ECE7115 ~~Multimodal VLM~~ LLM

6. Scaling Laws

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Scaling

- Imagine the following scenario…
  - *Your friend has given you 10,000 H100s for a month, and asked you to build a good open source LLM*

- What do you do?
  - Put together your infra team and distributed training framework
  - Put together a great pre-training dataset
  - Run a big model (but which one??) ← we will learn this here

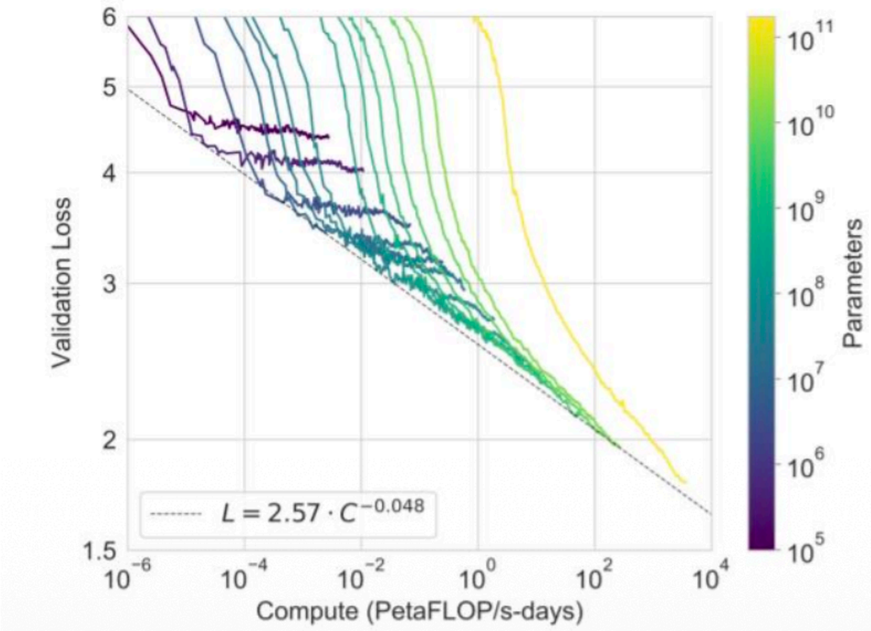
How to Scale Models?

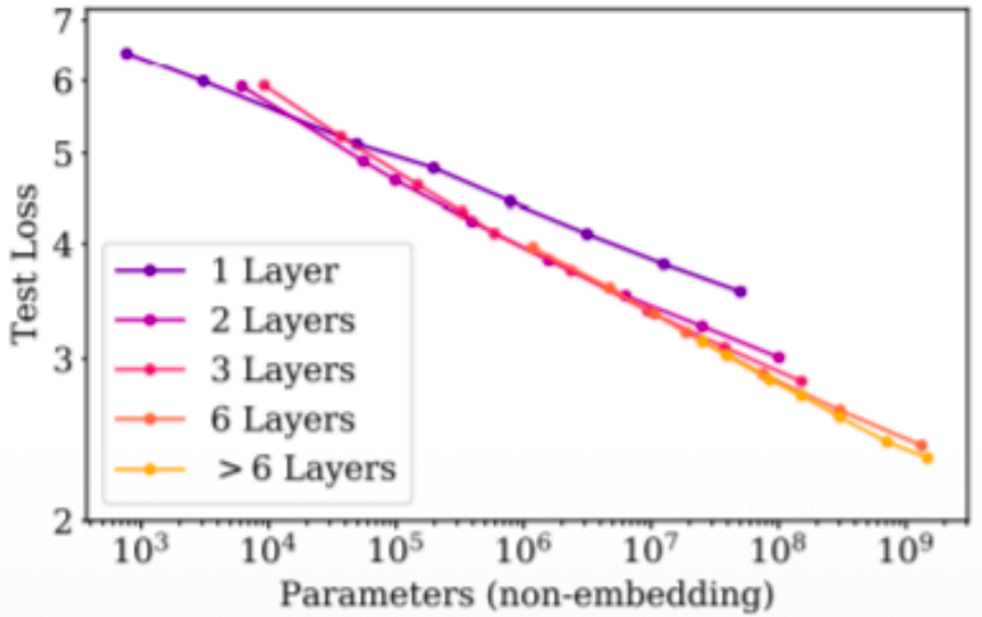
- We will probably use Transformer, but,
  - Wide or deep model?
  - Which model architecture?
  - How many heads?
  - Which nonlinearity?
  - How to search optimal hyperparameters?

- We could follow things from existing LLMs…
  - but how do these get optimized in the first place?

Today: Simple, Predictive "Laws"

- Scaling laws: Simple and predictive rules for model performance
  - Old way: tune hyperparameters on big models
  - New way: tune on small models, extrapolate to large ones





Scaling Laws

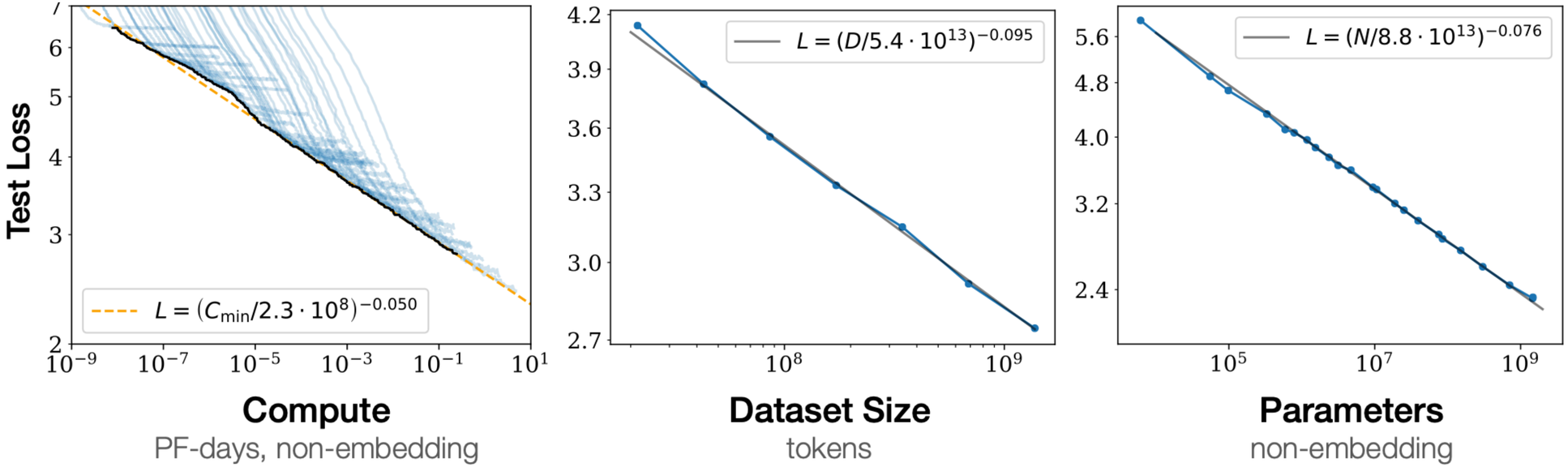
- Single Variable Scaling Laws
  - Are there rules that determine how data/model affects performance?
  - Data vs. Performance
  - Model size vs. Performance

- Scaling Laws for Model Engineering
  - How should we set hyperparameters on the big model?

- Compute Allocation
  - Do we train on more data or bigger models?
  - Data vs. Model size; which one is better?

Scaling Laws [Kaplan+ 2020]

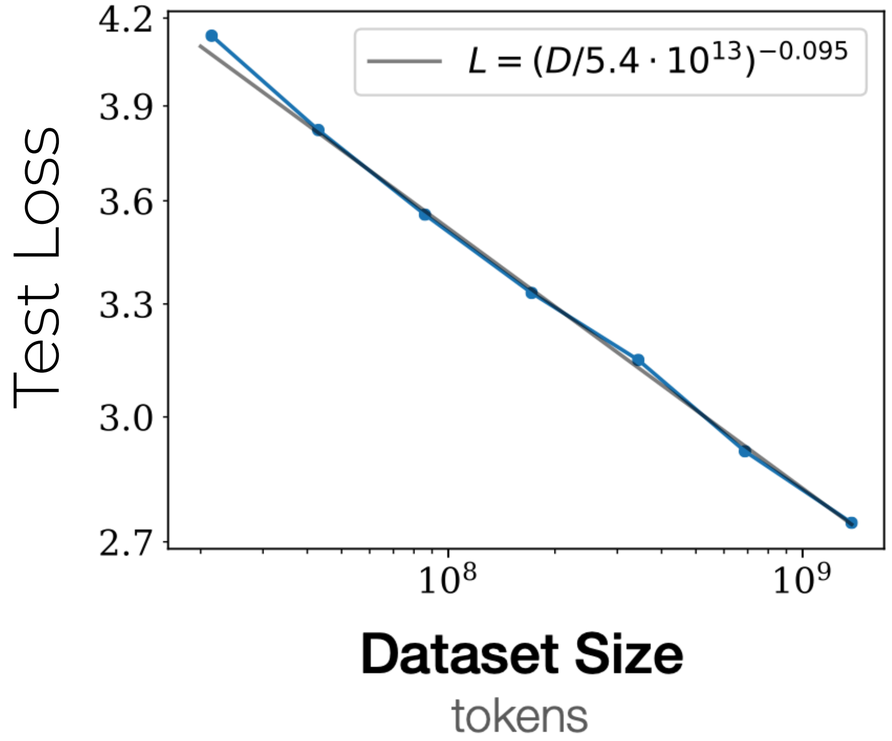
- Power law relationships for many factors
  - These scaling laws hold on many different kinds of phenomena!



Single Variable Scaling Laws

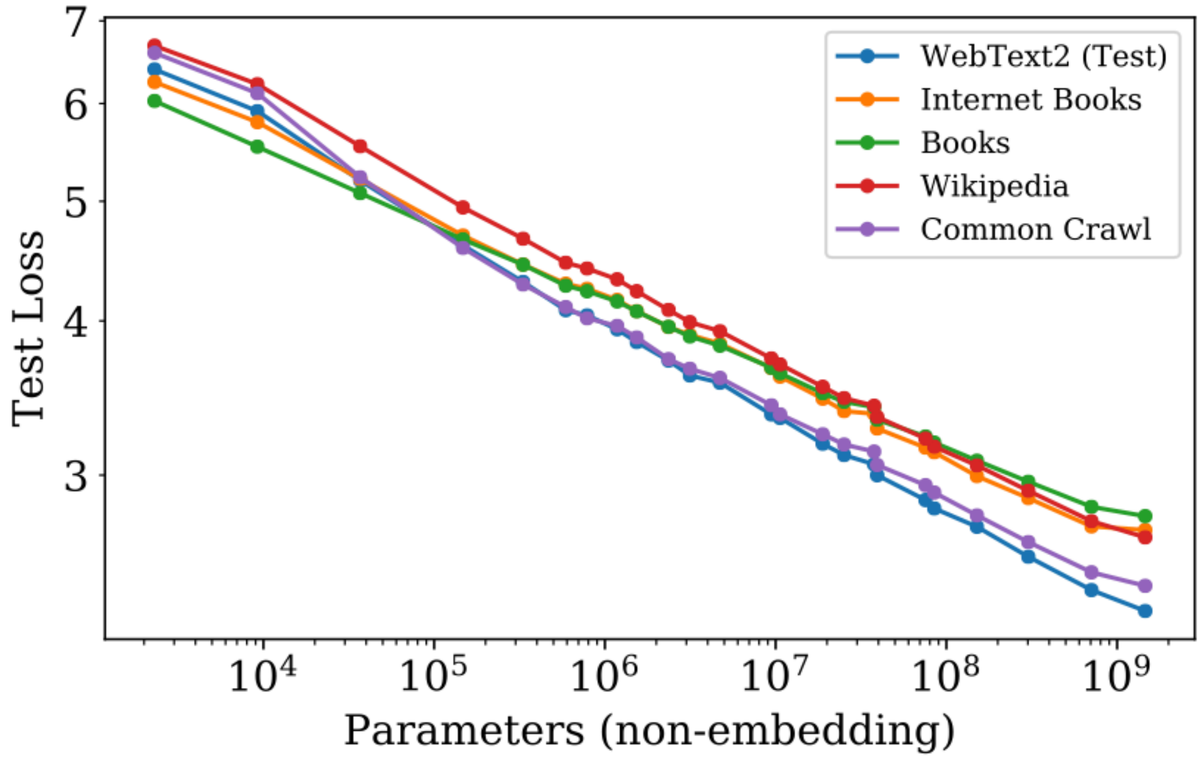
Data Scaling Laws [Kaplan+ 2020]

- TL;DR: Performance has a power-law relationship with data size
  - With a limited dataset with early stopping
  - $L(D) = (D_c/D)^{\alpha_D}$; $\alpha_D \sim 0.095, \quad D_c \sim 5.4 \times 10^{13}$ (tokens)



