constraining M_ν with ***the bispectrum***

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Bringing Science Solutions to the World
BERKELEY CENTER *for* COSMOLOGICAL PHYSICS

arXiv:1909.05273
arXiv:1909.11107

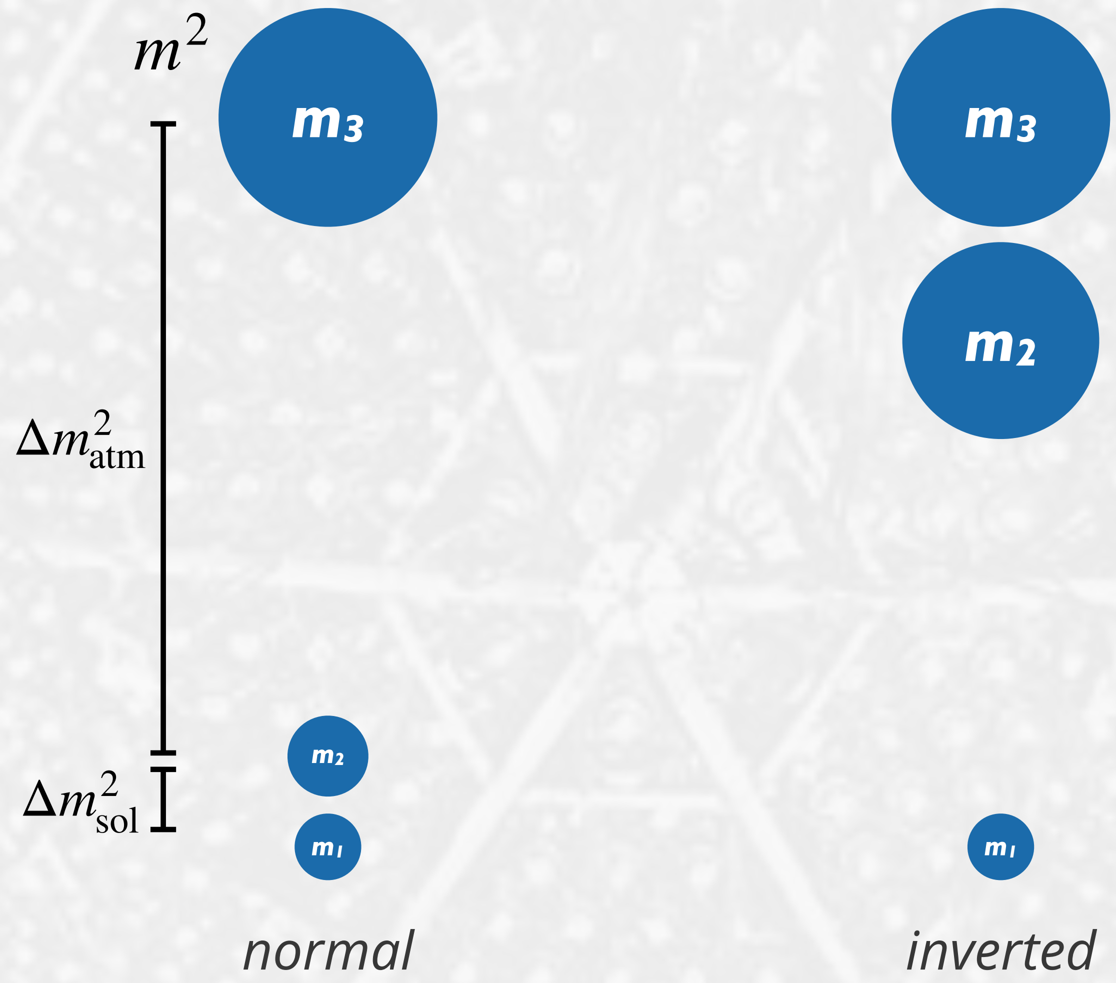
Cosmology from Home

neutrino oscillation experiments established a **lower bound** on the sum of neutrino masses $M_\nu \gtrsim 0.06\ \mathrm{eV}$

but they don't measure M_ν

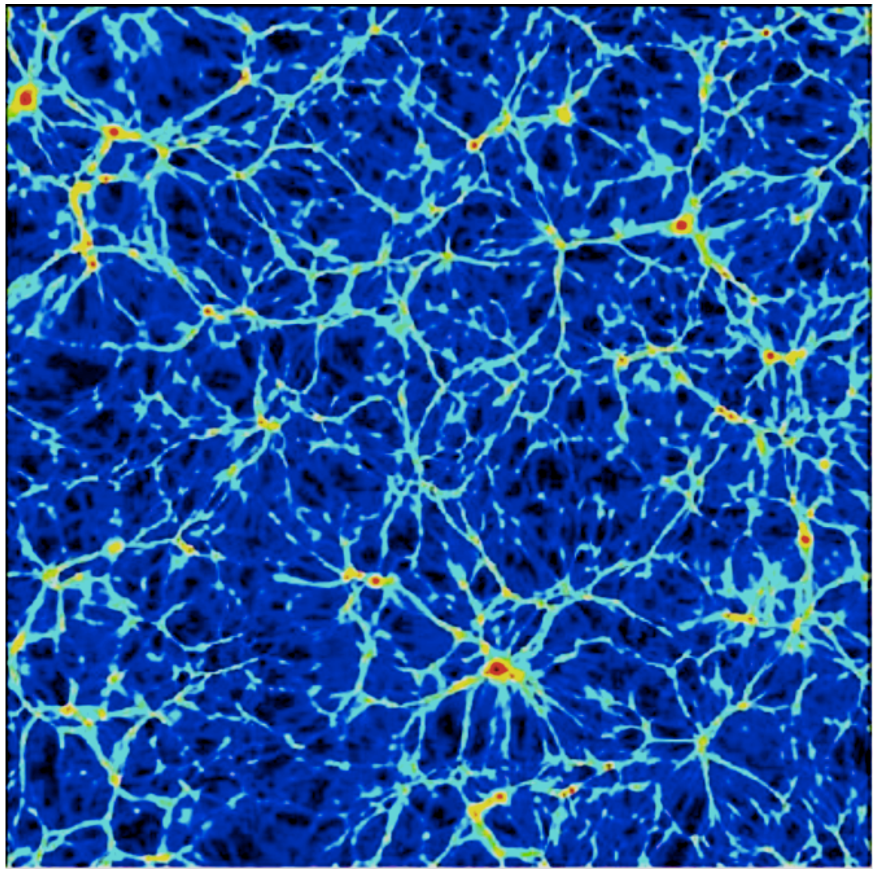
sunbury neutrino oscillatory

precise M_ν can distinguish between *“normal” and “inverted" hierarchies* and reveal physics **beyond the Standard Model**

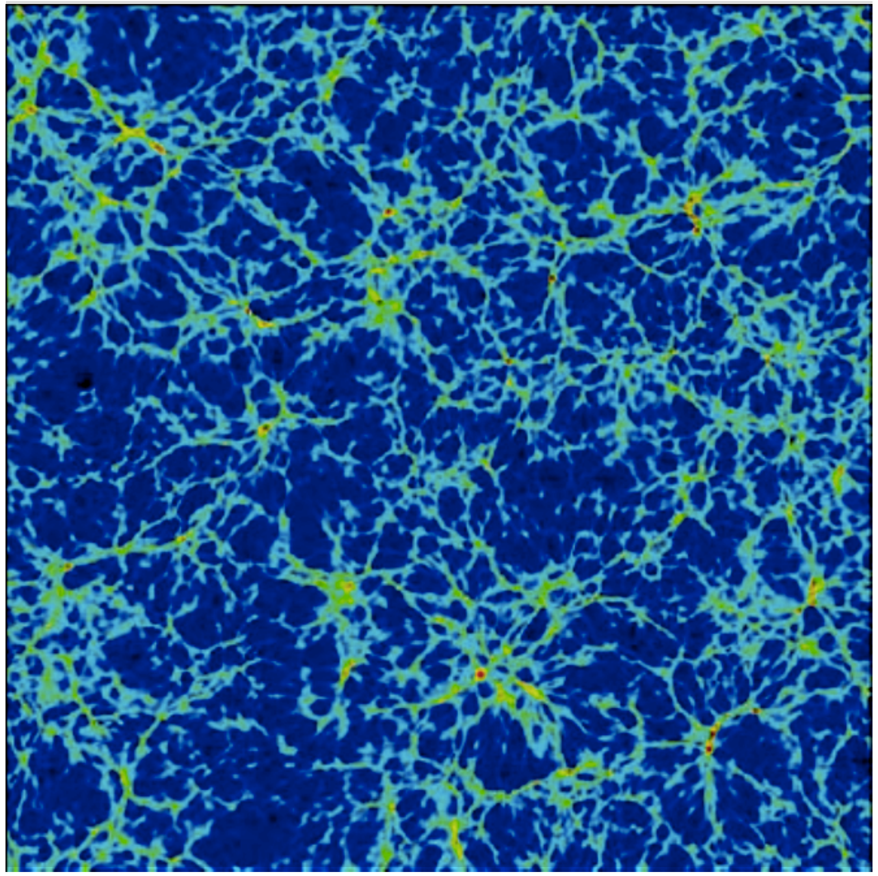


upcoming laboratory experiments are ***not sensitive enough***

$M_\nu > 0$ eV **suppresses the growth of structure** on *small scales* below their free-streaming scale



$M_\nu = 0$ eV



$M_\nu = 1.9$ eV

credit: Agarwal & Feldman (2011)

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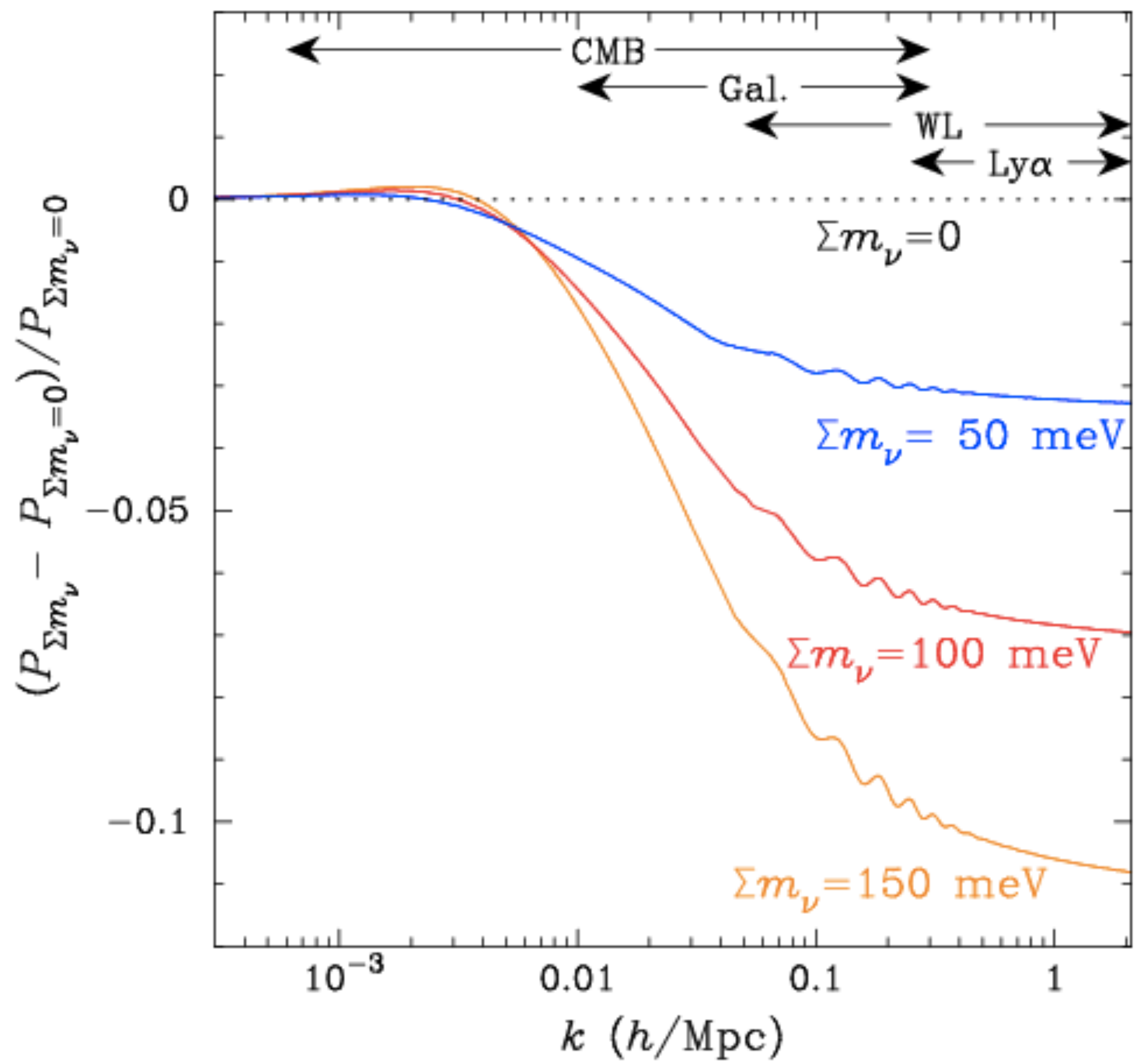


credit: Lesgourgues+(2013)

best constraints currently come from cosmology: **CMB + LSS**

$M_\nu < 0.13$ eV (*95%, Planck TT+lowE+lensing+BAO*)

Planck Collaboration (2018)

best constraints currently come from cosmology: **CMB + LSS**

$M_\nu < 0.13$ eV (*95%, Planck TT+lowE+lensing+BAO*)

