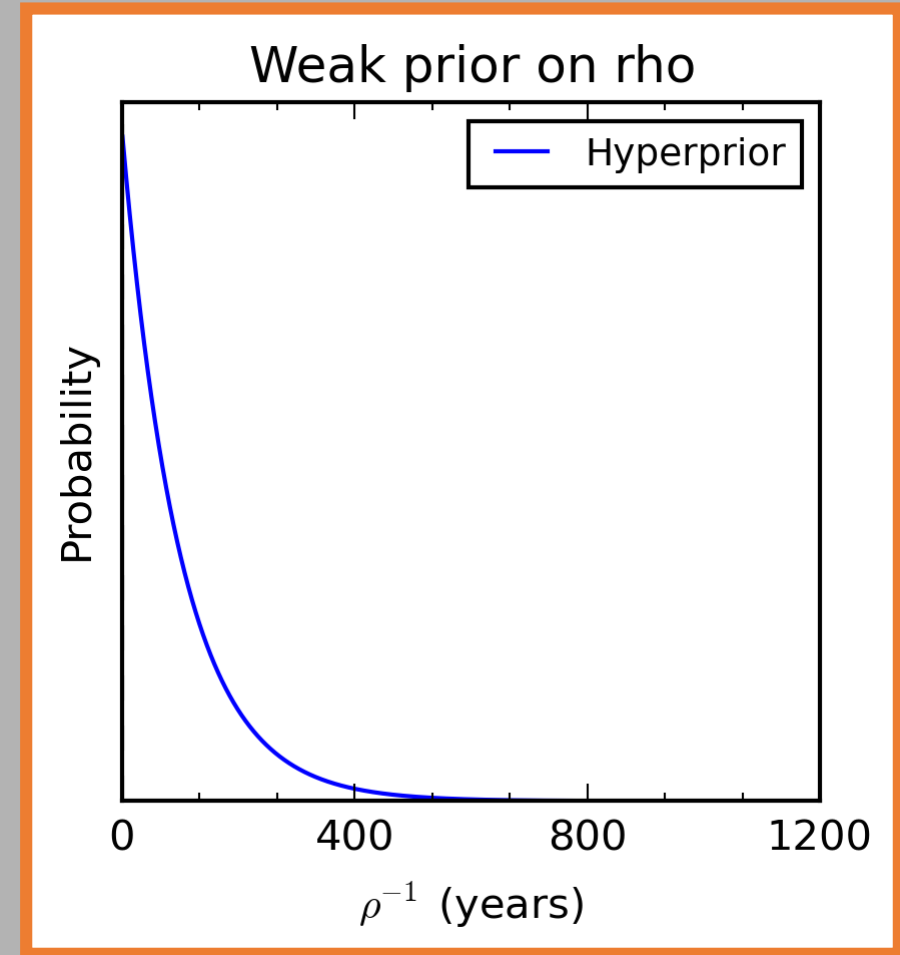
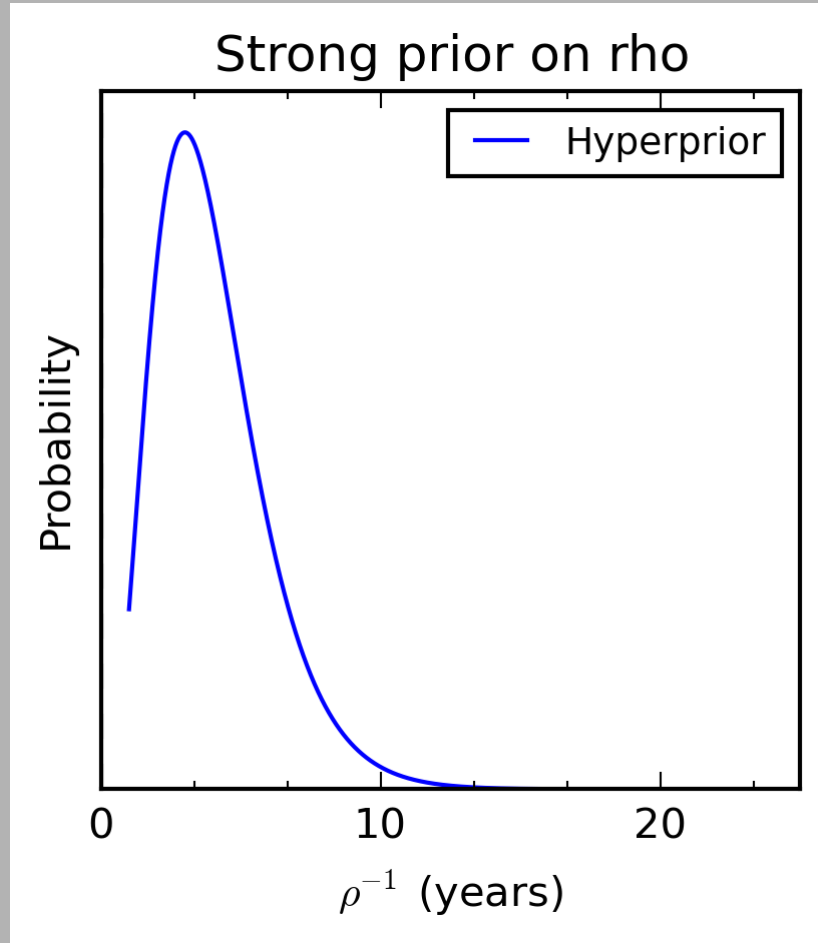


