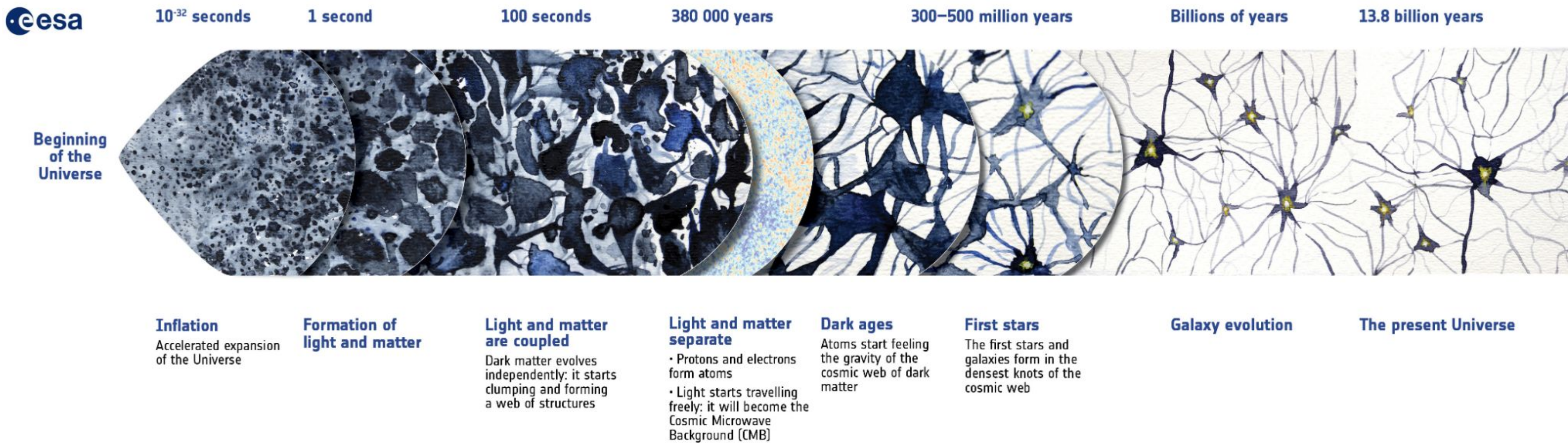
EXTRACTING FUNDAMENTAL PHYSICS OUT OF THE LARGE-SCALE STRUCTURE OF THE UNIVERSE

CAROLINE GUANDALIN (QMUL)

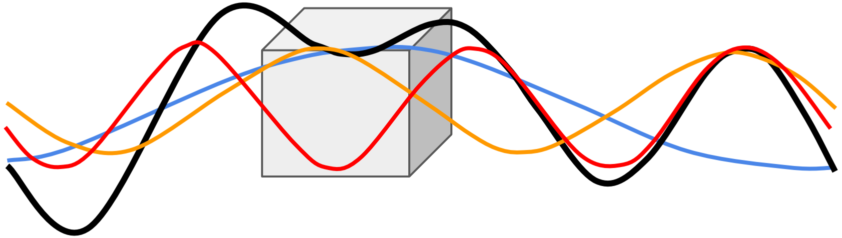
WORKSHOP ON CLASSICAL GRAVITY AND APPLICATIONS

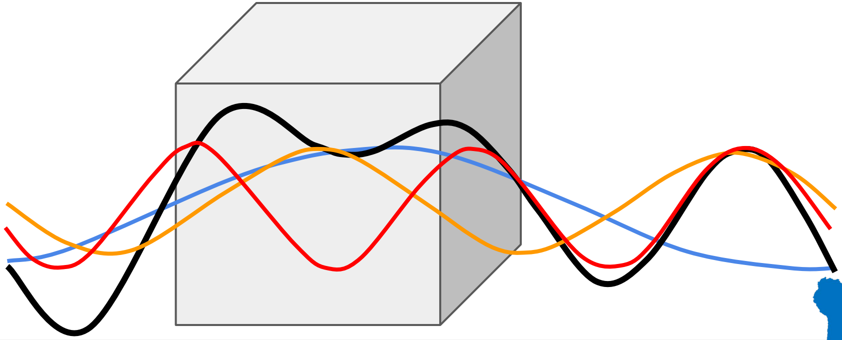
ICTP | International Centre for Theoretical Physics
SAIFR | South American Institute for Fundamental Research

Why LSS?



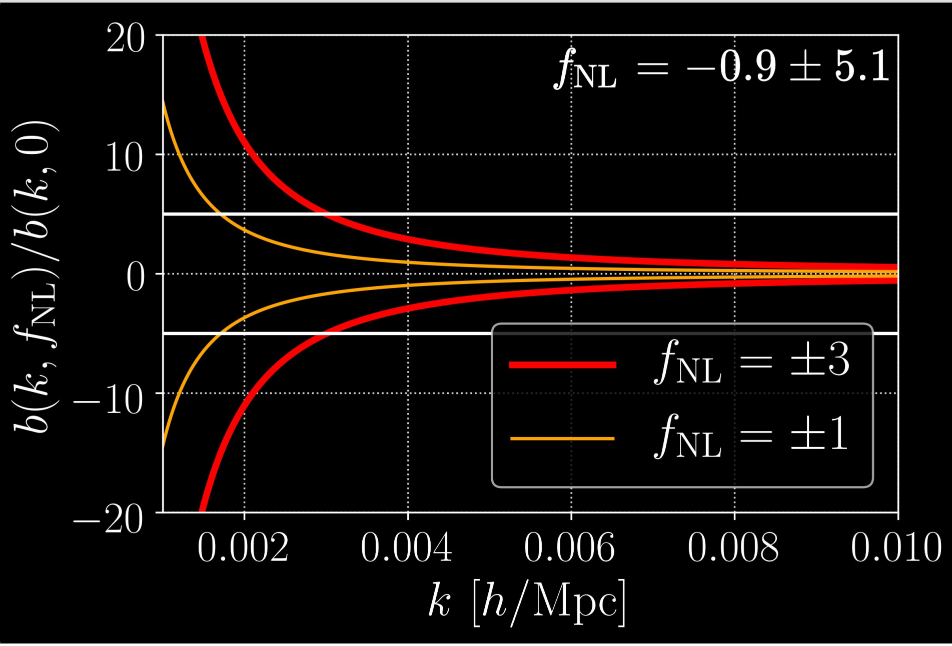
More volume, more modes!





Why LSS?

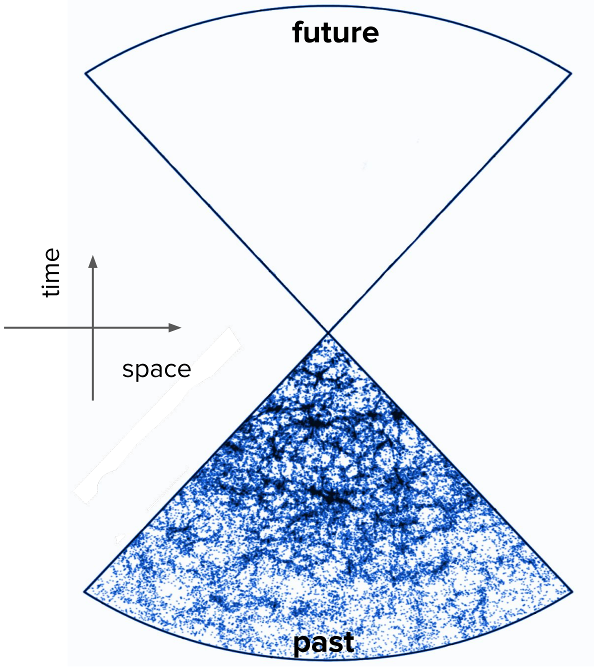
Initial conditions!



More volume, more modes!

Larger scales!

Why LSS?



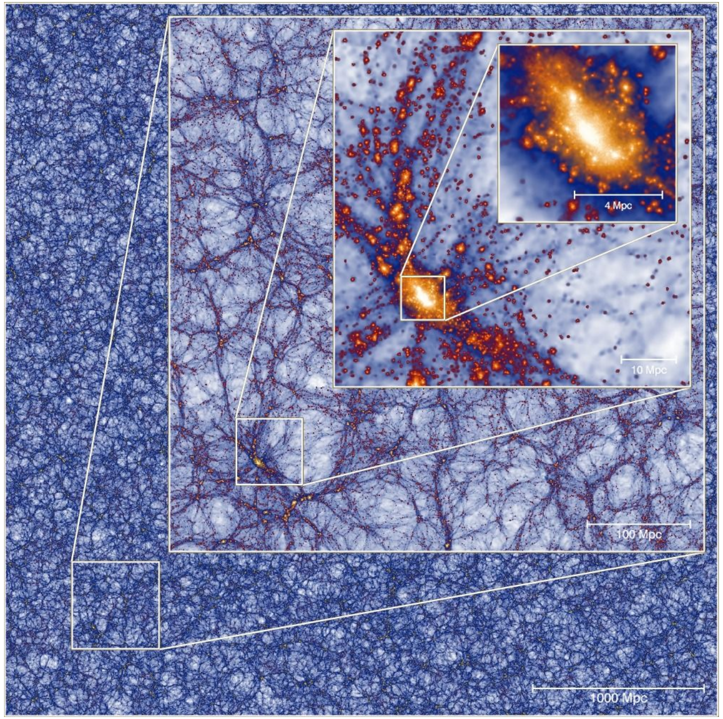
More volume, more modes!

Larger scales!

Why LSS?

More volume, more modes!

Larger scales!



Credit: Millennium-XXL

Nonlinear physics!

General considerations

Understanding the large-scale distribution of dark matter

$$\delta(\boldsymbol{x}, t) = \frac{\rho(\boldsymbol{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)} \Rightarrow \Delta(\boldsymbol{n}, z) = \frac{N(\boldsymbol{n},z) - \bar{N}(z)}{\bar{N}(z)}$$

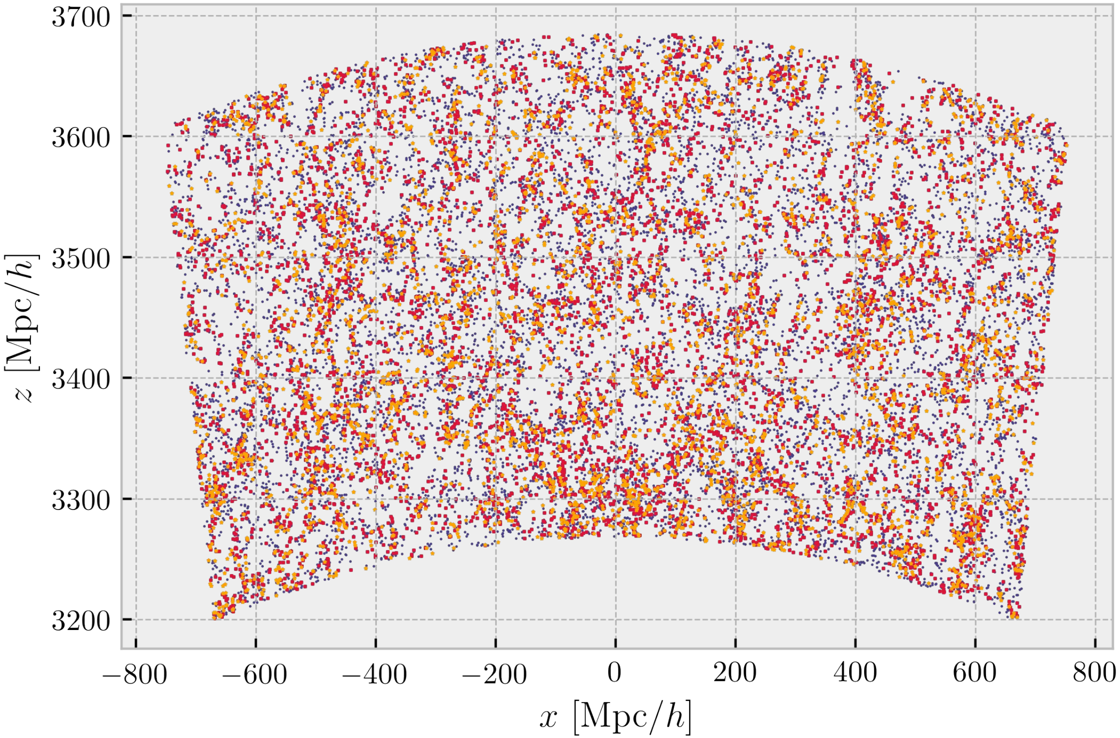
Different objects will trace the dark matter distribution differently.