*KATRIN 1.1eV upper limit (Aker+2019)**

**not a fair comparison but still…*

CMB measures $A_s e^{-2\tau}$ and thus **heavily rely on** τ **constraints**

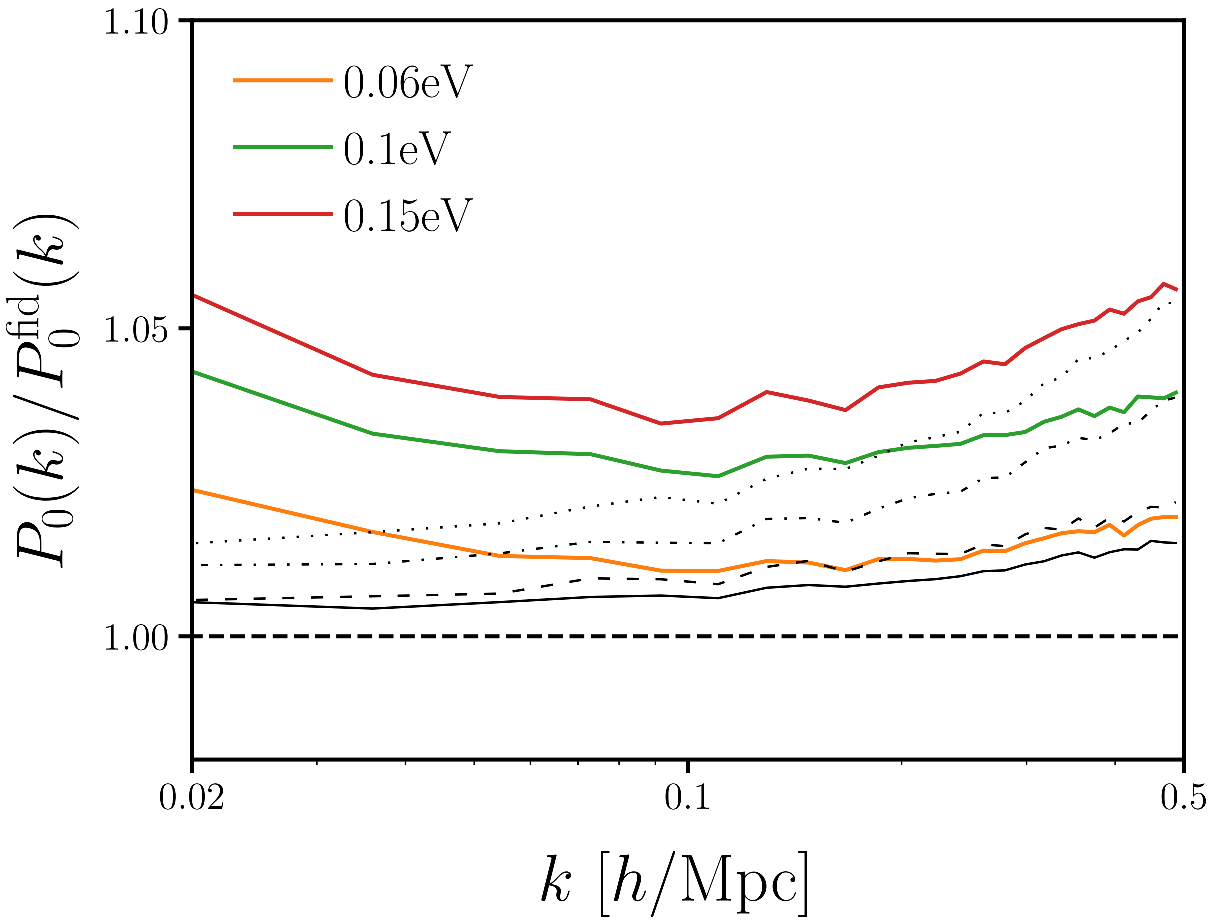
but upcoming ground-based experiments (*CMB-S4*)
will not directly constrain τ … *LiteBIRD?, LiteCOrE?*

Allison et al. (2015), Mishra-Sharma et al. (2018)

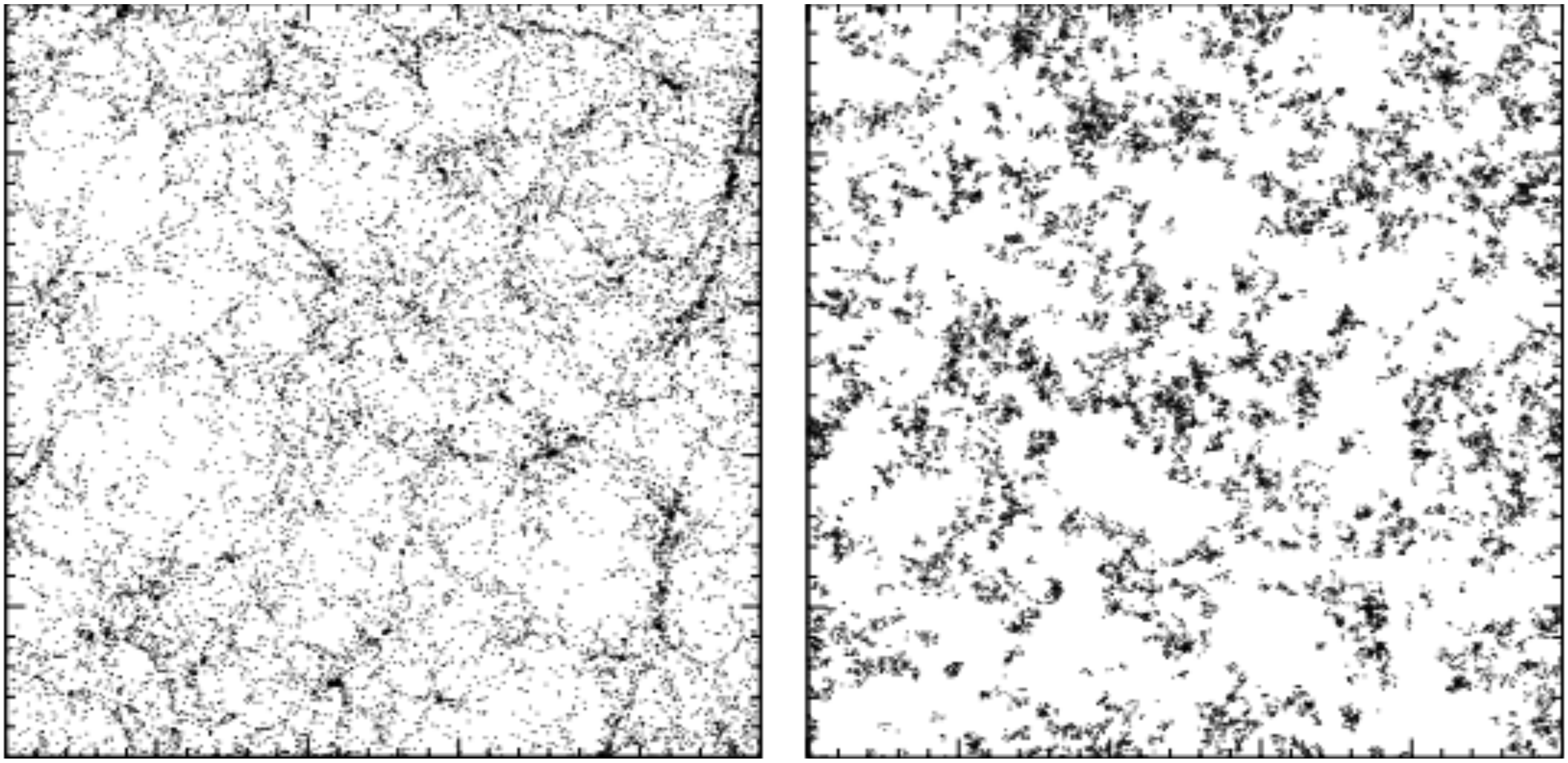
imprint of M_ν can also be measured from **galaxy clustering**

upcoming surveys: *PFS, DESI, Euclid, WFIRST*

$M_\nu - \sigma_8$ **degeneracy is a major limitation** for the redshift-space *power spectrum*



HADES simulation (Villaescusa-Navarro+2018) information in the *nonlinear regime* cascades from the power spectrum to **higher-order statistics** these two distributions have the ***same power spectrum***



Sefusatti+(2005)

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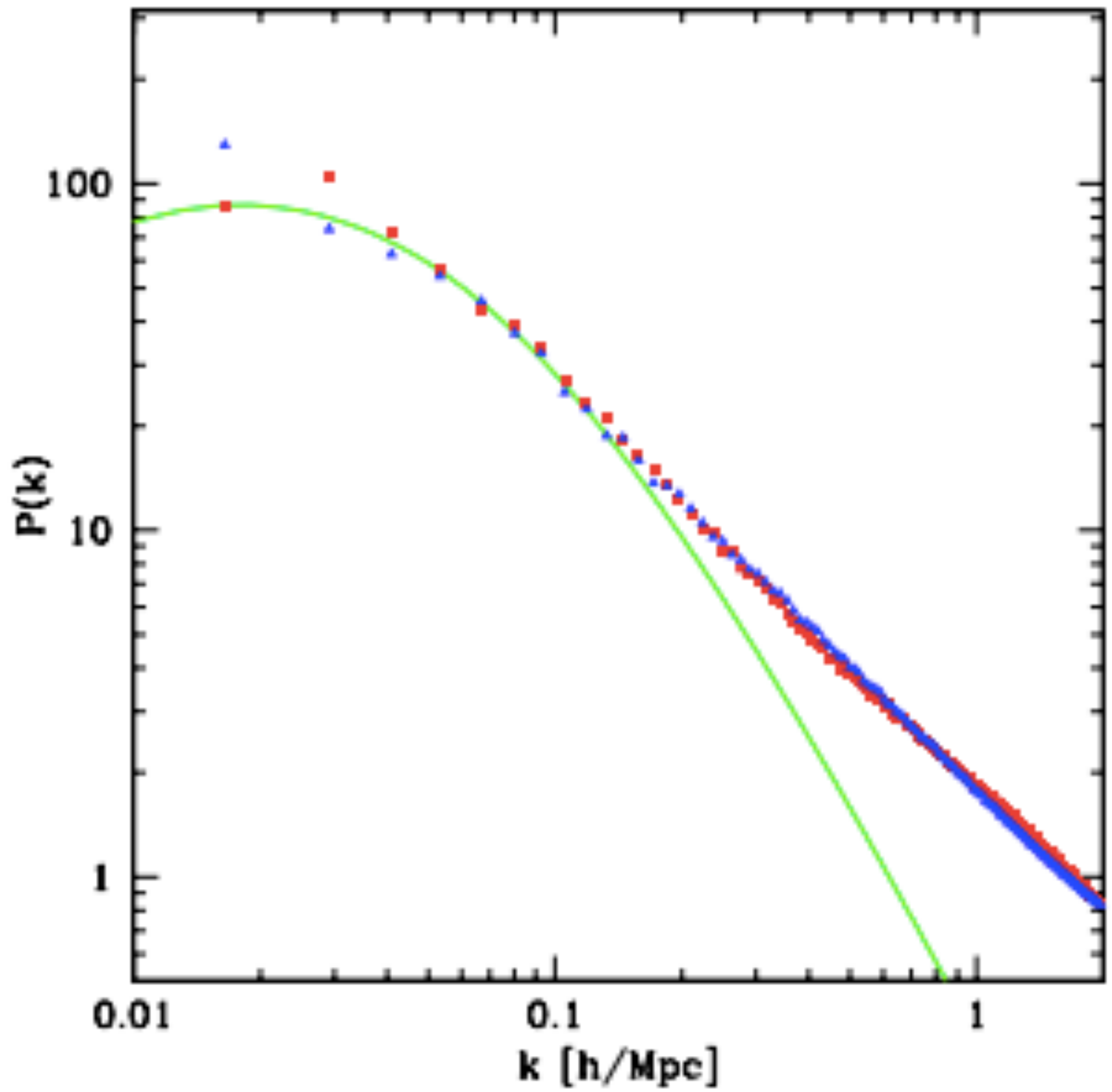
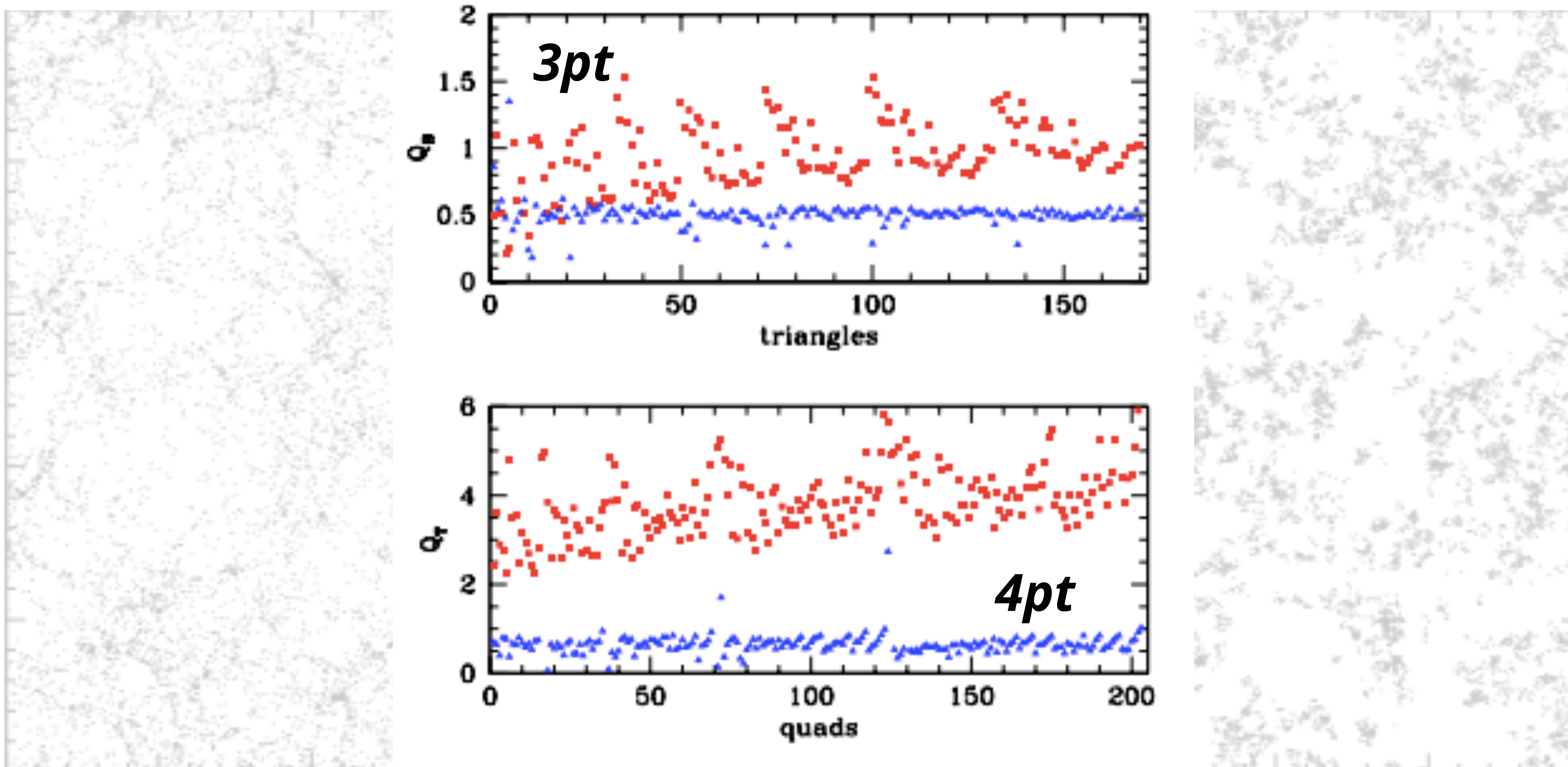


