Probing parity violation in the early universe using galaxy spins

arXiv:2406.06080

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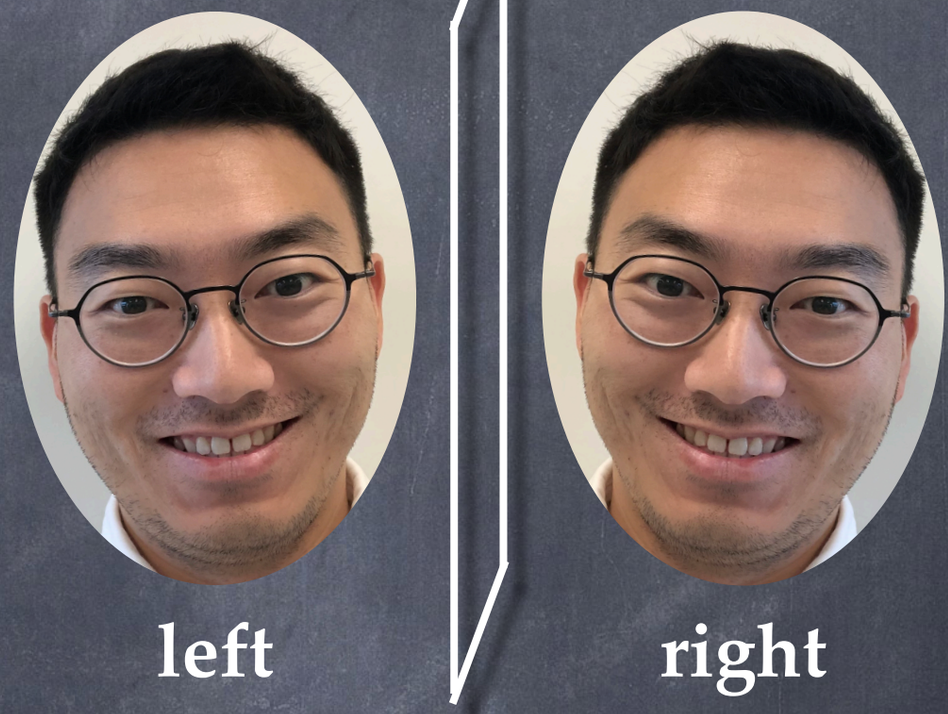
Parity violation (PV)

- **Parity: Operation transforming into its mirrored image**

$$\mathbb{P}(\vec{x}) = -\vec{x}$$



- **Consequence of PV : Imbalance btwn. right- & left-handed (*"helical"*) modes**

Types & Examples of PV

- **Tensorial PV : primordial GWs with net helicities**
  (Lue+99; Jackie & Pi 03; Saito+07; Contaldi+08; Jeong & Kamionkowski 12; Masui+17; Nishizawa & Kobayashi 18)

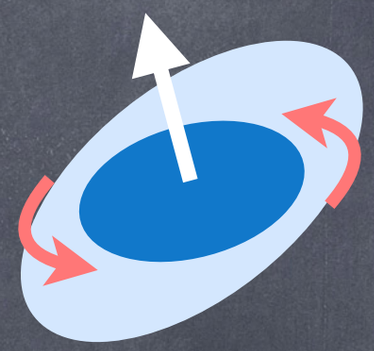
- **Vectorial PV ? : displacement vector field with net helicities**

In this talk,

we assess the detectability of PV in a primordial vector fossil using galaxy spins.

Initial spin field

$$\vec{J} \propto \epsilon_{ijk} I_{jl} T_{lk} \quad (I_{jl} = \partial_j \partial_l \rho_s \,,\; T_{lk} = \partial_l \partial_k \phi_s)$$



(TTT; Peebles 69, Doroshkevich 70, White 84)

