Galaxy formation and primordial non-Gaussianities

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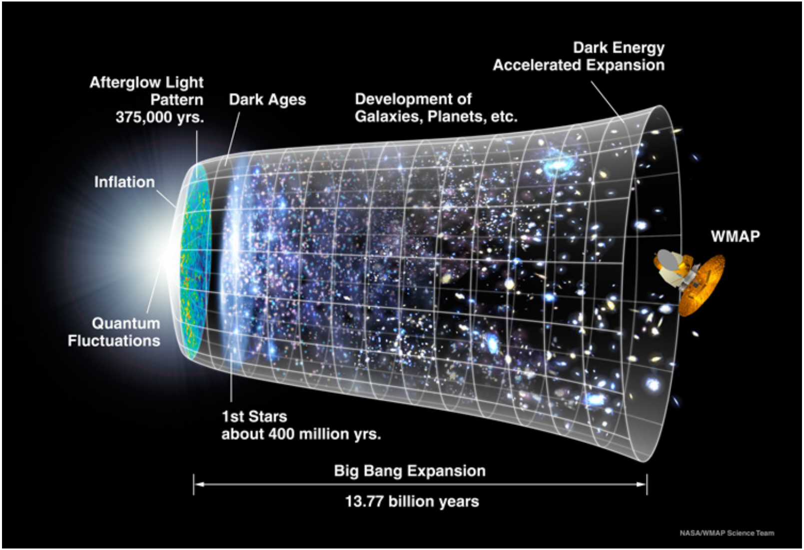
Based on 2209.15038, 2307.03300

Collaborators: T. Montandon, Y. Dubois, B. Famaey, O. Hahn, K. Kraljic, R. Ibata.

Large Scale Structures (LSS) formation



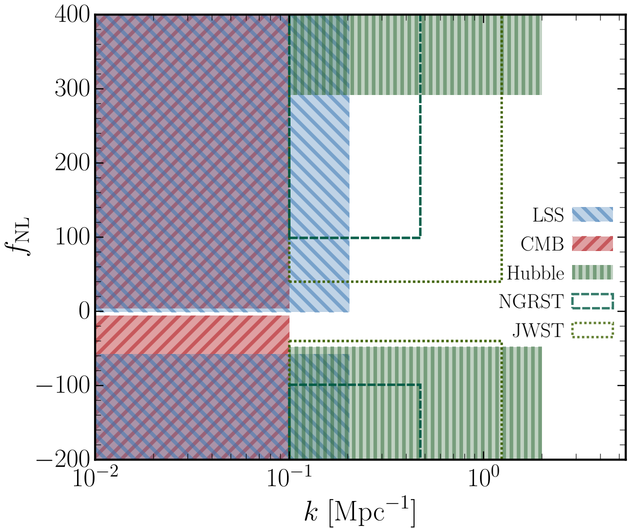
Cosmological structures formation

Fluids mechanics in an expanding universe.

Primordial non-Gaussianities (PNG) on small scales: current status

propagate Primordial non-Gaussianities → test inflationary physics

$$\Phi(\mathbf{x}) = \Phi_G(\mathbf{x}) + f_{\rm NL}\left(\Phi_G^2(\mathbf{x}) - \langle\Phi_G^2\rangle\right) . \quad (1)$$



Scale dependant PNG

Several models of strongly scale dependant PNG

Beyond slow roll

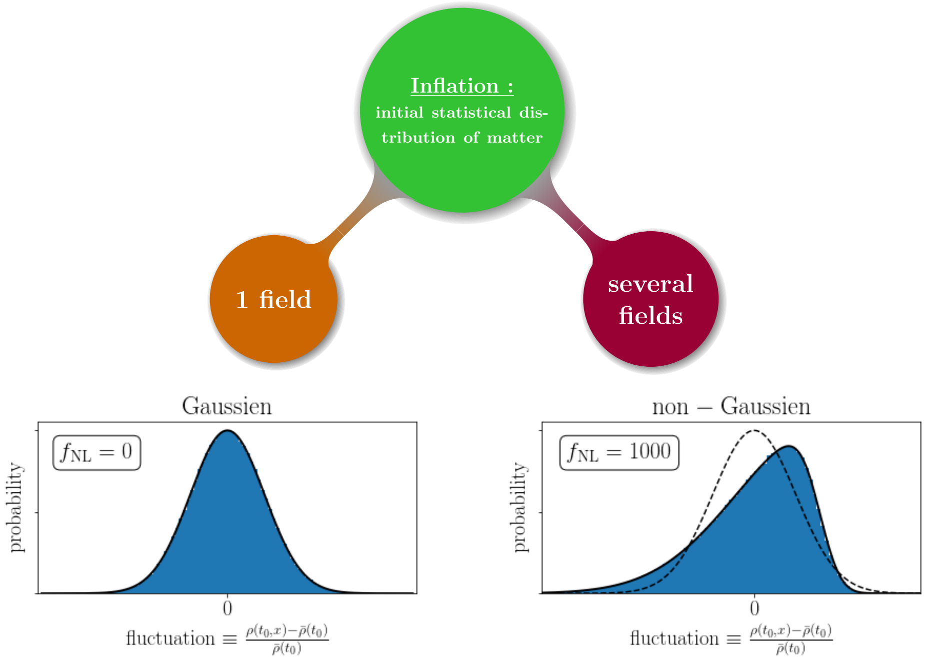
- Khoury 0811.3633: time-dependant sound speed
- Riotto 1009.3020: scalar field with abrupt change of mass
- Byrnes 1108.2708: curvaton-self interactions

- Can parametrize with $n_{f_{NL}} \equiv \frac{d \ln f_{NL}}{d \ln k}$
- Planck 1905.05697: constraints on running NG $\rightarrow$ compatible with 0.

