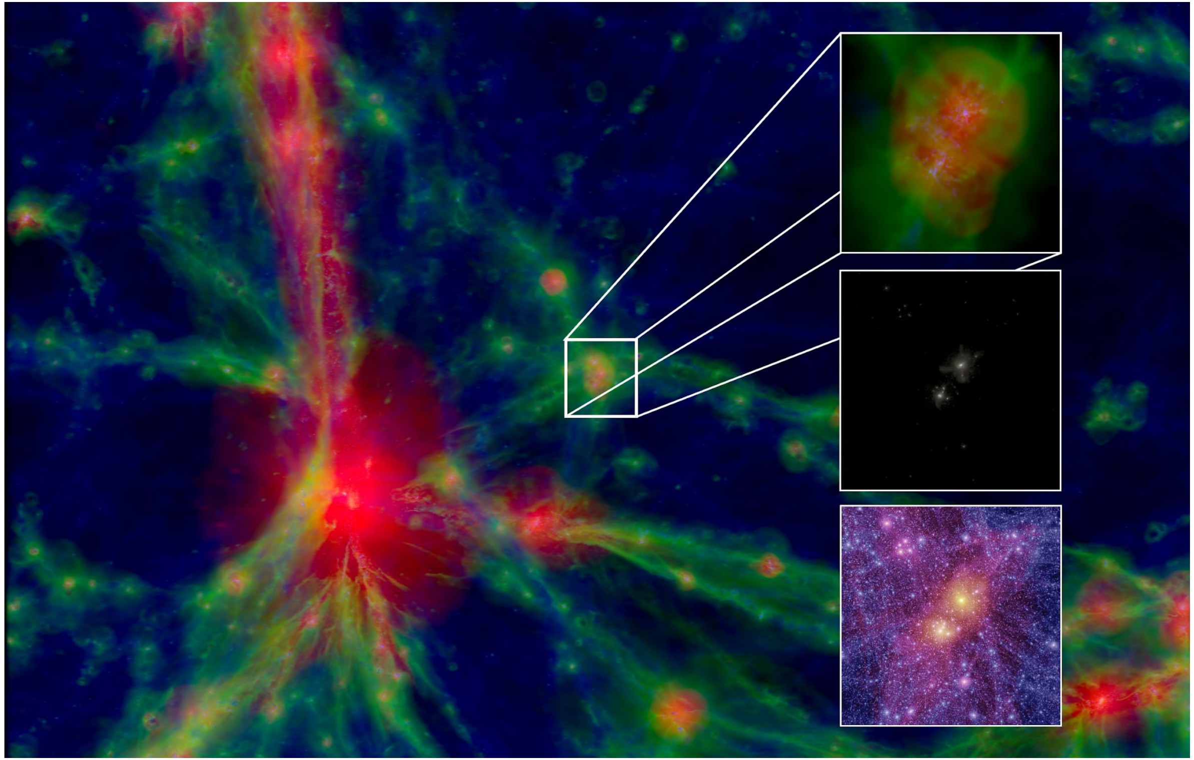
Cosmic web or cosmic variance?

The impact on the large-scale environment on various dark matter observables



Credit: EAGLE simulation & The VIRGO consortium

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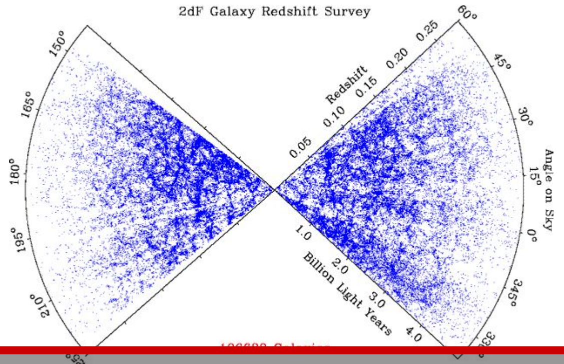
Feven Markos-Hunde

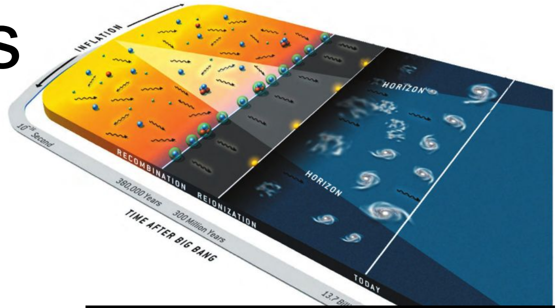
Oliver Newton

Maciej Bilicki

From smooth background to specks

WMAP Cosmological Parameters Model: lcdm Data: all		
$10^2\Omega_b h^2$	=	$2.19^{+0.06}_{-0.08}$
A	=	$0.67^{+0.04}_{-0.05}$
$A_{0.002}$	=	$0.81^{+0.04}_{-0.05}$
$\Delta^2_{\mathcal{R}}$	=	$(20 \times 10^{-10} \pm 1 \times 10^{-10}) \times 10^{-10}$
$\Delta^2_{\mathcal{R}}(k = 0.002/Mpc)$	=	$(24 \times 10^{-10}{}^{+1\times10^{-10}}_{-2\times10^{-10}}) \times 10^{-10}$
h	=	$0.71^{+0.01}_{-0.02}$
H_0	=	71^{+1}_{-2} km/s/Mpc
ℓ_A	=	$303.0^{+0.9}_{-1.3}$
n_s	=	$0.938^{+0.013}_{-0.018}$
$n_s(0.002)$	=	$0.938^{+0.012}_{-0.023}$
Ω_b	=	$0.044^{+0.002}_{-0.003}$
$\Omega_b h^2$	=	$0.0220^{+0.0006}_{-0.0008}$
Ω_c	=	$0.22^{+0.01}_{-0.02}$
Ω_Λ	=	0.74 ± 0.02
Ω_m	=	$0.26^{+0.01}_{-0.03}$
$\Omega_m h^2$	=	$0.131^{+0.004}_{-0.010}$
r_s	=	148^{+1}_{-2} Mpc
b_{SDSS}	=	$0.95^{+0.05}_{-0.06}$
σ_8	=	$0.75^{+0.03}_{-0.04}$
$\sigma_8\Omega_m^{0.6}$	=	$0.34^{+0.02}_{-0.03}$
A_{SZ}	=	$0.78^{+0.23}_{-0.78}$
t_0	=	$13.8^{+0.1}_{-0.2}$ Gyr
τ	=	$0.069^{+0.026}_{-0.029}$
θ_A	=	0.594 ± 0.002 °
z_{eq}	=	3135^{+85}_{-159}
z_r	=	$9.3^{+2.8}_{-2.0}$





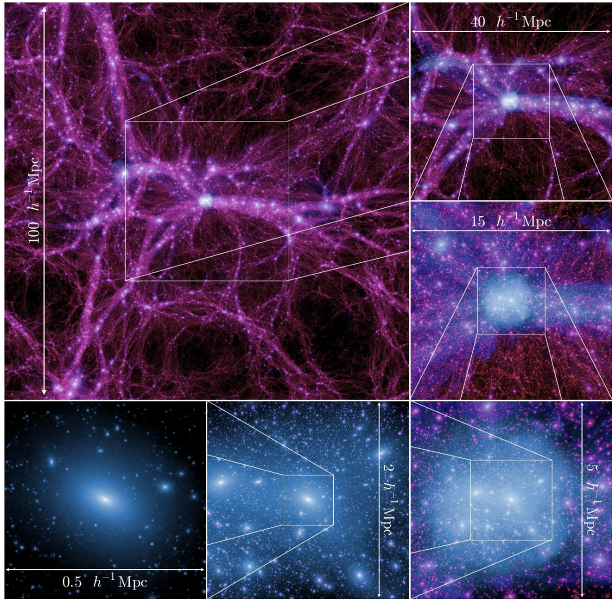
Non-relativistic (remnant) gravitating Dark Matter?

The initial conditions of the Universe can be summarized on a single sheet of paper, yet thousands of books cannot fully describe the complex structures we see today… Why?

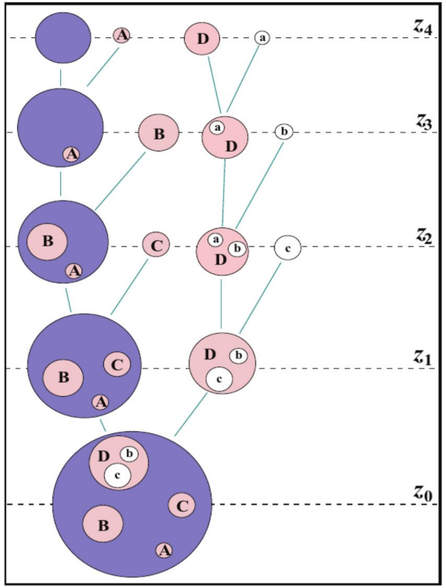
GRAVITATIONAL INSTABILITY!

