Accurate Modeling of the Redshift-Space Distortions of Biased Tracers

based on arXiv:1106.4562

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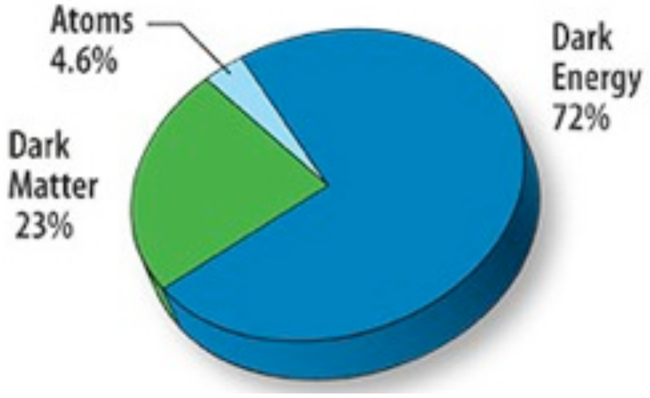
with **Atsushi Taruya** (RESCEU)

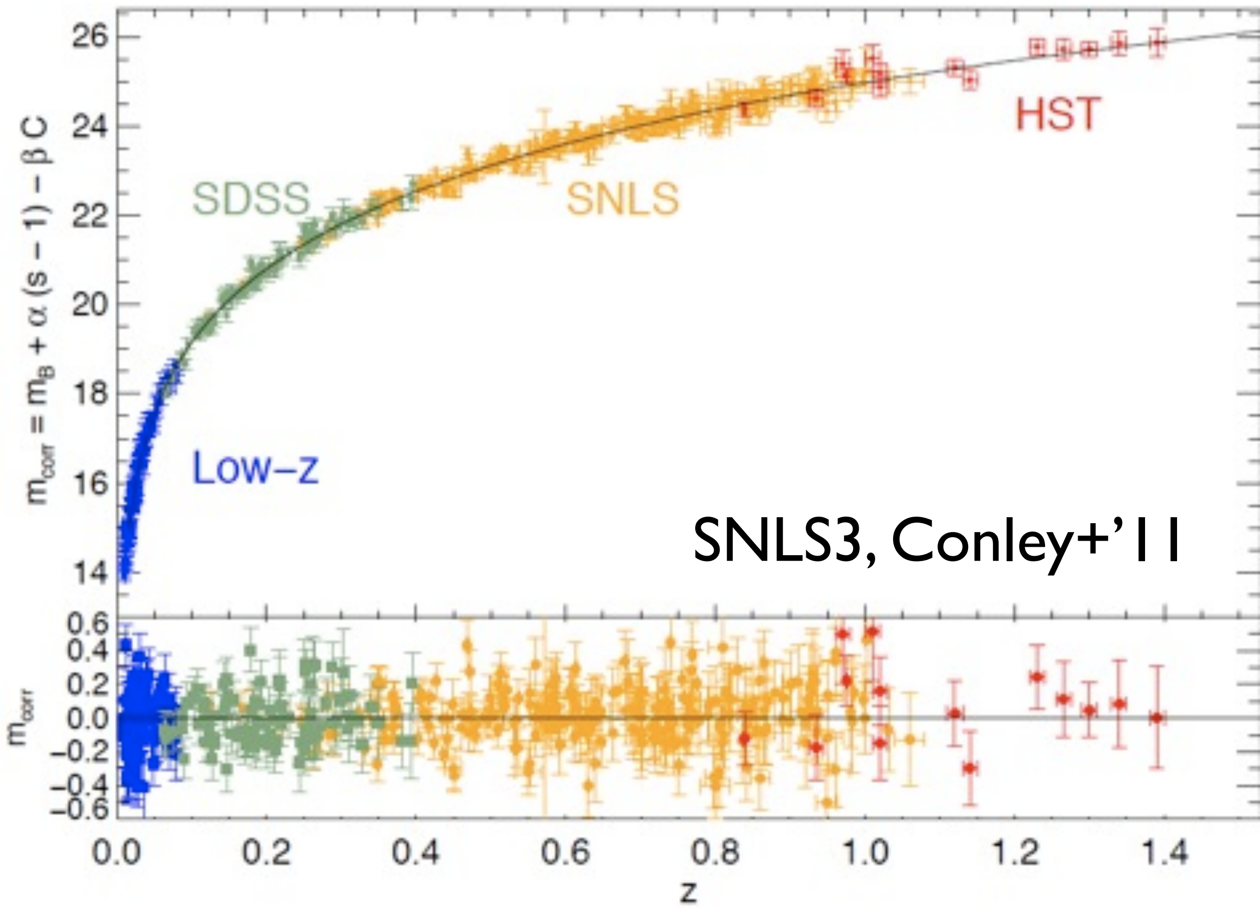
RESCEU/DENET summer school in Aso, Kumamoto, July 28 2011

Dark Energy? Modified Gravity?

observations → acceleration of cosmic expansion

- ✓type-Ia supernova
- ✓BAOs
- ✓CMB
- ✓...





SNLS3, Conley+'11

f(R), DGP, ...

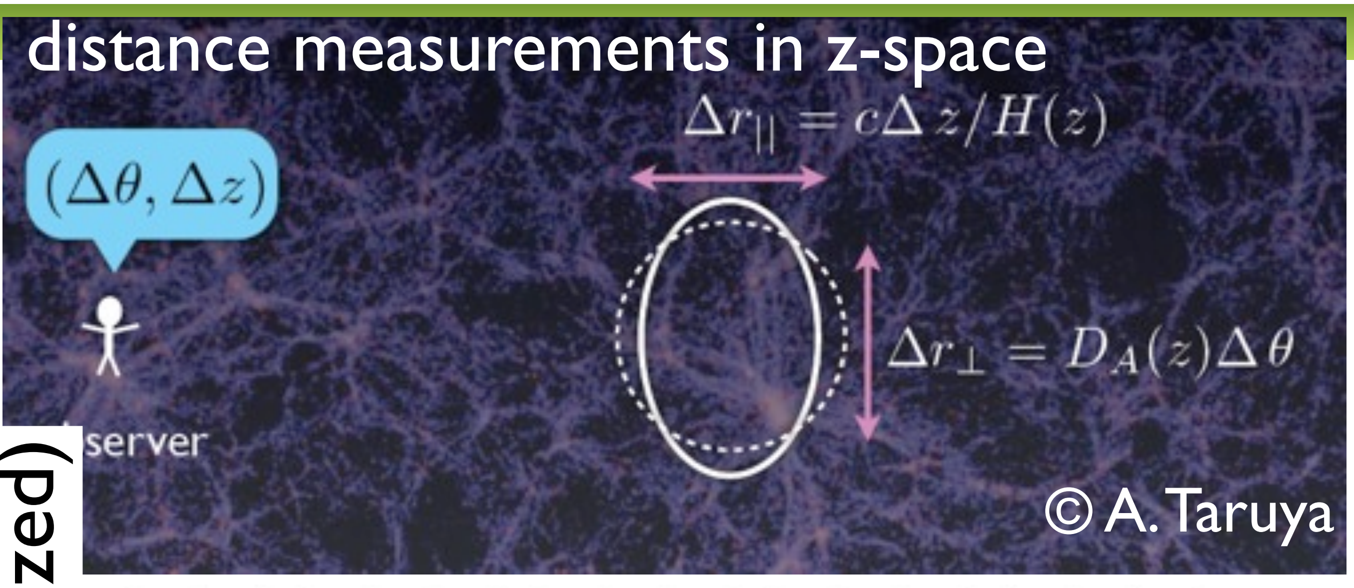
$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

modified gravity? dark energy?

expansion history in a DE model may be mimicked by a MG model

geometrical + growth tests are essential!