Large PNG on scales smaller than $k_{CMB/LSS} \equiv k_{\text{cut}} = \mathcal{O}(0.1)$ Mpc^{-1}

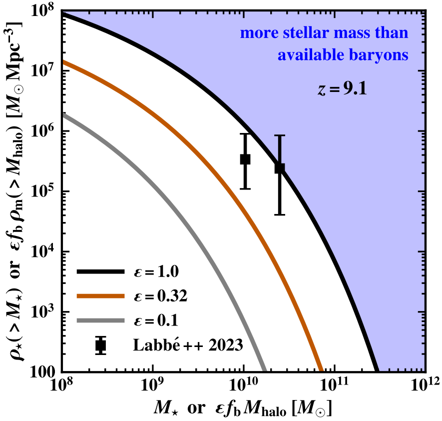
$$B_{\Phi} = f_{NL} P_{\Phi}(k_1) P_{\Phi}(k_2) \Theta(k_i - k_{\text{cut}}) + 5 \text{ perm.} \quad (2)$$

Scale dependant PNG

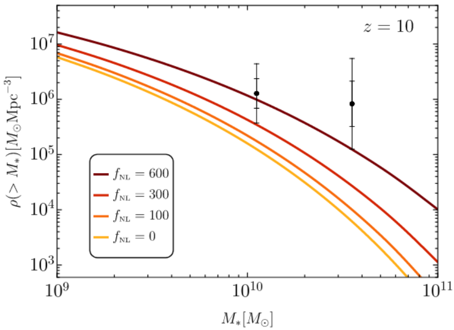


Bright massive galaxies at high redshift?

Boylan-Kolchin 2208.01611



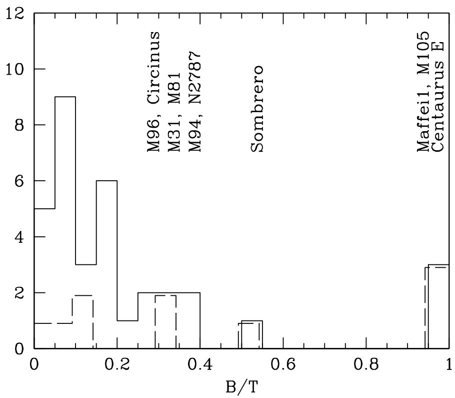
Biagetti 2210.04812



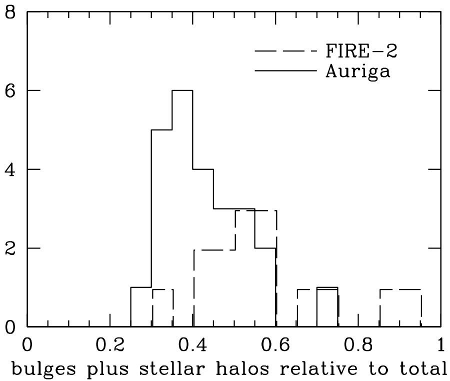
- Presence of massive galaxies naturally solved if structure formation started "earlier" $\rightarrow$ PNG favouring overdensities.
- Still, as all the other beyond ΛCDM solutions, the evolution of those massive galaxies between redshift 10 and 8 requires fine tuning in the models.
- Preliminaries observations. Take it with a grain of salt.

Peebles 2005.07588: study bulge to total luminosity of galaxies

Observations

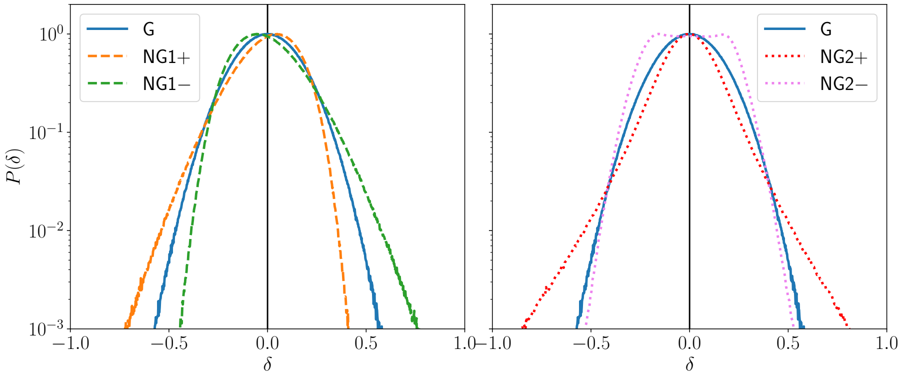


Simulations



- "Hot orbit problem" naturally solved if galaxies have a calmer environment, and form through a calmer history.
- Baryon feedback play a crucial role here
- Initial condition modification has also been tested: *genetic modification* (Stopyra 2006.01841), splicing (Cadiou 2107.03407), modify initial angular momentum (Cadiou 2206.11913).

