2.5 — Precision and Diagnostics

ECON 480 • Econometrics • Fall 2022

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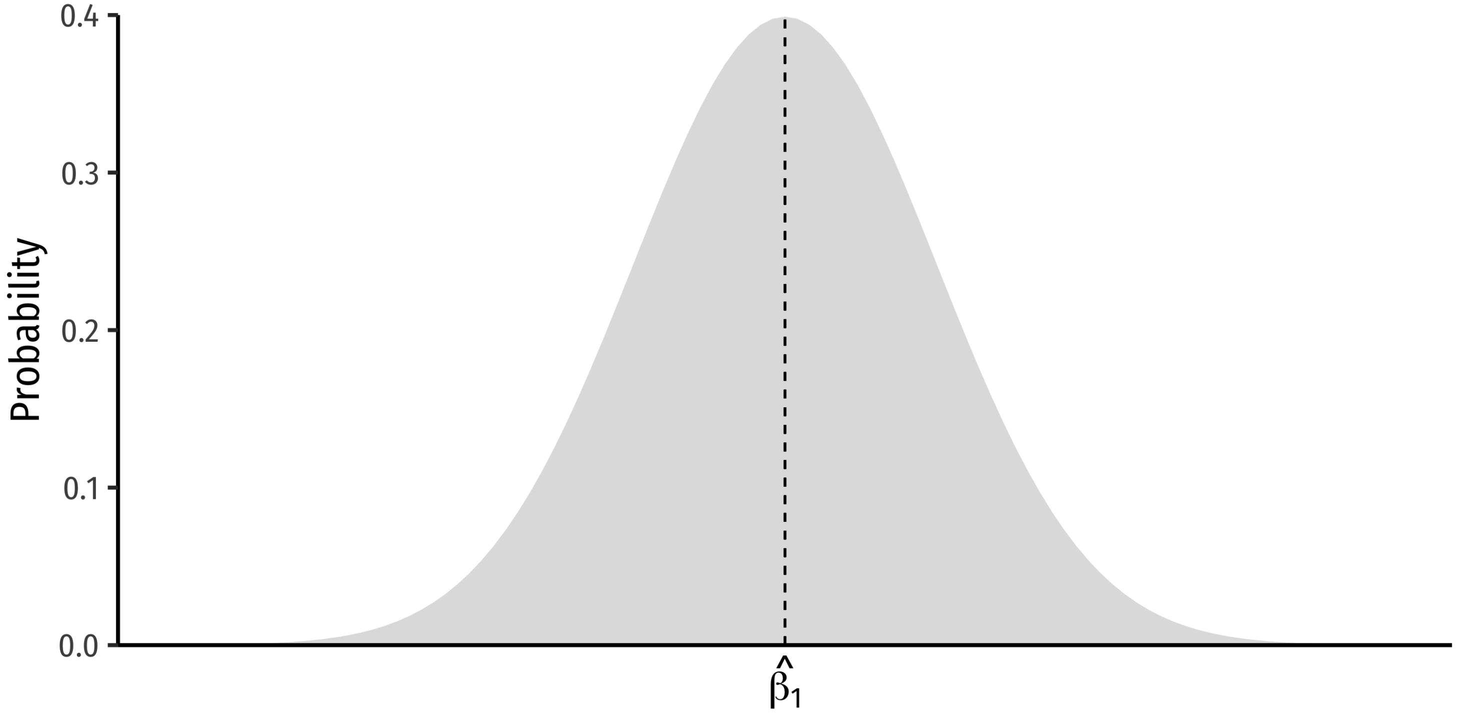
The Sampling Distribution of $\hat{\beta}_1$

$$\hat{\beta}_1 \sim N(\mathbb{E}[\hat{\beta}_1], \sigma_{\hat{\beta}_1})$$



The Sampling Distribution of $\hat{\beta}_1$

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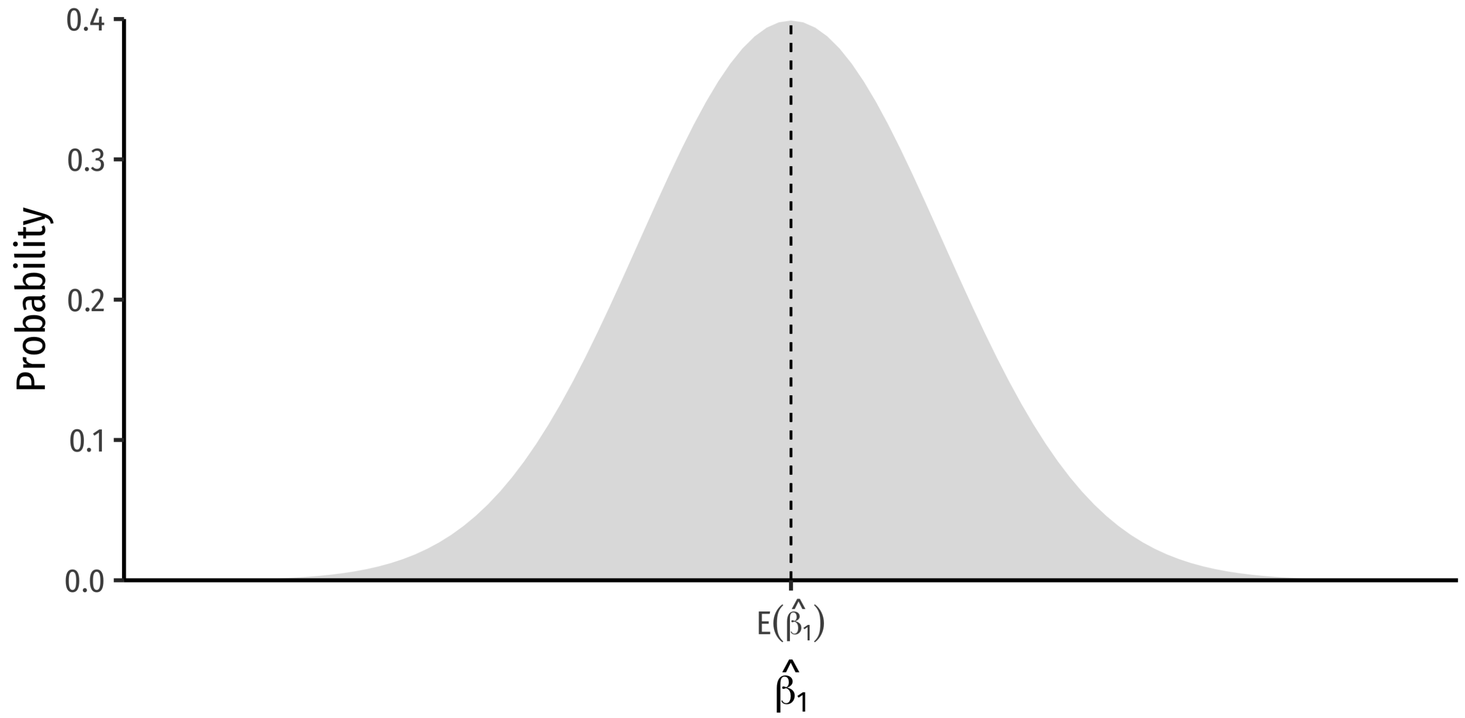
1. **Center**[1] of the distribution: $\mathbb{E}[\hat{\beta}_1]$ **(last class)**



1. Under the 4 assumptions about u, particularly $cor(X, u) = 0$

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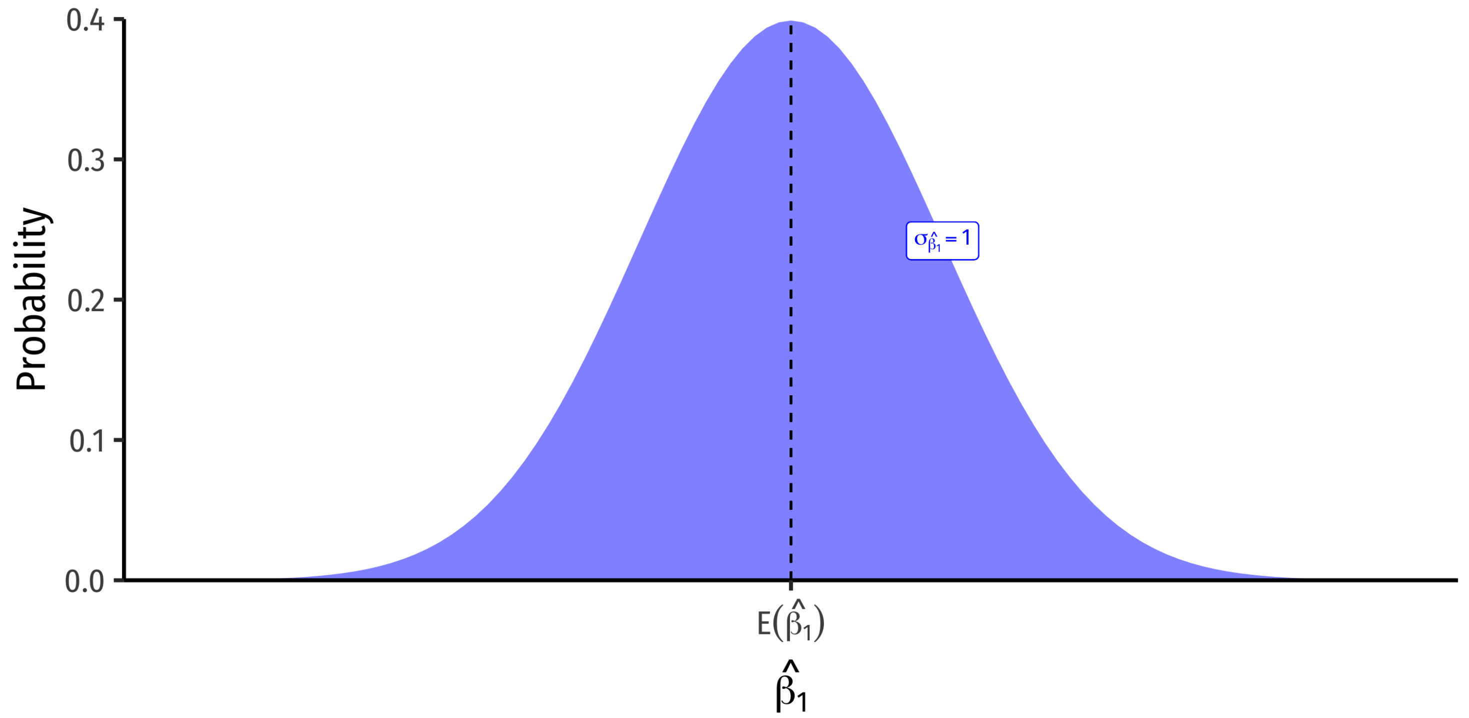

1. **Center**[1] of the distribution: $\mathbb{E}[\hat{\beta}_1]$ (**last class**)
2. **Precision** or **uncertainty** of the estimate (**today**)
   - **Variance** $\sigma^2_{\hat{\beta}_1}$
   - **Standard error**[2] $\sigma_{\hat{\beta}_1} = \sqrt{var(\hat{\beta}_1)}$

1. Under the 4 assumptions about u, particularly, $cor(X, u) = 0$
2. Standard **"error"** is the analog of standard *deviation* when talking about the *sampling distribution* of a sample statistic (such as $\bar{X}$ or $\hat{\beta}_1$).

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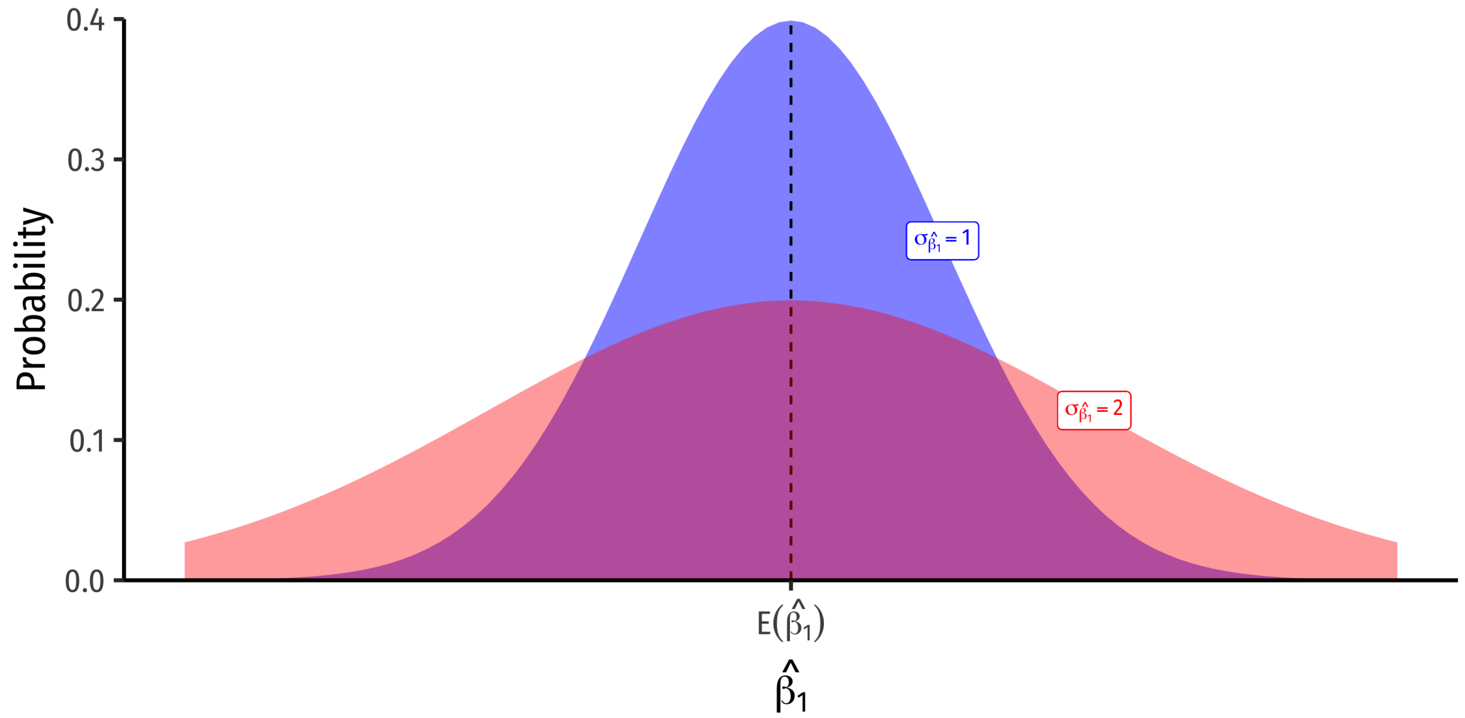

