Cosmological Hydrodynamical Simulations of Structure Formation

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Aknowldegements: Collaborators

- Tiziana Di Matteo, Rupert Croft, Yu Feng(Carnegie Mellon University, LBNL)
- Colin DeGraf (Cambridge)
- Stephen Wilkins (University of Sussex)
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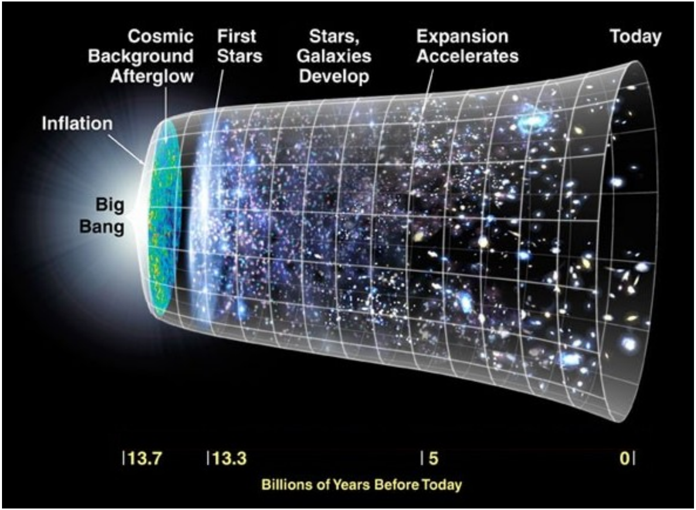
Plan of the Talk

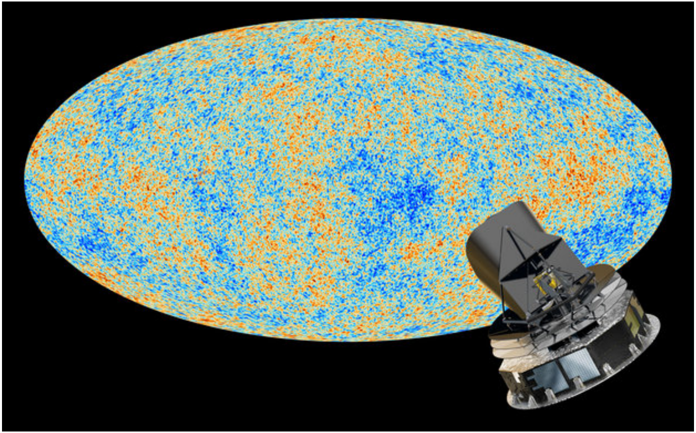
- Introduction
- Cosmological Simulations: A Tool for Studying Structure and Galaxy Formation
- Galaxy Formation and High and Low Redshifts
- Neutral Hydrogen in the local (and Post-Reionization) Universe
- Revisiting the pair-velocity - correlation function relation as a probe of cosmology

A Brief History of the Universe



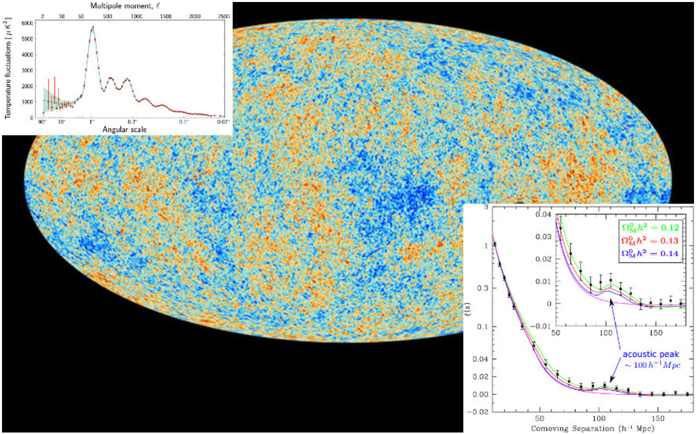
http://map.gsfc.nasa.gov/

The Standard Model of Cosmology



http://www.esa.int/ESA (Planck Team 2013)

The Standard Model of Cosmology

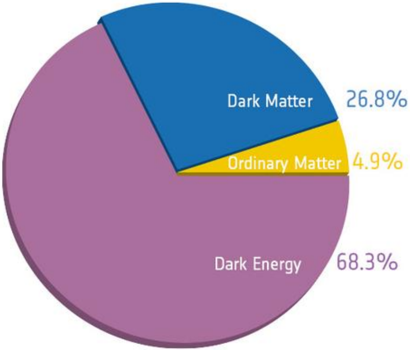


Planck Team 2013

Eisenstein et al. 2005

The Standard Model of Cosmology: The ΛCDM model

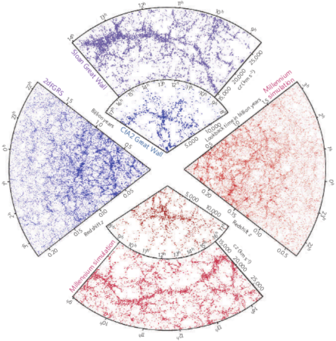
- Big Bang followed by a brief period of inflation
- Matter/Energy density:



Planck Team 2013

Structure Formation

Structure Formation: How can we explain the distribution and properties of objects that we see in the Universe?



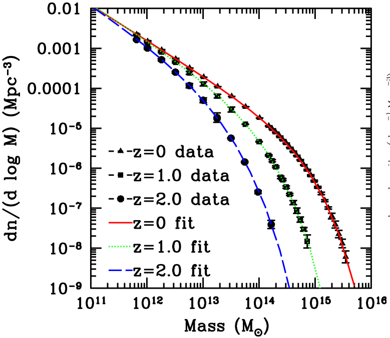
Springel et al, 2004 2dF and SDSS survey

Galaxy Formation and Cosmology

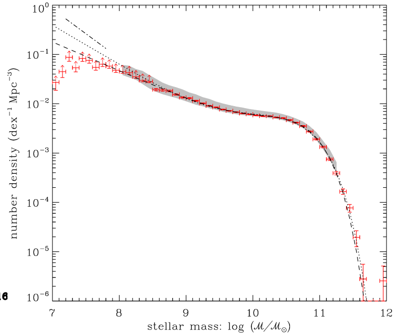
- Can we predict the number of spirals and elliptical galaxies?
- Can we predict the SEDs of galaxies and how they evolve across cosmic time?
- What are the important mechanisms affecting the formation and and evolution of galaxies?
- How do galaxies obtain gas and convert it to stars?
- What is the relation between galaxies and their host dark matter halos?

- Observational Cosmology is currently putting constraints at the percent level.
- Limitations are due to poor understanding of galaxy formation.

Schecter Functions: Mass Functions



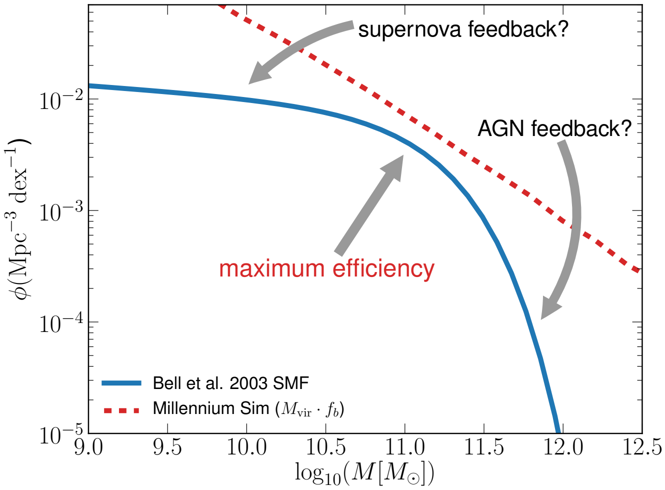
Bhattacharya et al 2010



Baldry et al 2008

$$\phi(\mathrm{M}) = \frac{dn}{dM} = \phi^* \left(\frac{M}{M_*}\right)^\alpha \exp\left(-\frac{M}{M_*}\right) \quad (1)$$

Baryonic Effects: The Galaxy Stellar Mass Function

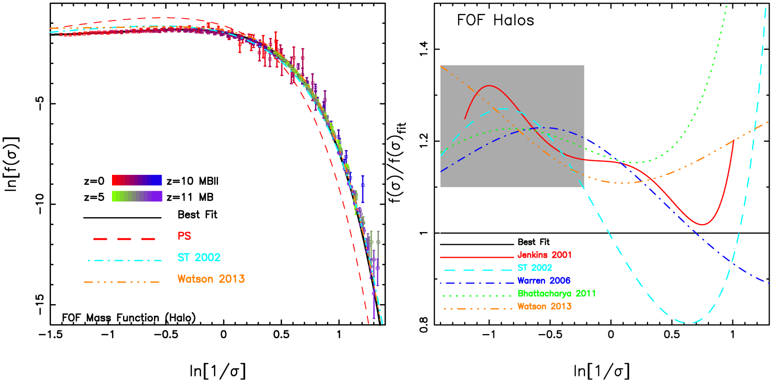


Mutch et al 2013

Baryonic Effects on Structure Formation

The Halo Mass Function:

$$\frac{dn}{d\log_{10} M} = \frac{M}{\rho}\frac{d\ln\sigma^{-1}}{d\log_{10} M} f(\sigma) \quad (2)$$



