

# Heteroskedasticity, Living in the Real World

EC 421, 005

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Spring 2021

# Prologue

# Schedule

## Last Time

Heteroskedasticity: Issues and tests

## Today

- **First assignment** due Next Week on Saturday (24 April.)
- Living with heteroskedasticity

## Upcoming

- **Second assignment** "released" on Friday
- Midterm ~3 weeks away (May 6th - in class, no late/early exam available)

## Goals

- Develop **intuition** for econometrics.
- Learn how to **apply** econometrics—strengths, weaknesses, *etc.*
- Learn **R**.

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This course has the potential to be one of the most useful/valuable/applicable/marketable classes that you take at UO.

# Heteroskedasticity

## *Review*

# Heteroskedasticity

## Review

Three review questions

**Question 1:** What is the difference between  $u_i$  and  $e_i$ ?

**Question 2:** We spend *a lot* of time discussing  $u_i^2$ . Why?

**Question 3:** We also spend *a lot* of time discussing  $e_i^2$ . Why?



# Heteroskedasticity

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$e_i$  gives the **regression residual (error)** for the  $i^{\text{th}}$  observation.  $e_i$  measures how far the  $i^{\text{th}}$  observation is from the **sample regression** line, i.e.,

$$e_i = y_i - \underbrace{(\hat{\beta}_0 + \hat{\beta}_1 x_i)}_{\text{Sample reg. line}=\hat{y}} = y_i - \hat{y}_i$$

# Heteroskedasticity

## Review

**Question 2:** We spend *a lot* of time discussing  $u_i^2$ . Why?

**Answer 2:**

One of major assumptions is that our disturbances (the  $u_i$ 's) are homoskedastic (they have constant variance), *i.e.*,  $\text{Var}(u_i|x_i) = \sigma^2$ .

We also assume that the mean of these disturbances is zero,  $\mathbf{E}[u_i|x_i] = 0$ .

$$\text{By definition, } \text{Var}(u_i|x_i) = \mathbf{E} \left[ u_i^2 - \underbrace{\mathbf{E}[u_i|x_i]^2}_{=0} \middle| x_i \right] = \mathbf{E}[u_i^2|x_i]$$

Thus, if we want to learn about the variance of  $u_i$ , we can focus on  $u_i^2$ .

# Heteroskedasticity

## Review

**Question 3:** We also spend *a lot* of time discussing  $e_i^2$ . Why?

**Answer 3:**

We cannot observe  $u_i$  (or  $u_i^2$ ).

But  $u_i^2$  tells us about the variance of  $u_i$ .

We use  $e_i^2$  to learn about  $u_i^2$  and, consequently,  $\sigma_i^2$ .

# Heteroskedasticity

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5. The disturbances have **constant variance**  $\sigma^2$  and **zero covariance**, i.e.,
  - $E[u_i^2|X_i] = \text{Var}(u_i|X_i) = \sigma^2 \implies \text{Var}(u_i) = \sigma^2$
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6. The disturbances come from a **Normal** distribution, i.e.,  $u_i \stackrel{\text{iid}}{\sim} N(0, \sigma^2)$ .

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Today we're focusing on assumption #5:

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**Violation of this assumption:** Our disturbances have different variances.

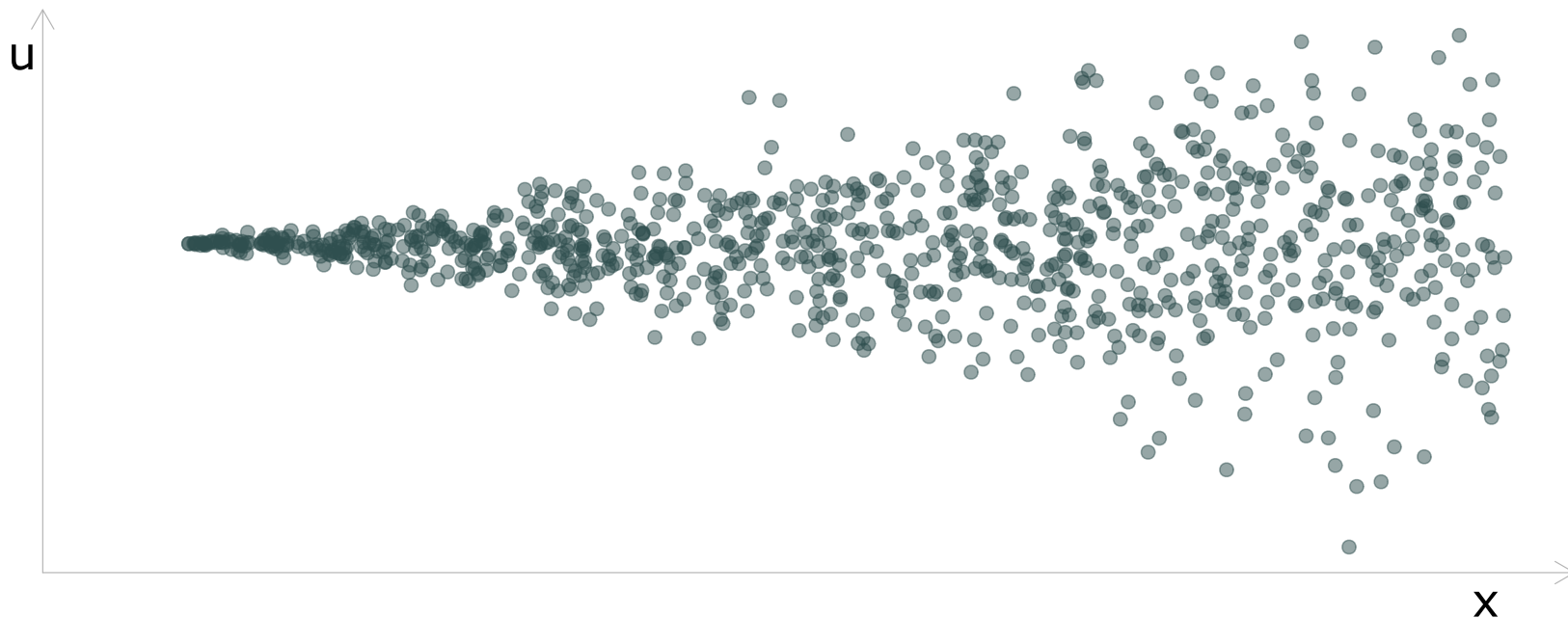
**Heteroskedasticity:**  $\text{Var}(u_i) = \sigma_i^2$  and  $\sigma_i^2 \neq \sigma_j^2$  for some  $i \neq j$ .

