Cosmology's Century
Large Scale Structure of Dark Universe

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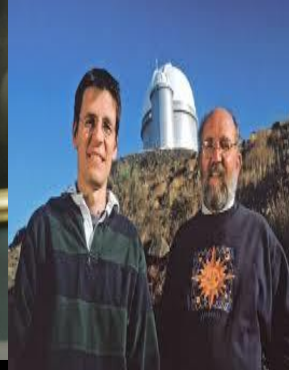
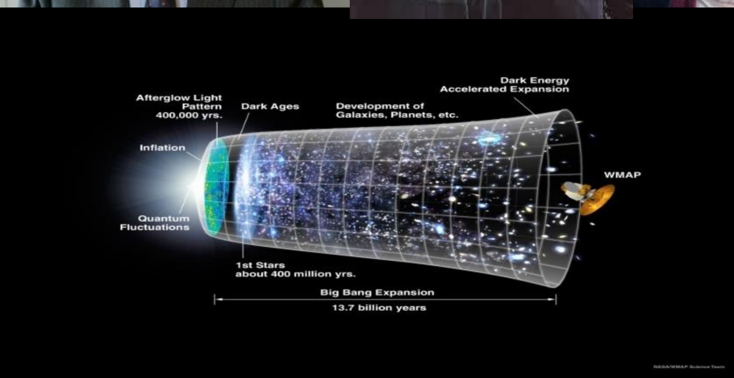
Colloquium 16 May 2021

Manoucher Yektai (1921 –2019)

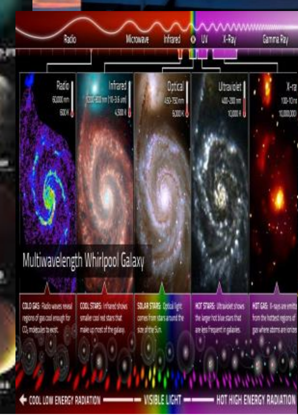
*Overture**

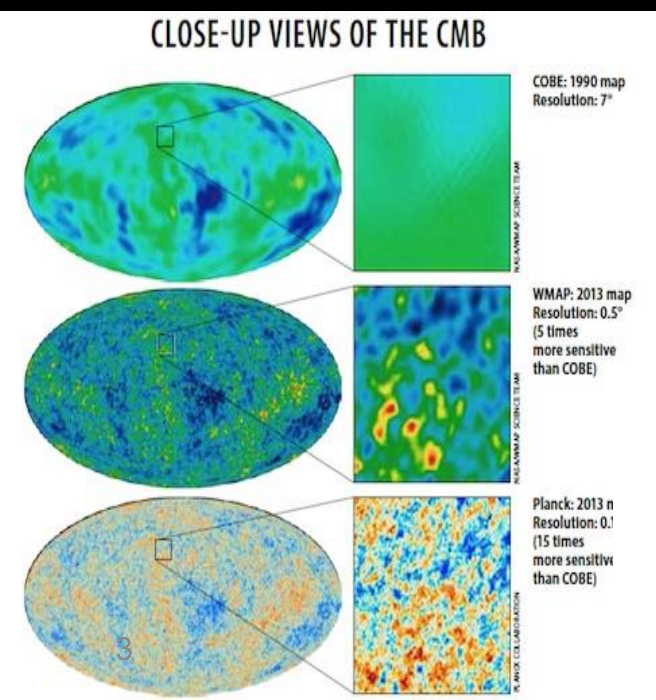
***Overture* in *music* was originally the instrumental introduction to a ballet, opera, or oratorio.

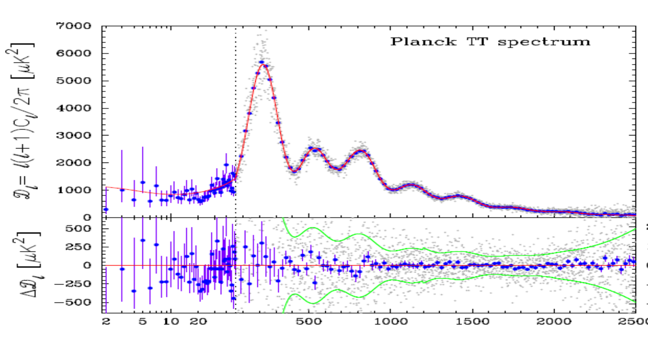


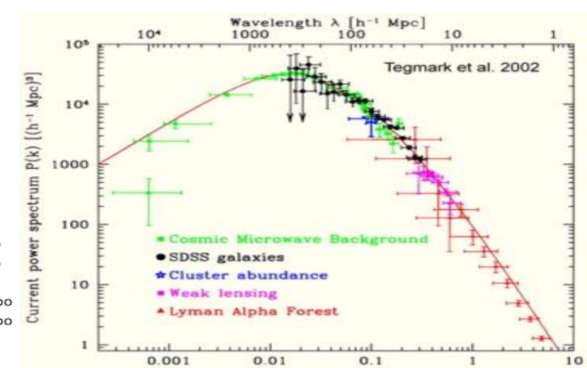

Afterglow Light Pattern 400,000 yrs.
Dark Ages
Development of Galaxies, Planets, etc.
Dark Energy Accelerated Expansion
Inflation
WMAP
Quantum Fluctuations
1st Stars about 400 million yrs.
Big Bang Expansion
13.7 billion years

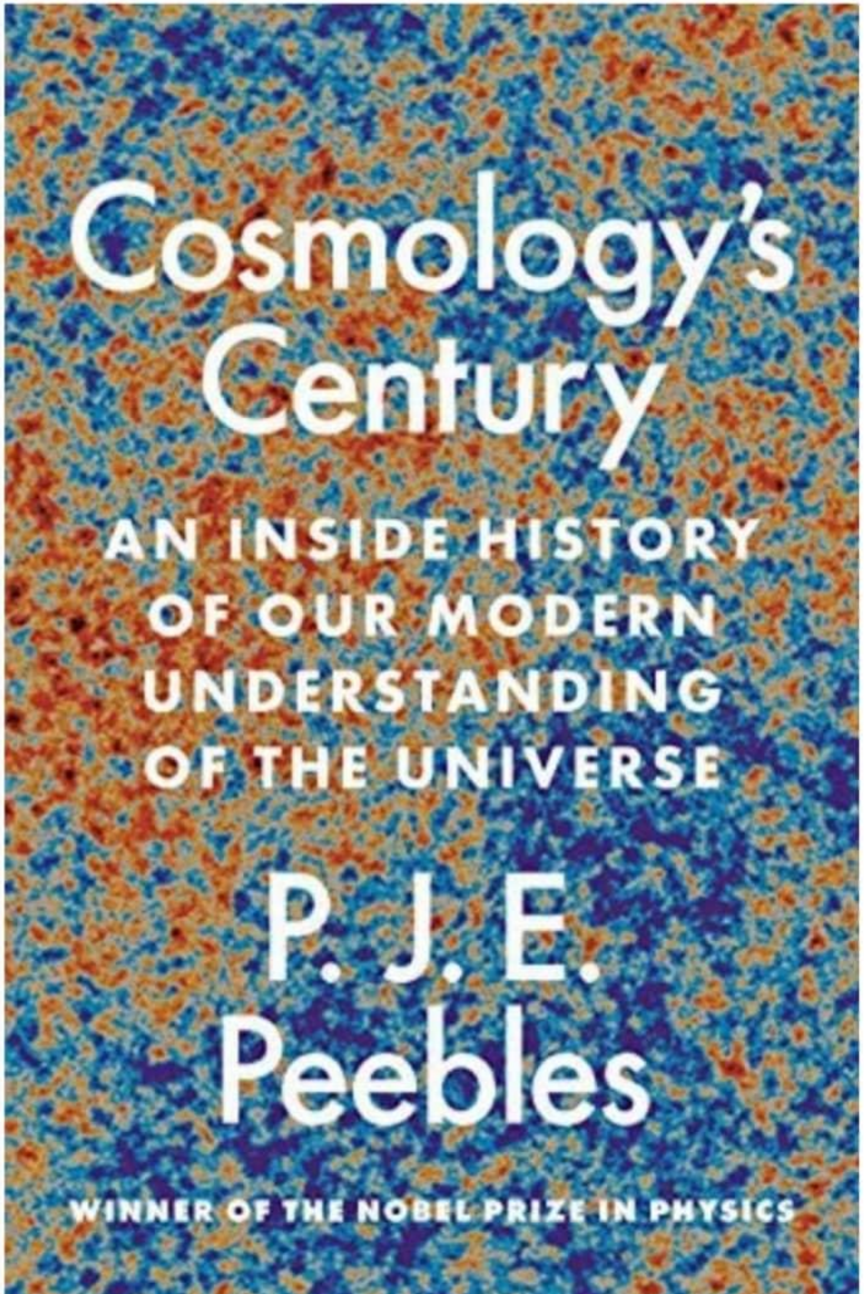

EXTRASOLAR PLANETS


Radio
Microwave
Infrared
UV
X-Ray
Gamma Ray
Multiwavelength Whirlpool Galaxy
COOL LOW ENERGY RADIATION
VISIBLE LIGHT
HOT HIGH ENERGY RADIATION


CLOSE-UP VIEWS OF THE CMB
COBE: 1990 map
Resolution: 7°
WMAP: 2013 map
Resolution: 0.5°
(5 times
more sensitive
than COBE)
Planck: 2013 n
Resolution: 0.1
(15 times
more sensitive
than COBE)


Planck TT spectrum
$\mathcal{D}_\ell = \ell(\ell+1)C_\ell/2\pi\ [\mu K^2]$
$\Delta\mathcal{D}_\ell\ [\mu K^2]$
Multipole ℓ


Wavelength λ [h⁻¹ Mpc]
Tegmark et al. 2002
Current power spectrum P(k) [(h⁻¹ Mpc)³]
Cosmic Microwave Background
SDSS galaxies
Cluster abundance
Weak lensing
Lyman Alpha Forest
Wavenumber k [h/Mpc]



You should enter science because you are fascinated by it. That's what I did!
James Peebles

Prelude*

**A prelude is a short piece of music, the form of which may vary from piece to piece. The prelude may be thought of as a preface*

"If you wish to make an apple pie from scratch you must first invent the universe." by Carl Sagan

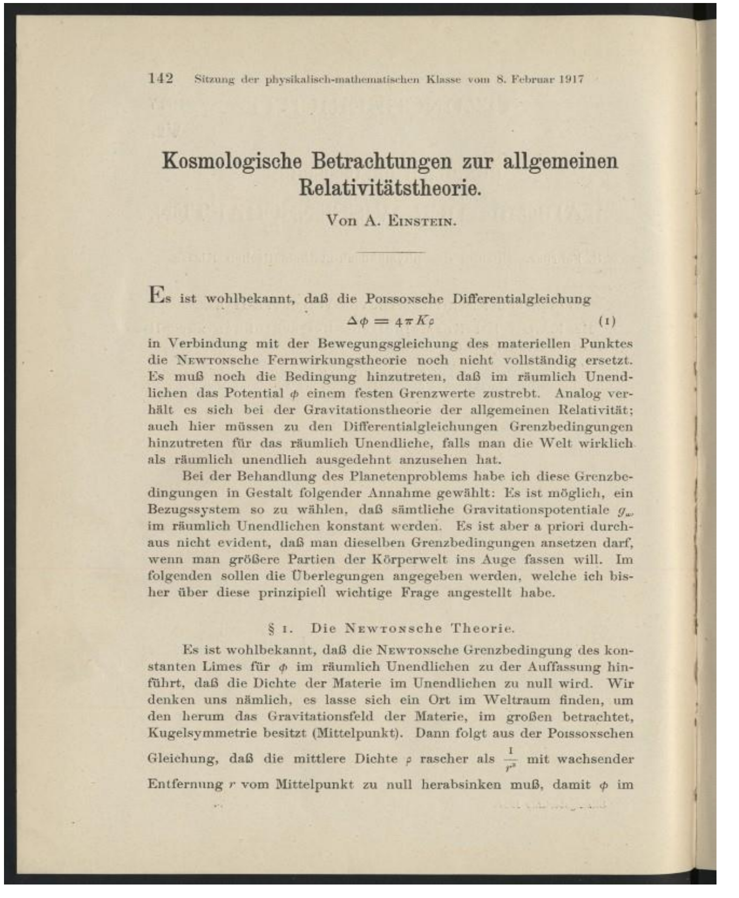
6 Lines of Thought to 6 parameter model

I. General relativity and the Universe

Asking for a Homogenous and Isotropic one!

GR+ Homogenous and Isotropic Universe (Einstein Cosmological Principle ECP)

- Nonemprerical theory assessment
- From solar system to the Universe



142 Sitzung der physikalisch-mathematischen Klasse vom 8. Februar 1917

Kosmologische Betrachtungen zur allgemeinen Relativitätstheorie.

Von A. Einstein.

Es ist wohlbekannt, daß die Poissonsche Differentialgleichung

$$\Delta\phi = 4\pi K\rho \qquad (1)$$

in Verbindung mit der Bewegungsgleichung des materiellen Punktes die Newtonsche Fernwirkungstheorie noch nicht vollständig ersetzt. Es muß noch die Bedingung hinzutreten, daß im räumlich Unendlichen das Potential ϕ einem festen Grenzwerte zustrebt. Analog verhält es sich bei der Gravitationstheorie der allgemeinen Relativität; auch hier müssen zu den Differentialgleichungen Grenzbedingungen hinzutreten für das räumlich Unendliche, falls man die Welt wirklich als räumlich unendlich ausgedehnt anzusehen hat.

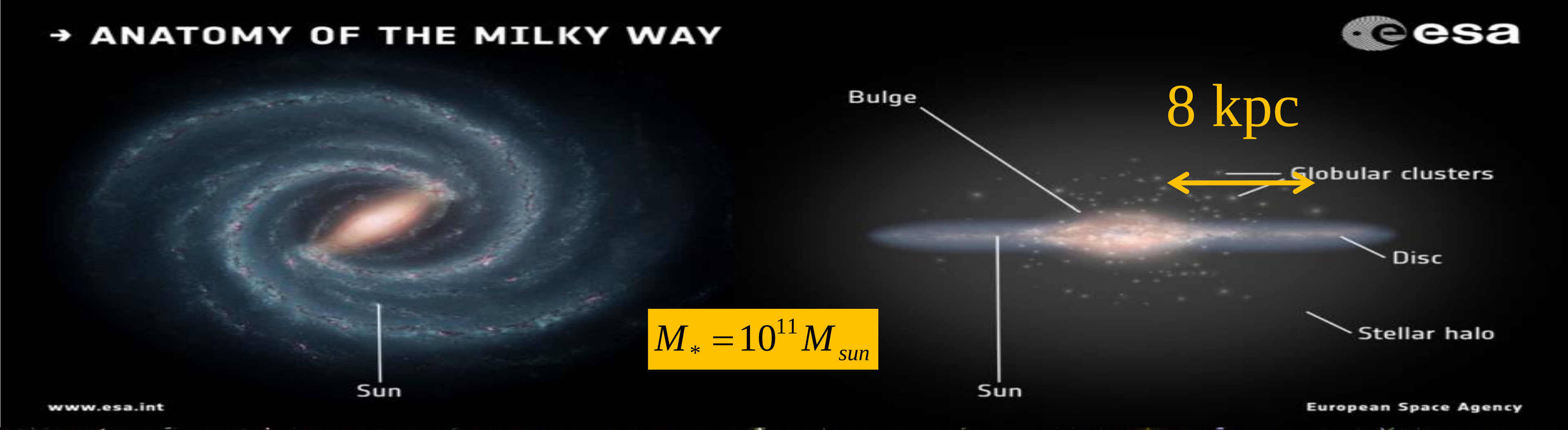
Bei der Behandlung des Planetenproblems habe ich diese Grenzbedingungen in Gestalt folgender Annahme gewählt: Es ist möglich, ein Bezugssystem so zu wählen, daß sämtliche Gravitationspotentiale $g_{\mu\nu}$ im räumlich Unendlichen konstant werden. Es ist aber a priori durchaus nicht evident, daß man dieselben Grenzbedingungen ansetzen darf, wenn man größere Partien der Körperwelt ins Auge fassen will. Im folgenden sollen die Überlegungen angegeben werden, welche ich bisher über diese prinzipiell wichtige Frage angestellt habe.

§ 1. Die Newtonsche Theorie.

Es ist wohlbekannt, daß die Newtonsche Grenzbedingung des konstanten Limes für ϕ im räumlich Unendlichen zu der Auffassung hinführt, daß die Dichte der Materie im Unendlichen zu null wird. Wir denken uns nämlich, es lasse sich ein Ort im Weltraum finden, um den herum das Gravitationsfeld der Materie, im großen betrachtet, Kugelsymmetrie besitzt (Mittelpunkt). Dann folgt aus der Poissonschen Gleichung, daß die mittlere Dichte ρ rascher als $\frac{1}{r^2}$ mit wachsender Entfernung r vom Mittelpunkt zu null herabsinken muß, damit ϕ im

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$ds^2 = -c^2 dt^2 + a^2(t)[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\varphi^2)]$$



8 kpc

$M_* = 10^{11} M_{sun}$

$\mathbf{1}\ \boldsymbol{parsec} = \mathbf{3.26}\ \boldsymbol{ly} = \mathbf{3.1} \times \mathbf{10^{16}}\ \boldsymbol{meter}$

Hubble deep field

Empirical Evidence of ECP

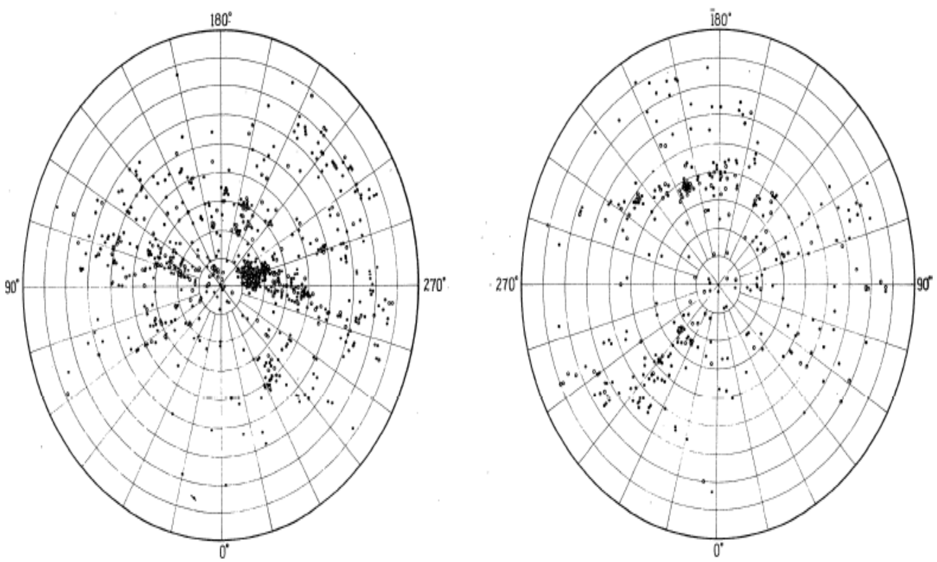
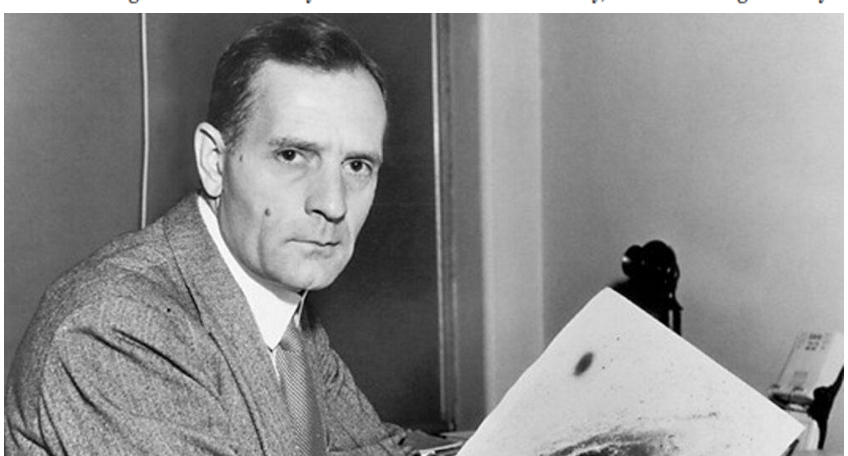


FIGURE 2.2. The Shapley and Ames (1932) map of galaxies brighter than apparent magnitude 13. Courtesy of the John G. Wolbach Library, Harvard College Library.



(1971-1885) Harlow Shapley

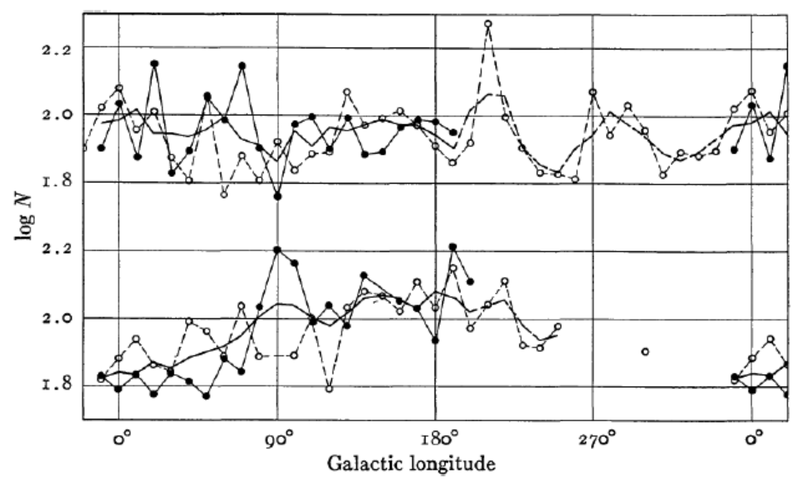


FIGURE 2.3. Hubble's (1934) counts of galaxies at high galactic latitudes in the upper curves, and at low latitudes in the lower curves. © AAS. Reproduced with permission.

Empirical Evidence of ECP

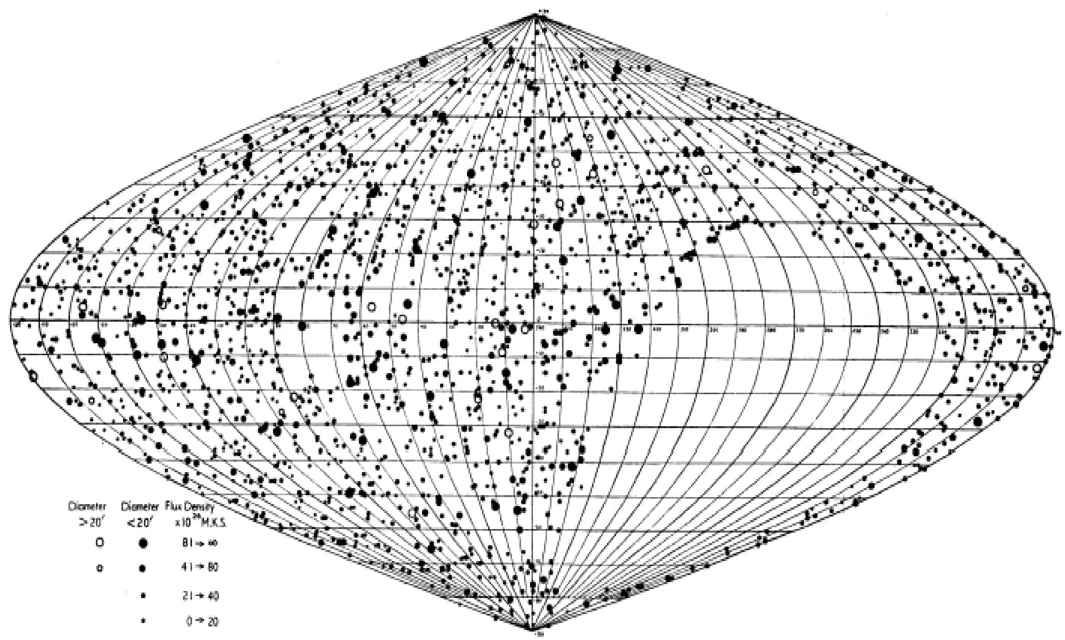
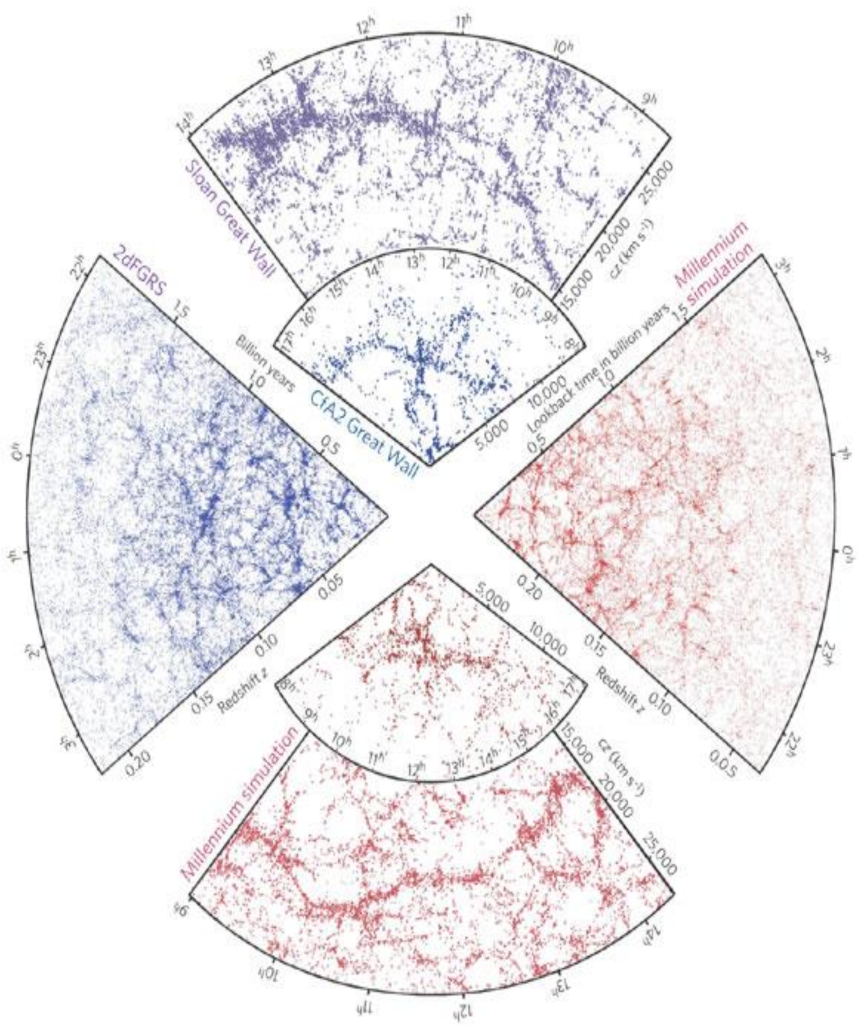


FIGURE 2.4. The Second Cambridge Catalog of Radio Sources (Shakeshaft, Ryle, Baldwin, et al. 1955).

One antenna of the One-Mile Telescope (left), two of the Half-Mile Telescope (centre) and the remains of the 4C Array (right)

Empirical Evidence of ECP



The Sloan Digital Sky Survey or SDSS is a major multi-spectral imaging and spectroscopic redshift survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico

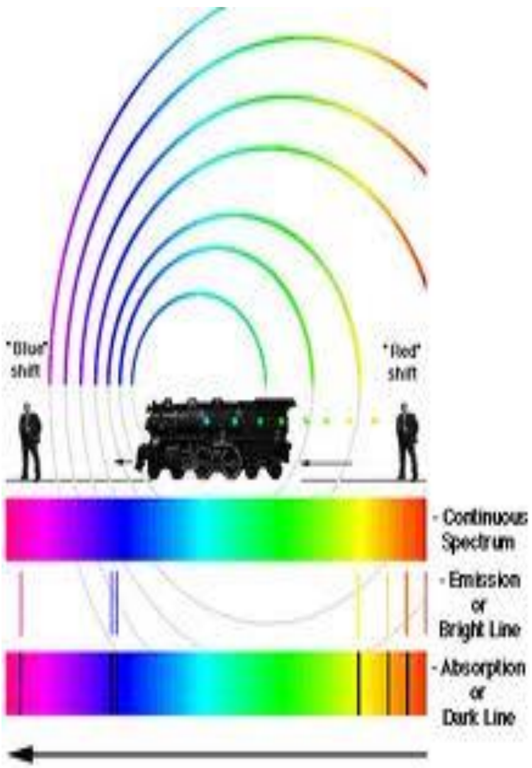
6 Lines of Thought to 6 parameter model

I. General relativity and the Universe

Asking for a Homogenous and Isotropic one!

II. Expanding Universe and measuring Ω

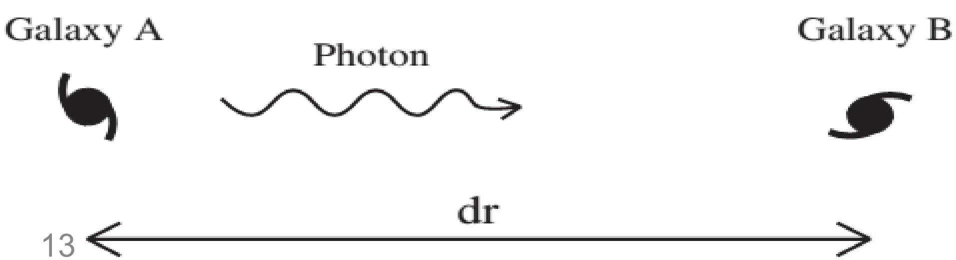
An idea from Mozart's Neighbor to Harvard Computers



Female astronomers at Harvard. Credit: Harvard University Archive, Williamina Fleming, Henrietta Leavitt Edward Pickering

$$z \sim \frac{v}{c}$$

$$z = \frac{\lambda_{obs} - \lambda_{em}}{\lambda_{em}}$$



Albert Einstein, Edwin Hubble, and Walter Adams (l-r) in 1931 at the Mount Wilson Observatory 100" telescope, in the San Gabriel Mountains of southern California.

