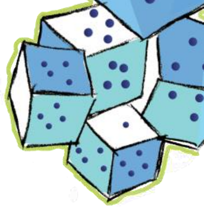

Estimating Higher-Order Moments Using Symmetric Tensor Decomposition

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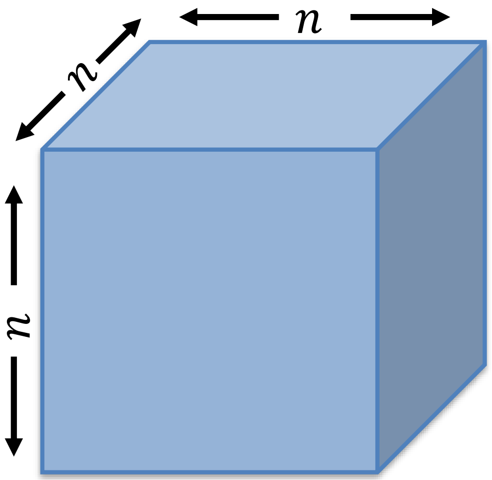
Symmetric Tensor Entries Invariant Under Permutation of Indices

A tensor is <u>symmetric</u> if its entries are invariant under permutation of the indices



For d-way tensor, of dimension n, number of unique entries is:

$$\binom{n+d-1}{d} \approx \frac{n^d}{d!}$$

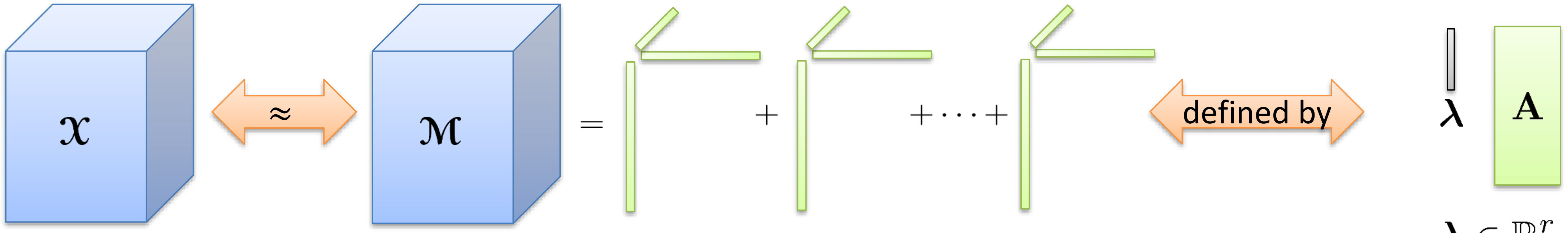
Example 1.2 from Nie (2014)
$3 \times 3 \times 3$ symmetric tensor (10 distinct entries)

$$\mathcal{X} = \left(\begin{array}{rrr|rrr|rrr} 7 & -3 & 9 & -3 & 13 & 20 & 9 & 20 & 19 \\ -3 & 13 & 20 & 13 & -27 & 6 & 20 & 6 & 6 \\ 9 & 20 & 19 & 20 & 6 & 6 & 19 & 6 & 45 \end{array} \right)$$

$$\begin{array}{rlrl} x(1,1,1) = & 7 & x(1,3,3) = & 19 \\ x(1,1,2) = & -3 & x(2,2,2) = & -27 \\ x(1,1,3) = & 9 & x(2,2,3) = & 6 \\ x(1,2,2) = & 13 & x(2,3,3) = & 6 \\ x(1,2,3) = & 20 & x(3,3,3) = & 45 \end{array}$$

Symmetric CP Tensor Decomposition Has Single Factor Matrix

Symmetric Data | Symmetric CP Model | Sum of r Symmetric Outer Product Tensors | Single Factor Matrix



$\mathcal{X} \in \mathbb{R}^{\underbrace{n \times n \times \cdots \times n}_{\text{order } d}}$

$\mathcal{M} \in \mathbb{R}^{n \times n \times \cdots \times n}$

$\boldsymbol{\lambda} \in \mathbb{R}^{r}$

$\mathbf{A} \in \mathbb{R}^{n \times r}$

Model Rank

$$m_{i_1 i_2 \dots i_d} = \sum_{j=1}^{r} \lambda_j \prod_{k=1}^{d} a(i_k, j)$$

$$\mathcal{M} = \sum_{j=1}^{r} \lambda_j \, \mathbf{a}_j^{\otimes d} \in \mathbb{R}^{n \times n \times \cdots \times n}$$

Symmetric Tensor Rank & Decomposition

Example 1.2 from Nie (2014)
$3 \times 3 \times 3$ symmetric tensor (10 distinct entries)

$$\mathcal{X} = \left(\begin{array}{ccc|ccc|ccc} 7 & -3 & 9 & -3 & 13 & 20 & 9 & 20 & 19 \\ -3 & 13 & 20 & 13 & -27 & 6 & 20 & 6 & 6 \\ 9 & 20 & 19 & 20 & 6 & 6 & 19 & 6 & 45 \end{array} \right)$$

$$\operatorname{rank}(\mathcal{X}) = \min \left\{ r \mid \mathcal{X} = \mathbf{a}_1^{\otimes d} + \cdots + \mathbf{a}_r^{\otimes d} \right\}$$

Rank decomposition

$$\mathcal{X} = 2 \cdot \begin{bmatrix} 1 \\ -2 \\ -1 \end{bmatrix}^{\otimes 3} + 5 \cdot \begin{bmatrix} 1 \\ 1 \\ 2 \end{bmatrix}^{\otimes 3} - \begin{bmatrix} 1 \\ 2 \\ -2 \end{bmatrix}^{\otimes 3}$$

- Symmetric tensor rank
  - For any given tensor, NP-hard to compute its rank (Hillar & Lim, 2013)
  - Typical rank known over $\mathbb{C}$ (Comon, Golub, Lim, Mourraine, 2008)
  - In practice, trial and error!
- Symmetric tensor decomposition
  - Waring decomposition (Landsberg, 2012; Oeding & Ottaviani, 2013)
  - Gröbner bases algebraic methods or numerical root-finding method (Nie, 2014)
  - Direct optimization formulation (Kolda, 2015)
  - Subspace power method (Kileel & Pereira, 2019)

Moment Tensors Arise in Inference of Gaussian Mixture Models (GMMs)

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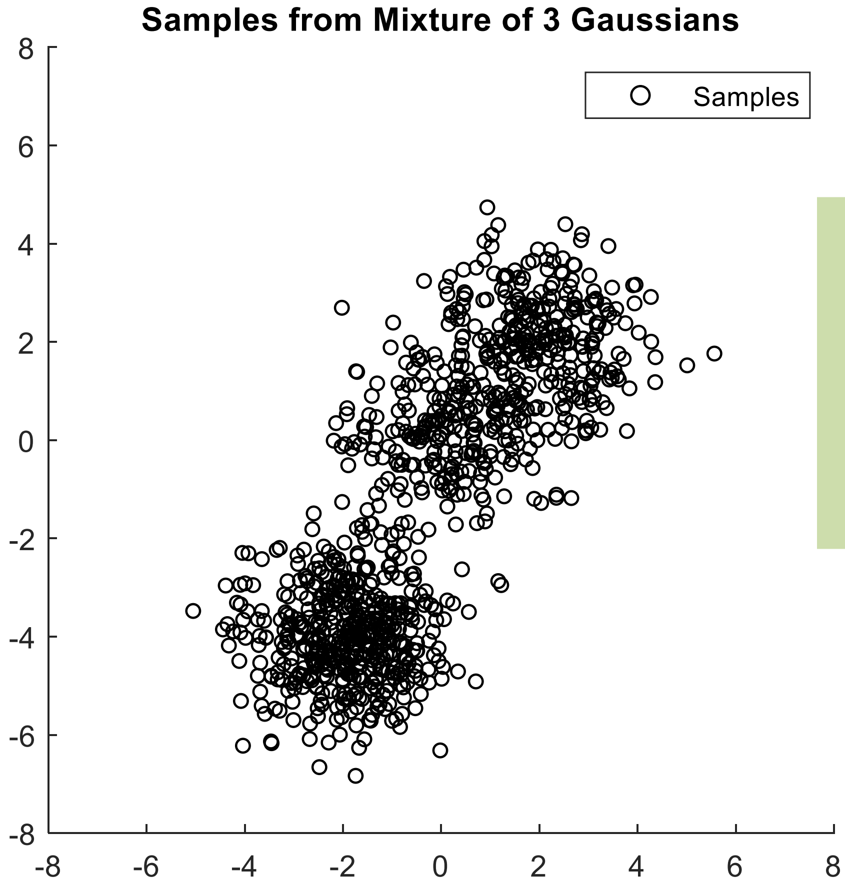
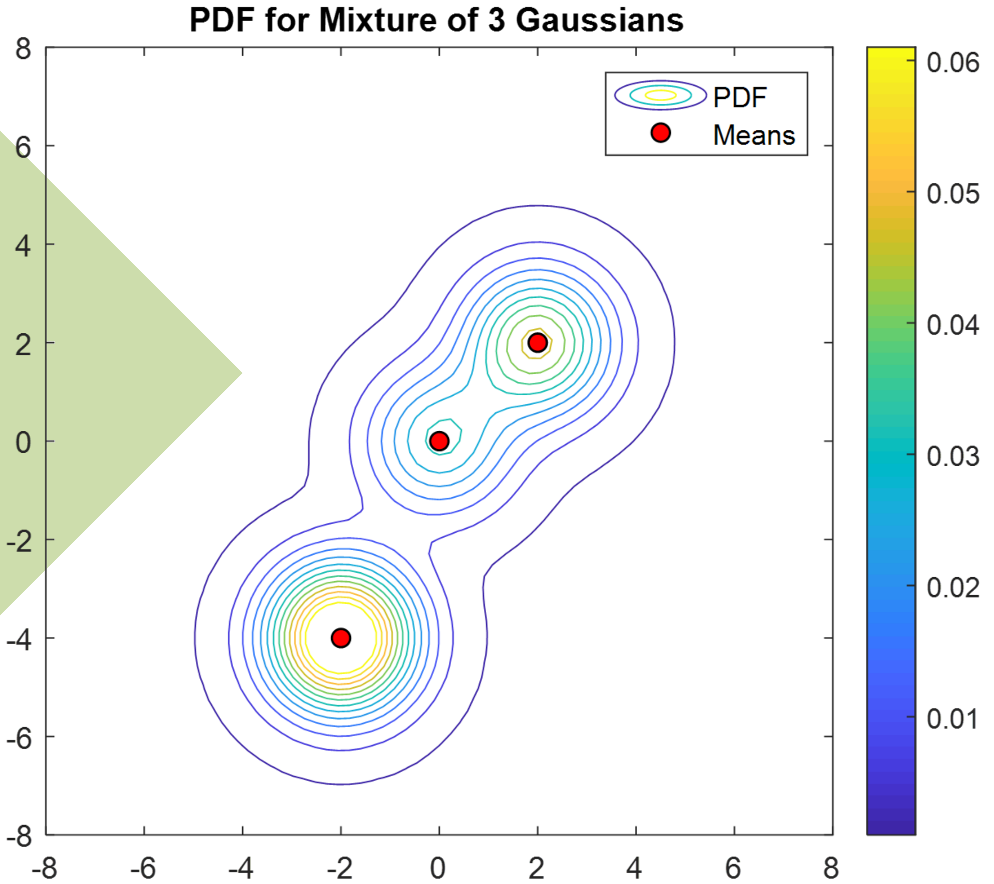
For ease of illustration, we focus on $n = 2$ dimensions.
Generally interested in much higher dimensions, i.e, $n = 500$!



