Quantifying (net) Energy and Complexity of the U.S. Economy

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Question:

Can we find a link among Energy and Modern Economic Structure?

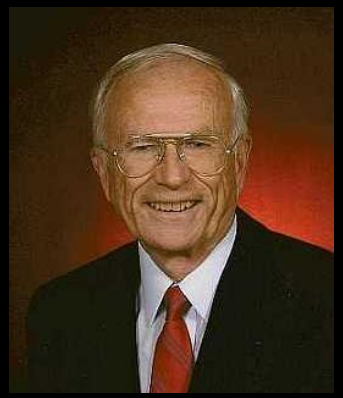
Data: U.S. Input-Output tables from Bureau of Economic Analysis

I use a combination of ideas to relate energy and economic structure

Howard T. Odum
(systems ecology)

Charles Hall
(ecology, net energy analysis)

Joseph A. Tainter
(anthropology)



Robert E. Ulanowicz
(systems ecology, information theory)

Me today
(engineer, systems)

Tainter: energy-complexity spiral

- Increased complexity needs resources
  - "… most of the time complexity increases to solve problems."
  - Societies "… subsequently must produce more energy and other resources to pay for the increased complexity."

    Tainter and Patzek (2012), *Drilling down : The Gulf Oil Debacle and Our Energy Dilemma.*

- Theory: Increasing gross &/or net energy resources facilitate increased complexity
- This presentation: quantify "structure" (~ complexity) of modern U.S. economy

C. Hall: EROI = energy return on energy invested (measure of net energy)

- How much energy to needed to obtain energy
- Concept is simple

$$\text{EROI} = \frac{\int (\text{Power Output})dt}{\int (\text{Power invested})dt}$$

- I use an interpretation with annual economic data (NPR=net power ratio; see King *et al.*, 2015, *Energies*):

$$\text{NPR}_{\text{econ}} = \frac{\$\text{ out}}{\$/\text{invested for energy}} = \frac{\text{GDP}}{\$/\text{yr spent by energy \& food sectors}}$$

Ulanowicz: Information theory metrics to quantify distribution of network *flows*

- X, Mutual Constraint
  - Increases with concentration of flows, "efficiency"
- Ψ, Conditional Entropy
  - Increases with more dispersed and uniform flows, "overhead" or "potential reserve"
- H = X + Ψ, Information Entropy
  - Total structural "capacity" (more enables more adaptation)

$$X = \sum_{i,j} \frac{T_{ij}}{T_{..}} \ln\left(\frac{T_{ij}T_{..}}{T_{i.}T_{.j}}\right)$$

$$\Psi = -\sum_{i,j} \frac{T_{ij}}{T_{..}} \ln\left(\frac{T_{ij}^2}{T_{i.}T_{.j}}\right)$$

$$H = -\sum_{i,j} \frac{T_{ij}}{T_{..}} \ln\left(\frac{T_{ij}}{T_{..}}\right)$$

$T_{..}$ = total flow in system

Ulanowicz (2009)

Understanding Ulanowicz's information theory interpretation for networks

1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4

- Uniform (fully connected)
  - X (Mutual Constraint) @ minimum (=0)
  - Ψ (Conditional Entropy) @ maximum
  - "redundant" undifferentiated organization

	1		
		1	
			1
1			

- One pathway of equal flows
  - X (Mutual Constraint) @ maximum
  - Ψ (Conditional Entropy) @ minimum (=0)
  - "efficient" differentiated organization

There is a defined information theory 'phase space' for networks

1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4

	1		
		1	
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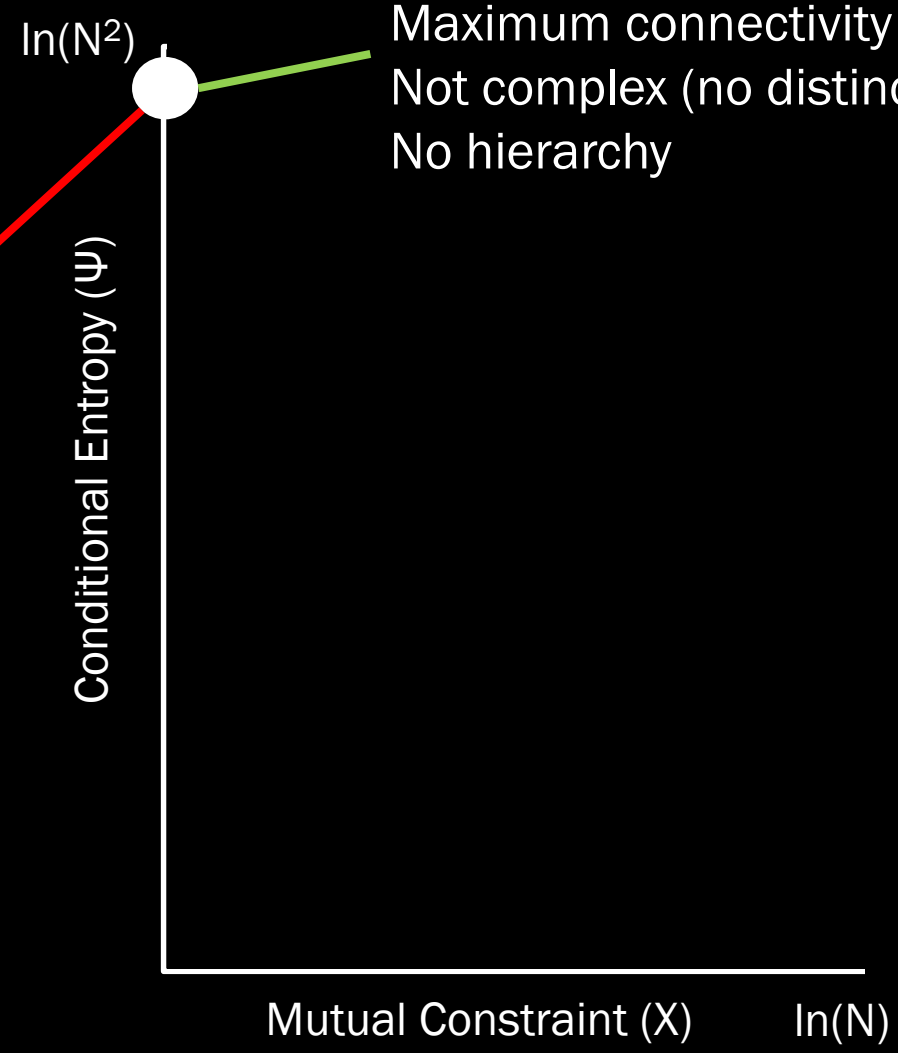

Point of maximum conditional entropy
Maximum connectivity
Not complex (no distinct parts)
No hierarchy

There is a defined information theory 'phase space' for networks

1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4
1/4	1/4	1/4	1/4

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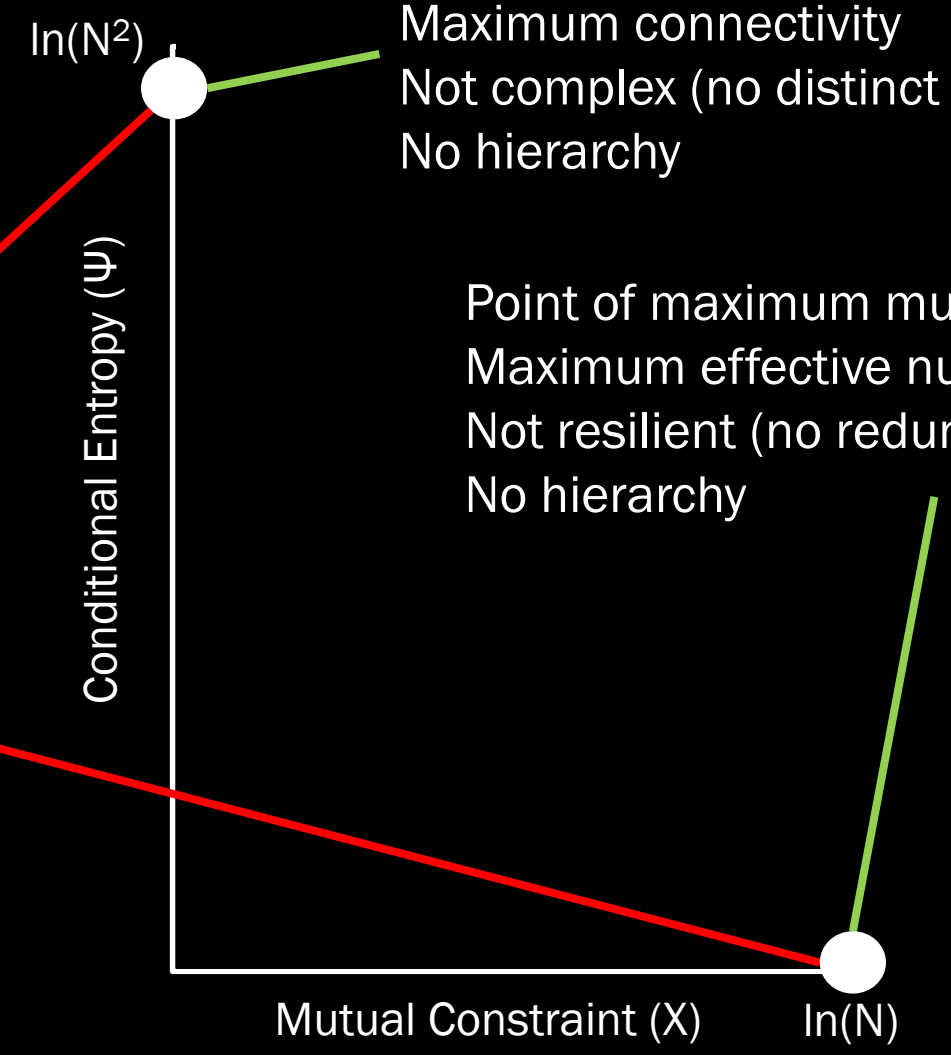
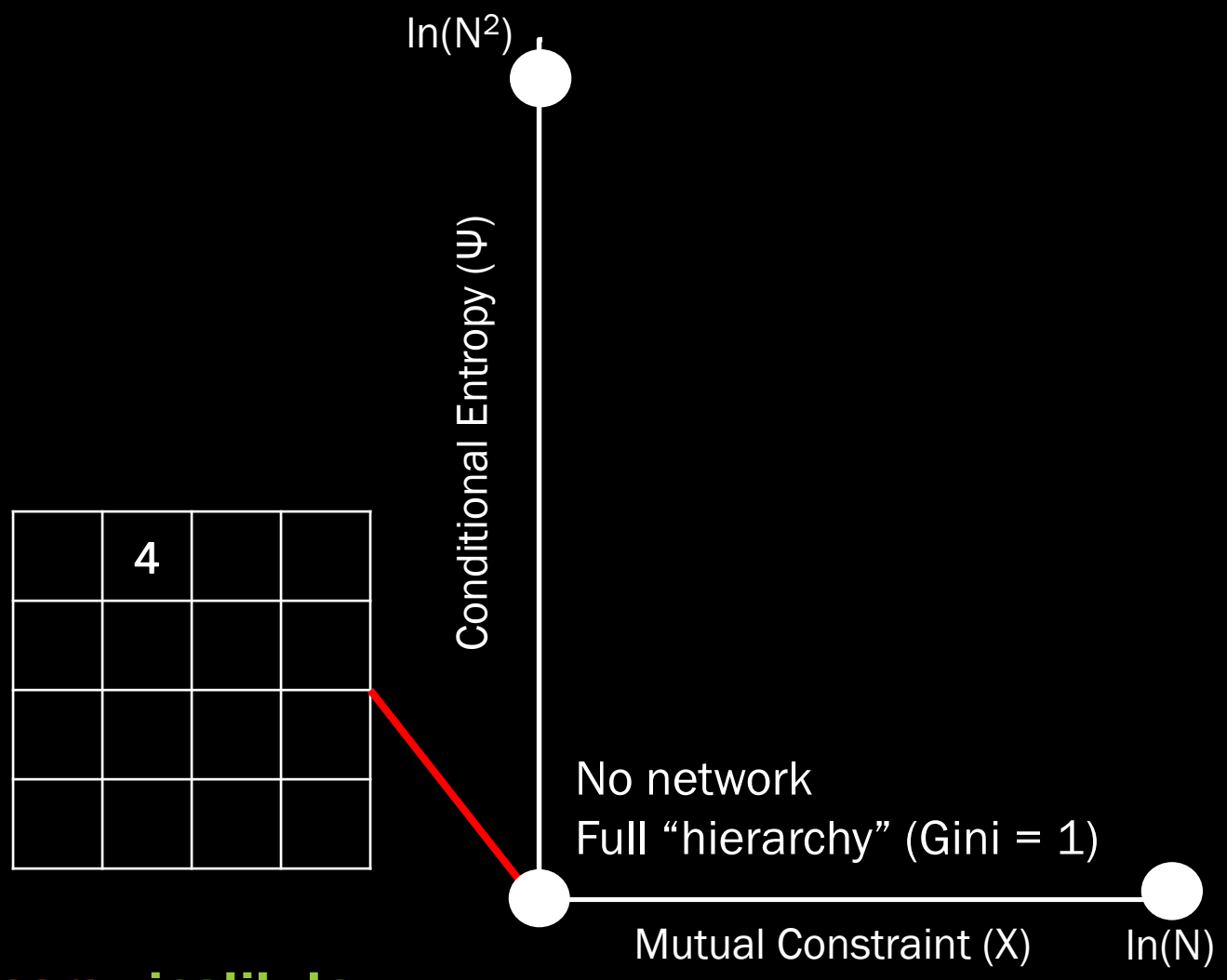


