National Aeronautics and Space Administration

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Postdoc Research

# Improving Single-Fiber Dynamic Modeling

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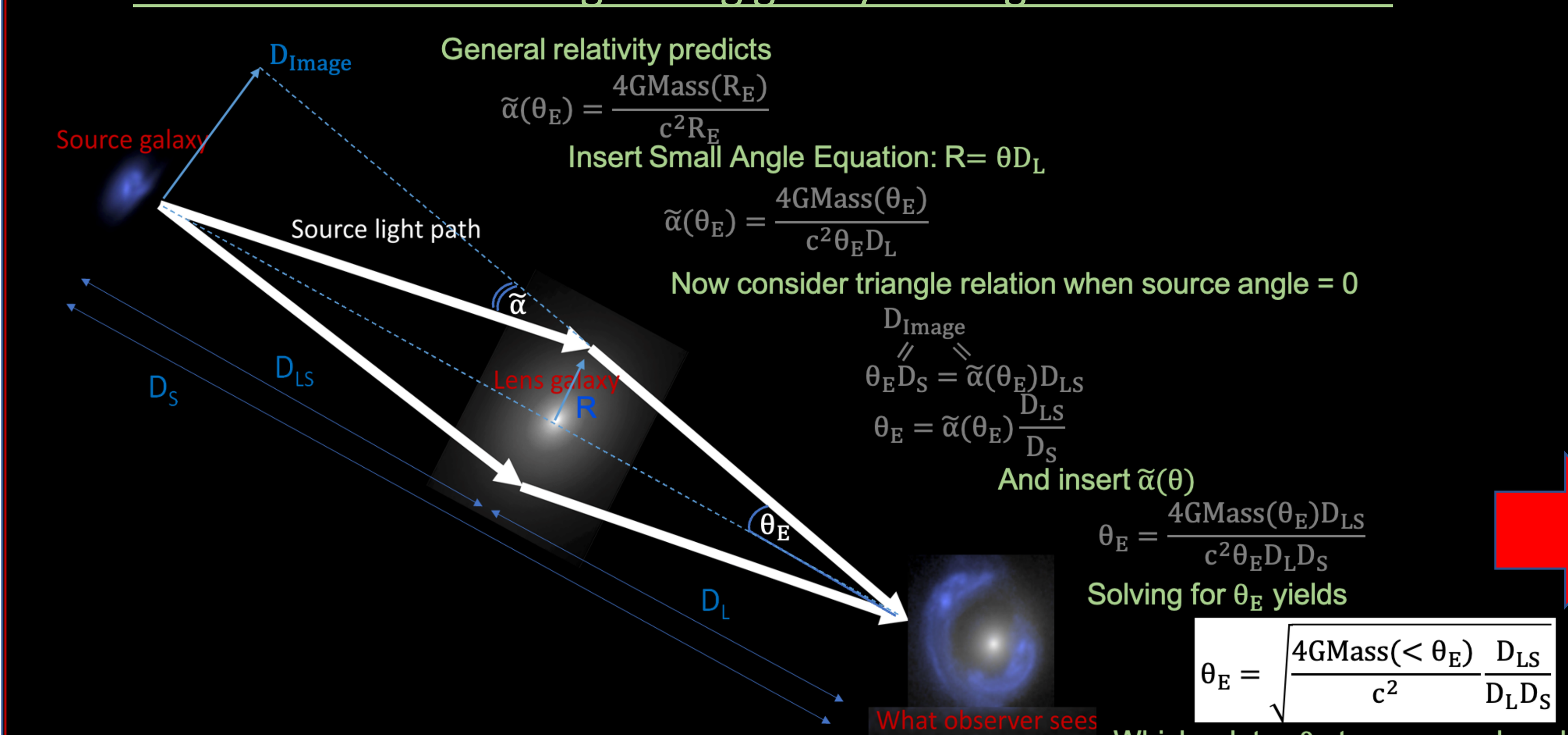
## Oversimplified Extragalactic Mass Modeling Can Bias Mass Projections at Cosmological Distances

Only two direct methods can effectively measure the total mass of galaxies at extreme distances where the angular size of the galaxy is on the order of 1/3600 of a degree:

### 1. Measurements using strong galaxy-scale gravitational lenses




General relativity predicts

$$\tilde{\alpha}(\theta_E) = \frac{4GMass(R_E)}{c^2 R_E}$$

Insert Small Angle Equation: $R = \theta D_L$

$$\tilde{\alpha}(\theta_E) = \frac{4GMass(\theta_E)}{c^2 \theta_E D_L}$$

Now consider triangle relation when source angle = 0

$$\underbrace{\theta_E D_S = \tilde{\alpha}(\theta_E) D_{LS}}_{D_{Image}}$$

$$\theta_E = \tilde{\alpha}(\theta_E)\frac{D_{LS}}{D_S}$$

And insert $\tilde{\alpha}(\theta)$

$$\theta_E = \frac{4GMass(\theta_E)D_{LS}}{c^2 \theta_E D_L D_S}$$

Solving for $\theta_E$ yields

$$\theta_E = \sqrt{\frac{4GMass(<\theta_E)}{c^2}\frac{D_{LS}}{D_L D_S}}$$

Which relates $\theta_E$ to mass enclosed

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### MEASUREMENTS DISAGREE!

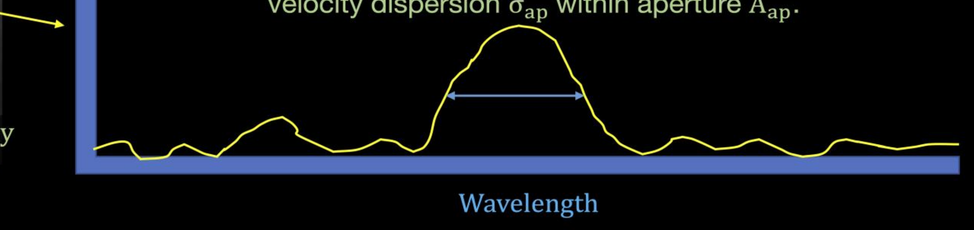
Isothermal power-law fits project lensing mass as 21% more massive than single-fiber dynamic mass approximations (Li et al. 2018), which isothermal slope is the best fit. Thus more advanced models may help reduce bias in past, present, and future research.

### 2. Measurements using velocity signature within an aperture

The aperture (ex., fiber represented by red circle) collects star and gas spectra.

Any atmosphere blurring of lens galaxy removes some light within aperture while adding some light from beyond.

- Spectra features are significantly broadened by cumulative relativistic doppler motions of completely or nearly randomly directed (i.e., isotropic-like) stars, which random motions are dominant in relatively more massive galaxies.
- Using a broadening measurement (ex., blue arrow for an intrinsically thin feature) in relativistic doppler broadening equations yields the luminosity weighted average of the line-of-sight (LOS) velocity dispersion $\sigma_{ap}$ within aperture $A_{ap}$.




- Galaxies tend to demonstrate nearly isothermal (i.e., similar to gravitationally bound gas at a single temperature) total density profile:

$$\rho(r) = \frac{\sigma_{ap}^2}{2\pi G r^2}$$

where velocity is assumed constant (i.e., flat) across radius (r) and LOS $\sigma_{ap}$ = true $\sigma_{ap}$ due to pure isotropic assumption (i.e., observed $\sigma_{ap}$ does not depend on observation angle). G = gravitational constant.

– Integrating the density profile across LOS and within radius $\theta_E$ yields:

$M(<\theta_E) = \frac{\pi}{G}\sigma_{ap}^2 R_E = \frac{\pi}{G}\sigma_{ap}^2 D_L \theta_E$ ***IF*** assume aperture bias minimized since averaging over constant $\sigma_{ap}$=constant $\sigma_{ap}$.

-This equation becomes more complex when the power-law slope is NOT assumed isothermal.

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## Spatially Resolved Spectra of Nearby Galaxies Enable Insights Into Model Improvements

### New Data for Investigation

Fiber-bundle (19 to 127 1" radius fibers) sampling of galaxy spectra (an example of an integral-field-unit or IFU), which is obtained from the Mapping of Nearby Galaxies at Apache Point Observatory (MaNGA; Bundy et al. 2015, a survey of SDSS), enabled the MaNGA Data Analysis Pipeline (DAP; Belfiore et al. 2019; Westfall et al. 2019) team to fit LOS radial and dispersion velocity models to the relativistic doppler shifted and broadened spectra, respectively.

