

| THE DISPUTED INTERNET: QUANTIFYING FRAGMENTATION IN THE IPV6 INTERNET

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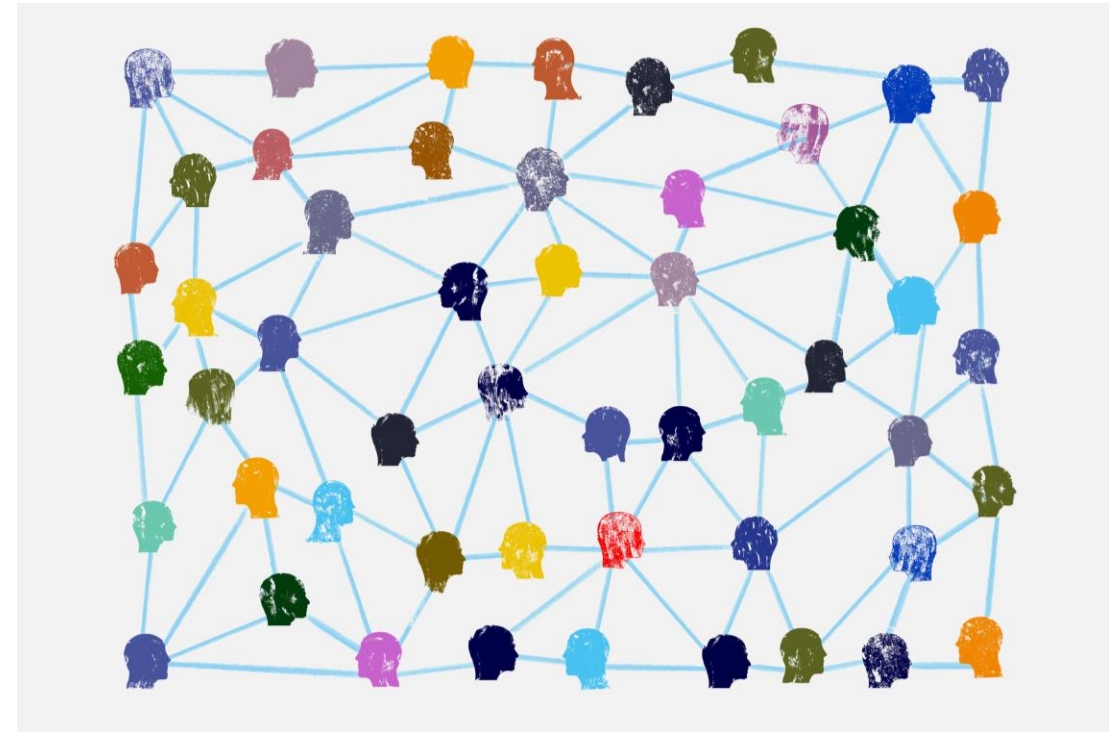
IJLlab seminar, July 7, 2026



THE INTERNET IS GLOBAL

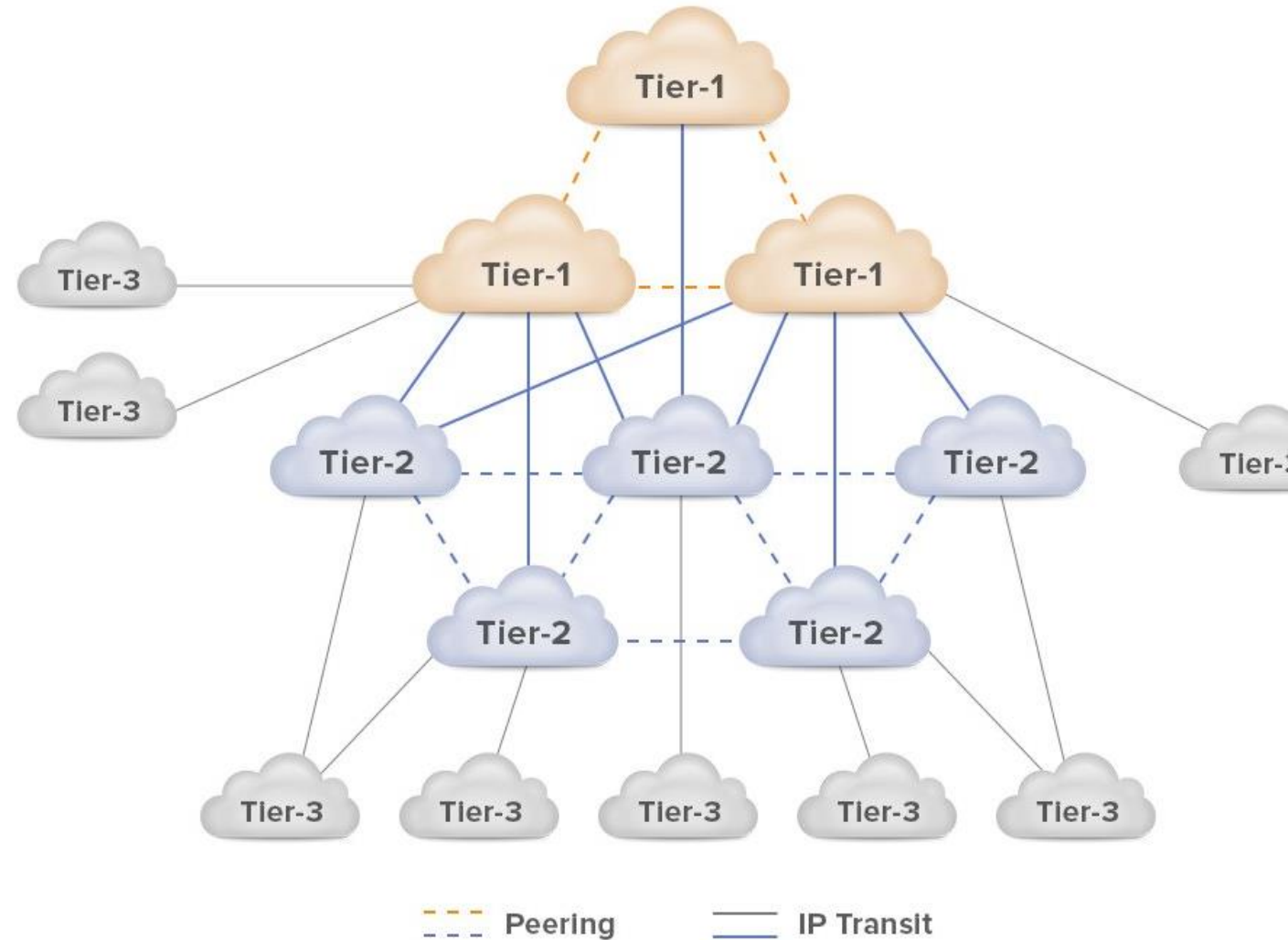
Basic principle of inter-domain routing

- A network connected to the Internet is reachable by any other network on the Internet
- Reachability ensured by BGP
- This presentation is not about:
 - Censorship
 - Outage
 - NAT/CGNAT