$$P_\alpha(k, z) = b_\alpha^2(z)\, P_m(k, z)$$

Understanding the large-scale distribution of dark matter

	# halos	Mean mass $[M_\odot/h]$	Bias (fit)	$\bar{n}(\bar{z})$ $[\mathrm{Mpc}/h]^{-3}$
		$\bar{z} = 1.89$		
All	480643	4.41×10^{12}	2.927	7.053×10^{-4}
H_0	160081	1.86×10^{12}	2.551	2.349×10^{-4}
H_1	160547	2.83×10^{12}	2.758	2.356×10^{-4}
H_2	160015	8.54×10^{12}	3.477	2.348×10^{-4}
		$\bar{z} = 2.29$		
All	326899	3.85×10^{12}	3.469	4.666×10^{-4}
H_0	109003	1.83×10^{12}	3.020	1.556×10^{-4}
H_1	108809	2.66×10^{12}	3.270	1.553×10^{-4}
H_2	109087	7.05×10^{12}	4.154	1.557×10^{-4}
		$\bar{z} = 2.69$		
All	205678	3.44×10^{12}	4.214	2.947×10^{-4}
H_0	68501	1.80×10^{12}	3.735	9.815×10^{-5}
H_1	68550	2.52×10^{12}	4.006	9.822×10^{-5}
H_2	68627	5.98×10^{12}	4.932	9.833×10^{-5}

$1.7 \leq z \leq 2.1$

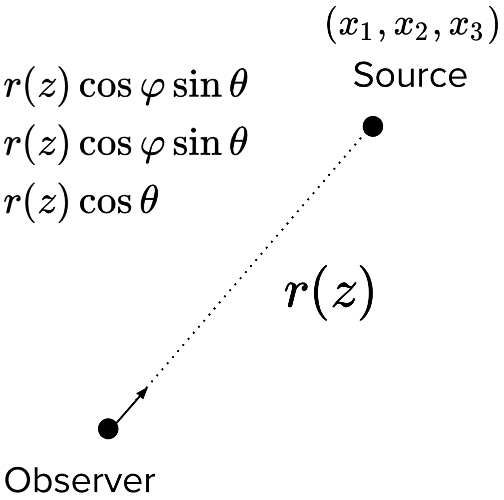


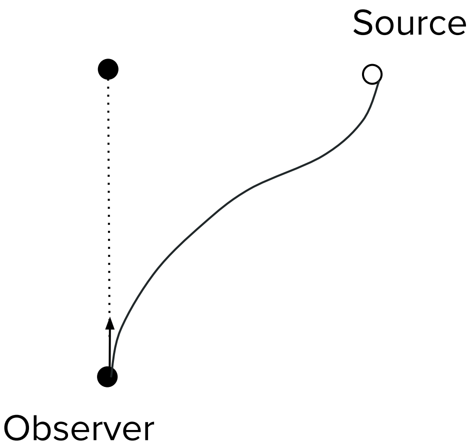
FAPESP 2018/10396-2

Understanding the large-scale distribution of dark matter

$$\delta(\boldsymbol{x}, t) = \frac{\rho(\boldsymbol{x},t) - \bar{\rho}(t)}{\bar{\rho}(t)} \Rightarrow \Delta(\boldsymbol{n}, z) = \frac{N(\boldsymbol{n},z) - \bar{N}(z)}{\bar{N}(z)}$$

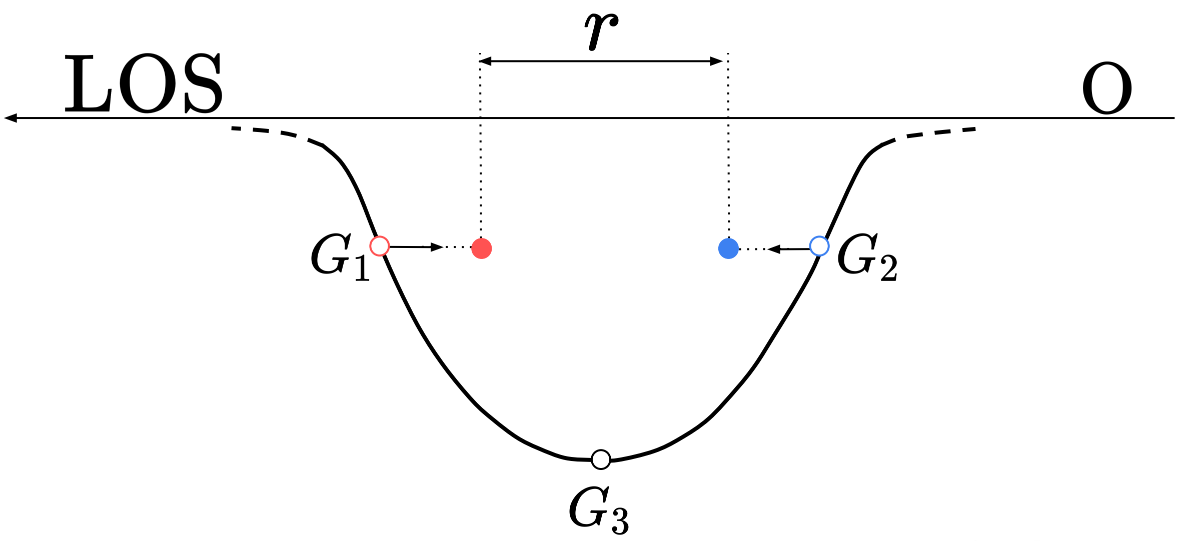
$$x_1 = r(z)\cos\varphi\sin\theta$$
$$x_2 = r(z)\cos\varphi\sin\theta$$
$$x_3 = r(z)\cos\theta$$

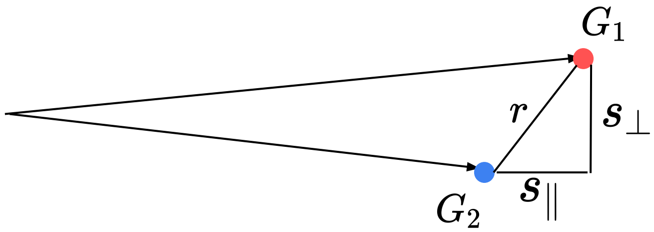


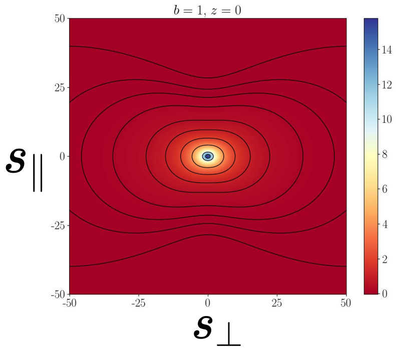


Credit: Camille Bonvin

Redshift-space distortions







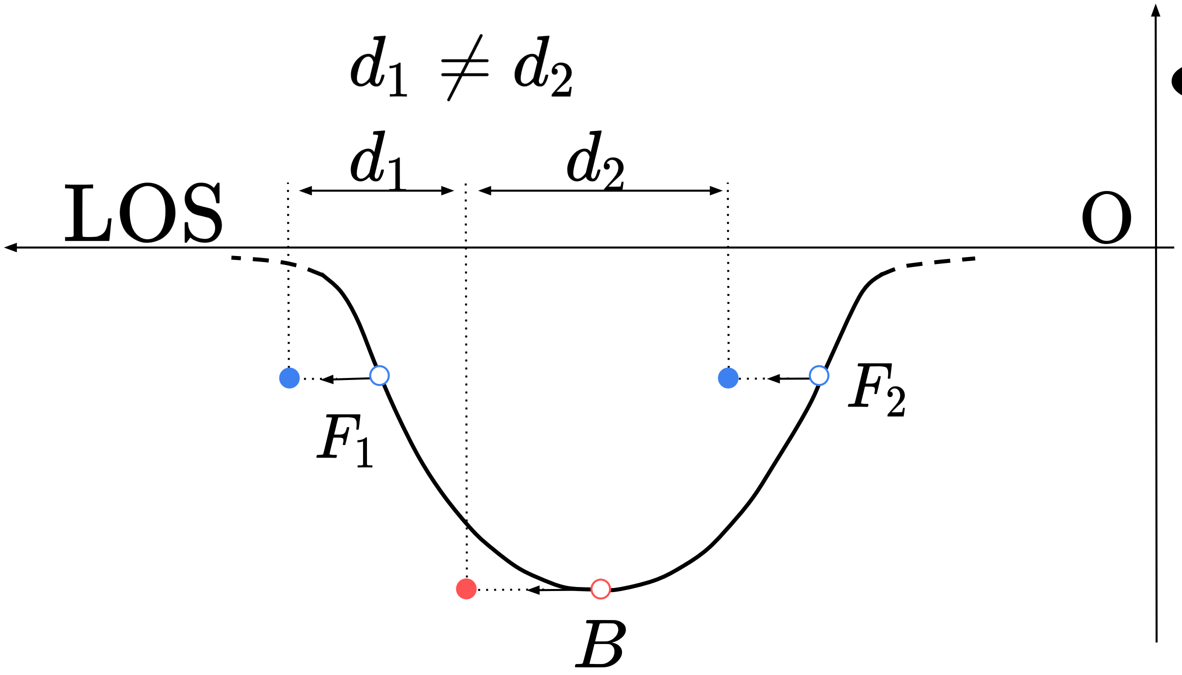
RELATIVISTIC FEATURES IN THE CLUSTERING OF DARK MATTER HALOS

Julian Adamek (UZH), Phil Bull (QMUL → Manchester), Chris Clarkson (QMUL), Raul Abramo (IFUSP) & Louis Coates (PhD at QM)

2009.02284
[MNRAS, 501(2), 2021, 2547-2561]

FAPESP 2018/10396-2

Relativistic effects: breaking the symmetry of the correlation function



Bonvin [1409.2224]

The theoretically observed number counts

e.g. Durrer 2021,
Bonvin 2014

$$\Delta(\boldsymbol{n}, z) = b_\alpha D - \frac{1}{\mathcal{H}}\partial_r(\boldsymbol{v}\cdot\hat{\boldsymbol{n}}) + \frac{1}{\mathcal{H}}\dot{\boldsymbol{v}}\cdot\hat{\boldsymbol{n}} + \left(1 - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2-5s}{r_s\mathcal{H}} - 5s + b_e\right)\boldsymbol{v}\cdot\hat{\boldsymbol{n}} + \frac{1}{\mathcal{H}}\partial_r\Phi$$

$$+ \frac{5s-2}{2r_s}\int_0^{r_s} \mathrm{d}r\, \frac{r_s - r}{r}\Delta_\Omega(\Phi+\Psi) + \left(\frac{\dot{\mathcal{H}}}{\mathcal{H}^2} + \frac{2-5s}{r_s\mathcal{H}} + 5s - b_e\right)\left[\Phi + \int_0^r \mathrm{d}r'\,(\dot{\Psi}+\dot{\Phi})\right]$$

$$+ \frac{1}{\mathcal{H}}\dot{\Psi} + \Phi - (2-5s)\Psi + \frac{2-5s}{2r_s}\int_0^{r_s}\mathrm{d}r\left[2 - \frac{r_s-r}{r}\Delta_\Omega\right](\Psi+\Phi)$$

$$\delta_\alpha^{(s)}(\boldsymbol{n}, z) = b_\alpha D - \frac{1}{\mathcal{H}}\partial_r(\boldsymbol{v}\cdot\hat{\boldsymbol{n}}) + \left(b_e^\alpha - 5s_\alpha - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2-5s_\alpha}{r_s\mathcal{H}}\right)\boldsymbol{v}\cdot\hat{\boldsymbol{n}}$$

Dipole in the cross-correlation

$$\delta_\alpha^{(s)}(\boldsymbol{n}, z) = D_l^{(g)} - \frac{1}{\mathcal{H}}\partial_r(\boldsymbol{v}\cdot\hat{\boldsymbol{n}}) + \left(b_e^\alpha - 5s_\alpha - \frac{\dot{\mathcal{H}}}{\mathcal{H}^2} - \frac{2-5s_\alpha}{r_s\mathcal{H}}\right)\boldsymbol{v}\cdot\hat{\boldsymbol{n}}$$

