

Data mining the EXFOR database

*John Hirdt, St. Joseph's College,
Patchogue, NY 11772*

David Brown, NNDC, BNL, Upton NY 11973

USNDP – Nuclear Data Week
18-22 November 2013, Brookhaven National Laboratory , New York



The EXFOR library contains nearly all experimental nuclear results

www.ndc.bnl.gov/exfor/exfor00.htm

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Experimental Nuclear Reaction Data (EXFOR)
Database Version of June 21, 2013
Software Version of 20120619

Reviews

- 2012/07 Start by publications with extended view [example]
- 2012/07 Searching reactions: mass, range, etc. [example]
- 2012/07 Improvements and extensions:
 - 1) Automatic data re-normalization (optional: for plots and output data only) [video]
 - 2) Web-2/View plotting: clipboard copy/paste
- 2011/12 Search in CINDA (+EXFOR) if data not found in EXFOR

[History](#)

The EXFOR library contains an extensive compilation of experimental nuclear reaction data. Neutron reactions have been compiled systematically since the discovery of the neutron, while charged particle and photon reactions have been covered less extensively. The library contains data from **20070** experiments (see statistics and recent updates)

Request [Complex requests...](#)

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Target

Reaction

Quantity

Product

Energy from to [Unit](#)

Author(s)

Publication year

Accession #

☐ Extended
☐ Keywords
☐ Expert

[Submit](#) [Reset](#)

Options
Ranges (Z,A)
Reaction Sub Fields
Feedback and User's Input

[Comments/Questions](#)
[Previously submitted comments](#)

Clone Request:
[CINDA](#) [EXFOR](#)

Tip of the day:
video-quiz

Notes:

- all criteria are optional (selected by checking ☒)
- selected criteria are combined for search with logical AND
- criteria separated in a field by ";" are combined with logical OR
- criteria starting with "~" will be used as logical NOT
- wildcards "*" and intervals "[" "]" are available

Database Manager: Boris Petrovskiy, NNDP, Brookhaven National Laboratory (petrovskiy@bnl.gov)
Web and Database Programming: Wilton Zeng, NNDP, International Atomic Energy Agency (w.zeng@iaea.org) 2012.06.19
Data Source: Network of Nuclear Reaction Data Centres

- Data from ~ 20,000 experiments
- Earliest experiments from 1935
- Most complete compilation of experimental nuclear data
- Mostly *n*-induced, but lots of CP-induced, photonuclear and other data

The EXFOR library contains nearly all experimental nuclear results

- Data from ~ 20,000 experiments

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Experimental Nuclear Reaction Data (EXFOR)

Database Version of June 21, 2013

Software Version of 20120619

2012/07 Sort by publications with extended view [example]

2012/07 Searching reactions: input, output, etc. [example]

2012/07 Improvements and extensions:

- 1) Automatic data re-normalization (optional: for plots and output data only)
- 2) Web-ZV-view plotting: clipboard copy/paste

2011/12 Search in CINDA (+EXFOR) if data not found in EXFOR

[History](#)

The EXFOR library contains an extensive compilation of experimental nuclear reaction data. New data is added systematically since the discovery of the reaction, while changed particle and photon reactions are corrected.

The library contains data from **20070** experiments (see [statistics](#) and [news](#))

Request [Complex](#) [Simple](#) [Advanced](#) [Help](#)

Target

Reaction

Quantity

Product

Energy from **to** [Unit](#)

Author(s)

Publication year

Accession #

☐ **Extended**

☐ **Keywords**

☐ **Expert**

[Submit](#) [Reset](#)

Options

Range (X,A)

Reaction Sub Fields

Feedback and User's

[Comments/Queries](#)

[Previously submit](#)

Clone Request:

[CINDA](#) [EXFOR](#)

Data Selection

[Retrieve](#) [Selected](#) [Unselected](#) [All](#) [Reset](#)

Output: ☒ X1+ ☒ EXFOR ☐ Bibliography ☐ TAB ☐ C4 ☐ PlotC4

Plot: ☐ Quick-plot (cross-sections only) ☐ Advanced plot [how-to] using ☐ C5 and ☐ converting ratios to cross sections using [IAEA standards,2006]

Narrow Energy (optional), eV: Min: Max:

☐ Apply* Data re-normalization (for advanced users, results in: C4, TAB and Plots)

Display	Year	Author-1	Energy range, eV	Points	Reference
1) 92-U-238(N,EL)92-U-238,,810 C4: NF3 NT2					
Quantity: [C5] Cross section					
1	1950	L.L.Litvinenko+	2.75e5	1	+ J.VF,52,(4),1025,199010
2	1957	L.L.Litvinenko+	5.50e4	2	+ J.AE,62,(3),192,198703
3	1964	Shen Guozhen+	1.42e7	1	[pdf]+ J.CND,6,193,198408
4	1962	G.Baouat+	7.00e5	4	[pdf]+ J.NSE,01,(4),481,0200
5	1978	F.B.Tsang+	1.44e5	1	[pdf]+ J.NSE,65,70,197801
6	1968	J.Volgaev	1.41e7	1	+ B.CEA-D-3503,6807
7	1966	E.Bernard+	7.50e5	5	[pdf]+ J.NE,00,46,6605
8	1965	R.Bachmann+	2.00e6	4	[pdf]+ J.NP,65,238,196503
9			2.00e6	4	
10	1966	R.C.Allen+	5.00e5	2	[pdf]+ J.FR,104,731,56
2) 92-U-238(N,EL)92-U-238,,510,,DBATV C4: MT3 NT2					
Quantity: [C5] Cross section					
11	1968	Ma Gongguo+	1.42e7	1	+ B.INDC(CNR)-11,195,196803
3) 92-U-238(N,EL)92-U-238,,510,,RDOCK C4: MT3 NT2					
Quantity: [C5] Cross section					
12	2006	S.P.Nagbagnab	2.55e-2	1	+ B.NEOT.DBS,,2006
4) 92-U-238(N,EL)92-U-238,,910,,NOM C4: NF=3 NT=7					
Quantity: [C5] Cross section					
13	1951	C.T.Hanson+	2.55e-2	1	+ B.ANL-4680,5,1951
5) 92-U-238(N,EL)92-U-238,,910,,9DA C4: NF=3 NT=7					
Quantity: [C5] Cross section					
14	1960	V.P.Veretennyy+	2.45e5	1	+ C.00RTEV,2,248,196009
6) 92-U-238(N,EL)92-U-238,,510+ [92-U-238(N,EL)92-U-238,948,510] C4: NF=3 NT=7					
Quantity: [C5] Cross section					
15	1962	A.B.Smith+	9.30e5	6	+ C.00RTEV,,39,5209
16	1959	L.Cranberg	9.50e5	1	+ B.LA-2177,5901

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Data Source: Network of Nuclear Reaction Data Centres

Brookhaven Science Associates

VEN
ATORY

ENTRY	11135	860905	20050926	0000
SUBENT	11135001	860905	20050926	0000
BIB	6	10		
INSTITUTE	(1USACOL)			
REFERENCE	(J,PR,60,702,4111)			
	(J,PR,58,1004,40) COMMENT ON SPECTRUM.			
AUTHOR	(H.CARROLL,J.R.DUNNING)			
TITLE	THE INTERACTION OF SLOW NEUTRONS WITH GASES.			
STATUS	(SCSRS)			
HISTORY	(760628T) TRANSLATED FROM SCISRS			
	(820108A) CONVERTED TO REACTION FORMALISM			
	(840217A) REFERENCE CORRECTED.			
	(860905A) ENERGY MOVED TO SAN 1.			
ENDBIB	10			
COMMON	1	3		
EN-DUMMY				
EV				
	0.0253			
ENDCOMMON	3			
ENDSUBENT	17			
SUBENT	11135009	860905	20050926	0000
BIB	3	12		
REACTION	(1-H-1(N,TOT),,SIG,,MXW)			
SAMPLE	H2O LIQUID			
	AUTHOR ALSO GIVES DATA FOR 10 OTHER SAMPLES -			
	H-2 GAS - 31.8+-0.5 B			
	CH(4) GAS - 45.4+-0.3 B			
	C(2)H(6) GAS - 46.4+-0.5 B			
	C(3)H(8) GAS - 46.9+-0.6 B			
	C(4)H(10) GAS - 48.7+-0.6 B			
	PARAFFIN - 49.8+-0.2 B			
	DOTRIACONTANE - 50.2+-0.2 B			
HISTORY	(780914C)			
	(860905A) REACTION CORRECTED.			
ENDBIB	12			
NOCOMMON	0	0		
DATA	2	1		
DATA	DATA-ERR			
B	B			
	44.6	0.5		
ENDDATA	3			
ENDSUBENT	20			
ENDENTRY	2			

