Looking into CDM predictions: from large- to small-scale structures

SPH simulation in $\Lambda$CDM (Yoshikawa et al. 2001)

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Outline of the talk

1. Convergence of cosmological N-body simulations
2. Clustering of the 2dF and the SDSS galaxies
3. Density profiles of dark matter halos
4. Estimate of the value of $\sigma_8$ from cluster abundances
5. Searching for cosmic missing baryon via oxygen emission lines (DIOS: Diffuse Intergalactic Oxygen Surveyor)
Part 1:
Convergence of cosmological N-body simulations
Comparison of T(k)

Fits of Bond & Efstathiou (1983) and Bardeen et al. (1986) against CMBFAST

$\Lambda CDM$ ($\Omega_m = 0.3, \Omega_\Lambda = 0.7, h = 0.7, \Omega_b = 0.02$)

Boltzmann codes

<table>
<thead>
<tr>
<th>$L_{\text{box}}[\text{h}^{-1}\text{Mpc}]$</th>
<th>N</th>
<th>$m[\text{h}^{-1}\text{M}_{\odot}]$</th>
<th>reference</th>
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<tr>
<td><strong>N-body</strong></td>
<td></td>
<td></td>
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<tr>
<td>100</td>
<td>256$^3$</td>
<td>5.0x10$^9$</td>
<td>Jing &amp; Suto (1998)</td>
</tr>
<tr>
<td>100</td>
<td>512$^3$</td>
<td>6.1x10$^8$</td>
<td>Jing (2001)</td>
</tr>
<tr>
<td>240</td>
<td>256$^3$</td>
<td>6.9x10$^{10}$</td>
<td>Jenkins et al. (1998; Virgo)</td>
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<td>300</td>
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<td>1.3x10$^{11}$</td>
<td>Jing &amp; Suto (1998)</td>
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<tr>
<td>1000</td>
<td>1024$^3$</td>
<td>7.6x10$^{10}$</td>
<td>Bode, Ostriker &amp; Xu (2000)</td>
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<tr>
<td>1000</td>
<td>512$^3$</td>
<td>6.1x10$^{11}$</td>
<td>Bode, Bahcall, Ford &amp; Ostriker (2001)</td>
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<tr>
<td>3000</td>
<td>1000$^3$</td>
<td>2.25x10$^{12}$</td>
<td>Evrard et al. (2002; Hubble vol.)</td>
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<td><strong>SPH</strong></td>
<td></td>
<td></td>
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<tr>
<td>1</td>
<td>324$^3$</td>
<td>730 (DM)</td>
<td>Yoshida et al. (2003)</td>
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<tr>
<td>75</td>
<td>128$^3$</td>
<td>2.4x10$^{10}$ (DM)</td>
<td>Yoshikawa, Jing &amp; Suto (2000)</td>
</tr>
<tr>
<td>100</td>
<td>216$^3$</td>
<td>7.0x10$^9$ (DM)</td>
<td>White, Hernquist &amp; Springel (2002)</td>
</tr>
</tbody>
</table>
Well-known exponential evolution of “N” in cosmological N-body simulations

The number of simulation particles in a $(1h^{-1}\text{Gpc})^3$ comoving cube exceeds the real number of CDM particles in the box

- December, 2348 (if $m_{\text{CDM}}=1\text{keV}$)
- February, 2386 (if $m_{\text{CDM}}=10^{-5}\text{keV}$)

$$N=400x10^{0.215(\text{Year}-1975)}$$
Two-point correlation functions from different simulations

The Peacock-Dodds fitting formula, Virgo simulation and Jing’s simulation agree within ±10% for $0.05h^{-1}\text{Mpc} < r < 20h^{-1}\text{Mpc}$.
Correlation functions of halos on the light-cone

Light-cone output from Hubble volume LCDM simulation

VS
Peacock-Dodds fitting formula
+ Halo bias
+ (redshift distortion)
+ average over lightcone

Hamana, Yoshida, Suto & Evrard (2001)
Finite mass resolution effect in cosmological N-body simulations

Beyond this redshift, dark matter clustering below the mean separation of particles in N-body method is seriously affected by discreteness.

