DEEP-Theory group meeting Monday 14 January 2019

Viraj Pandya - Aligned prolate galaxies project progress report

Galaxy 2-point angular correlation functions: mock & CANDELS agree

Christoph Lee - Deep Learning detection of clumps in CANDELS images

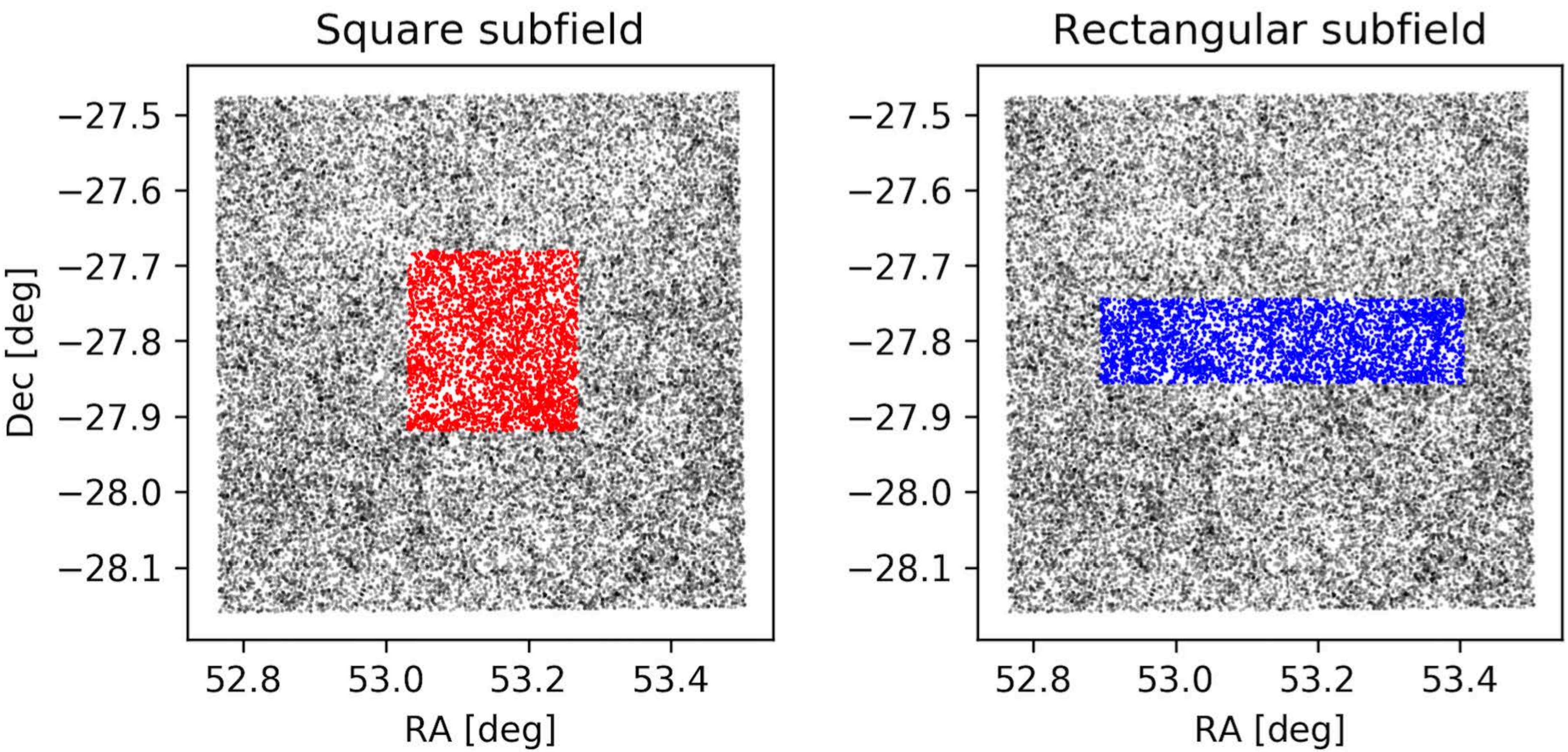
Note that Christoph will be defending his PhD dissertation in ISB 102 on Friday morning January 25

Brain and Cosmic Web Art Project - Joel, working with brain connection expert Olaf Sporns (University of Indiana) and artists Esther Mallouh and Forrest Stearns. Meeting Saturday February 16 in ISB 310 10 am to 3 pm including them (Olaf electronically) and also Elliot Eckholm, Doug Hellinger, and other interested participants.

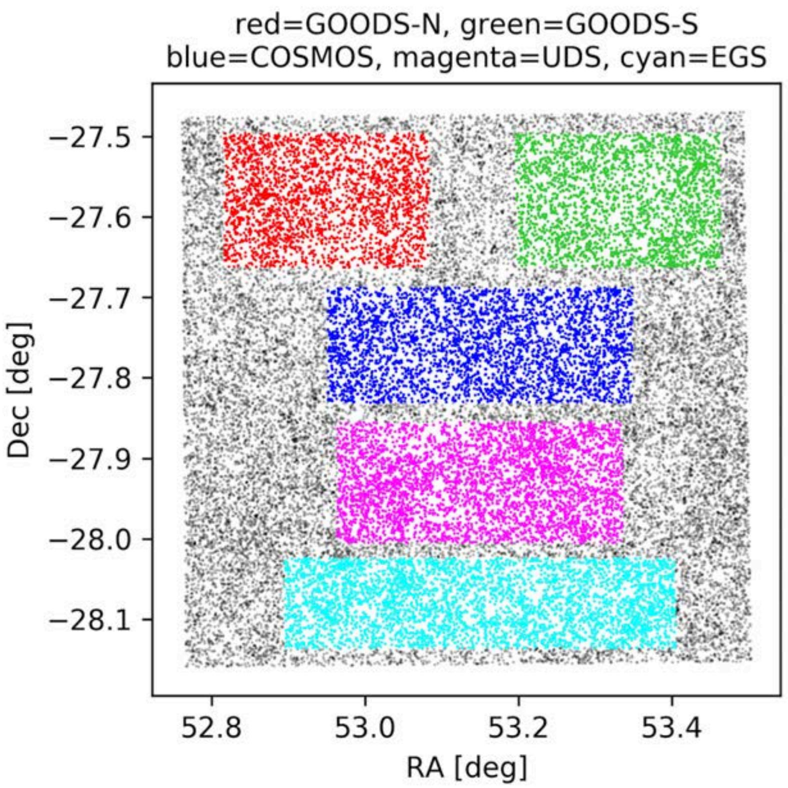
Viraj Pandya - Aligned prolate galaxies project progress report

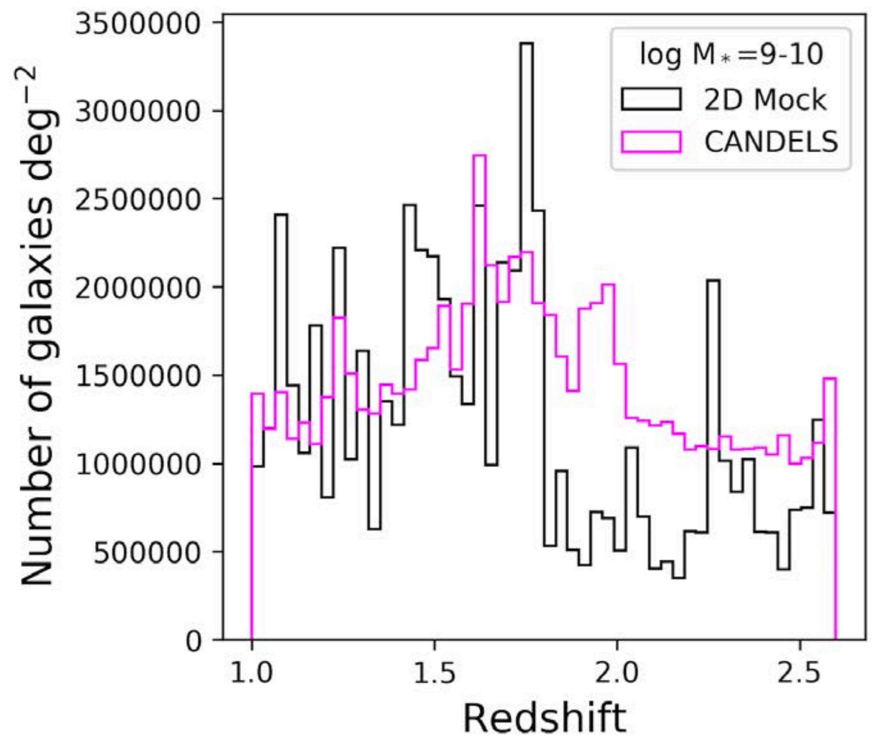
Galaxy 2-point angular correlation functions: mock & CANDELS agree

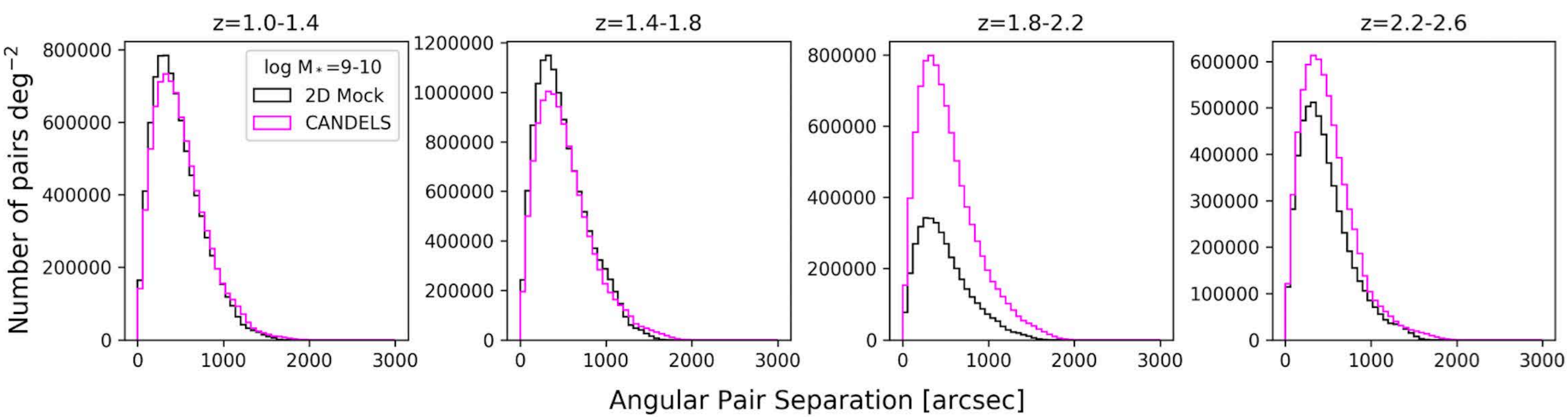
I finished doing the exercise of computing correlation functions in a square vs a rectangular field with the same area (0.05 sq deg), as Sandy suggested. There is definitely a difference -- since the rectangular FOV allows for larger pair separations (along the longer axis), you end up with a longer tail in the rectangular correlation function. The square correlation function shows a steeper drop-off on the scale of the size (diagonal) of the square.