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Variation in $\hat{\beta}_1$

What Affects Variation in $\hat{\beta}_1$

$$var(\hat{\beta}_1) = \frac{(SER)^2}{n \times var(X)}$$

$$se(\hat{\beta}_1) = \sqrt{var(\hat{\beta}_1)} = \frac{SER}{\sqrt{n} \times sd(X)}$$

- Variation in $\hat{\beta}_1$ is affected by 3 things:

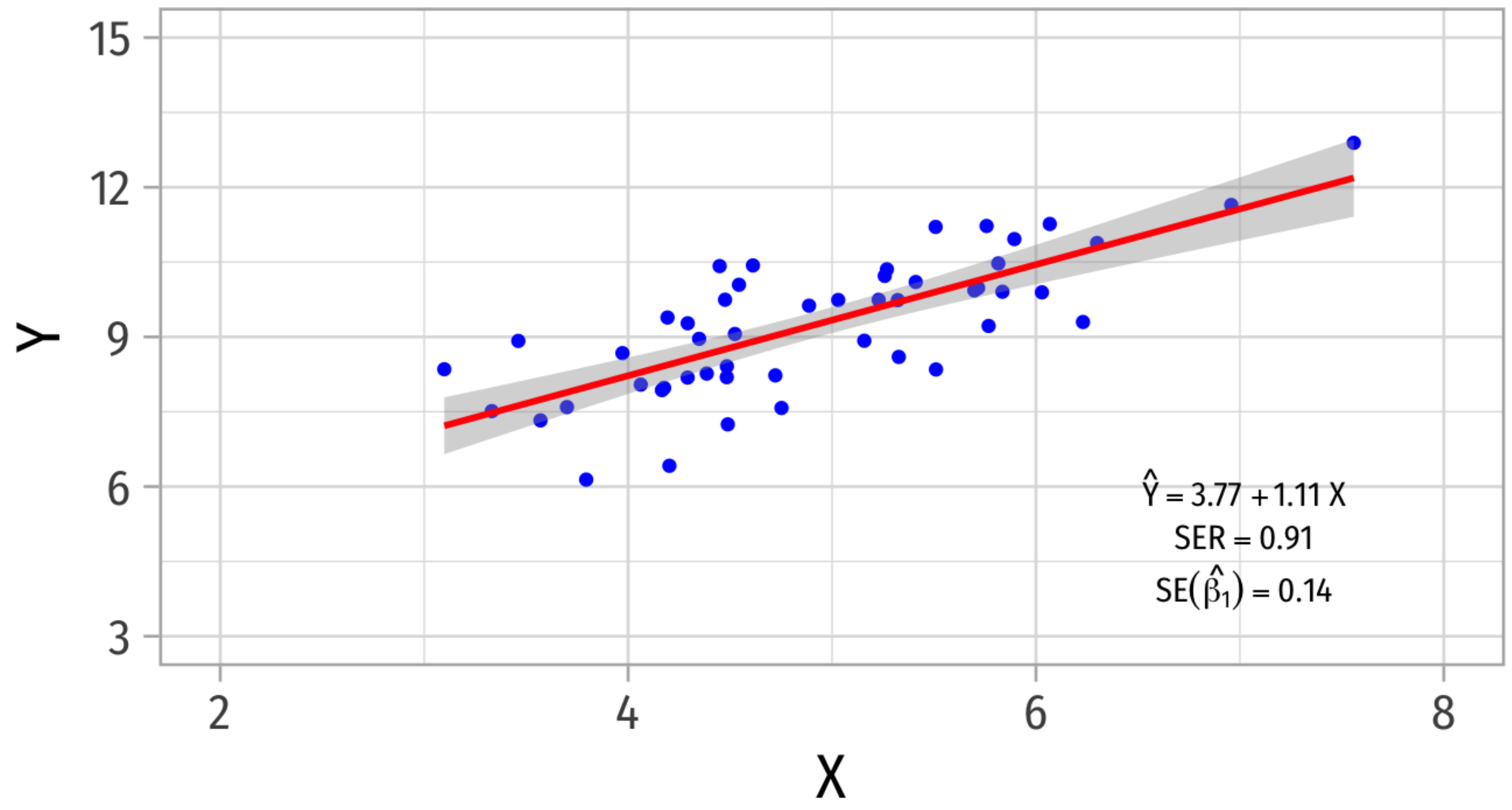
1. **Goodness of fit of the model (SER)**[1]
   - Larger $SER \rightarrow$ larger $var(\hat{\beta}_1)$
2. **Sample size, n**
   - Larger $n \rightarrow$ smaller $var(\hat{\beta}_1)$
3. **Variance of X**
   - Larger $var(X) \rightarrow$ smaller $var(\hat{\beta}_1)$

1. Recall from last class, the **S**tandard **E**rror of the **R**egression $\hat{\sigma}_u = \sqrt{\frac{\sum \hat{u}_i^2}{n-2}}$

Variation in $\hat{\beta}_1$: Goodness of Fit

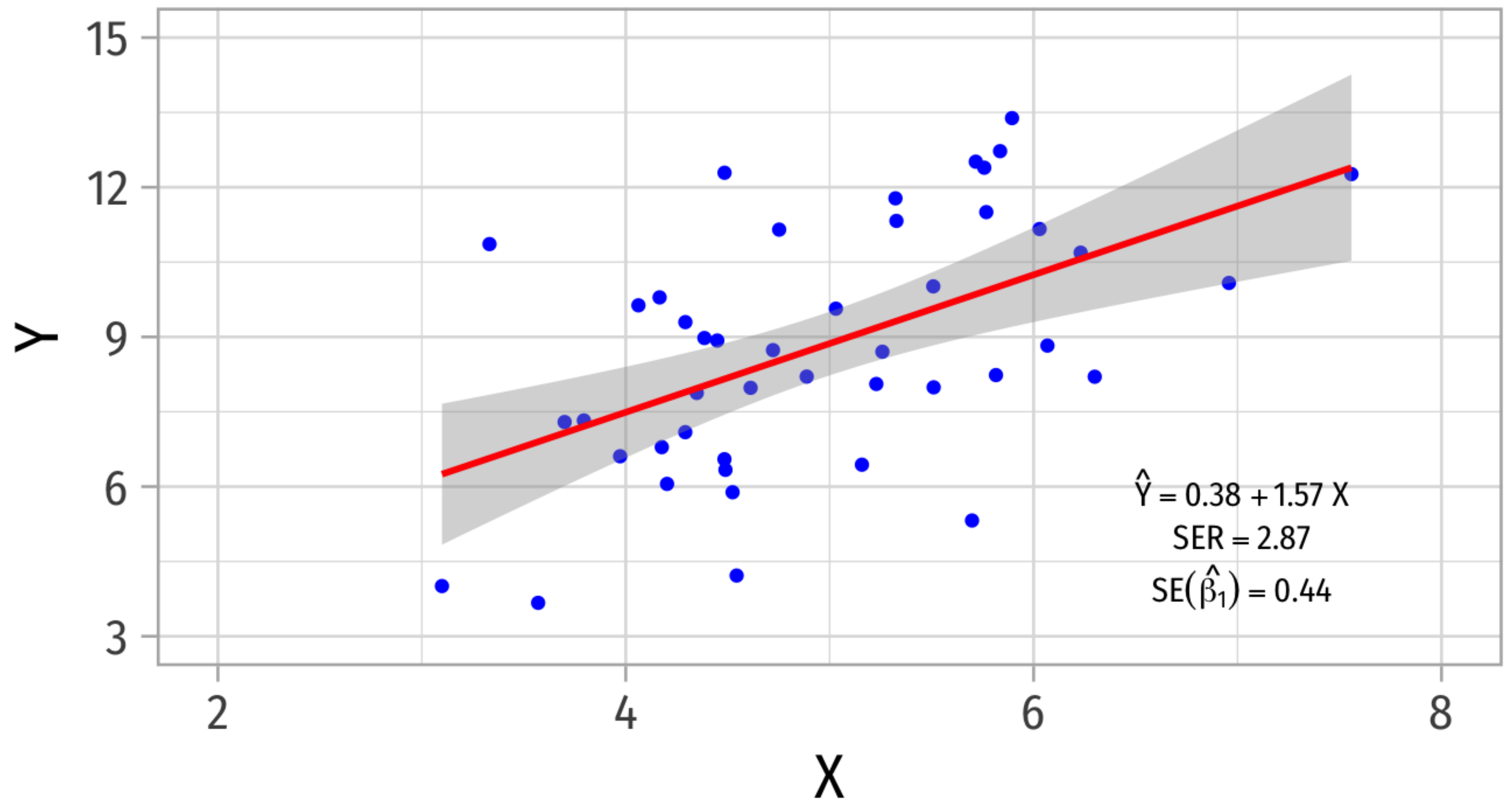
Model With Better Fit

Lower SER lowers variation in $\hat{\beta}_1$



Model With Worse Fit

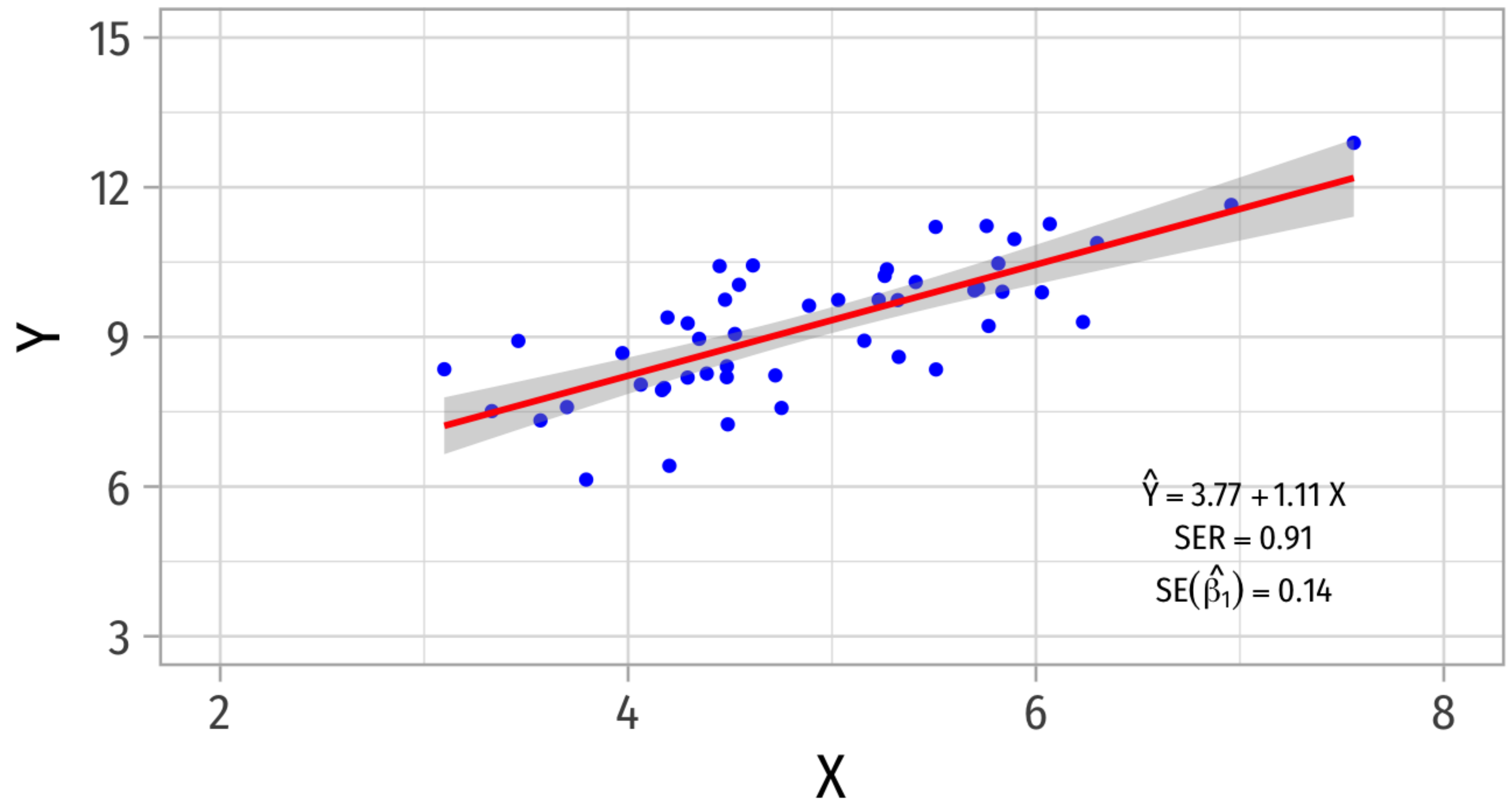
Higher SER raises variation in $\hat{\beta}_1$



