# 銀河スピン分布解析：
# 宇宙の渦度分布の分析から銀河形成史に迫る

家正則（国立天文台）、福本英也（放送大）、八木雅文（国立天文台）

- 写真乾板時代からTomo-e GozenによるTime Domain Astronomyへの見事な変革ぶり、お祝い致します。
- 本テーマは今回の主流テーマから外れていますが、Palomar Schmidt Altas から始まった研究ということで紹介させてください。



Basic Question: Do galaxies spin randomly?

（1）Scalar Density Perturbation： CMB, Galaxy Distribution
Vector Field Perturbation: Vortex Distribution

（2）Theoretical Scenarios of galaxy spin
(a) Primordial Swirl, (b) Pan-cake Shock, (c) Tidal Torque,
(d) ΛCDM fluctuation

（3）Observational Test Methods
(a) galaxy axis ratio distribution, (b) position angle distribution
(c) Spin Parity distribution

（4）S/Z Database
SDSS, Pan Starrs, DES, ESO DSS, HSC, => Human＋AI Classification of S/Z

**（5）Formalism of dipole analysis and Early results on Local Universe disproving Shamir's papers.**

**(Iye, Yagi & Fukumoto, 2021, ApJ 907,123)**

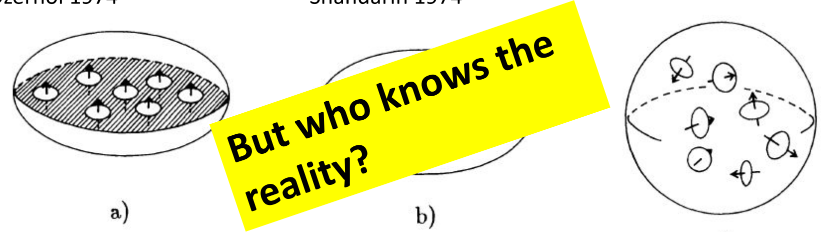


# （1）Cosmic vortex field: Observations and Theories

(a) Primordial Whirl
Weizsaecker 1951
Gamow 1952
Ozernoi 1974

(b) Pan cake collapse
Zeldovich 1978
Doroshkevich 1973
Shandarin 1974

(c) Tidal torque
Peebles 1978
Barnes Efstathiou 1987




a) b) c)

Modern Standard
(d) ΛCDM Structure Formation
Random Gaussian,
Harrison-Zel'dovich spectrum

cluster-galaxy tidal force
galaxy-galaxy tidal force
Orbital mixing



## Search for Large Scale Anisotropy in Spin Parity Distribution of Galaxies

- Anisotropy in scalar density : CMB〈z=1100〉, Galaxy Distribution（z=0~1）
  ＝＞ Constraint on Cosmic Expansion Model, Galaxy Formation Scenario
- Anisotropy in vector field : Vorticity field (z=0~1)
  ＝＞ Structure Formation Scenario
- ● Galaxy Spin Vector Field（HSC, PanSTARRS)
  ＊ Complementary and more robust to studies using distributions of the axis ratio and/or the position angle

## (1) S/Z Spiral Winding

not "Snyaev-Zeldovich"

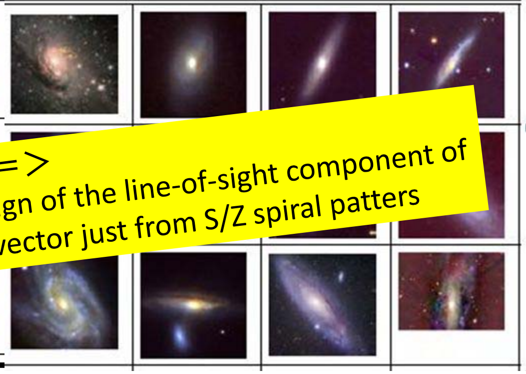
S


Z


## "Corroborative Evidence for Trailing Spirals"
### ー 146 Spiral Galaxiesー
論文I ： Iye, Tadaki, Fukumoto 2019: ApJ, 886, 133.

