Advective Flux Transport:

A Window into the Past – Simulating the Sun’s Photospheric Magnetic Field for a Historical TSI Reconstruction.

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2023 Sun Climate Symposium
October 17th 2021

- **Goal:** Improve the historical TSI reconstructions from both the NRLTSI and SATIRE models by incorporating three primary improvements to the models' inputs.

- **Objectives:**
  - Update the 400-year sunspot record used in TSI models for historical reconstructions (SILSO)
  - **Re-compute flux-transport results to improve historical solar-variability estimates (This talk)**
  - Improve the TSI-measurement composite, providing a reference for TSI models (Next Talk - Greg)

The Advective Flux Transport Model

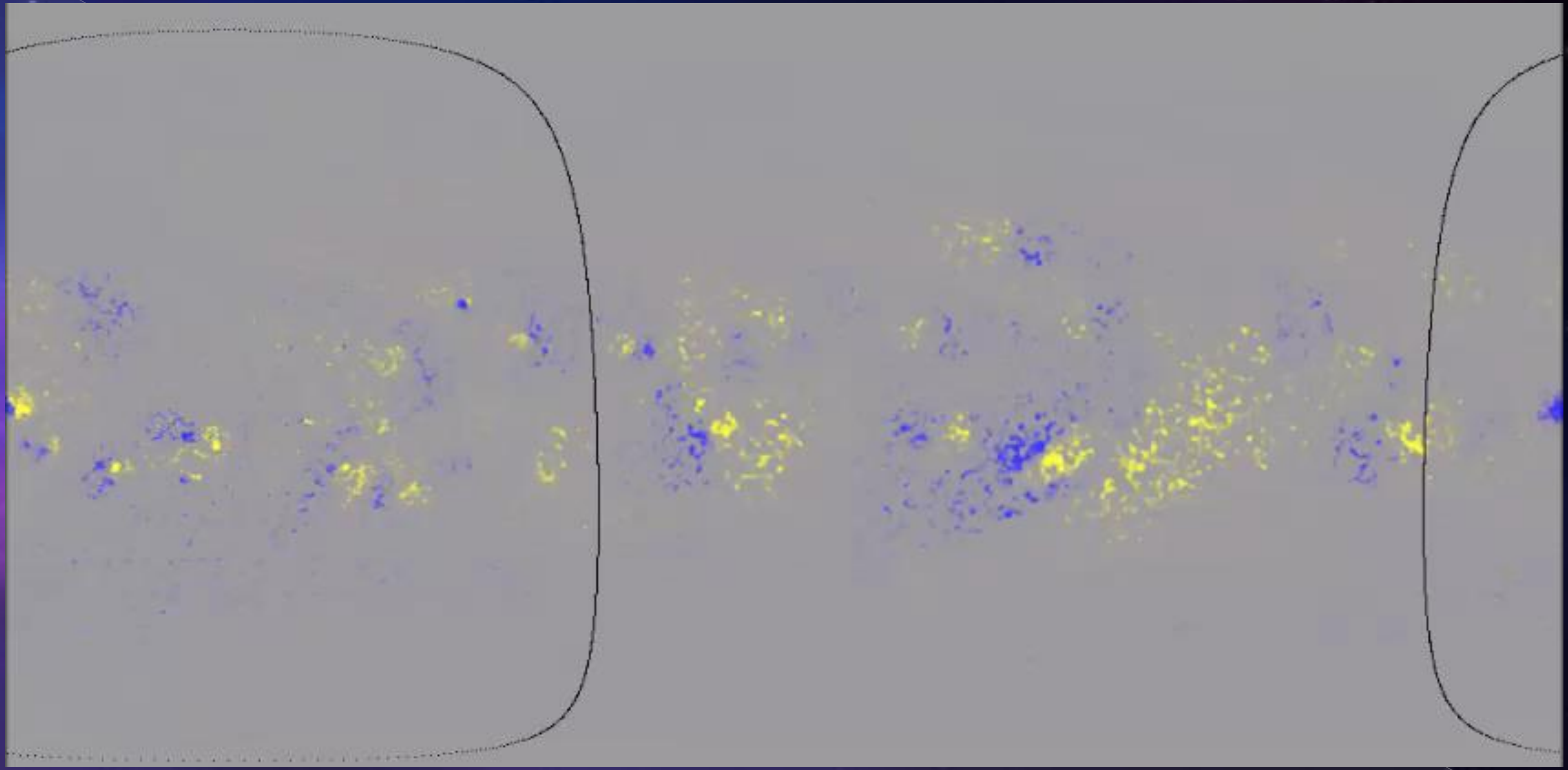
Upton & Hathaway have developed a state of the art SFT model, the Advective Flux Transport (AFT) model. This advanced model advects the surface field with the observed flows, reproducing magnetic field evolution.

- Observed Surface Flows
- Magnetic Field
  - Simulated (synthetic BMRs)
  - Observed(data assimilation)

- **Flux Maps of entire Sun**
- **Butterfly diagrams**
- **Polar Field Plots**
- **AR evolution**

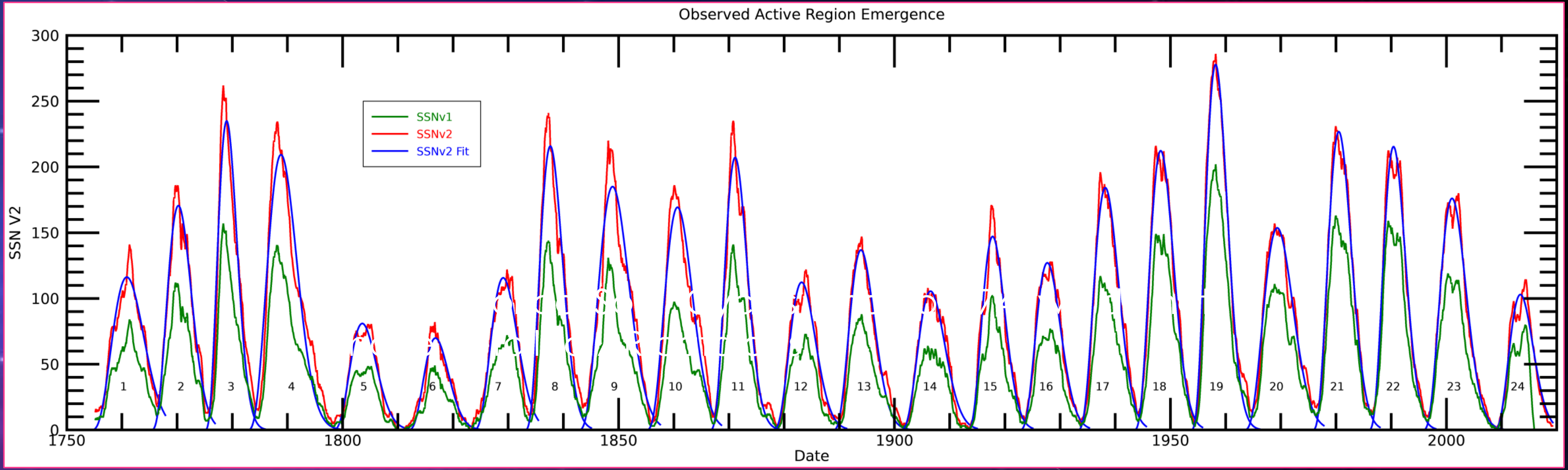
Upton, L., & Hathaway, D. H. 2014a, ApJ, 792, 142
Upton, L., & Hathaway, D. H. 2014b, ApJ, 780, 5

The Advective Flux Transport Model



- The Advective Flux Transport Model (AFT) transports magnetic flux with the observed flows (Meridional Flow, Differential Rotation, and Evolving Convection).
- AFT produces magnetic maps of the entire surface Sun.

