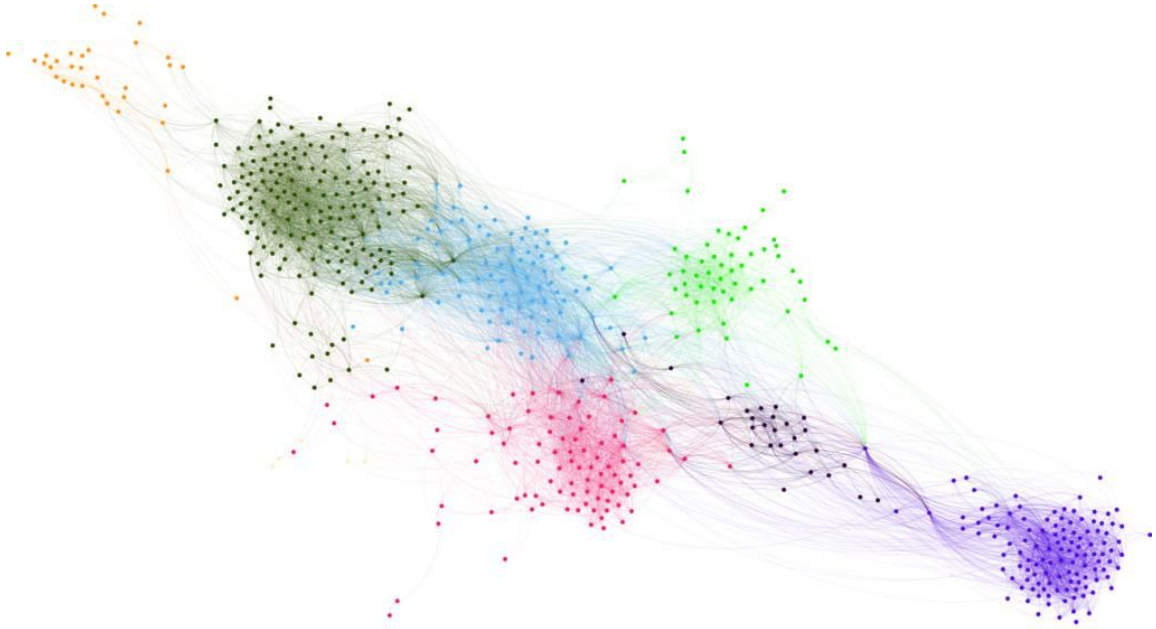
Numerical Methods 15.10.2025



Data Visualization

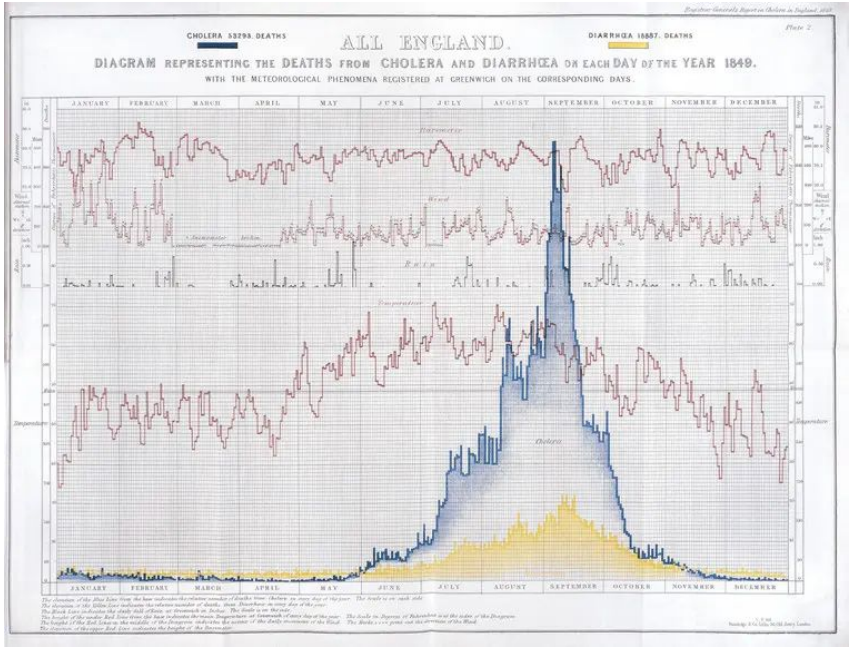
Outline

- Historical perspective
- Purpose - what a graphic should do
- Aspects of effective visualization
- Context and convention
- Multi-purpose visualization (paper plots/talks/outreach/PR)
- Tools (exploratory vs. publication quality)
- Types of plots

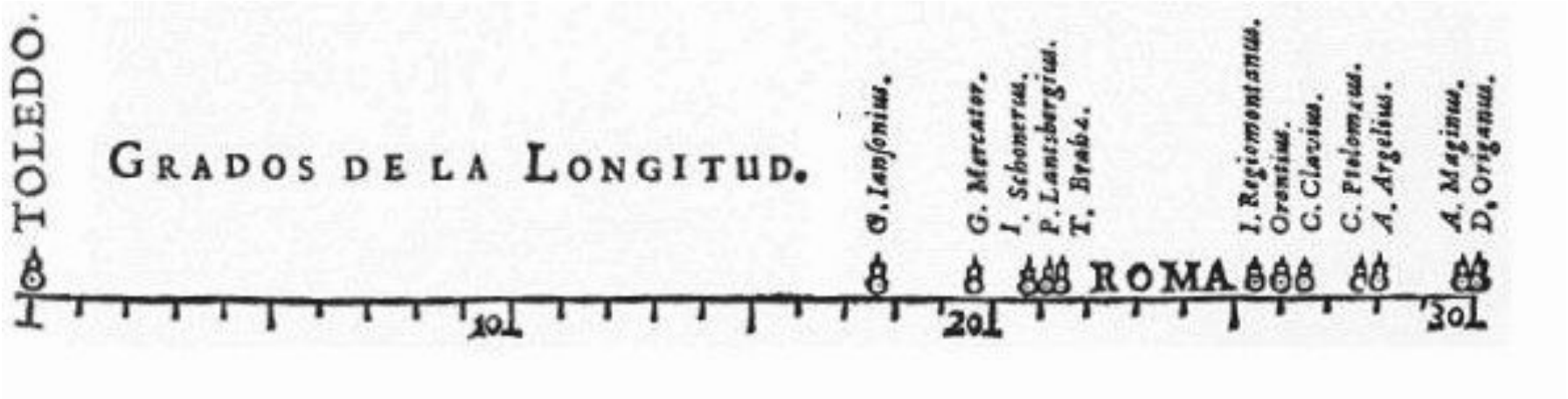
*Adapted from superb presentations developed by M. Fousneau, T. Herbst at MPIA

Some historical novelties...

- Visually representing statistical trends of a data set is *mostly* a modern concept
- This is typically because dedicated surveys or census information on a particular topic was not a priority in earlier centuries
- However there are some interesting examples even a few centuries ago...



1643 - First statistical graphic



Flemish cartographer Michaël Florent van Langren (Langrenus) attempted to visually quantify the large uncertainties in contemporary estimates of the longitudinal distance between Toledo and Rome

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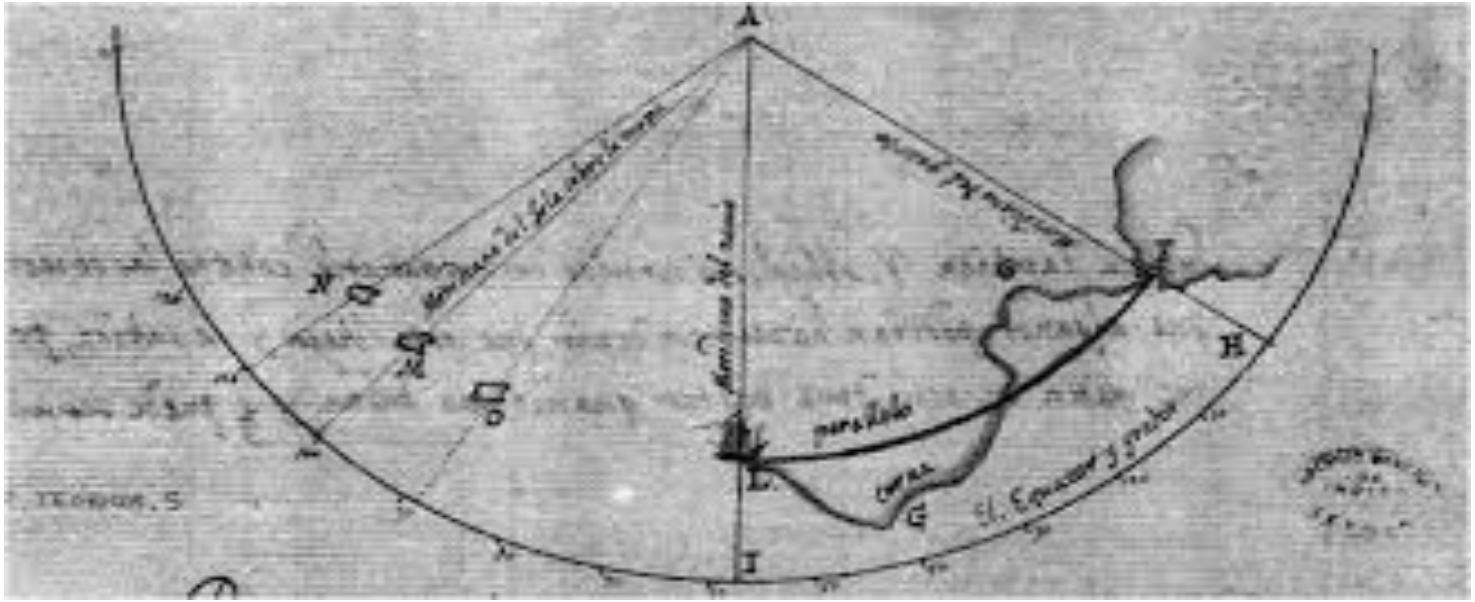
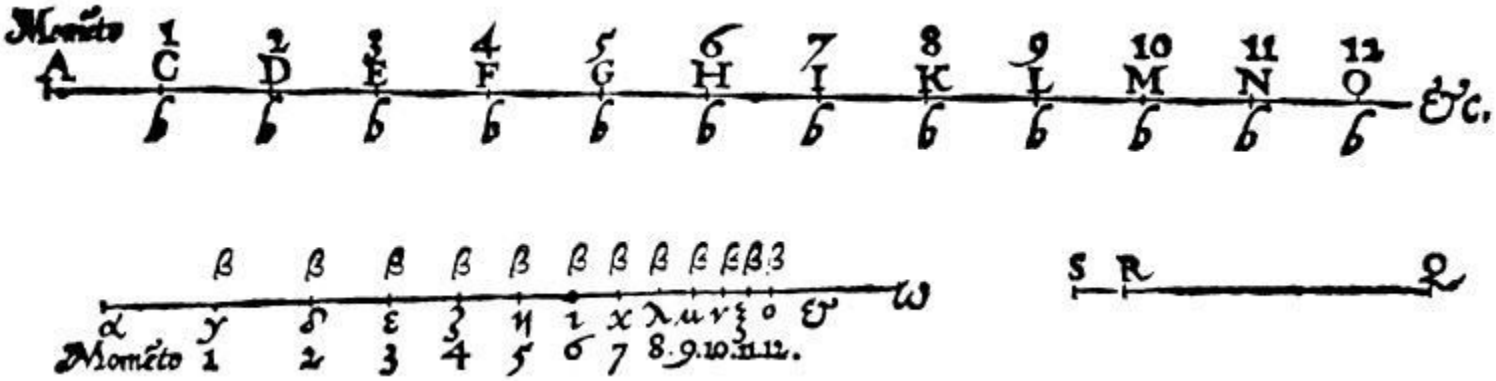


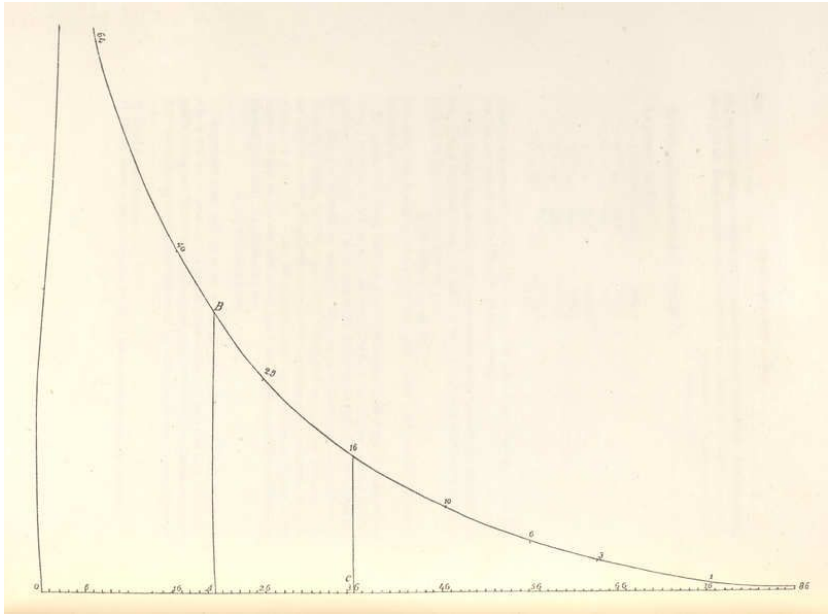
Flemish cartographer Michaël Florent van Langren (Langrenus) attempted to visually quantify the large uncertainties in contemporary estimates of the longitudinal distance between Toledo and Rome

1614 - Logarithmic scales



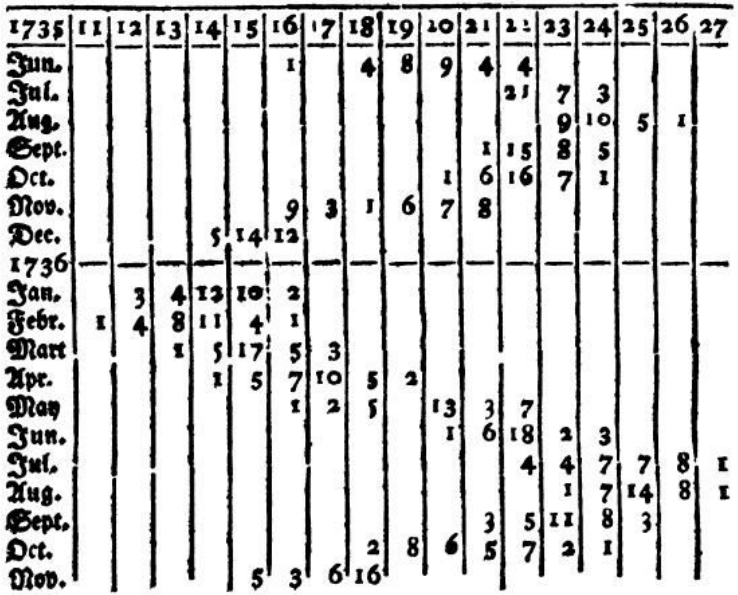
John Napier and others identified visually useful tools for compression of data sets through the use of logarithmically spaced axes

1669 - (Useful) continuous distributions



Christiaan Huygens took tabulated life expectancy data and computed one of the first continuous distribution functions which describes the probability of surviving past a given age.

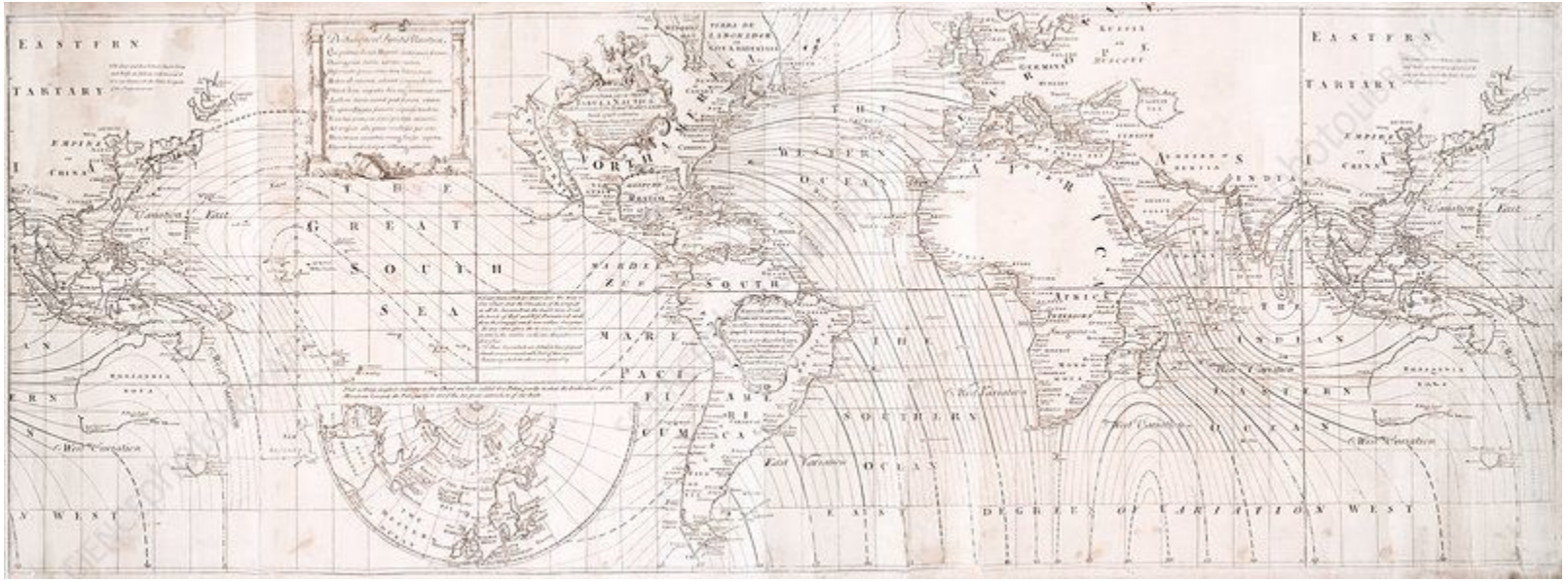
1700s - Graphical tabulated data



1735	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Jun.						1		4	8	9	4	4					
Jul.												21	7	3			
Aug.													9	10	5	1	
Sept.											1	15	8	5			
Oct.										1	6	16	7	1			
Nov.						9	3	1	6	7	8						
Dec.				5	14	12											
1736																	
Jan.		3	4	13	10	2											
Febr.	1	4	8	11	4	1											
Mart			1	5	17	5	3										
Apr.				1	5	7	10	5	2								
May						1	2	5		13	3	7					
Jun.										1	6	18	2	3			
Jul.												4	4	7	7	8	1
Aug.													1	7	14	8	1
Sept.											3	5	11	8	3		
Oct.								2	8	6	5	7	2	1			
Nov.					5	3	6	16									

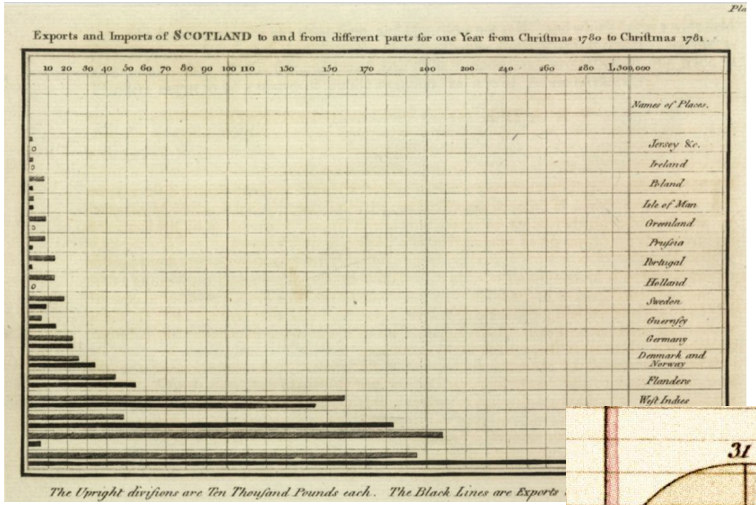
Johann Lambert visualized temperature frequency variations across calendar years - far more illustrative of cyclical time-series data than a simple histogram

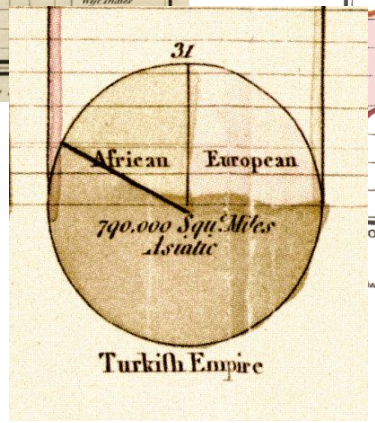
1700s - Contour plots

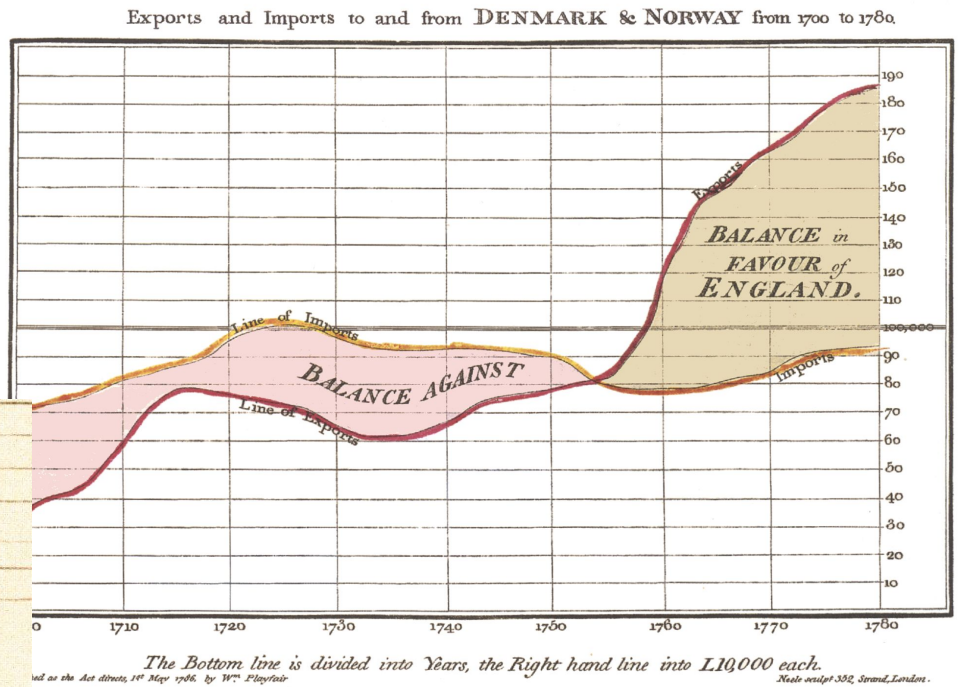


Edmund Halley produced likely the first contour plot (of magnetic compass readings) overlaid on a geographic background

Late 18th Century - Bar charts and line graphs



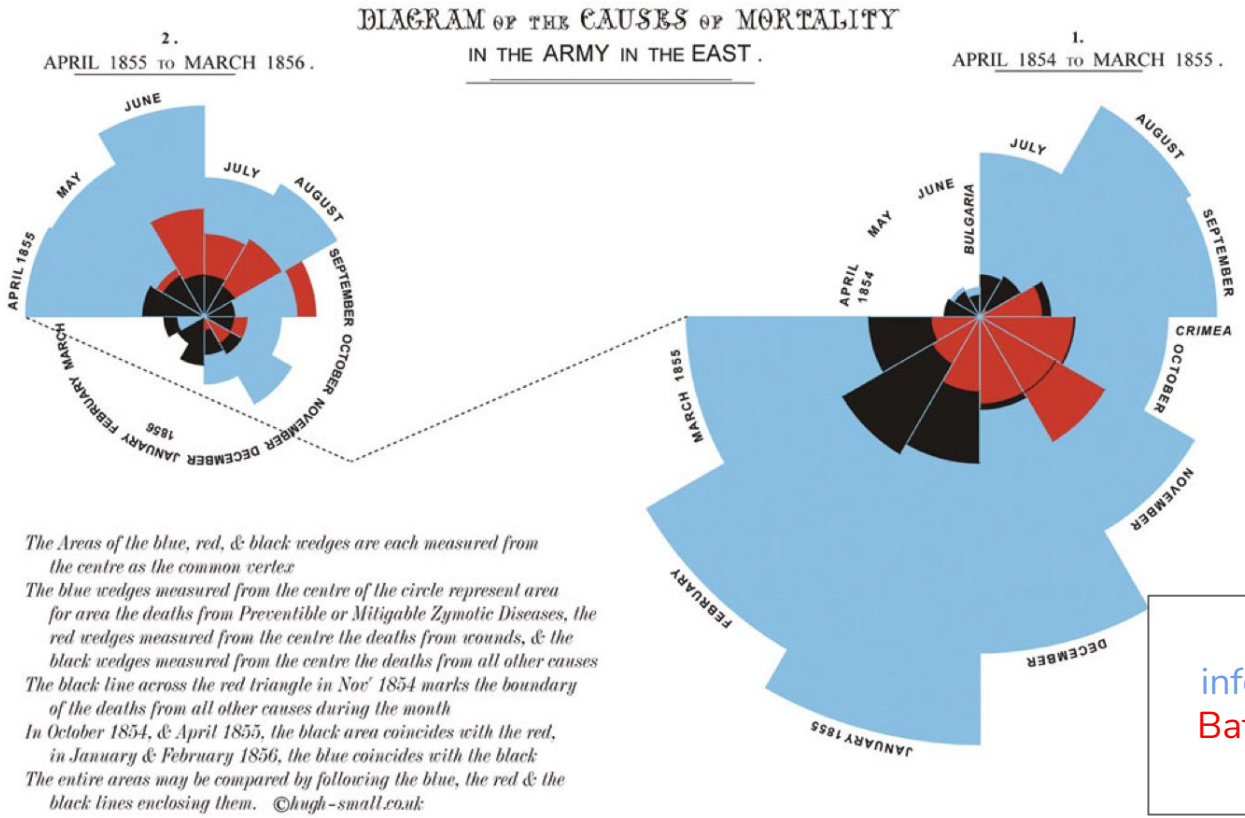




The ancestor of

Examples popularized by William Playfair

Some revolutionary statistical visualizations



Florence Nightingale's statistical analysis on cause of deaths in the Crimean War even more ground breaking

Preventable infections/disease
Battlefield deaths
Other causes

Why should **we** care about graphics?

