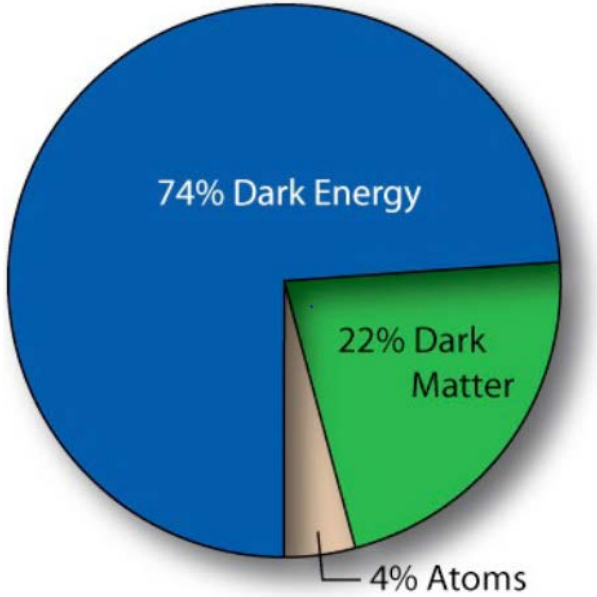


Simulating the 4% Universe

Hydro-cosmology simulations and data analysis

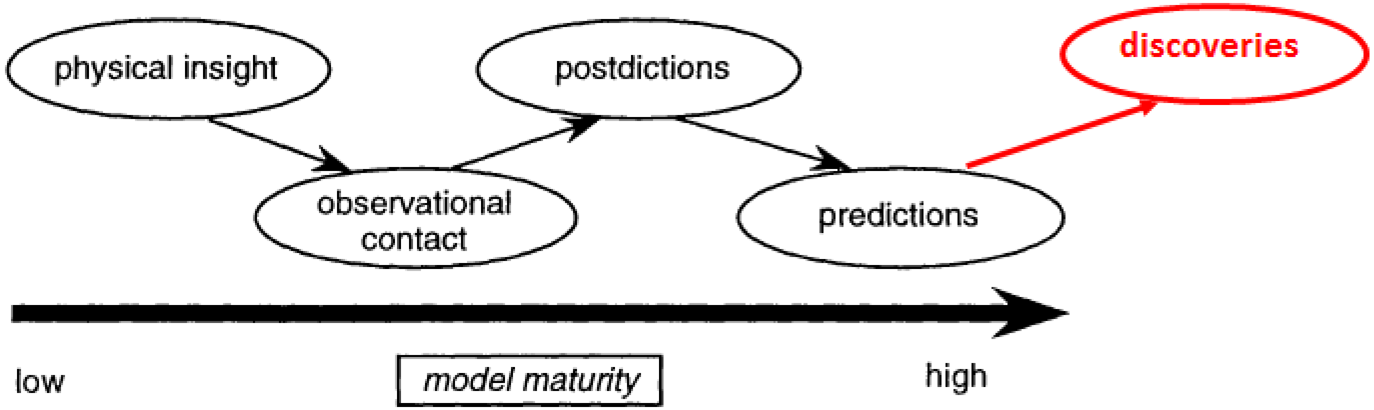
Michael L. Norman
SDSC/UCSD

Lecture Plan

- Lecture 1: Hydro-cosmology simulations of baryons in the *Cosmic Web*
  - Lyman alpha forest (LAF)
  - Baryon Acoustic Oscillation (BAO)
- Lecture 2: Radiation hydro-cosmology simulations of *Cosmic Renaissance*
  - Epoch of Reionization (EOR)
  - First Galaxies

Motivation

- It's the part of the Universe we can see
- Involves real astrophysics which is complicated and interesting
- Can place constraints on the dark universe
- Computational discoveries



Norman (1997)

Computational Discoveries

- Physical nature of Lyman alpha forest absorption systems

  Cen+1994, Zhang+1995, Hernquist+1996

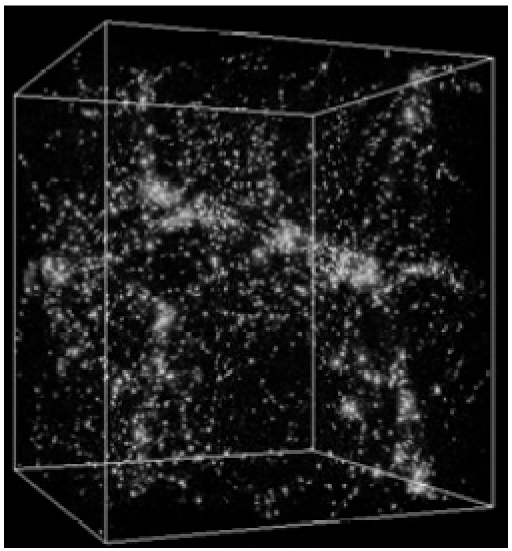
- Existence of the warm-hot intergalactic medium

  Cen & Ostriker 1999

- Mass scale of Pop III stars

  Abel+2001, Bromm+2002

What is Hydro-cosmology?



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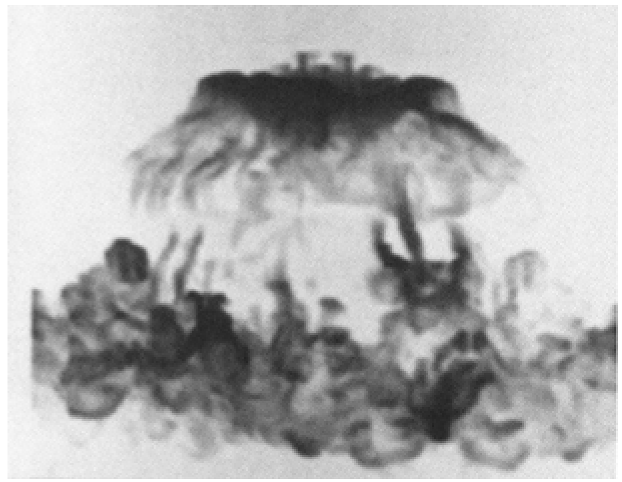

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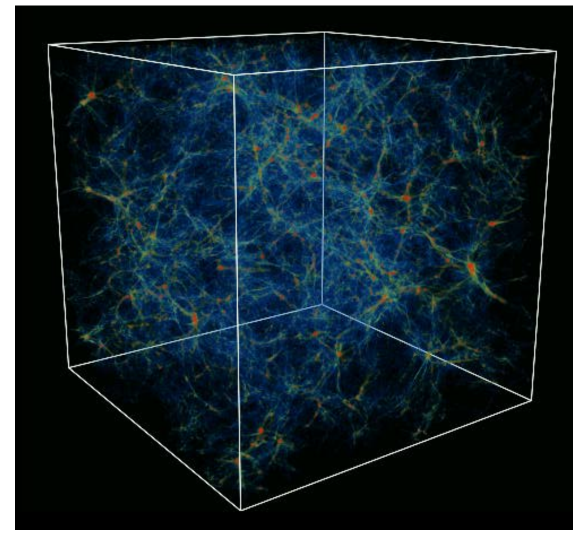


dark matter
+
gravity

ideal gas dynamics
+
"microphysics"

hydrodynamic
cosmology

THE ASTROPHYSICAL JOURNAL, 362:L41–L45, 1990 October 20

1990

THE UNIVERSE IN A BOX: THERMAL EFFECTS IN THE STANDARD COLD DARK MATTER SCENARIO

R. Y. CEN,[1] ANTONY JAMESON,[2] FENG LIU,[2] AND JEREMIAH P. OSTRIKER[1]

Received 1990 April 23; accepted 1990 August 7

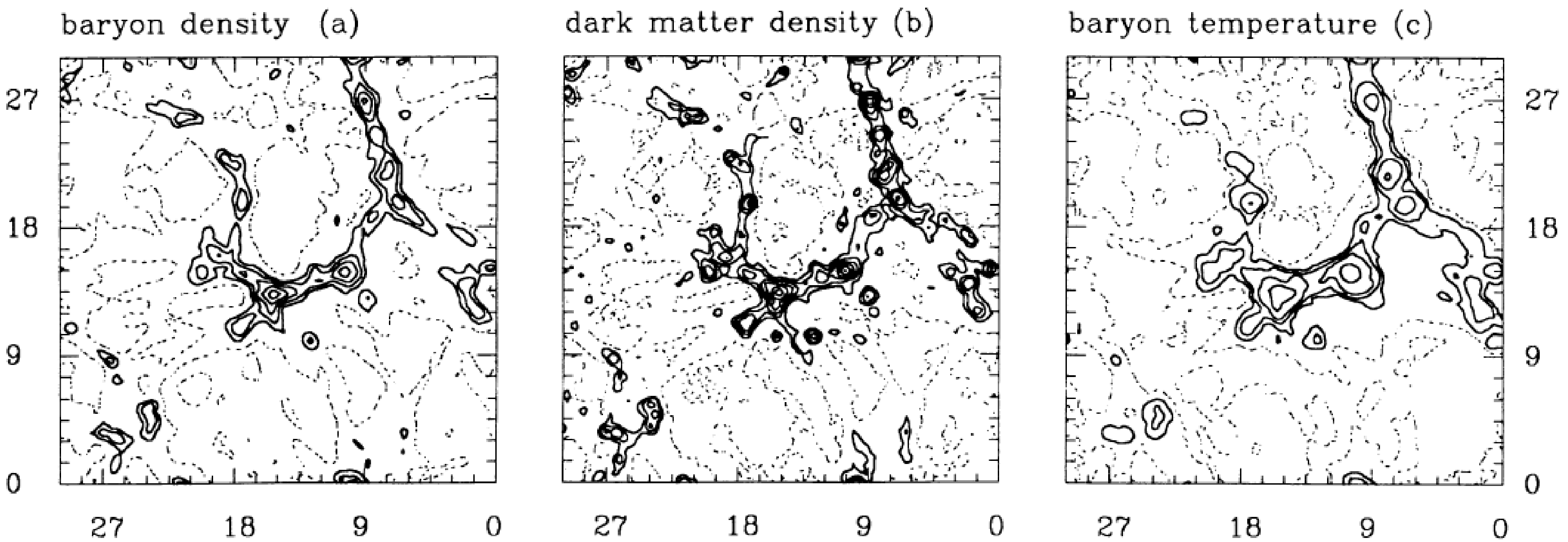


FIG. 3.—Contour plots at $z = 0$ for baryon density, (*b*) dark matter density, and (*c*) baryon temperature, respectively. Contour levels are as following: $(1 + \sigma)^{I/2}$, $I = 1, 2, 3, \ldots$ for solid contour lines; $(1 + \sigma)^{-I+1/2}$, $I = 1, 2, 3, \ldots$ for dotted contour lines, with σ the rms fluctuation of the plotted quantity in the baryonic matter.

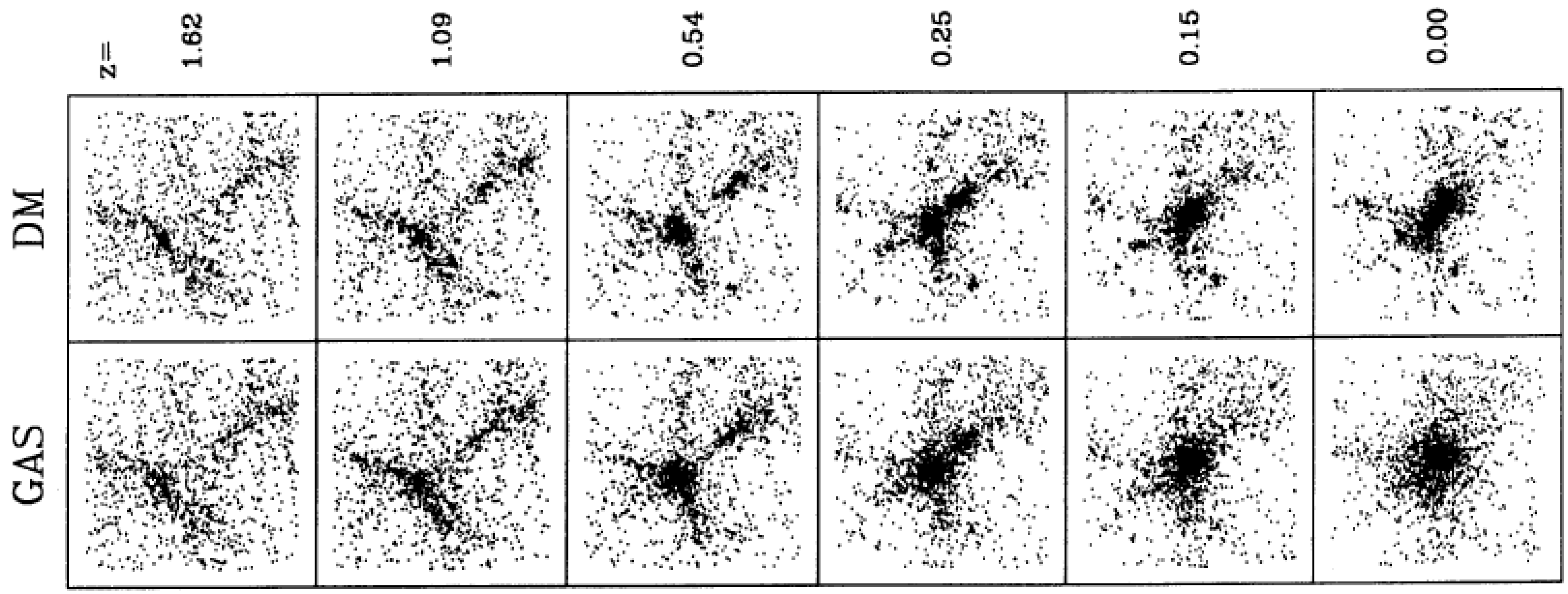
adiabatic gas dynamics

THE ASTROPHYSICAL JOURNAL, 363:349–366, 1990 November 10

1990

FORMATION AND EVOLUTION OF X-RAY CLUSTERS: A HYDRODYNAMIC SIMULATION OF THE INTRACLUSTER MEDIUM

AUGUST E. EVRARD
Department of Astronomy, University of California, Berkeley
Received 1989 June 22; accepted 1990 May 2



adiabatic gas dynamics

THE ASTROPHYSICAL JOURNAL, 376:L29–L32, 1991 August 1

1991

THE FRAGMENTATION OF "PANCAKES" IN A DARK MATTER–DOMINATED UNIVERSE

WENBO YUAN AND JOAN M. CENTRELLA
Department of Physics and Atmospheric Science, Drexel University, Philadelphia, PA 19104

AND

MICHAEL L. NORMAN
National Center for Supercomputing Applications, Beckman Institute, D-25, 405 N. Mathews Street, Urbana, IL 61801
Received 1991 March 11; accepted 1991 May 16

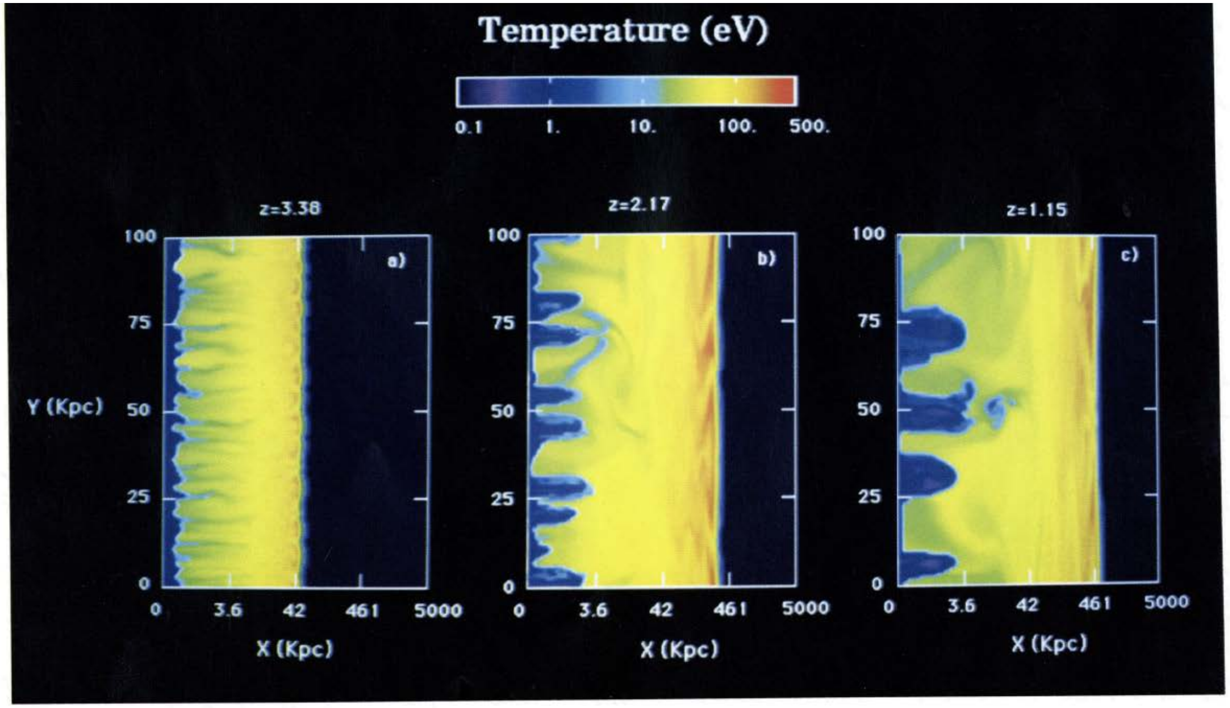
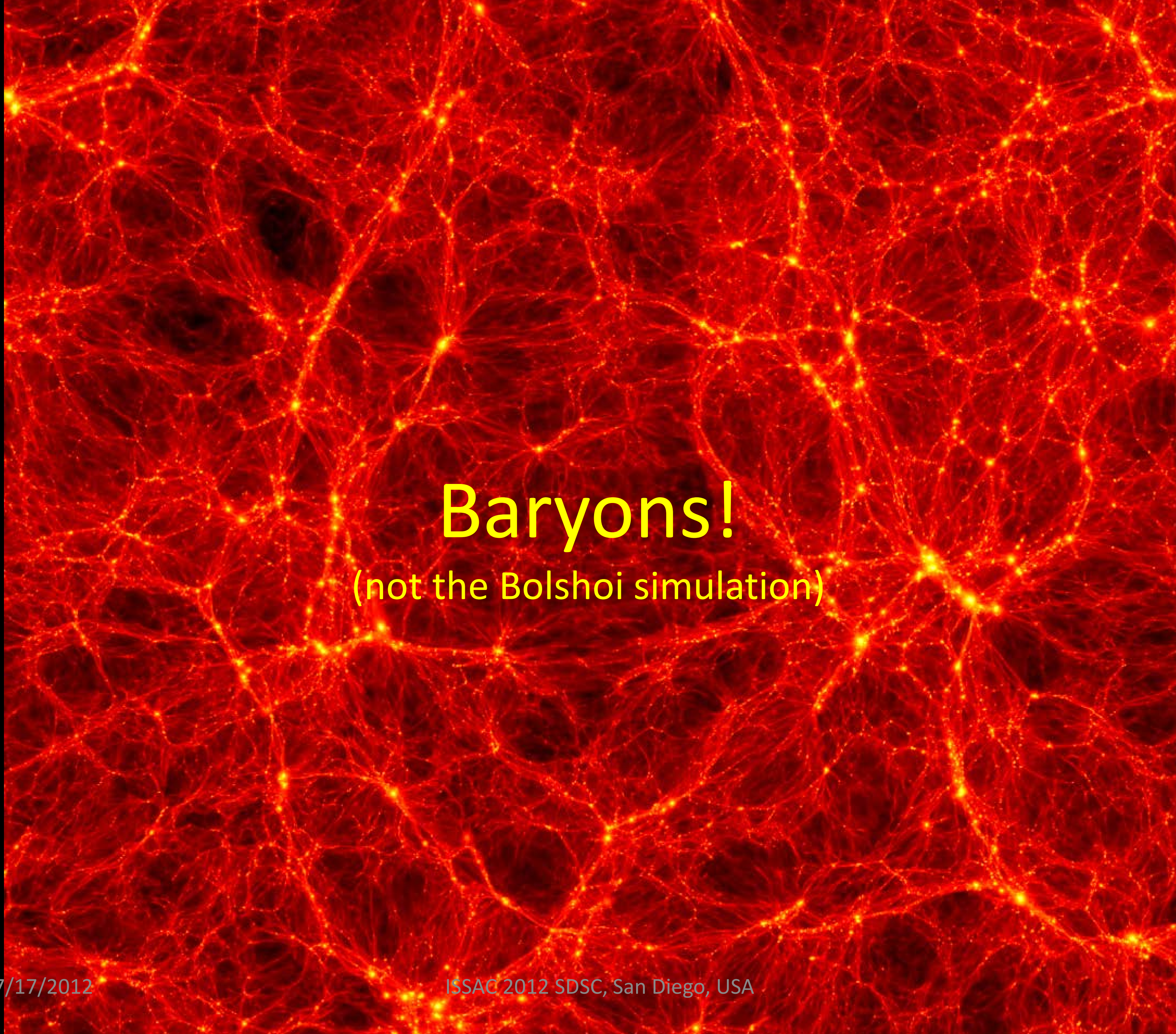


FIG. 4.—Temperature distribution in the fragmenting pancake. Midplane is along the left edge with the pancake collapsing to the left. (*a*) At $z = 3.88$ fragmentation is just beginning; (*b*) by $z = 2.17$ merging has begun; (*c*) merging continues at $z = 1.15$.

gas dynamics + radiative cooling



Baryons!