\[ z_{\text{crit}} = 0.72 \left\{ \log_{10} \left( \frac{2 \times 10^{15} h^{-1} M_{\odot}}{n_{\text{halo}} m_{\text{part}}} \right) \right\}^{1.25} - 1 \]
Universal mass function of dark halos

\[ n(\sigma^{-1}(M)) = A \exp[-|\ln \sigma^{-1}(M) + B|^{\varepsilon}] \]

Jenkins et al. (2001)

Figure 7. The FOF(0.2) mass functions of all the simulation outputs listed in Table 2. Remarkably, when a single linking length is used to identify halos at all times and in all cosmologies, the mass function appears to be invariant in the \( f - \ln \sigma^{-1} \) plane. A single formula (eqn. 9), shown with a dotted line, fits all the mass functions with an accuracy of better than about 20% over the entire range. The dashed curve show the Press-Schechter mass function for comparison.

Figure 8. The residual between the fitting formula, eqn. 9, and the FOF(0.2) mass functions for all the simulation outputs listed in Table 2. Solid lines correspond to simulations with \( \Omega = 1 \), short dashed lines to flat, low \( \Omega_0 \) models, and long dashed lines to open models.
Dark matter virial theorem: halo mass - velocity dispersion relation for different mass definitions

\[ \Delta = 324 \text{ (background)} \]

\[ \Delta = 200 \text{ (critical)} \]

In contrast to a simple theory, numerical simulations prefer halos defined by overdensity of 200 with respect the critical mean density independently of the background cosmology (puzzling...)
Dark halo mass functions

Claim:
- Dark halos should be defined by critical $SO(200)$, i.e., spherically averaged density exceeds 200 times the critical density (independently of the background cosmology).
- Then the resulting mass functions are “universal”.

What’s wrong with the conventional spherical infall model prediction?
- Why universal scaling is desired (even if the scaling itself is surprising)?
What is the definition of galaxy clusters?

**Abell (optical) clusters**
- The Abell radius
- \( m_3 < m < m_3 + 2 \)
- Richness class

**Press-Schechter halos**
- Spherical collapse
- \( \rho_{\text{vir}} = 18 \pi^2 \Omega_m^{-0.6} \)

**SZ clusters**
- \( I_{SZ} \)
- \( n_e T_e \)

**X-ray clusters**
- \( S_x \)
- \( n_e^2 T_e^{1/2} \)

**Halos in N-body simulations**
- Friend-of-friend
- Linking length = 0.2, \( \rho_{\text{vir}} = 200 \)?

Apparently they are closely related, but we desperately need to understand better what we mean by clusters.
Part 2:

Clustering of the 2dF and the SDSS galaxies
$\Omega_m$ from power spectrum of 2dFGRS

luminosity dependence of $w(r_p)$ from SDSS volume-limited galaxy sample

- early-types are more strongly biased than late-types
- for late-types, luminous galaxies show stronger clustering
- for early-types, the clustering amplitudes are fairly independent of the absolute luminosities of galaxies
Luminosity and color dependence of $w(r_p)$ from SDSS volume-limited galaxy sample

- red/luminous galaxies show stronger clustering
- the slope of the red-galaxy correlation is steeper

Zehavi et al. (2001)
Morphology-dependence of galaxy bias from SDSS magnitude-limited sample

- Early-type average late-type

\[ b \equiv \sqrt{\frac{\xi(\text{galaxies})}{\xi(\Lambda CDM)}} \]

- Galaxy bias is fairly scale-independent
- Clear morphology dependence with respect to \( \Lambda CDM \) (computed semi-analytically over light-cone)

Kayo et al. (2003)
Previous predictions from SPH simulations with “galaxy” formation

- Simulated “galaxies” formed earlier are more strongly biased.
- Recently formed galaxies preferentially avoid high-density regions.
- Quite consistent with the morphology-dependent galaxy bias derived from the recent SDSS DR1.