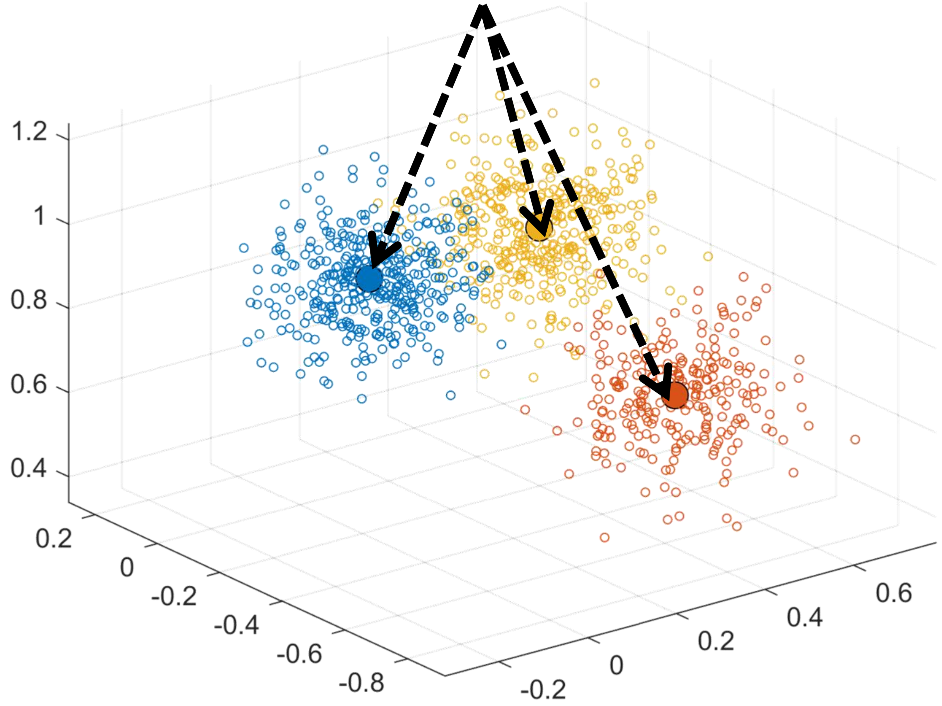
Given just the samples (point cloud), can we recover the means?



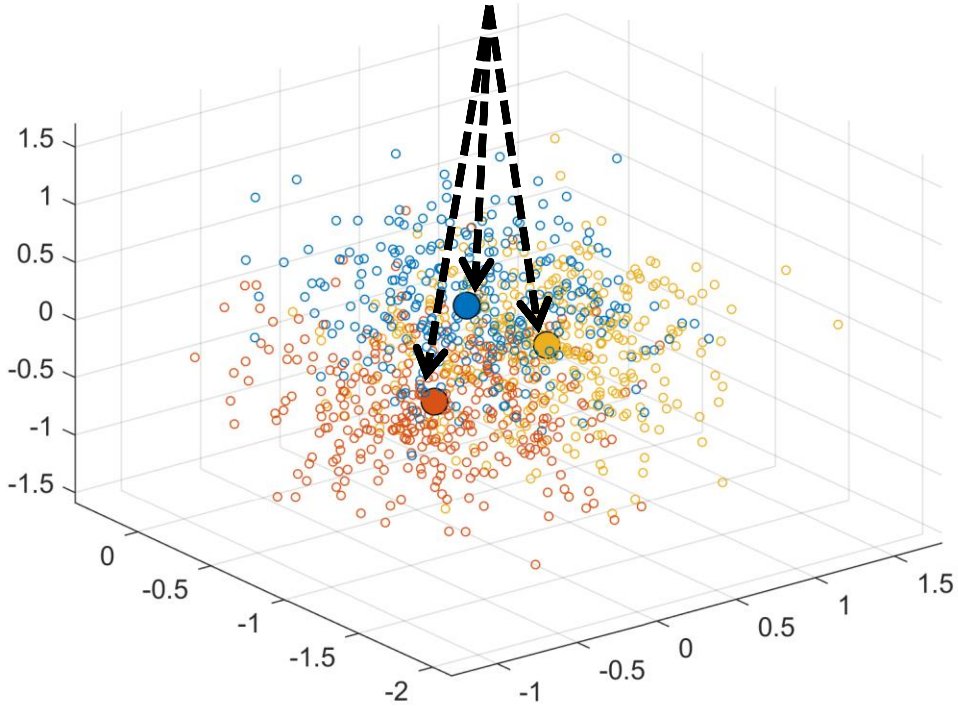
Machine Learning Motivation: Observations from Unknown Mixture of Gaussians

We observe p random vectors of length n coming from a mixture of r Gaussian distributions.
Can we recover the means of the Gaussians?

Easy: Means Well Separated



Hard: Means Close Together



For these pictures: $p = 1000, n = 3, r = 3$. Means shown as filled in larger circles. Samples as open circles.
We care about larger values of n!

Moment Structure for Spherical GMMs Corresponds to CP Model

Data Model: $V \sim \mathcal{N}(\boldsymbol{\mu}_\xi, \sigma^2 \mathbf{I}), \quad \xi \sim \textsc{Multi}(w_1, \ldots, w_r)$

Multivariate Normal

Probability to select jth center is w_j

3rd-order Moment: $\boxed{\mathbb{E}[V^{\otimes 3}]} + O(\sigma^2) = \boxed{\sum_{j=1}^{r} w_j \boldsymbol{\mu}_j^{\otimes 3}}$

