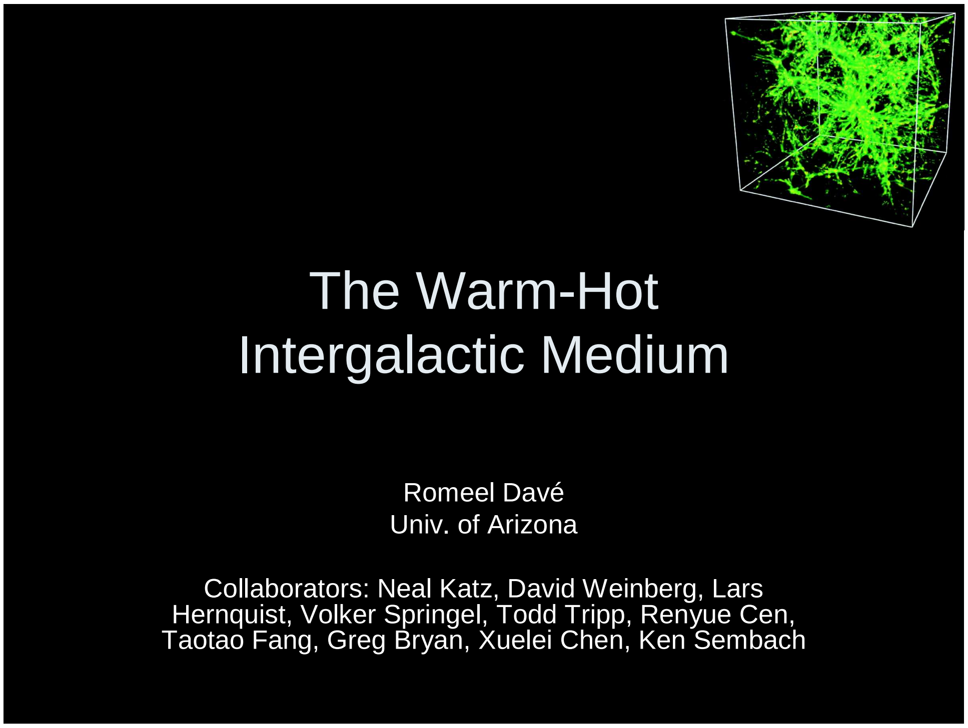

The Warm-Hot Intergalactic Medium

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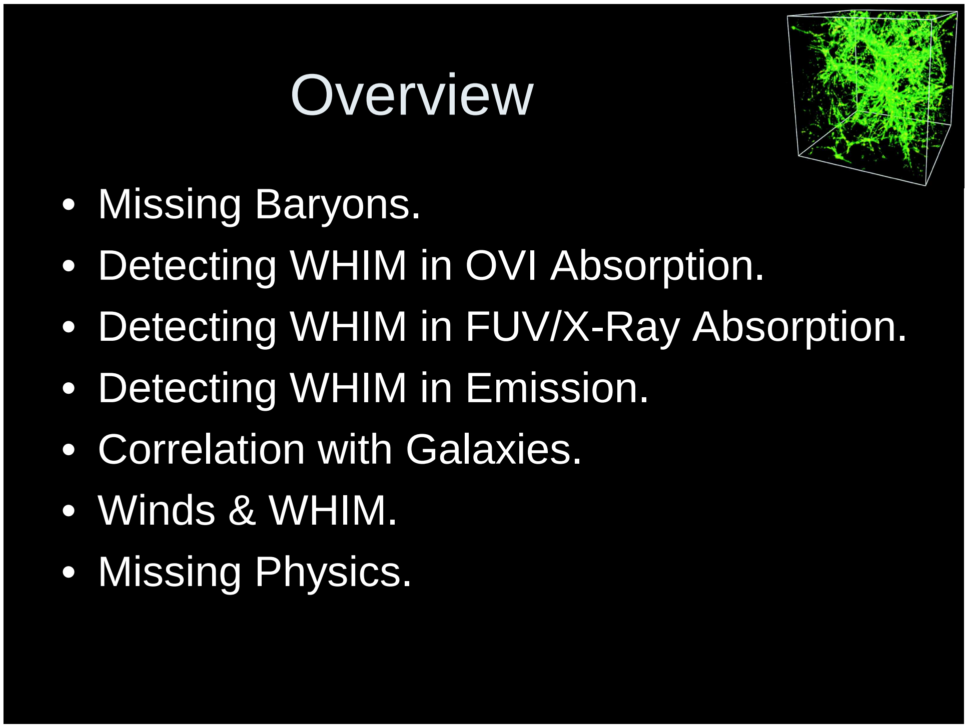
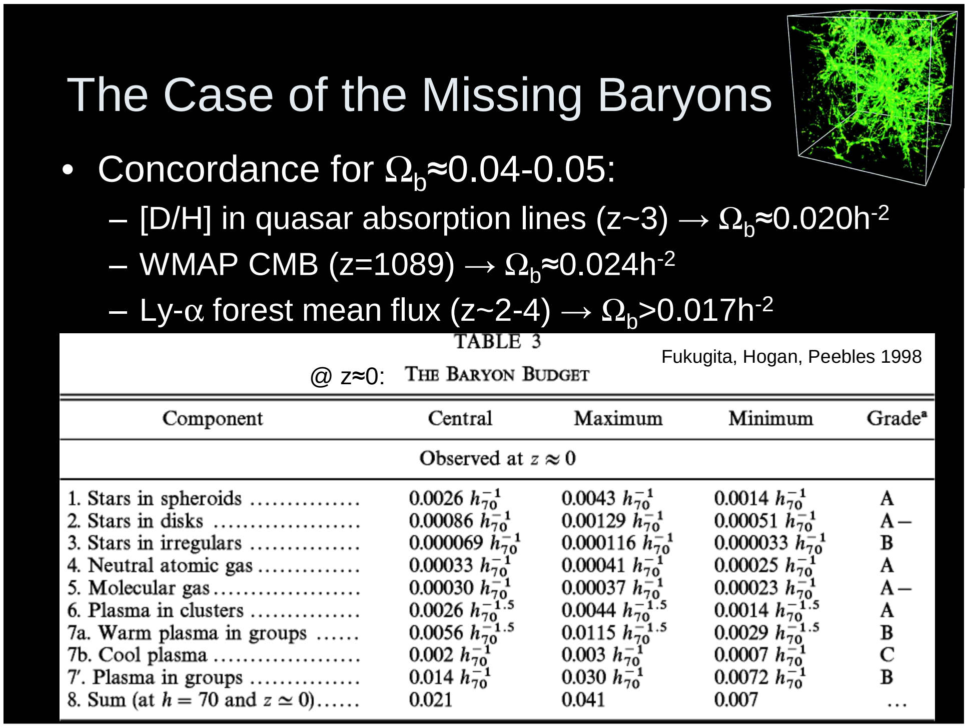


Overview

- Missing Baryons.
- Detecting WHIM in OVI Absorption.
- Detecting WHIM in FUV/X-Ray Absorption.
- Detecting WHIM in Emission.
- Correlation with Galaxies.
- Winds & WHIM.
- Missing Physics.