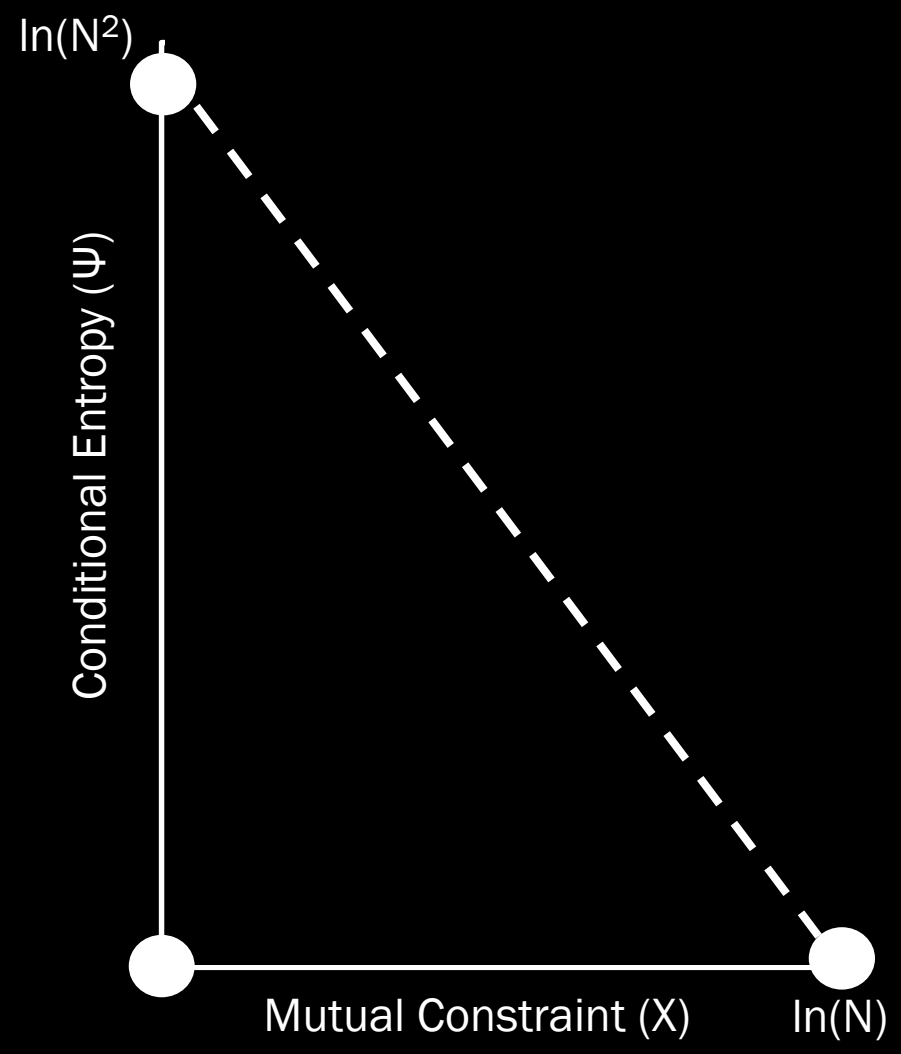
Point of maximum conditional entropy
Maximum connectivity
Not complex (no distinct parts)
No hierarchy

Point of maximum mutual constraint
Maximum effective number of roles
Not resilient (no redundancy)
No hierarchy

There is a defined information theory 'phase space' for networks



There is a defined information theory 'phase space' for networks

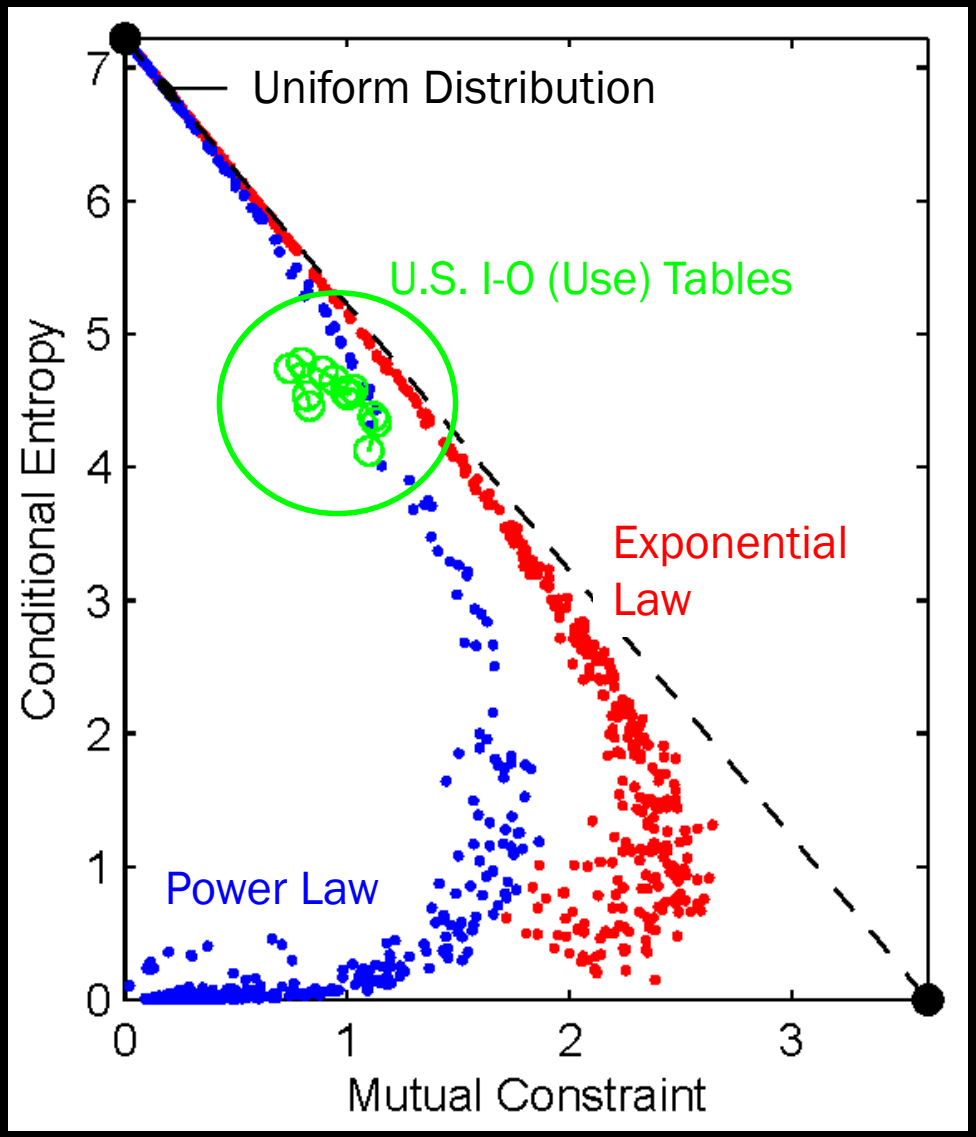


Short description of U.S. Input-Output data

- U.S. input-output (Use) summary benchmark tables 1947 to 2012
  - 79 sectors 1947-1992 (SIC format)
  - 69 sectors 1997-2012 (NAICS format)
- "Harmonized" to a consistent 37-sector description across all years
  - There are 5 "energy and food" sectors
    - Important for relating to net energy concept

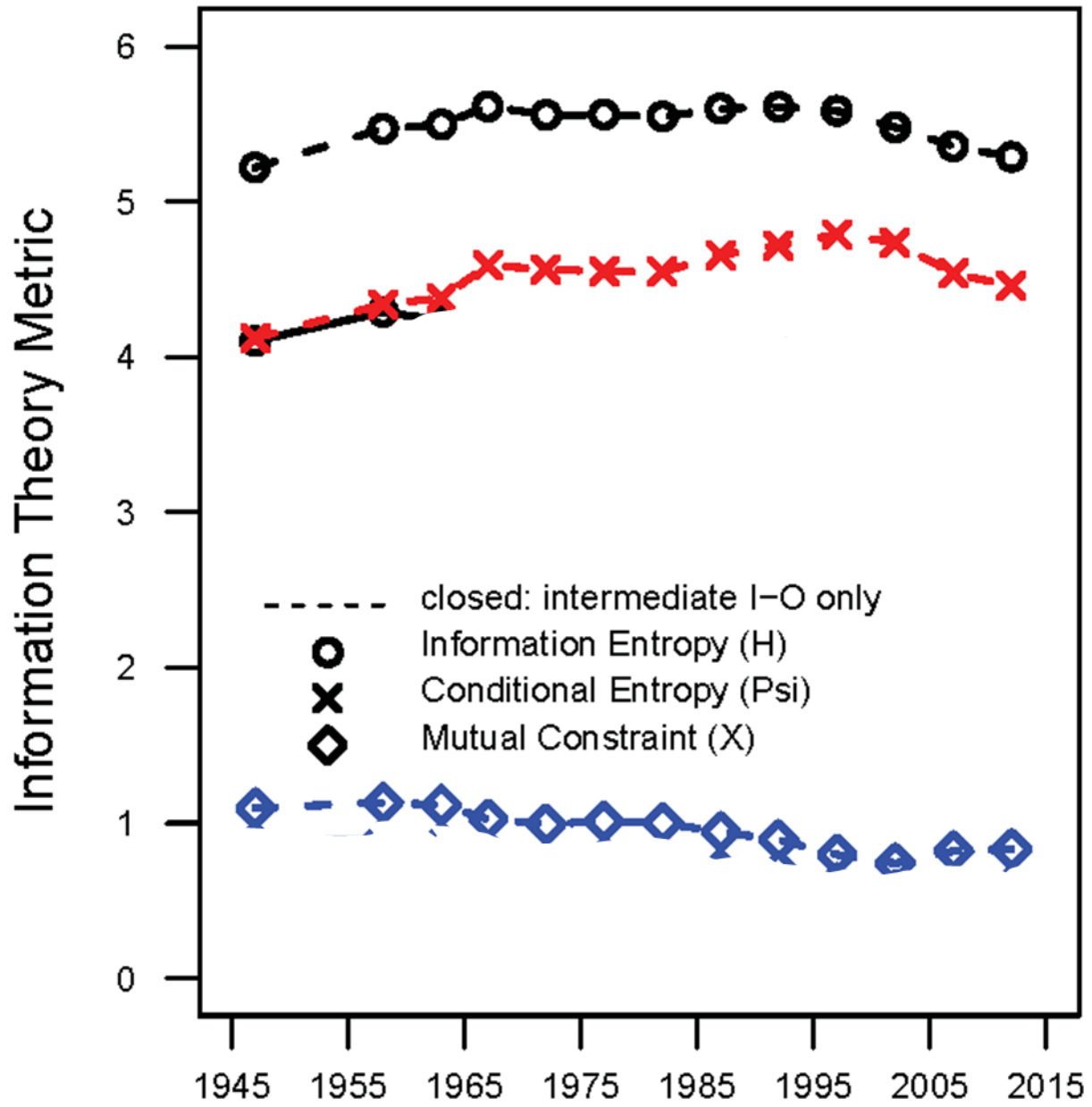
Where do the U.S. Input-Output (Use) Tables reside?

- Shown:
  - Intermediate transactions only
  - No GDP (output) or Value Added (input)



King, C.W. (*in review*)

Results vs. time



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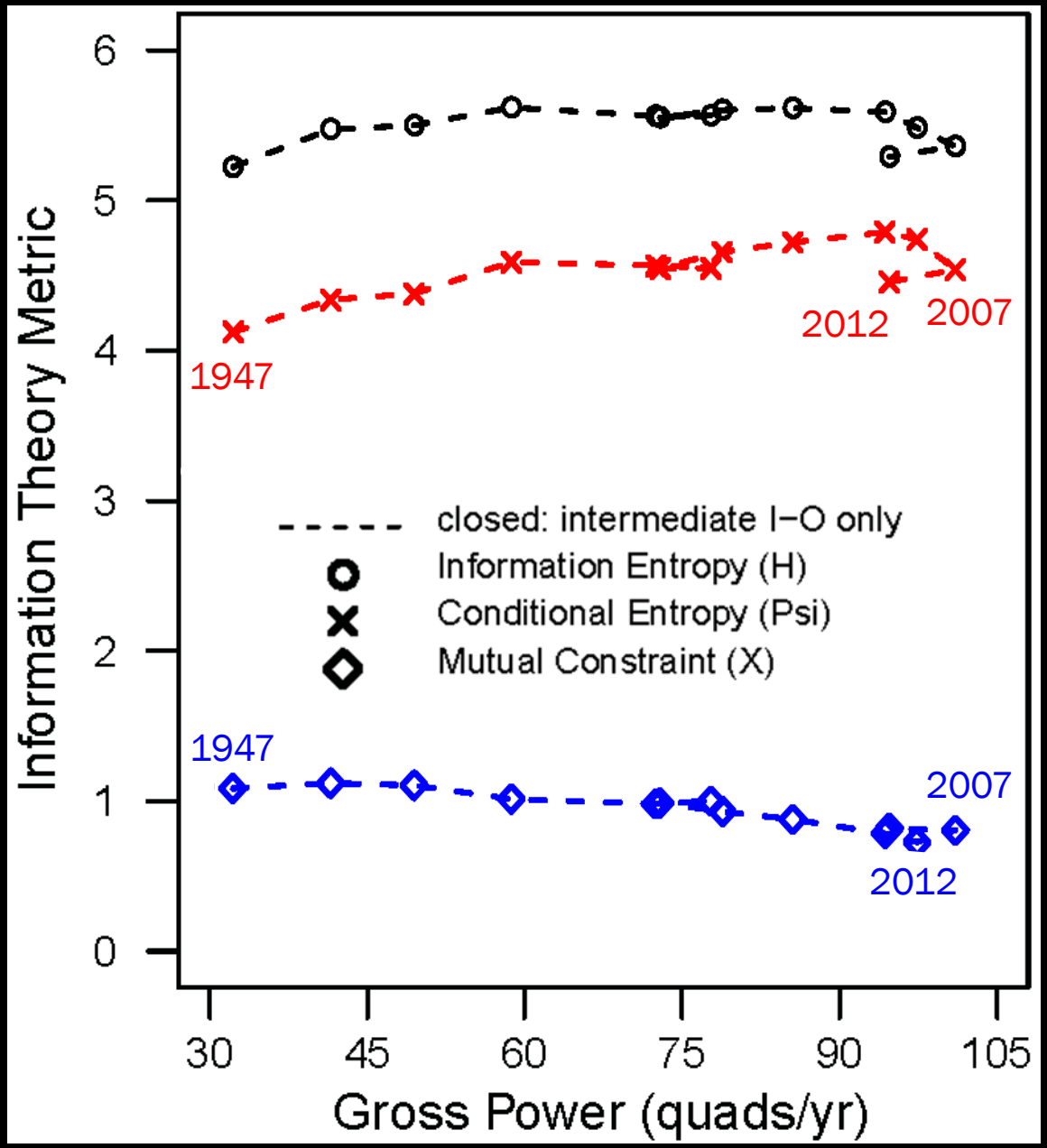
Results vs. Gross Power