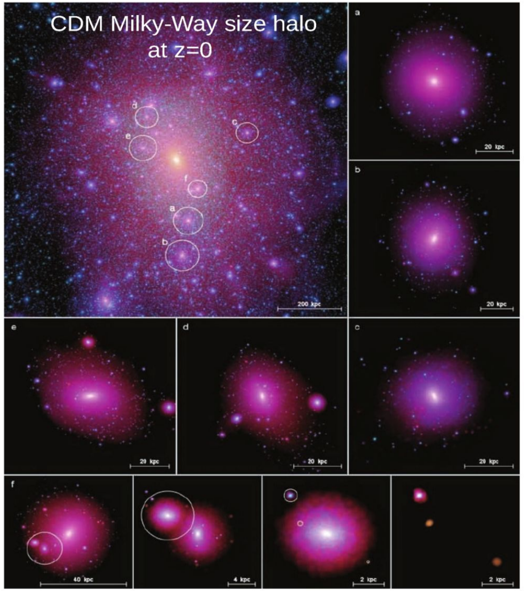
Non-relativistic DM:
- scale-free initial P(k);
- bottom-up (hierarchical) structure assembly

→ DM haloes are self-similar



Boylan-Kolchin et al. 2009





Springel et al. 2008

PROMISE: I will show you that the Cosmic Web matters dearly if you want to lower the systematic errors!

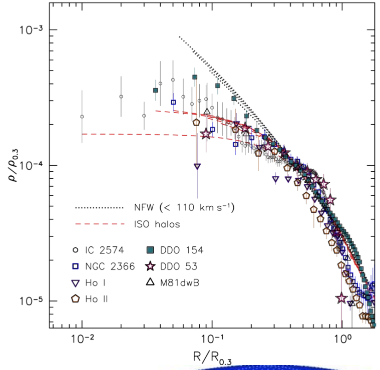
Resolving and assessing internal DM halo (and subhalo) properties is important for number of reasons:

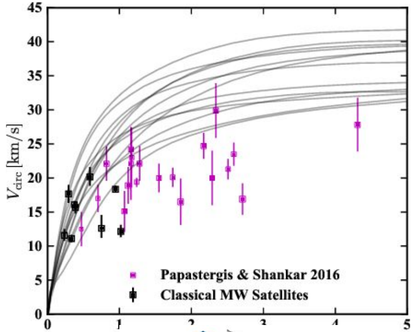
- internal halo/galaxy kinematics
  (core-cusp, too big to fail)

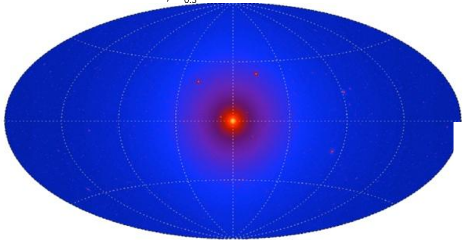
- density profiles
  (γ-rays annihilation signal, X-ray decay, strong lensing)

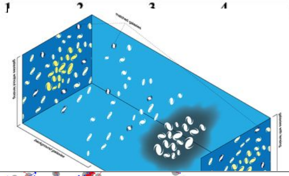
- shapes
  (weak lensing, intrinsic alignments)

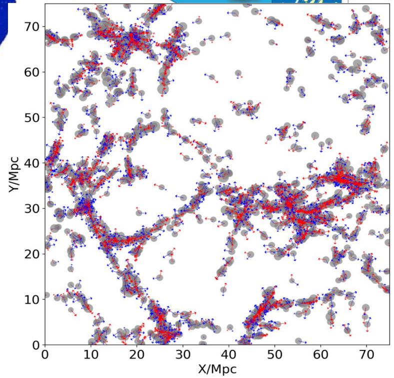
- spins
  (LSS alignment, TTT)