Good plots are a reminder to...

Remember that we need to explain our work to the taxpayers who fund us

Avoid becoming so specific/detailed that even experts in our field can't understand it

Not lose sight of how to convey a key message of our research

Robert FitzRoy daily weather forecast chart

vice-admiral
Robert FitzRoy

1861

THE WEATHER.

METEOROLOGICAL REPORTS.

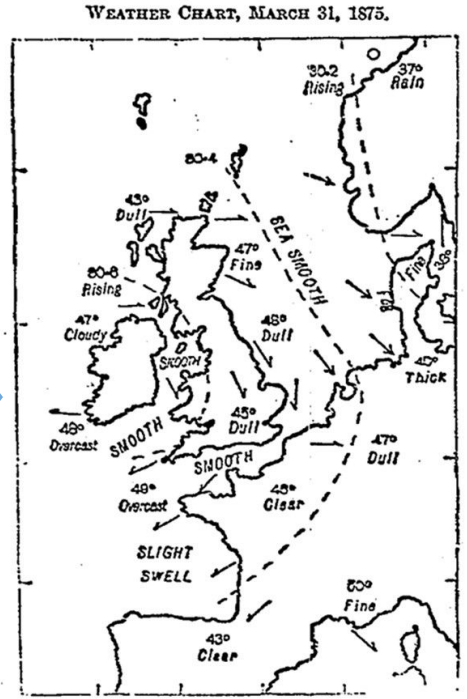
Wednesday, July 31, 8 to 9 a.m.	B.	E.	M.	D.	F.	C.	I.	S.
Nairn..	29·54	57	56	W.S.W.	6	9	o.	3
Aberdeen	29·60	59	54	S.S.W.	5	1	b.	3
Leith	29·70	61	55	W.	3	5	c.	2
Berwick	29·69	59	55	W.S.W.	4	4	c.	2
Ardrossan . ..	29·73	57	55	W.	5	4	c.	5
Portrush	29·72	57	54	S.W.	2	2	b.	2
Shields	29·80	59	54	W.S.W.	4	5	o.	3
Galway	29·83	65	62	W.	5	4	c.	4
Scarborough ..	29·86	59	56	W.	3	6	c.	2
Liverpool.. ..	29·91	61	56	S.W.	2	8	c.	2
Valentia	29·87	62	60	S.W.	2	5	o.	3
Queenstown ..	29·88	61	59	W.	3	5	c.	2
Yarmouth.. ..	30·05	61	59	W.	5	2	c.	3
London	30·02	62	56	S.W.	3	2	b.	—
Dover..	30·04	70	64	S.W.	3	7	o.	2
Portsmouth ..	30·01	61	59	W.	3	6	o.	2
Portland	30·03	63	59	S.W.	3	2	c.	3
Plymouth.. ..	30·00	62	59	W.	5	1	b.	4
Penzance	30·04	61	60	S.W.	2	6	c.	3
Copenhagen ..	29·94	64	—	W.S.W.	2	6	c.	3
Helder	29·99	63	—	W.S.W.	6	5	c.	3
Brest	30·09	60	—	S.W.	2	6	c.	5
Bayonne	30·13	68	—	—	—	9	m.	5
Lisbon	30·18	70	—	N.N.W.	4	3	b.	2

General weather probable during next two days in the—
North—Moderate westerly wind ; fine.
West—Moderate south-westerly ; fine.
South—Fresh westerly ; fine.

Explanation.

B. Barometer, corrected and reduced to 32° at mean sea level ; each 10 feet of vertical rise causing about one-hundredth of an inch diminution, and each 10° above 32° causing nearly three-hundredths increase. E. Exposed thermometer in shade. M. Moistened bulb (for evaporation and dew-point). D. Direction of wind (true—two points *left* of magnetic). F. Force (1 to 12—estimated). C. Cloud (1 to 9). I. Initials :—b., blue sky ; c., clouds (detached) ; f., fog ; h., hail ; l., lightning ; m., misty (hazy) ; o., overcast (dull) ; r., rain ; s., snow ; t., thunder. S. Sea disturbance (1 to 9).

1875



The dotted lines indicate the gradations of barometric pressure The variations of the temperature are marked by figures, the state of the sea and sky by descriptive words, and the direction of the wind by arrows—barbed and feathered according to its force. ⊙ denotes calm.

Today's evolution

1861

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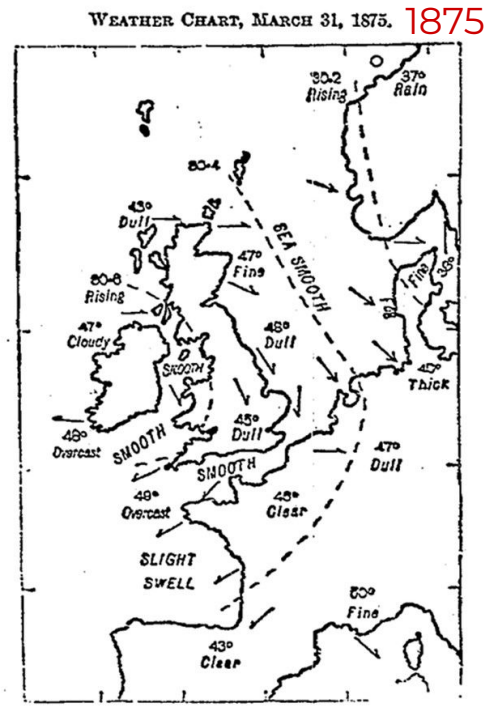

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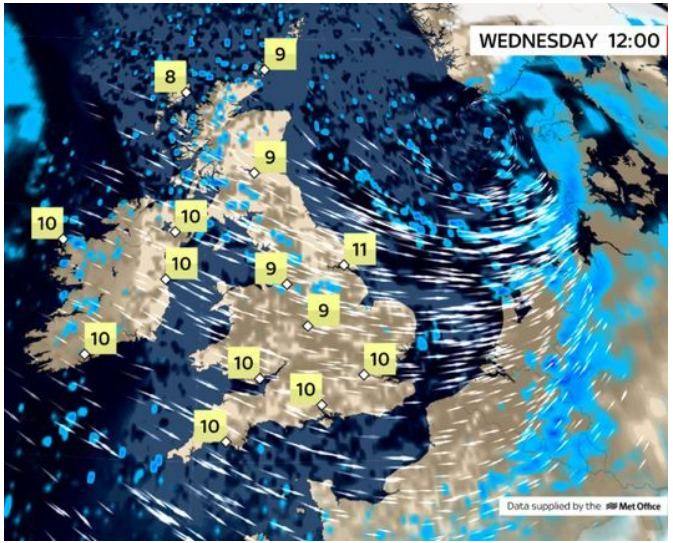
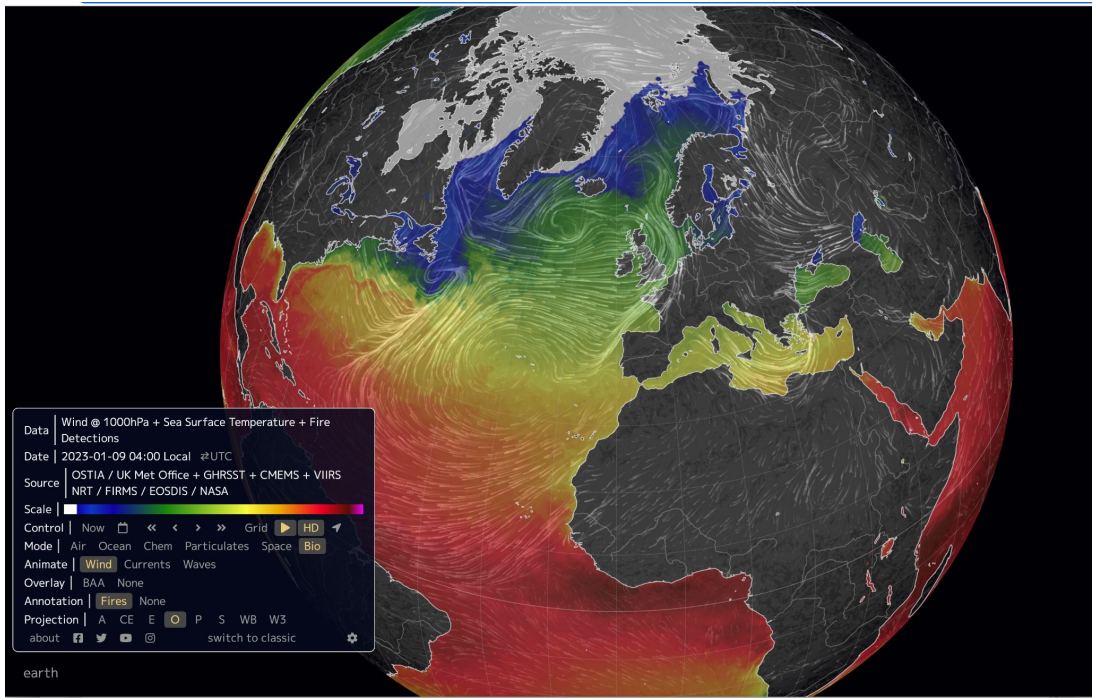
2019



Taken from March 13 forecast (also animated)

Keep in mind your goal…



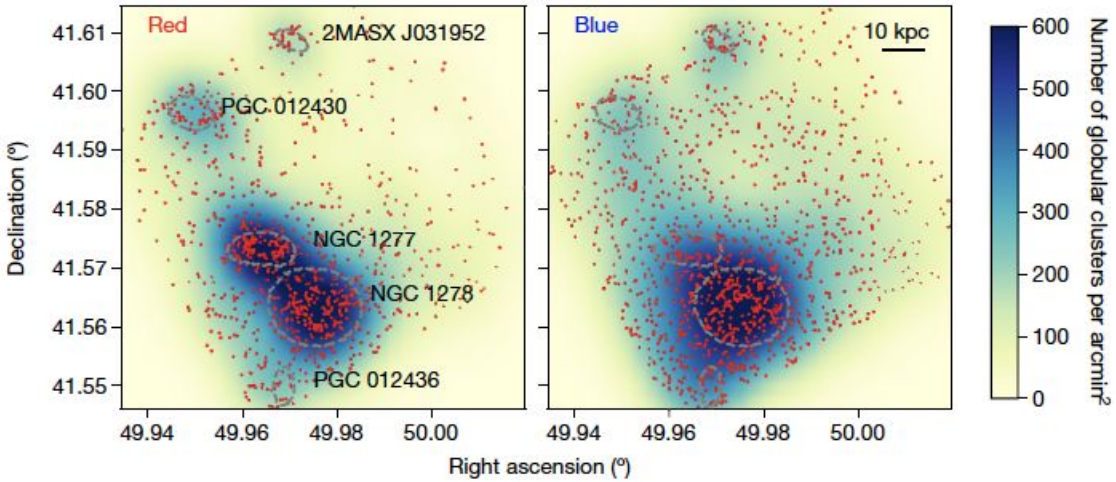
1) **Massive amount of information delivered in a concise, visually intuitive way**

[Spinny weather stuff]

Any graphical display should

- Show the data
- Induce the reader to think about the message
  - Not about methodology, graphic design, ...
- Avoid distorting what the data have to say
- Present concisely many numbers in a small space
- Serve a reasonably clear purpose
  - Description, exploration, tabulation~~, or decoration~~ (not in science)
- Closely integrated with the descriptions of a data set.

Keep in mind your goal...

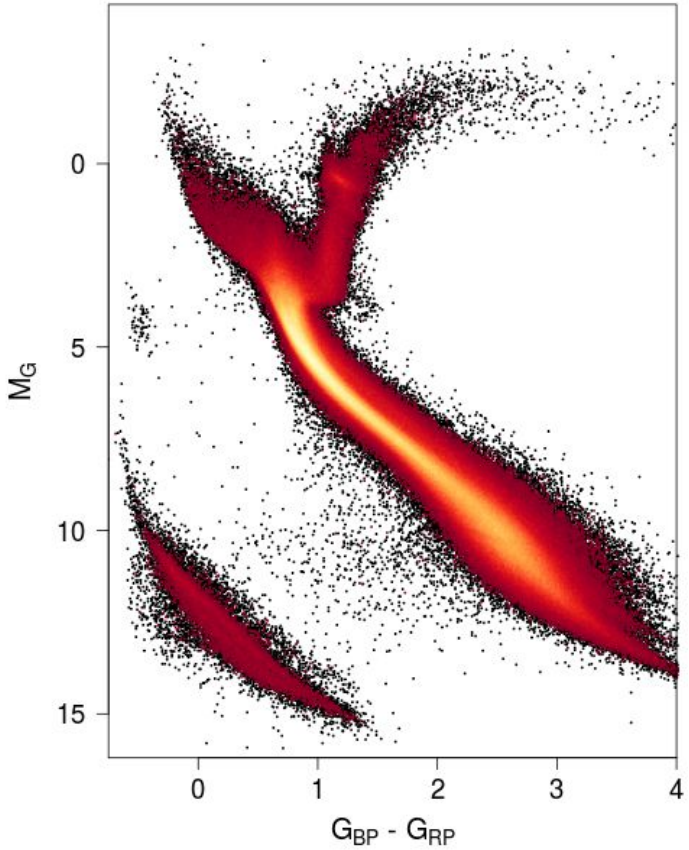


2) a plot (*and its caption*) may be the only thing a reader views!

There are so many papers (>50 per day) which appear. We do not have time to even skim all of them.

Your research will gain traction if there is **one key figure**, and it is **clear** and **visually appealing.**

Keep in mind your goal…

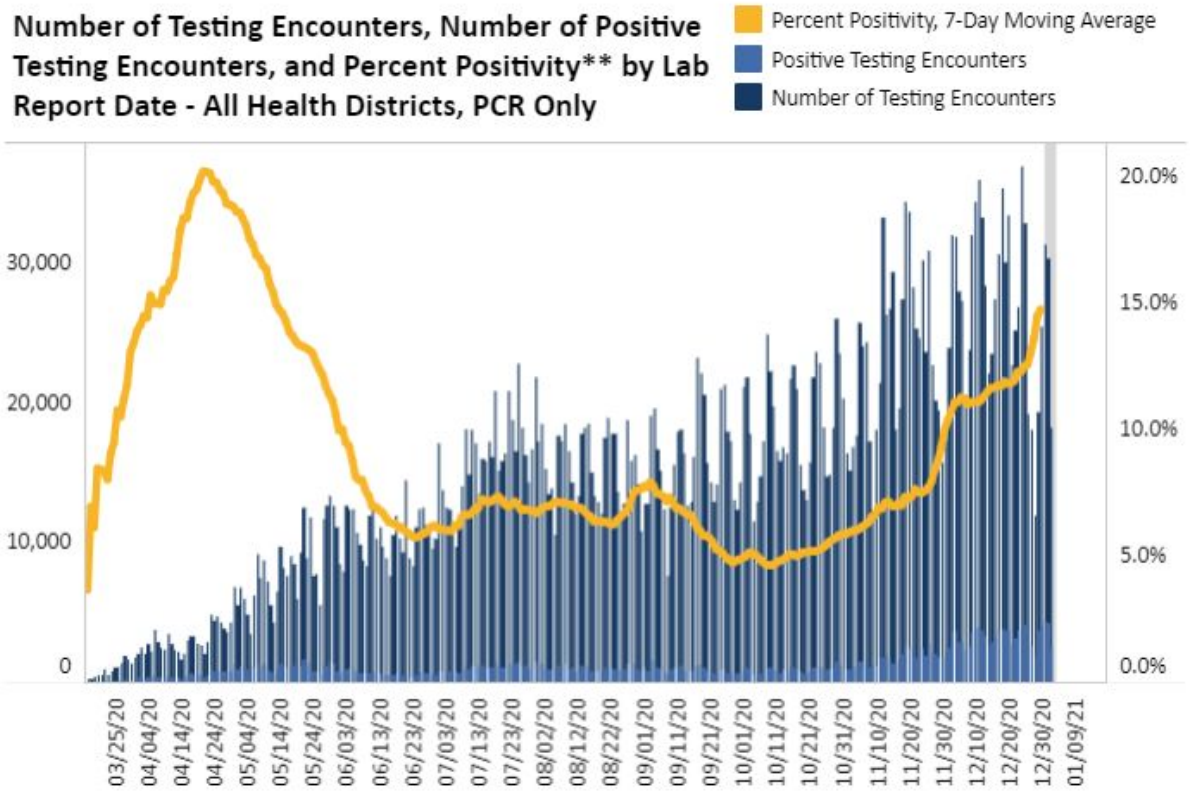


2) a plot (*and its caption*) may be the only thing a reader views!

Similarly your goal for a presentation should be to make figures that are eye-catching and effective enough that other speakers ‘steal’ them to use in a summary talks.

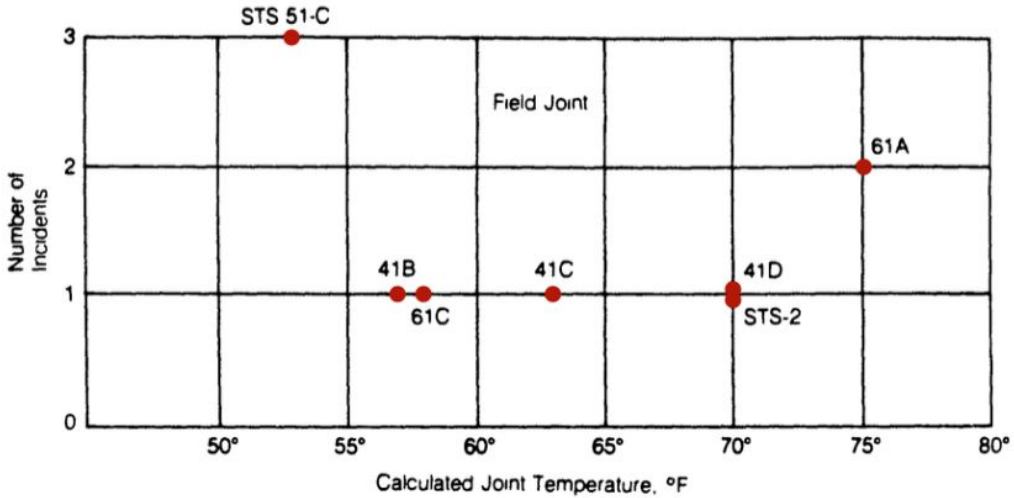
Any graphical display should

- **Show the data**



Poor plots can do the opposite!

- Show the data
- **Do not omit data, no matter how deviant from a trend or typical population**.



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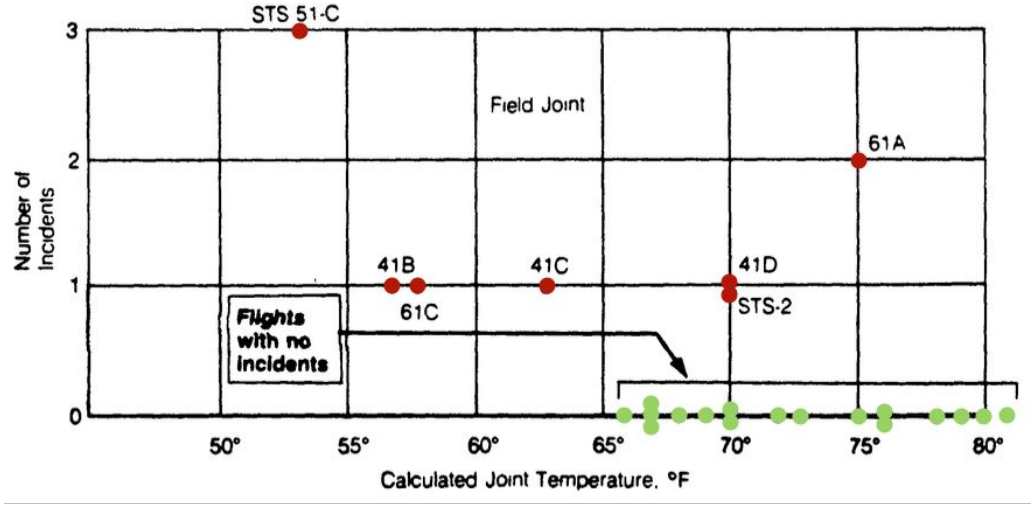
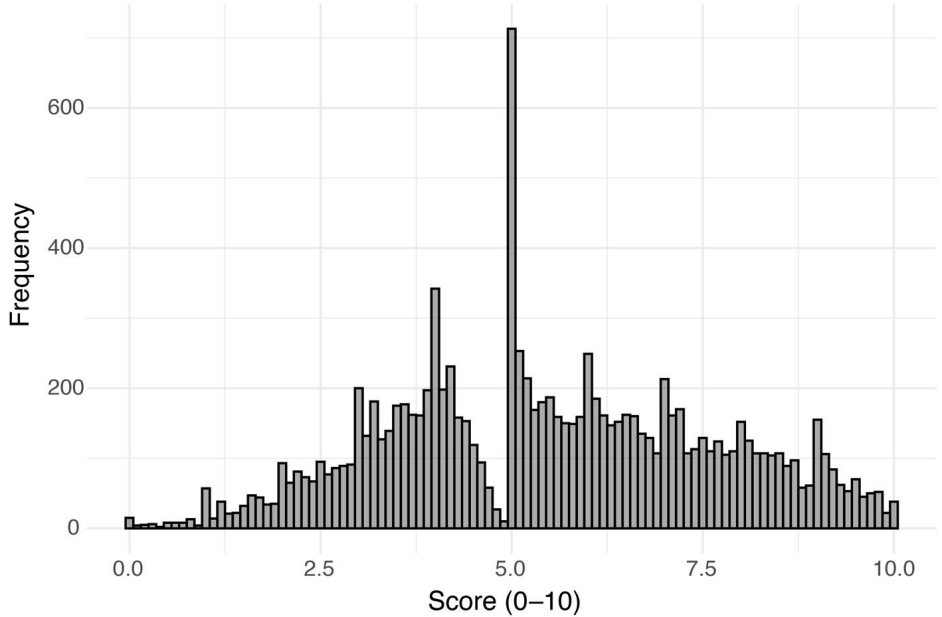


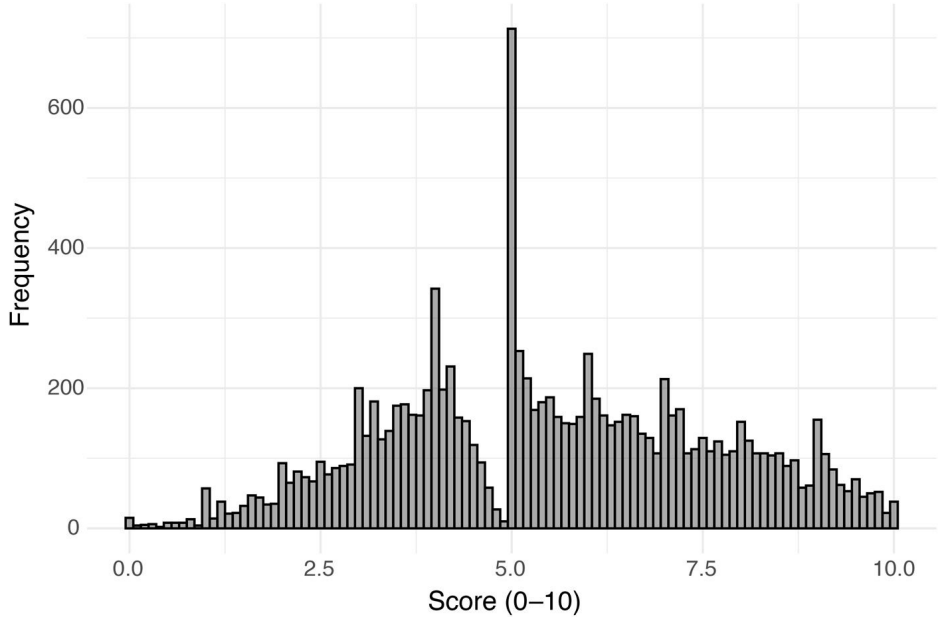
Poor plots can do the opposite!

