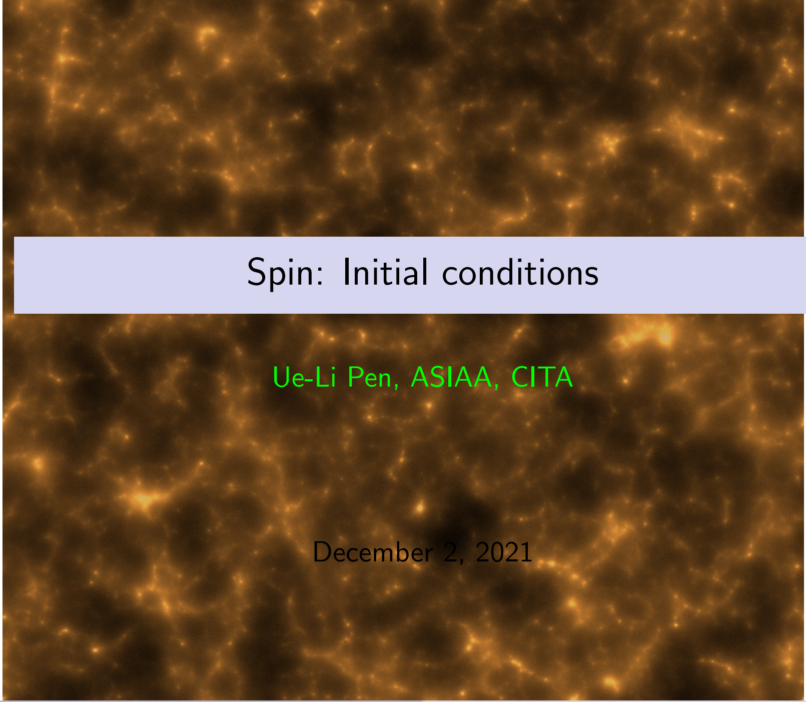


Spin: Initial conditions

Ue-Li Pen, ASIAA, CITA

December 2, 2021

Galaxy Spins

- most galaxies are rotating disks of stars and gas
- dust lanes, trailing spiral arms, HI velocity (rotation) field
- readily identifyable spin axis in 3-D (see Motloch talk)
- spin direction well preserved from initial conditions (Haoran's talk), ~ 0.5 correlation with primordial IC. Much stronger than shape alignment, *conservation of angular momentum*
- potentially vast reservoir of fossils from initial conditions ($\gtrsim 10^8$ modes)
- direct probe of primordial helicity, cosmic neutrino background

Observable

(M51, from Wikipedia)

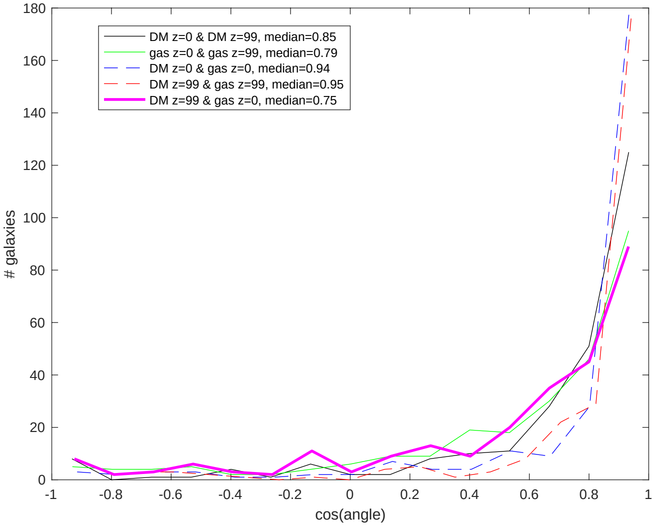
Angular momentum ("spin")