Yoshikawa, Taruya, Jing & Suto (2001)
Three-point correlation functions in redshift space

\[ Q \sim 0.5 - 1.5 \]

- Weak dependence on scale of triangles (hierarchical ansatz is valid)
- Weak dependence on Luminosity
- Weak dependence on Morphology

\[ Q_{\text{red}} \equiv \frac{\zeta(s_1, s_2, s_3)}{\xi(s_1)\xi(s_2) + \xi(s_2)\xi(s_3) + \xi(s_3)\xi(s_1)} \]
Comparison with previous work on three-point correlation functions

Jing & Börner (1998)
LCRS: 20,000 galaxies

Kayo et al. (2003)
SDSS: 90,000 galaxies
Comparison with theoretical predictions in real space

Very different behaviour, but maybe mostly due to the redshift-space distortion effects that theoretical models are not yet successful in incorporating properly.
Redshift-space distortion from simulations

N-body simulations imply a significant degree of redshift-space distortion

Matsubara & Suto (1994)
Topology of SDSS galaxy distribution

- Topology of SDSS galaxy distribution (measured with Minkowski Functionals) is consistent with those originated from the primordial random-Gaussian field in $\Lambda$CDM (Hikage, Schmalzing, Buchert, Suto et al. 2003 PASJ).
SDSS data represent a fair sample of the universe?

Hikage et al. (2003)
- Difference of MFs for two independent regions of SDSS
- Two regions in Sample 12 barely converge within the error bars from Mock samples
Part 3: Density profiles of dark matter halos
Importance of high-resolution simulations

- low mass/force resolutions
  - shallower potential than real
  - artificial disruption/overmerging
    (especially serious for small systems)

\[ \varepsilon = 1\, \text{kpc} \quad \varepsilon = 7.5\, \text{kpc} \]

Moore (2001)

central 500kpc region of a simulated halo in SCDM
Profiles in higher-resolution simulations

- Moore et al. (1998)
- Fukushige & Makino (1997)

Inner slope is steeper (~ 1.5) than the NFW value (1.0)
Density profiles of collisionless CDM halos are well approximated by the following expression, but not necessarily universal:

\[
\rho(r) = \frac{\delta_c \rho_{\text{crit}}}{(r / r_s)^\alpha (1 + r / r_s)^{3-\alpha}} \quad \alpha \approx 1.5
\]
More recent simulations I:

\[ N = 10^6 \]
\[ N = 1.4 \times 10^7 \]
\[ N = 2.9 \times 10^7 \]

SCDM

LCDM

Fukushige, Kawai & Makino (2003)
More recent simulations II:

Claim: hydrodynamic/gas effect results in the compression of the halo density profiles at large radius (?)
Inner profiles of clusters from lensing analysis

Sand, Treu, Smith & Ellis (2003)
Time-delays in QSO multiple images to probe the halo density profile

- Time-delay is very sensitive to the inner slope, but insensitive to cosmological parameters (except $H_0$!)
- Steeper inner profile $\Rightarrow$ larger $\Delta t$
Tentative applications to 4 lens systems

- **Observed time-delays generally prefer a steeper central cusp**
  \[ r^{-1.5} \]

- **needs future statistical study**

Oguri, Taruya, Suto & Turner (2002)
Comparison with observed arc statistics

Previous model predictions are known to be significantly smaller than the observed number of lensed arcs (Luppino et al. 1999)

More realistic modeling of dark halos from simulations (inner slope of $\alpha=1.5$ and non-sphericity) reproduces the observed frequency of arcs.

Oguri, Lee + YS (2003)
Density profile of collisionless CDM halos: still confusing

**High-resolution simulations**

*universal central cusp* \( \rho \propto r^{-1.5} \)

- Navarro, Frenk & White (1996)
- Fukushige & Makino (1997, 2001)
- Moore et al. (1998)
- Jing & Suto (2000)

**Theory**

- Central cusp or softened core?
- Dependent on initial condition?


