Galaxy scaling relations as distance indicators

by **Christoph Saulder**
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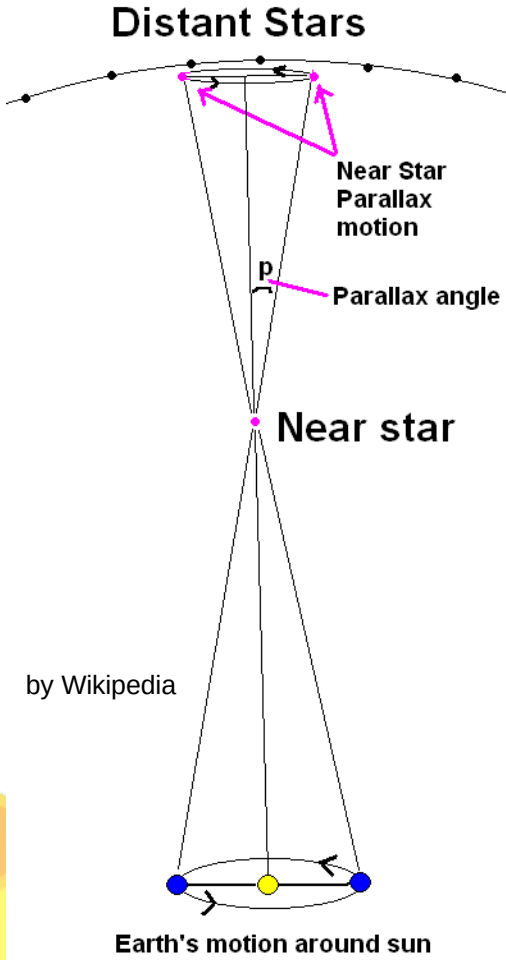
Measuring distances in the universe

Measuring distances in the universe

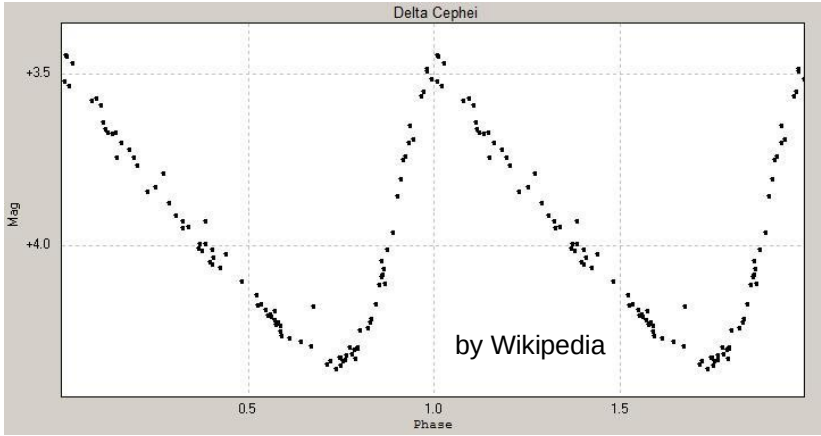
- Solar system:
  - direct measurements via Radar
  - Indirect measurements via Kepler’s laws
  - Transits and parallaxes
- Stars in the Milky Way
  - Parallaxes
  - Eclipsing binaries
  - Various types of variable stars

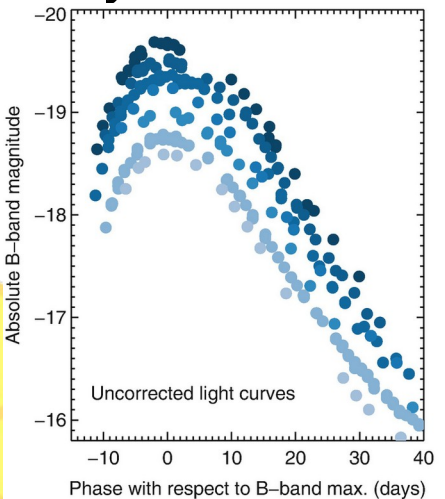


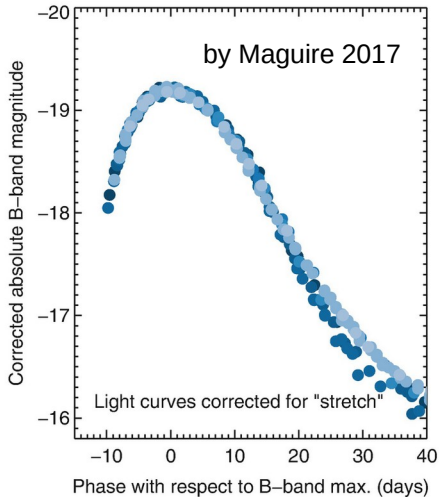
by Wikipedia

Measuring distances in the universe

- Extragalactic objects
  - Cepheids
  - Surface brightness fluctuations
  - Tip of the red giant branch
  - Planetary nebula/globular cluster luminosity function
  - Supernovae Type Ia







Measuring distances in the universe

- Extragalactic objects
  - Cepheids
  - Surface brightness fluctuations
  - Tip of the red giant branch
  - Planetary nebula/globular cluster luminosity function
  - Supernovae Type Ia
  - **Galaxy scaling relations:**
    - **Tully-Fisher relation**
    - **Fundamental plane**
    - **S_k-relation or complete kinematic models of galaxies**

Established galaxy scaling relations

- **Faber-Jackson relation**
- Kormedy-relation
- **D_n-σ relation**
- **Fundamental plane**
- Stellar mass fundamental plane

- **Tully-Fisher relation**
- Baryonic Tully-Fisher relation

- Sk-relation
- Universal Fundamental Plane

The fundamental plane (of early-type galaxies)

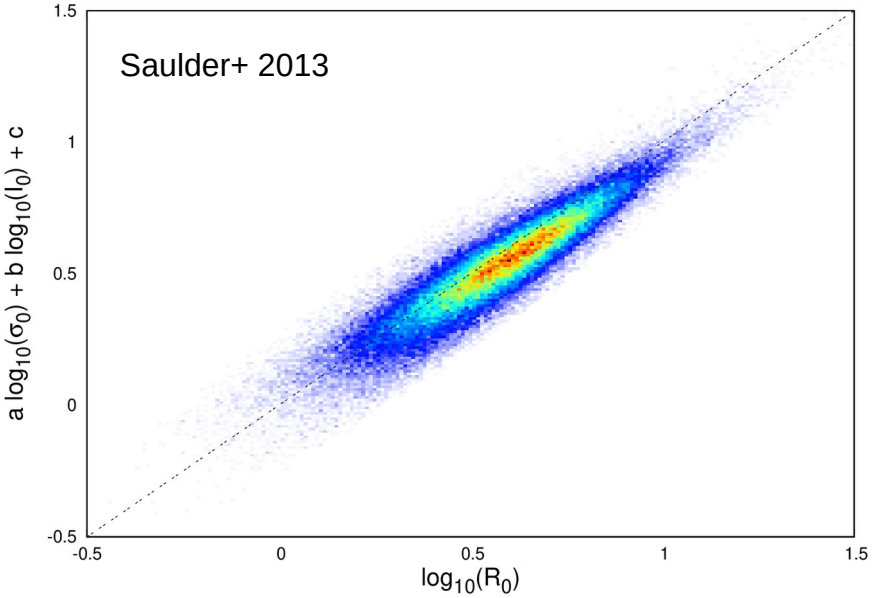
- Unification of previously established scaling relation

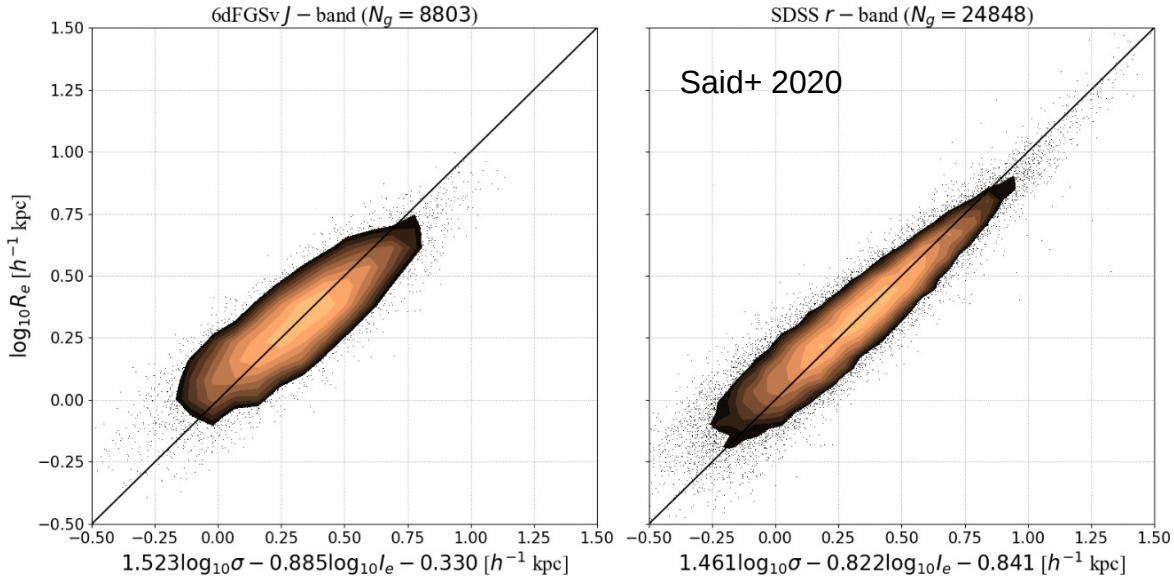
- Faber-Jackson relation: $L \sim \sigma^4$ (Faber&Jackson 1976)
- Kormendy relation: $\mu_e = a \log (R_e) + b$ (Kormendy 1977)
- D_n-σ relation: $\log(D_n) = a \log(\sigma_0) + b$ (Dressler+ 1987)

$$\rightarrow \log (R_e) = a \log(\sigma_e) + b\, \mu_e + c$$

(Dressler+ 1987 and Djorgovski&Davis 1987)

