

Probing the first instants of the universe with large scale structure

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1 Cosmology, Linear Structure formation

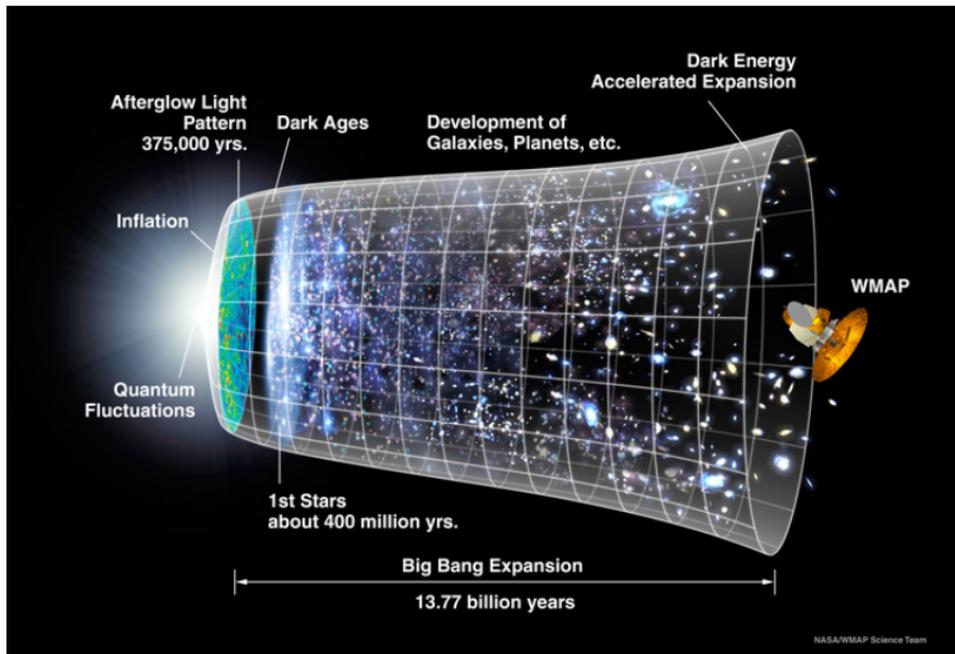
2 Beyond linear regime

- Analytics techniques
- N-body simulations

3 Beyond Poisson equation

- from Poisson to General Relativity
- from one Poisson to two Poisson
- from Poisson to Polarized Poisson

Large Scale Structures (LSS) formation



Cosmological structures formation

Fluids mechanics in an expanding universe.

Large Scale Structures (LSS) formation

In LSS, split between large scales *background*: $\bar{\rho}(t)$ (expanding universe, well defined mean density) and intermediate scales *perturbations* $\delta(\vec{x}, t) \equiv \frac{\rho(\vec{x}, t) - \bar{\rho}(t)}{\bar{\rho}(t)}$ (density differs little from background).

Perturbation theory

- Assumptions: Linear fluids mechanics in an expanding universe.
- Boltzmann-Poisson : $\mathcal{L}[f] = 0$ and $\Delta\phi = 4\pi G a^2(t)\delta(\vec{x}, t) \rightarrow \ddot{\delta}(\vec{x}, t) + (\text{expansion})\dot{\delta}(\vec{x}, t) - (\text{gravity})\delta(\vec{x}, t) = 0$

Statistical properties

- One universe = one realization. $\delta(\vec{x}, t)$ not very useful \rightarrow statistical properties.
- $\langle \delta(\vec{x}, t) \rangle = 0$ by construction
- Variance $\langle \delta(\vec{x}, t)^2 \rangle$ useful but there is more..
- 2-point correlation function $\langle \delta(\vec{x}, t)\delta(\vec{y}, t) \rangle$ or in Fourier space power spectrum P : $\langle \delta(\vec{k}_1, t)\delta(\vec{k}_2, t) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2) P(k_1, t)$ contain most information
- Bispectrum B
 $\langle \delta(\vec{k}_1, t)\delta(\vec{k}_2, t)\delta(\vec{k}_3, t) \rangle = (2\pi)^3 \delta_D(\vec{k}_1 + \vec{k}_2 + \vec{k}_3) B(k_1, k_2, k_3, t)$ and higher-order correlations, also very interesting.

Queen observable: Matter power spectrum

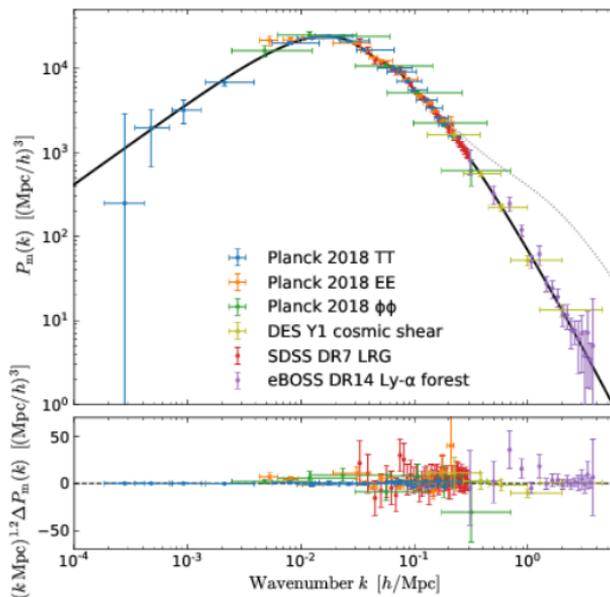


Image credit: Chabanier 1905.08103

Linear regime: BAO <https://www.youtube.com/watch?v=jpXuYc-wzk4>

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- Cosmic structures grow out of tiny initial fluctuations $\delta_l(\vec{k}, t)$ and become non-linear.
- Linear perturbation theory fails big time for $k > 0.1 h/\text{Mpc}$ Possible to push perturbation theory to obtain some non-linear term :

