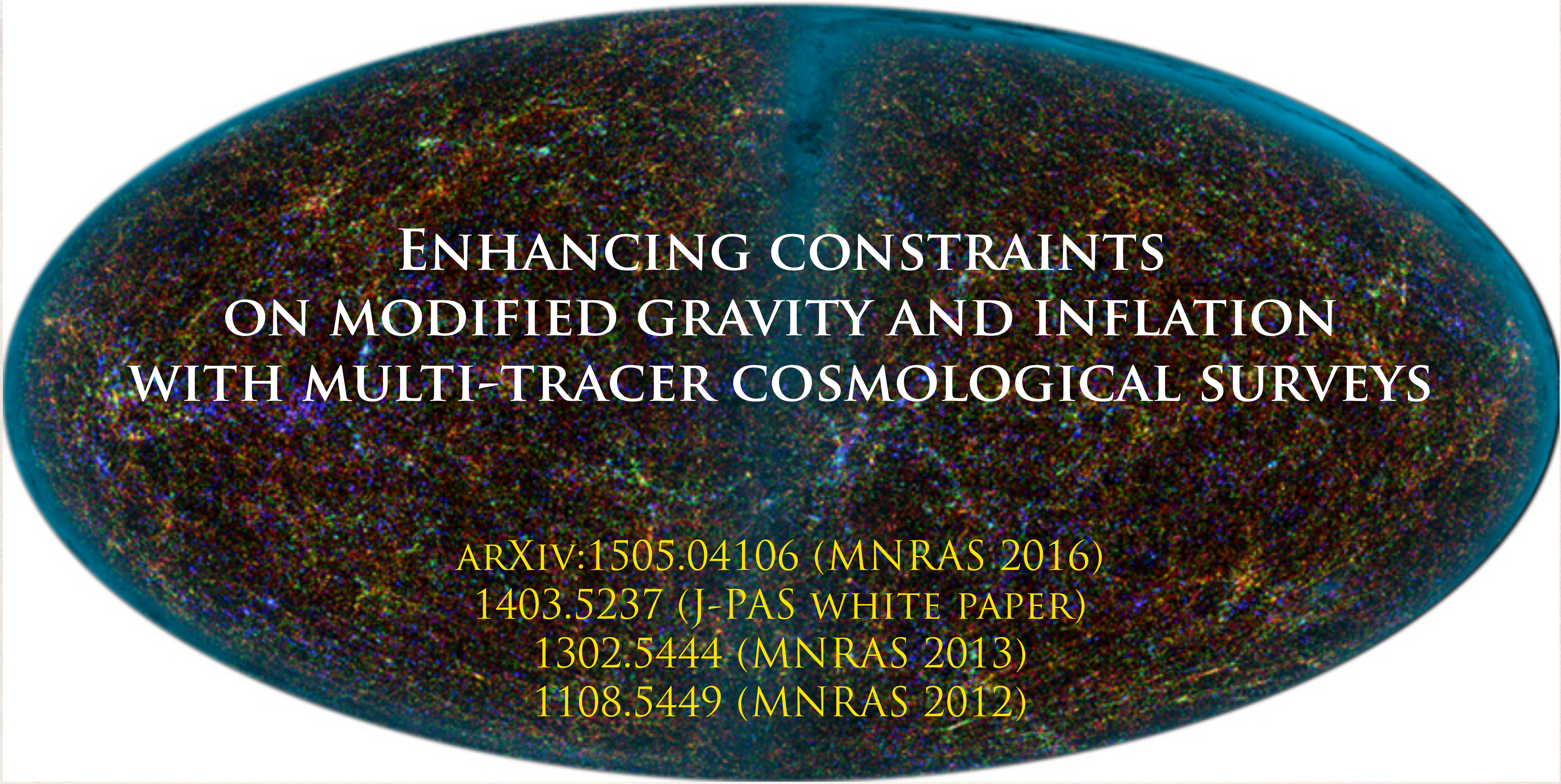


Enhancing constraints on modified gravity and inflation with multi-tracer cosmological surveys

arXiv:1505.04106 (MNRAS 2016)
1403.5237 (J-PAS white paper)
1302.5444 (MNRAS 2013)
1108.5449 (MNRAS 2012)