Historical Solar Cycles (prior to1874) we do not have detailed AR catalogs.

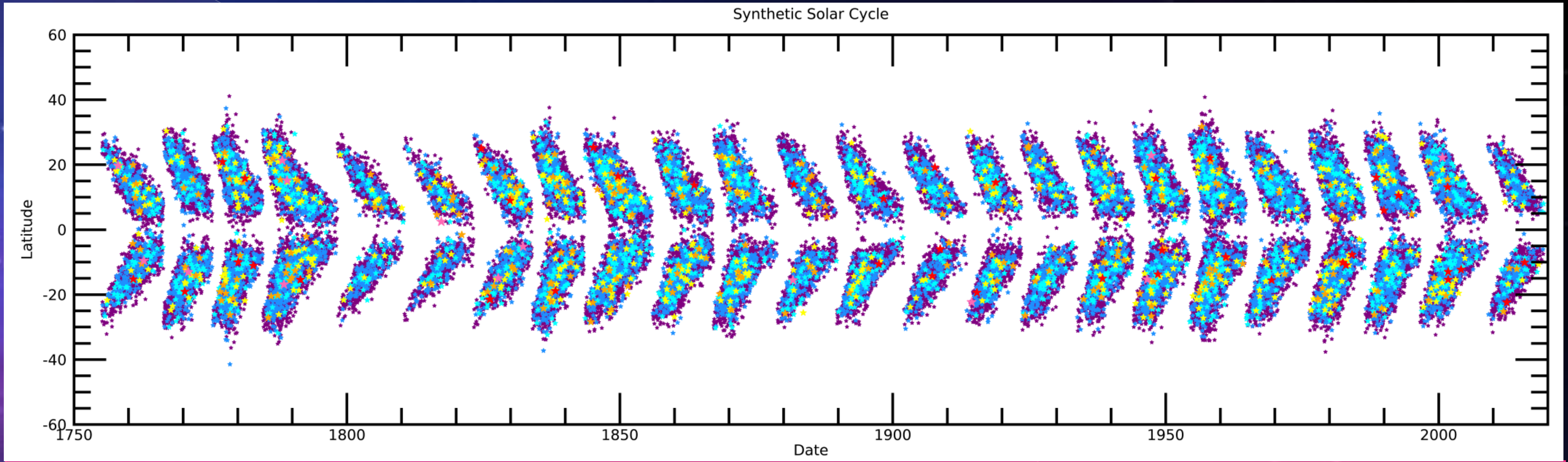


- We've developed a Synthetic AR Generator (SARG) to create artificial catalogs.
- We define the strength and timing of each cycle using SILSO SSN v2.0.
- We apply the Hathaway fitting function to each cycle (blue) to define the Start/End of each cycle (time when the blue fits cross the Zero line).
- This is used to set the cadence of spot emergence as a function of the cycle strength (which in essence sets the amplitude of the cycle).

SARG AR Properties

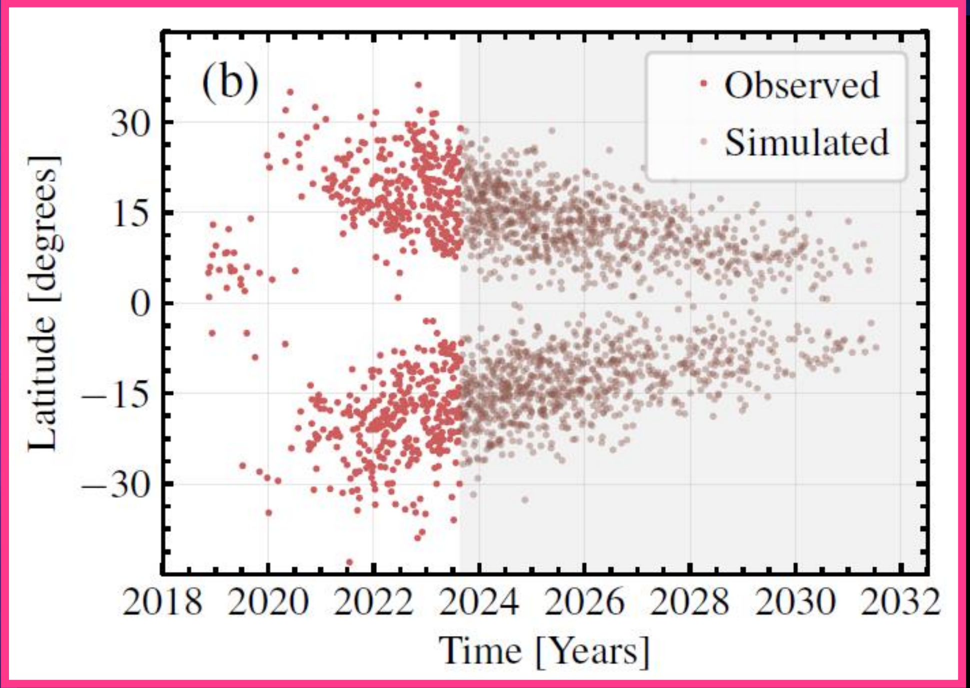
- We define the number of days between subsequent AR emergence as $30.4368/(0.3 + 0.269736 \times SSN)$.
- Flux as described in Munoz-Jaramillo et al. (2021) from the KPVT/SOLIS BMR Flux log-normal distribution .
- We determine the location of the AR:
  - The Latitude given by the standard law for the equator-ward drift of the active latitudes described in Hathaway (2011)
  - Longitude of the active region is drawn from a random uniform distribution.
- We determine the relative locations of both polarities:
  - Hale's Polarity based on the cycle & hemisphere
  - We assign the tilt of the AR based on the Gaussian distribution for Joy's Law detailed in (Hale et al. 1919; Munoz-Jaramillo et al. 2021)
  - The separation distance (Upton et al. 2023, in Prep.)
- The time till the next emergence is determined, as described above, and the process is for the rest of the time series.