The Dynamics of the Universe

- The fundamental equations that governs the dynamics + GR

$$H^2 = (\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}(\rho_\gamma + \rho_m + \rho_b + \rho_\nu + \rho_\Lambda) - \frac{k}{a^2}$$

$$\rho_c = \frac{3H_0^2}{8\pi G} \rightarrow \Omega_i = \rho_i / \rho_c$$

- For a flat (Omega=1) homogenous and isotropic universe

$$H^2 = H_0^2(\Omega_\gamma (1+z)^4 + \Omega_{m(dm+baryon)}(1+z)^3 + \Omega_\Lambda)$$

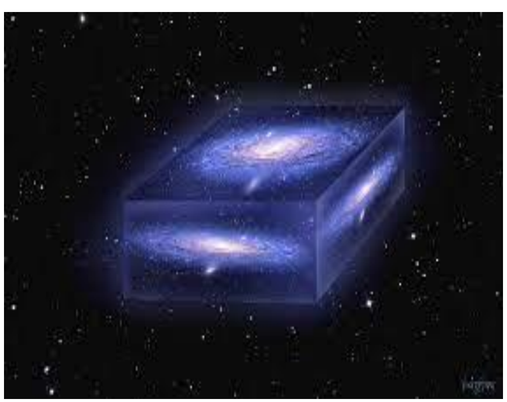
	Source	Ω_m	Comment
1	Hubble (1936)	0.002	galaxy counts and masses
2	Hubble (1936)	0.2	mass per galaxy in clusters
3	Oort (1958)	0.03	$j = 2.9 \times 10^8 h, M/L = 29h$
4	van den Bergh (1961)	0.024	$j = 2.7 \times 10^8 h, M/L = 25h$
5	Fall (1975)	0.01 to 0.05	Irvine-Layzer equation
6	Gott and Turner (1976)	0.08	$j = 0.9 \times 10^8 h, M/L = 240h$
7	Seldner and Peebles (1977)	0.69 ± 0.11	cluster ξ_{cp} and ξ_{cg}
8	Peebles (1979)	0.4 ± 0.2	relative velocity dispersion
9	Yahil, Sandage, and Tammann (1980)	0.04 ± 0.02	Virgocentric flow
10	Davis et al. (1980)	0.4 ± 0.1	Virgocentric flow
11	Tonry and Davis (1981)	$0.5^{+0.3}_{-0.15}$	Virgocentric flow
12	Aaronson et al. (1982)	0.10 ± 0.03	Virgocentric flow
13	Davis and Peebles (1983a)	$0.2e^{\pm 0.4}$	relative velocity dispersion
14	Bean et al. (1983)	$0.14 \times 2^{\pm 1}$	relative velocity dispersion
15	Loh and Spillar (1986b)	$0.9^{+0.7}_{-0.5}$	redshift-magnitude relation[c]
16	Peebles (1986)	0.2 to 0.35	cluster ξ_{cp} and ξ_{cg}
17	Yahil, Walker, and Rowan-Robinson (1986)	0.85 ± 0.16	motion of the Local Group
18	Strauss and Davis (1988)	0.4 to 0.9	motion of the Local Group
19	Blumenthal, Dekel, and Primack (1988)	~ 0.3	large-scale clustering[a]
20	Regős and Geller (1989)	$\lesssim 0.5$	clustercentric flow
21	Lynden-Bell, Lahav, and Burstein (1989)	~ 0.2	motion of the Local Group
22	Efstathiou, Sutherland, and Maddox (1990)	~ 0.3	large-scale clustering[a]
23	Bahcall and Cen (1992)	~ 0.25	rich clusters in CDM[a,c]
24	Strauss et al. (1992)	0.27 to 0.76	motion of the Local Group
25	Vogeley et al. (1992)	~ 0.3	large-scale clustering[a]
26	Briel, Henry, and Böhringer (1992)	0.14 ± 0.07	cluster baryon fraction[b,c]
27	White et al. (1993)	$\simeq 0.2$	cluster baryon fraction[b,c]
28	Dekel et al. (1993)	0.5 to 3	velocity and gravity fields
29	Fisher et al. (1994)	0.1 to 0.6	mean flow convergence
30	Hudson et al. (1995)	0.61 ± 0.18	velocity and gravity fields
31	Shaya, Peebles, and Tully (1995)	0.17 ± 0.10	Virgocentric flow
32	Davis, Nusser, and Willick (1996)	0.2 to 0.4	velocity and gravity fields
33	Bahcall, Fan, and Cen (1997)	0.34 ± 0.13	evolution of rich clusters[a,c]
34	Carlberg et al. (1997)	0.19 ± 0.06	cluster masses
35	Eke et al. (1998)	0.36 ± 0.25	evolution of rich clusters[a,c]
36	Willick and Strauss (1998)	0.31 ± 0.05	velocity and gravity fields
37	Schmoldt et al. (1999)	$0.43^{+0.29}_{-0.17}$	motion of the Local Group
38	Tadros et al. (1999)	$0.28^{+0.18}_{-0.14}$	mean flow convergence
39	Hamilton, Tegmark, and Padmanabhan (2000)	$0.23^{+0.13}_{-0.11}$	mean flow convergence
40	Percival et al. (2001)	0.29 ± 0.04	BAO[a,c]
41	Hawkins et al. (2003)	0.31 ± 0.09	mean flow convergence
42	Feldman et al. (2003)	$0.30^{+0.17}_{-.07}$	relative peculiar velocities[c]

Vacant and Vast

- Critical Density $\rho_c = \dfrac{3H_0^2}{8\pi G}$

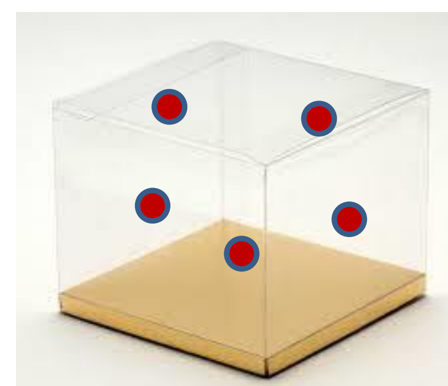
$$H_0 = 100h[km/s/Mpc](h \sim 0.7) \rightarrow \begin{matrix} H_0^{-1} = 9.77h^{-1} \times 10^9 yr \\ cH_0^{-1} = 3000h^{-1} Mpc \end{matrix}$$

$$H_0 \approx 70[km/s/Mpc] \rightarrow \rho_c = 1.88h^2 \times 10^{-26} kgm^{-3}$$

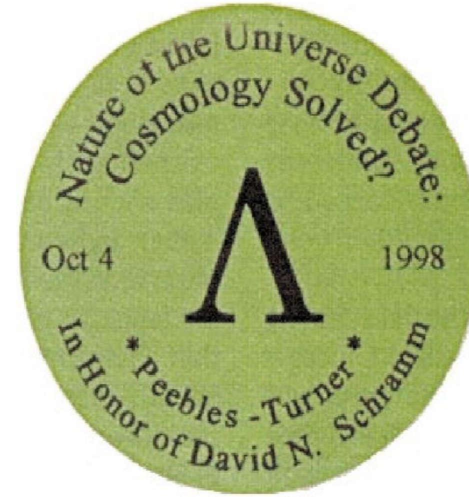


$0.1 Milky-way/Mpc^3$

$5\, proton/m^3$



Science of 2010-1926 –Alan Sandage
measuring two quantities + DE



$$H=\frac{\dot a}{a},\ q=-\frac{\ddot a}{a\dot a}$$

$$\frac{\ddot a}{a}=-\frac{4\pi G}{3}(\rho+3p)>0$$

Photo: Lawrence Berkeley National Lab — **Saul Perlmutter**

Photo: Belinda Pratten, Australian National University — **Brian P. Schmidt**

Photo: Scanpix/AFP — **Adam G. Riess**

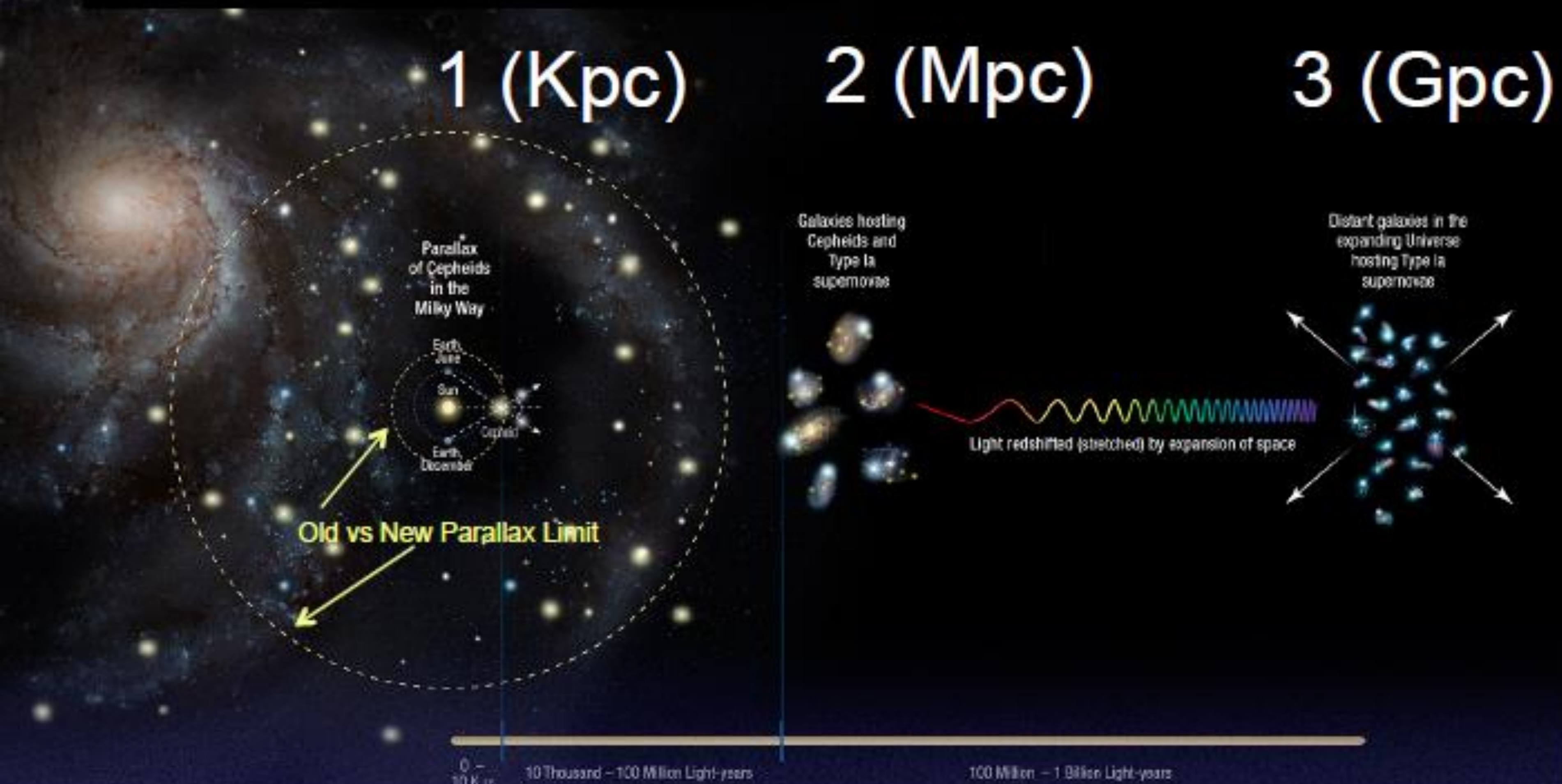
The Nobel Prize in Physics 2011 was awarded *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"* with one half to Saul Perlmutter and the other half jointly to Brian P. Schmidt and Adam G. Riess.

Artist's rendition of a white dwarf accumulating mass from a nearby companion star. This type of progenitor system would be considered single degenerate.

Image courtesy of David A. Hardy, © David A. Hardy/www.astroart.org.

Adam Riess et al. Astron.J. 116 (1998) 1009-1038 (H-z)
Perlmutter et al. Astrophys.J. 517 (1999) 565-586 (SCP)

Our route: 3 Steps to H_0



 1:Geometry→Cepheids 2: Cepheids→SN Ia 3:SN Ia →z,H_0

6 Lines of Thought to 6 parameter model

I. General relativity and the Universe

Asking for a Homogenous and Isotropic one!

II. Expanding Universe and measuring Ω

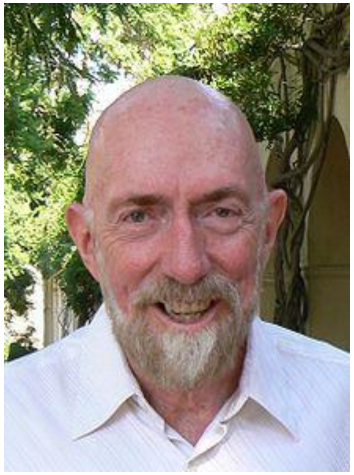
III. Cosmic Microwave Background Radiation

After World war II – Princeton days

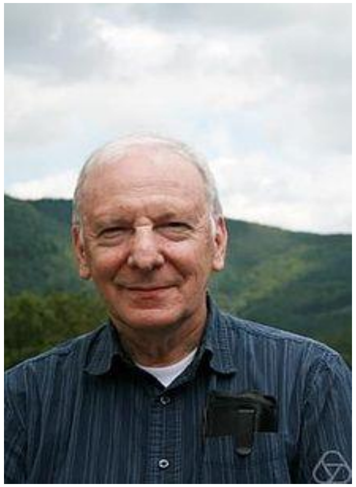
Fig. 1. Members of the senior faculty in the Department of Physics, Palmer Physical Laboratory, Princeton University, in about 1950: from the left Rubby Sherr, Allen Shenstone, Donald Hamilton, Eric Rogers, Robert Dicke, Walker Bleakney, John Wheeler, Rudolf Ladenburg, and Eugene Wigner.

R. Feymann

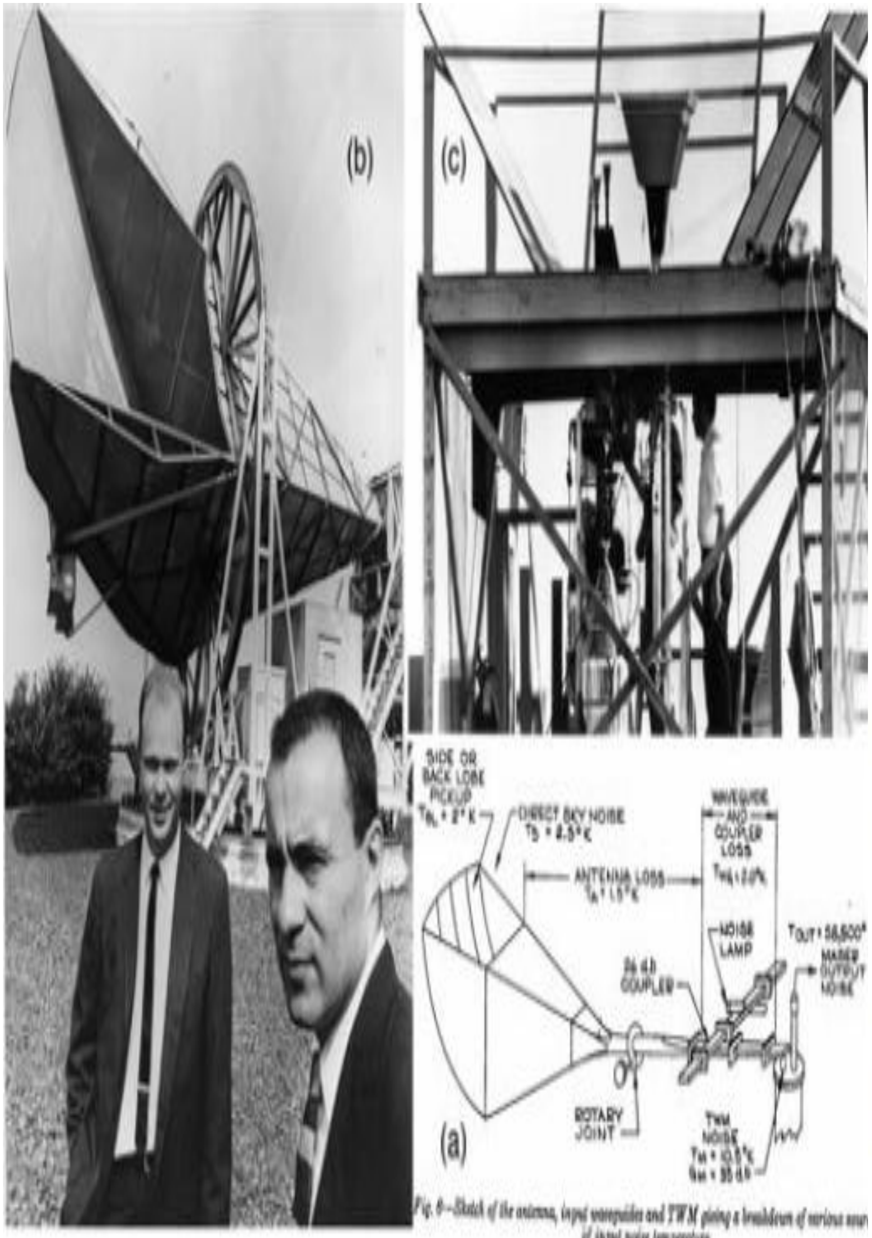
B. Mashhoon



K. Thorne



R. Wald



Identifying the sea of thermal radiation.

Wilkinson, Peebles, and Dicke left to right, in the late 1970s.

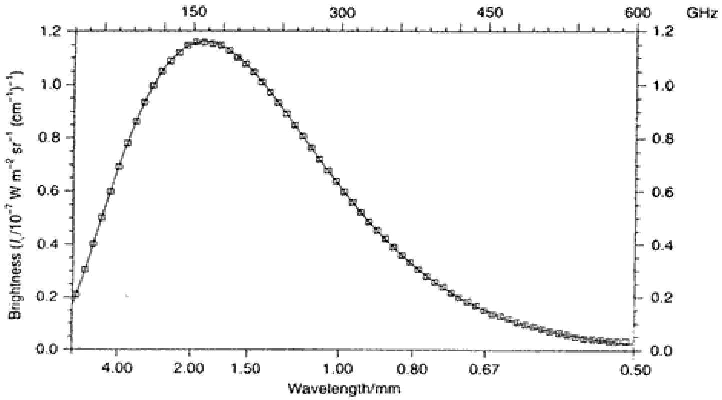
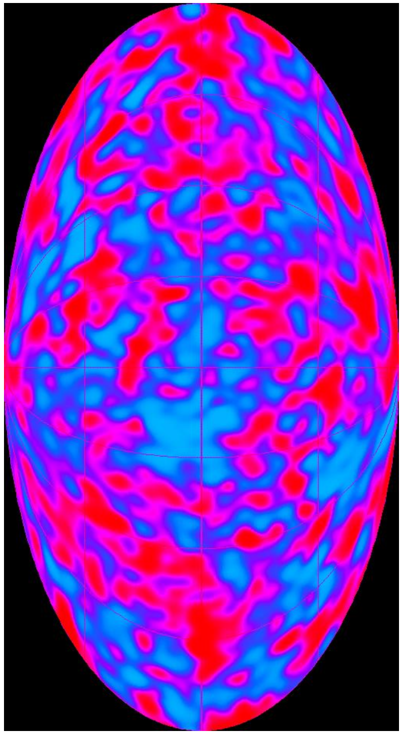
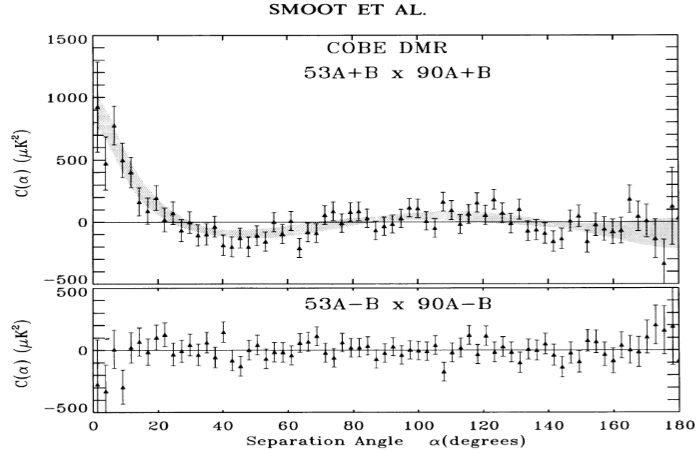


Fig. 2.1. The first published spectrum of the Cosmic Microwave Background Radiation as measured by the COBE satellite in the direction of the North Galactic Pole (Mather *et al.* 1990). Within the quoted errors, the spectrum is precisely that of a perfect black body at radiation temperature 2.735 ± 0.06 K. The more recent spectral measurements are discussed in the text. The units adopted for frequency on the ordinate are cm^{-1}. A useful conversion to more familiar units is 10^{-7} W m^{-2} sr^{-1} (cm^{-1})$^{-1}$ = 3.34×10^{-18} W m^{-2} Hz^{-1} sr^{-1} = 334 MJ sr^{-1}.

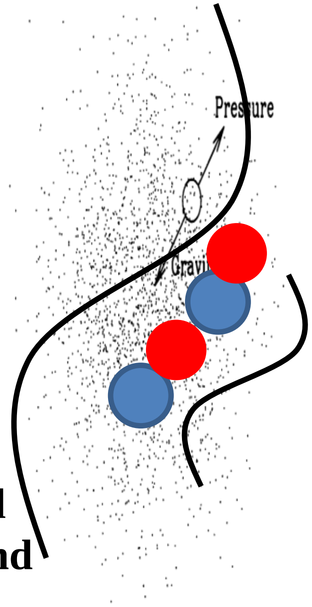


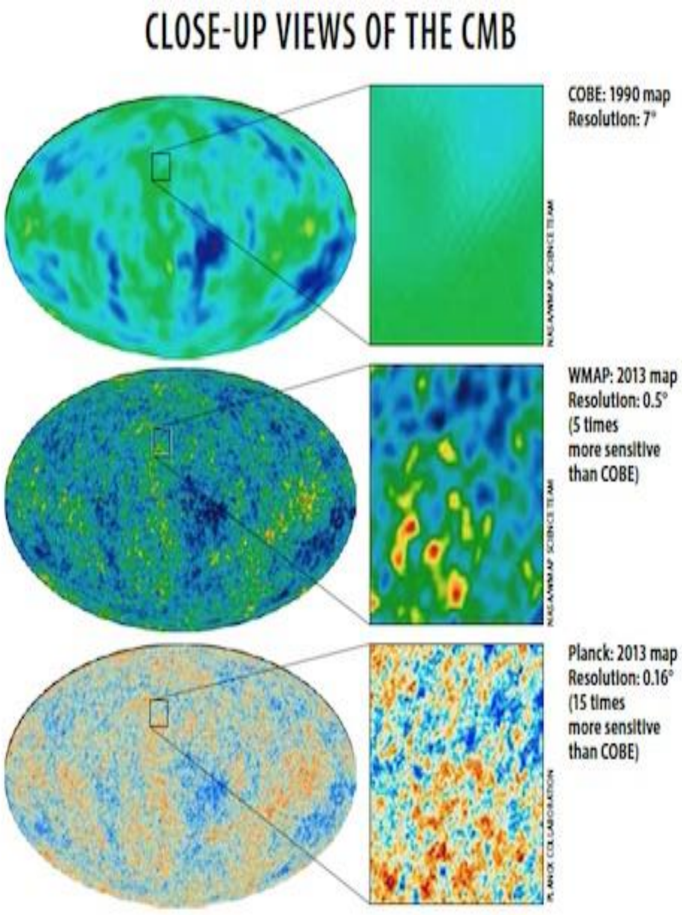


$$\varepsilon(\nu)d\nu = \frac{8\pi h}{c^3}\frac{\nu^3 d\nu}{e^{h\nu/kT}-1}$$

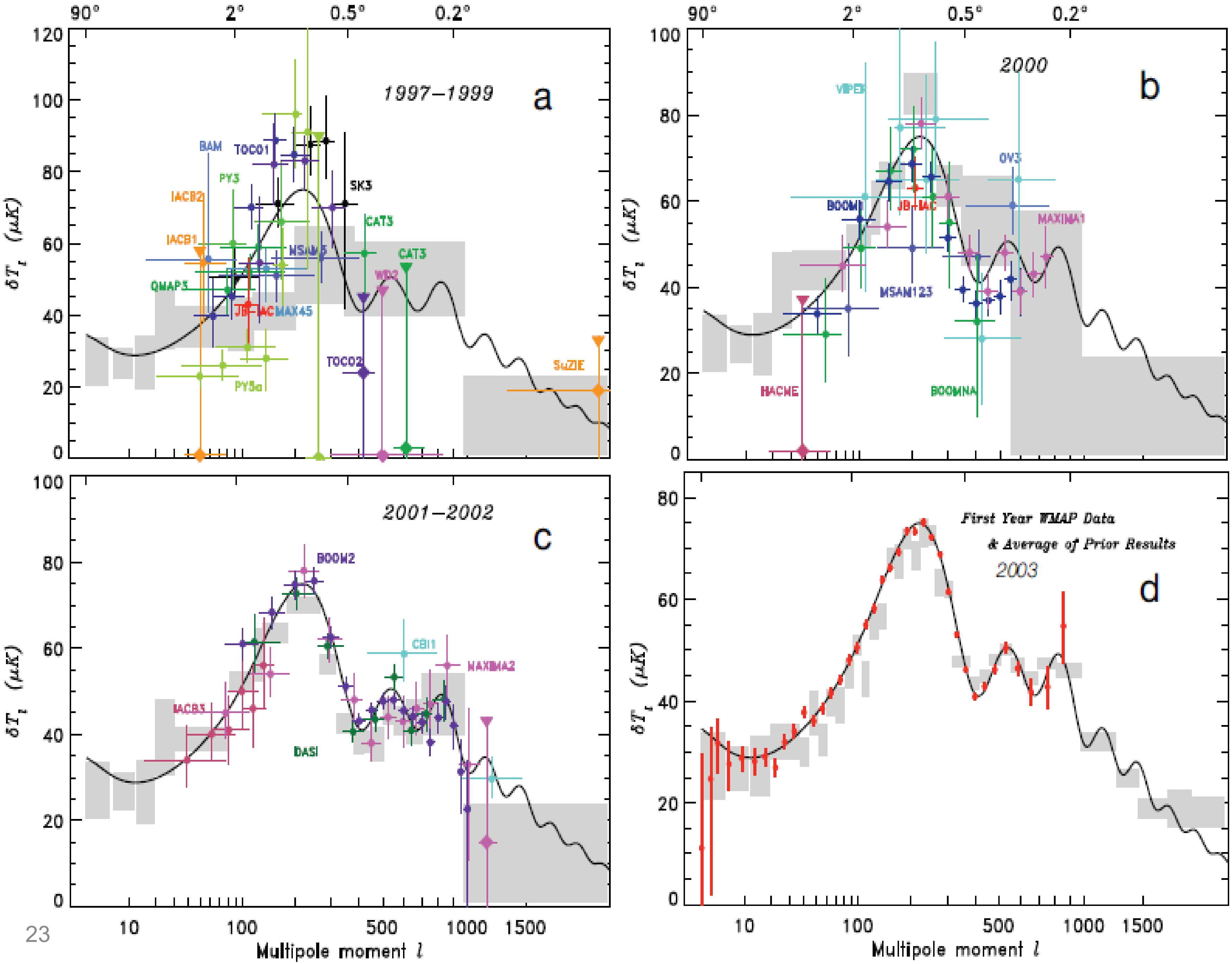
$$\varepsilon_{rad} = \alpha T^4$$

$$\alpha = 7.565\times10^{-16}\,Joule.m^{-3}Kelvin^{-4}$$



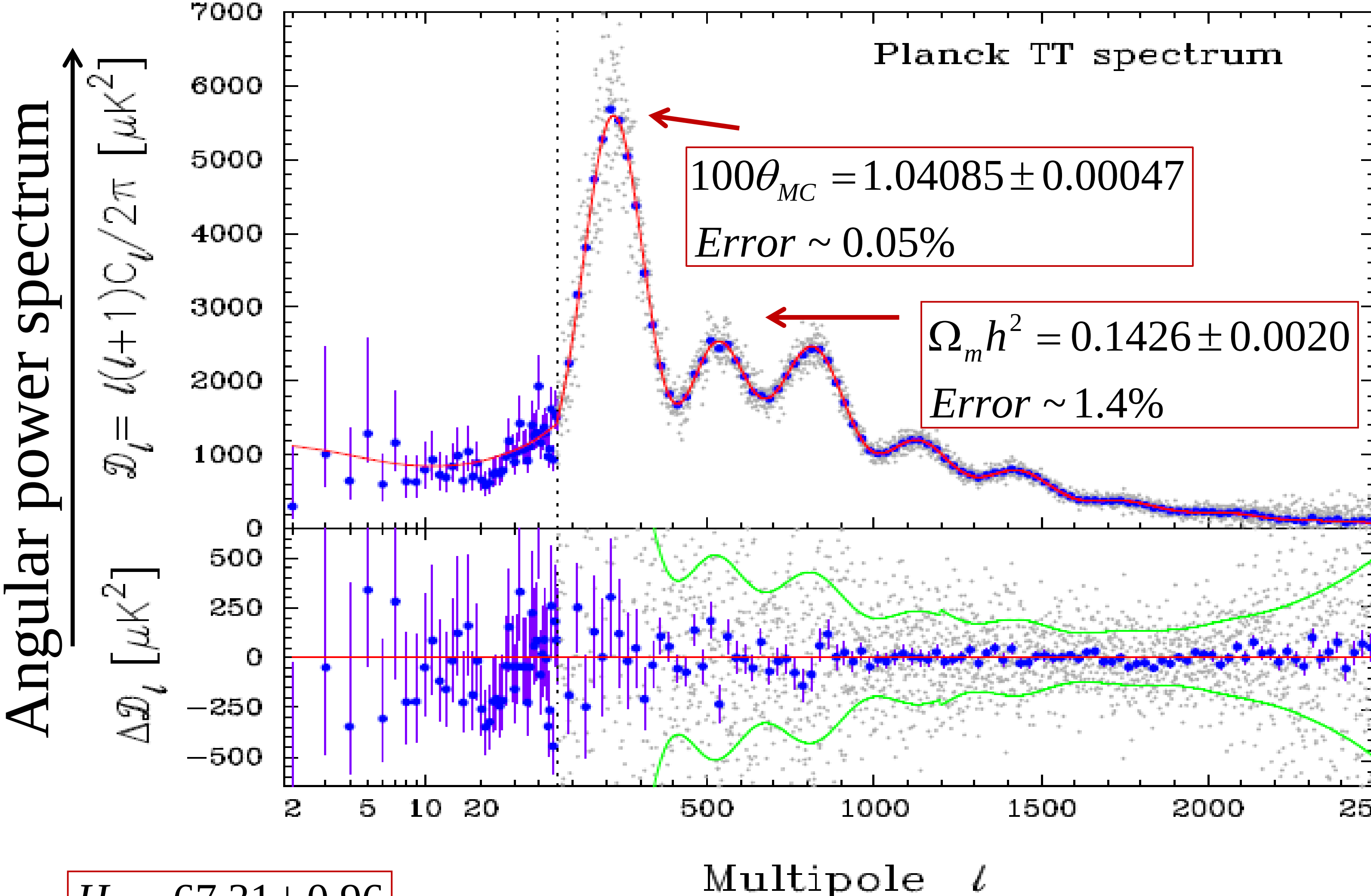


The Nobel Prize in Physics 2006
John C. Mather and George F. Smoot
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"



1997–1999
a
2000
b
2001–2002
c
First Year WMAP Data
& Average of Prior Results
2003
d
90°
2°
0.5°
0.2°
δT_l (μK)
Multipole moment l
10
100
500
1000
1500
BAM
TOCO1
PY3
SK3
IACB2
IACB1
CAT3
MSAM3
QMAP3
JB-IAC
MAX45
TOCO2
WD2
PY5a
SuZIE
VIPER
BOOMI
JB-IAC
OV3
MAXIMA1
MSAM123
HACME
BOOMNA
BOOM2
CBI1
MAXIMA2
IACB3
DASI

The Early Universe with the eyes of Planck



$100\theta_{MC} = 1.04085 \pm 0.00047$

$Error \sim 0.05\%$

$\Omega_m h^2 = 0.1426 \pm 0.0020$

$Error \sim 1.4\%$

Ω_b

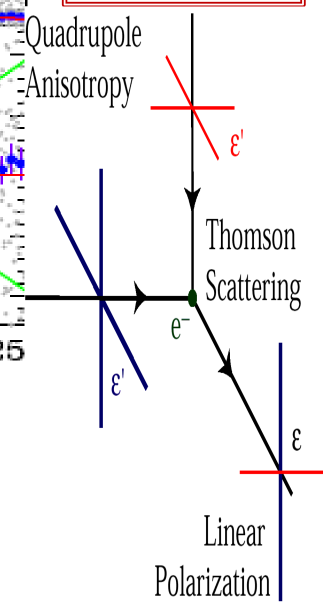
Ω_c

$100\theta_{MC}$

τ

A

n_s



$H_0 = 67.31 \pm 0.96$

$Error \sim 1.4\%$

Planck 2015 results. XIII. Cosmological parameters

6 Lines of Thought to 6 parameter model

I. General relativity and the Universe

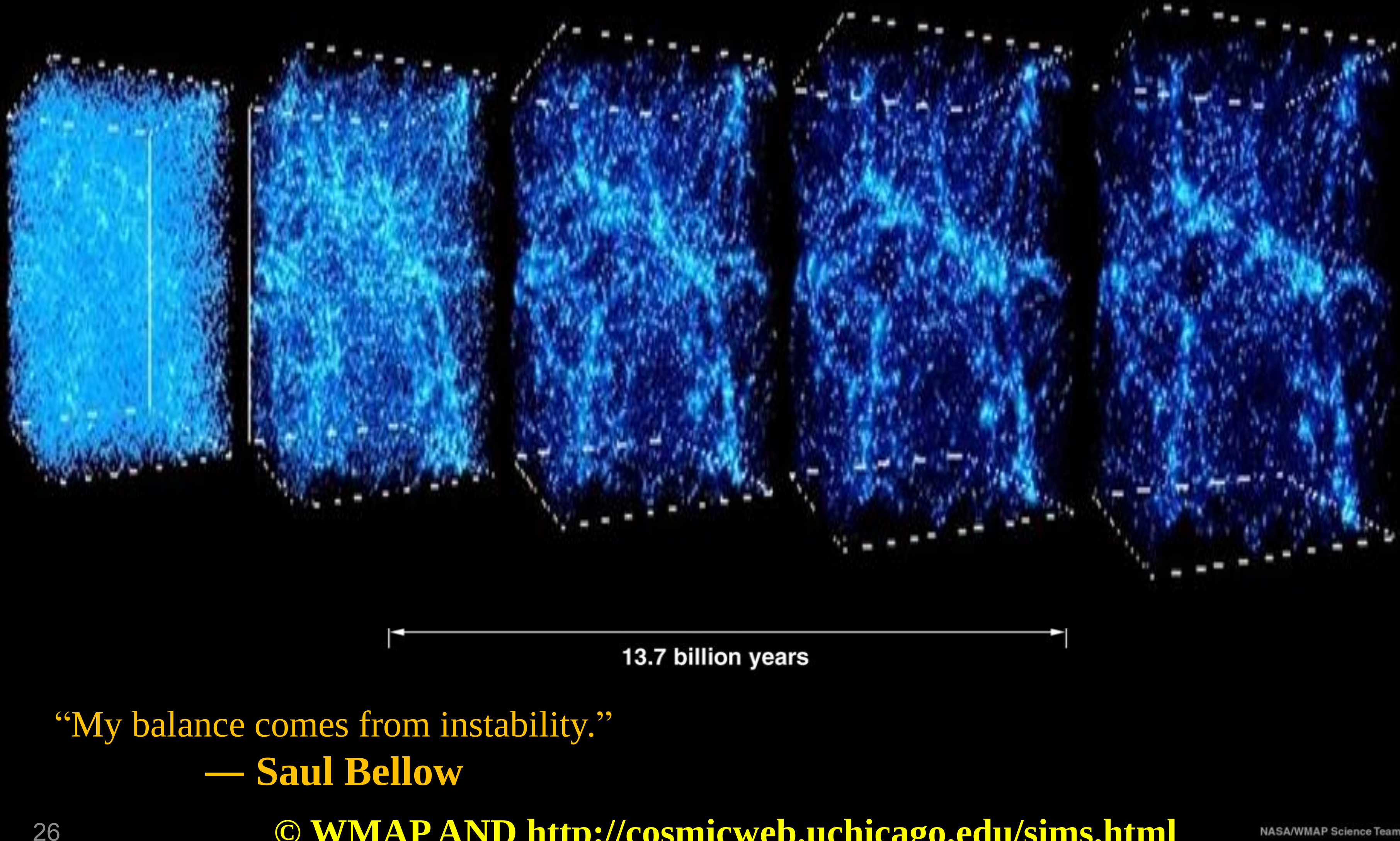
Asking for a Homogenous and Isotropic one!