The Case of the Missing Baryons

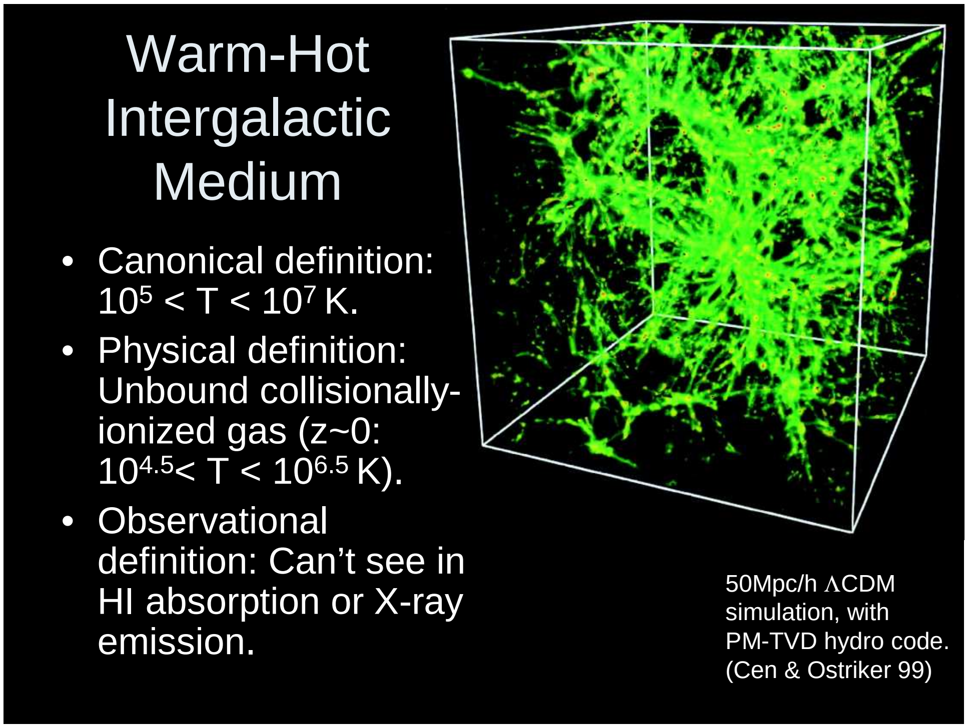
- Concordance for $\Omega_b \approx 0.04-0.05$:
  - [D/H] in quasar absorption lines (z~3) → $\Omega_b \approx 0.020h^{-2}$
  - WMAP CMB (z=1089) → $\Omega_b \approx 0.024h^{-2}$
  - Ly-α forest mean flux (z~2-4) → $\Omega_b > 0.017h^{-2}$

TABLE 3

@ $z \approx 0$: THE BARYON BUDGET

Fukugita, Hogan, Peebles 1998

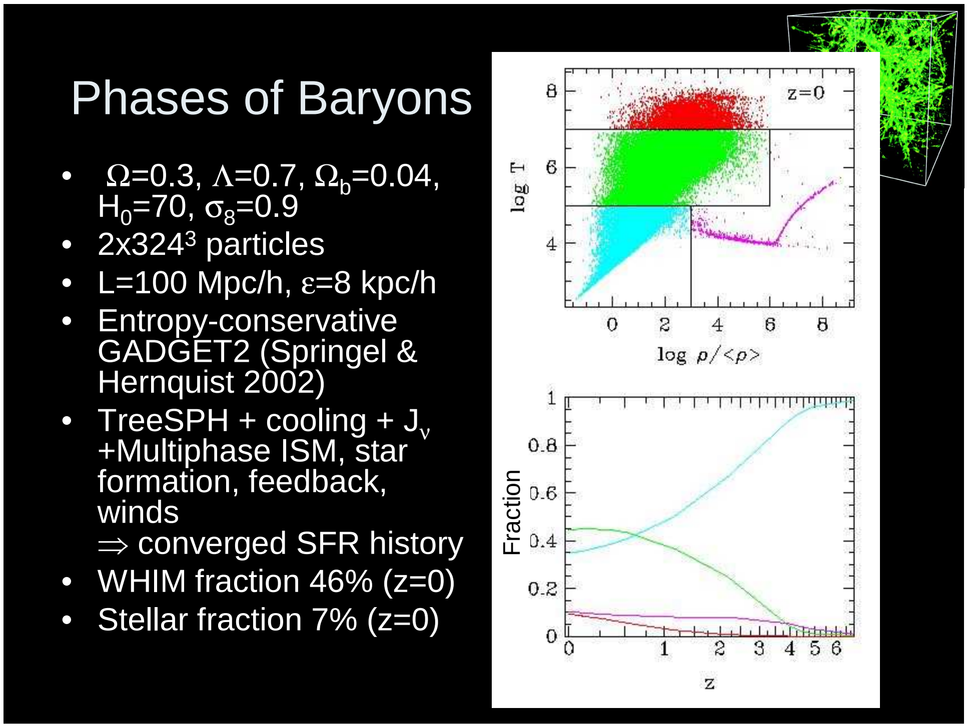
Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A−
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A−
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)......	0.021	0.041	0.007	...



