

R&E Routing Policy: Inference and Implication

Matthew Luckie
CAIDA

Steven Wallace
Internet2

Karl Newell
Internet2

Jeff Bartig
Internet2

Sadi Koçak
SURF

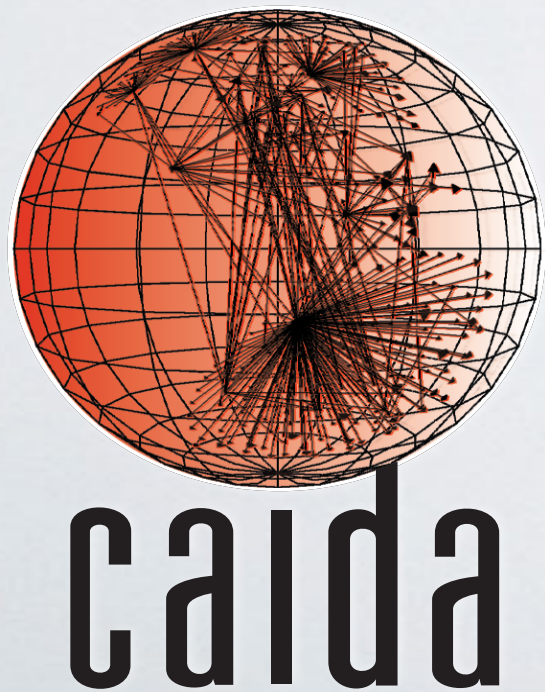
Niels den Otter
SURF

Kaj Koole
SURF

James Deaton
Internet2

k claffy
CAIDA

Internet Measurement Conference 2025



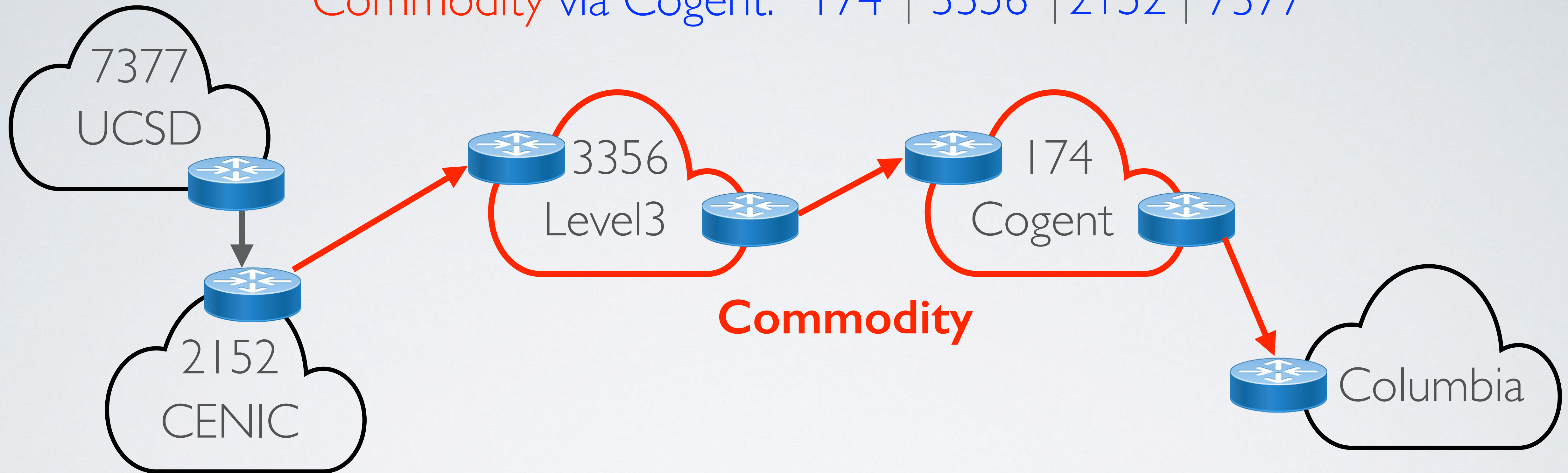
Research and Education (R&E) Networking: Primer

- **Specialized R&E networking infrastructure bridges a gap:**
 - R&E institutions need to exchange large volumes of scientific data globally
 - Impractical using commercial CDNs
- Primary focus of R&E networking is on high-speed low-latency connectivity between members
- Members may have to arrange their own commodity transit

BGP Route Selection: Primer

Columbia receives two routes to UCSD:

Commodity via Cogent: 174 | 3356 | 2152 | 7377

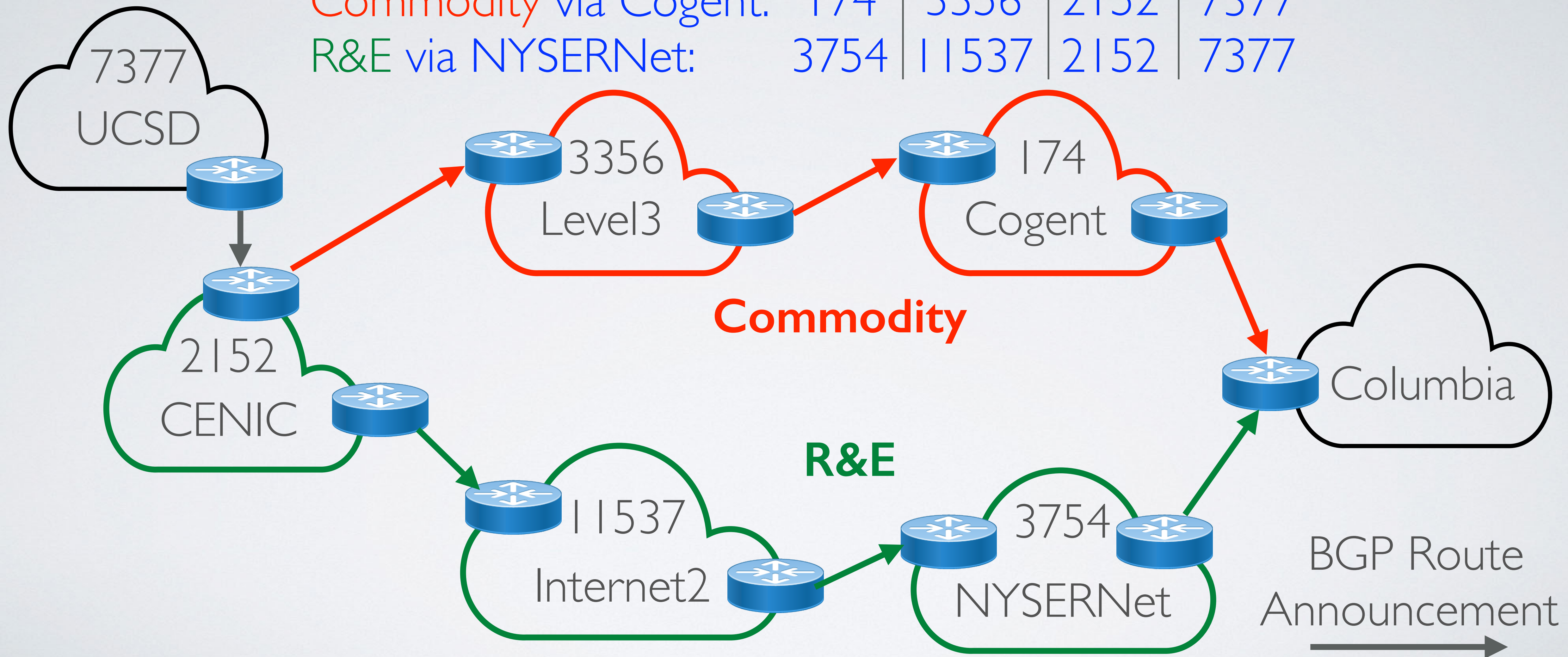


BGP Route
Announcement
→

BGP Route Selection: Primer

Columbia receives two routes to UCSD:

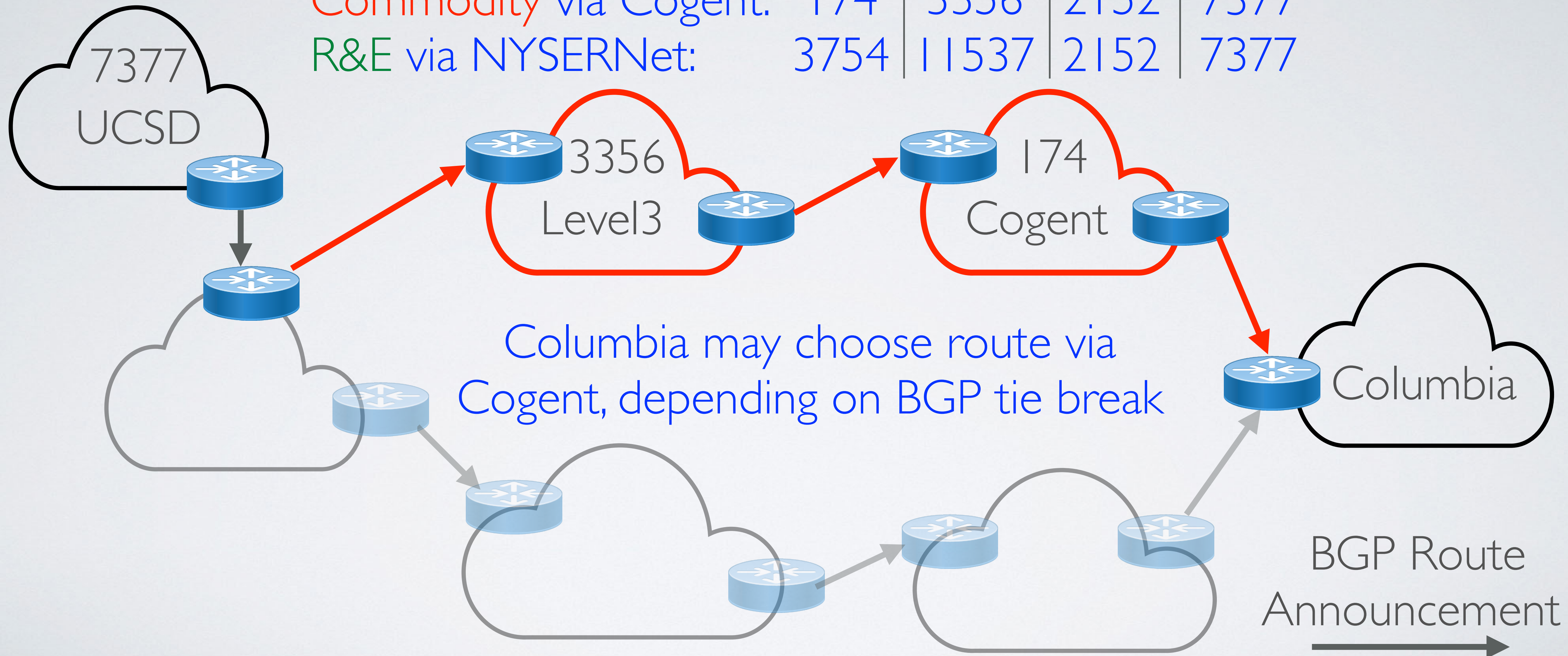
Commodity via Cogent:	174	3356	2152	7377
R&E via NYSERNet:	3754	11537	2152	7377



