Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Second Order Non-Gaussianity - SONG

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Today

What Is SONG?

A Boltzmann code like CAMB or CLASS, but at second order in cosmological perturbation theory

Advantages of going to second order

- Higher precision
- New physics
  - ➔ Non-Gaussianity
  - ➔ Mode coupling
  - ➔ Scalar-Vector-Tensor coupling
  - ➔ New source terms

$$\Delta^{(1)}(\vec{k}) = T^{(1)}(k)\Phi(\vec{k})$$

$$\Delta^{(2)}(\vec{k}) = \int\int d\vec{k}_1\, d\vec{k}_2 \delta^3(\vec{k} - \vec{k}_1 - \vec{k}_2)\, T^{(2)}(k, \vec{k}_1, \vec{k}_2)\Phi(\vec{k}_1)\Phi(\vec{k}_2)$$

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The SONG Code

- Source available at https://github.com/coccoinomane/song
- Based on CLASS, installation and running the code work the same
- provide .ini and .pre file in CLASS conventions, containing both SONG and CLASS parameters

```
include_sachs_wolfe_in_los_1st_order = no
include_integrated_sachs_wolfe_in_los_1st_order = no


*****   Second-order line of sight (LOS) sources   *****

use_test_source = no

include_pure_scattering_in_los_2nd_order = yes
include_quad_scattering_in_los_2nd_order = yes
include_metric_in_los_2nd_order = yes

include_quad_metric_in_los_2nd_order = no
include_time_delay_in_los_2nd_order = no
include_redshift_in_los_2nd_order = no
include_lensing_in_los_2nd_order = no

Abracadabra
use_delta_tilde_in_los = yes
use_delta_tilde_approx_in_los = no

Should we include the Sachs-Wolfe and integrated Sachs-Wolfe effects at second
order? Note that turning on the SW or the ISW effect will automatically turn
off the include_metric_in_los_2nd_order option.
include_sachs_wolfe_in_los_2nd_order = no
```

Structure Of SONG

For a run computing intrinsic non-Gaussianity

- perturbations2.c: Solve the differential system from the deep radiation era, till last scattering
  - ➔ Instead of $T(k)$ on a grid in k, we have $T(k, k_1, k_2)$ on a 3-D grid
  - ➔ Cannot focus on scalar modes alone
  - ➔ Many source terms that are constructed from CLASS output
- perturbations2.c: Build the line-of-sight sources
  - ➔ Sources cannot be recast into $l = 0$, but exist for all multipoles
- transfer2.c and bessel2.c: Line-of-sight integration is used to evolve the photon perturbations until today
- spectra2.c / bispectra2.c: Compute spectrum or bispectrum
  - ➔ Integration of bispectra for a completely general shape
- fisher.c: Compute the f_{NL} contamination and signal-to-noise