NKet al 2014

The Need for Cosmological Simulations

- Fluctuations amplifier: Gravity $\Rightarrow$ long range force
- Non-linear process $\Rightarrow$ Evolution of ρ at different scales are coupled.
- Exact Force Computation $\Rightarrow$ Expensive $\sim \mathcal{O}(N^2)$
- Use approximate algorithms which scale as $\sim \mathcal{O}(N \log N)$

Particle Dynamics in an Expanding Universe

EOM Physical Coordinates

$$
\begin{aligned}
\ddot{\mathbf{r}}(t) &= \ddot{a}(t)\mathbf{x}(t) + 2\dot{a}(t)\dot{\mathbf{x}}(t) + a\ddot{\mathbf{x}}(t) = -\nabla\Phi_{tot} = -\nabla(\Phi_{av} + \phi) \\
\nabla_r^2 \Phi_{tot} &= \nabla_r^2(\Phi_{av} + \phi) = 4\pi G\rho - \Lambda = (4\pi G\bar{\rho} - \Lambda) + 4\pi G\bar{\rho}\delta \\
\rho(\mathbf{r}) &= \sum_i m_i \delta_D^3(\mathbf{r} - \mathbf{r}_i) \qquad \delta(\mathbf{r}, t) = \frac{\rho(\mathbf{r}, t) - \bar{\rho}(t)}{\bar{\rho}(t)} \qquad (3)
\end{aligned}
$$

EOM Comoving Coordinates: $\mathbf{r} = a(t)\mathbf{x}$

$$
\begin{aligned}
\ddot{\mathbf{x}} + 2\frac{\dot{a}}{a}\dot{\mathbf{x}} &= -\frac{\nabla_r \phi(\mathbf{x}, t)}{a} = -\frac{\nabla_x \phi(\mathbf{x}, t)}{a^2} \\
\nabla_x^2 \phi &= 4\pi G a^2 \bar{\rho}\delta = \frac{3}{2} H_0^2 \Omega_{nr} \frac{\delta}{a} \qquad \rho = \bar{\rho}(1 + \delta) \\
\rho(\mathbf{x}) &= \sum_i m_i \delta_D^3(\mathbf{x} - \mathbf{x}_i) \approx \sum_i m_i W(\mathbf{x} - \mathbf{x}_i, \epsilon) \qquad (4)
\end{aligned}
$$

Friedmann Equation:

$$
\frac{\dot{a}^2}{a^2} + \frac{k}{a^2} = H_0^2 \left[\Omega_{rad} \left(\frac{a_0}{a} \right)^4 + \Omega_{nr} \left(\frac{a_0}{a} \right)^3 + \Omega_\Lambda \right] \qquad (5)
$$

Basic Equations

The Linear Limit

$$\ddot{\delta} + 2\frac{\dot{a}}{a}\dot{\delta} = 4\pi G\bar{\rho}_{nr}\delta \quad (6)$$

$$\delta_{\mathbf{x}}(t) = \int \frac{d^3\mathbf{k}}{(2\pi)^3}\delta_{\mathbf{k}}(t)\exp(i\mathbf{k}.\mathbf{x}) \quad (7)$$

$$\delta_{\mathbf{k}}(t) = \int \frac{d^3\mathbf{x}}{V}\delta_{\mathbf{x}}(t)\exp(-i\mathbf{k}.\mathbf{x}) \quad (8)$$

$$\ddot{\delta}_{\mathbf{k}} + 2\frac{\dot{a}}{a}\dot{\delta}_{\mathbf{k}} = 4\pi G\bar{\rho}_{nr}\delta_{\mathbf{k}} \quad (9)$$

Hubble's parameter $H(a) = \dot{a}/a$ is a solution (decaying).
Second solution can be constructed using the Wronskian.

$$\begin{aligned} X &= 1 + \Omega_{nr}\left(\frac{1}{a} - 1\right) + \Omega_\Lambda(a^2 - 1) \\ b(t) &\propto \frac{X^{1/2}}{a}\int^a \frac{da}{X^{3/2}} \end{aligned} \quad (10)$$

Approximate N-Body techniques: Grid Based Methods

- EOM is simple to integrate $\Rightarrow \mathcal{O}(N)$.
- Time consuming part is the force calculation due to gravitational interaction $\Rightarrow \mathcal{O}(N^2)$.
- $\mathcal{O}(N^2) \Rightarrow$ due to pairwise interaction of gravity and its long-range nature.
- N-Body methods: resort to quicker and approximate techniques to compute the gravitational interactions between particles.
- Also need to soften forces since systems are collisionless.

- Broadly 2 methods to compute interactions (third hybrid one)

- Important: need to also assign size to particles, since we are dealing with a collisionless system.

Eulerian or Grid Based methods (PM)

- Method One: solve the Poisson Equation to get the potential (hence force):

$$\begin{aligned} \nabla^2\phi(\mathbf{r}) &= 4\pi G\rho(\mathbf{r}) && (11) \\ -k^2\phi_k &\propto \rho_k \qquad \text{In Fourier space} && (12) \end{aligned}$$

Use the $\mathcal{O}(N \log N)$ Fast Fourier Transform to do the forward and inverse transform.

PM Method Continued

- Pros
  - $\mathcal{O}(N \log N) \Rightarrow$ extremely fast.
  - Simple to implement, algebraic equations.
  - Easy to Parallelise with MPI (not OpenMP)
  - Periodic Boundary Conditions from FFT.
- Cons
  - Resolution limit $\Rightarrow$ grid size.
  - Parallisation limited to slab parallisation in FFTW.
- Remedy
  - Use PencilFFT for further parallisation (See Blue Waters Simulation by Feng et al)
  - Adaptive meshes which adjust to local density, AMR
  - ART (Kravtsov, Klypin, Kokhlov), MLAPM (Knebe et al), Nyx (Almgren et al), Enzo (Bryan, Norman et al)

Lagrangian or Particle Based methods (BH-Tree)

- Compute direct forces in real space.
- Approximation: Structure the entire mass distribution into groups nested into larger groups $\Rightarrow$ Tree.
- Can keep the monopole term or higher order multipoles (expensive)
- Pros:
  - Scales as $\mathcal{O}(N \log N)$
  - Extremely Accurate
- Cons:
  - Slower than PM by ~ 100
  - Consumes more memory
  - Need to add terms due to periodic boundary conditions.
- Remedy:
  - Combine with PM to get both speed and accuracy,
    TPM: Bode & Ostriker TreePM:Bagla 2002

BH-Tree

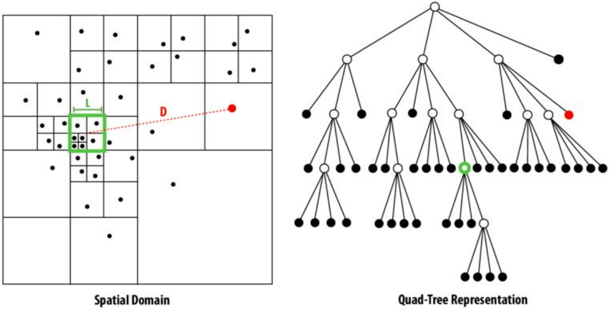


Figure : BH-Quad Tree: Credits cs.cmu.edu

- Cell Opening Criterion $\theta < L/D$, Choice of $\theta < 1.0$
- Other Multipole Methods (not covered) Fast Multipole Method (memory intensive)

TreePM Method: Bagla

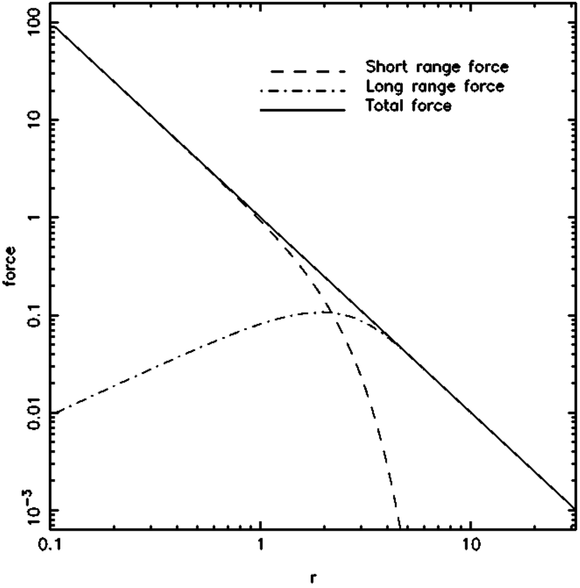


Figure : TreePM: Bagla 1999

Cosmological Simulations of Galaxy Formation

- N-Body simulations ⇒ predict the distribution of dark matter halos.
- For Galaxy Formation need Baryonic processes
- For the rest of the talk we use Gadget (Springel 2002) which includes:
  - TreePM gravity solver (Bagla 2002, **NK**& Bagla 2009)
  - Smoothed Particle Hydrodynamics (SPH) ⇒ evolution of baryons
  - Heating/Cooling ⇒ external radiation background
  - Subgrid recipes for star formation, feedback, metal enrichment (Springel & Hernquist 2003)
  - Subgrid recipes for the growth of Super Massive Blackholes (SMBH) and feedback (DiMatteo, Springel & Hernquist 2005