- 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

predicting spin

- Tidal Torque Theory (TTT): relates spin to initial Inertia and Tide
- Inertia tensor not easily identified, requires running N-body simulation.
- approximate Inertia by Tide (Zeldovich), torqued by external tide.
- IC-TTT: $j_\alpha = \epsilon_{\alpha\beta\gamma}\mathcal{T}_{\beta\kappa}\mathcal{T}^{+}_{\kappa\gamma}$
- $\mathcal{T} = \bar{\phi}_{,\beta\kappa}$ smoothed tidal field
- $\mathcal{T}^{+}_{\beta\kappa} = \bar{\phi}^{+}_{,\beta\kappa}$ tidal field smoothed on slightly larger scale, Taylor approximated by $\mathcal{T}^{+}_{\beta,kappa} = \bar{\rho}_{,\beta\kappa}$
- ~ 0.5 correlation with actual eulerian spin at optimal mass filter
- "best one can hope for" in data reconstruction

Gas-DM simulations



Shy Genel, Illustris, private communication

Measurement

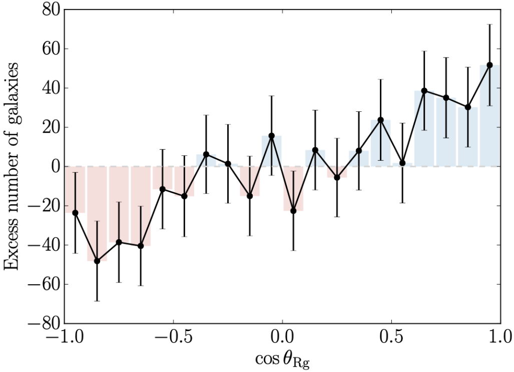
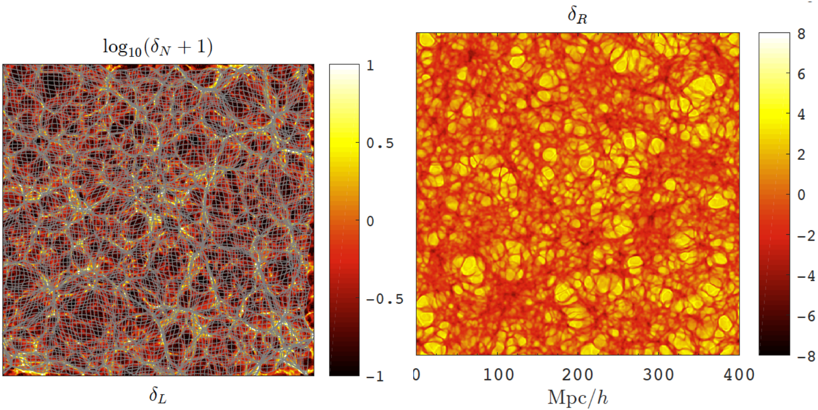


FIG. 4. Excess of galaxies in bins of $\cos\theta_{Rg}$ over what would be expected if there was no correlation between $\boldsymbol{j}_g$ and $\boldsymbol{j}_R$, the galaxy spins measured and predicted. For our fiducial sample of 15155 galaxies and $r = 3\,\mathrm{Mpc/h}$. The (correlated) error bars assume $\boldsymbol{j}_g$ and $\boldsymbol{j}_R$ are independent.

Motloch+ 2021

3-D: E-mode Lagrangian



Eulerian (L) vs Lagrangian (R) (from Yu et al 2016, 1610.7112)

E-mode Coordinate

reduce 3-D Lagrangian map to 1-D potential (*max Zeldovich*):