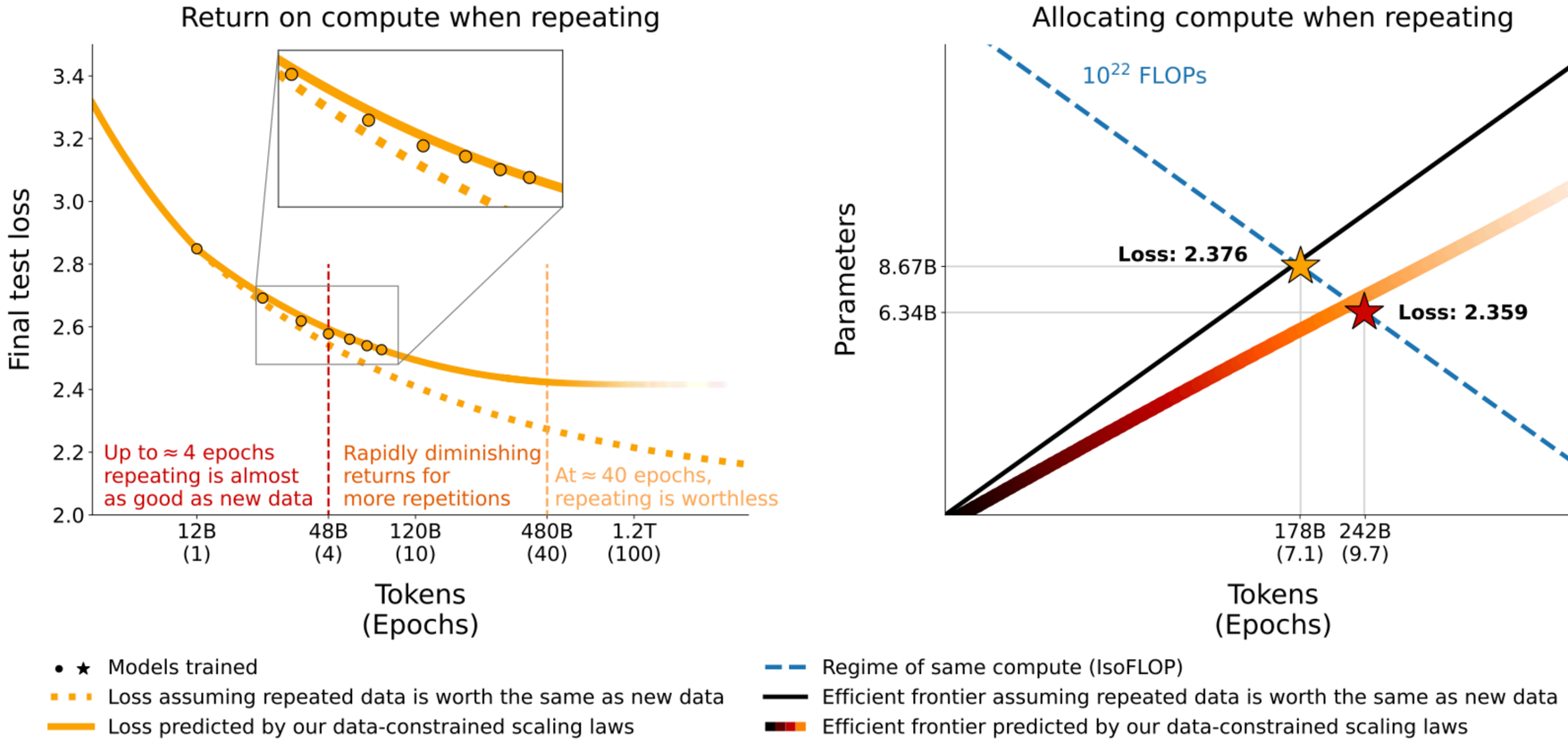
Data Scaling Laws [Kaplan+ 2020]

- So, how does dataset composition affect performance?
  - Dataset composition affects the offset, not the slope



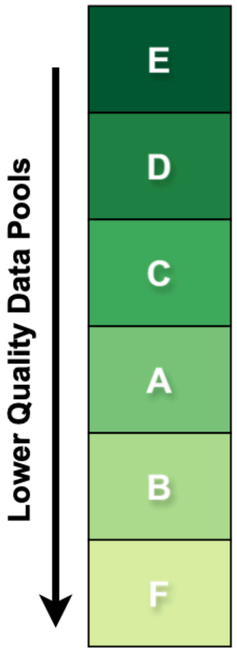
Data Scaling Laws [Muennighoff+ 2023]

- In practice, we have finite data (data constrained scenarios)
  - How does repeating examples affect scaling?

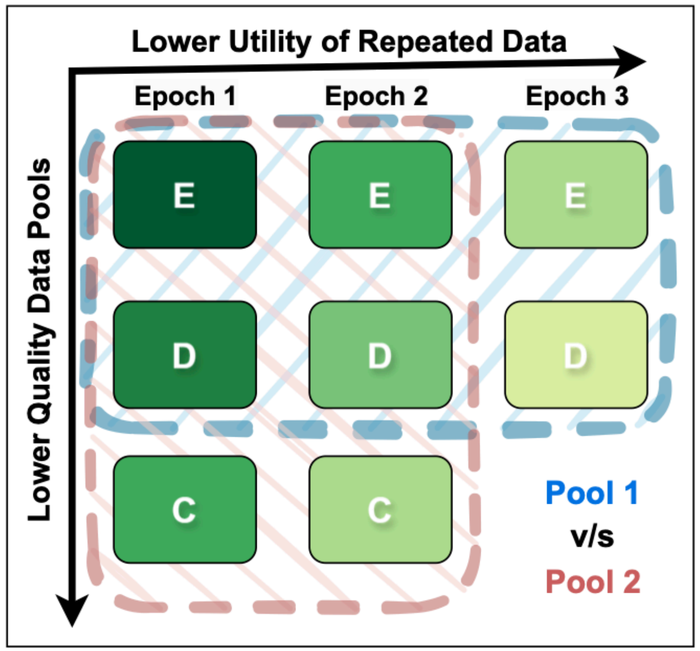


Data Scaling Laws [Goyal+ 2024]

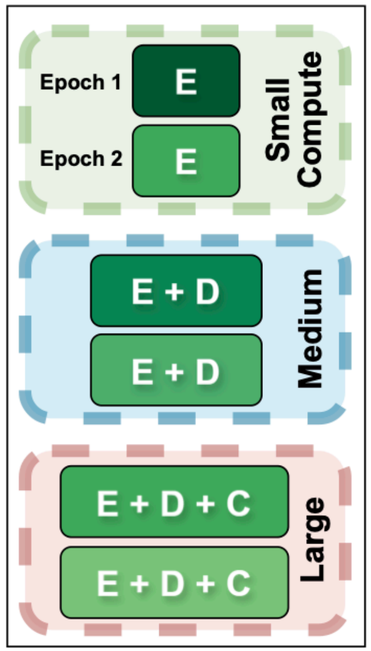
- Data filtering (curation) should be adaptive to scale
  - Less compute: higher filtering / high compute: lower filtering



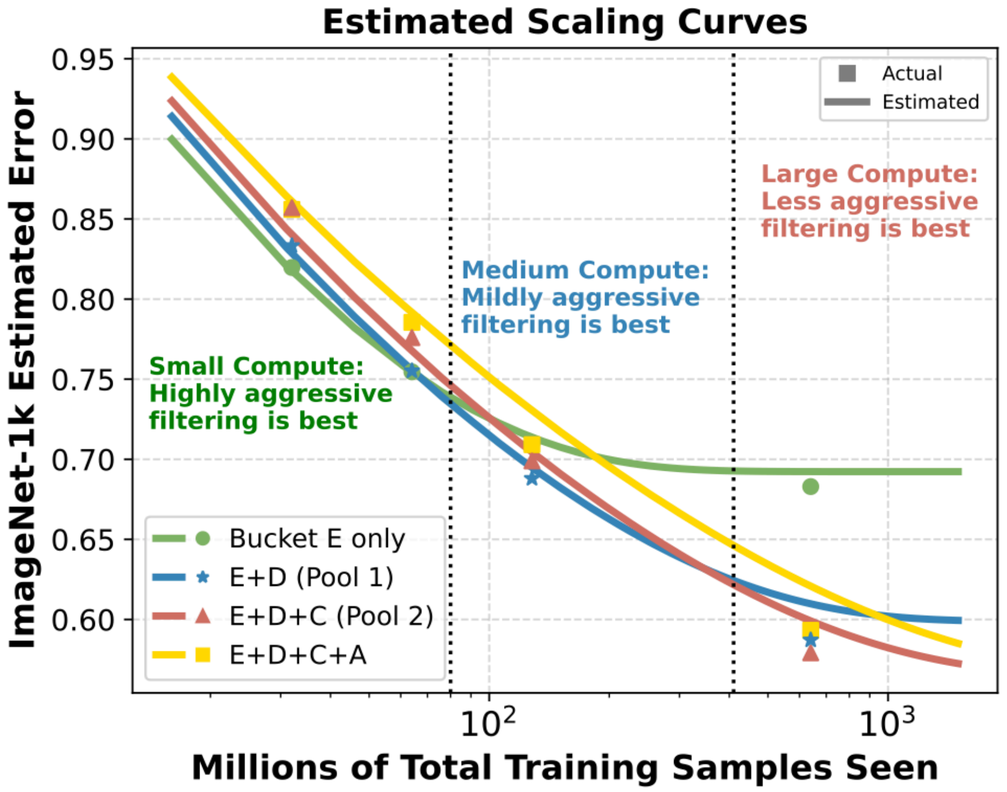
Web Data is Non-Homogenous



Quality-Quantity Tradeoff (QQT) for Data Filtering

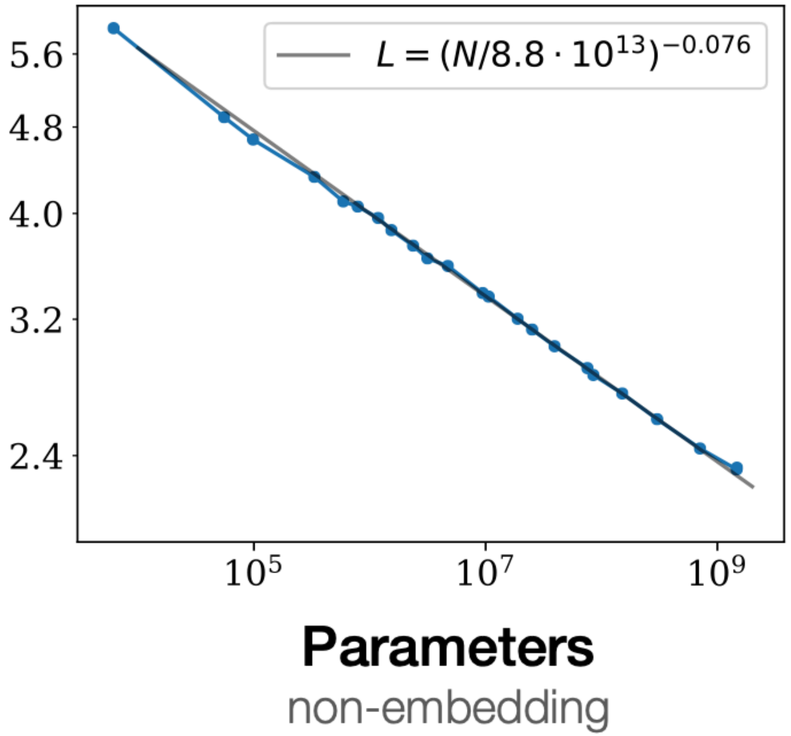


Best Data Pool Changes with Total Compute



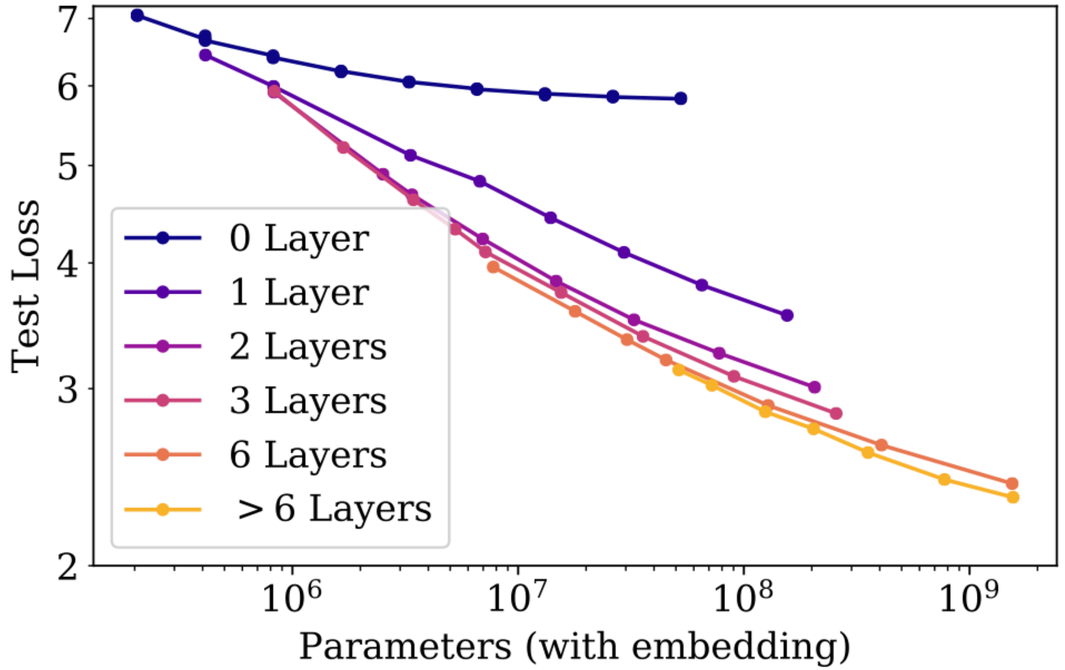
Model Scaling Laws [Kaplan+ 2020]

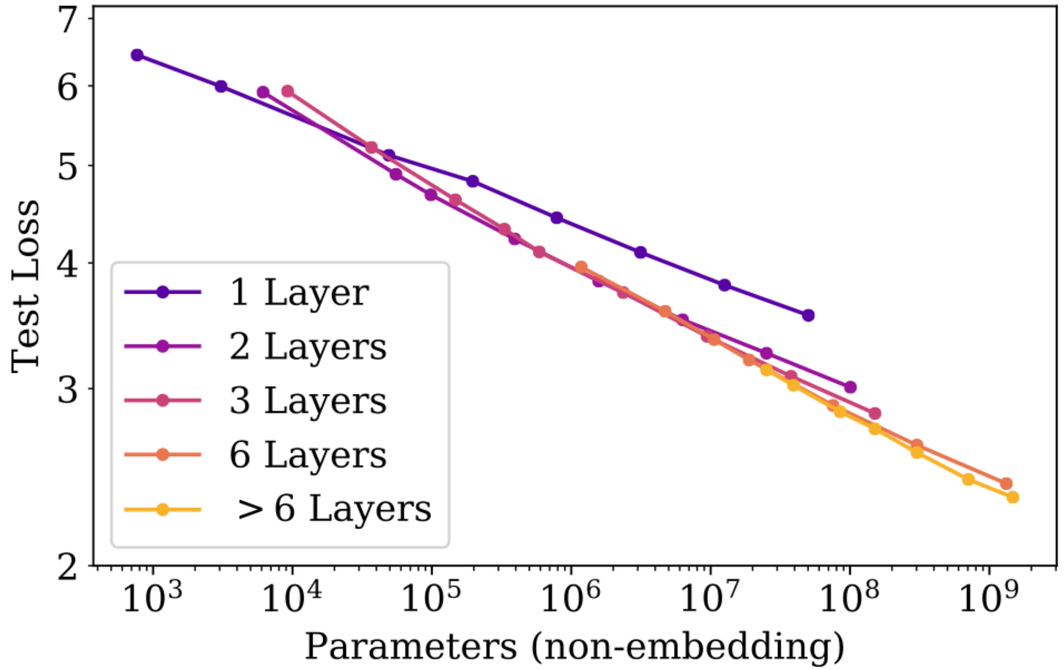
- Performance has (also) a power-law relationship with model size
  - Performance depends strongly on scale, weakly on model shape
  - $L(N) = (N_c/N)^{\alpha_N}$; $\alpha_N \sim 0.076$, $N_c \sim 8.8 \times 10^{13}$ (non-embedding parameters)