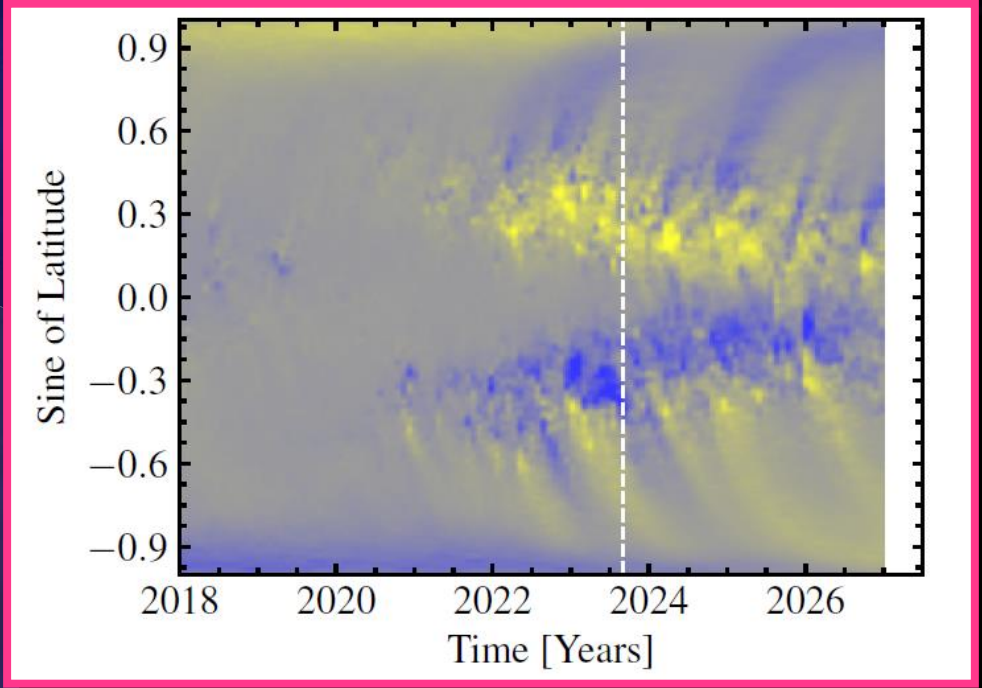
EXAMPLE SARG REALIZATION



- Here we show the timing, location, and flux for one realization of Synthetic Active Regions for all Solar Cycles 1-24.
- Flux (and area) are indicated by symbol size and color.
- In this realization, there are a total of ~73000-74000 Active Regions.
- AR Flux ranges of ~2.e+20 to ~1.5e+23 Maxwells.