$$\delta(\vec{k}, t) = \sum_{n=1}^{\infty} a^n(t) \int_{\vec{k}_1 \dots \vec{k}_n} F_n(\vec{k}_1, \dots, \vec{k}_n) \delta_l(\vec{k}_1) \dots \delta_l(\vec{k}_n) \equiv \sum_{n=1}^{\infty} \delta^{(n)}. \quad (1)$$

$$P_{1\text{-loop}} = \langle \delta \delta \rangle = \langle \delta^{(2)} \delta^{(2)} \rangle + \langle \delta^{(1)} \delta^{(3)} \rangle = P_{22} + P_{13}. \quad (2)$$

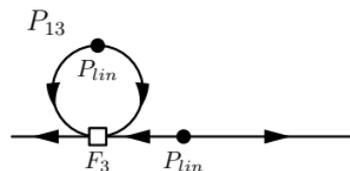
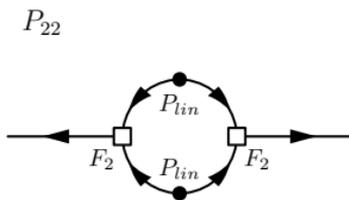
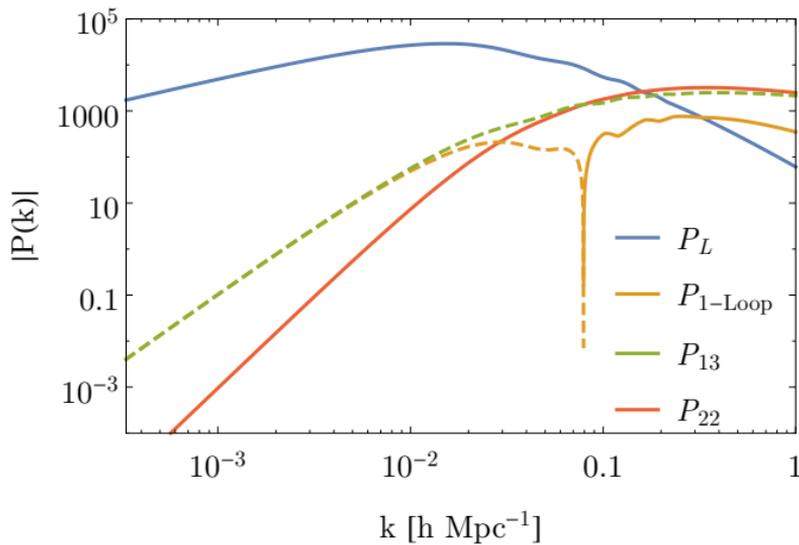


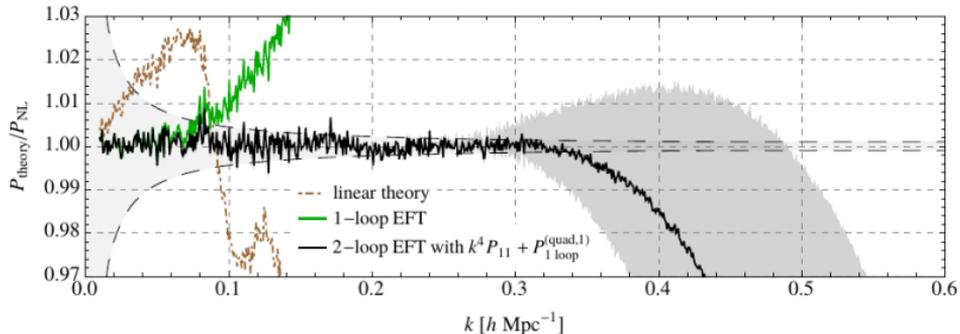
Image credit: [Simonović 1708.08130](#)



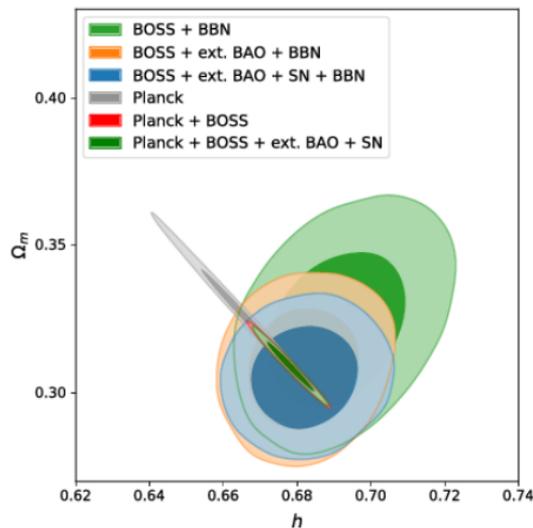
- Recursive relations for kernels F_n (Bernardeau 0112551, eq. 43), but still need to calculate multi dimensional integrals in an efficient way (see Simonović 1708.08130 for a technique).
- Import techniques from field theory to improve the convergence properties of perturbation theory: regularized perturbation theory, path integral formalism, renormalization group flow, coarse grained perturbation theory, effective field theory, kinetic field theory... (see **Castiblanco** 1910.03931 for references).