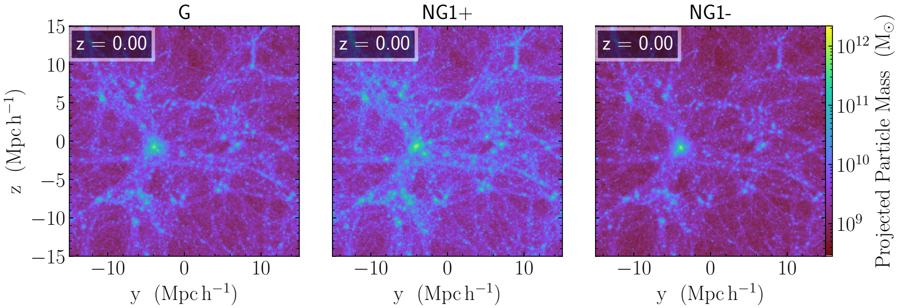
Numerical setup



- Toy models: NG of $f_{NL} = \pm\mathcal{O}(1000)$.
- 20 Dark Matter Only simulations[a]
- Grid : 512^3, BoxSize : 30 Mpc/h, softening length 1 kpc/h.
- Total mass in the box: $3.4 \times 10^{15} M_\odot$, mass of DM particles $2.6 \times 10^7 M_\odot$

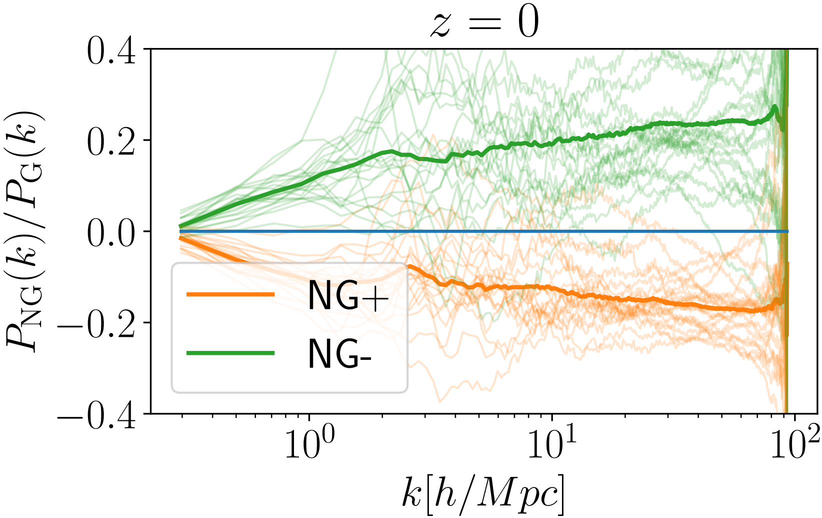
[a] Work with Gadget4 (https://wwwmpa.mpa-garching.mpg.de/gadget4/) and Monofonic (https://bitbucket.org/ohahn/monofonic/src).

Halos in quieter environments

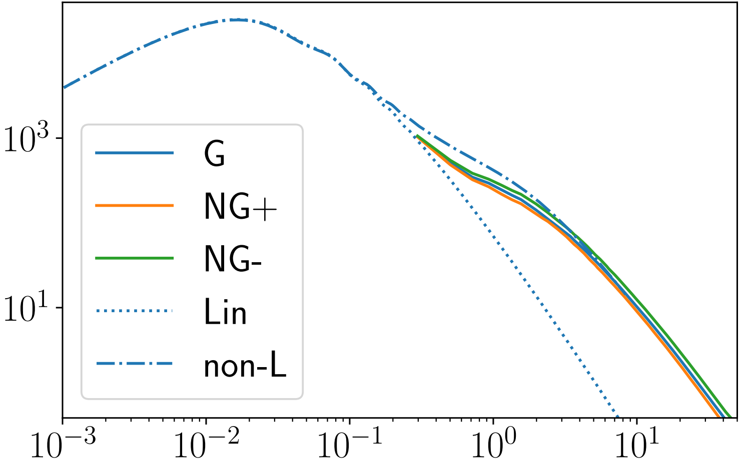


Matter power spectrum

$$\langle\delta(\vec{k}_1,t)\delta(\vec{k}_2,t)\rangle = (2\pi)^3\delta_D(\vec{k}_1+\vec{k}_2)P_m(k_1,t) \tag{3}$$

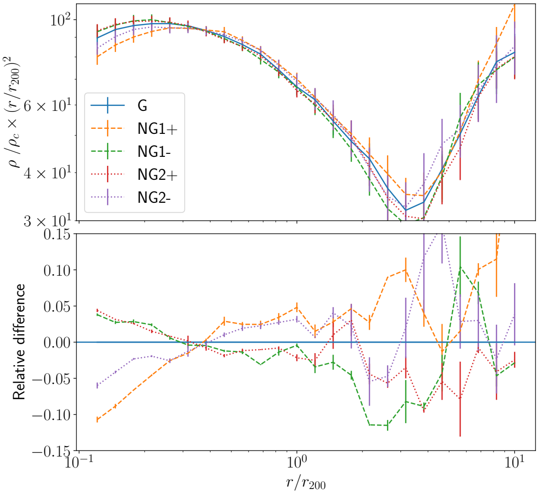


Matter power spectrum



Amon 2206.11794: a 30% decrease of the non-linear power spectrum solves the S8 tension (3σ discrepancy between Planck and large scale structures observations)

Density profiles



- Stacked result on our sample of the 100 more massive halo found in each simulation. $M_h \in \left[1.6 \times 10^{14}; 1.1 \times 10^{12}\right] M_\odot$.
- Similar study to Smith 1009.5085, though our box is much smaller.

Planar subhalos?