- Show the data
- **This can sometimes mean visualizing data in different ways to identify biases**

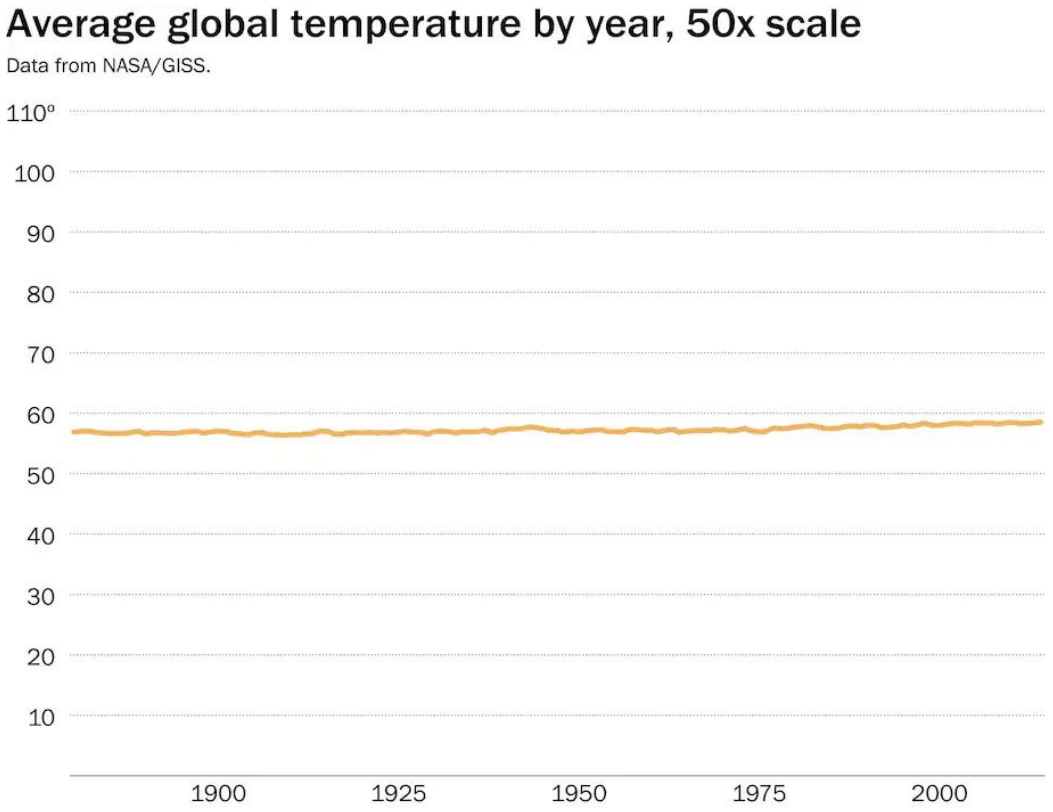


Poor plots can do the opposite!

- Can you guess what the pass/fail threshold was?



Poor plots can conceal the message!



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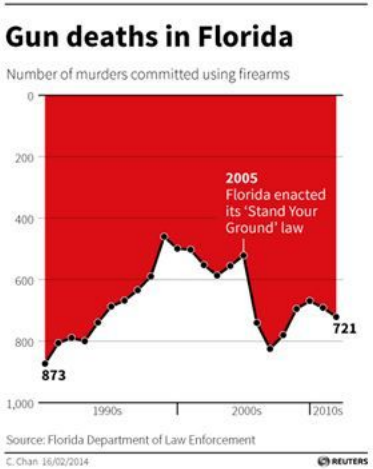

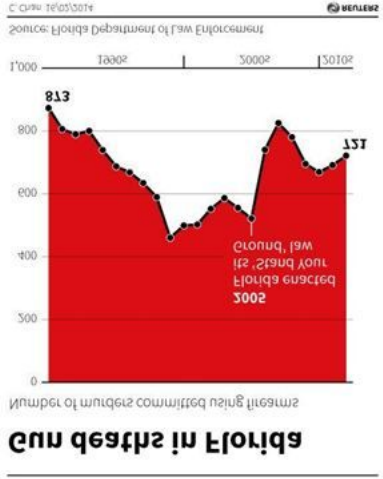

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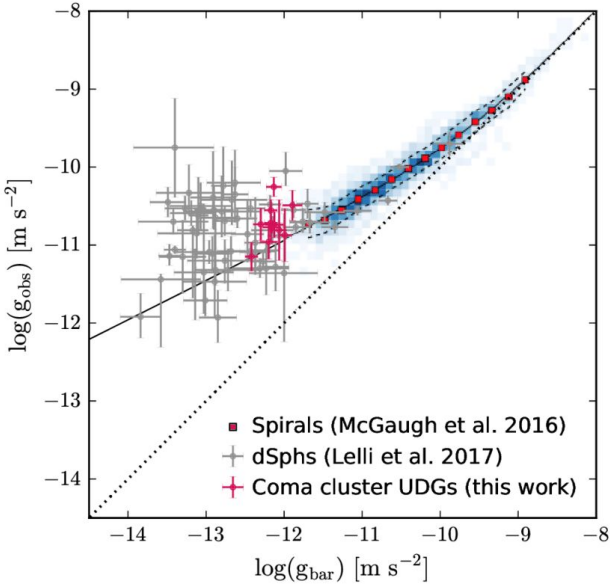
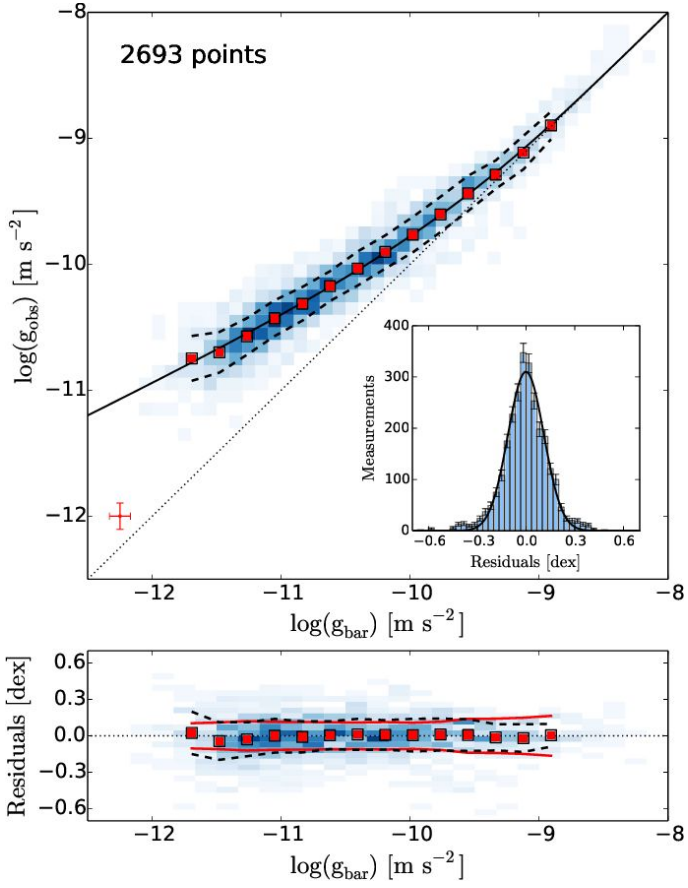
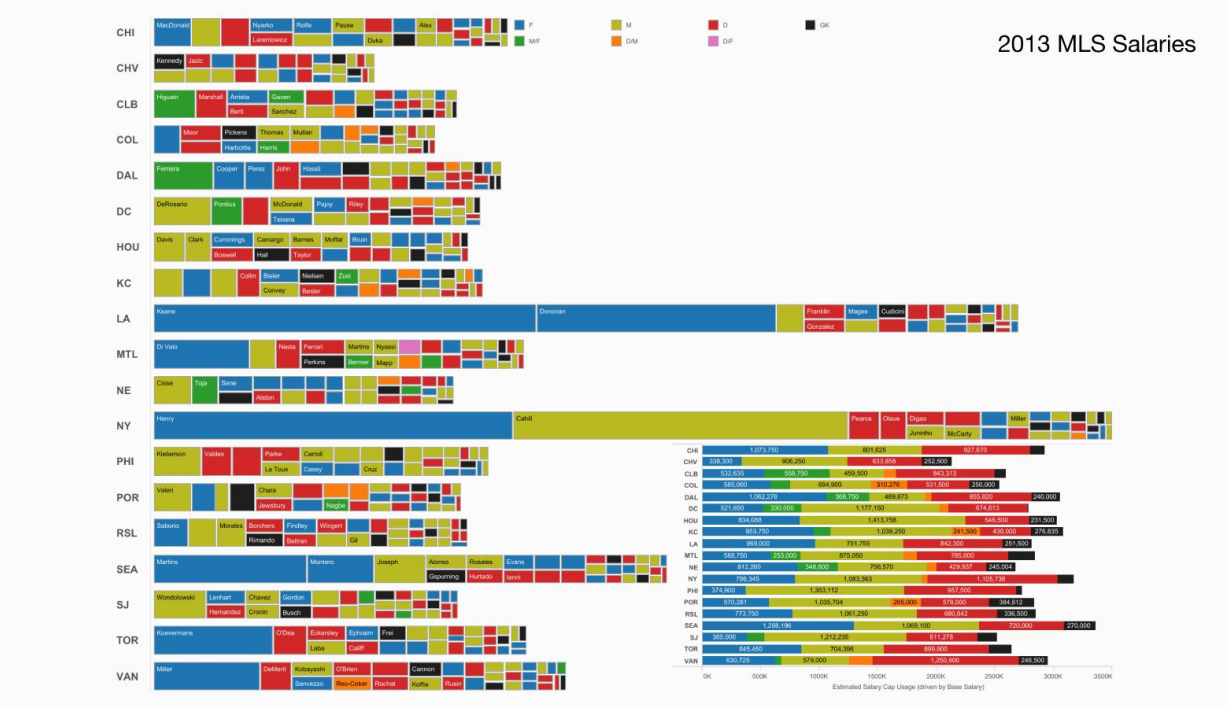
- **Serve a reasonably clear purpose**





Poor plots can do the opposite!!!

- **Concise and clear??**



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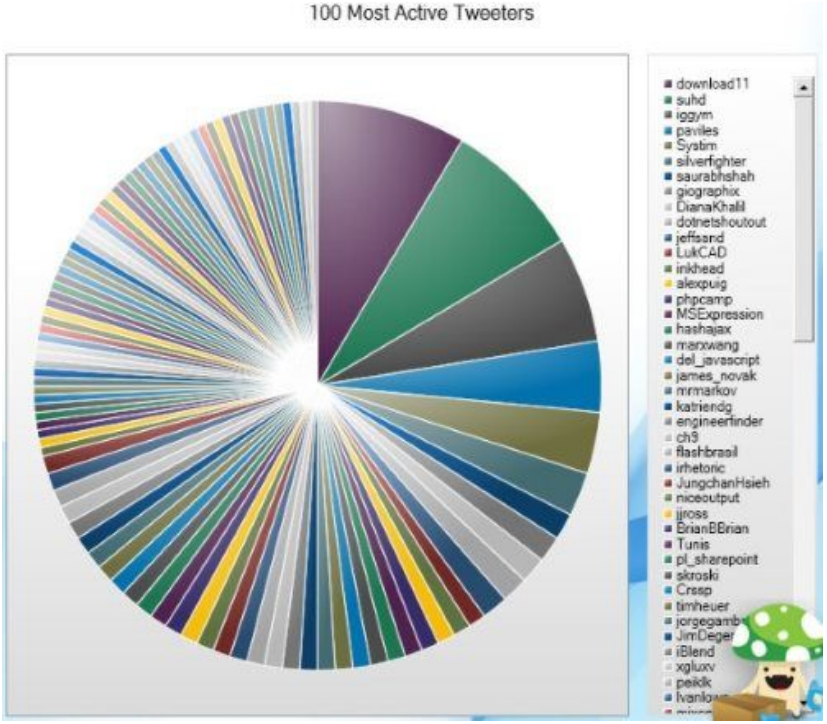

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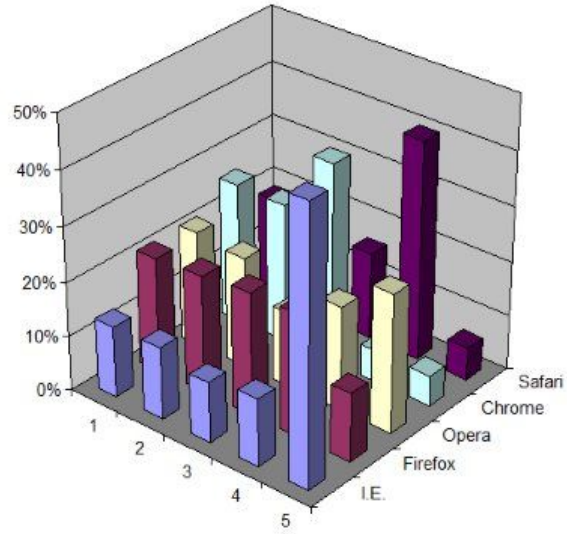
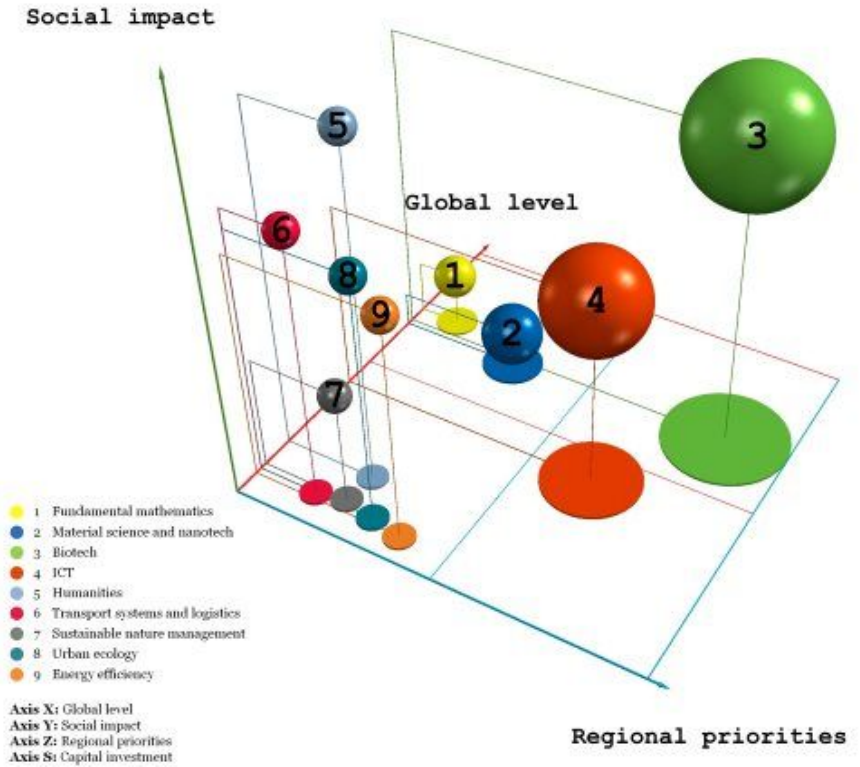
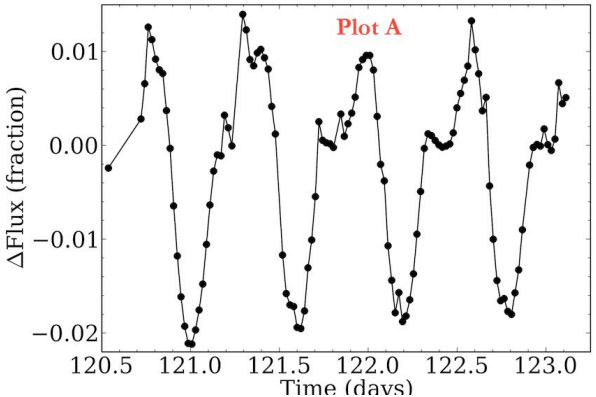
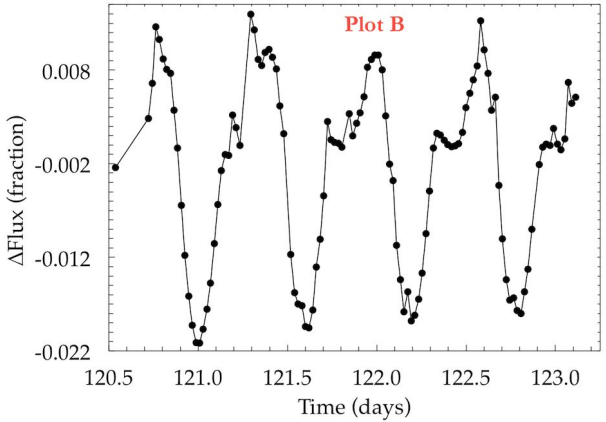


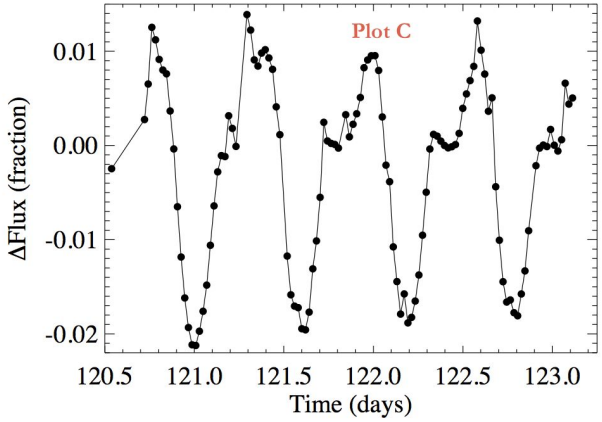


Your visualization tool **doesn't** matter

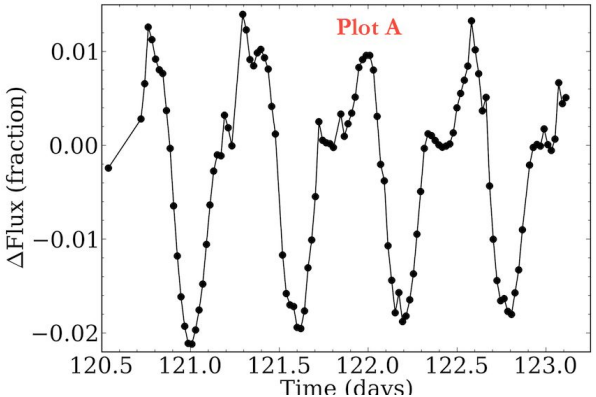
If We Assume: Excel vs Python vs IDL

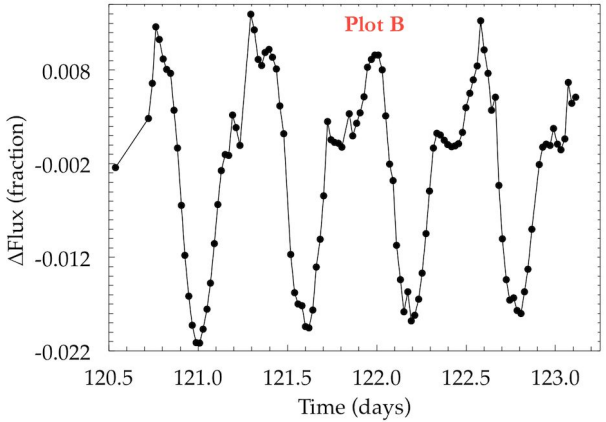


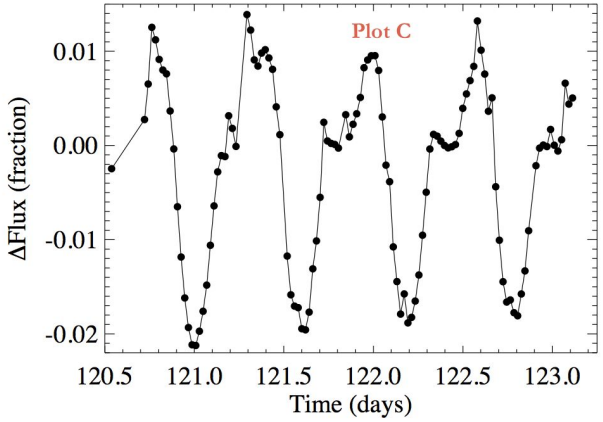




If We Assume: Excel vs Python vs IDL







The tool is **not an excuse** for bad graphics.

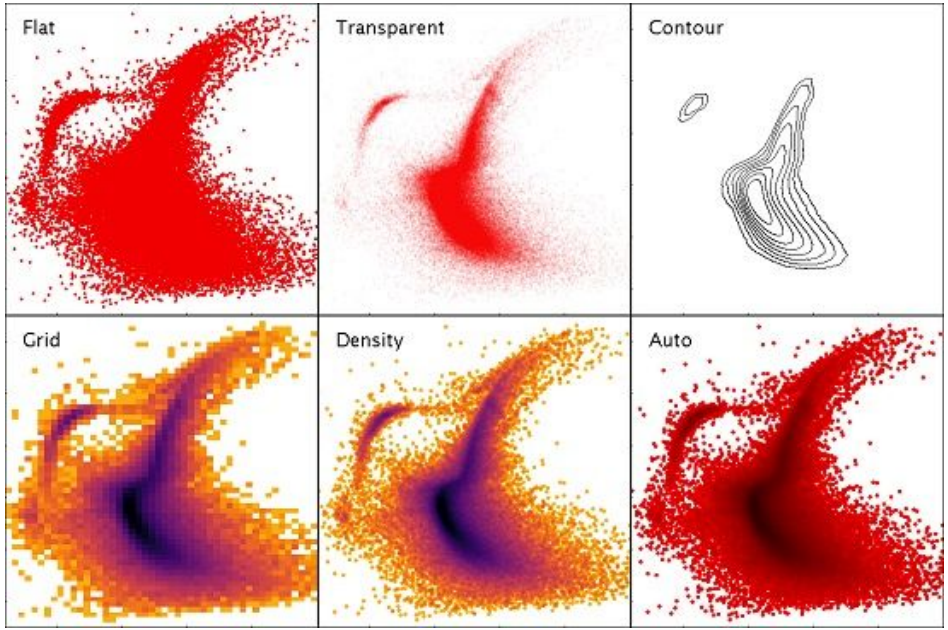
- Any tool can produce the same figure (with more or less the same effort/work)

A=Python, B=Excel, C=IDL

However different tools....

May be better for:

- Exploratory visualization (**TOPCAT, DataWrapper** demos)

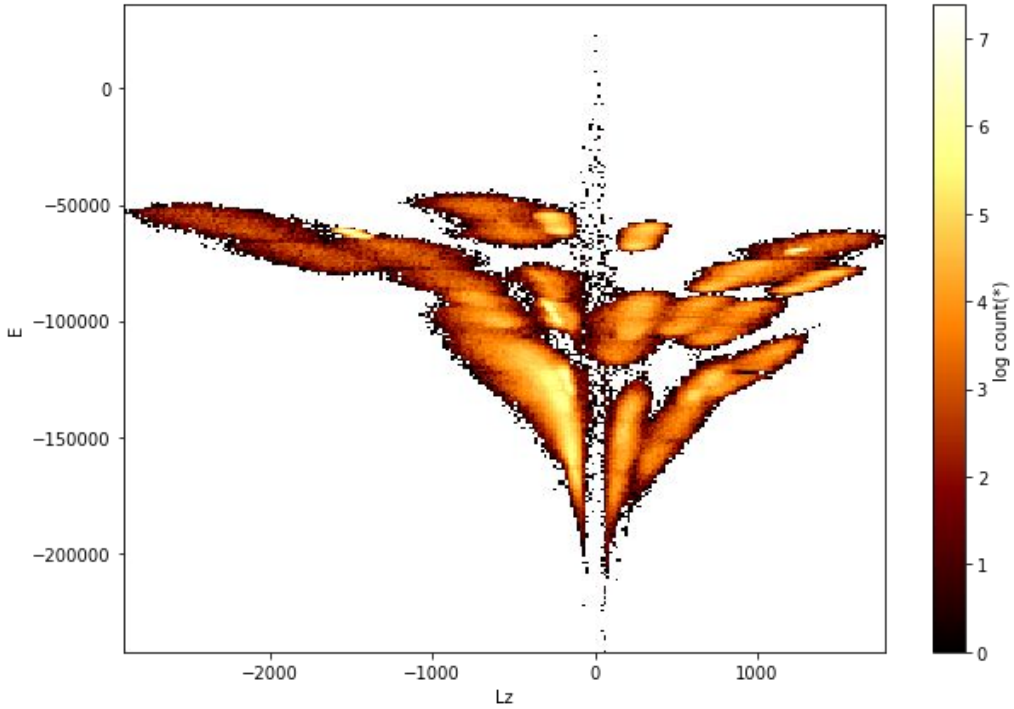


However different tools....