97% probability that mass shooting rate has increased ($\mu_b > 0$)

Alternate Prior

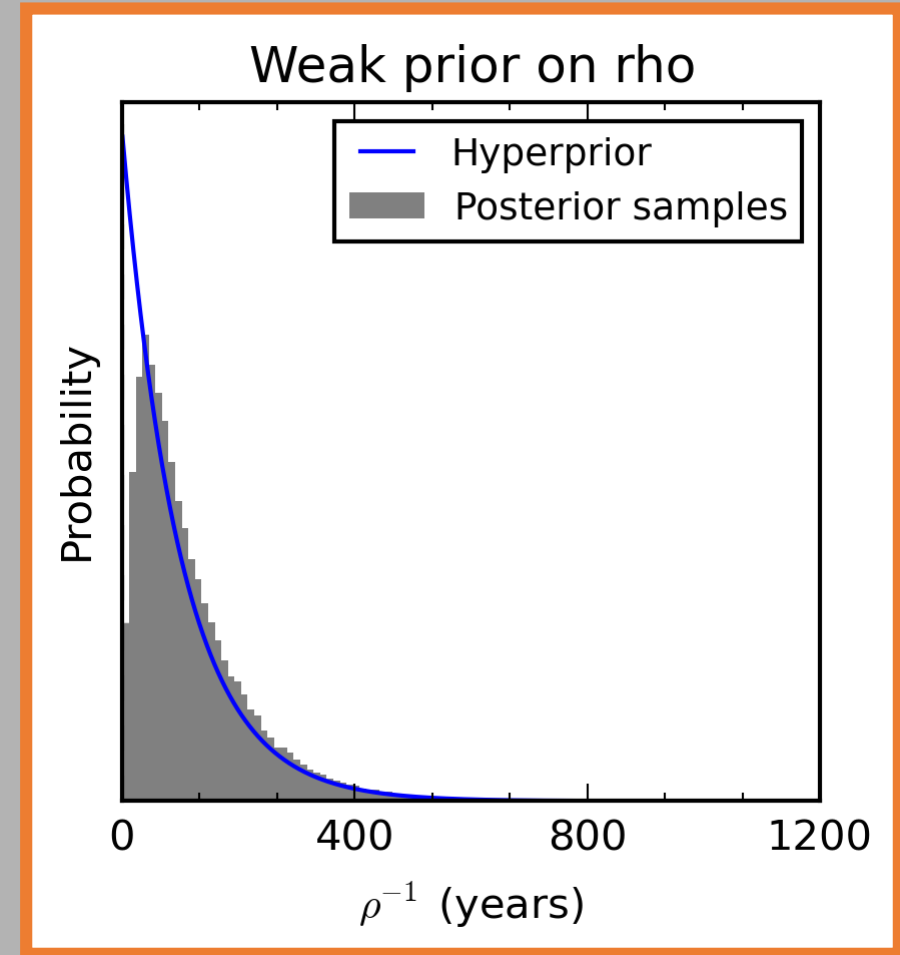
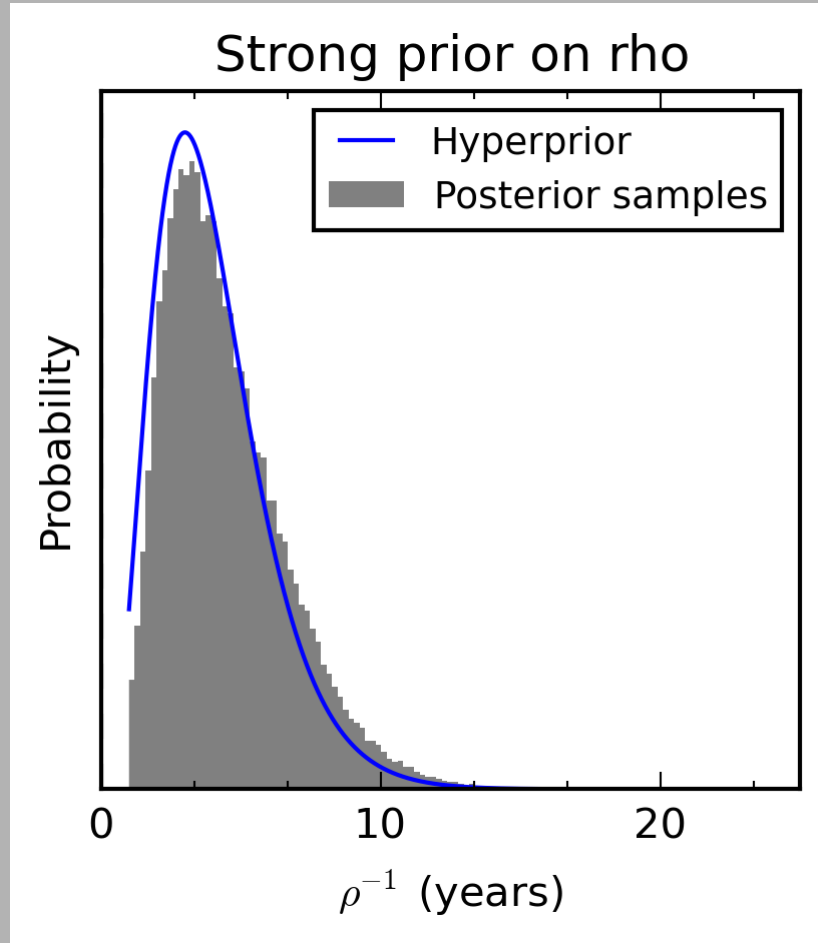
What are the
consequences of allowing
longer timescale evolution?

Alternate Prior



What are the consequences of allowing for longer timescale evolution?