Warm-Hot Intergalactic Medium

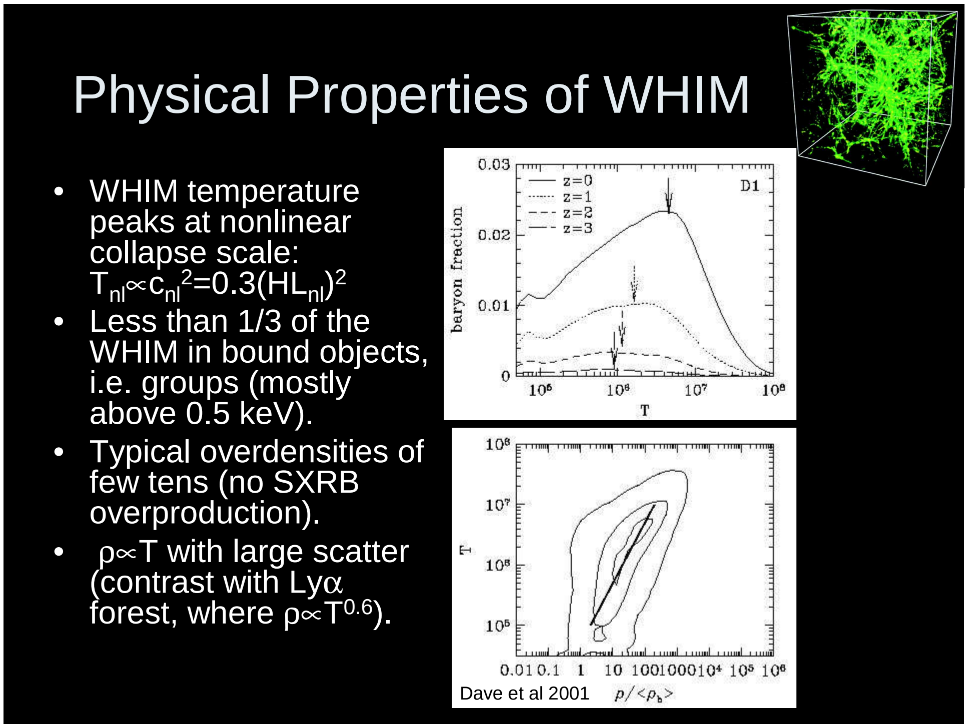
- Canonical definition: $10^5 < T < 10^7$ K.
- Physical definition: Unbound collisionally-ionized gas (z~0: $10^{4.5} < T < 10^{6.5}$ K).
- Observational definition: Can't see in HI absorption or X-ray emission.

50Mpc/h ΛCDM simulation, with PM-TVD hydro code. (Cen & Ostriker 99)



Phases of Baryons

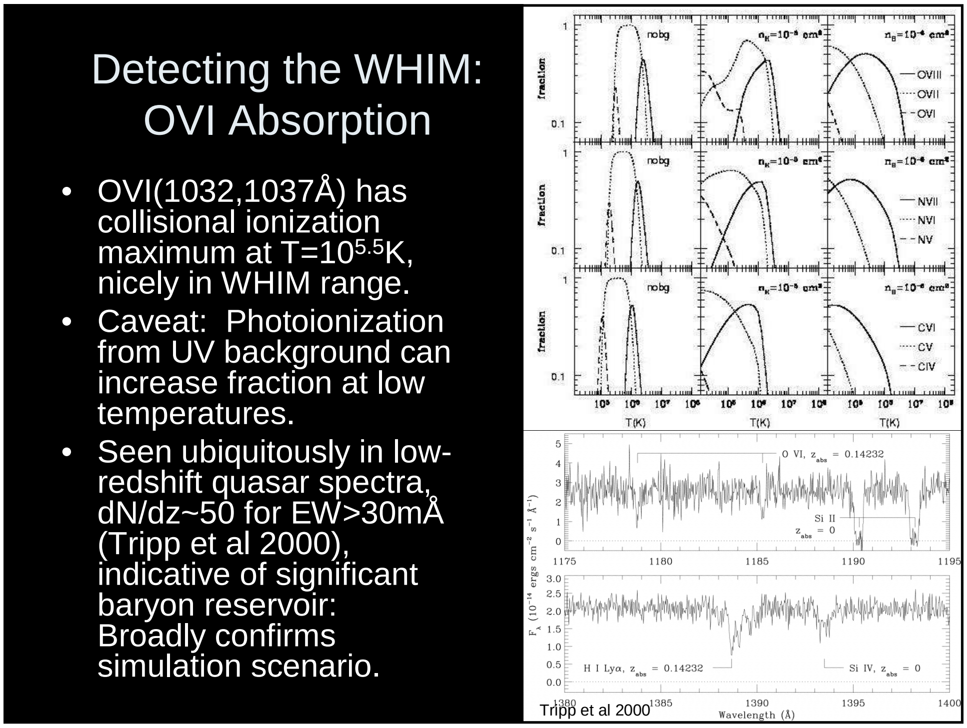
- $\Omega=0.3$, $\Lambda=0.7$, $\Omega_b=0.04$, $H_0=70$, $\sigma_8=0.9$
- 2×324^3 particles
- L=100 Mpc/h, $\varepsilon=8$ kpc/h
- Entropy-conservative GADGET2 (Springel & Hernquist 2002)
- TreeSPH + cooling + J_ν +Multiphase ISM, star formation, feedback, winds $\Rightarrow$ converged SFR history
- WHIM fraction 46% (z=0)
- Stellar fraction 7% (z=0)



