Matplotlib for Publication

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Part 1. Basics of Matplotlib

Introducing Matplotlib

Matplotlib is *the* standard Python library for visualizing data for print or digital media.

- Figures may be static, interactive, animated, and/or embedded in a Jupyter notebook
- Plots can be 2D or 3D, single or tiled as part of a larger figure
- Cartesian, polar, and many other coordinate systems supported, including map projections and sky coordinates
- Excellent documentation with many, MANY tutorials

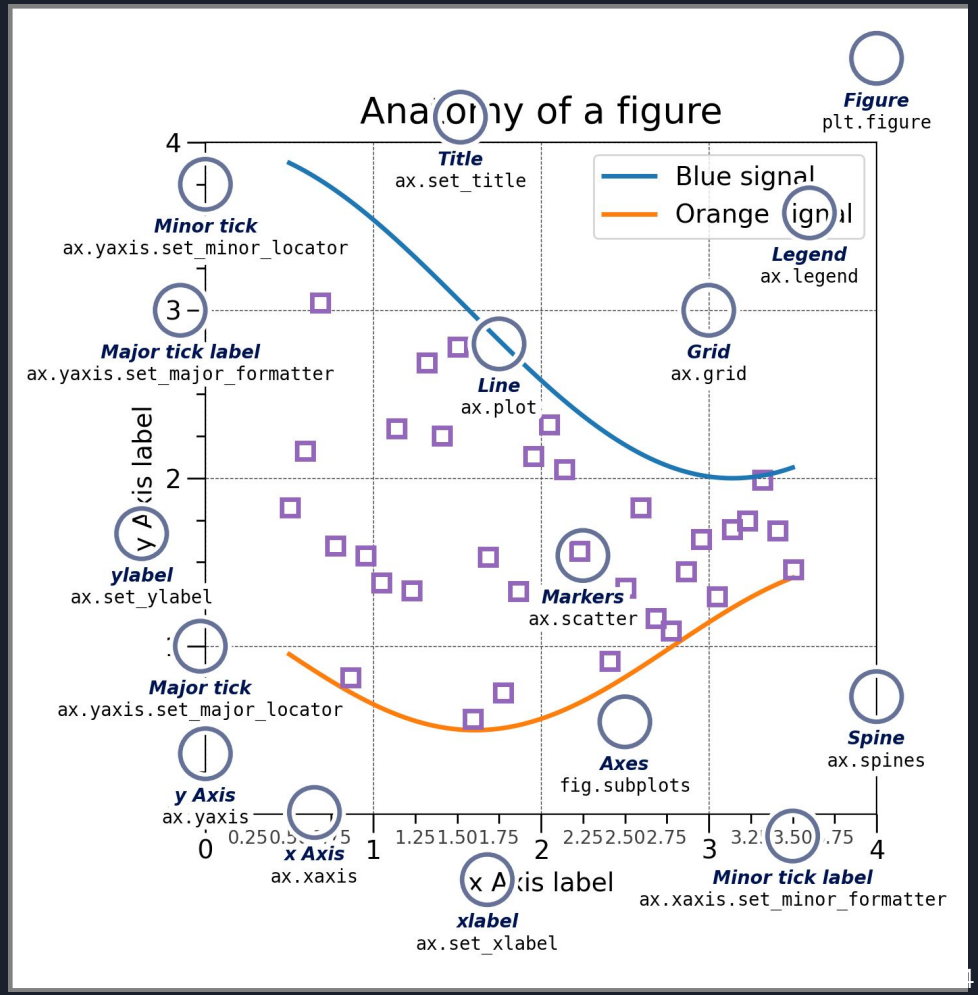
Basic Terms

Names of plot elements→

- **Figure (fig)** = frame & all (sub)plots inside (may have >1 set of axes)
- **Axis instance (ax)** = one pair (or trio) of axes, their labels, & all data enclosed

Terms to know for functions:

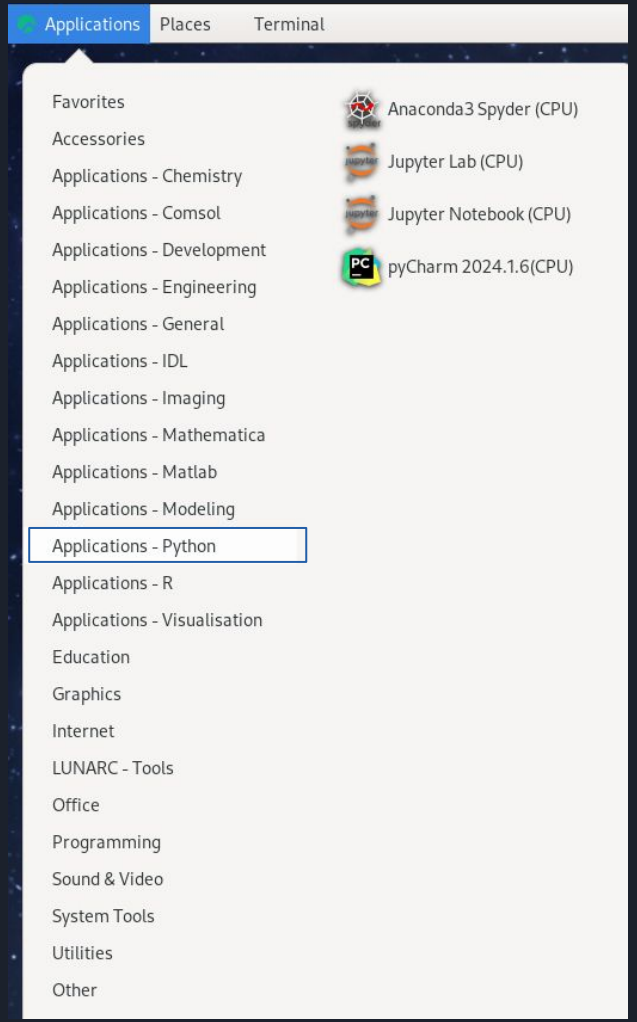
- **args** = positional **arg**uments; usually mandatory
- **k**wargs = **k**eyword **arg**uments; usually optional



Run Matplotlib On-Demand

LUNARC HPC Desktop (COSMOS): recommended to use Spyder, Jupyter, or another scripting program from the On-Demand Applications menu to work with Matplotlib interactively.

Jupyter modules default to latest Anaconda3 version. Spyder currently uses Python 3.11.7.



Load & Run Matplotlib Module

Command line or SLURM script: modules to load depend on whether you use Anaconda or PyPi

- **Anaconda**: `ml Anaconda3` loads everything needed (but environments can mess with your .bashrc & disrupt access to other modules)
- **PyPi**: GCC determines version of Matplotlib & all dependencies
  - Use `ml spider <dependency>` to check Python or other dependency versions to see which GCC you need
  - Then `ml GCC/1x.x.x matplotlib` loads with all dependencies.
  - Matplotlib/3.9.2 has a malfunctioning display backend on COSMOS

Code along to get started!

Project: lu2025-7-37 on COSMOS

Pyplot: the Workhorse

The minimum working matplotlib code will virtually always require you to import matplotlib.pyplot (and usually also NumPy)

- Provides MATLAB-like functions to create or alter plots and their components
- In older code you may see matplotlib.pylab, which is now deprecated and risks overwriting some built-in functions.

Standard call: `from matplotlib import pyplot as plt`
If in Jupyter, add `%matplotlib inline` after import line

Minimal working examples

Single data series, no typesetting (implicit application programming interface, or API):

```
from matplotlib import pyplot as plt

plt.plot( x, y, 'k-' )
plt.xlabel('X')
plt.ylabel('Y')
plt.show()
```

Format string may include single-letter color specifier & linestyle specifier (‘-’, ‘:’, ‘-.’, ‘--’). Will show more options later.

Any data you want to add to, typeset, or include as a subplot (explicit API):

```
from matplotlib import pyplot as plt

fig, ax = plt.subplots(**kwargs)
ax.plot( x, y, 'k-' )
ax.set_xlabel('X')
ax.set_ylabel('Y')
plt.show()
```

Formatting commands for axis objects typically have `set_` in front

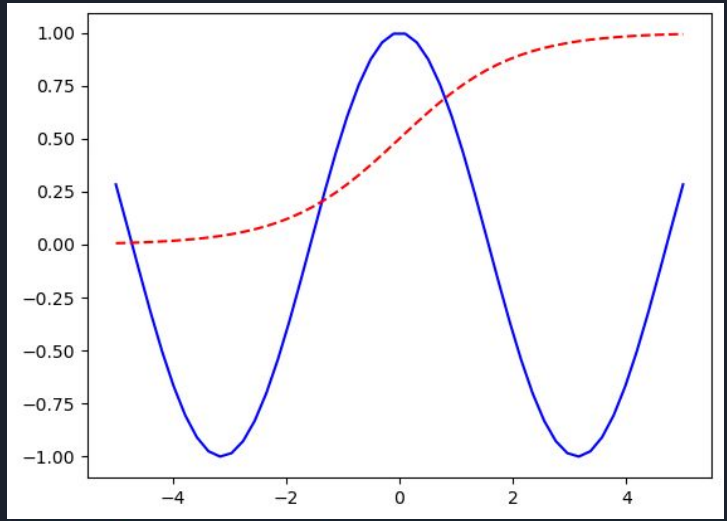
Now you try!

Let x = np.linspace(-5, 5, 50).

On the same axes, plot

- np.cos(x) as a solid blue line, &
- 1/(1-np.exp(-x)) as a dashed red line

Use the *explicit* API. We will come back to this plot later to add to it.




```
import numpy as np
import matplotlib.pyplot as plt
#import matplotlib as mpl
#mpl.use('TkAgg') #use at command line
#mpl.use('Qt5Agg') #if PyQt5 loaded

x = np.linspace(-5,5)
fig, ax = plt.subplots()
ax.plot(x, np.cos(x),'b-')
ax.plot(x, 1/(1+np.exp(-x)), 'r-')
plt.show()
```

Labels, Legends, & Titles

Set x & y axis labels & plot title:

```
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.set_title('[Sub]plot Title')
```

for the *explicit* API, or

```
plt.xlabel('X')
plt.ylabel('Y')
plt.title('Plot Title')
```

for the *implicit* API.

To title a figure with subplots (always explicit API), use fig.suptitle()

Most plotting functions include a label kwarg to pass to ax.legend().

- Control legend position with loc (in plot area) or bbox_to_anchor (in or out of plot area; more exact)
- Some plotting functions (e.g. .bar()) take array of labels as 1st arg instead of label kwarg
- Can explicitly pass lines/data handles & labels for e.g. multiple sets of contours

Placement of Text, Legends, etc.

2 functions for adding text to plots at arbitrary points: .annotate() & .text()

- .text() is base function; it only adds & formats text
- .annotate() adds & formats connectors (e.g., arrows) from points to text
- Positions for both are in data coordinates by default unless ax.transAxes is used

ax.transAxes switches from data coordinates to axes-relative coordinates where x & y axes are unit length & (0,0) is lower left corner.

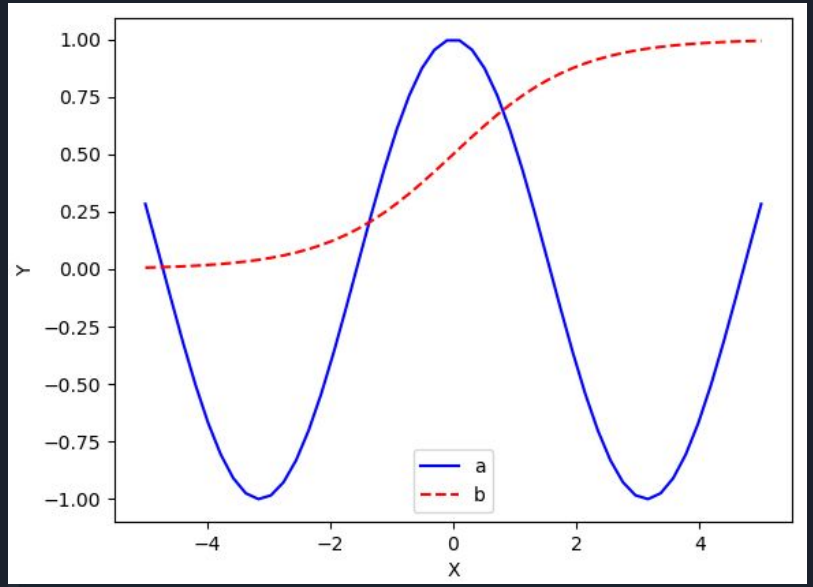
Legend placement via bbox_to_anchor uses unit-axes coordinates by default.

- Legend position loc can be set to integer or 2-word string like 'lower left' or 'upper center'
- Whole-figure legends can use loc='outside <va> <ha>'

Now you try!

Return to your earlier plotting code. Label the horizontal & vertical axes “X” & “Y”, respectively. Label the blue solid curve “a” & the red dashed curve “b”. Add a legend to the plot in the lower center.

*If you plotted both lines in the same plot() command earlier, you will have to split them up.



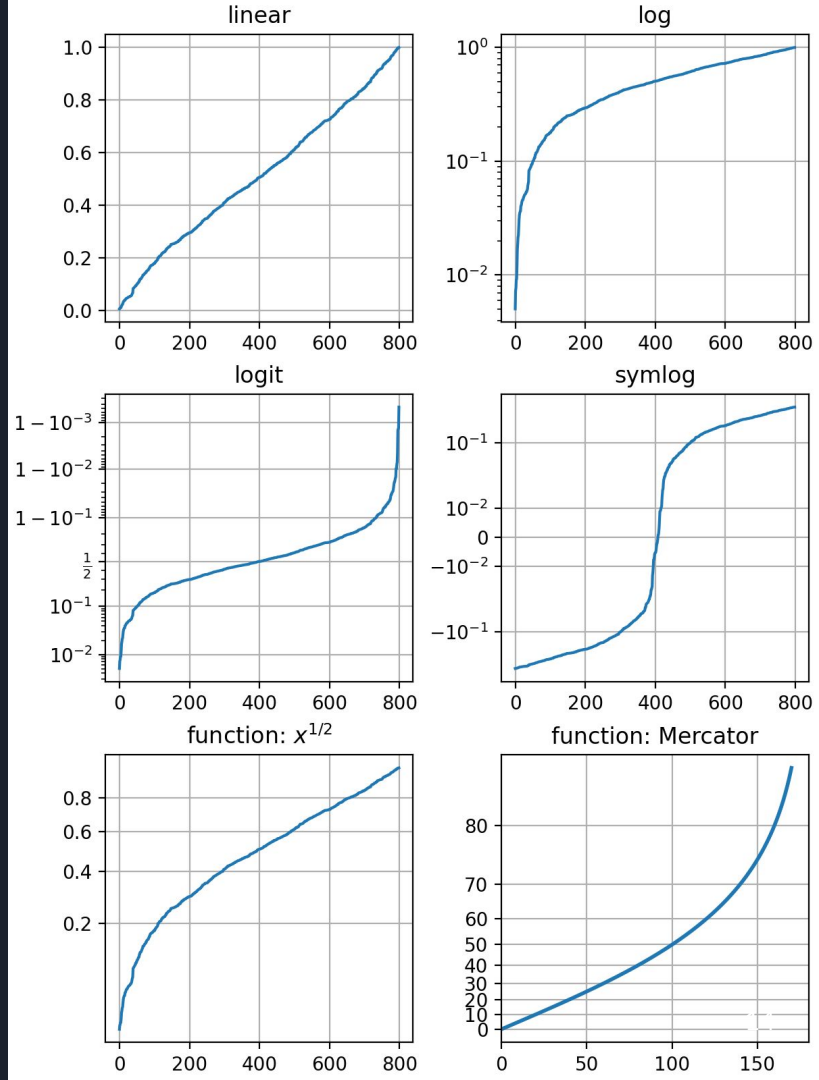

```
x = np.linspace(-5,5)
fig, ax = plt.subplots()
ax.plot(x, np.cos(x),'b-', label='a')
ax.plot(x, 1/(1+np.exp(-x)), 'r--',label='b')
ax.set_xlabel('X')
ax.set_ylabel('Y')
ax.legend(loc='lower center')
plt.show()
```

Axis Scales

Some plotting functions have xscale & yscale kwargs. For others, you can set ax.set_xscale()/ax.set_yscale():

- If scale arg is 'function', must define both forward & reverse transformations & pass as tuple of function names
- Axes scales can be shared across subplots

Usually automatic tick spacing is fine. If not, refer to these examples



Subplots

Axes created with plt.subplot**s**() are **iterable** if nrows &/or ncols are >1. These can be set to share x & y axes labels, & .subplots_adjust() can adjust or remove column/row spacing:

```
fig, axes = plt.subplots(nrows=3, ncols=2, sharex=True,
        sharey=True)
plt.subplots_adjust(hspace=0, wspace=0)
for i in range(3):
  for j in range(2):
          k = (i%3)*2+j
          axes[i][j]=plt.plot(x,y[k])
          if j==0:
                  axes[i][j].set_ylabel('Y')
  if i==2:
          axes[i][j].set_xlabel('X')
```

plt.subplot() (singular) is more tedious but allows separate projections for each plot.