May be better for:

- Extremely large data sets (**vaex**)

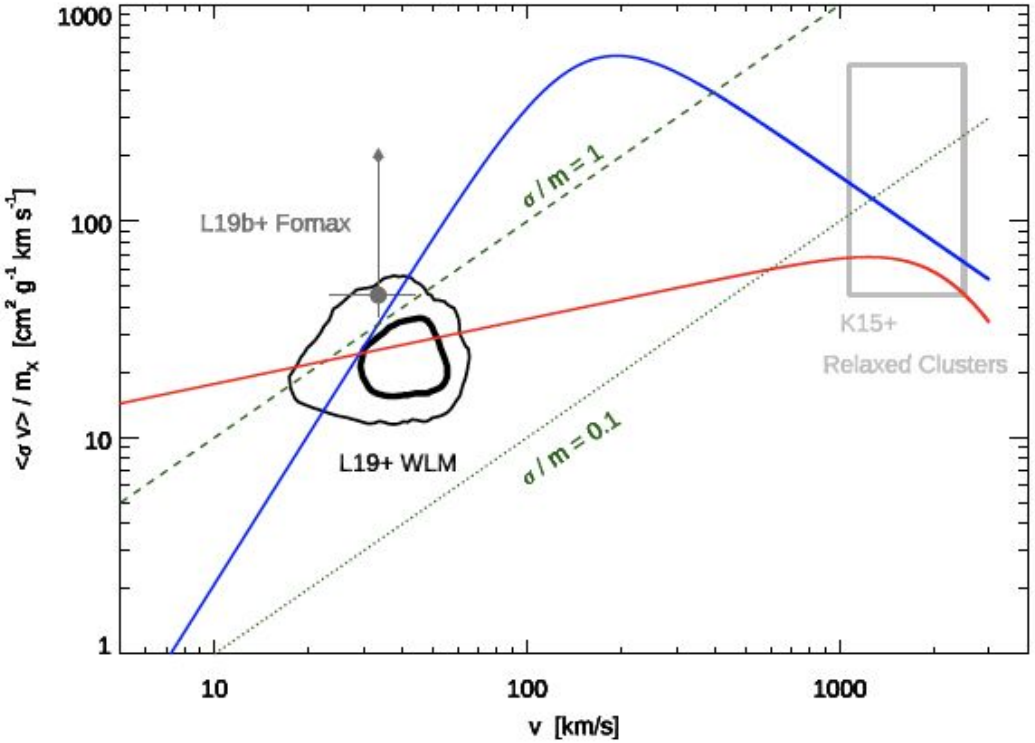
  https://vaex.io/example/dash-and-vaex-big-data-exposed



However different tools....

May be better for:

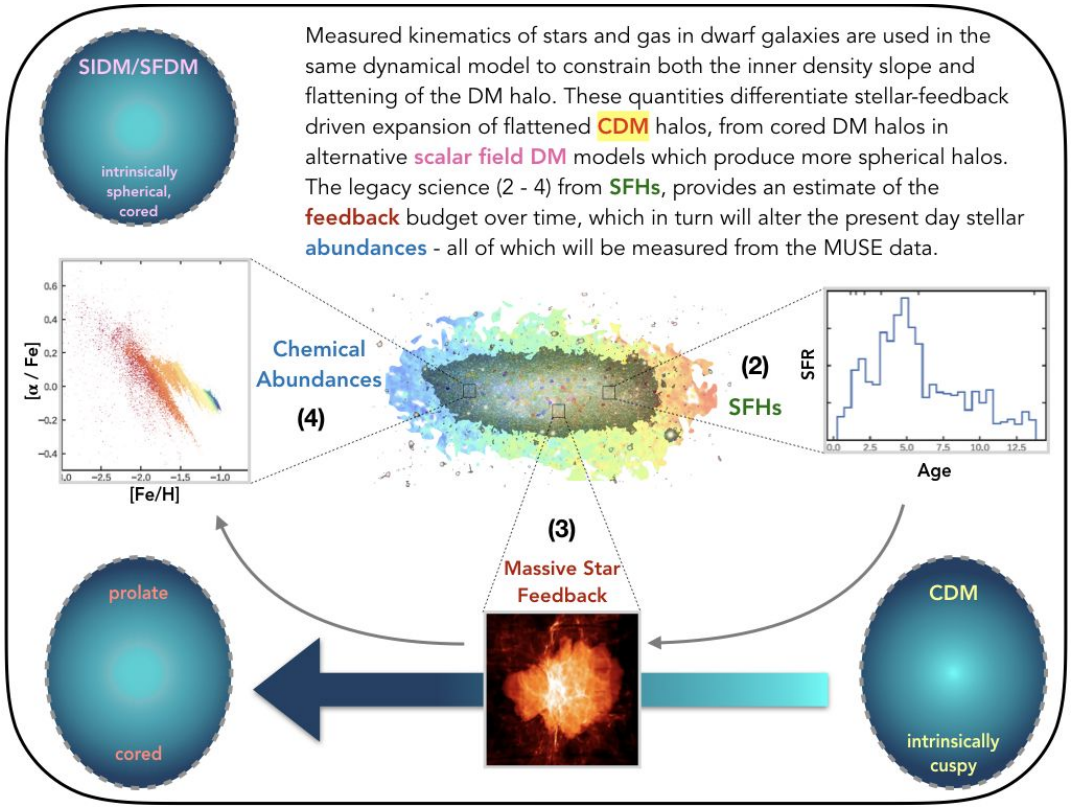
- Paper-quality publications (**IDL, Python**)



However different tools....

May be better for:

- Highly annotated presentation or proposal quality figures (**keynote/powerpoint**)



What makes **good** visualizations?

Rule of thumb

- Do not need more than 1 minute to present a figure
  - Decompose into panels if needed
- No more than 2 messages! (only one is best but not always feasible)
- Use the caption wisely: e.g., frame the key point of the figure, refer to text section(s) etc.
- Think about reusability: figure for paper used in your talk, or other's talks.
- Make it clear and easy to dissect/share/understand = more citations!

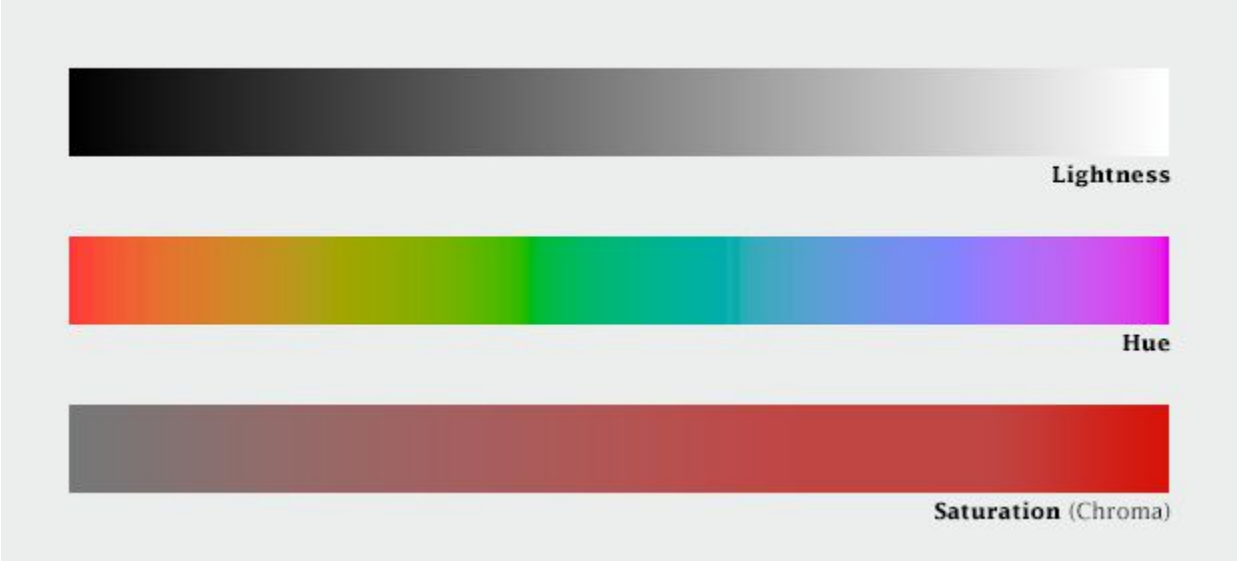
Important aspects to consider

- **Color choices**
- Fonts size, notations, axis labels
- Wise use of the figure caption to complement the figure
- Think of reusability to increase your impact

Pick colors

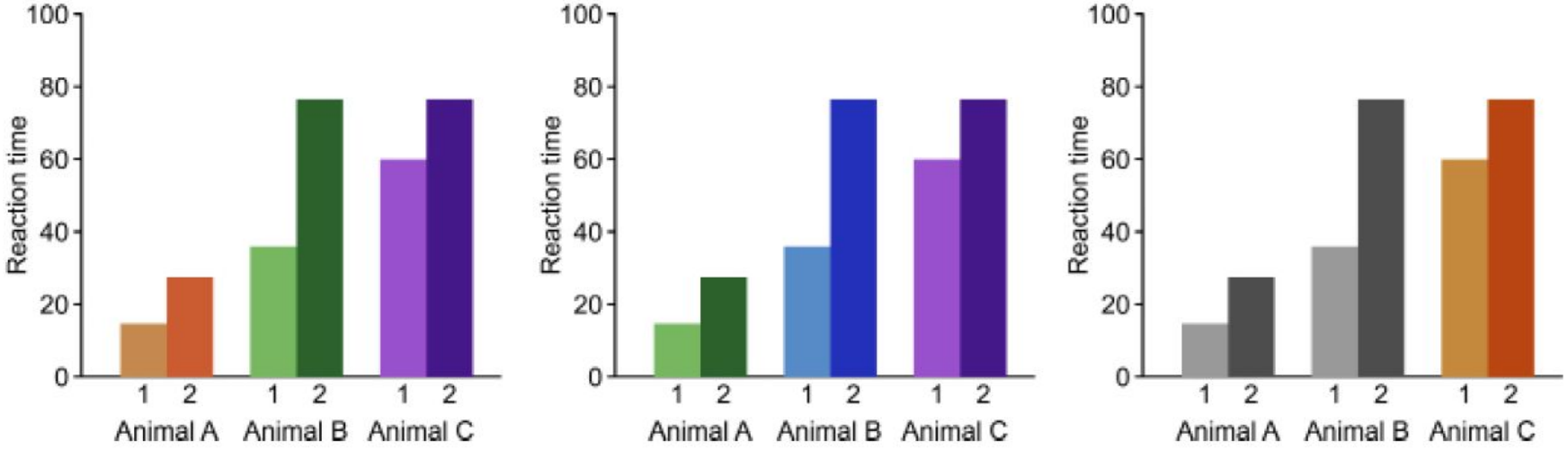
appropriately

Color perception - Basics



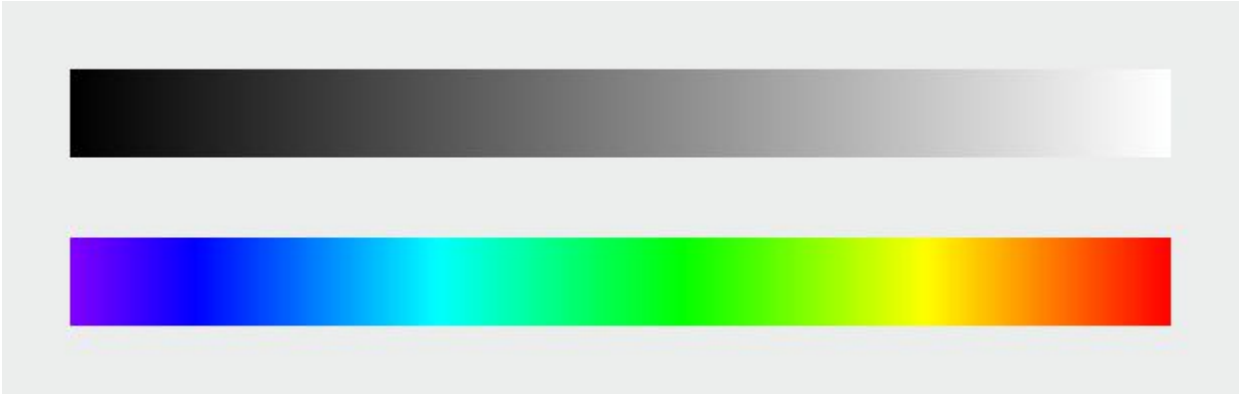
Complementary, analogous, triad

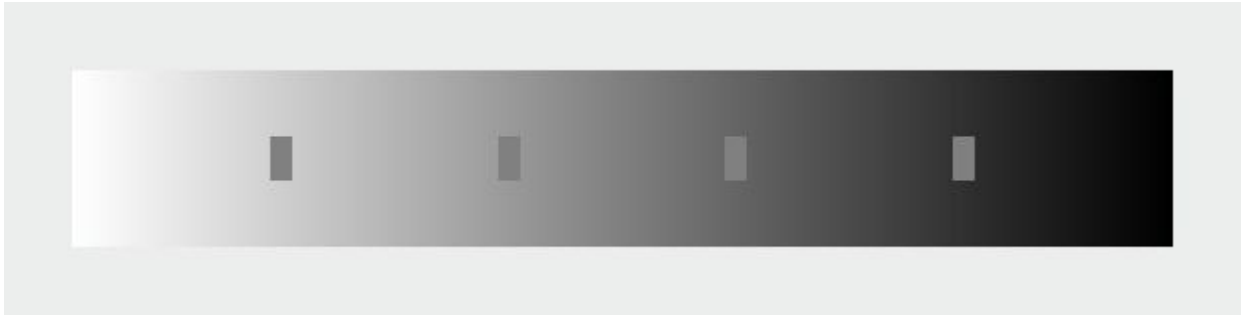
Complementary, analogous, triad - examples



