PROGRAMME INSTITUTS ET INITIATIVES

Appel à projet – campagne 2021

Proposition de projet de recherche doctoral (PRD)

Intitulé du projet de recherche doctoral (PRD):
Développement de nouveaux outils statistiques pour la mesure de la masse des neutrinos

Directeur.rice de thèse porteur.euse du projet (titulaire d'une HDR) :

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Unité de Recherche :
Intitulé : Institut d'Astrophysique de Paris
Code *(ex. UMR xxxx)* : UMR7095

École Doctorale de rattachement de l'équipe (future école doctorale du.de la doctorant.e) : ED127

Doctorant.e.s actuellement encadré.e.s par la.e directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1e inscription et la quotité d'encadrement) :

- 1 doctorant, 1ere année d'inscription 2020, quotité 100%

Co-encadrant.e :

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Unité de Recherche :
Intitulé : Institut d'astrophysique de Paris
Code *(ex. UMR xxxx)* : UMR7095

École Doctorale de rattachement : ED 127

Doctorant.e.s actuellement encadré.e.s par la.e co-directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1e inscription et la quotité d'encadrement) :

1 doctorant 1ere année d'inscription 2020, quotité 50%

Co-encadrant.e :

NOM : **ZARROUK** Prénom : **Pauline**
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Unité de Recherche :
Intitulé : Laboratoire de Physique Nucléaire et de Hautes Énergies
Code *(ex. UMR xxxx)* : UMR7095

École Doctorale de rattachement : Ou si ED non Alliance SU :

Doctorant.e.s actuellement encadré.e.s par la.e co-directeur.rice de thèse (préciser le nombre de doctorant.e.s, leur année de 1e inscription et la quotité d'encadrement) : pas de doctorant mais un candidat pour commencer en octobre 2021

Cotutelle internationale : ☑ Non ☐ Oui, précisez Pays et Université :

Selon vous, ce projet est-il susceptible d'intéresser une autre Initiative ou un autre Institut ?
x Non ☐ Oui, précisez

Description du projet de recherche doctoral ***(en français ou en anglais) :***

Contexte

Modern fundamental physics faces many challenges and unanswered questions. Among these problems, neutrinos would seem to be fairly well understood and controlled by laboratory experiments. The mass of neutrinos is however only hinted to be strictly positive thanks to the observation of solar and atmospheric neutrinos that have undergone at least one flavour change. Though this observation constrains the squared difference between neutrino masses, it does not give the absolute scaling. Getting such a measurement is extremely difficult on earth. Cosmological observations on the other hand are sensitive to the sum of the masses of the neutrinos. Indeed, even if neutrinos are very light particles their collective gravitational effects are enough to modify the evolution of the distribution of the large scale structures, modifying the shape and evolution of the matter clustering. The latest cosmological constraints indicate that the mass must be ≲0.2 eV (e.g. Ivanov et al 2020). Those are obtained using the two-point statistics of the distribution of matter in the Universe. These constraints will likely not improve much by considering two point statistics alone. Planck has extracted the maximal amount of information on large scales from temperature fluctuations and while the polarization constraint will be improved by ground based experiment, there is little new information on the neutron masses from its large scales. Gravitational lensing of the polarized CMB will provide some further constraining power on neutrino masses. Those measurements provide observations at higher redshift than large scale structure surveys, which have the potential to bring further down the constraints (Abazajian et al. 2013 Snowmass report). However, large scale structure experiments are plagued by the determination of the scale dependent bias of the tracers and subtle systematic effects (Lavaux et al. 2019, Verde et al 2019, Chabanier et al. 2019).

The source of the difficulties for measuring neutrino masses are multiple:

- At the level of the 2 point statistics, many degeneracies exist between the parameters, including the ones introduced to account for observational modeling such as the galaxy bias. For the case of interest here, the degeneracy is between the amplitude of scalar fluctuations, the mean matter density and the mass of neutrinos.
- The sought signal is very small: given the present constraints, the effect of neutrinos on the clustering of galaxies is expected to be of order of 1-10%.This also relies on our capability to avoid systematic effects on the clustering to be able to compare very large (k<0.01 h/Mpc) and small scales (k>=0.1 h/Mpc).
- The present 3-point statistics estimators are still of limited use for real data, though some preliminary work (Hahn et al. 2020) shows some tantalizing possibilities based on an ensemble of idealized N-body simulations. Such possibilities also exist when considering velocity fields (Kuruvila & Aghanim 2021). This indicates that further information is ready to be collected in present and future data.