Variation in $\hat{\beta}_1$: Sample Size

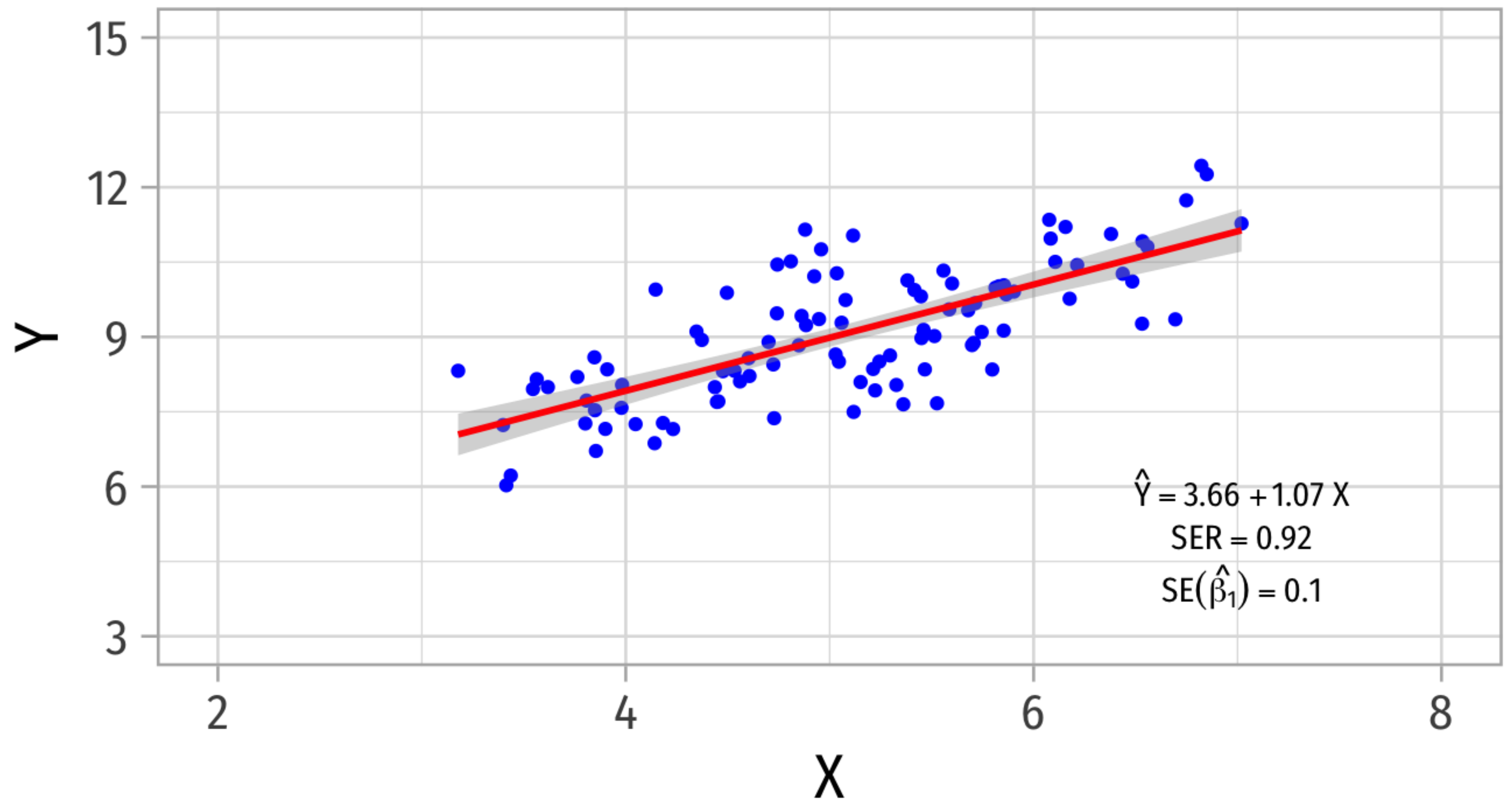
Model With Fewer Observations

Smaller n raises variation in $\hat{\beta}_1$

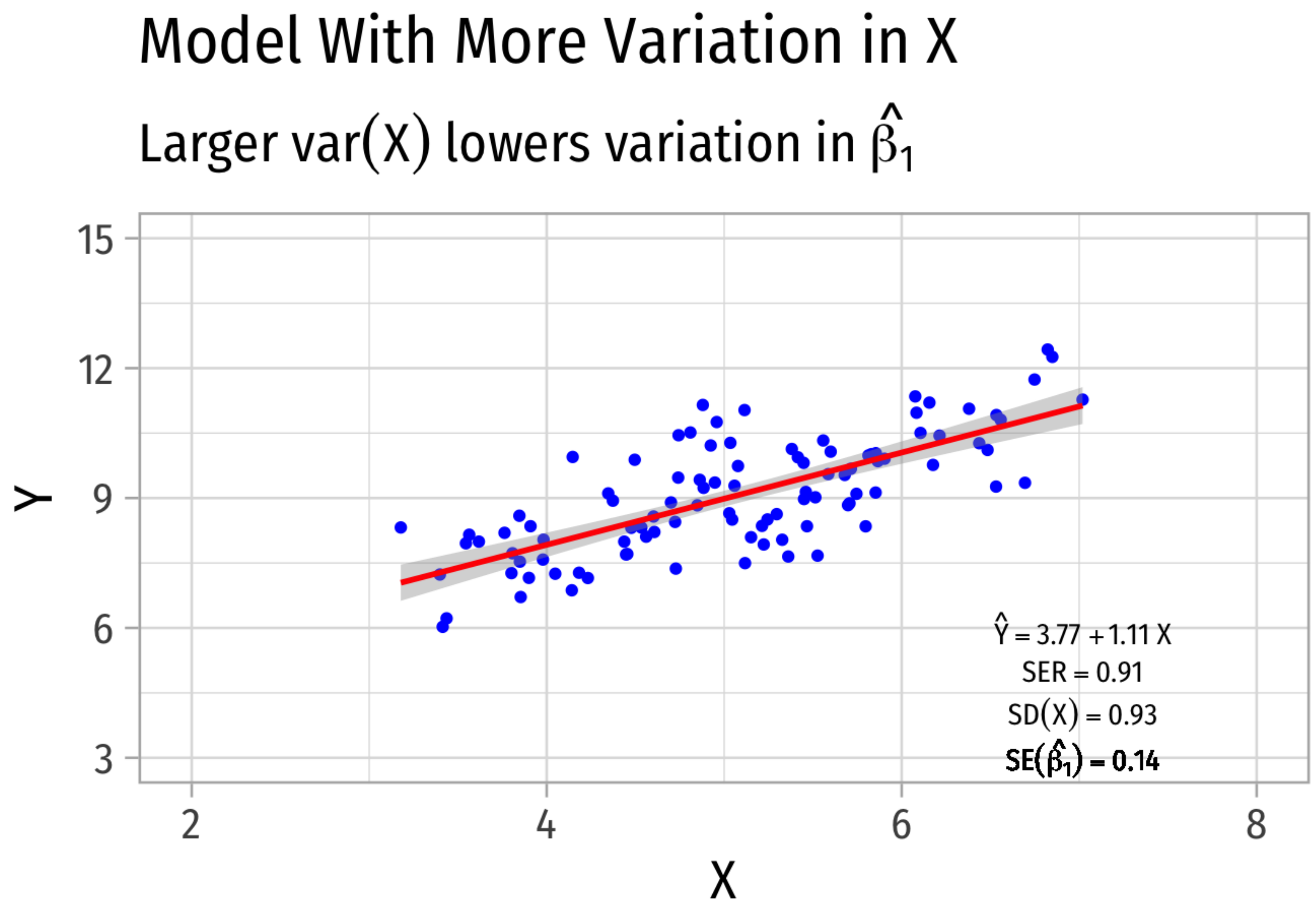


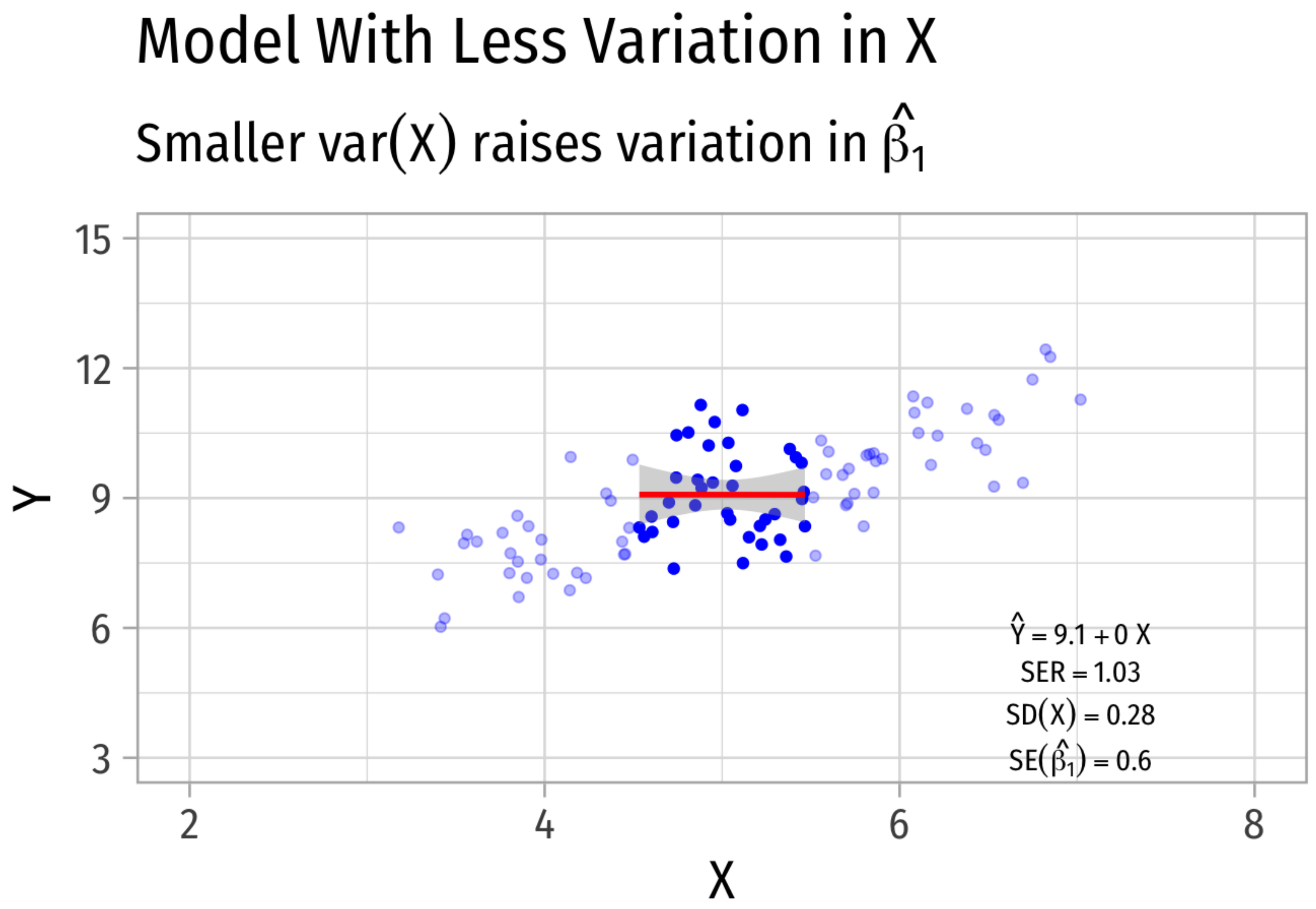
Model With More Observations

Larger n lowers variation in $\hat{\beta}_1$



Variation in $\hat{\beta}_1$: Variation in X





Presenting Regression Results

Our Class Size Regression

```
1 school_reg %>% summary()
```

```
Call:
lm(formula = testscr ~ str, data = ca_school)

Residuals:
    Min      1Q  Median      3Q     Max 
-47.727 -14.251   0.483  12.822  48.540 

Coefficients:
            Estimate Std. Error t value Pr(>|t|)    
(Intercept) 698.9330     9.4675  73.825  < 2e-16 ***
str          -2.2798     0.4798  -4.751 2.78e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

- How can we present all of this information in a tidy way?

Our Class Size Regression

```r
library(broom)
school_reg %>% tidy()
```

term	estimate	std.error	statistic	p.value
(Intercept)	698.932952	9.4674914	73.824514	0.0e+00
str	-2.279808	0.4798256	-4.751327	2.8e-06

```r
school_reg %>% glance()
```

r.squared	adj.r.squared	sigma	statistic	p.value	df	logLik	AIC	BIC	d
0.0512401	0.0489703	18.58097	22.57511	2.8e-06	1	-1822.25	3650.499	3662.62	1

- Better (?), but still not how you see regressions reported in reports…especially when you have many regression models!

Regression Tables

- Professional journals and papers often have a **regression table**, including:
  - Estimates of $\hat{\beta}_0$ and $\hat{\beta}_1$
  - Standard errors of $\hat{\beta}_0$ and $\hat{\beta}_1$ (often below, in parentheses)
  - Indications of statistical significance (often with asterisks)
  - Measures of regression fit: R^2, SER, etc
- Later: multiple rows & columns for multiple variables & models

	Test Score
Constant	698.93***
	(9.47)
STR	-2.28***
	(0.48)
n	420
R^2	0.05
SER	18.54

* p < 0.1, ** p < 0.05, *** p < 0.01

Regression Output Tables

- A number of packages (and documentation/guides) that will make nice regression output tables for you:
  - modelsummary
  - stargazer (and a good cheat sheet)
  - huxtable

	Test Score
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Using `modelsummary` I

- You will need to first `install.packages("modelsummary")`
- Load with `library(modelsummary)`
- Command: `modelsummary()`
- Main argument is the name of your `lm` regression object
- Default output is *fine*, but often we want to customize a bit!