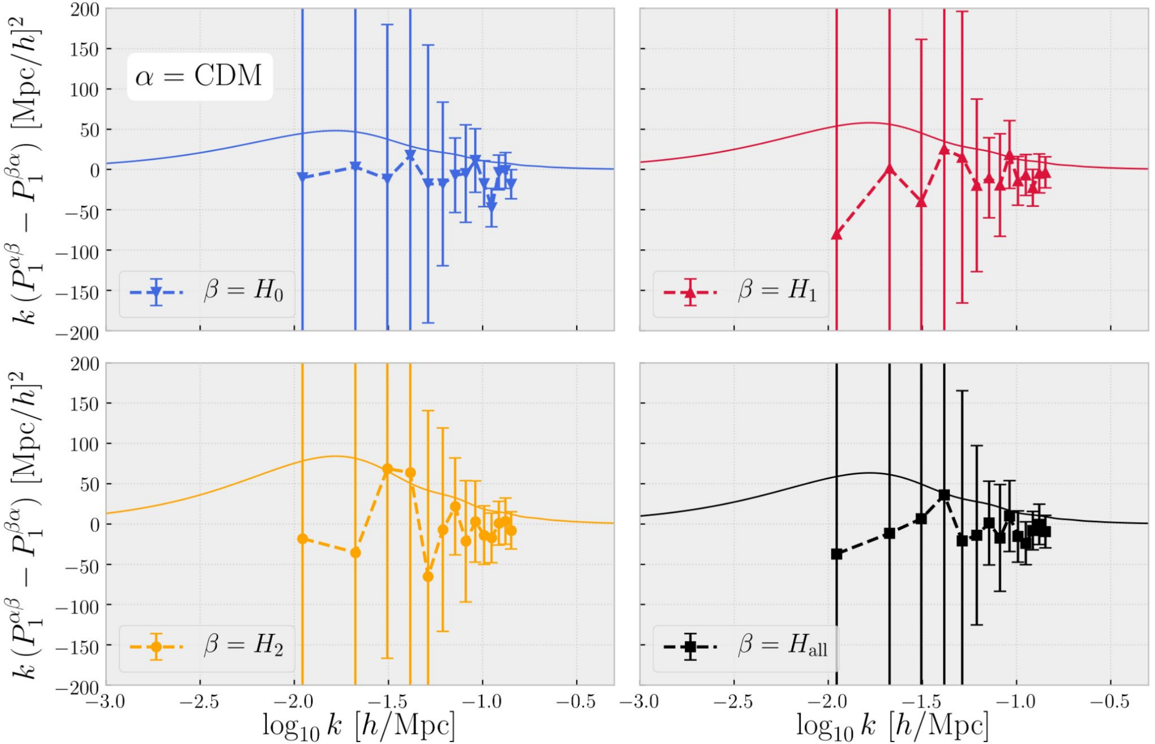
$$\delta_\alpha^{(s)}(\boldsymbol{k}) = \delta^{(r)}(\boldsymbol{k})\left[b_\alpha + f\mu_{\boldsymbol{k}}^2 + if(\mathcal{H}k^{-1})A_\alpha\mu_{\boldsymbol{k}}\right]$$

$$P_{\alpha\beta}^{(s)}(\boldsymbol{k}) = P^{(r)}(k)\left[(b_\alpha + f\mu^2)(b_\beta + f\mu^2) + A_\alpha A_\beta f^2\mu^2\frac{\mathcal{H}^2}{k^2} + if\mu\left[(b_\beta + f\mu^2)A_\alpha - (b_\alpha + f\mu^2)A_\beta\right]\frac{\mathcal{H}}{k}\right]$$

$$P_1^{(s)}(k) = iP^{(r)}(k)\frac{f}{5}\left[A_\alpha(3f+5b_\beta) - A_\beta(3f+5b_\alpha)\right]\frac{\mathcal{H}}{k}$$

Relativistic effects: attempted measurement

$$P_1^{\alpha\beta} - P_1^{\beta\alpha} \propto 2[A_\alpha(3f + 5b_\beta) - A_\beta(3f + 5b_\alpha)]$$



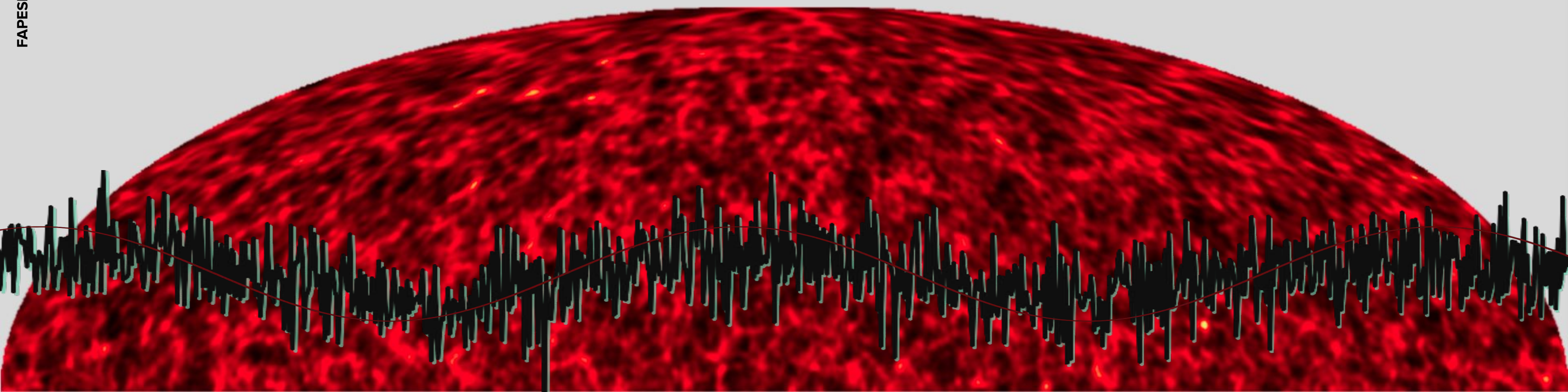
FAPESP 2018/10396-2

CLUSTERING REDSHIFTS WITH THE GALAXY-HI CROSS-BISPECTRUM

Isabella P. Carucci (UniTO), David Alonso (Oxford) &
Kavilan Moodley (UKZN)

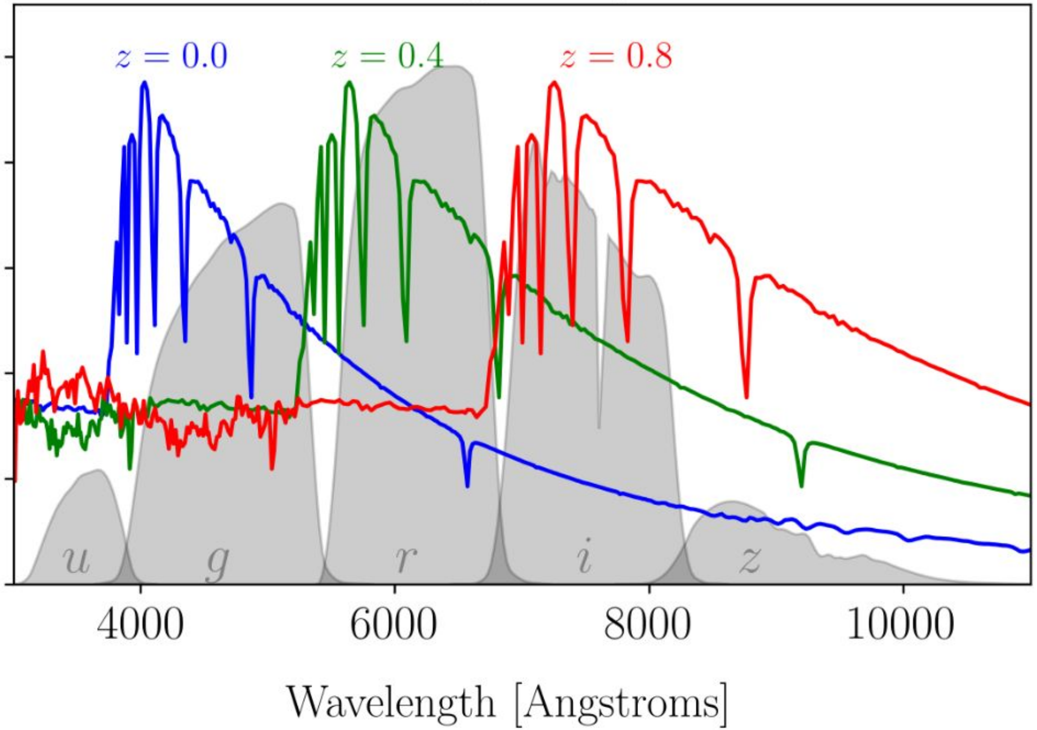
2112.05034
(published in MNRAS)

FAPESP 2018/10396-2

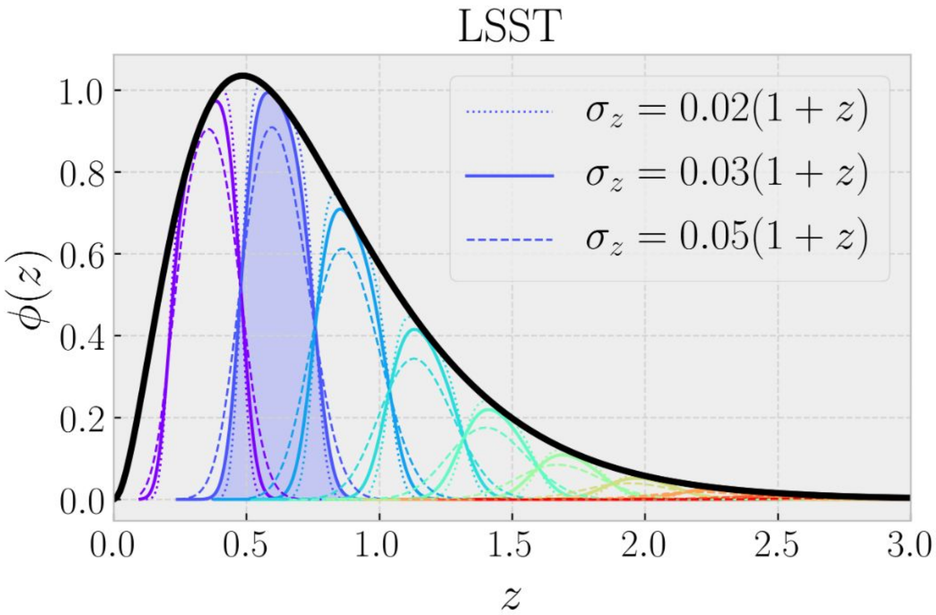


Photometric redshift surveys

Broad-band photometry



Photometric redshifts

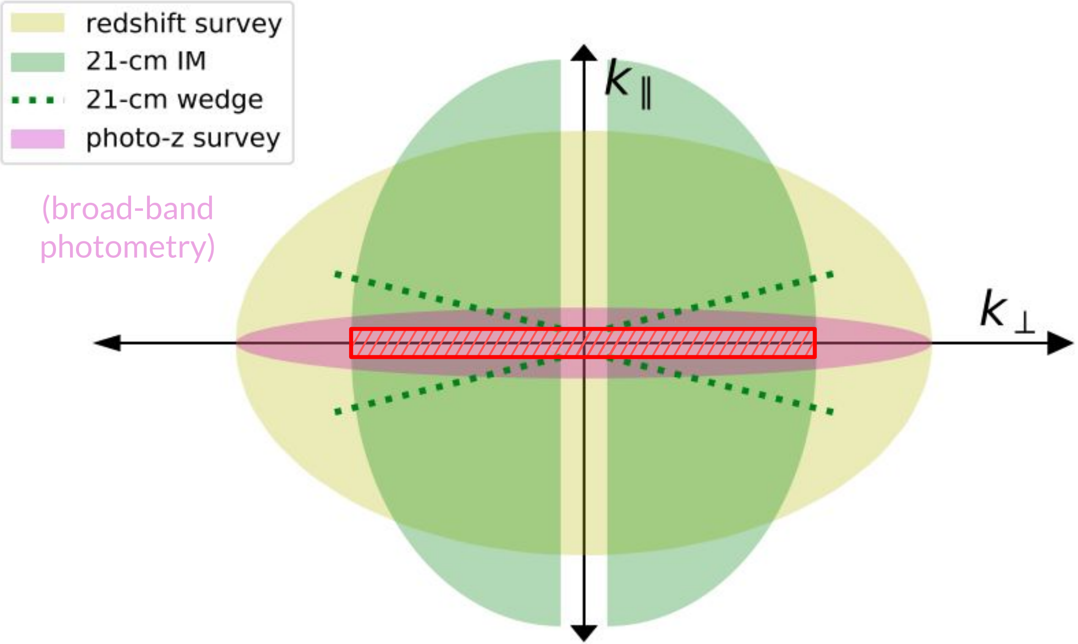


$$\Delta_g(\boldsymbol{r}_\perp) = \int \mathrm{d}r_\parallel \; \phi(r_\parallel)\, \delta_g(r_\parallel, \boldsymbol{r}_\perp)$$

$$\phi_i(z) = n_g(z) \int_{z^i_{\rm ph}}^{z^{i+1}_{\rm ph}} \mathrm{d}z_{\rm ph} P(z_{\rm ph}|z)$$

$$P(z_{\rm ph}|z) = \frac{1}{\sigma_z\sqrt{2\pi}} \exp\left[-\frac{1}{2}\frac{(z_{\rm ph}-z)}{\sigma_z^2}\right]$$