BGP Route Selection: Primer

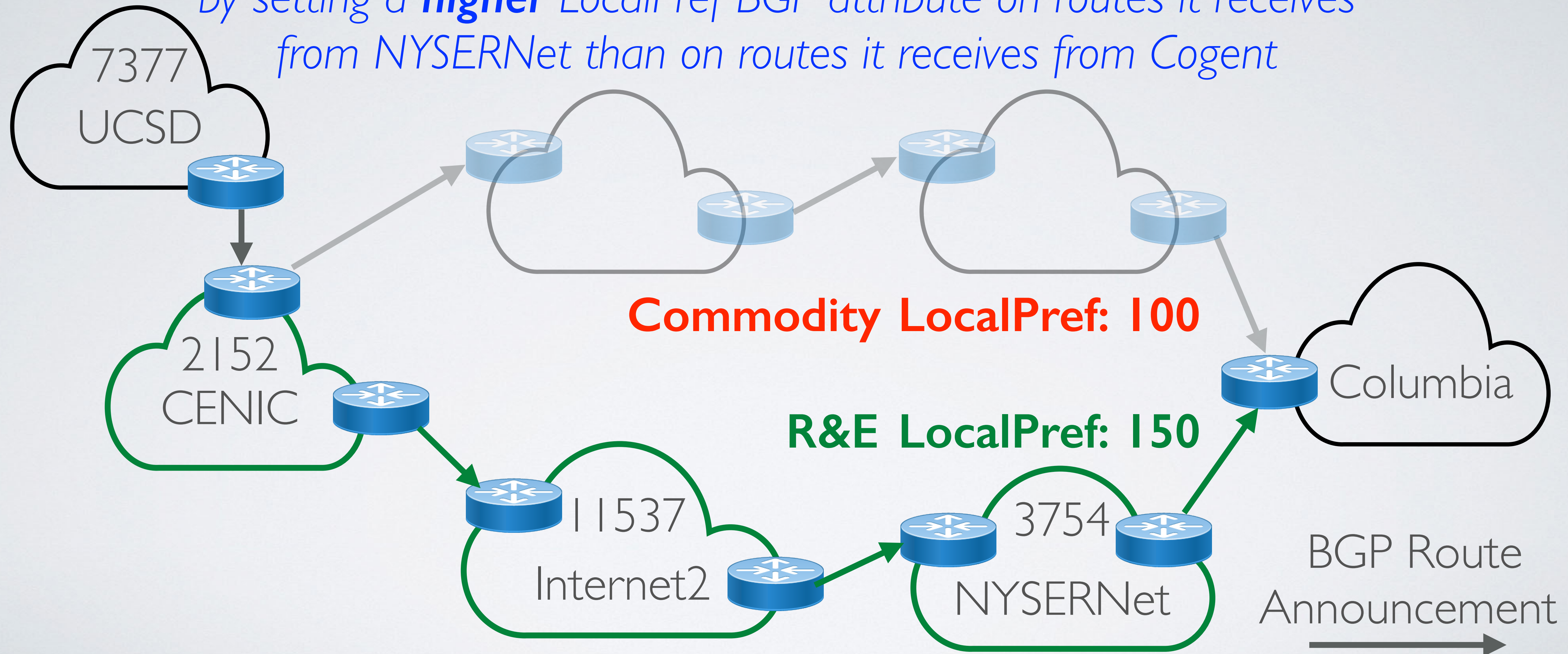
Columbia receives two routes to UCSD:

Commodity via Cogent:	174	3356	2152	7377
R&E via NYSERNet:	3754	11537	2152	7377



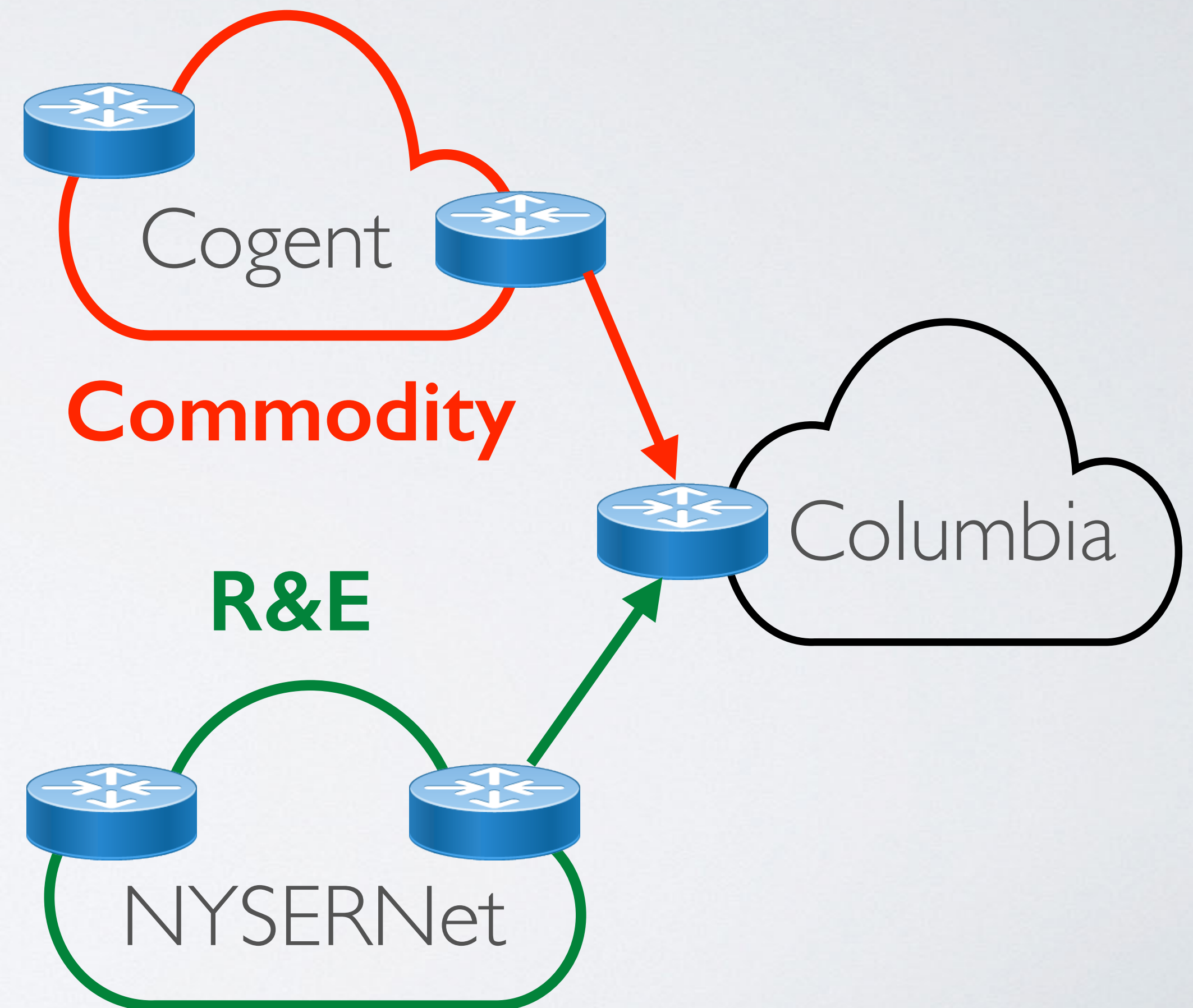
BGP Local Preference

*Columbia can configure BGP to choose the R&E route to UCSD by setting a **higher** LocalPref BGP attribute on routes it receives from NYSErNet than on routes it receives from Cogent*



Research Question

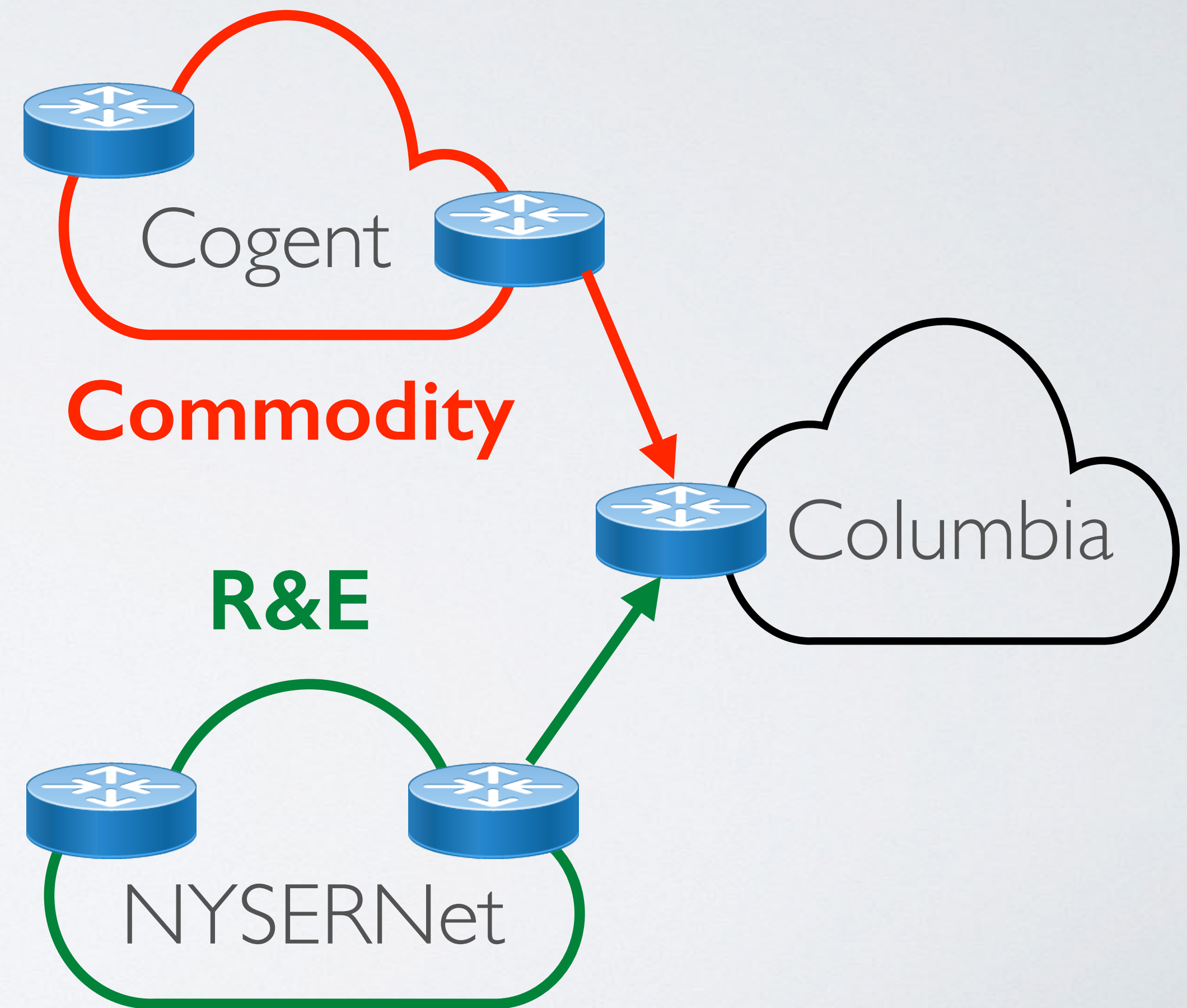
- Assumption: R&E-connected networks should prefer R&E routes over commodity routes
- **Do they?**