```r
# install.packages("modelsummary") # install first
# load package
library(modelsummary)

modelsummary(school_reg) # our regression
```

	Model 1
(Intercept)	698.933
	(9.467)
str	-2.280
	(0.480)
Num.Obs.	420
R2	0.051
R2 Adj.	0.049
AIC	3650.5
BIC	3662.6
F	22.575
RMSE	18.54

Using `modelsummary` II

- Whole command is `modelsummary()`, everything will go in `()`

1. `models`, a `list()` of models to use, can give a name to each model, will show up as column title in table

```
models = list("Test Score" = school_reg) # set name to "Test Score"
```

2. `coef_rename` if you want to rename any independent variables as something nicer than their names in the dataset
   - `"old name" = "new name"` (yes annoying!)

```
coef_rename = list("(Intercept)" = "Constant",
                   "str" = "Student Teacher Ratio")
```

Using modelsummary III

- Whole command is `modelsummary()`, everything will go in `()`

3. `gof_map`: a `list()` of goodness of fit statistics, can customize what you want to include/exclude, what you want to label them in the table...a bit advanced, here's what I like:

```r
gof_map = list(
  list("raw" = "nobs", "clean" = "n", "fmt" = 0),
  list("raw" = "r.squared", "clean" = "R<sup>2</sup>", "fmt" = 2),
  #list("raw" = "adj.r.squared", "clean" = "Adj. R<sup>2</sup>", "fmt" = 2), # we'll want this later!
  list("raw" = "rmse", "clean" = "SER", "fmt" = 2)
  )
```

4. Other minor options (combine with commas):

```r
fmt = 2, # round to 2 decimals
output = "html" # depending on type of document creating; pdf would be "latex"
escape = FALSE # allows formatting of things like <sup>2</sup>
stars = c('*' = .1, '**' = .05, '***' = 0.01) # show significance levels if set to true, I don't like the c
```

Using `modelsummary` IV

```r
modelsummary(models = list("Test Score" = school_reg),
             fmt = 2, # round to 2 decimals
             output = "html",
             coef_rename = c("(Intercept)" = "Constant",
                             "str" = "STR"),
             gof_map = list(
               list("raw" = "nobs", "clean" = "n", "fmt" = 0)
               list("raw" = "r.squared", "clean" = "R<sup>2</
               #list("raw" = "adj.r.squared", "clean" = "Adj.
               list("raw" = "rmse", "clean" = "SER", "fmt" =
             ),
             escape = FALSE,
             stars = c('*' = .1, '**' = .05, '***' = 0.01)
)
```

	Test Score
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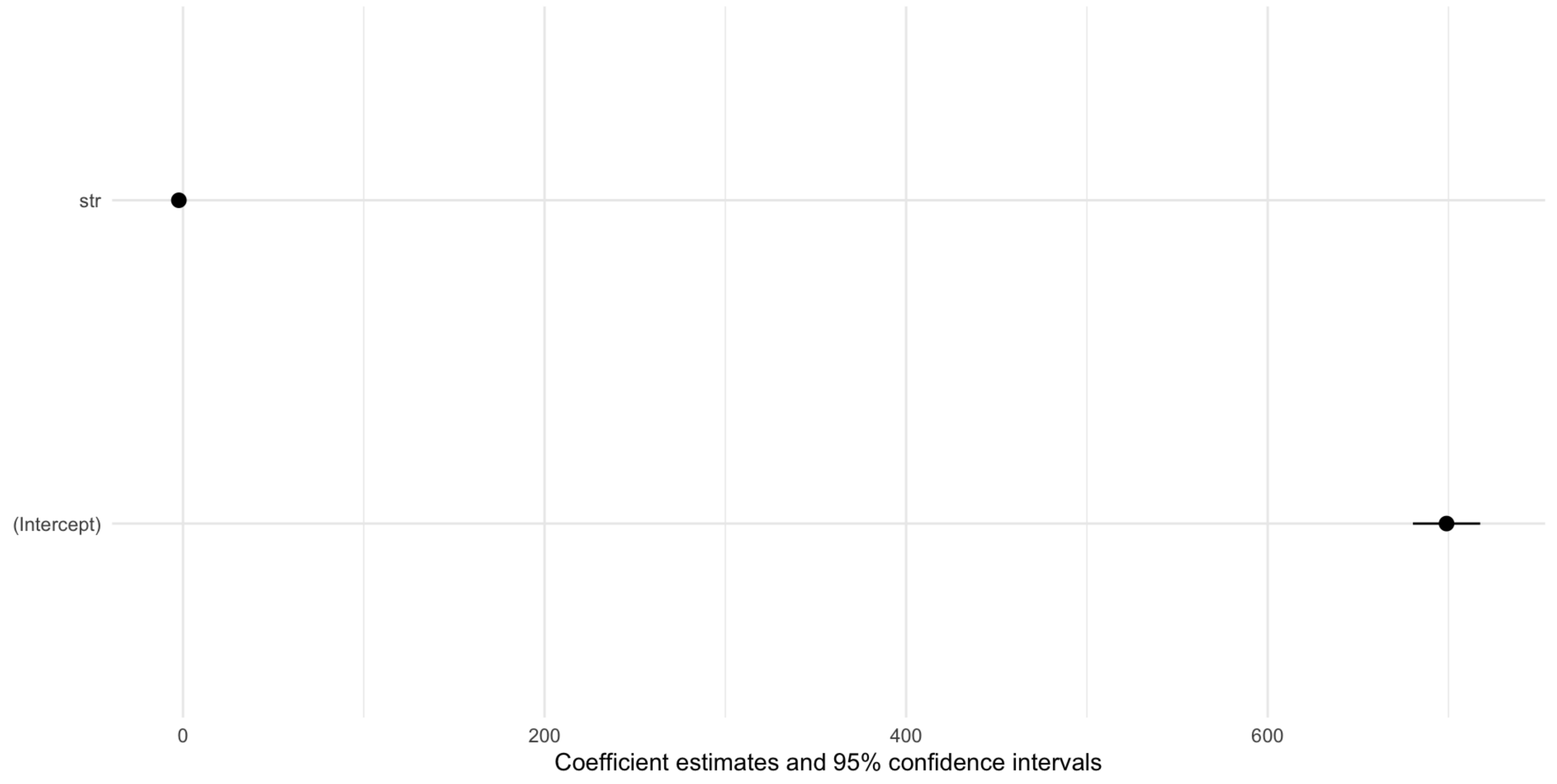
modelplot() in modelsummary

Also nice about the modelsummary package is the command modelplot()

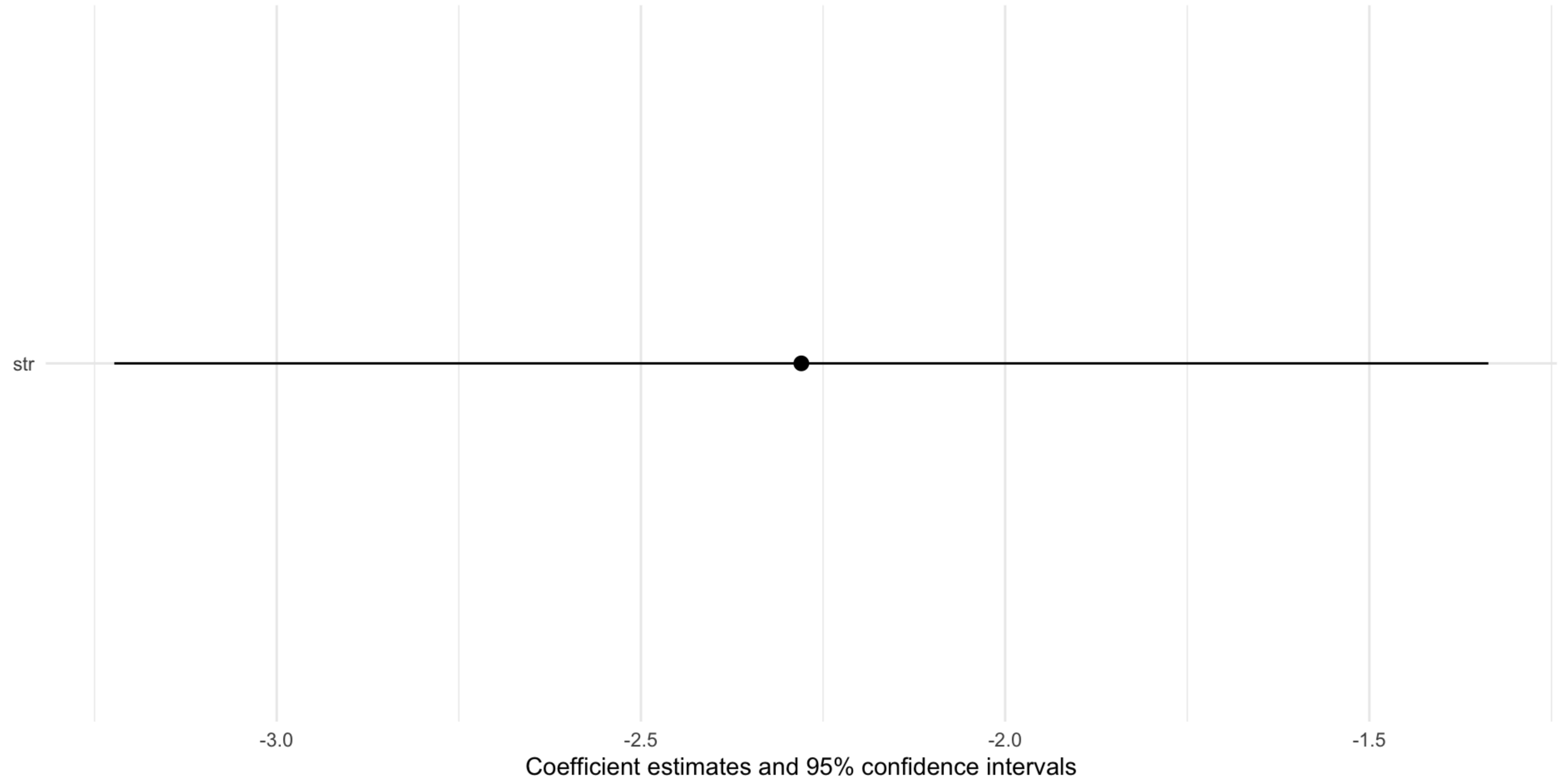
```r
modelplot(school_reg)
```



modelplot() in modelsummary

Also nice about the modelsummary package is the command modelplot()

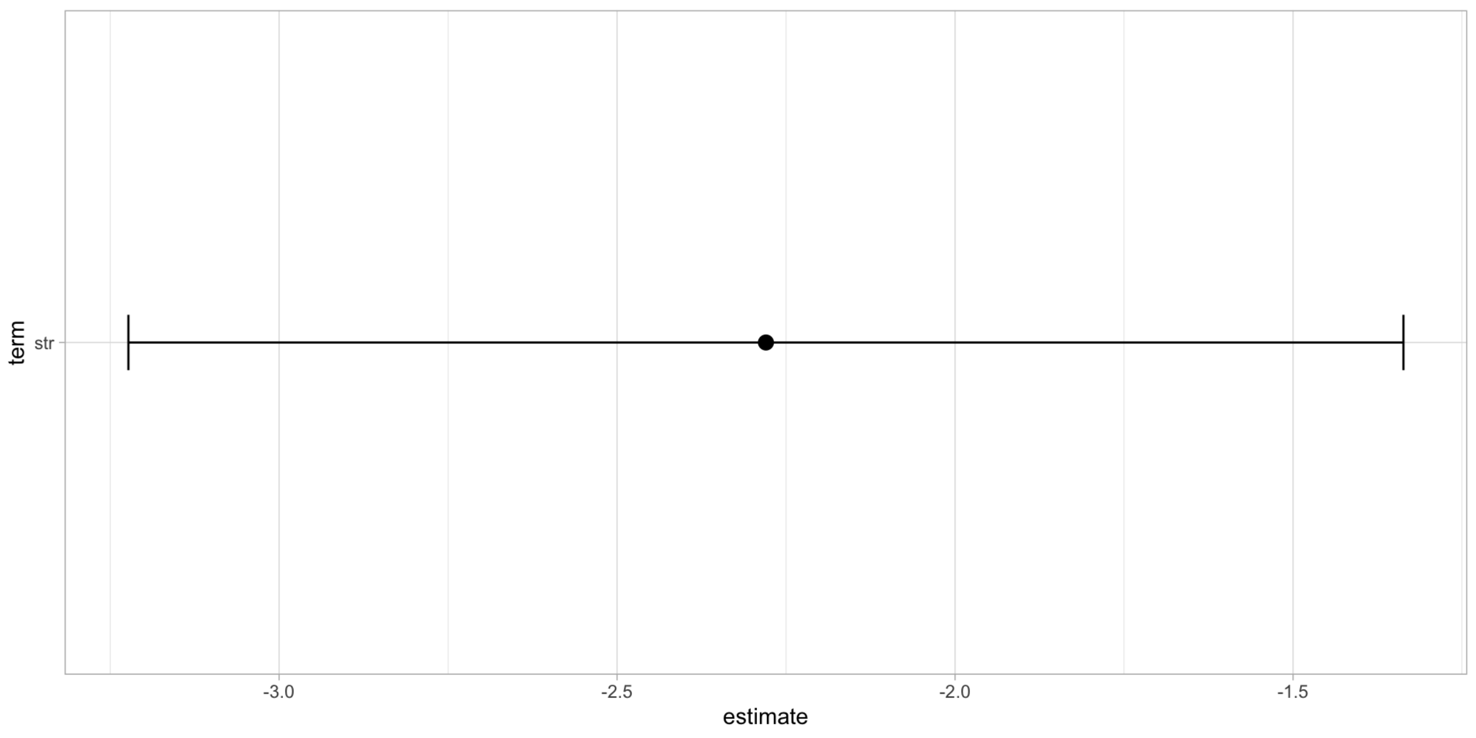
```r
modelplot(school_reg,
          coef_omit = 'Intercept') # don't show intercept
```



Though You Could Make It Yourself in `ggplot`

- Use the `conf.low` and `conf.high` (from a `tidy` regression) as `xmin` and `xmax` `aes`thetics inside `geom_errorbarh()`.