- Take the 11 more massive subhalos of the 100 more massive halos ($M_h \in 1.6 \times 10^{14}$ to $1.1 \times 10^{12}\, M_\odot$)
- inertia tensor:

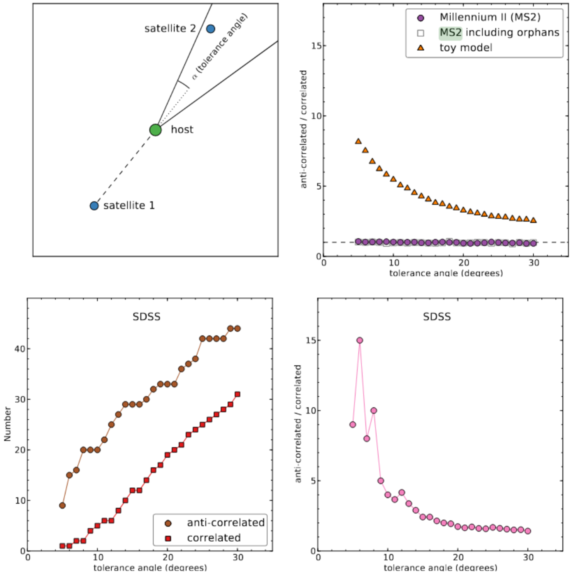
$$I_{ij} = \sum_{n=1}^{N} x_{n,i} x_{n,j} \tag{4}$$

- eigenvalue $\equiv a^2, b^2, c^2$.
- For the MW, 'Vast Polar Structure' (VPOS)=rotating plane of satellite galaxies, observations: $c/a = 0.182$ (Pawlowski 1204.5176).
- Gaia proper motion: 50% to 75% of the satellites within the VPOS are orbiting around that structure (Li 2104.03974)
- Difficult to account for in traditional N-body, see however Sawala 2205.02860

Simulation	G	NG1+	NG1-	NG2+	NG2-
c/a	0.33 ± 0.01	0.34 ± 0.01	0.32 ± 0.02	0.31 ± 0.01	0.37 ± 0.02

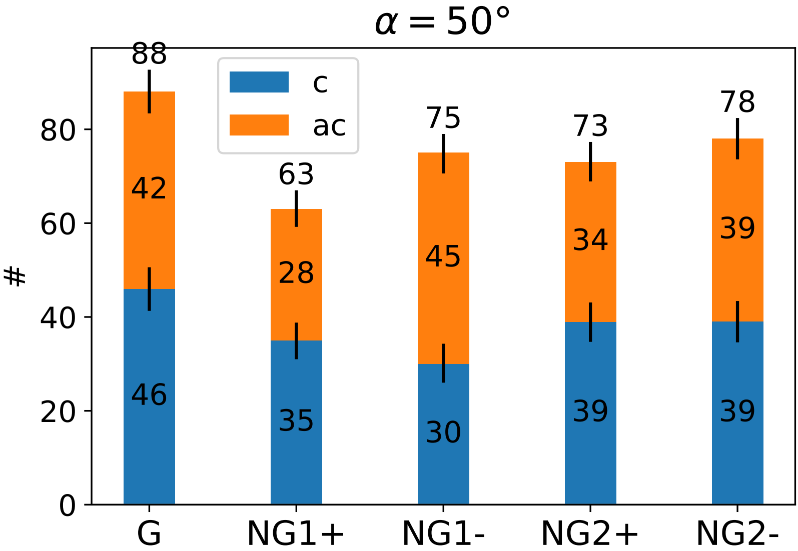
Correlated subhalos?

A classical test of the litterature (Ibata 1407.8178): dwarf satellite galaxies are aligned in thin and kinematically coherent planar structures



Correlated subhalos?

Simulation	G	NG1+	NG1-	NG2+	NG2-
AC/C, $\alpha = 10$ deg	1.1 $\pm$0.5	1.0 $\pm$0.8	1.3 $\pm$0.6	0.9 $\pm$0.6	1.0 $\pm$0.8
AC/C, $\alpha = 50$ deg	0.9 $\pm$0.2	0.8 $\pm$0.2	1.5 $\pm$0.3	0.9 $\pm$0.2	1.0 $\pm$0.2

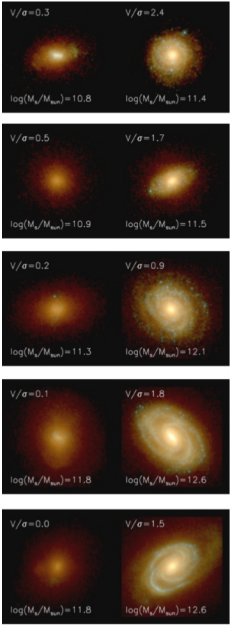


Numerical setup

- Same random seed, same setup
- Hydrodynamical simulation for the baryons following the Horizon-AGN code (Dubois 1606.03086).
- Dynamics of gas, cooling and heating.
- Mass in the box: $3.4 \times 10^{15} M_{\odot}$, mass of DM particles $2.2 \times 10^{7} M_{\odot}$.
- 2 Mhours of CPU time.

Subgrid model

- Star formation
- Feedback of stars (stellar winds, supernovae type II and Ia)
- 6 chemical species (O, Fe, C, N, Mg, Si)
- Feedback of Active Galactic Nuclei