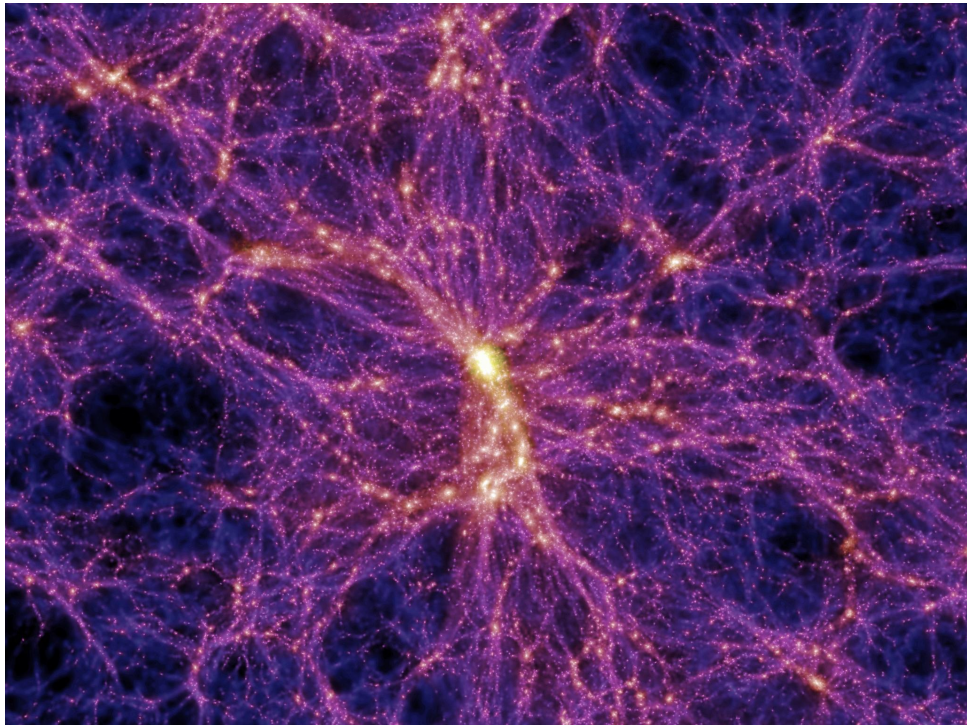
Qualitative data

Sequential data



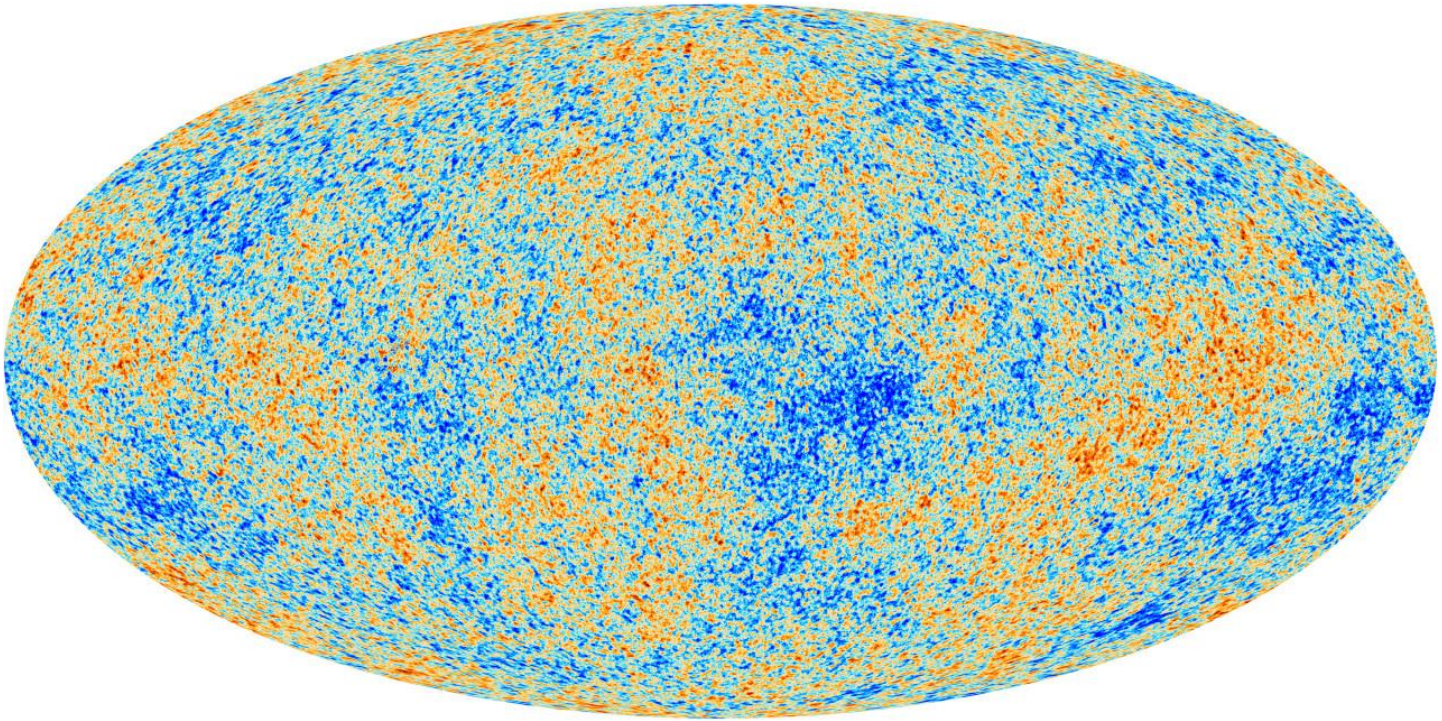


Sequential data - example

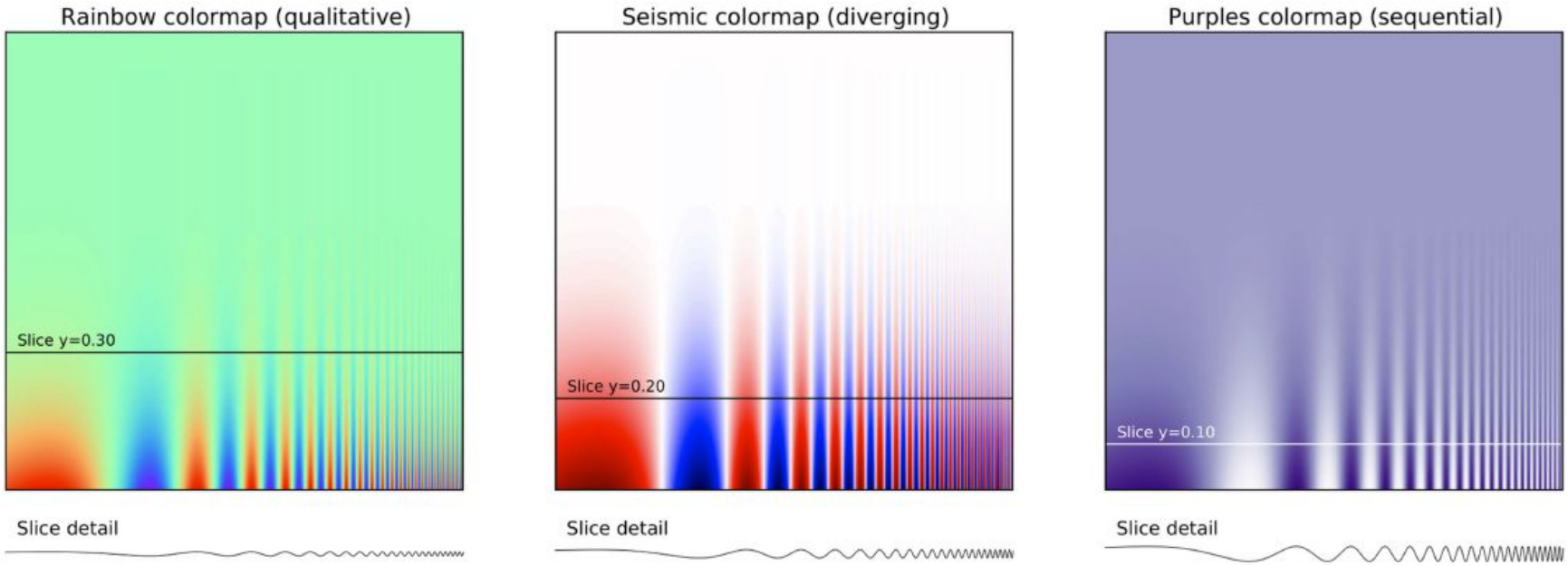


Diverging data

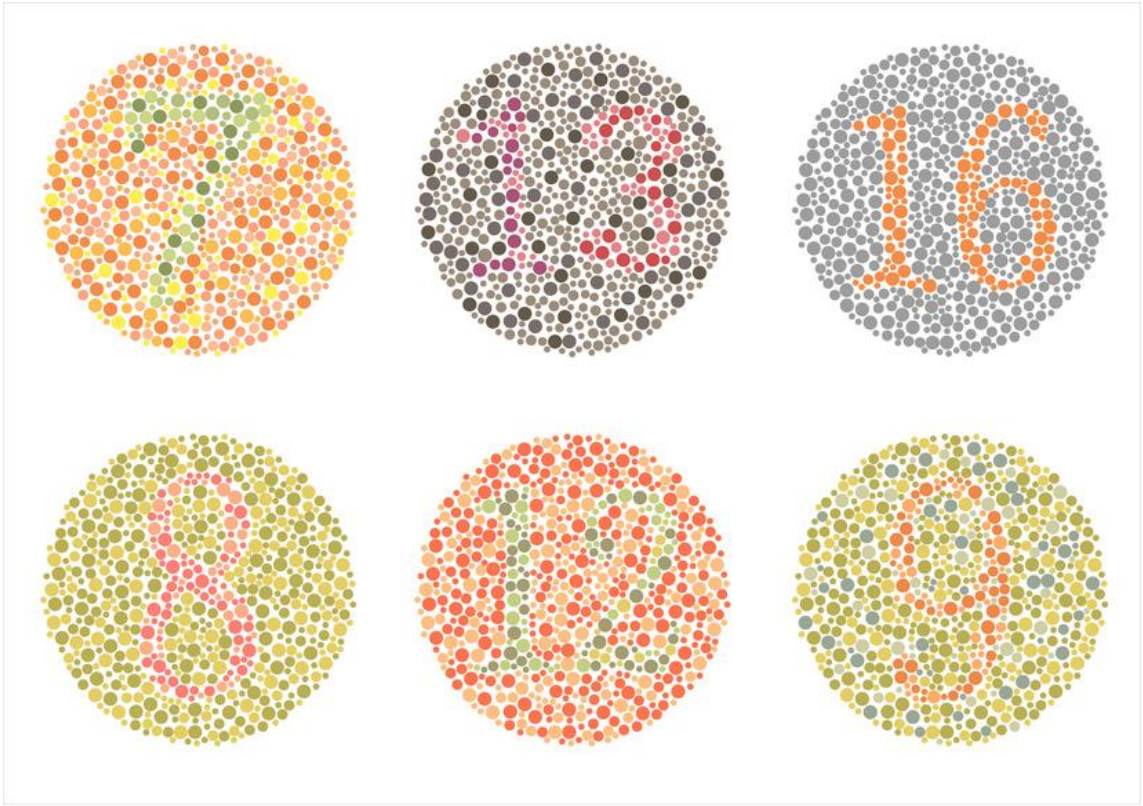
Diverging data - example



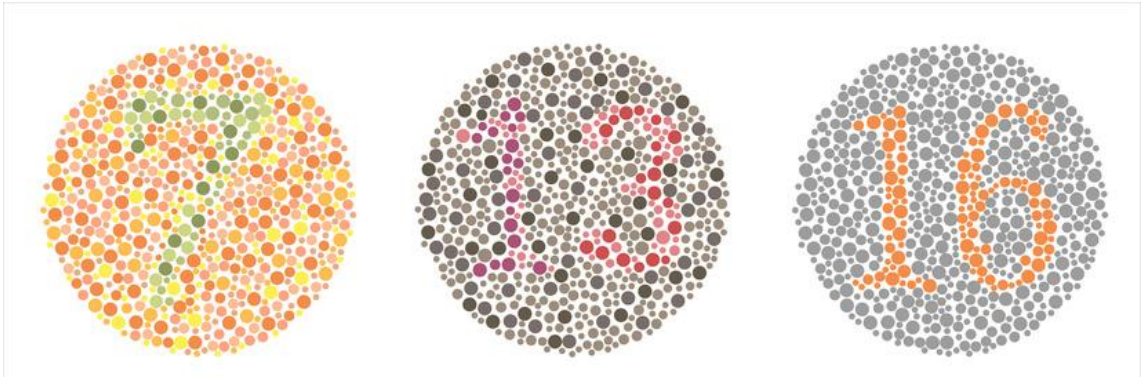
Color schemes may change perceptions



Color Blindness



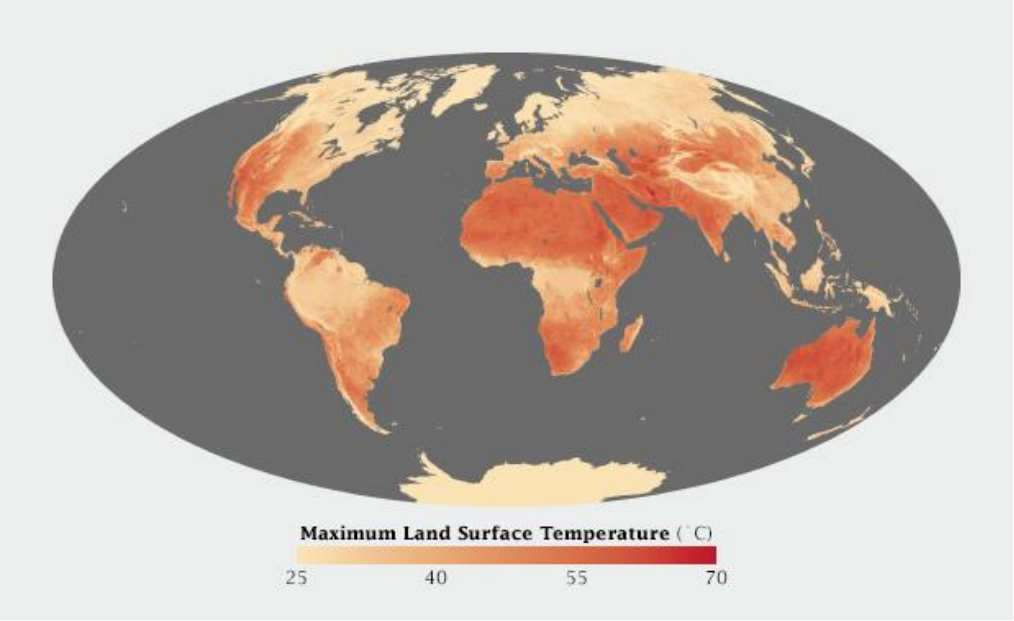
Color Blindness

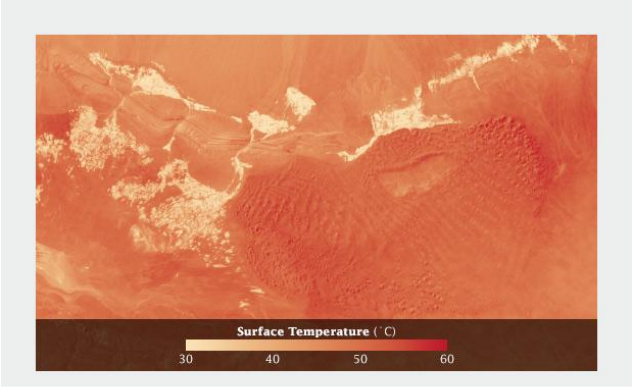


- Red-green: 8% males, 0.5% females (Northern European descent) commonly inherited from mutations on the X chromosome,

  Source: Facts About Color Blindness

There is no general/perfect solution !





[2]

Some advice

- Use color **consciously** - less is more!
- Apply color **appropriately**
  - for qualitative, sequential, diverging data
- Design color **inclusively**
  - color palettes, thickness of lines & symbols
- Remember:
  - There is no general/perfect solution.
  - Do not go against intuition.

Further reading:

Rainbow Color Map (Still) Considered Harmful

- https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=4118486

How Bad Is Your Colormap? (Or, Why People Hate Jet – and You Should Too)

- https://jakevdp.github.io/blog/2014/10/16/how-bad-is-your-colormap/

How to Graph Badly or What NOT to Do

- http://www-personal.umich.edu/~jpboyd/sciviz_1_graphbadly.pdf

References for color section :

[1]http://sci.esa.int/planck/51551-simple-but-challenging-the-universe-according-to-planck/

[2]https://earthobservatory.nasa.gov/blogs/elegantfigures/2013/08/05/subtleties-of-color-part-1-of-6/

[3]https://www.aje.com/dist/docs/Using_Color_In_Your_Manuscript_Figures.pdf

[4]https://wwwmpa.mpa-garching.mpg.de/galform/millennium/seqF_037.jpg

[5]https://journals.plos.org/ploscompbiol/article?id=10.1371/journal.pcbi.1003833

[6]http://www.somersault1824.com/tips-for-designing-scientific-figures-for-color-blind-readers/

[7]https://www.nature.com/articles/nmeth.1618 (Wong, B. 2011, Nature Methods)

[8] https://hbr.org/2014/04/the-right-colors-make-data-easier-to-read

Use **common sense** for figure size, fonts, notations, axis labels

Figure size - example

arXiv:1810.04449v2

Faster Hamiltonian Monte Carlo by Learning Leapfrog Scale

Changye Wu* · Julien Stoehr* · Christian P. Robert

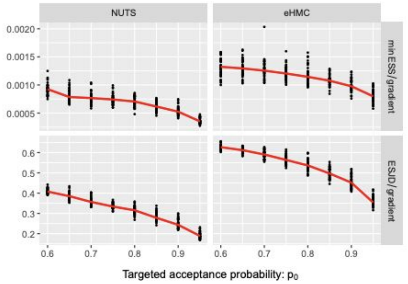


Fig. 1 Comparison between NUTS and eHMC samplers for a multivariate Normal distribution target: the x-axis is indexed by the targeted acceptance probability, p_0, associated with the primal-dual averaging step, and the y-axis in both plots corresponds to the minimum ESS across all parameter coordinates (first row) and to the ESJD (second row) per evaluation of ∇U, respectively. A black dot indicates the performance for a single experiment and the red curve is the resulting median of the 40 black-dot values for a particular p_0.

Figure size, use all the available space

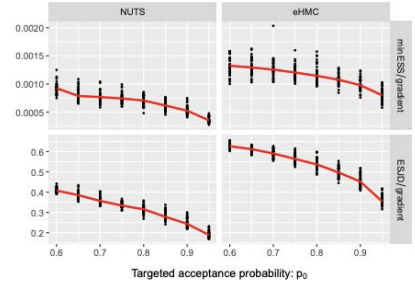
make sure you have attractive **key figures**

arXiv:1810.04449v2

Faster Hamiltonian Monte Carlo by Learning Leapfrog Scale

Changye Wu* · Julien Stoehr* · Christian P. Robert

columnwidth



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pagewidth

Figure size - example

arXiv:1810.04449v2

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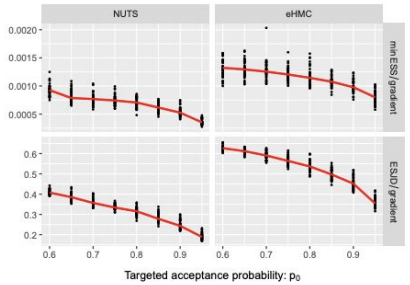
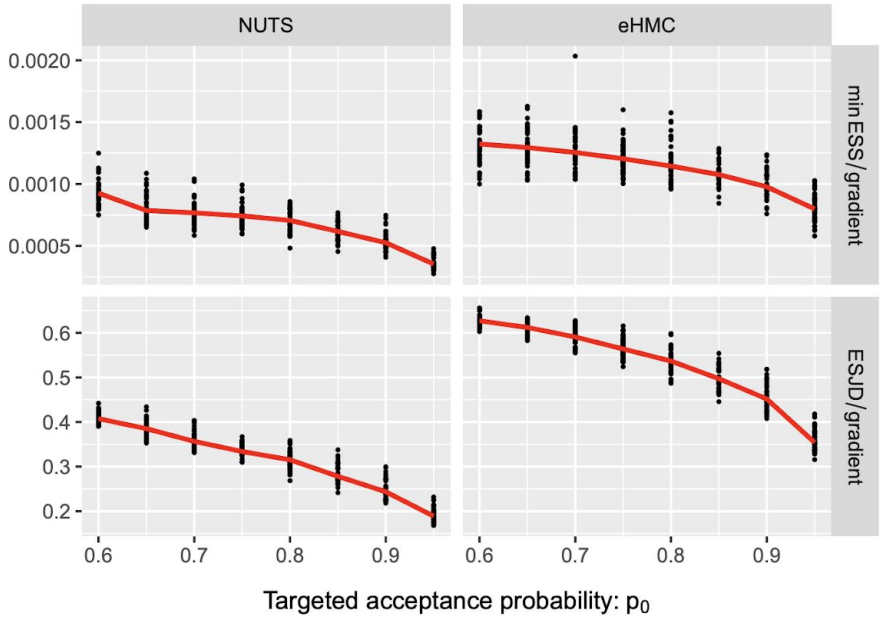


Key plot demonstrating the superiority of the eHMC sampling over NUTS

Selling well don't you think?

Fig. 1 Comparison between NUTS and eHMC samplers for a multivariate Normal distribution target: the x-axis is indexed by the targeted acceptance probability, p_0, associated with the primal-dual averaging step, and the y-axis in both plots corresponds to the minimum ESS across all parameter coordinates (first row) and to the ESJD (second row) per evaluation of ∇U, respectively. A black dot indicates the performance for a single experiment and the red curve is the resulting median of the 40 black-dot values for a particular p_0.

Fonts size - same example

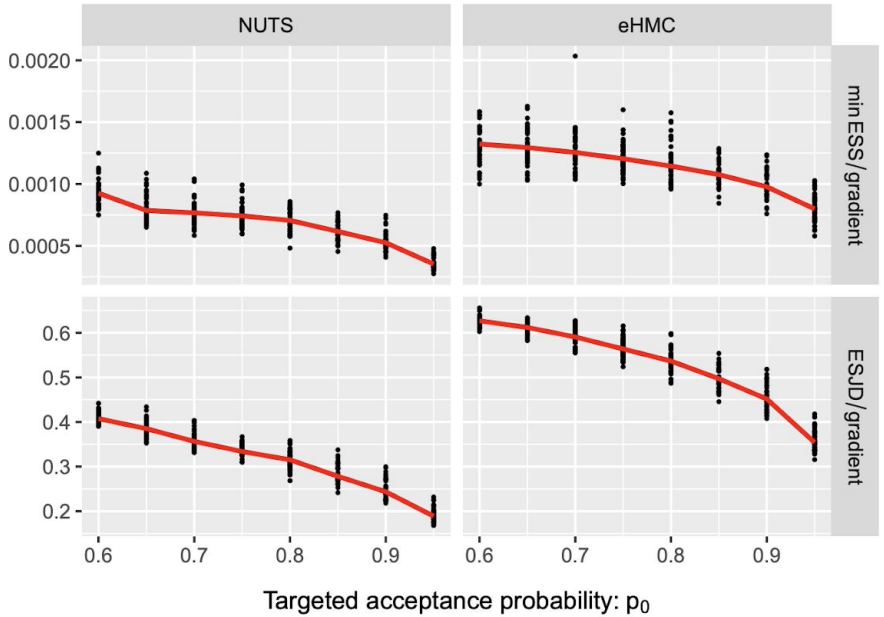


arXiv:1810.04449v2

Fig. 1 Comparison between NUTS and eHMC samplers for a multivariate Normal distribution

Fonts size - never smaller than the text

Axis-labels & legends should never be smaller than the article's text



ggplot defaults

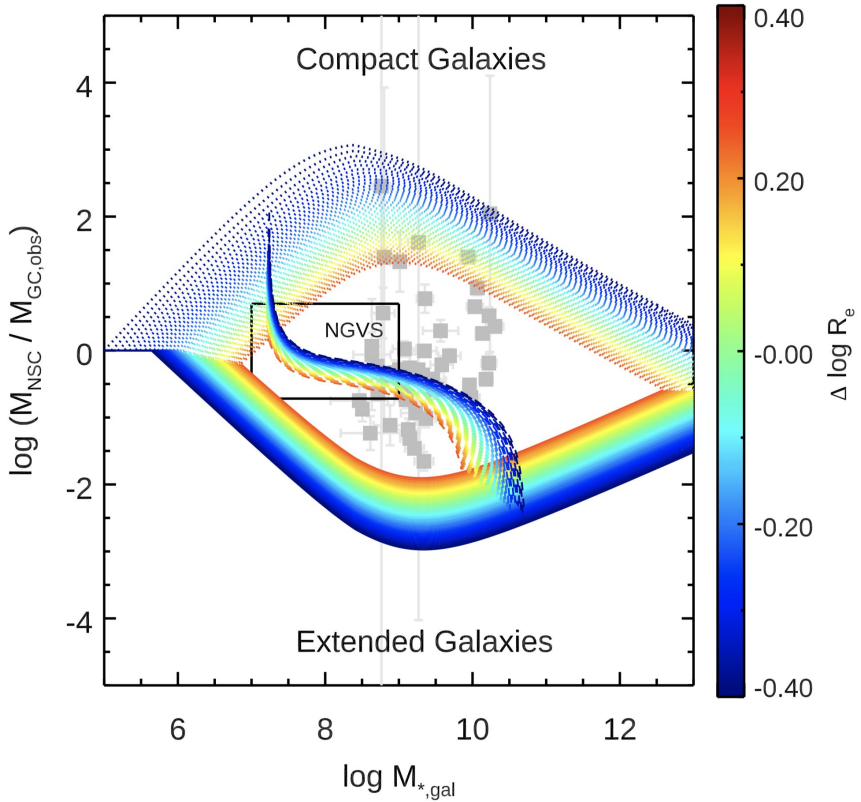
We'll come back to that

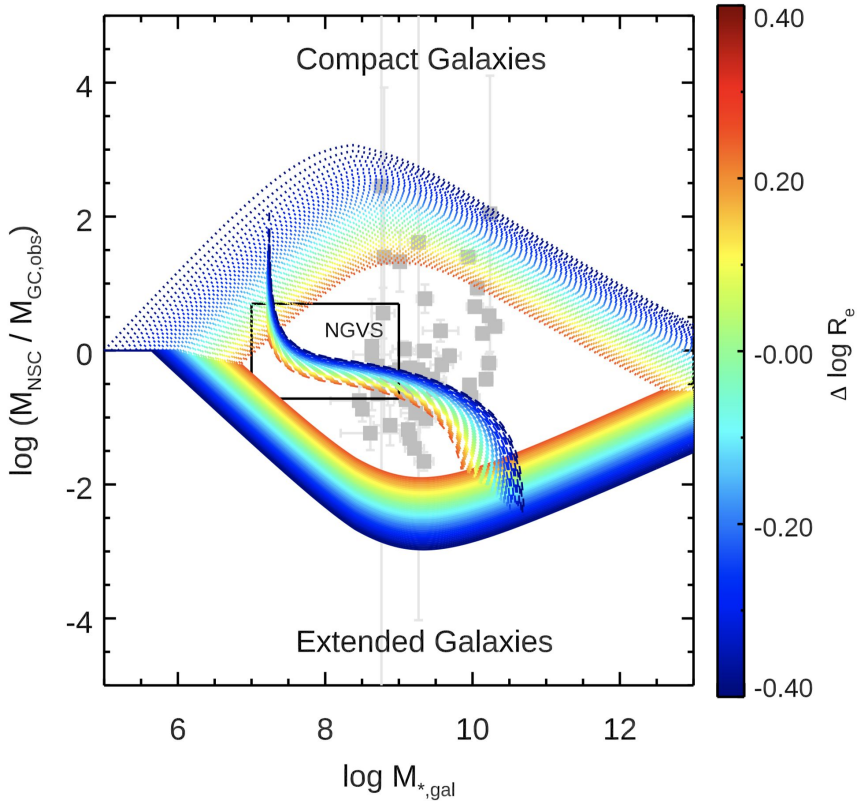
arXiv:1810.04449v2

Fig. 1 Comparison between NUTS and eHMC samplers for a multivariate Normal distribution

Avoid

overcrowding


Compact Galaxies
NGVS
Extended Galaxies
log (M_NSC / M_GC,obs)
log M*,gal
Δ log Re
0.40
0.20
-0.00
-0.20
-0.40
4
2
0
-2
-4
6
8
10
12


Compact Galaxies
NGVS
Extended Galaxies
log (M_NSC / M_GC,obs)
log M*,gal
Δ log Re
0.40
0.20
-0.00
-0.20
-0.40
4
2
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-2
-4
6
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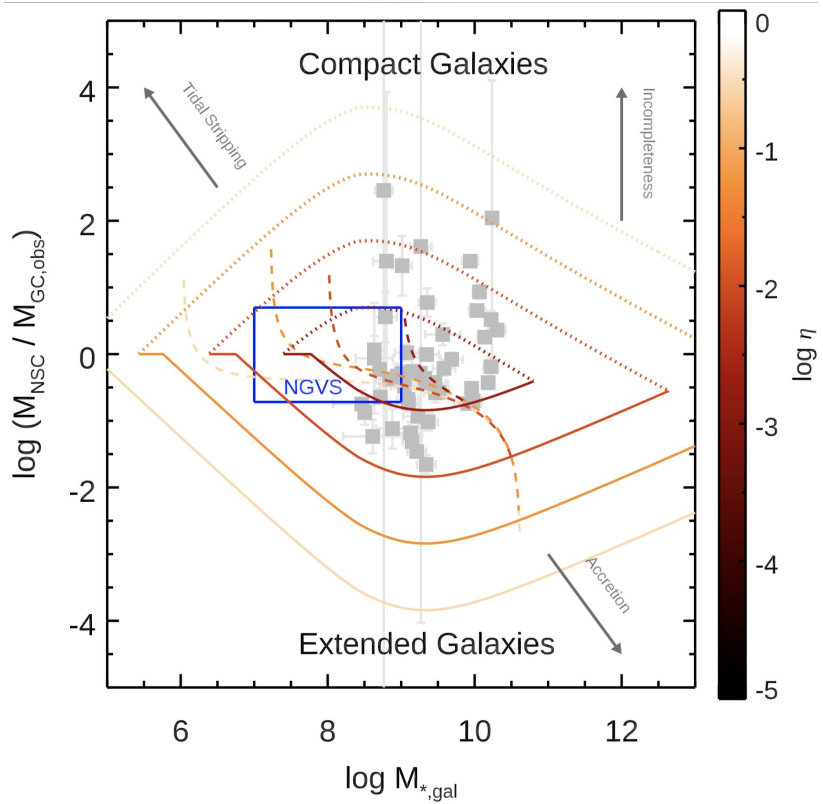
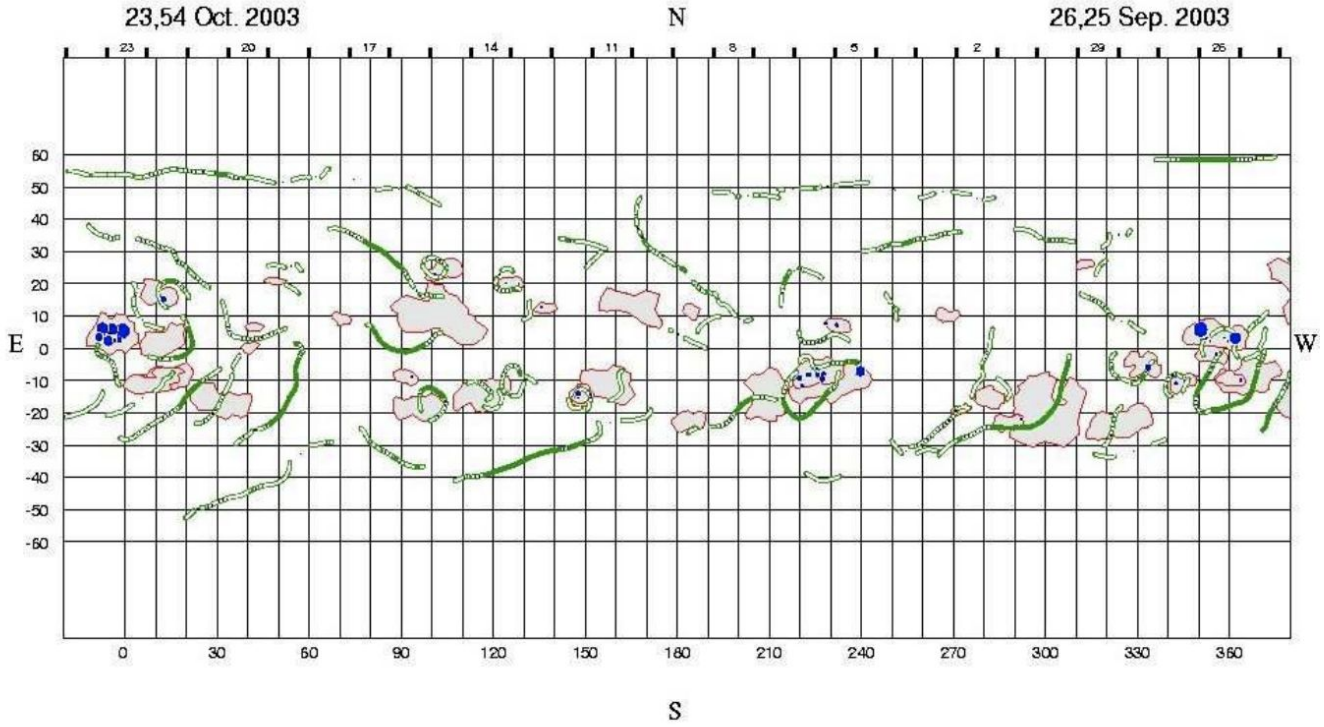

Compact Galaxies
Tidal Stripping
Incompleteness
NGVS
Accretion
Extended Galaxies
log (M_NSC / M_GC,obs)
log M*,gal
log η
0
-1
-2
-3
-4
-5
4
2
0
-2
-4
6
8
10
12

Use figure captions **wisely** to complement the figures

Example of bad use of caption

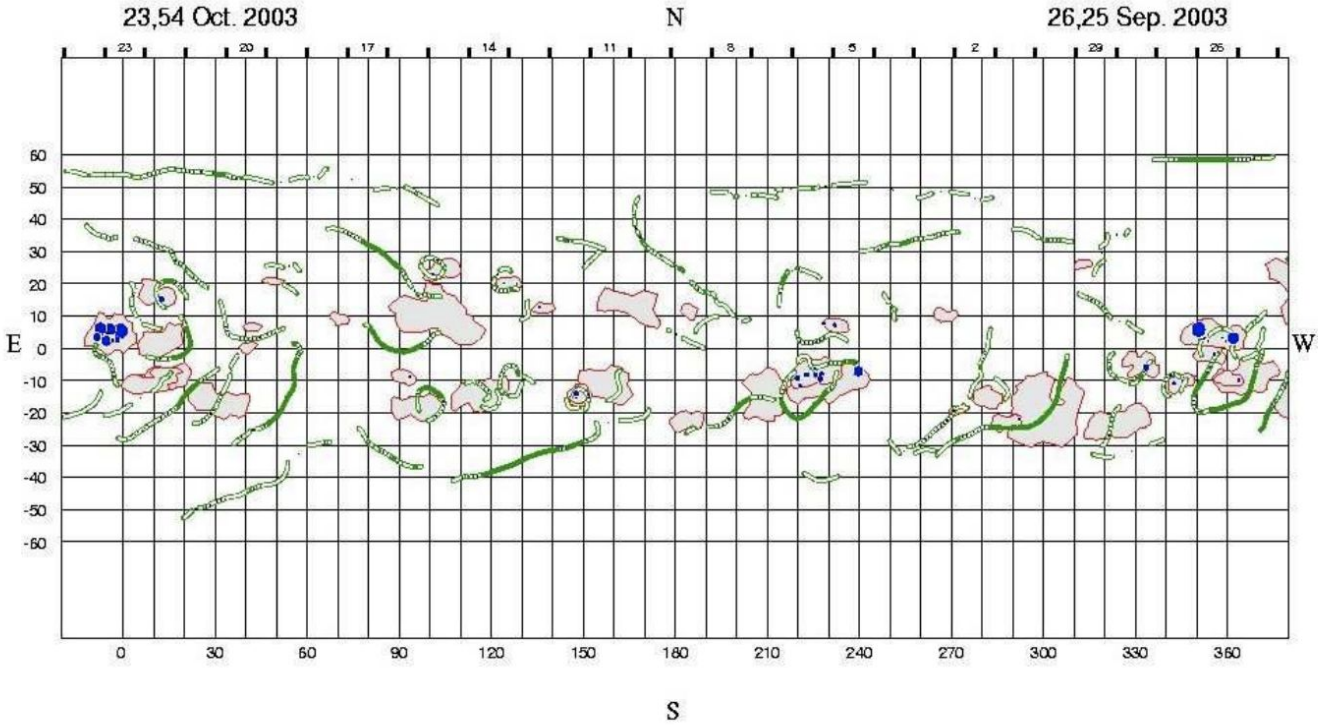


Very useful! So what are the green worms living on the Sun?