The fundamental plane



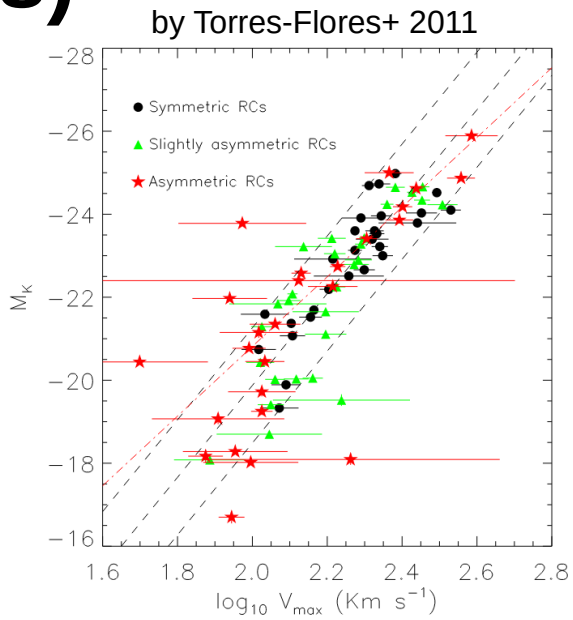


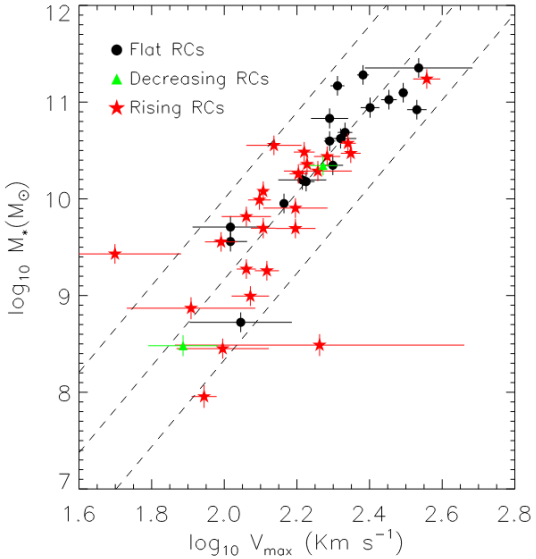
The Tully-Fisher relation(s) (of late-type galaxies)

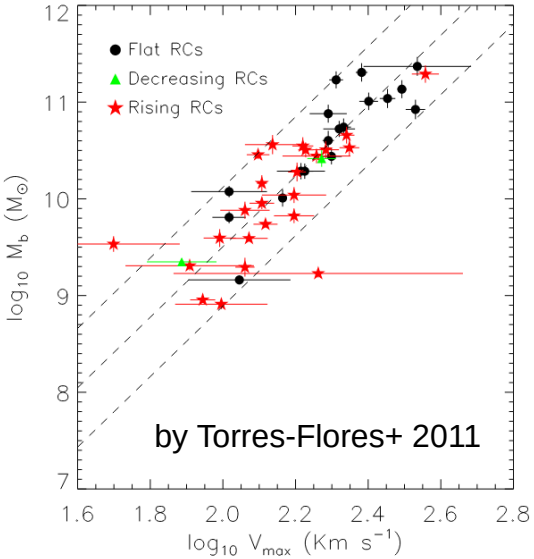
- $M_{abs} = b \log(V_{max}) + c$ (Tully&Fisher 1977)

- $\mathrm{Log}\ (M_{b/*}) = b \log(V_{max}) + c$ (McGaugh 2005)

by Torres-Flores+ 2011







by Torres-Flores+ 2011

The S_K-parameter

- $S_K^2 = K\, v_{rot}^2 + \sigma^2$
- Modified V_{rms}
- K depends on morphology, often set to ~0.5 be a good fit for all

- Scaling relations:
- S_K-relation: $\log(S_{0.5}) = a + b \log(M_*)$ (Kassin+ 2007)
- Universal fundamental plane:

  $\log(Y_e)=\log(S_{0.5}^2)-\log(I_e)-\log(R_e)+c$

  (Aquino-Ortíz+ 2020)

What makes it a redshift-independent distance indicator?

- Observable quantises: either photometric or spectroscopic with a clear (and mostly agreed upon) derivation
- All but one quantity are distance-independent (except maybe for evolutionary effects)
- No quantities that depend on redshift as a cosmological distance

The redshift traps

- Example 1: **K-correction:** redshift dependent correction of observed magnitude as the band shifts due to redshift (it doesn't care for the reason of the redshift)
  → "cosmological redshift"-independent
- Example 2: **surface brightness:** corrected for the cosmological dimming (Tolman-effect), depends on redshift, but physical effect directly from the theory → also fine
- Example 3: **stellar masses:** measured using spectroscopic or photometric templates, their value depend on the absolute magnitude, which required a distance (usually redshift based)
  → **cannot be used for distance indicators**

Why are the Tully-Fisher relation and the fundamental plane used in surveys?

Why are the Tully-Fisher relation and the fundamental plane used in surveys?

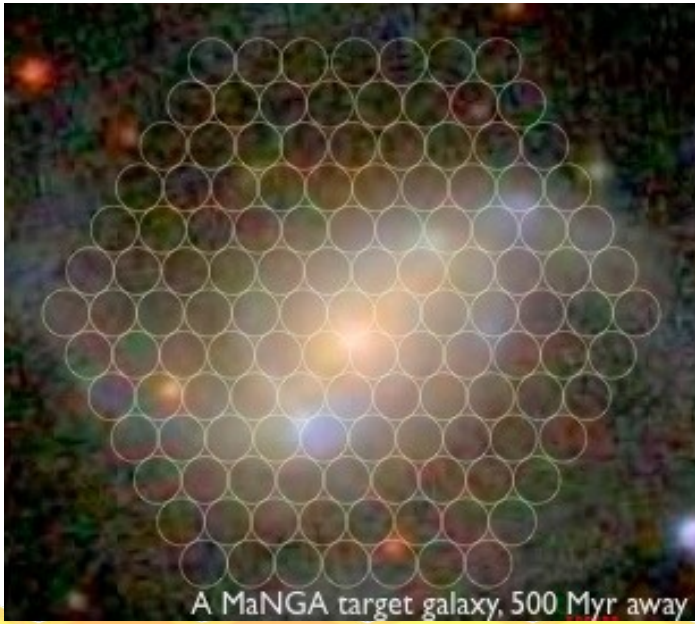
- **Easy to measure**

- Redshift surveys use fibre spectroscopy on galaxy centre any ways: if S/N is good enough
  → velocity dispersion σ obtained for free
- Long-slit spectroscopy for Tully-Fisher relation: relatively fast way to get rotation curves

- All other necessary parameters are already obtained by photometric surveys used for target selection

The age of integral field spectroscopy

- An increasing number of IFU surveys during the past decade:
- SAURON & ATLAS3D
- CALIFA
- SAMI
- MANGA
- MASSIVE
- …
- More than 15000 galaxies with IFU data



by SDSS

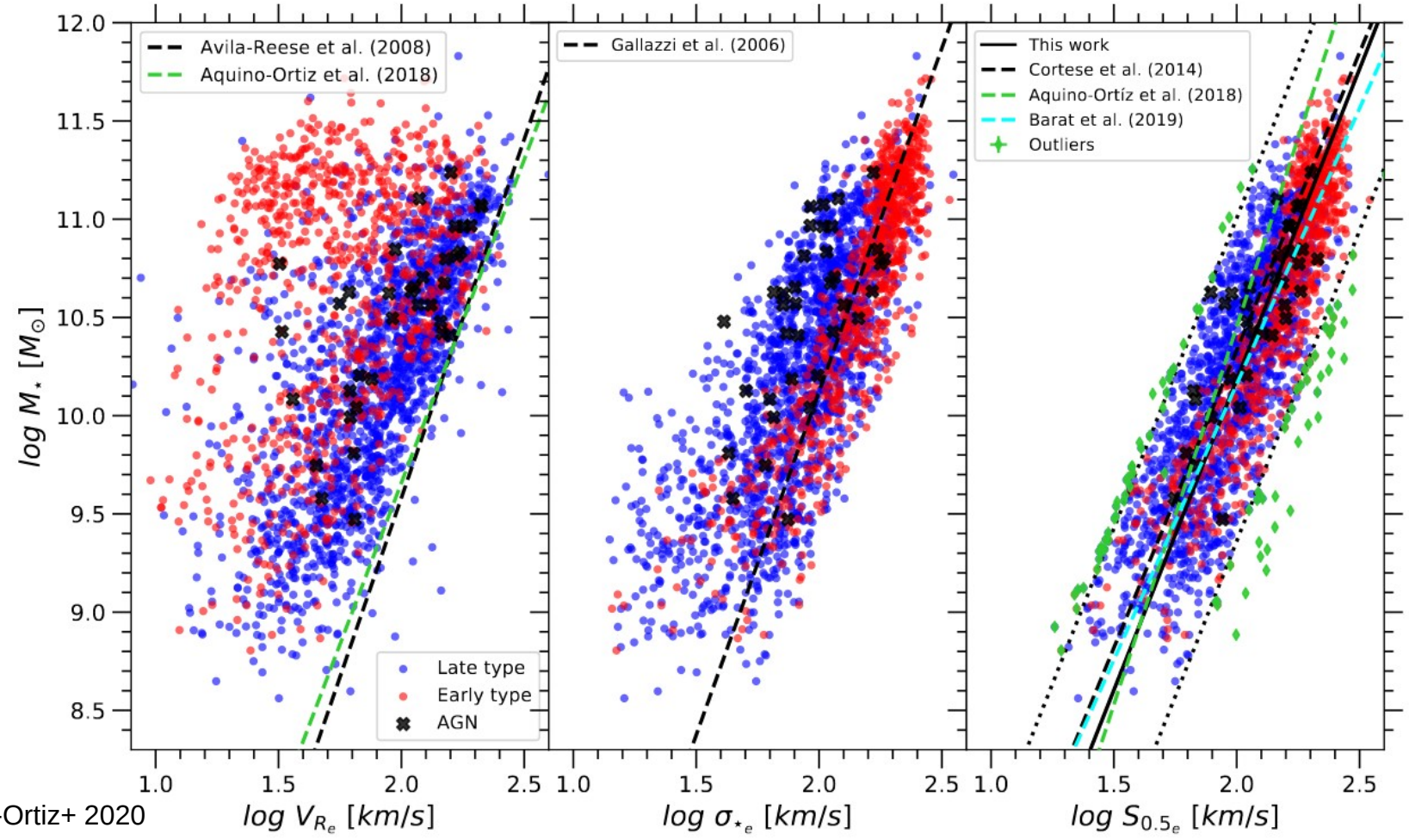
Kinematic measurements for better distance indicators