Model Scaling Laws [Kaplan+ 2020]

- Note: Be aware that we use non-embedding parameters
  - Embedding parameters is $V \times d_{model}$, which is fixed
  - Model size is small: # embedding params could be dominant
  - Model size is big: # embedding params is negligible





Recap

- Remarkably linear relationship between log-data size and log-error
- Remarkably linear relationship between log-model size and log-error

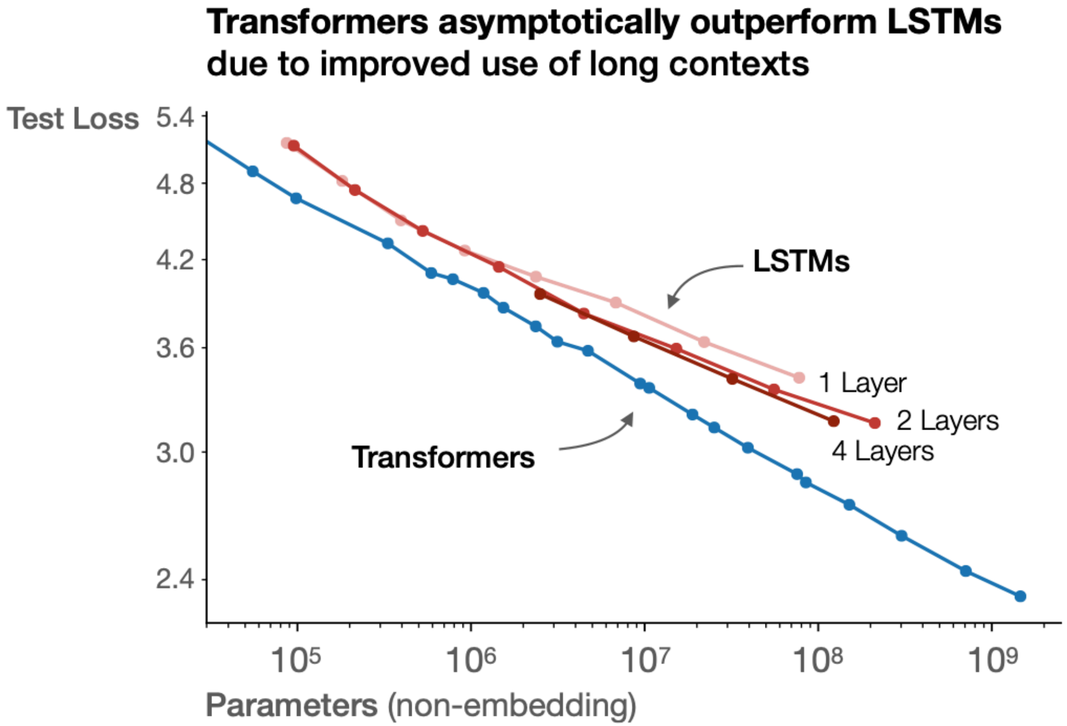
Scaling Laws for Model Engineering

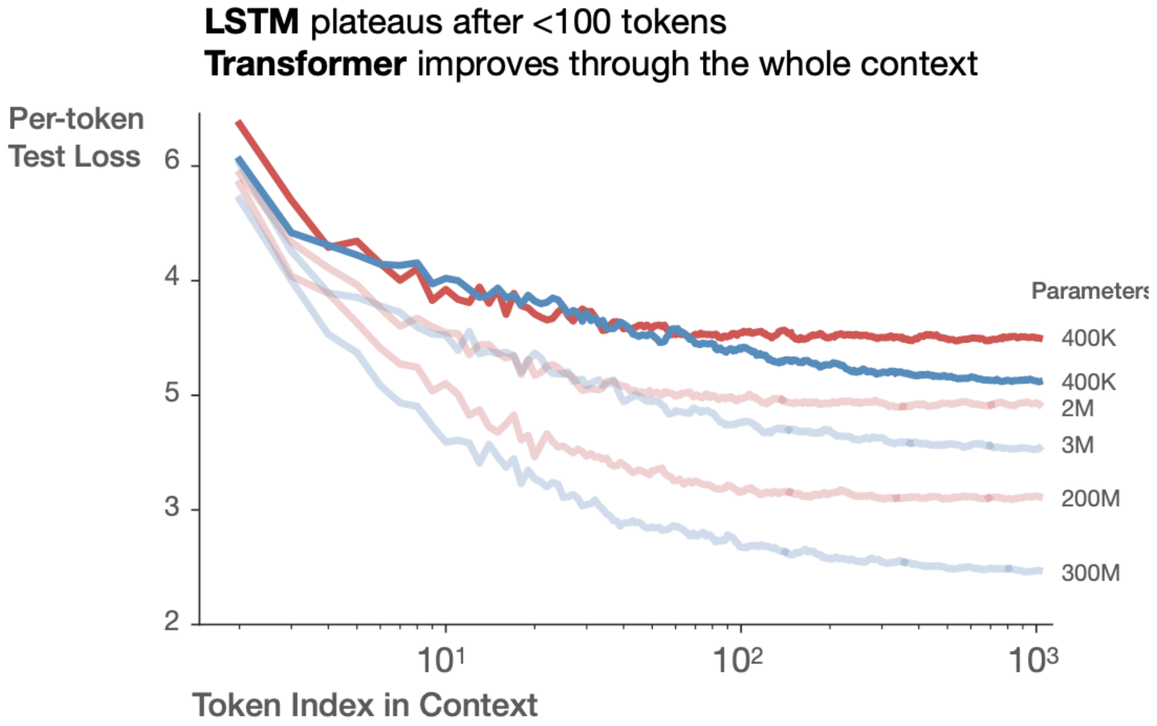
Hyperparameter Questions

- We'll consider some of these choices in the context of [Kaplan+ 2020]
  - Model architecture
  - Optimizer
  - Aspect ratio / depth
  - MoE
  - Batch size

Architecture: Transformer vs. LSTMs [Kaplan+ 2020]

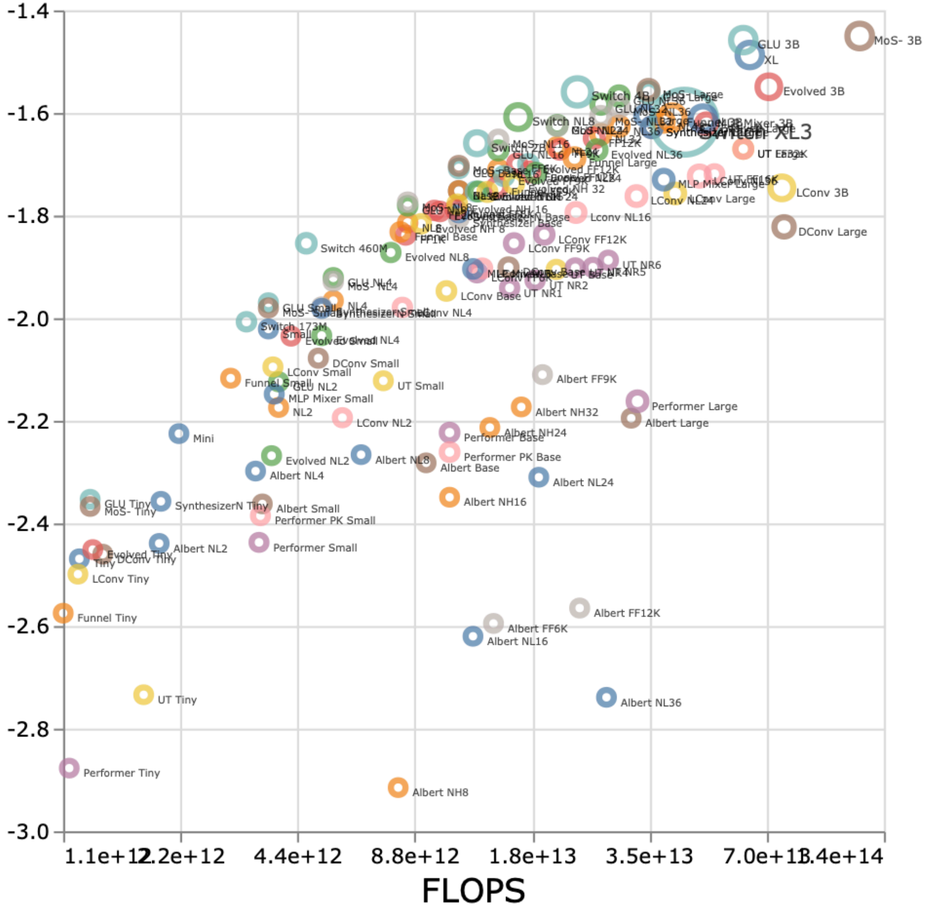
- Q: Are transformers better than LSTMs?
  - A1: Brute force way: spend tens of millions to train an LSTM GPT-3
  - A2: Scaling law way:





Architecture: Transformer vs. LSTMs

- Cross-architecture scaling in [Tay+ 2022]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GLU 3B
XL
Evolved 3B
LConv 3B
DConv Large
Switch NL8
Switch 460M
Evolved NL8
GLU NL4
LConv Base
UT NR1
UT NR2
LConv FF12K
LConv FF9K
Albert FF9K
Performer Large
Albert Large
Albert NH32
Albert NH24
Performer Base
Performer PK Base
Albert Base
Albert NL24
Albert NH16
Albert FF12K
Albert FF6K
Albert NL16
Albert NL36
Albert NH8
Mini
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Albert NL8
Albert NL4
GLU Tiny
SynthesizerN Tiny
Albert Small
Performer PK Small
Albert NL2
Performer Small
Evolved Tiny
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LConv Tiny
Funnel Tiny
UT Tiny
Performer Tiny
DConv Small
Funnel Small
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LConv NL2
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LConv NL16
LConv FF12K
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Switch 2650275968094451590791467844933789640933274108963293865187083271798784B
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Switch 10601103872377806363165871379735158563733096435853175460748333087195136B
Switch 21202207744755612726331742759470317127466192871706350921496666174390272B
Switch 42404415489511225452663485518940634254932385743412701842993332348780544B
Switch 84808830979022450905326971037881268509864771486825403685986664697561088B
Switch 169617661958044901810653942075762537019729542973650807371973329395122176B
Switch 339235323916089803621307884151525074039459085947301614743946658790244352B
Switch 678470647832179607242615768303050148078918171894603229487893317580488704B
Switch 1356941295664359214485231536606100296157836343789206458975786635160977408B
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Switch 173688485845037979454109636685580837908203052005018426748900689300605108224B
Switch 347376971690075958908219273371161675816406104010036853497801378601210216448B
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Switch 5558031547041215342531508373938586813062497664160589655964822057619363463168B
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Switch 22232126188164861370126033495754347252249990656642358623859288230477853672672B
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Switch 2030768051584386896990848590397853019345330757569379654160712001461234492645174769195077906955565735709238357789531355348992B
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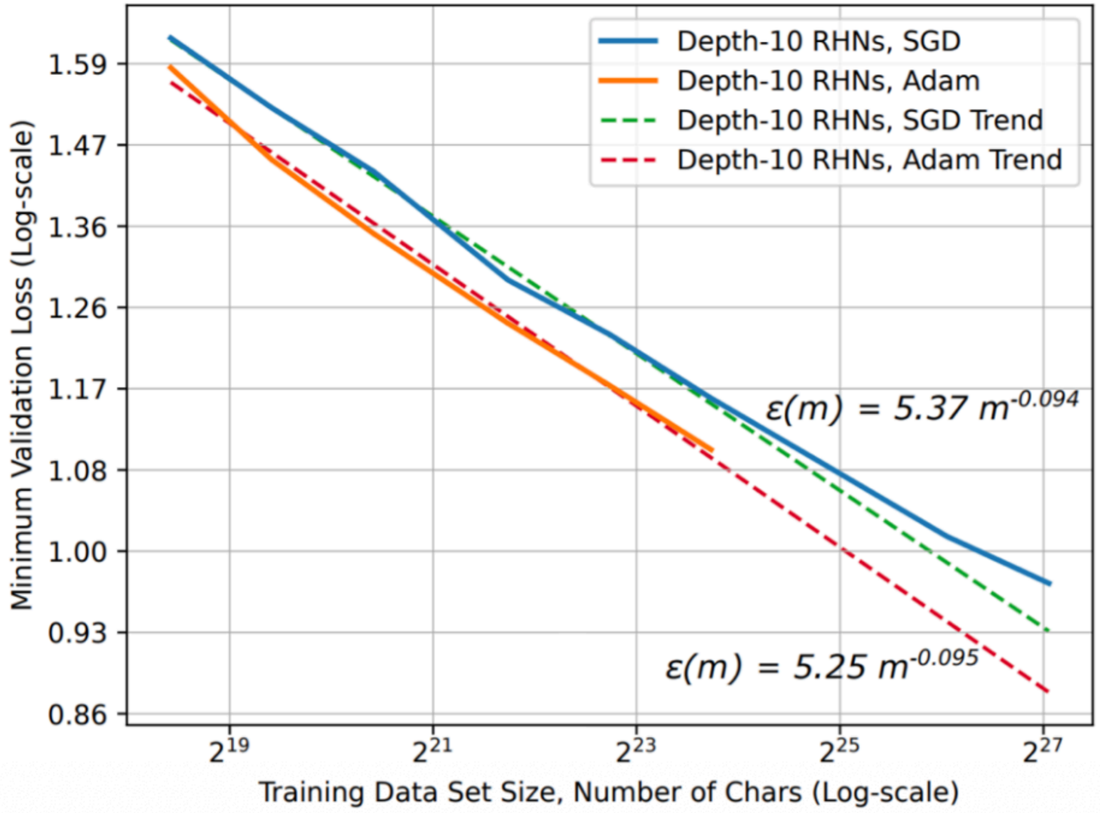
Optimizer Choice [Hestness+ 2017]