**Observations**

- Core from dwarf galaxies
- Cusp from lensing

- Moore et al. (1999), de Blok et al. (2000)
- Salucci & Burkert (2000)
Part 4:
Estimate of the value of $\sigma_8$ from cluster abundances
Mass fluctuation amplitude: $\sigma_8$

- **WMAP ($\Lambda$CDM)**
  - $\sigma_8 = 0.9 \pm 0.1$

- **WMAP + ACBAR + CBI + 2dFGRS + Ly$\alpha$ ($\Lambda$CDM)**
  - $\sigma_8 = 0.84 \pm 0.04$

- **Lensing**
  - $\sigma_8 = 0.7 \sim 1.0$

- **Cluster abundance**
  - $\sigma_8 = 0.7 \text{ or } 1.0$ ???

<table>
<thead>
<tr>
<th>Method</th>
<th>$\sigma_8$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>PL CDM + WMAP</td>
<td>0.9 ± 0.1</td>
<td>Spergel et al. 03</td>
</tr>
<tr>
<td>Weak lensing</td>
<td>0.72 ± 0.18</td>
<td>Brown et al. 02</td>
</tr>
<tr>
<td>Weak lensing</td>
<td>0.86</td>
<td>Hoekstra et al. 02</td>
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<td>Weak lensing</td>
<td>0.69</td>
<td>Jarvis et al. 02</td>
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<tr>
<td>Weak lensing</td>
<td>0.96 ± 0.12</td>
<td>Bacon et al. 02</td>
</tr>
<tr>
<td>Weak lensing</td>
<td>0.92 ± 0.2</td>
<td>Refregier et al. 02</td>
</tr>
<tr>
<td>Weak lensing</td>
<td>0.98 ± 0.12</td>
<td>Van Waerbeke et al. 02</td>
</tr>
<tr>
<td>Galaxy vel. fields</td>
<td>0.73 ± 0.1</td>
<td>Willick &amp; Strauss 98</td>
</tr>
<tr>
<td>CBI SZ detection</td>
<td>1.04 ± 0.12</td>
<td>Komatsu &amp; Seljak 02</td>
</tr>
<tr>
<td>High-z clusters</td>
<td>0.95 ± 0.1</td>
<td>Bahcall &amp; Bode 02</td>
</tr>
</tbody>
</table>

Scaled to $\Lambda$CDM case with $\Omega_m = 0.28$

Spergel et al. (2003)
from cluster abundances and lensing


From mass to temperature of X-ray clusters

\[ n(M) \xrightarrow{\text{Virial Theorem}} n(\sigma_{\text{DM}}) \xrightarrow{\beta} n(T_X) \]

\[ \alpha' = \left. \frac{\partial \ln \sigma_8}{\partial \ln M} \right|_n \]

\[ M \propto \sigma_8^{5/2} \quad M \propto T_X^{3/2} \]

\[ \beta \propto \sigma_8^{5/3} \]

Evrard et al. (2002)
Fitting to the local temperature function

Evrard (2003)

best fit:

$$\beta = (1.10 \pm 0.07) \sigma_8^{5/3}$$

from the observed $n(>T)$ by Markevitch (1998) and the Hubble volume simulations (Evrard et al. 2002)

+ virial theorem ($\sigma_{\text{DM}} - \text{M}$)
  - mass scale calibration ($c = 5 \text{ NFW}$)

$$hM_{500}^{\text{tot}}(6 \text{ keV}) = (0.64 \pm 0.06) \sigma_8^{5/2} \times 10^{15} M_{\text{sun}}$$
What is the absolute mass scale of cosmic structure?