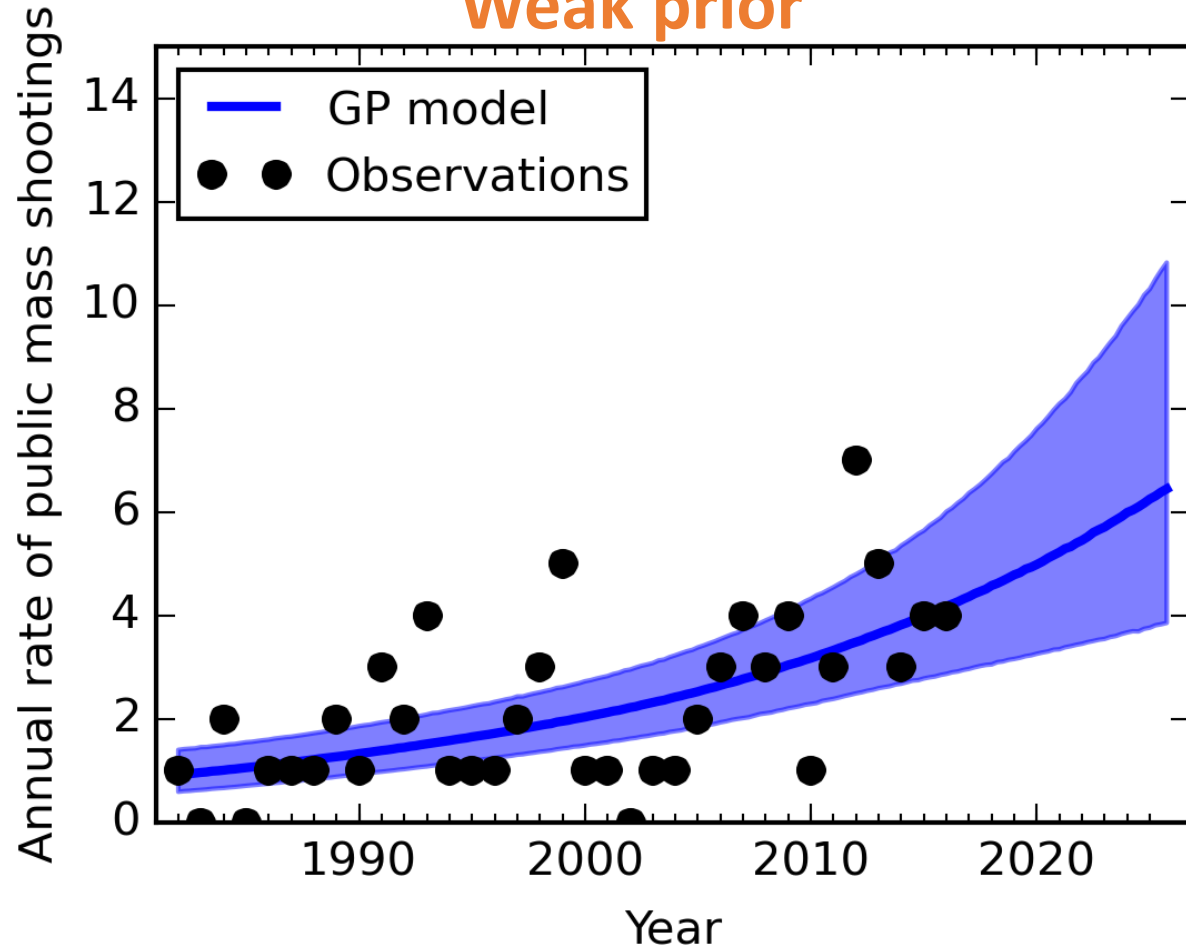
Alternate Prior: ρ^{-1} Posterior



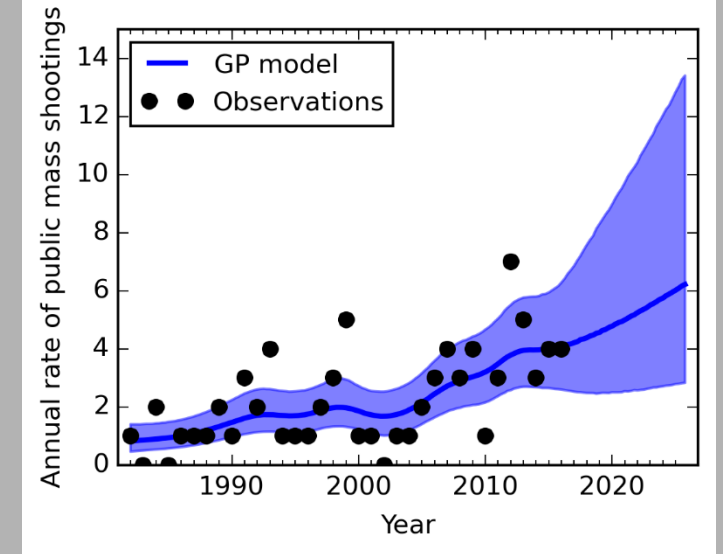
Data identifies other parameters, but ρ samples from prior