TIER-1 NETWORKS

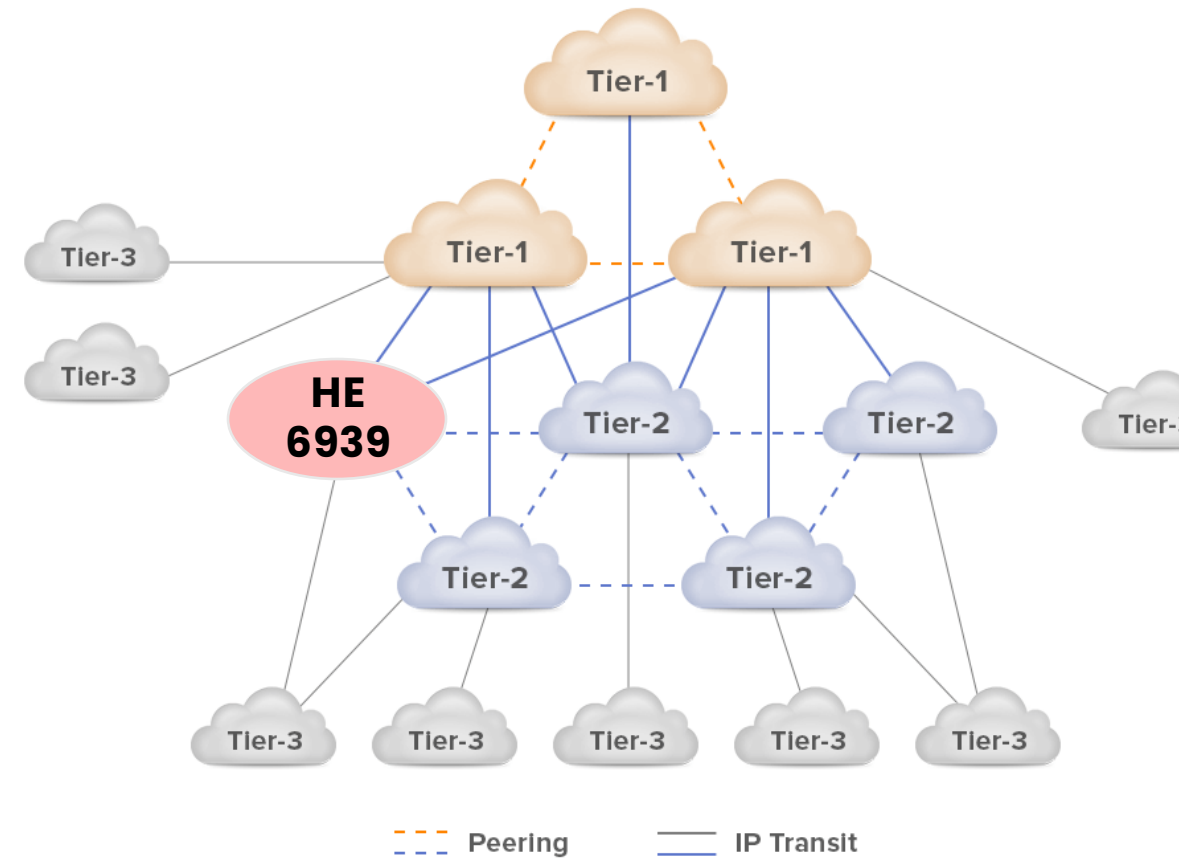
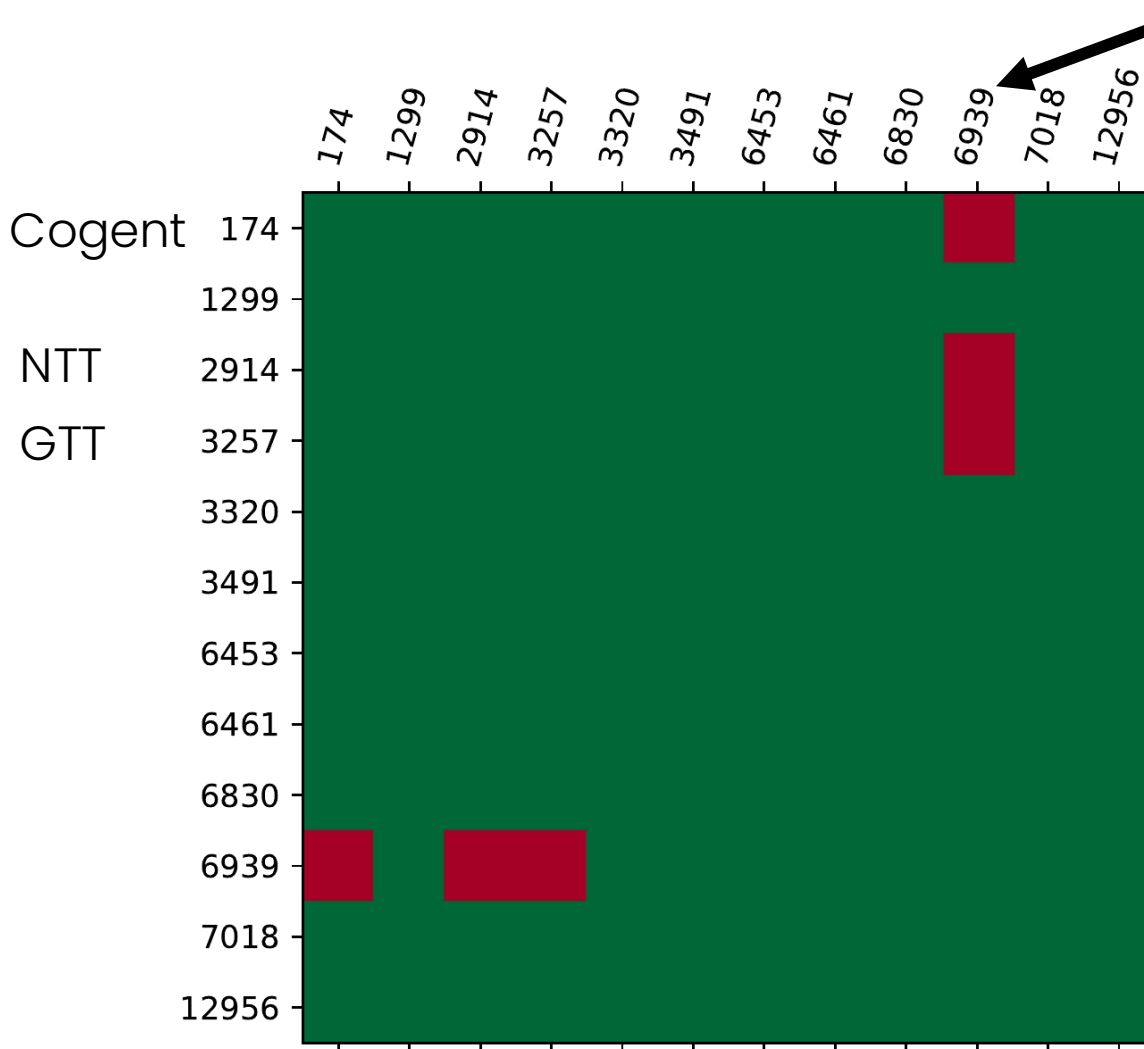
- Ensures global connectivity
- Top of the hierarchy
- Transit-free
- Complete mesh
- Reach the whole Internet via free peering links & customer links