Fig. 2. Example of a Meudon Synoptic Map of Solar Activity.

Example of caption

Example of an automated Meudon Synoptic Map of Solar activity. Automated construction detailed in sect. 2. This map summarizes the time tracking of the filaments (green), the faculae (gray), and sunspots (blue) in the Carrington reference frame (see sect. 1). Solar features are to scale. Filament's higher hashing density encodes higher magnetic intensity (sect. 2).



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Take away-message

Note the text links to find rapidly details if interested.

Warning: you do not always write a proposal!

Figure simplified as much as possible.

Annotated

and very detailed caption.

Clear take-away message

Never a good practice for a paper!

Example from a
granted multi-cycle HST proposal

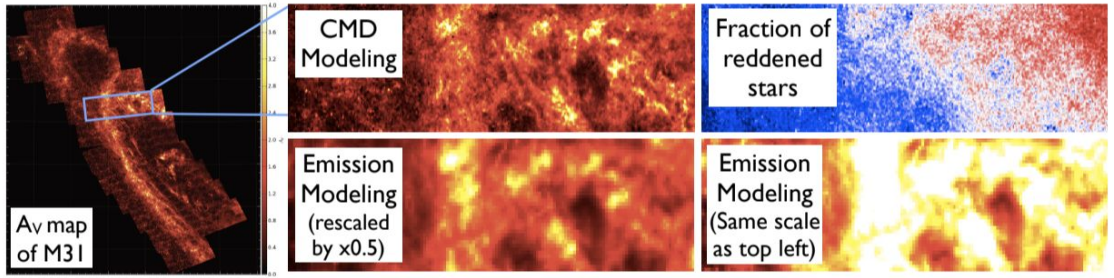


FIGURE 5: *Dust Extinction from NIR CMDs vs from MIR/FIR Emission:* We infer the A_V column in 25 pc pixels by modeling the distribution of RGB stars in a CMD (lower left) as an unreddened foreground and a reddened background that samples a log-normal distribution of A_V. **Left:** The resulting map of the mean A_V of the reddened stars for M31. **Top Middle:** Detail of the map derived from the NIR CMD. **Bottom Middle & Right:** Comparison with Draine et al. (2014) maps derived from dust emission, divided by 2 to better show the agreement in the morphology of structures (left). However, the true scale (right), shows the dramatic overprediction of the extinction by the emission-based model. **Top Right:** The fraction of reddened stars (where redder = higher reddening fraction) derived from the NIR CMD. The spatial variation is due to the geometry of a thick inclined disk, and thus constrains the 3-dimensional structure of the stellar disk. This proposal will allow identical mapping for M33, for a less-inclined galaxy with lower metallicity, higher SFR density, and spiral arms.

Good captions should

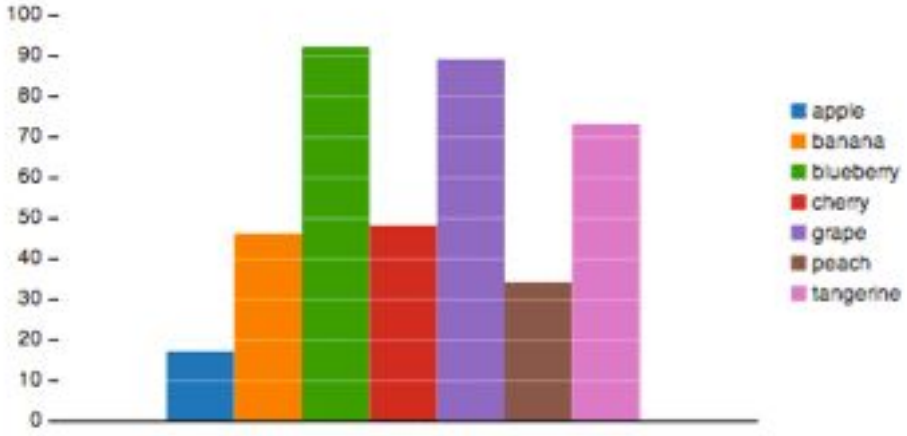
- Describe the figure and its relevant part/components
  - left panel shows x in farenheit vs. y in candella color coded by z in stones. Solid lines represent ...
- State the take-away message of the figure!
  - A good figure will make it redundant but “teaching is the art of repetition”
- Standalone without the rest of the paper
  - Refer to the text sections/equations for specific details. (easier to skim your papers)
- Clearly mention units either on the figure or in the caption
  - What magnitude system is on your color-magnitude diagram? (Vega, AB, ST...)

Warning: do not use with excess

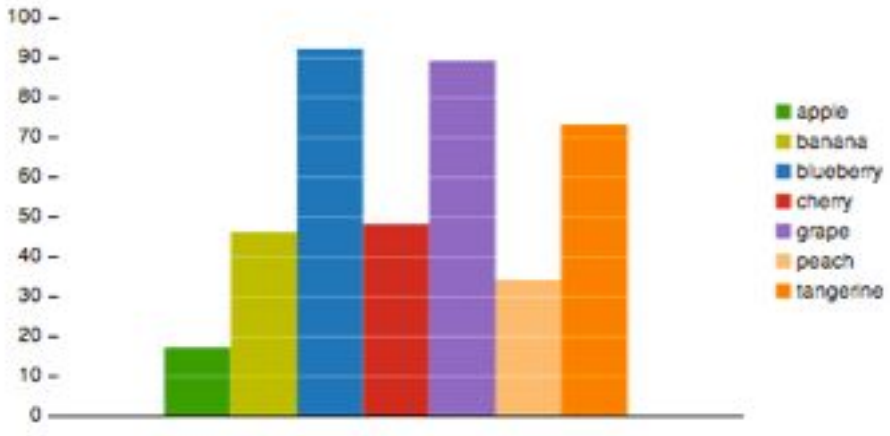
- complement the figure but not a paragraph of the main text (unless writing a proposal)

Do not go against **intuition** or **conventions**

Do not go against Intuition ! [8]

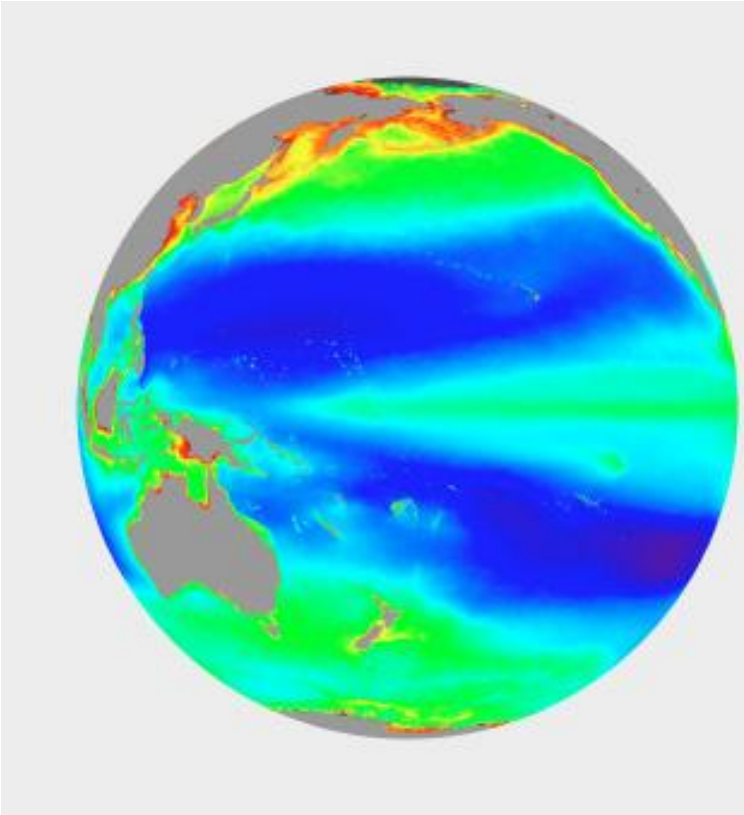


Default color assignment



Semantically resonant color assignment

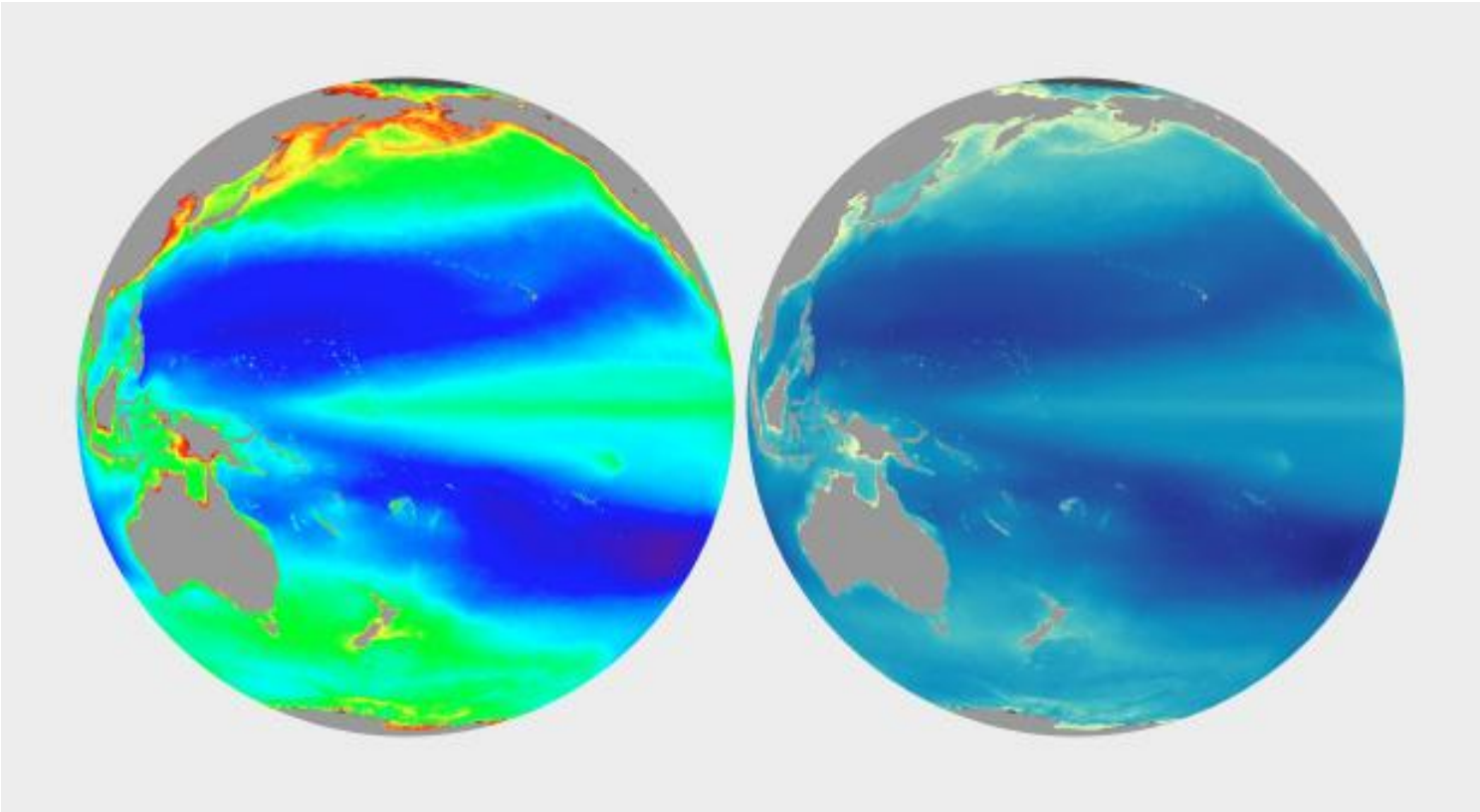
Avoid going against Intuition !



How long did you take to see colors associate with water?

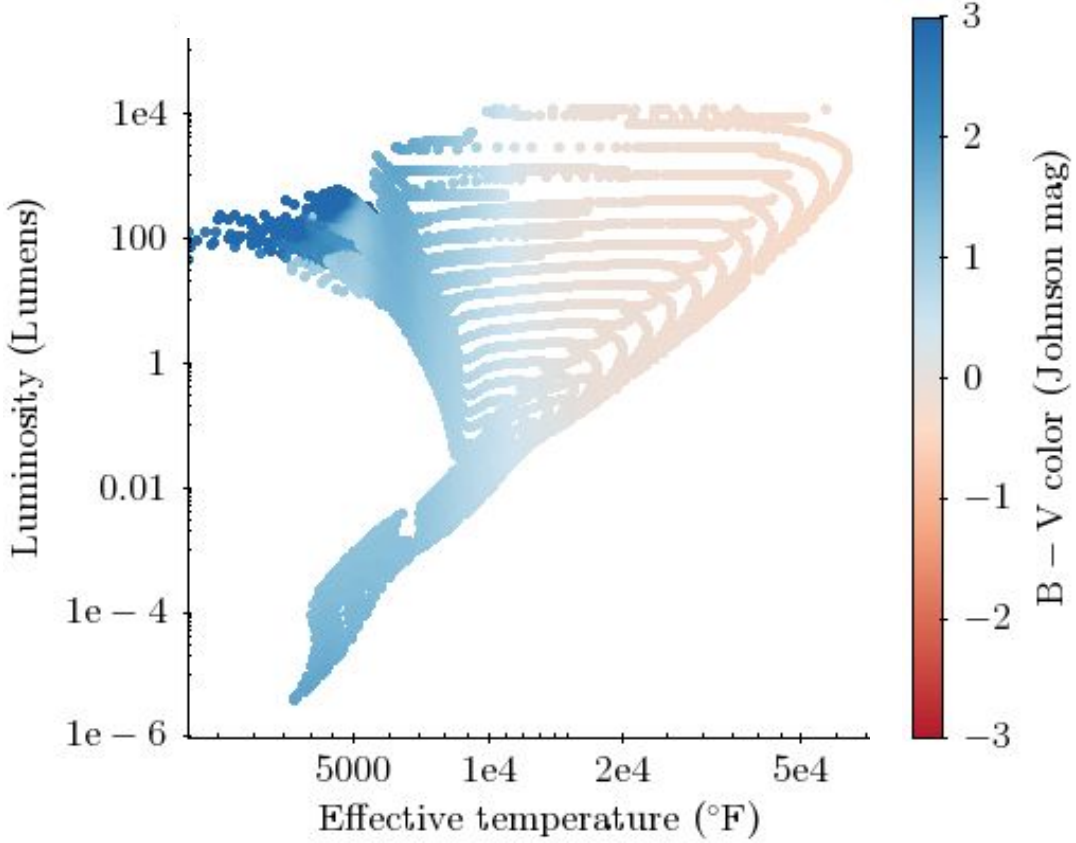
[2]

Avoid going against Intuition !



[2]

Astronomy has strange conventions but still!



Think of **reusability** to increase your impact

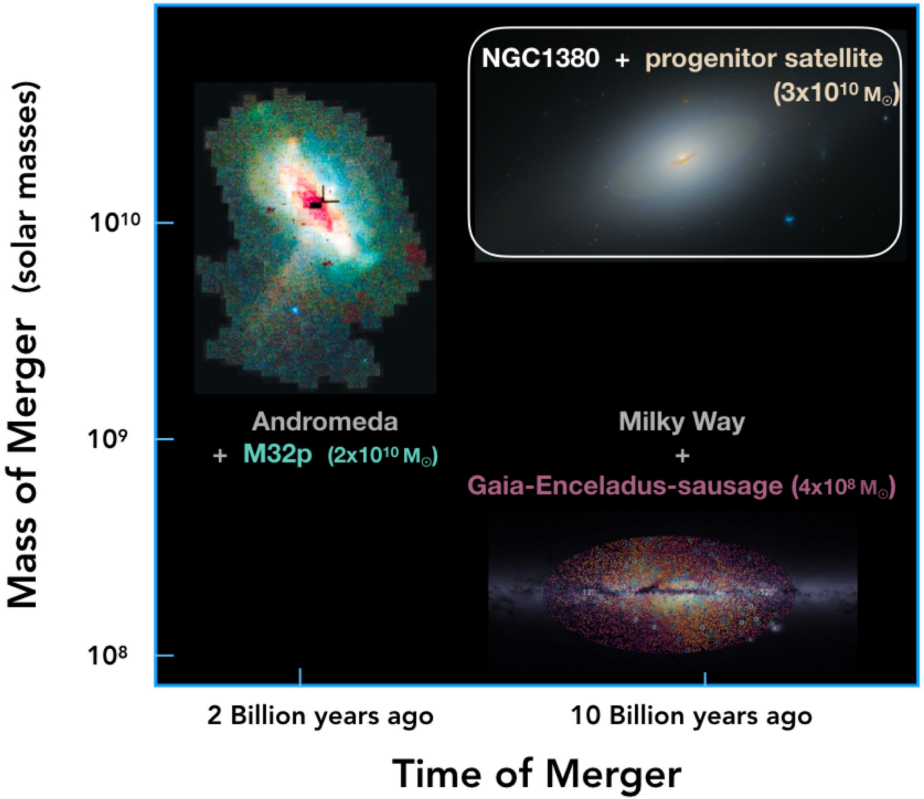
Discussion: Designing for Reusability

Pros:

- One can design figures for both papers and talks.
- Easier to make a presentation plot out of a paper plot.

Cons:

- Designing the same figure for both talk and paper may not be optimal



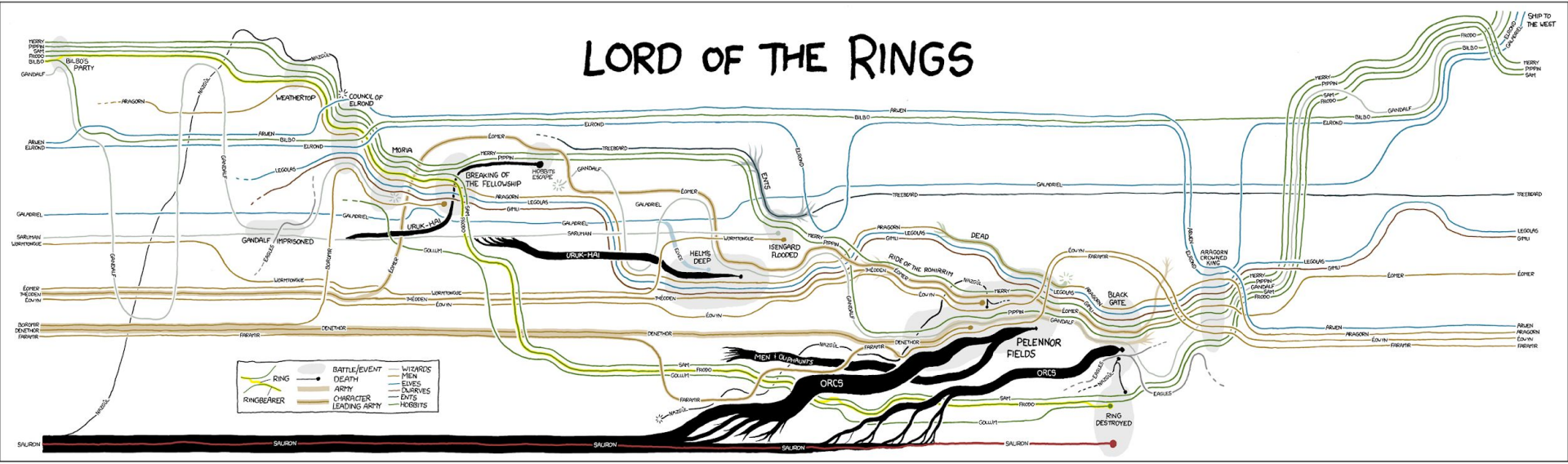
Most important things to consider

- Annotations: balance between cartoonish and pure data
  - Use sub-panels or layered slides to avoid all on one plot
- Pick appropriate colors for your message (sequential, divergence,...)
  - About 3 color max to be colorblind friendly, gradient if need more.
- Axis labels - figure/font sizes - notations (e.g, units...)
- Good use of captions - rule of thumb: figure-to-caption-text ratio > 1
- Don’t go against intuition or culture/conventions
- Reusability - Think about paper and talks at the same time

Focus on the message you want to convey

Know the rules to
break them all!

THE HORIZONTAL AXIS IS TIME. THE VERTICAL GROUPING OF THE LINES INDICATES WHICH CHARACTERS ARE TOGETHER AT A GIVEN TIME.



Astrophysics visualization examples and python tools

Commonly used plots

- Higher dimensional data often requires **illustrating correlations in more than 2 dimensions.**

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  https://www.python-graph-gallery.com/
  https://seaborn.pydata.org/examples/index.html
  https://matplotlib.org/stable/gallery/index.html

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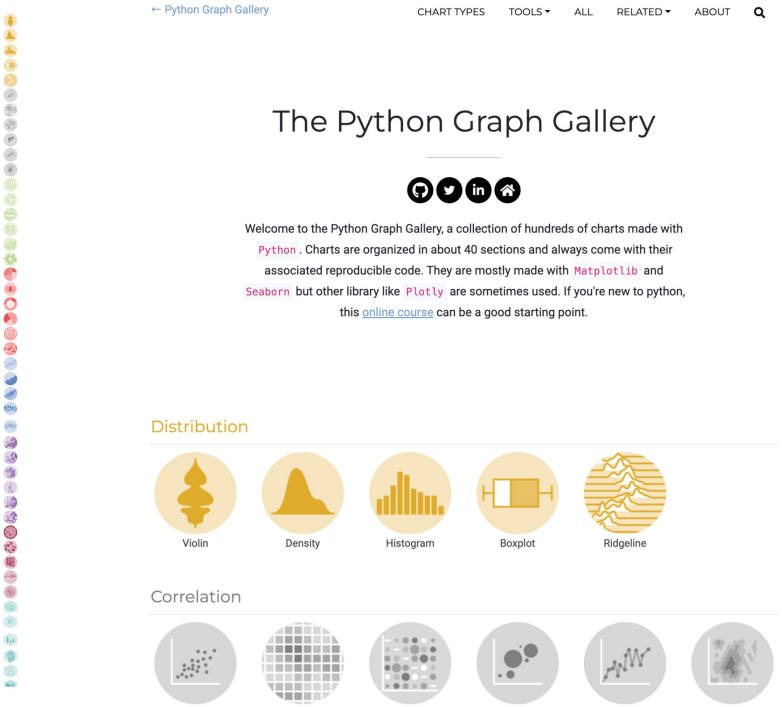
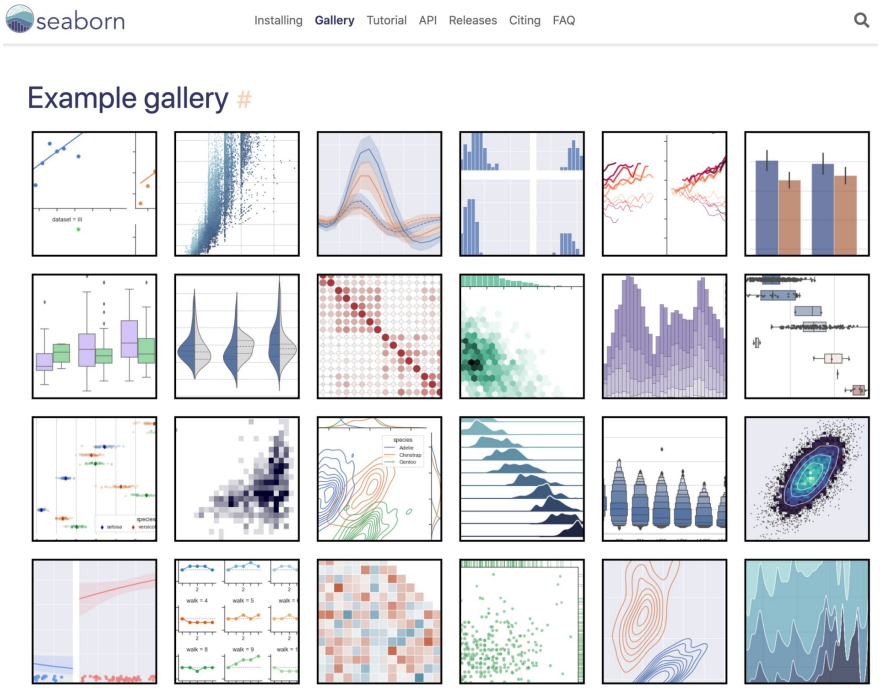
- There are a variety of ways (of varying complexity) to do this using **matplotlib / seaborn / plotly** (as a few examples) in python.
- Best way to learn is to **explore the plot galleries** here:
  https://www.python-graph-gallery.com/
  https://seaborn.pydata.org/examples/index.html
  https://matplotlib.org/stable/gallery/index.html
- These will provide example code you need to make various plot types. Make sure you look through the documentation for a particular routine to see options you can customize.

