An AS Topology View of IPv6 Adoption

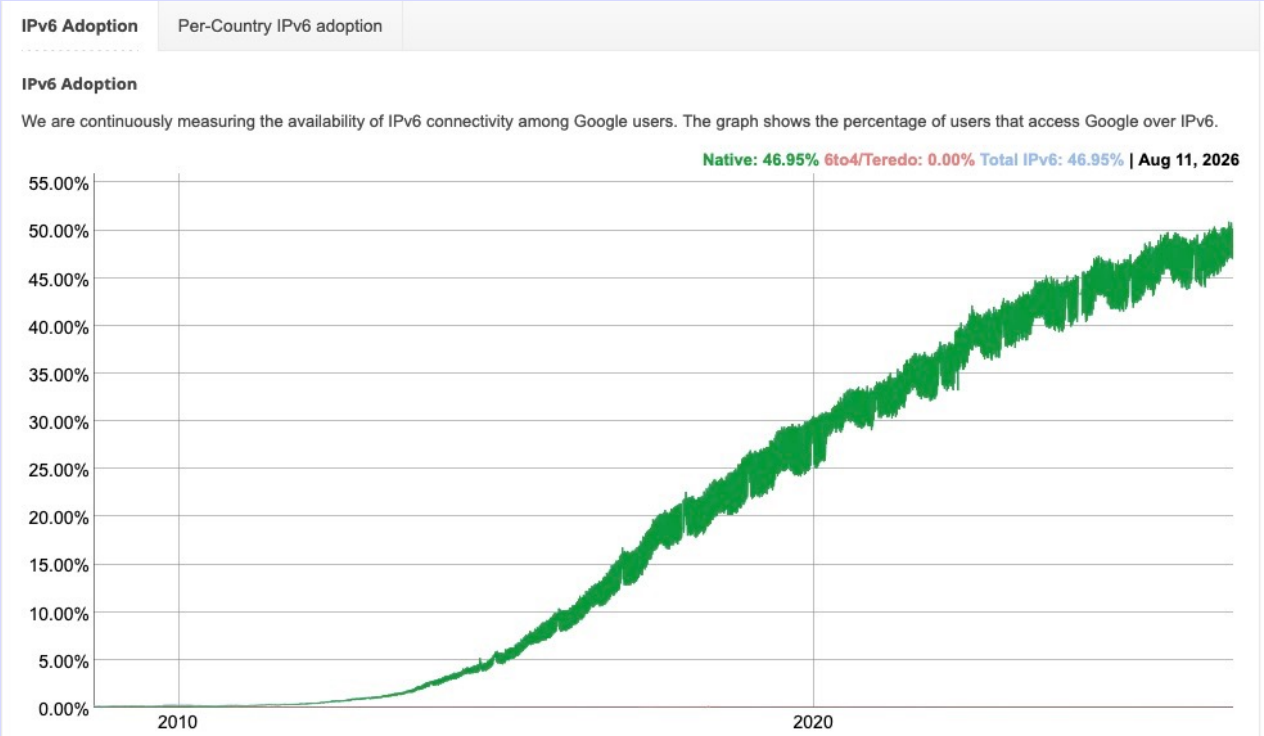
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Romain Fontugne
Malte Tashiro
Randy Bush
IIJ Research Laboratory



So, after 30 years, How are we doing with the IPv6 Transition?

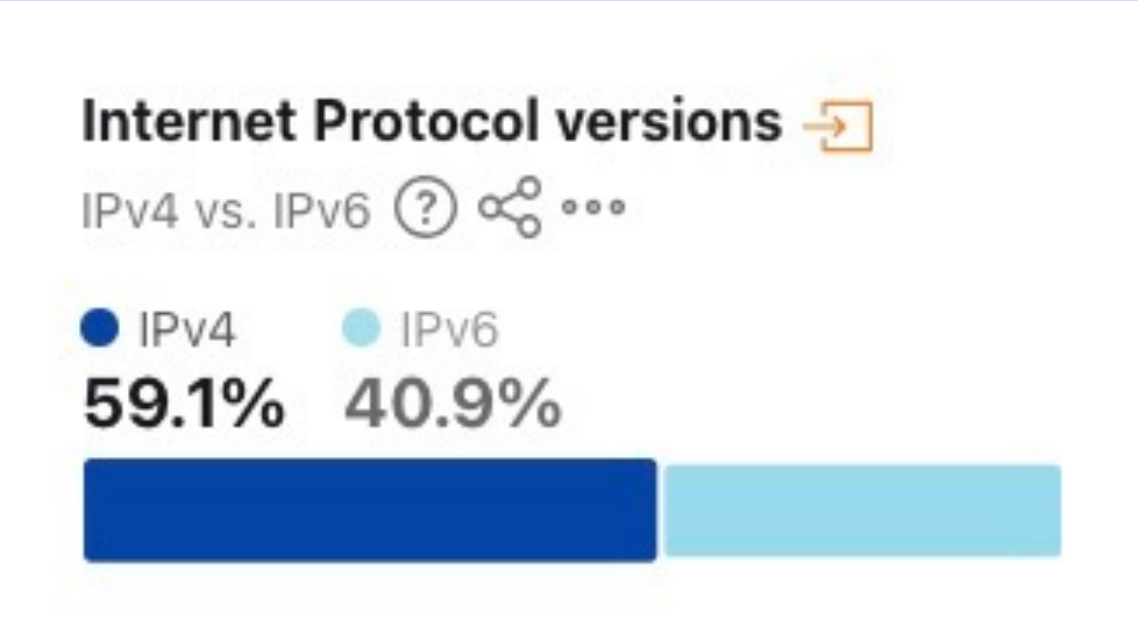
Google Tells Us 50%

https://www.google.com/intl/en/ipv6/statistics.html



Cloudflare Tells Us 41%

https://radar.cloudflare.com/#internet-protocol-versions



Global Tier-1s Tell Us 10-15%

[private communications]

Trans-Pacific Links 10-15%

[private communications]

Intra-Japan Peering Links 40%

[private communication]

Internet Exchanges >=10%

[e.g. https://www.seattleix.net/statistics/]

And, of course, they are not all measuring the same thing

Google and Cloudflare are measuring "completed connections"

Individual TCP sessions

ISPs are measuring Traffic, i.e. bits

Google and Cloudflare are Consumer Edge

What will Inter-AI Agent Traffic be?