(total primary energy consumption per year)



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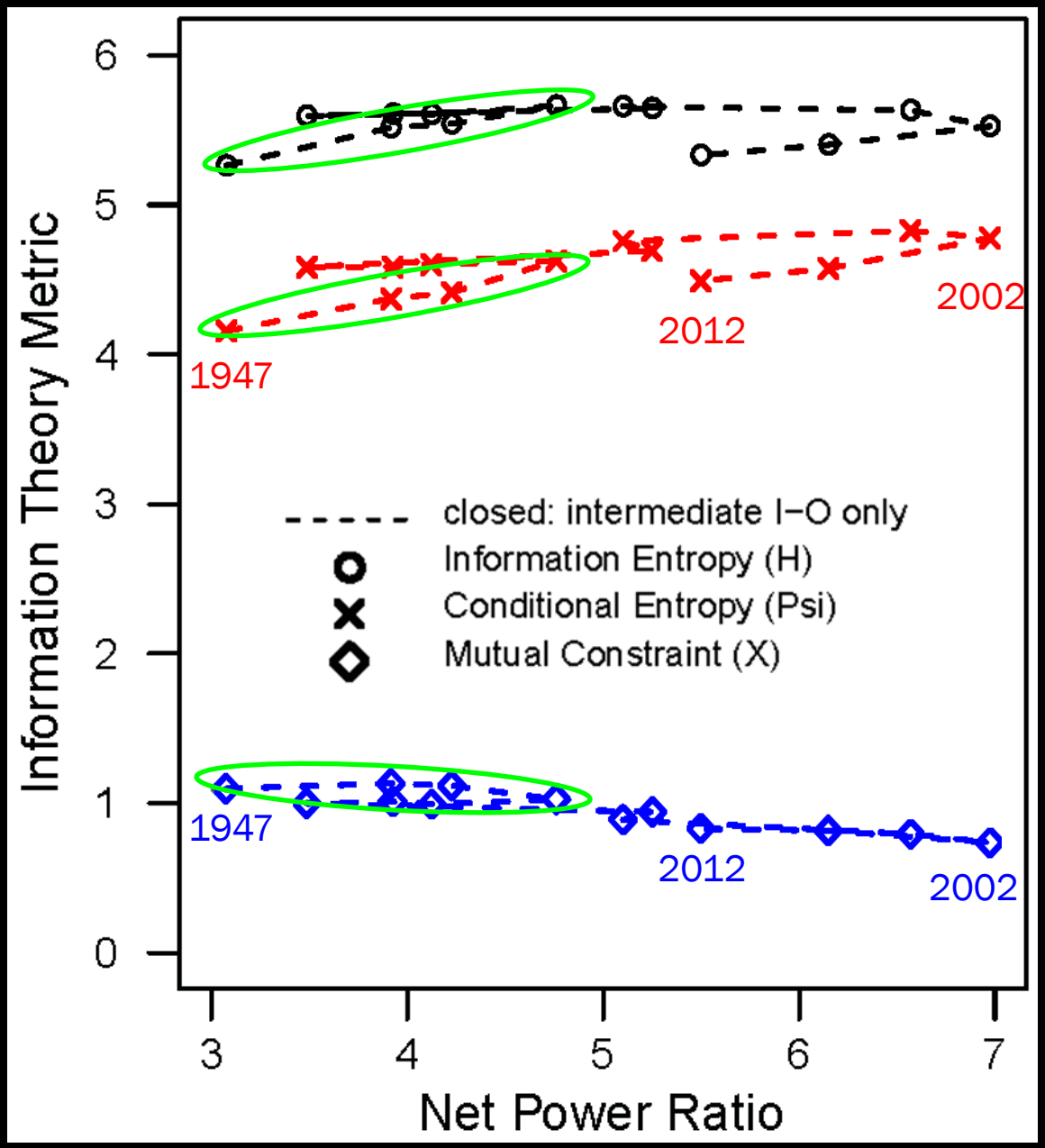
Results vs. Net Power

Phase 1:

(1947-1967)

Metric	Change (%/yr)
Gross Power	+4.1
Net Power Ratio	+2.7
H (info. Entropy)	+0.4
Ψ (cond. Entropy)	+0.6
X (mutual const.)	-0.3



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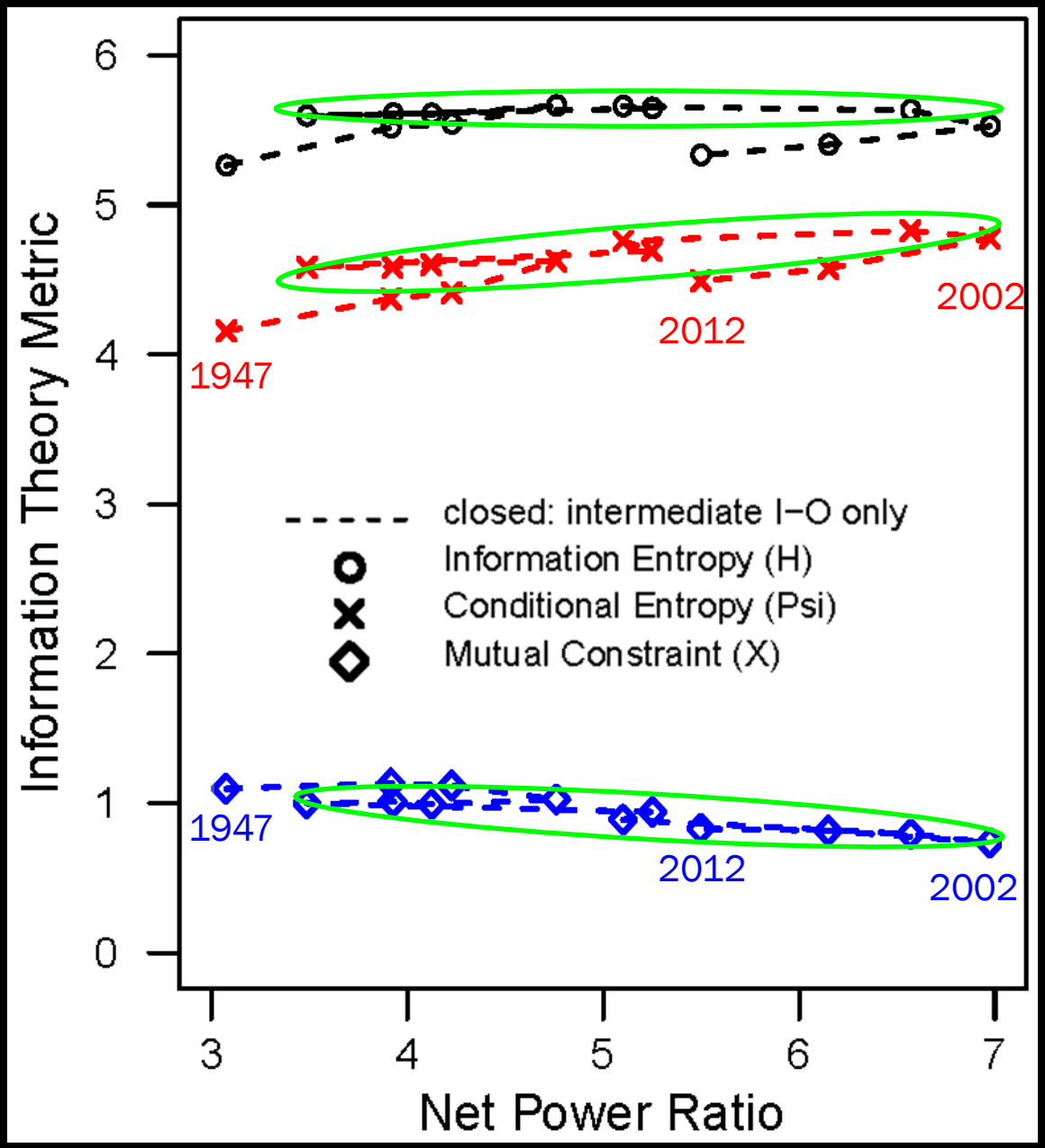
Results vs. Net Power

Phase 2:

(1967-2002)

Metric	Change (%/yr)
Gross Power	+1.9
Net Power Ratio	+1.3
H (info. Entropy)	-0.1
Ψ (cond. Entropy)	+0.1
X (mutual const.)	-0.8



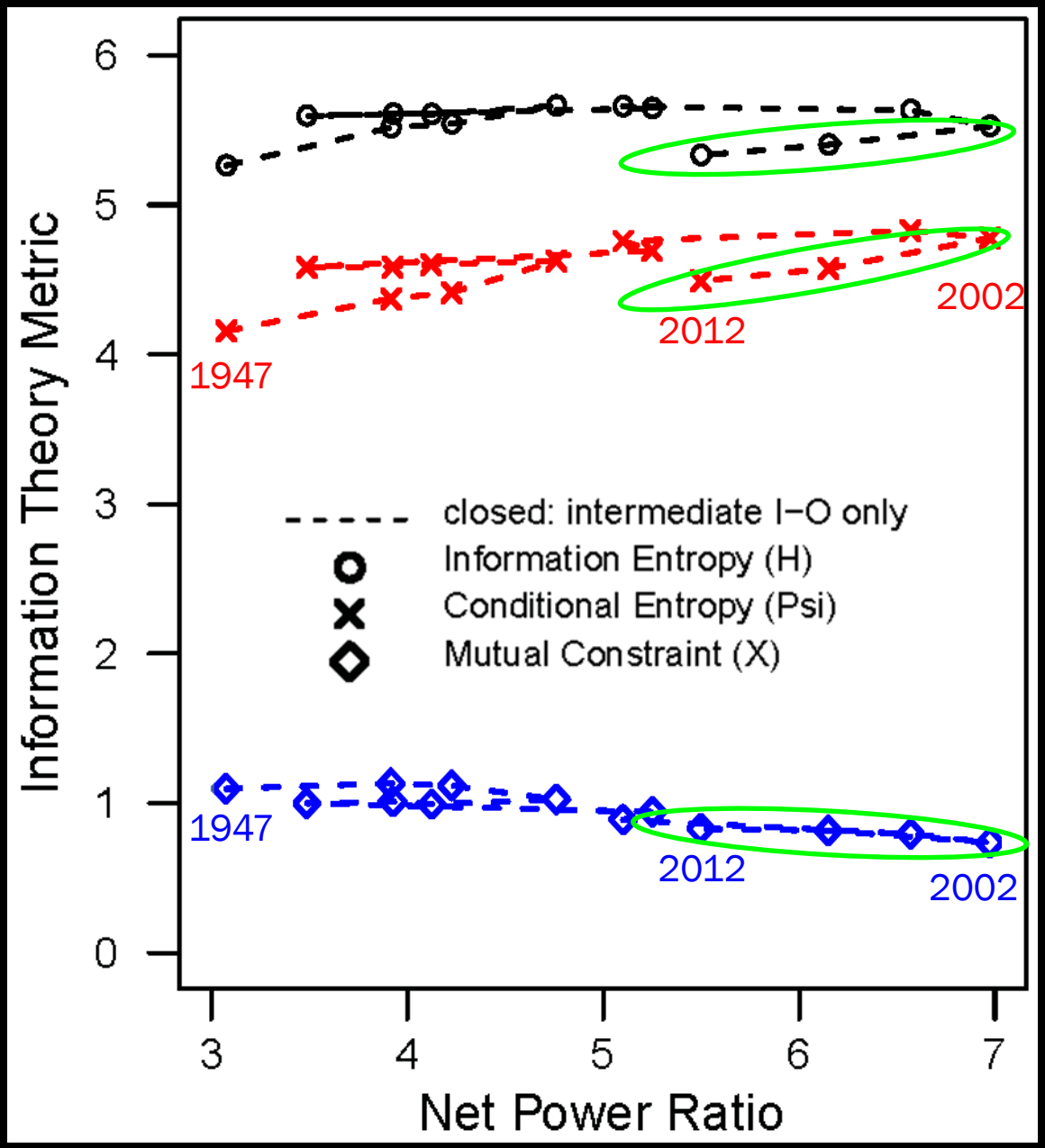
King, C.W. (*in review*)

Results vs. Net Power

Phase 3:

(2002-2012)

Metric	Change (%/yr)
Gross Power	-0.3
Net Power Ratio	-2.1
H (info. Entropy)	-0.4
Ψ (cond. Entropy)	-0.6
X (mutual const.)	+1.2