Commonly used plots





Commonly used plots

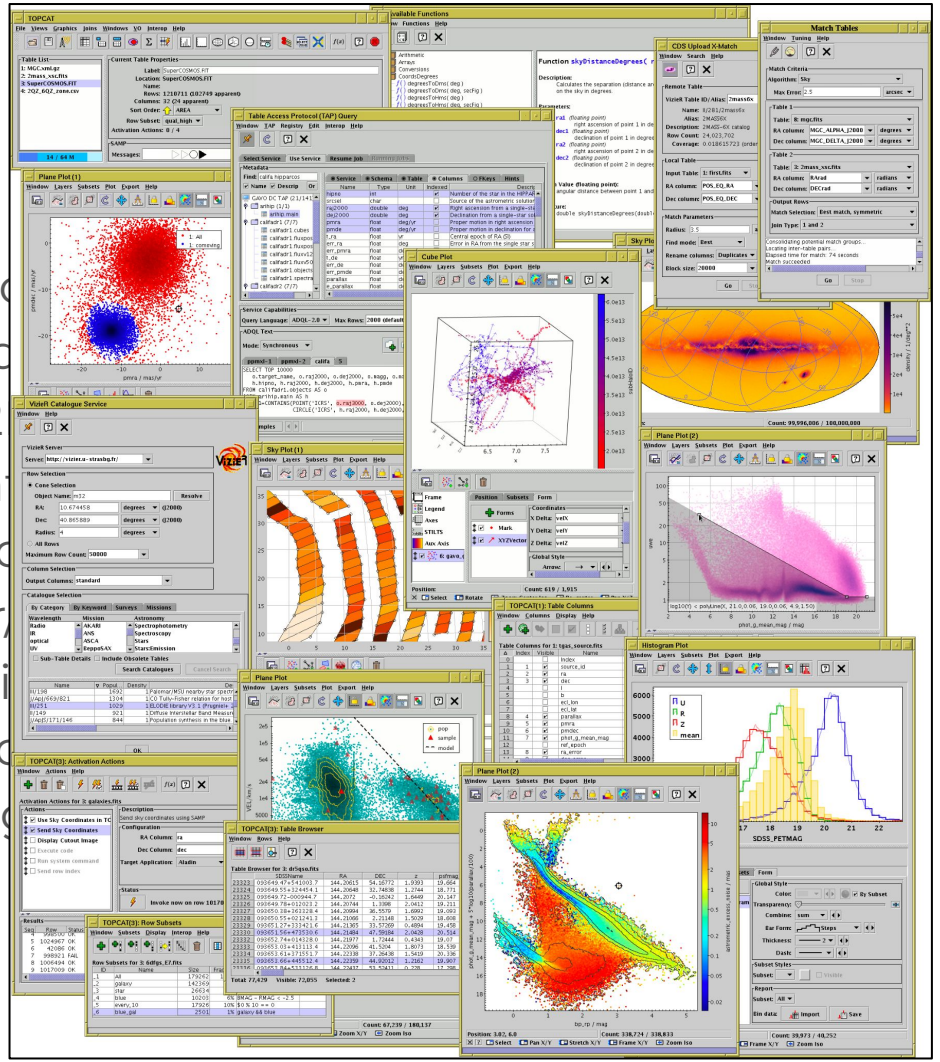
- Line/scatter plots with colour/size/symbol variations
- Weighted histograms
- Auxiliary 2D histograms
- Weighted 2D histograms
- Contour plots
- 3D scatter/surface plots
- Violin plots
- Specialized visualizations: Voronoi Binning, Animations/Movies, Coordinate projections, Image overlays, Periodograms/PSD

Commonly used plots

Most can be explored quickly within **TOPCAT!**

Super useful for slicing and dicing multi-dimensional datasets before you know what you are looking at!

Then later you can make publication level plots in python/IDL/R etc.

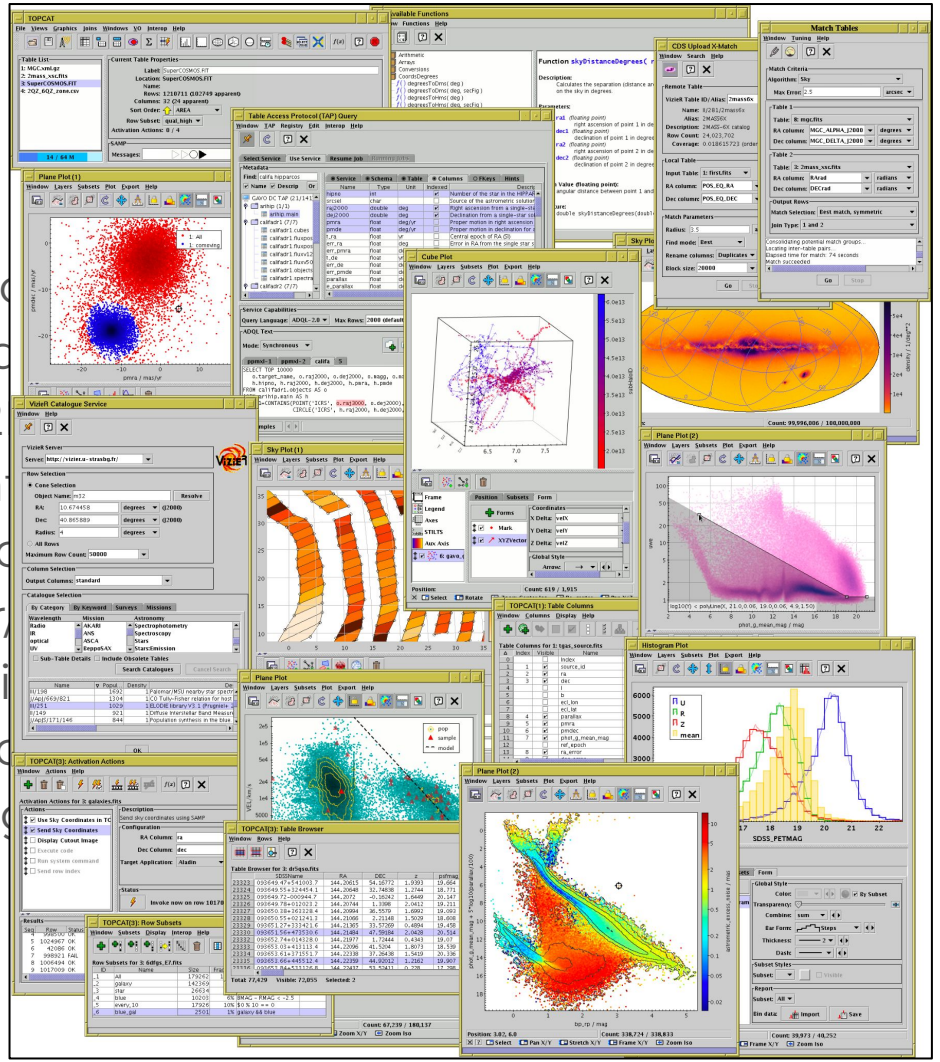


Commonly used plots

re: *TOPCAT*... we will post installation and intro examples on moodle so you can try this interactive tool as well.

It is really a great tool which helps save time to figure out what correlations you might want to explore and properly visualize further!

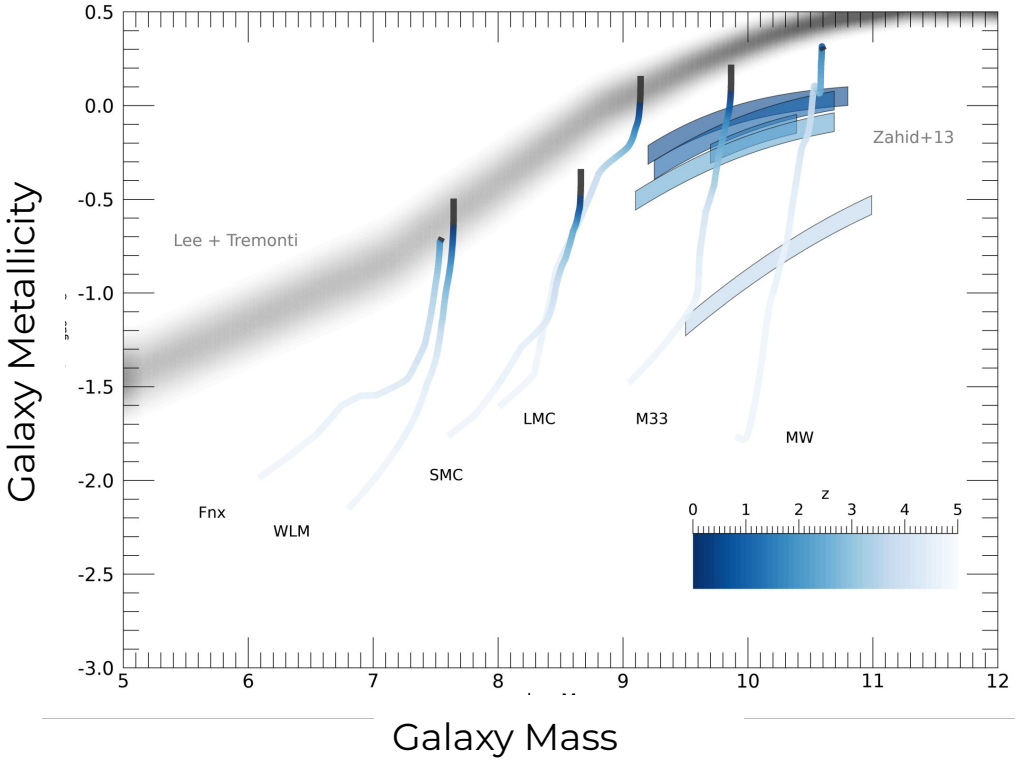
[no exercise questions, nor exam questions will use/require TOPCAT - we just hope it is a fun tool to try!]



Commonly used plots

- **Line/scatter plots with colour/size/symbol variations**

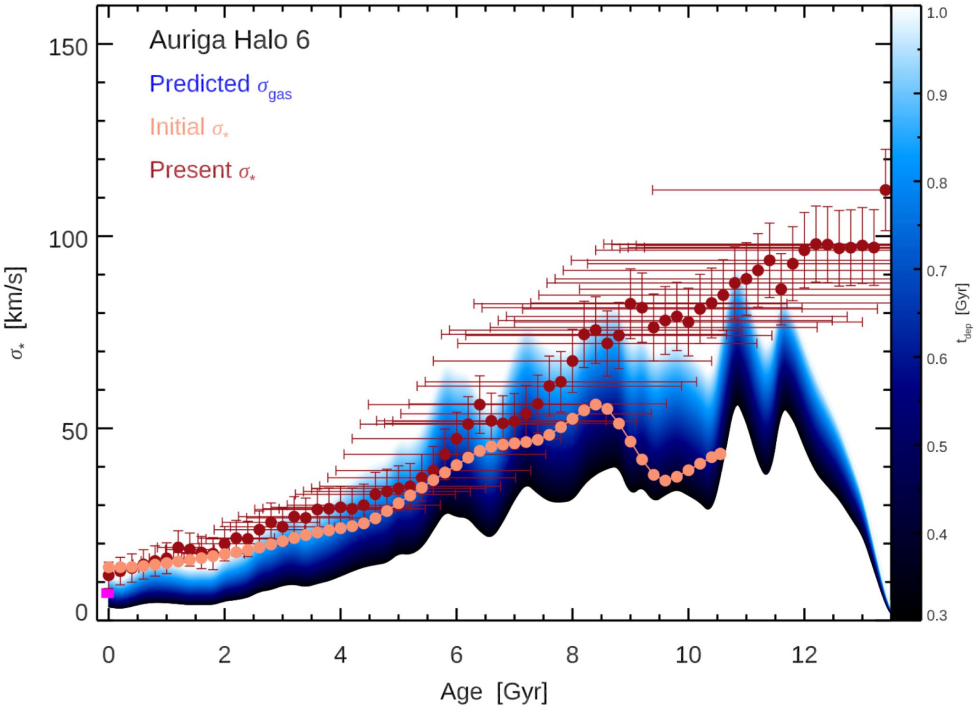
  - usually would try to use only one or two of colour/size/symbol for your scatter or line plot so you don't overwhelm the figure
  - further color scaling can be helpful to visualize e.g., time evolution of two correlated quantities



Commonly used plots

- **Line/scatter plots with colour/size/symbol variations**

  - also can show parameter variations clearly if there is a sequential colour scheme

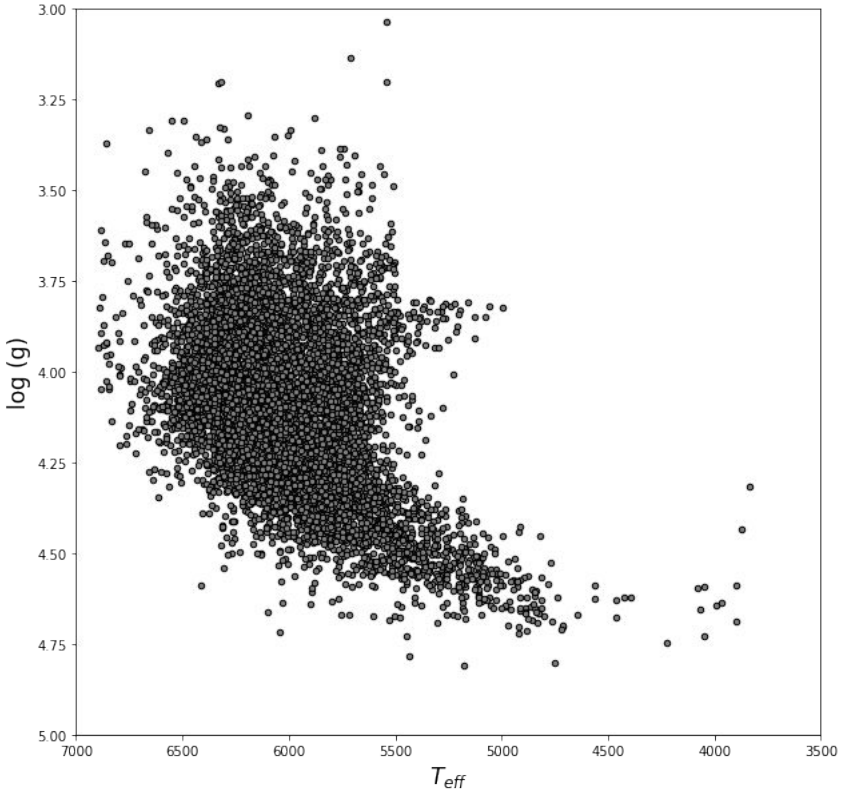


Commonly used plots

- **2D density distributions/histograms/ contours**

  - Here we want to illustrate how tightly clustered points are on a 2D plane

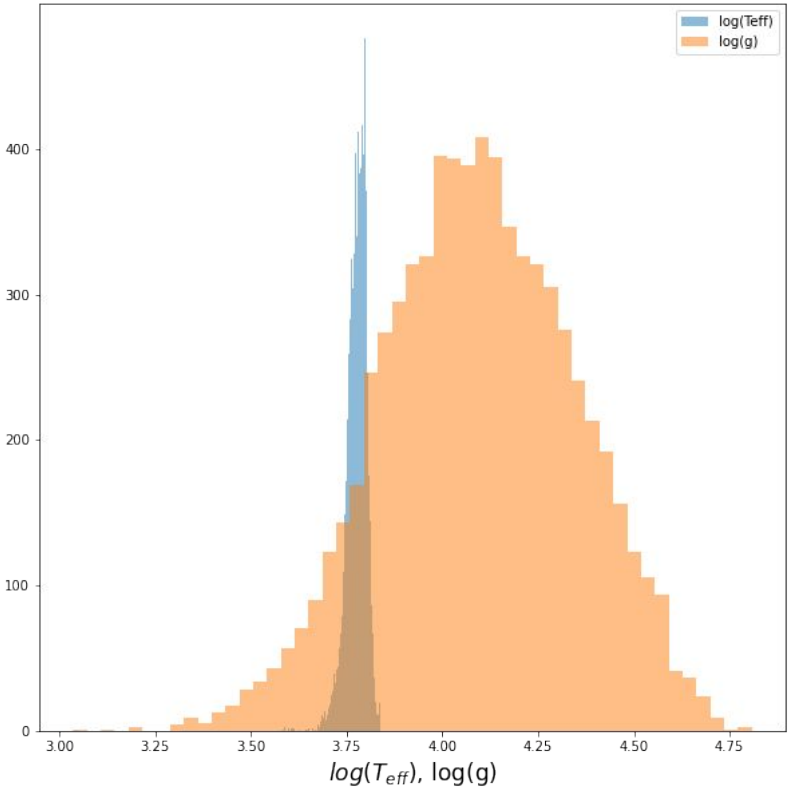
  - Scatter plots for very large data sets might not indicate the density well.



Commonly used plots

- **2D density distributions/histograms/ contours**

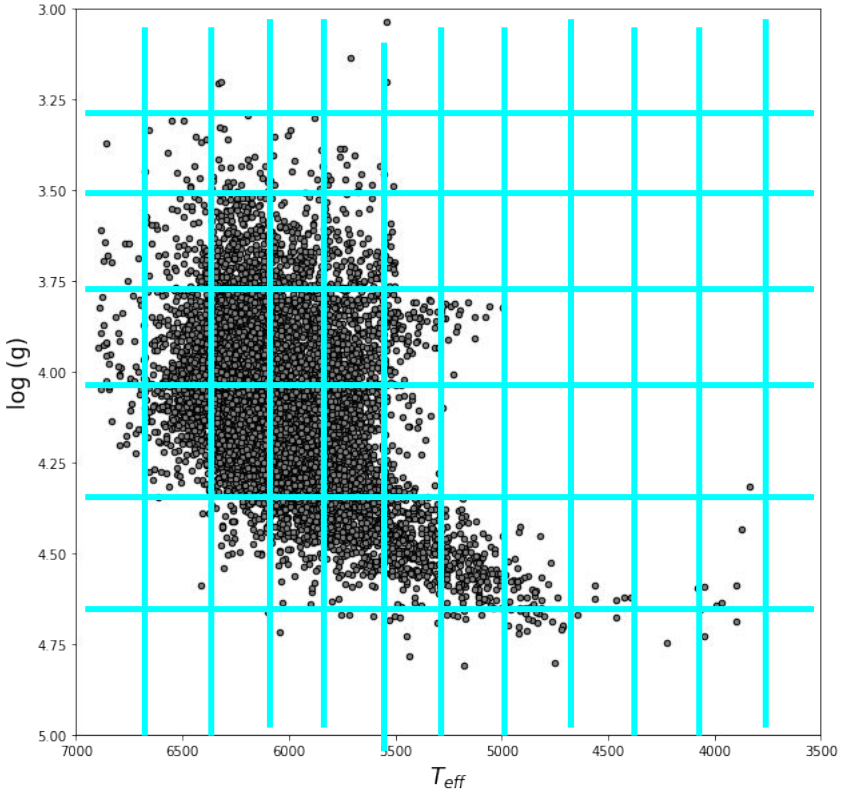
  - Marginalized histograms can do this, but are not very effective for the reader



Commonly used plots

- **2D density distributions/histograms/ contours**

  - Idea is to bin up parameter space and construct histograms or parametric representation of the density distribution in pseudo-discrete cells



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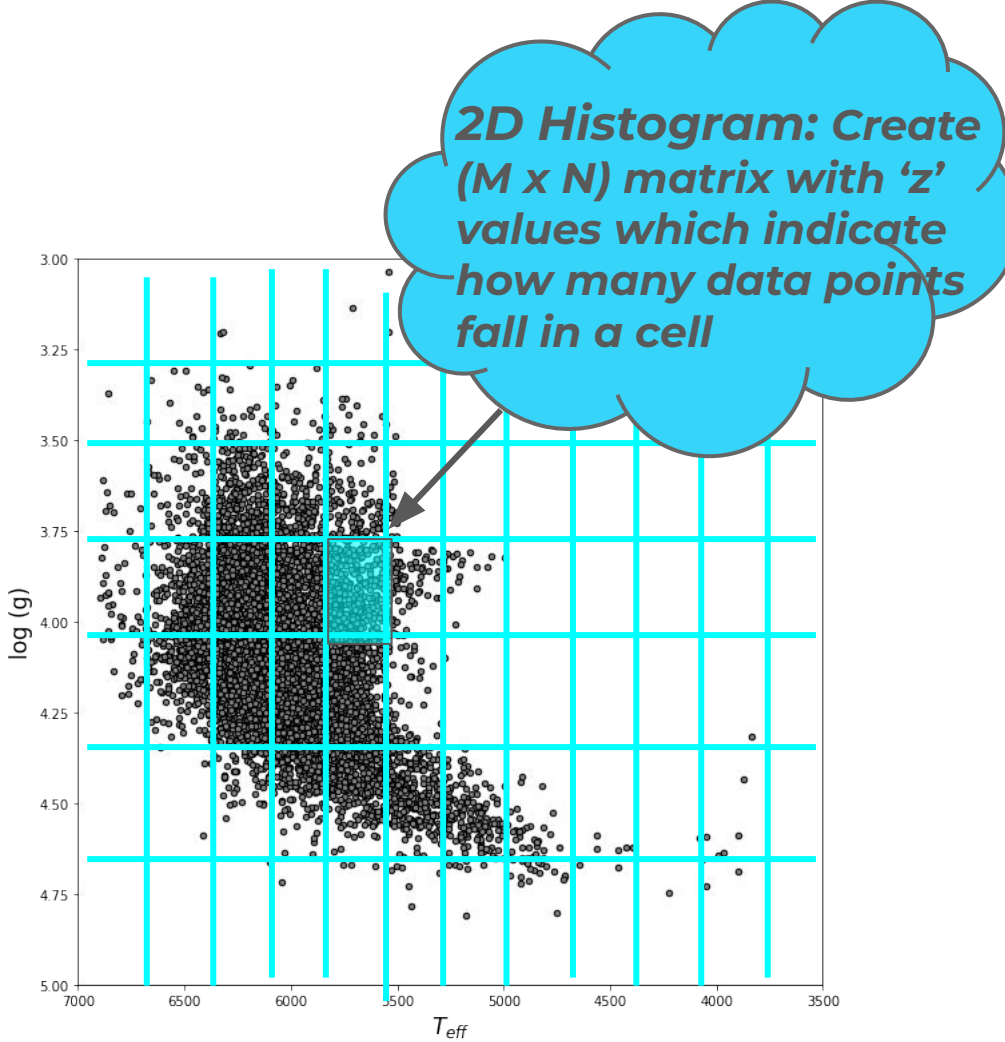