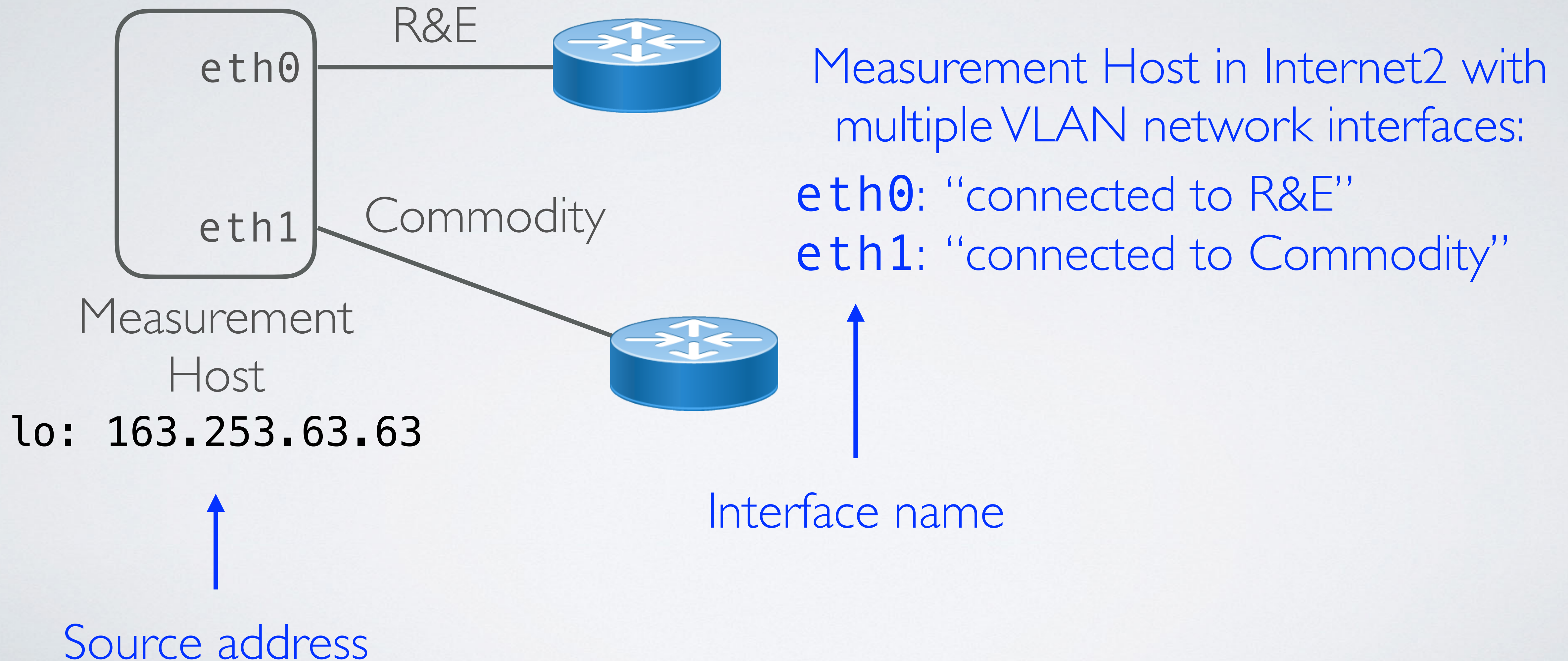
Challenge: Limited Visibility of Routing Policies

See paper for further details on related work

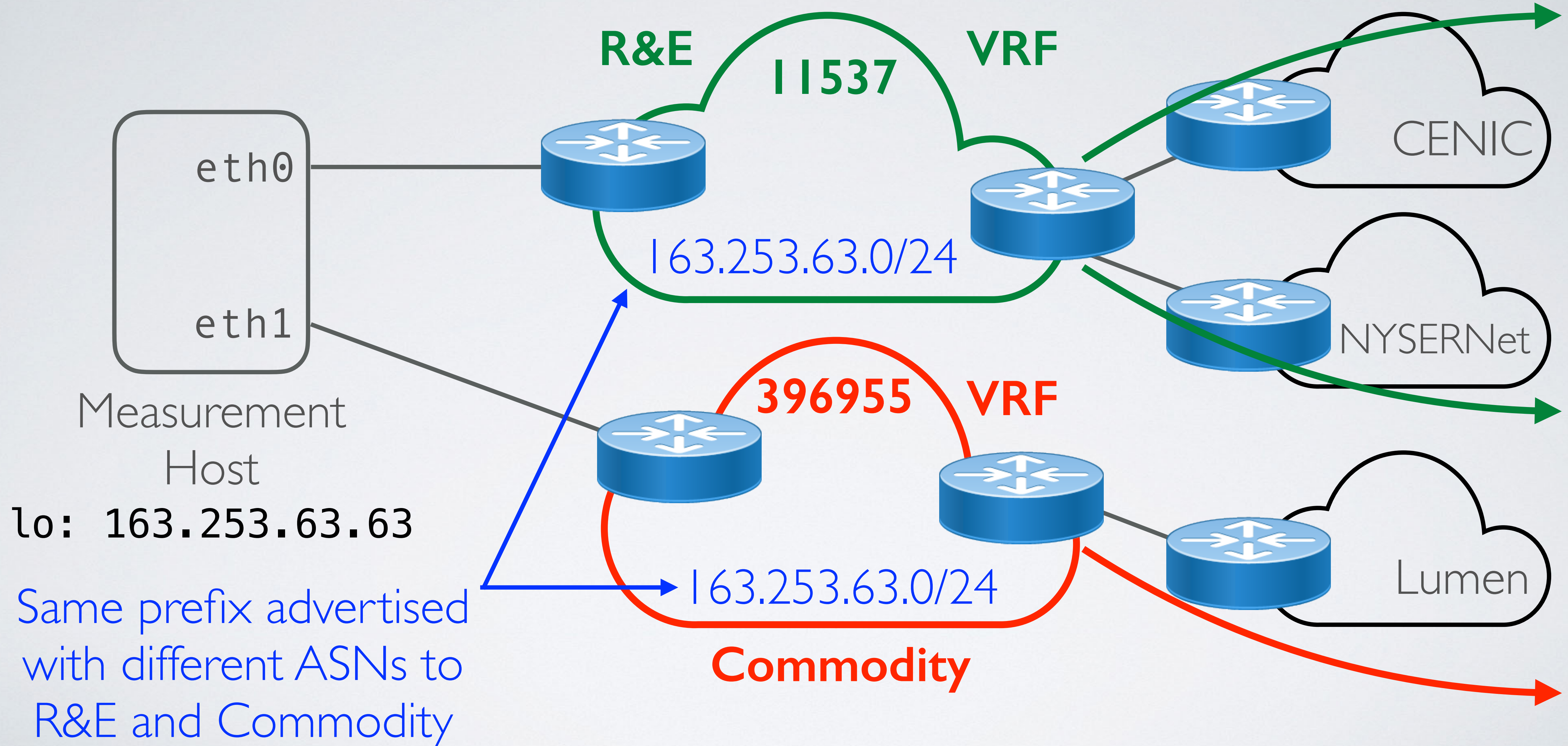
- **BGP is an information hiding protocol**
- BGP does not provide visibility into decisions downstream of a view
- Research community has struggled over 20+ years to accurately model global routing policies (still unsolved)