# Heteroskedasticity

## Review

Classic example of heteroskedasticity: The funnel

Variance of  $u$  increases with  $x$

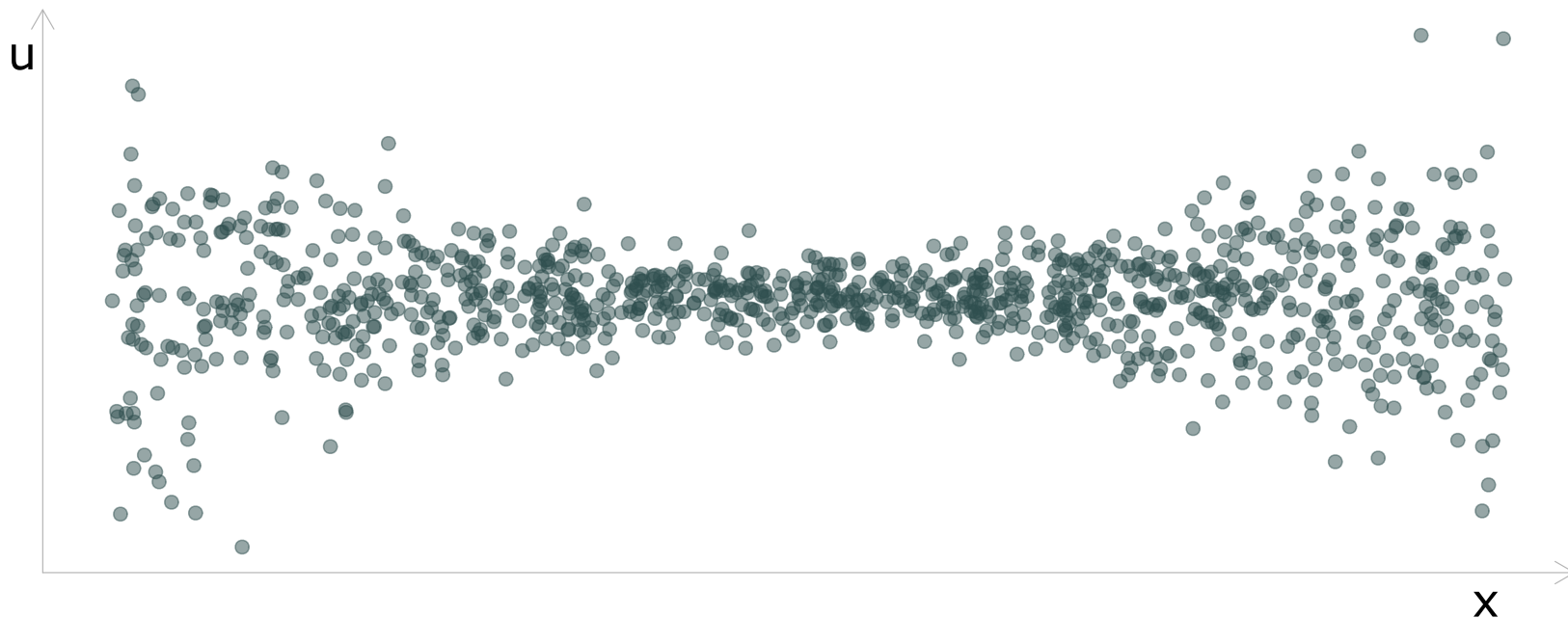


# Heteroskedasticity

## Review

Another example of heteroskedasticity: (double funnel?)

Variance of  $u$  increasing at the extremes of  $x$

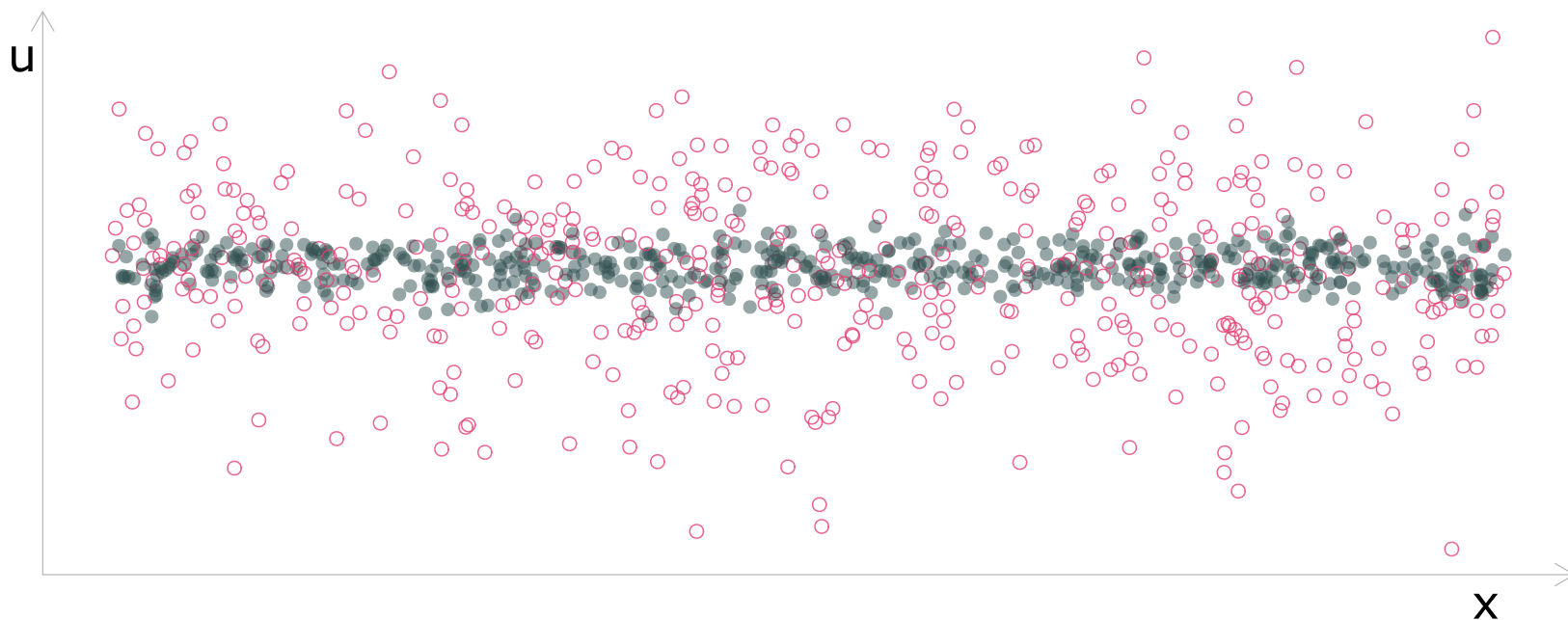


# Heteroskedasticity

## Review

Another example of heteroskedasticity:

Differing variances of  $u$  by group



# Heteroskedasticity

## Review

**Heteroskedasticity** is present when the variance of  $u$  changes with any combination of our explanatory variables  $x_1$  through  $x_k$ .

# Testing for heteroskedasticity

We have some tests that may help us detect heteroskedasticity.

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What do we do if we detect it?



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In the presence of heteroskedasticity, OLS is

- still **unbiased**
- **no longer the most efficient** unbiased linear estimator

On average, we get the right answer but with more noise (less precision).

*Also:* Our standard errors are biased.

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On average, we get the right answer but with more noise (less precision).

Also: Our standard errors are biased.

## Options:

1. Check regression **specification**.
2. Find a new, more efficient **unbiased estimator** for  $\beta_j$ 's.
3. Live with OLS's inefficiency; find a **new variance estimator**.
  - Standard errors
  - Confidence intervals
  - Hypothesis tests

# Living with heteroskedasticity

## Misspecification

As we've discussed, the specification<sup>†</sup> of your regression model matters a lot for the unbiasedness and efficiency of your estimator.

**Response #1:** Ensure your specification doesn't cause heteroskedasticity.

<sup>†</sup> *Specification*: Functional form and included variables.

# Living with heteroskedasticity

## Misspecification

*Example:* Let the population relationship be

$$y_i = \beta_0 + \beta_1 x_i + \beta_2 x_i^2 + u_i$$

with  $\mathbf{E}[u_i|x_i] = 0$  and  $\mathbf{Var}(u_i|x_i) = \sigma^2$ .