II. Expanding Universe and measuring Ω

III. Cosmic Microwave Background Radiation

IV. Structure Formation and LSS

Cosmic Evolution and Gravitational instability



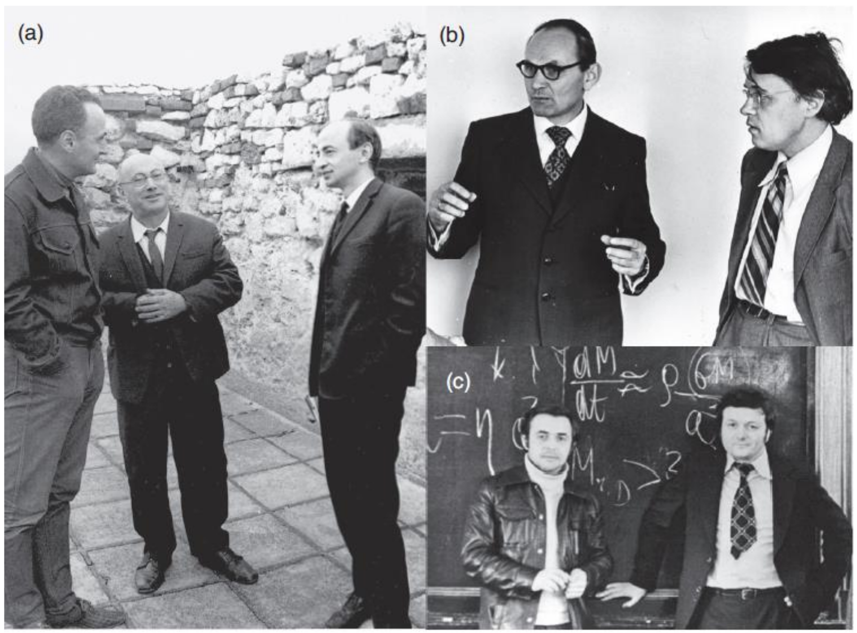
"My balance comes from instability."

— Saul Bellow

Statistical Methods and 2 point correlations and the story of the two schools

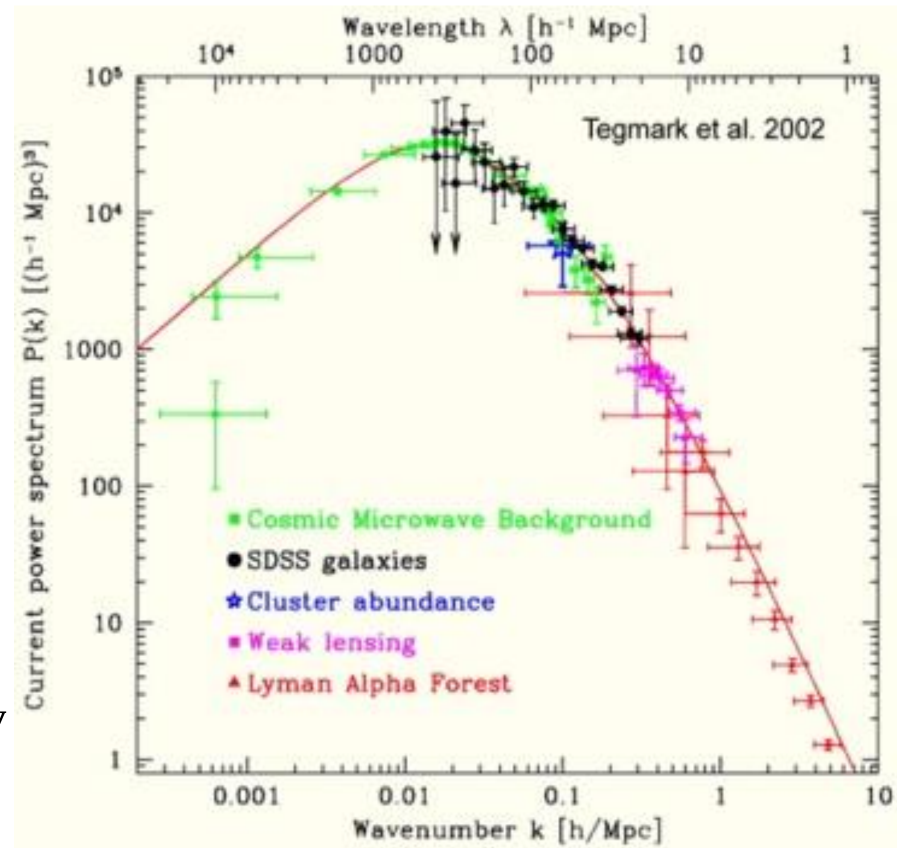
$$P(k) = \langle |\delta_k|^2 \rangle \leftrightarrow \delta_m = \frac{\rho}{\bar{\rho}} - 1$$

$$\xi(\vec{r}) = \langle \delta(\vec{x})\delta(\vec{x}+\vec{r}) \rangle$$



Cosmology in the Soviet Union.

(a) George Marx, Yakov Zel’dovich, and Igor Novikov (left to right) in Hungary in about 1970
(b) Jaan Einasto, left, and Andrei Doroshkevich at a Conference in Tallinn in 1977 and
(c)Nikolay Shakura, left, and Rashid Sunyaev in the 1970s.

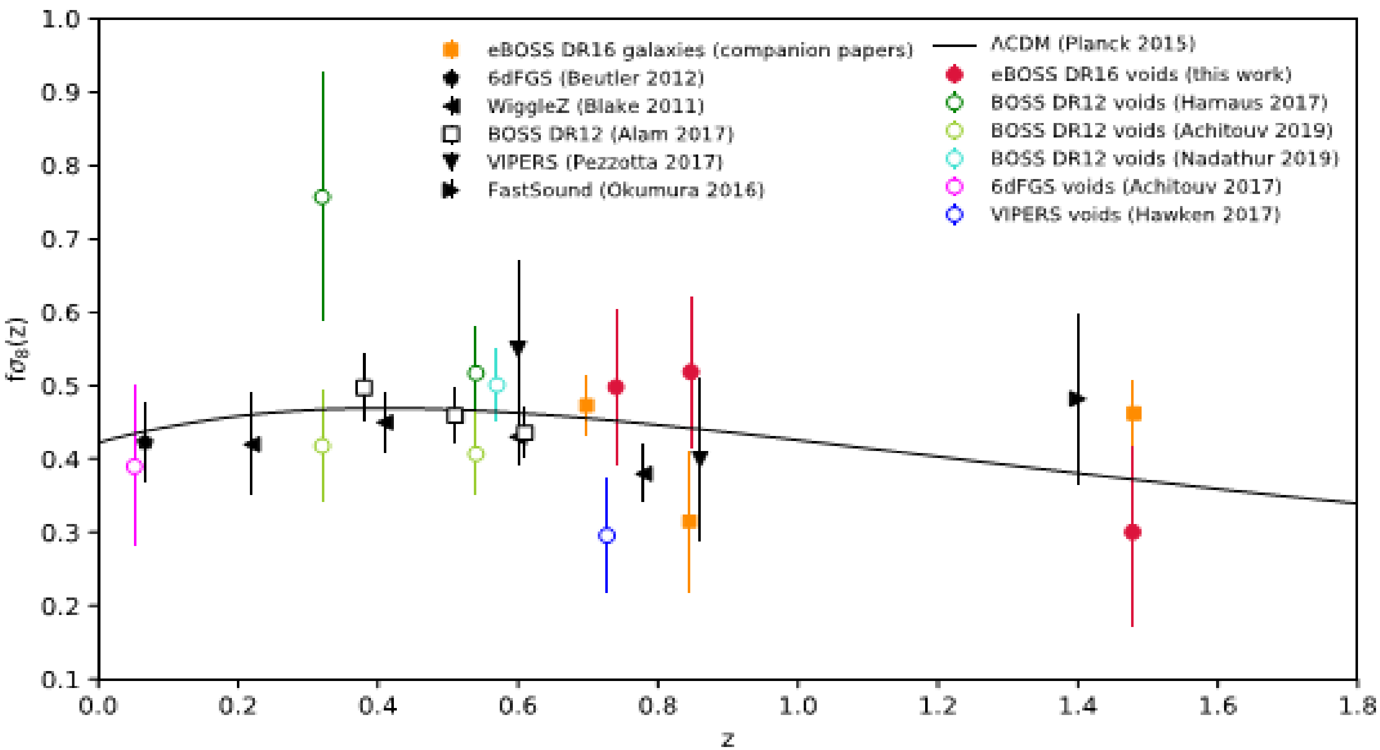


MNRAS 000, 1–18 (2020) Preprint 20 July 2020 Compiled using MNRAS LATEX style file v3.0

https://arxiv.org/abs/2007.09013

The Completed SDSS-IV Extended Baryon Oscillation Spectroscopic Survey: Growth rate of structure measurement from cosmic voids

Marie Aubert[1⋆], Marie-Claude Cousinou[1], Stéphanie Escoffier[1], Adam J. Hawken[1], Seshadri Nadathur[2], Shadab Alam[3], Julian Bautista[2], Etienne Burtin[4], Arnaud de Mattia[4], Héctor Gil-Marín[5,6] Jiamin Hou[7], Eric Jullo[8], Richard Neveux[4], Graziano Rossi[9], Alex Smith[4], Amélie Tamone[10], Mariana Vargas Magaña[11]



6 Lines of Thought to 6 parameter model

I. General relativity and the Universe

Asking for a Homogenous and Isotropic one!

II. Expanding Universe and measuring Ω

III. Cosmic Microwave Background Radiation

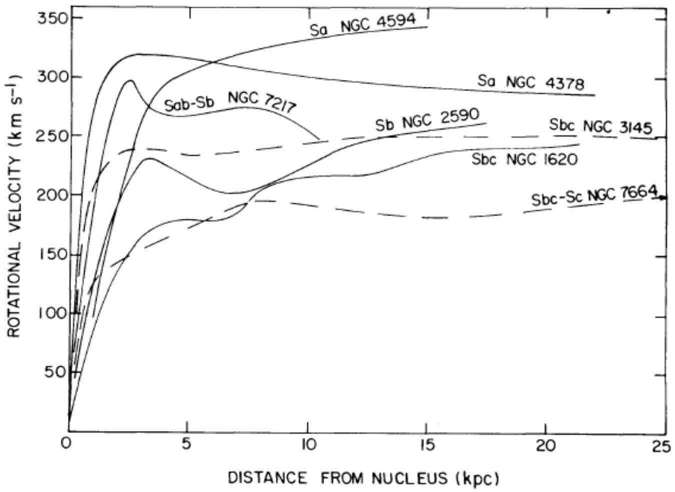
IV. Structure Formation and LSS

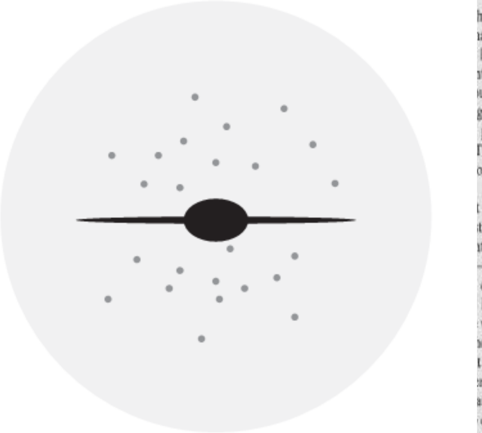
V. Subluminal matter

VI. Non-baryonic Dark Matter

Something is missing! + Neutrinos

Vera Rubin and Kent Ford.





Feynman's Preface

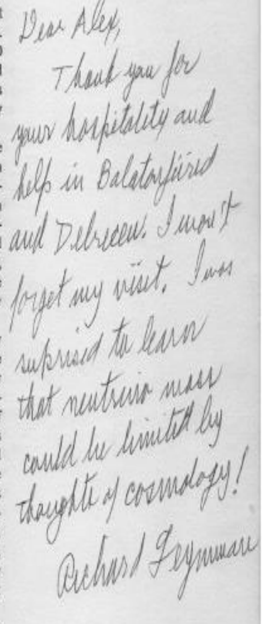
These are the lectures in physics that I gave last year and the year before to the freshman and sophomore classes at Caltech. The lectures are, of course, not verbatim—they have been edited, sometimes extensively and sometimes less so. The lectures form only part of the complete course. The whole group of 180 students gathered in a big lecture room twice a week to hear these lectures and then they broke up into small groups of 15 to 20 students in recitation sections under the guidance of a teaching assistant. In addition, there was a laboratory session once a week.

h these lectures was to maintain the
art students coming out of the high
lot about how interesting and excit-
tum mechanics, and other modern
us course, many would be very dis-
grand, new, modern ideas presented
planes, electrostatics, and so forth,
The problem was whether or not we
ore advanced and excited student by

t to be a survey course, but are very
t intelligent in the class and to make
t student was unable to completely
—by putting in suggestions of appli-
directions outside the main line of
hard to make all the statements as
where the equations and ideas fitted
hey learned more—things would be
t is important to indicate what it is
r—be able to understand by deduc-
it is being put in as something new.
deduce them if they were deducible,
or to explain that it was a new idea which hadn't any basis in terms of things they had already learned and which was not supposed to be provable—but was just added in.

At the start of these lectures, I assumed that the students knew something when they came out of high school—such things as geometrical optics, simple chemistry ideas, and so on. I also didn't see that there was any reason to make the lectures

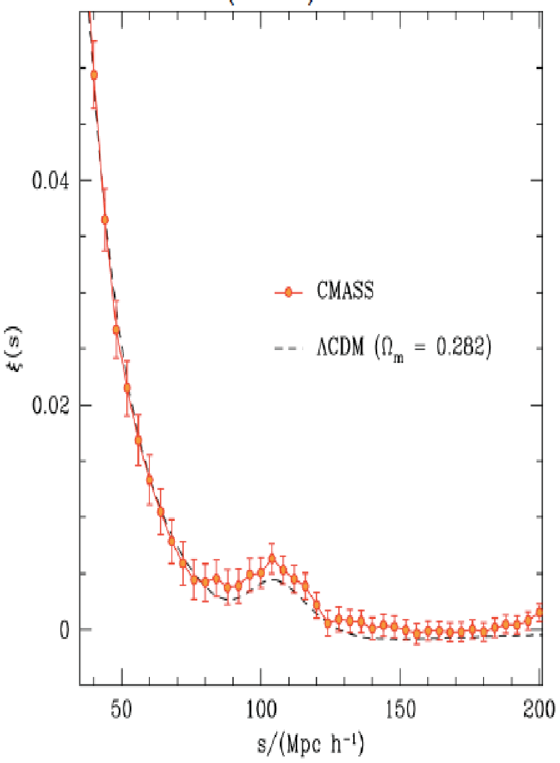
3

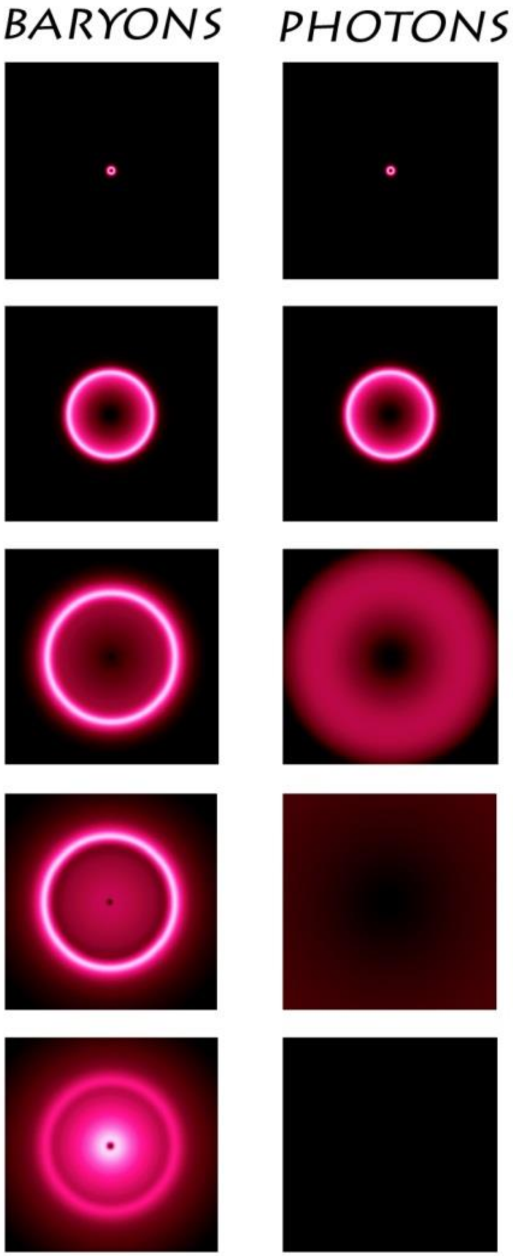


(Rubin,V.C., Ford, W.K. & Thonnard, N. 1978, Astrophys. J. 225, L107)

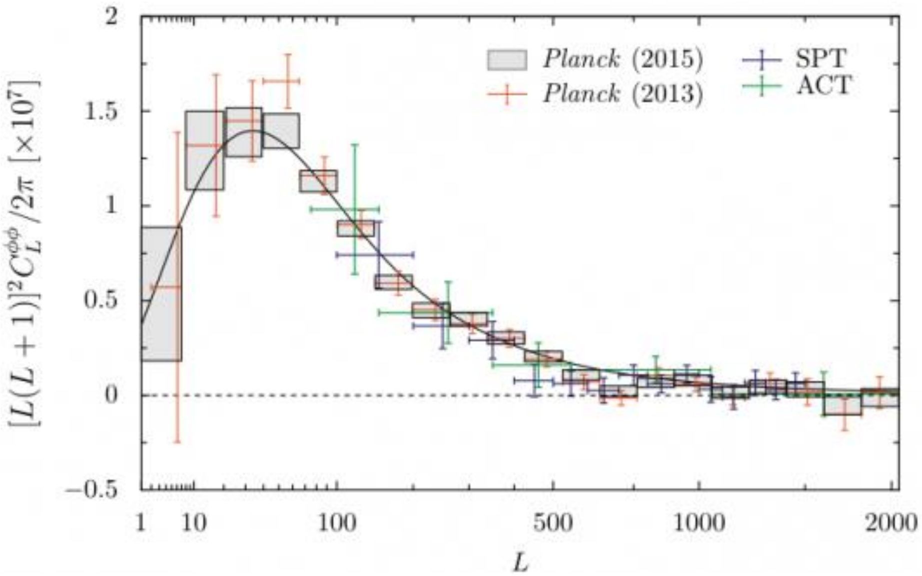
Mesmerizing Evidence of DM

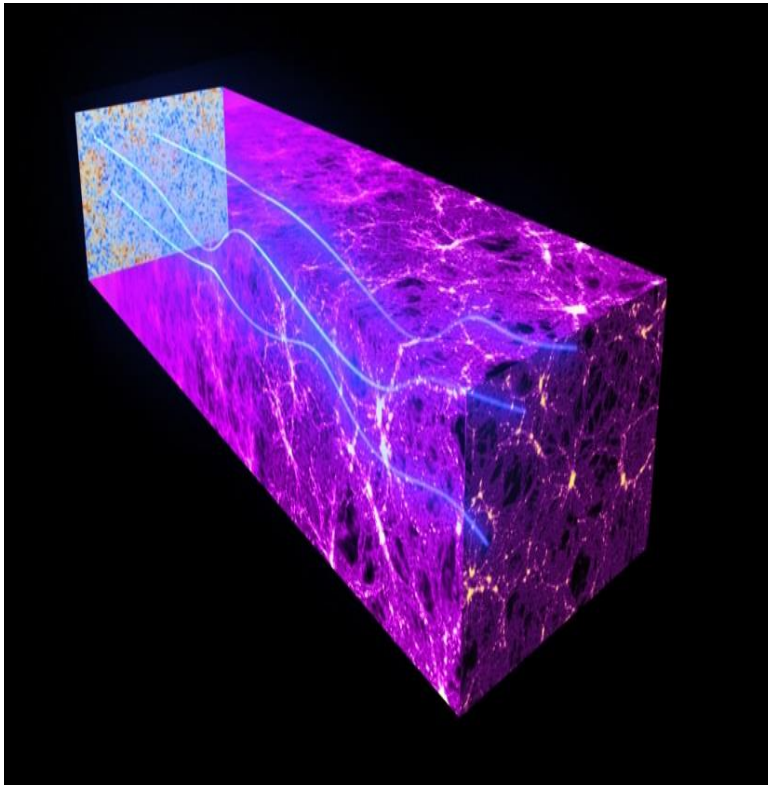
Sanchez+(2012)





CMB Lensing as an evidence of the DM





$$\tilde{\Theta}(\widehat{x}) = \Theta(\widehat{x'}) = \Theta(\widehat{x} + \overrightarrow{\nabla}\psi)$$

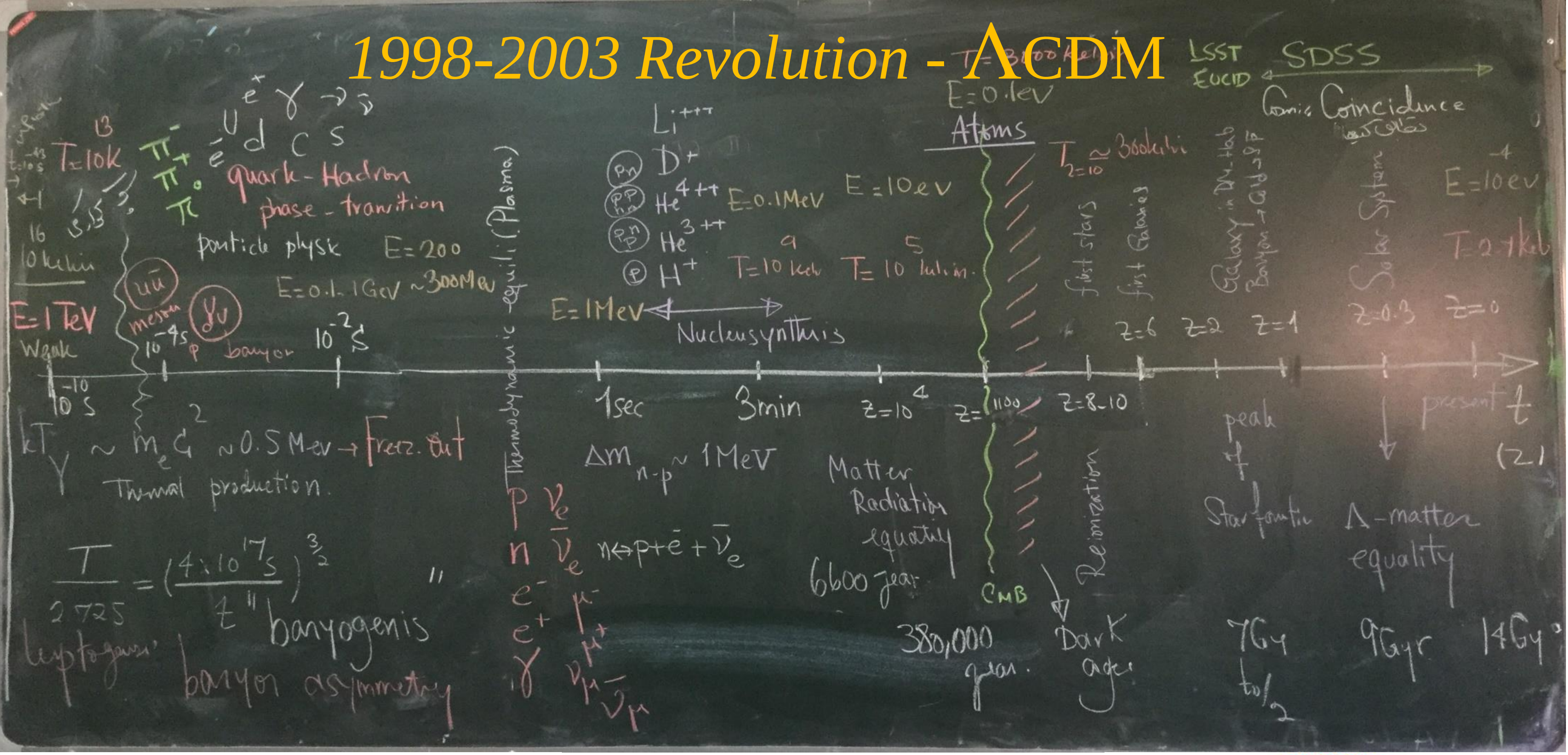
$$\psi(\widehat{n}) \equiv -2\int_0^{\chi_\infty} d\chi \left(\frac{\chi_\infty - \chi}{\chi_\infty \chi}\right) \Psi(\overrightarrow{x}, \eta)$$

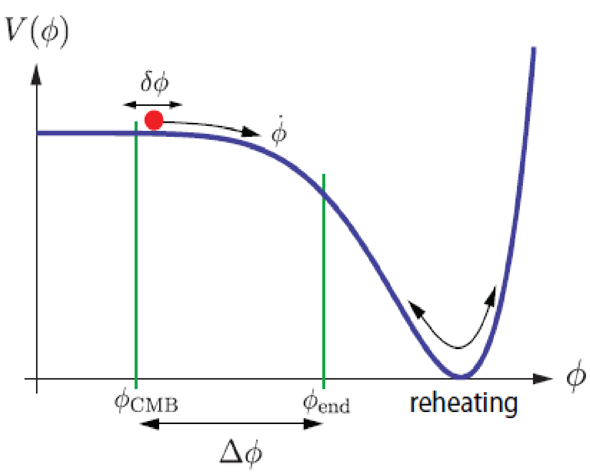
$$\overrightarrow{x} = \chi\widehat{n};\, \eta = \eta_0 - \chi$$

Cosmic Shear @ KIDs
M. Asgari

Farbod Hassani, SB, Hassan Firouzjahi, arXiv:1511.05534
Mohammad Ansari – Master Thesis.

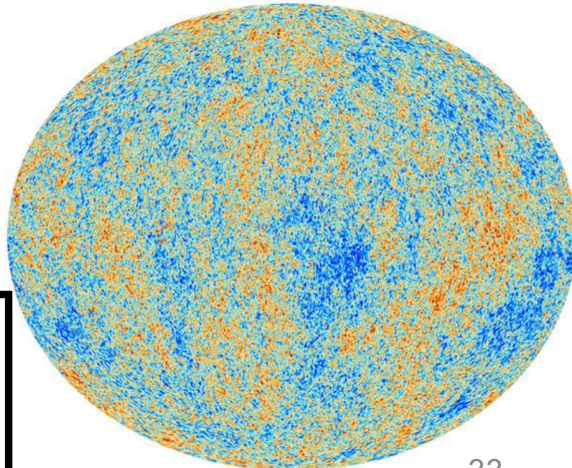
1998-2003 Revolution - ΛCDM





Ali Akbar Abolhasani

$$\Delta_s^2 = \frac{1}{2\pi^2} k^3 P_s(k) = A_s \left(\frac{k}{k_p}\right)^{n_s - 1}$$



1998-2003 Revolution - ΛCDM

- The universe is very old and very big!

  Dark Energy
- The Gravity is the most essential force!

  Dark Matter
- The initial condition of the Universe is very simple!

  Early Universe Physics

ΛCDM with flat 6 parameter model with

nearly Gaussian, isotropic, adiabatic, nearly scale invariant initial conditions

and

GR+ECP

Oratorio*

Based on:

- Encieh Erfani, Hamed Kameli, **SB**, Accepted for publication in MNRAS (2021)
- Hamed Kameli, **SB**, arXiv:2008.13175, submitted to MNRAS (2021)
- Hossein Moshafi, **SB**, Nima Khosravi, submitted to PRD, arXiv:2012.14377 (2021)
- Hamed Kameli, **SB**, 2020, MNRAS, V. 494, Issue 4, 4907
- Alireza Maleki, **SB**, Sohrab Rahvar, Phys. Rev. D 101, 103504, (2020)
- Nima Khosravi, **SB**, Niayesh Afshordi, Natacha Altamirano, Phys. Rev. D 99, 103526 (2019)
- **SB** et al. Physical Review E 99, 062101 (2019)
- Farnik Nikakhtar, Mohammadreza Ayromlou, **SB**, Sohrab Rahvar, M. Reza Rahimi Tabar, Ravi K. Sheth, MNRAS, 478, no.4, 5296-5300, (2018)

***An oratorio is a large musical composition for orchestra, choir, and soloists.**

6 Lines of Thought to 6 parameter model

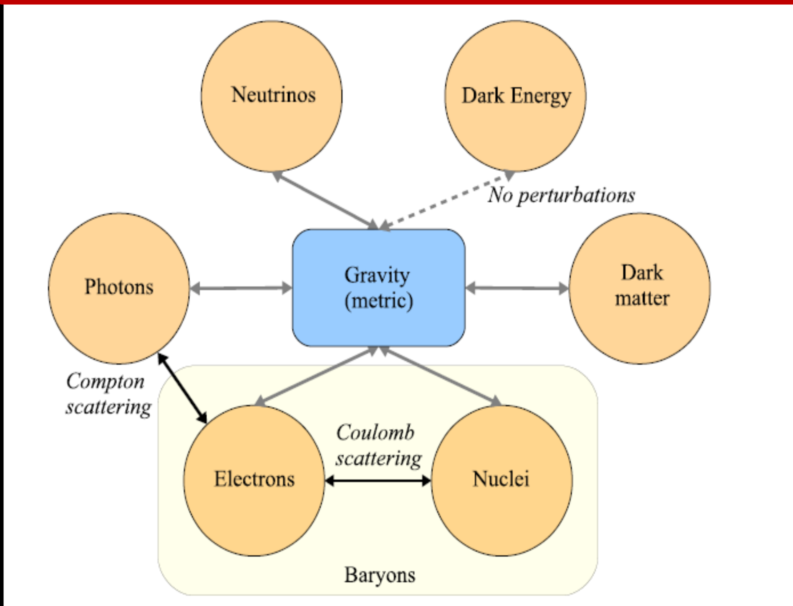
I.General relativity and the Universe
Asking for a Homogenous and Isotropic one!
II. Expanding Universe and measuring Ω
III. Cosmic Microwave Background Radiation

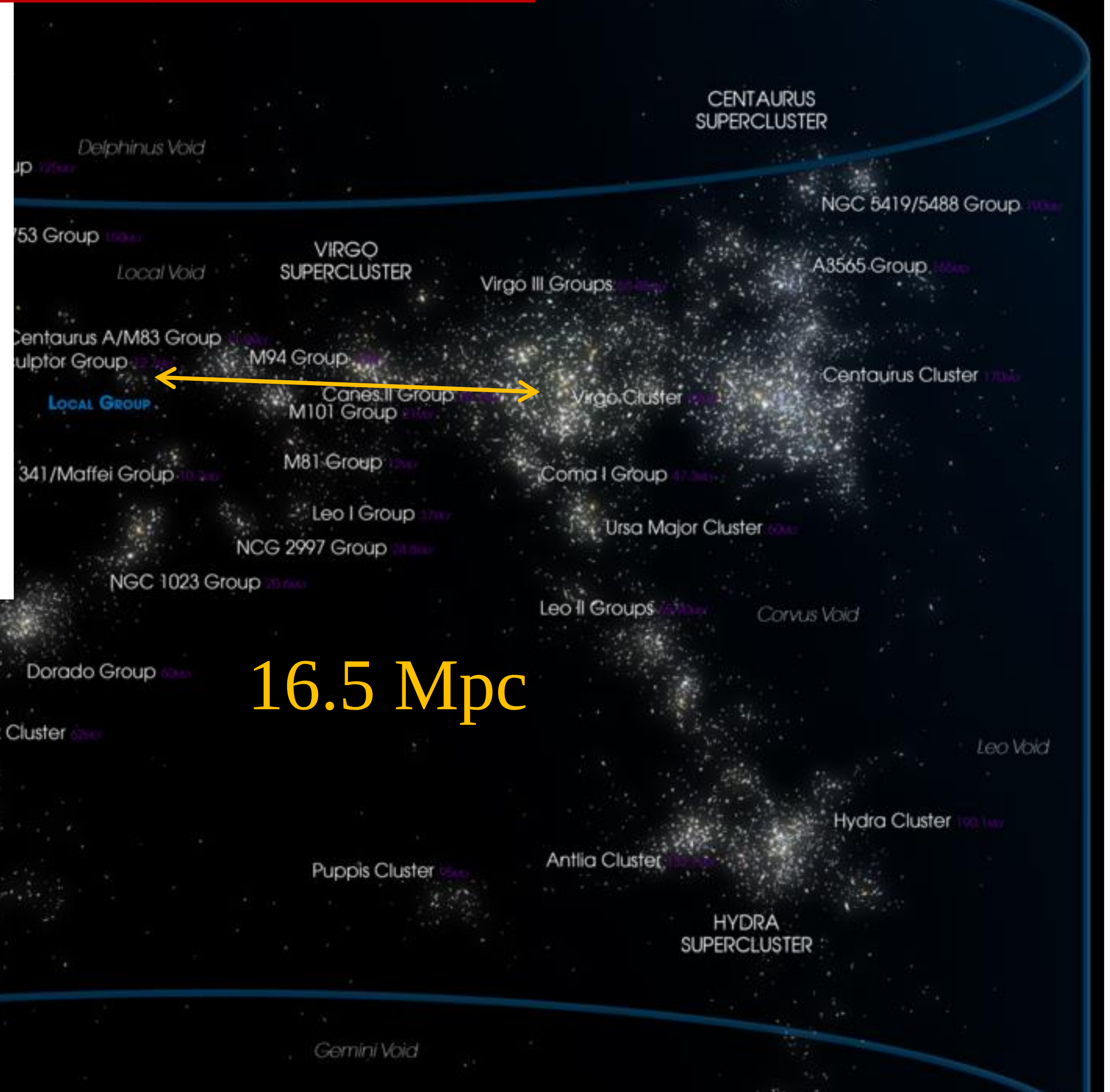
IV. Structure Formation and LSS

V. Subluminal matter
VI. Non-baryonic Dark Matter

- **More insight in LSS in non-linear scale to introduce new Probes**

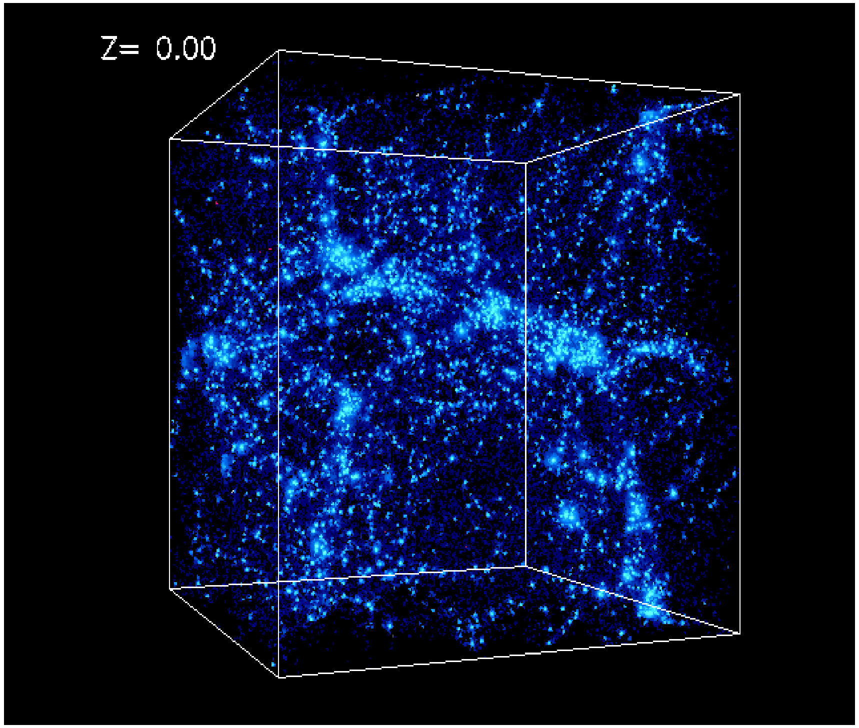
$$ds^2 = -(1+2\Psi(\vec{x},t))dt^2 + a^2(t)\delta_{ij}(1+2\Phi(\vec{x},t)+h_{ij})dx^i dx^j$$

