Cosmological Colliders in the Nonlinear Universe

Fundamental physics from weak lensing

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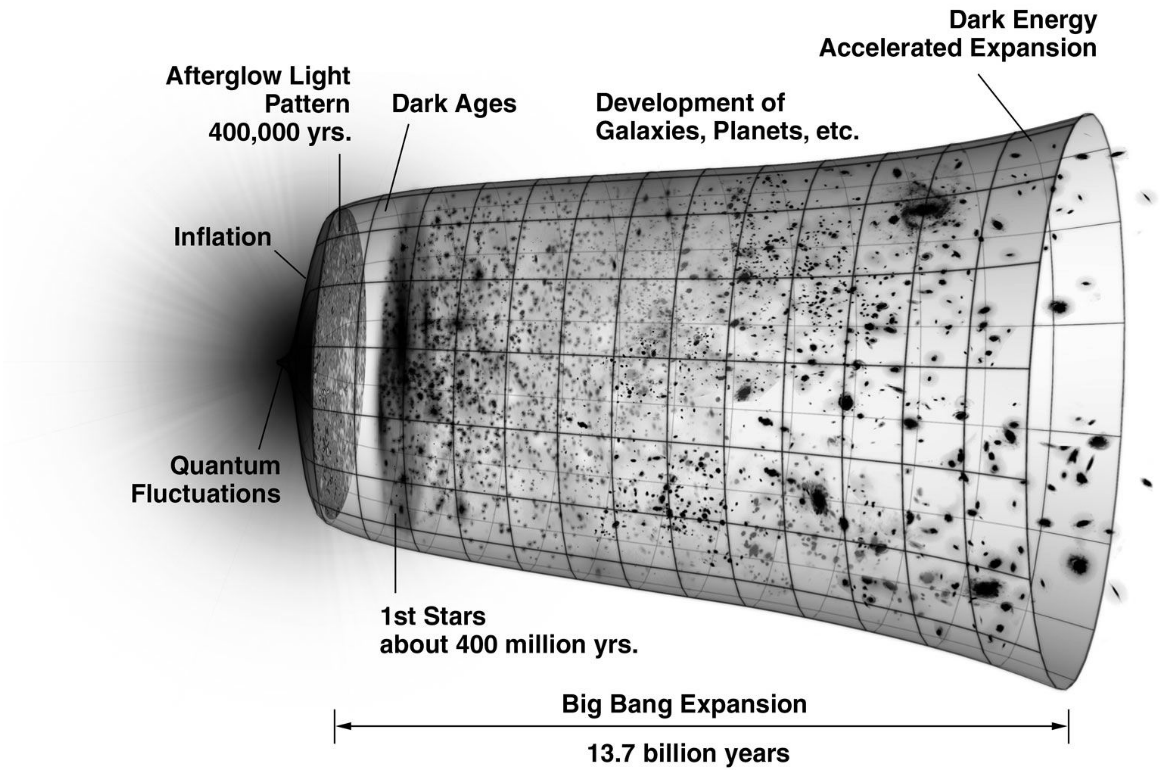
Outline

1. The primordial Universe
    a. Primordial physics with galaxy surveys
    b. What and why weak lensing?

2. Cosmological Colliders
    a. From particles physics to LSS
    b. Robust N-body simulations of collider models
    c. What can lensing surveys achieve?

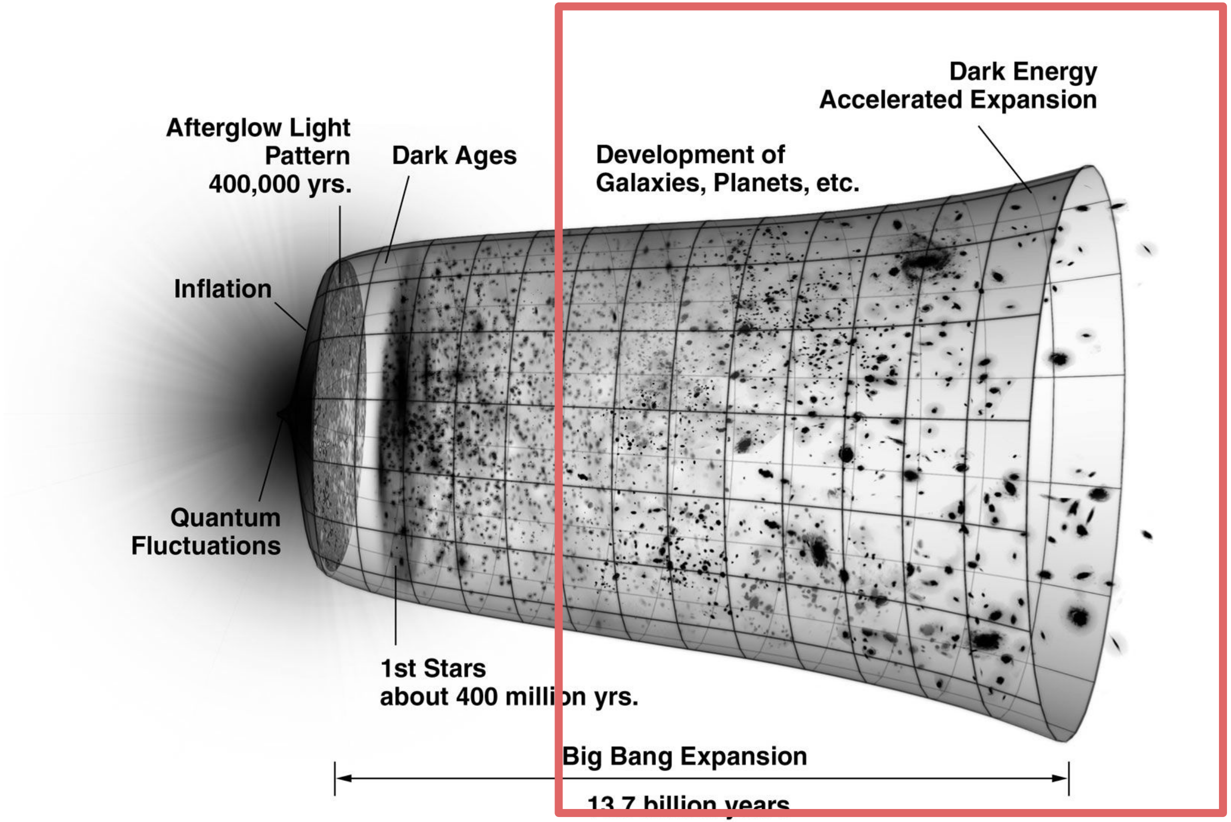
3. Beyond Colliders

The cosmology story



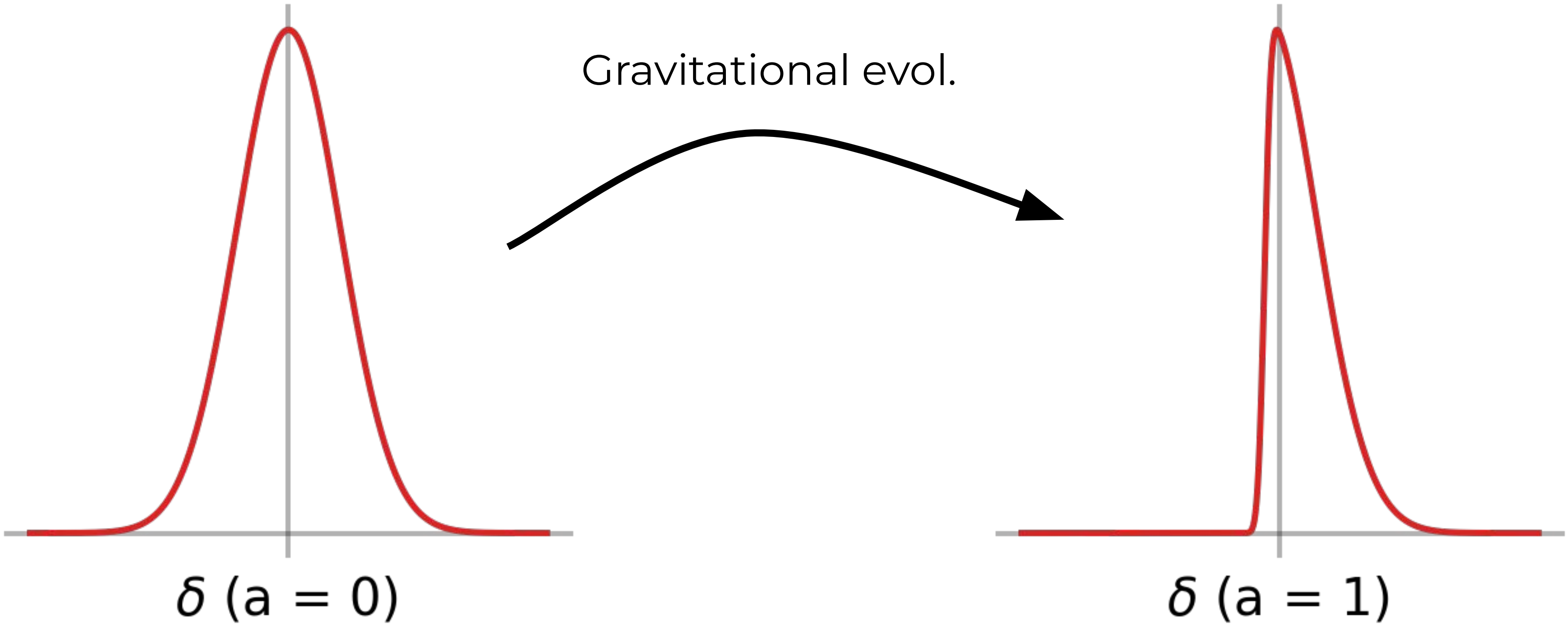
NASA/WMAP Science Team

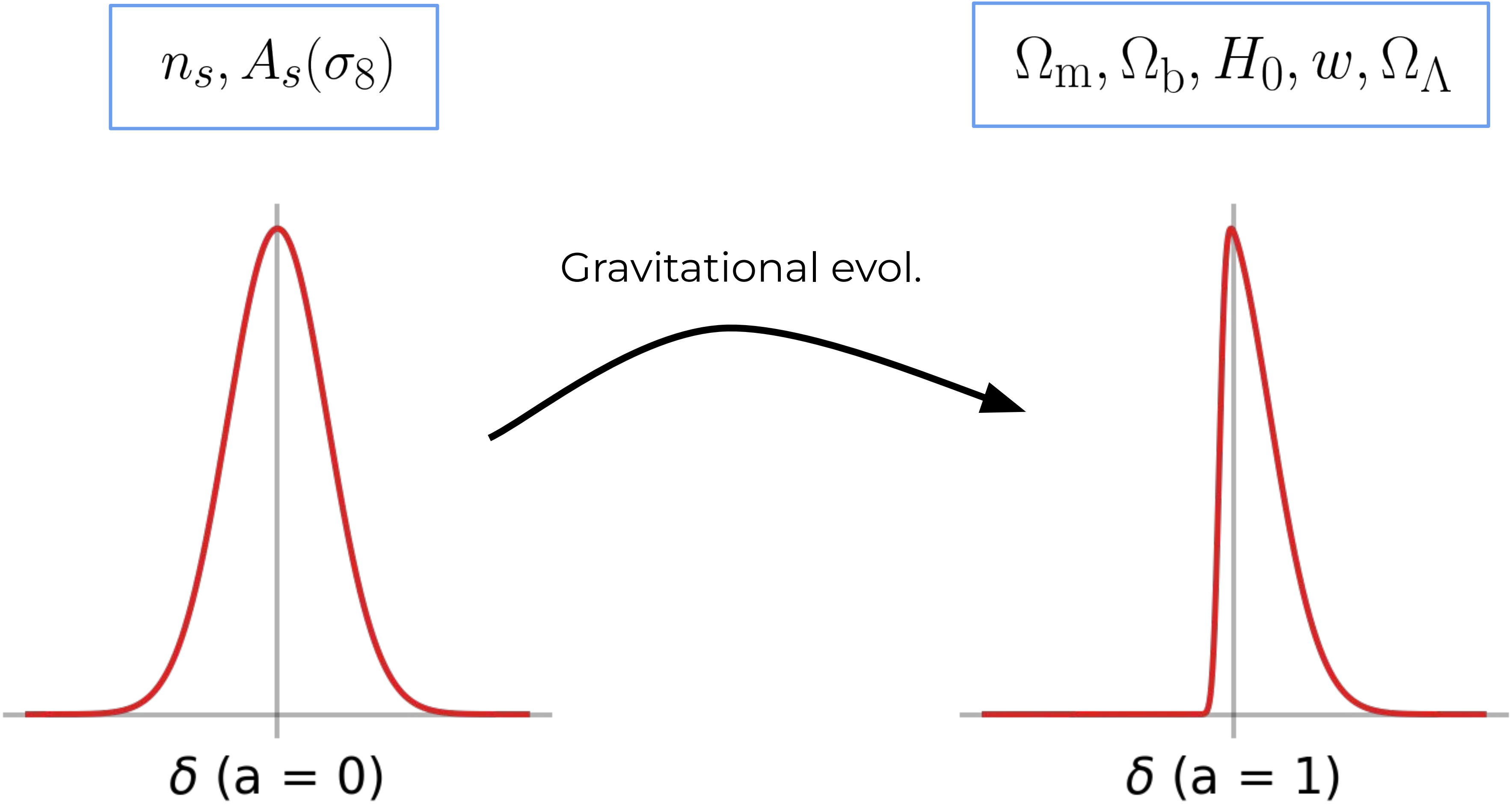
Galaxy surveys



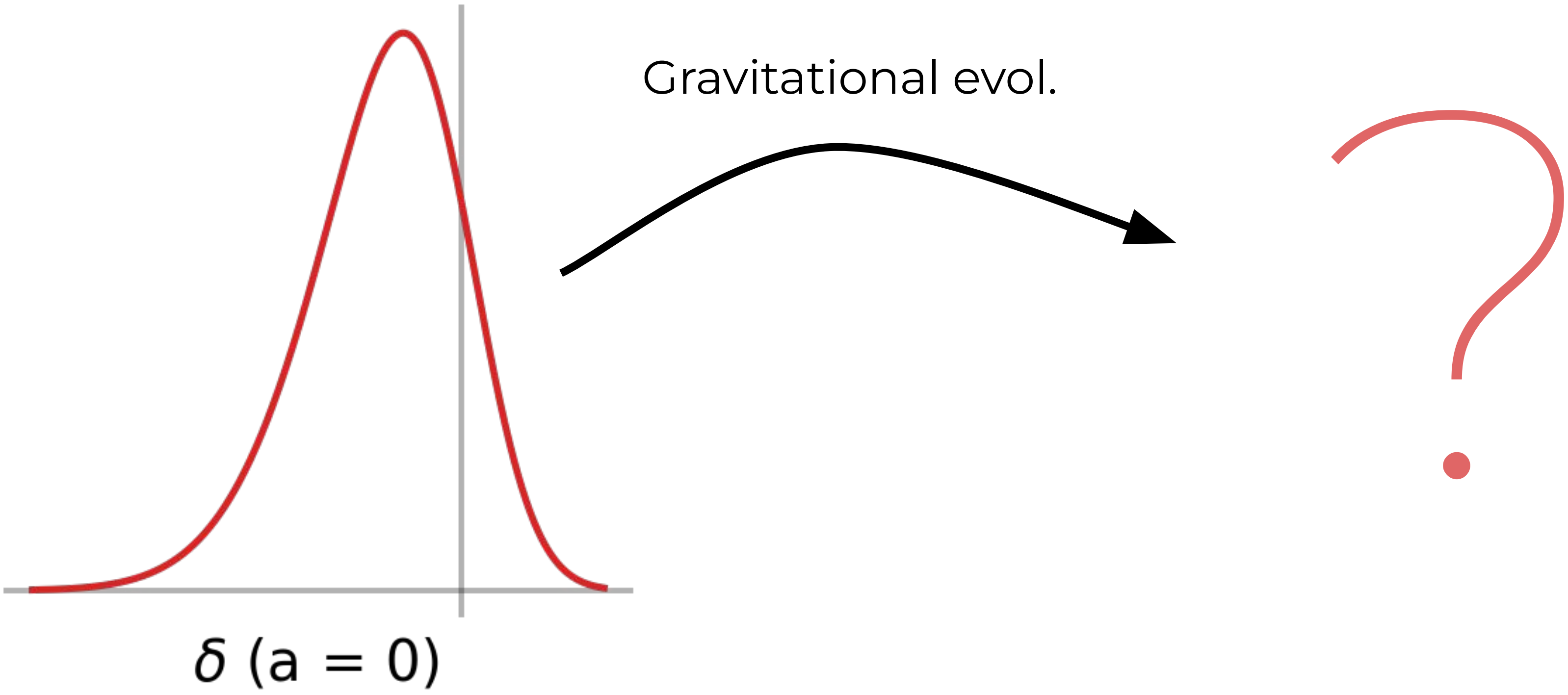
NASA/WMAP Science Team

LSS cosmology



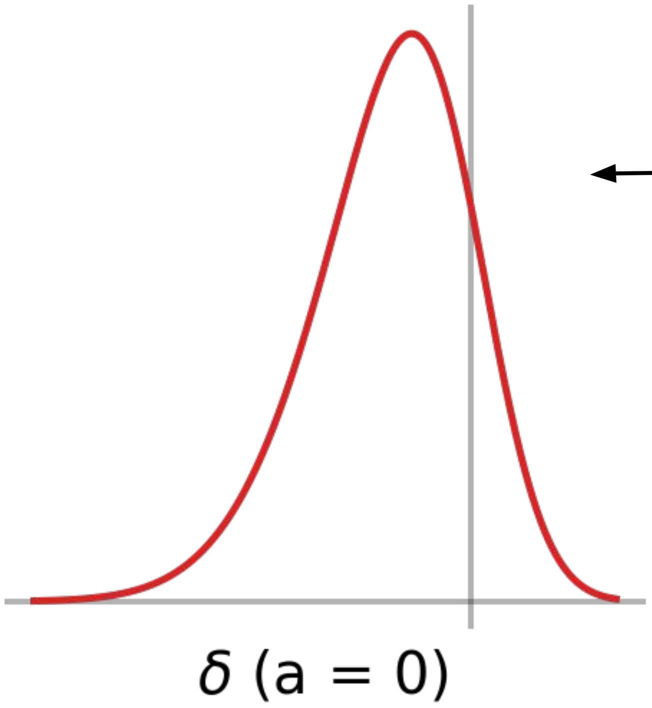

$n_s, A_s(\sigma_8)$
$\Omega_{\rm m}, \Omega_{\rm b}, H_0, w, \Omega_\Lambda$
Gravitational evol.
δ (a = 0)
δ (a = 1)

Inflation



Inflation

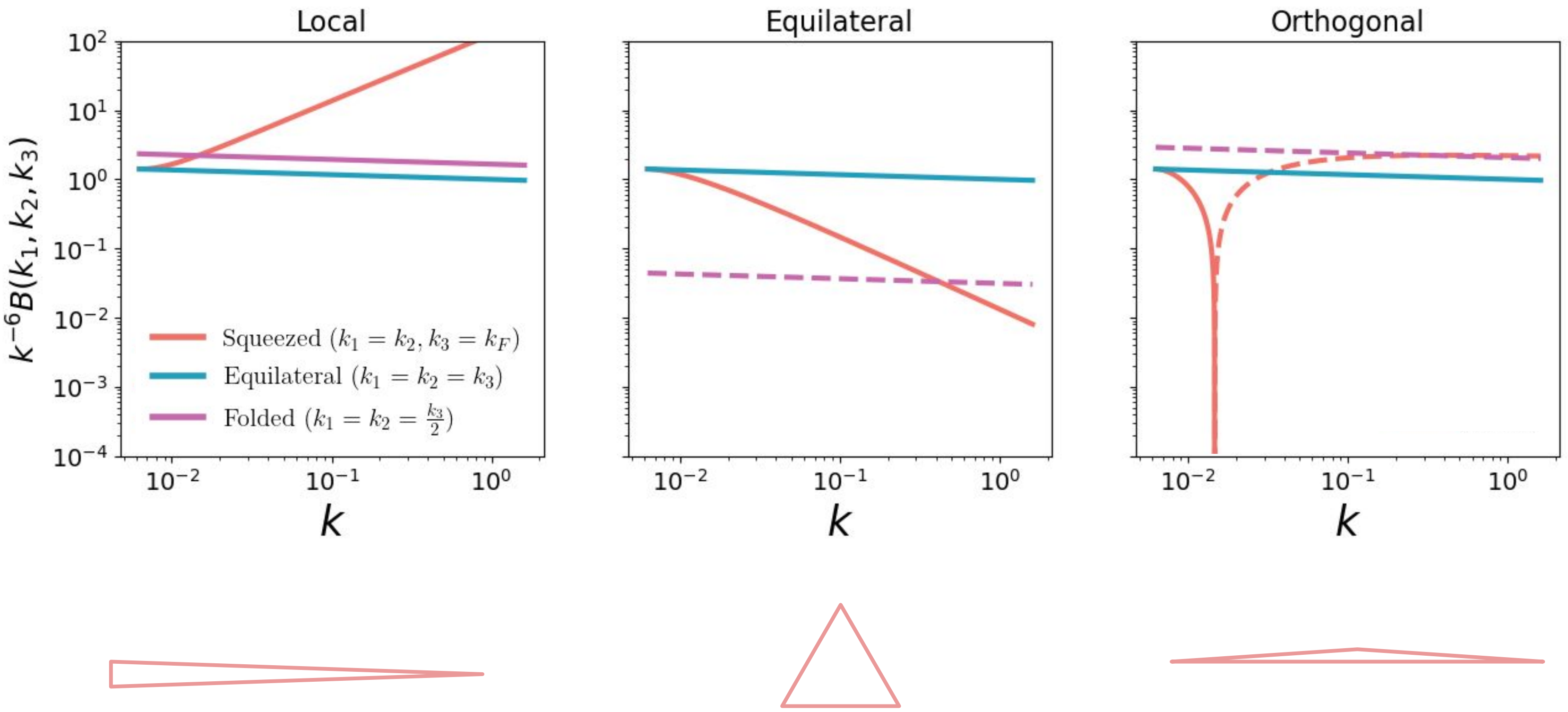
$$f_{\mathrm{NL}}^{\mathrm{loc}}, f_{\mathrm{NL}}^{\mathrm{eq}}, f_{\mathrm{NL}}^{\mathrm{ortho}}, \ldots$$



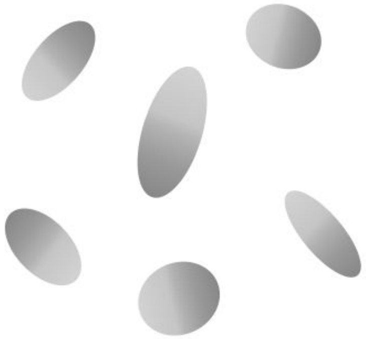
Different types of PNG —> Different physics

How many particles?
How strongly interacting?

Inflationary Bispectra

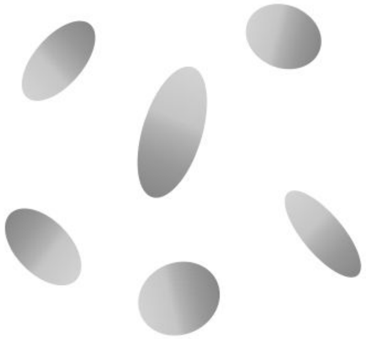


What is weak lensing?



Galaxies randomly distributed

What is weak lensing?

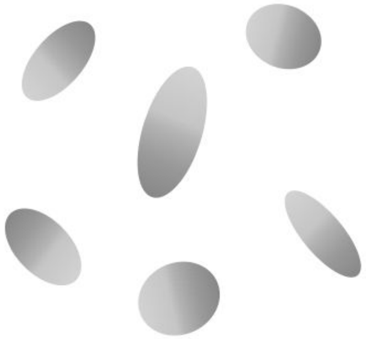


Galaxies randomly distributed

+

Massive object in the foreground

What is weak lensing?

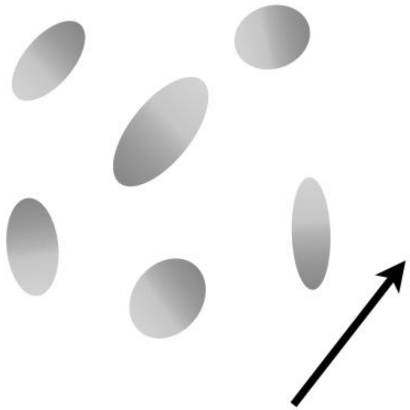


Galaxies randomly distributed

+

Massive object in the foreground

=



Slight alignment

What is weak lensing?

$$\mathbf{e}_{\text{obs}} = \mathbf{e}_{\text{gal}} + \mathbf{e}_{\text{shear}}$$

Measure a galaxy shape/orientation

What is weak lensing?

$$\mathbf{e}_{\mathrm{obs}} = \mathbf{e}_{\mathrm{gal}} + \mathbf{e}_{\mathrm{shear}}$$

$$\langle \mathbf{e}_{\mathrm{obs}} \rangle = \langle \mathbf{e}_{\mathrm{gal}} \rangle + \langle \mathbf{e}_{\mathrm{shear}} \rangle$$

Average over many galaxies

What is weak lensing?

$$\mathbf{e}_{\text{obs}} = \mathbf{e}_{\text{gal}} + \mathbf{e}_{\text{shear}}$$

$$\langle \mathbf{e}_{\text{obs}} \rangle = \cancelto{0}{\langle \mathbf{e}_{\text{gal}} \rangle} + \langle \mathbf{e}_{\text{shear}} \rangle$$

Average over many galaxies
to remove the random component

What is weak lensing?

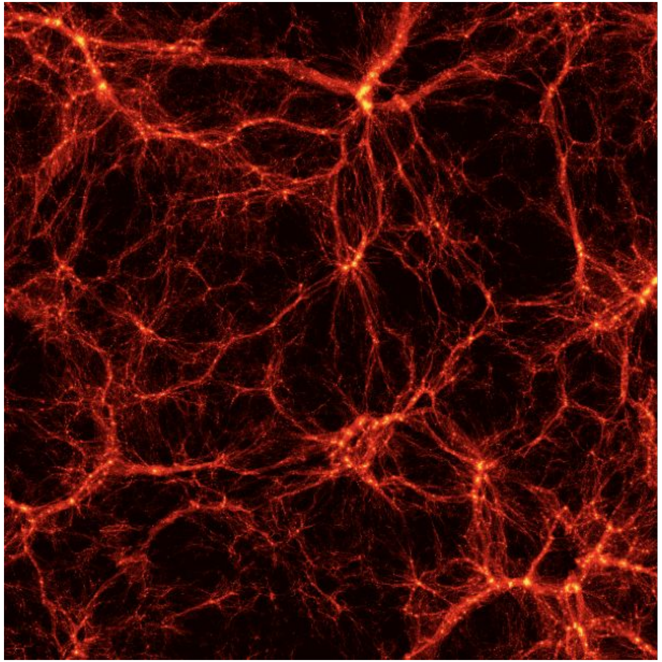
$$\mathbf{e}_{\text{obs}} = \mathbf{e}_{\text{gal}} + \mathbf{e}_{\text{shear}}$$

$$\langle \mathbf{e}_{\text{obs}} \rangle = \cancelto{0}{\langle \mathbf{e}_{\text{gal}} \rangle} + \langle \mathbf{e}_{\text{shear}} \rangle$$

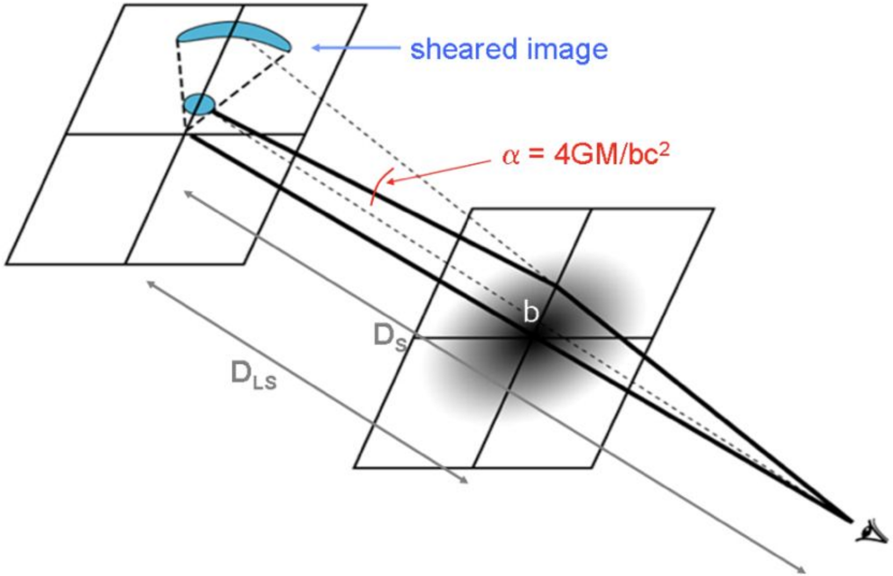
Keep just the cosmological part $\langle \mathbf{e}_{\text{obs}} \rangle = \langle \mathbf{e}_{\text{shear}} \rangle$

What is weak lensing?

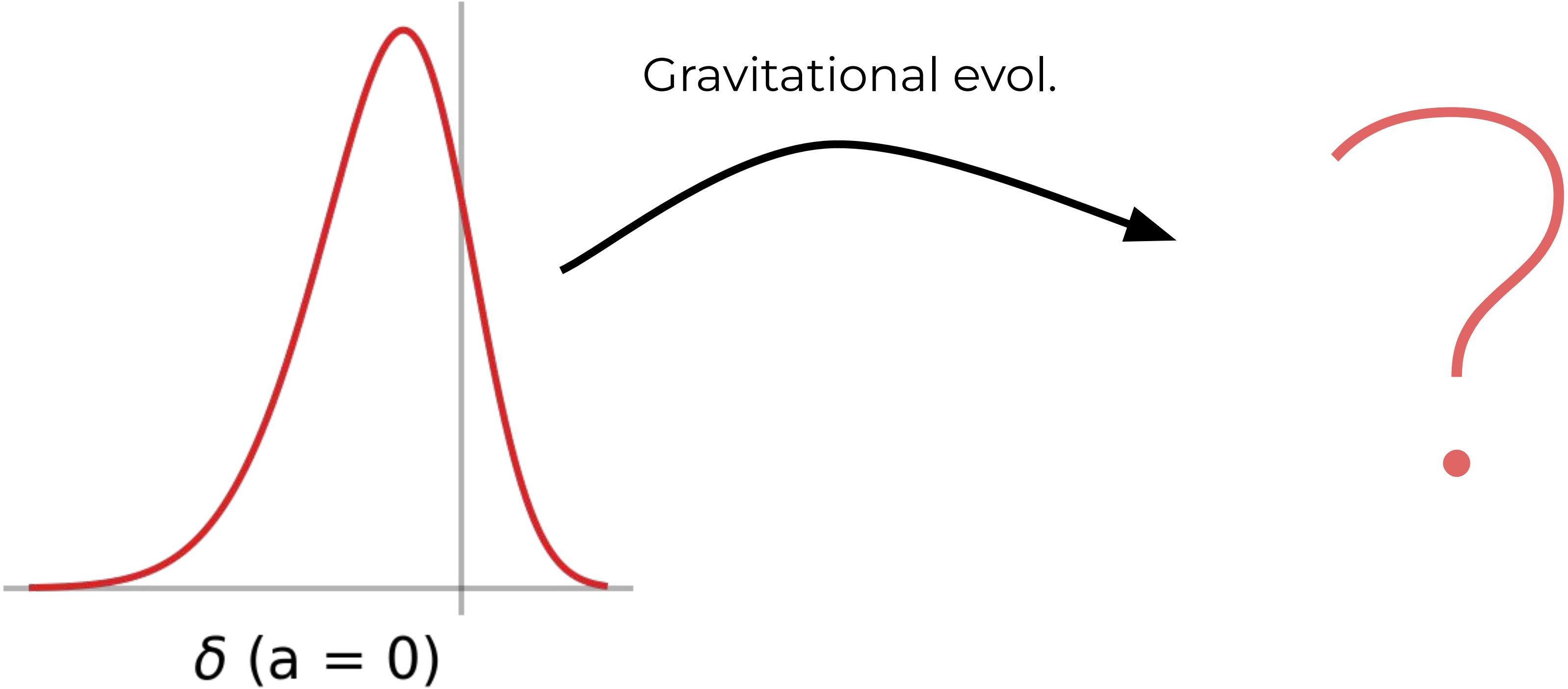
Light bundles travel through a highly inhomogeneous universe...