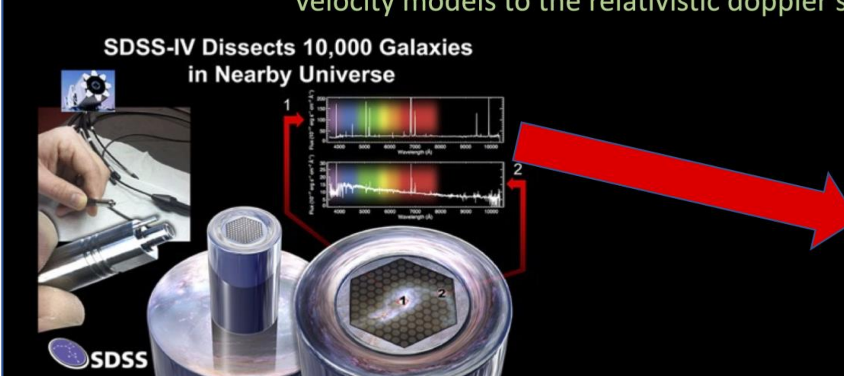
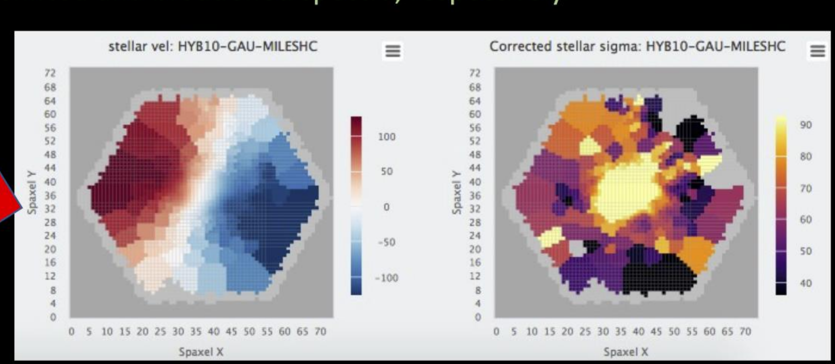
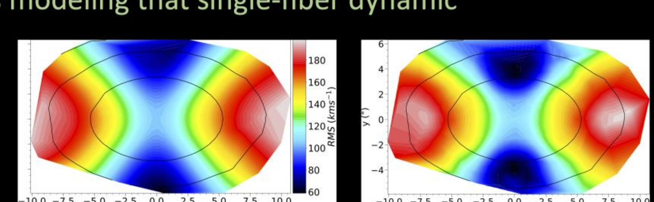



Image Credit of MaNGA fiber bundle and sampling example: Dana Berry / SkyWorks Digital Inc., David Law, and the SDSS collaboration.




Radial (left) and dispersion (right) velocity plots from MaNGA Plate: 8606, IFU: 12701 obtained via Marvin (Cherinka et al., 2019) website: https://dr16.sdss.org/marvin/

The spatially resolved kinematics enable tighter stellar+dark matter fits (ex., Talbot et al. 2022, Zhu et al. 2023) for the 10,000+ MaNGA galaxies since overall stellar orbit details (ex., inclination, anisotropy) can be modeled to better translate observed LOS kinematics into orbit velocity fields, which thus reduces uncertainties in mass modeling that single-fiber dynamic approximations inherit due to lack of orbit pattern information.