```
school_reg %>%
  tidy(conf.int = TRUE) %>%
  filter(term == "str") %>%
  ggplot()+
  aes(x = estimate,
      y = term)+
  geom_point(size = 3)+
  geom_errorbarh(aes(xmin = conf.low, xmax = conf.
                 height = 0.1)+ # height of whiske
  theme_light()
```



Diagnostics About Regression

Diagnostics: Residuals I

- We often look at the residuals of a regression to get more insight about its **goodness of fit** and its **bias**
- Recall `broom`'s `augment` creates some useful new variables
  - `.fitted` are fitted (predicted) values from model, i.e. $\hat{Y}_i$
  - `.resid` are residuals (errors) from model, i.e. $\hat{u}_i$

Diagnostics: Residuals II

- Often a good idea to store in a new object (so we can make some plots)

```
aug_reg <- augment(school_reg)

aug_reg %>% head()
```

testscr	str	.fitted	.resid	.hat	.sigma	.cooksd	.std.resid
690.80	17.88991	658.1474	32.65260	0.0044244	18.53408	0.0068925	1.7612148
661.20	21.52466	649.8608	11.33917	0.0047485	18.59490	0.0008927	0.6117112
643.60	18.69723	656.3069	-12.70689	0.0029742	18.59279	0.0006996	-0.6848850
647.70	17.35714	659.3620	-11.66198	0.0058575	18.59441	0.0011673	-0.6294767
640.85	18.67133	656.3659	-15.51592	0.0030072	18.58766	0.0010548	-0.8363024
605.55	21.40625	650.1308	-44.58076	0.0044603	18.47411	0.0129531	-2.4046387

Recall: Assumptions about Errors

- We make **4 critical assumptions about u**:

1. The expected value of the errors is 0

$$\mathbb{E}[u] = 0$$

2. The variance of the errors over X is constant:

$$var(u|X) = \sigma_u^2$$

3. Errors are not correlated across observations:

$$cor(u_i, u_j) = 0 \quad \forall i \neq j$$

4. There is no correlation between X and the error term:

$$cor(X, u) = 0 \text{ or } E[u|X] = 0$$

Assumptions 1 and 2: Errors are i.i.d.

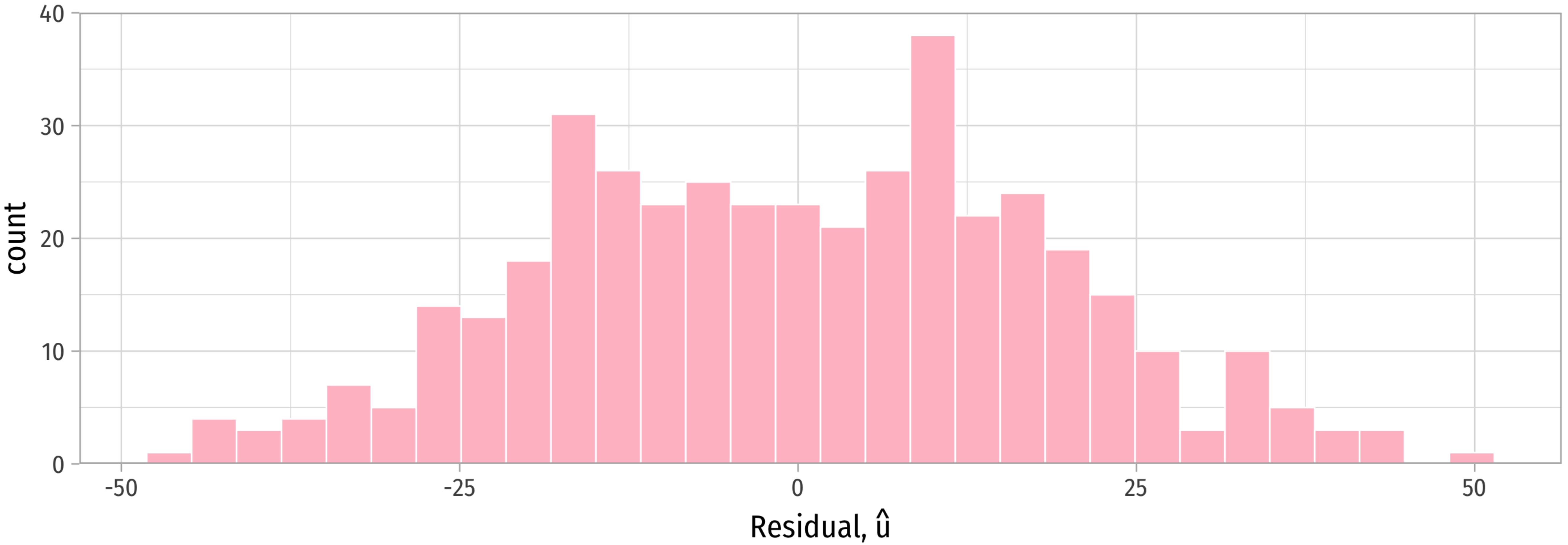
- Assumptions 1 and 2 assume that errors are coming from the same (*normal*) distribution

$$u \sim N(0, \sigma_u)$$

- Assumption 1: $E[u] = 0$
- Assumption 2: $sd(u|X) = \sigma_u$
  - virtually always unknown...
- We often can visually check by plotting a **histogram** of u

Plotting a Histogram of Residuals

Plot | Code



Checking the Distribution of Residuals

```r
school_reg %>% summary()
```

```

Call:
lm(formula = testscr ~ str, data = ca_school)

Residuals:
    Min      1Q  Median      3Q     Max 
-47.727 -14.251   0.483  12.822  48.540 

Coefficients:
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(Intercept) 698.9330     9.4675  73.825  < 2e-16 ***
str          -2.2798     0.4798  -4.751 2.78e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

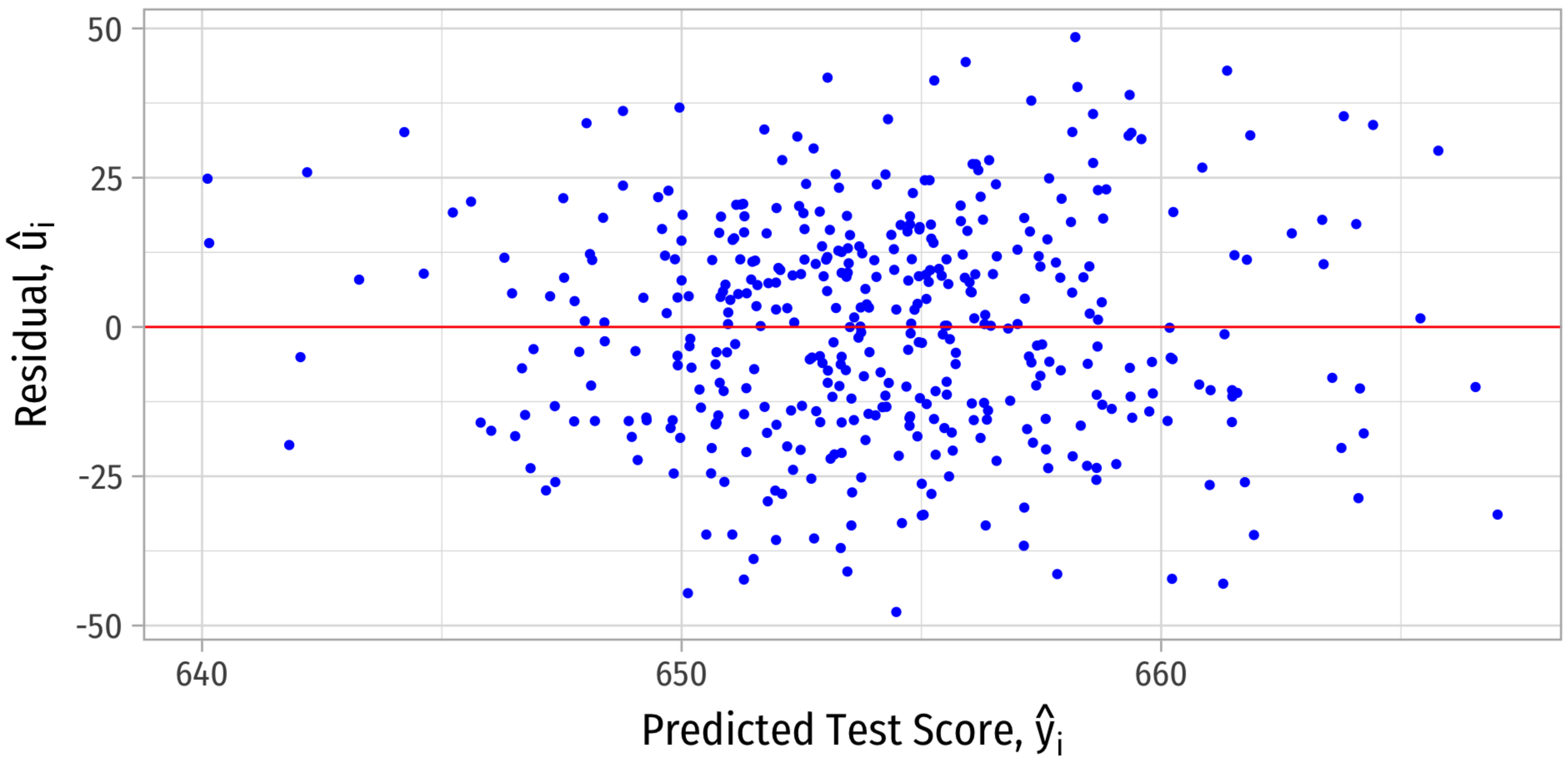
```r
aug_reg %>%
  summarize(E_u = mean(.resid),
            sd_u = sd(.resid))
```

E_u	sd_u
0	18.55878

Residual Plot

- We often plot a **residual plot** to see any odd patterns about residuals
  - x-axis are $\hat{Y}_i$ values (`.fitted`)
  - y-axis are u_i values (`.resid`)

Plot | Code


50
25
0
-25
-50
Residual, $\hat{u}_i$
640
650
660
Predicted Test Score, $\hat{y}_i$

Heteroskedasticity

Homoskedasticity

- "**Homoskedasticity**:" variance of the residuals over X is constant, written:

$$var(u|X) = \sigma_u^2$$

- Knowing the value of X does not affect the variance (spread) of the errors

Heteroskedasticity I

- "**Heteroskedasticity**:" variance of the residuals over X is **NOT** constant:

$$var(u|X) \neq \sigma_u^2$$

- **This does not cause $\hat{\beta}_1$ to be biased**, but it does cause the standard error of $\hat{\beta}_1$ to be incorrect
- This **does** cause a problem for **inference**!
  - Specifically, it will make $se(\hat{\beta}_1)$ wrong (often too small)[1]

1. Later, when we learn about hypothesis testing, having standard errors incorrectly too small will *overstate* the significance of the finding

Heteroskedasticity II

- Recall the formula for the standard error of $\hat{\beta}_1$:

$$se(\hat{\beta}_1) = \sqrt{var(\hat{\beta}_1)} = \frac{SER}{\sqrt{n} \times sd(X)}$$

- This *assumes* homoskedasticity (Assumption 2)

