Nonlinear Structure Formation at Two Scales: from Bispectrum Baryon Acoustic Oscillations to Evolution of Halo Profiles

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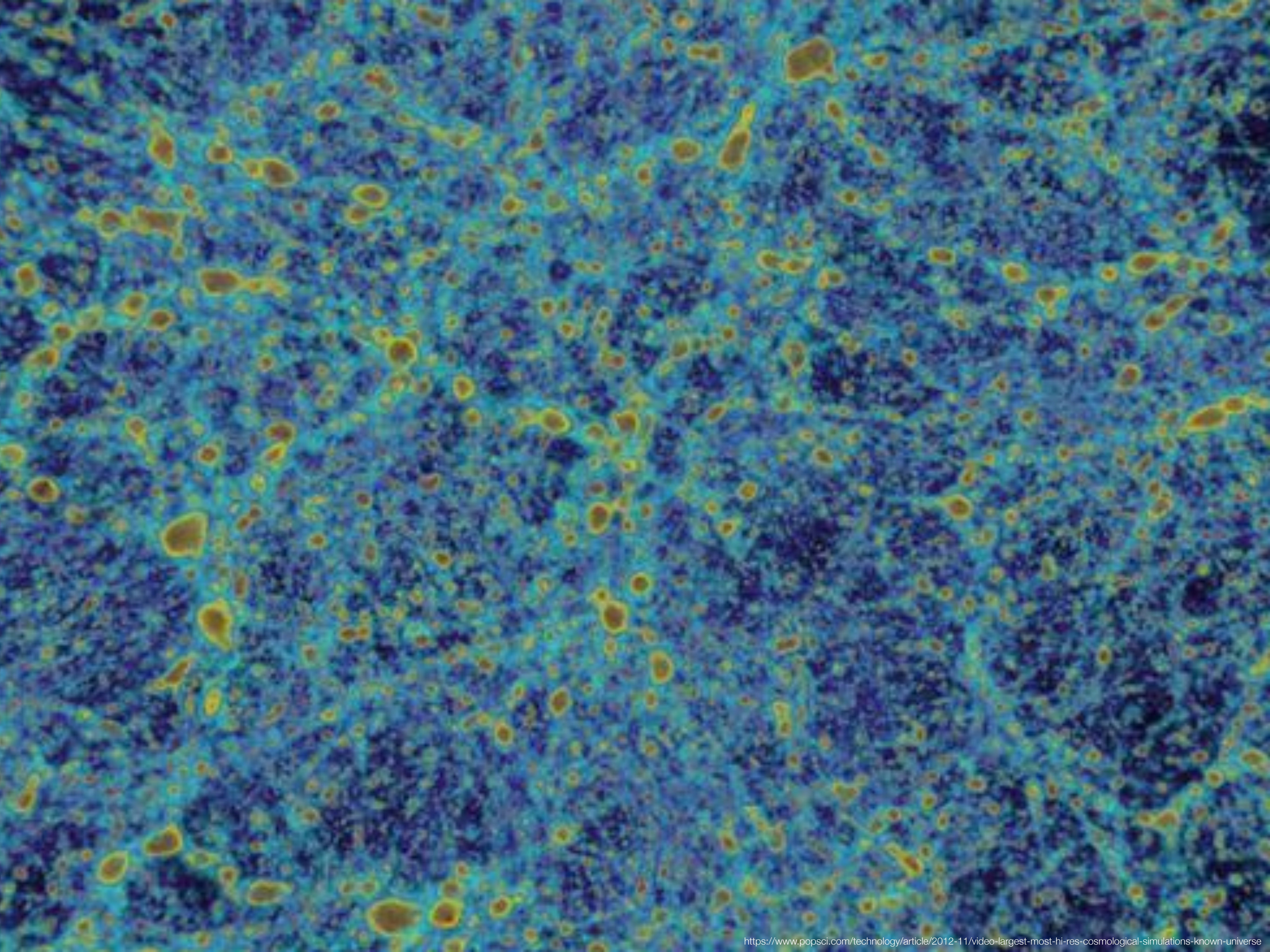
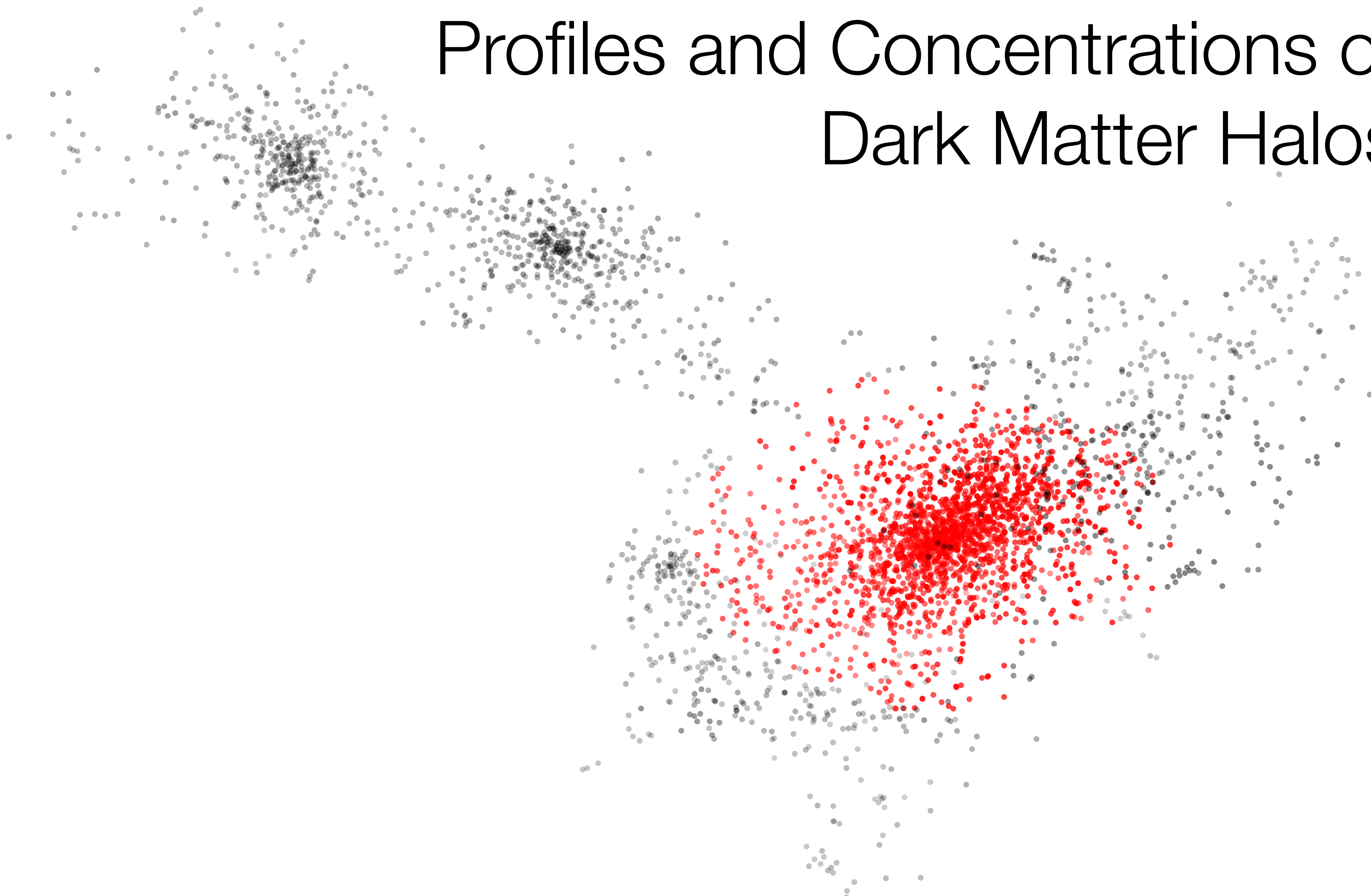
https://cdn.spacetelescope.org/archives/images/screen/heic0406b.jpg

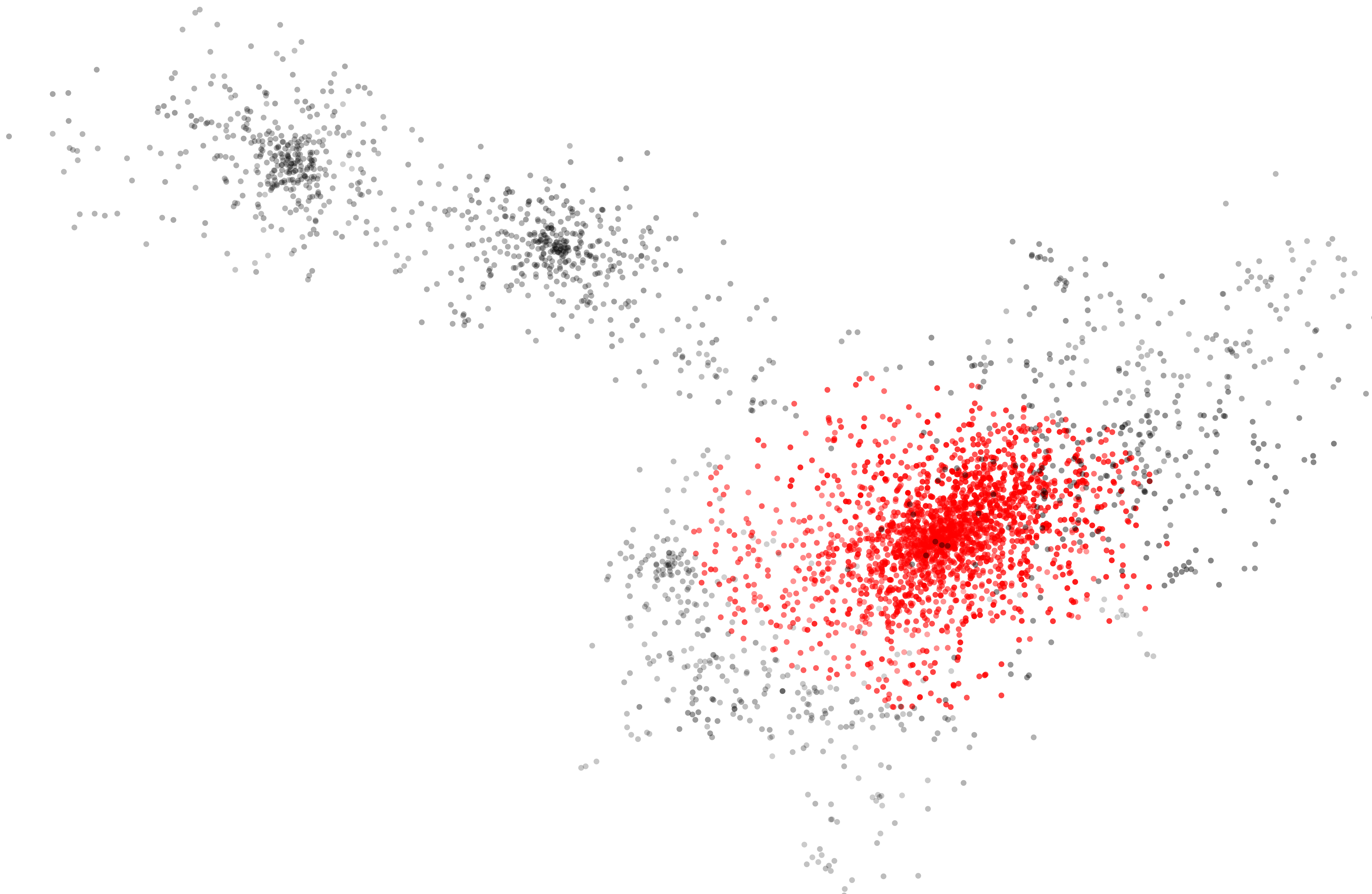


https://www.popsci.com/technology/article/2012-11/video-largest-most-hi-res-cosmological-simulations-known-universe

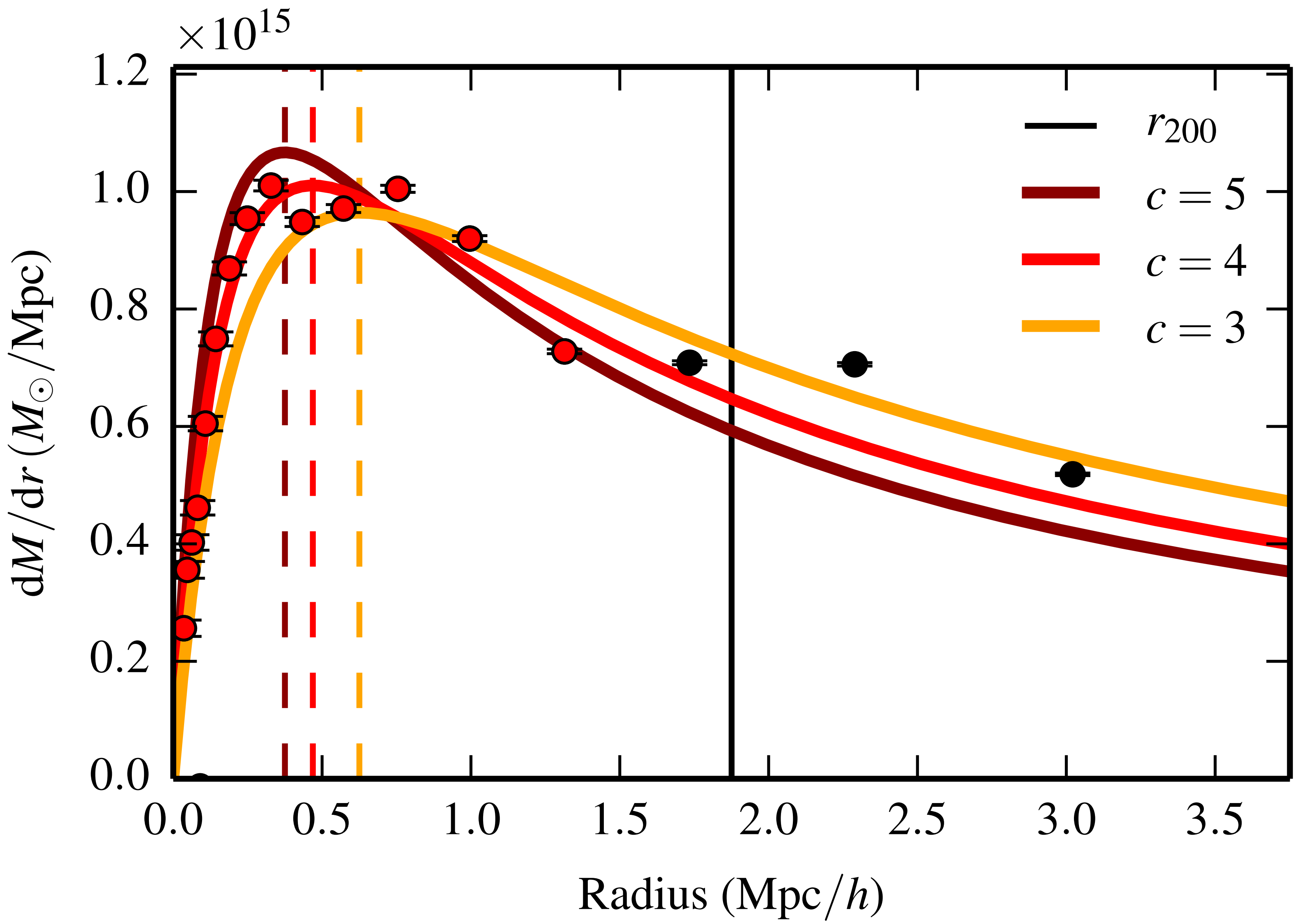
Deeply Nonlinear Regime: Profiles and Concentrations of Dark Matter Halos



Why Concentrations?



Navarro-Frenk-White (NFW) profile describes spherically-averaged halo density



Concentration: $$c_\Delta = \frac{r_\Delta}{r_s}$$

State-of-the-art simulations

Q Continuum

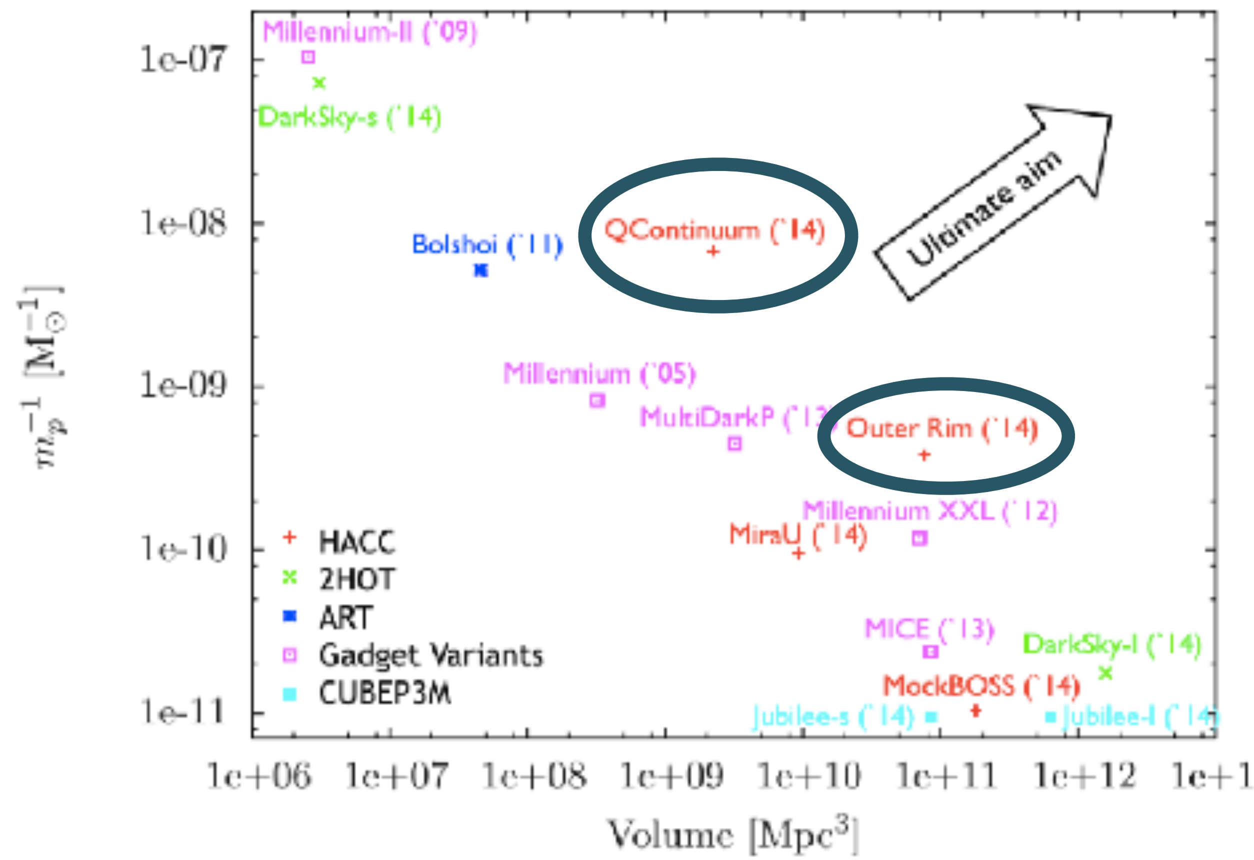
0.55 trillion particles

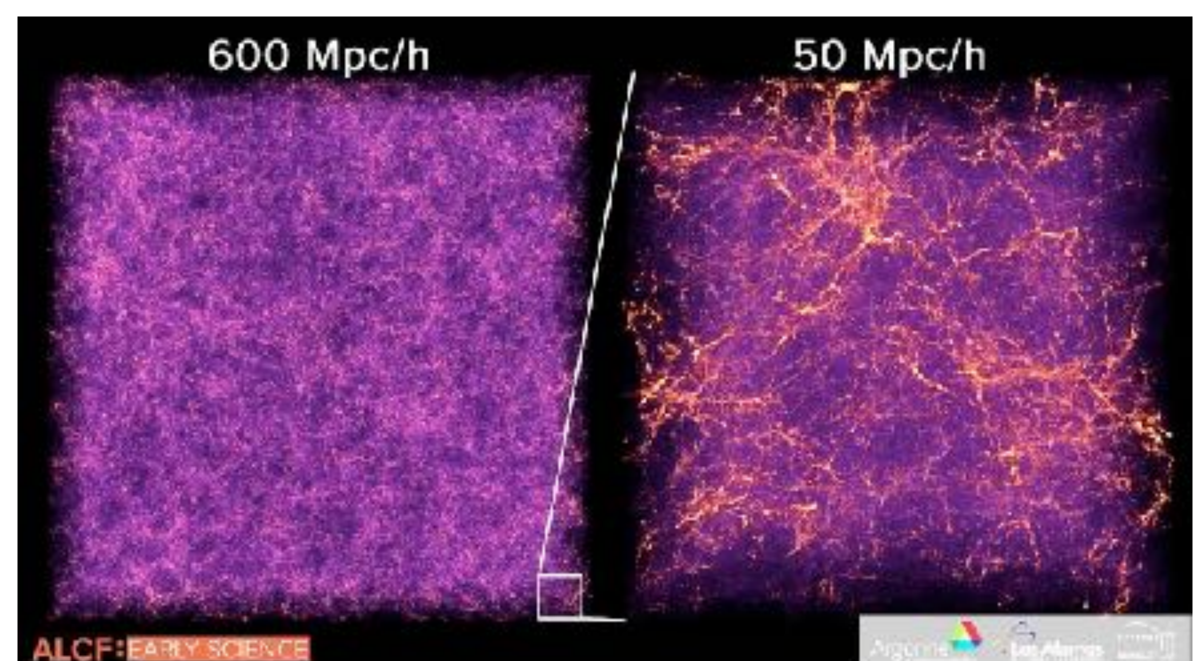
concentrations for 10 million halos at z=0

Outer Rim

1.1 trillion particles

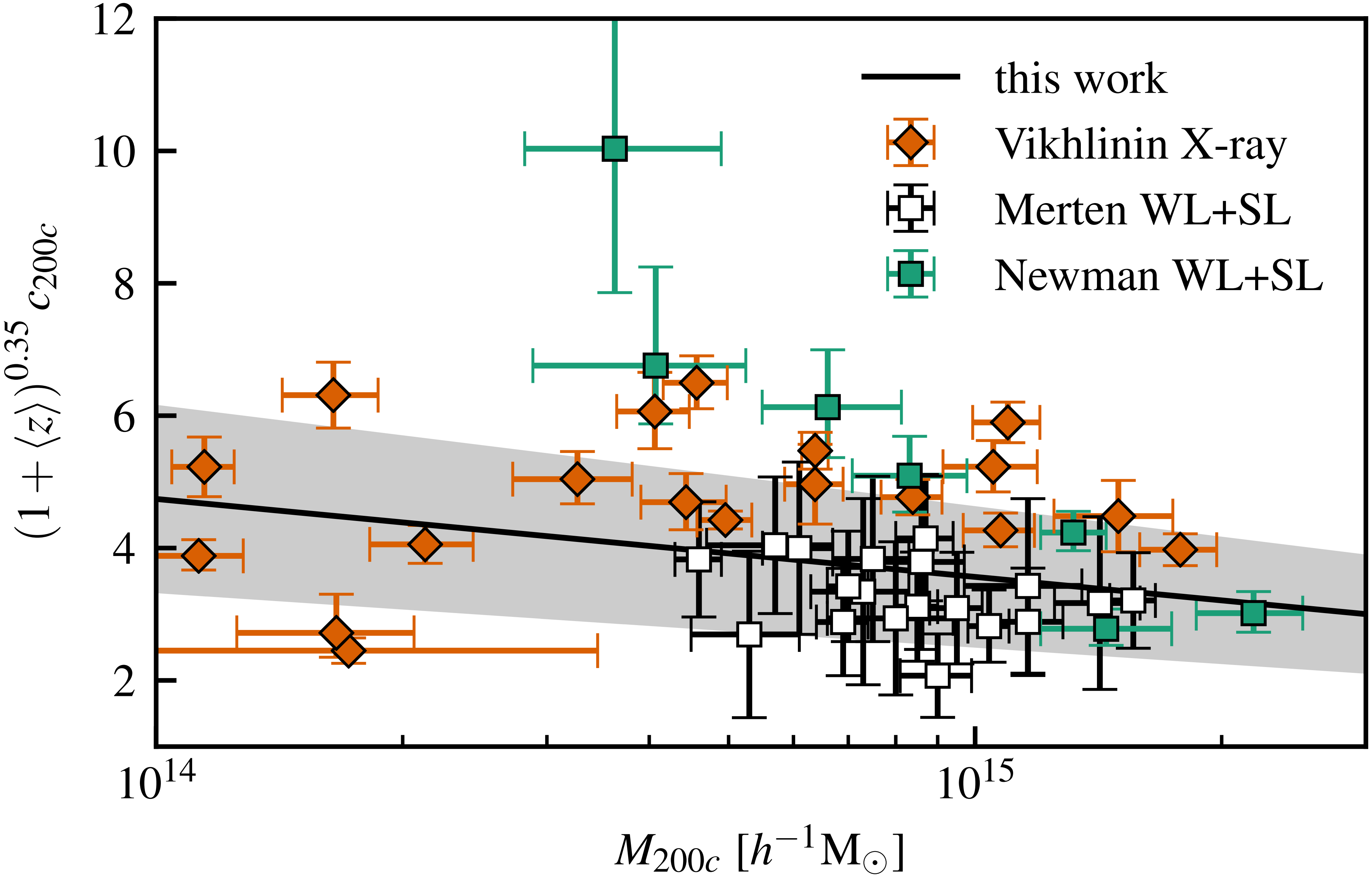
concentrations for 20 million halos at z=0