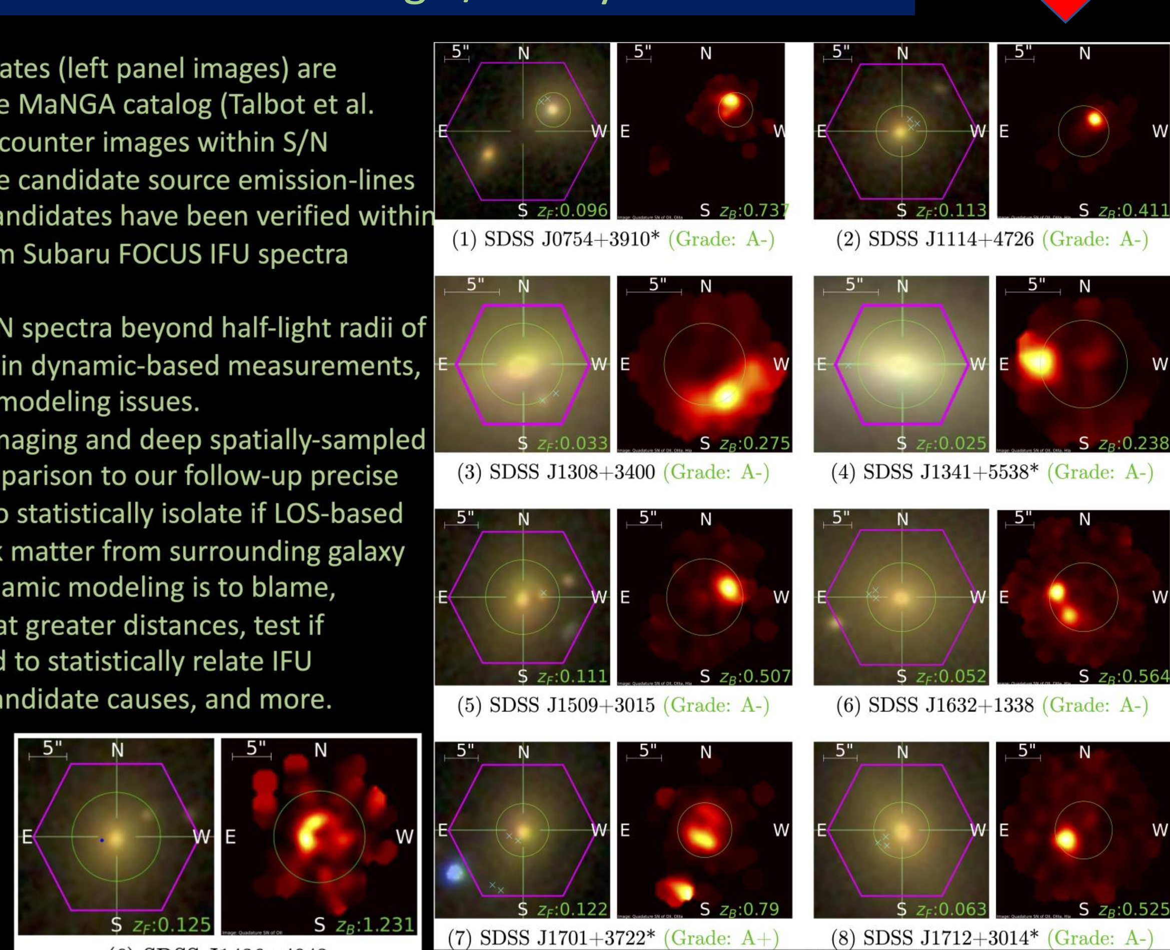
These kinematic fit examples from Talbot et al. 2022 demonstrate the similarity of the fitted root-mean-square of the combined LOS radial and dispersion map (right) to a MaNGA target (left), enabling their use in comparing lensing and single-fiber dynamics to IFU-based dynamics.

### Follow-up to Test Lens VS Single/IFU Dynamics

-Nine low-z (i.e., nearby) lens candidates (left panel images) are spectroscopically detected within the MaNGA catalog (Talbot et al. 2018, 2022) and display arcs and/or counter images within S/N narrowband images created from the candidate source emission-lines (right panel images), of which two candidates have been verified within narrowband images constructed from Subaru FOCUS IFU spectra (Smith et al. 2020).