L. Raul Abramo

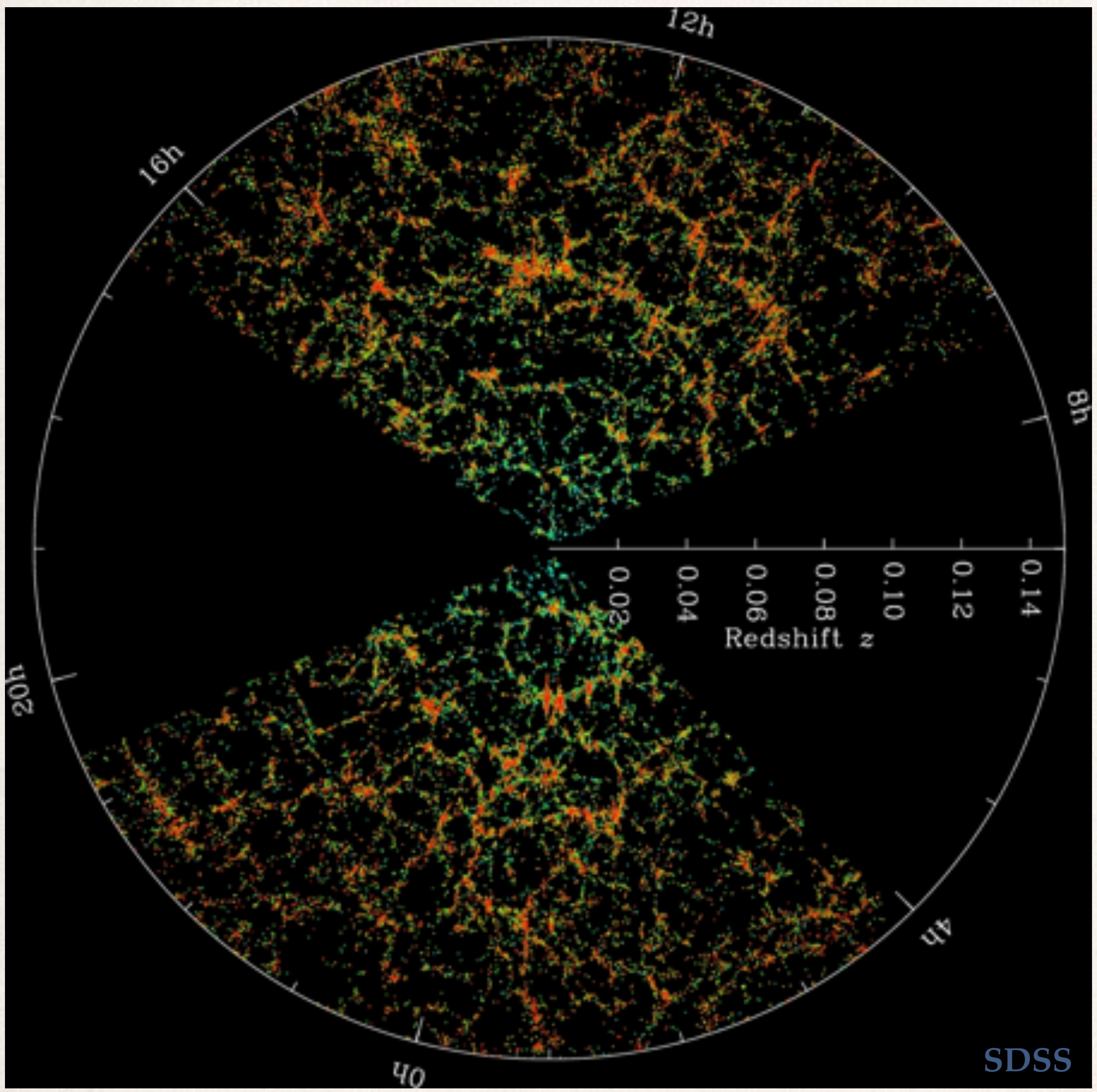
Instituto de Fisica & LabCosmos

Universidade de São Paulo

LABCOSMOS
http://www.iag.usp.br/labcosmos/en/

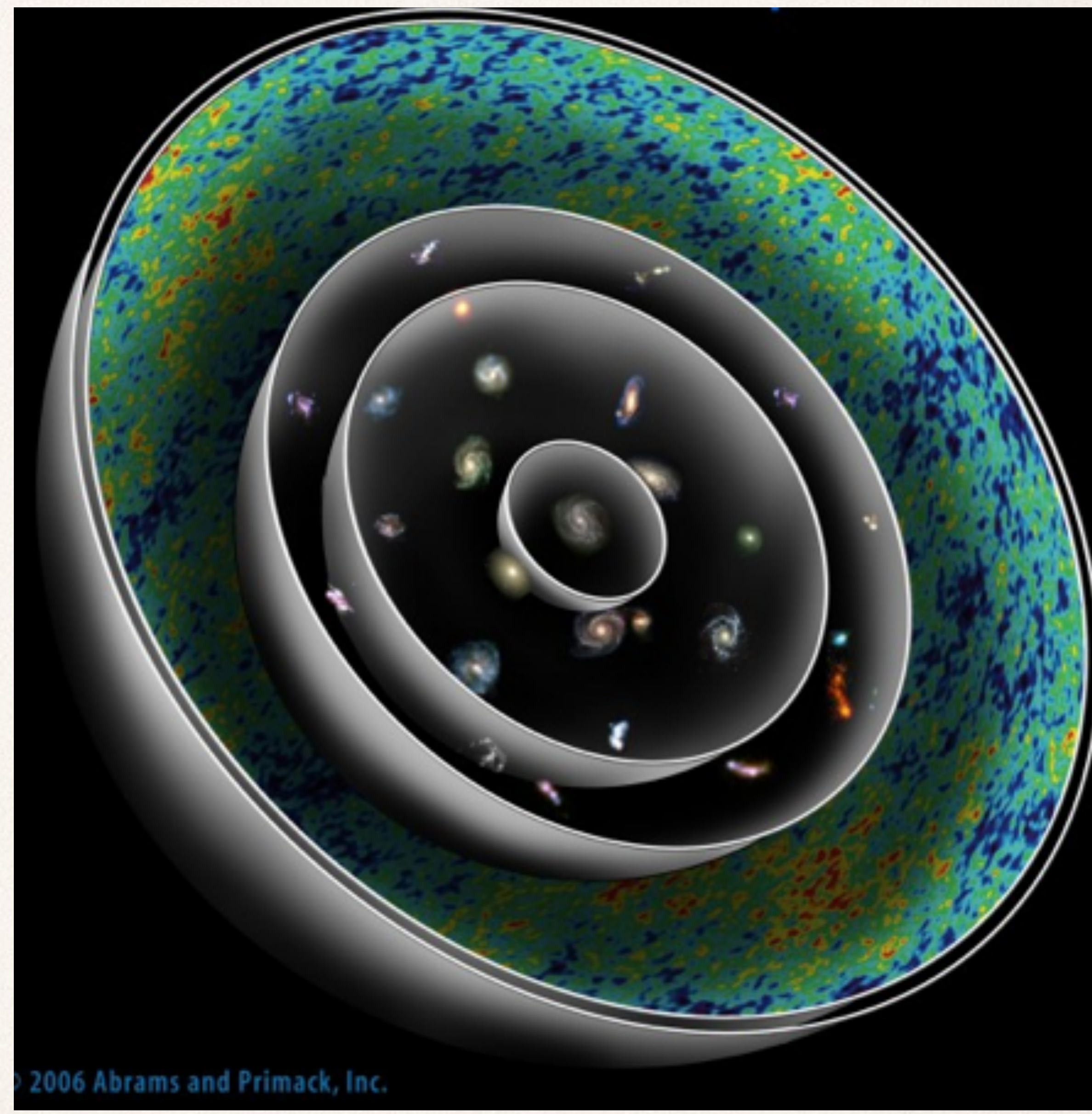
Galaxy surveys are evolving

We used to live in an
era of shot ("counts") noise



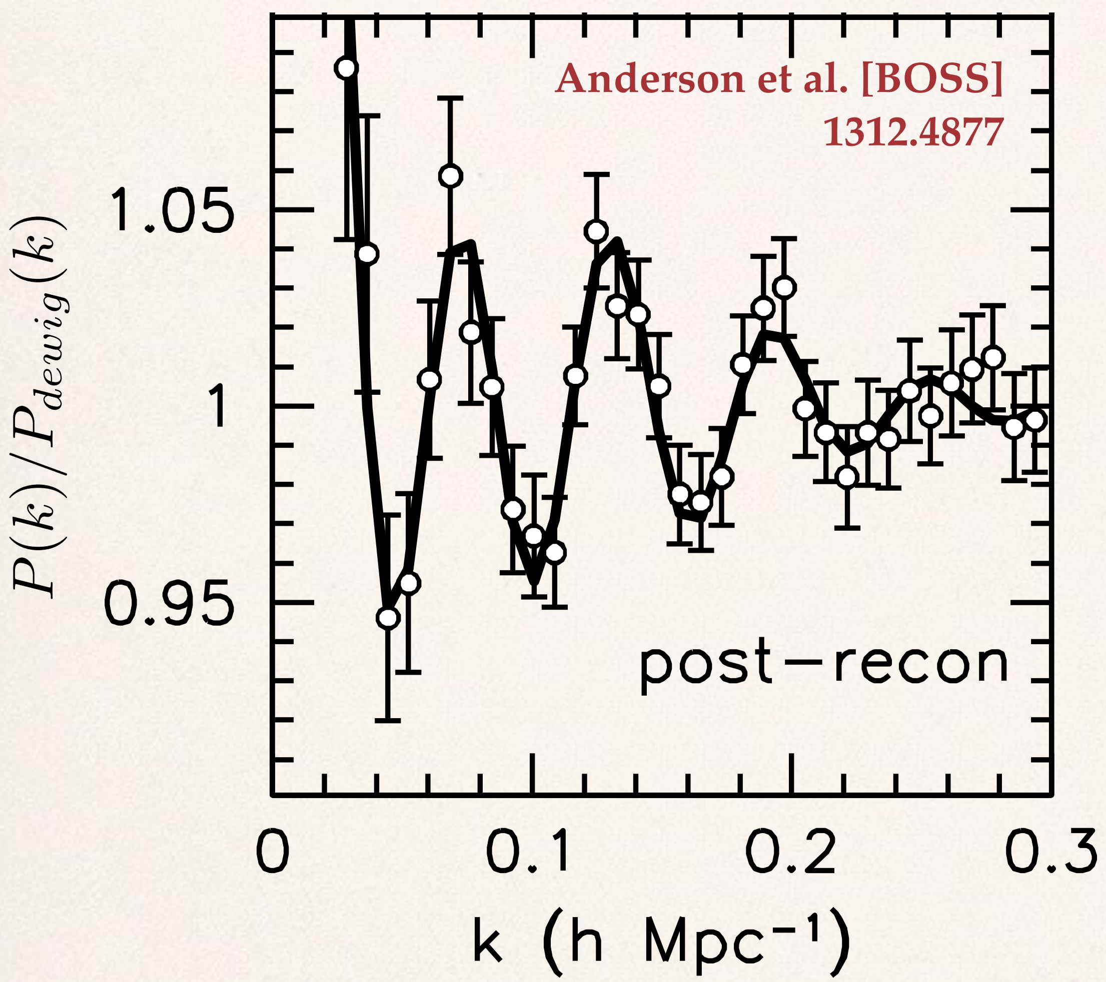
[**Finding galaxies** was the limiting factor]

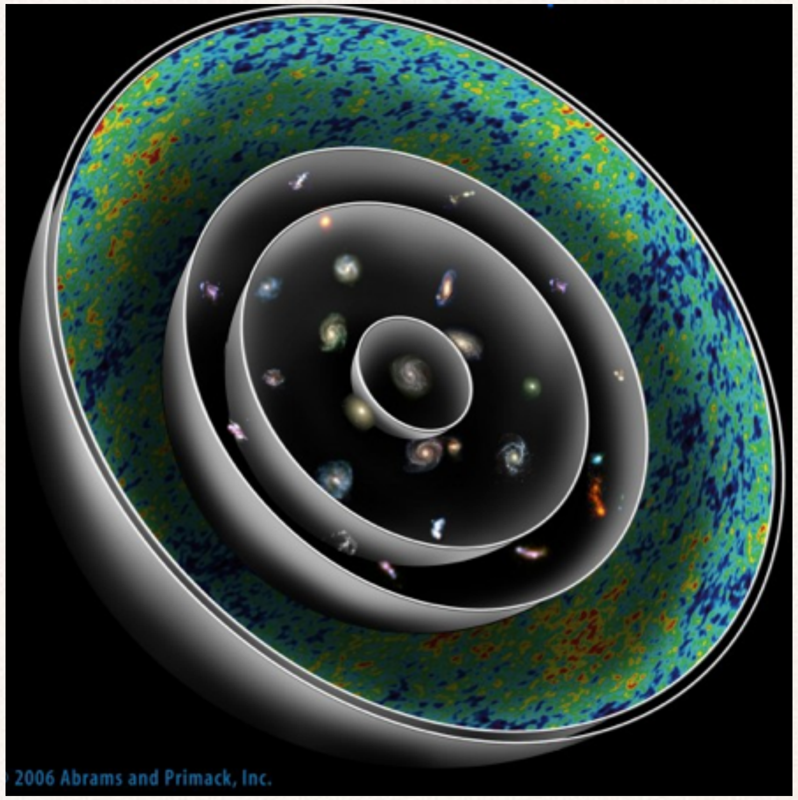
We are now in the **age of**
cosmic variance and systematics



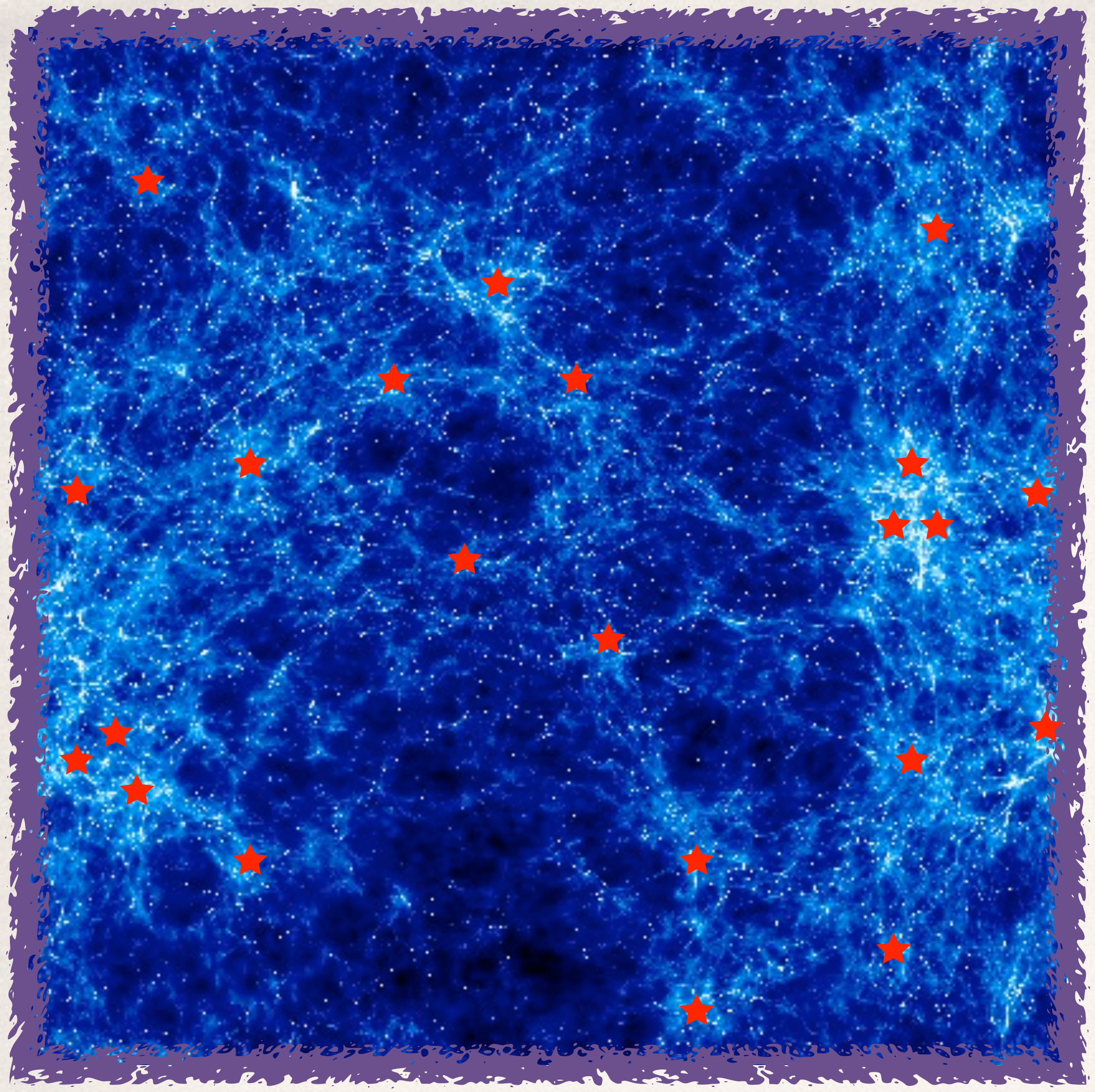
[**Volume and control** are the limiting factors]

Surveys of large-scale structure are now limited by **cosmic variance and systematics**





However, up to any given redshift there is only a finite volume.
Moreover, we are reaching closer to the limits of the observable Universe!



Shot noise:

finite number of **counts** of the tracers of the underlying density field (Poisson statistics)

Cosmic variance:

finite **volume** inside which we can estimate the **amplitudes and phases** of the (Gaussian) random **modes** of the density field

$$P_g(\vec{k}) \simeq b_g^2 \, P_m(\vec{k}) + \frac{1}{\bar{n}_g}$$

Clustering in units of shot noise

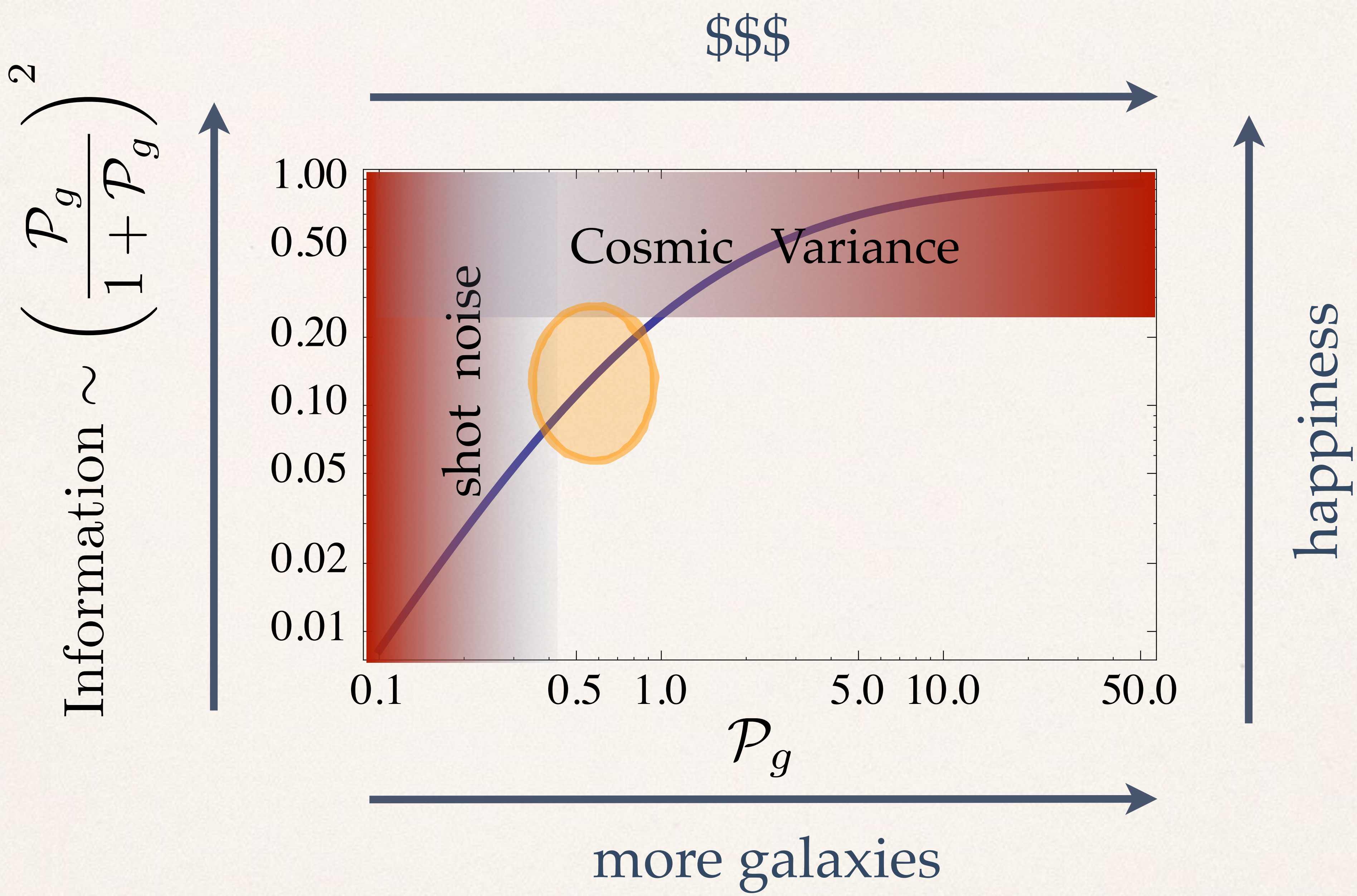
$$\boxed{\bar{n}_g \, P_g(\vec{k}) \simeq \bar{n}_g \, b_g^2 \, P_m(\vec{k}) + 1}$$