COMMONLY RECOGNIZED TIER1

Name	Headquarters	AS number	CAIDA AS rank ^[16]	Fiber route (km)	Peering policy
AT&T ^[17]	 United States	7018	31	660,000 ^[18]	AT&T Peering policy
Deutsche Telekom Global Carrier ^[19]	 Germany	3320	20	250,000 ^[20]	DTAG Peering Details
GTT Communications	 United States	3257	4	232,934 ^[21] ^[22]	GTT Peering Policy
Liberty Global ^{[23][24]}	 United States  United Kingdom  Netherlands ^[25]	6830	30	800,000 ^[26]	Peering Principles
Lumen Technologies (formerly CenturyLink, formerly Level 3) ^[27] ^{[28][29]}	 United States	3356	1	885,139 ^[30] ^[31]	Lumen Peering Policy
NTT Communications (formerly Verio) ^[32]	 Japan	2914	5	?	Global Peering Policy
Orange ^[33]	 France	5511	12	495,000 ^[34]	OTI peering policy
PCCW Global	 Hong Kong	3491	11	?	Peering policy
Tata Communications (prev. VSNL prev. Teleglobe) ^[35]	 India	6453	7	700,000 ^[36]	Peering Policy
Telecom Italia Sparkle (Seabone) ^[37]	 Italy	6762	9	560,000	Peering Policy
Arelion (formerly Telia Carrier) ^[38]	 Sweden	1299	2	70,000 ^[39]	Arelion's IP Network Peering Policy
Telxius (Subsidiary of Telefónica) ^[40]	 Spain	12956	14	65,000 ^[41]	Peering Policy
Verizon Enterprise Solutions (formerly UUNET) ^[46]	 United States	701	33	805,000 ^[47]	Verizon UUNET Peering policy 701, 702, 703
Zayo Group (formerly AboveNet) ^[48]	 United States	6461	8	196,339 ^[49]	Zayo Peering Policy