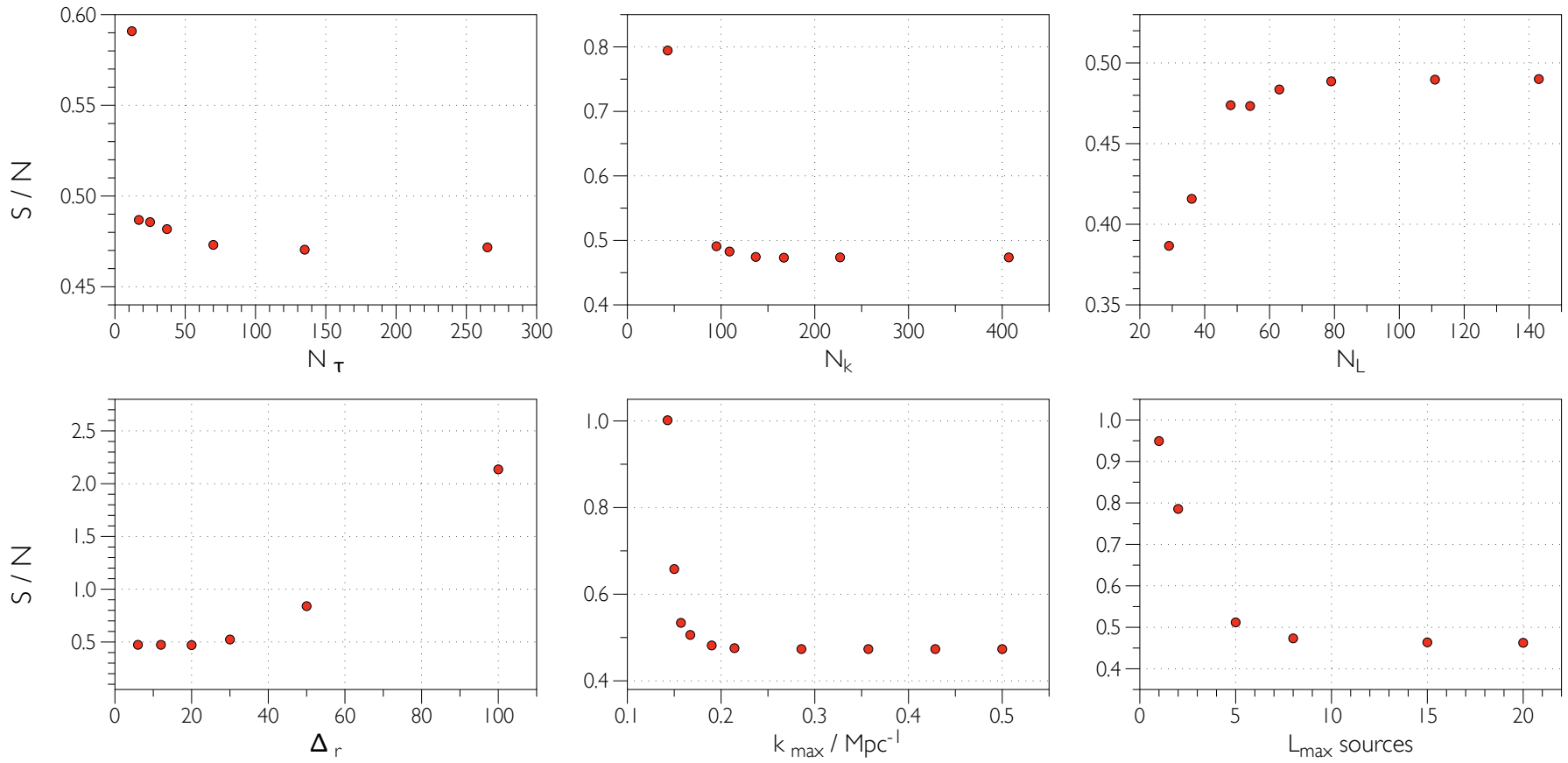
Numerical Stability

The second order computations are very complicated needing a lengthy code. To reduce the risk of mistakes we performed many test with SONG:

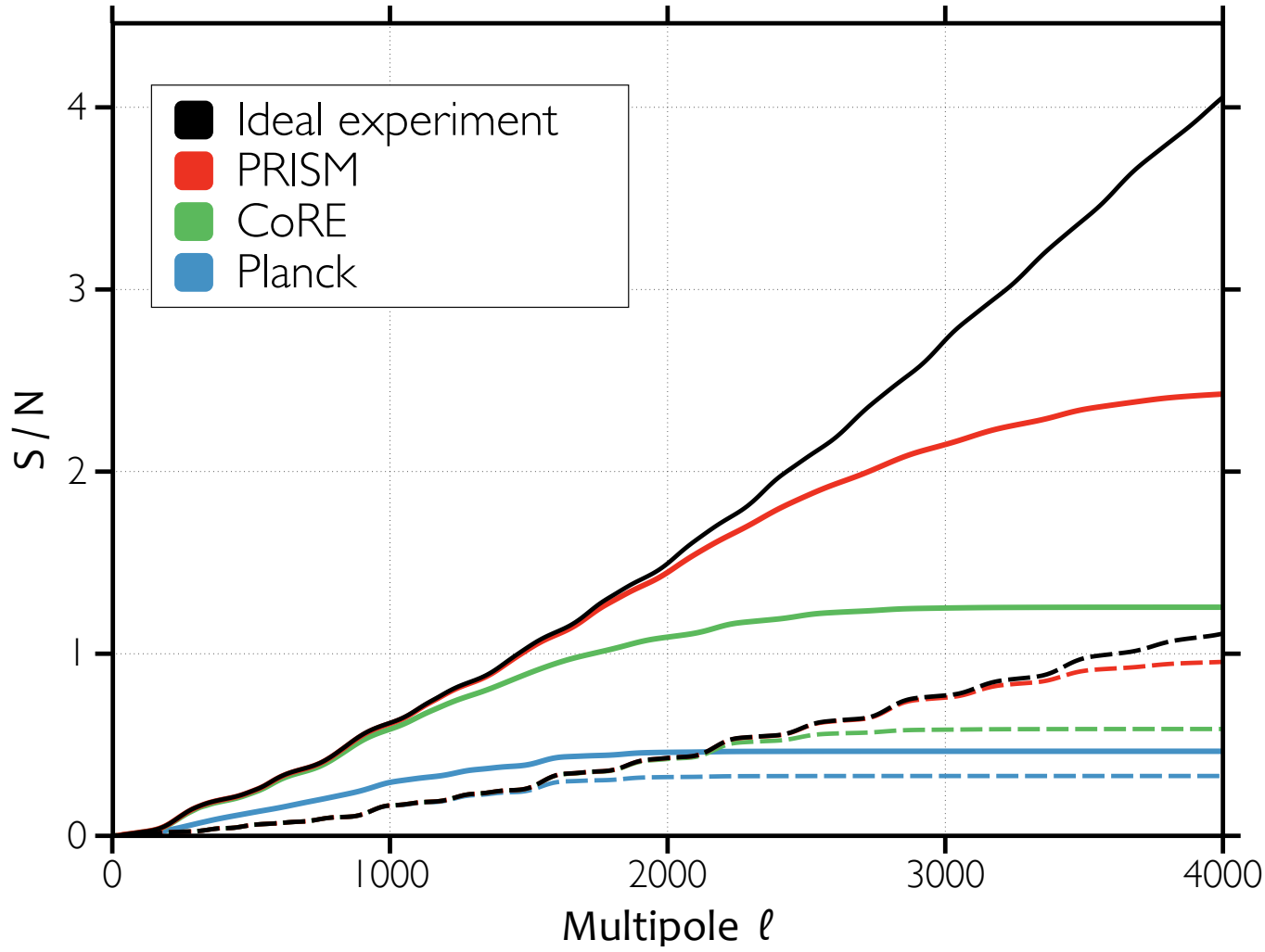
- We match many analytical limits for the sub horizon transfer functions
  Goroff, Grinstein, et al., 1986; Makino, Sasaki & Suto, 1992; Jain & Bertschinger, 1994; Bernardeau et al., 2002; Bartolo, Matarrese & Riotto 2006; Matarrese, Mollerach & Bruni 1998; Boubeker et al. 2009
- Match to the squeezed limit analytic approximation for the bispectrum (Assumes CDM domination and instantaneous recombination)
  Creminelli et al. 2011; Bartolo et al. 2011; Lewis 2012
- Performed detailed convergence and consistence checks
- Code is double checked against independent codes
  Beneke, Fidler & Klingmuller 2011; Huang & Vernizzi 2013; Su & Shellard 2013