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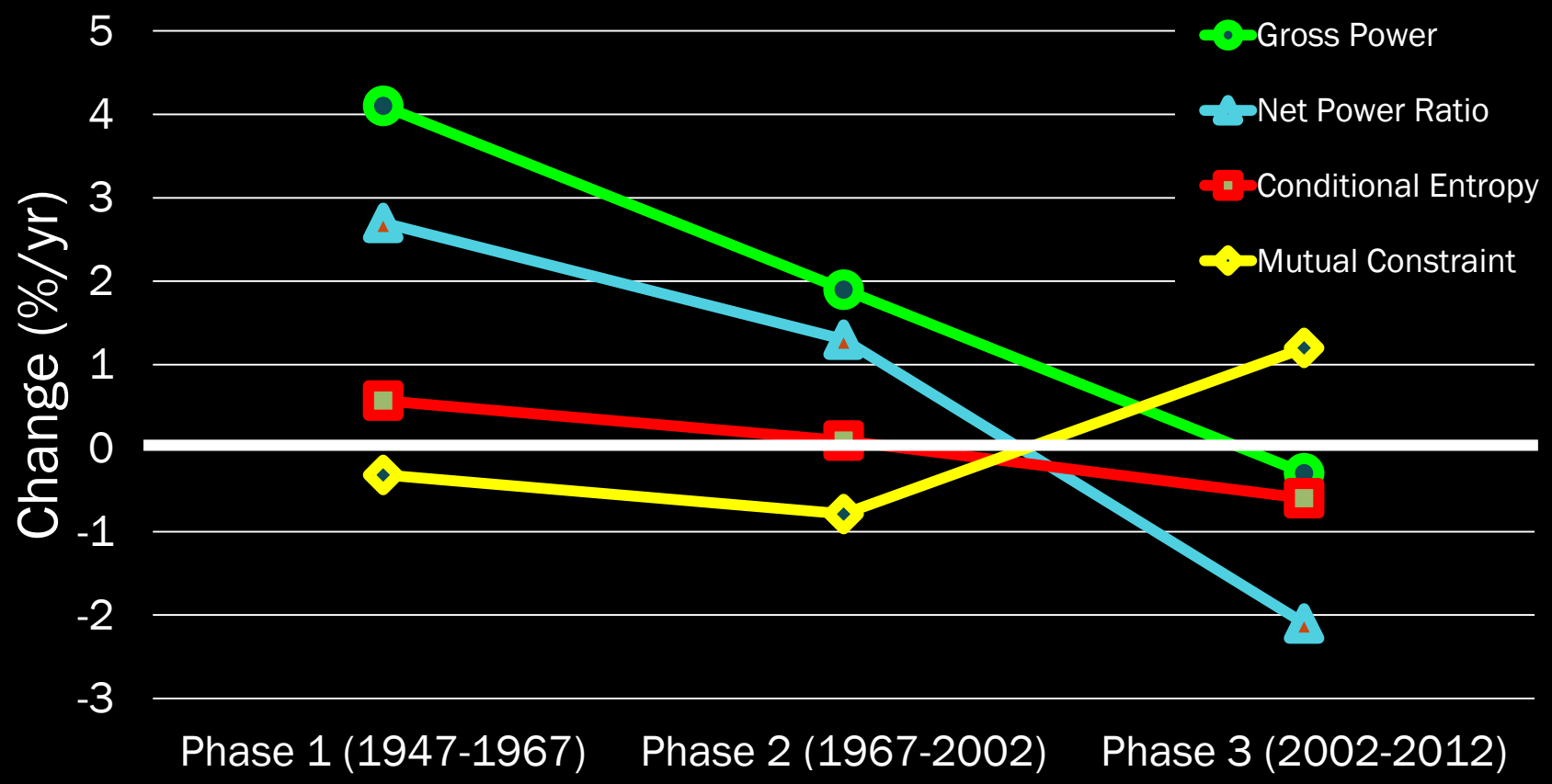
Summary of Trends

	Gross Power	Net Power (economic)	Conditional Entropy	Mutual Constraint
1947-1967	↑	↑	↑	↓
1967-2002	↑	↑	↔	↓
2002-2012	↓	↓	↓	↑



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Takeaways

- There is a connection between the structure of the (U.S.) economy and net energy
  - Economy started concentrating flows more after "food and energy" became more expensive
- Energy and food have stopped getting cheaper since ~2000
  - Fundamental economic structural change related to energy (food = energy)

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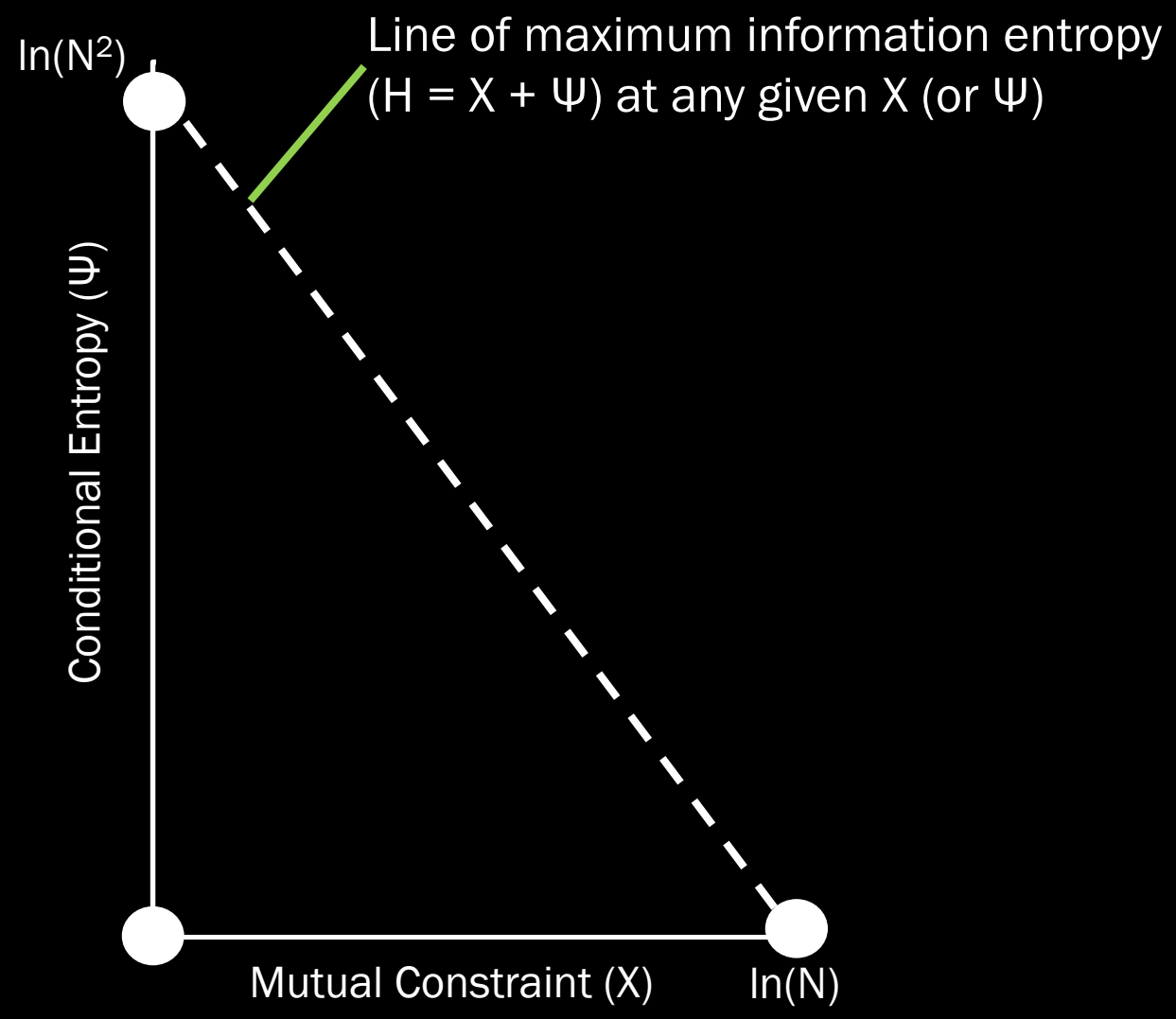
There is a defined information theory 'phase space' for networks



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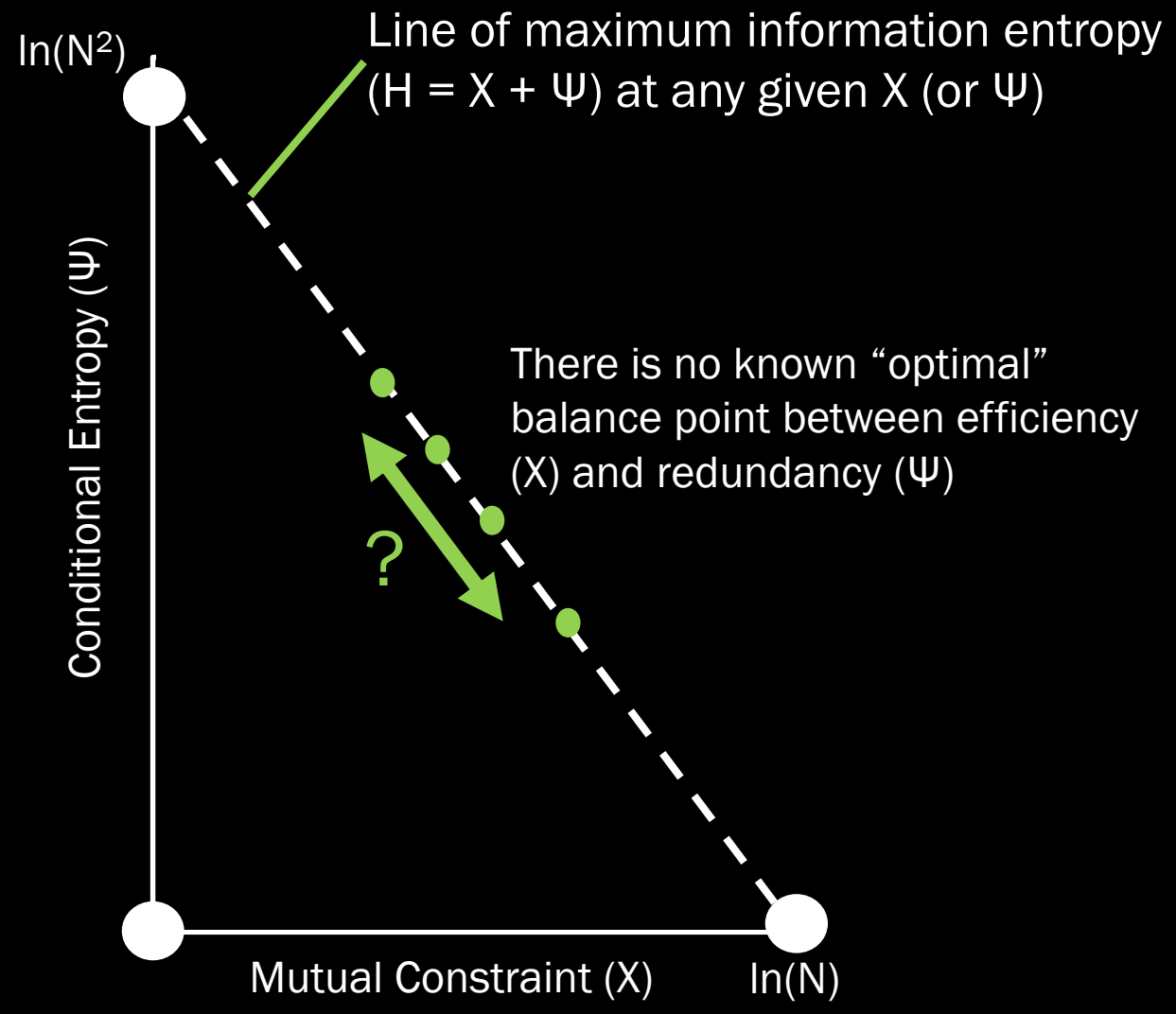


How do metrics change as you simplify the model?

Info. Entropy = Mutual Constraint + Cond. Entropy ($H = X + \Psi$)

Table 3 Table showing correlations for 37, 12, 7, and each 2-sector breakdown for ***information entropy for the closed model*** *without Value Added as inputs and GDP as outputs.*

37	12	7	2						
			Energy & Food	Health	Govt.	Elec. & Info.	Banking	Mfg. & Const.	Business
1	0.46	0.14	-0.15	-0.044	0.19	0.31	-0.18	0.37	0.081
–	1	0.94	-0.76	0.79	-0.2	0.7	0.73	-0.63	0.85
–	–	1	-0.83	0.87	-0.21	0.68	0.91	-0.85	0.96
–	–	–	1	-0.55	-0.099	-0.86	-0.86	0.7	-0.91
–	–	–	–	1	-0.61	0.31	0.76	-0.79	0.75
–	–	–	–	–	1	0.27	-0.14	0.23	-0.018
–	–	–	–	–	–	1	0.65	-0.51	0.72
–	–	–	–	–	–	–	1	-0.95	0.94
–	–	–	–	–	–	–	–	1	-0.86
–	–	–	–	–	–	–	–	–	1

King, C.W. (*in review*)

How do metrics change as you simplify the model?

Info. Entropy = Mutual Constraint + Cond. Entropy ($H = X + \Psi$)

Table 5 Table showing correlations for 37, 12, 7, and each 2-sector breakdown for ***mutual constraint for the closed model*** *without Value Added as inputs and GDP as outputs.*

37	12	7	2						
			Energy & Food	Health	Govt.	Elec. & Info.	Banking	Mfg. & Const.	Business
1	0.98	0.86	0.93	0.24	0.34	-0.92	-0.8	0.93	-0.73
–	1	0.9	0.96	0.18	0.28	-0.87	-0.86	0.94	-0.71
–	–	1	0.89	0.12	0.17	-0.68	-0.77	0.84	-0.5
–	–	–	1	0.035	0.2	-0.87	-0.84	0.9	-0.59
–	–	–	–	1	0.82	-0.29	-0.37	0.3	-0.46
–	–	–	–	–	1	-0.48	-0.45	0.43	-0.59
–	–	–	–	–	–	1	0.71	-0.85	0.7
–	–	–	–	–	–	–	1	-0.89	0.74
–	–	–	–	–	–	–	–	1	-0.8
–	–	–	–	–	–	–	–	–	1

King, C.W. (*in review*)

How do metrics change as you simplify the model?