Sefusatti+(2005)

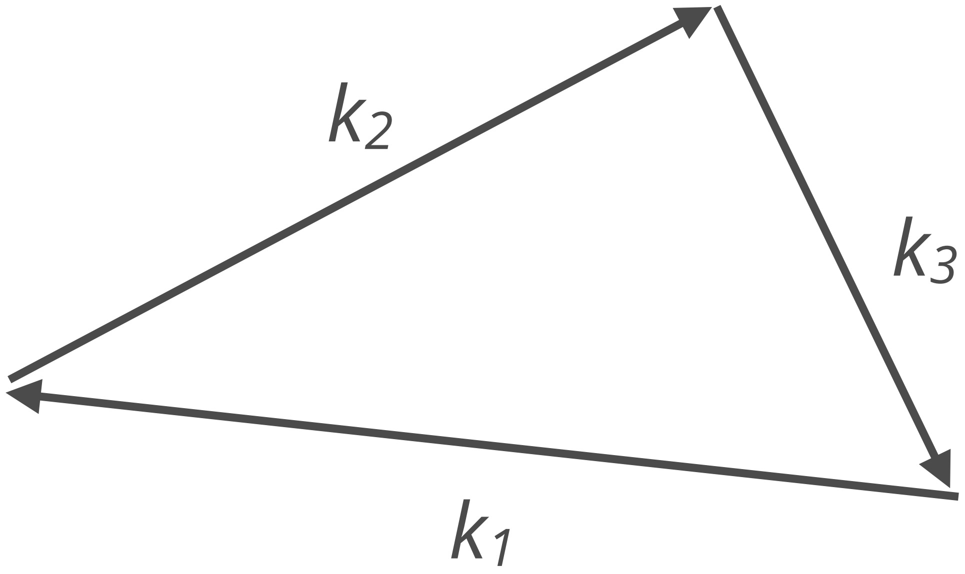
but very ***different higher-order statistics***



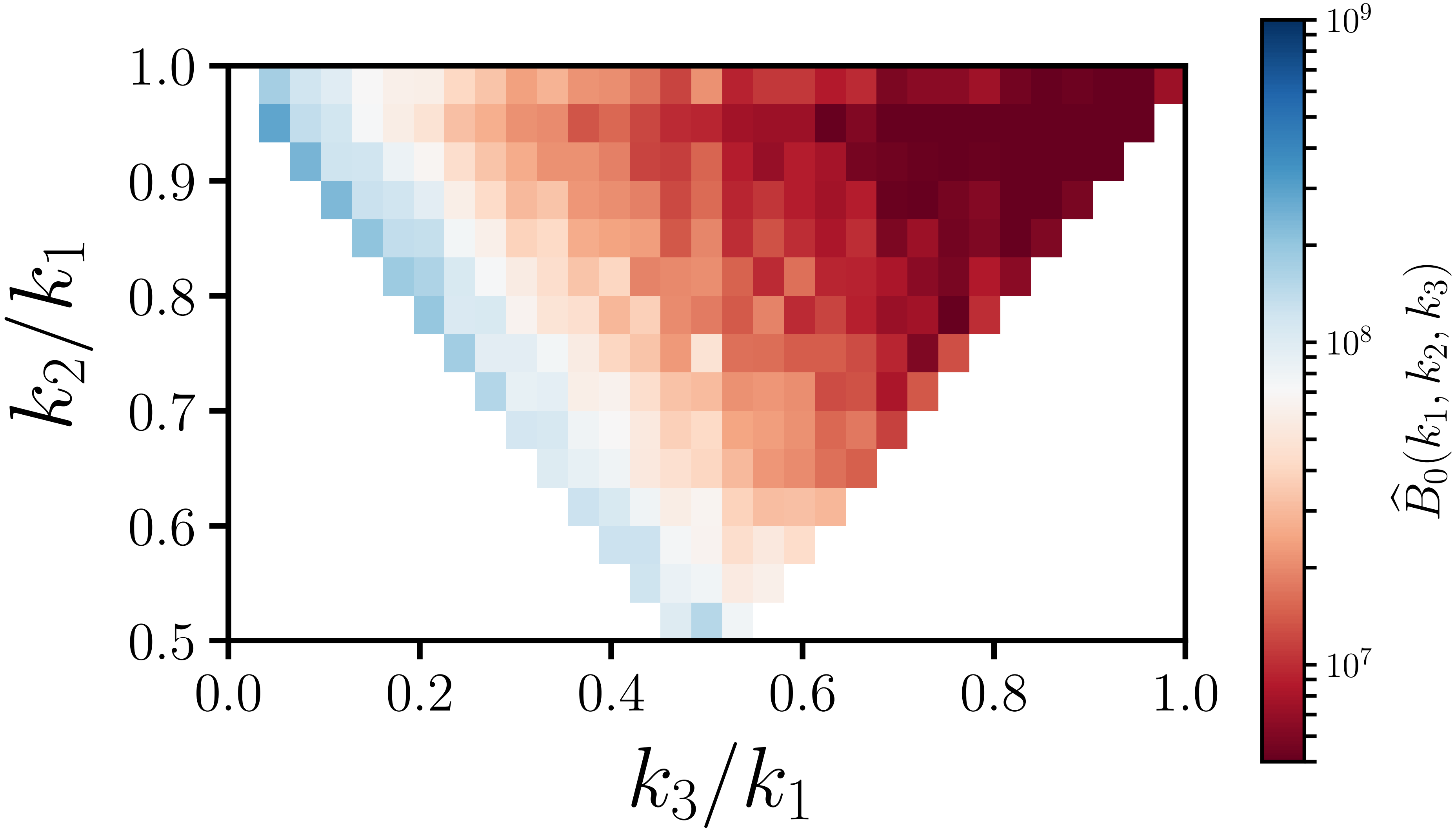
Sefusatti+(2005)

introduction to ***the bispectrum***

$$\langle \delta(\mathbf{k_1}), \delta(\mathbf{k_2}), \delta(\mathbf{k_3}) \rangle = \delta_D(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3}) B(\mathbf{k_1}, \mathbf{k_2}, \mathbf{k_3})$$

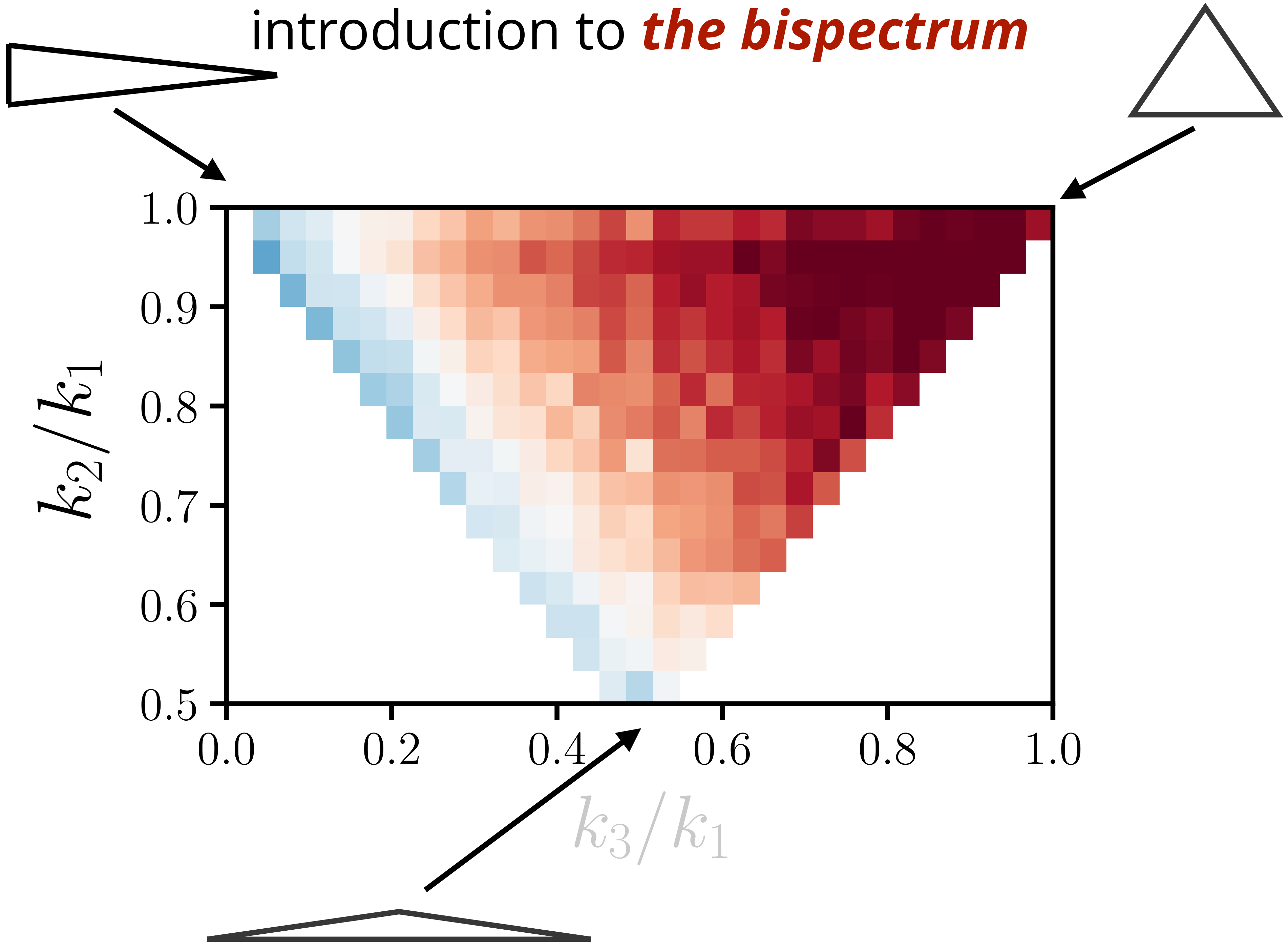


introduction to ***the bispectrum***



github.com/changhoonhahn/pySpectrum

introduction to ***the bispectrum***



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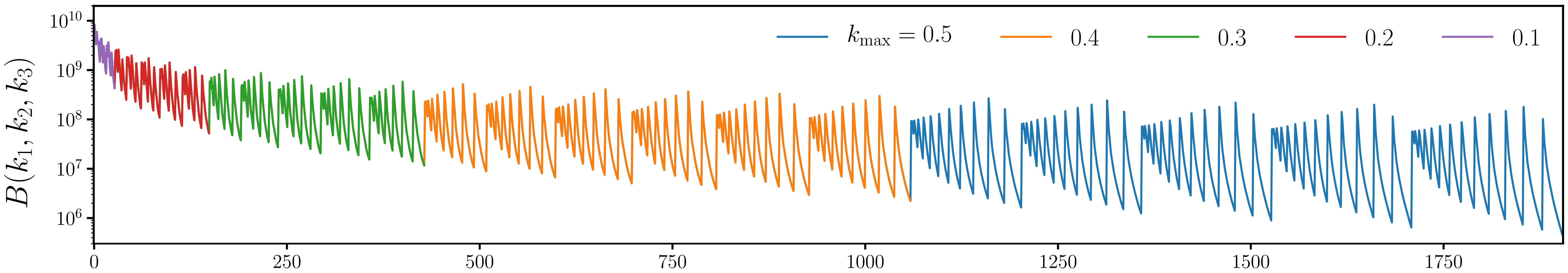

$k_1 \geq k_2 \geq k_3$

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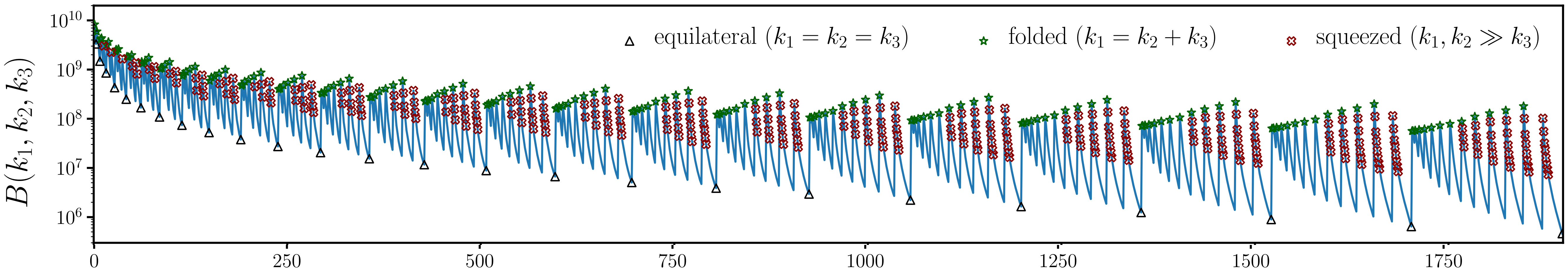
introduction to ***the bispectrum***



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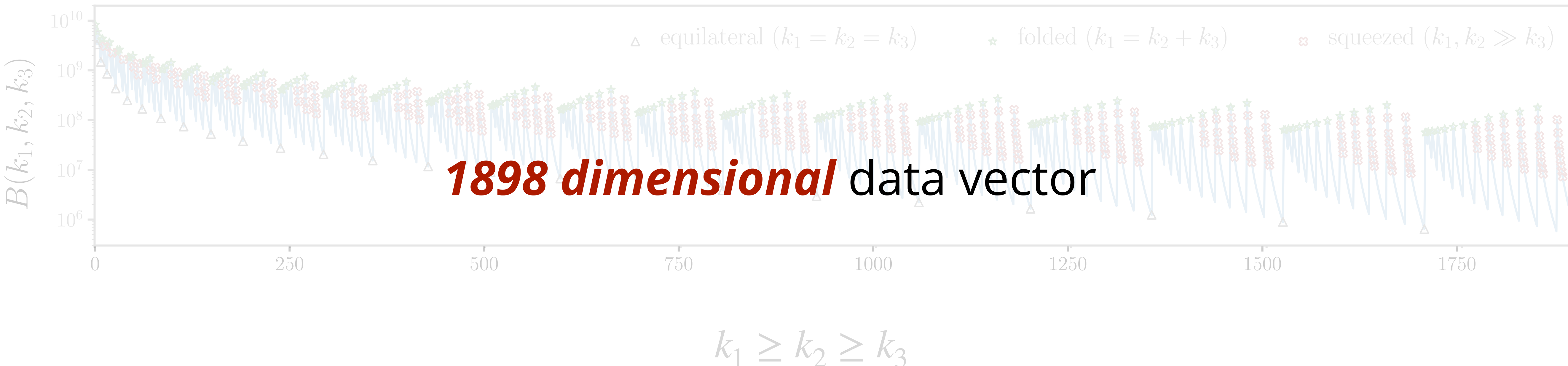
introduction to ***the bispectrum***



1898 dimensional data vector

github.com/changhoonhahn/pySpectrum

does ***the bispectrum improve*** M_ν ***constraints***?