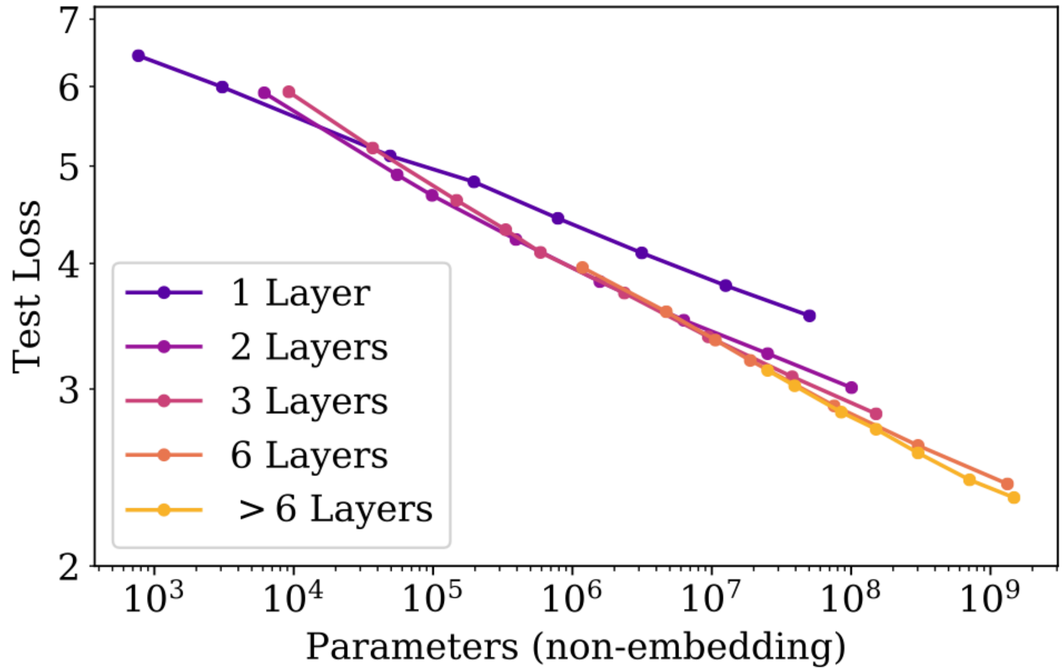
- Q: What about Adam vs. SGD?
  - A: Similar slope, but offsets are different



Note: below results are not Transformer

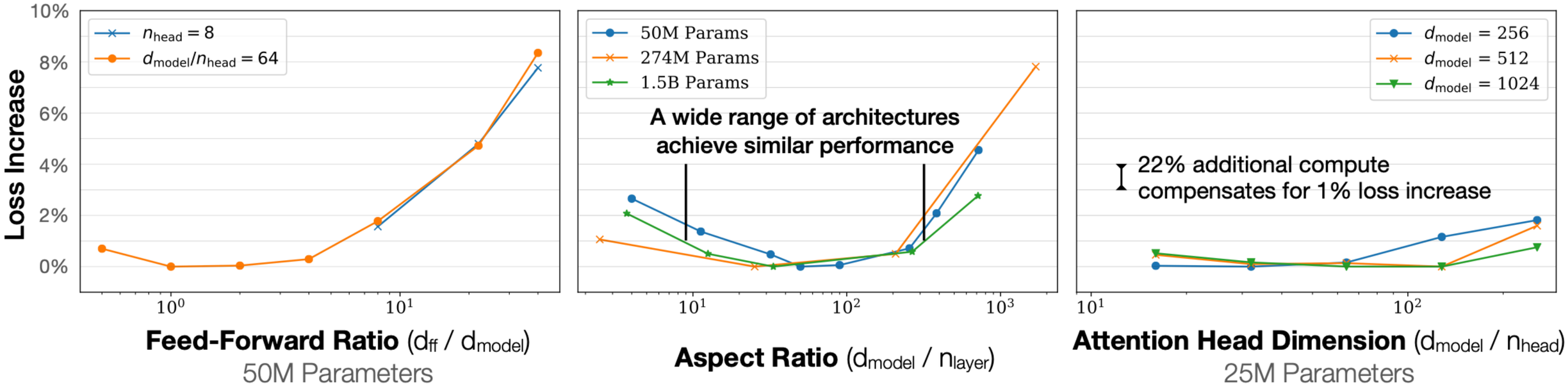
Depth/Width: # of Layers [Kaplan+ 2020]

- Q: Does depth or width make a huge difference?
  - A: 1 vs 2 layers makes a huge difference
  - A: More layers have diminishing returns below 10^7 params



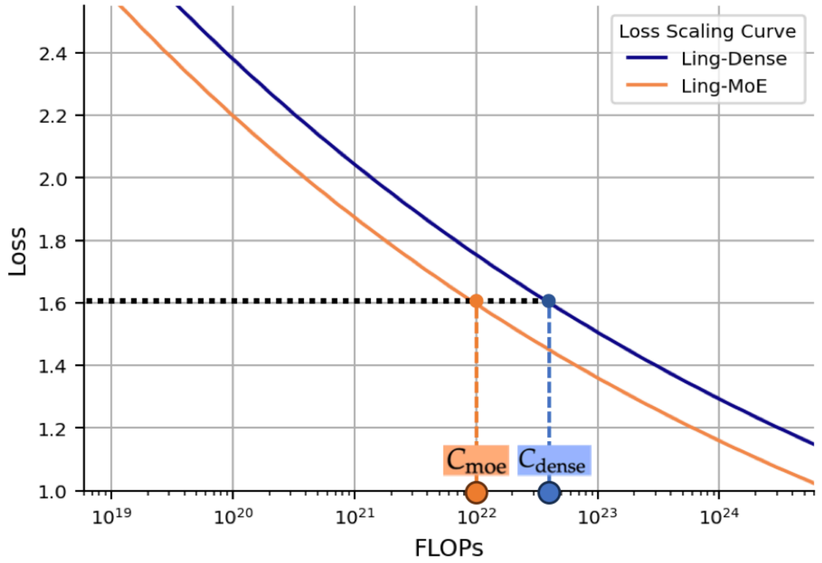
Other Hyperparameters [Kaplan+ 2020]

- Q: Do hyperparameters like the aspect ratio depend on scale?
  - A: Performance depends very mildly on model shape



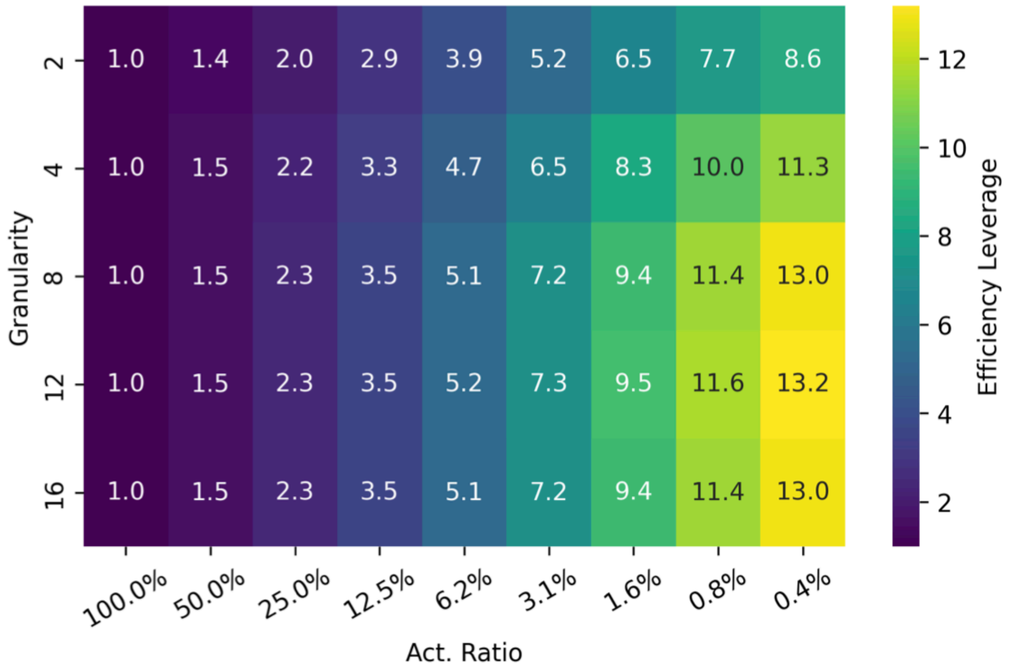
Scaling Laws for MoE [Tian+ 2025]

- MoEs decouples total params from compute cost → hard to predict loss
- Efficiency Leverage: compute efficiency of MoE vs. dense counterpart



$$EL(\mathcal{X}_{\text{MoE}} \mid \mathcal{X}_{\text{Dense}}) = \frac{C_{\text{dense}}}{C_{\text{moe}}}$$

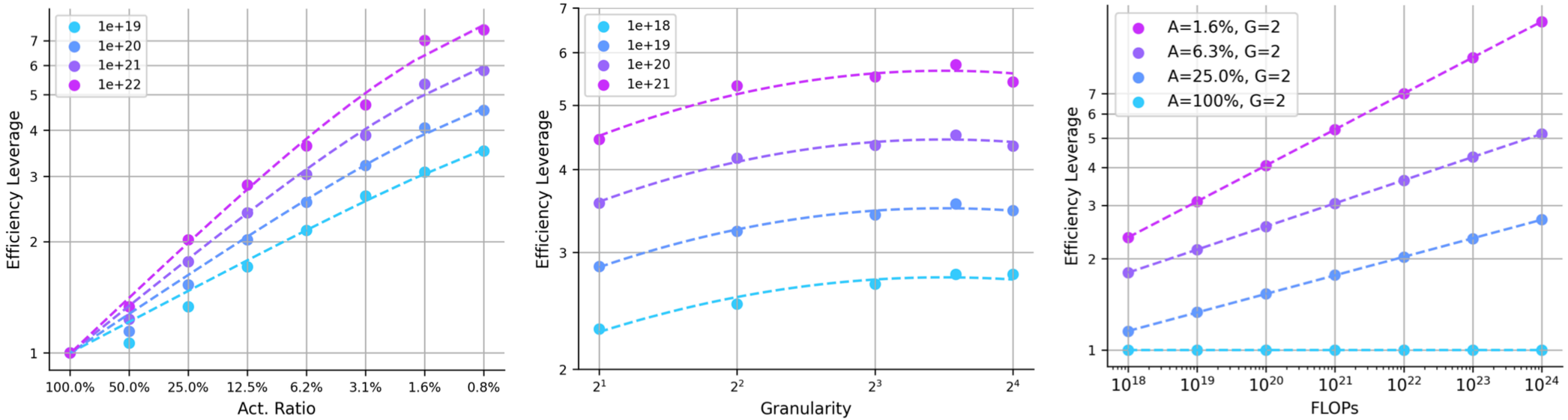
(a) Definition of Efficiency Leverage (EL)



(b) Estimated EL at 1e22 FLOPs

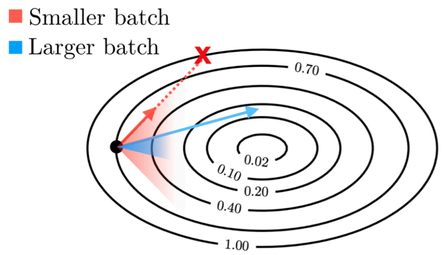
Scaling Laws for MoE [Tian+ 2025]

- Key factors of MoE scaling laws
  - Activation ratio: more sparse, more efficient (monotonically)
  - Expert granularity: there is an optimal granularity (around 12)
  - Compute budget: the bigger model, the effect of MoEs is greater



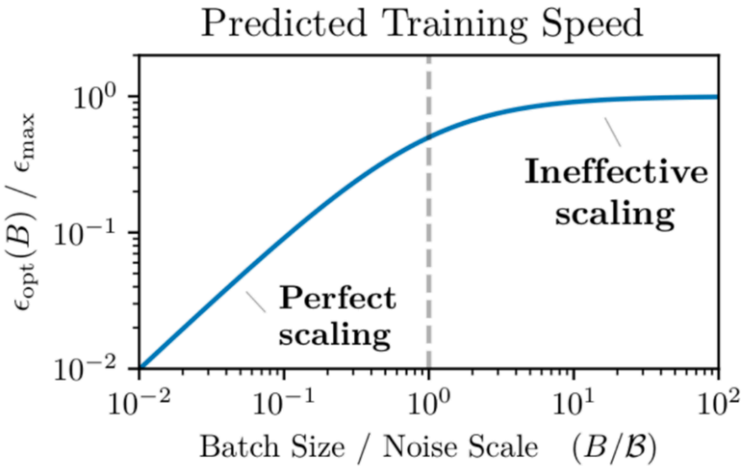
(a) Scaling with Activation Ratio (A) **(b)** Scaling with Granularity (G) **(c)** Scaling with Compute Budget (C)

Batch Size: "Critical Batch Size"



- Batch size has strong diminishing returns past a certain point
  - Small batch size: high-variance gradient (noisy)
  - Large batch size: low-variance gradient
  - Very large batch size: redundant signal; not much gain from it

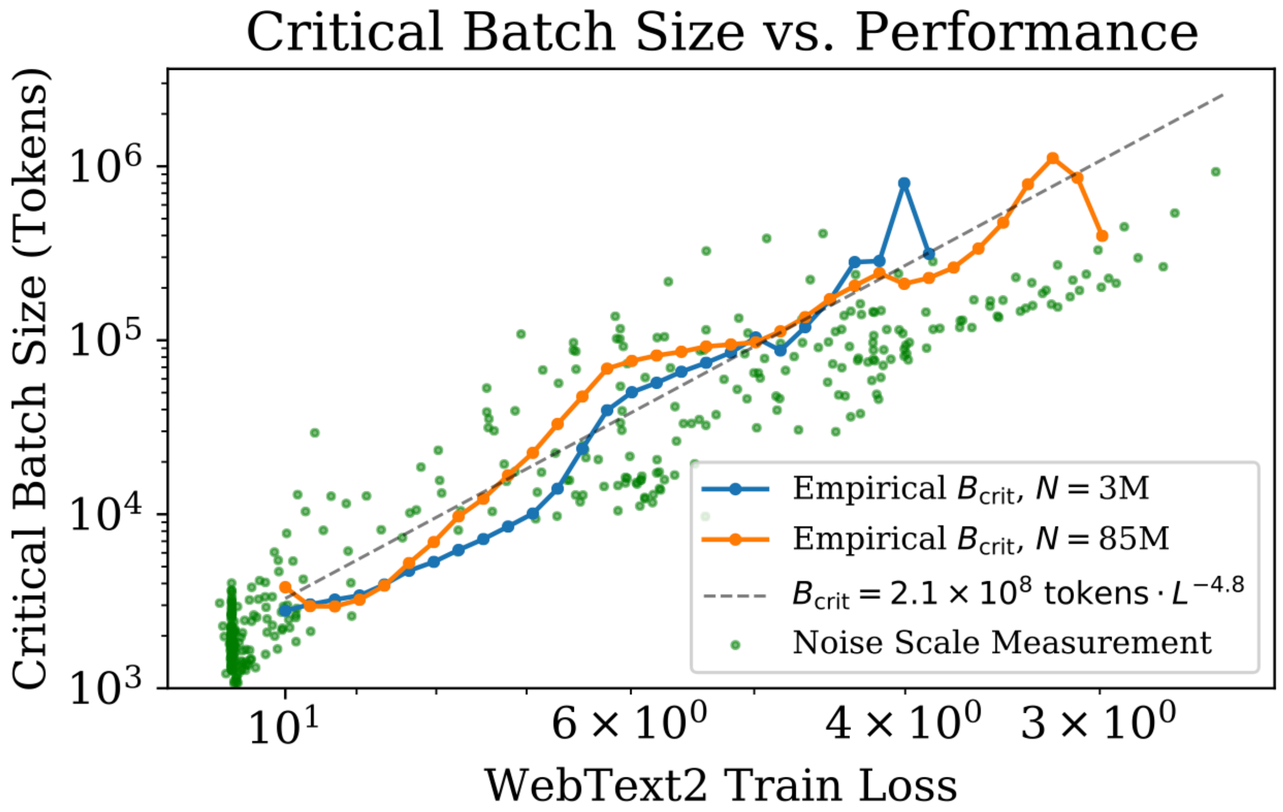
- Critical batch size: $\dfrac{\min(\#\text{ of data for target loss})}{\min(\#\text{ of steps for target loss})}$