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

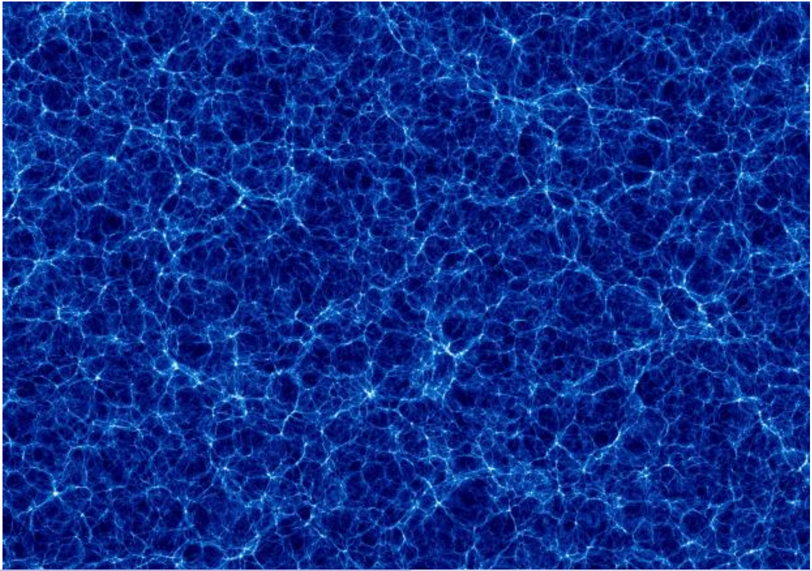
Solve Monge-Ampére eqn (1) using multigrid (Pen 1995): unique bijective mass coordinate. See also Tully/Peebles, Mohayaee+, Goldberg, Schmidtfull, Wang+, Seljak, Zaldarriaga, Hada/Eisenstein, Shi/Brikin/Li+, Jasche+, Sarpa+

Predicting Neutrino Torques

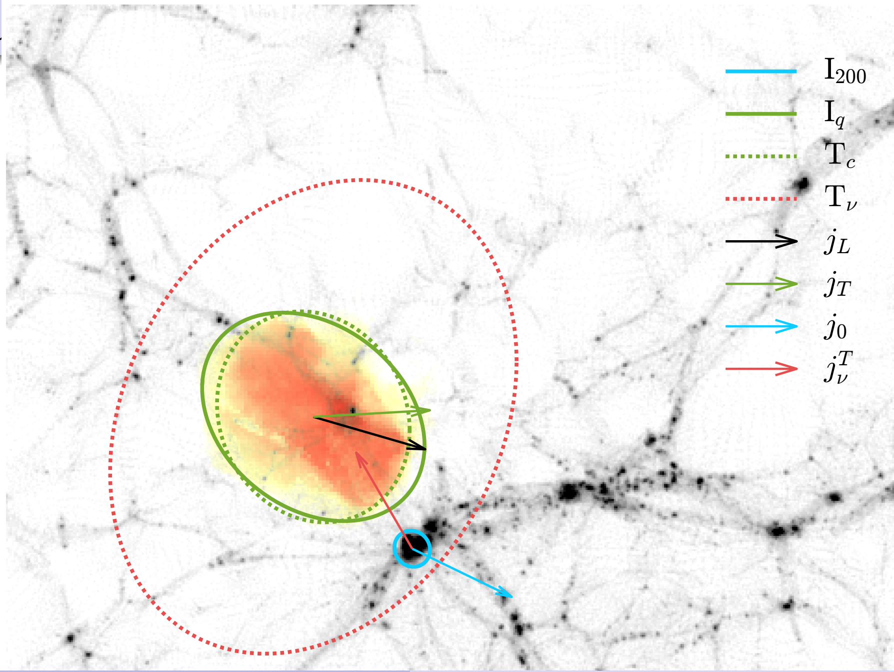
- ν gravitational field (large scale tide) torques CDM (small scale inertia)
- $\Delta x(q) = q^j \partial_i \partial_j \psi$
- $I_c \sim T_c$: both describe particle displacement
- $j_\nu = \epsilon I_c T_\nu \sim \epsilon T_c T_\nu$
- Neutrino tidal torque is predictable observable from displacement potential

Movie

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



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

Helicity

- statistical isotropy and homogeneity allows for helicity asymmetry (e.g. weak force)
- NOT Goedel/Longo effect ("net k independent left/right spin")
- angular momentum measures twist of tidal tensor
- helicity measures twist projected along k vector

Nat

NEWS & VIEWS

MATERIALS SCIENCE

A fresh twist for self-assembly

Molecular helicity affects many of the bulk properties of materials. A study finds that helicity also controls the self-assembly of colloidal particles, opening the door to a new generation of functional materials. SEE LETTER P.348

VOLKER SCHALLER & ANDREAS R. BAUSCH

The next time you go to the supermarket, take a look at the pasta. You'll probably find everything from long, thin spaghetti to butterfly-shaped farfalle and twisted fusilli. On closer inspection, you'll see that the strands of spaghetti readily align and pack closely together, whereas the packing of the fusilli is considerably more complex. This complexity is due to the fusilli's chirality — its helical geometry. On page 348 of this issue, Gibaud *et al.*[1] report that such complexity of packing can be exploited to control the self-assembly of nanometre-scale particles, allowing the reversible formation of various architectures*.