For correlation functions in pencil beam surveys like CANDELS, geometry is important. So I extracted 5 CANDELS-sized fields from the larger mock lightcone, and computed the correlation function in each subfield independently. The combined correlation functions in the 4 redshift slices and 1 stellar mass bin (below) agree for the 5 combined mock subfields and CANDELS fields. The disagreement at z=1.8-2.2 (mock is lower than CANDELS) is probably due to cosmic variance (the redshift distribution below shows that the mock has less # galaxies per sq degree than the five CANDELS fields at z=1.8-2.2), though this is one last remaining thing I need to check explicitly with a few of the other mock LCs....



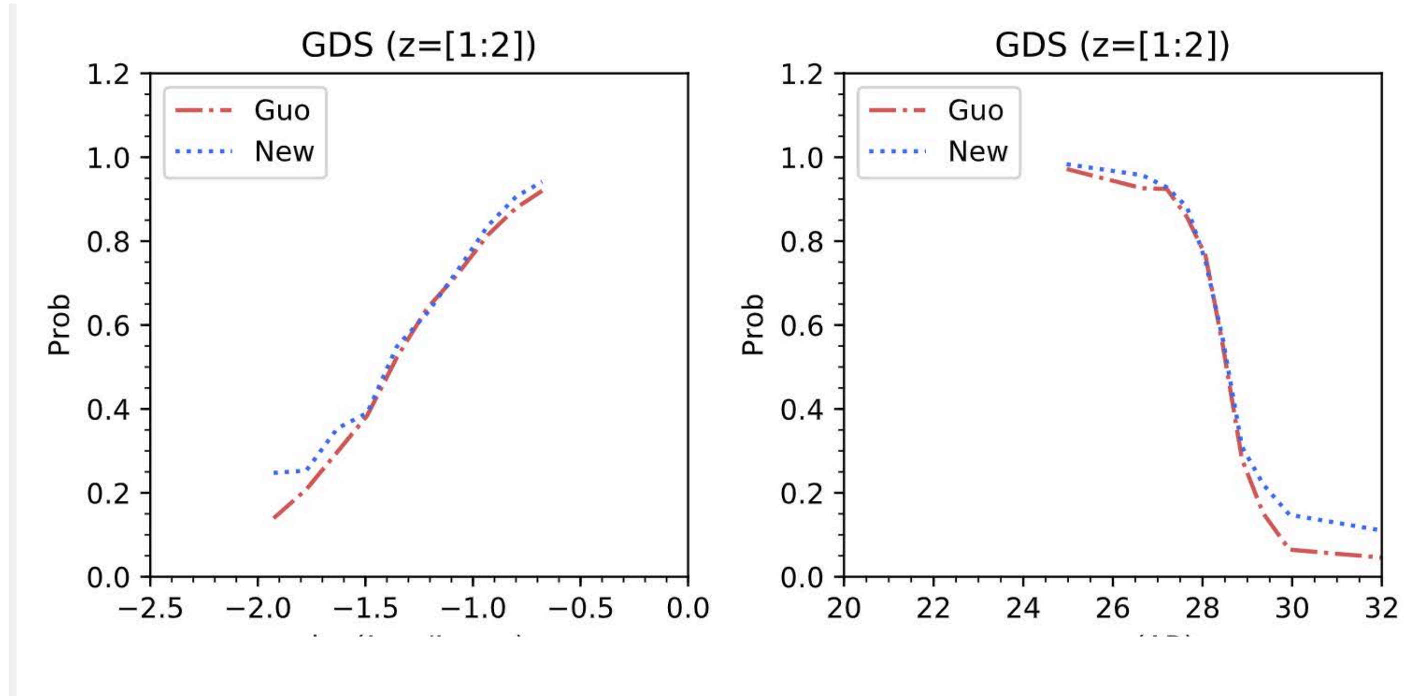




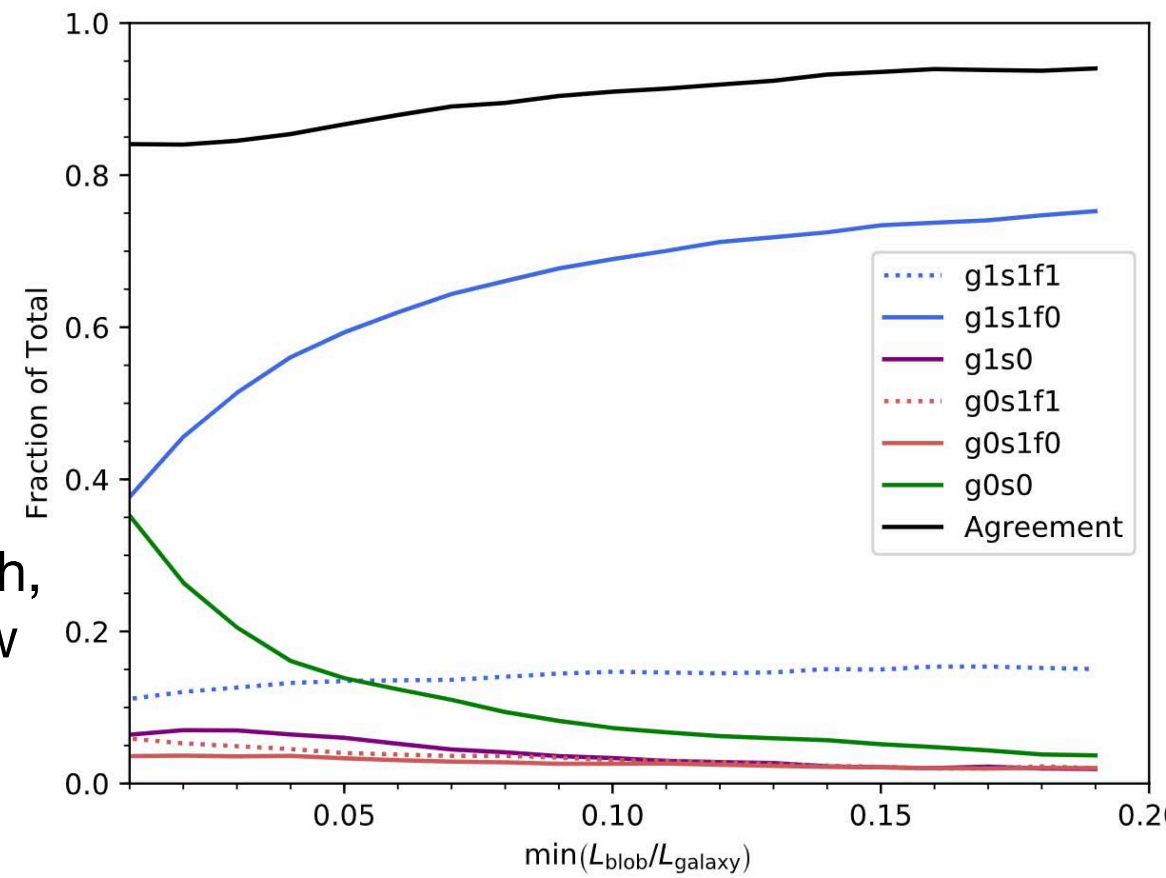
Christoph Lee - Deep Learning detection of clumps in CANDELS images

I've now recomputed the clump detection probability comparison between the DL model and Yicheng's method, using my new 128x128 cutouts with Yicheng's fake clumps added. Images that are not completely covered by the camera are excluded (i.e. those which have any zero regions).

To generate these results, I'm using approximately 10,000 images (~330 different galaxies) from GOODSS v-band, z = 1-2. The plot at right shows that the model achieves approximately equivalent clump detection probability as a function of clump relative flux for this set of images, except at the faint end where the detection probability is slightly higher.



The plot at right shows a breakdown of how well the two clump detection methods (Yicheng Guo's and my Deep Learning code) agree as a function of clump luminosity. The agreement is very strong above a relative clump flux L_{blob}/L_{galaxy} of ~10%.