However, we omit  $x^2$  and estimate

$$y_i = \gamma_0 + \gamma_1 x_i + w_i$$

Then

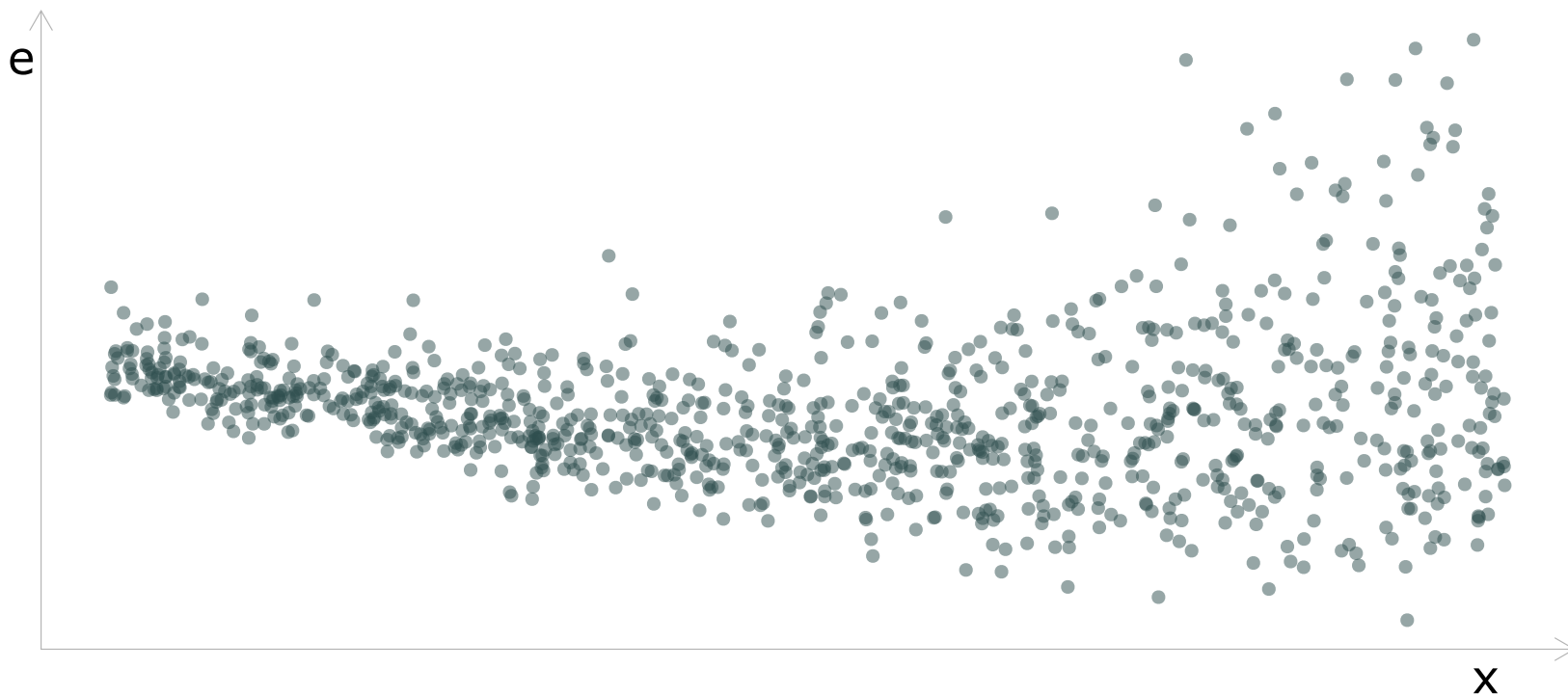
$$w_i = u_i + \beta_2 x_i^2 \implies \mathbf{Var}(w_i) = f(x_i)$$

*i.e.*, the variance of  $w_i$  changes systematically with  $x_i$  (heteroskedasticity).

# Living with heteroskedasticity

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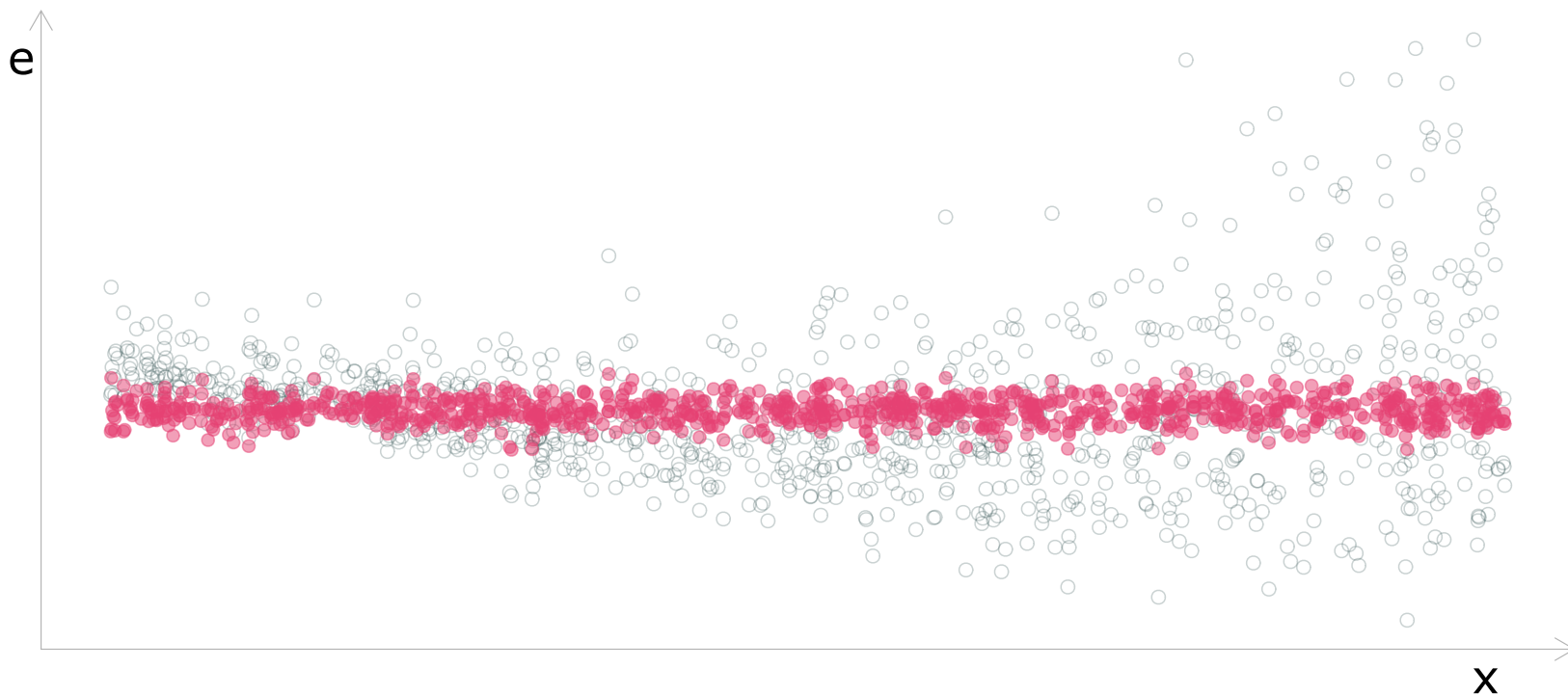
Truth:  $\log(y_i) = \beta_0 + \beta_1 x_i + u_i$     Misspecification:  $y_i = \beta_0 + \beta_1 x_i + v_i$



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More generally:

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### New problems:

- We often don't know the *right* specification.
- We'd like a more formal process for addressing heteroskedasticity.

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### **New problems:**

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- We'd like a more formal process for addressing heteroskedasticity.

**Conclusion:** Specification often will not "solve" heteroskedasticity. However, correctly specifying your model is still really important.

# Living with heteroskedasticity

## Weighted least squares

Weighted least squares (WLS) presents another approach.

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Let the true population relationship be

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Now transform (1) by dividing each observation's data by  $\sigma_i$ , i.e.,

$$\frac{y_i}{\sigma_i} = \beta_0 \frac{1}{\sigma_i} + \beta_1 \frac{x_i}{\sigma_i} + \frac{u_i}{\sigma_i} \quad (2)$$

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WLS is great, but we need to know  $\sigma_i^2$ , which is generally unlikely.

We can *slightly* relax this requirement—instead requiring

1.  $\text{Var}(u_i|x_i) = \sigma_i^2 = \sigma^2 h(x_i)$
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As before, we transform our heteroskedastic model into a homoskedastic model. This time we divide each observation's data<sup>†</sup> by  $\sqrt{h(x_i)}$ .

<sup>†</sup> Divide *all* of the data by  $\sqrt{h(x_i)}$ , including the intercept.

# Living with heteroskedasticity

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$$y_i = \beta_0 + \beta_1 x_i + u_i \quad (1)$$

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$$\text{Var}\left(\frac{u_i}{\sqrt{h(x_i)}} \middle| x_i\right) = \frac{1}{h(x_i)} \text{Var}(u_i|x_i) = \frac{1}{h(x_i)} \sigma^2 h(x_i) = \sigma^2$$

**Homoskedasticity!**

# Living with heteroskedasticity

## Weighted least squares

**Weighted least squares** (WLS) estimators are a special class of **generalized least squares** (GLS) estimators focused on heteroskedasticity.

# Living with heteroskedasticity

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**Weighted least squares** (WLS) estimators are a special class of **generalized least squares** (GLS) estimators focused on heteroskedasticity.

$$y_i = \beta_0 + \beta_1 x_{1i} + u_i \quad \text{vs.} \quad \frac{y_i}{\sigma_i} = \beta_0 \frac{1}{\sigma_i} + \beta_1 \frac{x_{1i}}{\sigma_i} + \frac{u_i}{\sigma_i}$$

Notes:

1. WLS **transforms** a heteroskedastic model into a homoskedastic model.
2. **Weighting:** WLS downweights observations with higher variance  $u_i$ 's.
3. **Big requirement:** WLS requires that we *know*  $\sigma_i^2$  for each observation.
4. WLS is generally **infeasible**. *Feasible* GLS (FGLS) offers a solution.
5. Under its assumptions: WLS is the **best linear unbiased estimator**.