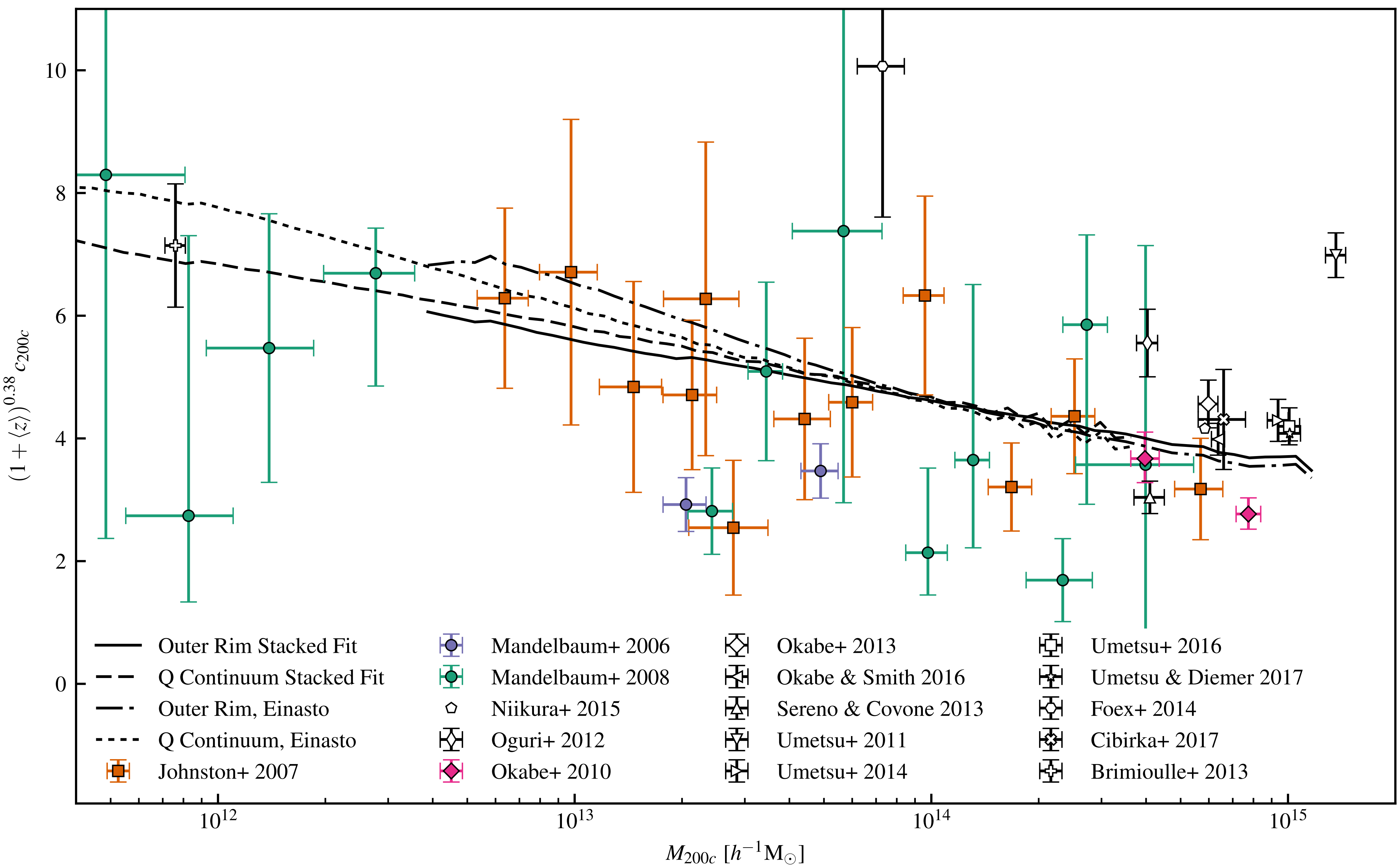
Heitmann+ 2015 ApJS 219, 34

Concentrations of individual halos



Child+ 2018a ApJ 859, 55

Concentrations of stacked halos



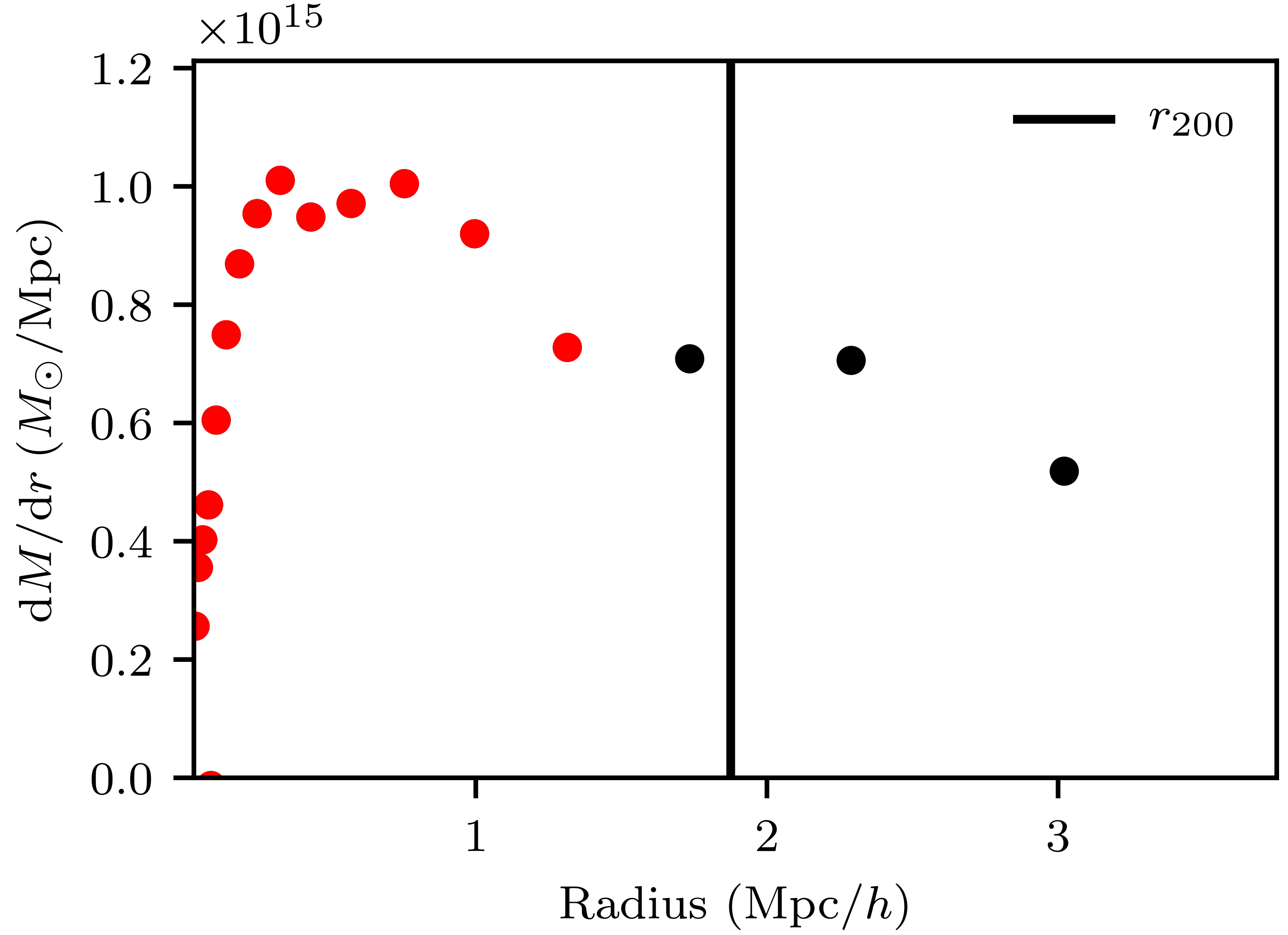
Child+ 2018a ApJ 859, 55

Does concentration depend on the method used to measure it?

1. **Fit**

2. Accumulated Mass

3. Peak



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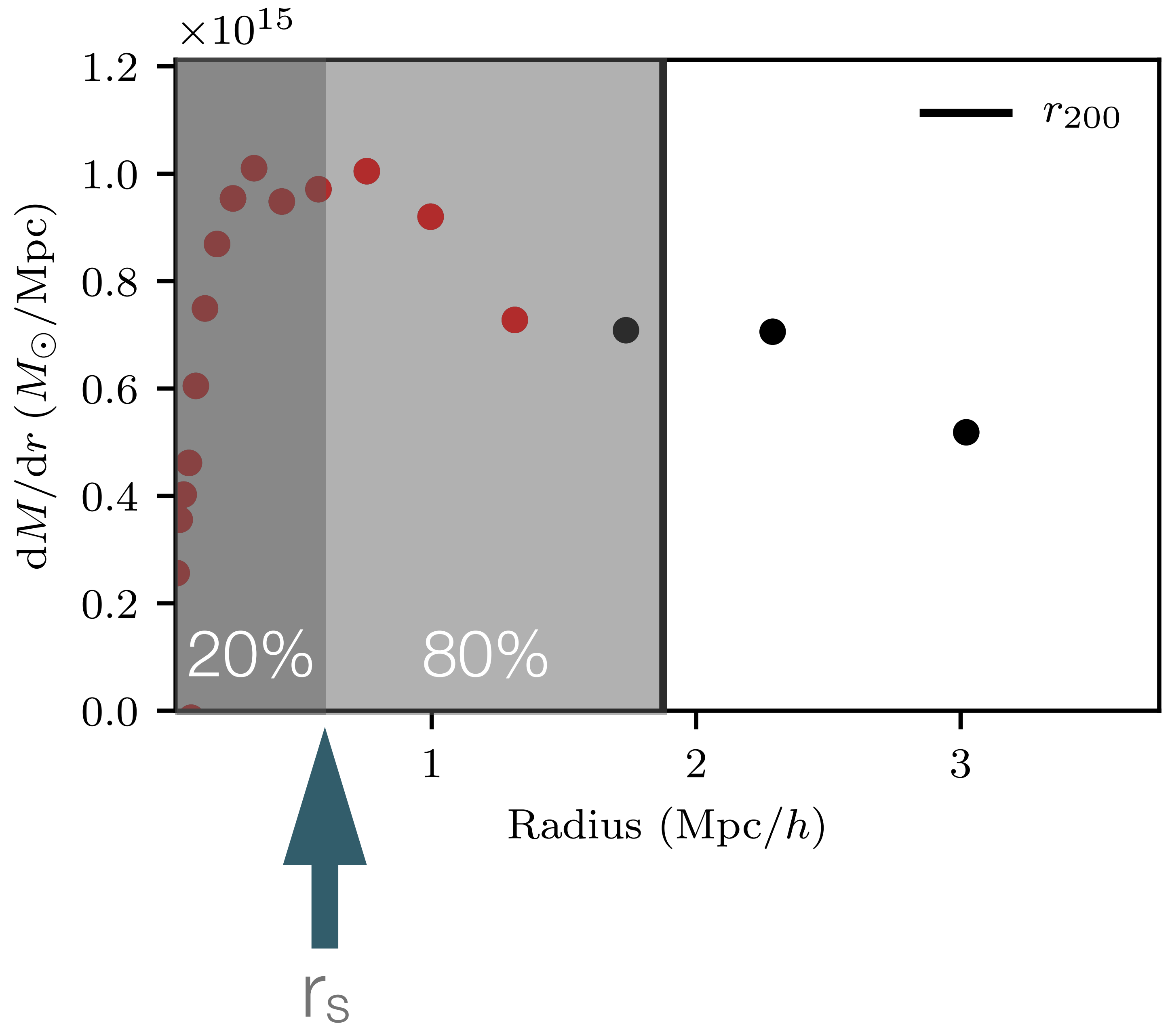

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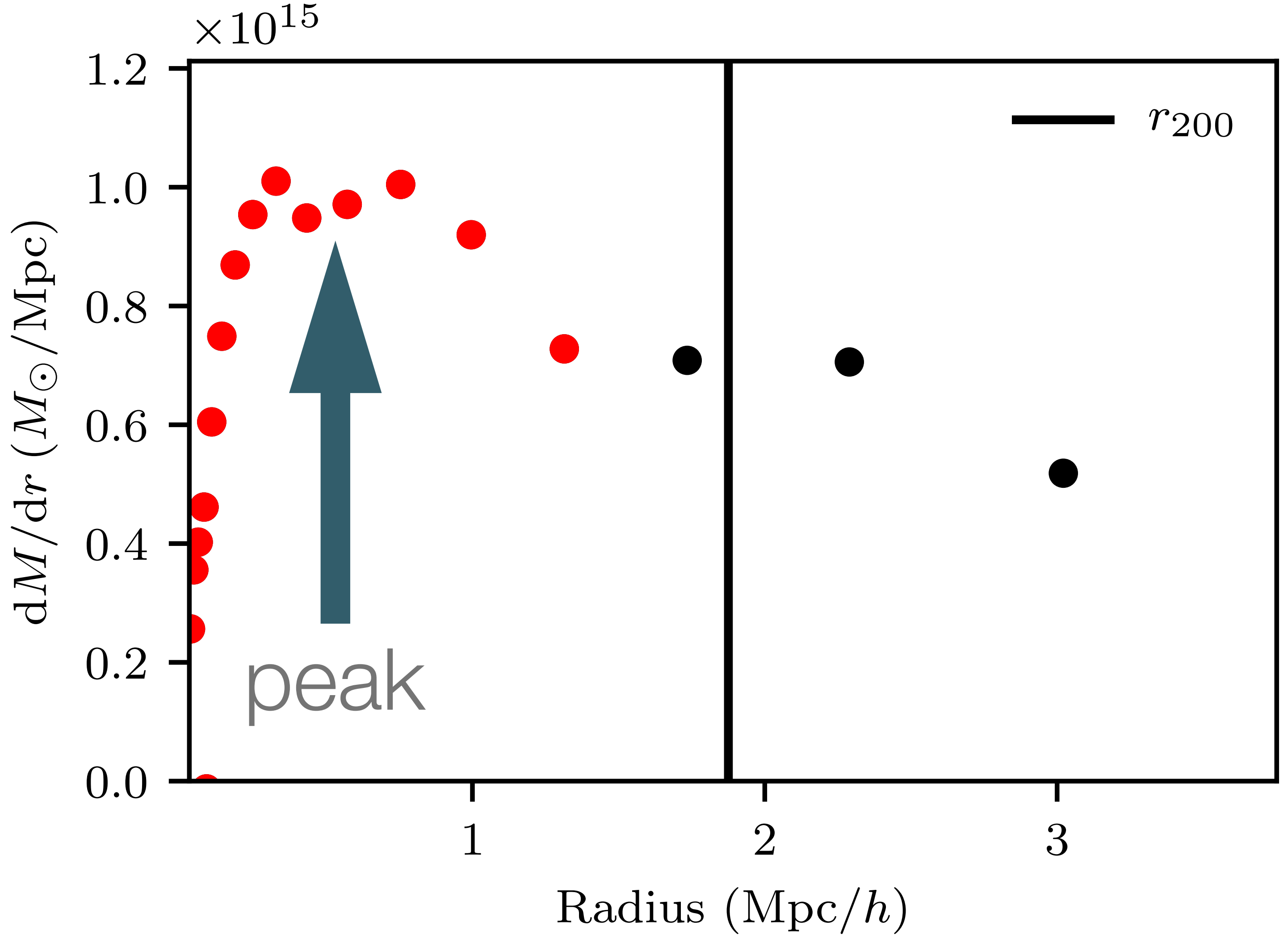
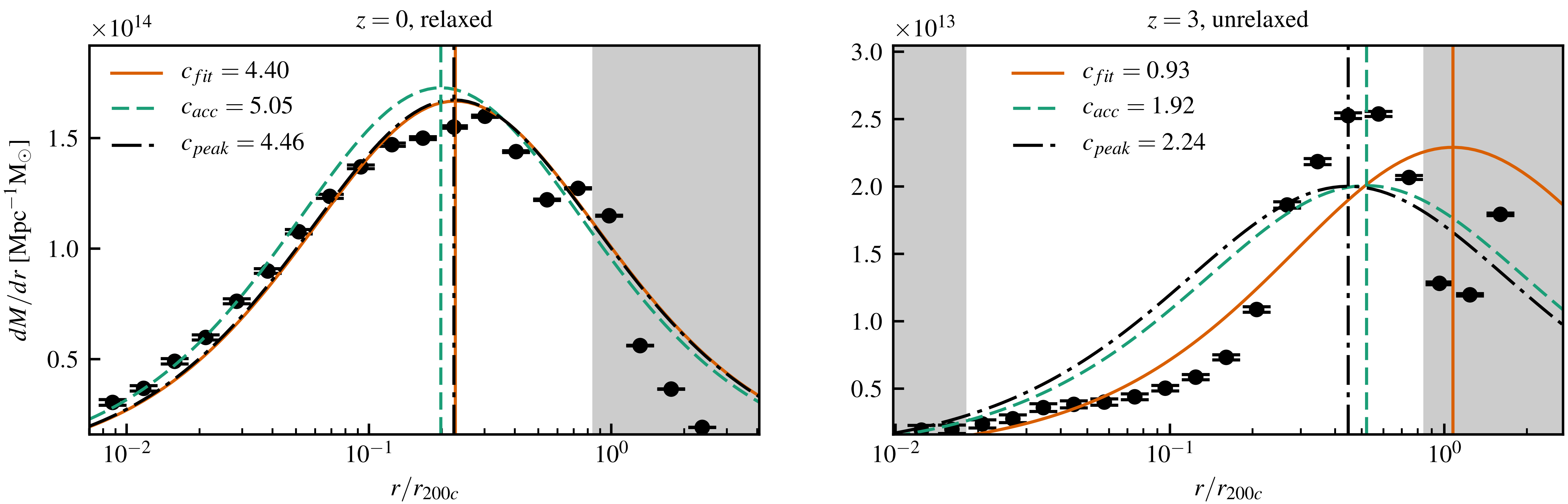
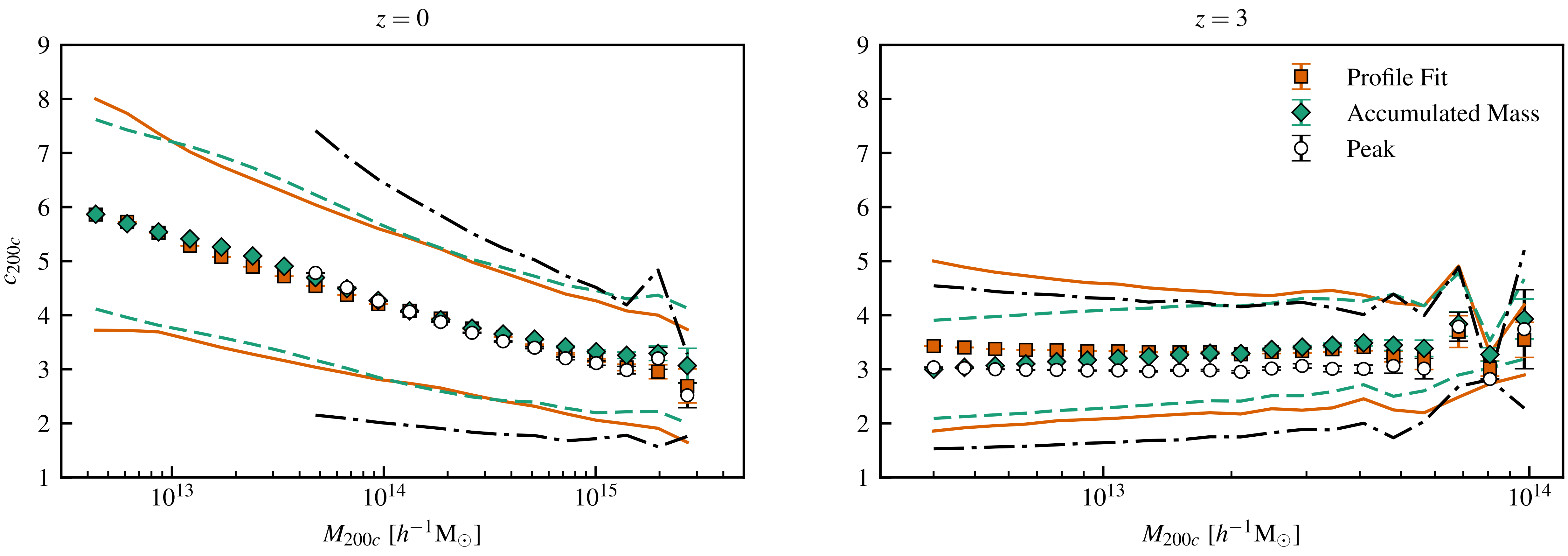