  - The Pareto-optimal (i.e. best batch size) that maximizes training speed while maintaining compute efficiency by avoiding the diminishing returns of gradient redundancy

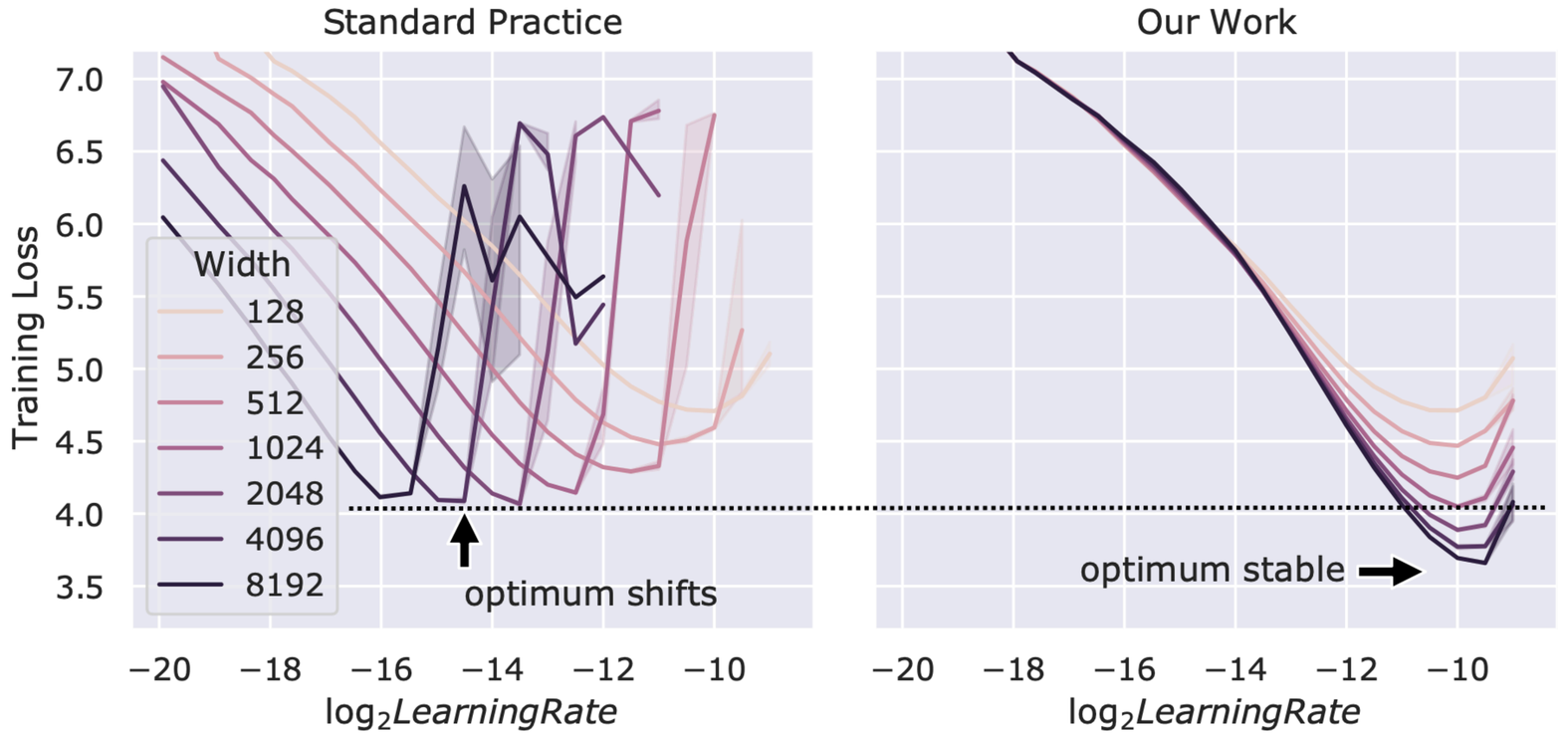
Batch Size: "Critical Batch Size" [Kaplan+ 2020]

- Q: Critical batch size is always the same?
  - A: No! the smaller the "target" loss, the bigger the critical batch size



Learning Rate: μP [Yang+ 2022]

- Q: Should we find optimal learning rate for each scaled-up model?
  - A1: In standard practice, yes 😢
  - A2: μP is scaling-aware initialization and learning rate scaling



Some Takeaways

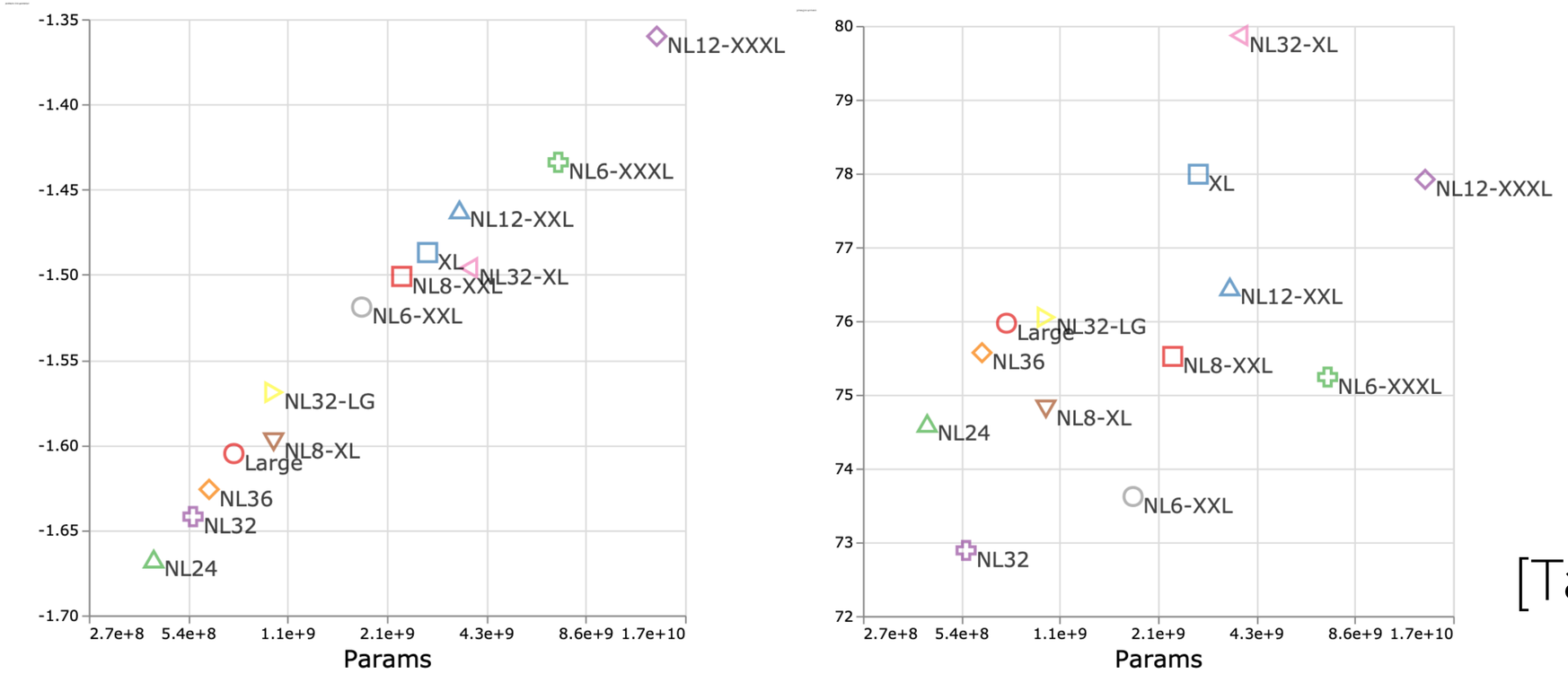
- Effect of HPs on big LLMs can be predicted before training
  - Optimizer choice
  - Model design (depth, aspect ratio, architecture choice, …)

- The scaling law based design procedure
  - Train a few smaller models with a small compute budget
  - Establish my own scaling law
  - Select optimal hyperparams based on the scaling law prediction

- If we don't have scaling laws…
  - We should tune very big models, and waste lots of computing

But Caution…

- Scaling behaviors can differ downstream
  - Thus far, we saw the scaling laws on the losses (i.e. upstream tasks)
  - But downstream scaling can often be much less predictable



[Tay+ 2021]

Compute Allocation

Compute Allocation

- Let's say we can use 1,000 H200 GPUs for a month

- How should we allocate our limited resources?
  - Train models longer vs train bigger models?
  - Collect more data vs get more GPUs?

- Scaling laws can also provide a simple procedure to answer this

Implications of Kaplan's Scaling Law

- Q: Do we need more data or bigger models?
  - A: Clearly, it seems that lots of data is wasted on small models

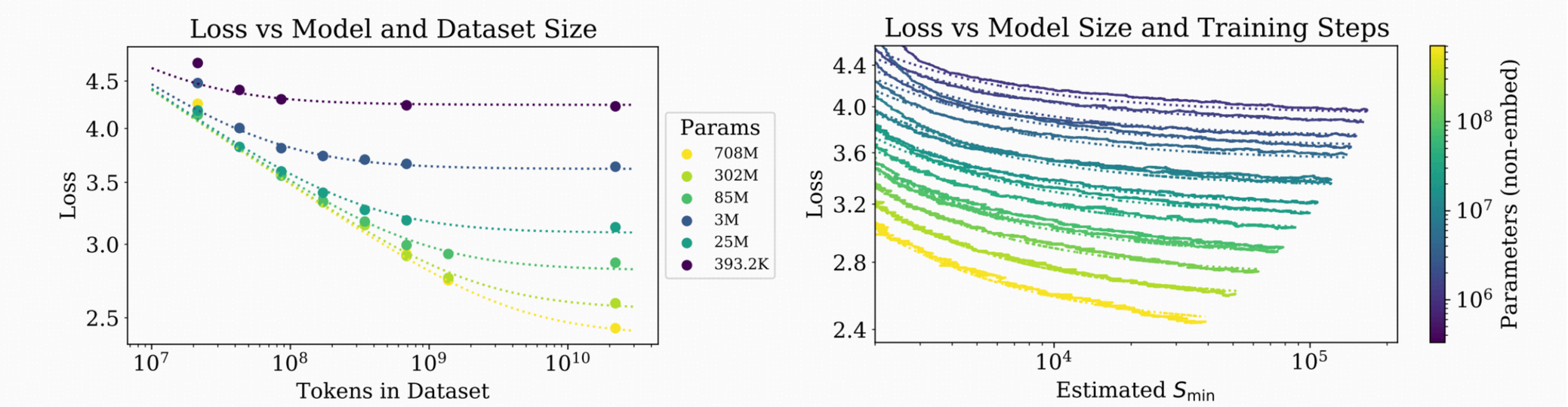
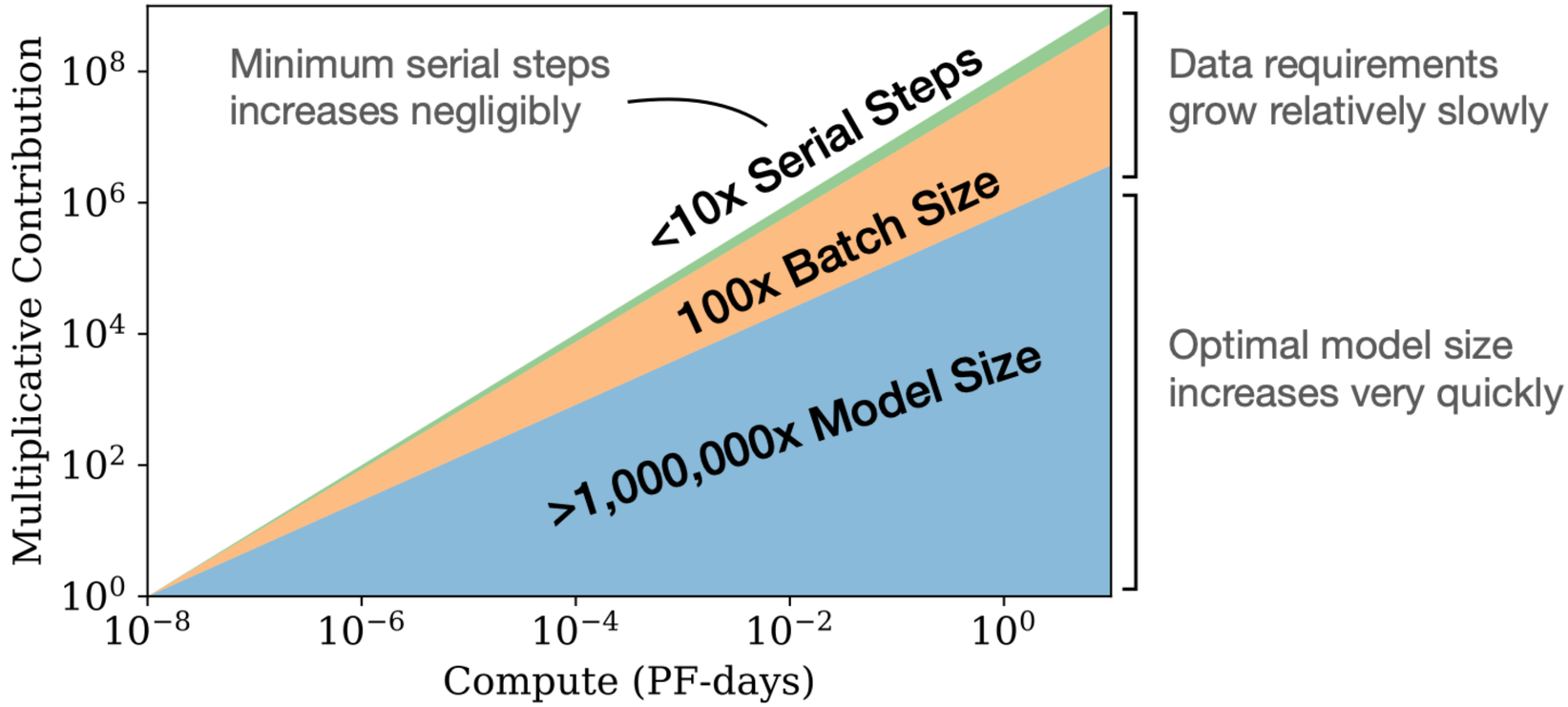


Figure 4 **Left**: The early-stopped test loss $L(N, D)$ varies predictably with the dataset size D and model size N according to Equation (1.5). **Right**: After an initial transient period, learning curves for all model sizes N can be fit with Equation (1.6), which is parameterized in terms of $S_{\min}$, the number of steps when training at large batch size (details in Section 5.1).