In parallel with this problem of method, new large galaxy surveys are under construction: Euclid (launch 2023), DESI (first data 2021), LSST (first light 2021), SPHEREx (launch 2024). These large surveys will provide an avalanche of data on the distribution of galaxies in the universe (several billion galaxies). They offer a unique possibility to further constrain the parameters of the Standard Model of Physics. Unfortunately, even with this quality of data, systematic effects may well prevent us from issuing stronger constraints on neutrino masses. One of the present measurement was done by relying on 1d auto-correlations of the Lyman alpha forest (e.g. Palanque-Delabrouille et al. 2020), which requires a significant amount of trust on the result of hydrodynamical simulations and a large amount of available computational time, which may be alleviated by relying on cross-correlation analysis. Additionally, large scale probes are more independent but also less constraining. Indeed it was found that even with information from the cosmic shear, CMB lensing and primary CMB temperature fluctuations, no new bounds are added to neutrino masses (Merkel & Schäfer 2017). On the other hand, many higher order statistics of the clustering are still not used. There are hints that higher order statistics can help in that regard (Boyle et al. 2020), increasing the constraints by ~30%. As indicated above, the bi-spectrum tentalizes that interesting constraints may be achieved by up to a factor of five on the mass of neutrinos (Hahn et al. 2020). Also the Lyman-alpha forest observation from Quasar observations in DESI are expected to provide constraints but the level of systematic effects is still unknown, which will require constraints from complementary observables. At the same time the information from the SZ cluster survey has not yet been used, and more data are coming everyday from ground CMB experiments (SPT, ACT, and later CMB-S4).

Now the time is right to explore new ways of correlating data-sets and make use of new statistical methods able to explore higher order correlations to put the tightest bounds on the neutrino masses from observations. We have seen that such higher order statistics can bring competitive constraints, even from present data (Ramanah et al. 2019).

Objectif scientifique

Through this thesis, we seek to investigate new possibilities to constrain the mass of neutrinos, either through more cross-correlations with complementary observables. Notably we seek to open new fields of Nx2pt cross-correlation inference. The involved probes in this cross-correlation attempt are: the CMB lensing, the galaxy clustering, the galaxy weak lensing (through shear measurement) and the Sunyaev-Zel'dovich observations. This involves 10 auto and cross-correlation functions. Using correlations from different probes and different redshift depth, we will seek to exploit fully the constraining power of the 2pt function. Besides this proven technique to reduce the impact of systematic effect and break degeneracies between parameters, the PhD candidate is expected to explore the power of new statistics probes, such as forward modeling or "likelihood free inference".

During pilot studies, we have shown that these new statistical techniques allow tight constraints for some parameters (Ramanah et al. 2019, Charnock et al. 2018). We intend to pursue this effort but with the specific emphasis on the mass of neutrinos for the specific characteristics of large incoming galaxy surveys.

This work will be done within the context of several international collaborations: G. Lavaux and K. Benabed are members of the Euclid consortium (https://www.euclid-ec.org/), P. Zarrouk is a member of the DESI collaboration (https://www.desi.lbl.gov/), K. Benabed is a member of the SPT consortium, observing the CMB polarization and its lensing effect (https://pole.uchicago.edu/public/Home.html). G. Lavaux is also a co-founder of the Aquila Consortium (https://www.aquila-consortium.org/), dedicated to the development of new statistical and physical tools with the aim of exploring the physics of the universe using complex observational data sets.

Justification de l'approche scientifique

As indicated in the context and objective section, the amplitude of the cosmological signal due to the mass of neutrinos is either weak (no clustering on small scales of neutrinos), or possibly degenerate with other observational systematics (scale dependent galaxy bias, mask vs scale dependent effect of neutrino clustering). The cross-correlation forecast analysis that we propose is a natural extension of past approaches to tame the effect of degeneracies and control systematic effects. In addition to this safe route, the research that we propose which would rely on higher order statistics is less explored, though show great promises through earlier pilot studies on other cosmological parameters.