Effective field theory of Large Scale Structures in a nutshell

- Follow philosophy to integrate out (unknown) small scales physics and encapsulate it in unknown coefficient compatible with symmetries of the problem (FLRW). Example of coefficient includes *effective* viscosities and speed of sound. → need to measure in the data or in a simulation these coefficients.
- In principle, these new terms can be compute from the knowledge of microphysics (galactic physics..). Possible to push perturbation theory to $k \sim 0.3 h/\text{Mpc}$.



Possible to look at the data !



Zhang 2110.07539, see also Colas 1909.07951

- No tension with Planck measurement (cf. H_0 tension)
- Similar lines of research developed with other field theory techniques (eg. Osato 1810.10104, Schmidt 2004.06707)
- Exciting for future galaxy surveys.

The future?

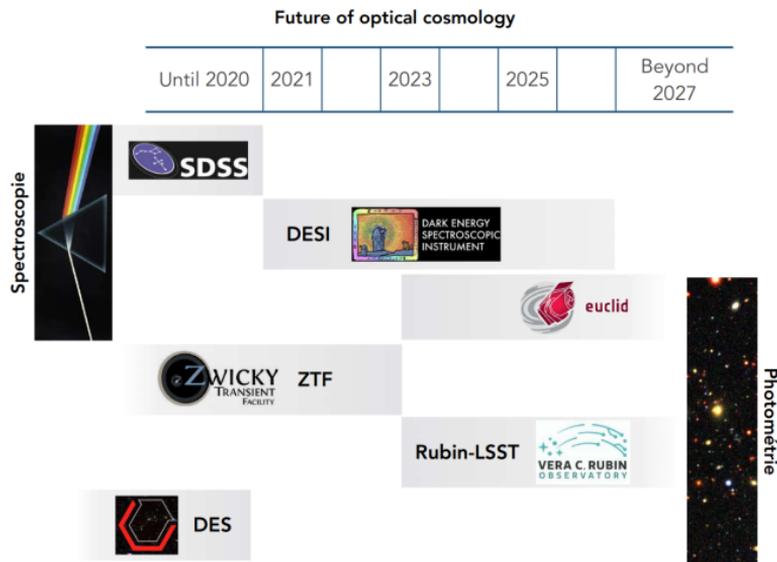
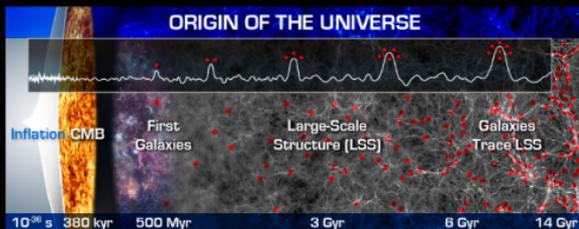


Image credit: J. Bautista

And many more: Roman Space Telescope (2022-2027), Mauna Kea Spectroscopic Explorer (MSE) (2030), Square Kilometre Array (SKA), LiteBird (2027), Simons Observatory, CMB-S4, LISA, Sphex, MegaMapper, PUMA....

Example: Spherex

SPHEREX HAS THREE CORE SCIENCE THEMES



NASA Goal: *Probe the origin and destiny of the Universe*

SPHEREx maps the large scale structure of galaxies to study the inflationary birth of the universe



NASA Goal: *Explore whether planets around other stars could harbor life*

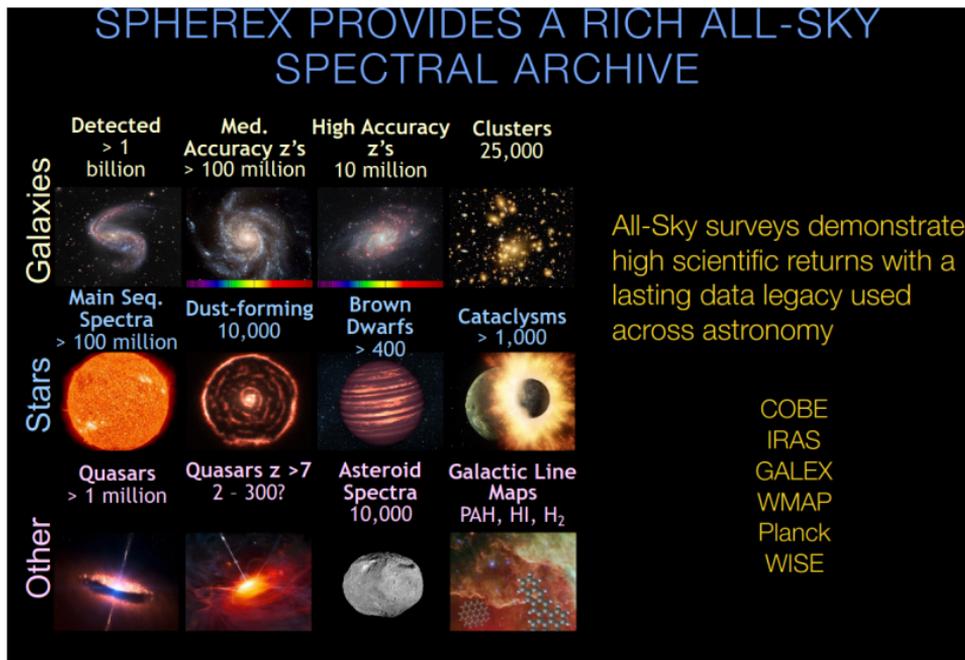
SPHEREx determines the abundance of interstellar water and organic ices available to proto-planetary systems