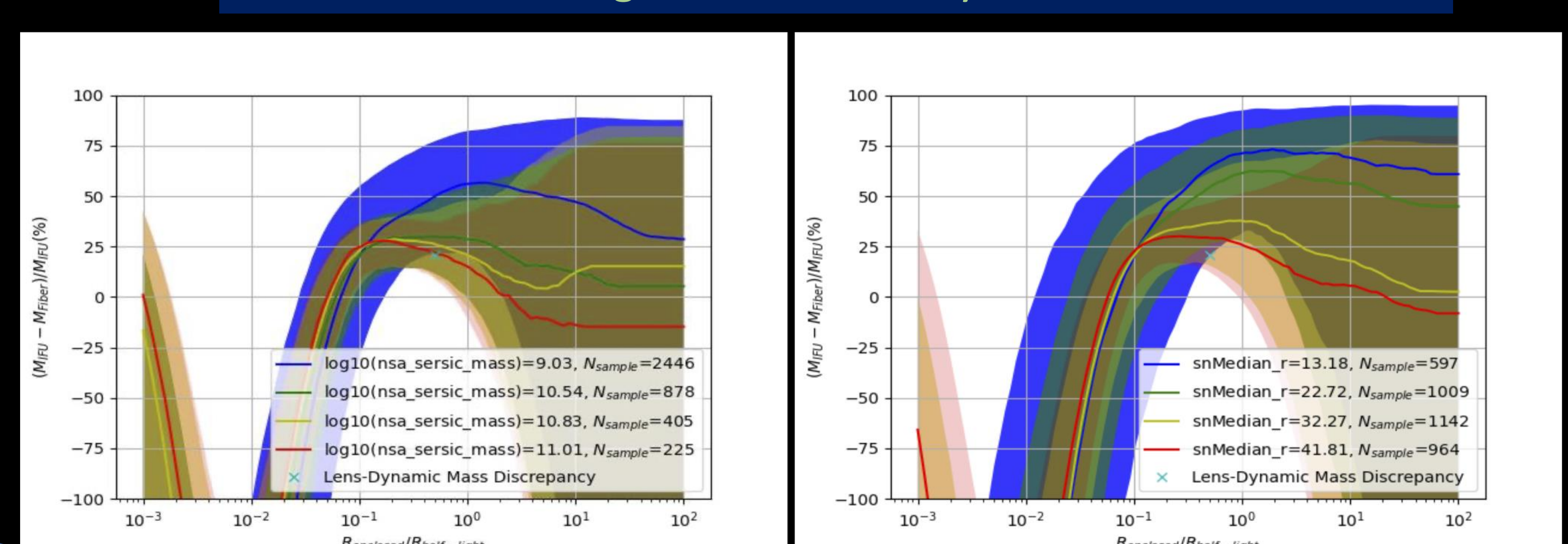
-Unfortunately, kinematics of low-S/N spectra beyond half-light radii of MaNGA targets inflate uncertainties in dynamic-based measurements, making it difficult to reject dynamic modeling issues.

-We are proposing high-resolution imaging and deep spatially-sampled spectra to analyze lens mass for comparison to our follow-up precise IFU-based dynamic measurements to statistically isolate if LOS-based potential mass contributors (ex. dark matter from surrounding galaxy cluster halo or other galaxies) or dynamic modeling is to blame, calibrate aperture dynamics for use at greater distances, test if MaNGA-based dynamics can be used to statistically relate IFU vs. aperture discrepancy trends to candidate causes, and more.