CloudFlare Claims 60% today

https://radar.cloudflare.com/traffic#bot-vs-human

But we're BGP kind of folk

So we want to see how IPv6 is deployed in the AS topology

Data extracted from RIPE/RIS and Route Views & Internet Yellow Pages

Classification – AS Type

IPv4-Only AS

- originates only IPv4 prefix(es)
- does not appear on any IPv6 ASpaths

Dual-Stack AS

- appears on both IPv4 and IPv6 ASpaths

IPv6-Only AS

- originates only IPv6 prefix(es)
- does not appear in any IPv4 ASpaths

Classification - Topology

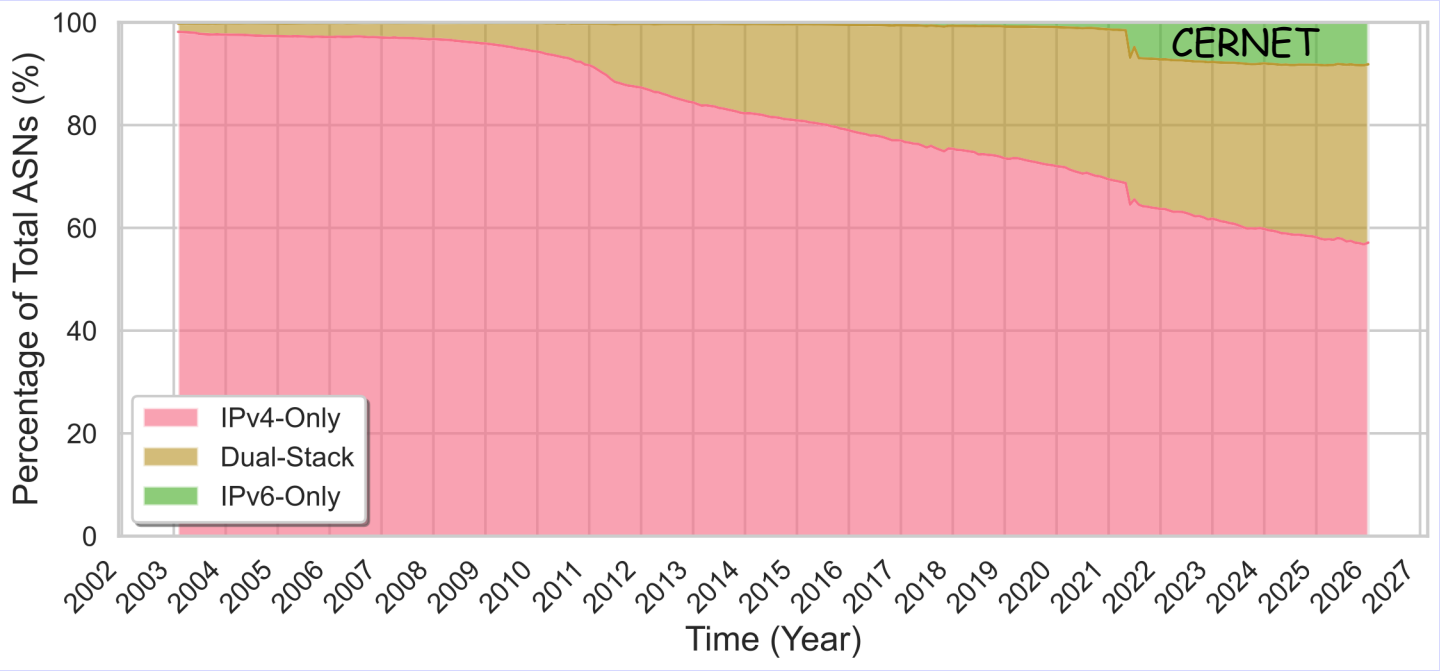
Stub AS

- appears only at origin of ASpaths

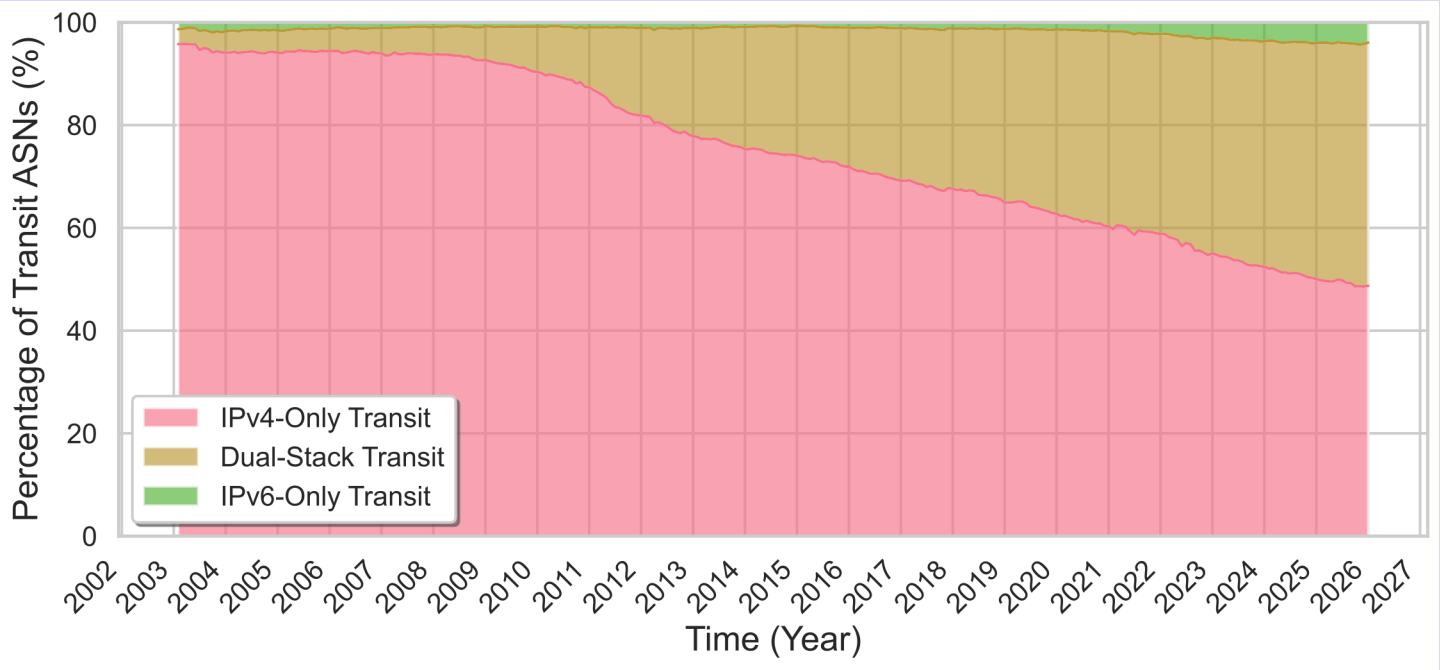
Transit AS

- appears mid-ASpath at least once

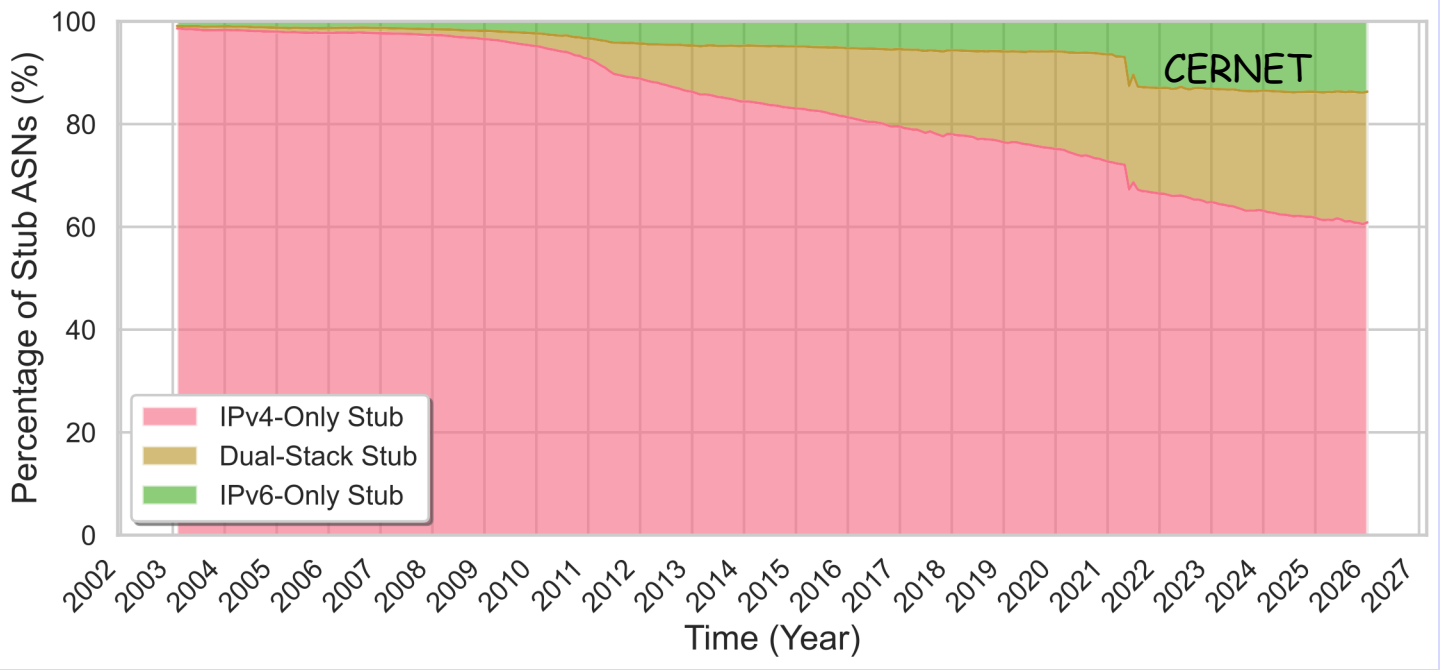
All ASs


CERNET
Percentage of Total ASNs (%)
100
80
60
40
20
0
IPv4-Only
Dual-Stack
IPv6-Only
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
Time (Year)