In our Jan 17 telecon (Marc, Yicheng, Christoph, and Joel) we agreed that Christoph should now run his code on the CANDELS galaxy images and compare with Yicheng's papers

Brain and Cosmic Web Art Project - organized by Esther Mallouh

Astrophysicists					Neuroscientists				
Amanda	Cook	http://www.astrochem.org/bios/cook.php	Amanda.M.Cook@nasa.gov	650-604-2831			role: communications		
Kimberly	Smith Ennico	https://www.sofia.usra.edu/science/science-team/kimberly-ennico-smith	kimberly.ennico@nasa.gov				role: communications		
Jeffrey	Kruk	https://science.gsfc.nasa.gov/sed/bio/jeffrey.w.kruk	jeffrey.w.kruk@nasa.gov	240-521-9218	Tamira	Elul	https://teluldevneurobiology.weebly.com/	tamira.elul@tu.edu	925-457-2368
							http://tu.edu/faculty_staff/elul_tamira.prof.html		
David	Weinberg	http://www.astronomy.ohio-state.edu/~dhw/	dhw@astronomy.ohio-state.edu	614-292-6543	Dan	Feldman	http://mcb.berkeley.edu/labs/feldman/index.html	dfeldman@berkeley.edu	510-643-1723
previous art project		http://www.astronomy.ohio-state.edu/~dhw/McElheny/							
Bridget	Falck	Department of Physics and Astronomy, Johns Hopkins University	bridget.falck@jhu.edu		Sarah	Banducci	https://sarahbanducci.com	sbanducci@gmail.com	814-460-6414
							https://sarahbanducci.com/content/scientific-publications		
Joel	Primack	http://scipp.ucsc.edu/personnel/profiles/primack.html	joel@ucsc.edu	831-345-8960	Olaf	Sporns	http://www.indiana.edu/~cortex/	osporns@indiana.edu	812-855-2772
previous art project		https://www.rachelsmith.online/bolshoi-cosmological-simulation					https://psych.indiana.edu/directory/faculty/sporns-olaf.html		
Benedikt	Diemer	http://www.benediktdiemer.com	benedikt.diemer@cfa.harvard.edu		Natalie	Zahr	https://www.sri.com/about/people/natalie-zahr	nzahr@stanford.edu	650-455-9957
previous art project		http://www.fabricoftheuniverse.org					http://med.stanford.edu/brainaddictionlab/meet.html		
							https://www.sri.com/sites/default/files/bios/cv/zahr_cv_2015.pdf		
Mark	Neyrinck	http://skysrv.pha.jhu.edu/~neyrinck/	Mark.Neyrinck@gmail.com	808 -232-7263			to be partnered		
previous art project		http://www.pbs.org/wgbh/nova/physics/origami-revolution.html							

Brain and Cosmic Webs
Similarities between Neurons and Galaxies interpreted through Art — see the 2017 article in *Nautilus* magazine by Vazza & Feletti on the next page

The Metaphor: There is more likely some unknown law that governs the way networks grow and change, from the smallest brain cells to the growth of mega-galaxies. Are we closer to understanding the communalities between networks large and small?

Brain and Cosmic Webs exhibit will interpret this metaphor that speaks to us of inner galaxies and allow us to intuit a wisdom and a connection between all the kingdoms in existence in the universe, at once the most immense with the very smallest.

The exhibit features digital and interactive media artists interpreting ramifications of the collaborations between Astrophysicists and Neuroscientists who are drawing new parallels between galactic and neuronal networks.

Process: 7 astrophysicists, 7 Neuroscientists, and 7 artists will participate in this project. Esther Mallouh (EM) will pair the astrophysicists with the Neuroscientists and artists to form 7 collaborations. My collaborators are neuroscientist Olaf Sporns (U Indiana) and artist Forrest Stearns (Google). (Scientists from both fields may suggest scientific collaborators to EM – should they choose to)

The scientists will define the subject matter of their projects (one similarity between the 2 fields) and inform EM of their subject of choice. Once defined, EM will assign an artist to each of the 7 groups of scientists. The 7 artists will transform the subject matter of their assigned projects into art installations. The artists will act as their own project managers – working with their collaborators as mutually agreed upon and as needed.

Time Frame: To be advised (most likely October 2019) **Location:** To be advised.
Curator/Producer: Esther Mallouh (EM) is an Art Liaison and a curator of exhibitions at the intersection of art, science, and technology. Her most recent curatorial project Mind Matters: Mapping the Human Mind through Neuroscience had at its heart the pursuit of new connections, explorations, and artistic presentations at the nexus of the arts and the neuroscience.

NAUTILUS

http://nautil.us/issue/50/emergence/the-strange-similarity-of-neuron-and-galaxy-networks

NUMBERS | MATH

The Strange Similarity of Neuron and Galaxy Networks

Your life's memories could, in principle, be stored in the universe's structure.

BY FRANCO VAZZA & ALBERTO FELETTI
PHOTO COLLAGE BY FRANCESCO IZZO
JULY 20, 2017

ADD A COMMENT | FACEBOOK | TWITTER | EMAIL | SHARING

Christof Koch, a leading researcher on consciousness and the human brain, has famously called the brain "the most complex object in the known universe." It's not hard to see why this might be true. With a hundred billion neurons and a hundred trillion connections, the brain is a dizzyingly complex object.

But there are plenty of other complicated objects in the universe. For example, galaxies can group into enormous structures (called clusters, superclusters, and filaments) that stretch for hundreds of millions of light-years. The boundary between these structures and neighboring stretches of empty space called cosmic voids can be extremely complex.[1] Gravity accelerates matter at these boundaries to speeds of thousands of kilometers per second, creating shock waves and turbulence in intergalactic gases. We have predicted that the void-filament boundary is one of the most complex volumes of the universe, as measured by the number of bits of information it takes to describe it.

This got us to thinking: Is it more complex than the brain?

So we—an astrophysicist and a neuroscientist—joined forces to quantitatively compare the complexity of galaxy networks and neuronal networks. The first results from our comparison are truly surprising: Not only are the complexities of the brain and cosmic web actually similar, but so are their structures. The universe may be self-similar across scales that differ in size by a factor of a billion billion billion.

http://nautil.us/issue/50/emergence/the-strange-similarity-of-neuron-and-galaxy-networks

Papers and popular articles about neural nets from Olaf Sporns

Excerpts are on the following pages, with links to these articles

Carl Zimmer, 100 Trillion Connections, Scientific American, January 2011

Tom Siegfried, Big Neuroscience, Science News, February 2014

Danielle Bassett and Olaf Sporns, Network Neuroscience, Nature Neuroscience, March 2017

Andrea Avena-Koenigsberger, Bratislav Misic and Olaf Sporns, Communication dynamics in complex brain networks, Nature Reviews Neuroscience, January 2018

Artist: Forrest Stearns (Google; TEDx talk **https://www.youtube.com/watch?v=P1_cNeUX-yE**; website **https://www.draweverywhere.com/**).

Online textbook *Network Science* by Albert-Laszlo Barabasi

http://networksciencebook.com/

Sandrine Codis's lecture about the cosmic web

http://sandrinecodis.wixsite.com/sandrinewebsite

Papers and popular articles about the cosmic web

Bond, Kofman, Pogosyan, How Filaments of Galaxies Are Woven Into the Cosmic Web, Nature, 1996

Coutinho et al., The Network Behind the Cosmic Web, arXiv:1604.03236v2

Interactive Website: http://cosmicweb.kimalbrecht.com/

Codis, Pogosyan, Pichon, On the Connectivity of the Cosmic Web, MNRAS, 479, 973, 2018

Primack, The Universe in a Supercomputer, IEEE Spectrum, October 2012

Primack & Bell, Universe in a Box, Sky & Telescope, July 2012

Dominguez-Puebla et al. 2016, Cosmic Halo Demographics, MNRAS, 462, 893, 2016

Primack, cosmic web seminar 2/16/2019 including Origin (Quantum fluctuations in cosmic inflation), Evolution (pancakes, filaments, nodes, motion toward dense regions, Dark Energy freezes structure), Structure (space tamed by gravity: galaxies, virialized halos, larger bound regions; wild space)

NEUROSCIENCE January 2011, ScientificAmerican

100 Trillion Connections

The noise of billions of brain cells trying to communicate with one another may hold a crucial clue to understanding consciousness

By Carl Zimmer

A SINGLE NEURON SITS IN A PETRI DISH, CRACKLING in lonely contentment. From time to time, it spontaneously unleashes a wave of electric current that travels down its length. If you deliver pulses of electricity to one end of the cell, the neuron may respond with extra spikes of voltage. Bathe the neuron in various neurotransmitters, and you can alter the strength and timing of its electrical waves. On its own, in its dish, the neuron can't do much. But join together 302 neurons, and they become a nervous system that can keep the worm *Caenorhabditis elegans* alive—sensing the animal's surroundings, making decisions and issuing commands to the worm's body. Join together 100 billion neurons—with 100 trillion connections—and you have yourself a human brain, capable of much, much more.

How our minds emerge from our flock of neurons remains deeply mysterious. It's the kind of question that neuroscience, for all its triumphs, has been ill equipped to answer. Some neuroscientists dedicate their careers to the workings of individual neurons. Others choose a higher scale: they might, for example, look at how the hippocampus, a cluster of millions of neurons, encodes memories. Others might look at the brain at an even higher scale, observing all the regions that become active when we perform a particular task, such as reading or feeling fear. But few have tried to contemplate the brain on its many scales at once. Their reticence stems, in part, from the sheer scope of the challenge. The interactions between just a few neurons can be a confusing thicket of feedbacks. Add 100 billion more neurons to the problem, and the endeavor turns into a cosmic headache.

Yet some neuroscientists think it is time to tackle the chal-

IN BRIEF

A single neuron cannot do much, but string a few hundred together and a primitive nervous system emerges, one sophisticated enough to keep a worm going.

More neurons equate to a more complex organism. A central preoccupation of neuroscience is deducing the way billions of neurons produce the human mind.

