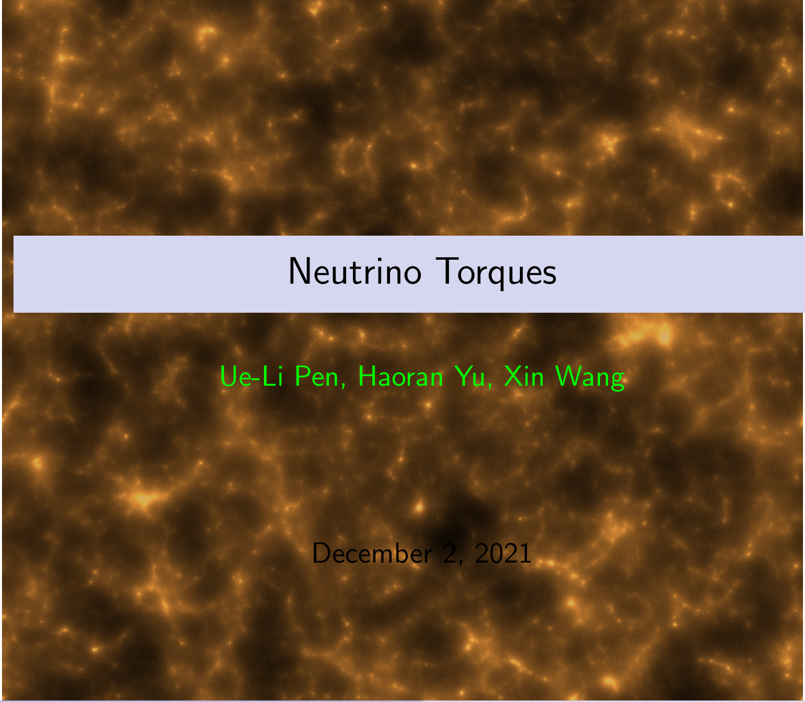

Neutrino Torques

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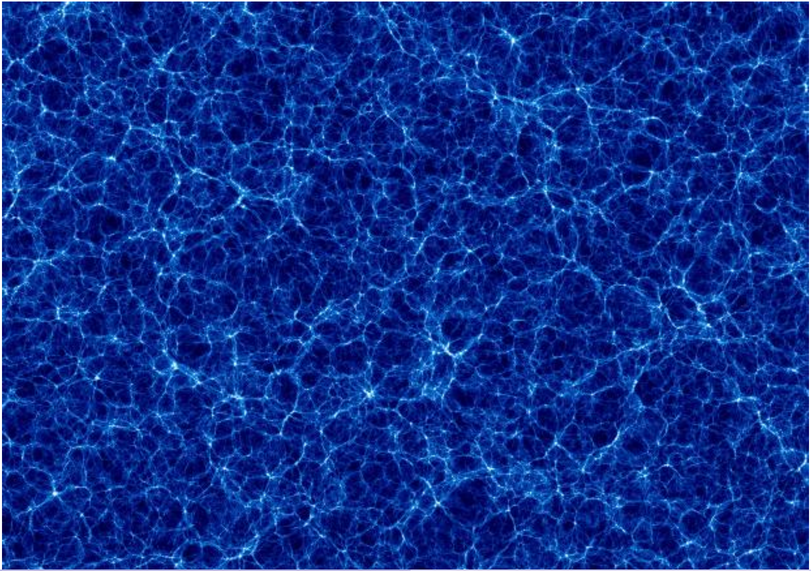
December 2, 2021

Observables

- CMB, gravitational lensing: 2-D projection,
- galaxies: 3-D biased displacement field
- Monge-Ampére equation/solution
- ideally measure 2 fields, infer 2 fields: CDM, neutrinos (HDM)

Movie

http://cita.utoronto.ca/~haoran/thnu/movie.html



Galaxy Spins

- most galaxies are rotating disks of stars and gas
- readily identifyable spin axis
- dust lanes, trailing spiral arms, HI velocity (rotation) field

Observable

(M51, from Wikipedia)

Angular momentum

- 1st order effect from misalignment of moment of inertia and tidal tensor
- torque: $\tau \equiv \int \rho \mathbf{r} \times \nabla \phi$
- Taylor expand: $\tau_i = \epsilon_{ijk} \int \rho x^j x^l \partial_l \partial_k \phi \equiv \epsilon_{ijk} I_{il} T_{lk}$
- Tensor form $\tau = *I \cdot T$
- first realized by S. White (1984), see also LP00