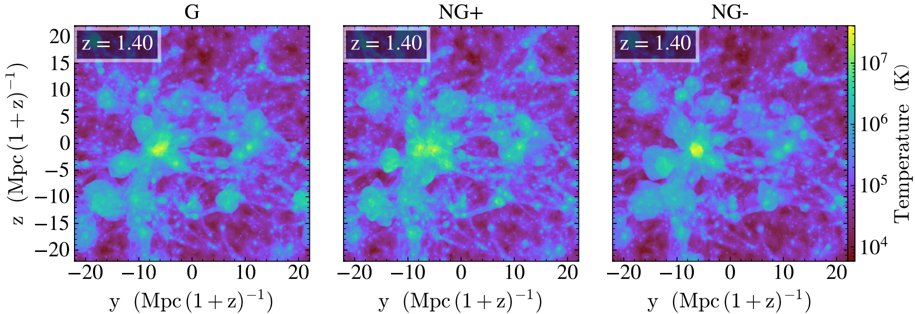
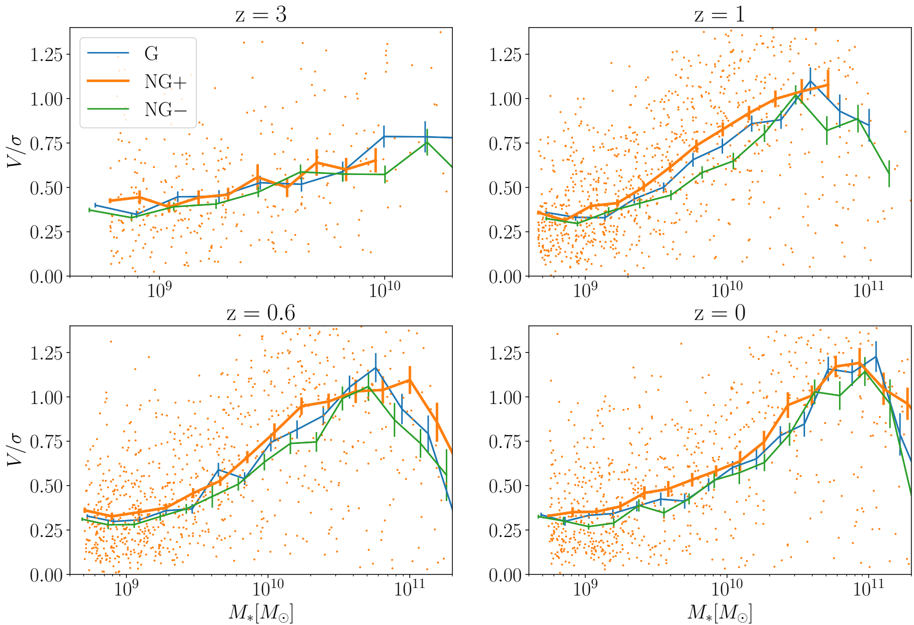


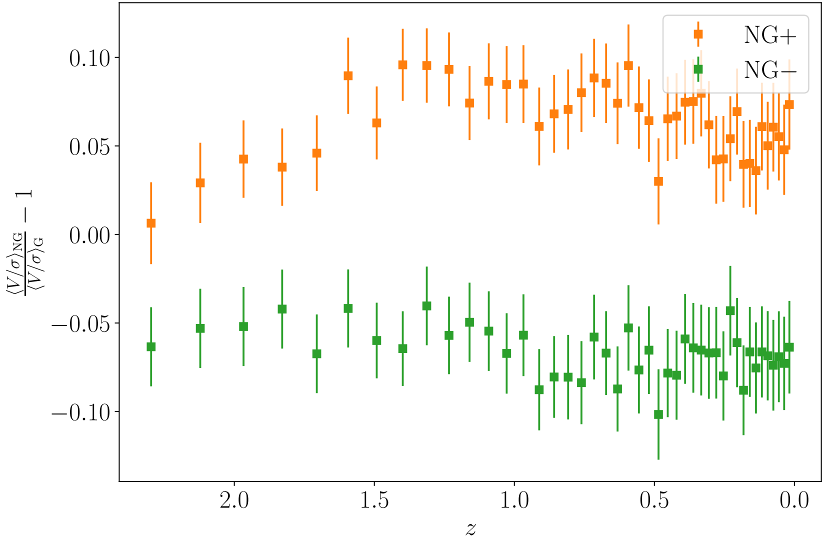
Figure: Temperature of the gas at redshift $z = 1.4$.

Disk kinematics



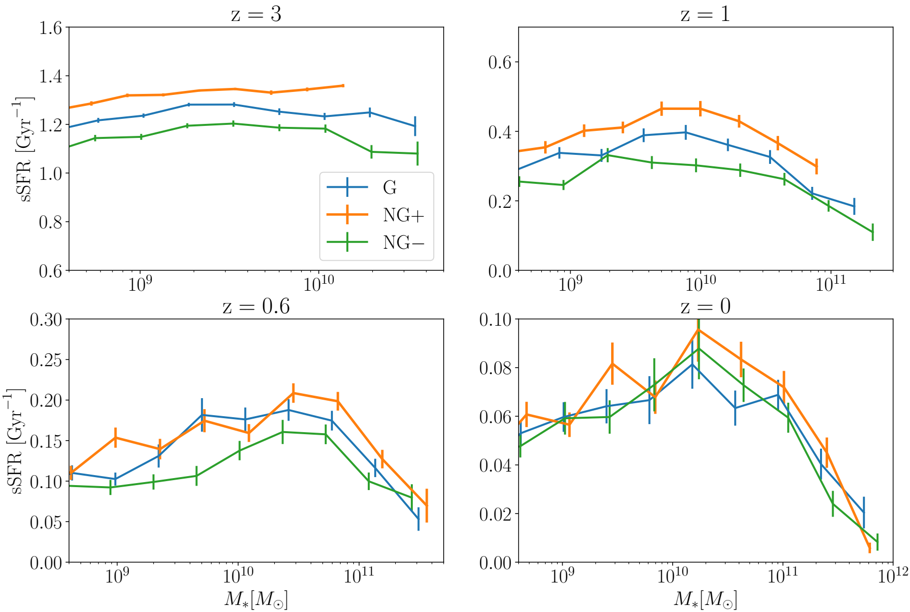
- Hierachy of the models similar as DMO simulations: NG+ > G > NG-