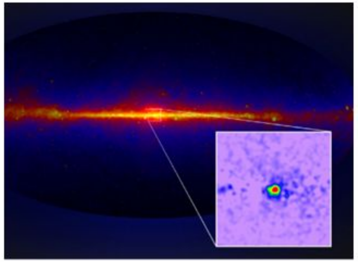




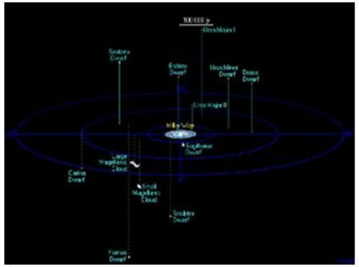


Indirect DM signals: where to look

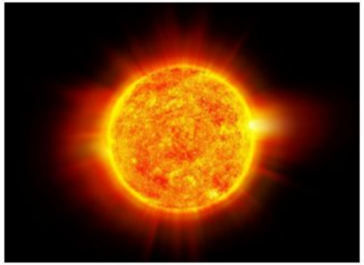
Local Cosmic Ray flux



Galactic center

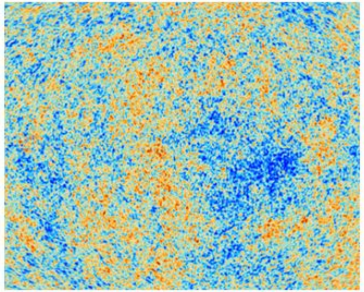


Dwarf galaxies



Solar neutrinos

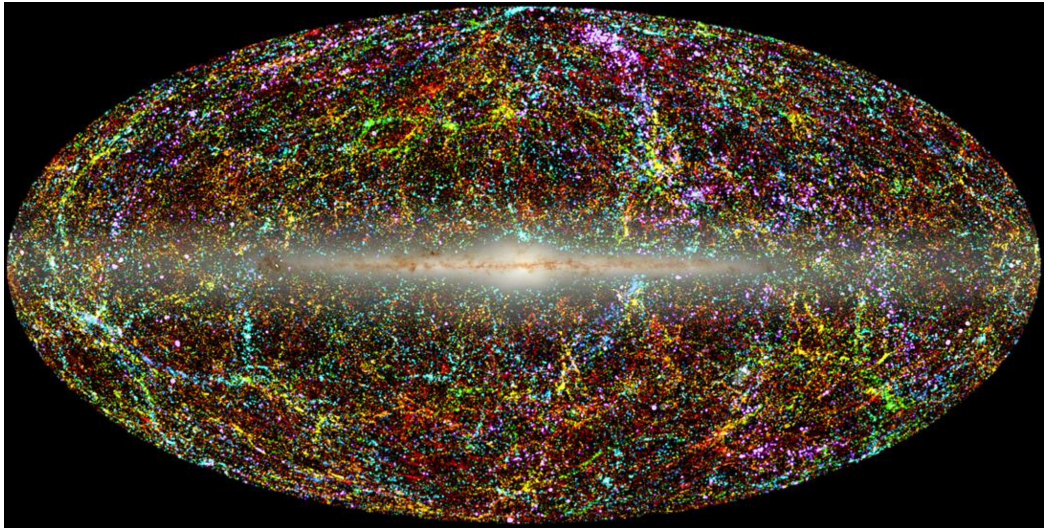
Galaxy Clusters



CMB + background light

Courtesy: Aaron Vincent

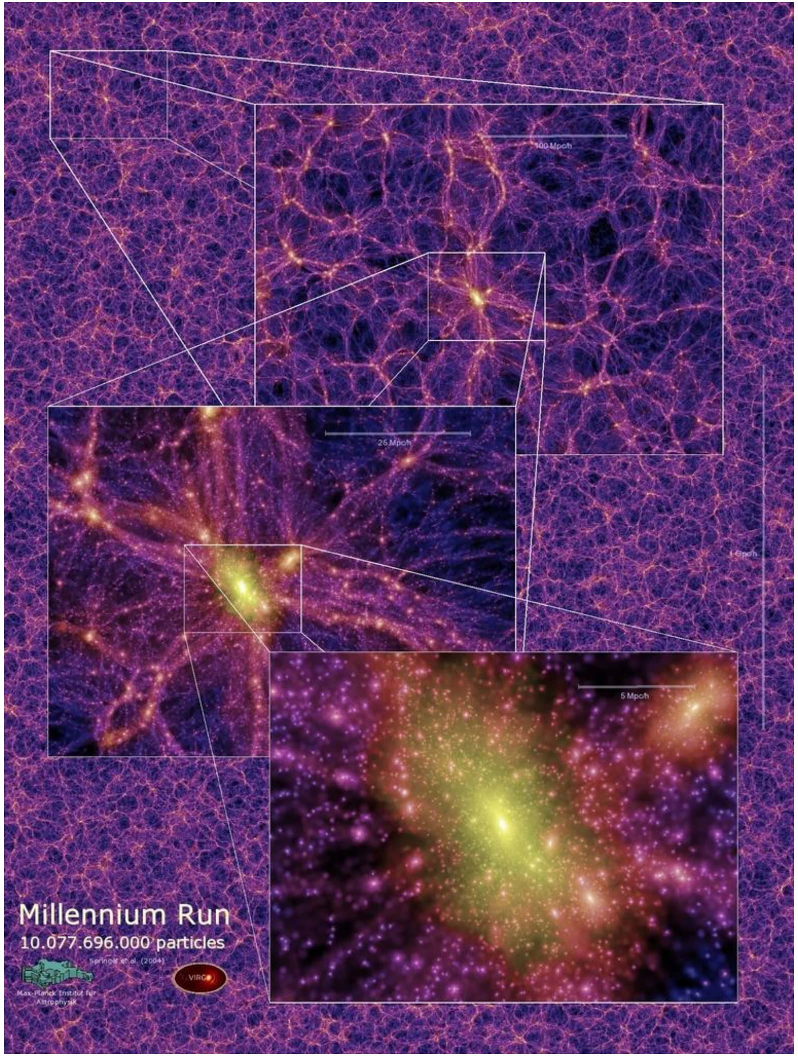
What is the Cosmic Web?



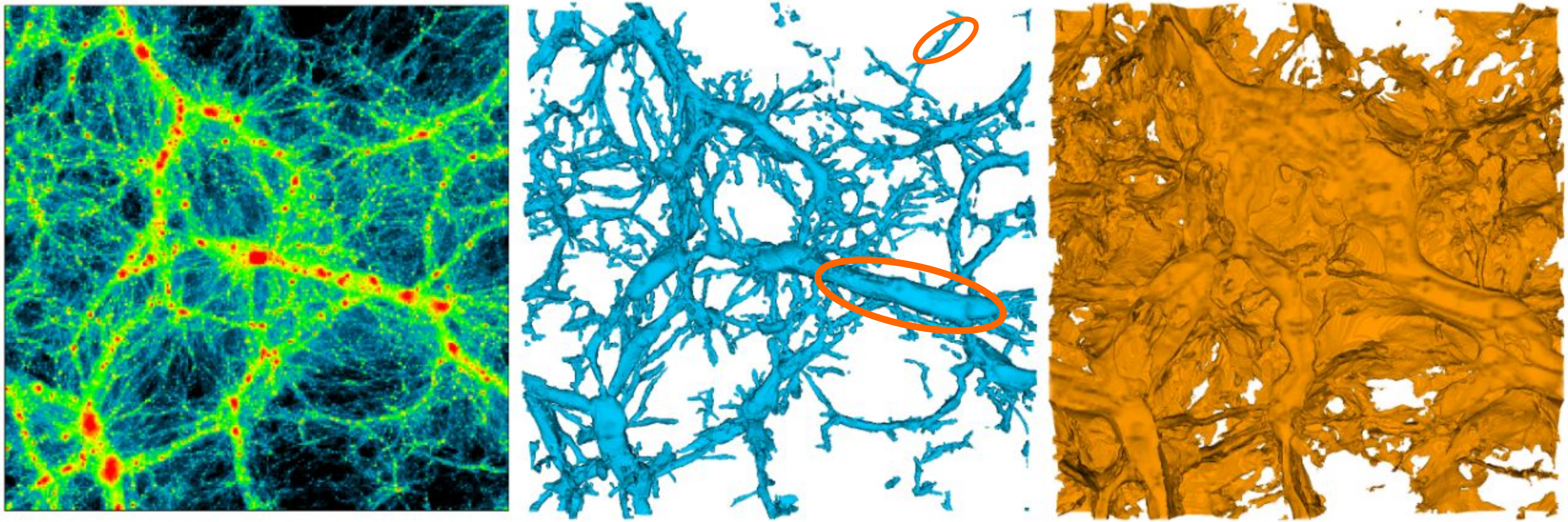
2MASS all sky (J. Huchra 2002)

Complex Web is a pattern

- emerges on Scales from ~1Mpc to 100s Mpc
- in which matter, gas and galaxies aggregate
- poses 4 main distinct “features”: **compact nodes** (galaxy clusters) connected via **elongated filaments** between which flattened **sheets** stretch, wrapping around empty **voids**.



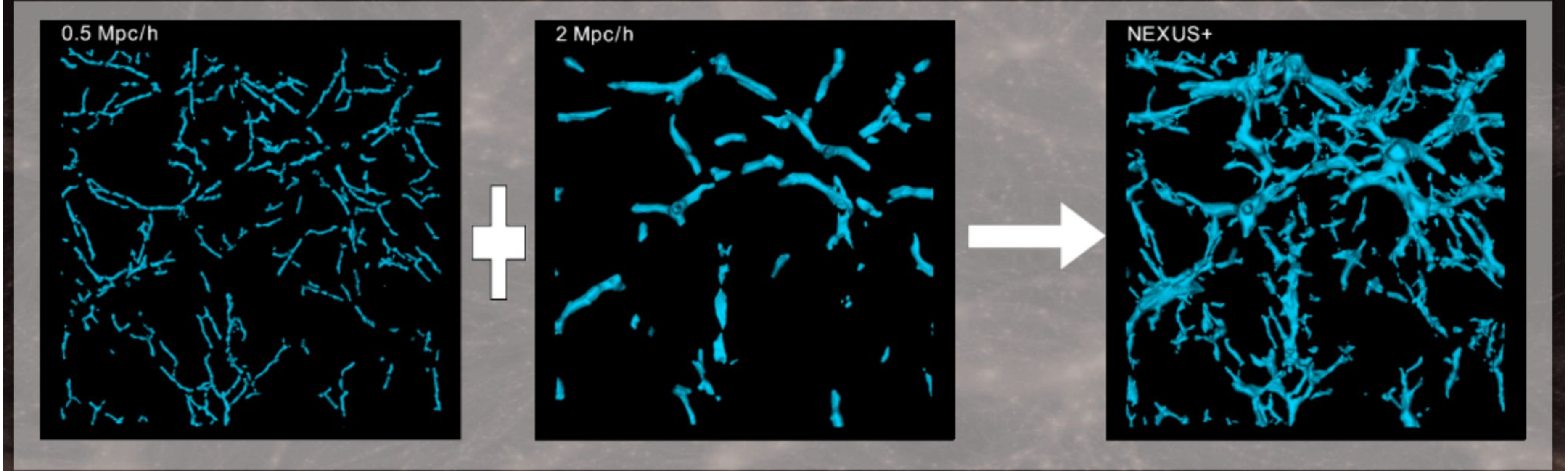
How to identify the Cosmic Web elements?