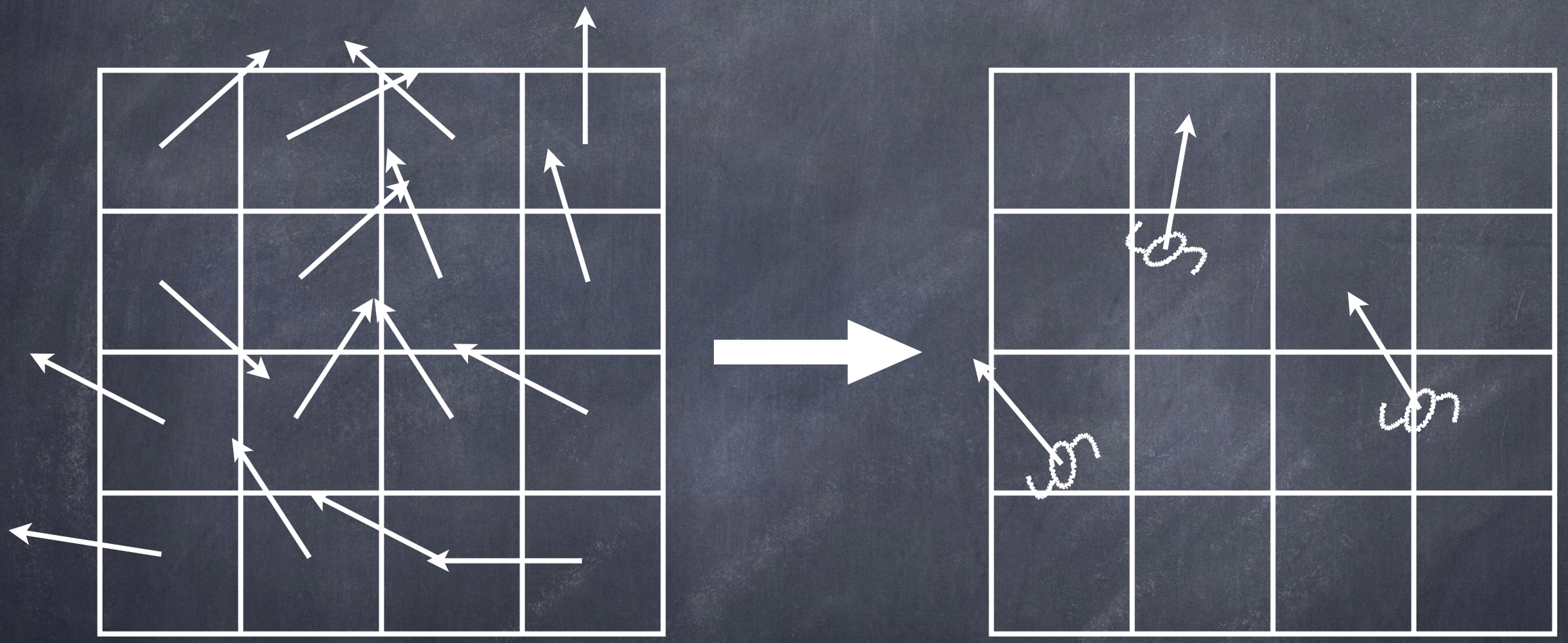
1) a reliable proxy for **halo & galaxy spins**

(Lee & Pen00, Porciani+02, Jiang+19, Yu+20, Motloch+21,22, Sheng+23)

2) a *"helical"* vector field

(i.e. rotational, $\nabla \cdot \vec{J} = 0$)

Parity violation



Helical asym. in
init. spin field

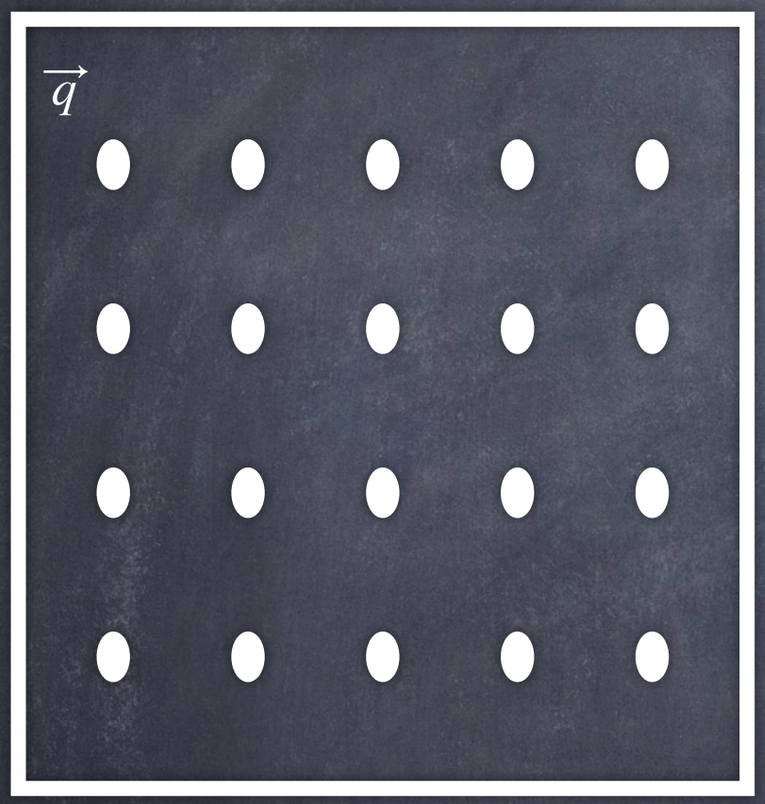
Helical asym. in
gal. spin field

Simulations

- **CUBE (P3M)** (Yu+18)
  - $L_{\rm box} = 100\ h^{-1}{\rm Mpc}$
  - $z_{\rm init} = 30$
  - $m_{\rm p} = 4.3 \times 10^9 h^{-1} M_\odot$
  - $N_{\rm p} = 256^3$
- **Halo spins as a reliable proxy for galaxy spins**

  (Hahn+10; Deason+11; Teklu+15; Sheng+23)