ENTRY 11135

Carroll & Dunning

“Interaction of slow neutrons with gases”

from Physics Reports 1941

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	(860905A) REACTION CORRECTED.			
ENDBIB	12			
NOCOMMON	0	0		
DATA	2	1		
DATA	DATA-ERR			
B	B			
	44.6	0.5		
ENDDATA	3			
ENDSUBENT	20			
ENDENTRY	2			

REACTION (1-H-1(N,TOT),,SIG,,MXW)

ENTRY 11135
 Carroll &
 Dunning
 “Interaction of
 slow neutrons
 with gases”
 from Physics
 Reports 1941;

This is 9th
 subentry on ¹H
 scattering

```

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SUBENT         11135001    860905      20050926      0000
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COMMON         1          3
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  0.0253
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NOCOMMON       0          0
DATA           2          1
DATA          DATA-ERR
B             B
  44.6        0.5
ENDDATA        3
ENDSUBENT      20
ENDENTRY       2

```

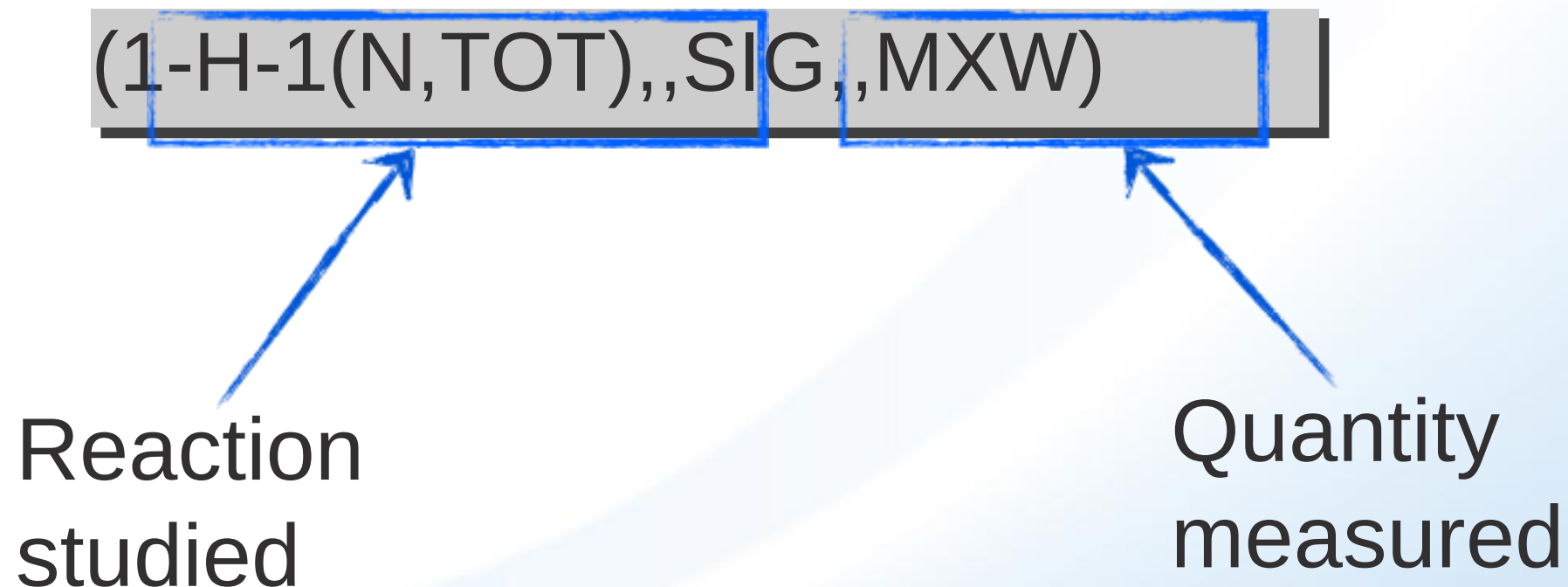
The data is
one spectrum
averaged point

ENTRY 11135
Carroll &
Dunning
“Interaction of
slow neutrons
with gases”
from Physics
Reports 1941;

This is 9th
subentry on ¹H
scattering

REACTION & MONITOR fields denote what reaction/quantity measured

- EXFOR REACTION fields and MONITOR fields have essentially the same format
 - REACTION denotes what is measured
 - MONITOR denotes what the REACTION is measured “relative” to
- For a simple measurement:



REACTIONS & MONITORs have complicated variants

■ Mathematical relations in REACTIONs and MONITORs:

- Reaction combinations:

(3-LI-6(N,T)2-HE-4,,SIG,,SPA)/(92-U-235(N,F),,SIG,,SPA)

any relation using +,-,*,/,//,= allowed

- “Isomer math”:

(72-HF-177(N,G)72-HF-178-M/T,,SIG/RAT)

■ Several reactions/quantities have special meanings:

- ALF: capture-to-fission ratio
- ETA: ave. neutron yield per nonelastic event for *n*-induced reactions
- RI: resonance integral
- NON, INEL, SCT: all obey sum rules

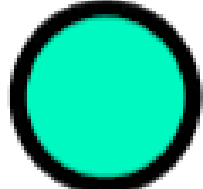
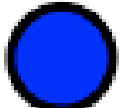
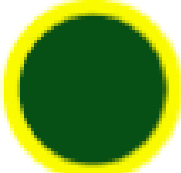
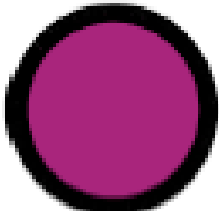
■ Elemental data

- weighted average of reaction on isotopes comprising element

**These variants encode connections
between simple REACTIONS**

**Can we learn anything just looking at
the REACTIONS and MONITORS
alone?**

Types of nodes

Description	Example
Regular node	
CIELO isotope Chadwick, M., "CIELO: A Future Collaborative International Evaluated Library", Proc. of the International Conference of Nuclear Data for Science and Technology (ND2013)	
ENDF/B-VII.1 Standards Carlson A.D. "International Evaluation of Neutron Cross Section Standards", Nuclear Data Sheets. 110.12 (2009) 3215-3324.	
Standards proposed at IAEA Technical Meeting, July '13	
Standards proposed in the past / Proposed by us	 
Mughabghab, S. F., <i>Atlas of Neutron Resonances</i>, Elsevier Science, April 17, 2006.	
Diagnostic radioisotopes and monitor reactions P. Oblozinsky, International Atomic Energy Agency IAEA, IAEA-TECDOC-1211 http://www-nds.iaea.org/medical/	
Isomer target	
Elemental target	

Types of connections

Edge type	Description	Example
MONITOR	Typically a, well characterized reaction used to reduce or eliminate systematic experimental errors.	
Mathematical relation (e.g. “isomer math”; sum rules; math is REACTION string; ALF, ETA, etc)	Connections representing a simple ratio or a more complex mathematical equation.	
Neutron Standards/CIELO	All evaluated simultaneously and therefore are linked.	
Elemental	Data on a elemental target is connected to every stable isotope of the element for the same measurement.	