Details of SMBH model

- Origins of SMBH are still not known.
- $M_{\text{seed}} = 5 \times 10^5 h^{-1} M_\odot$ inserted in FOF halo with mass $M_{\text{halo}} \geq 5 \times 10^{10} h^{-1} M_\odot$ if it does not contain one.
  - PopIII stars $M_{\text{BH}} \sim 10^2 M_\odot$ at $z \sim 30$ (Bromm and Larson 2004).
  - Direct collapse of gas $M_{\text{BH}} \sim M_{\text{seed}}$ (Bromm and Loeb 2003).
- Black hole growth through Bondi-Hoyle accretion

$$\dot{M}_{\text{BH}} = \alpha \frac{4\pi G^2 M_{\text{BH}}^2 \rho}{\left(c_s^2 + v^2\right)^{3/2}}$$

BH mergers if $v < c_s$ within ϵ

- Black hole radiates with a bolometric luminosity

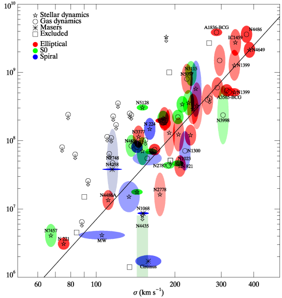
$$L_{\text{bol}} = \eta \dot{M}_{\text{BH}} c^2 \qquad \eta = 10\%$$

- 5% of liberated energy couples to surrounding gas.

Requirements for a Cosmological Simulation

- $L_{box} \Rightarrow$ larger than the nonlinear scale at the epoch of interest.
- $N_{part} \Rightarrow$ large so as to sufficiently resolve an object of interest.

Part I: Super Massive Blackholes and Galaxy Formation



NGC 5128 Guiltekin et al 2009

- Origins of SMBH are still not known.
- Two possible mechanisms to produce $M_{\rm seed} \sim \times 10^5 h^{-1} M_{\odot}$
  - PopIII stars $M_{\rm BH} \sim 10^2 M_{\odot}$ at $z \sim 30$ (Bromm and Larson 2004).
  - Direct collapse of gas $M_{\rm BH} \sim M_{\rm seed}$ at $z \sim 12$ (Bromm and Loeb 2003).

Structure Formation at $z \sim 6$

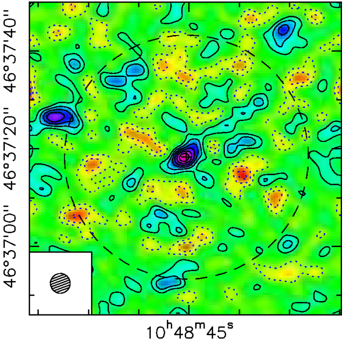
- Observations of $z \sim 6$ quasars (~ 30) suggest that they are powered by $10^9 M_\odot$ blackholes (Fan et al 2006)
- Abundances $\Longrightarrow$ hosts halos $M_{\rm halo} \sim 10^{13} M_\odot$.
- Extremely rare: $n \sim$ a few Gpc^{-3}.
- SED of quasars $\Longrightarrow$ fully developed by $z \sim 6$ (Wang et al 2008).
- Question: How can we form such extreme objects so rapidly (≤ 1 billion years)
- What about properties of host galaxies ?

Molecular Gas and Star Formation in $z \sim 6$ QSO hosts

- CO $\Longrightarrow$ trace molecular gas for host galaxies: $M_{\rm mol} \sim 10^{10} M_\odot$ (Wang et al 2010, 2011)

- FIR $\Longrightarrow$ SFR $\sim 10^2 - 10^3 M_\odot.yr^{-1}$ for quasar hosts.

J1048+4637 $z_{CO} = 6.2284$



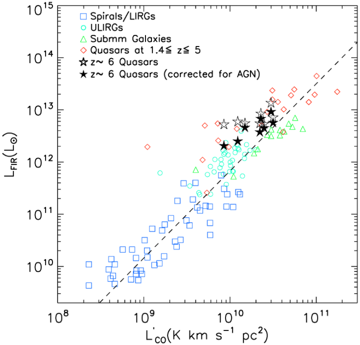


Figure : Wang et al, 2010

The ***MassiveBlack*** (-II) Simulation

Run	N_{part}	L_{box} (Mpc/h)	ϵ (kpc/h)	N_{cores}	z_f	CPU Hours $\times 10^6$
MB	2×3200^3	533	5.0	98304	4.75	7
MB-II	2×1792^3	100	1.85	24576	0.0625	21

$\sim$ 350 Tb of data generated.

- Gadget3: DM, Gas, Star, Black Holes and Feedback
- Cosmology: WMAP7
- Halofinder: SUBFIND with 20 bound particles.

Figure : NICS, University of Tennessee

Team: **NK**, Di Matteo, Croft, Feng, Degraf...

Visualisation: The first Terapixel Image

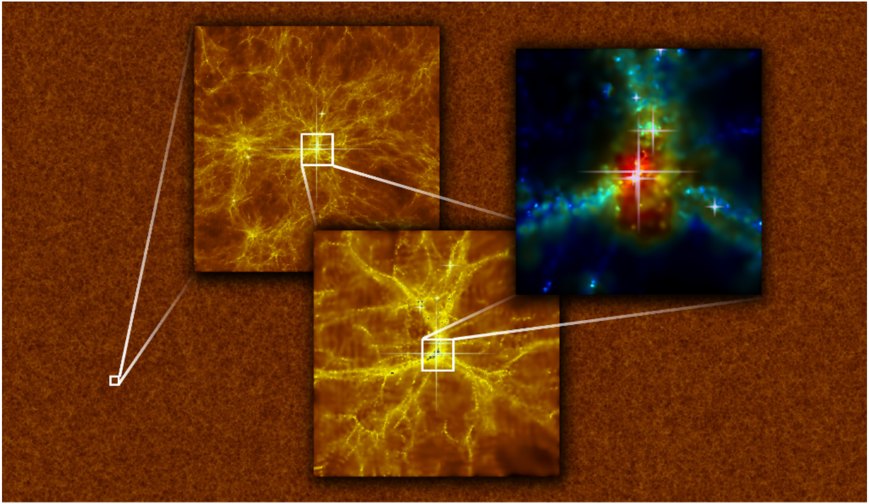


Figure : Feng, Croft, DiMatteo, **NK** et al 2011

See: http://gigapan.com/gigapans/76215/

Growth of Blackhole through cold flows

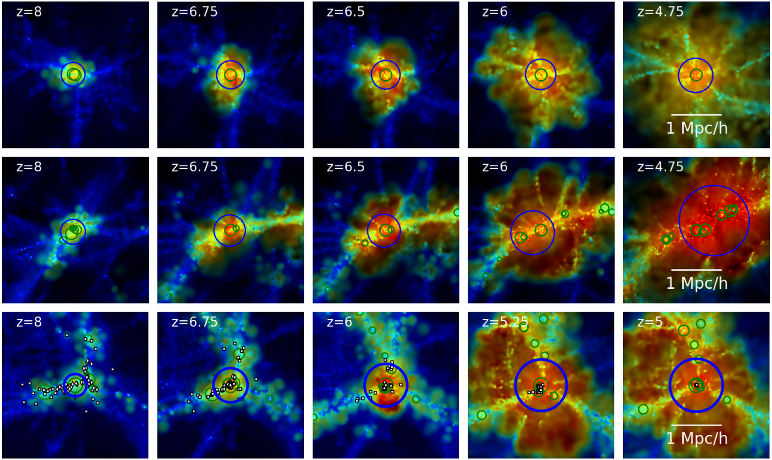


Figure : DiMatteo, **NK**, DeGraf, Feng, Croft et al (2012)

Growth of Blackhole through cold flows

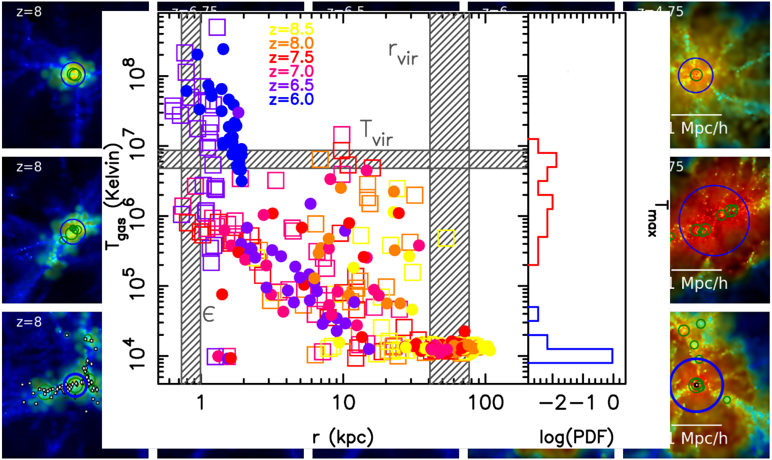


Figure : DiMatteo, **NK**, DeGraf, Feng, Croft et al (2012)

