Pinning the cosmic web to massive halos

Joanne Cohn

Web tracer here: dark matter density
Web finder: Disperse

Dark matter density in the Millennium simulation (Springel++05,Lemson++06)

N-body, 500 Mpc/h side box

Fixed time, z ~0.1

Specifically using from it:

- Dark matter densities in 256^3 pixels (1.95 Mpc/h each)
- Gaussian smoothing 1.25 Mpc/h, 2 Mpc/h 2.5 Mpc/h, 5 Mpc/h

(Drawback) **old** Millennium cosmology:

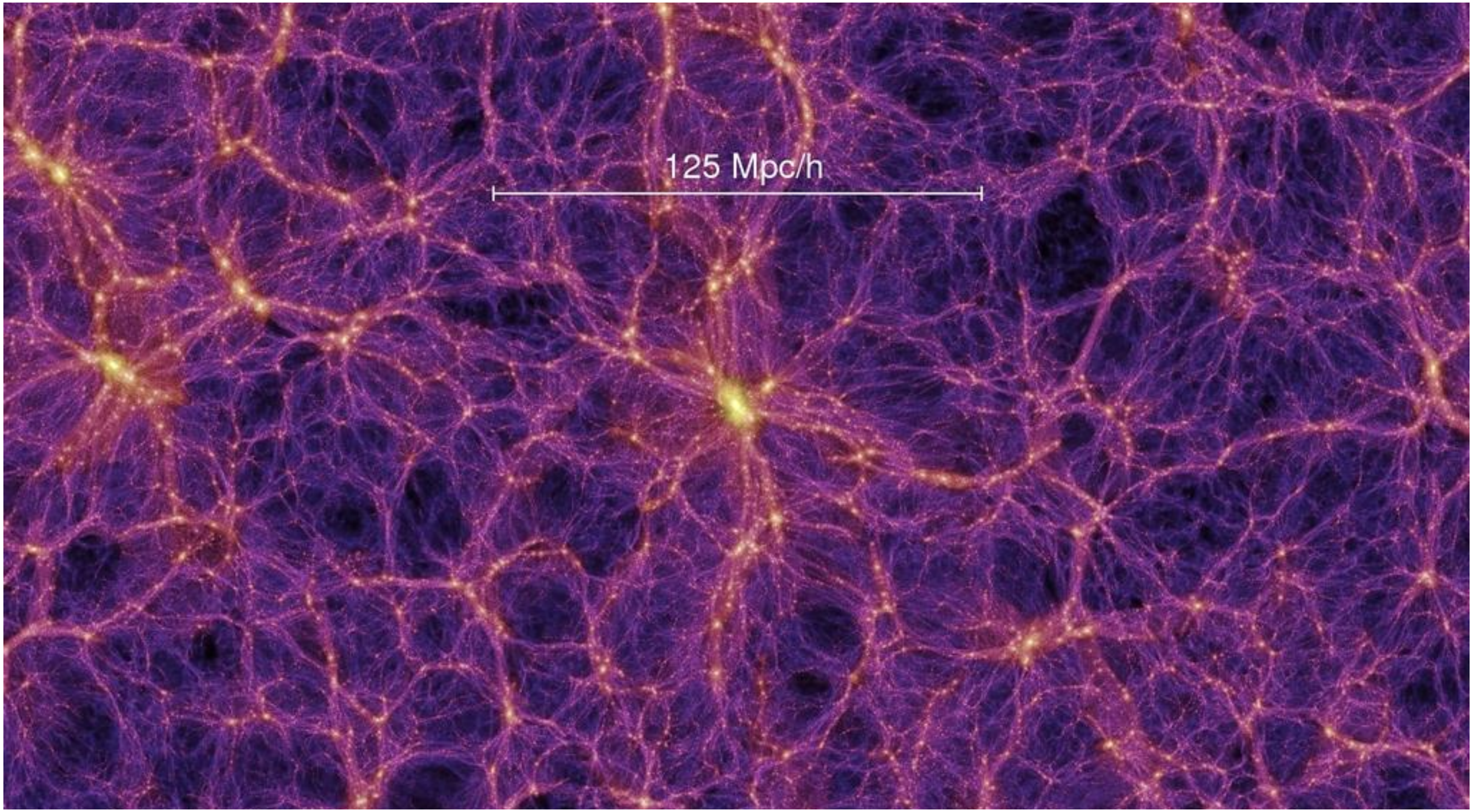
density rescaling to Planck Millennium unavailable, thus relevant galaxy observables unavailable. 🙁

(Ωm = 0.25, Ωb = 0.045, h = 0.73, n=1, σ 8 = 0.9)

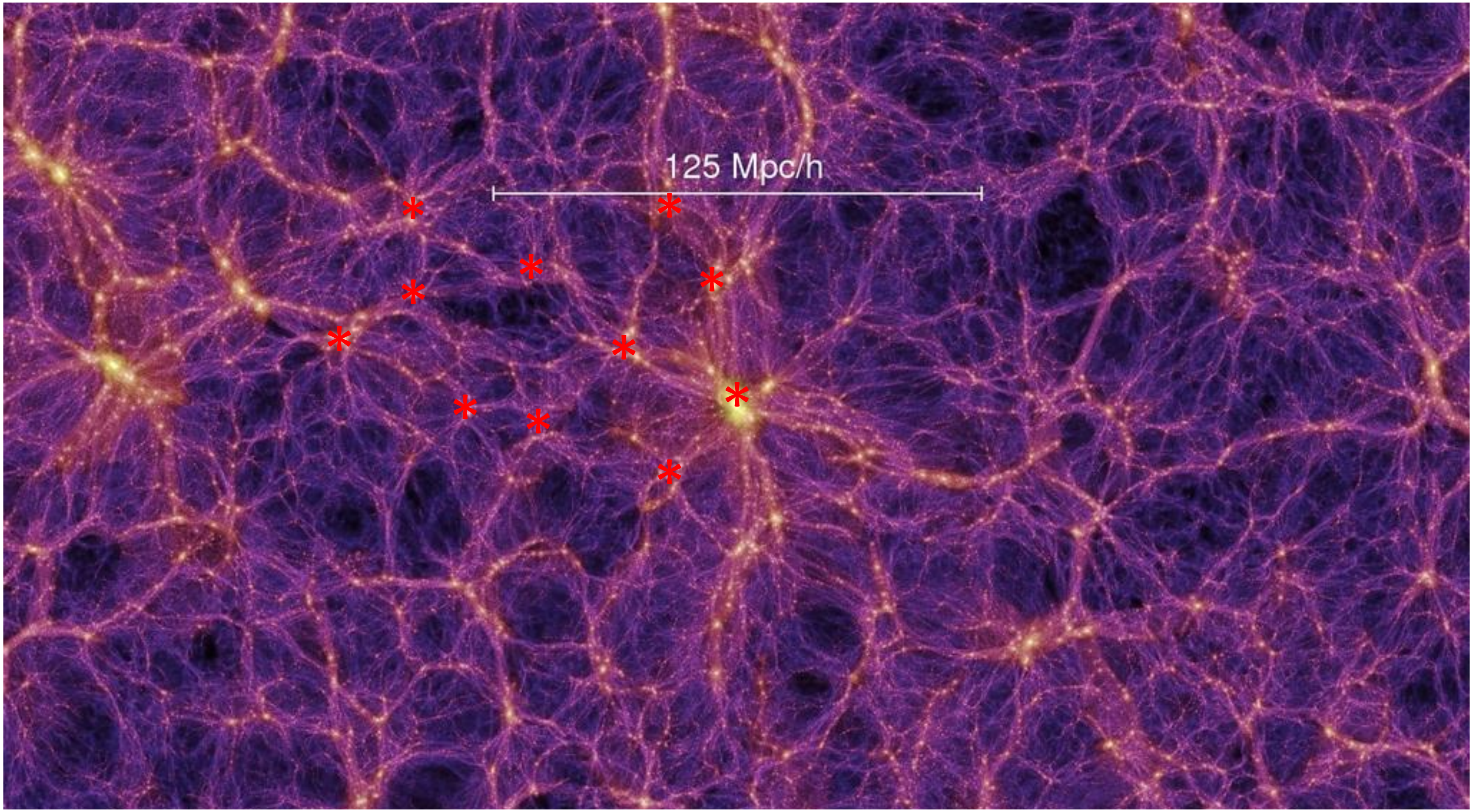
Lengths< than pixel scale (~2 Mpc/h) not well described

⇒Web of interest will be at larger scales

Cartoon idea

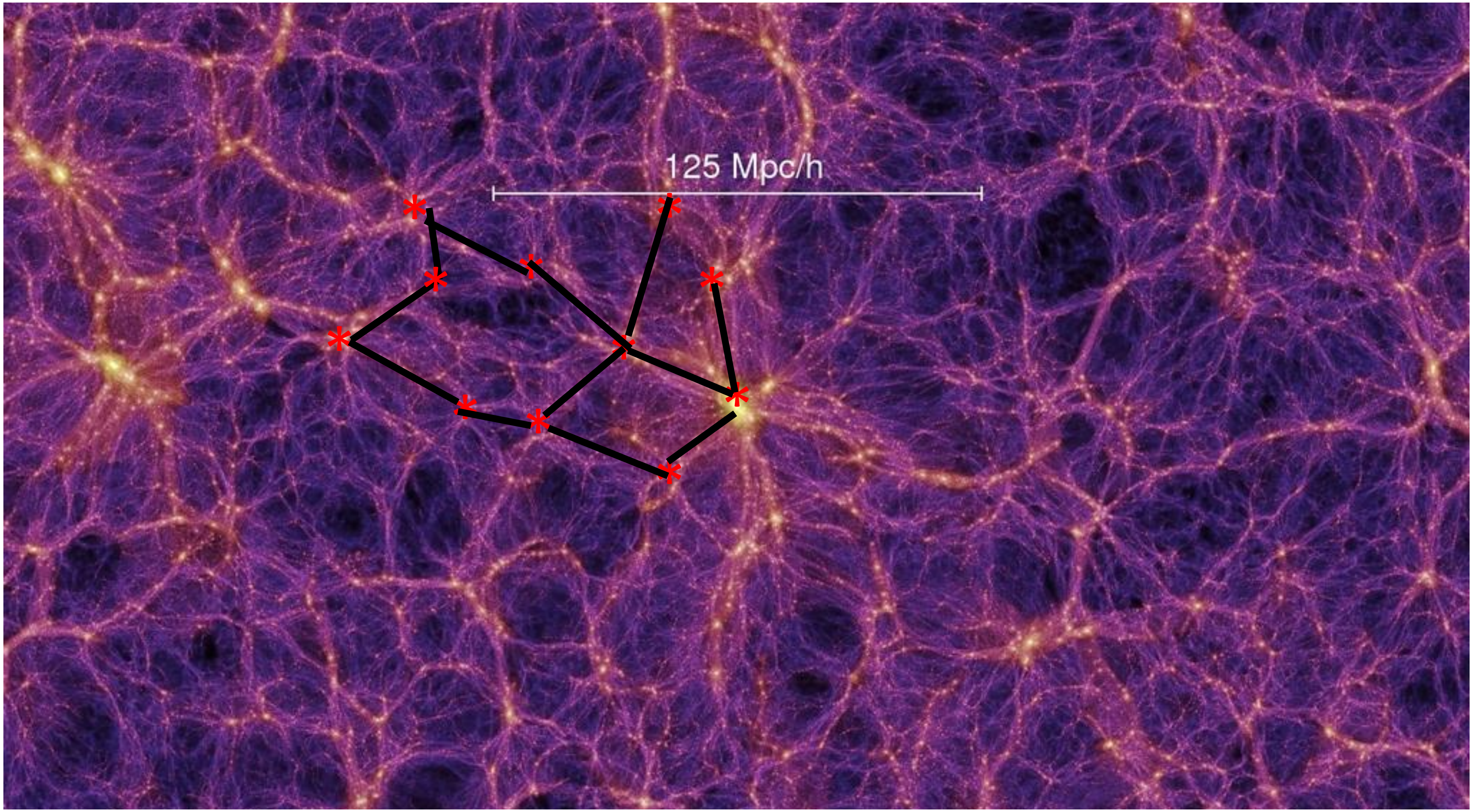


Cartoon idea



* = Massive nodes

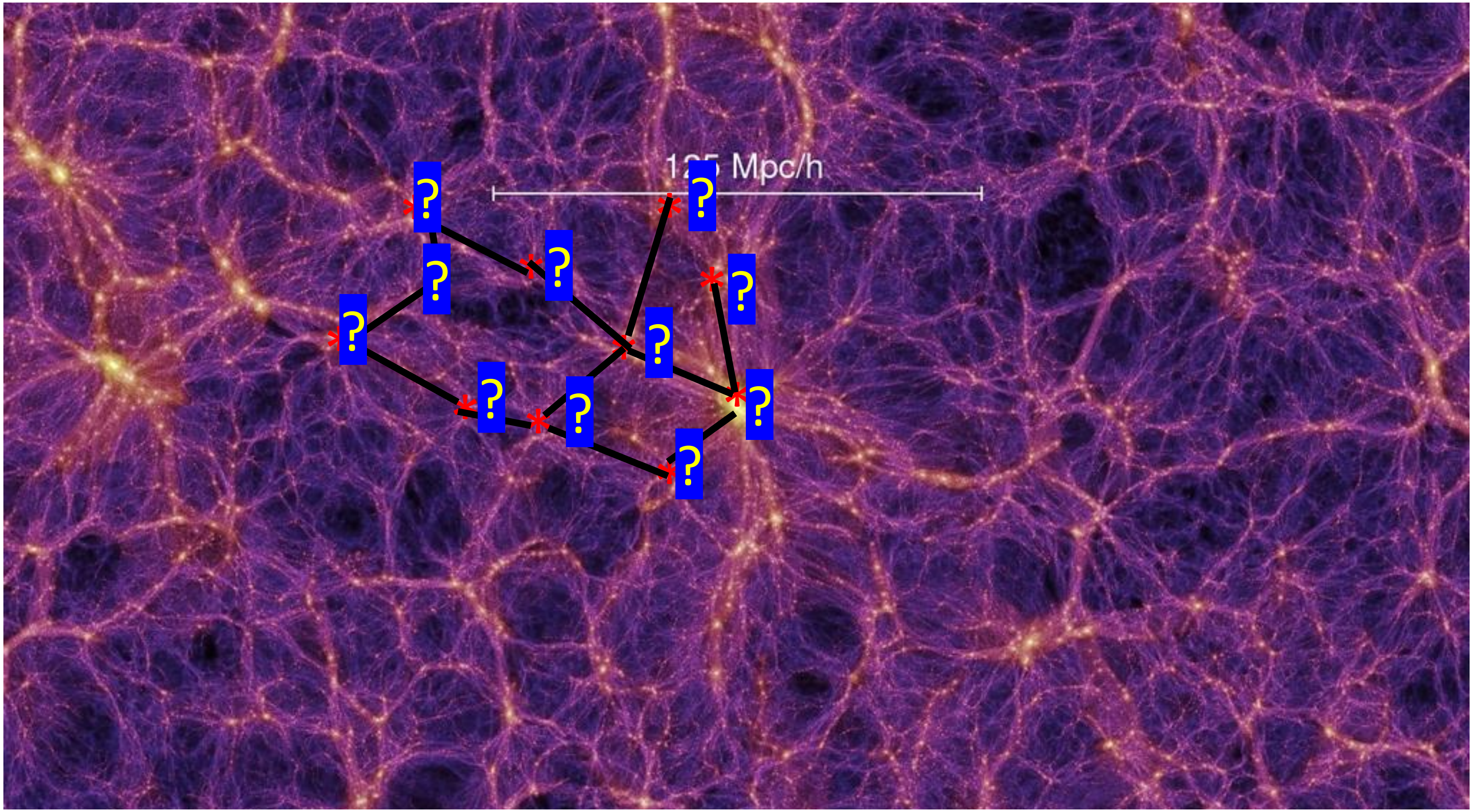
Cartoon idea



✶ = Massive nodes, —= filament

(Note: some overdensities might be projection)

Cartoon idea



* = Massive nodes, —= filament ?? clusters ~ nodes?

(Note: some overdensities might be projection)

Often said clusters are nodes of cosmic web

Reasonable:

- For many finders, nodes are peaks in the density, like clusters
- both probe/affect larger scales around them
- in some finders, nodes are **required** to have large cluster like densities, e.g. Cautun++14, or nodes are **defined** to be clusters (& sometimes groups), e.g., Alpaslan++13
- clusters as (part of) node population may capture web-like features
  - *Anisotropy*: special directions to other clusters
  - *Connectivity:* cluster-cluster pairs might be filaments

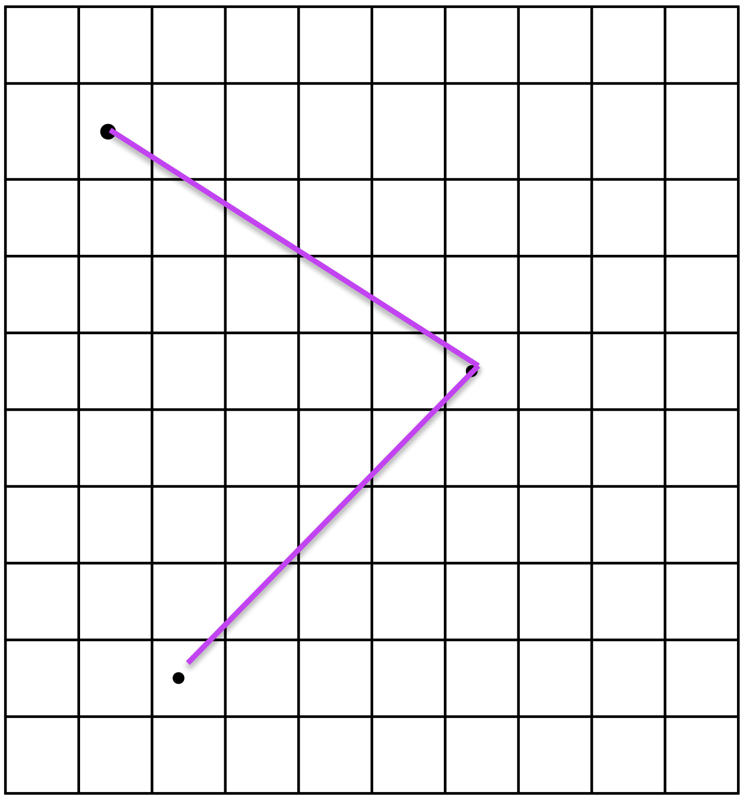
What ***is*** the correspondence between clusters and nodes?