- Scaling relations use an estimate for dynamical mass from kinematics (rotational velocity or velocity dispersion)

- Adapting the SK-relation or Universal fundament plane as a distance indicator
- Alternatively: a more sophisticated estimate of dynamical mass

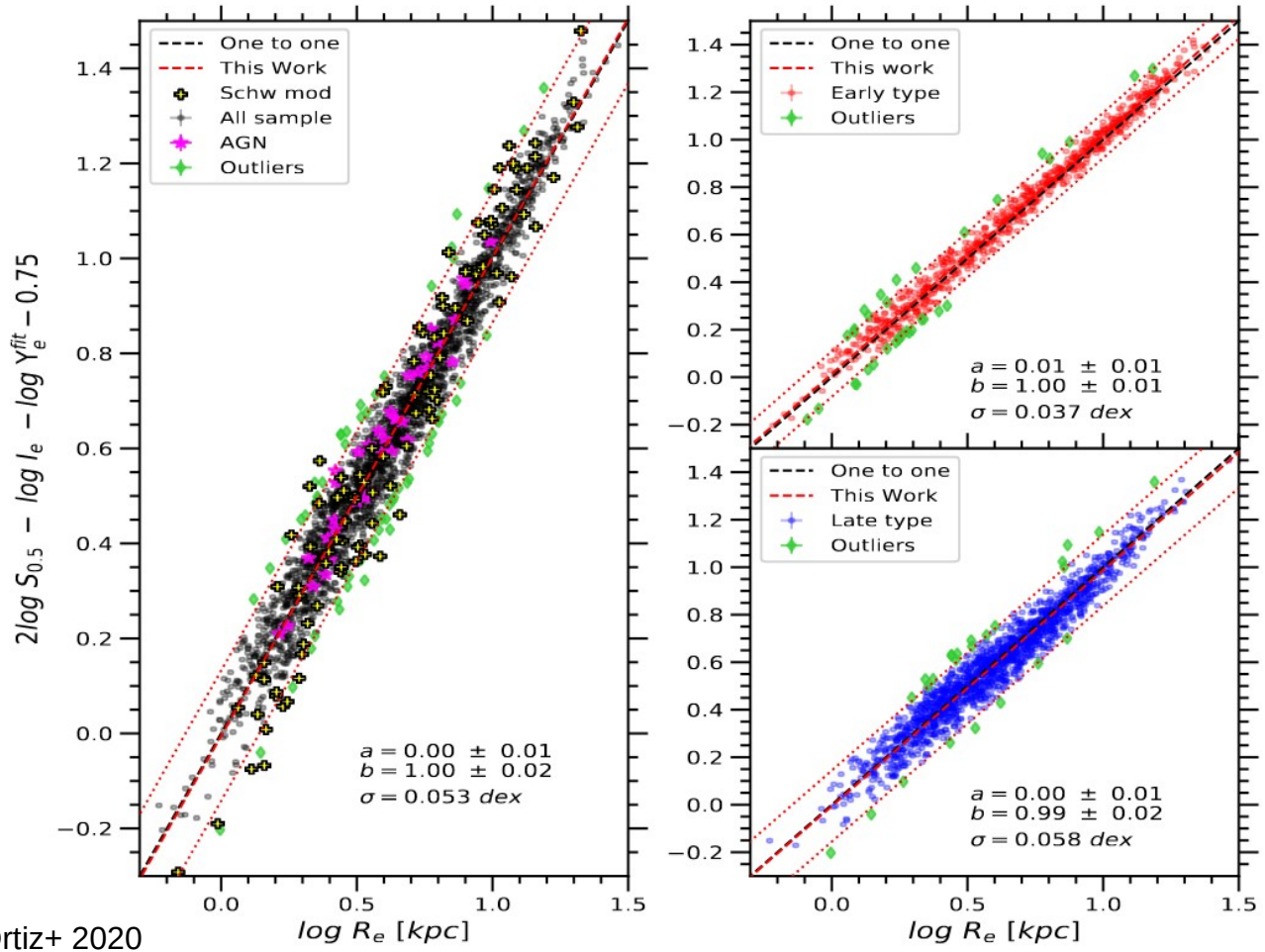
- Indirectly using stellar mass (or light) to dynamical mass ratio with scale radii

Independent of morphological type



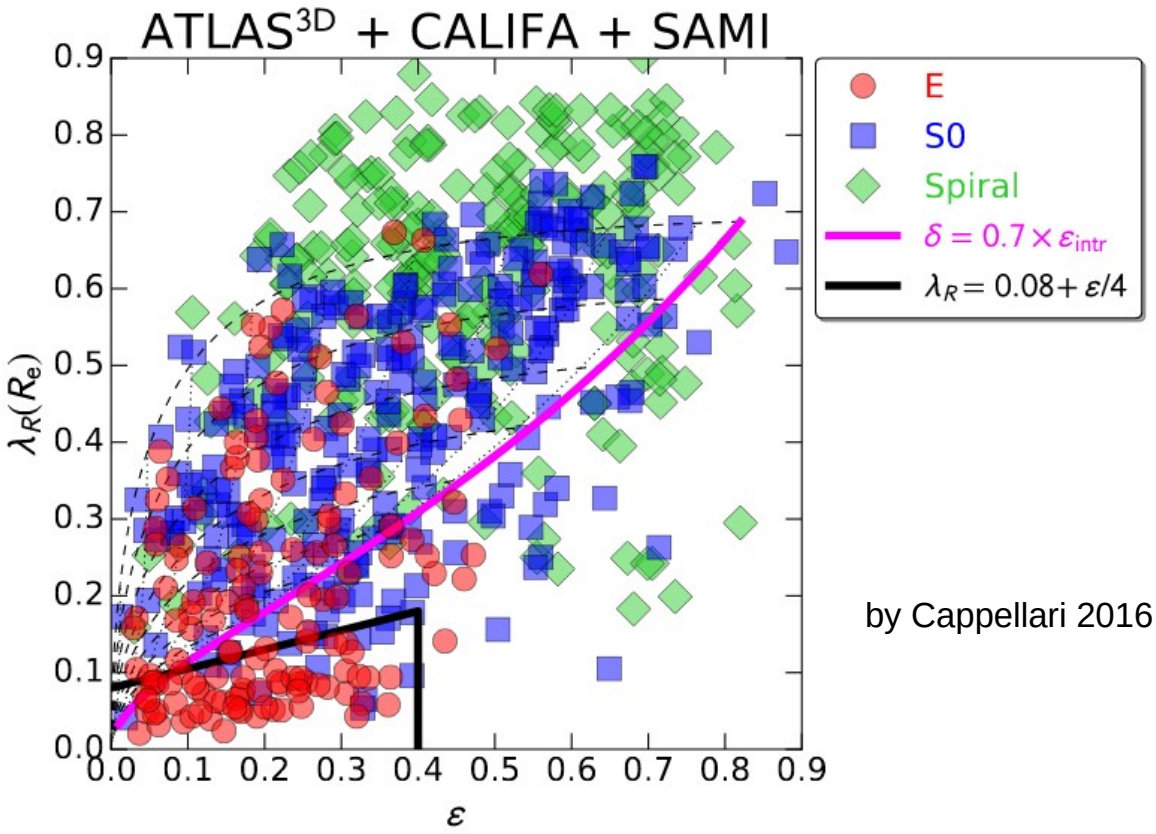
by Aquino-Ortiz+ 2020

Independent of morphological type

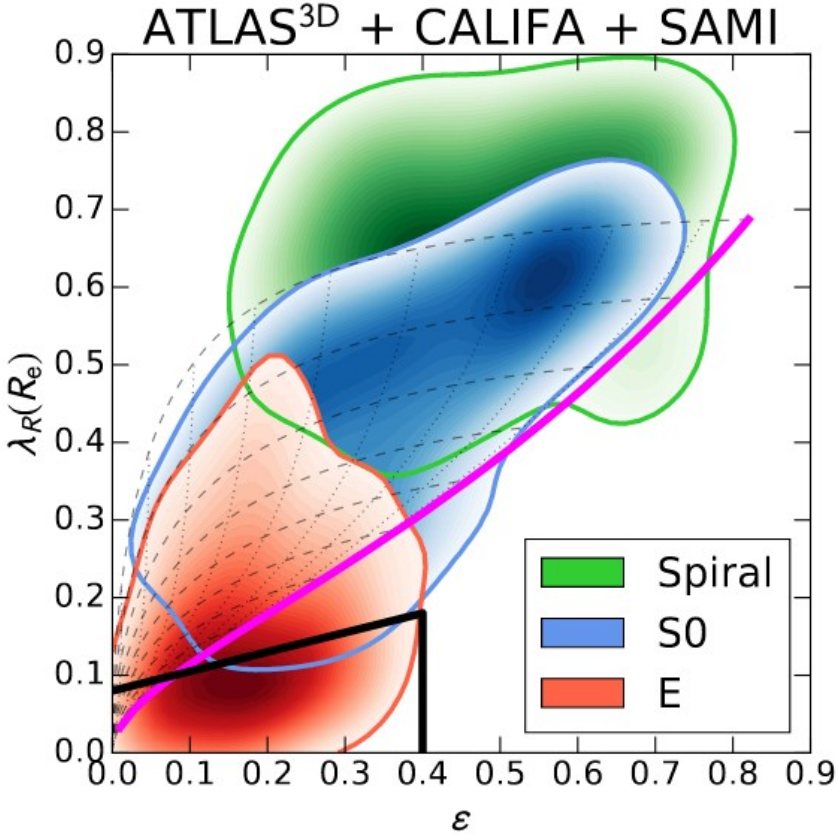


by Aquino-Ortiz+ 2020

What is the impact of the kinematic type?