Parity violating ICs

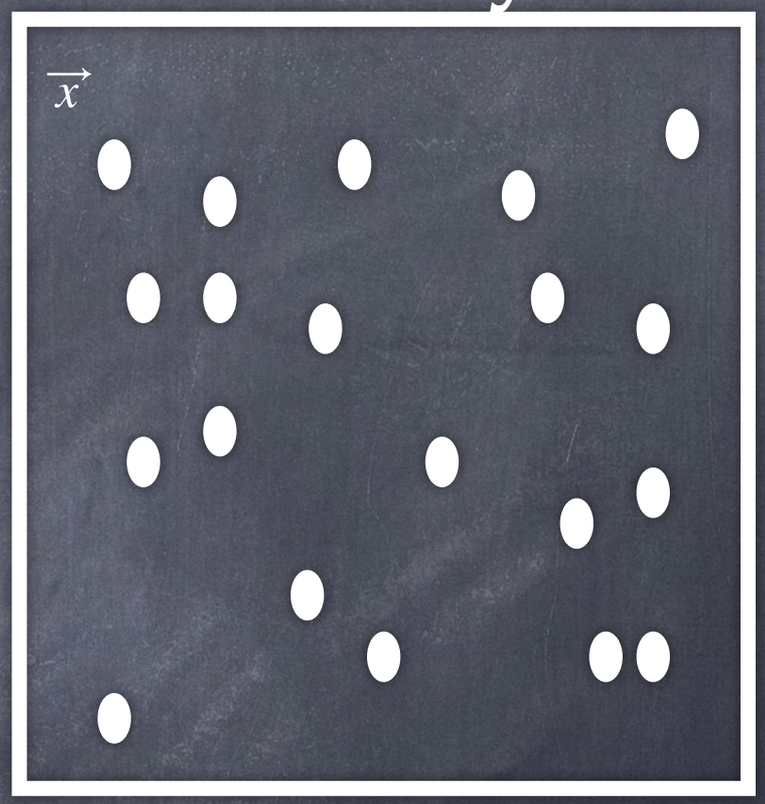


$$\vec{x} = \vec{q} + \vec{\Psi}(\vec{q})$$

$\vec{\Psi}$: disp. field

$(\delta(\vec{q}) \propto -\nabla_q \vec{\Psi})$

init. density fluc.



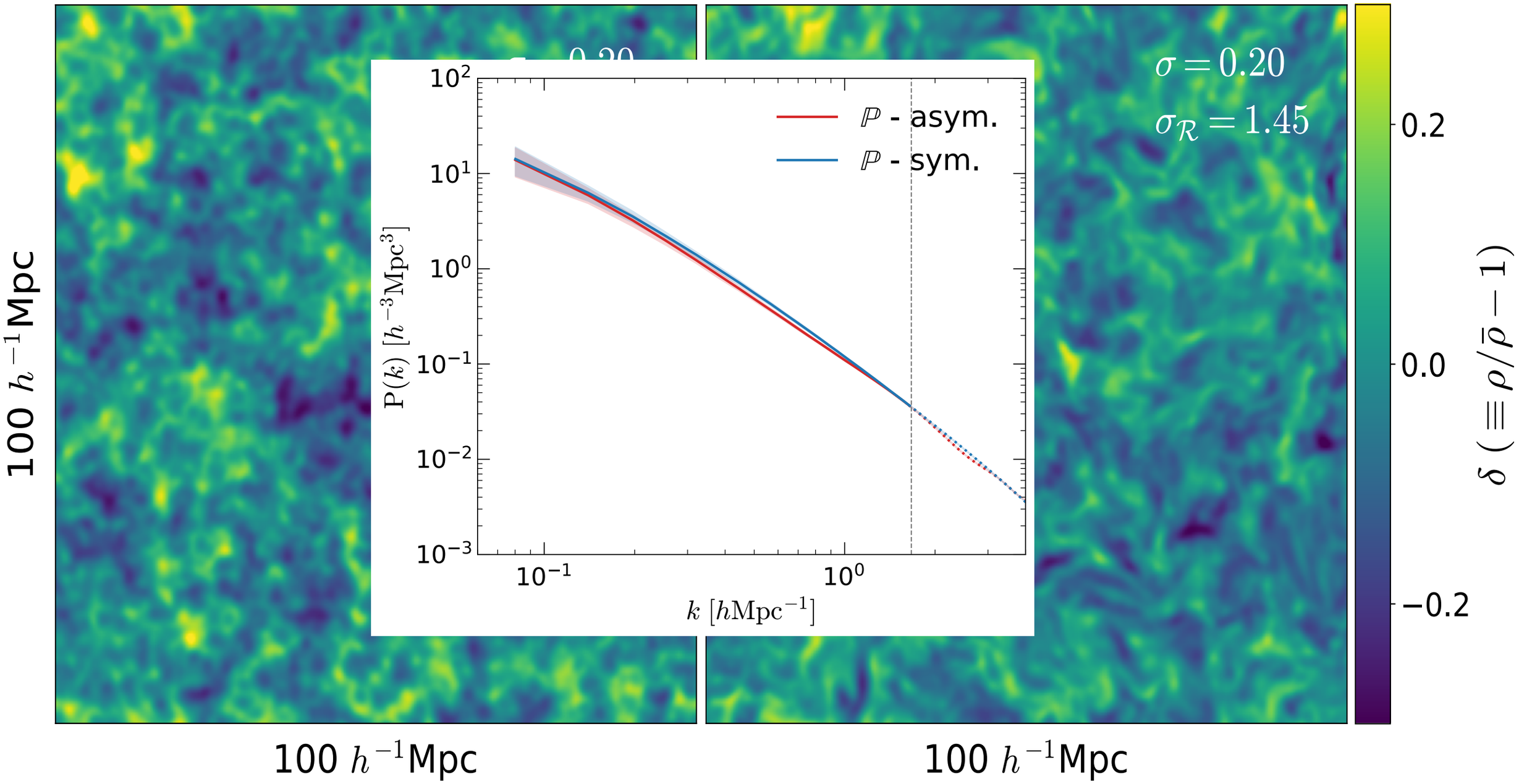
parity sym. $\vec{\Psi} = \vec{\Psi}_{ZA} = -\nabla_q \Phi$