"TIER1" CONNECTIVITY IN IPV4



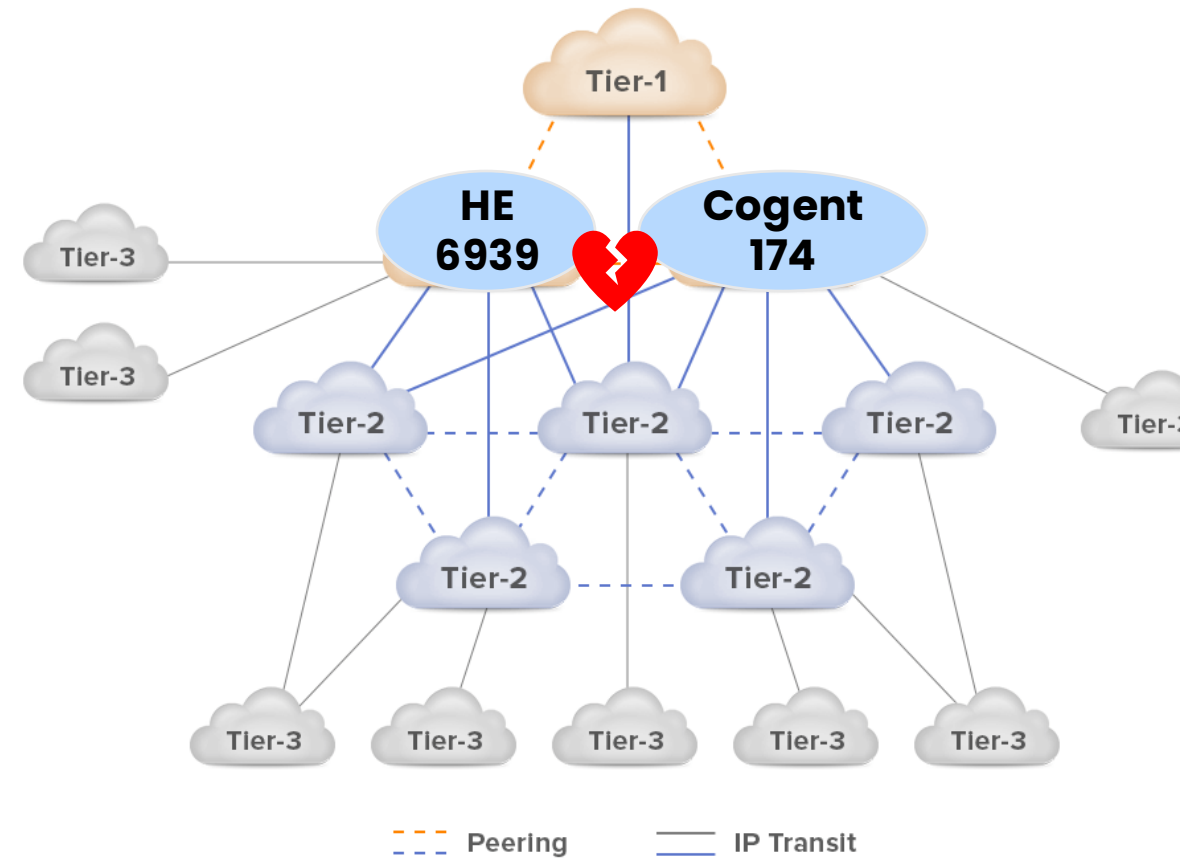
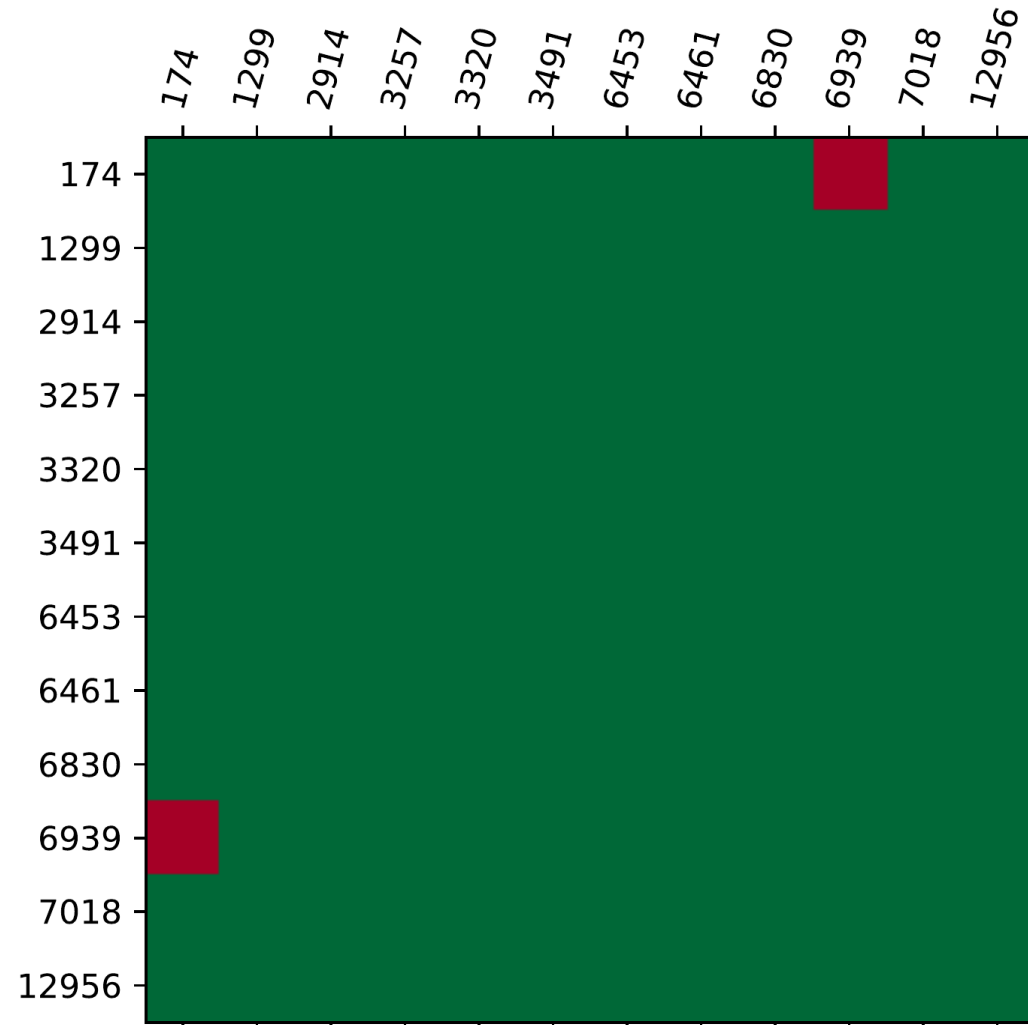
→ All Tier1 networks peering with each other

TIER1?

- IPv4 – Cogent
- IPv6 – Hurricane Electric

Name	Headquarters	AS Number	CAIDA AS Rank ^[16]	Reason
China Telecom	 China	4134/4809	125	Purchases transit from Lumen /AS3356, Cogent /AS174, Verizon /AS701.
China Unicom	 China	4837	215	Purchases transit from Cogent /AS174, Verizon /AS701, Lumen /AS3356, Orange /AS5511.
Singtel ^[52]	 Singapore	7473	17	Purchases transit from Arelion /AS1299, Zayo /AS6461, Tata Communications /AS6453.
Cogent Communications (formerly PSINet) ^[53]	 United States	174	3	No IPv6 routes to Hurricane Electric /AS6939. ^{[54][55]}
Hurricane Electric ^[56]	 United States	6939	6	IPv4: Purchases transit from Arelion /AS1299 to reach GTT /AS3257, NTT /AS2914 and Cogent /AS174. IPv6: Lack of peering with Cogent /AS174. ^{[54][55]}
RETN ^[57]	 United Kingdom	9002	10	Purchases transit from Lumen /AS3356 to reach Cogent /AS174 and NTT /AS2914.
Vodafone Carrier Services (formerly Cable & Wireless) ^[58]	 United Kingdom	1273	13	Purchases transit from Arelion /AS1299 to reach AT&T /AS7018 and part of NTT /AS2914. ^[59]
Telstra ^[60]	 Australia	4637	15	Purchases transit from Lumen /AS3356, Arelion /AS1299, Zayo /AS6461.
Comcast ^[61]	 United States	7922	37	Purchases transit from Tata /AS6453

"TIER1" CONNECTIVITY IN IPV6



→ Transit free networks NOT peering with each other!

PEERING DISPUTES

No incentive to peer

- Cogent  HE
- Free  Google
- Cogent  Google

Etc...



RESEARCH QUESTION

How global is the current Internet?

- Especially IPv6?
- What is the fraction of the Internet not globally reachable?
- Is it getting better? Worst?