SNR

noise

Feldman, Kaiser & Peacock 1994 (**FKP**)
Tegmark et al. 1997, 1998

Fisher information of galaxy surveys



Signal/Noise:
Clustering strength
of galaxy type "*g*" in redshift space

$$\mathcal{P}_g(\vec{x},\vec{k}) \equiv \bar{n}_g(\vec{x}) \left[b_g(z,k) + f(z)\,\mu_k^2\right]^2 G^2(z)\, P_m(k)$$

FKP 1994
Hamilton 2005
R. A. 2012

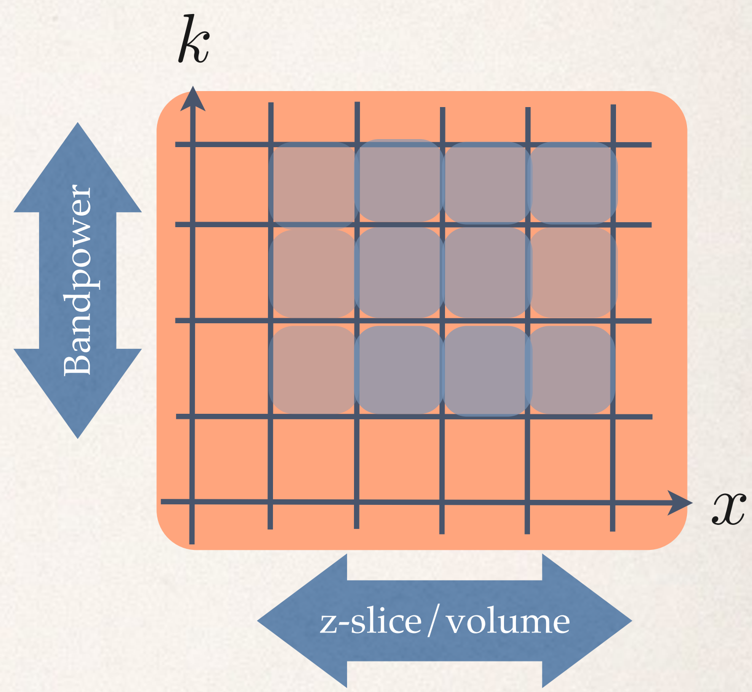
Fisher information in phase space

On each **unit volume** of **phase space** there is a certain **amount of information** about the clustering strength:

$$F[\log \mathcal{P}_g] \times \frac{\Delta V_x \, \Delta V_k}{(2\pi)^3} = \frac{1}{2}\left(\frac{\mathcal{P}_g}{1+\mathcal{P}_g}\right)^2 \times \frac{\Delta V_x \, \Delta V_k}{(2\pi)^3}$$

Fisher information / (phase space volume)

phase space **volume =** $\Delta \mathcal{V}$.

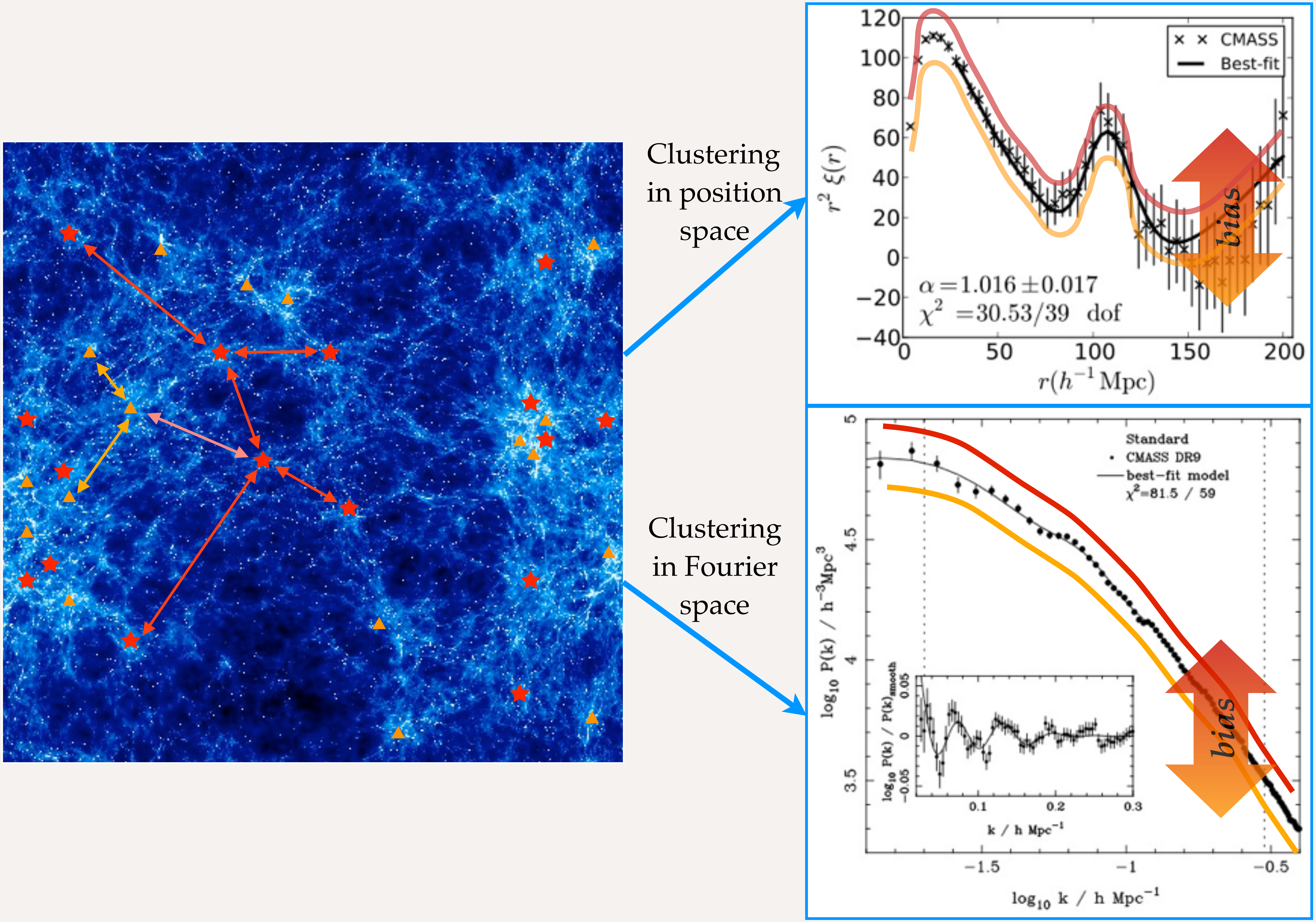


The **precision** (SNR) with which we can **estimate the clustering strength** is:

$$\frac{\mathcal{P}_g^2}{\sigma^2(\mathcal{P}_g)} = F[\log \mathcal{P}_g] \times \Delta \mathcal{V} = \frac{1}{2}\left(\frac{\mathcal{P}_g}{1+\mathcal{P}_g}\right)^2 \Delta \mathcal{V}$$

$$F = \frac{1}{2}\left(\frac{\text{signal}}{\text{signal} + \text{noise}}\right)^2 \leq \frac{1}{2}$$

The Universe has **many different types** of galaxies, halos, etc…



Multi-tracer Fisher information matrix

R.A. 2012
R.A. & Katie Leonard 2013

Let's say we have **several** (α = 1,2, ... *N*) **different types of tracers** of large-scale structure. E.g. : α=1=LRGs , α=2=ELGs , α=3=quasars , etc.

$$\mathcal{P}_\alpha(k,\mu_k;z) = n_\alpha(z)\ \left[b_\alpha(z) + f(z)\,\mu_k^2\right]^2\ P(k;z) \qquad \mu_k = \frac{k_{||}}{k}$$

The **Fisher matrix** for the N clustering strengths (power spectra) is:

$$F_{\alpha\,\beta} = F(\log\mathcal{P}_\alpha, \log\mathcal{P}_\beta) = \frac{1}{4}\left[\delta_{\alpha\beta}\frac{\mathcal{P}_\alpha\,\mathcal{P}}{1+\mathcal{P}} + \frac{\mathcal{P}_\alpha\,\mathcal{P}_\beta\,(1-\mathcal{P})}{(1+\mathcal{P})^2}\right] \quad , \quad \mathcal{P} = \sum_\alpha \mathcal{P}_\alpha$$

Multi-tracer Fisher information

Multi-tracer technique:
Seljak 2008
McDonald & Seljak 2008
Gil-Marín et al. 2011
Hamaus et al. 2011,2012
Cai & Bernstein 2011

Fisher matrix:
R.A. 2012
R.A. & K. Leonard 2013

$$F[\log \mathcal{P}_\alpha, \log \mathcal{P}_\beta] = \frac{1}{4}\left[\frac{\mathcal{P}_\alpha \mathcal{P}_\beta (1-\mathcal{P})}{(1+\mathcal{P})^2} + \delta_{\alpha\beta}\frac{\mathcal{P}_\alpha \mathcal{P}}{1+\mathcal{P}}\right]$$

1 tracer $F = \frac{1}{2}\left(\frac{\mathcal{P}}{1+\mathcal{P}}\right)^2$

2 tracers $\Longrightarrow \frac{1}{4}\begin{pmatrix} \frac{\mathcal{P}_1^2(1-\mathcal{P})}{(1+\mathcal{P})^2} + \frac{\mathcal{P}_1\mathcal{P}}{1+\mathcal{P}} & \frac{\mathcal{P}_1\mathcal{P}_2(1-\mathcal{P})}{(1+\mathcal{P})^2} \\ \frac{\mathcal{P}_1\mathcal{P}_2(1-\mathcal{P})}{(1+\mathcal{P})^2} & \frac{\mathcal{P}_2^2(1-\mathcal{P})}{(1+\mathcal{P})^2} + \frac{\mathcal{P}_2\mathcal{P}}{1+\mathcal{P}} \end{pmatrix}$

3 tracers $\Longrightarrow \frac{1}{4}\begin{pmatrix} \frac{\mathcal{P}_1^2(1-\mathcal{P})}{(1+\mathcal{P})^2} + \frac{\mathcal{P}_1\mathcal{P}}{1+\mathcal{P}} & \frac{\mathcal{P}_1\mathcal{P}_2(1-\mathcal{P})}{(1+\mathcal{P})^2} & \frac{\mathcal{P}_1\mathcal{P}_3(1-\mathcal{P})}{(1+\mathcal{P})^2} \\ \frac{\mathcal{P}_1\mathcal{P}_2(1-\mathcal{P})}{(1+\mathcal{P})^2} & \frac{\mathcal{P}_2^2(1-\mathcal{P})}{(1+\mathcal{P})^2} + \frac{\mathcal{P}_2\mathcal{P}}{1+\mathcal{P}} & \frac{\mathcal{P}_2\mathcal{P}_3(1-\mathcal{P})}{(1+\mathcal{P})^2} \\ \frac{\mathcal{P}_1\mathcal{P}_3(1-\mathcal{P})}{(1+\mathcal{P})^2} & \frac{\mathcal{P}_2\mathcal{P}_3(1-\mathcal{P})}{(1+\mathcal{P})^2} & \frac{\mathcal{P}_3^2(1-\mathcal{P})}{(1+\mathcal{P})^2} + \frac{\mathcal{P}_3\mathcal{P}}{1+\mathcal{P}} \end{pmatrix}$

OK… but are we in fact **gaining** any information by **splitting galaxies** into **types**, or are we just "shuffling around" the information**?**

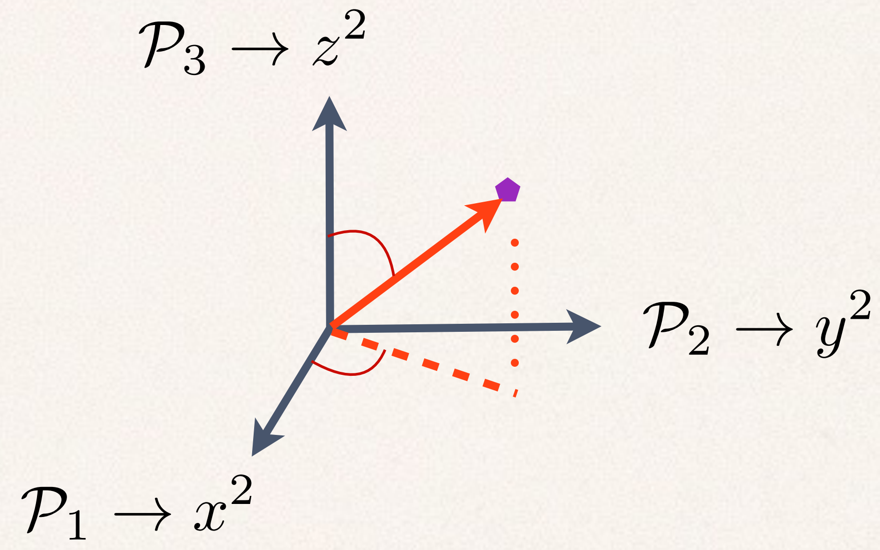
Multi-tracer Fisher information

Yes, we **gain** information

> In fact, with **multiple tracers** the Fisher information is **unbounded**!