Anisotropies in galaxy clustering

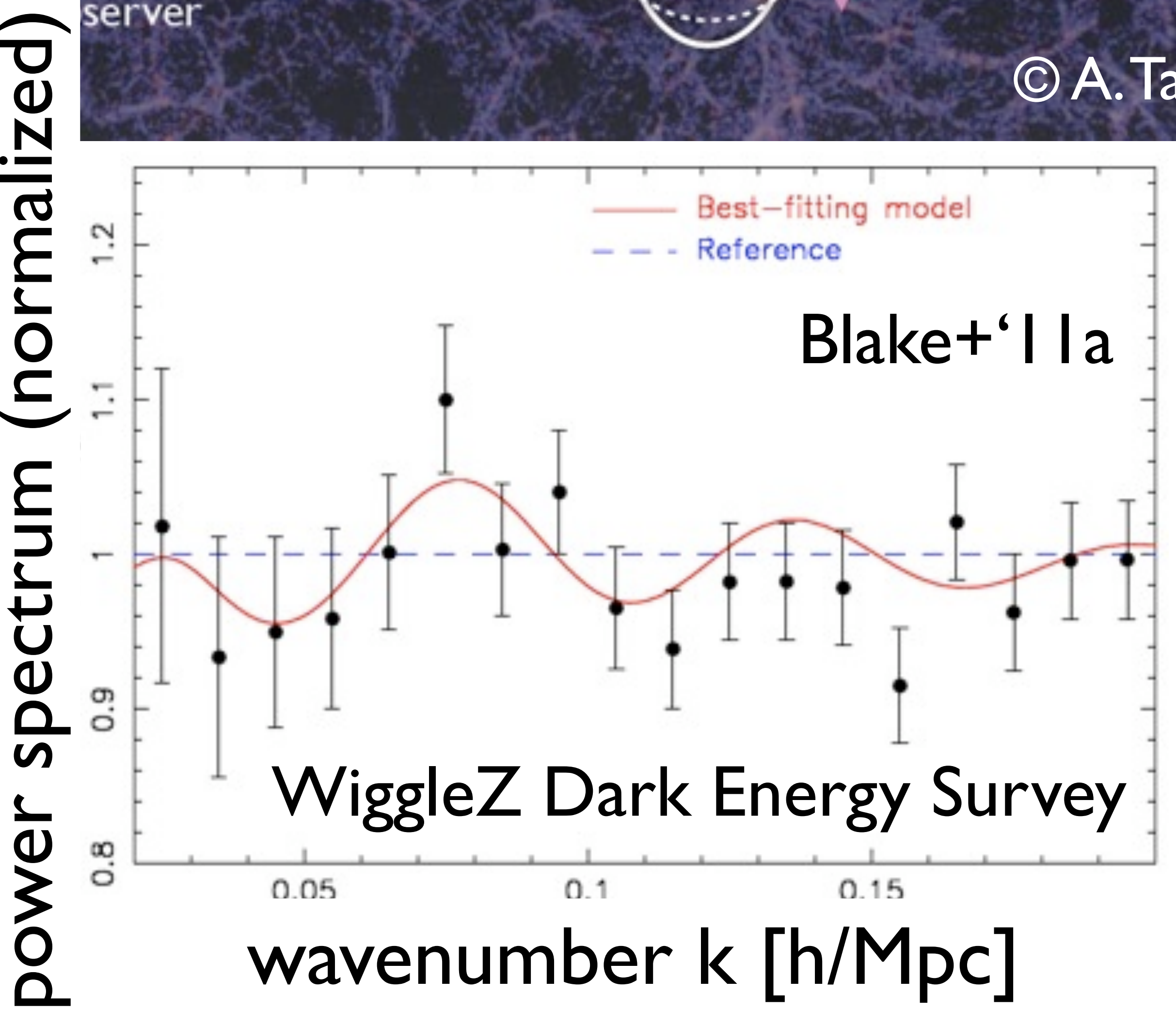


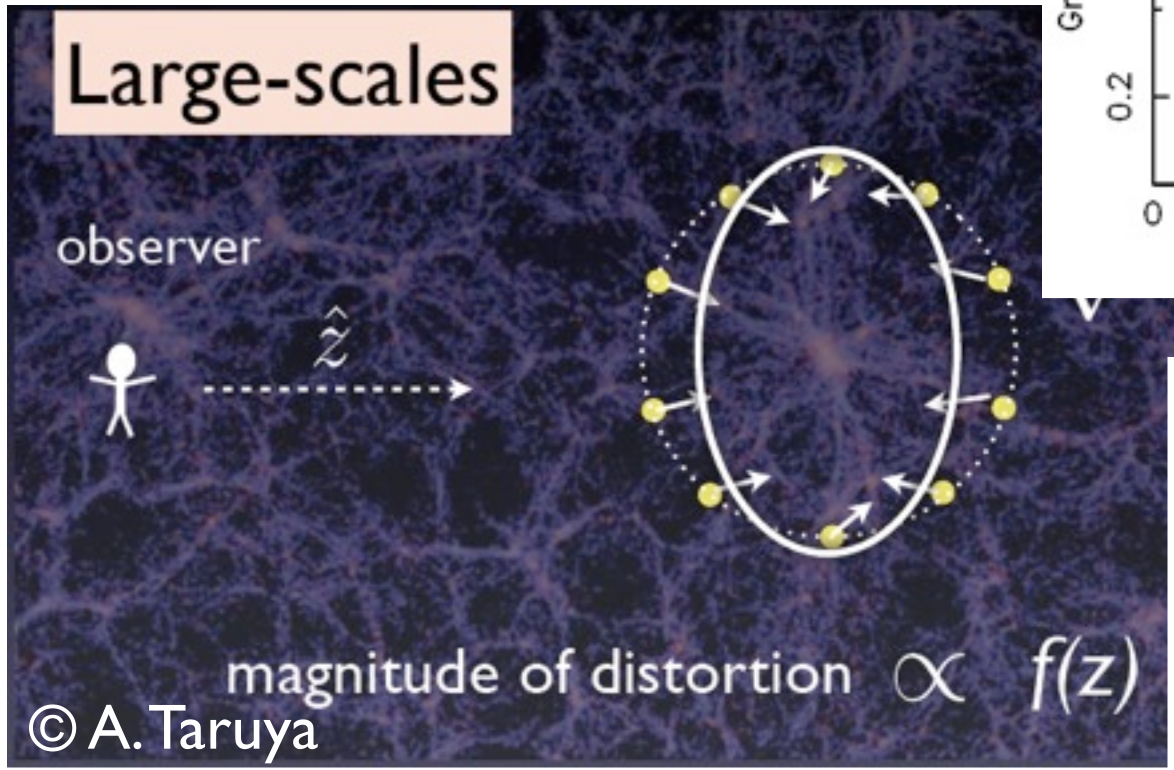
BAOs + Alcock & Paczynski test

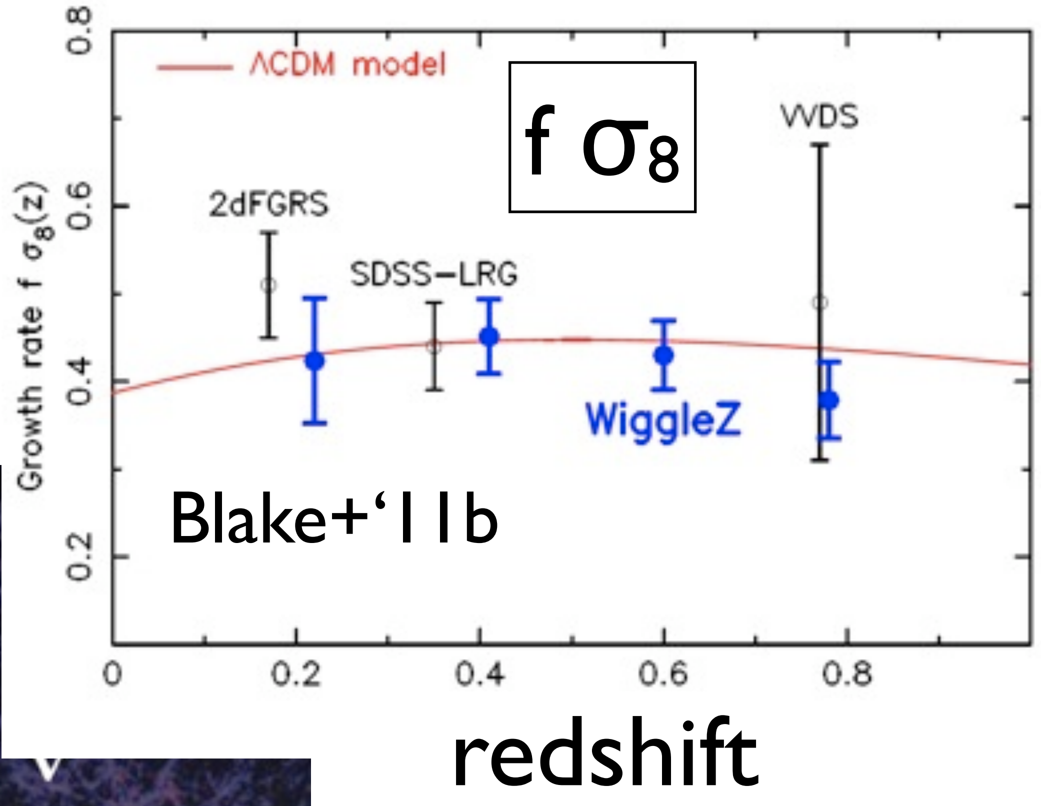
→ H(z) & $D_A(z)$

z-space distiontions

$$\rightarrow f(z) \equiv \frac{d \ln D(z)}{d \ln a}$$







z space

real space

$$\mathbf{s} = \mathbf{r} + \frac{1+z}{H(z)} v_z(\mathbf{r})\,\hat{\mathbf{z}}$$

peculiar velocity

Redshift-space distortions

z-space → s, r-space → r

$$\mathbf{s} = \mathbf{r} + \frac{1+z}{H(z)} v_z(\mathbf{r})\,\hat{\mathbf{z}},$$

peculiar velocity ($v_z(\mathbf{r})$)

Kaiser Effect

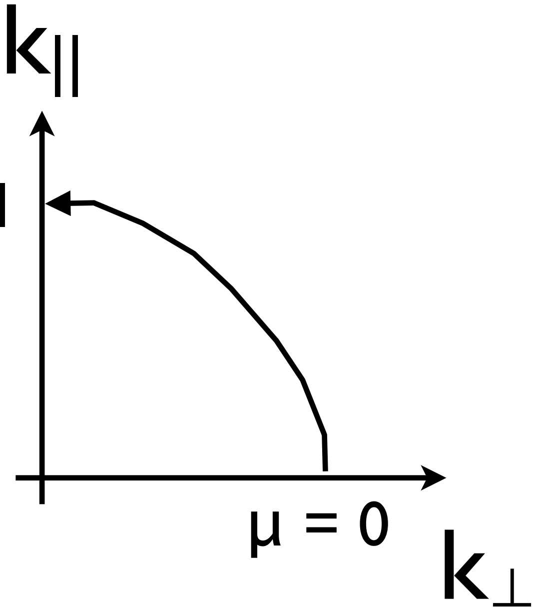
large-scale coherent motion

→ enhancement of clustering

Finger-of-God Effect

small-scale random motion

→ suppression of clustering

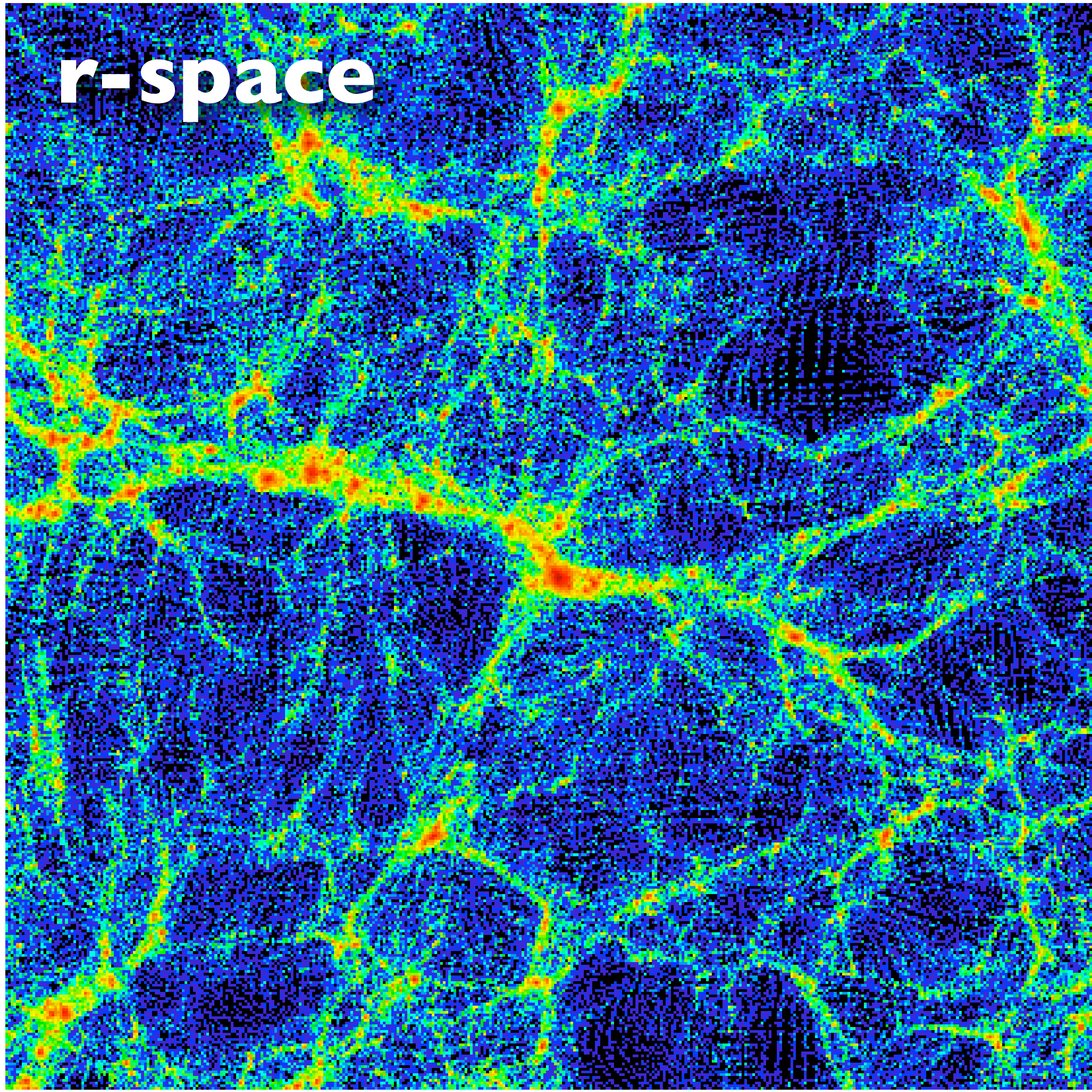


e.g., Scoccimarro'04

$$P(k,\mu) = D_{\rm f}(k\mu\, f\,\sigma_{\rm v}) \times \left[P_{\delta\delta}(k) + 2\,f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right]$$

streaming model

vel. divergence: $\theta \equiv -(1+z)/(Hf)\nabla\mathbf{v}$ vel. dispersion: $\sigma_{\rm v}$



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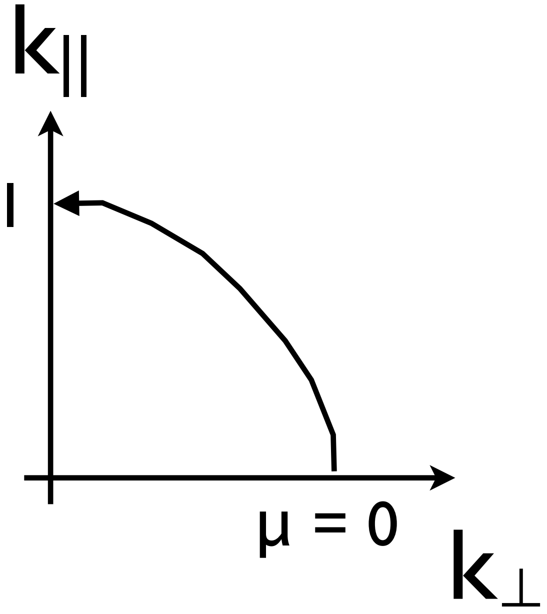

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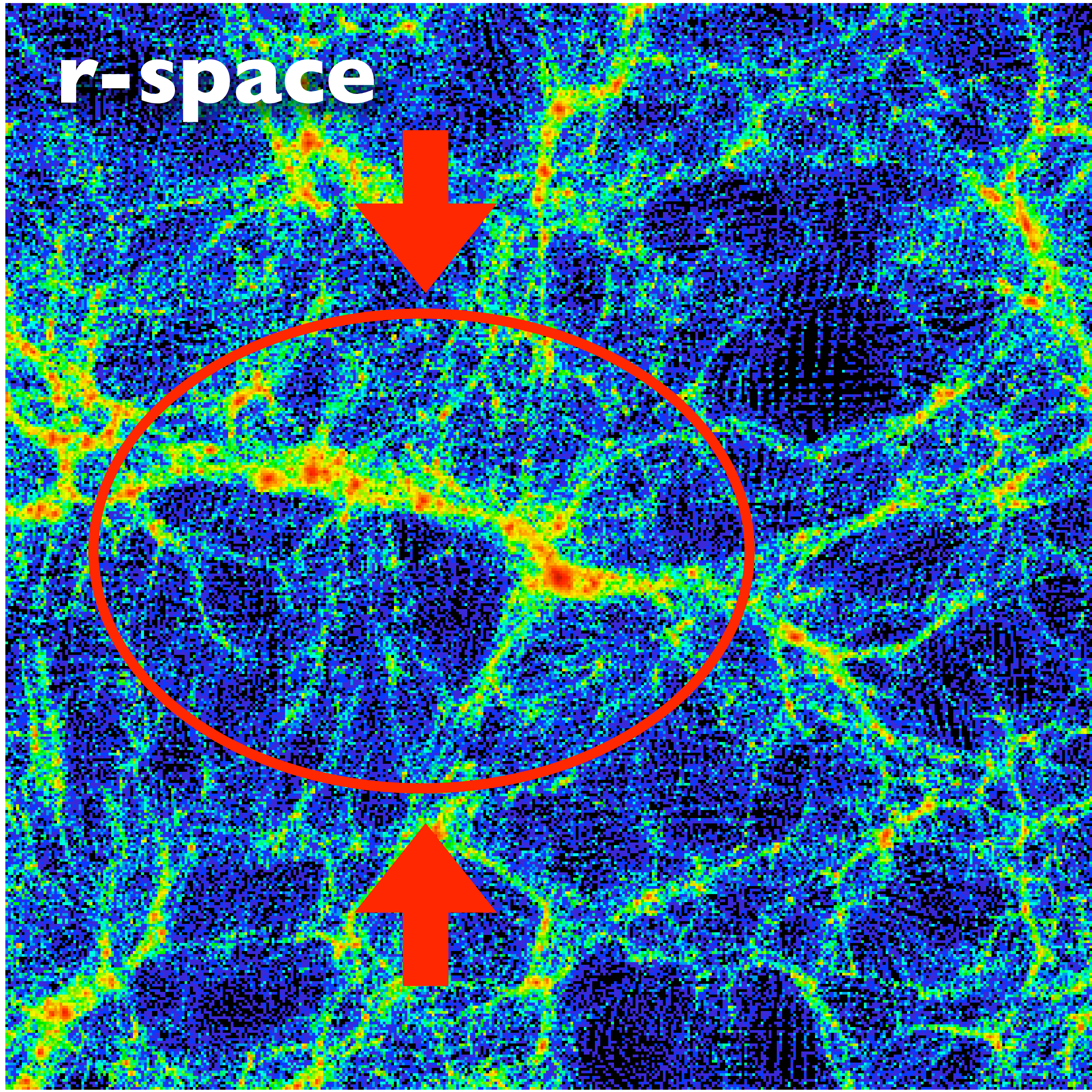

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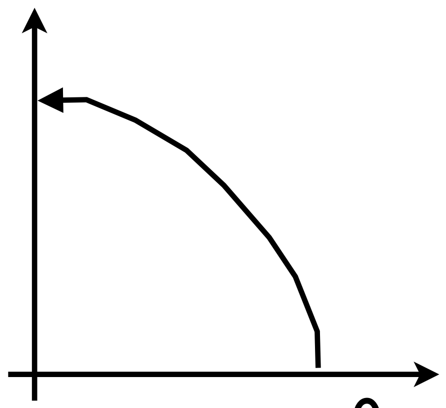

