Galaxy-Halo Spin Alignment and Conservation in the IllustrisTNG Simulation

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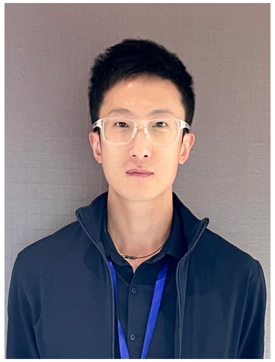
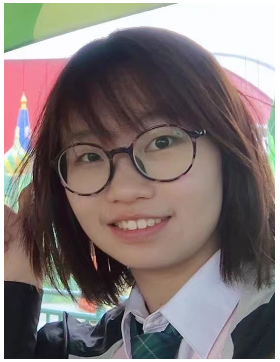
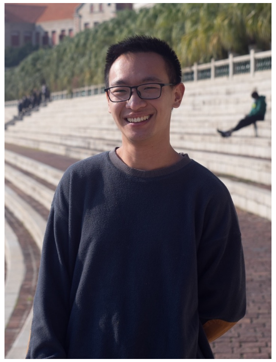
The 2nd Shanghai Assembly on Cosmology and Structure Formation
Oct. 31. 2023

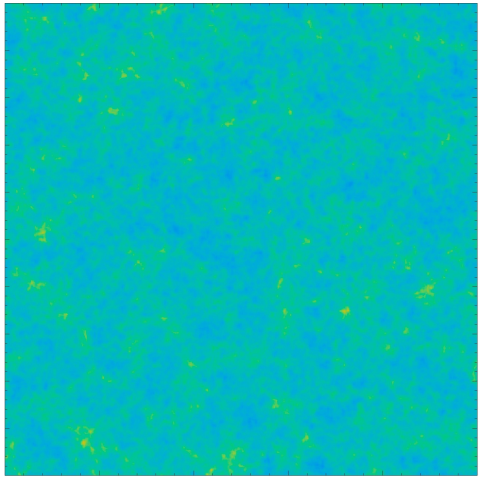
Group members: Hao-Ran Yu (于浩然), Sijia Li (李思佳), Binghang Chen (陈冰航), Lin Zhu (朱琳)

Collaborators: Peng Wang (王鹏), Shihong Liao (廖世鸿), Xi Kang (康熙), Huiyuan Wang (王慧元), Min Du (杜敏), Yipeng Jing (景益鹏), et al.

Outline

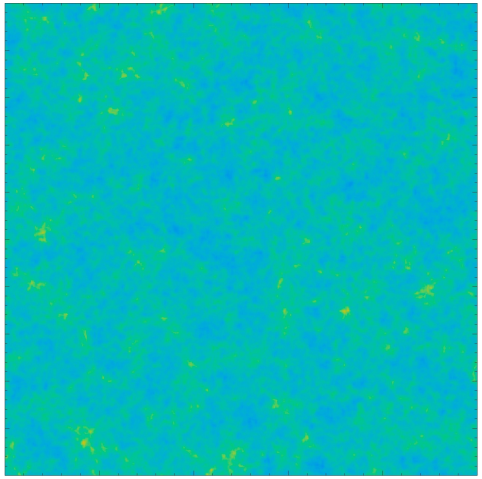
- Background
- Spin Conservation of Dark Matter Clustering
- Comparison of Baryonic Spin in Observation and Simulation
- Prospects and Summary

Density correlations: scale-limited

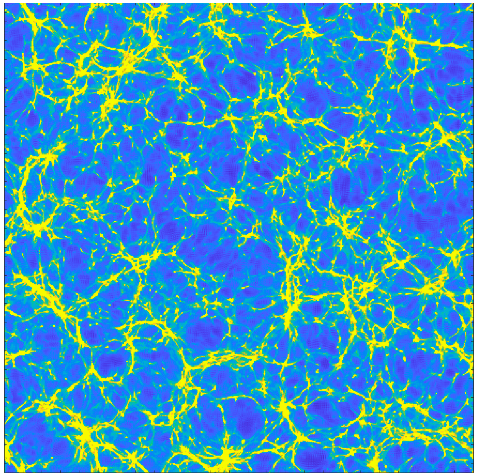


Primordial perturbation

Density correlations: scale-limited

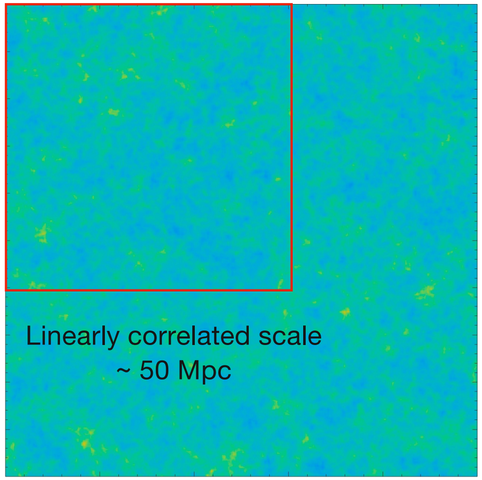


Primordial perturbation

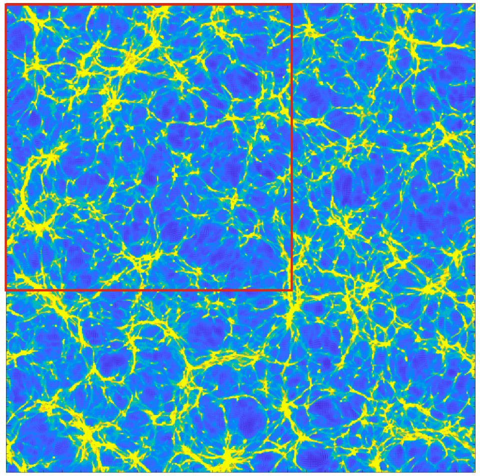


Cosmic web

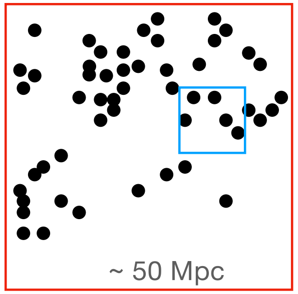
Density correlations: scale-limited



Primordial perturbation

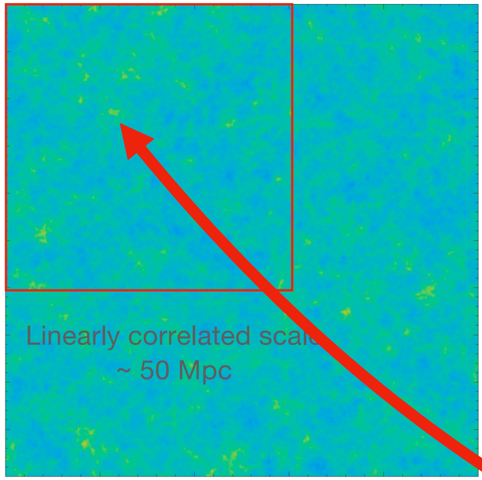


Cosmic web

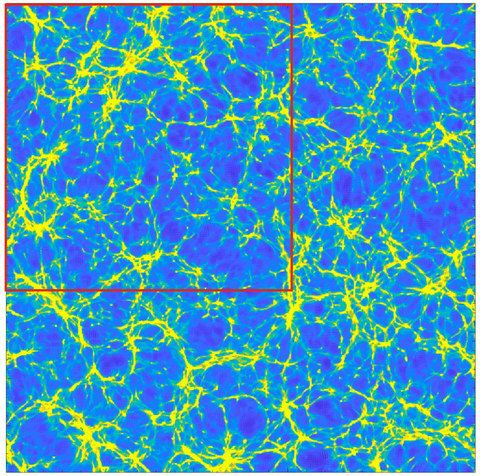


Tracers of cosmic web:
halo and galaxy number
densities

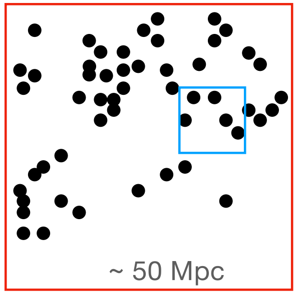
Density correlations: scale-limited



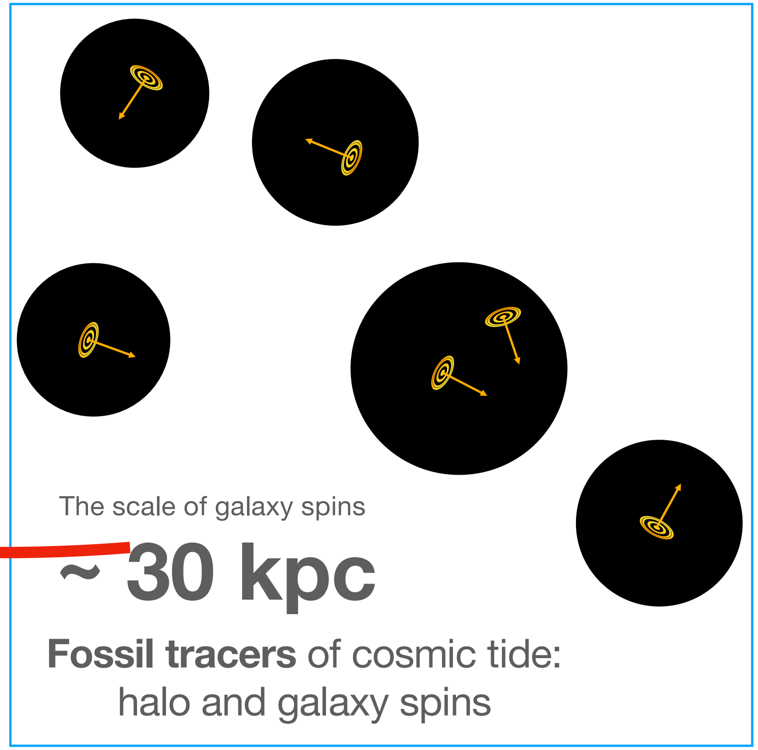
Primordial perturbation



Cosmic web



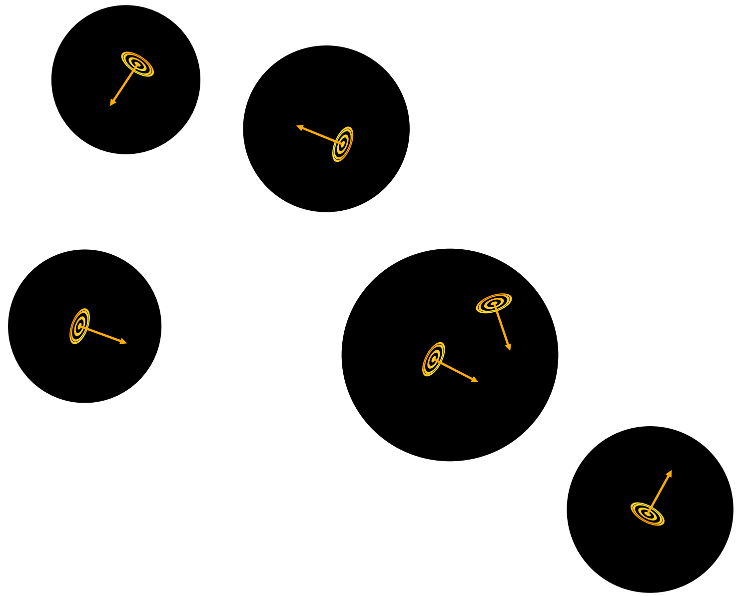
Tracers of cosmic web: halo and galaxy number densities