We can **diagonalize** the multi-tracer Fisher matrix by changing variables:

$\Rightarrow$ (hyper) **spherical coordinates!**



$$\begin{Bmatrix} \mathcal{P}_1 \\ \mathcal{P}_2 \\ \mathcal{P}_3 \end{Bmatrix} = \begin{Bmatrix} x^2 \\ y^2 \\ z^2 \end{Bmatrix} \iff \begin{Bmatrix} r^2 \\ \tan^2\theta \\ \tan^2\phi \end{Bmatrix} = \begin{Bmatrix} \mathcal{P} \\ \frac{\mathcal{P}_3}{\mathcal{P}_1+\mathcal{P}_2} \\ \frac{\mathcal{P}_2}{\mathcal{P}_1} \end{Bmatrix}$$

Total clustering strength

Relative clustering strengths

Multi-tracer Fisher information matrix

In “spherical" coordinates (i.e., using the total clustering strength and the relative clustering strengths) the **Fisher matrix becomes diagonal**!

E.g.: three species of tracers

Total clustering:
< 1/2

$$F_{Sph} = \left\{ \begin{array}{ccc} \boxed{\frac{1}{2}\left(\frac{\mathcal{P}}{1+\mathcal{P}}\right)^2} & 0 & 0 \\ 0 & \boxed{\frac{1}{4}\frac{\mathcal{P}^2}{1+\mathcal{P}}\sin^2\theta\cos^2\theta} & 0 \\ 0 & 0 & \boxed{\frac{1}{4}\frac{\mathcal{P}^2}{1+\mathcal{P}}\sin^2\theta\sin^2\phi\cos^2\phi} \end{array} \right\}$$

Relative clusterings: information ~ $\mathcal{P} = \sum_\alpha \bar{n}_\alpha b_\alpha^2 P_m$
- ☛ **unbounded**
- ☛ **extra information!**

Seljak 2008
McDonald & Seljak 2008

Why?

Cosmic variance is only inherited through the **spectrum**

By **comparing** the clustering between **different tracers** of large-scale structure (e.g.: LRGs, ELGs, etc.), we can **measure with arbitrary accuracy*** the physical parameters that distinguish the different **clustering strengths**:

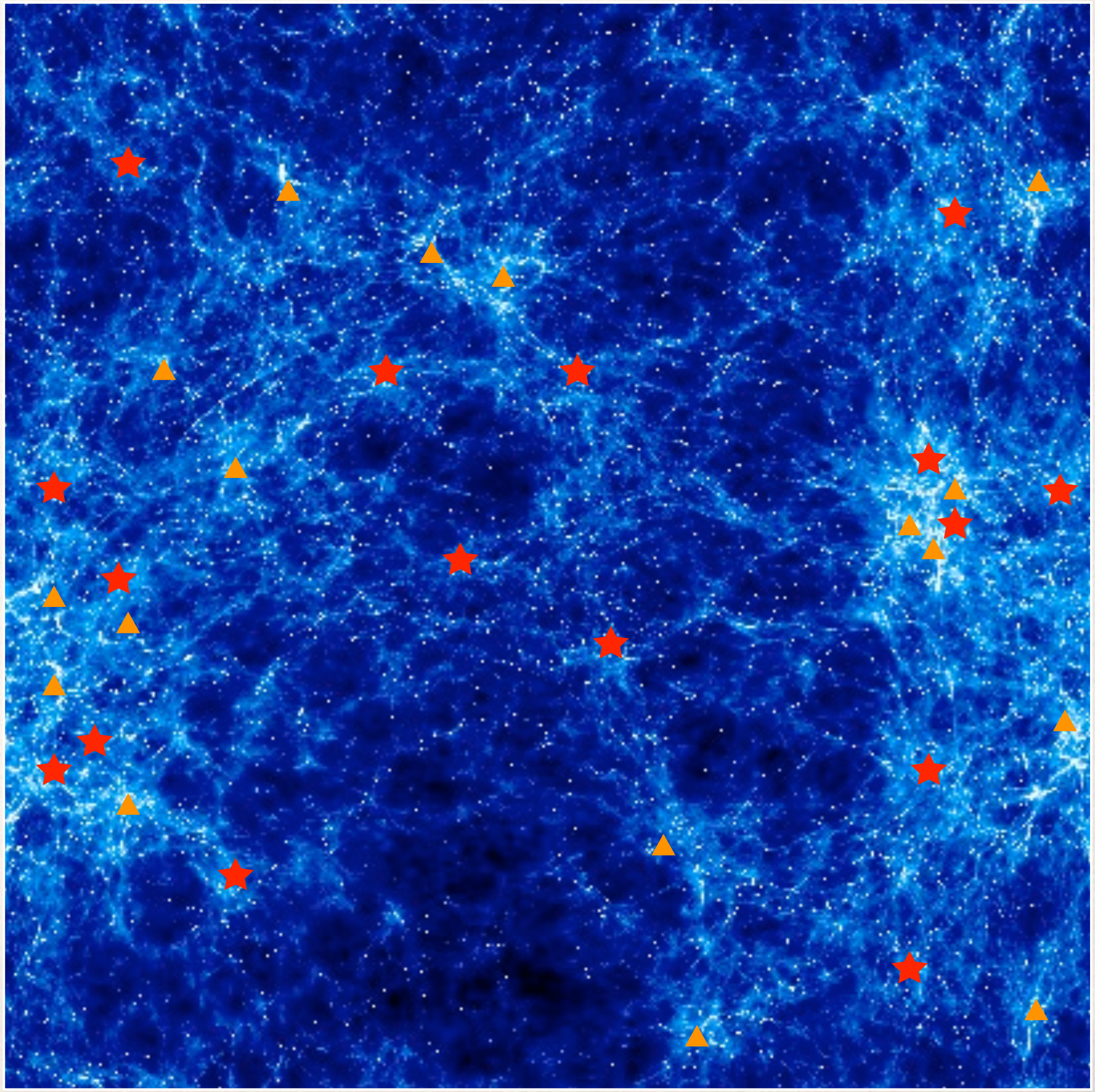
$$\mathcal{P}_1 = n_1\,(b_1 + f\,\mu_k^2)^2\,P(k;z)$$

$$\mathcal{P}_2 = n_2\,(b_2 + f\,\mu_k^2)^2\,P(k;z)$$

$$\frac{\mathcal{P}_1}{\mathcal{P}_2} = \frac{n_1\,(b_1 + f\,\mu_k^2)^2}{n_2\,(b_2 + f\,\mu_k^2)^2}$$

Cosmic variance does **not** apply:
- ***bias *RSDs**
- ***PNGs *HOD**

The key: **high number densities** of distinct types of tracers (red galaxies, blue galaxies, emission-line galaxies, quasars, etc.)



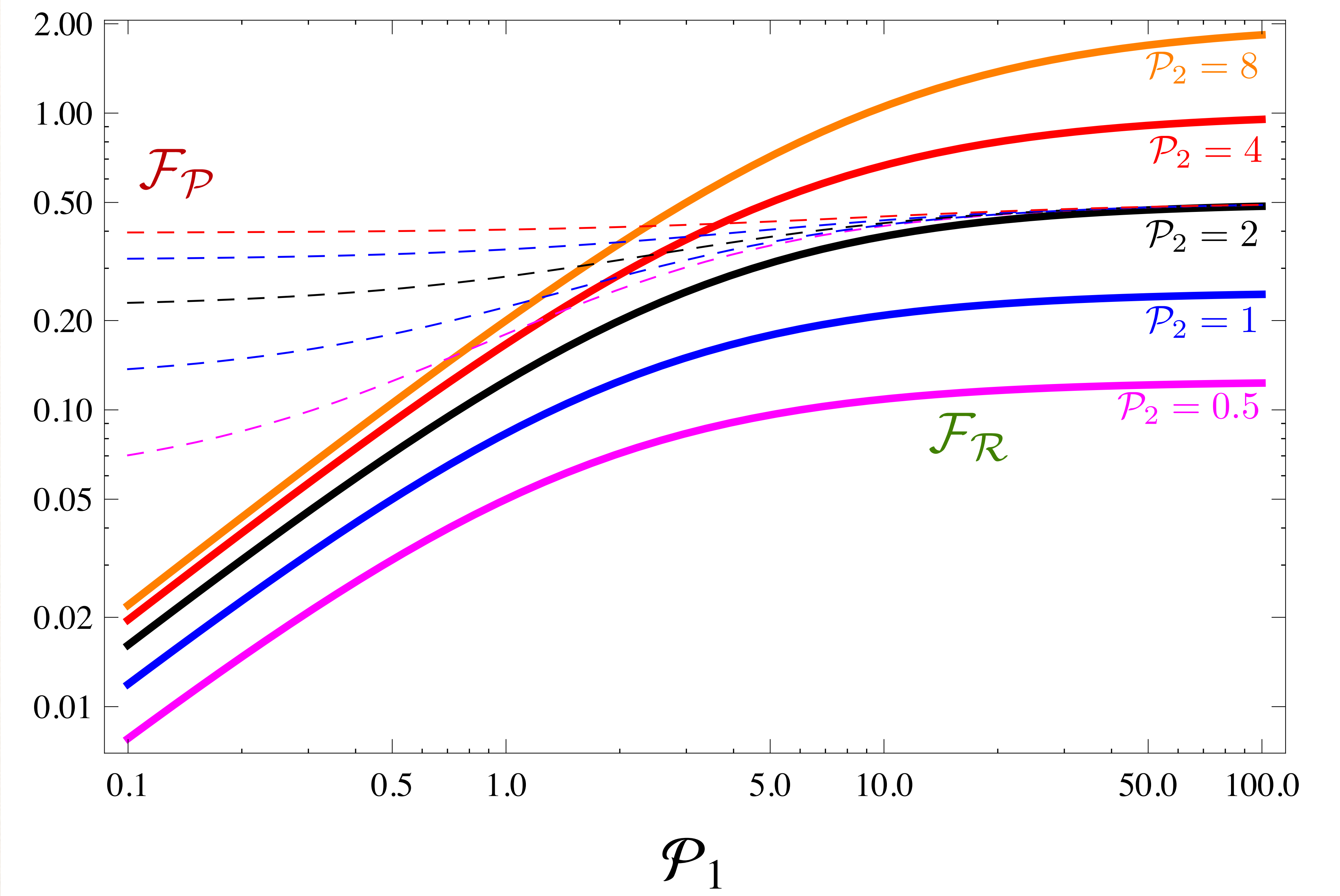
Simplest example:
<u>two</u> types of tracers of large-scale structure

Total clustering

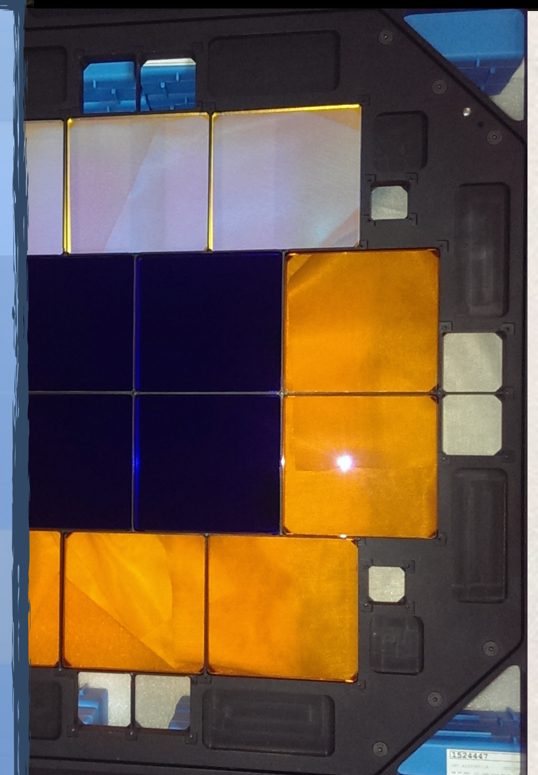
$$\mathcal{F}_\mathcal{P} = \frac{\mathcal{P}^2}{\sigma^2(\mathcal{P})} = \frac{1}{2}\frac{\mathcal{P}^2}{(1+\mathcal{P})^2}$$

Relative clustering

$$\mathcal{F}_\mathcal{R} = \frac{(\mathcal{P}_2/\mathcal{P}_1)^2}{\sigma^2(\mathcal{P}_2/\mathcal{P}_1)} = \frac{1}{4}\frac{\mathcal{P}_1\,\mathcal{P}_2}{1+\mathcal{P}}$$



Where the hell are we going to get all those galaxies — with decent redshifts??