by Cappellari 2016



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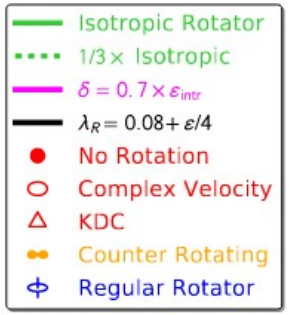

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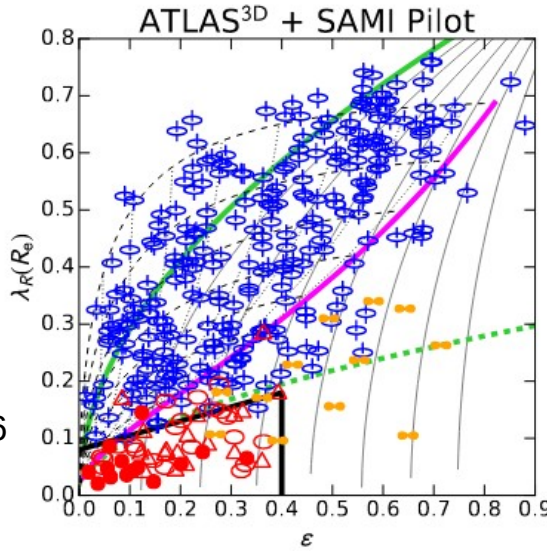
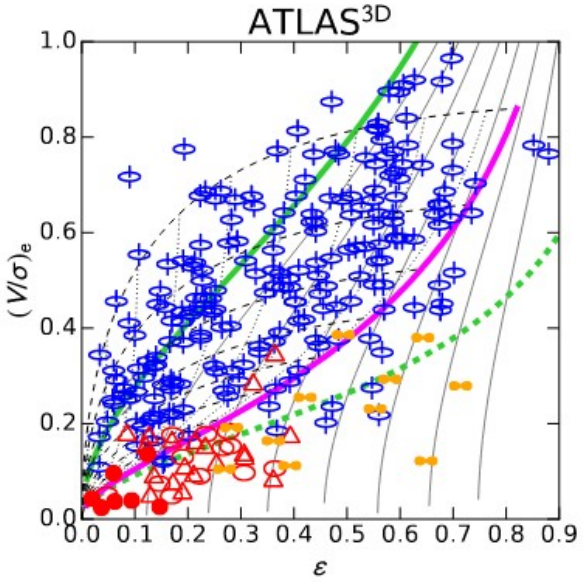
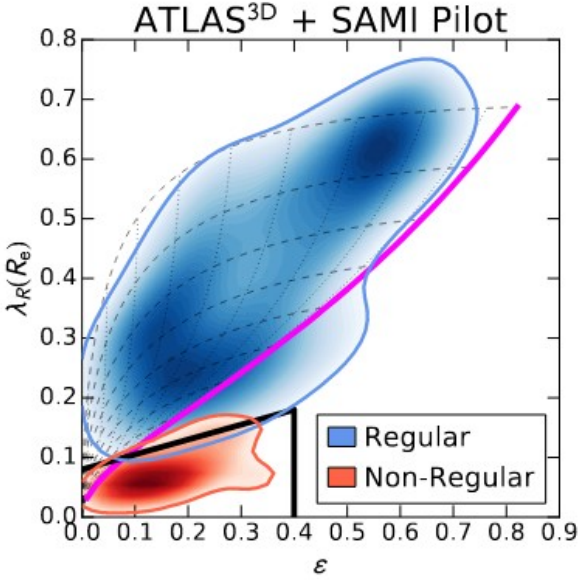


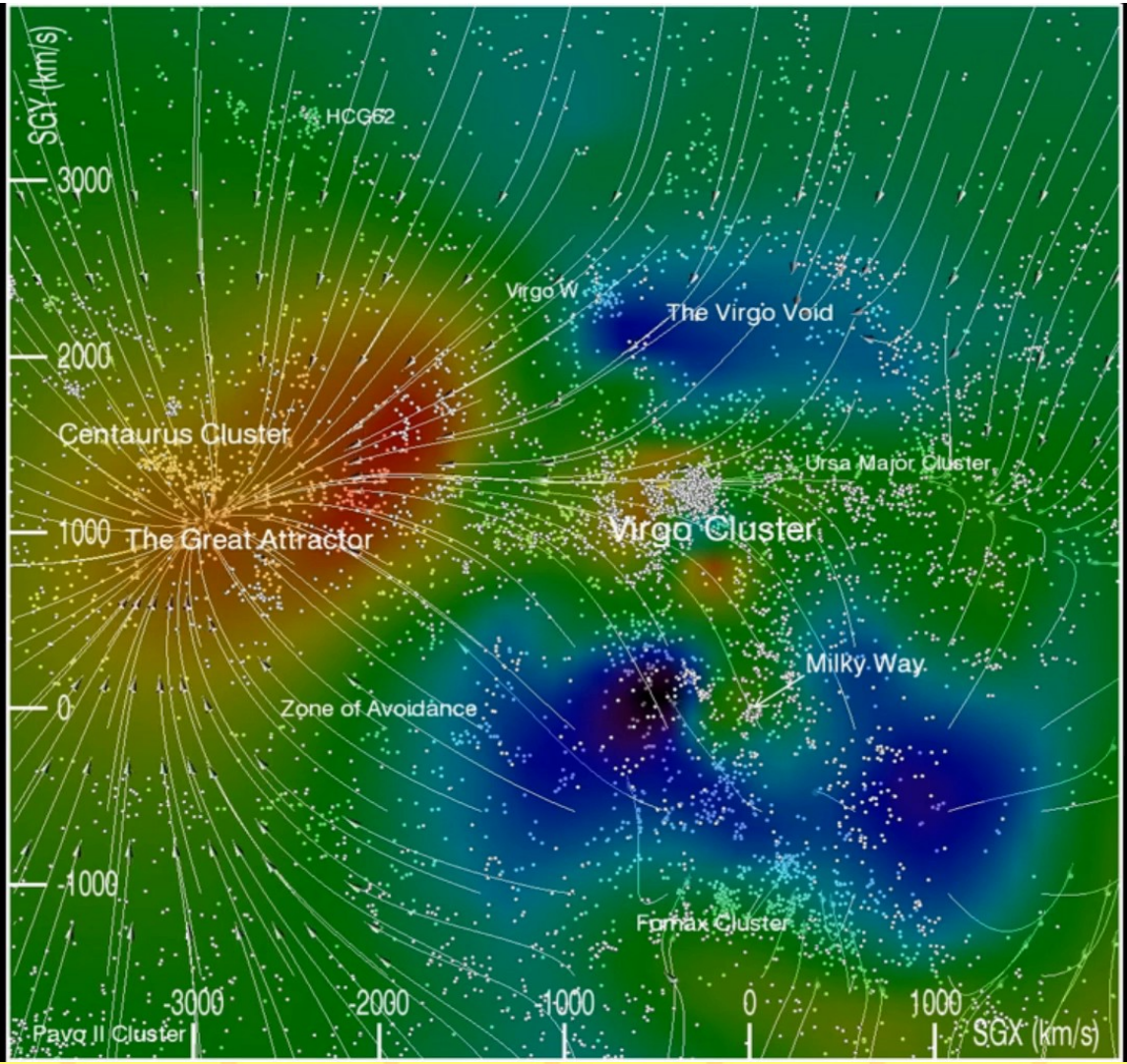




Cosmic Flows

- Collecting data from various existing surveys and methods
- Supplemented with additional observations
  (mostly Tully-Fisher relation)
- Current version: CosmicFlows-4
- Latest public version CosmicFlows-3 (Tully+ 2016)