Growth of Black Hole and its Host Galaxy

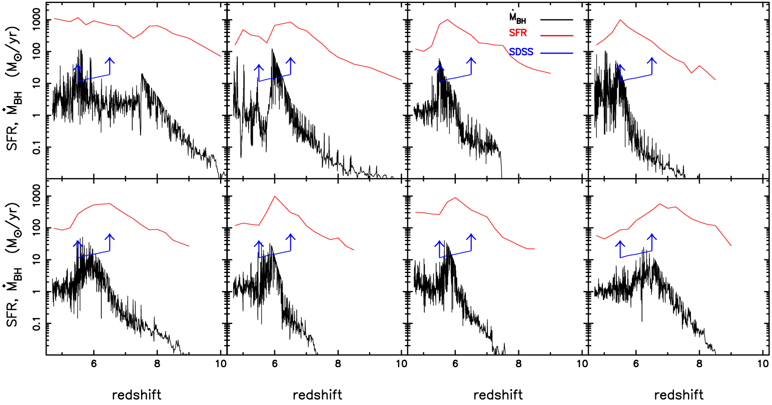


Figure : **NK**, Feng, DeGraf, DiMatteo, Croft, (2012)

High-z BH Luminosity Function

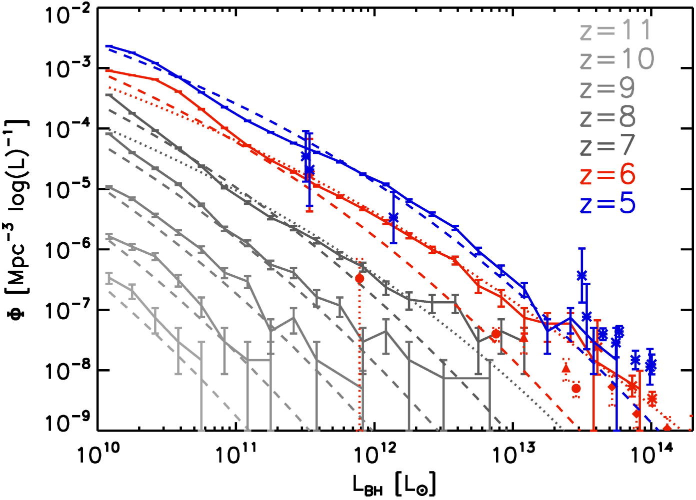


Figure : DeGraf, DiMatteo, **NK**et al (2012)

Evolution of SFR Density

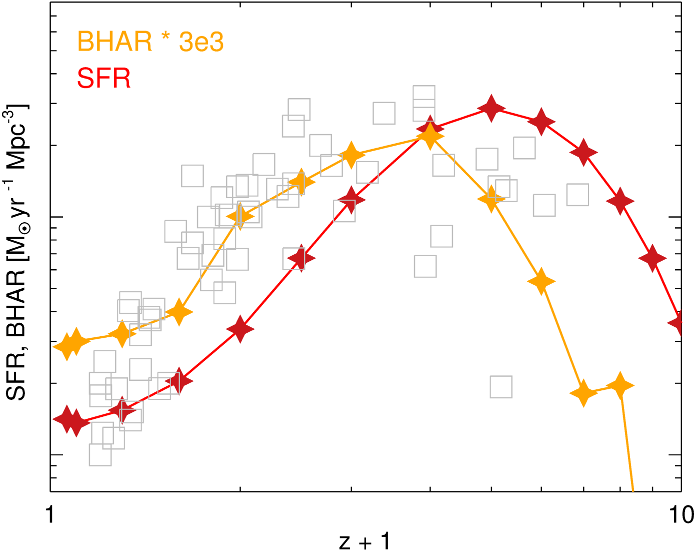


Figure : **NK**, DiMatteo, Croft, et al (2014)

Dusty Galaxies at High Redshift

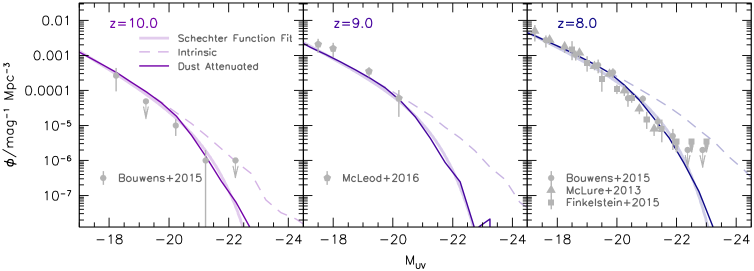


Figure : Wilkins et al 2017

Cosmic Spectral Energy Distribution of Galaxies

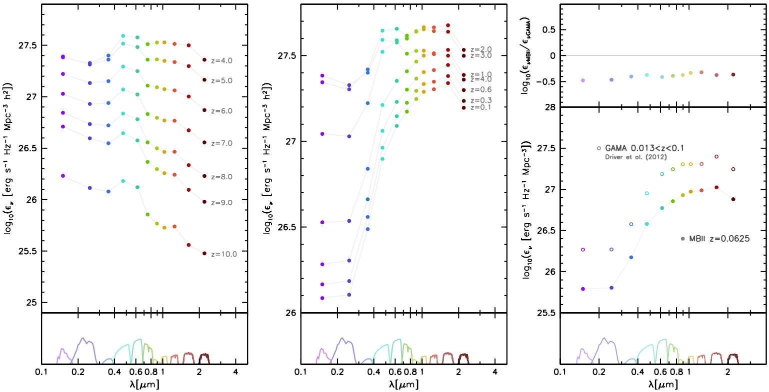
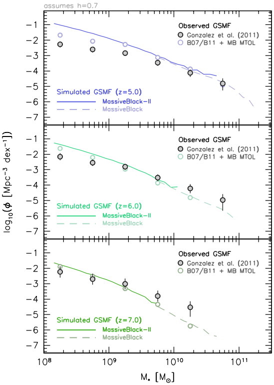
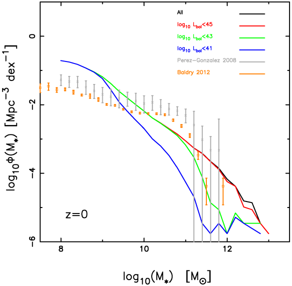


Figure : **NK**, DiMatteo, Croft, et al (2014)

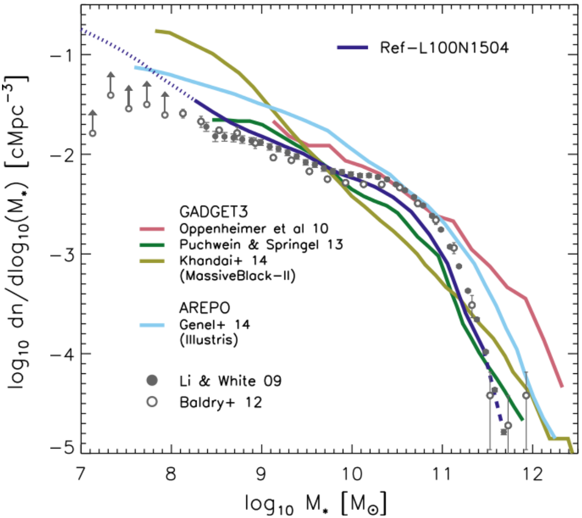
Galaxy Stellar Mass Function





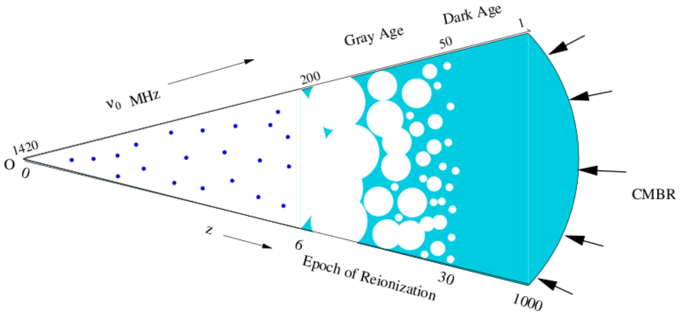
Left: Wilkins, DiMatteo, Croft, **NK** et al (2013)
Right: **NK**, DiMatteo, Croft, et al (2014)

Comparison



Schaye et al (2015)

Evolution of Neutral Hydrogen (HI)