Alternate Prior: Posterior Visualization

Weak prior



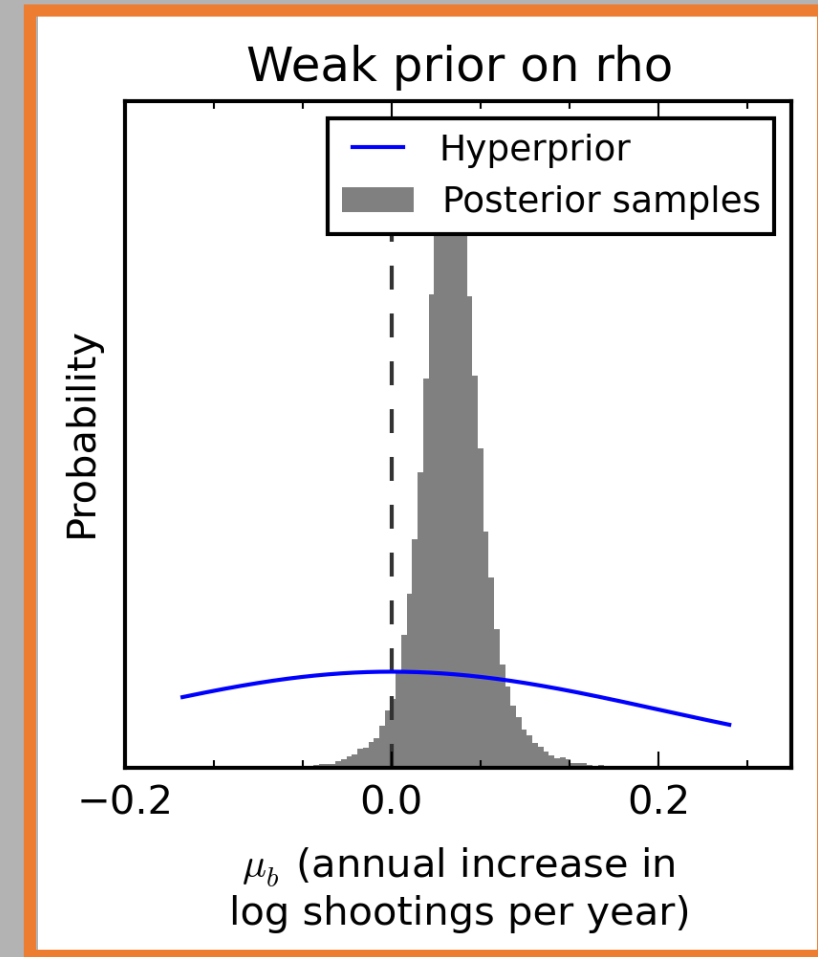
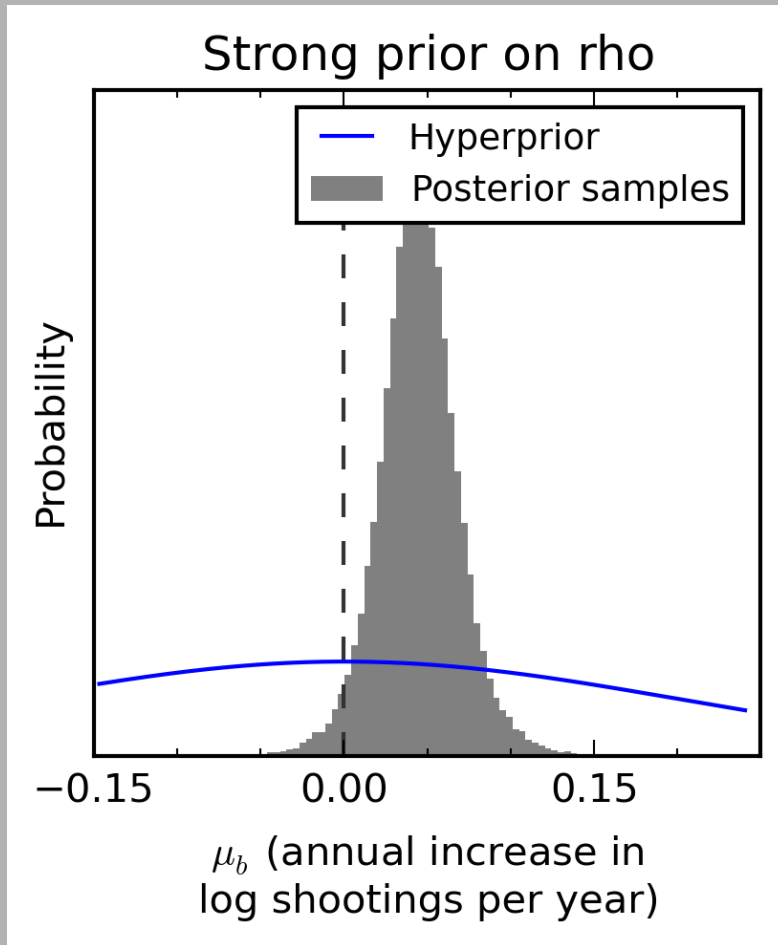
Strong prior