Reoccurring motifs

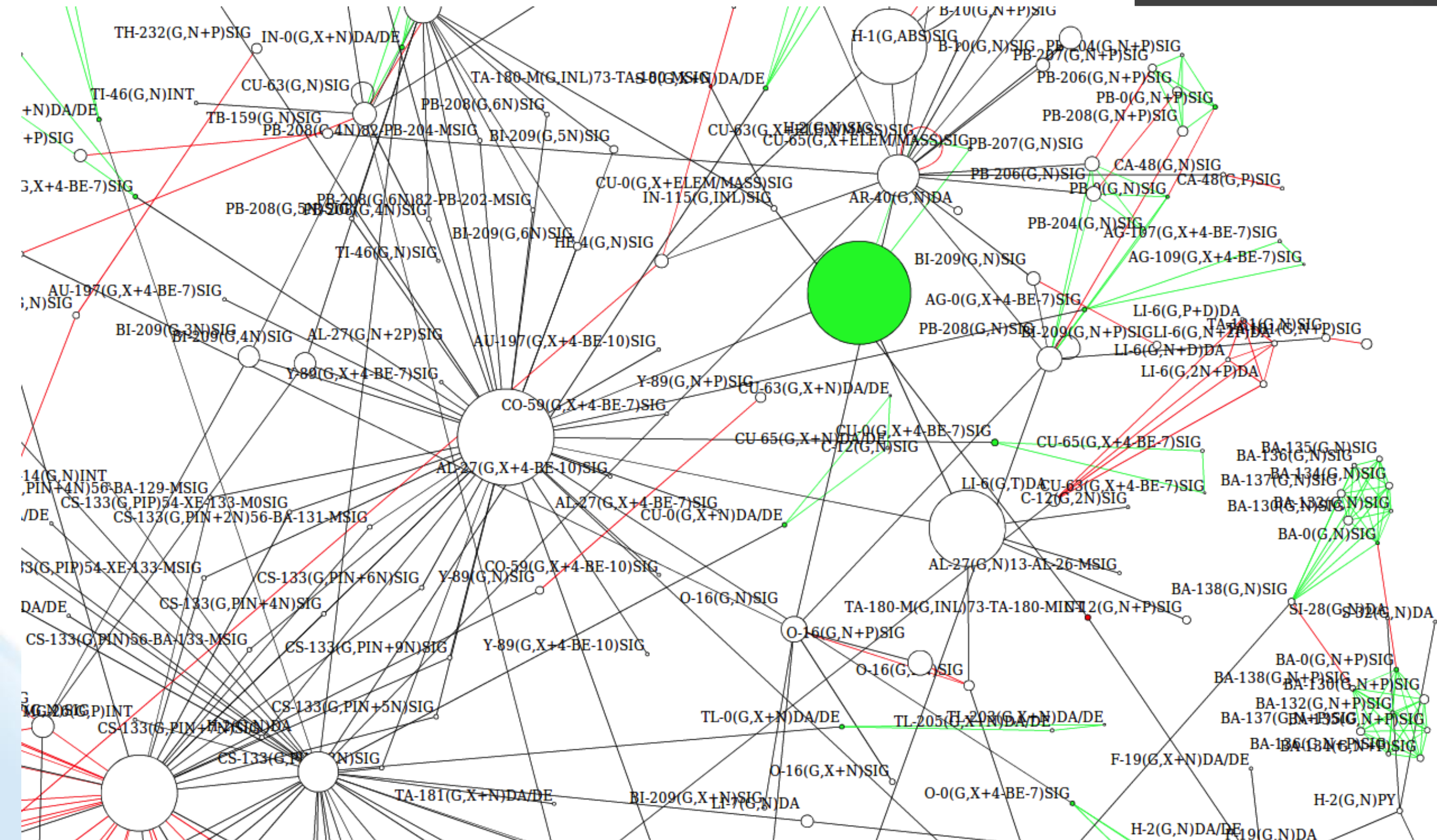
EXFOR Quantity	Definition	Example
ALF	σ_γ / σ_f	
ETA	$\bar{\nu} \sigma_f / (\sigma_\gamma + \sigma_f)$	
SCT	$\sigma_{el} + \sigma_{inel}$	

EXFOR Quantity	Definition	Example
NON	$\sigma_{tot} - \sigma_{el}$	
RI	$\int_0^\infty dE \frac{\sigma(E)}{E}$	
(elemental)	$\sum_i w_i \sigma_i(E)$	

The network

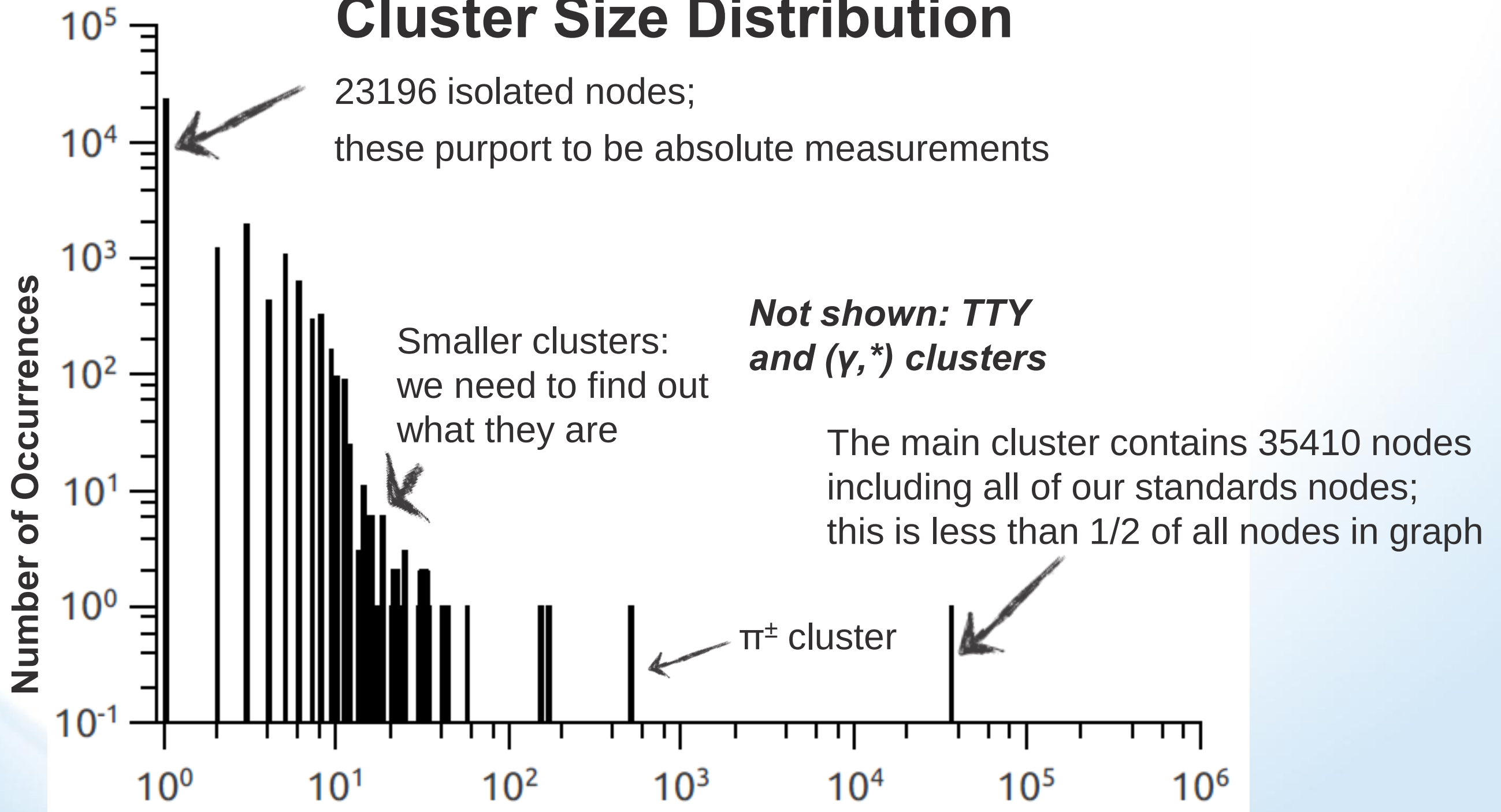
(a closeup of the photonuclear cluster)