NASA Objective: *Explore the origin and evolution of galaxies*

SPHEREx measures the total light produced by stars and galaxies over cosmic history

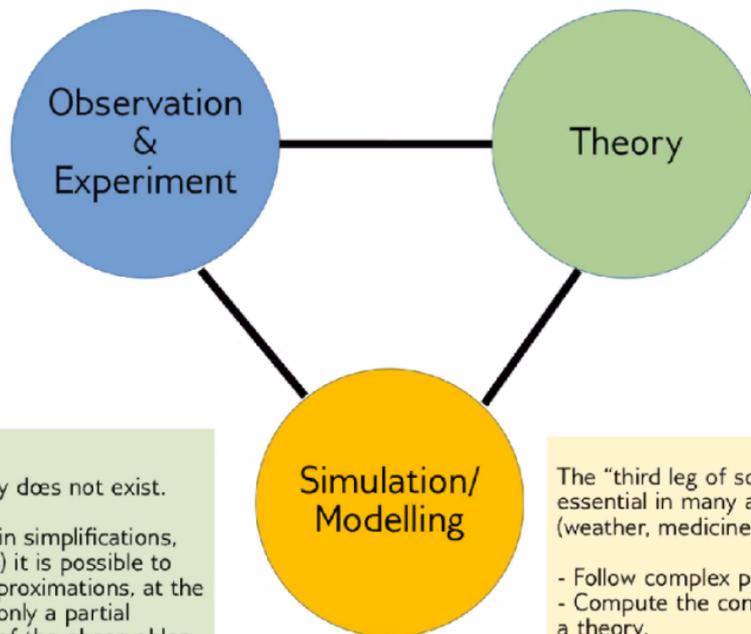
Bottom line: data will be amazing



Credit: O. Doré

Need to improve the theory and data analysis pipeline.

What about N-body simulations



A LSS theory does not exist.

Under certain simplifications, (large-scales) it is possible to get good approximations, at the expense of only a partial description of the observables.

The “third leg of science” is essential in many areas of science (weather, medicine, astrophysics)

- Follow complex physics,
- Compute the consequences of a theory.
- Perform “numerical experiments”

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Before:

$$\Delta\phi = 4\pi G a^2(t)\delta(\vec{x}, t) \quad (3)$$

After:

$$e^{2\phi}\Delta\phi = 4\pi G a^2\delta - \frac{3}{2}e^{-2\psi}(\mathcal{H} - \phi')^2 + \frac{e^{2\phi}}{2}\phi_{,i}^2 \quad (4)$$

follows from metric in Poisson gauge

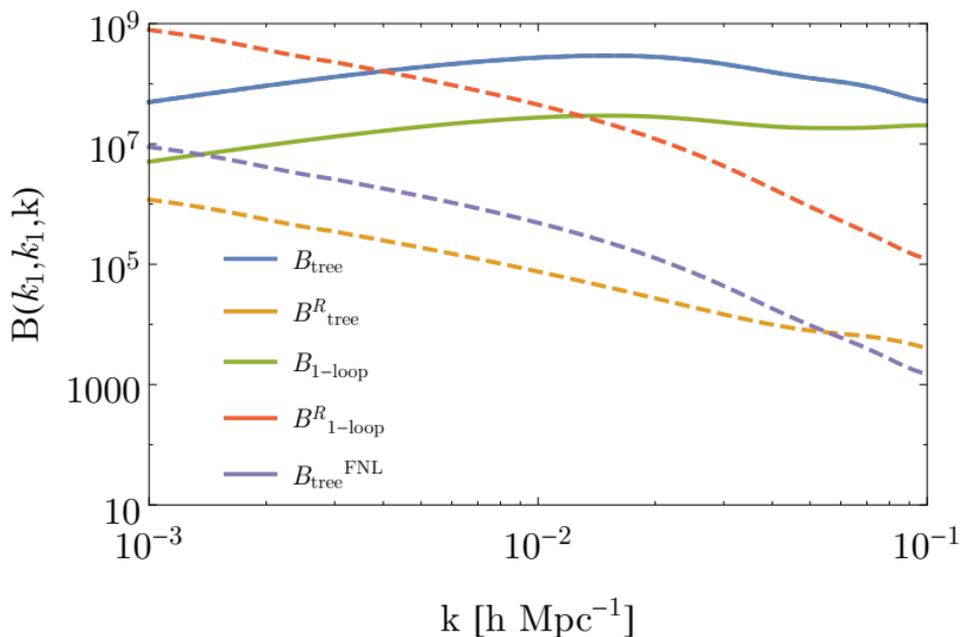
$$ds^2 = -a^2 e^{2\psi} d\tau^2 + a^2 e^{-2\phi} \delta_{ij} (dx^i + \beta^i d\tau) (dx^j + \beta^j d\tau). \quad (5)$$