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

### Response #3:

- Ignore OLS's inefficiency (in the presence of heteroskedasticity).
- Focus on **unbiased estimates for our standard errors**.
- In the process: Correct inference.

# Living with heteroskedasticity

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**Q:** What is a standard error?



# Living with heteroskedasticity

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**A:** The **standard deviation of an estimator's distribution**.

# Living with heteroskedasticity

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- Focus on **unbiased estimates for our standard errors**.
- In the process: Correct inference.

**Q:** What is a standard error?

**A:** The **standard deviation of an estimator's distribution**.

Estimators (like  $\hat{\beta}_1$ ) are random variables, so they have distributions.

Standard errors give us a sense of how much variability is in our estimator.

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

*Recall:* We can write the OLS estimator for  $\beta_1$  as

$$\hat{\beta}_1 = \beta_1 + \frac{\sum_i (x_i - \bar{x}) u_i}{\sum_i (x_i - \bar{x})^2} = \beta_1 + \frac{\sum_i (x_i - \bar{x}) u_i}{\text{SST}_x} \quad (3)$$

# Living with heteroskedasticity

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Let  $\text{Var}(u_i | x_i) = \sigma_i^2$ .

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

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Let  $\text{Var}(u_i|x_i) = \sigma_i^2$ .

We can use (3) to write the variance of  $\hat{\beta}_1$ , i.e.,

$$\text{Var}(\hat{\beta}_1|x_i) = \frac{\sum_i (x_i - \bar{x})^2 \sigma_i^2}{\text{SST}_x^2} \quad (4)$$

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

If we want unbiased estimates for our standard errors, we need an unbiased estimate for

$$\frac{\sum_i (x_i - \bar{x})^2 \sigma_i^2}{\text{SST}_x^2}$$

Our old friend Hal White provided such an estimator:<sup>†</sup>

$$\widehat{\text{Var}}(\hat{\beta}_1) = \frac{\sum_i (x_i - \bar{x})^2 e_i^2}{\text{SST}_x^2}$$

where the  $e_i$  comes from the OLS regression of interest.

<sup>†</sup> This specific equation is for simple linear regression.

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

Our heteroskedasticity-robust estimators for the standard error of  $\beta_j$ .

**Case 1** Simple linear regression,  $y_i = \beta_0 + \beta_1 x_i + u_i$

$$\widehat{\text{Var}}(\hat{\beta}_1) = \frac{\sum_i (x_i - \bar{x})^2 e_i^2}{\text{SST}_x^2}$$

**Case 2** Multiple (linear) regression,  $y_i = \beta_0 + \beta_1 x_{1i} + \cdots + \beta_k x_{ki} + u_i$

$$\widehat{\text{Var}}(\hat{\beta}_j) = \frac{\sum_i \hat{r}_{ij}^2 e_i^2}{\text{SST}_{x_j^2}}$$

where  $\hat{r}_{ij}$  denotes the  $i^{\text{th}}$  residual from regressing  $x_j$  on all other explanatory variables.

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

With these standard errors, we can return to correct statistical inference

*E.g.*, we can update our previous  $t$  statistic formula with our new heteroskedasticity-robust standard errors.

$$t = \frac{\text{Estimate} - \text{Hypothesized value}}{\text{Standard error}}$$



# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

### Notes

- We are still using **OLS estimates for  $\beta_j$**
- Our het.-robust standard errors use a **different estimator**.
- Homoskedasticity
  - Plain OLS variance estimator is more efficient.
  - Het.-robust is still unbiased.
- Heteroskedasticity
  - Plain OLS variance estimator is biased.
  - Het.-robust variance estimator is unbiased.

# Living with heteroskedasticity

## Heteroskedasticity-robust standard errors

These standard errors go by many names

- Heteroskedasticity-robust standard errors
- Het.-robust standard errors
- White standard errors
- Eicker-White standard errors
- Huber standard errors
- Eicker-Huber-White standards errors
- (some other combination of Eicker, Huber, and White)

**Do not say:** "Robust standard errors". The problem: "robust" to what?

# Living with heteroskedasticity

## *Examples*

# Living with heteroskedasticity

## Examples

Back to our test-scores dataset...

```
# Load packages
library(pacman)
p_load(tidyverse, Ecdat)
# Select and rename desired variables; assign to new dataset; format as tibble
test_df <- Caschool %>% select(
  test_score = testscr, ratio = str, income = avginc, enrollment = enrltot
) %>% as_tibble()
# View first 2 rows of the dataset
head(test_df, 2)
```

```
#> # A tibble: 2 x 4
#>   test_score ratio income enrollment
#>   <dbl> <dbl> <dbl>     <int>
#> 1     691.   17.9   22.7       195
#> 2     661.   21.5    9.82       240
```

# Living with heteroskedasticity

## Example: Model specification

We found significant evidence of heteroskedasticity.

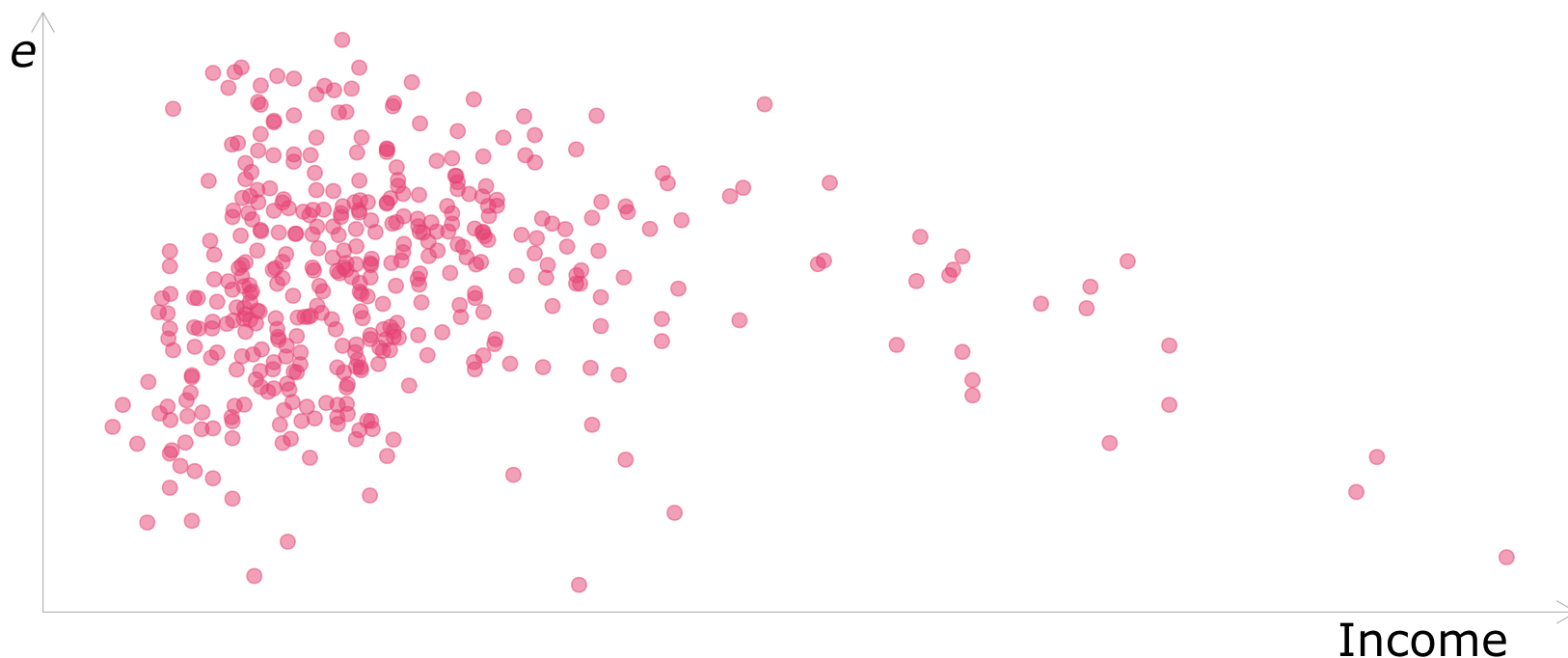
Let's check if it was due to misspecifying our model.