nodes: 87925
edges: 276852



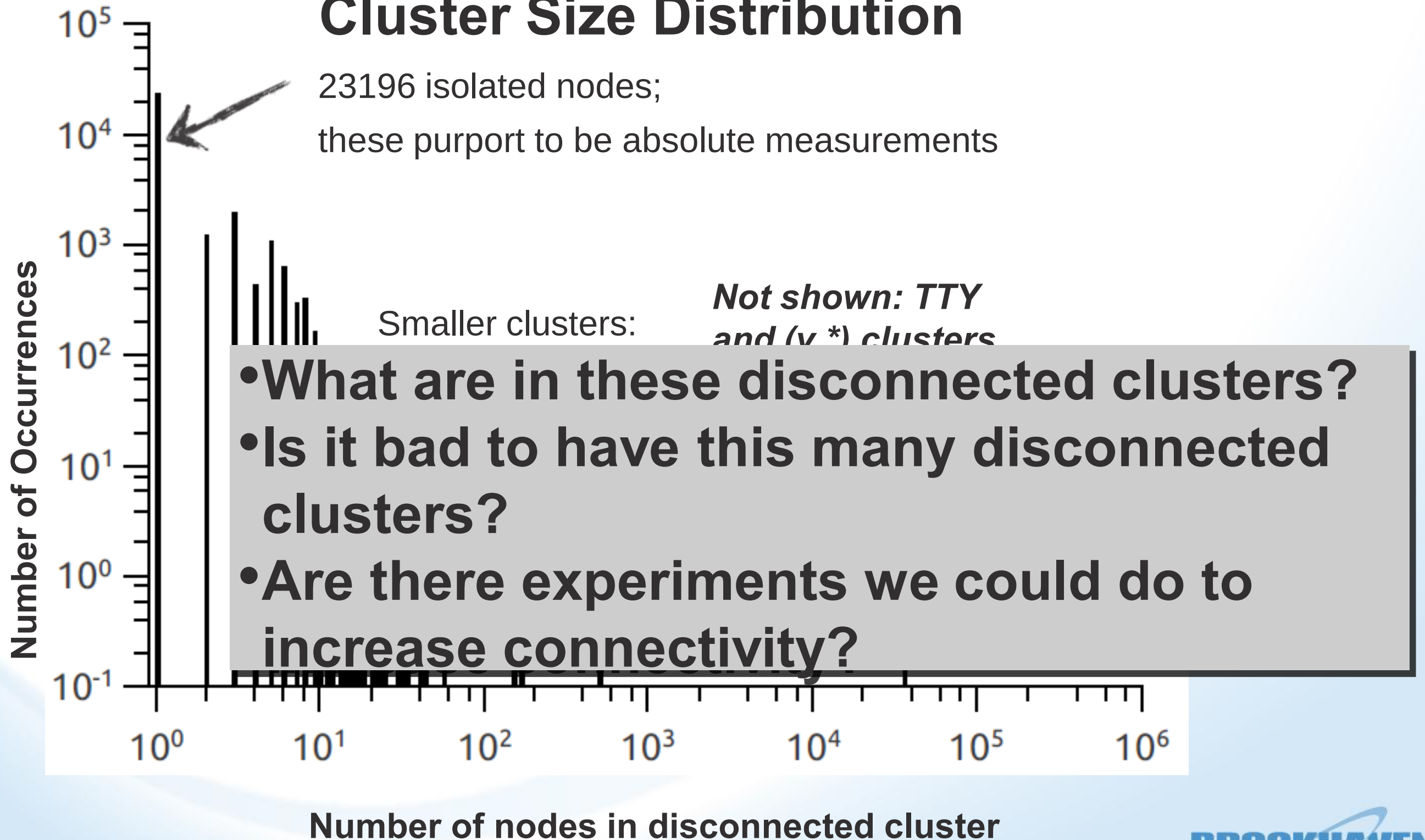
The graph is not fully connected; *probability any 2 nodes connected is $7.162e-05$*

Cluster Size Distribution



The graph is not fully connected; *probability any 2 nodes connected is $7.162e-05$*

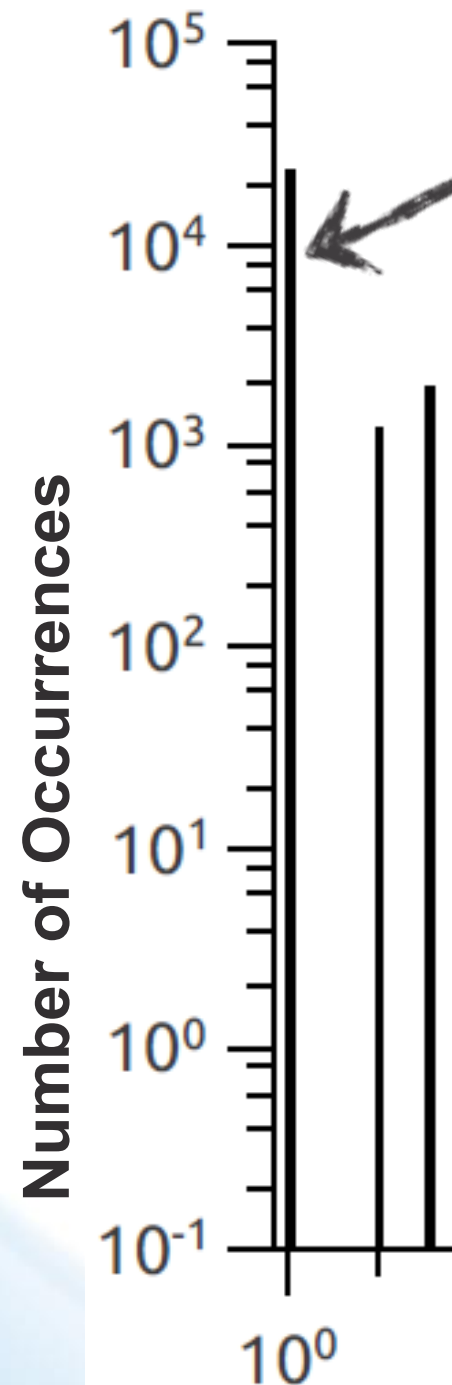
Cluster Size Distribution



The graph is not fully connected; *probability any 2 nodes connected is $7.162e-05$*

Cluster Size Distribution

23196 isolated nodes;
these purport to be absolute measurements



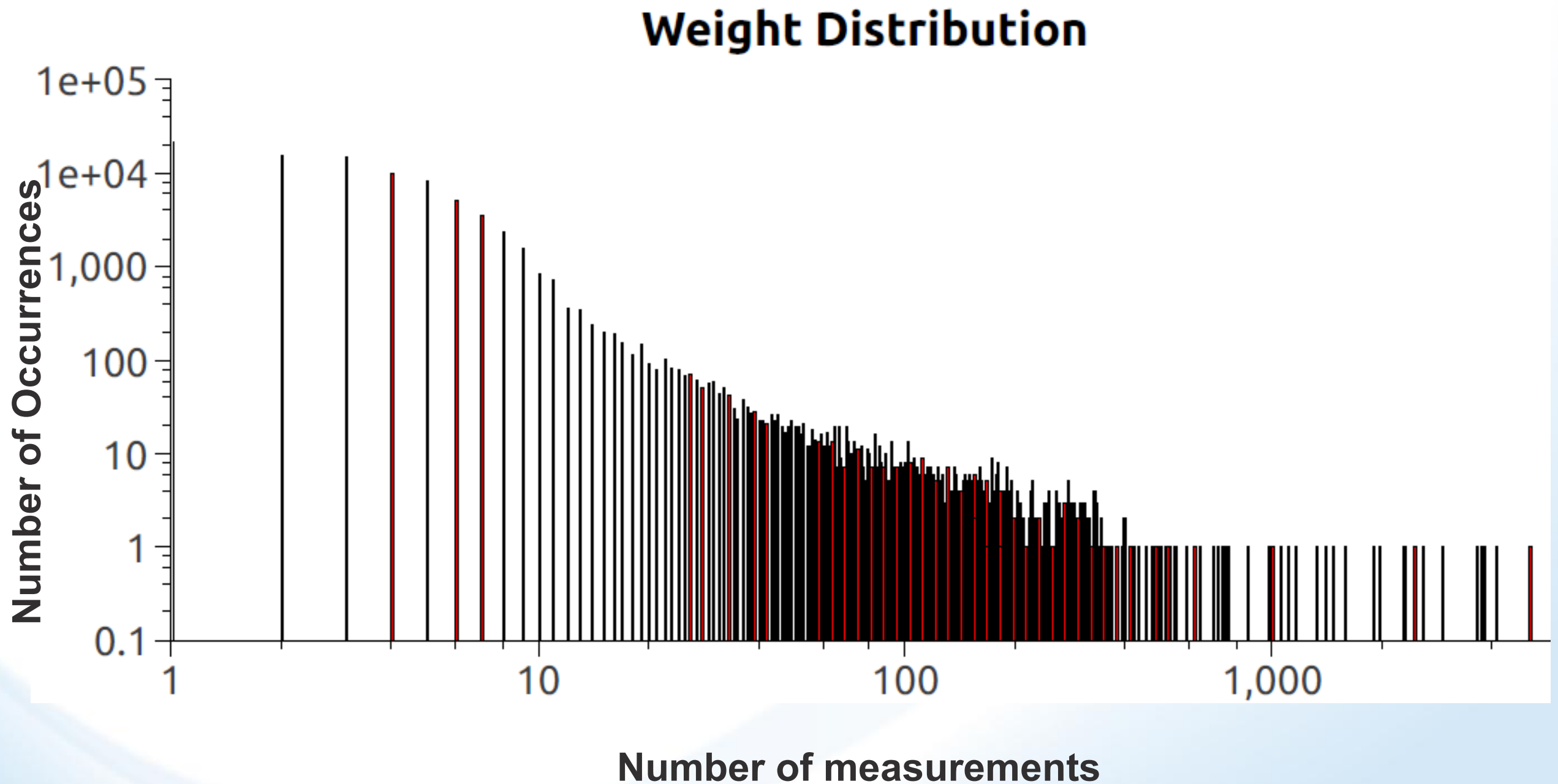
- What are in these disconnected clusters?
- Is it bad to have this many disconnected clusters?
- Are there experiments we could do to increase connectivity?

we still need to investigate...