Problem of cross-correlating photometric galaxies with HI IM

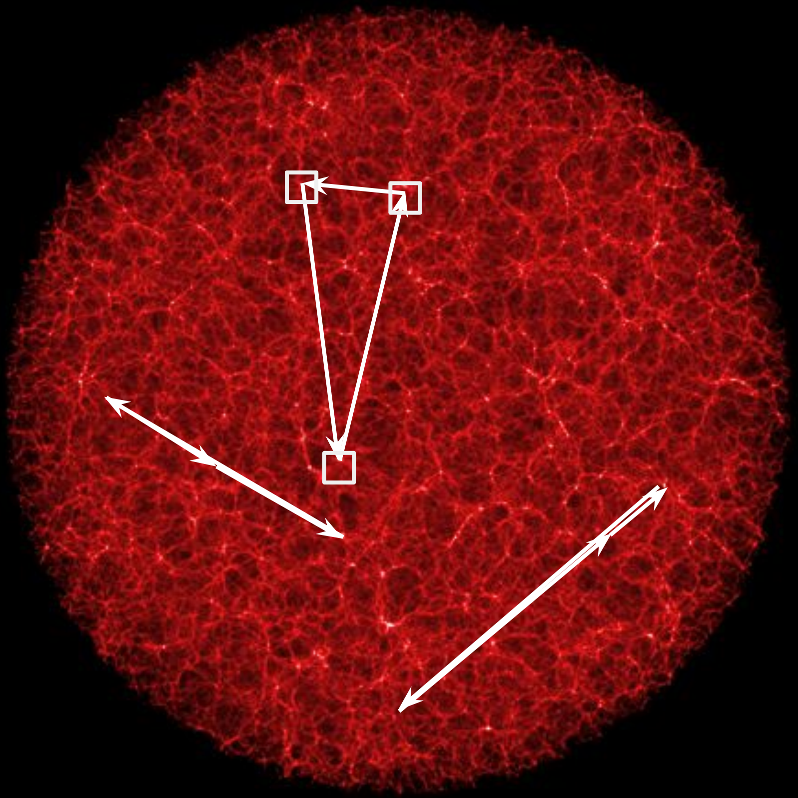


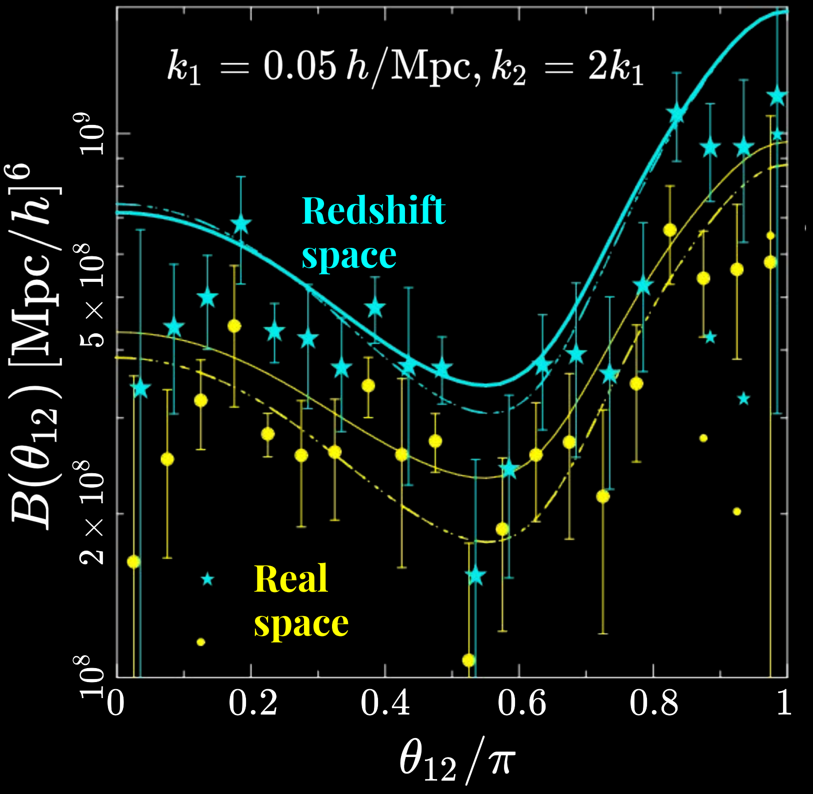
(broad-band photometry)

Modi et al. [2102.08116]

Jessica Muir's talk (photo-z)

Bispectrum





Smith et al. [0712.0017]

2- and 3- point statistics

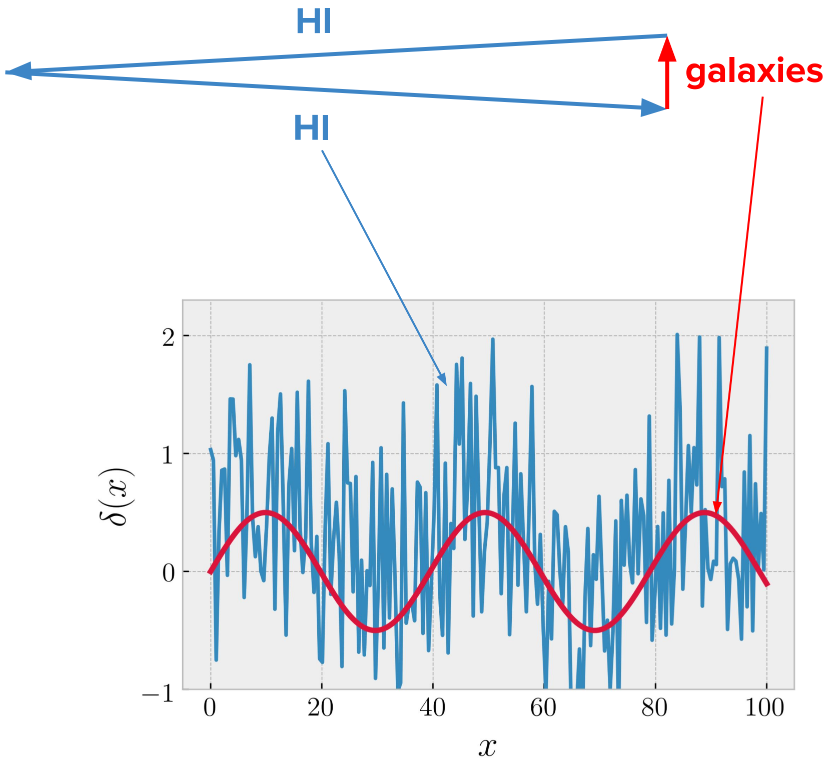
Power spectrum

$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\, \delta_{xy}$$

Bispectrum

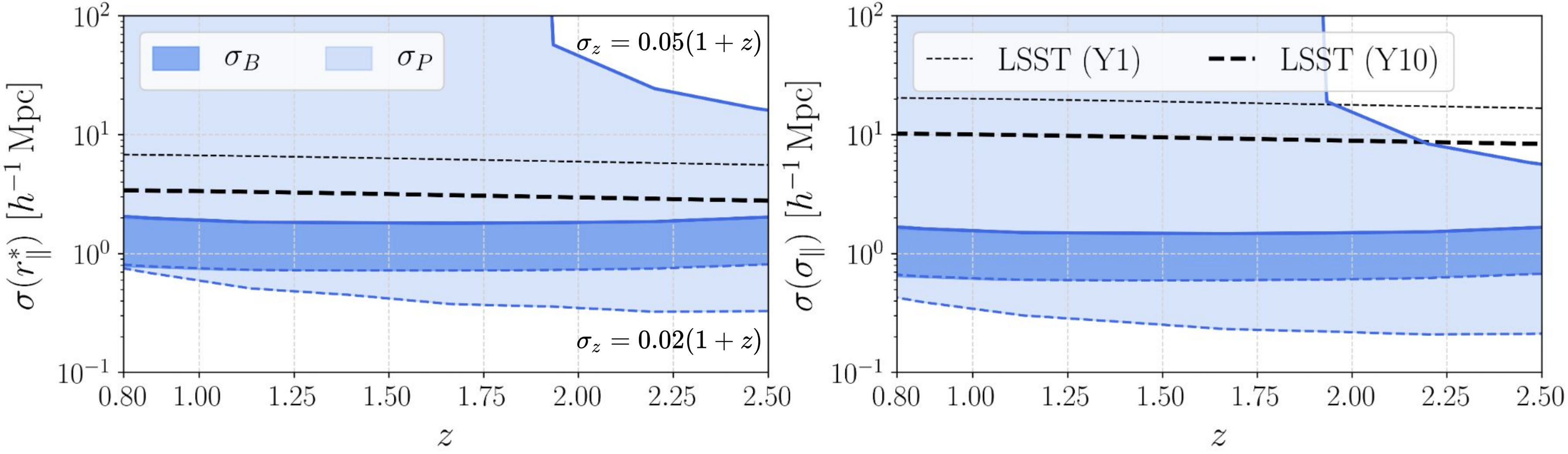
$$B_{xyz}(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) = \mathcal{K}_{xyz} B(\boldsymbol{k}_1, \boldsymbol{k}_2, \boldsymbol{k}_3) + \mathcal{J}^{112}_{xyz} P(k_1)P(k_2) + \mathcal{J}^{121}_{xyz} P(k_1)P(k_3) + \mathcal{J}^{211}_{xyz} P(k_2)P(k_3)$$

Attempt to reconstruct the long-wavelength modes



Impact of photo-z width

$$k_{\parallel}^{\rm FG} = 0.02\, h\, {\rm Mpc}^{-1},\ k_{\rm max} = 0.3\, h\, {\rm Mpc}^{-1}$$



$$\phi(r_{\parallel}) \propto \exp\left[-\frac{(r_{\parallel}-r_{\parallel}^*)^2}{2\sigma_{\parallel}^2}\right]$$

$$\sigma_z = \sigma_{z,0}(1+z)$$

FAPESP 2018/10396-2

Conclusions

Relativistic effects:

- A dipole signal emerges from relativistic corrections in the cross-power spectrum of dark matter tracers;
- We developed a pipeline to model, estimate and interpret the dipolar modulation induced by relativistic effects in the 3d clustering of halos obtained from a fully relativistic simulation;
- Integrated effects were neglected;
- No dipole detection could be claimed with our simulations.

Clustering redshifts:

- We employed the multiple-tracers technique to combine photometric galaxies with 21-cm intensity mapping to recover the redshift distribution of a photometric galaxy sample;
- The galaxy-HI bispectra helps to recover the large radial scales apparently lost to foreground contamination;
- The bispectrum is capable of calibrating the redshift distribution in situations where the two-point function is not.

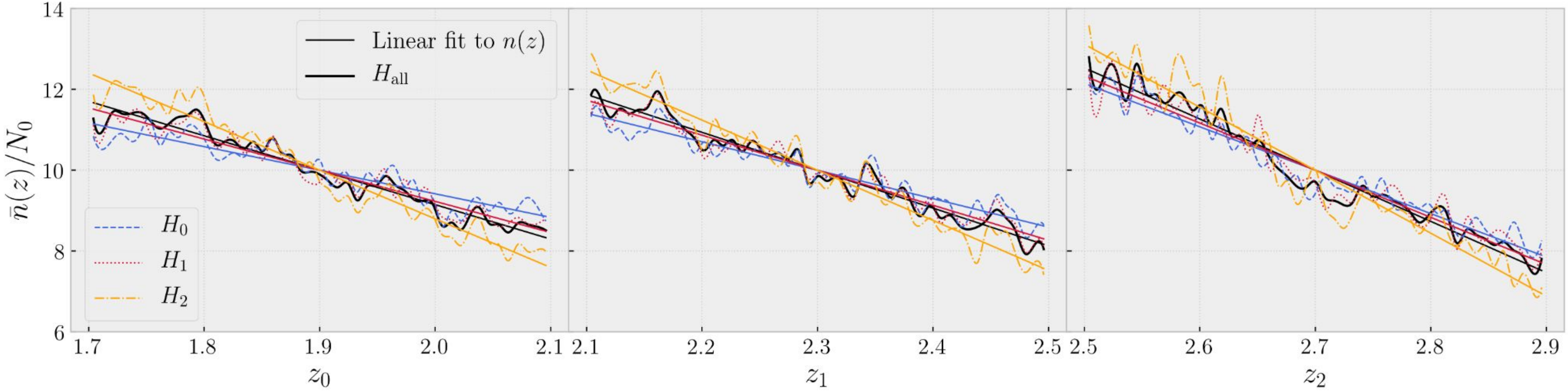
ICTP SAIFR

Relativistic effects (extra)

Obtaining the halo properties

$$P_1^{(s)}(k) = iP^{(r)}(k)\frac{f}{5}\left[A_\alpha(3f+5b_\beta) - A_\beta(3f+5b_\alpha)\right]\frac{\mathcal{H}}{k}$$

$$-\frac{(2-5s_\alpha)}{\mathcal{H}r} + \frac{\partial(a^3\bar{n}_\alpha)}{\partial \ln a} - \frac{\mathcal{H}'}{\mathcal{H}^2} - 5s_\alpha$$



$$\bar{n}(z) \approx a + bz$$

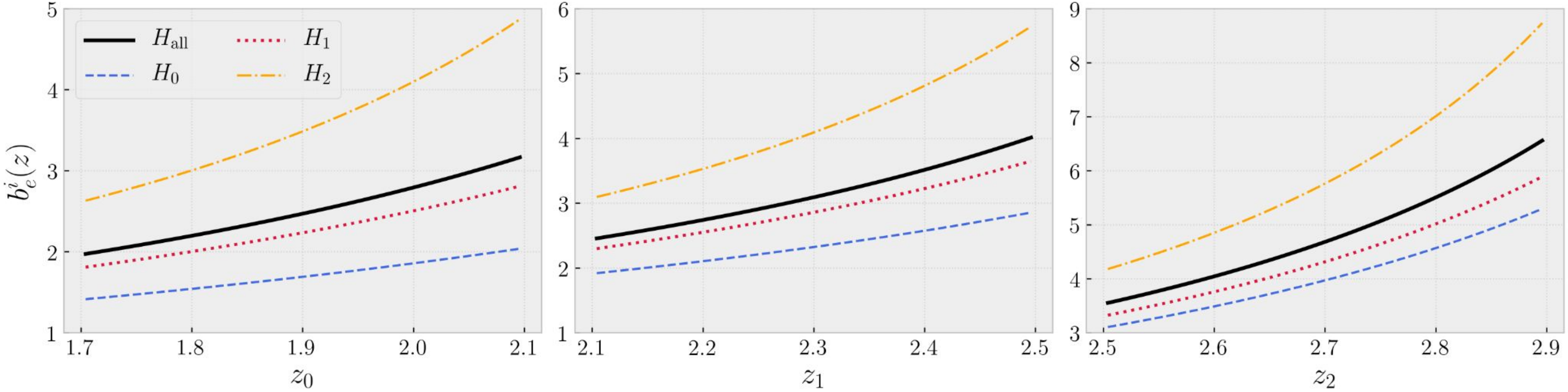
following Beutler & Di Dio [2004.08014]