Example:

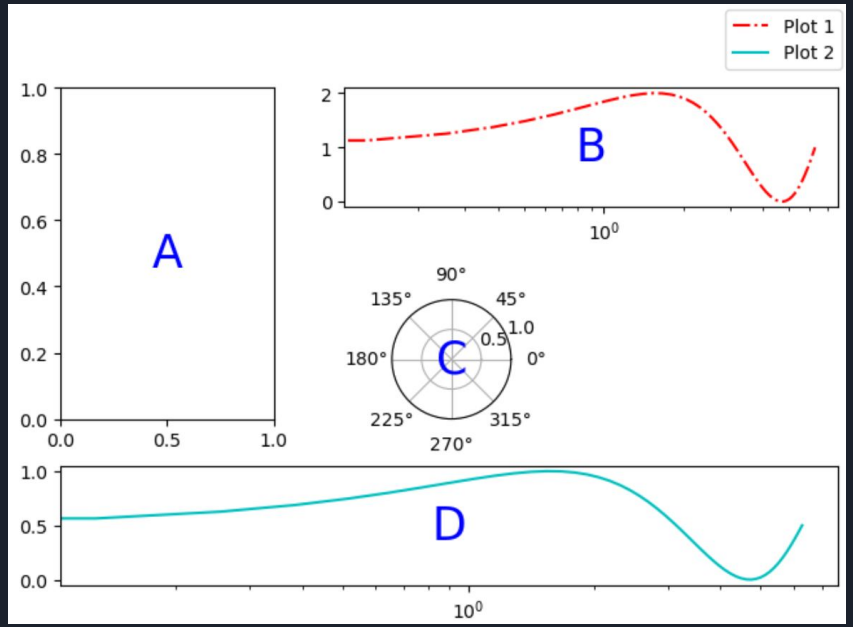
```
fig = plt.figure(figsize=(8,4))
ax1 = plt.subplot(121)
ax1.plot(x, 3+3*np.sin(x), 'b-')
ax1.set_xlabel('x [rads]')
ax1.set_ylabel('y')
ax2 = plt.subplot(122, projection= 'polar')
ax2.plot(x, 3+3*np.sin(x), 'b-')
```

Subplot Mosaics

The API for subplot mosaics lets you lay out subplots so some plots span multiple rows or columns (`"."` denotes gaps). Example:

```
fig, axd = plt.subplot_mosaic(
    """
    ABB
    AC.
    DDD
    """, layout="constrained",
    per_subplot_kw={"C": {"projection": "polar"},
                    ('B','D'): {'xscale':'log'}})
for k, ax in axd.items():
    ax.text(0.5, 0.5, k, transform=ax.transAxes,
            ha="center", va="center",  color="b",
            fontsize=25)
axd['B'].plot(x, 1+np.sin(x), 'r-.',
              label='Plot 1')
axd['D'].plot(x,0.5+0.5*np.sin(x), 'c-',
              label='Plot 2')
fig.legend(loc='outside upper right')
```

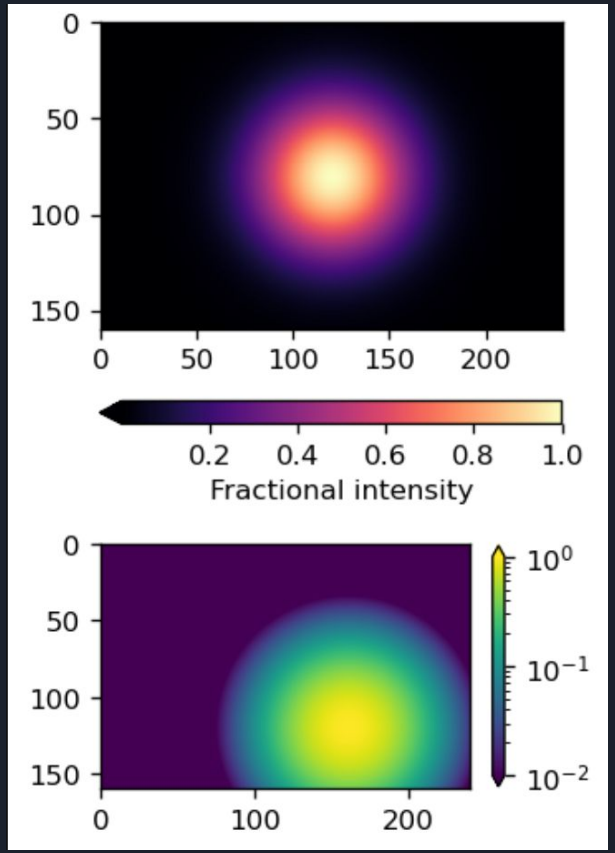
This layout can also be rendered `"ABB;AC.;DDD"`



Colorbars

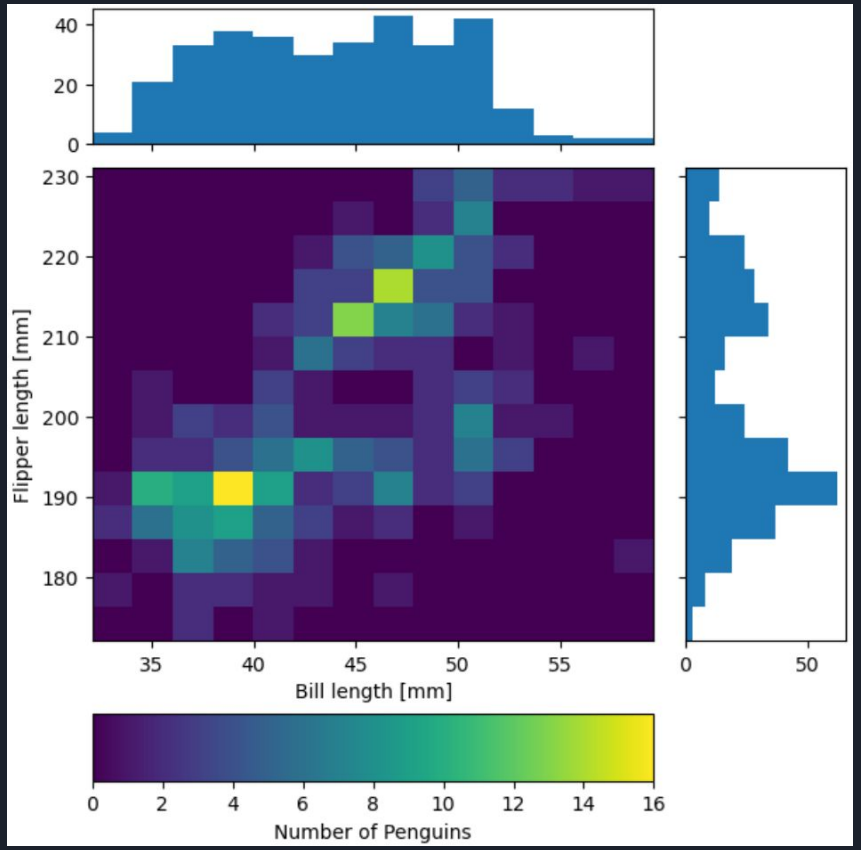
Colorbars are methods of Figure, not Axes. Axis objects must be passed to colorbar() explicitly, & first arg must be a mappable (a plot; check docs). Example:

```
fig, (ax1, ax2) = plt.subplots(nrows=2,
                               figsize=[3,6],
                               dpi=120)
plt.subplots_adjust(hspace=-0.1)
img1 = ax1.imshow(Z1, cmap='magma')
img2 = ax2.imshow(Z2, norm='log', vmin=0.01)
cbar1 = fig.colorbar(img1, ax=ax1, extend='min',
                     orientation='horizontal')
cbar1.set_label('Fractional intensity')

cbar2 = fig.colorbar(img2, ax=ax2, shrink=0.5,
                     extend='both')
```



```python
def corner_2p(x, y, ax2d, ax_histx, ax_histy):
    # no labels
    ax_histx.tick_params(axis="x", labelbottom=False)
    ax_histy.tick_params(axis="y", labelleft=False)

    nbins = int(np.ceil(2*len(x)**(1/3))) #Rice binning rule
    # the central 2D histogram:
    n,xb,yb,img = ax2d.hist2d(x, y, bins = [nbins,nbins])
    #use x- & y-bins from 2D histogram to align them
    ax_histx.hist(x, bins=xb)
    ax_histy.hist(y, bins=yb, orientation='horizontal')
    ax_histx.sharex(ax2d)
    ax_histy.sharey(ax2d)
    return img
```

```python
fig, axd = plt.subplot_mosaic("a.;Bc;d.",layout="constrained",
                              height_ratios=[1, 3.5, 0.5],
                              width_ratios=[3.5, 1],
                              figsize=(6,6), dpi=120)
jointhist = corner_2p(penguins.dropna()['bill_length_mm'],
                      penguins.dropna()['flipper_length_mm'],
                      axd['B'], axd['a'], axd['c'])
axd['B'].set_xlabel('Bill length [mm]')
axd['B'].set_ylabel('Flipper length [mm]')
cb = fig.colorbar(jointhist,cax=axd['d'],
                  orientation='horizontal')
cb.set_label('Number of Penguins')
```



Example: 1- & 2D histograms on a scaled subplot mosaic with a separate colorbar axis. Note that hist2d() returns 3 parameters before the mappable. Adapted from this.

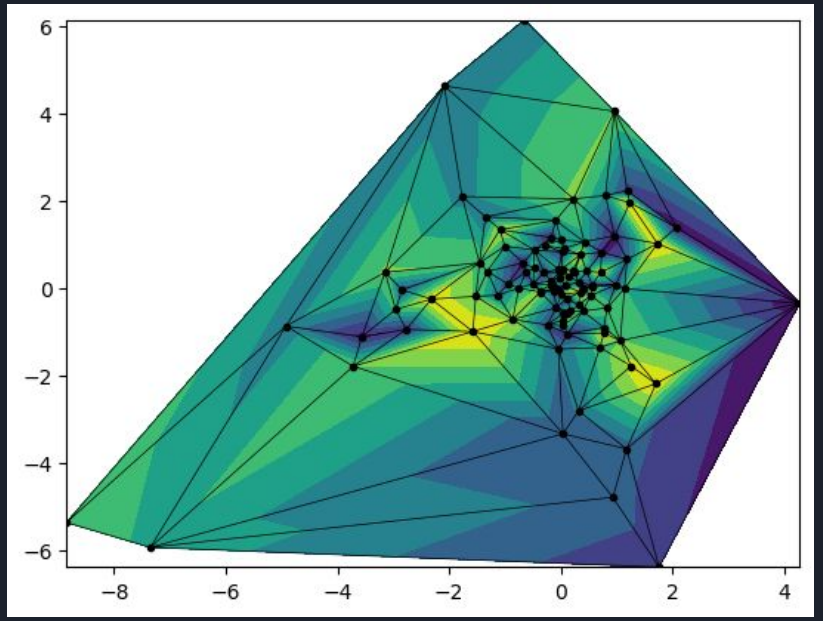
Figure Output Formats

Matplotlib's default figure size is 6.4" x 4.8" (16.26 x 12.19 cm) with 100 dpi resolution. Jupyter Lab's inline backend defaults to 80 dpi (usually too low).

- Adjust figure resolution, size, & aspect ratio with dpi & figsize kwargs (*figsize in inches*) in plt.figure() or plt.subplots() at runtime, or plt.savefig() or plt.imsave() (RGB[A] images) for only the saved figure
- **Recommended output format: PDF (widely supported & efficient).**
    - PNG (default) is large in memory, JPEG is lossy, & (E)PS requires special viewers & lacks transparency support.

Full plot type browser with documentation here: https://matplotlib.org/stable/plot_types/index.html

Note on Irregularly Gridded Data



tricontour, & tricontourf on one plot

triplot, tripcolor, tricontour, & tricontourf are all based on triangular meshes (x,y) with values at vertices (z)

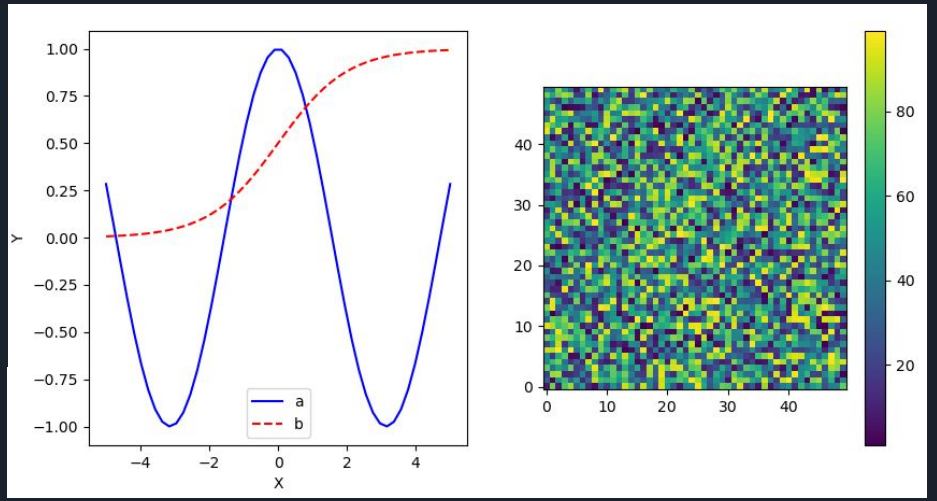
- Only contour or shade the mesh if points are spatially correlated; otherwise, indicate z (value at x,y) with marker size/color or something else.
- **Not to be used for contouring/shading by point *density*!** If you want that, you want a histogram or KDE plot, & will have to interpolate to a regular grid.

Now you try!

Return to your earlier plot code. Let Z = np.random.randint(1, 100, (50,50))

Plot Z with imshow() on a second set of axes, with the bottom left corner at (0,0), & add a colorbar. Adjust figsize to keep the subplots roughly square.

```
fig, axes = plt.subplots(ncols=2, figsize=(10,5))
axes[0].plot(x, np.cos(x),'b-', label='a')
axes[0].plot(x, 1/(1+np.exp(-x)), 'r--',label='b')
axes[0].set_xlabel('X')
axes[0].set_ylabel('Y')
axes[0].legend(loc='lower center')
Z = np.random.randint(1, 100, (50,50))
img = axes[1].imshow(Z, origin='lower')
cb = plt.colorbar(img)
plt.show()
```



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Questions?

Part 2. Formatting & Accessibility

Elements of Plot Accessibility

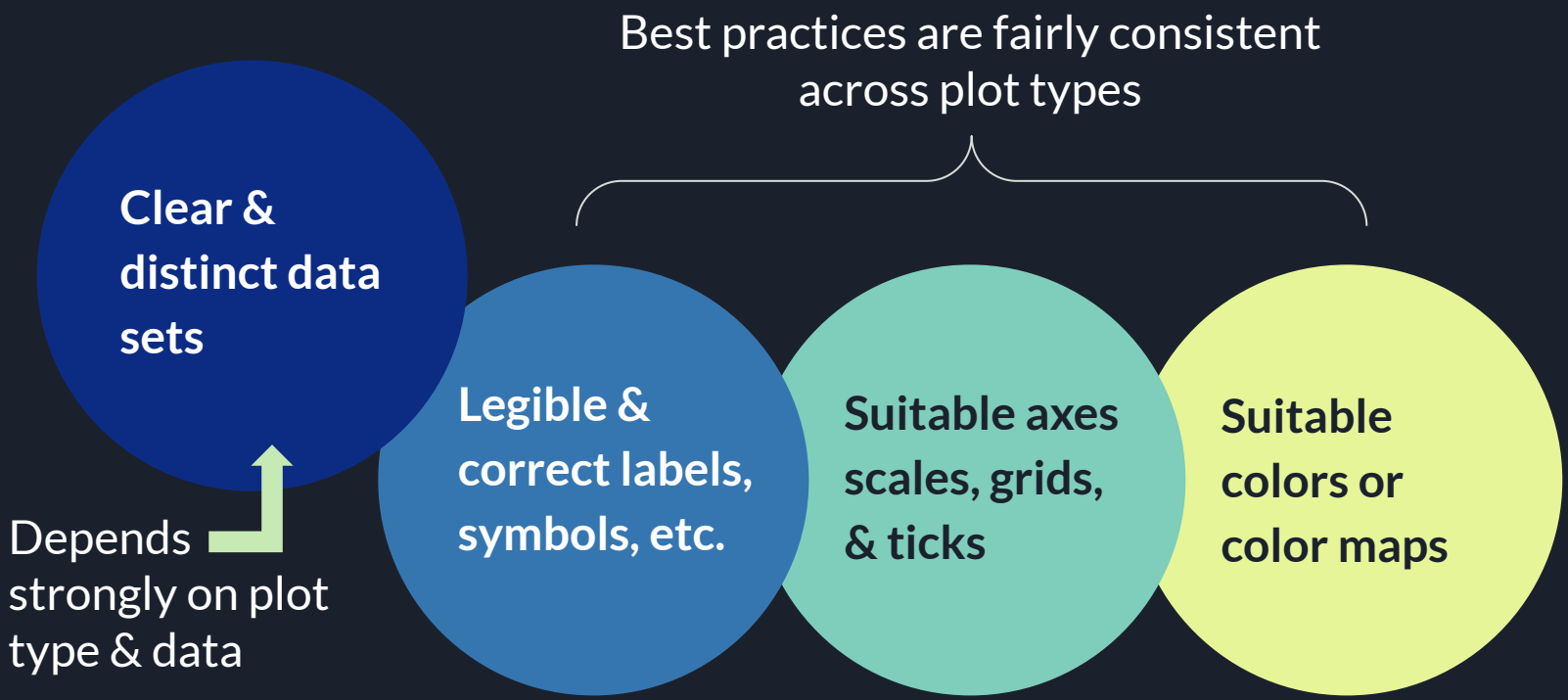


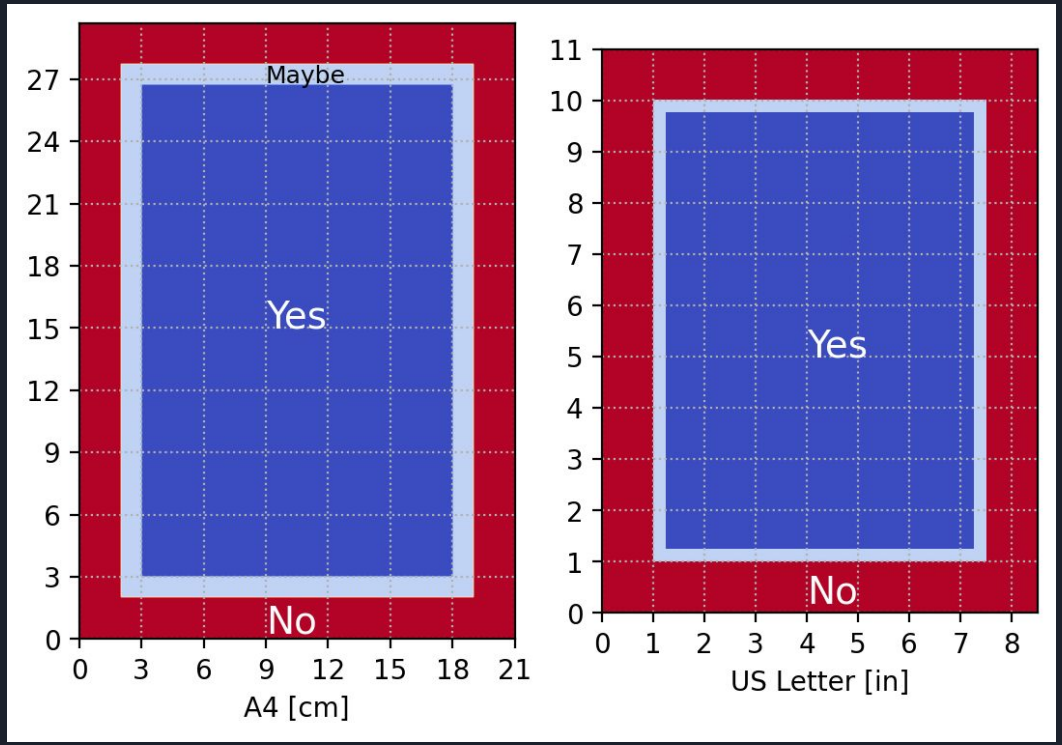
Figure sizes

Maximum figure size is determined by the journal's printable area, especially the width along the minor axis.