[reductionist/rough question: how much do clusters capture of the web?

Variants of this asked many times, starting e.g. with Bond & Myers '96]

Disperse based web(s)

- crit points
  - nodes-peaks
  - filaments have saddles in centers
- *no volumes*-lines and points
- based on critical points in **density**



One Simulation & One Finder

Different webs:

different smoothings

1.25, 2, 2.5 (& 5) Mpc/h

different persistence [ncut-note added]

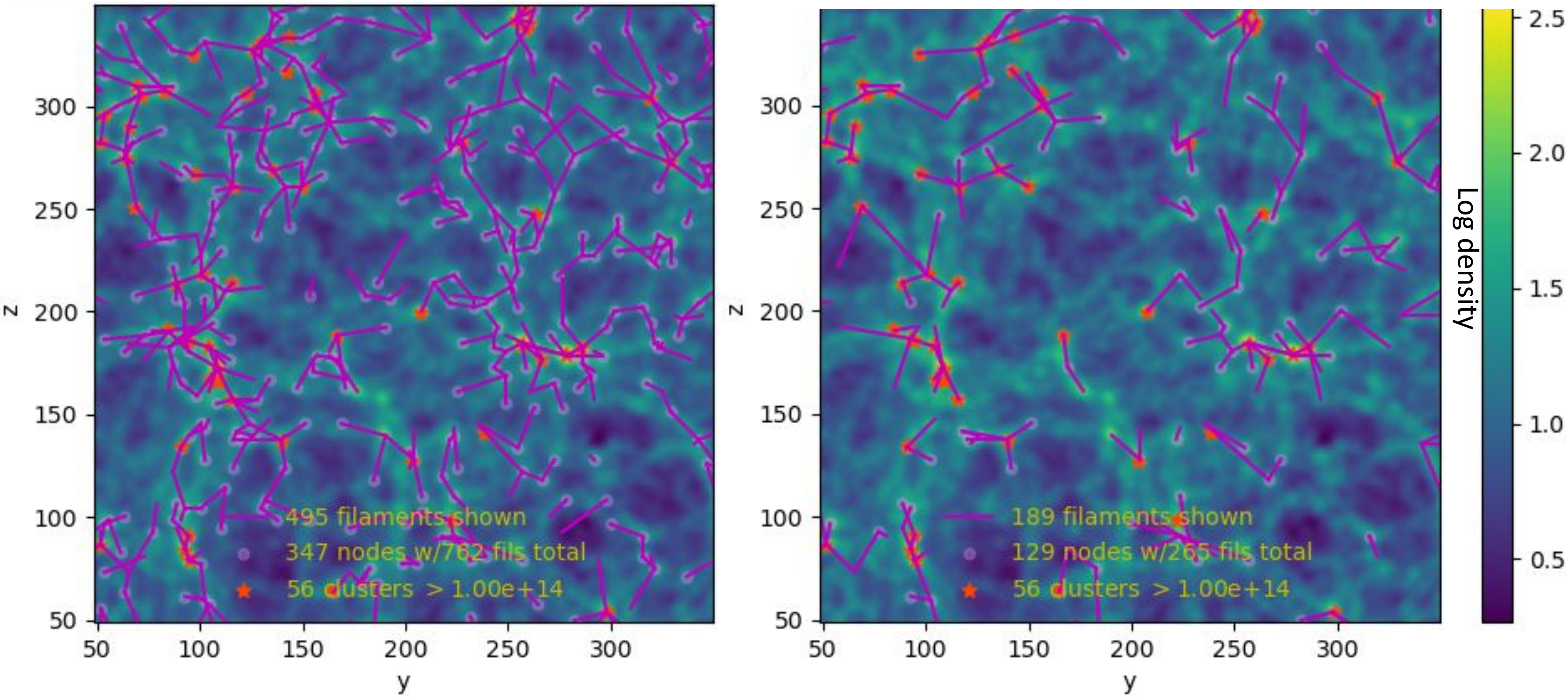
1σ, 2σ, 3σ

(~criteria to distinguish peaks)

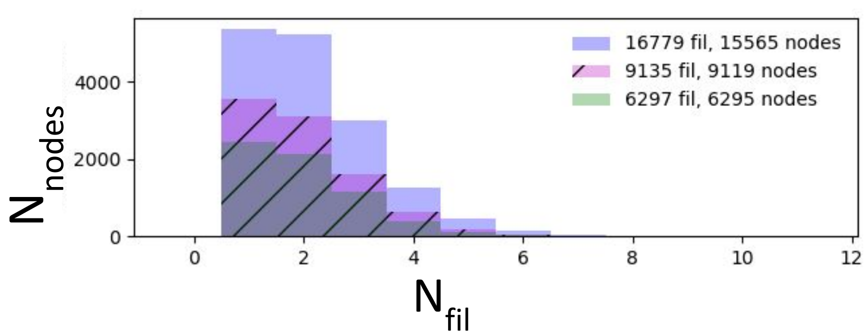
Use these 9 webs hereon
(see momentarily that 5 Mpc/h smoothing case too degenerate)

…What do they look like?

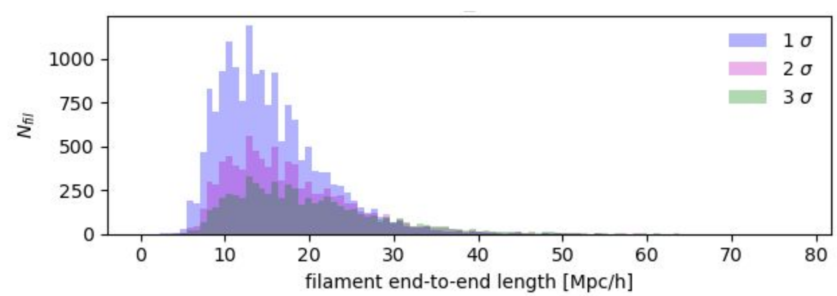
1σ persistence 2 Disperse webs 3σ persistence (2Mpc/h smoothing)



Connectivity (1σ,2σ,3σ)

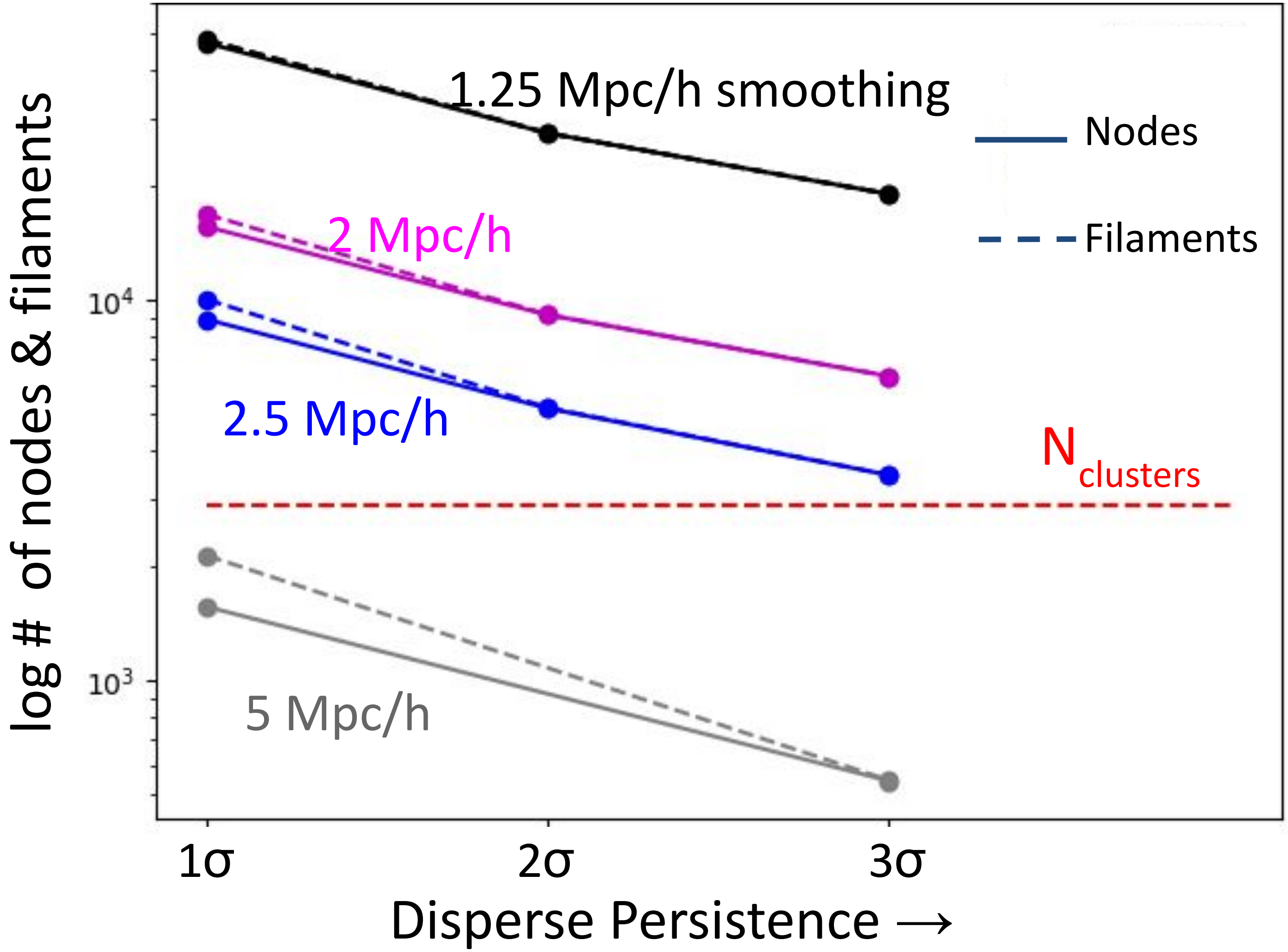


Filament lengths (1σ,2σ,3σ)



Numbers of nodes & filaments for different webs

Compare to 2898 cluster ($\geq 10^{14} M_o$) halos

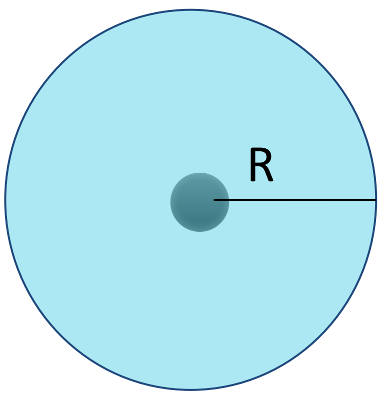


Aside from 5 Mpc/h (discard), **more nodes than clusters**, sometimes many more!

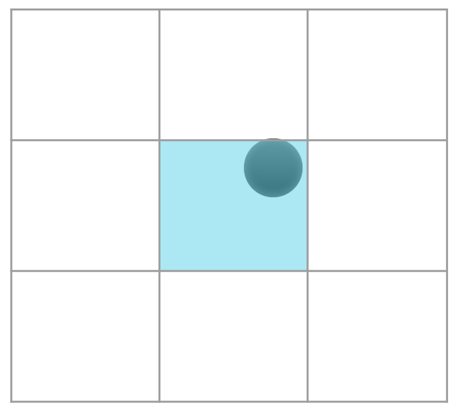
cluster ↔ node matching

Disperse identifies critical *points*

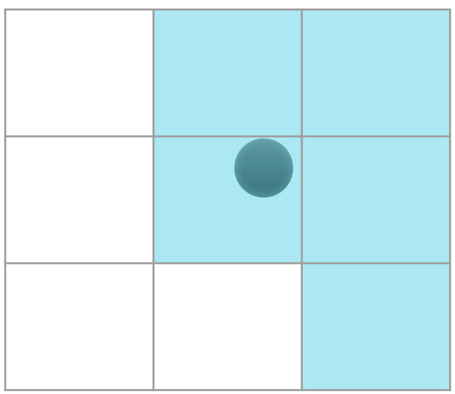
Assign volume to nodes* and see if cluster centers are inside



R ~ 2x smoothing
"nearest/fixed"



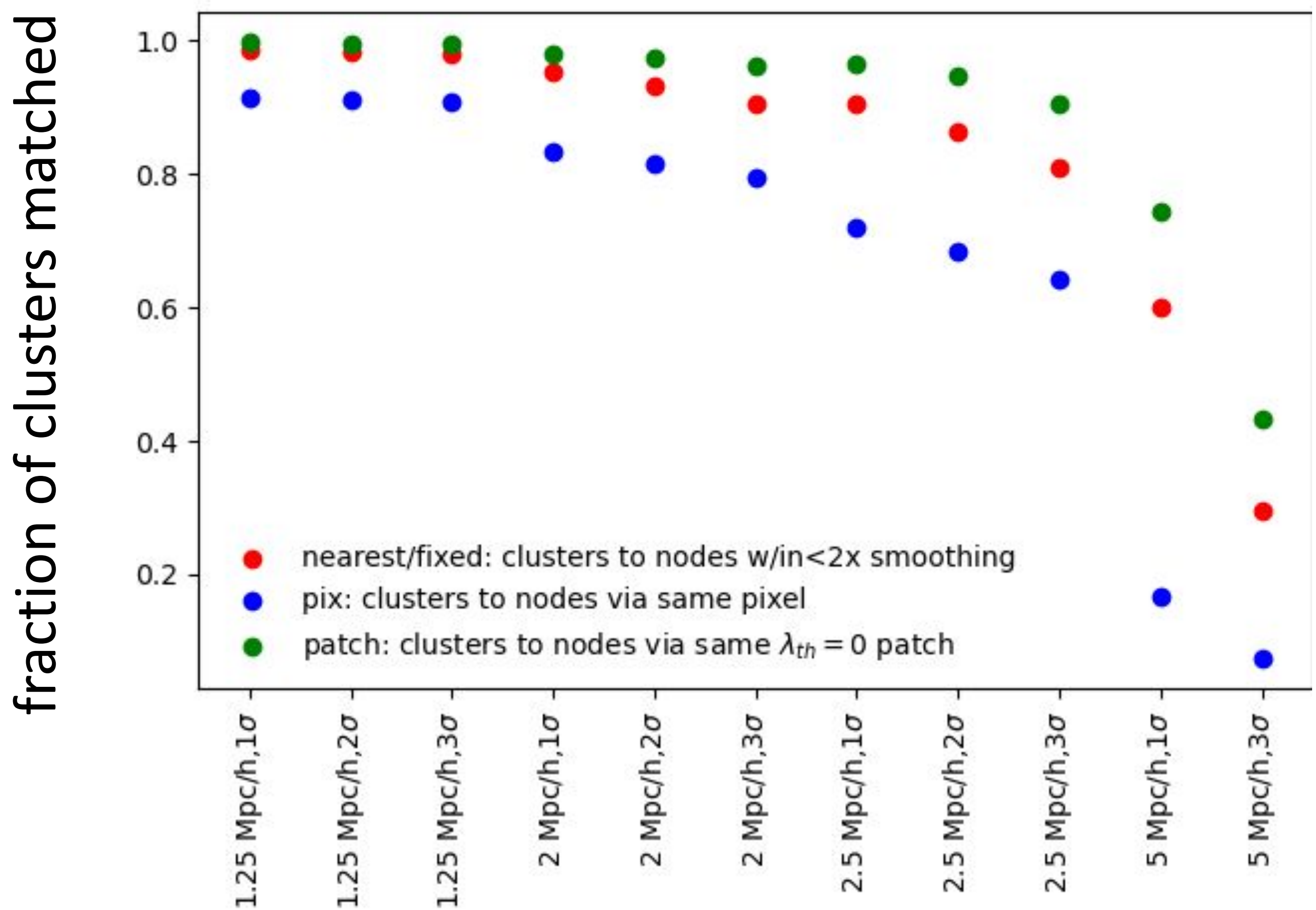
density pixel
"pix"



Hessian patch with $\partial_i \partial_j \varphi$ ev's
+++ = node
node= continguous +++ patch
"patch"

*Could also try to put nodes "in" clusters, which have a natural radius

Clusters matched to nodes?



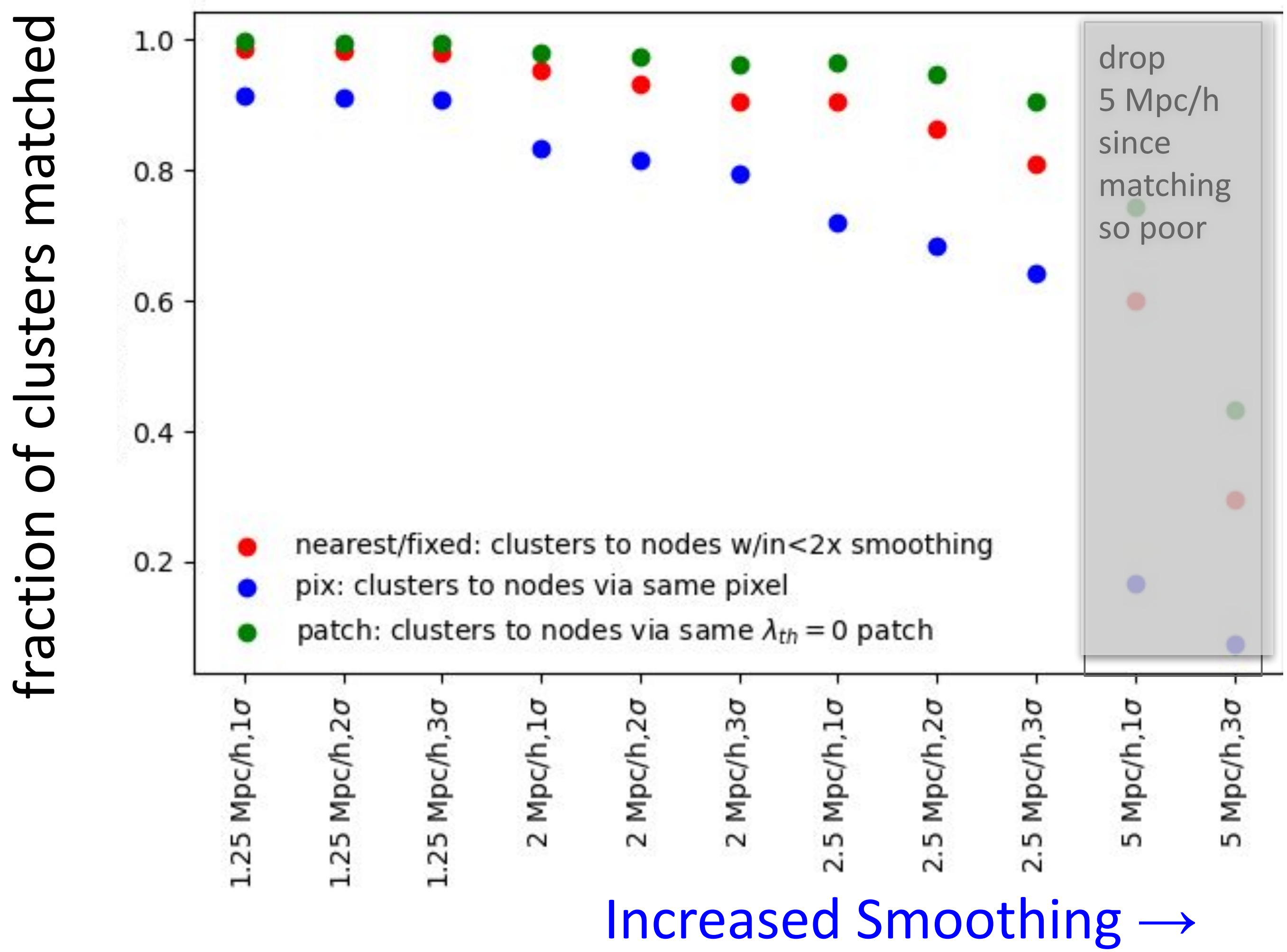
Increased Smoothing →

Most clusters are matched
(~100%* to 64%) depends on web

Fewer matched as web smoothing ↑ persistence ↑

*missing only 9/2898

Clusters matched to nodes?