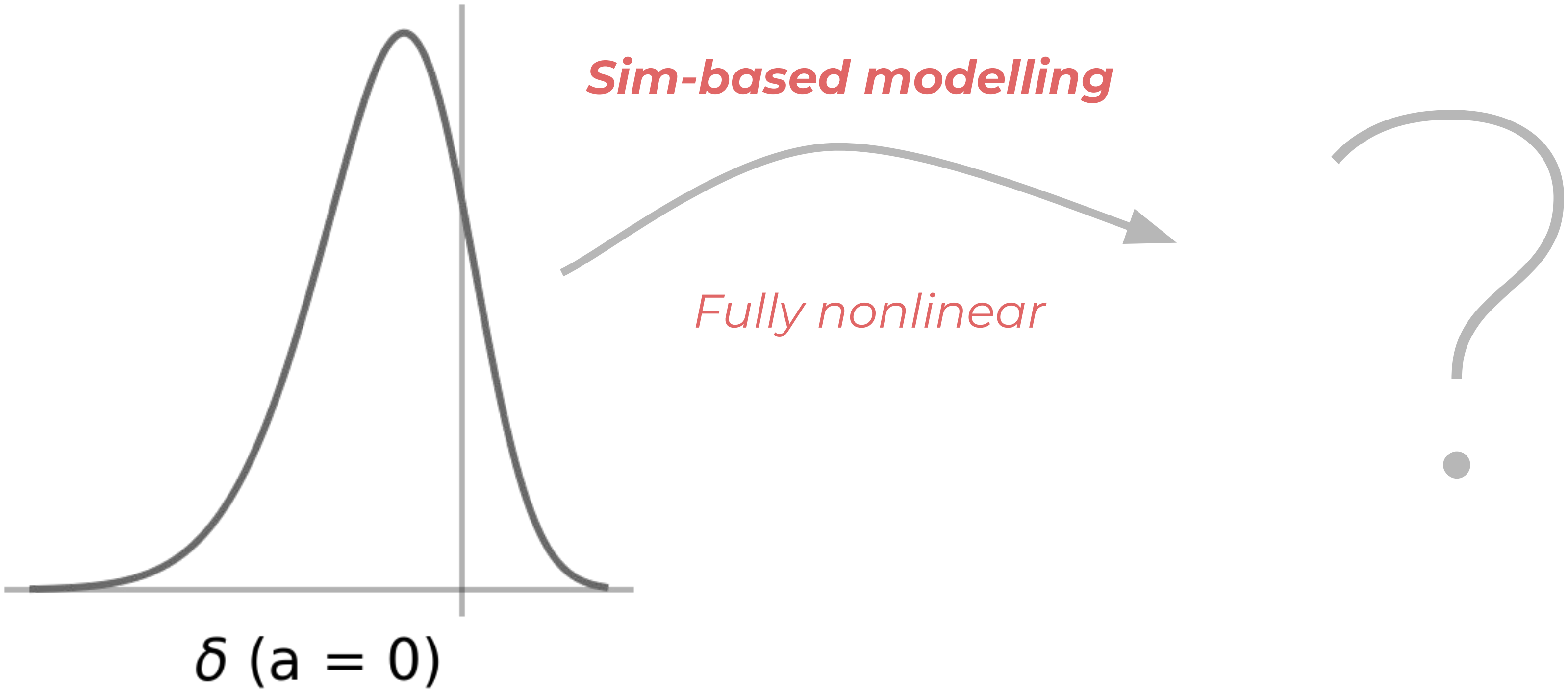
... and get deflected and sheared along the way according to GR



Inflation



Inflation

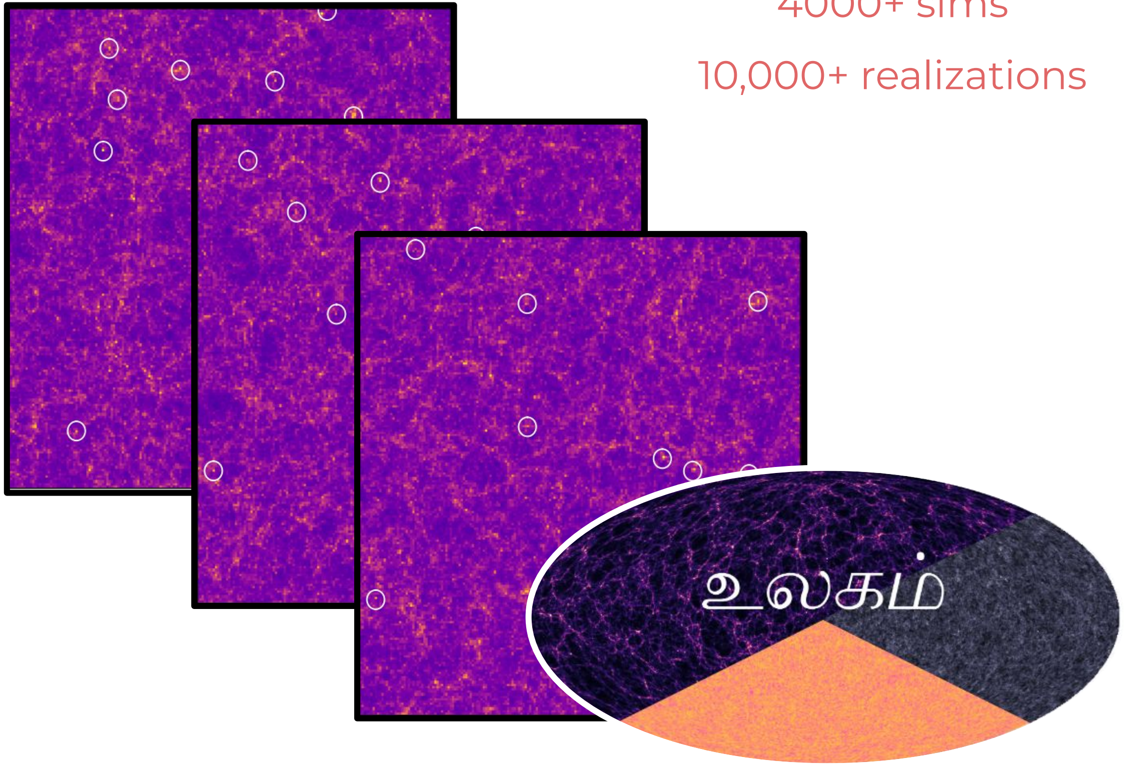


The Ulagam simulations

ulagam-simulations.readthedocs.io

Anbajagane, Chang, Lee & Gatti 2024

Anbajagane & Lee 2025a, 2025b



4000+ sims

10,000+ realizations

Sim setup

$$N = 512^3$$

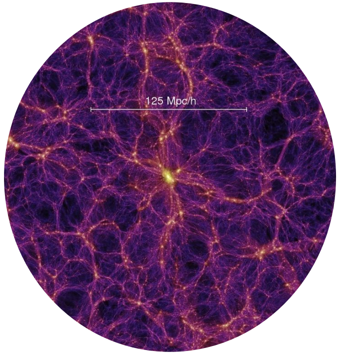
$$L = 1\ \mathrm{Gpc}/h$$

$$\{\Omega_\mathrm{m}, \sigma_8, n_s, w, f_\mathrm{NL}^\mathrm{X}\}$$

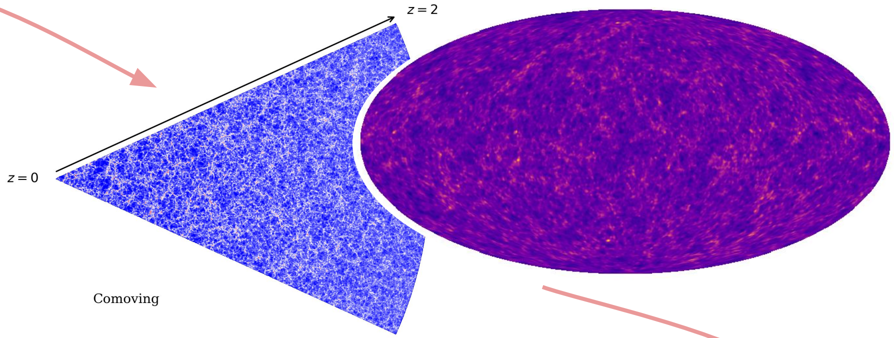
Accurate to k < 1 [h/Mpc]

ℓ < 1000

Modelling/forecast pipeline

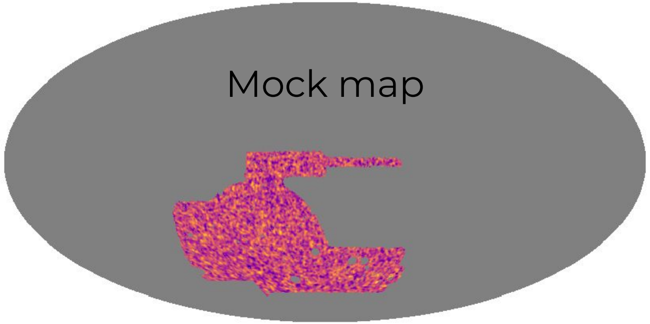


Make lightcones

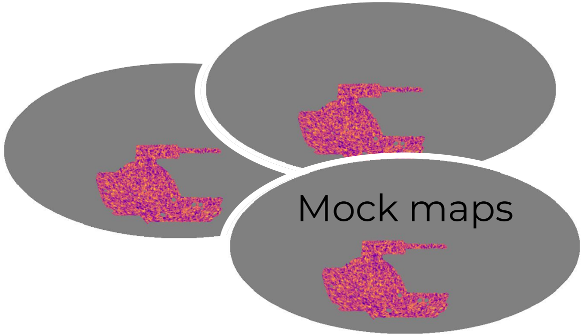


Survey properties

Sky mask, noise etc.



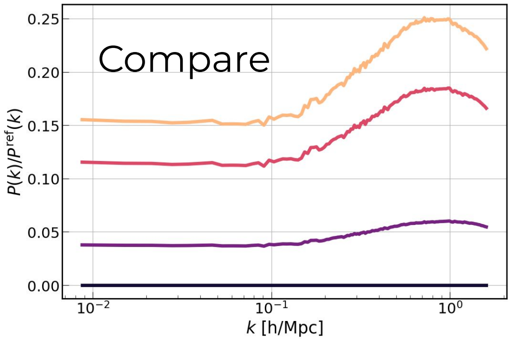
From maps to constraints

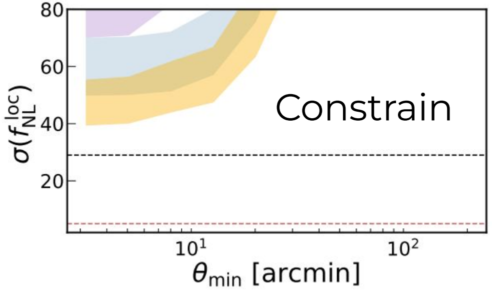


Summary statistic

P(k), Moments, Counts-in-cells, kNNs,

Homology, Minkowski funcs, ...





From maps to constraints

Using moments of the convergence field

$$\langle \kappa^{(1)} \kappa^{(2)} \ldots \kappa^{(N)} \rangle(\theta) = \frac{1}{N_{\rm pix} - 1} \sum_{i=1}^{N_{\rm pix}} \kappa_i^{(1)} \kappa_i^{(2)} \ldots \kappa_i^{(N)}$$

Anbajagane, Chang, Banerjee+ 2023a

From maps to constraints

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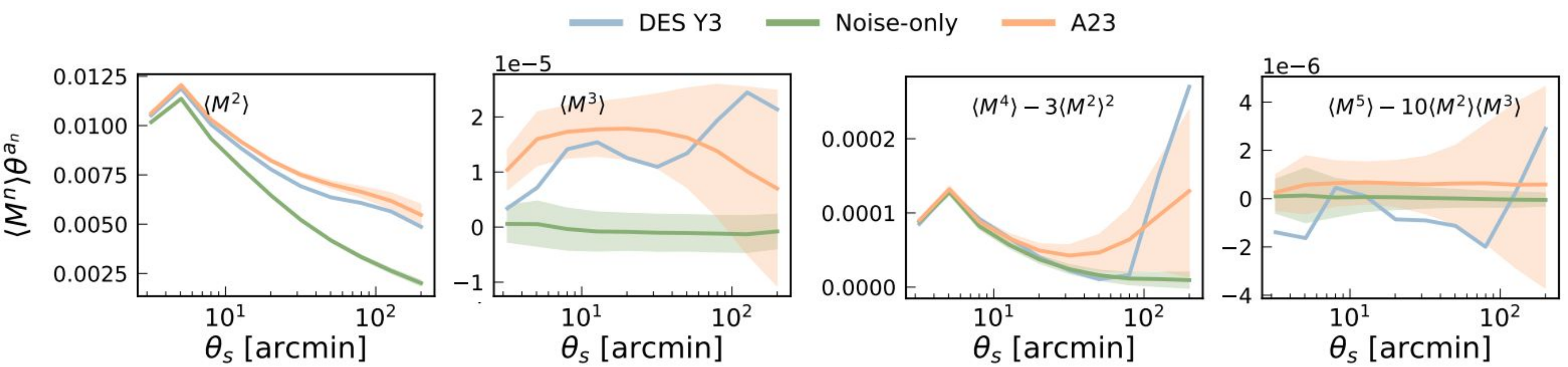

Anbajagane, Chang, Banerjee+ 2023a

From maps to constraints

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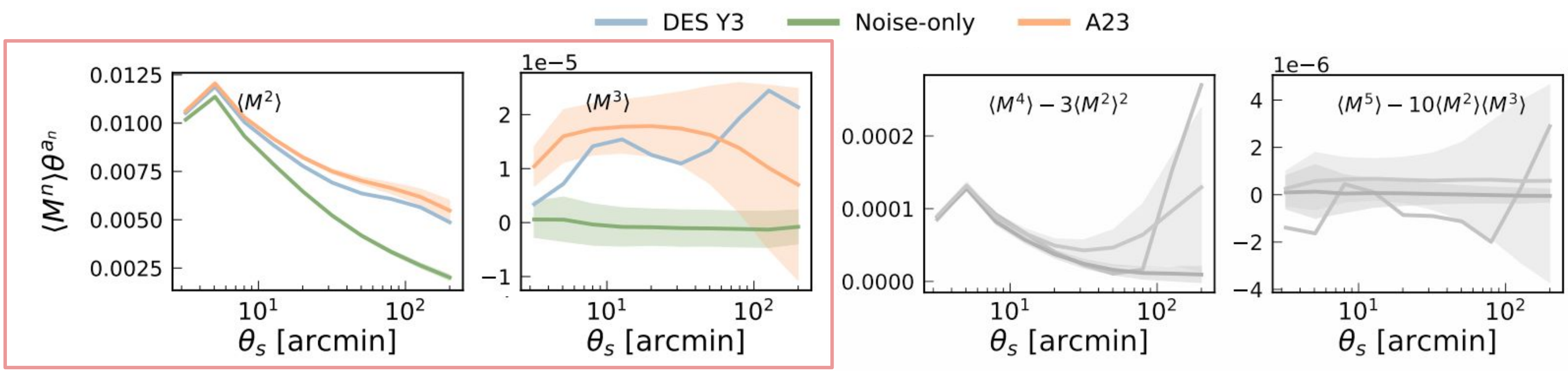
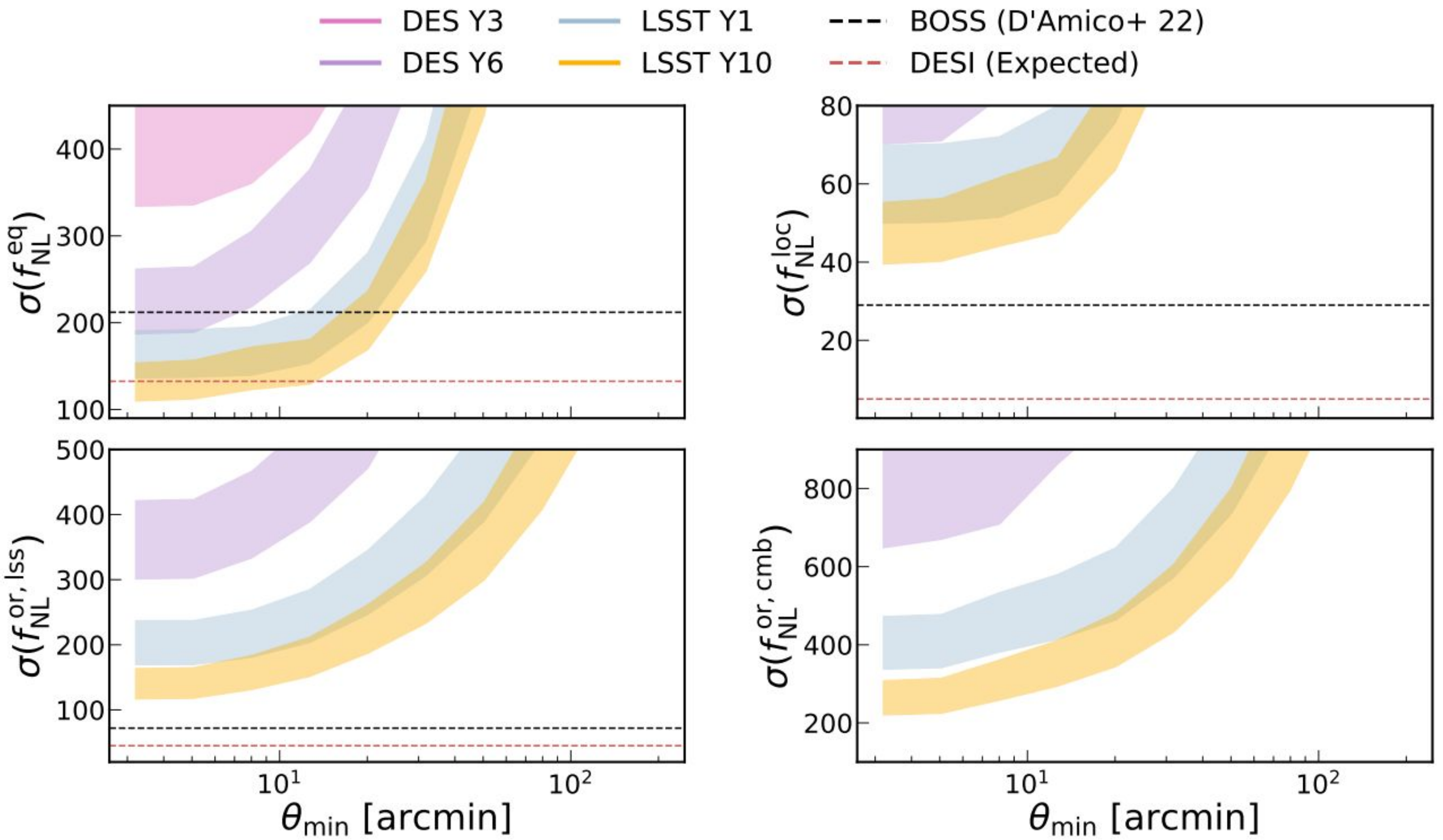
$$\langle \kappa^{(1)} \kappa^{(2)} \dots \kappa^{(N)} \rangle(\theta) = \frac{1}{N_{\rm pix} - 1} \sum_{i=1}^{N_{\rm pix}} \kappa_i^{(1)} \kappa_i^{(2)} \dots \kappa_i^{(N)}$$



Anbajagane, Chang, Lee & Gatti 2023b

What can lensing do?



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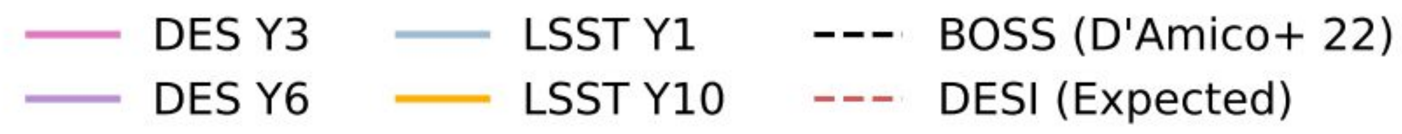

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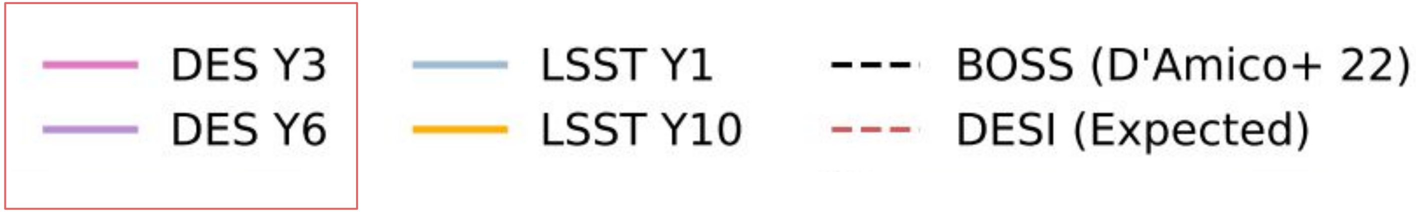

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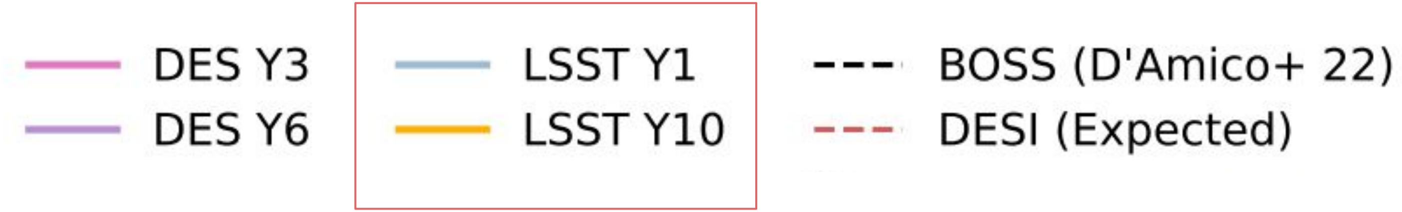

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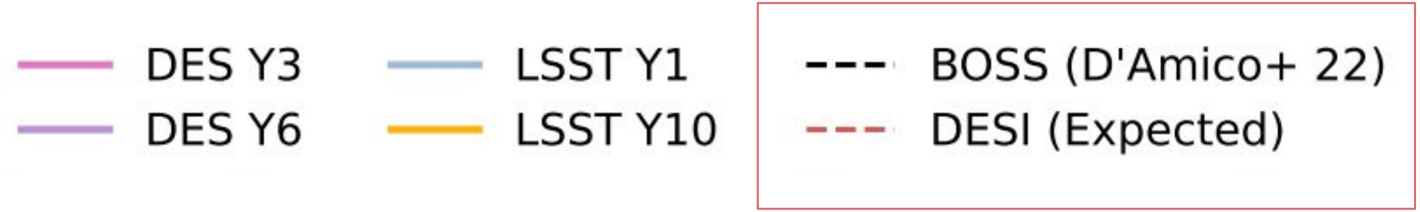

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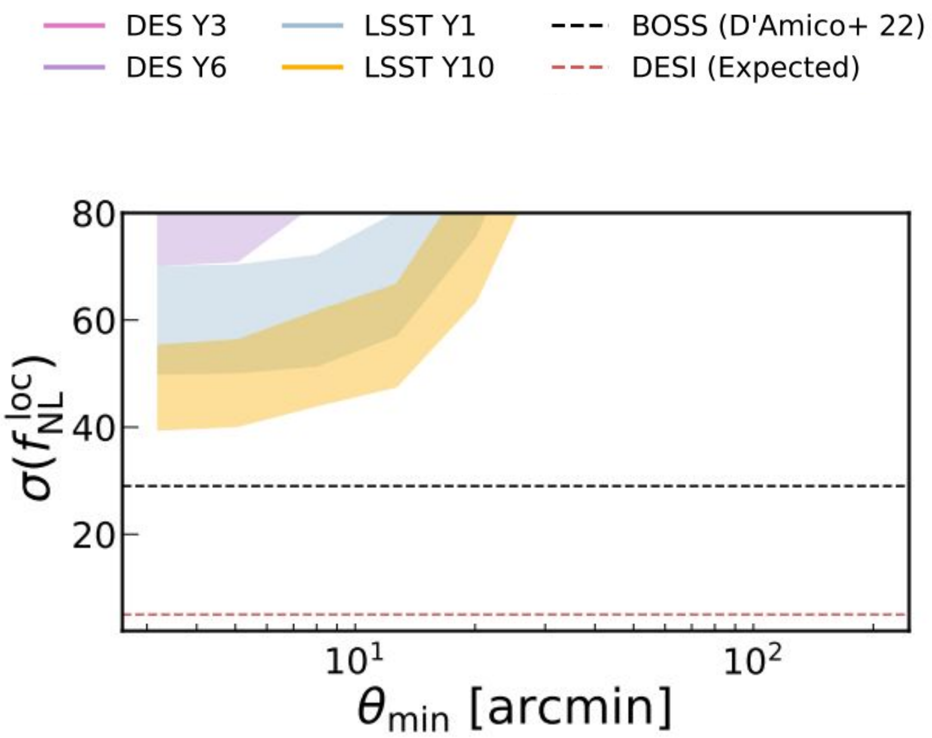
What can lensing do?

LSST Y10 is 8x weaker than DESI*



* Depends on galaxy bias choices

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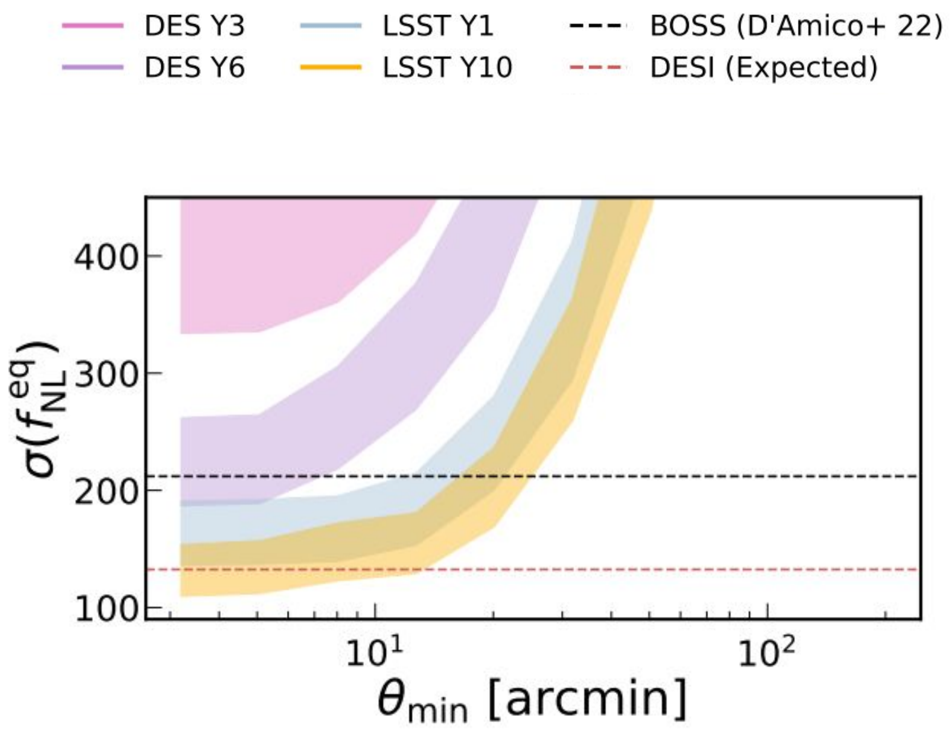
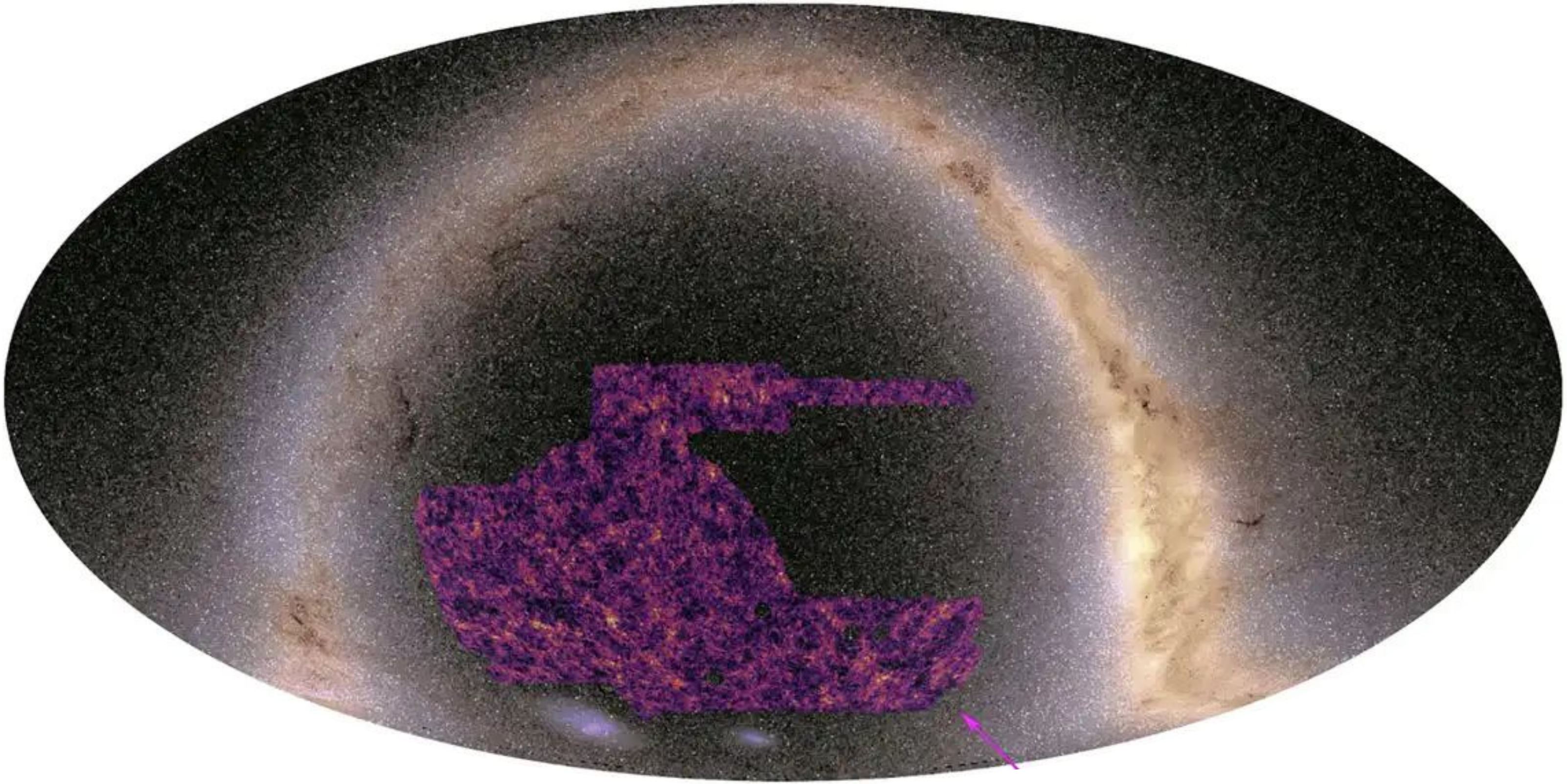
What can lensing do?

DES Y6 competitive w/ BOSS

LSST Y10 competitive w/ DESI



Where is the information?



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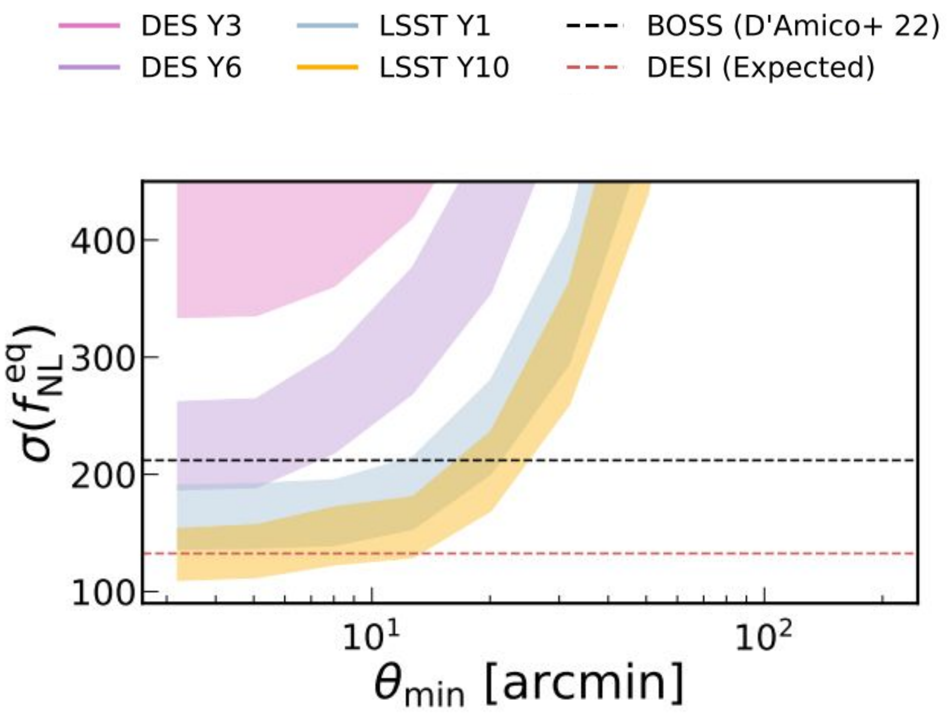
Where is the information?