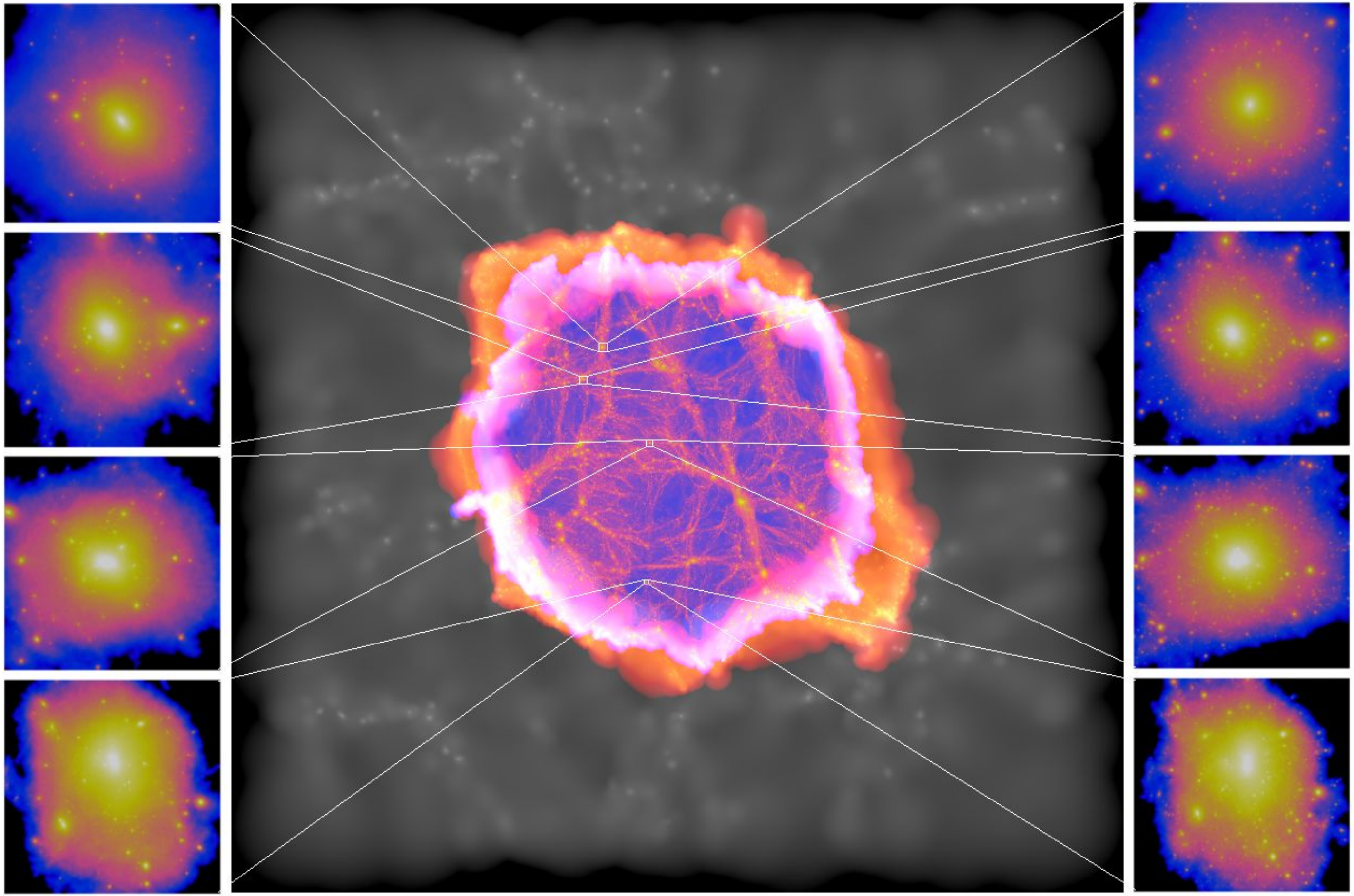
Standard answer:
use eigenvalues of density/velocity field Hessian matrix.
Pros: easy and straightforward
Cons: user dependent (scale and threshold), require fine tuning

Multi-scale approach in NEXUS (III)

Combine the webs identified at various scales into a single map.



Copernicus Complexio: zoom-in simulation suite

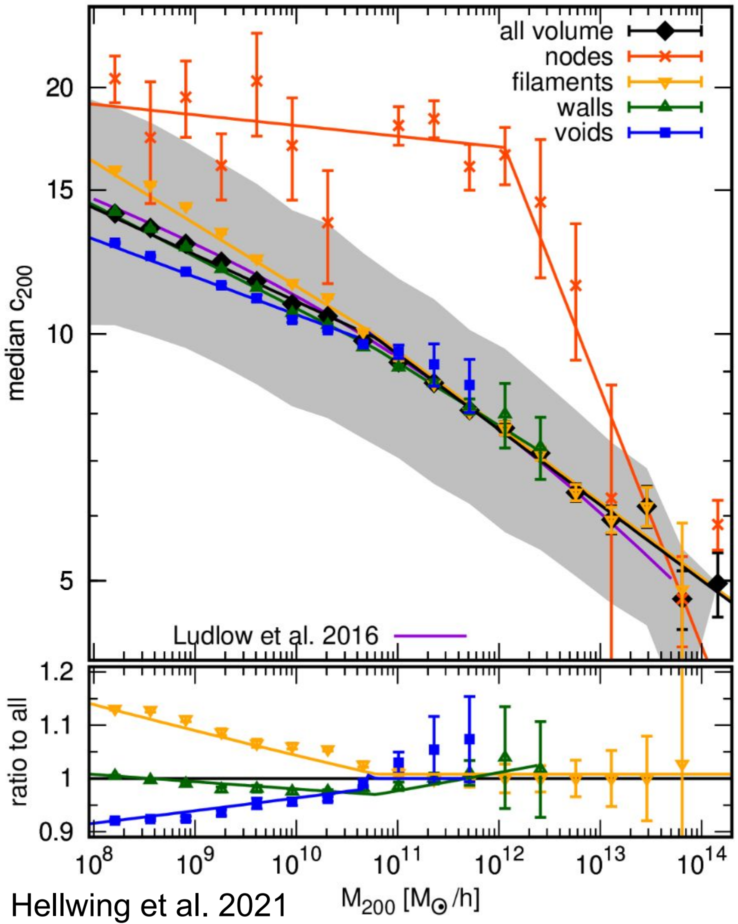


Mass resolution:
$1.35 \times 10^5 M_\odot/h$

Force resolution:
$\varepsilon = 230$ pc/h

high-res volume:
$\sim 2.2 \times 10^4 (\text{Mpc}/h)^3$

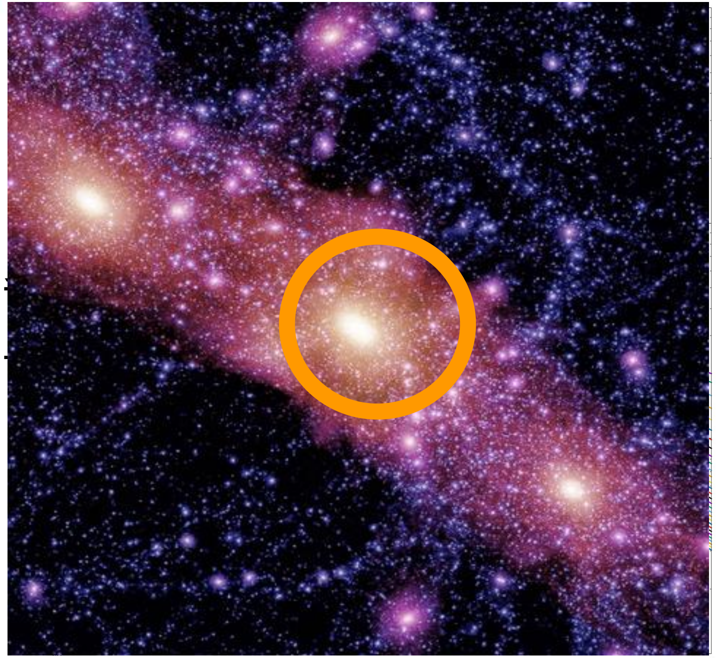
Concentration-mass: first look



Hellwing et al. 2021

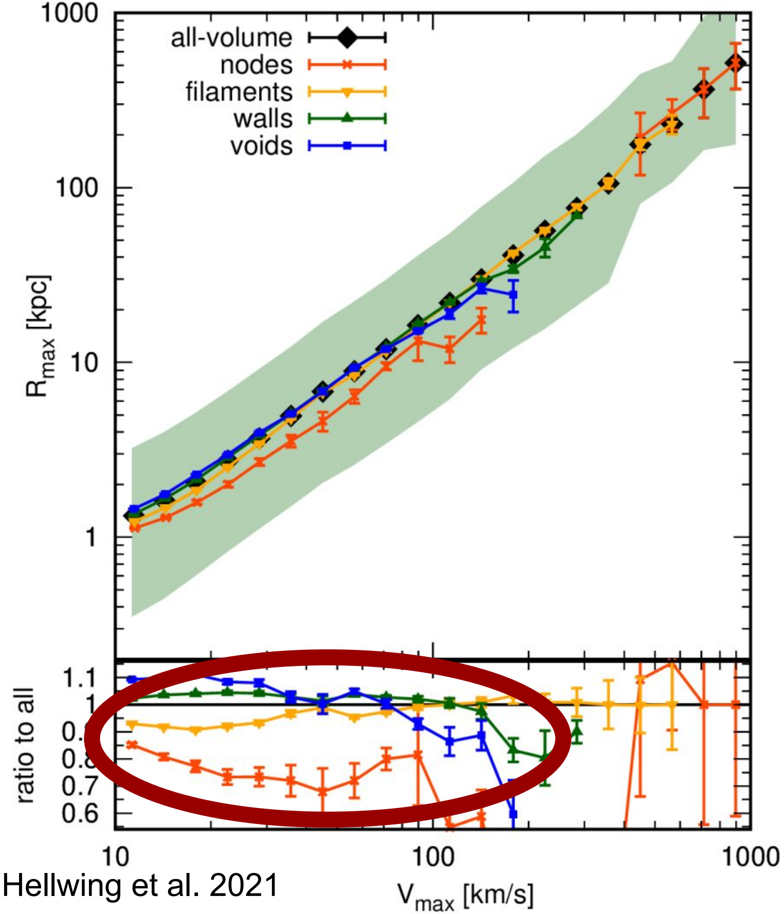
$$\rho_{NFW}(R) = \frac{\rho_0}{(R/R_s)(1+R/R_s)^2}$$

