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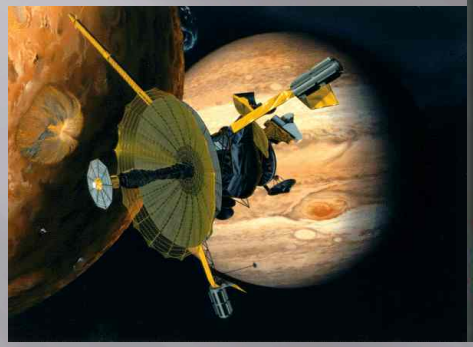

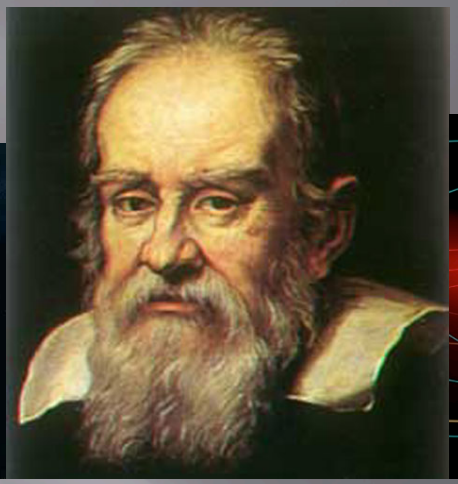

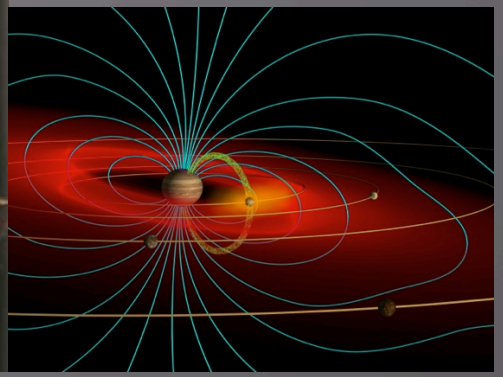

ANALYSIS OF VARIATIONS IN THE IO PLASMA TORUS USING GALILEO PLS DATA

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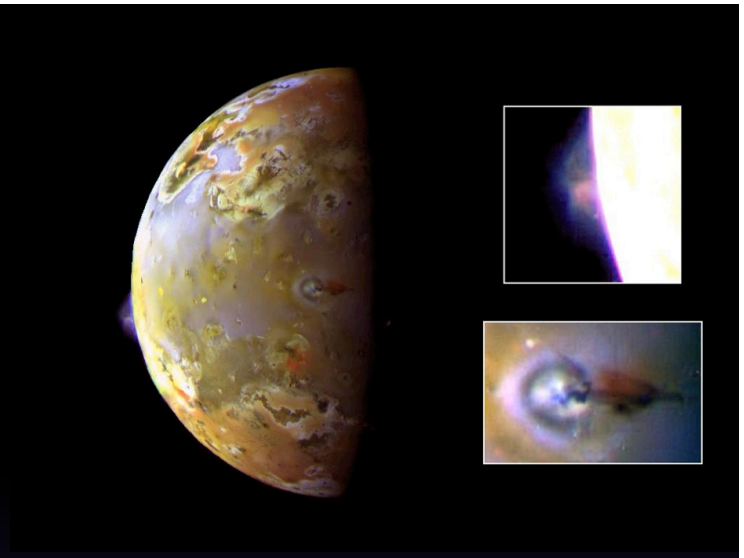
University of Colorado at Boulder
Laboratory for Atmospheric and Space Physics

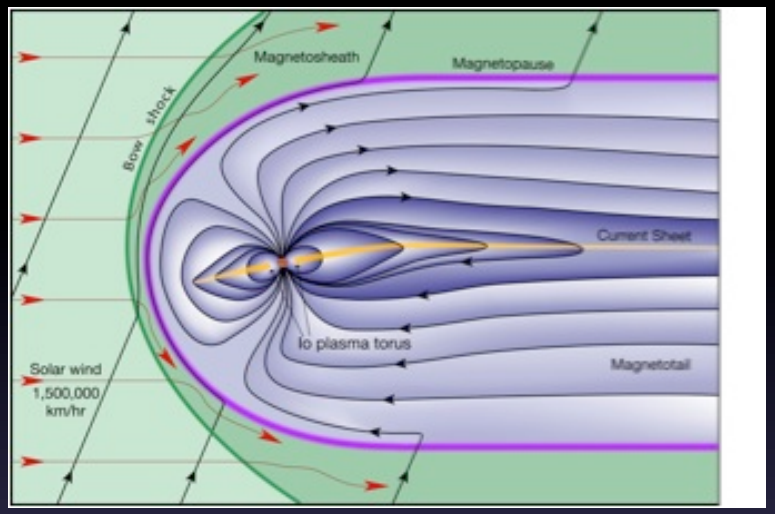
What's all this then?