All methods agree on relaxed halos, but not on unrelaxed halos



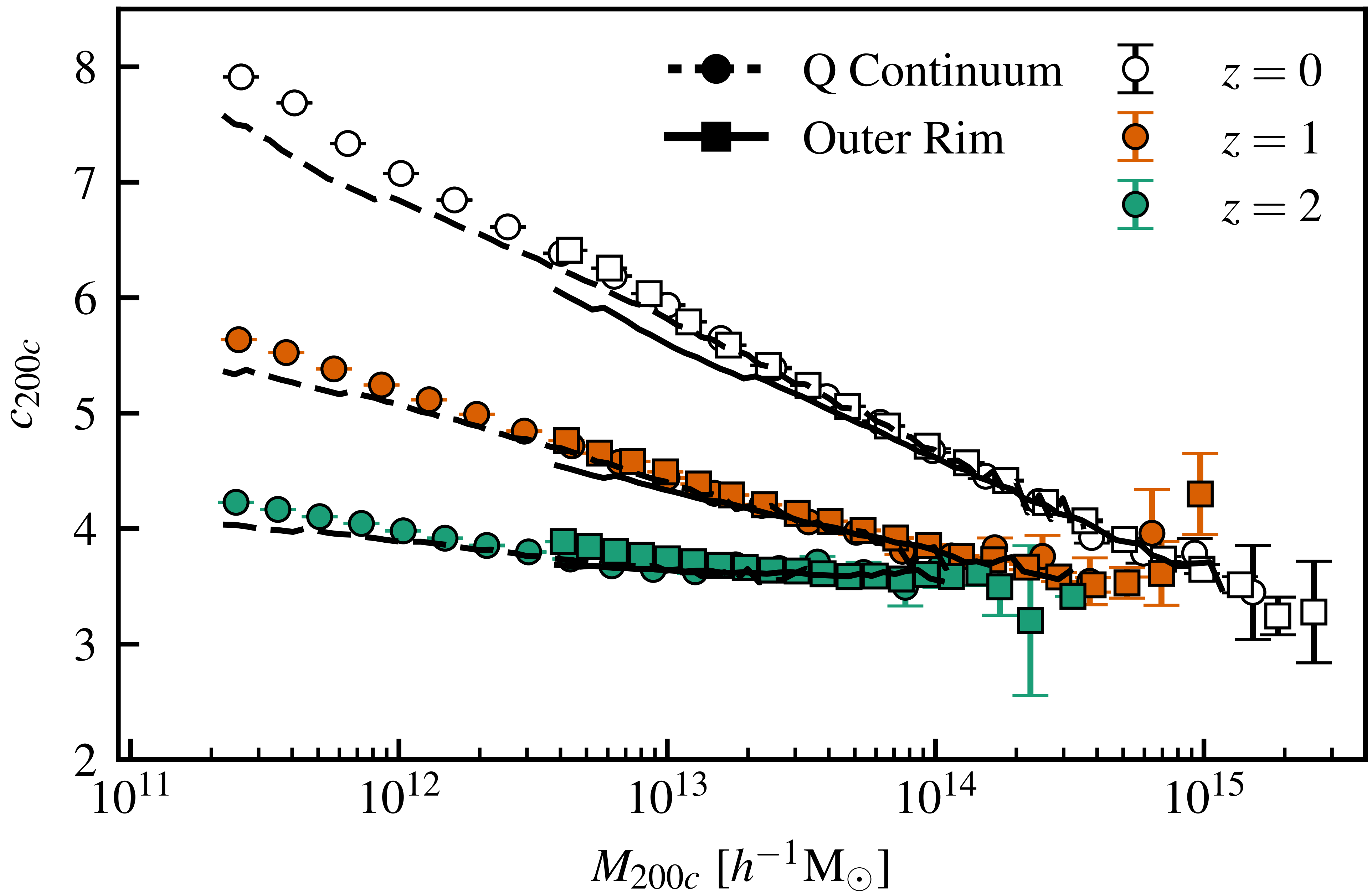
Child+ 2018a ApJ 859, 55

Population statistics: average concentrations



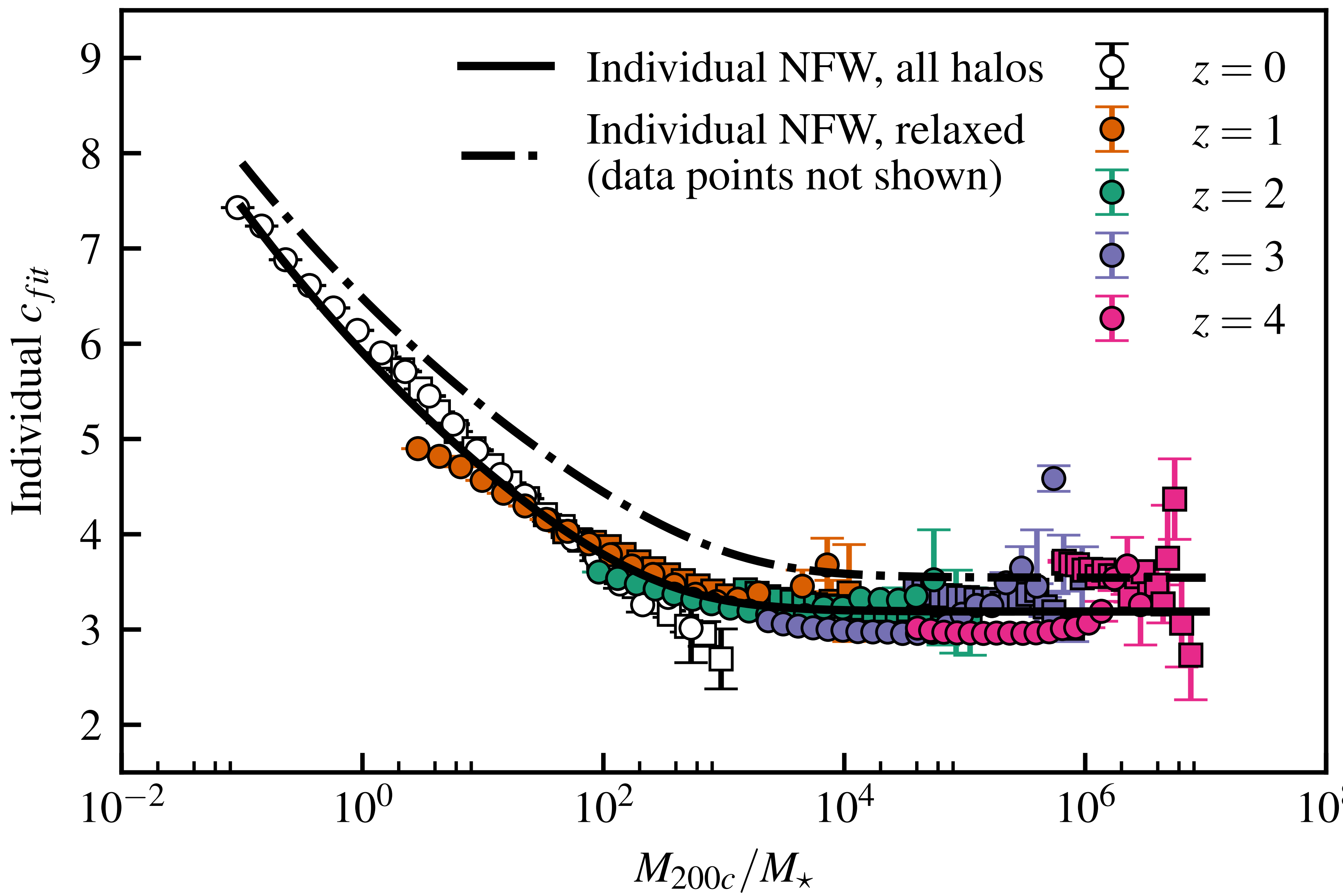
Child+ 2018a ApJ 859, 55

Concentration falls at high redshift



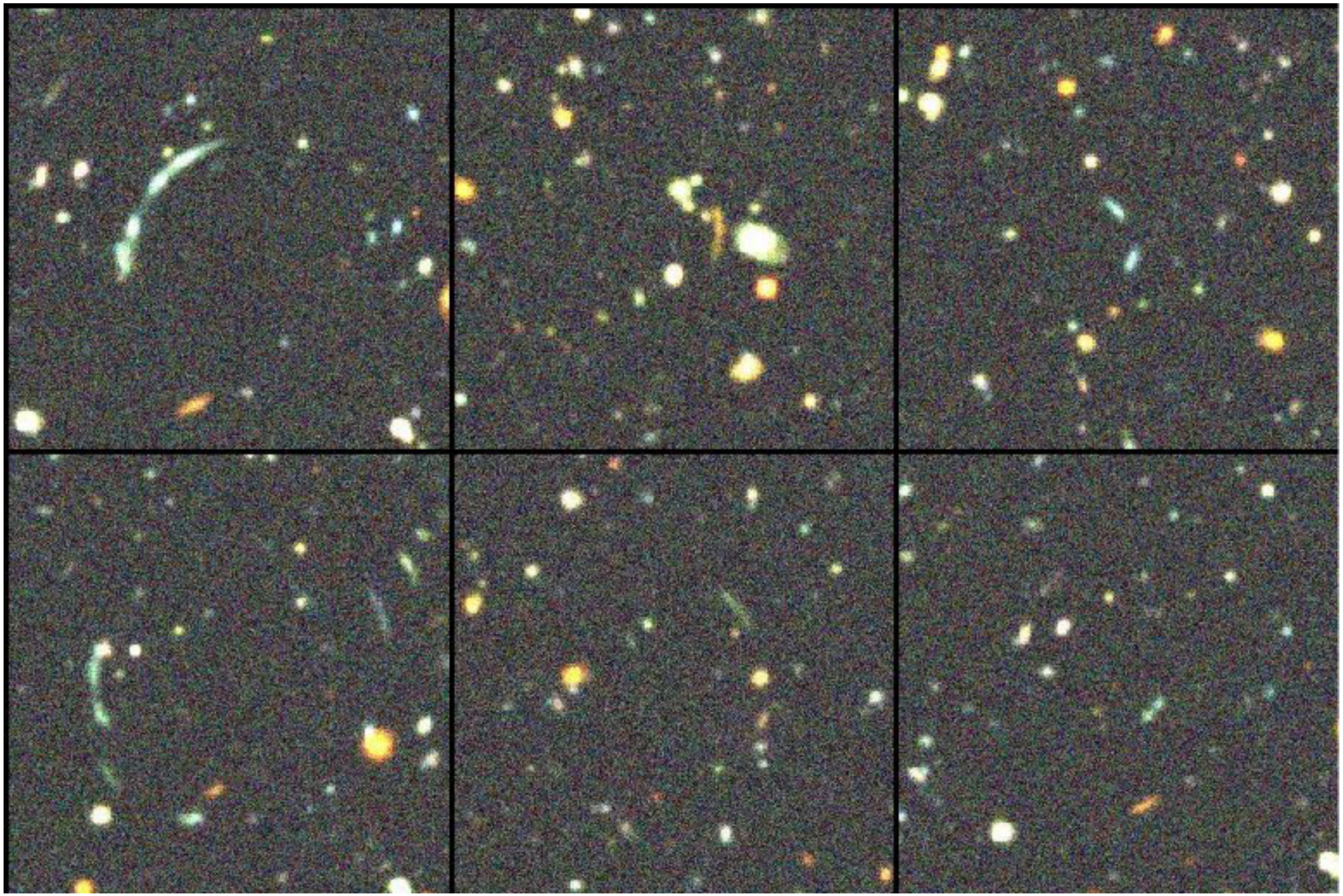
Child+ 2018a ApJ 859, 55

When mass is scaled by the nonlinear mass M*, concentration is a simple function of M/M*



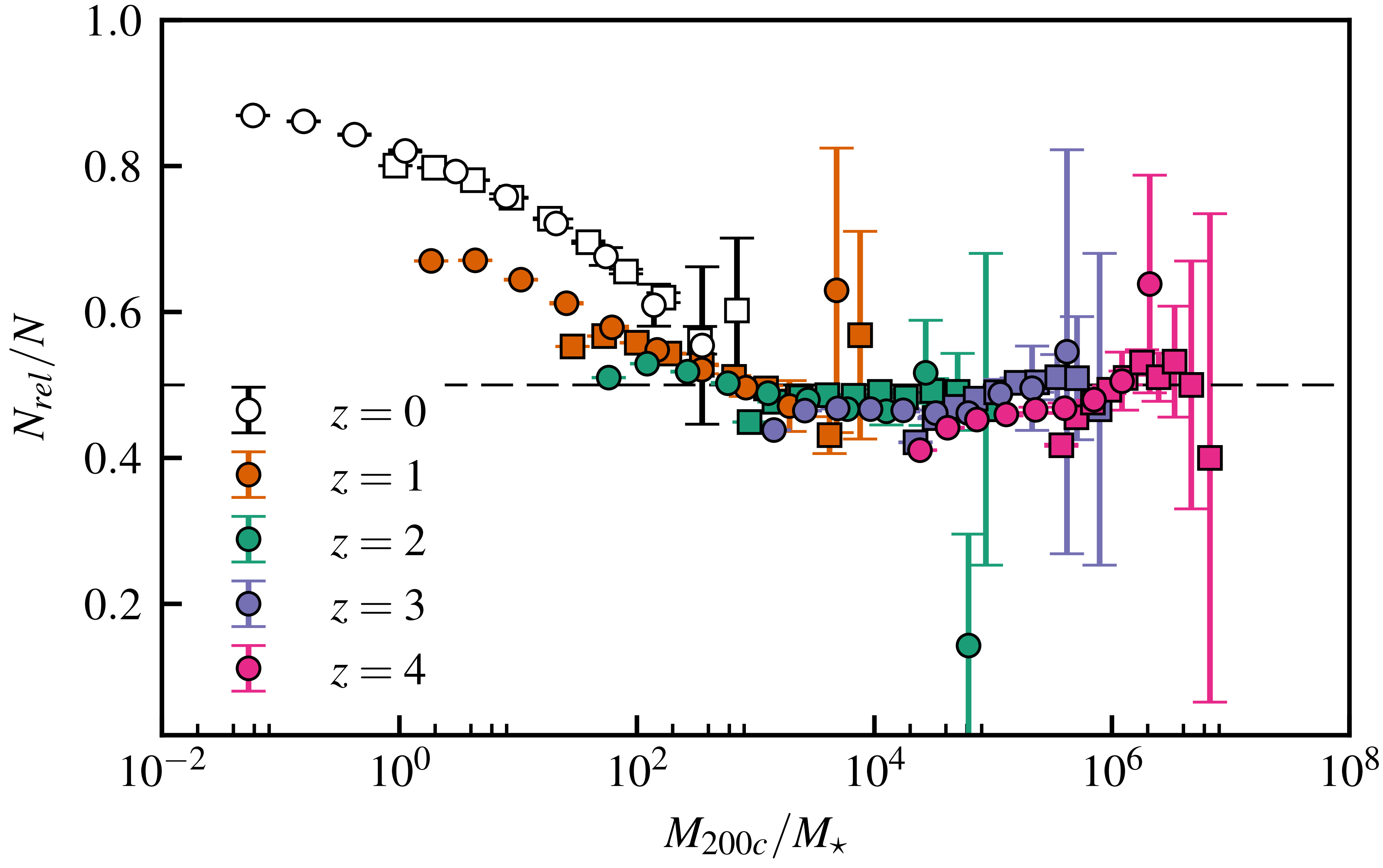
Child+ 2018a ApJ 859, 55

Application: Strong Lensing



Li, …, Child+ 2018 [arXiv: 1810.13330]

Relaxed fraction similarly depends on M/M*



Child+ 2018a ApJ 859, 55

Merger trees track halo evolution

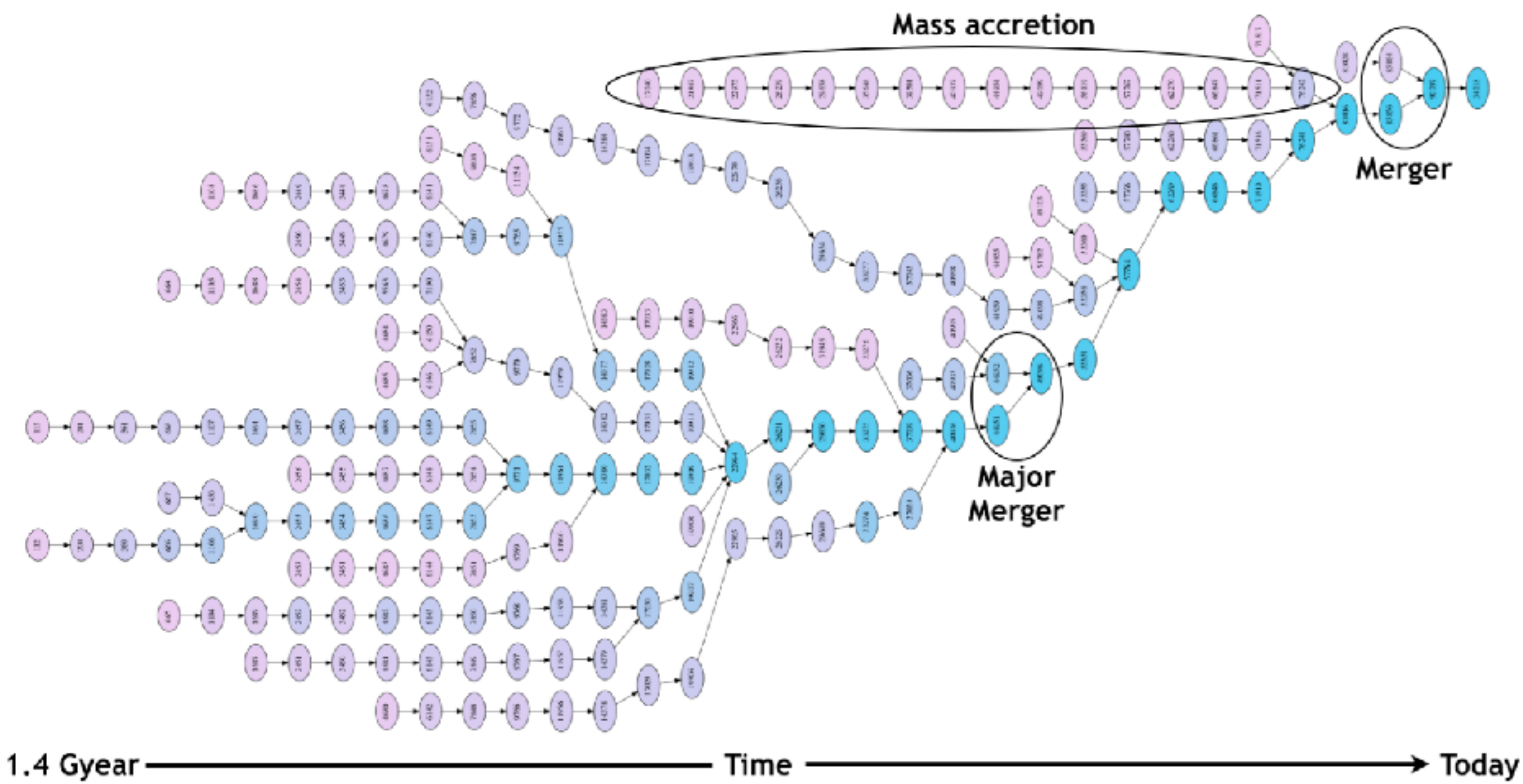


figure courtesy of Eve Kovacs and Steve Rangel

Merger trees track halo evolution

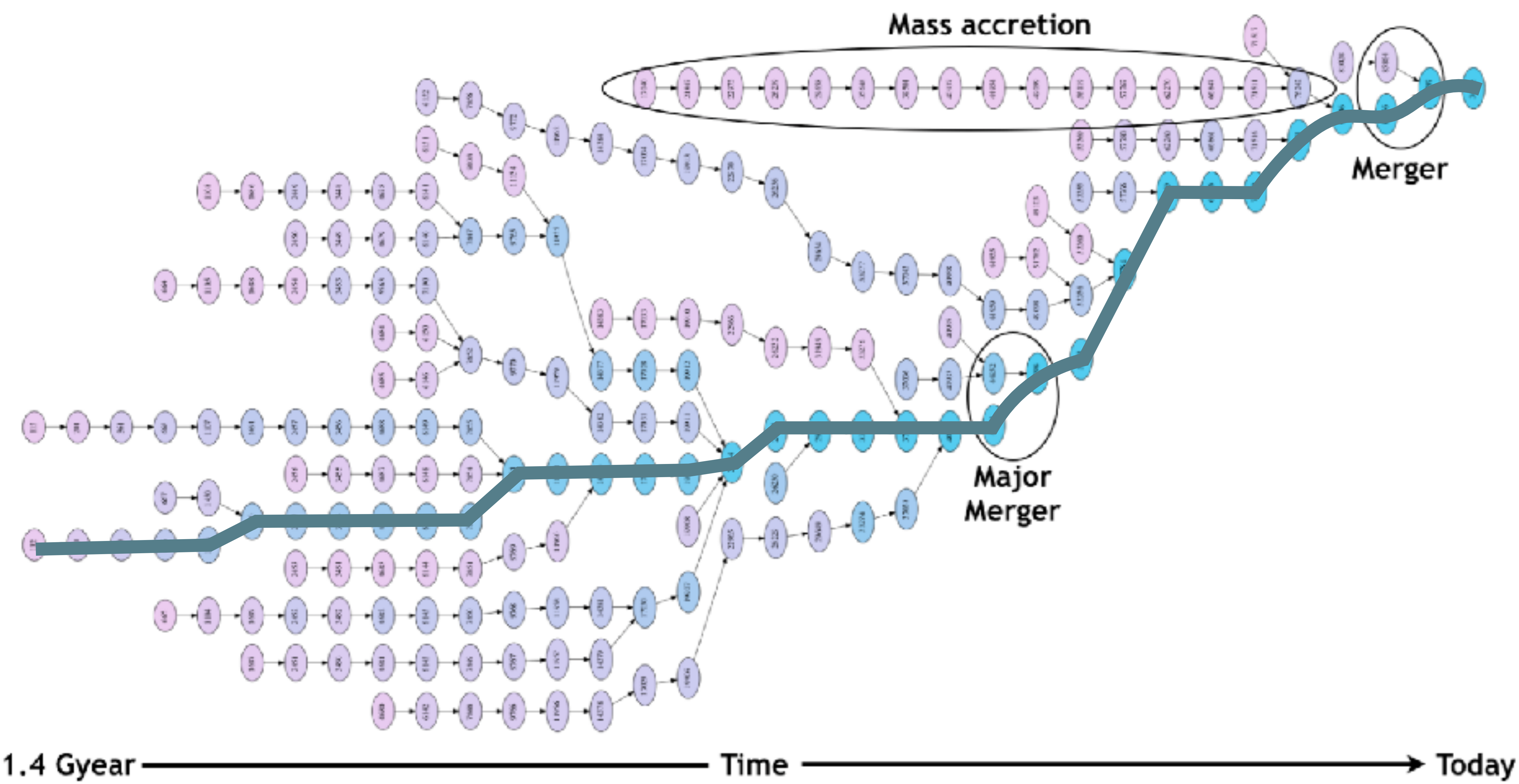
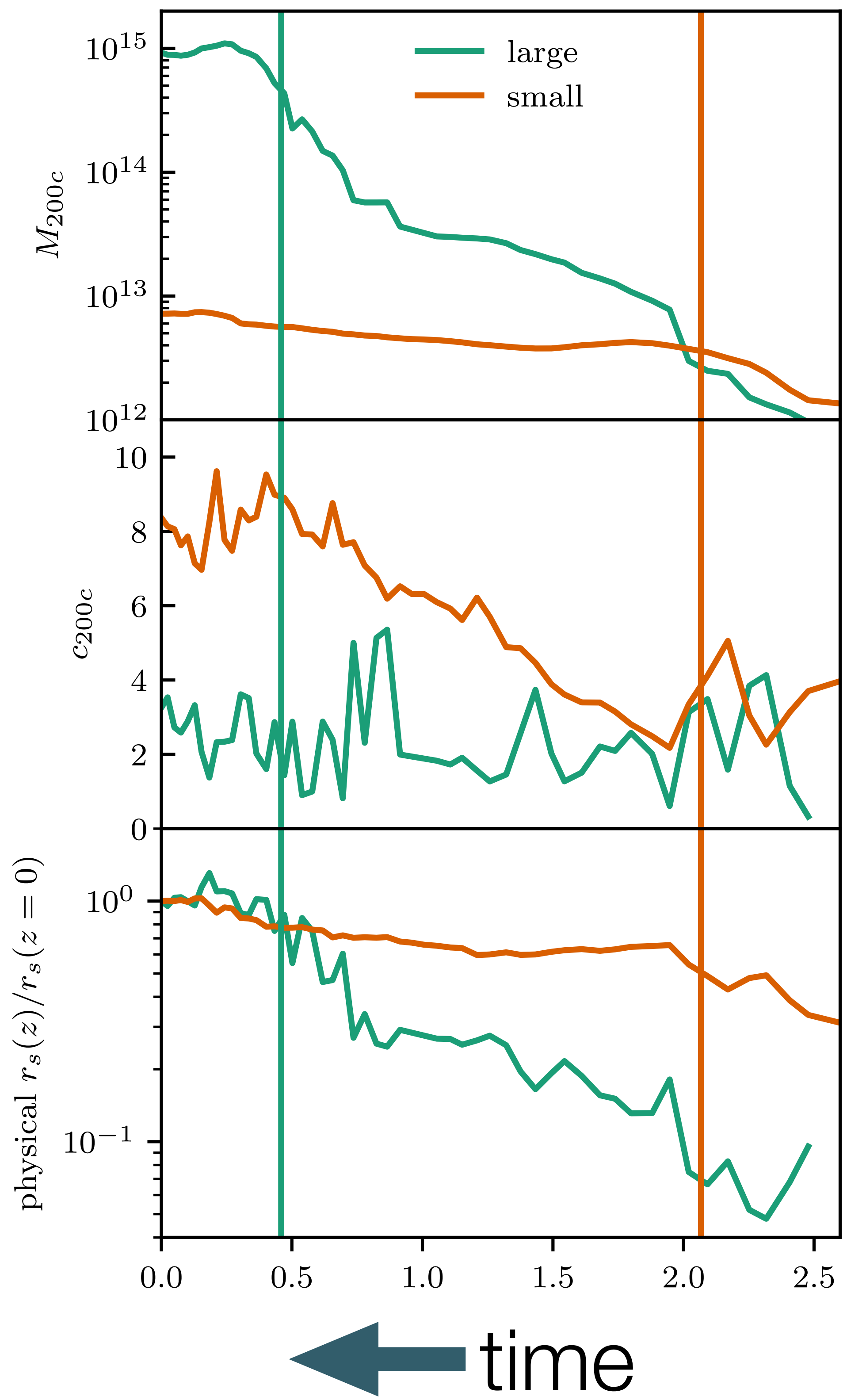


figure courtesy of Eve Kovacs and Steve Rangel

Halo backbones



mass grows through mergers
mass grows smoothly

concentration remains ~3
concentration grows to 8-10

scale radius grows ~ x50
scale radius grows ~ x2

Pseudo-evolution: halos accrete mass only at their outskirts, without disrupting the inner profile