Can also do higher - order moments

Calculate empirically from data

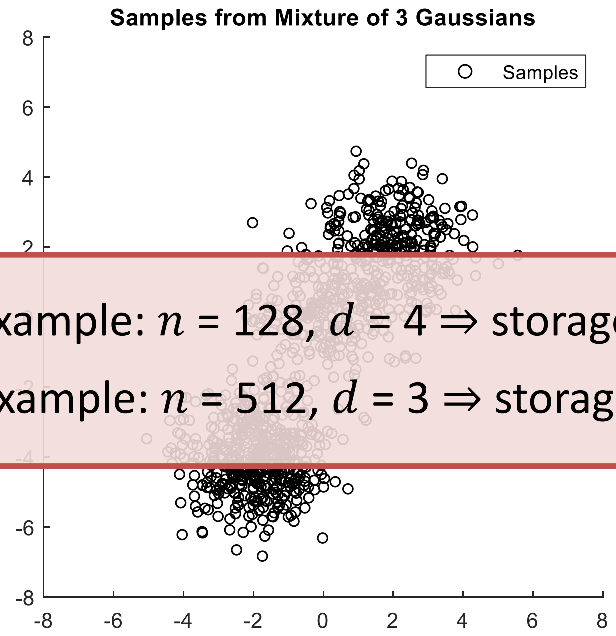
CP-like Model

$$\mathcal{X} = \frac{1}{p} \sum_{\ell=1}^{p} \mathbf{v}_\ell^{\otimes 3}$$

$$\mathcal{M} = \sum_{j=1}^{r} \lambda_j \, \mathbf{a}_j^{\otimes 3}$$

Bottlenecks:
$O(pn^d)$ to compute,
$O(n^d)$ to store

Hsu and Kakade, 2013



Example: n = 128, d = 4 ⇒ storage = 2 GB

Example: n = 512, d = 3 ⇒ storage = 1 GB

Simplifying assumptions for this work

$$\|\boldsymbol{\mu}_j\|_2 = 1 \; \forall j \in [r]$$

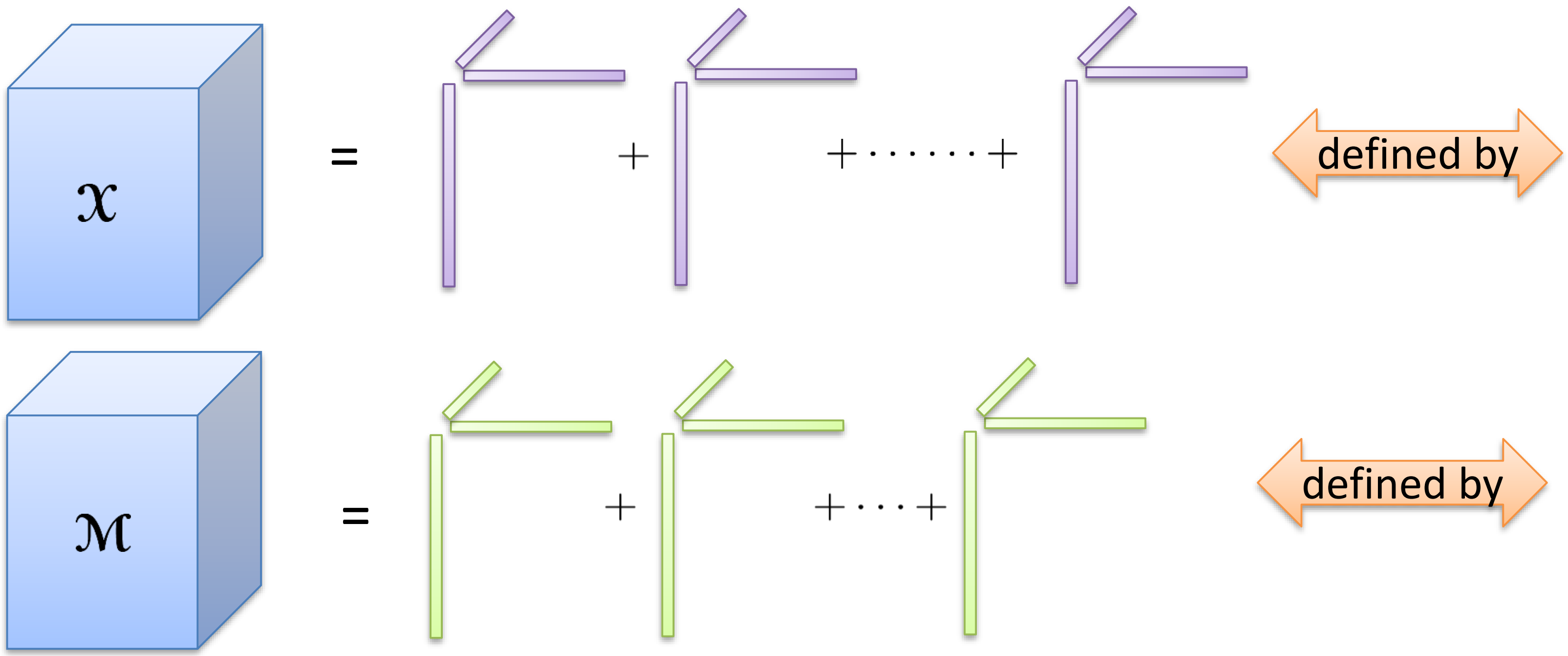
$$\omega_j = \frac{1}{r} \; \forall j \in [r]$$

Our Focus Today: Accelerating Computation for Special Case of Moment Tensors

$$\mathcal{X} = \frac{1}{p} \sum_{\ell=1}^{p} \mathbf{v}_\ell^{\otimes d}$$

Symmetric Data

Symmetric CP Model



$$\mathcal{M} = \sum_{j=1}^{r} \lambda_j \, \mathbf{a}_j^{\otimes d}$$

Given Observations

$\mathbf{V} \in \mathbb{R}^{n \times p}$

Want to Find Compact Representation

$\mathbf{A} \in \mathbb{R}^{n \times r}$

$r \ll p$

Optimization Approach for Symmetric CP of Symmetric Tensor Requires TTSV

Optimization Problem

$$\min_{\boldsymbol{\lambda},\mathbf{A}} F(\mathcal{X},\mathcal{M}) \equiv \frac{1}{2}\|\mathcal{X}-\mathcal{M}\|^2 \text{ where } \mathcal{M} = \sum_{j=1}^{r} \lambda_j \, \mathbf{a}_j^{\otimes d}$$

Gradients $\forall j \in [r]$

$$\frac{\partial F}{\partial \mathbf{a}_j} = -d\lambda_j \boxed{\mathcal{X}\mathbf{a}_j^{d-1}} + d\lambda_j \sum_{k=1}^{r} \lambda_k \langle \mathbf{a}_j, \mathbf{a}_k \rangle^{d-1} \mathbf{a}_k$$

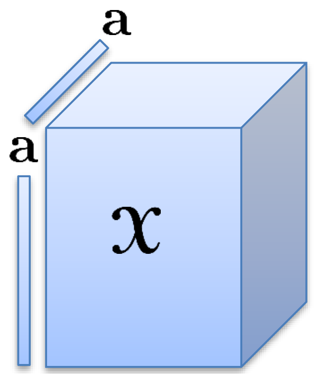
$$\frac{\partial F}{\partial \lambda_j} = -\mathcal{X}\mathbf{a}_j^{d} + \sum_{k=1}^{r} \lambda_k \langle \mathbf{a}_j, \mathbf{a}_k \rangle^{d}$$

Plug function and gradient into favorite optimization method. My favorite: L-BFGS.

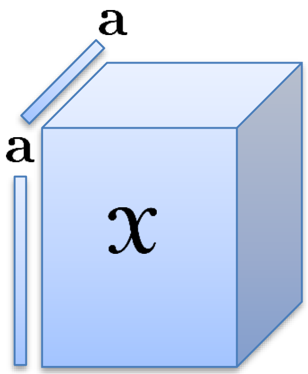
Key Kernel: Tensor Times Single Vector (TTSV)

$$\left(\mathcal{X}\mathbf{a}^{d-1}\right)_{i_1} = \sum_{i_2=1}^{n} \cdots \sum_{i_d=1}^{n} \left(x_{i_1 i_2 \ldots i_d} \prod_{k=2}^{d} a_{i_k} \right) \quad \forall i_1 \in [n]$$

Bottleneck is TTSV which costs $O(n^d)$



Key Result: Implicit Computation of TTSV



TTSV Definition: $$(\mathcal{X}\mathbf{a}^{d-1})_{i_1} = \sum_{i_2=1}^{n} \cdots \sum_{i_d=1}^{n} \left(x_{i_1 i_2 \ldots i_d} \prod_{k=2}^{d} a_{i_k} \right) \quad \forall i_1 \in [n]$$

Lemma. Let $\mathcal{X} = \frac{1}{p} \sum_{\ell=1}^{p} \mathbf{v}_\ell^{\otimes d}$ and $\mathbf{V} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \cdots & \mathbf{v}_p \end{bmatrix}$, then

Entry-wise Power

$$\mathcal{X}\mathbf{a}^{d-1} = \frac{1}{p} \mathbf{V} \, [\mathbf{V}^{\intercal}\mathbf{a}]^{d-1}$$

$O(n^d)$ $O(pn)$

Minimal Change in Function/Gradient Calculation Replaces Expensive TTSV

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function FG_EXPLICIT$(\mathfrak{X}, \boldsymbol{\lambda}, \mathbf{A}, \alpha)$
  for $j = 1, \ldots, r$, **do** $\mathbf{y}_j = \mathfrak{X}\mathbf{a}_j^{d-1}$, **end**
  for $j = 1, \ldots, r$, **do** $w_j = \mathbf{a}_j^T \mathbf{y}_j$, **end**
  $\mathbf{B} = \mathbf{A}^T \mathbf{A}$
  $\mathbf{C} = [\mathbf{B}]^{d-1}$
  $\mathbf{u} = (\mathbf{B} * \mathbf{C})\boldsymbol{\lambda}$
  $f = \alpha + \boldsymbol{\lambda}^T \mathbf{u} - 2\mathbf{w}^T \boldsymbol{\lambda}$
  $\mathbf{g}_{\boldsymbol{\lambda}} = -2(\mathbf{w} - \mathbf{u})$
  $\mathbf{G}_{\mathbf{A}} = -2d(\mathbf{Y} - \mathbf{A}\mathbf{D}_{\boldsymbol{\lambda}}\mathbf{C})\mathbf{D}_{\boldsymbol{\lambda}}$
  return $f, \mathbf{g}_{\boldsymbol{\lambda}}, \mathbf{G}_{\mathbf{A}}$
end function

function FG_IMPLICIT$(\mathbf{V}, \boldsymbol{\lambda}, \mathbf{A}, \alpha)$
  $\mathbf{Y} = \frac{1}{p}\mathbf{V}[\mathbf{V}^\intercal \mathbf{A}]^{d-1}$
  for $j = 1, \ldots, r$, **do** $w_j = \mathbf{a}_j^T \mathbf{y}_j$, **end**
  $\mathbf{B} = \mathbf{A}^T \mathbf{A}$
  $\mathbf{C} = [\mathbf{B}]^{d-1}$
  $\mathbf{u} = (\mathbf{B} * \mathbf{C})\boldsymbol{\lambda}$
  $f = \alpha + \boldsymbol{\lambda}^T \mathbf{u} - 2\mathbf{w}^T \boldsymbol{\lambda}$
  $\mathbf{g}_{\boldsymbol{\lambda}} = -2(\mathbf{w} - \mathbf{u})$
  $\mathbf{G}_{\mathbf{A}} = -2d(\mathbf{Y} - \mathbf{A}\mathbf{D}_{\boldsymbol{\lambda}}\mathbf{C})\mathbf{D}_{\boldsymbol{\lambda}}$
  return $f, \mathbf{g}_{\boldsymbol{\lambda}}, \mathbf{G}_{\mathbf{A}}$
end function

Implicit up to 16X Faster than Explicit for Smaller Problems

Rank-r Symmetric CP Tensor Factorization
for d-way tensor of size n

$$r < n < p$$

Method	Storage	Per-Iteration
Explicit	$O(n^d)$	$O(rn^d)$
Implicit	$O(pn)$	$O(pnr)$