# Living with heteroskedasticity

## Example: Model specification

Model<sub>1</sub>:  $\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$

```
lm(test_score ~ ratio + income, data = test_df)
```

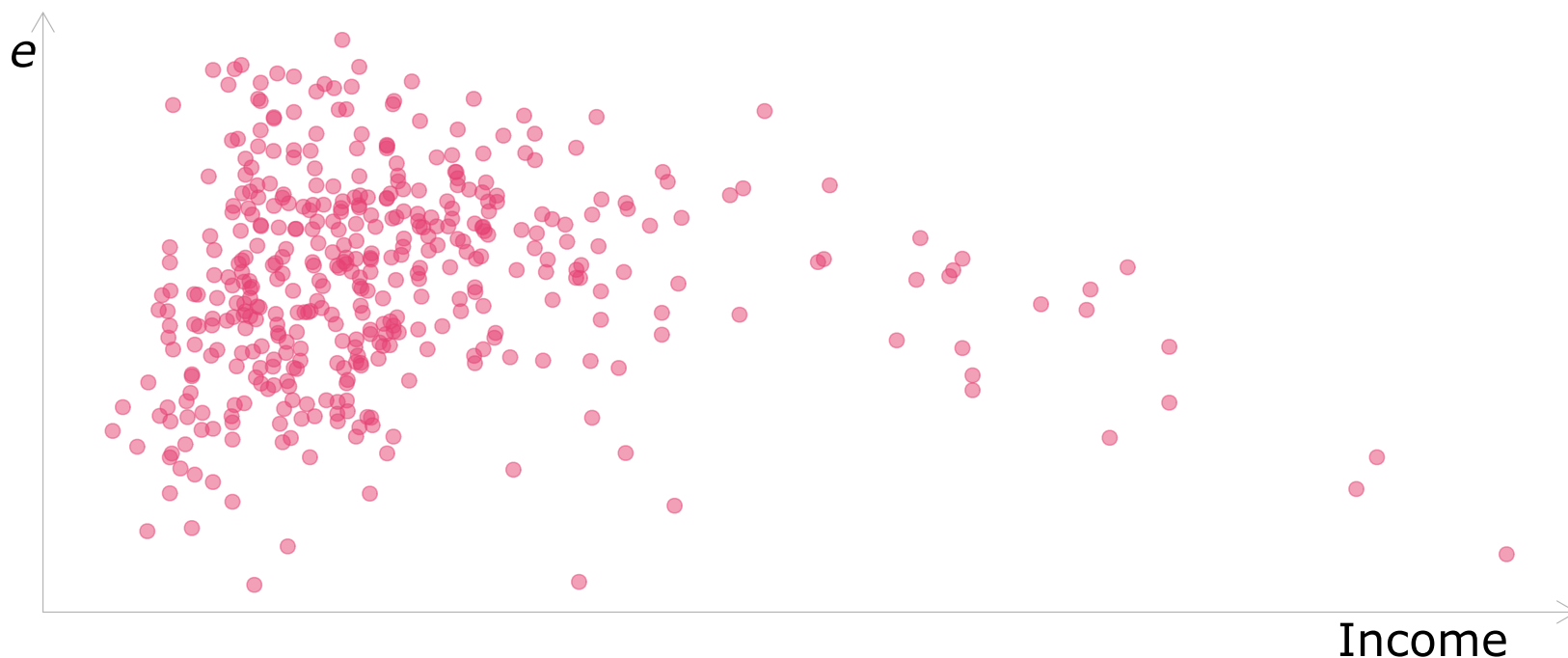


# Living with heteroskedasticity

## Example: Model specification

Model<sub>2</sub>:  $\log(\text{Score}_i) = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$

```
lm(log(test_score) ~ ratio + income, data = test_df)
```

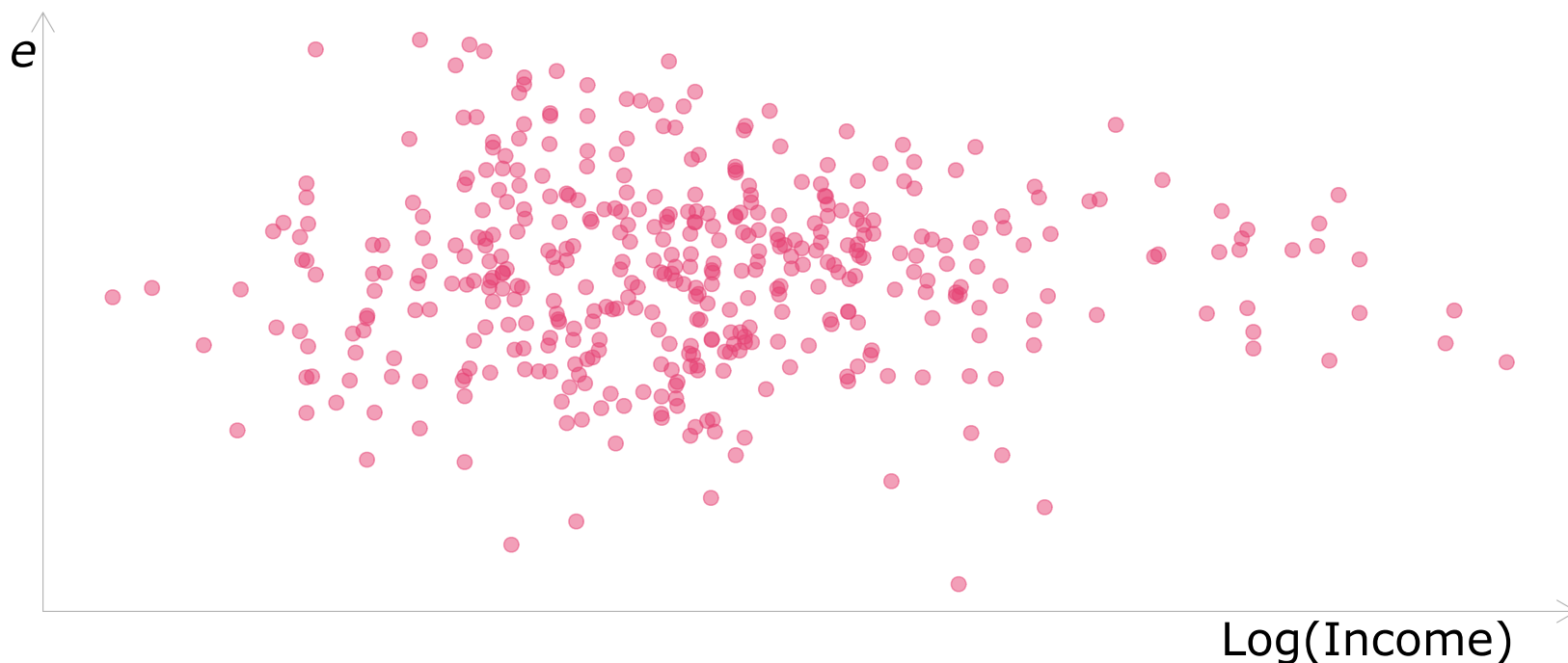


# Living with heteroskedasticity

## Example: Model specification

Model<sub>3</sub>:  $\log(\text{Score}_i) = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \log(\text{Income}_i) + u_i$

```
lm(log(test_score) ~ ratio + log(income), data = test_df)
```





# Living with heteroskedasticity

## Example: Model specification

Let's test this new specification with the White test for heteroskedasticity.

$$\text{Model}_3: \log(\text{Score}_i) = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \log(\text{Income}_i) + u_i$$

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The regression for the White test

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The regression for the White test

$$e_i^2 = \alpha_0 + \alpha_1 \text{Ratio}_i + \alpha_2 \log(\text{Income}_i) + \alpha_3 \text{Ratio}_i^2 + \alpha_4 (\log(\text{Income}_i))^2 \\ + \alpha_5 (\text{Ratio}_i \times \log(\text{Income}_i)) + v_i$$

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yields  $R_e^2 \approx 0.029$

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yields  $R_e^2 \approx 0.029$  and test statistic of  $\widehat{\text{LM}} = n \times R_e^2 \approx 12.2$ .

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Under  $H_0$ ,  $\text{LM}$  is distributed as

# Living with heteroskedasticity

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# Living with heteroskedasticity

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yields  $R_e^2 \approx 0.029$  and test statistic of  $\widehat{\text{LM}} = n \times R_e^2 \approx 12.2$ .

Under  $H_0$ ,  $\text{LM}$  is distributed as  $\chi_5^2 \implies p\text{-value} \approx 0.033$ .