$$R_{200} = c_{200} \cdot R_s$$

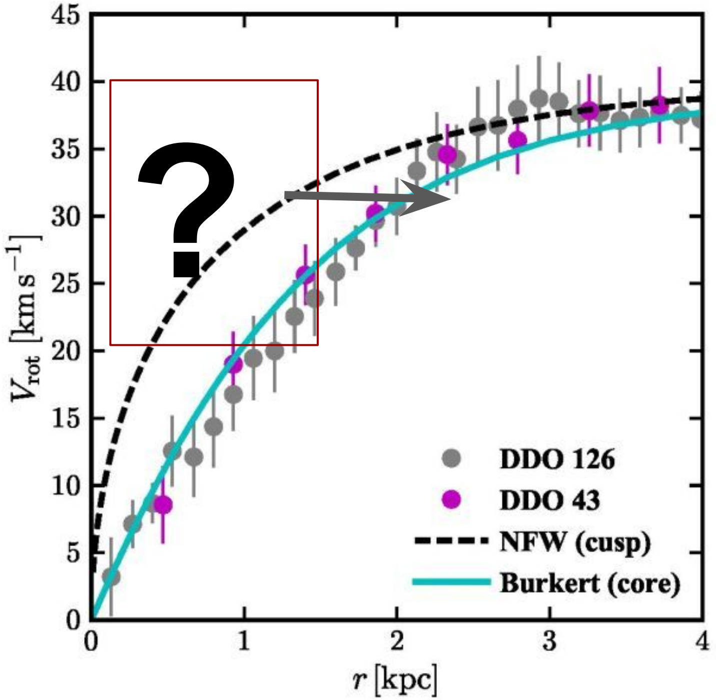


Concentration-mass: vmax-rmax

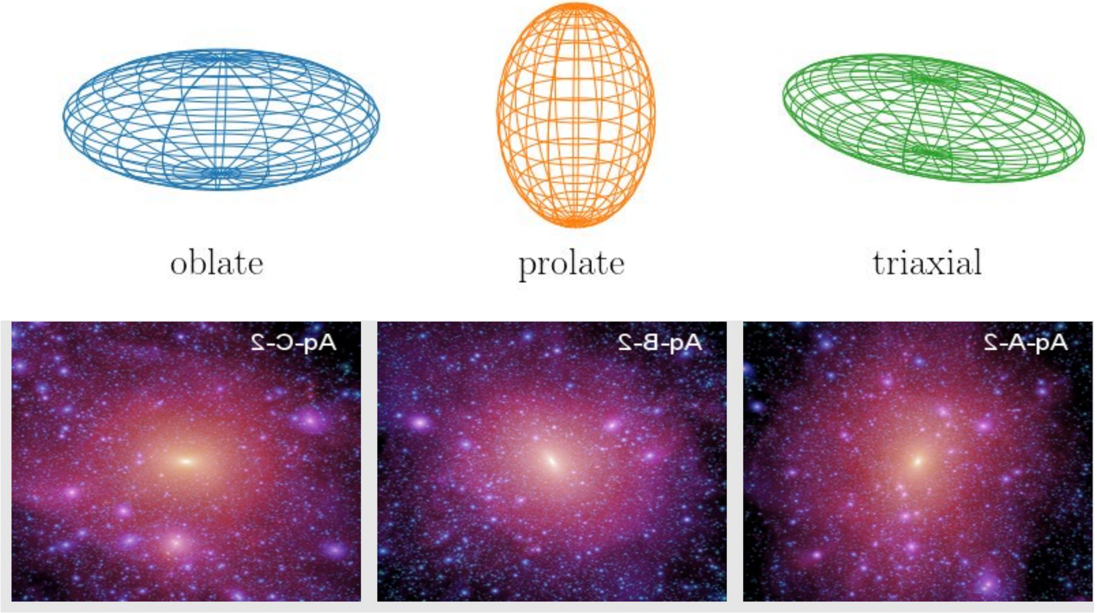
$$V_{circ}(r) = \sqrt{\frac{GM(<r)}{r}}$$