Motivations

- Future surveys will probe scales close to the Horizon scale \rightarrow Newtonian physics is not enough
- Relativistic degree of freedom, allow to probe GR on the largest scales
- Relativistic species (neutrinos, cosmic strings, DDE, IDE.)
- Backreaction: how non-linear evolution impacts means quantities.
- Observations are made on the relativistic perturbed light cone.

What we did

Analytic approach: Calculate the non-linear relativistic corrections to F_2, F_3 and $\overline{F_4}$. These relativistic effects are totally degenerated with primordial signal that may come from fundamental physics: primordial non-gaussianities (**Castiblanco** 1811.05452, **Calles** 1912.13034).



Fundamental physics

Inflation models with energy scale below 10^{16} GeV have no observable primordial gravitational waves. Class these models using **primordial non-gaussianities**: complements GW searches (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 $f_{\text{NL}} \simeq \frac{5}{12}(1 - n_S) \simeq 0.02$. A detection of $f_{\text{NL}} \gg 0.02$ rules out all single inflation.

Way out of the theorem:

- Several fields active during inflation Sugiyama 1101.3636
- higher spin Arkani-Hamed 1503.08043
- 'modified' gravity Tahara 1805.00186
- anisotropic inflation Emami 1511.01683
- electromagnetic field Chua 1810.09815 **Stahl** 1507.01686

These theorems also apply to the late universe (Creminelli 1309.3557)
→ probe the early universe with LSS observables.

Inflation

Single field

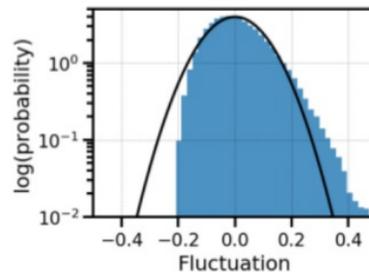
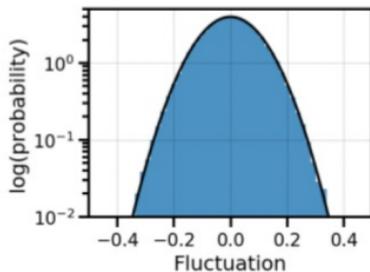
Multi-field

Gaussian fluctuations

Non-Gaussian fluctuations

$$f_{\text{NL}} \ll 1$$

$$f_{\text{NL}} \gtrsim 1$$



Slide from M. Schmittfull.

Non-gaussianities and relativistic corrections require non-linear initial conditions. Numerical approach: Complement our analytical approach by introducing in the general relativistic N-body code *gevolution* (relativistic version of *Gadget*) non-gaussian initial conditions. (**Adamek** 2110.11249)

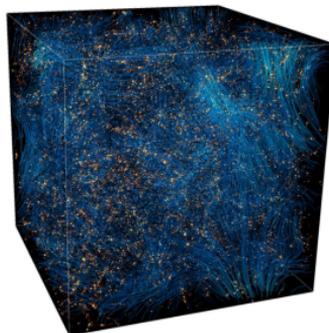


Figure: Spin one metric perturbation. <https://youtu.be/9y6T5CoZgi4>

Conclusions

- GR corrections to Poisson equation are totally degenerated with primordial non-gaussianities.
- We probe for the first time a bispectrum in a relativistic N-body simulation.
- Ray tracing exists within *gevolution*. Include the travel of the photons in a clumpy universe (cf. redshift space distortion, finger of god like effects).

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Dirac-Milne: an invitation to reinterpret cosmological observations

- Ambitious framework without dark energy and dark matter.
- Exotic gravity with

$$\Delta\phi_1 = 4\pi G(\rho_1 - \rho_2) \quad (6)$$

$$\Delta\phi_2 = 4\pi G(-\rho_1 - \rho_2) \quad (7)$$

Repulsion between matter and antimatter. Antimatter *antigravitates*.

- Solve in passing the matter-antimatter asymmetry problem.
- Milne cosmology :

$$a(t) \propto t \quad (8)$$

On large scales: void universe: $\bar{\rho}(t) = 0$. Only coordinate expansion.

- See Levy 1110.3054 for a discussion on nucleosynthesis, the position of the first peak of the CMB and supernovae IA in Dirac-Milne cosmology.
- In Manfredi 1804.03067 and Manfredi 2010.07776 structure formation was studied using a N-body code which assumes spherical symmetry.