The yearly milestones that we expect for the PhD thesis are the following:

- First year: bibliography on cross-correlation estimators, likelihood free inference, forward modeling. Basic Fisher forecast experiment on simplistic models of galaxy surveys like DESI and Euclid joined with Planck/future CMB experiment (paper 1).
- Second year: development of a forward pipeline to run N-body simulations with neutrino effect up to a finer representation of a realistic galaxy survey and CMB experiment. This in practice involves setting up a cosmological simulation, running it, identifying halos for creating mock catalog and apply selection function. Photons will need to be raytraced to obtain crude lensing maps. We can rely on existing tools (MADlens, MAGRAthea, ...). If execution delays are occurring we can scale this down to only the halo mock catalogues (paper 2). This pipeline must be executed automatically to form automatic optimal summary statistics which could be run with the IMNN technique (Charnock et al. 2018) and DELFI (Alsing et al. 2019).

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- Third year: run an integrated forward model with parameter sampling as part of the BORG analysis software. Develop and check robustified likelihood techniques from statistical principles (paper 3).

Adéquation initiative/institut

This subject is particularly relevant for the "Initiative des 2 infinis" as it seeks to establish properties of elementary particles (neutrinos) using data coming from the largest scales of the universe. Also we have assembled a team of advisors in two institutes (IAP and LPNHE) whose expertise covers the different fields required for this thesis to be a success.

Rôle de chaque encadrant

G. Lavaux will act as the main co-supervisor of the thesis. His expertise is on the modeling of large scale structures, the application of statistical methods to large galaxy surveys and cross-correlation between CMB and LSS.
K. Benabed will be the co-supervisor with a large expertise on the statistical analysis of the cosmic microwave background (Planck data and ground based data), gravitational lensing (CMB and galaxy).
P. Zarrouk will advise the PhD student on observational data of modern large galaxy surveys, notably DESI. She will provide inputs for the development of new analysis techniques for neutrino detection and/or tests of gravity on large scale. She is the co-project leader for the key project DESI on constraining growth, the neutrino masses and primordial non gaussianities with the full power spectrum shape of DESI data.

Publication

Publication G. Lavaux

- Automatic physical inference with information maximising neural networks; T. Charnock, G. Lavaux, B. D. Wandelt; Phys. Rev. D; 97, 083004; http://arxiv.org/pdf/1802.03537
- Physical Bayesian modelling of the non-linear matter distribution: new insights into the Nearby Universe; J. Jasche, G. Lavaux; A&A; 625, A64; http://arxiv.org/pdf/1806.11117
- A rigorous EFT-based forward model for large-scale structure; F. Schmidt, F. Elsner, J. Jasche, N. M. Nguyen, G. Lavaux; http://arxiv.org/pdf/1808.02002

Publication K. Benabed:

- Breaking the degeneracy between polarization efficiency and cosmological parameters in CMB experiments; Silvia Galli, W.L. Kimmy Wu, Karim Benabed, François Bouchet, Thomas M. Crawford, Eric Hivon; submitted; https://arxiv.org/abs/2102.03661

Publication P. Zarrouk

- Baryon Acoustic Oscillations in the projected cross-correlation function between the eBOSS DR16 quasars and photometric galaxies from the DESI Legacy Imaging Surveys; P. Zarrouk et al.; MNRAS submitted; https://arxiv.org/pdf/2009.02308

Publication neutrino

- An optimal nonlinear method for simulating relic neutrinos; Willem Elbers, Carlos S. Frenk, Adrian Jenkins, Baojiu Li, Silvia Pascoli; submitted to MNRAS; https://arxiv.org/abs/2010.07321
- The Cosmic Linear Anisotropy Solving System (CLASS) IV: efficient implementation of non-cold relics; J. Lesgourgues, T. Tram; JCAP 09, 032 (2011); https://arxiv.org/pdf/1104.2935

Publication corrélations croisées:

- Cosmological constraints from a joint analysis of cosmic microwave background and spectroscopic tracers of the large-scale structure; Doux, Cyrille; Penna-Lima, Mariana; Vitenti, Sandro D. P.; Tréguer, Julien; Aubourg, Eric; Ganga, Ken; MNRAS 2018, 480, 4; https://arxiv.org/pdf/1706.04583

Profil de l'étudiant

Idéalement l'étudiant doit maîtriser les fondamentaux de la physique fondamentale et de la cosmologie.
Une formation incluant la maîtrise du langage Python est souhaitable pour démarrer efficacement.
Il est aussi très souhaitable que l'étudiant ait une bonne maîtrise de l'anglais.

Merci d'enregistrer votre fichier au format PDF et de le nommer :
«ACRONYME de l'initiative/institut – AAP 2021 – NOM Porteur.euse Projet »

Fichier envoyer simultanément par e-mail à l'ED de rattachement et au programme :
cd_instituts_et_initiatives@listes.upmc.fr avant le 20 février.