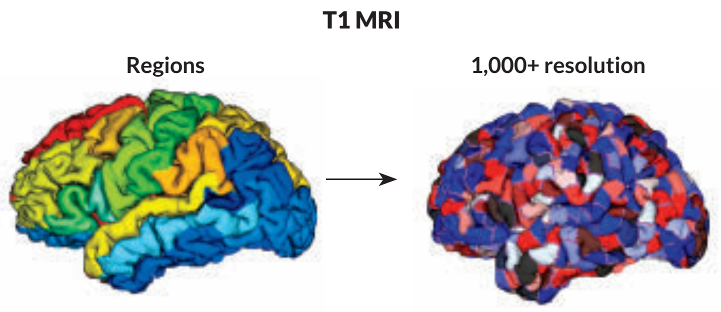
Neuroscientists have begun to unravel the brain's complexity by adopting research on other elaborate systems, ranging from computer chips to the stock market.

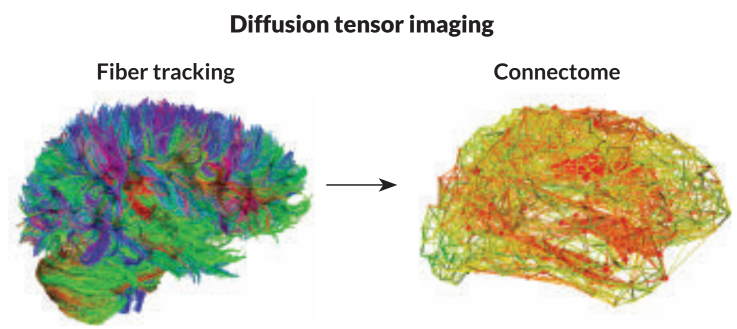
Understanding the workings of the brain's intricate networks may provide clues to the underlying origins of devastating disorders, including schizophrenia and dementia.

https://www.dropbox.com/s/z1q99jgrq6m80f6/ScienceNews_Article_Feb2014.pdf?dl=0

The structural connectome

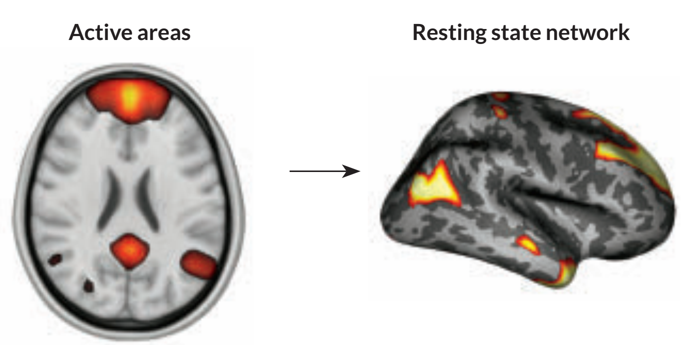
T1 magnetic resonance scans identify the various anatomical regions of the brain and subdivide them into small parcels of gray matter tissue roughly equal in size (typically totaling more than 1,000 pieces). Another form of MRI, called diffusion tensor imaging, traces the paths of white matter fibers that connect the brain's various structural areas. The locations of the white matter fibers allow the construction of a connectome map that reveals how the parcels of gray matter are physically connected.





The functional connectome

Functional magnetic resonance imaging, or fMRI, records brain activity in different regions by measuring blood flow. Detecting parcels of brain tissue that are simultaneously active allows scientists to identify "resting state networks," functional modules of brain tissue involved in the performance of various tasks. By representing parcels of gray matter as nodes in a network, and white matter fibers as the links, scientists can apply graph theory (the mathematics of networks) to analyze how the structural and functional connectomes interact, thereby gaining insights into how the brain works as a whole.



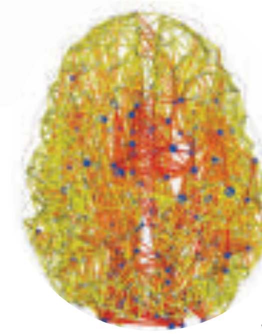
383

Number of neurons in a male *C. elegans*

85

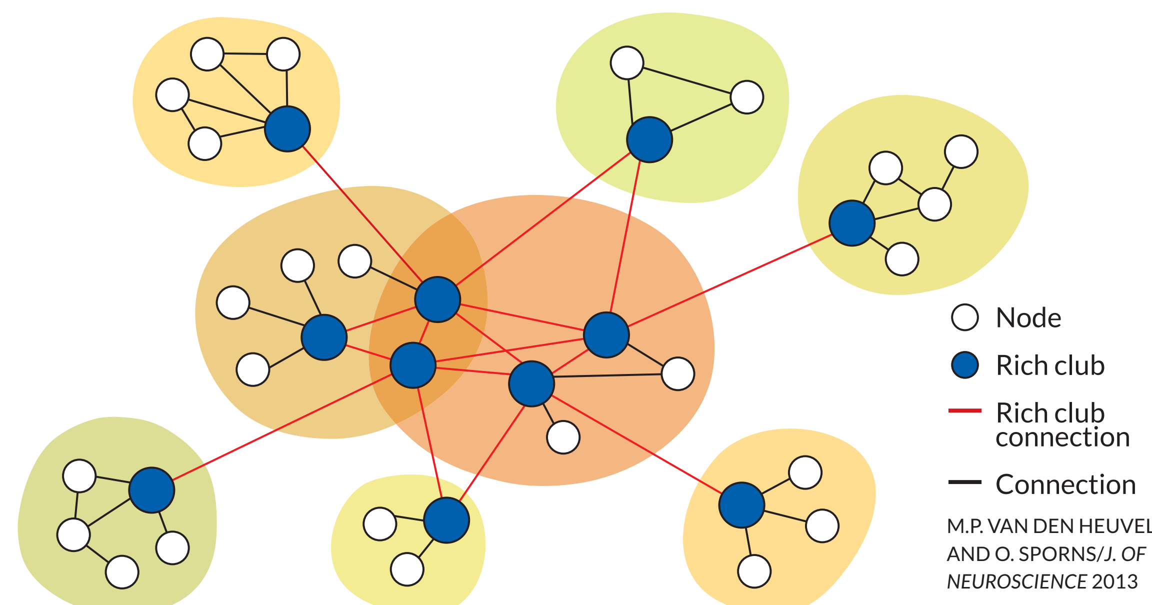
billion

Number of neurons in a human brain



Network analysis

Within various brain regions, some parcels of gray matter (nodes, in network language) possess a substantially higher than average number of connections to other nodes. These highly linked nodes, or "hubs," are common in resting state networks (color shaded, below) associated with specific brain functions. Recent studies have shown that the hubs within a resting state network are also highly connected to hubs in other resting state networks (red lines). These "rich club" hubs (blue circles) probably play a major role, therefore, in merging the activity of various brain networks into the unified whole underlying consciousness.



M.P. VAN DEN HEUVEL AND O. SPORNS/*J. OF NEUROSCIENCE* 2013

Explore more

- Human Connectome Project website: www.neuroscienceblueprint.nih.gov/connectome

---

Tom Siegfried is the former editor in chief of Science News.

NATURE REVIEWS | NEUROSCIENCE
VOLUME 19 | JANUARY 2018 | 17
https://www.dropbox.com/s/tqm9r5c9pw1go8u/communication_dynamics_NRN.pdf?dl=0

Communication dynamics in complex brain networks

Andrea Avena-Koenigsberger[1], Bratislav Misic[2] and Olaf Sporns[1,3]

[1]Department of Psychological and Brain Sciences, Indiana University, Bloomington, Indiana 47405, USA. [2]Montreal Neurological Institute, McGill University, Montreal, Quebec H3A 2B4, Canada. [3]IU Network Science Institute, Indiana University, Bloomington, Indiana 47405, USA.
Correspondence to osporns@indiana.edu

Abstract | Neuronal signalling and communication underpin virtually all aspects of brain activity and function. Network science approaches to modelling and analysing the dynamics of communication on networks have proved useful for simulating functional brain connectivity and predicting emergent network states. This Review surveys important aspects of communication dynamics in brain networks. We begin by sketching a conceptual framework that views communication dynamics as a necessary link between the empirical domains of structural and functional connectivity. We then consider how different local and global topological attributes of structural networks support potential patterns of network communication, and how the interactions between network topology and dynamic models can provide additional insights and constraints. We end by proposing that communication dynamics may act as potential generative models of effective connectivity and can offer insight into the mechanisms by which brain networks transform and process information.

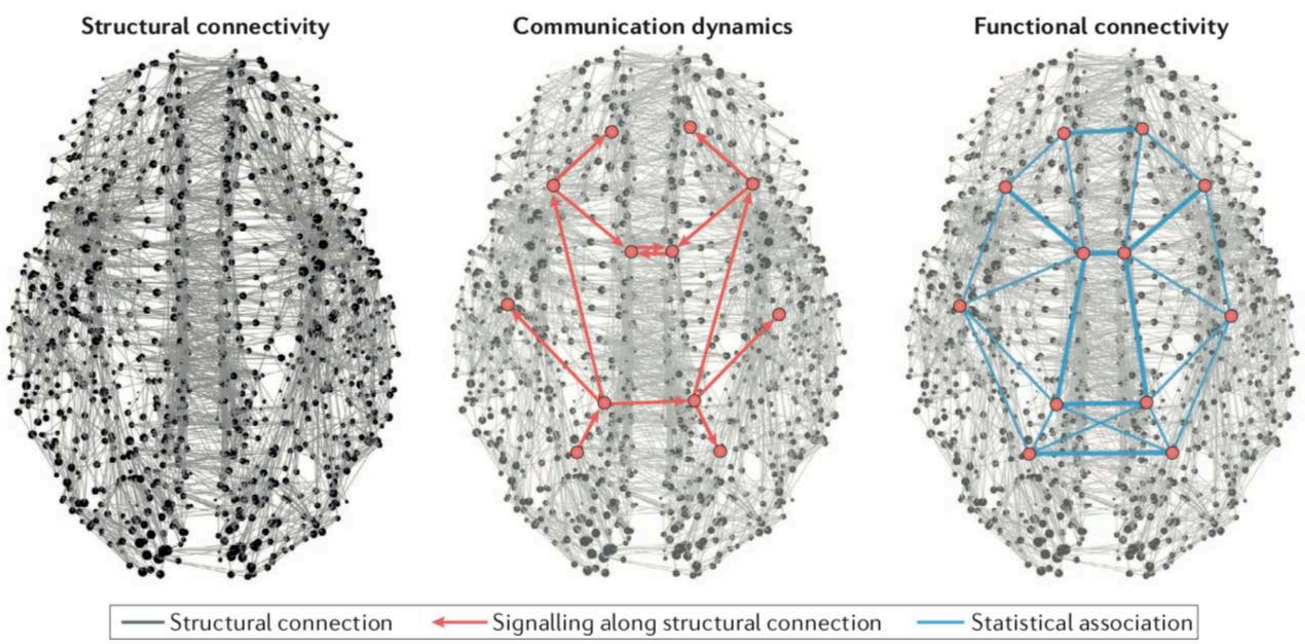


Figure 1 | **A conceptual framework for linking structural connectivity and functional connectivity.** The left panel shows a network of structural connections (grey lines) that link distinct neural elements (brain regions; black dots). Neural activity gives rise to signalling events that propagate, at each given point in time, along distinct subsets of structural connections (middle panel; signalling routes and implicated neural elements in orange). The resulting statistical dependencies (in blue; right panel) among regional time series can be captured as functional connectivity.