Implicit cheaper if $p < O(n^{d-1})$

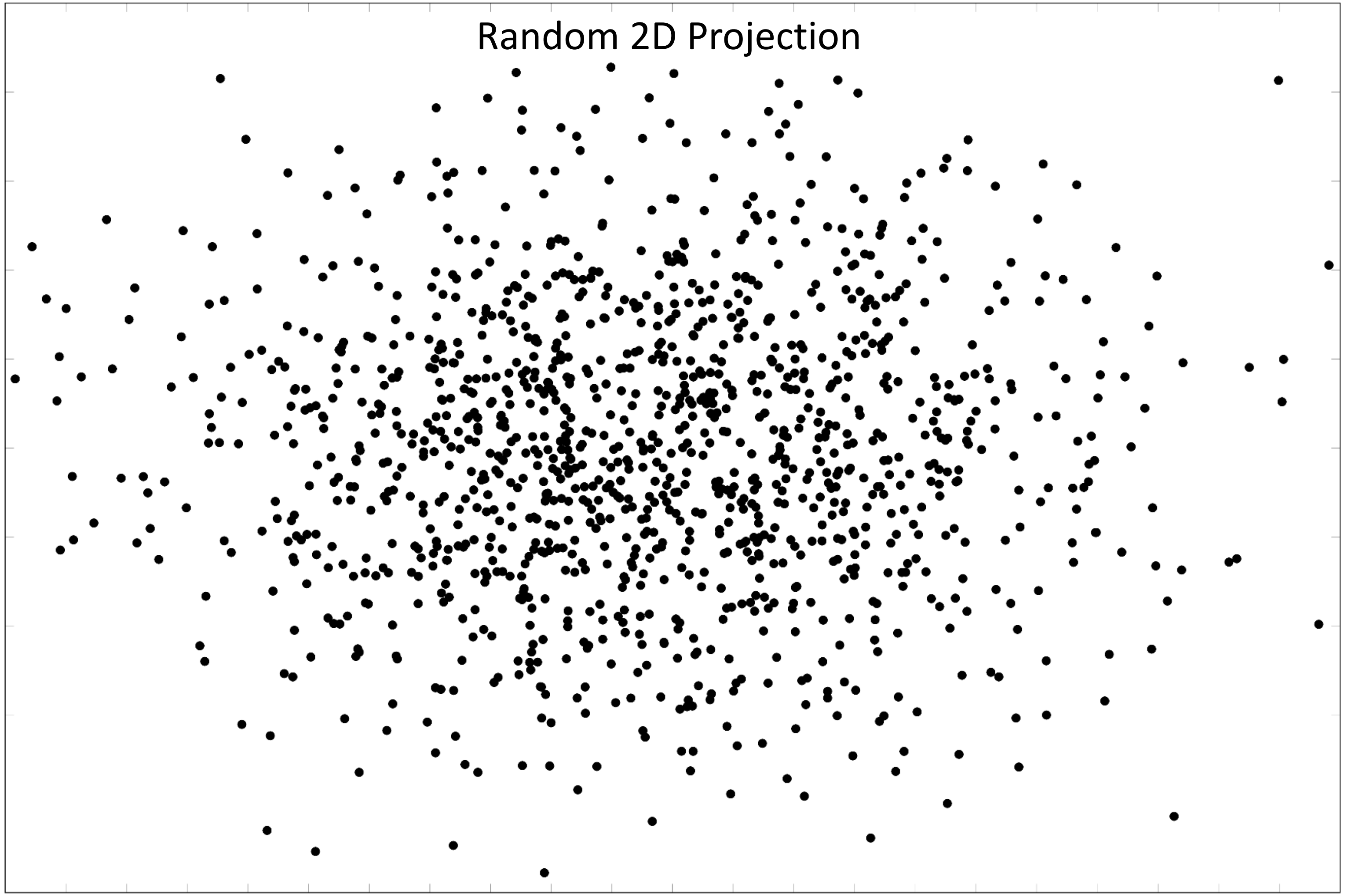
Average cost per iteration for $r = 5$ over 10 runs

d	n	p	n^{d-1}	Explicit	Implicit	Ratio
3	75	3750	5625	5e-4 sec.	8e-4 sec.	1x
3	375	3750	140625	2e-2	5e-3	5x
4	75	3750	421875	1e-2	9e-4	16x

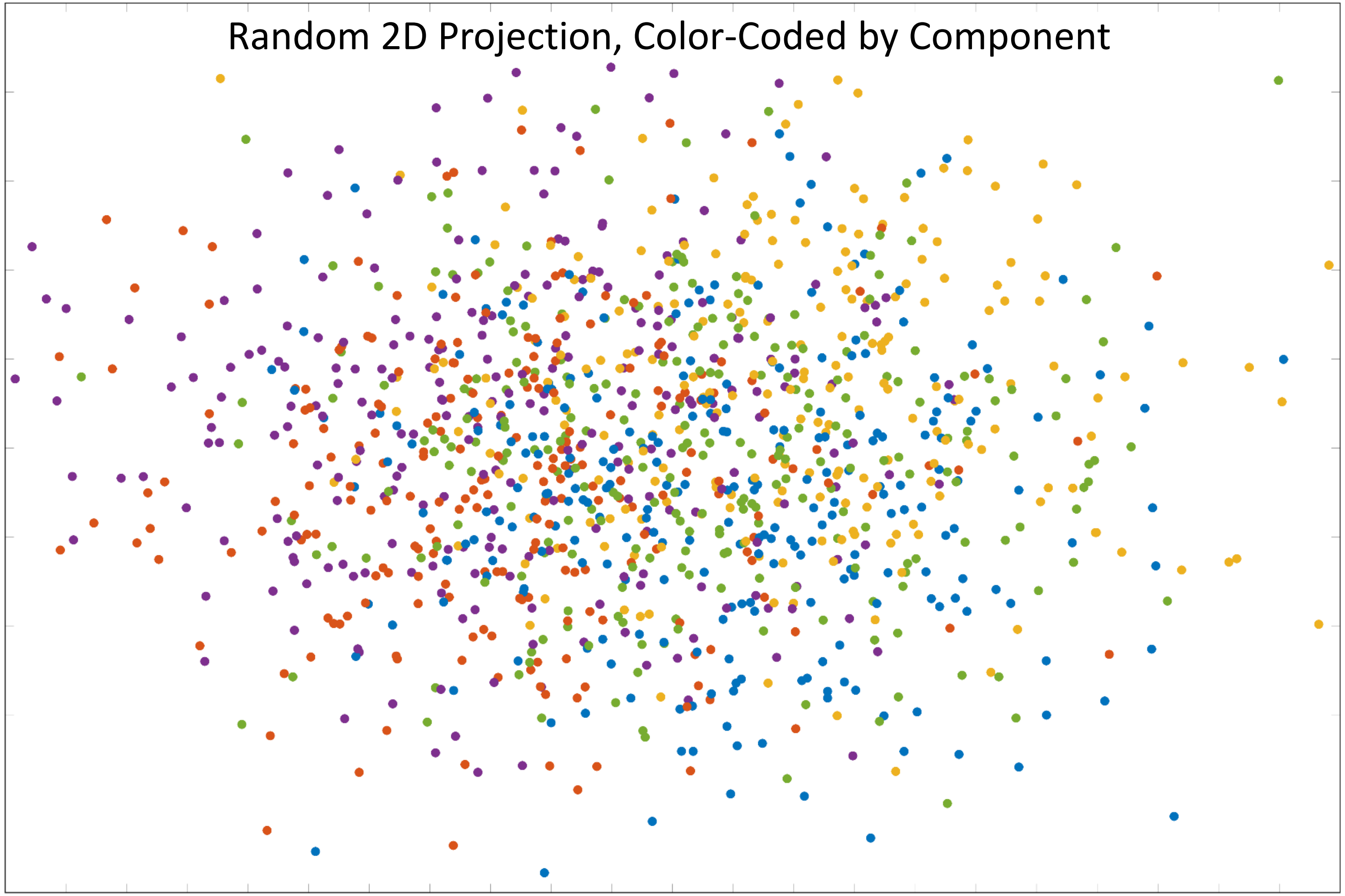
GMM Example with r=5 (components), n=500 (dim.), σ=.1 (noise), and p=1250 (obs.)

For $d = 3$, explicit method requires 1 GB storage

For d =4, explicit method requires 500 GB storage



GMM Example with r=5 (components), n=500 (dim.), σ=.1 (noise), and p=1250 (obs.)



GMM Example with r=5 (components), n=500 (dim.), σ=.1 (noise), and p=1250 (obs.)

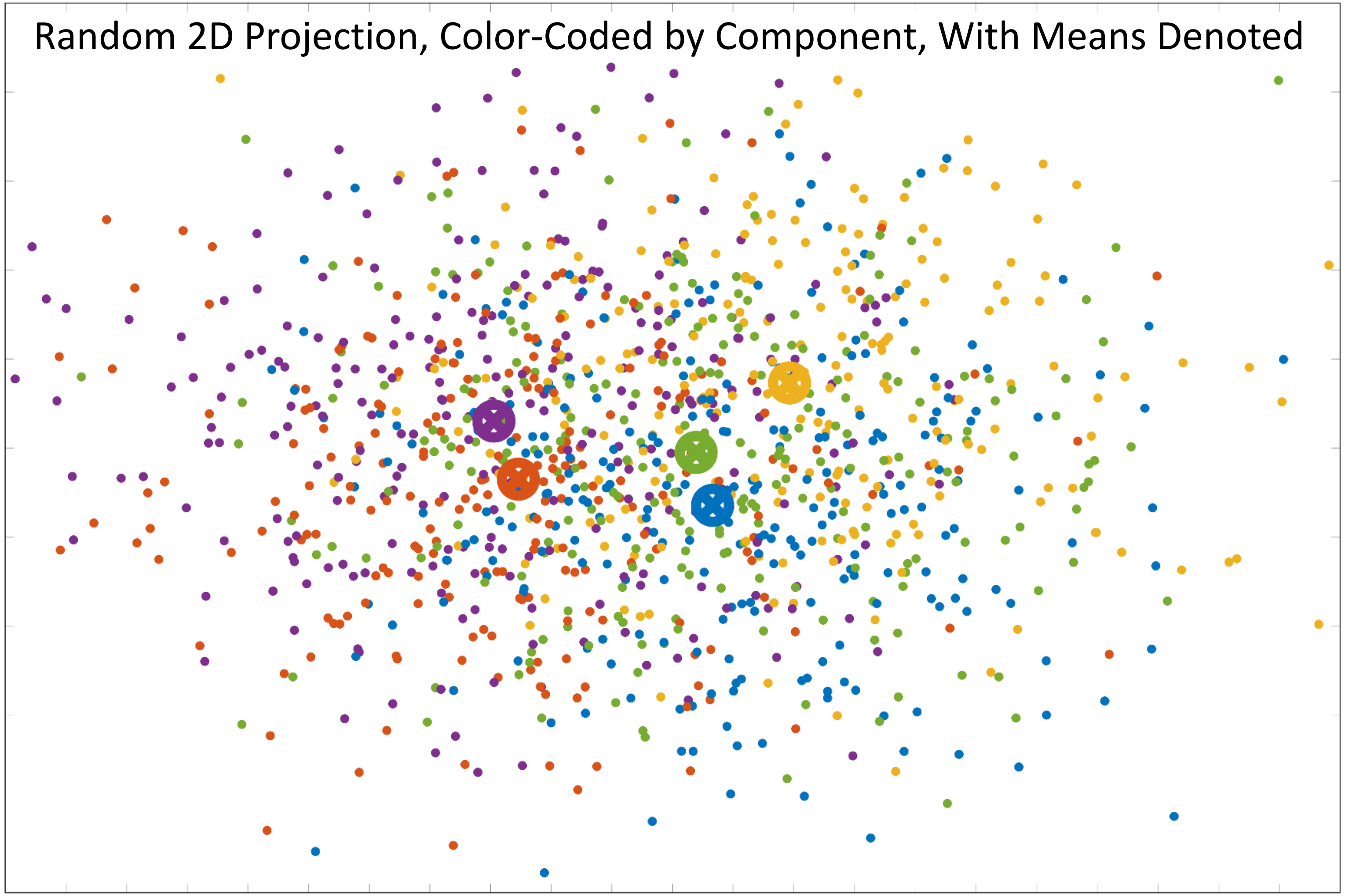
$$\boldsymbol{\mu}_j \in \mathbb{R}^{500}$$

