

- Basics of standard cosmological model
- Constraints on the model
- Anomalies: merging rate, giant galaxies, reionization epoch, voids, etc
- Remedy: scalar interaction in the dark sector

Collaborators:

Steve Gubser (Princeton)

Jim Peebles (Princeton)

The VIRGO Collaboration 1996

The galaxy distribution are the traditional probes of the power spectrum

APM Survey picture of a large part of the sky, about 30 degrees across, showing almost a million galaxies out to a distance of about 2 billion light years.

MAP990047

The 2dF Galaxy Redshift Survey: Power-spectrum analysis of the final dataset and cosmological implications. radial selection via a new empirical treatment of the contractionis of interest to see how our earlier conclusions and the see how our earlier conclusions and the see \mathbf{r}

Shaun Cole¹, Will J. Percival², John A. Peacock², Peder Norberg³, Carlton M.
Bough¹, Carles S. Frenkl. Jyen Beldry⁴, Jess Bland Hauthorn⁵, Terry Bridges⁶ Baugh¹, Carlos S. Frenk¹, Ivan Baldry⁴, Joss Bland-Hawthorn⁵, Terry Bridges⁶, Russell Cannon⁵, Matthew Colless⁵, Chris Collins⁷, Warrick Couch⁸, Nicholas J.G.
Chara^{4,2}, Carrie, Deltar⁹, V.B. Elsel, Rebecte De Preprie¹⁰, Simon, B. Driver¹¹ Cross^{4,2}, Gavin Dalton⁹, V.R. Eke¹, Roberto De Propris¹⁰, Simon P. Driver¹¹, George Efstathiou¹², Richard S. Ellis¹³, Karl Glazebrook⁴, Carole Jackson¹⁴, Adrian Jenkins¹, Ofer Lahav¹⁵, Ian Lewis⁹, Stuart Lumsden¹⁶, Steve Maddox¹⁷, Darren Madgwick¹², Bruce A. Peterson¹¹, Will Sutherland¹², Keith Taylor¹³ (The 2dF- $CDSF$) GRS Team) 2dFGRS power spectrum can be used to infer the matter log^3 Carlton M M^5 , Terry Bridges⁶,
 M^5 , Nicholas LC S_{R} models to P . Driver¹¹, Maddox^{17} , Darren For the choice of model, we adopted the philosophy of Per-