# Living with heteroskedasticity

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yields  $R_e^2 \approx 0.029$  and test statistic of  $\widehat{\text{LM}} = n \times R_e^2 \approx 12.2$ .

Under  $H_0$ ,  $\text{LM}$  is distributed as  $\chi_5^2 \implies p\text{-value} \approx 0.033$ .

$\therefore$

# Living with heteroskedasticity

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yields  $R_e^2 \approx 0.029$  and test statistic of  $\widehat{\text{LM}} = n \times R_e^2 \approx 12.2$ .

Under  $H_0$ , LM is distributed as  $\chi_5^2 \implies p\text{-value} \approx 0.033$ .

$\therefore$  **Reject  $H_0$ .**

# Living with heteroskedasticity

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yields  $R_e^2 \approx 0.029$  and test statistic of  $\widehat{\text{LM}} = n \times R_e^2 \approx 12.2$ .

Under  $H_0$ , LM is distributed as  $\chi_5^2 \implies p\text{-value} \approx 0.033$ .

**$\therefore$  Reject  $H_0$ . Conclusion:**

# Living with heteroskedasticity

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yields  $R_e^2 \approx 0.029$  and test statistic of  $\widehat{\text{LM}} = n \times R_e^2 \approx 12.2$ .

Under  $H_0$ ,  $\text{LM}$  is distributed as  $\chi_5^2 \implies p\text{-value} \approx 0.033$ .

$\therefore$  **Reject  $H_0$ . Conclusion:** There is statistically significant evidence of heteroskedasticity at the five-percent level.

# Living with heteroskedasticity

## Example: Model specification

Okay, we tried adjusting our specification, but there is still evidence of heteroskedasticity.

**Next:** In general, you will turn to heteroskedasticity-robust standard errors.

- OLS is still unbiased for the **coefficients** (the  $\beta_j$ 's)
- Heteroskedasticity-robust standard errors are unbiased for the **standard errors** of the  $\hat{\beta}_j$ 's, i.e.,  $\sqrt{\text{Var}(\hat{\beta}_j)}$ .

# Living with heteroskedasticity

## Example: Het.-robust standard errors

Let's return to our model

$$\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$$

We can use the `lfe` package in R to calculate standard errors.

# Living with heteroskedasticity

## Example: Het.-robust standard errors

$$\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$$

1. Run the regression with `feIm()` (instead of `lm()`)

```
# Load 'lfe' package  
p_load(lfe)  
# Regress log score on ratio and log income  
test_reg <- feIm(test_score ~ ratio + income, data = test_df)
```



# Living with heteroskedasticity

## Example: Het.-robust standard errors

$$\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$$

1. Run the regression with `fe lm()` (instead of `lm()`)

```
# Load 'lfe' package  
p_load(lfe)  
# Regress log score on ratio and log income  
test_reg <- fe lm(test_score ~ ratio + income, data = test_df)
```

Notice that `fe lm()` uses the same syntax as `lm()` for this regression.

# Living with heteroskedasticity

## Example: Het.-robust standard errors

$$\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$$

2. Estimate het.-robust standard errors with `robust = T` option in `summary()`

```
# Het-robust standard errors with 'robust = T'  
summary(test_reg, robust = T)
```

```
#>           Estimate Robust s.e t value Pr(>|t|)  
#> (Intercept) 638.7292      7.3012  87.482  <2e-16 ***  
#> ratio       -0.6487      0.3533  -1.836   0.0671 .  
#> income       1.8391      0.1147  16.029  <2e-16 ***
```

# Living with heteroskedasticity

## Example: Het.-robust standard errors

Coefficients and **heteroskedasticity-robust standard errors**:

```
summary(test_reg, robust = T)
```

```
#>           Estimate Robust s.e t value Pr(>|t|)
#> (Intercept) 638.7292      7.3012  87.482   <2e-16 ***
#> ratio       -0.6487      0.3533  -1.836   0.0671 .
#> income       1.8391      0.1147  16.029   <2e-16 ***
```

Coefficients and **plain OLS standard errors** (assumes homoskedasticity):

```
summary(test_reg, robust = F)
```

```
#>           Estimate Std. Error t value Pr(>|t|)
#> (Intercept) 638.72915      7.44908  85.746   <2e-16 ***
#> ratio       -0.64874      0.35440  -1.831   0.0679 .
#> income       1.83911      0.09279  19.821   <2e-16 ***
```

# Living with heteroskedasticity

## Example: WLS

We mentioned that WLS is often not possible—we need to know the functional form of the heteroskedasticity—either

**A.**  $\sigma_i^2$

or

**B.**  $h(x_i)$ , where  $\sigma_i^2 = \sigma^2 h(x_i)$

# Living with heteroskedasticity

## Example: WLS

We mentioned that WLS is often not possible—we need to know the functional form of the heteroskedasticity—either

**A.**  $\sigma_i^2$

or

**B.**  $h(x_i)$ , where  $\sigma_i^2 = \sigma^2 h(x_i)$

There *are* occasions in which we can know  $h(x_i)$ .

# Living with heteroskedasticity

## Example: WLS

Imagine individuals in a population have homoskedastic disturbances.

However, instead of observing individuals' data, we observe (in data) groups' averages (*e.g.*, cities, counties, school districts).

If these groups have different sizes, then our dataset will be heteroskedastic—in a predictable fashion.

**Recall:** The variance of the sample mean depends upon the sample size,

$$\text{Var}(\bar{x}) = \frac{\sigma_x^2}{n}$$

# Living with heteroskedasticity

## Example: WLS

Imagine individuals in a population have homoskedastic disturbances.

However, instead of observing individuals' data, we observe (in data) groups' averages (*e.g.*, cities, counties, school districts).

If these groups have different sizes, then our dataset will be heteroskedastic—in a predictable fashion.

**Recall:** The variance of the sample mean depends upon the sample size,

$$\text{Var}(\bar{x}) = \frac{\sigma_x^2}{n}$$

**Example:** Our school testing data is averaged at the school level.

# Living with heteroskedasticity

## Example: WLS

*Example:* Our school testing data is averaged at the school level.

Even if individual students have homoskedastic disturbances, the schools would have heteroskedastic disturbances, *i.e.*,

**Individual-level model:**  $\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$

**School-level model:**  $\overline{\text{Score}}_s = \beta_0 + \beta_1 \overline{\text{Ratio}}_s + \beta_2 \overline{\text{Income}}_s + \bar{u}_s$

where the  $s$  subscript denotes an individual school (just as  $i$  indexes an individual person).

$$\text{Var}(\bar{u}_s) = \frac{\sigma^2}{n_s}$$



# Living with heteroskedasticity

## Example: WLS

For WLS, we're looking for a function  $h(x_s)$  such that  $\text{Var}(\bar{u}_s | x_s) = \sigma^2 h(x_s)$ .

# Living with heteroskedasticity

## Example: WLS

For WLS, we're looking for a function  $h(x_s)$  such that  $\text{Var}(\bar{u}_s | x_s) = \sigma^2 h(x_s)$ .

We just showed<sup>†</sup> that  $\text{Var}(\bar{u}_s | x_s) = \frac{\sigma^2}{n_s}$ .

<sup>†</sup> Assuming the individuals' disturbances are homoskedastic.

# Living with heteroskedasticity

## Example: WLS

For WLS, we're looking for a function  $h(x_s)$  such that  $\text{Var}(\bar{u}_s | x_s) = \sigma^2 h(x_s)$ .

We just showed<sup>†</sup> that  $\text{Var}(\bar{u}_s | x_s) = \frac{\sigma^2}{n_s}$ .

Thus,  $h(x_s) = 1/n_s$ , where  $n_s$  is the number of students in school  $s$ .

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# Living with heteroskedasticity

## Example: WLS

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To implement WLS, we divide each observation's data by  $1/\sqrt{h(x_s)}$ , meaning we need to multiply each school's data by  $\sqrt{n_s}$ .

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The variable `enrollment` in the `test_df` dataset is our  $n_s$ .

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# Living with heteroskedasticity

## Example: WLS

Using WLS to estimate  $\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$

**Step 1:** Multiply each variable by  $1/\sqrt{h(x_i)} = \sqrt{\text{Enrollment}_i}$

```
# Create WLS transformed variables, multiplying by sqrt of 'pop'
test_df <- mutate(test_df,
  test_score_wls = test_score * sqrt(enrollment),
  ratio_wls      = ratio * sqrt(enrollment),
  income_wls     = income * sqrt(enrollment),
  intercept_wls  = 1 * sqrt(enrollment)
)
```

Notice that we are creating a transformed intercept.