Format	Dimensions	Margins	Printable area
A4	21 × 29.7 cm *8.3" × 11.7"*	2-3 cm *0.8-1.2"*	15-17 × 23.7-25.7 cm *6-6.5" × 9.3-10.1"*
US Letter	8.5" × 11" *21.6 × 27.9 cm*	1-1.25" *2.5-3.2 cm*	*6-6.5" × 8.5-9"* *15-17 × 21.6-22.9 cm*

Sub-Figure Sizes

- Minimum subfigure size varies, but try to avoid panels <1” or <3 cm on a side (labels get too small)
- Color bars, axis labels, & captions take up space, too, so roughly 4×6 subplots max



Matplotlib & LaTeX

Need to know LaTeX basics to typeset plot text & symbols as they appear in journal text:

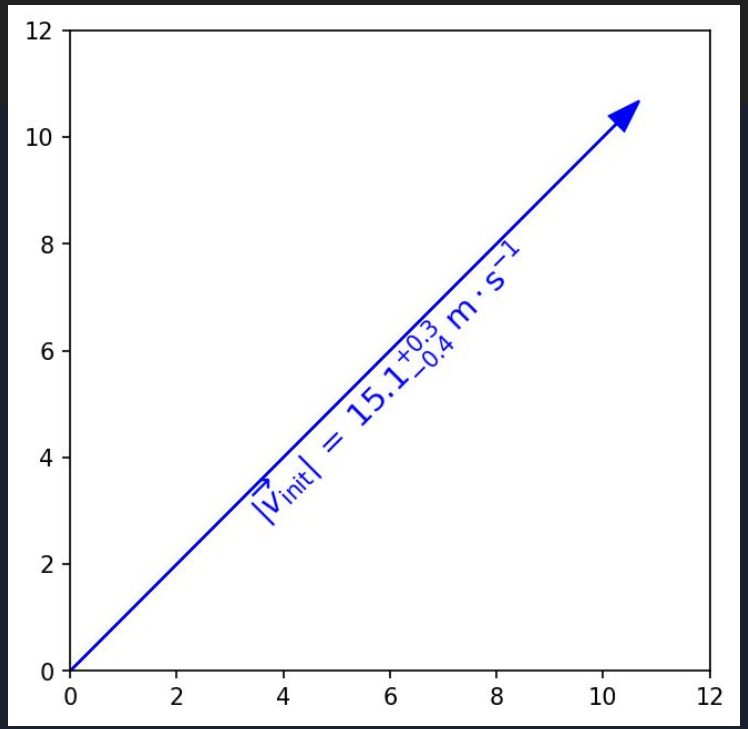
- LaTeX expressions (even just italicized variables) must be bracketed by '$ $' (US dollar signs); e.g., "sin(A)" to render sin(A)
- Syntax of most LaTeX functions to modify characters: "$\function{char}$"
    - Superscript ("^") & subscript ("_") operators without "{}" only work on the first character that follows.
- Conventionally italicized (math-text) letters indicate variables. Use \mathrm{char} to un-italicize letters in, e.g. super- or subscripts
- See Matplotlib's mathtext docs for symbols, operators, & other commands

Matplotlib & LaTeX (Cont.)

- String insertion (‘{ }’.format()) creates conflict between Matplotlib & LaTeX → must double all {} associated with LaTeX commands
- Most Greek letters & ±/∓ symbols require the input string to have r before the first quote mark (e.g., r'β' prints β)
- Operators with special meanings in LaTeX or Python (e.g. %, $, [], &, ~, #) must have backslash(es) (\ for LaTeX commands, \\ for Python operators) to render as text.
- Spaces inside $$ are not rendered: use \, or \: or \; to insert them
  - \! removes unwanted space (e.g. after > or <)

```
v_init=15.1
error_arr=[-0.4,0.3]
fig,ax=plt.subplots(dpi=150,figsize=(5,5))
ax.set_aspect('equal') #arrowheads will slant if axes are not equal
ax.arrow(0,0,10.68,10.68,length_includes_head=True,color='b',
         head_width=0.4)
ax.text(6, 5.4, r"$|\vec{{v}}_{{\mathrm{{init}}}}|$ = ${:.1f}_{{{:.1}}}^{{+{:.1}}}\;\mathrm{{m\cdot s}}^{{-1}}$".format(v_init,*error_arr),
        ha='center',va='center',rotation=45.,size=14, color='b')

ax.set_xlim(0,12)
ax.set_ylim(0,12)
plt.show()
```



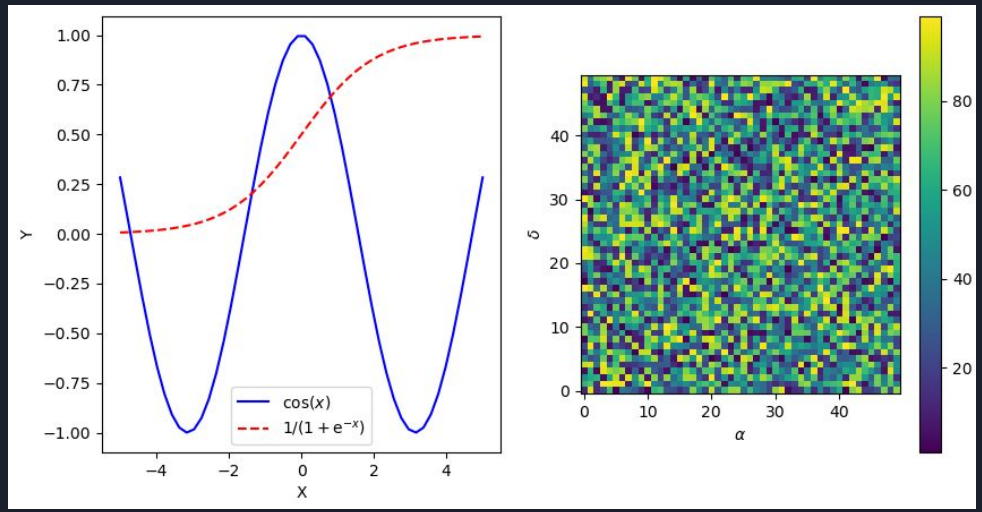
No, you cannot break the string over multiple lines with a backslash, even outside of a TeX expression. A backslash with nothing after it is treated like \n but leaves the '\' in the output.

Now You Try!

Return to your plotting code from the first lecture. Replace the “a” & “b” line labels with mathtext typeset equations (in-line fractions are fine). For the image, label the horizontal axis “α” (Greek alpha) & the vertical axis “δ” (delta).

```
fig, axes = plt.subplots(ncols=2, figsize=(10,5))
axes[0].plot(x, np.cos(x),'b-', label=r'cos($x$)')
axes[0].plot(x, 1/(1+np.exp(-x)), 'r--',
             label=r'$1/(1+\mathrm{e}^{-x})$')
axes[0].set_xlabel('X', fontsize=14)
axes[0].set_ylabel('Y', fontsize=14)
axes[0].legend(loc='lower center')

Z = np.random.randint(1, 100, (50,50))
img = axes[1].imshow(Z, origin='lower')
axes[1].set_xlabel(r'$\alpha$', fontsize=14)
axes[1].set_ylabel(r'$\delta$', fontsize=14)
cb = plt.colorbar(img)
plt.show()
```



Axis Ticks

Matplotlib's default is outward-pointing ticks on the left & bottom. Ticks on all sides are preferred for readability.

- To add outward ticks on top and right:

```
ax.tick_params(axis='both', which='both', top=True, right=True)
```

- To set inward ticks all the way around:

```
ax.xaxis.set_tick_params(direction='in', which='both')
ax.yaxis.set_tick_params(direction='in', which='both')
ax.tick_params(axis='both', which='both', top=True, right=True)
```

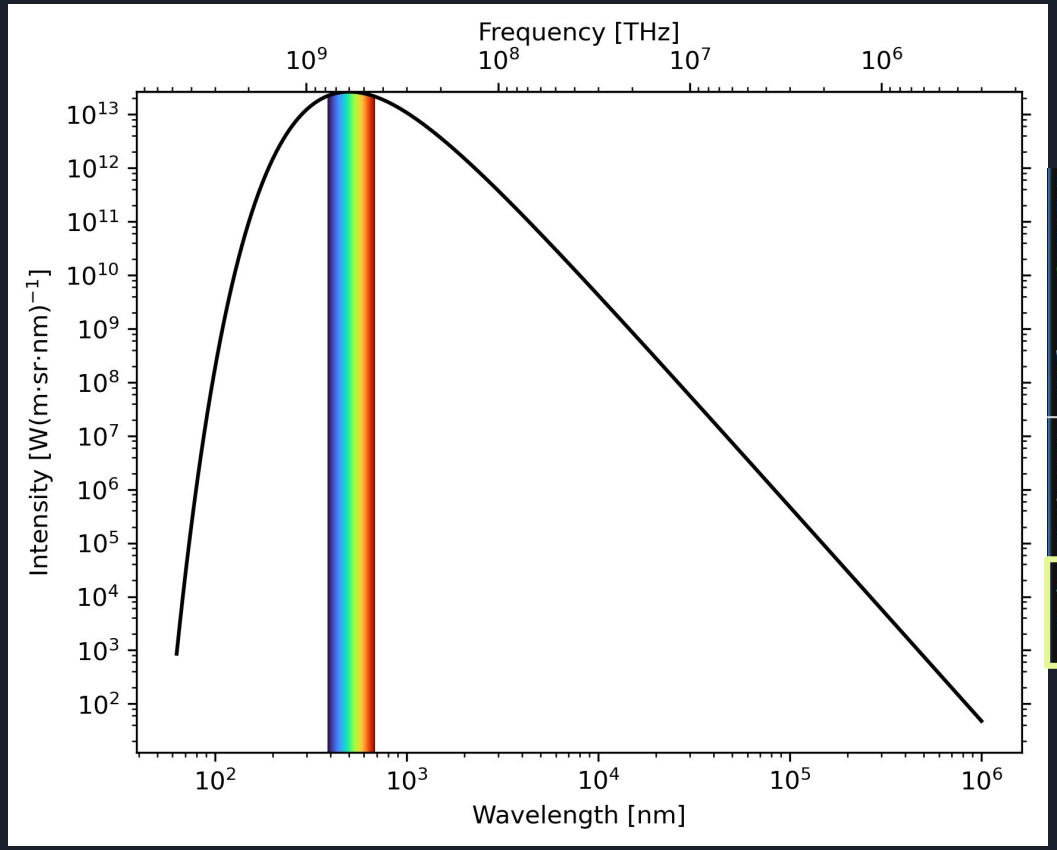
Remember: **Be consistent throughout your article!**

Tick Labels & Locators

May need to modify or manually set tick locators & labels if you want:

- Units with special formats or symbols (dates, fractions, money, etc.)
- Categorical variables (e.g. countries, species, sex, etc.)
- Axis tick labels centered between major ticks
- Secondary axes that are transformations of the primary axes
- Custom or power-law axis scales
- Log-, symlog-, or asinh scaling with labels on every decade & visible minor ticks over >7 decades

on one or more axes, or if you want any of the above on a colorbar.



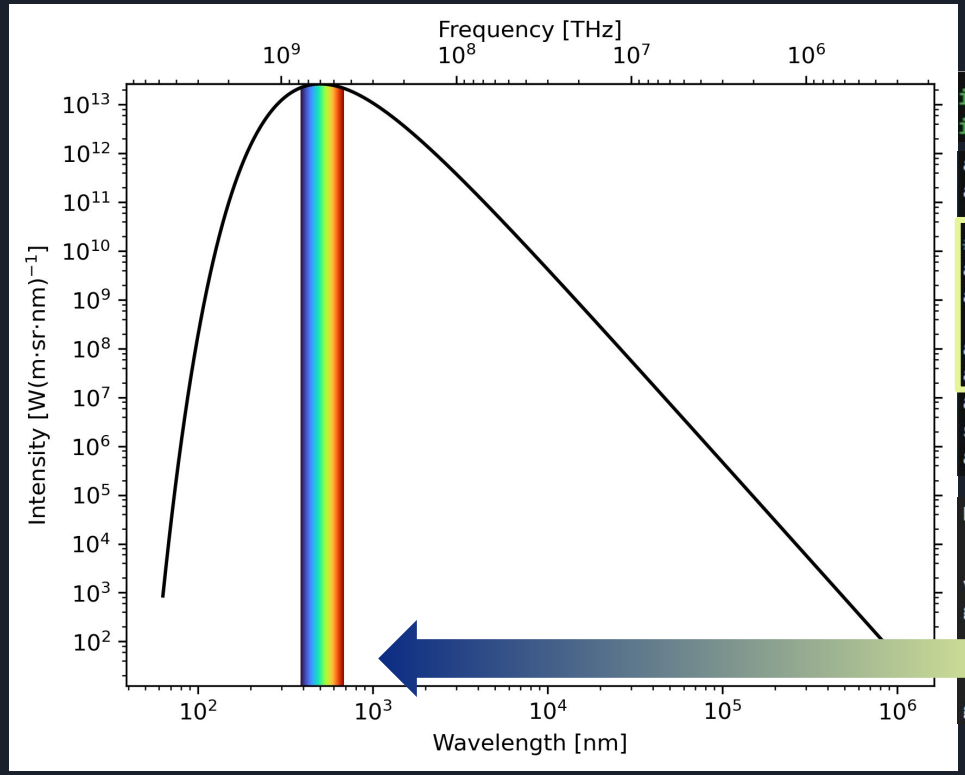

```
c = 2.998*10**8.
k_b = 1.380649*10**-23.
hc = (2.998*10**8.)*(6.626*10**-34.)
def bb(wvl,T):
    return ((2*hc*c)/(wvl**5)) * 1/(np.exp(hc/(wvl*k_b*T)) - 1)

wvs = np.logspace(-7.2,-3.0,471)
bb5777 = bb(wvs,5777.)
```

```
import matplotlib as mpl
import matplotlib.ticker as ticks
fig, ax = plt.subplots(dpi=300)
ax.plot(wvs*10**9,bb5777,'k-')
```

```
# 1 nm = 10^-9 m, 1 THz = 10^12 Hz
secax = ax.secondary_xaxis('top',functions=(lambda x: 1000*c/x,
                                            lambda x: 0.001*c/x))
```

Example of ax.secondary_xaxis('top', functions=(prim2sec,sec2prim)) & mpl.ticker.LogLocator()




```
import matplotlib as mpl
import matplotlib.ticker as ticks
```

```
ax.set_xscale('log')
ax.set_yscale('log')
```

```
# PAY SPECIAL ATTENTION TO THE NEXT 4 LINES
ax.yaxis.set_major_locator(ticks.LogLocator(base=10,numticks=99))
ax.yaxis.set_minor_locator(ticks.LogLocator(base=10.0,subs=(0.2,0.4,0.6,0.8),
                                            numticks=99))
ax.yaxis.set_minor_formatter(ticks.NullFormatter())
ax.tick_params(axis='y',which='both',right=True)
```

```
ax.set_xlabel('Wavelength [nm]')
secax.set_xlabel('Frequency [THz]')
ax.set_ylabel('Intensity [W(m$\cdot$sr$\cdot$nm)$^{-1}$]')
```

```
poly=ax.fill_between(wvs[np.where(np.logical_and(wvs>3.8*10**-7,wvs<7*10**-7))]*10**9,
                     bb5777[np.where(np.logical_and(wvs>3.8*10**-7,wvs<7*10**-7))],
                     color='none') #mark off polygon to fill later
verts = np.vstack([p.vertices for p in poly.get_paths()])
gradient = plt.imshow(np.linspace(0,1, 256).reshape(1, -1),
                      cmap=mpl.colormaps['turbo'], aspect='auto',
                      extent=[verts[:, 0].min(), verts[:, 0].max(),
                              verts[:, 1].min(), verts[:, 1].max()])
gradient.set_clip_path(poly.get_paths()[0], transform=plt.gca().transData)
```

In case you're interested in the rainbow

Example of ax.secondary_xaxis('top',functions=(prim2sec,sec2prim)) & mpl.ticker.LogLocator()

Final notes on ticks & tick locators

For color bars, use ticks & format kwargs of colorbar()

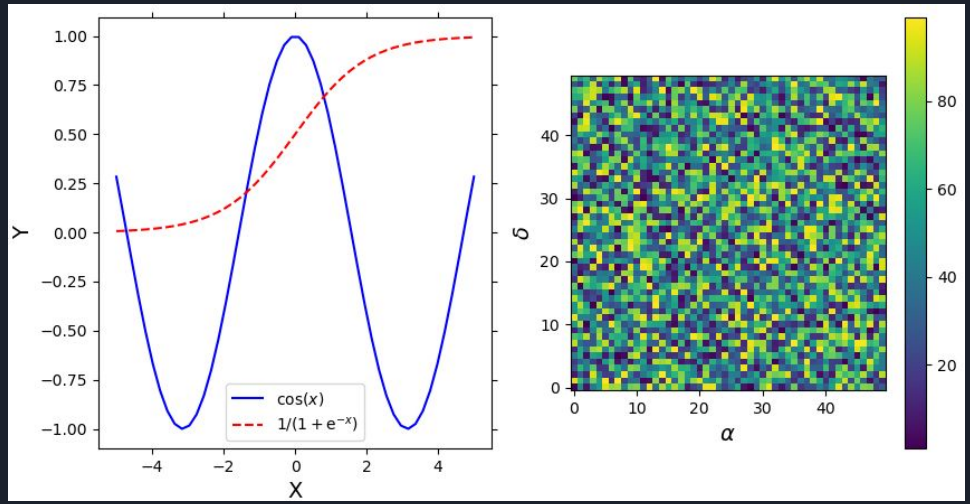
- Format kwarg accepts all the same locator functions as ax.[x|y]axis.set_[major|minor]_locator()

Scales that are neither linear nor logarithmic are not suitable for histograms, contours, or image-like data

- Contours don’t work well with log axes either; must work in log units & use tick label formatters to override the labels

Code Along!