Box 4. From classic connectionism to network computation

Classic models of information processing are based on theories that conceptualize neural computation as the transformation of activity patterns (representations), from inputs into outputs within distributed networks[181–183]. Under this framework, each neural component performs specific computations, and the results of these computations are relayed between components through neuronal connections. In simple physiological terms, neurons perform computations on their synaptic inputs and relay these outputs of these computations to other neurons through axonal connections. Neuronal signalling, then, represents the exchange of information, encoded in the form of spike trains. This exchange of information unfolds across sensory and motor systems within processing hierarchies that generate increasingly complex neuronal representations. One of the central objectives of the classic models is to identify the computational steps that underpin cognitive behaviours. How do the concepts in the classic models differ from a perspective based on concepts of network science and dynamics? …

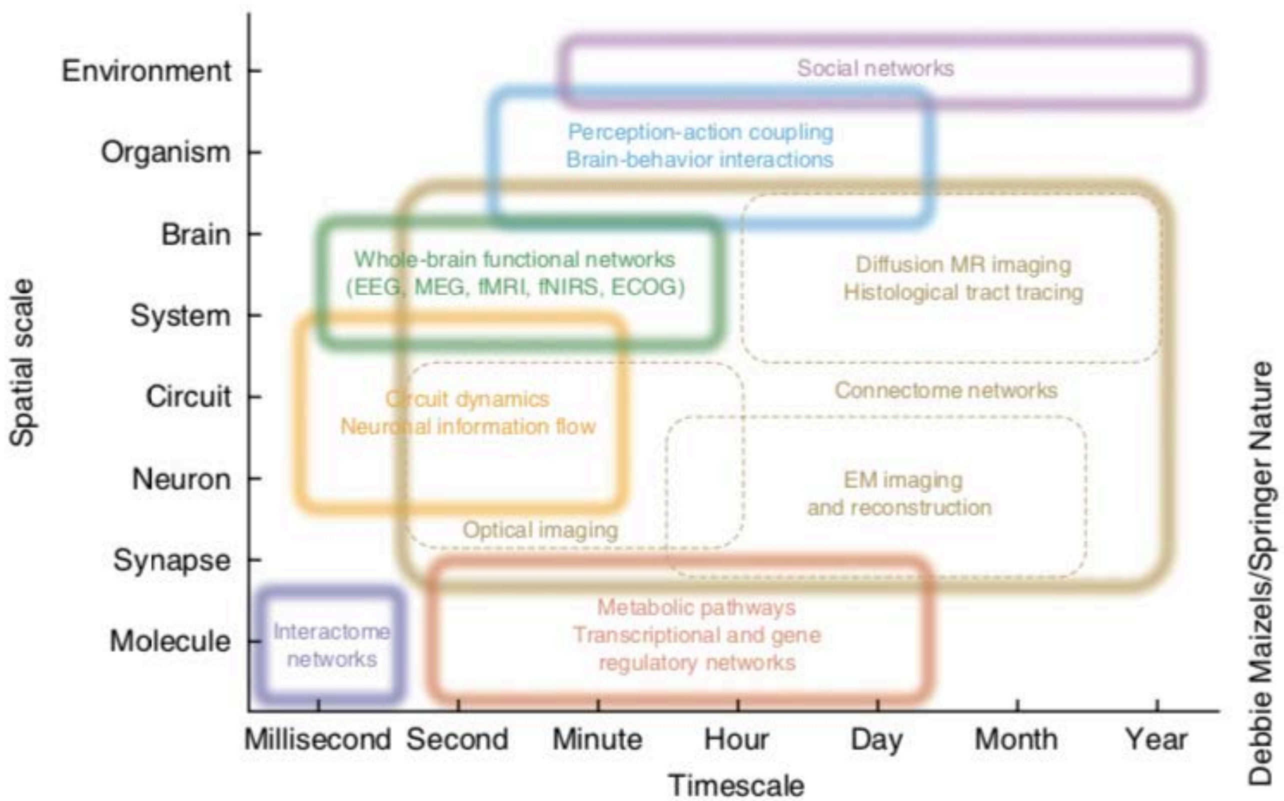
nature neuroscience

https://www.dropbox.com/s/92fj6yj4h4uc3np/NetworkNeuroscience.4502.pdf?dl=0

Network neuroscience

Danielle S Bassett[1,2] & Olaf Sporns[3,4]

Despite substantial recent progress, our understanding of the principles and mechanisms underlying complex brain function and cognition remains incomplete. Network neuroscience proposes to tackle these enduring challenges. Approaching brain structure and function from an explicitly integrative perspective, network neuroscience pursues new ways to map, record, analyze and model the elements and interactions of neurobiological systems. Two parallel trends drive the approach: the availability of new empirical tools to create comprehensive maps and record dynamic patterns among molecules, neurons, brain areas and social systems; and the theoretical framework and computational tools of modern network science. The convergence of empirical and computational advances opens new frontiers of scientific inquiry, including network dynamics, manipulation and control of brain networks, and integration of network processes across spatiotemporal domains. We review emerging trends in network neuroscience and attempt to chart a path toward a better understanding of the brain as a multiscale networked system.



Conclusion In this review, we have attempted to sketch the outlines of a new interdisciplinary field, which we call network neuroscience. The field gathers momentum as networks have become ubiquitous phenom- ena encountered in empirical investigation as well as computational analysis and modeling of neurobiological systems at all scales. The ever-growing volume of big data in neuroscience demands not only advanced analytics and sound statistical inference, but it also calls for theoretical ideas that can unify our understanding of brain structure and function. Theory is indispensable, as it allows us to transform big data into 'small data' and, ultimately, knowledge —delivering compact descriptions of regularities, principles and laws that apply to the architecture and functioning of neural systems. We believe that network neuroscience can make an important contribution toward unifying an otherwise fractured discipline by providing a common conceptual framework and a common toolset to meet the challenges of modern neuroscience. Network neuroscience naturally connects with other important theoretical approaches such as dynamical systems, neural coding and statistical physics.

Network Science

by Albert-László Barabási

http://networksciencebook.com/

Start Reading

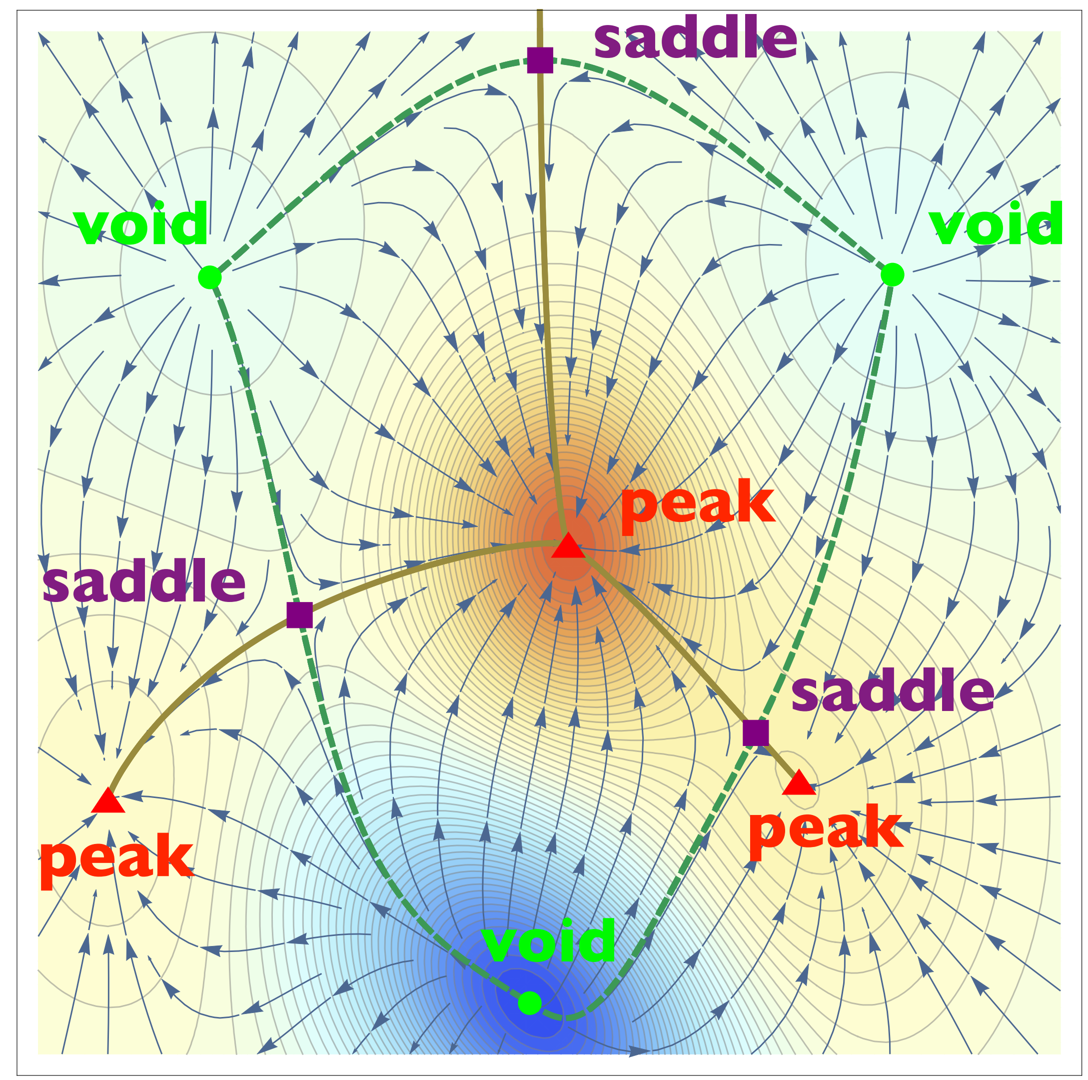
The skeleton picture

Filaments are the field lines joining the maxima through saddle points.