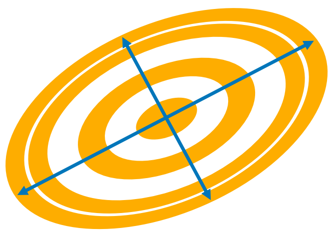


Spin correlations: 3 orders of mag. smaller in scale

Tracers of spin: spiral galaxies

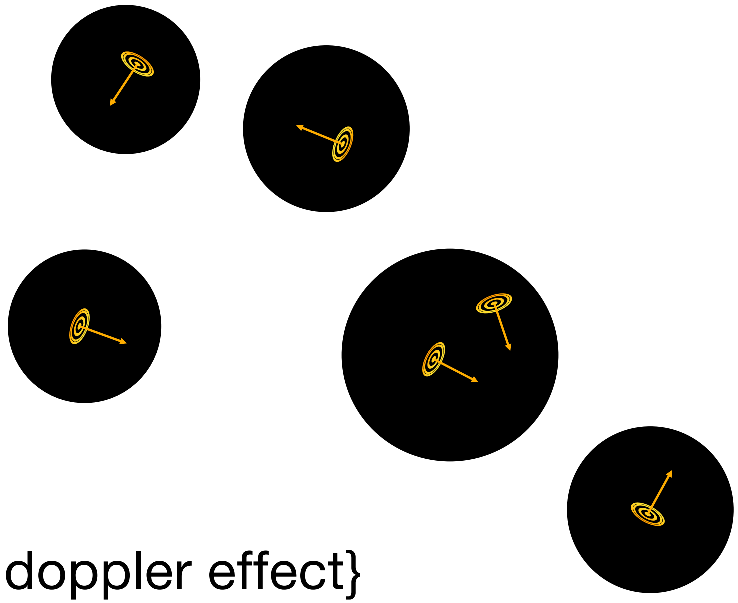
- Ellipticity
- Sky alignment





Ellipticity & sky alignment

Tracers of spin: spiral galaxies



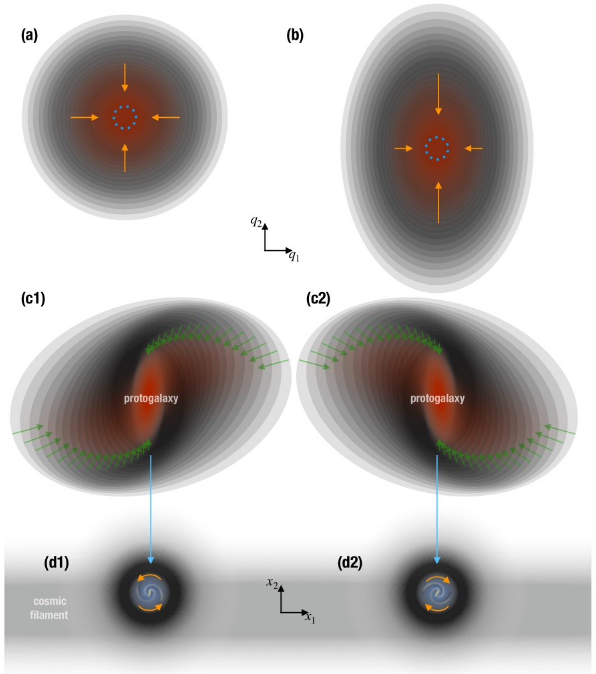
- Ellipticity
- Sky alignment
- Two of {spiral parity, dust absorption, relative doppler effect}

Ellipticity & sky alignment

Spiral parity

Spin conservation of DM halo

- Tidal torque theory



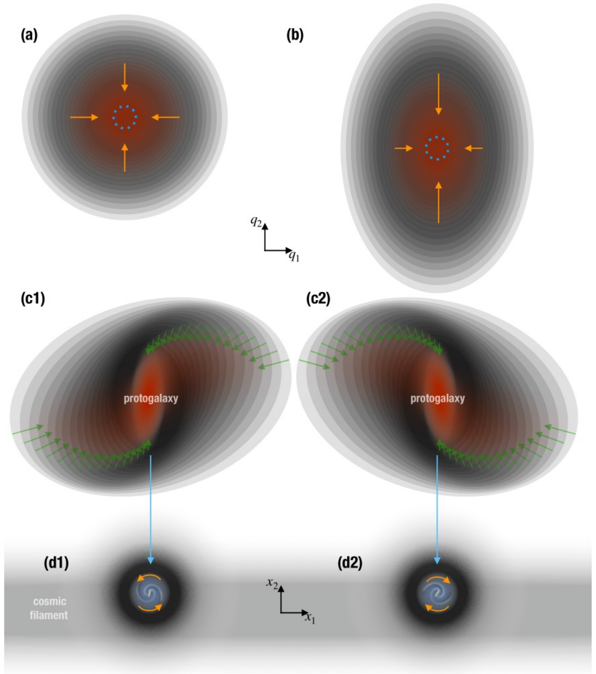
Spin construction method:
Yu*+, PRL, 2020

Figure from:
Motloch*, Yu*+, Nat. Astron., 2021

- Misalignment between the inertia tensor $\mathbf{I}$ of the protogalaxies and the large scale tidal field $\mathbf{T}$ they feel.

Spin conservation of DM halo

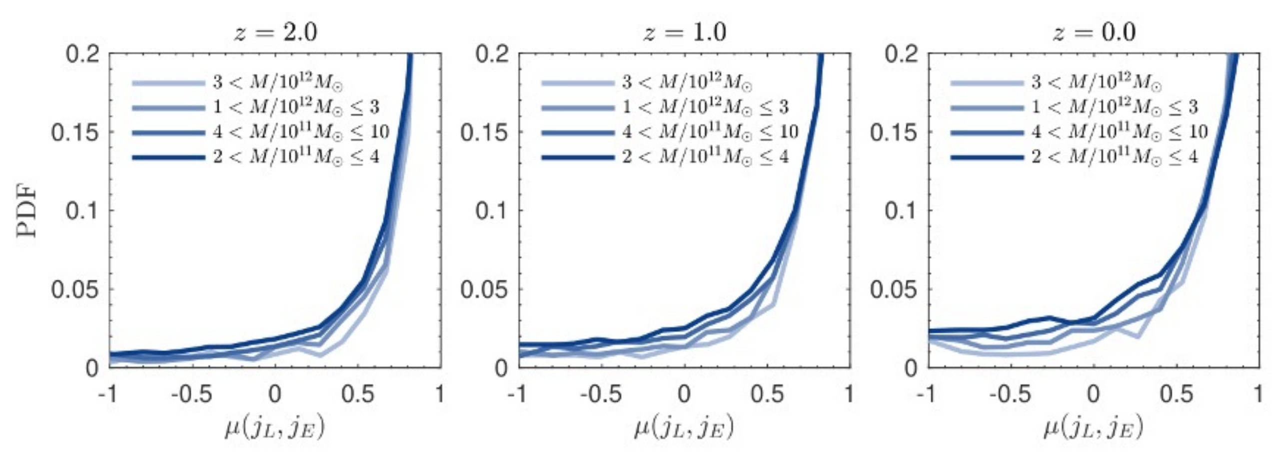
- Tidal torque theory



- Misalignment between the inertia tensor $\mathbf{I}$ of the protogalaxies and the large scale tidal field $\mathbf{T}$ they feel.

- N-body simulation and code: by CUBE (Yu*+, ApJS, 2018)

Qiaoya Wu 吴巧雅



Wu, Yu*+, PRD, 2021

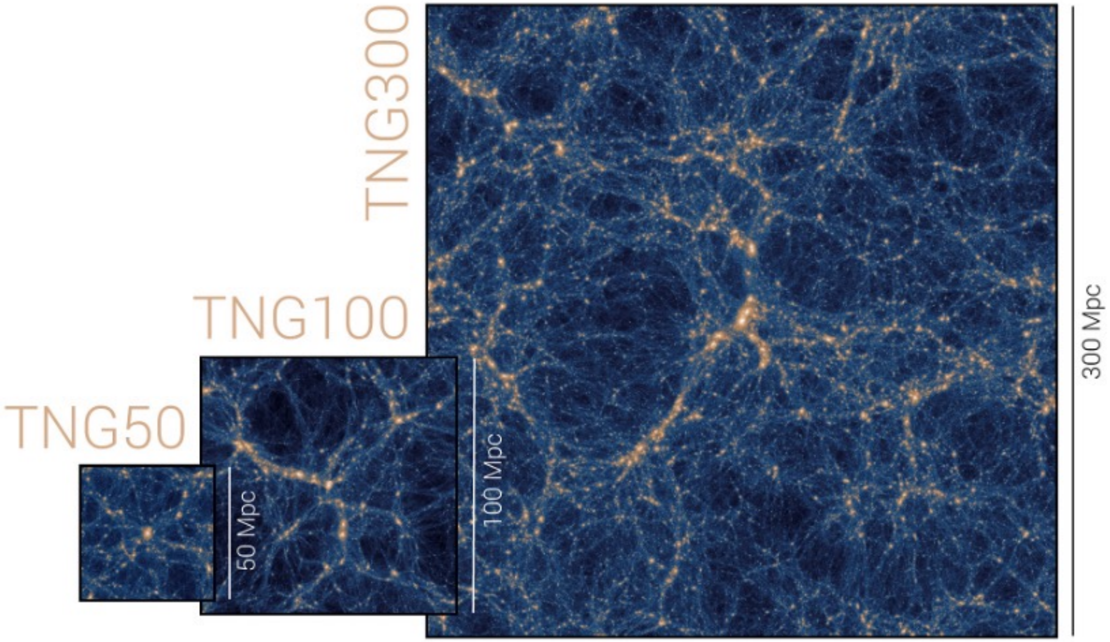
- Initial spin well modeled by the tidal torque theory
- The potential field remains constant
- Spin freezes at low redshift: fossil observable

IllustrisTNG simulation

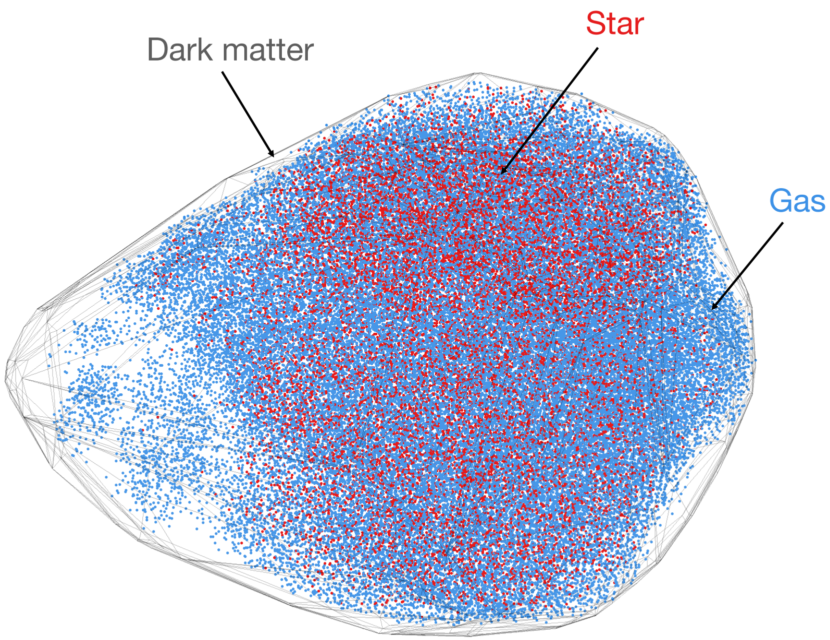
Parameter Description	Value
simulation name	TNG100-1
side length of simulation box [Mpc/h]	75
dark matter particles	1820^3
gas cells	1820^3
tracer particles	2×1820^3
dark matter particle mass [$M_\odot/h$]	5.1×10^6
average gas cell mass [$M_\odot/h$]	9.4×10^5
redshift	127~0
sample counts	4546

Counts of Halos and Mean Galaxy Counts per Halo (Galaxies with Stellar Mass Threshold $M_s = 10^9\ h^{-1}\ M_\odot$) in Different Mass Bins (Mass Units: $h^{-1}\ M_\odot$)

Halo Mass	Halo Counts	Mean Galaxy Counts per Halo
$[10^{11.5}, 10^{12})$	2956	1.2
$[10^{12}, 10^{12.5})$	1051	2.1
$[10^{12.5}, 10^{13})$	355	4.9
$[10^{13}, 10^{13.5})$	124	13.2
$[10^{13.5}, +\infty)$	60	63.6

