Exploration of measured galaxy pitch angle variation

We have reason to suspect that our errors on galaxy pitch angle are incorrect. This notebook is an exploration of this problem.

TL;DR

The problem seems to arise when we only pick up a subset of the available arms, a subsection of an arm or some combination of the above. Galaxies show large inter-arm variances in pitch angle (though potentially small intra-arm variance, interestingly), therefore different combinations of detected arms can produce large variances in reported "Length-weighted pitch angle" (ϕ_{LW}).

Define the error on ϕ_{LW}, $\sigma_{\phi_{\mathrm{LW}}}$, to be the sample variance of the pitch angle of the galaxy's identified arms .

```
Performing initial setup 📖
```

[2]
```
plt.style.use('seaborn-dark')
data = np.load('lib/duplicate_galaxies.npy')
```

Select a galaxy to explore:

Papermill - Parametrized

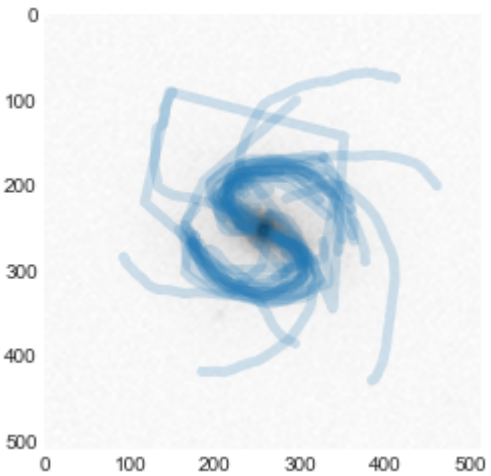
[3]
```
# test galaxy from paper (dr8id 588023240206516423) has index 94
gal_index = 59
gal_dr8id = None
```

[4]
```
if gal_dr8id is not None:
    gal_index = np.where(dr8id == gal_dr8id)[0][0]
dr8id, ss_id, val_id = data[gal_index]
print(dr8id, ss_id, val_id)
```

```
587742062121582703 20902065 21686594
```

[5]
```
gal, angle = gu.get_galaxy_and_angle(ss_id)
pic_array, _ = gu.get_image(gal, ss_id, angle)

all_cls = gu.classifications.query(
    '(subject_ids == {}) or (subject_ids == {})'.format(
        ss_id, val_id
    )
)
drawn_arms_all = get_drawn_arms(
    (ss_id, val_id),
    all_cls
)
plt.imshow(pic_array)
for a in drawn_arms_all:
        plt.plot(*a.T, '-', c='C0', alpha=0.2, linewidth=5)
```

