*Work in progress with Marilena Loverde

Neutrinos in N-body simulations

Caio Nascimento

Stony Brook/UW

September 23, 2020

Table of contents

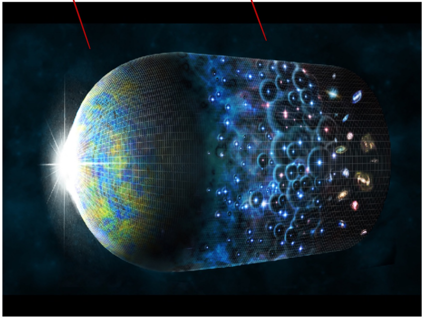
Introduction to N-body simulations

e.g. 1. Euclid
2. Nancy Grace Roman Space Telescope (WFIRST)
3. Large Synoptic Survey Telescope (LSST)
4. Dark Energy Spectroscopic Instrument (DESI)

$M_\nu, \omega_{de}, N_{eff}$

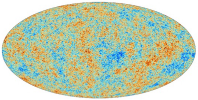
CMB Experiments: Probing the early universe

Large Scale Structure Surveys: Structure at late times



Harvard & Smithsonian Center for Astrophysics

Introduction to N-body simulations



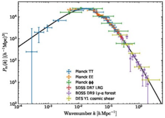
European Space Agency Planck satellite

$$\frac{\delta T}{T} \sim 10^{-5}$$

R. Jay GaBany/NASA.

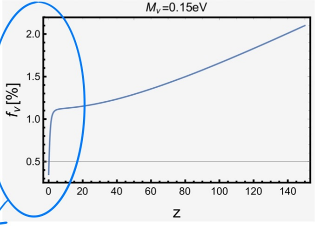
$$\frac{\rho_{galaxy}}{\rho_{crit}} \sim 10^{6}$$

Non-linear regime -> Newtonian N-body simulations



Observables: Correlation functions!
e.g. Matter power spectrum

Neutrinos in cosmology



% level contribution to the total energy density, for z~100 and below

Neutrino free-streaming

$$\frac{P(k > k_{sh})|_{f_\nu}}{P(k > k_{sh})|_{f_\nu=0}} \approx 1 - 8 f_\nu$$

Up to 2-3% effect on the matter power spectrum today

(e.g. Lesgourgues, Pastor arxiv:astro-ph/0603494)

Sources of errors in N-body sims

Large scales, Radiation
Under control:
Zennard et al. arxiv: 1605.05283
Fidler et al. arxiv: 1606.05588

Relativistic Effects for neutrinos
Estimated to be small, but very few systematic studies in the literature.

Focus of our work!

Relativistic effects for neutrinos

Metric perturbed flat FRW, Newtonian gauge:

$$ds^2 = -(1+2\psi)dt^2 + a^2(1-2\phi)d\vec{x}^2$$

Geodesic equation:

$$\frac{1}{\gamma}\frac{d}{dt}(\gamma\vec{v}) + \frac{1}{a}\vec{\nabla}\psi + H\vec{v} - \dot{\phi}\vec{v} + \frac{1}{a}\vec{v}\times(\vec{\nabla}\phi\times\vec{v}) = 0$$

Relativistic particle in a gravitational potential

Hubble friction

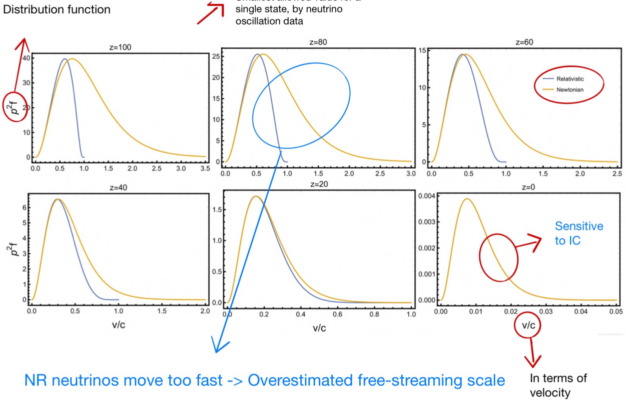
$O(v^2) \to 0$ Non-relativistic (NR) limit

$$\frac{d\vec{v}}{dt} + (H-\dot{\phi})\vec{v} + \frac{1}{a}\vec{\nabla}\psi = 0$$

$\dot{\phi} \to 0$ In N-body codes, but we keep it non-zero

Relativistic effects for neutrinos

Neutrino mass of 0.05eV
Smallest allowed value for a single state, by neutrino oscillation data



NR neutrinos move too fast -> Overestimated free-streaming scale

OBS: Doesn't impact evolution of Hubble rate H, in N-body sims.

$$\lambda_{fs} = \frac{c_s}{aH}$$

Relativistic effects for neutrinos

Linear Perturbations

1: CDM + b = d -> Pressureless fluid

2: Neutrinos

i) Fully-relativistic -> CLASS fluid approximation (arxiv:1104:2935)

ii) Non-relativistic -> $$\frac{\partial f}{\partial \tau} + \frac{d\vec{x}}{d\tau} \cdot \frac{\partial f}{\partial \vec{x}} + \frac{d\vec{q}}{d\tau} \cdot \frac{\partial f}{\partial \vec{q}} = 0$$

+

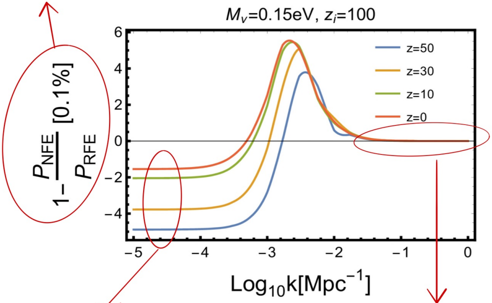
Fluid variables, compatible with the NR limit ($\gamma \sim 1$)

-> Fluid approximation for NR neutrinos

3: Geometry: Einstein's Eqs.

Relativistic effects for neutrinos

Relative difference in the matter power spectrum, obtained with (NFE) and without (RFE) the NR limit



Additional sourcing due to kinetic energy of neutrinos

Peaked in the scale of sound horizon

$$\lambda_{sh} = \int d(\ln a)\frac{c_s}{aH} = \int d\tau c_s$$

↓

Overall error <0.5% for all masses and scales

Neutrino perturbations get washed-out below the free-streaming scale

Summary

- N-body simulations play an important role in obtaining cosmological observables, in the non-linear regime.
- Relic neutrinos affect cosmology (i.e. free-streaming).
- Newtonian N-body simulations overestimate the scale of neutrino sound horizon, with an associated <0.5% error in the matter power spectrum.