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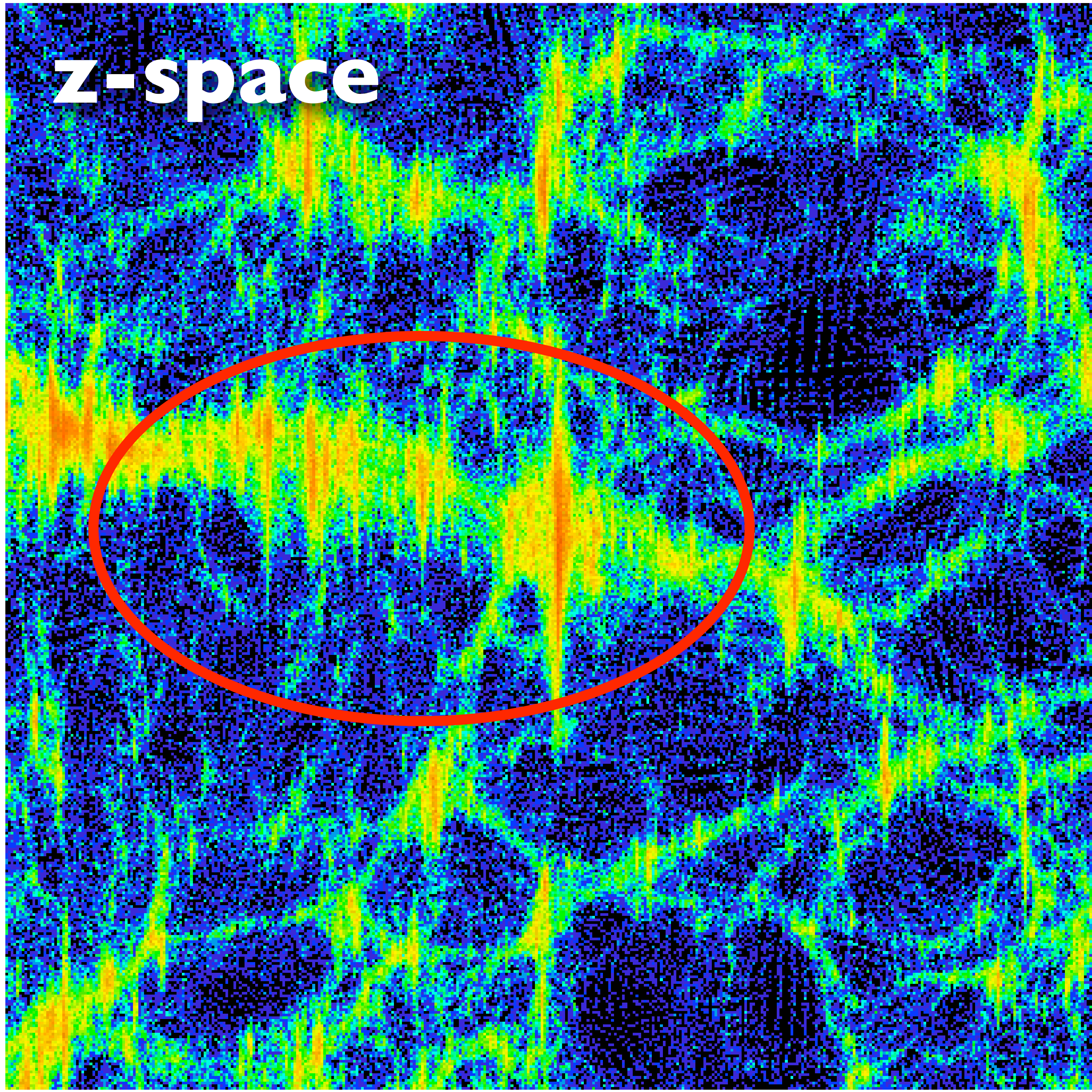

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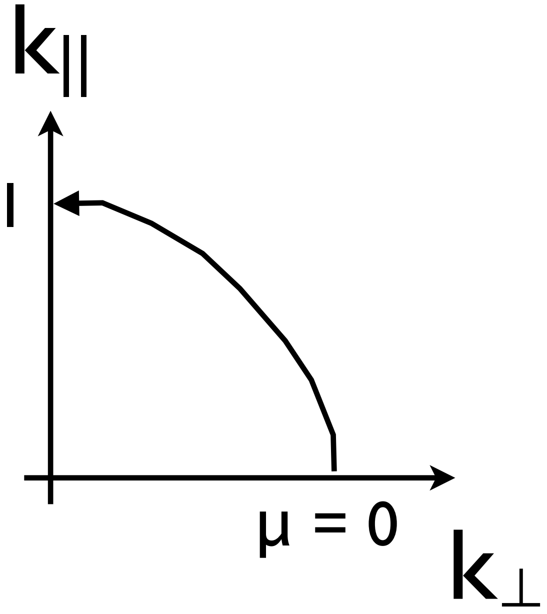

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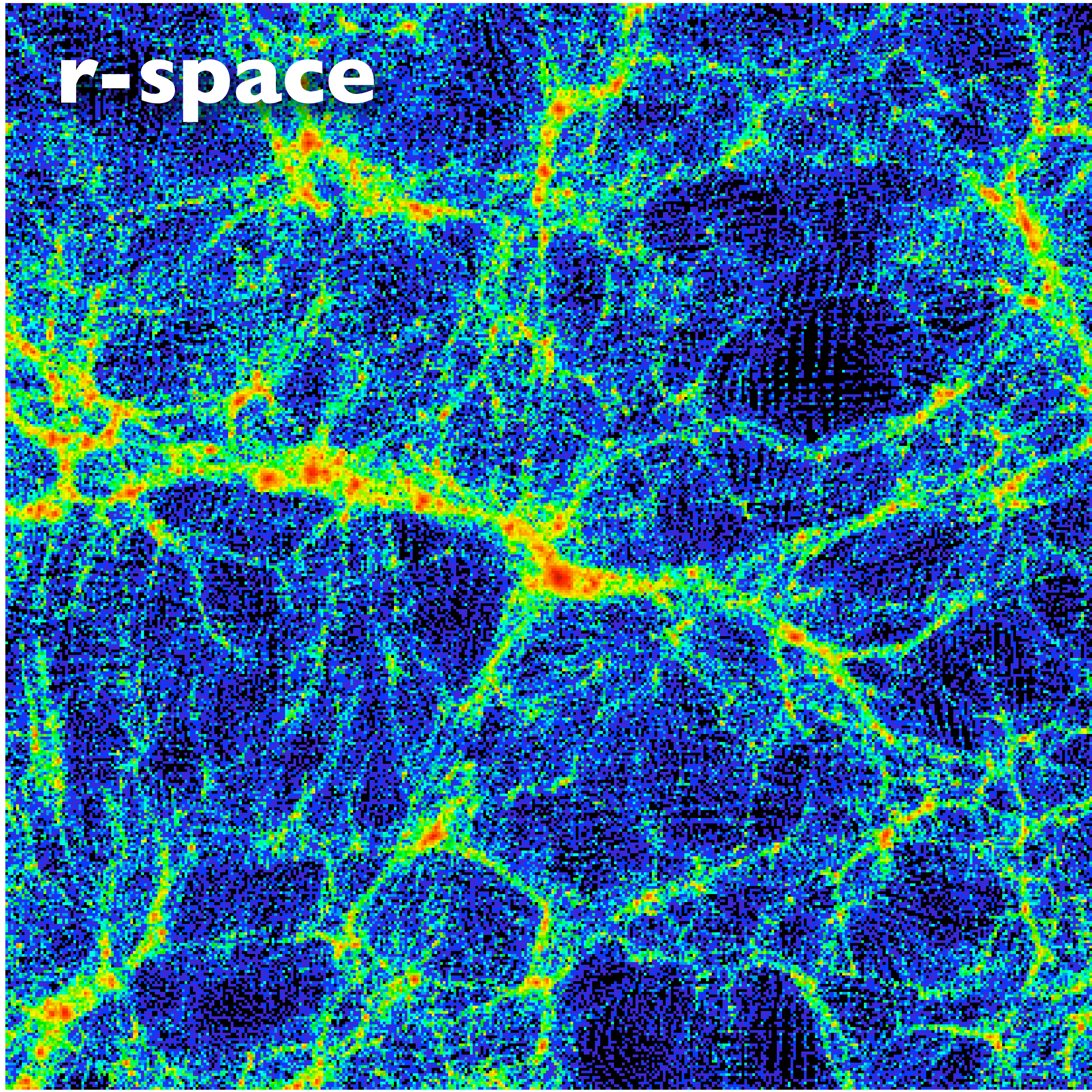

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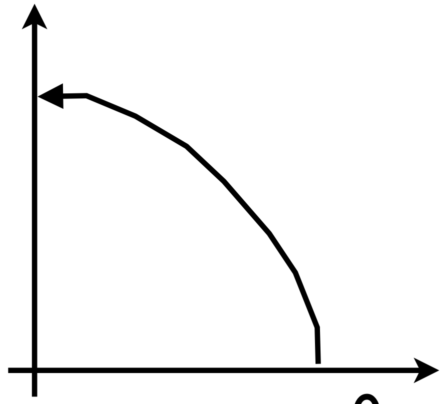

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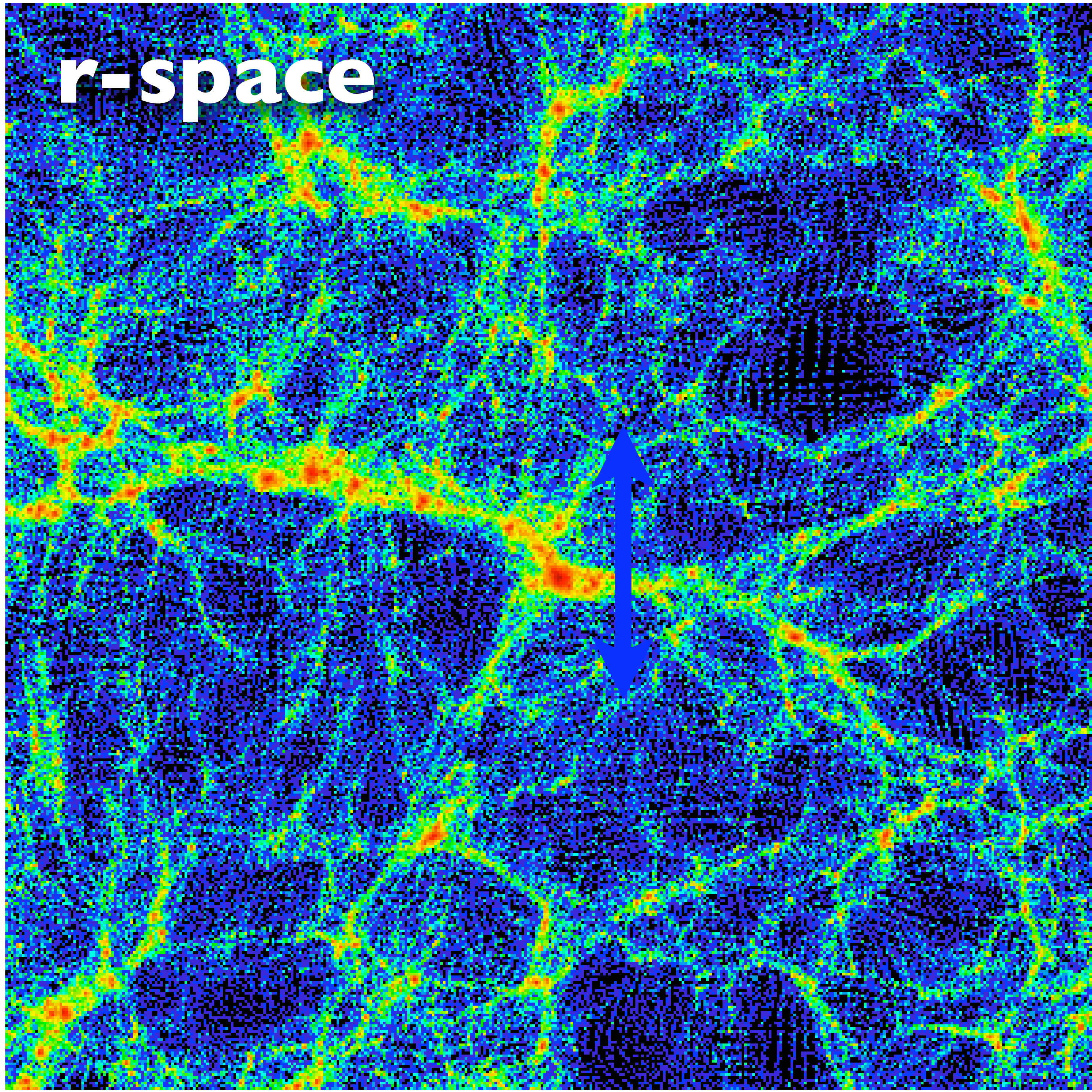

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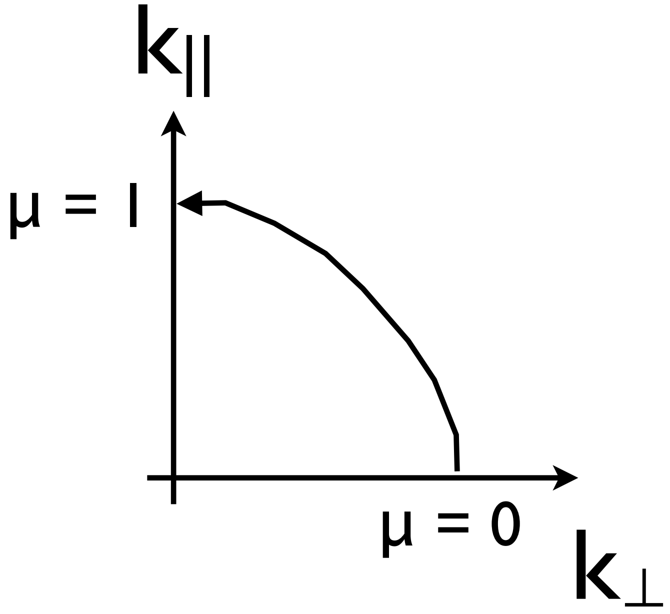