 \mathbf{c} is the main anual component \mathbf{c}

 $\frac{1}{\sqrt{2}}$ $\frac{1}{2}$ Astronomie, $\frac{1}{2}$ as transmitted Physical Zurich, Switzerland, S κ / II Mpc_{in}s $\frac{1}{2}$ M₁ 0.05 0.1 ⁷Astrophysics Research Institute, Liverpool John Moores University, Twelve Quays House, Egerton Wharf, Birkenhead, L14 1LD, UK ⁸School of Physics, University of New South Wales, Sydney, NSW2052, Australia \bullet 2dFGRS - Cole et al. 2004 $10H.$ Minds P_{infinite} 1004 Fort, Tyndall Avenue, Tyndall 1.8 cm of cm cm 2dFGRS - Percival et al. 2001 $2dFGRS - Tegmark$ et al. 2002 14August Telescope National Facility, Political Facility, Political Facility, Political Poli \sim 5Department of Physics and Astronomy, University College London, \sim 1004 ¹⁶Department of Physics & Astronomy, E C Stoner Building, Leeds LS2 9JT, UK 17 School of Physics and Astronomy, University Γ \wedge \wedge ABSTRACT $\mathbf{u} \cdot \mathbf{b} = \mathbf{0} \cdot \mathbf{c}$ employing a direct Fourier method. The sample used comprises 221 414 galaxies with measured redshifts. We investigate in the modelling of the sample selection, \mathbf{r} in the proving on proving on $p = 0$ is tion is determined by dividing the survey according to rest-frame colour, and deducing to rest-frame colour, and deducing to $\frac{1}{2}$ and the self-constructions and evolutions and evolutions and evolutions and evolution for each population. The ϵ covariance matrix for the power-spectrum estimates is determined using the power-spectrum estimates in $n_c \equiv$ 1.1 approximately to the construction of $n_{\rm s} = 1.027 \pm 0.050$. the input cosmological model can be correctly recovered. We discuss in detail the possible differences between the galaxy and mass power spectra, and treat these using simulations, analytic models, and a hybrid empirical approach. Based on these investigations, we are confident that the 2dFGRS power spectrum can be used that the 2dFGRS power spectrum can to infer the matter content of the universe. On large scales, our estimated power spectrum shows evidence for the 'baryon oscillations' that are predicted in CDM models. Fitting to a CDM model, assuming a primordial ns = 1 spectrum, h = 0.72 and neutrino mass, the preferred parameters are $\mathcal{L}(\mathcal{A},\mathcal{A})$ $\mathbf{P} = \mathbf{P} \mathbf$ than the 0.20 ± 0.03 in our 2001 analysis of the partially complete 2dFGRS. This shift is largely due to the signal from the newly-sampled regions of space, rather than the refinements in the treatment of observational selection. This analysis therefore implies a density significantly below the standard Q \bar{Q} in combination with Q \bar{Q} in combination with with Q \bar{Q} in Q \bar{Q} in Q in Q CMB data from WMAP, we infer 2021 On acceptance of this paper, power spectrum data will be made available at $log_{10} k / h \text{ Mpc}^{-1}$ k / h Mpc ~ 0.28 $\frac{1}{24ECRS} = \text{Cole et al } 2004$ $\frac{1}{2}$ $\frac{\log_{10} P(k)}{4} / h^{-3} Mpc^3$
4.5 Ωb/Ω^m = 0.185 ± 0.046. (40) These figures assume h = 0.72, but are insensitive to this These values represent in some respects an important c_n $\frac{1}{n}$ $\frac{1}{$ and Ωb/Ω^m = 0.15 ± 0.07. Statistically, the shift in the pre-

is greatly improved, by nearly a factor 2. This reflects a sub-

 $h = 0.766 \pm 0.032$ $\Omega_{\rm m} = 0.231 \pm 0.021$ $\Omega_{\rm b} = 0.042 \pm 0.002$

Cosmology with the Ly-alpha forest

$$
F = \exp(-\tau) , \quad \tau \propto n_{_{HI}}
$$

Models, scales, redshifts

Joint modeling of the probability distribution and power spectrum of the $Ly\alpha$ forest : comparison with observations at $z = 3$

Vincent Desjacques¹ and Adi Nusser^{1,2}

1.

particle in the control of the control of

¹The Physics Department and the Asher Space Research Institute, Technion, Haifa 32000, Israel

 $I_4 = I.5$. The errorbars attached to the n column densities N_{HI} exceeding 10^{20} cm corresponds to a redshift interval $\Delta z \sim 0.04$ at $z = 3$. $\sigma_8 = 0.72$ (solid), 0.82 (long-dashed); 0.9 (short dashed) and 1 (dashed-dotted curve). The RSI model is shown as dotted curves. All the Γ 1 with σ_8 show our estimate of the cosmic he comoving length of each spectrum is L $\frac{\sigma_8}{\sigma_8}$ Figure 2. Synthetic spectra extracted from each of the simulations at z = 3. The vertical bars above the spectra show the position of the lines with fitted column densities $N_{\text{H}I}$ exceeding $10^{12.5}$ cm². The comoving length of each spectrum is $L = 25 h^{-1}$ Mpc, which models have a temperature Tˆ⁴ = 1.5. The errorbars attached to the model with σ⁸ show our estimate of the cosmic variance error (cf. text).

"Concordance" model fits the power spectrum data

credit: Garcia-Bellido 02

Anomalies of the ΛCDM model

ΛCDM του στο συνεργασία του προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπι
Προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσωπικού του προσω

 $\Lambda \textbf{CDM}$ tends to produce too much merging at $z < 1$

Fig. 2.— Images of the mass distribution at $z = 0, 1$ and 3 in our 8 simulations of the assembly of cluster mass halos. Each plot shows only those particles which lie within r_{200} of halo center at $z = 0$. Particles which lie within $10h^{-1}$ kpc of halo center at this time are shown in black. Each image is $5h^{-1}\text{Mpc}$ on a side in physical (not comoving) units.