3-D: E-mode

Figures/nonlinear.png

Lagrangian coordinates

Figures/delta_reco_raw.pdf

Coordinate freedom

$$
\begin{aligned}
\text{potential deformation} \qquad x^i &= \xi^\mu \delta^i_\mu + \frac{\partial \phi}{\partial \xi^\mu} \delta^{i\mu} \\
\text{dreibein} \qquad e^i_\mu &\equiv \partial x^i / \partial \xi^\mu \\
\text{volume element} \qquad \sqrt{g} &\equiv \det \left| e^i_\mu \right| \\
\text{mass coordinate} \qquad \rho\sqrt{g} &= \text{Const.} \\
\partial_\mu (\rho \sqrt{g} e^\mu_i \delta^{i\nu} \partial_\nu \dot{\phi}) &= \langle \rho \rangle - \rho \sqrt{g} \qquad (1)
\end{aligned}
$$

Solve Monge-Ampére eqn (1) using multigrid (Pen 1995): unique bijective mass coordinate. See also Tully/Peebles, Mohayaee+, Goldberg, Schmidtfull, Wang+, Seljak, Zaldarriaga, Hada/Eisenstein, Shi/Brikin/Li+, Jasche+, Sarpa+

Multigrid solution

Figures/map0512-0128_i1500_xz222.pdf

Redshift space

Zhu et al 1610.09638

Figures/map0512-0128_i0900_xz222_rsd3.pdf

Low noise limit

Figures/rk.pdf

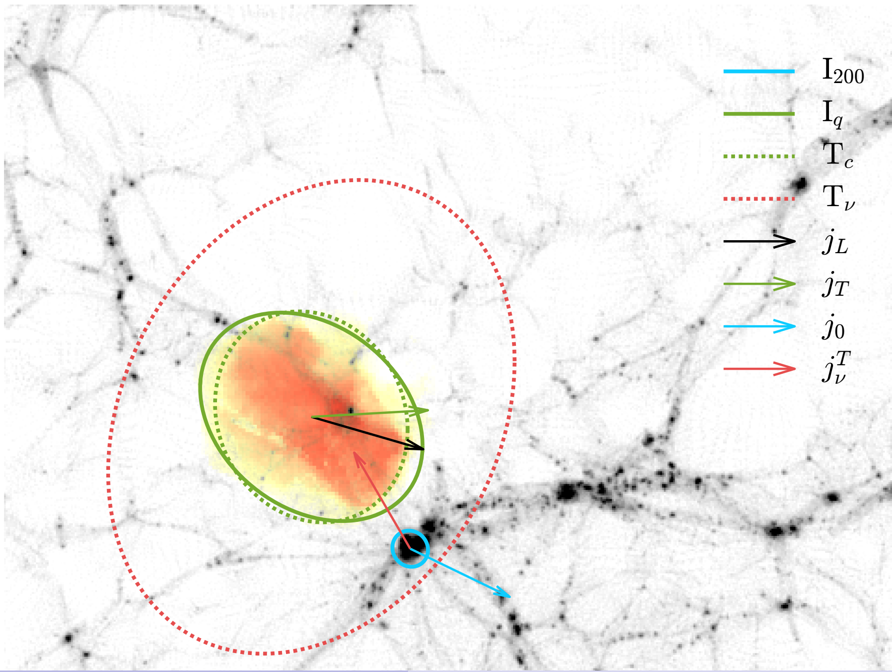
Halos

es/halocc.pdf

Predicting Neutrino Torques

- $\Delta x(q) = q^j \partial_i \partial_j \psi$
- $I_c \sim T_c$: both describe particle displacement
- $j_\nu = \epsilon T_c T_\nu$
- Neutrino tidal torque is predictable observable from displacement potential

Illu



Size estimate

- $|j_\nu/j_c| \sim 10^{-4}(f_\nu/0.003)[\sqrt{P(k_{\rm FS})/P(k_{\rm vir})}/0.03]$
- agrees with simulation measurement
- need $n > 10^8$ galaxy spins
- accessible in next generation 21cm surveys

Future 21cm Surveys

- expand on HSHS (Peterson et al 2006), CHIME
- build on economy of scale, map 10^{11} galaxies

More cosmological applications

- map initial (linear) tidal field
- BAO, standard ruler (Alcock-Paczynski effect)
- modified gravity, time evolving neutrino mass

Conclusions

- galaxy spins: new probe of initial conditions
- predictable from observable displacement field using non-linear reconstruction
- computationally straightforward, mass coordinate similar to Lagrangian
- already observable, scalable to much larger surveys
- parity odd field, less likely to be contaminated
- enables measurement of 2 cosmic scalar fields: potential beat cosmic variance limits, etc