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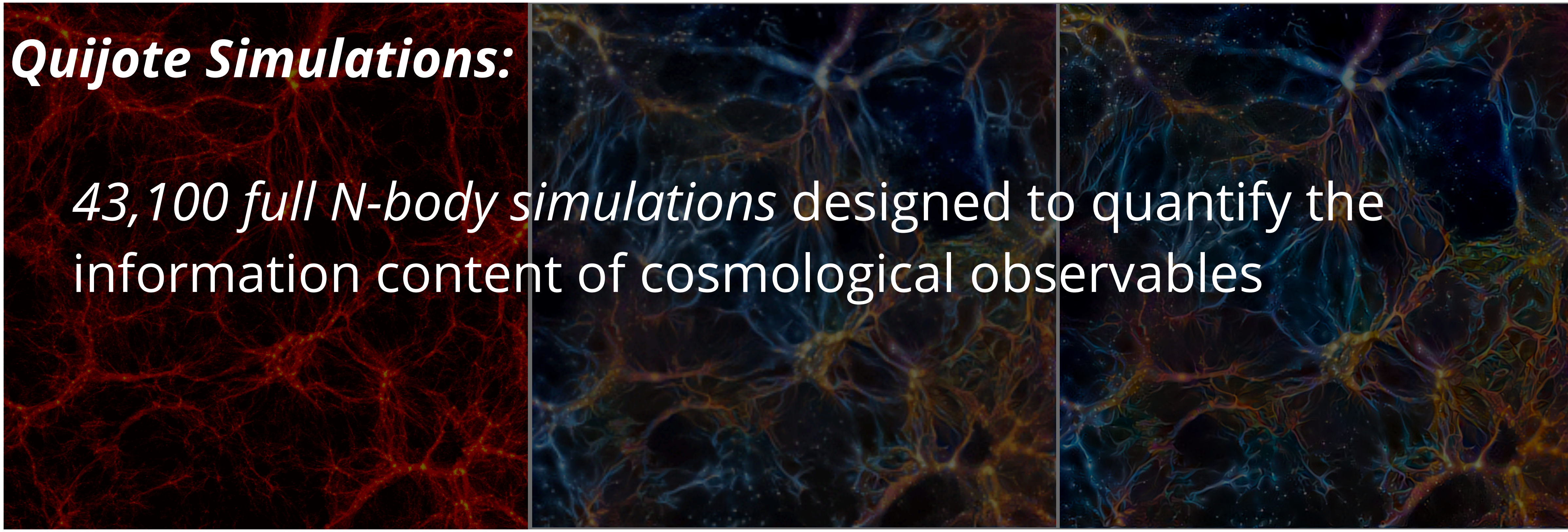
what's the **total information content** of *the bispectrum*?



Quijote Simulations:

43,100 full N-body simulations designed to quantify the information content of cosmological observables

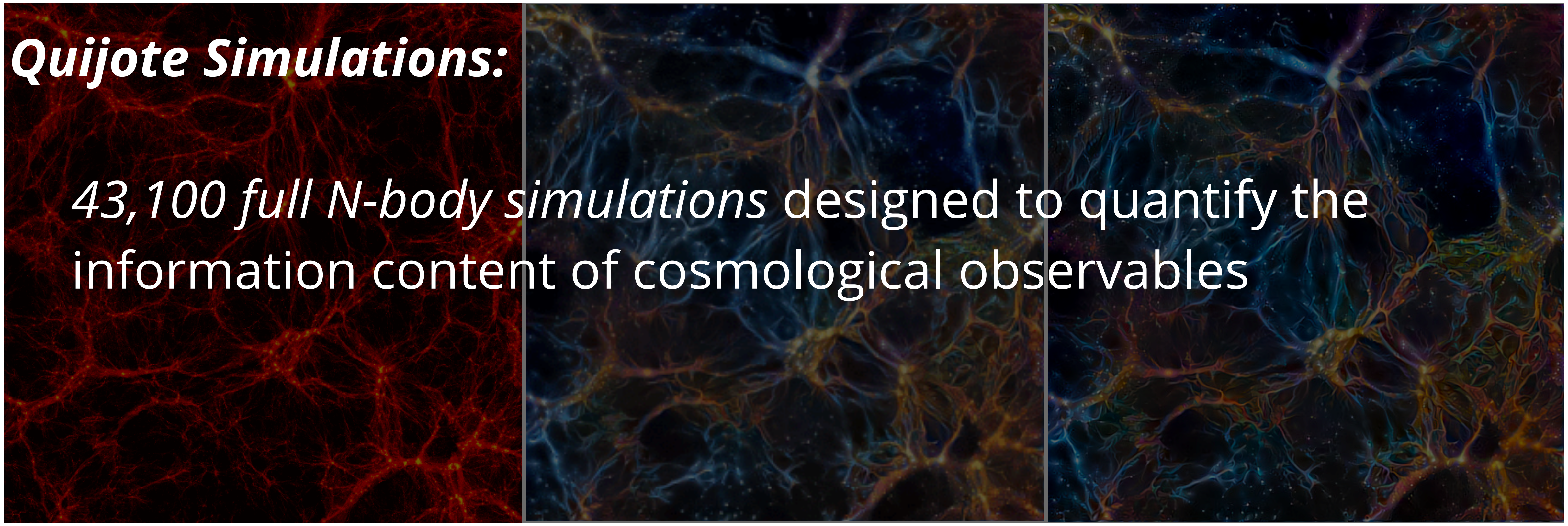
Features

- Simulations run with the TreePM code Gadget-III
- More than 35 Million CPU hours
- Boxes of 1 Gpc/h. Combined total volume of 43100 (Gpc/h)^3
- 17100 simulations for a fiducial Planck cosmology
- Between 500 and 1000 simulations/cosmology for 17 different cosmologies
- 11000 simulations in different latin-hypercubes
- More than 8.5 trillions of particles at a single redshift
- Billions of halos and voids identified
- Full snapshots at redshifts 0, 0.5, 1, 2, 3 and 127 (initial conditions)
- More than 200000 halo catalogues
- More than 200000 void catalogues
- More than 1 million power spectra
- More than 1 million bispectra
- More than 1 million correlation functions
- More than 1 million marked power spectra
- More than 1 million probability distribution functions
- More than 1 Petabyte of data publicly available

all publicly available

github.com/franciscovillaescusa/Quijote-simulations

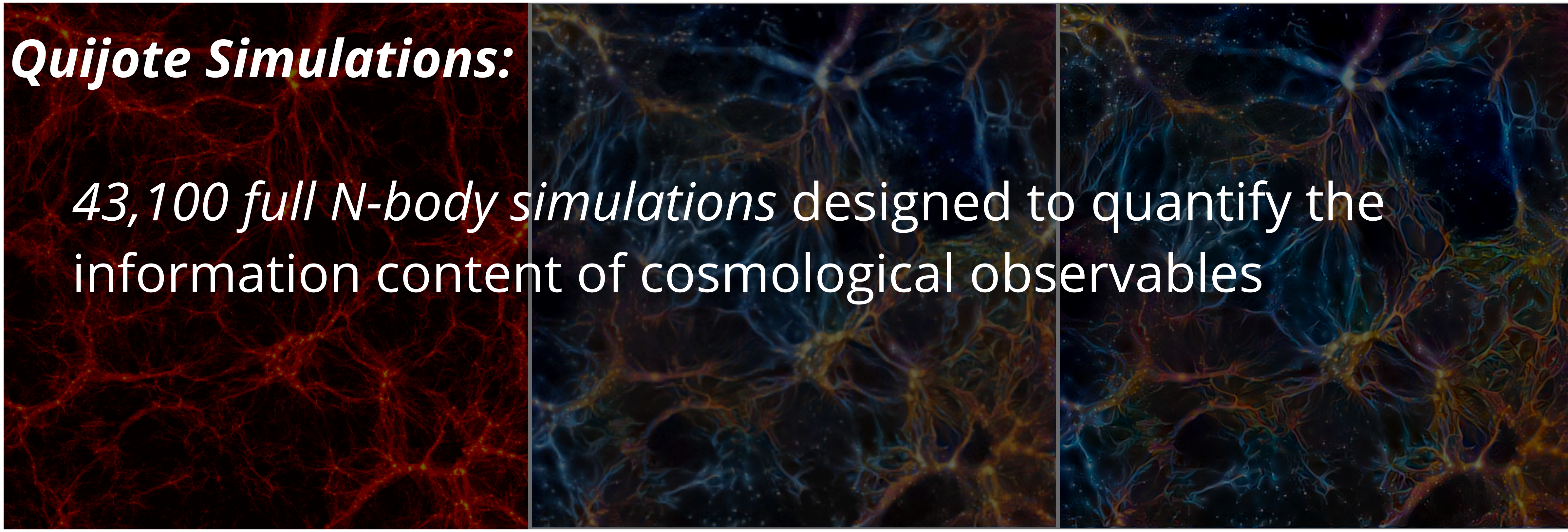
Villaesucsa-Navarro, CHH+(2019)



Quijote Simulations:

43,100 full N-body simulations designed to quantify the information content of cosmological observables

$$F_{ij} = \frac{1}{2}\mathrm{Tr}\left[\mathbf{C}^{-1}\left(\frac{\partial B}{\partial \theta_i}^T \frac{\partial B}{\partial \theta_j} + \frac{\partial B}{\partial \theta_i}^T \frac{\partial B}{\partial \theta_j}\right)\right]$$



Quijote Simulations:

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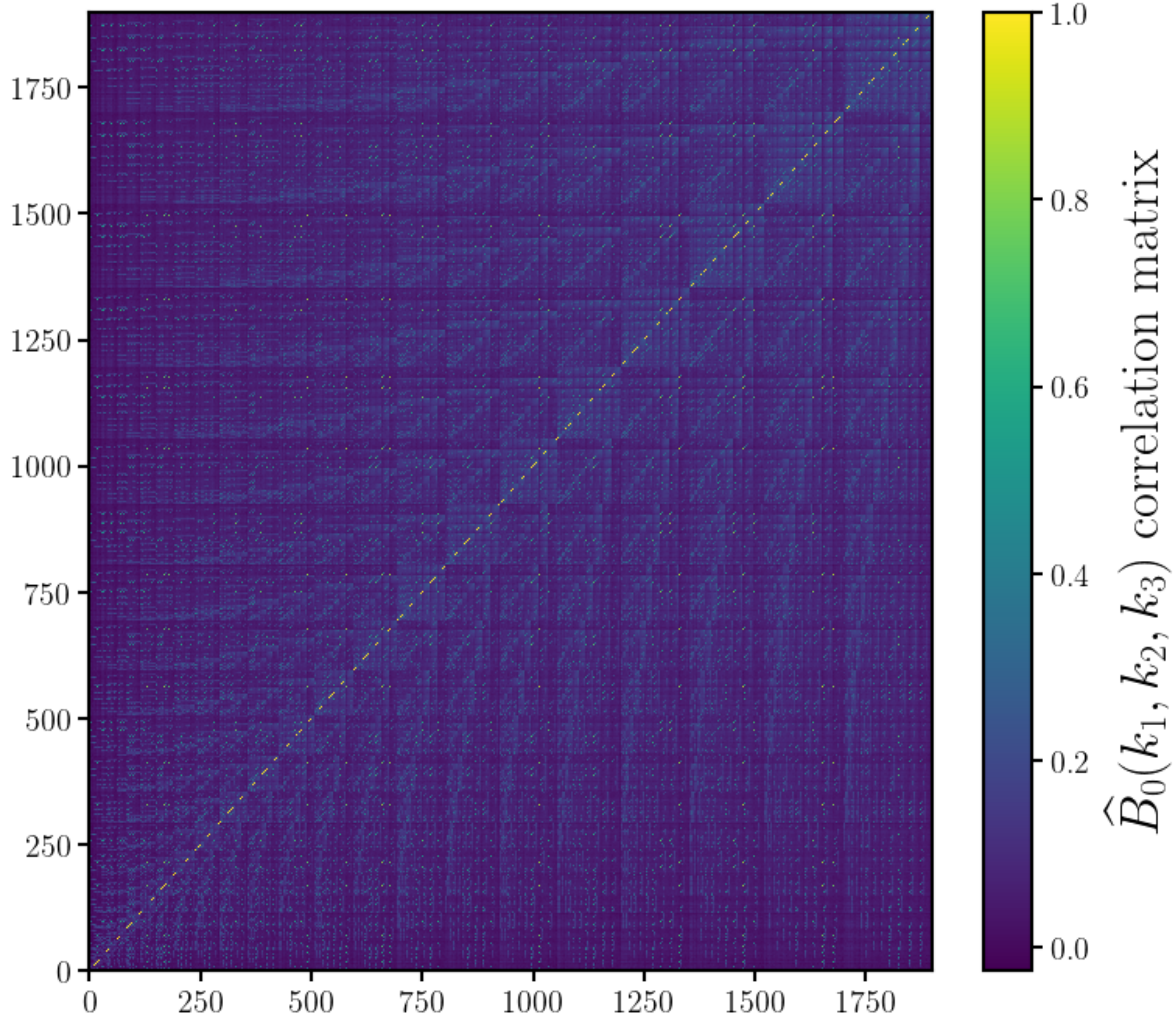
difficult to accurately estimate the **1898x1898 covariance matrix**

previous work used fewer triangles, PT estimates, ignored non-Gaussian term, etc

C estimated using ***15,000 N-body simulations***!