Numerical Stability

Convergence tests



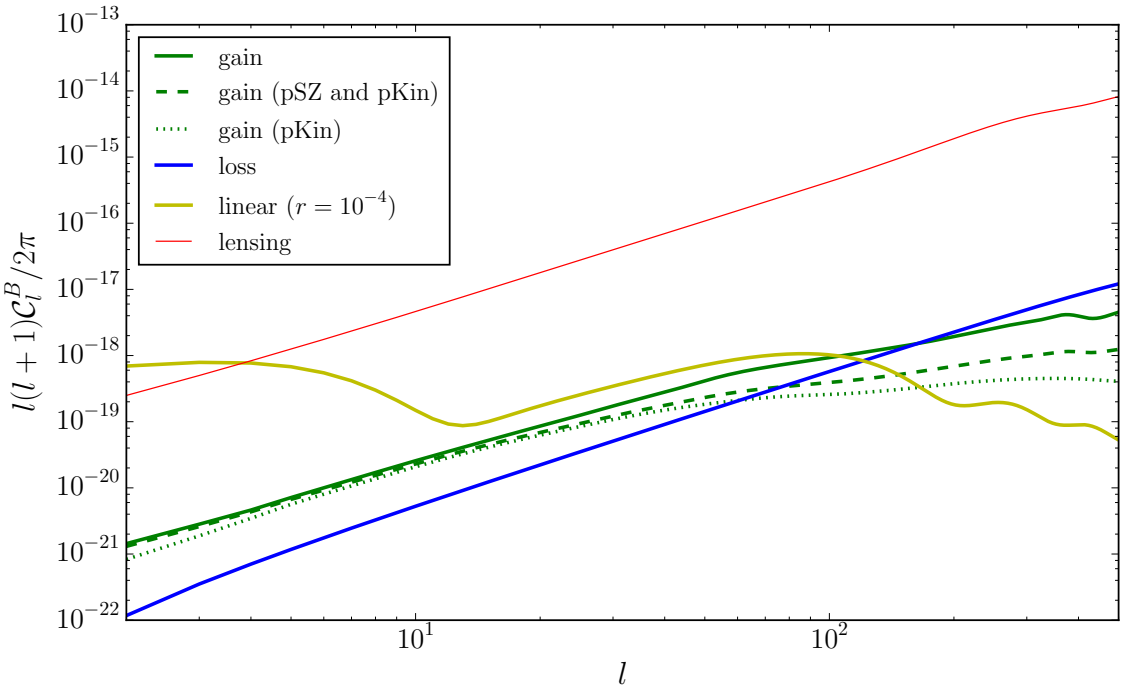
Non-Gaussianity



Late Time Effects

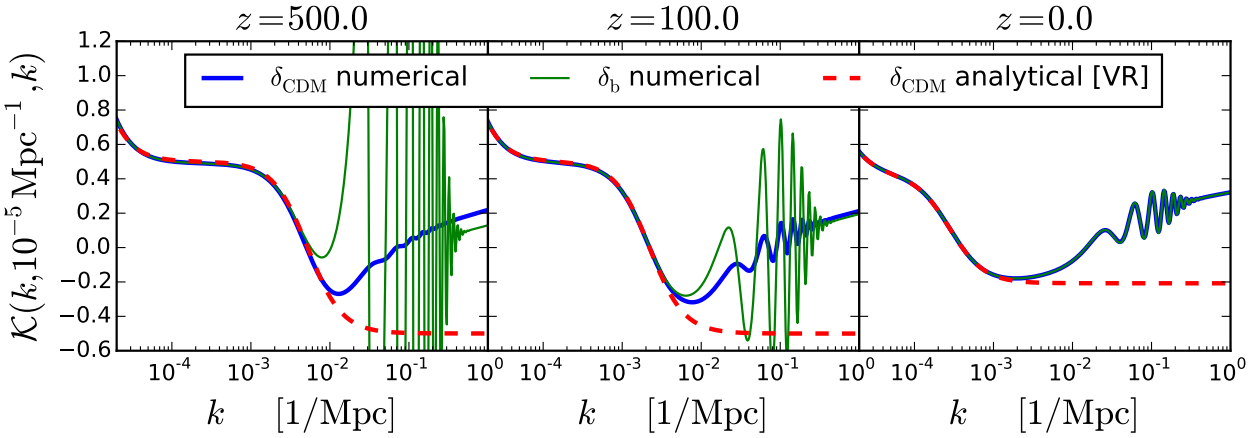
Late effects require an alternative approach as the amount of multipoles becomes impossible to include. Individual treatment is required

- Lensing: expand in deflection angles
- Redshift: modify LOS-sources plus analytical residual
- Reionisation: blurring + low-l residuals

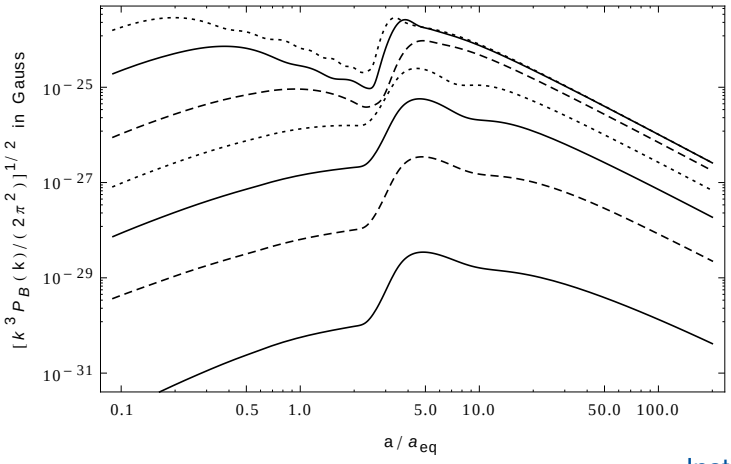


Further Applications

SONG can compute matter perturbations beyond linear perturbation theory



SONG can solve other perturbations such as magnetic fields



Summary

- SONG is a tool to simulate the Universe in full general relativity to second order in perturbation theory
- Many applications for CMB, but also in other areas of cosmology
- Based on CLASS, inherits the structure and is comparably easy to pick up if you already know CLASS
- Made easy to modify; more than 10.000 lines of comments
- Interested to support further applications and developments
  - ➔ Spectral distortions
  - ➔ 21-cm
  - ➔ Intensity mapping