Evolution with redshift



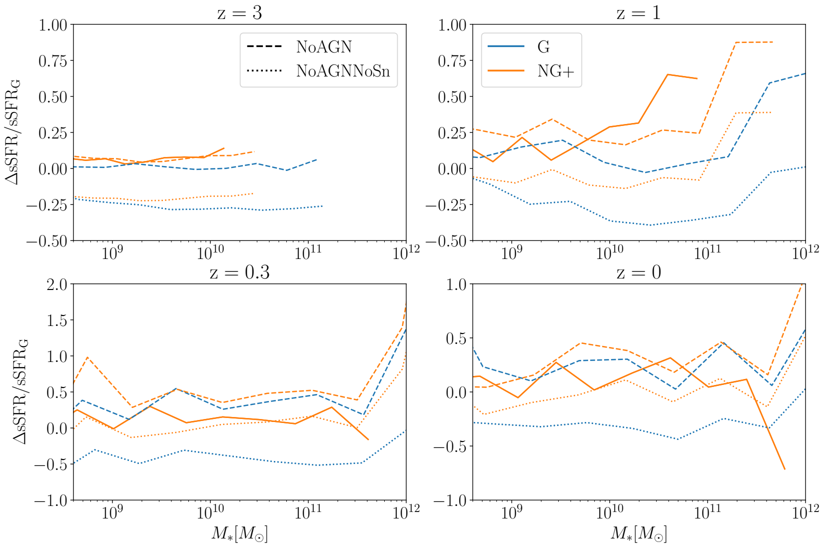
- About 5% effect at all z<3

specific Star Formation Rate



- Hierachy of the models similar as DMO simulations: NG+ > G > NG-

Impact of the feedback?

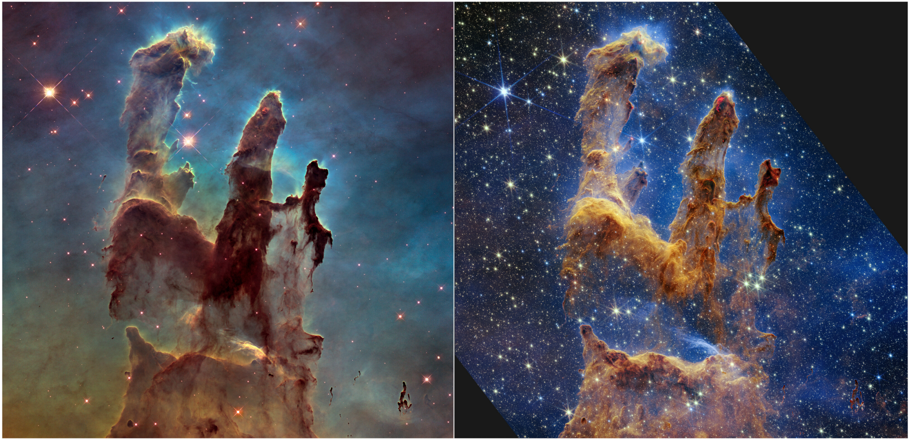


- AGN shut down star formation at high mass
- Supernovae (stellar winds) impact at low ($<10^{11} M_\odot$) mass

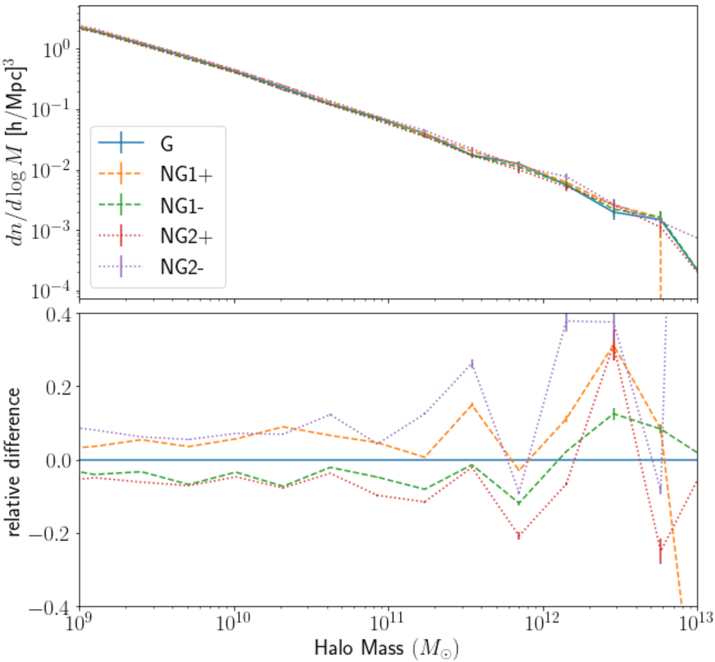
Conclusions

- Large PNG on small scales: potential to impact open questions in galaxies
- Massive high-z galaxies are also easier to form in that context?
- Would NFW still be a nice fit to dark matter profiles with PNG?
- Feedback parameters vs inflationary parameters $\rightarrow$ impact of fundamental physics to galaxies ; memory of the galaxies of their initial conditions?
- Need to back up these explorations with more simulations: zoom on one galaxy in a cosmological background...
- Refine my templates of PNG: low pass filter, power laws, inflationary sounds models (Riotto 1009.3020).
- Easy to extend to WDM or Effective Theory of DM (α, β, γ parametrization of Murgia 1704.07838 already implemented by us in `Monofonic`.)
- Primordial Black Holes: a natural dark matter candidate with large PNG.