[Kaplan+ 2020]

Implications of Kaplan's Scaling Law

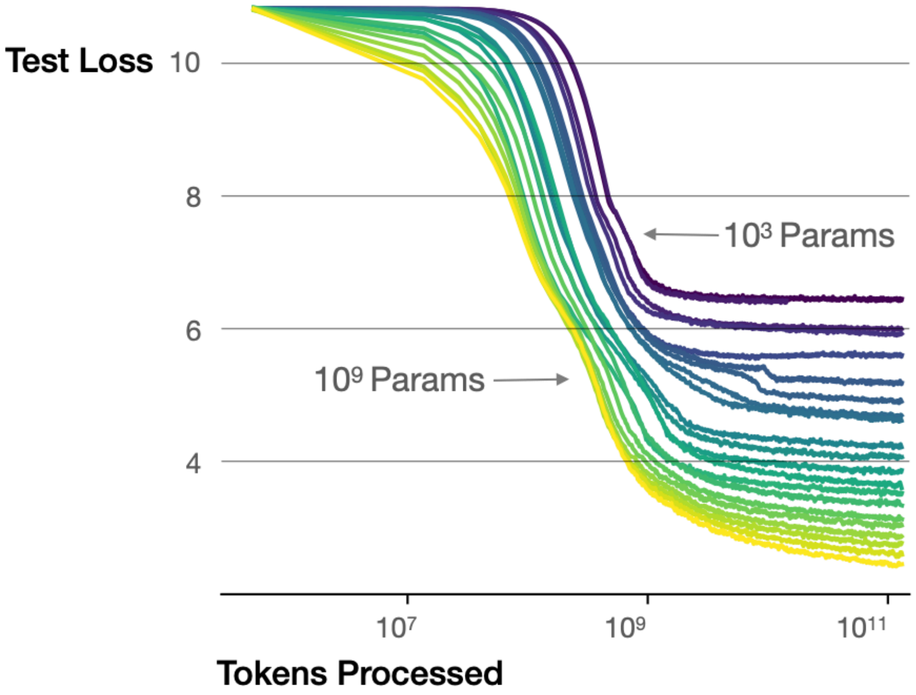
- Q: Do we need more data or bigger models?
  - A: Clearly, it seems that lots of data is wasted on small models



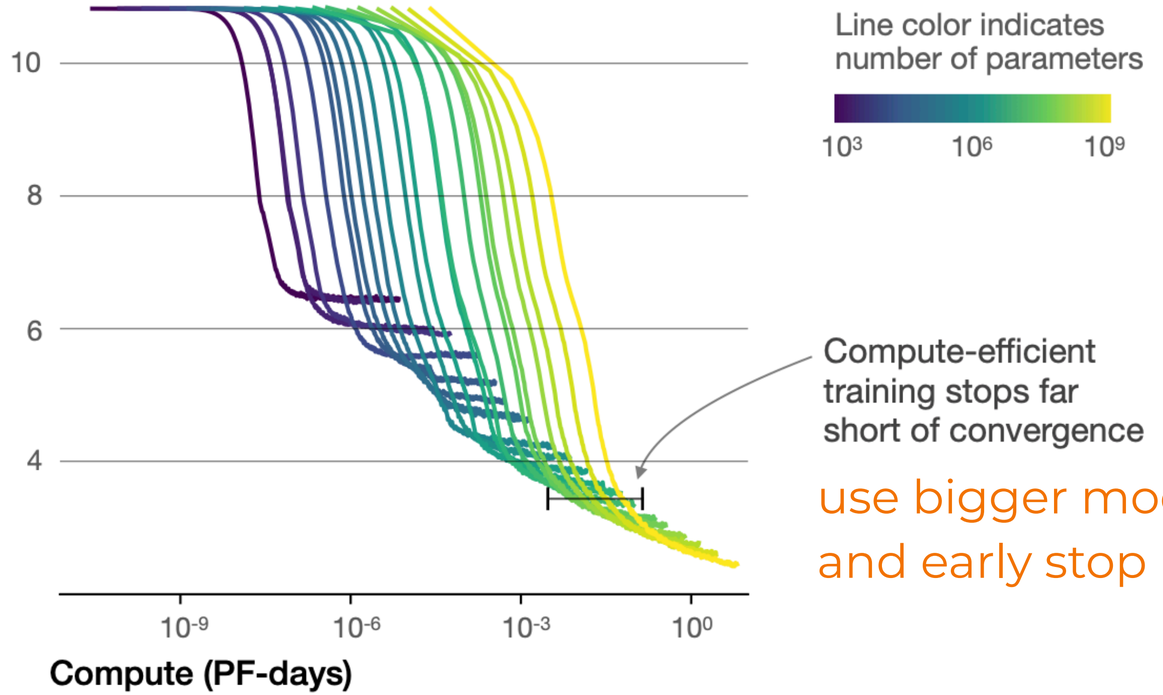
[Kaplan+ 2020]

Training a Bigger Model [Kaplan+ 2020]

Larger models require **fewer samples** to reach the same performance



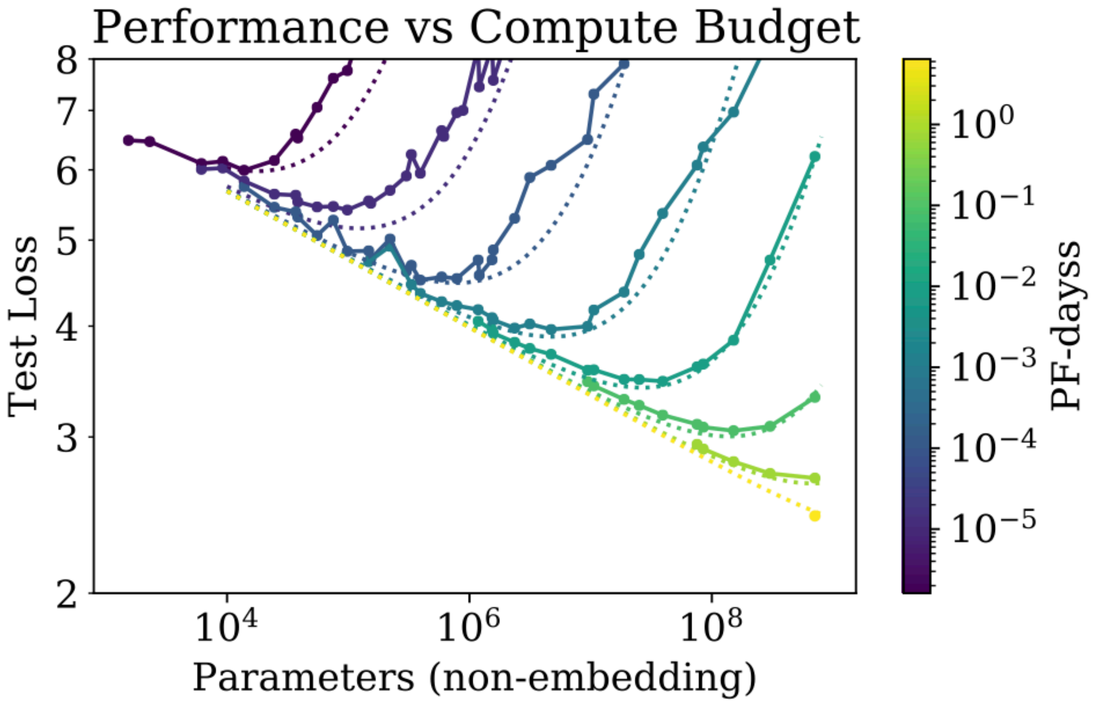
The optimal model size grows smoothly with the loss target and compute budget

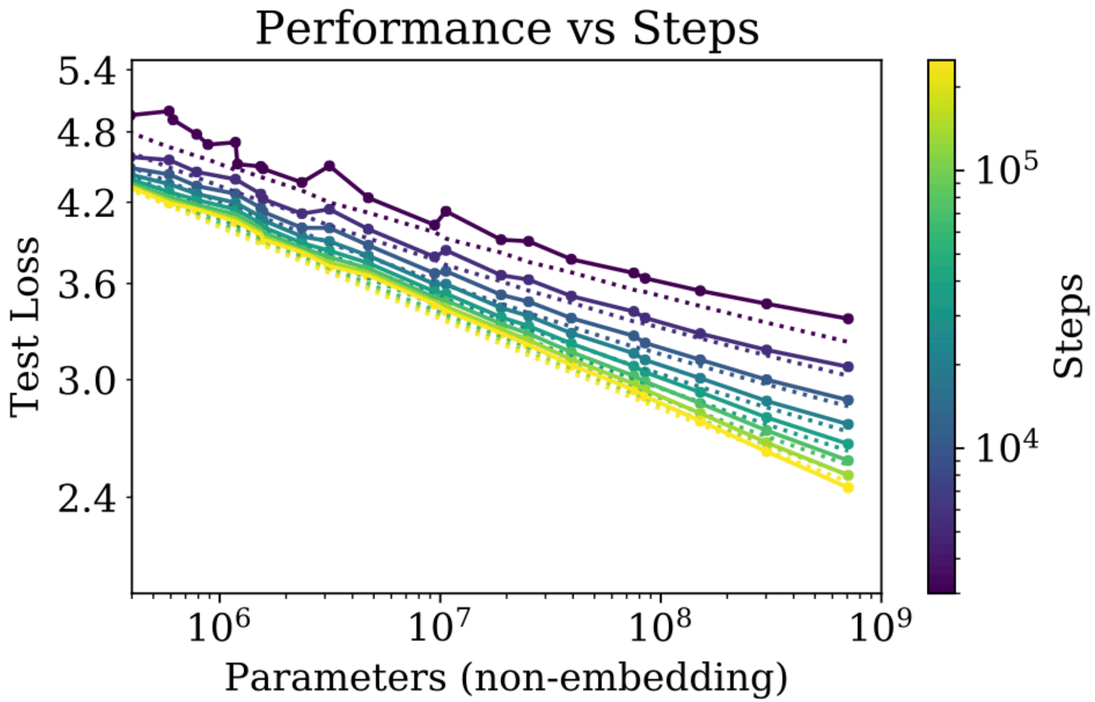


use bigger model, and early stop

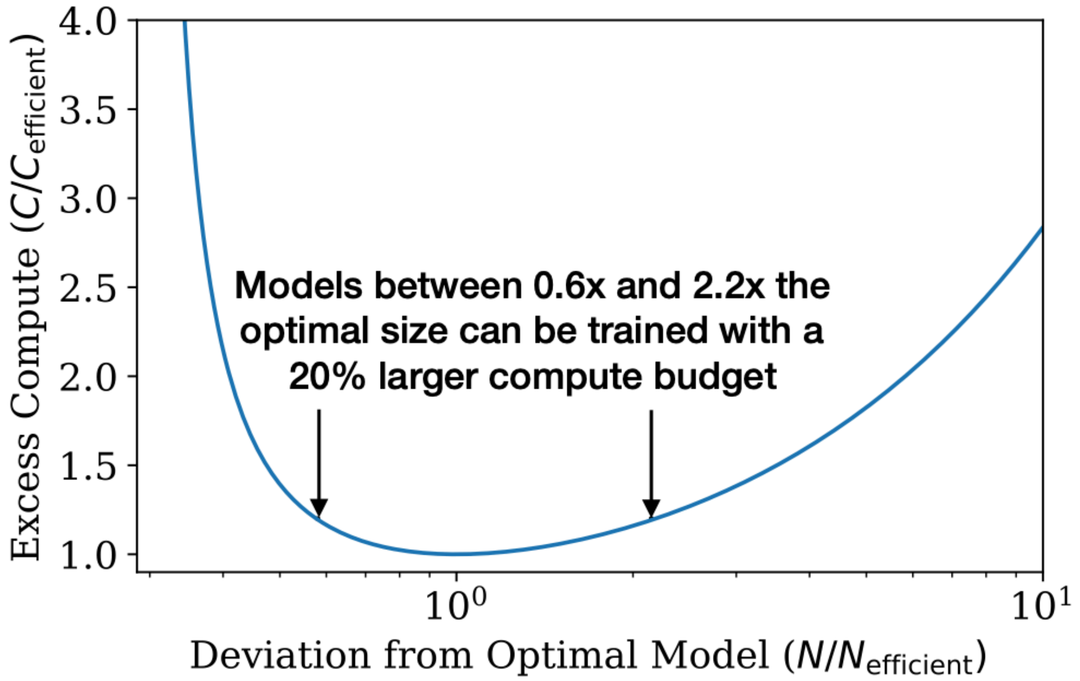
Compute vs. Performance [Kaplan+ 2020]