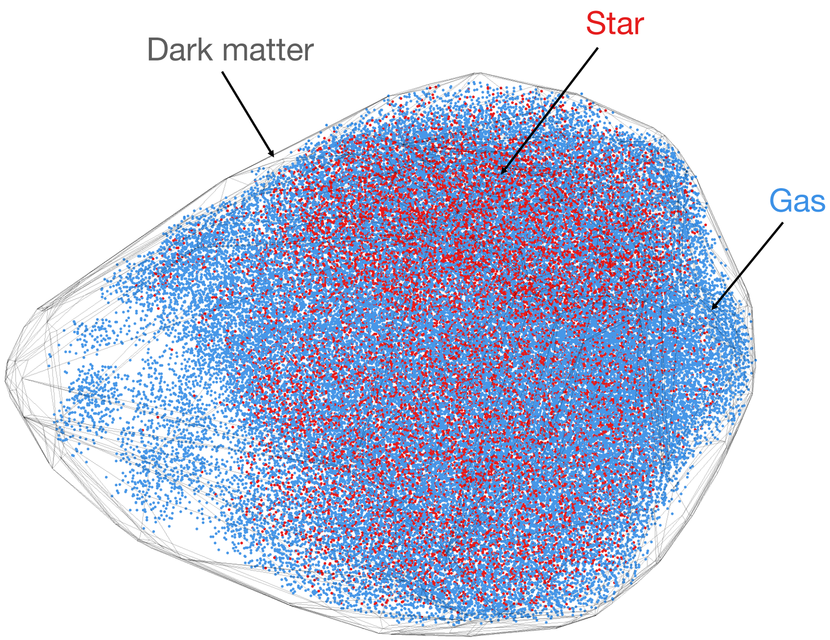


Halo & galaxy evolution



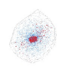
Early Universe,
protohalo & protogalaxy

Halo & galaxy evolution



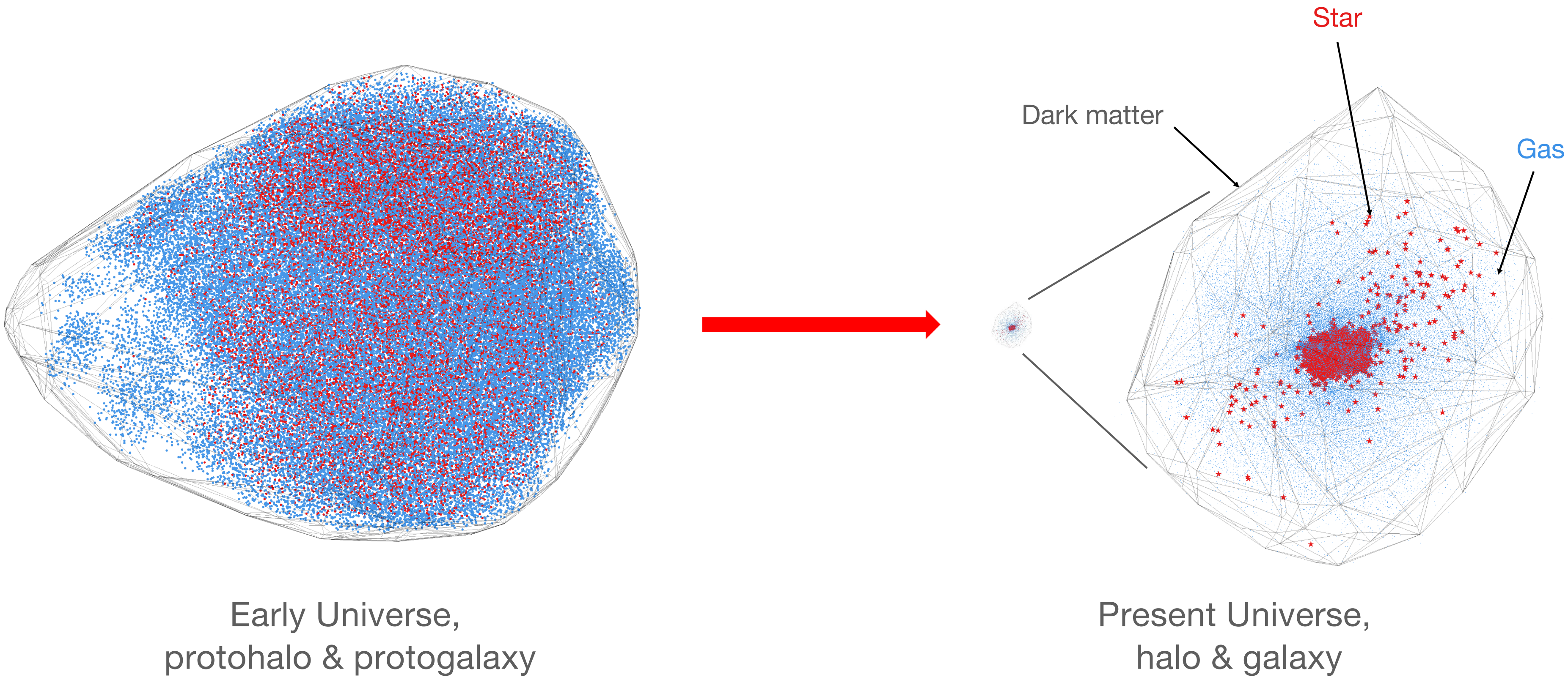
Early Universe,
protohalo & protogalaxy

1 order of mag. smaller

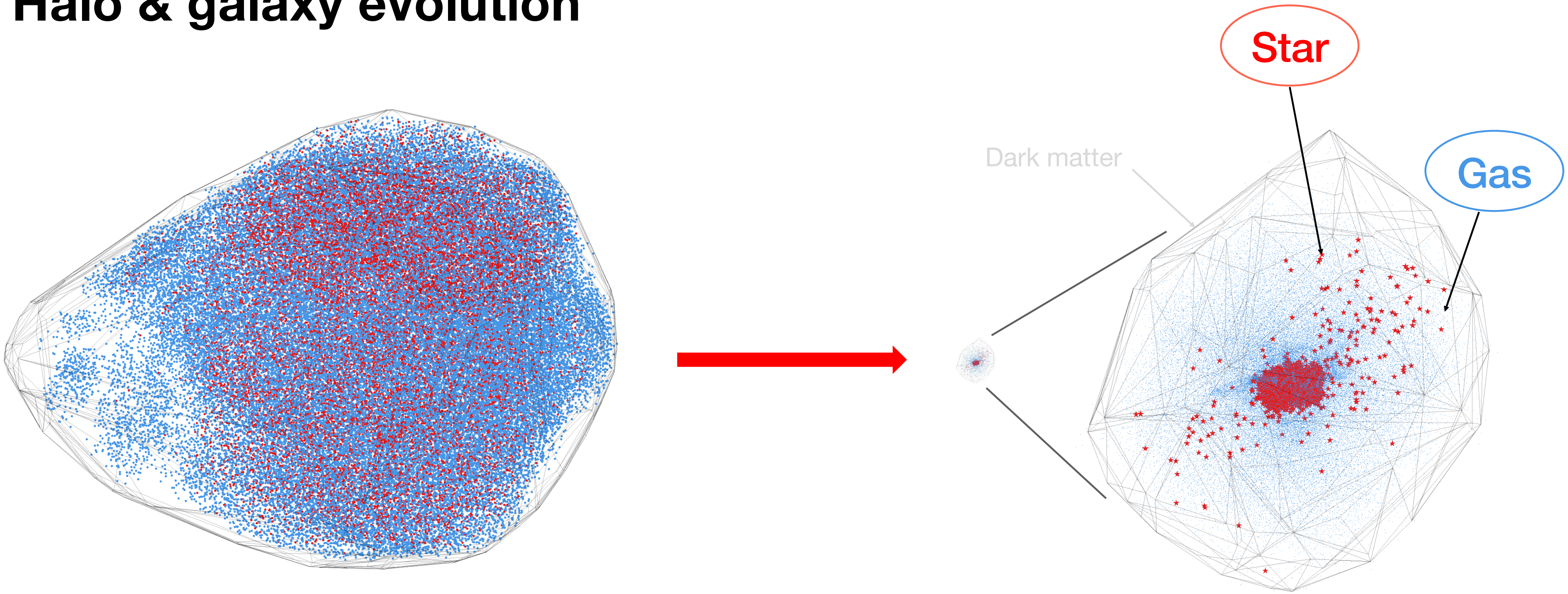


Present Universe,
halo & galaxy

Halo & galaxy evolution



Halo & galaxy evolution

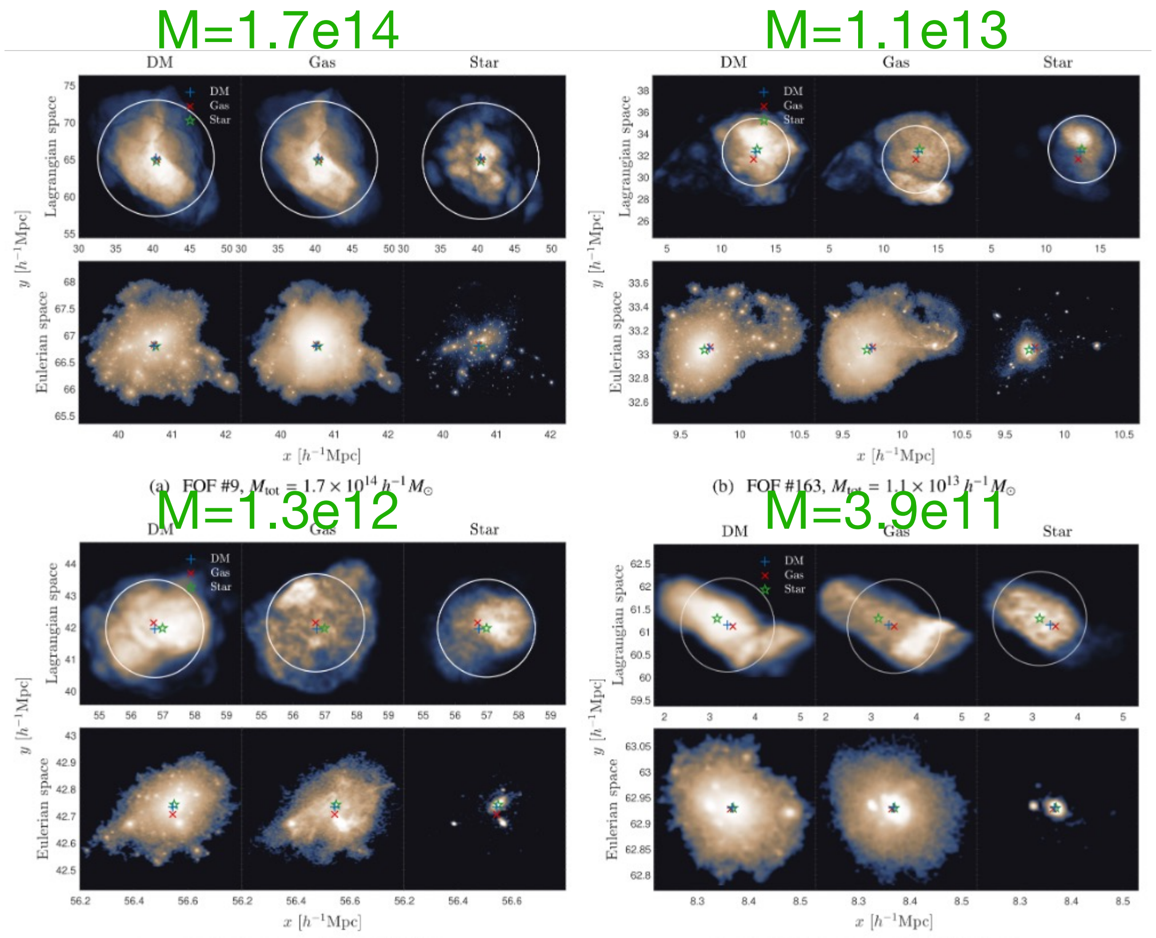


Early Universe,
protohalo & protogalaxy

Present Universe,
halo & galaxy

Lagrangian mass distribution

Sheng, Yu*+, ApJ, 2023,
Baryonic Effects on Lagrangian Clustering
and Angular Momentum Reconstruction