- cosmic web extractors (water-shedding, discrete topology, …) *Sousbie+08, Sousbie+11, …**

- local theory allowing for theoretical predictions for extrema counts, length of filaments, surface of voids, curvature … which are very competitive cosmological probes! *BBKS, Pogosyan+09, Gay+12, …**

- Cosmic connectivity κ: typically, how many filaments connect to a node? *SC+18*

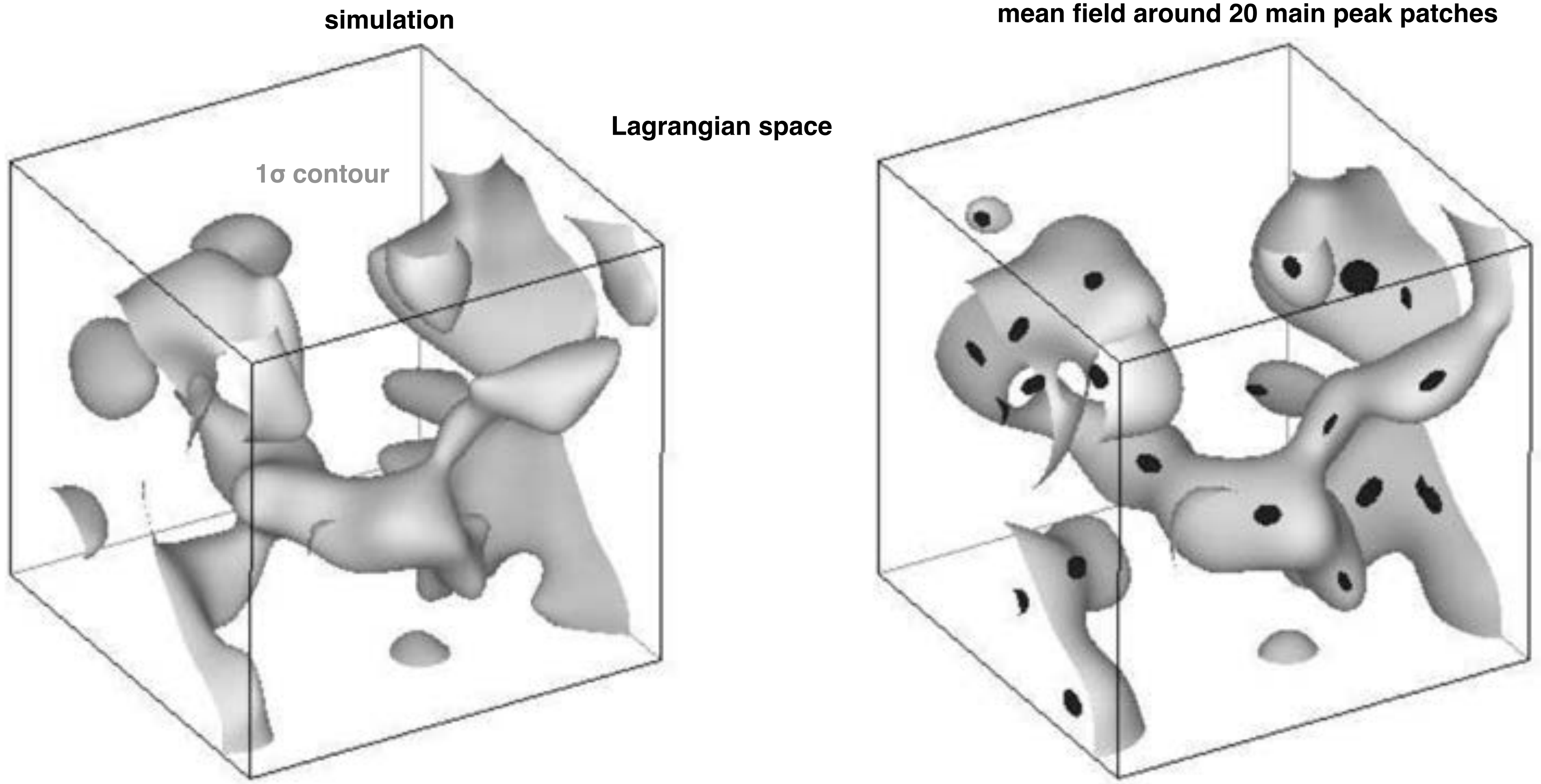


The connected cosmic web

Bond, Kofman, Pogosyan 1996: first *understanding* of the origin of the cosmic web.
https://www.dropbox.com/s/34n5lnoto05kgss/BondKofmanPogosyan-CosmicWeb-Nature1996.pdf?dl=0

The seeds of walls, filaments and nodes lie in the asymmetries of the primordial Gaussian random field then amplified by gravitational instability.

Rare *peaks* in the ICs will become the nodes of the cosmic web i.e rich clusters. Their initial *shear* will set the preferred directions along which correlation bridges will connect them to other nodes.



Importance of peak & constrained random field theories

The Network Behind the Cosmic Web

Interactive Website: http://cosmicweb.kimalbrecht.com/

B. C. Coutinho,[1] Sungryong Hong,[2, 3] Kim Albrecht,[1] Arjun Dey,[2] Albert-L´aszl´o Barab´asi,[1,4,5,6] Paul Torrey,[7,8] Mark Vogelsberger,[9] and Lars Hernquist[9]

http://adsabs.harvard.edu/abs/2016arXiv160403236C

The concept of the cosmic web, viewing the Universe as a set of discrete galaxies held together by gravity, is deeply engrained in cosmology. Yet, little is known about the most effective construction and the characteristics of the underlying network. Here we explore seven network construction algorithms that use various galaxy properties, from their location, to their size and relative velocity, to assign a network to galaxy distributions provided by both simulations and observations. We find that a model relying only on spatial proximity offers the best correlations between the physical characteristics of the connected galaxies. We show that the properties of the networks generated from simulations and observations are identical, unveiling a deep universality of the cosmic web.