J-PAS

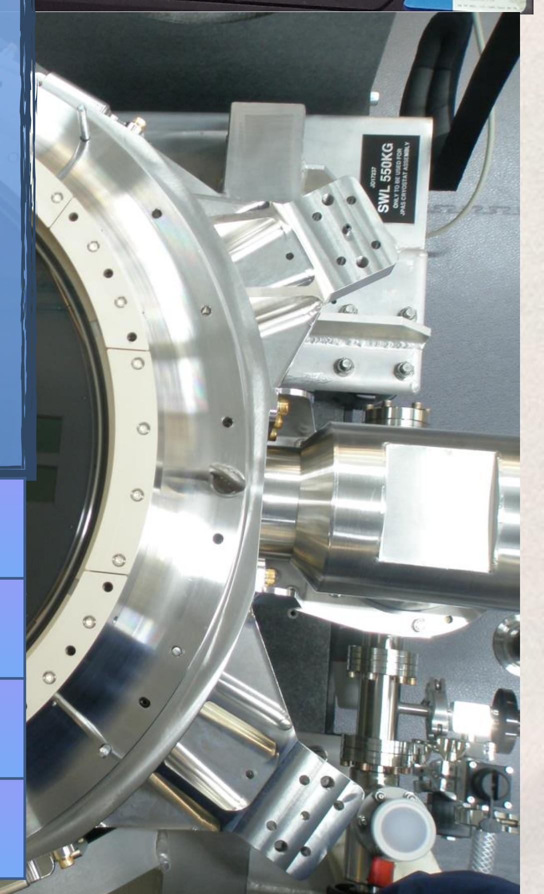
- 1/5 of full sky (8500 deg^2)
- ~3 mags > SDSS
- $\sigma_z \sim 0.003(1+z)$

survey starts in

Q1 2017 !

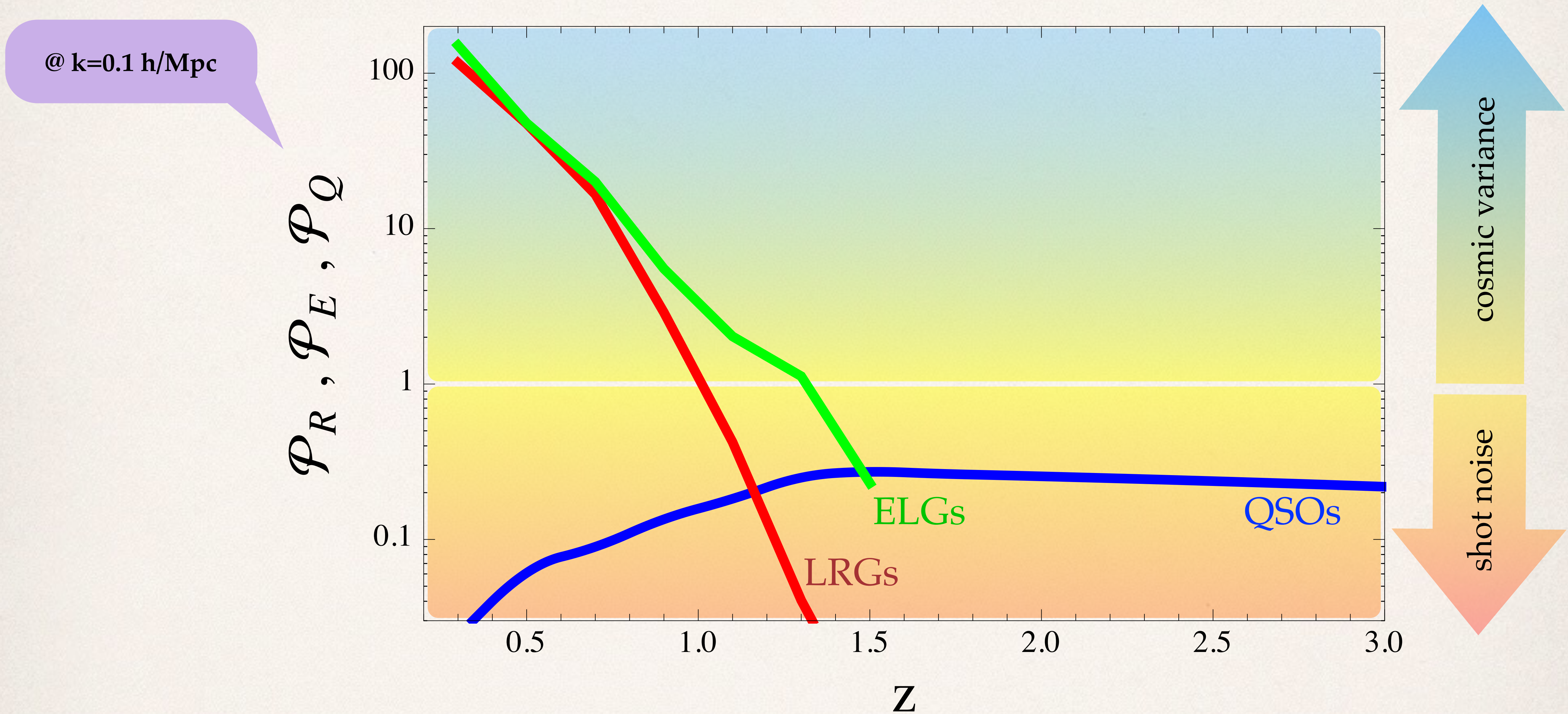
Benítez et al., 1403.5237

Benítez et al. 2016 (to appear)



2017	2018	2019	2020	2021	2022	2023
J-PAS	J-PAS	J-PAS	J-PAS[1]	J-PAS	J-PAS[2]	
		DESI (?)	DESI	DESI	DESI	
			Euclid	Euclid	Euclid	Euclid

Massive & deep multi-tracer survey with J-PAS



* GAMA - Blake et al., MNRAS 2013 : $\mathcal{P}_1$ >10 for z<0.25

* Radio galaxies & SKA - Ferramacho et al. 2014, Camera et al. 2015, …

* 21cm intensity mapping - Bull, Ferreira, Patel & Santos 2015

* SKA + optical surveys - Fonseca, Camera, Santos & Maartens 2015

* DESI, Euclid…

R.A. & Leonard 2013
Benítez et al. 2014

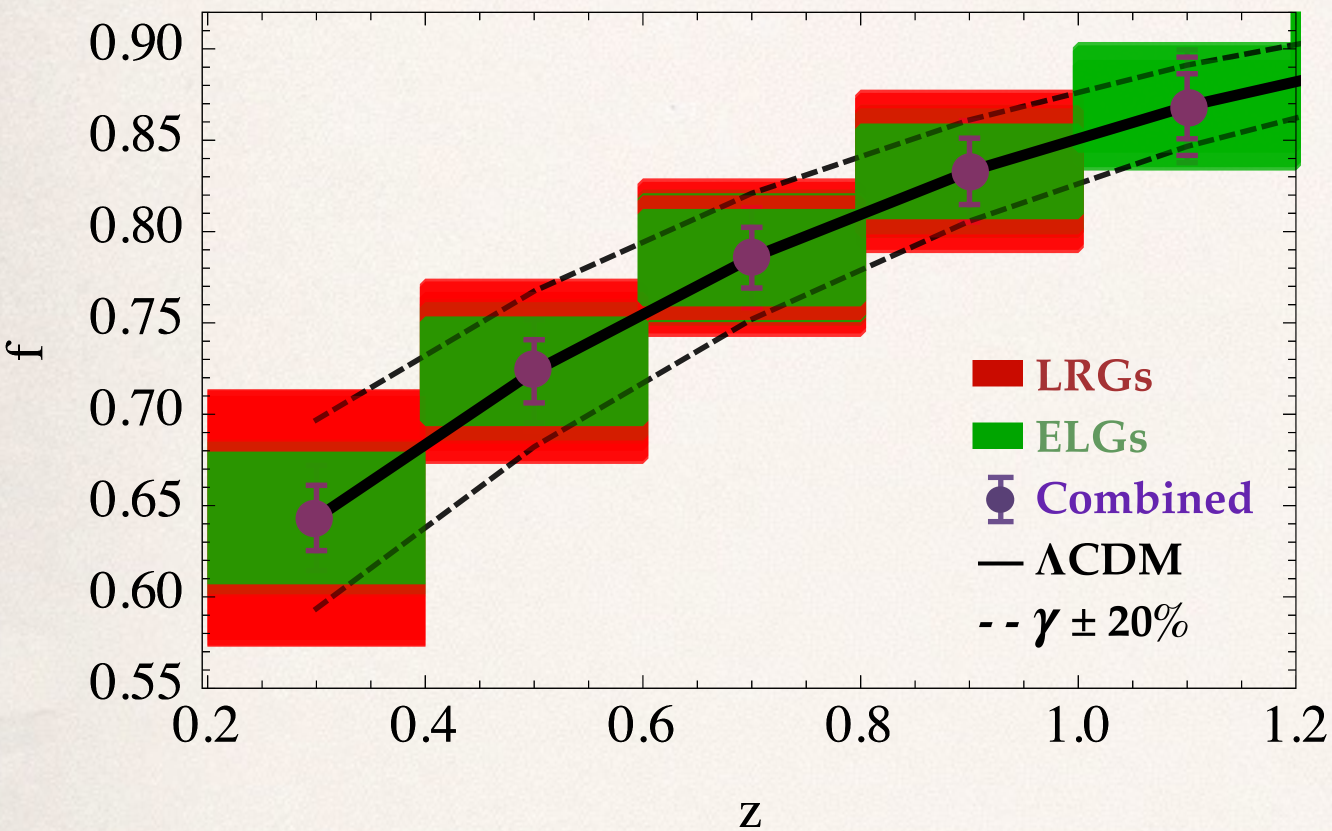
Application: RSDs in J-PAS

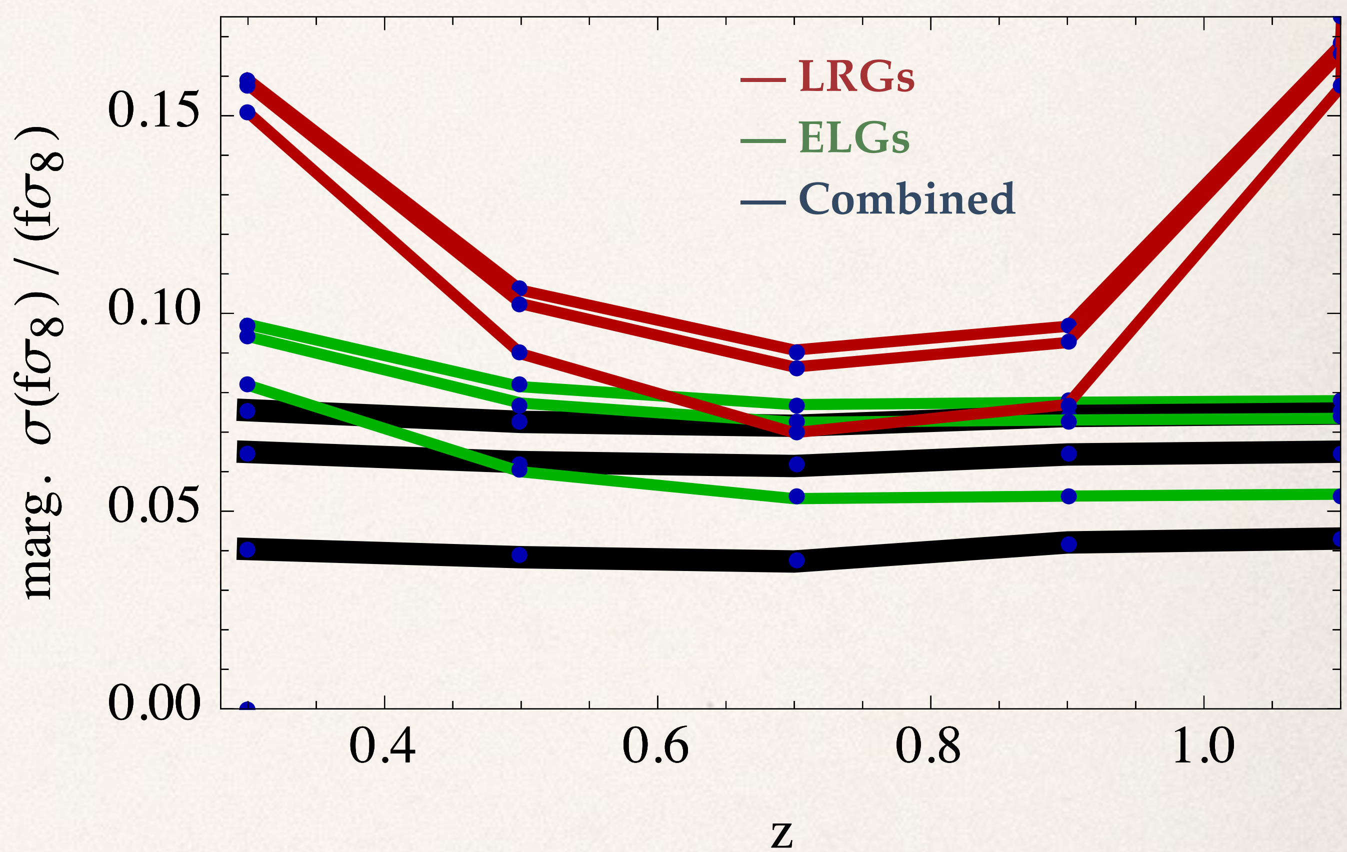
Marginalized* errors on matter growth rate

$$\mathcal{P}_g = n_g \left(b_g + f \mu_k^2\right)^2 P(k;z)$$

$$f = \frac{d \ln G}{d \ln a} \simeq \Omega_m^{\gamma}$$

~modified gravity
($\gamma_{GR} \cong 0.55$)