- Peculiar motions field in the local universe

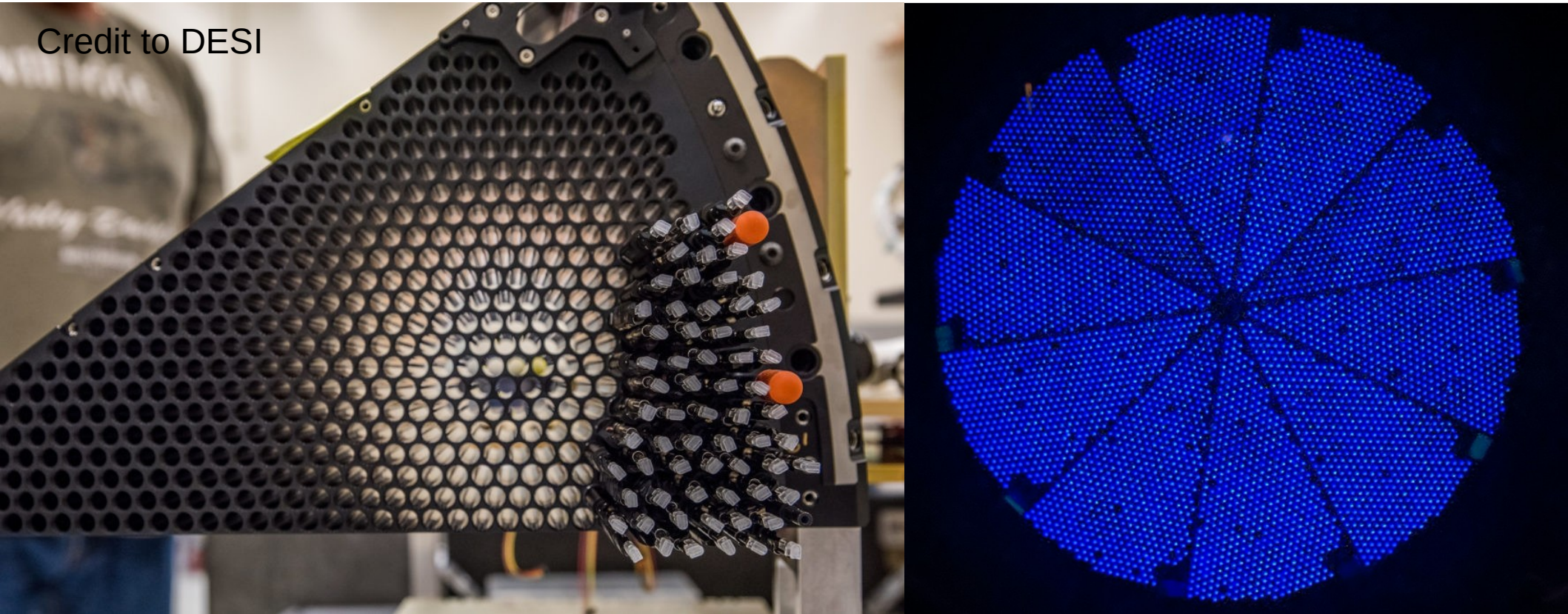

SGY (km/s)
3000
2000
1000
0
-1000
HCG62
Virgo W
The Virgo Void
Centaurus Cluster
Ursa Major Cluster
The Great Attractor
Virgo Cluster
Milky Way
Zone of Avoidance
Fornax Cluster
Pavo II Cluster
-3000
-2000
-1000
0
1000
SGX (km/s)

DESI

- Dark Energy Spectroscopic Instrument (survey)
- Ongoing spectroscopic survey
  - Survey validation (will become part of the Early Data Release, that will become public likely near the end of 2022) since March 2020 (including Covid related delays).
  - Main survey since May 2021
  - ~5 years in total
- Large footprint: ~14000 square degree
- DESI Legacy Imaging Survey DR9
  - Photometric survey for target selesction (grz+WISE)

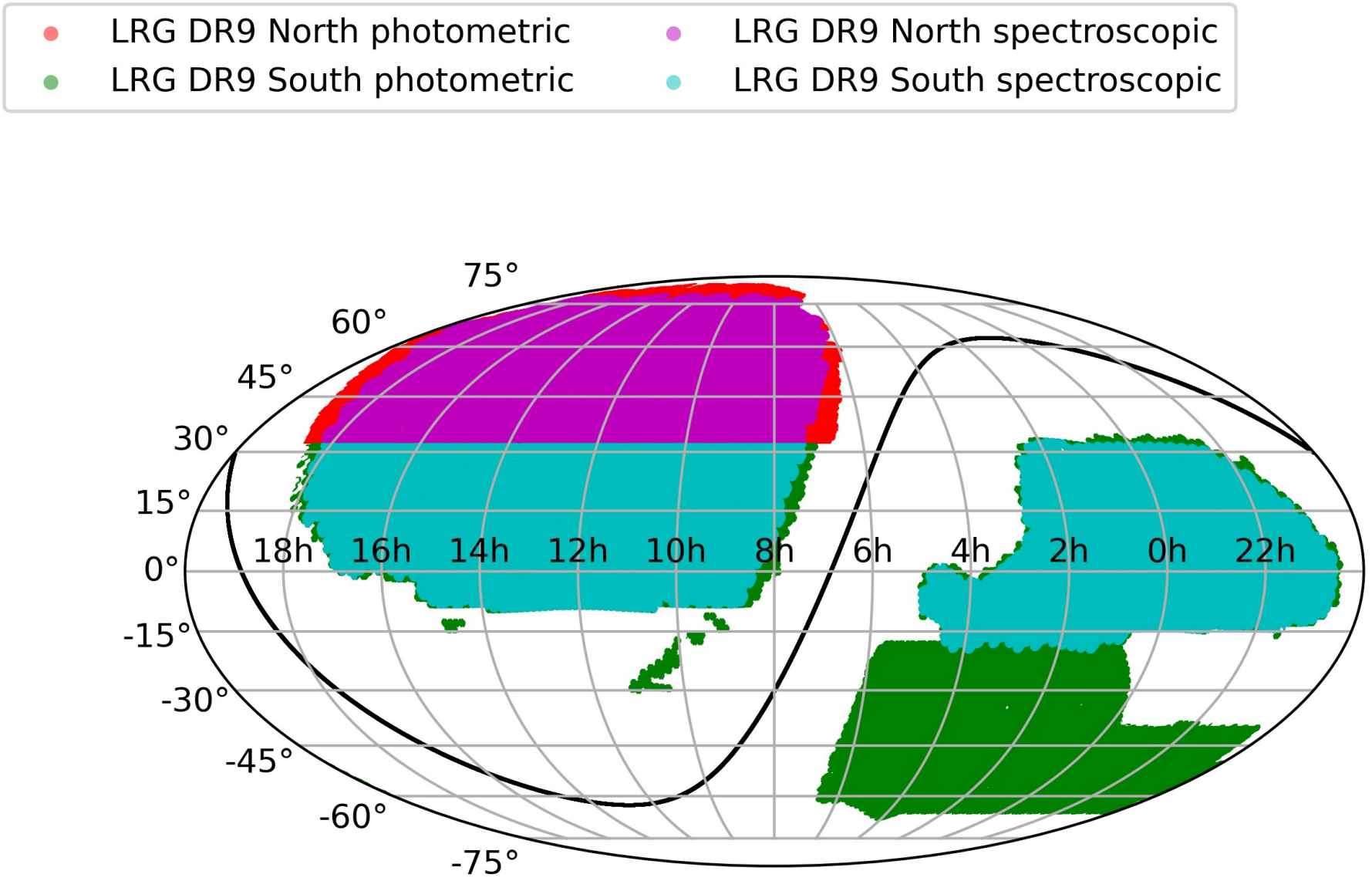
DESI focal plane layout

- 5000 fibres that move within a patrol radius (10 petal of 500 fibres)



Understanding DESI fibre assignment

- Fibres can move in patrol radius, many competing targets
- Multiple passes (up to 7), observations in dark time and bright time

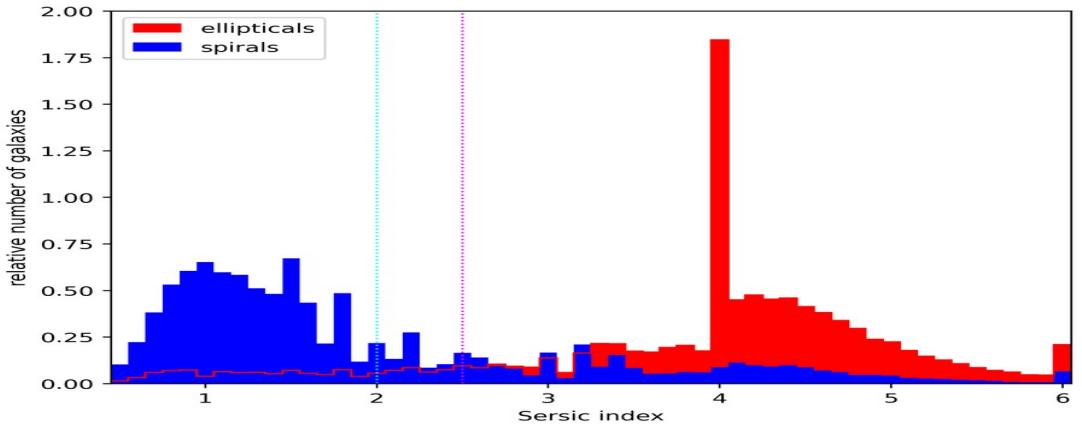

LRG DR9 North photometric
LRG DR9 North spectroscopic
LRG DR9 South photometric
LRG DR9 South spectroscopic
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
18h
16h
14h
12h
10h
8h
6h
4h
2h
0h
22h

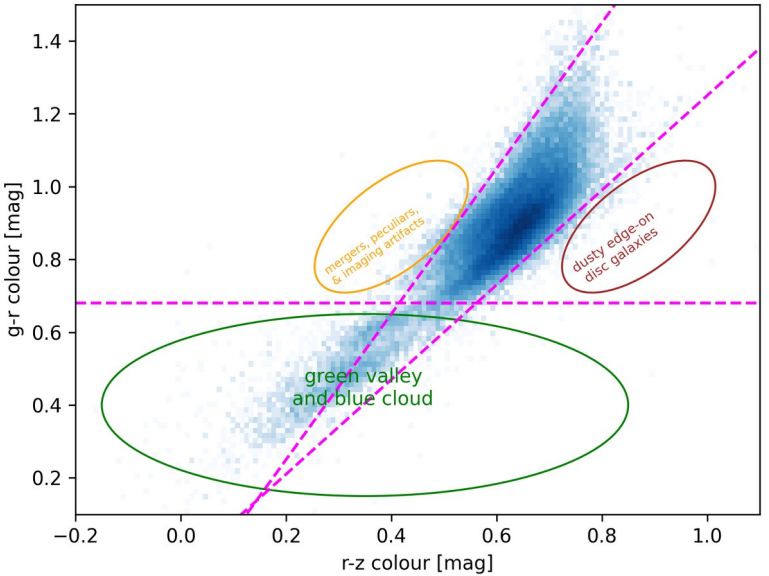
The DESI peculiar velocity survey

- Observations of fundamental plane galaxies (ETG) and Tully-Fisher relation galaxies (LTG)
- Target selection done using the DESI Legacy Imaging Survey DR9
- Secondary targeting programme: uses spare fibres for additional observations (FP during dark time and off-centre fibres for TF)
- ~200 000 fundamental plane distances and up to 50 000 Tully-Fisher relation distances by the end of the DESI survey (depending on selection and quality)
- Many test observations during Survey Validation