Dave et al 2001

Physical Properties of WHIM

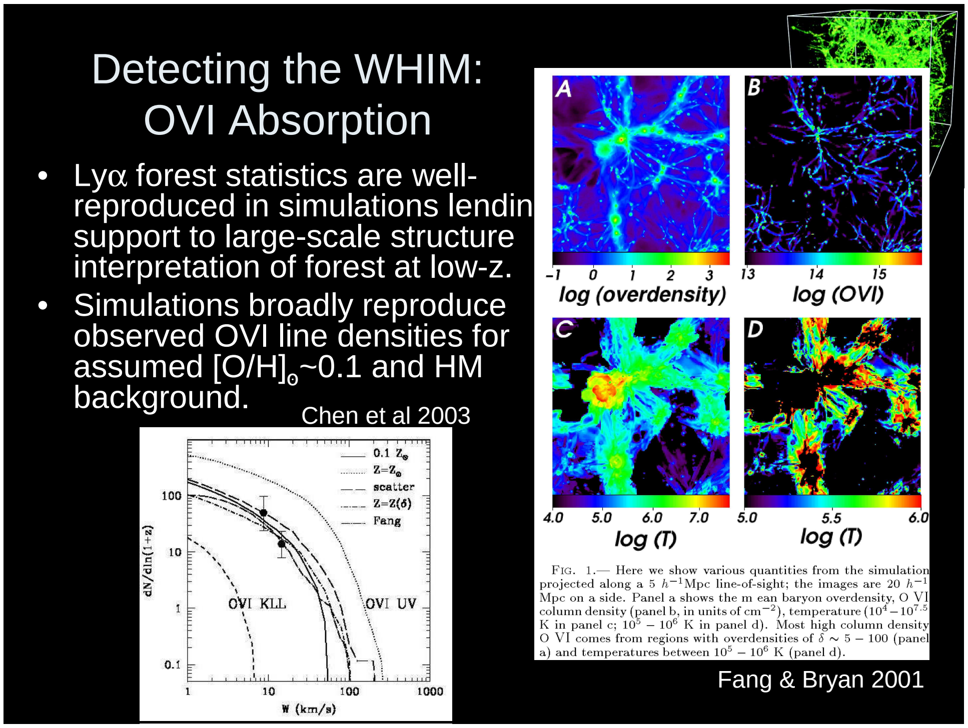
- WHIM temperature peaks at nonlinear collapse scale: $T_{nl} \propto c_{nl}^2 = 0.3(HL_{nl})^2$
- Less than 1/3 of the WHIM in bound objects, i.e. groups (mostly above 0.5 keV).
- Typical overdensities of few tens (no SXRB overproduction).
- $\rho \propto T$ with large scatter (contrast with Lyα forest, where $\rho \propto T^{0.6}$).



Detecting the WHIM: OVI Absorption

- OVI(1032,1037Å) has collisional ionization maximum at T=$10^{5.5}$K, nicely in WHIM range.
- Caveat: Photoionization from UV background can increase fraction at low temperatures.
- Seen ubiquitously in low-redshift quasar spectra, dN/dz~50 for EW>30mÅ (Tripp et al 2000), indicative of significant baryon reservoir: Broadly confirms simulation scenario.

Tripp et al 2000



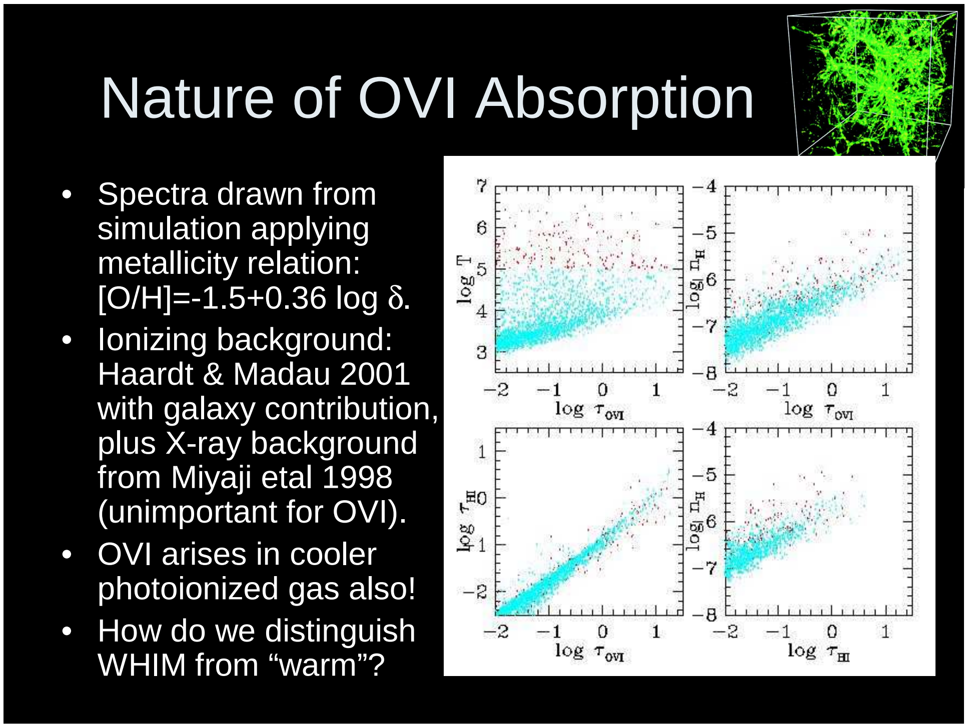
Detecting the WHIM: OVI Absorption

- Lyα forest statistics are well-reproduced in simulations lendin support to large-scale structure interpretation of forest at low-z.
- Simulations broadly reproduce observed OVI line densities for assumed $[O/H]_\odot$~0.1 and HM background.

Chen et al 2003

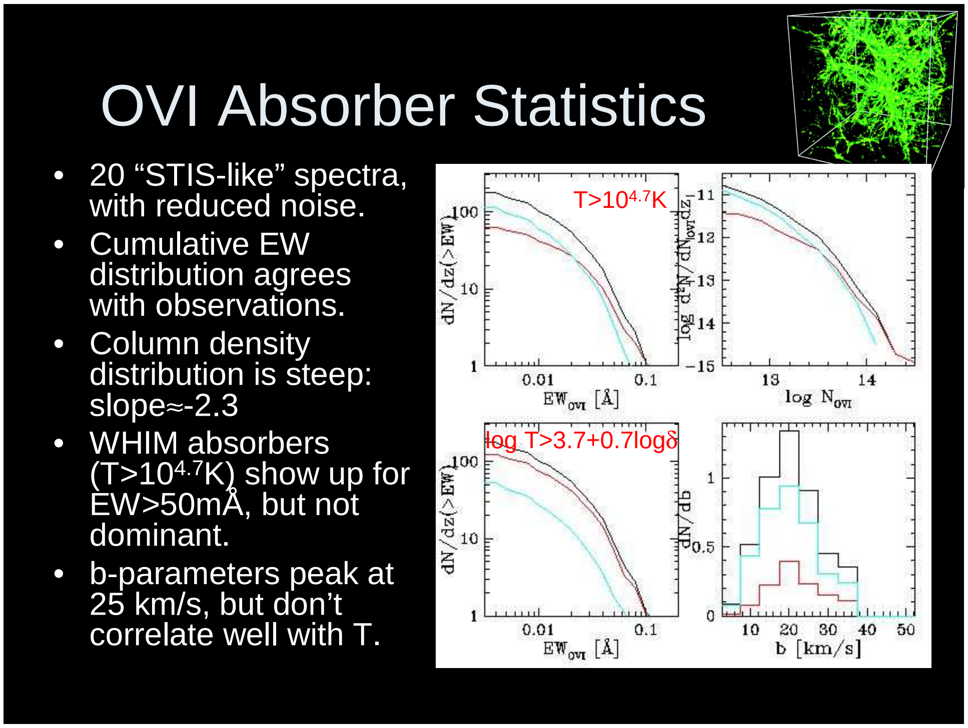
FIG. 1.— Here we show various quantities from the simulation projected along a 5 h^{-1}Mpc line-of-sight; the images are 20 h^{-1} Mpc on a side. Panel a shows the m ean baryon overdensity, O VI column density (panel b, in units of cm^{-2}), temperature ($10^4 - 10^{7.5}$ K in panel c; $10^5 - 10^6$ K in panel d). Most high column density O VI comes from regions with overdensities of $\delta \sim 5 - 100$ (panel a) and temperatures between $10^5 - 10^6$ K (panel d).