Info. Entropy = Mutual Constraint + Cond. Entropy ($H = X + \Psi$)

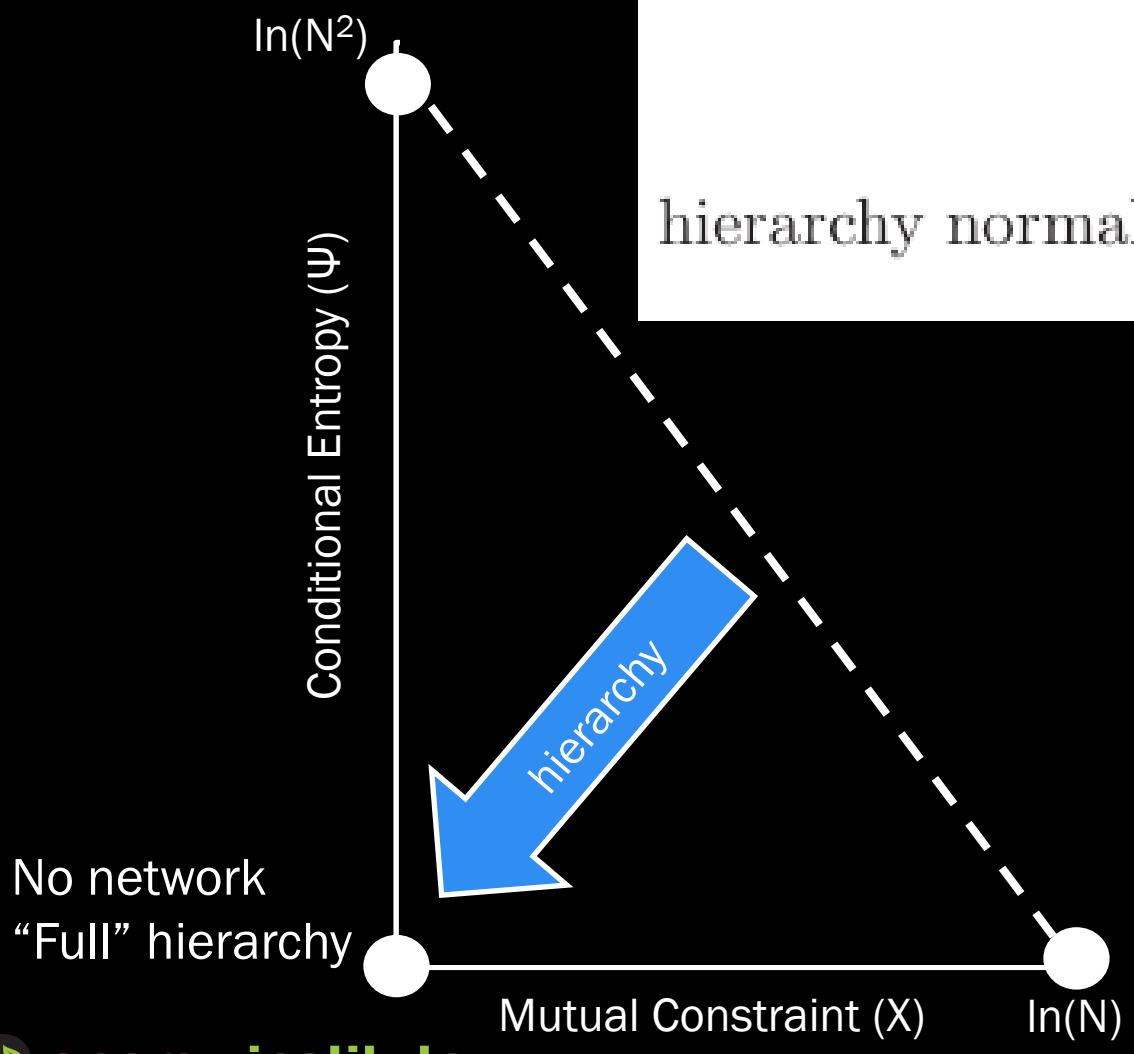
Table 7 Table showing correlations for 37, 12, 7, and each 2-sector breakdown for ***conditional entropy for the closed model*** *without Value Added as inputs and GDP as outputs.*

37	12	7	2						
			Energy & Food	Health	Govt.	Elec. & Info.	Banking	Mfg. & Const.	Business
1	0.89	0.79	-0.56	0.56	-0.1	0.65	0.48	-0.3	0.7
–	1	0.98	-0.66	0.82	-0.23	0.61	0.79	-0.69	0.9
–	–	1	-0.7	0.86	-0.22	0.57	0.88	-0.8	0.95
–		–	1	-0.38	-0.2	-0.77	-0.8	0.6	-0.84
–	–	–	–	1	-0.62	0.13	0.72	-0.74	0.72
–	–	–	–	–	1	0.4	-0.1	0.21	0.012
–	–	–	–	–	–	1	0.52	-0.35	0.64
–	–	–	–	–	–	–	1	-0.95	0.93
–	–	–	–	–	–	–	–	1	-0.83
–	–	–	–	–	–	–	–	–	1

King, C.W. (*in review*)

$$\text{hierarchy} = ln(N^2) - \sqrt{X^2 + \Psi^2}$$

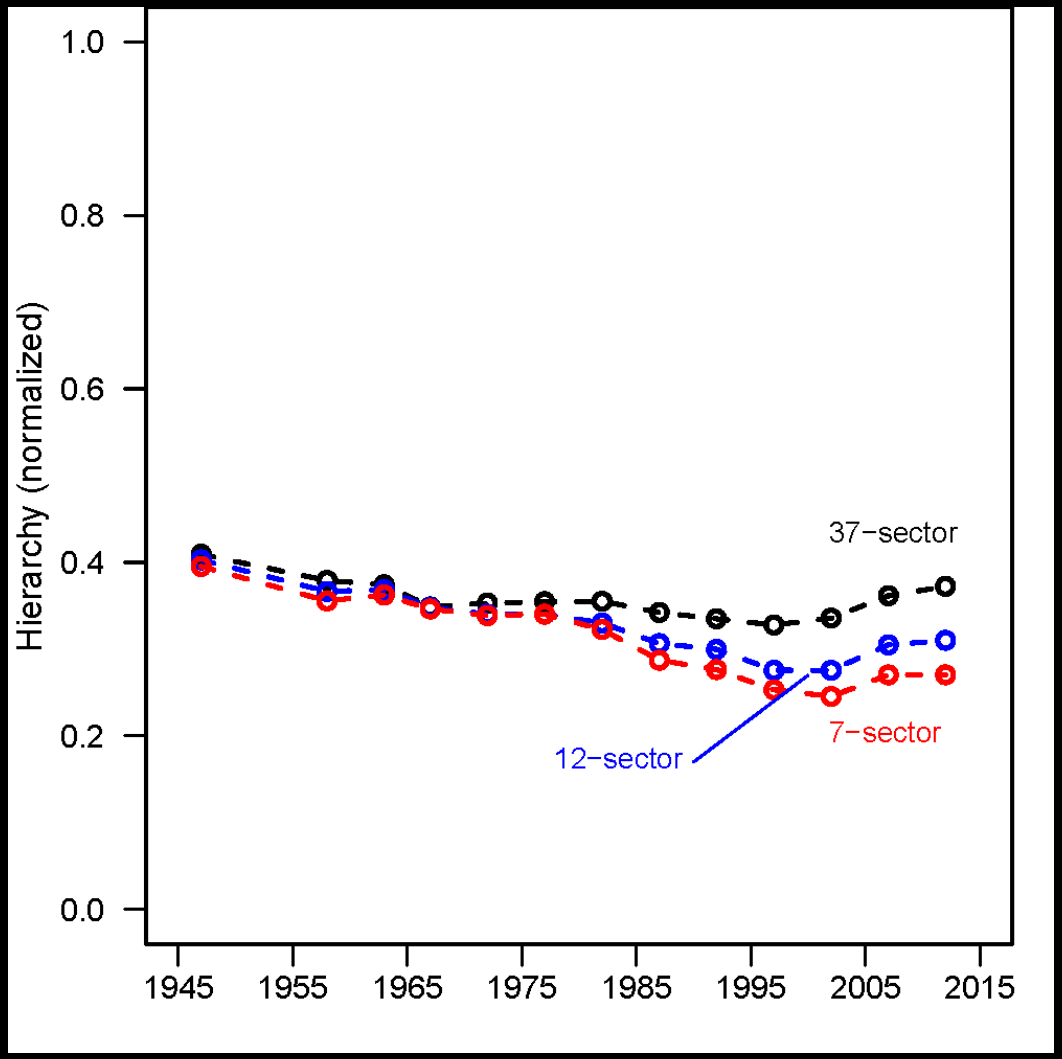
$$\text{hierarchy normalized} = 1 - \frac{\sqrt{X^2 + \Psi^2}}{ln(N^2)}$$



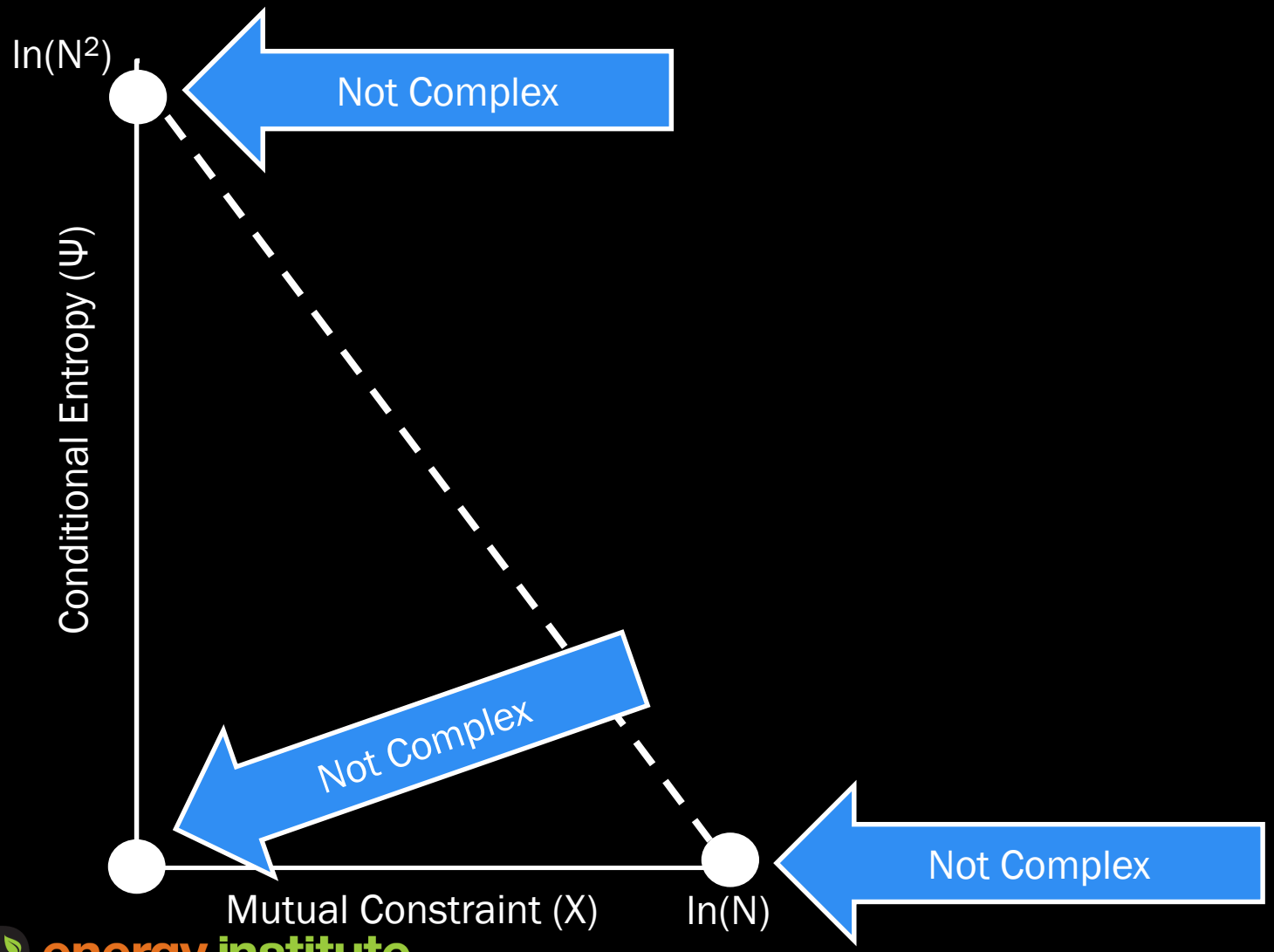
“Hierarchy” started increasing from 1997 to 2002