parity asym. $\vec{\Psi} = \vec{\Psi}_{ZA} + \vec{\Psi}_{hel}$ $(\vec{\Psi} = \nabla\phi + \vec{\nabla} \times \vec{A})$

Initial density fields

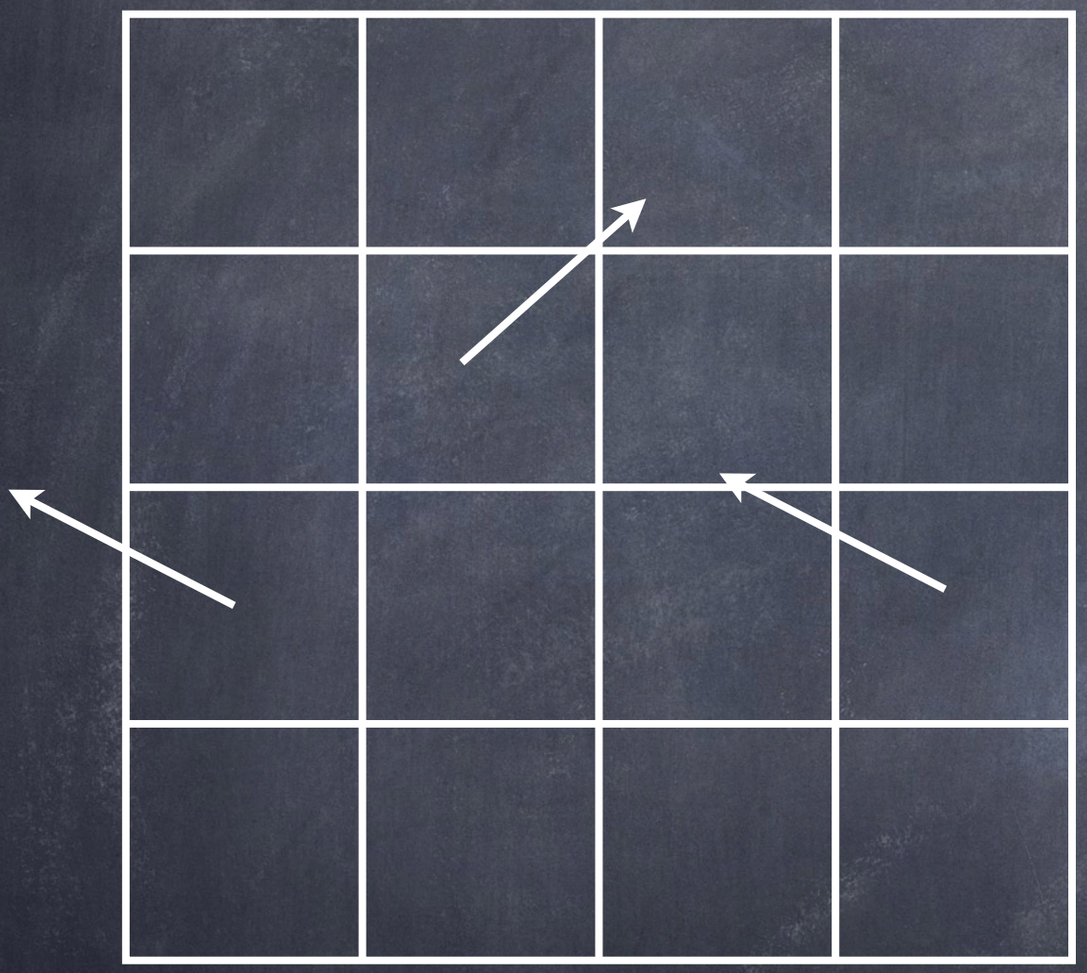
$\mathbb{P}$ - symmetric

$\mathbb{P}$ - asymmetric



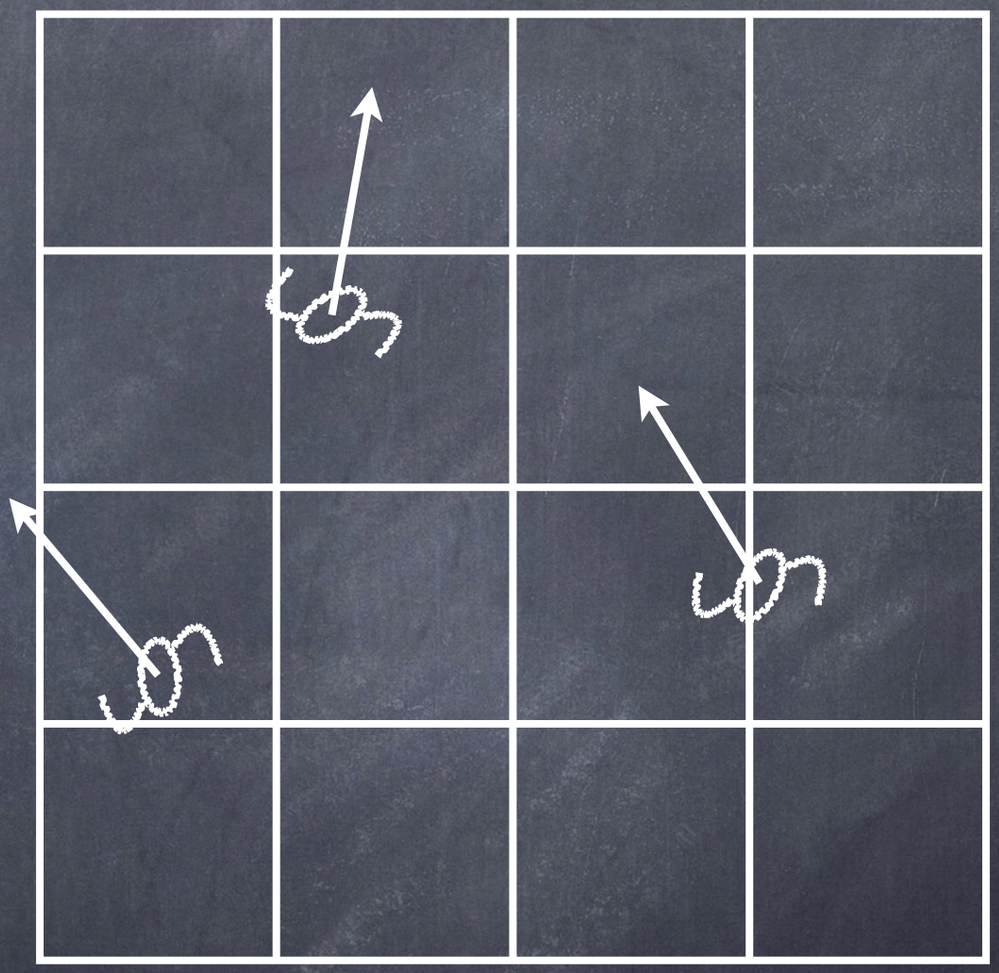
(Shim+24, arXiv:2406.06080)