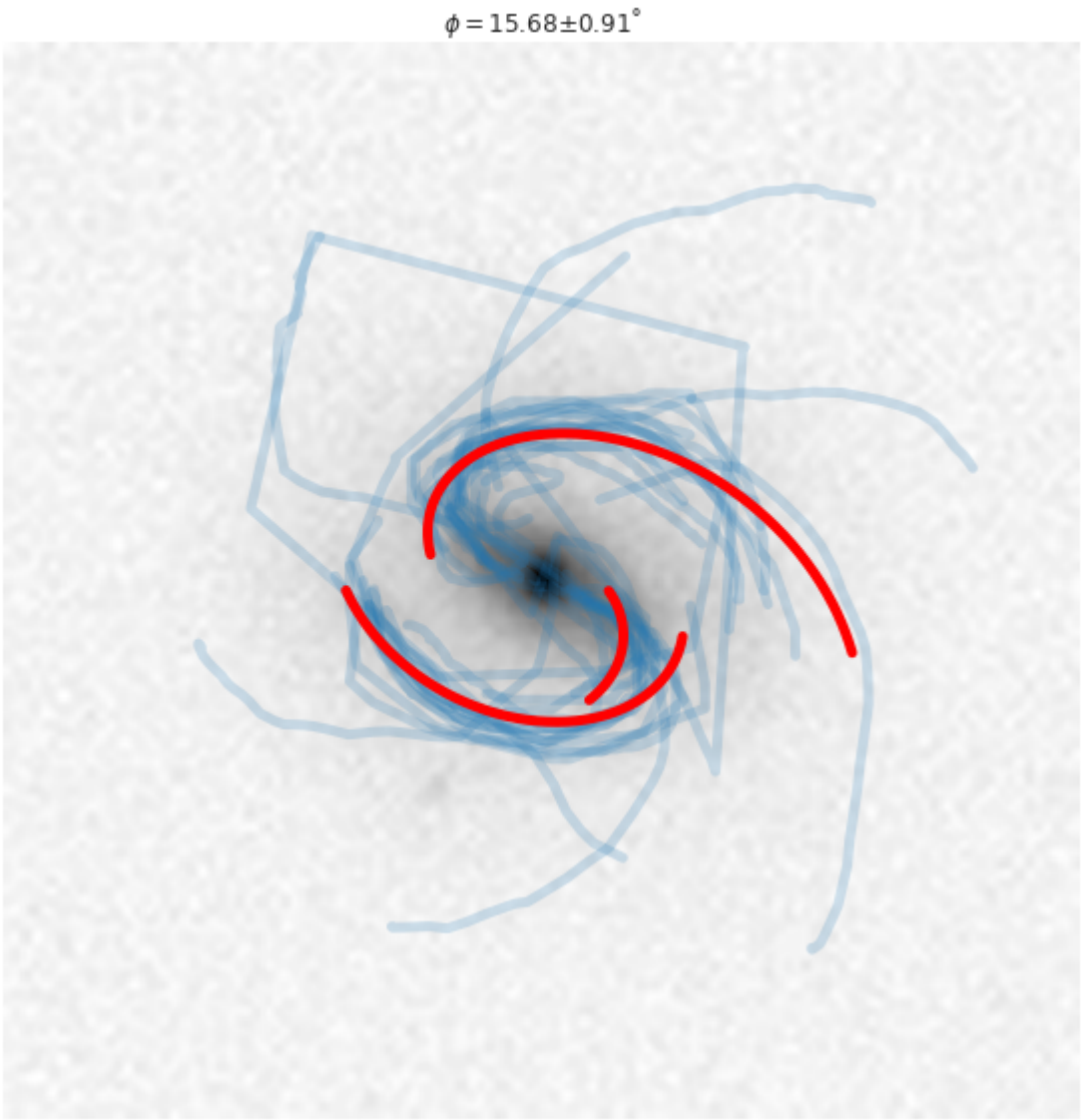


Given all the 60 classifications, the aggregated log-spirals look like:

[6]
```
drawn_arms_all = get_drawn_arms(
    (ss_id, val_id),
    all_cls
)
p_all = Pipeline(drawn_arms_all, phi=angle, ba=gal['PETRO_BA90'],
             image_size=512, parallel=True)
arms_all = p_all.get_arms()
gal_pa = p_all.get_pitch_angle(arms_all)

plt.figure(figsize=(8, 8))
for b in drawn_arms_all:
        plt.plot(*b.T, '-', c='C0', alpha=0.2, linewidth=5)
for a in arms_all:
    plt.plot(*a.reprojected_log_spiral.T, 'r', linewidth=5)
plt.figure
plt.imshow(pic_array, cmap='gray_r')
plt.axis('off');
```

```
    plt.tight_layout()
    plt.title('$\phi = {:.2f} ± {:.2f}˚$'.format(
        *gal_pa
    ));
```



Denote the pitch angle for each of these arms as ϕ_{60} and the length-weighted pitch angle for the combined galaxy as

$$\Phi_{60} = \frac{\sum_{i=0}^{n} L_i \phi_{60,i}}{\sum_{i=0}^{n} L_i},$$

where L_i is the length of the i^{th} arm.

Now let's randomly choose 30 classifications from the pool and observe the resulting spirals (and repeat `N_SPLITS` times). The distribution of pitch angles for each arm in each split will be denoted ϕ_{30}, and each split's combined pitch angle (Φ_{30}) calculated as above.