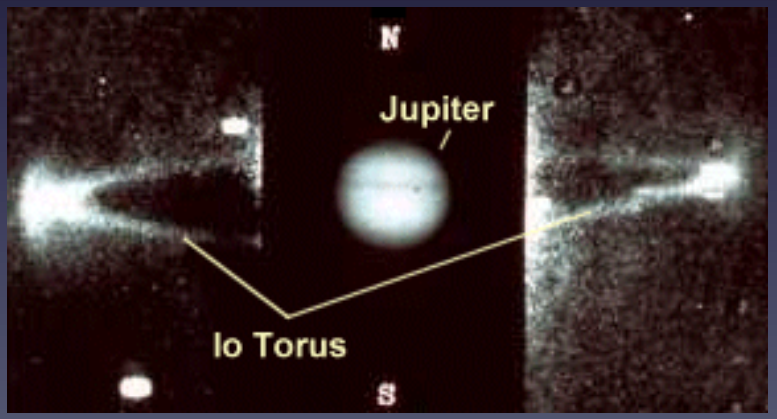


- We all know Jupiter's pretty awesome, but how awesome???? Can learn a lot with ground observations, but nothing beats in-situ data
- Two primary things to investigate: temporal variation and local time variation

Why do we care?

- Gives us insight about magnetospheres in general
- Very limited data set on extra-terrestrial systems, especially over the long term
- Much left to be understood about physics behind mass loading of Jupiter's inner magnetosphere by ions from Io's volcanoes



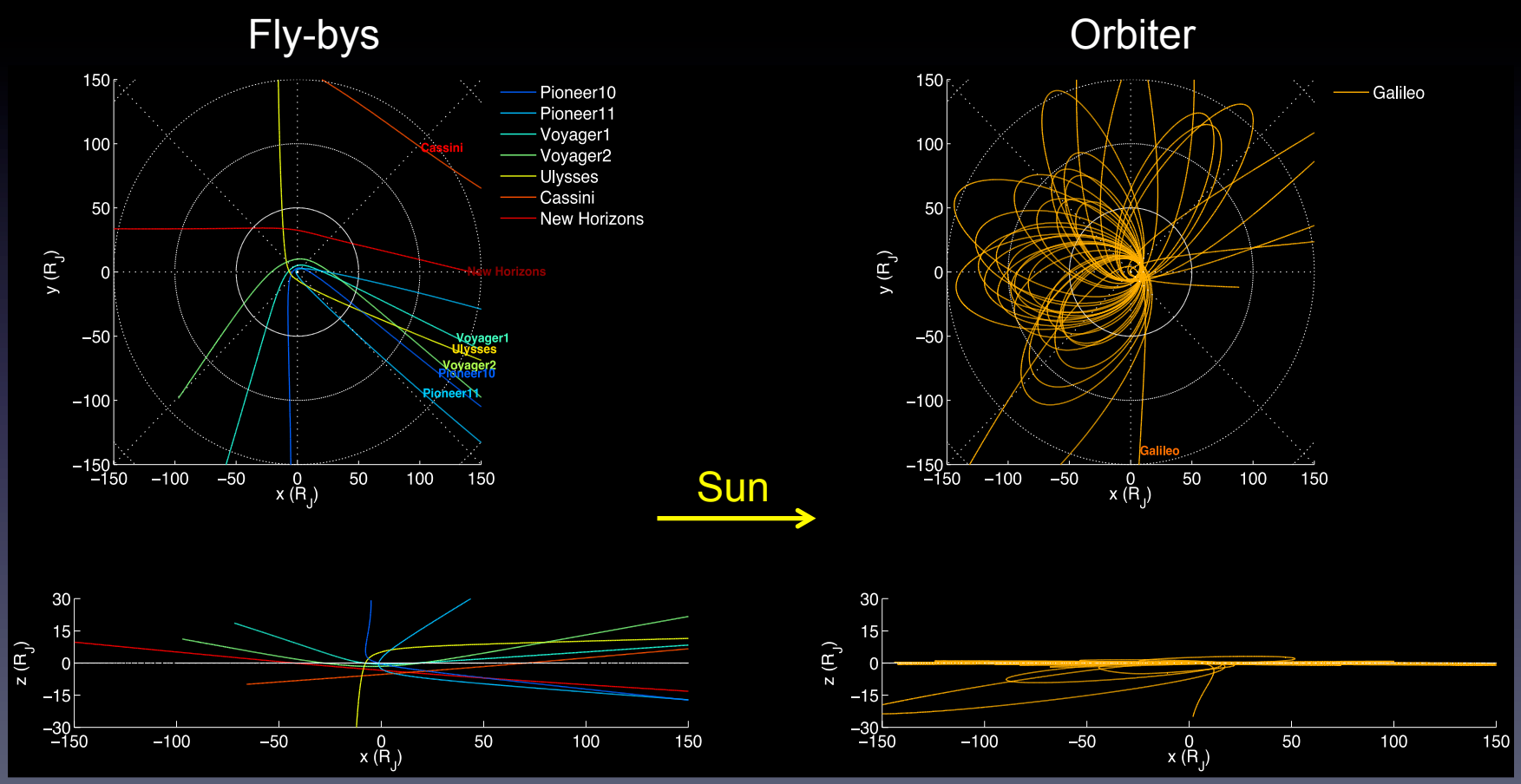


Why do we care?