Init. spin vs. halo spin



init. spin field

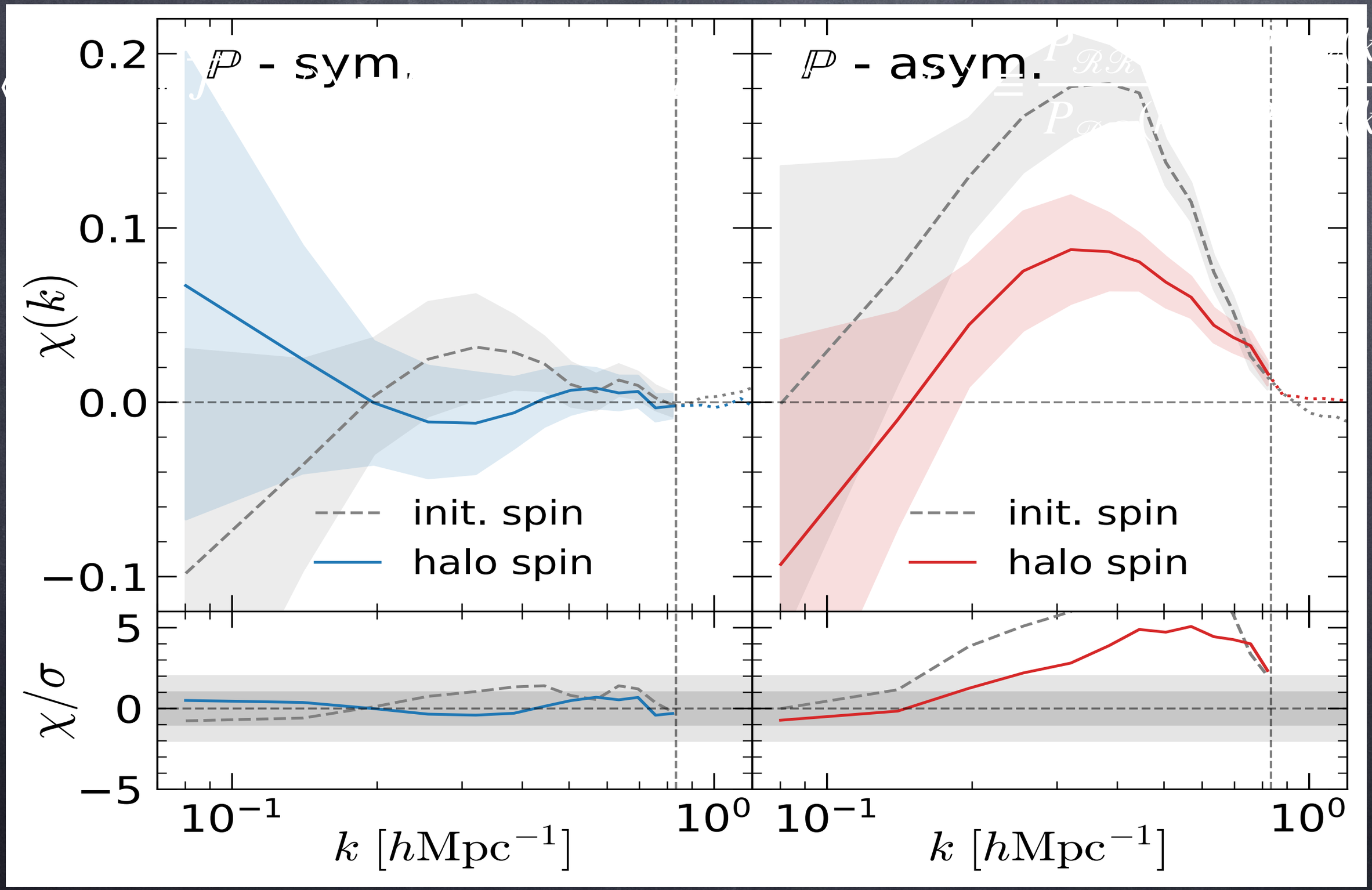
(subsampled)



halo spin field

$N_{\rm h} \approx 10^6$ $(M_{\rm h} \geq 10^{12} h^{-1} M_\odot)$

Init. spin vs. halo spin



(Shim+24, arXiv:2406.06080)

Summary

- We explore the potential of using galaxy spins to test primoridial PV.
- Primordial helical asymmetry is well preserved in halo spins.

Thank you

Generating IC (1)

- **(Disp.) Vector field decomposition**

$$\vec{\Psi} = \nabla\phi + \vec{\nabla} \times \vec{A}$$

$$\vec{\Psi}(\vec{k}) = \vec{\Psi}_E(\vec{k}) + \vec{\Psi}_R(\vec{k}) + \vec{\Psi}_L(\vec{k})$$

$$\phi_E \hat{e}_E \qquad\qquad \phi_{R/L} \hat{e}_{R/L}$$

using eigenvectors of curl operator,

$$\hat{e}_{\mathrm{E}} = \frac{1}{k}\begin{pmatrix} k_x \\ k_y \\ k_z \end{pmatrix} \qquad \hat{e}_{\mathrm{R/L}} = \frac{1}{\sqrt{2}k}\frac{1}{\sqrt{k_y^2 + k_z^2}}\begin{pmatrix} k_y^2 + k_z^2 \\ -k_x k_y \pm ikk_z \\ -k_x k_z \mp ikk_y \end{pmatrix}$$

Generating IC (2)

- (standard) **Parity symmetric IC**

$$\langle \delta(\vec{k})\delta^*(\vec{k}')\rangle \equiv (2\pi)^3\delta_{\rm D}(\vec{k}-\vec{k}')\mathrm{P}(k)$$

$$\sigma^2 \equiv \frac{1}{2\pi}\int k^2 P(k)dk$$

- **Parity asymmetric IC**

$$\langle k^2\Phi_R(\vec{k})k'^2\Phi_R^*(\vec{k}')\rangle \equiv (2\pi)^3\delta_{\rm D}(\vec{k}-\vec{k}')\mathrm{P}_R(k)$$