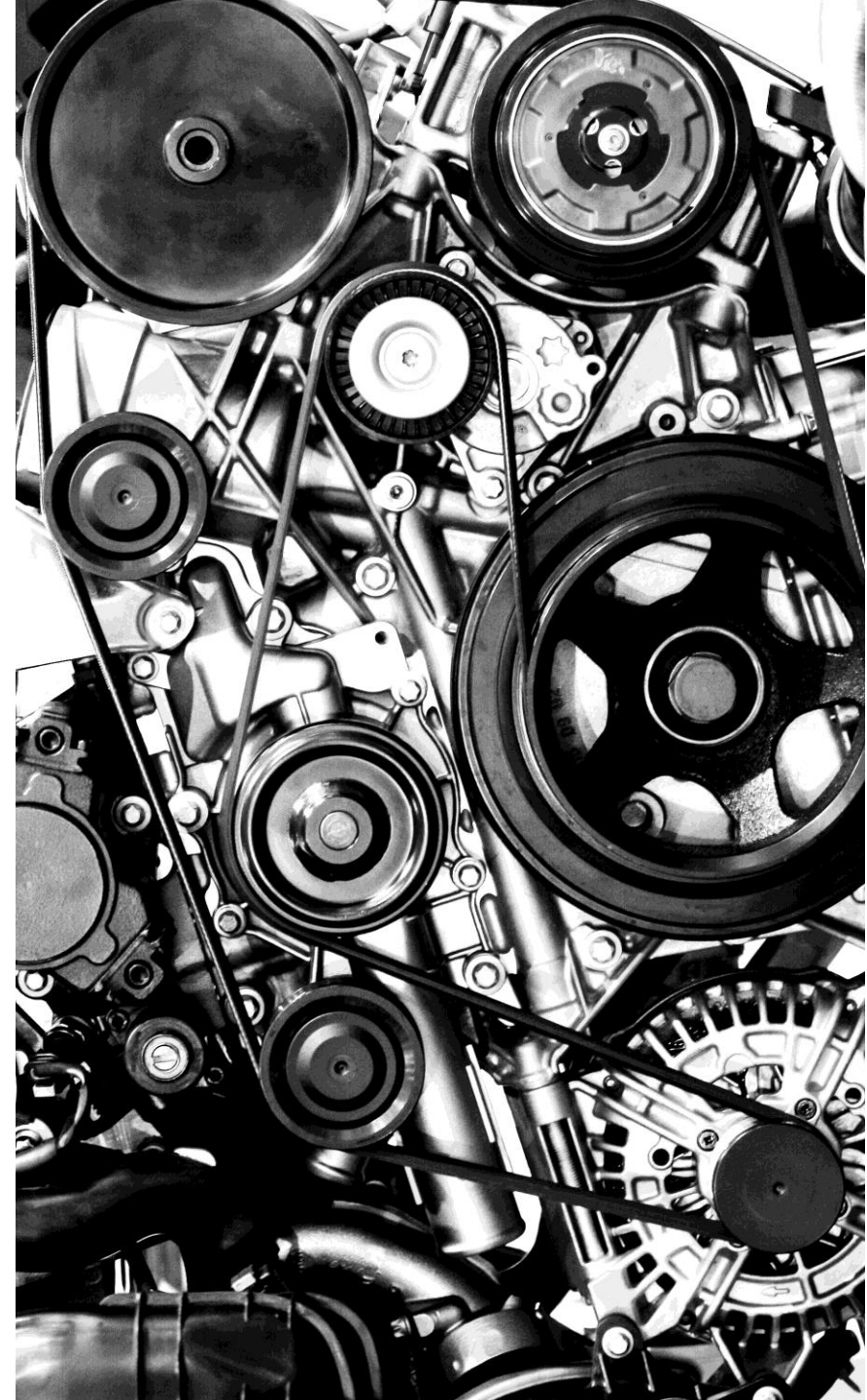


(although, yes, IPv6 troubles are hidden by IPv4 but still...)

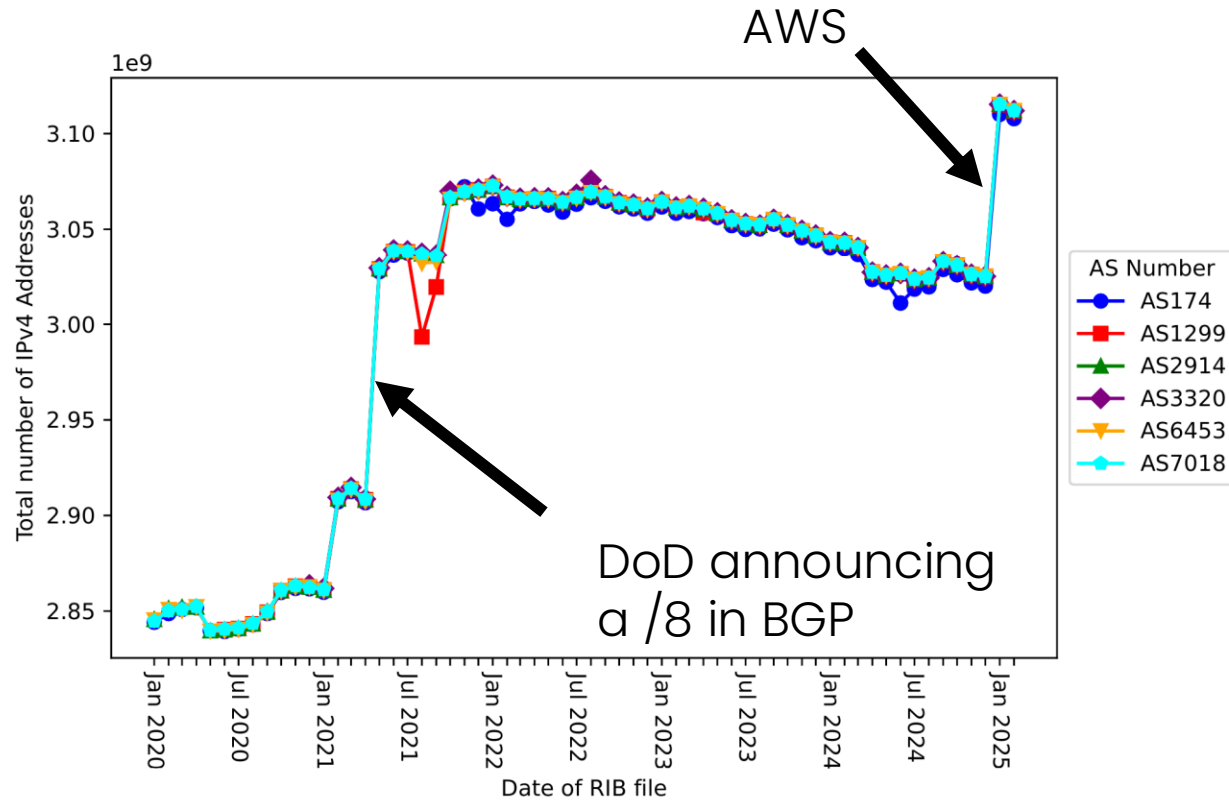
METHODOLOGY

Focus on 12 higher-tier transit networks

- Control plane reachability
 - RIPE RIS data
 - 5 years of data (2020–2025)
 - 12 higher-tier transit networks
- Service/Data plane analysis
 - Tranco & OpenINTEL DNS data
 - Traceroute using RIPE Atlas
 - HE and Cogent