Call .tick_params(axis='both', which='both', top=True, right=True) on the first (left) axis object of your plotting code to turn on axis ticks on the right and top axes.



Grids

Essential for non-Cartesian coordinate systems, discouraged otherwise. Matplotlib defaults reflect this (for polar & axes3d plots)

- Newer releases include matplotlib.projections.geo → support for map projections (like Mollweide), with customizable GeoAxes base class (examples lacking in docs).
- Matplotlib also accepts AstroPy WCS as axes transformations.
- Syntax sample: ax.grid(ls=':', color='silver', lw=2) turns grid on with defaults altered. Leave () empty to turn on default grid

Grids & data format

Images & 2D histograms: use contrasting but neutral color; best line style depends on variability of image data

Scattered data: choose light, thin, solid lines in a neutral color.

- Set zorder=0 to put grid behind sparse data. Leave grid atop dense data
- Online-only figures: can use styles with light grids on dark backdrop

Lines, bars, & stems: thin lines in neutral color set behind data

- **Bar & stem plots:** only turn on grid lines perpendicular to the bars/stems using the which kwarg of grid()

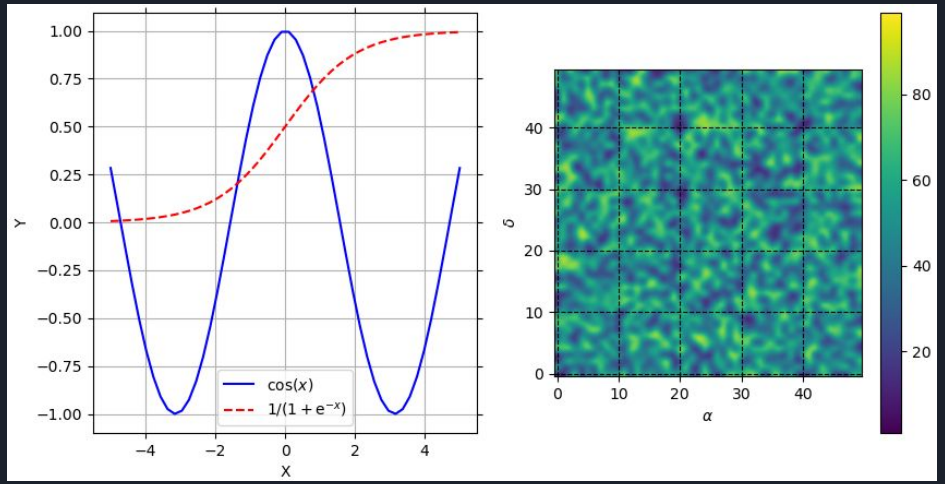
Now You Try!

Return to your code-along code & add interpolation='bicubic' as a kwarg to the imshow() plot (it makes gridlines easier to see). Then turn on grids for both plots. Use the defaults on the left plot & black dashed lines on the right.

Solutions:

Left: axes[0].grid()

Right:
axes[1].grid(color='k', ls='--')



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Questions?

Part 2. Formatting & Accessibility (Continued)

Fonts & Font Sizes

Text base class & all derivatives (titles, legends, etc.) have fontsize kwarg.

- Most journals set hard minimum font size ~9-10 pt. **Prefer 11-14 pt font** & **err larger for older readers**.
- Pick a common font style (or similar) & stick with it. Default is fine.
  - No consensus whether serif or sans-serif fonts are more legible

Setting Fonts with rcParams

plt.rcParams['font.size'] = 14 sets all labels to size 14 font, for example. Can set font family as shown below:

```
import matplotlib as mpl
### To select a sans-serif font:
mpl.rc('font',**{'family':'sans-serif','sans-serif':['Helvetica']})
### To select a serif font:
#mpl.rc('font',**{'family':'serif','serif':['Liberation Serif']})
mpl.rc('text', usetex=False)
```

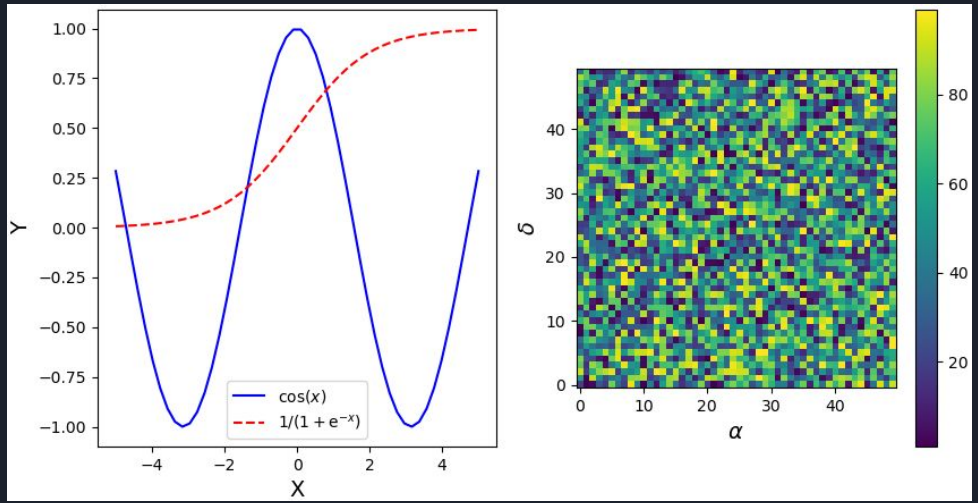
Don't set usetex=True unless you want to ensure italicized serif math text AND you have very obscure LaTeX symbols to typeset.

```
### To reset to defaults:
mpl.rcParams.update(mpl.rcParamsDefault)
```

Now You Try!

Return to your plotting code from the past several “Now You Try!” exercises. Increase the font sizes of the X & Y axes labels to size 14.

```
fig, axes = plt.subplots(ncols=2, figsize=(10,5))
axes[0].plot(x, np.cos(x),'b-', label=r'cos($x$)')
axes[0].plot(x, 1/(1+np.exp(-x)), 'r--',
             label=r'$1/(1+\mathrm{e}^{-x})$')
axes[0].set_xlabel('X', fontsize=14)
axes[0].set_ylabel('Y', fontsize=14)
axes[0].legend(loc='lower center')

Z = np.random.randint(1, 100, (50,50))
img = axes[1].imshow(Z, origin='lower')
axes[1].set_xlabel(r'$\alpha$', fontsize=14)
axes[1].set_ylabel(r'$\delta$', fontsize=14)
cb = plt.colorbar(img)
plt.show()
```



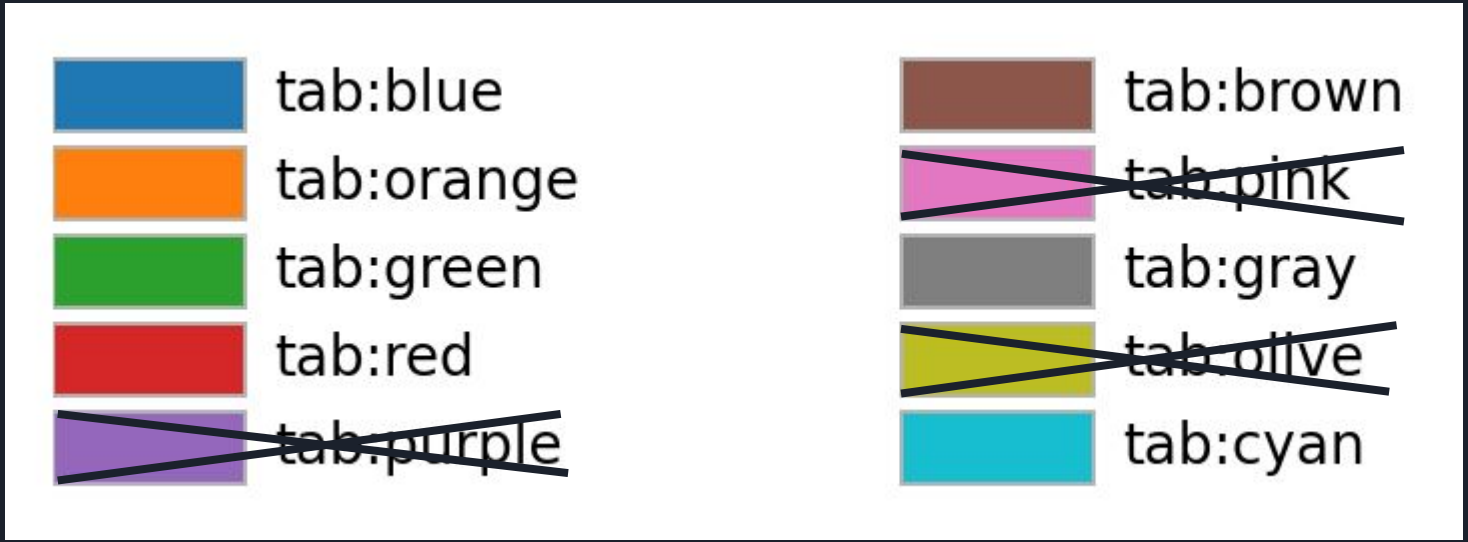
Choosing color palettes

Color blindness affects 1/12 people with 1 X-chromosome & 1/200 with at least 2 X chromosomes; try to make plots colorblind friendly.

- Lots of online simulators to help → I like Coblis

Shades of **blue** & **orange** are most easily distinguished colors for all 3 types of dichromacy (& the best 3rd color is either gray or cyan).

- Can import Tableau's colorblind10 palette with `plt.style.use('tableau-colorblind10')` (more on styles later)
- Can use `plt.colormaps['your_cmap'](np.linspace(0.1, 0.9, n))` to generate *n*-color palettes from colormap



Default color cycle is not very good for >4 colors

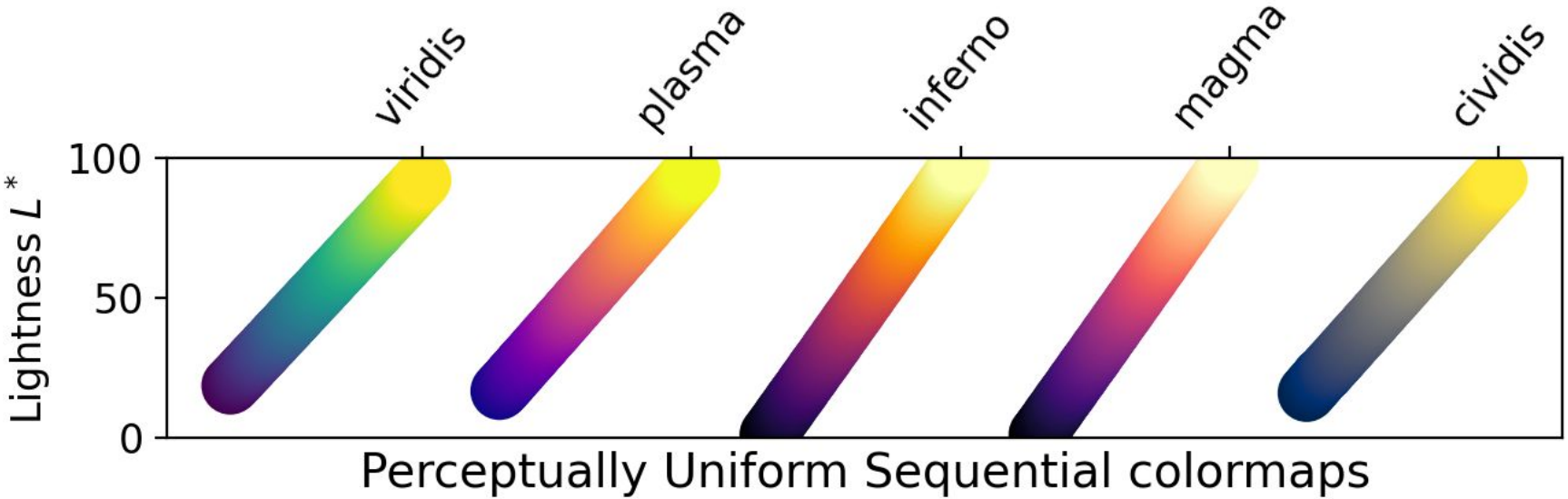
But should vary marker/line styles for >4 data sets anyway

Choosing colormaps

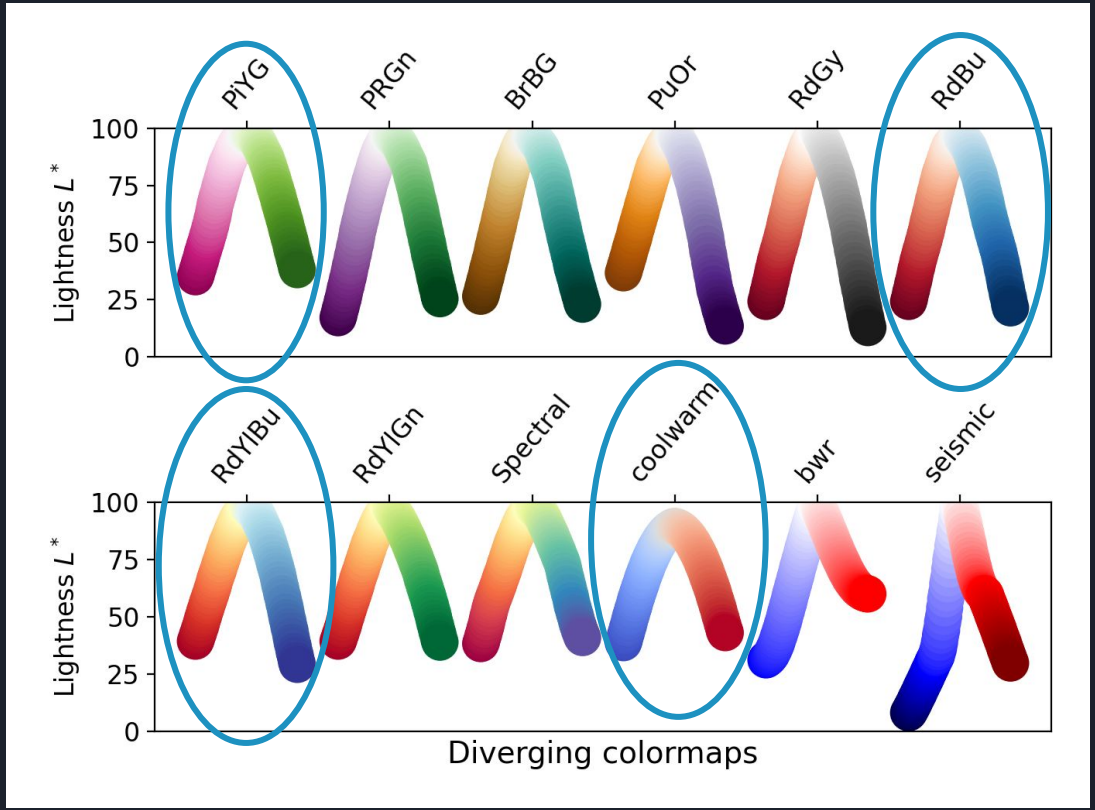
Matplotlib docs mostly cover this. In short, consider:

- **Data type requirements:** should colormap be sequential, diverging, cyclical (only 1 good option), or categorical?
- **Dynamic range:** enough contrast between lights & darks?
- **Monotonicity:** does brightness vary smoothly & linearly so that it still reads correctly in black & white?

Note: all colormaps can be reversed by appending '_r' to colormap name string.