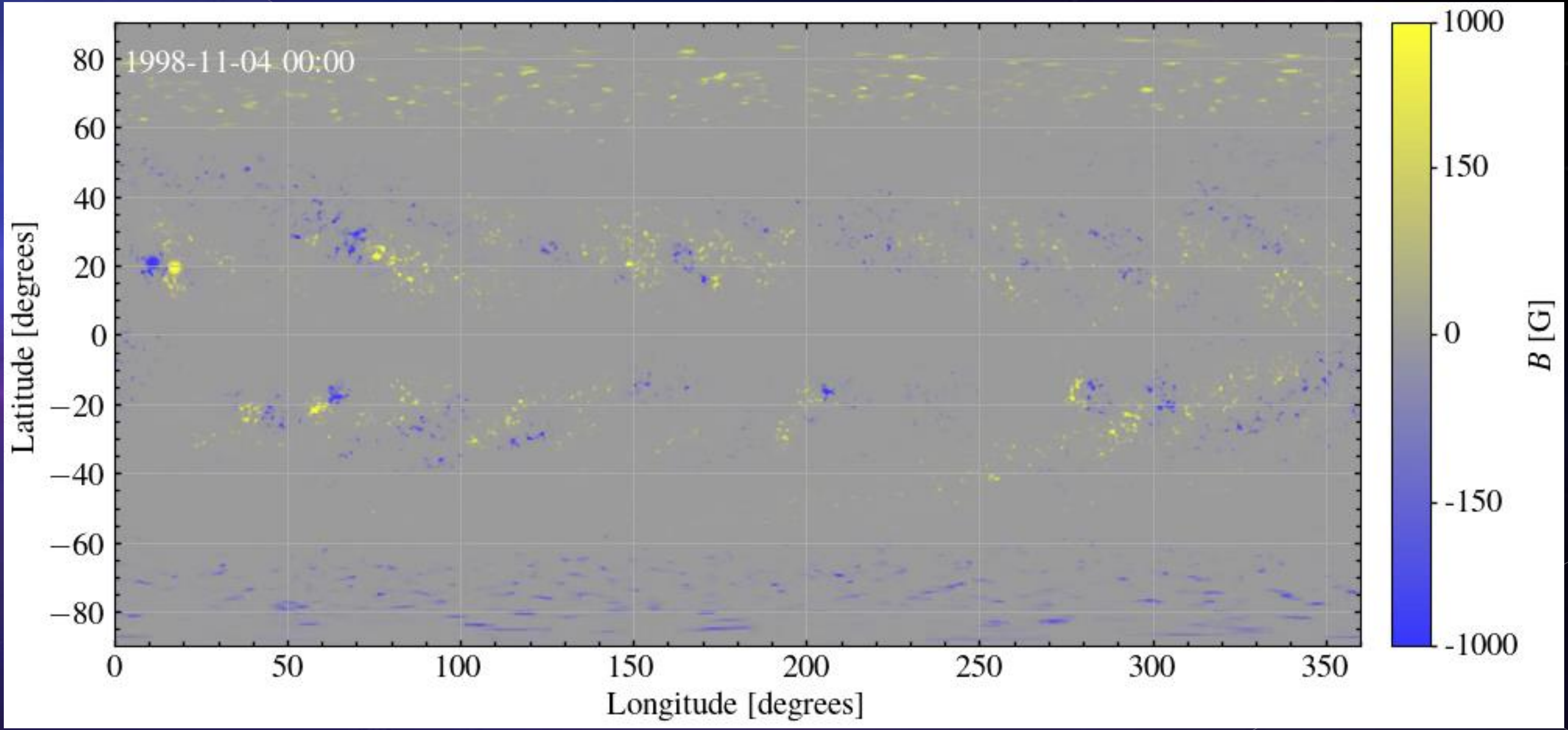
SARG Compared to Observations



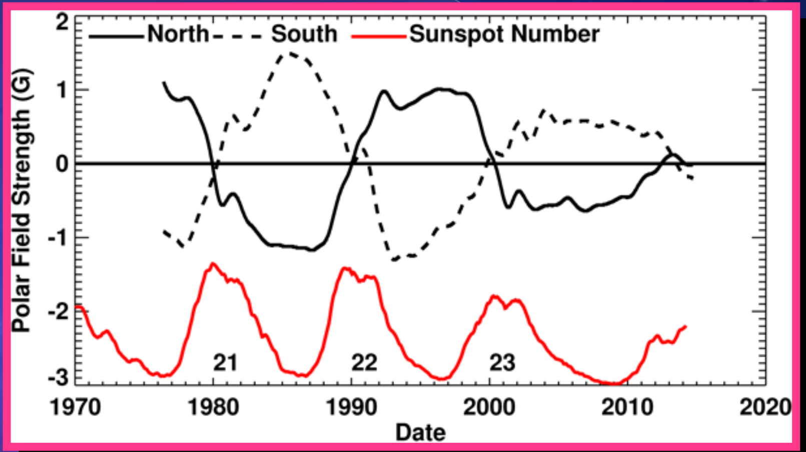


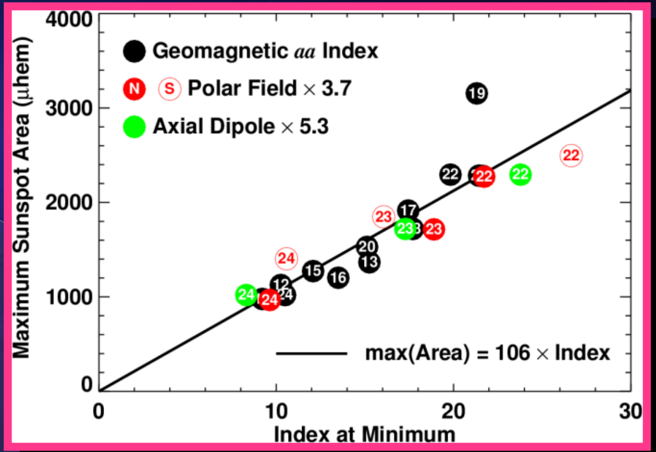
- Simulated Cycles show good agreement with observed cycles.
- Both in terms of emergence pattern and evolution (e.g., butterfly diagram).

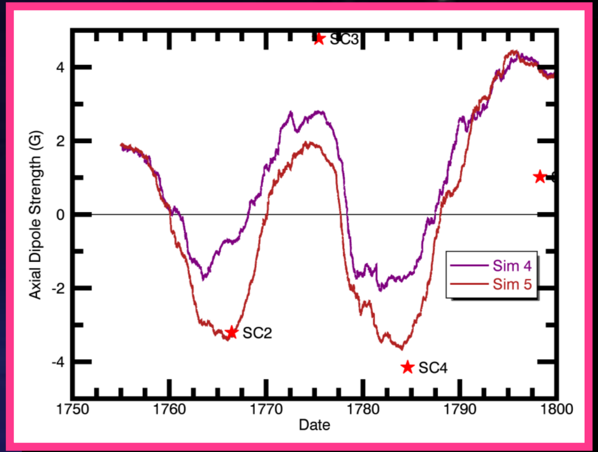
Example of SARG in AFT



Polar Field Evolution





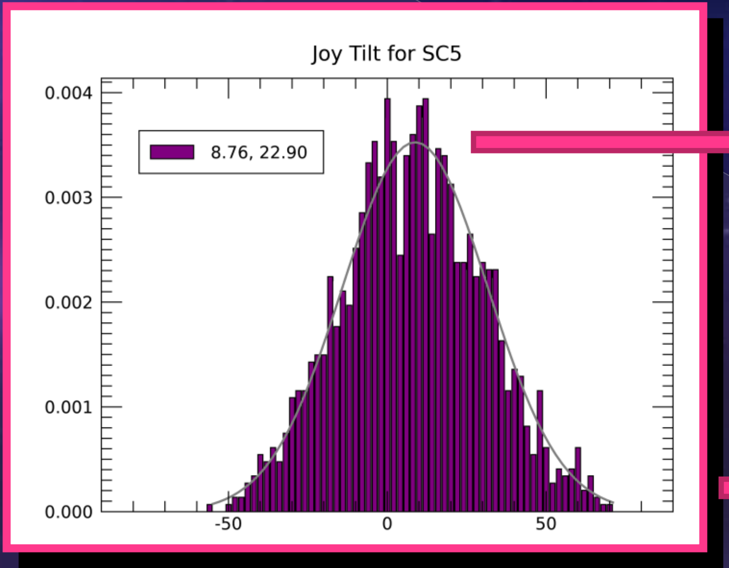


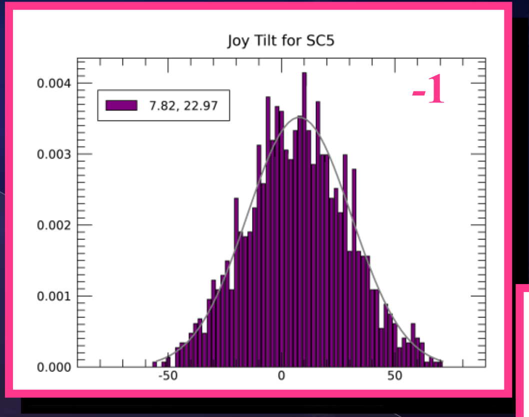
- The strength of the polar magnetic fields at solar cycle minimum have been well established as one of the best predictors of the amplitude of the following cycle.
- To ensure that a cycle realization is a good representation of the historical cycles, we must make sure that this condition is satisfied as well.
- This can be achieve in a number of ways (e.g., Flows, Tilts, Rogue ARs).
- For this work, we achieve this by shifting the mean of the AR tilt distribution.

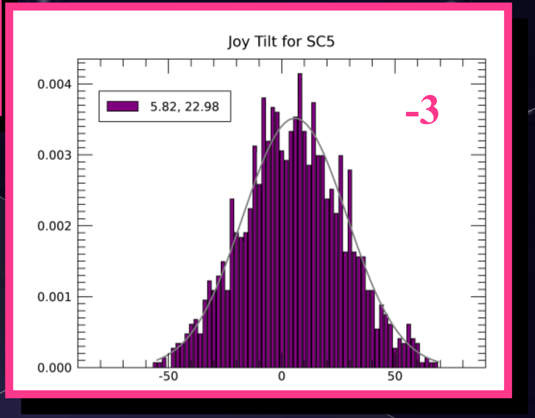
Shifting The AR Tilt Distribution

SC	End Year	End Month	End Goal
0	1755	2	1.8804144
1	1766	6	-3.2057492
2	1775	6	4.7761088
3	1784	8	-4.1507612
4	1798	4	1.01970928
5	1810	7	-0.7485228
6	1823	4	1.8666528
7	1833	12	-4.3104104
8	1843	8	3.5588172
9	1856	1	-3.1752248
10	1867	3	4.0995456
11	1878	11	-1.7840344
12	1889	10	2.382176
13	1902	1	-1.6194076
14	1913	7	2.6343012
15	1923	8	-2.1454472
16	1933	10	3.5375404
17	1944	2	-4.2249616
18	1954	5	5.822332
19	1964	10	-2.7936088
20	1976	5	4.5772732
21	1986	7	-4.3000404
22	1996	8	3.34073
23	2009	1	-1.556846
24	2020	1	1.95