$$\|\boldsymbol{\mu}_j\|_2 = 1$$

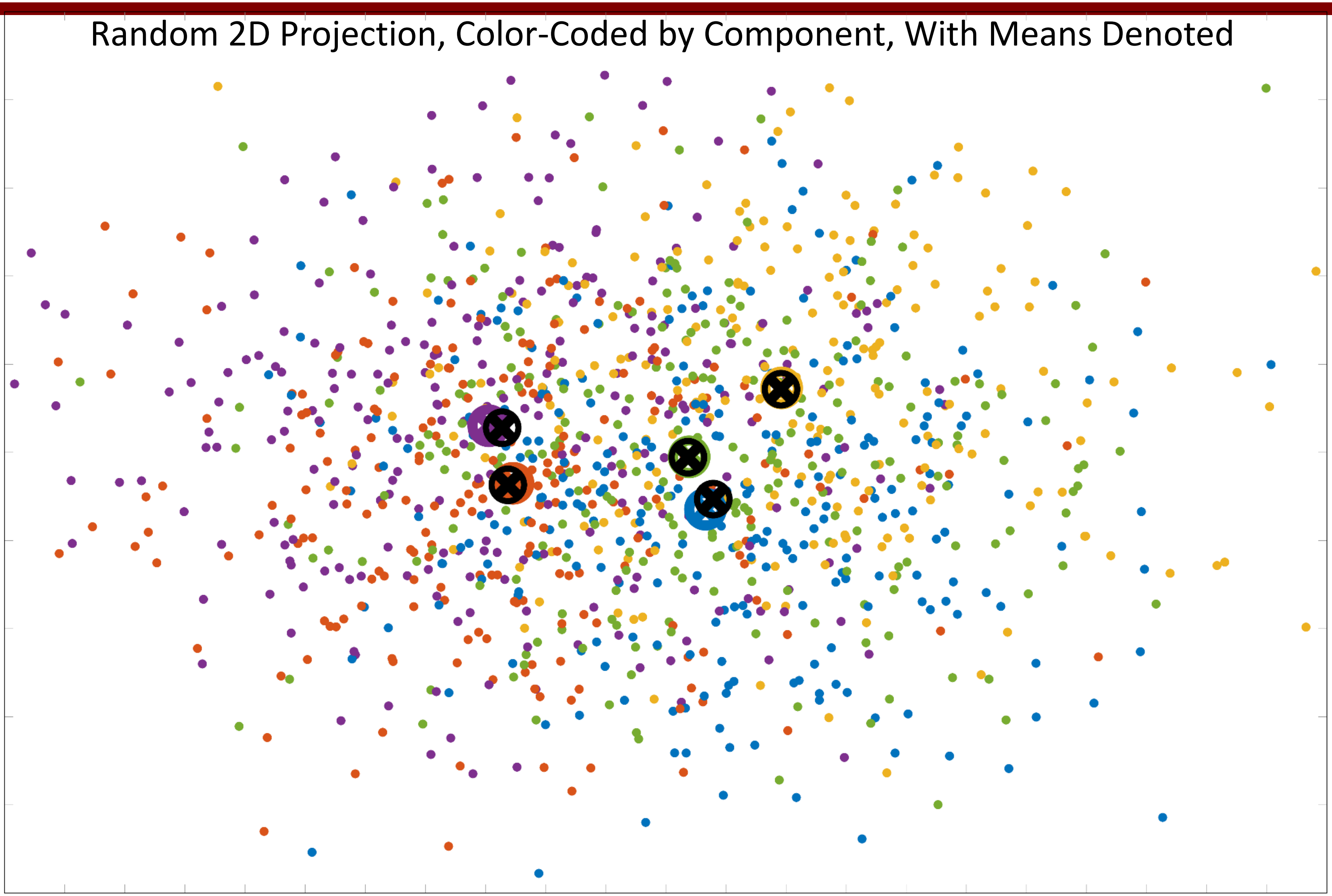
$$\forall j \in [r]$$

$$\boldsymbol{\mu}_j^T \boldsymbol{\mu}_k = 0.5$$

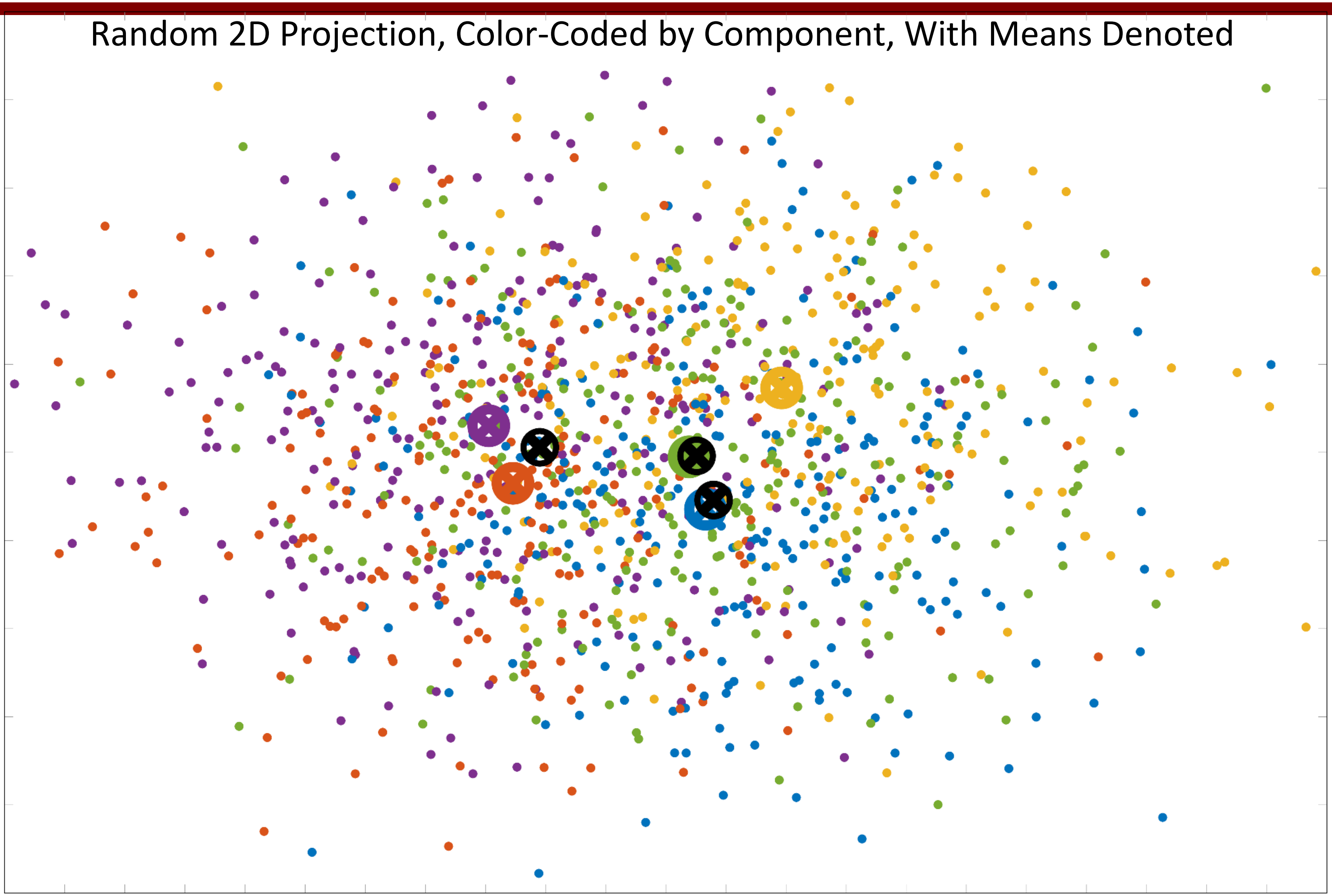
$$\forall j \neq k$$



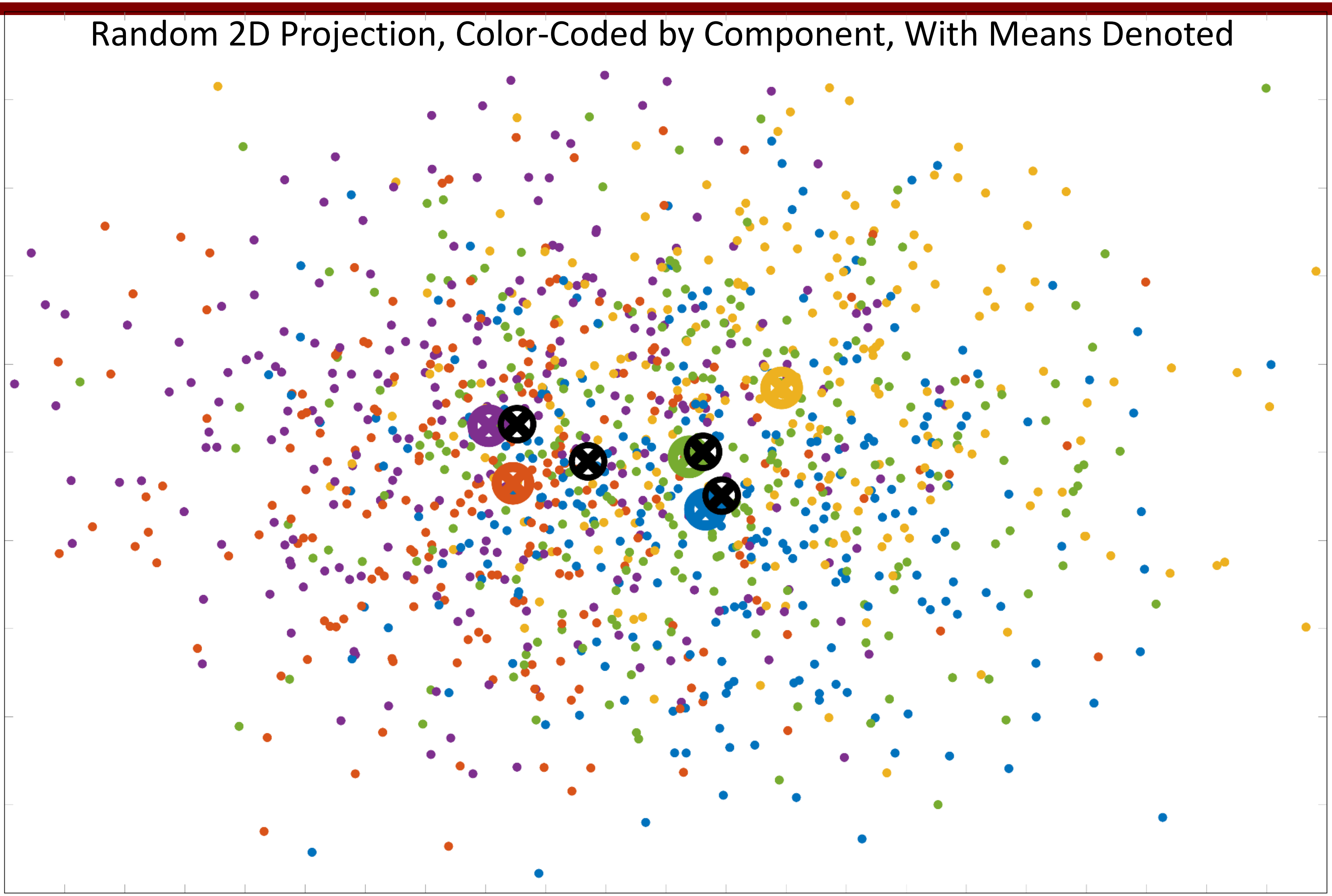
Identified Factors for $\hat{r}$=5



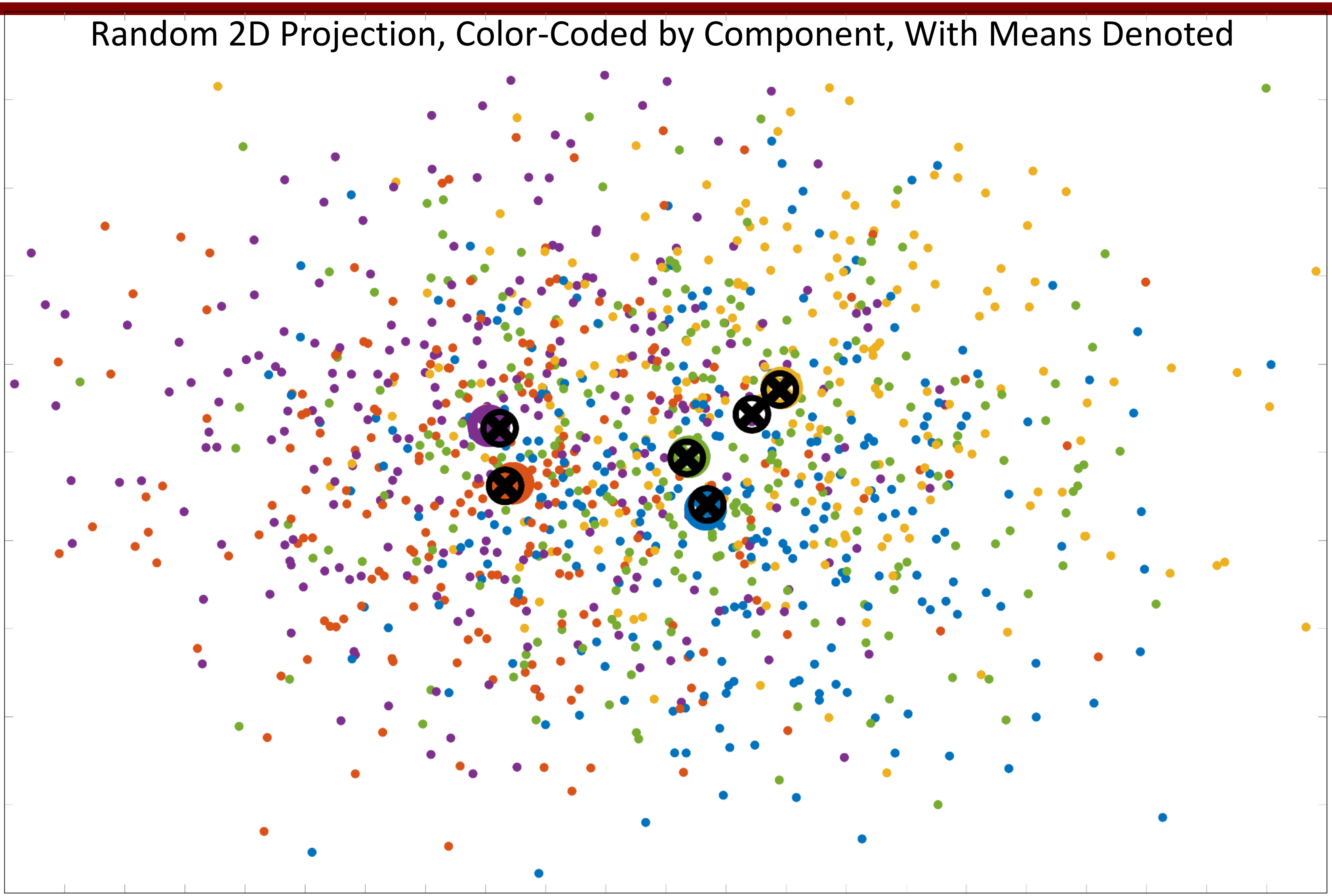
Identified Factors for $\hat{r}$=3



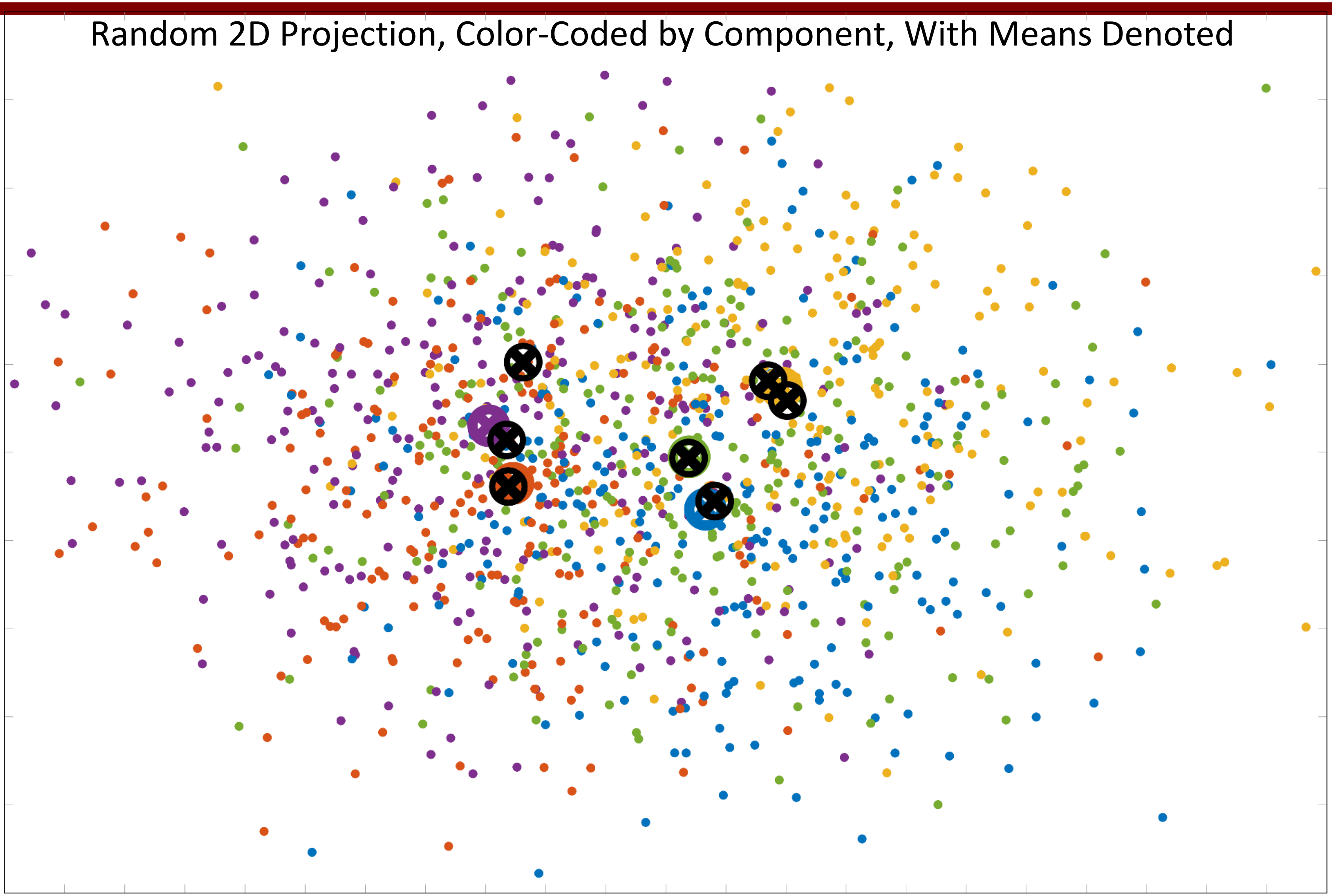
Identified Factors for $\hat{r}$=4



Identified Factors for $\hat{r}$=6