Hahn+(2020)

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fiducial $M_\nu = 0.0\mathrm{eV}$ $\Omega_m = 0.3175$ $\Omega_b = 0.049$ $h = 0.6711$ $n_s = 0.9624$ $\sigma_8 = 0.834$

Hahn+(2020)

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$\Omega_m^+ = 0.3275$

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$\Omega_m^- = 0.3075$

Hahn+(2020)

$$F_{ij} = \frac{1}{2}\mathrm{Tr}\left[\mathbf{C}^{-1}\left(\frac{\partial B}{\partial \theta_i}^T \boxed{\frac{\partial B}{\partial \theta_j}} + \frac{\partial B}{\partial \theta_i}^T \frac{\partial B}{\partial \theta_j}\right)\right]$$

	$M_\nu^{+++} = 0.4$					
	$M_\nu^{++} = 0.2$					
	$M_\nu^{+} = 0.1$	$\Omega_m^+ = 0.3275$	$\Omega_b^+ = 0.051$	$h^+ = 0.6911$	$n_s^+ = 0.9824$	$\sigma_8^+ = 0.849$
fiducial	$M_\nu = 0.0\mathrm{eV}$	$\Omega_m = 0.3175$	$\Omega_b = 0.049$	$h = 0.6711$	$n_s = 0.9624$	$\sigma_8 = 0.834$
		$\Omega_m^- = 0.3075$	$\Omega_b^- = 0.047$	$h^- = 0.6511$	$n_s^- = 0.9424$	$\sigma_8^- = 0.819$

$$\frac{\partial B}{\partial \theta} \approx \frac{B(\theta^+) - B(\theta^-)}{\theta^+ - \theta^-}$$

Hahn+(2020)

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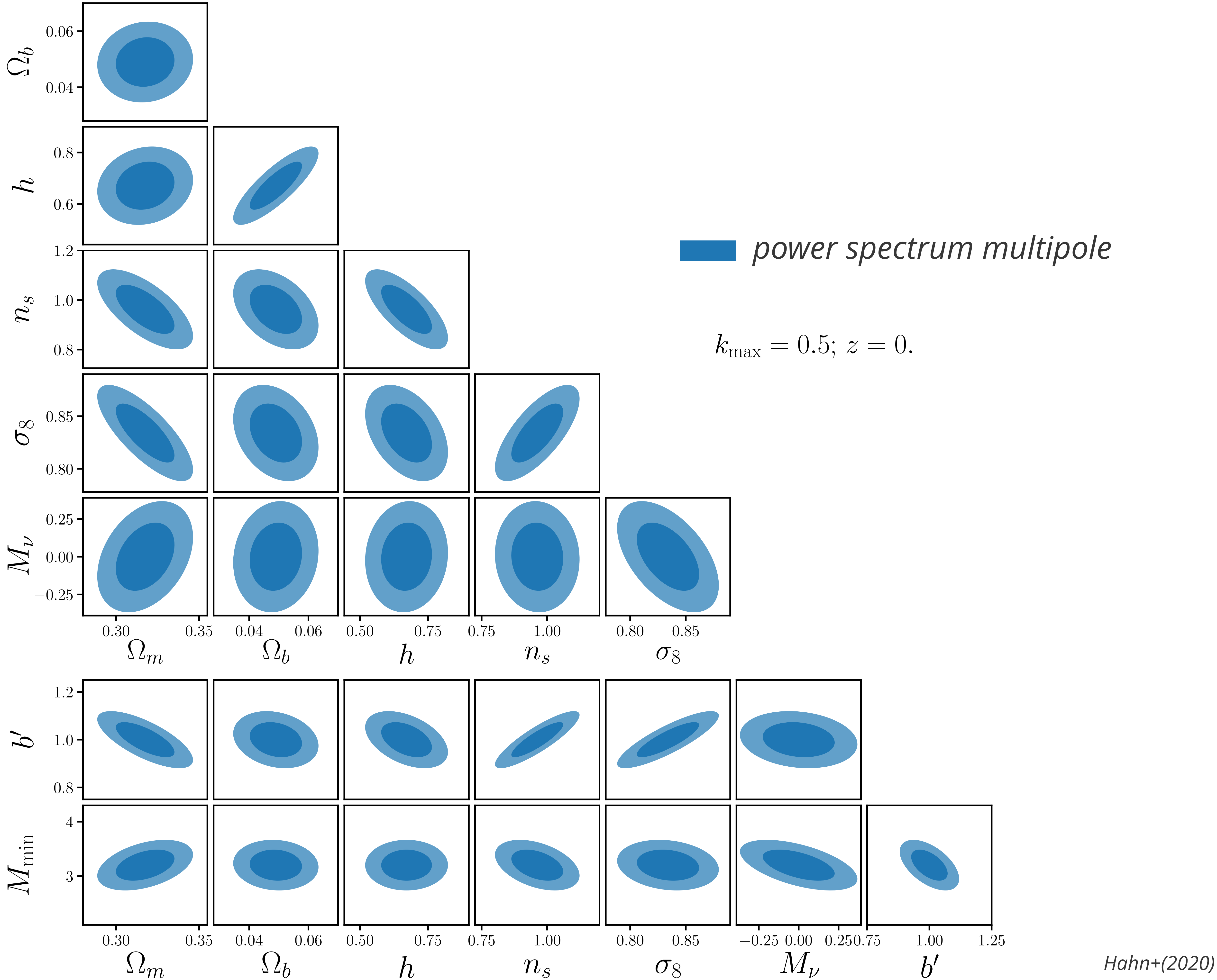
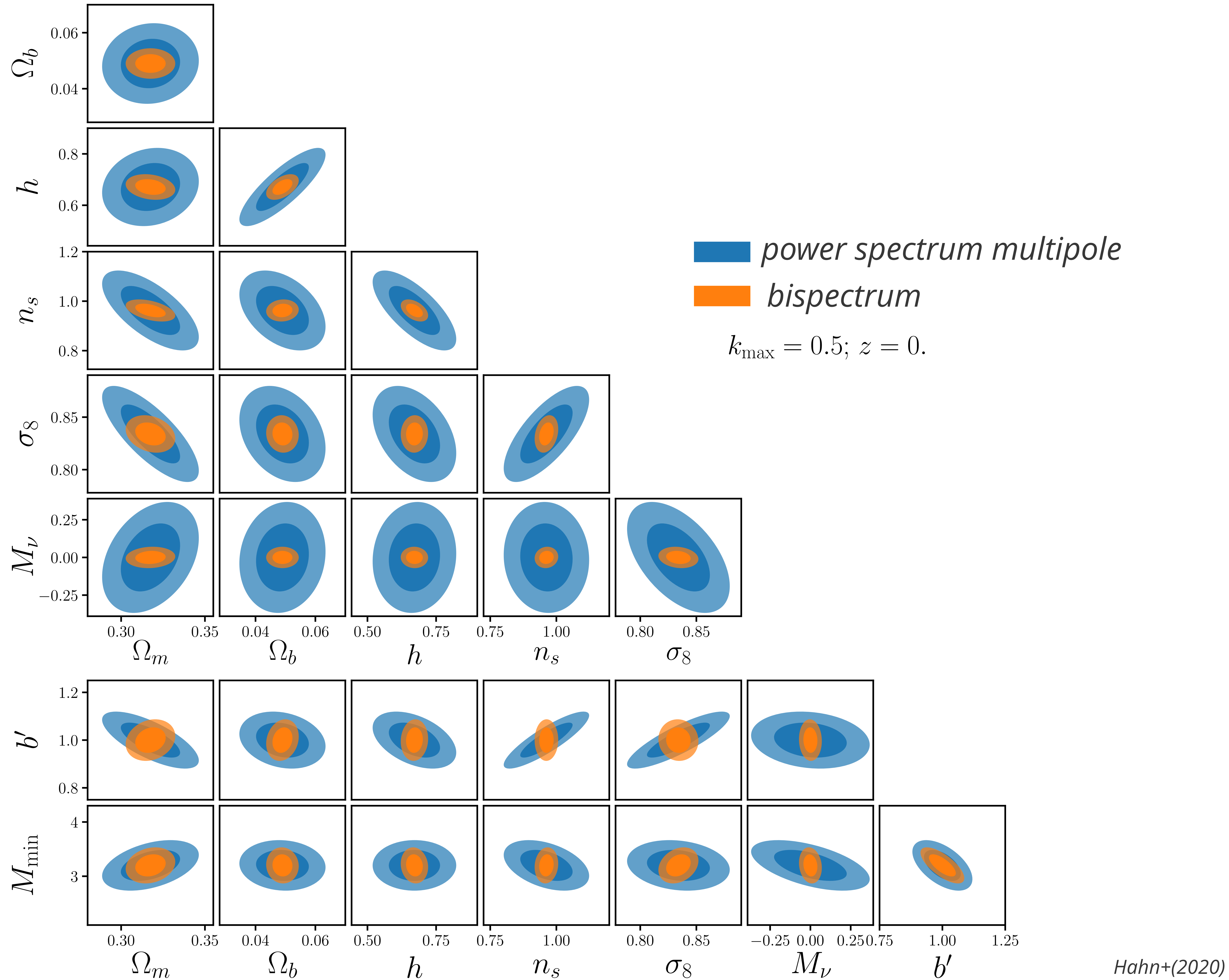
$$\frac{\partial B}{\partial \theta} \approx \frac{B(\theta^+) - B(\theta^-)}{\theta^+ - \theta^-}$$

each box is a different cosmology with ***500 N-body*** simulations

Hahn+(2020)


power spectrum multipole
$k_{\rm max} = 0.5;\ z = 0.$
Ω_b
h
n_s
σ_8
M_ν
b'
$M_{\rm min}$
Ω_m
Hahn+(2020)


power spectrum multipole
bispectrum
$k_{\rm max} = 0.5;\ z = 0.$
Ω_b
h
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b'
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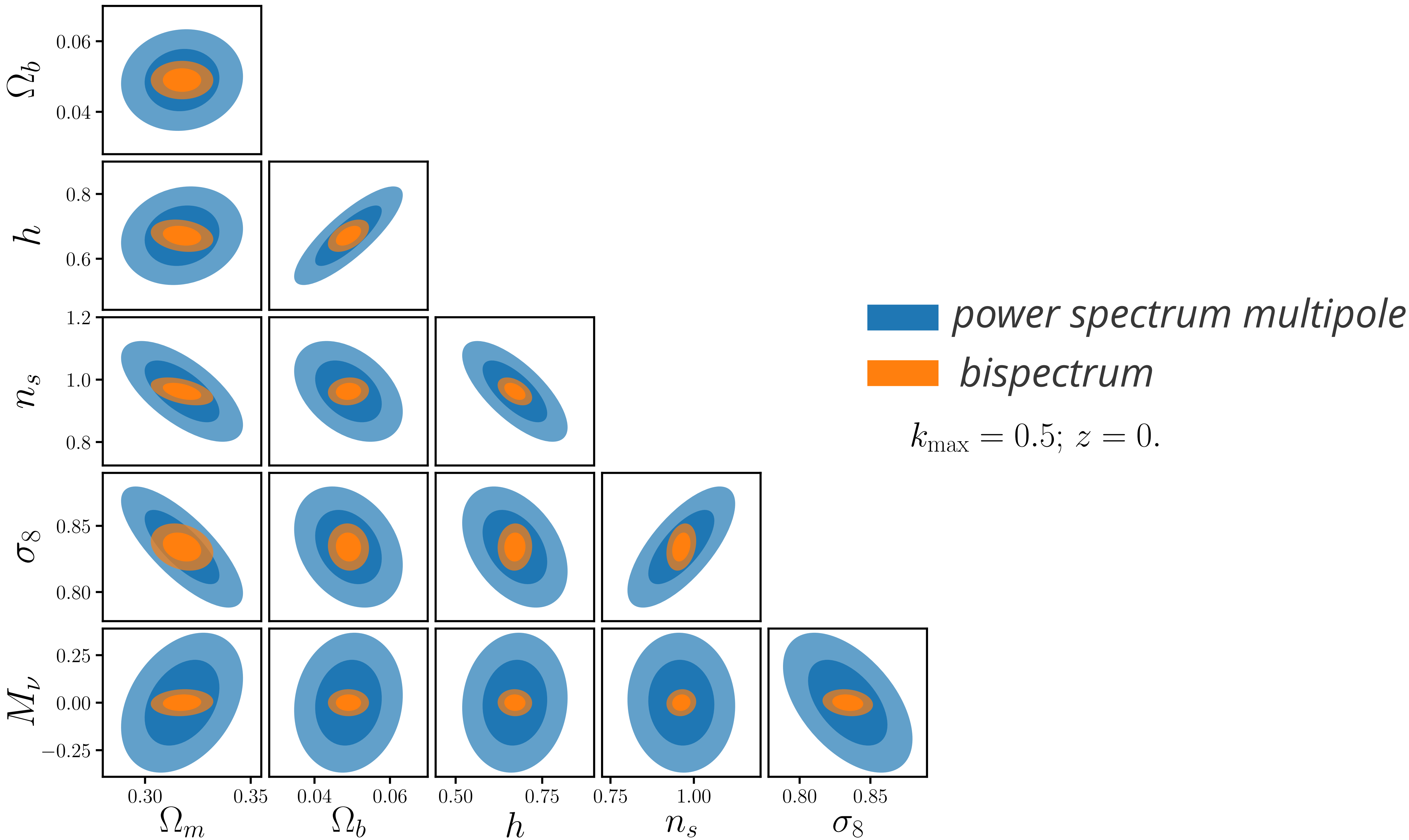
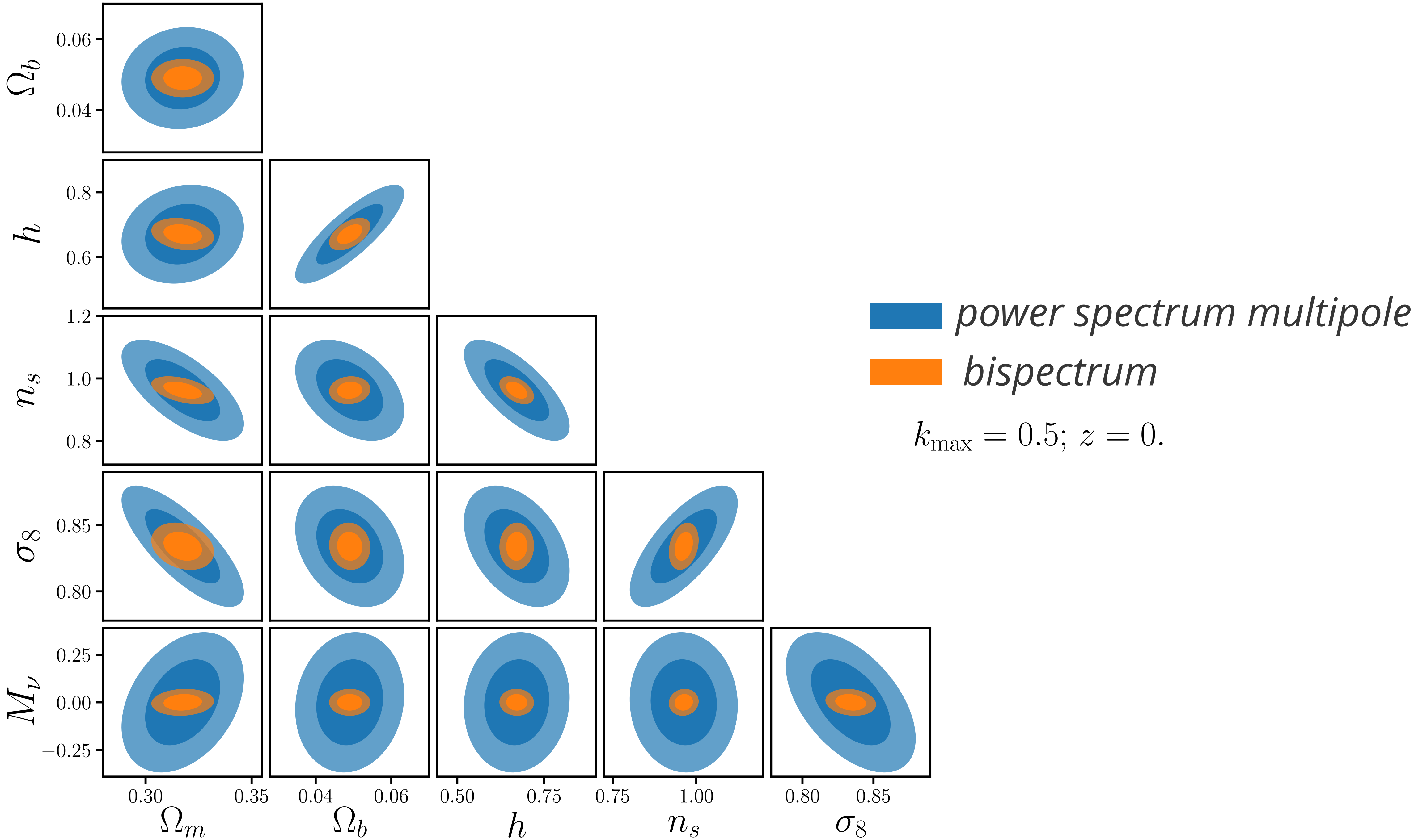
Hahn+(2020)