Results and conclusions

Chardin 2102.08834, https://github.com/cspotz/RAMSES_Bi-Poisson,
<https://youtu.be/aqyuDYrwyBQ>

- Explored scaling relation (Tully-Fischer) and find an exponent quite low (2.56)
- Currently the Radial Acceleration Relation is not explained in this model but the phenomenology goes into the right direction.
- Rich interesting phenomenology at galactic scales
- Need to move to baryons and feedback.
- May allow to perform global fit to galactic observables.
- Prediction 1: acceleration scale of MOND is time dependant $a_0(z)$. → rotation curves of galaxies at high redshift.
- No known linear regime in Dirac-Milne cosmology. Need resolution of 100 ckpc. → computationally expensive to simulate the largest scales.
- Prediction 2: More small scales structures at high redshift (non-linear regime all the way from $z = 1080$). → observation of high redshift quasars.
- Prediction 3: Antimatter *antigravitates*. → Gbar, ALPHA-g and AEGIS @CERN
- BiPoisson is flexible and may be applied to other gravitational setups.

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Dipolar dark matter

- Analogy with polarized medium in electromagnetism where permittivity is present in Maxwell equations.
- Blanchet 0901.3114 proposed gravitational polarization as a candidate for dark matter and dark energy.
- Polarized Poisson reads:

$$\Delta\phi = 4\pi G \left(\rho - \vec{\nabla} \cdot \vec{\Pi}_{\perp} \right), \quad (9)$$

where Π follow a second order differential equation (see Eq. 3.5 of Blanchet 0901.3114)

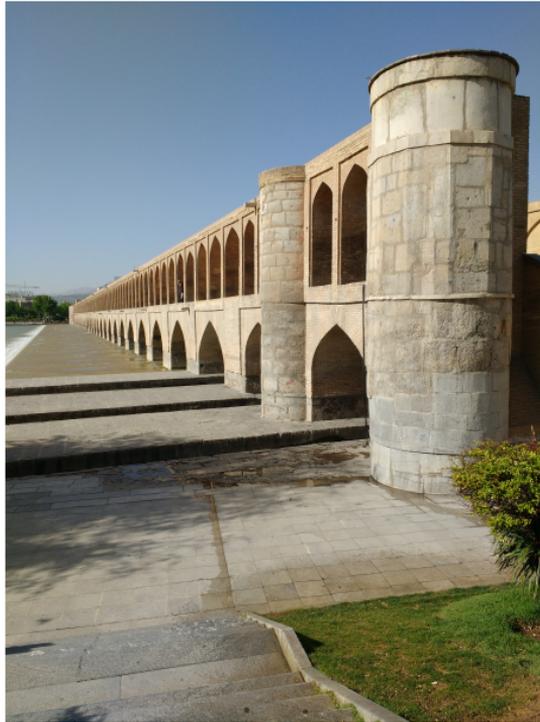
- Equilibrium solutions for galaxies with secular instabilities.
- Trying to run a cosmological simulation.

Conclusions

- My current main: extend the gravitational part of the N-body codes:
 $\Delta\phi = 4\pi G a^2 \delta$ upgrades into:
 - ① $e^{2\phi} \Delta\phi = 4\pi G a^2 \delta - \frac{3}{2} e^{-2\psi} (\mathcal{H} - \phi')^2 + \frac{e^{2\phi}}{2} \phi_{,i}^2$
 - ② $\Delta\phi_1 = 4\pi G(\rho_1 - \rho_2)$ and $\Delta\phi_2 = 4\pi G(-\rho_1 - \rho_2)$
 - ③ $\Delta\phi = 4\pi G \left(\rho - \vec{\nabla} \cdot \vec{\Pi}_\perp \right),$
- Many other modifications of the Poisson equations on the market not discussed here: k-evolution Hassani 1910.01104, MG-PICOLA^a, Cusin 1712.02783, fuzzy dark matter Mina 2007.04119...
- Exciting time for cosmology with tensions, dark species, amazing data to arrive. Stay tuned !

^a<https://github.com/HAWinther/MG-PICOLA-PUBLIC>

Thank you for your attention



Signature of multi-field inflation for galaxies

Galaxies form at peaks of the dark matter distribution

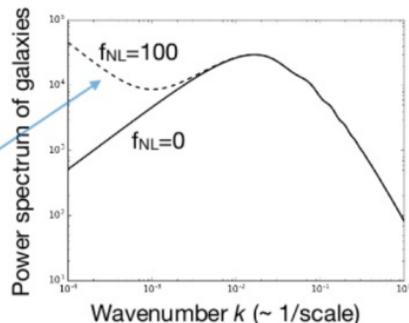
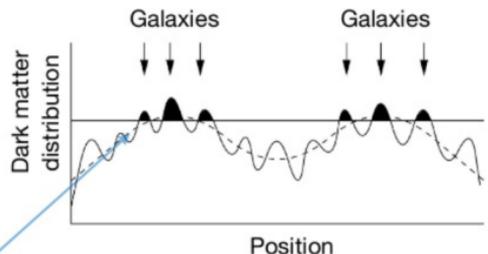
Multi-field inflation couples those peaks to the background potential