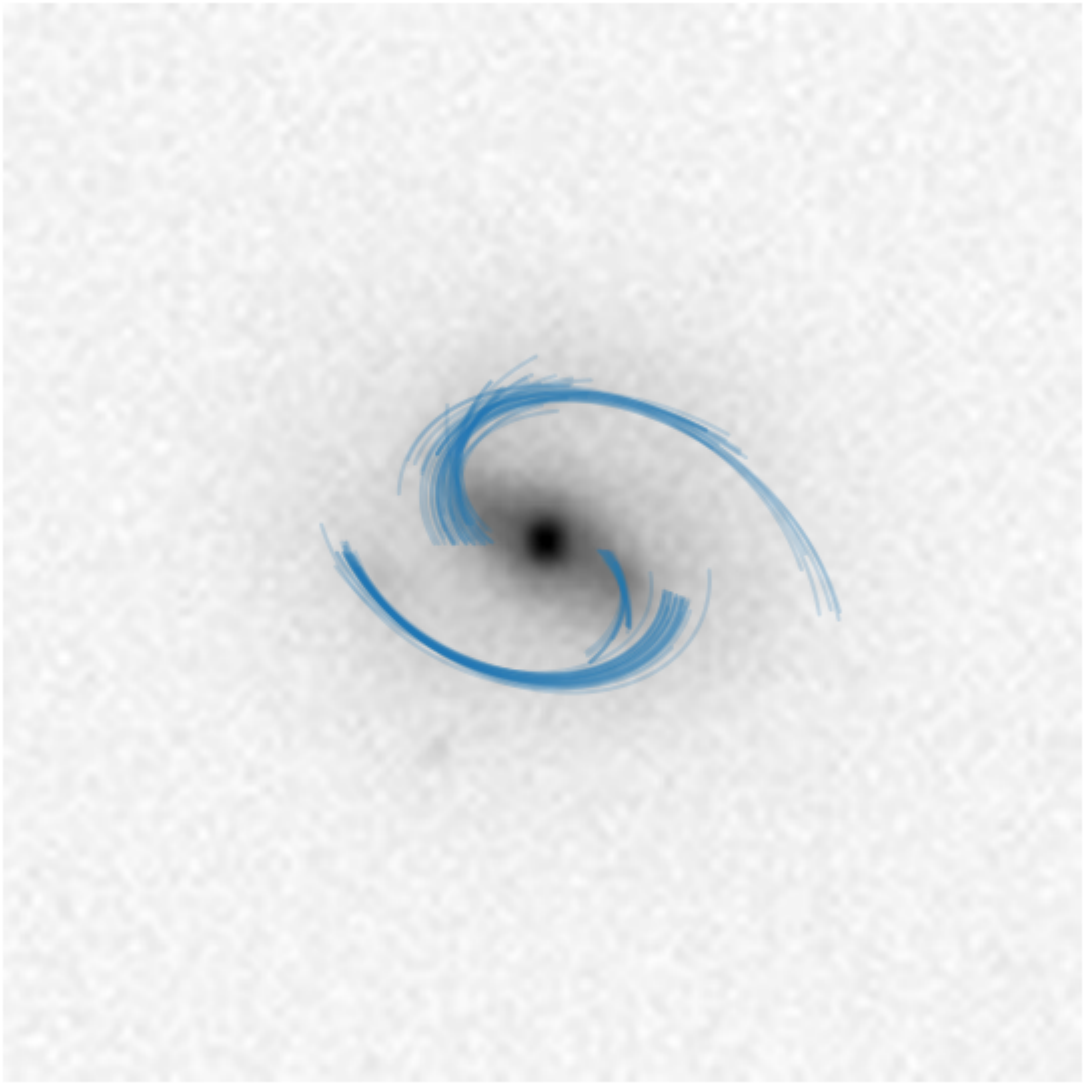
[7]
```
N_SPLITS = 50
```

[8]
```
ss = ShuffleSplit(n_splits=N_SPLITS, test_size=0.5,
random_state=0)
pas = np.zeros((N_SPLITS, 2))
arms = []
for i, (train_index, _) in enumerate(ss.split(all_cls)):
    if i%10 == 0:
        print('Calculating split {}/{}'.format(i, N_SPLITS))
    drawn_arms = get_drawn_arms(
        (ss_id, val_id),
        all_cls.iloc[train_index]
    )
    p = Pipeline(drawn_arms, phi=angle, ba=gal['PETRO_BA90'],
                 image_size=512, parallel=True)
    arms.append(p.get_arms())
```

```
Calculating split 0/50
Calculating split 10/50
Calculating split 20/50
Calculating split 30/50
Calculating split 40/50
```