Fang & Bryan 2001



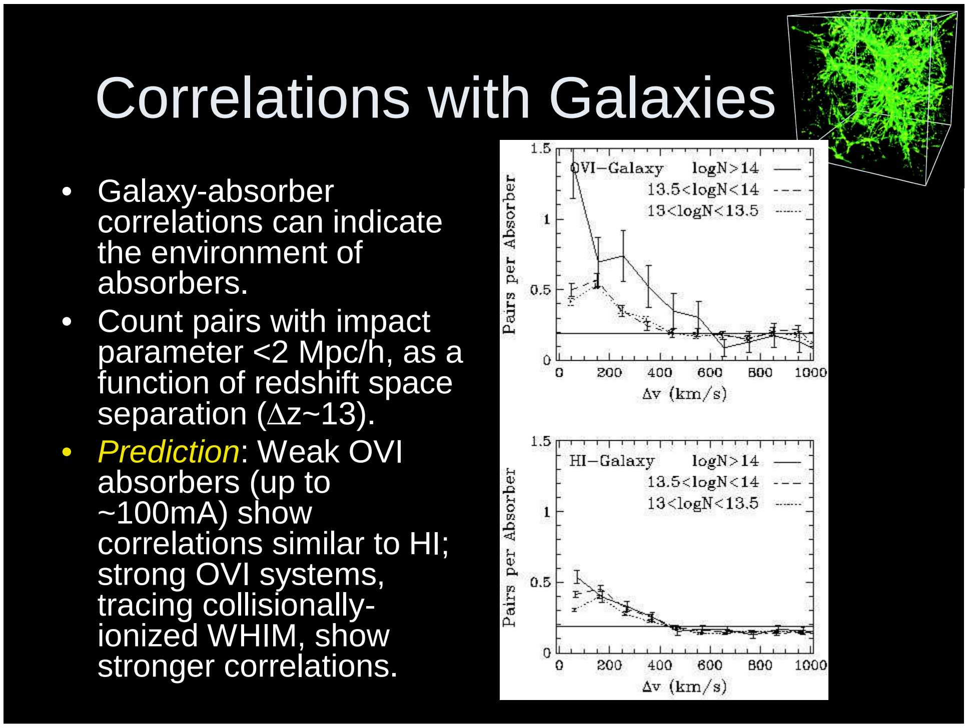
Nature of OVI Absorption

- Spectra drawn from simulation applying metallicity relation: $[O/H]=-1.5+0.36 \log \delta$.
- Ionizing background: Haardt & Madau 2001 with galaxy contribution, plus X-ray background from Miyaji etal 1998 (unimportant for OVI).
- OVI arises in cooler photoionized gas also!
- How do we distinguish WHIM from “warm”?



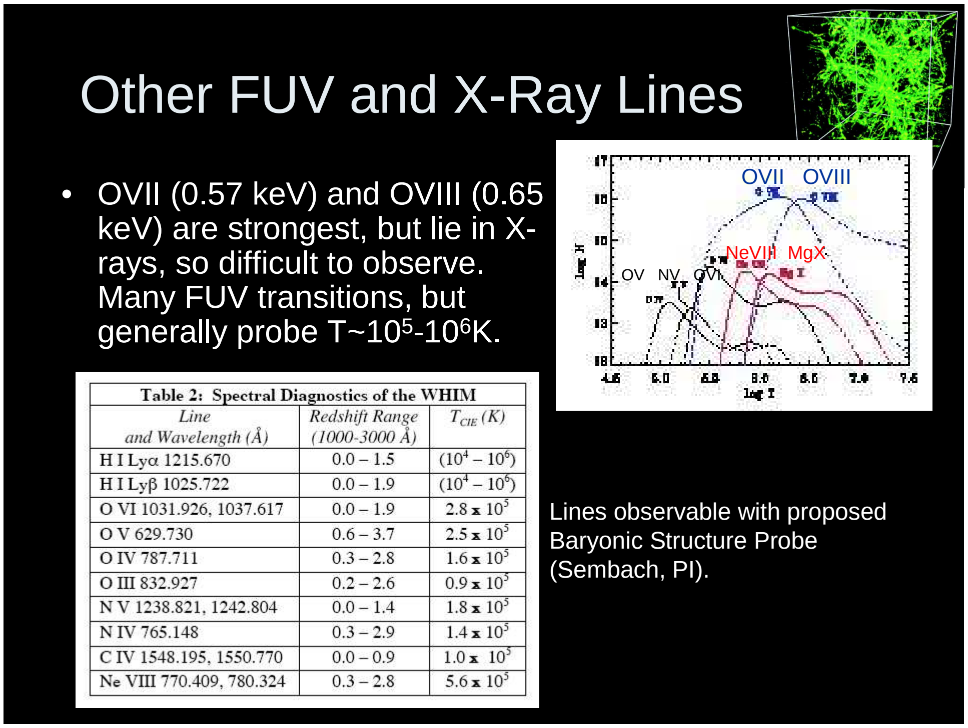
OVI Absorber Statistics

- 20 “STIS-like” spectra, with reduced noise.
- Cumulative EW distribution agrees with observations.
- Column density distribution is steep: slope≈-2.3
- WHIM absorbers ($T>10^{4.7}$K) show up for EW>50mÅ, but not dominant.
- b-parameters peak at 25 km/s, but don’t correlate well with T.