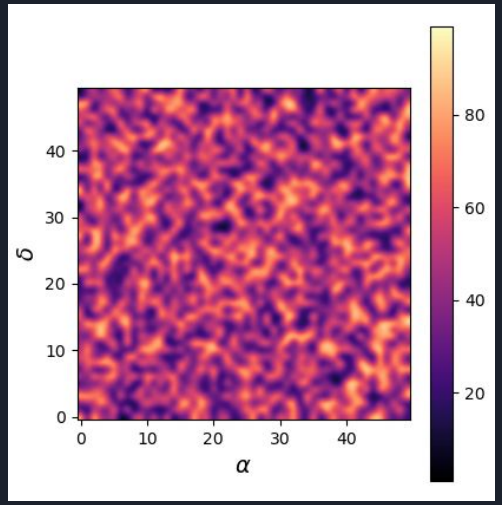
These 5, ‘binary’, ‘gray’, & ‘bone’ are good sequential colormaps.
The rest…not so much. Avoid ‘rainbow’ & ‘jet’.



Avoid diverging color maps with very different lightness at each end.
For that & colorblind accessibility, avoid the colormaps not circled.

Now You Try!

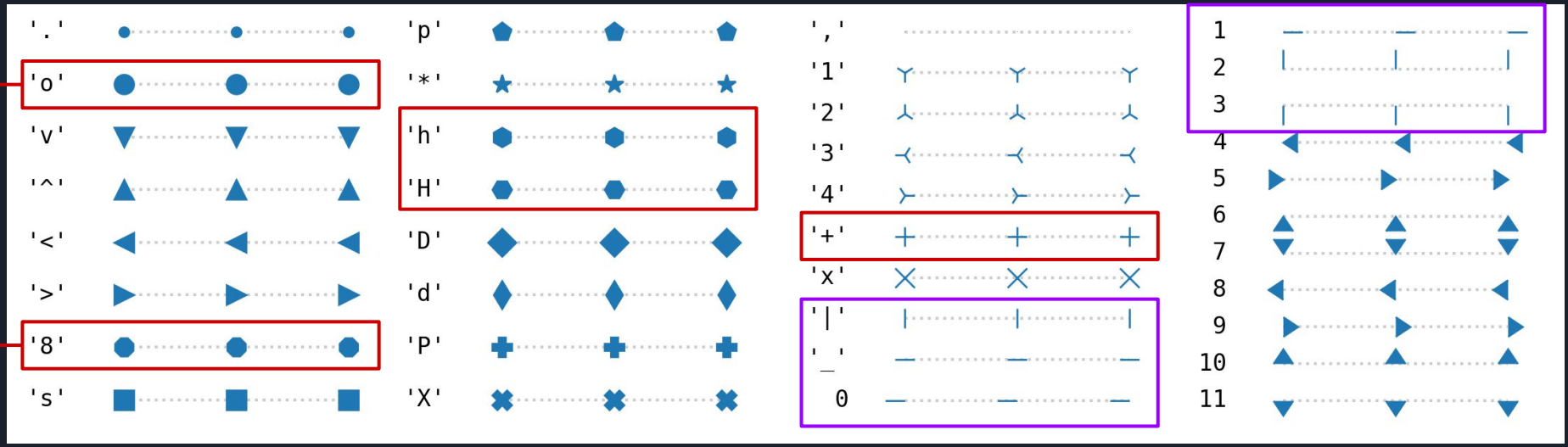
Return to your plotting code & change the color map for the image to ‘magma’.



All you had to do was add cmap=‘magma’ to the list of kwargs in imshow().

Most plots now have a cmap kwarg if it makes sense & accept color map names as strings. Older versions & other color-related functions may require you to import matplotlib.colors & select the colormap like a dict entry, e.g. matplotlib.colors[‘magma’]

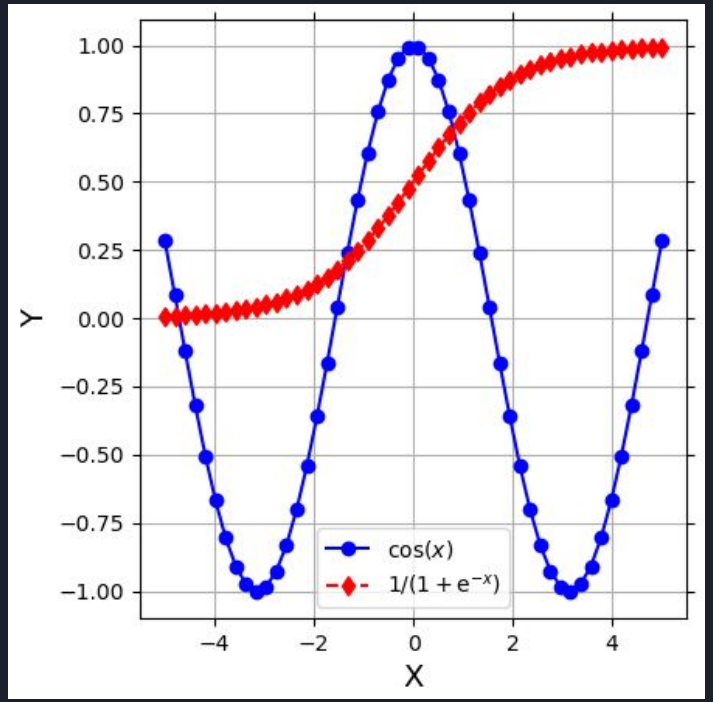
Choosing Markers



- If using easily confused shapes or the same shape in different rotations, choose different colors with different values (brightness)
- “+” can be confused for error bars if error bars don’t have caps.
- Reserve | & – for specialty plots (event plots & rug plots)

Now you try!

Return to your plotting code & add markers to the red & blue lines in the left panel. Use large circles (‘o’) for the blue cosine curve, & diamonds/rhombuses (‘d’) for the exponential curve. All you have to do is add a shape code to each format string.

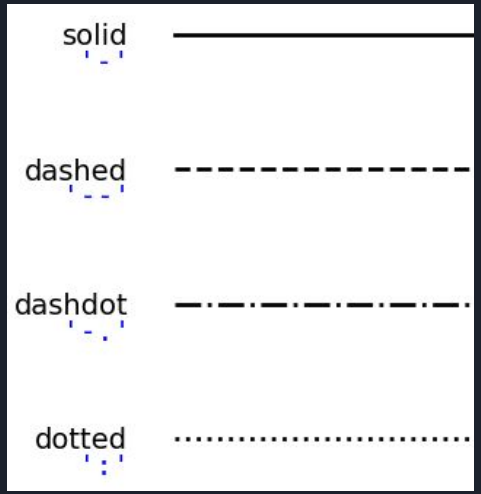



```
axes[0].plot(x, np.cos(x),'bo-',  label=r'cos($x$)')
axes[0].plot(x, 1/(1+np.exp(-x)), 'rd--',
             label=r'$1/(1+\mathrm{e}^{-x})$')
```

Choosing Line Styles

Line styles vary in clarity → unspoken hierarchy to consider for your narrative (subject to change if you adjust dash/dot spacing)

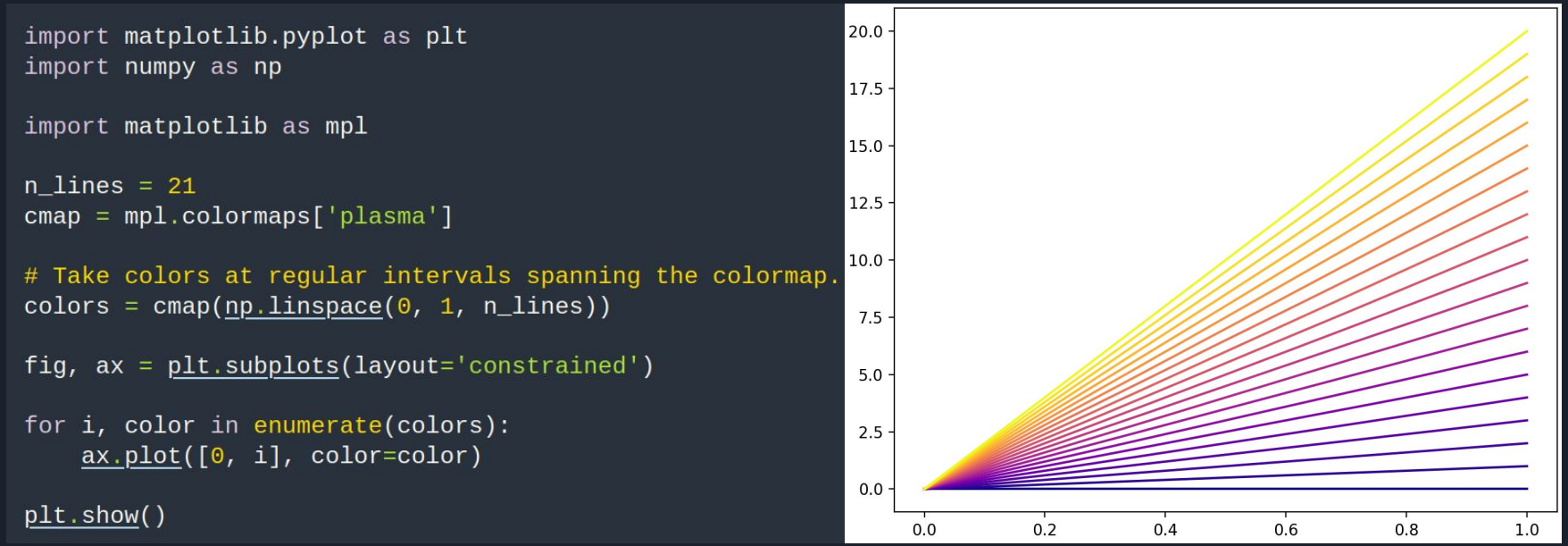
1. Solid lines (ls='-'): clearest → **most important**
2. Dashed lines (ls='--') (could argue if #2 or #3)
3. Dash-dotted lines (ls='-.') (↑ ditto)
4. Dotted lines (ls=':'): easiest to lose among scattered data → **least important**



Practical limits of lines

Max # of lines per figure depends heavily on other content.

- Lines with error margins &/or underlying scattered data: **4-5 curves** depending on whether overlying data have color
- Lines without error margins & no underlying scattered data:
  - **8-10 independent curves** of similar importance
  - **10-20 curves** in a hierarchy, with little to no crossing
  - Many if data are correlated & evolving with a 3rd variable (e.g., monthly mean temperatures over years - let older curves fade out)



```
import matplotlib.pyplot as plt
import numpy as np

import matplotlib as mpl

n_lines = 21
cmap = mpl.colormaps['plasma']

# Take colors at regular intervals spanning the colormap.
colors = cmap(np.linspace(0, 1, n_lines))

fig, ax = plt.subplots(layout='constrained')

for i, color in enumerate(colors):
    ax.plot([0, i], color=color)

plt.show()
```


Example: 21 lines of increasing slope, with colors drawn from a colormap

Questions?

Part 3. Dos and Don’ts of Data Representation

Standard representations for most data:

Data type	Plot Format
Time Series	Line, stem, or stack plots (like stacked fill_between)
Probability Distributions	Histograms or Kernel Density Estimations (KDEs); Box plots or violin plots to compare different populations; Corner plots for MCMC simulations of model parameters
Budgets & Fractions	Proportional area charts (pie chart is most [in]famous)
Vector fields	Quiver or stream plots
Spectra	Line of intensity vs frequency, wavelength, or wave number
Elevation or Intensity	Contour maps, (pseudo)color images, or surface plots

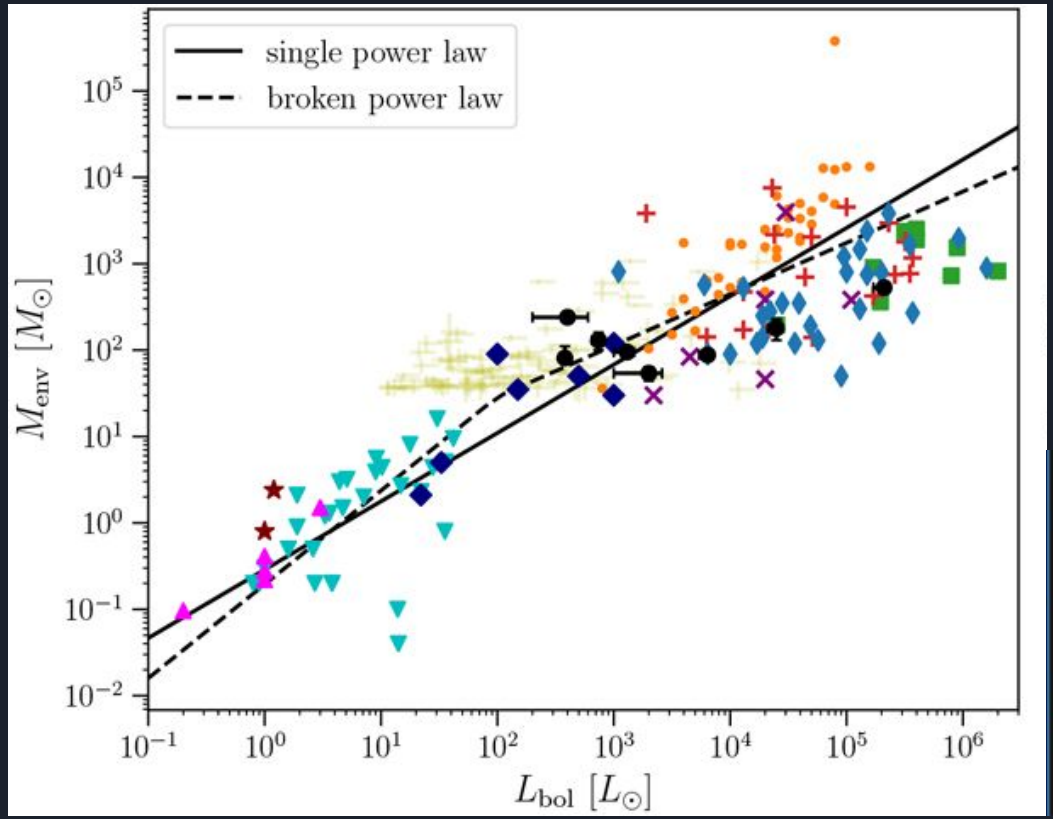
Main Challenges

- How best to combine different data types/sets for ease of comparison, &
- How to make the key result(s) easy to see & understand

Do: distinguish your data on communal plots

When adding data to a figure from (others') previous research, **it is OK to deemphasize other data & highlight what is yours &/or new by…**

- Decreasing the opacity (alpha) or marker sizes of other data.
- Showing error bars only for your own data.
- Coloring your data black & all other data lighter colors, e.g. with custom color cycler from itertools.cycle
- Emphasizing line(s) with thicker, darker, or more solid line style



I set the markers & colors in the ASCII table, but this is how you might handle it in a script:

```
from itertools import cycle
c_cycle = cycle(['tab:orange','tab:blue','tab:red',
                 'tab:green','tab:cyan','m',# m = magenta
                 'navy','maroon','purple'])
m_cycle = cycle(['.', 'd', '+',
                 's', 'v', '^',
                 'D', '*', 'x'])
#pretend we have a dict of studies & data by author group
for authors,study in studies.items():
    plt.scatter(study[:,0],study[:,1], c = next(c_cycle),
                ms = next(m_cycle), ls='', label=authors)
```

Example plot from R. L. Pitts et al. 2021b using many of the previous tips (data & markers were labelled in a caption)

Do: include error bars however feasible

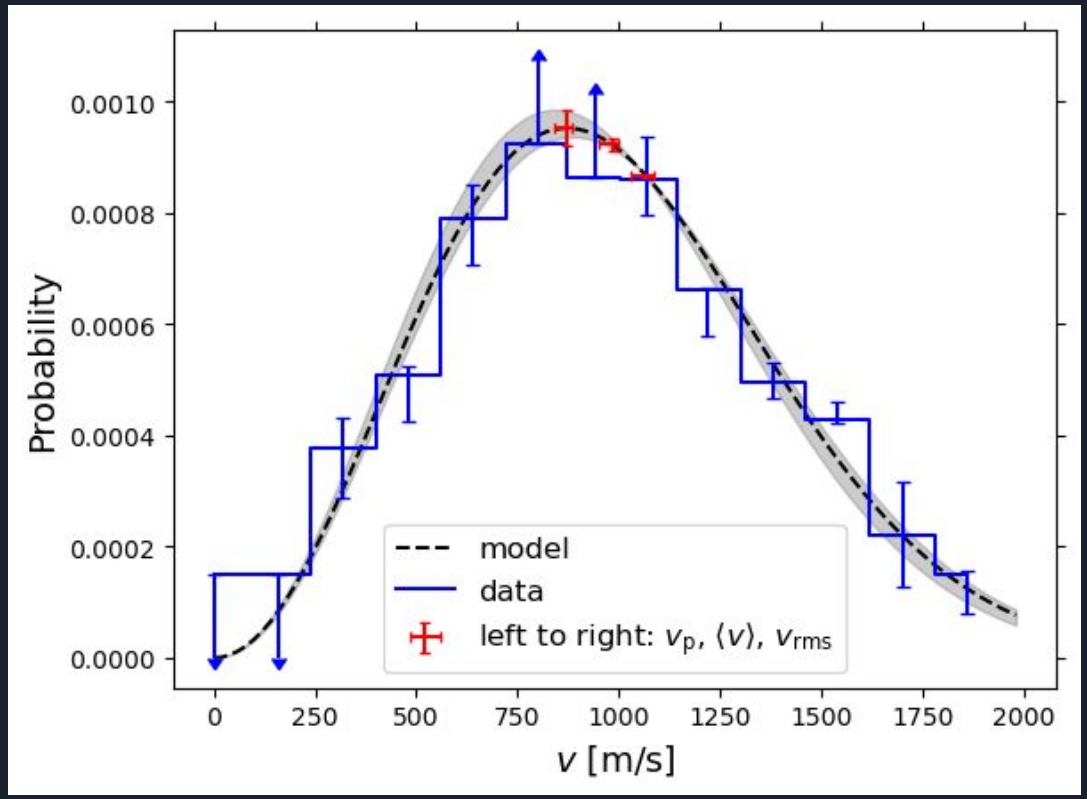
# of data points	Best error bars/limits format
Up to a few 10s	Error bars/limits on every point, with caps if large
Few 10s to ~100	Error bars on every point; omit caps
Few 100s	Error bars on every nth point (errorevery kwarg)
Many 100s & up	Representative error bar(s) in an unoccupied corner

Lines: use fill_between(x, yerr_lo, yerr_up) in a light or translucent color under the main line. Separate upper & lower margin lines are less intuitive.