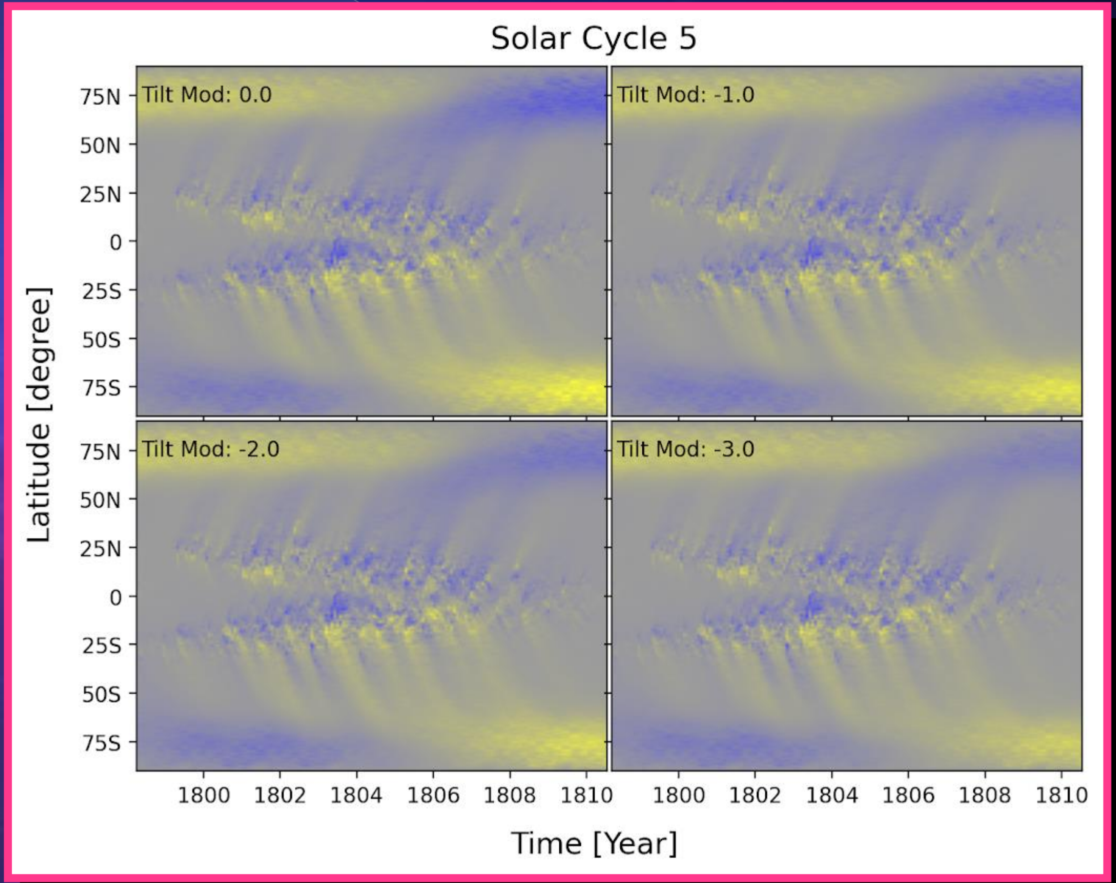
- We determine the expected polar field from the following cycle strength.
- We run each cycle with a goal for the axial dipole moment (ADM).
- To achieve the desired ADM, we shift the mean of the tilt distribution.
  - Negative/Positive shifts produce smaller/larger ADM.