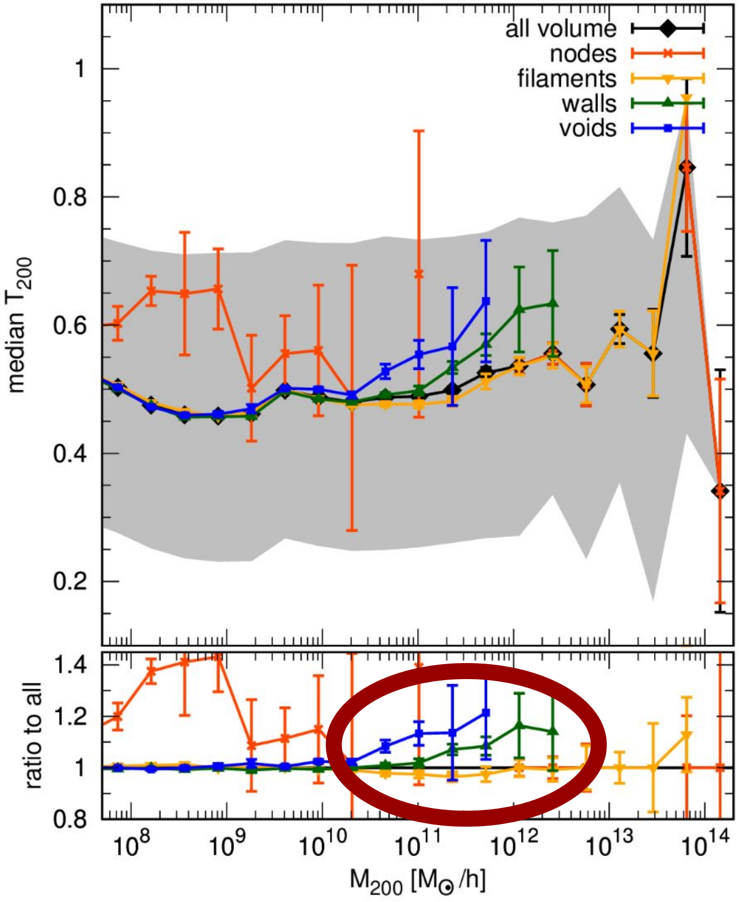


Hellwing et al. 2021

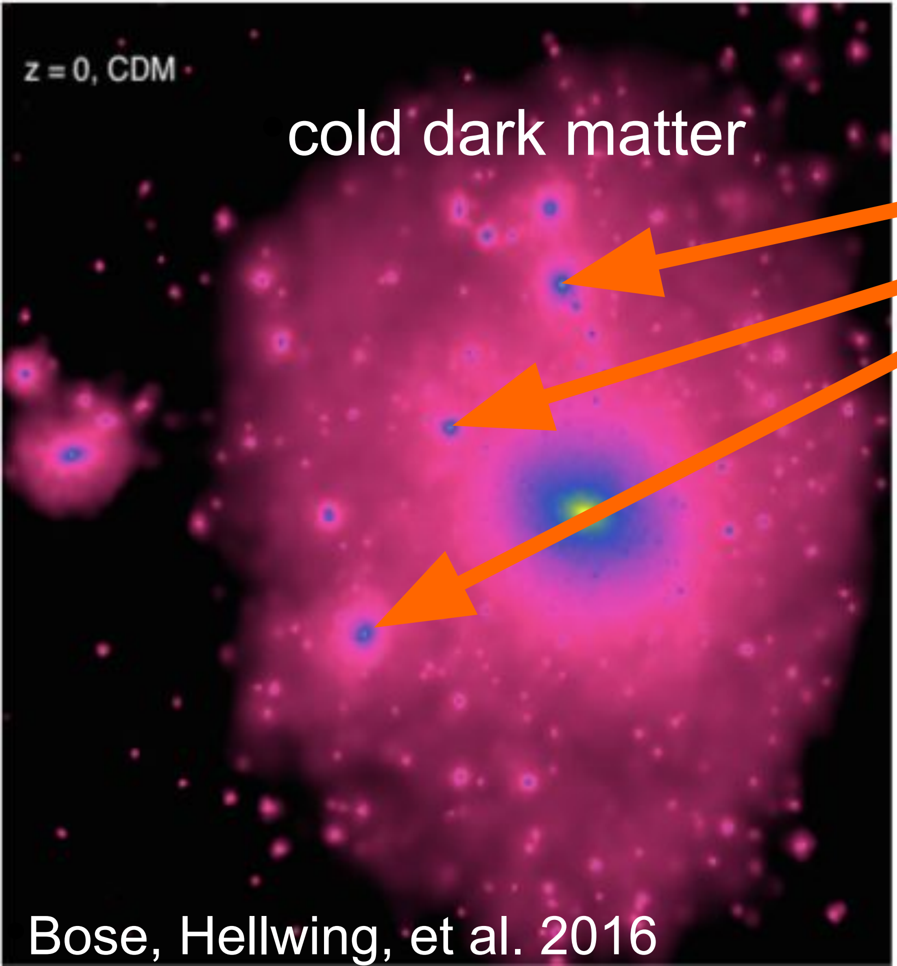


Shape-web effect has a different nature though…





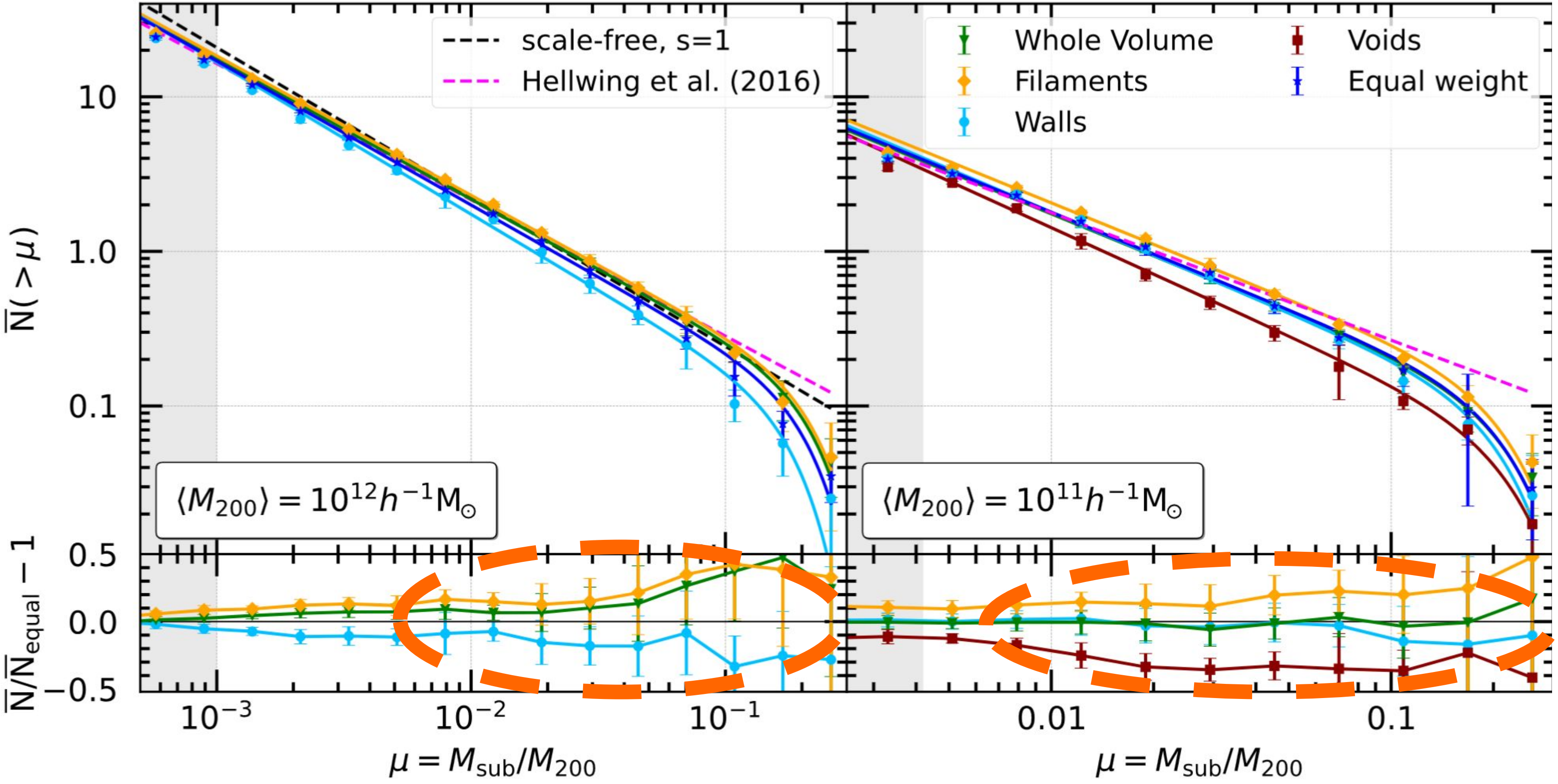
Bonus track: subhaloes (means satellites!)



MW satellites would reside in DM subhaloes. The numbers and properties of those we can predict from simulations.

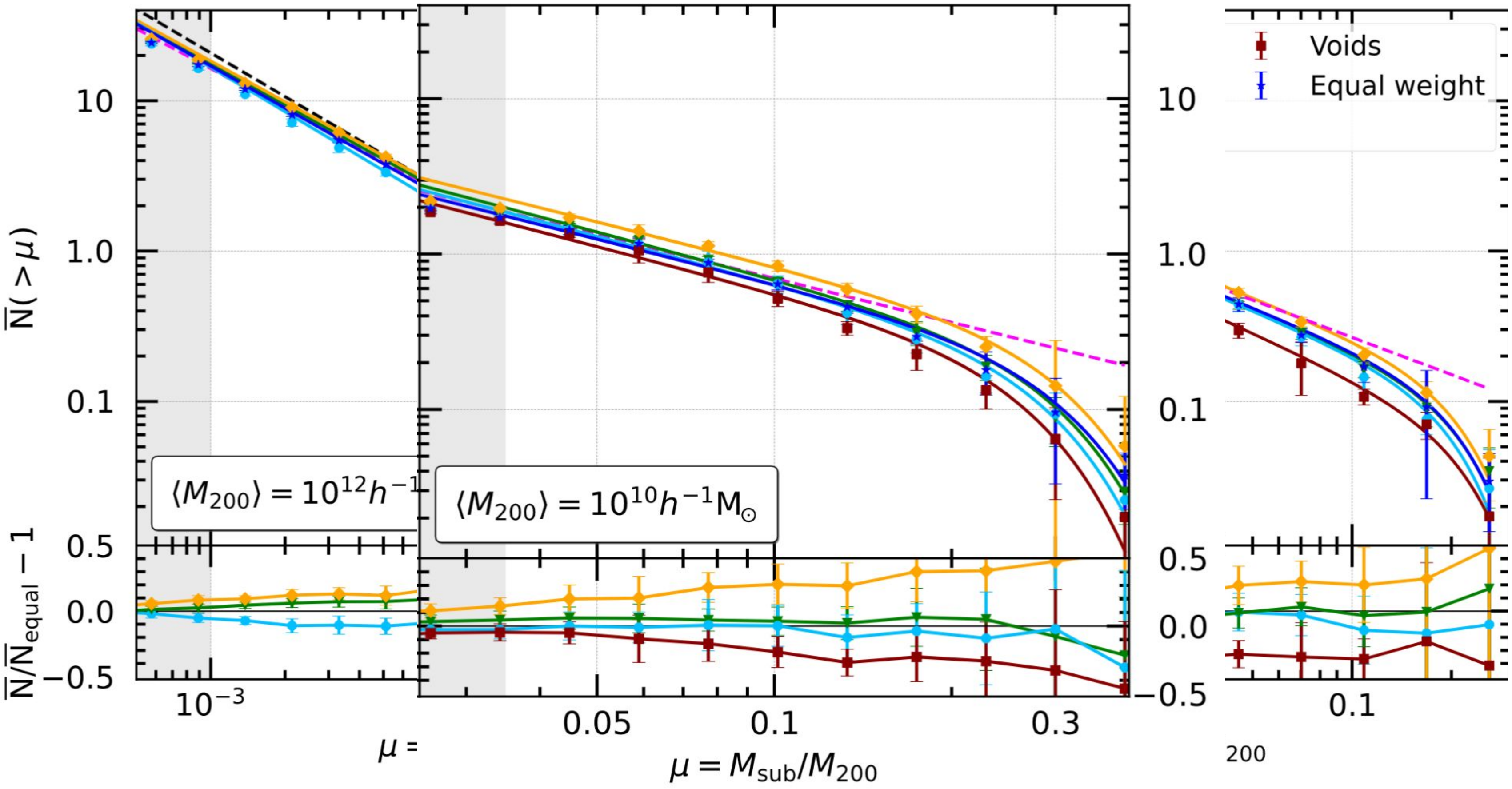
Project() in development with my PhD student: **Feven Marcos-Hunde**