Don't: set error margins to 0 for limits

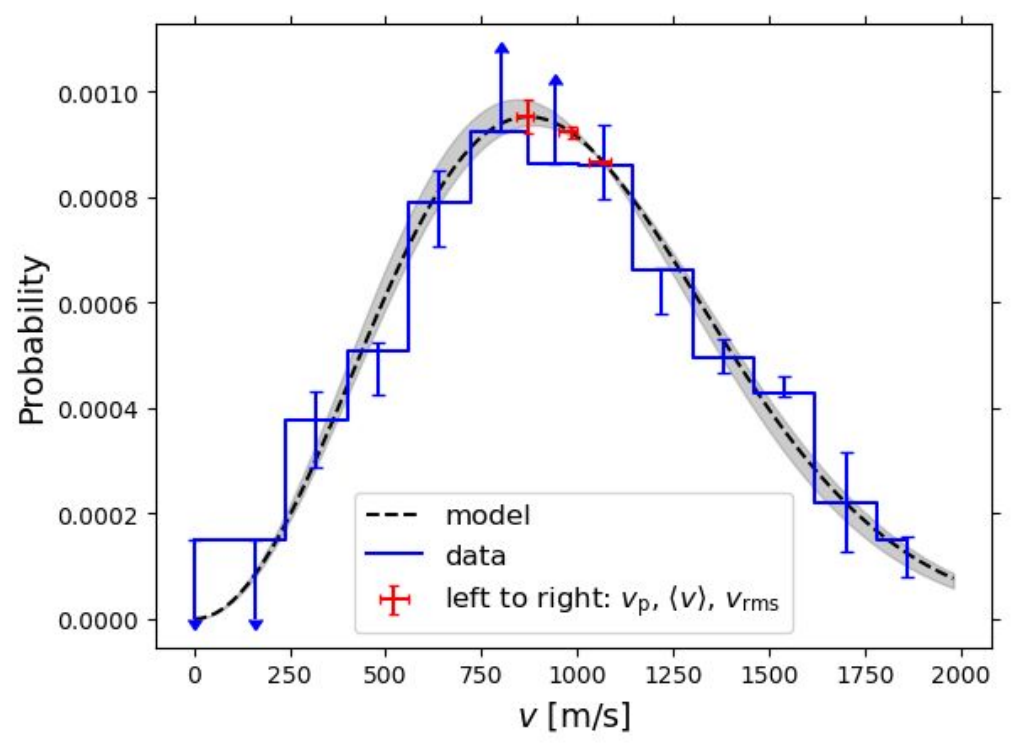
Error bars can be tricky if asymmetric or mixed with limits.

- lolims, uplims, xlolims, & xuplims kwargs take boolean mask arrays.
- Where limit masks are True, xerr &/or yerr arrays *must still have values for limit arrow lengths.*
- If error bars are asymmetric, wherever there is a limit, xerr or yerr must have a value >0 in the direction that the limit arrow points.
    - Any value on the other side will be ignored unless it raises a ValueError (e.g. 0 on a log-log plot).




```
k_B = 1.380649*10**-23
m_amu = 1.660539*10**-27 #atomic mass unit
def max_boltz_pdf(v,m_u,T):
    m2kT = m_u*m_amu / (2*k_B*T)
    return (((m2kT / np.pi)**1.5) * (4*np.pi*v**2)
            * np.exp(-(v**2) * m2kT))
mpvs = np.sqrt(2*k_B*np.array([5600.,6000.,6200.]) /
               (131.293*m_amu) ) # = 872 m/s at T=6000 K
mv = mpvs*2/np.sqrt(np.pi)
rmsv = mpvs*np.sqrt(1.5) #most probable, mean, & rms velocities

x = np.array([mpvs[1],mv[1],rmsv[1]])
vs = np.sort(np.concatenate((np.arange(0.,2000.,20.),x)))
mbd_6000 = max_boltz_pdf(vs,131.293,6000.)
mbd_5600 = max_boltz_pdf(vs,131.293,5600.)
mbd_6200 = max_boltz_pdf(vs,131.293,6200.)
y = max_boltz_pdf(x,131.293,6000.)
#Mock up some errors
xerrs = [x-np.array([mpvs[0],mv[0],rmsv[0]]),
         np.array([mpvs[2],mv[2],rmsv[2]])-x]
yerrs = np.zeros((2,3))
for i,xi in enumerate(x):
    vi = np.where(vs == xi)
    if mbd_6000[vi]-mbd_5600[vi] > 0:
        yerrs[0][i] = mbd_6000[vi]-mbd_5600[vi]
    else:
        yerrs[1][i] = abs(mbd_6000[vi]-mbd_5600[vi])
    if mbd_6200[vi]-mbd_6000[vi] > 0:
        yerrs[1][i] = mbd_6200[vi]-mbd_6000[vi]
    else:
        yerrs[0][i] = abs(mbd_6000[vi]-mbd_5600[vi])
# fudge some noise and limits
probs = mbd_6000[::8]+np.random.default_rng()\
    .uniform(-1,1,len(vs[::8]))*0.0001
probs[np.where(probs<0.00015)]=0.00015
```

Example: faux Maxwell-Boltzmann distribution of a hot (5600-6200 K)) Xenon arc lamp




```
fig, ax = plt. subplots(dpi=100)
ax.fill_between(vs, mbd_5600, mbd_6200, alpha=0.4, color='gray')
ax.plot(vs, mbd_6000, 'k--', label='model')
ax.errorbar(x, y, xerr=xerrs, yerr=yerrs, linestyle='',
            ecolor='r', capsize=2, zorder=20,
            label = r'left to right: $v_{\mathrm{p}}$, \
            $\langle v \rangle$, $v_{\mathrm{rms}}$')
ax.set_xlabel('$v$ [m/s]',fontsize=14)
ax.set_ylabel('Probability',fontsize=14)
ax.tick_params(top=True, right=True)
ax.step(vs[::8], probs,color='b', where='mid', label='data')
ax.errorbar(vs[::8], probs, yerr=perrs,
            uplims=puplims, lolims=plolims,
            linestyle='', ecolor='b', capsize=3)
#Note: capsize also controls arrow size
ax.legend(loc=8,fontsize=12)
plt.show()
```

Example: faux Maxwell-Boltzmann distribution of a hot (5600-6200 K))
Xenon arc lamp

Scattered Data by the Numbers 1.
A few × 10 to a few × 100 data points

- Do: Vary color (c kwarg of scatter()) &/or marker style for different datasets or values of a categorical parameter
  - If feasible, vary both colors & markers together for colorblind accessibility & so data are still distinct in grayscale
  - Keep in mind: some markers are hard to tell apart (e.g., large circles & octagons)
- Don't: color by numerical 3rd parameter (cmap kwarg of scatter()) unless it's correlated with at least 1 axis parameter

Scattered Data by the Numbers 2.

A few × 100 to a few × 1000 data points

Do: use scatter() with transparency, or hist2d() or hexbin() with logarithmic bins if outliers are important

- Reduce scatter plot opacity: set alpha kwarg ~0.2-0.5
- **Many rules for histogram binning, but generally, distribute *n* data points over $n^{1/2}$ to $n^{1/3}$ bins** (empty bins don't count)
- Distinct datasets can be shown in different colors as points or line contours

Don't: try to contour a histogram or overlay multiple 2D histograms

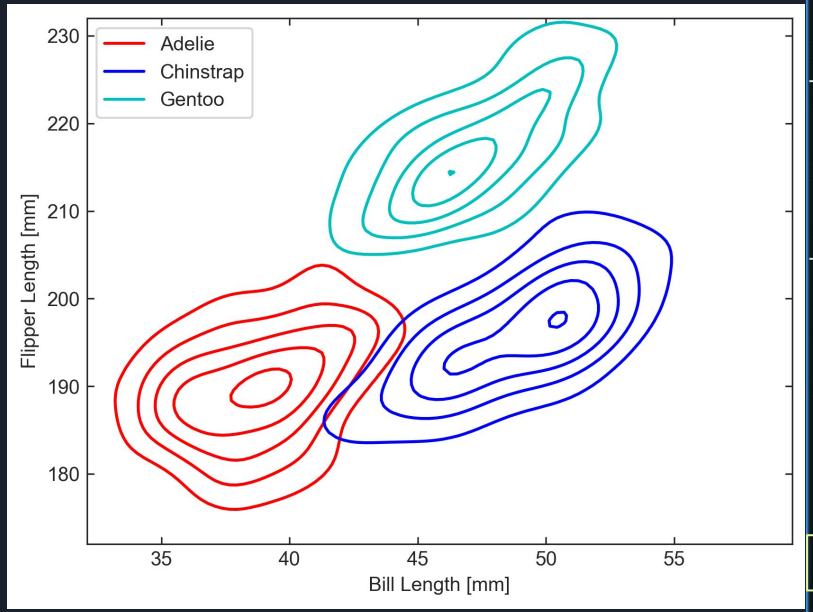
Scattered Data by the Numbers 3.
1000s of data points or more

Do: Use histograms, Gaussian Kernel Density Estimations (KDEs), or contours*, or corner.hist2d() if outliers are important

- Gaussian KDEs ≈ histograms smoothed by summing bell curves of unit height & width = kernel bandwidth centered at each point.
  - **Pros:** continuous functions, smooth contours of scattered data
  - **Cons:** require SciPy or Seaborn (much easier); slow processing

*Without Seaborn, multiple sets of contours require a proxy artist to be added to a legend.

2D KDE example with SciPy



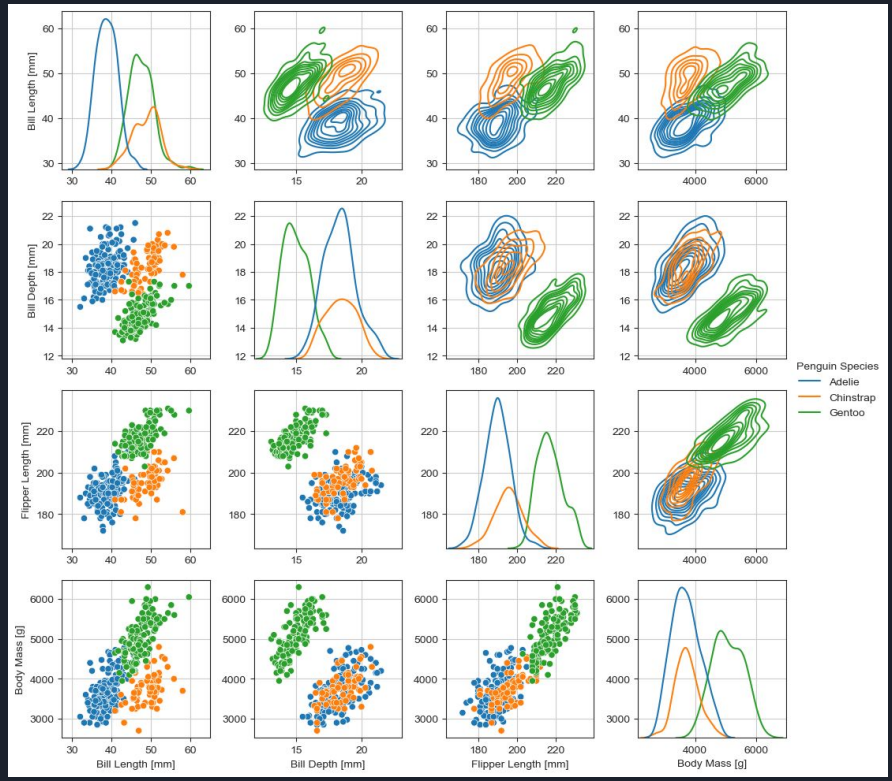

```
lenbill, lenflip = penguins[['bill_length_mm',
                             'flipper_length_mm']].to_numpy().T
species = penguins['species'].to_numpy()
```

```
from scipy.stats import gaussian_kde

X, Y = np.mgrid[min(lenbill):max(lenbill):100j,
                min(lenflip):max(lenflip)+1:100j]
pos = np.vstack([X.ravel(), Y.ravel()])
```

```
lines = []
fig, ax = plt.subplots(dpi=300)
labels = sorted(list(set(species)))
cc = ['r','b','c']
for j,s in enumerate(labels):
    inds = np.where(np.logical_and(species == s, np.isfinite(lenbill)))
    kernel = gaussian_kde(np.array([lenbill[inds],lenflip[inds]]))
    Z = np.reshape(kernel(pos).T, X.shape)
    pcp = ax.contour(X,Y,Z, colors=cc[j], levels=5)
    lines.append( mpl.lines.Line2D([], [], color=cc[j], label=s) )
ax.legend(handles=lines, loc=2)
ax.set_xlabel('Bill Length [mm]')
ax.set_ylabel('Flipper Length [mm]')
ax.tick_params(direction='in',right=True, top=True)
plt.show()
```

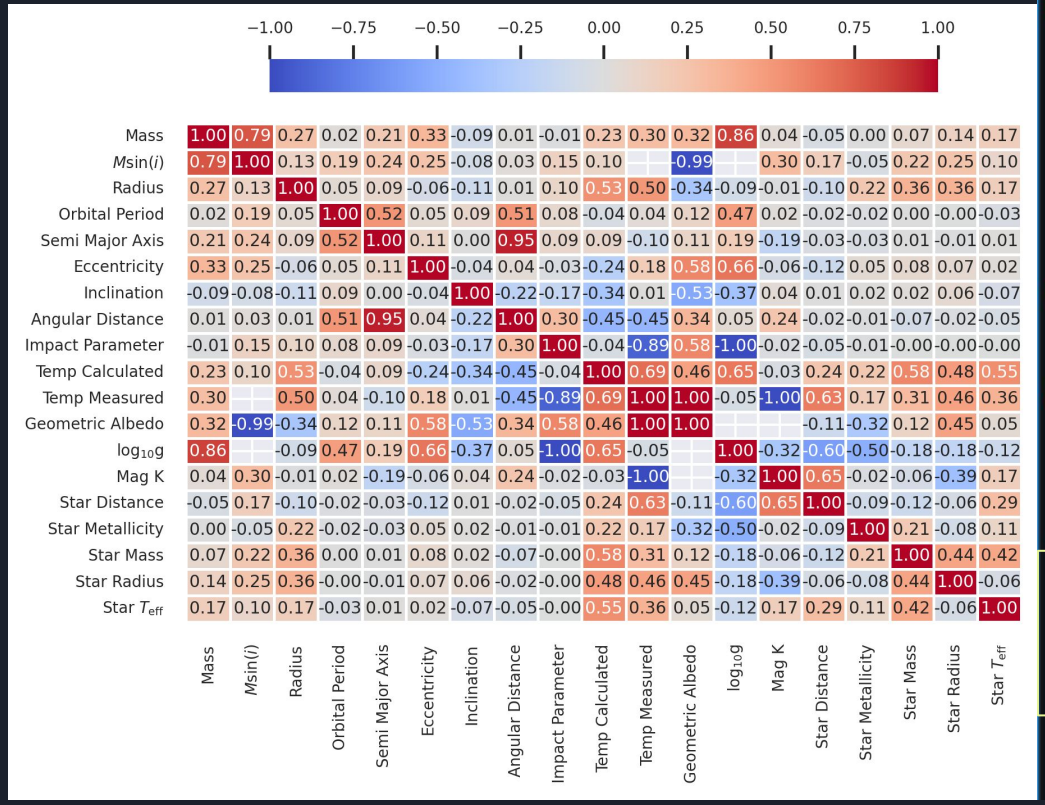
Do: Use Corner/Pair Plots for (some) Correlated Variables

- Great for showing correlations between up to ~5 parameters
- Easy with Seaborn package if you know Pandas (but can be hard to typeset) →
  - Built-in method to color by categorical variable
- Can also use corner.py package



Don't: Use Corner/Pair plots for >>6 parameters

- For ~10-30 numerical parameters, only a heatmap of correlation coefficients will fit
  - Journal-mandated minimum font size sets hard upper limit
- Ask yourself: "Do I *really* have to plot that many variables on one figure? Can I not break them up?"
- If you absolutely must, use either imshow()-based heatmap (more flexible) or seaborn.heatmap() (more straightforward if you know Pandas)




```
import requests,string
import seaborn as sb
exops = pd.read_csv('https://exoplanet.eu/catalog/csv/') #98 cols!
dropkeys = [title for title in exops.columns if any(
            t in title for t in ['error', 'name',
                                 'tzero', 'mag_'])]
exops1=exops.drop(columns=[*dropkeys,'planet_status','omega',
                           'ra','dec','k','discovered',
                           'tperi','tconj','star_age',
                           'hot_point_lon','lambda_angle'])
corrs=exops1.corr(numeric_only=True)
print(corrs.shape) # = 18 x 18

annot_labels = np.ma.masked_inside(corrs.to_numpy(),-0.1,0.1)
axlabs = corrs.columns.to_numpy()
for i,lbl in enumerate(axlabs):
    axlabs[i] = string.capwords(lbl.replace('_',' '))\
                .replace('Mass Sini',r'$M$sin($i$)')\
                .replace('Log G',r'log$_{{10}}$g')\
                .replace('Teff',r'$T_{{\mathrm{{eff}}}}$')
#can't use replacement by dict due to implicit '{}'.format()
plt.figure(dpi=300)
sb.set(font_scale=0.6)
hm = sb.heatmap(corrs, cmap="coolwarm", annot=annot_labels,
                cbar_kws={'shrink':0.8, 'location':'top'},
                xticklabels=axlabs, yticklabels=axlabs,
                linewidth=0.75, fmt='.2f', square=False)
sb.set_style('ticks')
plt.show()
sb.set(font_scale=1)
```