Heteroskedasticity III

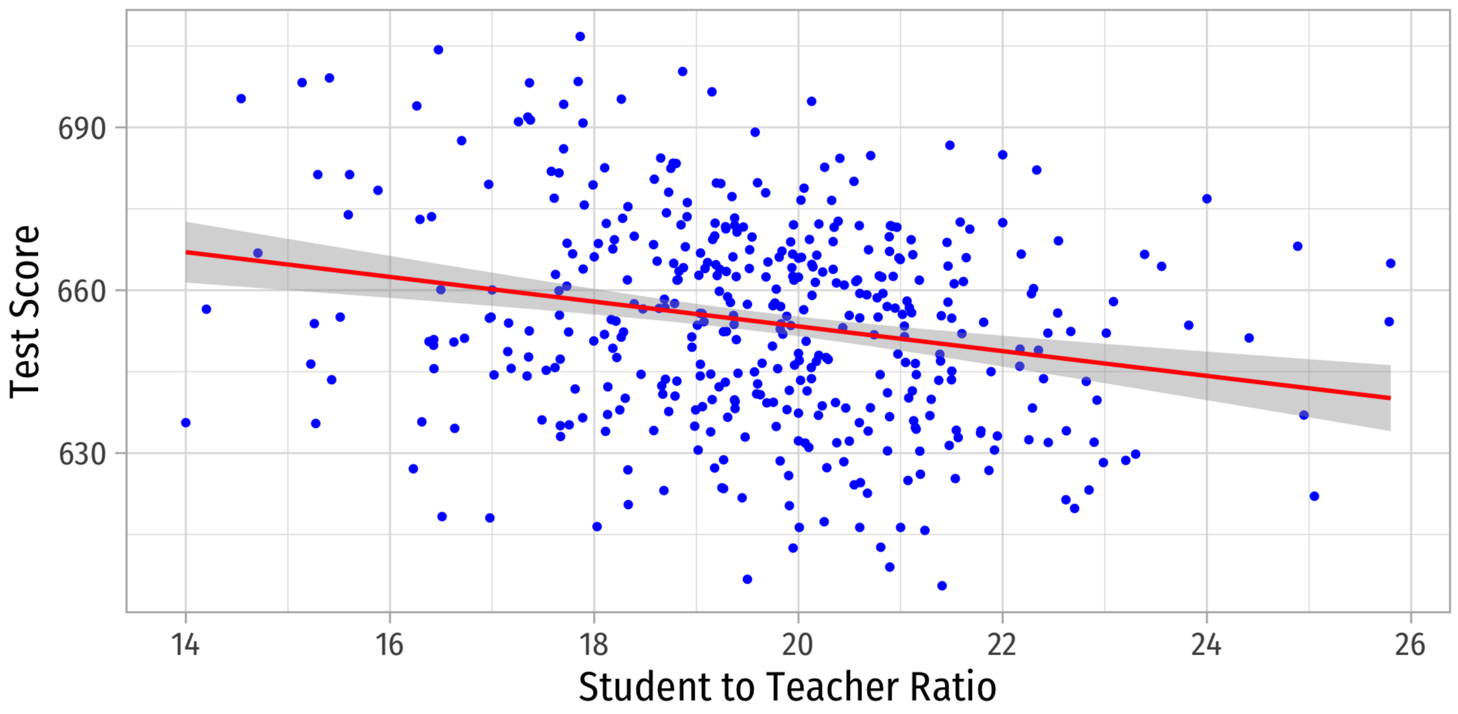
- A better formula for estimating standard errors that are **robust** to heteroskedasticity (called .hi[“robust standard errors”]):

$$se(\hat{\beta}_1) = \sqrt{\frac{\displaystyle\sum_{i=1}^{n}(X_i - \bar{X})^2\hat{u}^2}{\left[\displaystyle\sum_{i=1}^{n}(X_i - \bar{X})^2\right]^2}}$$

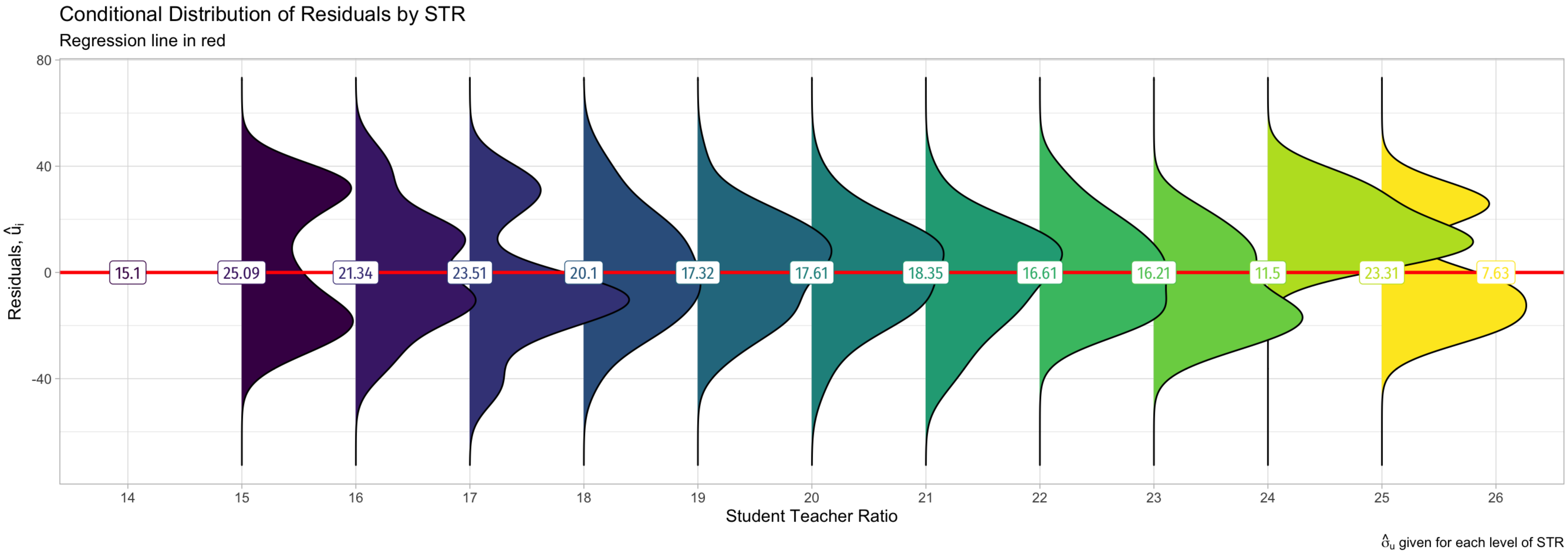
- Don’t learn formula, **do learn what heteroskedasticity is and how it affects our model!**

Visualizing Heteroskedasticity I

- Our original scatterplot with regression line
- Does the spread of the errors change over different values of str?
  - No: homoskedastic
  - Yes: heteroskedastic



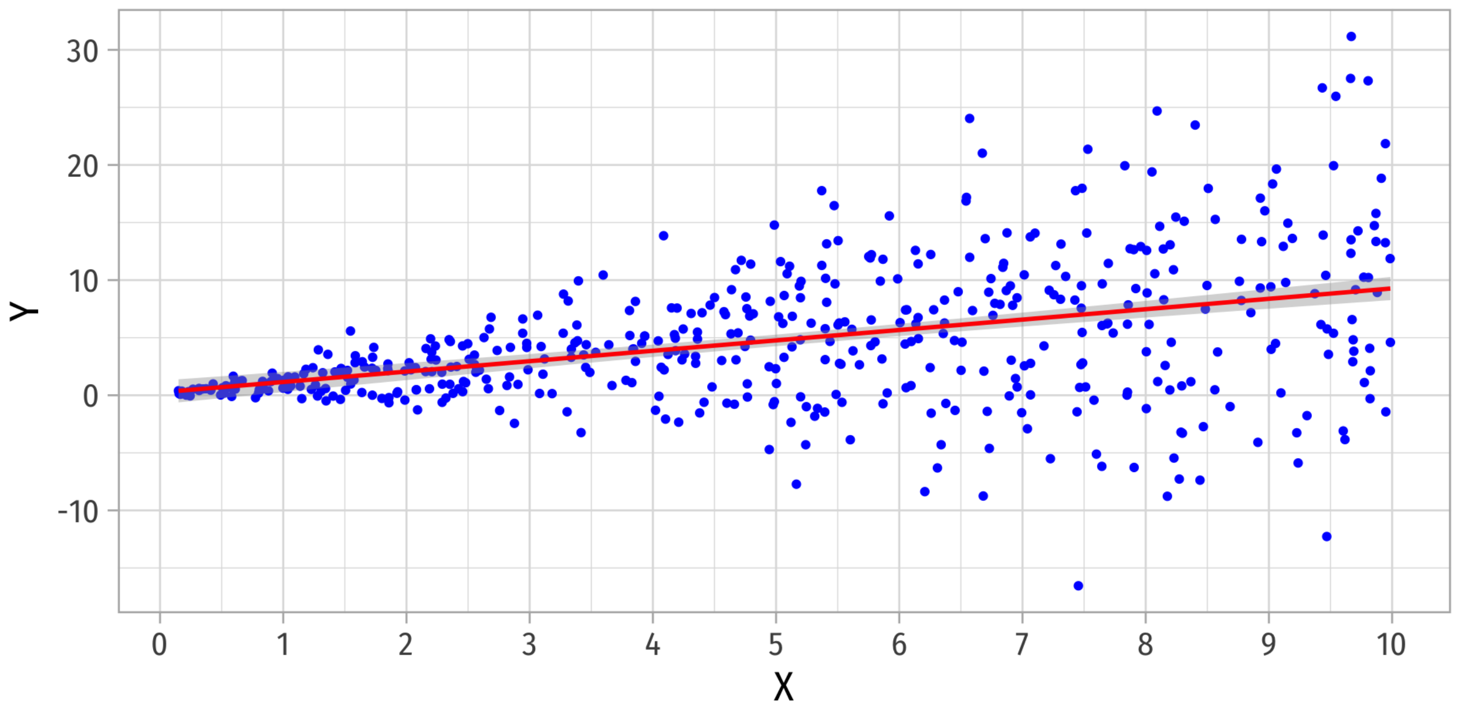
Visualizing Heteroskedasticity



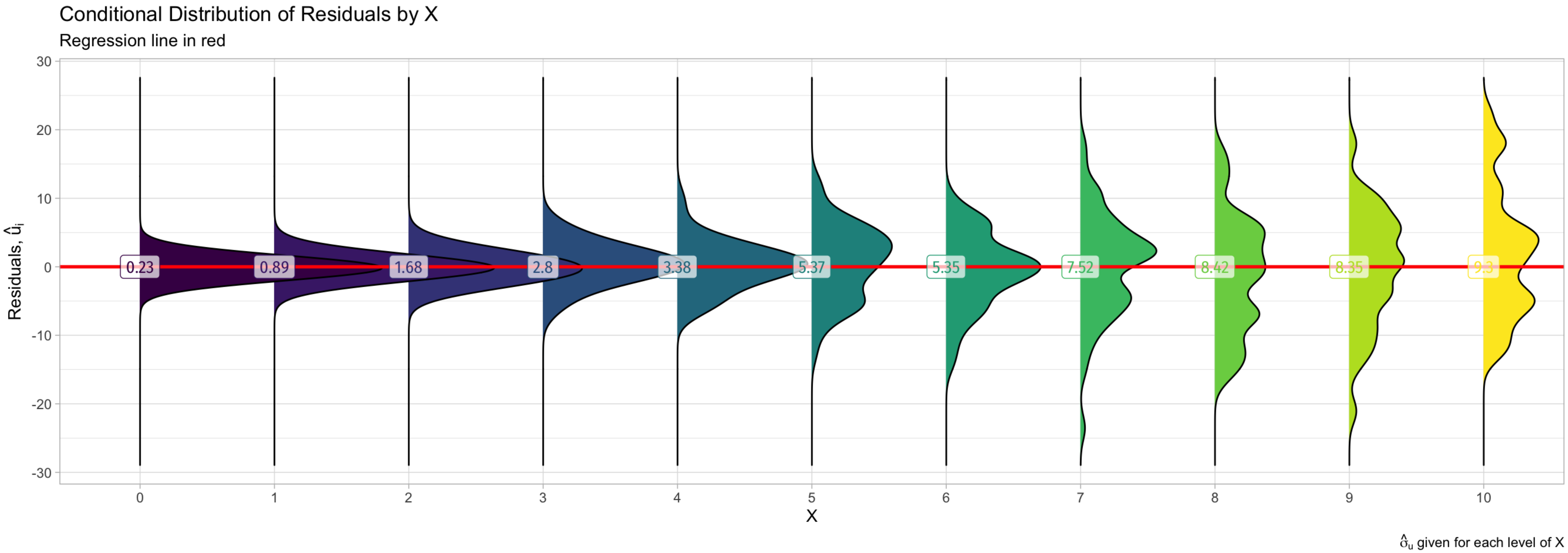
- Notice the distribution of $\hat{u}$, changes for different values of STR, and $\sigma_{\hat{u}}$ is not constant

More Obvious Heteroskedasticity

- Visual cue: data is “fan-shaped”
  - Data points are closer to line in some areas
  - Data points are more spread from line in other areas