Mean function dominates

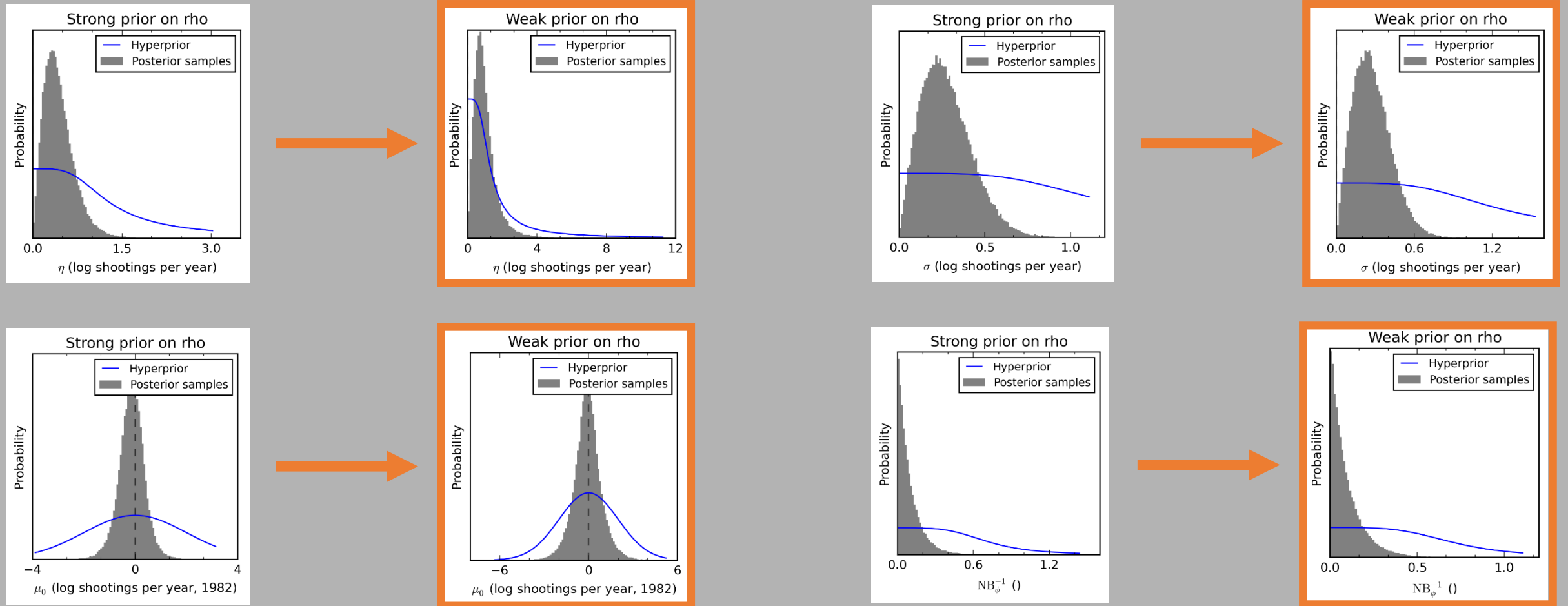
Inference on year-to-year variation depends on timescale prior

Alternate Prior: μ_b Posterior



μ_b inference unchanged under alternate prior

Alternate Priors: Other Hyperparameters



Marginalized hyperparameter posteriors largely identical

2D Posterior Slice

Use linear models to guide
exploration of
posterior correlations

inv_rho ~ ...