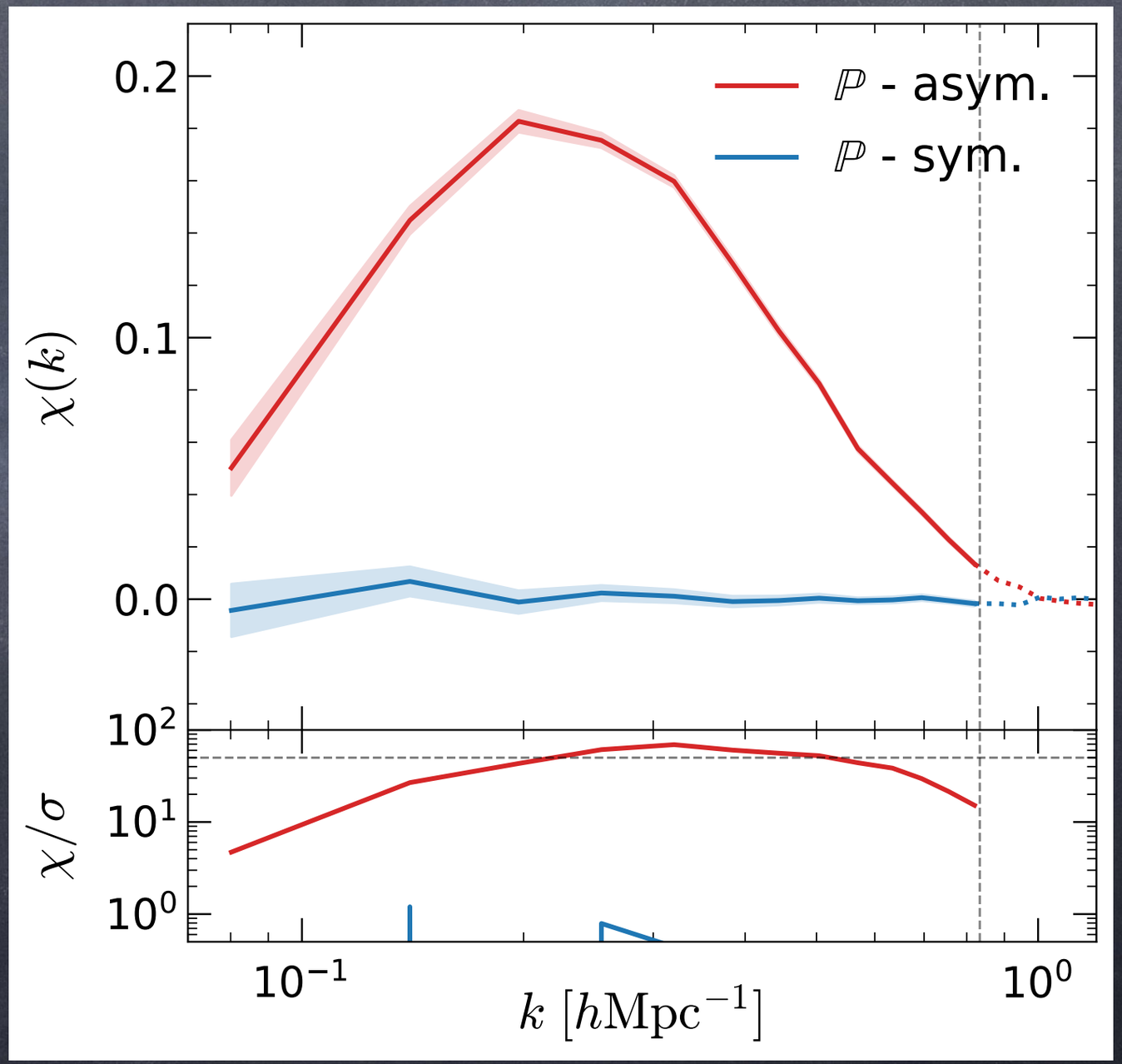
$$\sigma_R^2 \equiv \frac{1}{2\pi}\int k^2 P_R(k)dk \qquad P_R(k)dk \equiv P(k)e^{-k^2R_h^2}$$

Initial spin fields

$$\langle \vec{J}_{\rm x}(\vec{k}) \cdot \vec{J}^{*}_{\rm x}(\vec{k}\,') \rangle \equiv P_{\rm xx}(k)(2\pi)^3 \delta_{\rm D}(\vec{k} - \vec{k}\,') \qquad \chi(k) \equiv \frac{P_{\mathscr{R}\mathscr{R}}(k) - P_{\mathscr{L}\mathscr{L}}(k)}{P_{\mathscr{R}\mathscr{R}}(k) + P_{\mathscr{L}\mathscr{L}}(k)}$$

Substantial helical asymmetry in $\mathbb{P}$-asym. ICs.

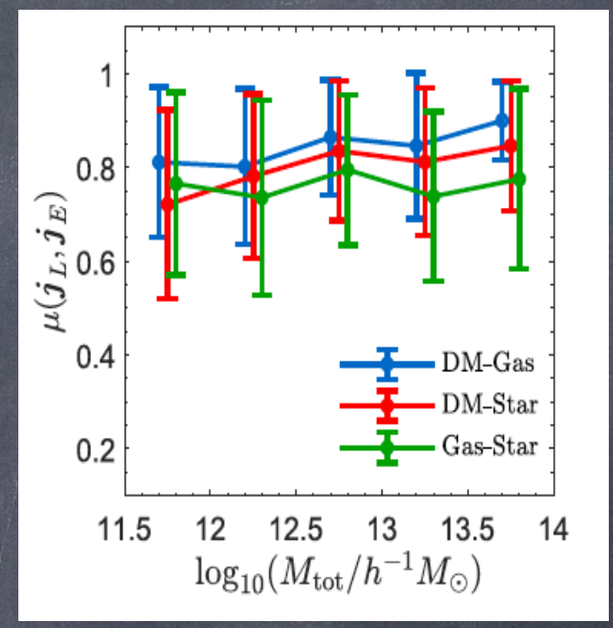
Consistent with helical symmetry in $\mathbb{P}$-sym. ICs.