Early Formation and Late Merging of the Giant Galaxies

Liang Gao¹ Abraham Loeb² P. J. E. Peebles³ Simon D. M. White¹ and Adrian Jenkins⁴

Kinematics of stars a few kpc above the midplane of the disk:

DECIPHERING THE LAST MAJOR INVASION OF THE MILKY WAY

Gerard Gilmore

Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, England, UK; gil@ast.cam.ac.uk

ROSEMARY F. G. WYSE^{1,2}

Johns Hopkins University, Department of Physics and Astronomy, 3400 North Charles Street, Baltimore, MD 21218; wyse@pha.jhu.edu

AND

JOHN E. NORRIS

Research School of Astronomy and Astrophysics, Australian National University, Mount Stromlo Observatory, Cotter Road, Weston Creek, Canberra, ACT 2611, Australia; jen@mso.anu.edu.au *Received 2002 May 10; accepted 2002 June 14; published 2002 June 25*

ABSTRACT

We present first results from a spectroscopic survey of ∼2000 F/G stars 0.5–5 kpc from the Galactic plane, obtained with the Two Degree Field facility on the Anglo-Australian Telescope. These data show the mean rotation velocity of the thick disk about the Galactic center a few kiloparsecs from the plane is very different than expected, being ∼100 km s⁻¹ rather than the predicted ∼180 km s⁻¹. We propose that our sample is dominated by stars from a disrupted satellite that merged with the disk of the Milky Way some 10–12 Gyr ago. We do not find evidence for the many substantial mergers expected in hierarchical clustering theories. We find yet more evidence that the stellar halo retains kinematic substructure, indicative of minor mergers.

if LCDM

Pieces of the puzzle: Ancient substructure in the Galactic disk entre A and periodisk and periodisk as well as the APL-space, and the

Amina Helmi^{*1}, J. F. Navarro $\dagger^{2,3}$, B. Nordström^{4,5}, J. Holmberg⁶, M. G. Abadi²^{\dagger} and M. Steinmetz⁷§

 $\begin{array}{c} \rm{pt}\hbox{at},\rm{al-1}\hbox{or}\ \sim\hbox{G}\ \rm{ic};\rm{ff},\rm{g} \ \rm{1\,fb} \end{array}$ these stars, that, in all likelihood, correspond to the remains of disrupted satellites. stellar populations of ~ 8 Gyr (33%) and ∼ 12 Gyr (67%) of age. The second Group $\frac{1}{2}$ and ghave avidence of three negation with $\langle [Fe/H] \rangle \sim -0.6$ dex has 86 stars, and shows evidence of three populations of 8 $\frac{1}{2}$ Cyr (40%) of 200 Finally the third Croun Gyr $(15\%),$ 12 Gyr (36%) and 16 Gyr (49%) of age. Finally, the third Group has 68 $\frac{\text{ound}}{\text{d}}$ $\frac{\text{d}}{\text{d}}$ a commonly showld satisfy $\frac{\text{d}}{\text{d}}$ a commonly showld stars, with typical metallicity around −0.8 dex, and a single age of ∼ 14 Gyr. The unts of debris in the Galactic disk whose ori identification of substantial amounts of debris in the Galactic disk whose origin can \mathbf{S} satellite \mathbf{z} alaxy, provides undisputable evid be traced back to more than one satellite galaxy, provides undisputable evidence of the hierarchical formation of the Milky Way. on orbits of common (moderate) eccentricity, analogous to the pattern expected for extra-Galactic provenance. It is possible to identify three coherent Groups among The most metal-rich group ($[Fe/H] > -0.45$ dex) has 120 stars distributed into two

have very distinct metallicity and age distributions, providing further evidence of their

merger debris. Besides being die 274 stars in the 274 stars in the 274 stars in the 274 stars in the 274 stars

probably not LCDM

SIMULATIONS OF GALAXY FORMATION IN A A COLD DARK MATTER UNIVERSE. II. THE FINE STRUCTURE OF SIMULATED GALACTIC DISKS

MARIO G. ABADI¹ AND JULIO F. NAVARRO² Department of Physics and Astronomy, University of Victoria, Victoria, BC V8P 1A1, Canada