(not the Bolshoi simulation)

http://enzo-project.org

The Enzo Project

Enzo 2.1.0 has been released!

What is Enzo?

Enzo is a community-developed adaptive mesh refinement simulation code, designed for rich, multi-physics hydrodynamic astrophysical calculations.

Enzo is freely available, developed in the open, with a strong support structure for assistance. Simulations conducted with Enzo have been featured in numerous refereed journal articles, and it is capable of running on computers from laptop to Top500.

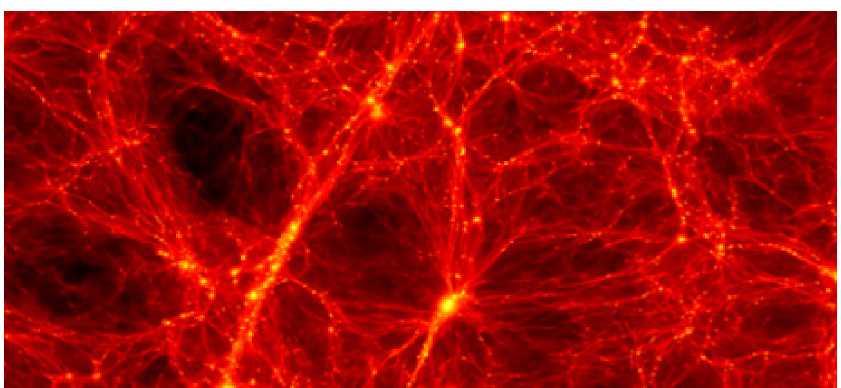


Image credit: Norman et al

Getting Enzo

Enzo can be obtained in several places, corresponding to the degree of stability and development accessibility.

Let's go! »

Help!

There are several places to get help with Enzo, from mailing lists to documentation to online tutorials and recordings of workshop presentations.

Help me out! »

Developing

Enzo is developed in the open by a community of developers from different institutions. Contributions, fixes, and changes are all welcomed!

Develop! »

Community

There are several places to get help with Enzo, from mailing lists to documentation to online tutorials and recordings of workshop presentations.

Engage »

http://hipacc.ucsc.edu/html/2010SummerSchool_archive.html

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HIPACC community

2010 Summer School

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2010 Program

The 2010 school ran from July 26 - August 13, and hosting it at UCSC allowed synergy with ISIMA, first International Summer Institute for Modeling in Astrophysics (July 5 - Aug 13) on Transport Processes in Astrophysics (see the ISIMA website for more information).

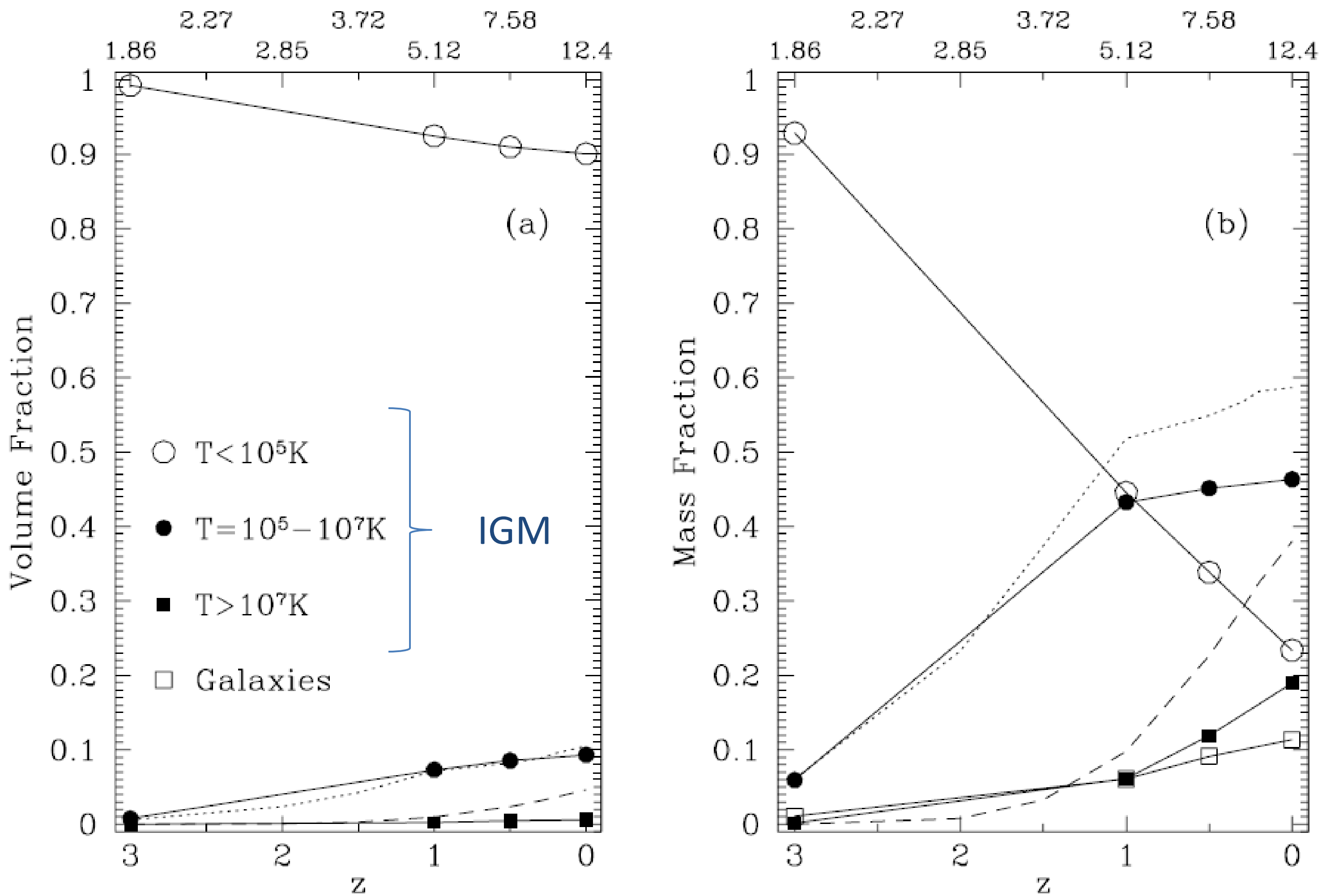
Our 2010 summer school included lectures on all the main codes currently used in high resolution simulations of galaxy formation and evolution: the adaptive mesh refinement codes ART, Enzo, and Ramses; the smooth particle hydro codes GADGET, Arepo and Gasoline/PKDGRAV; and also the Sunrise code for creating images of simulated galaxies in all wavebands including scattering, absorption, and reemission by dust.

Anatoly Klypin (NMSU), who directed the

ipacc.ucsc.edu/images/UCHIPACC2010SummerSchool_poster.jpg

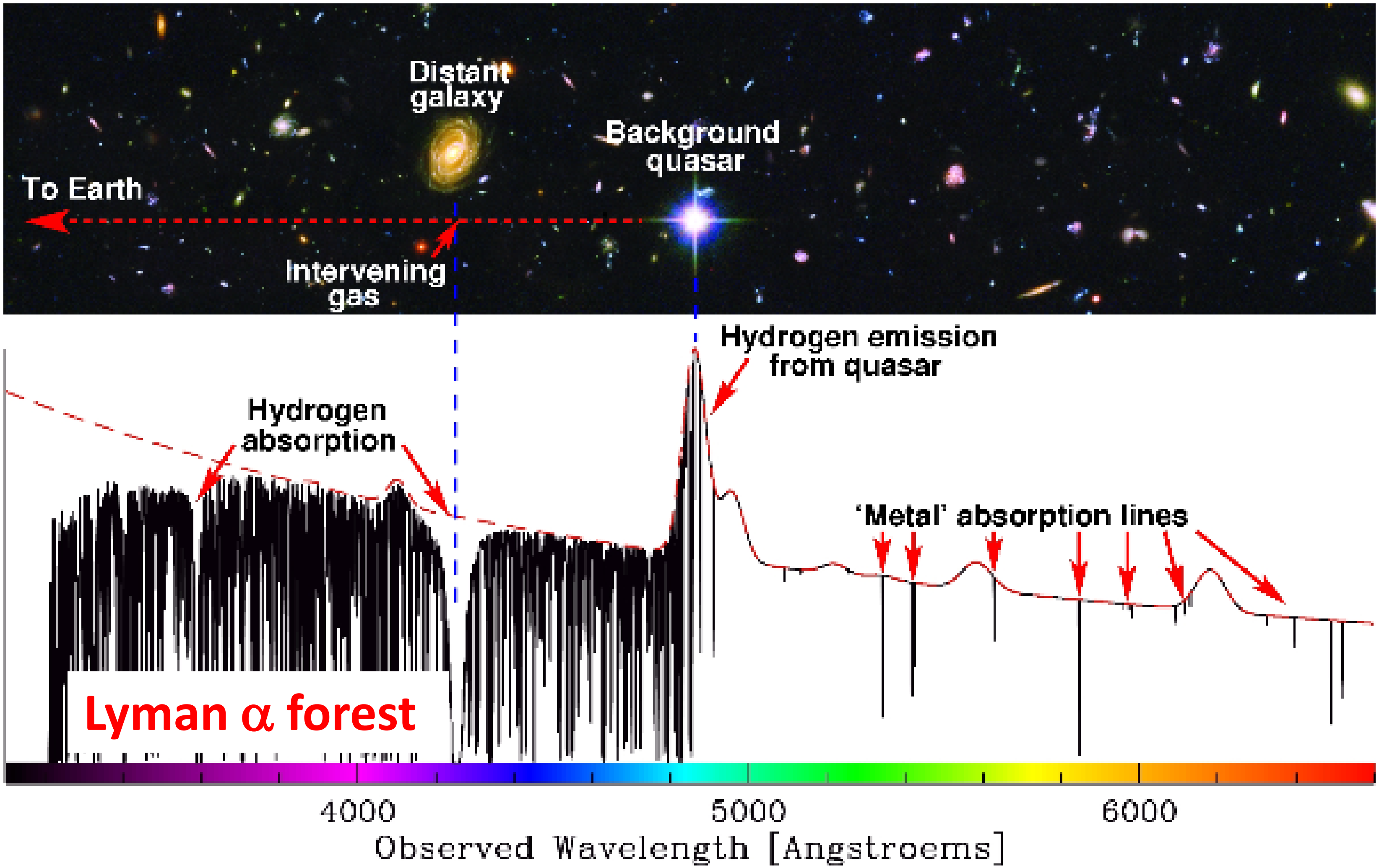
LECTURE 1
Hydro-cosmology simulations of baryons in the cosmic web
***
(Lyman α forest)

Q: Where are the baryons?
A: In the IGM mostly



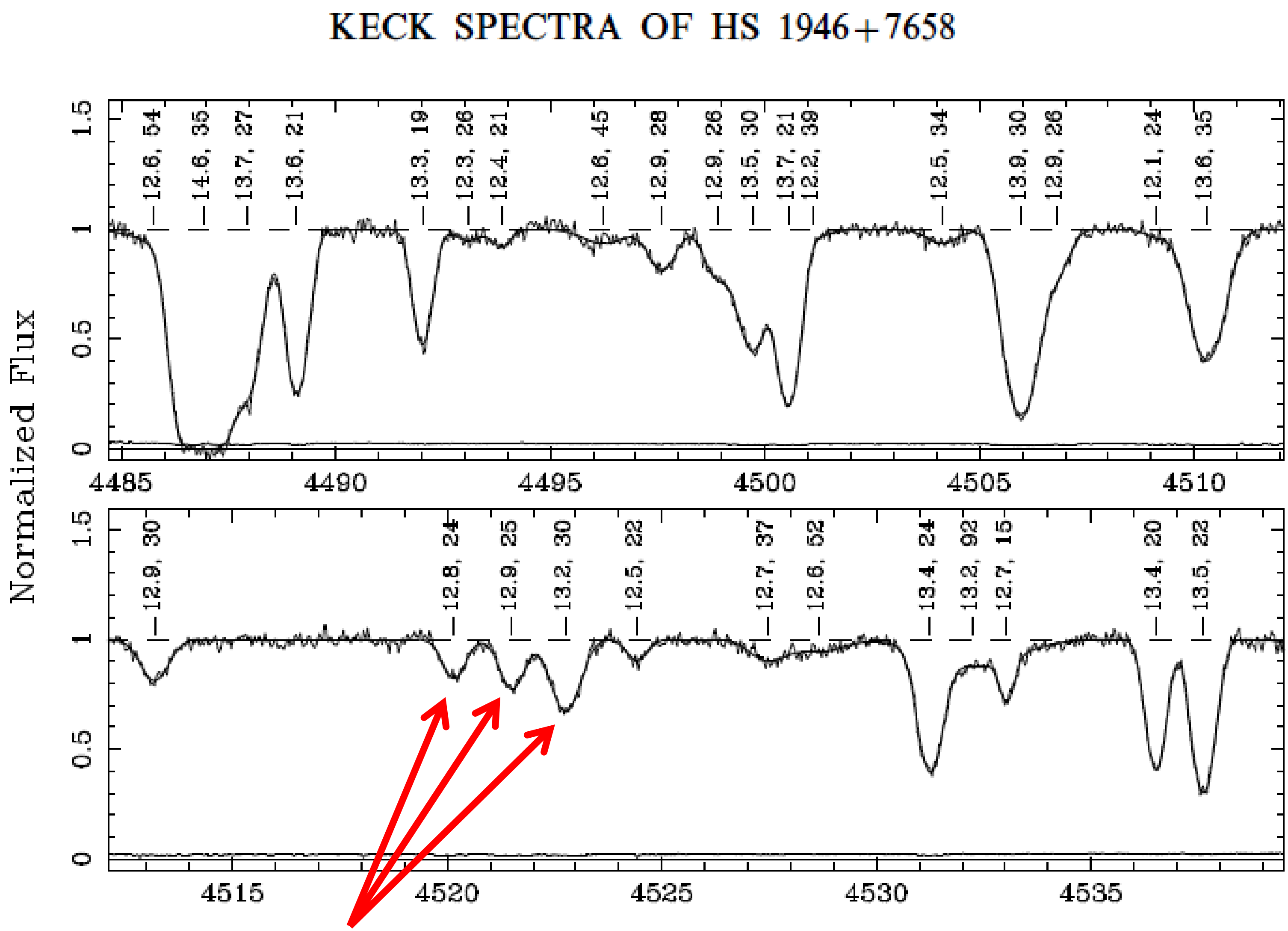
Cen & Ostriker (1999)

Observing the intergalactic medium in quasar absorption line spectra



Source: M. Murphy

High Resolution Spectrum

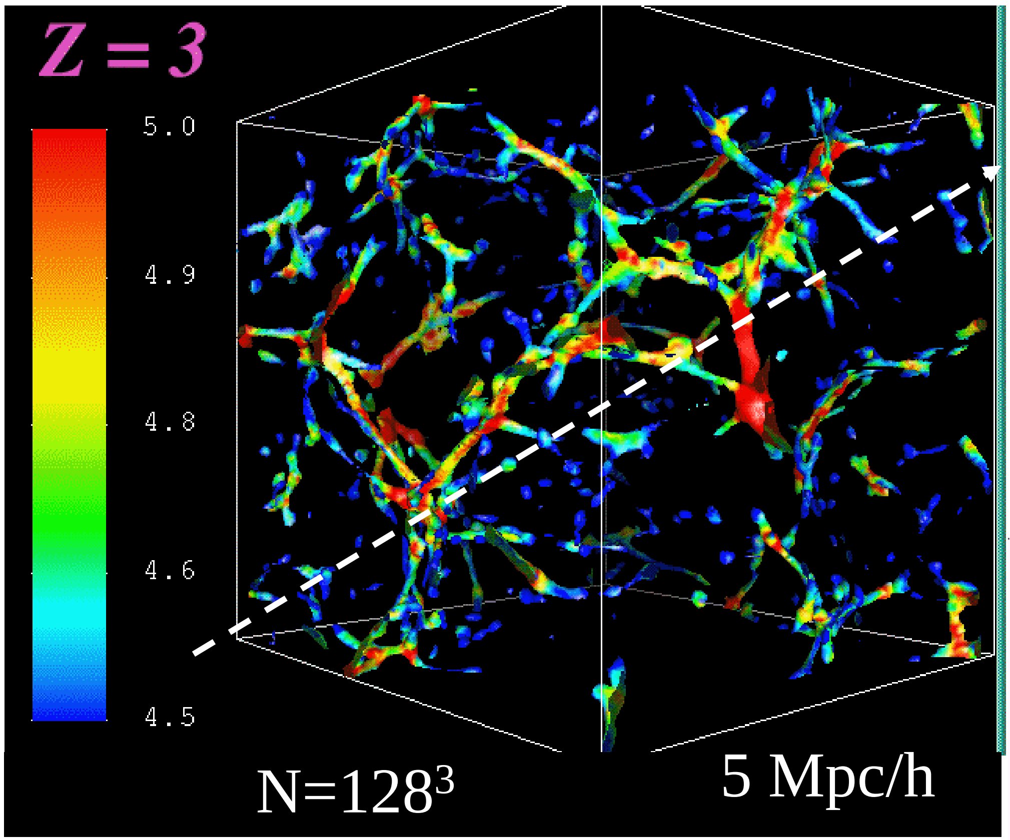


Kirkman & Tytler (1997)

Physical Origin of the Lyman Alpha Forest

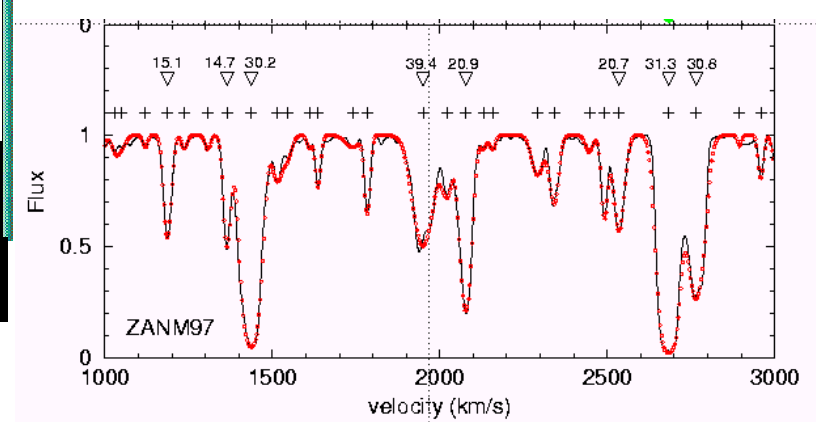
Cen et al. 1994, Zhang et al. 1995, Hernquist et al. 1996

"The Cosmic Web"