Identified Factors for $\hat{r}$=7

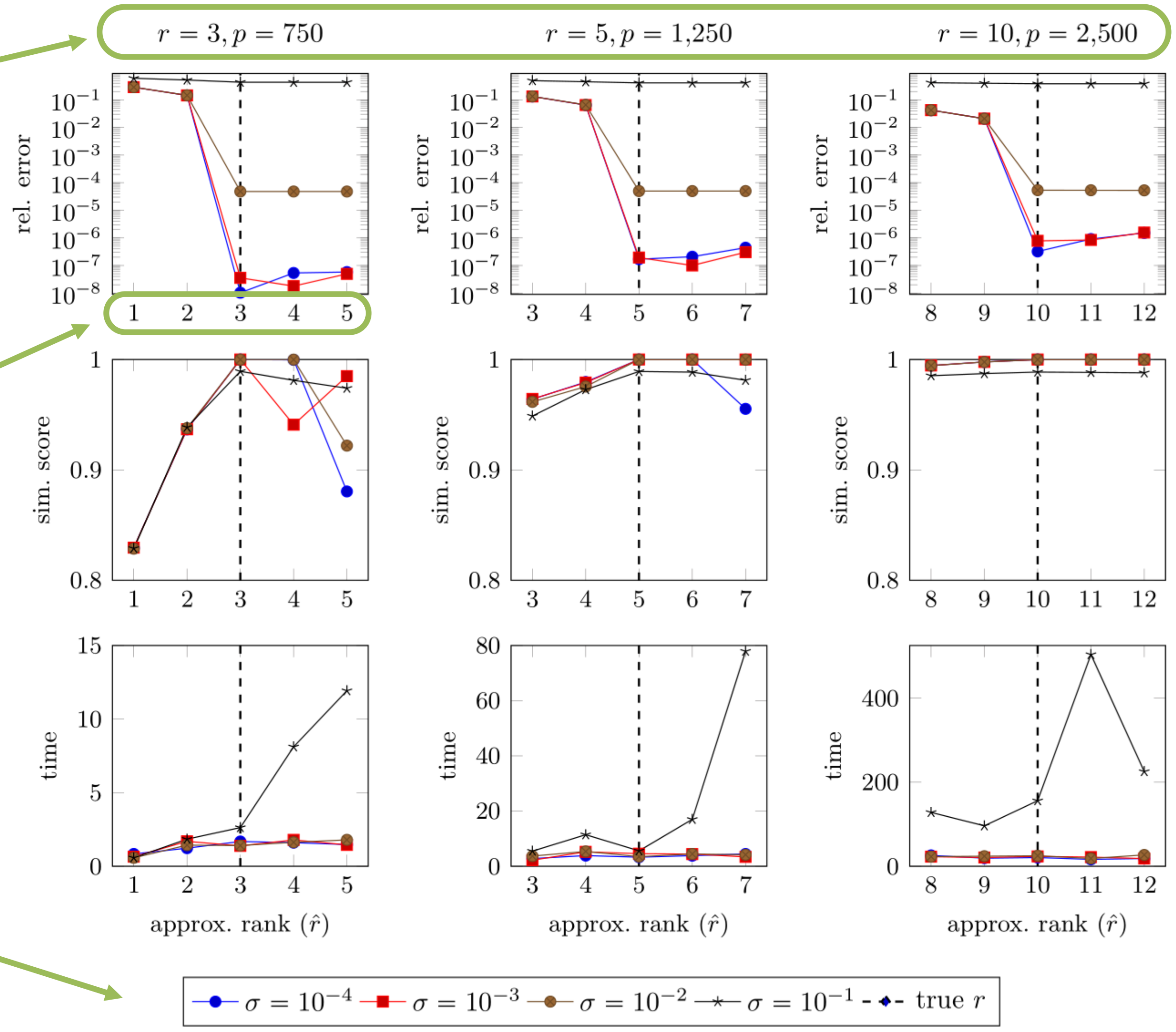


GMM Performance for Third-Order (d=3)

Varying Number of True Components

Varying Number of Computed Components (Over/Under Estimate)

Varying Noise



Best Error over 10 Runs Compared to Empirical Moment Tensor

$$\mathcal{X} = \frac{1}{p} \sum_{\ell=1}^{p} \mathbf{v}_\ell^{\otimes 3}$$

Average Cosine of Angle Between True Means and Computed (1 = perfect match)

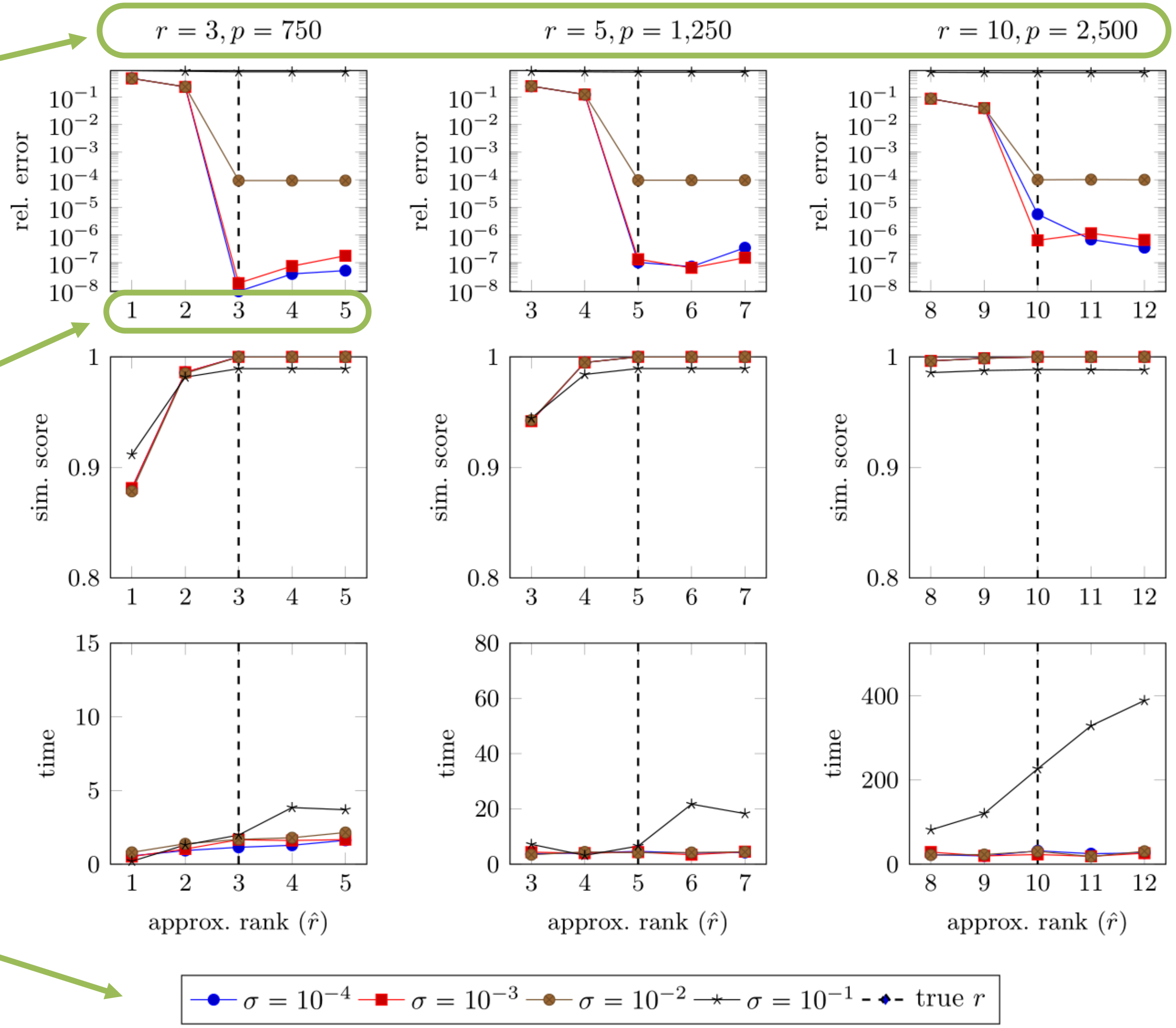
Total Time for Ten Runs