Thank you for your attention



Halo Mass Function



In-situ vs ex-situ stars

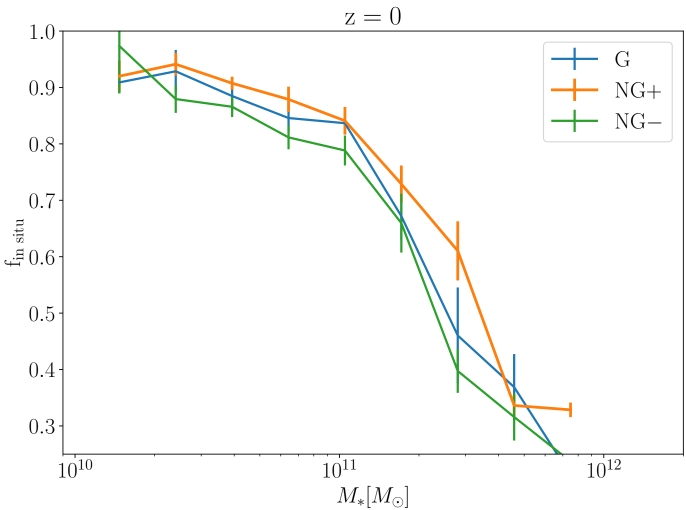


Figure: Mean fraction of in situ formed stars as a function of stellar mass at $z = 0$.

- Hierachy of the models similar as DMO simulations: NG+ > G > NG-

M_*-M_h relation

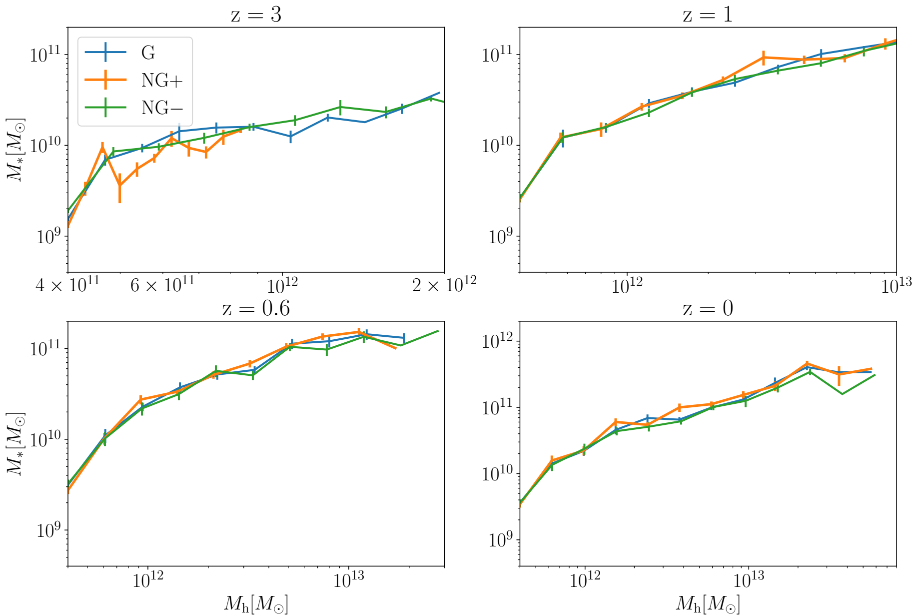
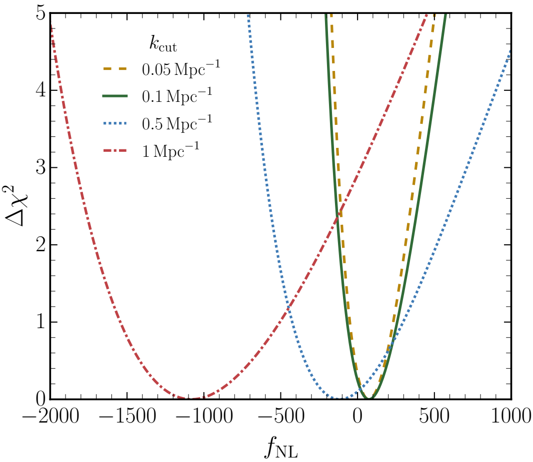


Figure: NG+ builds its galaxies later: at $z = 3$, it has fewer stars at fixed halo mass but it catches up at later times to slightly dominate at $z = 0$.

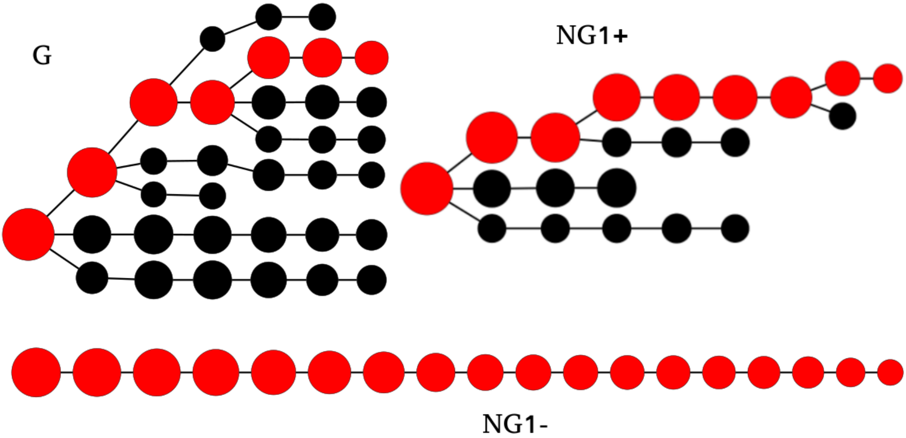
Primordial non-Gaussianities (PNG) on small scales



Sabti 2009.01245

- Study UV galaxy luminosity function of Hubble telescope
- A detection at 1.7 σ.
  Most likely a bump in the data, but who knows... $\rightarrow$ JWST, NGRST
- Using another model of dust extinction, no more detection