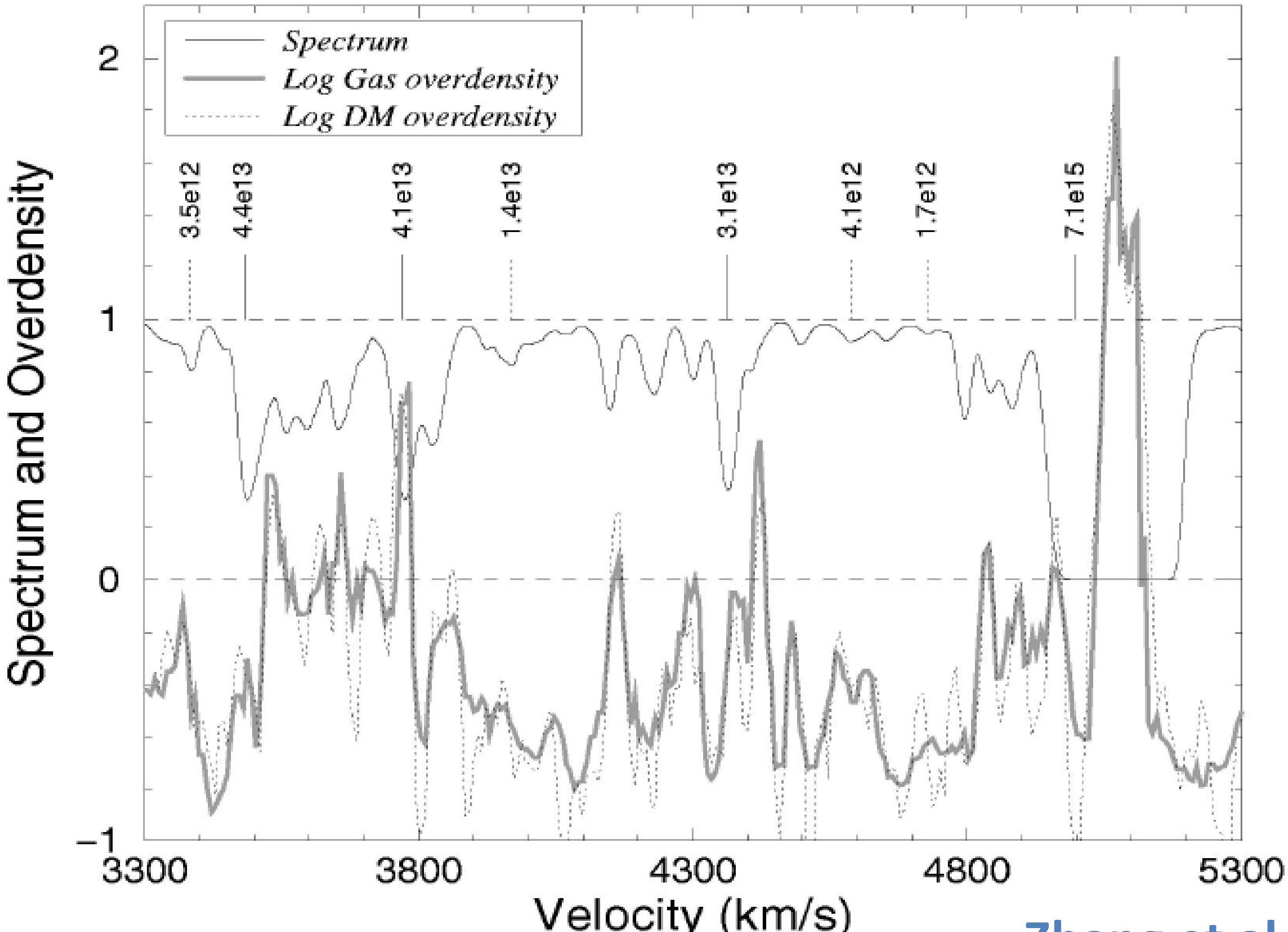


Zhang, Anninos, Norman (1995)

- intergalactic medium exhibits cosmic web structure at high z
- models explain observed hydrogen absorption spectra

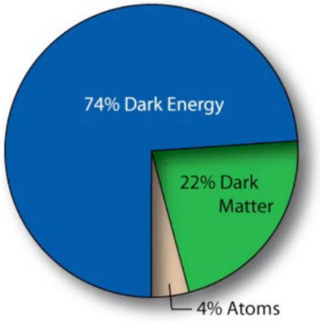


Ly α absorption directly probes DM distribution



Zhang et al. (1998)

Cosmology from the Ly α Forest

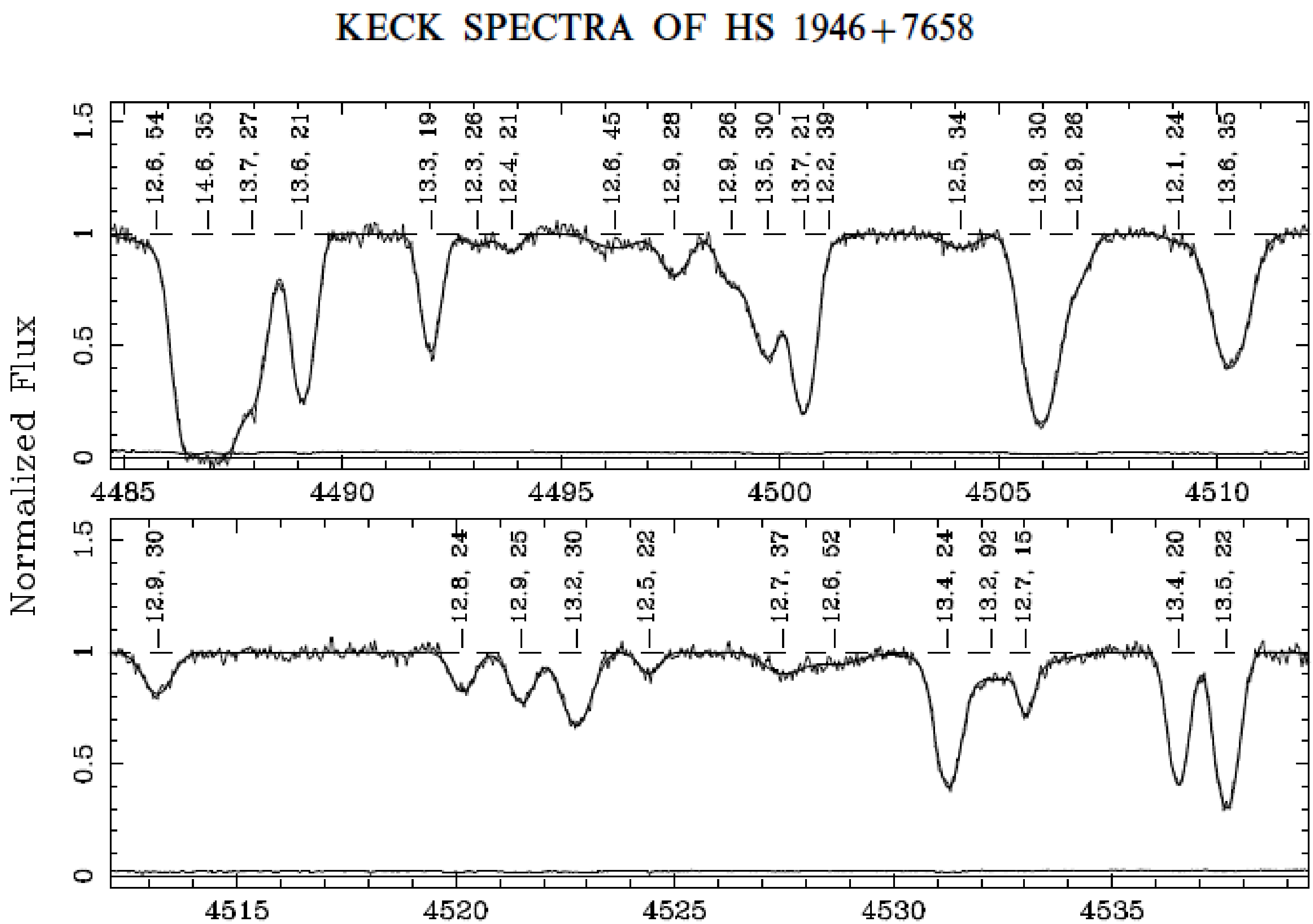


- What is measured
- The standard model
- Observations vs. simulations I:
  - spectacular agreement at the ~10% level
- DM power spectrum estimation
- Observations vs. simulations II:
  - discrepancies at the 1-2% level

The Standard Model

- Your favorite cosmological model (Ω_{dm}, Ω_b, Ω_Λ, H_0, σ_8, n_s)
- IGM of primordial H and He photoionized by homogeneous but evolving UVB due to GALS and QSOs ($J_{UVB}(z)$)
- Ly α forest due to optically thin absorption in highly ionized gas in intergalactic filaments tracing the DM distribution
- LLS and DLAs due to optically thick absorption in denser ionized gas in halos

What is Observed



Kirkman & Tytler (1997)

TABLE 1

ABSORBERS WITH LINES BETWEEN 4170 AND 4923 Å

z	log N (cm^{-2})	b (km s^{-1})	σ_z	σ_N	σ_b	Ion	$\lambda_{observed}$ (Å)
1.119017......	12.02	5.6	0.000002	0.02	0.4	Fe II	4767.53, 4790.63, 4967.43
1.738178......	14.36	2.8	0.000001	0.03	0.5	Fe II	4350.11, 4404.23, 4411.75
1.738179......	14.51	2.7	0.000001	0.01	0.3	Si II	4180.40, 4950.66
1.738201......	12.95	7.5	0.000003	0.02	0.6	Ni II	4664.27, 4681.23, 4768.71, 4797.08
1.738242......	12.16	1.2	0.000009	0.15	4.3	C IV	4239.33, 4246.38
1.738249......	14.12	12.4	0.000013	0.06	1.1	Fe II	4350.22, 4404.34, 4411.87
1.738253......	14.43	11.3	0.000003	0.02	0.3	Si II	4180.51, 4950.80
1.738434......	13.64	8.8	0.000002	0.02	0.3	C IV	4239.63, 4246.68
1.738750......	13.35	50.5	0.000367	0.40	21.1	C IV	4240.12, 4247.17
1.738799......	12.64	7.0	0.000013	0.15	2.4	C IV	4240.19, 4247.25
1.738970......	13.09	9.0	0.000007	0.08	1.4	C IV	4240.46, 4247.51
2.176945......	12.35	9.2	0.000014	0.09	1.9	C IV	4918.53, 4926.71
2.177267......	13.42	15.6	0.000007	0.03	1.0	C IV	4919.03, 4927.21
2.177533......	13.04	13.1	0.000013	0.06	1.1	C IV	4919.44, 4927.22
2.430432......	12.79	38.7	0.000046	0.06	6.4	H I	4170.27
2.431397......	13.16	27.3	0.000013	0.02	1.8	H I	4171.45
2.432004......	12.05	7.6	0.000023	0.13	3.6	H I	4172.18
2.432759......	12.58	19.3	0.000023	0.06	3.1	H I	4173.10
2.433959......	12.99	61.3	0.000060	0.05	9.6	H I	4174.56
2.434924......	12.52	17.8	0.000027	0.10	3.9	H I	4175.73
2.435871......	12.74	10.1	0.000012	0.07	1.8	H I	4176.89
2.437110......	14.35	107.0	0.000031	0.02	2.1	H I	4178.39
2.437501......	14.72	41.6	0.000012	0.07	2.3	H I	4178.87
2.439909......	12.35	10.3	0.000015	0.09	2.3	H I	4181.79
2.440449......	12.87	86.9	0.000205	0.14	31.8	H I	4182.45
2.441634......	12.67	33.2	0.000039	0.14	6.7	H I	4183.89
2.443398......	12.54	26.9	0.000034	0.06	4.4	H I	4186.04
2.444537......	13.38	32.7	0.000008	0.01	1.0	H I	4187.42
2.446516......	12.84	24.4	0.000021	0.04	2.7	H I	4189.83
2.446887......	12.65	2.1	0.000000	0.00	0.0	H I	4190.28

And hundreds more…

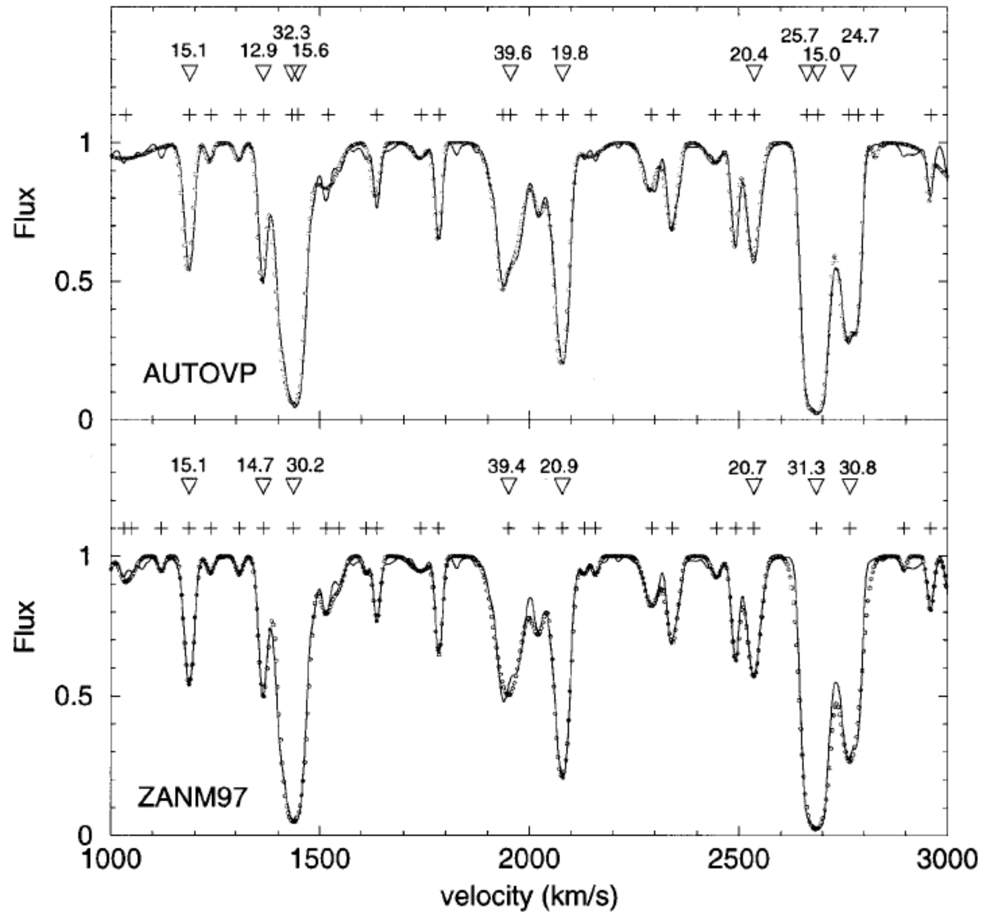
Simulated Spectra and Fitting

$$\tau_\nu(t) \equiv \int_t^{t_0} n_{\mathrm{H\,I}}(t)\sigma_\nu c\,\mathrm{d}t\,,$$

$$\tau_\nu(z) = \frac{c^2\sigma_0}{\sqrt{\pi}\nu_0}\int_z^{z_0}\frac{n_{\mathrm{H\,I}}(z')}{b}\frac{a^2}{\dot a} \times \exp\left\{-\left[(1+z')\frac{\nu}{\nu_0}-1+\frac{v}{c}\right]^2\frac{c^2}{b^2}\right\}\mathrm{d}z'\,,$$

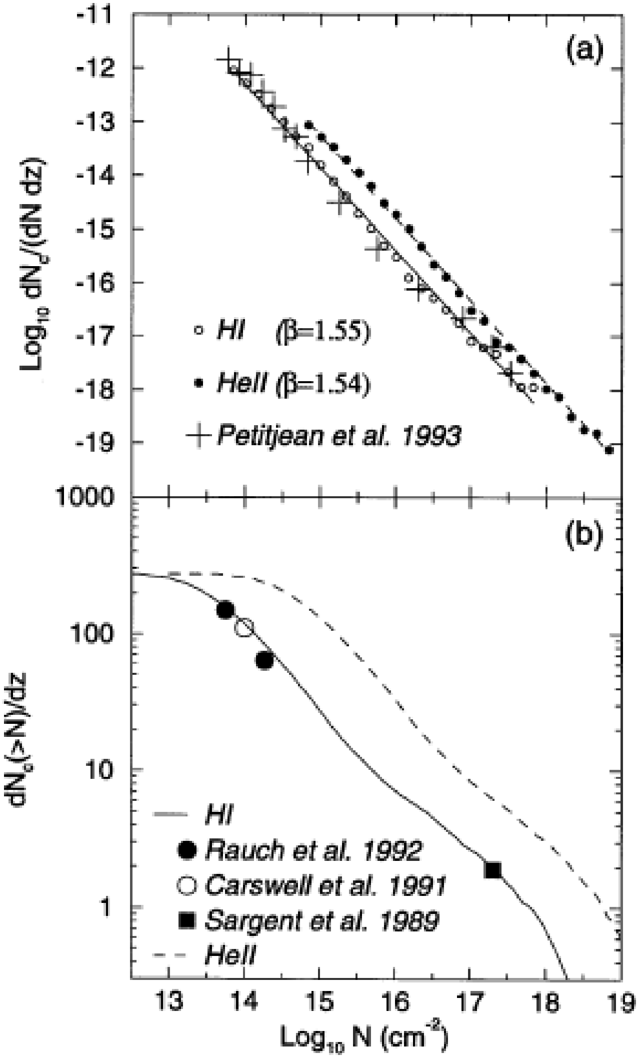
Zhang et al. (1997)

BRYAN ET AL.

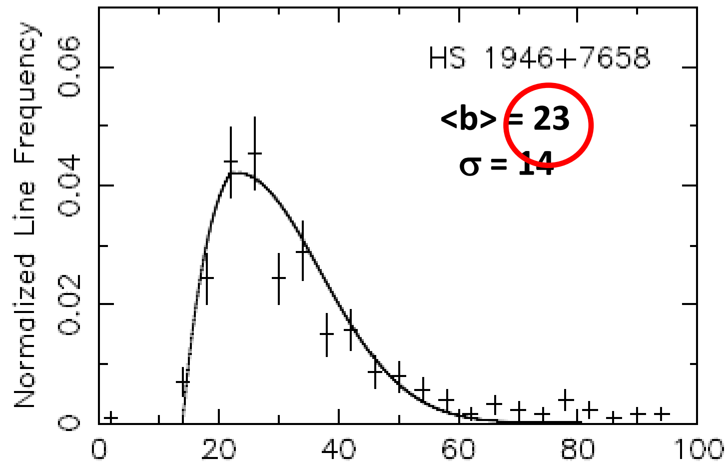


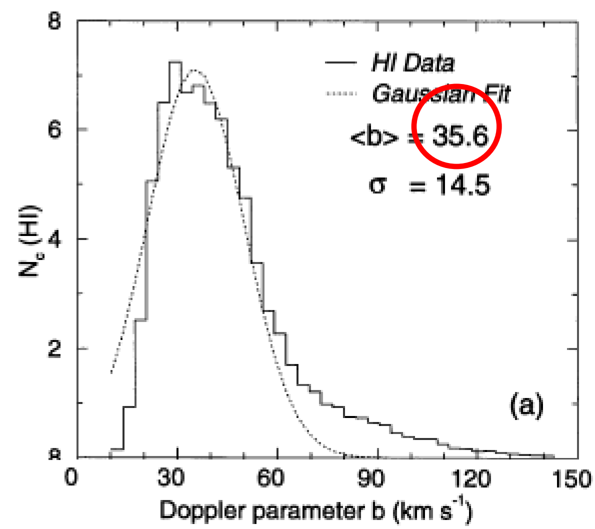
Observations vs. Simulations I.