GMM Performance for Fourth-Order (d=4)

Varying Number of True Components

Varying Number of Computed Components (Over/Under Estimate)

Varying Noise



Best Error over 10 Runs Compared to Empirical Moment Tensor

$$\mathcal{X} = \frac{1}{p}\sum_{\ell=1}^{p} \mathbf{v}_\ell^{\otimes 3}$$

Average Cosine of Angle Between True Means and Computed (1 = perfect match)

Total Time for Ten Runs

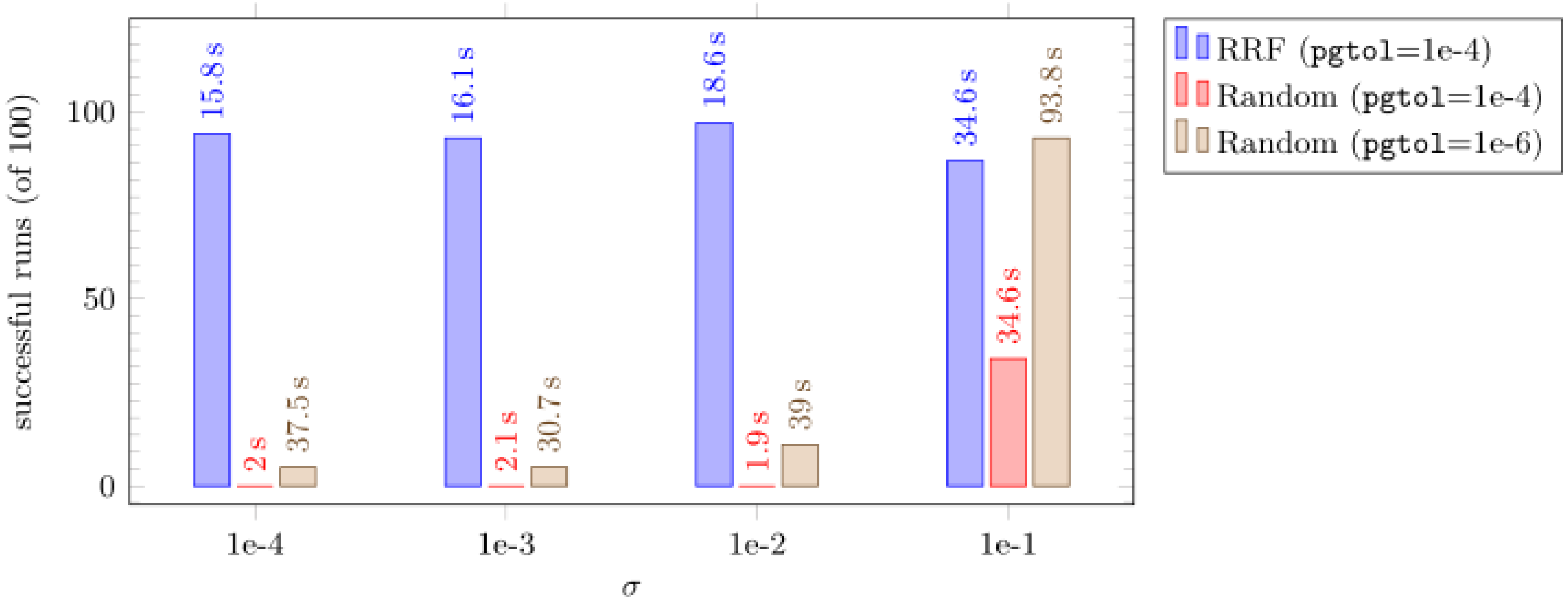
Choosing Starting Guess Within Range of Observations is Key for Low Noise!