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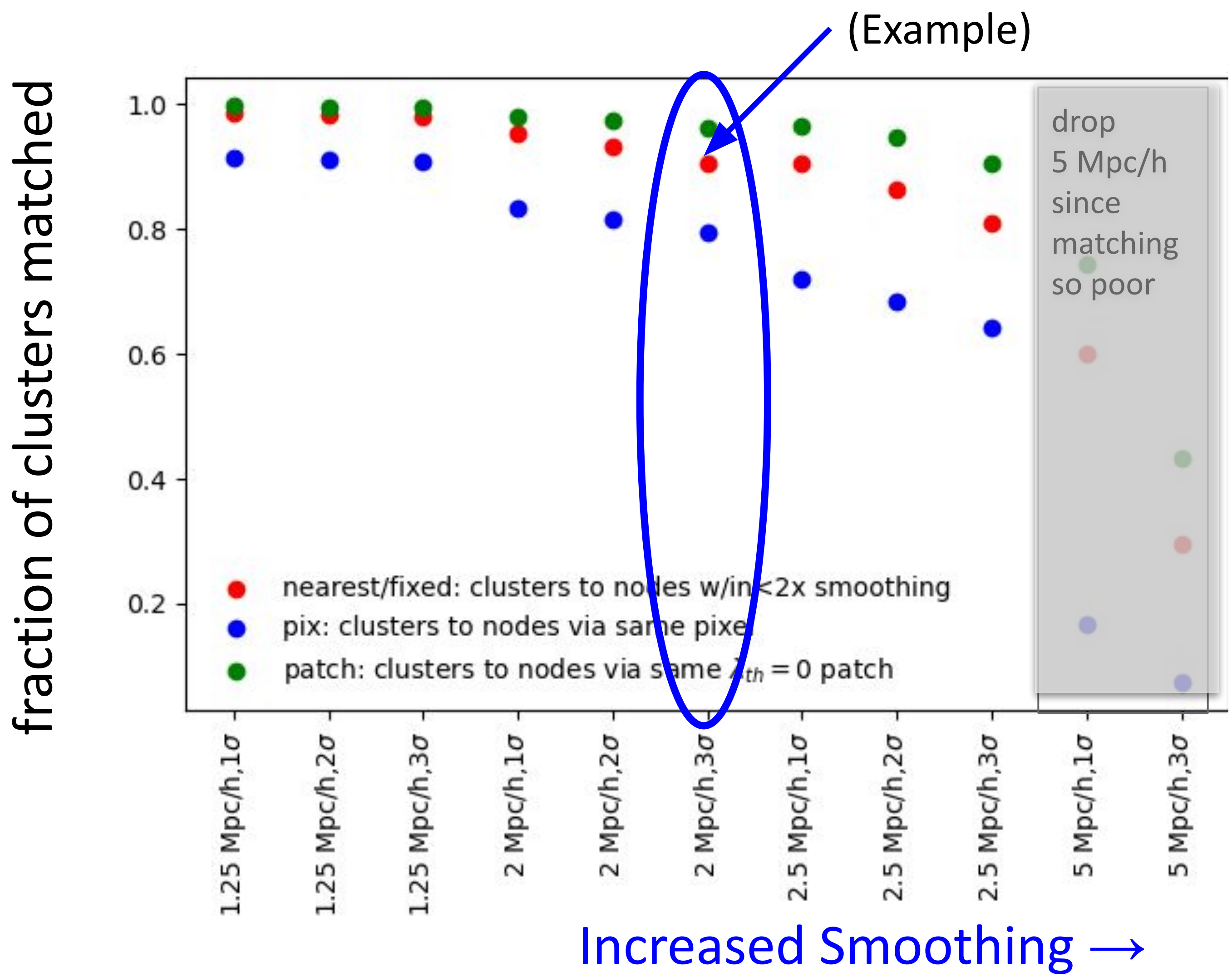

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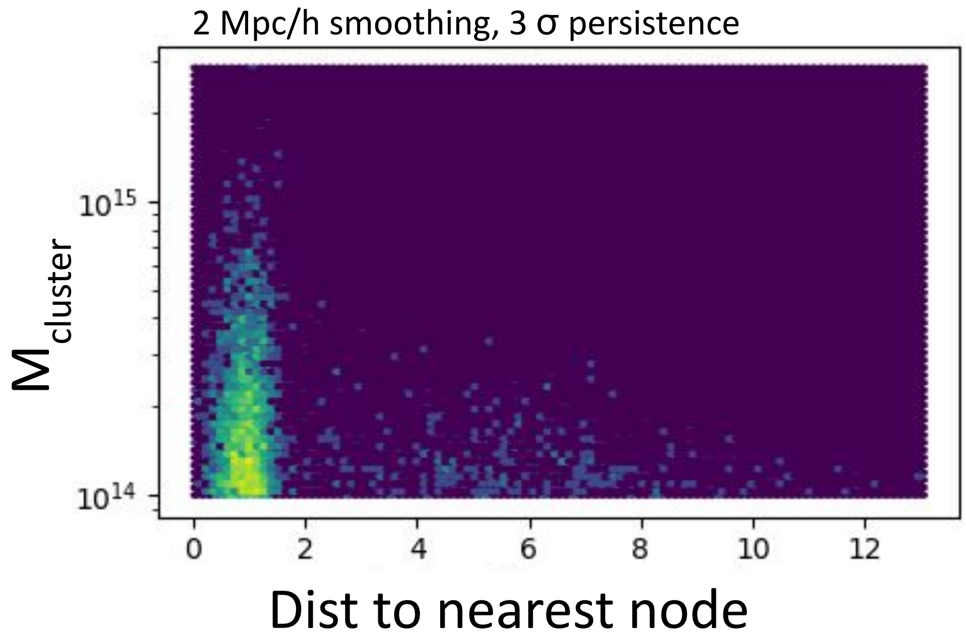
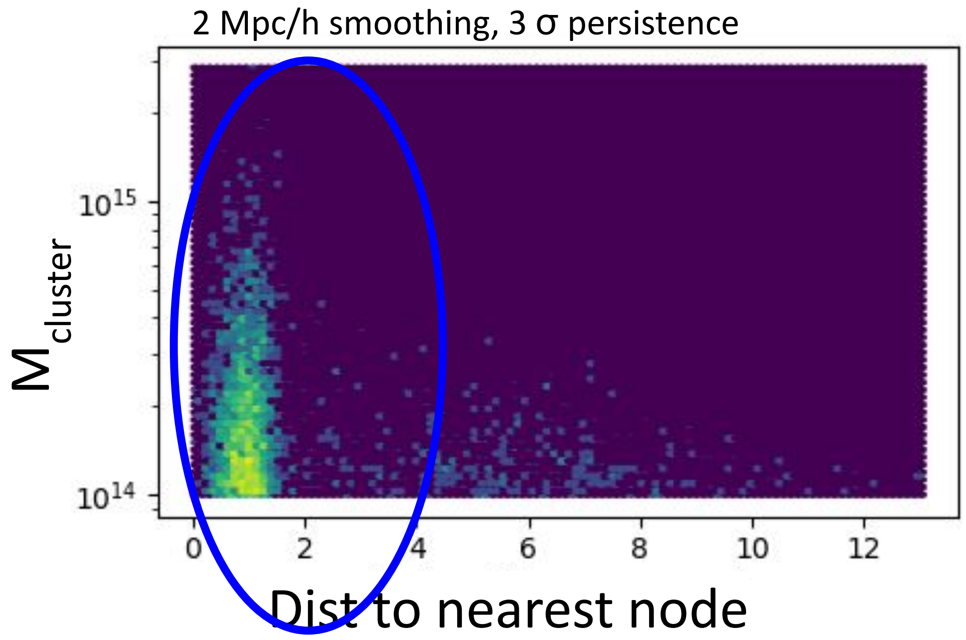
Matching example:"nearest/fixed"



two populations:

- clusters near nodes-"matched"
- clusters not near nodes

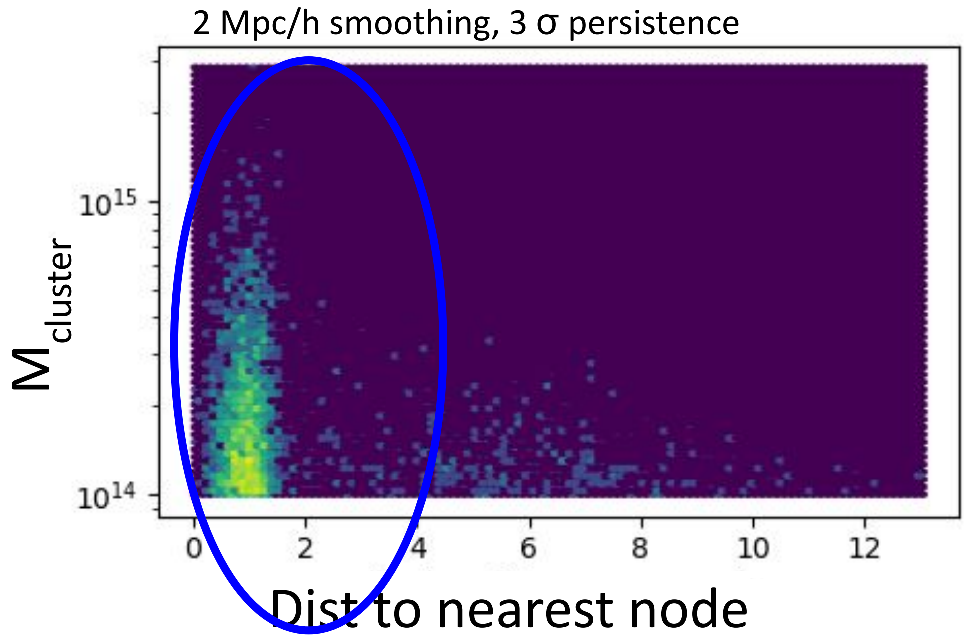
Matching example:"nearest/fixed"



two populations:

- clusters near nodes-"matched"
- clusters not near nodes (272/2898)

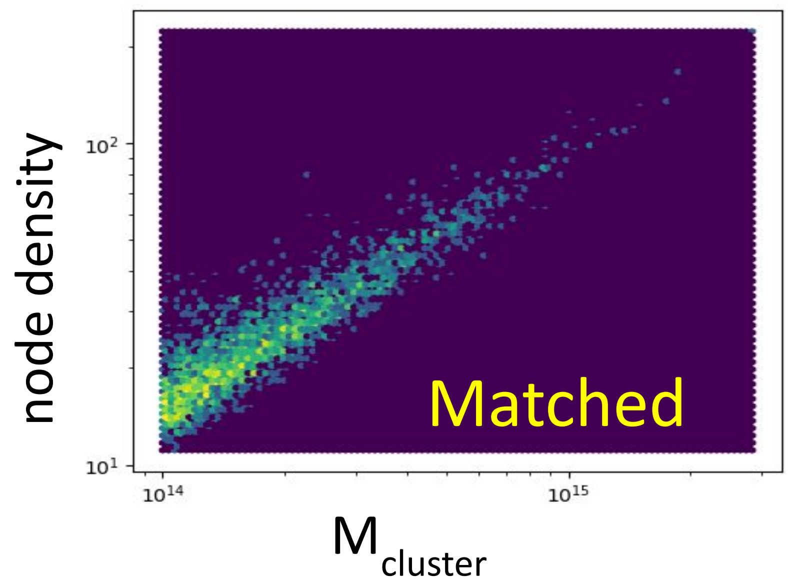
Matching example:"nearest/fixed"



two populations:

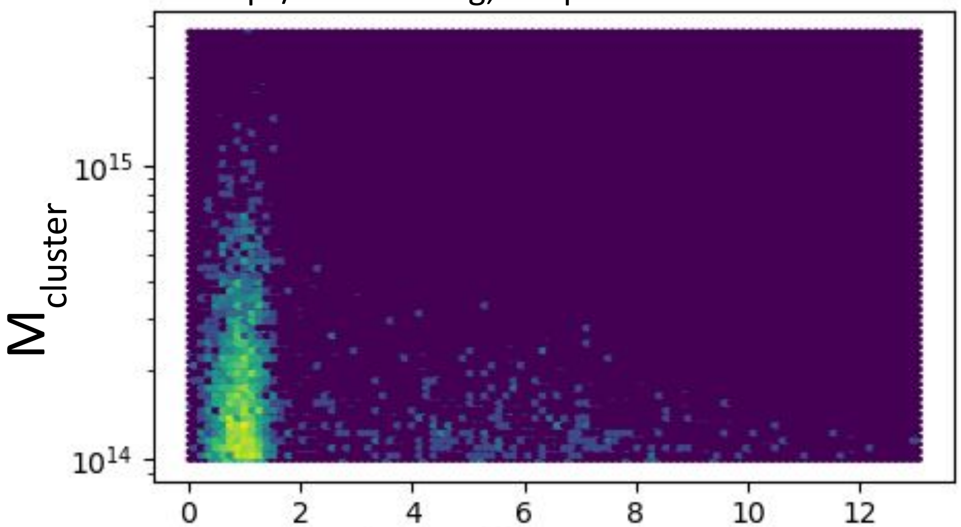
- clusters near nodes-"matched"
- clusters not near nodes (272/2898)

Matched clusters: cluster mass - node density relation



Matching example:"nearest/fixed"

2 Mpc/h smoothing, 3 σ persistence



two populations:

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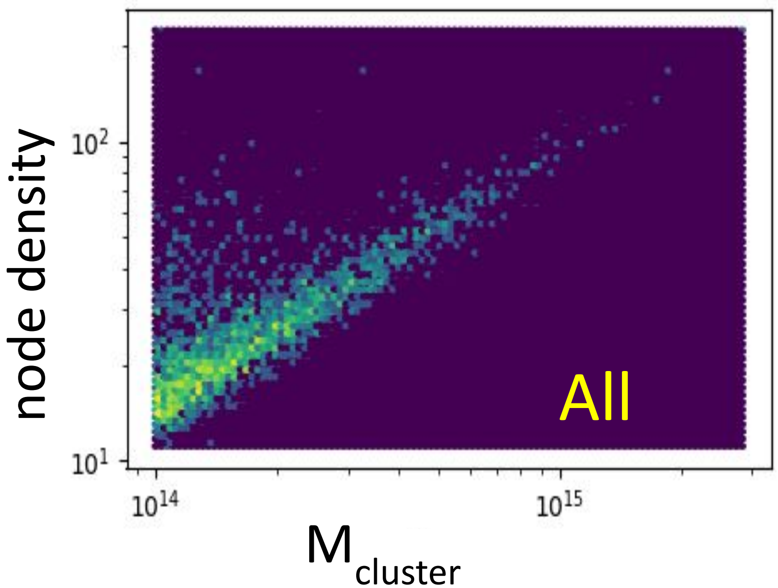