(a) FOF #9, $M_{\rm tot} = 1.7 \times 10^{14}\, h^{-1} M_\odot$

(b) FOF #163, $M_{\rm tot} = 1.1 \times 10^{13}\, h^{-1} M_\odot$

(c) FOF #1322, $M_{\rm tot} = 1.3 \times 10^{12}\, h^{-1} M_\odot$

(d) FOF #3760, $M_{\rm tot} = 3.9 \times 10^{11}\, h^{-1} M_\odot$

Lagrangian

Eulerian

Lagrangian

Eulerian

Lagrangian mass distribution

Sheng, Yu*+, ApJ, 2023,
Baryonic Effects on Lagrangian Clustering
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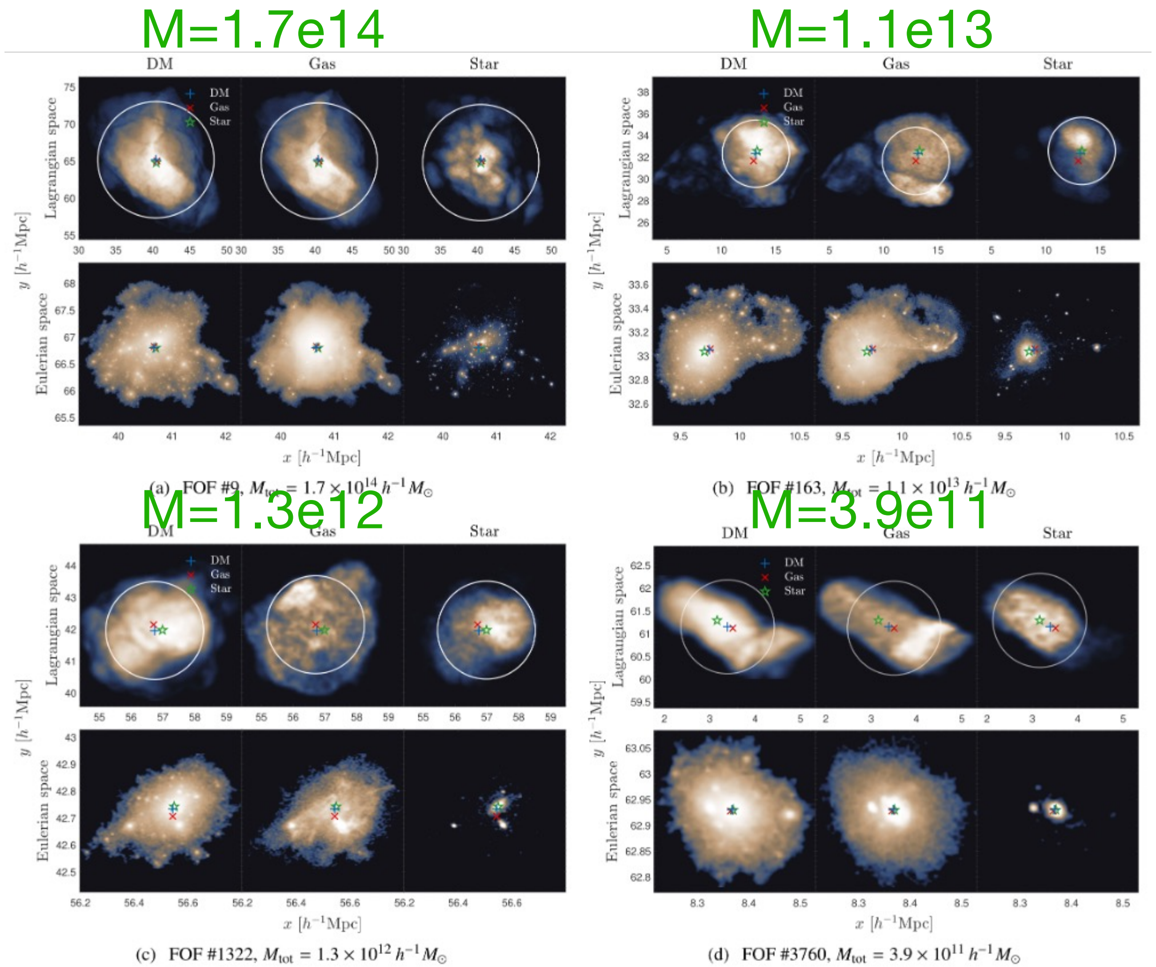
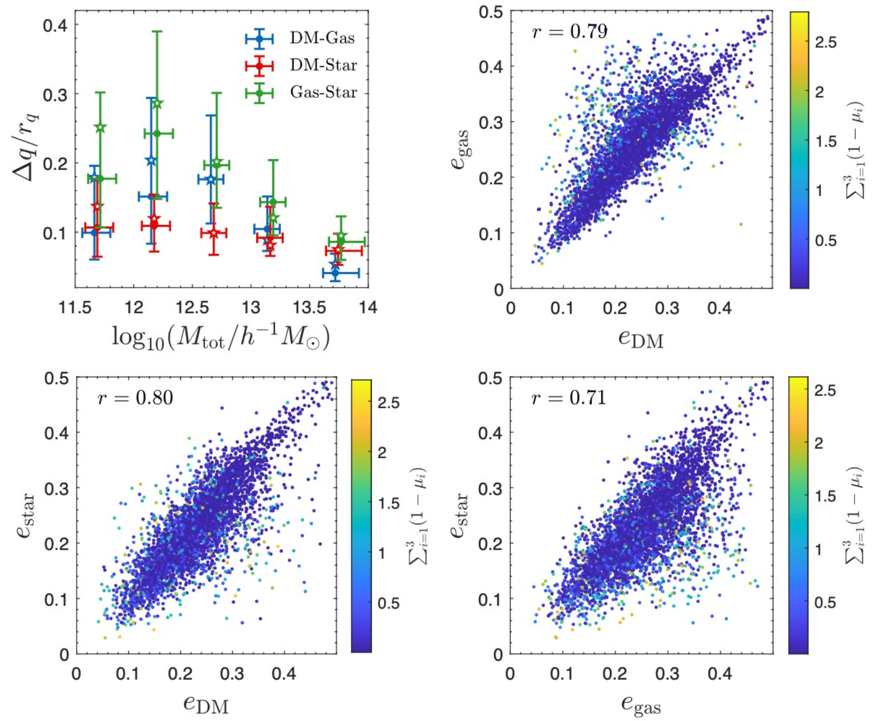
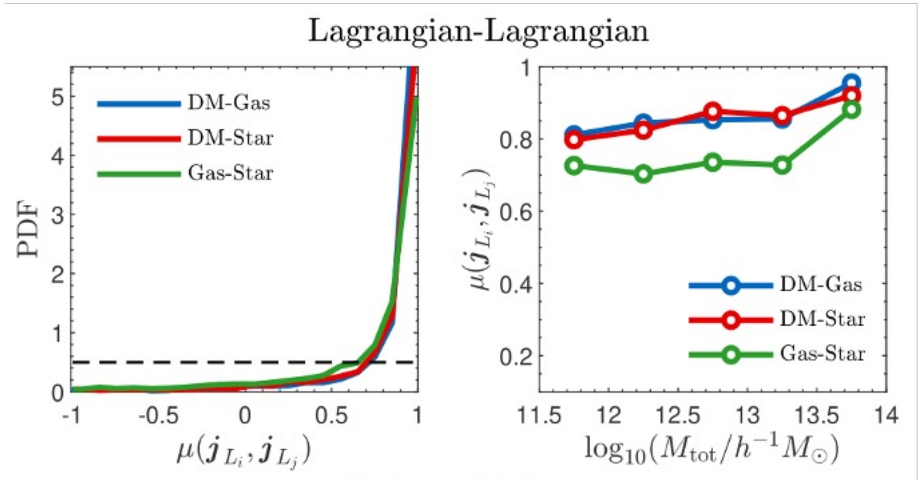


- Equivalent Lagrangian radii

$$r_q = \sqrt[3]{\frac{2M_{\rm tot}G}{\Omega_{\rm m}H_0^2}}$$



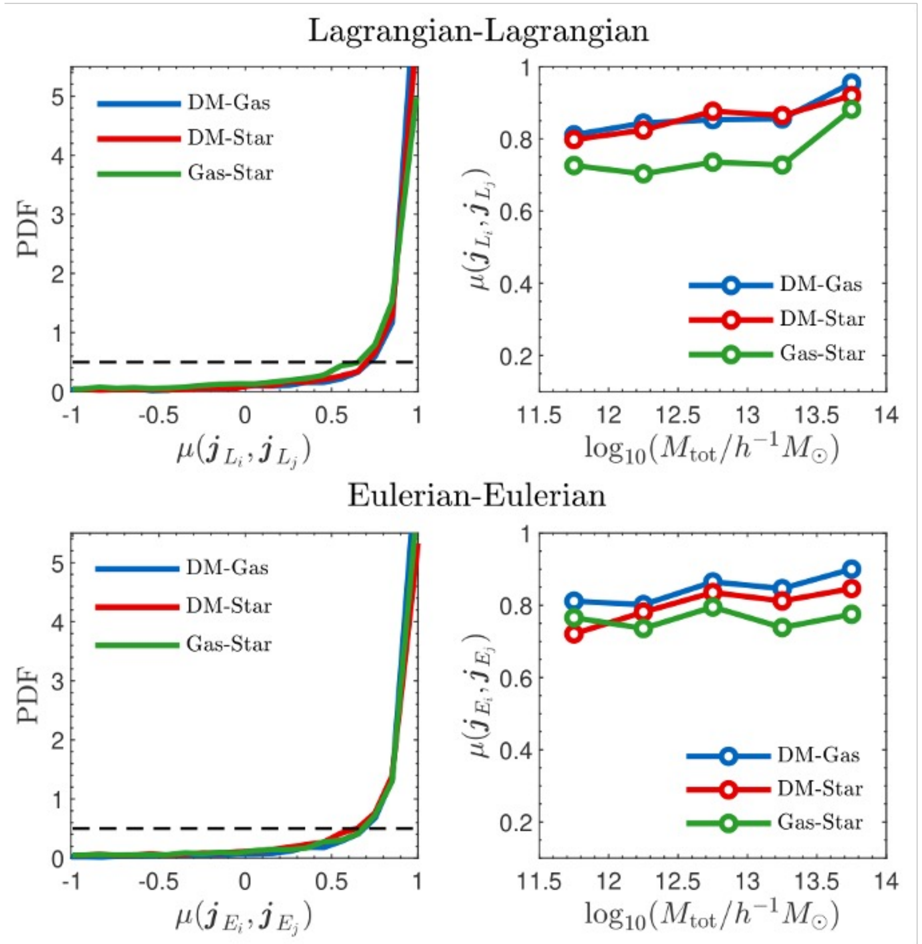
Angular momentum direction correlations



- Similar mass distributions → Strong spin correlations

Sheng, Yu*+, ApJ, 2023

Angular momentum direction correlations



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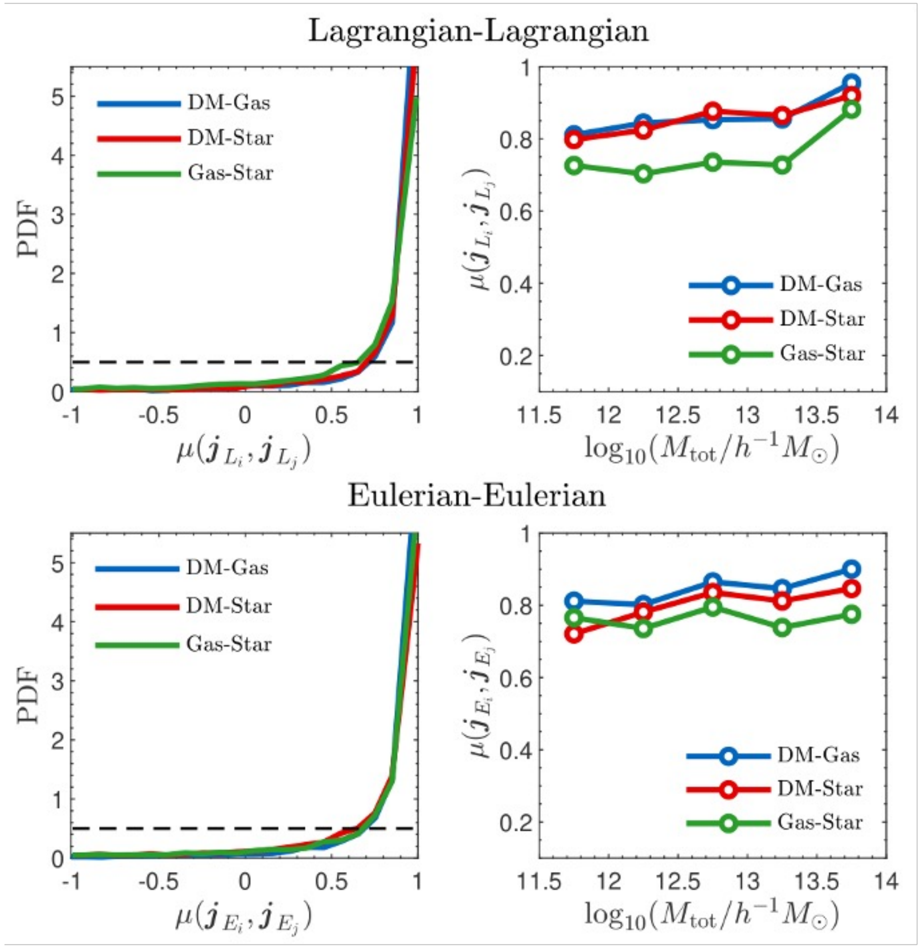
Sheng, Yu*+, ApJ, 2023