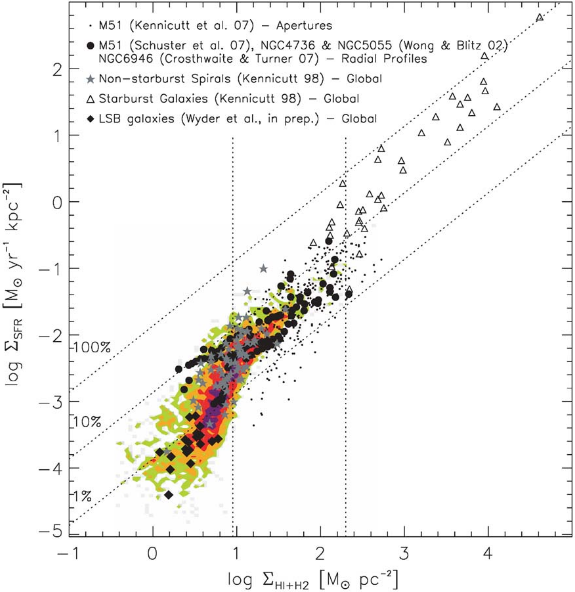


Ali & Bharadwaj 2005

Basic Ingredients of Galaxy Formation

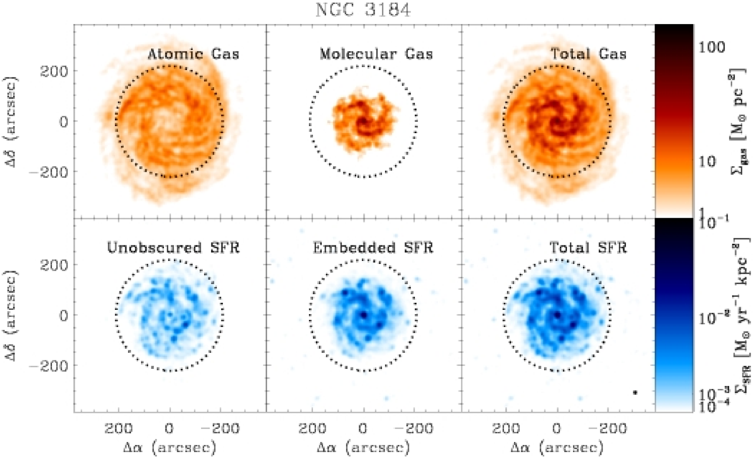
- Fuel: Cold Gas (*HI* and H_2)
- Star Formation: Conversion of cold gas into stars $SFR(t) \propto \rho_{gas}^{\gamma}$
- Stellar Mass: $M_{\star}(t) = \int^{t} SFR(t') \; dt'$

The Kennicutt-Schmidt Law



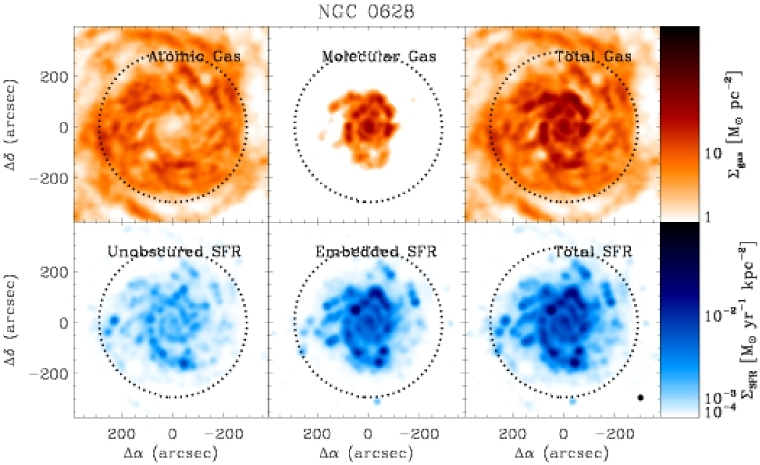
Bigiel et al 2008

Cold Gas and Star Formation



Leroy et al 2008

Cold Gas and Star Formation



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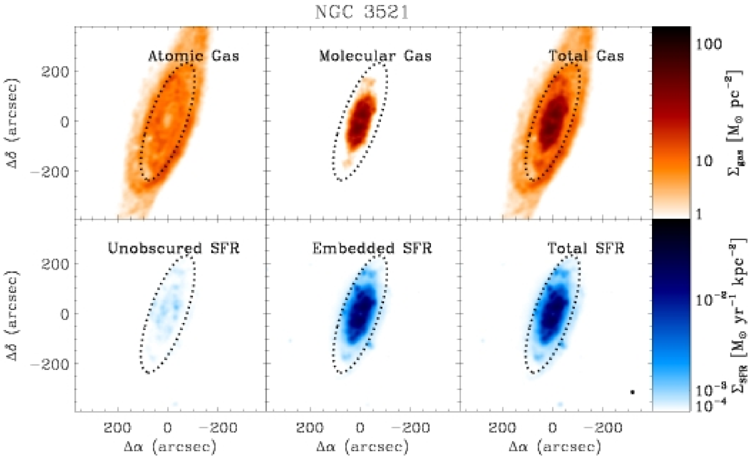
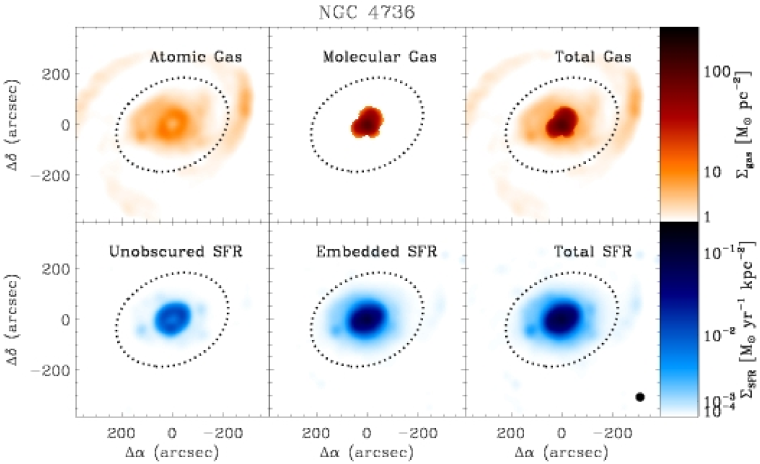


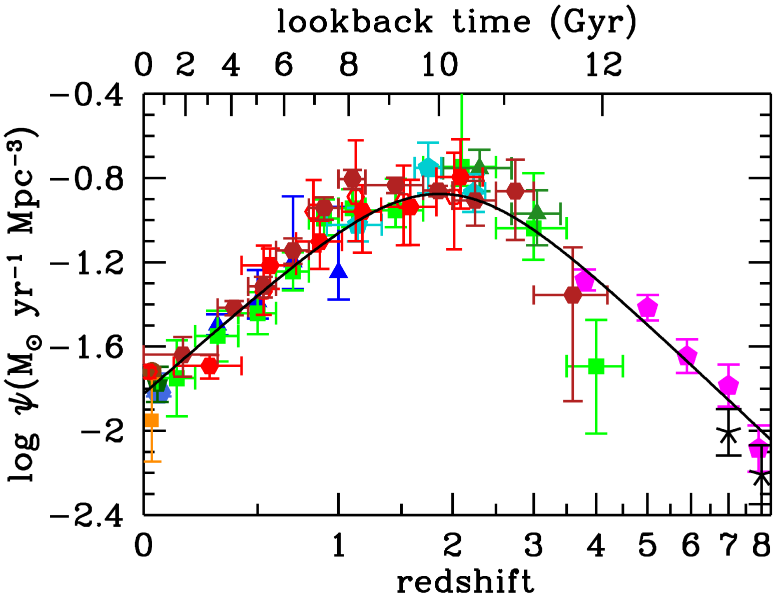
Leroy et al 2008

Cold Gas and Star Formation



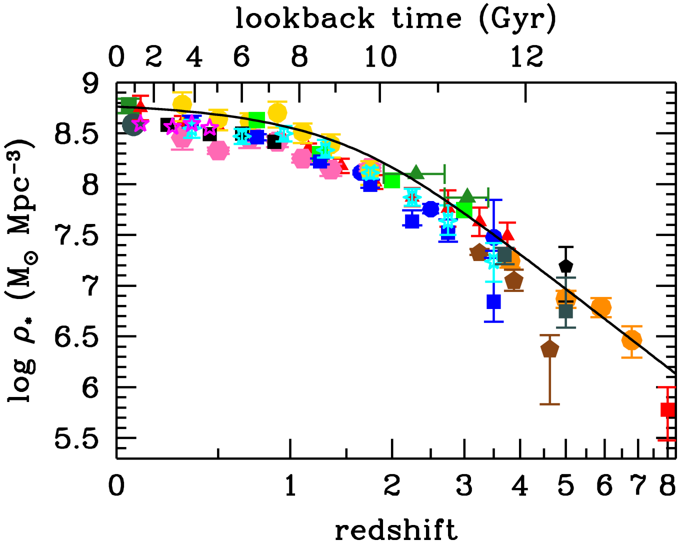
Leroy et al 2008

HI and Galaxy Formation



Madau and Dickinson. 2014

HI and Galaxy Formation



Madau and Dickinson. 2014

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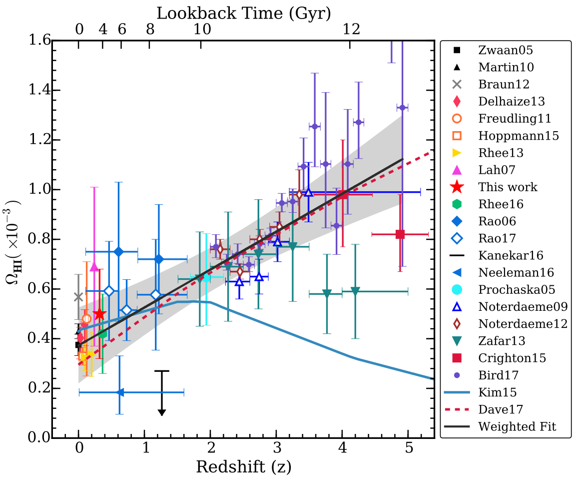


Rhee et al. 2018

21cm Cosmology

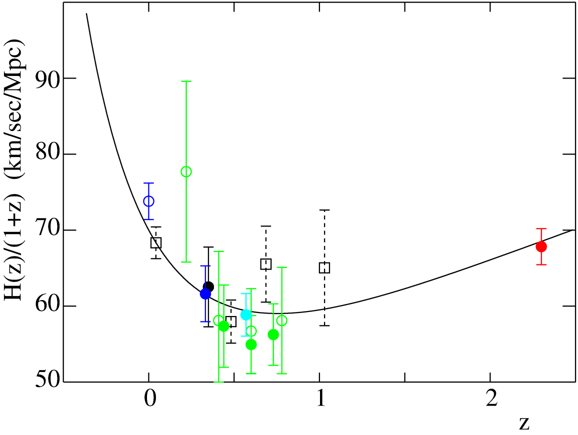


Figure : Busca et al 2013

- Current estimates on Ω_{HI} based on DLAs and direct detection in the local Universe.