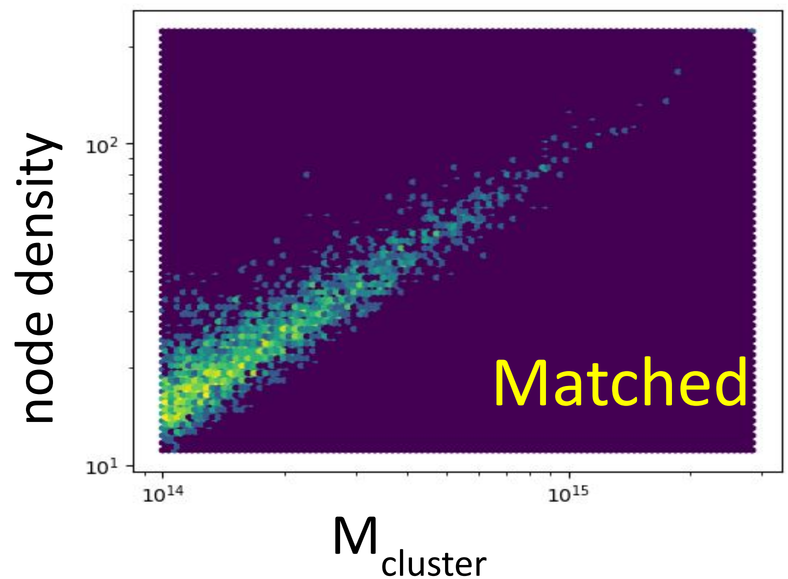

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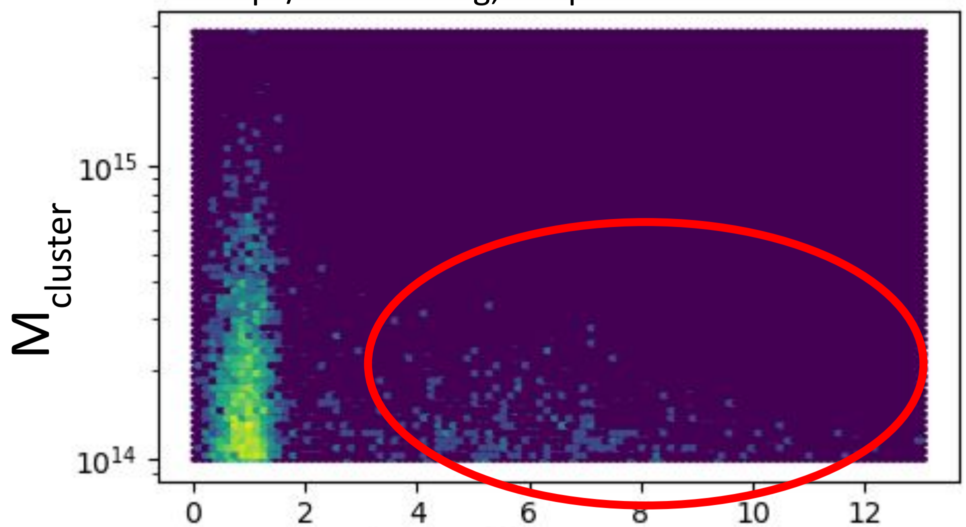
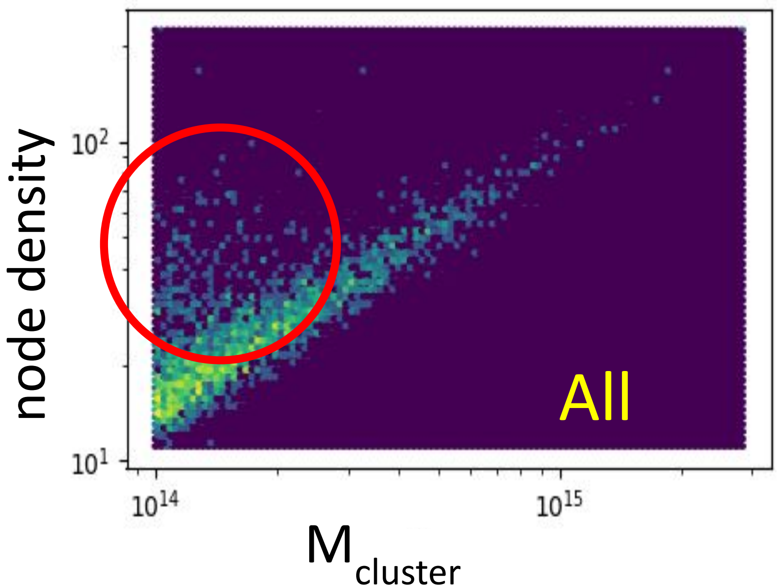
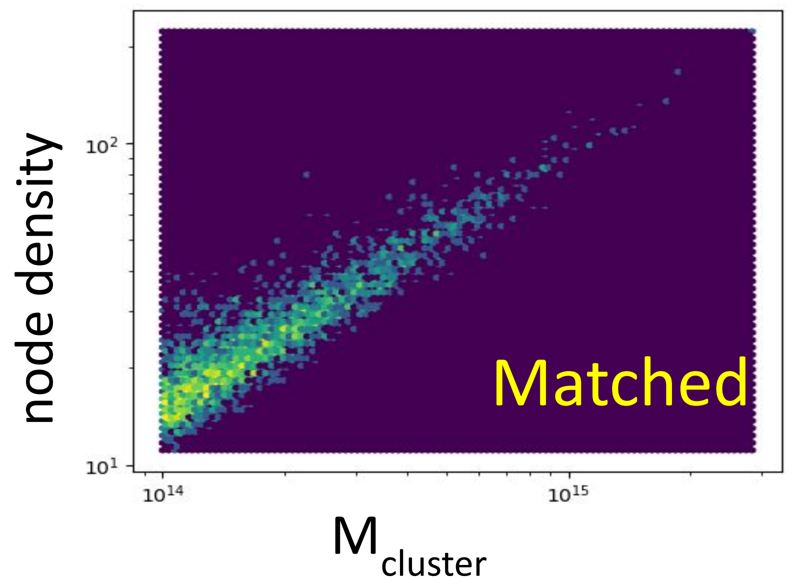


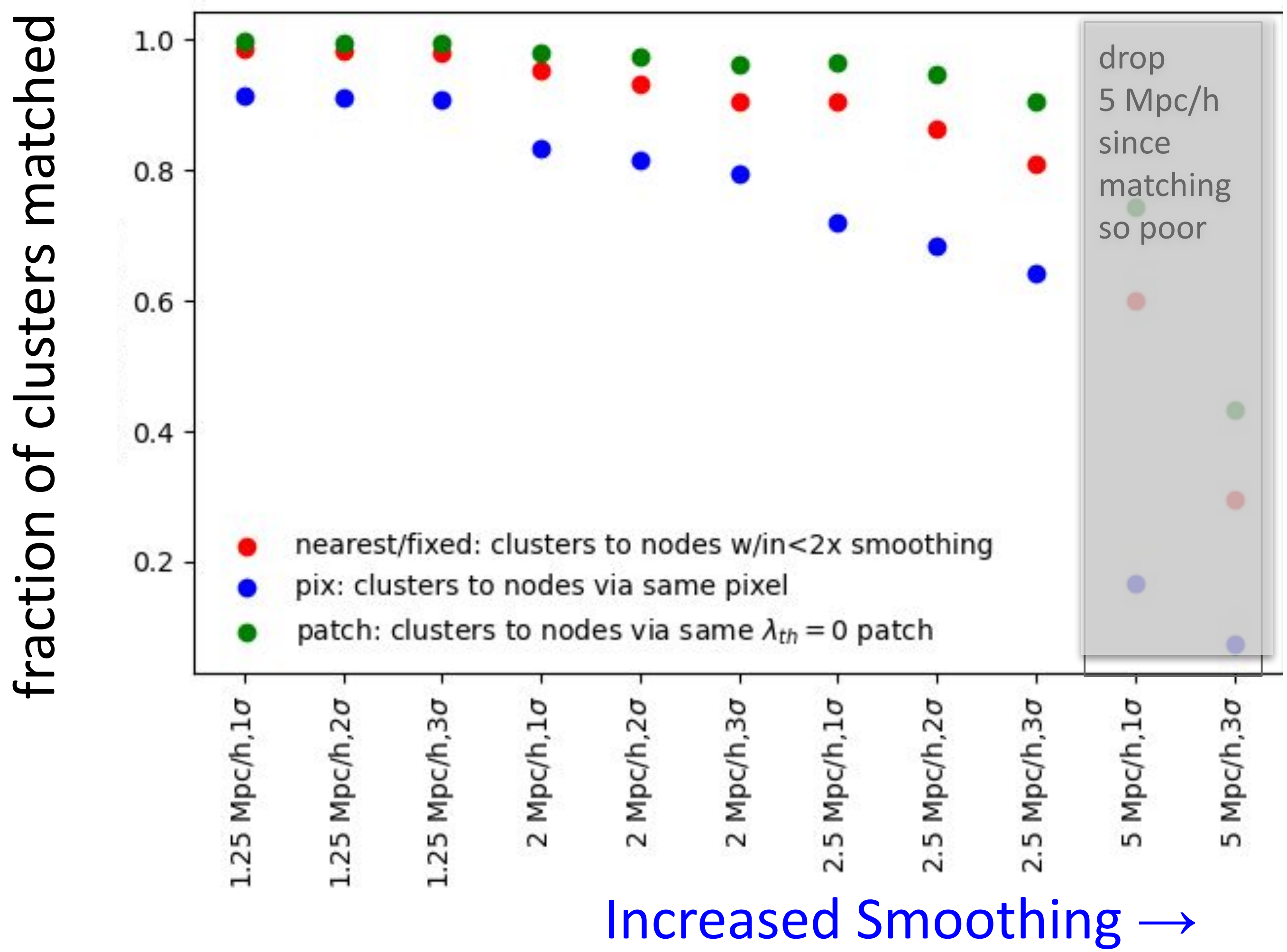
two populations:

- clusters near nodes-"matched"
- clusters not near nodes–**9% no nodes**





Unmatched clusters more generally?



Most clusters are matched
(~100%* to 64%)
depends on web

Fewer
matched as web
smoothing ↑
persistence ↑

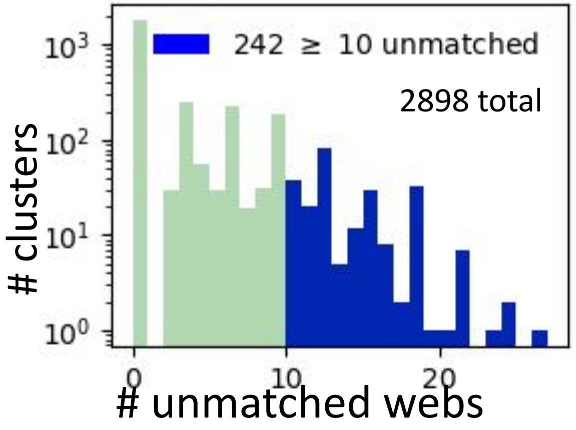
*missing only 9/2898

Unmatched clusters
different webs/matching methods

Matched clusters: 64% -~100%   - - 63% of clusters match every time

[drop "pix" method 81%- ~100%] - - 78% of clusters match every time

"pix" -match same pixel, very restrictive, perhaps too much so



How many times each cluster is unmatched, in all web/matching combinations

Unmatched clusters
different webs/matching methods

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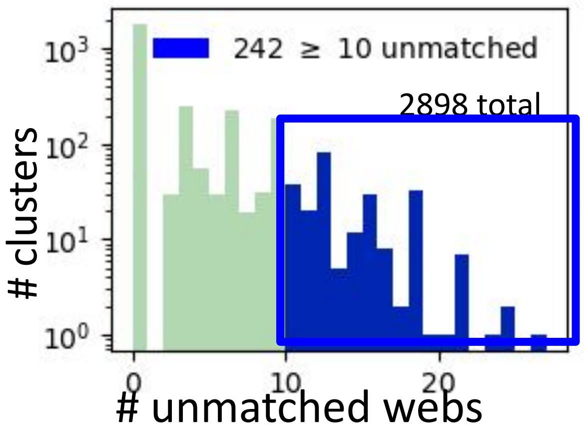


How many times each cluster is unmatched, in all web/matching combinations

Take clusters unmatched >= 10 times

Unmatched clusters
different webs/matching methods

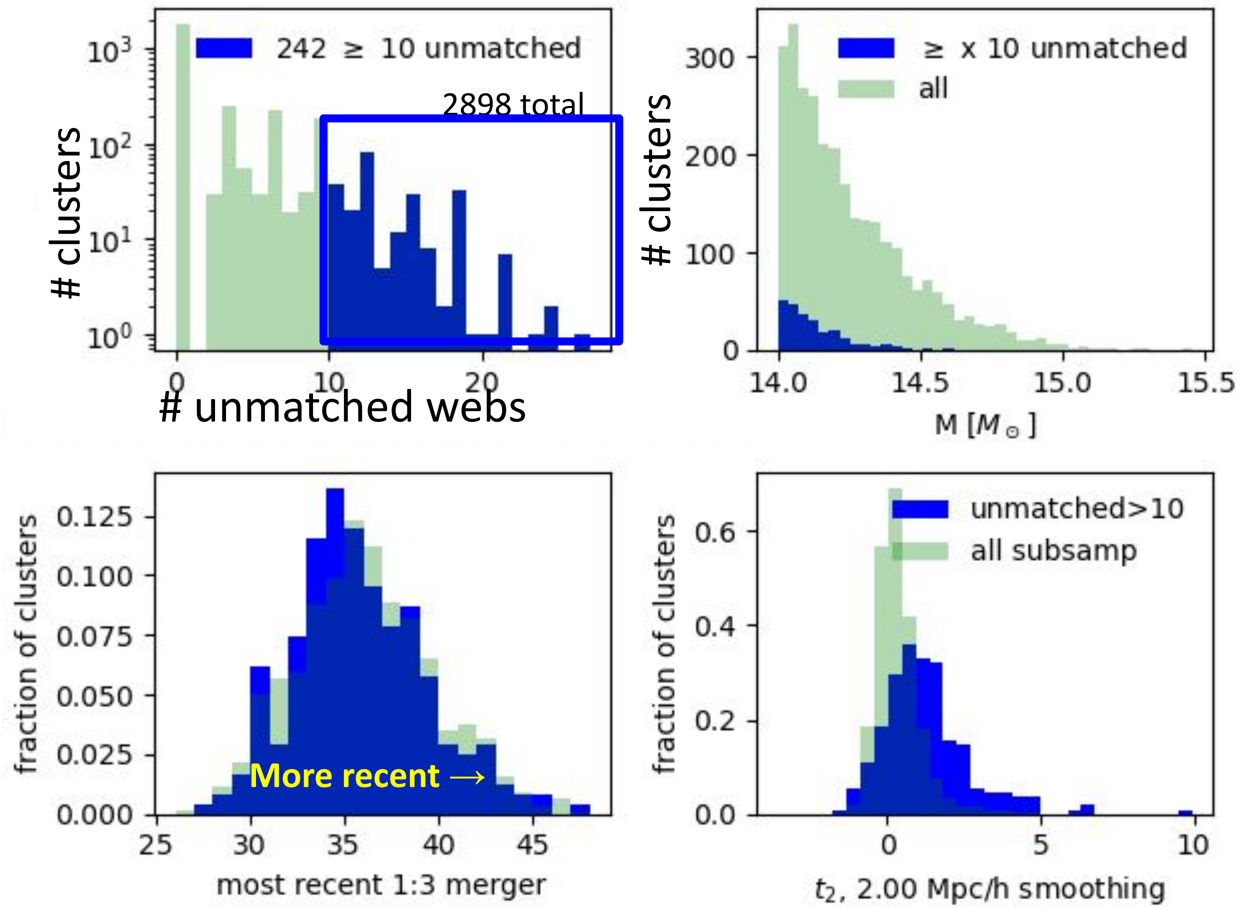
Matched clusters: 64% -~100% - - 63% of clusters match every time

[drop "pix" method 81%- ~100%] - - 78% of clusters match every time

"pix" -match same pixel, very restrictive, perhaps too much so

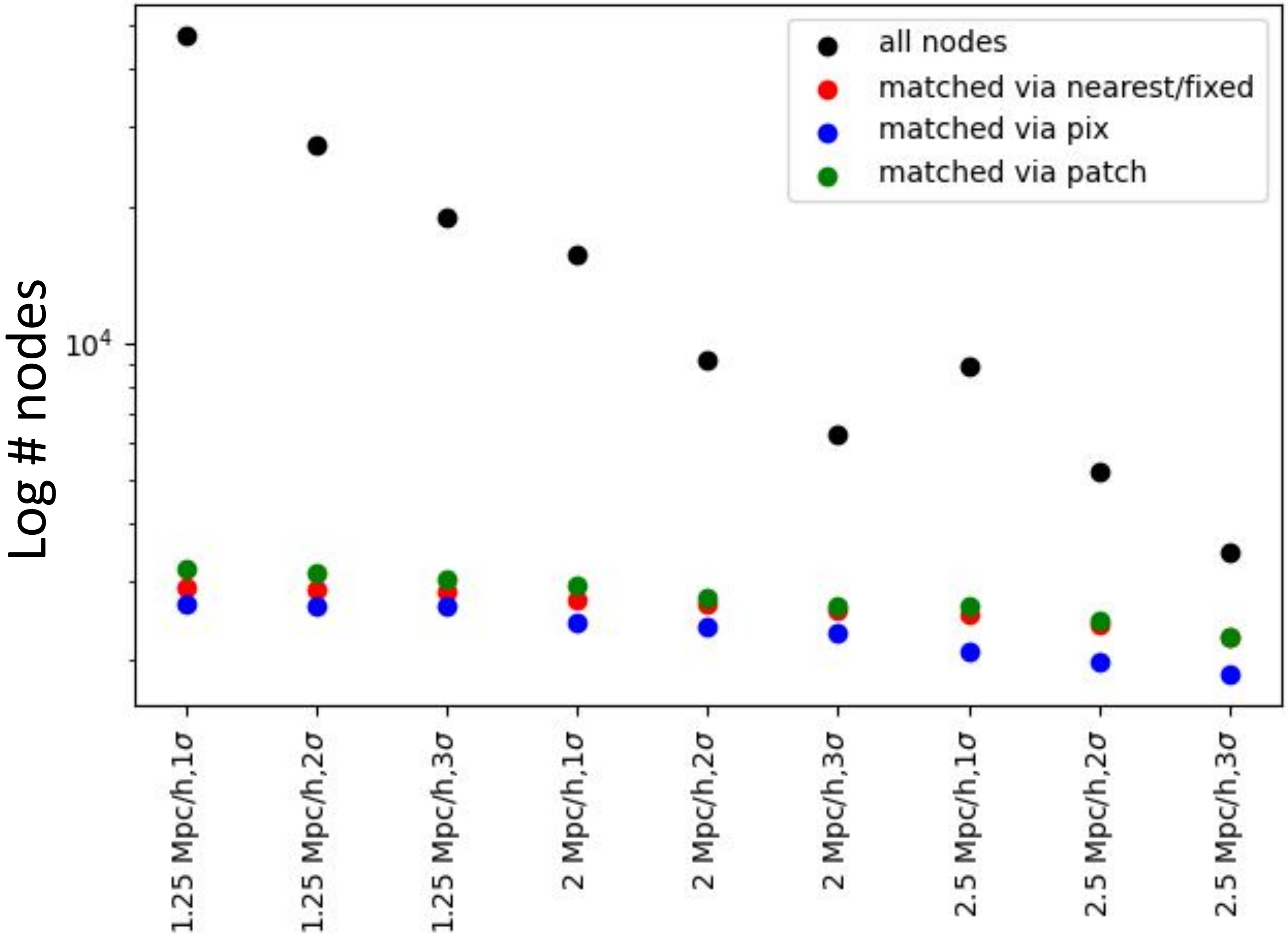
frequently unmatched clusters tend to:

- have lower mass
- slightly less recent major mergers
- higher $t_2 = \lambda_2 - \delta/3$



Nodes: most are unmatched!