FAPESP 2018/10396-2

Obtaining the halo properties

$$P_1^{(s)}(k) = iP^{(r)}(k)\frac{f}{5}\left[A_\alpha(3f+5b_\beta) - A_\beta(3f+5b_\alpha)\right]\frac{\mathcal{H}}{k}$$

$$-\frac{(2-5s_\alpha)}{\mathcal{H}r} + \frac{\partial(a^3\bar{n}_\alpha)}{\partial \ln a} - \frac{\mathcal{H}'}{\mathcal{H}^2} - 5s_\alpha$$



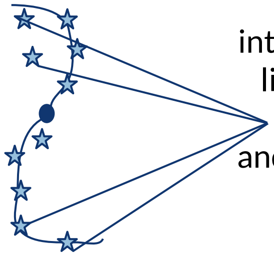
$$b_e(z) = \frac{c+1}{c-z} - 1 \quad c = \frac{a}{-b}$$

following Beutler & Di Dio [2004.08014]

FAPESP 2018/10396-2

Galaxy-HI complementarity (extra)

Galaxies-HI/IM synergies



integrate the light of all stars
and resolve a galaxy

Photometric surveys

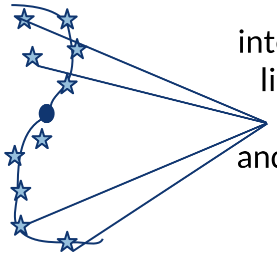
Individually resolved galaxies

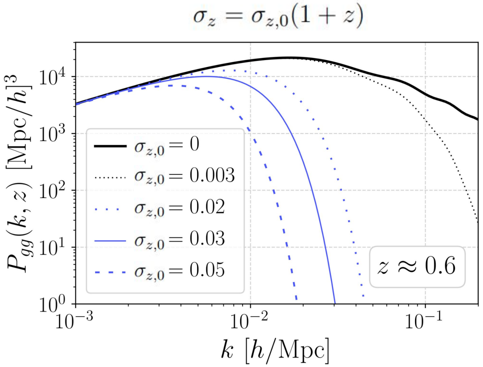
High number density

Poorer redshifts

Low-pass k-filter

Galaxies-HI/IM synergies





Photometric surveys

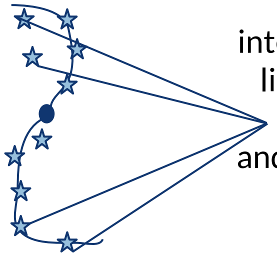
Individually resolved galaxies

High number density

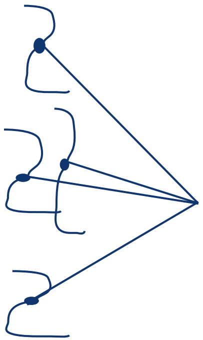
Poorer redshifts

Low-pass k-filter

Galaxies-HI/IM synergies



integrate the light of all stars and resolve a galaxy

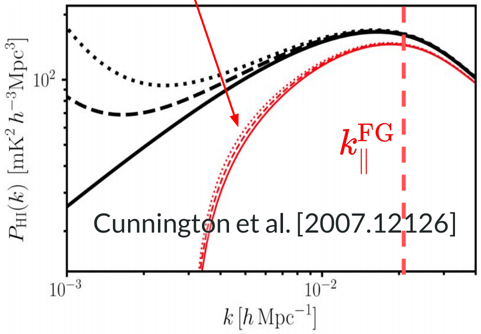


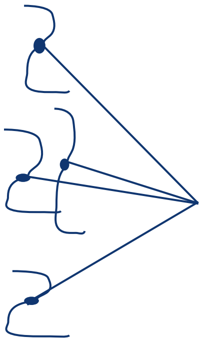
integrate the HI emission of many galaxies to resolve large-scale fluctuations

Photometric surveys	Intensity Mapping
Individually resolved galaxies	Unresolved map (intensity)
High number density	Large volumes
Poorer redshifts	Excellent redshifts
Low-pass k-filter	High-pass k-filter

Galaxies-HI/IM synergies

foregrounds





integrate the HI emission of many galaxies to resolve large-scale fluctuations

Photometric surveys	**Intensity Mapping**
Individually resolved galaxies	Unresolved map (intensity)
High number density	Large volumes
Poorer redshifts	Excellent redshifts
Low-pass k-filter	**High-pass k-filter**

Clustering-z (extra)

Clustering-z to calibrate the redshift distribution

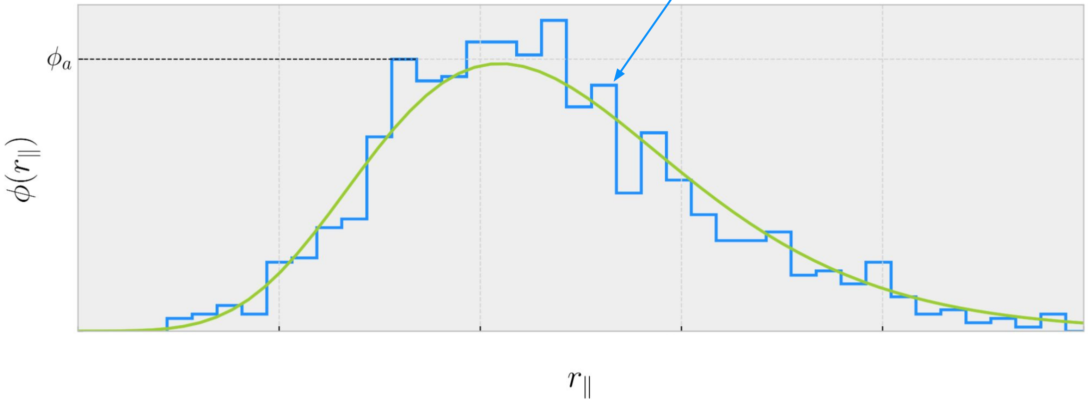
$$\phi(r_\parallel) \propto \exp\left[-\frac{(r_\parallel - r_\parallel^*)^2}{2\sigma_\parallel^2}\right]$$

$$\phi(r_\parallel) = \sum_a \phi_a \, w_a(r_\parallel)$$

$$\sigma_z = \sigma_{z,0}(1+z)$$

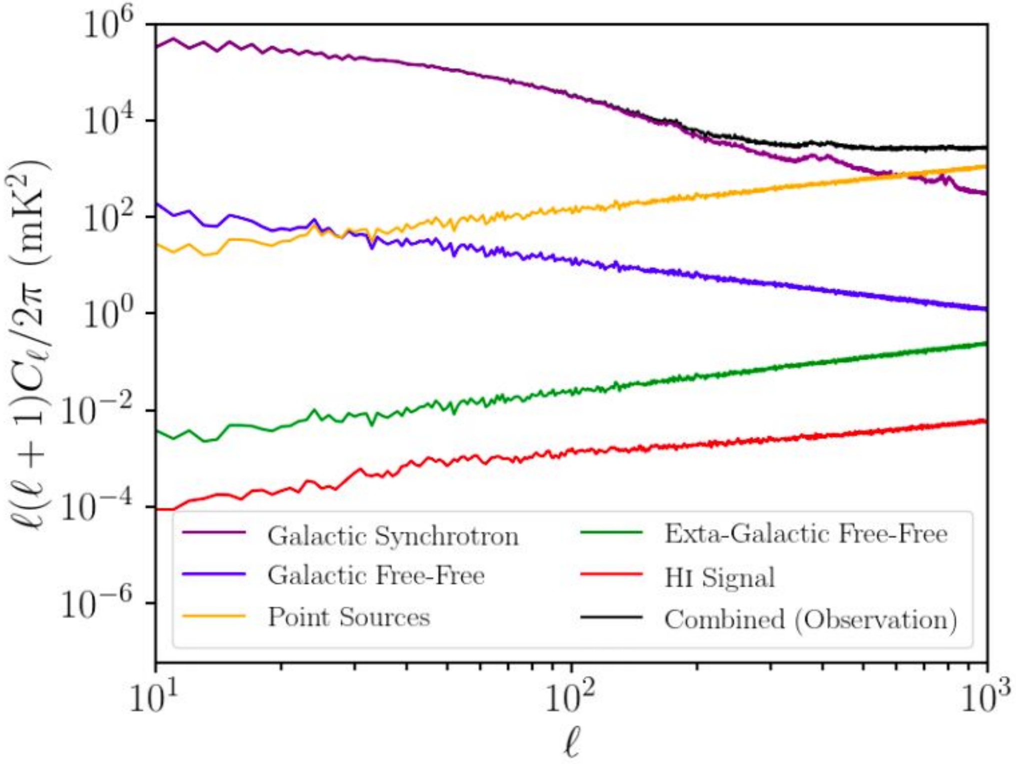
$$\Delta_g(\boldsymbol{r}_\perp) = \sum_a \phi_a \, \delta_g^a(\boldsymbol{r}_\perp), \quad \delta_g^a(\boldsymbol{r}_\perp) \equiv \int \mathrm{d}r_\parallel \; w_a(r_\parallel) \, \delta_g(r_\parallel, \boldsymbol{r}_\perp)$$

e.g. HI slices [Alonso et al., 1704.01941]



FAPESP 2018/10396-2

Foregrounds



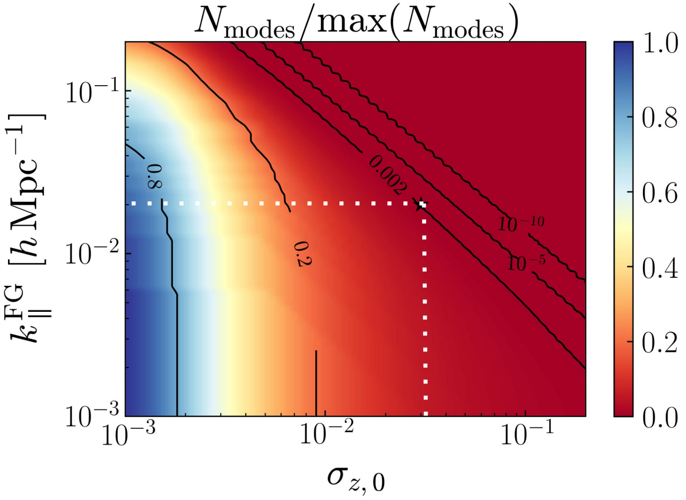
Cunnington et al. [1904.01479]

Clustering redshifts with 2-point statistics

$$F^P_{\alpha\beta} = \sum_{XX'} \frac{A}{4\pi} \int_0^\infty \mathrm{d}k_\perp\, k_\perp\, \partial_\alpha \mathcal{P}^{XY}(k_\perp)\, \partial_\beta \mathcal{P}^{X'Y'}(k_\perp)\, \mathcal{I}^{XX'}(k_\perp)\, \mathcal{I}^{YY'}(k_\perp)$$

$$\sigma_P^{-1}(\theta) \propto \int \frac{\mathrm{d}k_\parallel}{2\pi}\, \mathcal{K}^2_\theta(k_\parallel, \sigma_\parallel)\, \mathrm{e}^{-k_\parallel^2 \sigma_\parallel^2} \frac{P^2_{gh}(k_\parallel, k_\perp)}{P_{hh}(k_\parallel, k_\perp)}$$

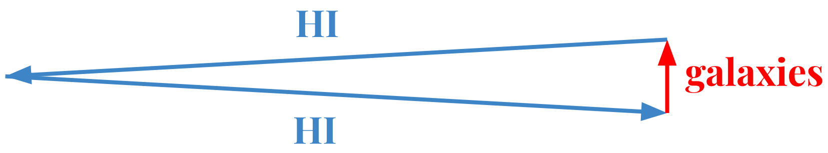
$$\phi(r_\parallel) \propto \exp\left[-\frac{(r_\parallel - r^*_\parallel)^2}{2\sigma^2_\parallel}\right]$$



$$\sigma_z = \sigma_{z,0}(1+z)$$

FAPESP 2018/10396-2

3-point statistics



FAPESP 2018/10396-2

$$F^B_{\alpha\beta} = \sum_{XX'} \frac{A}{4\pi}\frac{1}{6}\int_0^\infty \mathrm{d}k_\perp\, \mathrm{d}q_\perp\, \mathrm{d}p_\perp\, \frac{k_\perp q_\perp p_\perp}{\pi^2 A_T}\, \partial_\alpha \mathcal{B}^{XYZ}(k_\perp, p_\perp, q_\perp)\, \partial_\beta \mathcal{B}^{X'Y'Z'}(k_\perp, p_\perp, q_\perp)\, \mathcal{I}^{XX'}(k_\perp)\, \mathcal{I}^{YY'}(q_\perp)\, \mathcal{I}^{ZZ'}(p_\perp)$$