**Table 1.** Observationally confirmed spin parity of spiral galaxies

| ID | S/Z Side | Dark Side | Appr. | T/L | Image1 | Image2 | Image3 | Image4 |
|---|---|---|---|---|---|---|---|---|
| Circinus Galaxy | S | SE | NE | T | | | | |
| IC1683 | Z | W | N | T | | | | |
| IC1755 | S | SW | SE | T | | | | |
| IC2101 | S | NE | NW | T | | | | |
| IC5376 | Z | W | N | T | | | | |
| MCG-02-02-030 | Z | [illegible] | [illegible] | [illegible] | | | | |
| NGC224 | S | NW | SW | T | | | | |
| NGC247 | S | E | N | T | | | | |



All the spirals are Trailing! => Enables identification of the sign of the line-of-sight component of the spin angular momentum vector just from S/Z spiral patters



## Dipole anisotropy (??) in Local Super Cluster

Shamir(2017) published S/Z catalog of 160k SDSS spirals.

He claimed to find 5σ anisotropy.

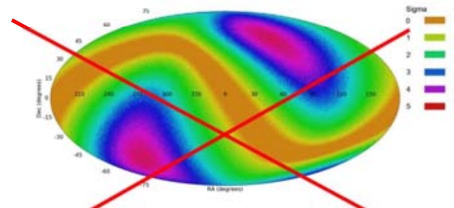


**Fig. 5.** The σ of the likelihood of a dipole axis of SDSS galaxies in different (α, δ) combinations

重大な結果なので独自に彼のデータを解析してみたら・・・

Iye et al. (2021) found serious data flaw of Shamir's catalog and denied anisotropy.

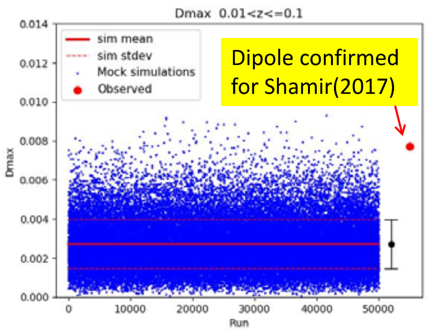
一方で、 Galaxy Zoo data of 20k spirals (z<0.10) shows 7 σ anisotropy？ (Fukumoto +2021 in prep).

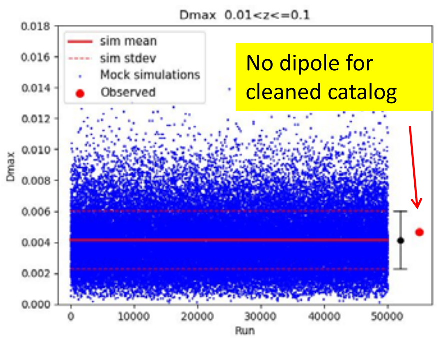


## 論文 III. Dipole Analysis of the Distribution of SDSS Spirals with 3D Random Walk Simulations
Iye, Yagi & Fukumoto (2021) ApJ 907, 123.

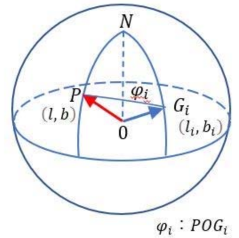
Developed a formulation to quantify dipole strength calibrated with 3D random flight (Chandrasekhar 1943!)
Confirmed Shamir(2017) catalog shows 4σ dipole anisotropy (left)!!!

But found a serious duplication of data entry. 160k sample=>75k sample
After removing the duplication, dipole has gone (right).
Shamir(2020) still publishes dipole finding(Shamir2020).






Formula to evaluate dipole signal

$$D(P) = \Sigma P \cdot G_i / N = \Sigma h_i \cos\varphi_i / N$$

$$h_i = \begin{cases} -1 & (S_{wise}) \\ 0 & (no\_spiral) \\ 1 & (Z_{wise}) \end{cases}$$

N 銀河数

3D random flight (Chandrasekhar 1943)

$$\overline{D}_{max} = \frac{\sqrt{2}\Gamma(2)}{\sqrt{3N}\Gamma(3/2)} = \frac{2\sqrt{2}}{\sqrt{3\pi N}} \sim \frac{0.921}{\sqrt{N}}. \quad (4)$$