Most nodes are not matched to clusters



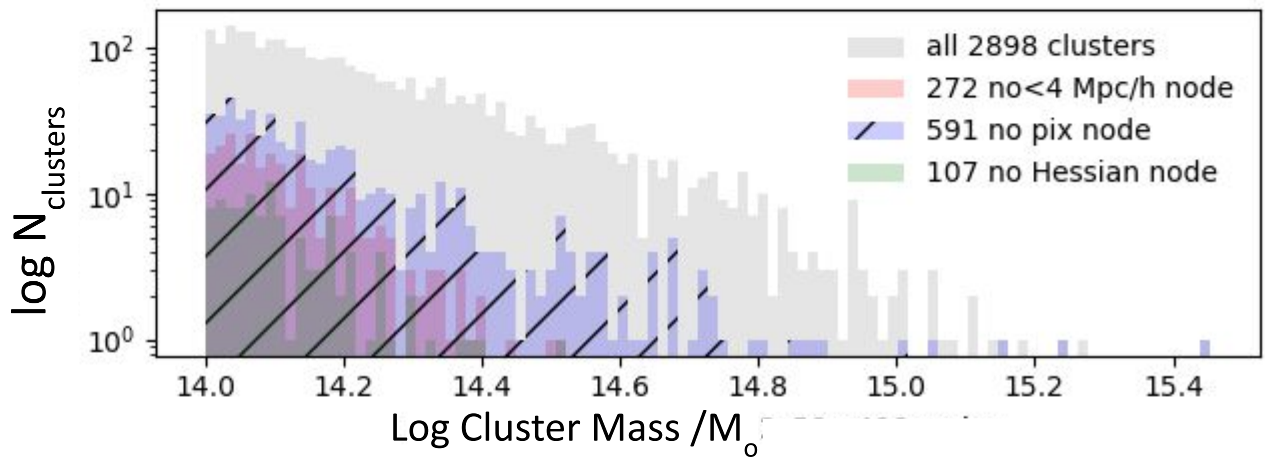
Increased Smoothing, Persistence →

A bit more about unmatched nodes
nodes >> # clusters > # matched clusters

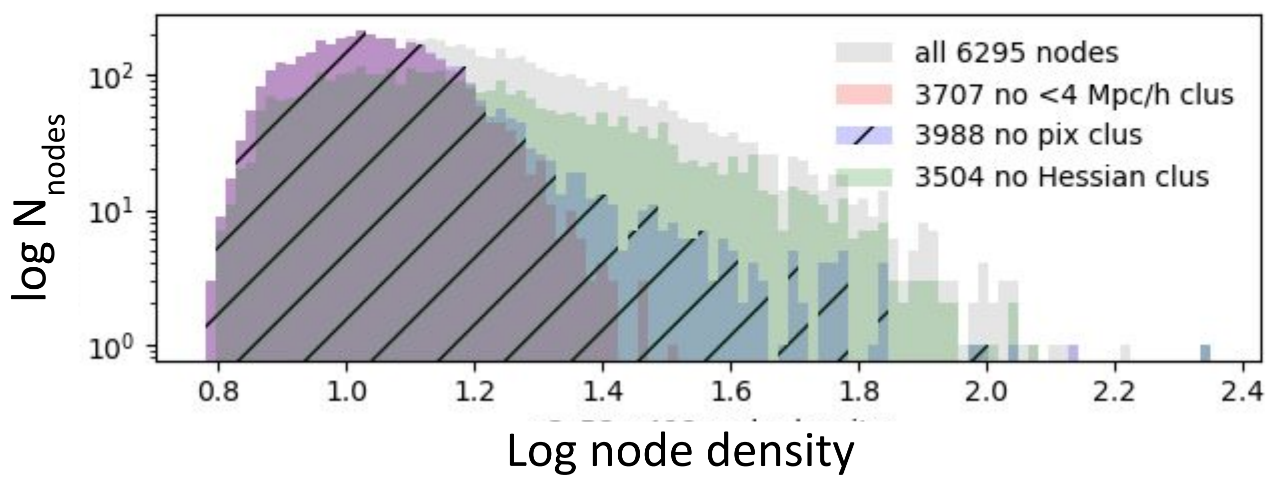
For main example web & several matching methods:

Unmatched clusters mostly low mass

2 Mpc/h smoothing, 3 σ persistence



Unmatched *node* density distribution **not just low density [except for 2x smoothing]**
Hess has fewest unmatched but goes to highest density



For these webs, now have (36 versions of)

clusters ↔ nodes

How about

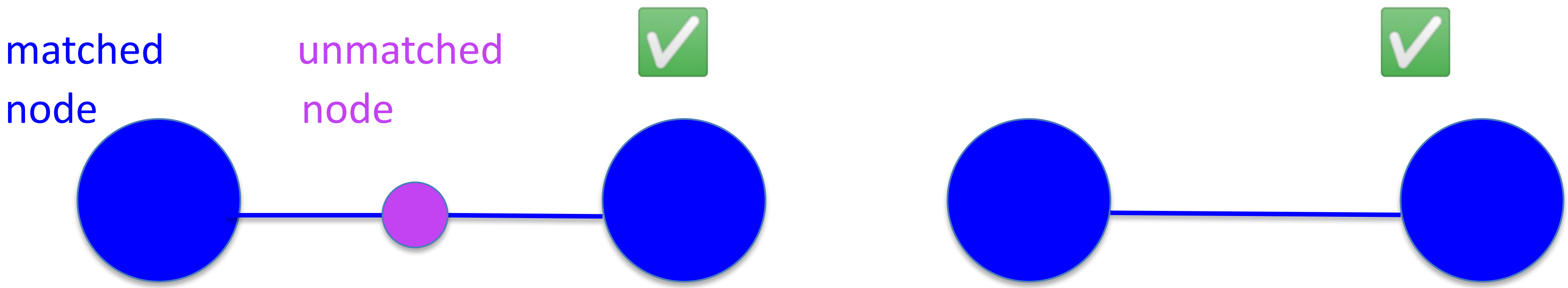
cluster pairs ↔ web filaments?

[connect clusters ↔ connect nodes]

- Sometimes it's implicitly assumed that cluster pairs have filaments
- Here, take nodes matched to clusters
  - If two cluster matched nodes share a filament-> cluster pair has a filament
  - Interpolate through nodes not matched to clusters

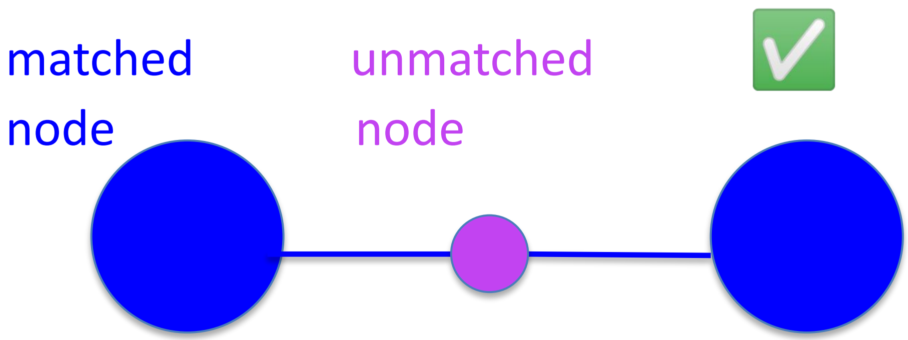
Truncated (‘approximate”) web

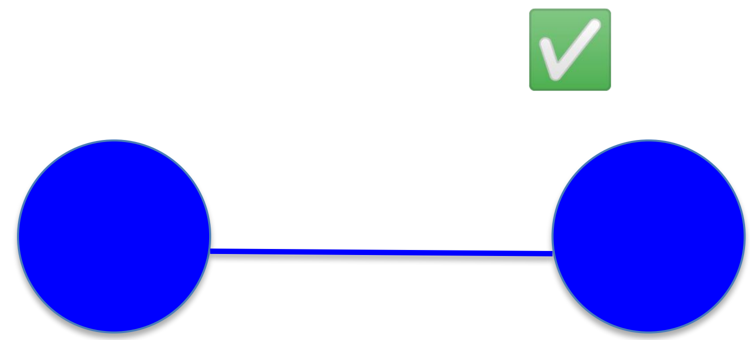
Connect nodes with non-matched node [ ] in between if angle > 120^{o} ; triples = 3 pairs, etc.

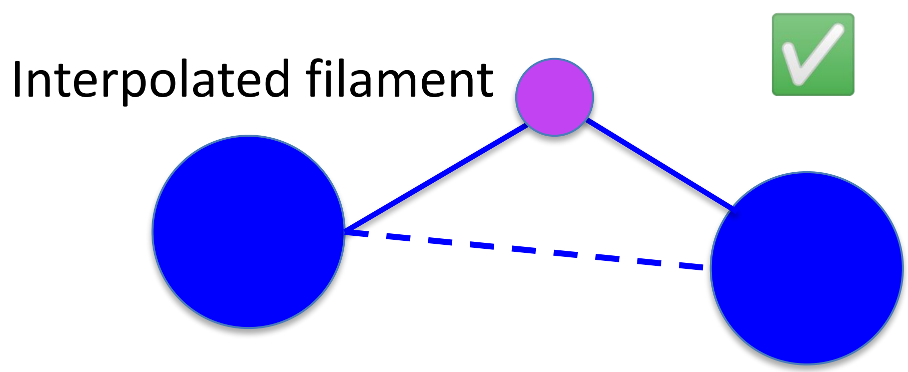


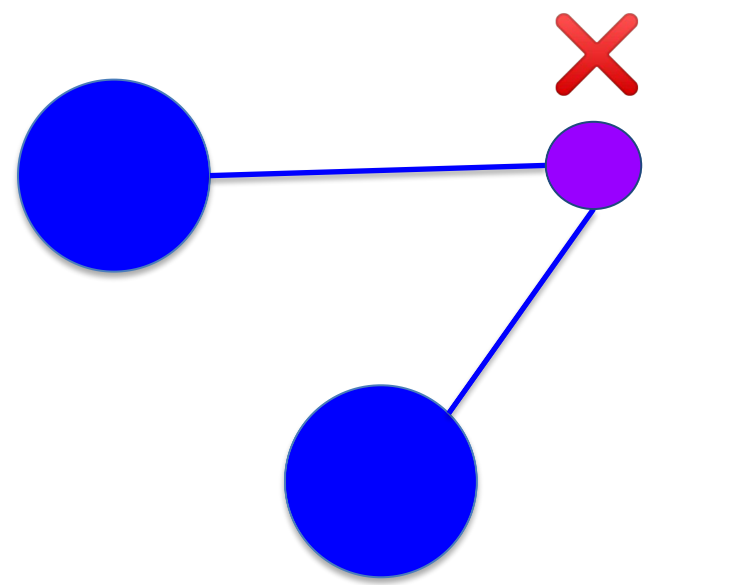
Truncated ('approximate") web

Connect nodes with non-matched node [●] in between if angle > 120^o ; triples = 3 pairs, etc., can drop > 1 in between.





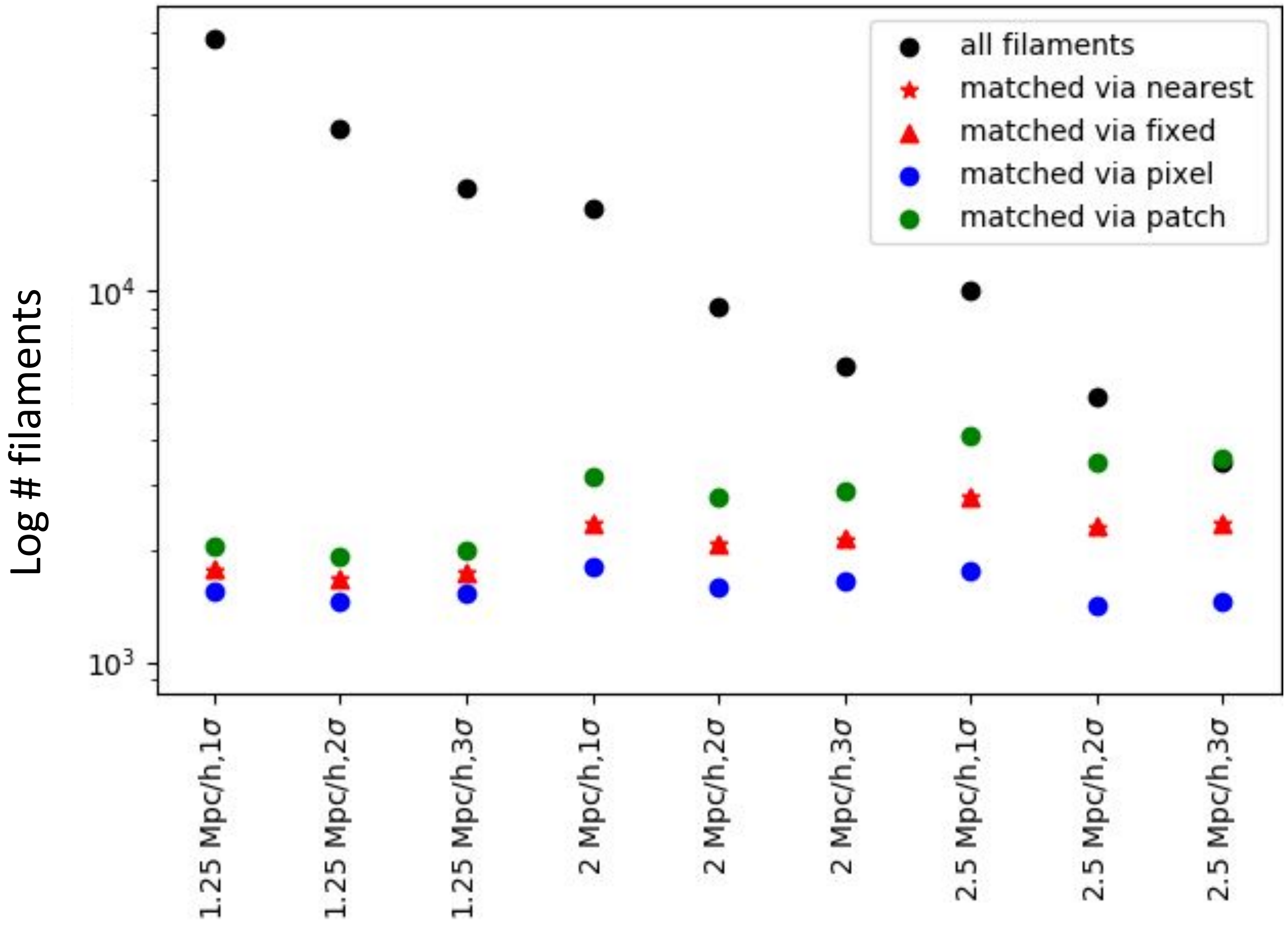




Interp Fraction of fils			
	1.25 Mpc/h	2 Mpc/h	2.5 Mpc/h
	34%-50%	15%-40%	7%-35%

Filament demographics after matching to cluster pairs

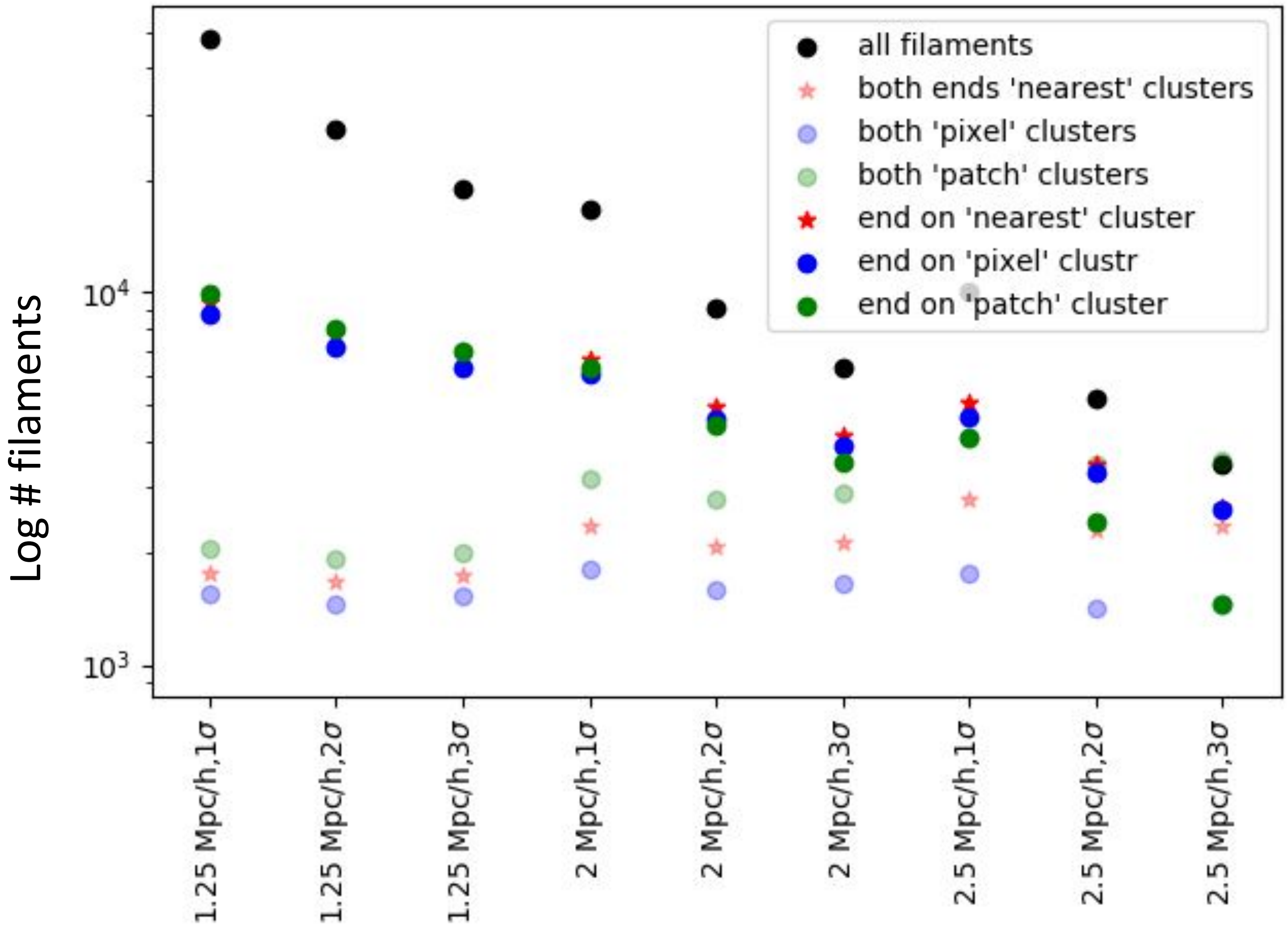
Most webs: most filaments are not matched to cluster pairs