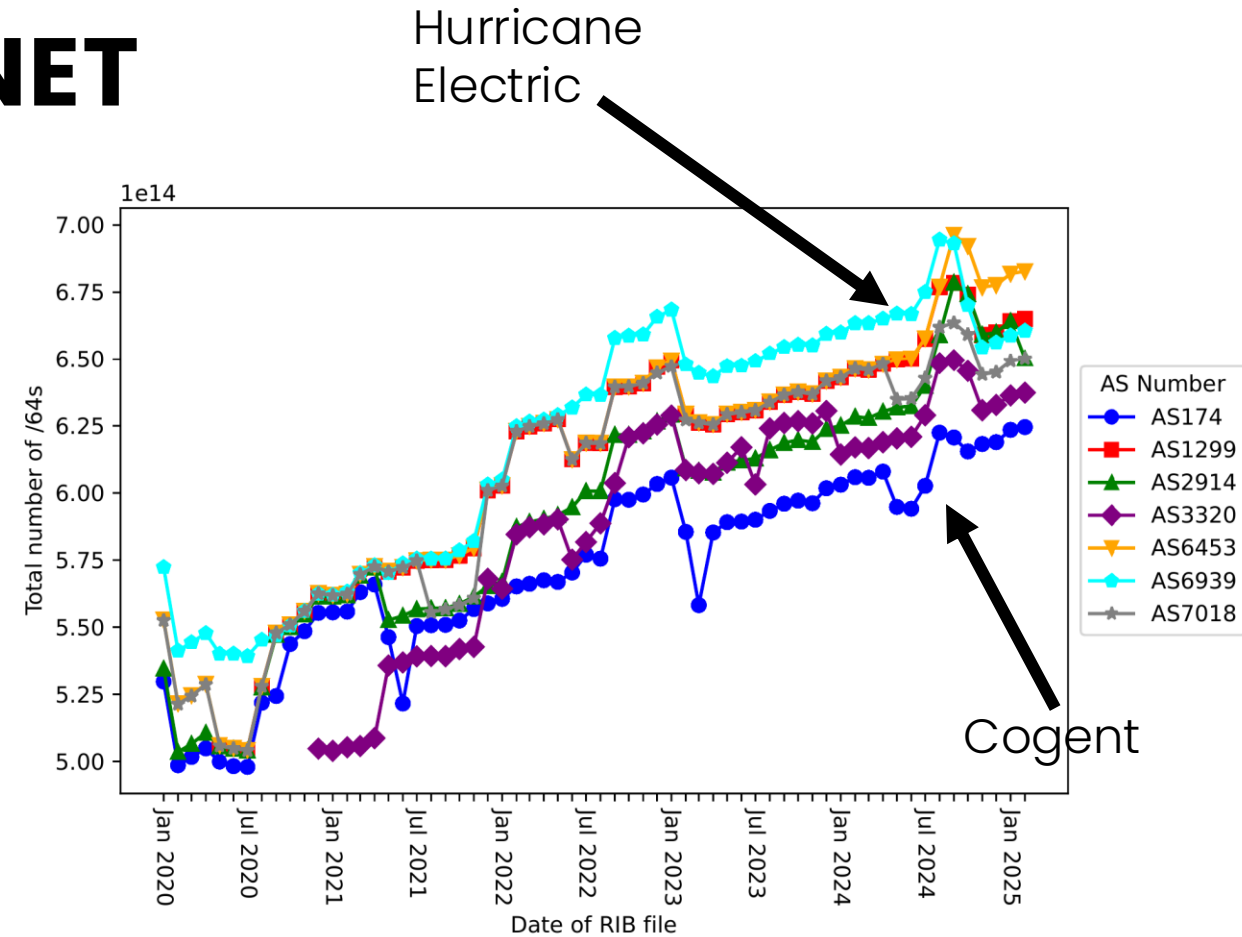


THE SIZE OF THE INTERNET



(a) Number of IPv4 addresses

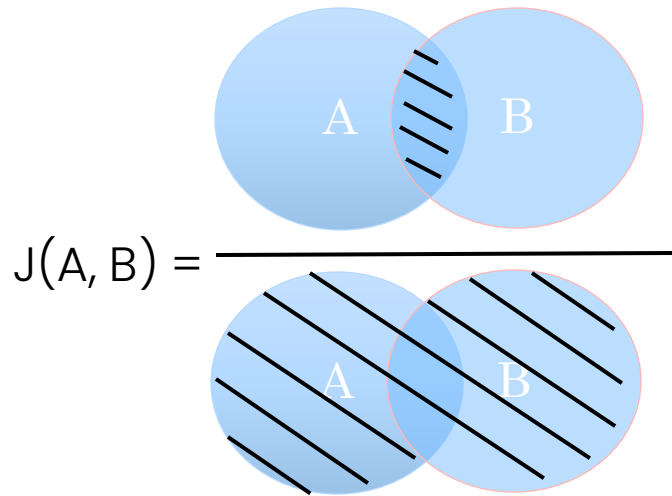
IPv4: Nearly identical routing tables!