Angular momentum direction correlations



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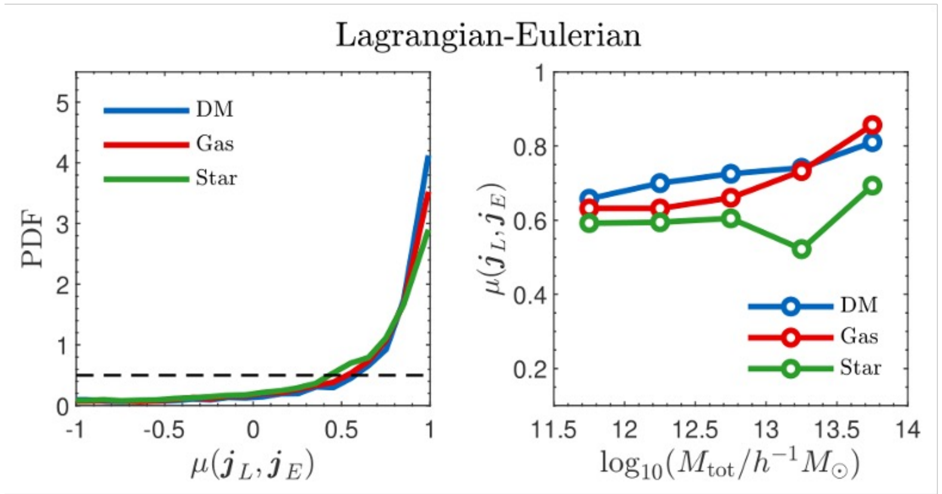
Sheng, Yu*+, ApJ, 2023



Spin direction reconstruction for baryons

- Spin reconstruction formula:

$$j_i^{\mathrm{reco}} = \epsilon_{ijk} \mathrm{T}_{jl}^{(r_q)} \mathrm{T}_{lk}^{(r_{q,+})},$$

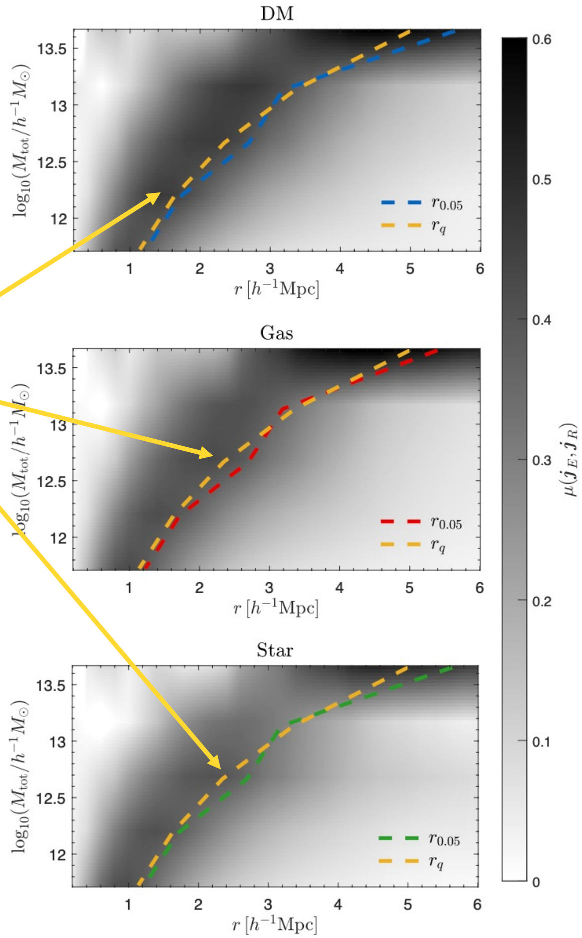
where r_q is the Lagrangian scale for the total mass (Yu+, PRL, 2020).

- Similar to the tidal torque theory

$$j_i^{\mathrm{TTT}} = \epsilon_{ijk} \mathrm{I}_{jl} \mathrm{T}_{lk}$$

Same proto-scales for all species

More massive

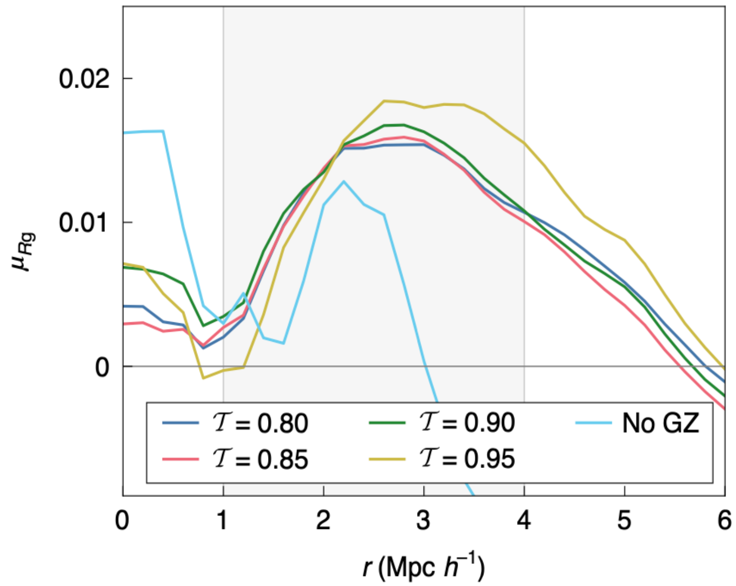


Larger Lagrangian torquing scale

Sheng, Yu*+, ApJ, 2023

Observations

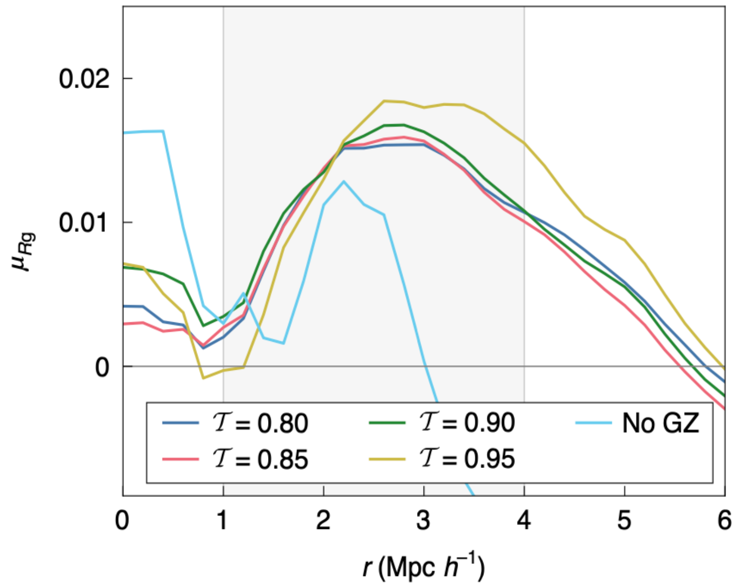
- For SDSS galaxies, weak (2%) but significant (3σ) detection of correlation between galaxy spin directions and cosmic initial conditions



Motloch*, Yu*+, Nat. Astron., 2021

Observations

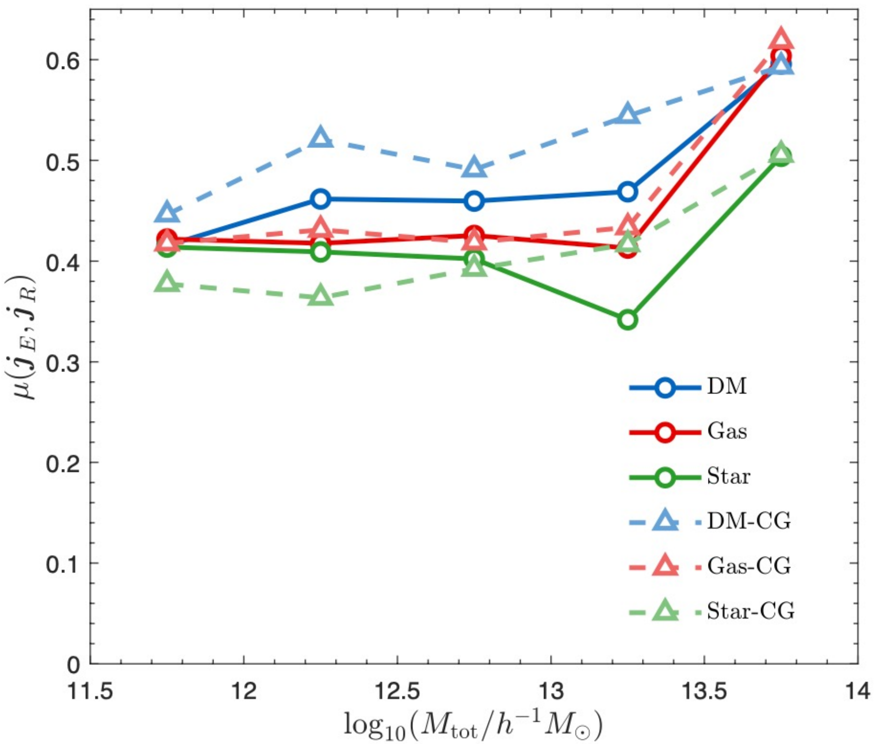
- For SDSS galaxies, weak (2%) but significant (3σ) detection of correlation between galaxy spins and cosmic initial conditions
- From galaxy locations (ELUCID, Wang+, 2014, 2016) we can infer (spin reconstruction) galaxy spins
- Many physical processes & systematics involved
  - Density **reconstruction** error
  - Lagrangian space **remapping**, **RSD**
  - **Observations** of spin
  - Baryonic processes



Motloch*, Yu*+, Nat. Astron., 2021

Maximally achievable spin direction correlation

- Baryon spins can also be reconstructed.
- Weak mass dependency
- Results are similar for total mass distribution of species, or only for the central galaxy (CG).

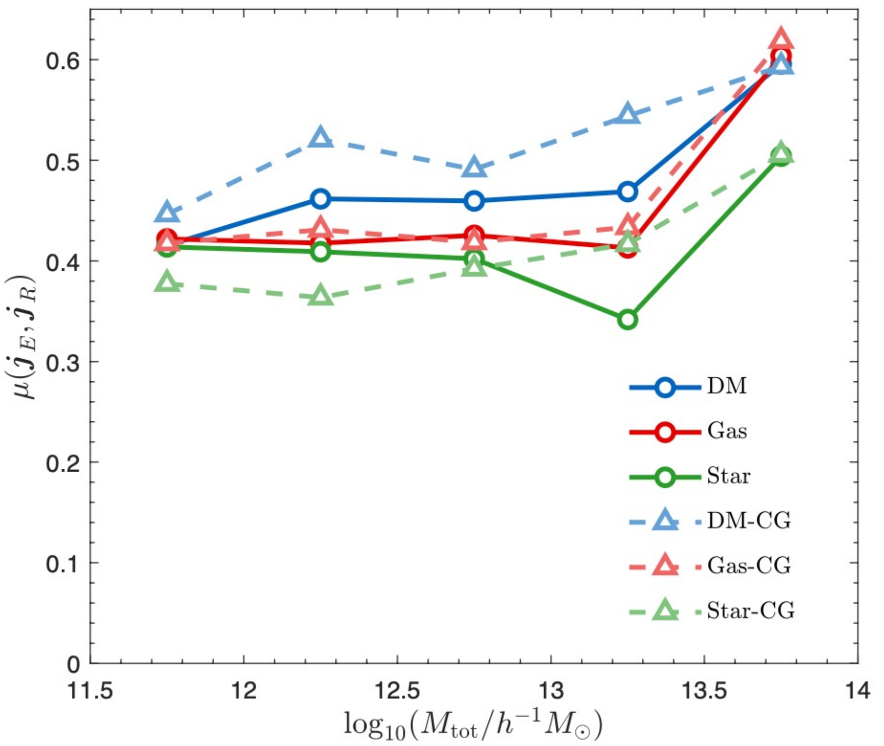


Sheng, Yu*+, ApJ, 2023

Maximally achievable spin direction correlation

- Baryon spins can also be reconstructed.
- Weak mass dependency
- Results are similar for total mass distribution of species, or only for the central galaxy (CG).