$\{\Omega_m, \Omega_b, h, n_s, \sigma_8\}$ constraints $\{1.9,\ 2.6,\ 3.1,\ 3.6,\ 2.6\times\}$ **tighter**

Hahn+(2020)



power spectrum
$\sigma_{M_\nu} = \pm 0.297$

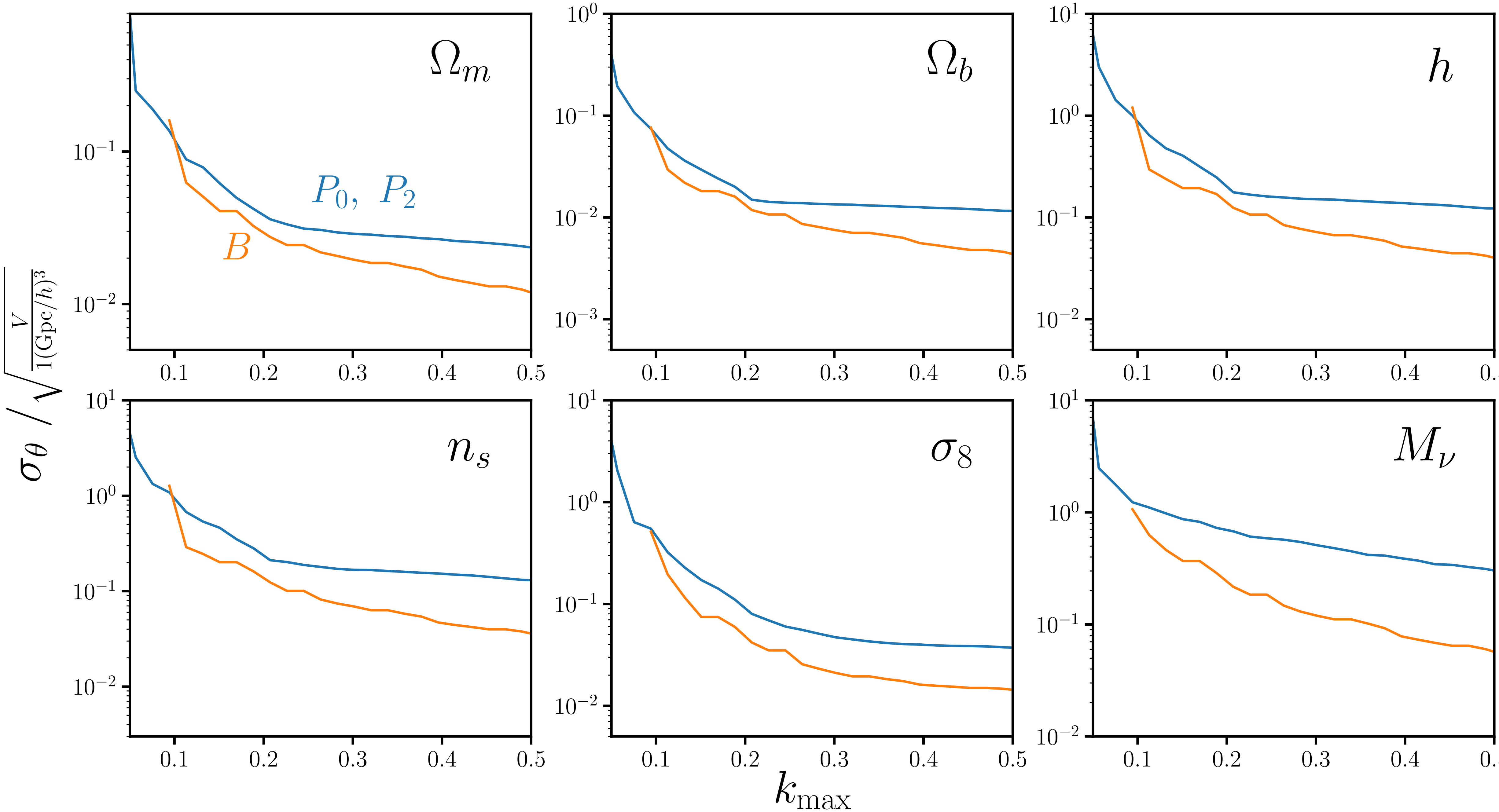
→

bispectrum
$\sigma_{M_\nu} = \pm 0.057$

>5x tighter M_ν constraints

Hahn+(2020)

the bispectrum improves parameter constraints **even at low** $k_{\rm max}$



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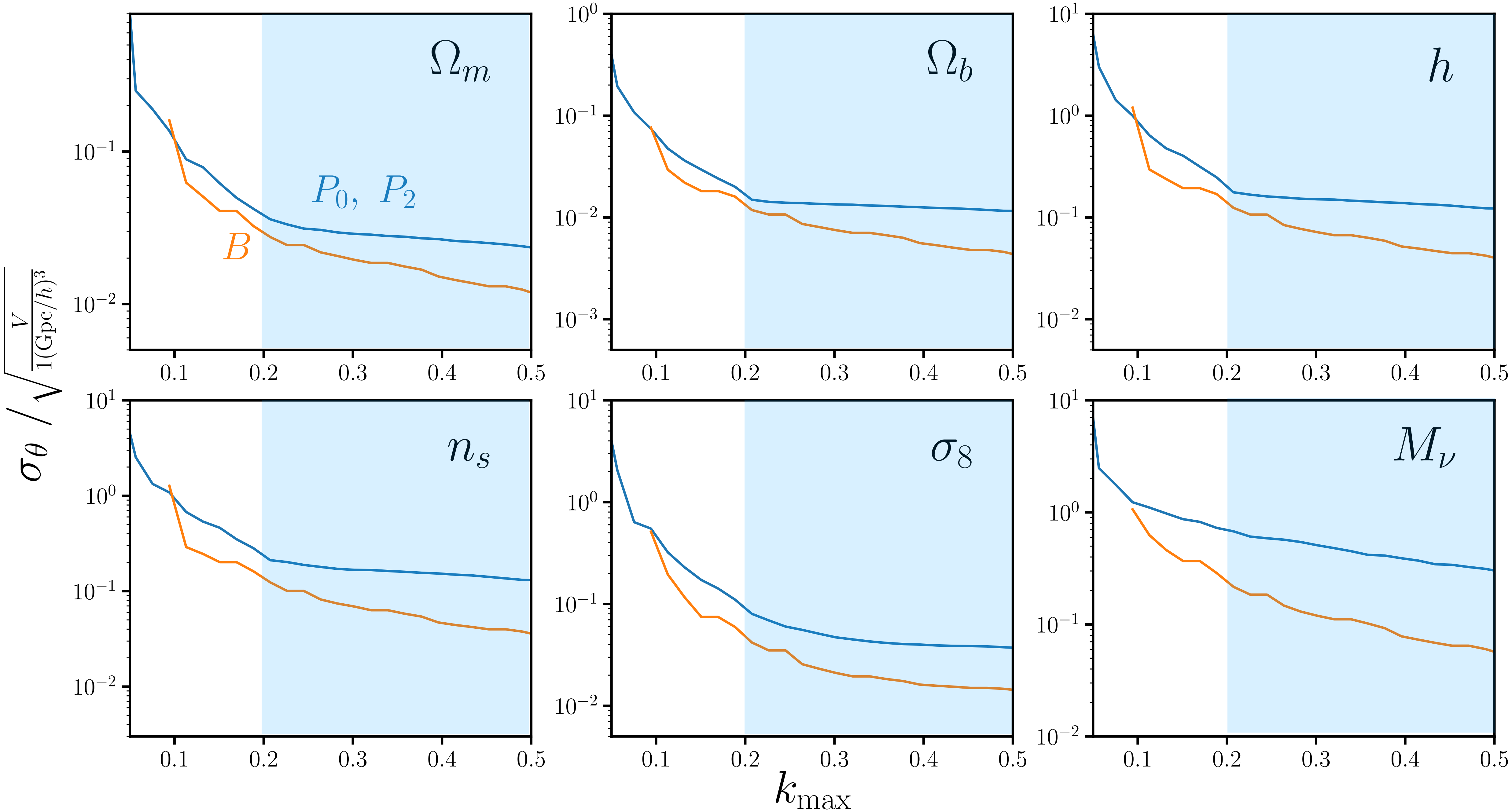
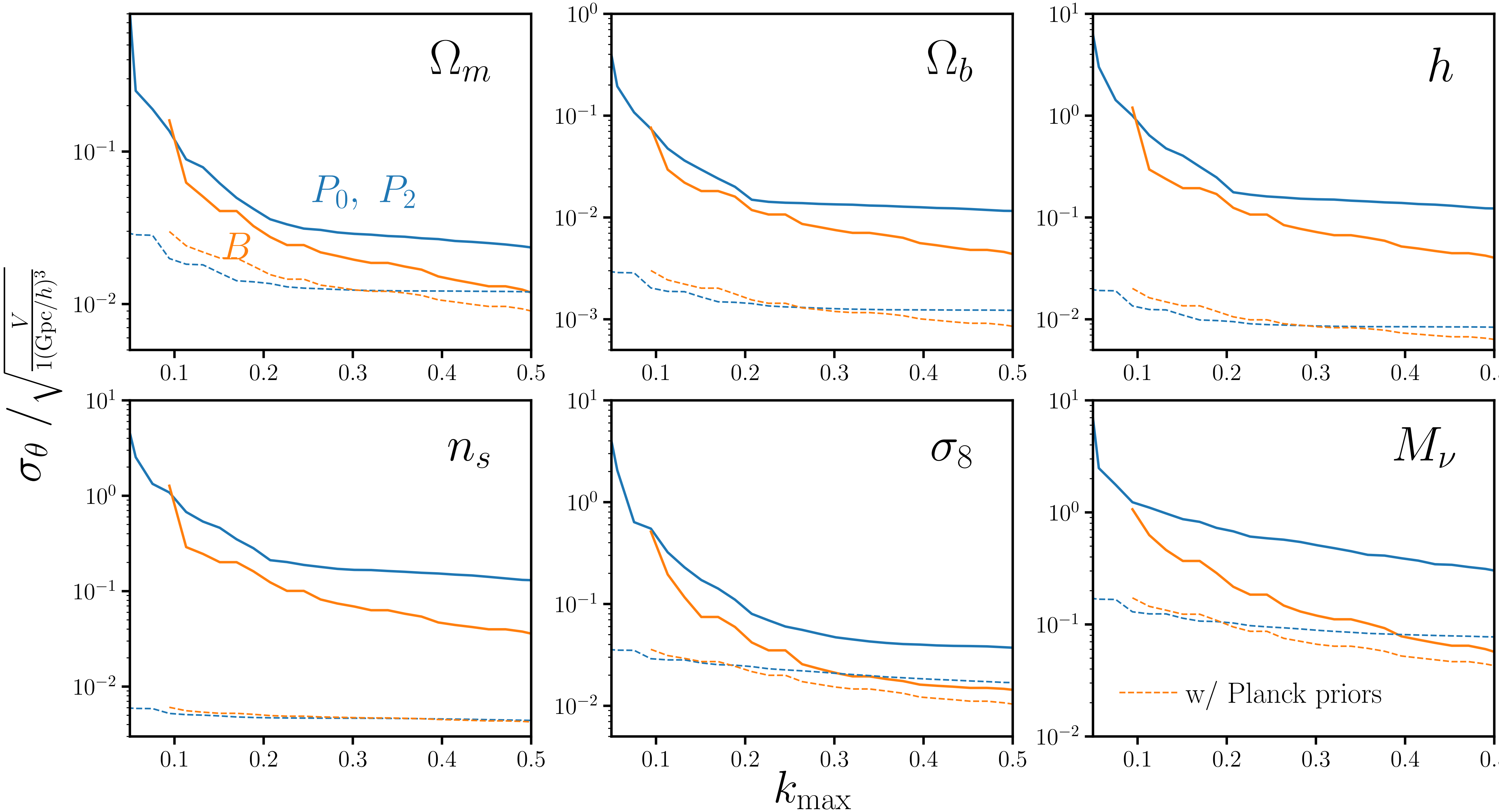


information content of P_ℓ saturates at $k_{\max} > 0.2\ h/\mathrm{Mpc}$

Hahn+(2020)

the bispectrum improves parameter constraints ***with Planck priors***



Hahn+(2020)

the redshift-space bispectrum breaks parameter degeneracies and ***significantly improves*** parameter constraints