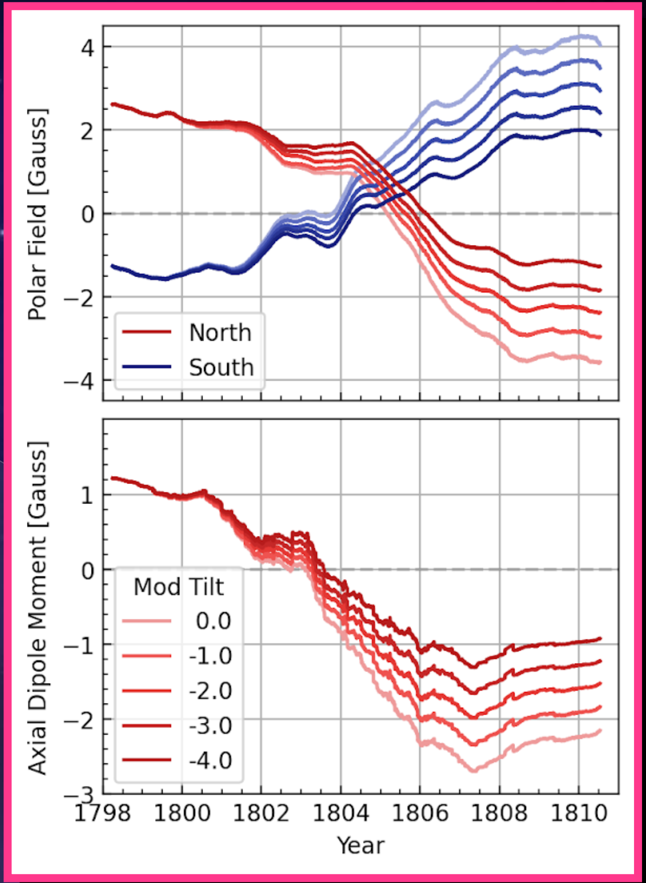






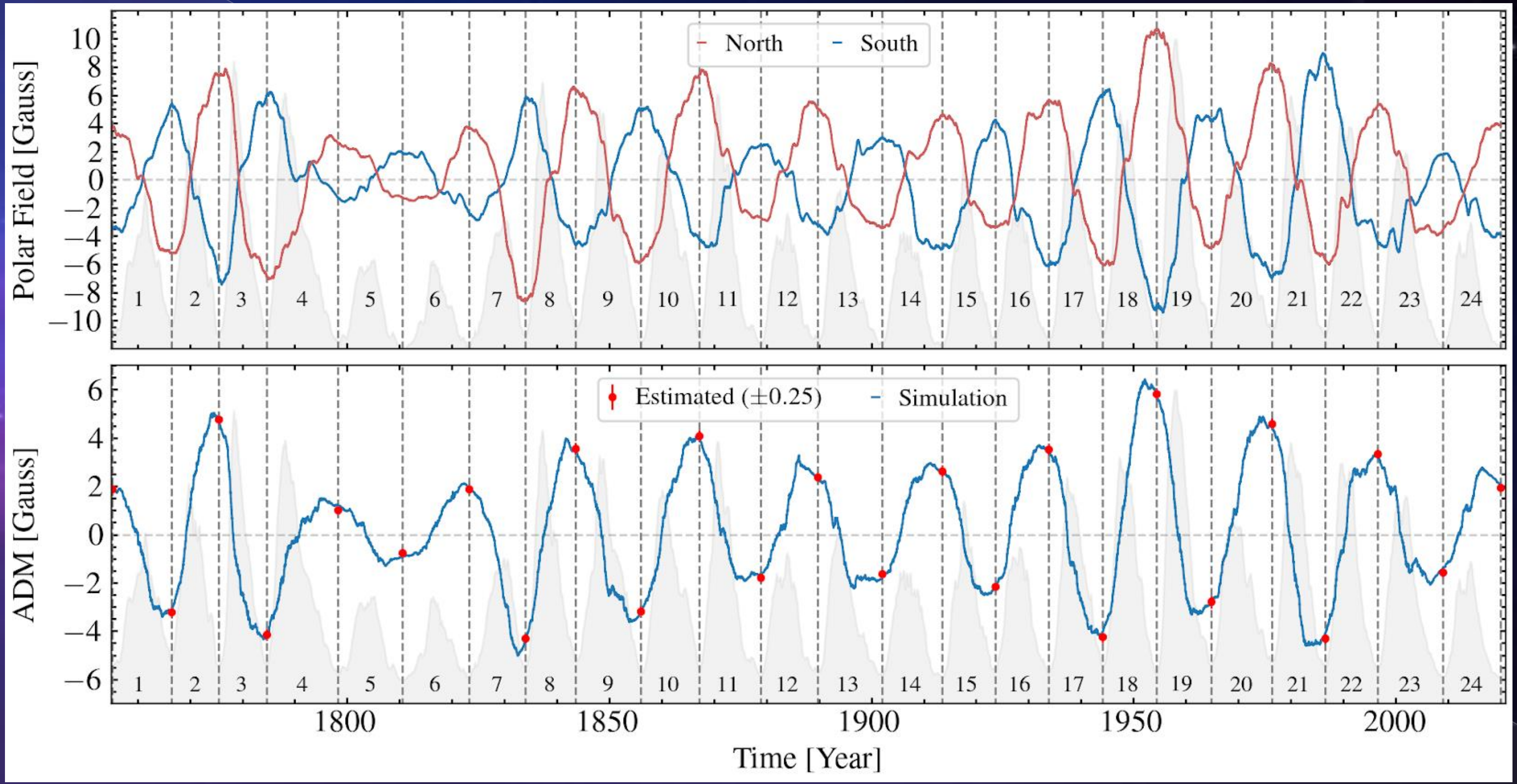
Shifting The AR Tilt Distribution





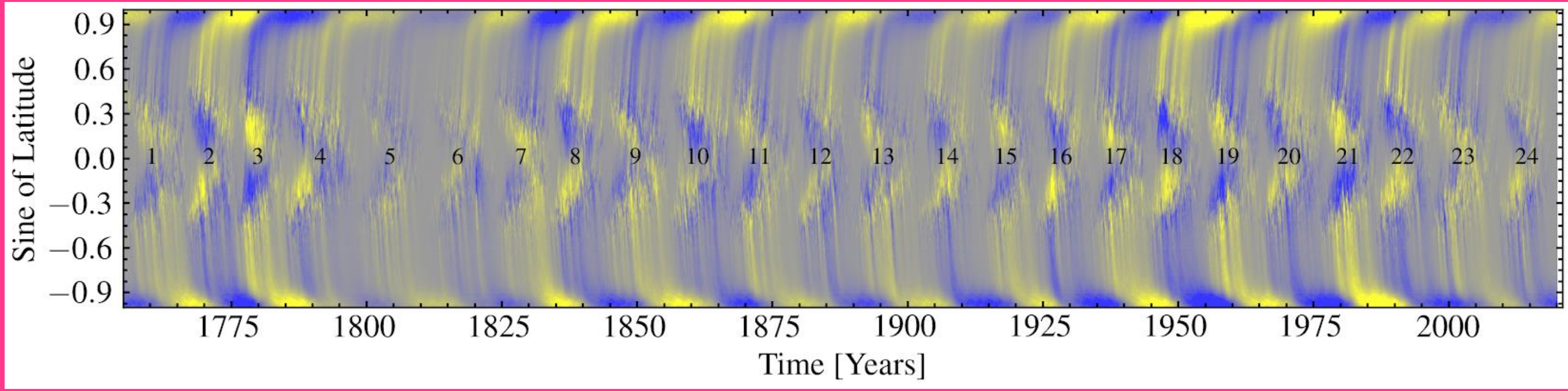
- Shifting the AR tilt allows us to tune the polar fields in a predictable way.
- We do this for each cycle individually to find the optimum shift.

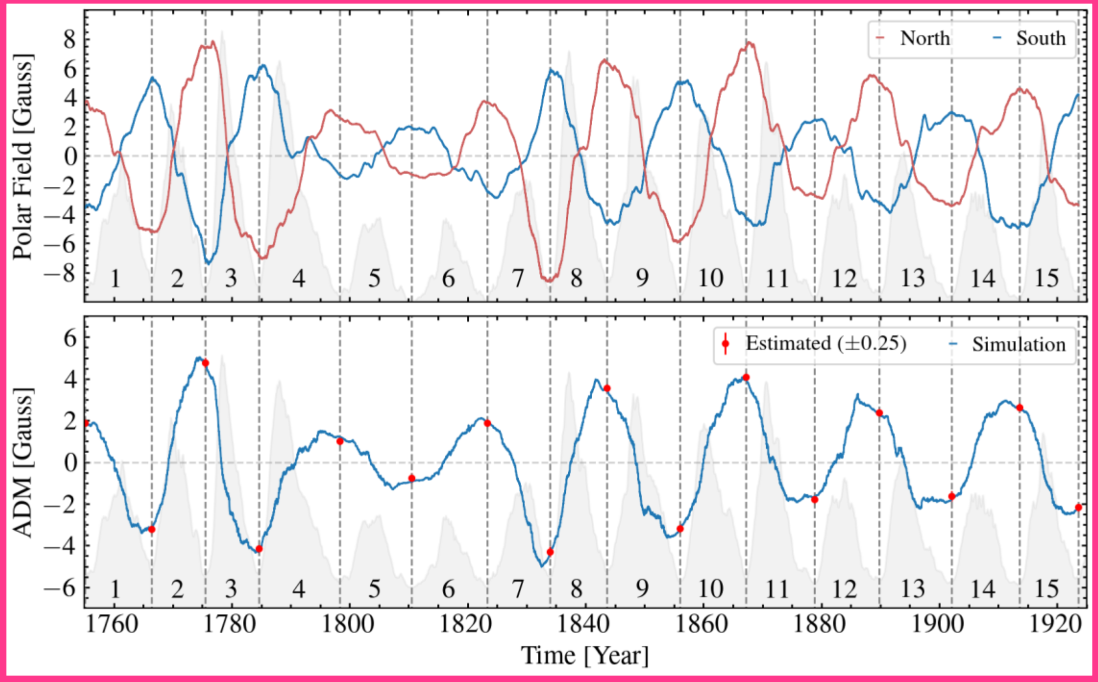
Successful 24 Cycle Simulation



- We then a continuous simulation of all cycles with the desired shifts. **Success!!!**
- Our job is done and maps from our simulation are then used in the TSI reconstruction.

Questions?