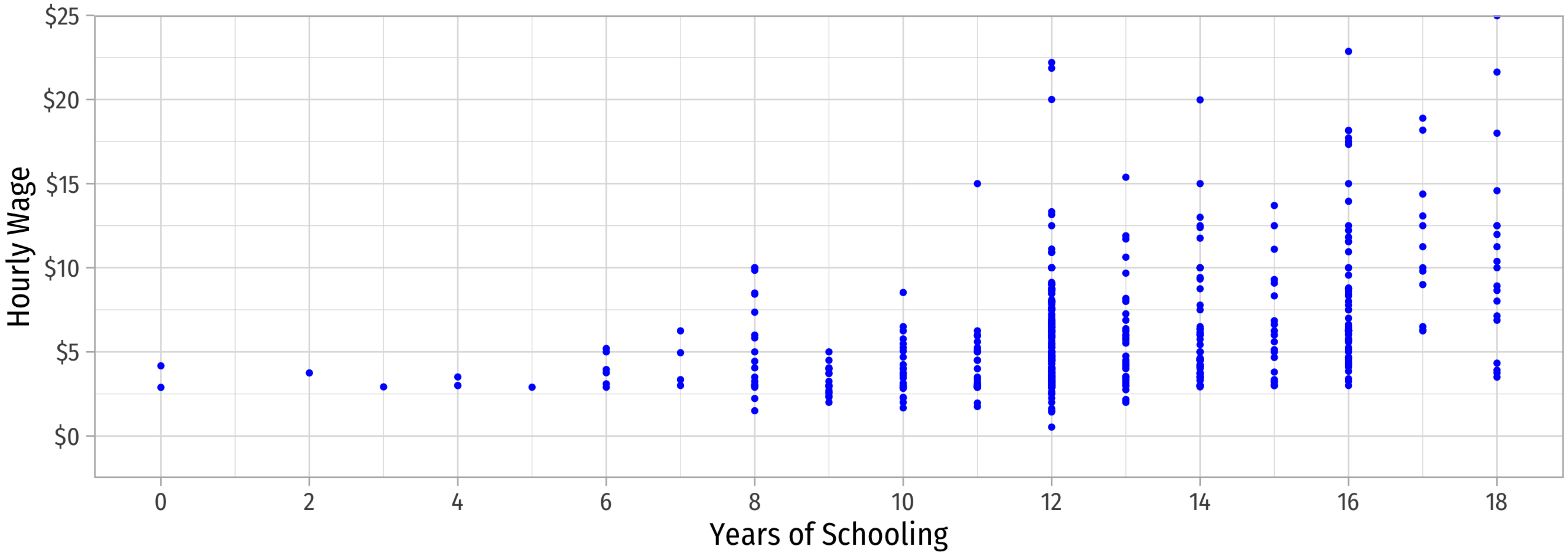


More Obvious Heteroskedasticity



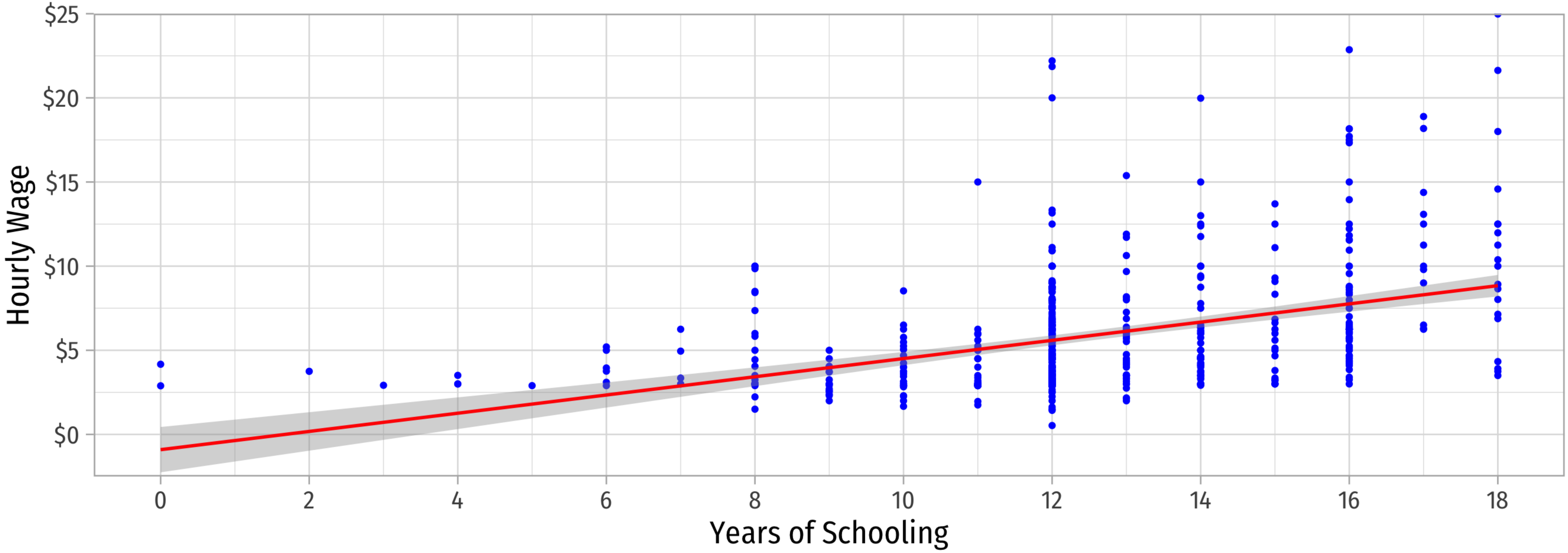
What Might Cause Heteroskedastic Errors?

$$wage_i = \beta_0 + \beta_1 educ_i + u_i$$



What Might Cause Heteroskedastic Errors?

$$wage_i = \beta_0 + \beta_1 educ_i + u_i$$

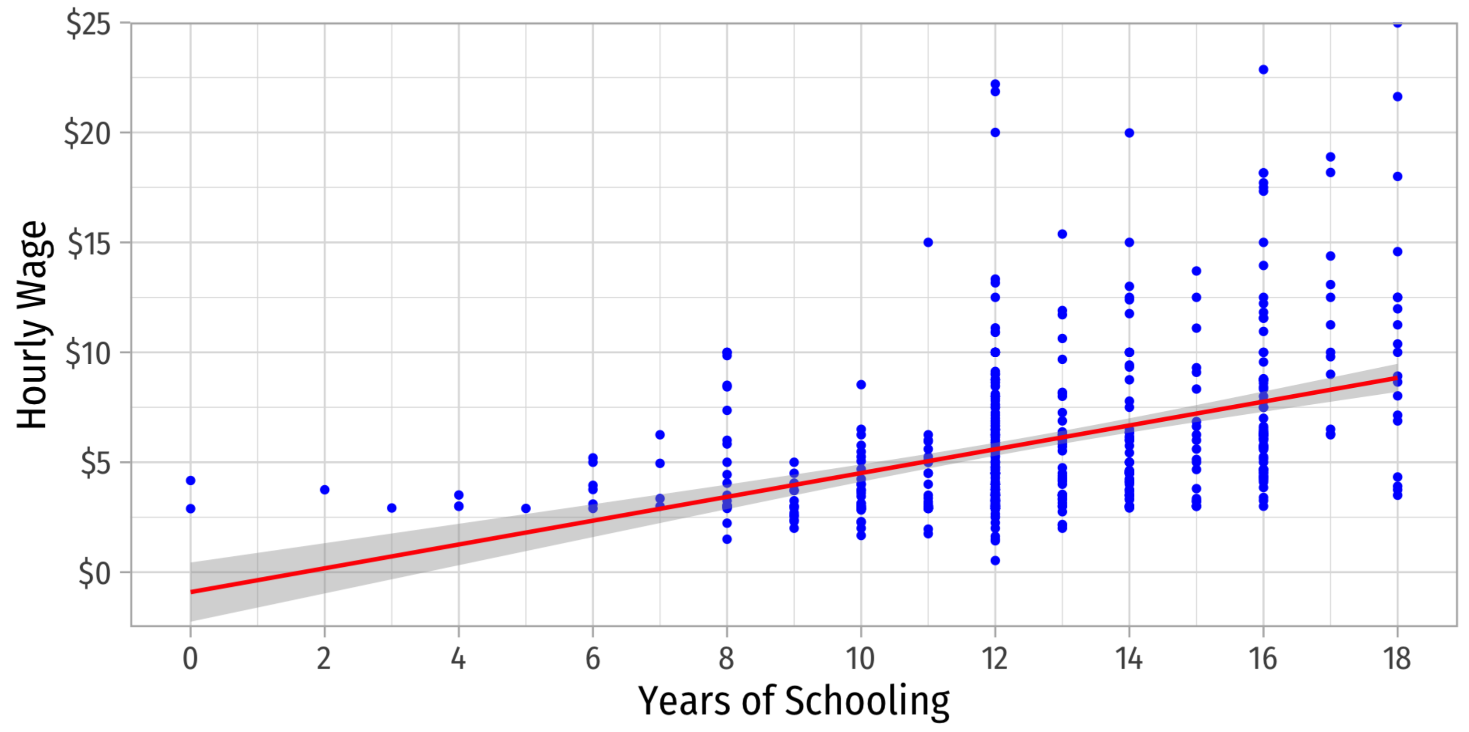


What Might Cause Heteroskedastic Errors?

$$wage_i = \beta_0 + \beta_1 educ_i + u_i$$

	Wage
Intercept	−0.90
	(0.68)
Years of Schooling	0.54***
	(0.05)
n	526
R^2	0.16
SER	3.37

* p < 0.1, ** p < 0.05, *** p < 0.01



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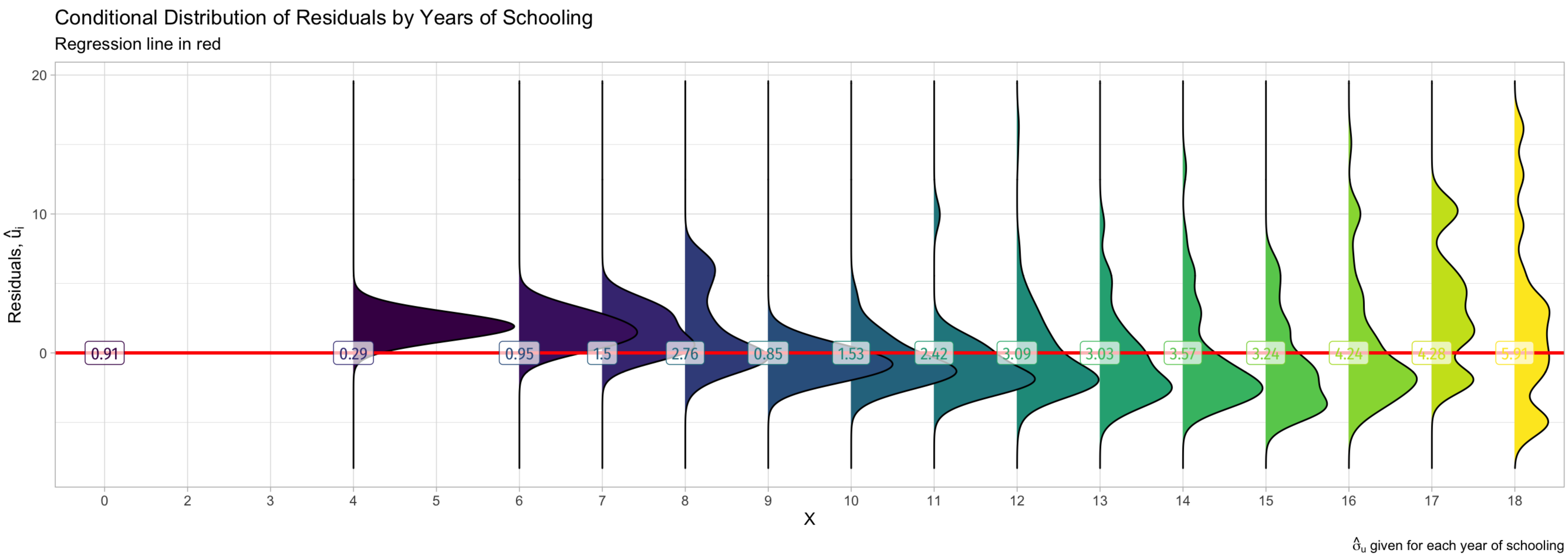


Detecting Heteroskedasticity I

- Several tests to check if data is heteroskedastic
- One common test is **Breusch-Pagan test**
- Can use the `lmtest` package's function `bptest()`
  - H_0: homoskedastic[1]
  - If p-value < 0.05, reject $H_0 \implies$ heteroskedastic

```r
library("lmtest")
school_reg %>% bptest()
```

```
	studentized Breusch-Pagan test

data:  .
BP = 5.7936, df = 1, p-value = 0.01608
```

- Since $p < 0.05$, can reject H_0 that errors are homoskedastic and conclude they are *heteroskedastic*

1. More on hypothesis testing next week!

How About the Wages Regression?

```r
wage_reg %>% bptest()
```

```
	studentized Breusch-Pagan test

data:  .
BP = 15.306, df = 1, p-value = 9.144e-05
```

Fixing Heteroskedasticity I

- Heteroskedasticity is easy to fix with software that can calculate **robust standard errors** (using the more complicated formula above)

- Easiest method is to use `estimatr` package
  - `lm_robust()` command (*instead* of `lm`) to run regression
  - set `se_type = "stata"` to calculate robust SEs using the formula above[1]

```
#install.packages("estimatr")
library(estimatr)
```


1. This uses the method that Stata uses with the `robust` command, one advantage Stata has over R

Fixing Heteroskedasticity II

```r
school_reg_robust <- lm_robust(testscr ~ str, data = ca_school,
                               se_type = "stata")

school_reg_robust
```

```
               Estimate Std. Error   t value      Pr(>|t|)   CI Lower   CI Upper
(Intercept) 698.932952 10.3643599 67.436191 9.486678e-227 678.560192 719.305713
str          -2.279808  0.5194892 -4.388557  1.446737e-05  -3.300945  -1.258671
             DF
(Intercept) 418
str         418
```

```r
school_reg_robust %>% summary()
```

```
Call:
lm_robust(formula = testscr ~ str, data = ca_school, se_type = "stata")

Standard error type:  HC1

Coefficients:
            Estimate Std. Error t value   Pr(>|t|) CI Lower CI Upper  DF
(Intercept)   698.93    10.3644  67.436 9.487e-227  678.560  719.306 418
str            -2.28     0.5195  -4.389  1.447e-05   -3.301   -1.259 418

Multiple R-squared:  0.05124 ,  Adjusted R-squared:  0.04897
F-statistic: 19.26 on 1 and 418 DF,  p-value: 1.447e-05
```

Fixing Heteroskedasticity III

```
# can tidy, glance, augment, etc
school_reg_robust %>% tidy()
```

term	estimate	std.error	statistic	p.value	conf.low	conf.high	df	ou
(Intercept)	698.932952	10.3643599	67.436191	0.00e+00	678.560192	719.305713	418	tes
str	-2.279808	0.5194892	-4.388557	1.45e-05	-3.300945	-1.258671	418	tes

```
school_reg_robust %>% glance()
```

r.squared	adj.r.squared	statistic	p.value	df.residual	nobs	se_type
0.0512401	0.0489703	19.25943	1.45e-05	418	420	HC1