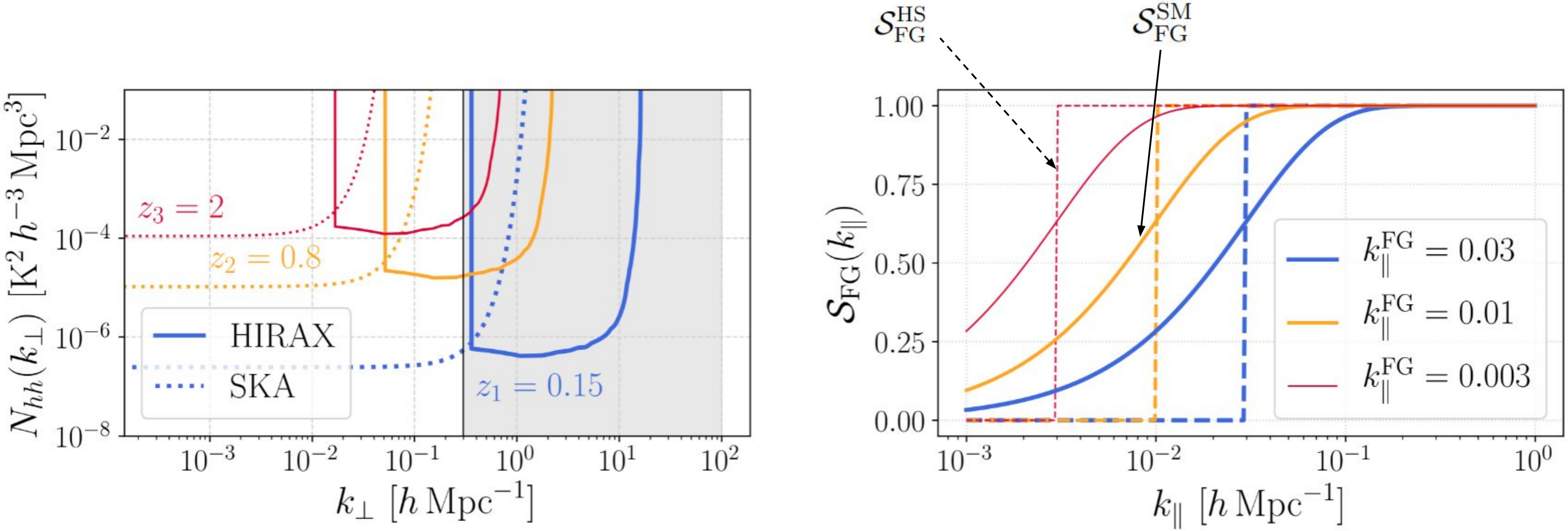
$$\sigma_B^{-1}(\theta) \propto \int \frac{\mathrm{d}p_\parallel}{2\pi}\frac{\mathrm{d}k_\parallel}{2\pi}\, \mathcal{K}^2_\theta(k_\parallel, \sigma_\parallel)\, \mathrm{e}^{-k_\parallel^2\sigma_\parallel^2}\, \frac{B^2_{ghh}(k_\parallel, p_\parallel, -k_\parallel - p_\parallel; k_\perp, p_\perp, q_\perp)}{P_{hh}(p_\parallel, q_\perp) P_{hh}(-k_\parallel - p_\parallel, p_\perp)}$$

We can avoid the foreground-dominated region!

Beam and noise

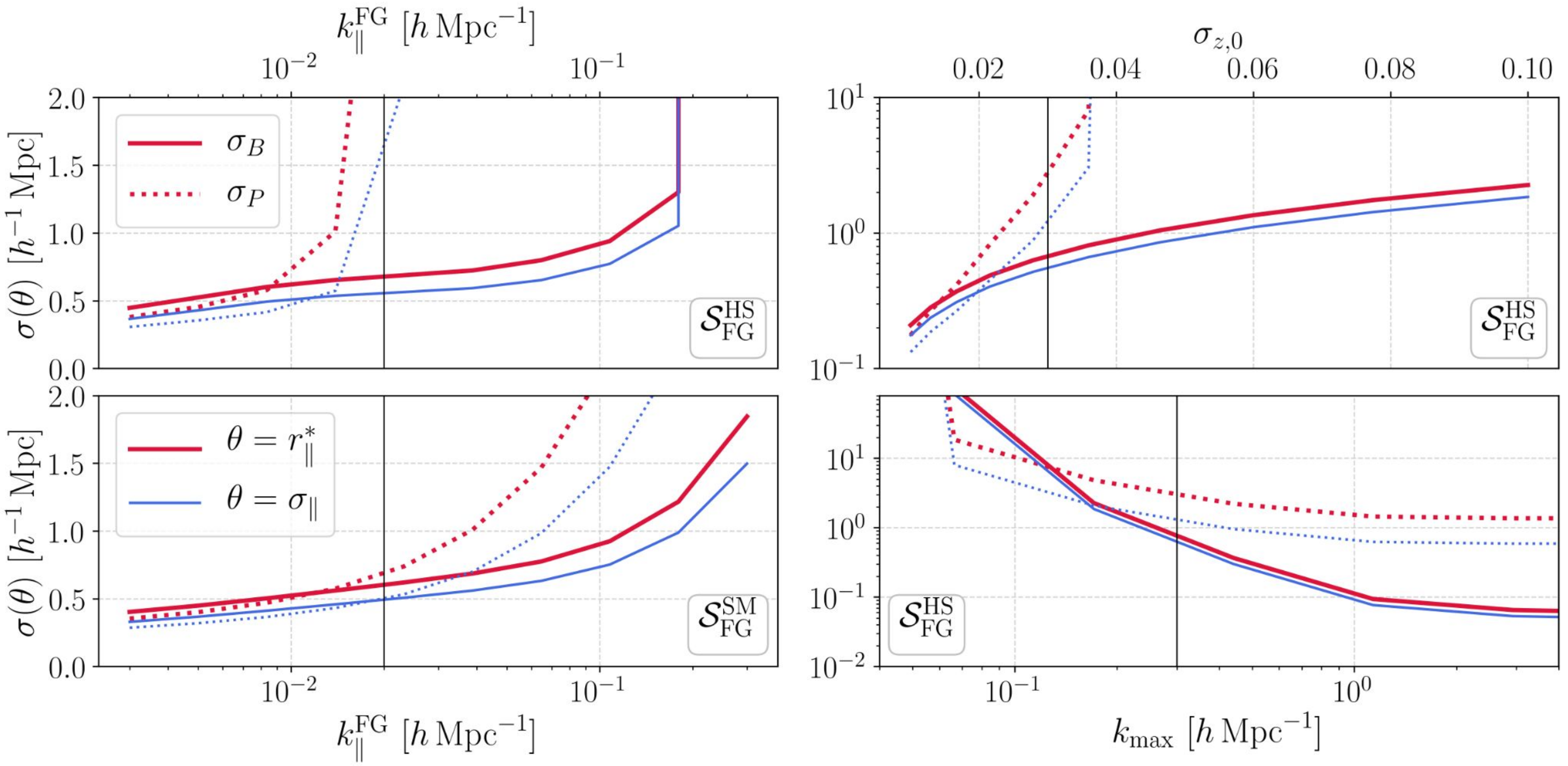
Single-dish mode
Area: 20000 deg²
Redshift coverage: 0-3