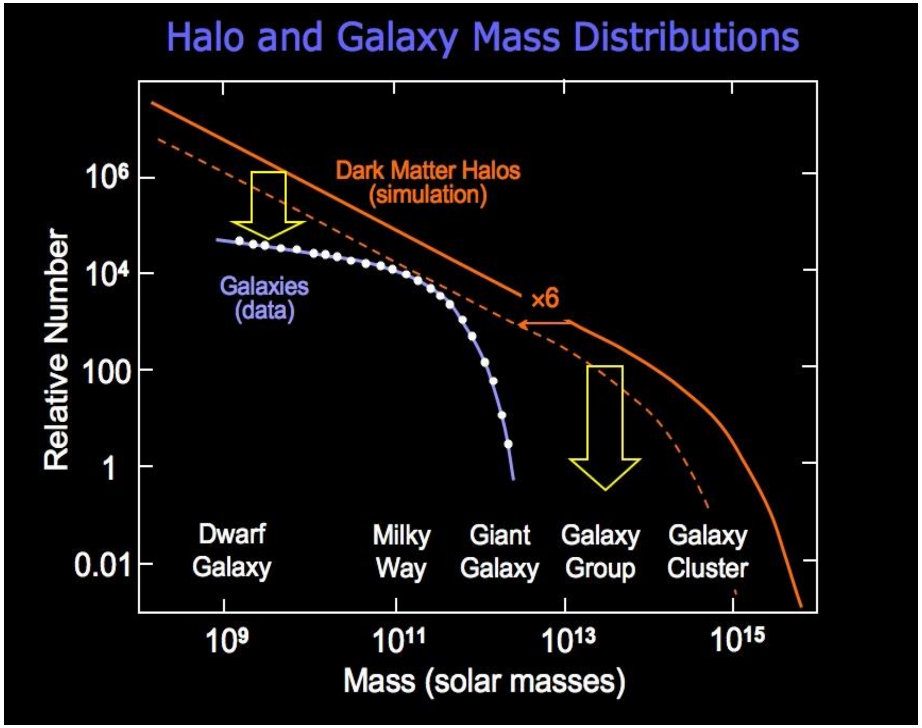




Tully, R. Brent; Courtois, Hélène; Hoffman, Yehuda; Pomarède, Daniel (Sep 2014). "The Laniakea supercluster of galaxies". Nature. 513 (7516): 71–73. arXiv:1409.0880. doi:10.1038/nature13674. ISSN 1476-4687

Non-linear Structures + baryonic physics





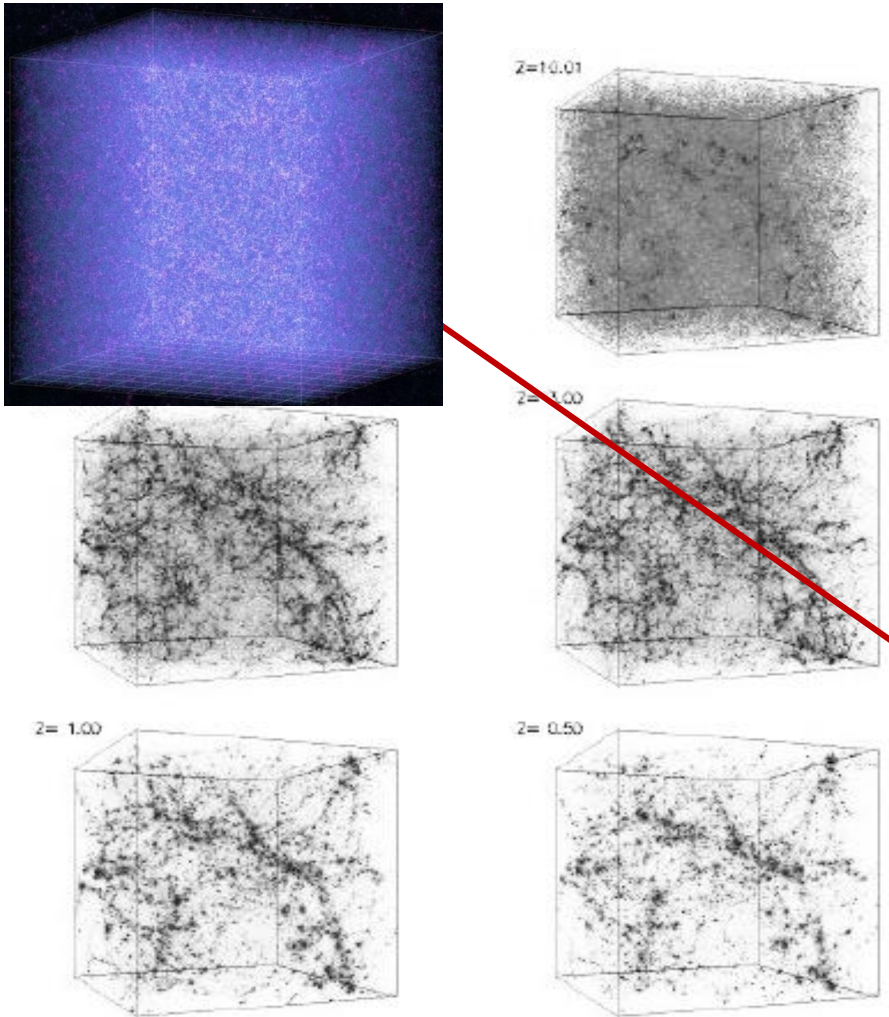
Cosmic Web: Halos, Filaments, Voids ,…

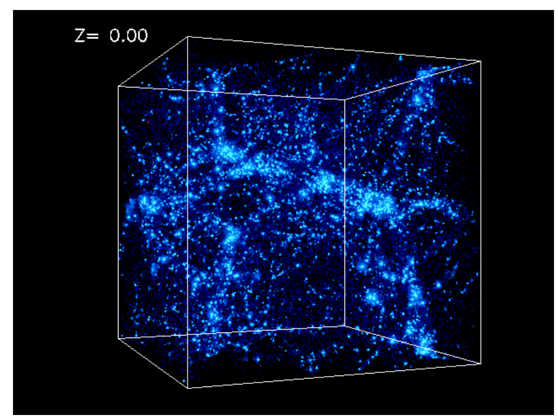
$$n = n(M, z, ...)$$

If you are an astrophysicist you will ask about

$$\phi = \phi(L, z, ...)$$

The musing of PS, BBKS, BCEK, ST





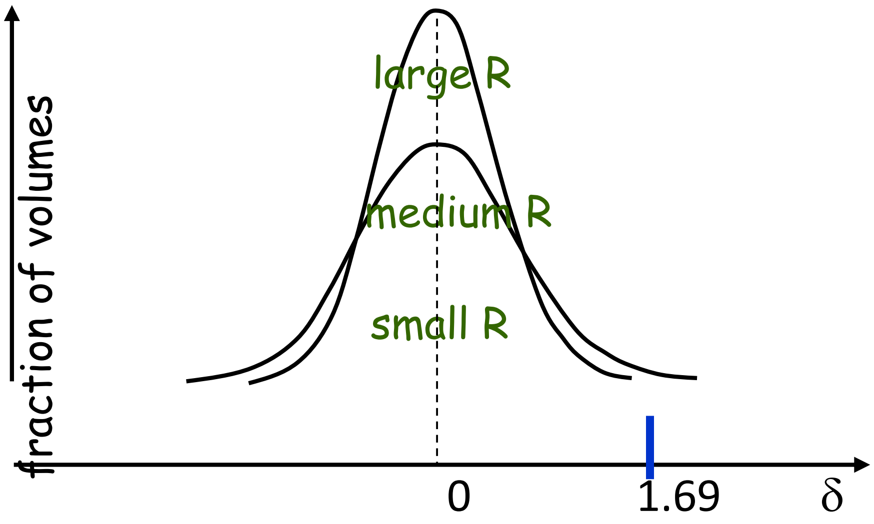
THE ASTROPHYSICAL JOURNAL, 187:425–438, 1974 February 1

FORMATION OF GALAXIES AND CLUSTERS OF GALAXIES BY SELF-SIMILAR GRAVITATIONAL CONDENSATION*

WILLIAM H. PRESS AND PAUL SCHECHTER

Press & Schechter 1974

Dark Matter as the host of Luminous matter

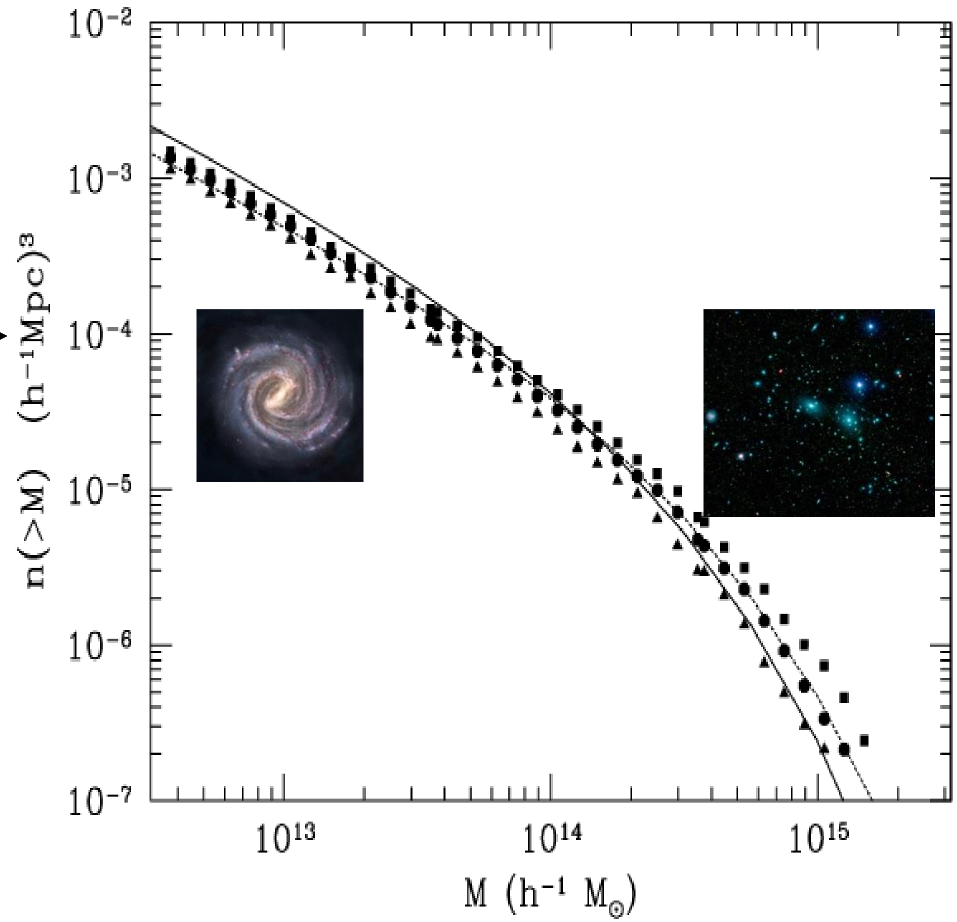


$$P(\delta) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\delta^2}{2\sigma^2(M)}}$$

$$P_{collapsed}(\delta > \delta_c) = \int_{\delta_c}^{\infty} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{\delta^2}{2\sigma^2(M)}}$$

$$f_{uni}(\nu) = \nu \frac{e^{-\frac{\delta_c^2}{2\sigma}}}{\sqrt{2\pi}}$$

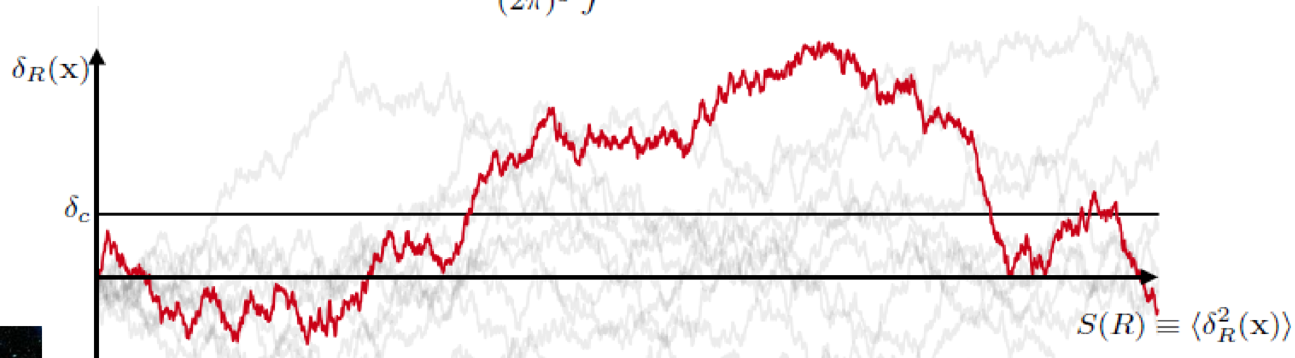
$$\nu \equiv \frac{\delta_c}{\sigma}, S = \sigma^2$$



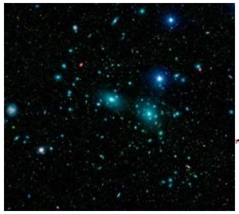
$$n(M)dM = 2\frac{\rho}{M^2} f_{uni}(\nu) \left| \frac{d\ln\sigma(M)}{d\ln M} \right| dM$$

Excursion Set theory of LSS

$$\delta_R(\mathbf{x}) = \frac{1}{(2\pi)^3}\int d^3k \tilde{W}(kR)e^{i\mathbf{k}.\mathbf{x}}\delta(\mathbf{k})$$



$$\delta_c(t) = \frac{\delta_c}{D(t)}$$



These random trajectories have the variance

$$S(R) \equiv \langle \delta_R^2(\mathbf{x}) \rangle = \frac{1}{2\pi^2}\int P(k)\tilde{W}^2(kR)k^2 dk$$

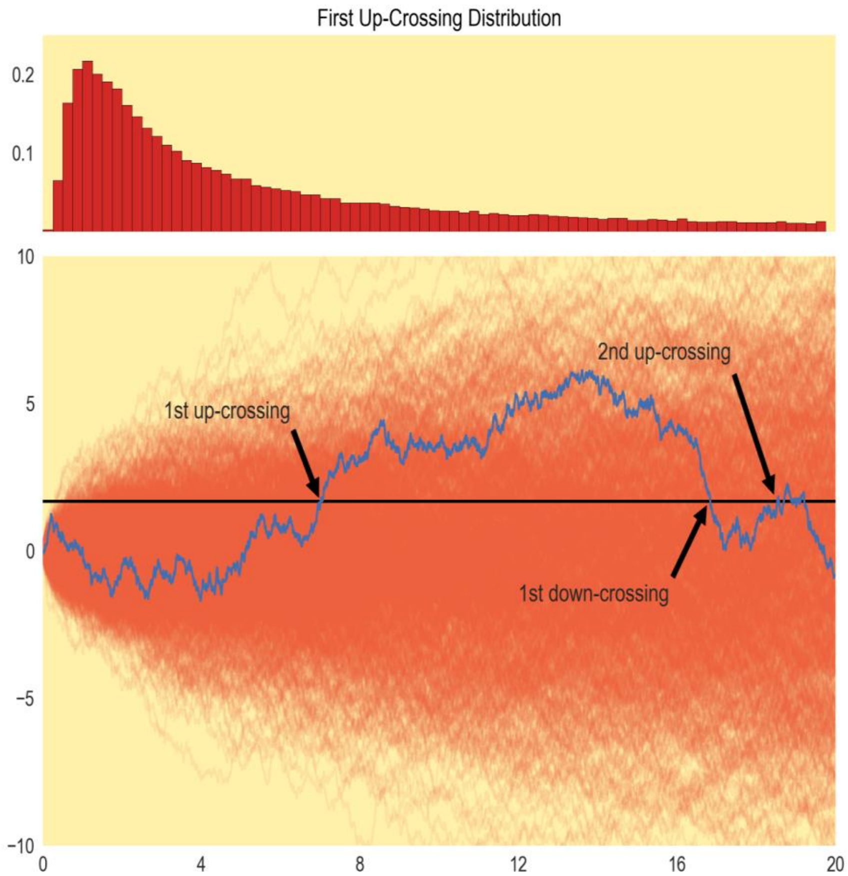
$$f_{FU}(S,\delta_c)dS = \frac{1}{\sqrt{2\pi}}\frac{\delta_c}{S^{3/2}}e^{-\frac{\delta_c^2}{2S}}dS$$

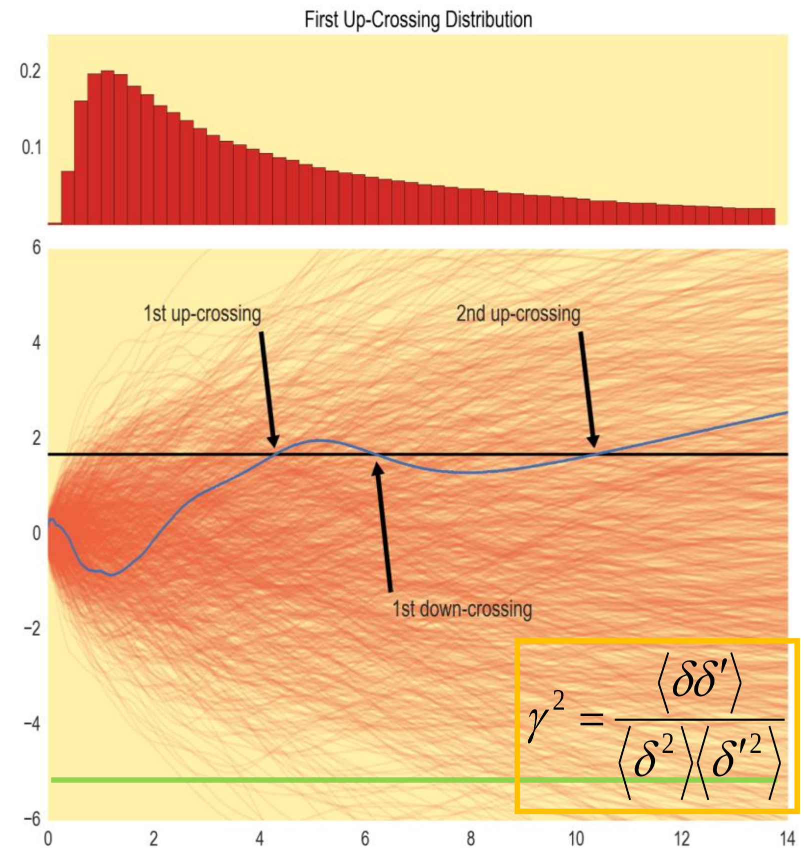
- SB et al. Physical Review E 99, 062101 (2019)
- Farnik Nikakhtar et al. , MNRAS, Volume 478, Issue 4, (2018)
- Farnik Nikakhtar, SB, Phys. Rev. D 96, 043524 (2017)

M. Reza Rahimitabar and Saman Moghimi @ SUT

Ravi K. Shet @ Pennsylvania

Stochastic Processes and Structure formation





$$\gamma^2 = \frac{\langle \delta\delta' \rangle}{\langle \delta^2 \rangle \langle \delta'^2 \rangle}$$

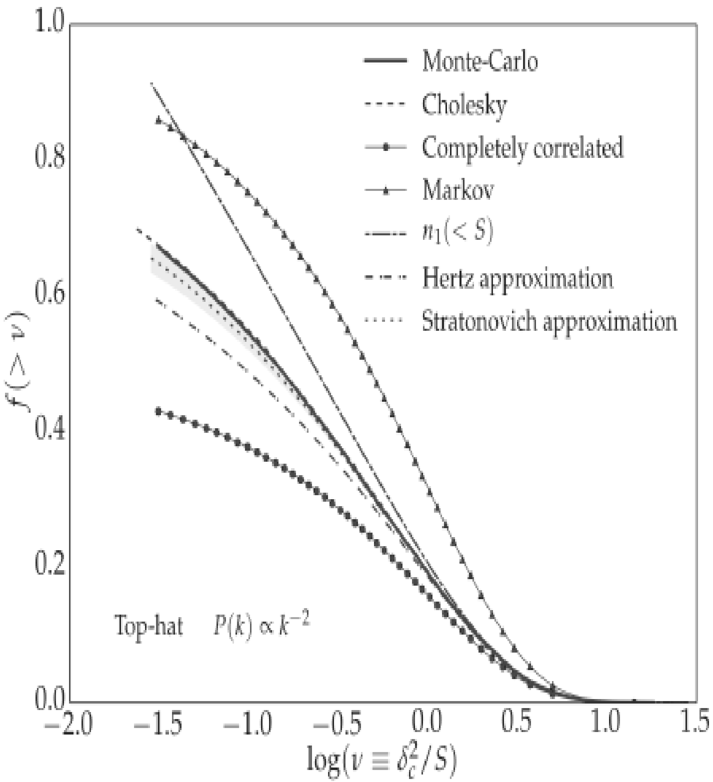
$$\delta(s-\Delta s) < B(s-\Delta s)$$
$$B(s) = \delta_c \rightarrow \delta_c \le \delta \le \delta_c + \Delta s \delta'$$

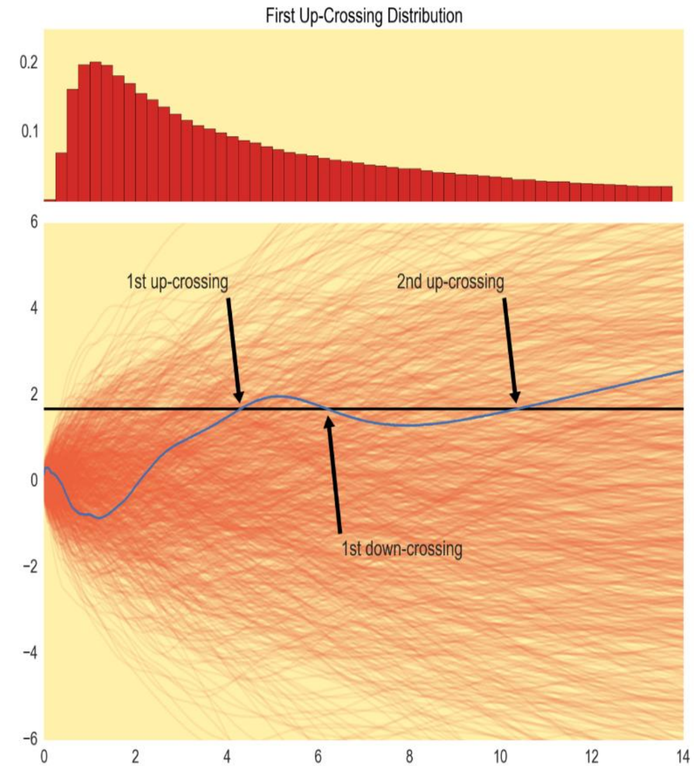
$$f(s)ds = \lim_{\Delta s \to 0} \int_0^\infty d\delta' \int_{\delta_c}^{\delta_c + \Delta s \delta'} d\delta P(\delta, \delta') \rightarrow f = f(\nu, \gamma)$$

One step beyond: The excursion set approach with correlated steps by Marcello Musso and Ravi K. Sheth, arXiv:1201.3876 , MNRAS, Letters 423, 1, 2012, L102

Stochastic Processes and Structure formation

F.Nikakhtar @ Pennsylvania – NSF Fellow





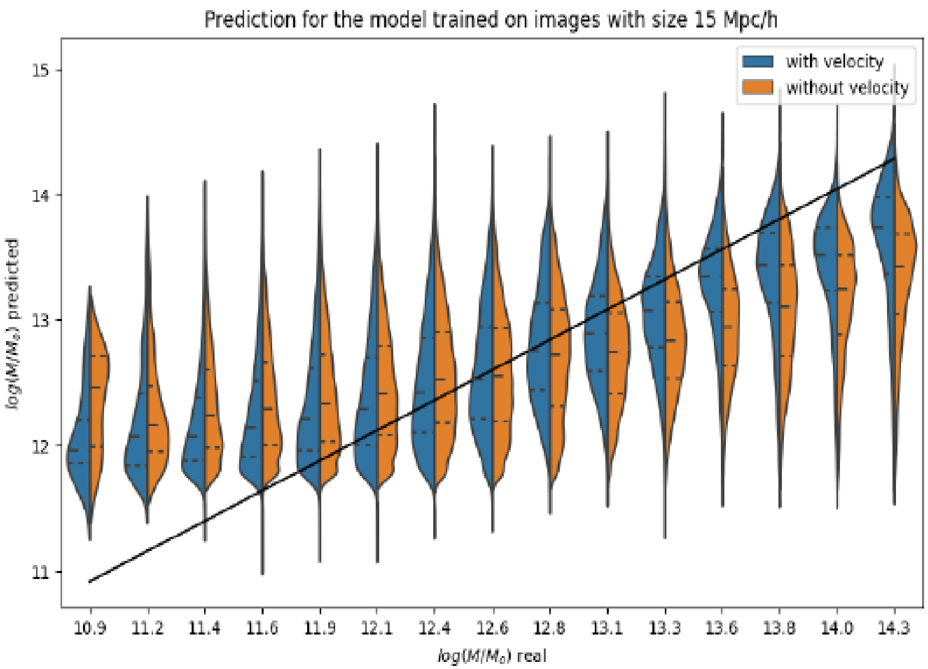
M.Ayromlou @ MPIA - Garching

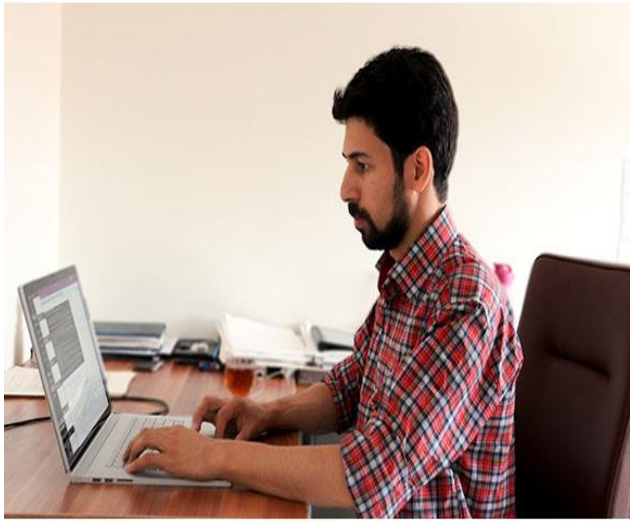
$$\langle \delta_i \delta_j \rangle = C_{ij} = \int \frac{dk}{k} \frac{k^3 P(k)}{2\pi^2} \tilde{W}(kR_i) \tilde{W}(kR_j)$$

$$\delta_i = L_{ij} \xi_j$$

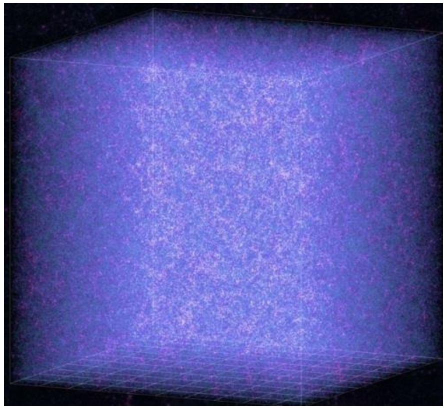
❖ **Farnik Nikakhtar, Mohammadreza Ayromlou et al. , MNRAS, Volume 478, Issue 4, (2018)**

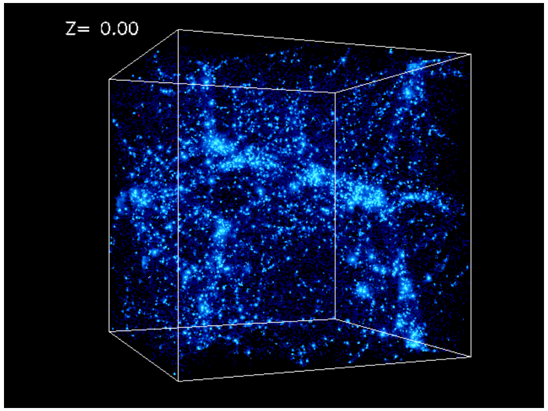
Small groups to Big science and Big Data



