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Beta and Dirichlet sub-Gaussianity

Olivier Marchal, Julyan Arbel

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Abstract

• **Optimal proxy variance** σ_{opt}^2 for the sub-Gaussianity of Beta distribution, improves recent conjecture σ_0^2 by Elder (2016): $\sigma_{opt}^2 \leq \sigma_0^2 = \frac{1}{4(\alpha+\beta+1)}$.

• Provide different proof techniques for
 (i) symmetrical case ($\alpha = \beta$): direct coef. comparison of entire series
 (ii) non-symmetrical case ($\alpha \neq \beta$): ordinary differential equation satisfied by moment-generating function, aka **confluent hypergeometric function**

• Derive optimal proxy variance for Dirichlet.

Optimal proxy variance for the Beta

Theorem Beta(α, β) is $\sigma_{opt}^2(\alpha, \beta)$ -sub-Gaussian with:

$$\left\{ \begin{array}{l} \sigma_{opt}^2(\alpha, \beta) = \frac{\alpha}{(\alpha + \beta)x_0} \left(\frac{{}_1F_1(\alpha + 1; \alpha + \beta + 1; x_0)}{{}_1F_1(\alpha; \alpha + \beta; x_0)} - 1 \right) \\ \text{where } x_0 \text{ is the unique solution of the equation} \\ \log({}_1F_1(\alpha; \alpha + \beta; x_0)) = \frac{\alpha x_0}{2(\alpha + \beta)} \left(1 + \frac{{}_1F_1(\alpha + 1; \alpha + \beta + 1; x_0)}{{}_1F_1(\alpha; \alpha + \beta; x_0)} \right). \end{array} \right.$$

Simple explicit upper bound to $\sigma_{opt}^2(\alpha, \beta)$ is $\sigma_0^2(\alpha, \beta) = \frac{1}{4(\alpha+\beta+1)}$:

$$\text{Var}[\text{Beta}(\alpha, \beta)] \leq \sigma_{opt}^2(\alpha, \beta) \leq \sigma_0^2 \text{ (strict when } \alpha \neq \beta)$$

Sub-Gaussianity & optimal proxy variance

• A random variable X with finite mean $\mu = \mathbb{E}[X]$ is **sub-Gaussian** if there is a positive number σ^2 (called a proxy variance) such that:

$$\mathbb{E}[\exp(x(X - \mu))] \leq \exp\left(\frac{x^2 \sigma^2}{2}\right) \text{ for all } x \in \mathbb{R}. \quad (1)$$

• If X is sub-Gaussian, the **optimal proxy variance** is:

$$\sigma_{opt}^2(X) = \min\{\sigma^2 \geq 0 \text{ such that } X \text{ is } \sigma^2\text{-sub-Gaussian}\}.$$

Variance lower bounds optimal proxy variance: $\text{Var}[X] \leq \sigma_{opt}^2(X)$. When $\sigma_{opt}^2(X) = \text{Var}[X]$, X is said to be strictly sub-Gaussian.

Sketch of proof

- $\alpha = \beta$: direct coef. comparison of entire series representations of (1)
- $\alpha \neq \beta$: study the MGF aka confluent hypergeometric function or Kummer's function