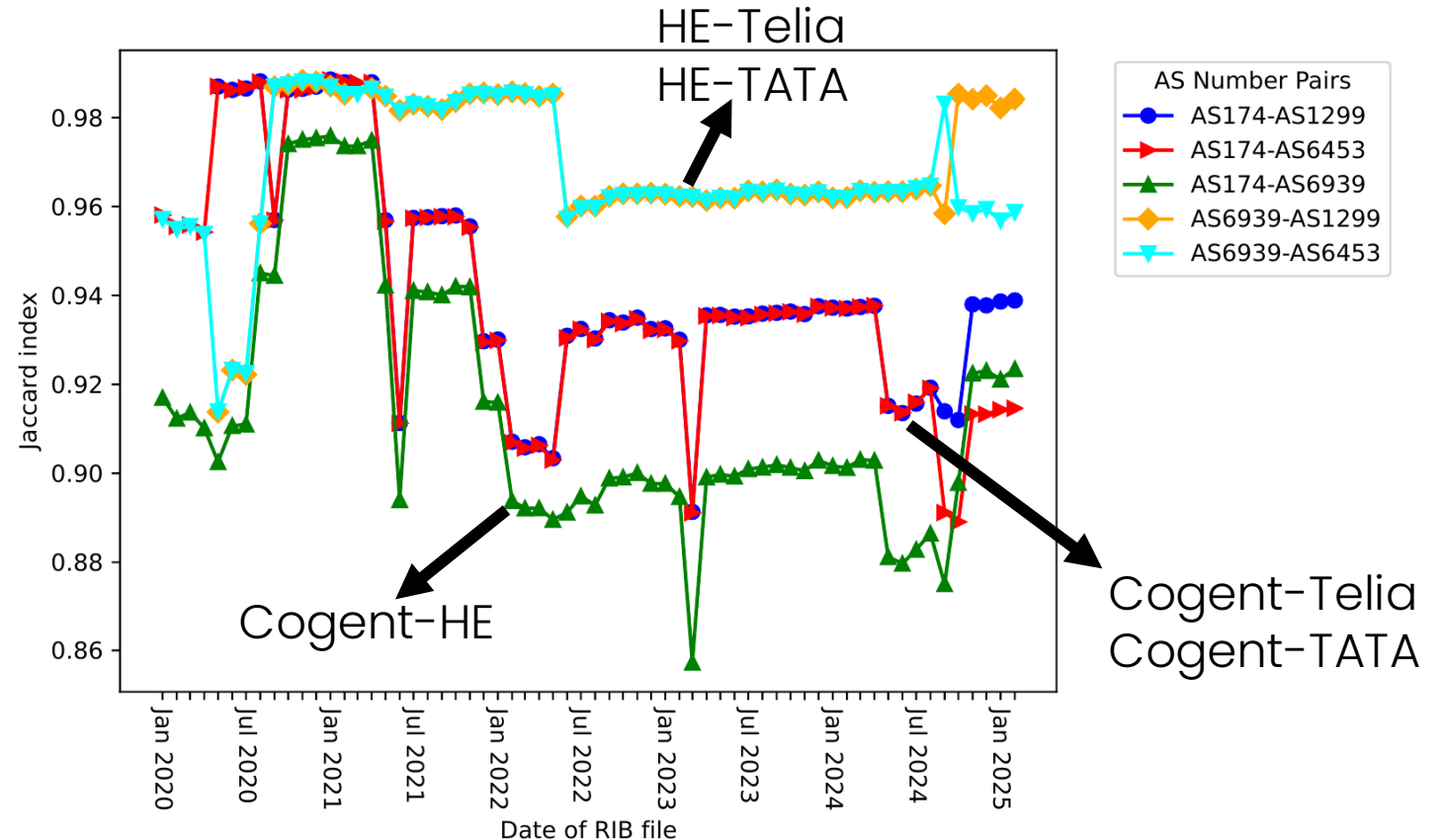
(b) Number of IPv6 /64s

**IPv6: - different views
- gap increases over time**

MEASURING FRAGMENTATION IN IPV6



For IPv4: usually 0.998~0.999

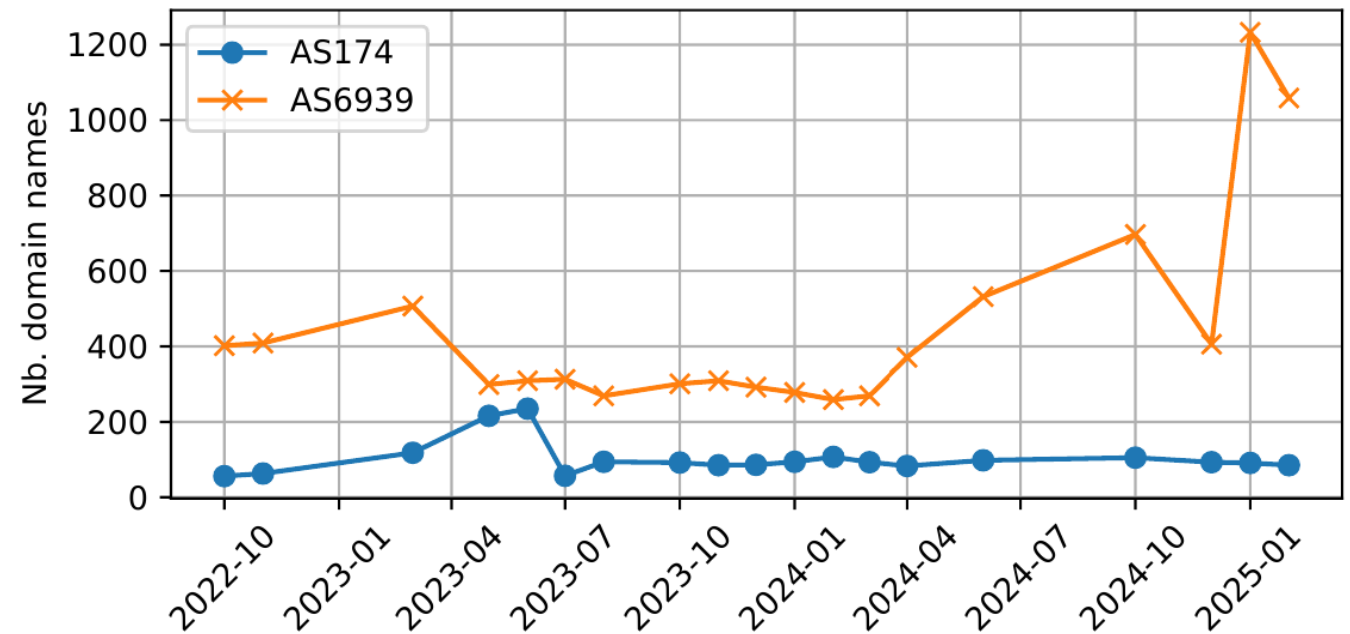


- Fragmentation growing over time
- Intersections with Cogent (AS174) decreasing over time

IMPACT OF WEBSITES

What's in partially reachable prefixes?