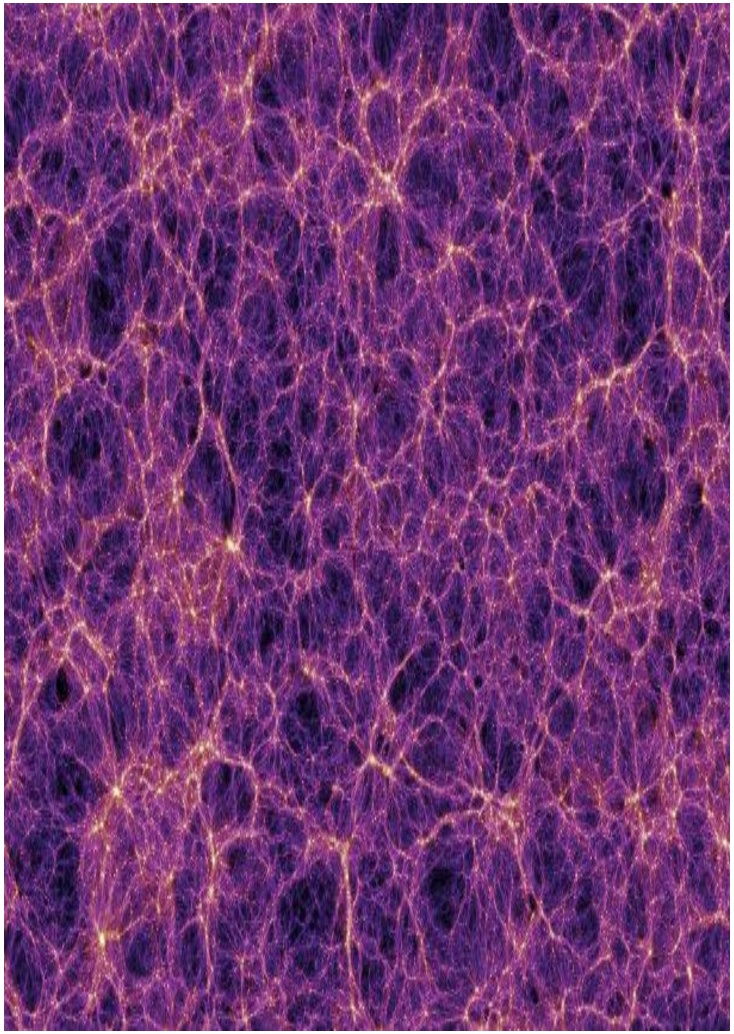


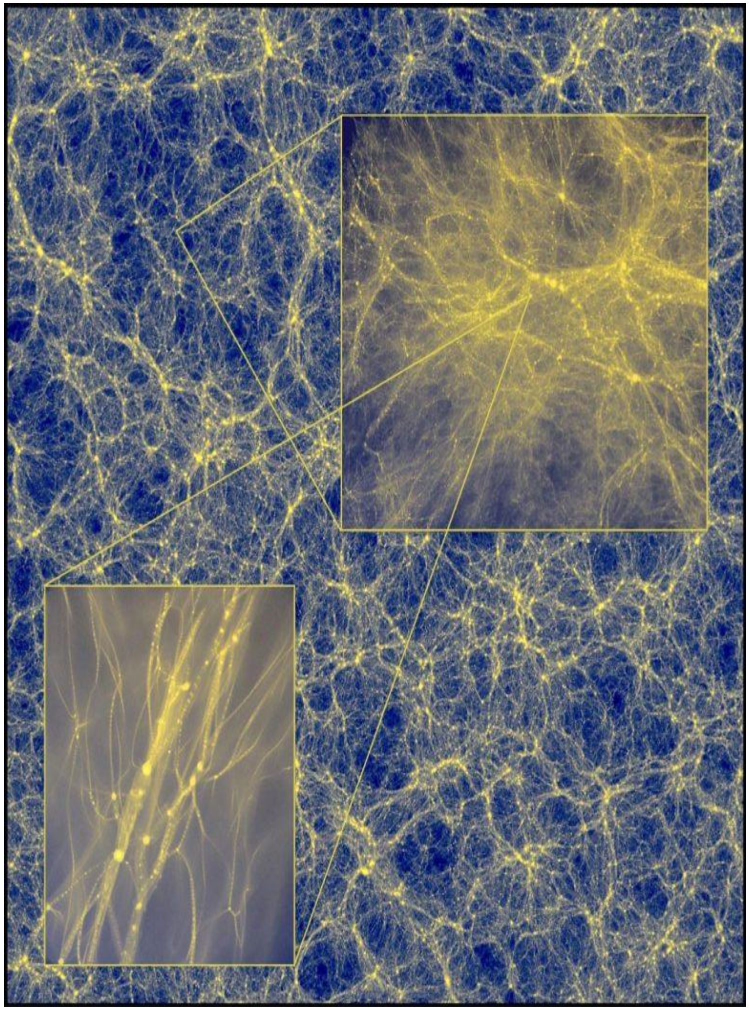
Sadegh Raiesi @ SUT





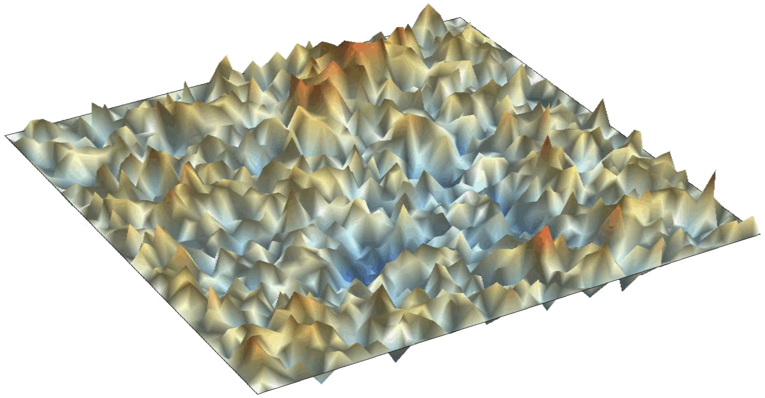
Cosmic Web

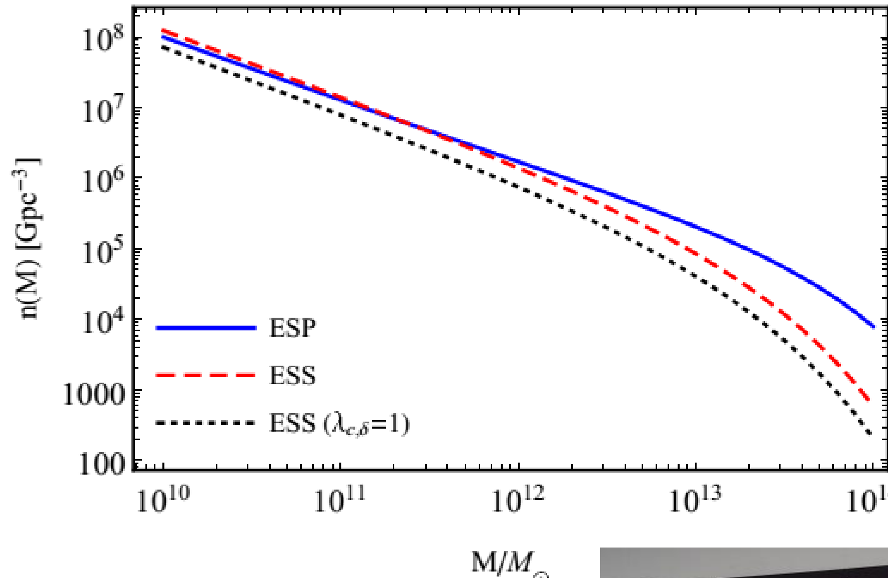




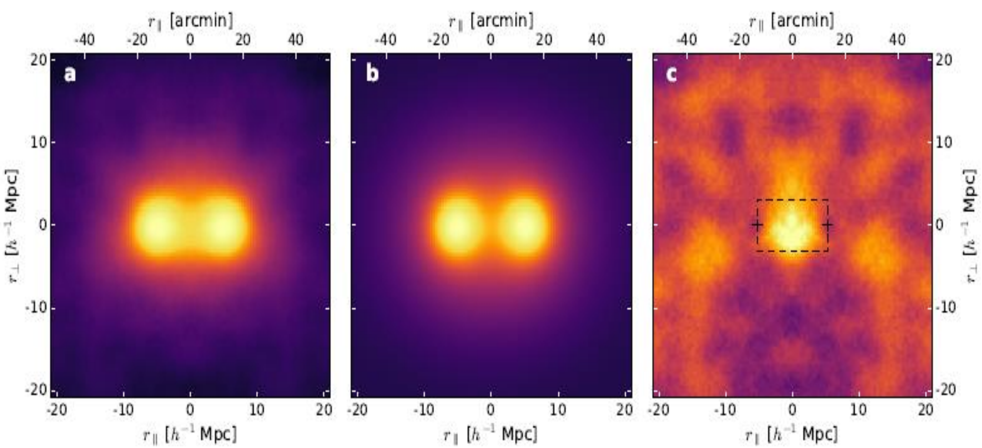
When the nettle is young, the leaves make excellent greens; when it grows old it has filaments and fibers like hemp and flax … **Victor Hugo**

Cosmic Web (Filaments, ...)





***Mohammad Ansari, Sina Taamoli* and SB**
arXiv:1811.12398 , MNRAS, 489, 1, 2019, Pages 900–909

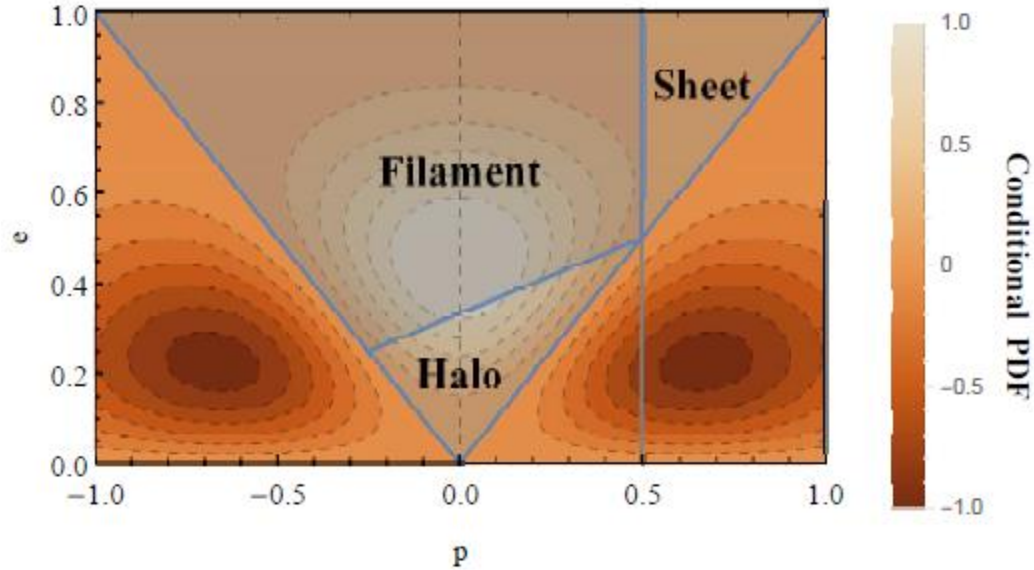


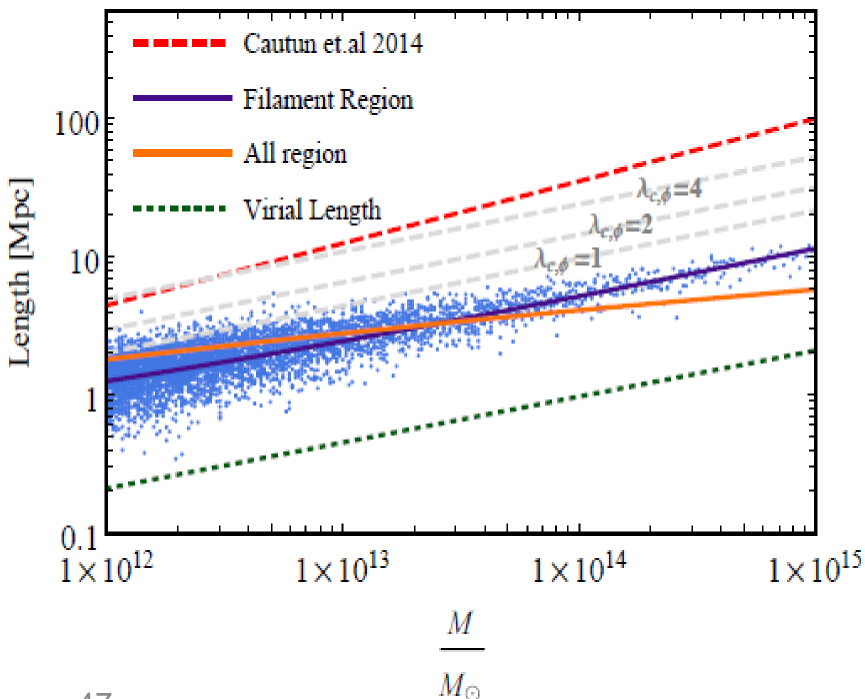
Missing baryons in the cosmic web revealed by the Sunyaev-Zel'dovich effect

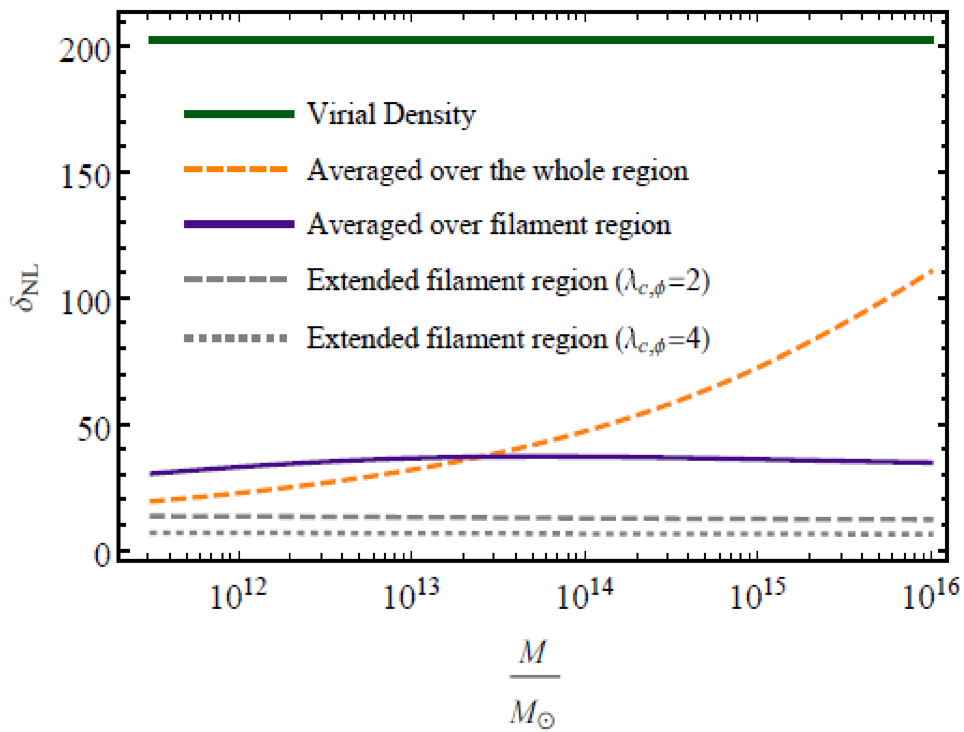
Anna de Graaff[1], Yan-Chuan Cai[1], Catherine Heymans[1] & John A. Peacock[1]

Mohammad Ansari
PhD candidate in SUT

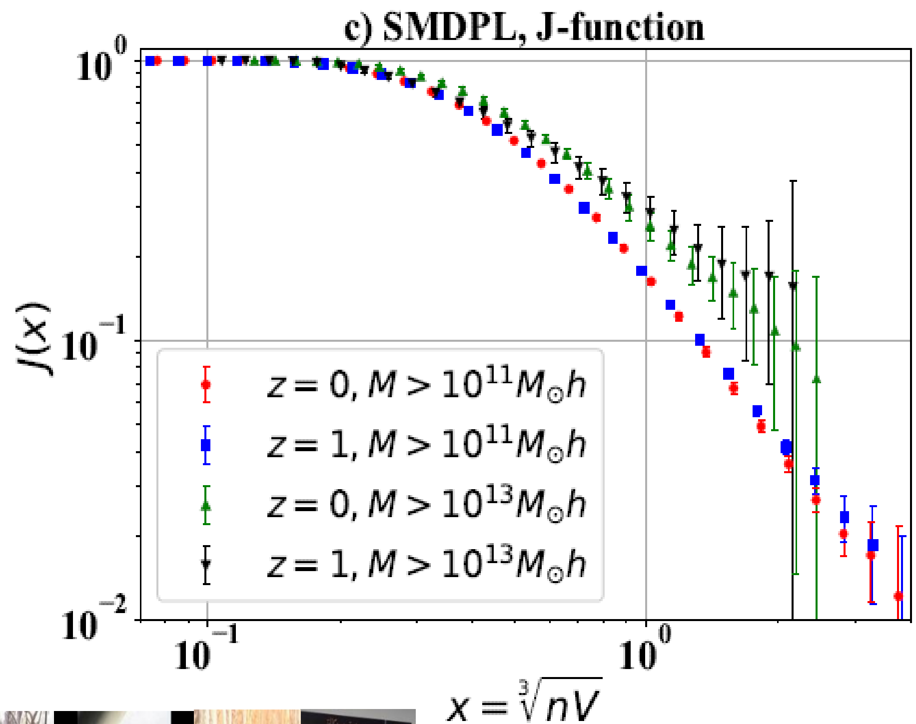
Filaments!ESS

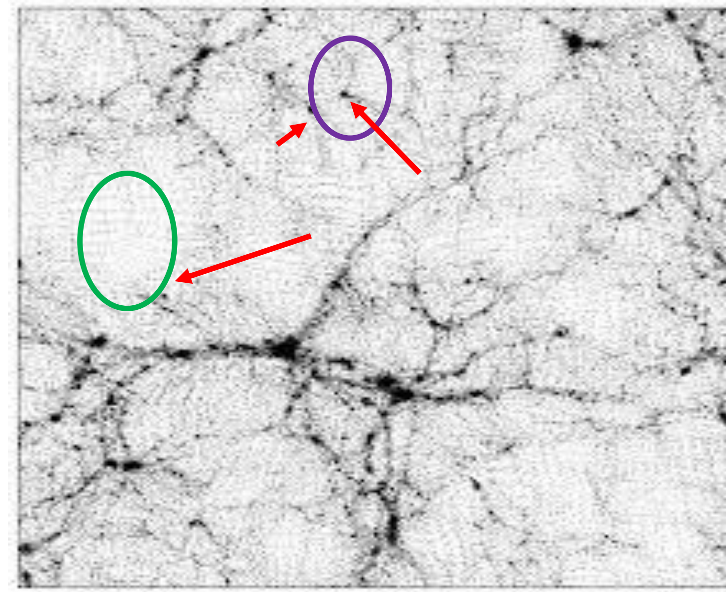






Distance Indicators…





$$J(r) = \frac{1 - NN(r)}{1 - SC(r)}$$

Nearest neighbour and spherical contact distribution in simulations and galaxy groups

Mohammad AnsariFard, [1] Zahra Baghkhani, [1] Laya Ghodsi, [2] Sina Taamoli, [3] Farbod Hassani, [4] Shant Baghram[1] *

Farbod Hassani @ Oslo

Rhapsody*

***A rhapsody in music is a one-movement work that is episodic yet integrated, free-flowing in structure, featuring a range of highly contrasted moods, colour, and tonality.**

Again P.J.E. Peebles

The natural science of cosmology

International Conference on Gravitation and Cosmology, Goa, December 2011

P J E Peebles
Joseph Henry Laboratories, Princeton University, Princeton NJ 08544, USA
E-mail: PJEP@Princeton.edu

1. Serendipitous discovery of suggestive phenomena
2. The philosophical appeal of ideas
3. Mathematical incompleteness

❖ Testing ideas

❖ Anomalies

1. Learning to compute
2. Adding decimal places

arXiv:1203.6334v1 [astro-ph.CO] 28 Mar 2012

James Peebles speaks to well wishers after his win.
(Eduardo Munoz/Reuters/TPX Images of the Day)

6 Lines of Thought to 6 parameter model

I.General relativity and the Universe

Asking for a Homogenous and Isotropic one!

II. Expanding Universe and measuring Ω

III. Cosmic Microwave Background Radiation

IV. Structure Formation and LSS

V. Subluminal matter

VI. Non-baryonic Dark Matter

❖ **Initial Conditions? ECP?**

Roya Mohayaee @ IAP

Hassan Firouzjahi @ IPM

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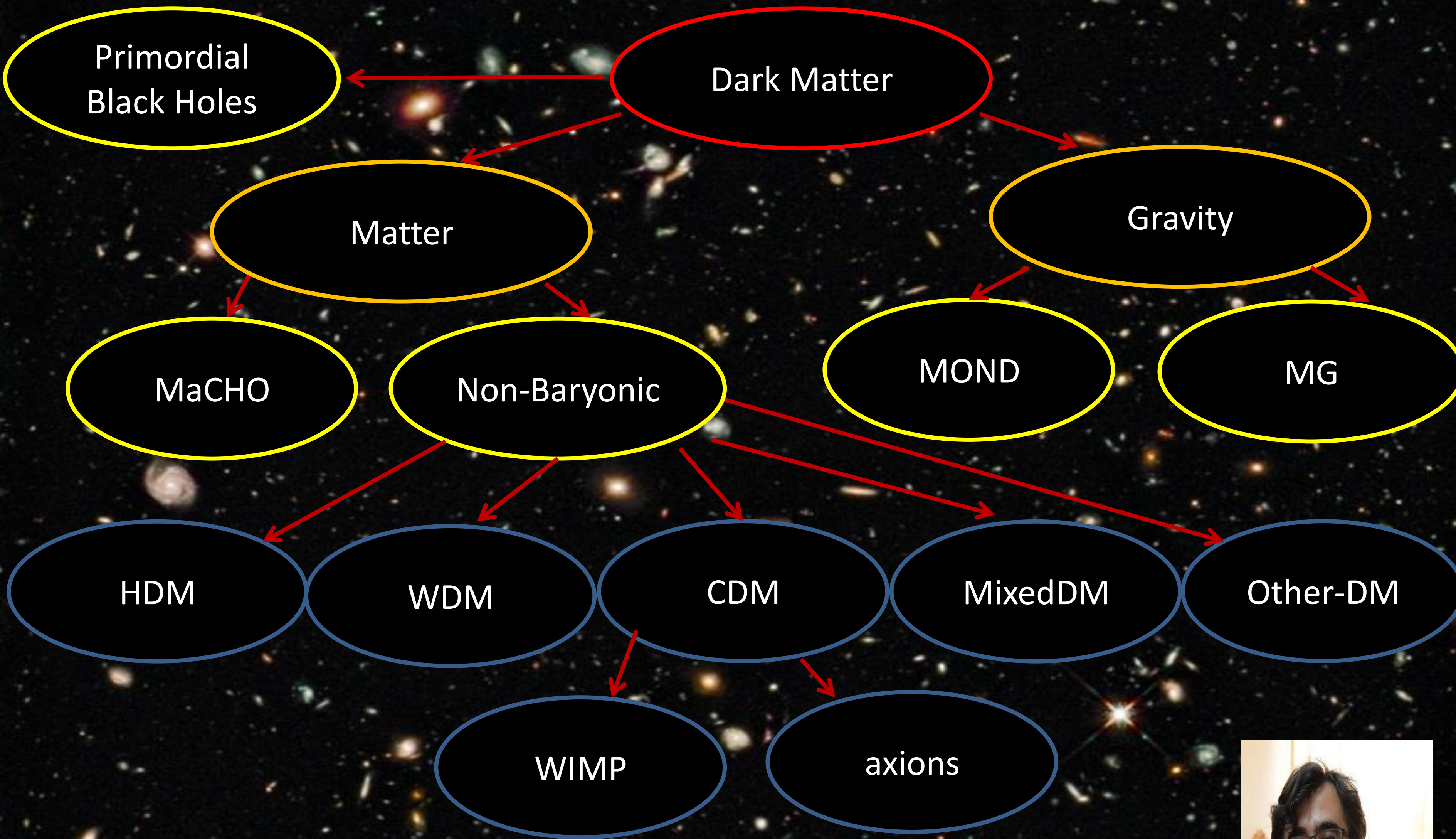
V. Subluminal matter

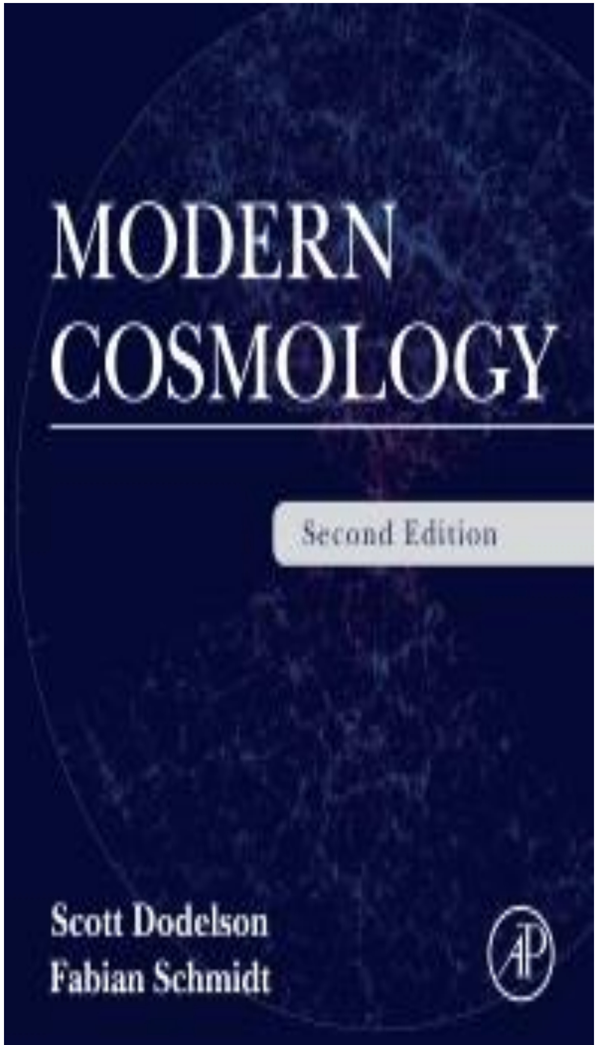
VI. Non-baryonic Dark Matter

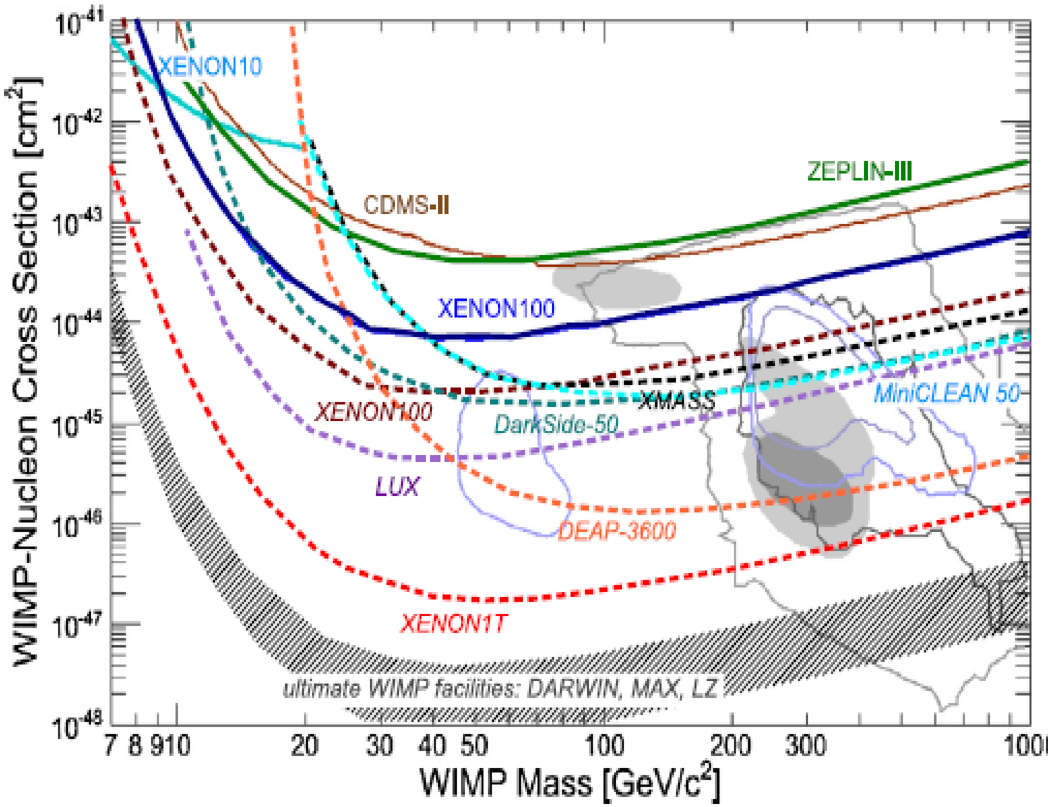
- **Dark matter in galactic scales… modified CDM?!**



Sohrab Rahvar
@ SUT

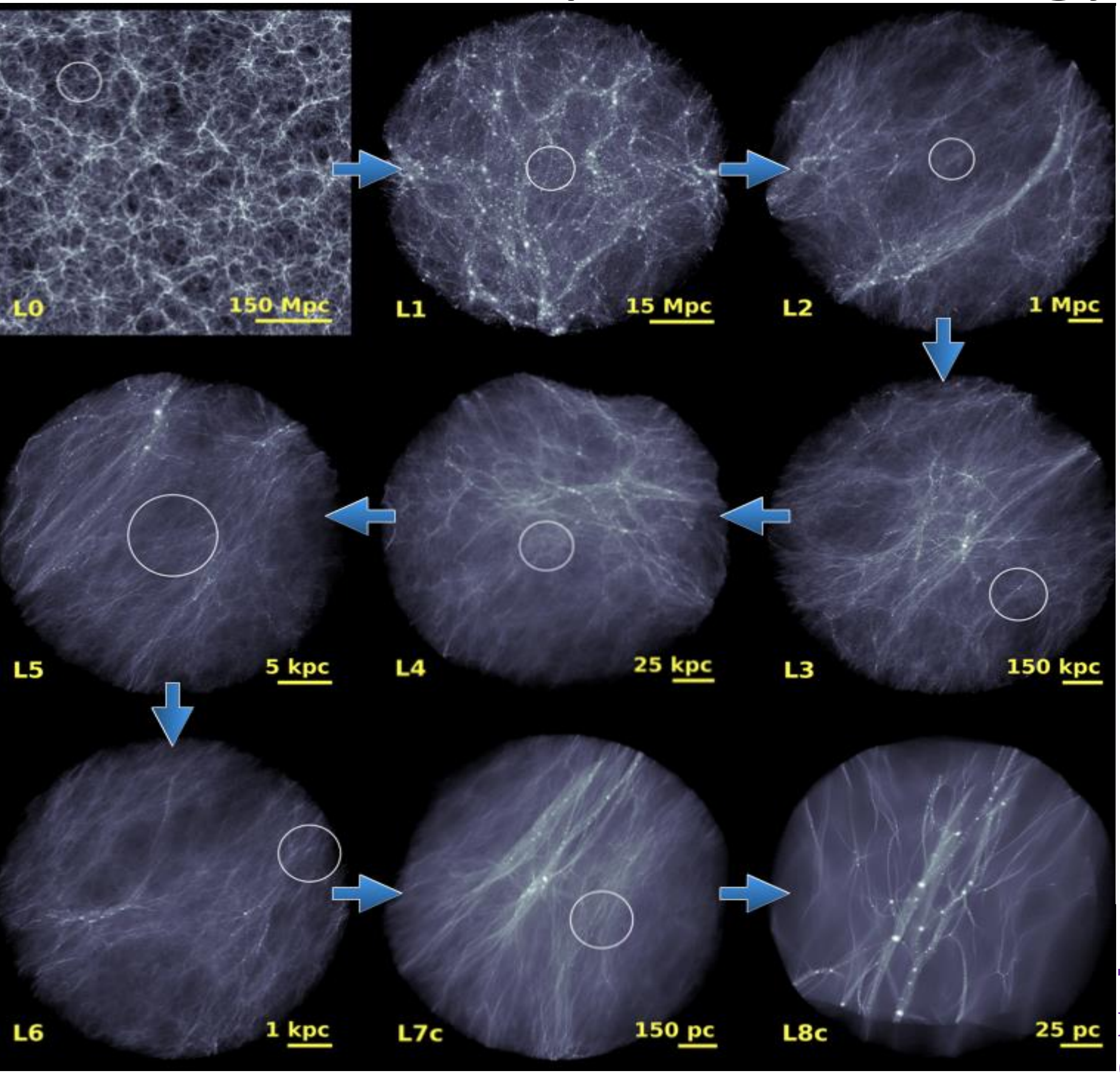
WIMPs

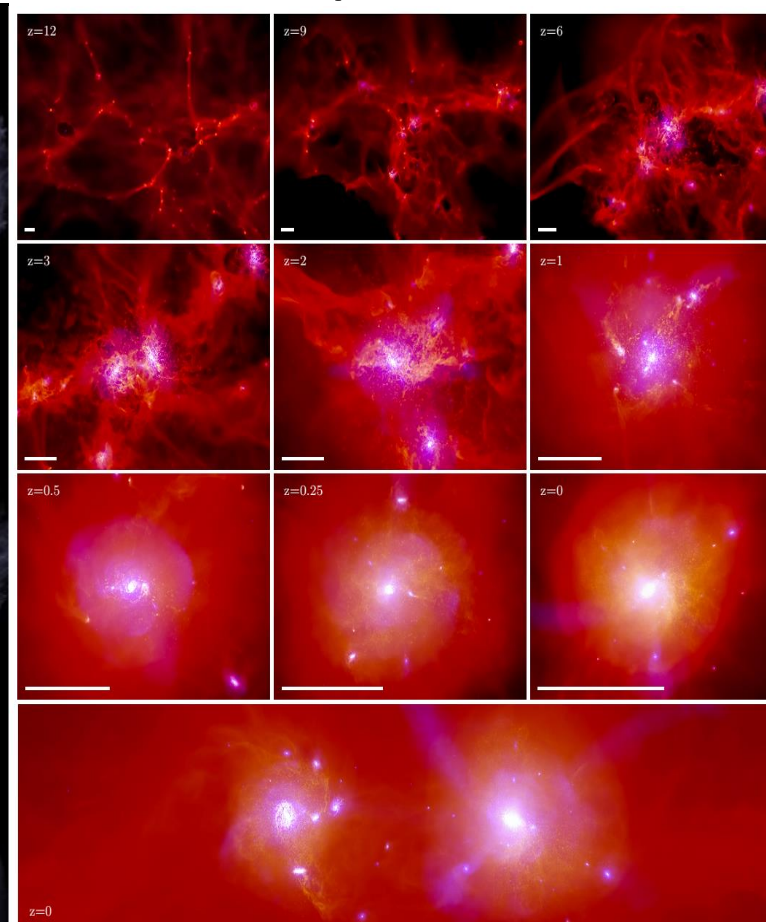




There are no classes in life for beginners; right away you are always asked to deal with what is most difficult, Rainer Maria Rilke

The triumph of cosmology and computers



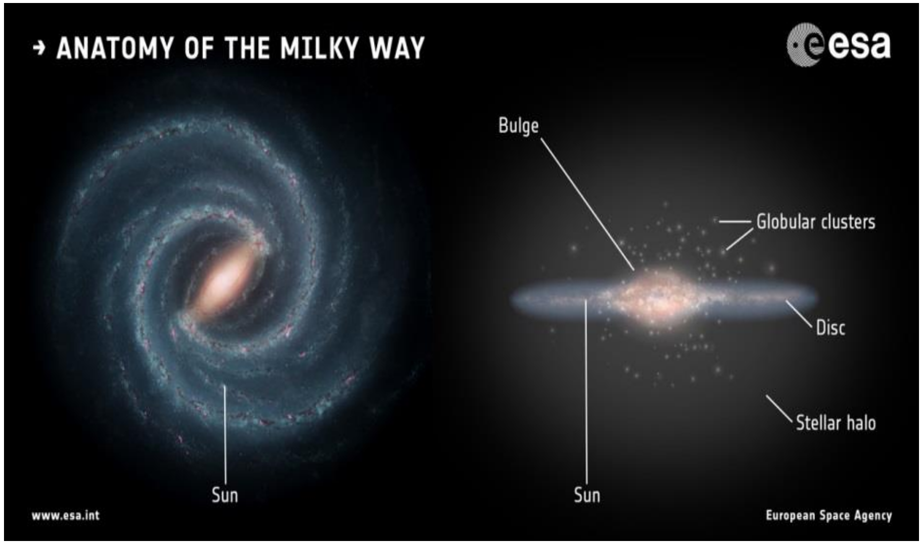


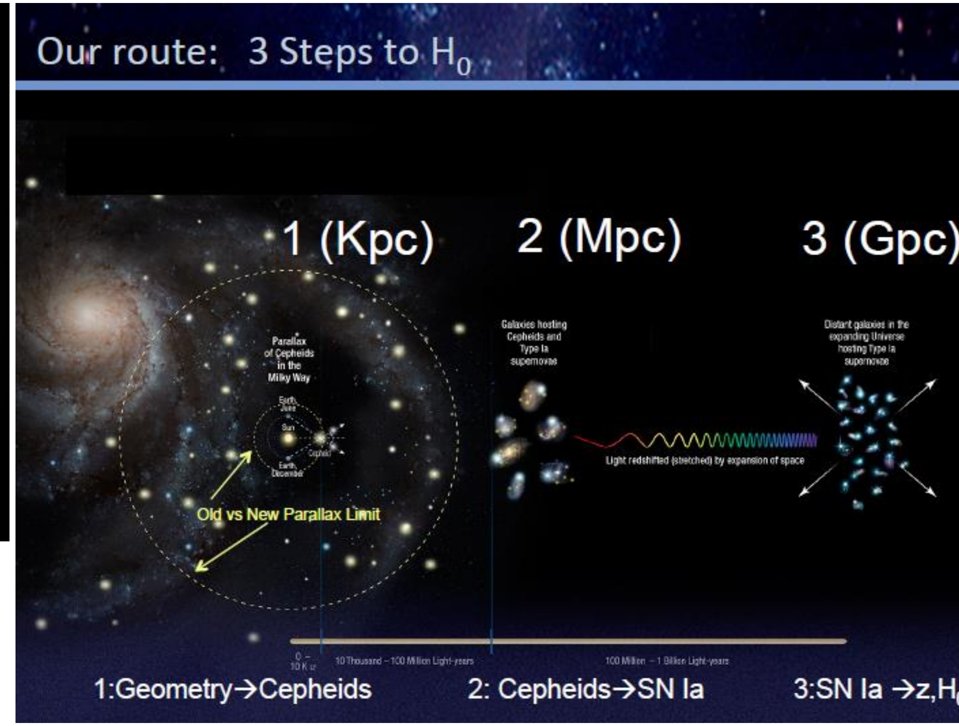
The APOSTLE simulations: solutions to the Local Group's cosmic puzzles Till Sawala , Carlos S. Frenk , Azadeh Fattahi , Julio F. Navarro et al. , Monthly Notices of the Royal Astronomical Society, Volume 457, Issue 2, 01 April 2016, Pages 1931–1943

Universal structure of dark matter haloes over a mass range of 20 orders of magnitude

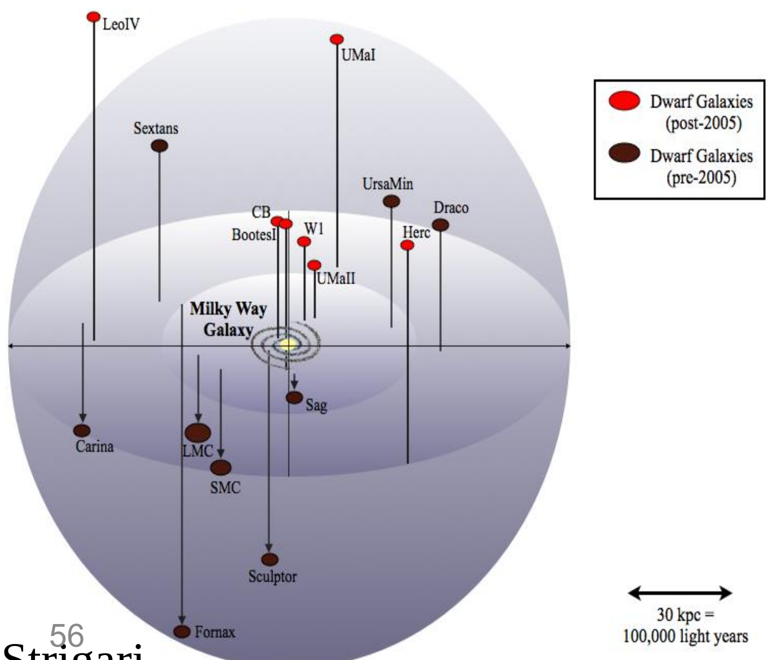
Wang, J.[1,5]*, Bose, S.[2], Frenk, C. S.[3]†Gao, L.[1,5], Jenkins, A.[3], Springel, V.[4] & White, S. D. M.[4]‡

All about our neighborhood!