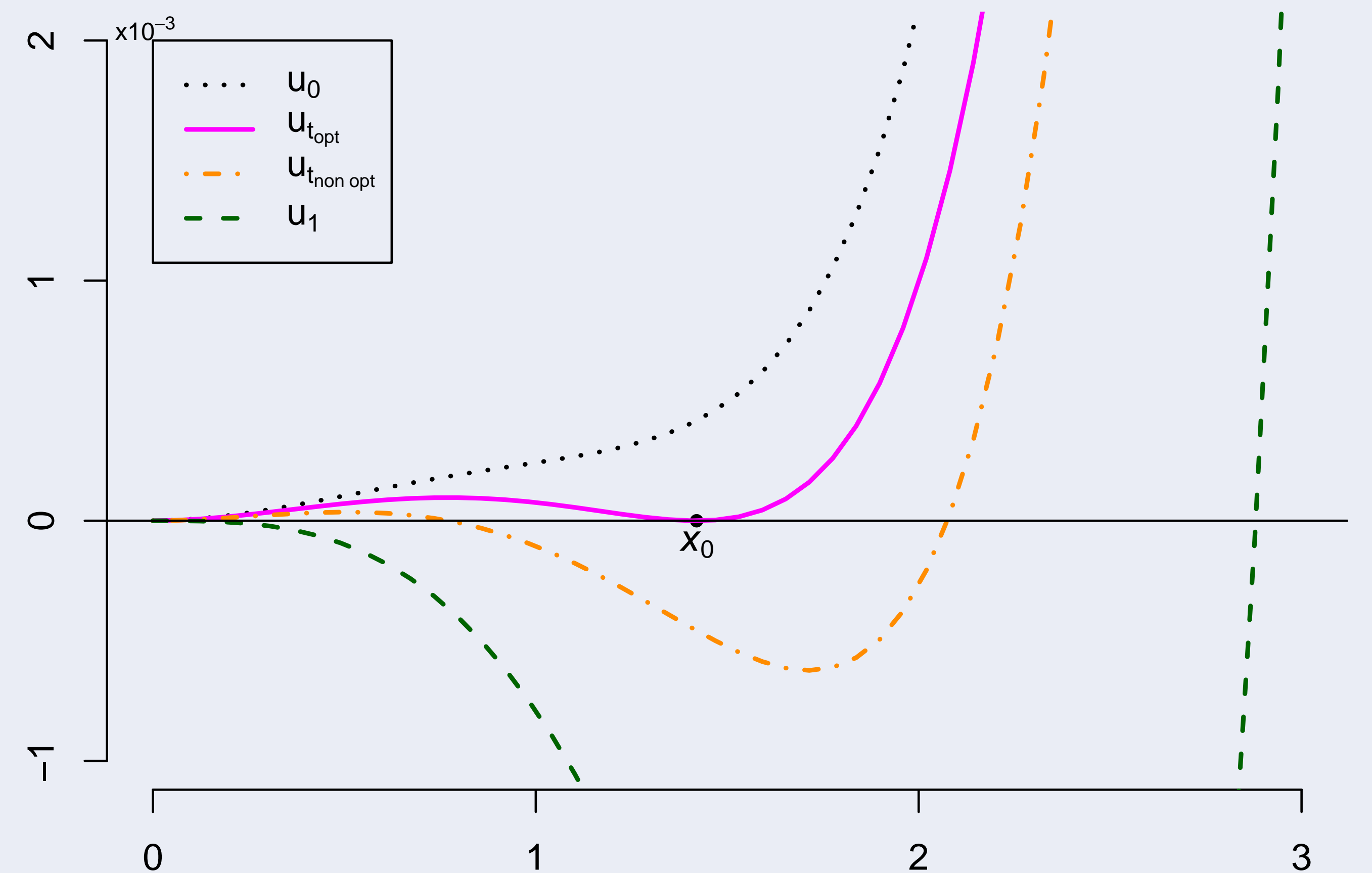
$$y(x) \stackrel{\text{def}}{=} \mathbb{E}[\exp(xX)] = {}_1F_1(\alpha; \alpha + \beta; \lambda) = \sum_{j=0}^{\infty} \frac{\Gamma(\alpha + j)\Gamma(\alpha + \beta)}{(j!) \Gamma(\alpha)\Gamma(\alpha + \beta + j)} x^j.$$