On nonlinear scales

$$10' \sim 5 - 15 \text{ Mpc}$$



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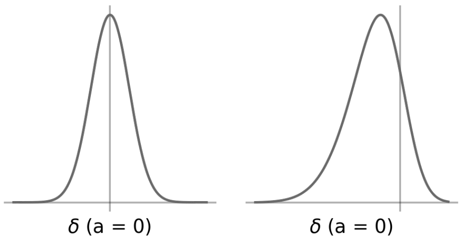
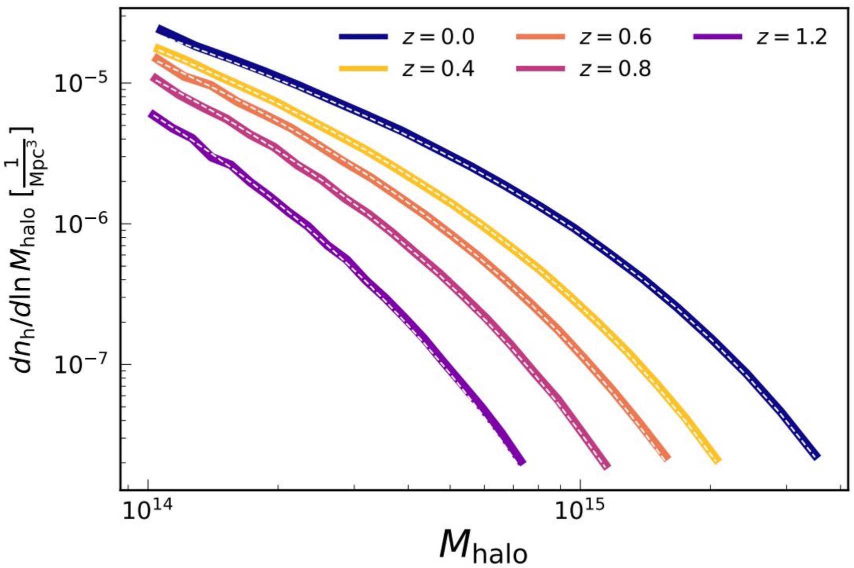
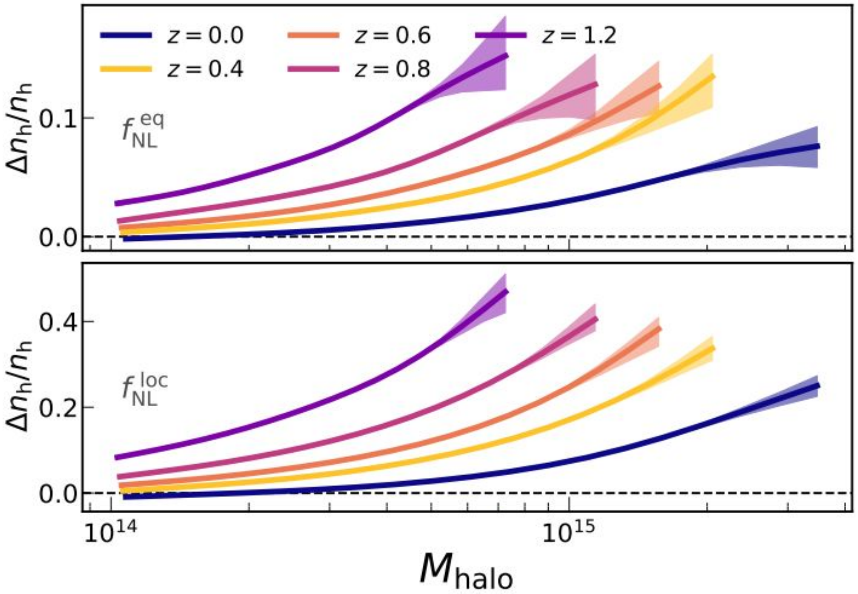
Cluster Cosmology 2.0

More skewness → More clusters







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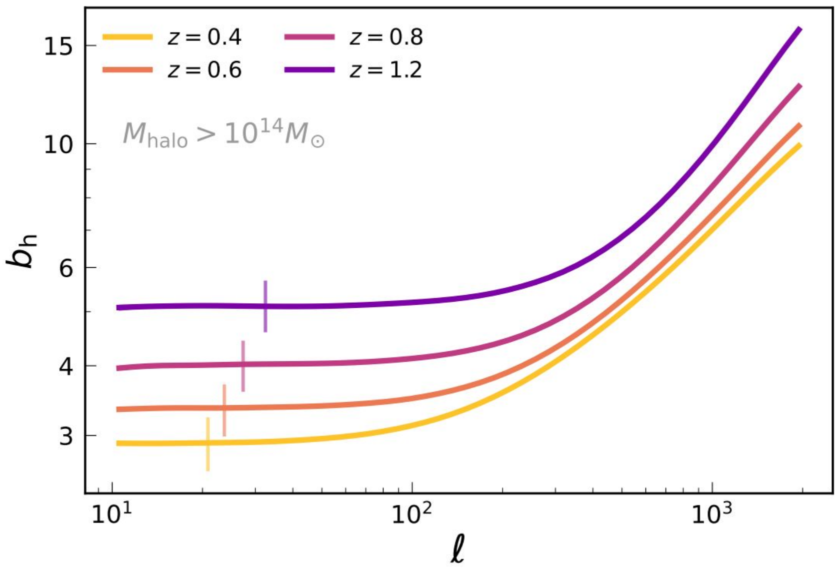
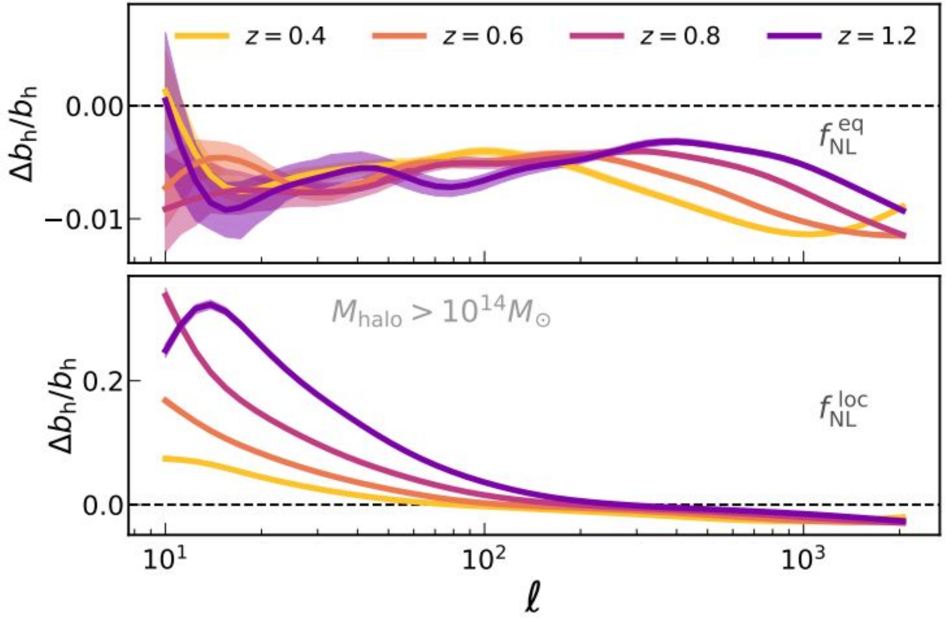
Spatial clustering

More skewness → Changes in halo clustering





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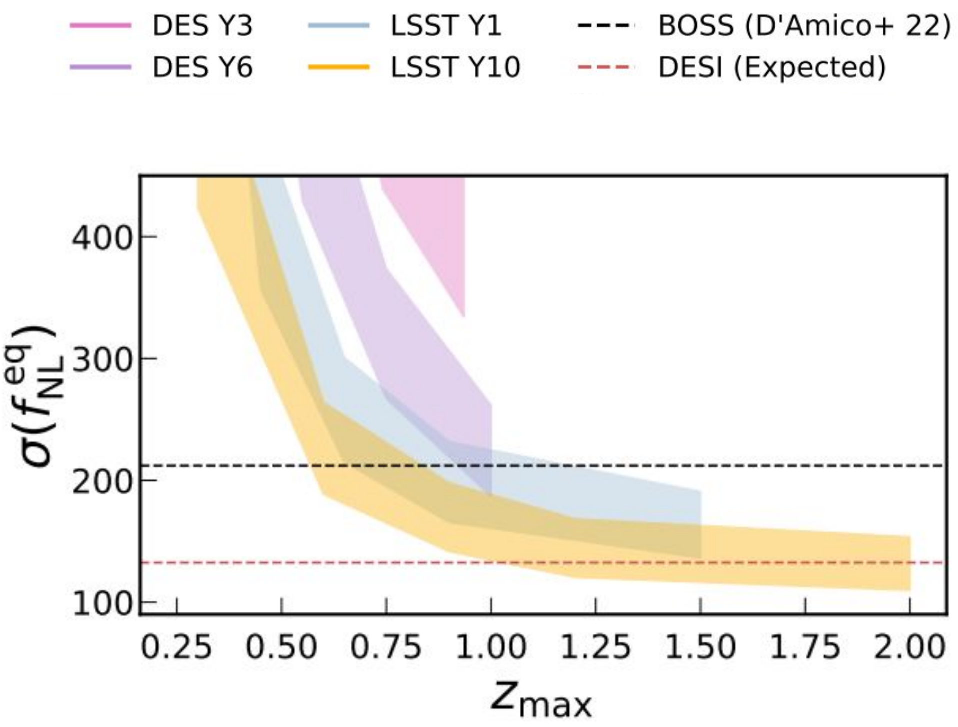
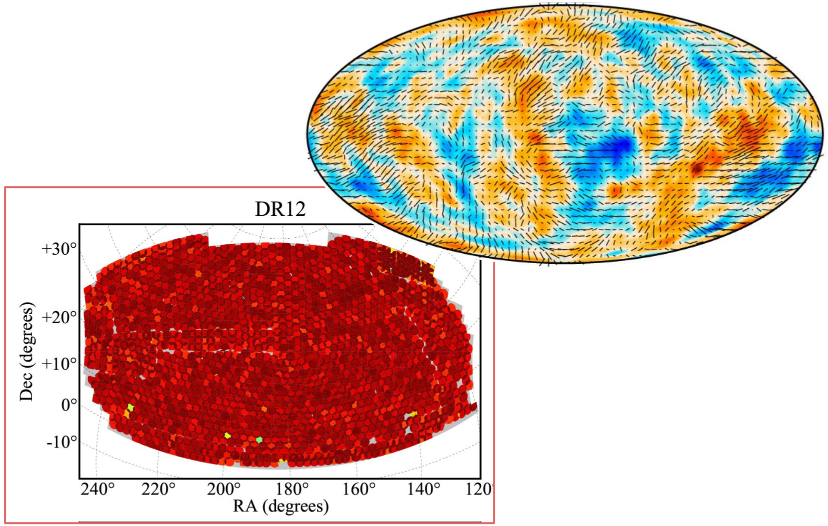
Where is the information?

At lower redshift (z < 1)

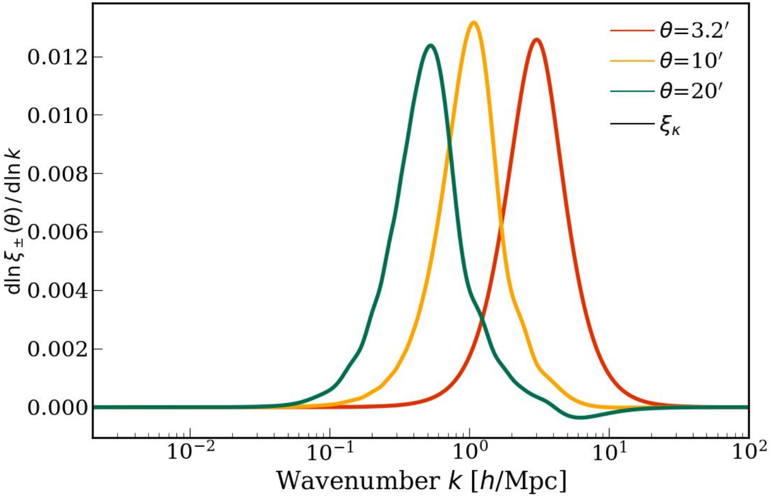


Synergies with other surveys

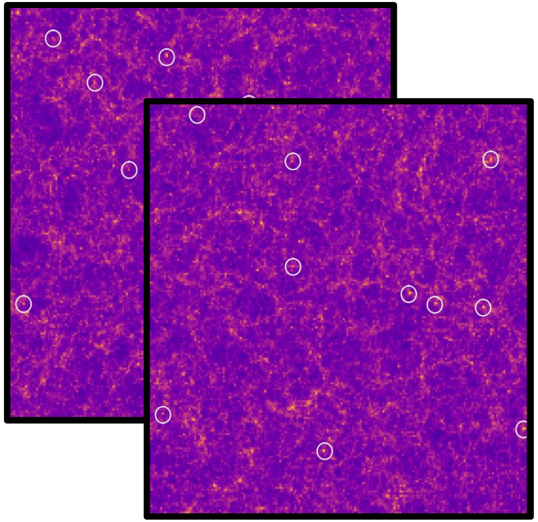
Consistency Checks



Scale dependent fNL



Synergies with galaxies



Fast simulations of non-linear scales

No galaxy/halo bias modelling

Simpler baryon models

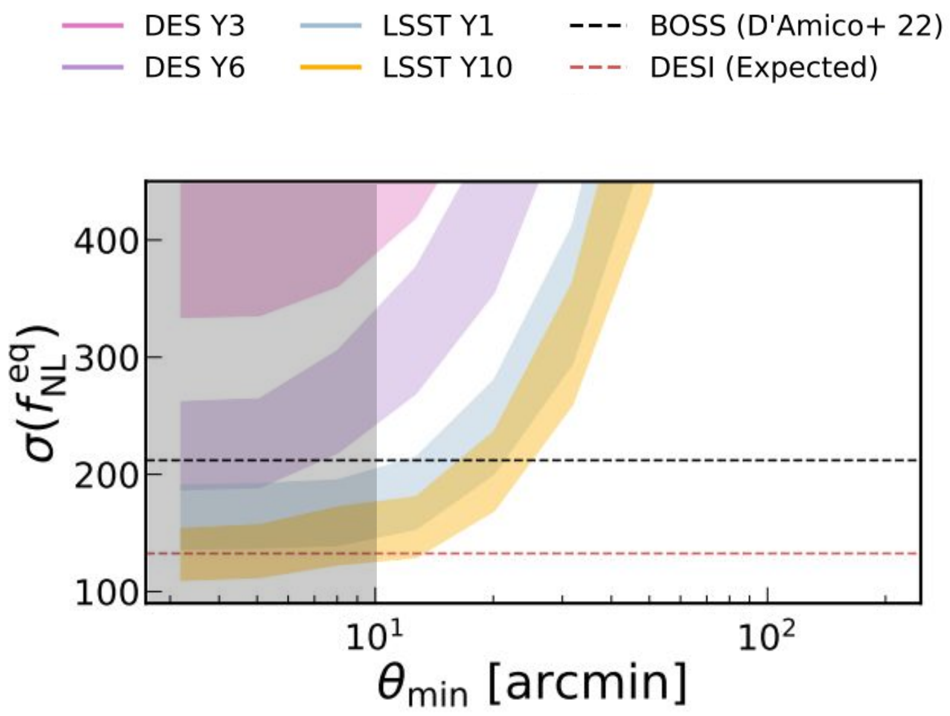
gg-lensing calibration

. . . . but what about the baryons?

Scale cut mitigation

Remove measurements we cannot model

$$10' \sim 5 - 15 \text{ Mpc}$$



Marginalizing over baryons

Account for galaxy formation params, X

$$P(\vec{\theta}|D) = \int P(\vec{\theta}|D, \vec{X})P(\vec{X})d\vec{X}$$

Variety of predictions

Anbajagane, Evrard & Farahi 2022a

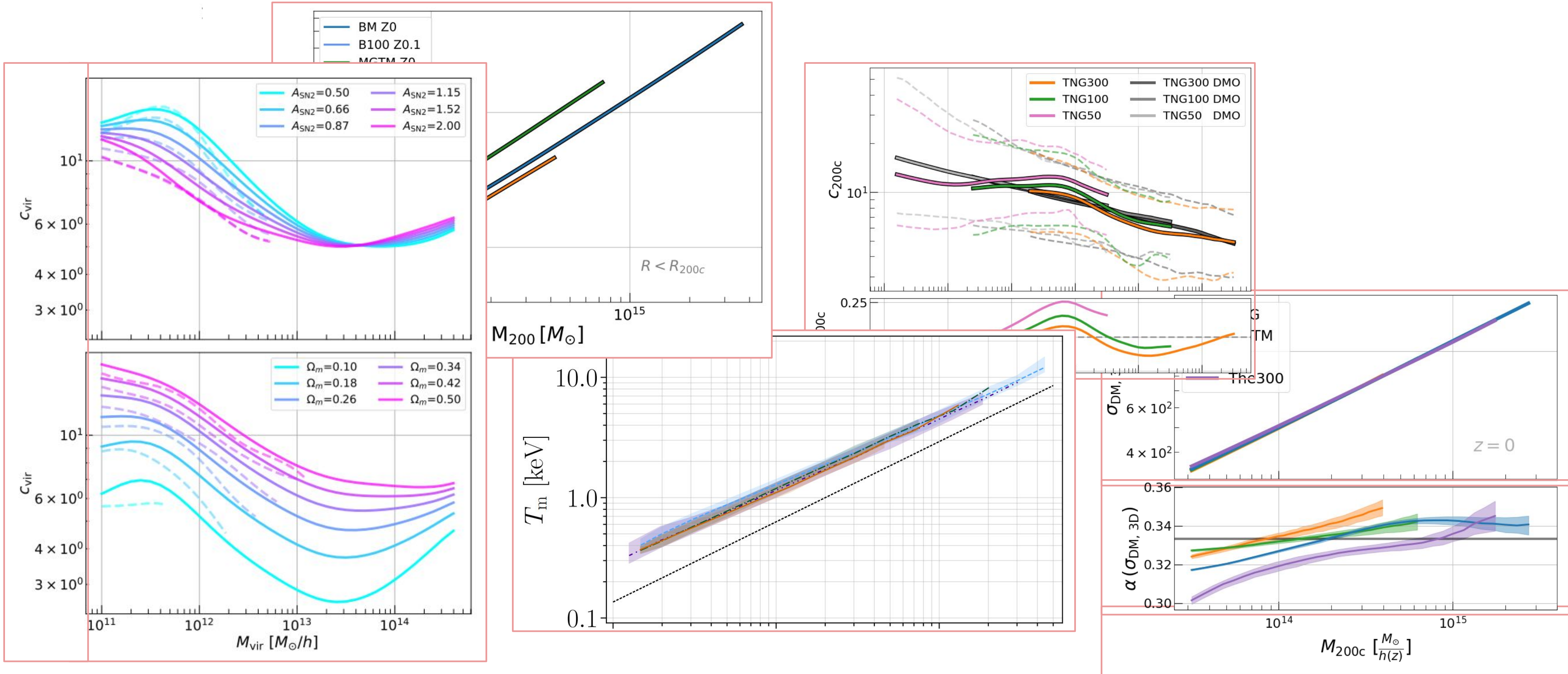
Farahi, Anbajagane & Evrard 2022

Anbajagane+ 2022b

Lee, Anbajagane, Singh, Nagai, Chluba+ 2022

Shao, Anbajagane & Chang 2023

Shao & Anbajagane 2024



Marginalizing over baryons

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$$P(\vec{\theta}|D) = \int P(\vec{\theta}|D, \vec{X})P(\vec{X})d\vec{X}$$

. . . . AND for different astrophysical models, M

$$P(\vec{\theta}|D) = \int\int P(\vec{\theta}|D, \vec{X}_M, M)P(\vec{X}_M)P(M)d\vec{X}_M dM$$

Marginalizing over baryons

Account for galaxy formation params, X

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. . . . AND for different astrophysical models, M

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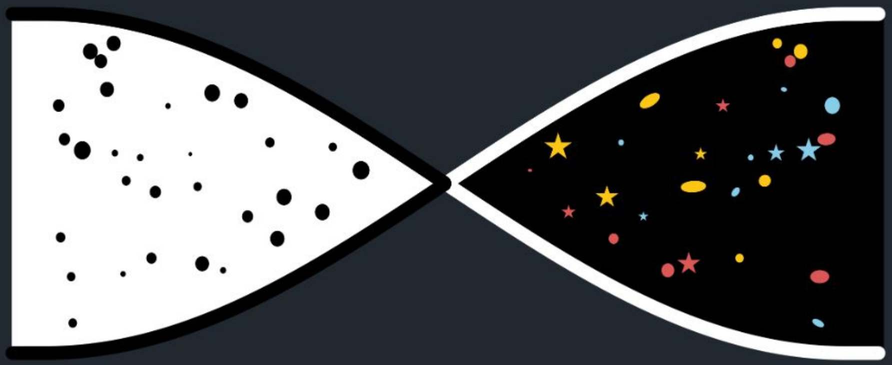
Anbajagane, Chang, & Pandey 2024
github.com/DhayaaAnbajagane/BaryonForge

Phenomenological models

README

The BaryonForge Pipeline



license MIT | python 3.6+ | docs passing

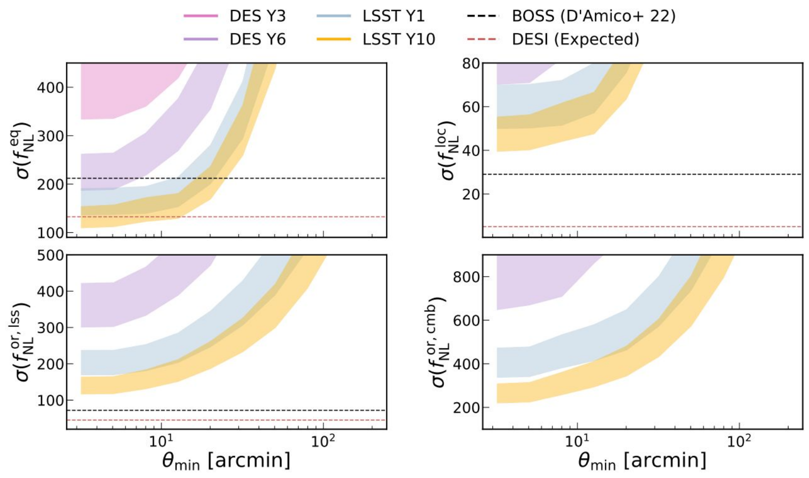
Overview

A pipeline for *Baryonifying* N-body simulations, by adding baryon-induced corrections to the density field and/or adding thermodynamic fields such as the gas pressure, temperature etc. The entire modelling pipeline is built out of

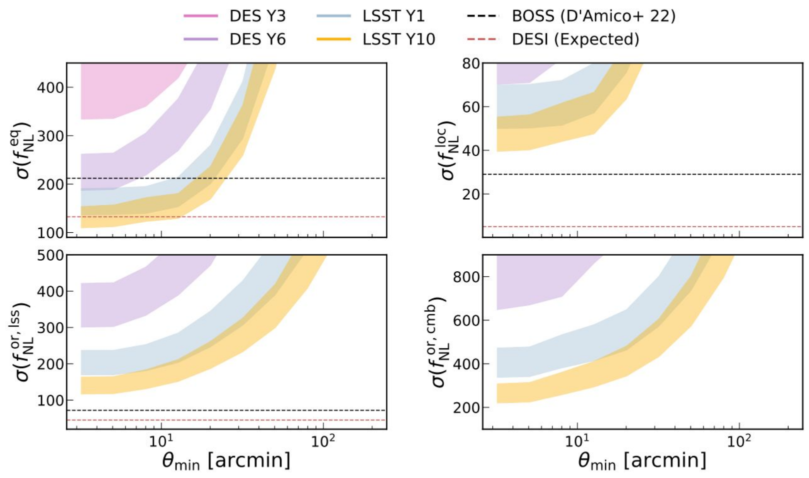
~~. . . . but what about the baryons?~~

. . . . but what about other f_{NL} models?

The primordial frontier



The primordial frontier



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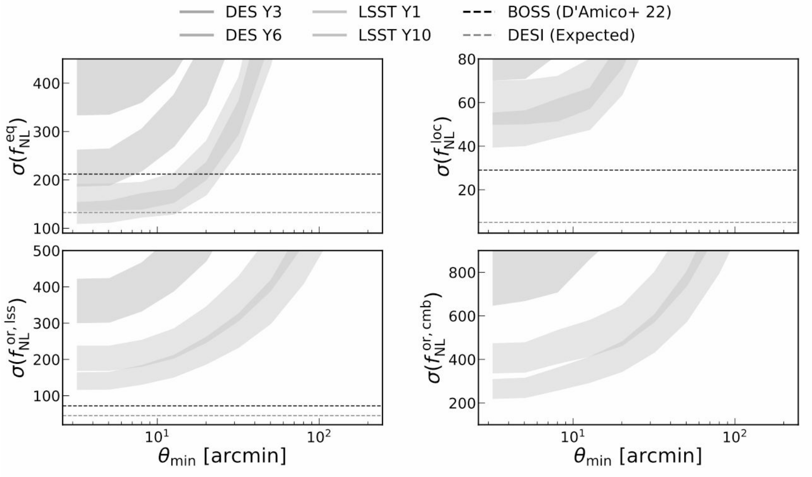


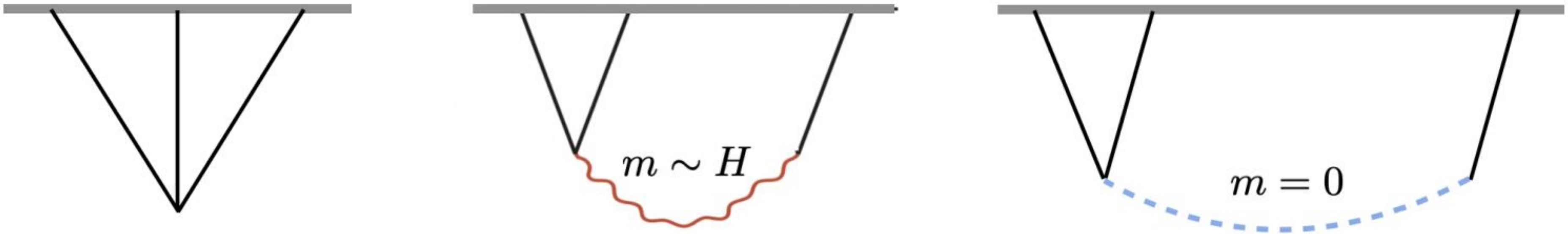
Colliders

$$B^{\rm A}(k_1,k_2,k_3) = \frac{P_s(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_3)}{k_2(k_1k_3)^{3-s}k_t^{2s+1}}\Big[(2s-1)\big((k_1+k_3)k_t+2sk_1k_3\big)+k_t^2\Big]+5\text{ perms}\,, \qquad (2.16)$$

$$B_\nu^{\rm NA}(k_1,k_2,k_3) = \frac{r^{(s)}(\nu)}{k_1^3k_3^3}\left(\frac{k_1}{k_3}\right)^{3/2}\cos\left[\nu\ln\frac{k_1}{k_3}+\varphi\right]P_s(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_3)\Theta(x_*k_3-k_1)+5\text{ perms}\,, \qquad (2.17)$$

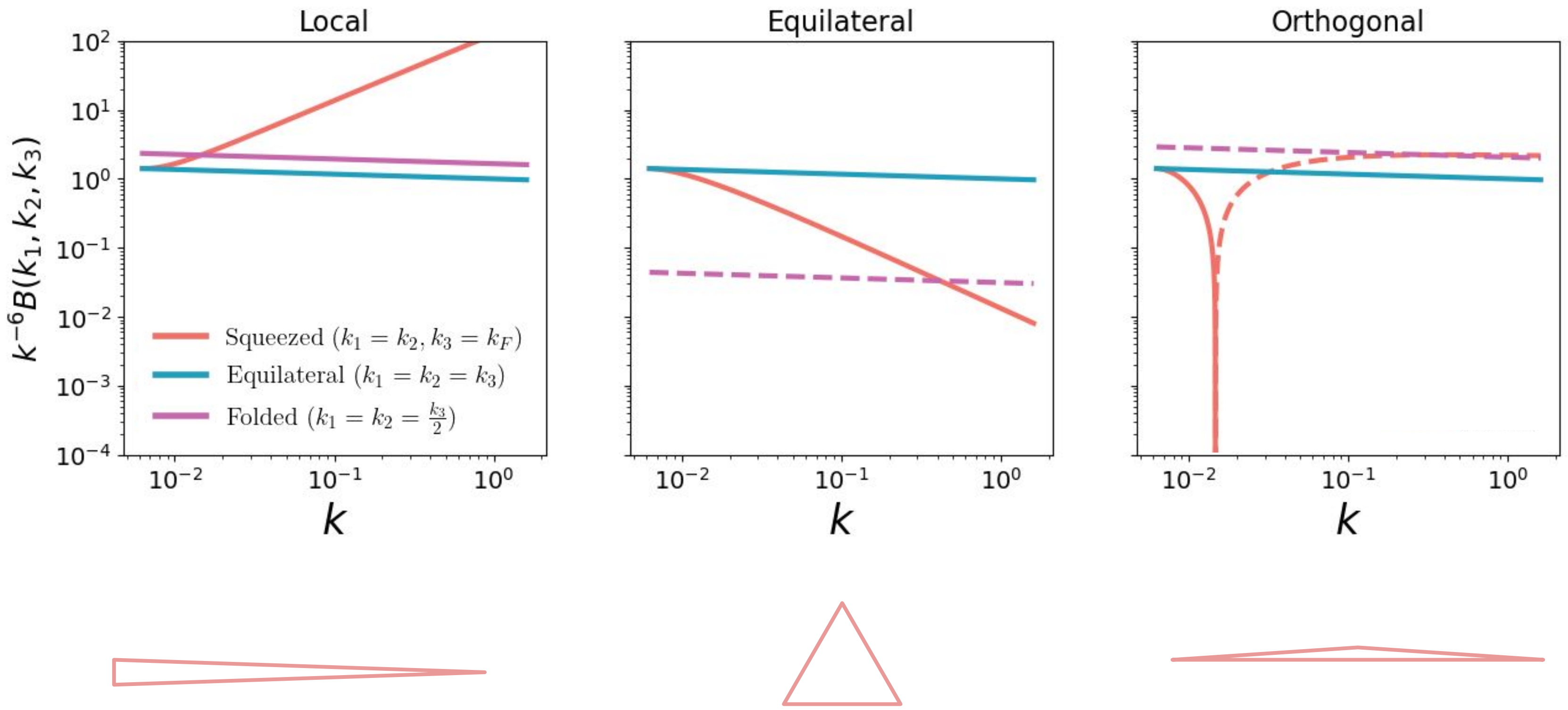
Sohn+ 2023

The Cosmological Collider



a) contact b) massive exchange c) massless exchange

Three standard templates



Non-Gaussian ICs

$$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) + f_{\mathrm{NL}} \int (2\pi)^3 \delta(\vec{\mathbf{k}} - \vec{\mathbf{k}}_{12}) K_{12}(\vec{\mathbf{k}}_1, \vec{\mathbf{k}}_2) \phi_G(\vec{\mathbf{k}}_1) \phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$$

Non-Gaussian ICs

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$$K_{12} = B/(P(k_1)P(k_2))$$

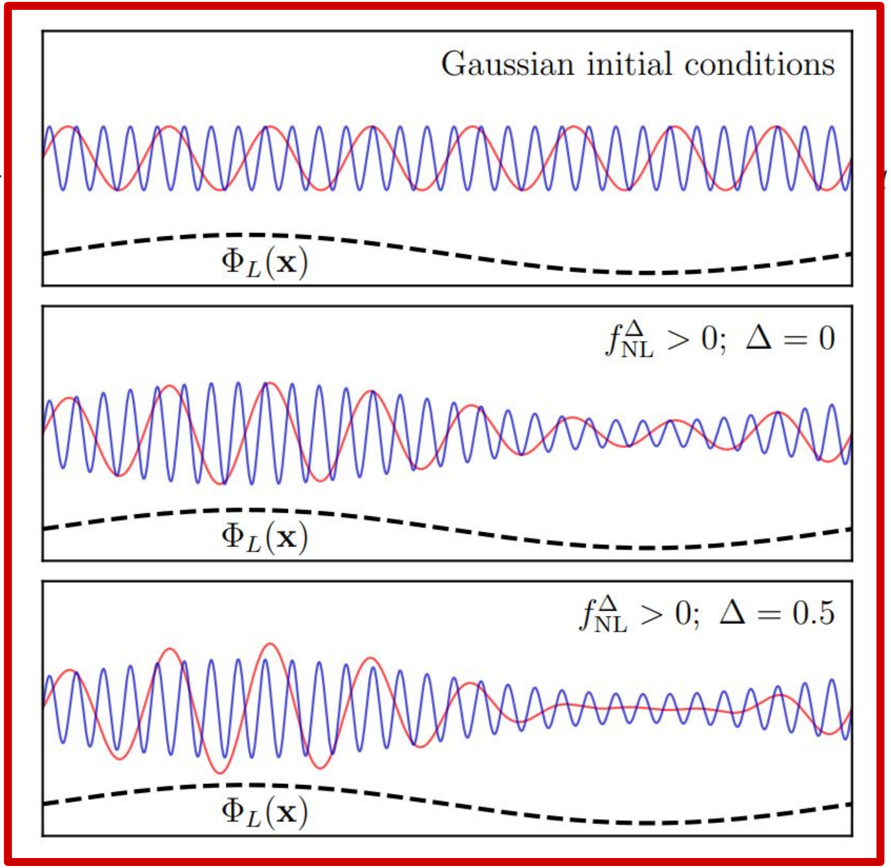
$$S = (k_1 k_2 k_3)^2 B$$

Non-Gaussian ICs

$$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) + f_{\mathrm{NL}} \int (2\pi)^3 \delta(\vec{\mathbf{k}} - \vec{\mathbf{k}}_{12}) K_{12}(\vec{\mathbf{k}}_1, \vec{\mathbf{k}}_2) \phi_G(\vec{\mathbf{k}}_1) \phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$$

Goldstein, Philcox++ 2024

Non-Gaussian ICs

$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) +$ 

$(\vec{\mathbf{k}}_1)\phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$

Non-Gaussian ICs

$$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) + f_{\mathrm{NL}} \int (2\pi)^3 \delta(\vec{\mathbf{k}} - \vec{\mathbf{k}}_{12}) K_{12}(\vec{\mathbf{k}}_1, \vec{\mathbf{k}}_2) \phi_G(\vec{\mathbf{k}}_1) \phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$$

Non-Gaussian ICs

$$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) + f_{\rm NL} \int (2\pi)^3 \delta(\vec{\mathbf{k}} - \vec{\mathbf{k}}_{12}) K_{12}(\vec{\mathbf{k}}_1, \vec{\mathbf{k}}_2) \phi_G(\vec{\mathbf{k}}_1) \phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$$

Non-Gaussian ICs

$$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) + f_{\mathrm{NL}} \int (2\pi)^3 \delta(\vec{\mathbf{k}} - \vec{\mathbf{k}}_{12}) K_{12}(\vec{\mathbf{k}}_1, \vec{\mathbf{k}}_2) \phi_G(\vec{\mathbf{k}}_1) \phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$$

Scales as $\mathbf{N^6}$

Takes $\mathbf{10^{20}}$ floating-point calculations

Non-Gaussian ICs

$$\phi_{NG}(\vec{\mathbf{k}}) = \phi_G(\vec{\mathbf{k}}) + f_{\rm NL} \int (2\pi)^3 \delta(\vec{\mathbf{k}} - \vec{\mathbf{k}}_{12}) K_{12}(\vec{\mathbf{k}}_1, \vec{\mathbf{k}}_2) \phi_G(\vec{\mathbf{k}}_1) \phi_G(\vec{\mathbf{k}}_2) d^3\vec{\mathbf{k}}_1 d^3\vec{\mathbf{k}}_2$$

Scal

Take

Scoccimaro+ 2011

Non-Gaussian ICs

$$\phi(\vec{x}) = \phi_G(\vec{x}) + f_{\rm NL} \mathrm{iFFT}\left[f_3(k_3) \times \mathrm{FFT}\left\{ \mathrm{iFFT}\left(f_1(k_1)\phi_G(k_1) \right) \times \mathrm{iFFT}\left(f_2(k_2)\phi_G(k_2) \right) \right\} \right]$$

$$K_{12}(\vec{k}_1, \vec{k}_2) = K_{12}(k_1, k_2, k_3) = f_1(k_1) f_2(k_2) f_3(k_3)$$

Non-Gaussian ICs

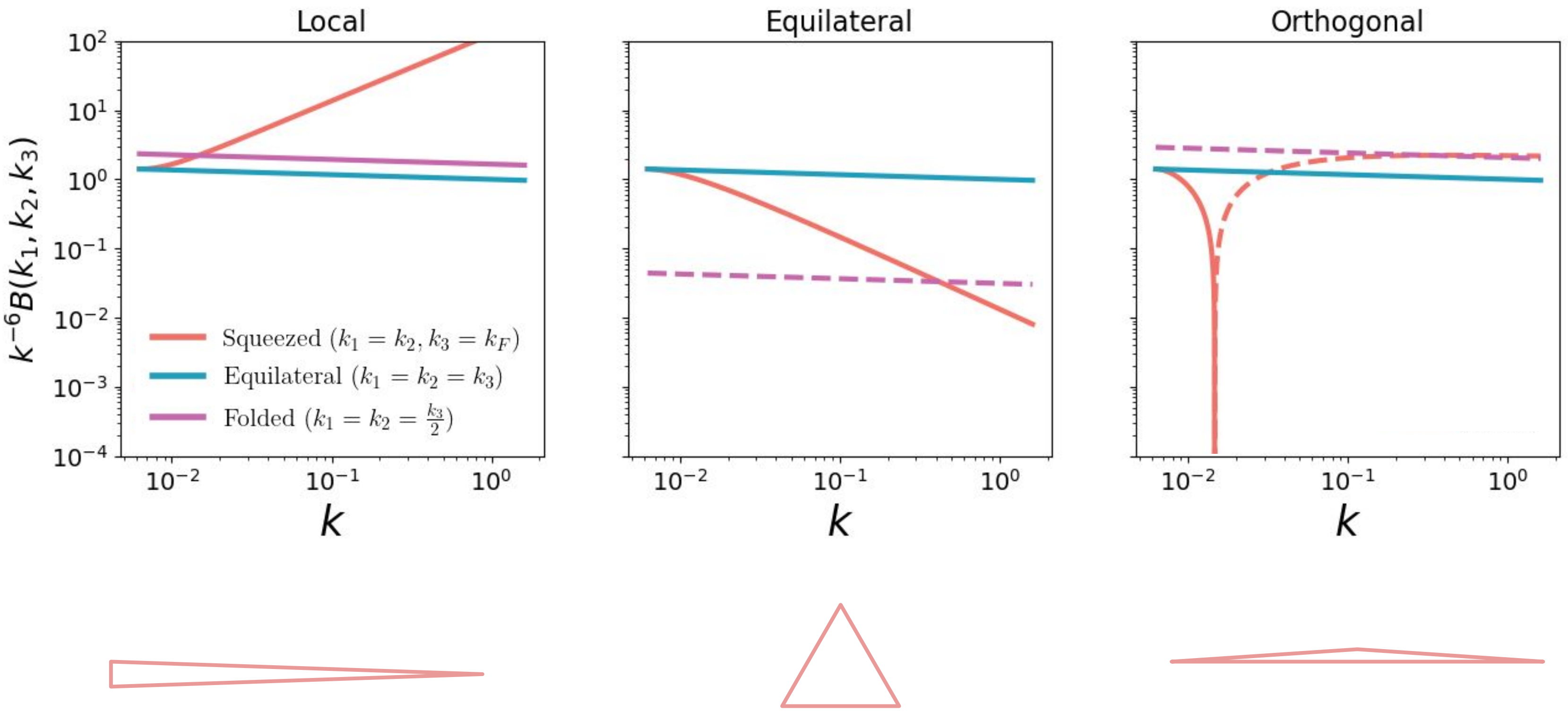
$$\phi(\vec{x}) = \phi_G(\vec{x}) + f_{\rm NL}\,\mathrm{iFFT}\left[f_3(k_3) \times \mathrm{FFT}\left\{\mathrm{iFFT}\left(f_1(k_1)\phi_G(k_1)\right) \times \mathrm{iFFT}\left(f_2(k_2)\phi_G(k_2)\right)\right\}\right]$$

$$K_{12}(\vec{k}_1, \vec{k}_2) = K_{12}(k_1, k_2, k_3) = f_1(k_1) f_2(k_2) f_3(k_3)$$

Scales as **N^3 log(N)**

Can be done on a laptop (if you really want to...)