The log spirals for these splits look like:

[9]
```
plt.figure(figsize=(8, 8))
tpl_arms = []
for i, group in enumerate(arms):
    for arm in group:
        plt.plot(*arm.reprojected_log_spiral.T, 'C0', alpha=0.2,
linewidth=2)
    pas[i] = p.get_pitch_angle(arms=group)
plt.imshow(pic_array, cmap='gray_r')
plt.axis('off');
plt.tight_layout()
```



How does this population of pitch angles compare to the arms from all classifications combined?

[10]
```
plt.figure(figsize=(10, 7))
plt.subplot(221)
plt.hist([i.pa for g in arms for i in g], density=True, zorder=1,
label='$\phi_{30}$')
lims = plt.gca().get_ylim()
for arm in arms_all:
    plt.vlines(arm.pa, 0, lims[1], color='r', linestyle='--')
    plt.fill_betweenx([0, lims[1]], arm.pa - arm.sigma_pa, arm.pa
+ arm.sigma_pa, color='r', alpha=0.2, zorder=2)
plt.plot([], [], 'r--', label='$\phi_{60}$')
plt.ylim(lims)
plt.legend()
plt.title('Calculated distribution of $\phi_{30}$')

plt.subplot(222)
```

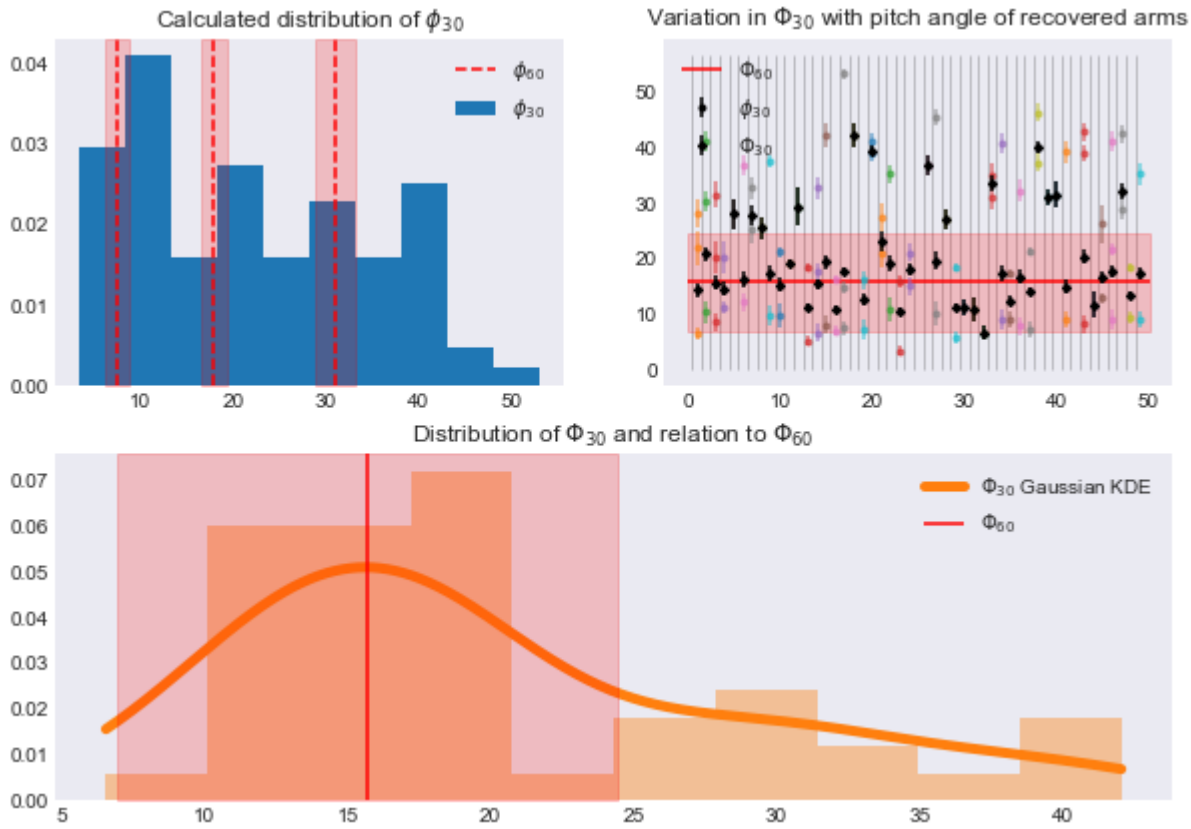
```
    all_combs = []
    for i, group in enumerate(arms):
        comb_pa = p.get_pitch_angle(group)
        all_combs += [comb_pa[0]]

    for i, group in enumerate(arms):
        for arm in group:
            all_pas.append(arm.pa)
            plt.errorbar(i, arm.pa, yerr=arm.sigma_pa, fmt='.',
    c='C{}'.format(i%10), alpha=0.6, zorder=2)
        comb_pa = p.get_pitch_angle(group)
        plt.errorbar(i, comb_pa[0], yerr=comb_pa[1], fmt='kD',
    zorder=3, markersize=3)

    plt.errorbar([], [], [],  fmt='k.', label='$\phi_{30}$')
    plt.errorbar([], [], [],  fmt='kD', markersize=3,
    label='$\Phi_{30}$')
    plt.hlines(gal_pa[0], 0, 50, color='r', label=r'$\Phi_{60}$',
    zorder=1)
    plt.fill_between(
        [0, 50], gal_pa[0] - np.nanstd(all_combs), gal_pa[0] +
    np.nanstd(all_combs),
        color='r', alpha=0.2, zorder=1
    )
    plt.vlines(np.arange(len(arms) - 1) + 0.5, 0, max(plt.ylim()),
    color='k', zorder=0, alpha=0.4, linewidth=0.5)