$1.9,\ 2.6,\ 3.1,\ 3.6,\ 2.6\times$ *tighter than* P_ℓ *for* $\Omega_m, \Omega_b, h, n_s, \sigma_8$

$5\times$ *tighter* M_ν *constraints* the redshift-space bispectrum* breaks parameter degeneracies and ***significantly improves*** parameter constraints

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$5\times$ *tighter* M_ν *constraints*

halo bispectrum

the redshift-space bispectrum* breaks parameter degeneracies and ***significantly improves*** parameter constraints

what about the redshift-space ***galaxy*** bispectrum?

halo bispectrum

marginalizing over $b_1, b_2, \gamma_2, M_{\rm min}, A_{\rm SN}, B_{\rm SN}$ **does not impact** the improvement *marginalizing over* $b_1, b_2, \gamma_2, M_{\rm min}, A_{\rm SN}, B_{\rm SN}$ **does not impact** the improvement but **perturbation theory is not enough** to exploit the *substantial constraining power on nonlinear scales* instead with **simulation-based methods** accuracy of *N-body simulations* can be exploited to analyze nonlinear scales

e.g.

emulation (Zhai+2019, Wibking+2019)

approximate bayesian computation (Hahn+2017)

evidence modeling (Lange+2019)

density estimation (Alsing+2018, Hahn+2019a)

...

Halo Occupation Distribution (HOD) is the primary *galaxy bias framework* for simulation based methods

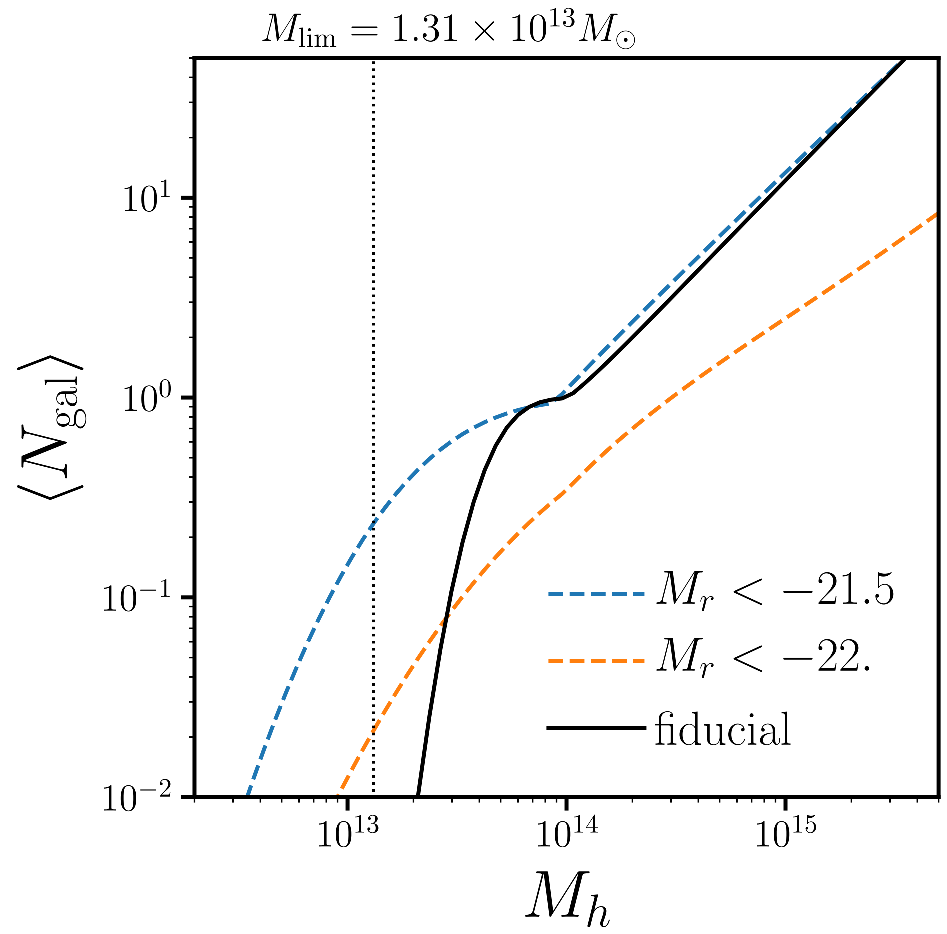
$$\langle N_{\rm cen} \rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log M_h - \log M_{\rm min}}{\sigma_{\log M}}\right)\right]$$

$$\langle N_{\rm sat} \rangle = \langle N_{\rm cen} \rangle \left(\frac{M_h - M_0}{M_1}\right)^{\alpha}.$$

Halo Occupation Distribution (HOD) is the primary *galaxy bias framework* for simulation based methods

with *HOD* + *Quijote*, we can quantify the **total information content** of ***the redshift-space galaxy bispectrum***

fiducial HOD based on best-fit HOD parameters for the *SDSS* $M_r < -21.5$ *and* $M_r < -22$ *samples*



Zheng+(2007)

15,000 covariance matrix N-body mocks +

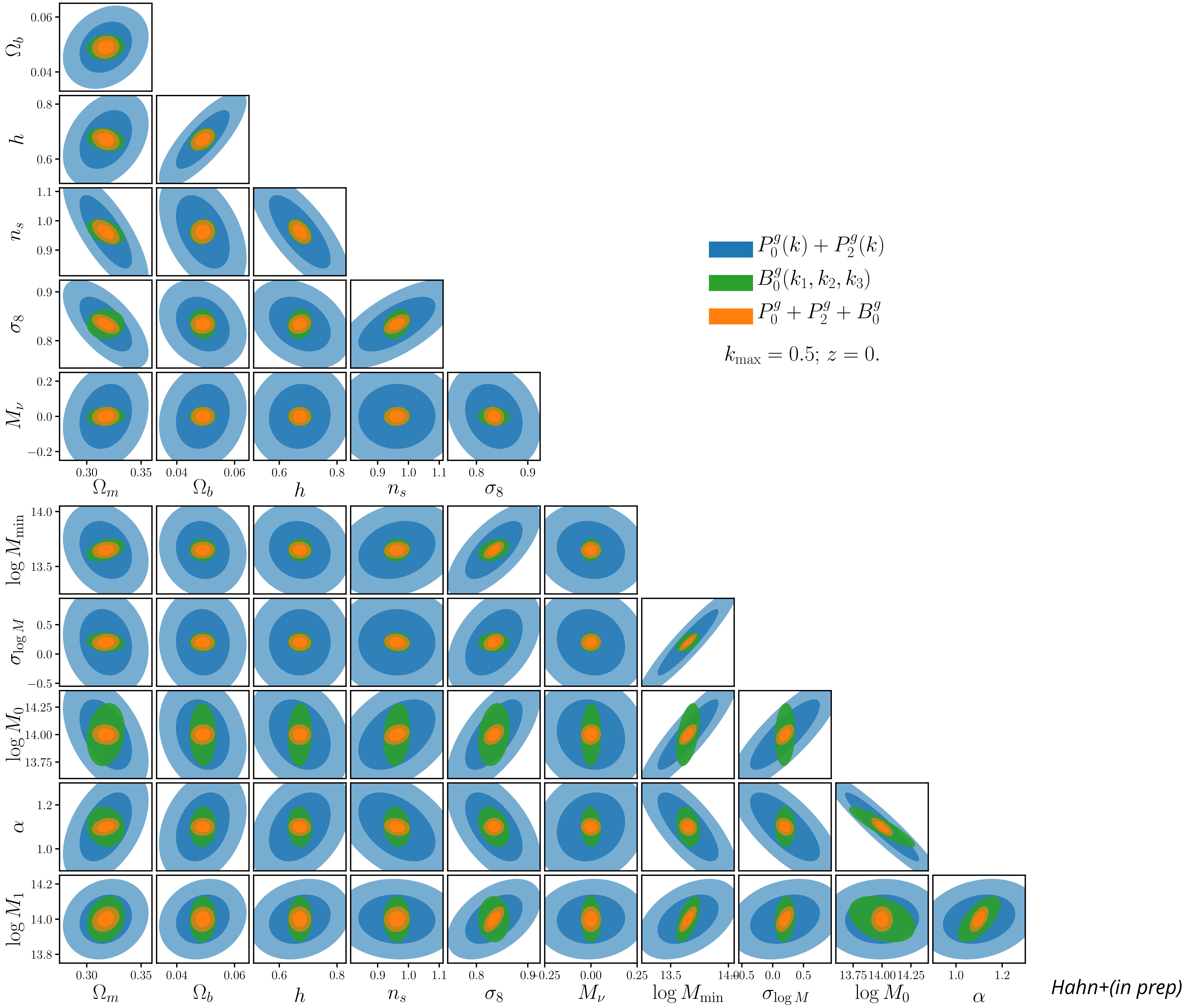
(*500 N-body*) x (*5 HOD*) x (*3 RSD dir.*) x (24 param)

= ***195,000 galaxy catalogs***

$M_\nu^{+++} = 0.4$										
$M_\nu^{++} = 0.2$										
$M_\nu^{+} = 0.1$	$\Omega_m^+ = 0.3275$	$\Omega_b^+ = 0.051$	$h^+ = 0.6911$	$n_s^+ = 0.9824$	$\sigma_8^+ = 0.849$	$M_{\rm min}^+ = 13.7$	$\sigma_{\log M}^+ = 0.22$	$\log M_0^+ = 14.2$	$\alpha^+ = 1.3$	$\log M_1^+ = 14.2$
$M_\nu = 0.0\text{eV}$	$\Omega_m = 0.3175$	$\Omega_b = 0.049$	$h = 0.6711$	$n_s = 0.9624$	$\sigma_8 = 0.834$	$M_{\rm min} = 13.65$	$\sigma_{\log M} = 0.2$	$\log M_0 = 14$	$\alpha = 1.1$	$\log M_1 = 14$
	$\Omega_m^- = 0.3075$	$\Omega_b^- = 0.047$	$h^- = 0.6511$	$n_s^- = 0.9424$	$\sigma_8^- = 0.819$	$M_{\rm min}^- = 13.6$	$\sigma_{\log M}^- = 0.18$	$\log M_0^+ = 13.8$	$\alpha^- = 0.9$	$\log M_1^- = 13.8$

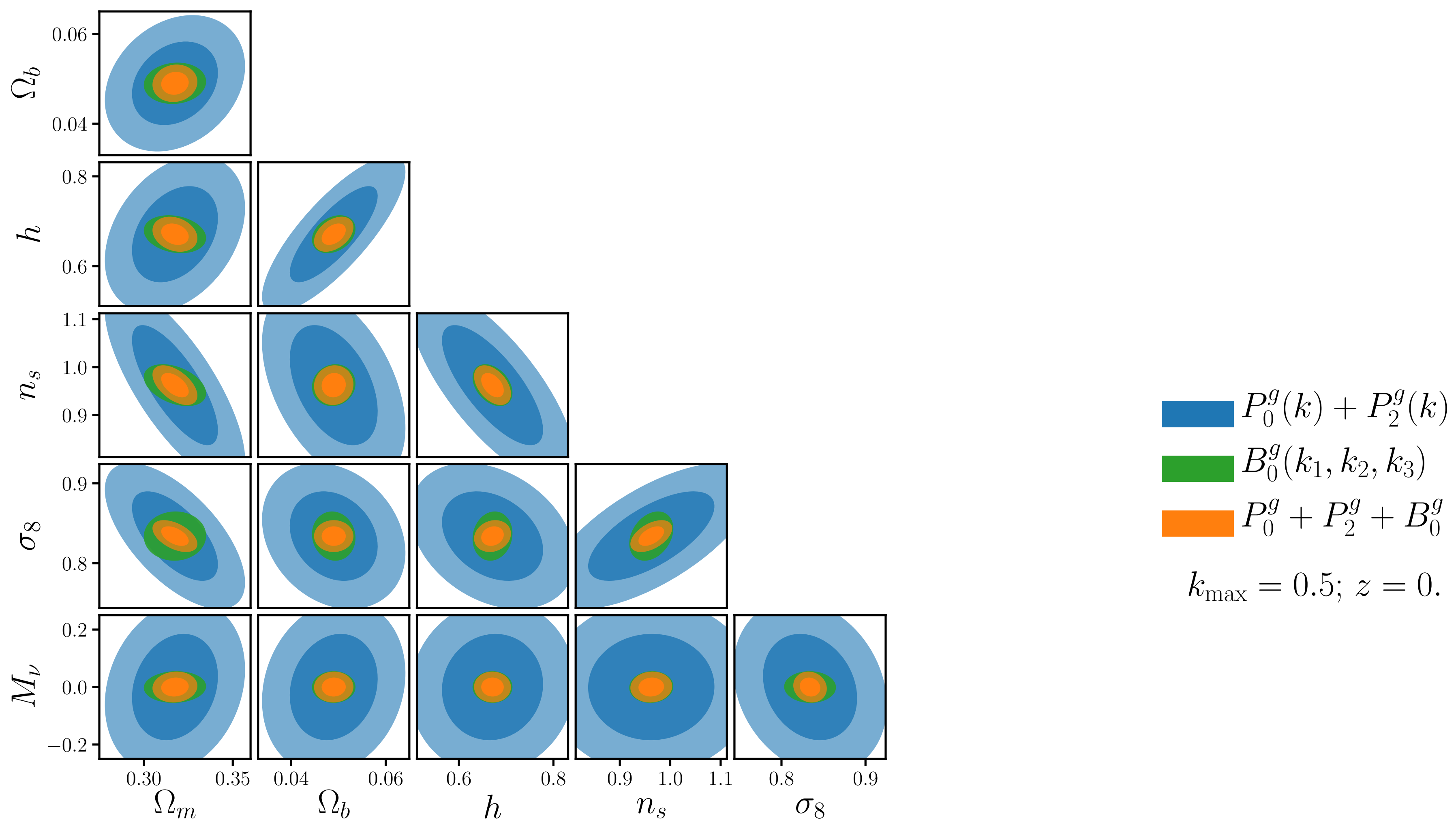
galaxy catalogs ***will be publicly available***