Remarkable Agreement on Line Statistics



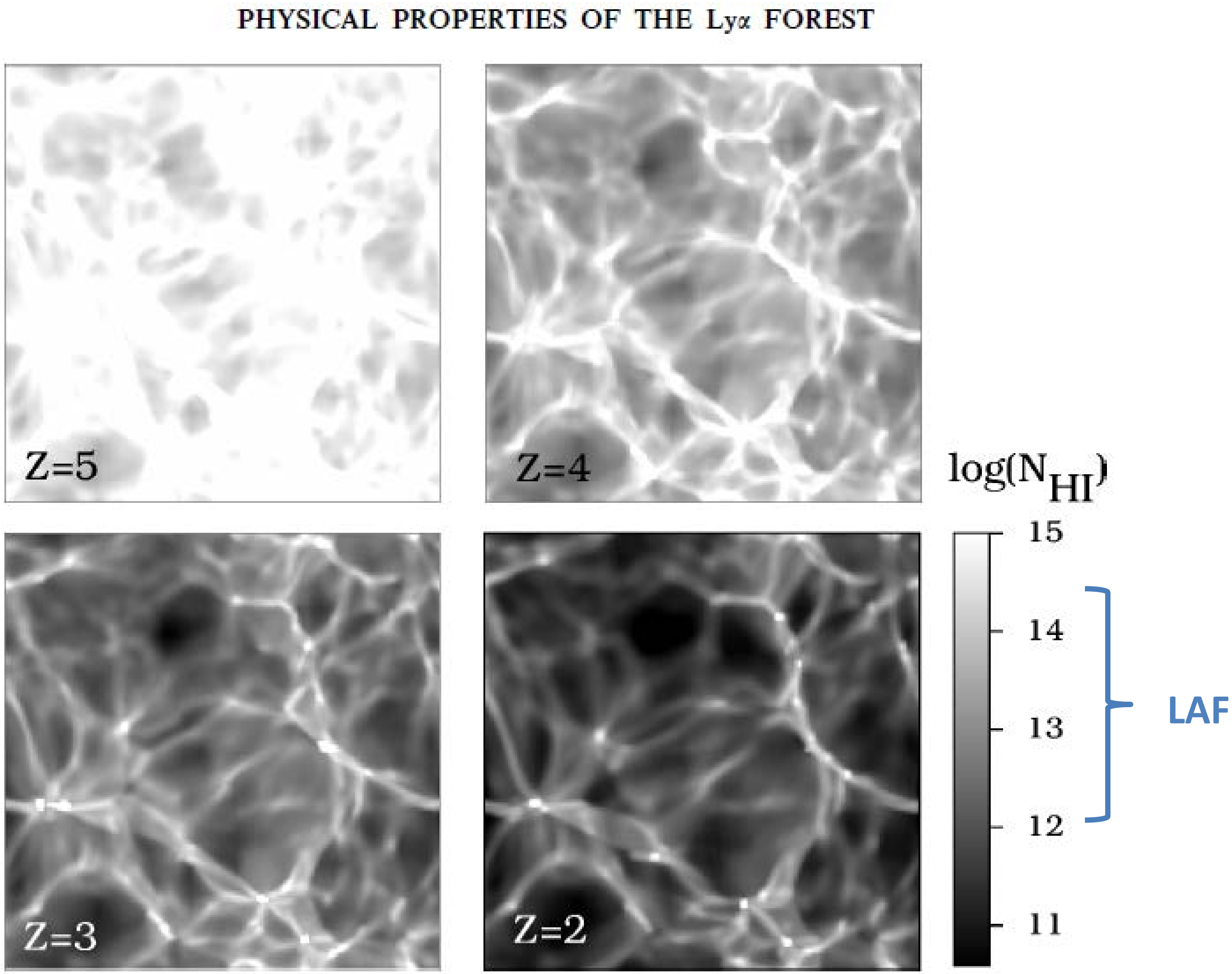
Kirkman & Tytler (1997)





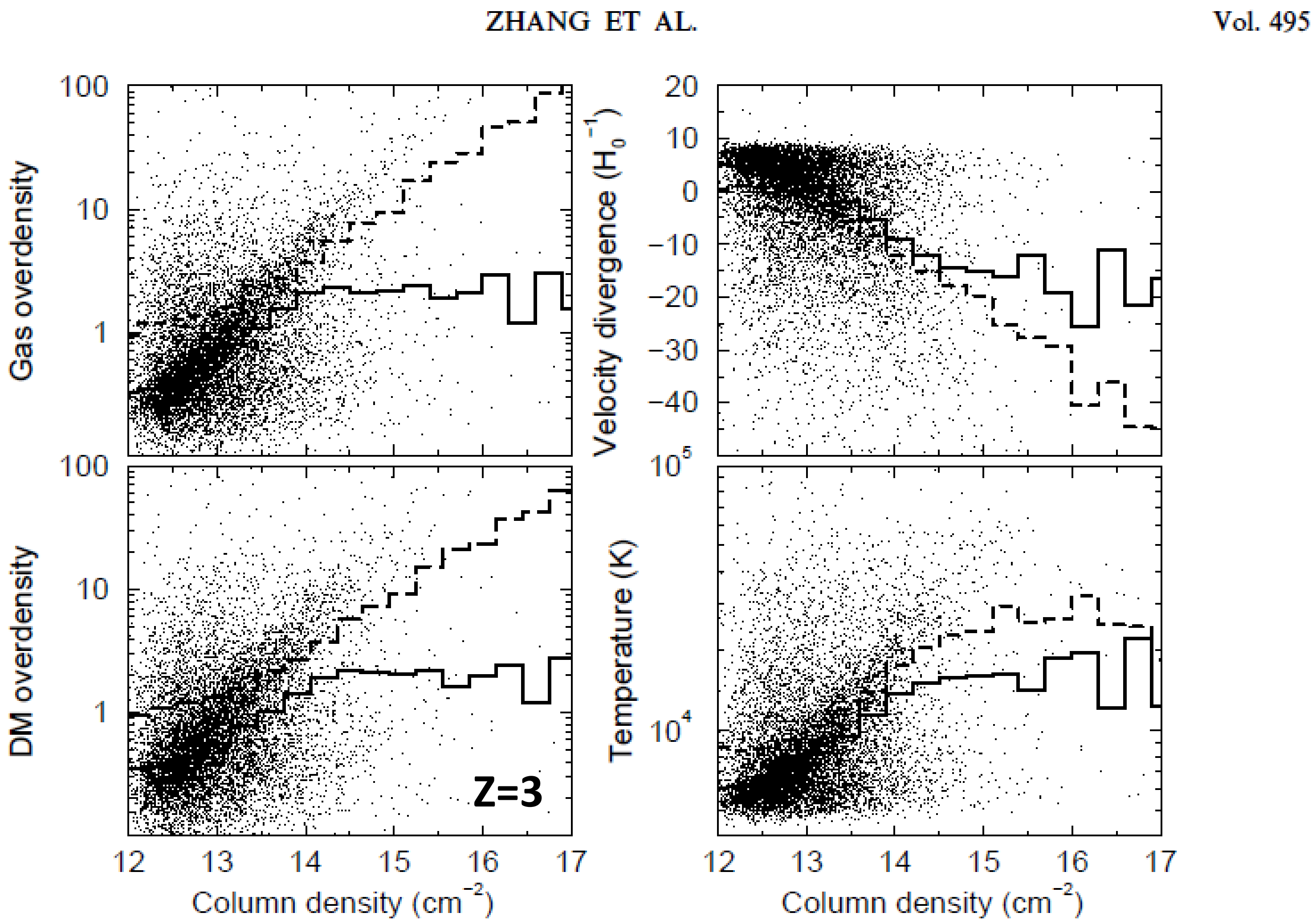
Zhang, Anninos, Norman (1995)

What is a Ly α Forest Absorber?



Zhang, Anninos, Meiksin & Norman (1998)

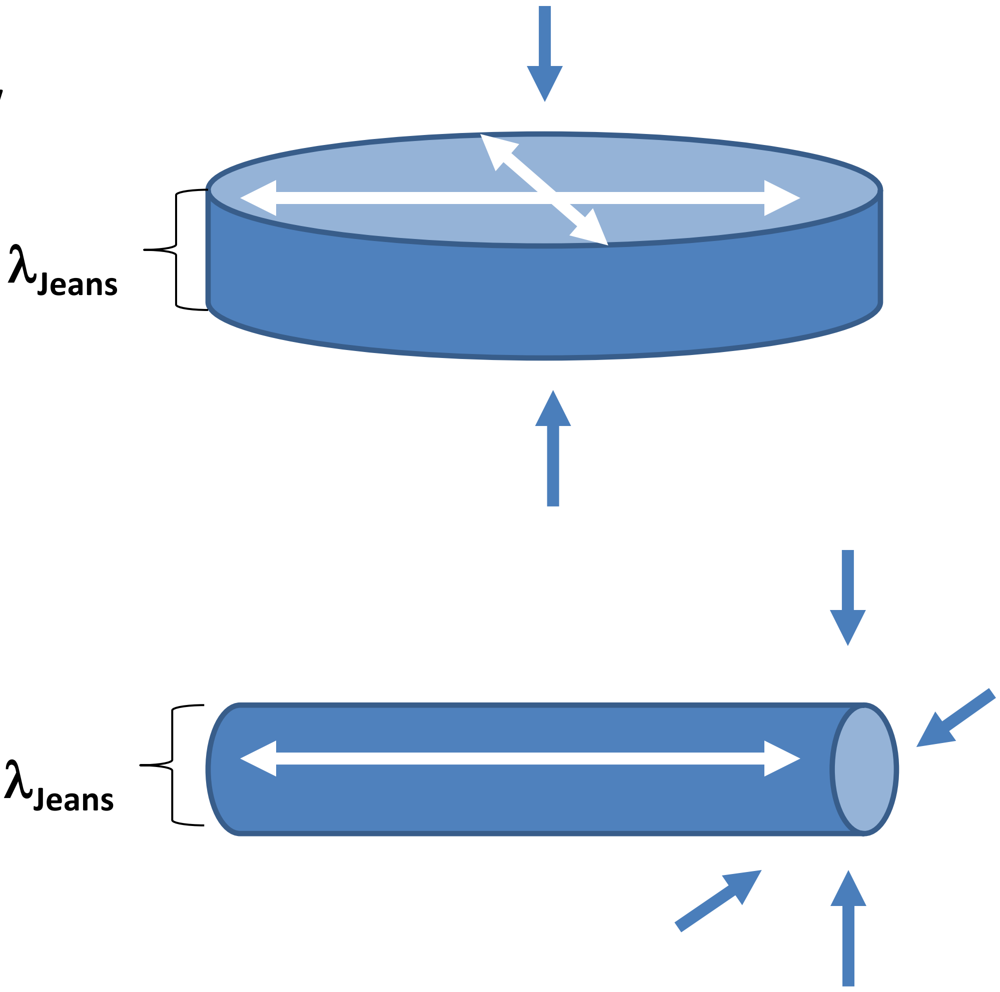
What is a Ly α Forest Absorber?



Zhang, Anninos, Meiksin & Norman (1998)

What is a Ly α Forest Absorber?

- Sheet or filament of low overdensity relative to the local mean
- Not gravitationally bound in 3D
- Unbiased WRT to dark matter
- Photo-ionized gas at ~10^4 K
- D ~ λ_{Jeans} ~ 100 kpc



Zhang, Anninos, Meiksin & Norman (1998)

Resolving the Ly α Forest

Bryan, Machacek, Anninos, Norman (1999)

- *Observed* linewidths reflect
  - Thermal broadening
  - Hubble broadening (redshift, LOS, and N_{HI} dependent)
  - Possibly turbulent broadening
- *Simulated* linewidths reflect above plus
  - Numerical resolution broadening

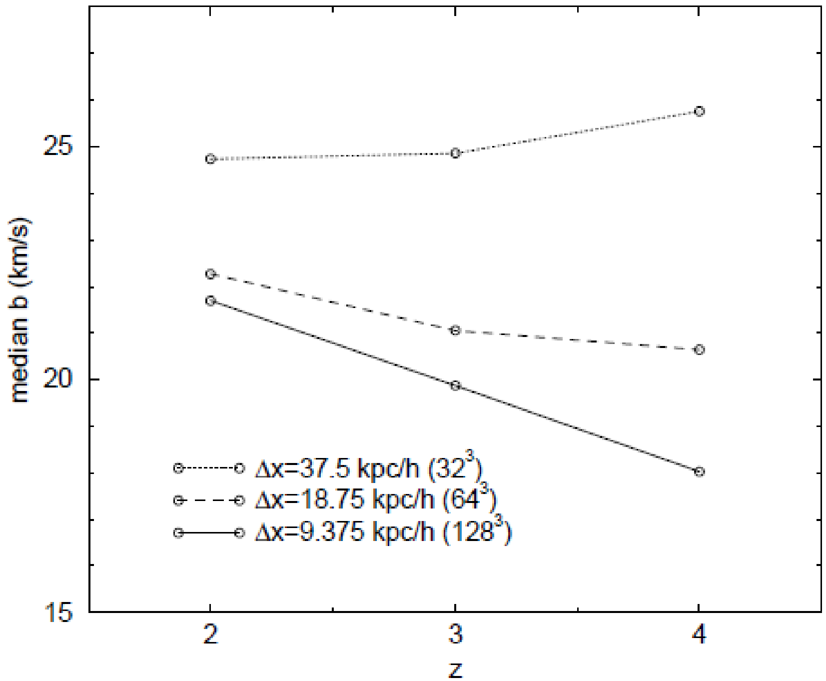
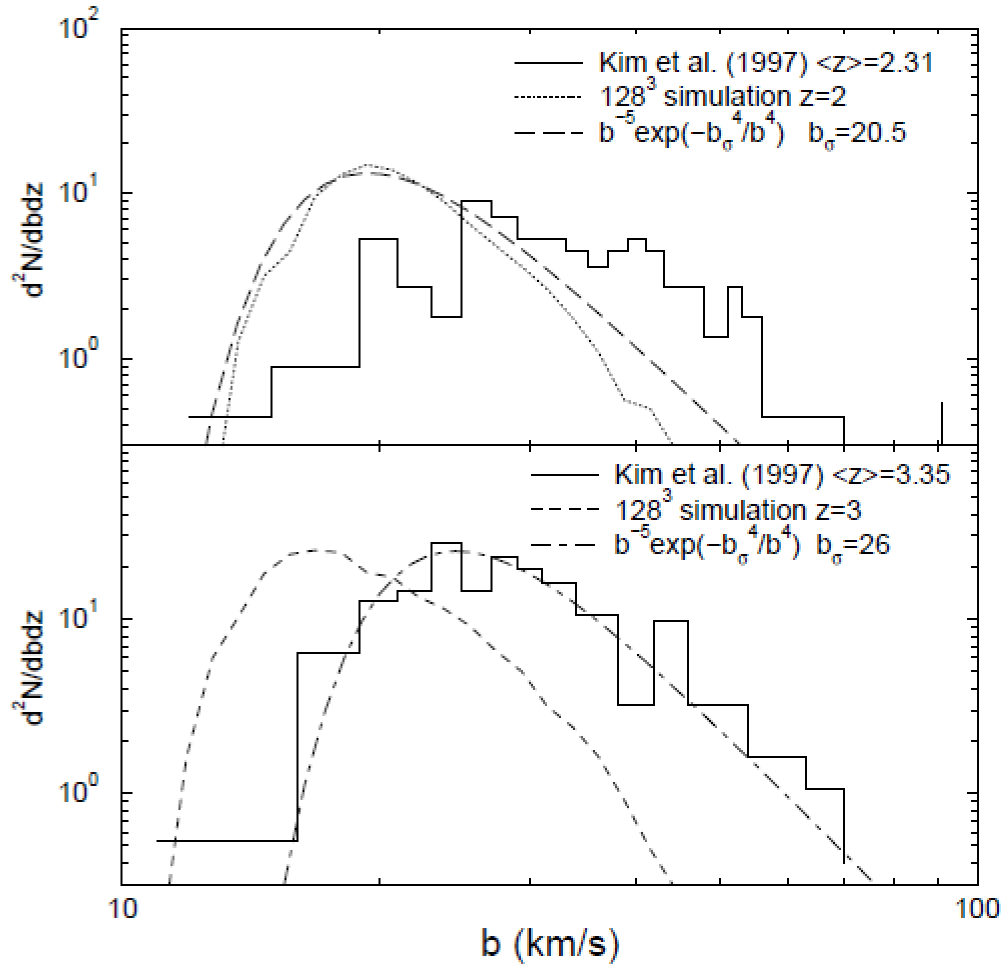


FIG. 6.—Median of the Doppler b distributions shown in Fig. 5 as a function of redshift and resolution (for lines in the $N_{\rm H\,I} = 10^{13}$–10^{14} cm^{-2} range). Higher resolution simulations produce thinner lines.

Higher resolution simulations predict lines that are *too narrow*



Bryan et al. (1999)

Higher resolution simulations predict lines that are *too narrow*

- Possible reasons
  - Cosmological model wrong
  - UV background model wrong
  - Box too small (large scale power missing)
  - Missing heat sources (He II reionization, X-rays, …)
  - Missing turbulent broadening (galactic winds?)
  - Magnetic support?

13 years later, this discrepancy has not been resolved
→Opportunity for a fundamental contribution

Jena et al. (2005)

- 40 fully hydrodynamic simulations* varying
  - Cosmological parameters
  - Box size
  - Numerical resolution
  - UV background intensity
  - Extra heating put in by hand
- Sensitivity analysis and uncertainty quantification
- Observations➔Concordance model @z=1.95

$N=1024^3$
L = 80 Mpc
Baryon Overdensity, z=3

*Data available at http://lca.ucsd.edu/data/concordance/

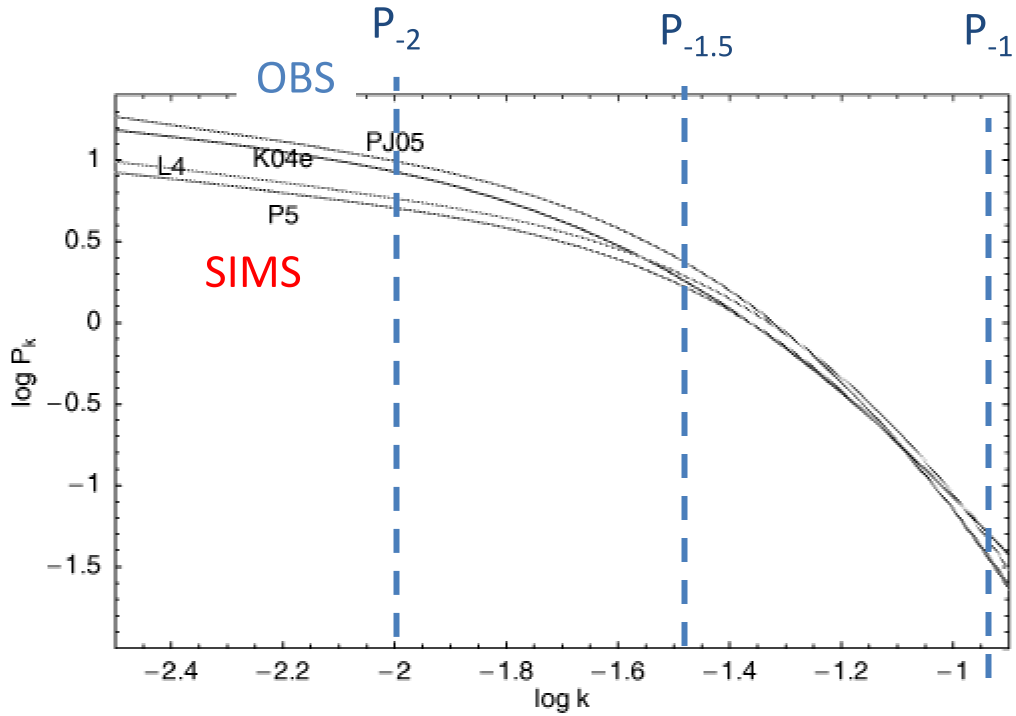
Sensitivity analysis and uncertainty quantification

- Derive simple parametric fits that connect key inputs to output
- Key inputs
  - σ_8: amplitude of matter fluctuations
  - γ_{912}: normalized HI photoionization rate
  - X_{228}: normalized HeII photoheating rate
  - L: simulation box size
  - C: cell resolution
- Key outputs
  - $\langle F \rangle = \exp(-\tau_{eff})$: mean transmitted flux
  - b_σ: median Doppler width
  - P_{-2}, $P_{-1.5}$, P_{-1}: flux power at log $k=10^{-2}$, $10^{-1.5}$, 10^{-1} s/km

Flux Power

$$\delta_f(\upsilon) \equiv \frac{f(\upsilon) - \bar{f}}{\bar{f}};\ \bar{f} \text{ is mean flux for spectrum}$$

$$P_f(k) = \delta_f(k) * \delta_f(k);\quad \delta_f(k) \text{ is 1D FT of } \delta_f(\upsilon)$$



Jena et al. (2005)