subhaloes in the cosmic web (abundance)



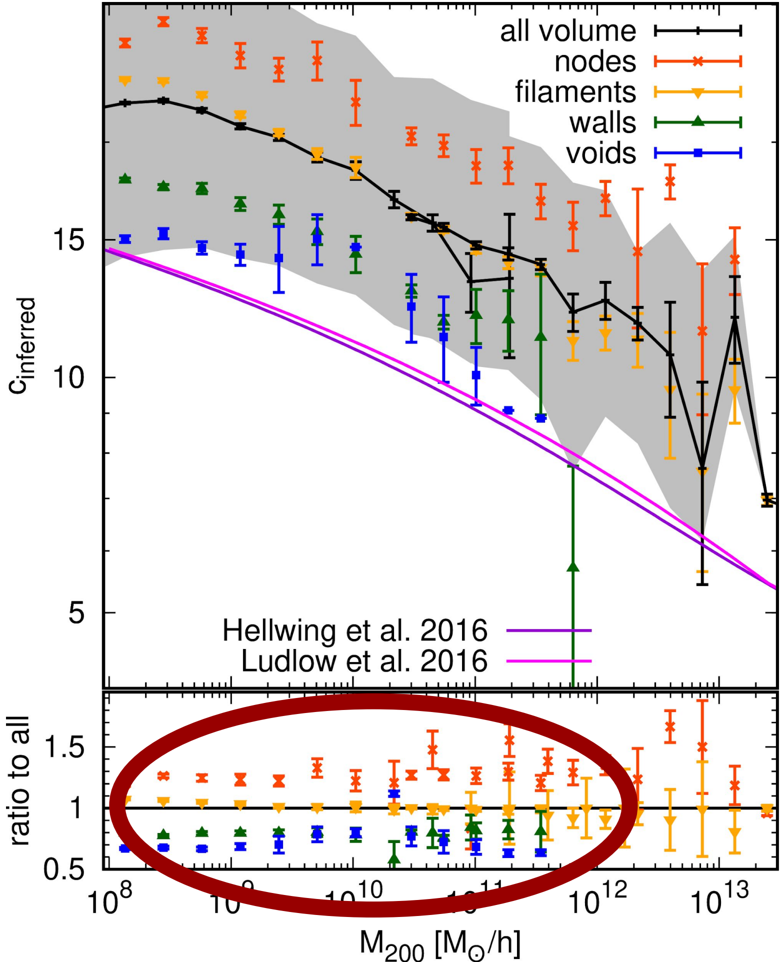
Hunde et al. (arXiv:2409.09226, submitted to A&A)

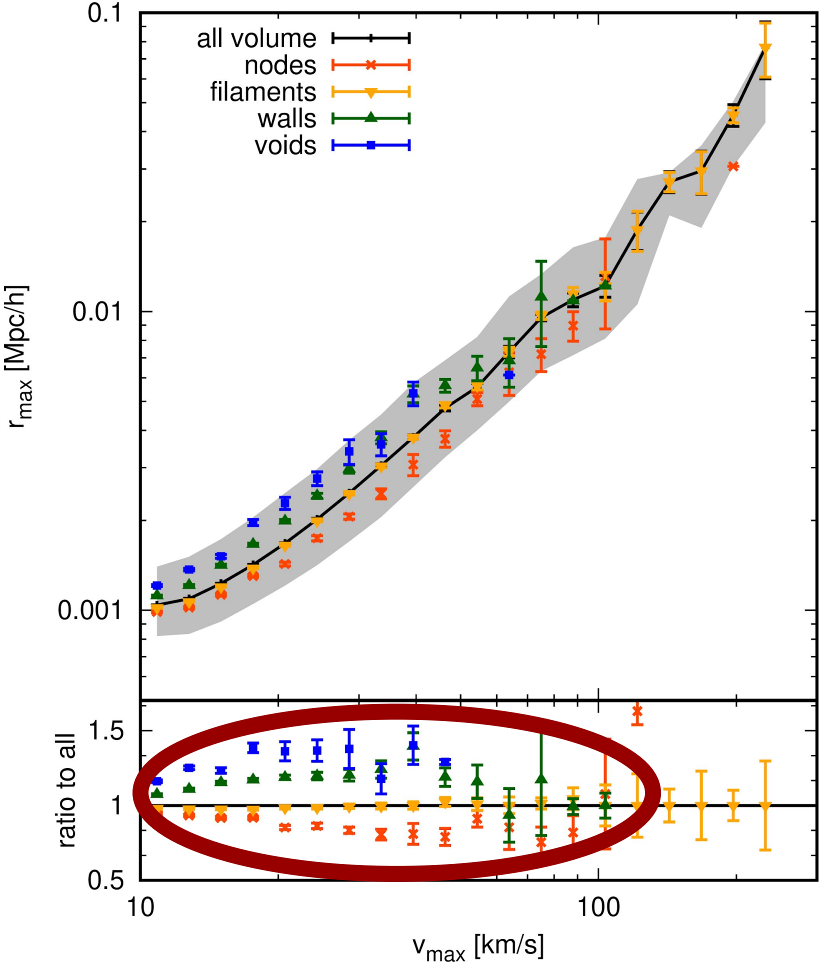
subhaloes in the cosmic web (abundance)



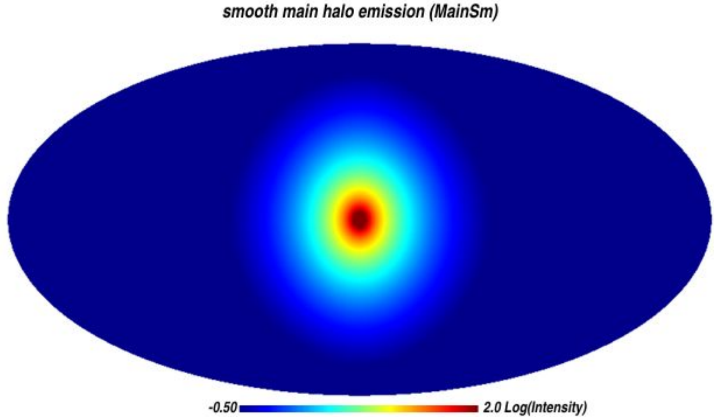
Hunde et al. (arXiv:2409.09226, submitted to A&A)

Satellites - subhaloes (compact vs loose)