Spacecraft (within 200 R_J)

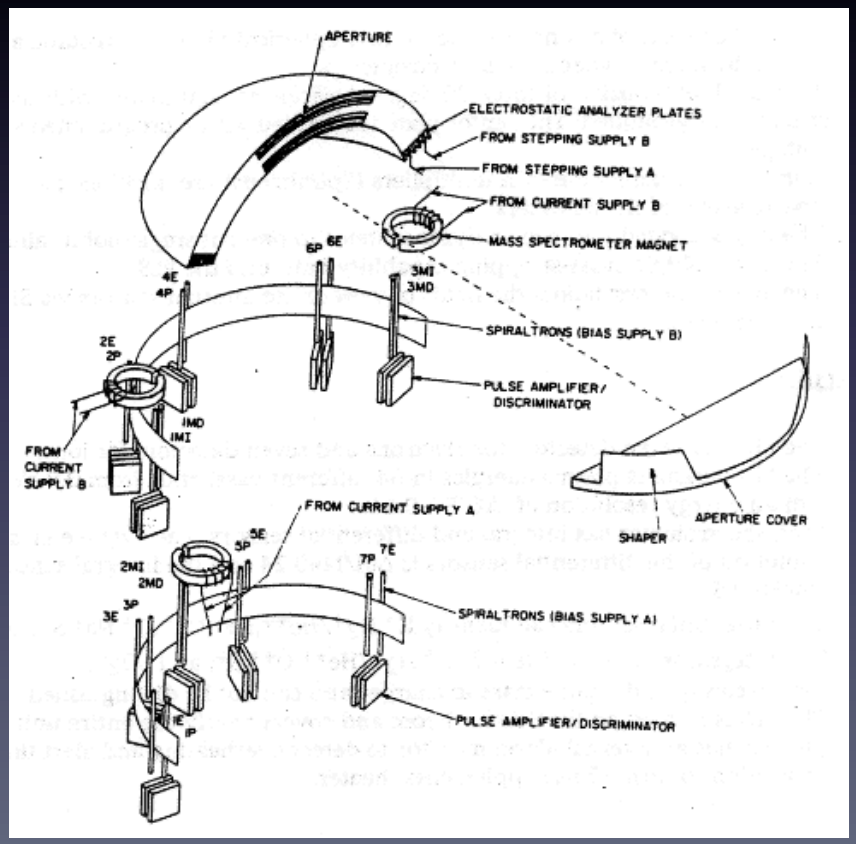
Spacecraft	Encounter Date/C.A.	Closest R (R_J)	Type	Spin	Energy Range (eV)
Pioneer 10	1973-Dec-04	2.9	Fly-by	Yes	100 – 4,800
Pioneer 11	1974-Dec-03	1.7	Fly-by	Yes	100 – 4,800
Voyager 1	1979-Mar-05	4.9	Fly-by	No	10 – 5,920
Voyager 2	1979-Jul-09	10.1	Fly-by	No	10 – 5,920
Ulysses	1992-Feb-08	6.3	Fly-by	Yes	255 – 34,400
Galileo	1995-Nov-10 to 2003-Sep-30	0 Perijoves: 5.5-9.5	Orbiter (Equatorial)	Yes (Spin Platform)	0.9 – 53,000
Cassini	2000-Dec-30	137	Fly-by	No, but has actuator	1 – 50,280
New Horizons	2007-Feb-28	32.2	Fly-by	No (fly-by) (Yes > 300R_J)	35 – 7,500
Juno	~2016-2017	1.06	Orbiter (Polar)	Yes	10 – 40,000

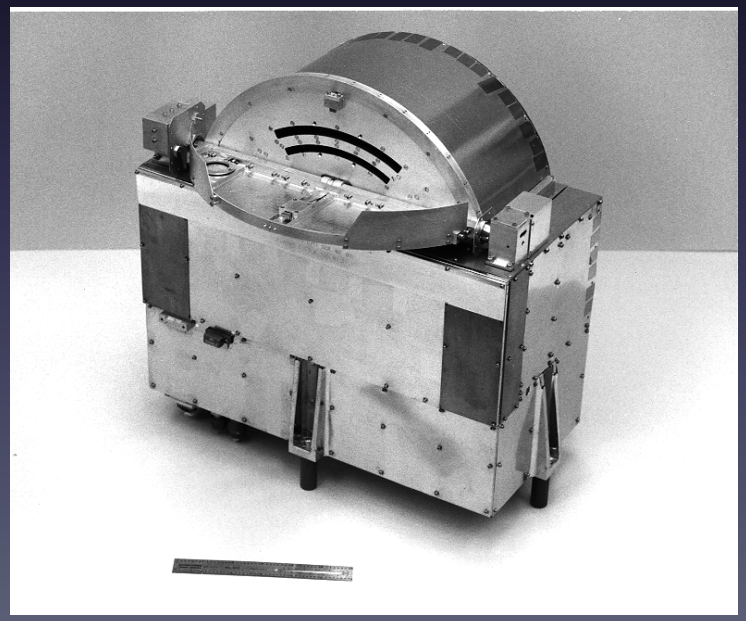
Why do we care?