Table of Simulations

Name	Ω_b	Ω_m	Ω_Λ	h	σ_8	γ_{912}	X_{228}	L	N	Cell	$\bar{F}$	P_{-2}	$P_{-1.5}$	P_{-1}	b_σ
$PJ05$											...	11.1	2.76	0.0755	...
M04a											...	6.7	...	...	...
Data											0.875	8.8	2.07	0.0841	23.6
σ (Data)											0.10	1.0	0.14	0.0067	1.5
A	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**76.8**	1024^3	75	0.8713	6.22448	2.00096	0.0580288	26.662
A2	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**38.4**	512^3	75	0.8779	5.26255	1.68276	0.0539609	25.741
A3	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**19.2**	256^3	75	0.8756	5.29052	1.80656	0.0633351	24.995
A5	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**19.2**	256^3	75	0.8762	5.23220	1.76246	0.0625227	24.560
A4	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**9.6**	128^3	75	0.8796	4.51003	1.73439	0.0820087	23.007
W1	0.044	0.27	0.73	0.71	0.94	1.0	3.3	**38.4**	512^3	75	0.896	4.59288	1.2719	0.025351	29.212
K2	0.044	0.27	0.73	0.71	0.94	1.0	3.3	**19.2**	256^3	75	0.897	4.17679	1.2170	0.028068	27.778
B2	0.044	0.27	0.73	0.71	0.90	1.0	1.8	9.6	512^3	**18.75**	0.8925	3.52847	1.47406	0.0770033	22.7964
B	0.044	0.27	0.73	0.71	0.90	1.0	1.8	9.6	256^3	**37.5**	0.8819	1.71394	4.62606	0.0789581	22.8300
A4	0.044	0.27	0.73	0.71	0.90	1.0	1.8	9.6	128^3	**75**	0.8796	4.51003	1.73439	0.082008	23.007
K1	0.044	0.27	0.73	0.71	0.94	1.0	3.3	19.2	512^3	**37.5**	0.902	3.85064	1.29774	0.0375323	27.110
K2	0.044	0.27	0.73	0.71	0.94	1.0	3.3	19.2	256^3	**75**	0.897	4.17679	1.21702	0.0280679	27.778
K3	0.044	0.27	0.73	0.71	0.94	1.0	3.3	19.2	128^3	**150**	0.891	4.46281	1.07452	0.0166946	32.892
L4	0.044	0.27	0.73	0.71	1.00	0.8	1.4	**19.2**	256^3	**75**	0.8664	5.82605	2.0934	0.0890899	22.577
U	0.044	0.27	0.73	0.71	1.00	0.8	1.4	**38.4**	256^3	**150**		6.36059	1.66403	0.0470178	
L5	0.044	0.27	0.73	0.71	1.09	0.8	1.4	**19.2**	256^3	**75**	0.8753	5.55675	1.89446	0.0871944	22.1579
Q1	0.044	0.27	0.73	0.71	1.09	0.8	1.4	**38.4**	256^3	**150**	0.86	6.93897	1.82575	0.0477104	27.516
A	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**76.8**	1024^3	**75**	0.8713	6.22448	2.00096	0.0580288	26.662
A2	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**38.4**	512^3	**75**	0.8779	5.26255	1.68276	0.0539609	25.741
A3	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**19.2**	256^3	**75**	0.8756	5.29052	1.80656	0.0633351	24.995
B2	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**9.6**	512^3	**18.75**	0.8925	3.52847	1.47406	0.0770033	22.7964
B	0.044	0.27	0.73	0.71	0.90	1.0	1.8	**9.6**	256^3	**37.5**	0.8819	1.71394	4.62606	0.0789581	22.8300
F	0.044	0.27	0.73	0.71	**0.90**	**1.04**	**1.8**	19.2	512^3	37.5	0.884	4.65843	1.7522	0.074021	23.325
K1	0.044	0.27	0.73	0.71	**0.94**	**1.0**	**3.3**	19.2	512^3	37.5	0.902	3.85064	1.29774	0.0375323	27.110
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

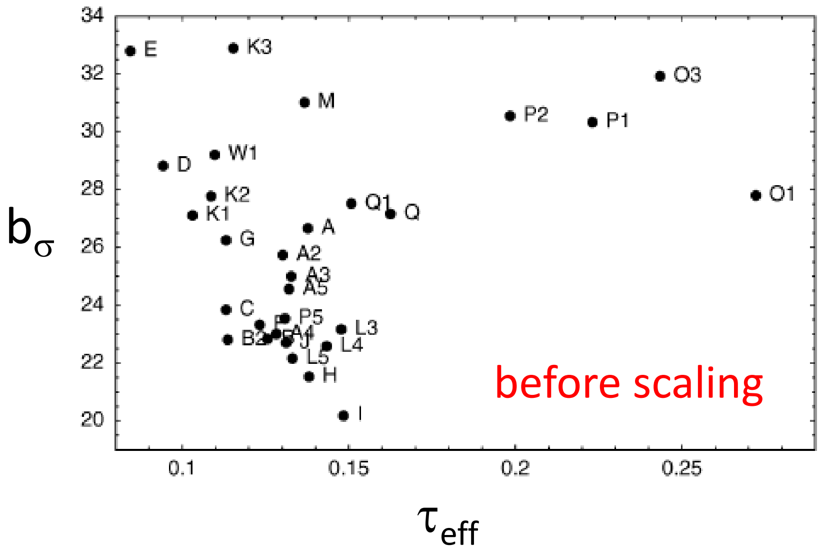
Table of Simulations, cont’d

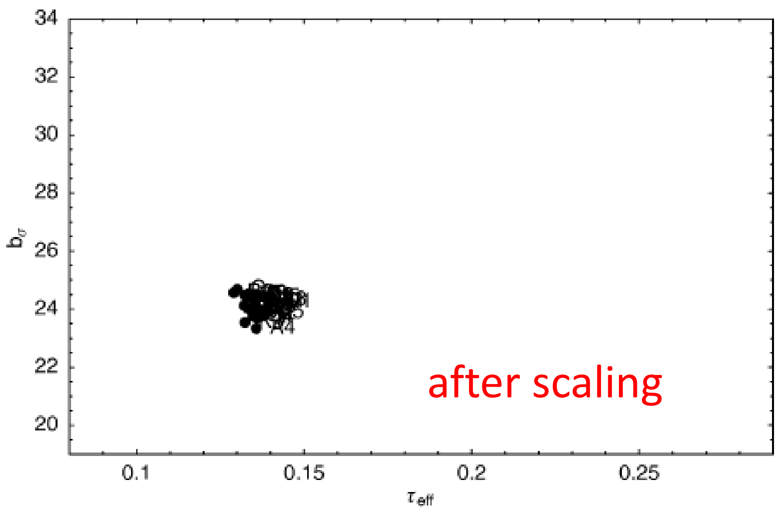
L1	0.044	0.27	0.73	0.71	**0.70**	0.8	1.4	19.2	256^3	75					25.426
L2	0.044	0.27	0.73	0.71	**0.79**	0.8	1.4	19.2	256^3	75	0.83	6.20307	2.51307	0.111913	
L3	0.044	0.27	0.73	0.71	**0.94**	0.8	1.4	19.2	256^3	75	0.8626	5.52899	2.11876	0.0947183	23.1608
L4	0.044	0.27	0.73	0.71	**1.00**	0.8	1.4	19.2	256^3	75	0.8664	5.82605	2.0934	0.0890899	22.577
L5	0.044	0.27	0.73	0.71	**1.09**	0.8	1.4	19.2	256^3	75	0.8753	5.55675	1.89446	0.0871944	22.1579
M	0.044	0.27	0.73	0.71	**0.70**	1.0	3.3	19.2	256^3	75	0.8722	4.62589	1.36509	0.0322525	31.015
K2	0.044	0.27	0.73	0.71	**0.94**	1.0	3.3	19.2	256^3	75	0.897	4.17679	1.21702	0.0280679	27.778
U	0.044	0.27	0.73	0.71	**1.00**	0.8	1.4	38.4	256^3	150		6.36059	1.66403	0.0470178	
Q1	0.044	0.27	0.73	0.71	**1.09**	0.8	1.4	38.4	256^3	150	0.86	6.93897	1.82575	0.0477104	27.516
P2	0.044	0.27	0.73	0.71	**0.84**	0.7	1.4	38.4	256^3	150	0.82	8.30225	2.28294	0.069514	30.5494
Q	0.044	0.27	0.73	0.71	**1.09**	0.7	1.4	38.4	256^3	150	0.85	7.55325	2.04882	0.0565825	27.159
O2	0.044	0.27	0.73	0.71	0.84	**0.5**	1.4	38.4	256^3	150	0.7741	10.8993	3.07758	0.108957	30.1342
P1	0.044	0.27	0.73	0.71	0.84	**0.6**	1.4	38.4	256^3	150	0.80	9.42176	2.61947	0.0854846	30.3377
P2	0.044	0.27	0.73	0.71	0.84	**0.7**	1.4	38.4	256^3	150	0.82	8.30225	2.28294	0.069514	30.5494
L3	0.044	0.27	0.73	0.71	0.94	**0.8**	1.4	19.2	256^3	75	0.8626	5.52899	2.11876	0.0947183	23.1608
P5	0.044	0.27	0.73	0.71	0.94	**1.0**	1.4	19.2	256^3	75	0.8774	5.08876	1.79106	0.0721239	23.542
C	0.044	0.27	0.73	0.71	0.94	**1.2**	1.4	19.2	256^3	75	0.893	4.48559	1.53054	0.0571994	23.842
Q	0.044	0.27	0.73	0.71	1.09	**0.7**	1.4	38.4	256^3	150	0.85	7.55325	2.04882	0.0565825	27.159
Q1	0.044	0.27	0.73	0.71	1.09	**0.8**	1.4	38.4	256^3	150	0.86	6.93897	1.82575	0.0477104	27.516
S2	**0.051**	0.27	0.73	**0.66**	0.94	1.0	3.3	19.2	256^3	75	0.892	4.42602	1.29656	0.031181	28.313
K2	**0.044**	0.27	0.73	**0.71**	0.94	1.0	3.3	19.2	256^3	75	0.897	4.17679	1.21702	0.0280679	27.778
S3	**0.038**	0.27	0.73	**0.76**	0.94	1.0	3.3	19.2	256^3	75	0.904	4.03904	1.16607	0.0262167	27.536
T	0.044	**0.22**	**0.78**	0.71	0.94	1.0	3.3	19.2	256^3	75	0.887	4.48482	1.36005	0.0315291	28.671
K2	0.044	**0.27**	**0.73**	0.71	0.94	1.0	3.3	19.2	256^3	75	0.897	4.17679	1.21702	0.0280679	27.778
K3	0.044	**0.27**	**0.73**	0.71	0.94	1.0	3.3	19.2	128^3	150	0.891	4.46281	1.07452	0.0166946	32.892
V	0.044	**0.32**	**0.68**	0.71	0.94	1.0	3.3	19.2	128^3	150	0.905	4.11799	1.15153	0.026181	27.318

Scaling Relations

Table 7. Scaling relations between input and output parameters.

Input Parameter	τ_{eff}	b_σ
Box size (L)	$0.124447 + 0.00015187\ L$	$-6.43176 + 24.9593\ L^{0.0465855}$
Cell size (C)	$0.132828 + 0.00016748\ C$	$24.0341 + 0.000244627\ C^{2.03635}$
X_{228}	$0.339854 - 0.194975\ X_{228}^{0.128823}$	$16.4342 + 6.31086\ X_{228}^{0.589379}$
γ_{912}	$0.0517116 + 0.0845752\ \gamma_{912}^{-1}$	$23.9792 + 0.150065\ \gamma_{912}$
σ_8	$0.243733 - 0.119478\ \sigma_8$	$41.1189 - 17.9121\sqrt{\sigma_8}$

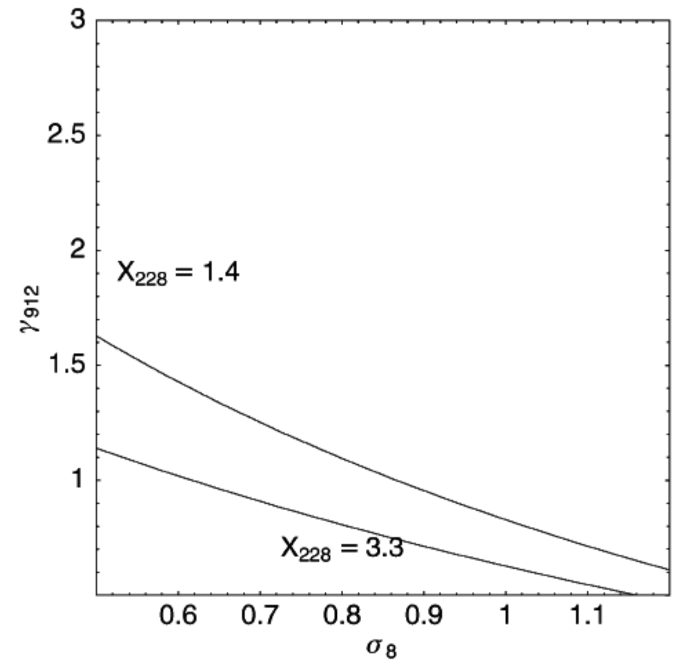


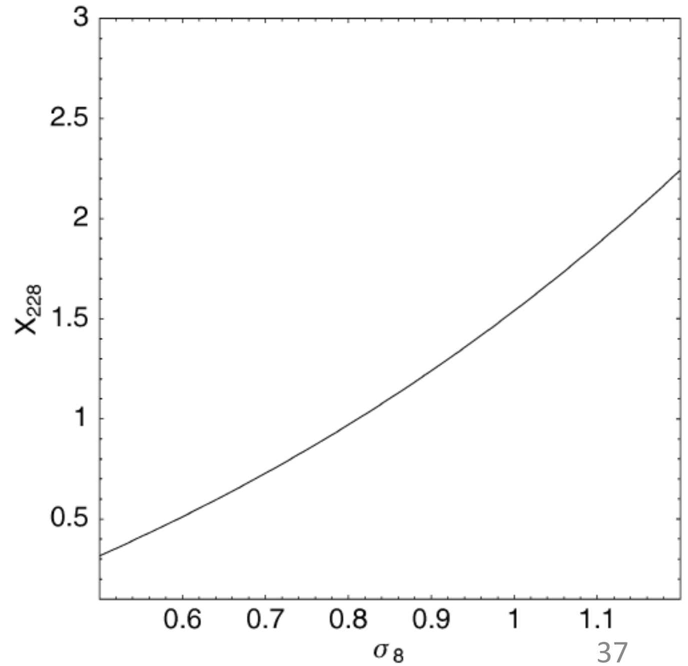


Jena et al. (2005)

Findings

- After scaling out boxsize and resolution effects, a wide range of σ_8 ($0.8 < \sigma_8 < 1.1$) fit observations ($<F>$, b_σ, P_{-1}) by adjusting γ_{912} and X_{228}
- Using only $<F>$, b_σ, P_{-1} cannot uniquely determine σ_8, γ_{912}, X_{228} because b_σ and P_{-1} are correlated
- Using $<F>$ to fix γ_{912}, then σ_8 and X_{228} *degenerate*

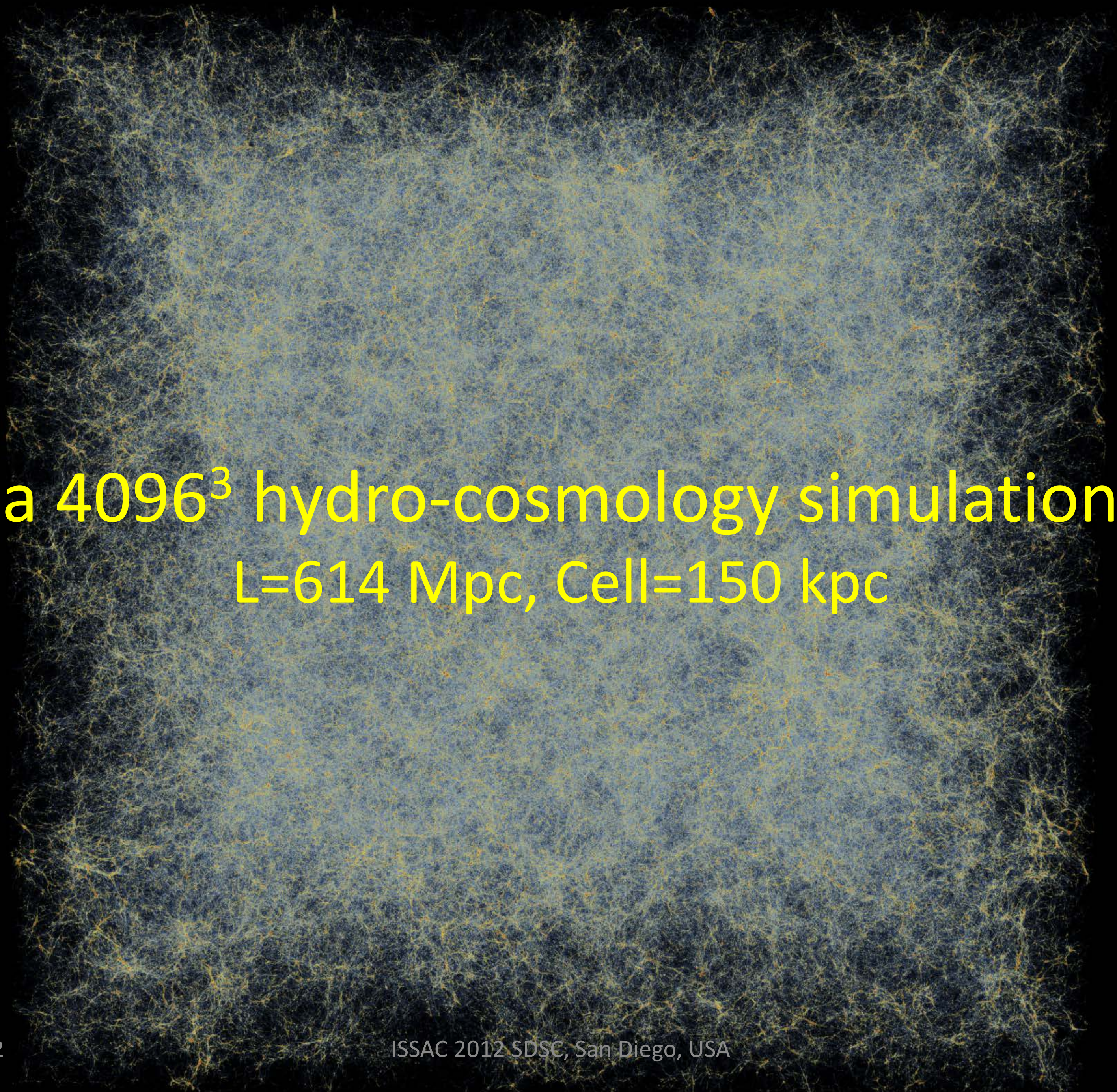




Jena et al. (2005)

Findings (cont'd)

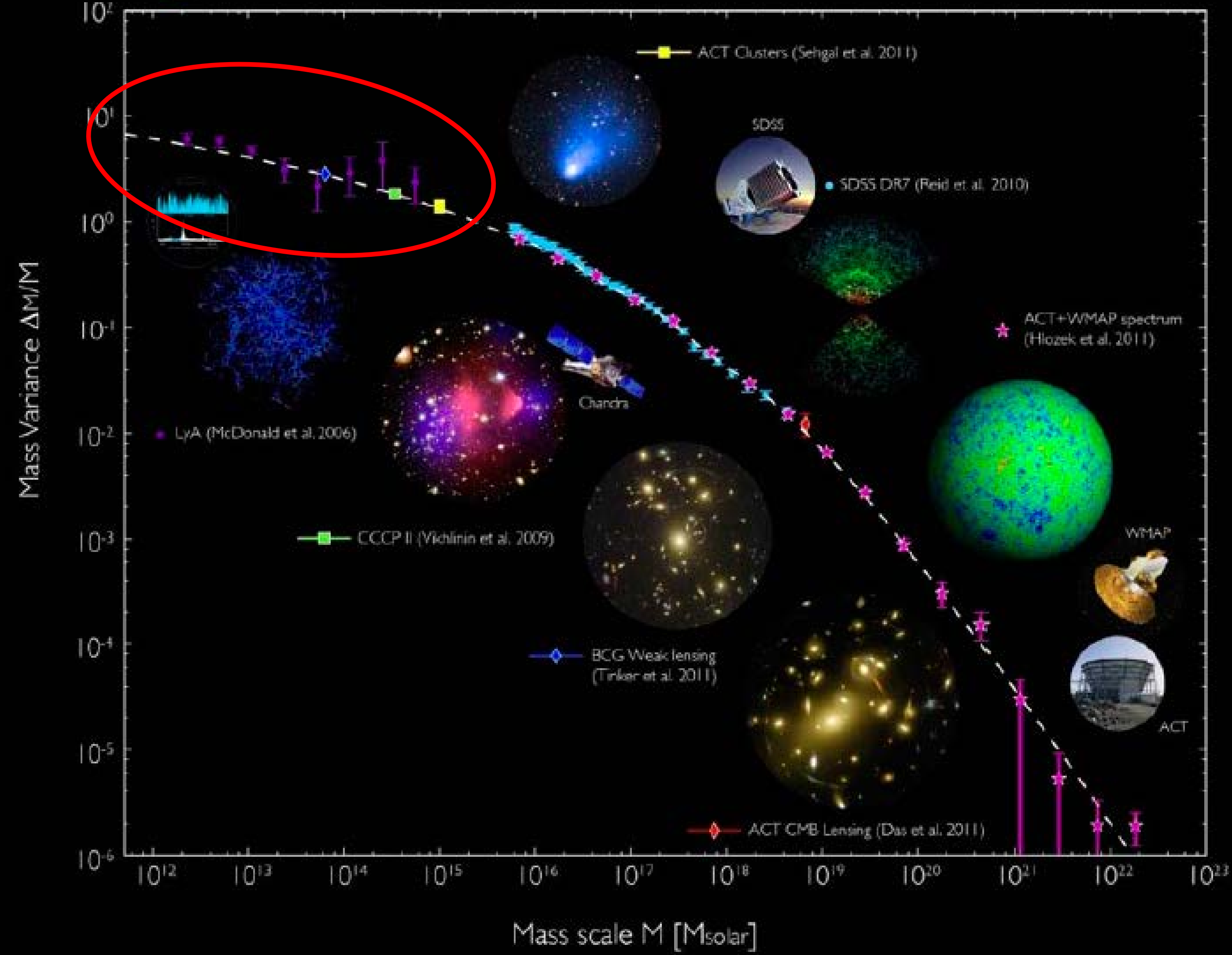
- Can potentially remove degeneracy using large scale flux power P_{-2}
- This was not explored in Jena+(2005)
  - box sizes too small
  - observational uncertainties at low k
- Based on scalings, need at least 100 Mpc boxes and at least 50 kpc resolution➔ 2000^3 but preferably 25 kpc➔ 4000^3
- Comparable to largest N-body simulations, but without the need to resolve halo substructure
  - Eulerian simulations on uniform grids are adequate



a 4096^3 hydro-cosmology simulation

L=614 Mpc, Cell=150 kpc

Distribution of Matter
Also Agrees with Double Dark Theory!