Three standard templates



Sohn+ 2023

$$
\begin{aligned}
S^{\rm II}_{\rm col.} = &\frac{k_3(k_3^2-k_1^2-k_2^2)}{\beta(k_1+k_2)^3}\left[6-\frac{6\beta k_3}{(\beta+2)k_T}+\frac{2\beta(\beta+1)k_3^2}{(\beta+2)^2k_T^2}+\frac{k_1^2+k_2^2}{k_1k_2}\left(2-\frac{\beta k_3}{(\beta+2)k_T}\right)\right]\left(\frac{k_T}{k_1+k_2}\right)^{-\frac{\beta}{\beta+2}}\\
&+\frac{k_3^2-k_1^2-k_2^2}{k_1k_2}\left(\frac{k_3}{k_1+k_2}\right)^{1/2}\left\{\sqrt{\frac{\pi^3(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_1\right]\right.\\
&\left.+\frac{k_1k_2}{(k_1+k_2)^2}\sqrt{\frac{\pi^3\beta(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_2\right]\right\}\\
&+\frac{k_3\left(k_1^2+k_2^2-k_3^2\right)}{12\cosh(\pi\mu)k_1k_2(k_1+k_2)^4}\left[2\left(2\mu^4-1\right)(k_1+k_2)\left((k_1^2+k_2^2+3k_1k_2)\log^2\left(\frac{k_T}{k_1+k_2}\right)\right.\right.\\
&+\frac{k_3}{k_T^2}(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+7k_1k_2(k_1+k_2)+5k_1k_2k_3)\log\left(\frac{k_T}{k_1+k_2}\right)+\left.\frac{k_1k_2k_3^2}{k_T^2}\right)\\
&+\mu^2k_3\left(\frac{k_3}{k_1+k_2}\right)^{\frac{8\mu^2}{8\mu^2+1}}\left(\frac{32\mu^2+3}{8\mu^2+1}\left(\frac{k_1k_2}{8\mu^2+1}-k_1^2-k_2^2-5k_1k_2\right)\log\left(\frac{k_T}{k_1+k_2}\right)\right.\\
&\left.\left.+\frac{2}{8\mu^2+1}\frac{k_1k_2k_3}{k_T}-\frac{k_3}{k_T^2}\left(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+11k_1k_2(k_1+k_2)+9k_1k_2k_3\right)\right)\right]+2\ \text{perms.}
\end{aligned}
$$

$$S^{\rm II}_{\rm col.} = \frac{k_3(k_3^2-k_1^2-k_2^2)}{\beta(k_1+k_2)^3}\Bigg[6-\frac{6\beta k_3}{(\beta+2)k_T}+\frac{2\beta(\beta+1)k_3^2}{(\beta+2)^2k_T^2}+\frac{k_1^2+k_2^2}{k_1k_2}\left(2-\frac{\beta k_3}{(\beta+2)k_T}\right)\Bigg]\left(\frac{k_T}{k_1+k_2}\right)^{-\frac{\beta}{\beta+2}}$$

$$+\frac{k_3^2-k_1^2-k_2^2}{k_1k_2}\left(\frac{k_3}{k_1+k_2}\right)^{1/2}\Bigg\{\sqrt{\frac{\pi^3(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_1\right]$$

$$+\frac{k_1k_2}{(k_1+k_2)^2}\sqrt{\frac{\pi^3\beta(\beta+2)}{\mu\sinh(2}}$$ [illegible]

$$+\frac{k_3\,(k_1^2+k_2^2-k_3^2}{12\cosh(\pi\mu)k_1k_2(k_1+}$$ [illegible] $$k_1k_2)\log^2\left(\frac{k_T}{k_1+k_2}\right)$$

$$+\frac{k_3}{k_T^2}(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+7k_1k_2(k_1+k_2)+5k_1k_2k_3)\log\left(\frac{k_T}{k_1+k_2}\right)+\frac{k_1k_2k_3^2}{k_T^2}\Bigg)$$

$$+\mu^2k_3\left(\frac{k_3}{k_1+k_2}\right)^{\frac{8\mu^2}{8\mu^2+1}}\Bigg(\frac{32\mu^2+3}{8\mu^2+1}\left(\frac{k_1k_2}{8\mu^2+1}-k_1^2-k_2^2-5k_1k_2\right)\log\left(\frac{k_T}{k_1+k_2}\right)$$

$$+\frac{2}{8\mu^2+1}\frac{k_1k_2k_3}{k_T}-\frac{k_3}{k_T^2}\Big(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+11k_1k_2(k_1+k_2)+9k_1k_2k_3\Big)\Bigg)\Bigg]+2\text{ perms.}$$

$$(\partial_i\phi)^2\sigma$$

Lorentz Invariance, Conformal symm., Unitarity, etc etc

$$(\partial_i\phi)^2\sigma$$

$$+\mu^2 k_3\left(\frac{k_3}{k_1+k_2}\right)^{\frac{8\mu^2}{8\mu^2+1}}\left(\frac{32\mu^2+3}{8\mu^2+1}\left(\frac{k_1k_2}{8\mu^2+1}-k_1^2-k_2^2-5k_1k_2\right)\log\left(\frac{k_T}{k_1+k_2}\right)\right.$$

$$\left.\left.+\frac{2}{8\mu^2+1}\frac{k_1k_2k_3}{k_T}-\frac{k_3}{k_T^2}\left(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+11k_1k_2(k_1+k_2)+9k_1k_2k_3\right)\right)\right]+2\text{ perms.}$$

$$
\begin{aligned}
S^{\mathrm{II}}_{\mathrm{col.}} = {} & \frac{k_3(k_3^2-k_1^2-k_2^2)}{\beta(k_1+k_2)^3}\left[6-\frac{6\beta k_3}{(\beta+2)k_T}+\frac{2\beta(\beta+1)k_3^2}{(\beta+2)^2k_T^2}+\frac{k_1^2+k_2^2}{k_1k_2}\left(2-\frac{\beta k_3}{(\beta+2)k_T}\right)\right]\left(\frac{k_T}{k_1+k_2}\right)^{-\frac{\beta}{\beta+2}} \\
& + \frac{k_3^2-k_1^2-k_2^2}{k_1k_2}\left(\frac{k_3}{k_1+k_2}\right)^{1/2}\left\{\sqrt{\frac{\pi^3(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_1\right]\right. \\
& \left. + \frac{k_1k_2}{(k_1+k_2)^2}\sqrt{\frac{\pi^3\beta(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_2\right]\right\} \\
& + \frac{k_3\left(k_1^2+k_2^2-k_3^2\right)}{12\cosh(\pi\mu)k_1k_2(k_1+k_2)^4}\left[2\left(2\mu^4-1\right)(k_1+k_2)\left((k_1^2+k_2^2+3k_1k_2)\log^2\left(\frac{k_T}{k_1+k_2}\right)\right.\right. \\
& \left. + \frac{k_3}{k_T^2}(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+7k_1k_2(k_1+k_2)+5k_1k_2k_3)\log\left(\frac{k_T}{k_1+k_2}\right)+\frac{k_1k_2k_3^2}{k_T^2}\right) \\
& + \mu^2k_3\left(\frac{k_3}{k_1+k_2}\right)^{\frac{8\mu^2}{8\mu^2+1}}\left(\frac{32\mu^2+3}{8\mu^2+1}\left(\frac{k_1k_2}{8\mu^2+1}-k_1^2-k_2^2-5k_1k_2\right)\log\left(\frac{k_T}{k_1+k_2}\right)\right. \\
& \left.\left. + \frac{2}{8\mu^2+1}\frac{k_1k_2k_3}{k_T}-\frac{k_3}{k_T^2}\left(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+11k_1k_2(k_1+k_2)+9k_1k_2k_3\right)\right)\right] + 2\ \text{perms.}
\end{aligned}
$$

$$
K_{12}(k_1,k_2,k_3) = f_1(k_1)f_2(k_2)f_3(k_3)
$$

$$
\begin{aligned}
S^{\mathrm{II}}_{\mathrm{col.}} = {} & \frac{k_3(k_3^2-k_1^2-k_2^2)}{\beta(k_1+k_2)^3}\Bigg[6-\frac{6\beta k_3}{(\beta+2)k_T}+\frac{2\beta(\beta+1)k_3^2}{(\beta+2)^2k_T^2}+\frac{k_1^2+k_2^2}{k_1k_2}\left(2-\frac{\beta k_3}{(\beta+2)k_T}\right)\Bigg]\left(\frac{k_T}{k_1+k_2}\right)^{-\frac{\beta}{\beta+2}} \\
& + \frac{k_3^2-k_1^2-k_2^2}{k_1k_2}\left(\frac{k_3}{k_1+k_2}\right)^{1/2}\Bigg\{\sqrt{\frac{\pi^3(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_1\right] \\
& + \frac{k_1k_2}{(k_1+k_2)^2}\sqrt{\frac{\pi^3\beta(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_2\right]\Bigg\} \\
& + \frac{k_3\left(k_1^2+k_2^2-k_3^2\right)}{12\cosh(\pi\mu)k_1k_2(k_1+k_2)^4}\Bigg[2\left(2\mu^4-1\right)(k_1+k_2)\Bigg((k_1^2+k_2^2+3k_1k_2)\log^2\left(\frac{k_T}{k_1+k_2}\right) \\
& + \frac{k_3}{k_T^2}(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+7k_1k_2(k_1+k_2)+5k_1k_2k_3)\log\left(\frac{k_T}{k_1+k_2}\right)+\frac{k_1k_2k_3^2}{k_T^2}\Bigg) \\
& + \mu^2k_3\left(\frac{k_3}{k_1+k_2}\right)^{\frac{8\mu^2}{8\mu^2+1}}\Bigg(\frac{32\mu^2+3}{8\mu^2+1}\left(\frac{k_1k_2}{8\mu^2+1}-k_1^2-k_2^2-5k_1k_2\right)\log\left(\frac{k_T}{k_1+k_2}\right) \\
& + \frac{2}{8\mu^2+1}\frac{k_1k_2k_3}{k_T}-\frac{k_3}{k_T^2}\left(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+11k_1k_2(k_1+k_2)+9k_1k_2k_3\right)\Bigg)\Bigg] + 2\text{ perms.}
\end{aligned}
$$

$$K(k_1,k_2,k_3) = \sum_{a,b,c} \alpha_{abc} \times q_a(k_1)q_b(k_2)q_c(k_3)$$

Anbajagane & Lee 2025a, 2025b

Basis functions

$$q_i(k) = \begin{cases} k^{\frac{4-n_s}{3}(i-3)} & \text{if } i \leq 3 \\ \mathcal{P}_{i-1}(\tilde{k}) - A_{i-1} & \text{if } i > 3 \end{cases}$$

$$K(k_1, k_2, k_3) = \sum_{a,b,c} \alpha_{abc} \times q_a(k_1) q_b(k_2) q_c(k_3)$$

Anbajagane & Lee 2025a, 2025b

Basis functions

$$q_i(k) = \begin{cases} k^{\frac{4-n_s}{3}(i-3)} & \text{if } i \leq 3 \\ \mathcal{P}_{i-1}(\tilde{k}) - A_{i-1} & \text{if } i > 3 \end{cases}$$

Using around

$$N_{\max} = 15, N_{\text{modes}} = 455$$

Anbajagane & Lee 2025a, 2025b

Basis functions

Local, Equil., Ortho.

$$q_i(k) = \begin{cases} k^{\frac{4-n_s}{3}(i-3)} & \text{if } i \leq 3 \\ \mathcal{P}_{i-1}(\tilde{k}) - A_{i-1} & \text{if } i > 3 \end{cases}$$

Anbajagane & Lee 2025a, 2025b

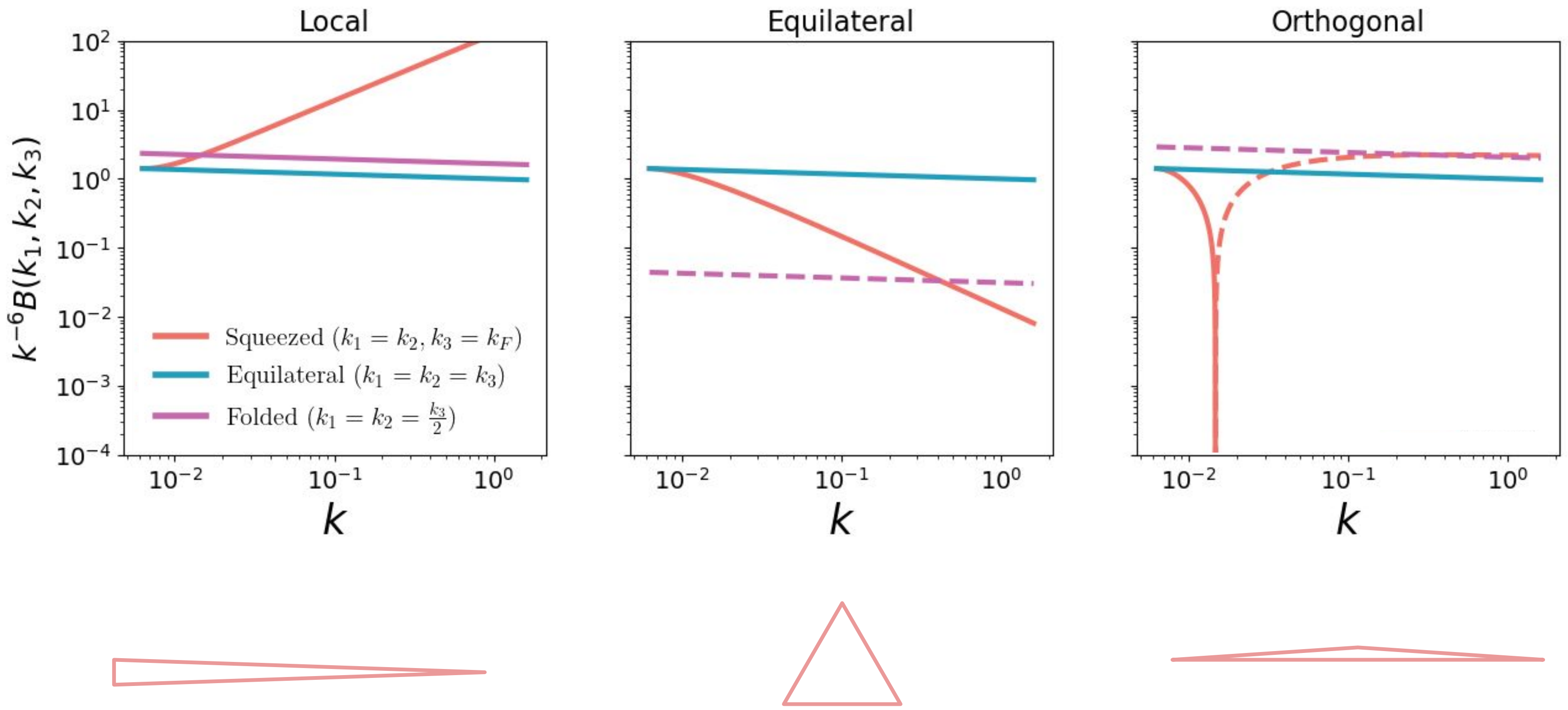
Basis functions

$$\tilde{k} = -1 + 2\frac{k^x - k^x_{\rm min}}{k^x_{\rm max} - k^x_{\rm min}}$$

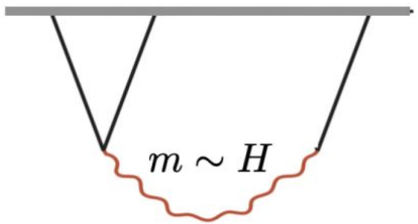
$$q_i(k) = \begin{cases} k^{\frac{4-n_s}{3}(i-3)} & \text{if } i \leq 3 \\ \mathcal{P}_{i-1}(\tilde{k}) - A_{i-1} & \text{if } i > 3 \end{cases}$$

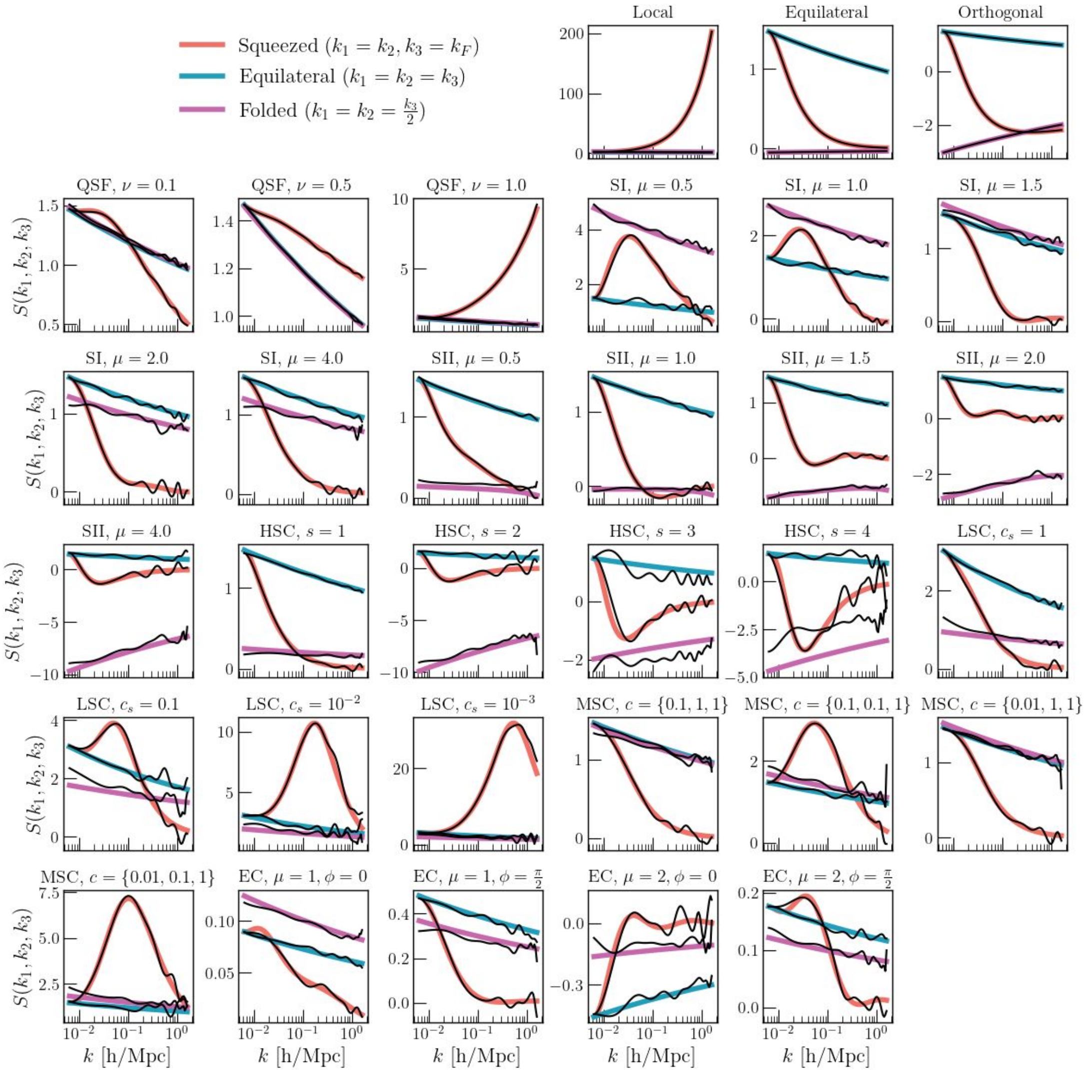
Modified legendre polynomials

Three standard templates



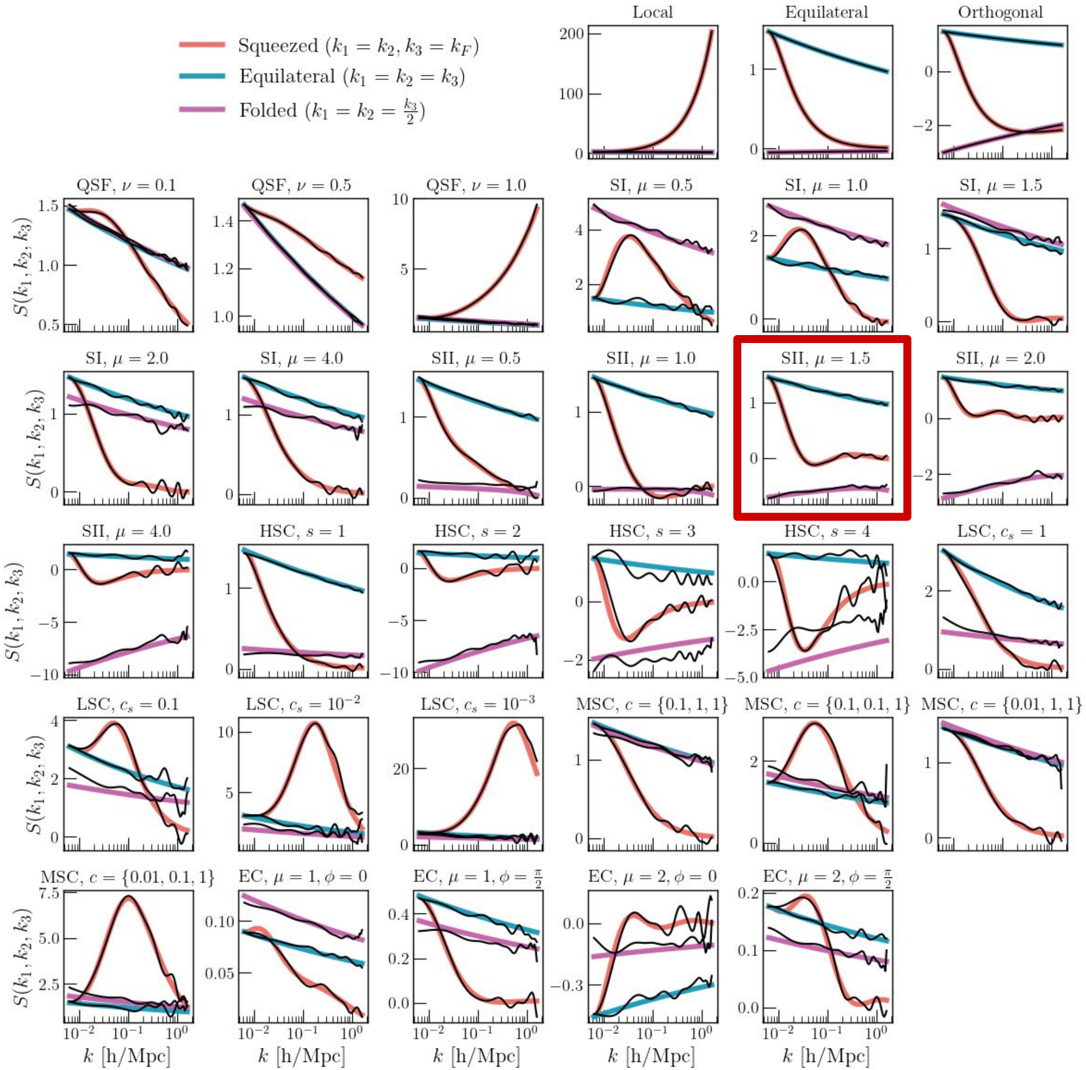
Thirty new templates





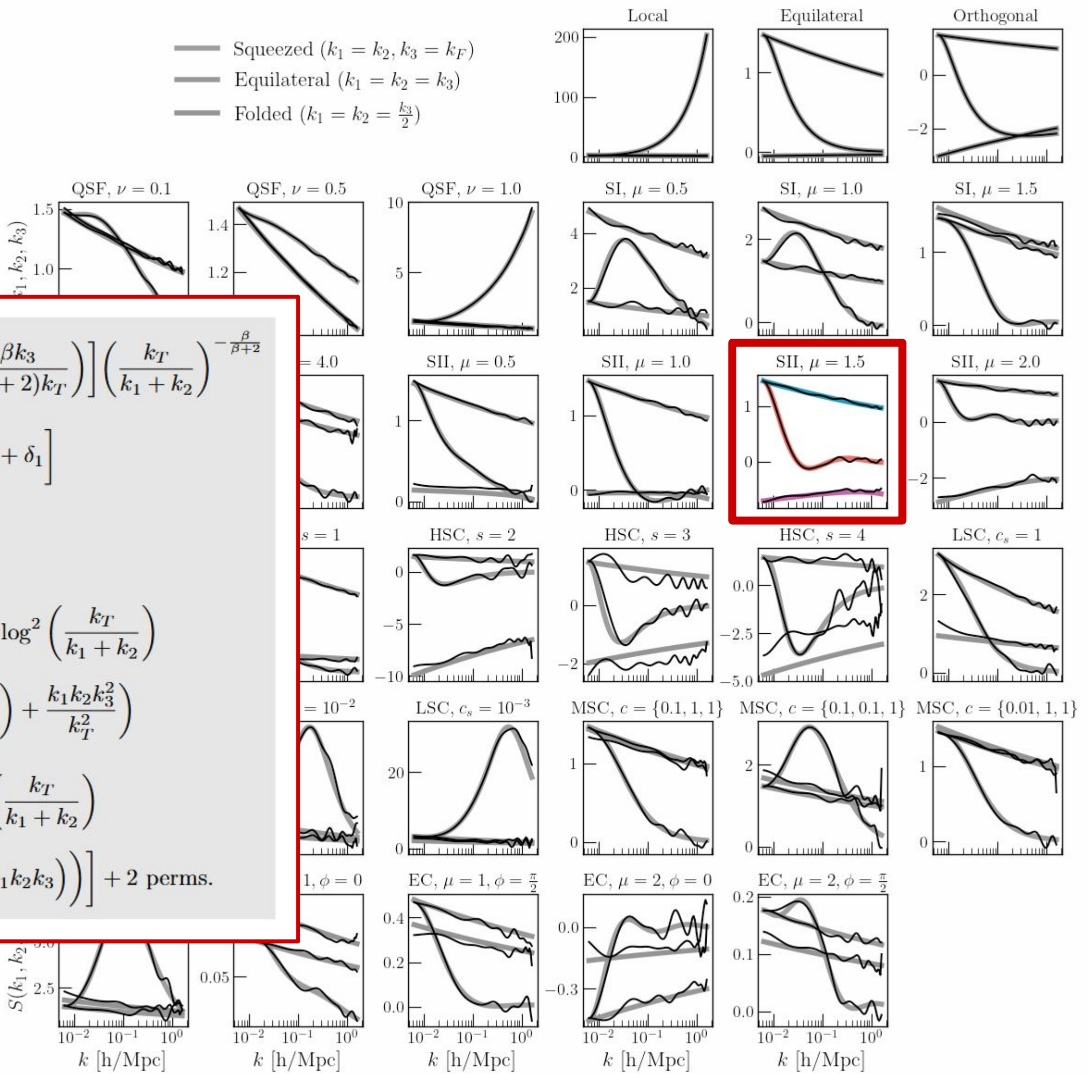
Anbajagane & Lee 2025a, 2025b

Thirty new templates



Anbajagane & Lee 2025a, 2025b

Thirty new templates



$$
\begin{aligned}
S^{\rm II}_{\rm col.} = {} & \frac{k_3(k_3^2-k_1^2-k_2^2)}{\beta(k_1+k_2)^3}\left[6-\frac{6\beta k_3}{(\beta+2)k_T}+\frac{2\beta(\beta+1)k_3^2}{(\beta+2)^2k_T^2}+\frac{k_1^2+k_2^2}{k_1k_2}\left(2-\frac{\beta k_3}{(\beta+2)k_T}\right)\right]\left(\frac{k_T}{k_1+k_2}\right)^{-\frac{\beta}{\beta+2}} \\
& + \frac{k_3^2-k_1^2-k_2^2}{k_1k_2}\left(\frac{k_3}{k_1+k_2}\right)^{1/2}\Bigg\{\sqrt{\frac{\pi^3(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_1\right] \\
& + \frac{k_1k_2}{(k_1+k_2)^2}\sqrt{\frac{\pi^3\beta(\beta+2)}{\mu\sinh(2\pi\mu)}}\cos\left[\mu\log\left(\frac{k_3}{2(k_1+k_2)}\right)+\delta_2\right]\Bigg\} \\
& + \frac{k_3\left(k_1^2+k_2^2-k_3^2\right)}{12\cosh(\pi\mu)k_1k_2(k_1+k_2)^4}\Bigg[2\left(2\mu^4-1\right)(k_1+k_2)\Bigg(\left(k_1^2+k_2^2+3k_1k_2\right)\log^2\left(\frac{k_T}{k_1+k_2}\right) \\
& + \frac{k_3}{k_T^2}\left(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+7k_1k_2(k_1+k_2)+5k_1k_2k_3\right)\log\left(\frac{k_T}{k_1+k_2}\right)+\frac{k_1k_2k_3^2}{k_T^2}\Bigg) \\
& + \mu^2k_3\left(\frac{k_3}{k_1+k_2}\right)^{\frac{8\mu^2}{8\mu^2+1}}\Bigg(\frac{32\mu^2+3}{8\mu^2+1}\left(\frac{k_1k_2}{8\mu^2+1}-k_1^2-k_2^2-5k_1k_2\right)\log\left(\frac{k_T}{k_1+k_2}\right) \\
& + \frac{2}{8\mu^2+1}\frac{k_1k_2k_3}{k_T}-\frac{k_3}{k_T^2}\left(k_1^3+k_2^3+(k_1^2+k_2^2)k_3+11k_1k_2(k_1+k_2)+9k_1k_2k_3\right)\Bigg)\Bigg] + 2\text{ perms.}
\end{aligned}
$$