⇒ Galaxies are modulated by the background potential

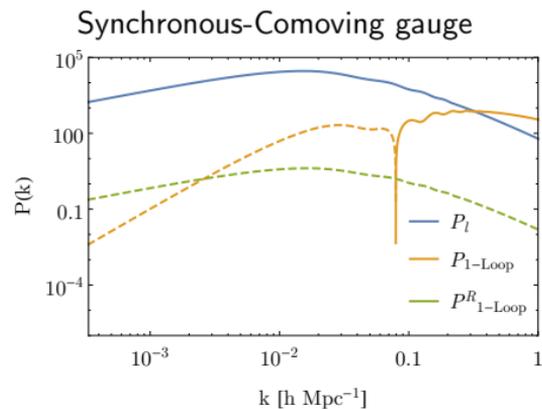
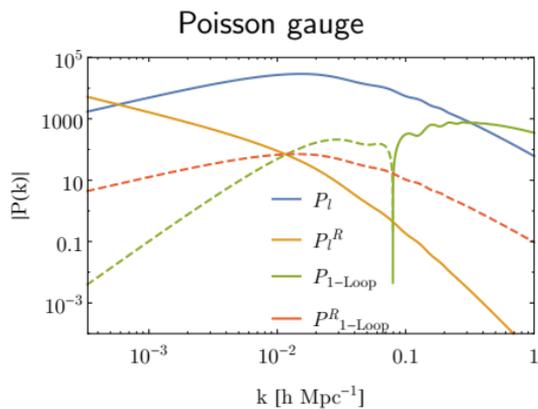
$$\phi \propto \frac{\delta}{k^2}$$

⇒ Enhancement of the power spectrum of galaxies $\sim f_{\text{NL}}/k^2$

'Scale-dependent galaxy bias'

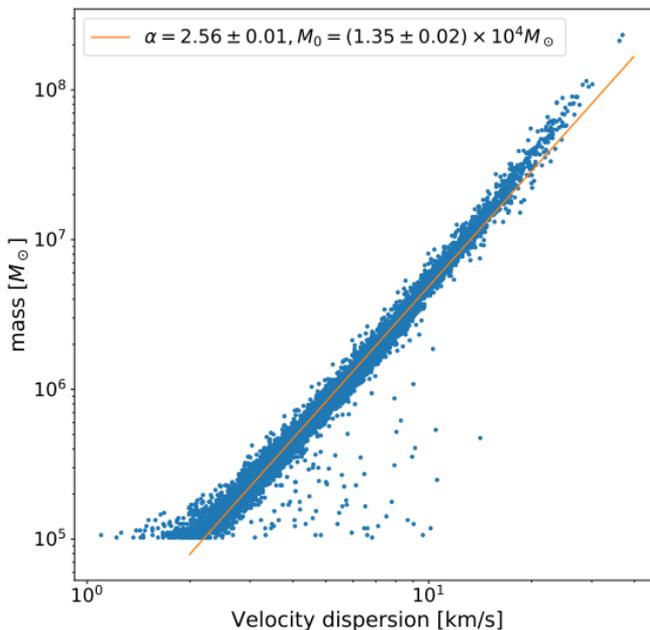


More Results



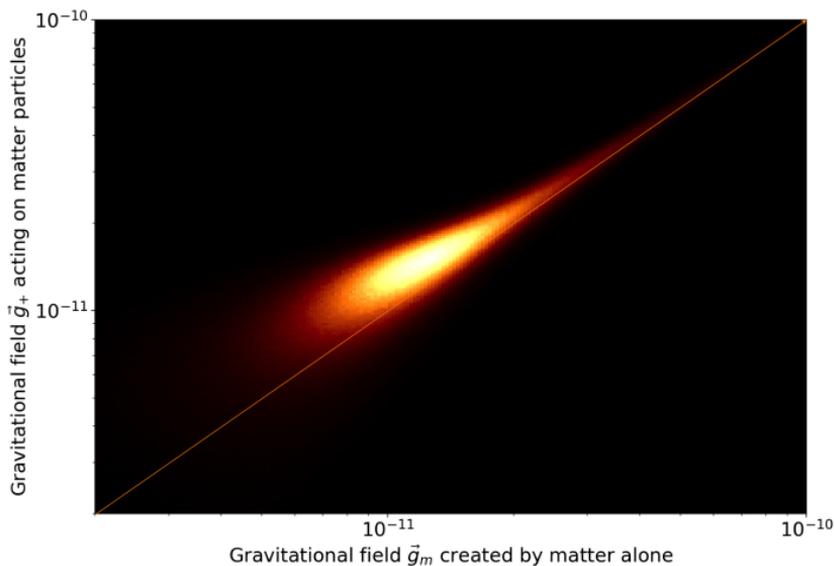
Main results: scaling relation (Tully-Fisher)

Tight scaling relation, slope closer from 3 than 4. See discussion in Lelli 1901.05966 or Ponomareva 1711.09112.



Main results: modified gravity

- Define $\vec{g}_m = -\vec{\nabla}(\phi_1 - \phi_2)/2$ and $\vec{g}_+ = -\vec{\nabla}\phi_1$.
- The matter field feels an extra force due to the coupled Poisson equations.



Interlude (advertisement): Schwinger effect in the early universe

Schwinger effect

Above a critical value for an electric field: particle production occurs 'Schwinger effect' (Sauter 1930, Schwinger 1954). Not detected today.

Cosmology: if during inflation, a strong electric field is present: particle production Fröb 1401.4137, Kobayashi 1408.4141.