Increased Smoothing, Persistence →

Filament demographics after matching to cluster endpoints (aside)

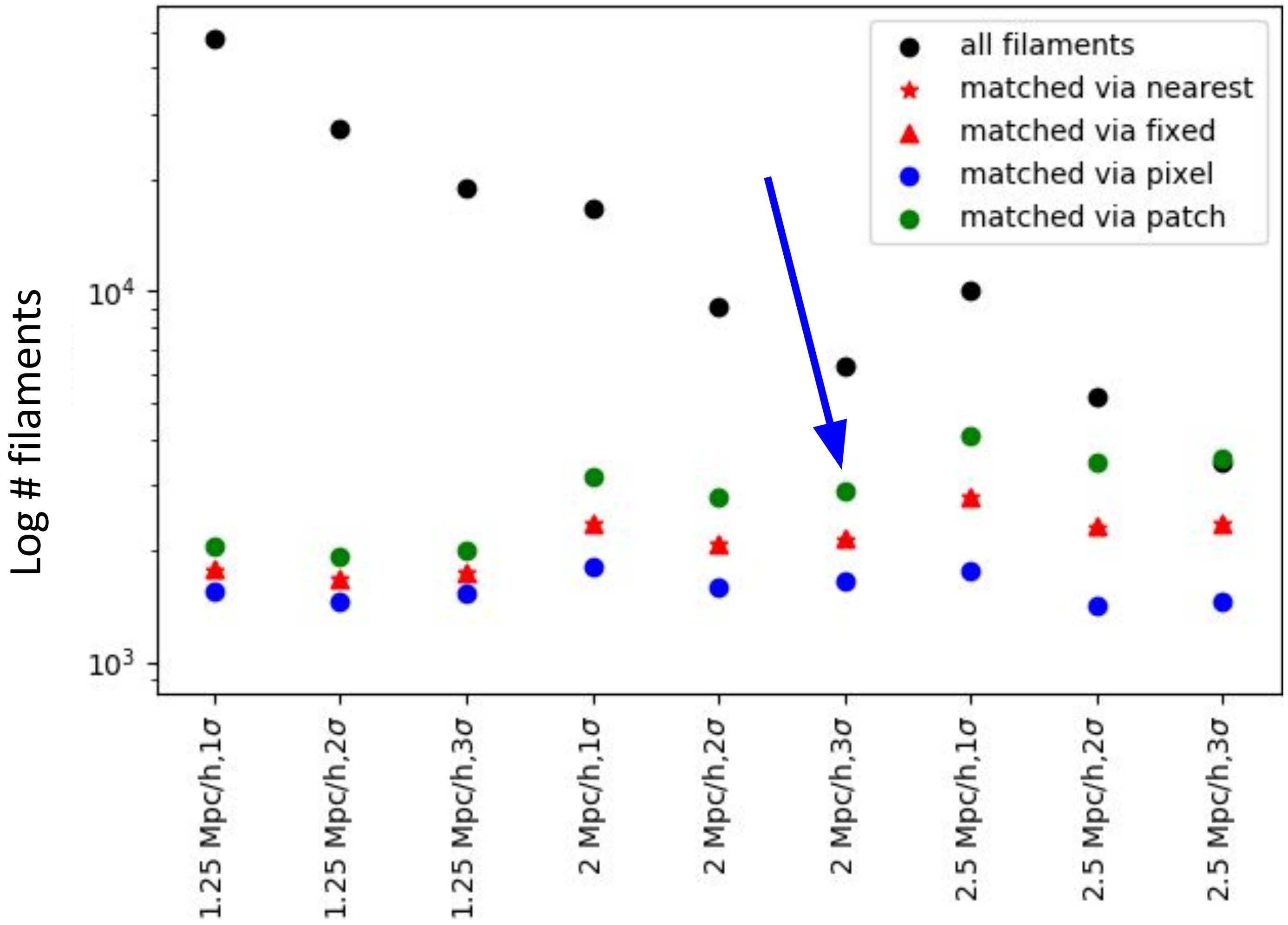
Most webs: many filaments have at least one cluster matched endpoint



Increased Smoothing, Persistence →

Filament demographics after matching to clusters

Most webs: most filaments are not matched to cluster pairs

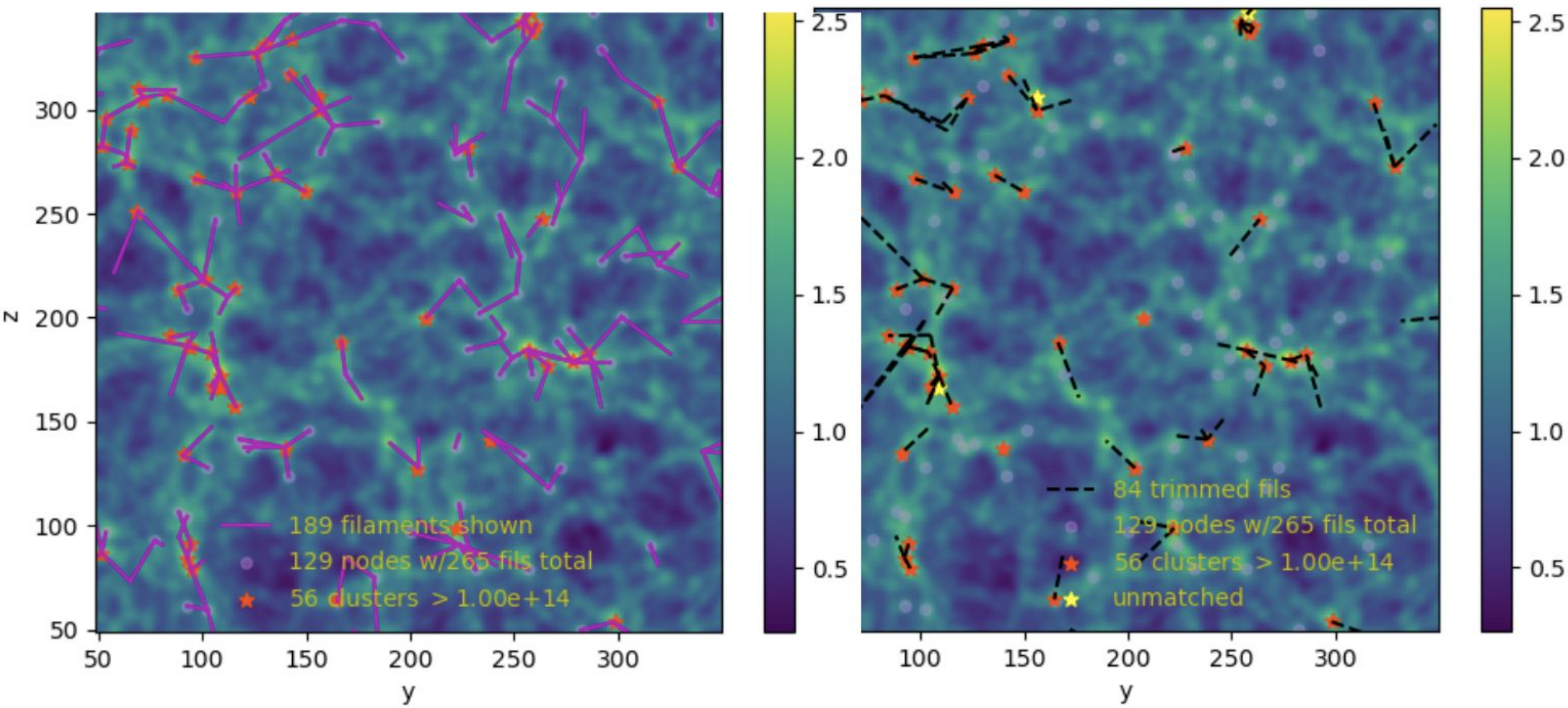


Increased Smoothing, Persistence →

Get very sparse web!

2 Mpc/h smoothing, 3 σ persistence

30 Mpc/h deep



189 filaments originally → **84 cluster-cluster filaments**

—— Disperse filaments

✳ clusters w/nodes

- - - - cluster-cluster filaments

✳ unmatched clusters

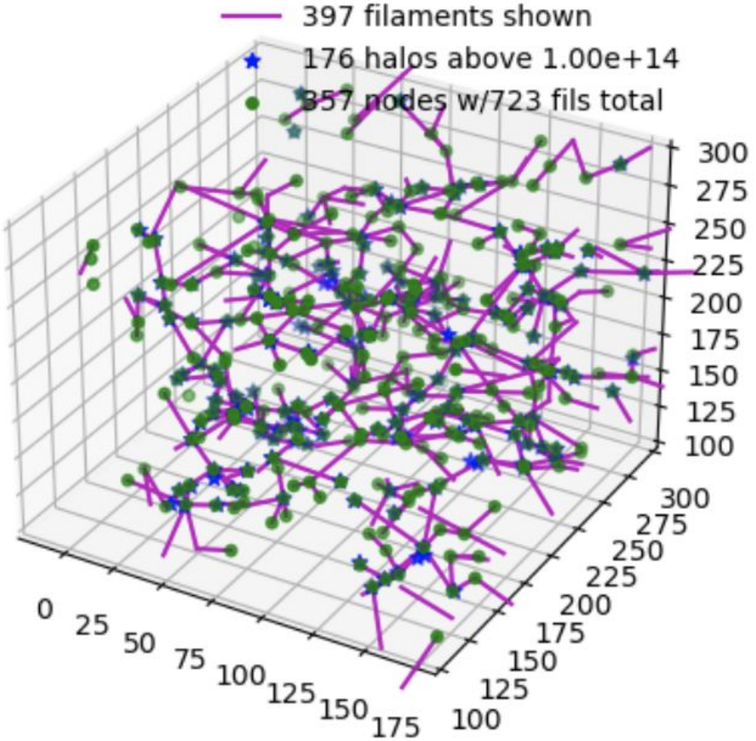
Another larger scale view of same system ($[200\ Mpc/h]^3$)

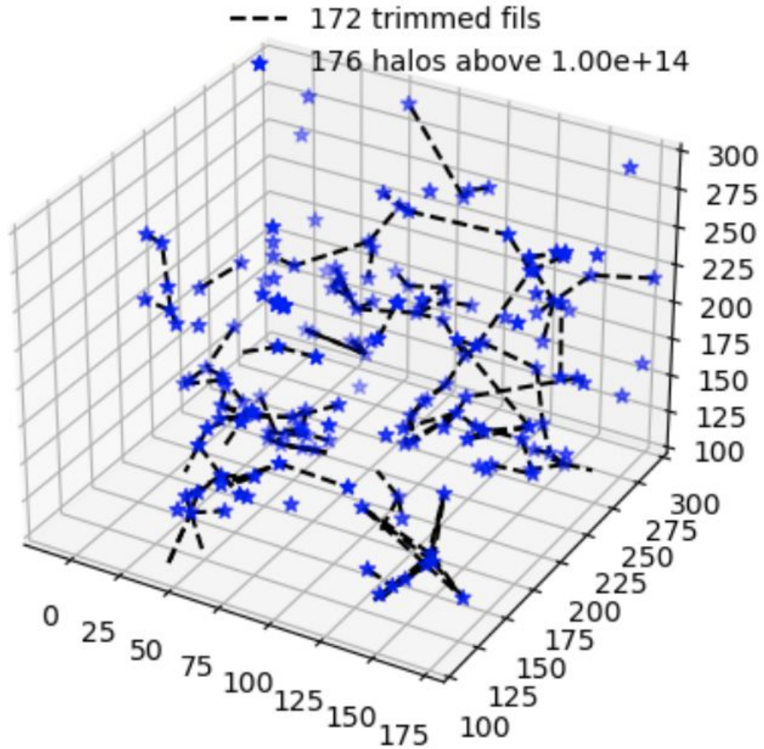
* Disperse Nodes

– Disperse Filaments

✶ Clusters

- - - Cluster pairs with filaments

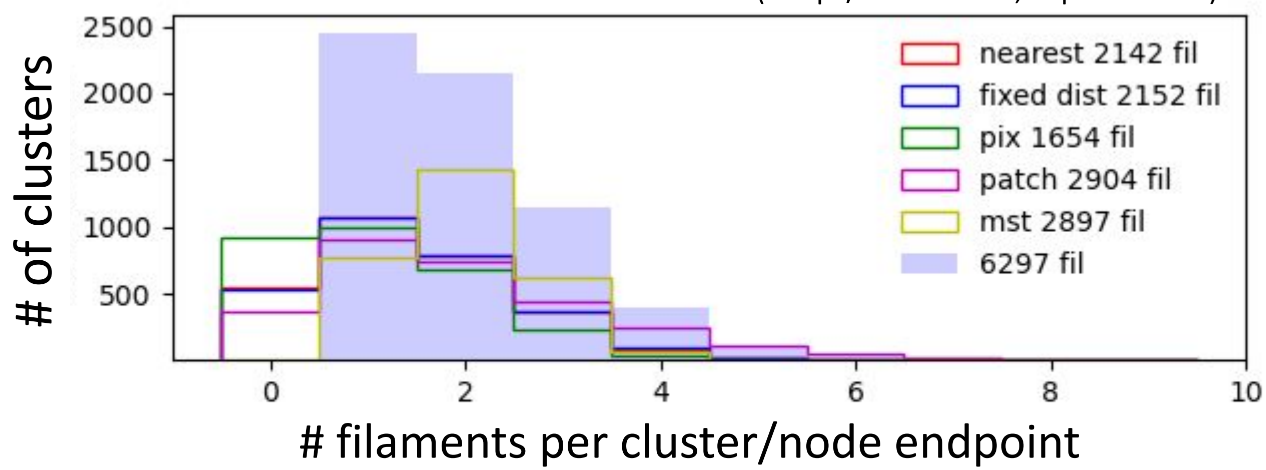




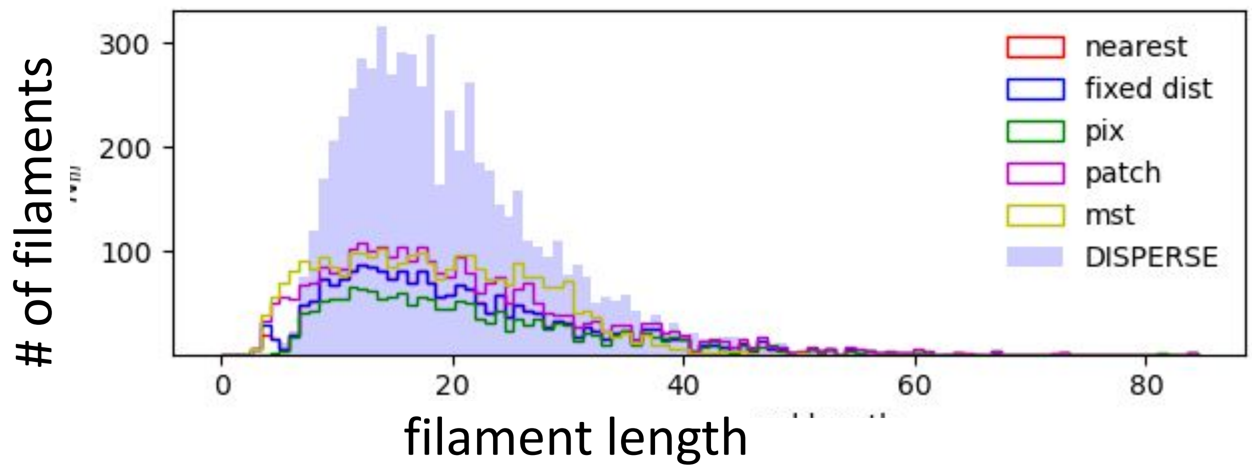
Statistics of all cluster webs from this Disperse web

(2 Mpc/h smoothed, 3 persistence)

Disperse
-more filaments (6297)
-all nodes get filaments



Cluster webs: (lines)
-1654 - 2904 filaments
-some clusters no filaments
-higher fraction of long filaments
-high density (at saddle) filaments more often matched to cluster pairs



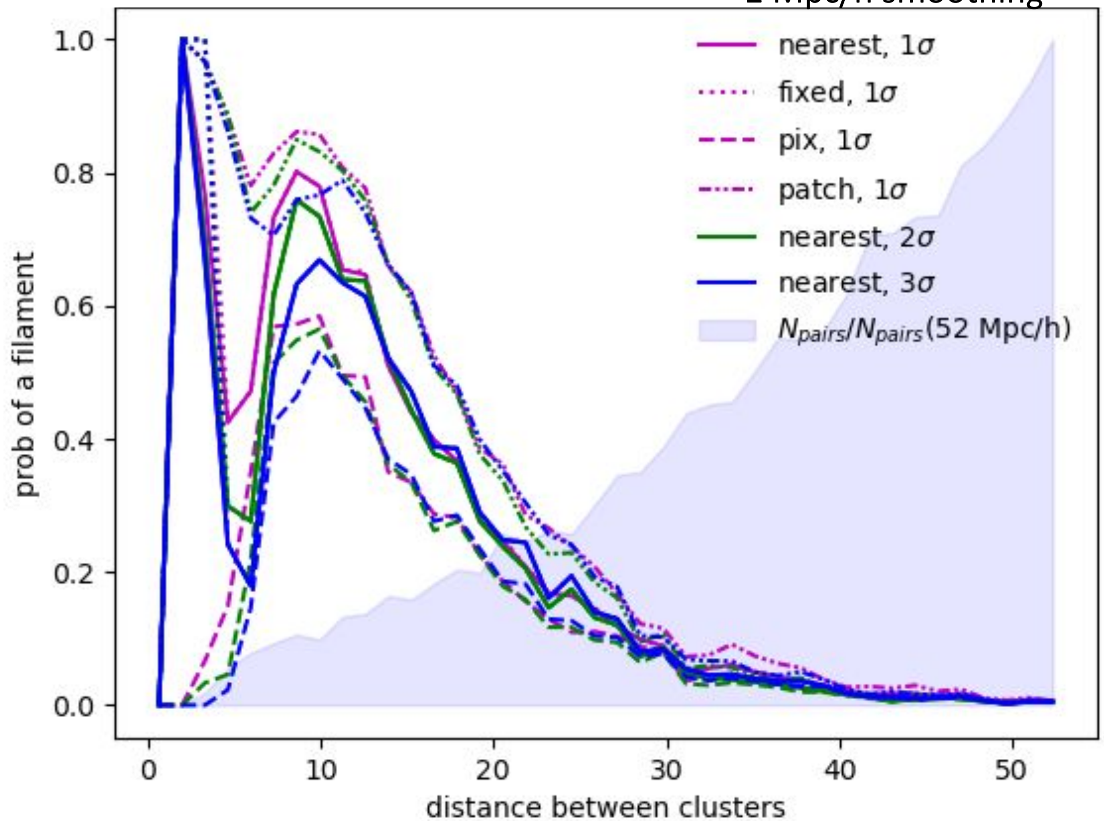
These are filament properties that match to cluster pairs, how about vice versa?