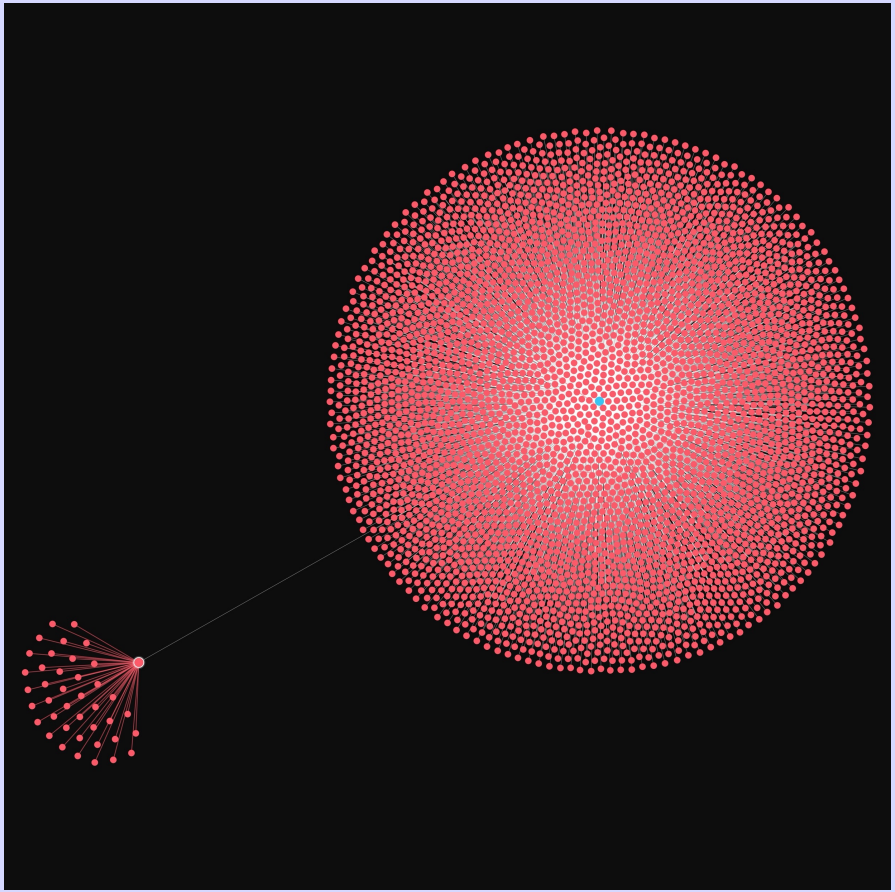
Transit ASs


Percentage of Transit ASNs (%)
100
80
60
40
20
0
IPv4-Only Transit
Dual-Stack Transit
IPv6-Only Transit
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
Time (Year)

Stub ASs


Percentage of Stub ASNs (%)
100
80
60
40
20
0
IPv4-Only Stub
Dual-Stack Stub
IPv6-Only Stub
CERNET
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
Time (Year)

CERNET – a 4,000 AS - Star

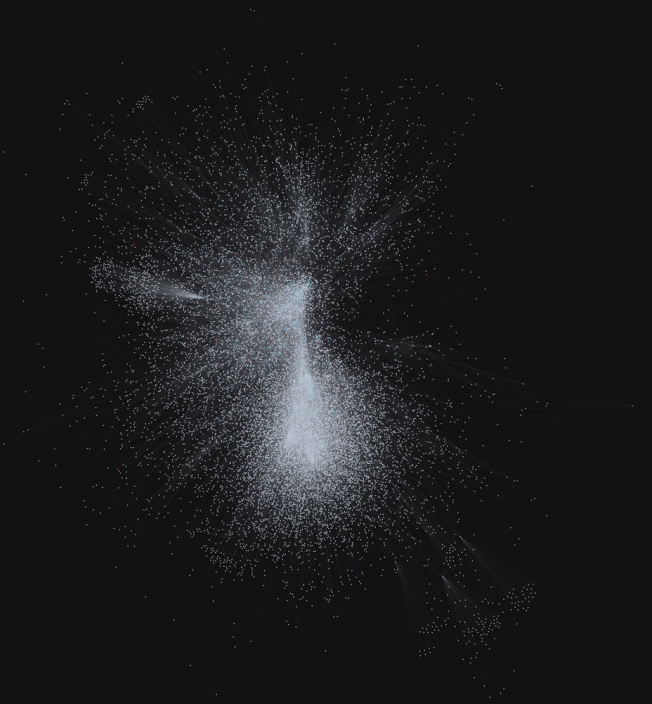


4,000
Stubs

The Evolution

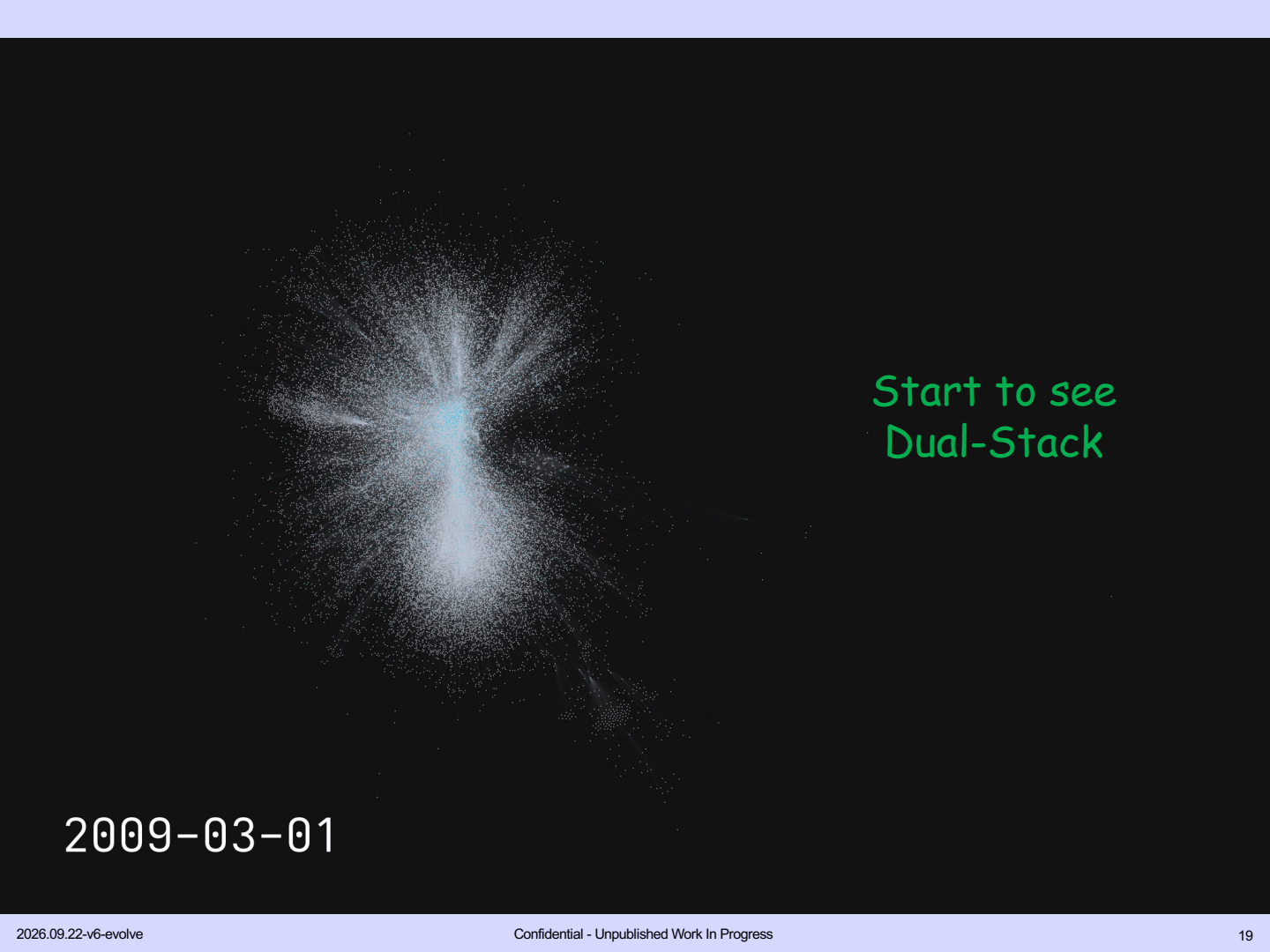
In '97 when RV and later RIS Started, IPv6 was already being slightly deployed