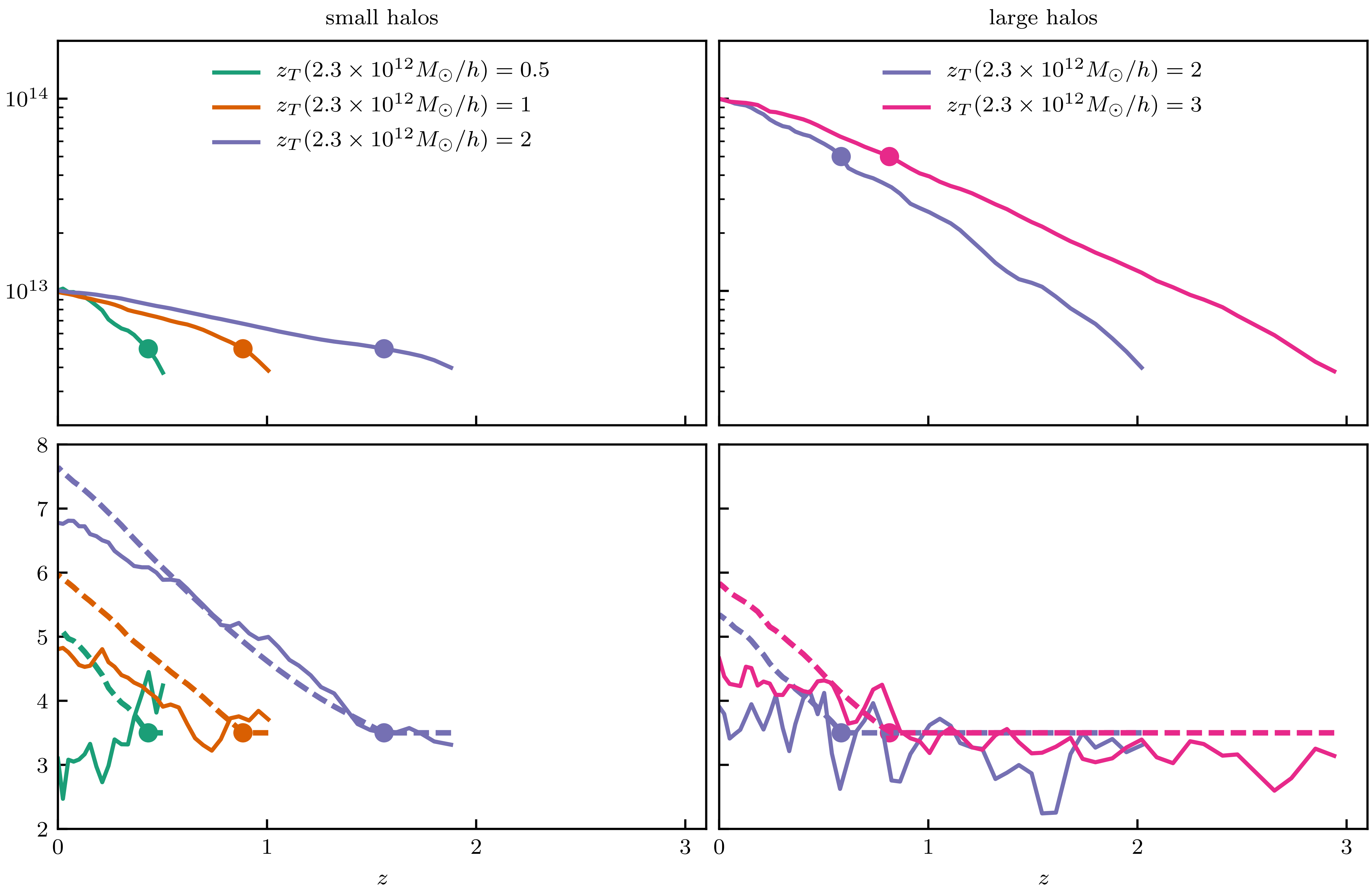
scale radius is constant

mass grows

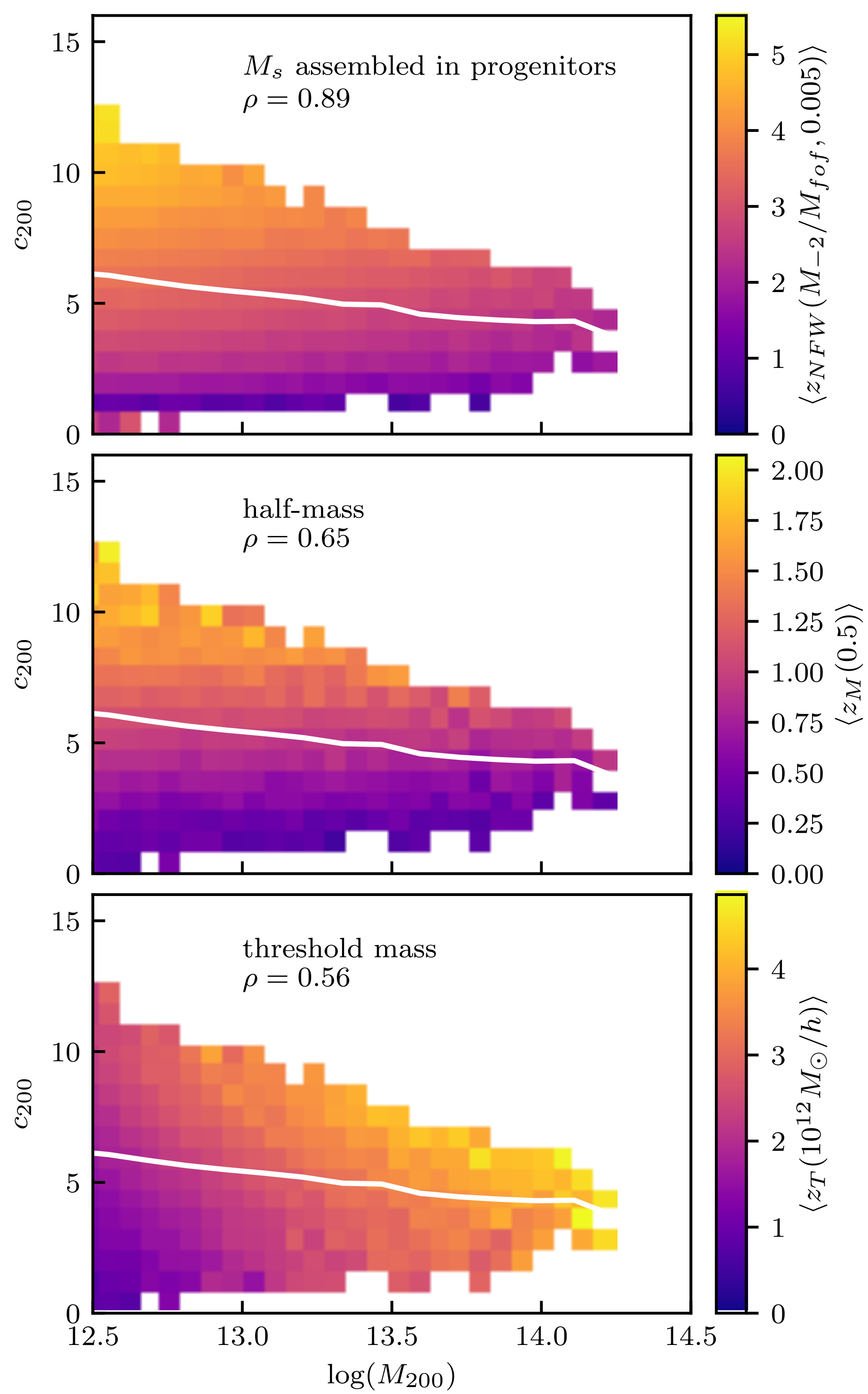
critical density falls

viral radius grows

Pseudo-evolution predicts concentrations for old, slowly-growing halos



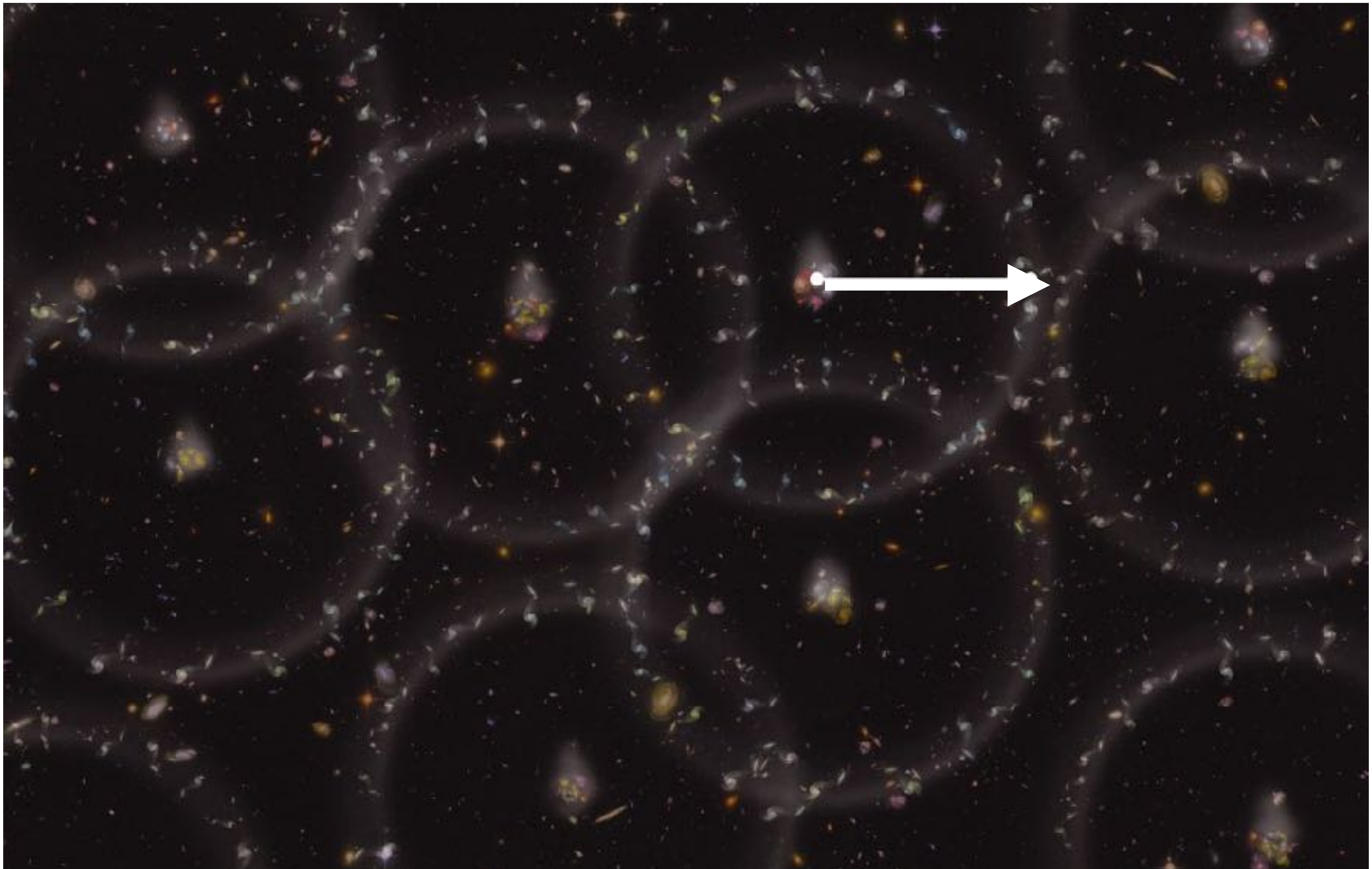
Old halos have high concentrations



Primary Results

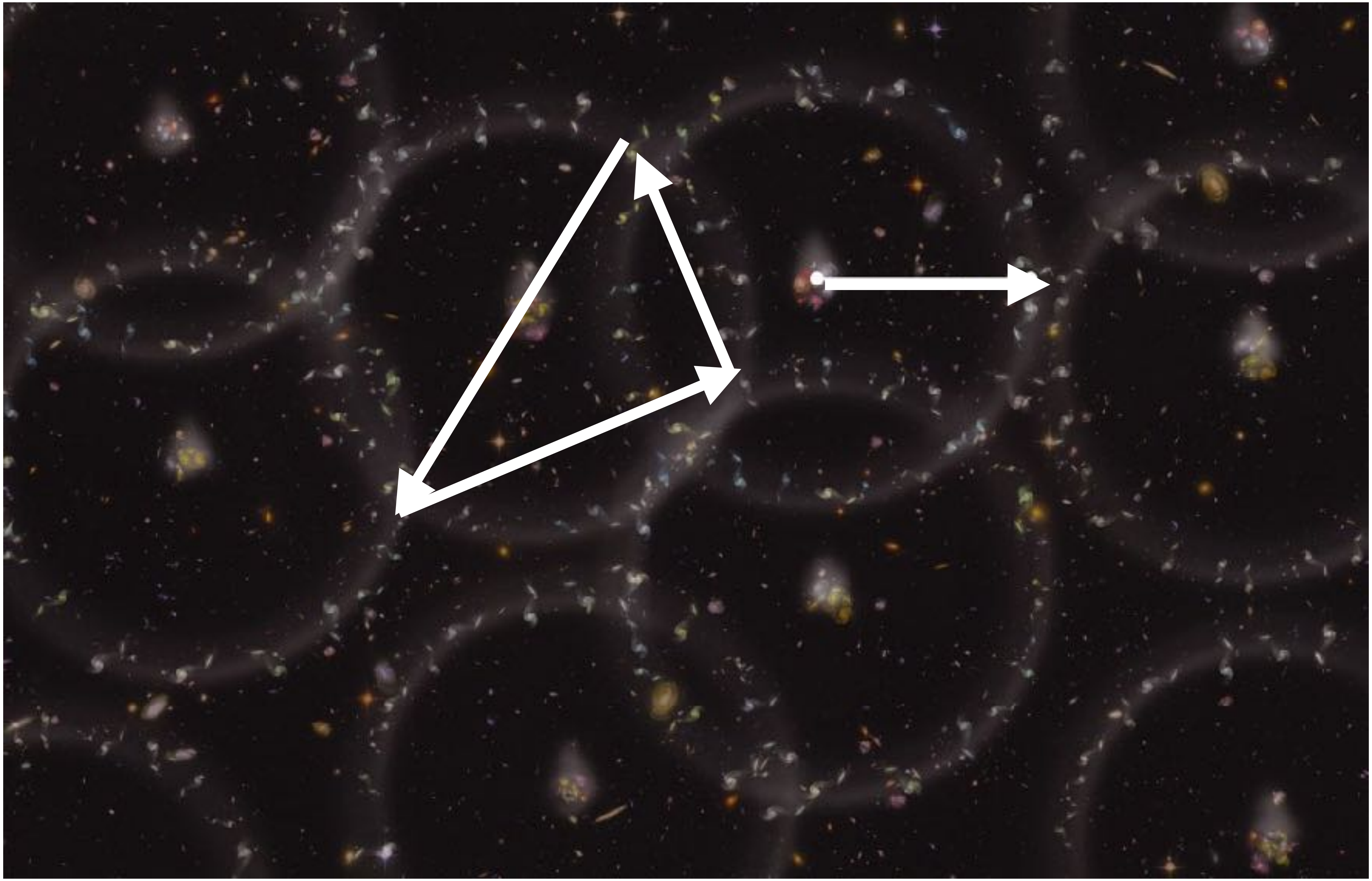
- State-of-the-art simulations provide superior statistics for robust concentration measurement
- Concentration-mass relation: agreement with observations and other simulations
- Scaling by M*: power-law behavior below a threshold mass, transition to constant
- Best correlated with concentration: definitions based on the time when the sum of all progenitor masses reaches the mass contained within the final scale radius
- Pseudoevolution describes concentration evolution well for slowly growing halos

Weakly Nonlinear Regime:
BAO Interferometry in the Bispectrum



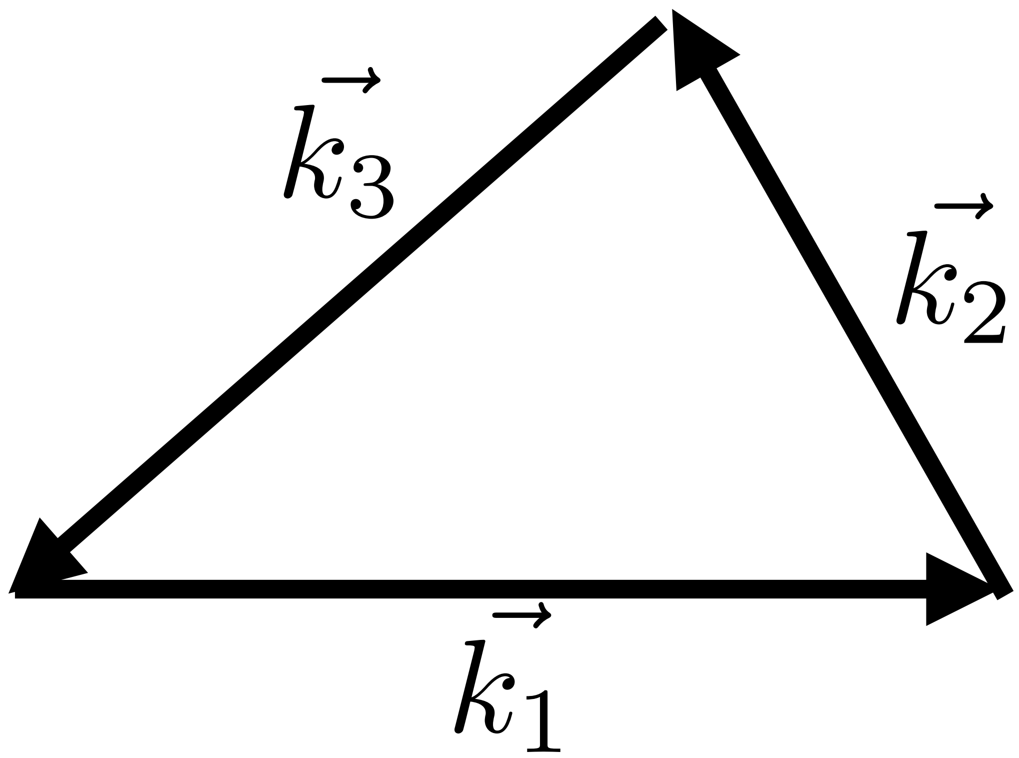
BOSS, http://www.astro.ucla.edu/~wright/BAO-cosmology.html