Interferometer mode
Area: 2000 deg²
Redshift coverage: 0.8-2.5



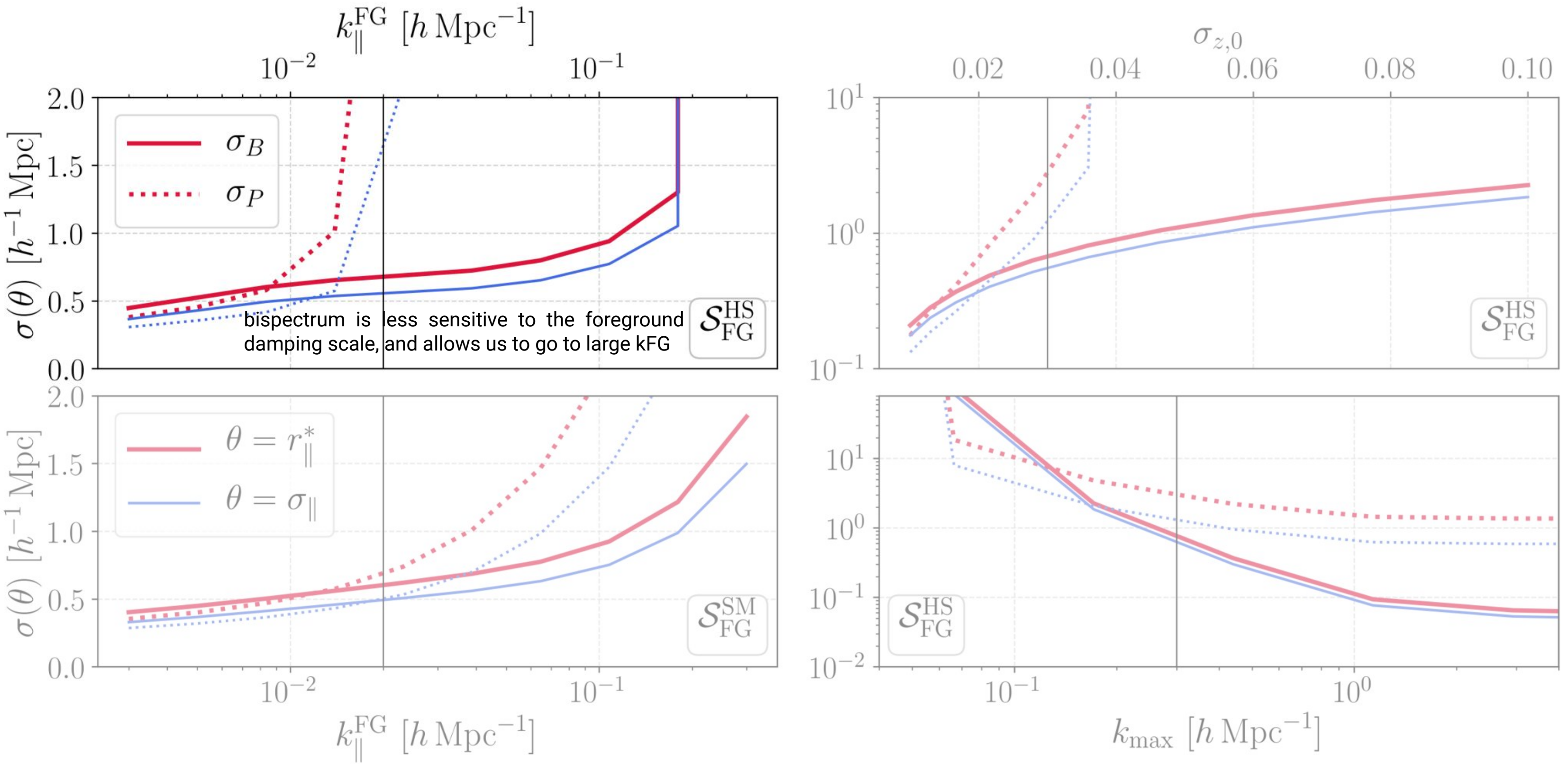
FAPESP 2018/10396-2

Intuition: behaviour with characteristic scales



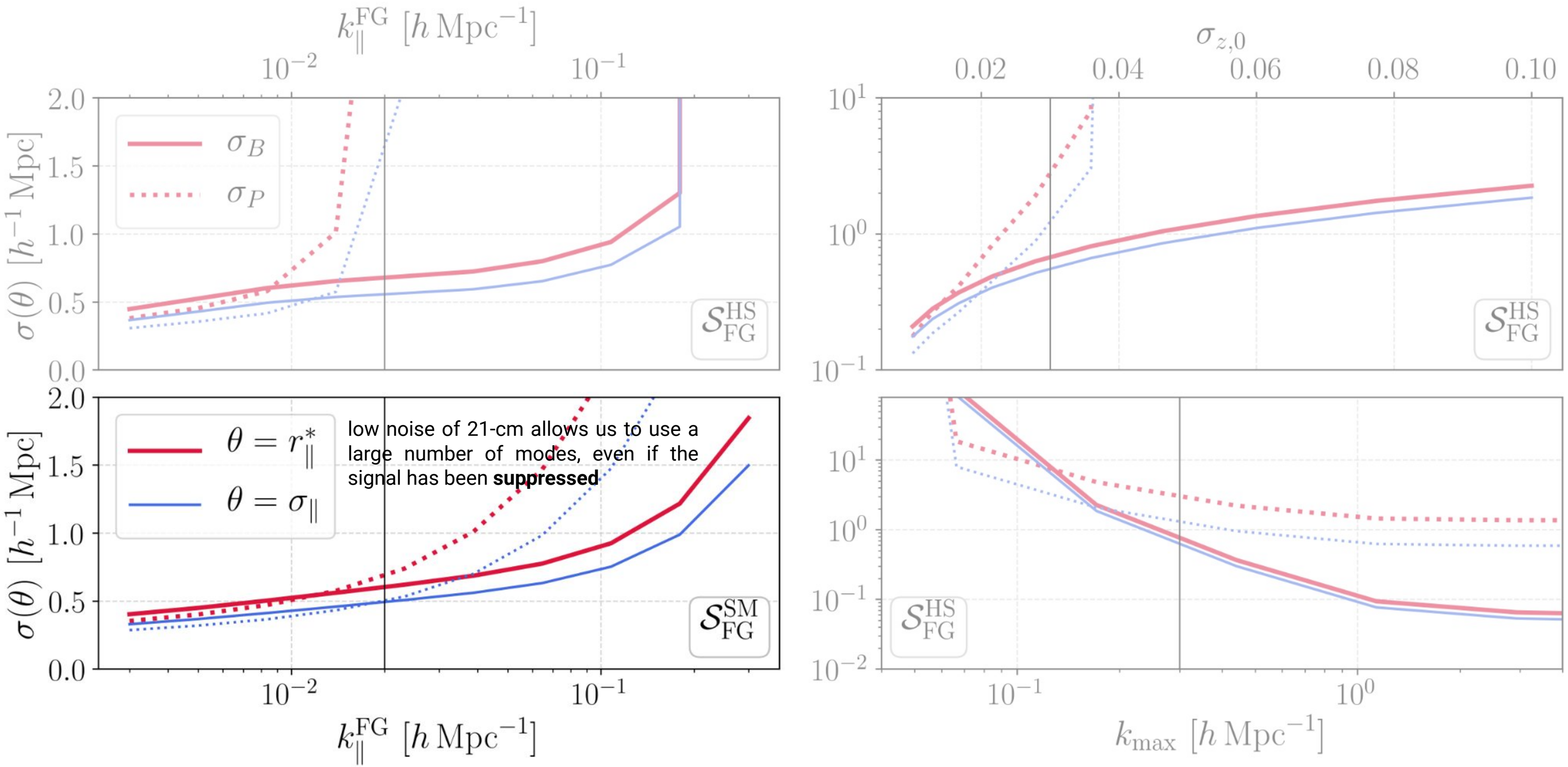
FAPESP 2018/10396-2

Intuition: behaviour with characteristic scales



FAPESP 2018/10396-2

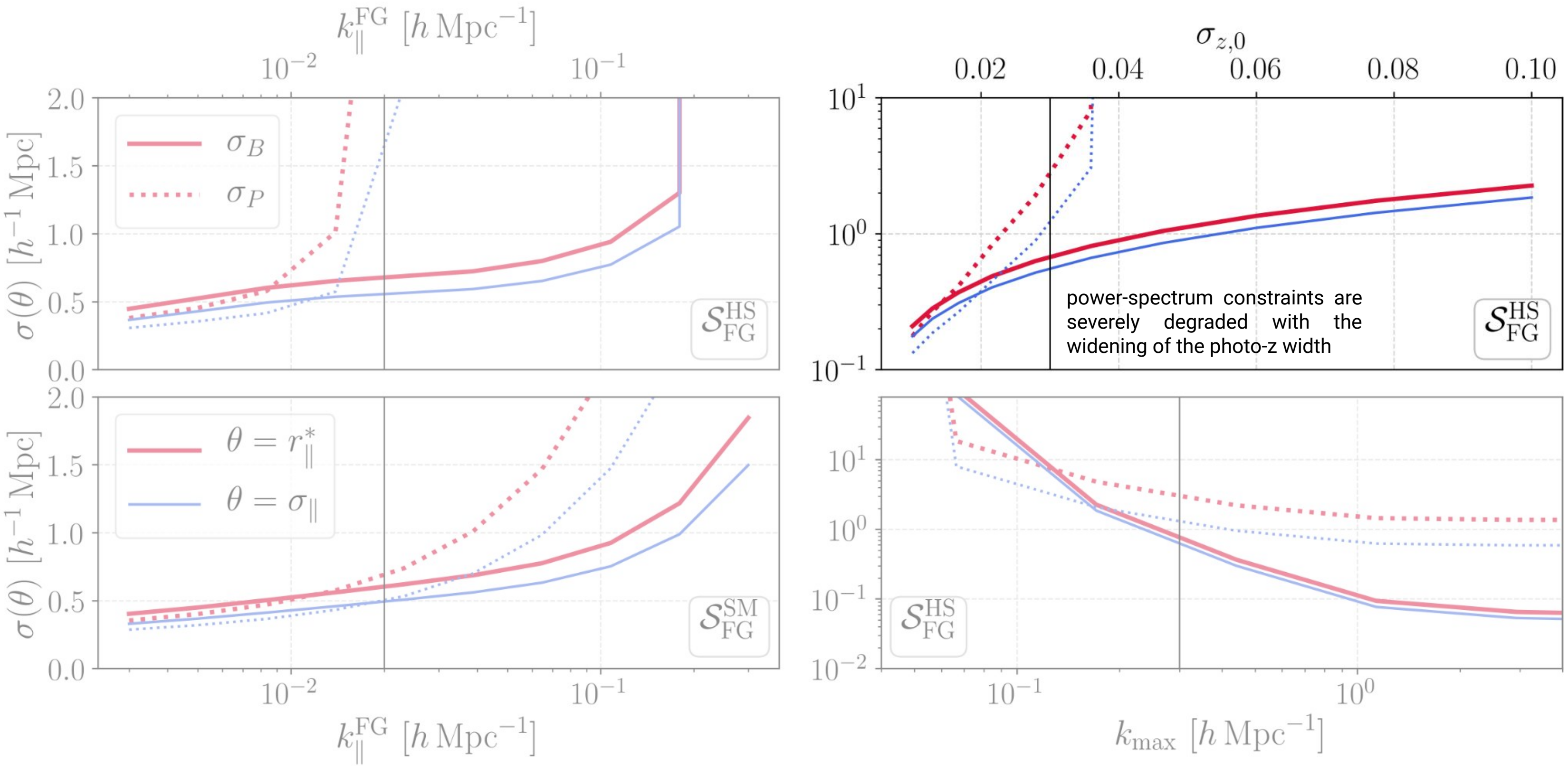
Intuition: behaviour with characteristic scales



low noise of 21-cm allows us to use a large number of modes, even if the signal has been **suppressed**

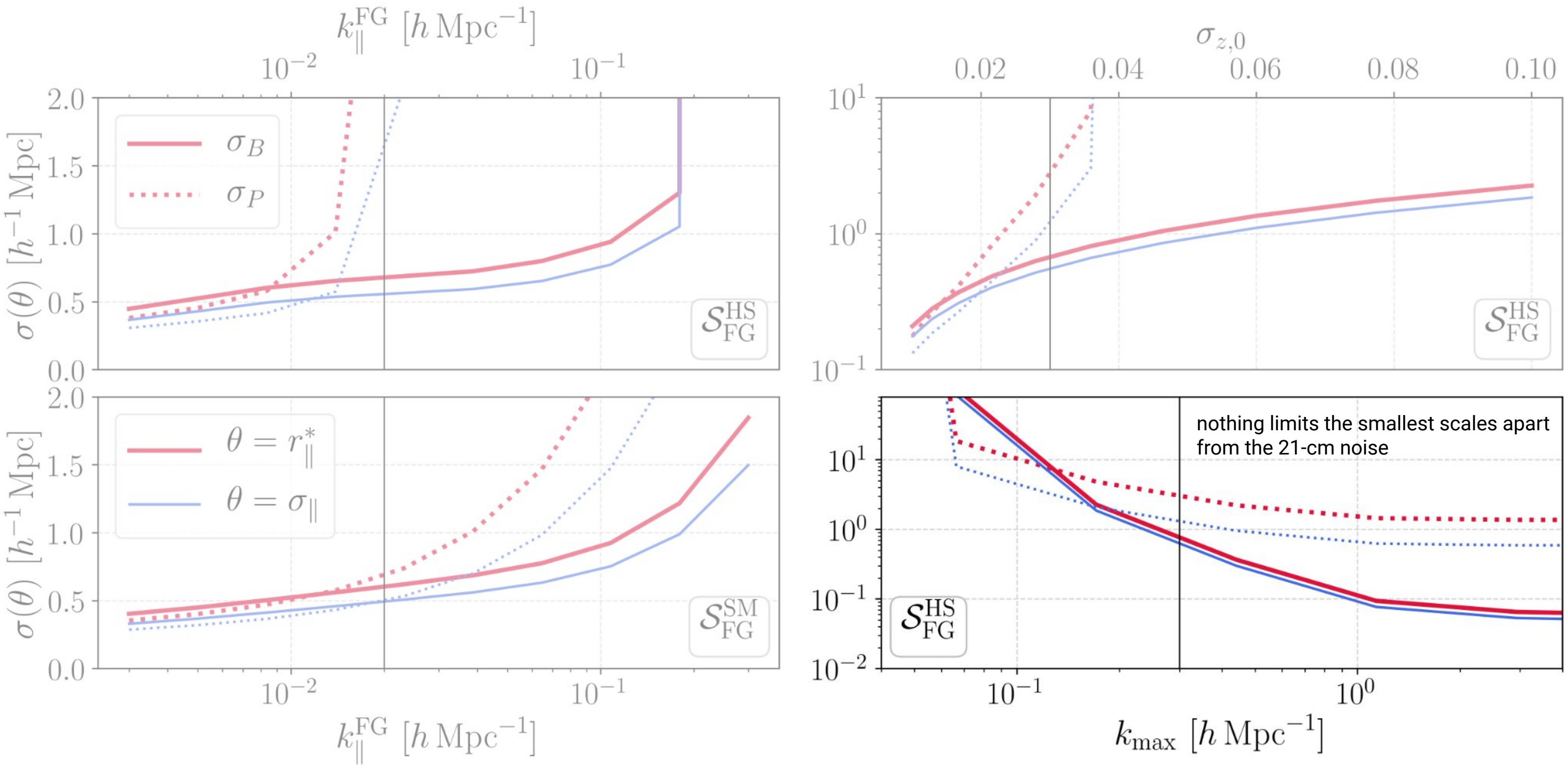
FAPESP 2018/10396-2

Intuition: behaviour with characteristic scales



FAPESP 2018/10396-2

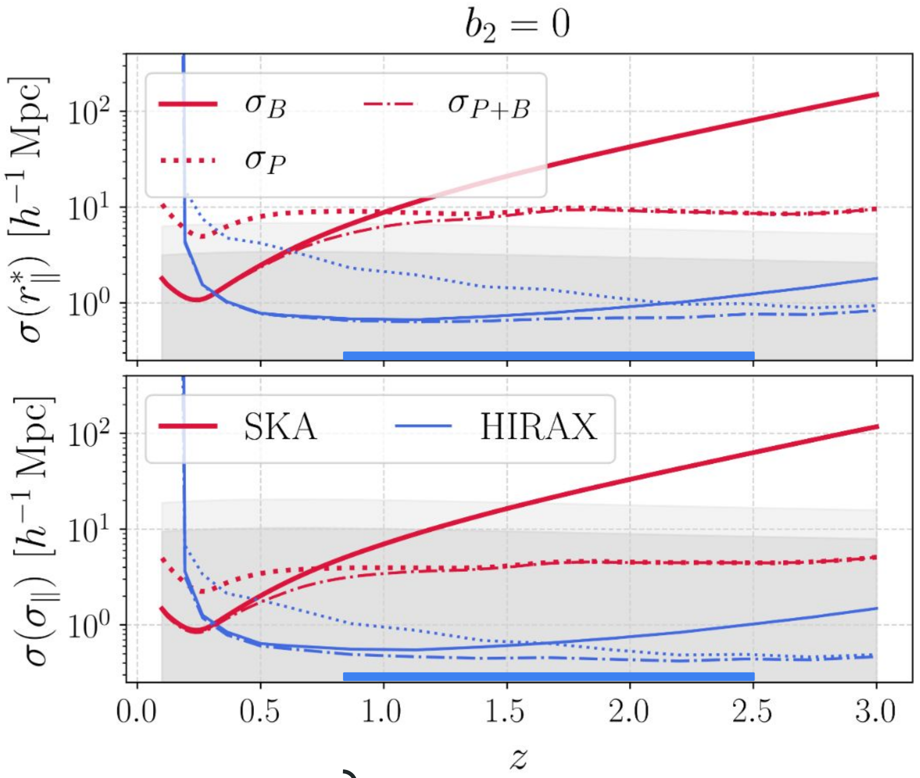
Intuition: behaviour with characteristic scales