What are we looking at?

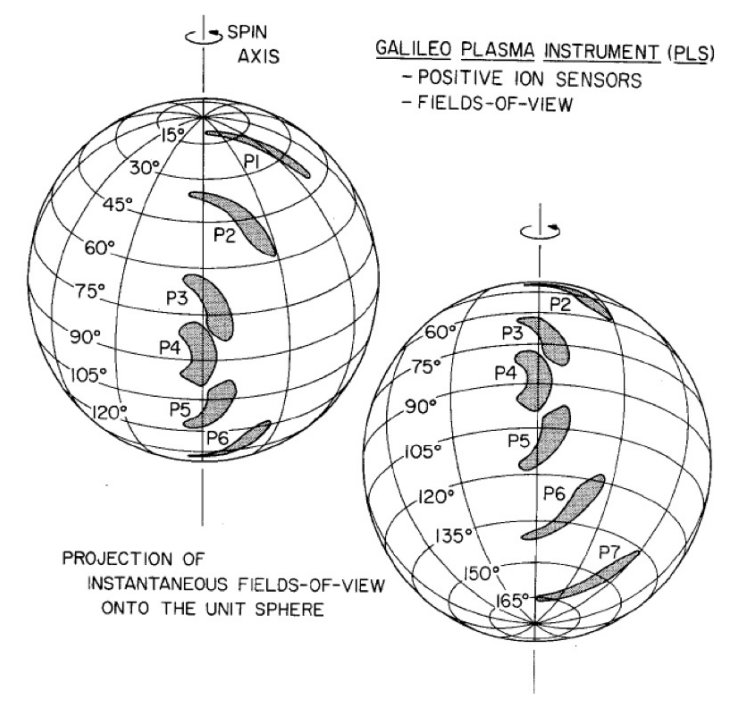
- Focused on a nested set of 3 quarter-spherical plate electrostatic analyzers





What are we looking at?

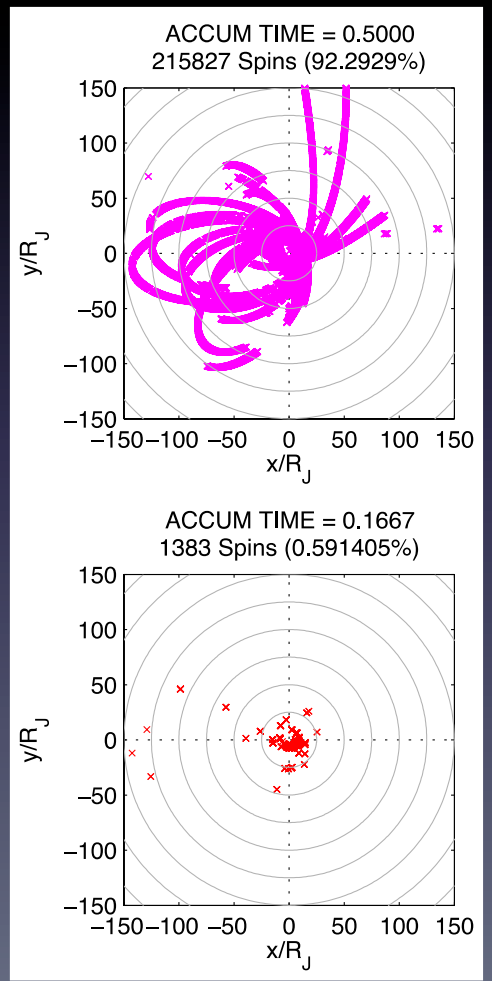
- ESA gives energy resolution. Imagine ions as basketballs that you give just enough energy for gravity to sink the shot
- Spacing of 7 anodes in a fan-shape on the side gives 3-D spatial resolution