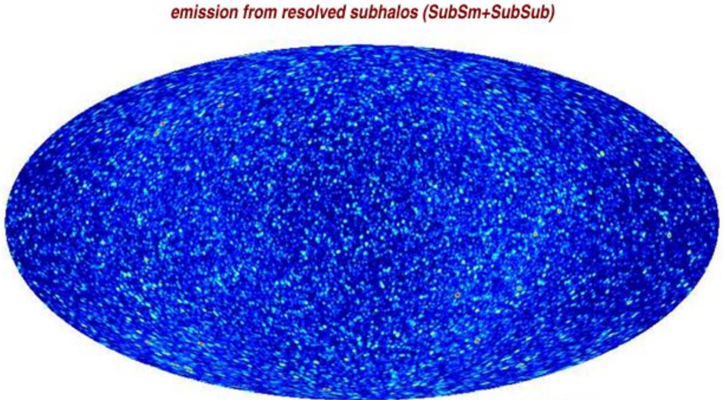


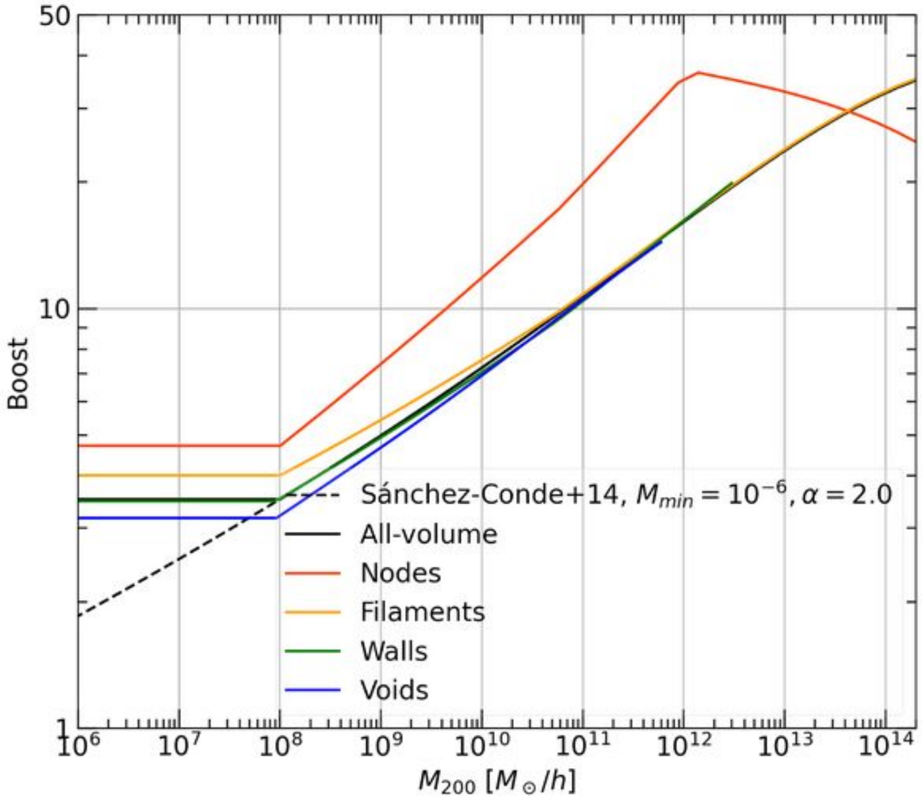


Example - effect on the ɣ-ray annihilation radiation boost factors from MW substructure



Springel et al. 2008





Markos-Hunde et al. (in prep)

Conclusions:

- DM haloes are sensitive to their environment (nature vs nurture)
- Big massive haloes resemble ‘island universes’
- Environment dependence moderate medians and variance of intrinsic properties
- DM haloes and subhaloes self-similarity is broken by CWEB
- Your (our) cosmic neighbourhood really matters!

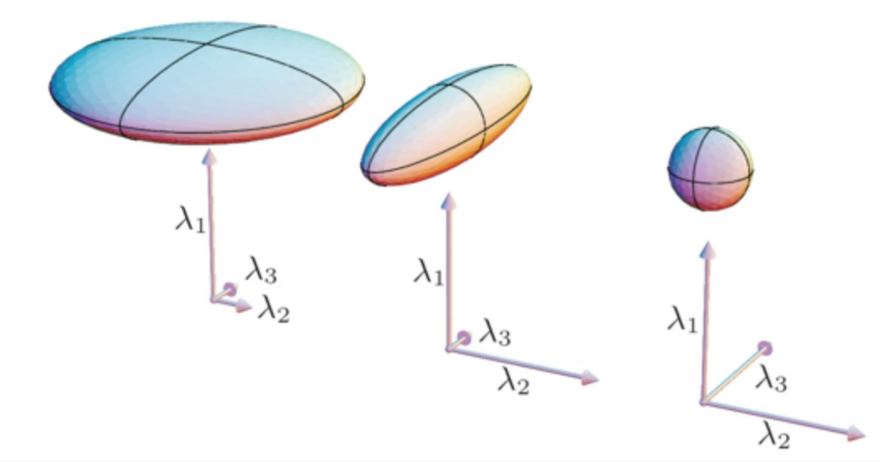
Scale Space Analysis

- Smooth the field over the range of relevant scales
- Select the characteristic scale of a particular (local) morphological element

Structure	λ ratios	λ constraints
Blob	$\lambda_1 \simeq \lambda_2 \simeq \lambda_3$	$\lambda_3 < 0$; $\lambda_2 < 0$; $\lambda_1 < 0$
Line	$\lambda_1 \simeq \lambda_2 \gg \lambda_3$	$\lambda_3 < 0$; $\lambda_2 < 0$
Sheet	$\lambda_1 \gg \lambda_2 \simeq \lambda_3$	$\lambda_3 < 0$

Nexus/MMF formalism:

Aragon-Calvo et al. 2007
Aragon-Calvo et al. 2010
Cautun et al. 2013
Cautun et al. 2014



Is the Cosmic Web a useful concept?

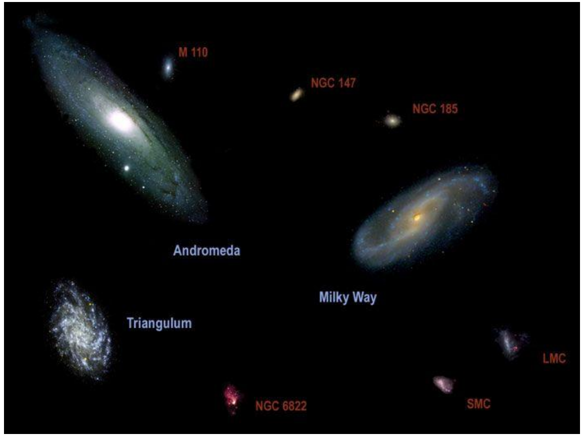
- clear manifestation in controlled environment
  (i.e. simulations)

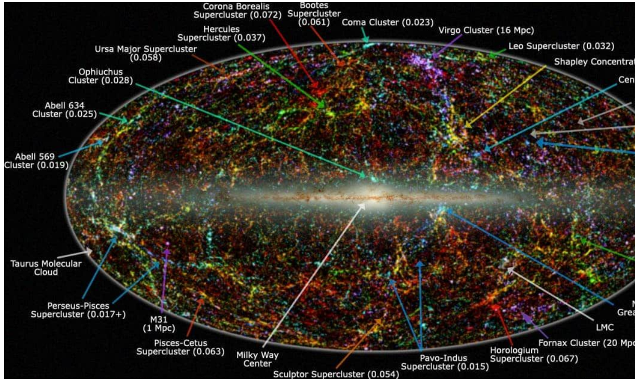
- multitude definitions, identification algorithms
  (i.e. lack of consensus in the community on common properties)

- seen in observed galaxy distribution, but hard to segment and analyse (RSD and selection effects)

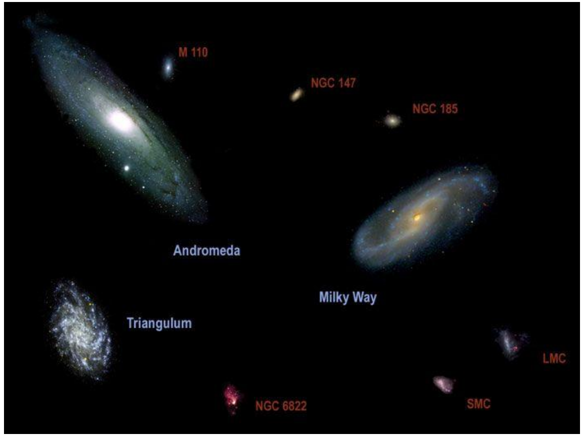
- if we can split observed galaxies/LSS into clear CWEB segments, what will we learn?

- Can adjusting for CWEB environment help to control/reduce some systematics/cosmic variance? For what observables?





So, why (or when and where) Cosmic Web matters?



Some ideas about this to provoke discussion:

- so-claimed LCDM problems (too big to fail, missing satellites, plane of satellites, core-cusp?)

- DM signal modelling (annihilation from subhaloes, dark subhaloes count)

- local galaxy/satellite statistics
- spin, shape alignment
- velocity fields statistics (local non-Gaussian cosmic variance)
- reconstructions (what we can learn from them?)
- distance ladder and H_0 tension
- more?