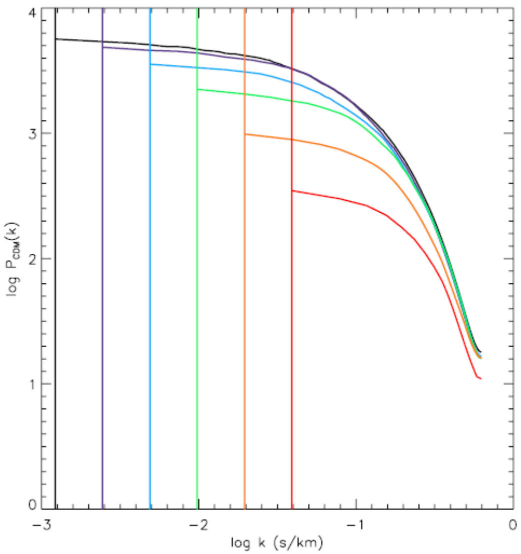
Estimating P(k) from SDSS Quasars
McDonald et al. (2005)

- Key ansatz: $P_F(k,z) = b^2(k) P_M(k,z)$
- Where bias *b(k)* is determined from hydro simulations (Croft et al. 1998, 2002)
- Difficulty with SDSS spectra is that lines are not resolved, and therefore $P_F(k)$ needs to be corrected for many systematics errors
  - Continuum level
  - Metal line contamination
  - High column density absorbers
  - Noise
  - UVB fluctuations
- In practice, *b(k)* is estimated on large scales from non-hydrodynamic simulations of the LAF that model the absorption phenomenologically
- UPSHOT: lots of systematic uncertainties

Observations vs. Simulations II.

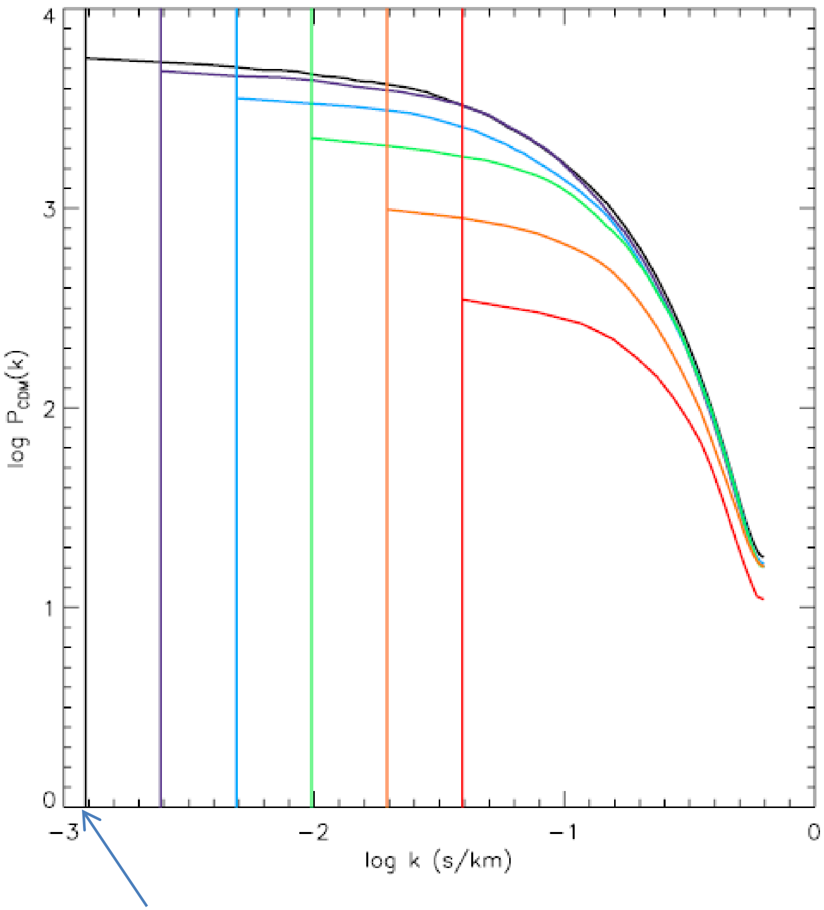
Tytler et al. (2009)

- Revisit Jena et al. (2005) suite of simulations with more analysis on the effect of box size on LAF observables, incl. $P_F(k)$
- All parameters except L kept constant (incl. resolution)
- Bigger box means:
  - More total power
  - Higher peak densities
  - Higher peculiar velocities
  - Hotter gas



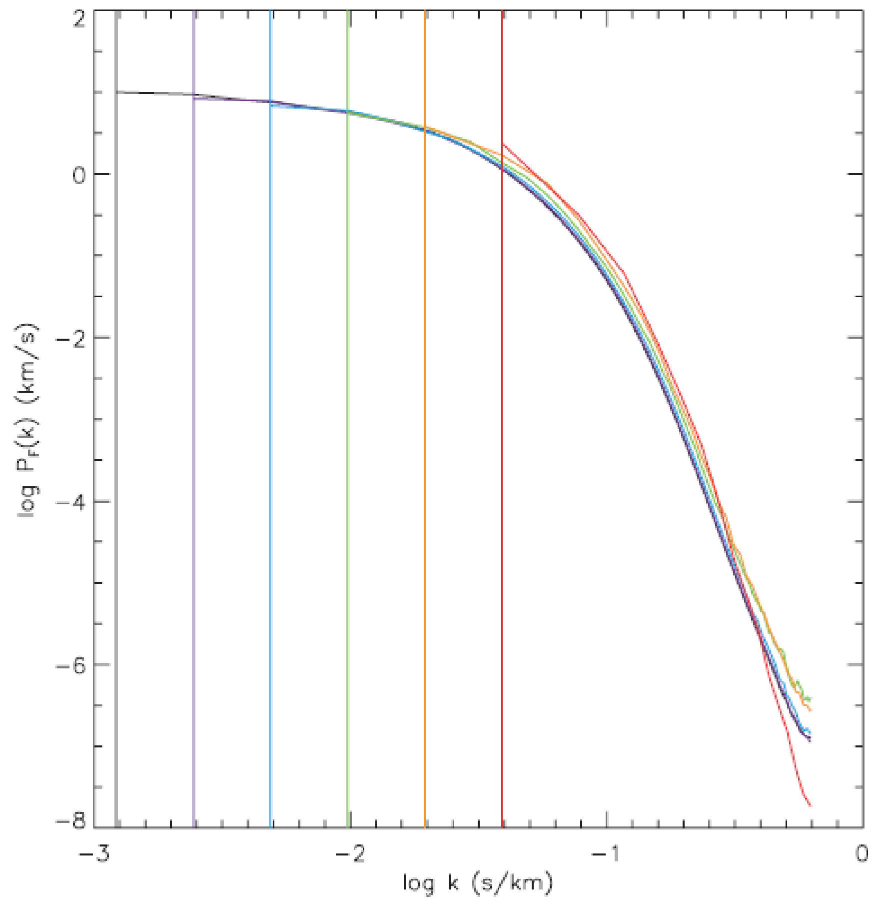
Effect of Box Size

IN: 1D Matter Power



76.8 Mpc

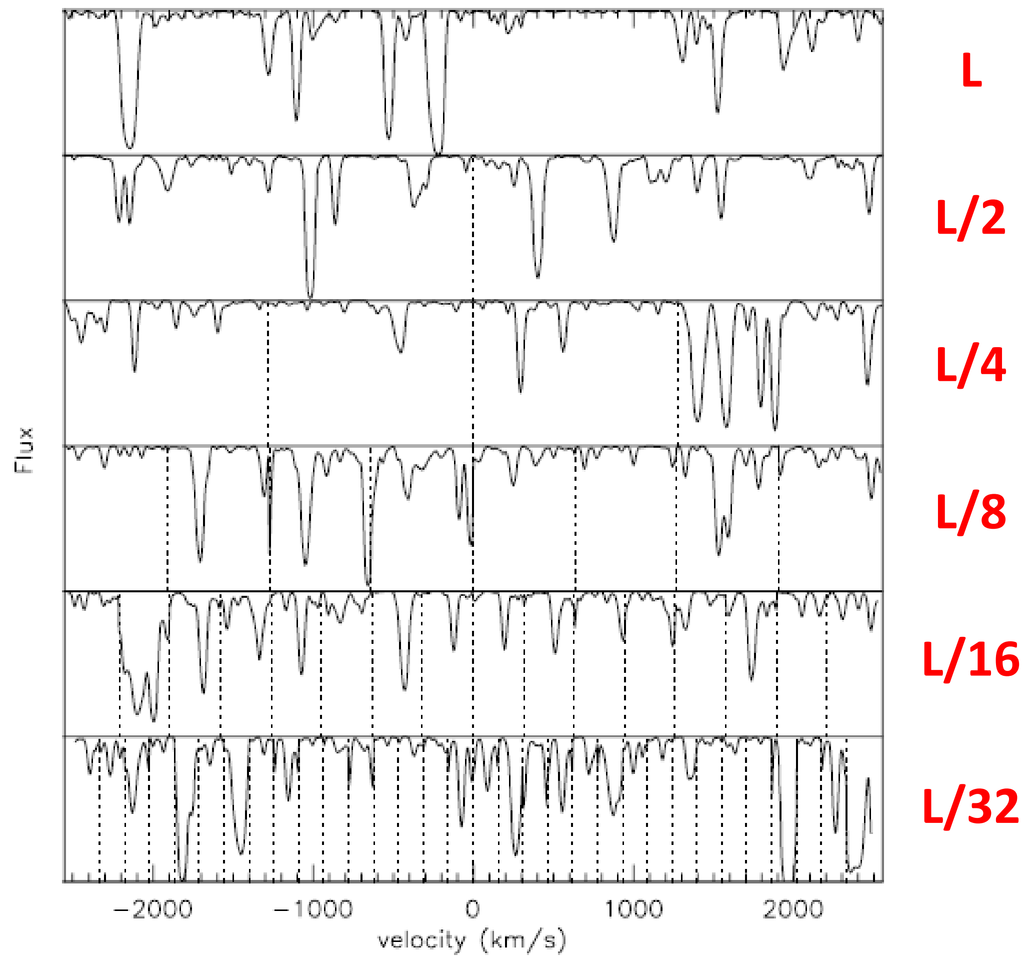
OUT: 1D Flux Power



Tytler et al. (2009)

Effect of Box Size

- Simulated spectra are visibly different for given path length
- As L increases:
  - Deeper absorption
  - Longer gaps
  - Wider lines

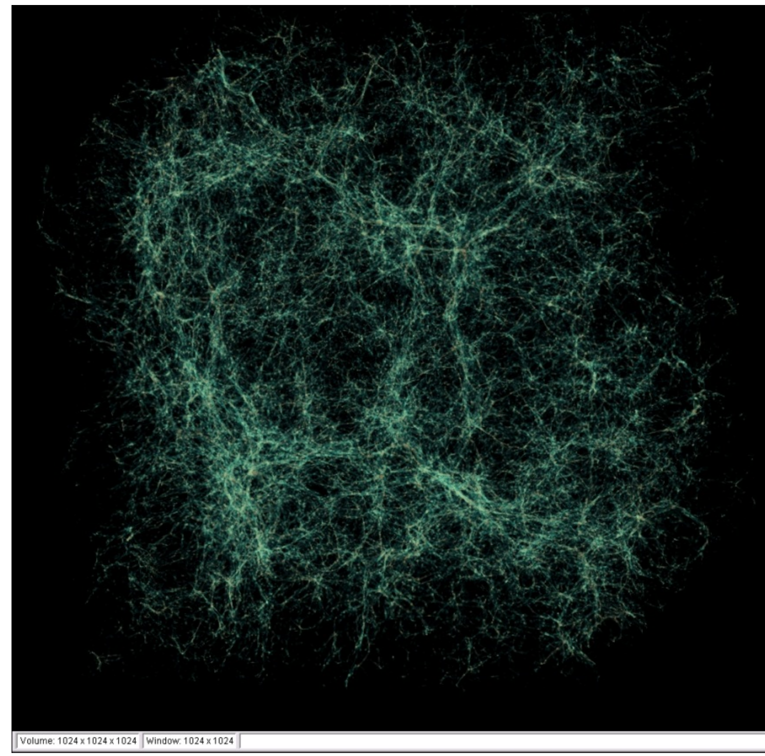


Tytler et al. (2009)

Have we converged?

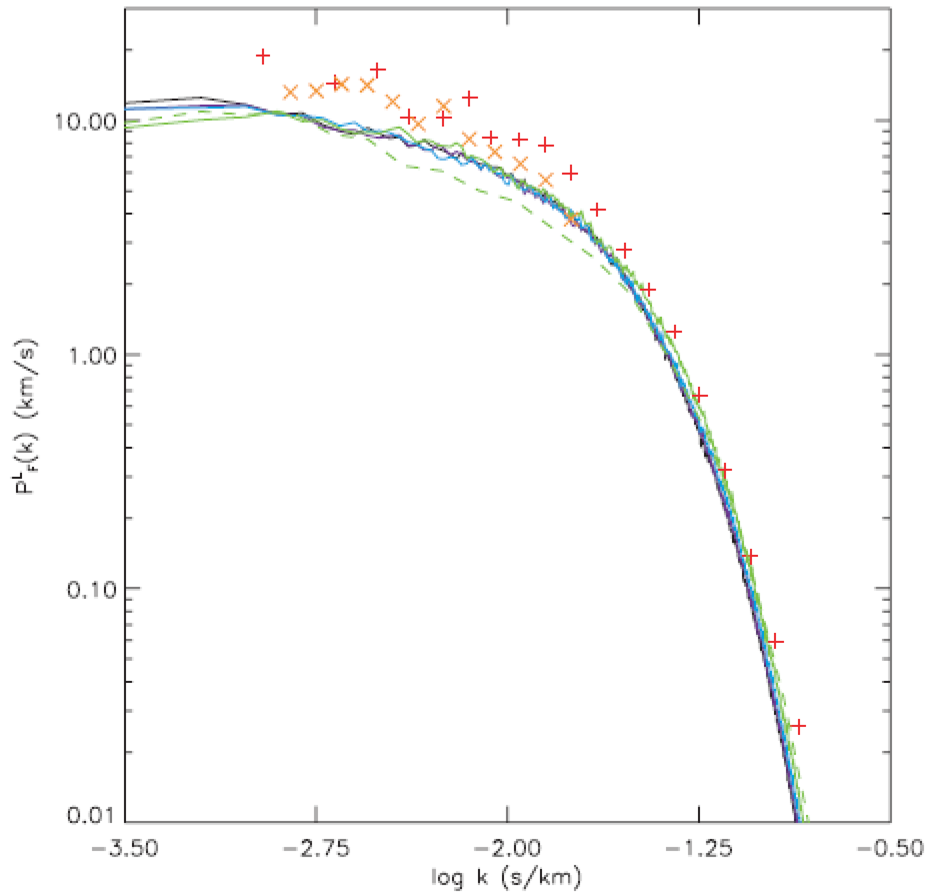
- Largest box has
  - Converged <F>
  - Essentially converged for $P_M(k)$ and $P_F(k)$
  - Approaching convergence for f(b), $f(N_{HI})$

1024^3



Does it agree with observations?

- Mean flux, line widths can be made to agree to 5% for suitable choices of parameters
- Flux power underestimated on large scales by 50-100%

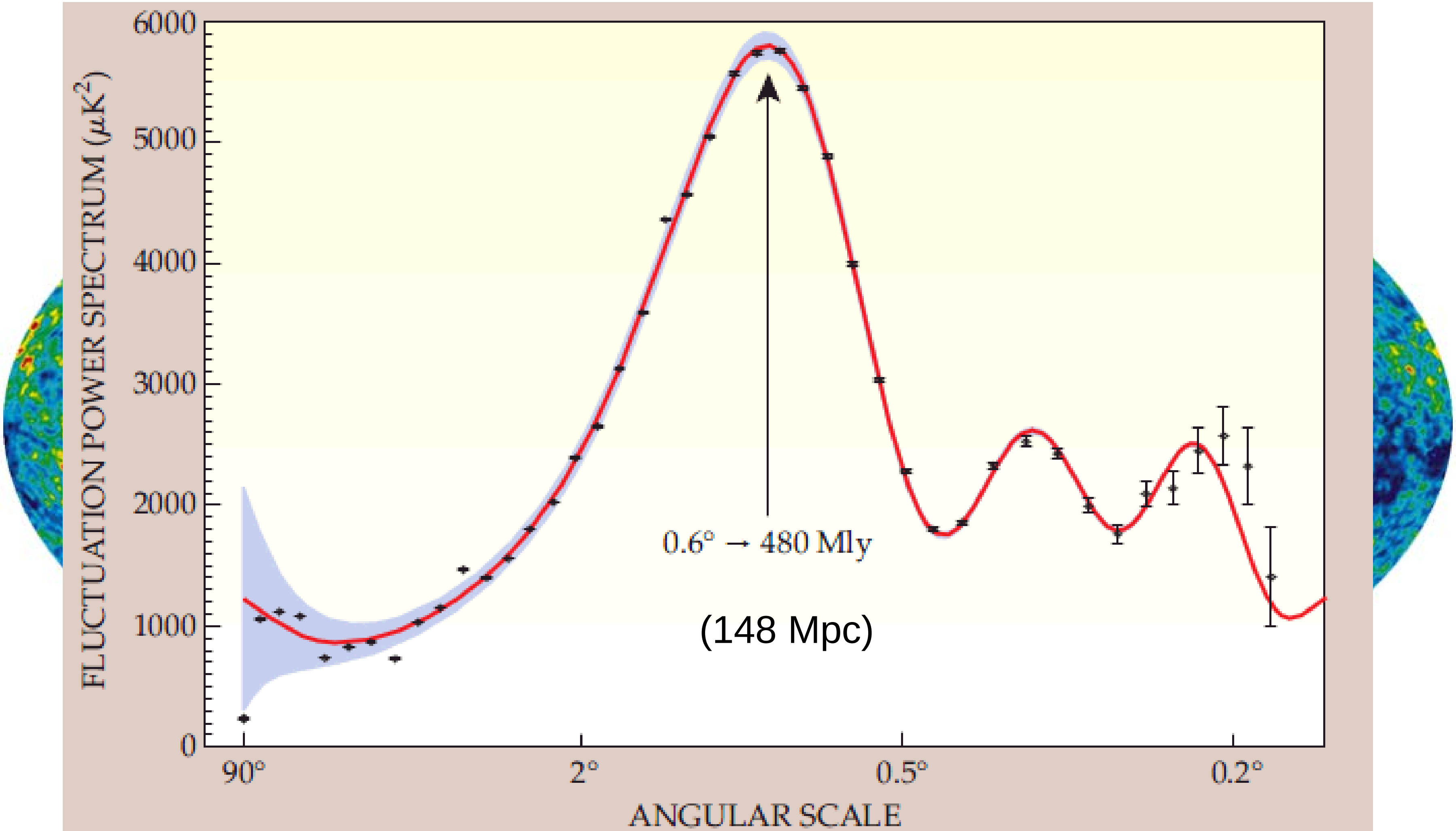


Baryon acoustic oscillations in the Lyman alpha forest
or
What can intergalactic gas tell us about dark energy?