Correlations with Galaxies

- Galaxy-absorber correlations can indicate the environment of absorbers.
- Count pairs with impact parameter <2 Mpc/h, as a function of redshift space separation (Δz~13).
- *Prediction*: Weak OVI absorbers (up to ~100mA) show correlations similar to HI; strong OVI systems, tracing collisionally-ionized WHIM, show stronger correlations.



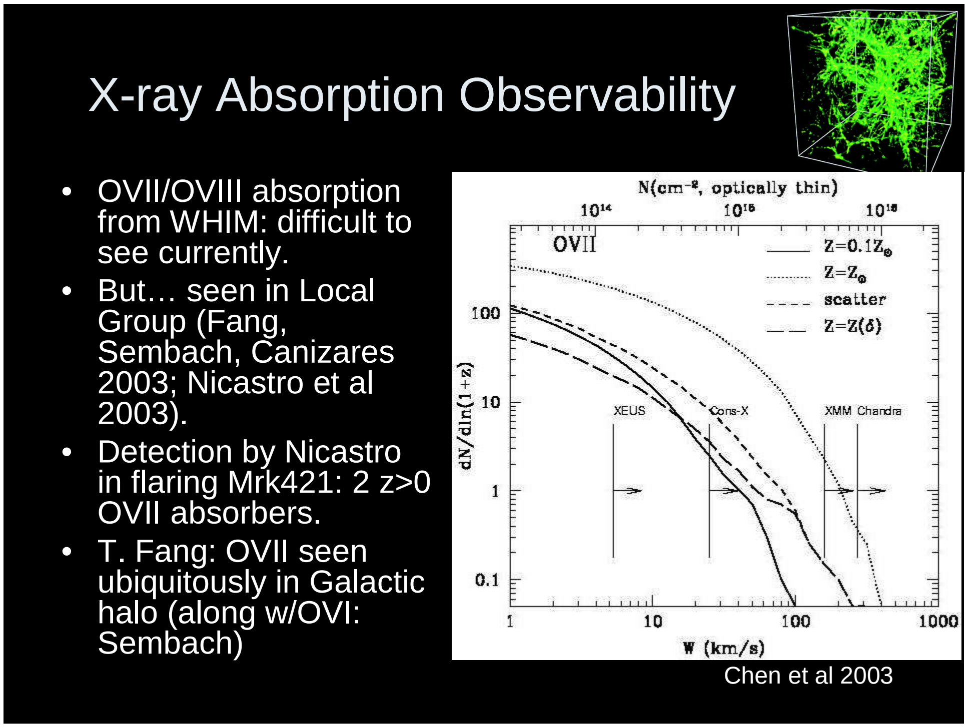
Other FUV and X-Ray Lines

- OVII (0.57 keV) and OVIII (0.65 keV) are strongest, but lie in X-rays, so difficult to observe. Many FUV transitions, but generally probe T~10^5-10^6K.

Table 2: Spectral Diagnostics of the WHIM

Line and Wavelength (Å)	*Redshift Range (1000-3000 Å)*	T_{CIE} *(K)*
H I Lyα 1215.670	0.0 – 1.5	$(10^4 - 10^6)$
H I Lyβ 1025.722	0.0 – 1.9	$(10^4 - 10^6)$
O VI 1031.926, 1037.617	0.0 – 1.9	2.8×10^5
O V 629.730	0.6 – 3.7	2.5×10^5
O IV 787.711	0.3 – 2.8	1.6×10^5
O III 832.927	0.2 – 2.6	0.9×10^5
N V 1238.821, 1242.804	0.0 – 1.4	1.8×10^5
N IV 765.148	0.3 – 2.9	1.4×10^5
C IV 1548.195, 1550.770	0.0 – 0.9	1.0×10^5
Ne VIII 770.409, 780.324	0.3 – 2.8	5.6×10^5

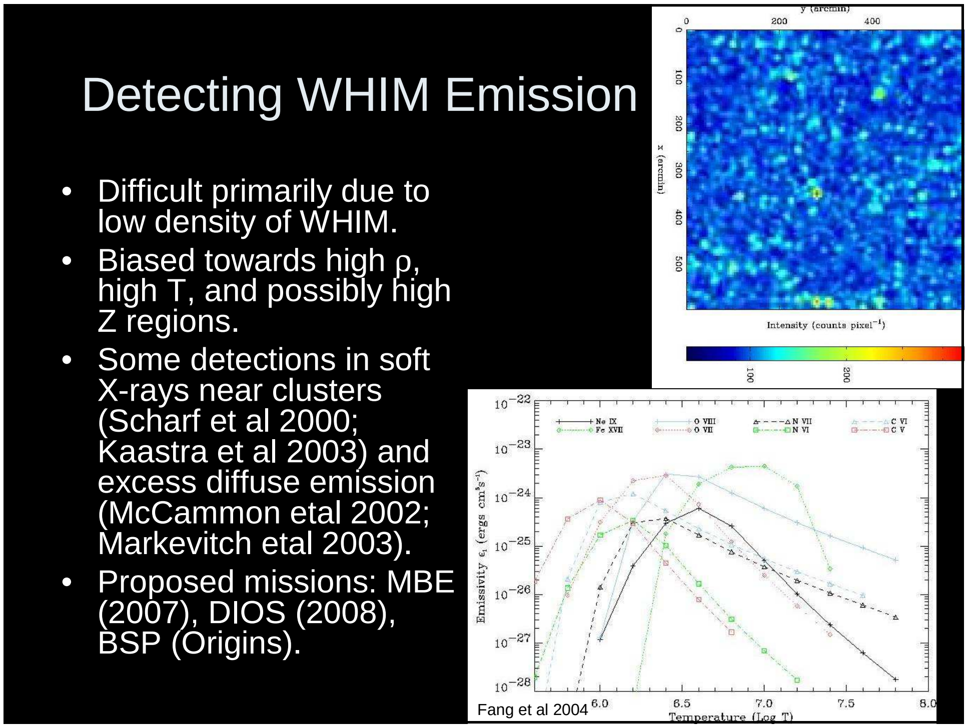
Lines observable with proposed Baryonic Structure Probe (Sembach, PI).