Target selection

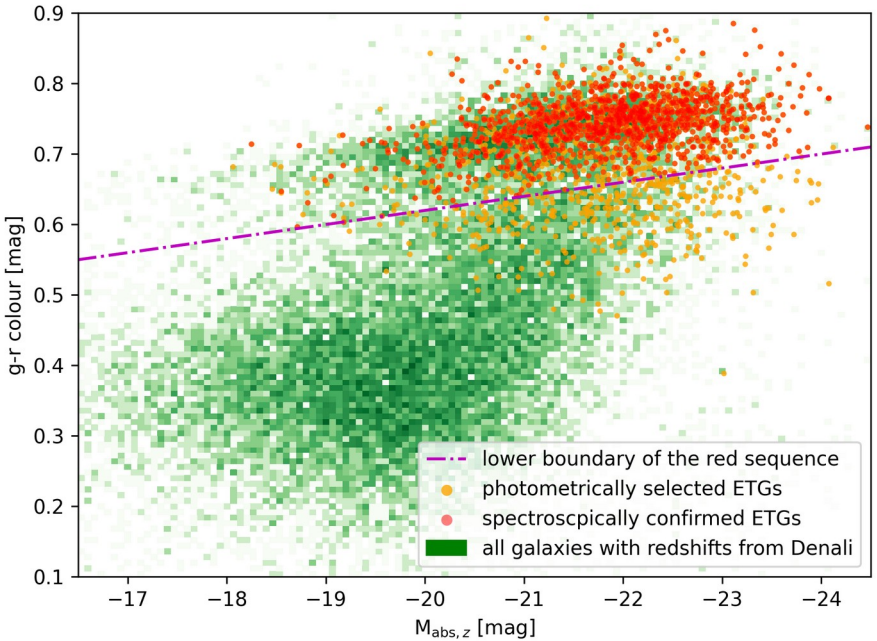
- Had to be done before start of spectroscopic observations
- Using DESI Legacy Imaging Survey DR9
- ETGs for FP and LTGs for TF-relation
- Truth catalogues from the Siena Galaxy Atlas and GalaxyZoo
- Colour cuts, inclination, photo-z, and profile fits (Sersic index)