Before: which clusters -> nodes?
Now: which cluster pairs -> filaments?

A pair is more likely to have a Disperse filament if the clusters:

- are close together
- have long axes aligned with cluster pair axis
- using ML (later)
    - cluster is one of closest other clusters
    - have long axes aligned with each other

2 Mpc/h smoothing



3 persistences shown here (3 webs)

Before: which clusters -> nodes?
Now: which cluster pairs -> filaments?

A pair is more likely to have a Disperse filament if the clusters:

- are close together
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- using ML (later)
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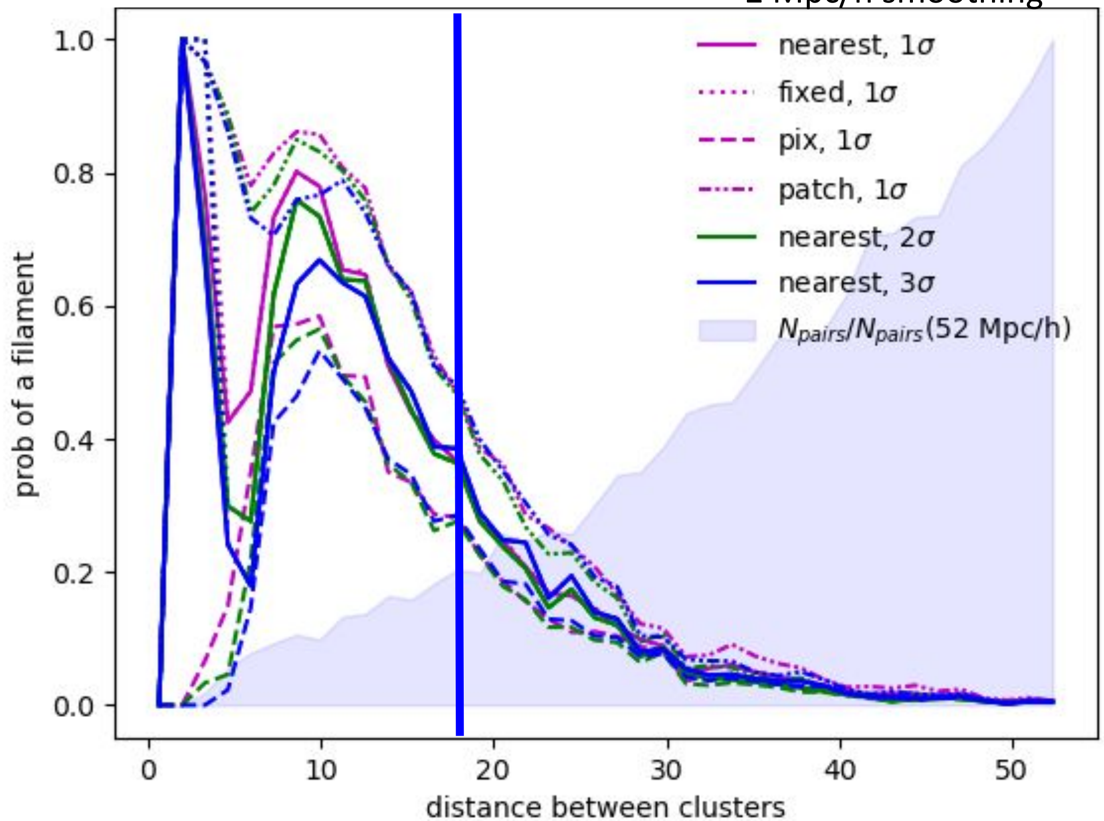
2 Mpc/h smoothing



For this 2 Mpc/h smoothing, median length for filaments matched to cluster pairs is about 18 Mph/h
(all filaments, median length~ 16 Mpc/h)

Profiles: on average, enhanced around cluster pairs (on axis)

Pairs < 40, 50, 60 Mpc/h

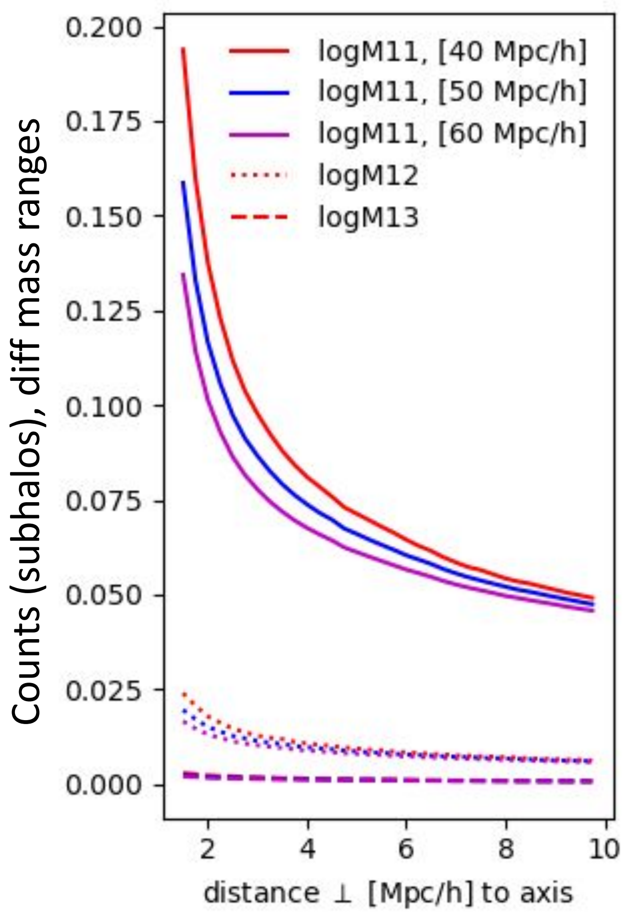
subhalo/halo mass ranges

10^{11} - 10^{12} M_o □

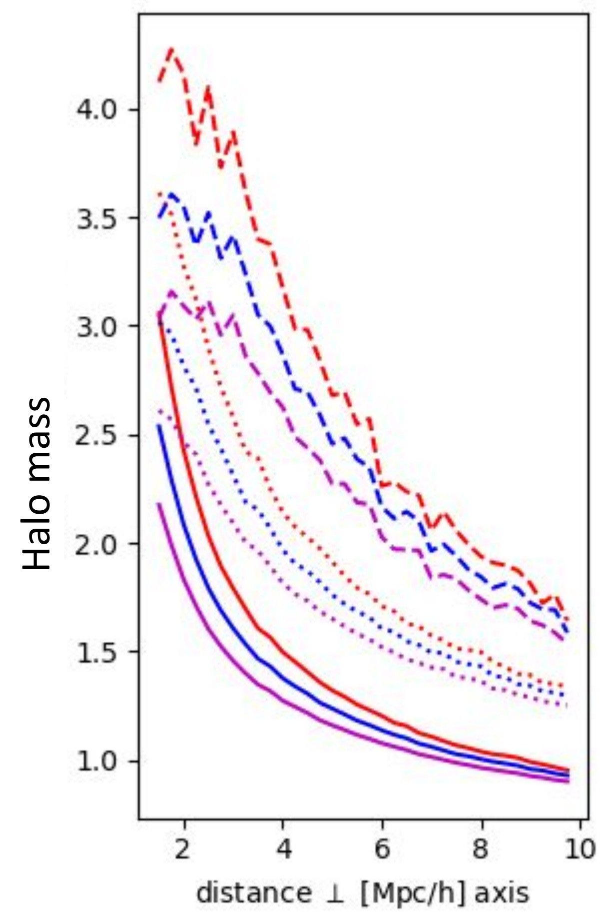
10^{12} - 10^{13} M_o ----

10^{13} - 10^{14} M_o ---

Counts (gal subhalos)



Mass (halo centers)



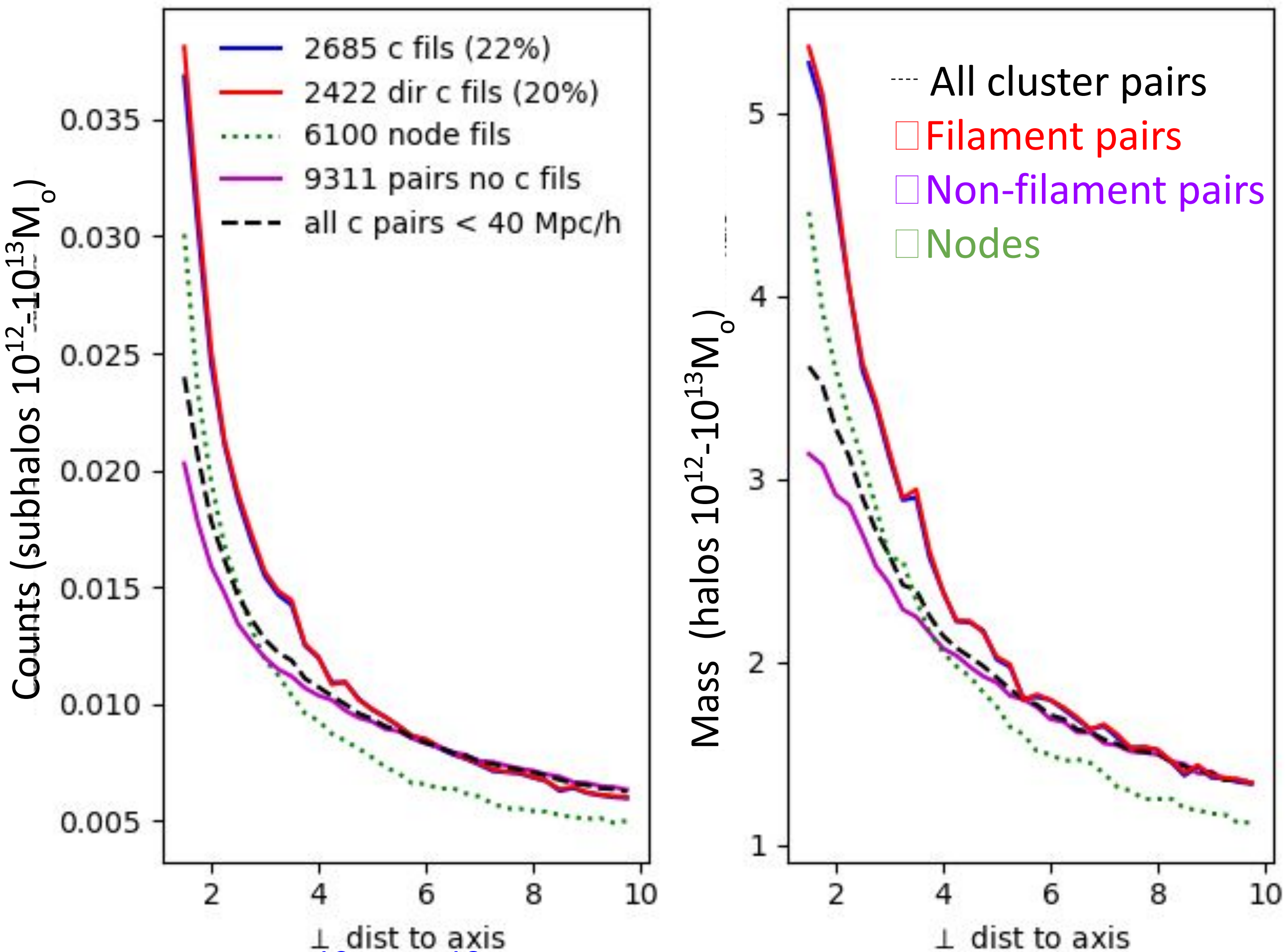
Profiles: density enhanced even more, on average, for filaments!

Different profiles:
-all cluster pairs
-filament pairs
-non-filament pairs
-nodes

from 2 Mpc/h, 3σ persistence web

profile ~ 1/r

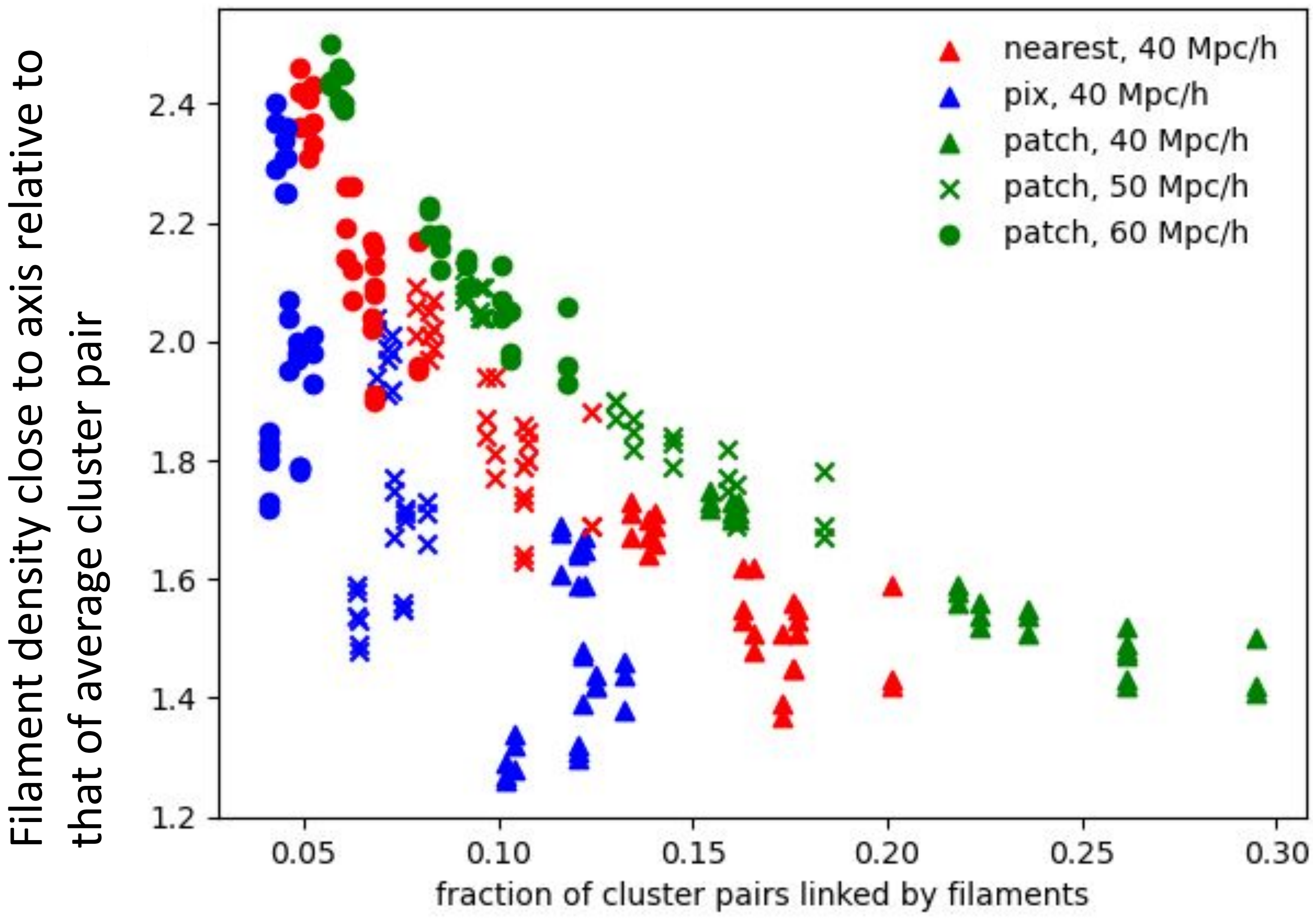
Counts (gal subhalos) Mass (halo centers)



10^{12} - $10^{13}M_o$, pairs < 40 Mpc/h

Filament density enhancement relative to all cluster pairs (@ max) for different webs, matching methods, max pair lengths

As might be expected, when *fewer cluster pairs* are assigned filaments, the cluster filament pair profile is *more enhanced* relative to all cluster pairs

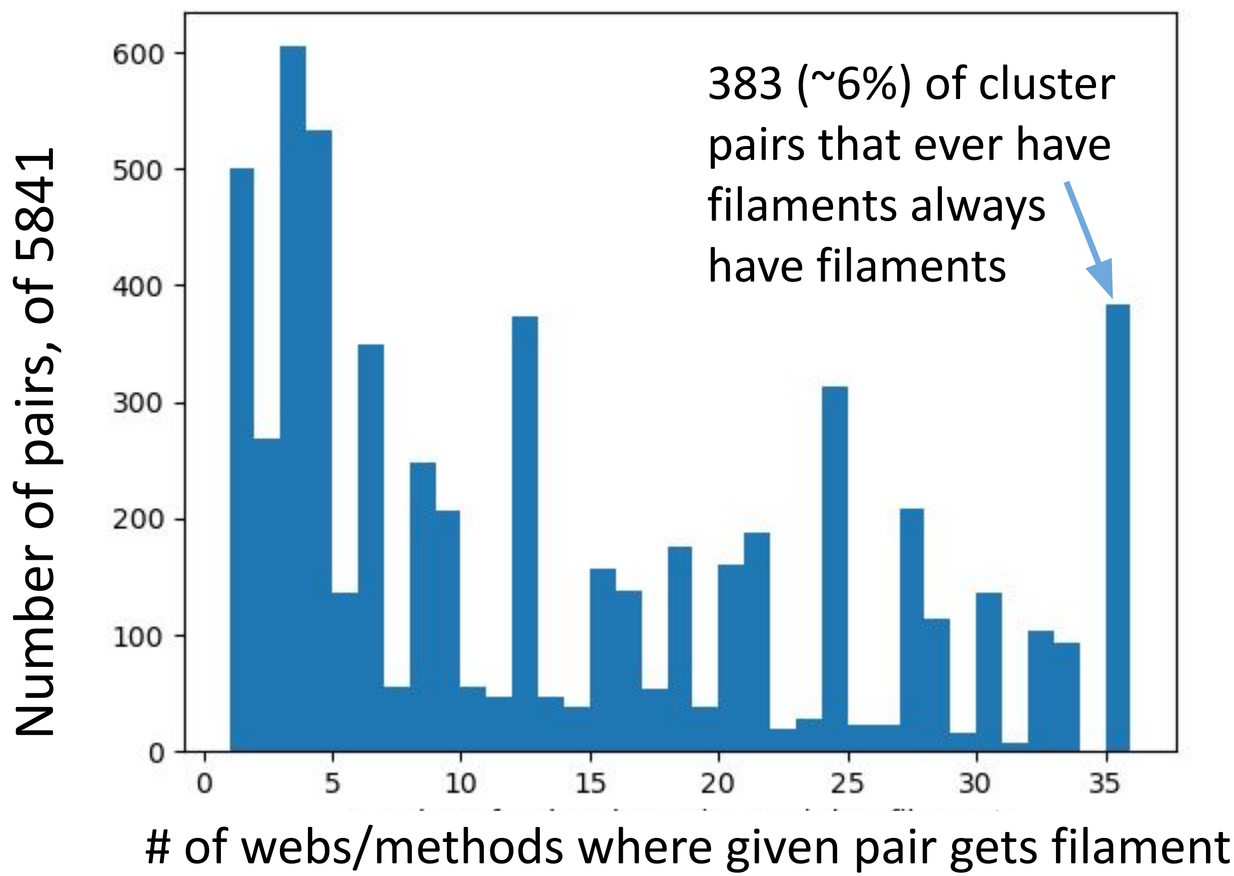


Different webs/matching→
(Before: different clusters get nodes)
Here: different cluster pairs get filaments

Clusters to nodes:
¾ of clusters always matched to nodes

Cluster pairs to filaments:
< 1/10 pairs which always match to filaments

(383 of 1400-3500 pairs always get filaments)



Filaments as operation on cluster pairs

Large scale filaments in a web$\longrightarrow$ map on cluster pairs

Have 11996, 20906, and 33842 pairs < 40 Mpc/h, 50 Mpc/h, 60 Mpc/h, respectively

Easy to set up as ML problem:

- each pair gets 1 (filament) or 0 (no filament)
- out of box algorithms not very successful for these filaments
  - misclassified 6%-12% of cluster pairs
  - inputs: distance, cluster axes dot product, cluster axes dot product with long axis, cluster density,etc.