To closely pack two individual pieces of fusilli, the pasta pieces have to twist

Figure 1 | Pasta packing. When constrained in a circular container, fusilli pasta pieces mostly pack together so that their long axes are vertically aligned. But at the edges of the container, the pasta twists away from this alignment. This packing arrangement is a consequence of the pasta's helicity (chirality). Gibaud *et al.*[1] report

V. SCHALLER

energetic cost, known as elastic energy. The formation of circular membranes with twisted margins is therefore the result of a trade-off between minimizing the phase interface and minimizing the elastic energy.

But what happens if the rods are chiral, so that twisted packing is preferred — just as it is for closely packed fusilli? Gibaud *et al.* addressed this question by performing experiments at lower temperatures, thereby 'switching on' the chirality of the viruses. They observed that increases in chirality — that is, increases in the contribution of chiral interactions to the energy balance of the system — reduce the elastic energy, thus lowering the energetic cost of creating a twist at the membrane's margin. This destabilizes the edges of the circular membrane and triggers the formation of ribbon-like structures that splay

V

Schaller & A. Bausch, Nature, 481, 268

Pastarimeter

The world's first "Pastarimeter" — lefty pasta and righty pasta

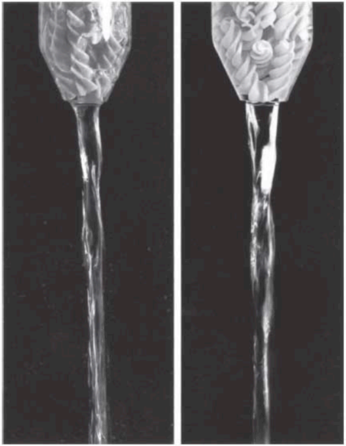


Figure 3. Left: Water flowing through counterclockwise *fusilli*; Right: Water flowing through clockwise *fusilli*.

Saxon et al 2002, J. Chem. Ed, 79, 1214

ELUCID projection

- $J_a^{\mathrm{IC}} = \epsilon_{abc}\partial_{bk}\phi^r\partial_{kc}\rho^r$
- $\mathbb{P}_{ab}^{L/R}(\mathbf{k}) = \frac{1}{2}\left[\delta_{ab} - \hat{k}_a\hat{k}_b \ \pm i\epsilon_{abc}\hat{k}_c\right.$
- $\tilde{J}_{L/R,a}^{\mathrm{IC}}(\mathbf{k}) \equiv \mathbb{P}_{ab}^{L/R}(\mathbf{k})\tilde{J}_b^{\mathrm{IC}}(\mathbf{k})$
- $\mu_X = \left\langle \frac{J^g}{|J^g|} \cdot \frac{J_X^{\mathrm{IC}}}{|J_X^{\mathrm{IC}}|} \right\rangle \qquad X \in \{L, R\}$
- $\mu_- = \mu_L - \mu_R$

Helicity results

- $\mu_L = 0.41 \pm 0.53\ \times 10^{-2}$ maximal left is allowed
- $\mu_R = 1.99 \pm 0.53\ \times 10^{-2}$ maximal right is disfavoured!
- $\mu_- = -1.58 \pm 0.75\ \times 10^{-2}$ Parity symmetry is allowed 🙂

Helicity IC

- Helicity is probe of primordial non-gaussianity 4 point function (e.g. Cahn+ 2021)
- constructable in N-body initial conditions
- maximal violation straightforward to implement numerically, consistent with observations
- potentially related to inflationary two field chiral coupling

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
- unique probes of neutrinos, helicities, etc...