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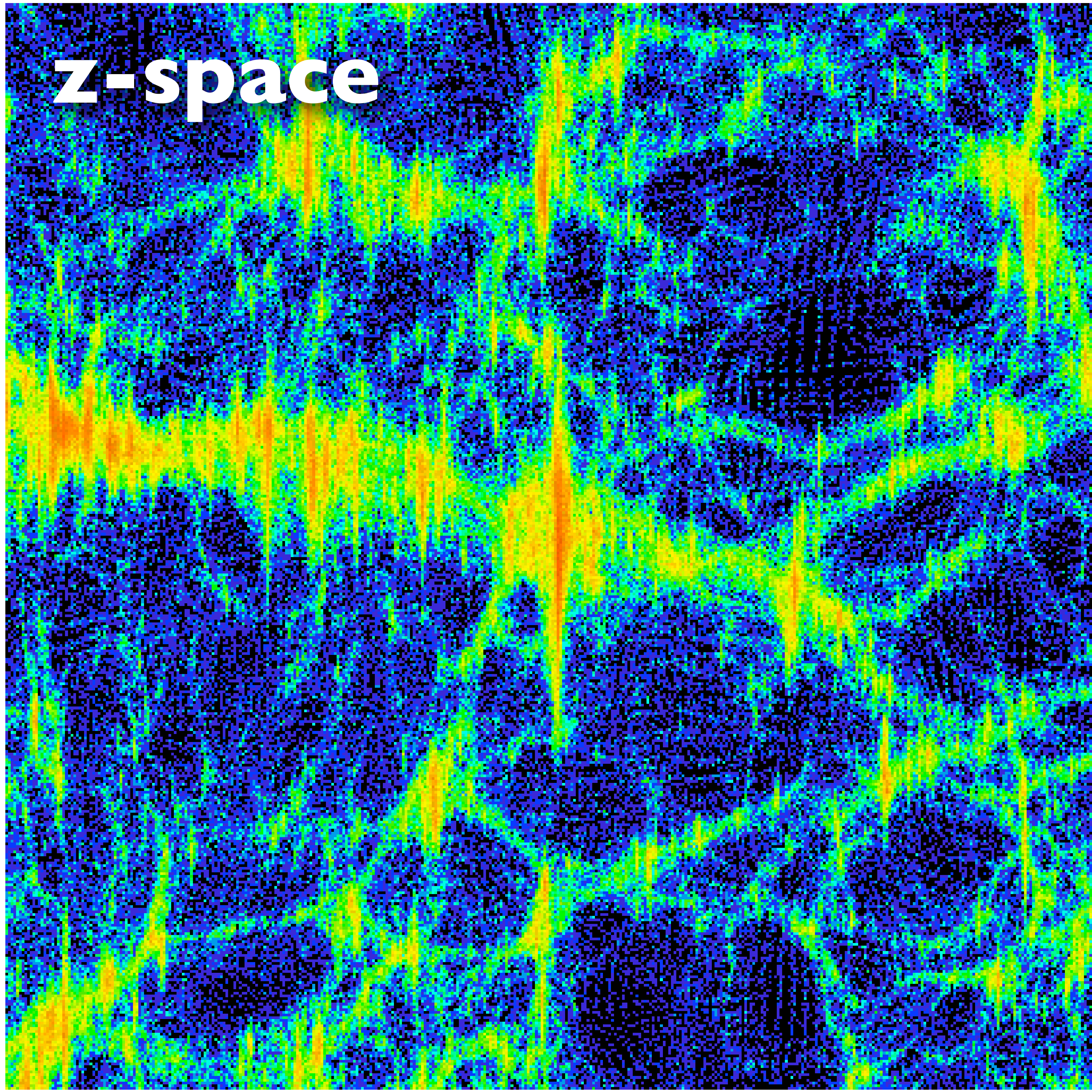


Redshift-space distortions (contd.): TNS model

Exact formula for the z-space P(k)

$$P^{(\mathrm{S})}(\boldsymbol{k}) = \int d^3\boldsymbol{x}\, e^{i\boldsymbol{k}\cdot\boldsymbol{x}} \langle e^{-ik\mu\, f\Delta u_z} \times \{\delta(\boldsymbol{r}) + f\nabla_z u_z(\boldsymbol{r})\}\{\delta(\boldsymbol{r}') + f\nabla_z u_z(\boldsymbol{r}')\}\rangle$$

notice $\langle e^A BC\rangle \neq \langle e^A\rangle\langle BC\rangle$

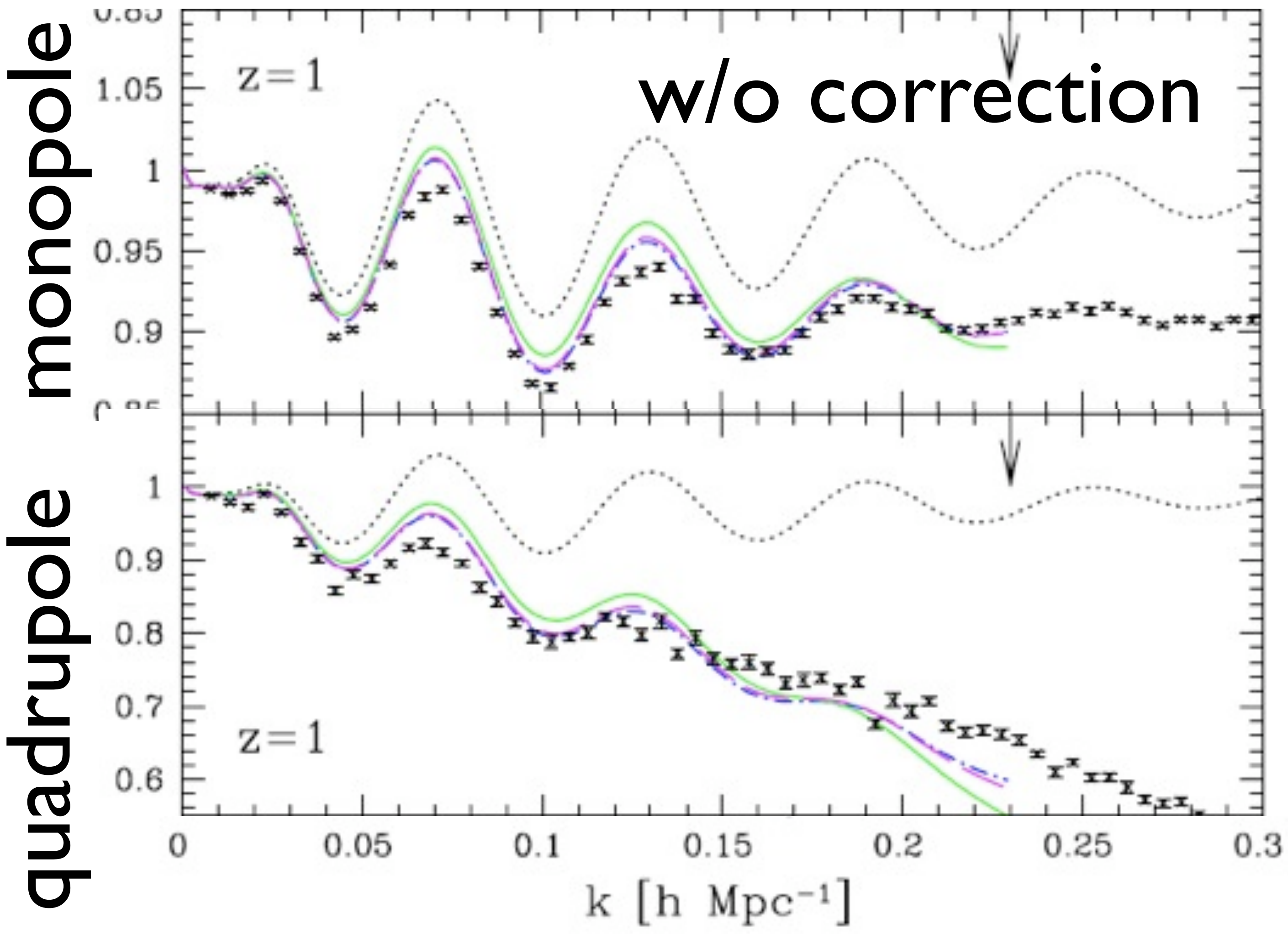
with a help of cumulant expansion theorem

$$P(k,\mu) = D_{\mathrm{f}}(k\,\mu\, f\sigma_{\mathrm{v}}) \times \Big[P_{\delta\delta}(k) + 2\, f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + \underline{A(k,\mu;f) + B(k,\mu;f)}\Big]$$

A term ∝ cross-bispectrum of δ & θ   new terms!

B term ∝ sum of convolutions of $P_{\delta\theta}$ & $P_{\theta\theta}$

Taruya, Nishimichi, Saito ('10)



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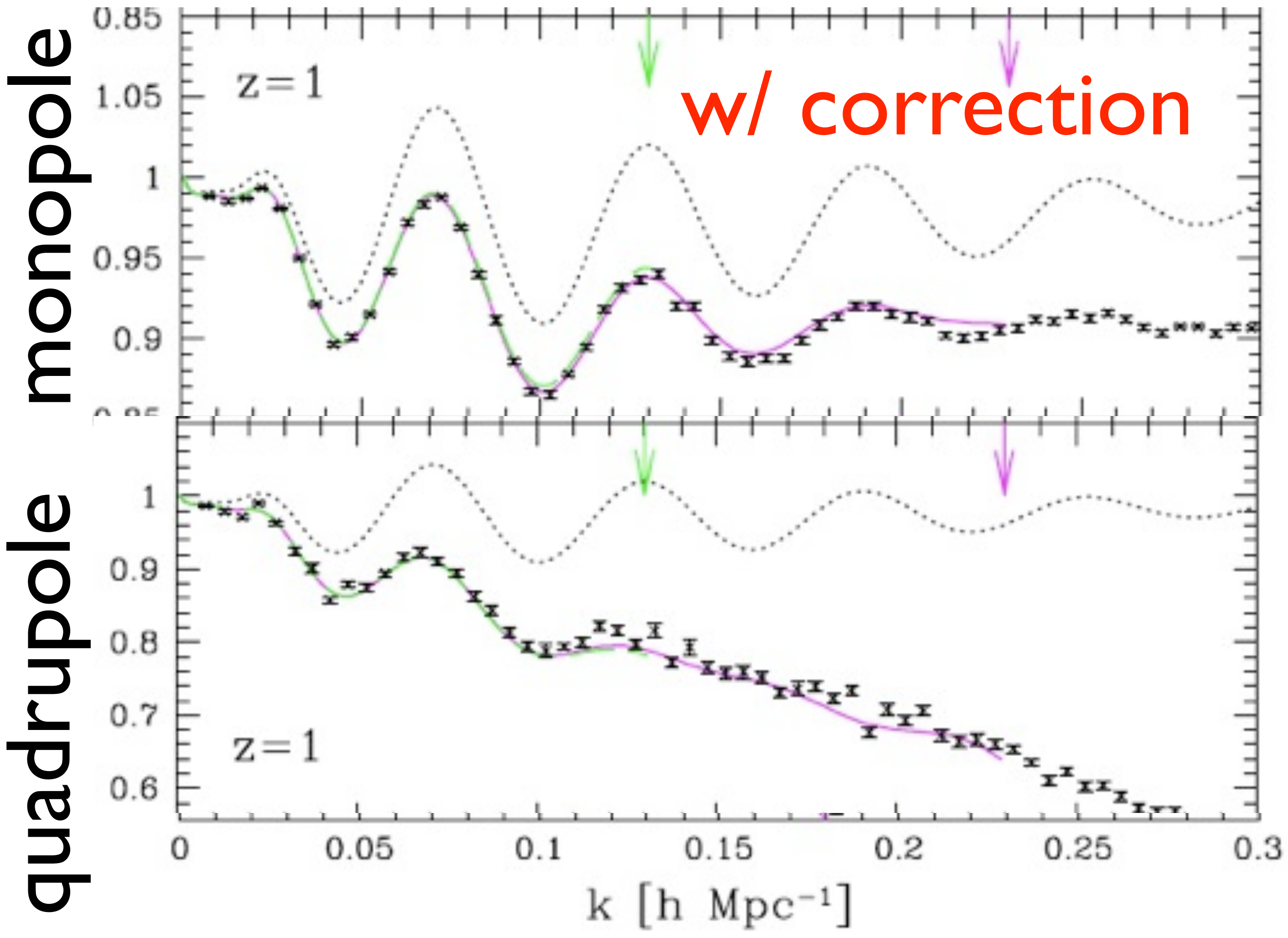
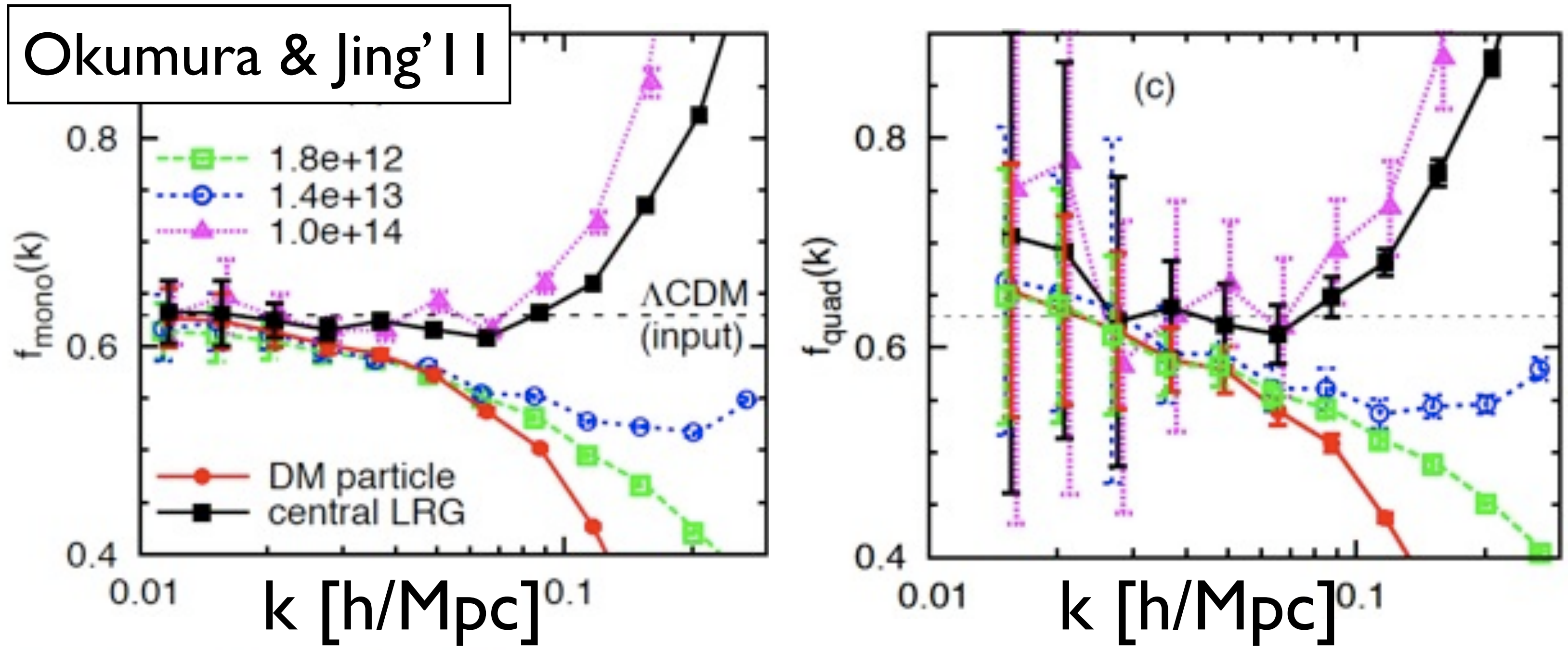


RSDs for biased tracers?