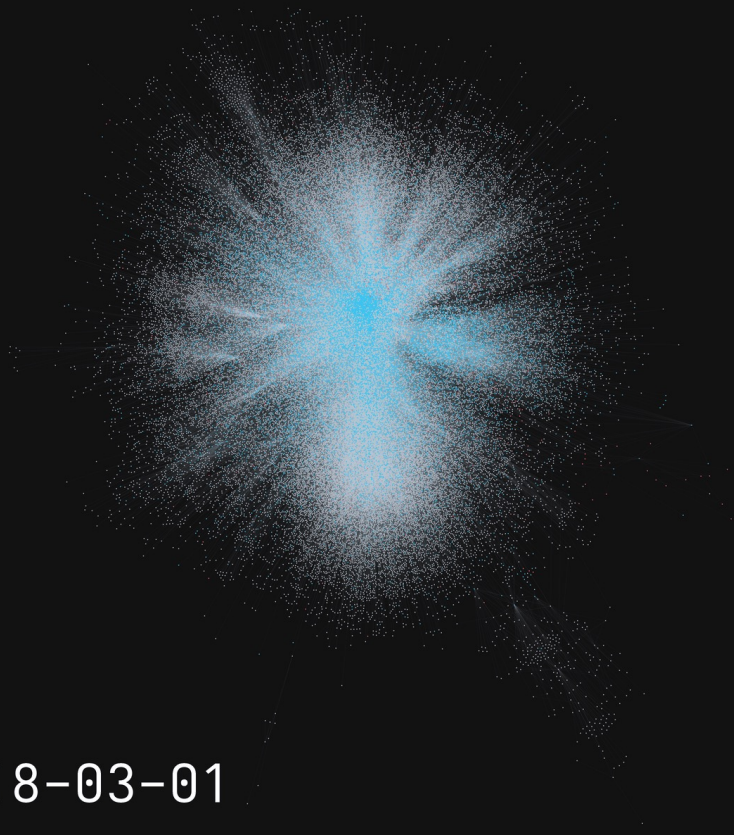
So we do not have pictures of the purely IPv4-Only Internet