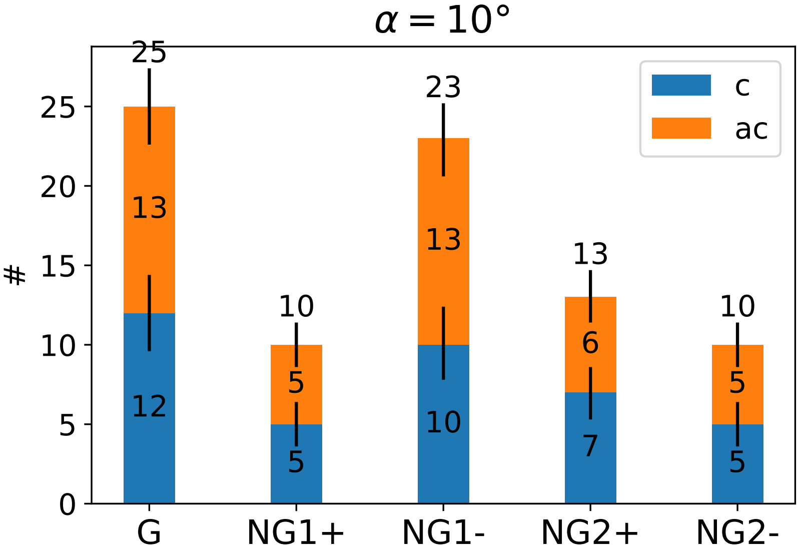
Merging history



Simulation	G	NG1+	NG1-	NG2+	NG2-
$z_{1/2}$	0.64 $\pm$0.01	0.59 $\pm$0.01	0.67 $\pm$0.02	0.64 $\pm$0.01	0.60 $\pm$0.01
MC	3.5 $\pm$0.1	3.5 $\pm$0.2	3.3 $\pm$0.2	2.8 $\pm$0.2	4.8 $\pm$0.2

Correlated subhalos?

Simulation	G	NG1+	NG1-	NG2+	NG2-
AC/C, $\alpha = 10$ deg	1.1 $\pm$0.5	1.0 $\pm$0.8	1.3 $\pm$0.6	0.9 $\pm$0.6	1.0 $\pm$0.8



Fundamental origin of our universe: Inflation

Image credit: Pablo Carlos Budassi

Inflation *explains* the origin of the primordial density perturbation. It predicts a Gaussian spectrum (nearly) scale invariant $P(k) = A_s k^{n_S - 1}$.

Fundamental origin of our universe: Inflation

Image credit: Pablo Carlos Budassi

Inflation *explains* the origin of the primordial density perturbation. It predicts a Gaussian spectrum (nearly) scale invariant $P(k) = A_s k^{n_S - 1}$.

The perturbations grow into the CMB anisotropies and eventually into the stars and galaxies we see around us.

We have a detection of a small departure from scale invariance, consistent with the expectations of simple inflationary models.

In inflationary paradigm, in the first fractions of second, the rapid expansion dillutes anything but quantum fluctuations which imprint into the *full* gravitational fields of the universe.

Fundamental origin of our universe: Inflation

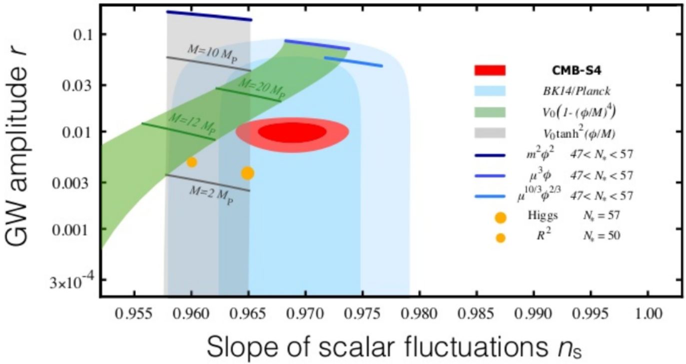
Successfull (and has no serious concurrent consistant with data) but... How did inflation occur? How did it begin? Are ground-state quantum fluctuations truly the source of density perturbations? What is the connection of inflation to the rest of physics? Are there observations that could falsify inflation?

Quite a zoology of inflation models (Encyclopaedia Inflationaris, Martin 1303.3787, 368 pages, 192 figures)

Fundamental origin of our universe: Inflation

Energy scale at which inflation occurs is unknown and can range across 10 orders of magnitude.

Quantum fluctuations imprint into the *full* gravitational fields of the universe $\rightarrow$ Production of gravitational waves! Potential observation for highest energy model of inflation ($>10^{16}$ Gev) through interaction with polarization of CMB photons (B-modes).



CMS-S4 Science book 1610.02743

$$\left(\frac{r}{0.01}\right) \simeq \frac{V^{1/4}}{10^{16}\text{Gev}}$$

Fundamental origin of our universe: Inflation

Models with energy scale below 10^{16} Gev have no observable primordial gravitational waves. Class these models using **primordial non-gaussianities** (PNG): complement GW seaches (Meerburg 1903.04409)

Theorem: (Consistency relations), Maldacena 0210603

If only one light scalar field is active during inflation, the behavior of the three-point correlation function, in the squeezed limit, is entirely fixed by the two-point correlation function.

Single field predicts $f_{\mathrm{NL}} \simeq \frac{5}{12}(1 - n_S) \simeq 0.02$.
A detection of $f_{\mathrm{NL}} \gg 0.02$ rules out all single inflation.

Constraints

$f_{\mathrm{NL}} = 37 \pm 20$ (WMAP 1212.5225),
$f_{\mathrm{NL}} = -0.9 \pm 5.1$ (Planck 1905.05697).
$f_{\mathrm{NL}} = -12 \pm 21$ (SDSS, 2106.13725)
Future LSS experiements (Euclid, DESI, SKA...) will improve this constraint by an order of magnitude: $\sigma(f_{\mathrm{NL}}) = \mathcal{O}(1)$