The BAO feature also appears in three-point statistics

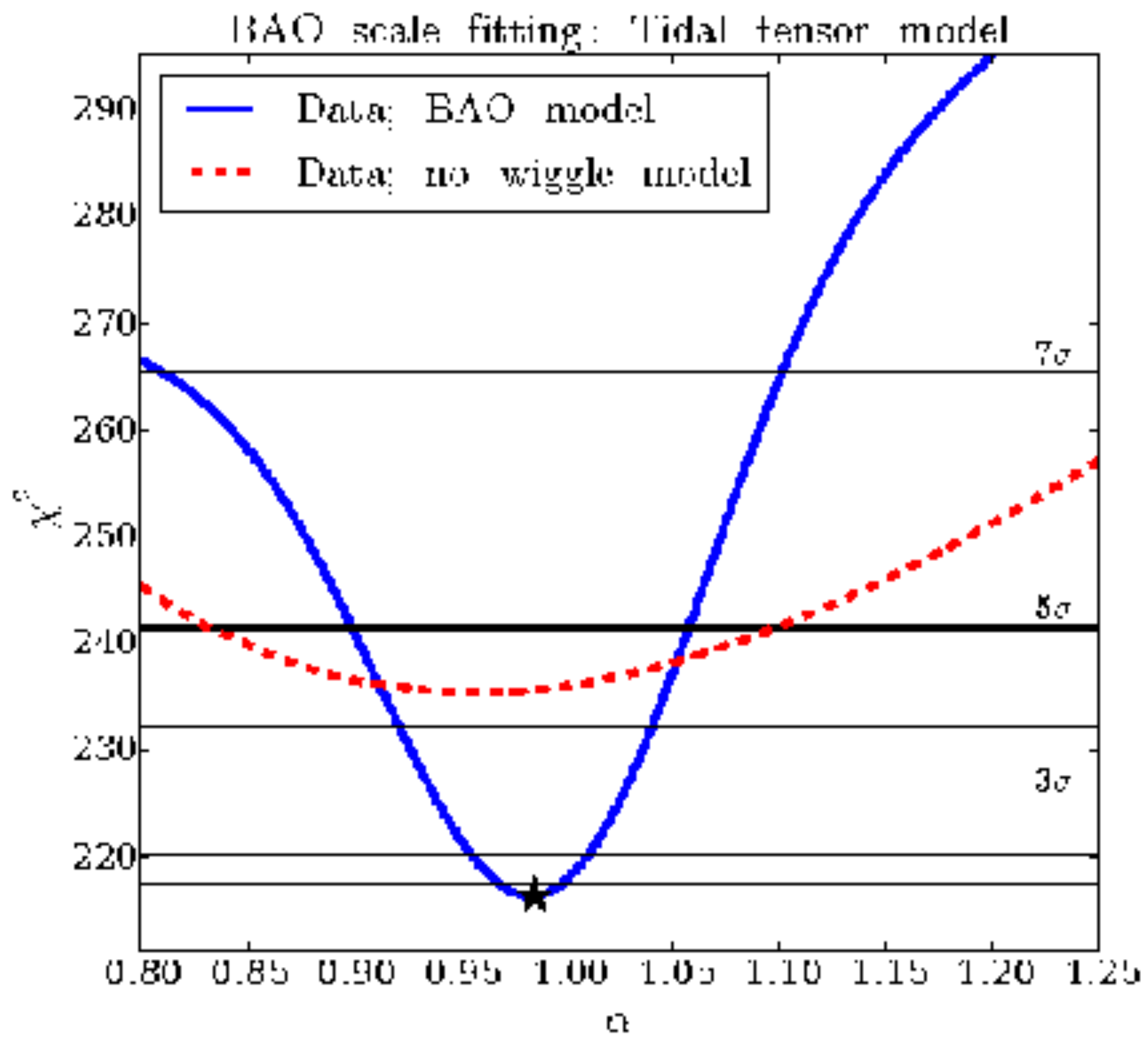


BOSS, http://www.astro.ucla.edu/~wright/BAO-cosmology.html

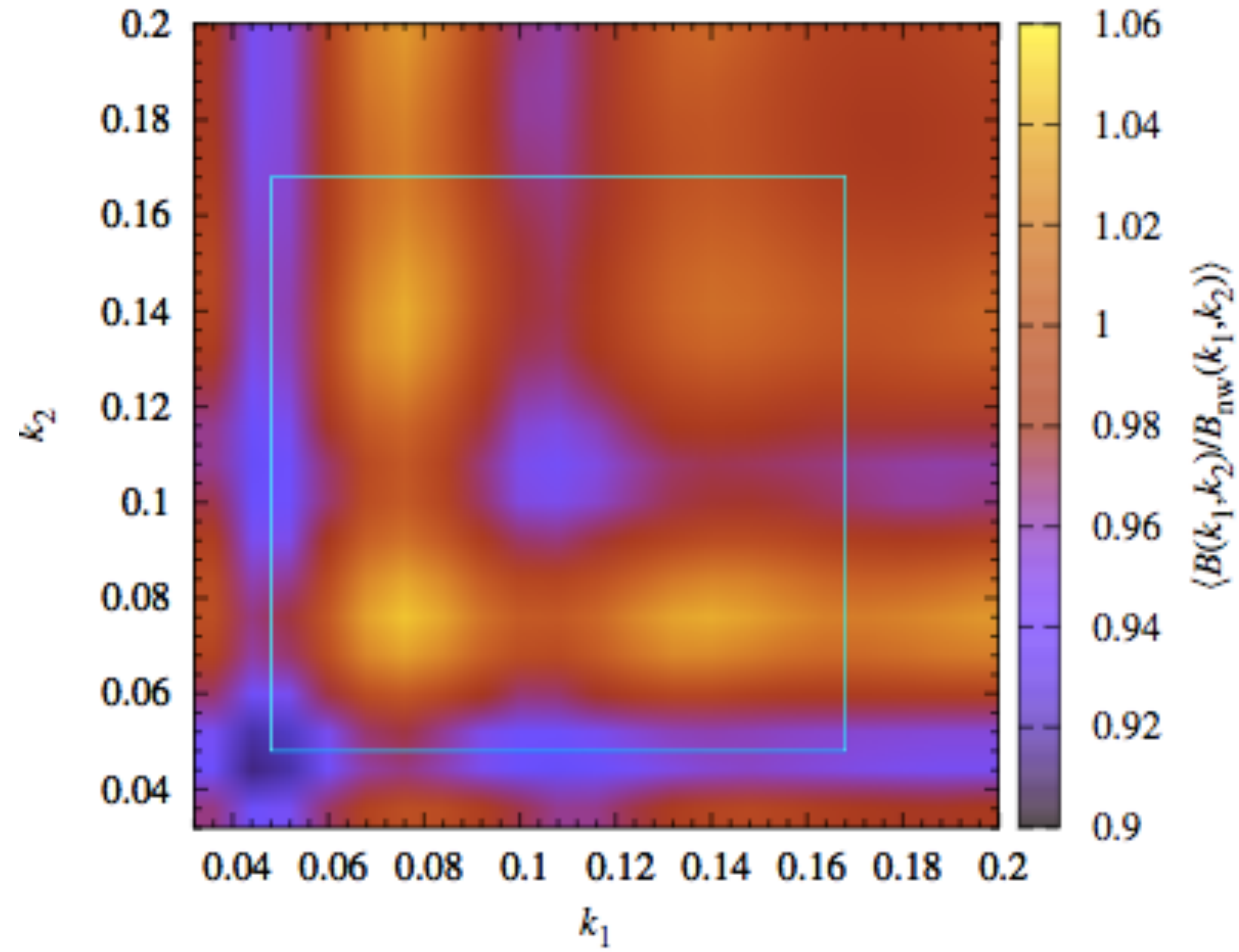
Triangles



BAO in three-point statistics



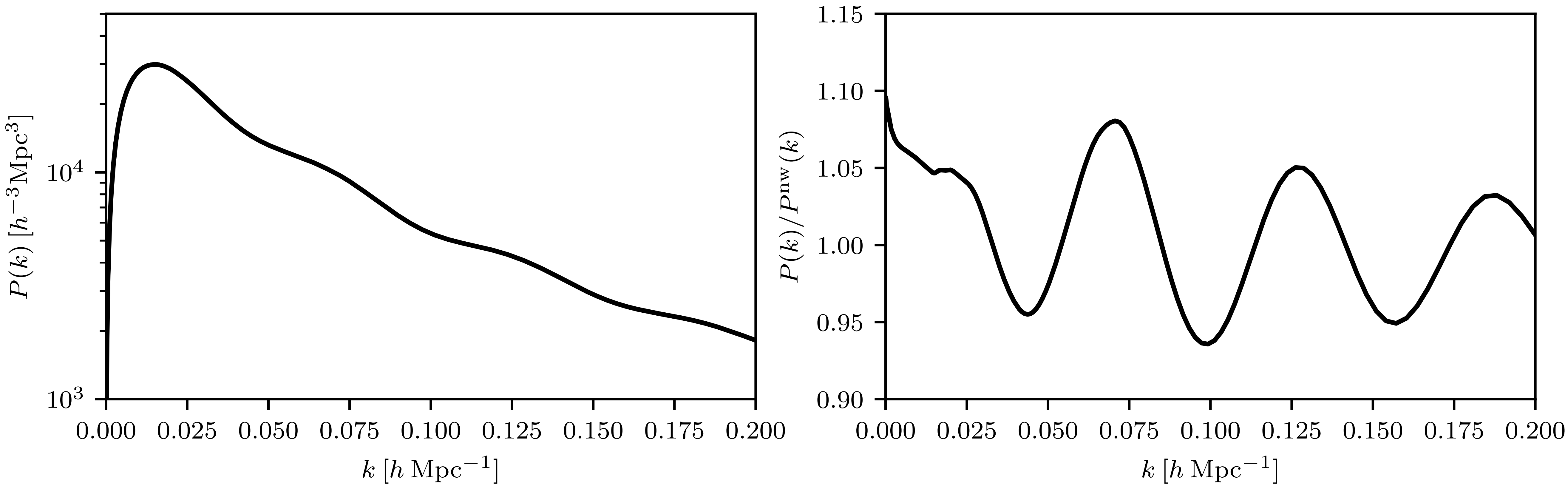
Slepian+ 2017
MNRAS 469, 1738



Pearson & Samushia 2017
MNRAS 478, 4500

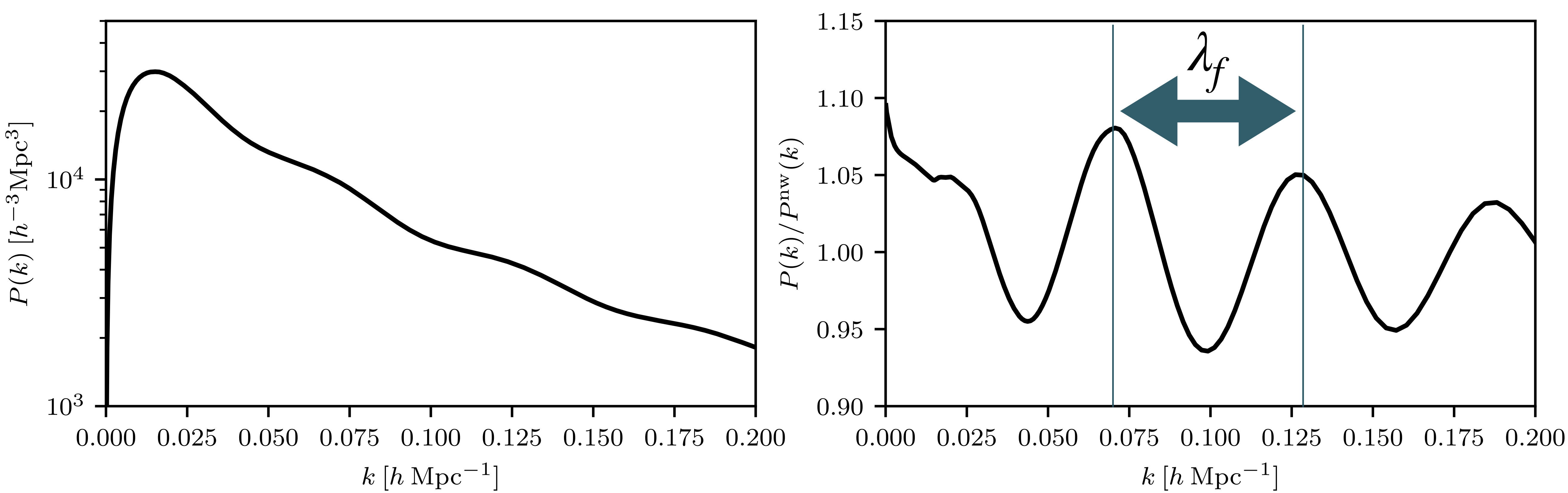
more BAO in 3PCF:
Gaztanaga+ 2009 (MNRAS 399, 801)
Slepian+ 2017 (MNRAS 468, 1070)

BAO in the power spectrum



T, P^{nw} from Eisenstein & Hu 1998, ApJ 496 605

BAO in the power spectrum



T, P^{nw} from Eisenstein & Hu 1998, ApJ 496 605

Bispectrum

initial density (Gaussian random) field

+ BAO signature in 2-point statistics

+ gravity

bispectrum (with BAO)

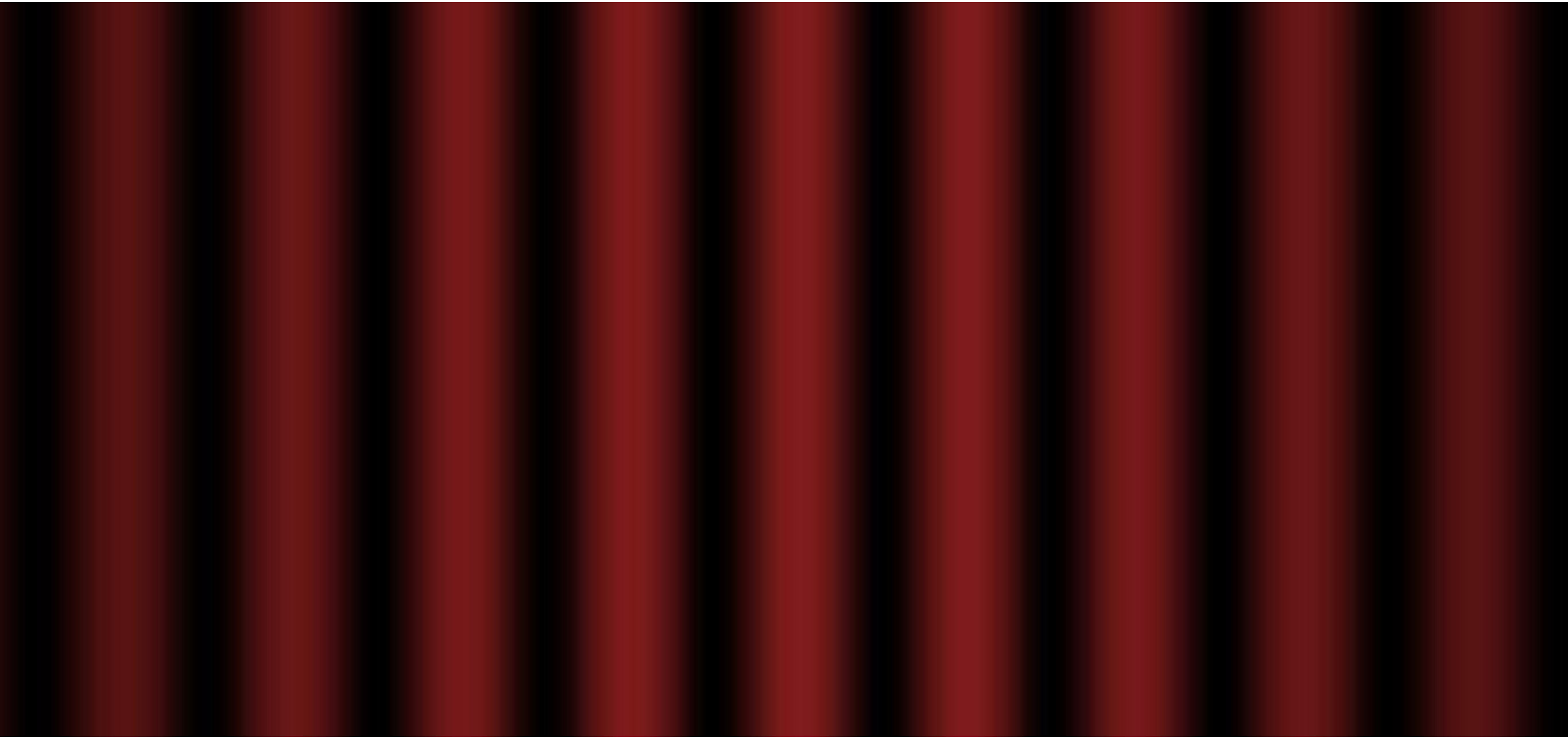
BAOs enter the bispectrum through a cyclic sum

$$B^{(0)}(k_1, k_2, k_3) = 2P^{(0)}(k_1)P^{(0)}(k_2)F_2^{(s)}(\mathbf{k_1}, \mathbf{k_2})$$
$$+ 2P^{(0)}(k_2)P^{(0)}(k_3)F_2^{(s)}(\mathbf{k_2}, \mathbf{k_3})$$
$$+ 2P^{(0)}(k_3)P^{(0)}(k_1)F_2^{(s)}(\mathbf{k_3}, \mathbf{k_1})$$

$$2F_2^{(s)}(\mathbf{k_i}, \mathbf{k_j}) = \frac{10}{7} + \hat{\mathbf{k_i}} \cdot \hat{\mathbf{k_j}} \left(\frac{k_i}{k_j} + \frac{k_j}{k_i} \right) + \frac{4}{7} \left(\hat{\mathbf{k_i}} \cdot \hat{\mathbf{k_j}} \right)^2$$

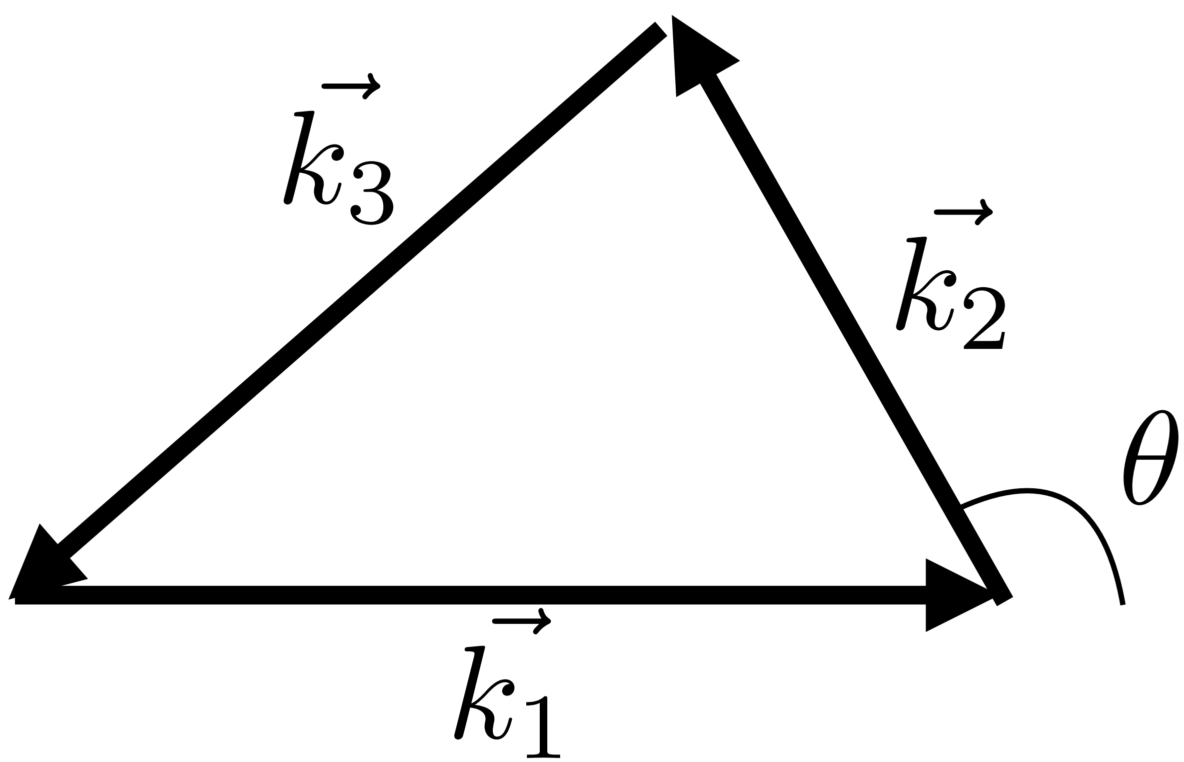
e.g. Scoccimarro et al. 1998, ApJ 496, 586

Sines interfere—destructively or constructively



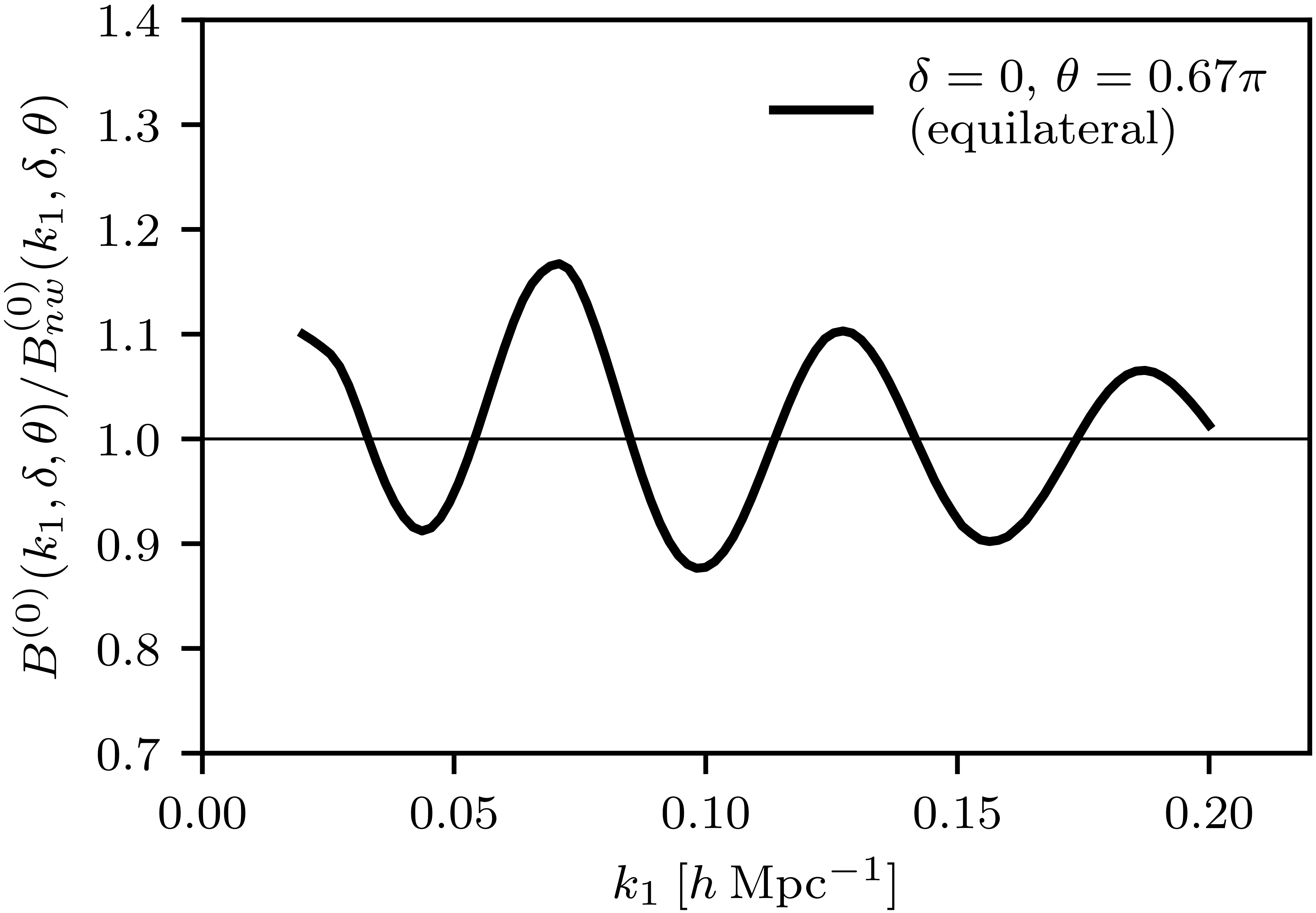
http://umdberg.pbworks.com/f/1335788316/2slitPattern.jpg

Interferometry



$$k_2 = k_1 + \delta\lambda_f/2$$

Destructive configurations minimize BAO amplitude



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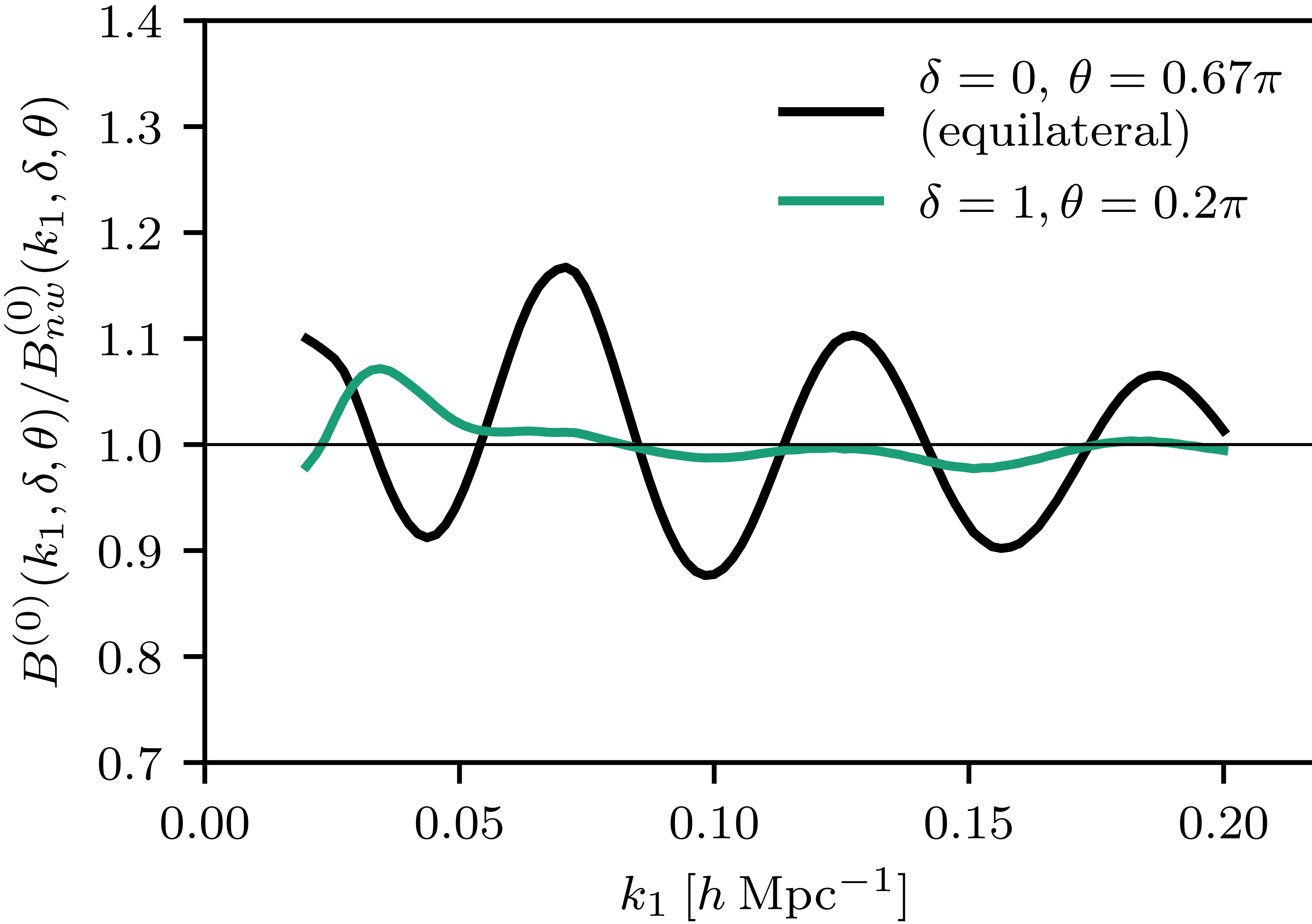
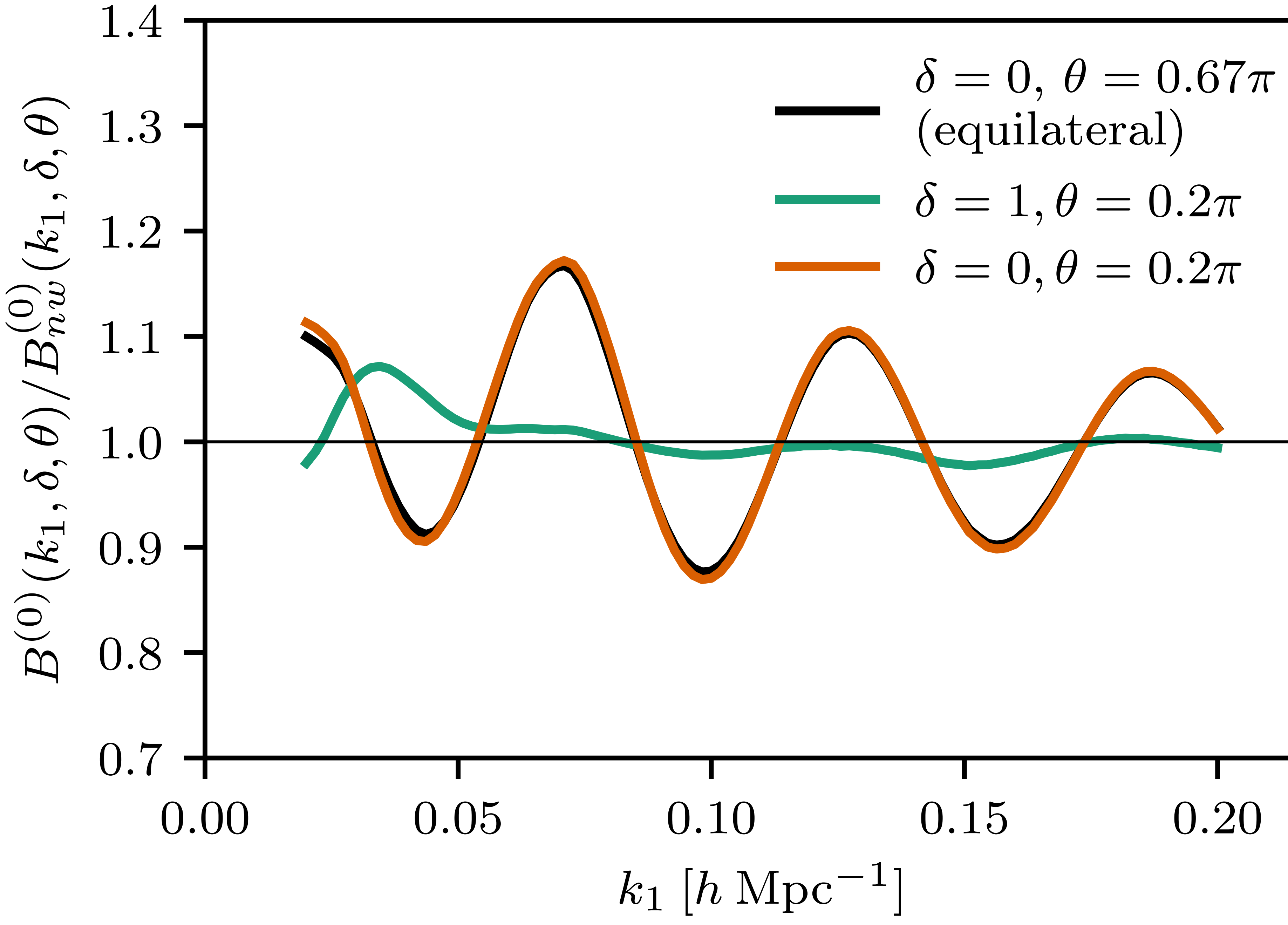
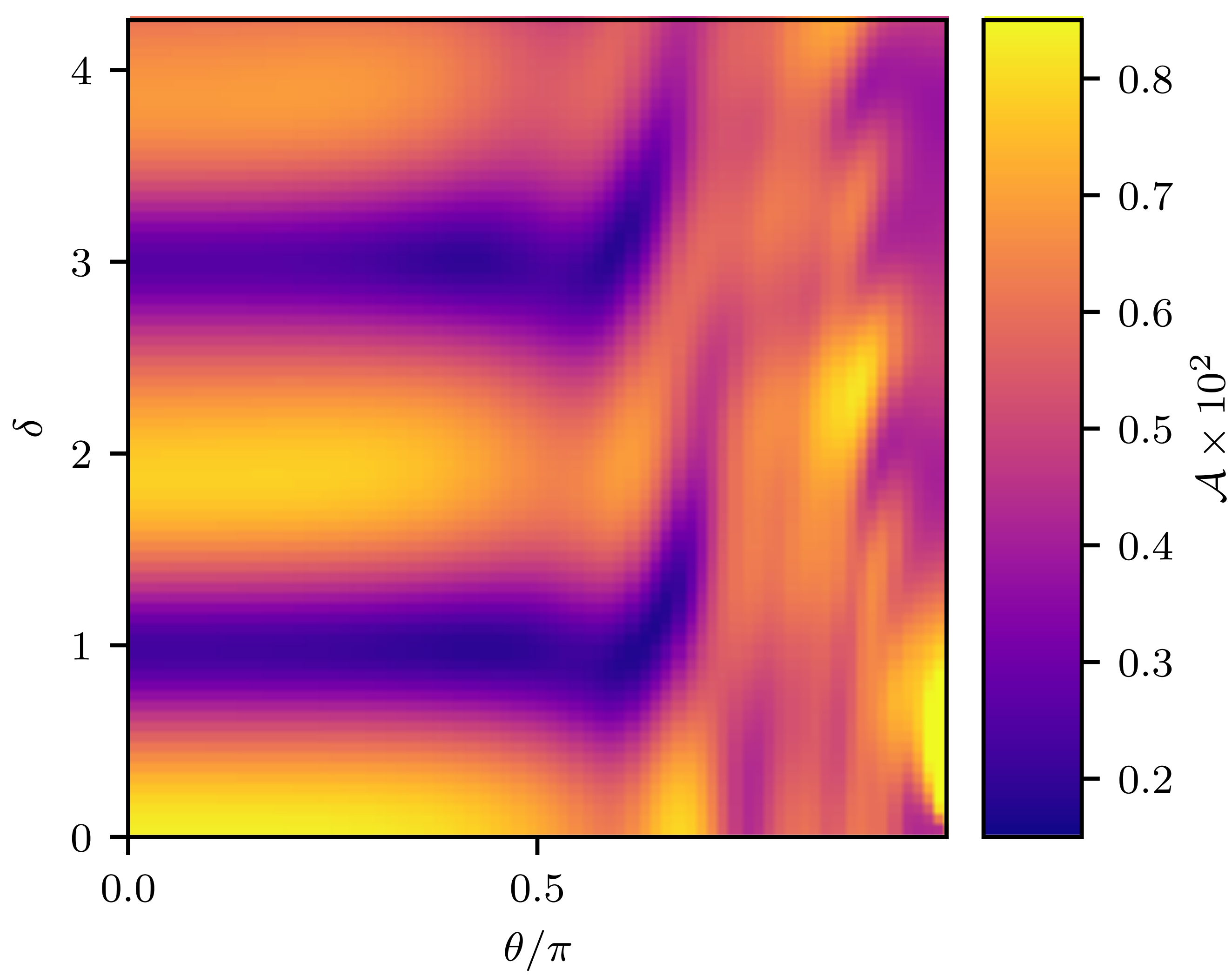