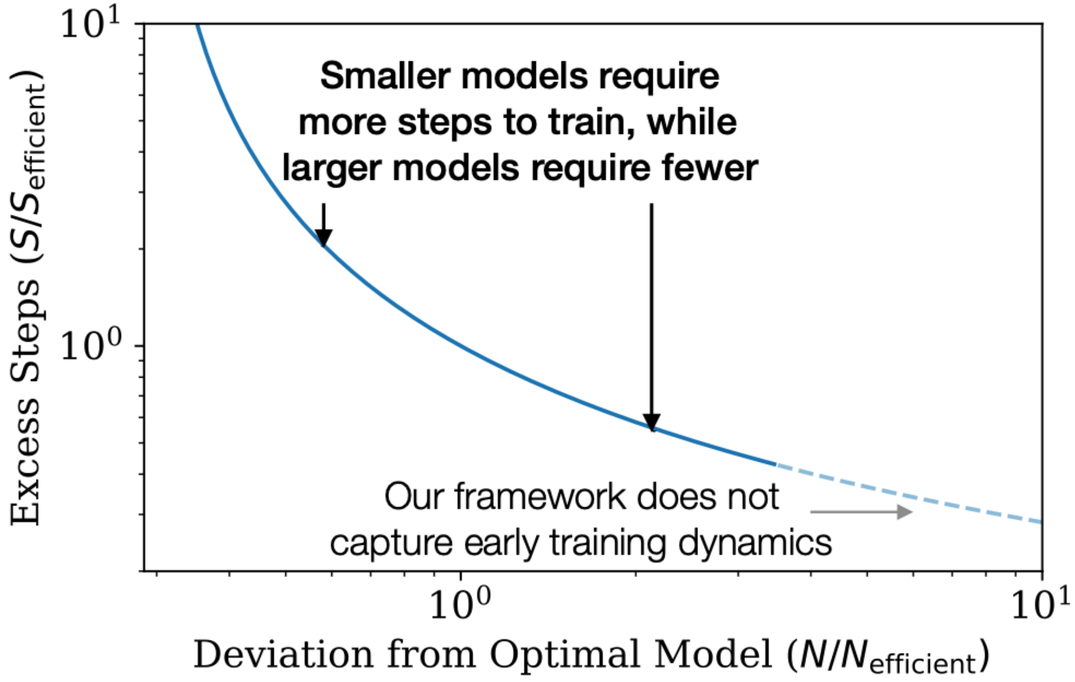
- For a fixed compute budget, there is an optimal model size
  - If we introduce more compute, optimal model size grows





Non-Optimal Model Size? [Kaplan+ 2020]

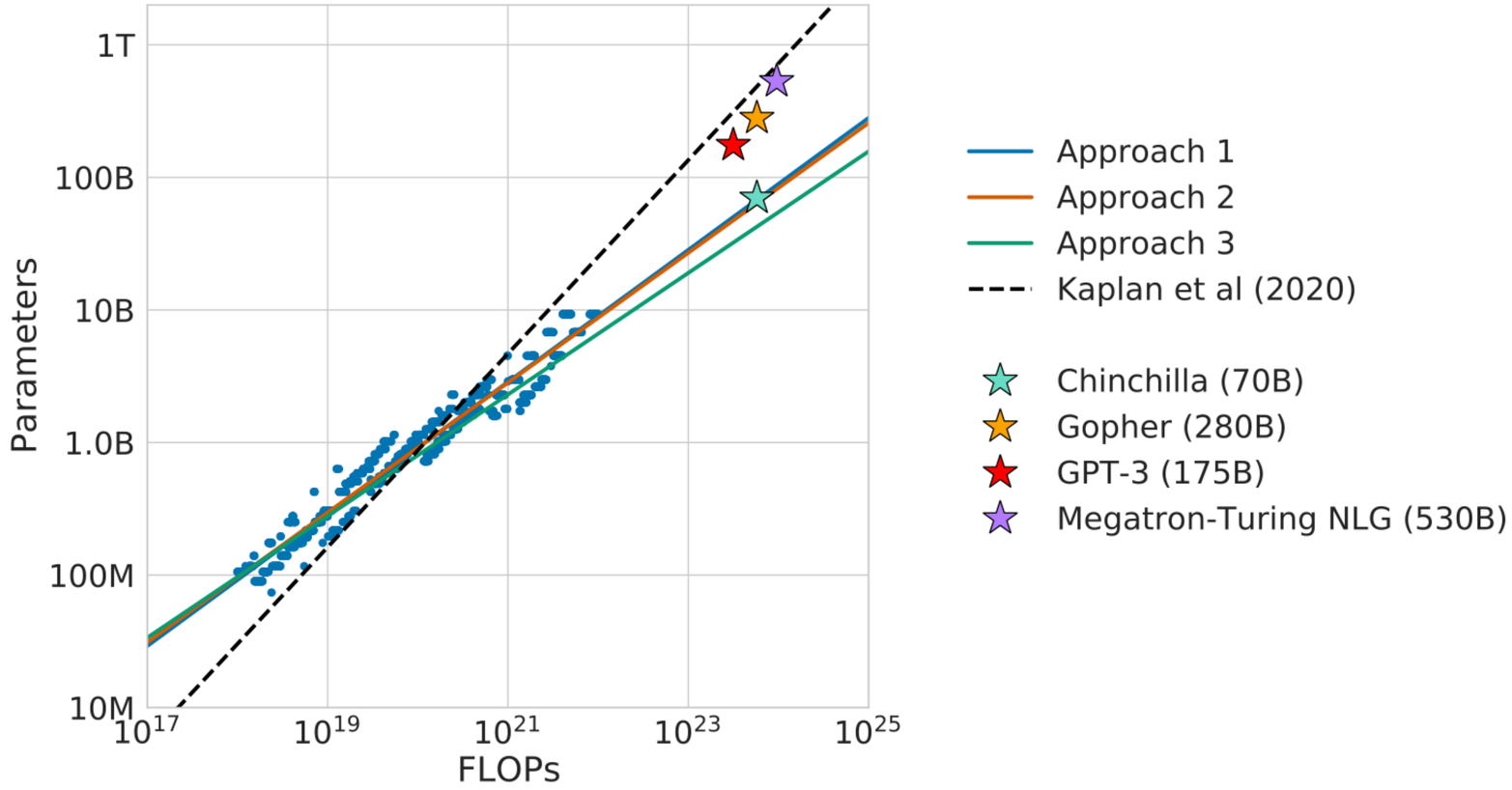




If we have unlimited resources,
train bigger model than the optimal one
with fewer steps

But, "Optimal" Scaling Laws Are Hard to Get

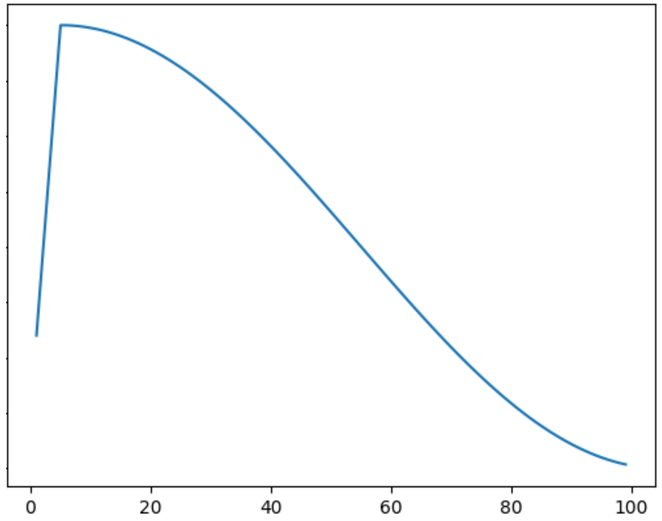
- [Hoffman+ 2022] argue that Kaplan's scaling laws are quite off-fit
  - Kaplan's scaling laws over-estimate the importance of model size



What Makes the Difference?

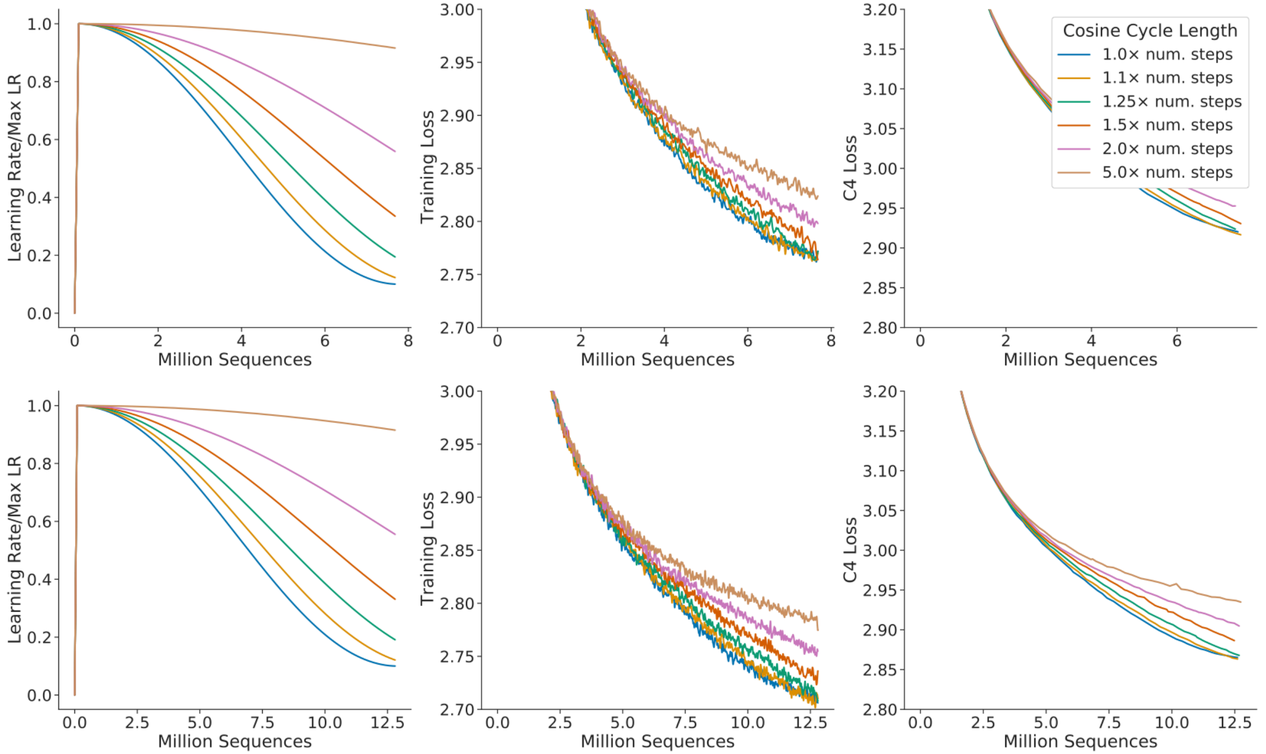
- Improperly configured cosine learning rate decay

- Recap: Cosine LR decay in PyTorch
  - `CosineAnnealingLR(optimizer, T_max, eta_min, last_epoch)`
  - `T_max: Maximum number of iterations`
  - `eta_min: Minimum learning rate. Default: 0.`



What Makes the Difference?

- Improperly configured cosine learning rate decay
- To get optimal loss, we should set **`T_max`** to actual end-training steps
  - But they used fixed scheduler so LR does not drop appropriately



[Hoffman+ 2022]

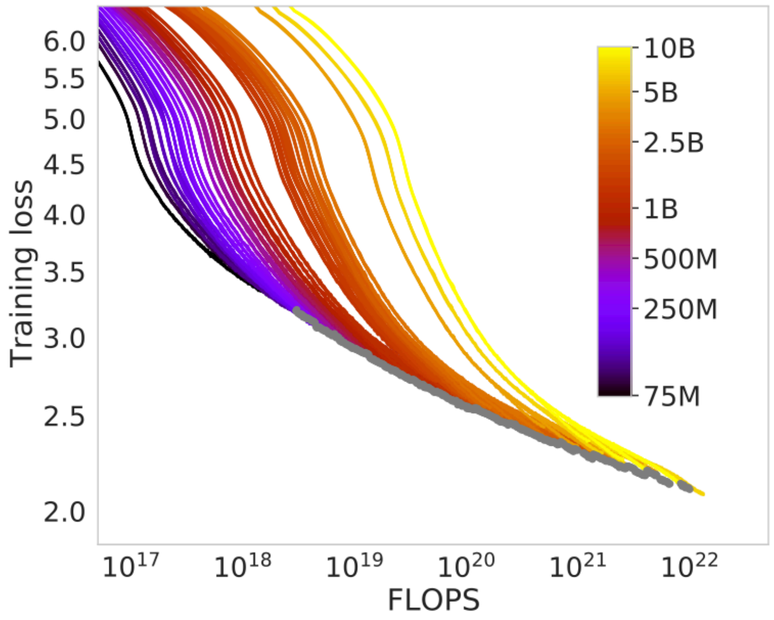
Chinchilla Scaling Laws [Hoffman+ 2022]

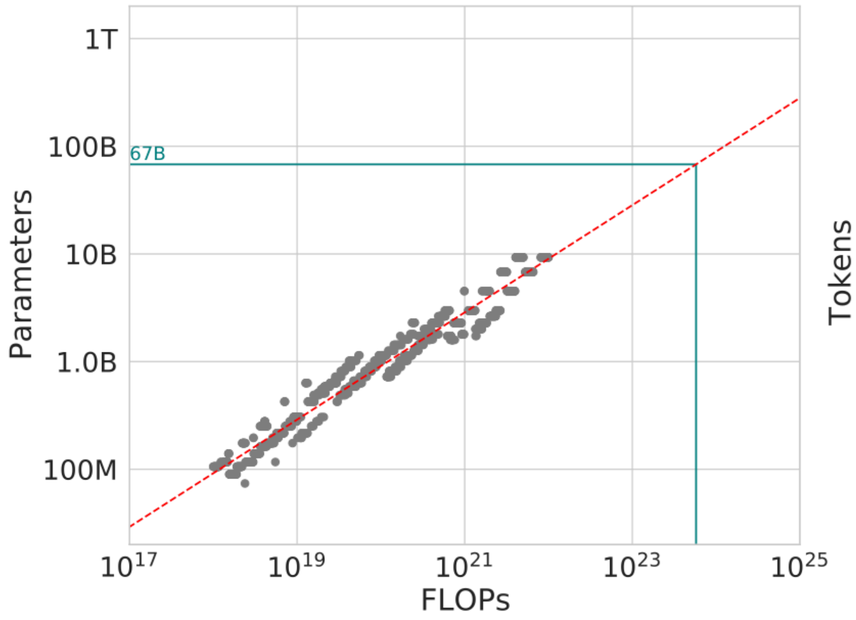
- They suggest 3 ways of fitting scaling laws
  - They mostly result similar constant