<table>
<thead>
<tr>
<th>References</th>
<th>$M_{500}(6\text{ keV})$ ((10^{15}h^{-1}M_{\odot}))</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evrard, Metzler &amp; Navarro 96</td>
<td>0.52</td>
<td>Lagrangian hydro</td>
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<tr>
<td>Bryan &amp; Norman 98</td>
<td>0.78</td>
<td>Eulerian hydro</td>
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<td>Mathiesen &amp; Evrard 01</td>
<td>0.87</td>
<td>spectral $T$, 0.5-9.5 keV</td>
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<td>0.83</td>
<td>spectral $T$, 2-9.5 keV</td>
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<td>Mohr, Mathiesen &amp; Evrard 99</td>
<td>0.47</td>
<td>from beta-model fit to A1795</td>
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<td>Nevalainen, Markevitch &amp; Forman 00</td>
<td>0.17</td>
<td>ASCA radial $T$ gradients</td>
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<td>Finoguenov, Reiprich &amp; Bohringer 01</td>
<td>0.30</td>
<td>ASCA radial $T$ gradients (larger sample)</td>
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<td>Allen, Schmidt &amp; Fabian 02</td>
<td>0.39</td>
<td>Chandra radial $T$ ($\Delta=2500$)</td>
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<tr>
<td>Shimizu, Kitayama, Sasaki &amp; Suto 03</td>
<td>0.40</td>
<td>Lx-$T$ relation &amp; XTF (Ikebe)</td>
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<tr>
<td>Henry 00</td>
<td>0.66</td>
<td>$\sigma_8 = 0.9$ ($\Omega_m = 0.3$)</td>
</tr>
<tr>
<td>Pierpaoli, Scott &amp; White 01</td>
<td>0.58</td>
<td>$\sigma_8 = 1.0$ ($\Omega_m = 0.3$)</td>
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<tr>
<td>Ikebe et al 02</td>
<td>0.59</td>
<td>$\sigma_8 = 0.9$ ($\Omega_m = 0.3$)</td>
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<td>Seljak 02</td>
<td>0.23</td>
<td>$\sigma_8 = 0.7$ ($\Omega_m = 0.35$)</td>
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<tr>
<td><strong>average</strong></td>
<td><strong>0.64$\sigma_8^{5/2}$</strong></td>
<td><strong>J MF+VT+local T-ftn ($\Lambda\text{CDM}$)</strong></td>
</tr>
</tbody>
</table>

Evrard (2003)
\( \delta^8 \) from the observed TF of X-ray clusters

Self-similar MT relation

XTF at \((5 \sim 7)\) keV

\[ \sigma_8 = 1.00 \text{ (PS)} \]
\[ \sigma_8 = 0.91 \text{ (Jenkins et al.)} \]

Best-fitted MT relation

XTF at \((2.5 \sim 10)\) keV

\[ \sigma_8 = 0.80 \text{ (PS)} \]
\[ \sigma_8 = 0.73 \text{ (Jenkins et al.)} \]

\( \Omega_0 = 0.3, \lambda_0 = 0.7, h = 0.7 \) CDM assumed (Shimizu et al. 2003)
A puzzling (?) summary on $\sigma_8$ from cluster abundance

- Recent mass ftn + virial thm calibrations allow precise calculation of the expected number of clusters as a function of their dark matter gravitational potential depth, $n(\sigma_{DM}^2)$

- Matching the observed temperature ftn, $n(T_X)$, requires that the ratio of specific energies in DM and ICM gas be $\beta=(1.10 \pm 0.07)\sigma_8^{5/3}$

**two scenarios for `standard’ $\Lambda$CDM ($\Omega_m=0.3$, $\Omega_\Lambda=0.7$)**

1) **high normalization**: $\sigma_8=1.0 \pm 0.1$ $\beta=(1.1 \pm 0.2)$
   - ICM thermal energy consistent with gravitational heating (+mild PH)
   - galaxies velocity dispersion matches that of dark matter

2) **low normalization**: $\sigma_8=0.7 \pm 0.1$ $\beta=(0.61 \pm 0.15)$
   - ICM must be heated to *1.8 times* level of gravitational infall
   - galaxies must be *hotter* than dark matter by a similar factor (in $\sigma^2$)

**Low $\sigma_8$ normalizations create problems for cluster energetics!**

Evrard (2003)
Enhanced heating model at high-z

- $\varepsilon_{\text{RG}} = 0$ for simplicity
- $\varepsilon_{\text{SN}} = 0.3$ (z<7) and $\varepsilon_{\text{SN}} = 1, 2, 4$ or 5 (z>7)

Shimizu et al. (2003)
Part 5:
Searching for cosmic missing baryon via oxygen emission lines

DIOS
Diffuse Intergalactic Oxygen Surveyor
A Japanese proposal of a dedicated X-ray mission to search for missing baryons