using the ordinary differential equation it satisfies

$$xy''(x) + (\alpha + \beta - x)y'(x) - \alpha y(x) = 0$$

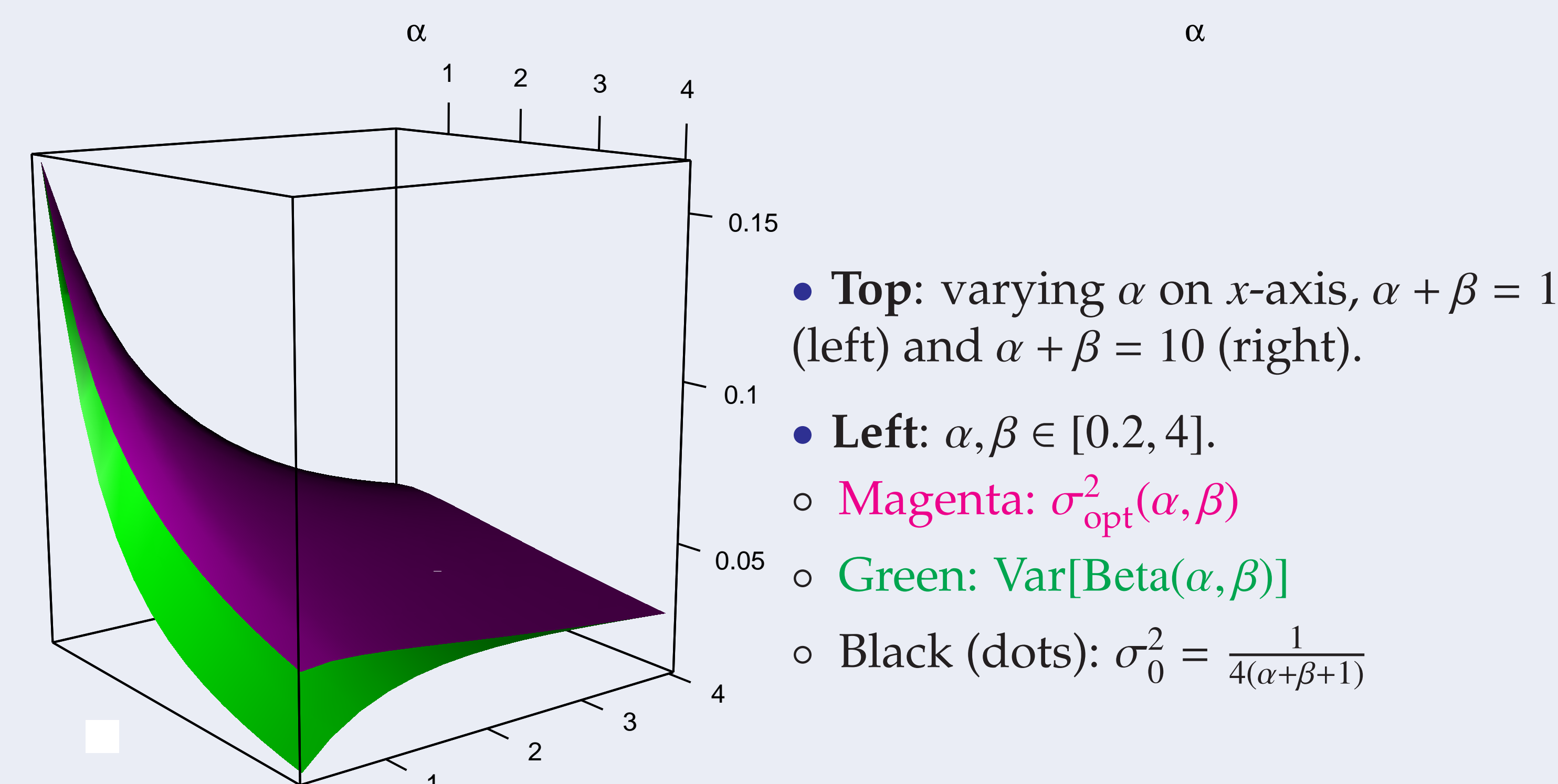
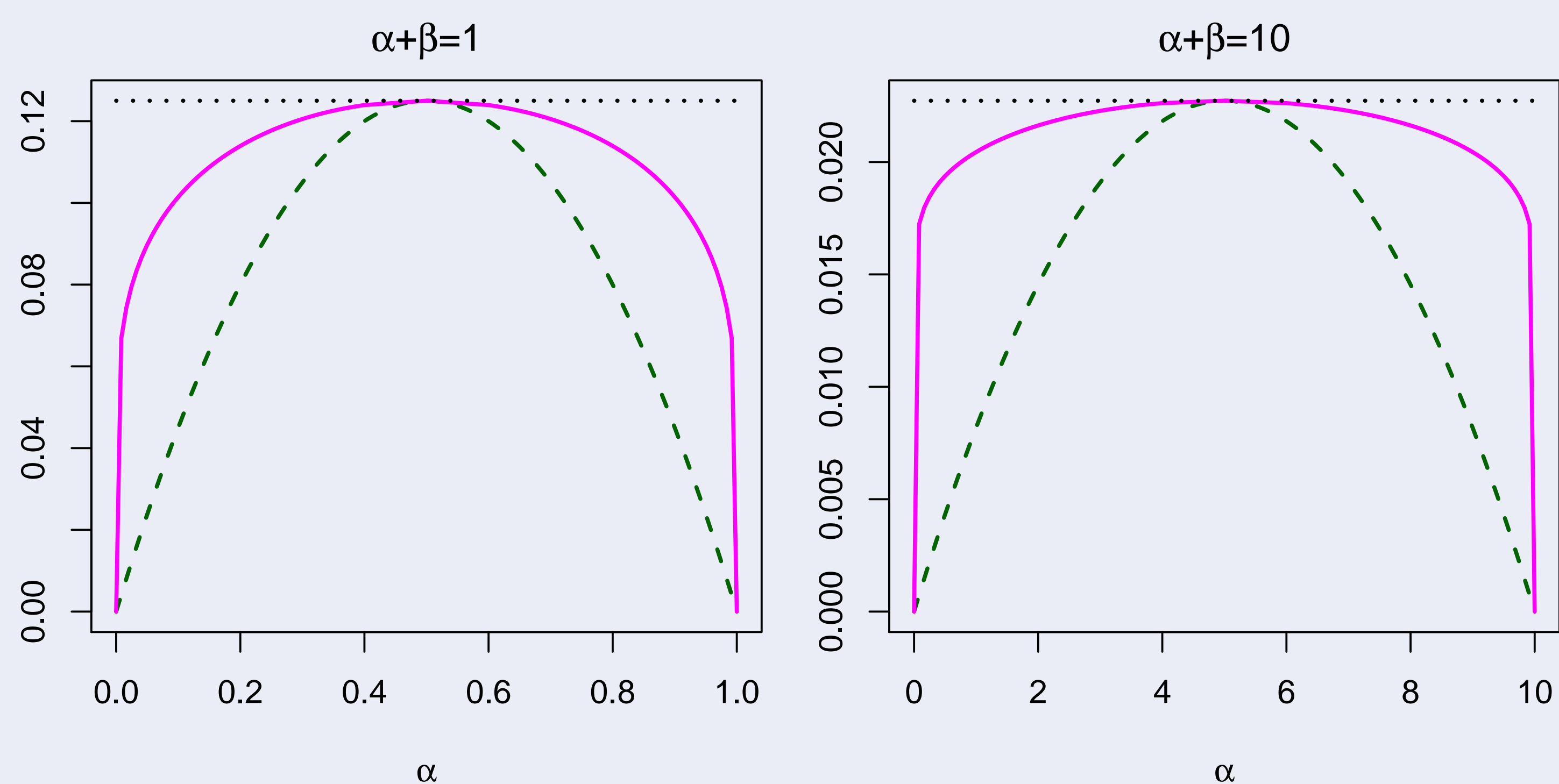
via the difference