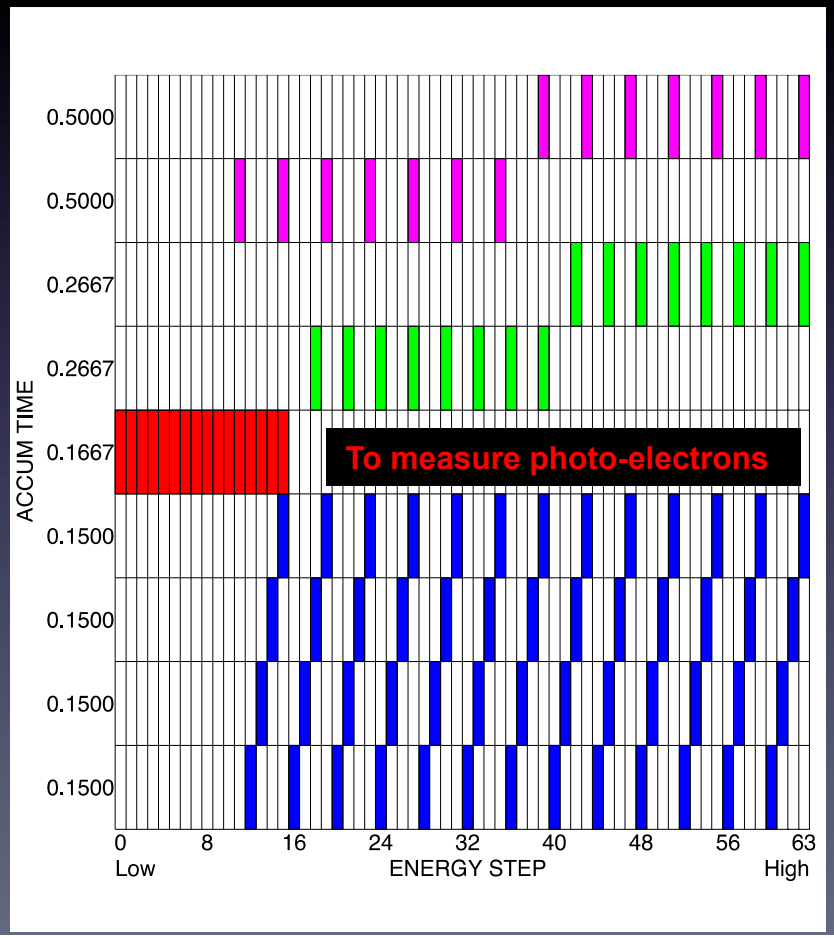


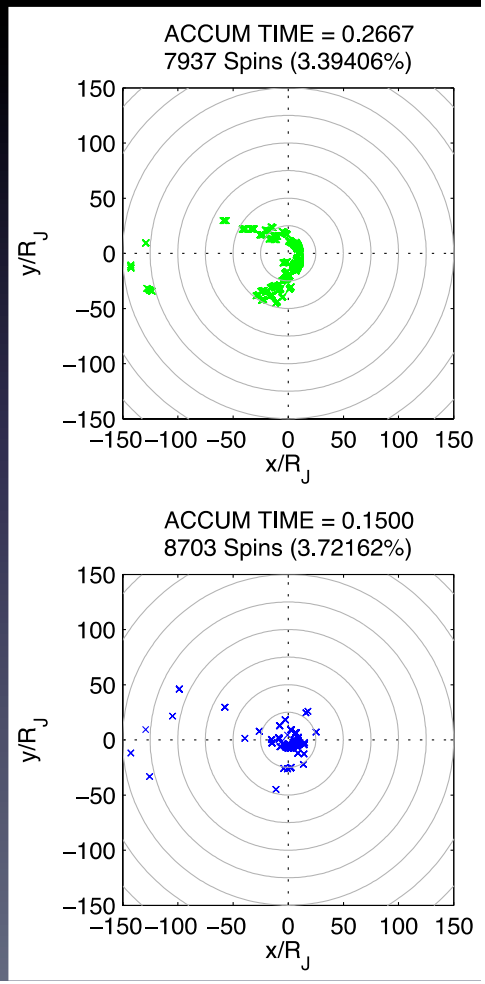
What are we looking at?