Many people are working hard on this!

e.g., Okumura & Jing'11
Tang, Kayo & Takada'11
Reid & White'11
Sato & Matsubara '11



biased tracer?

assume $\delta_g = b\delta$

$$P(k,\mu) = D_{\rm f}(k\,\mu\,f\sigma_{\rm v}) \times \Big[P_{\delta\delta}(k) + 2\,f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k) + A(k,\mu;f) + B(k,\mu;f)\Big]$$

$$P_{\rm h}(k,\mu) = D_{\rm f}(k\,\mu\,f\sigma_{\rm v}) \times b^2\Big[P_{\delta\delta}(k) + 2\,\beta\,\mu^2 P_{\delta\theta}(k) + \beta^2\mu^4 P_{\theta\theta}(k) + b\,A(k,\mu;\beta) + b^2\,B(k,\mu;\beta)\Big]$$

$\beta = f / b$

A term ∝ cross-bispectrum of δ & θ

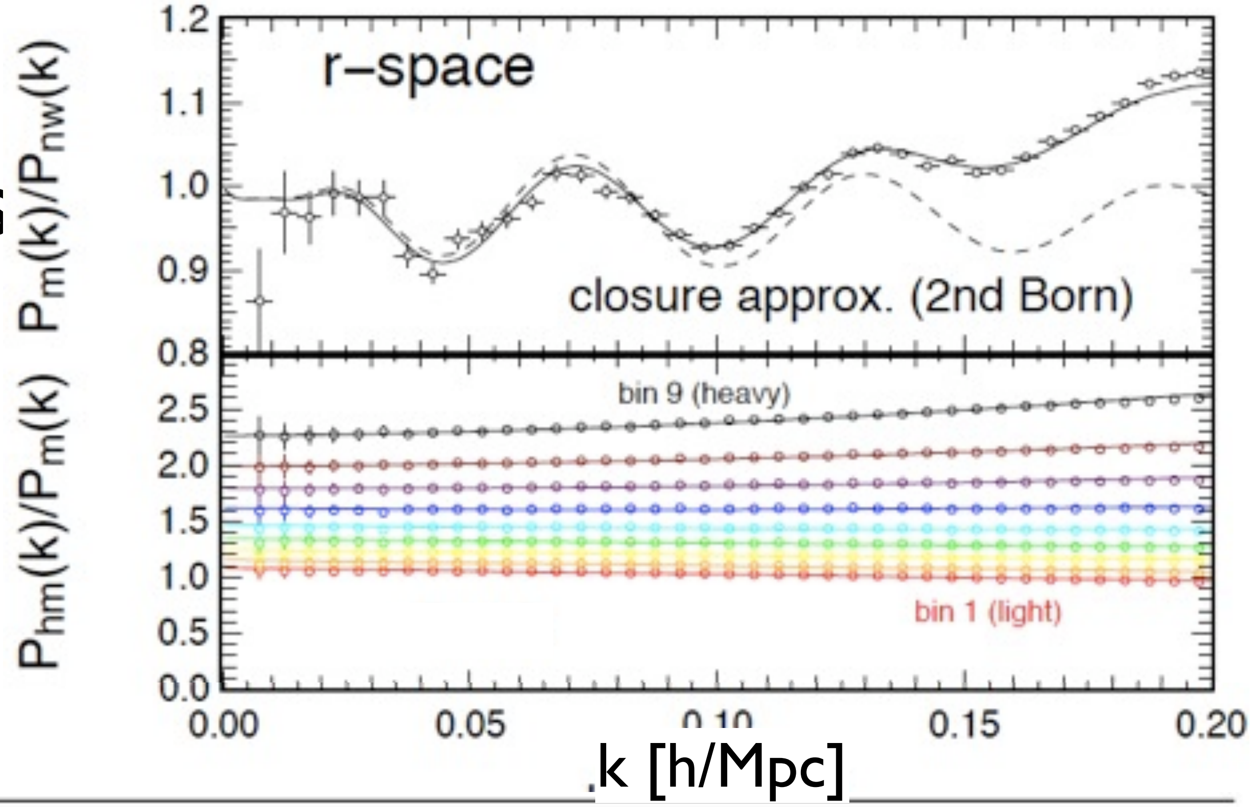
B term ∝ sum of convolutions of $P_{\delta\theta}$ & $P_{\theta\theta}$

Are correction terms *enhanced* by bias?

Analysis

Large N-body simulations ($L=1.14$Gpc/h, $N=1{,}280^3$) starting with 2LPT initial conditions x 15 realizations

- ✓ 9 halo catalogs over a wide mass range @ z=0.35
- ✓ volume & number density ≒ SDSS DR7 LRGs
- ✓ b(k) is directly measured from r-space clustering
- ✓ σ_v is treated as a free fitting parameter



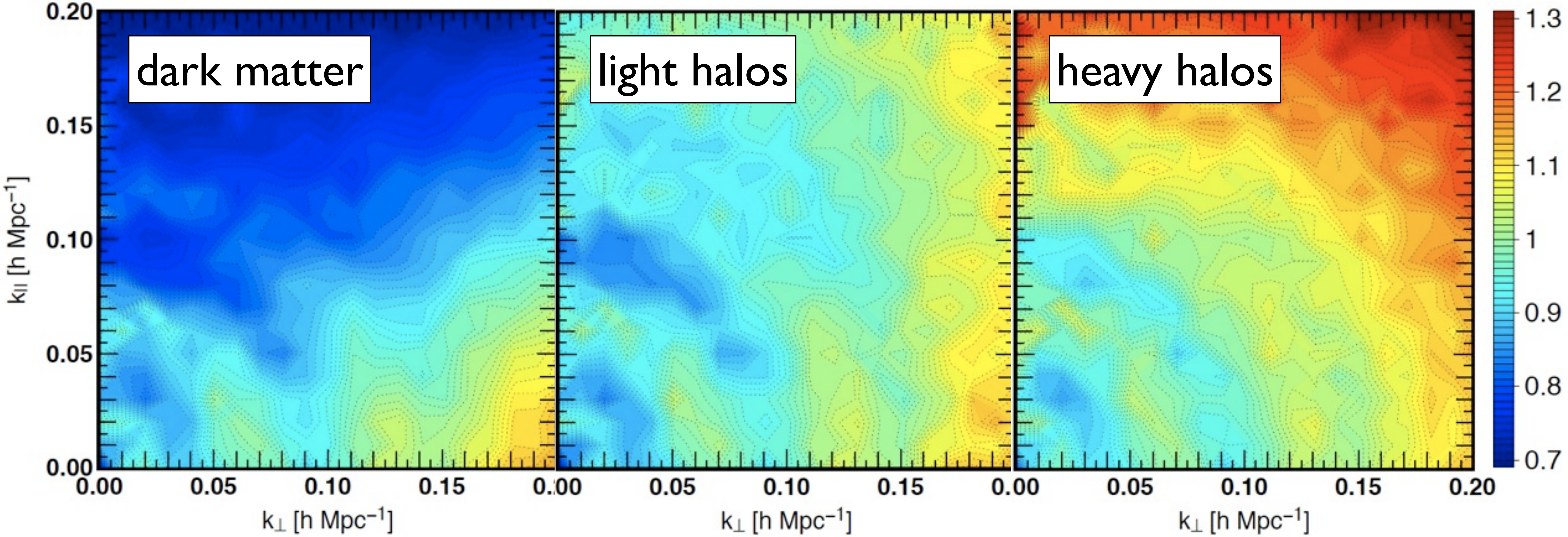
mass: $h^{-1}M_{sun}$, density: h^3Mpc^{-3}

Sample	bin 1 (light)	bin 2	bin 3	bin 4	bin 5	bin 6	bin 7	bin 8	bin 9 (heavy)
$M_{\rm min}$	1.77×10^{12}	2.49×10^{12}	3.54×10^{12}	4.98×10^{12}	7.09×10^{12}	1.00×10^{13}	1.42×10^{13}	2.01×10^{13}	2.84×10^{13}
$M_{\rm max}$	5.54×10^{12}	1.02×10^{13}	1.74×10^{13}	2.66×10^{13}	4.04×10^{13}	6.76×10^{13}	1.19×10^{14}	2.08×10^{14}	-
$\overline{M}_{\rm h}$	2.96×10^{12}	4.65×10^{12}	7.08×10^{12}	9.37×10^{12}	1.47×10^{13}	2.18×10^{13}	3.21×10^{13}	4.63×10^{13}	7.03×10^{13}
n_h	1.57×10^{-3}	1.26×10^{-3}	9.46×10^{-4}	6.87×10^{-4}	4.87×10^{-4}	3.47×10^{-4}	2.43×10^{-4}	1.64×10^{-4}	1.09×10^{-4}
b_0	1.08	1.16	1.25	1.35	1.47	1.62	1.80	1.99	2.26

Result

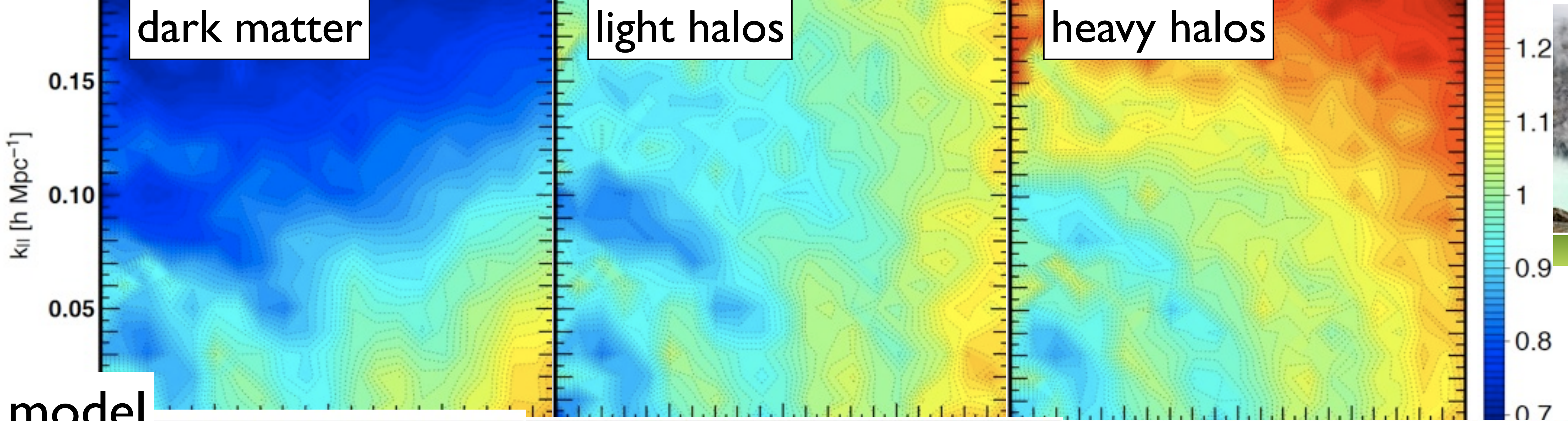
$$\frac{P_{\rm halo}(k_{||}, k_\perp)}{(b^2 + f\,\mu^2)^2 P_{\rm lin,no\text{-}wiggle}(k)}$$