Randomized Range Finder (RRF): $\mathbf{A}_0 = \mathbf{V}\boldsymbol{\Omega},\ \boldsymbol{\Omega} \sim \mathcal{N}(0,1)^{p \times \hat{r}}$

Random: $\mathbf{A}_0 \sim \mathcal{N}(0,1)^{n \times \hat{r}}$

[with columns normalized in both cases]

Results of computing $\hat{r} = 3$ approximation for moment tensor of order $d = 3$, with $r = 3$ components, $n = 500$ dimensions, and $p = 750$ observations



For Massive Numbers of Observations, Use Stochastic Variants

$\mathbf{V} \in \mathbb{R}^{n \times p}$

Sample columns
with replacement

$\tilde{\mathbf{V}} \in \mathbb{R}^{n \times s}$

$$\mathcal{X} = \frac{1}{p} \sum_{\ell=1}^{p} \mathbf{v}_\ell^{\otimes d}$$

$$\tilde{\mathcal{X}} = \frac{1}{s} \sum_{\ell=1}^{s} \tilde{\mathbf{v}}_\ell^{\otimes d}$$

$$\Rightarrow \quad \mathbb{E}[\tilde{\mathcal{X}}\mathbf{a}^{d-1}] = \mathcal{X}\mathbf{a}^{d-1}$$

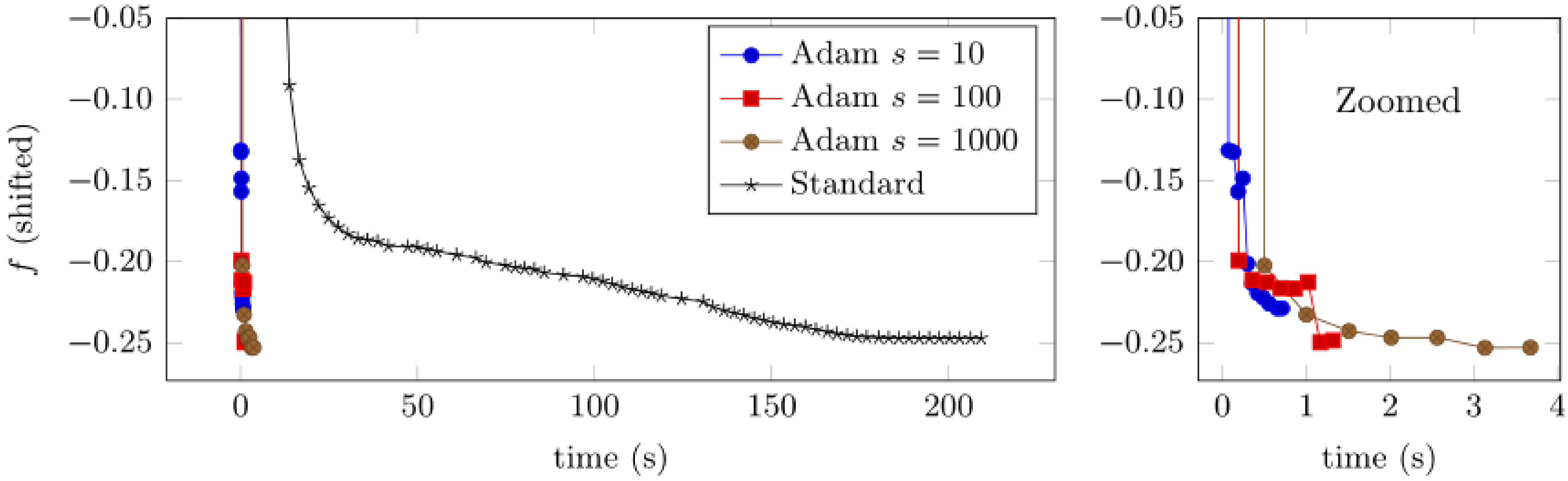
Example Results
$\hat{r} = r = 10, n = 500,$
$\sigma = 0.1, d = 3$
$p = 100{,}000$

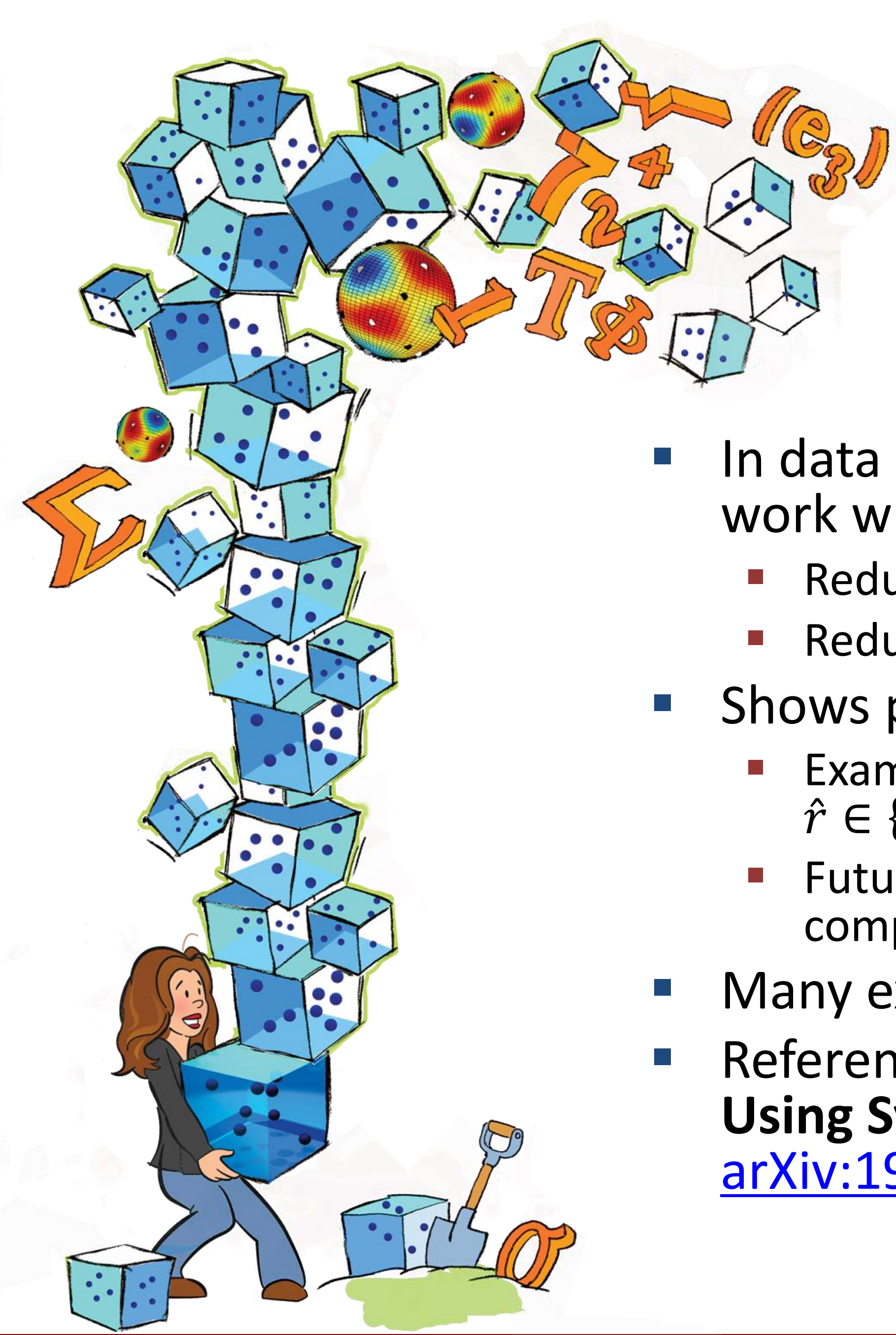
Method	Best f (shifted)	Sim. Score	Total Time (s)
standard	−0.2471	0.9998	2166.70
Adam, s=10	−0.2209	0.9225	8.03
Adam, s=100	−0.2427	0.9929	10.48
Adam, s=1000	−0.2464	0.9990	41.00

Speed Advantage for Stochastic Methods

Best Runs (of 10)

$$\hat{r} = r = 10, n = 500, \sigma = 0.1, d = 3, p = 100{,}000$$





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Conclusions and Future Work

- In data analysis, dth-order moment is expensive to compute – instead work with implicit moment
  - Reduces storage from $O(n^d)$ to $O(np)$
  - Reduces computation per iteration from $O(rn^d)$ to $O(rnp)$
- Shows promise for fitting spherical GMMs
  - Example with $n = 500$ (dimension), $r \in \{3,5,10\}$ (components), $p = 250r$, $\hat{r} \in \{r-2, \dots, r+2\}$, and $d = 3,4$ (orders)
  - Future work will incorporate lower-order terms, different σ for each component, multiple values for d simultaneously, etc.
- Many extensions possible, e.g., for subspace power method
- Reference: S. Sherman, T. G. Kolda. **Estimating Higher-Order Moments Using Symmetric Tensor Decomposition**, to appear in SIMAX, arXiv:1911.03813