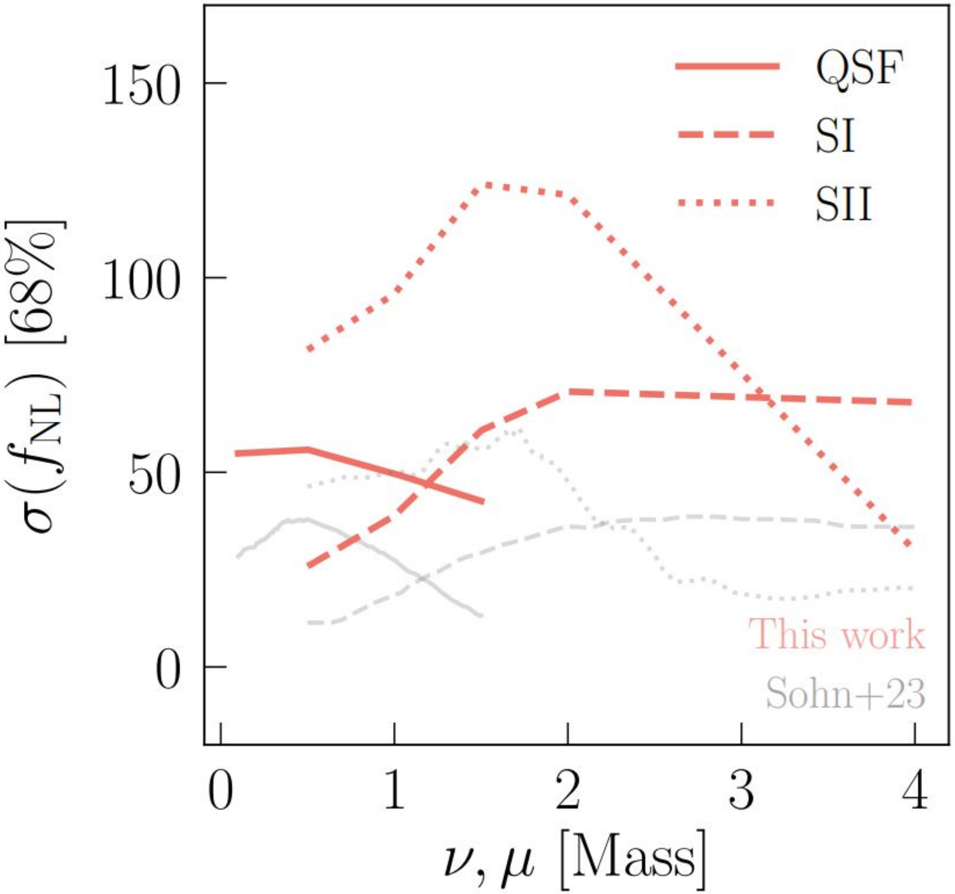
Consistency checks

Consistency checks

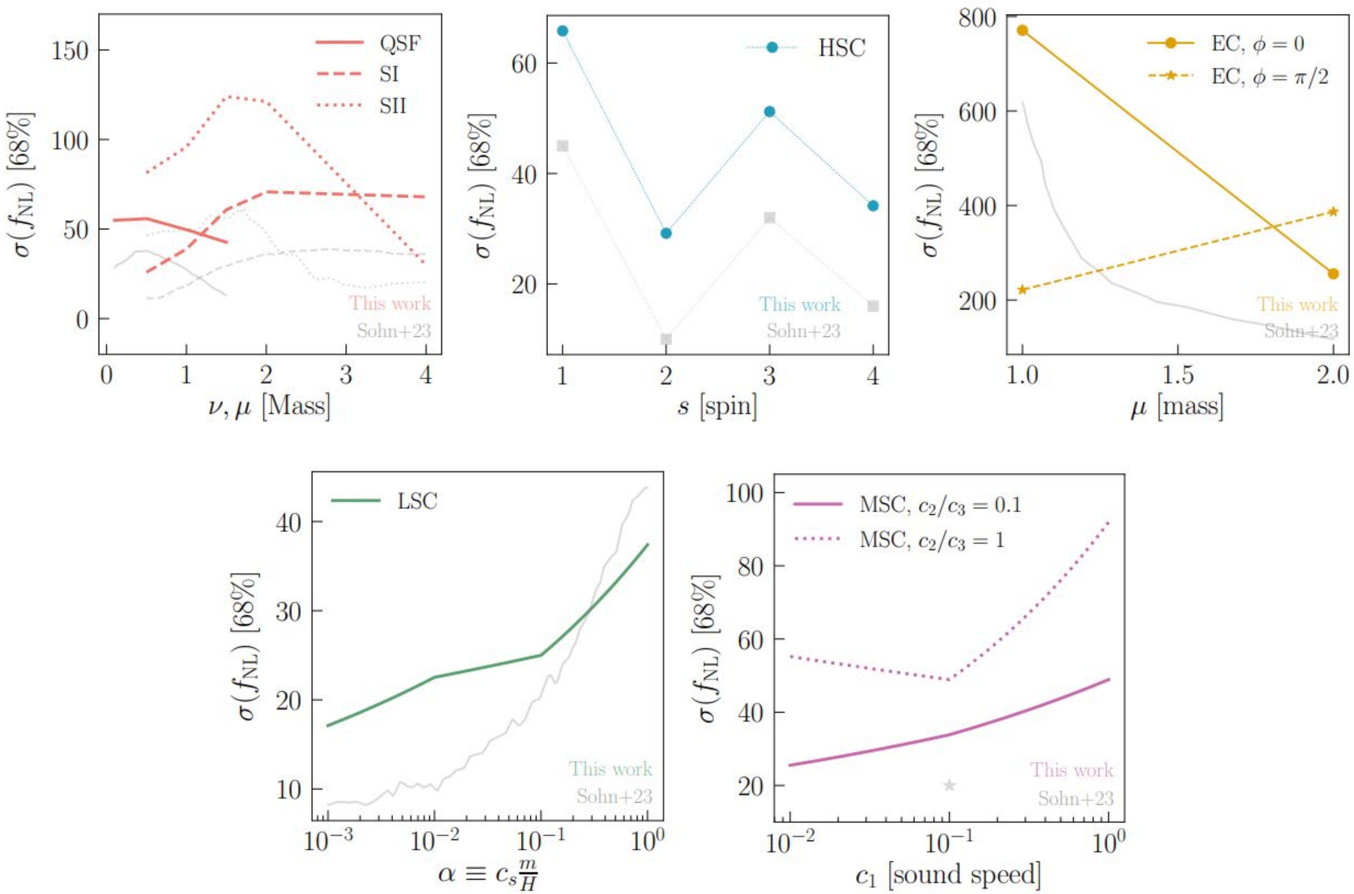
1. Recover the input B(k) ✅
2. Preserve tree-level P(k) ✅
3. Suppressed T(k) terms ✅

Anbajagane & Lee 2025a, 2025b

Constraints from LSST Y10 lensing

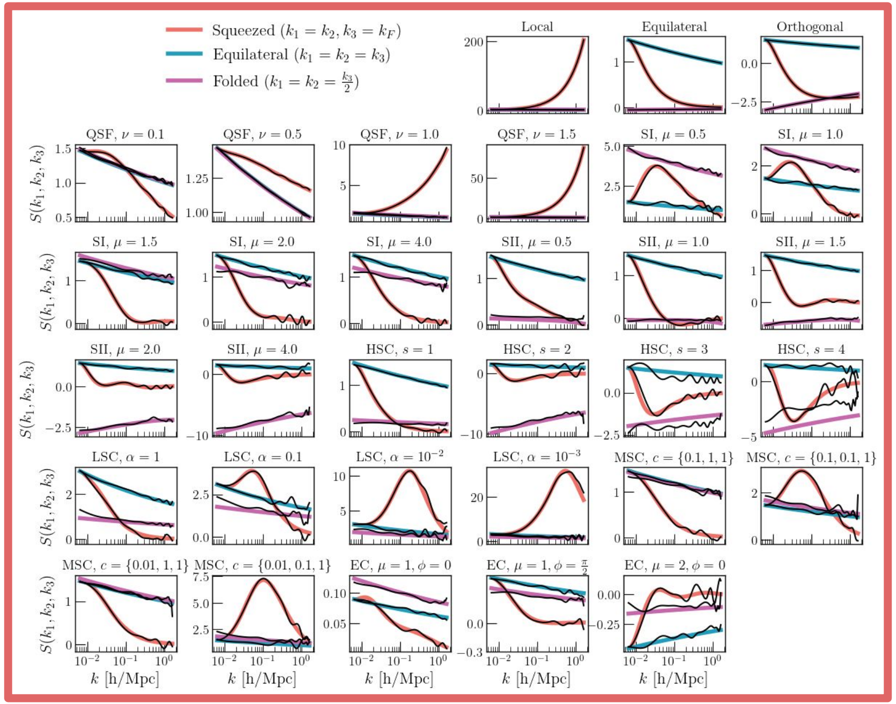


Constraints from LSST Y10 lensing



Beyond Colliders

Many more templates



Beyond Colliders

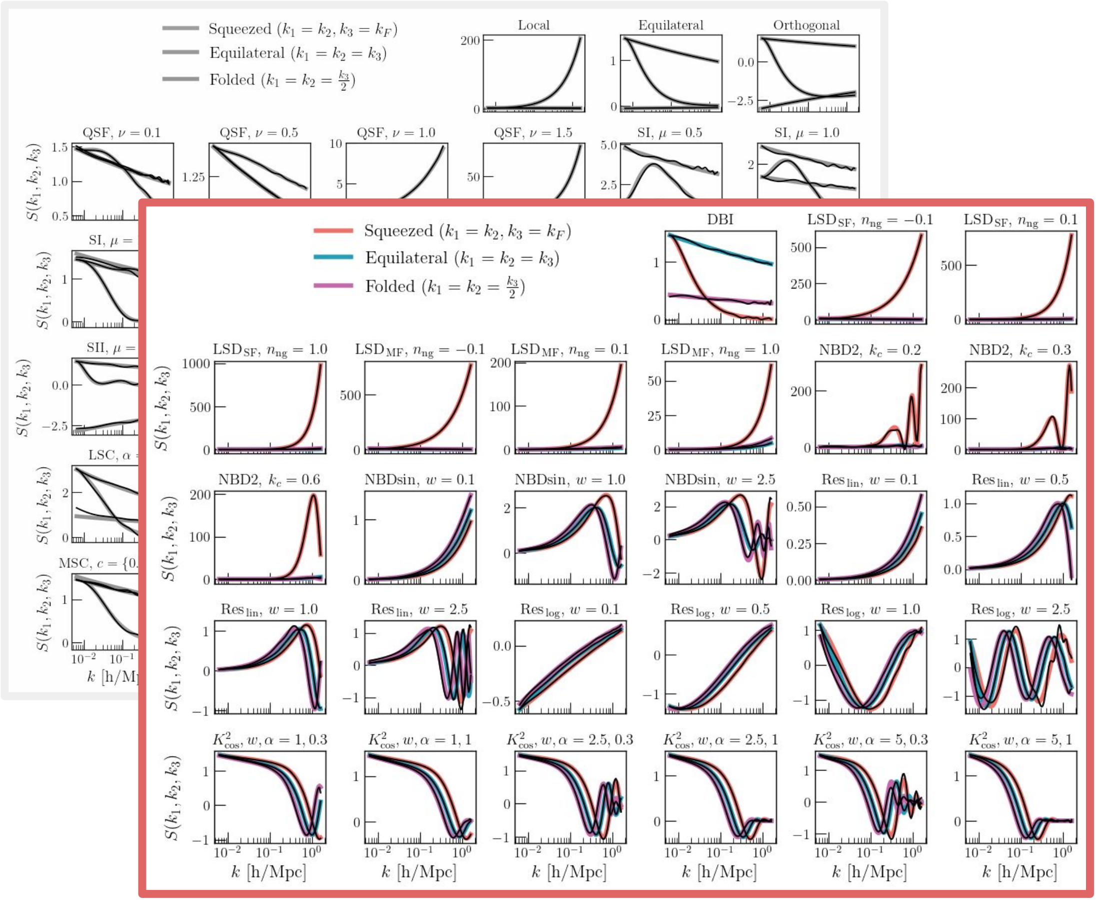
Many more templates

Resonant particle prod.

Scale dependence

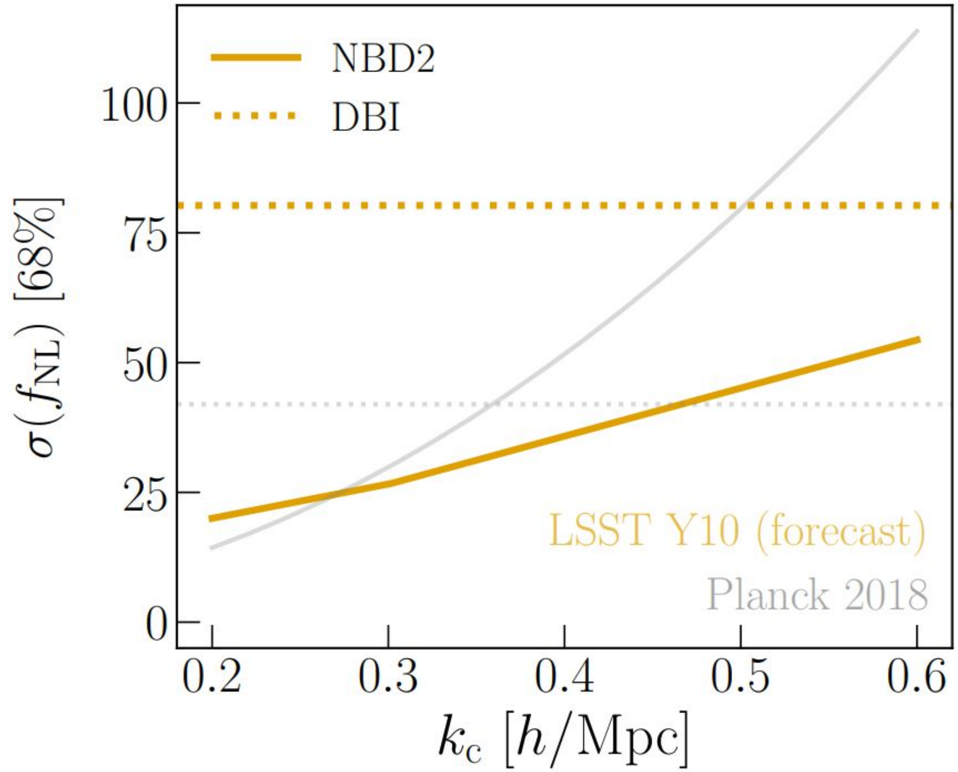
Excited initial states

More!



[Anbajagane & Lee 2025a](), [2025b]()

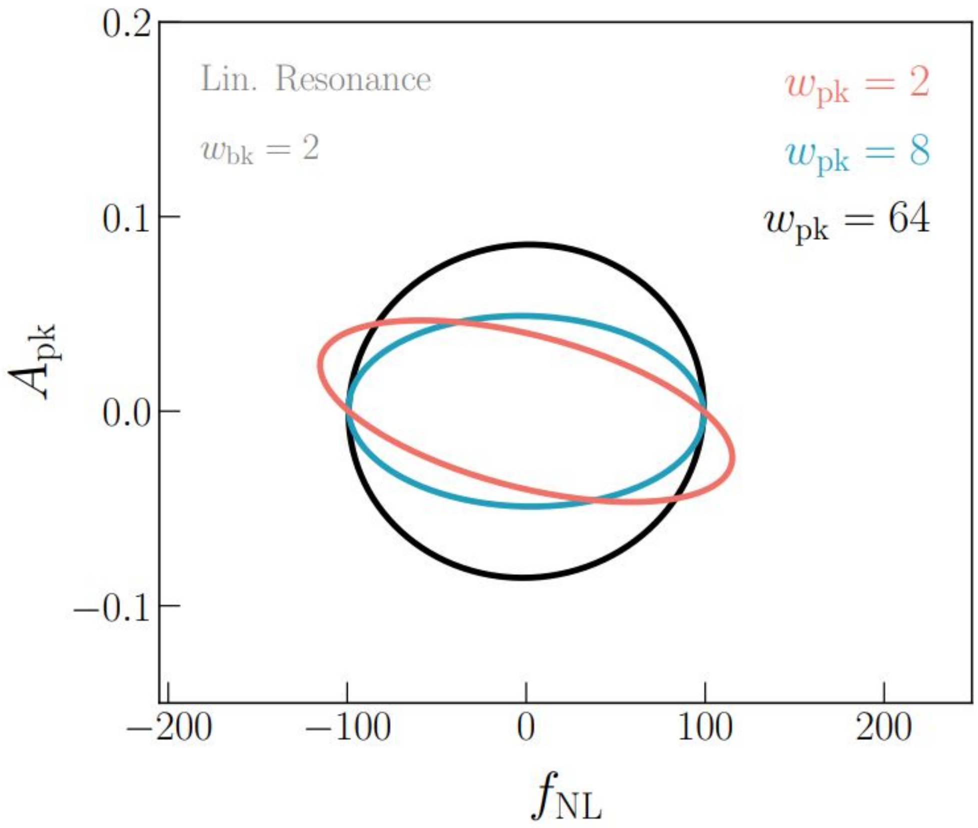
Particularly good when signals are on small scales!



Anbajagane & Lee 2025a, 2025b

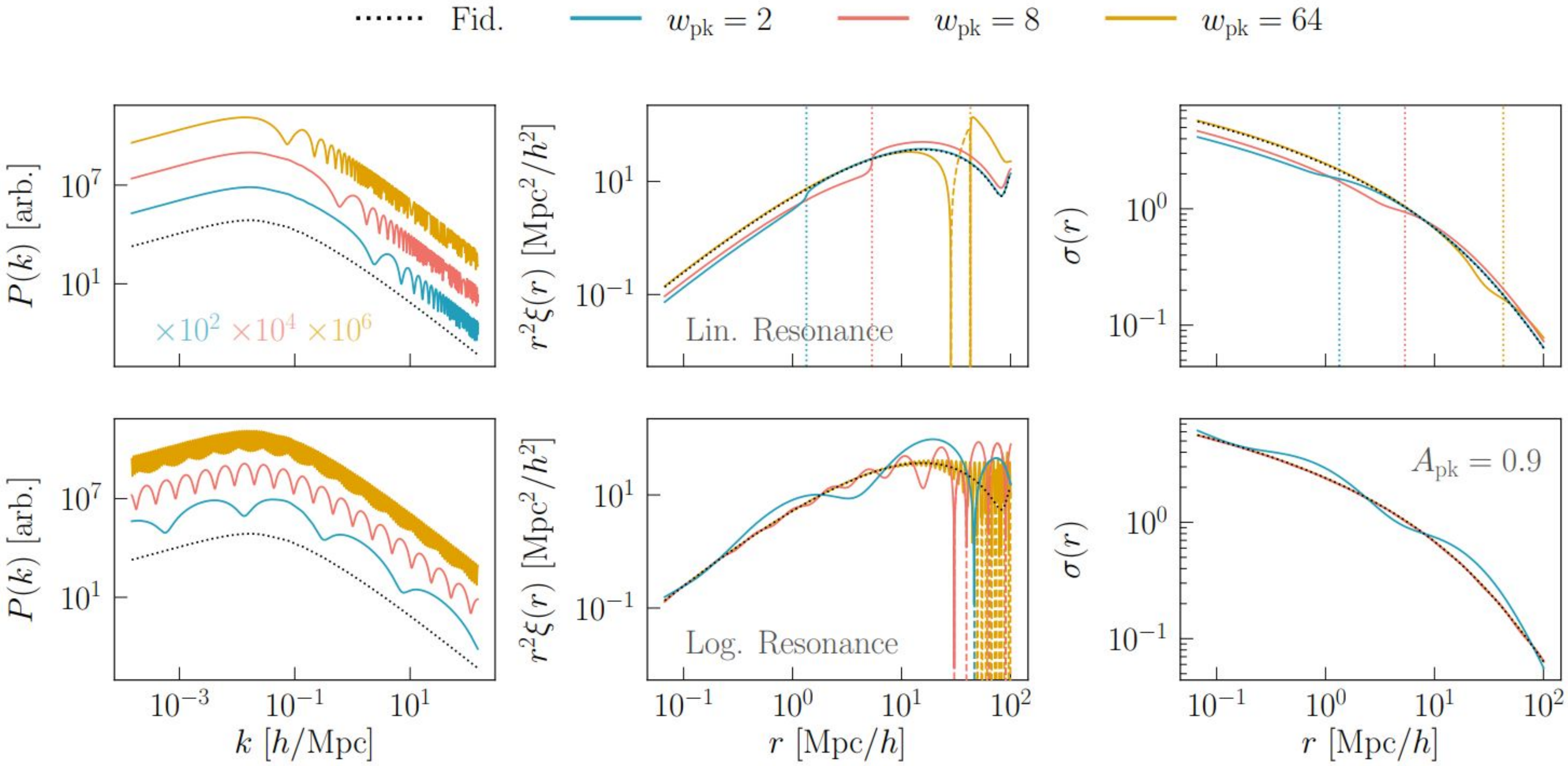
P(k) signals are distinct from the B(k) signals!

A_{pk} is an order-of-mag better



Anbajagane & Lee 2025a, 2025b

Intuition from linear theory



Make your own!

Anbajagane & Lee 2025a, 2025b

github.com/DhayaaAnbajagane/Aarambam

README

license GPL | python 3.6+ | docs passing

Overview

`Aarambam` *(pronounced "Aah-rum-bum", named after the Tamil word for beginnings)* is a codebase for generating initial conditions (ICs) corresponding to arbitrary bispectrum templates.

In under 10 lines of code!

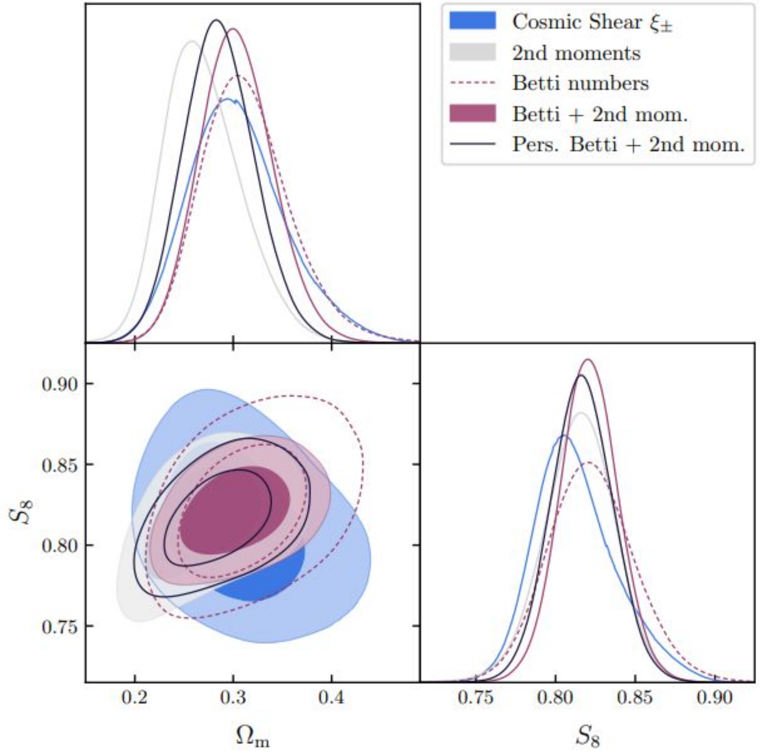
Anbajagane & Lee 2025a, 2025b

github.com/DhayaaAnbajagane/Aarambam

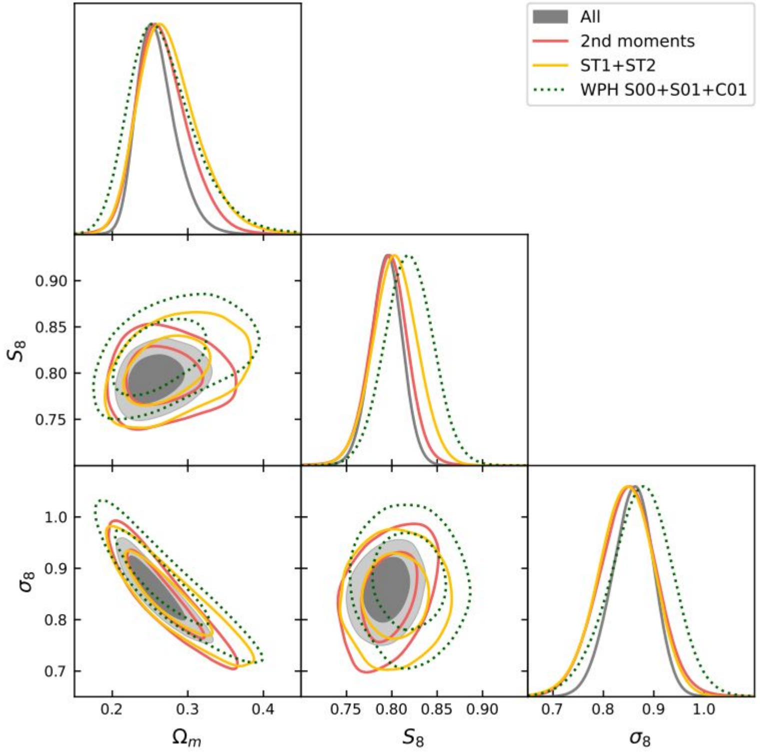
```
import Aarambam as Am
import numpy as np, subprocess as sp

#This is the main code needed for decomposing a given template. Swap "ScalarI" with
#other options to decompose more models. It is very easy to implement your own :)
#If you pass "outdir" then this will also write the coefficient tables in the right
#format into those directories
Unit   = Am.utils.Decomposer(N_modes = N_modes, n_s = n_s, Lbox = Lbox, Nmax = Nmax,
                             ModeTol = ModeTol, MaxModeCount = MaxModeCount)
coeffL = Unit.go(Am.models.Local,   Am.basis.BasicBasisDecompose, outdir = outdir)
coeffS = Unit.go(Am.models.ScalarI, Am.basis.BasicBasisDecompose, mass = 1, outdir = outdir) #This will

#Use the helper function to make the config in the right format
#and write it to dir. You will need to pass a bunch of
#values into make_config
CONFIG = Am.utils.make_config_basis(...)
with open(outdir + '/LPTconfig', 'w') as f: f.write(CONFIG)

#Doing a pip install will provide you with executables in your env.
#The Aarambam-2LPT-Basis one is the main LPT one for us. We run it with
#subprocess just for simplicity. You could also run it from cmd line
sp.run(f"mpirun -np {Nprocs} Aarambam-2LPT-Basis {outdir + '/LPTconfig'}", shell = True, env = os.envir

#Finally, here's a helpful executable to combine I/O from individual processes.
sp.run(f"Aarambam-collate-potential --file_dir {outdir}", shell = True, env = os.environ)
```

Where to next?

More statistics



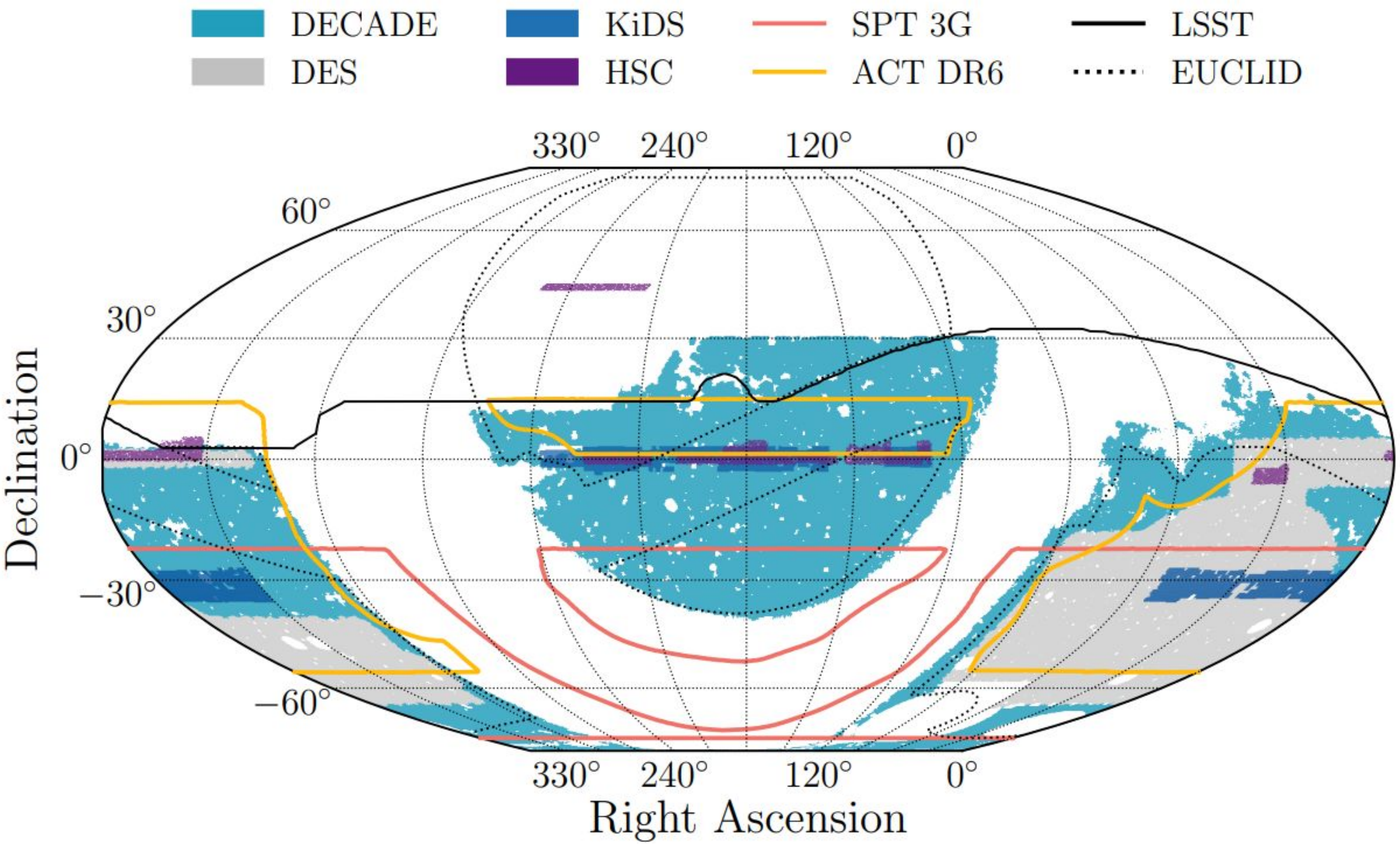
Prat et. al (incl. Anbajagane) 2025



Gatti et. al (incl. Anbajagane) 2024

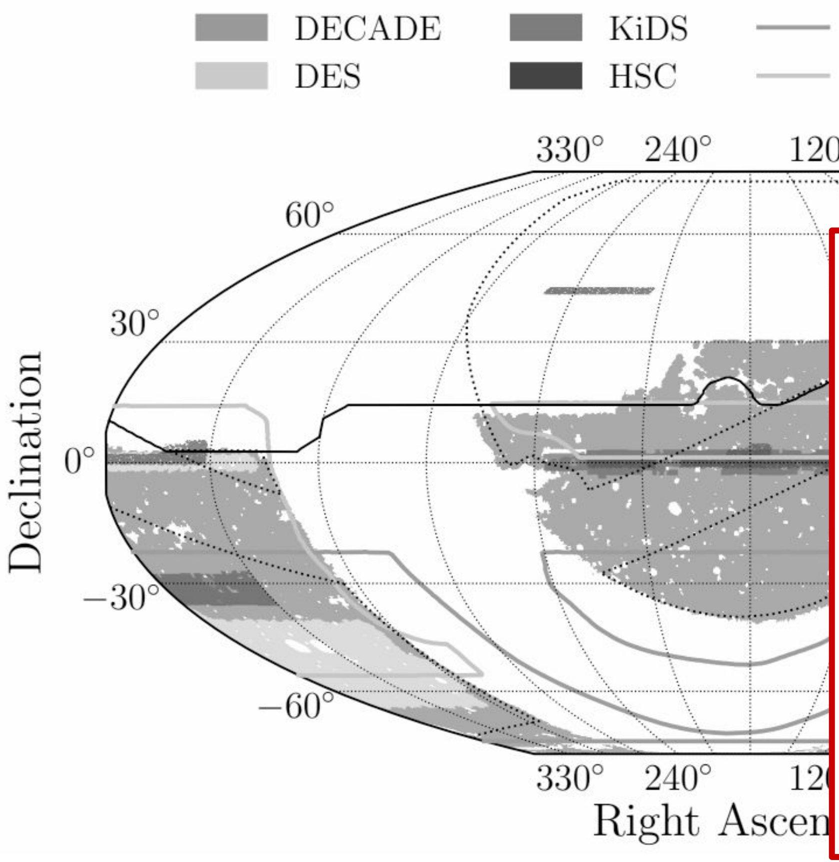
Anbajagane+ 2025a, 2025b, 2025c, 2025d, 2025e