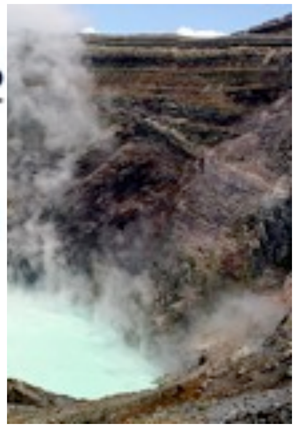
N-body simulations



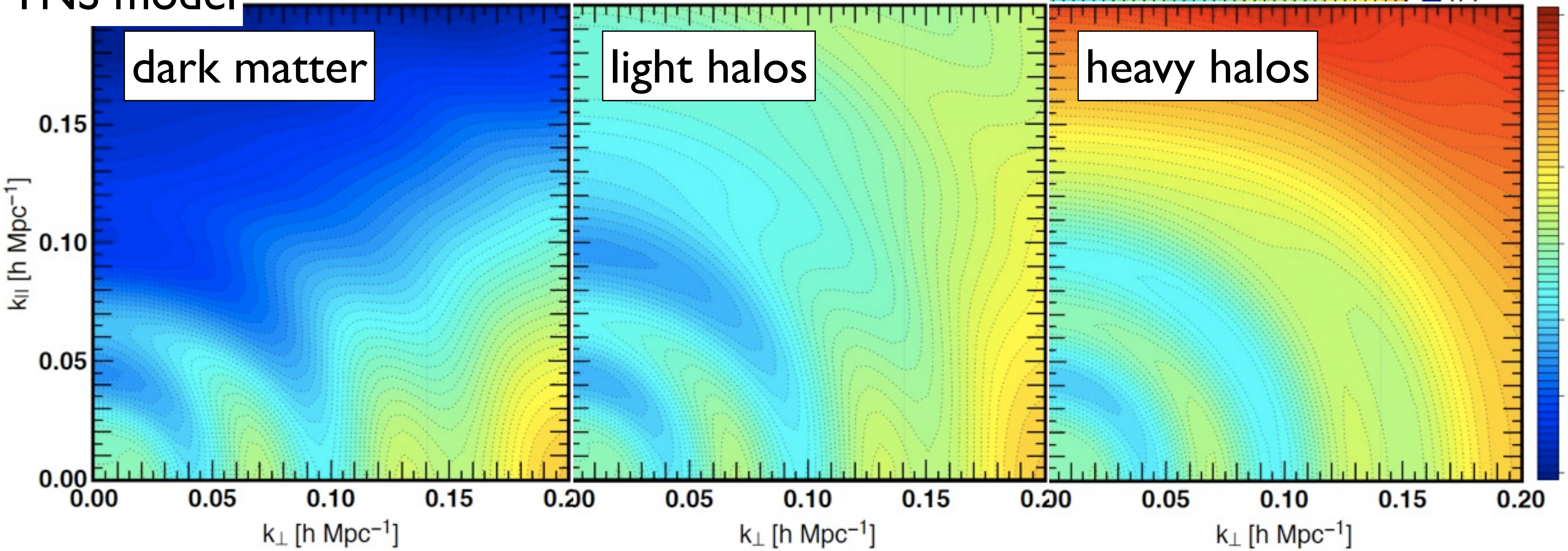
Re

$(b^2 +$





TNS model



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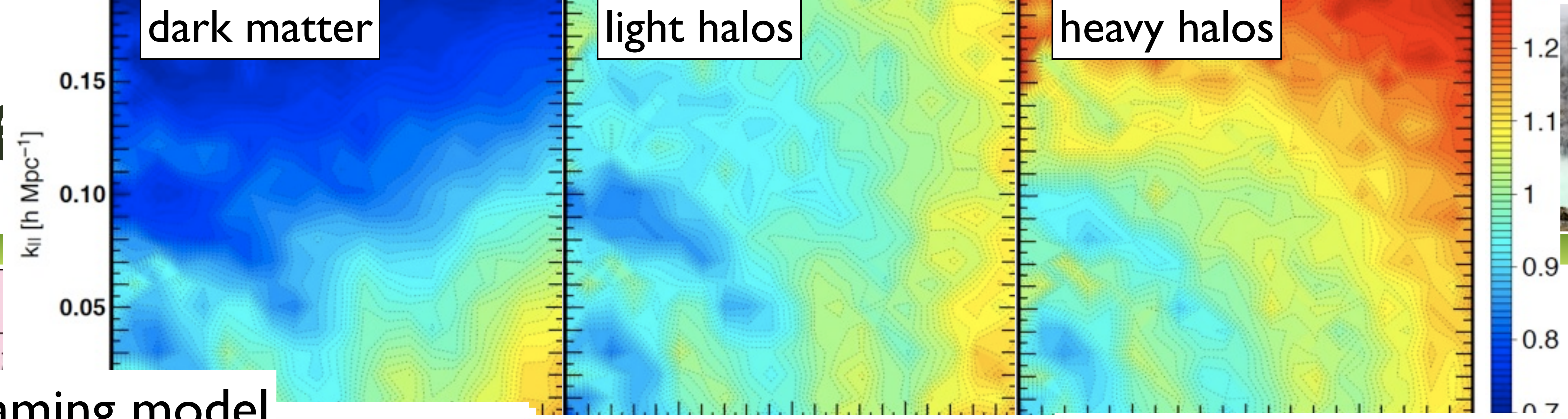
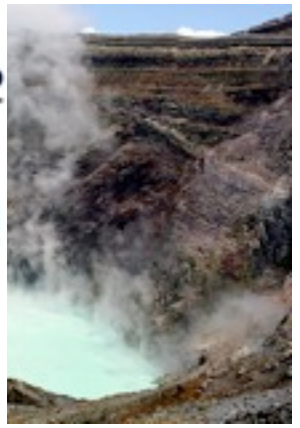
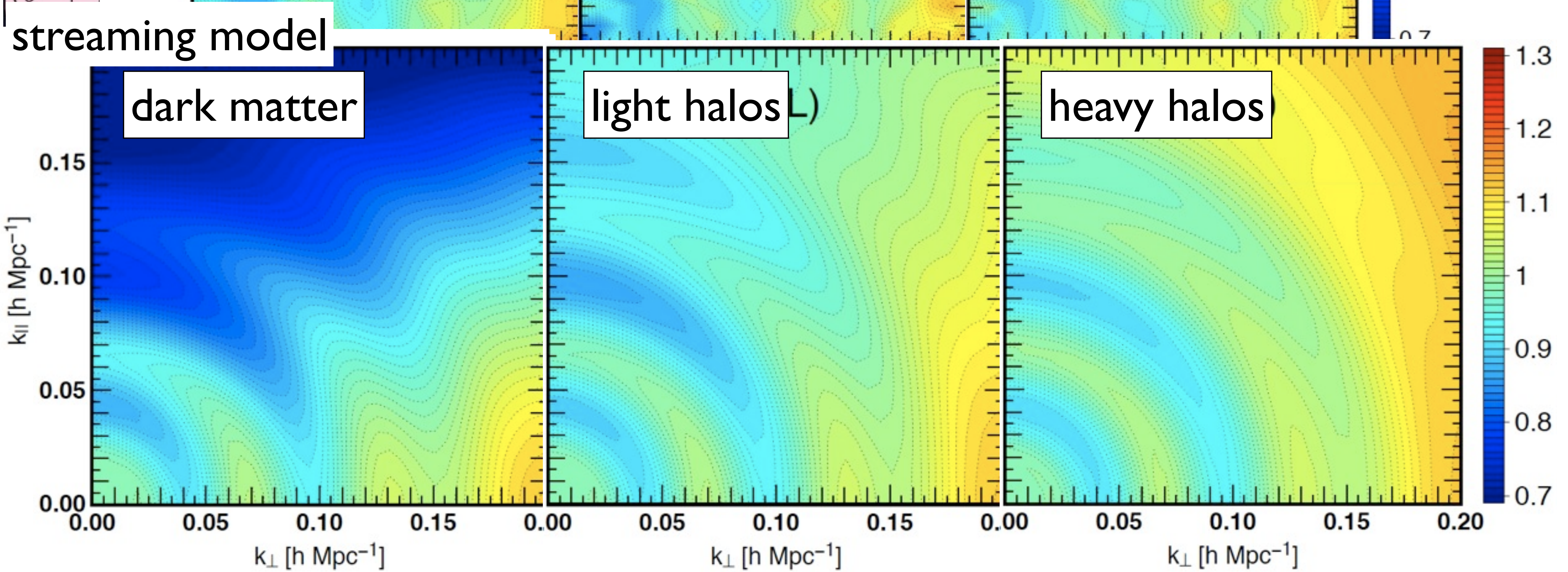

dark matter
light halos
heavy halos
0.15
0.10
0.05
k|| [h Mpc^{-1}]
1.2
1.1
1
0.9
0.8




streaming model
dark matter
light halos
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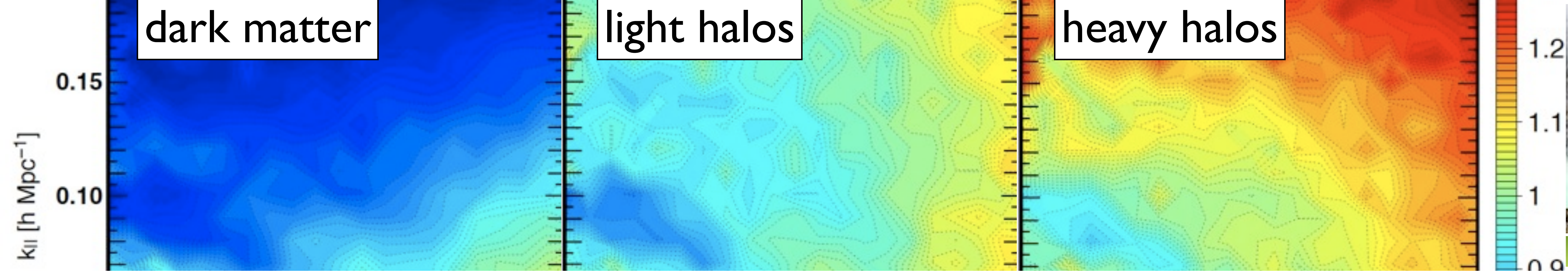
0.15
0.10
0.05
0.00
k|| [h Mpc^{-1}]
0.00
0.05
0.10
0.15
0.20
k⊥ [h Mpc^{-1}]
1.3
1.2
1.1
1
0.9
0.8
0.7

Re


dark matter
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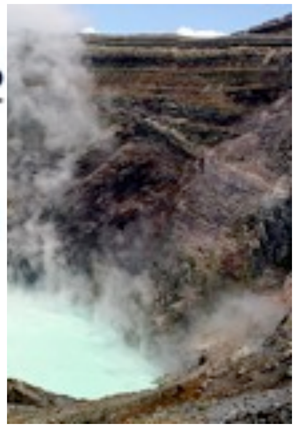
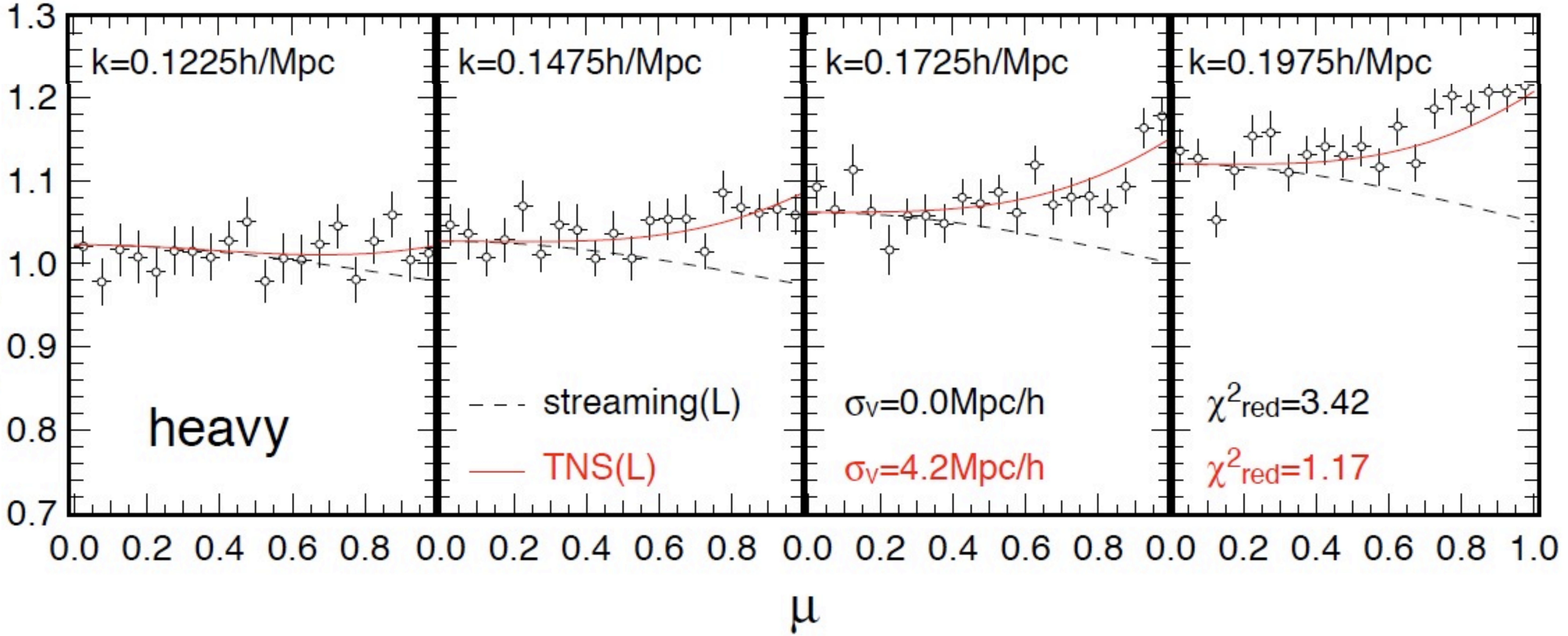
0.15
0.10
k|| [h Mpc⁻¹]
1.2
1.1
1




k=0.1225h/Mpc
k=0.1475h/Mpc
k=0.1725h/Mpc
k=0.1975h/Mpc
heavy
streaming(L)
TNS(L)
σ_v=0.0Mpc/h
σ_v=4.2Mpc/h
χ^2_{red}=3.42
χ^2_{red}=1.17
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.0 0.2 0.4 0.6 0.8 0.0 0.2 0.4 0.6 0.8 0.0 0.2 0.4 0.6 0.8 0.0 0.2 0.4 0.6 0.8 1.0
μ

Goodness of fits

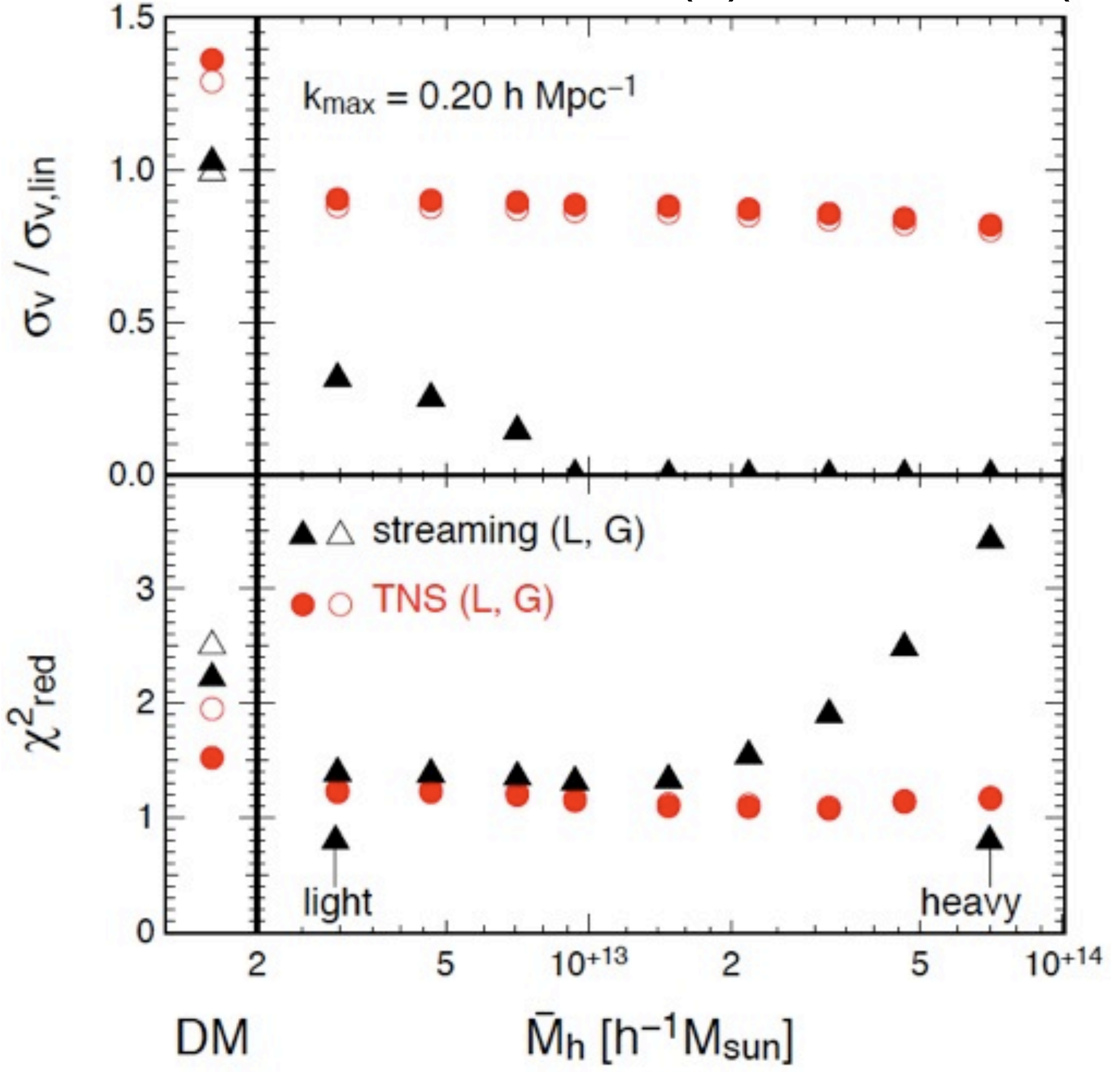
best-fit values of σ_v:

- smaller for streaming model
- consistent with 0 for massive halos
- consistent with the linear theory for TNS
- does not depend the halo mass

goodness of fit:

- worse for streaming model
- especially for massive halos
- reduced χ^2 are close to 1 for TNS
- independent of the halo mass

FoG function: Lorentzian (L), Gaussian (G)



Recovery of f(z)

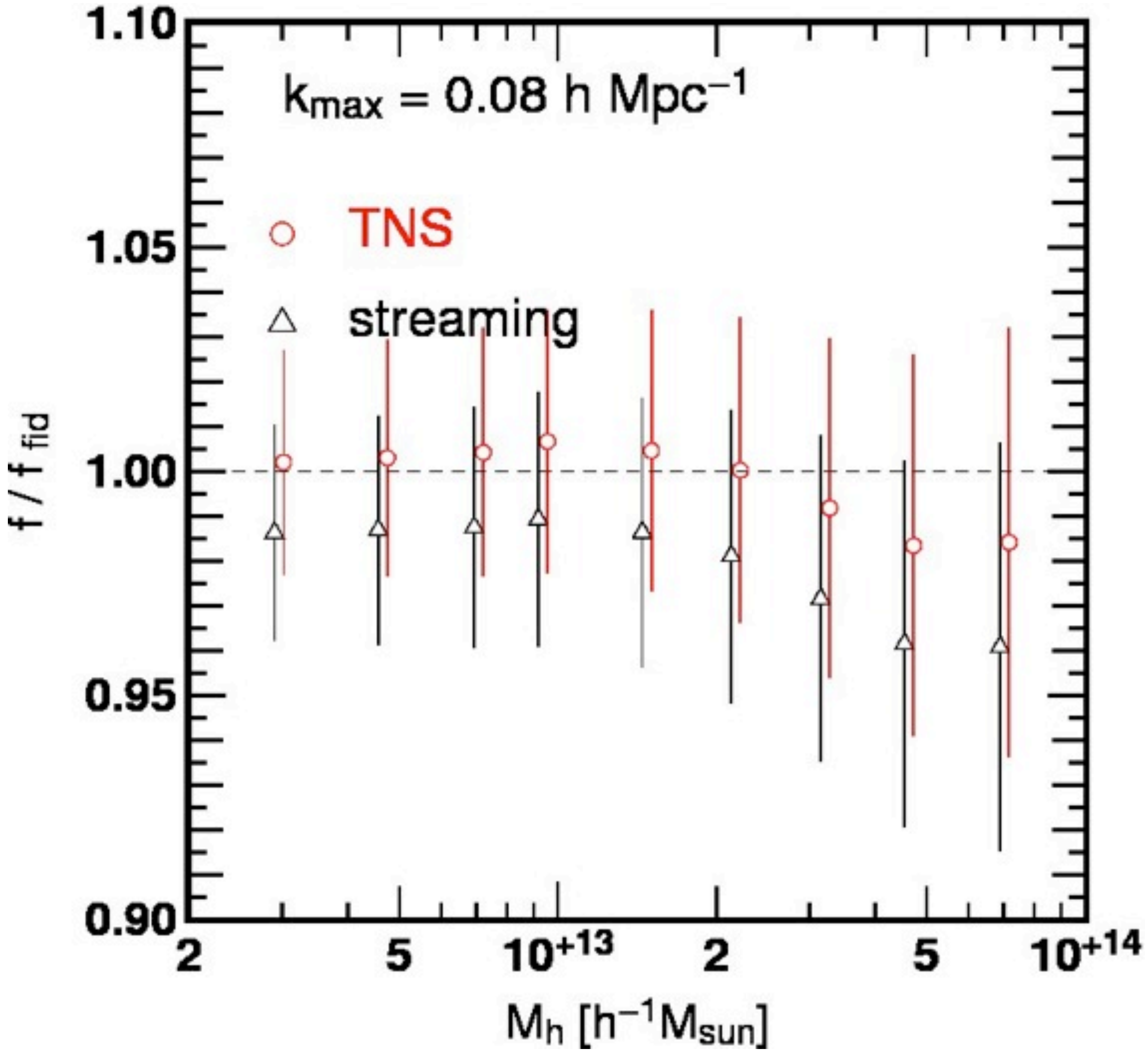
2 parameter fit to N-body data: f and σ_v

✓ streaming model

- seams OK only at k_{max}<0.1h/Mpc
- typically ~5% underestimate of f

✓ TNS model

- gives unbiased estimate of f
- up to k_{max} ~ 0.2 h/Mpc



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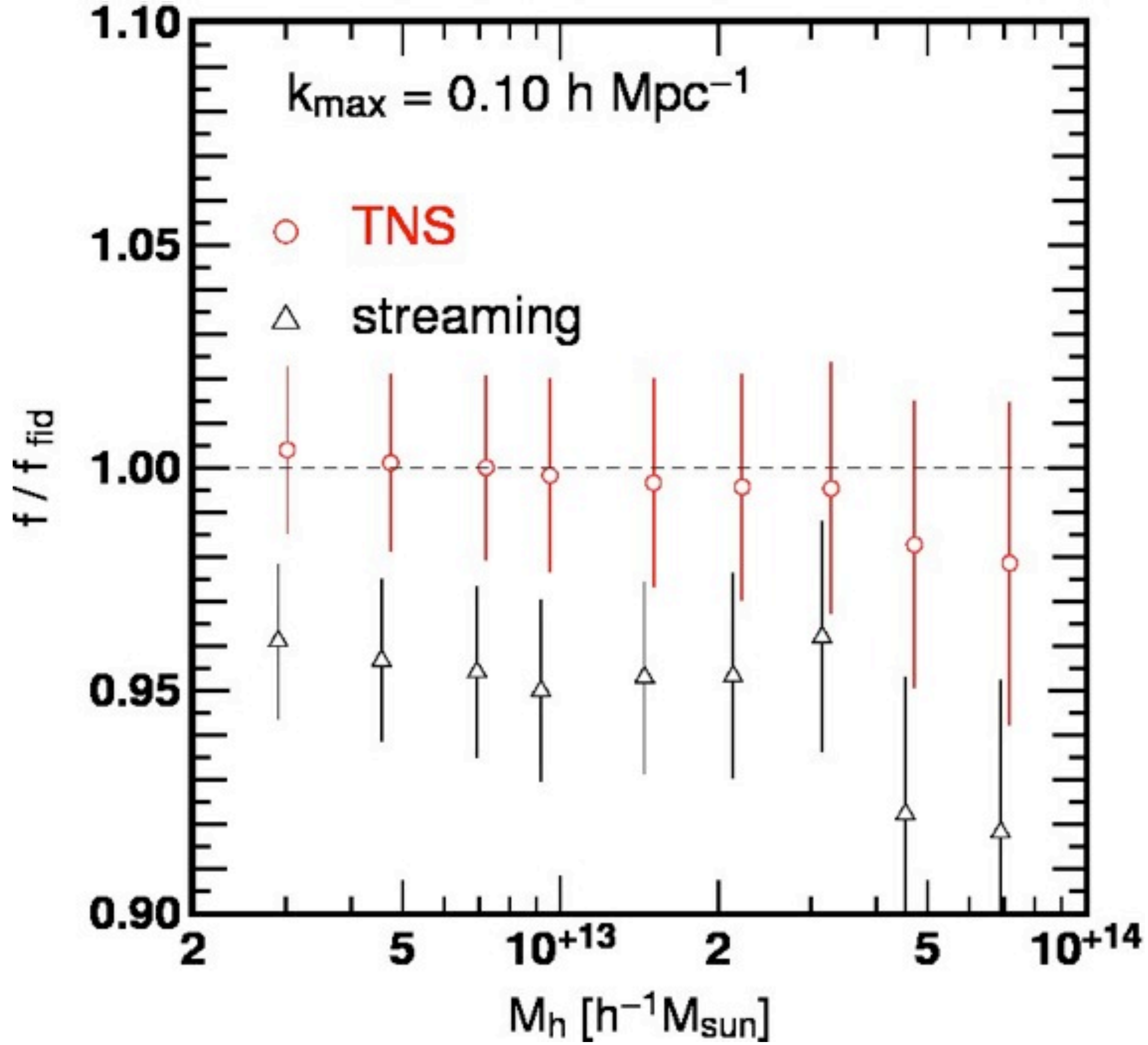

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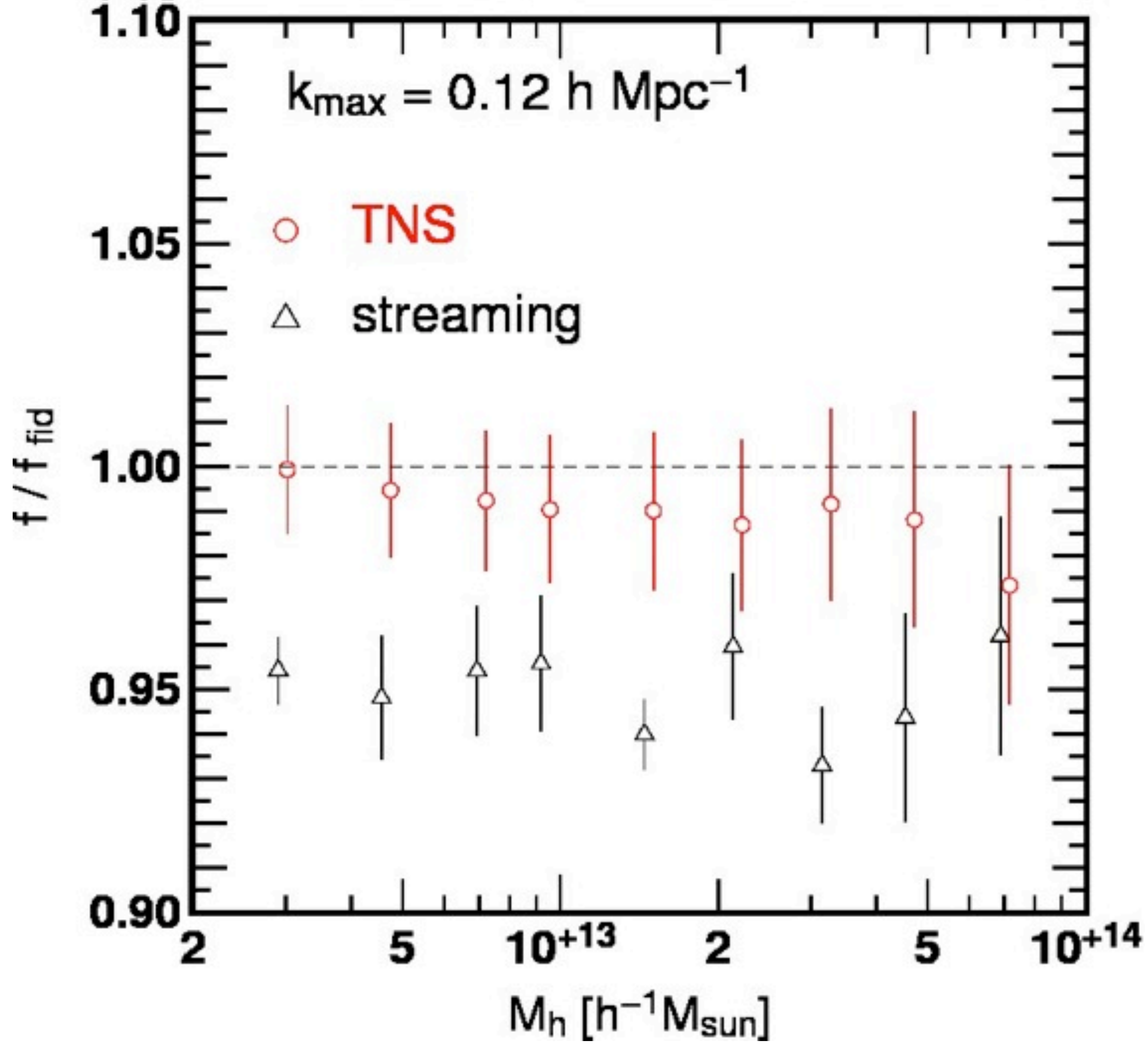

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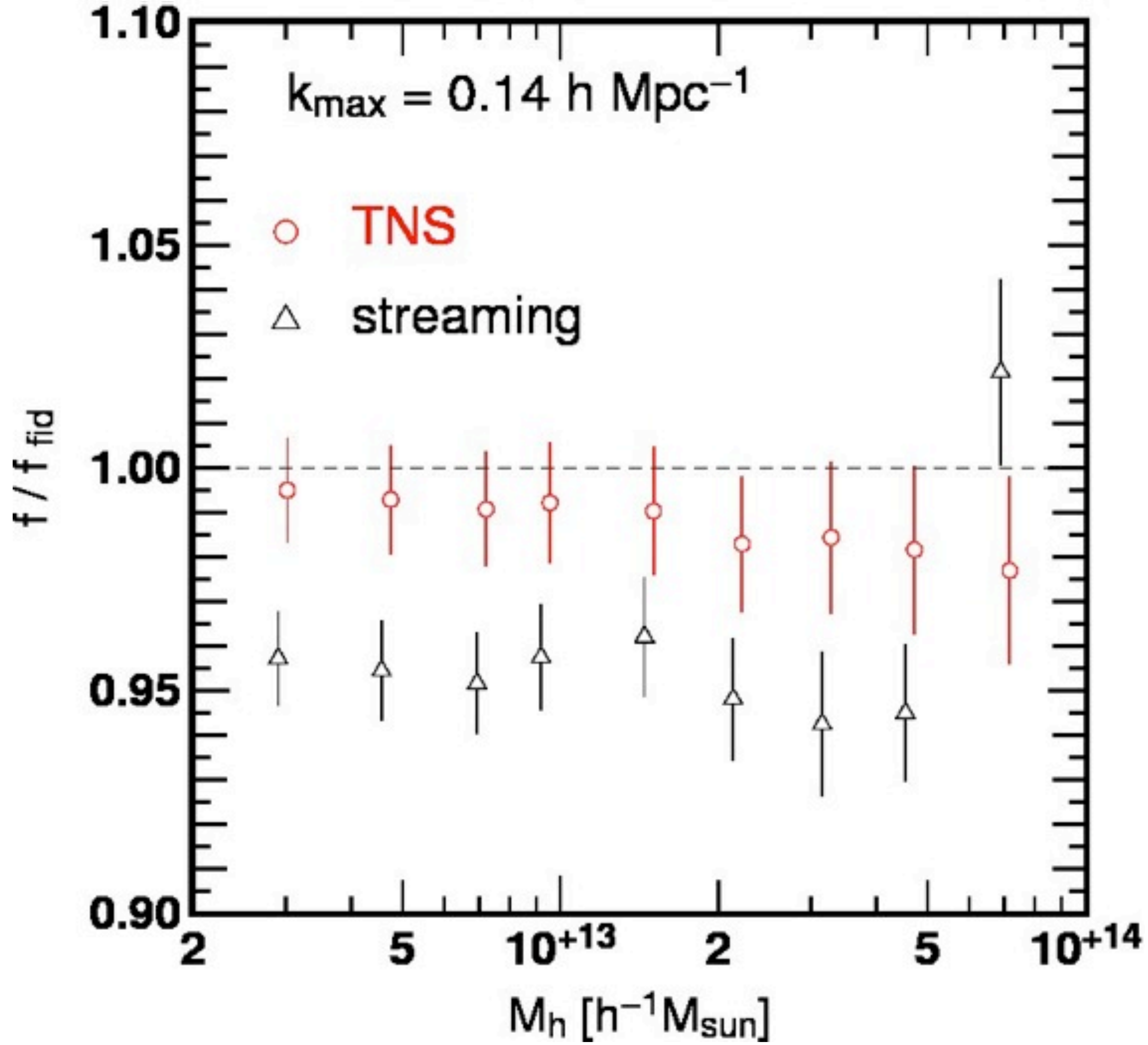