© Riess



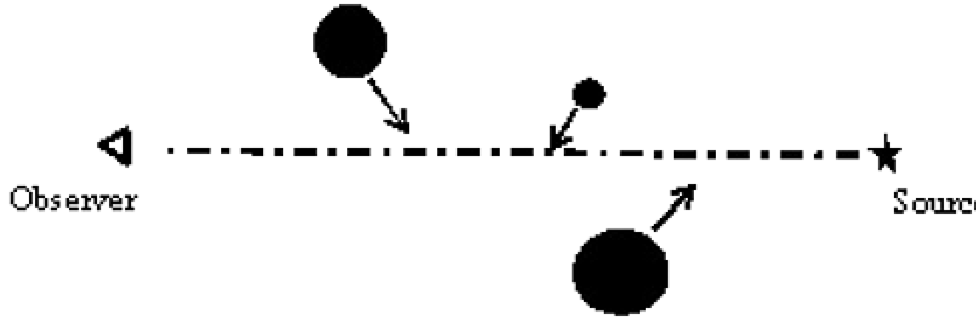
© Strigari

- *SB, Niayesh Afshordi, and Kathryn M. Zurek, PRD 84, 043511 (2011)*
- *Sohrab Rahvar, SB and Niayesh Afshordi, PRD 89, 063001 (2014)*
- *Alireza Maleki, SB, Sohrab Rahvar, Phys. Rev. D 101, 023508 (2020)*
- *Alireza Maleki, SB, Sohrab Rahvar, Phys. Rev. D 101, 103504 (2020)*
- *Hamed kameli and SB, MNRAS, V. 494, Issue 4, 2020, 4907*

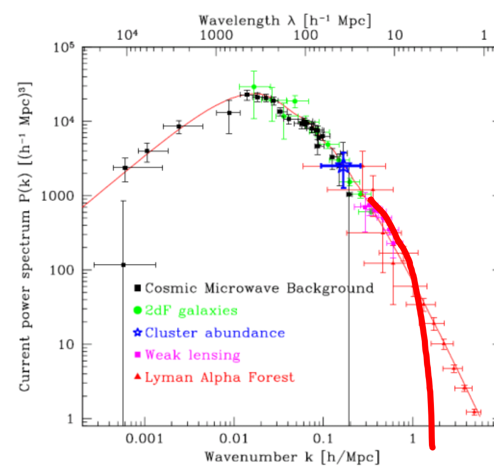
Searches for Dark Matter substructures

Sohrab Rahvar @ SUT

Niayesh Ashordi@ PI/Waterloo

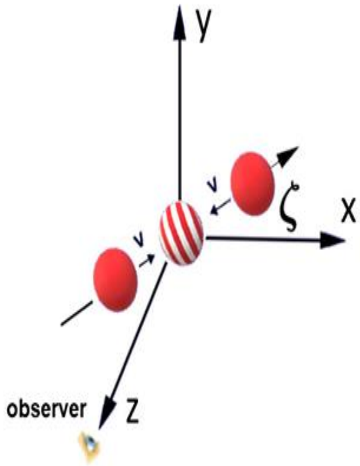


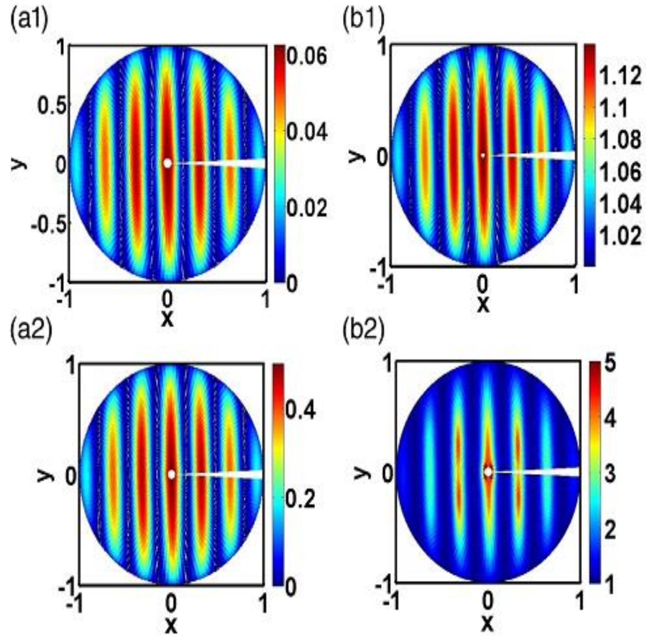
$$\omega P(\omega) = 18\pi^2 H_0^4 \Omega_m^{(0)2} \int_0^{\chi_s} \left(1 - \frac{\chi'}{\chi_s}\right)^2 \chi'^2 d\chi' \times \int_0^{\infty} dv e^{-v^2/2\sigma^2} \left[\frac{v}{\sigma(\frac{\omega}{v}, z_{\chi'})}\right]^2 \times \frac{\Delta^2(\frac{\omega a}{v}, z_{\chi'})}{\omega} (1 + z_{\chi'})^3,$$

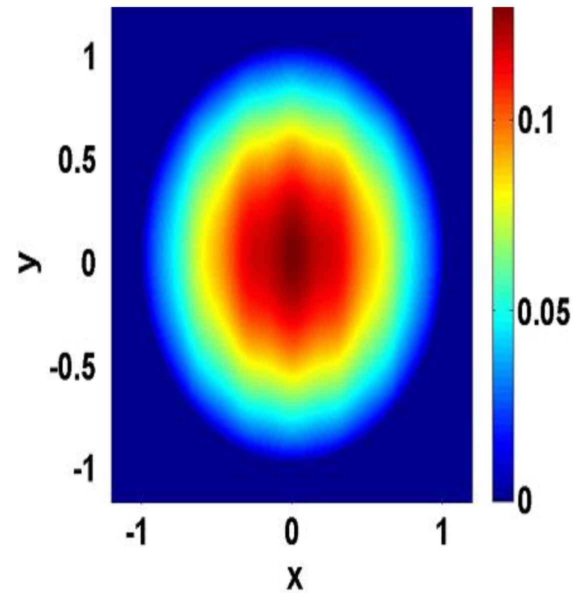


SB, Niayesh Afshordi, and Kathryn M. Zurek, PRD 84, 043511 (2011)
Sohrab Rahvar, SB and Niayesh Afshordi, PRD 89, 063001 (2014)

Modified CDM and alternatives







Alireza Maleki @ SUT

PHYSICAL REVIEW D **101,** 023508 (2020)

Investigation of two colliding solitonic cores in fuzzy dark matter models

Alireza Maleki, Shant Baghram, and Sohrab Rahvar
Department of Physics, Sharif University of Technology, P. O. Box 11155-9161 Tehran, Iran

What are the solutions galactic scale challenges of CDM?

- Baryonic Physics
- Modified CDM
- Modified Initial Condition

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

MNRAS 494, 4907–4913 (2020) doi:10.1093/mnras/staa1058

Advance Access publication 2020 April 21

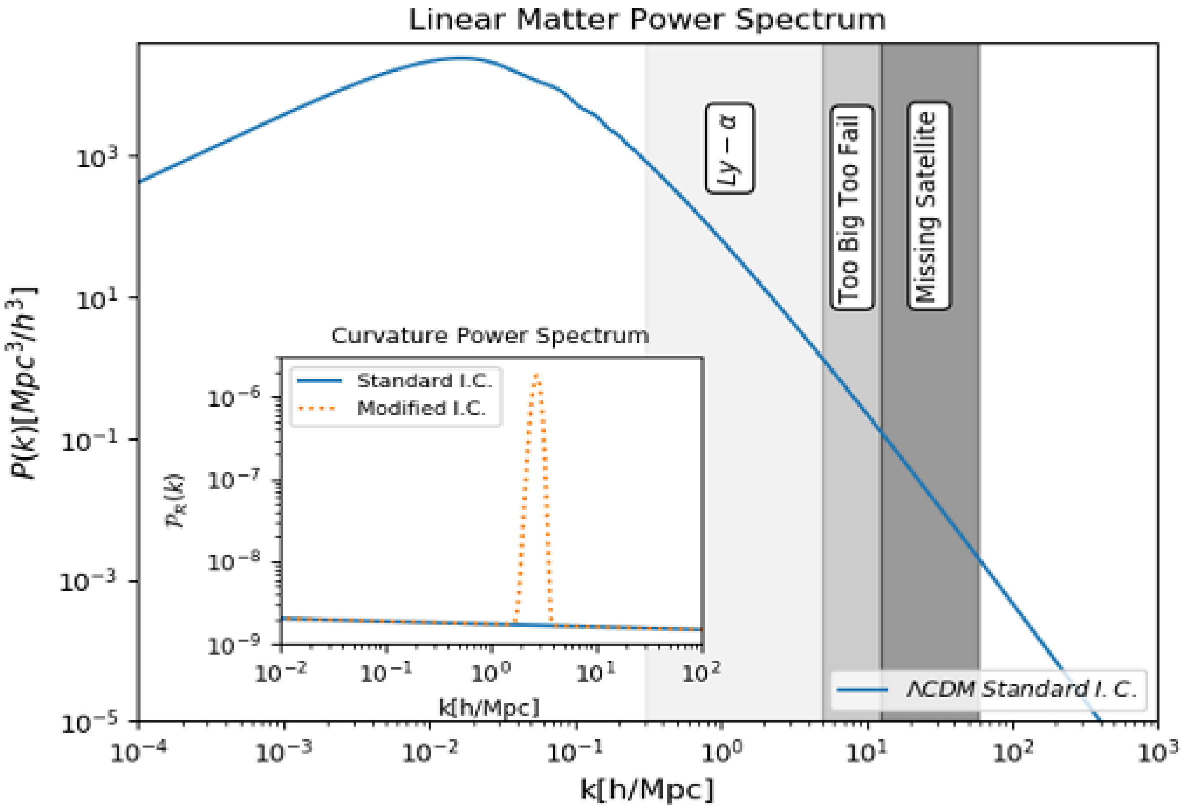
Modified initial power spectrum and too big to fail problem

Hamed Kameli and Shant Baghram ★

Department of Physics, Sharif University of Technology, PO Box 11155-9161, Tehran, Iran

Hamed Kameli @ SUT

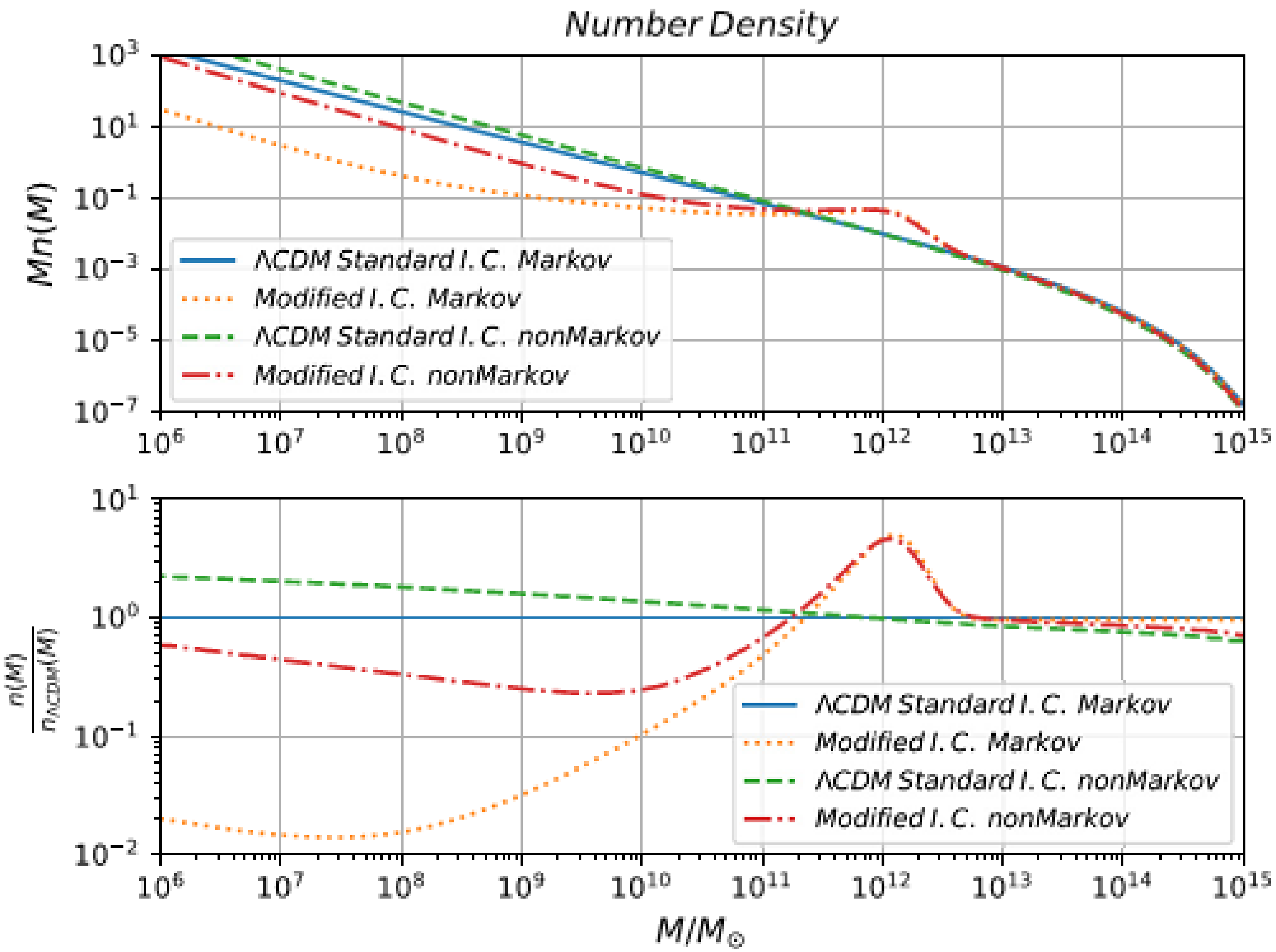
Small Scale power spectrum



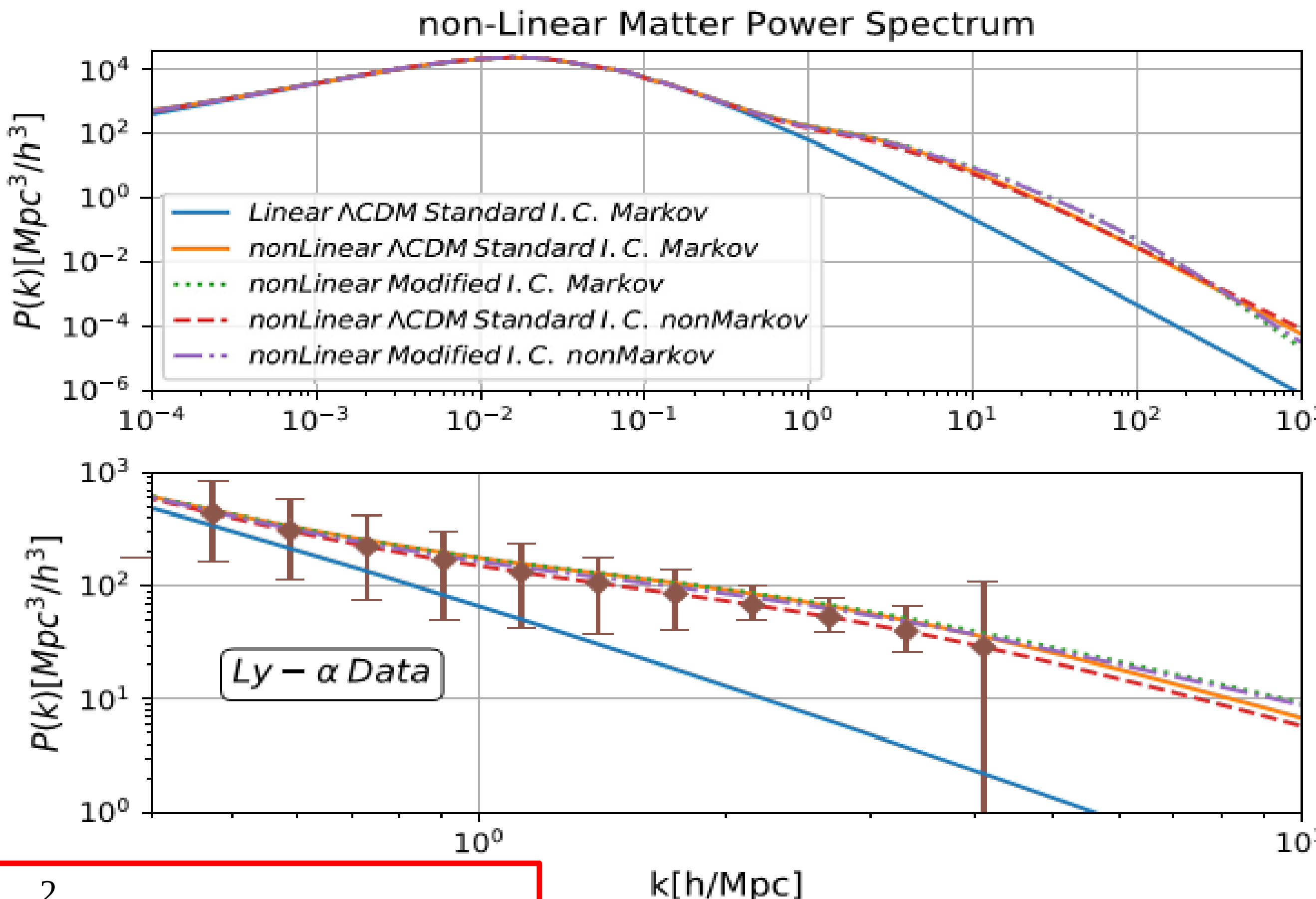
$$\mathcal{P}_{\mathcal{R}}^{\text{bump}}(k) = \frac{A_{\text{b}}}{\sqrt{2\pi}\sigma_{\text{b}}} \exp\left[-(k-k_*)^2/2\sigma_{\text{b}}^2\right],$$

$$k_* = 2.7 hMpc^{-1} \Leftrightarrow M_* = 10^{11} M_{sun}$$

Number density of dark matter halos



Non linear Power spectrum and Lyman Alpha data



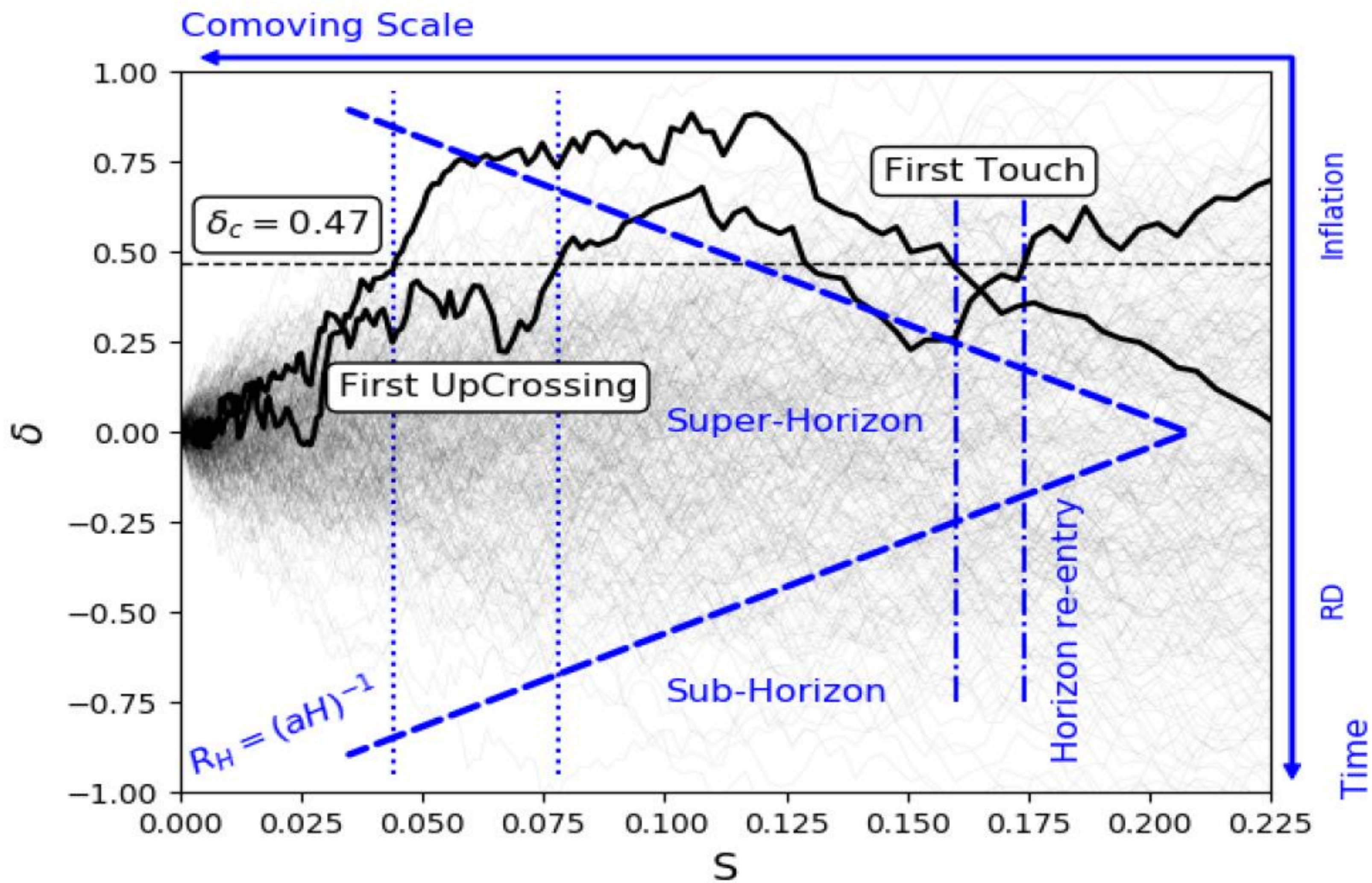
$$P^{1h}(k) = \int dm\, n(m) \left(\frac{m}{\bar{\rho}}\right)^2 |u(k|m)|^2$$

$$P^{2h}(k) = \int dm_1 n(m_1) \left(\frac{m}{\bar{\rho}}\right) |u(k|m_1)|$$

$$\times \int dm_2 n(m_2) \left(\frac{m_2}{\bar{\rho}}\right) |u(k|m_2)|\, P_{hh}(k|m_1, m_2)$$

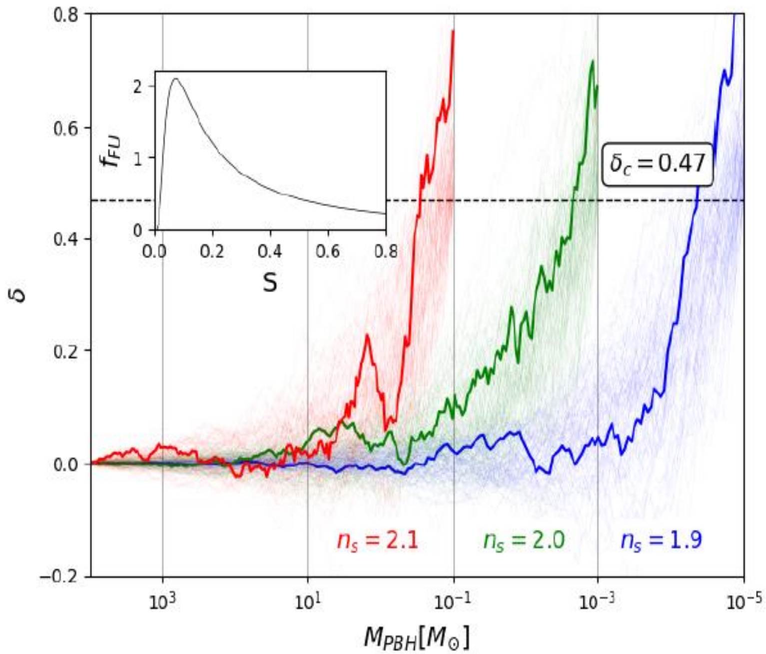
Primordial Black Holes

Primordial Black Holes



New constraints on primordial PS

	mass range	f_{PBH}	lower bound of mass range	spectral index EST	spectral index PS
asteroid mass range	$(10^{16}-10^{17})$ g	1	10^{16} g	1.490	1.616
sublunar mass range	$(10^{20}-10^{24})$ g	1	10^{20} g	1.540	1.703
			10^{22} g	1.600	1.756
Subaru HSC	$(10^{-11}-10^{-6})\ M_\odot$	10^{-3}	$10^{-10}\ M_\odot$	1.604	1.560
			$10^{-8}\ M_\odot$	1.666	1.605
OGLE	$(10^{-6}-10^{-3})\ M_\odot$	10^{-2}	$10^{-6}\ M_\odot$	1.729	1.757
			$10^{-4}\ M_\odot$	1.845	1.835
EROS/MACHO	$(10^{-3}-10^{-1})\ M_\odot$	0.04	$10^{-3}\ M_\odot$	1.862	1.947
			$10^{-2}\ M_\odot$	1.942	1.970
sub-Solar mass range*	$(0.2-1.0)\ M_\odot$	0.02	$0.2\ M_\odot$	2.018	2.046
			$0.6\ M_\odot$	2.115	2.078
		1	$0.2\ M_\odot$	2.028	2.258
			$0.6\ M_\odot$	2.126	2.297
intermediate mass range	$(10^{1}-10^{3})\ M_\odot$	10^{-4}	$10\ M_\odot$	2.103	1.848
			$10^{2}\ M_\odot$	2.204	1.911
SLABs	$\geq 10^{11}\ M_\odot$	1	$10^{11}\ M_\odot$	5.220	5.598
			$10^{12}\ M_\odot$	6.660	6.891



*Intermezzo**

* In music, an intermezzo, in the most general sense, is a composition which fits between other musical or dramatic entities, such as acts of a play or movements of a larger musical work.

Every evening words, not stars, light the sky Umberto Saba
1883 – 1957 live and write in Trieste

6 Lines of Thought to 6 parameter model

I.General relativity and the Universe

Asking for a Homogenous and Isotropic one!