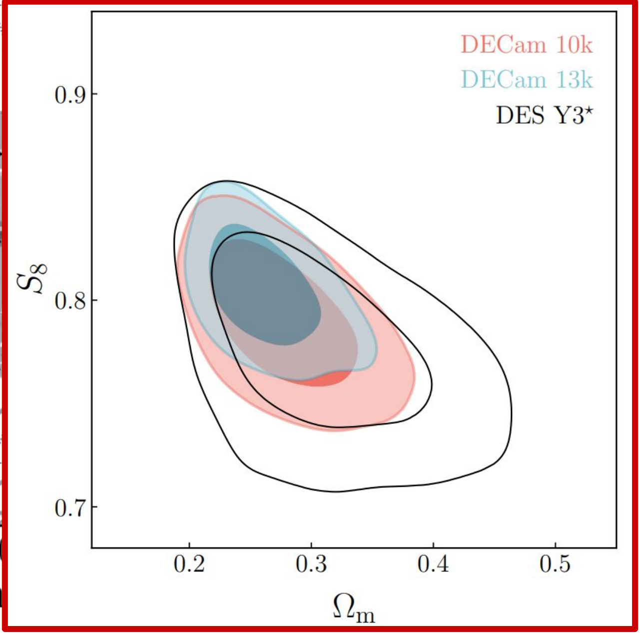
More data



Anbajagane+ 2025a, 2025b, 2025c, 2025d, 2025e

More data





Summary

- Lensing is a complementary probe of primordial physics
  - Nonlinear scales provide new information
  - Enables LSS as a whole to become competitive with the CMB
- Extracting collider signals on nonlinear scales
  - New techniques to produce robust N-body sims
  - Can use the full array of mature nonlinear probes for constraints
- An arena of even more models to be explored on nonlinear scales!
  - Nonlinear structure can deliver leading constraints in some cases.

dhayaa@uchicago.edu

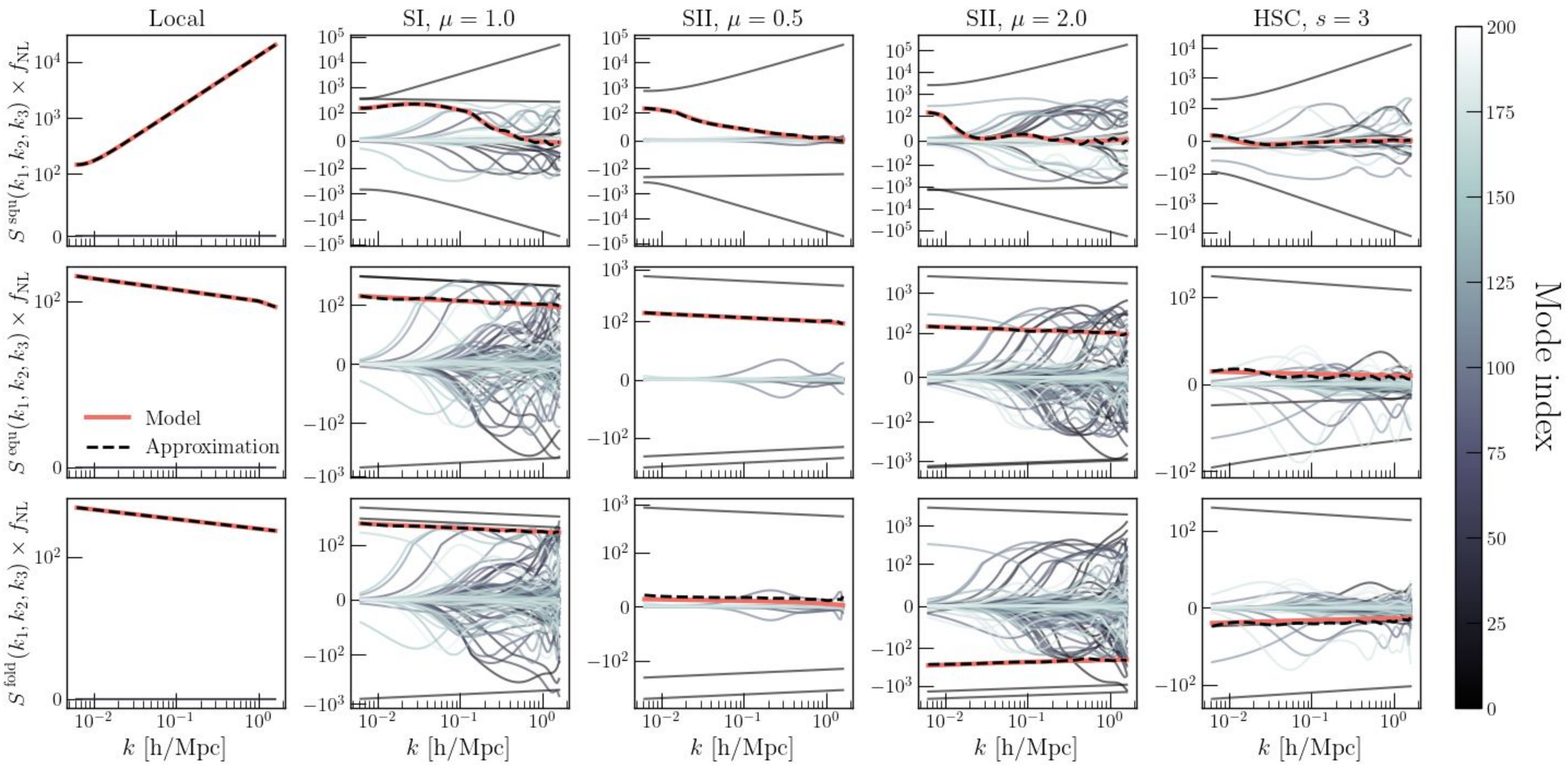
I’m here till Thursday!

?

Extra Slides

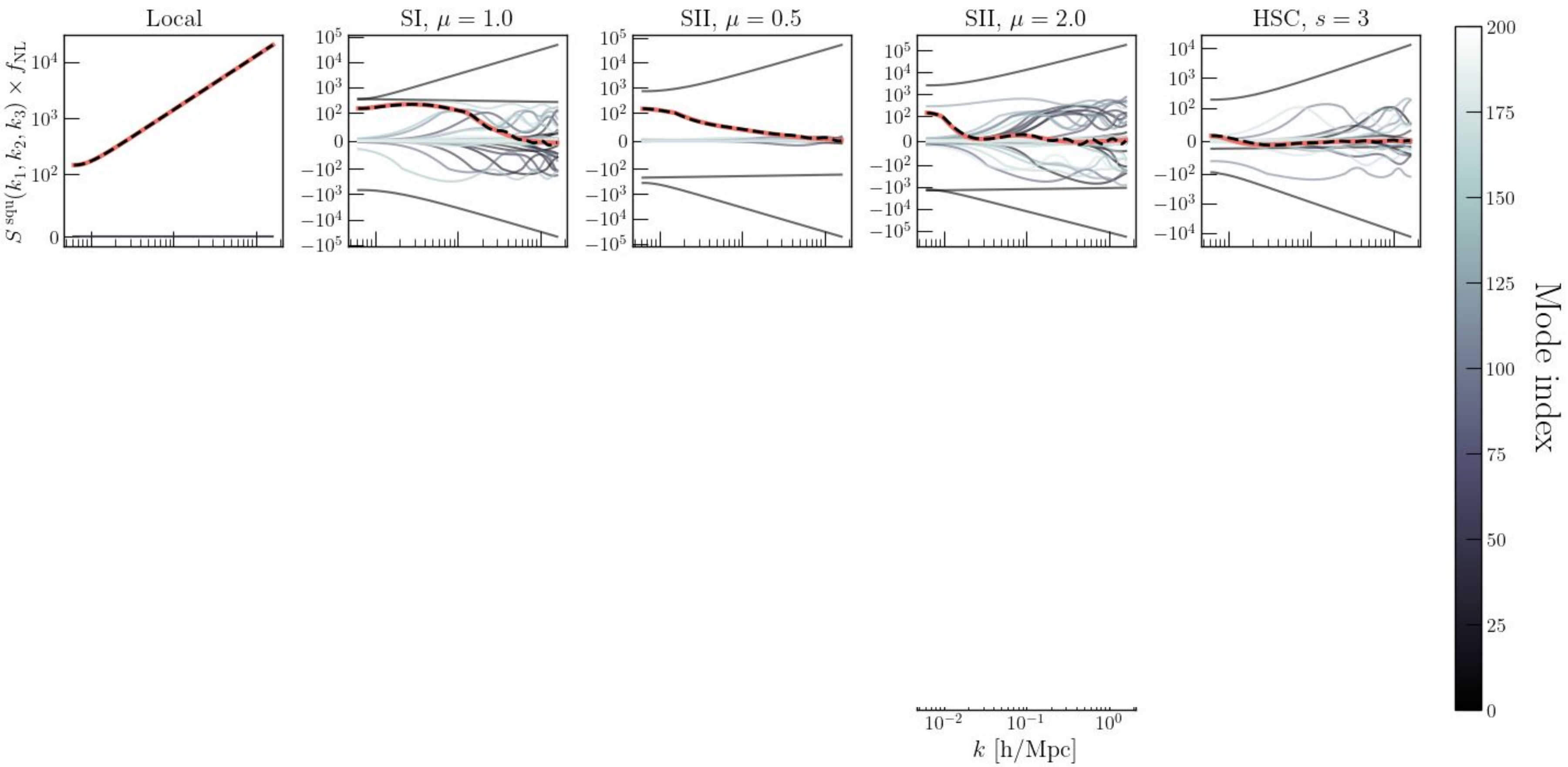
Anbajagane & Lee, in prep

Basis functions



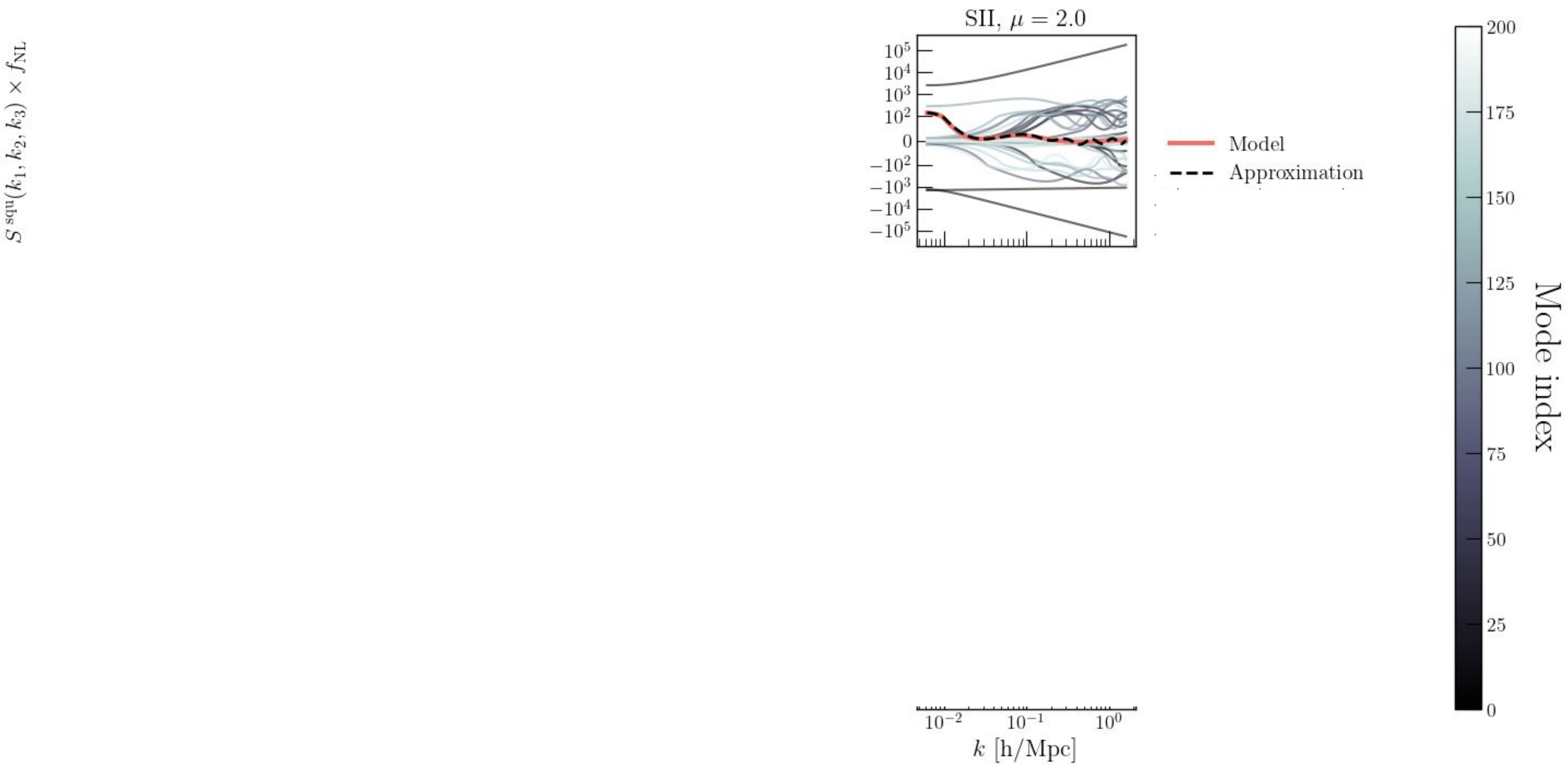
Anbajagane & Lee, in prep

Basis functions



Anbajagane & Lee, in prep

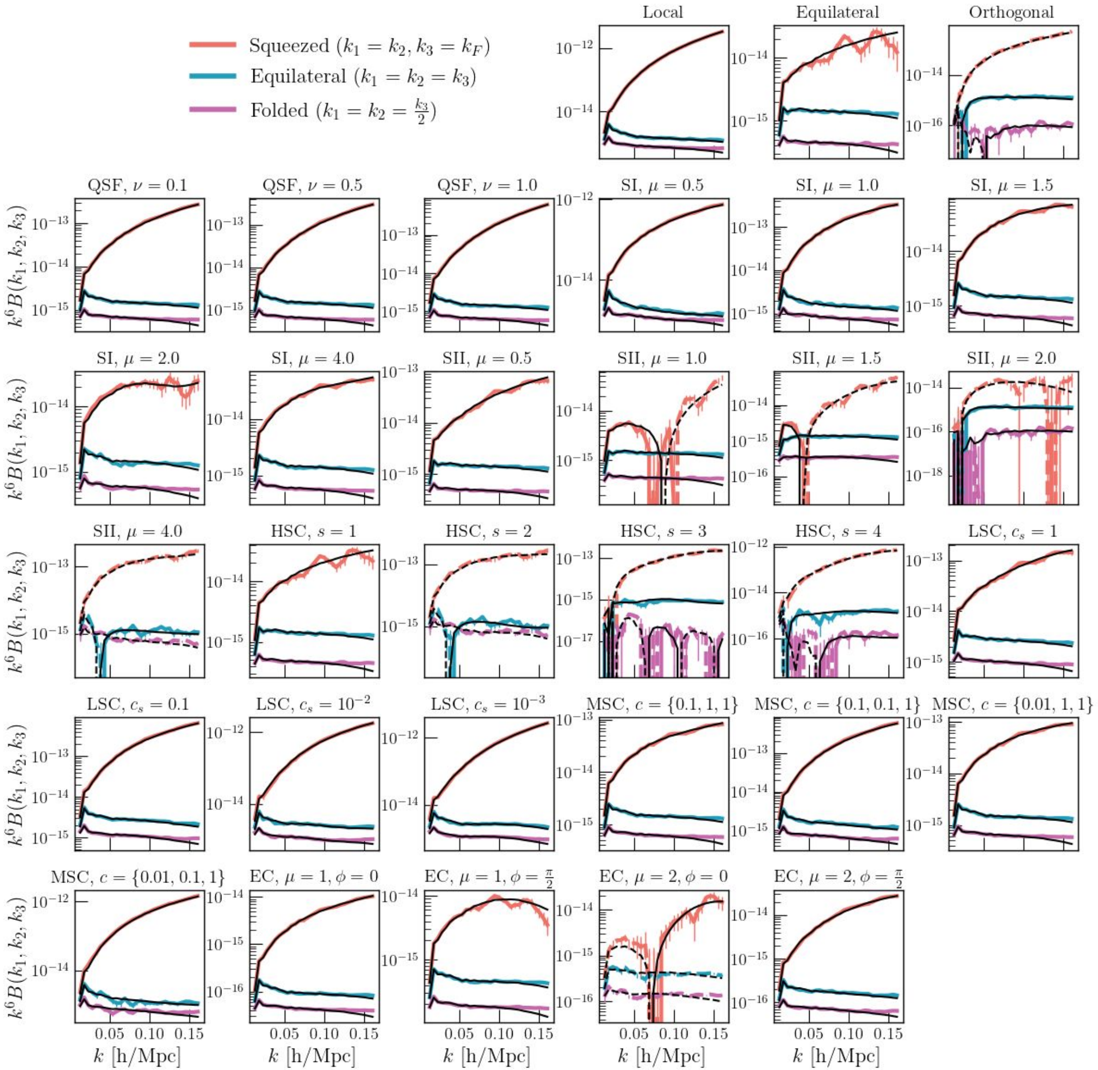
Basis functions



Consistency checks

1. Recover the input B(k)
2. Preserve tree-level P(k)
3. Suppressed T(k) terms

Recover the input bispectrum

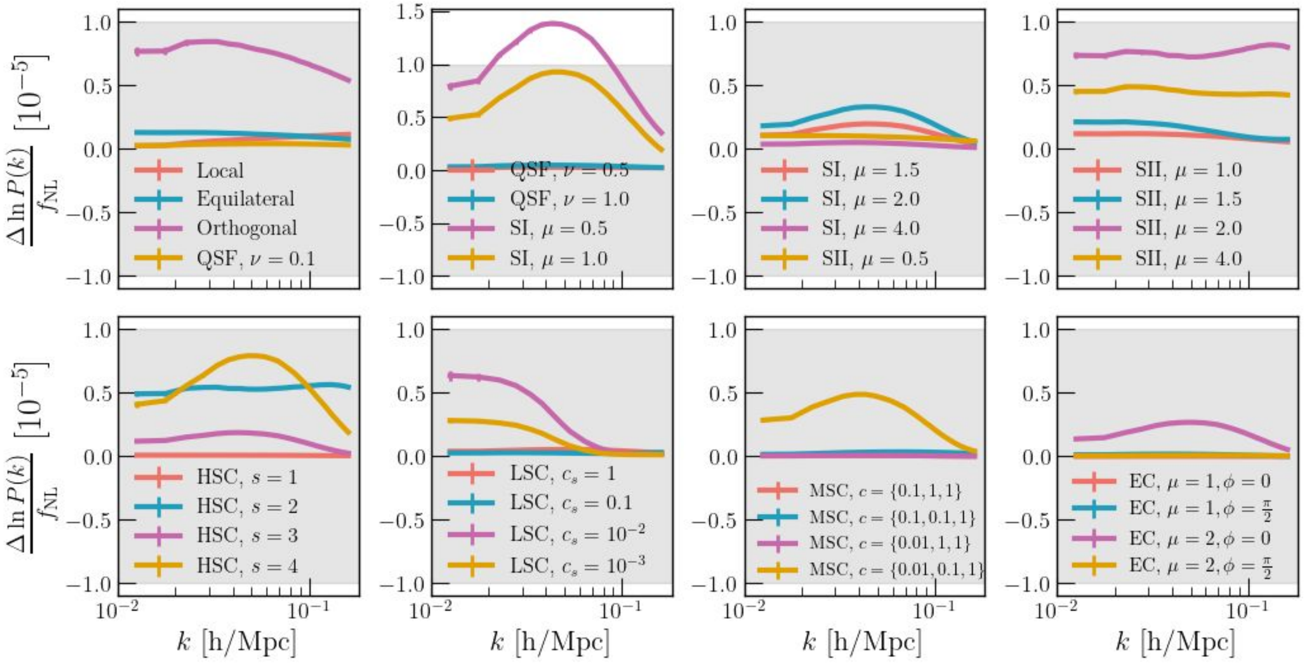


Anbajagane & Lee, in prep

Anbajagane & Lee, in prep

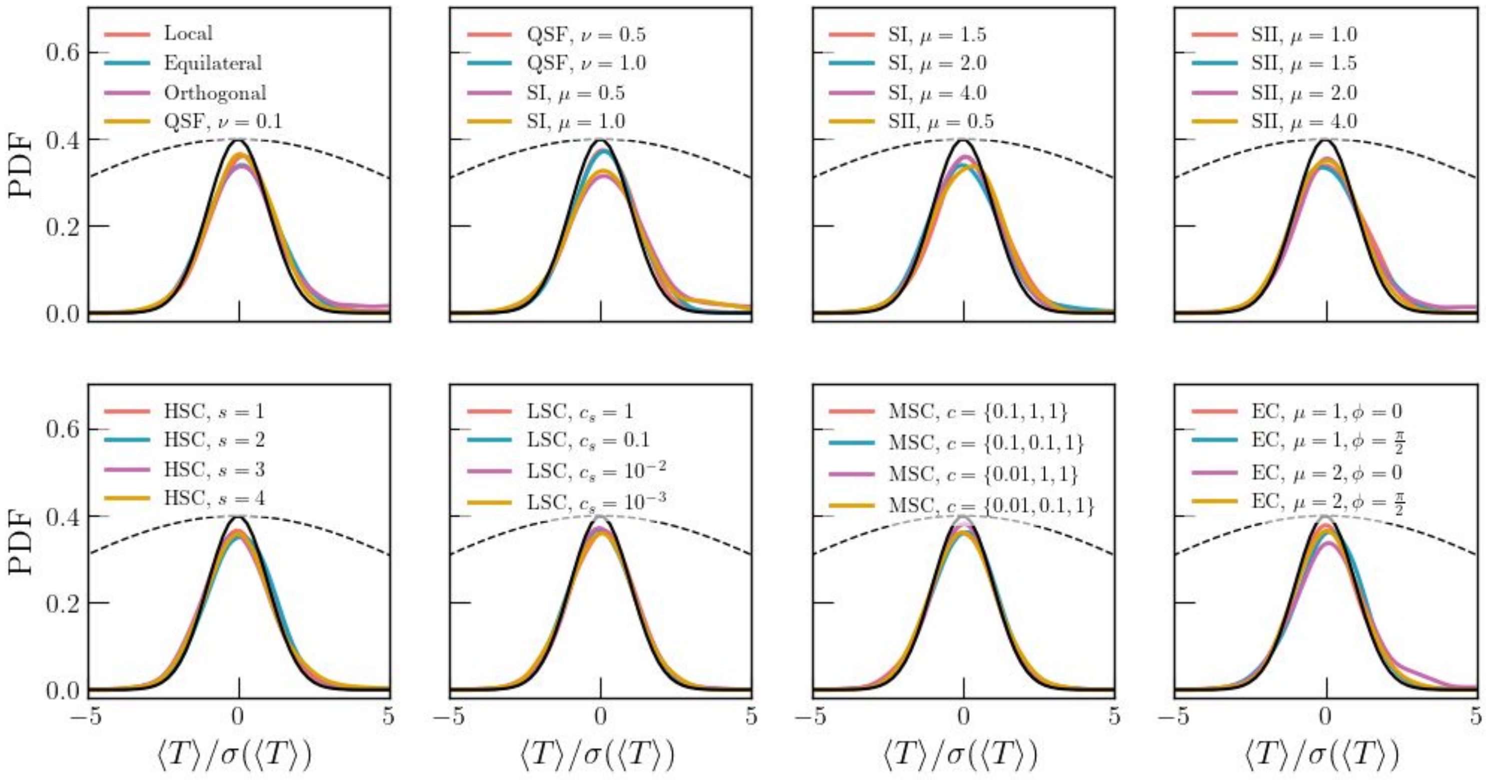
No divergent corrections to P(k)

$$\delta P^{1-\mathrm{loop}}(k) = \int dq^3 K_{12}^2(q, |\vec{k} - \vec{q}|, k) P(q) P(|k-q|)$$



No unphysical T(k)

Anbajagane & Lee, in prep



Inflation kernels

$$\Phi^{\mathrm{loc}}(\mathbf{x}) = \phi(\mathbf{x}) + f_{\mathrm{NL}}^{\mathrm{loc}}\left[\phi(\mathbf{x})^2 - \langle\phi(\mathbf{x})^2\rangle\right]$$

$$\Phi^{\mathrm{eq}}(\mathbf{x}) = \phi + f_{\mathrm{NL}}^{\mathrm{eq}}\Big[-3\phi^2 + 4\partial^{-1}(\phi\partial\phi) + 2\nabla^{-2}(\phi\nabla^2\phi) + 2\nabla^{-2}(\partial\phi)^2\Big]$$

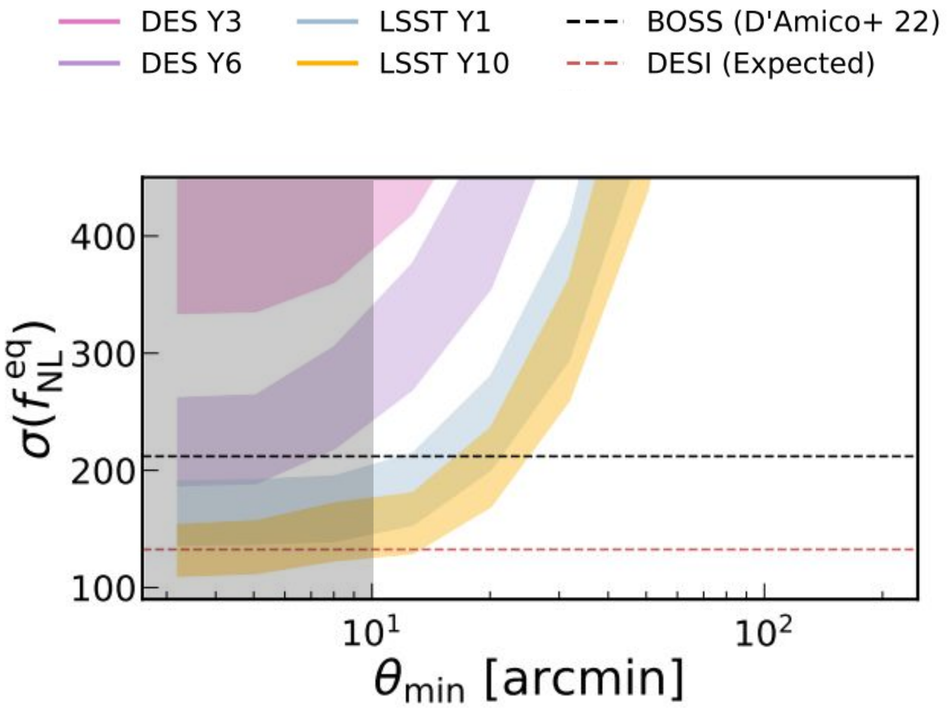
. . . . but what about the baryons?

Anbajagane, Chang, Lee & Gatti 2023b

Scale cut mitigation

Remove measurements we cannot model

$$10' \sim 5 - 15 \text{ Mpc}$$

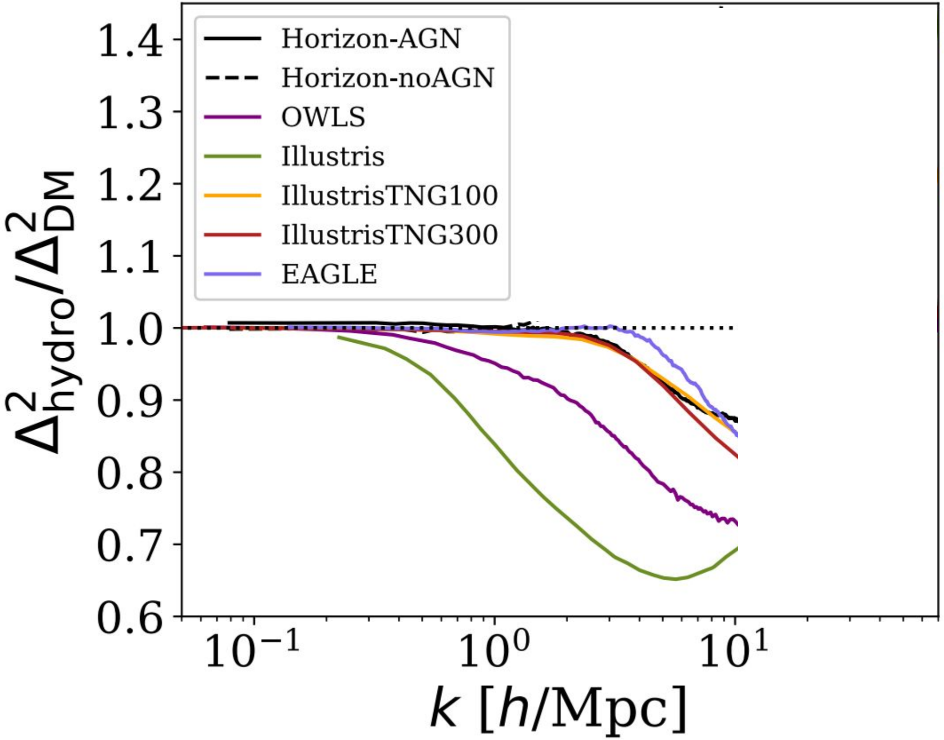


What do the baryons do?

Chisari+ 2018

What do the baryons do?

Decorrelates on small scales

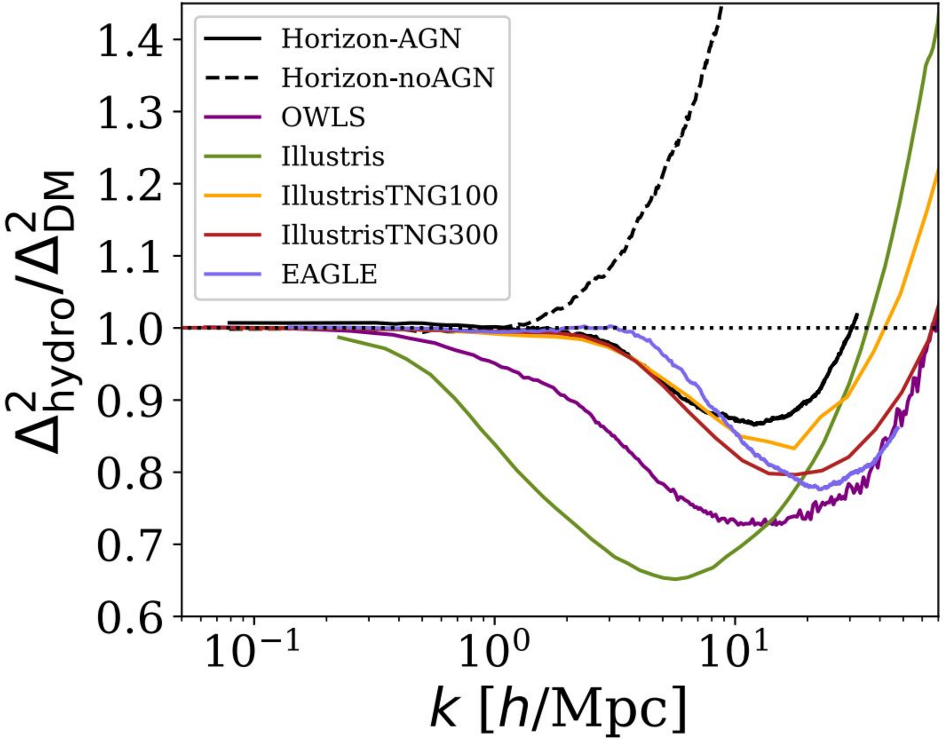


Chisari+ 2018

What do the baryons do?

Decorrelates on small scales

Correlates on even *smaller* scales



Variety of predictions

Anbajagane, Evrard & Farahi 2022a

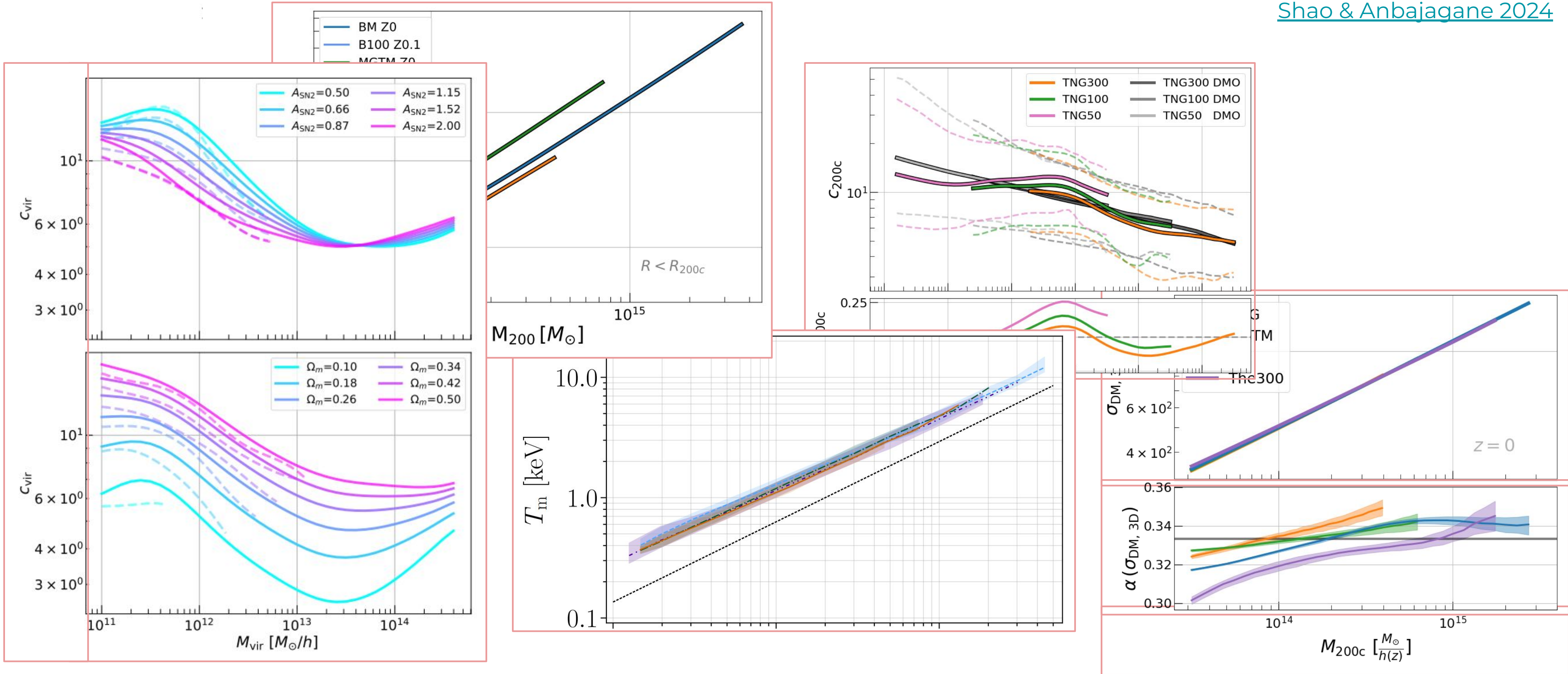
Farahi, Anbajagane & Evrard 2022

Anbajagane+ 2022b

Lee, Anbajagane, Singh, Nagai, Chluba+ 2022

Shao, Anbajagane & Chang 2023

Shao & Anbajagane 2024



Marginalizing over baryons

Account for galaxy formation params, X

$$P(\vec{\theta}|D) = \int P(\vec{\theta}|D, \vec{X})P(\vec{X})d\vec{X}$$

Marginalizing over baryons

Account for galaxy formation params, X

$$P(\vec{\theta}|D) = \int P(\vec{\theta}|D, \vec{X})P(\vec{X})d\vec{X}$$

. . . . AND for different astrophysical models, M

$$P(\vec{\theta}|D) = \int\int P(\vec{\theta}|D, \vec{X}_M, M)P(\vec{X}_M)P(M)d\vec{X}_M dM$$

Marginalizing over baryons

Account for galaxy formation params, X

$$P(\vec{\theta}|D) = \int P(\vec{\theta}|D, \vec{X})P(\vec{X})d\vec{X}$$

. . . . AND for different astrophysical models, M

$$P(\vec{\theta}|D) = \int\int P(\vec{\theta}|D, \vec{X}_M, \boxed{M})P(\vec{X}_M)P(M)d\vec{X}_M\boxed{dM}$$

Baryonification

N-body sims

Density field, halo catalog etc.