MATTHIAS STEINMETZ³ \mathbf{M}_ATTH

Steward Observatory, 933 North Cherry Avenue, Tucson, AZ 85721; and Astrophysikalisches Institut Potsdam, An der Sternwarte 16, D-14482 Potsdam, Germany

> **AND** \bf{AND} abundances \bf{AND} abundances \bf{AND}

> V incent R. Eke⁴

common origin in a single system. This is in agreement with the conclusions of Wyse & Gilmore (1995), who argue that

> cosmolective are easily identified solely in a dark matter halo chosen in a dark matter halo chosen so that mergers and accretion events are unimportant dynamically after $z \sim 1$. ρ is stars on α is nearly circuit and a hotter, this component with orbital parameters ρ nents of a galaxy simulated in the '' concordance '' in the '' concordance '' in the '

> between the thin disk and the spheroid. Supporting evidence for the presence of distinct thin disk and thin-disk and thin-di

galaxy is largely driven by the rate at which gas cools and

Downsizing: big galaxies are old, small galaxies are young

The observed correlation function function function function function of galaxies is a powerful to galaxies in

The SAURON project – IV. The mass-to-light ratio, the virial mass estimator and the fundamental plane of elliptical and lenticular galaxies

Michele Cappellari, $1 \star R$. Bacon, 2 M. Bureau, 3 M. C. Damen, 1 Roger L. Davies, 3 P. Tim de Zeeuw, 1 Eric Emsellem, 2 Jesús Falcón-Barroso, 1 Davor Krajnović, 3 Harald Kuntschner,⁴ Richard M. McDermid,¹ Reynier F. Peletier,⁵ Remco C. E. van den Bosch, 1 and Glenn van de Ven 1 ¹*Leiden Observatory, Postbus 9513, 2300 RA Leiden, The Netherlands Fig.* **and Olem van de ven**

 Λ CDM does not comfortably account for early $(z > 6)$ hydrogen reionization

$\tau_T = 0.166 \pm 0.071$

If reionization is sudden and complete by Z_i then $12 < z_i < 16$

Benson, Nusser & Sugiyama 04

it seems that voids in ΛCDM are not large enough

down to very small scales and scales and

The observed correlation function of galaxies is a power down to very small scales

A. J. Benson, 1^{\star} S. Cole, 1^{\star} C. S. Frenk, 1^{\star} C. M. Baugh¹^{*} and C. G. Lacey^{1,2*} ¹Physics Department, University of Durham, Durham DH1 3LE ²Theoretical Astrophysics Center, Copenhagen, Denmark

Accepted 1999 September 10. Received 1999 September 2; in original form 1999 March 26

Partial remedy with minimal $#$ of new free parameters

non-casing the sinah scale crustering rate. Increasing the small scale clustering rate:

NON-standard solution with minimal and solution with minimal and solution with minimal and solution with minimal minimal and solution with minimal and solution with minimal and solution with minimal and solution with minim

I. will give more objects at high redshift I. WIII give more objects at might reusing II. will suppress merging at low redshift

II. will suppress merging at low redshift

Long Range Interactions in the Dark Sector

Collaborators: Jim Peebles & Steve Gubser

Assume two species of dark matter particles of masses $M_+(\Phi)$ and $M_-(\Phi)$ that depend on a scalar field Φ . Consider the action

$$
\int d^4x \Phi_{,i} \Phi^{,i} - \sum_{particles} \int [m_+(\Phi)\,ds_+ + m_-(\Phi)\,ds_-]
$$

where
$$
\frac{dM_{+}}{d\Phi} < 0, \qquad \frac{dM_{-}}{d\Phi} > 0.
$$

To minimize the energy the field will acquire large values where there are $(+)$ particles and smaller values where there are $(-)$ particles. I.e., like particles will attract, unlike particles will repel.