The associated standard deviation from this expected mean distance is given by

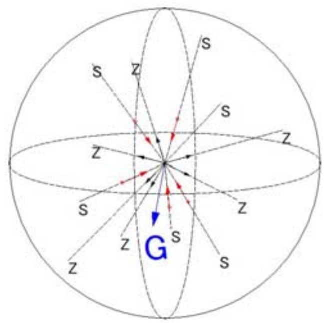
$$Stddev = \sqrt{\frac{2[\Gamma(3/2)\Gamma(5/2) - \Gamma(2)^2]}{3\Gamma(3/2)^2 N}} = \sqrt{\frac{3\pi - 8}{3\pi N}} \sim \frac{0.389}{\sqrt{N}}. \quad (5)$$

Required sample N to detect residual dipole signal p at s-sigma level

$$N \geq \left(\frac{0.921(1-p)(1+s)}{0.5p}\right)^2 \quad (8)$$

If random

$h^i$ = +1(Z-wise)
-1(S-wise)




G: N step 3D random flight

## 銀河分布の異方性をスピン分布の異方性解析にあたり考慮した解析結果

| Red Shift | $D^{obs}_{max}$ | $l^{obs}_{max}$ | $b^{obs}_{max}$ | $mean$ | $stddev$ | $\sigma$ | $mean^{local}$ | $stddev^{local}$ | $\sigma^{local}$ | $mean^{iso}$ | $stddev^{iso}$ | $\sigma^{iso}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $z \leq 0.01$ | 0.0147 | 331 | -13 | 0.0234 | 0.0110 | -0.80 | 0.0179 | 0.0073 | -0.044 | 0.0185 | 0.0078 | -0.49 |
| $z \leq 0.02$ | 0.0189 | 74 | -83 | 0.0112 | 0.0052 | 1.49 | 0.0127 | 0.0059 | 1.05 | 0.0141 | 0.0059 | 0.81 |
| $z \leq 0.03$ | 0.0144 | 44 | -80 | 0.0067 | 0.0031 | 2.44 | 0.0083 | 0.0035 | 1.63 | 0.0086 | 0.0036 | 1.59 |
| $z \leq 0.04$ | 0.0079 | 110 | -79 | 0.0050 | 0.0023 | 1.26 | 0.0068 | 0.0029 | 0.39 | 0.0067 | 0.0028 | 0.43 |
| $z \leq 0.05$ | 0.0086 | 170 | -76 | 0.0041 | 0.0019 | 2.36 | 0.0056 | 0.0023 | 1.33 | 0.0054 | 0.0023 | 1.43 |

$\sigma$ は従来法評価方法による評価結果

$\sigma^{local}$ は2千万回のシミュレーション方法による評価結果

$\sigma^{iso}$ はランダムフライトモデル方法による評価結果

z ≦0.03と z ≦0.05の評価結果に注目すると

従来の評価方法では、$\sigma$＝2.44、2.36とやや有意性があるように見える。

新しい方法方法では、 $\sigma^{local}$＝1.63、1.33、 $\sigma^{iso}$＝1.59、1.43となり、2つの方法はよく一致しており、双方ともに有意性は見られない。

14/12



- 3D distribution of 280k PanStarrs spirals studied (z<0.05) (Fukumoto+ 2021)

S/Z Catalog of Dark Energy Survey samples by deep learning for the southern sky (Umayahara+2022, in prep.)

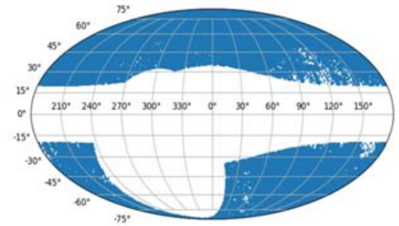
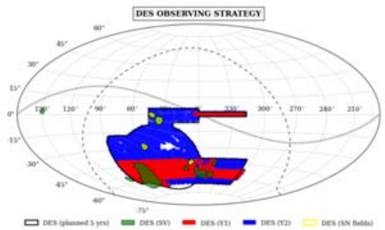