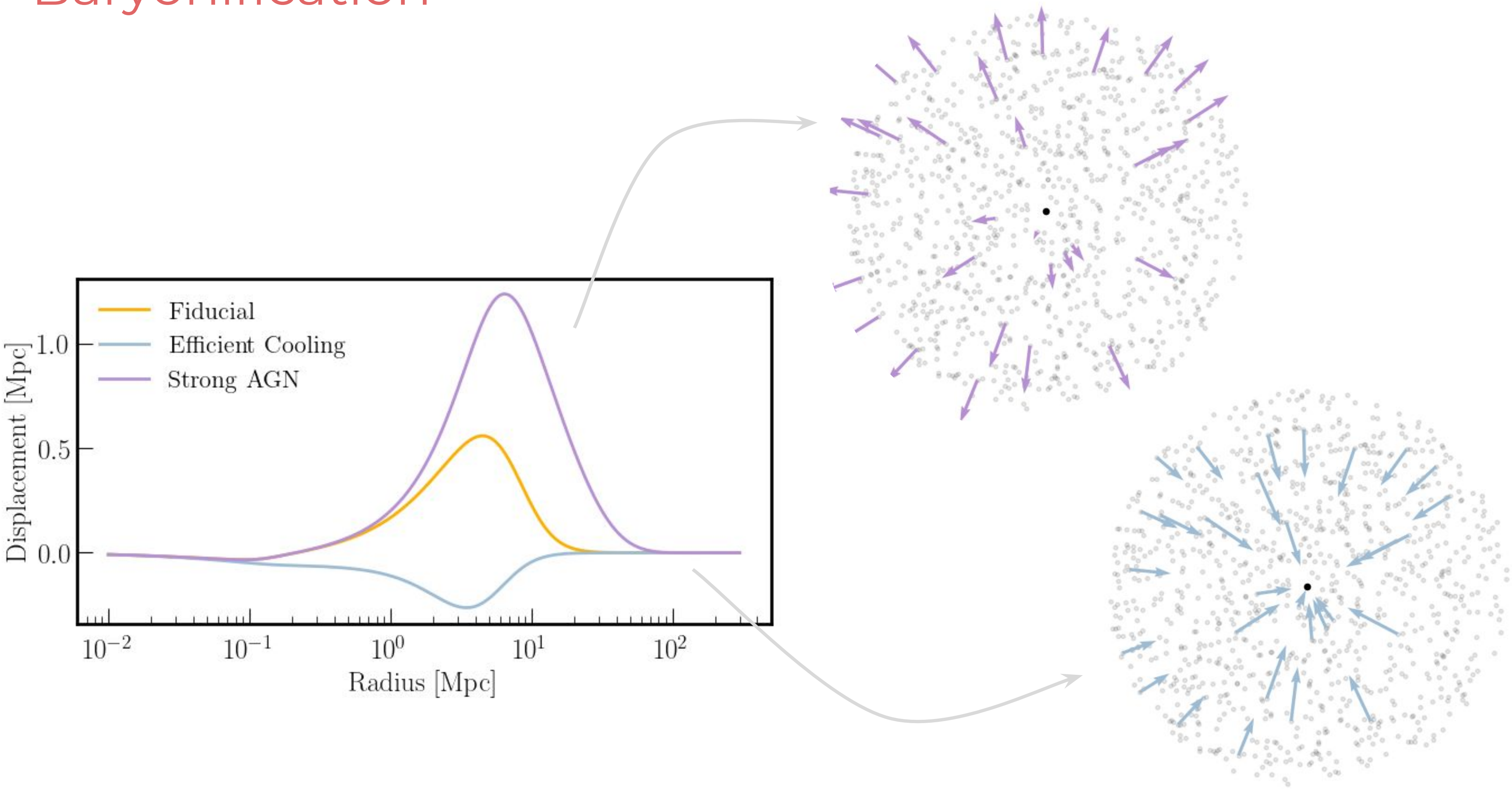
+

Prescription for moving the DM

"Baryonified" sims

Baryonification

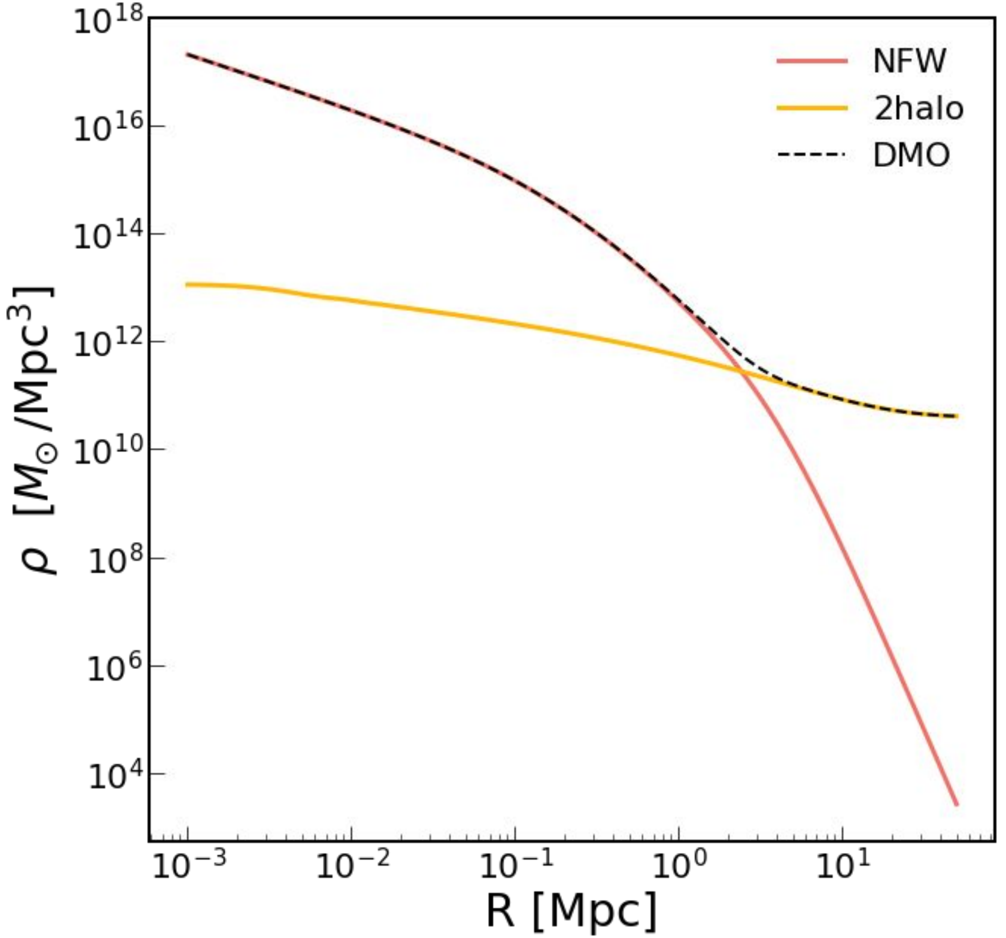
[Anbajagane, Chang, & Pandey 2024]



Baryonification

Anbajagane, Chang, & Pandey 2024

Matter distribution around halos in N-body sims

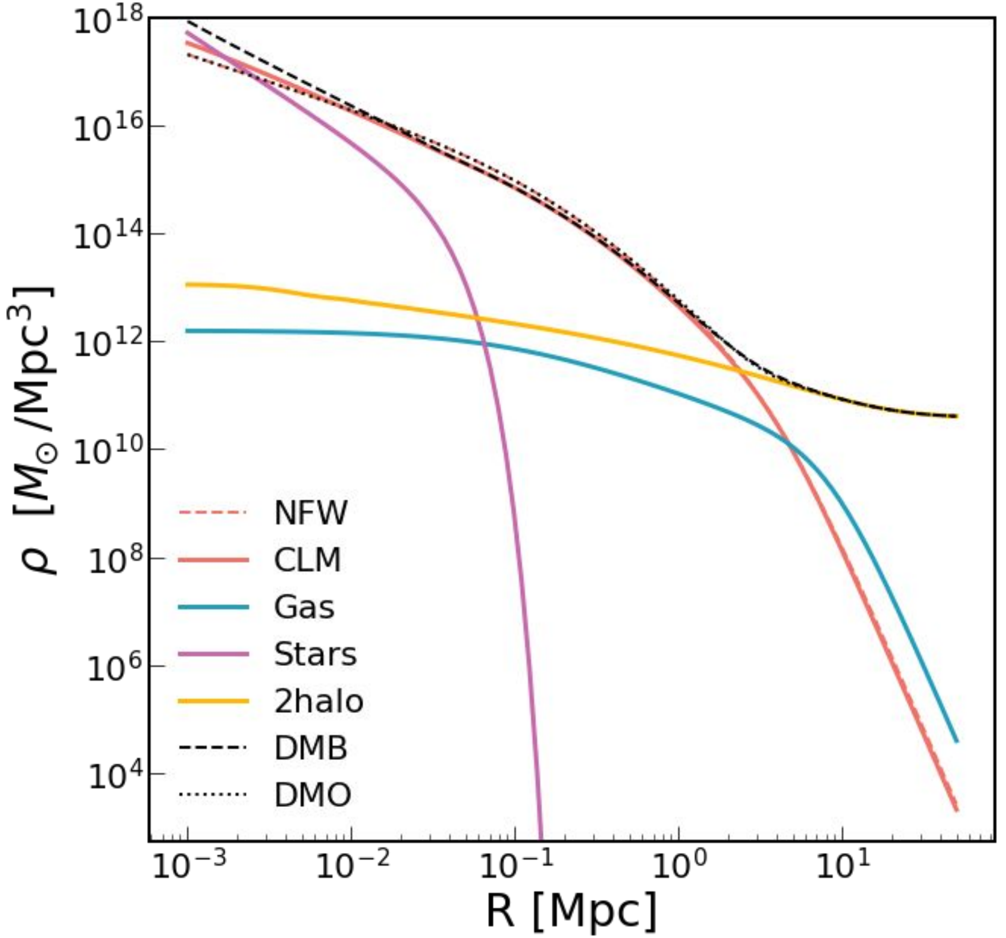


Baryonification

Anbajagane, Chang, & Pandey 2024

Matter distribution around halos in N-body sims

What about hydro sims?

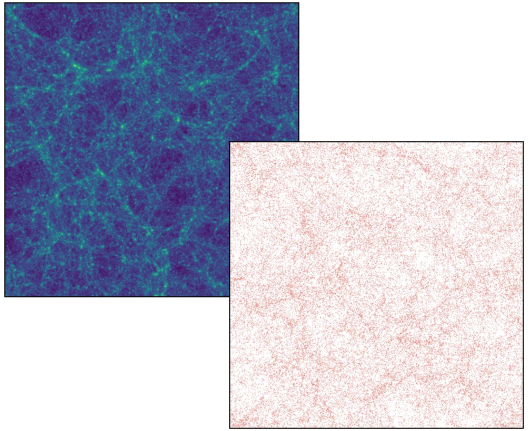


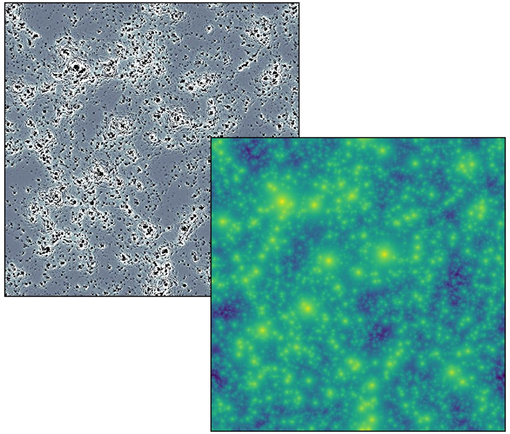
Validation using TNG

N-body Density map → "Hydro" Density map

Halo Catalog → "Hydro" Density map

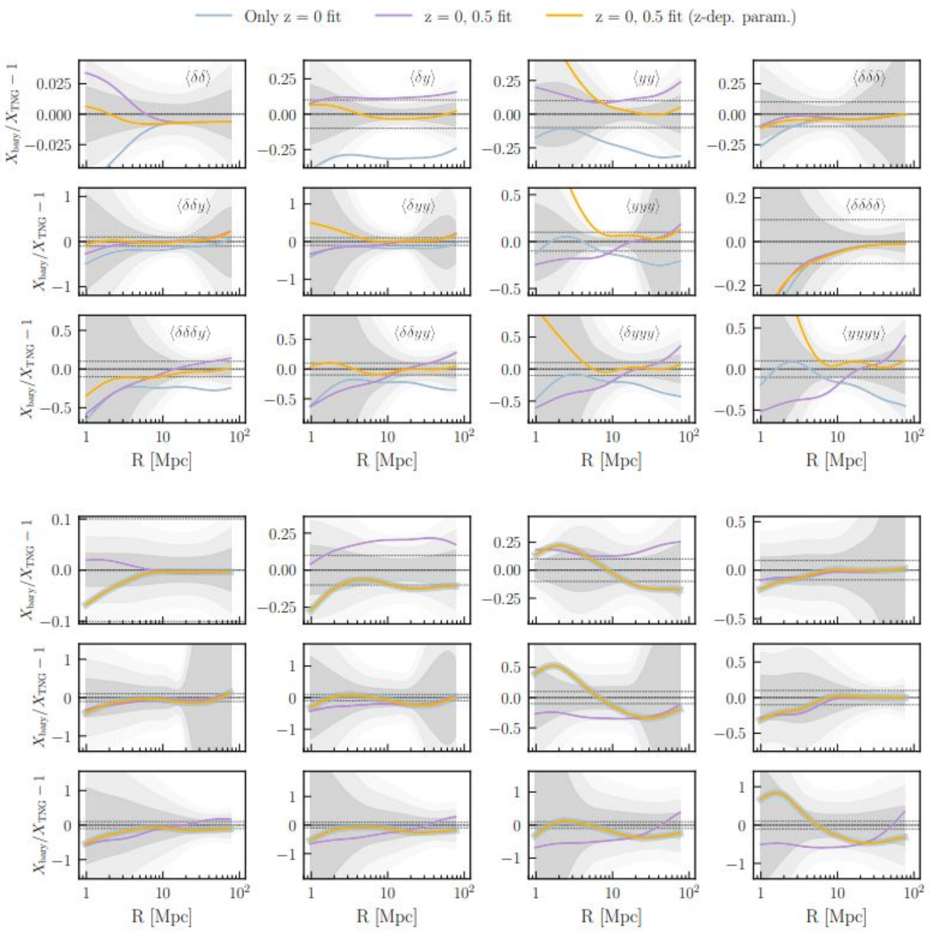
Halo Catalog → tSZ (pressure) field





Statistics

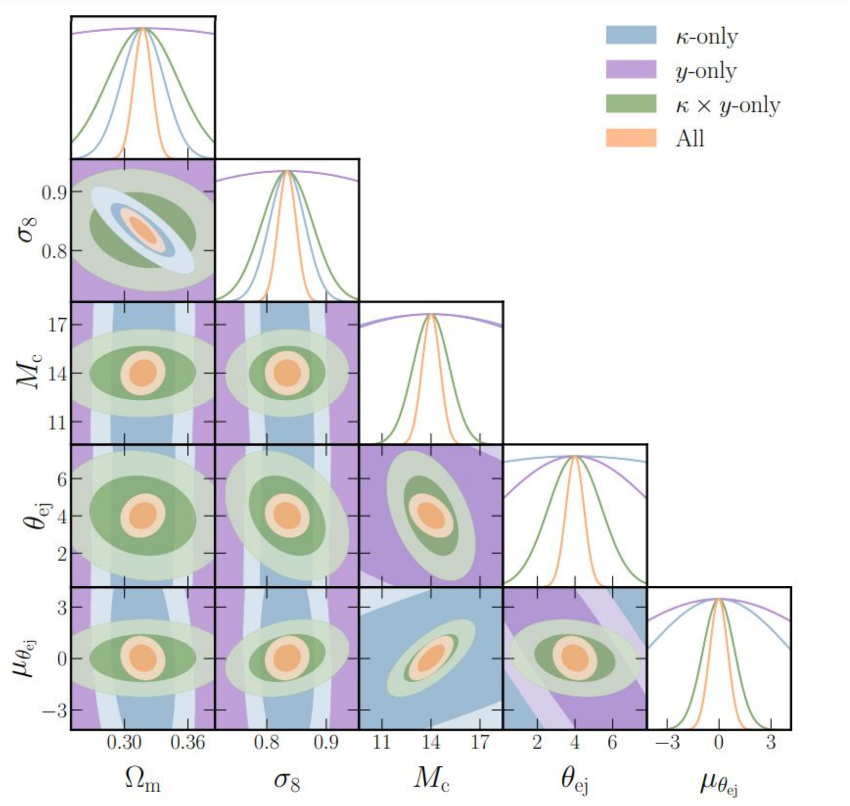
Can fit multiple statistics and redshifts to within statistical uncertainties



Anbajagane, Chang, & Pandey 2024

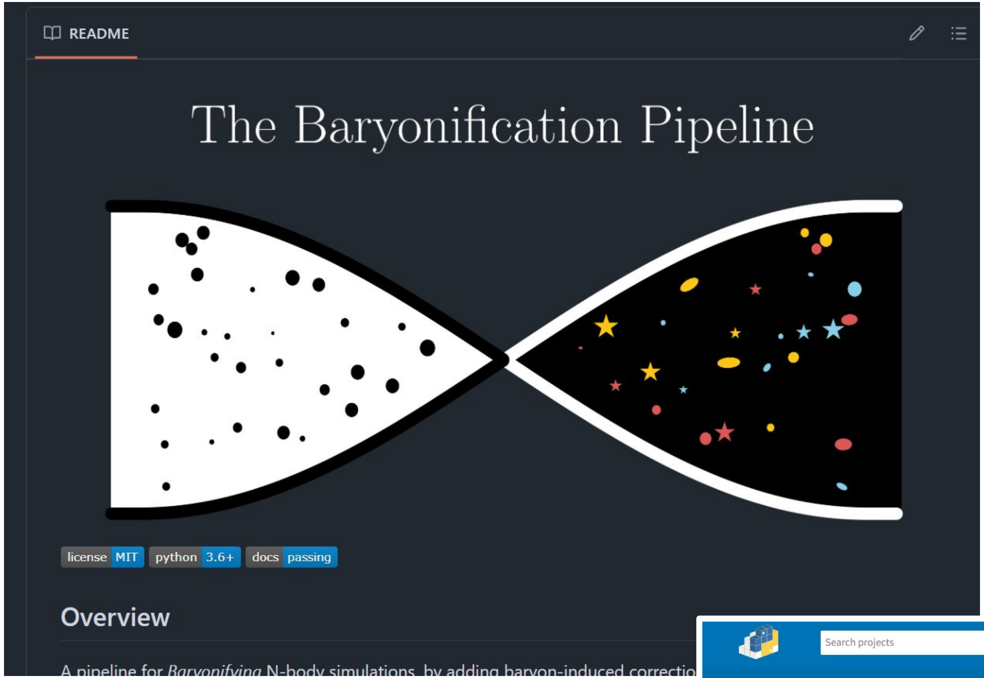
Forecasting

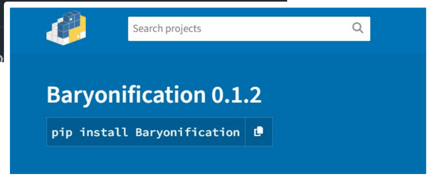
- Possible to use small-scales for cosmology in robust way
- Different cosmological probes have very different degeneracies.
    - Many more can be added



Full framework is easily available, usable, modifiable! :)

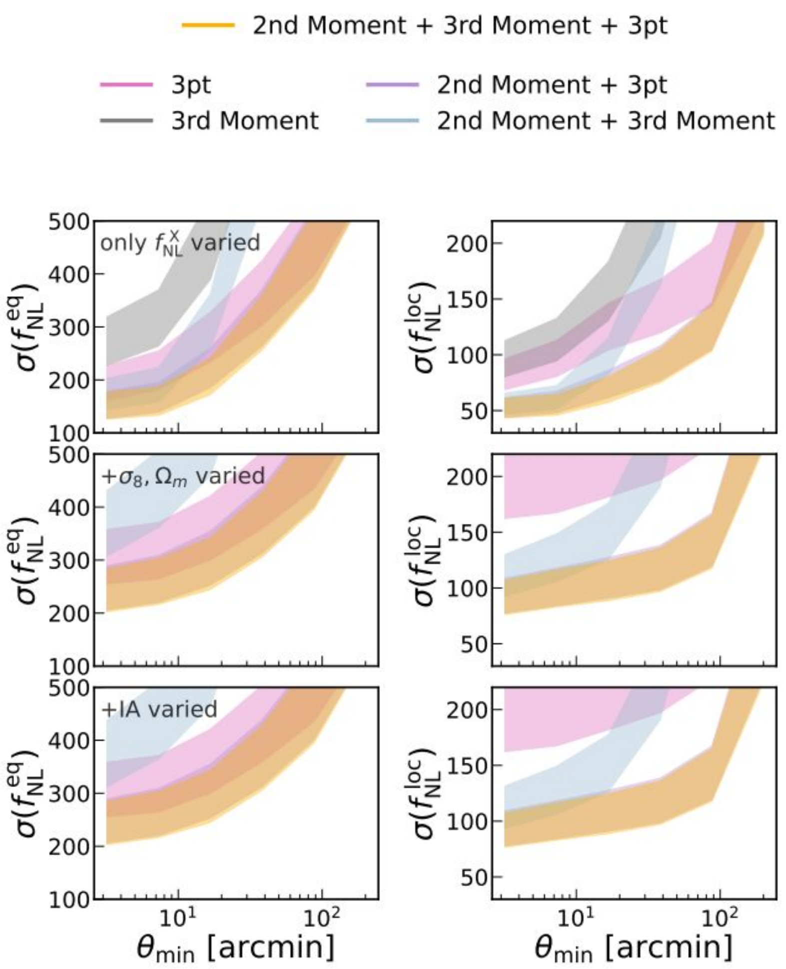
- Profiles
- Pixel smoothing
- Projection scale
- Baryonify delta
- Paint tSZ





What can lensing do?

- 2nd Mom + 3pt same as all combined
- Tested we get no 3pt signal on Gaussian maps
- 3pt constraints converged to 10-20%
    - N_{dof} is ~8000



From maps to constraints

Using moments of the convergence field

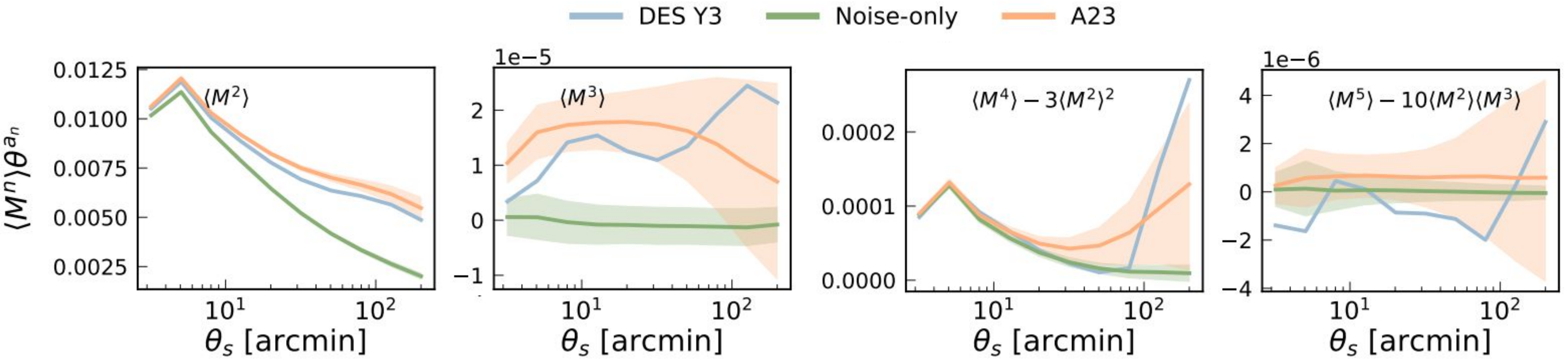
$$\langle \kappa^{(1)} \kappa^{(2)} \dots \kappa^{(N)} \rangle(\theta) = \frac{1}{N_{\rm pix} - 1} \sum_{i=1}^{N_{\rm pix}} \kappa_i^{(1)} \kappa_i^{(2)} \dots \kappa_i^{(N)}$$

Anbajagane, Chang, Banerjee+ 2023a

From maps to constraints

Using moments of the convergence field

$$\langle \kappa^{(1)} \kappa^{(2)} \ldots \kappa^{(N)} \rangle(\theta) = \frac{1}{N_{\rm pix} - 1} \sum_{i=1}^{N_{\rm pix}} \kappa_i^{(1)} \kappa_i^{(2)} \ldots \kappa_i^{(N)}$$



Anbajagane, Chang, Banerjee+ 2023a

From maps to constraints

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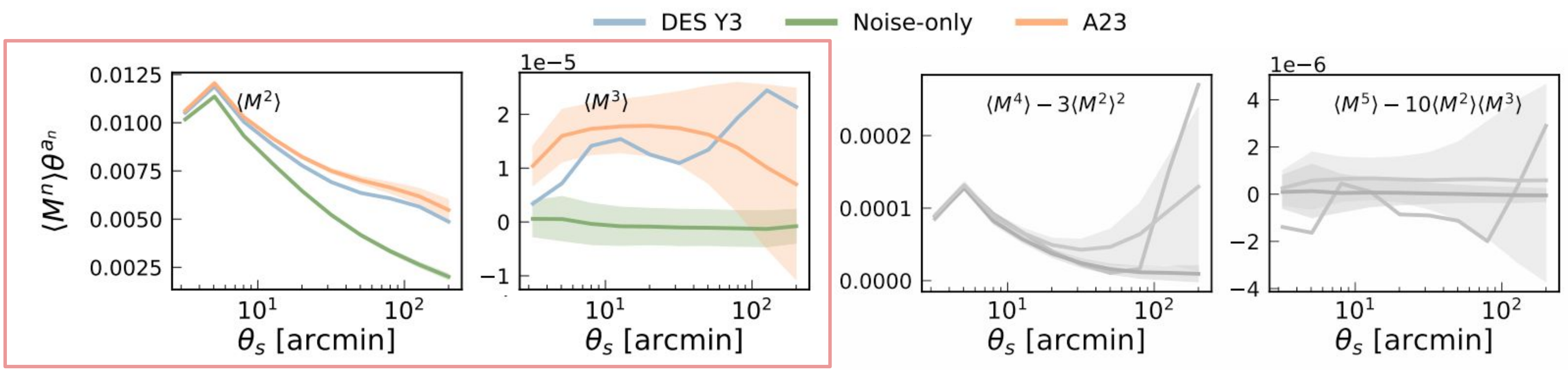
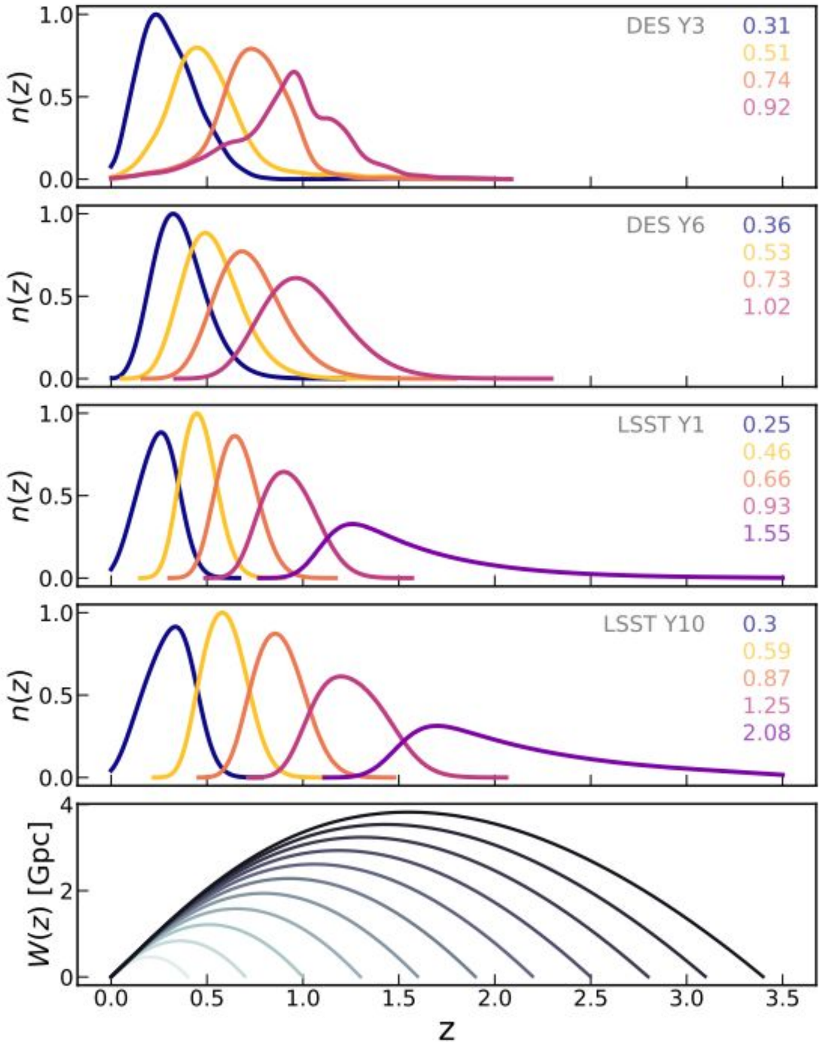
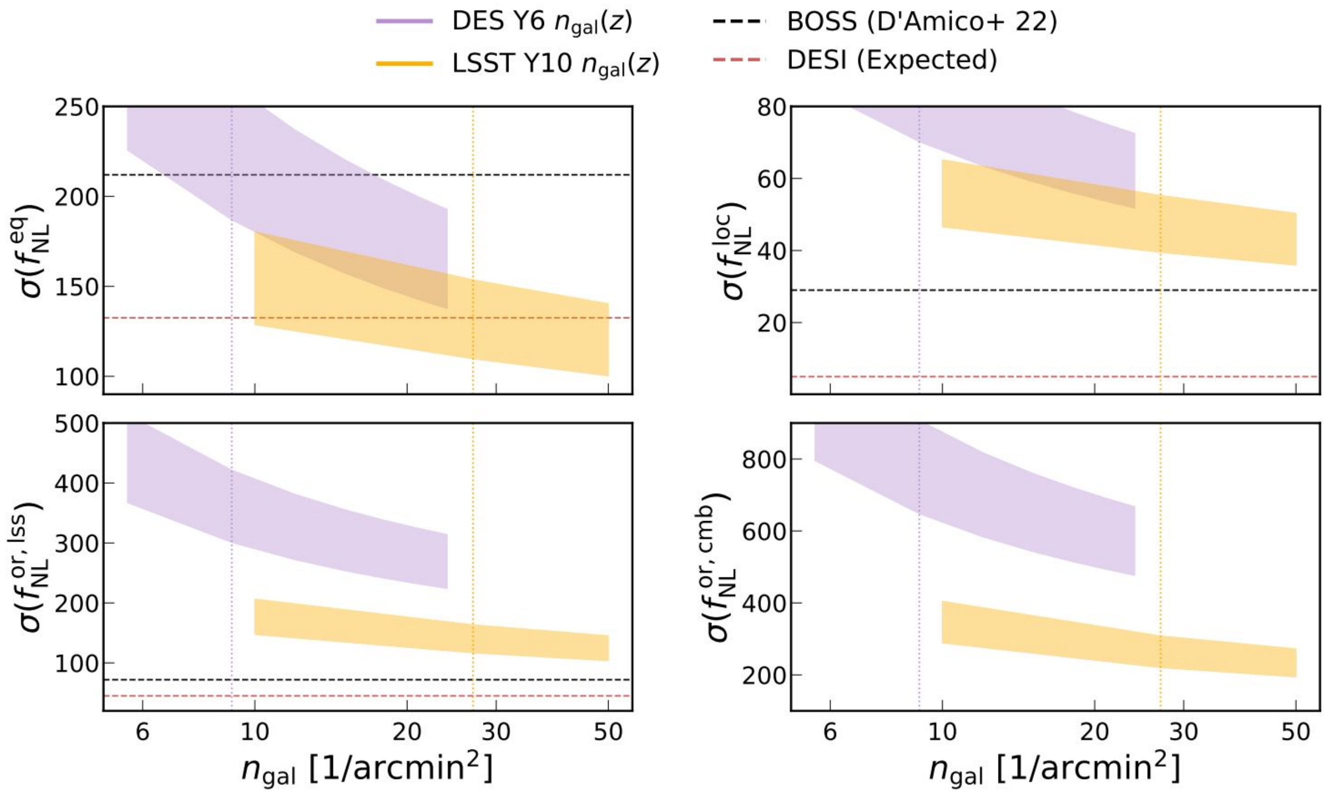


n(z)s

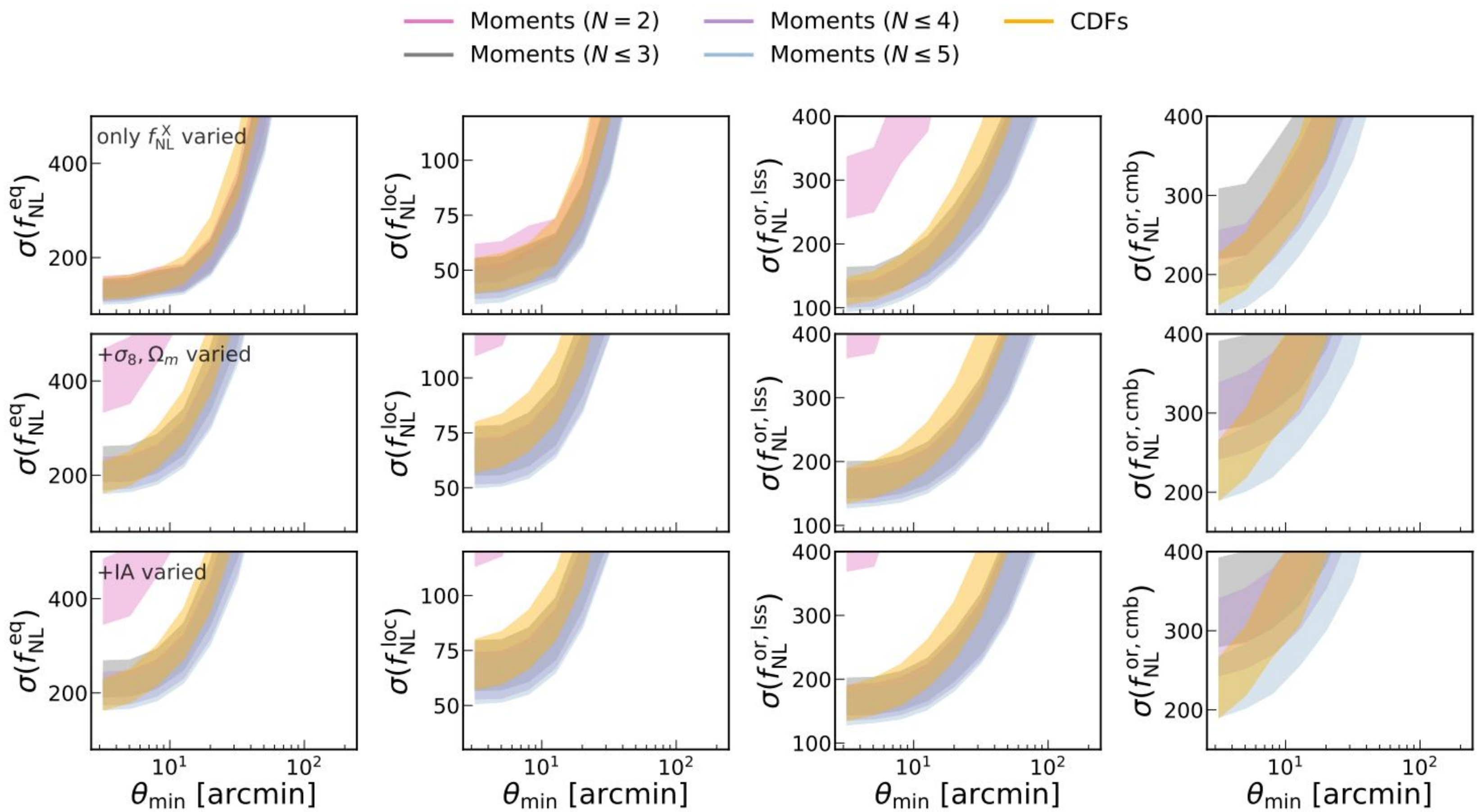
- DES Y3 is actual data
- Everything else is forecast
- LSST high-z isn't a problem