Brandenberger-Vafa: If $M_+ = M_{0+} - y_+ \Phi$, $M_- = M_{0-} + y_- \Phi$., then minimization of the actions yields Brandenberger-Value If $M_+ = M_0 + y_+ + \cdots$, $M_+ = M_0 - \cdots$, then minimization of the actions vields then minimization of the actions yields

$$
\nabla^2 \Phi = -y_+ n_+(r) + y_- n_-
$$

$$
F_{++}=-\frac{y_+^2}{4\pi r^2}\,,\quad F_{+-}=\frac{y_+^2}{4\pi r^2}\,,\quad F_{--}=-\frac{y_-^2}{4\pi r^2}
$$

Compare with electromagentism! Compare with electromagentism¹ where r and depends on a combination of \mathcal{A} and depends on a combination of \mathcal{A}

Screening mechanism:

$$
M_+ = M_{DM} - y\Phi , \qquad M_- = y_-\Phi \approx 0
$$

 $\text{he}(-)$ $\binom{n}{2}$ $\sqrt{1 + 2}$ I.e., the (-) particles are relativistic and the (+) are not. In this case

$$
\nabla^2 \Phi = \frac{\Phi}{r_s^2} - y n_{_{DM}}(r)
$$

where $r_s \propto a(t)$ and depends on a combination of y− and the assumed energy of the relativistic species. assumed energy of the relativistic species. assumed energy of the relativistic species.

The scalar attraction force between two DM particles is The scalar attraction force between two DM particles is ^F^s ⁼ ^y² ^e[−]r/rs

$$
F_s = y^2 \frac{e^{-r/rs}}{r^2}
$$

to be added to
$$
Gm_{_{DM}}^2/r^2.
$$

matter and baryons smoothed with a top-hat spherical window of radius $1.5h^{-1}$ Mpc at the present epoch. The standard model is the solid curve, the dotted curve shows the effect of the scalar force with $r_s = 0.78h^{-1}$ Mpc, and the dashed curve shows $r_s = 1.56h^{-1}$ Mpc. The simulation box width is $50h^{-1}$ Mpc. FIG. 3: The distributions of the density contrasts in dark $50h^{-1}$ Mpc.

Mass function at high z (simulation by R. Cen)

TMP4, DISP=0.008, $rs=$ infty, beta=1.4²

screening with A/ϕ^α I was not in your original discussions. $SCTee1$ α $\text{Sctcelling within } \Delta / \psi$ know of any objections to the contract of any objections to the contract of any objections to the contract of $\text{screening with } A/\phi^{\alpha}$ density of the species. Because of the absolute value, the minimum is clearly not the minimum is clearly not m

at φ = ω. Let s find it at φ0 + ω. Lets find it at φ0 + molecule that the minimum is at φ0 + m0/y. The must be

$$
V(\phi)=\frac{A}{\phi^\alpha}+n_1|m_0-y\phi|+n_2(m_0+y\phi)
$$

know of any objective to the second terms to the second terms to the second terms of a

in comoving coordinates. Maybe this is interesting. It might be old-hat for you but

density of either species. Because of the absolute value, the minimum is clearly not
at $\phi = \infty$. Lets find it. Assume that the minimum is at $\phi_0 > m_0/y$. Then we must the function A_{ϕ} is the conclusion species can be reduced to a single species can be reduced to a single species species can be reduced to a single species can be reduced to a single species can be reduced to a single Lets look for the minimum of $V(\phi)$ for $n_1 = n_2 = \bar{n}$ with \bar{n} being the mean number at $\phi = \infty$. Lets find it. Assume that the minimum is at $\phi_0 > m_0/y$. Then we must minimize the function Lets look for the minimum of V (φ) for n¹ = n² = n¯ with n¯ being the mean number Let's look for the minimum of $V(\varphi)$ for $n_1 = n_2 = n$ with n being the mean number Lets look for the minimum of $V(\phi)$ for $n_1 = n_2 = \bar{n}$ with \bar{n} being the mean number density of either species. Because of the absolute value, the minimize the function α ne minimum is at ϕ_0