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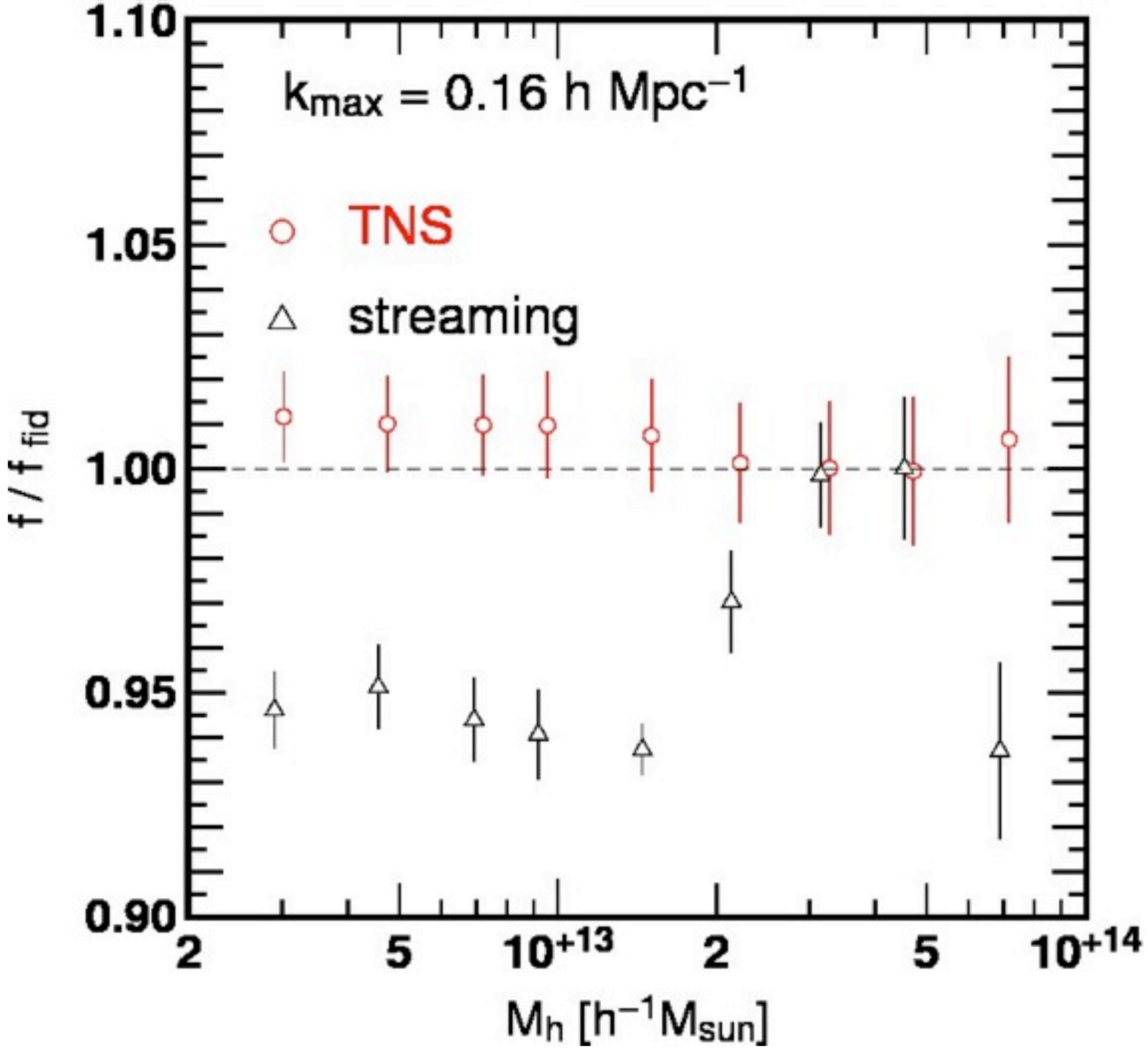
- typically ~5% underestimate of f

✓ TNS model

- gives unbiased estimate of f
- up to k_{max} ~ 0.2 h/Mpc



Recovery of f(z)

2 parameter fit to N-body data: f and σ_v

✓ streaming model
- seams OK only at k_{max}<0.1h/Mpc
- typically ~5% underestimate of f

✓ TNS model
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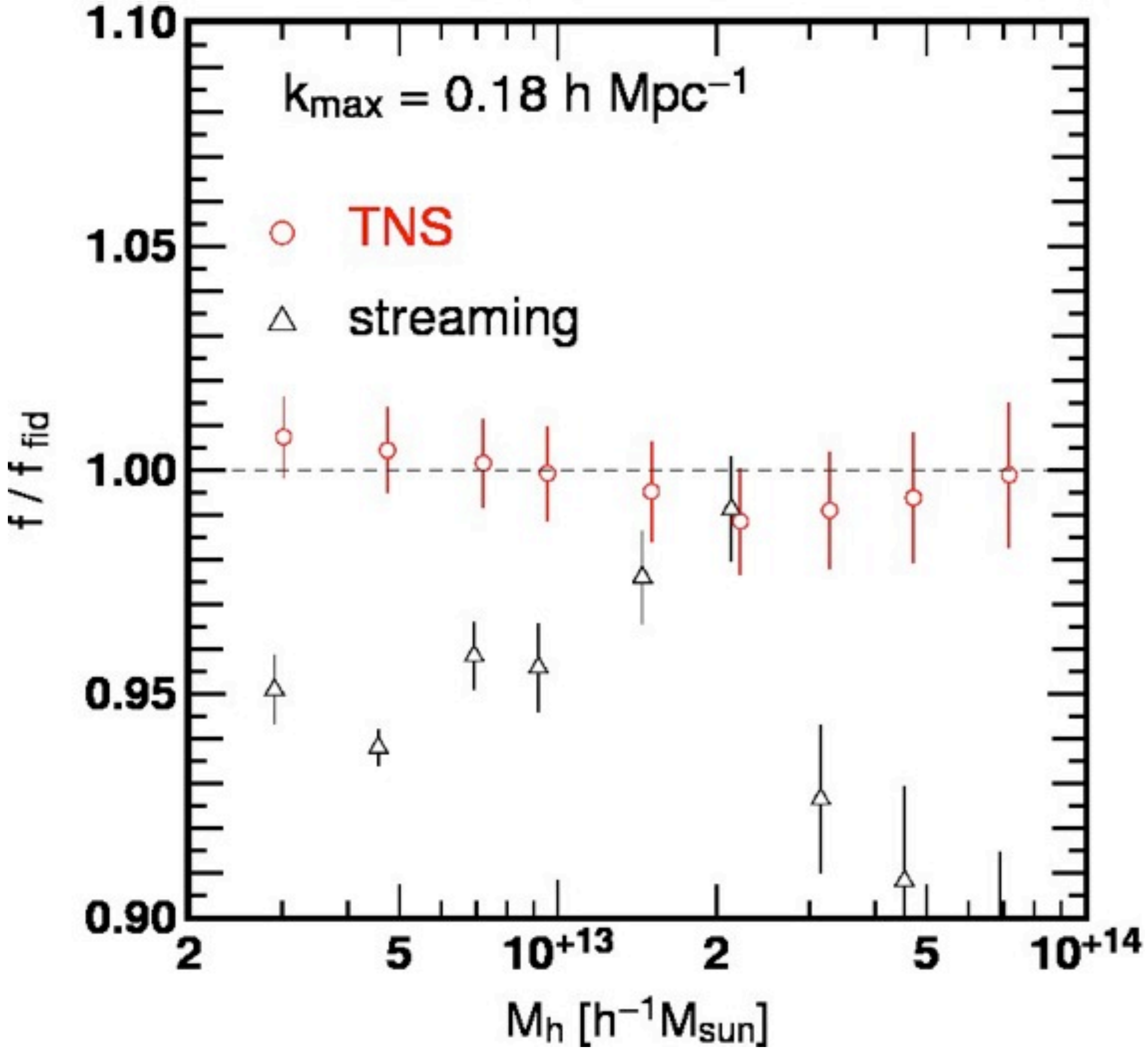
- up to k_{max} ~ 0.2 h/Mpc



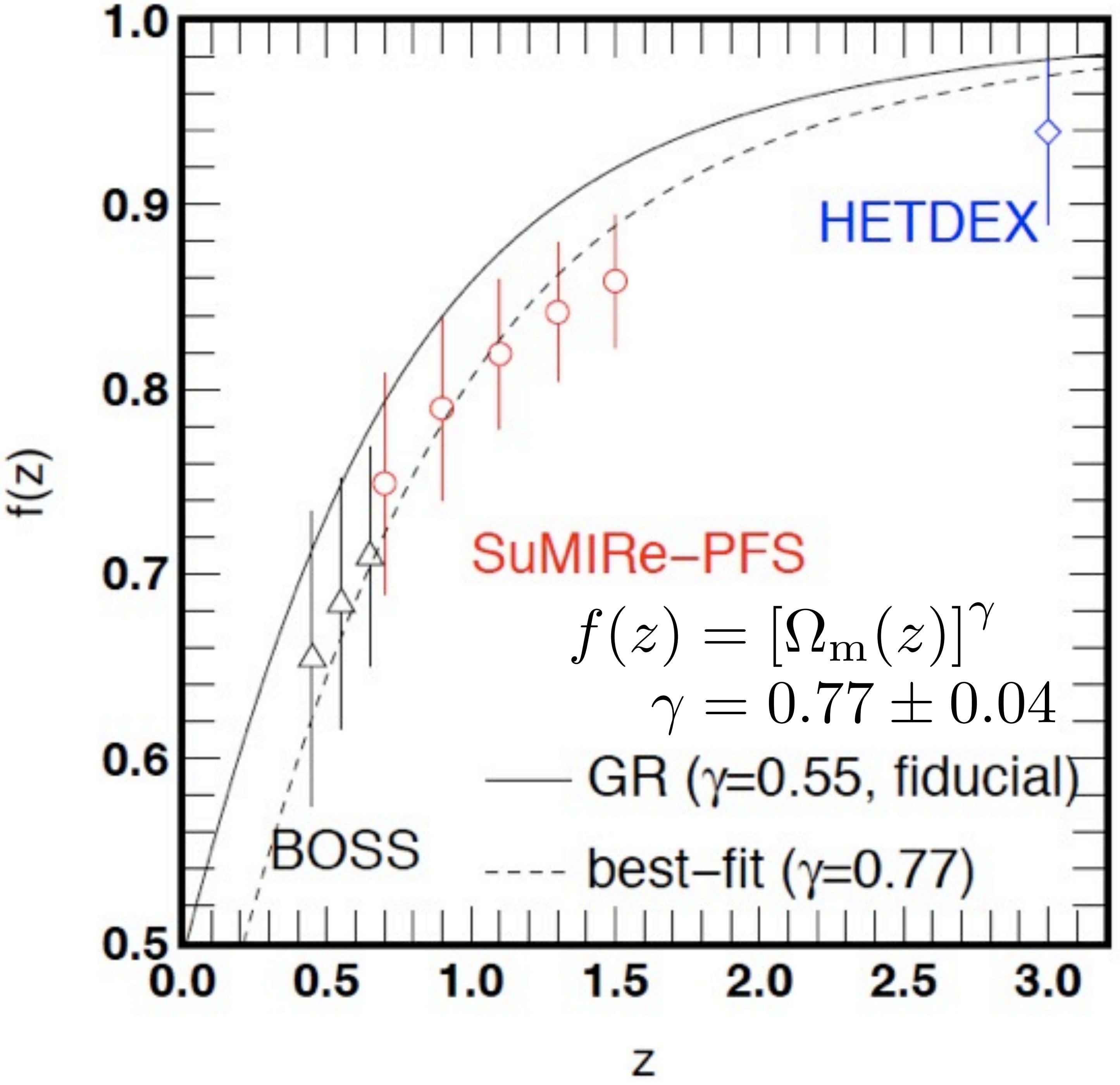
Future/on-going surveys

Fisher matrix analysis with 5 parameters

(b, σ_v, H, D_A, f)

Assumption: TNS model is true, but adopt streaming model

	z_c	V ($h^{-3}Gpc^3$)	n_g (h^3Mpc^{-3})	b	k_{max} ($h\ Mpc^{-1}$)
BOSS	0.45	1.1	3×10^{-4}	2.2	0.15
	0.55	1.5	3×10^{-4}	2.2	0.15
	0.65	1.9	3×10^{-4}	2.2	0.15
SuMIRe-PFS	0.7	0.8	3×10^{-4}	1.5	0.2
	0.9	1.1	3×10^{-4}	1.5	0.2
	1.1	1.4	4×10^{-4}	1.5	0.2
	1.3	1.6	4×10^{-4}	1.5	0.2
	1.5	1.7	4×10^{-4}	1.5	0.2
HETDEX	3.0	3.0	2.5×10^{-4}	2.5	0.4



Summary

- tested the clustering of halos in z-space by N-body simulations ...
  - frequently used phenomenological model is not sufficient

    ~5% systematic bias in f(z)
  - correction terms in TNS model

    more prominent for more massive halos or more biased objects

- codes for our model are publicly available!!

visit CPT library: http://www-utap.phys.s.u-tokyo.ac.jp/~ataruya/cpt_pack.html