1997 had fewer intermediate energy expenditures

2002 had fewest intermediate “food and energy” expenditures



Quantifying "complexity" as a single number is problematic …



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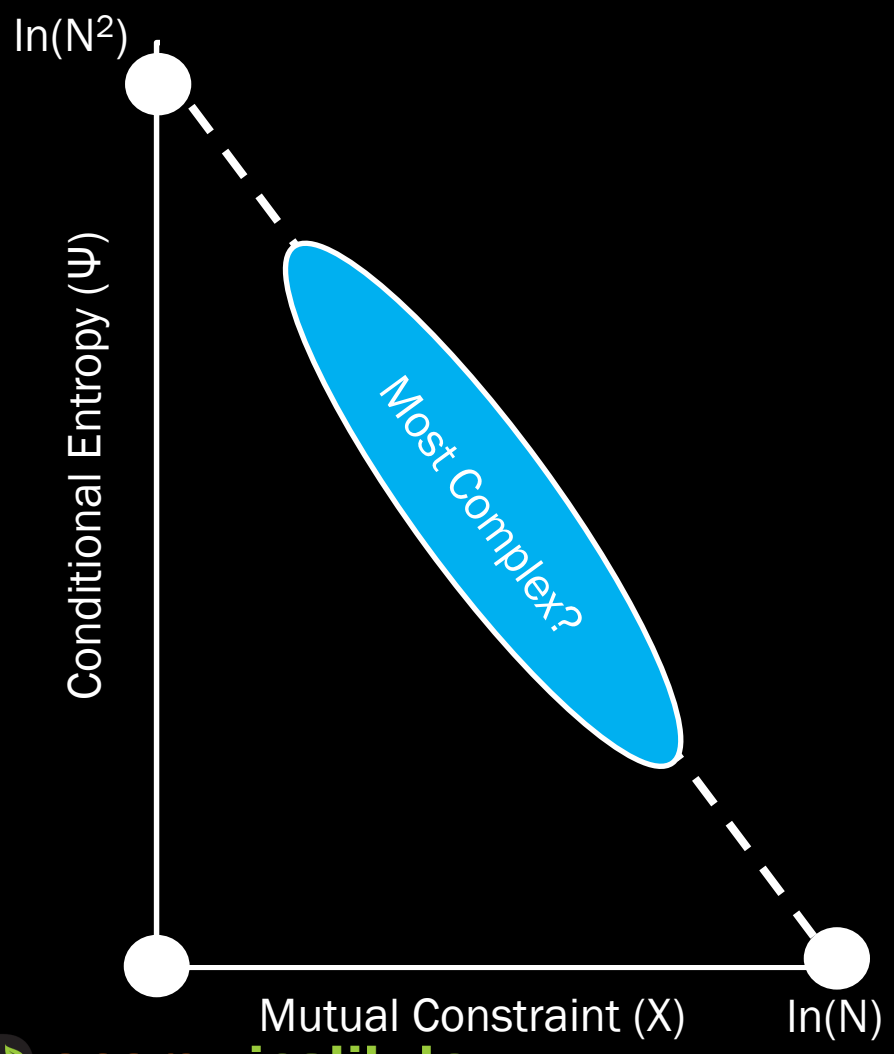

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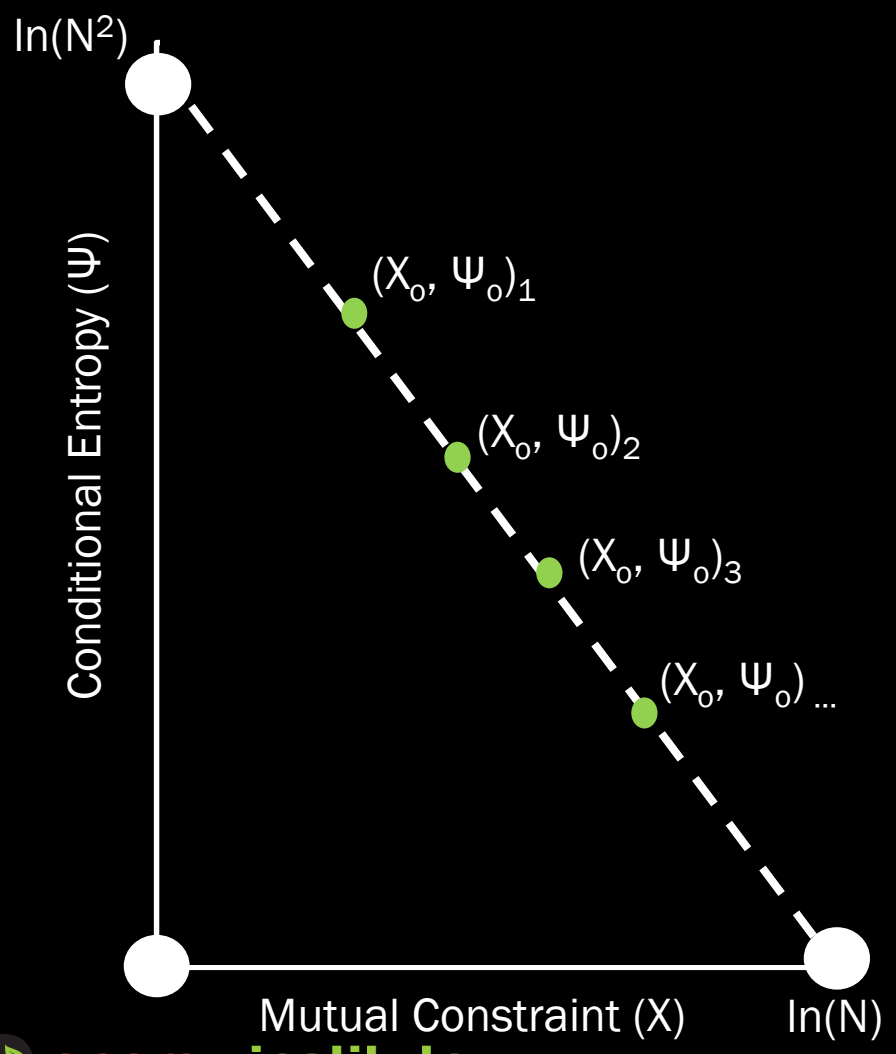

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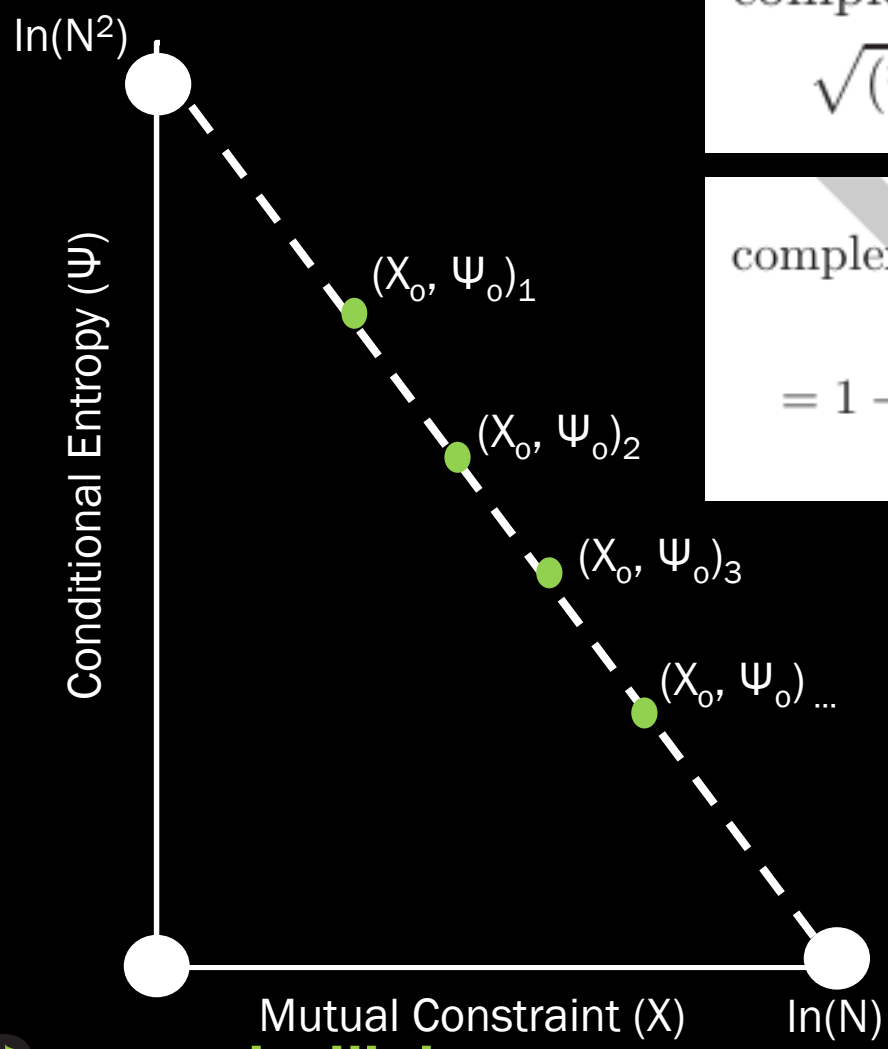
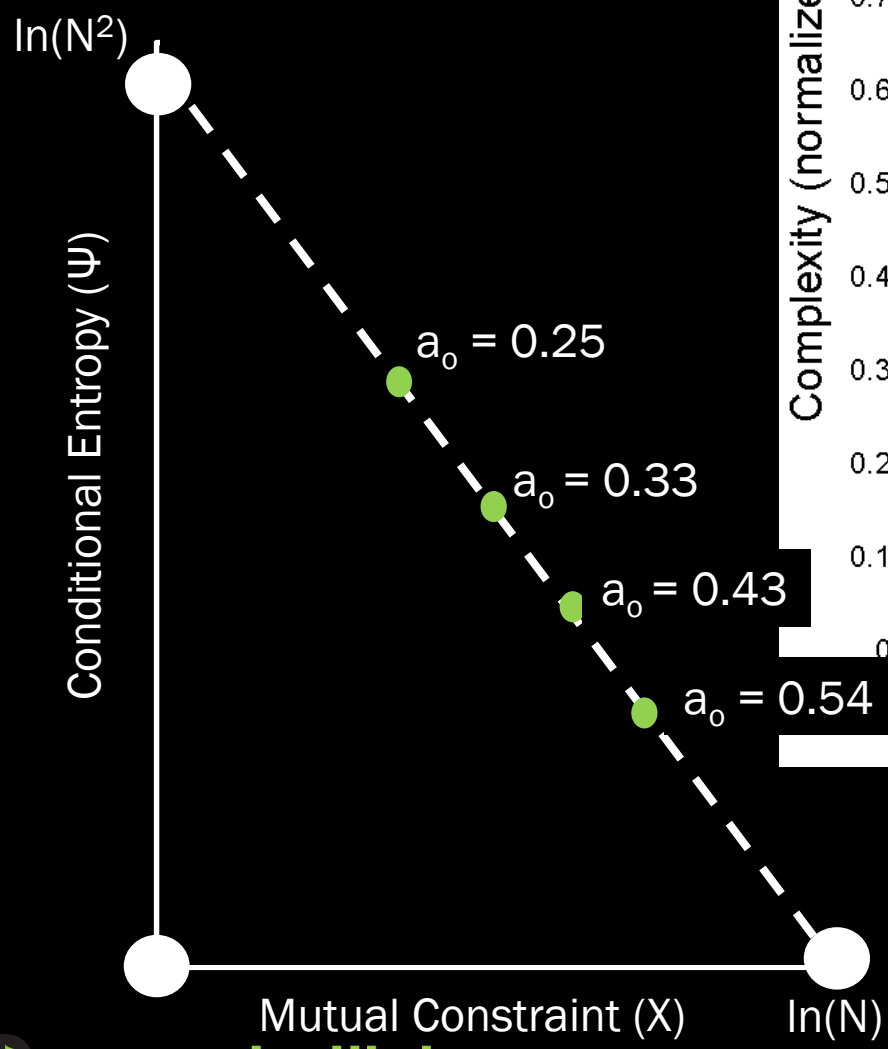
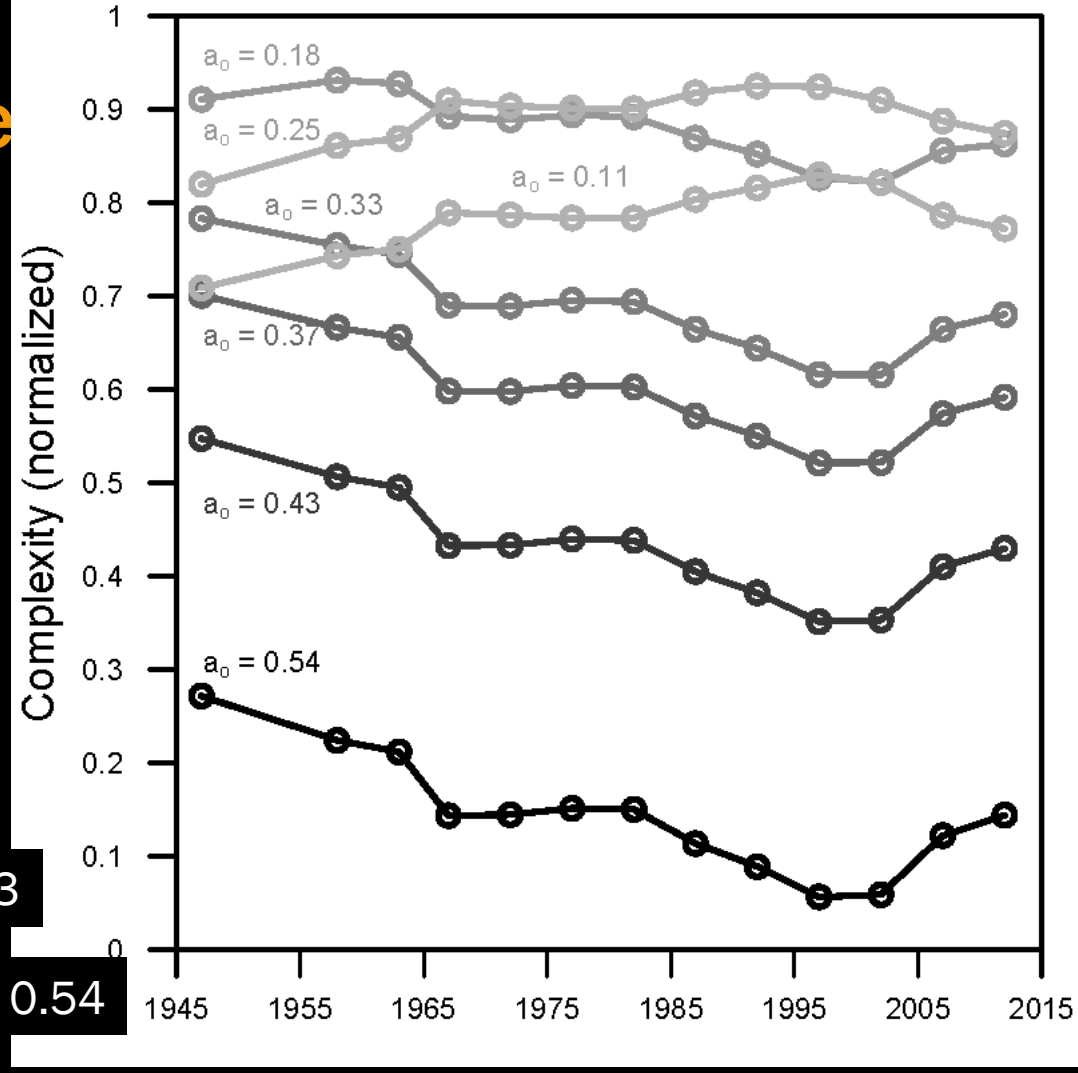


$$\text{complexity} = \sqrt{(ln(N^2) - 2X_o)^2 + X_o^2} - \sqrt{(\Psi - (ln(N^2) - 2X_o))^2 + (X - X_o)^2}$$

$$\text{complexity normalized} = \frac{\text{complexity}}{\text{maximum complexity}} = 1 - \frac{\sqrt{(\Psi - (ln(N^2) - 2X_o))^2 + (X - X_o)^2}}{\sqrt{(ln(N^2) - 2X_o)^2 + X_o^2}}$$