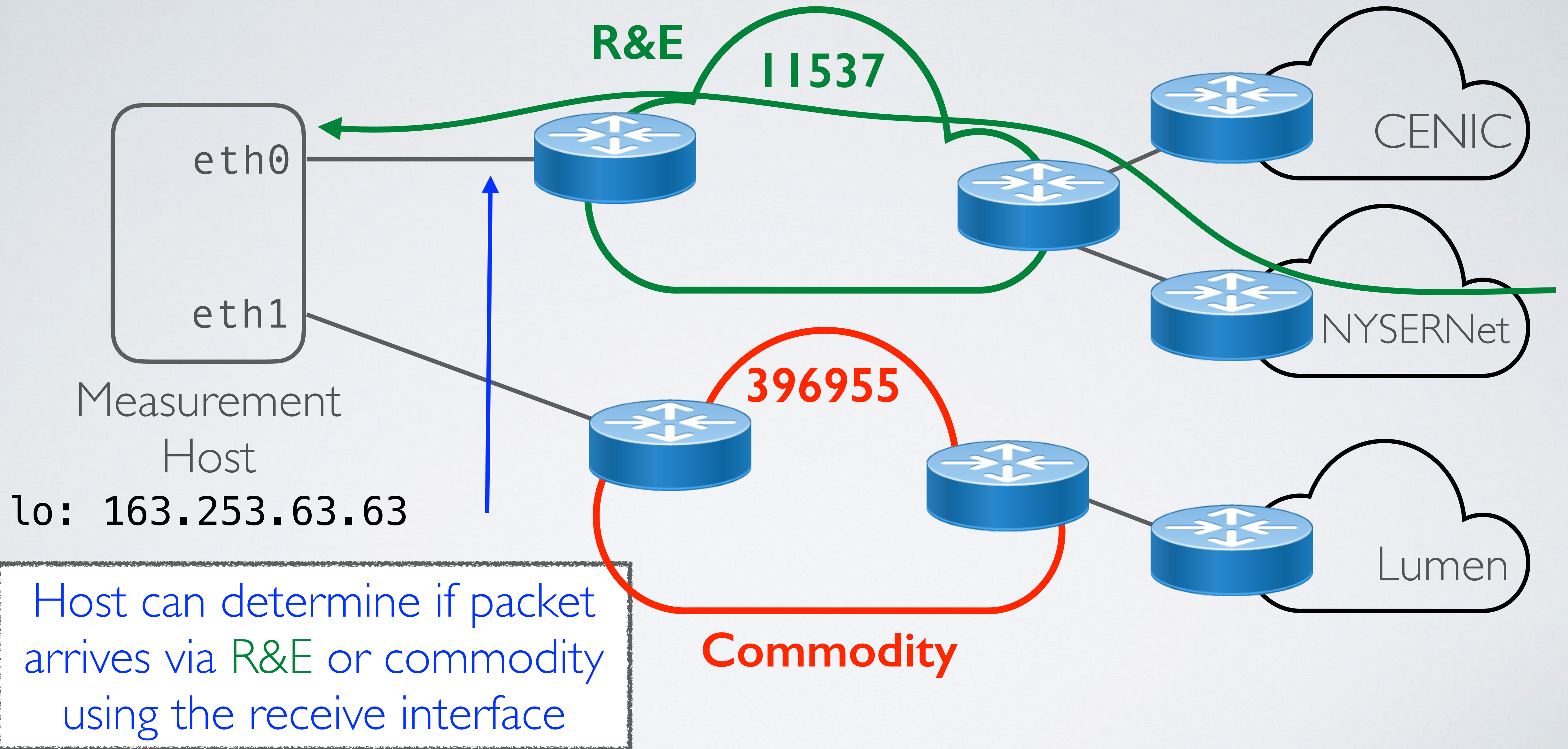
Experimental Approach: Measurement Host



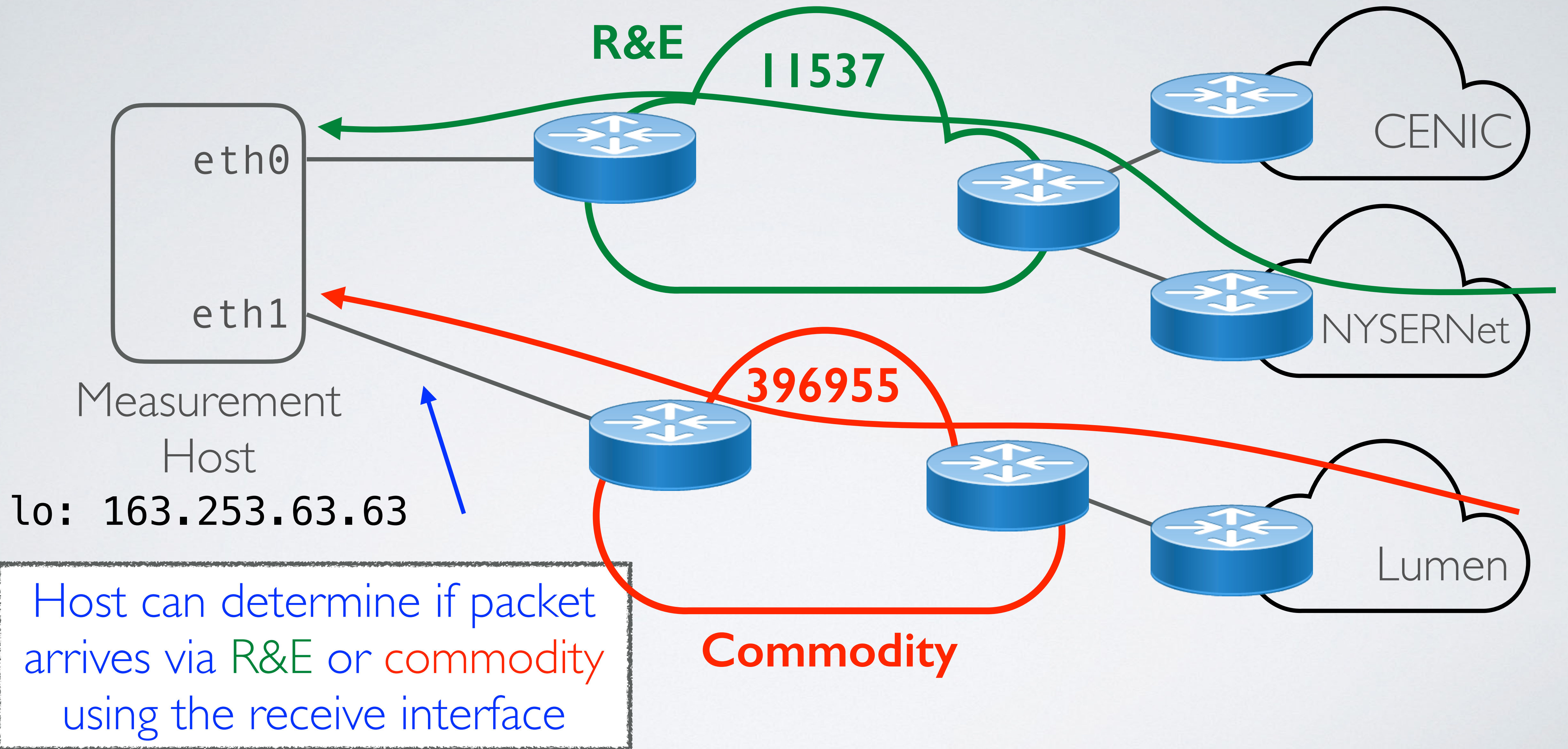
Experimental Approach: BGP Routing



Experimental Approach: Forwarding



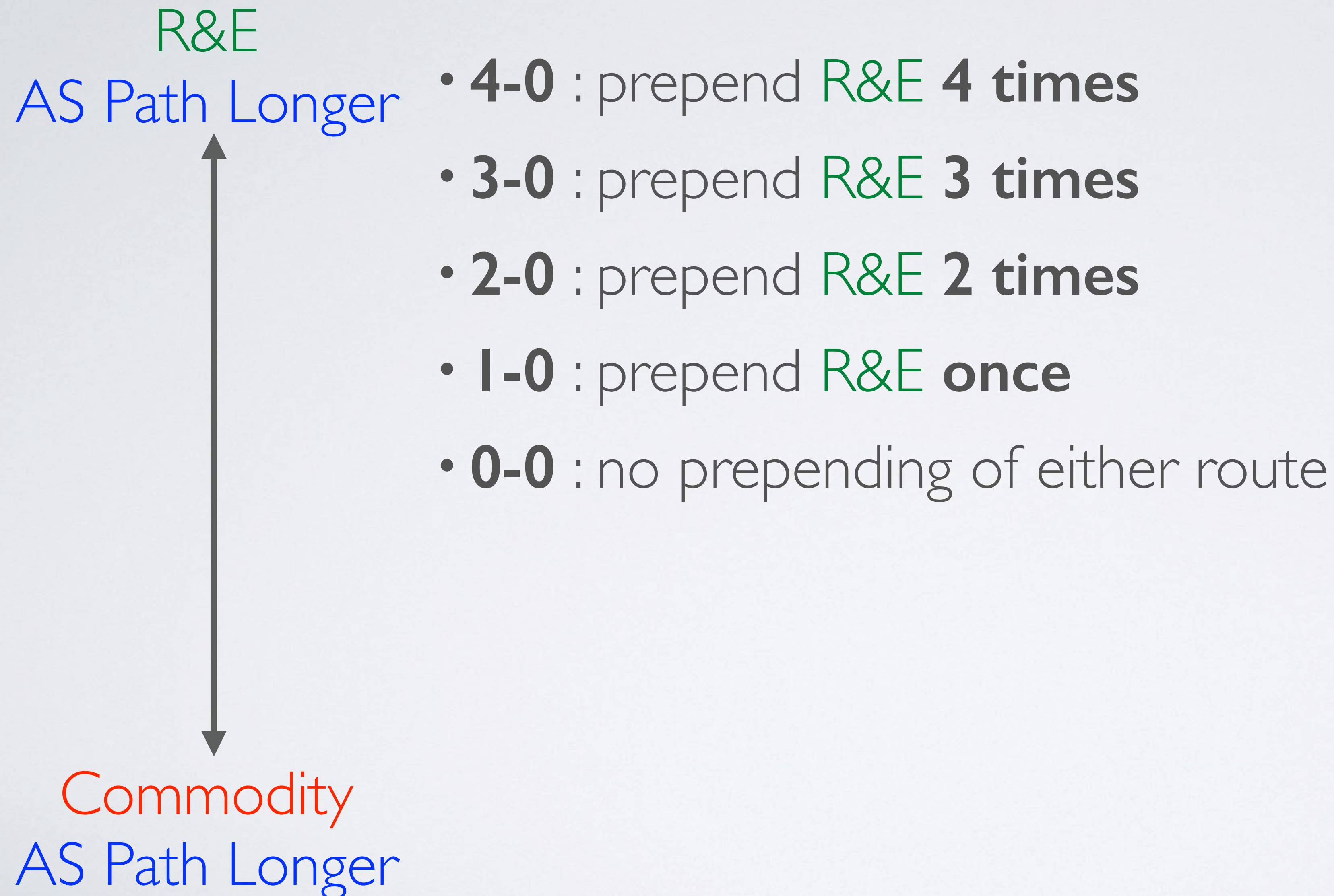
Experimental Approach: Forwarding



Experimental Approach: Packet Probing

- Goal: probe **three responsive addresses** in 17,989 IPv4 R&E prefixes originated by 2,653 ASes, recording arrival interfaces of responses
- Seed probing with two comprehensive and complementary datasets
 - ISI Internet address IPv4 Response History dataset (ICMP)
 - Censys search engine of Internet-wide scan results (UDP and TCP)
- Experiments from SURF (Netherlands R&E, May 29th 2025) and Internet2 (U.S. R&E, June 5th 2025) to compare results
- Experiments on June 5th 2025 covers 12,077 prefixes in 2,578 ASes
(67.1%) (97.5%)

Experimental Approach: Vary AS Prepending



Routers that localpref
R&E will select
R&E route even
when AS path is long

Experimental Approach: Vary AS Prepending



Routers that localpref
R&E will select
R&E route even
when AS path is long

Routers that localpref
commodity will select
commodity route even
when AS path is long

Experimental Approach: Vary AS Prepending



Routers that localpref
R&E will select
R&E route even
when AS path is long

Routers tie-breaking
with AS path length
will switch from
commodity to R&E

Routers that localpref
commodity will select
commodity route even
when AS path is long

Result Summary - June 5th 2025

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%
Switch to commodity	3	0.0%	3	0.1%
Mixed R&E and commodity	371	3.1%	228	8.8%
Oscillating	2	0.0%	2	0.1%
Total:	12,077		2,578	

Majority always used the R&E route
(regardless of prepend configuration)

Result Summary - June 5th 2025

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%
Switch to commodity	3	0.0%	3	0.1%
Mixed R&E and commodity	371	3.1%	228	8.8%
Oscillating	2	0.0%	2	0.1%
Total:	12,077		2,578	

Small fraction always used the commodity route
(regardless of prepend configuration)

Result Summary - June 5th 2025

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%
Switch to commodity	3	0.0%	3	0.1%
Mixed R&E and commodity	371	3.1%	228	8.8%
Oscillating	2	0.0%	2	0.1%
Total:	12,077		2,578	

Small fraction used route with shortest AS path
(assigned same localpref to both commodity and R&E routes)

Result Summary - June 5th 2025

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%
Switch to commodity	3	0.0%	3	0.1%
Mixed R&E and commodity	371	3.1%	228	8.8%
Oscillating	2	0.0%	2	0.1%
Total:	12,077		2,578	

Three ASes unexpectedly switched to commodity.
In a prior experiment, an operator reported that the
switch was due to an unrelated outage.

Result Summary - June 5th 2025

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%
Switch to commodity	3	0.0%	3	0.1%
Mixed R&E and commodity	371	3.1%	228	8.8%
Oscillating	2	0.0%	2	0.1%
Total:	12,077		2,578	

Some prefixes contain systems with different return paths.
(likely neighbor routers with address in probed prefix for interconnection)

See the paper for:

- **Validation:**

- 22 of 25 localpref inferences were congruent with observations in public BGP data for those networks.
- 2 of 3 incongruent observations were because the AS provided a commodity VRF to the BGP collector — our localpref inferences were correct. No response from third.

- **Comparison of May 2025 (SURF) and June 2025 (Internet2) experiments**

- 96.9% of comparable prefixes had the same inference between experiments
- 44.4% of differences were due to configuration by a single R&E transit network

See the paper for:

- **Comparison of localpref inference (egress policy) with AS path prepending observations (ingress policy)**
 - When we validated localpref inferences with operators, they volunteered their prepending policy
 - Often R&E institutions prepended their commodity announcements when they assigned a higher localpref to R&E
 - The small fraction of institutions that prepended their R&E announcements more than their commodity announcements had unpredictable in localpref assignment
- **Application of the approach outside of R&E networking**

Effect of Equal localpref: case study

What happens when a network assigns equal localpref to R&E and commodity?

- RIPE NCC assigns equal localpref to its neighbors, so tie breaks with AS path length and other metrics.
- RIPE is a key source of public BGP data used in the research community.
- RIPE provides a BGP view of its own routing.
- Does RIPE reach R&E-connected networks via R&E or commodity?

Effect of Equal localpref: case study

What happens when a network assigns equal localpref to R&E and commodity?

- RIPE NCC assigns equal localpref to its neighbors, so tie breaks with AS path length and other metrics.
- RIPE is a key source of public BGP data used in the research community.
- RIPE provides a BGP view of its own routing.
- Does RIPE reach R&E-connected networks via R&E or commodity?