Galileo PLS Energy steps and Coverage

<u>SKIPPED STEPPING DUE TO ANTENNA ISSUE</u>







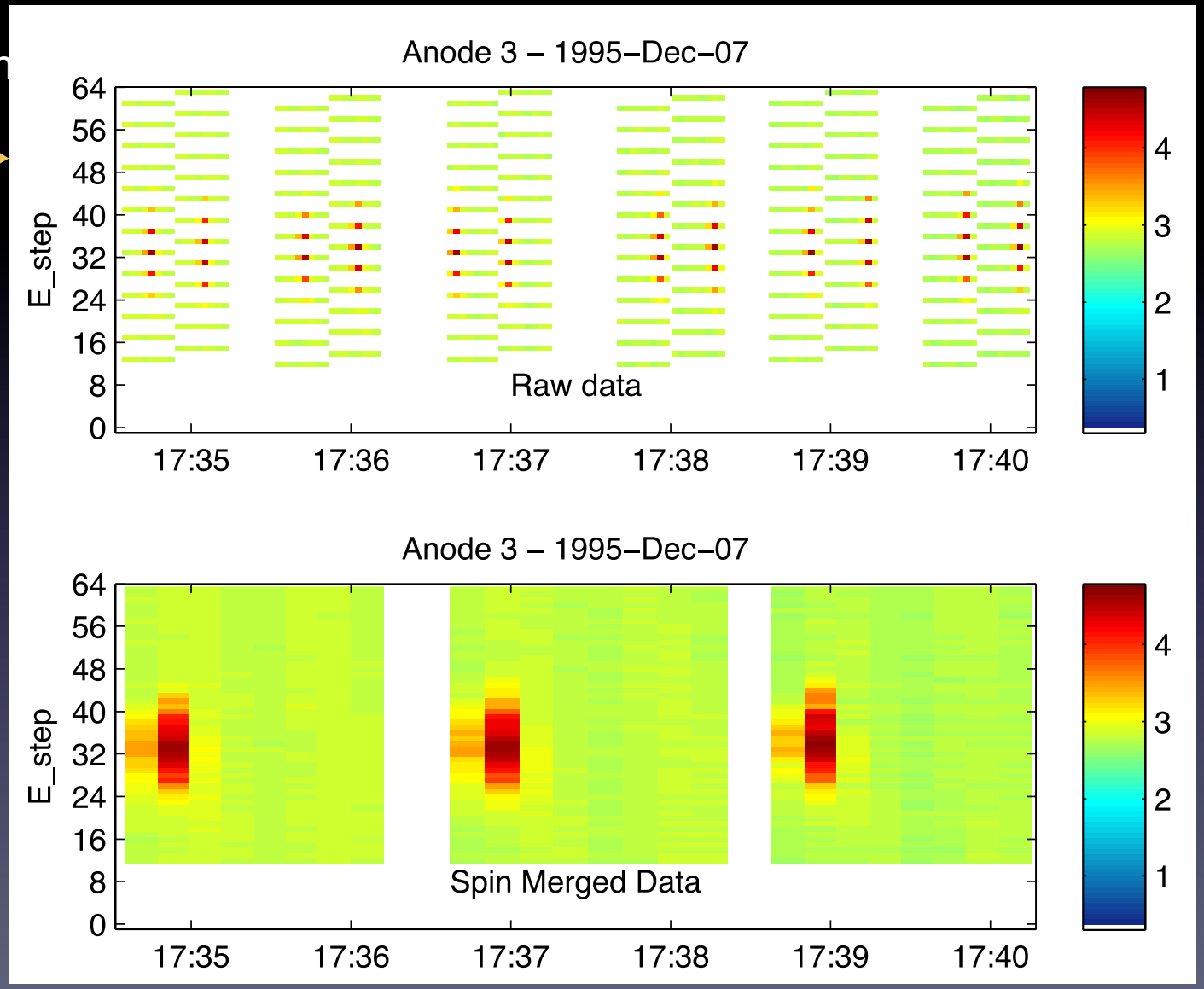
What are we looking at?

- 4 (low/mid) or 8 (high) sweeps in a spin
- Counts accumulated over time (determined by resolution setting)
- Accumulated sweeps over one spin are "merged"
- Our available data set: 114133 total merged spins

Galileo Merging of Data Spins

How data is taken on Galileo

Note different data spins start at different phases.



Data after merging and realigning spin phases.

Quality spectra, both in energy and all sky!

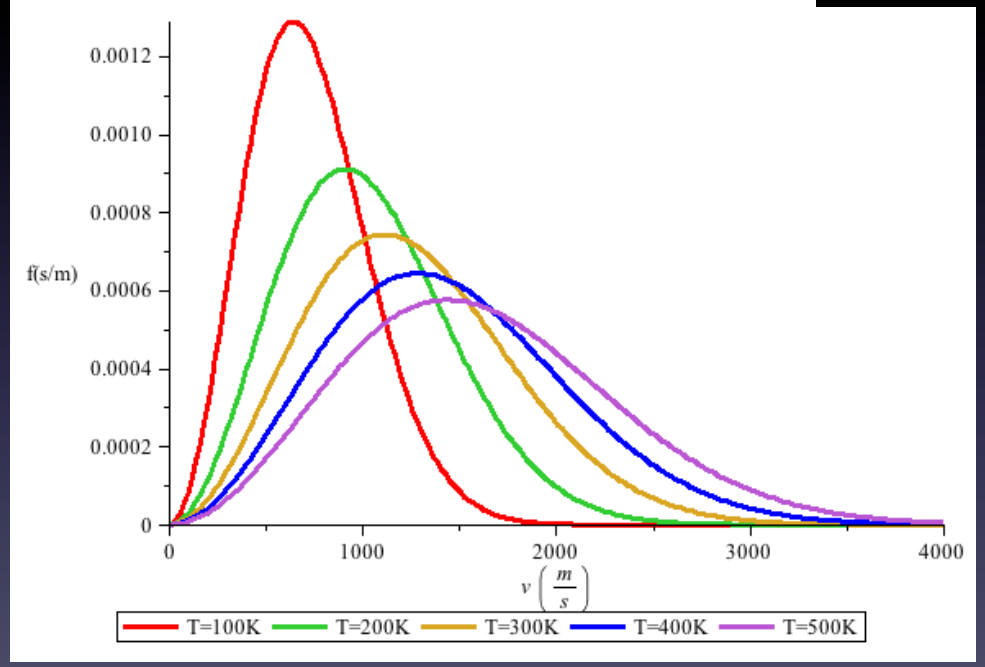
How are we analyzing the data?