Number of nodes in disconnected cluster

What is most measured?

These are what experimenters view as important.



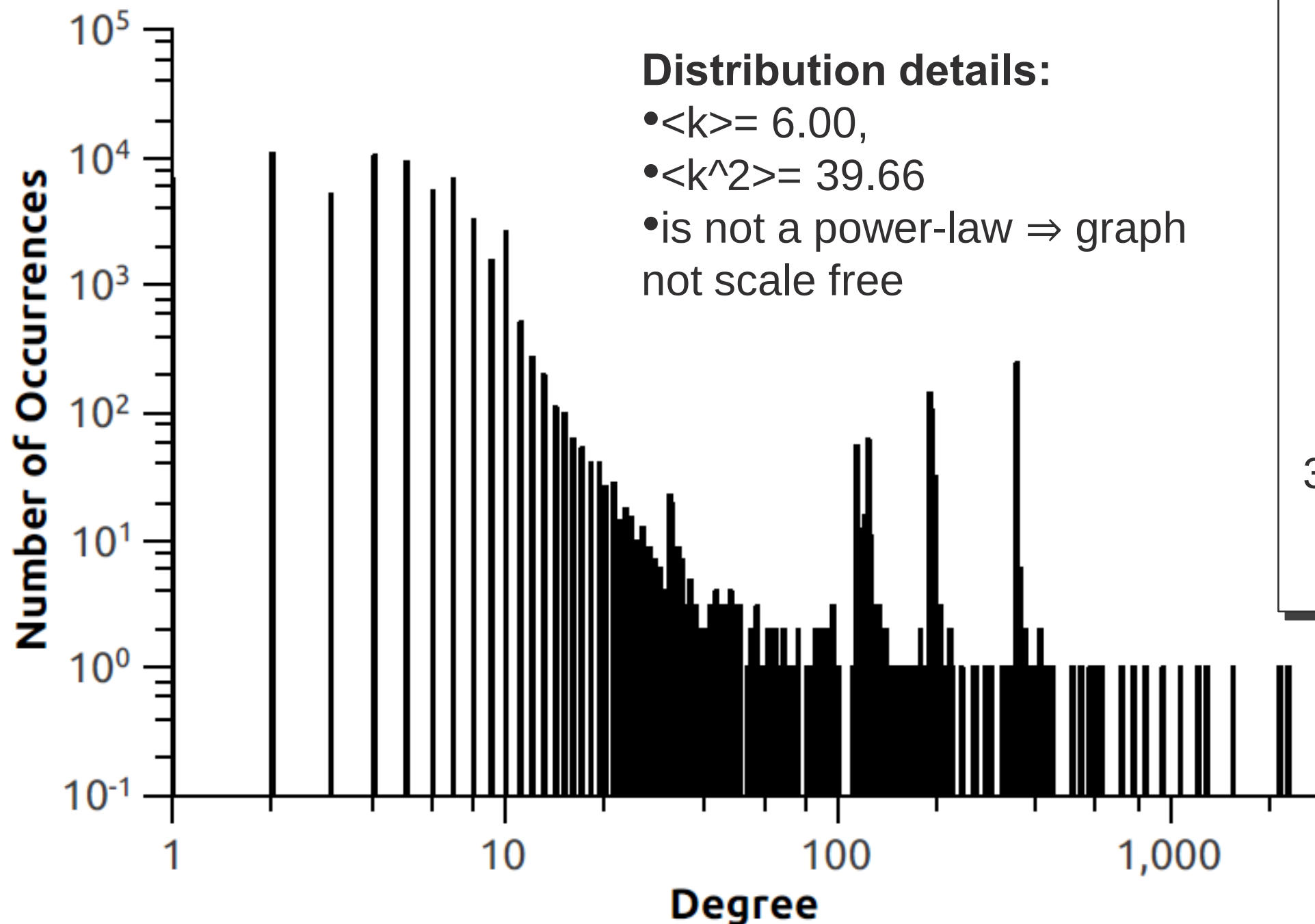
What is most measured?

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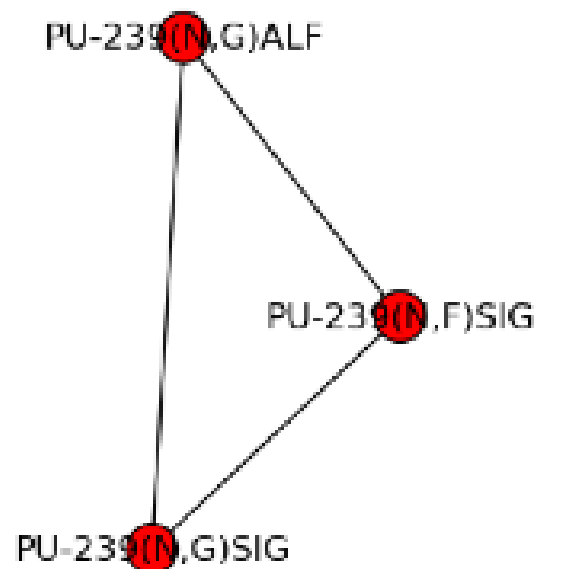
Node	# Measurements	Degree	Note
27Al(n, α): σ	5049	1281	
197Au(n, γ): σ	4106	1073	ENDF/Atlas Neutron Standard
27Al(p, X+22Na): σ	3806	2276	IAEA Charged-particle Monitor
235U(n, f): σ	3707	774	ENDF Neutron Standard/CIELO
27Al(p, X+24Na): σ	3626	2122	IAEA Charged-particle Monitor
1H(n, el): σ	2903	1207	ENDF Neutron Standard/CIELO
1H(n, el): $d\sigma/d\Omega$	2601	953	ENDF Neutron Standard/CIELO
93Nb(n, 2n)92mNb: σ	2465	710	
27Al(p, n+3p): σ	2316	1535	
56Fe(n, p)56Mn: σ	2272	833	CIELO
197Au(n, γ): RI	1961	440	ENDF/Atlas Neutron Standard
27Al(n, p)27Mg: σ	1902	544	
natCu(p, X+65Zn): σ	1899	627	IAEA Charged-particle Monitor
59Co(n, γ): RI	1582	410	Atlas Neutron Standard
58Ni(n, p): σ	1477	344	
238U(n, f): σ	1394	511	ENDF Neutron Standard/CIELO
59Co(n, γ): σ	1332	578	Atlas Neutron Standard
115In(n, inel): σ	1161	235	
natMo(p, X+96Tc): σ	1109	600	
27Al(12C, X+24Na): σ	1060	610	

The degree of a node is the number of other nodes connected to it

Degree Distribution



Example:



3 nodes, each with
a degree of 2

Most important, by degree

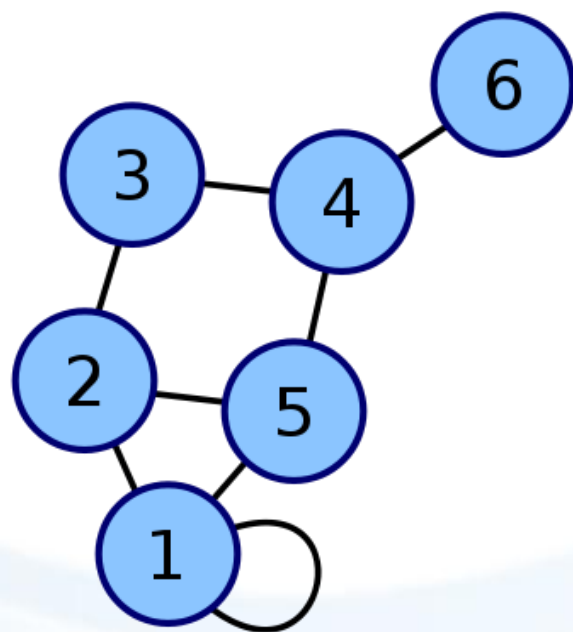
Node	# Measurements	Degree	Note
$^{27}\text{Al}(p, X+^{22}\text{Na}): \sigma$	3806	2276	IAEA Charged-particle Monitor
$^{27}\text{Al}(p, X+^{24}\text{Na}): \sigma$	3626	2122	IAEA Charged-particle Monitor
$^{27}\text{Al}(p, n+3p): \sigma$	2316	1535	
$^{27}\text{Al}(n, \alpha): \sigma$	5049	1281	
$^1\text{H}(n, \text{el}): \sigma$	2903	1207	ENDF Neutron Standard/CIELO
$^{197}\text{Au}(n, \gamma): \sigma$	4106	1073	ENDF/Atlas Neutron Standard
$^1\text{H}(n, \text{el}): d\sigma/d\Omega$	2601	953	ENDF Neutron Standard/CIELO
$^{56}\text{Fe}(n, p)^{56}\text{Mn}: \sigma$	2272	833	CIELO
$^{235}\text{U}(n, f): \sigma$	3707	774	ENDF Neutron Standard/CIELO
$^{93}\text{Nb}(n, 2n)^{92\text{m}}\text{Nb}: \sigma$	2465	710	
$\text{natCu}(p, X+^{65}\text{Zn}): \sigma$	1899	627	IAEA Charged-particle Monitor
$^{27}\text{Al}(^{12}\text{C}, X+^{24}\text{Na}): \sigma$	1060	610	
$\text{natMo}(p, X+^{96}\text{Tc}): \sigma$	1109	600	
$\text{natMo}(p, X+^{97}\text{Ru}): \sigma$	547	594	
$^{59}\text{Co}(n, \gamma): \sigma$	1332	578	Atlas Neutron Standard
$^{27}\text{Al}(n, p)^{27}\text{Mg}: \sigma$	1902	544	
$^{238}\text{U}(n, f): \sigma$	1394	511	ENDF Neutron Standard/CIELO
$^{27}\text{Al}(d, X+^{24}\text{Na}): \sigma$	990	507	IAEA Charged-particle Monitor
$^{197}\text{Au}(n, \gamma): Rf$	1961	440	ENDF/Atlas Neutron Standard
$^{10}\text{B}(n, \alpha): \sigma$	860	432	ENDF Neutron Standard

Other measures of importance

■ Other measures:

- Eigenvalue centrality
- Flow centrality
- Betweenness
- ...

■ Rely on adjacency matrix: the matrix of connections between nodes



$$\begin{pmatrix} 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

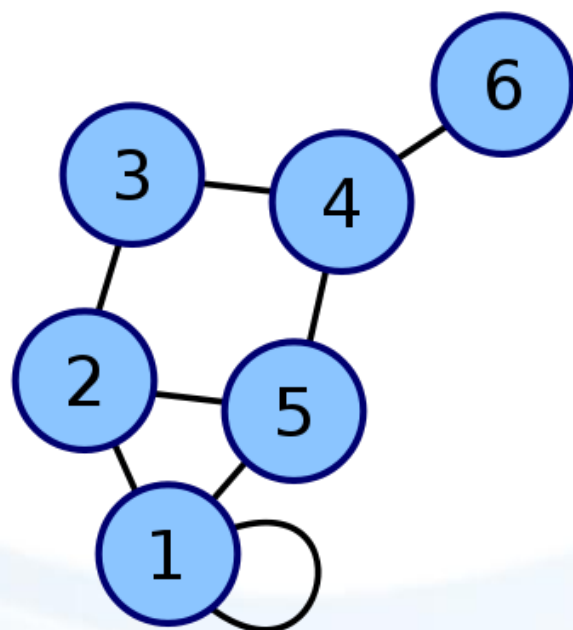
Other measures of importance

All require complicated linear algebra on adjacency matrix so behave badly for large graphs

- **Other measures:**

- Eigenvalue centrality
- Flow centrality
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- ...

- **Rely on adjacency matrix: the matrix of connections between nodes**



$$\begin{pmatrix} 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

Other measures of importance

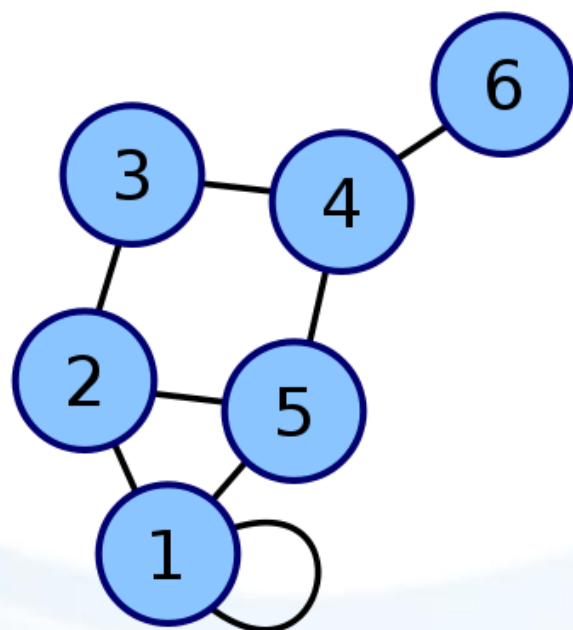
All require complicated linear algebra on adjacency matrix so behave badly for large graphs

Testing on subgraphs suggest our graph does not map to a random matrix

■ Other measures:

- Eigenvalue centrality
- Flow centrality
- Betweenness
- ...

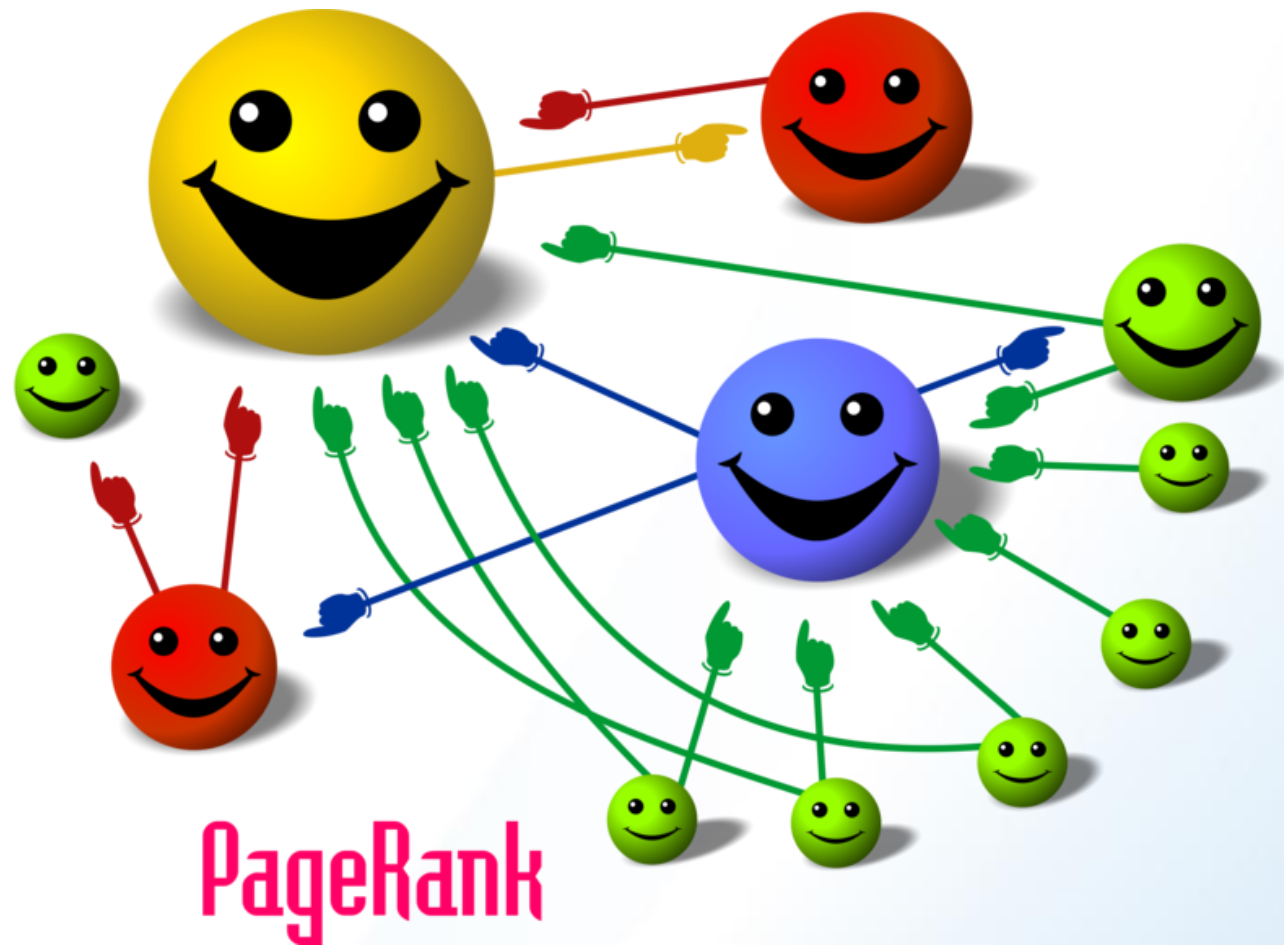
■ Rely on adjacency matrix: the matrix of connections between nodes



$$\begin{pmatrix} 1 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{pmatrix}$$