- With **known** ICs, **known** Lagrangian coordinates, **known** 3D angular momenta at low-redshifts, the spin direction correlation is around 40%.
- Cf. 2% in Motloch*, Yu*+ 2021.



Sheng, Yu*+, ApJ, 2023

Angular momentum magnitude correlations

Sheng, Zhu, Yu*+, in preparation,
Spin Speed and Supportedness Correlation and Evolution of Galaxy-Halo Systems

Spin speed $\omega_{\rm K}^{\rm Eul} \equiv \frac{\int_{V_x} \hat{j}_i \epsilon_{ijk} x'_j v'_k \,\mathrm{d}M}{2\pi \int_{V_x} r_i^2 \,\mathrm{d}M}$

Spin supportedness $\lambda_{\rm K}^{\rm Eul} \equiv \frac{\int_{V_x} \hat{j}_i \epsilon_{ijk} x'_j v'_k \,\mathrm{d}M}{\int_{V_x} x' v' \,\mathrm{d}M}$

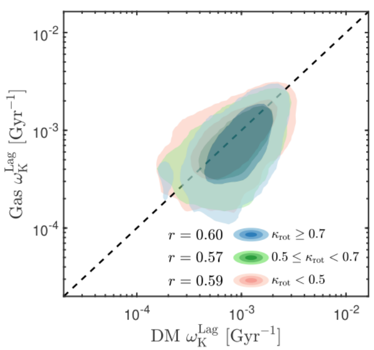
DM vs Gas

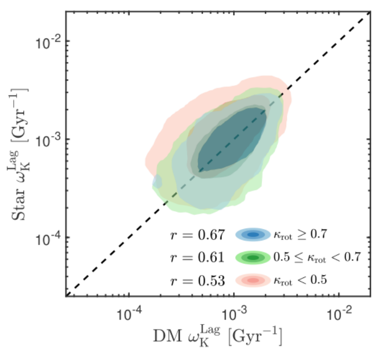
DM vs Stars

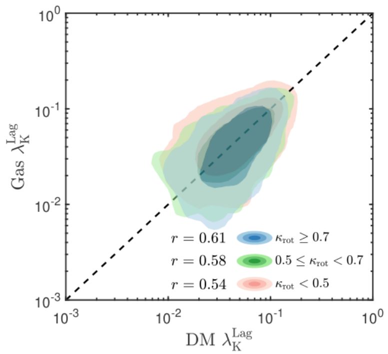
DM vs Gas

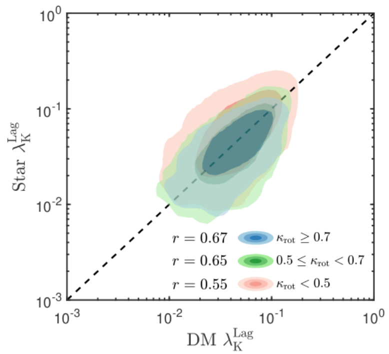
DM vs Stars

Lagrangian









Lagrangian

Angular momentum magnitude correlations

Sheng, Zhu, Yu*+, in preparation,
Spin Speed and Supportedness
Correlation and Evolution of Galaxy-Halo
Systems

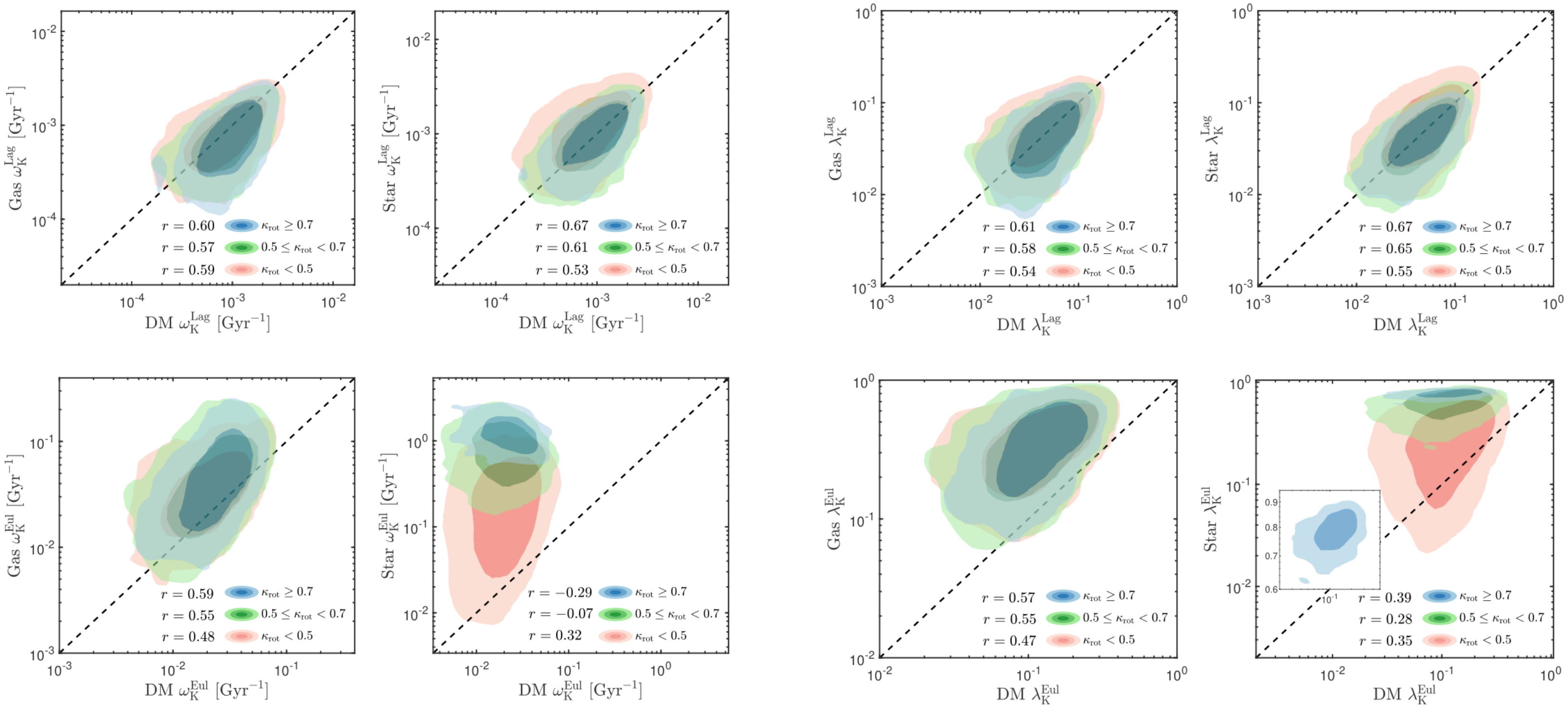
Spin speed $\omega_{\rm K}^{\rm Eul} \equiv \dfrac{\int_{V_x} \hat{j}_i \epsilon_{ijk} x'_j v'_k \, {\rm d}M}{2\pi \int_{V_x} r_i^2 \, {\rm d}M}$

Spin supportedness $\lambda_{\rm K}^{\rm Eul} \equiv \dfrac{\int_{V_x} \hat{j}_i \epsilon_{ijk} x'_j v'_k \, {\rm d}M}{\int_{V_x} x' v' \, {\rm d}M}$

DM vs Gas | DM vs Stars | DM vs Gas | DM vs Stars

Lagrangian

Eulerian



Lagrangian

Eulerian

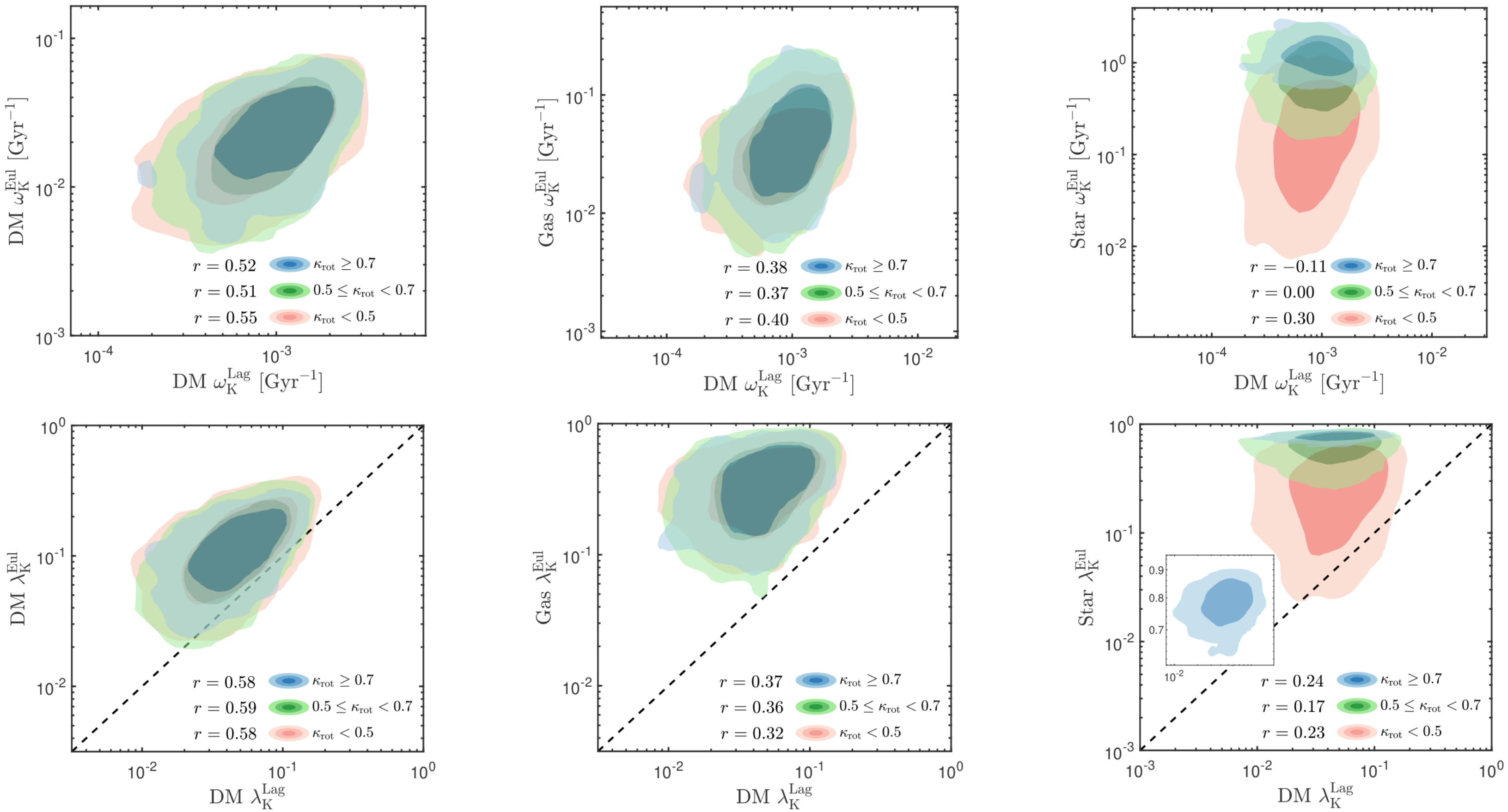
Angular momentum magnitude correlations

Sheng, Zhu, Yu*+, in preparation

DM Lagrangian vs Eulerian | Gas Lagrangian vs Eulerian | Star Lagrangian vs Eulerian