X-ray Absorption Observability

- OVII/OVIII absorption from WHIM: difficult to see currently.
- But… seen in Local Group (Fang, Sembach, Canizares 2003; Nicastro et al 2003).
- Detection by Nicastro in flaring Mrk421: 2 z>0 OVII absorbers.
- T. Fang: OVII seen ubiquitously in Galactic halo (along w/OVI: Sembach)

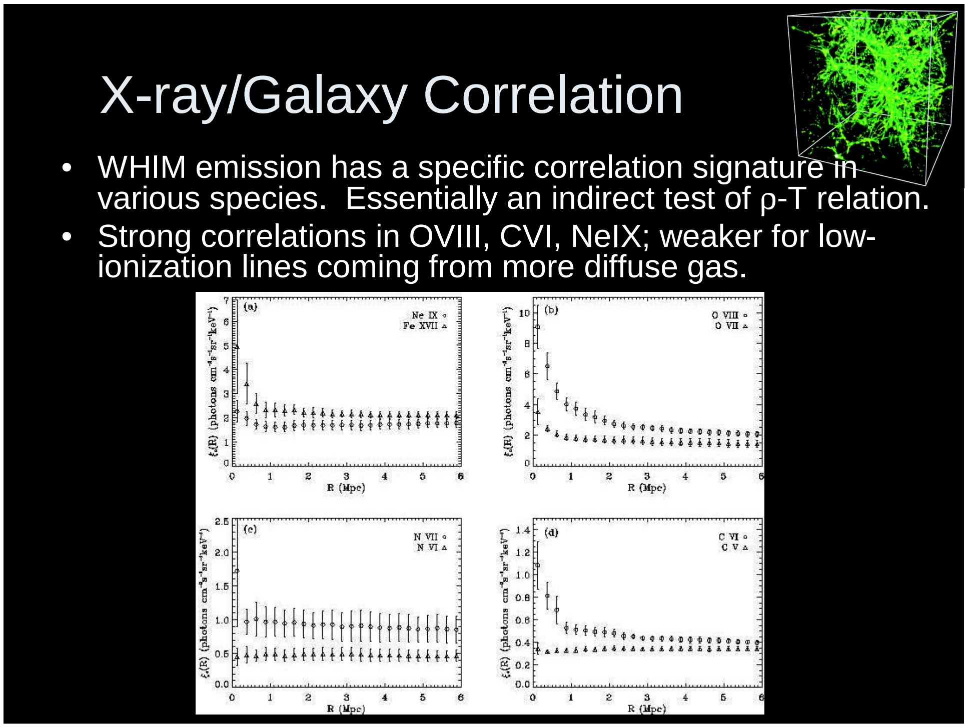
Chen et al 2003



Detecting WHIM Emission

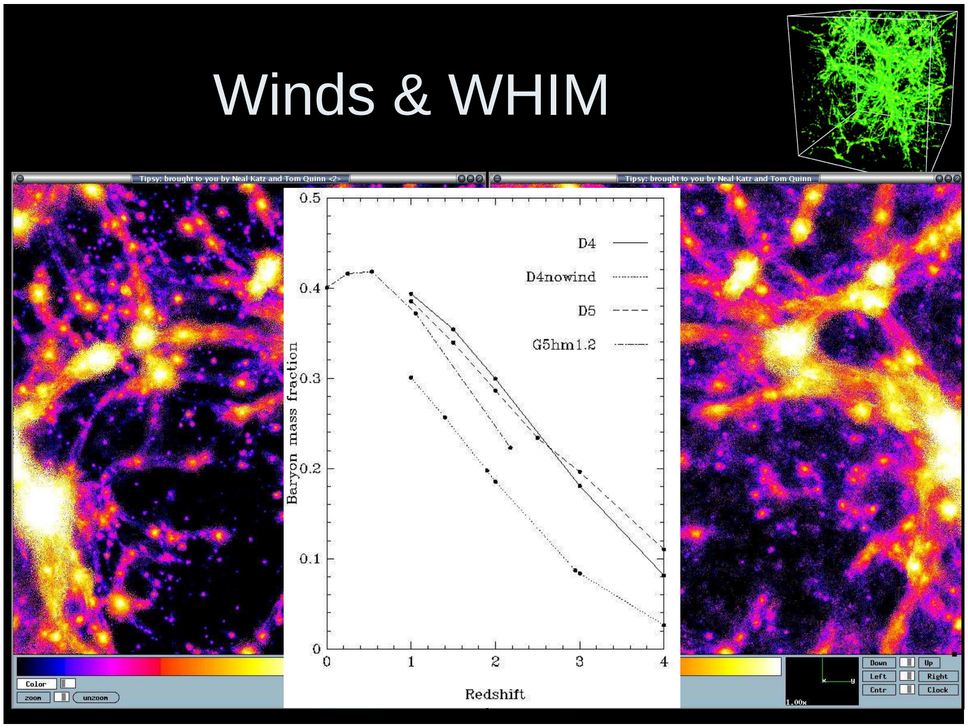
- Difficult primarily due to low density of WHIM.
- Biased towards high ρ, high T, and possibly high Z regions.
- Some detections in soft X-rays near clusters (Scharf et al 2000; Kaastra et al 2003) and excess diffuse emission (McCammon etal 2002; Markevitch etal 2003).
- Proposed missions: MBE (2007), DIOS (2008), BSP (Origins).

Fang et al 2004



X-ray/Galaxy Correlation

- WHIM emission has a specific correlation signature in various species. Essentially an indirect test of ρ-T relation.
- Strong correlations in OVIII, CVI, NeIX; weaker for low-ionization lines coming from more diffuse gas.



Winds & WHIM

Modeling caveats

- Metal line cooling: Important in emission regions.
- Non-equilibrium ionization: Important for recombinations to lower ions.
- Electron vs. ion temperature: T_e lower.