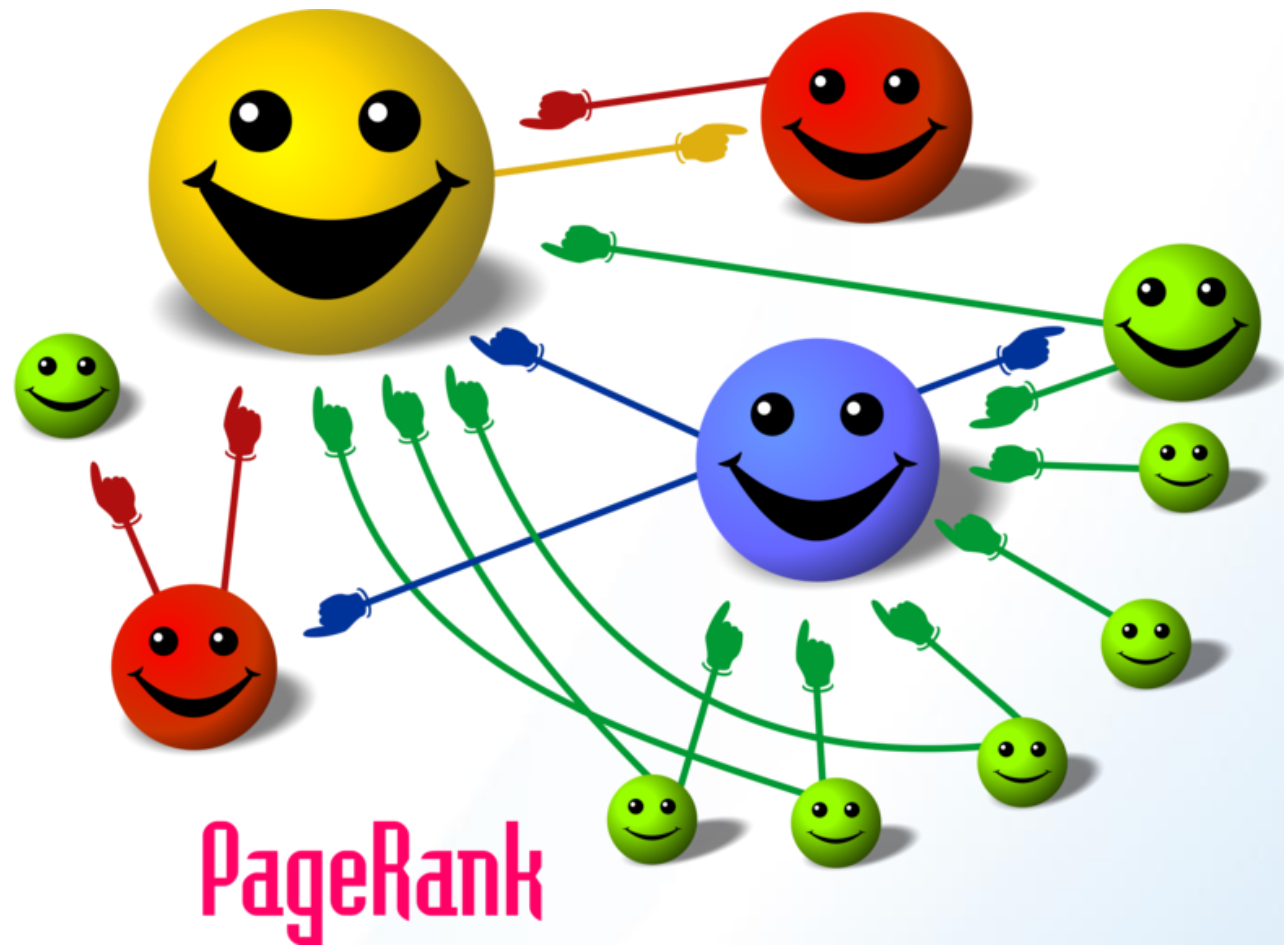
Google PageRank

- Developed by Larry Page and Sergey Brin
- Google's “secret weapon”
- Iterative process determines probability to connect to a node
- Algorithm:
 - All nodes start with $PR(A)=1$
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 $PR(A)=PR(B)+PR(C)+PR(D)+..$
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Robust: doesn't need linear algebra that gets flakey with large graphs

Most important by PageRank

Node	# Meas.	PageRank	Note
27Al(p, X+22Na): σ	3806	0.00614361883184	IAEA Charged-particle Monitor
27Al(p, X+24Na): σ	3626	0.00589970042155	IAEA Charged-particle Monitor
27Al(p, n+3p): σ	2316	0.00462137473353	
1H(n, el): σ	2903	0.00205056586495	ENDF Neutron Standard/CIELO
27Al(n, α): σ	5049	0.0020053191131	
27Al(12C, X+24Na): σ	1060	0.00198377702452	
1H(n, el): $d\sigma/d\Omega$	2601	0.00166716109304	ENDF Neutron Standard/CIELO
197Au(n, γ): σ	4106	0.00161174920126	ENDF/Atlas Neutron Standard
natMo(p, X+96Tc): σ	1109	0.00151848784518	
natMo(p, X+97Ru): σ	547	0.00150681290335	
natCu(p, X+65Zn): σ	1899	0.00139242891398	IAEA Charged-particle Monitor
27Al(d, X+24Na): σ	990	0.00125807852791	IAEA Charged-particle Monitor
56Fe(n, p)56Mn: σ	2272	0.00111172026737	CIELO
93Nb(n, 2n)92mNb: σ	2465	0.00104560418528	
65Cu(p, n): σ	514	0.000851363612779	
59Co(n, γ): σ	1332	0.000825522215299	Atlas Neutron Standard
natCu(p, X+62Zn): σ	985	0.000815833146368	IAEA Charged-particle Monitor
27Al(n, p)27Mg: σ	1902	0.000759255422463	
27Al(p, 3n+3p): σ	528	0.000730486791991	
natTi(p, X+48V): σ	731	0.000711817973821	IAEA Charged-particle Monitor

Recommendations: need to expand our suite of structural materials

- ***Aluminum***: cheap, monoisotopic and easy to work with; the most important structural material next to Iron
 - $n+^{27}\text{Al}$: (n,α) , (n,p)
 - $p+^{27}\text{Al}$: $(n,n+3p)$, ^{22}Na and ^{24}Na production
 - $^{12}\text{C}+^{27}\text{Al}$: ^{24}Na production
- ***Molybdenum and Niobium*** also very important structural materials:
 - $n+^{93}\text{Nb}$: $^{93}\text{Nb}(n,2n)^{92\text{m}}\text{Nb}$
 - $p+^{\text{nat}}\text{Mo}$: ^{96}Tc and ^{97}Ru production
- **Other important structural materials:**
 - $n+^{58}\text{Ni}$: (n,p)
 - $n+^{115}\text{In}$: (n,inel)

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Yes, ^{12}C as a projectile!