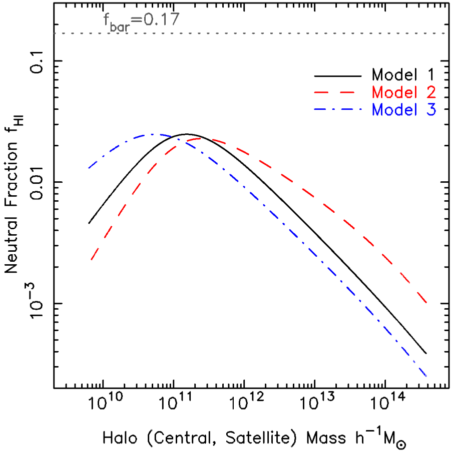
- The neutral fraction has remained consistent with a constant value of $\Omega_{HI} \sim \mathcal{O}(10^{-3})$ $z > 1$ with large errors.

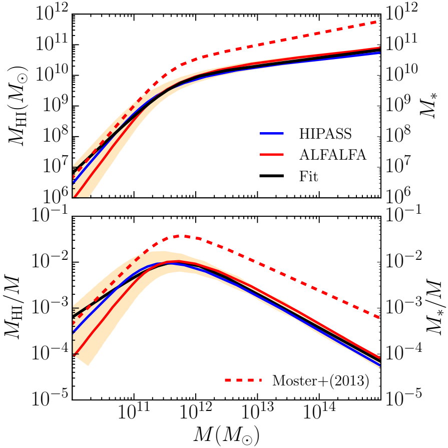
- SFR determined out to redshift ~ 8, however measurements of cold gas in galaxies have been made out to only $z = 0.37$. (Lah et. al 2009)

- A census of cold gas is crucial for galaxy formation models at moderate redshifts.

- Clustering of HI selected galaxies $\Rightarrow$ halo occupation.

Neutral Fraction





Khandai et al 2012

See also Papastergis et al 2012

Padmanabhan et al 2017

Detection of HI in the DEEP2 field with GBT

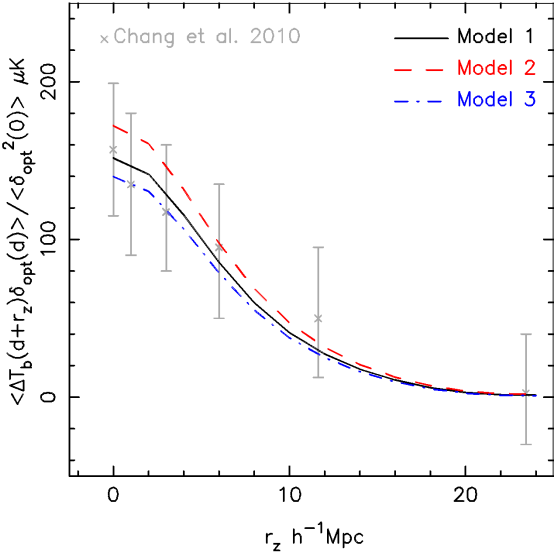


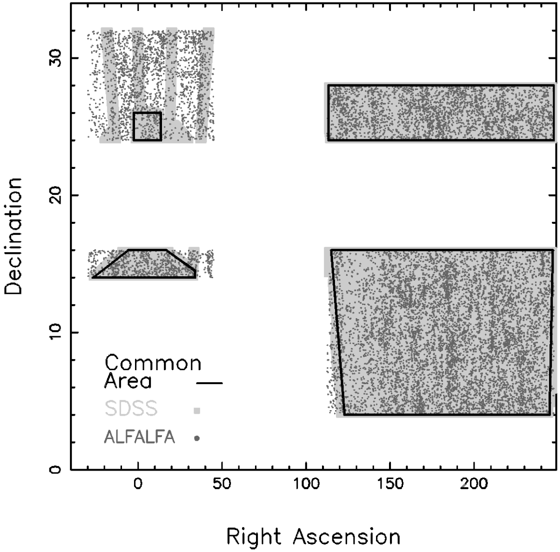
Figure : Khandai et al. 2012

Local Surveys and Observed Galaxy Occupation

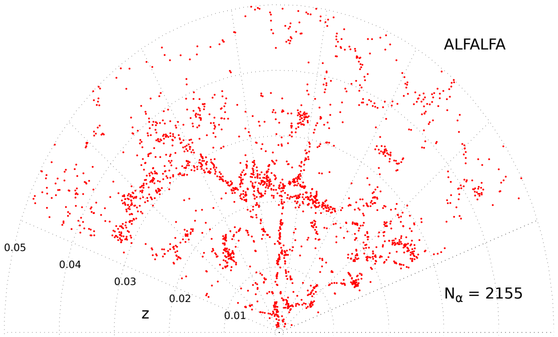
HALO $\Longleftrightarrow$ GALAXY (stars) $\Longleftrightarrow$ GALAXY (HI)

- Halo based models $\Rightarrow$ useful for Intensity Mapping signal at $z \geq 1$.
- Semianalytical models in principle predict HI in Galaxies
- Need a robust relation between starlight and cold gas (available only locally).
- ALFALFA + SDSS