(Shim+24, arXiv:2406.06080)

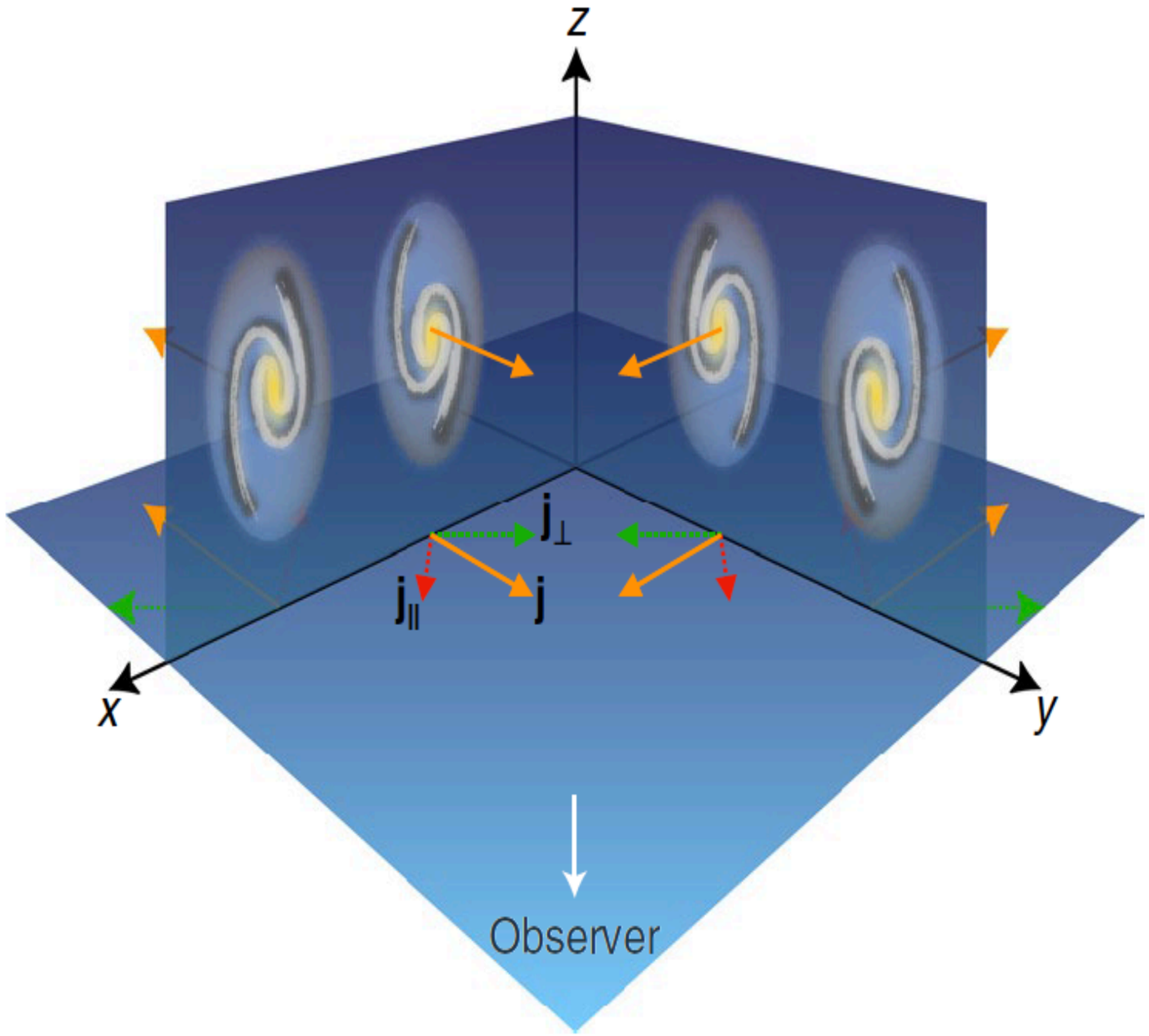
Observational feasibility

- Baryon and halo spins are misaligned by ~35°
- Hel. asym. in gal. spin decreases by ~30%
- With DESI BGS, detection significance can reach ~11σ



(Sheng+23)

Obs. spin determination



- $\vec{J} \perp$ gal's disk
- S-Z spiral arm
- projected gas velocity
- color gradient

(Motloch+21)

Late-time density fields

$\mathbb{P}$-sym.

$\mathbb{P}$-asym.