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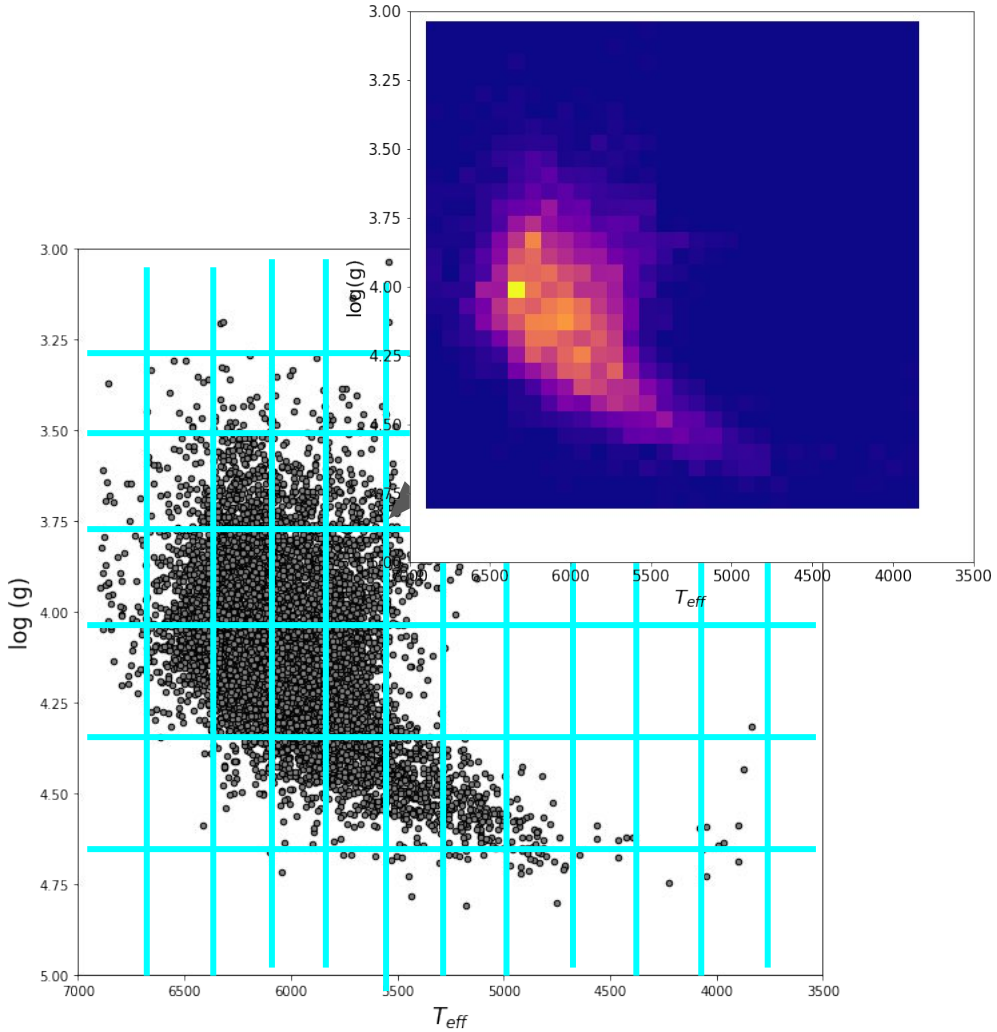
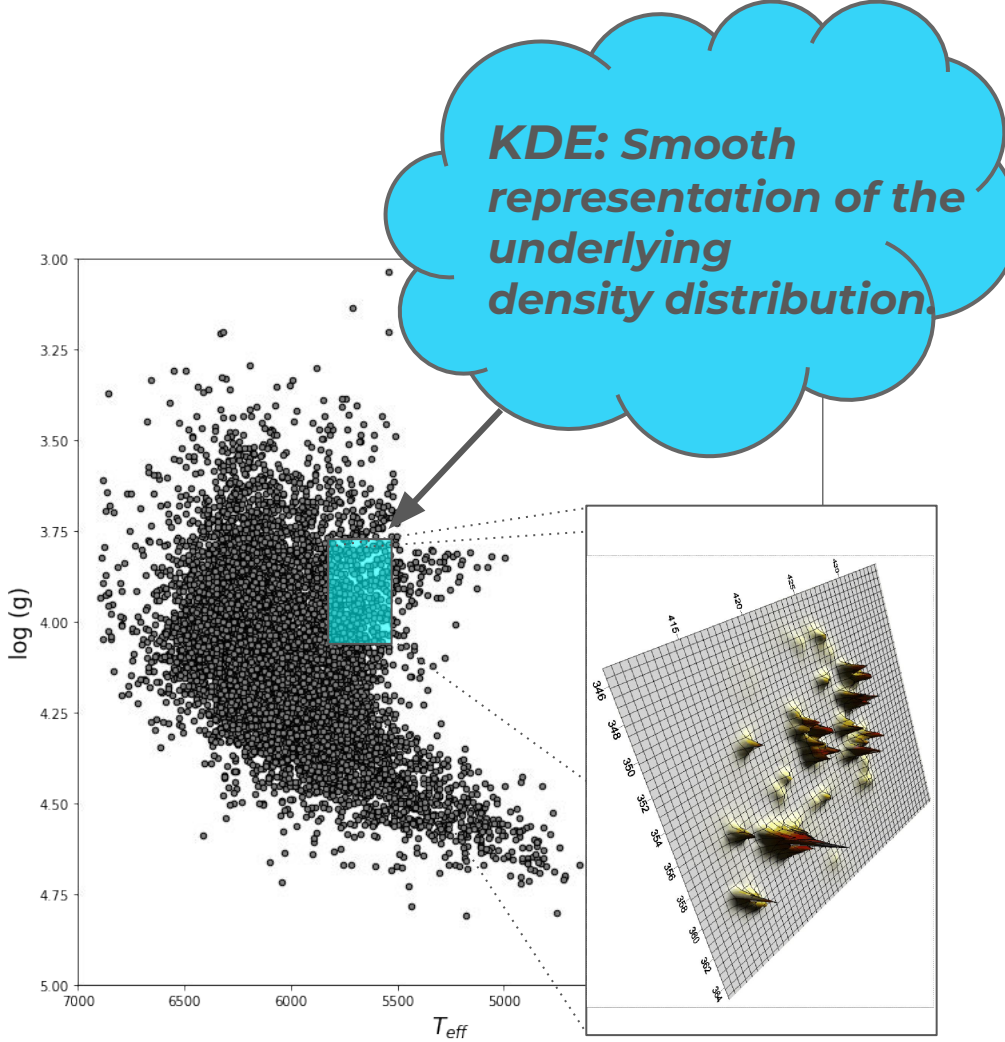


Commonly used plots

- **2D density distributions/histograms /contours**

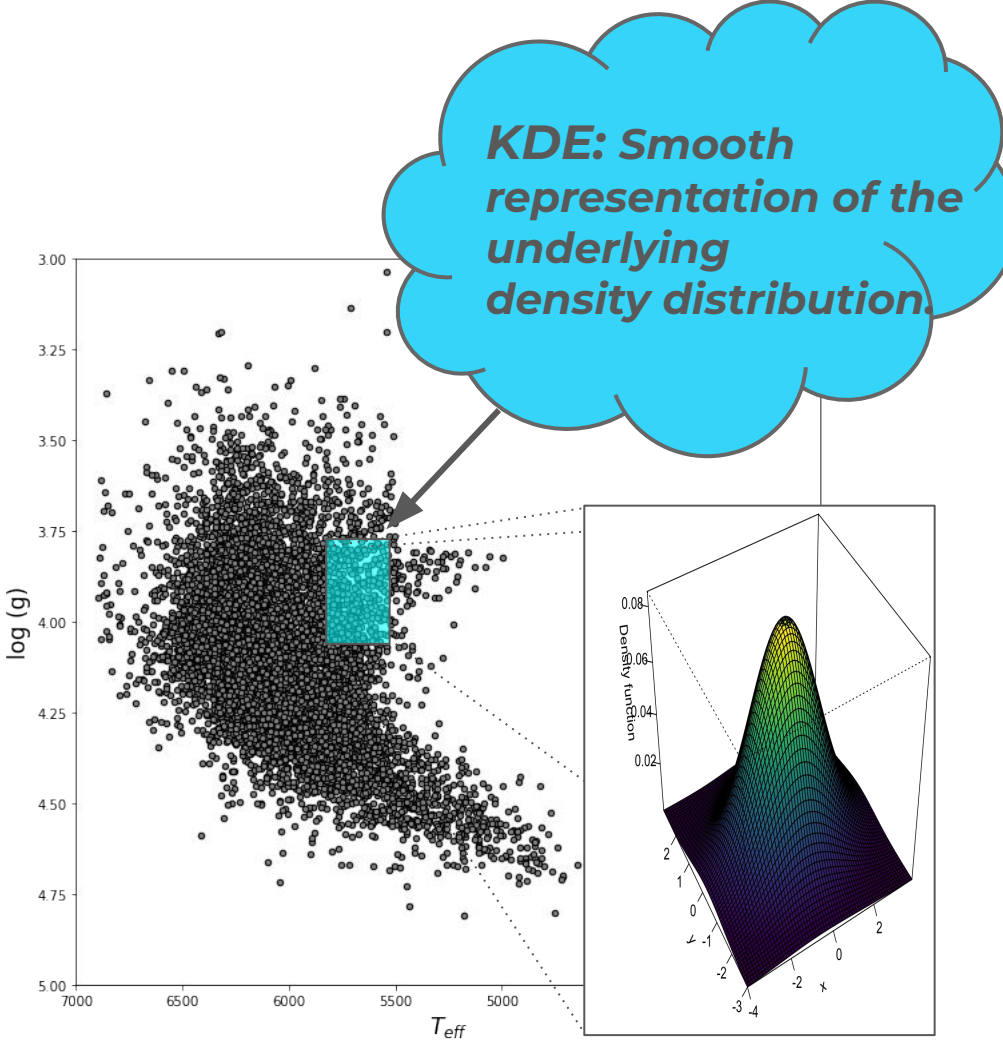
  - Can also use kernel density estimators which try to describe the PDF of f(x,y) via a superposition of (usually Gaussian) kernels of user specified width/connectivity



Commonly used plots

- **2D density distributions/histograms/contours**

  - These can be very useful to incorporate uncertainties into the density estimation (*imagine a superposition of Gaussians whose width depends on the uncertainties of a given point*)



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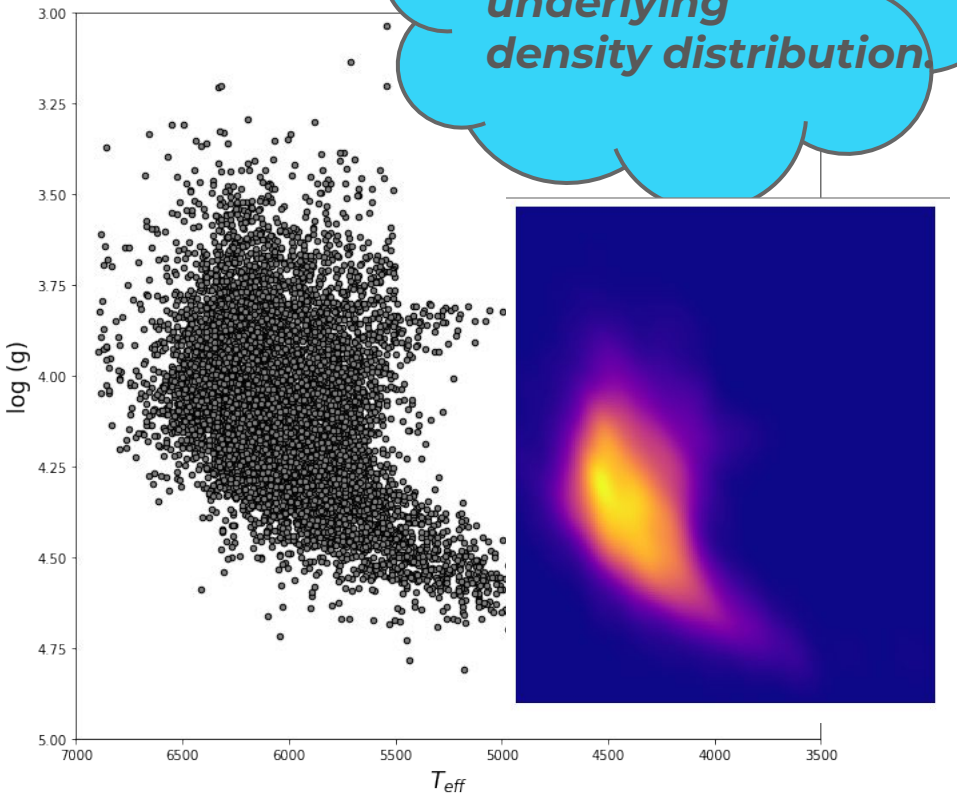
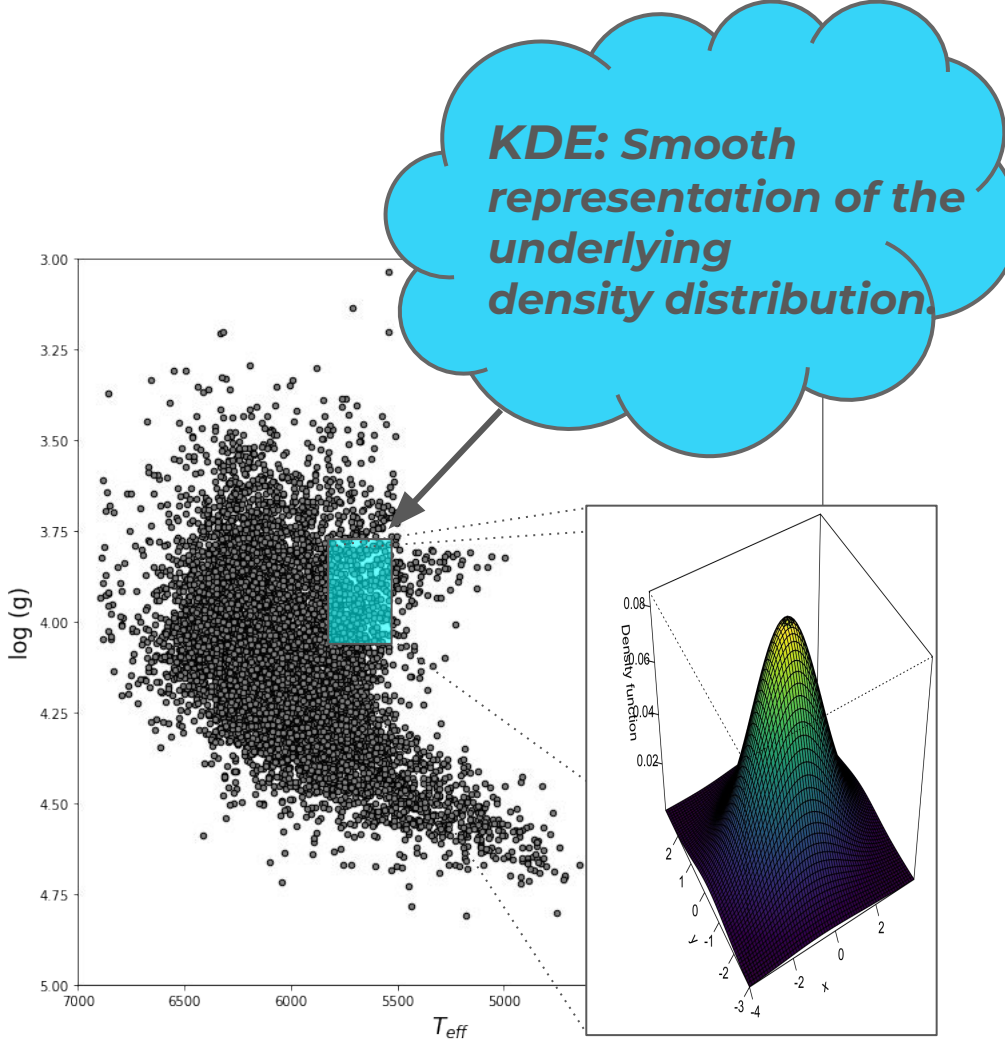


Commonly used plots

- **2D density distributions/histograms /contours**

  - Similar to bin size choices with 2D histograms, the KDE density appearance will depend on choice of kernel size/bandwidth

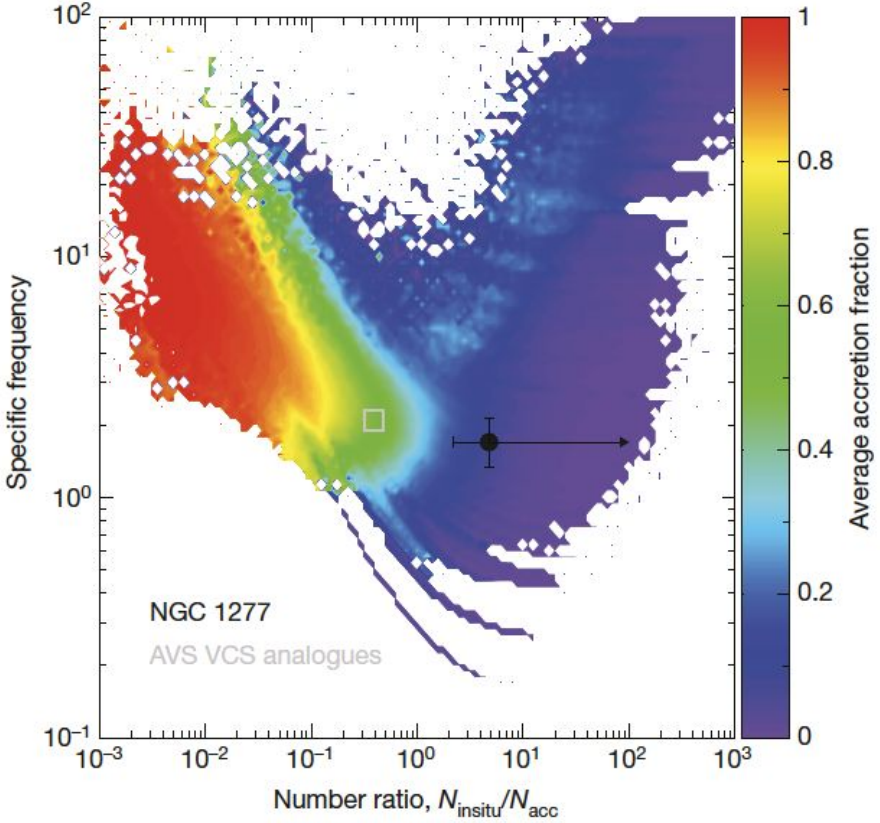
  - as with interpolation, approximation and other methods, you need to try multiple methods/instances



Commonly used plots

- **2D weighted/auxiliary histograms**

  -usually is a clearer way to visualize 3rd variable correlations, compared to 3D scatter plot (imo)



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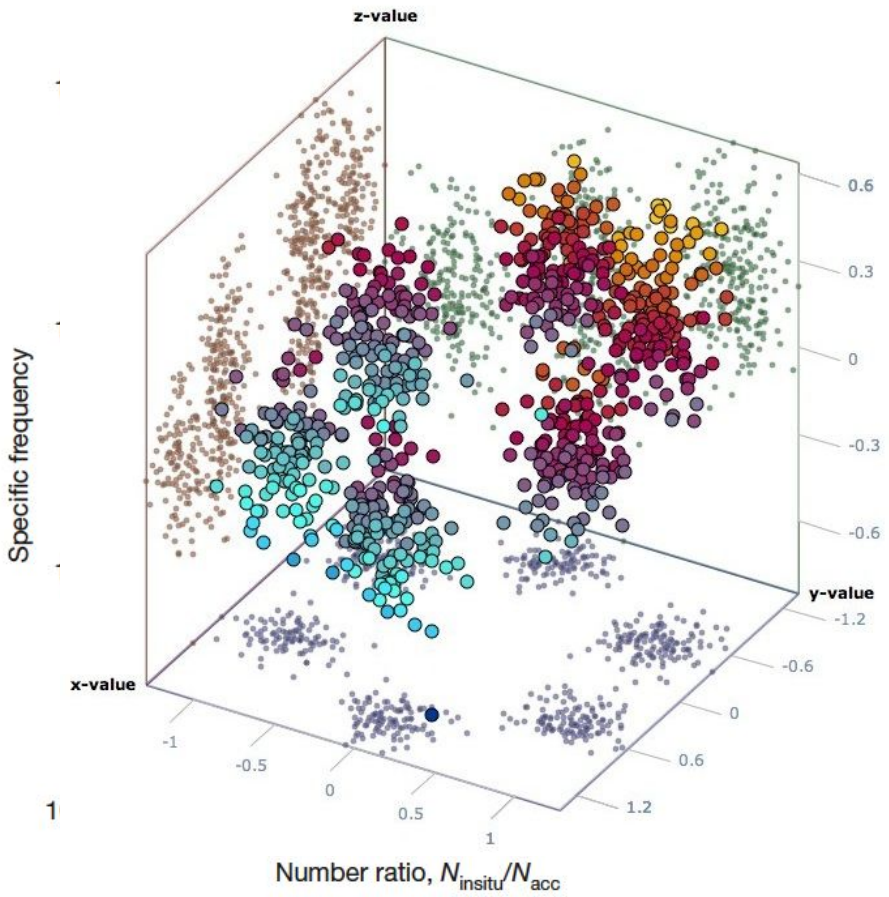
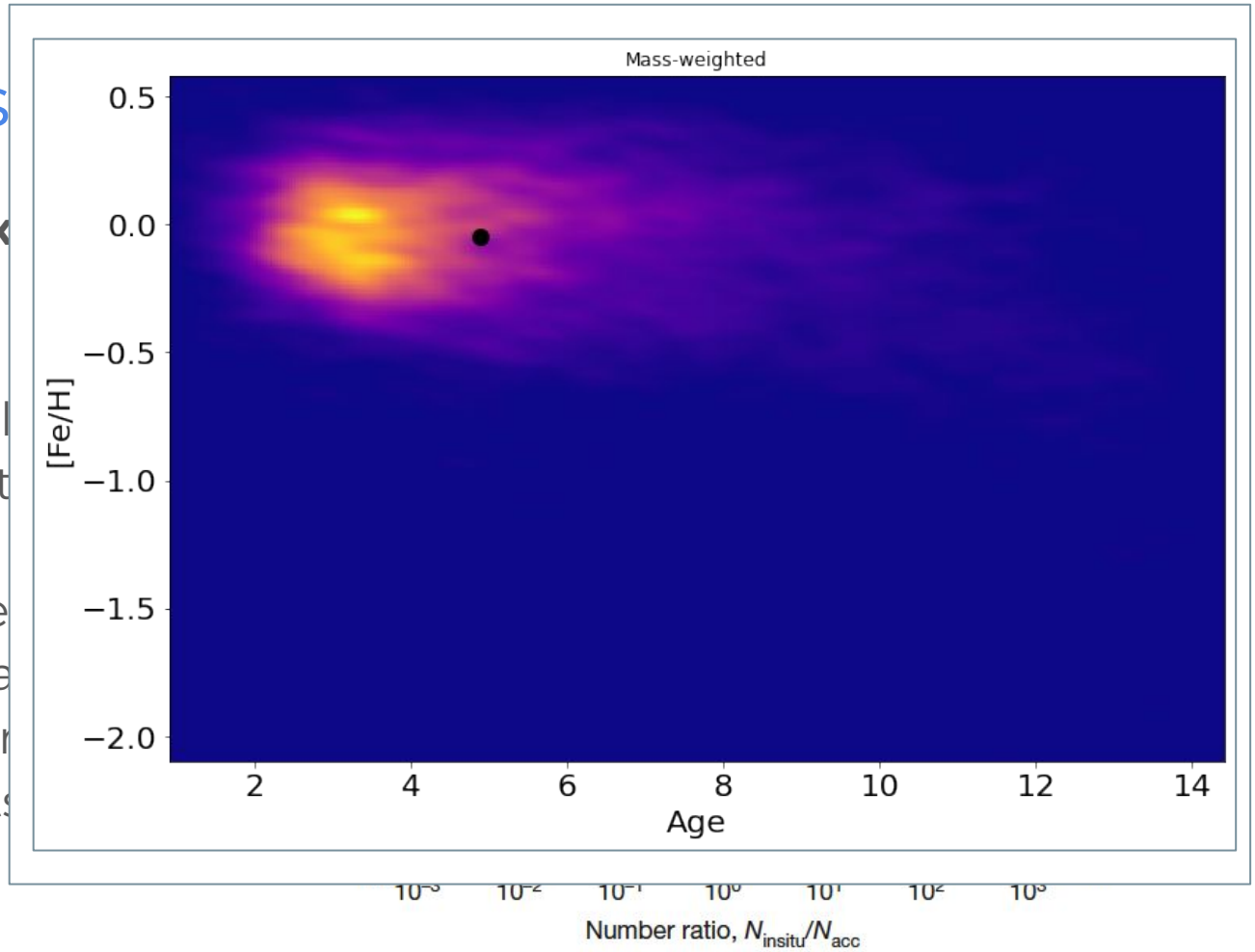


Commonly us

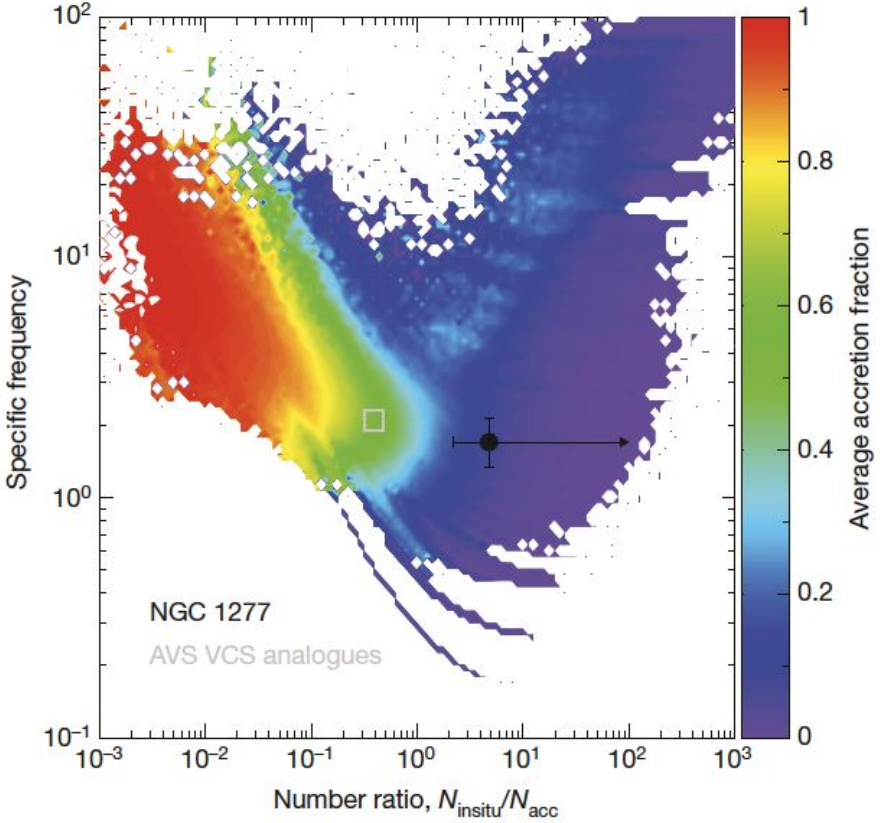
- **2D weighted/aux histograms**

  - here for each cel want to represent density of points, the average value statistics like varia 3rd parameter acr data/model points local 2D region.



Takeaway Points

- **Visualization is arguably the most time consuming, yet impactful aspect of a research project.**
- **It can make or break how a project is received**
- **Given your hard work on your project, spend time to explore what types of visualizations work best, and try to follow good practices for plot creation**



Takeaway points

- **Think about what formats get across your key message**
- **Use colours/sizes/shapes wisely and sparingly**
- **Captions and the plot should help sell your key message - but don't be afraid to think outside of the 'python' box**
- **Be adventurous and dive into the plot resources and ideas we linked to!**