Their behavior depends on their spin (**Stahl** 1507.01686), on the spatial dimensions (**Bavarsad** 1602.06556) and changes if one adds a magnetic field (**Bavarsad** 1707.03975).

Produce non-gaussianities

'Cosmic-collider': to couple the pairs created to the inflaton leads to a unique signal Chua 1810.09815.

Impact primordial gravitational waves

Only for higher spin like $SU(2)$ fields Lozanov 1805.09318.

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Stability of de Sitter space

backreaction to the inflation dynamics (**Bavarsad** 1602.06556)

Primordial magnetogenesis

Triggering particle production may help to generate the seed for the large scale magnetic field observed today **Stahl** 1603.07166, **Stahl** 1806.06692, Sobol 1807.09851.

Bispectrum for Fundamental physics: Inflation

The squeezed limit contains model independent information about the physics during *inflation*.

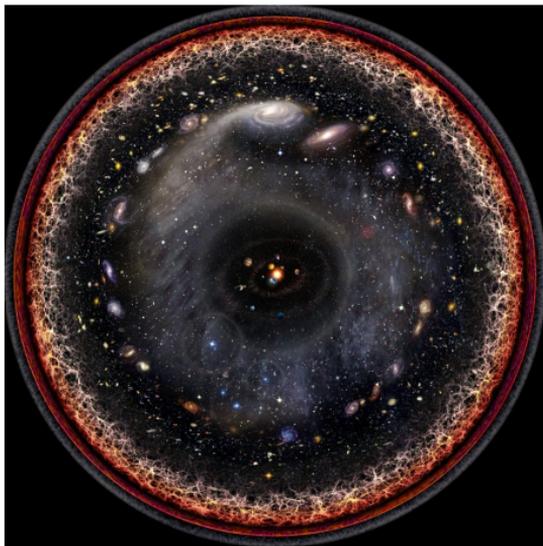


Image credit: Pablo Carlos Budassi

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

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 dilutes anything but quantum fluctuations which imprint into the *full* gravitational fields of the universe.

Bispectrum for Fundamental physics: Inflation

Successfull (and has no serious concurrent consistent 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)

5.16 Supergravity Brane Inflation (SBI)	180
5.17 Spontaneous Symmetry Breaking Inflation (SSBI)	183
5.18 Inverse Monomial Inflation (IMI)	192
5.19 Brane Inflation (BI)	194
6 Three parameters Models	203
6.1 Running-mass Inflation (RMI)	203
6.2 Valley Hybrid Inflation (VHI)	207
6.3 Dynamical Supersymmetric Inflation (DSI)	212
6.4 Generalized Mixed Inflation (GMLFI)	215
6.5 Logarithmic Potential Inflation (LPI)	218
6.6 Constant n_s D Inflation (CNDI)	221

3 Zero Parameter Models	23
3.1 Higgs Inflation (HI)	23
4 One Parameter Models	31
4.1 Radiatively Corrected Higgs Inflation (RCHI)	31
4.2 Large Field Inflation (LFI)	37
4.3 Mixed Large Field Inflation (MLFI)	41
4.4 Radiatively Corrected Massive Inflation (RCMI)	44
4.5 Radiatively Corrected Quartic Inflation (RCQI)	47
4.6 Natural Inflation (NI)	49
4.7 Exponential SUSY Inflation (ESI)	54
4.8 Power Law Inflation (PLI)	57
4.9 Kähler Moduli Inflation I (KMII)	60
4.10 Horizon Flow Inflation at first order (HF1I)	65
4.11 Coleman-Weinberg Inflation (CWI)	68
4.12 Loop Inflation (LI)	72
4.13 $(R + R^{2p})$ Inflation (RpI)	77
4.14 Double-Well Inflation (DWI)	81
4.15 Mutated Hilltop Inflation (MHI)	85
4.16 Radion Gauge Inflation (RGI)	87
4.17 MSSM Inflation (MSSMI)	89
4.18 Renormalizable Inflection Point Inflation (RIPI)	96
4.19 Arctan Inflation (AI)	100
4.20 Constant n_s A Inflation (CNAI)	103
4.21 Constant n_s B Inflation (CNBI)	108
4.22 Open String Tachyonic Inflation (OSTI)	111
4.23 Witten-O'Raifeartaigh Inflation (WRI)	115
5 Two Parameters Models	120
5.1 Small Field Inflation (SFI)	120
5.2 Intermediate Inflation (II)	123
5.3 Kähler Moduli Inflation II (KMIII)	128
5.4 Logarithmic Inflation (LMI)	134
5.5 Twisted Inflation (TWI)	138
5.6 Generalized MSSM Inflation (GMSSMI)	143
5.7 Generalized Renormalizable Point Inflation (GRIP1)	148
5.8 Brane SUSY breaking Inflation (BSUSYBI)	152
5.9 Tip Inflation (TI)	155
5.10 β exponential inflation (BEI)	161
5.11 Pseudo Natural Inflation (PSNI)	163
5.12 Non Canonical Kähler Inflation (NCKI)	167
5.13 Constant Spectrum Inflation (CSI)	170
5.14 Orientifold Inflation (OI)	173
5.15 Constant n_s C Inflation (CNCI)	177