- Expect the plasma to be in thermal equilibrium, follows a convective Maxwellian velocity distribution
- Predicted number of counts given by:

C = dt*GF*v^4*f(v)

- Adjustable parameters are n, T, Vo (3 components)

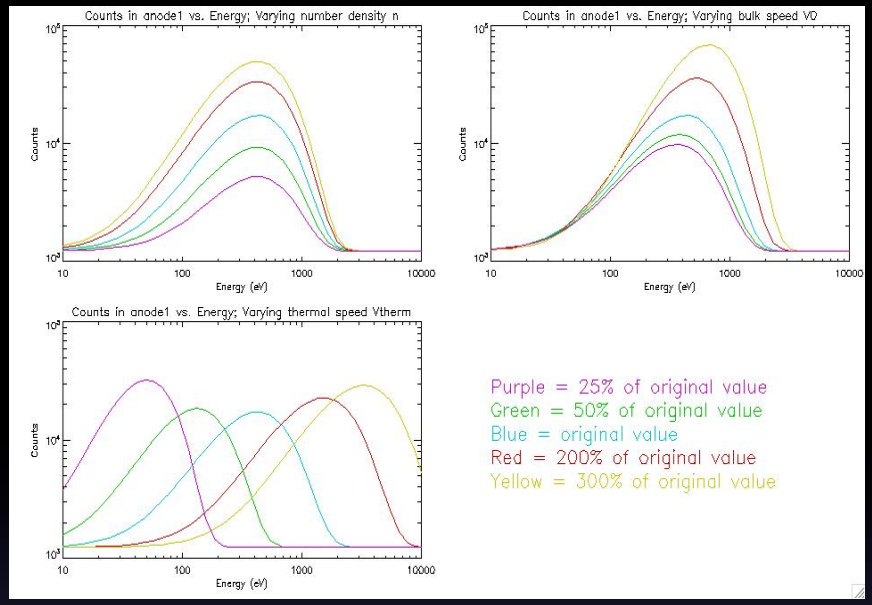
$$f(v) = n\left(\frac{m}{2\pi k_B T}\right)^{3/2} \exp\left(-\frac{m(\mathbf{v}-\mathbf{V}_0)^2}{2k_B T}\right)$$