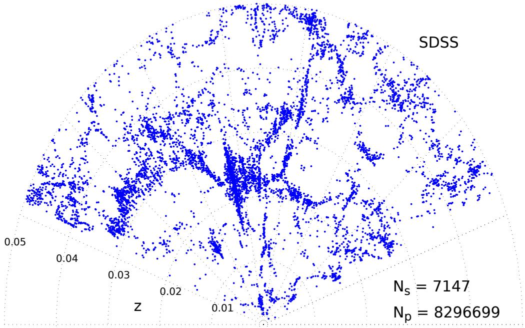
The ALFALFA and SDSS Surveys



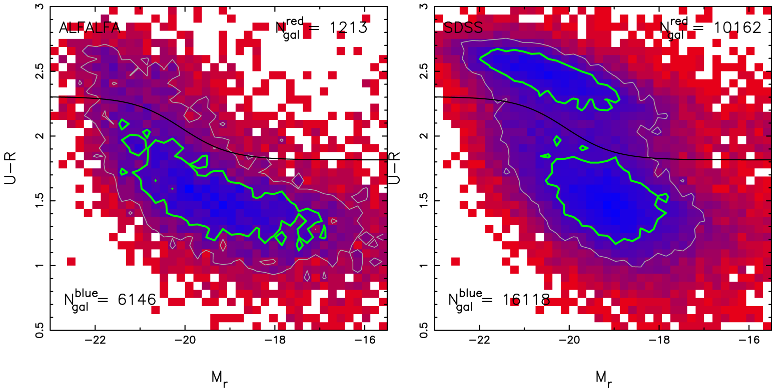
ALFALFA and SDSS



ALFALFA and SDSS

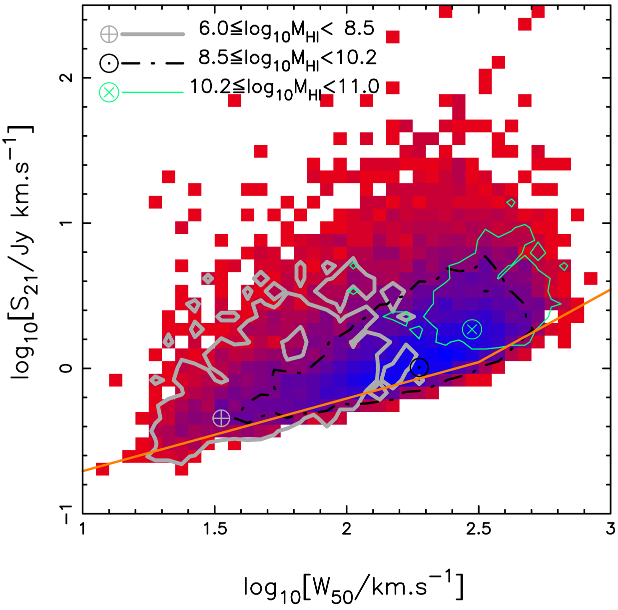


ALFALFA and SDSS

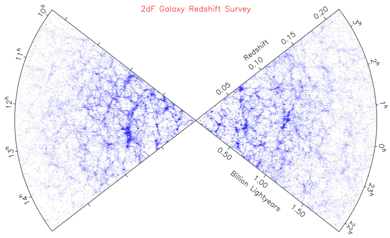


ALFALFA SDSS

ALFALFA Completeness



Estimates of the HI Mass Function



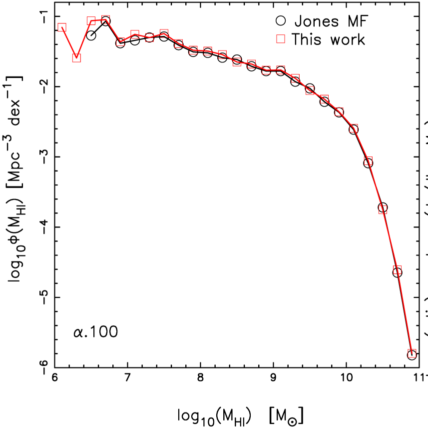
2dF

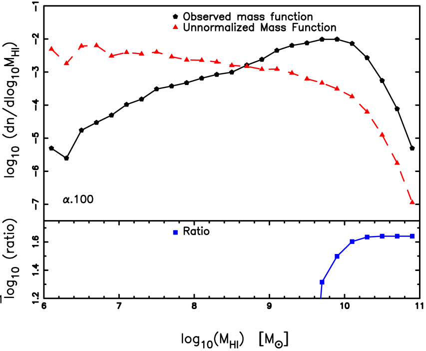
- The $1/V_{max}$ method (Schmidt 1968)
$$\phi^j = \sum \frac{1}{V^j_{max,i}}$$

- The 2D Stepwise Max Likelyhood method (Loveday 2000)

$$p_i(M^i, w^i_{50}|D_i) = \frac{\phi(M^i, W^i_{50})}{\int_0^\infty \int_{M^i_{lim}}^\infty \phi dMdW}$$

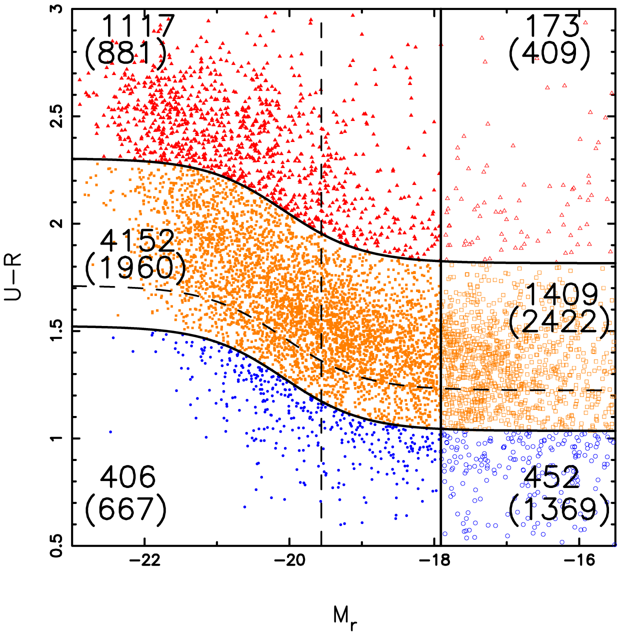
The HI Mass Function



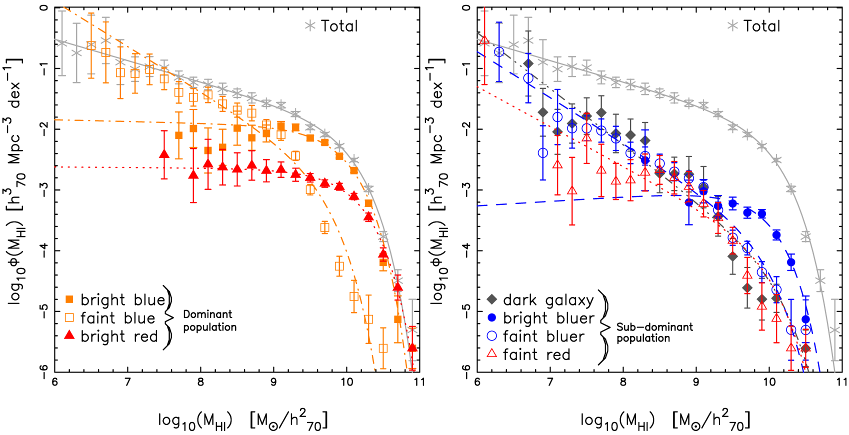


Dutta, **NK**, Dey 2019

The HIMF for Different Populations



The HI Mass Function: 1.5σ sample



Dutta, **NK**, Dey 2019

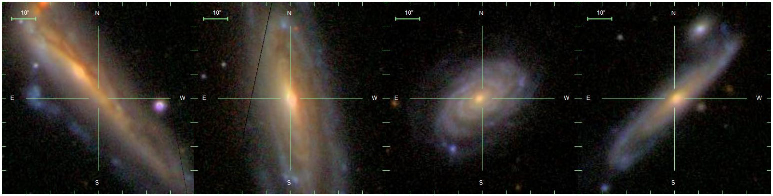
Contribution to Ω_{HI}

$\Omega_{HI} \propto M_* \phi_*$

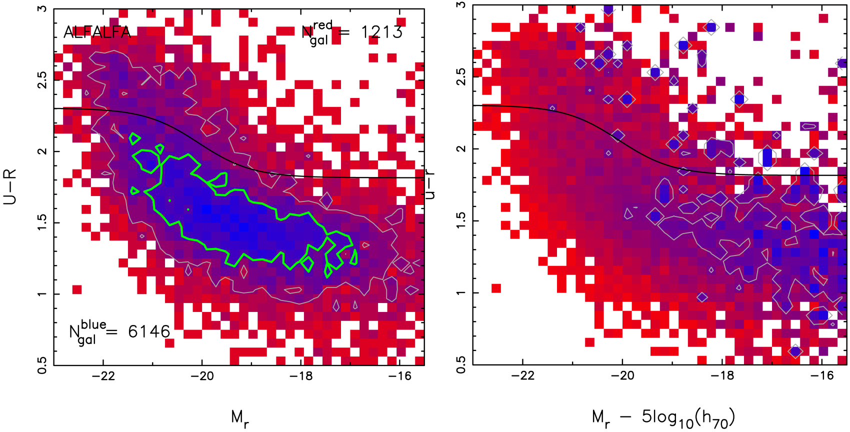
region	$\Omega_{HI}[10^{-4} h_{70}^{-1}]$	$\Omega_{HI}/\Omega_{HI}^{total}$
total	4.894 ± 0.424	1.00
bright blue	2.243 ± 0.174 (1.057 ± 0.095)	0.458 (0.216)
faint blue	1.317 ± 0.299 (2.202 ± 0.296)	0.269 (0.450)
bright red	0.668 ± 0.079 (0.560 ± 0.071)	0.136 (0.114)
bright bluer	0.207 ± 0.064 (0.333 ± 0.426)	0.042 (0.068)
faint bluer	0.078 ± 0.014 (0.328 ± 0.048)	0.016 (0.067)
faint red	0.032 ± 0.014 (0.099 ± 0.022)	0.007 (0.020)
dark	0.329 ± 0.237	0.067

Dutta, **NK**, Dey 2019

Dusty Red Galaxies

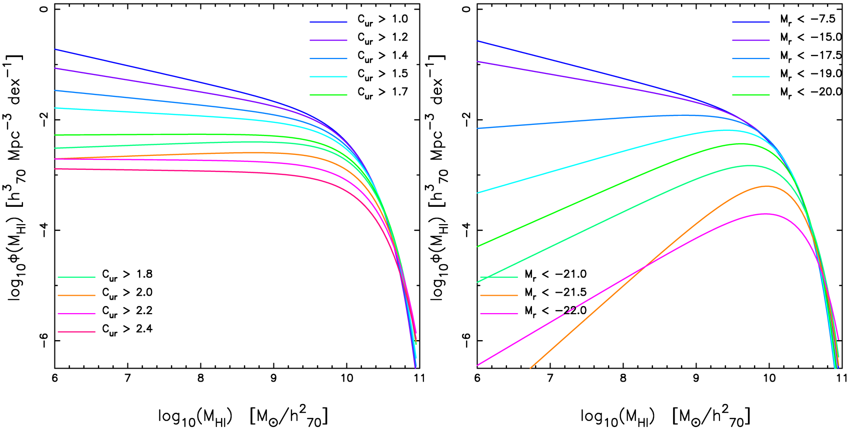


Conditional HI Mass Function



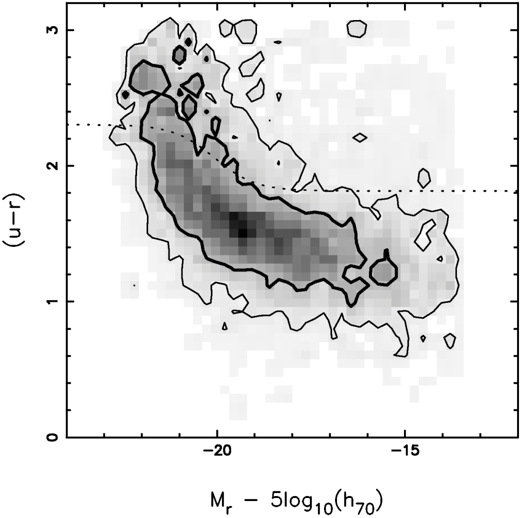
Dutta and **NK**(in prep)