Seaborn Heatmap demo

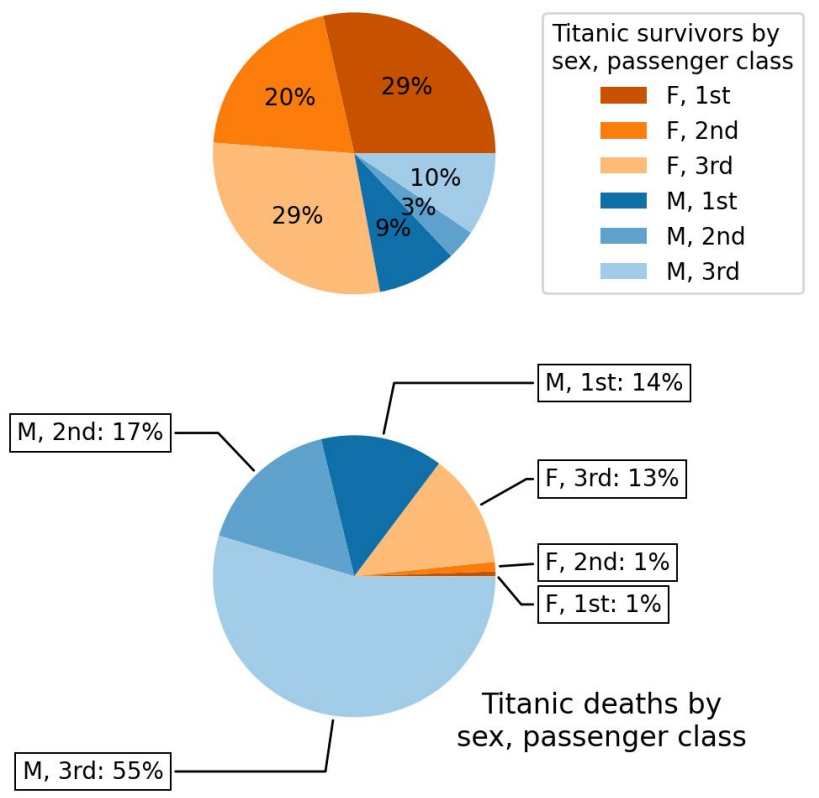
Best not to plot more variables than heatmap() can annotate

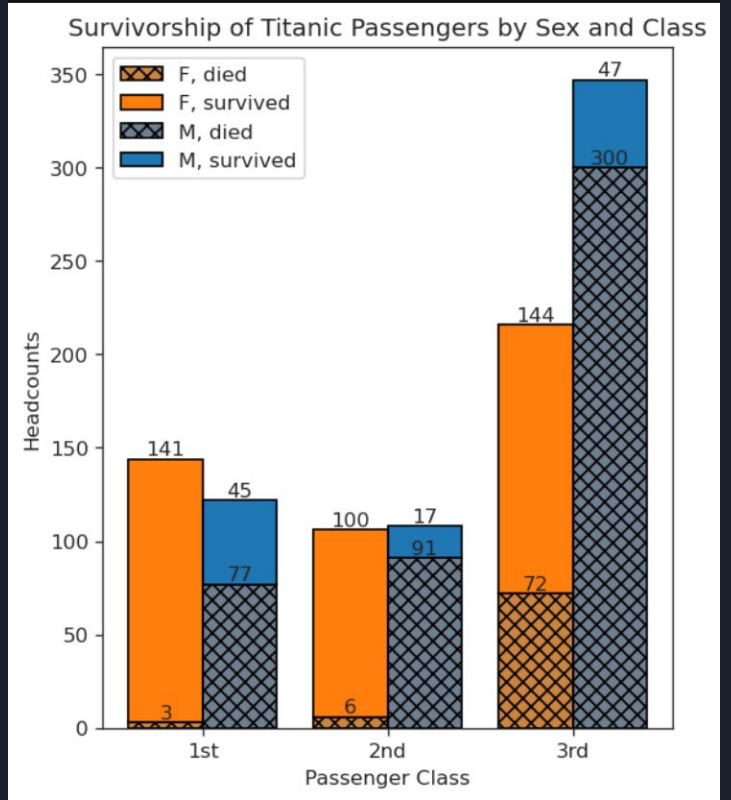
heatmap() has built-in kwargs to replace labels with typeset versions

Don't: Use Pie or Donut Charts

Why should you NOT use pie or donut charts? Per *many* studies...

- Pie & donut charts are inefficient (low info for space occupied)
- Humans are better at judging relative lengths than angles
- Pie charts are easier to read when categories are ordered by fractional size, which may conflict with more natural orders, e.g. alphabetical.
- **State of belonging is usually less important than actual quantities**
- **Inappropriate aggregation can obscure important category-specific details (this applies to many plot formats, e.g. stack/stream plots)**


Titanic survivors by sex, passenger class
F, 1st
F, 2nd
F, 3rd
M, 1st
M, 2nd
M, 3rd
20%
29%
29%
10%
3%
9%
M, 1st: 14%
M, 2nd: 17%
F, 3rd: 13%
F, 2nd: 1%
F, 1st: 1%
M, 3rd: 55%
Titanic deaths by sex, passenger class

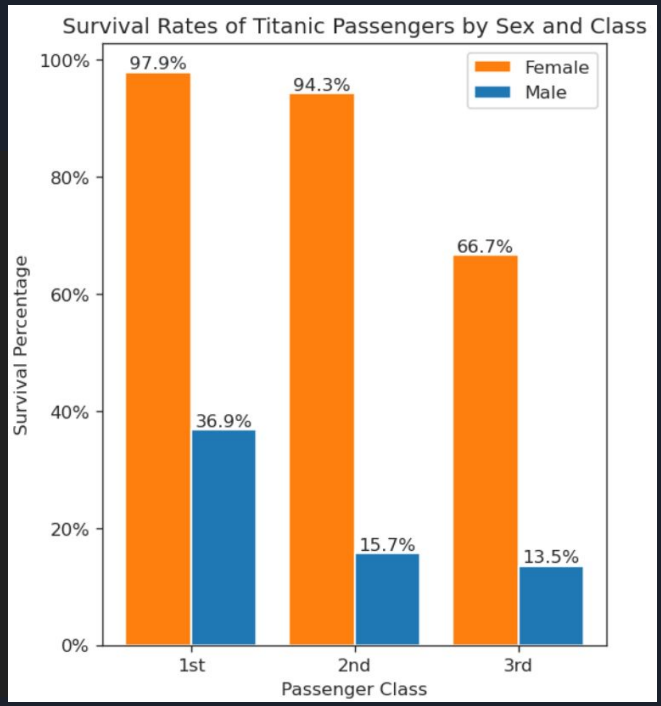

Survivorship of Titanic Passengers by Sex and Class
F, died
F, survived
M, died
M, survived
Headcounts
Passenger Class
1st
2nd
3rd
141
45
3
77
100
17
6
91
144
47
72
300

Compare

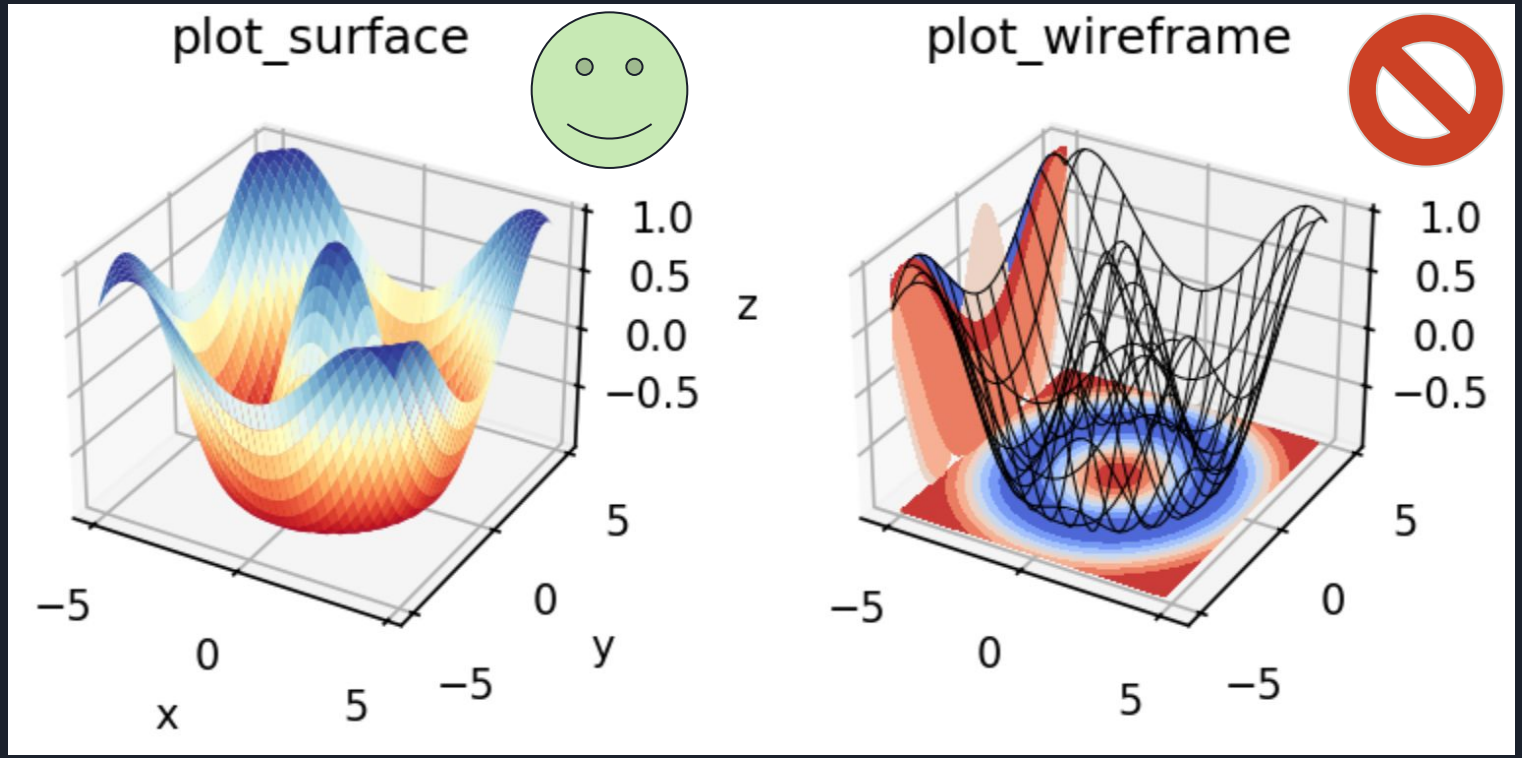
Do: Use Rectilinear Proportional Area Charts

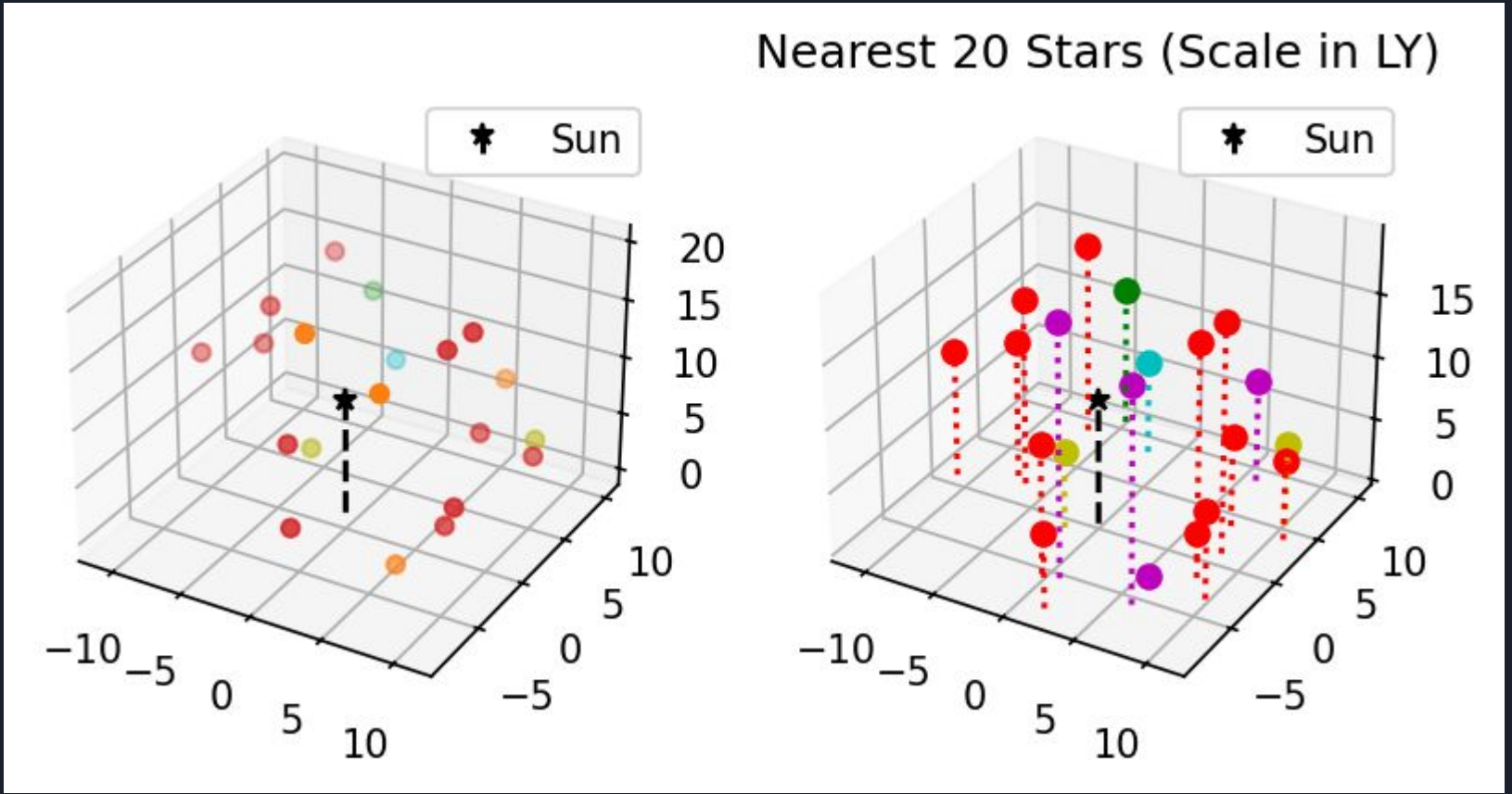
Bar charts are the classic. Others like waffle plots & treemaps require external packages.

```
x = np.arange(3)  # classes
width = 0.4  # the width of the bars (there will be 2)
multiplier = 0

for sex, npclass in live.items():
    offset = width * multiplier
    pcts =  npclass/(npclass+dead[sex])
    live_recs = ax2.bar(x + offset, pcts, width,
                        label='Male' if sex =='m' else 'Female',
                        color='tab:blue' if sex == 'm' else 'tab:orange')
    ax2.bar_label(live_recs, labels = ['{:.1%}'.format(p) for p in pcts])
    multiplier += 1
ax2.yaxis.set_major_formatter(mpl.ticker.PercentFormatter(1.0))
ax2.set_xticks(x+0.5*offset, ['1st','2nd','3rd'])
ax2.set_title('Survival Rates of Titanic Passengers by Sex and Class')
ax2.set_xlabel("Passenger Class")
ax2.set_ylabel("Survival Percentage")
ax2.legend()
plt.show()
```