$$
\frac{A}{\phi^\alpha} + \bar{n}(y\phi + m_0) + \bar{n}(m_0 + y\phi)
$$

his gives $\phi_0 = \left[\frac{2n}{\alpha A} \right]^{1+\alpha}$. This gives $\phi_0 = \left[\frac{2\bar{n}}{\alpha A}\right]^{\frac{1}{1+\alpha}}$. which is easy. The control of the c This gives $\phi_0 =$ $\sqrt{2n}$ αA $\frac{1}{1+\alpha}$ $\mathcal{L}_{\mathcal{R}}$, $\mathcal{L}_{\mathcal{R}}$, This gives $\phi_0 = \left[\frac{2i}{2}\right]$

Following Jim, Let me begin with

^V (φ) ⁼ ^A

First lets assume that $y\phi_0 \gg m_0$ (the condition \gg is for simplicity only). Lets write en to $y\varphi_0 \gg m$
csmall δd $\phi = \phi_0 + \delta \phi$. Then for small $\delta \phi$ we have n_0 (\det \mathcal{L} is for simplicity only \det First lets assume that $y\phi_0 \gg m_0$ (the condition \gg is for simplicity only). Lets write $\phi + \delta\phi$ Then for small $\delta\phi$ we have ϕ = ϕ + ϕ = ϕ and for small ϕ we have

$$
V(\delta\phi) \approx -\alpha \frac{A}{\phi_0^{\alpha+1}} \delta\phi + \alpha(\alpha+1) \frac{A}{2\phi_0^{\alpha+2}} (\delta\phi)^2 + n_1(y\delta\phi + m_1) + n_2(y\delta\phi + m_2)
$$

where $m_1 = |m_0 - y\phi_0| \approx y\phi_0$ and $m_2 = m_0 + y\phi_0 \approx m_1$. From this we get the equation

$$
\frac{1}{a^2}\nabla_x^2 \delta\phi = \frac{\delta\phi}{R_s^2} + y(\delta n_1 + \delta n_2)
$$

where $x \in \mathbb{R}$ and $x \in \mathbb{R}$ and $x \in \mathbb{R}$, $x \in \mathbb{R}$ we get $x \in \mathbb{R}$ we get $x \in \mathbb{R}$ we get

where \mathbb{R}^n

 $h(x) = \frac{1}{2} \left(\frac{x+2}{4} + 1 + \frac{1}{2} \right)$ with $\frac{3(\alpha+2)}{2(\alpha+3)} = 1 \cdot 1$. from the screening we had in our paper in that the here is $R_s \propto a^{\beta}$ with $\beta > 1.5$ which is not bad at all. where $R_s = \phi_0^{\alpha+2}/A/\alpha/(\alpha+1) \propto a$ $3(\alpha+2)$ $\frac{2(a+1)}{a+1}$ which is constant neither in comoving nor in physical coordinates. Note that the equation of motion for any of the two species is $F = -y\nabla\phi$. Therefore, this model naturally gives you screening. This differs from the screening we had in our paper in that the the screening length

Final Remarks

• We have a good working model: the "concordance" ΛCDM

–good match to power spectra

- No One owes Humanity Anything: the dark sector physics of this model is extremely simple
- **Anomalies:** galaxy evolution, rotation curves, properties of X-ray clusters... might be a reflection of new physics in the dark sector
- Scalar interactions in the dark sector are useful –merging is suppressed at low redshifts –reionization at high redshift is easier –voids are emptier
	- –mass functions looks closer to the luminosity function
- Potentially serious problems for scalar interactions:
	- –I. how much substructure should we expect?

–II. halo profiles?

• Future work on scalar interactions: –semi-analytic galaxy formation models

–better estimates of the expected initial power spectrum

–higher resolution simulations targeted at specific effects: reionization (R. Cen), halo profiles, hydrodynamics, Ly- α forest...

– exploring other variants of the model