Constructive configurations maximize BAO amplitude



RMS map shows configurations where BAO is amplified or suppressed

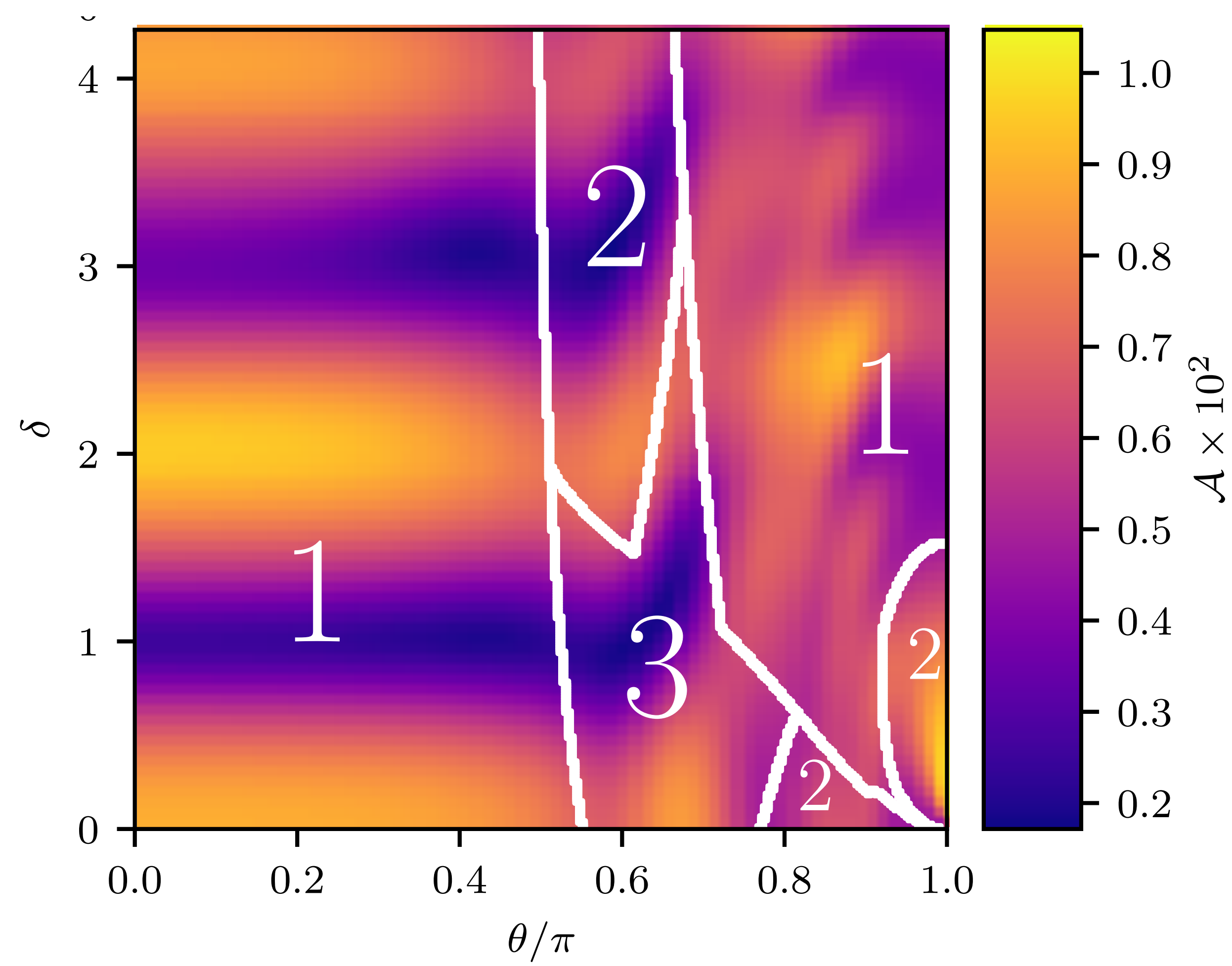
$$\mathscr{A}^2(\delta,\theta) \equiv \int_{0.01}^{0.2} \left[R(k_1,\delta,\theta) - \bar{R}(\delta,\theta)\right]^2 \frac{\mathrm{d}k_1}{[h/\mathrm{Mpc}]}$$



Child, …, Slepian+ 2018b PRD 98, 123521

Single terms or pairs of terms dominate the cyclic sum

$$\begin{aligned} B^{(0)}(k_1,k_2,k_3) &= 2P^{(0)}(k_1)P^{(0)}(k_2)F_2^{(s)}(\mathbf{k_1},\mathbf{k_2}) \\ &+ 2P^{(0)}(k_2)P^{(0)}(k_3)F_2^{(s)}(\mathbf{k_2},\mathbf{k_3}) \\ &+ 2P^{(0)}(k_3)P^{(0)}(k_1)F_2^{(s)}(\mathbf{k_3},\mathbf{k_1}) \end{aligned}$$



Child, Slepian & Takada 2018 [arXiv: 1811.12396]

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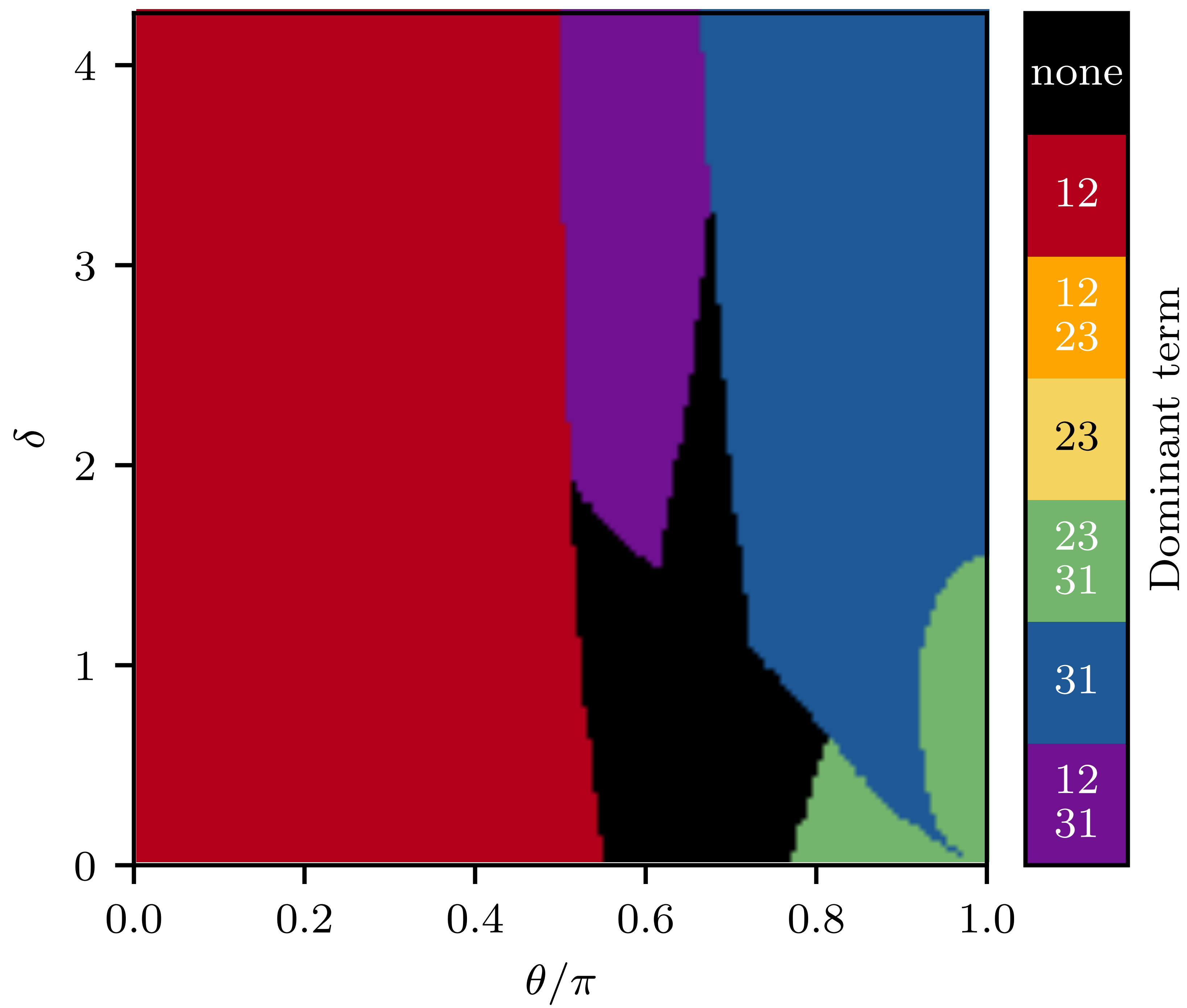

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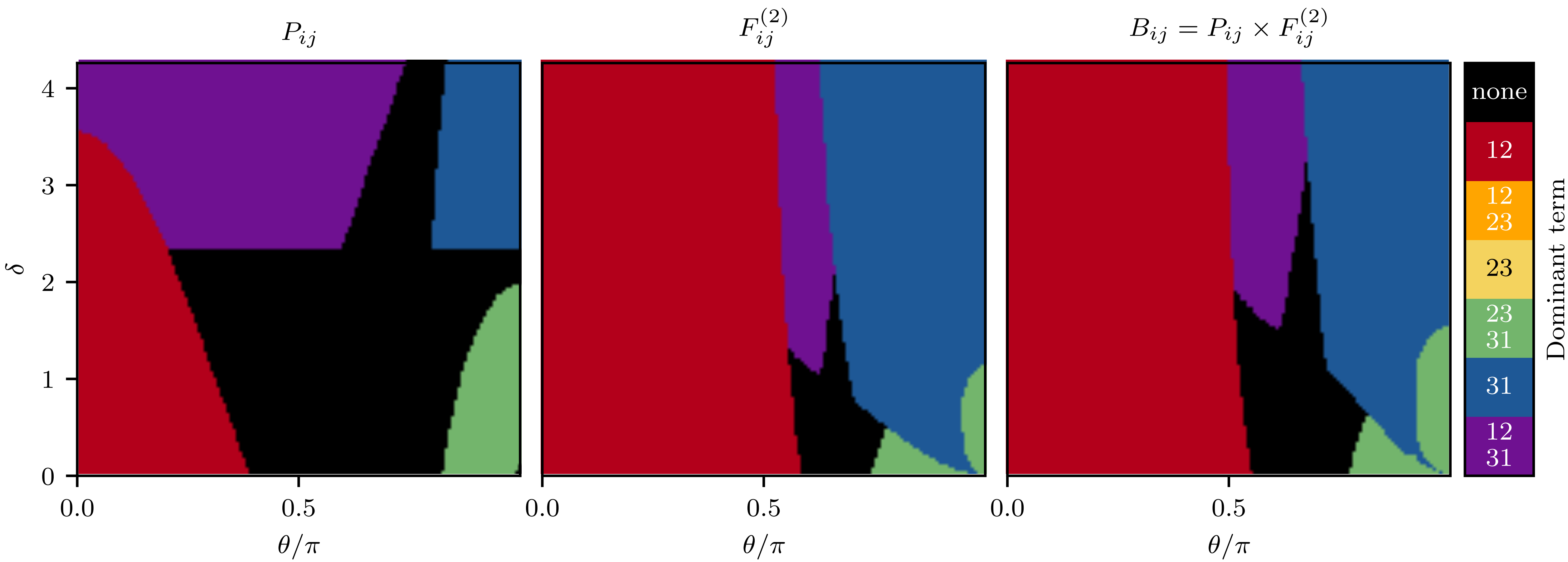
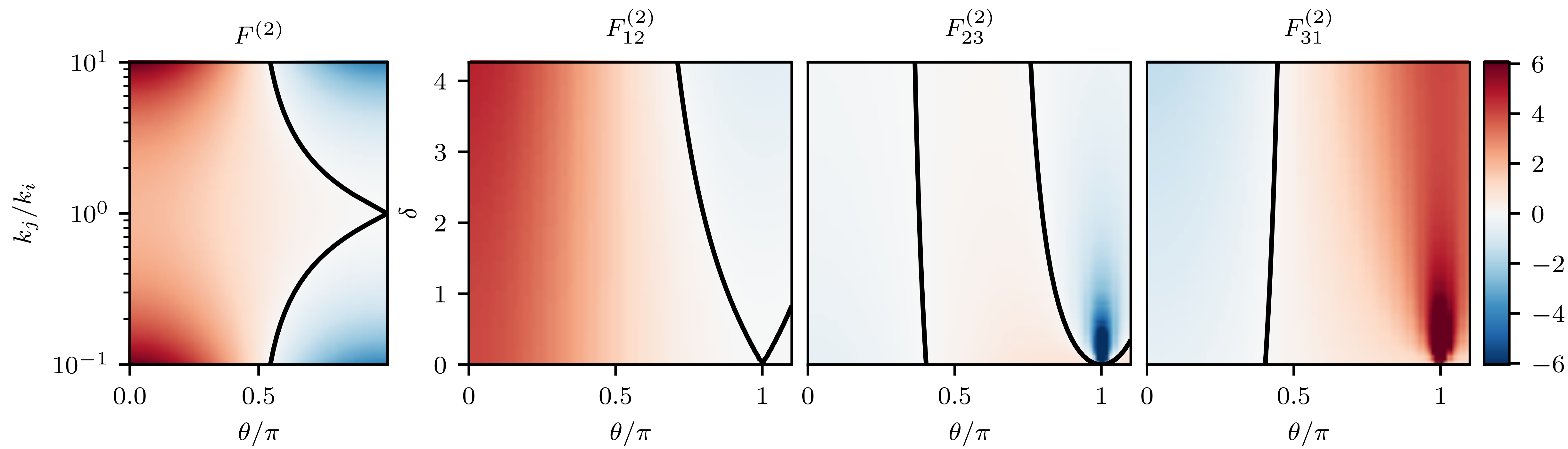
$F^{(2)}$ kernel drives dominance structure

power spectra | $F^{(2)}$ kernel | bispectrum



Child, Slepian & Takada 2018 [arXiv: 1811.12396]

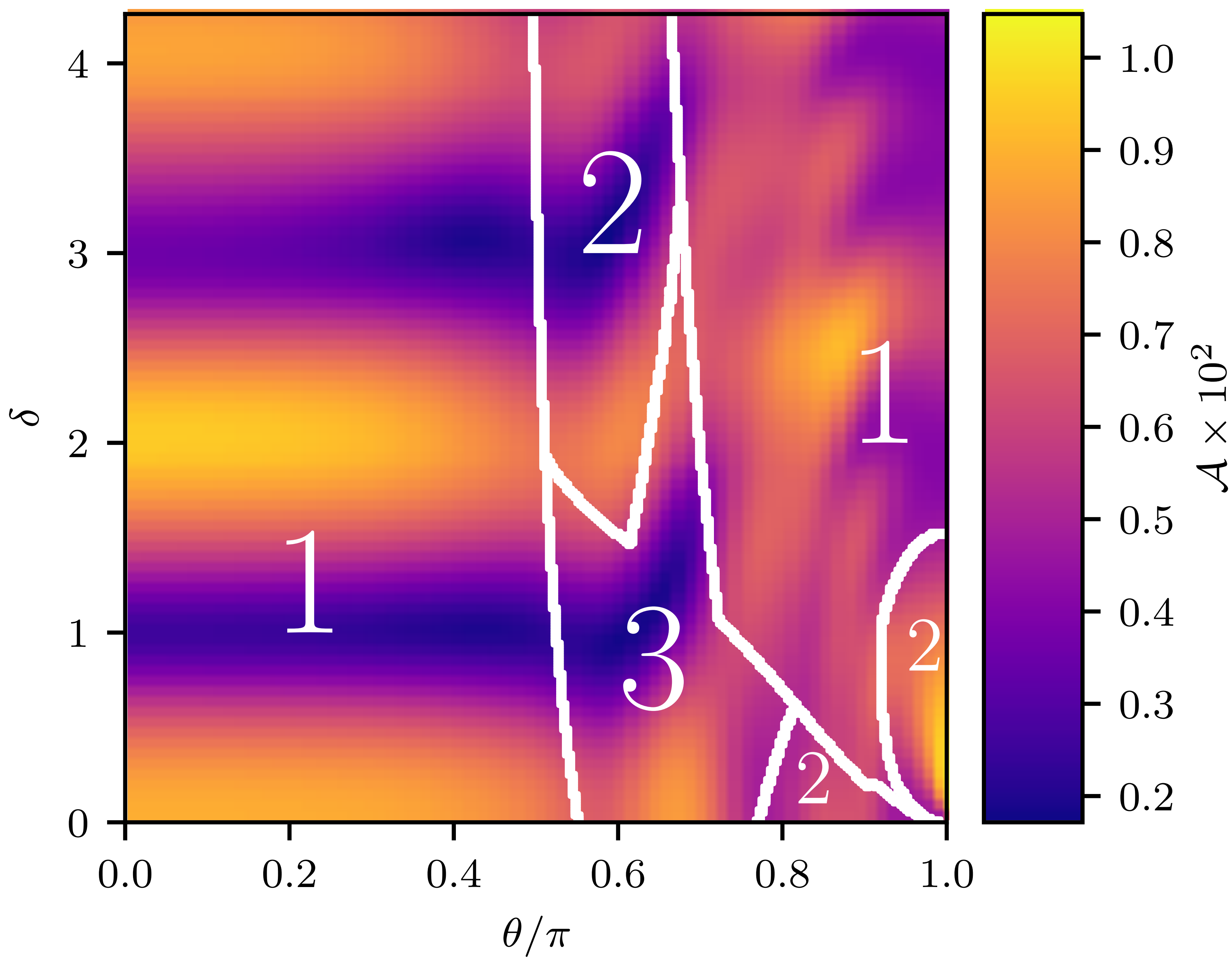
Large dynamic range of the $F^{(2)}$ kernel drives dominance structure



zero crossings

Child, Slepian & Takada 2018 [arXiv: 1811.12396]

Single terms or pairs of terms dominate the cyclic sum



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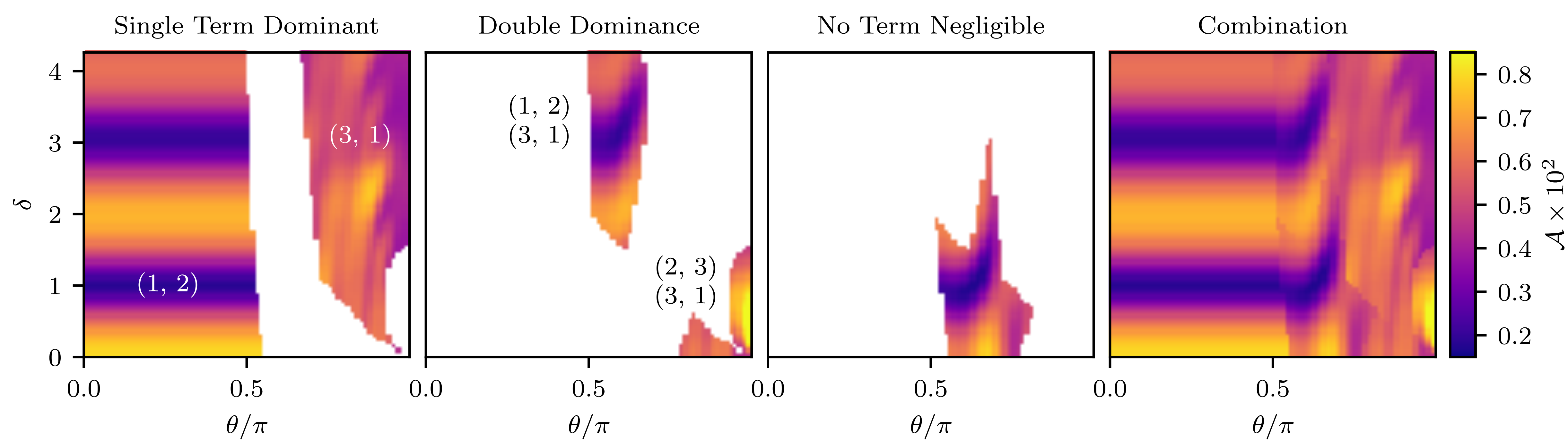
BAO amplitudes in regions dominated by one or two terms build a good approximation of the full RMS map



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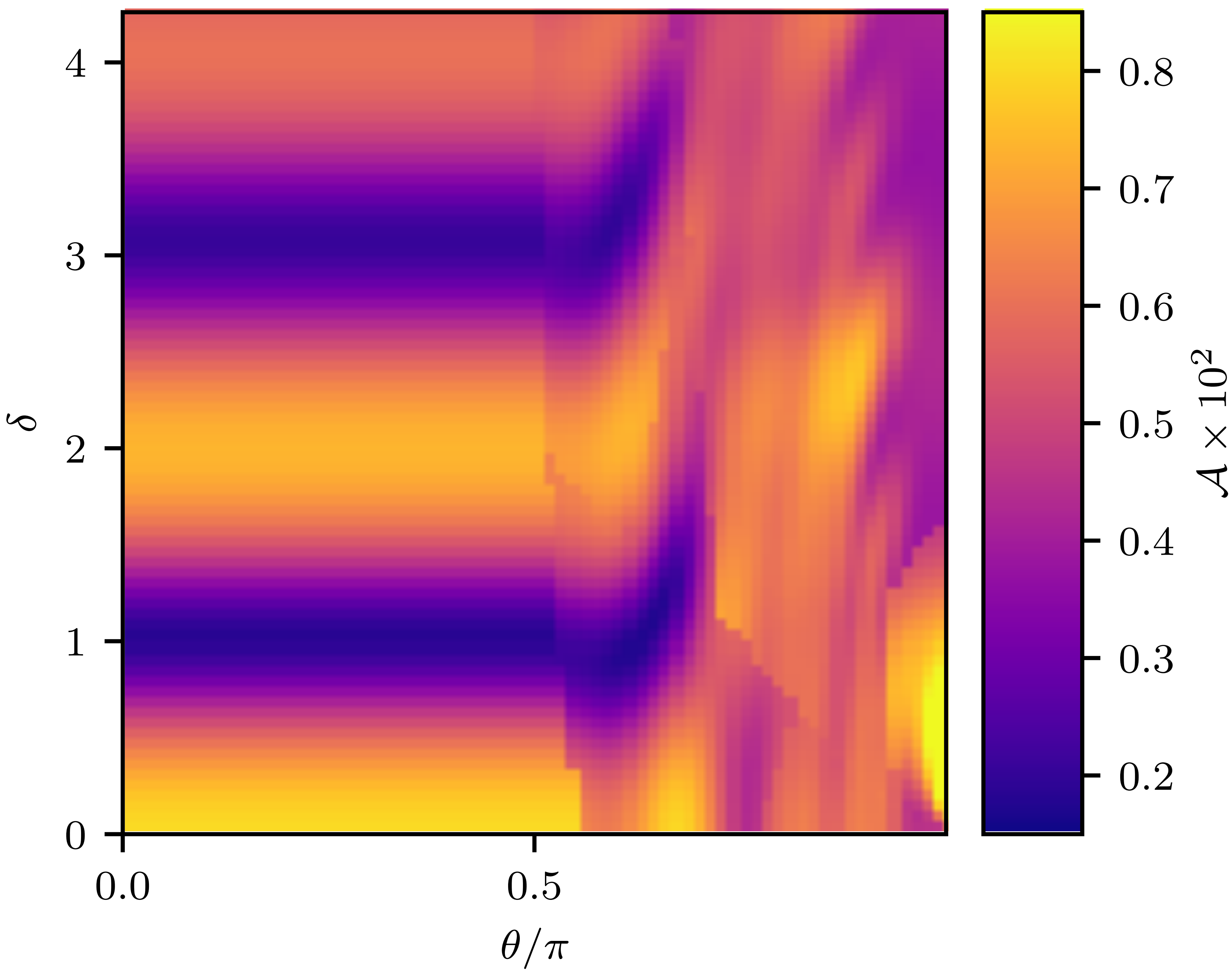