J-PAS forecast for constraint on γ:

$\sigma(\gamma)=0.025$

No prior on bias

Weak (~20%) prior on bias

Strong (~5%) prior on bias

* Marginalized 7 "global" cosmological parameters ($\boldsymbol{\Omega}_{\rm m}$, h, etc.) + 5 parameters on ***each*** redshift slice

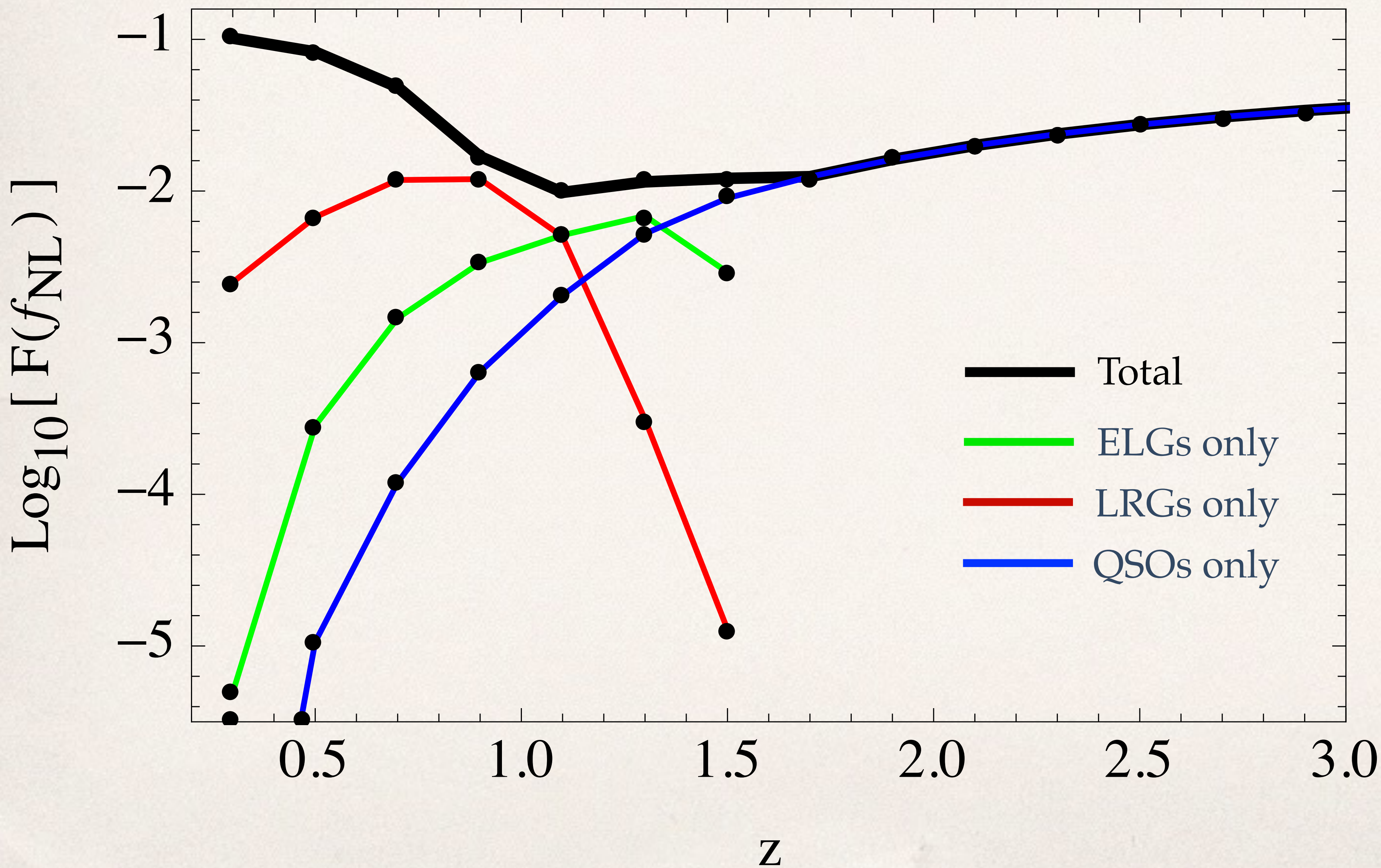
R.A. & Leonard 2013
Benítez et al. 2014

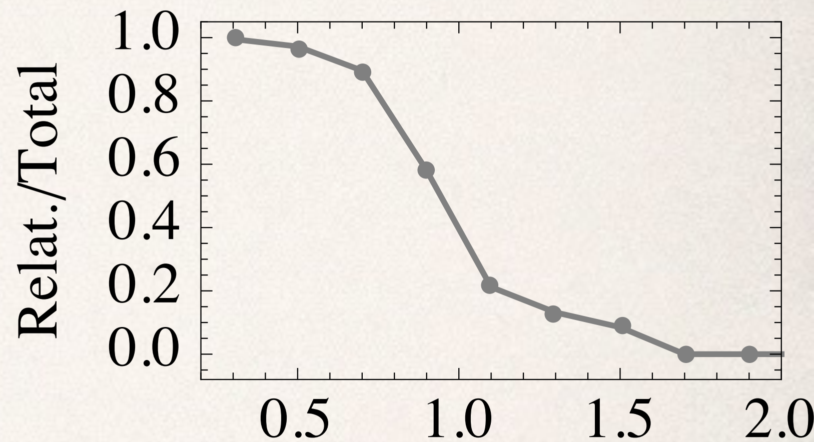
J-PAS constraints on local non-Gaussianity parameter f_{NL}

$$\mathcal{P}_g = n_g \, (b_g + f\,\mu_k^2)^2 \, P(k;z)$$

$$b_g \to b_g + \Delta b_g(f_{NL}, k)$$

$$F(\theta) = \frac{1}{\sigma_c^2(\theta)}$$





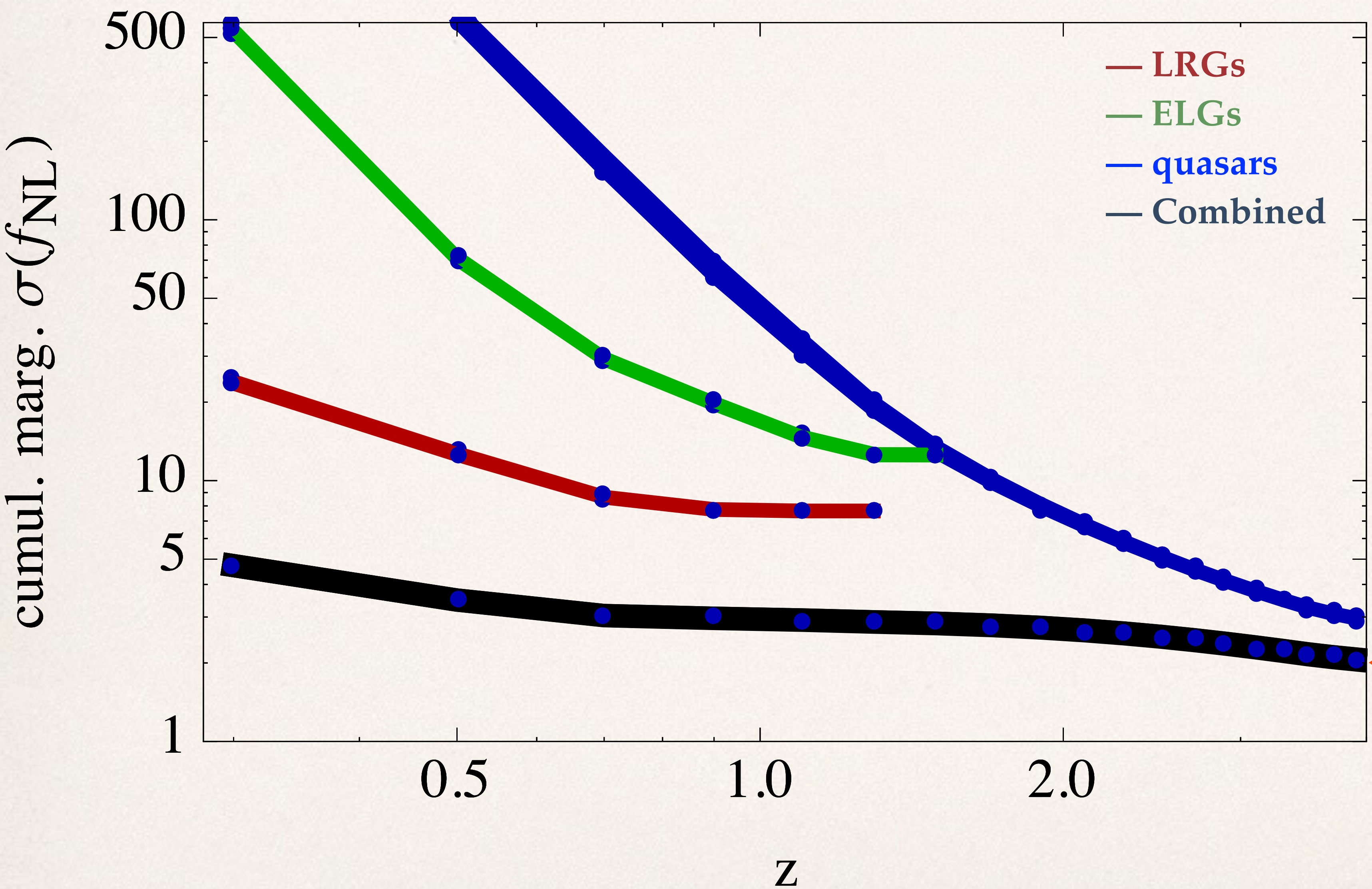
Information from relative clustering can improve constraints on f_{NL} by ~5 at low-z!

R.A. & Leonard 2013
Benítez et al. 2014

f_{NL} is almost unaffected by marginalization w.r.t. bias

The k-dependence of $\Delta b_{NL} \sim f_{NL} \times k^{-2}$ helps break the degeneracy