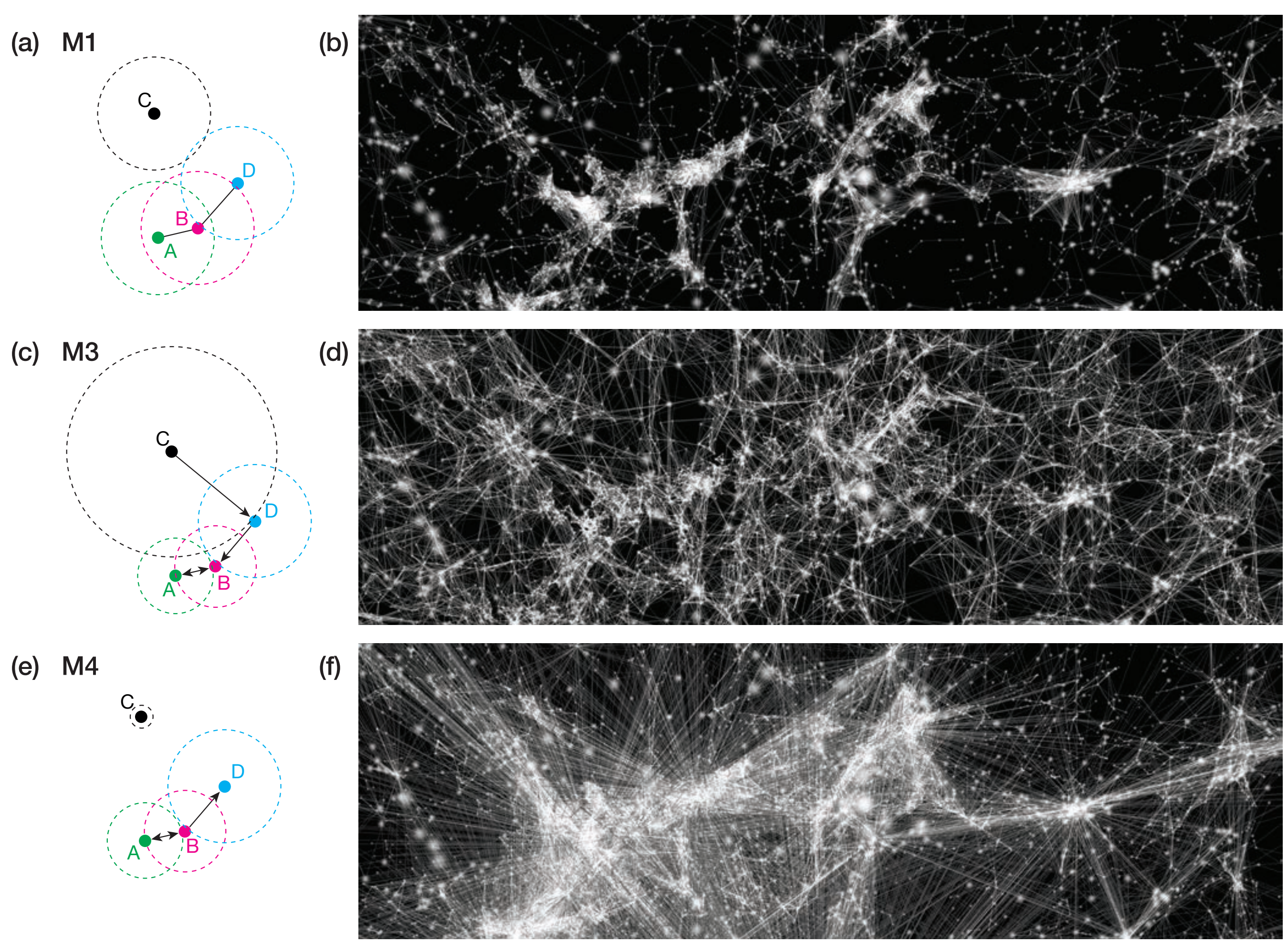


FIG. 1: Building networks from galaxy data. The circles represent the linking lengths for models M1, M3 and M4. (a) In M1 all galaxies within distance l are connected by an undirected link. (c) In M3 a galaxy is connected to the closest galaxy with a directed link; therefore the linking length depends on the position of the closest galaxy. (e) In M4, the linking length scales with the galaxy size, $l = a\,R^{1/2}$. (b),(d) and (f) Visualization of the cosmic web for i redhshift 0 produced by the respective models, for $\langle k \rangle = 40$. For simplicity the direction of the links is not present in the visualization. For interactive visualization see http://kimalbrecht.com/ccnr/04-networkuniverse/17-network-interface. Models M2,5,6,7 are generated from the three models shown above. In M2 the directions of the M3 links are inverted; in M5 the direction of the M4 links are inverted. M6(7) are similar to M4(5) but computed in the phase space.

Codis, Pogosyan, Pichon, On the Connectivity of the Cosmic Web, MNRAS, 479, 973, 2018

https://www.dropbox.com/s/lg96bb0zrebekux/CodisPogosyanPichon-CosmicWebConnectivity-MNRAS2018.pdf?dl=0

ABSTRACT Cosmic connectivity and multiplicity, i.e. the number of filaments globally or locally connected to a given cluster is a natural probe of the growth of structure and in particular of the nature of dark energy. It is also a critical ingredient driving the assembly history of galaxies as it controls mass and angular momentum accretion. …

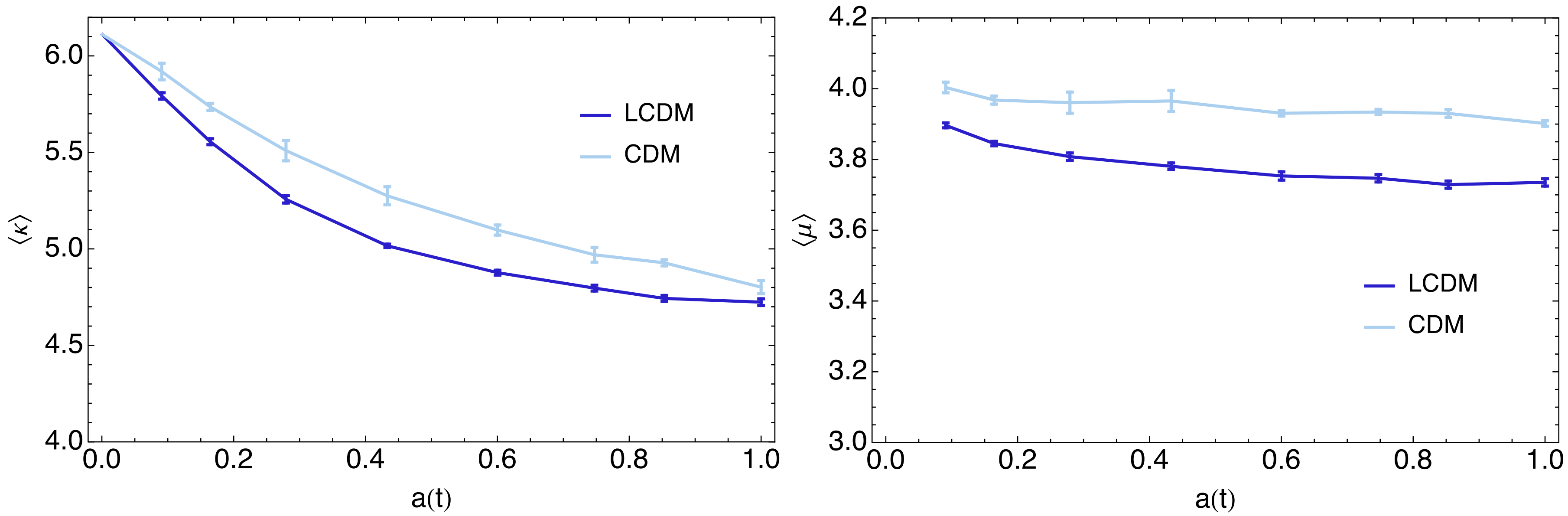


Figure 22. Mean connectivity (left-hand panel) and multiplicity (right-hand panel) of the skeleton as a function of the expansion factor for ΛCDM and CDM simulations as labelled. As expected, the CDM simulation is essentially featureless, whereas the ΛCDM connectivity changes slope when the dark energy expansion kicks in.

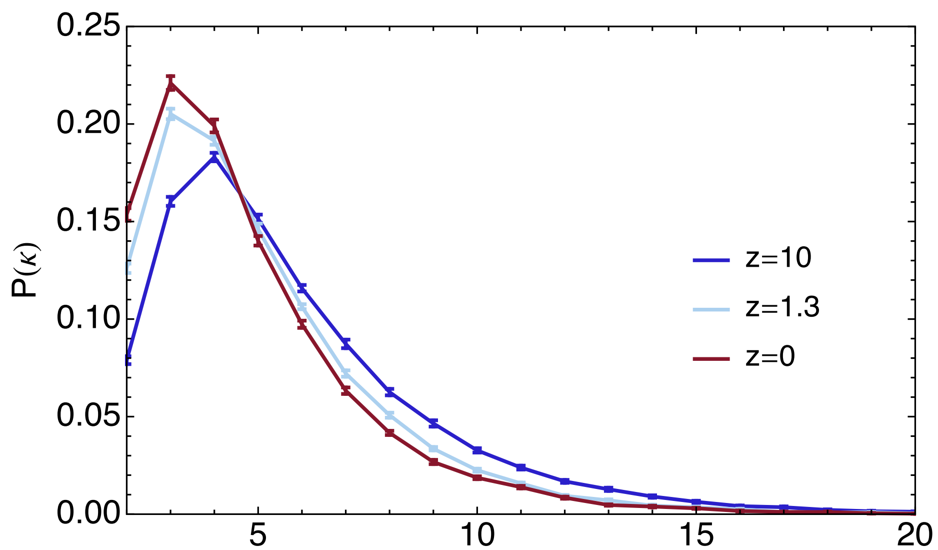


Figure 23. PDF of cosmic connectivity κ at various redshifts as labelled is the ΛCDM simulations smoothed on a constant comoving length $R \approx 0.8\text{Mpc}h^{-1}$.