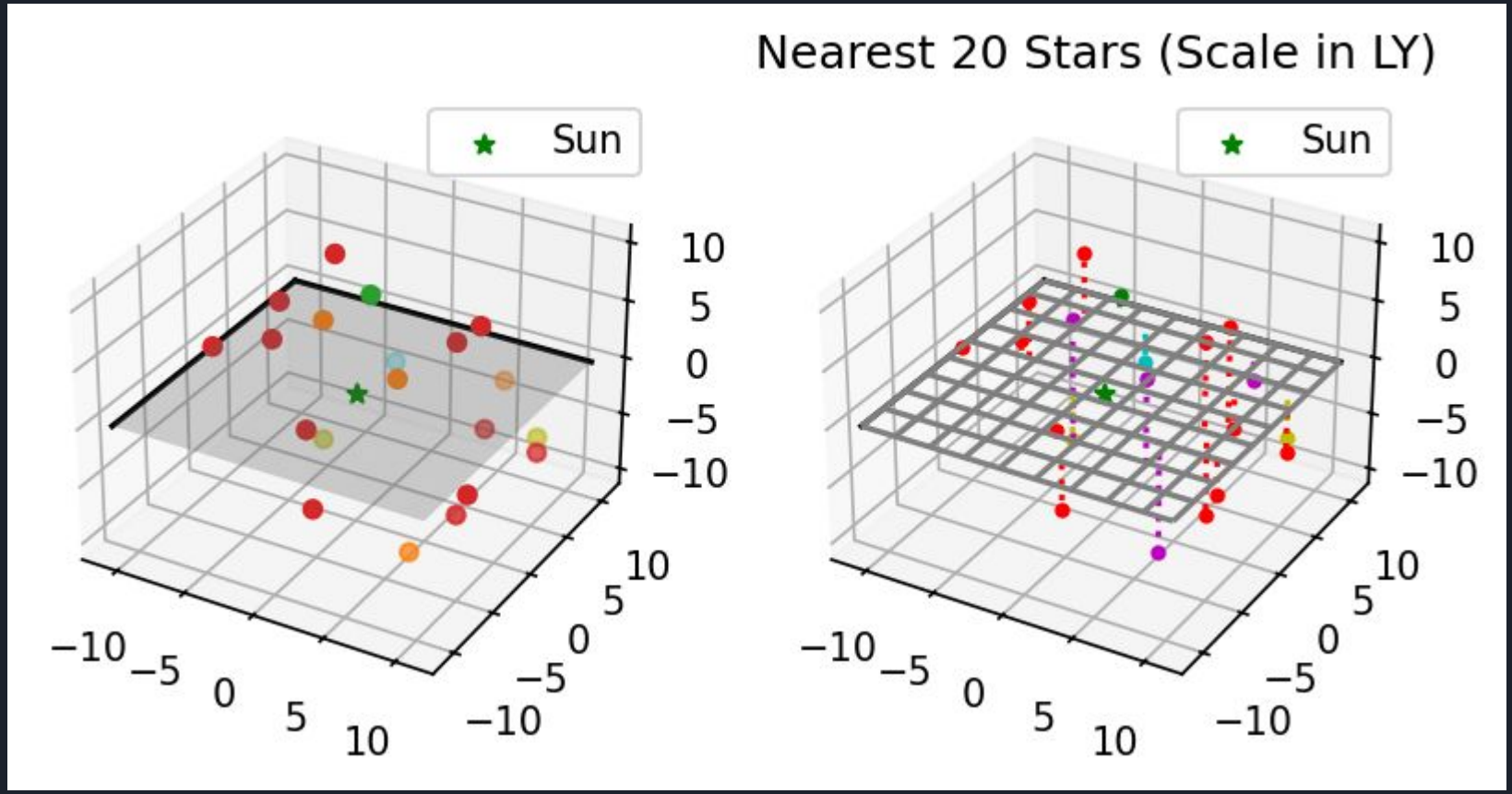


Do: consider depth rendering limitations in 3D



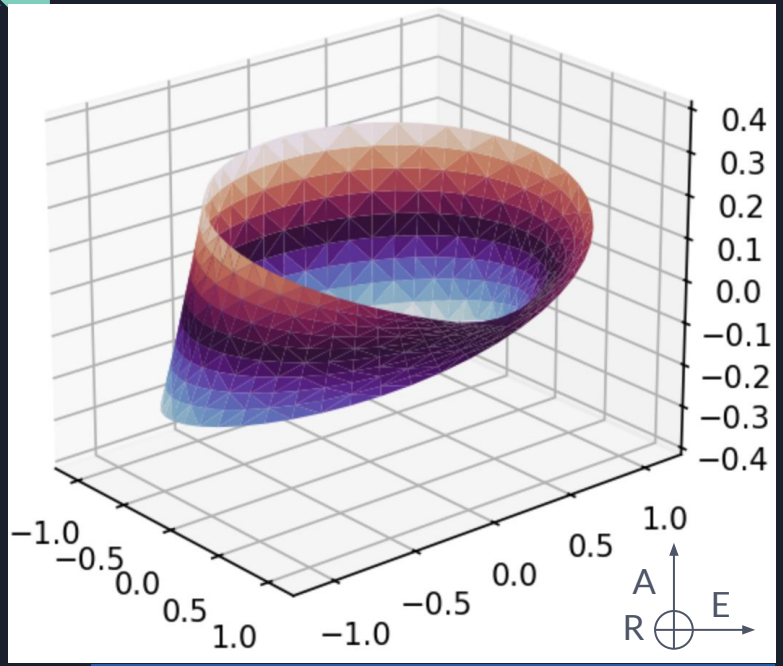


In 3D, scatter() renders depth within a dataset using transparency (no such effects for other 3D versions of 2D plots)



Matplotlib can layer data *within* 1 dataset, but multiple datasets tend to resist proper layering, even with `zorder` set for every element

Do: Control viewing angle with view_init()



set_box_aspect() & its zoom kwarg help with cropping

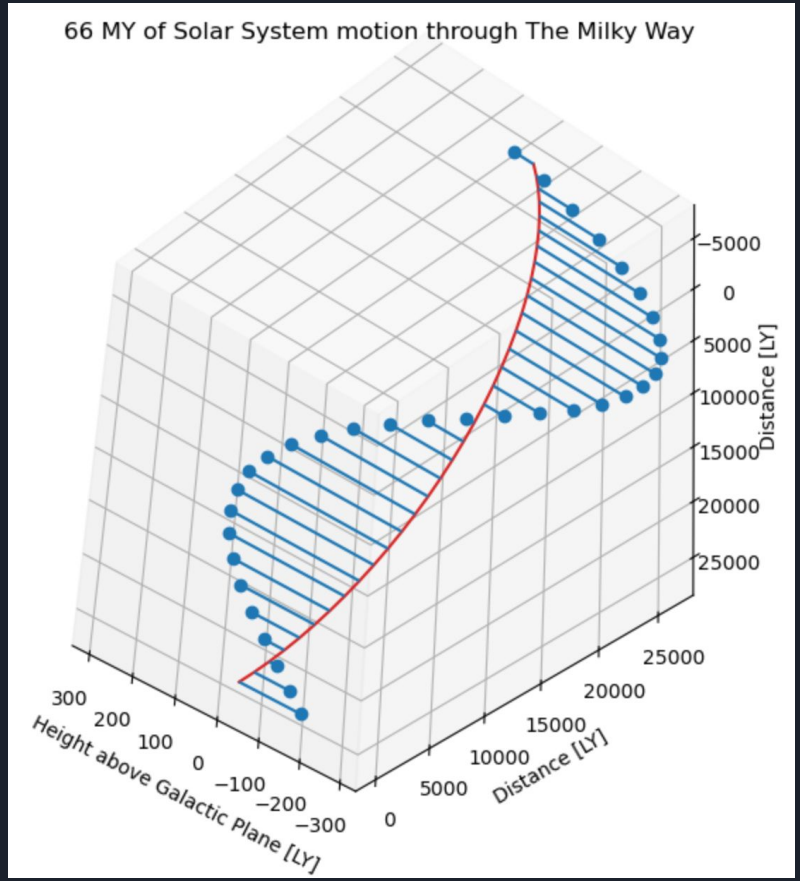
```python
import matplotlib.tri as mtri

fig, ax = plt.subplots(dpi=150, subplot_kw = {"projection": "3d"})

# Make mesh in space of parameterisation variables (u, v)
u = np.linspace(0, 2.0 * np.pi, endpoint=True, num=50)
v = np.linspace(-0.5, 0.5, endpoint=True, num=10)
u, v = np.meshgrid(u, v)
u, v = u.flatten(), v.flatten()

# Mobius mapping: takes (u, v) pair and returns (x, y, z)
x = (1 + 0.5 * v * np.cos(u / 2.0)) * np.cos(u)
y = (1 + 0.5 * v * np.cos(u / 2.0)) * np.sin(u)
z = 0.5 * v * np.sin(u / 2.0)

# Triangulate parameter space
tri = mtri.Triangulation(u, v)
```

```python
# Plot surface. Triangles in parameter space determine which
# (x, y, z) points are connected by edges.
ax.plot_trisurf(x, y, z, triangles=tri.triangles,
                cmap=plt.cm.twilight)#, antialiased=False)
ax.set_xlim(-1.2, 1.2)
ax.set_ylim(-1.2, 1.2)
ax.set_zlim(-0.4, 0.4)
ax.view_init(elev=22, azim=-40, roll=0, vertical_axis='z')
ax.set_box_aspect((3, 4, 3), zoom=1.3)
```

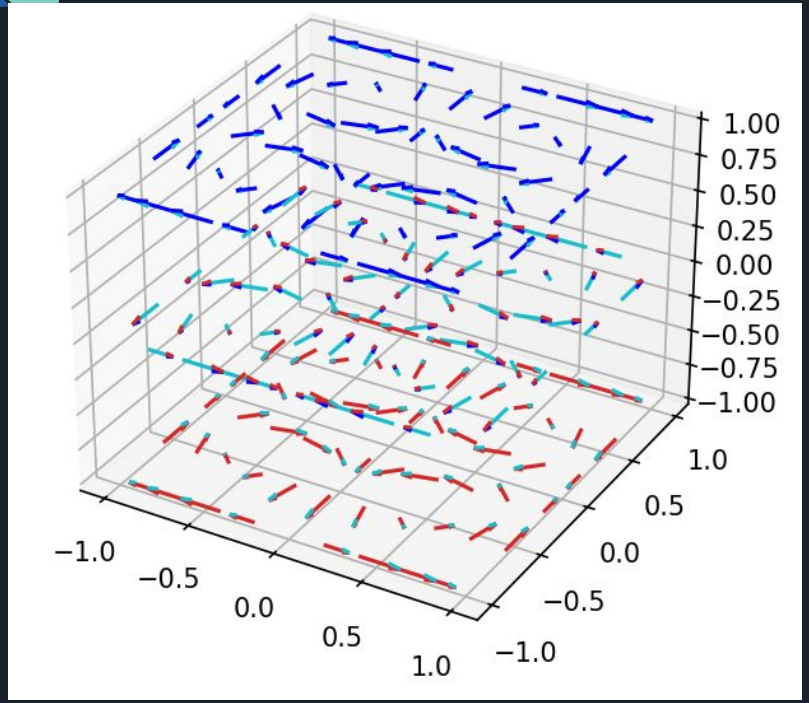
Now you try!

In the day 1 exercises, you made a 3D stem plot of the Sun's motion through The Milky Way over the past 66 million years. (You can use the solutions file if you didn't finish.)

Set roll=60 to see how that motion looks when standing (floating?) so that the plane of the Solar System is horizontal & celestial north is up.



Don't: use 3D vector plots for the time being




```
x, y, z = np.meshgrid(np.arange(-1, 1.2, 0.2),
                      np.arange(-1, 1.2, 0.4),
                      np.arange(-1, 1.5, 1))

# Make direction data for arrows
u = np.sin(np.pi*x)*np.cos(np.pi*y)*np.cos(np.pi*z)
v = -np.cos(np.pi*x)*np.sin(np.pi*y)*np.cos(np.pi*z)
w = (np.sqrt(0.75)*np.cos(np.pi*x)*np.cos(np.pi*y)*
     np.sin(np.pi*z))
# Plot
fig, ax = plt.subplots(subplot_kw={"projection": "3d"},
                       dpi=150)
ax.quiver(x,y,z, u,v,w, length=0.25,
          color=['tab:red','tab:cyan','b'])
```

Arrows are blunt, drawn with 3 line segments, & colors are applied by line segment instead of to the whole arrow.

Wait for devs to figure out polygonal arrows.

Do: Be consistent throughout your paper! (rcParams & style files can help)

MANY plot properties set internally by Matplotlib's default runtime configuration parameters, or rcParams, including but not limited to:

- (Sub)figure formatting
- Text/font formatting
- Marker/line formatting & color palettes/maps
- Axes tick configurations

Any can be set at runtime with dict-like syntax, or imported from file.

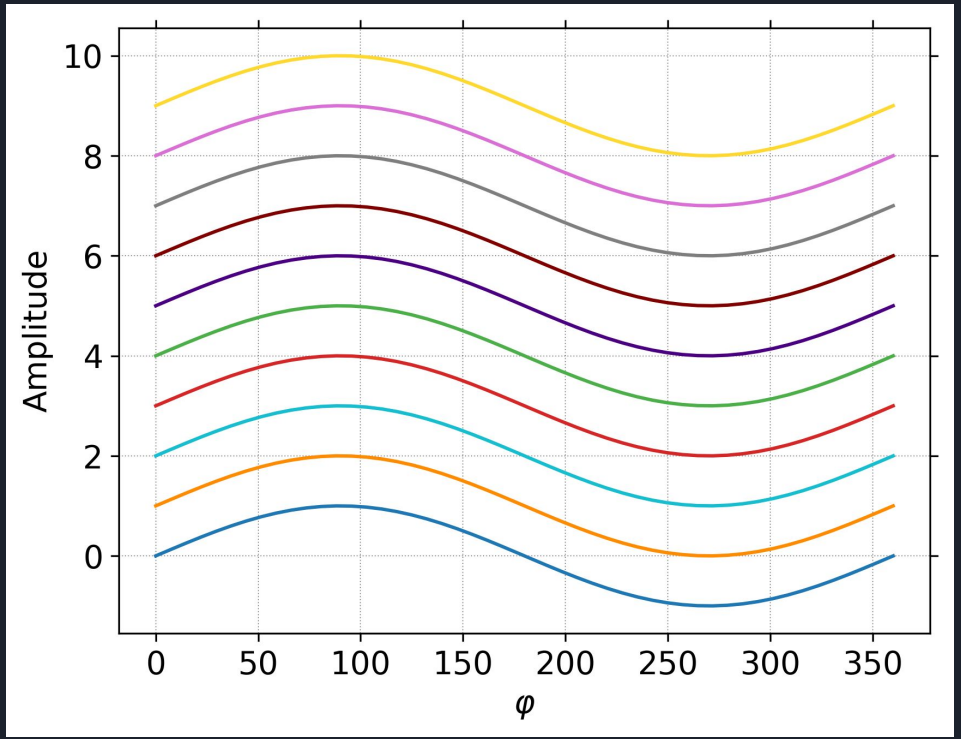
rcParams & .mplstyle files

A .mplstyle file is a text file of key-value pairs where each key is the rcParam to modify. See, e.g., mpl4publication.mplstyle

- Can create & import list of style sheets for different sets of rcParams.
- **Need only include rcParams to be changed from defaults**
- Built-in style sheets can be called by name without full path

Set for whole session: plt.style.use('./your_style.mplstyle')

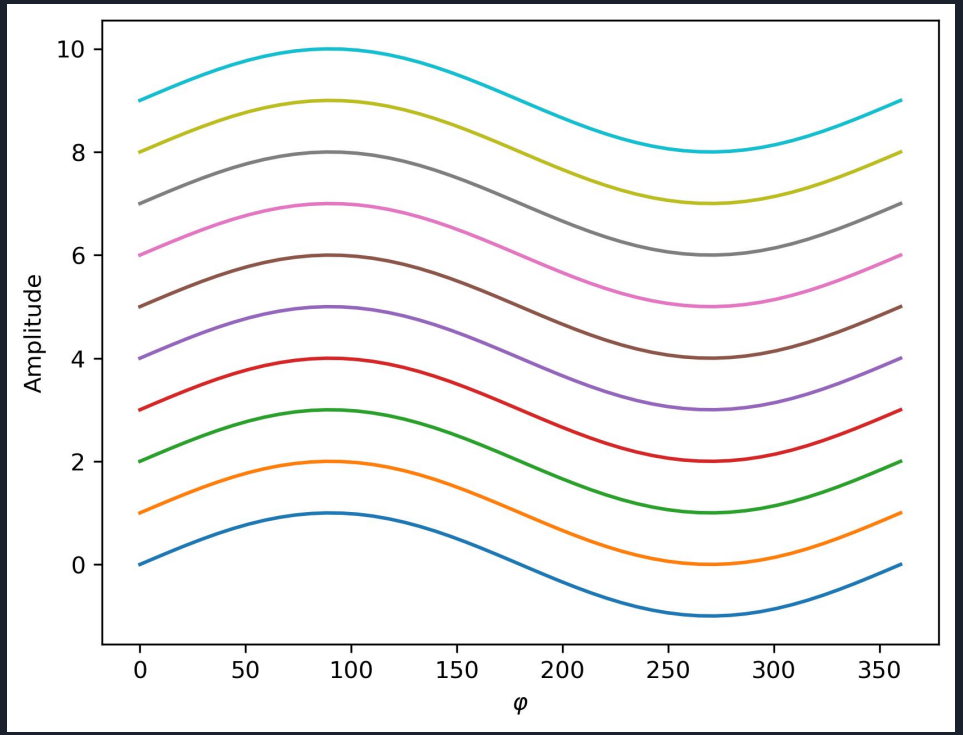
Set for one plot: with plt.style.context('./your_style.mplstyle'): …




```python
plt.figure(dpi=300)
with plt.style.context('./mpl4publication.mplstyle'):
    for i in range(10):
        y = i+np.sin(np.linspace(0, 2 * np.pi))
        plt.plot(np.linspace(0,360,len(y)),y)
        plt.xlabel(r'$\varphi$')
        plt.ylabel('Amplitude')
plt.show()
```

```python
#mpl.rcParams.update(mpl.rcParamsDefault)
plt.figure(dpi=300)
y = np.sin(np.linspace(0, 2 * np.pi))
for i in range(10):
    y = i+np.sin(np.linspace(0, 2 * np.pi))
    plt.plot(np.linspace(0,360,len(y)),y)
    plt.xlabel(r'$\varphi$')
    plt.ylabel('Amplitude')
plt.xlabel('Phase Angle')
plt.ylabel('Amplitude')
plt.show()
```

Example with mpl4publication.mplstyle (plot from with clause)




```python
plt.figure(dpi=300)
with plt.style.context('./mpl4publication.mplstyle'):
    for i in range(10):
        y = i+np.sin(np.linspace(0, 2 * np.pi))
        plt.plot(np.linspace(0,360,len(y)),y)
        plt.xlabel(r'$\varphi$')
        plt.ylabel('Amplitude')
plt.show()
```

```python
#mpl.rcParams.update(mpl.rcParamsDefault)
plt.figure(dpi=300)
y = np.sin(np.linspace(0, 2 * np.pi))
for i in range(10):
    y = i+np.sin(np.linspace(0, 2 * np.pi))
    plt.plot(np.linspace(0,360,len(y)),y)
    plt.xlabel(r'$\varphi$')
    plt.ylabel('Amplitude')
plt.xlabel('Phase Angle')
plt.ylabel('Amplitude')
plt.show()
```

Example with mpl4publication.mplstyle (after with clause)

Questions?