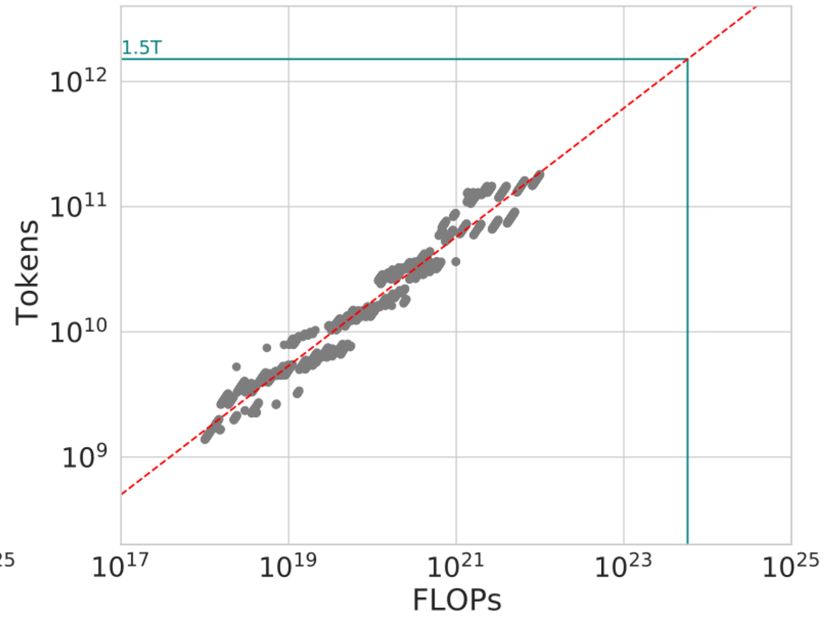
Approach	Coeff. a where $N_{opt} \propto C^a$	Coeff. b where $D_{opt} \propto C^b$
1. Minimum over training curves	0.50 (0.488, 0.502)	0.50 (0.501, 0.512)
2. IsoFLOP profiles	0.49 (0.462, 0.534)	0.51 (0.483, 0.529)
3. Parametric modelling of the loss	0.46 (0.454, 0.455)	0.54 (0.542, 0.543)
Kaplan et al. (2020)	(param) 0.73	(data) 0.27

Method 1: Minimum Over Runs [Hoffman+ 2022]

- Fix model sizes and vary number of training tokens
  - For each model size, train with four different training tokens
  - Then, get minimum loss envelopes and fit curve

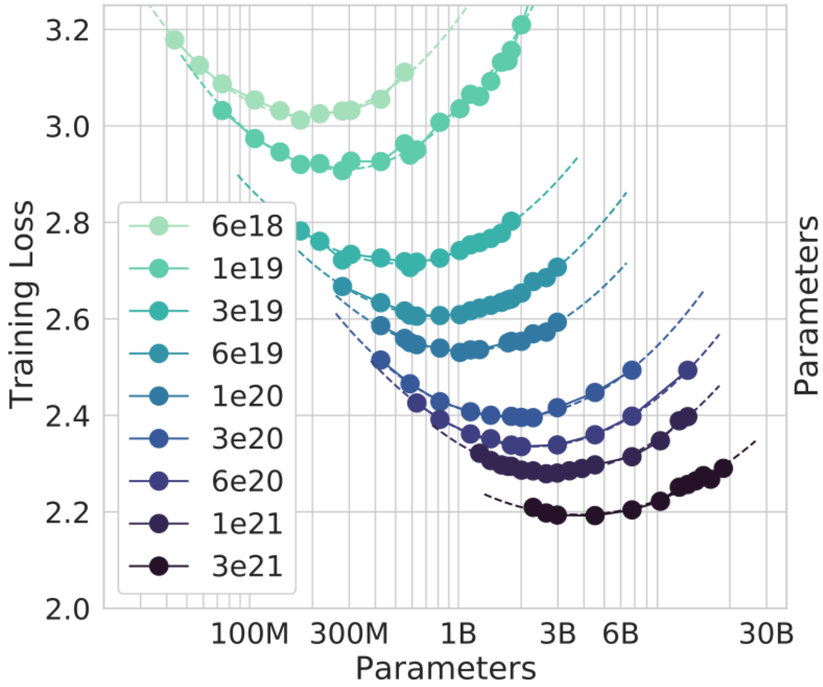


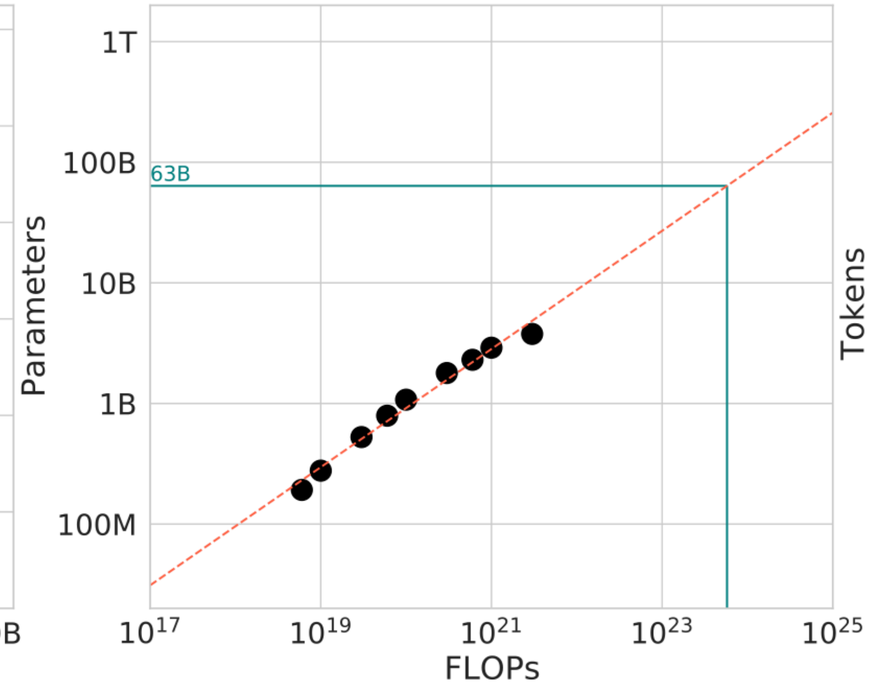


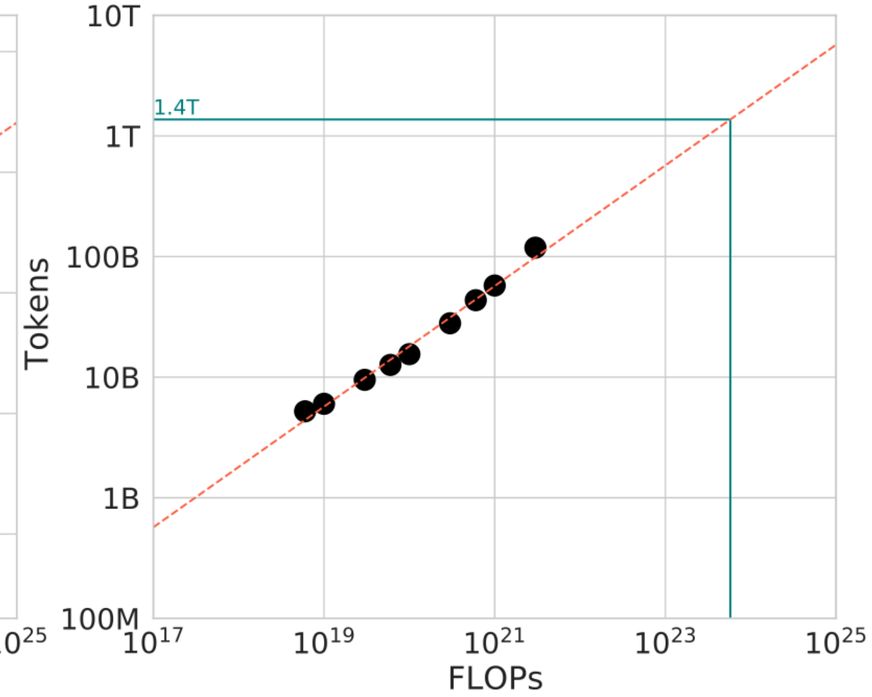


Method 2: IsoFLOPs [Hoffman+ 2022]

- Pick a range of FLOPs budgets, vary the model size for each FLOPs
- The min over these convex shapes form a power law

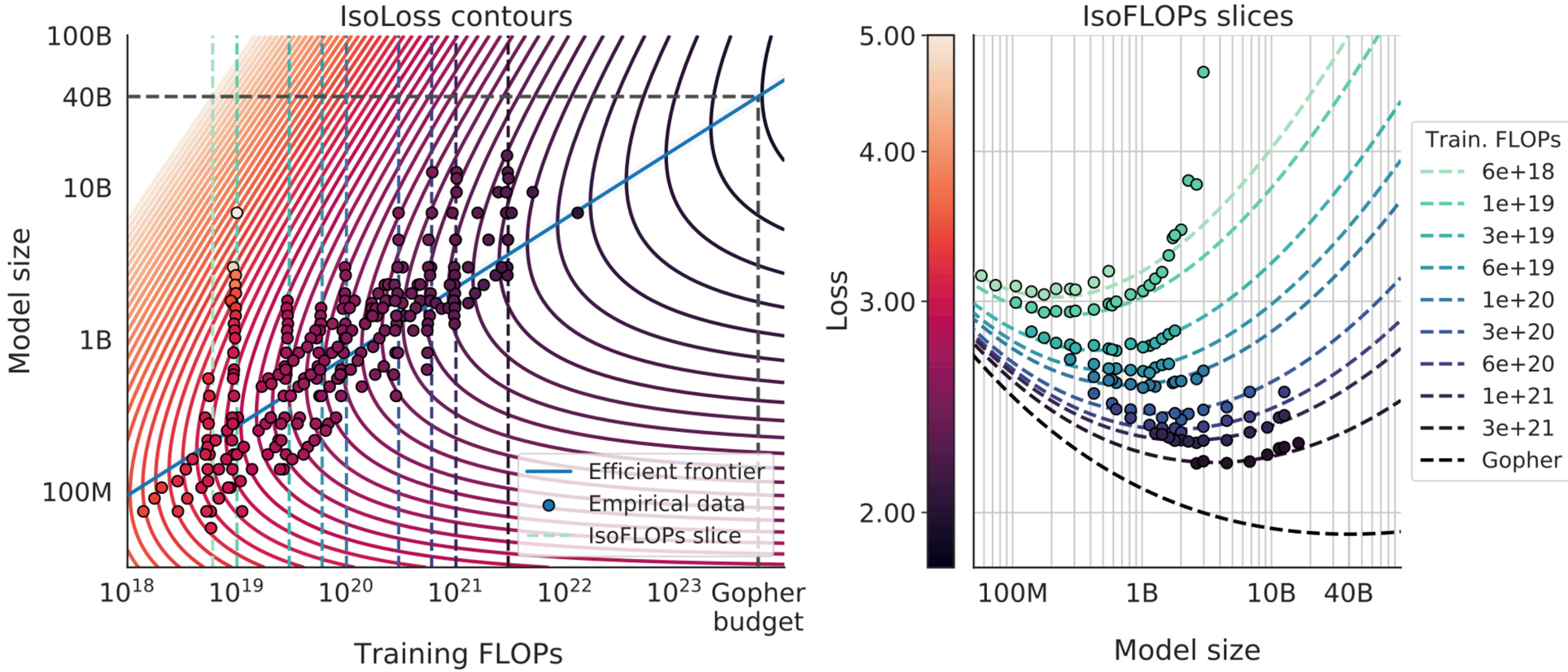






Method 3: Parametric Modeling [Hoffman+ 2022]

- Run a bunch of models on the size-data grid
- Use least squares to fit a joint scaling law



Chinchilla Model [Hoffman+ 2022]

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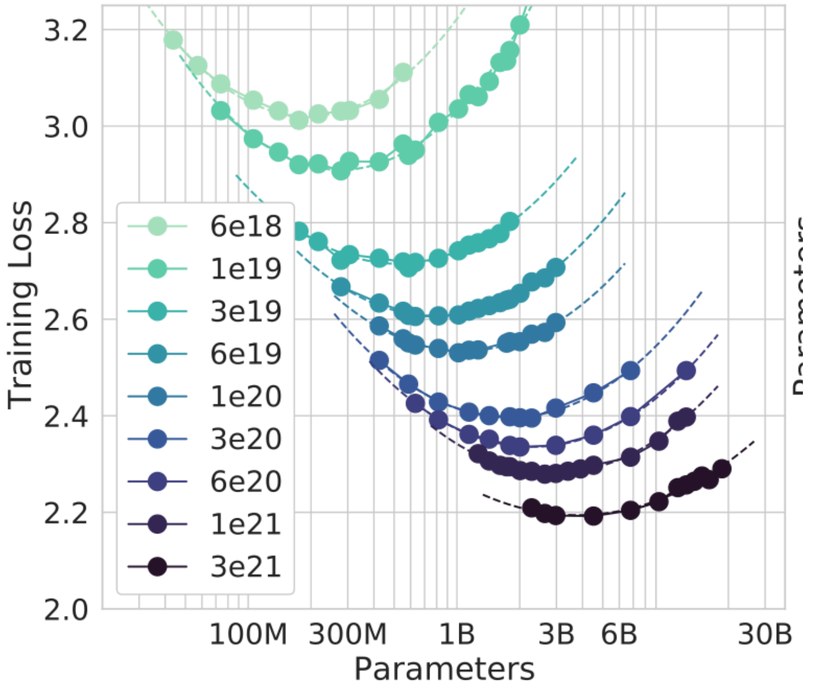
A new scaling laws and a new model

Model	Size (# Parameters)	Training Tokens
LaMDA (Thoppilan et al., 2022)	137 Billion	168 Billion
GPT-3 (Brown et al., 2020)	175 Billion	300 Billion
Jurassic (Lieber et al., 2021)	178 Billion	300 Billion
Gopher (Rae et al., 2021)	280 Billion	300 Billion
MT-NLG 530B (Smith et al., 2022)	530 Billion	270 Billion
Chinchilla	70 Billion	1.4 Trillion

But Train-Optimal May Not Be What We Want

- Chinchilla tells what gives the best model for fixed training compute
- But most of the compute in a real deployment is inference
  - So we should over-train

- Some examples:
  - GPT3 – 2 tokens / param
  - Chinchilla – 20 tokens / param
  - LLaMA 65B – 22 tokens / param
  - LLaMA 2 70B – 29 tokens / param
  - Mistral 7B – 110 tokens / param
  - LLaMA 3 70B – 215 tokens / param



Summary

- We can extend log-linearity (power law) to model size and compute

- Rethink the scenario
  - *Your friend has given you 10,000 H100s for a month, and asked you to build a good open source LLM*

- What do you do?
  - Lets us set the hyperparameters based on small models
  - Lets us make smart resource tradeoffs (model size vs. data size)
  - Scale up the model!

Summary

- Scaling laws are really surprising and useful tools

- Data scaling: understand how data affects models
- Model scaling: dramatically reduce costs for training
- Scaling as prediction: understand what problems can be brute forced

- Without scaling laws, we might…
  - Waste millions of dollars on "blind" trial-and-error
  - Produce "under-trained" models without knowing it
  - Fail to distinguish between "bad architecture" and "insufficient scale"
  - Lose the "extrapolation" advantage (train and pray 😢)