Speed

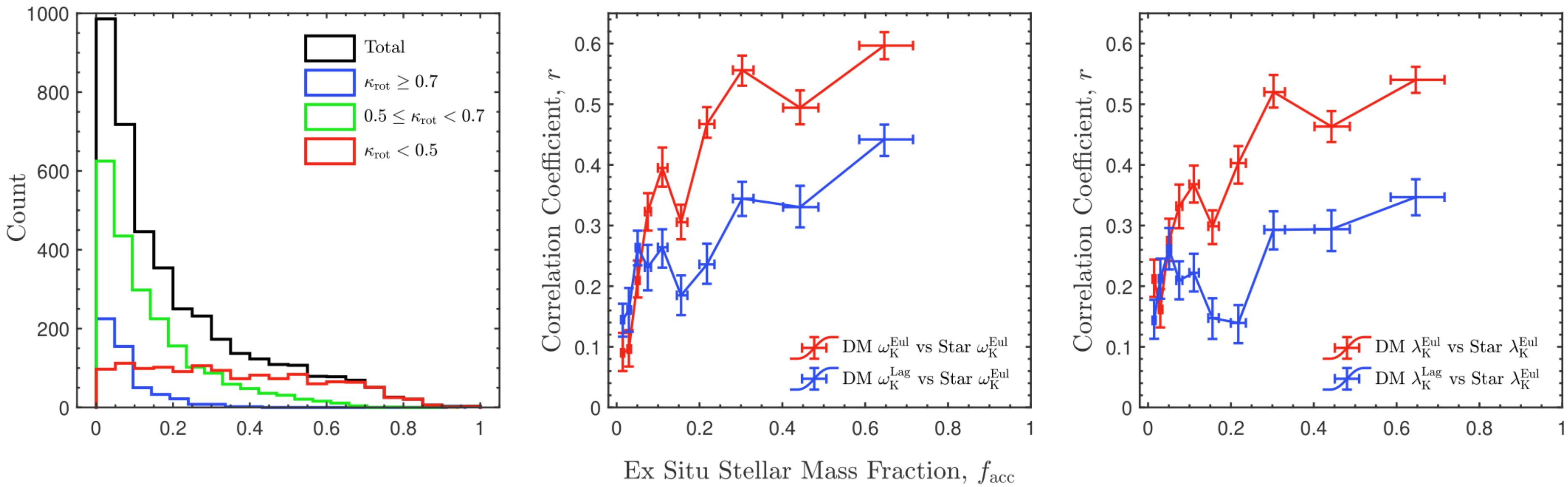
Supportedness



Angular momentum magnitude correlations

Sheng, Zhu, Yu*+, in preparation

- Gas traces the spin magnitude of DM halo and the primordial spin magnitude;
- The traceability of stars depends on $f_{\rm acc}$;
- Galaxy-halo correlations are effected by the similarity of their co-evolution histories.



Summary

CUBE simulations (*N*-body simulations):

- The correlation between **DM halo** and protohalo spin;
- Spin **reconstruction** method.

IllustrisTNG simulations:

- **Baryonic effects** on spin correlation;
- Galaxy **baryonic spins** can potentially be used in reconstructing the cosmic initial perturbations.

Observational data:

- The correlation between **galaxy spins** and cosmic **initial conditions.**

Reference:

Sheng, Zhu, Yu* et al., in preparation, *Spin Speed and Supportedness Correlation and Evolution of Galaxy-Halo Systems*

Sheng, Yu* et al., ApJ, 2023, *Baryonic Effects on Lagrangian Clustering and Angular Momentum Reconstruction*

Sheng, Li, Yu* et al., PRD, 2022, *Spin conservation of cosmic filaments*

Wu, Yu* et al., PRD, 2021, *Spin Mode Reconstruction in Lagrangian Space*

Motloch*, Yu* et al., Nat. Astron., 2021, *Observational detection of correlation between galaxy spins and initial conditions*

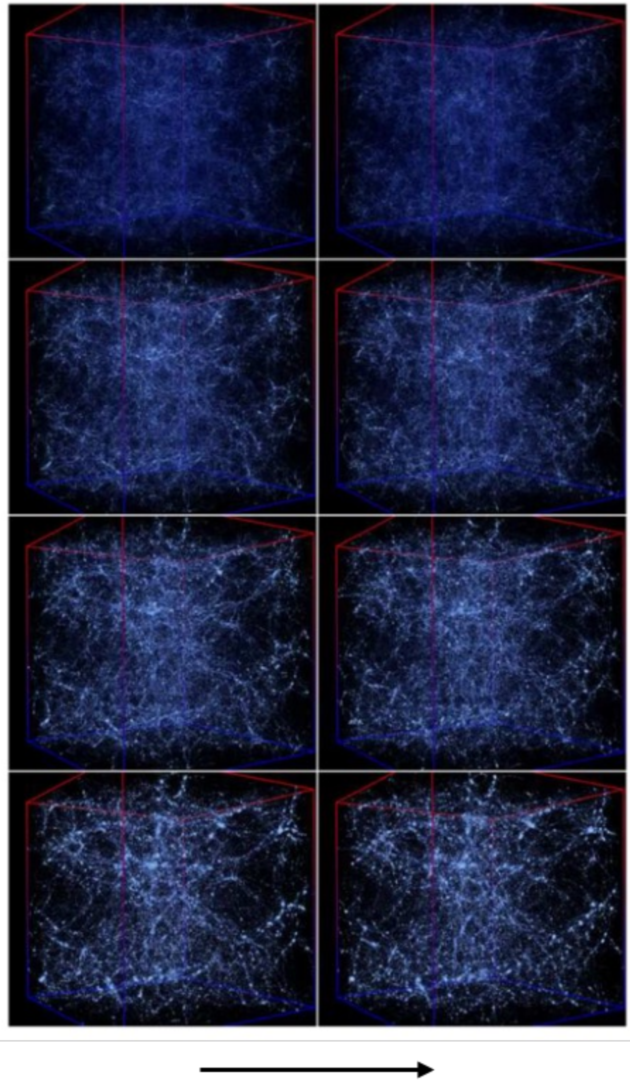
Yu* et al., PRL, 2020, *Probing Primordial Chirality with Galaxy Spins*

Thank you

ELUCID
HMC method
Density reconstruction

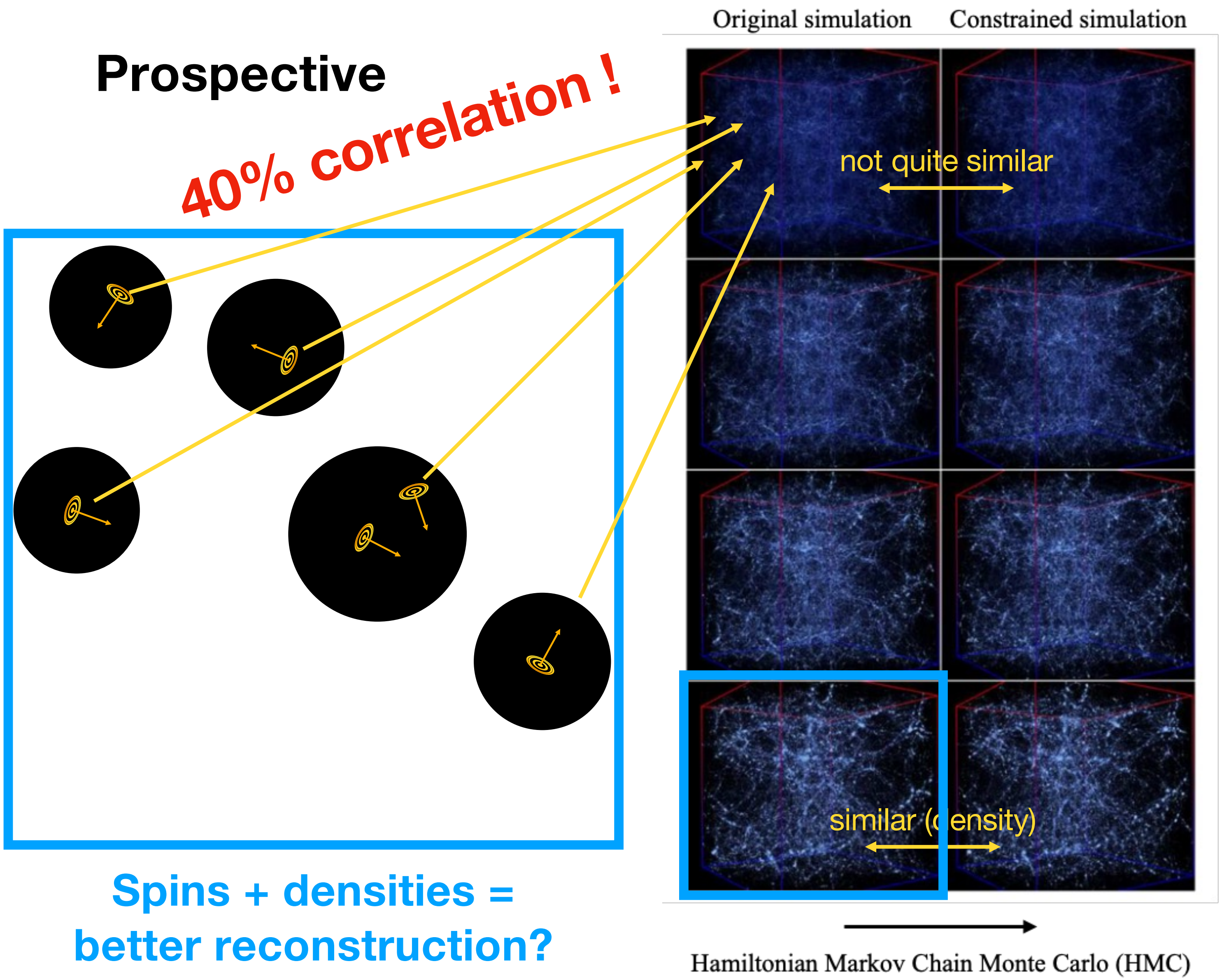
Huiyuan Wang+, 2014, 2016

Original simulation Constrained simulation



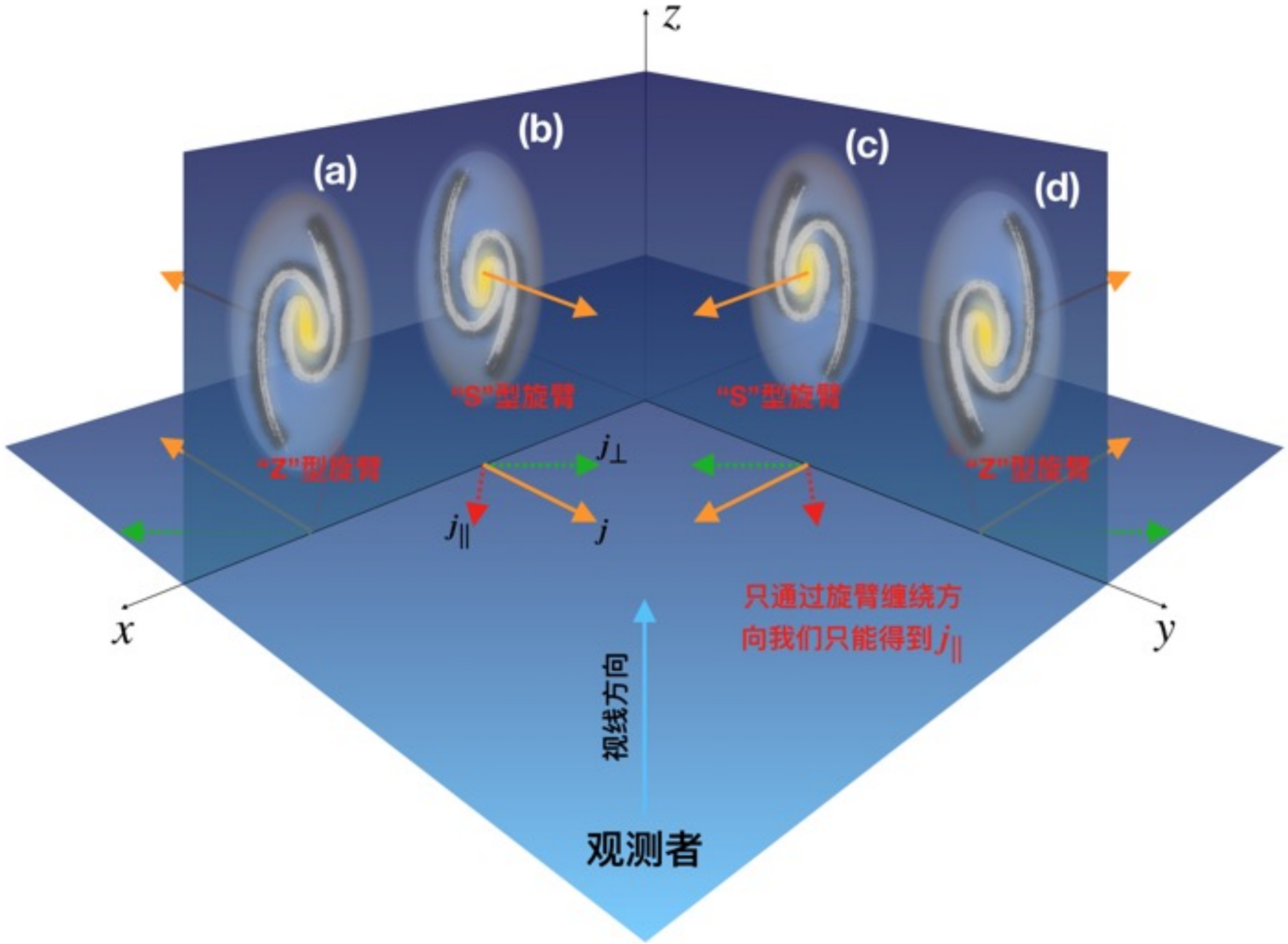
Hamiltonian Markov Chain Monte Carlo (HMC)