図３ $S_{wise}$ と $Z_{wise}$ 銀河の銀河座標での分布図、銀河は不均一に分布している






# (2) Observables of spin vectors

- Galaxy axis ratio distribution
- Galaxy position angle distribution

(MacGillivray et al 1982, Helou 1984, Trujillo et al 2006, Lee & Erdogdu 2006)

Error ambiguity

- Spiral winding sense S/Z

＝＞ 1 bit info but robust

（Thompson 1973, Borchkhadze&Kogoshvili 1976, Yamagata et al 1981, Iye ＆ Sugai1991, Sugai & Iye 1995)

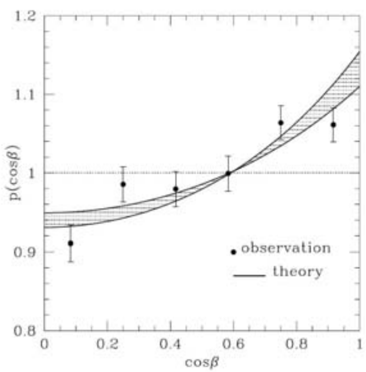



Fig. 3.—Probability density distribution of the cosines of the angles between the spiral galaxy's spin axes and the intermediate principal axes of the local tidal tensors. The dots with Poisson errors represent the observational results, the solid lines correspond to the analytic predictions, and the dotted line represents the case of no correlation. The shaded area represents 1 σ of the correlation parameter. A total of 12,347 spiral galaxies with all morphological types are used.

Spin-filament axis correlation



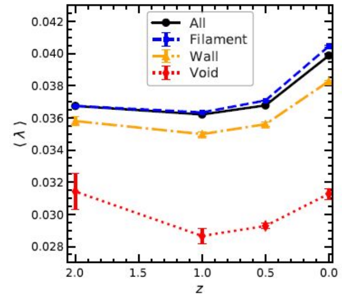
- **Veena et al(2020)** arXiv:2007.10365v1

"The Cosmic Ballet III: halo spin evolution in the cosmic web"

・Analysis of ΛCDM galaxy formation simulations

・**specific spin λ increases toward z=> 0, especially at filament regions**

・**spin axis tends to be orthognal (massive haloes) parallel (low mass haloes) to the filament axis.**



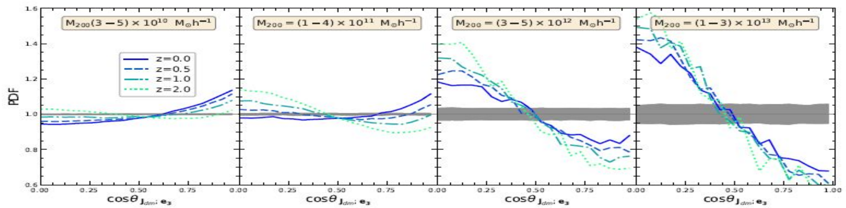



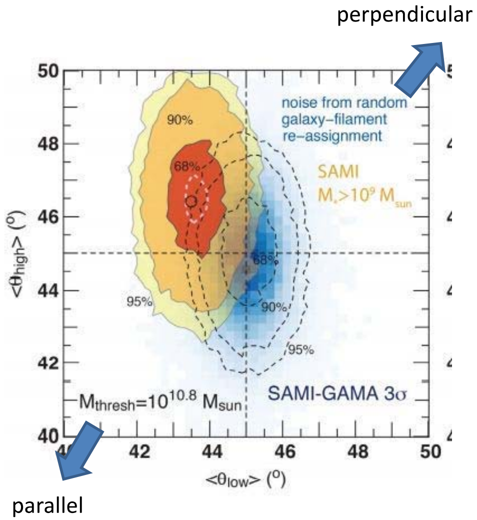
**Figure 6. PDF of the halo spin–filament alignment angle:** Each panel shows the distribution of the spin–filament alignment angle for haloes in different mass bins, with halo mass increasing from left to right (see upper text label in each panel). Coloured lines correspond to different redshifts (see the legend in the left-most panel). The grey horizontal line and its associated shaded region show respectively the mean expectation and the 68 percentile confidence interval when no alignment is expected. Low-mass haloes have an excess of parallel orientations (i.e. PDF is highest at cos θ = 1), while high-mass ones have a propensity for perpendicular orientations (i.e. the PDF is highest at cos θ = 0). The transition halo mass between the two regimes varies with redshift.