    plt.title('Variation in $\Phi_{30}$ with pitch angle of recovered
    arms')
    plt.legend()

    plt.subplot2grid((2, 1), (1, 0))
    kde = st.gaussian_kde(np.array(all_combs)[~np.isnan(all_combs)],
    'silverman')
    _, bins, _ = plt.hist(all_combs, density=True, color='C1',
    alpha=0.4)
    xx = np.linspace(bins.min(), bins.max(), 1000)
    plt.plot(xx, kde(xx), color='C1', linewidth=5, label='$\Phi_{30}$
    Gaussian KDE', zorder=1)
    lims = plt.gca().get_ylim()
    plt.fill_betweenx(
        [0, lims[1]], gal_pa[0] - np.nanstd(all_combs), gal_pa[0] +
    np.nanstd(all_combs), color='r', alpha=0.2, zorder=2
    )
    plt.vlines(gal_pa[0], 0, lims[1], color='r', zorder=2,
    label='$\Phi_{60}$')
    plt.ylim(lims)
    plt.legend()
    plt.title(r'Distribution of $\Phi_{30}$ and relation to
    $\Phi_{60}$');
    plt.savefig('method-paper-plots/pitch-angle-variation.pdf',
    bbox_inches='tight');
```

```
/Users/tlingard/anaconda3/lib/python3.6/site-
packages/numpy/lib/histograms.py:824: RuntimeWarning: invalid value
encountered in greater_equal
  keep = (tmp_a >= first_edge)
/Users/tlingard/anaconda3/lib/python3.6/site-
packages/numpy/lib/histograms.py:825: RuntimeWarning: invalid value
encountered in less_equal
  keep &= (tmp_a <= last_edge)
```



There is a large observed variance in the recovered spiral arms, with arms taking on pitch angles across almost all the possible range.

The pitch angle of the galaxy as a whole is very dependant on which arms have been detected; the problem seems to arise when we only pick up a subset of the available arms, a subsection of an arm or some combination of the above. Galaxies show large inter-arm variances in pitch angle (though potentially small intra-arm variance, indicated by the goodness of fit of logarithmic spirals), therefore different combinations of detected arms can produce large variances in reported length-weighted pitch angle.