Quantifying "comple
is problematic …

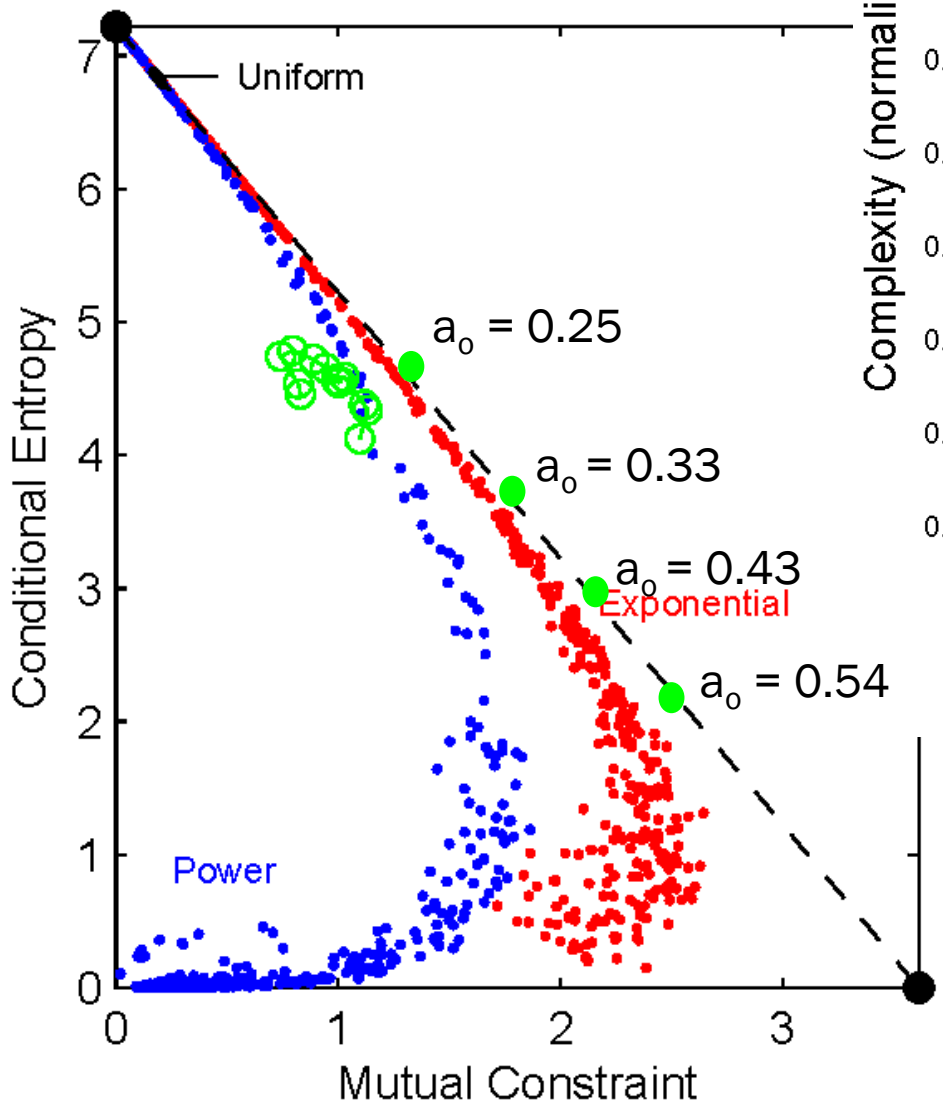


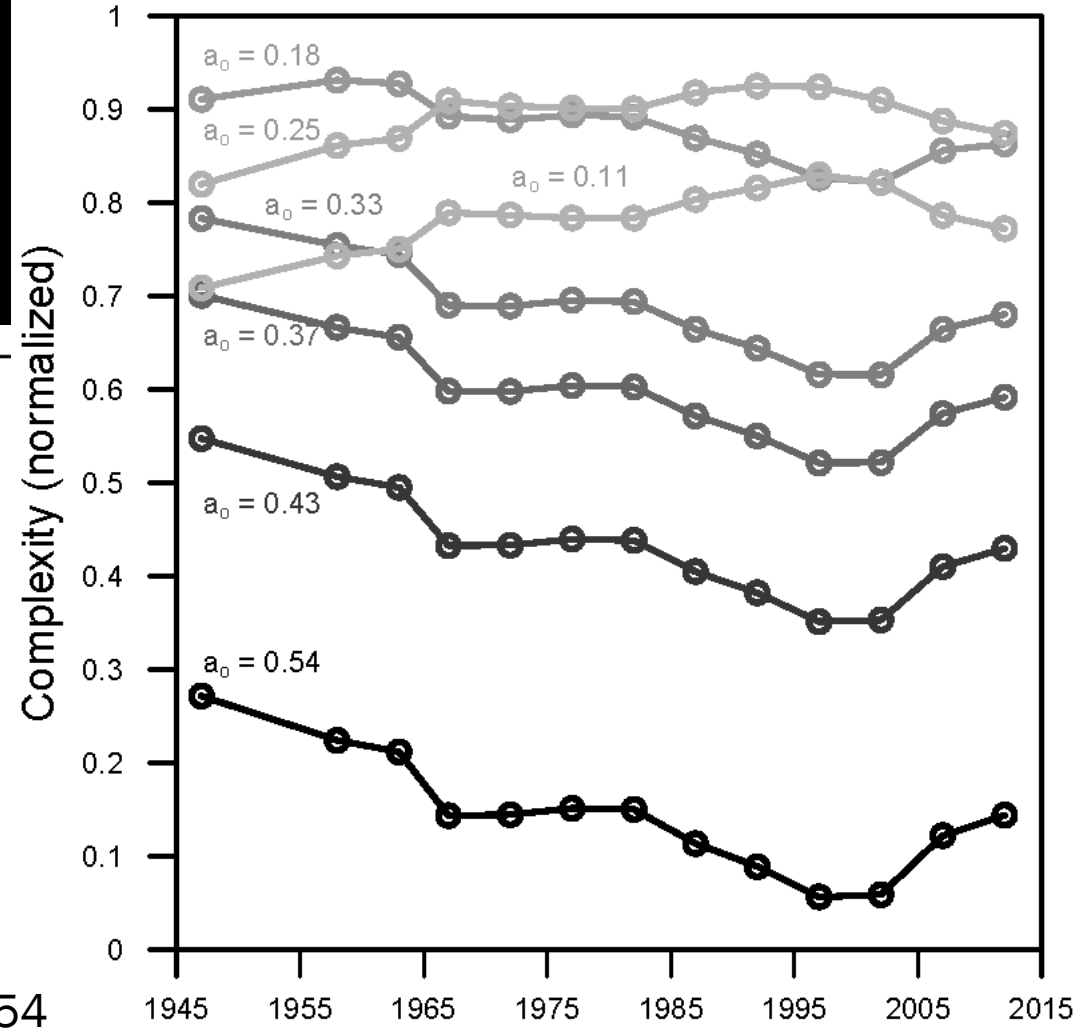


"Optimal point":