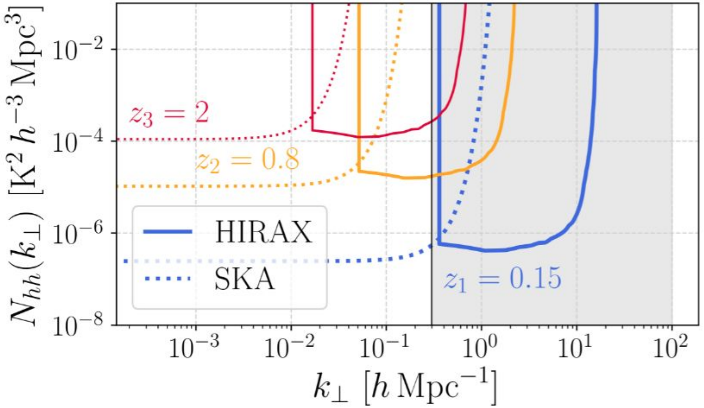
FAPESP 2018/10396-2

Forecast for Stage-IV surveys

(single-dish vs. interferometer)



$\sigma_{z,0} = 0.03,\ k_\parallel^{\mathrm{FG}} = 0.02\,h\,\mathrm{Mpc}^{-1},\ k_{\max} = 0.3\,h\,\mathrm{Mpc}^{-1}$



LSST Y1
LSST Y10
} requirements for 3x2 analyses

FAPESP 2018/10396-2

Forecast specifications

$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\, \delta_{xy}$$

$$B_{ghh}(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) = \bar{T}_h^2(z)\mathcal{S}_b(p_\perp, q_\perp)\mathcal{S}_{\rm FG}(p_\parallel, q_\parallel) \times \\ \left[b_{g,1}b_{h,1}^2 B(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) + b_{g,1}b_{h,1}b_{h,2}P(k)P(p) + b_{g,1}b_{h,2}b_{h,1}P(k)P(q) + b_{g,2}b_{h,1}^2 P(p)P(q)\right]$$

21-cm signal

$$\delta T_h(\boldsymbol{x}) \equiv \bar{T}_h(z)\delta_h(\boldsymbol{x}) \equiv \bar{T}_h(z)\left[b_{h,1}(z)\delta(\boldsymbol{x}) + \frac{b_{h,2}(z)}{2}\delta^2(\boldsymbol{x})\right]$$

$$b_h(z) = 1.307\left(0.66655 + 0.17765\, z + 0.050223\, z^2\right)$$

$$\bar{T}_h(z) = \left(0.055919 + 0.23242\, z - 0.024136\, z^2\right)\ [\mathrm{mK}]$$

FAPESP 2018/10396-2

Forecast specifications

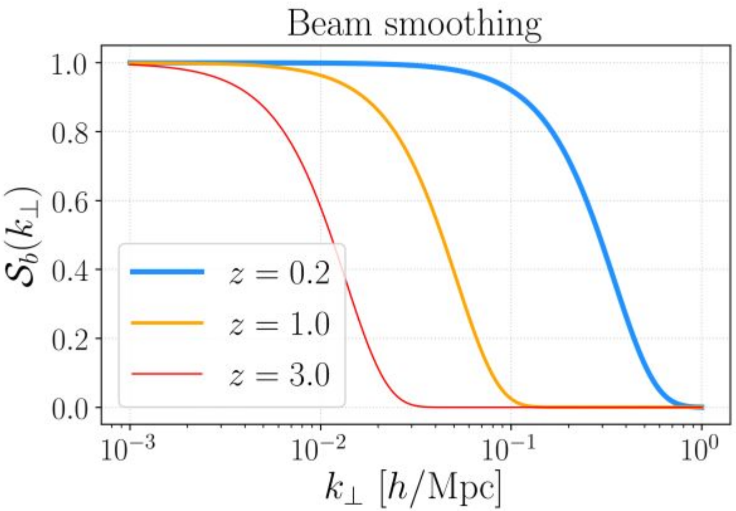
$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\, \delta_{xy}$$

$$B_{ghh}(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) = \bar{T}_h^2(z)\mathcal{S}_b(p_\perp, q_\perp)\mathcal{S}_{\rm FG}(p_\parallel, q_\parallel) \times \left[b_{g,1}b_{h,1}^2 B(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) + b_{g,1}b_{h,1}b_{h,2}P(k)P(p) + b_{g,1}b_{h,2}b_{h,1}P(k)P(q) + b_{g,2}b_{h,1}^2 P(p)P(q)\right]$$

FAPESP 2018/10396-2

Single dish (SKA-like survey)

$$\delta T_h^{\rm obs}(\boldsymbol{k}) = \boxed{\mathcal{S}_{\rm b}(k_\perp)}\,\mathcal{S}_{\rm FG}(k_\parallel)\, \delta T_h(\boldsymbol{k})$$



Forecast specifications

$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\, \delta_{xy}$$

$$B_{ghh}(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) = \bar{T}_h^2(z)\mathcal{S}_b(p_\perp, q_\perp)\mathcal{S}_{\rm FG}(p_\parallel, q_\parallel) \times \left[b_{g,1}b_{h,1}^2 B(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) + b_{g,1}b_{h,1}b_{h,2}P(k)P(p) + b_{g,1}b_{h,2}b_{h,1}P(k)P(q) + b_{g,2}b_{h,1}^2 P(p)P(q)\right]$$

FAPESP 2018/10396-2

Single dish (SKA-like survey)

$$\delta T_h^{\rm obs}(\boldsymbol{k}) = \mathcal{S}_{\rm b}(k_\perp)\, \mathcal{S}_{\rm FG}(k_\parallel)\, \delta T_h(\boldsymbol{k})$$

$$N_{hh} = \sigma_{\rm pix}^2\, V_{\rm pix}$$

$$\sigma_{\rm pix}^2 = T_{\rm sys}^2 \frac{1}{\Delta\nu\, t_{\rm tot}} \frac{\Omega_{\rm tot}}{\Omega_{\rm pix}} \frac{1}{N_{\rm dishes} N_{\rm beams}}$$

Pourtsidou, Bacon & Crittenden [1610.04189]

3 K 2.7 K

$$T_{\rm sys} = T_{\rm rx} + T_{\rm spill} + T_{\rm CMB} + T_{\rm gal}$$

$$T_{\rm gal} = 25 \left(\frac{408\ {\rm MHz}}{\nu}\right)^{2.75} {\rm K}$$

$$T_{\rm rx} = 15\,{\rm K} + 30\,{\rm K}\left(\frac{\nu}{\rm GHz} - 0.75\right)^2$$

Bacon et al. 2020

Forecast specifications

$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\, \delta_{xy}$$

$$B_{ghh}(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) = \bar{T}_h^2(z)\mathcal{S}_b(p_\perp, q_\perp)\mathcal{S}_{\rm FG}(p_\parallel, q_\parallel) \times$$
$$\left[b_{g,1}b_{h,1}^2 B(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) + b_{g,1}b_{h,1}b_{h,2}P(k)P(p) + b_{g,1}b_{h,2}b_{h,1}P(k)P(q) + b_{g,2}b_{h,1}^2 P(p)P(q)\right]$$

FAPESP 2018/10396-2

Single dish (SKA-like survey)

$$\delta T_h^{\rm obs}(\boldsymbol{k}) = \mathcal{S}_{\rm b}(k_\perp)\, \mathcal{S}_{\rm FG}(k_\parallel)\, \delta T_h(\boldsymbol{k})$$

$$N_{hh} = \sigma_{\rm pix}^2\, V_{\rm pix}$$

$$\sigma_{\rm pix}^2 = T_{\rm sys}^2 \frac{1}{\Delta\nu\, t_{\rm tot}} \frac{\Omega_{\rm tot}}{\Omega_{\rm pix}} \frac{1}{N_{\rm dishes} N_{\rm beams}}$$

Pourtsidou, Bacon & Crittenden [1610.04189]

SKA1-MID: **133 dishes** with **15 m** in diameter. While it is required Bands 1 and 2 to fully observe the redshift range 0 < z < 3 [Santos et al. 1501.03989], for simplicity we fixed **Band 1 specifications**: sky coverage of **20000 deg²**, frequency resolution of **15.2 kHz**, and integration time of **10000 hours** [SKASWG: Bacon et al. 2019].

Forecast specifications

$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\, \delta_{xy}$$

$$B_{ghh}(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) = \bar{T}_h^2(z)\mathcal{S}_b(p_\perp, q_\perp)\mathcal{S}_{\rm FG}(p_\parallel, q_\parallel) \times \left[b_{g,1}b_{h,1}^2 B(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) + b_{g,1}b_{h,1}b_{h,2}P(k)P(p) + b_{g,1}b_{h,2}b_{h,1}P(k)P(q) + b_{g,2}b_{h,1}^2 P(p)P(q)\right]$$

Interferometer (HIRAX-like survey)

$$\delta T_h^{\rm obs}(\boldsymbol{k}) = \mathcal{S}_{\rm FG}(k_\parallel)\,\delta T_h(\boldsymbol{k})$$

$$N_{hh}(k_\perp) = \frac{4\pi f_{\rm sky}\,\chi^2(z)\,(1+z)\,T_{\rm sys}^2\,\theta_{\rm FWHM}^2}{H(z)\,t_{\rm tot}\,\lambda_{21}(z)\,N_d(\boldsymbol{d} = \boldsymbol{k}_\perp\,\chi(z)\,\lambda_{21}(z)/2\pi)}$$

$$T_{\rm sys} = 50\,{\rm K} + 60\left[\frac{\nu_{21}(z)}{300\,{\rm MHz}}\right]^{-2.5}\,{\rm K}$$

e.g. Alonso et al. [1704.01941]

Forecast specifications

$$P_{xy}(k) = \mathcal{K}_{xy}\, P_{\rm nl}(k) + N_{xy}\,\delta_{xy}$$

$$B_{ghh}(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) = \bar{T}_h^2(z)\mathcal{S}_b(p_\perp,q_\perp)\mathcal{S}_{\rm FG}(p_\parallel,q_\parallel)\times \left[b_{g,1}b_{h,1}^2 B(\boldsymbol{k},\boldsymbol{p},\boldsymbol{q}) + b_{g,1}b_{h,1}b_{h,2}P(k)P(p) + b_{g,1}b_{h,2}b_{h,1}P(k)P(q) + b_{g,2}b_{h,1}^2 P(p)P(q)\right]$$

FAPESP 2018/10396-2

Galaxy survey (LSST-like)

$$N_{gg} = \frac{1}{\bar{n}_g}$$

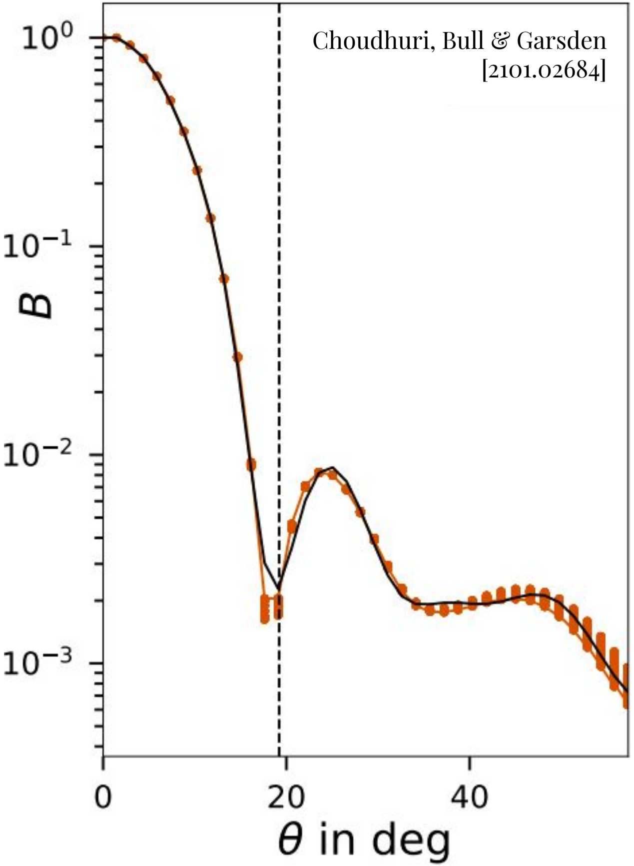
$$n_g(z) = A\, z^\alpha\, \exp\left[-\left(\frac{z}{z_0}\right)^\beta\right]$$

$$b_{g,1}(z) = 0.95\, D^{-1}(z)$$

$\Omega_{\rm sky}$ (deg^2)	$n_{\rm sources}$	$z_{\rm min}$	$z_{\rm max}$	z_0	α	β
13800	48	0.2	3	2	0.9	0.28

e.g. Ballardini, Matthewson & Maartens [1906.04730]

Horizon and primary-beam wedges



Primary-beam wedge

$$V_{ij}^{\text{true}}(\nu) = \int_\Omega B_{ij}(\boldsymbol{\theta}, \nu) I(\boldsymbol{\theta}, \nu) e^{2\pi i \mathbf{u}_{ij} \cdot \boldsymbol{\theta}} d^2\Omega$$

Horizon wedge

Impact of horizon wedge

$$k_{\parallel} < k_{\parallel}^{\rm hor} \equiv \frac{\chi(z)\, H(z)}{c\,(1+z)} k_{\perp}$$