# Living with heteroskedasticity

## Example: WLS

Using WLS to estimate  $\text{Score}_i = \beta_0 + \beta_1 \text{Ratio}_i + \beta_2 \text{Income}_i + u_i$

**Step 2:** Run our WLS (transformed) regression

```
# WLS regression
wls_reg <- lm(
  test_score_wls ~ -1 + intercept_wls + ratio_wls + income_wls,
  data = test_df
)
```

# Living with heteroskedasticity

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  data = test_df
)
```

*Note:* The `-1` in our regression tells R not to add an intercept, since we are adding a transformed intercept (`intercept_wls`).



# Living with heteroskedasticity

## Example: WLS

The **WLS estimates and standard errors:**

```
#>               Estimate Std. Error t value Pr(>|t|)
#> intercept_wls 618.78331      8.26929  74.829  <2e-16 ***
#> ratio_wls     -0.21314      0.37676  -0.566    0.572
#> income_wls     2.26493      0.09065  24.985  <2e-16 ***
```

# Living with heteroskedasticity

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```

The **OLS estimates** and **het.-robust standard errors**:

```
#>               Estimate Robust s.e t value Pr(>|t|)
#> (Intercept) 638.7292     7.3012  87.482  <2e-16 ***
#> ratio        -0.6487     0.3533  -1.836    0.0671 .
#> income        1.8391     0.1147  16.029  <2e-16 ***
```

# Living with heteroskedasticity

## Example: WLS

Alternative to doing your own weighting: feed `lm()` some `weights`.

```
lm(test_score ~ ratio + income, data = test_df, weights = enrollment)
```

# Living with heteroskedasticity

In this example

- **Heteroskedasticity-robust standard errors** did not change our standard errors very much (relative to plain OLS standard errors).
- **WLS** changed our answers a bit—coefficients and standard errors.

# Living with heteroskedasticity

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- **Heteroskedasticity-robust standard errors** did not change our standard errors very much (relative to plain OLS standard errors).
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These examples highlighted a few things:

1. Using the correct estimator for your standard errors really matters.<sup>†</sup>
2. Econometrics doesn't always offer an obviously *correct* route.

<sup>†</sup> Sit in on an economics seminar, and you will see what I mean.

# Living with heteroskedasticity

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- **Heteroskedasticity-robust standard errors** did not change our standard errors very much (relative to plain OLS standard errors).
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These examples highlighted a few things:

1. Using the correct estimator for your standard errors really matters.<sup>†</sup>
2. Econometrics doesn't always offer an obviously *correct* route.

To see #1, let's run a simulation.

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# Living with heteroskedasticity

## Simulation

Let's examine a simple linear regression model with heteroskedasticity.

$$y_i = \underbrace{\beta_0}_{=1} + \underbrace{\beta_1}_{=10} x_i + u_i$$

where  $\text{Var}(u_i|x_i) = \sigma_i^2 = \sigma^2 x_i^2$ .

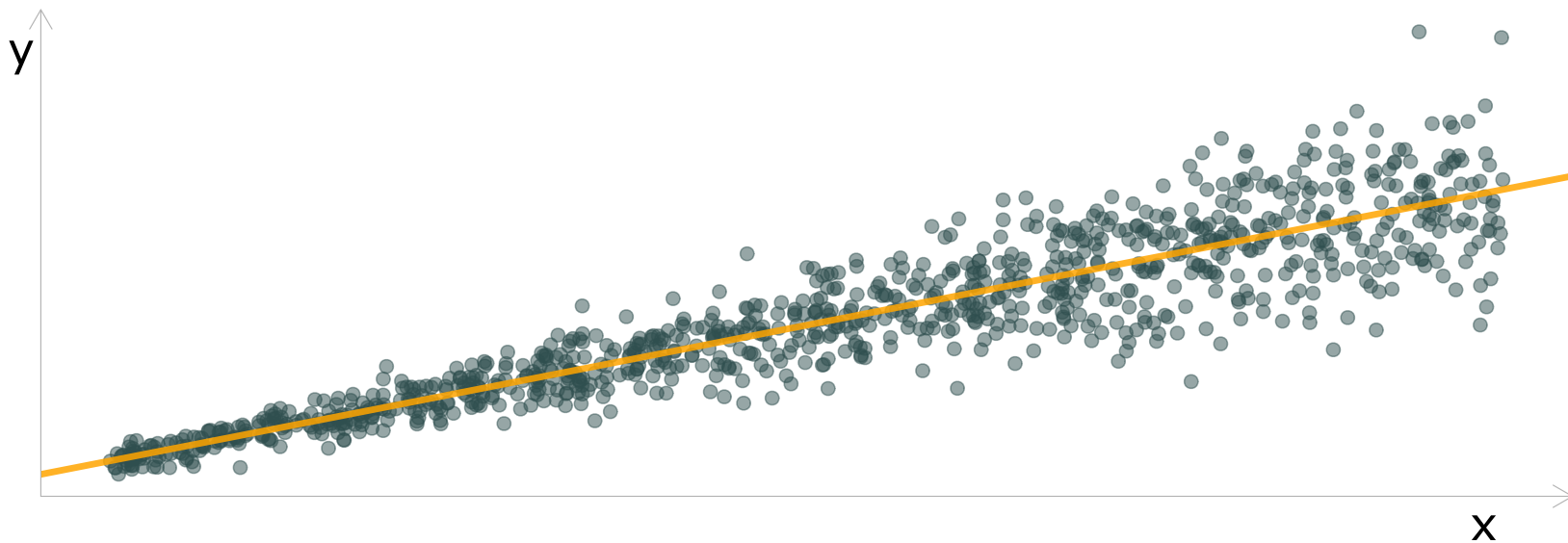
# Living with heteroskedasticity

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# Living with heteroskedasticity

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# Living with heteroskedasticity

## Simulation

*Note regarding WLS:*

Since  $\text{Var}(u_i|x_i) = \sigma^2 x_i^2$ ,

$$\text{Var}(u_i|x_i) = \sigma^2 h(x_i) \implies h(x_i) = x_i^2$$

WLS multiplies each variable by  $1/\sqrt{h(x_i)} = 1/x_i$ .

# Living with heteroskedasticity

## Simulation

In this simulation, we want to compare

1. The **efficiency** of
  - OLS
  - WLS with correct weights:  $h(x_i) = x_i$
  - WLS with incorrect weights:  $h(x_i) = \sqrt{x_i}$
2. How well our **standard errors** perform (via confidence intervals) with
  - Plain OLS standard errors
  - Heteroskedasticity-robust standard errors
  - WLS standard errors

# Living with heteroskedasticity

## Simulation

The simulation plan:

Do 10,000 times:

1. Generate a sample of size 30 from the population
2. Calculate/save OLS and WLS ( $\times 2$ ) estimates for  $\beta_1$
3. Calculate/save standard errors for  $\beta_1$  using
  - Plain OLS standard errors
  - Heteroskedasticity-robust standard errors
  - WLS (correct)
  - WLS (incorrect)

# Living with heteroskedasticity

## Simulation

### For one iteration of the simulation:

Code to generate the data...