	Coef.	Std.Err.

const	0.0000	0.0034
NB_phi_inv	-0.0065	0.0034
eta	0.1635	0.0034
mu_0	0.0101	0.0037
mu_b	-0.0321	0.0037
sigma	-0.0116	0.0034

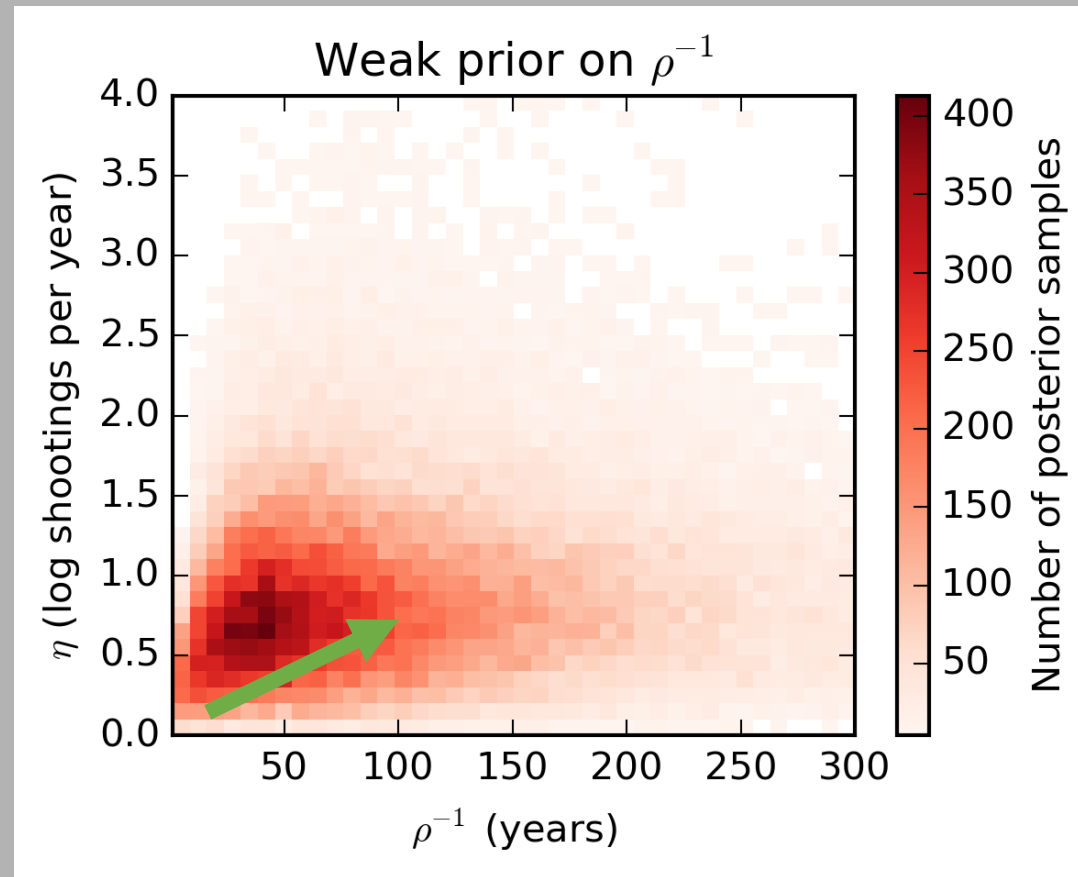
2D Posterior Slice

Use linear models to guide exploration of posterior correlations

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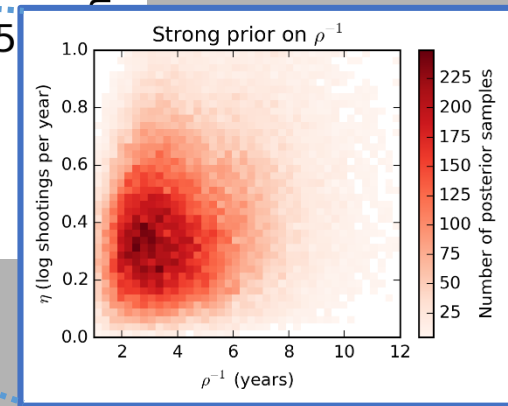
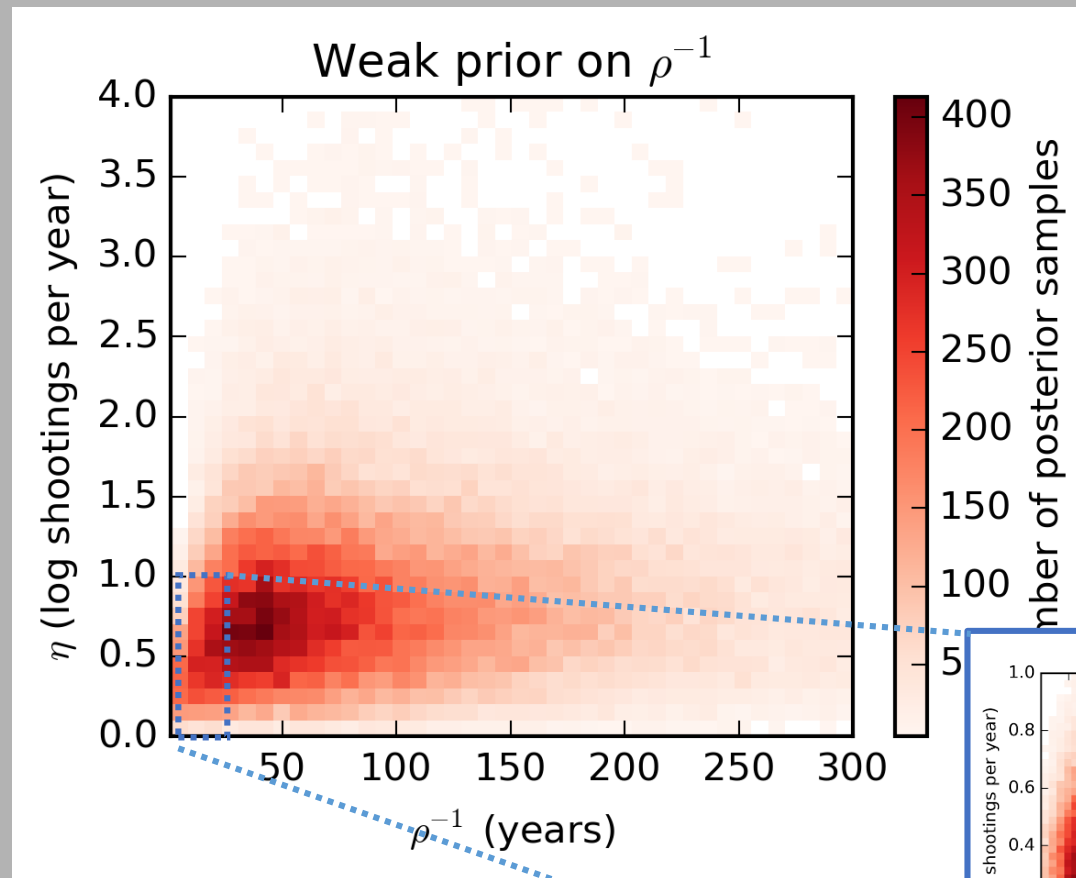


When timescale is long, amplitude is unconstrained

2D Posterior Slice

Benefit of Stan:

Efficient sampler supports inspection of posterior curvature



When timescale is long, amplitude is unconstrained

Possible Policy Implications

- The rate of mass shootings has almost certainly been increasing
- Is near-term change possible, through policy intervention or cultural change?
 - The data alone do not tell us
 - If theory (priors) asserts that evolution is fast, then the amplitude of past effects has been small

Conclusions

- 97% prob. that mass shootings have increased since '82
- Beliefs about timescale of change impacts interpretation of policy interventions and cultural shifts
- Benefits of Bayesian approach
 - Quantification of uncertainty in predictions and parameters
 - Testbed for the implications of prior information
- Benefits of Stan
 - PPL supports testing of arbitrary priors and mean functions
 - Efficient sampler supports inspection of posterior curvature