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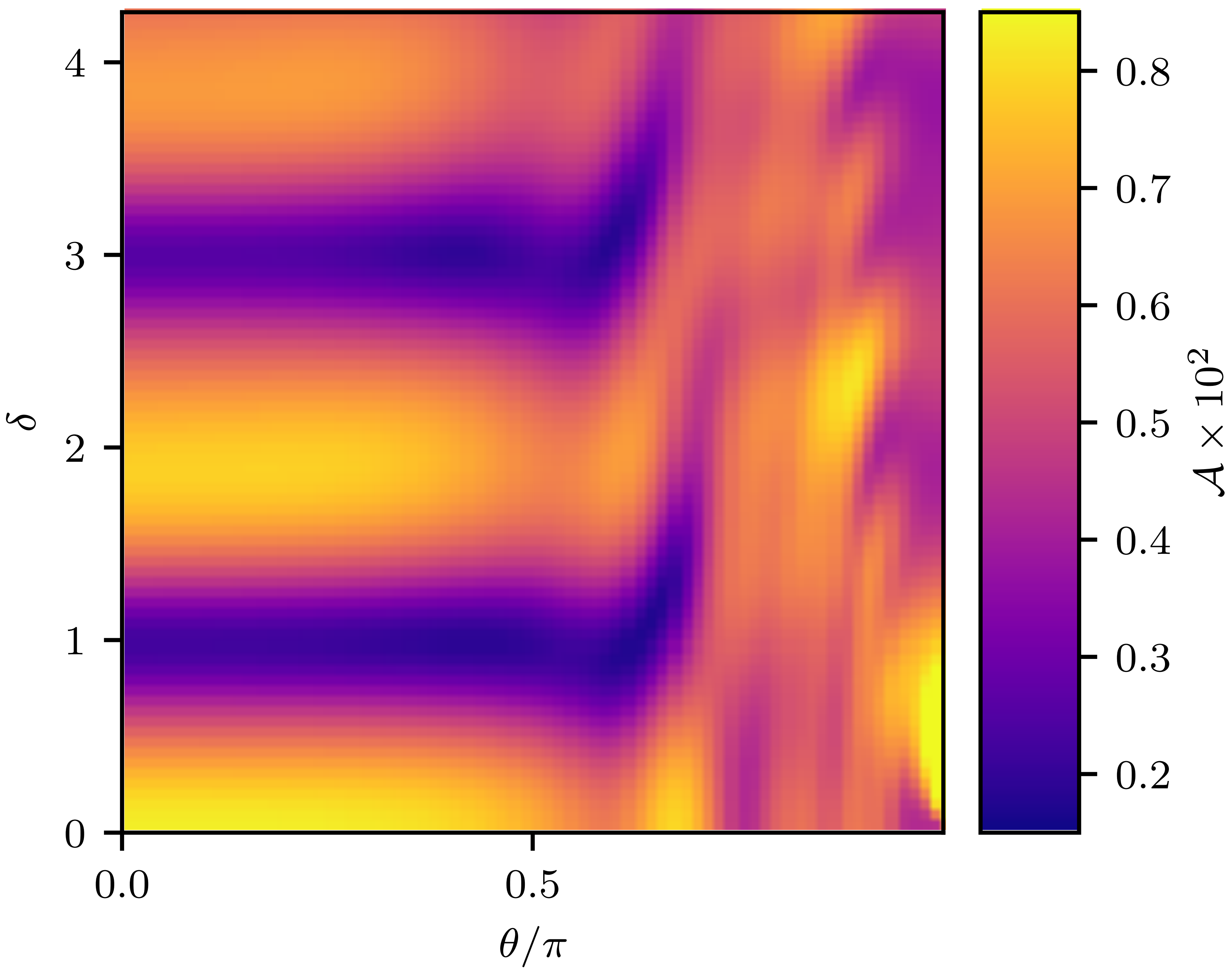

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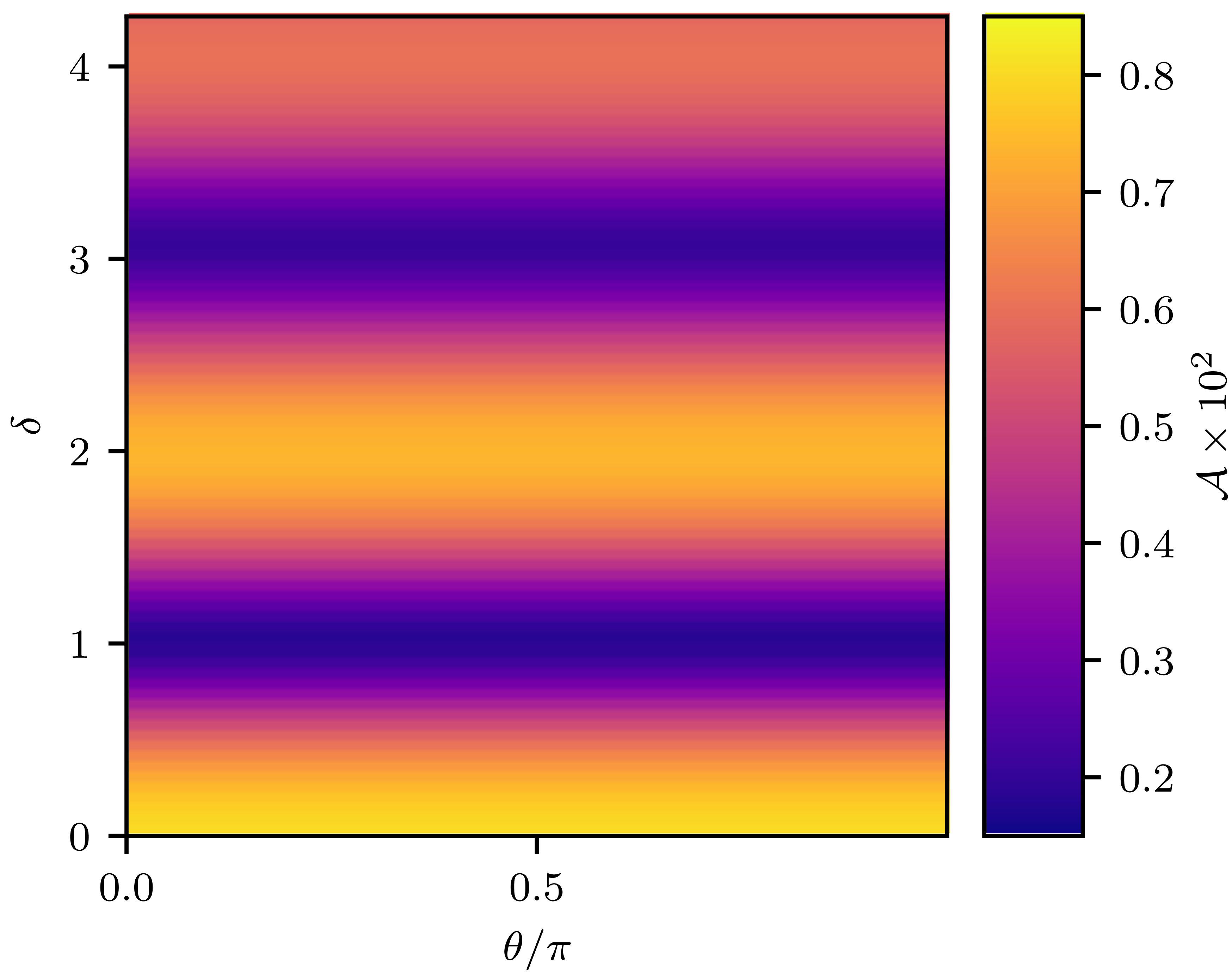
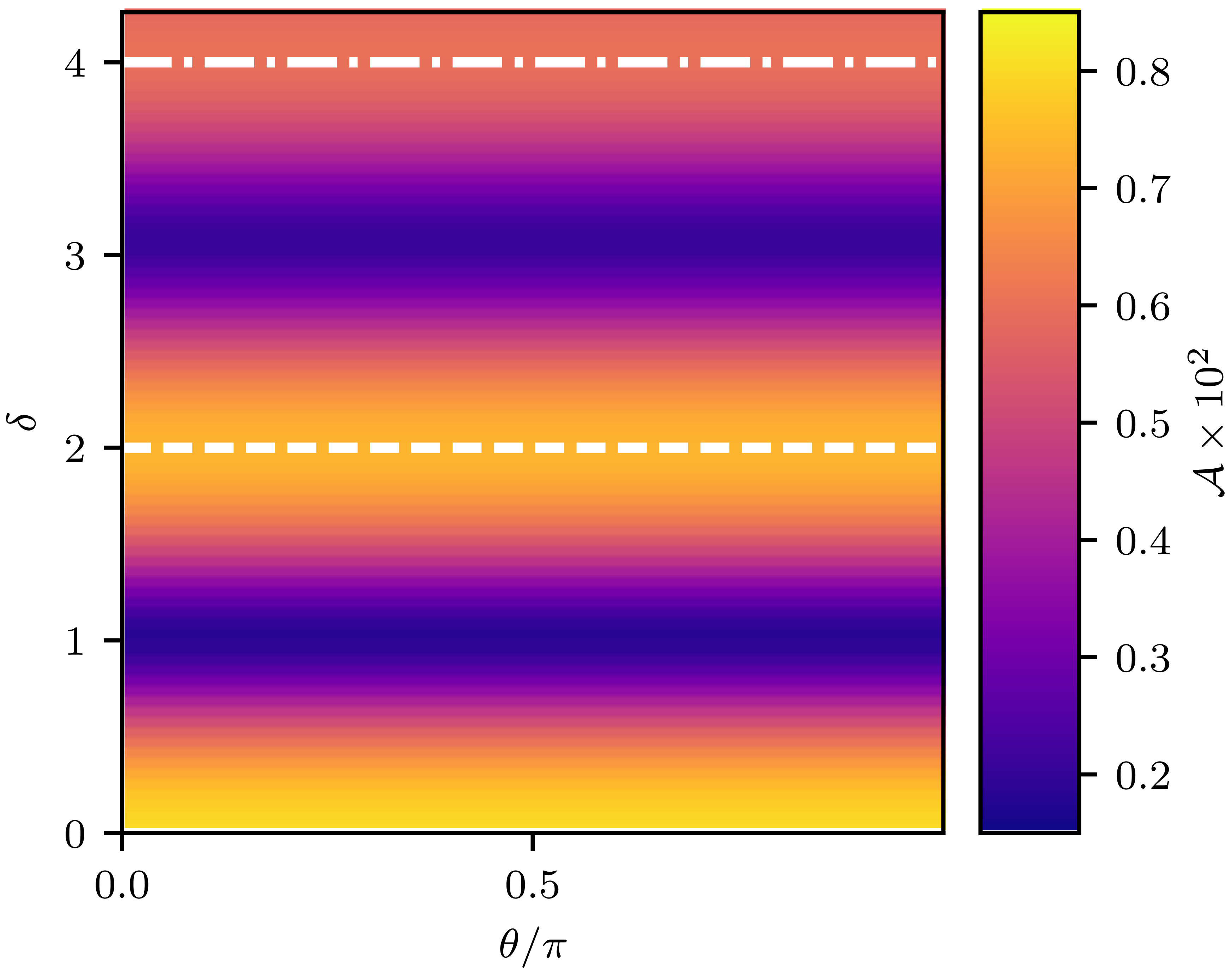
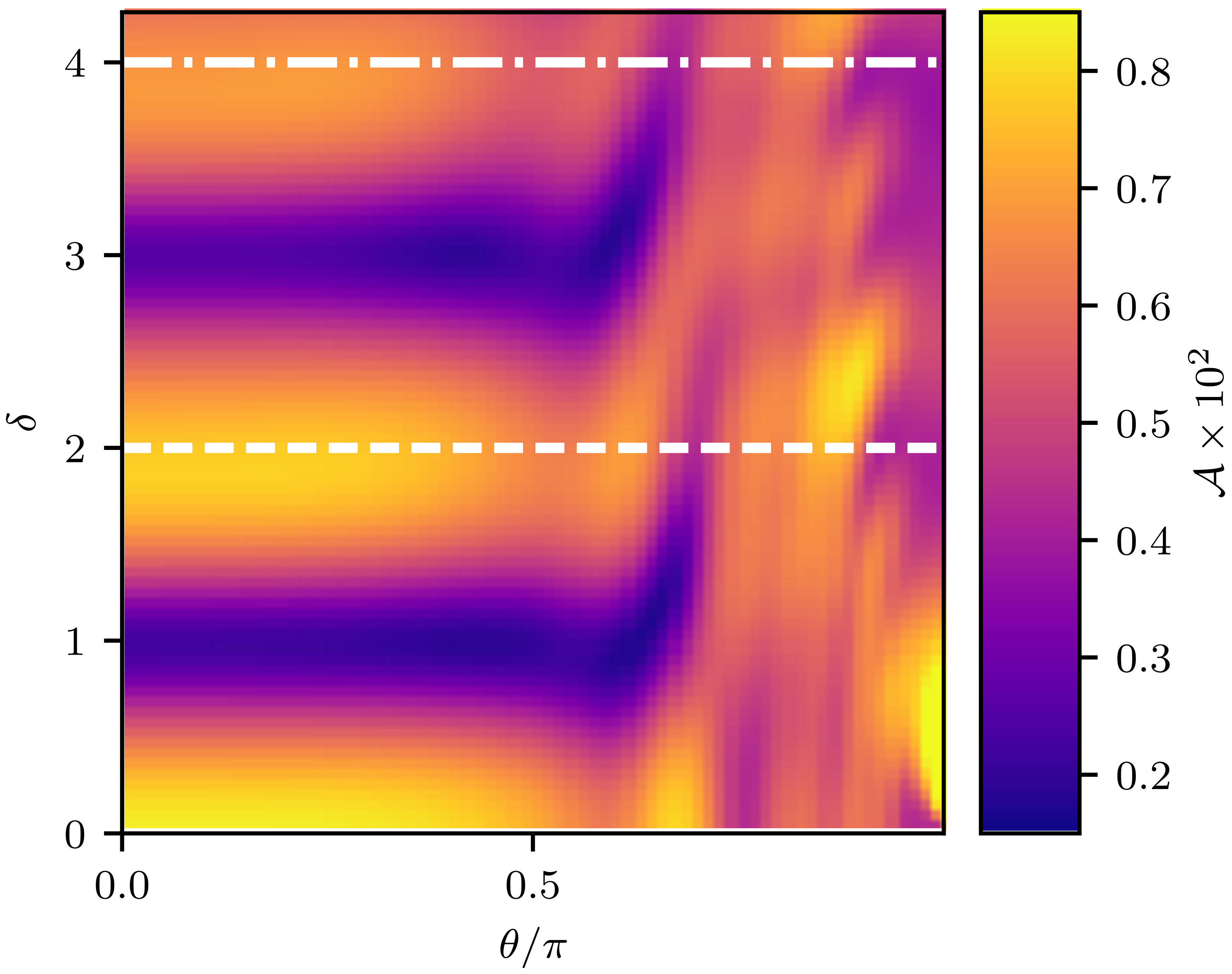
(1, 2) term RMS map



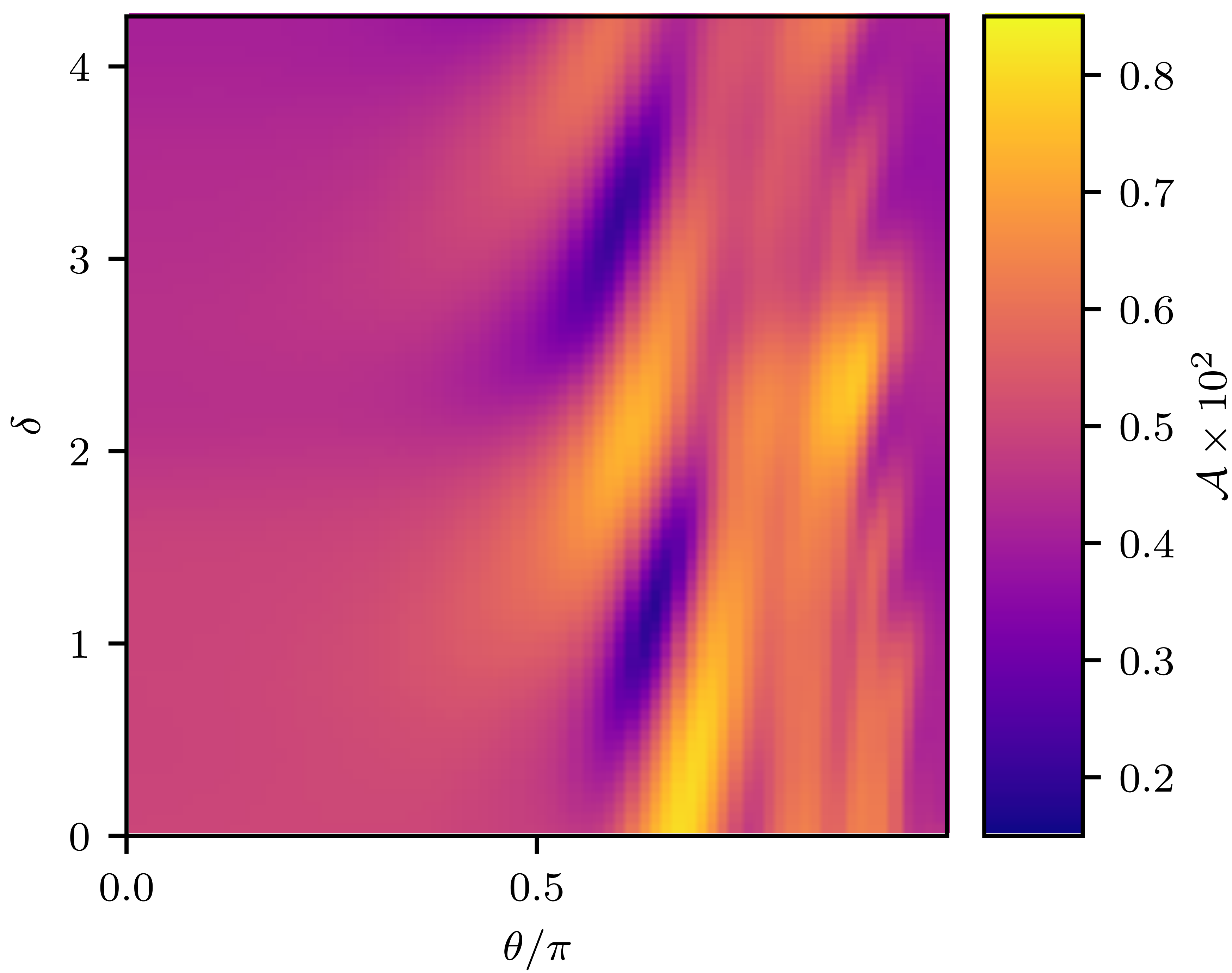
(1, 2) term RMS map



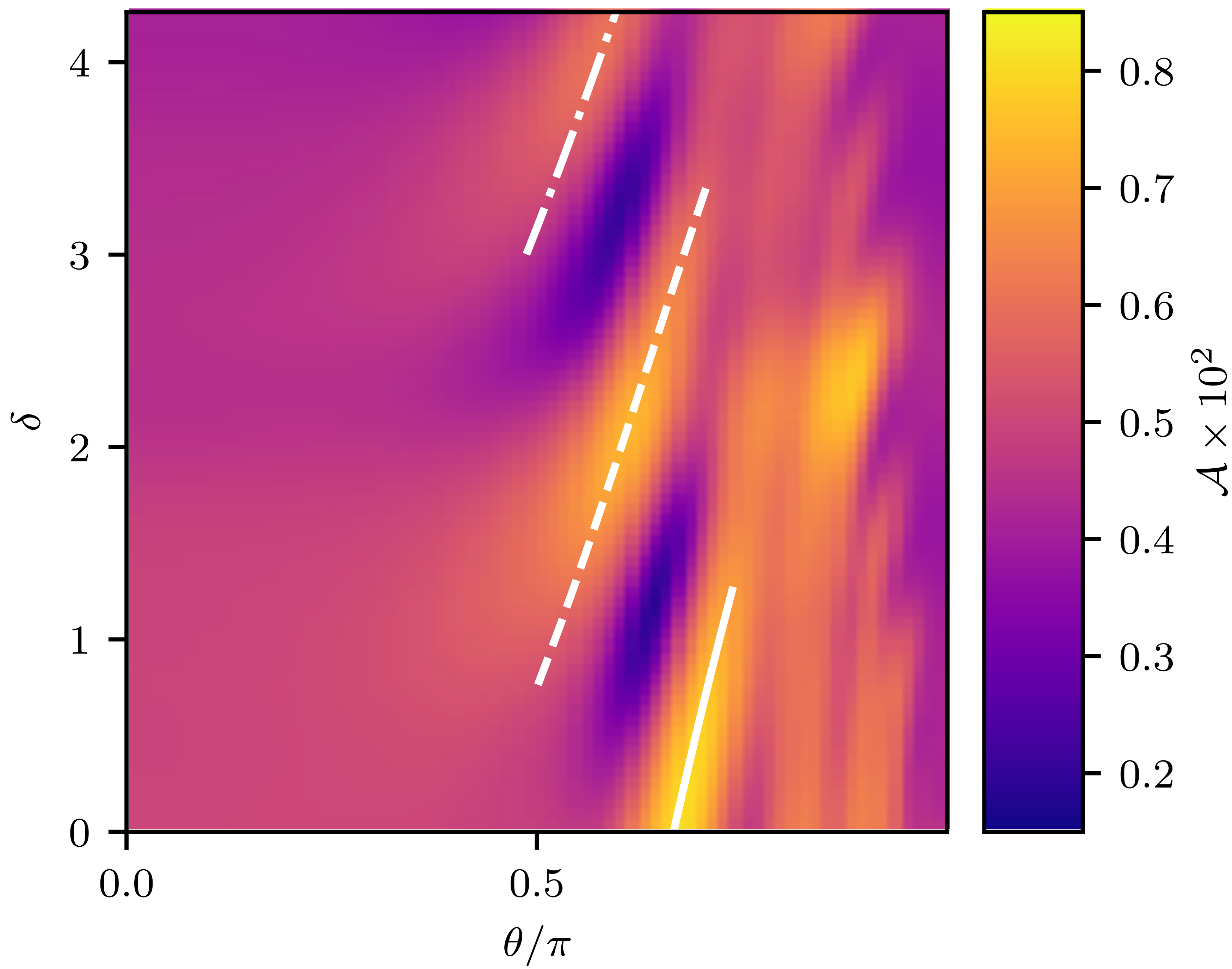
Interference creates bright ridges of high BAO amplitude in the (1, 2) term