$$u_t(x) \stackrel{\text{def}}{=} \exp(\mu x + \sigma_t^2 x^2 / 2) - \mathbb{E}[\exp(xX)], \quad \sigma_t^2 = t \text{Var}[X] + (1 - t)\sigma_0^2$$



- For $t = 0$ (σ_0^2), dotted black curve remains > 0
- For $t = t_{opt}$ (σ_{opt}^2), magenta curve has minimum = 0 at x_0
- For $t = 1$ ($\text{Var}[X]$), dashed green curve has negative second derivative at $x = 0$, directly negative around 0
- For $t_{non\ opt} \in (t_{opt}, 1)$, orange, dash and dots curve is first positive, then negative, and positive again

Optimal proxy variance illustrated & compared



- **Top**: varying α on x -axis, $\alpha + \beta = 1$ (left) and $\alpha + \beta = 10$ (right).
- **Left**: $\alpha, \beta \in [0.2, 4]$.
 - **Magenta**: $\sigma_{opt}^2(\alpha, \beta)$
 - **Green**: $\text{Var}[\text{Beta}(\alpha, \beta)]$
 - **Black (dots)**: $\sigma_0^2 = \frac{1}{4(\alpha+\beta+1)}$

Looking for connections with literature

- Compare with **Bernoulli setting** (Berend and Kontorovich, 2013; Buldygin and Moskvichova, 2013)
- Possible links of our non-uniform sub-Gaussian result with
 - **transportation inequalities**
 - **logarithmic Sobolev inequalities**

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