# spin-filament alignment

Welkar+2020
Massive disks are perpendicular,
while light disks are parallel,
to the local filament axis.

Indicates early spin build up.
Question to tidal torquing.

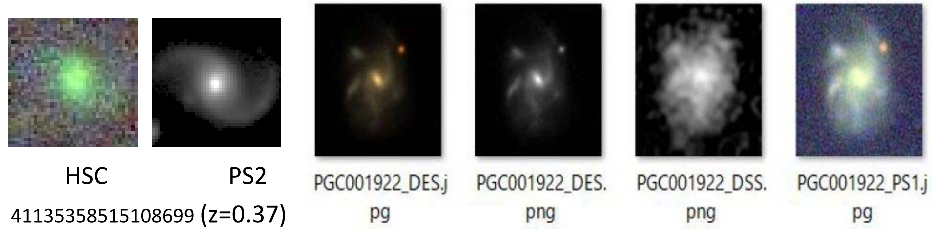
=>
Can OUTAP group make independent original analysis?





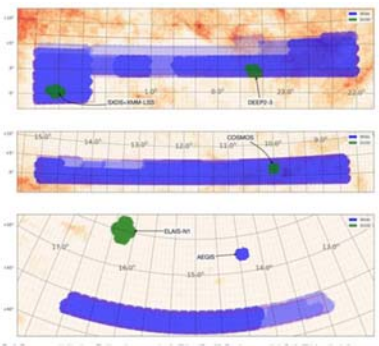

# Galaxy Image Archives

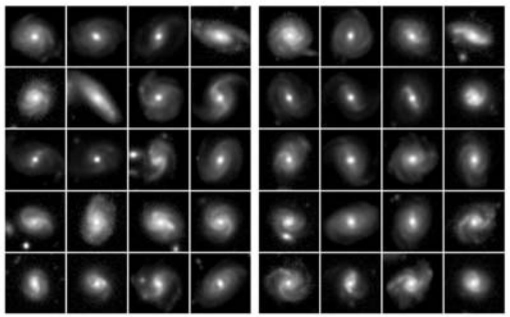
| | HSC | DES | PanStarrs | SDSS |
|---|---|---|---|---|
| Depth | **r<26.5** | R<24.4 | r<23.2 | r<20.8 |
| redshift | <0.8 | <0.1 | <0.1 | <0.05 |
| Area(deg^2) | 456 | 5,000 (**South**) | **30,000** | 14,055 |






## HSC DR2 80k spiral (z<0.8)についてS/Zを深層学習判定
## 論文II: Tadaki+ 2020 MNRAS 496, 4276





- 3D distribution of 500M HSC-DR3 galaxies

(Aihara+ 2021) to be studied.



まとめ

０． S/Z異方性解析（Sugai＆Iye 1995）、Galaxy Zoo（2007）

１。 渦巻きはTrailingであることを146個について確認（論文I: Iye＋2019）

２． HSCの渦巻き8万個のS/Z形態のAI判定（論文II: Tadaki＋2020）

３． ｚ＜0.05の279,258個の銀河を二人で独立目視判定。*S_wise* 24,405個、*Z_wise* 24,109個からなるスピン新カタログを作成した（論文IV: Fukumoto＋準備中）。

４。 Shamir(2017)で報告された双極子偏りは、彼のカタログのデータ重複が原因であることを確認した。双極子強度を、ランダムシミュレーション法と、３次元ランダムフライト法で、その有意度を校正した。赤方偏移0.05までの局所宇宙全体については、有意な双極子偏りは見られなかった。（論文III：Iye＋2021）。

５。 スピン分布の双極子強度のランダムシミュレーションによる有意性評価には、銀河分布の不均一性を考慮する必要があることを確認した（八木＋準備中）。

６。 一方で、Galaxy Zooの結果は有意な双極子偏りを示す。原因要調査。

７。 南天のDESサーベイ、HSC-DR3サーベイの銀河のスピン分布解析（フィラメント構造との関係他）を行う予定。