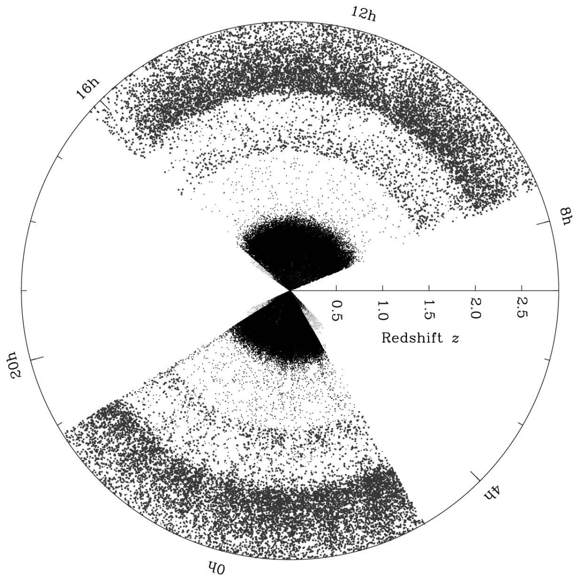
Noise dependence

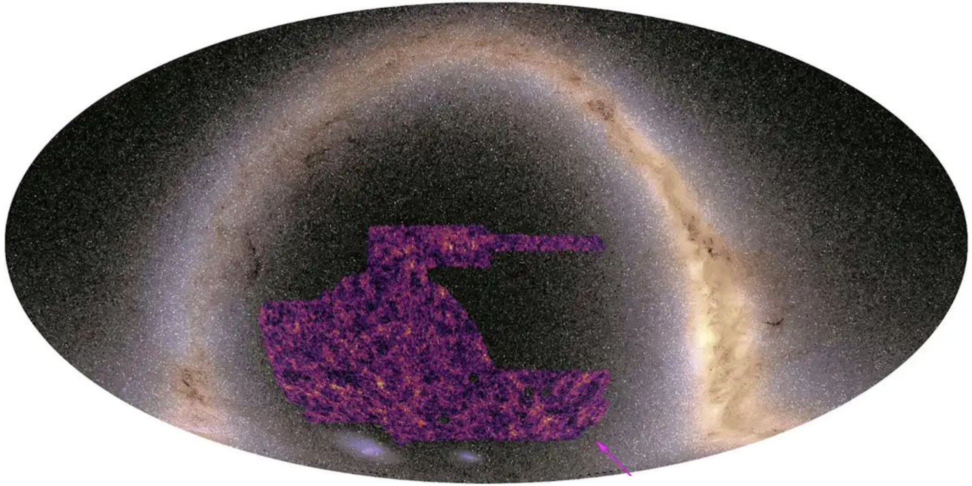


Stat dependence

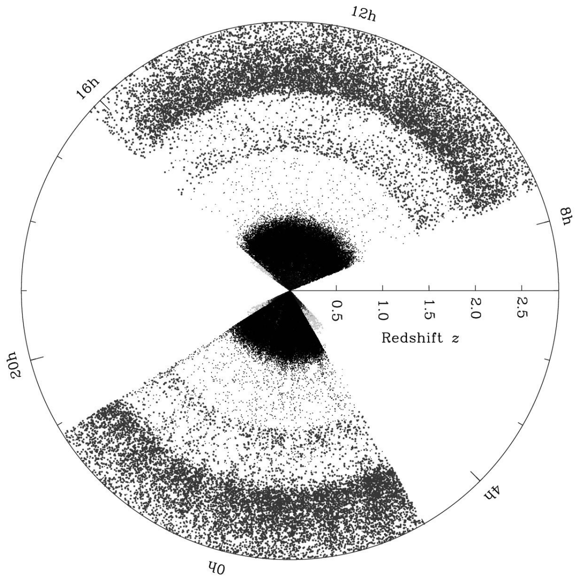


The landscape of LSS cosmology





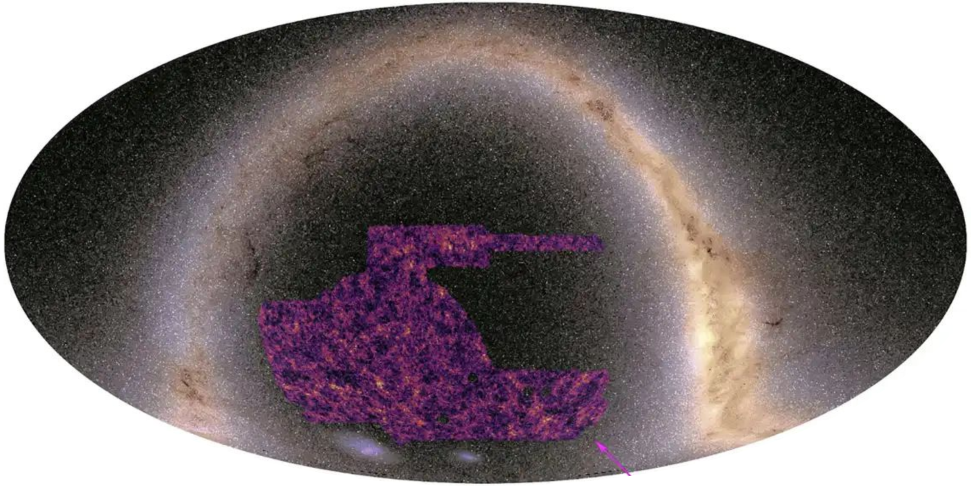
Galaxy clustering probes



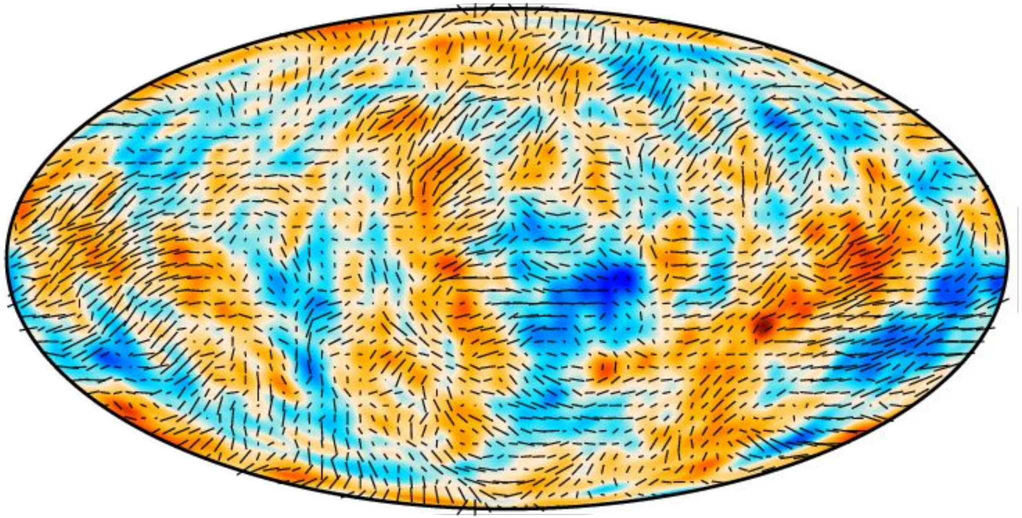
- Measure full 3D volumes
- High SNR
- Requires galaxy-halo connection

Weak lensing probes

- Measure 2.5D “volume”
- Lower SNR than clustering
- Density field observable



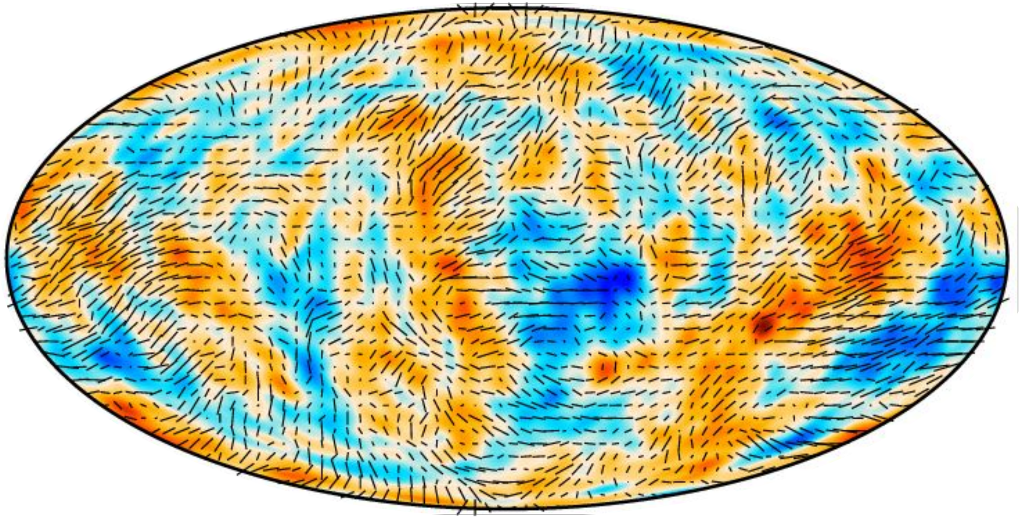
Didn’t Planck already do this?



- Large scales
- Linear physics, perturbation theory
- Completely analytic

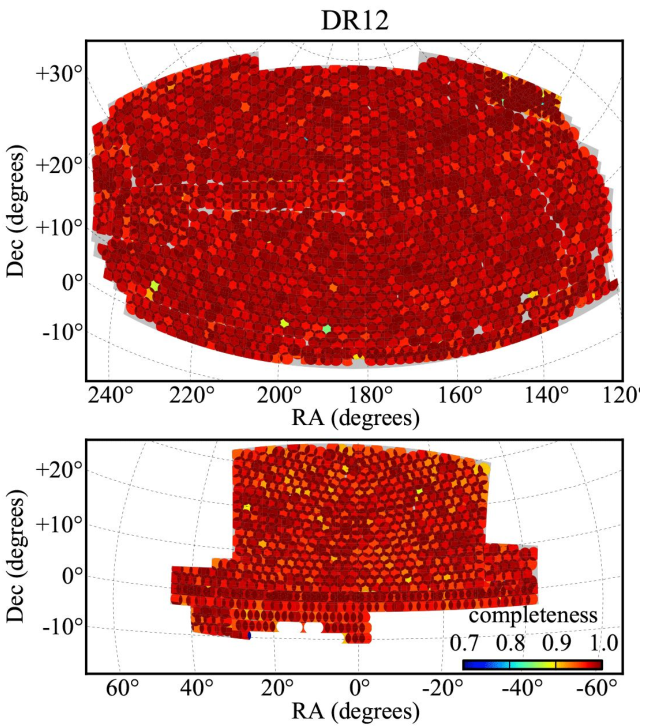
Didn't Planck already do this?

Shape	Independent	Joint
f_{NL}^{local}	-0.1 ± 5.6	5.0 ± 8.4
f_{NL}^{equil}	26 ± 69	5 ± 73
f_{NL}^{ortho}	-11 ± 39	-5 ± 44



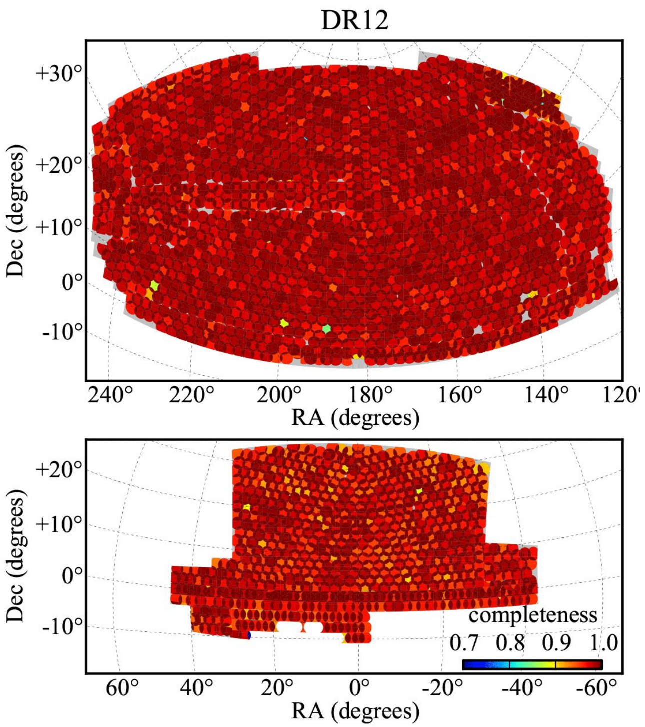
Planck 2018+
arxiv:1905.05697

Didn't BOSS already do this?



- Measure full 3D volumes
- High SNR
- *Galaxy bias is a problem*

Didn't BOSS already do this?



$f_{\rm NL}^{\rm equil.}$	2 ± 212
$f_{\rm NL}^{\rm orth.}$	126 ± 72
$f_{\rm NL}^{\rm loc.}$	-30 ± 29

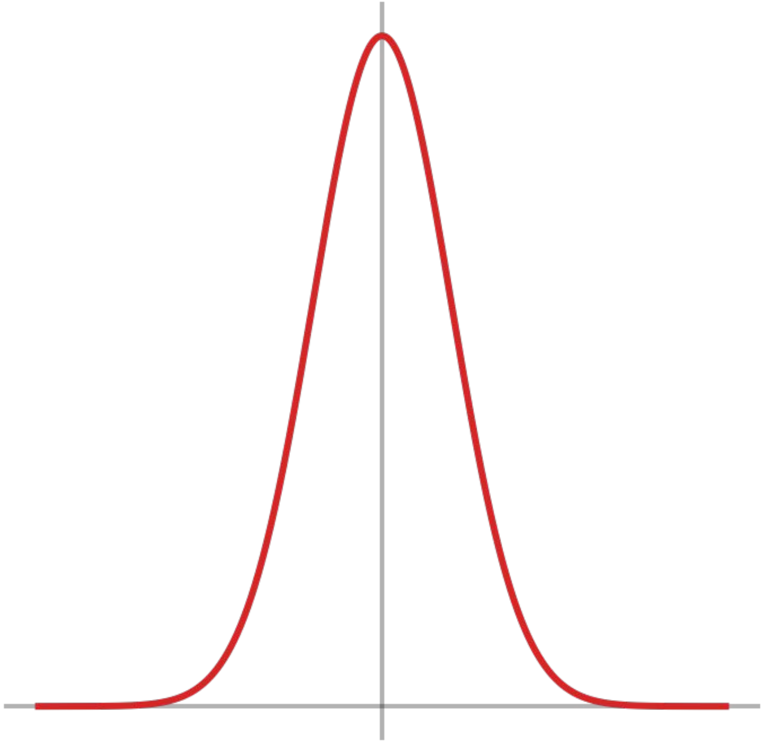
D'Amico+2022
arxiv:2201.11518

Didn't BOSS already do this?

$f_{\rm NL}^{\rm equil.}$	2 ± 212
$f_{\rm NL}^{\rm orth.}$	126 ± 72
$f_{\rm NL}^{\rm loc.}$	-30 ± 29

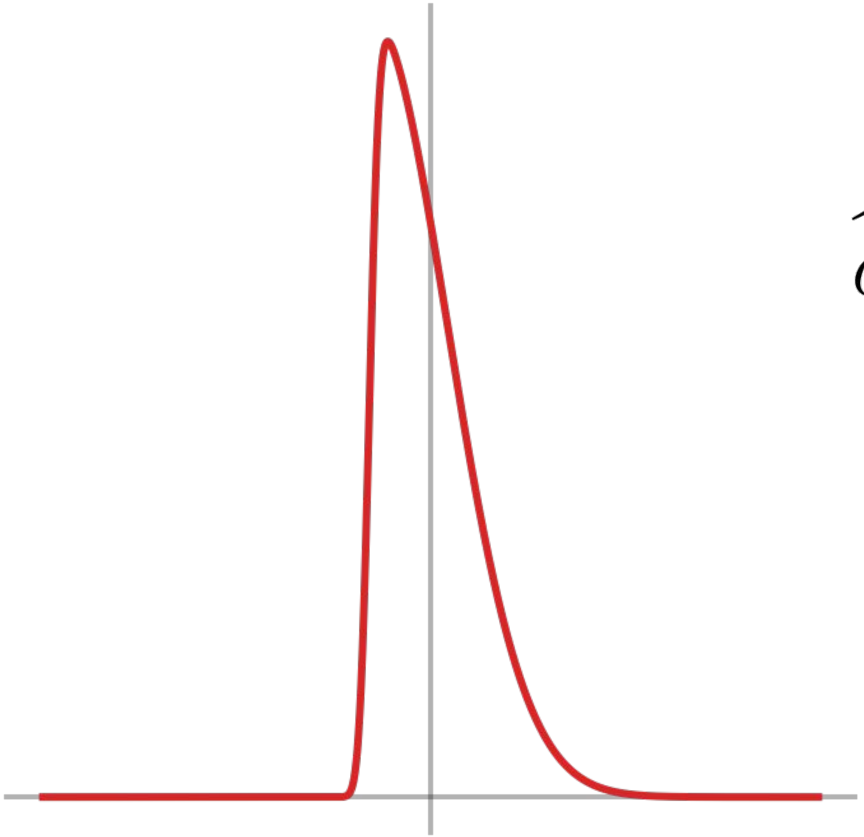
Potentially too optimistic

Canonical inflation



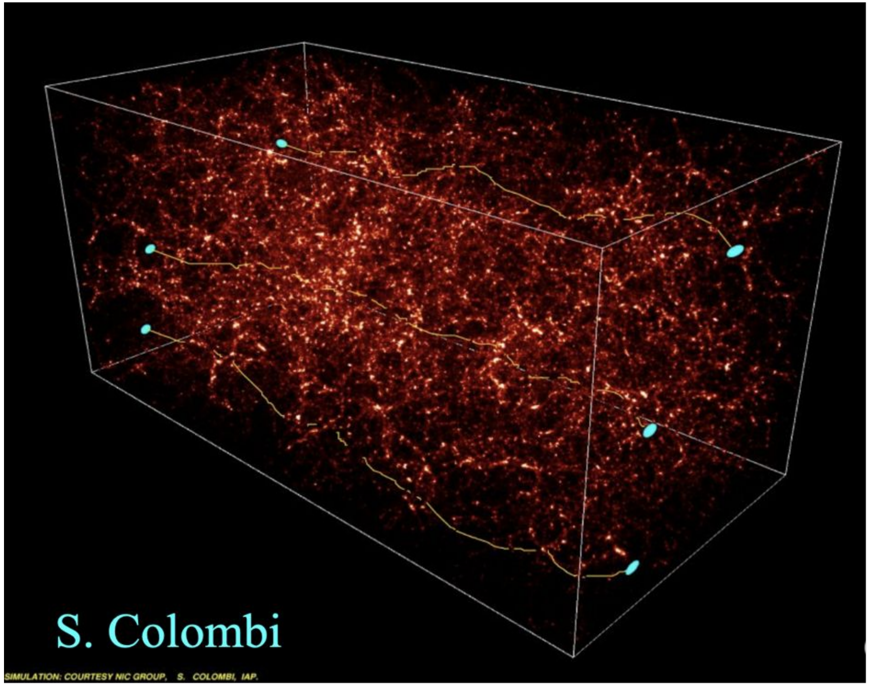
$$P(\delta) \sim e^{-\delta^2/\sigma^2}$$

Multi-field, self-int. inflation



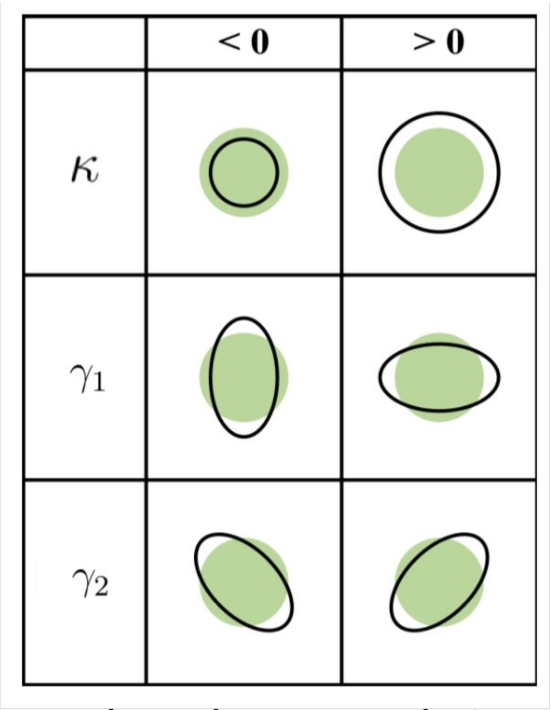
$$\widehat{\delta} = \delta + f_{\mathrm{NL}}(\delta^2 - \langle \delta^2 \rangle)$$

Why weak lensing?



$$\kappa(\vec{\theta}) = \int dz\, W(\chi(z))\delta(\chi(z)\vec{\theta}, z)$$

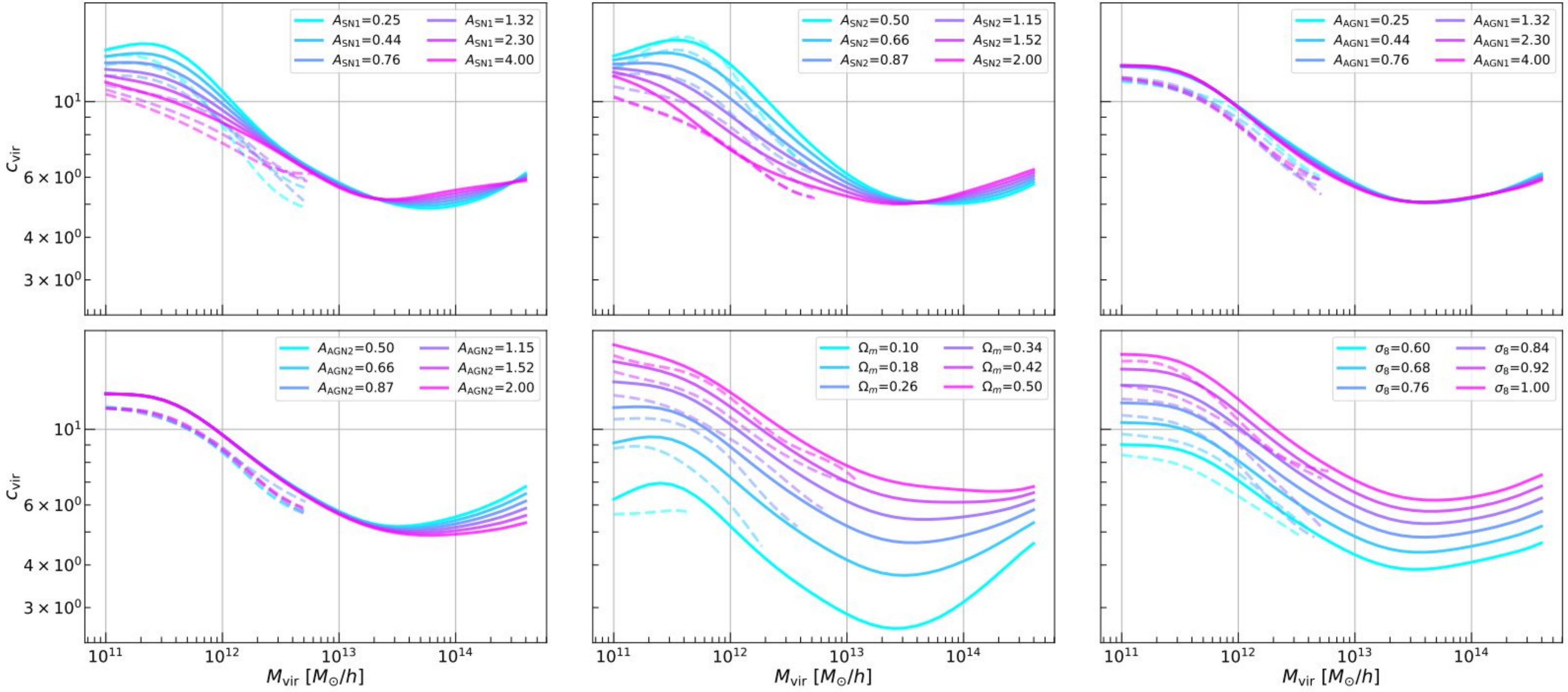
→



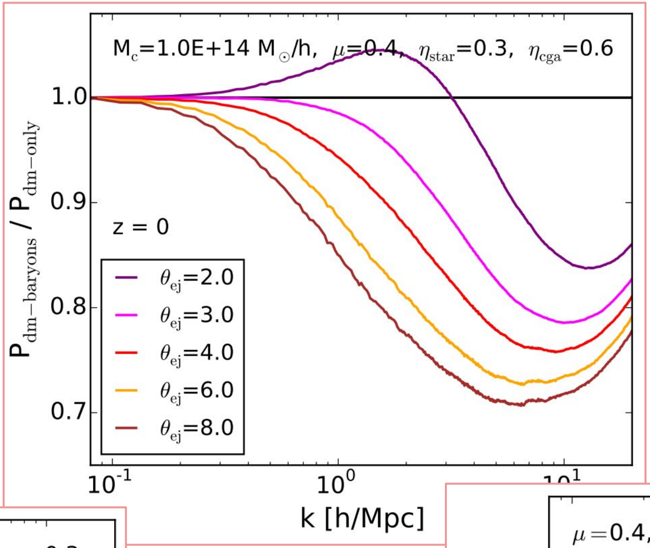
Galaxy shape correlations as a function of Ω, **Λ**, ***h***, ...

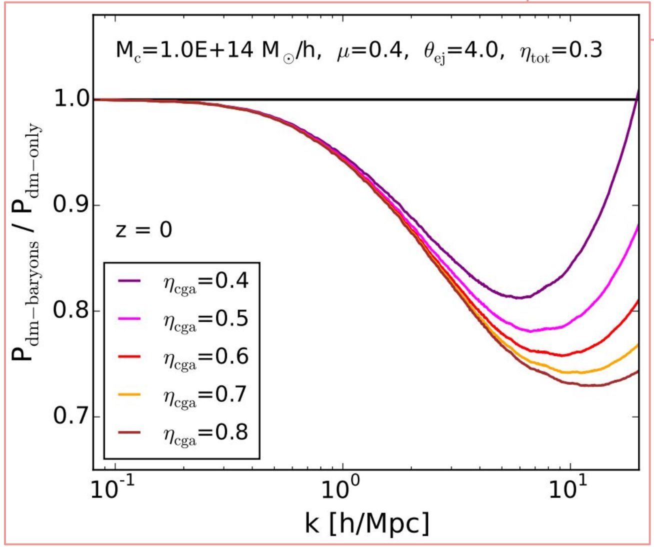
Shao, **Anbajagane** & Chang 2022

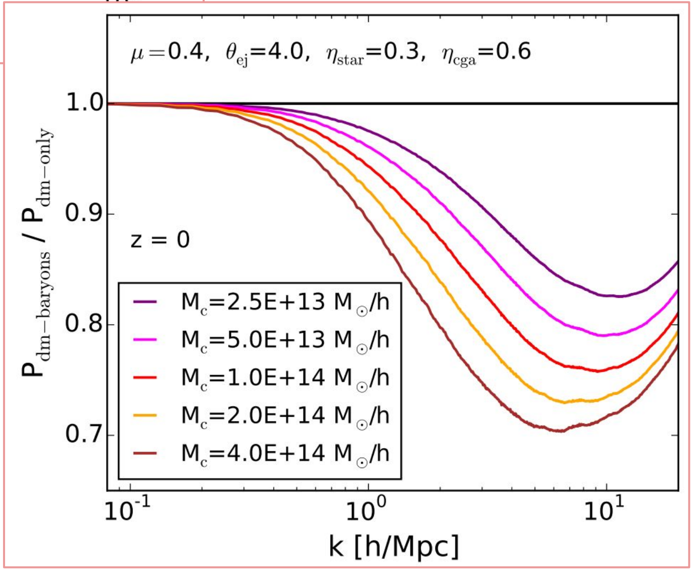
Baryon imprints



Impact on P(k)


M_c=1.0E+14 $M_\odot$/h, μ=0.4, η_{star}=0.3, η_{cga}=0.6
z = 0
θ_{ej}=2.0
θ_{ej}=3.0
θ_{ej}=4.0
θ_{ej}=6.0
θ_{ej}=8.0
$P_{dm-baryons} / P_{dm-only}$
1.0
0.9
0.8
0.7
10^{-1}
10^{0}
10^{1}
k [h/Mpc]


M_c=1.0E+14 $M_\odot$/h, μ=0.4, θ_{ej}=4.0, η_{tot}=0.3
z = 0
η_{cga}=0.4
η_{cga}=0.5
η_{cga}=0.6
η_{cga}=0.7
η_{cga}=0.8
$P_{dm-baryons} / P_{dm-only}$
1.0
0.9
0.8
0.7
10^{-1}
10^{0}
10^{1}
k [h/Mpc]


μ=0.4, θ_{ej}=4.0, η_{star}=0.3, η_{cga}=0.6
z = 0
M_c=2.5E+13 $M_\odot$/h
M_c=5.0E+13 $M_\odot$/h
M_c=1.0E+14 $M_\odot$/h
M_c=2.0E+14 $M_\odot$/h
M_c=4.0E+14 $M_\odot$/h
$P_{dm-baryons} / P_{dm-only}$
1.0
0.9
0.8
0.7
10^{-1}
10^{0}
10^{1}
k [h/Mpc]