$a_o = X_O/(X_O + \psi_O)$

Quantifying "complexity" is problematic



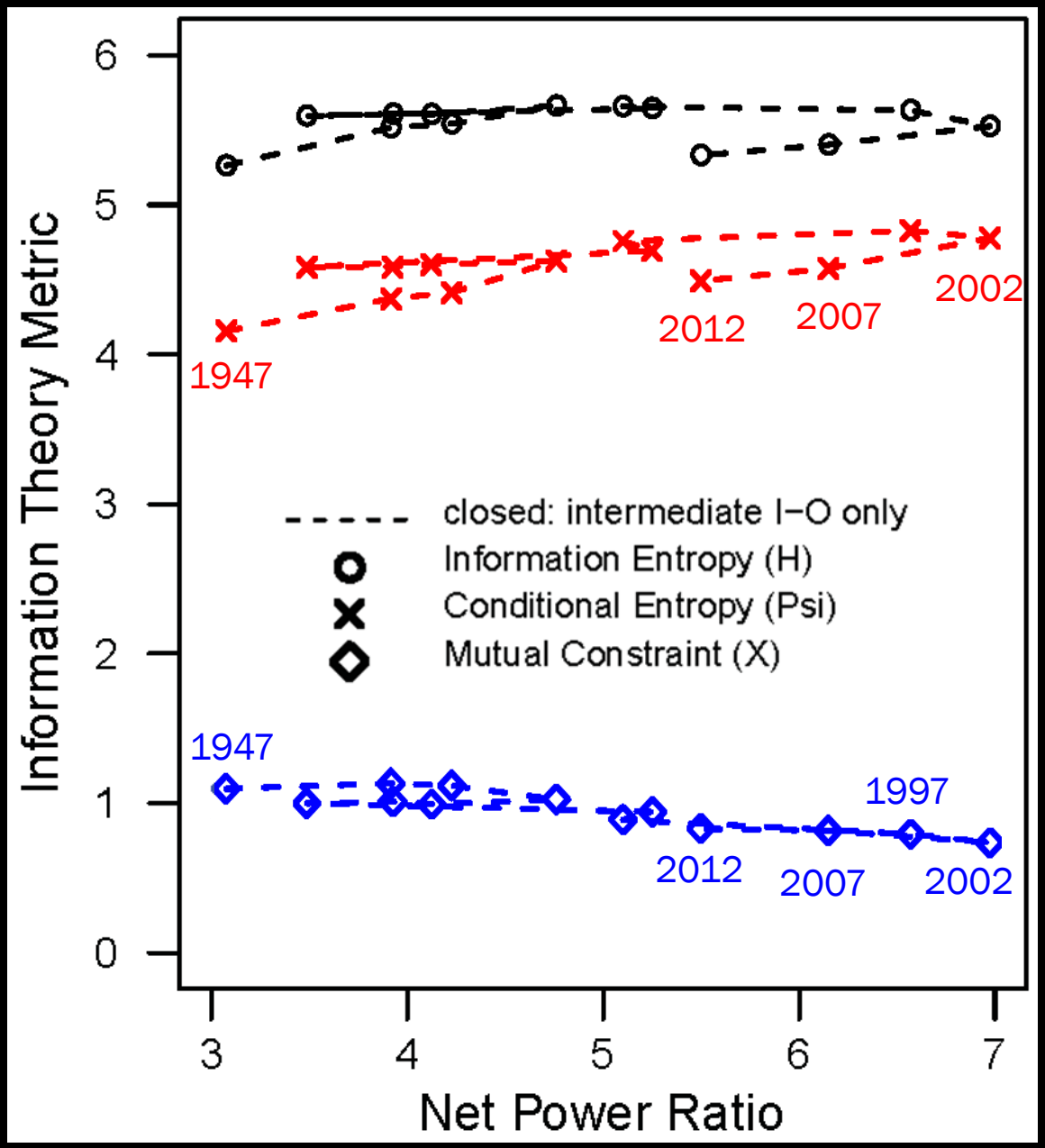


Results vs. Net Power

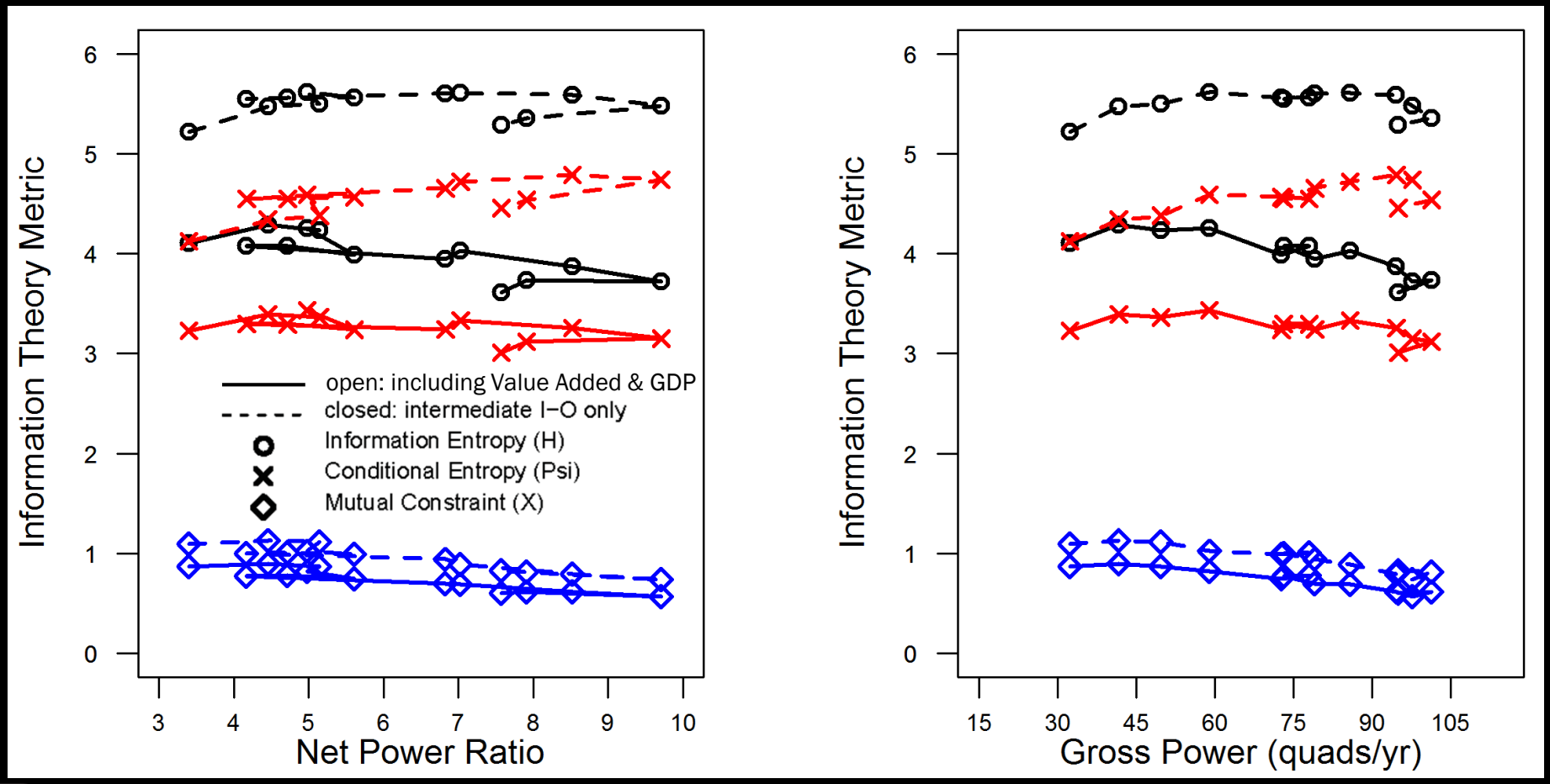
- Net Power Ratio =

GDP /

(food and energy sector intermediate spending)

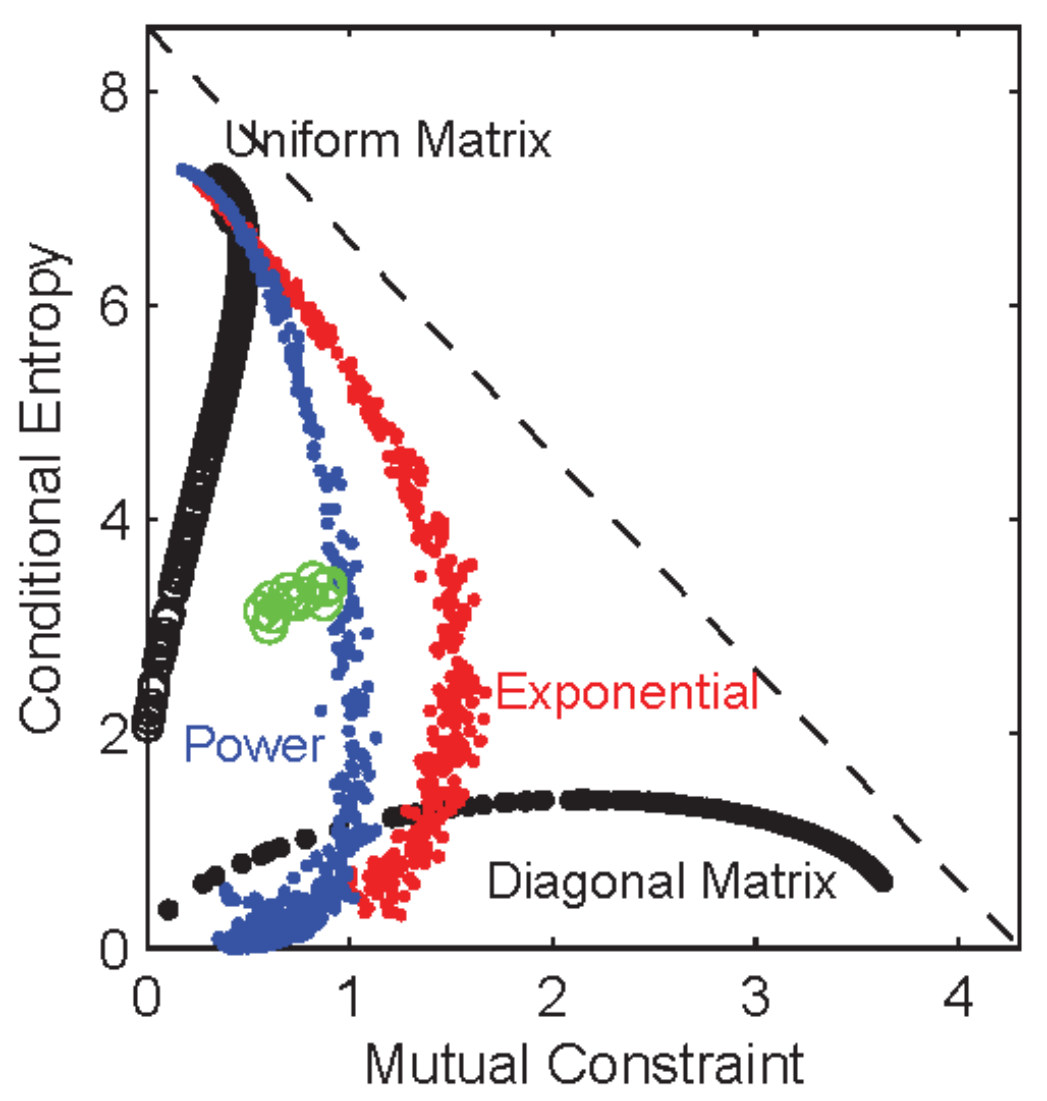


When you consider inputs (Value Added) and outputs (GDP) the trends are a little different

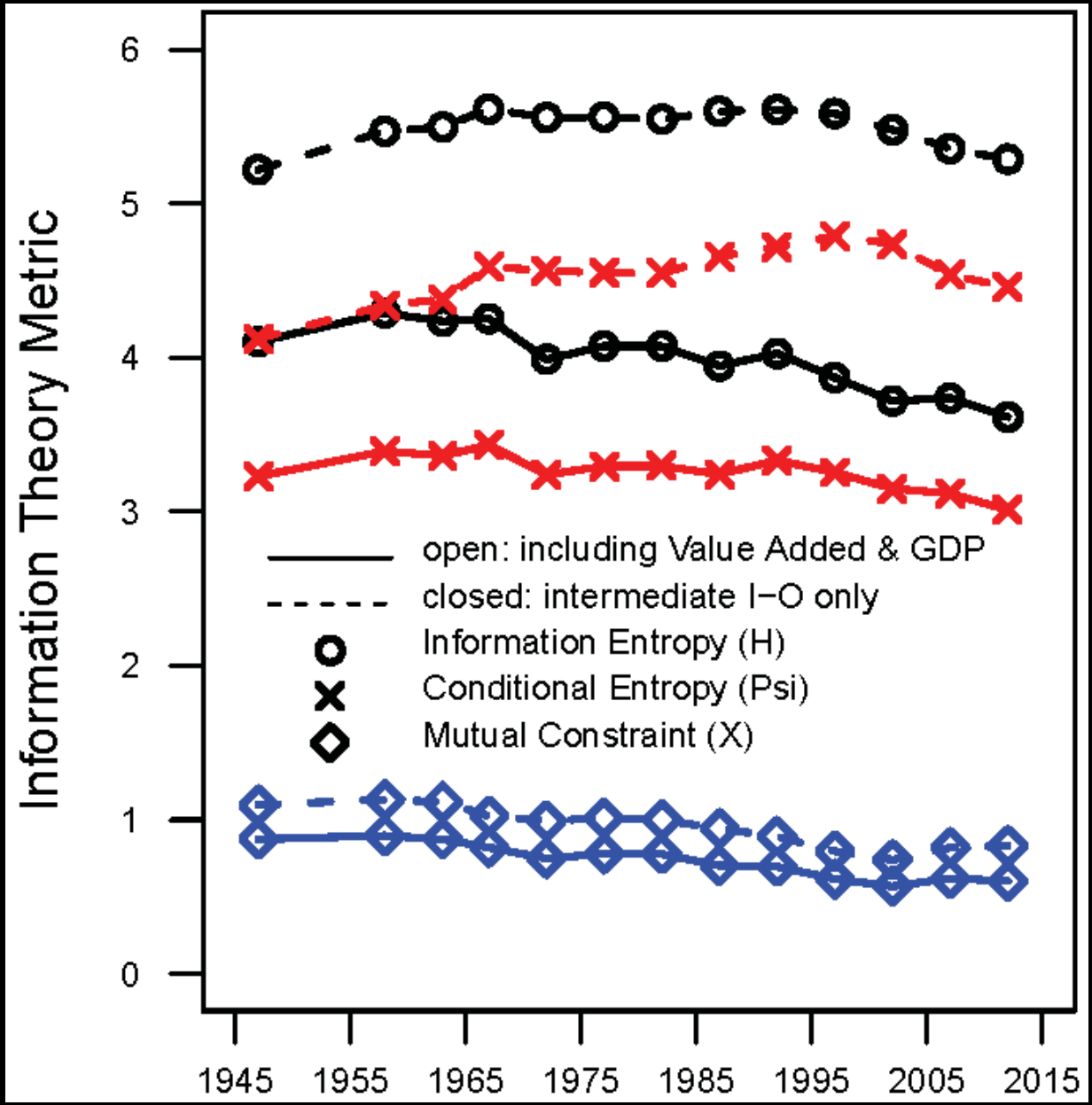


Where do the U.S. Input-Output (Use) Tables reside?

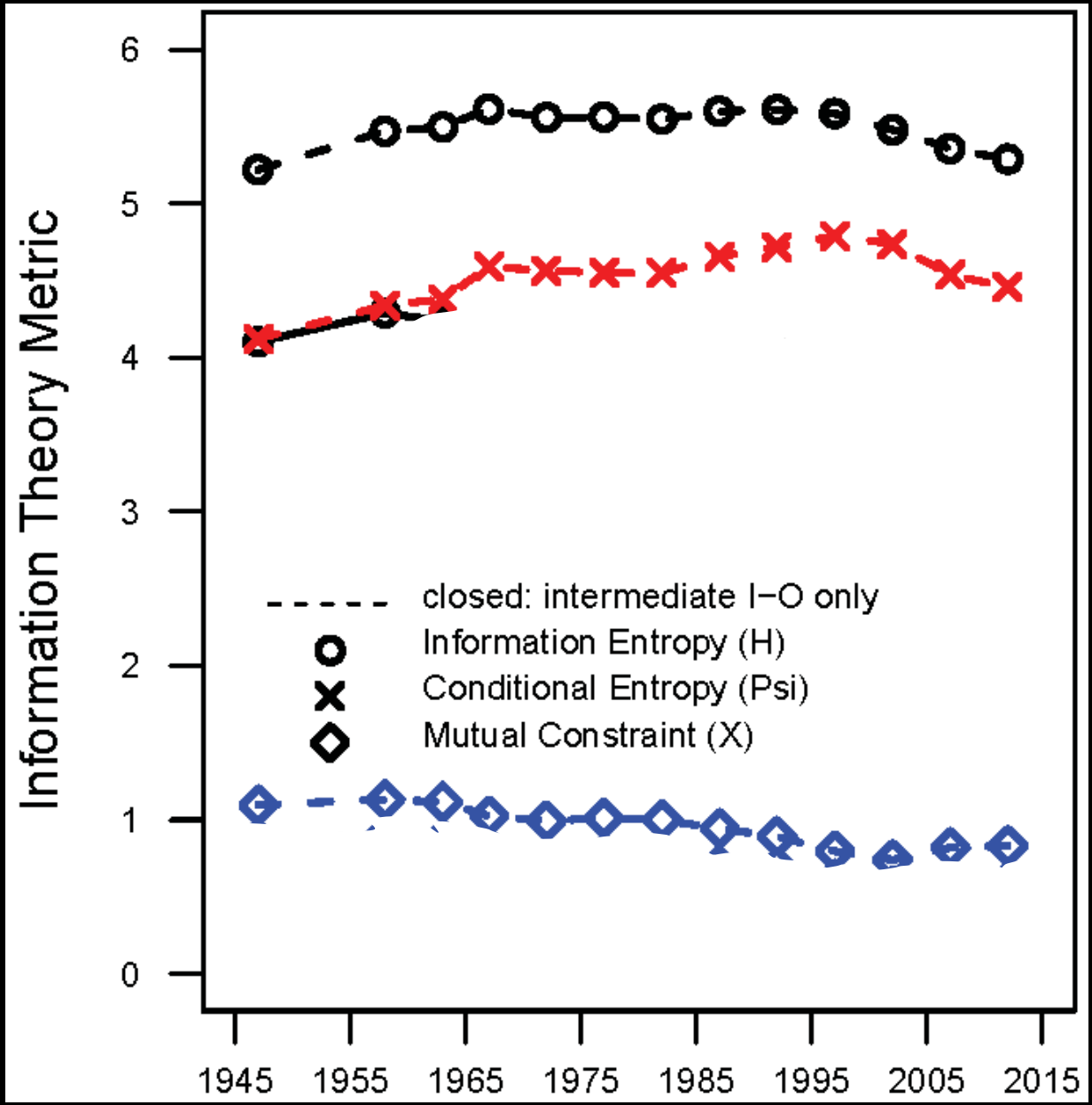
- Shown:
  - Intermediate transactions with GDP (outputs) and Value Added (inputs)



Results vs. time



Results vs. time



Results vs. Net Power