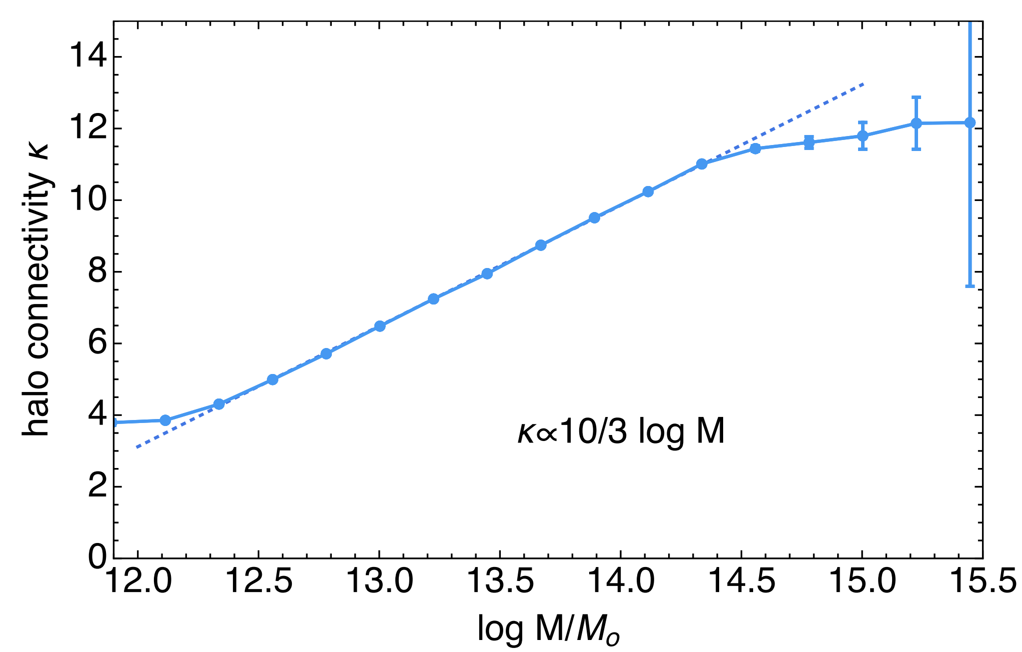
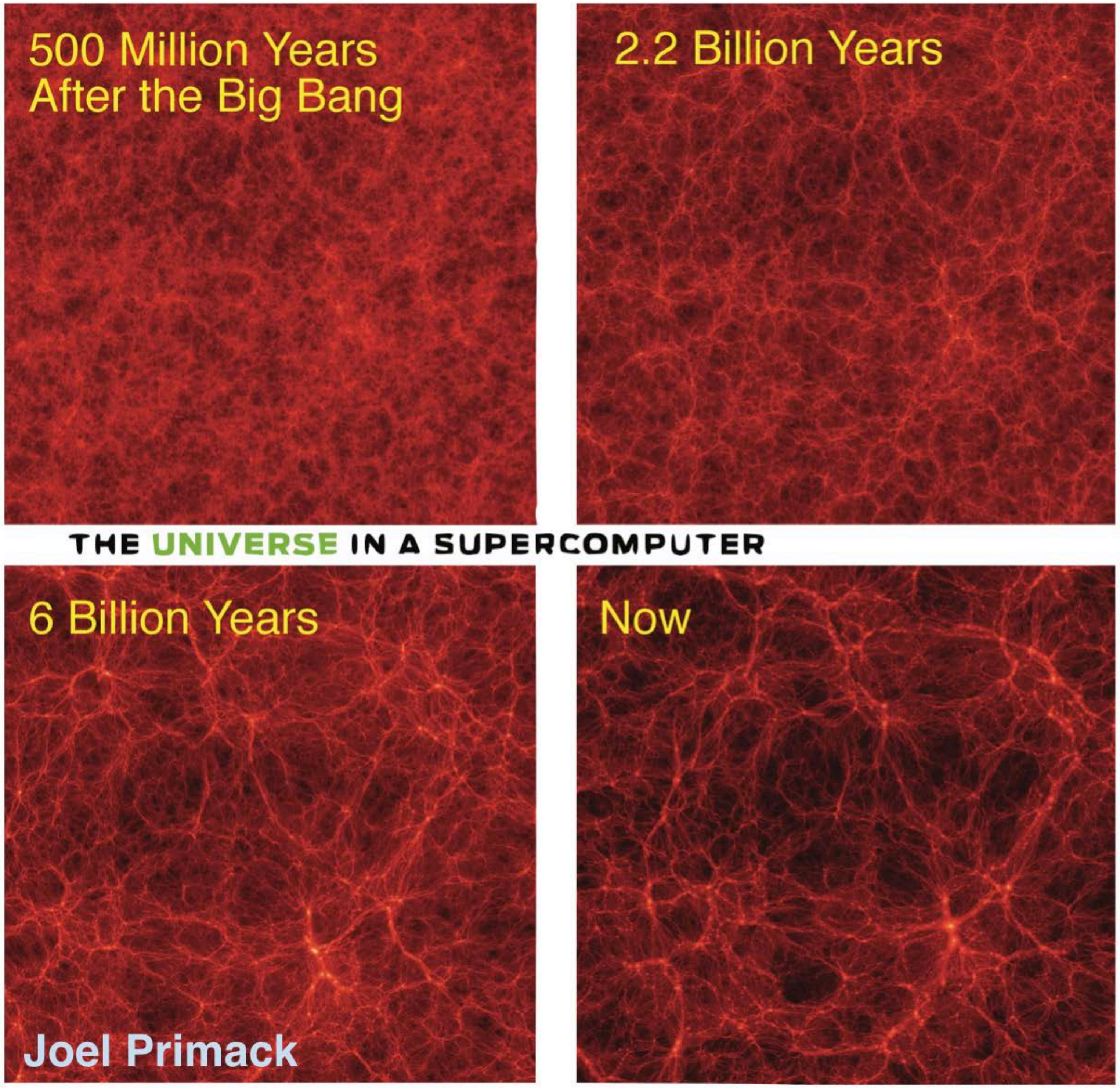


Figure24. Mean connectivity of dark haloes at redshift zero as a function of mass, as labeled for about on million nodes of the cosmic web. The mean cosmic connectivity here is found to be well approximated by the simple linear relation $\varkappa(M) \approx 10/3\log(M/10^{11}M_\odot)$.



COSMIC WEB: The Bolshoi simulation models the evolution of dark matter, which is responsible for the large scale structure of the universe. Here, snapshots from the simulation show the dark matter distribution at 500 million and 2.2 billion years [top] and 6 billion and 13.7 billion years [bottom] after the big bang. These images are 50 million light year thick slices of a cube of simulated universe that today would measure roughly 1 billion light years on a side and encompass about 100 galaxy clusters.

SOURCES: SIMULATION, ANATOLY KLYPIN AND JOEL R. PRIMACK; VISUALIZATION, STEFAN GOTTL BER/LEIBNIZ INSTITUTE FOR ASTROPHYSICS POTSDAM

http://physics.ucsc.edu/~joel/Primack-IEEE%20Spectrum%20Oct2012.pdf

To understand the cosmos, we must evolve it all over again

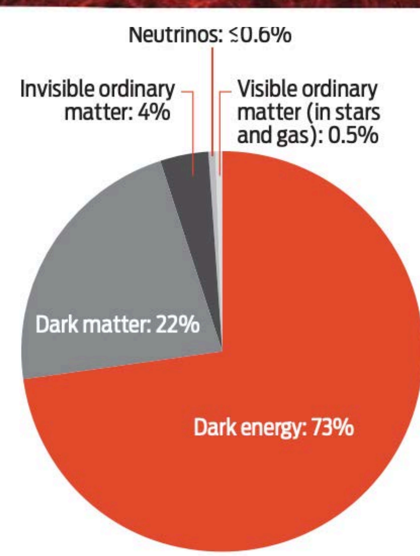
By Joel R. Primack

WHEN IT COMES TO RECONSTRUCTING THE PAST, you might think that astrophysicists have it easy. After all, the sky is awash with evidence. For most of the universe s history, space has been largely transparent, so much so that light emitted by distant galaxies can travel for billions of years before nally reaching Earth. It might seem that all researchers have to do to nd out what the universe looked like, say, 10 billion years ago is to build a telescope sensitive enough to pick up that ancient light.

Actually, it s more complicated than that. Most of the ordinary matter in the universe the stuff that makes up all the atoms, stars, and galaxies astronomers can see is invisible, either sprinkled throughout intergalactic space in tenuous forms that emit and absorb little light or else swaddled inside galaxies in murky clouds of dust and gas. When astronomers look out into the night sky with their most powerful telescopes, they can see no more than about 10 percent of the ordinary matter that s out there.

To make matters worse, cosmologists have discovered that if you add up all the mass and energy in the universe, only a small fraction is com posed of ordinary matter. A good 95 percent of the cosmos is made up of two very different kinds of invisible and as yet unidenti ed stuff that is dark, meaning that it emits and absorbs no light at all. One of these mysterious components, called dark matter, seems immune to all fundamental forces except gravity and perhaps the weak interaction, which is responsible for

MOSTLY DARK: If you add up all the matter and energy in the universe, you'd find little that is familiar. The stars and gas that astronomers see in their telescopes make up just 0.5 percent of the cosmos. Just 0.01 percent of the universe is made of elements heavier than hydrogen or helium. Because of uncertainties, the numbers in this chart do not add up to 100 percent.




SKY
& TELESCOPE
Dive Deep In
the Lagoon p. 61
JULY 2012
http://physics.ucsc.edu/~joel/PrimackBell-Bolshoi-S&T-July2012-opt.pdf
Universe in
a Box
From the Big Bang to Now p. 26

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS **462,** 893–916 (2016) doi:10.1093/mnras/stw1705
Advance Access publication 2016 July 15

Halo and subhalo demographics with Planck cosmological parameters: Bolshoi–Planck and MultiDark–Planck simulations

Aldo Rodríguez-Puebla,[1★] Peter Behroozi,[2★†] Joel Primack,[3] Anatoly Klypin,[4] Christoph Lee[3] and Doug Hellinger[3]

[1] *Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA*
[2] *Astronomy and Physics Departments and Theoretical Astrophysics Center, University of California, Berkeley, Berkeley CA 94720, USA*
[3] *Physics Department, University of California, Santa Cruz, CA 95064, USA*
[4] *Department of Astronomy, New Mexico State University, Las Cruces, NM 88001, USA*

Accepted 2016 July 13. Received 2016 July 11; in original form 2016 February 13

ABSTRACT

We report and provide fitting functions for the abundance of dark matter haloes and subhaloes as a function of mass, circular velocity, and redshift from the new Bolshoi–Planck and MultiDark–Planck ΛCDM cosmological simulations, based on the Planck parameters. We also report halo mass accretion rates and concentrations. We show that the higher cosmological matter density of the Planck parameters compared with the *WMAP* parameters leads to higher abundance of massive haloes at high redshifts. We find that the median halo spin parameter $\lambda_{\rm B} = J(\sqrt{2}M_{\rm vir}R_{\rm vir}V_{\rm vir})^{-1}$ is nearly independent of redshift, leading to predicted evolution of galaxy sizes that is consistent with observations, while the significant decrease with redshift in median $\lambda_{\rm P} = J|E|^{-1/2}G^{-1}M^{-5/2}$ predicts more decrease in galaxy sizes than is observed. Using the Tully–Fisher and Faber–Jackson relations between galaxy velocity and mass, we show that a simple model of how galaxy velocity is related to halo maximum circular velocity leads to increasing overprediction of cosmic stellar mass density as redshift increases beyond $z \sim 1$, implying that such velocity–mass relations must change at $z \gtrsim 1$. By making a realistic model of how observed galaxy velocities are related to halo circular velocity, we show that recent optical and radio observations of the abundance of galaxies are in good agreement with our ΛCDM simulations. Our halo demographics are based on updated versions of the Rockstar and Consistent Trees codes, and this paper includes appendices explaining all of their outputs. This paper is an introduction to a series of related papers presenting other analyses of the Bolshoi–Planck and MultiDark–Planck simulations.