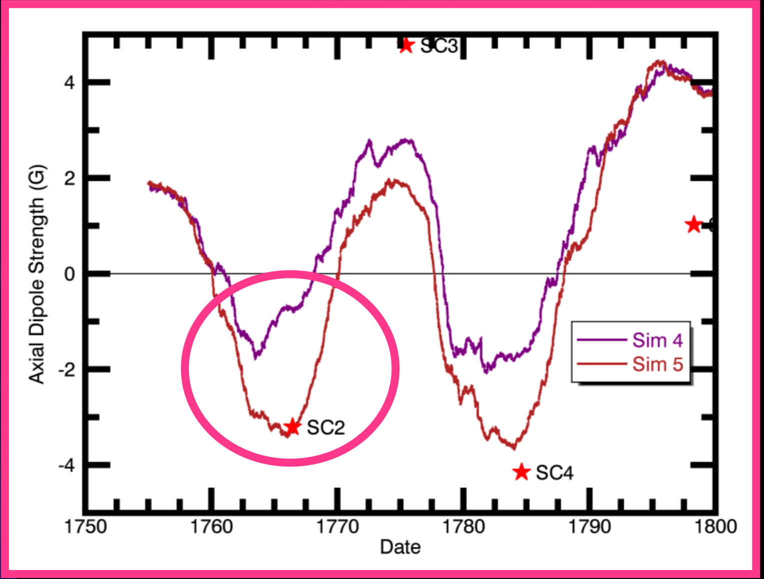


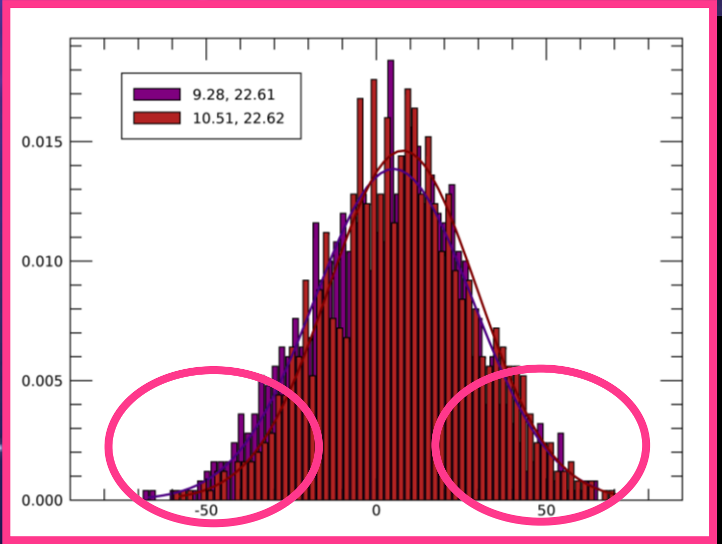


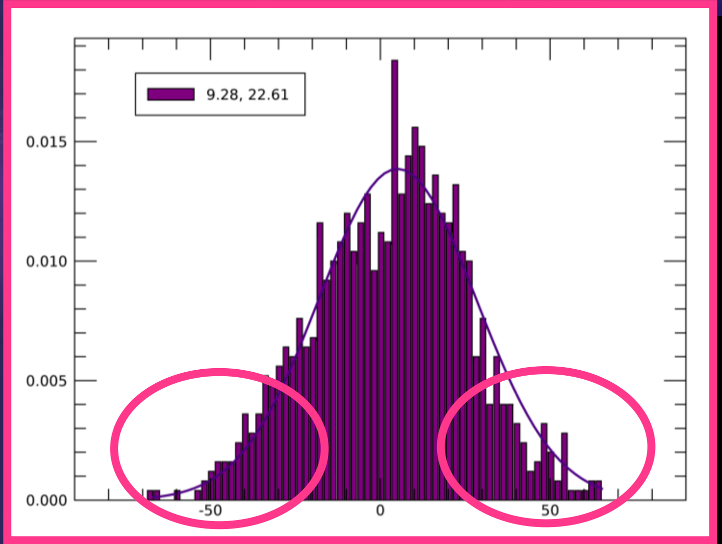
CN	End Year	End Month	End Goal	Sim	Tilt Mod	Diff
0	1755	2	1.8804	1.8800		0.0004
1	1766	6	-3.2057	-3.1910	0	-0.0147
2	1775	6	4.7761	4.8220	1.5	-0.0459
3	1784	8	-4.1508	-4.3050	1.5	0.1542
4	1798	4	1.0197	1.2140	-5	-0.1943
5	1810	7	-0.7485	-0.9320	-4	0.1835
6	1823	4	1.8667	1.9400	-1.5	-0.0733
7	1833	12	-4.3104	-4.4530	1.5	0.1426
8	1843	8	3.5588	3.5050	0	0.0538
9	1856	1	-3.1752	-3.2050	-3	0.0298
10	1867	3	4.0995	3.9840	-1	0.1155
11	1878	11	-1.7840	-1.9880	-4	0.2040
12	1889	10	2.3822	2.3050	-1	0.0772
13	1902	1	-1.6194	-1.8160	-3	0.1966
14	1913	7	2.6343	2.6460	0	-0.0117
15	1923	8	-2.1454	-2.2320	-0.5	0.0866

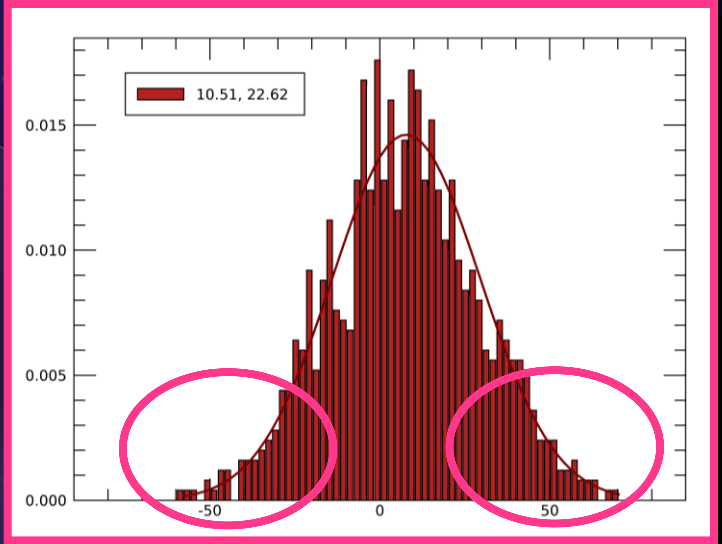
Rogue Active Regions

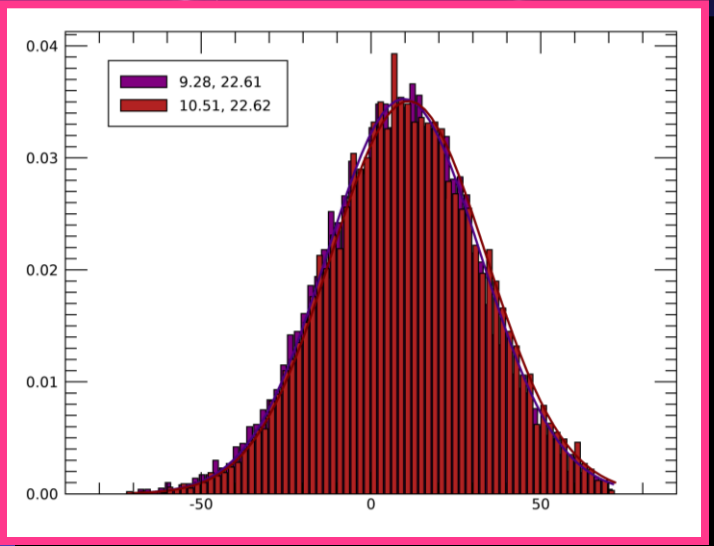
- Rogue occur naturally as a consequence of the broad distribution.
- However, they only become important when there is a significant imbalance between positive and negative rogues.