Showing The Effect of Heteroskedasticity (on $se(\hat{\beta}_1)$)

```r
modelsummary(models = list("Normal SE" = school_re
                           "Robust SE" = school_re
             fmt = 2, # round to 2 decimals
             output = "html",
             coef_rename = c("(Intercept)" = "Cons
                             "str" = "STR"),
             gof_map = list(
               list("raw" = "nobs", "clean" = "n",
               list("raw" = "r.squared", "clean" =
               #list("raw" = "adj.r.squared", "cle
               list("raw" = "rmse", "clean" = "SER
             ),
             escape = FALSE,
             stars = c('*' = .1, '**' = .05, '***'
)
```

	Normal SE	Robust SE
Constant	698.93***	698.93***
	(9.47)	(10.36)
STR	−2.28***	−2.28***
	(0.48)	(0.52)
n	420	420
R^2	0.05	0.05
SER	18.54	18.54

* p < 0.1, ** p < 0.05, *** p < 0.01

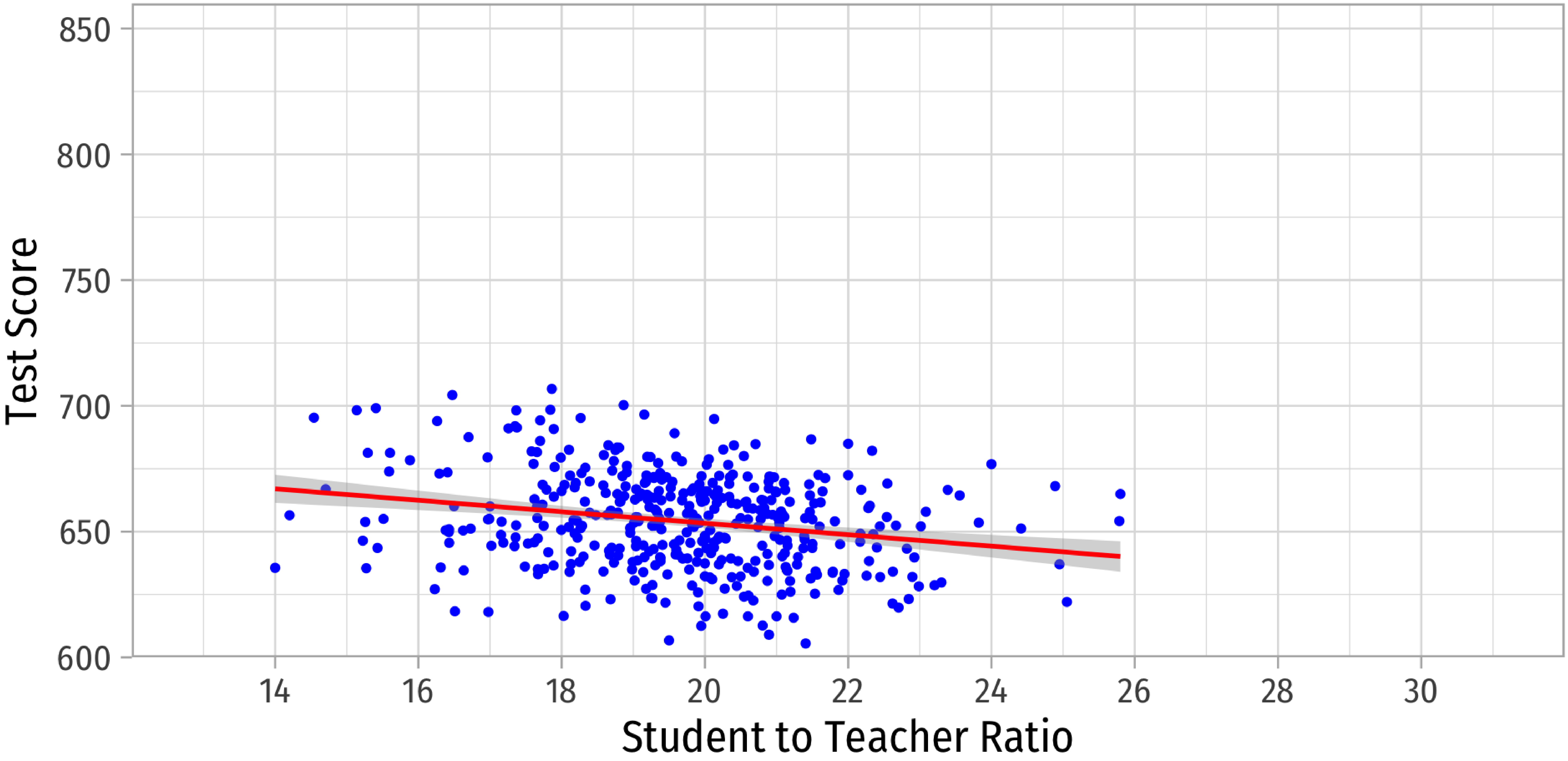
- What changed?

Outliers

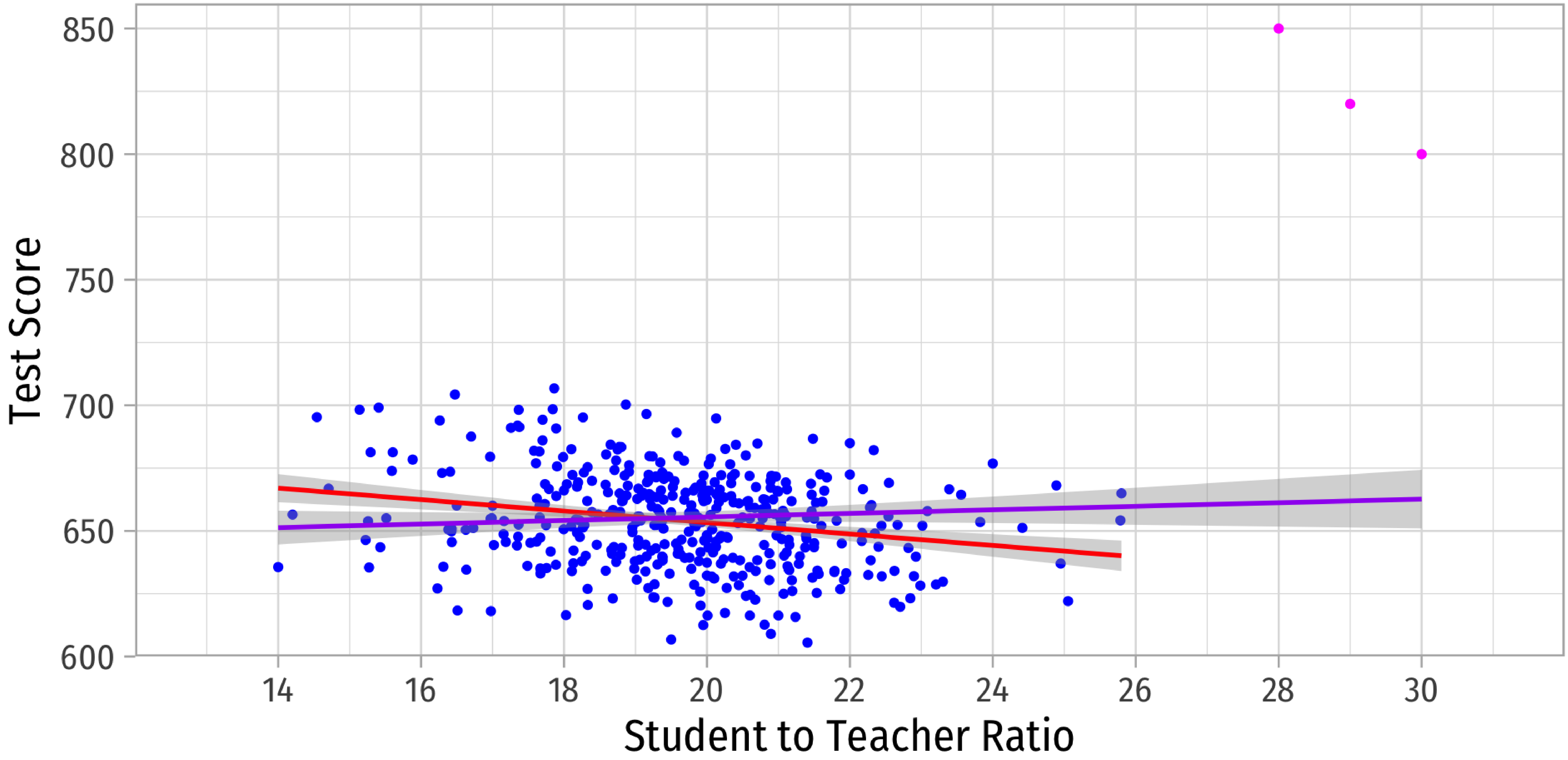
Outliers Can Bias OLS! I

- **Outliers** can affect the slope (and intercept) of the line and add **bias**
  - May be result of human error (measurement, transcribing, etc)
  - May be meaningful and accurate
- In any case, compare how including/dropping outliers affects regression and always discuss outliers!

Outliers Can Bias OLS! II



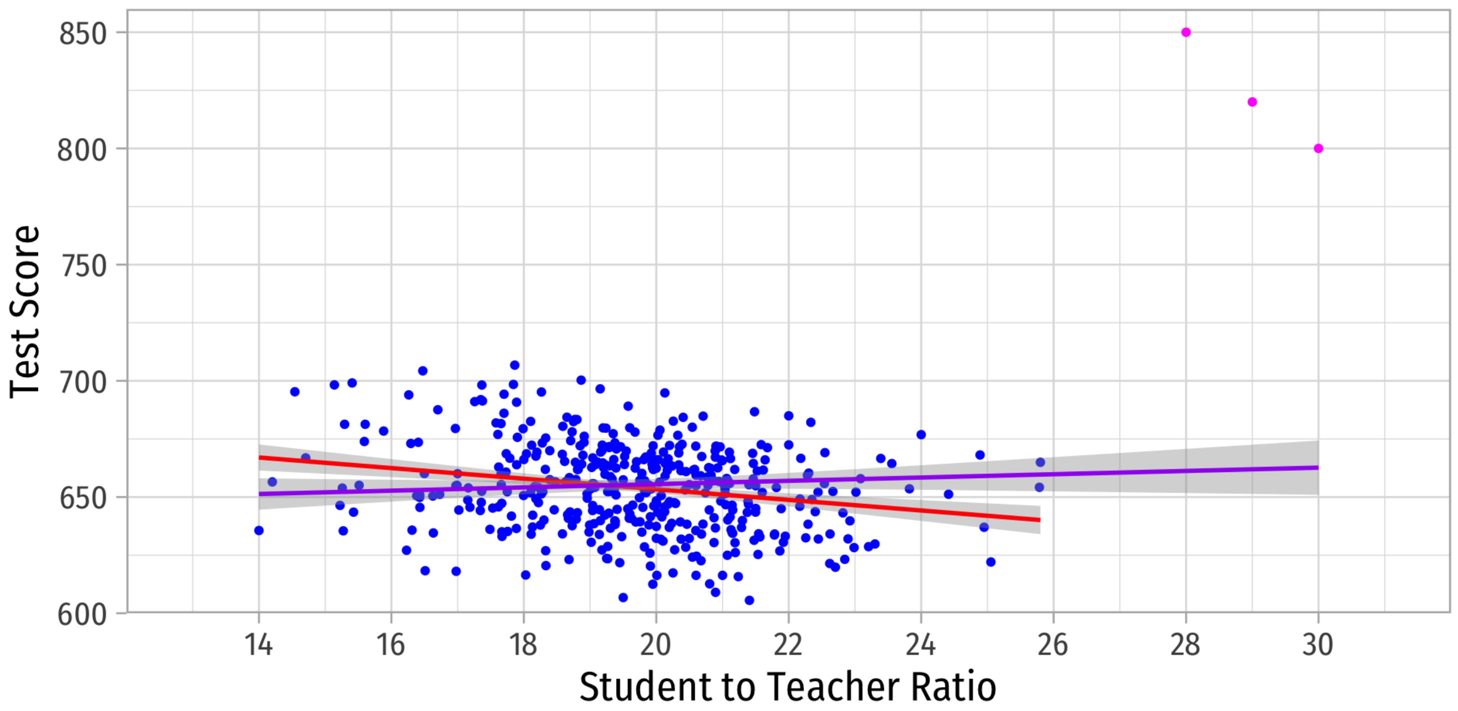
Outliers Can Bias OLS! II



Outliers Can Bias OLS! III

	Original	With Outliers
Constant	698.93***	641.40***
	(9.47)	(11.21)
STR	-2.28***	0.71
	(0.48)	(0.57)
n	420	423
R^2	0.05	0.00
SER	18.54	23.71

* p < 0.1, ** p < 0.05, *** p < 0.01



Detecting Outliers

- The `car` package has an `outlierTest` command to run on the regression

```r
# install.packages("car")
library("car")

# Use Bonferonni test
outlierTest(school_outlier_reg) # will point out which obs #s seem outliers
```

```
    rstudent unadjusted p-value Bonferroni p
422 8.822768         3.0261e-17   1.2800e-14
423 7.233470         2.2493e-12   9.5147e-10
421 6.232045         1.1209e-09   4.7414e-07
```

```r
# find these observations
ca_school_outliers %>%
  slice(c(422,423,421)) # find observations 422, 423, 421
```

observat	district	testscr	str
422	Crazy District 2	850	28
423	Crazy District 3	820	29
421	Crazy District 1	800	30