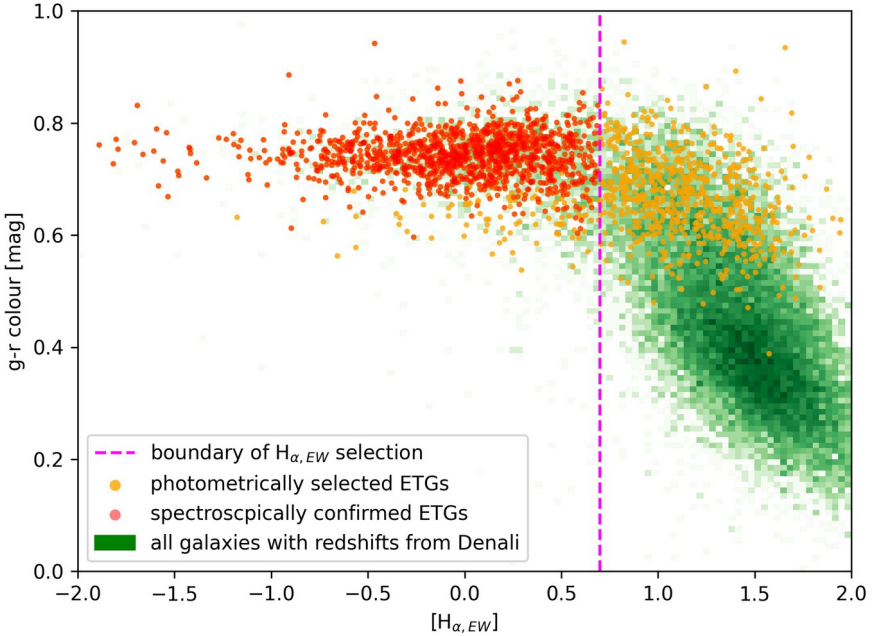




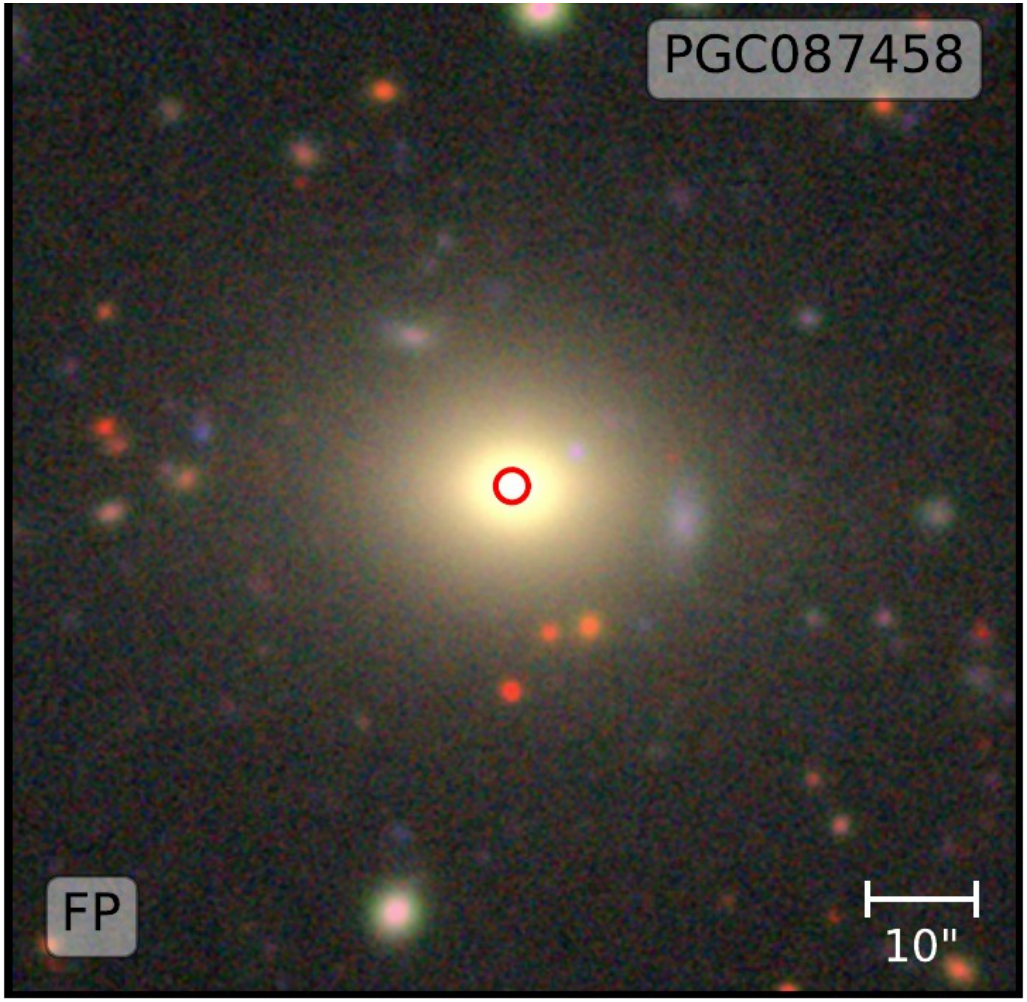
Target selection

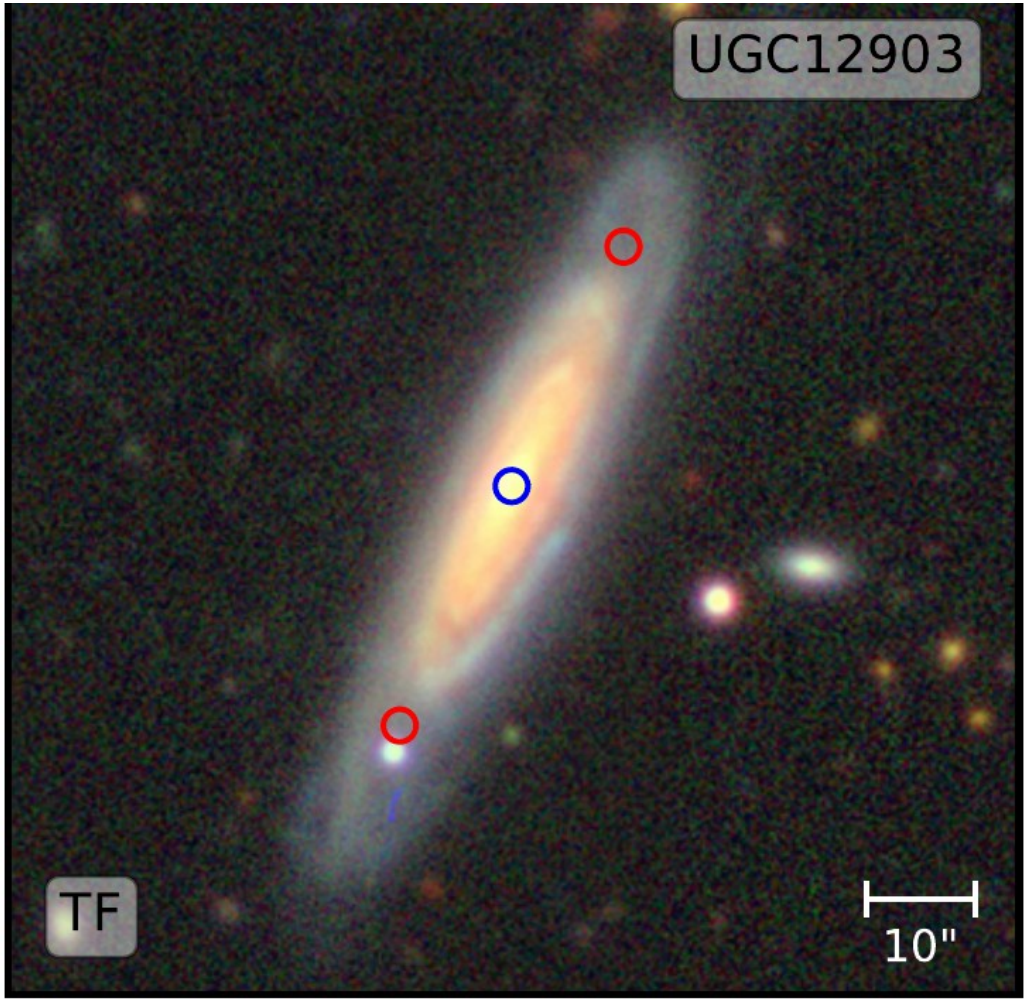
- Using the science verification data (observation before the main survey) to test our criteria and refine them further
- Using fastspec data to further clean the sample (~2/3rd remain)
- Work in progress → see upcoming papers