- A dedicated satellite with cost < 40M USD to fill the gap between Astro-E2 (2005) and NeXT (2010?). Launch at Japan in 2008 (?).
- Unprecedented energy spectral resolution $\Delta E=2eV$ in soft X-ray band (0.1-1keV)
- Aim at detection of (20-30) percent of the total cosmic baryons via Oxygen emission lines
  - $\Delta E=2eV, \ S_{\text{eff}} \Omega=100 \ [\text{cm}^2 \ \text{deg}^2]$
  - flux limit = $6\times10^{-11} \ [\text{erg/s/cm}^2/\text{str}]$
- PI: Takaya Ohashi (Tokyo Metropolitan Univ.)
Light-cone output from simulation

- **Cosmological SPH simulation** in $\Omega_m=0.3$, $\Omega_\Lambda=0.7$, $\sigma_8=1.0$, and $h=0.7$ CDM with $N=128^3$ each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- **Light-cone output from $z=0.3$ to $z=0$** by stacking 11 simulation cubes of $(75h^{-1}\text{Mpc})^3$ at different $z$
- **5 × 5 FOV mock data** in 64x64 grids on the sky
- 128 bins along the redshift direction ($\Delta z=0.3/128$)
Surface brightness on the sky

Bolometric X-ray emission

OVII and OVIII line emission
Metallicity models

Oxygen enrichment scenario in IGM

Type-II SNe → galaxy wind merging → metal pollution in IGM

Metallicity of WHIM is quite uncertain

Adopted models for metallicity distribution

**Model I**: uniform and constant
\[ Z = 0.2 \, Z_{\odot} \]

**Model II**: uniform and evolving
\[ Z = 0.2 \, Z_{\odot} \left( \frac{t}{t_0} \right) \]

**Model III**: density-dependent (Aguirre et al. 2001)
\[ Z = 0.005 \, Z_{\odot} \left( \frac{\rho}{\rho_{\text{mean}}} \right)^{0.33} \] (galactic wind driven)

**Model IV**: density-dependent (Aguirre et al. 2001)
\[ Z = 0.02 \, Z_{\odot} \left( \frac{\rho}{\rho_{\text{mean}}} \right)^{0.3} \] (radiation pressure driven)
Simulated spectra: region A

\[0.94 \times 0.94 = 0.88 \text{ deg}^2\]

\[T_{\text{exposure}} = 3 \times 10^5 \text{ sec}\]
Simulated spectra: region D

$19' \times 19' = 0.098 \text{ deg}^2$

$T_{\text{exposure}} = 10^6 \text{sec}$
Physical properties of the probed baryons

Each symbol indicates the temperature and the over-density of gas at each simulation grid (4x4 smoothed pixels over the sky and $\Delta z=0.3/128$):

- $S_x > 3 \times 10^{-10}$ [erg/s/cm$^2$/sr]
- $S_x > 6 \times 10^{-11}$ [erg/s/cm$^2$/sr]
- $S_x > 10^{-11}$ [erg/s/cm$^2$/sr]
Expected fraction of WHIM detectable via Oxygen emission lines (in principle)

Our proposed mission (flux limit = $6 \times 10^{-11} \text{[erg/s/cm}^2/\text{str}]$) will be able to detect (20-30) percent of the total cosmic baryons via Oxygen emission lines in principle.
Detectability of Warm-Hot Intergalactic Medium via Oxygen emission lines

- Mock spectra from cosmological SPH simulation
- **With our proposed mission (20-30) percent of the total cosmic baryons will be detected via Oxygen emission lines** in principle.
  - $\Delta E=2\text{eV}, \ S_{\text{eff}} \Omega=100 \ [\text{cm}^2 \ \text{deg}^2]$
  - flux limit $= 6 \times 10^{-11} \ [\text{erg}/\text{s}/\text{cm}^2/\text{str}]$
- **Things remain to be checked**
  - Validity of the collisional ionization equilibrium ?
  - How to properly identify the oxygen lines from the background/noises in reality ?
DI OS: Japanese proposal of a dedicated X-ray mission to search for missing baryons

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