Sancho Panza (?) galaxy catalogs (Hahn+in prep)



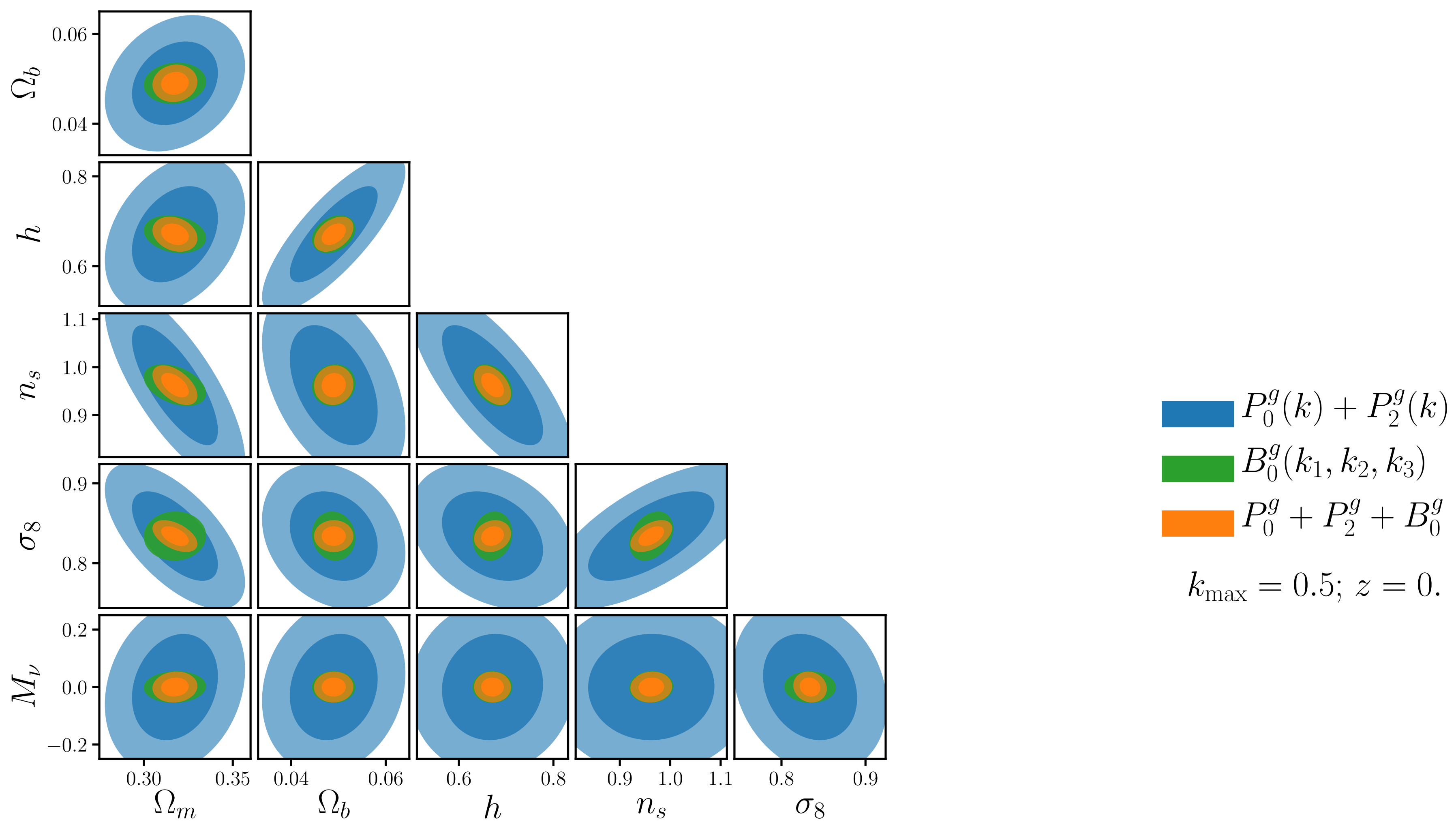
$P_0^g(k) + P_2^g(k)$
$B_0^g(k_1, k_2, k_3)$
$P_0^g + P_2^g + B_0^g$
$k_{\rm max} = 0.5$; $z = 0$.
Hahn+(in prep)

joint galaxy $P_\ell + B$ constraints on Ω_m, Ω_b, h, n_s, σ_8 are **$\gtrsim 3\times$ tighter** than the galaxy P_ℓ alone



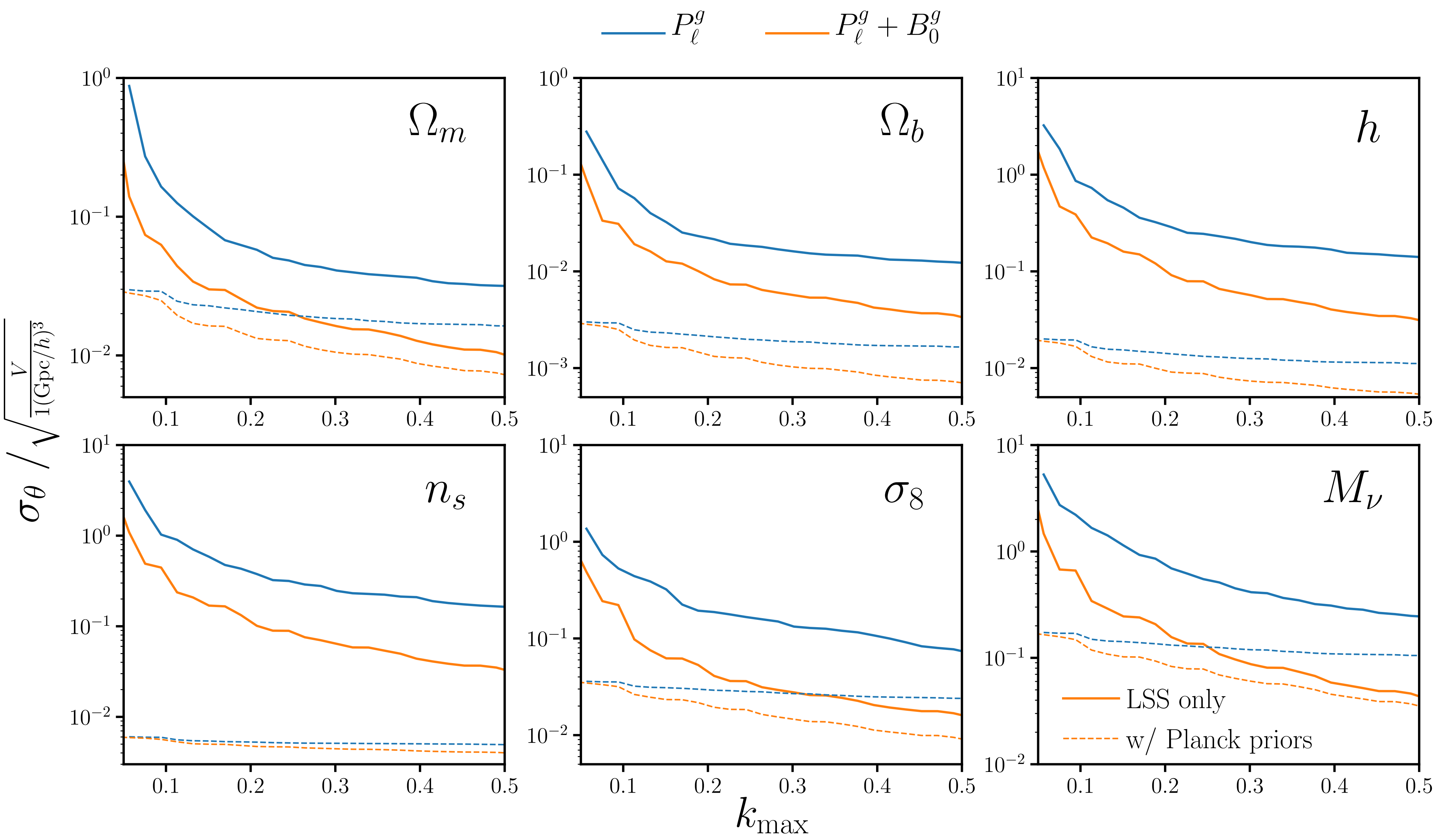
Hahn+(in prep)

joint galaxy $P_\ell + B$ constraints on Ω_m, Ω_b, h, n_s, σ_8 are $\gtrsim 3\times$ **tighter** than the galaxy P_ℓ alone ; M_ν *constraint* is $\gtrsim 5\times$ **tighter**



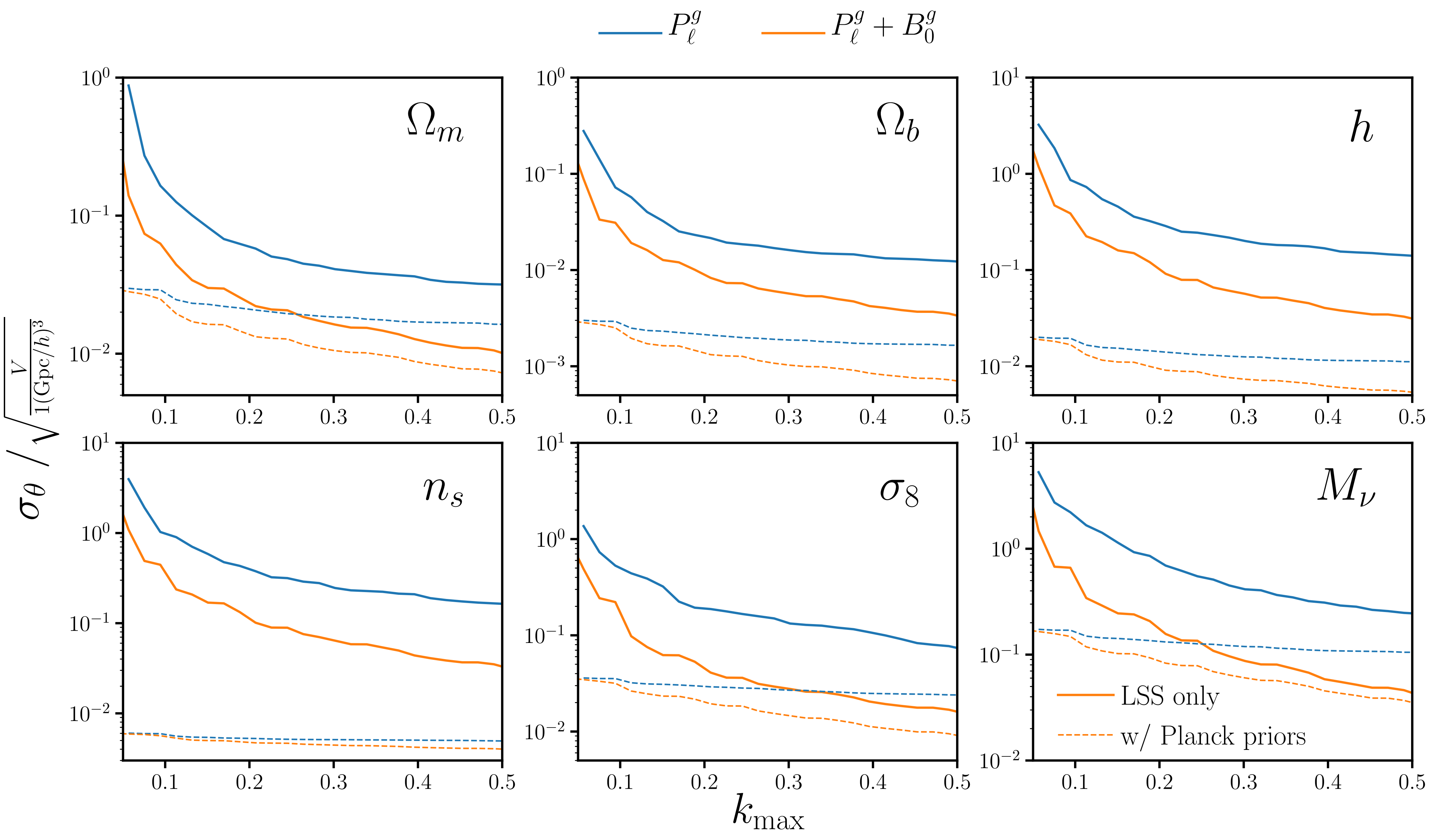
Hahn+(in prep)

significant **constraining power** on small *nonlinear scales*



Hahn+(in prep)

$\gtrsim 2\times$ **tighter** parameter constraints even *with Planck priors*



Hahn+(in prep)

some **caveats**: *assembly bias, velocity biases, baryonic effects, fisher forecast, survey geometry*

these caveats will also affect the power spectrum!

some **caveats**: *assembly bias, velocity biases, baryonic effects, fisher forecast, survey geometry*

forecasts are *for* $(1 \text{ Gpc}/h)^3$ *box* and $\bar{n}_g \sim 1.64 \times 10^{-4}$ sample

PFS $9 \ (\text{Gpc}/h)^3$
DESI $50 \ (\text{Gpc}/h)^3$
DESI BGS sample 20x higher $\bar{n}$
DESI LRG sample 3x higher $\bar{n}$

the ***galaxy bispectrum*** significant improves parameter constraints beyond the power spectrum — 5x tighter M_ν constraints

the significant constraining power in the *nonlinear regime* can be exploited using **simulation-based methods**

next up: data compression, forward modeling systematics, fully simulation-based P_ℓ and B SDSS-III *BOSS reanalysis*

credit: desi.lbl.gov