Candidates images from Talbot et al. 2022, 2018

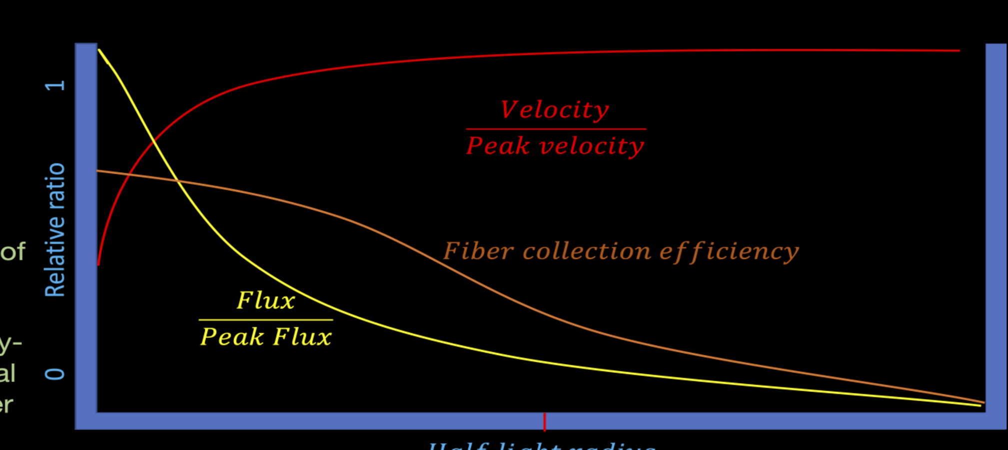
### Single-fiber vs IFU Dynamics




-Our comparison of mass projections between single-fiber mass approximations (using SDSS kinematics) vs dynamic fits of MaNGA IFU data from our fits (Talbot et al., 2022) and utilizing Dynpop (see Zhu et al., 2023 for target summary information of dynamic fits, which we combine with our light profile fits to radially project the discrepancy across radius.) reveal a similar discrepancy (plots above from ours and Dynpop hybrid comparison) as previously detected in Li et al 2018 (97 massive lenses tested at ~0.75 the half-light radius).

-The discrepancy is persistent across all comparisons to quality of fit and model parameters, and increases with decreasing galaxy mass and S/N (Talbot et al. in prep).

#### Potential cause examples and deepening the investigation



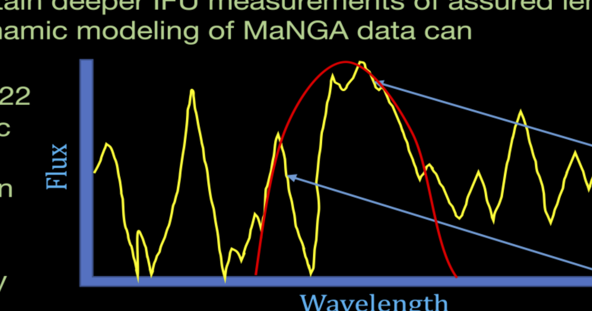

The inferred single-aperture dynamic underestimation may be rooted in multiple causes, which can be categorized into the following types:

1. Small sampling apertures. Observations of nearby galaxies often demonstrate circular velocity dips that may lead to an underestimation of the constant and radially-independent velocity projected in isothermal fits, which impact may increase with smaller sampling since the impact from the bright galaxy center and higher fiber light collection efficiency enable the dip to more effectively impact the luminosity-weighted kinematic signal. Trends in orbital anisotropy is also an issue at small sampling radii. Thus comparing physical radii coverage of the single-aperture with IFU vs. aperture-based dynamic measurements will help illuminate any bias scaling with aperture coverage.

2. A fitted and non-evolving power-law slope may significantly miss-model radial extremes. Power law models often fit data with one slope, which often fails to account for central density flattening or shallower slopes of the dark matter halo. Thus trends in measurables (ex., galaxy mass and sampling aperture), as well as contrast of the IFU-based baryon and dark matter contributions to the total density profile, can illuminate is dark matter halos are under-modeled or if other trends suggest a different impactor.

**2.** Kinematics bias from measuring low S/N spectra within outskirts of galaxies. MaNGA observations yield spectra that lack high S/N beyond a half-light radius. As a result, fits of the velocity dispersion may become inflated by noise and other issues that the DAP (Belfiore et al. 2019, Westfall et al. 2019) has previously encountered and likely mitigated by Voronoi-binning the lower S/N regions to have a binned S/N of 10 (which tends to fail at edges of IFU due to lack of remaining area to bin). However, any kinematic bias can translate into a dynamic modeling bias, which effect should be mitigated at least in Talbot et al. 2022 since bins with S/N<5 are not considered and kinematic artifacts are filtered for. However, such cuts come at the costs of reducing the sampling to ~1-1.5 half-light radii. Thus, we plan to obtain deeper IFU measurements of assured lens candidates found in MaNGA (Talbot et al. 2018, 2022) to test if dynamic modeling of MaNGA data can

Thus, we plan to obtain deeper IFU measurements of assured lens candidates listed in Talbot et al. 2018, 2022 to check if MaNGA kinematics and IFU-based dynamic modeling are sufficiently accurate to conclude single-aperture dynamic underestimation and what trends can lead to modeling improvements. Follow-up imaging of these candidates will enable a lens vs IFU-dynamic contrast to test for LOS mass contamination and if any local galaxy cluster may be to blame.




Cartoon fit of dispersion model (red) to low S/N signal can cause model expansion to fit noise.

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Talbot et al. 2018, MNRAS, 477, 195.
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