    (only use properties of cluster population)

Clusters and other webs?

Beyond Disperse:

Sometimes hard to compare webs to each other

Change webs–cluster pairs are fixed, but connectivity and matching to nodes change

- Can use clusters & cluster pairs to compare webs to each other, fixed reference point
- Useful if consistent mapping to clusters used (doesn't have to be ones suggested here)

[Again, there are a ton of different web definitions, in part, because there are a ton of different web uses.]

Directions

- More properties of this restricted web?
- Different webs:
  - Use level instead of persistence
  - Drop lower persistence webs when look for filaments that persist
- Cluster pairs do indicate where mass density will likely go
  - How much can one infer from pairs-> filaments, etc?*
    - How much of rest of mass distribution? Shear field?
- Build up web? Go below cluster mass:
  - some halos will be most massive halo near a node–which ones?

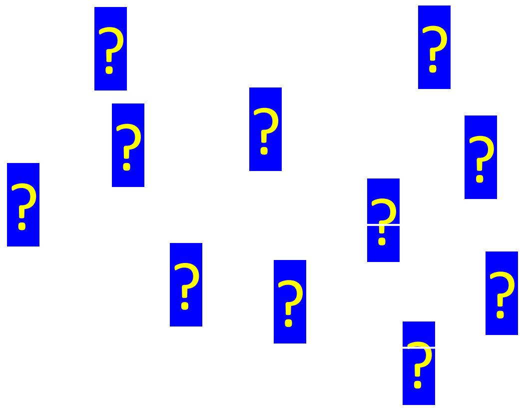
*Note: can reconstruct web from clusters other ways

- Use clusters to get initial conditions & evolve → everything

  (Bos, van de Weygaert, Kitaura, Cautun '16, esp. clusters; also via ic: Leclercq, Lavaux, Jasche,Wandelt '16

Just trying reductionist approach here to see how far it can go….

Cartoon idea

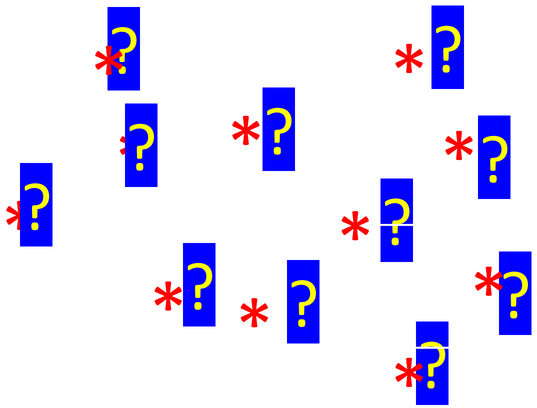


Start with clusters

✶ = Massive nodes, —— = filament ?? clusters

(Note: some overdensities might be projection)

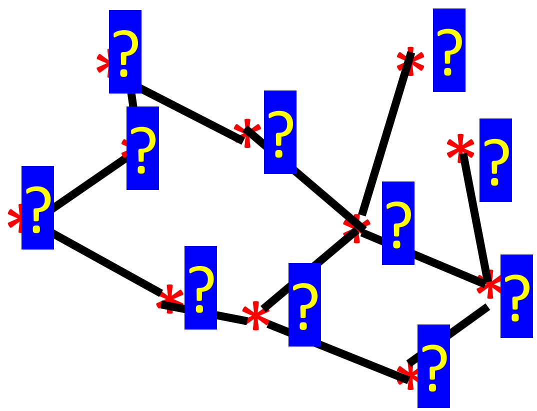
Cartoon idea



Start with clusters
Most massive *likely* to be nodes

✶ = Massive nodes, —= filament ?? clusters
(Note: some overdensities might be projection)

Cartoon idea

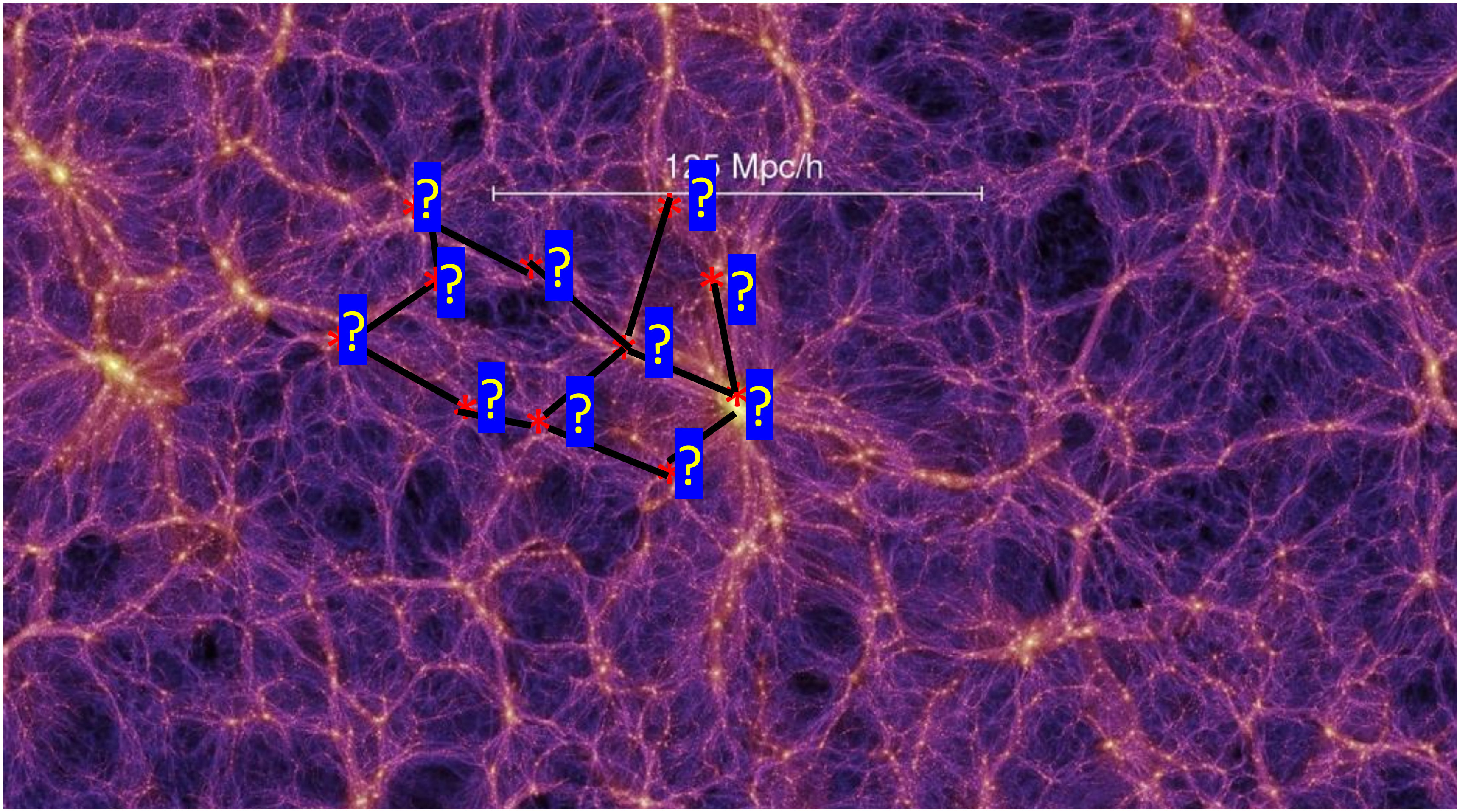


Start with clusters
Most massive *likely* to be nodes
Clusters close by often connected by filaments…
But often not, and over half of the filaments aren't to close-by clusters

* = Massive nodes, — = filament ?? clusters

(Note: some overdensities might be projection)

Cartoon idea



✶ = Massive nodes, —— = filament ?? clusters?

(Note: some overdensities might be projection)

Started with:

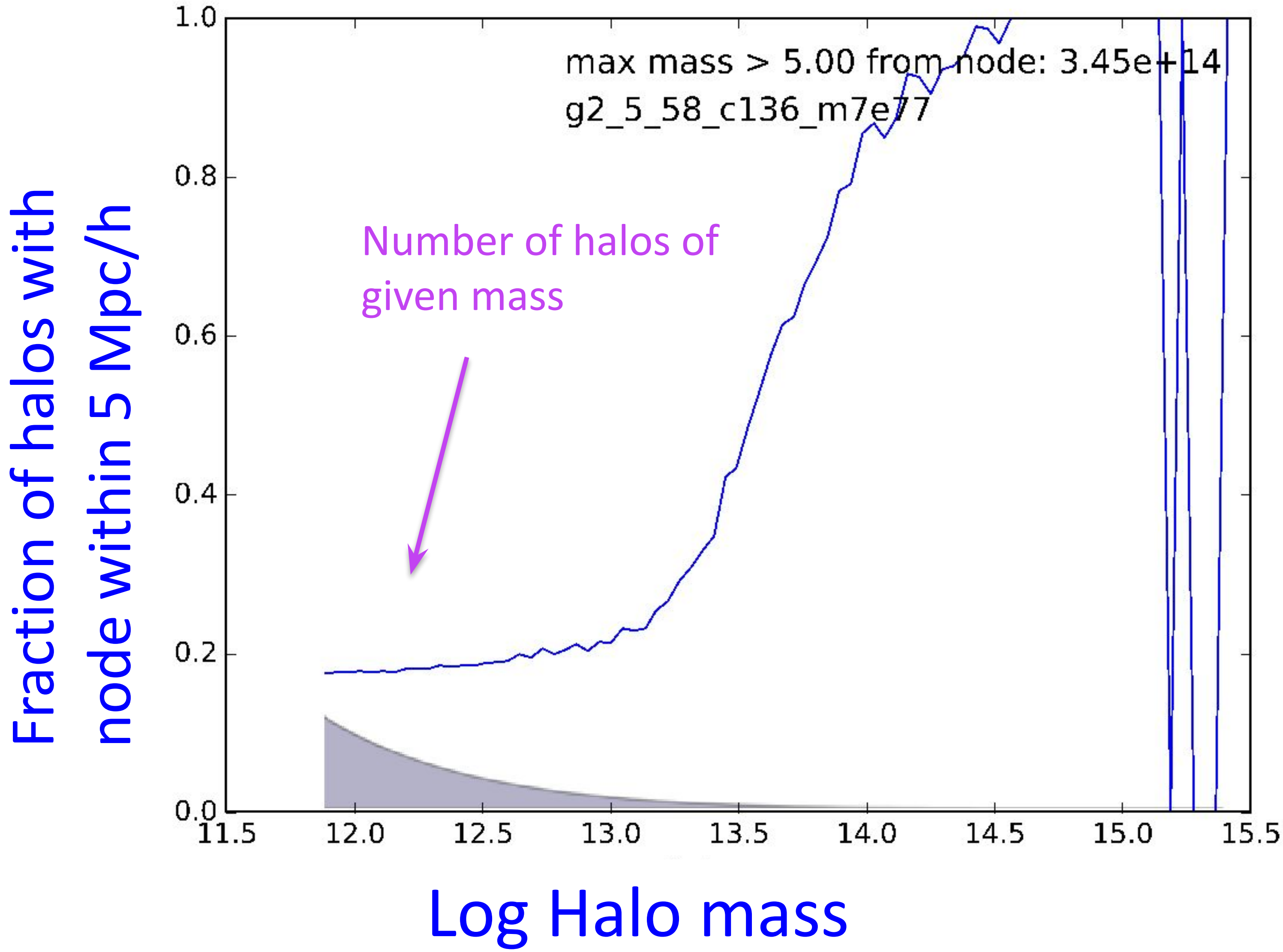
Webs		Halos in web
nodes	↔	clusters
&		↓
filaments	↔	cluster pairs w/filaments

Some points:

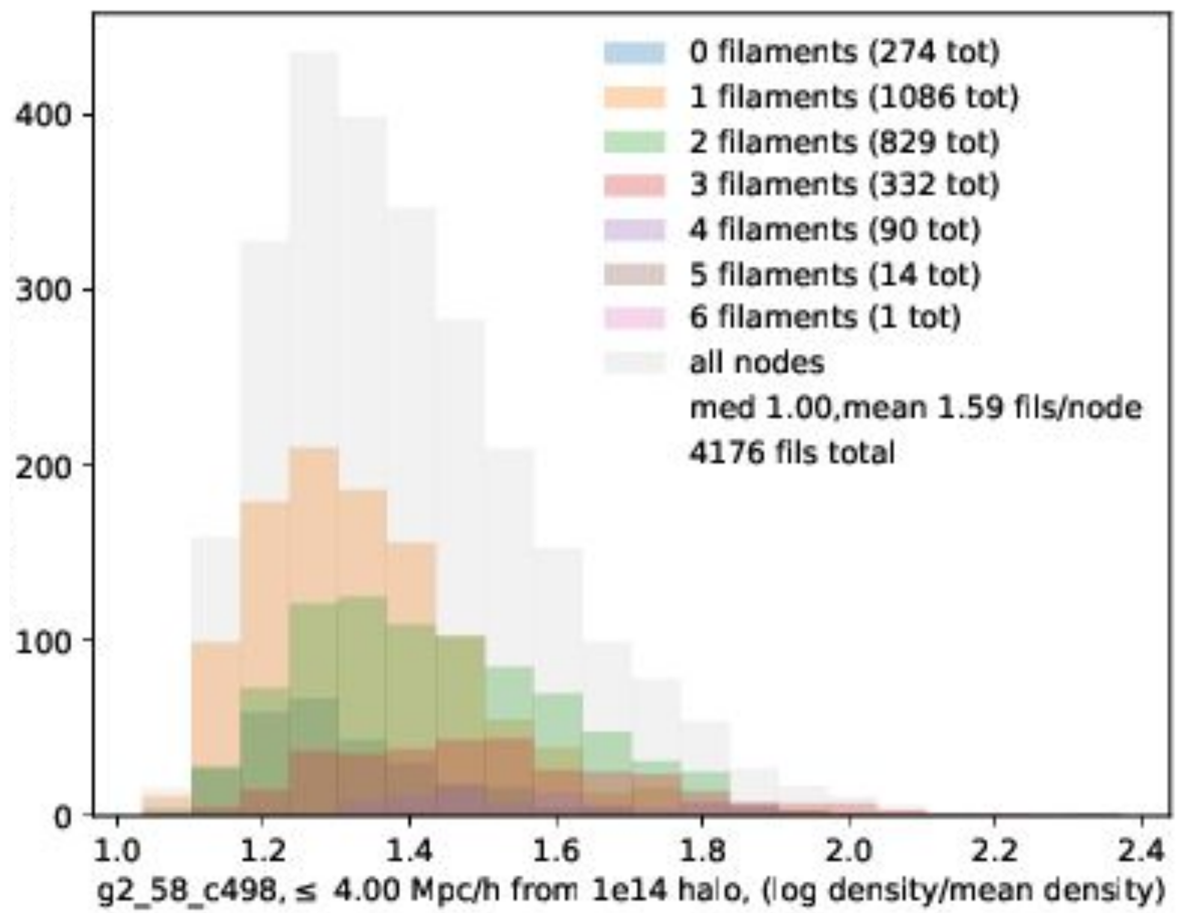
- Most, but not all clusters match to nodes, across different webs
  - high mass clusters more likely, cluster mass ~ node density
- Cluster pairs have enhanced average density profile, filament pairs even more so, but which cluster pairs are assigned filaments varies significantly as webs vary
- higher density nodes & filaments more likely to match to clusters & cluster pairs
- web restricted to clusters very sparse!

Thank you!

Completeness?
Fraction of halos with "nearby" node
(Disperse pixel based web,smoothing 2.5 Mpc/h)



connectivity of “matched” nodes to other “matched” nodes **only**



Number of nodes (of 2588 matched)

log (pixel density/mean density)