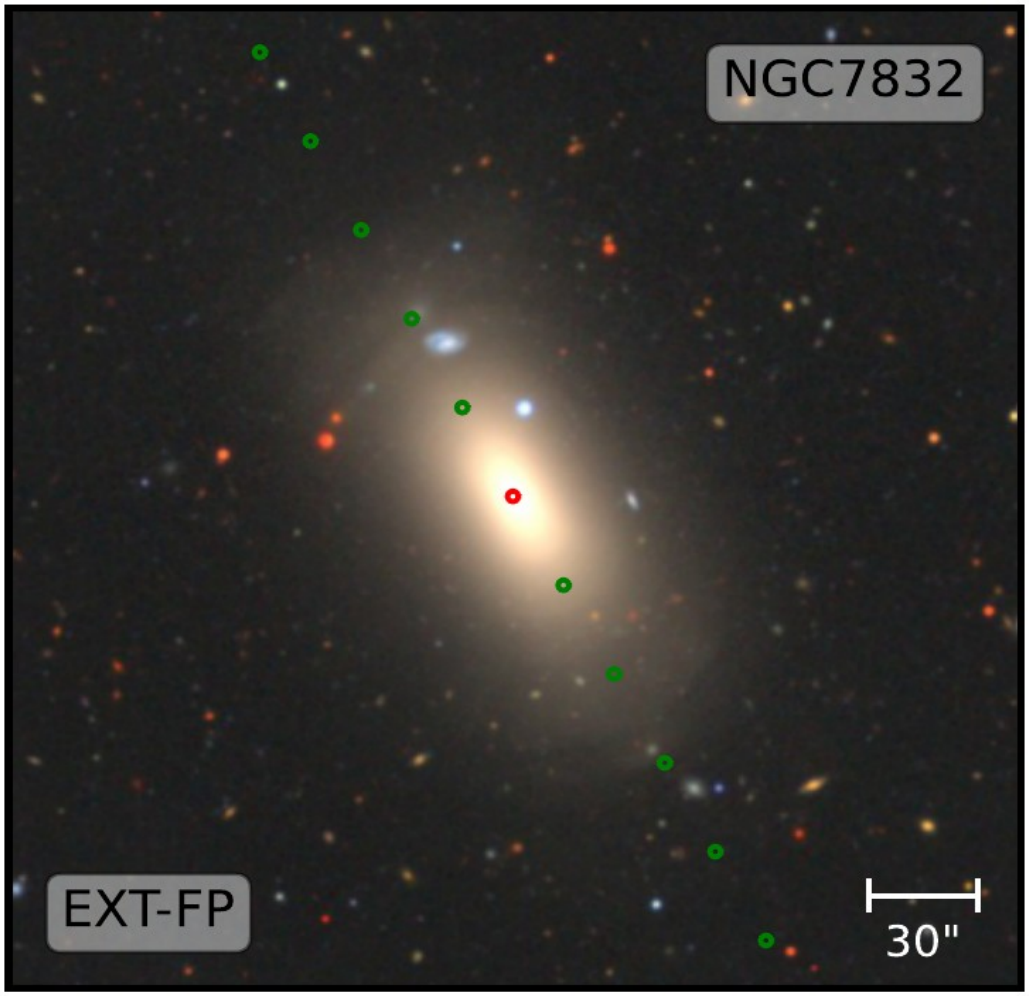


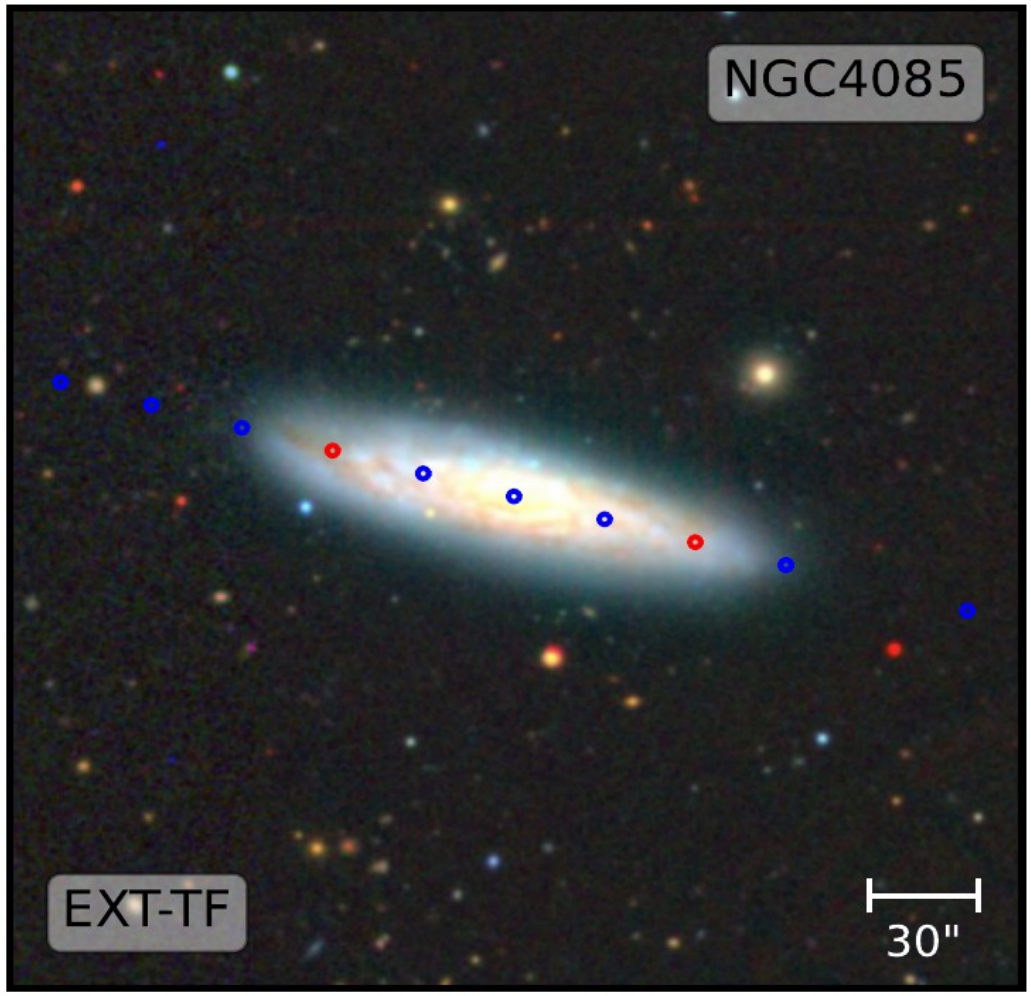
Default fibre placements



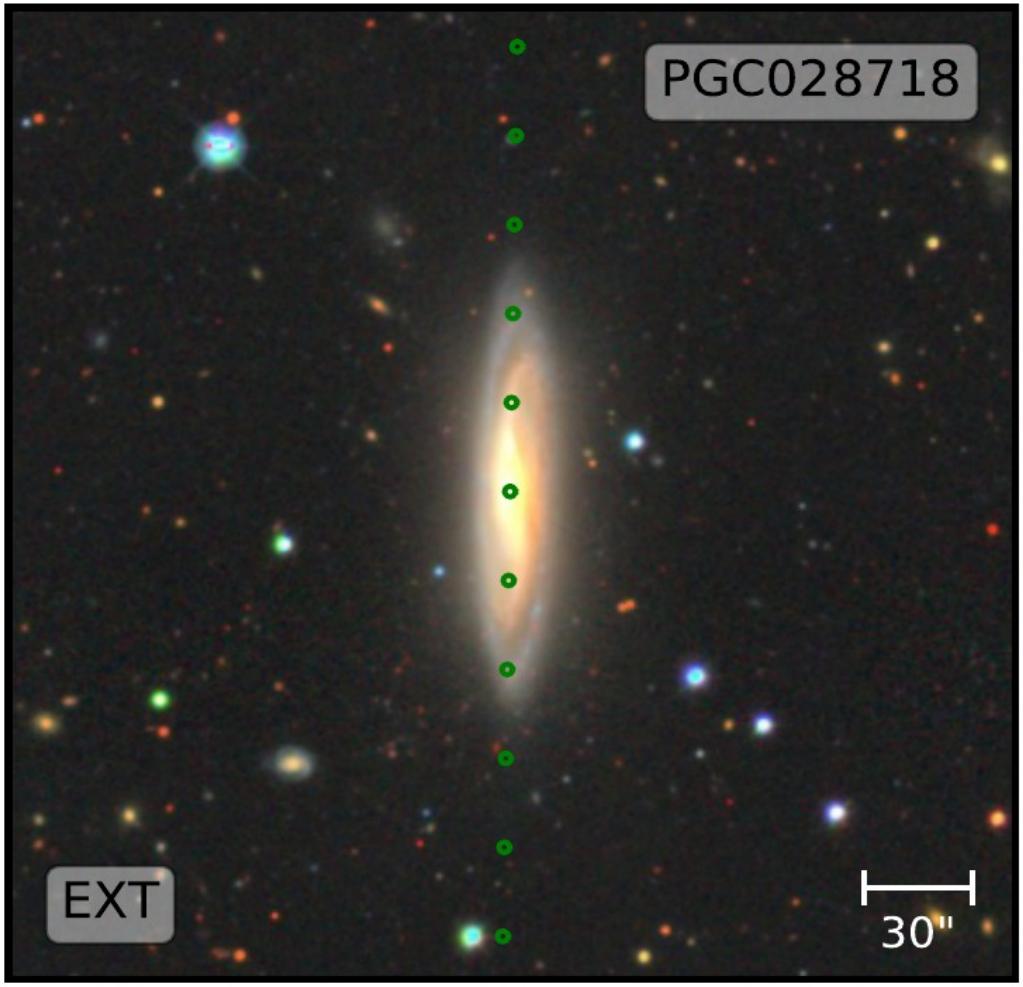


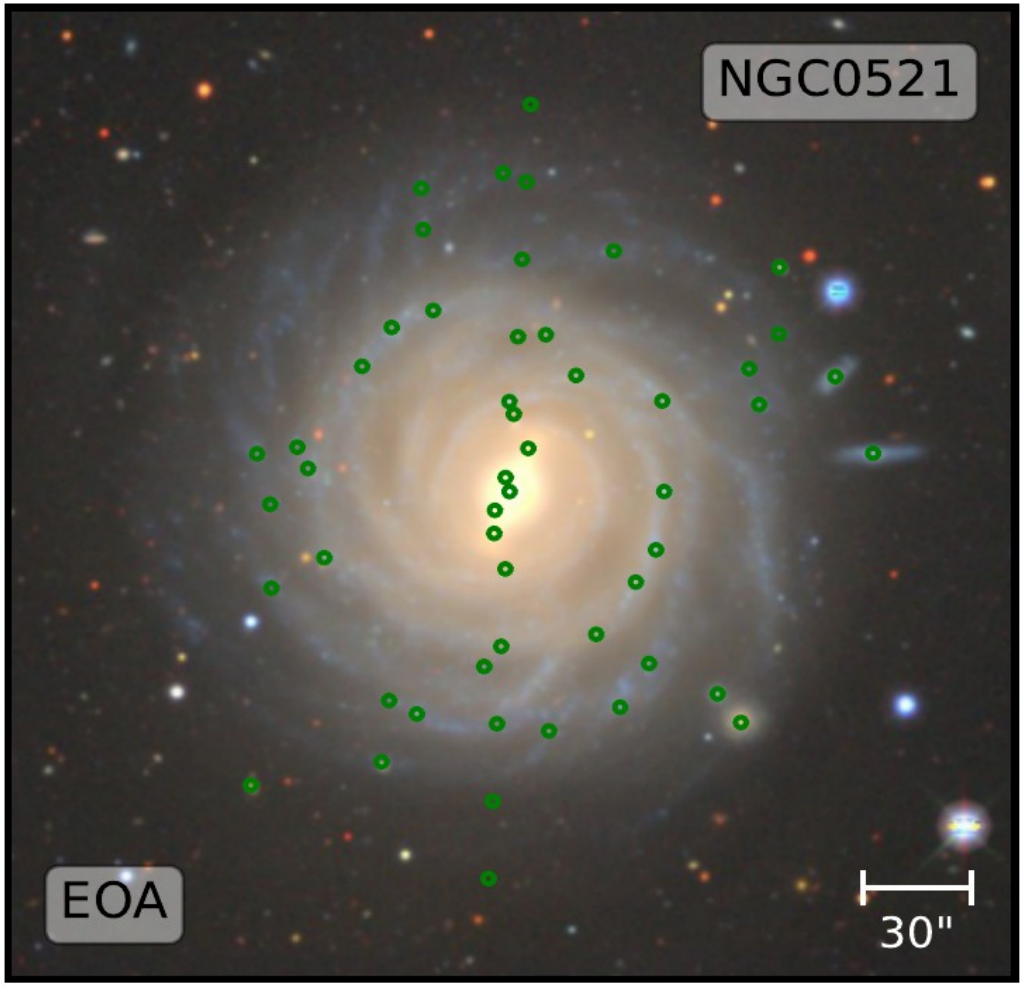
Additional fibre placements for calibrations





Low resolution integral field spectroscopy





DESI II / DESI-futures

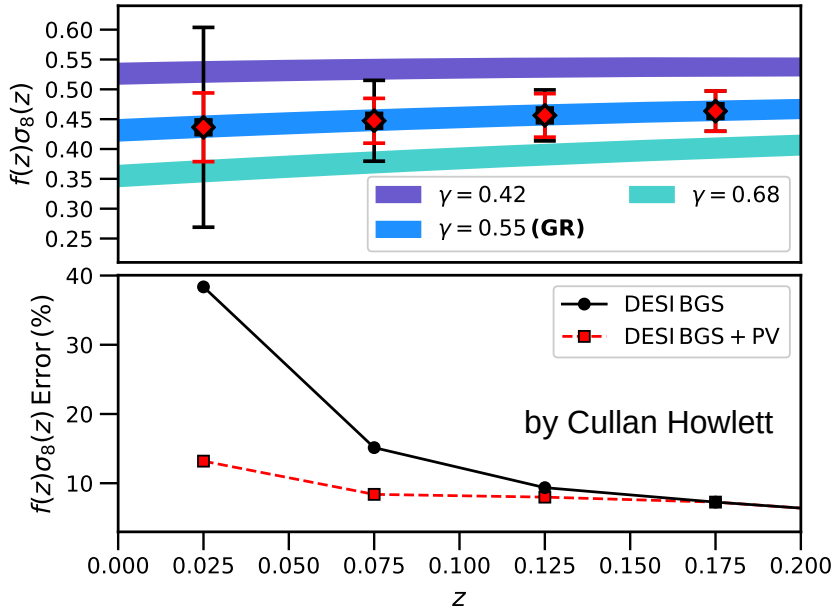
- Possible extension of DESI after the initial 5-year run
- New science cases needed
- One possibility: repeat observations of current area for additional targets
- Chance for low-res integral field spectroscopy of big galaxies

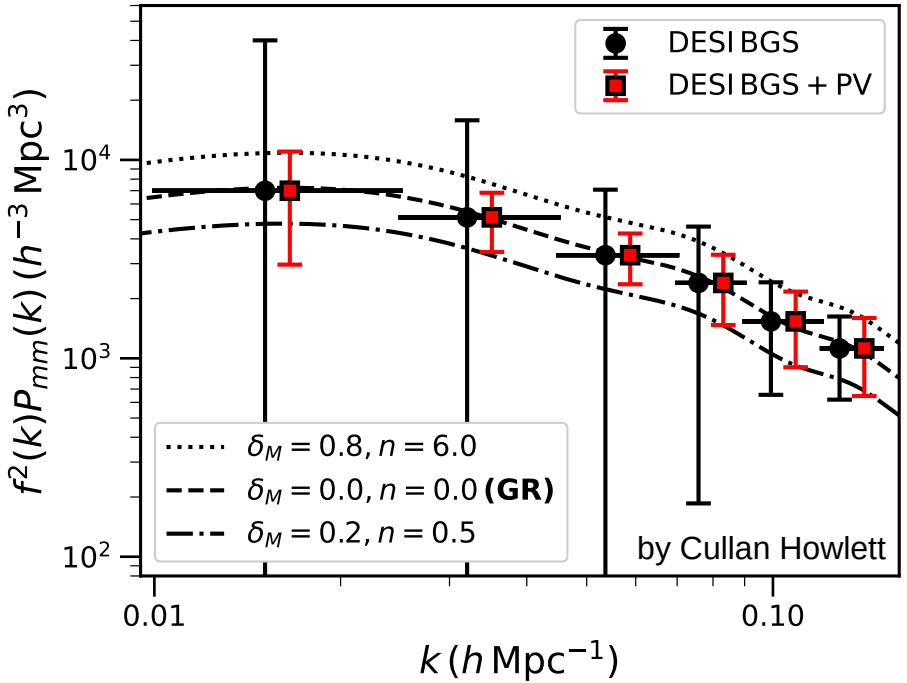
For what do we need peculiar velocities?

- Redshift independent distances + redshifts → peculiar velocities

For what do we need peculiar velocities?

- Redshift independent distances + redshifts → peculiar velocities
- Matter distribution in the local universe
- Growth rate: $f\sigma_8$, improving constraints from DESI BGS for the evolution and scale-dependence





Summary

- Scaling relations have a long history for being used as redshift-independent distance indicators
- IFU surveys provide a new opportunity to improve them
- S_K parameter or other kinematic measurements might allow a further generalisations → large samples of (all) morphologies
- Additional opportunities to further explore our assumptions with DESI data in the future

ANY QUESTIONS?