II. Expanding Universe and measuring Ω

III. Cosmic Microwave Background Radiation

IV. Structure Formation and LSS

V. Subluminal matter

VI. Non-baryonic Dark Matter

- **Beyond Einstein in cosmological scales? The legacy of Λ?**

A four sigmaish tension - 2019

Any cracks in this standard cosmological
model might herald yet another surprise in our understanding of the cosmos

$$H_0 = 74.03 \pm 1.42 km/s/Mpc$$

1.9% Measurement

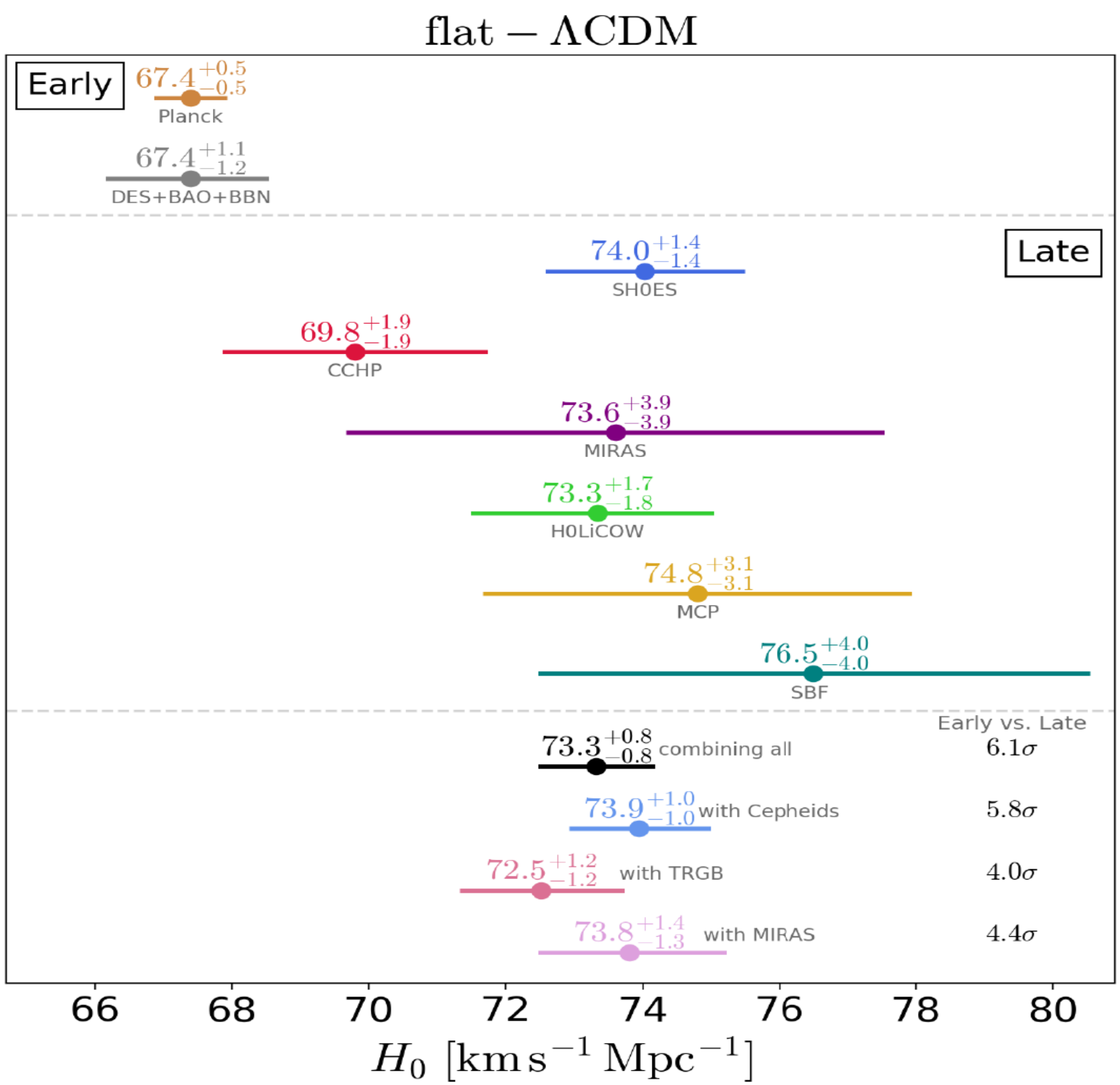
$$H_0 = 67.27 \pm 0.60 km/s/Mpc$$

0.9% Measurement

$$H^2 = (\frac{\dot{a}}{a})^2 = \frac{8\pi G}{3}(\rho_\gamma + \rho_{\nu(rel)}(N_\nu T^4) + \rho_m + \rho_b + \rho_\Lambda a^{-3(1+w)})$$

- **Planck 2018 results. VI. Cosmological parameters, arXiv:1807.06209**
- **Adam G. Riess, Stefano Casertano, Wenlong Yuan, Lucas M. Macri, Dan Scolnic, The Astrophysical Journal, Volume 876, Number 1, 2019, https://arxiv.org/abs/1903.07603v2**

A challenge in cosmological scales



Tensions between the Early and the Late Universe L. Verde , T. Treu , A.G. Riess, Nature Astronomy volume 3, pages891–895(2019)

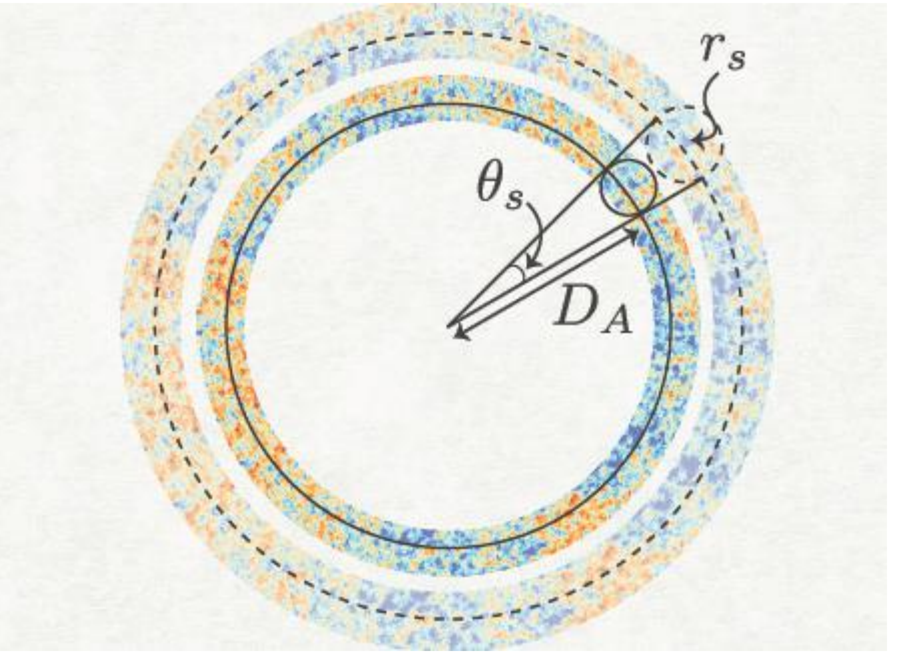
Angular diameter distance to CMB

- The angle in which we see the first peak of CMB is an observable

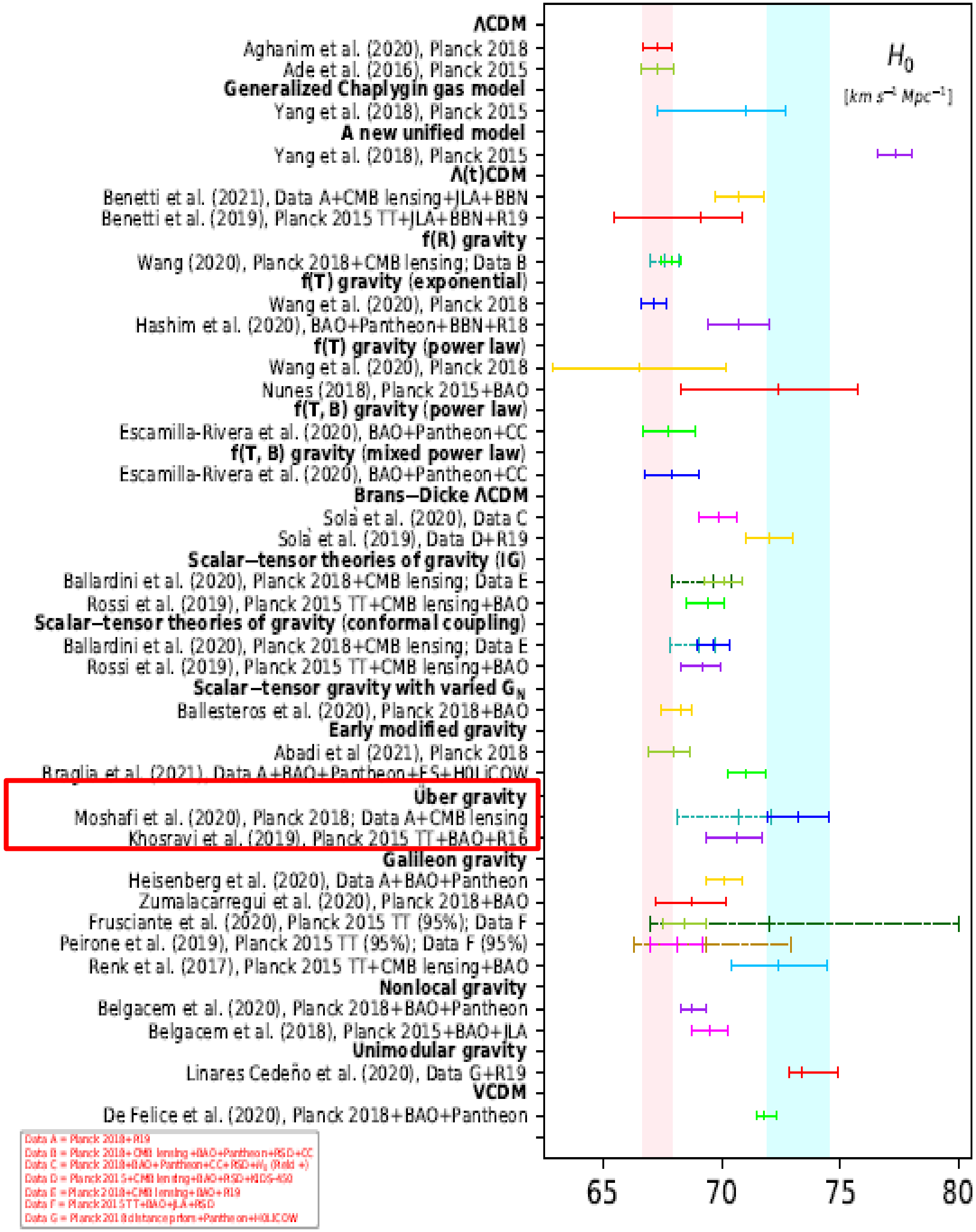
$$\theta = \frac{r_s^*}{d_A}$$

$$d_A = \frac{1}{1+z} c H_0^{-1} \int \frac{dz}{E(z)}$$

$$r_s^* = \int_0^{t_*} \frac{dt\, c_s(t)}{a(t)} = \int_{z_*}^{\infty} \frac{dz\, c_s(t)}{H(z)}$$



- Higher H_0 means smaller d_A in order to compensate, we should have smaller r_s^*
- **Early Universe** Solutions and **Late Time** Solutions



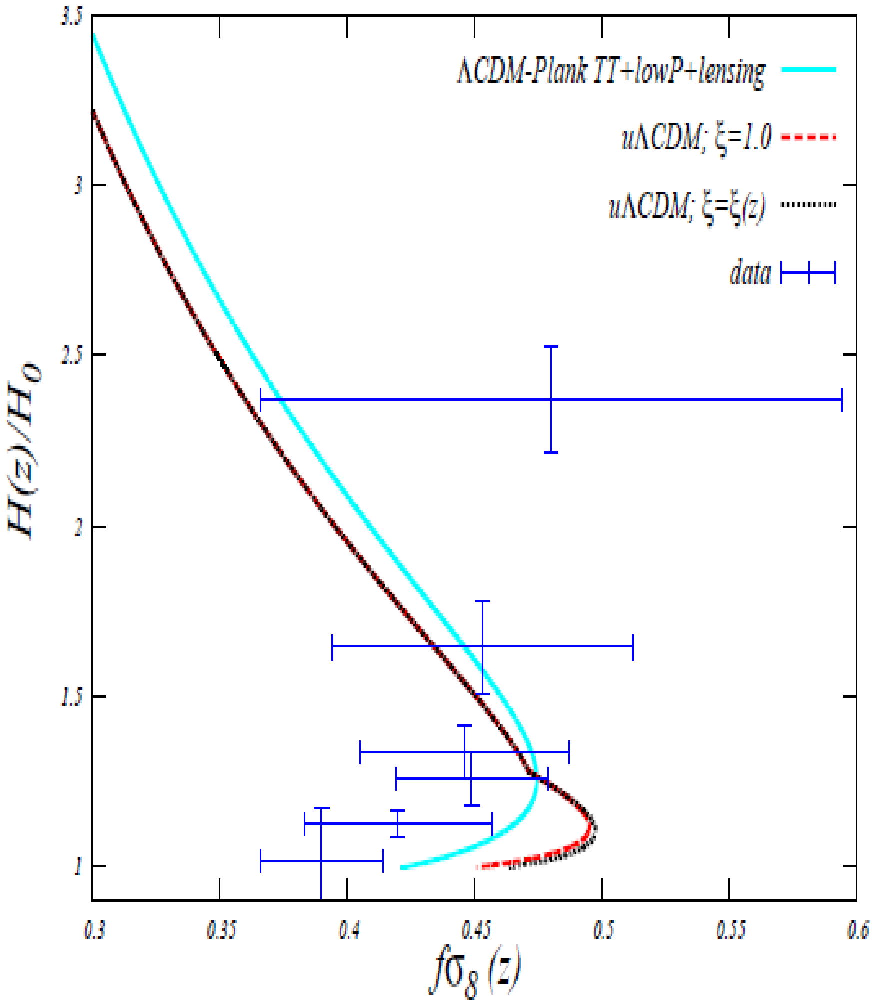
Nima Khosravi @ SBU

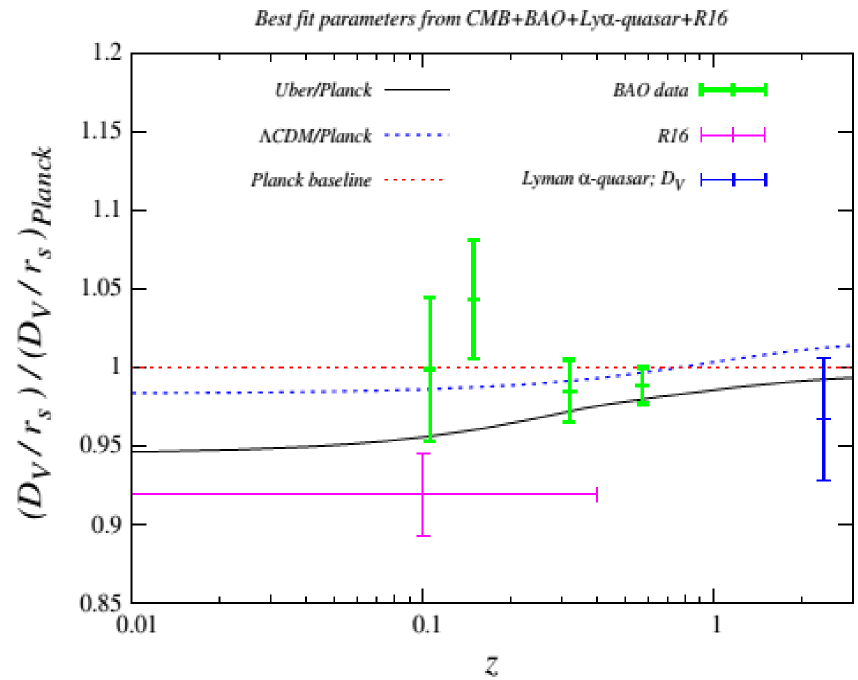
Niayesh Ashordi@ PI/Waterloo

Hossein Moshafi @ IPM

NatachaAltamirano @ PI/Waterloo

üΛCDM as an example of late time solution to the H_0 problem





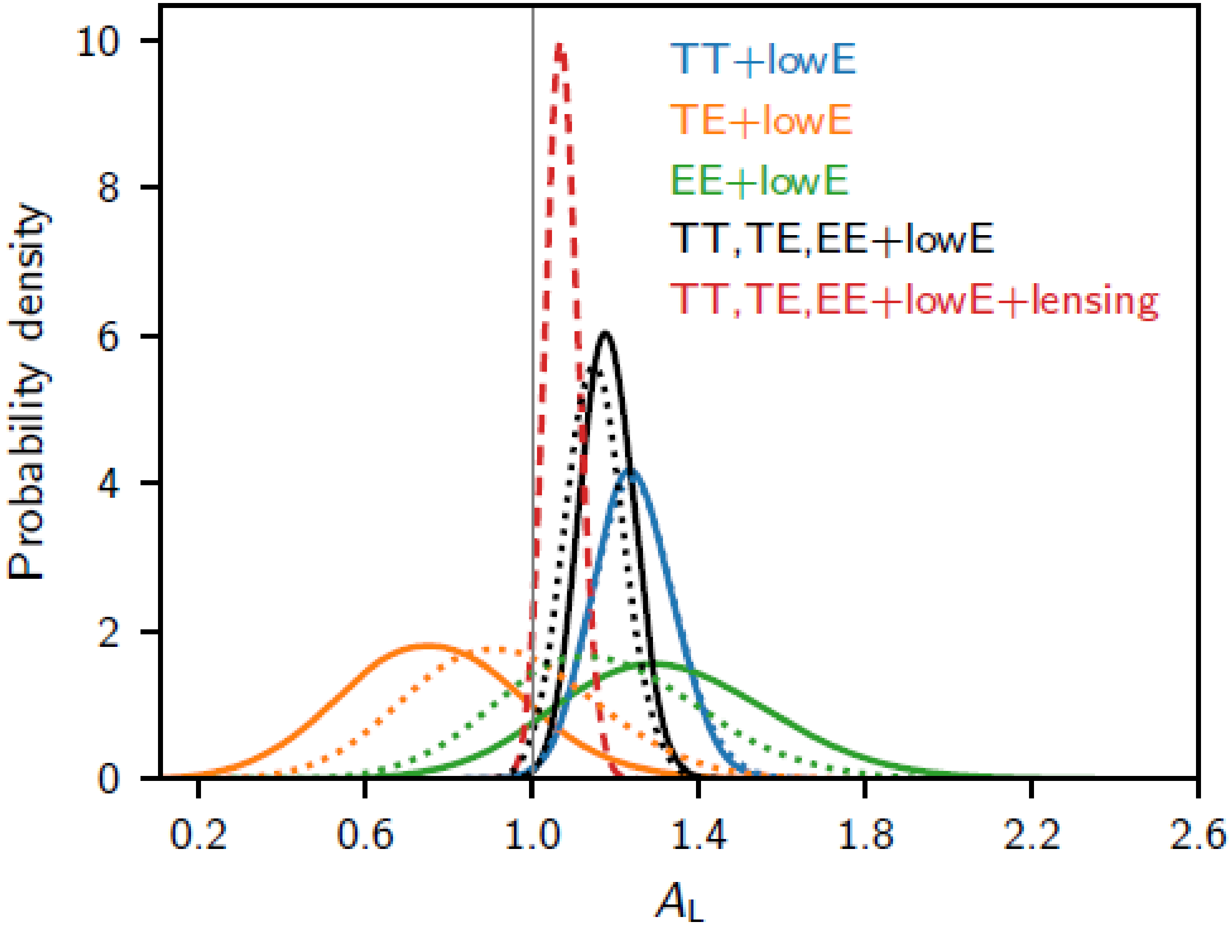
$$E^2(z) = \Omega_m(1+z)^3 + \Omega_\Lambda, \tag{6}$$

where $E(z) \equiv H(z)/H_0$ and H_0 is Hubble parameter at $z = 0$. For $z < z_\oplus$ we have

$$E^2(z) = \frac{1}{2}\bar{R}_0 + (1 - \frac{1}{2}\bar{R}_0)(1+z)^4 \tag{7}$$

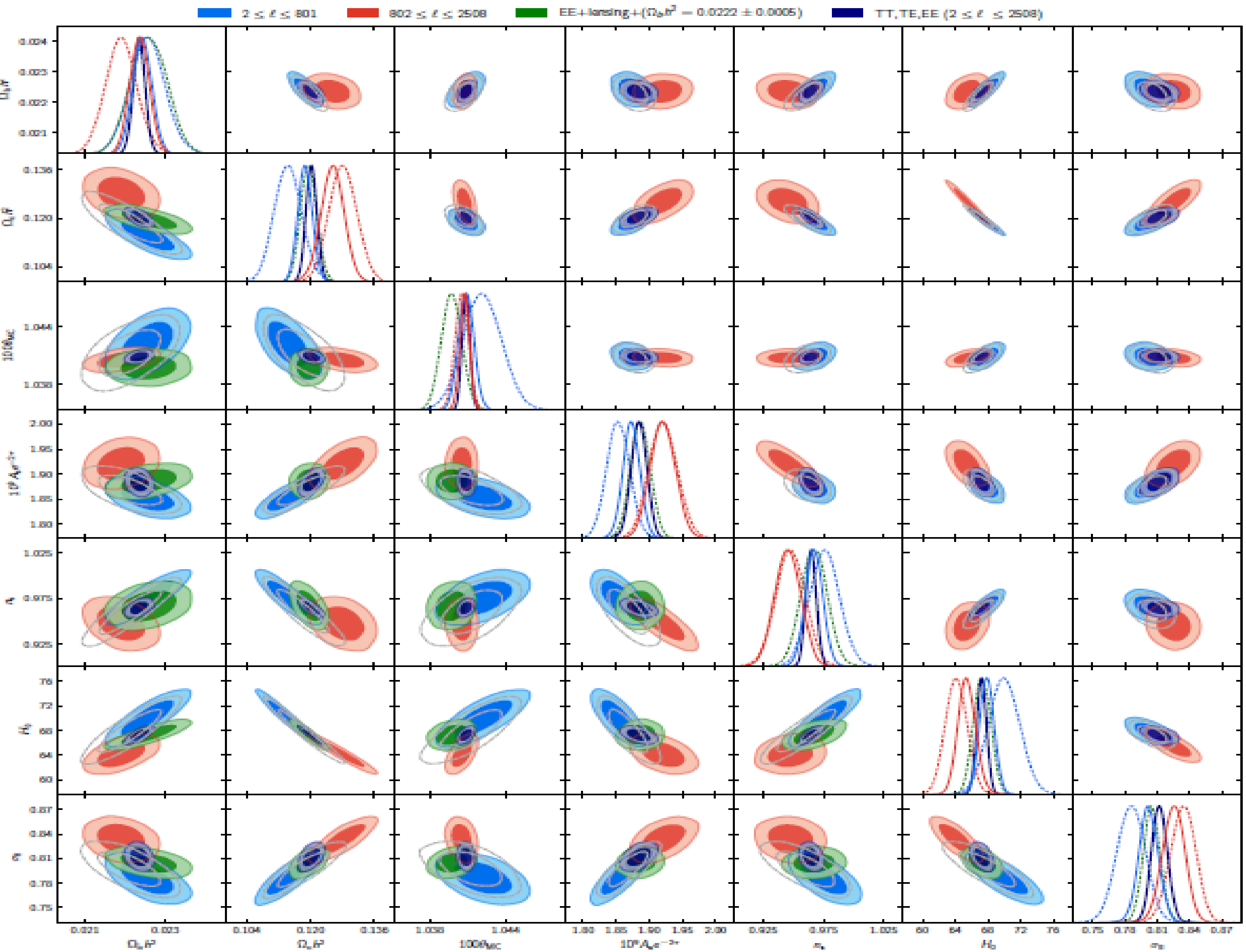
Nima Khosravi, Shant Baghram, Niayesh Afshordi, and Natacha Altamirano, PHYSICAL REVIEW D 99, 103526 (2019)

Self consistent CMB?

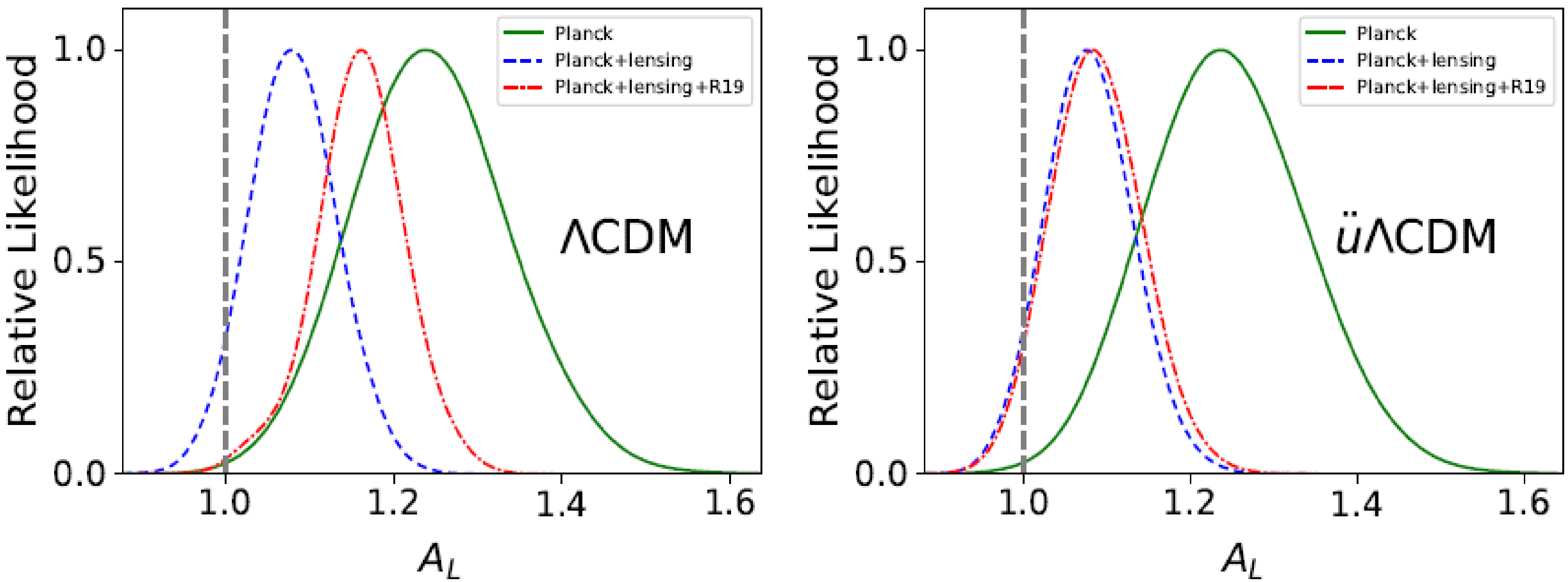


 Planck **2018 results. VI. Cosmological parameters**

Self consistent CMB?



H_0 and CMB lensing!



$$\ell^4 C_\ell^{\phi\phi} = 18\Omega_m^2 H_0^4 \int_0^{\chi_*} d\chi \chi^2 \left(\frac{\chi_* - \chi}{\chi_* \chi}\right)^2 P_m^{\ddot{u}}(\frac{\ell}{\chi})$$
$$\times \left[\frac{D^{\ddot{u}}(z)(1+z)}{D^{\ddot{u}}(z=0)\xi(z)}\right]^2,$$

Hossein Moshafi, Shant Baghram, Nima Khosravi, arXiv:2012.14377

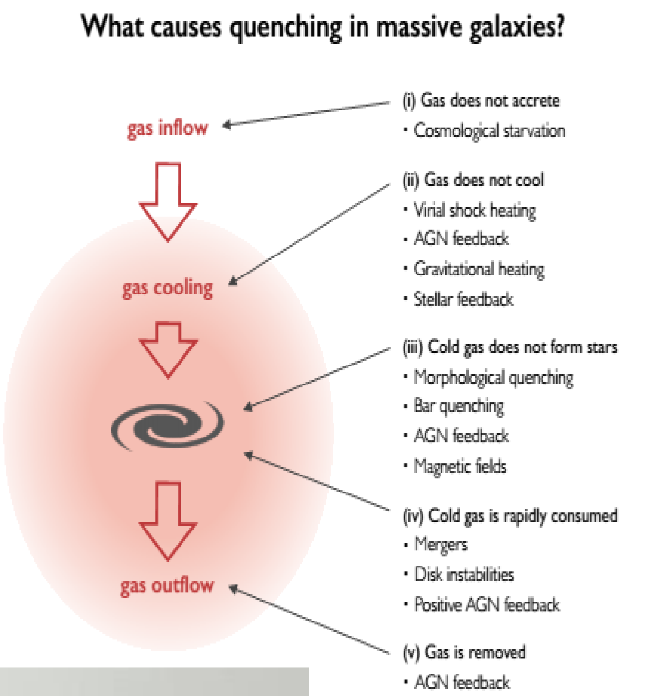
*Postlude**

*The final part of a piece; especially music played (normally on the organ)

New ideas in NL-structure formation

- GRAVITATIONAL WAVE ASTRONOMY!
- Seed of SMBH

Timothy M. Heckman and Philip N. Best, Annual Review of Astronomy and Astrophysics Vol. 52:589-660 (Volume publication date August 2014)



- Quenching of galaxies and mergers

More massive galaxies have systematically older stars

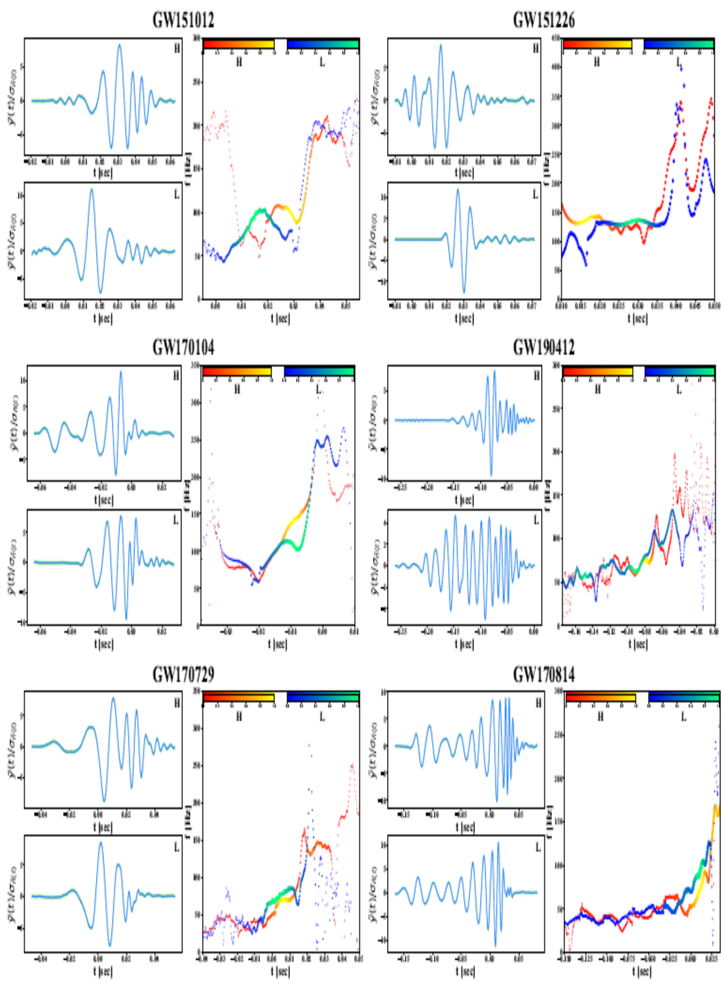
Star formation quenching in massive galaxies Allison Man, Sirio Belli, arXiv:1809.00722

- Flat disk galaxies

Formation of the Large Nearby Galaxies P. J. E. Peebles, arXiv:2005.07588

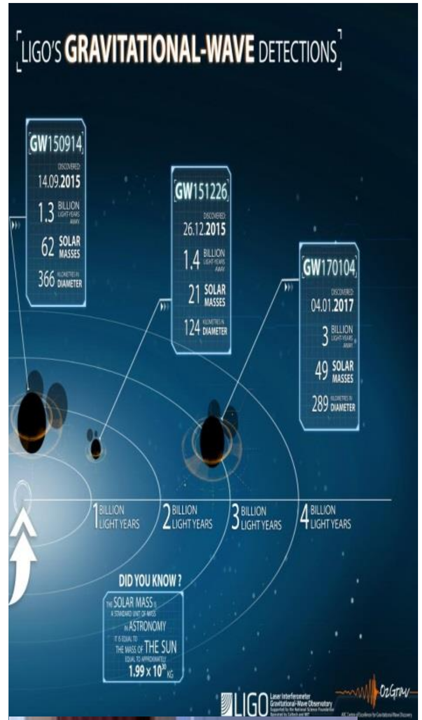
Hamed Kameli
PhD candidate in SUT

Gravitational Wave Astronomy

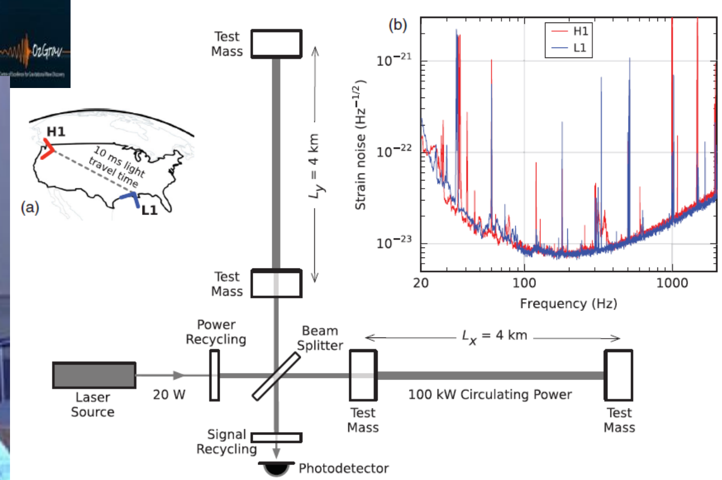


A Data-Driven Approach for the Extraction of Gravitational Waveforms

A. Akhshi[1], H. Alimohammadi[1,2], S. Baghram[1], S. Rahvar[1], M. Reza Rahimi Tabar[1,3,†], and H. Arfaei[1,2]



H. Arfaei @ SUT



M. Reza Rahimitabar + Akhshi and Alimohammadi

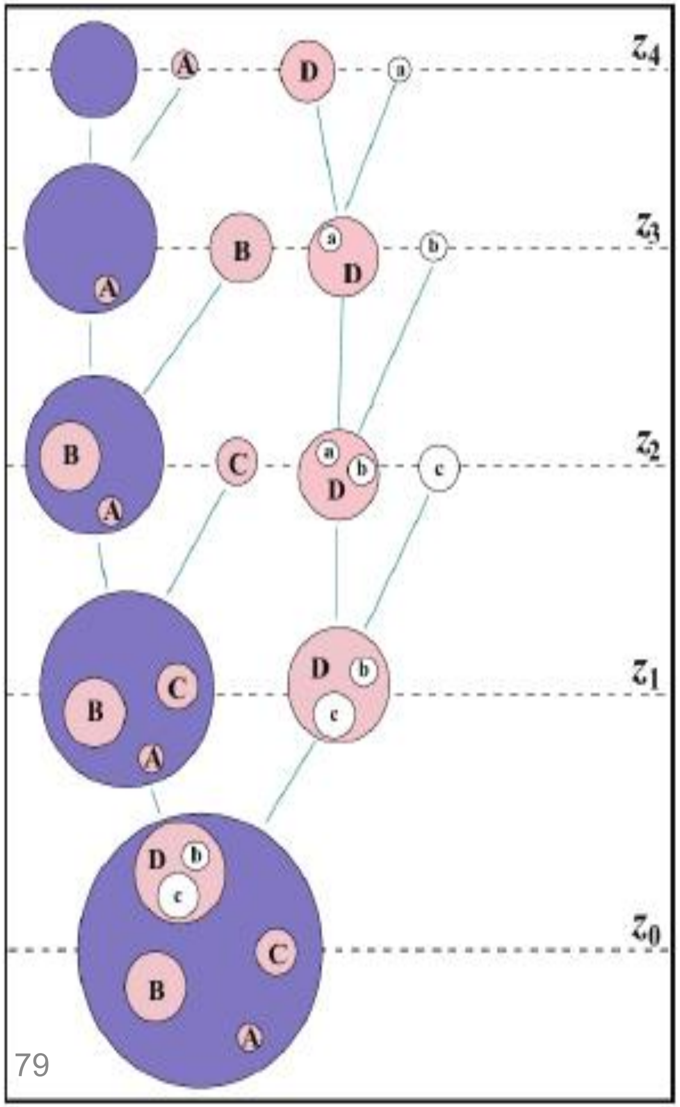
DM Halo Mergers and emergence of sub-halos