It is hard to see Dual-Stack in 2003

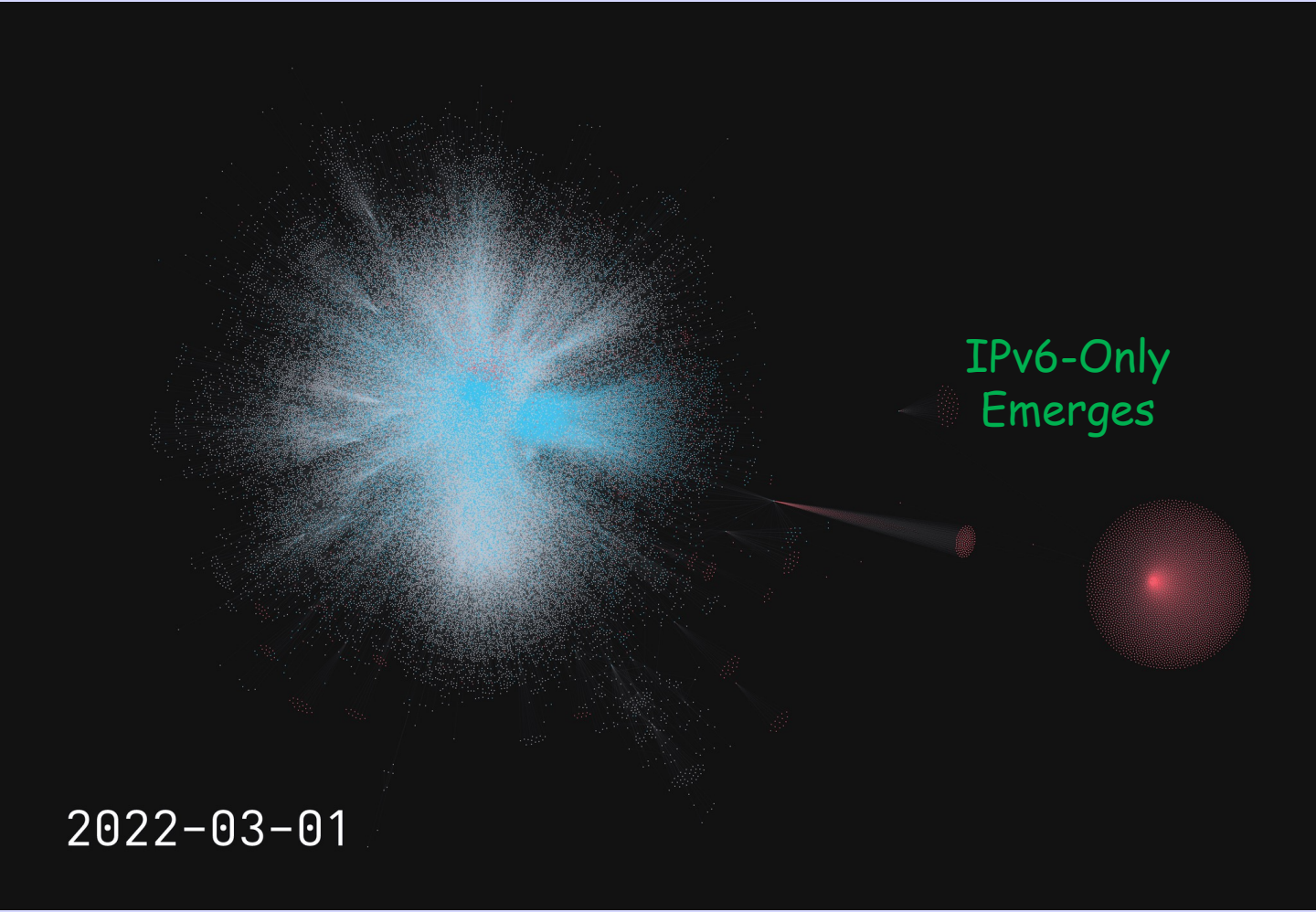
2003-03-01

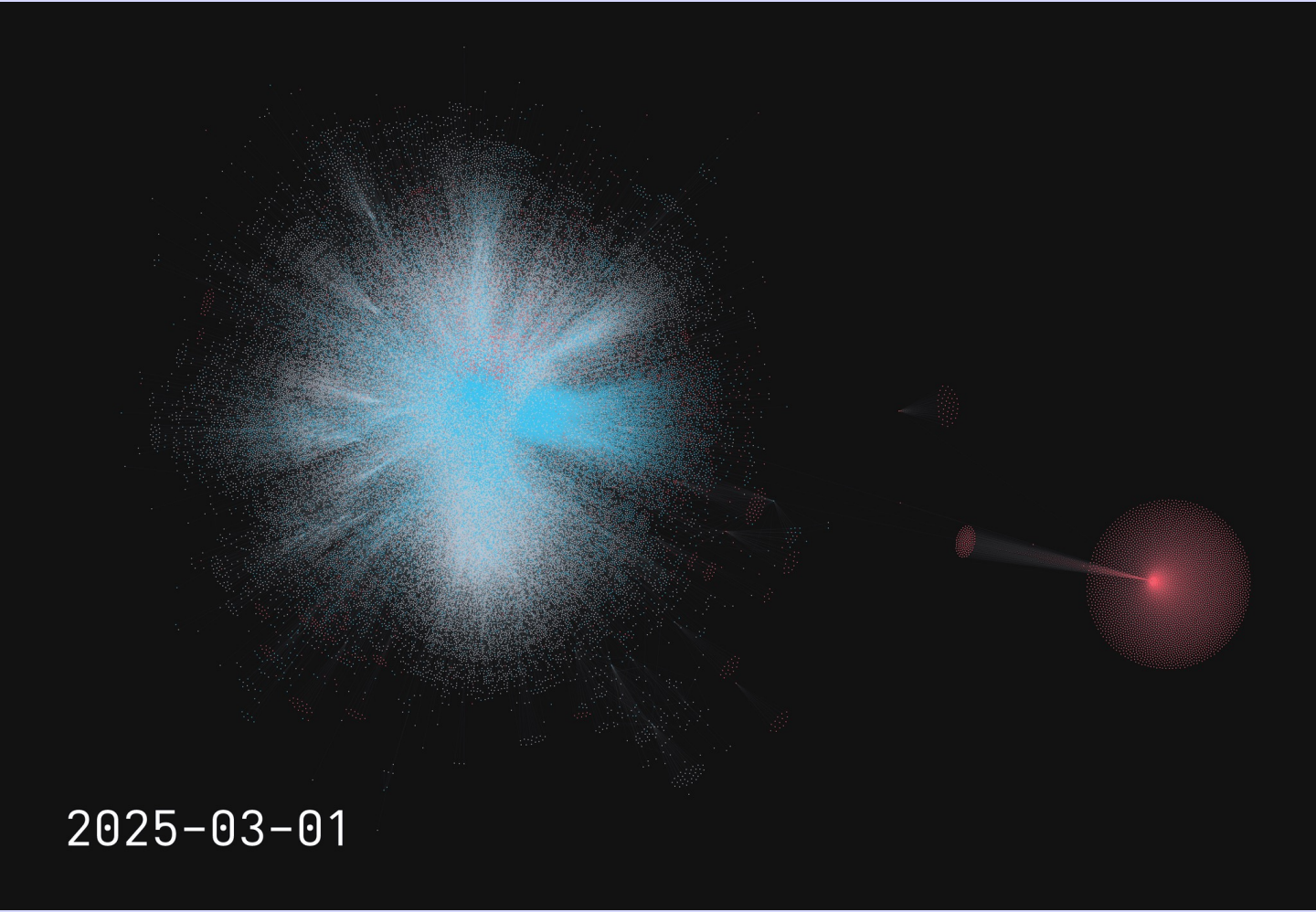

Start to see
Dual-Stack
2009-03-01



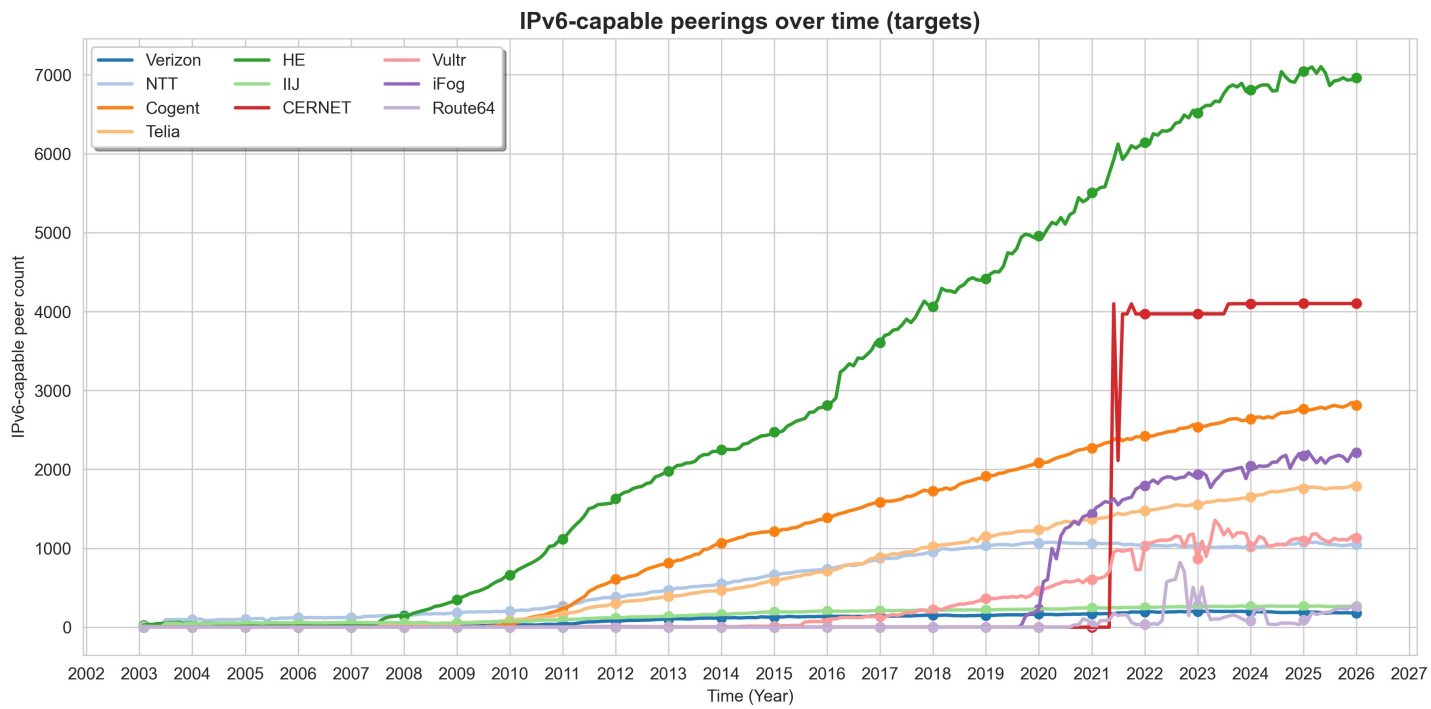
Dual-Stack in the Core

2018-03-01


IPv6-Only
Emerges
2022-03-01


2025-03-01

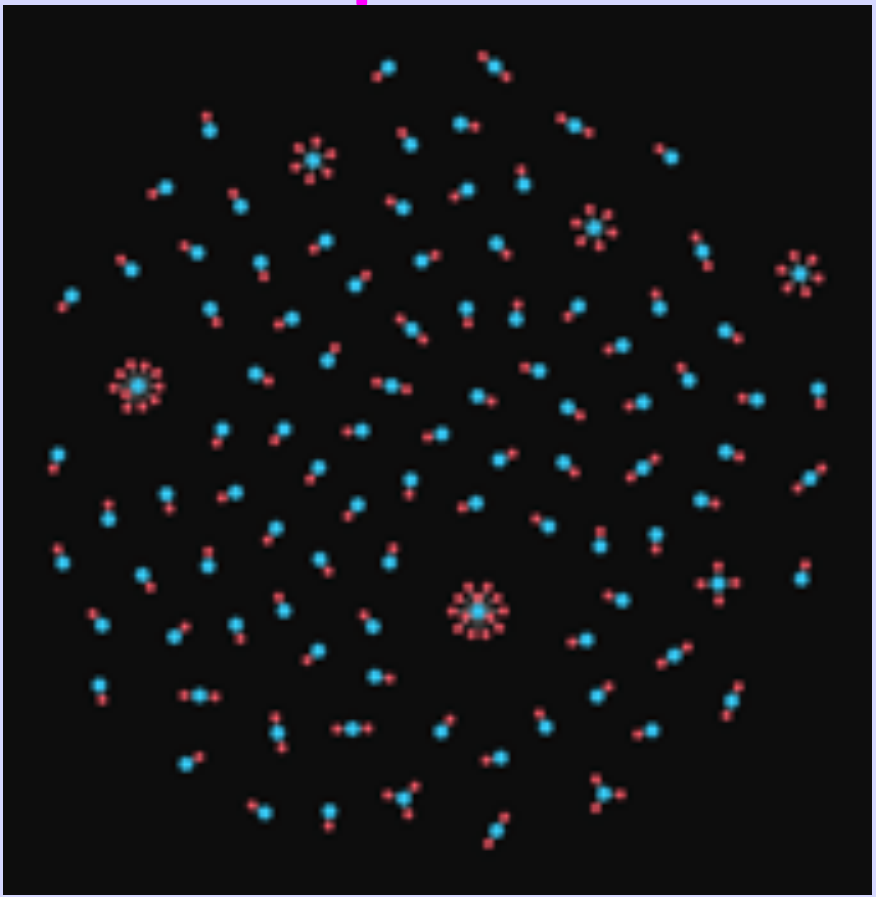
IPv6-Capable Inter-AS Links