Conditional HI Mass Function



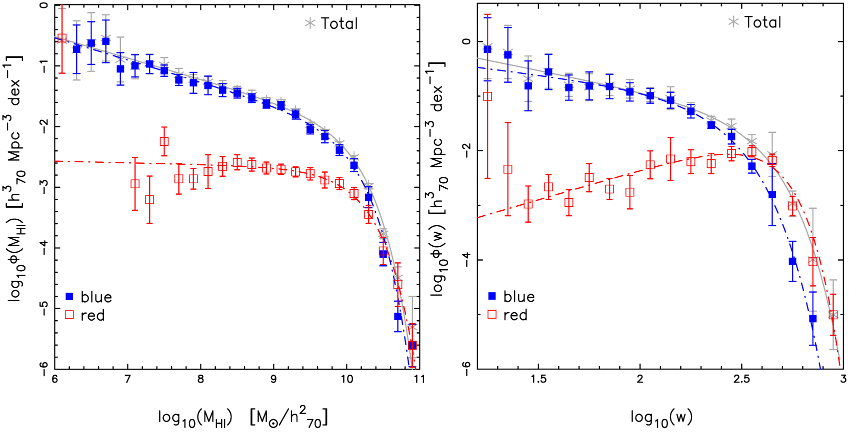
Dutta and **NK**(in prep)

Distribution of Ω_{HI} in the color-magnitude plane of galaxies



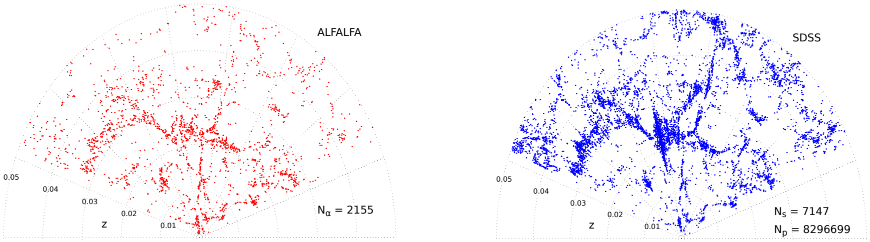
Dutta and **NK**(in prep)

The HI Velocity Width Function



Dutta and **NK**(in prep)

Abundance Matching ALFALFA and SDSS

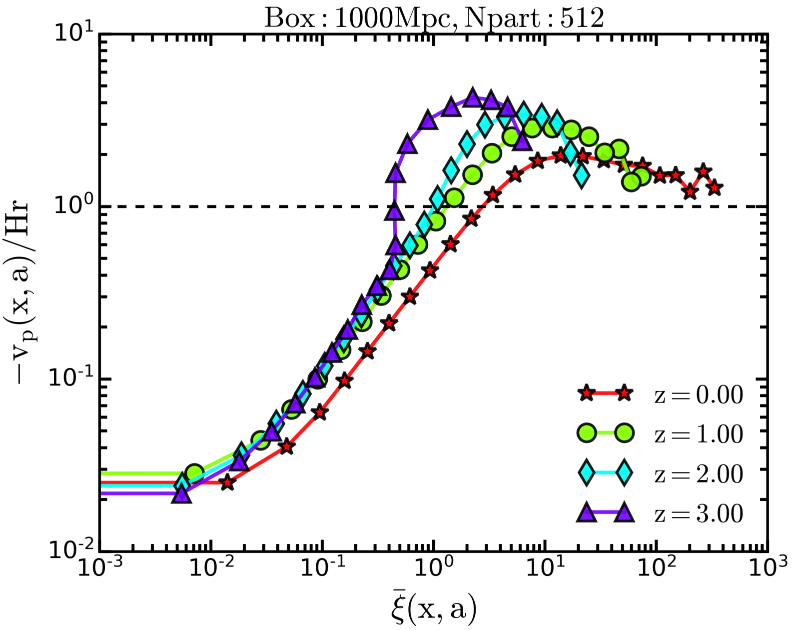


The Pair-Velocity - Correlation Function Relation

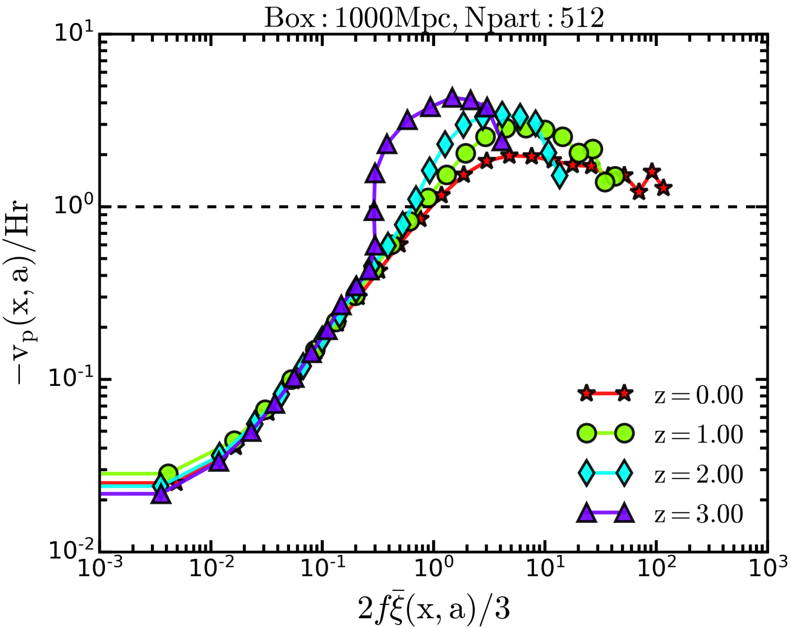
- On large (linear) scales, pair conservation equation leads to:

$$-\frac{v_p(r)}{Hr} = \frac{2}{3}\bar{\xi}(r) f \qquad f = \frac{d \ln b}{d \ln a} \simeq \Omega_m^{0.6} \tag{15}$$

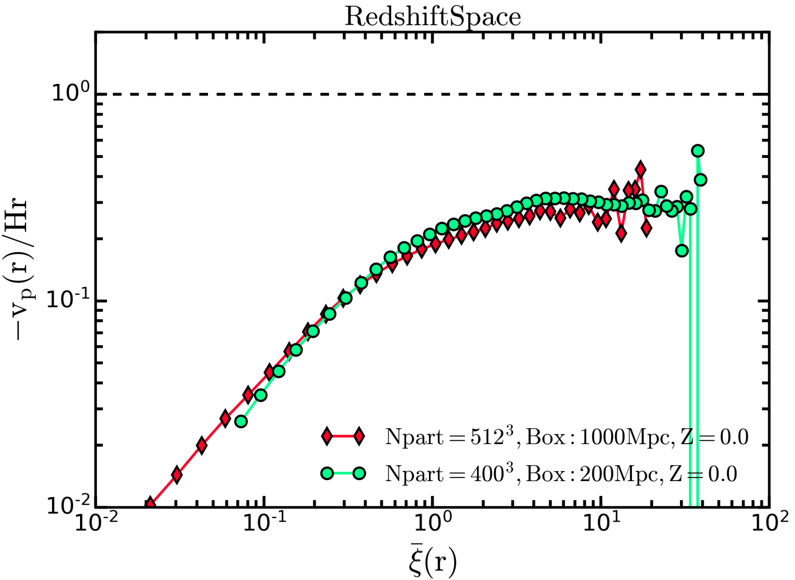
Peebles 1980



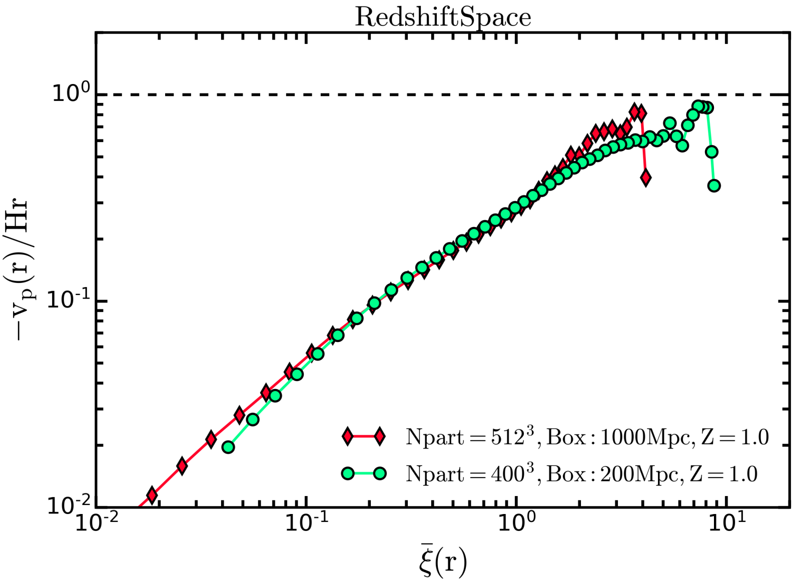
Rana and **NK**(in progress)



Rana and **NK**(in progress)



Rana and **NK**(in progress)



Rana and **NK**(in progress)