Cumulative uncertainty on f_{NL} when the redshift slices are combined



No prior on bias

Weak (~20%) prior on bias

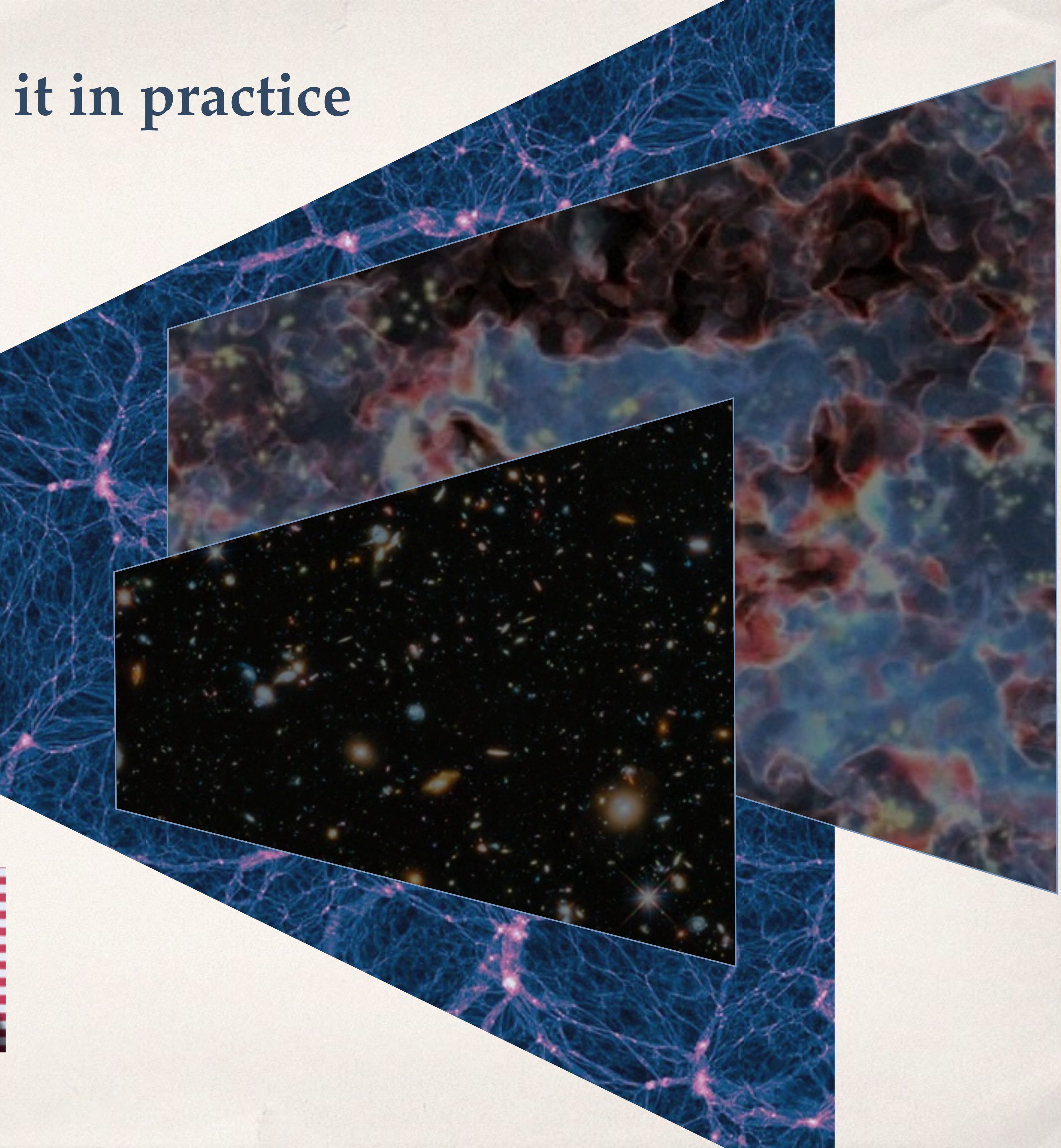
Strong (~5%) prior on bias

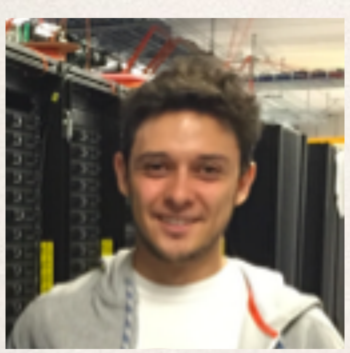
1σ : ~2

Planck: $\sigma(f_{NL})$~5
arXiv: 1502.01592

WARNING: this is *Fisherology* — not robust w.r.t. *systematics*

How to do it in practice

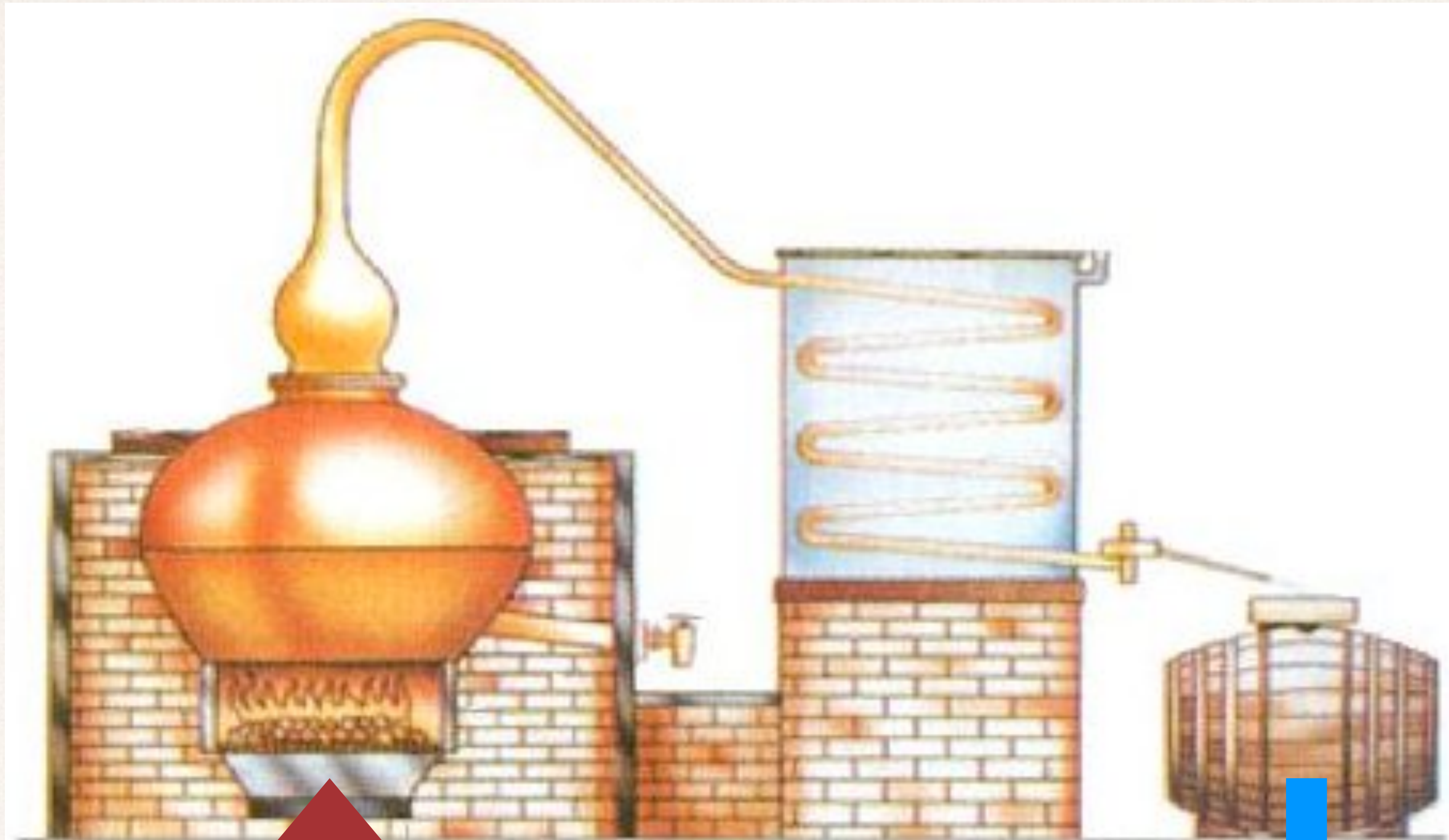




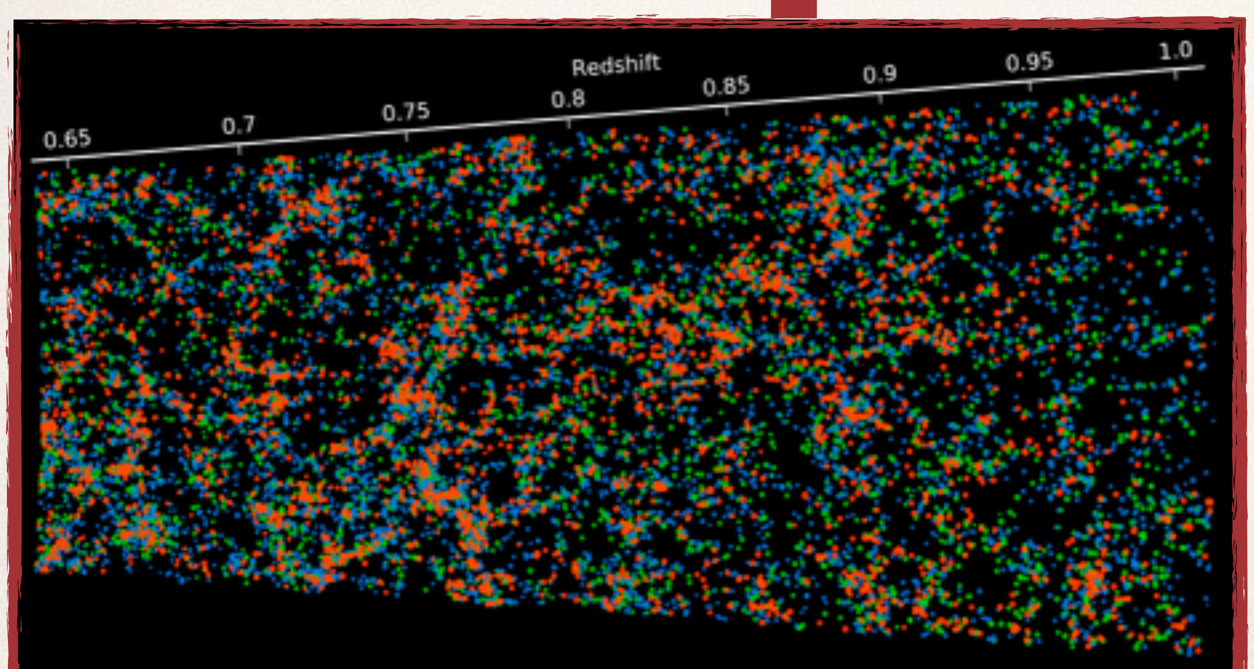
Lucas ⇨ UPenn

Arthur ⇨ UCL

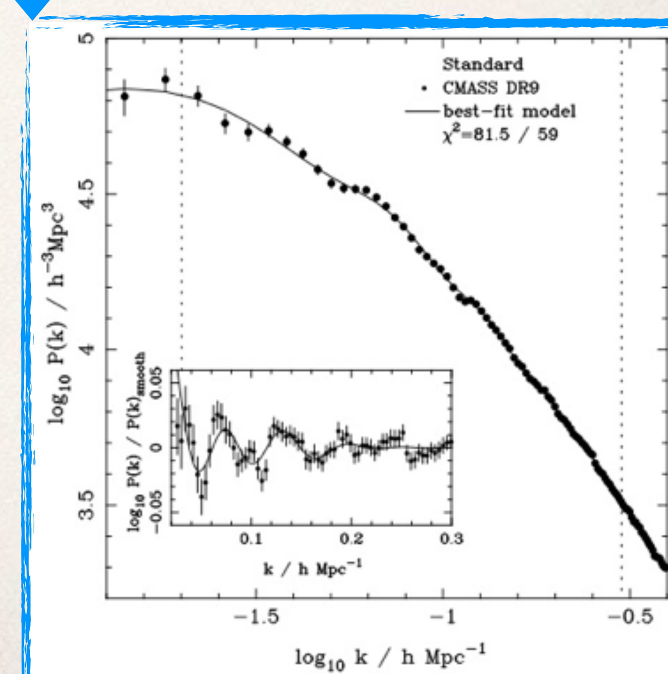
From catalogs to the power spectrum



Types and positions of galaxies



P(k), BAOs
RSDs
NGs, etc.



Feldman, Kaiser & Peacock, 1994 (**FKP**)

Fourier analysis of galaxy surveys

Given a **galaxy catalog $n_g(x)$**, the **optimal estimator** for the spectrum (FKP) is:

$$\frac{\delta n_g(x)}{\bar{n}_g} = \delta_g(x) \;\longrightarrow\; f_g(x) = w_{_{FKP}}(x)\, \delta_g(x)$$

The **FKP weights** express the best **compromise** between **cosmic variance** and **shot noise**:

$$w_{_{FKP}} = \frac{1}{1+\mathcal{P}_g}\, \bar{n}_g\, B_g \qquad\qquad B_g = b_g(z) + f(z)\mu_k^2 + \ldots$$

The **estimated spectrum** for a Fourier bin k_i (the *bandpower*) is then:

$$\hat{P}_g(k_i) = \frac{1}{N}\, \langle |\tilde{f}_g|^2 \rangle_{k_i} \qquad\qquad \tilde{f}_g(\mathbf{k}) = \mathrm{FFt}[f_g(\mathbf{x})]$$

The FKP estimator is **optimal** — it is **unbiased**, and it saturates the **Cramér-Rao bound**:

$$Cov[\hat{P}_g(k_i), \hat{P}_g(k_j)] \to [\mathrm{Fisher}]^{-1}$$

Fourier analysis of multi-tracer surveys

Given **any number of galaxy catalogs *$n_\mu(x)$***, the **weighted fields** are:

$$\delta_\mu(x) \;\longrightarrow\; f_\mu(x) = \sum_\nu w_{\mu\nu}\,\delta_\nu(x)$$

The multi-tracer **weights** are:

$$w_{\mu\nu} = \left[\delta_{\mu\nu} - \frac{\mathcal{P}_\mu}{1+\mathcal{P}}\right]\bar{n}_\nu B_\nu$$