Michael L. Norman
Pascal Paschos
Robert Harkness
SDSC and UCSD

Standard rulers to measure dark energy

Baryon Acoustic Oscillations (BAO) in the Cosmic Microwave Background



BAO: Origin of Standard Ruler

Overdense perturbations launch a spherical acoustic wave in the photon-baryon fluid which moves at speed c/sqrt(3) in a frame comoving with the expanding universe

$$D = \frac{c}{\sqrt{3}} t_{rec}$$

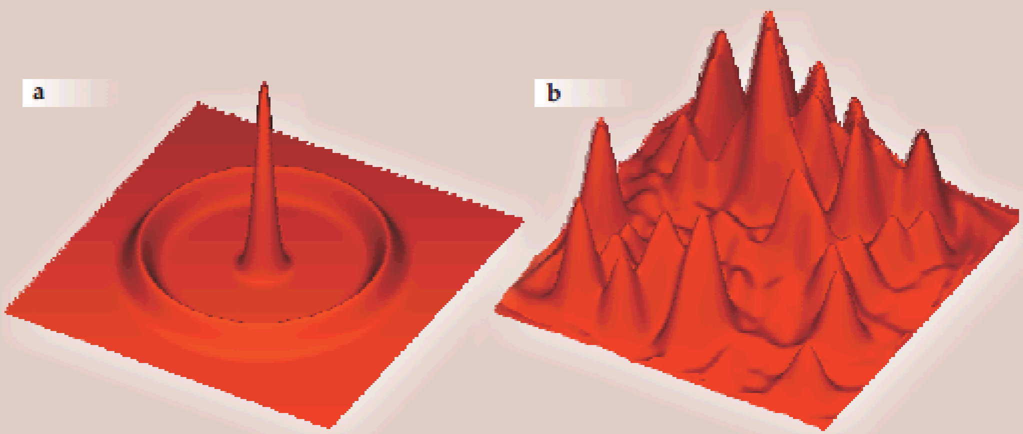
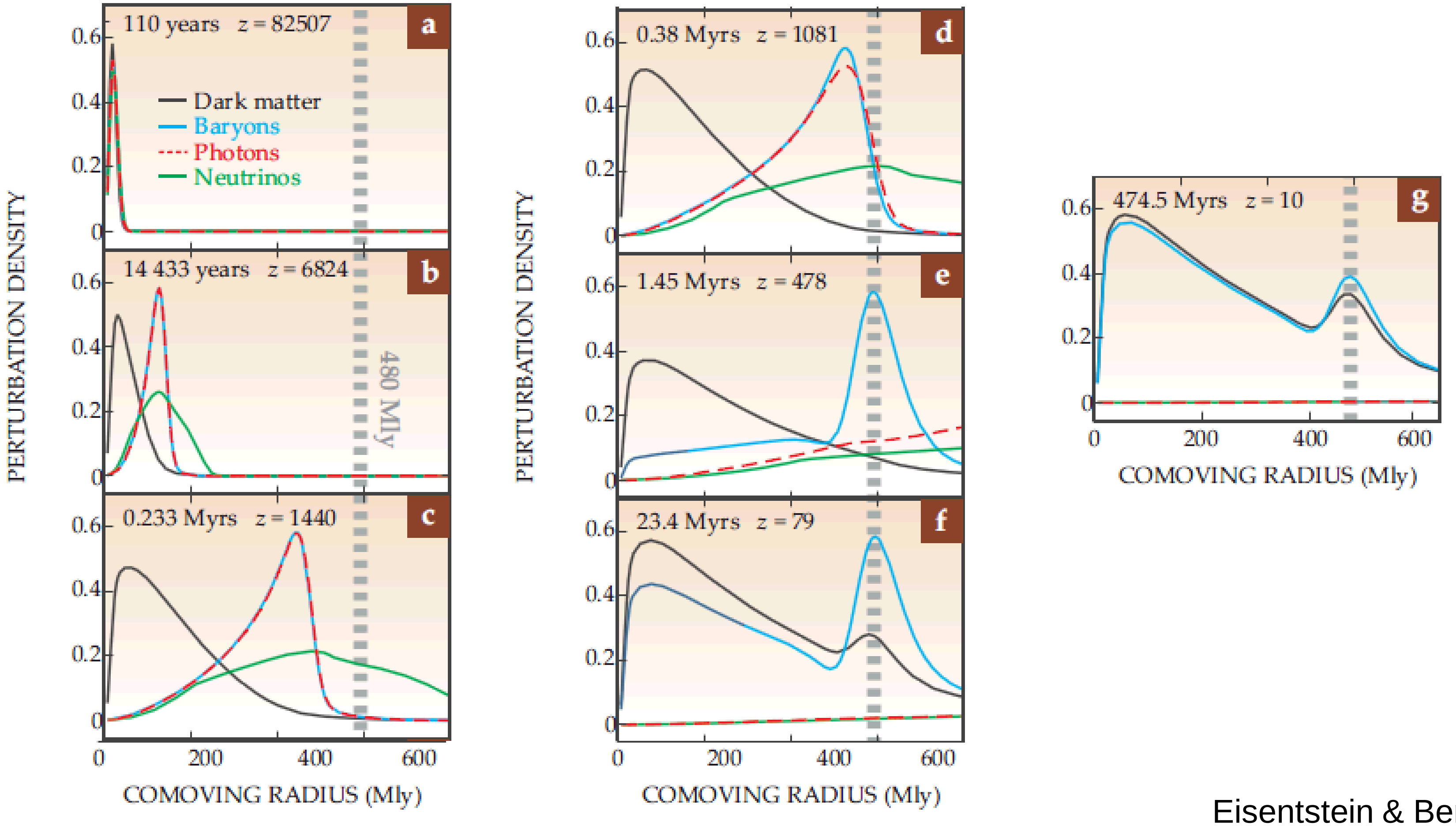


Figure 3. Sound waves propagating in the plasma epoch. **(a)** A spherical sound wave from a small overdense region at the start of the plasma epoch spreads until baryonic matter decouples from radiation 380 000 years later, when the plasma has cooled enough for neutral hydrogen to survive. The radius of the acoustic shell (seen here as a ring) provides cosmologists a characteristic length scale—essentially the sound speed times the duration of the plasma epoch. **(b)** The later universe evolved from a hodgepodge superposition of such spherical sound waves, but the characteristic size can still be extracted from statistical correlations in the large-scale distribution of galaxies.

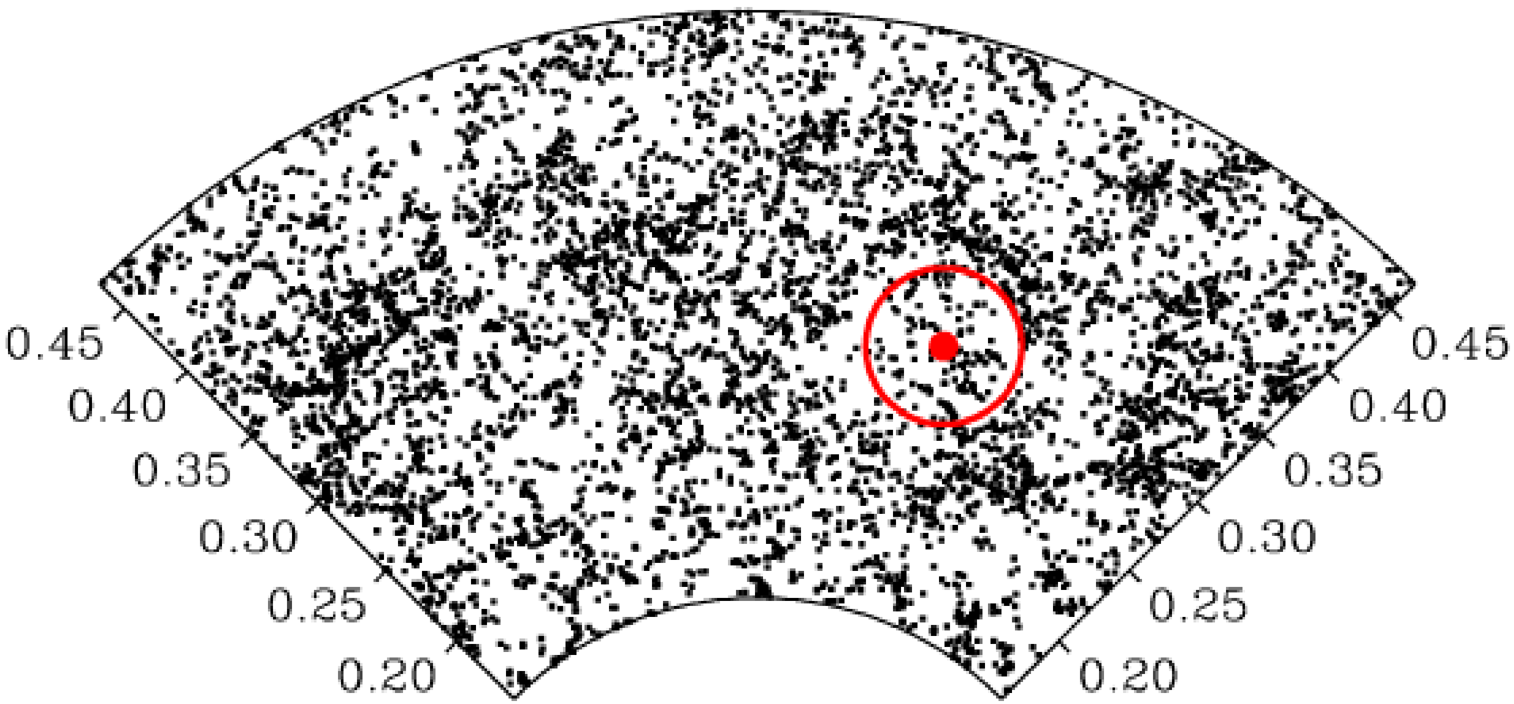
Eisentstein & Bennett
Physics Today 2008

Evolution of Point Perturbation



Eisentstein & Bennett
Physics Today 2008

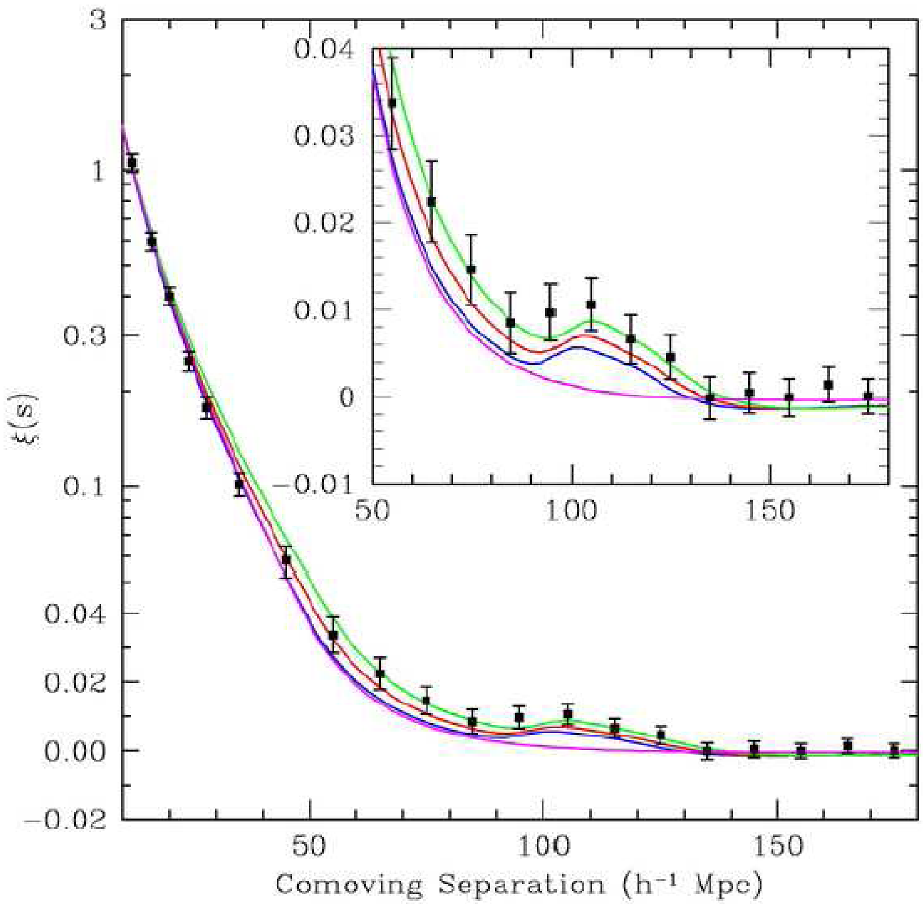
BAO in Galaxy LSS



A map of luminous red galaxies, as seen by the SDSS. The large red circle shows the characteristic scale of baryon acoustic oscillations.

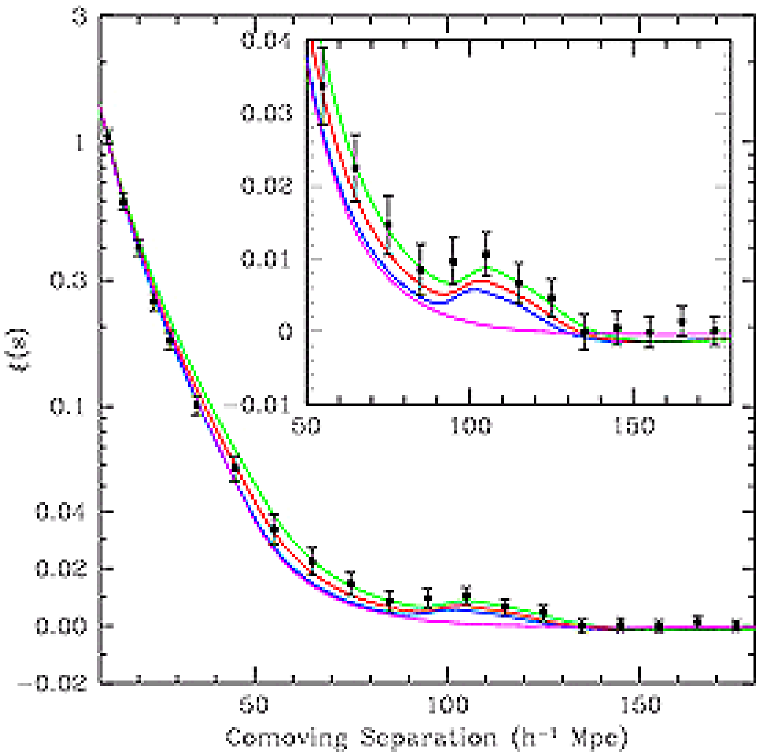
Detection of BAO in SDSS luminous red galaxy LSS (Eisenstein et al. 2005)

Galaxy 2–pt
correlation
function



Existence proof of BAO technique

Baryon Oscillation Spectroscopic Survey (BOSS)



BOSS at a glance

- Dark time observations
- Fall 2009 - Spring 2014
- 1,000-fiber spectrograph, resolutic R~2000
- wavelengths 360-1000 nm
- 10,000 square degrees
- Redshifts of 1.5 million luminous galaxies to z = 0.7
- Lyman-α forest spectra of 160,000 quasars at redshifts 2.2 < z < 3

BAO in the Ly α Forest

- Not yet detected
- BAO method more powerful at higher redshift where survey volumes are larger
- BAO modes are long wavelength (150 Mpc) and in the linear part of the CDM spectrum
- Ly α absorption arises near mean density of the IGM and should show BAO modulation with minimal redshift space distortion
- Large numbers of absorbers per LOS, and large number of quasars makes for a very large statistical sample

Simulating BAO in the Lyman Alpha Forest

Technical Difficulty: Range of Scales

- Wavelength of BAO is 150 Mpc
  - Need a box at least 4 x this to contain enough modes
- Absorption filaments are 100 Kpc thick
- N_{cell}=4 x 150,000 Kpc/100 Kpc = 6000
- Need 3D grid of size 6000^3
  - 216 BILLION CELLS
  - 216 BILLION DARK MATTER PARTICLES

Simulation Campaign

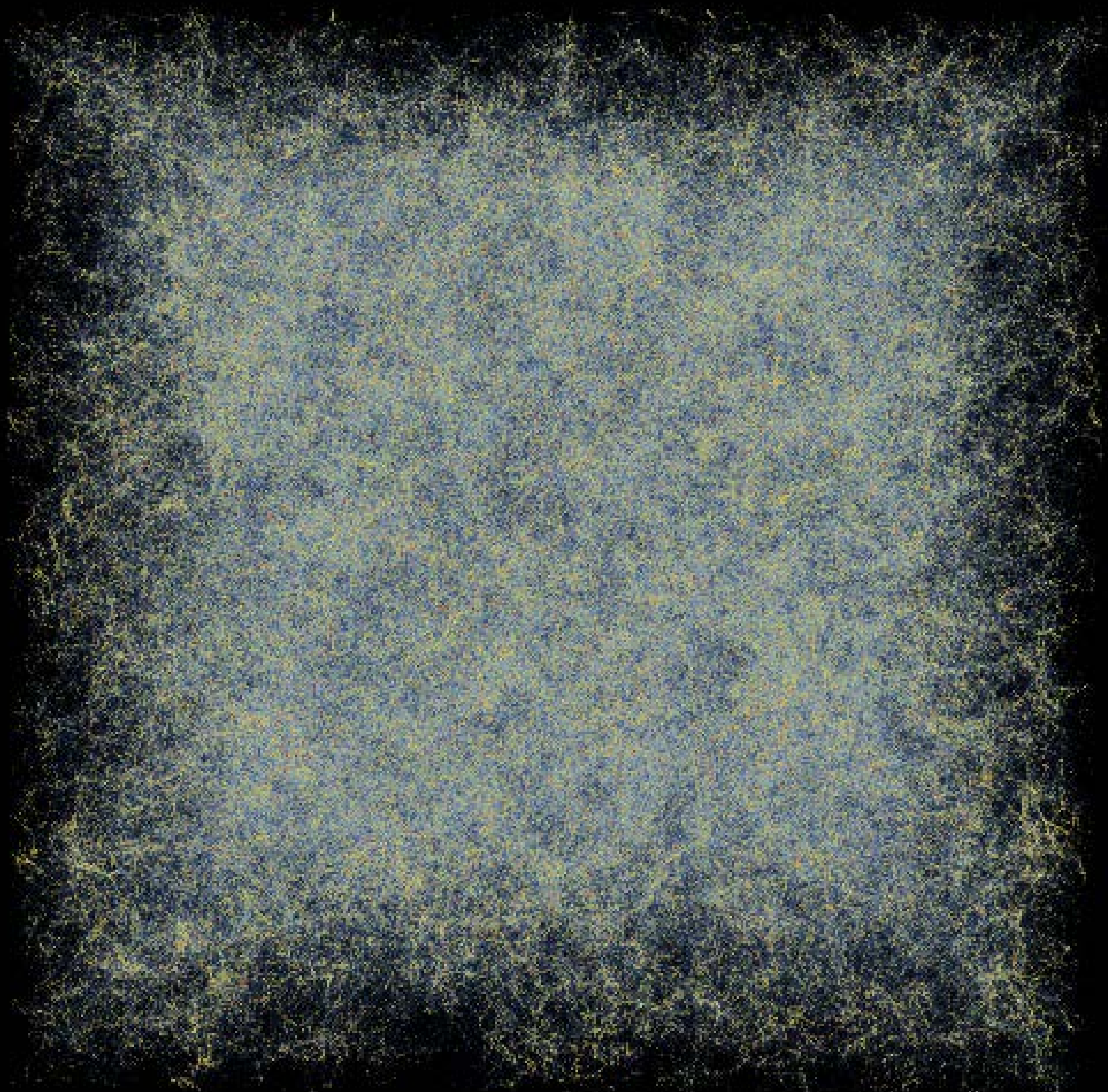
Grid	Box size (Mpc)	Cell size (kpc)	ICs
1024^3	614	600	WMAP5 no BAO
2048^3	307, 614	150, 300	WMAP3 WMAP5
4096^3	614	150	WMAP5