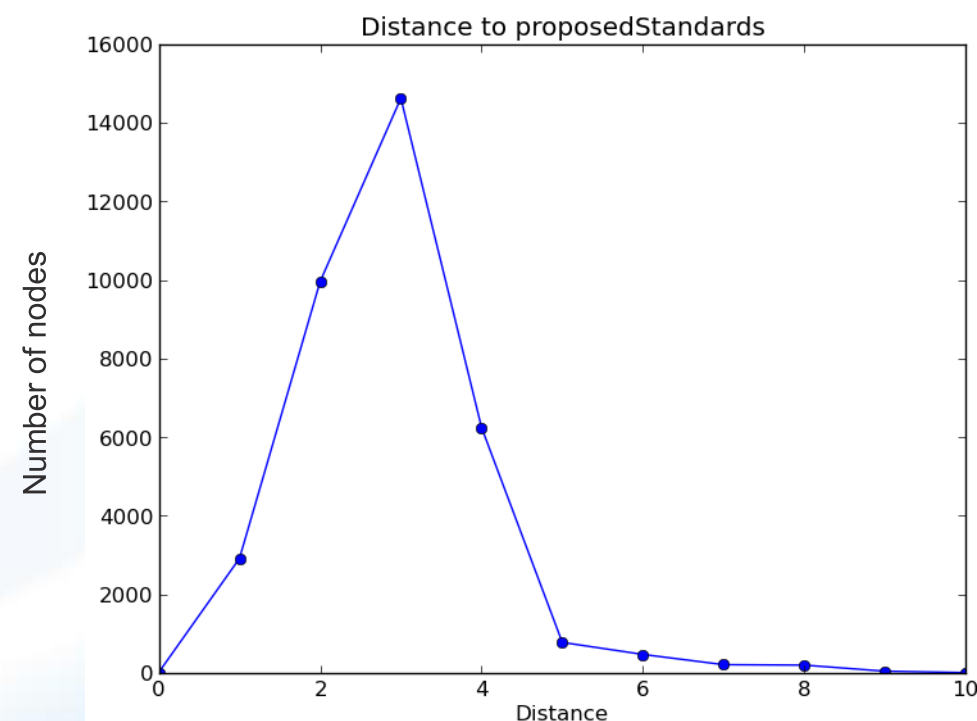
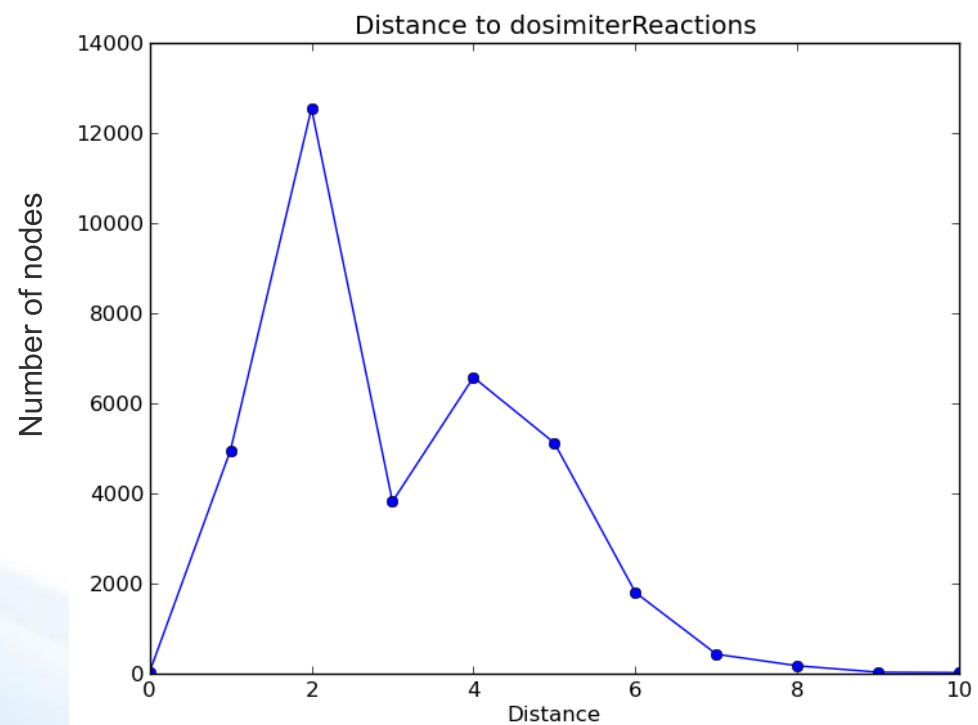
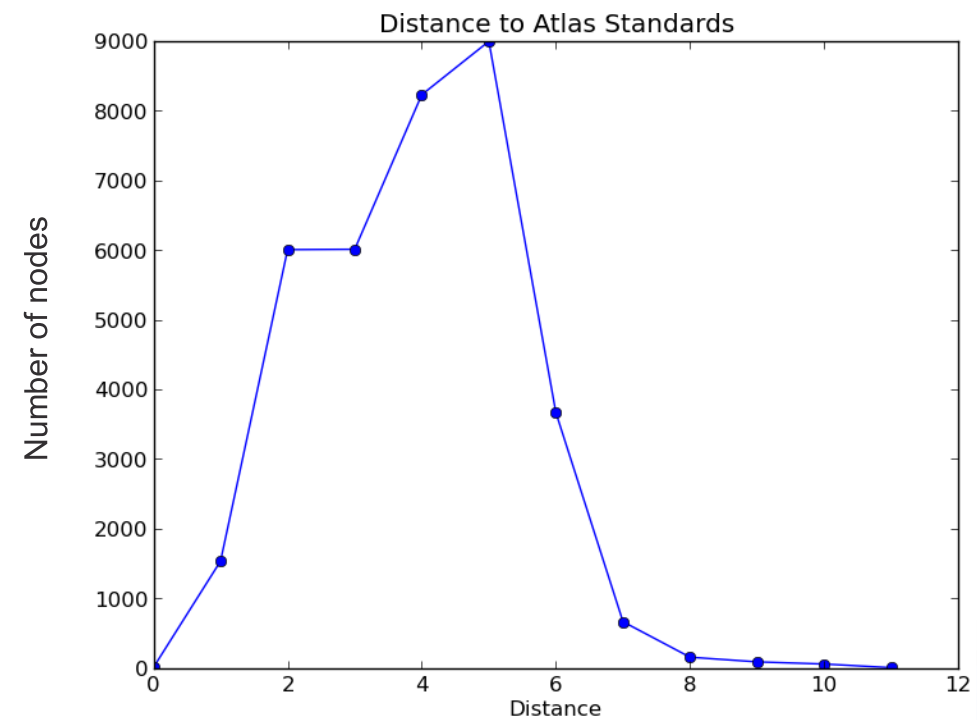
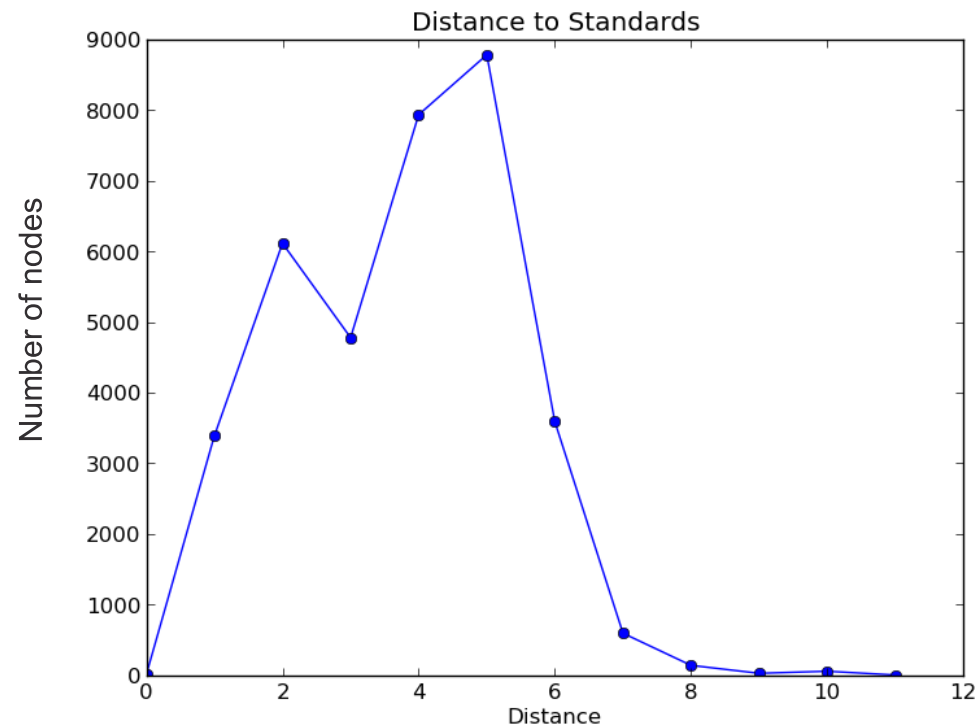
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Naively, everything should be connected to a monitor of some sort



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