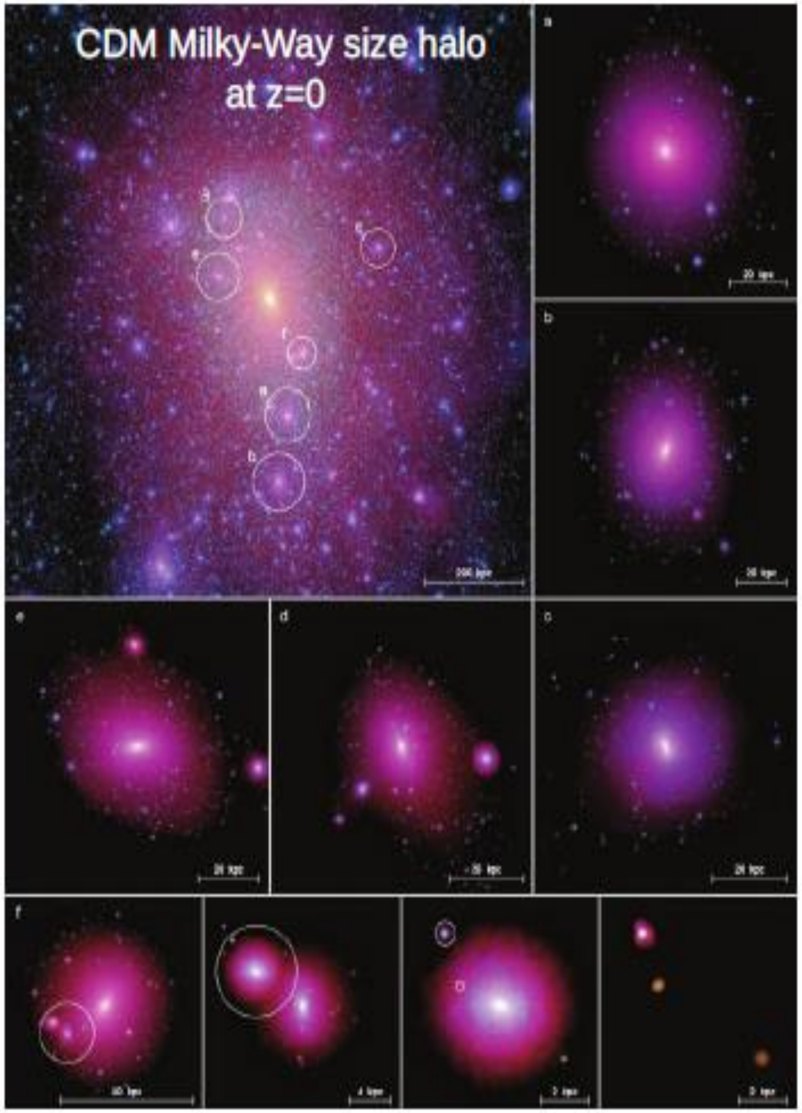
Review

Dark matter haloes and subhaloes

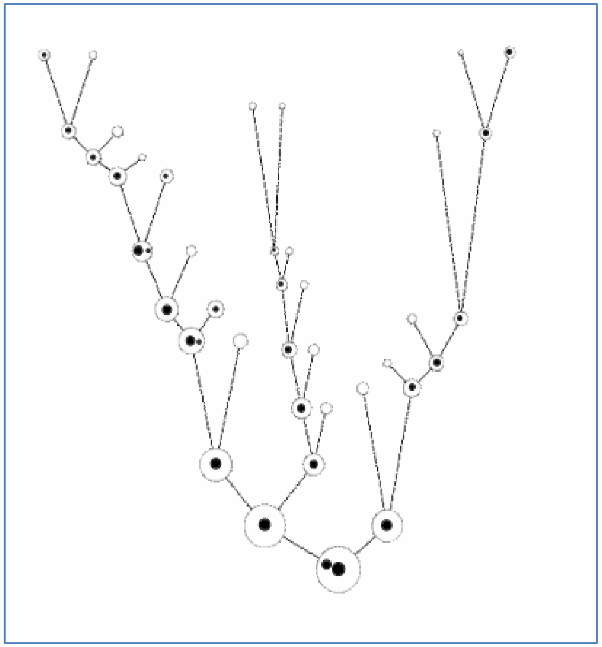
Jesús Zavala[1], Carlos S. Frenk[2]

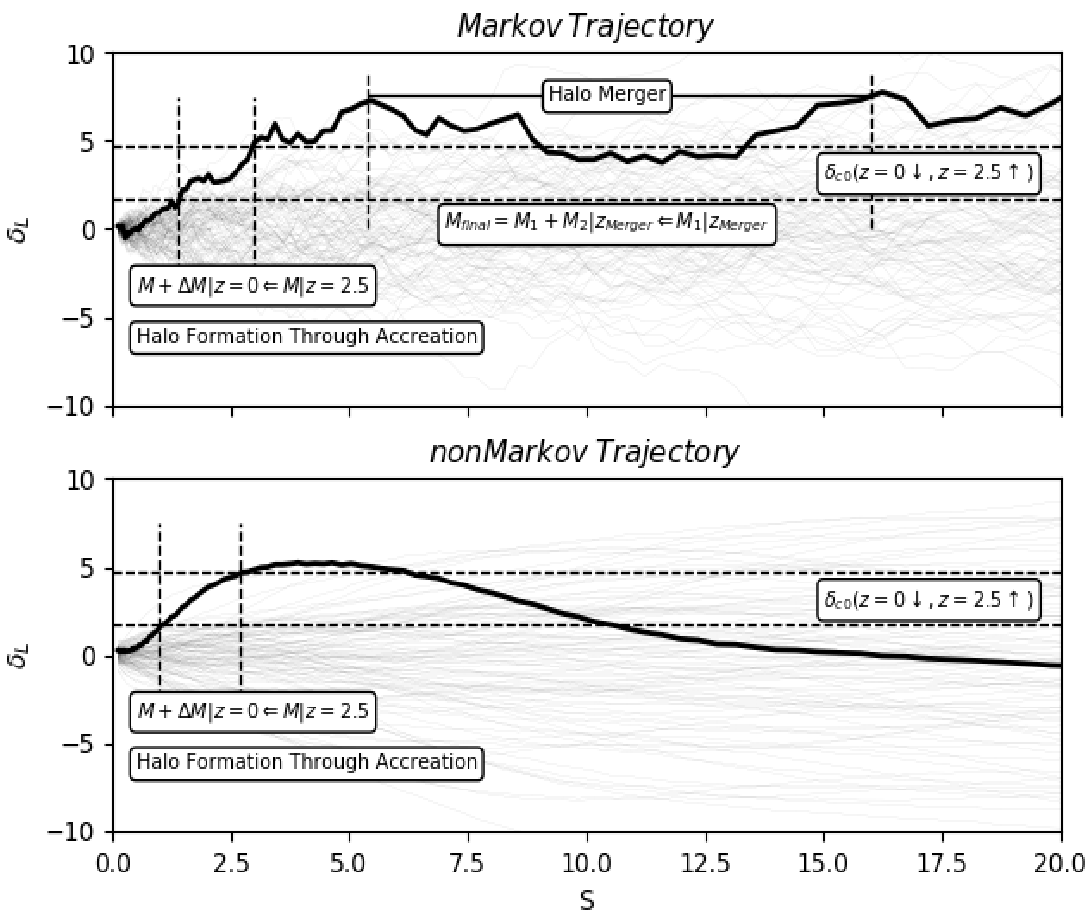
https://arxiv.org/pdf/1907.11775.pdf

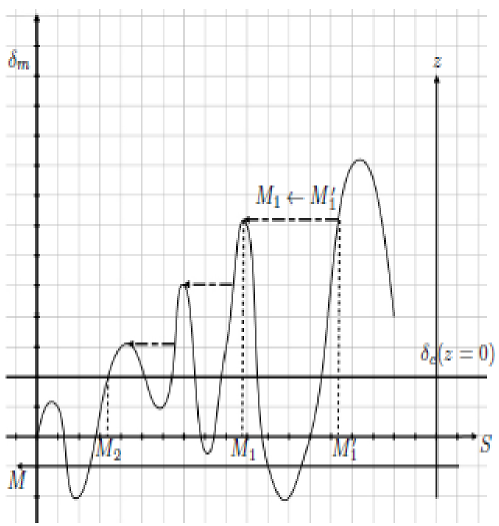




Hierarchical Structure Formation and EST





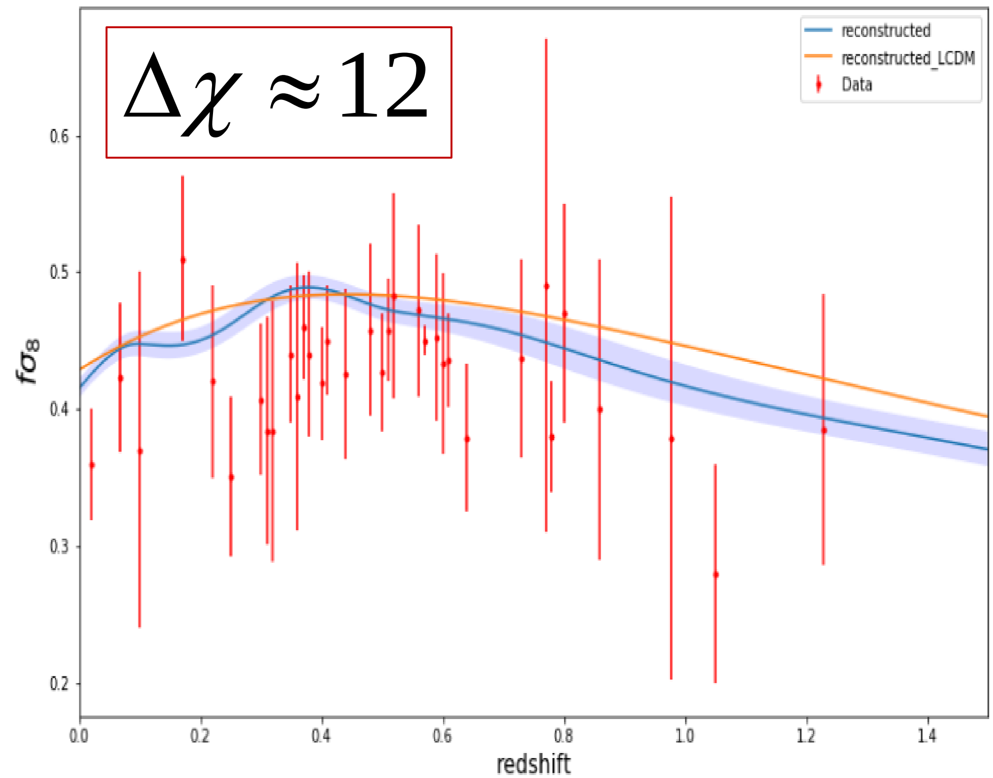


- **Farnik Nikakhtar, Shant Baghram, Phys. Rev. D 96, 043524 (2017)**
- **Merger history of dark matter halos in the light of H0 tensionHamed Kameli, Shant Baghram, arXiv:2008.13175**

Reconstructed Hubble parameter and linear theory

Table I: A compilation of recent RSD data from different surveys.

Index	Dataset	z	$f\sigma_8(z)$	Refs.	Year
1	THF	0.020	0.360±0.0405	[44]	2013
2	6dFGRS	0.067	0.423±0.055	[45]	2012
3	SDSS-veloc	0.100	0.370±0.130	[46]	2015
4	2dFGRS	0.170	0.510±0.060	[47]	2009
5	WiggleZ	0.220	0.420±0.070	[48]	2011
6	SDSS-LRG-200	0.250	0.3512±0.0583	[49]	2012
7	SDSS-BOSS	0.300	0.407±0.055	[50]	2012
8	SDSS-BOSS DR12	0.310	0.384±0.083	[51]	2017
9	BOSS-LOWZ	0.320	0.384±0.095	[52]	2013
10	SDSS-LRG	0.350	0.440±0.050	[47]	2009
11	SDSS-BOSS DR12	0.360	0.409±0.098	[51]	2017
12	SDSS-LRG-200	0.370	0.4602±0.0378	[49]	2011
13	GAMA	0.380	0.440±0.060	[53]	2013
14	SDSS-BOSS	0.400	0.419±0.041	[50]	2012
15	WiggleZ	0.410	0.450±0.040	[48]	2011
16	SDSS-BOSS DR12	0.440	0.426±0.062	[51]	2017
17	SDSS-BOSS DR12	0.480	0.458±0.063	[51]	2017
18	SDSS-BOSS	0.500	0.427±0.043	[50]	2012
19	BOSS DR12	0.510	0.458±0.038	[54]	2016
20	SDSS-BOSS DR12	0.520	0.483±0.075	[51]	2017
21	SDSS-BOSS DR12	0.560	0.472±0.063	[51]	2017
22	SDSS-LRG-200	0.570	0.423±0.052	[55]	2014
23	SDSS-BOSS DR12	0.590	0.452±0.061	[51]	2017
24	SDSS-BOSS	0.600	0.433±0.067	[50]	2012
25	BOSS DR12	0.610	0.436±0.034	[54]	2016
26	SDSS-BOSS DR12	0.640	0.379±0.054	[51]	2017
27	WiggleZ	0.730	0.437±0.072	[56]	2012
28	VVDS	0.770	0.490±0.018	[47]	2009
29	Vipers	0.800	0.470±0.080	[57]	2013
30	Vipers PDR-2	0.860	0.400±0.110	[58]	2016
31	eBOSS DR14	0.978	0.379±0.176	[59]	2018
32	Vipers v7	1.050	0.280±0.080	[60]	2016
33	eBOSS DR14	1.230	0.385±0.099	[59]	2018
34	eBOSS DR14	1.526	0.342±0.070	[59]	2018
35	eBOSS DR14	1.944	0.364±0.106	[59]	2018



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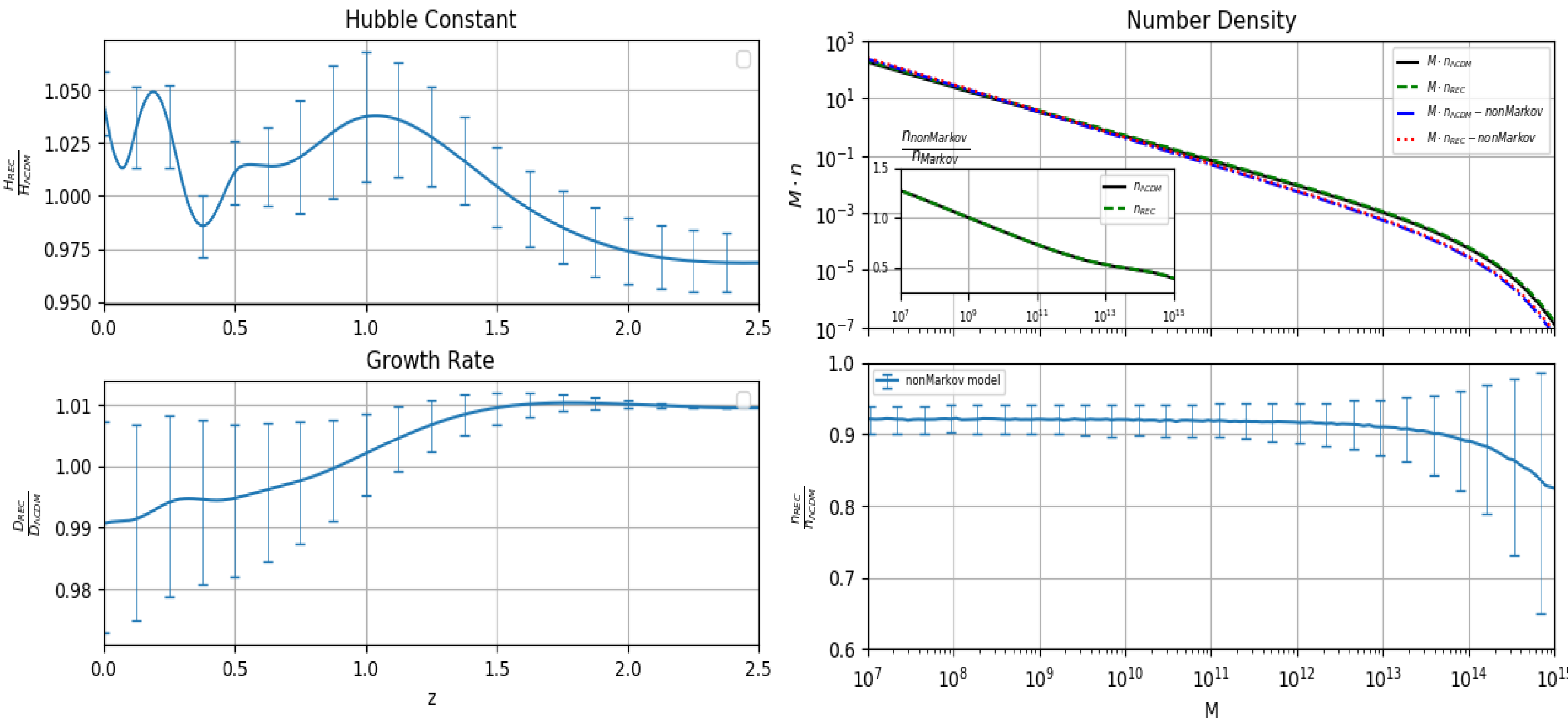
Ming-Jian Zhang, Hong Li وEur. Phys. J. C (2018) 78:460

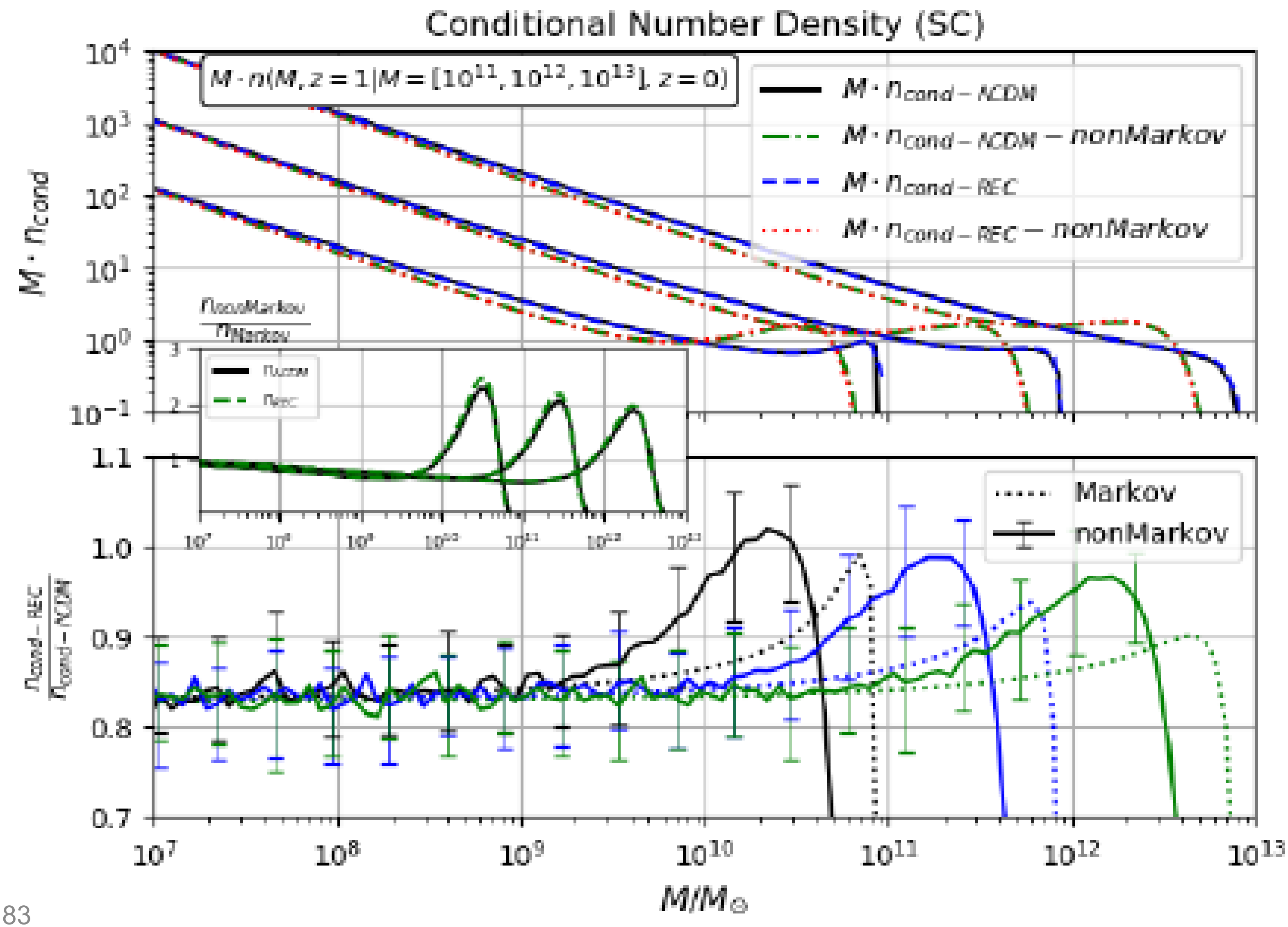
From Reconstructed Hubble to DM halos



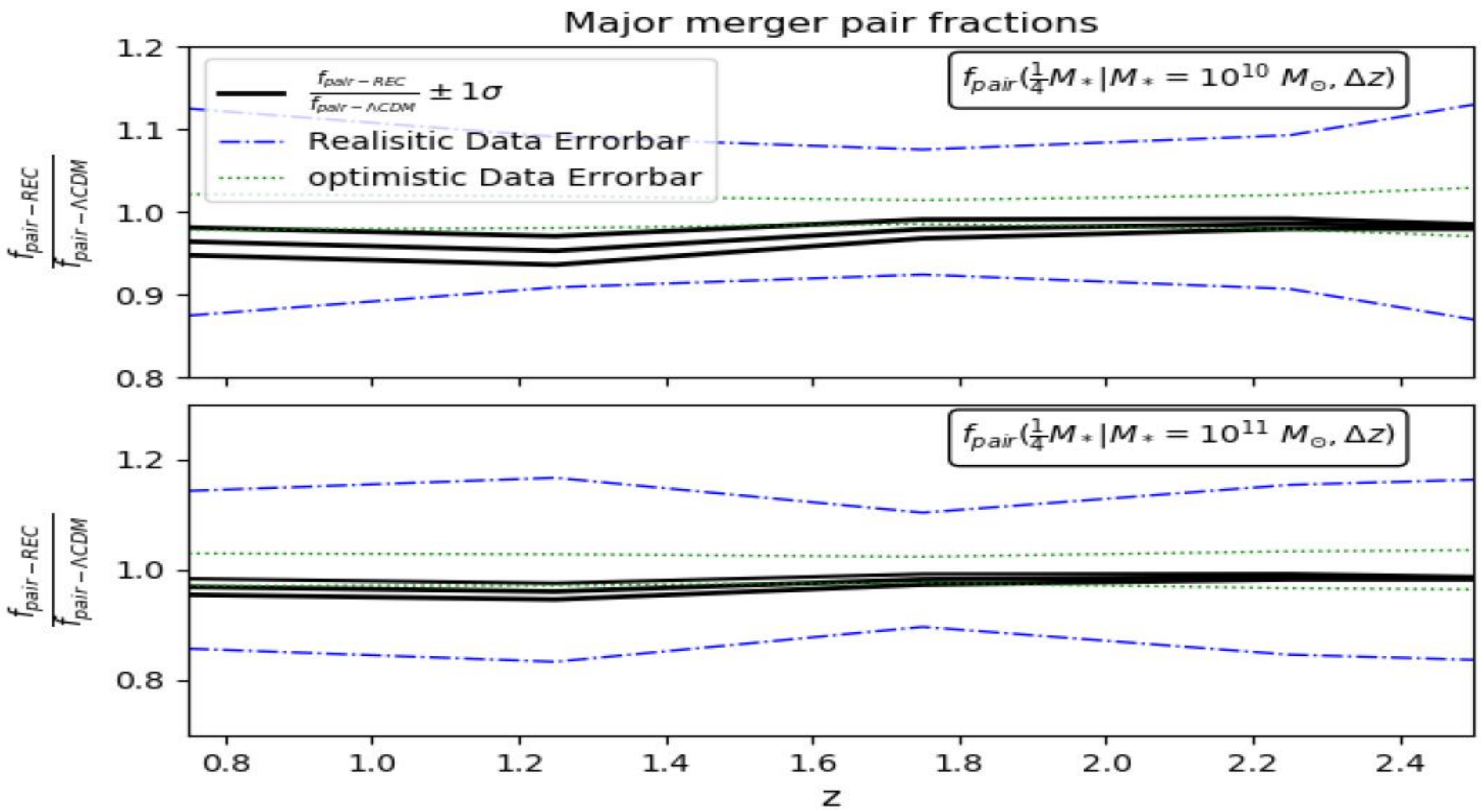
$$f_{\mathrm{FU}}(S_2,\delta_2|S_1,\delta_1)\,\mathrm{d}S_2 = \frac{f_{\mathrm{FU}}(S_1,\delta_1|S_2,\delta_2)\,f_{\mathrm{FU}}(S_2,\delta_2)}{f_{\mathrm{FU}}(S_1,\delta_1)}\,\mathrm{d}S_2$$

$$= \frac{1}{\sqrt{2\pi}}\frac{\delta_2(\delta_1-\delta_2)}{\delta_1}\left[\frac{S_1}{S_2(S_1-S_2)}\right]^{3/2}\exp\left[-\frac{(\delta_2 S_1-\delta_1 S_2)^2}{2S_1S_2(S_1-S_2)}\right]\mathrm{d}S_2$$

Merger Rate and observations



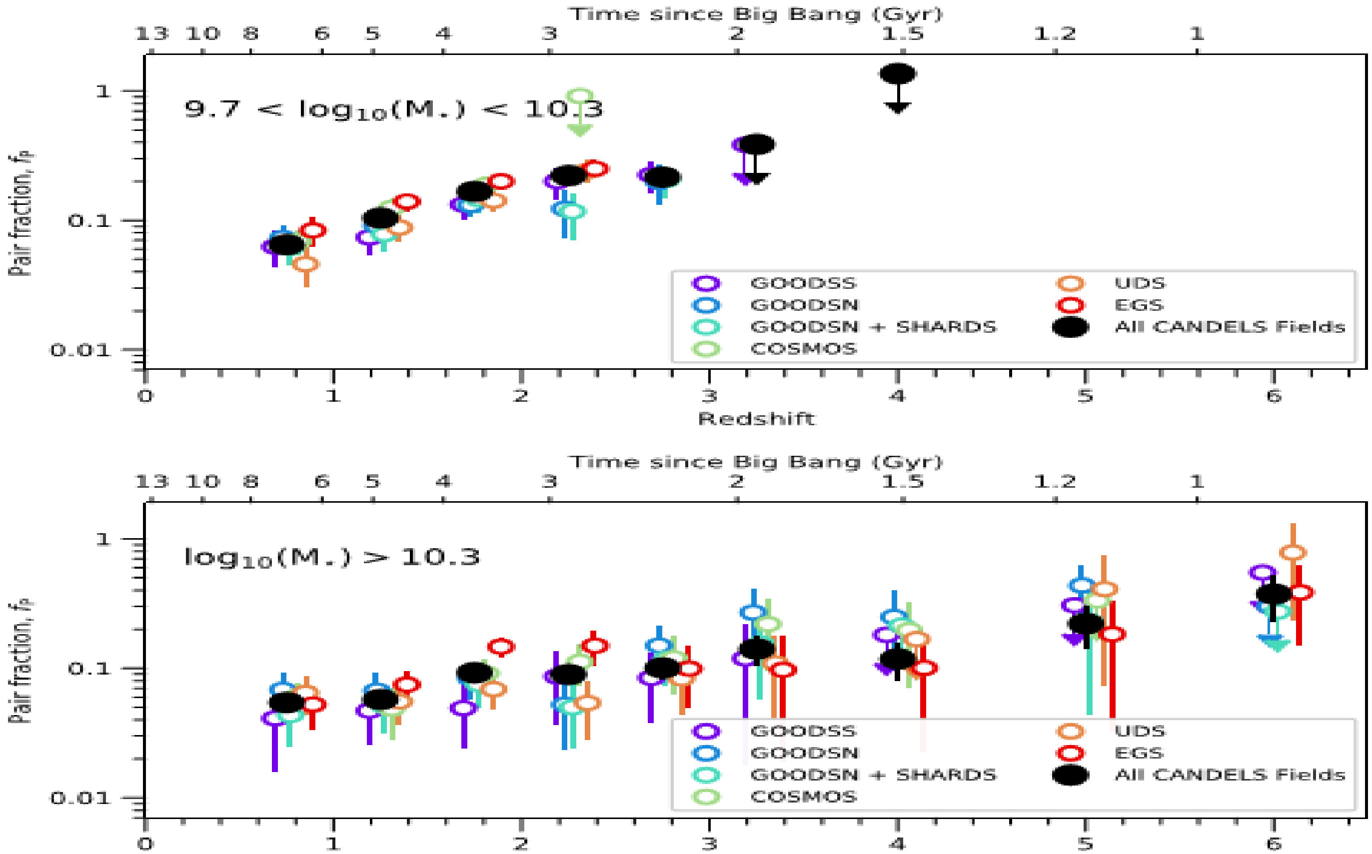
conclude: Merger rate can be a new probe of H_0



Observational constraints on the merger history of galaxies since $z \approx 6$:
Probabilistic galaxy pair counts in the CANDELS fields

Kenneth Duncan,[1,2] Christopher J. Conselice,[2] Carl Mundy,[2] Eric Bell,[3] Jennifer Donley,[4] Audrey Galametz,[5] Yicheng Guo,[6] Norman A. Grogin,[7] Nimish Hathi,[7] Jeyhan Kartaltepe,[8] Dale Kocevski,[9] Anton M. Koekemoer,[7] Pablo G. Pérez-González,[10,11] Kameswara B. Mantha,[12] Gregory F. Snyder,[7] and Mauro Stefanon[1]

Observation: Merger rate can be a new probe of H_0



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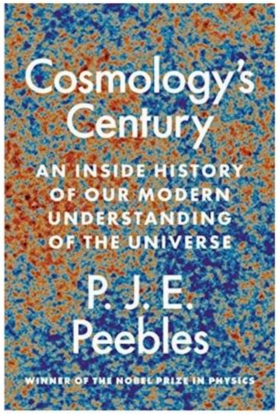
Conclusion and F.R.

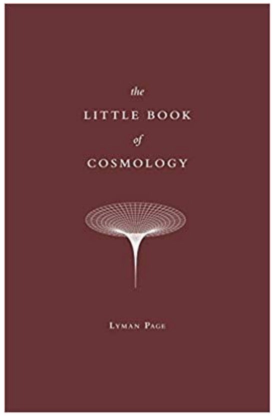
- A more sophisticated version of EST to study non-linear structure formation →Voids, galaxy-DM relation,…
- Filaments in ESS context
- Developing the methods to look at cosmic web
- Statistics of PBH as a DM
- Observational proposal for DM in galactic scale
- Uber-gravity hint to H_0
- Reconstructed H_0 merger tree and LSS

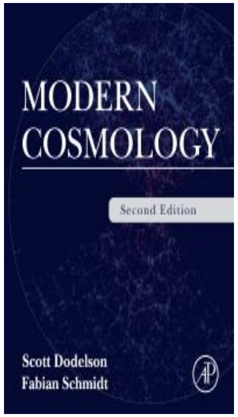
An updated reviews and books

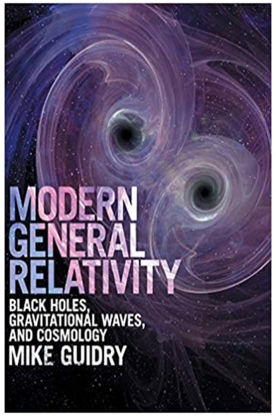
- http://sharif.edu/~baghram/talks.html

- In the Realm of the Hubble tension − a Review of Solutions; Eleonora Di Valentino, et al. https://arxiv.org/abs/2103.01183.
- Challenges for ΛCDM: An update Leandros Perivolaropoulos, Foteini Skara https://arxiv.org/abs/2105.05208
- Primordial Black Holes as Dark Matter: Recent Developments Bernard Carr, Florian Kuhnel https://arxiv.org/abs/2006.02838
- Dark matters on the scale of galaxies Ivan de Martino, Sankha S. Chakrabarty, Valentina Cesare, Arianna Gallo, Luisa Ostorero, Antonaldo Diaferio et al. https://arxiv.org/abs/2007.15539










Euclid
Swift
WFIRST (N.R.)
Kepler
Hubble
Herschel
James Web Telescope
Spektr-R
Fermi
Chandra
Lisa
NuSTAR
GALEX
Spitzer
Planck
gamma ray
X-ray
ultraviolet
visible
infrared
microwave
radio
GW-net
SOFIA
Vera Rubin Telescope
Large Synoptic Survey Telescope
Keck
HESS
SALT
Gemini
CARMA
Greenbank
VLA
SKA

Final Word!

- Probably Tensions will open new possibilities
- LSST (V. Rubin) + EULCID + WFIRST (Nancy Roman)+ JWT + eLISA+ SKA + GAIA + … + Big data + ML+…
- More insight to Structure Formation is crucial!
- GW Astronomy is just here !!!

A little and a little, collected together, become a great deal; the heap in the barn consists of single grains, and drop and drop make the inundation. Saadi