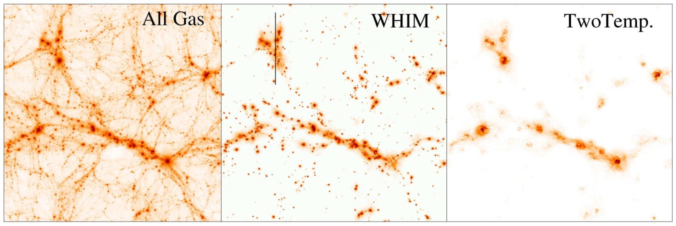
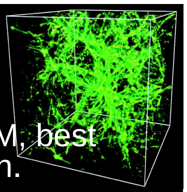


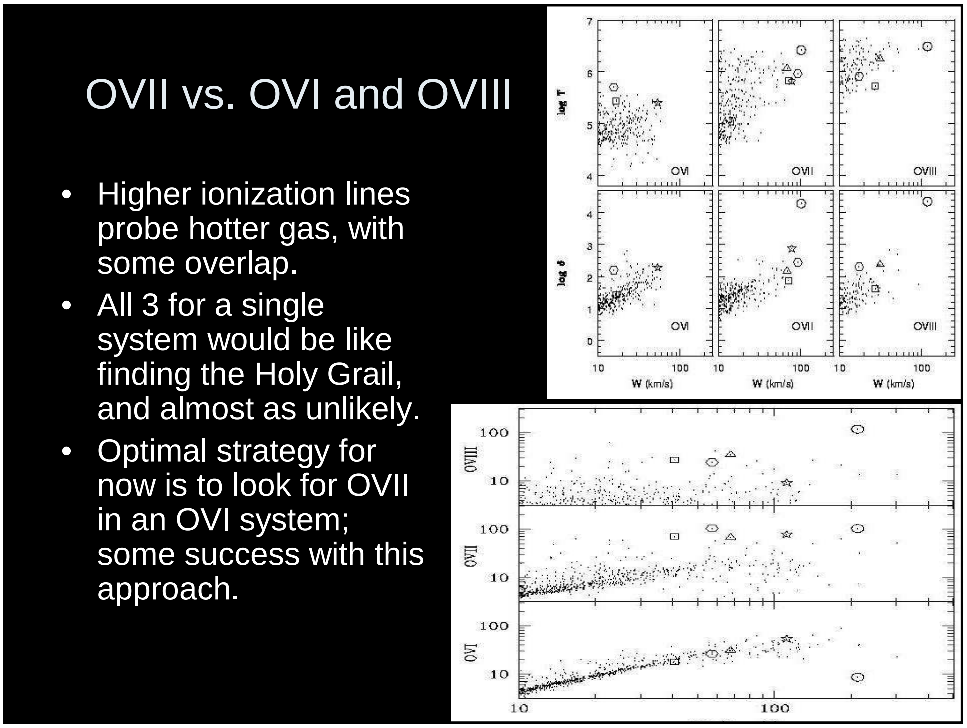
FIG. 1.— The distribution of baryons (left), the warm/hot component with $10^6 < T < 10^7$ K (middle), and gas with $T_e < 0.5 T_i$ (right) in a slab of $100 \times 100 \times 20$ $(h^{-1}\mathrm{Mpc})^3$ at $z = 0$. The vertical bar in the middle panel indicates a 'super-cluster' region, for which we compute the soft X-ray intensity (see section 4 and Figure 5).

Yoshida, Furlanetto, Hernquist 2004

Conclusions

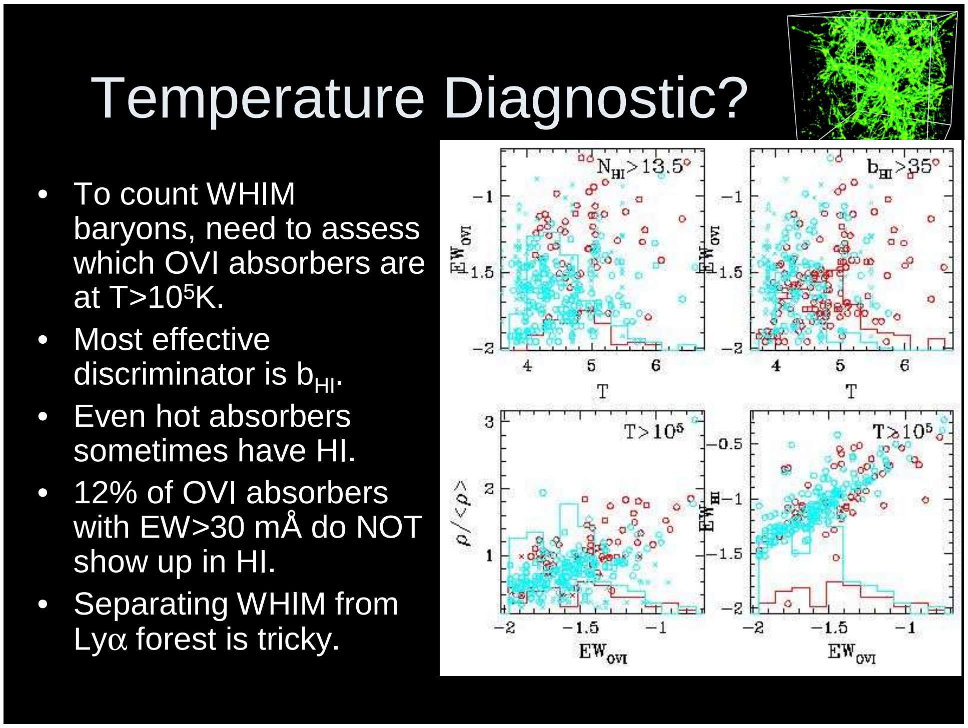


- Current IGM simulations predict a sizeable WHIM, best detectable in FUV and X-ray absorption/emission.
- For EW_{OVI}>50 mÅ (STIS-detectable), OVI absorbers are generally above photoionization temperatures but only ~half have $T>10^5$K.
- Extracting the physical state of the gas from OVI+HI data is not straightforward, but simulations may suggest trends that correlate with temperature (e.g. b_{HI}>35 km/s).
- X-ray absorption traces greater bulk of WHIM gas, but is more difficult to detect observationally; likely requires next-generation X-ray telescopes for large samples.
- Studying galaxy/absorber correlations in X-rays and UV can provide clues to nature of absorption.
- Emission is difficult but not hopeless to detect, though will generally trace hottest, densest WHIM gas.
- Impact of winds/preheating may be substantial ($\sim +0.1\Omega_b$) and models may be constrained by high-z WHIM data.



OVII vs. OVI and OVIII

- Higher ionization lines probe hotter gas, with some overlap.
- All 3 for a single system would be like finding the Holy Grail, and almost as unlikely.
- Optimal strategy for now is to look for OVII in an OVI system; some success with this approach.



Temperature Diagnostic?

- To count WHIM baryons, need to assess which OVI absorbers are at T>10^{5}K.
- Most effective discriminator is b_{HI}.
- Even hot absorbers sometimes have HI.
- 12% of OVI absorbers with EW>30 mÅ do NOT show up in HI.
- Separating WHIM from Lyα forest is tricky.