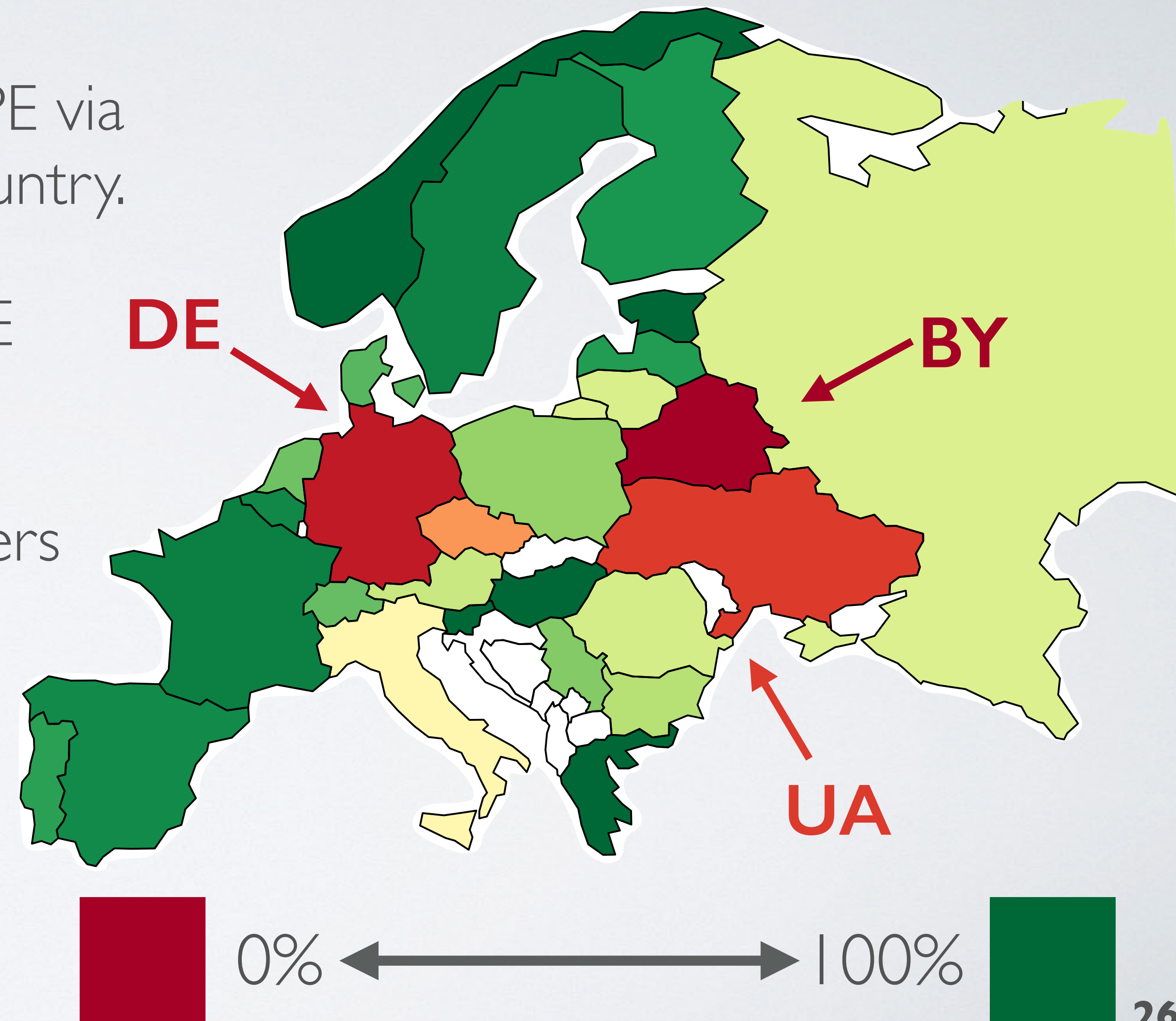
RIPE used an **R&E route** to reach **64%** of R&E prefixes.

RIPE reached the remainder over a commodity route.

Effect of Equal localpref: case study

What happens when a network assigns equal localpref to R&E and commodity?

- The distribution of R&E-connected ASes originating at least one route reached by RIPE via R&E route was not evenly distributed by country.
- Countries with ASes reached mostly via R&E typically had a National R&E Network that:
 1. Provided commodity transit to its members
 2. Prepended commodity routes
 3. Had members single-homed



Implications

- Most R&E connected networks preferred R&E routes
- **Some data-intensive R&E users may not benefit from the global R&E infrastructure due to local routing policies**
- The persistence of these policy-driven detours suggest that the value of the R&E infrastructure is unevenly realized across the community

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%

Acknowledgments

- Code and data: see link in paper
- This work was funded by NSF OAC-2131987 and OAC-2530871
- Thanks to:
 - Censys for providing research access to their Internet scanning results
 - ISI for providing research access to their ISI history dataset
 - R&E Operators for providing feedback and ground truth

Backup Slides

Related Work: brief summary

See paper for further details

Measuring with VP from inside:

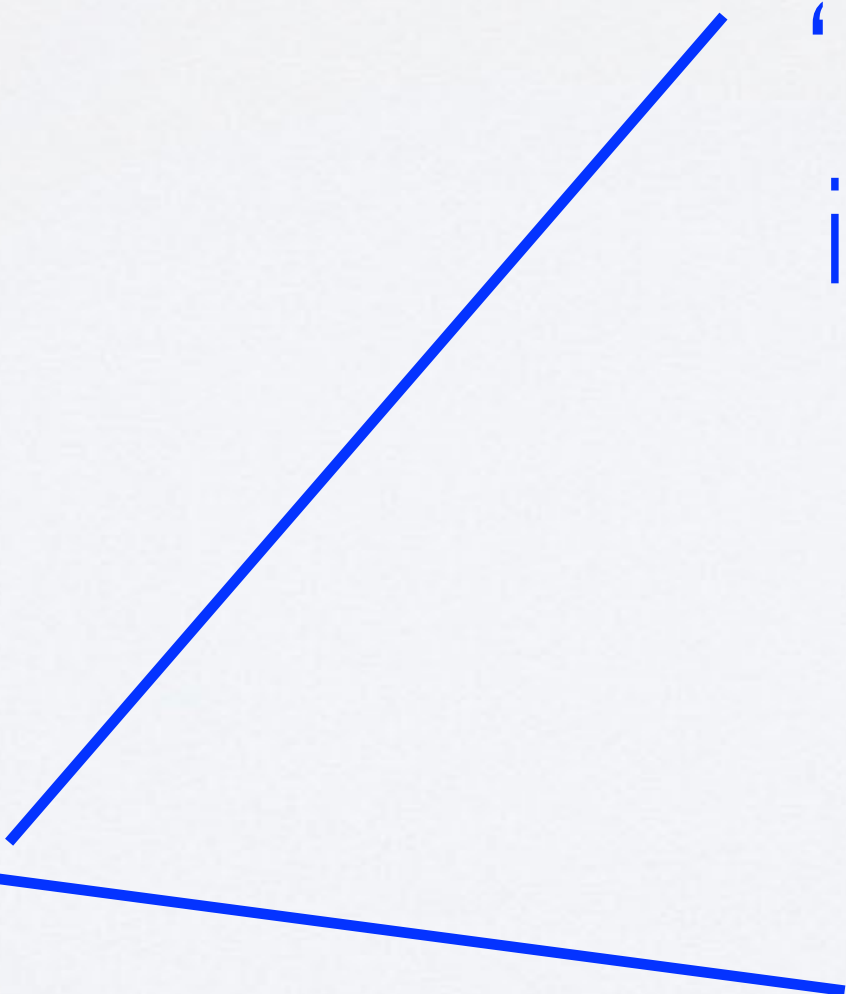
- Using IRR / Looking glasses / BGP / traceroute restricts localpref inferences to networks with those VPs

- Wang + Gao - IMC 2003

- Colitti *et al.* - ISCC 2006

- Anwar *et al.* - IMC 2015

- Kastanakis *et al.* - IMC 2023



“Future work can put more emphasis in the inference of locpref allocations independently of AS relationships, given the scarcity of large-scale locpref data which are only available from a limited number of LGs.”

Related Work: brief summary

See paper for further details

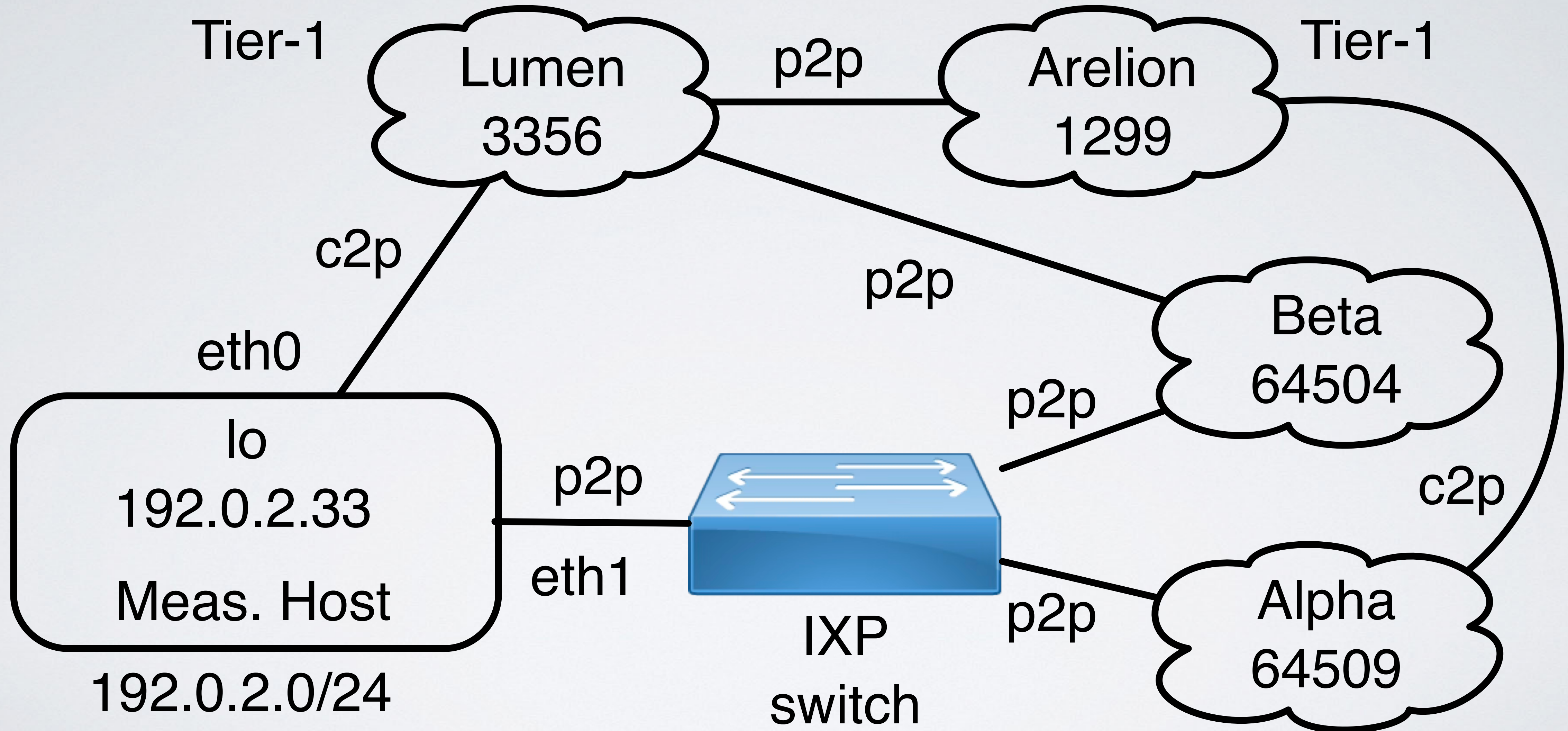
Measuring with VP from inside:

- Using IRR / Looking glasses / BGP / traceroute restricts localpref inferences to networks with those VPs
- Wang + Gao - IMC 2003
- Colitti *et al.* - ISCC 2006
- Anwar *et al.* - IMC 2015
- Kastanakis *et al.* - IMC 2023

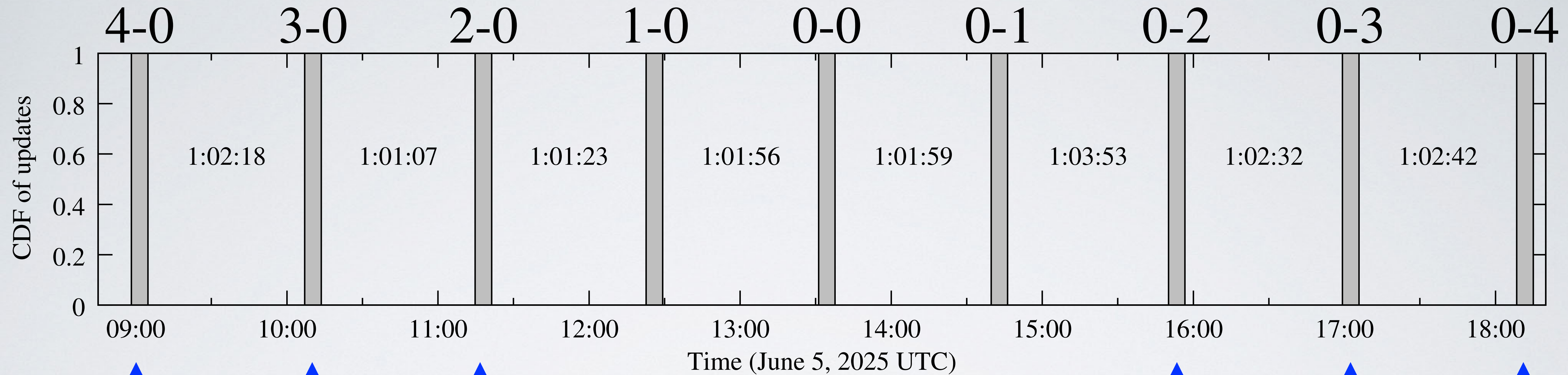
Measuring from outside:

- Responses to pings sourced from an address within a BGP route gives signal on how those destinations route, e.g.:
- Convergence - SIGCOMM 2000
- Default routes - IMC 2009
- Anycast catchments - IMC 2017
- RPKI ROV deployment - BenJojo 2018

Inference of LocalPref Peer/Prov assignments



Experiment Flow



Nine ~7 minute probing windows (grey bars)

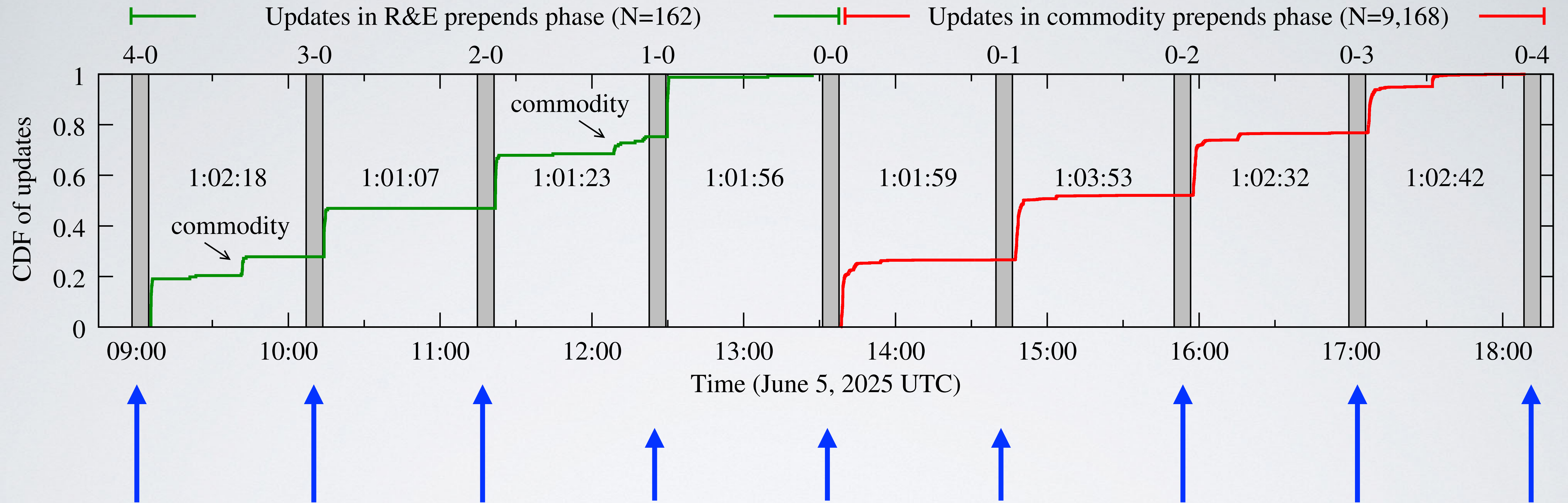
R&E

Commodity

AS Path Longer

AS Path Longer

Experiment Flow



Nine ~7 minute probing windows (grey bars)
followed BGP configuration change, and then
~1 hour cool-off to allow BGP to converge

R&E
AS Path Longer

Commodity
AS Path Longer

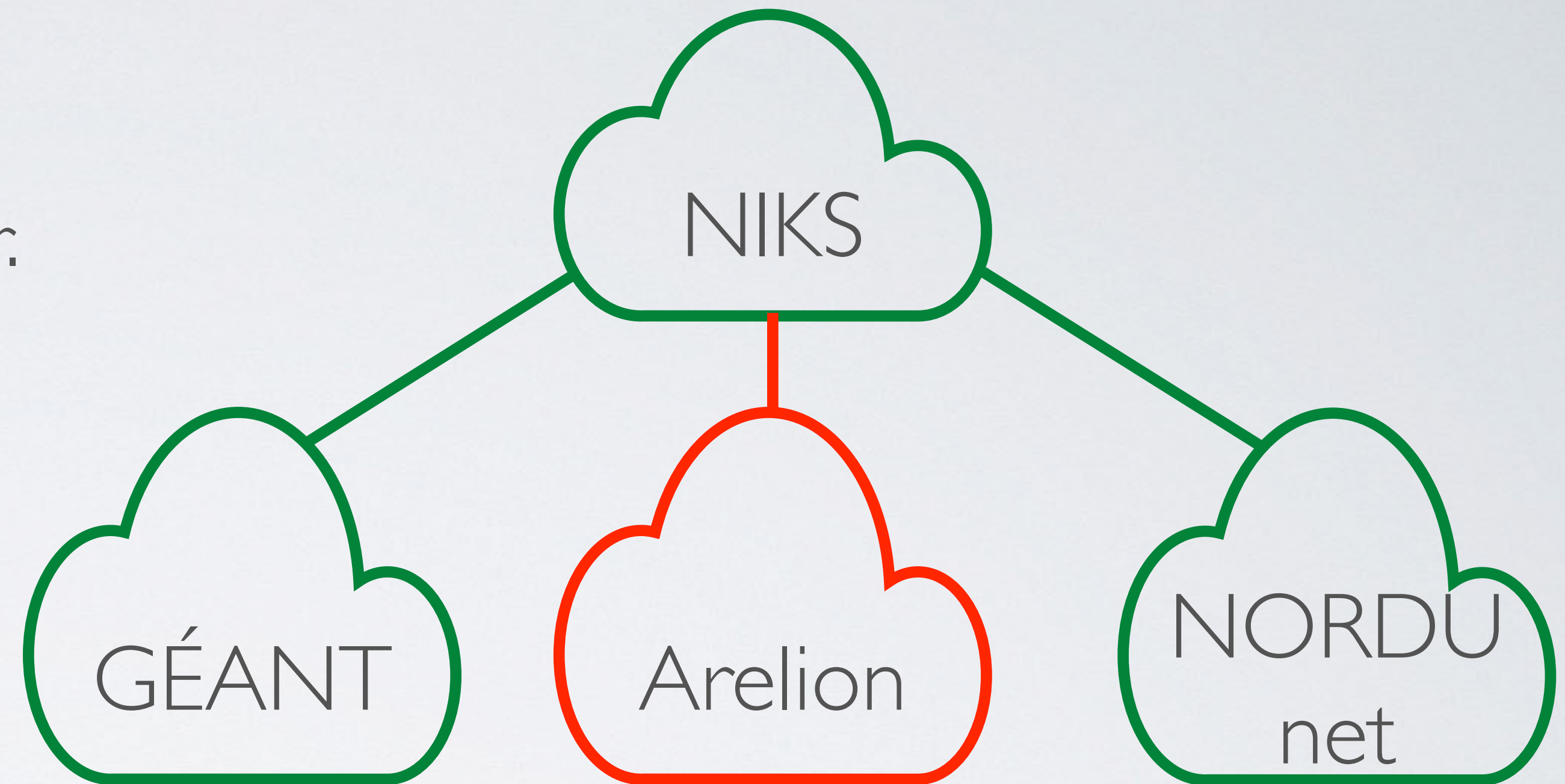
Result Summary - June 5th 2025

Inference	Prefixes		ASes	
Always R&E	9,758	80.8%	1,940	75.3%
Always commodity	840	7.0%	353	13.7%
Switch to R&E	1,103	9.1%	322	12.5%
Switch to commodity	3	0.0%	3	0.1%
Mixed R&E and commodity	371	3.1%	228	8.8%
Oscillating	2	0.0%	2	0.1%
Total:	12,077		2,578	

The percentages in the ASes column add to more than 100%
because some ASes are included in multiple categories

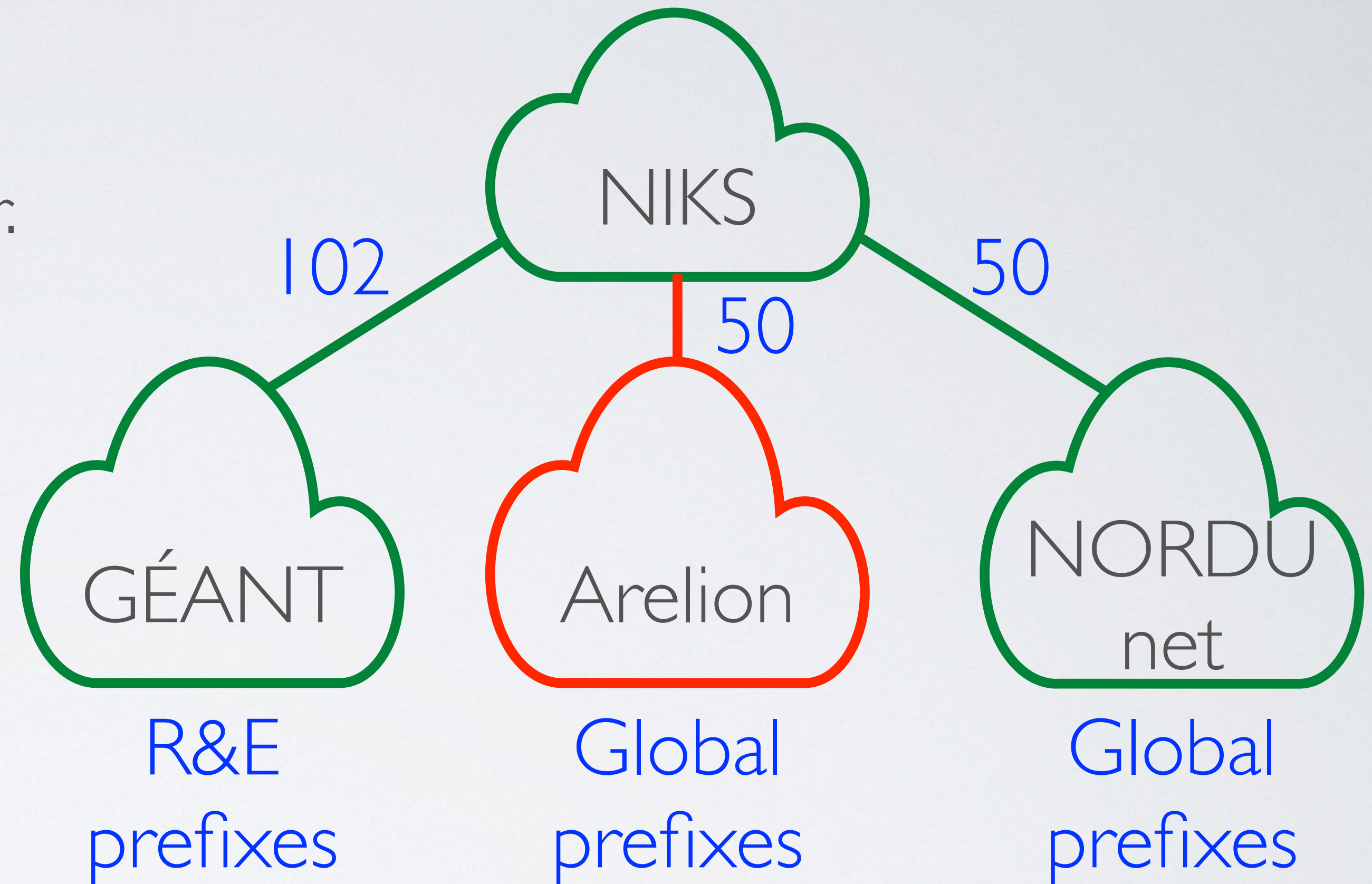
Result Comparison: Internet2 and SURF

- We probed the same addresses while SURF originated the route a week earlier.
- 96.9% of comparable prefixes had the same inference between experiments.
- 44.4% of differences were due to configuration by NIKS - a Russian R&E transit network