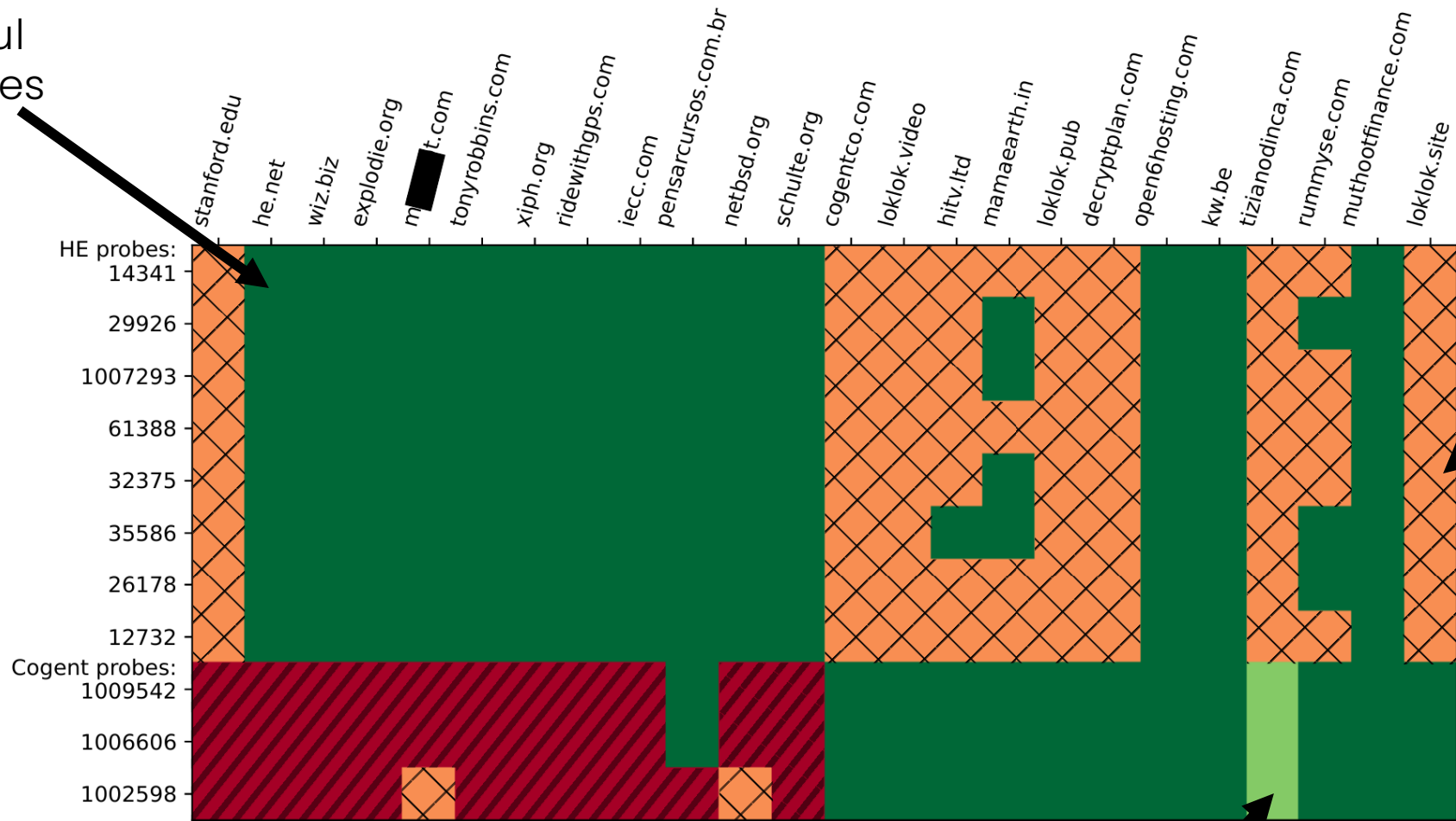
- Tranco top 1M websites
- OpenINTEL forward DNS data
- Examples:
 - `stanford.edu`
 - OpenStreetMap (historically)



-> Few services but upward trend

TRACEROUTE TO TOP 24 PARTIALLY REACHABLE WEBSITES

Successful
traceroutes



Incomplete
traceroutes

ICMP errors
Network unreachable

ICMP errors
Host unreachable

CONCLUSION

IPv6 is fragmented

- IPv4 is not
- Cogent / HE dispute is the main cause

Fragmentation has increased over the last five years

- Tier1 tend to align more with HE

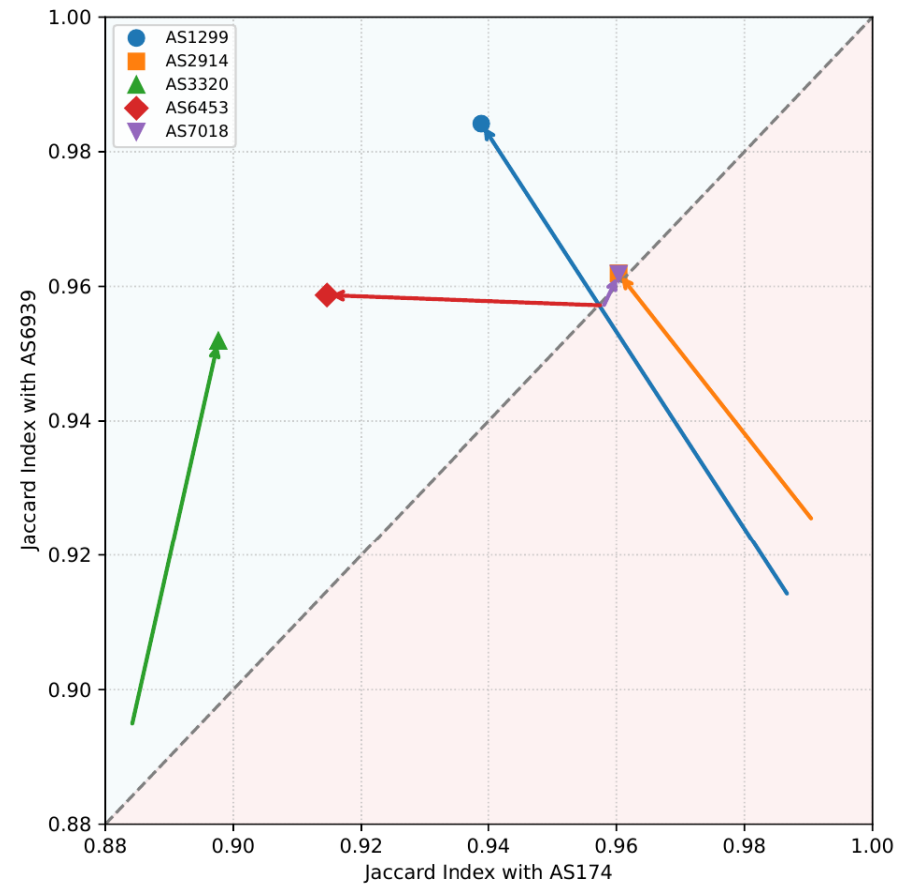
Popular IPv6 services are partially unreachable

- IPv4 fallback currently hides the problem
- future IPv6-only Internet requires restoring global reachability

BACKUP

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Fragmentation change over time



- Fragmentation growing over time
- Intersections with Cogent (AS174) decreasing over time