```
# Parameters
b0 ← 1
b1 ← 10
s2 ← 1
# Sample size
n ← 30
# Generate data
sample_df ← tibble(
  x = runif(n, 0.5, 1.5),
  y = b0 + b1 * x + rnorm(n, 0, sd = s2 * x^2)
)
```

# Living with heteroskedasticity

## Simulation

### For one iteration of the simulation:

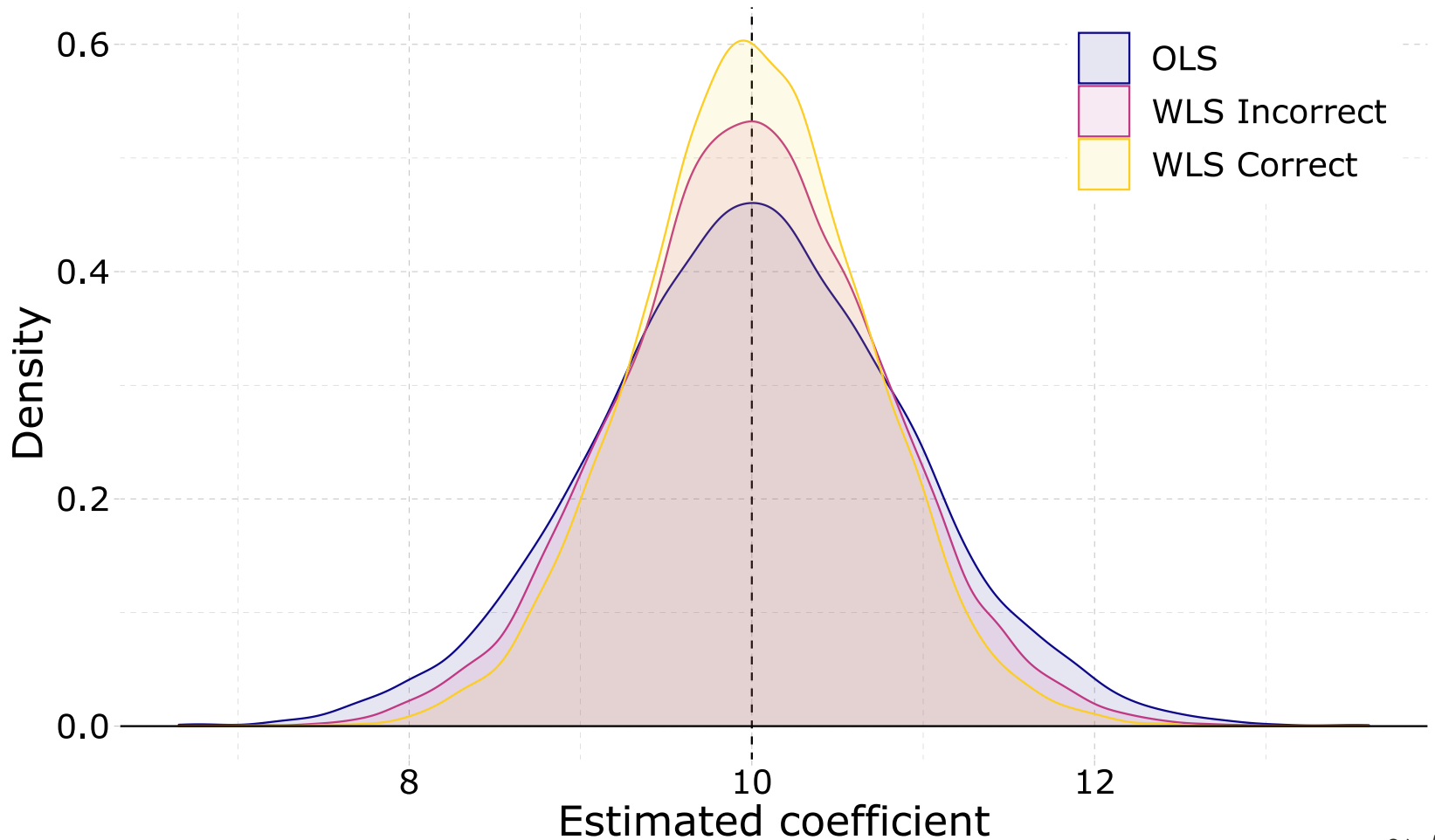
Code to estimate our coefficients and standard errors...

```
# OLS
ols <- feIm(y ~ x, data = sample_df)
# WLS: Correct weights
wls_t <- lm(y ~ x, data = sample_df, weights = 1/x^2)
# WLS: Correct weights
wls_f <- lm(y ~ x, data = sample_df, weights = 1/x)
# Coefficients and standard errors
summary(ols, robust = F)
summary(ols, robust = T)
summary(wls_t)
summary(wls_f)
```

Then save the results.

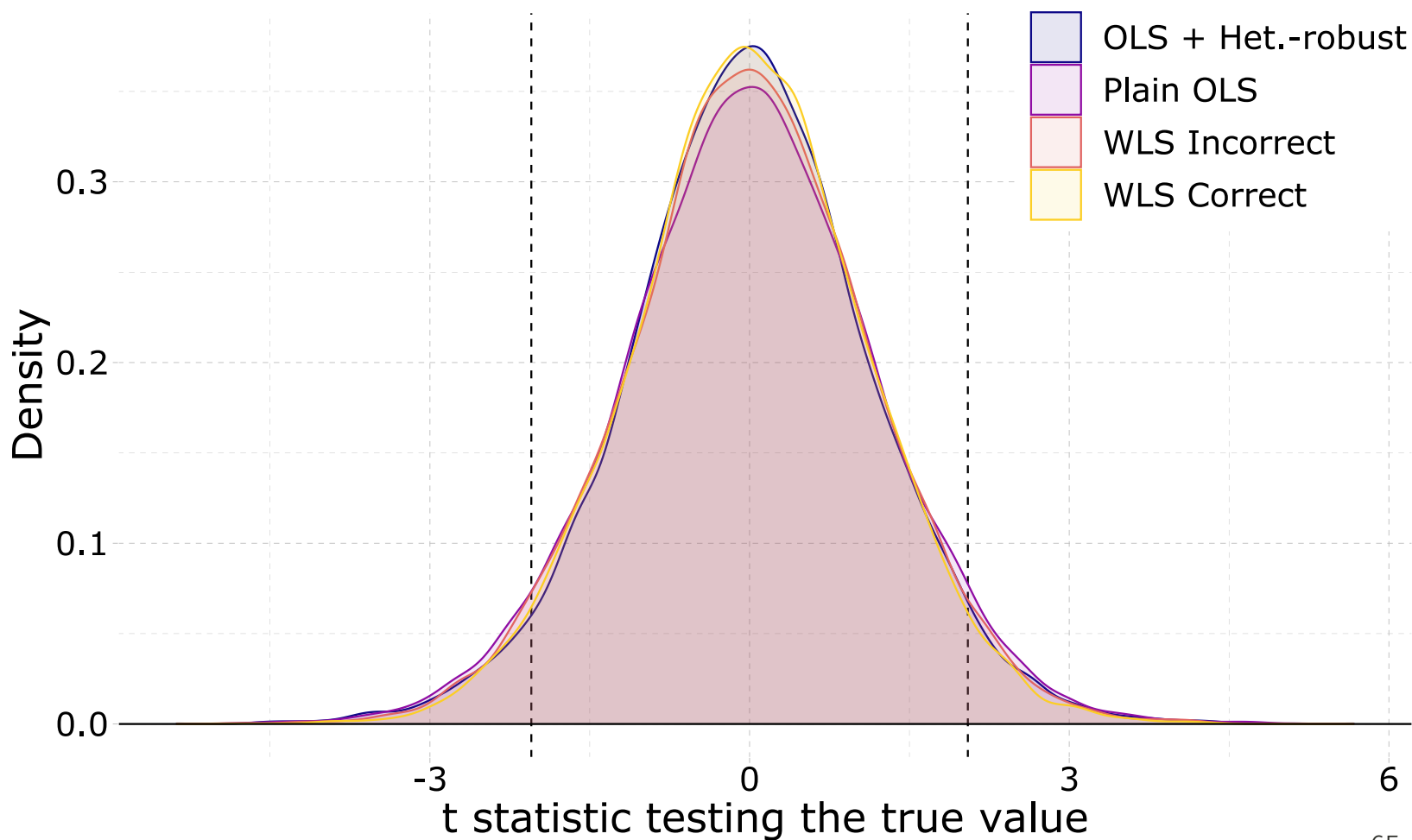
# Living with heteroskedasticity

## Simulation: Coefficients



# Living with heteroskedasticity

## Simulation: Inference





# Living with heteroskedasticity

## Simulation: Results

Summarizing our simulation results (10,000 iterations)

**Estimation:** Summary of  $\hat{\beta}_1$ 's

Estimator	Mean	S.D.
OLS	10.004	0.897
WLS Correct	10.000	0.677
WLS Incorrect	10.001	0.768

# Living with heteroskedasticity

## Simulation: Results

Summarizing our simulation results (10,000 iterations)

**Estimation:** Summary of  $\hat{\beta}_1$ 's

Estimator	Mean	S.D.
OLS	10.004	0.897
WLS Correct	10.000	0.677
WLS Incorrect	10.001	0.768

**Inference:** % of times we reject  $\beta_1$

Estimators	% Reject
OLS + Het.-robust	7.4
OLS + Homosk.	8.7
WLS Correct	6.4
WLS Incorrect	7.6