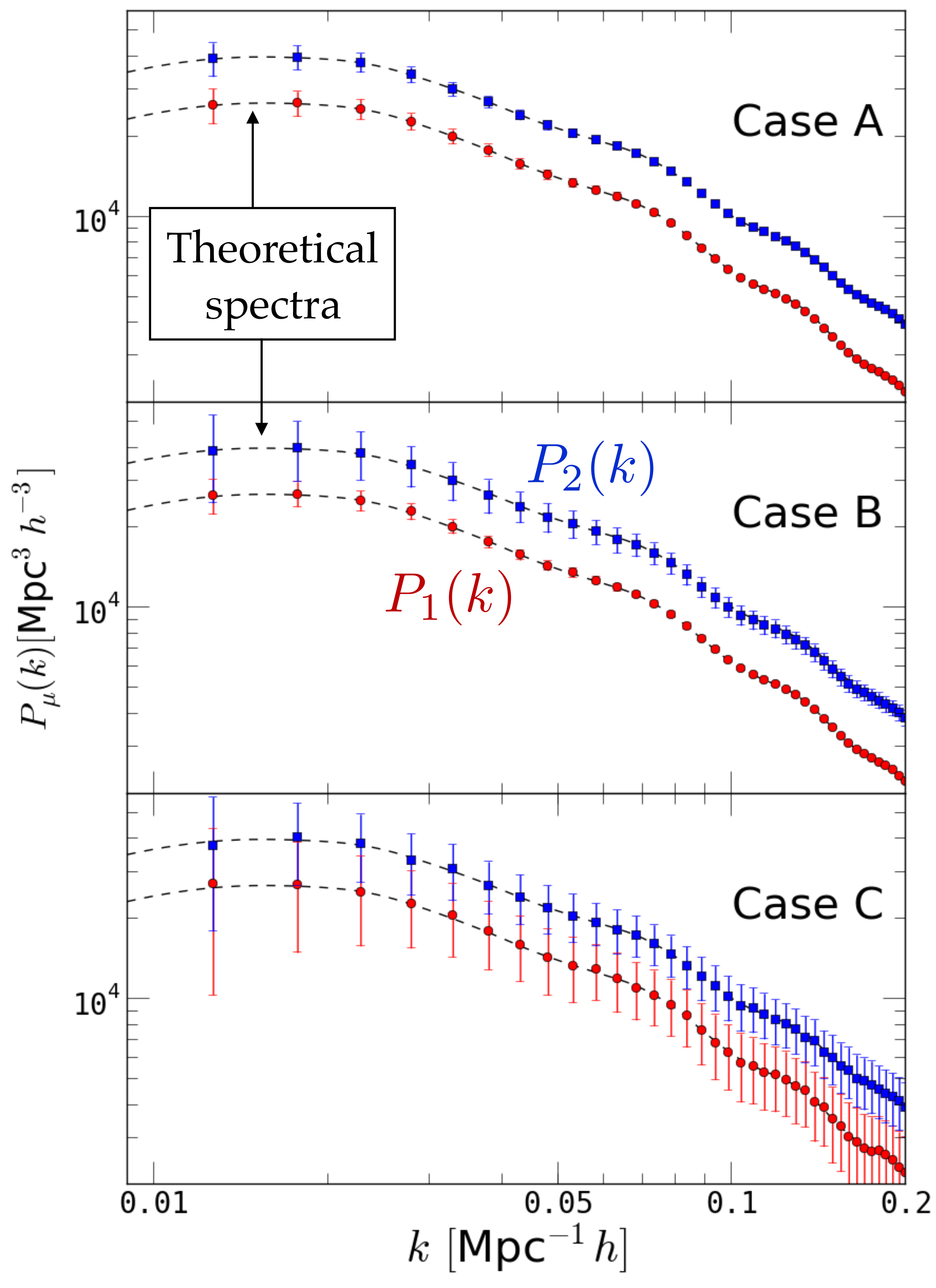
The **estimated auto-spectra** are:

$$\hat{P}_\mu(k_i) = \sum_\nu N^{-1}_{\mu\nu}\,\langle|\tilde{f}_\nu|^2\rangle_{k_i}$$

These estimators are **optimal**: their **covariance** is the **inverse of the Fisher matrix**!

$$Cov[\hat{P}_\mu, \hat{P}_\nu] = [F_{\mu\nu}]^{-1}$$

Testing and validating the multi-tracer estimators



Case	$\bar{n}_1\ (h^3\ \mathrm{Mpc}^{-3})$	b_1	$\bar{n}_2\ (h^3\ \mathrm{Mpc}^{-3})$	b_2
A	$1.\,10^{-2}$	1.0	$1.\,10^{-2}$	1.2
B	$1.\,10^{-2}$	1.0	$1.\,10^{-5}$	1.2
C	$1.\,10^{-5}$	1.0	$1.\,10^{-5}$	1.2

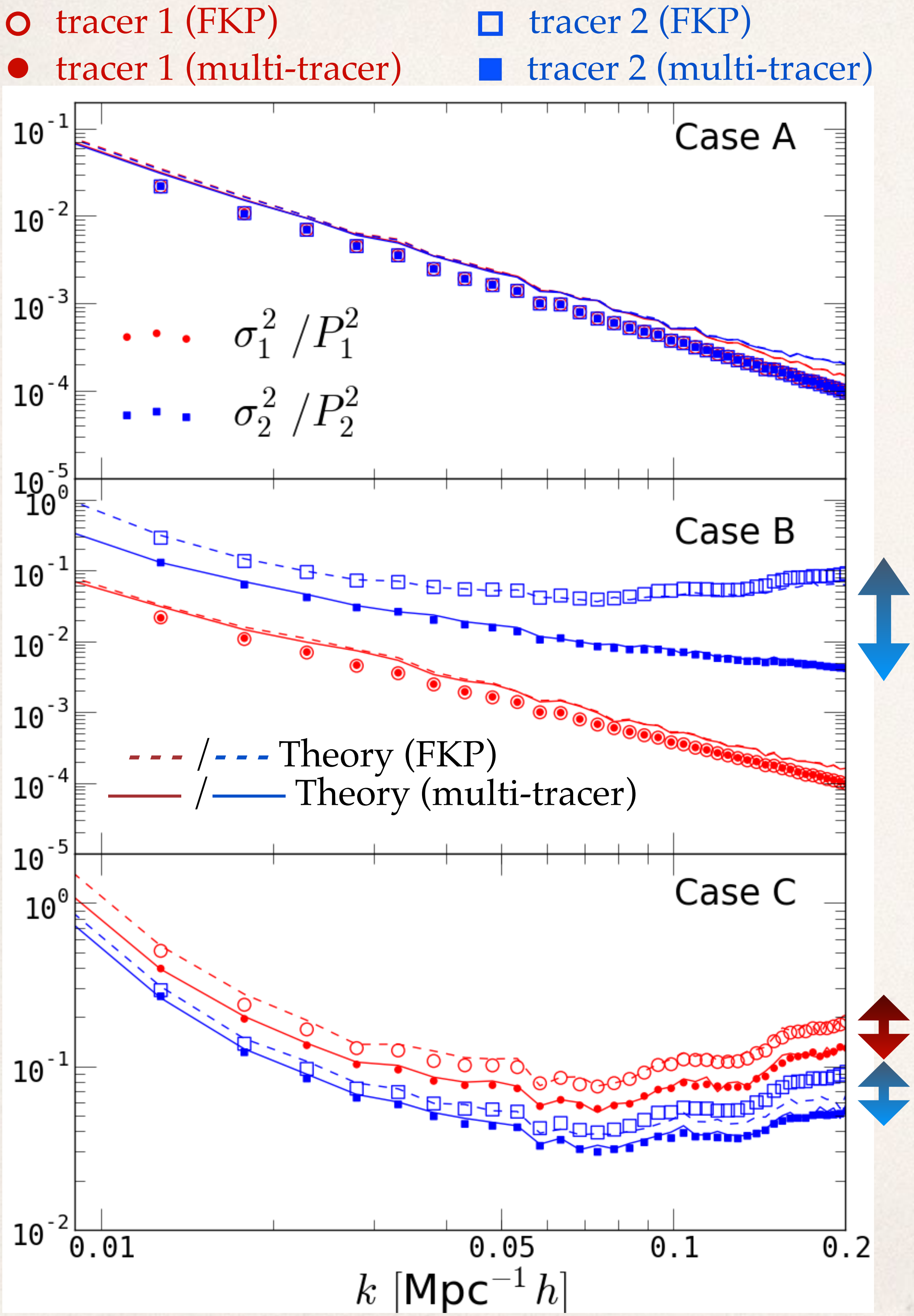
* Volume = (1280 h^{-1} Mpc)^3 = (128 x 10 h^{-1} Mpc)^3

* 10^3 lognormal realizations

* Planck-vanilla fiducial parameters

✓ Unbiased

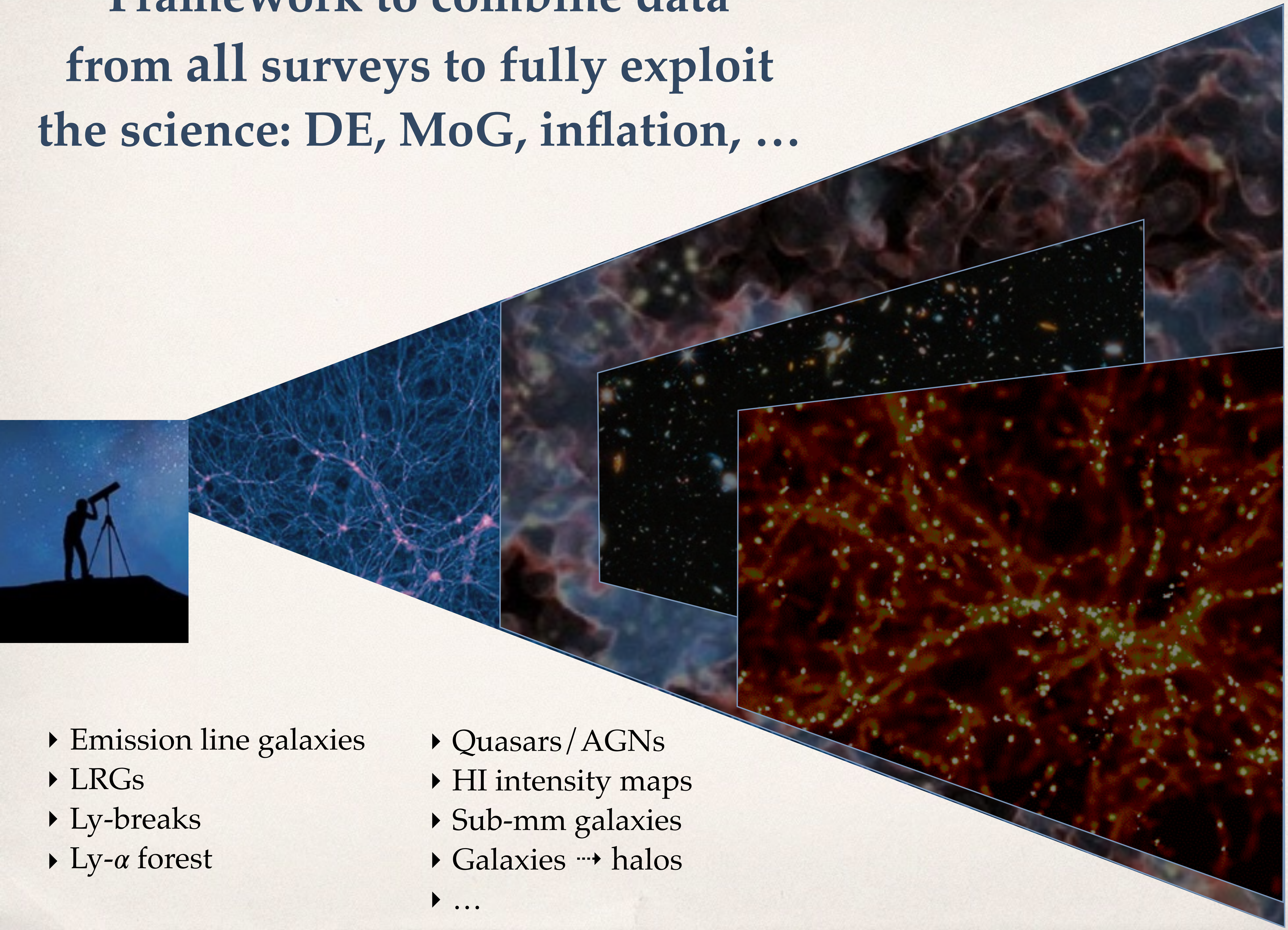
Testing and validating the multi-tracer estimators



Case	$\bar{n}_1$ (h^3 Mpc^{-3})	b_1	$\bar{n}_2$ (h^3 Mpc^{-3})	b_2
A	$1.\,10^{-2}$	1.0	$1.\,10^{-2}$	1.2
B	$1.\,10^{-2}$	1.0	$1.\,10^{-5}$	1.2
C	$1.\,10^{-5}$	1.0	$1.\,10^{-5}$	1.2

✓ Unbiased
✓ Optimal

Framework to combine data from all surveys to fully exploit the science: DE, MoG, inflation, …



- Emission line galaxies
- LRGs
- Ly-breaks
- Ly-α forest
- Quasars / AGNs
- HI intensity maps
- Sub-mm galaxies
- Galaxies ⇢ halos
- …

The End