9.28, 22.61
10.51, 22.62
0.04
0.03
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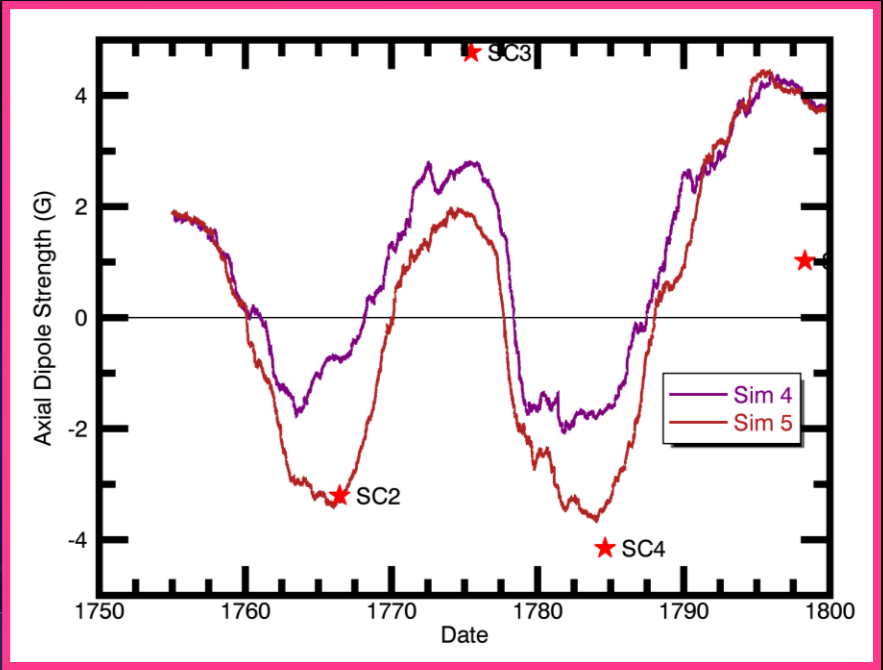
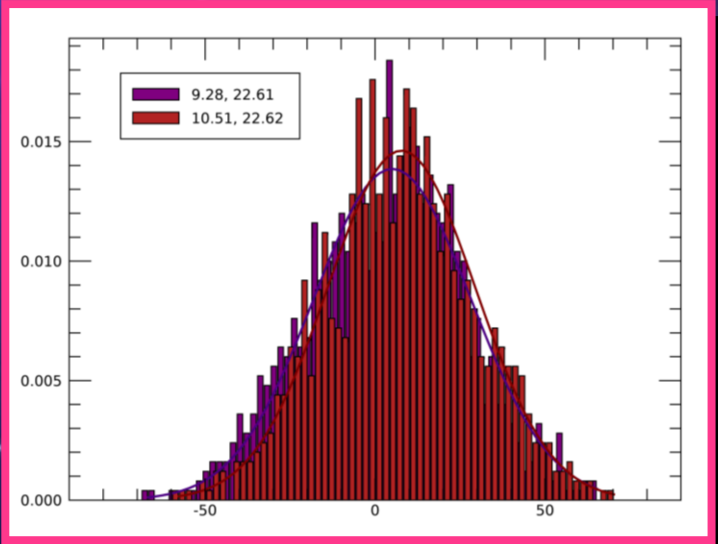
50


Axial Dipole Strength (G)
Date
4
2
0
-2
-4
1750
1760
1770
1780
1790
1800
SC2
SC3
SC4
Sim 4
Sim 5


9.28, 22.61
10.51, 22.62
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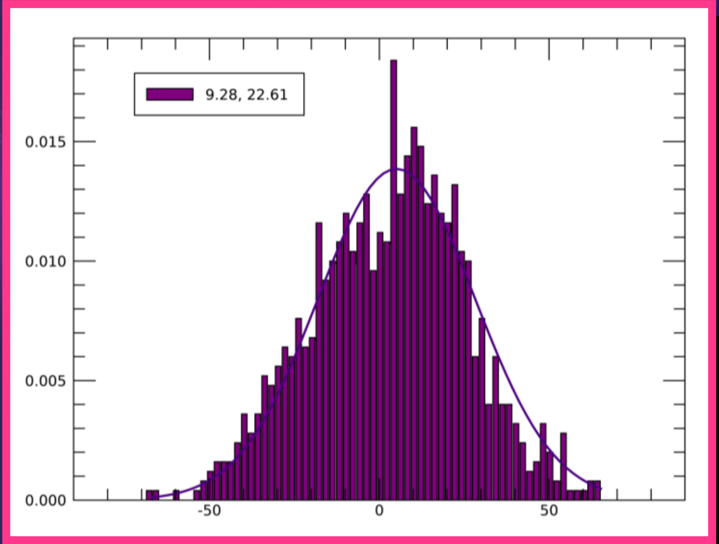
50


9.28, 22.61
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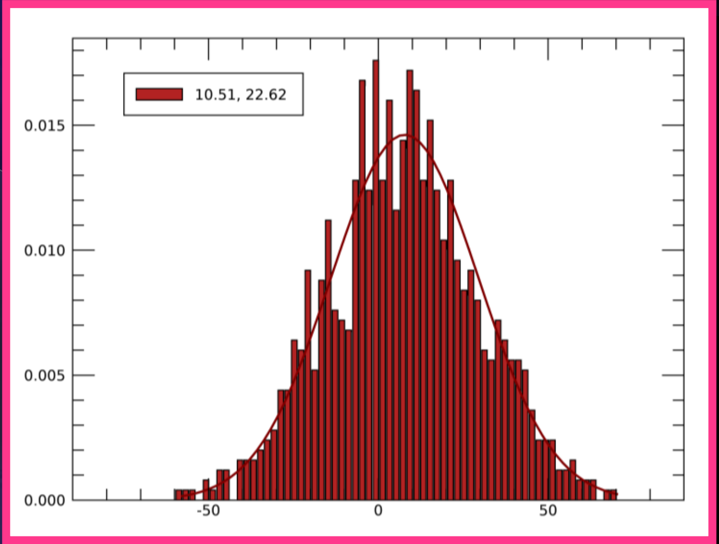
10.51, 22.62
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