ENZO
Hydrodynamic
Cosmology
code

4096^3 =
68.7 billion cells
and particles

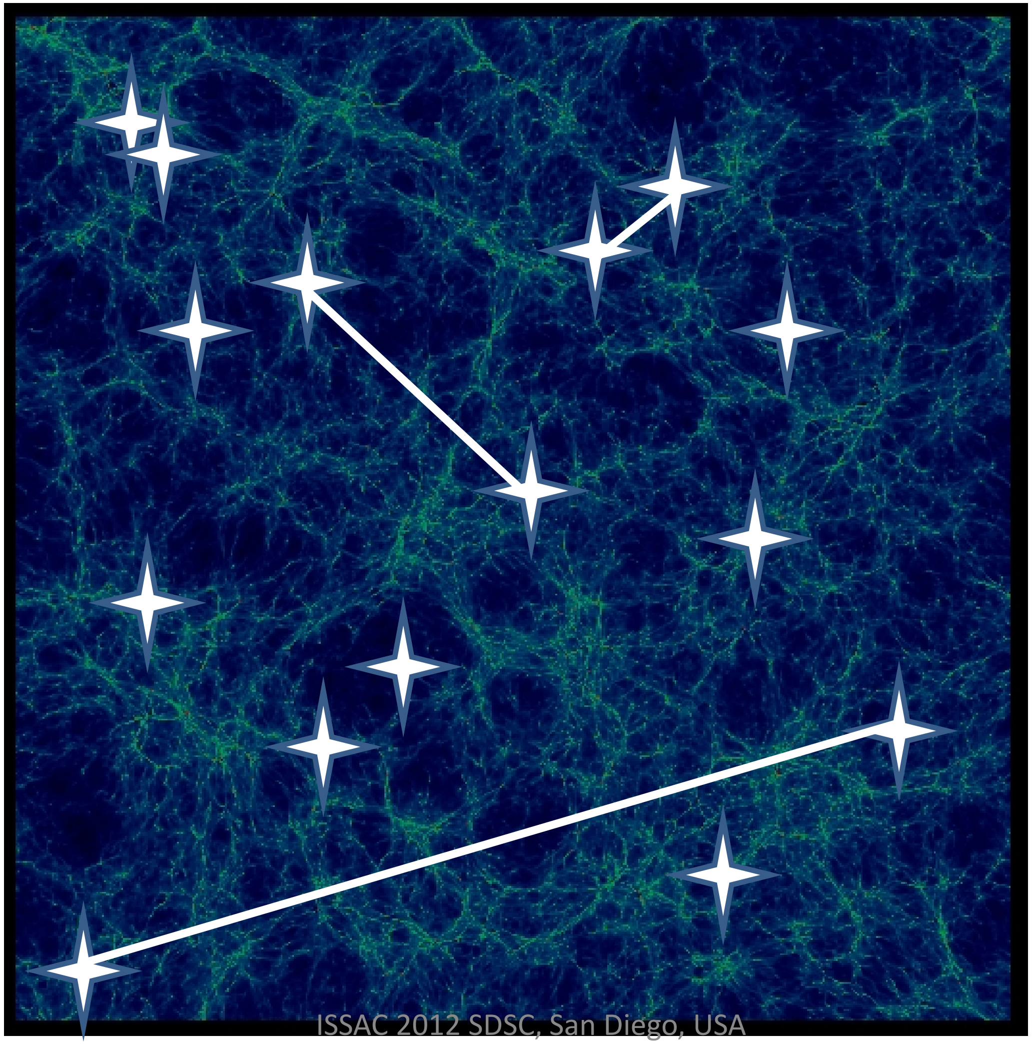
16,384 processors

2 million CPU-hrs
NICS Kraken

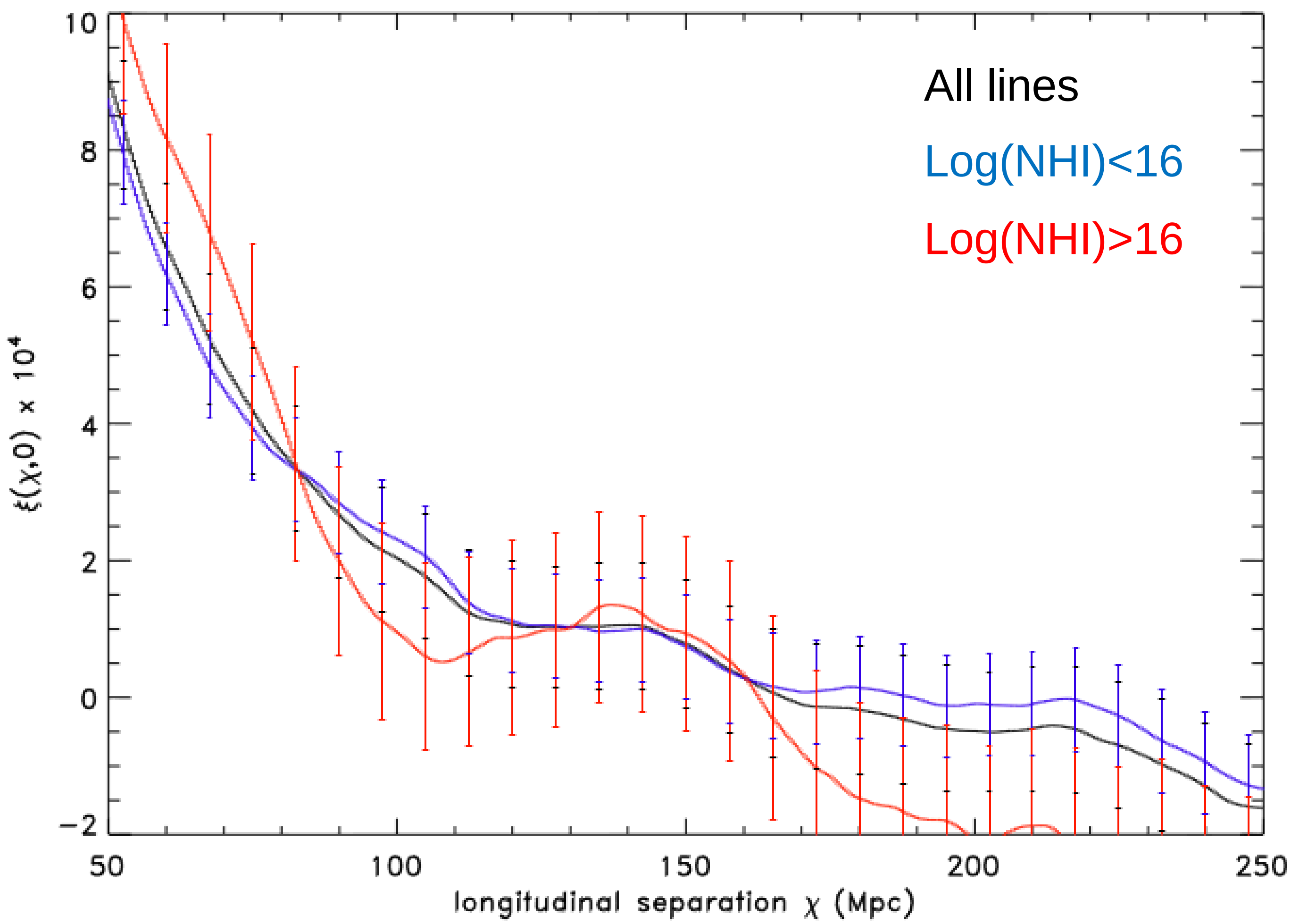


614 Mpc

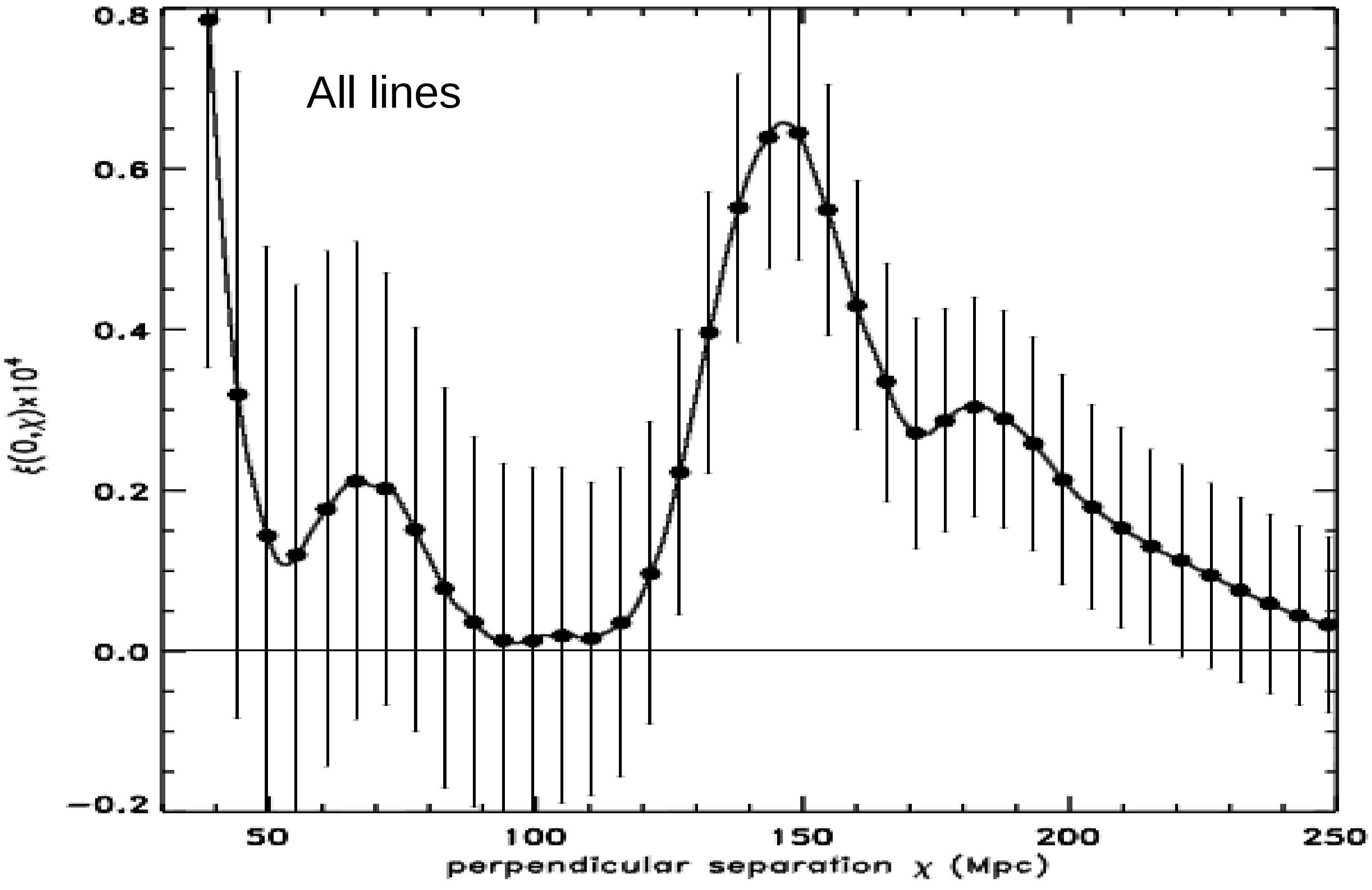
Correlation Analysis:
5,000 random lines-of-sight
~12.5 million pairs



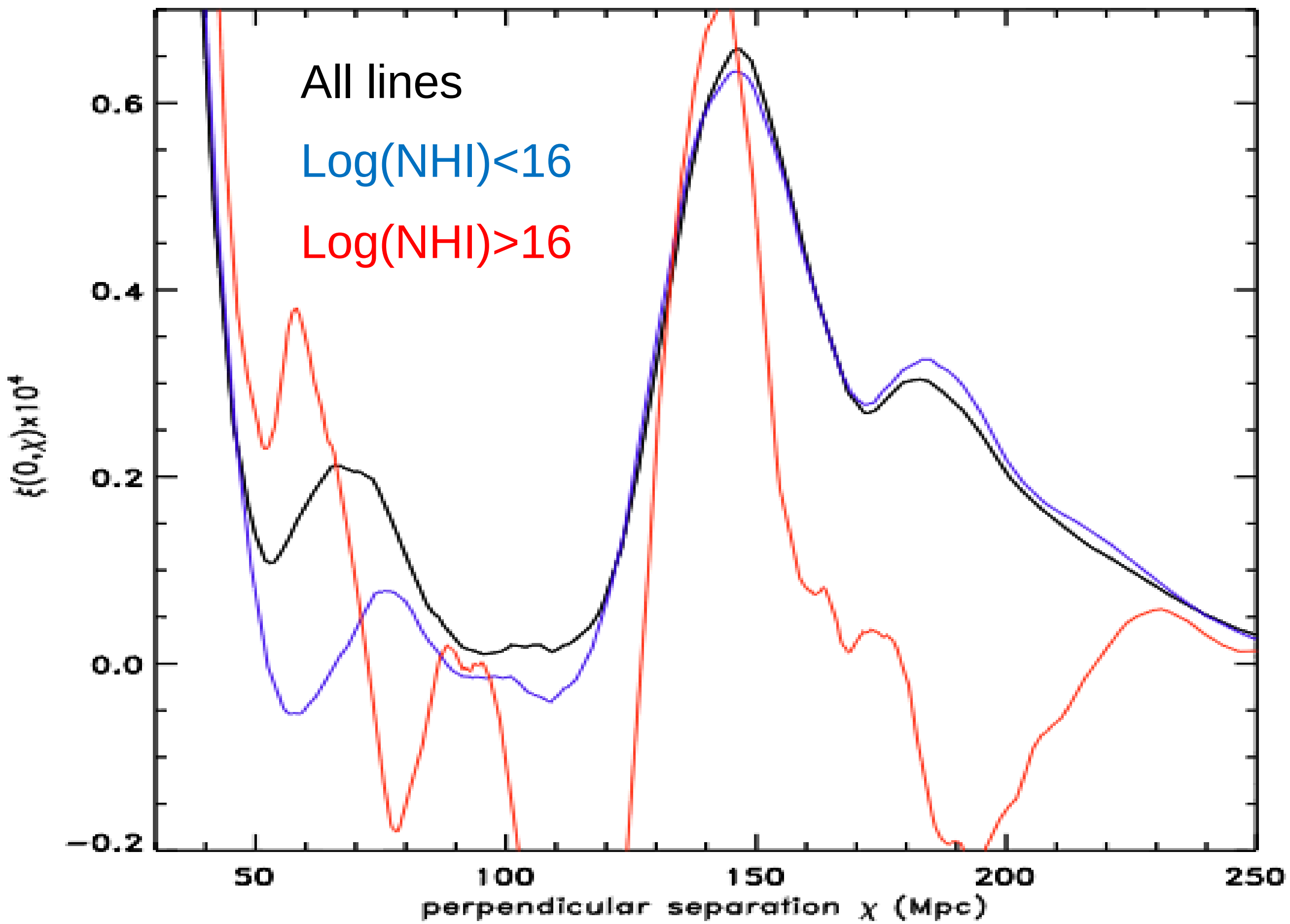
Flux autocorrelation 2048^3



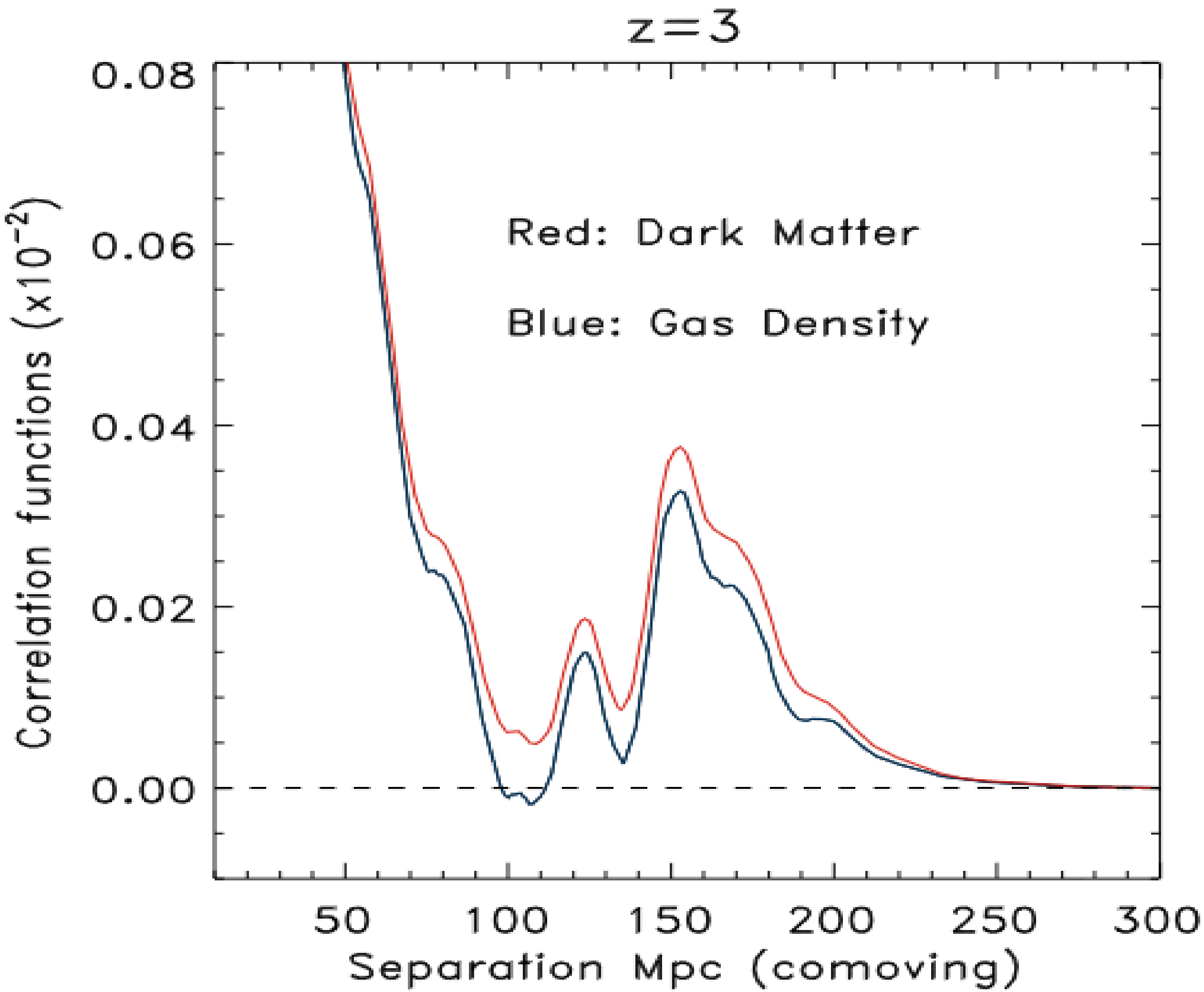
Flux cross-correlation 2048^3



Flux cross-correlation 2048^3



Cross-correlation of matter properties along LOS



Findings and Implications

- Detecting the BAO in the Lyman alpha forest is feasible
- based on synthetic observations of fully hydrodynamic simulations
  - Signal is statistically significant in flux cross-correlation but not in the auto-correlation
  - Higher column density systems show signal better, but are rarer and hence have higher statistical error
  - Signal more sensitive to spectroscopic resolution than numerical resolution of simulation

Future Simulation Work

- Need to understand why auto-correlation signal is so weak (signal should be there!)
  - Redshift space distortion?
  - Masking by high column systems?
- Need to investigate reality of satellite peaks in cross-correlation
- Quantify effects of
  - spatial resolution (4096^3)
  - redshift evolution
  - a variety of astrophysical effects