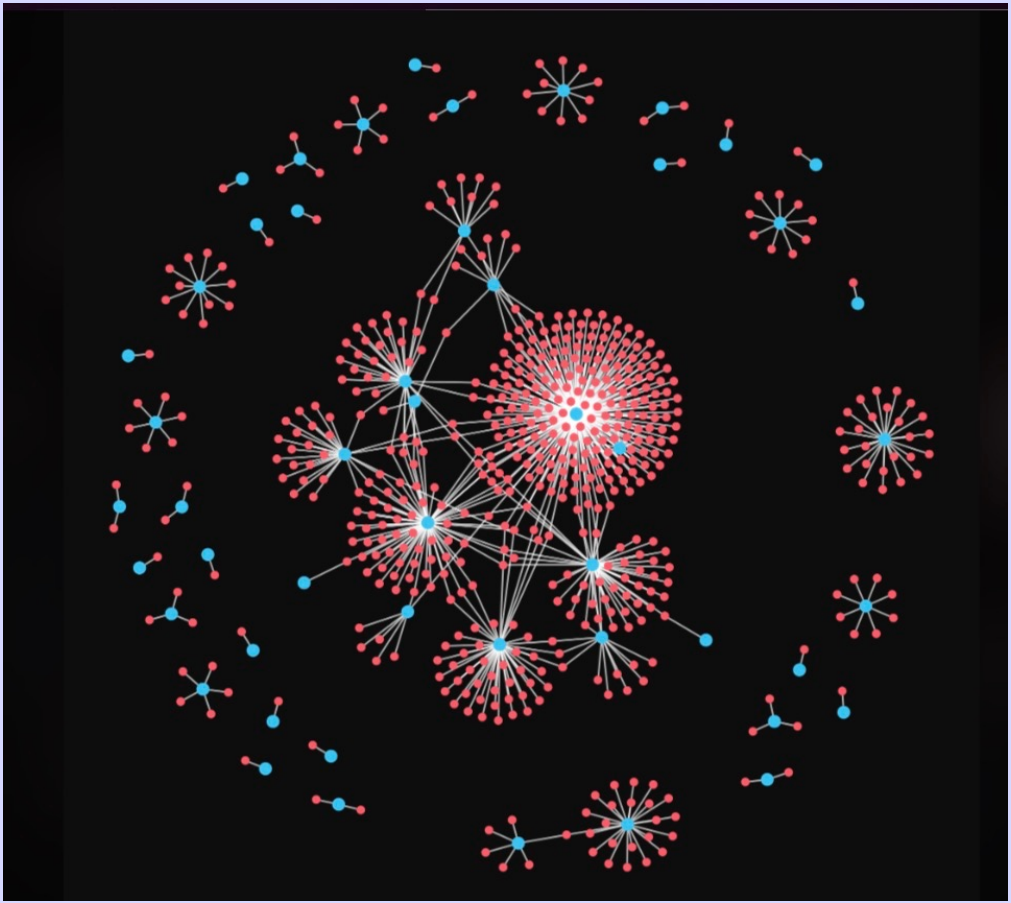
Early IPv6-Only Experiments



More Wide-Spread w/ Clusters

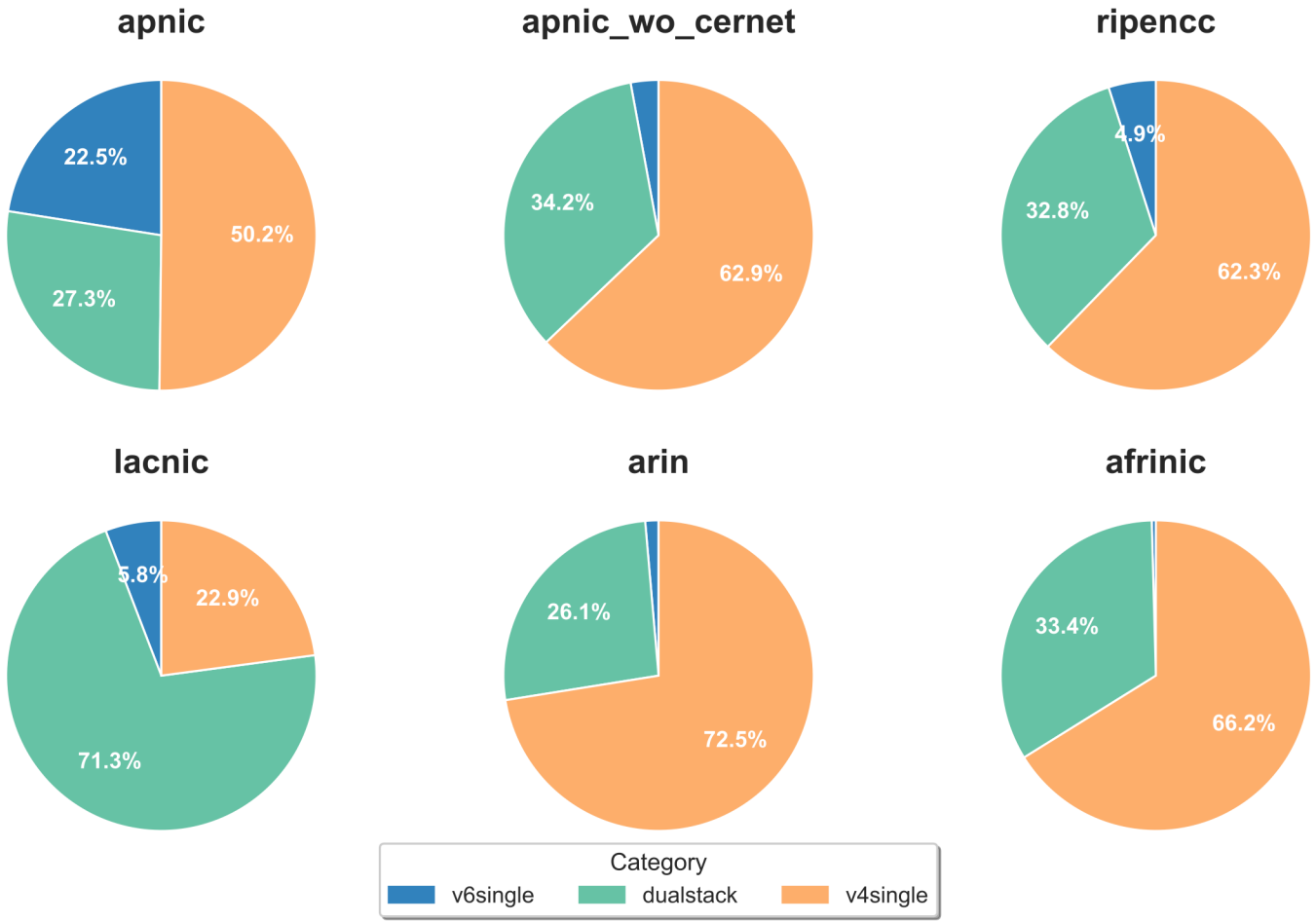


Emerging IPv6-Only Frontier

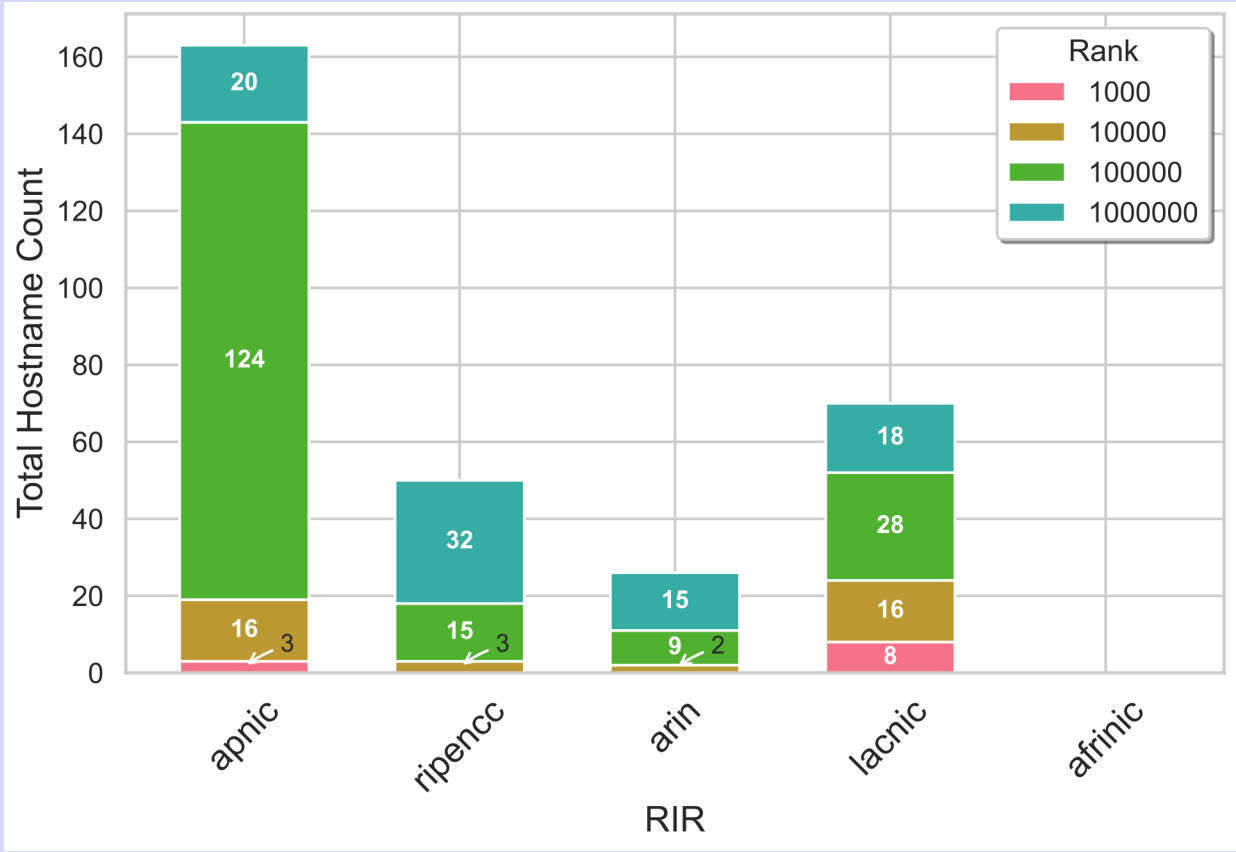


Frontier – what to display

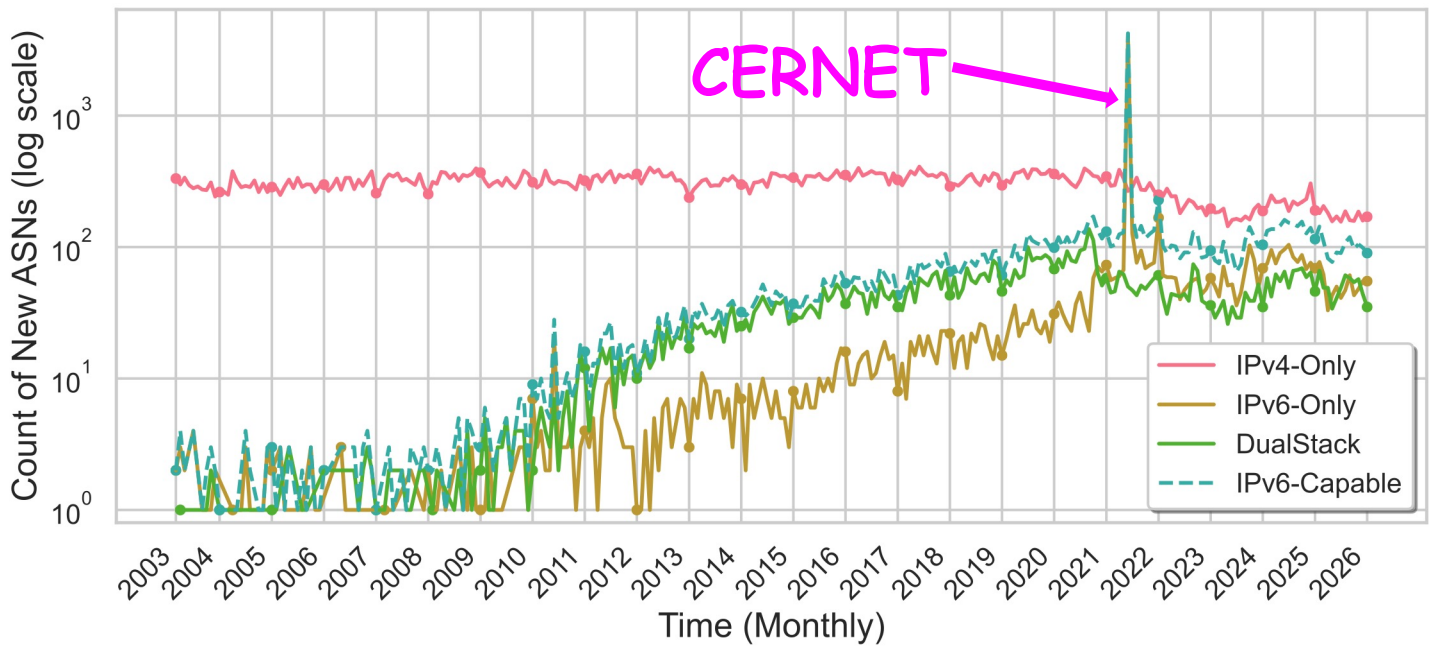
- 2026
- Extract all Dual-Stack ASs
- Sort by number of IPv6-Only peers with <= 3 Dual-Stack peers
- Pick 50 random of the Dual-Stack ASs weighted by their number of IPv6-only peers
- display with their IPv6-only peers


apnic
22.5%
50.2%
27.3%
apnic_wo_cernet
34.2%
62.9%
ripencc
4.9%
32.8%
62.3%
lacnic
5.8%
22.9%
71.3%
arin
26.1%
72.5%
afrinic
33.4%
66.2%
Category
v6single
dualstack
v4single