Result Comparison: Internet2 and SURF

- We probed the same addresses while SURF originated the route a week earlier.
- 96.9% of comparable prefixes had the same inference between experiments.
- 44.4% of differences were due to configuration by NIKS - a Russian R&E transit network

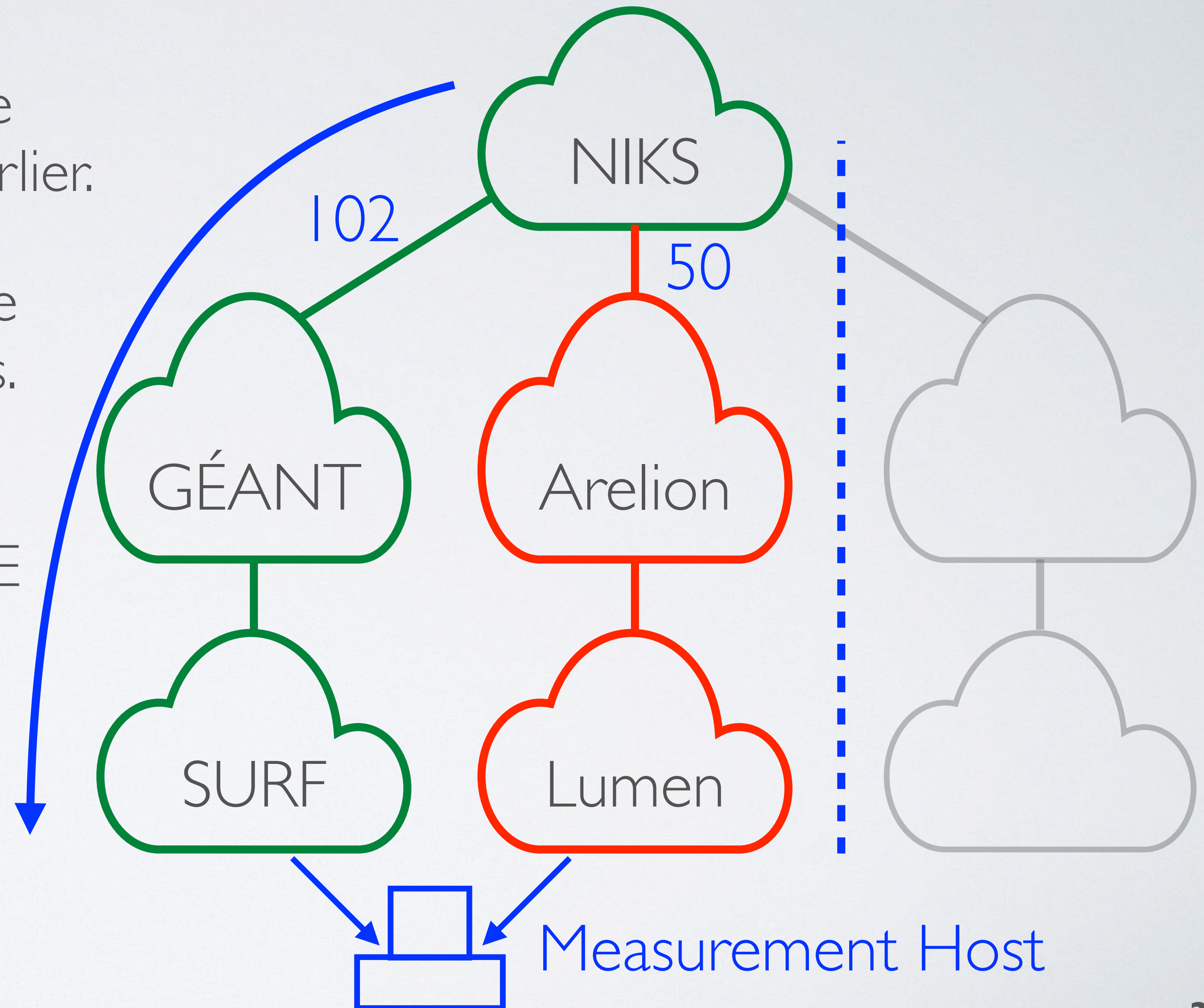


NIKS assigned a higher localpref to GÉANT than it did to Arelion and NORDU net

Result Comparison: Internet2 and SURF

- We probed the same addresses while SURF originated the route a week earlier.
- 96.9% of comparable prefixes had the same inference between experiments.
- 44.4% of differences were due to configuration by NIKS - a Russian R&E transit network

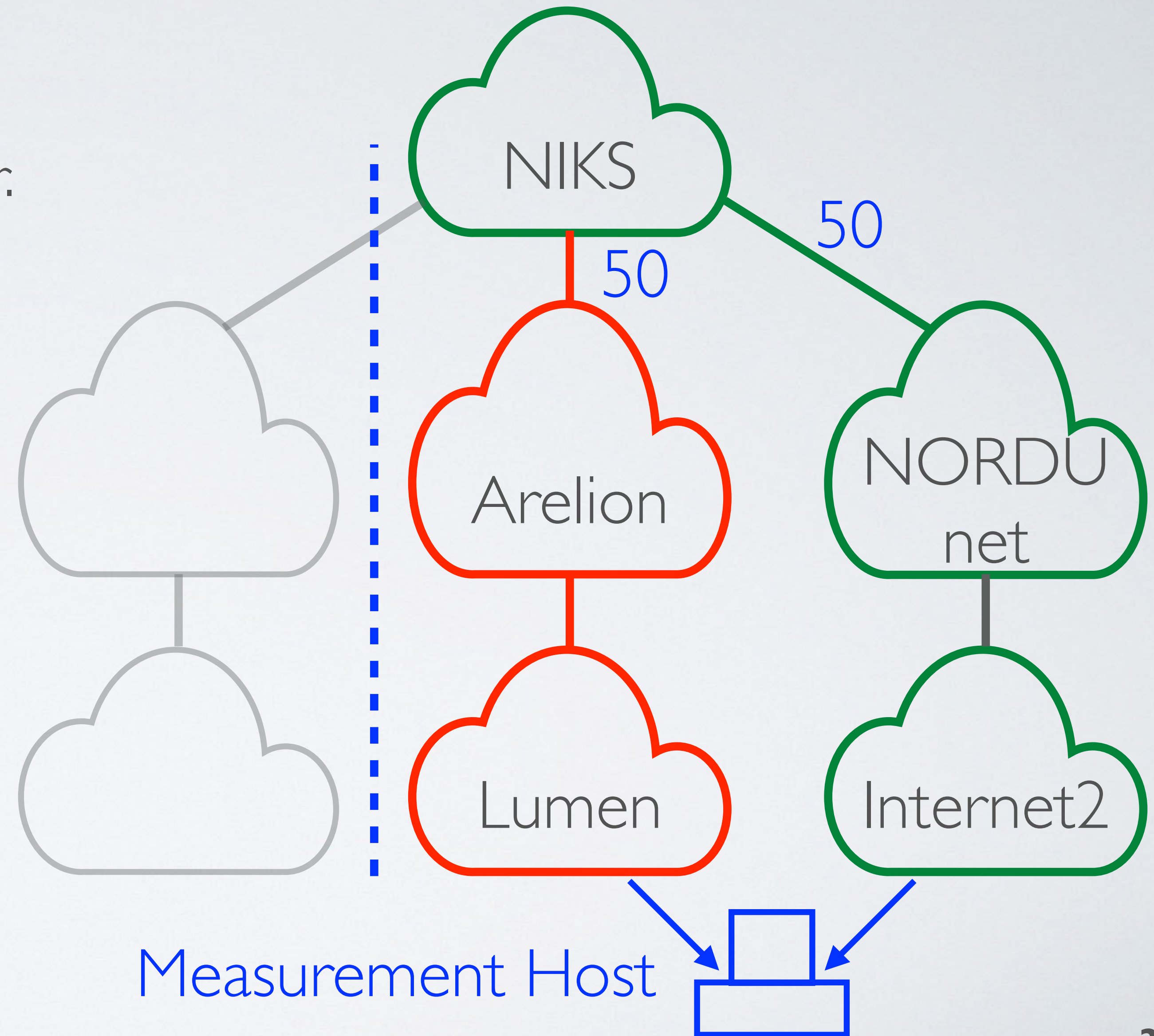
In May 2025, responses from R&E networks downstream of NIKS always arrived at our measurement host over R&E



Result Comparison: Internet2 and SURF

- We probed the same addresses while SURF originated the route a week earlier.
- 96.9% of comparable prefixes had the same inference between experiments.
- 44.4% of differences were due to configuration by NIKS - a Russian R&E transit network

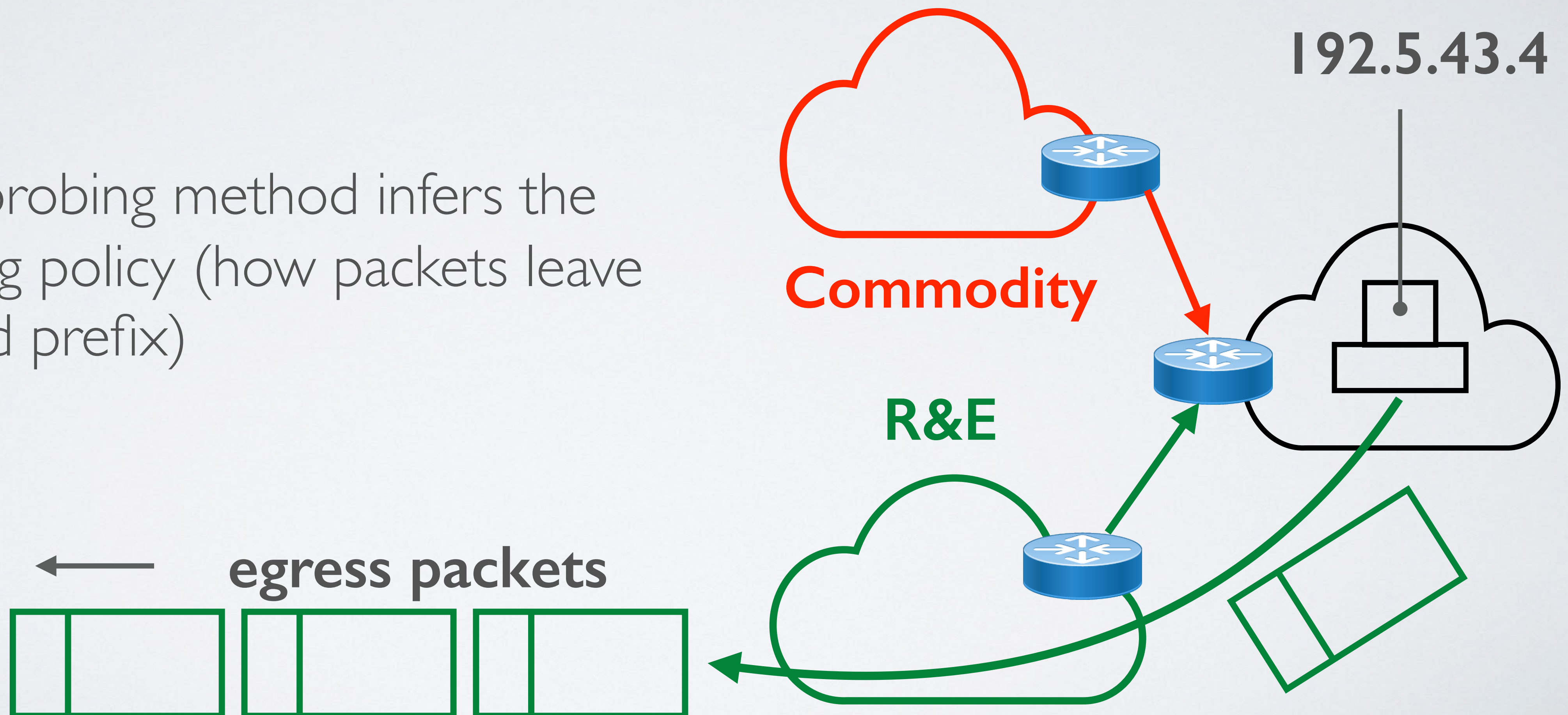
In June 2025, responses from R&E networks downstream of NIKS arrived over R&E or commodity depending on AS path length.



Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

- Our packet probing method infers the **egress** routing policy (how packets leave the measured prefix)



Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Commodity prepended **4x**

174 14 14 14 14 14

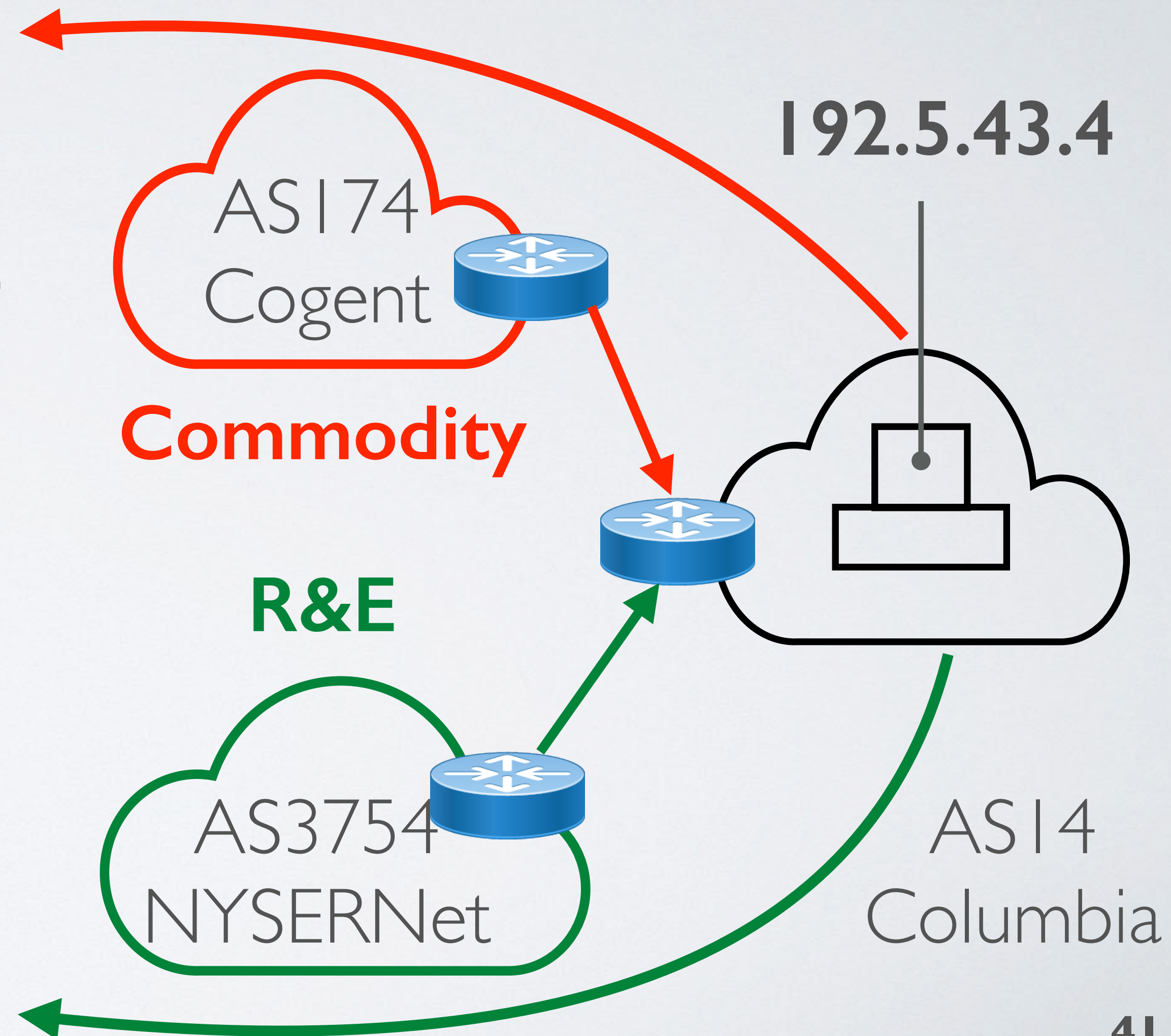
- How do R&E enterprises influence **ingress** routing with AS prepending?

ingress packets →



R&E prepended **2x**

3754 14 14 14



Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference	Prepends			No
	$R = C$	$R < C$	$R > C$	Comm.
Always R&E				
Always commodity				
Switch to R&E				
Total:				

Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference

Prepends

No

$R = C$

$R < C$

$R > C$

Comm.

Always R&E

Always commodity

Switch to R&E

Total:

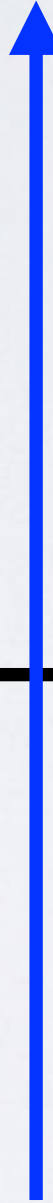
Equal
prepends

More prepends
towards commodity

More prepends
towards R&E

Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference	Prepends			No
	$R = C$	$R < C$	$R > C$	Comm.
Always R&E				
Always commodity				
Switch to R&E				
Total:				No commodity provider

Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference	Prepends			No
	$R = C$	$R < C$	$R > C$	Comm.
Always R&E				
Always commodity				
Switch to R&E				
Total:	4,072	3,158	402	4,440

Networks were unlikely to prepend more towards R&E than towards commodity

Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference	Prepends			No
	$R = C$	$R < C$	$R > C$	Comm.
Always R&E		83.2%		88.3%
Always commodity				
Switch to R&E				
Total:	4,072	3,158	402	4,440

Networks prepending towards commodity, or with no observed commodity provider, generally always used R&E outbound

Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference	Prepends			No
	$R = C$	$R < C$	$R > C$	Comm.
Always R&E		83.2%		88.3%
Always commodity				
Switch to R&E	15.0%	7.9%		4.9%
Total:	4,072	3,158	402	4,440

Networks with equal prepending were 2-3x more likely to localpref R&E and commodity equally than the other common policies

Ingress / Egress Route Policy Correlation

(Do ASes that use localpref also prepend commodity route announcements?)

Inference	Prepends			No
	$R = C$	$R < C$	$R > C$	Comm.
Always R&E	73.8%	83.2%	50.7%	88.3%
Always commodity	7.8%	6.1%	37.1%	4.1%
Switch to R&E	15.0%	7.9%	7.0%	4.9%
Total:	4,072	3,158	402	4,440

Networks prepending more towards R&E were more unpredictable than networks with other inbound policies

Validation

(Are our inferences congruent with BGP views provided to RouteViews and RIPE RIS?)

Inference	Congruent	Incongruent	Total
Always R&E	15	3*	18
Always Commodity	3	0	3
Switch to R&E	4	0	4
Total	22	3*	25

22/25 were congruent.

We contacted operators at the three incongruent ASes.

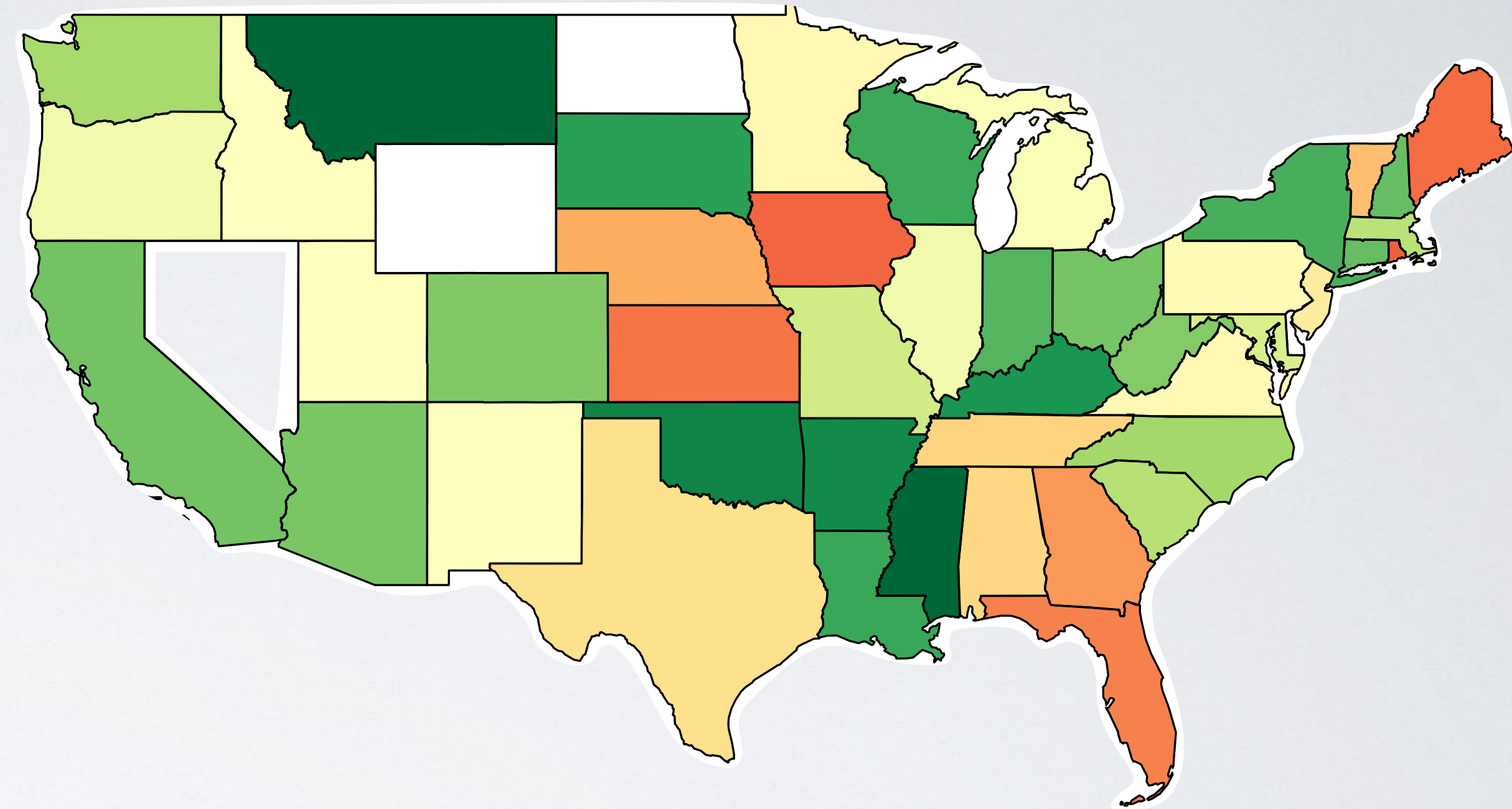
Two ASes preferred R&E, but provided a commodity VRF to RouteViews.

We received no reply from the third incongruent AS.

Effect of Equal localpref: RIPE NCC case study

What happens when a network assigns equal localpref to R&E and commodity?

- Different R&E networks in the U.S. have different operational models. For example:
 - CENIC (CA) provides commodity transit, prepends its ASN toward commodity
 - NYSERNet (NY) does not provide commodity
- 84% of 74 NY-mapped ASes were reached via an R&E path, while 78% of 127 CA-mapped ASes were.



- Most NY-mapped ASes prepend their ASN toward commodity
- Some CA-mapped ASes arrange their own commodity transit and do not prepend

Effect of Equal localpref: RIPE NCC case study

What happens when a network assigns equal localpref to R&E and commodity?