Prospective

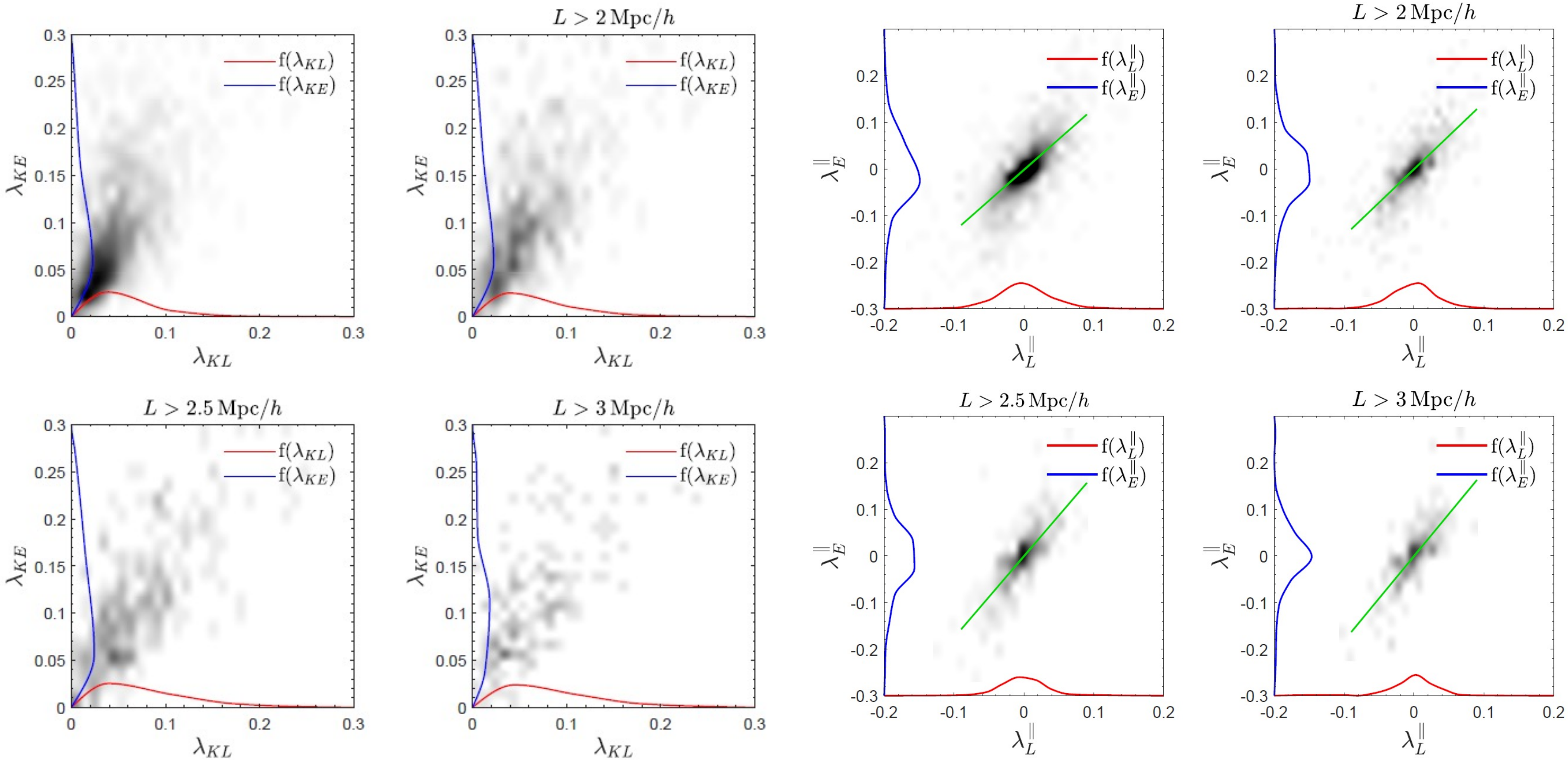


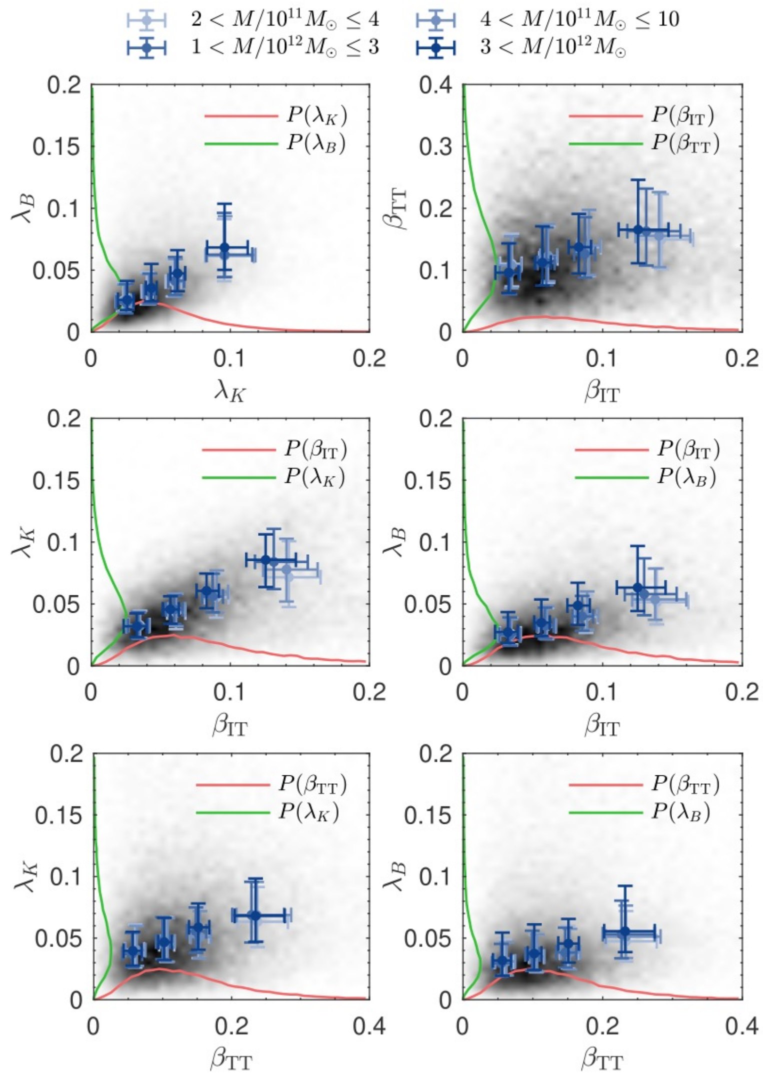
Spins + densities = better reconstruction?

Appendix


z
(a)
(b)
(c)
(d)
"S"型旋臂
"S"型旋臂
"Z"型旋臂
"Z"型旋臂
$j_\perp$
$j_\parallel$
j
x
y
只通过旋臂缠绕方
向我们只能得到$j_\parallel$
视线方向
观测者

Appendix



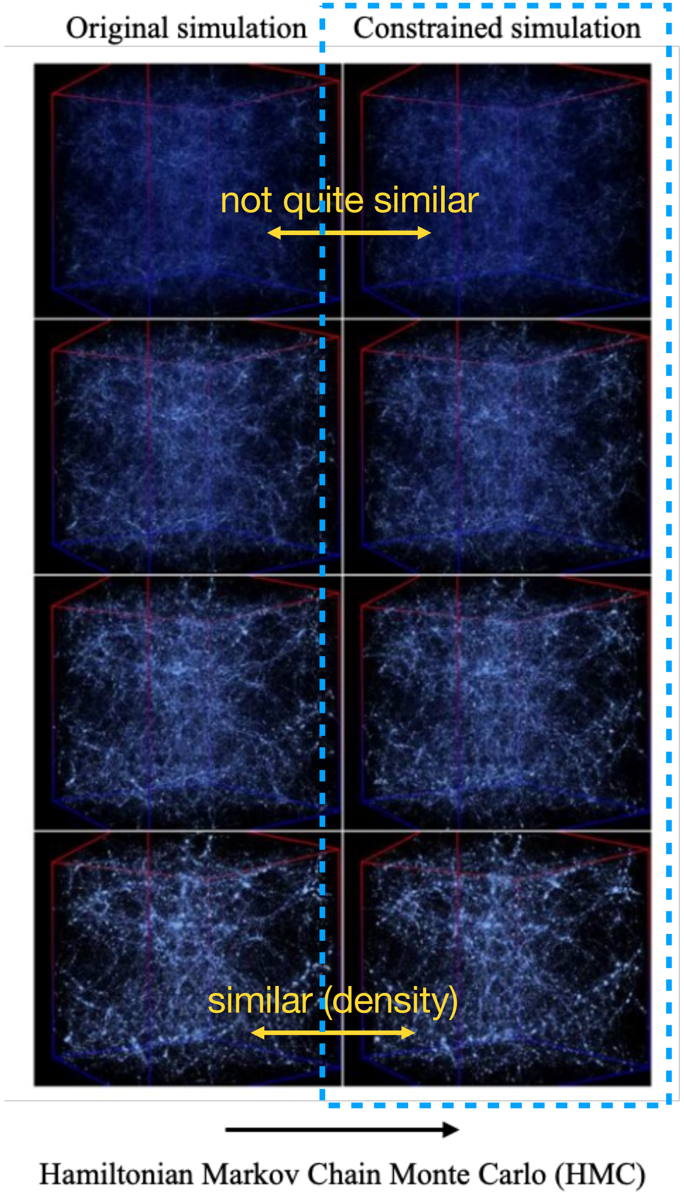


$2 < M/10^{11}M_\odot \leq 4$
$4 < M/10^{11}M_\odot \leq 10$
$1 < M/10^{12}M_\odot \leq 3$
$3 < M/10^{12}M_\odot$
$P(\lambda_K)$
$P(\lambda_B)$
λ_B
λ_K
$P(\beta_{IT})$
$P(\beta_{TT})$
β_{TT}
β_{IT}
$P(\beta_{IT})$
$P(\lambda_K)$
λ_K
β_{IT}
$P(\beta_{IT})$
$P(\lambda_B)$
λ_B
β_{IT}
$P(\beta_{TT})$
$P(\lambda_K)$
λ_K
β_{TT}
$P(\beta_{TT})$
$P(\lambda_B)$
λ_B
β_{TT}

ELUCID
HMC method
Density reconstruction

Wang+, 2014, 2016

try



result