IPv6-Only in Production CrUX-1M

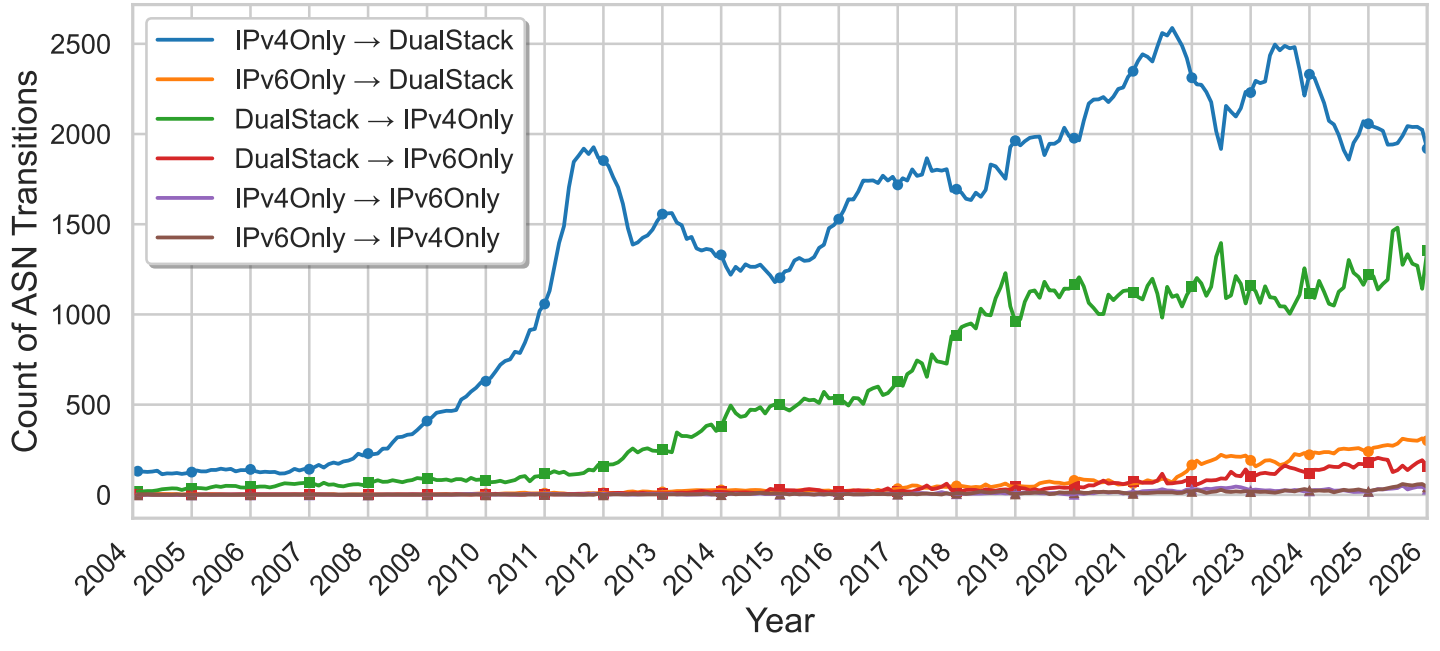


New ASs

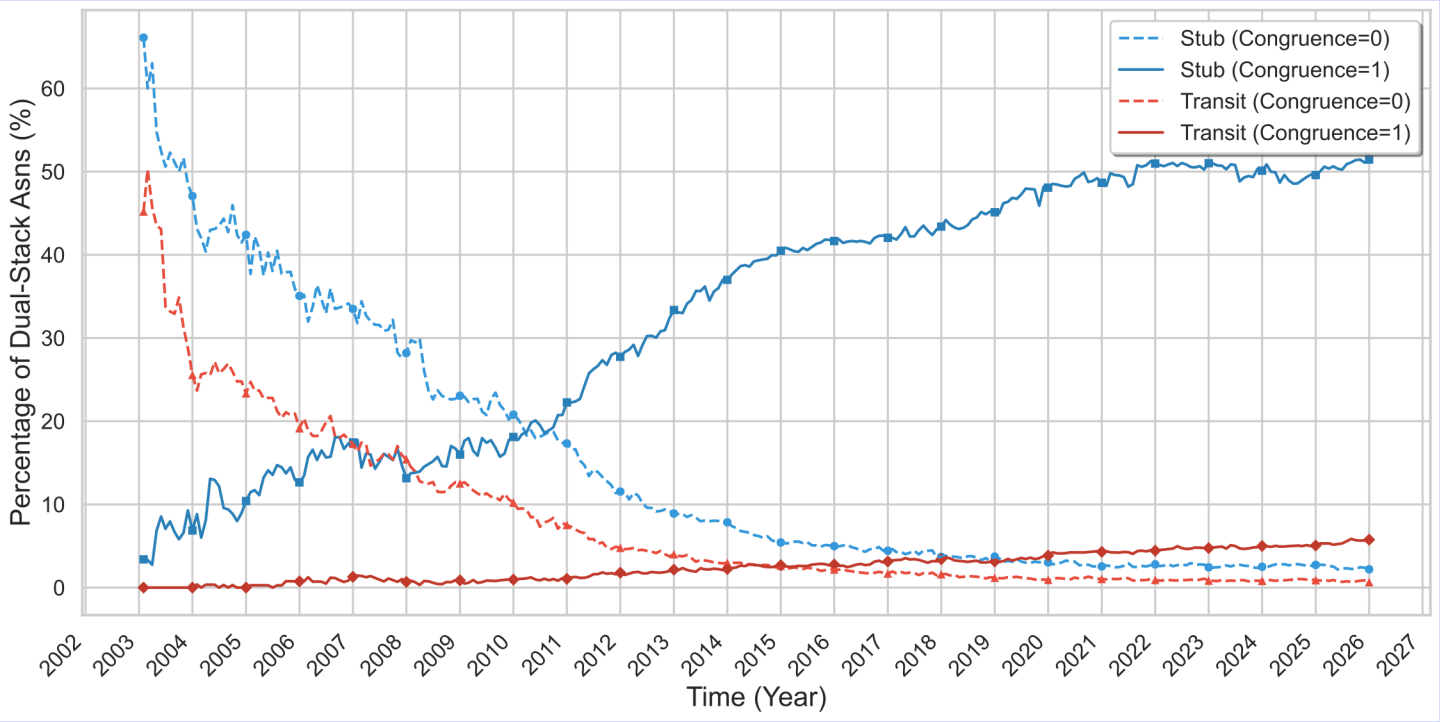


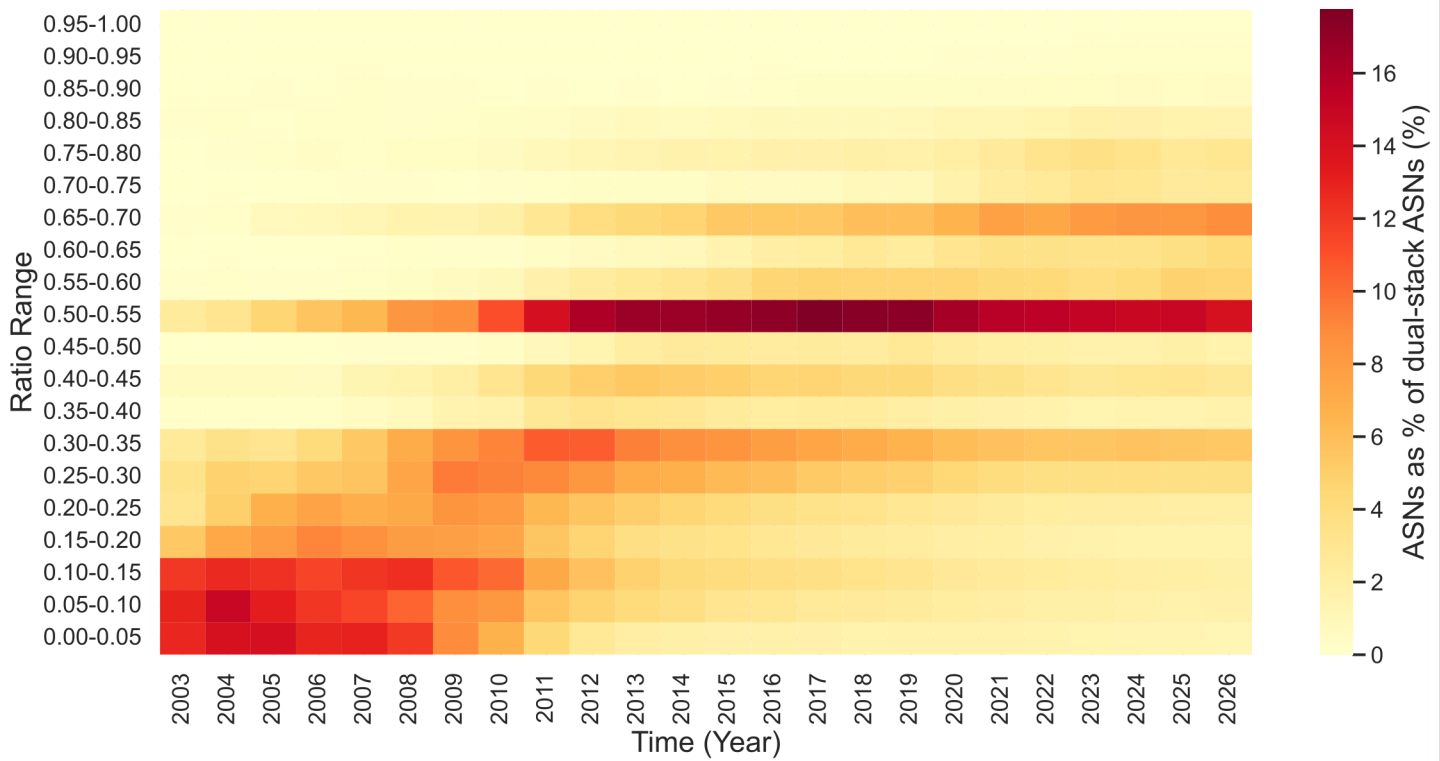
We suspect a lot of networks come up IPv4-Only and then add IPv6 a month or two later

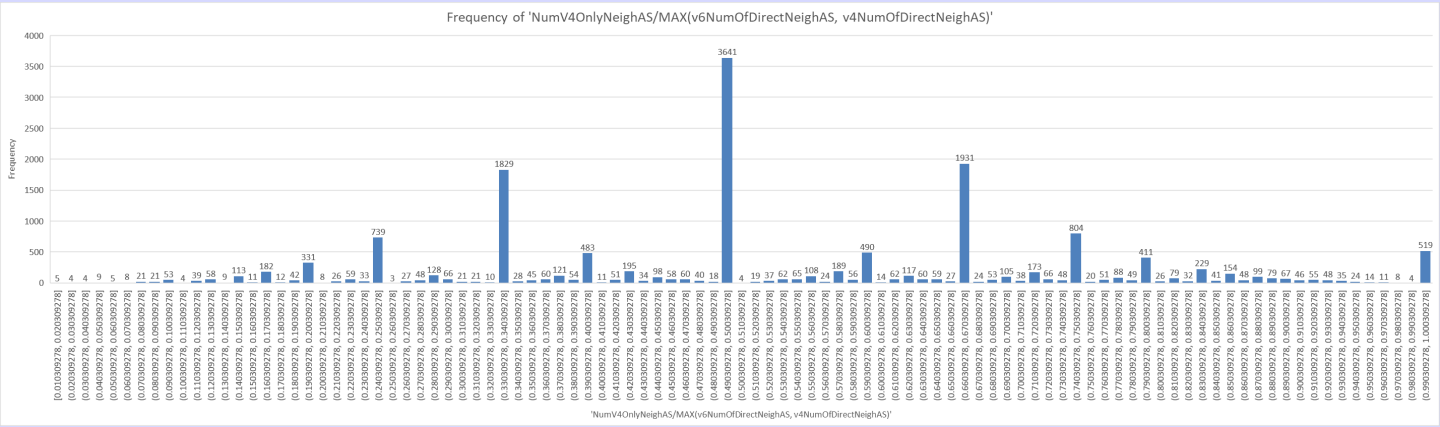
Transitions



Congruence: Ratio of IPv4 peers to IPv6 peers in a Dual Stack AS


Stub (Congruence=0)
Stub (Congruence=1)
Transit (Congruence=0)
Transit (Congruence=1)
Percentage of Dual-Stack Asns (%)
0
10
20
30
40
50
60
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2027
Time (Year)


Ratio Range
0.95-1.00
0.90-0.95
0.85-0.90
0.80-0.85
0.75-0.80
0.70-0.75
0.65-0.70
0.60-0.65
0.55-0.60
0.50-0.55
0.45-0.50
0.40-0.45
0.35-0.40
0.30-0.35
0.25-0.30
0.20-0.25
0.15-0.20
0.10-0.15
0.05-0.10
0.00-0.05
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
Time (Year)
ASNs as % of dual-stack ASNs (%)
0
2
4
6
8
10
12
14
16


Frequency of 'NumV4OnlyNeighAS/MAX(v6NumOfDirectNeighAS, v4NumOfDirectNeighAS)'
Frequency
'NumV4OnlyNeighAS/MAX(v6NumOfDirectNeighAS, v4NumOfDirectNeighAS)'

Conclusion

The IPv6 transition is slow, but we knew that

The core has pretty much gone Dual-Stack

The edge, enterprise, is massively IPv4-Only

and we are not optimistic that they will move

There is an IPv6-Only frontier, experimental at first, but production is emerging

Hetrogenous geographic distribution


THE END
THANK YOU!