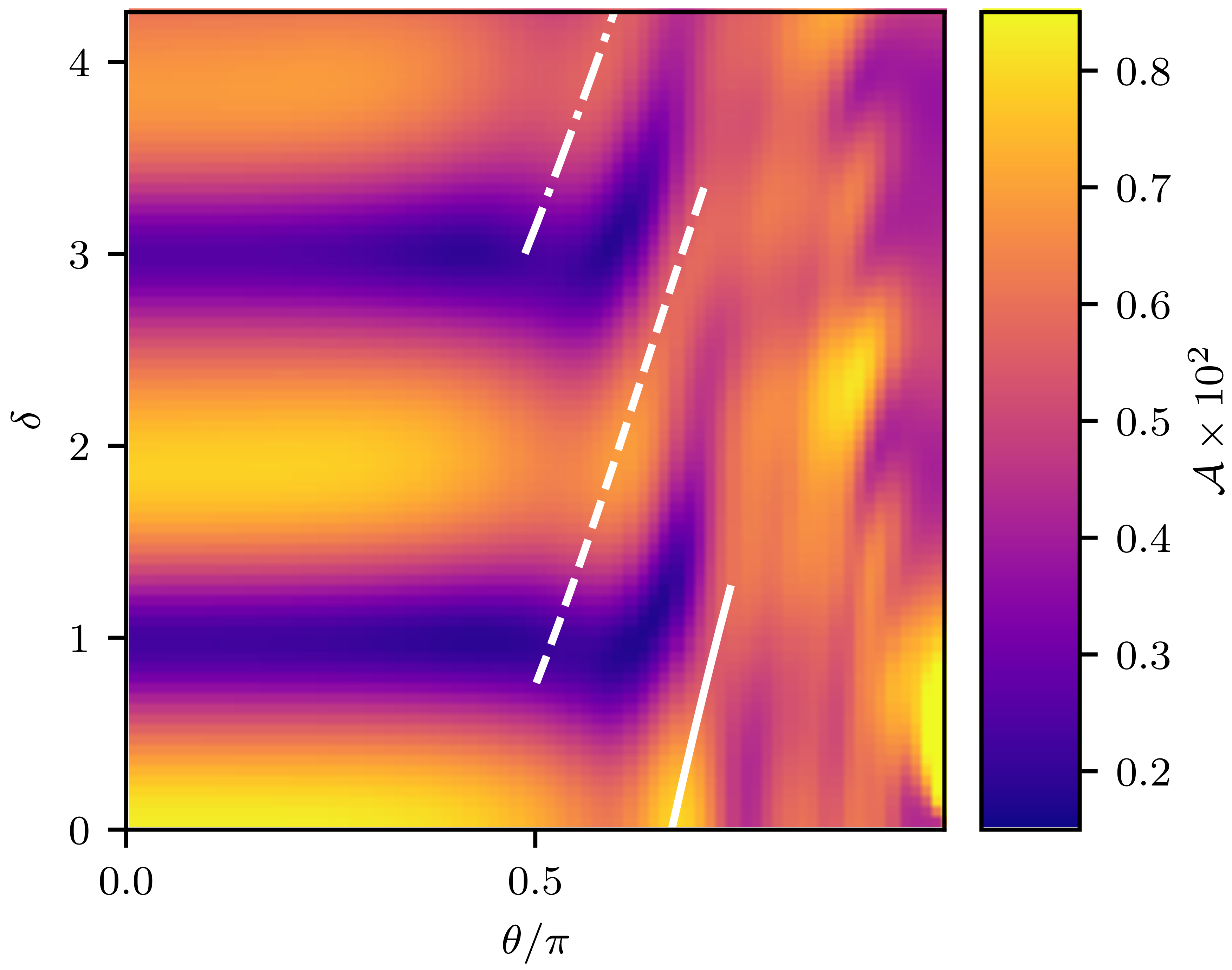
(3, 1) term RMS map



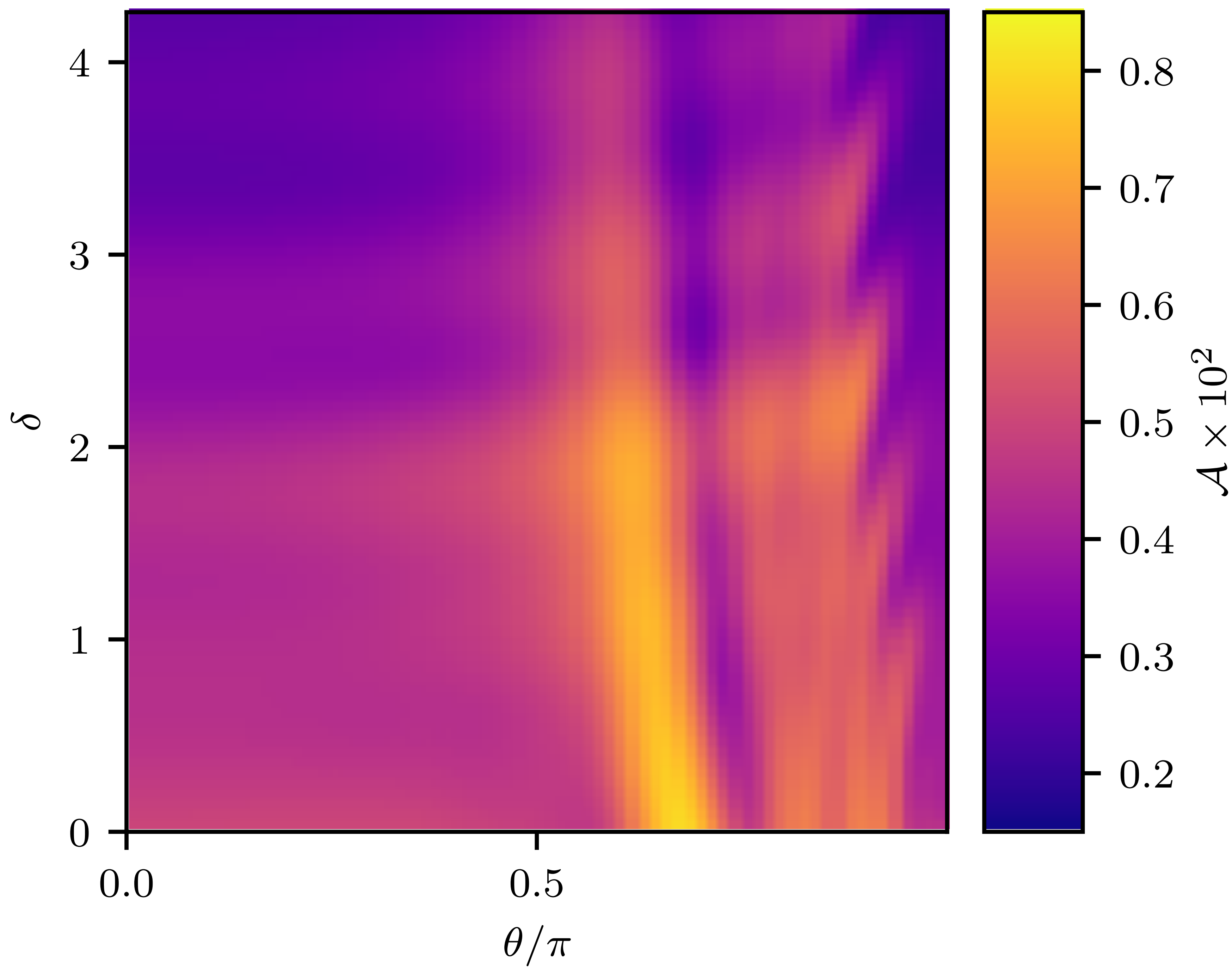
(3, 1) term RMS map



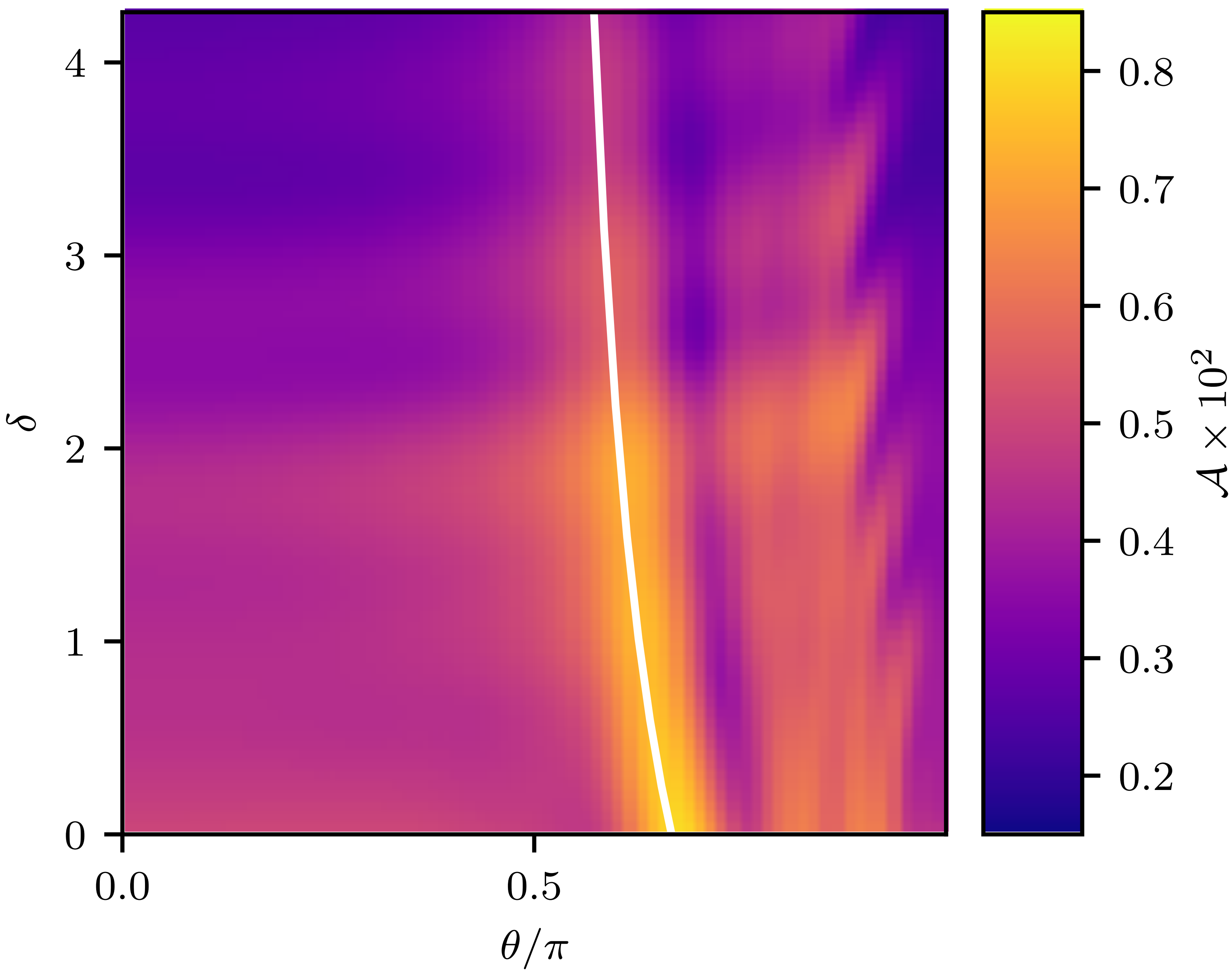
Interference creates bright ridges of high BAO amplitude in the (3, 1) term



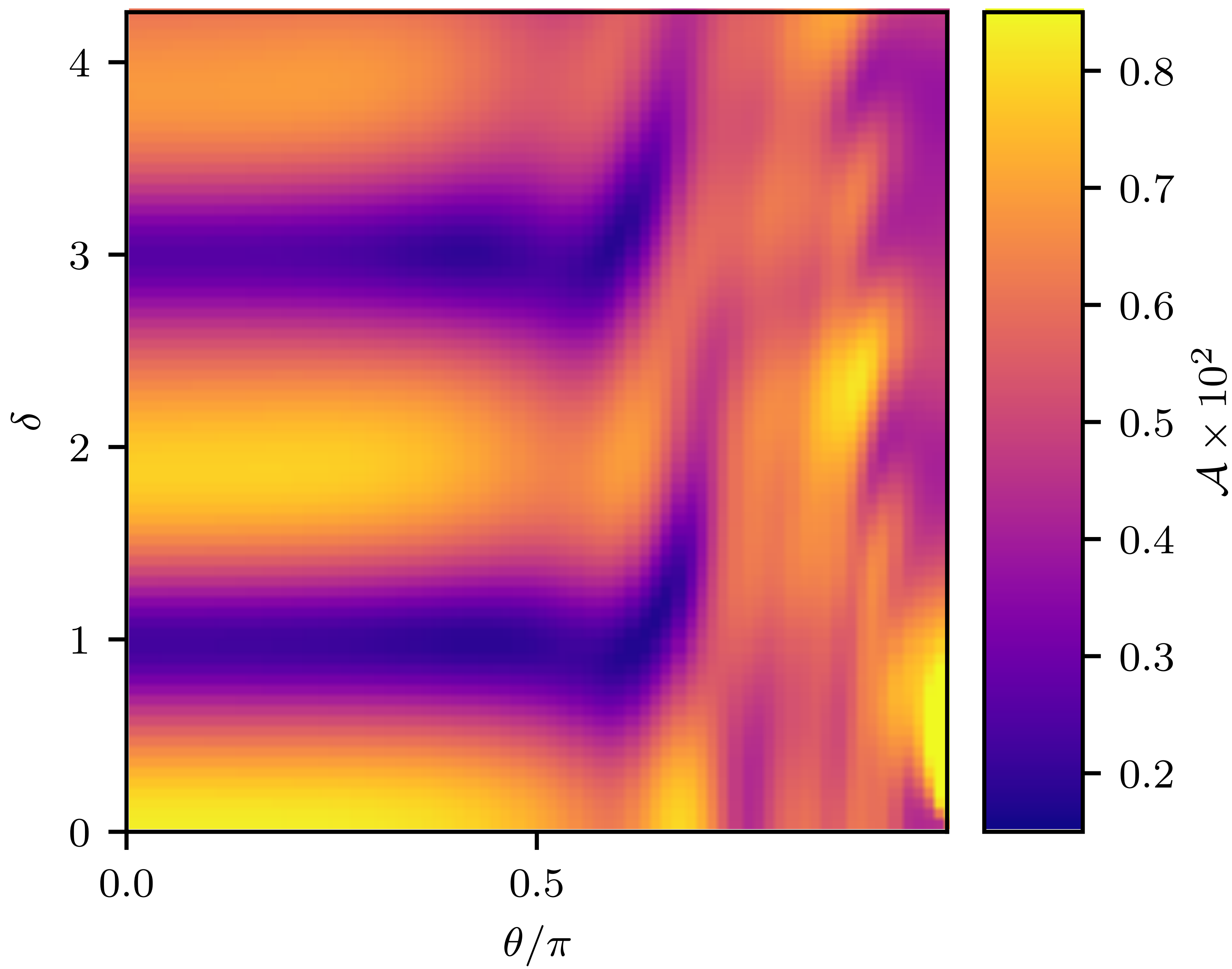
(2, 3) term RMS map



(2, 3) term RMS map



To constrain BAO in the bispectrum, first strategically select configurations from the RMS map



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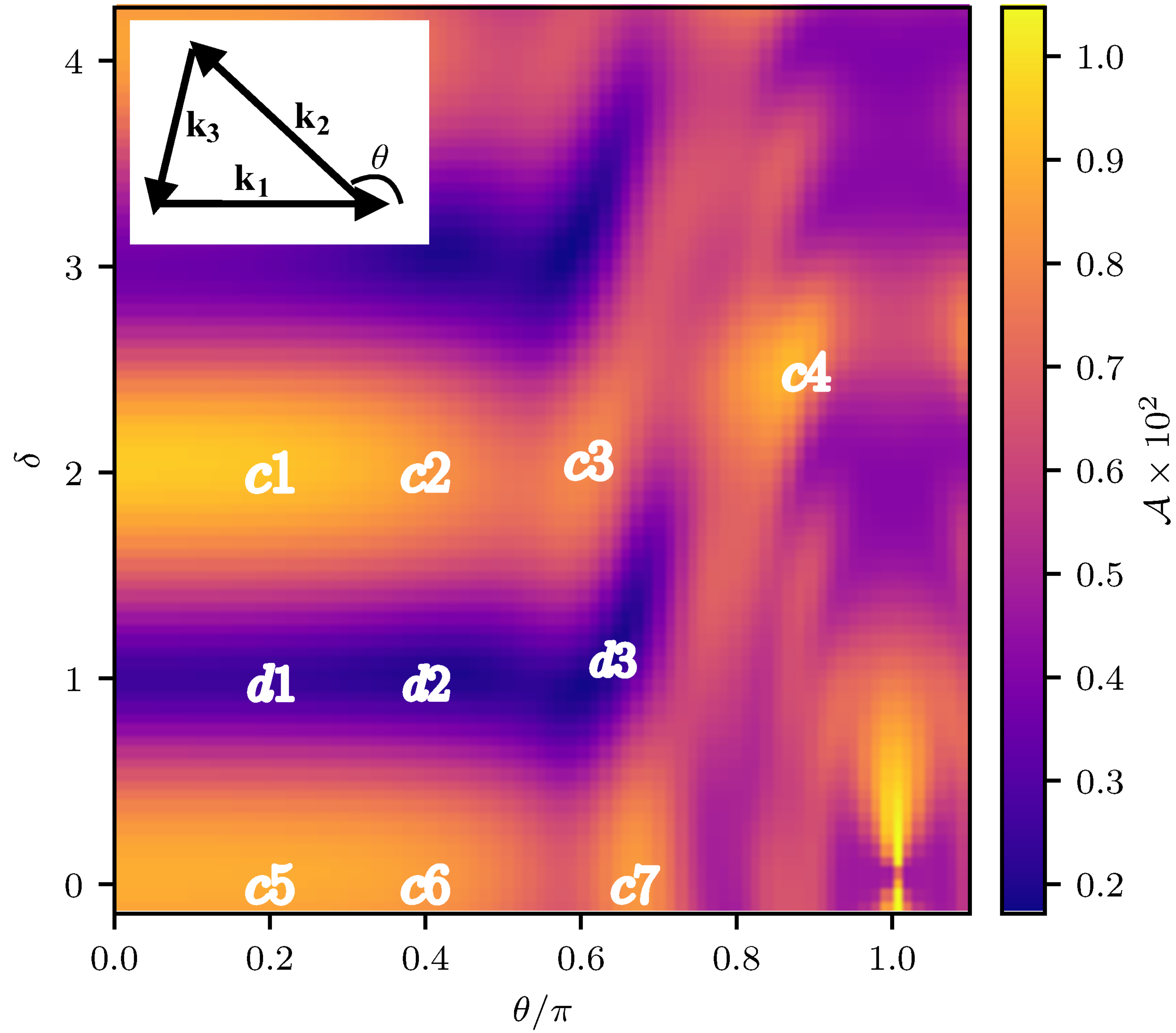
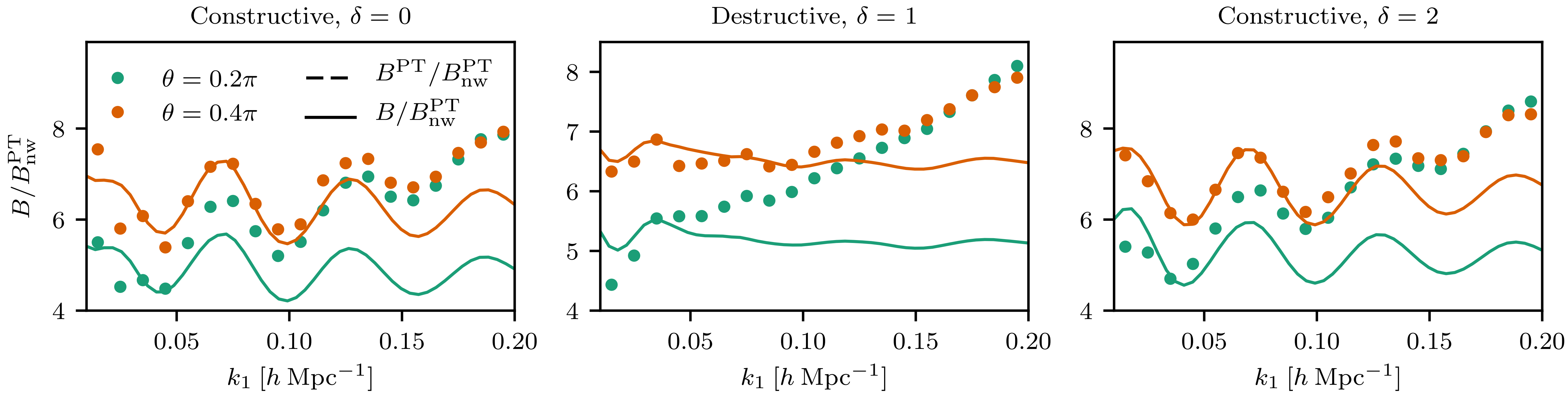


Child, …, Slepian+ 2018b PRD 98, 123521

Bispectra measured from simulations show expected interference



Child, …, Slepian+ 2018b PRD 98, 123521

Bispectrum measurements improve BAO constraints

Fisher matrix analysis to estimate improvement in constraints on BAO scale, compared to P(k) alone

3 constructive configurations — ~8%

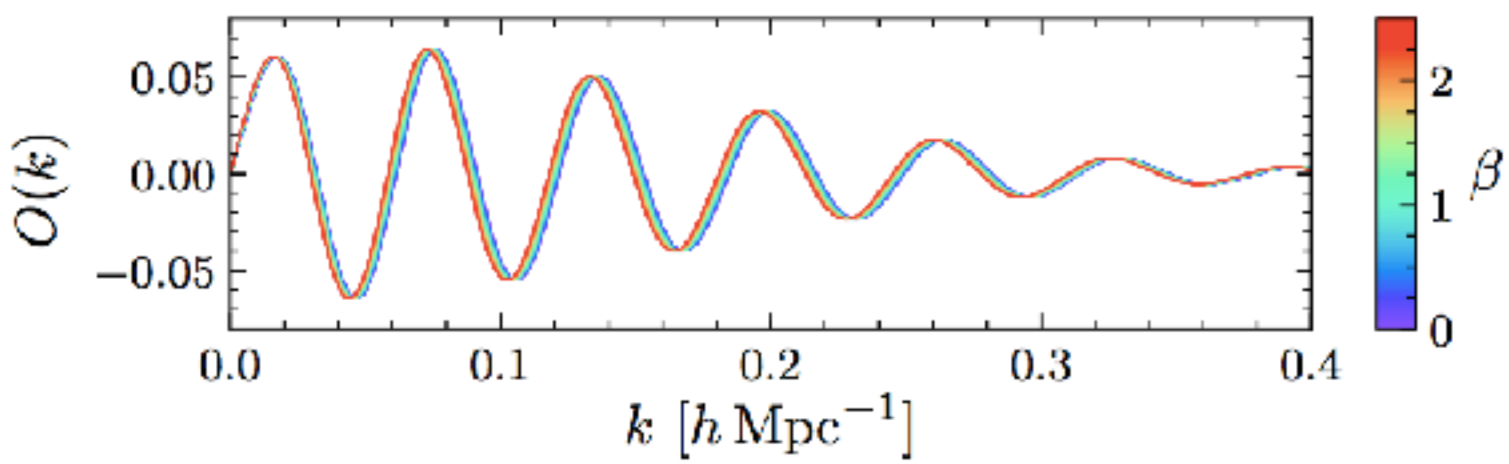
3 destructive configurations — ~3%

10 configurations (3 destructive + 7 constructive)— ~14%

Child, …, Slepian+ 2018b PRD 98, 123521

Extensions

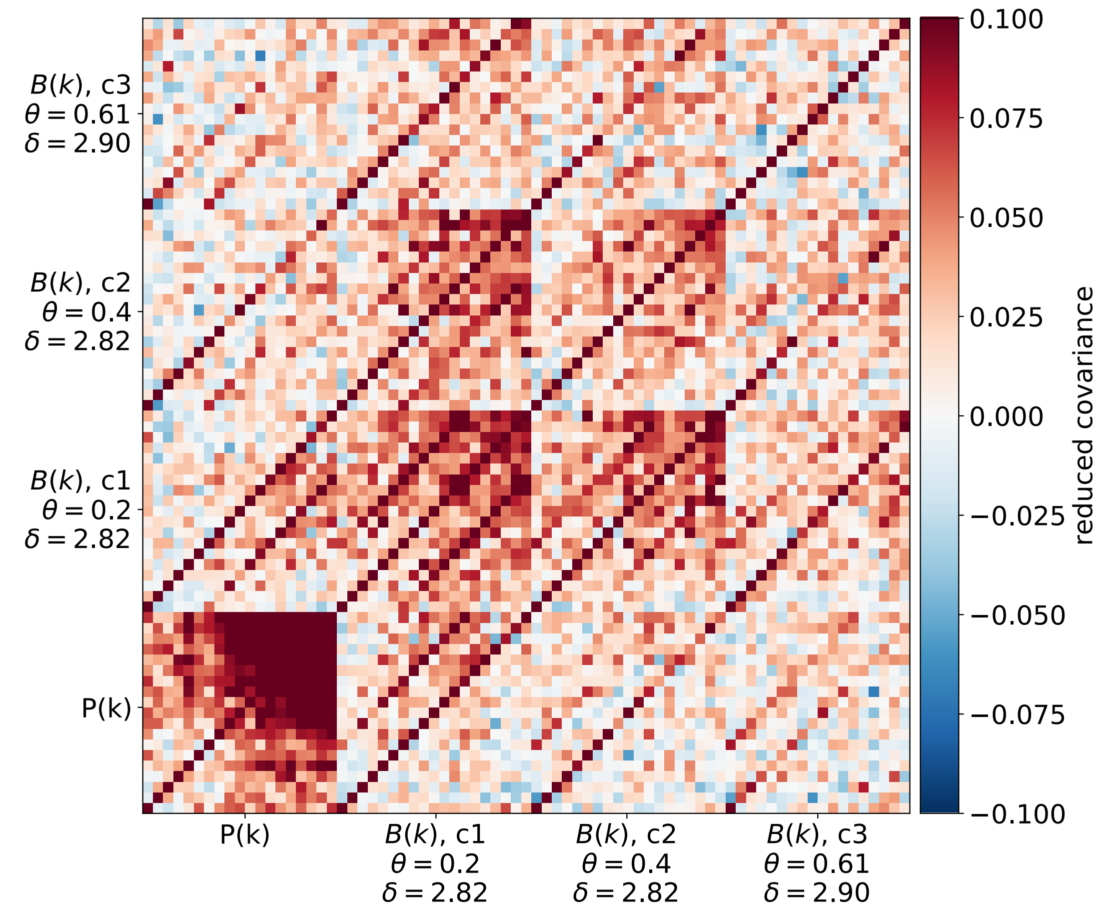
1.phase effects, e.g. relativistic neutrinos at high redshift



Baumann+ 2018
arXiv: 1803.10741

2. how best to select triangles

3. independence from reconstruction



Thank you!