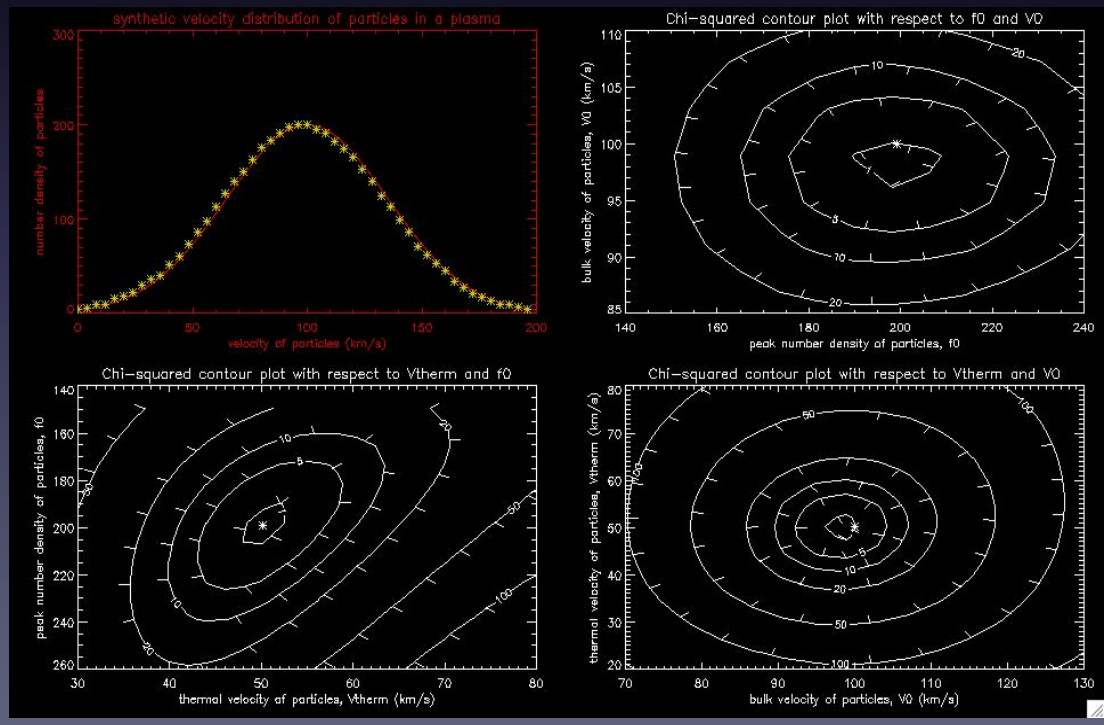


Fitting

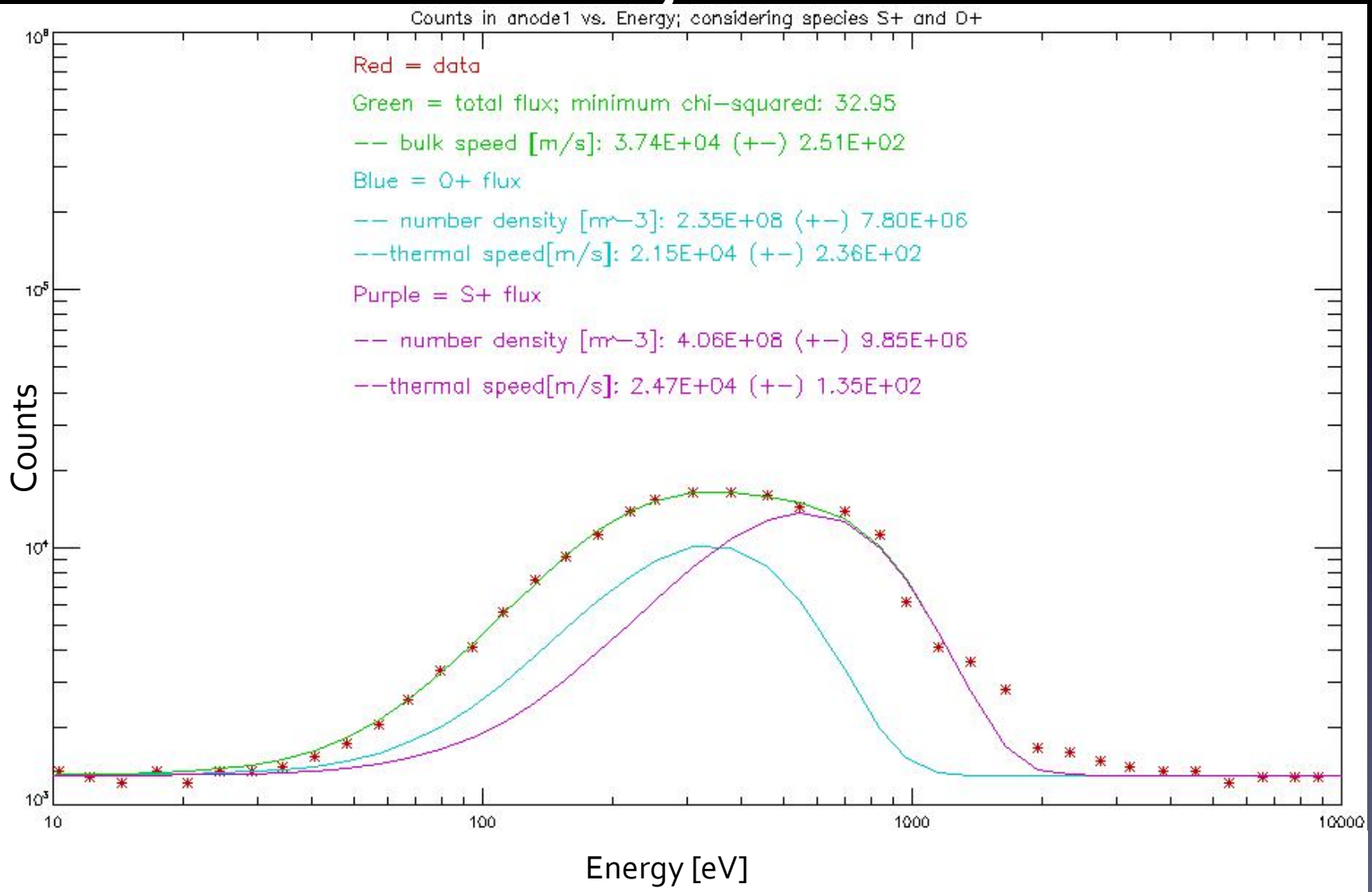
- (Careful) chi-squared minimization allows us to eek out best fit parameter values
- Errors on parameters are essentially the width of the hyperdimensional chi-squared well

$$\chi_r^2 = \frac{1}{\nu}\sum\frac{(y_f - y_i)^2}{\sigma_i^2} = \frac{1}{\nu}\chi^2$$





Getting started

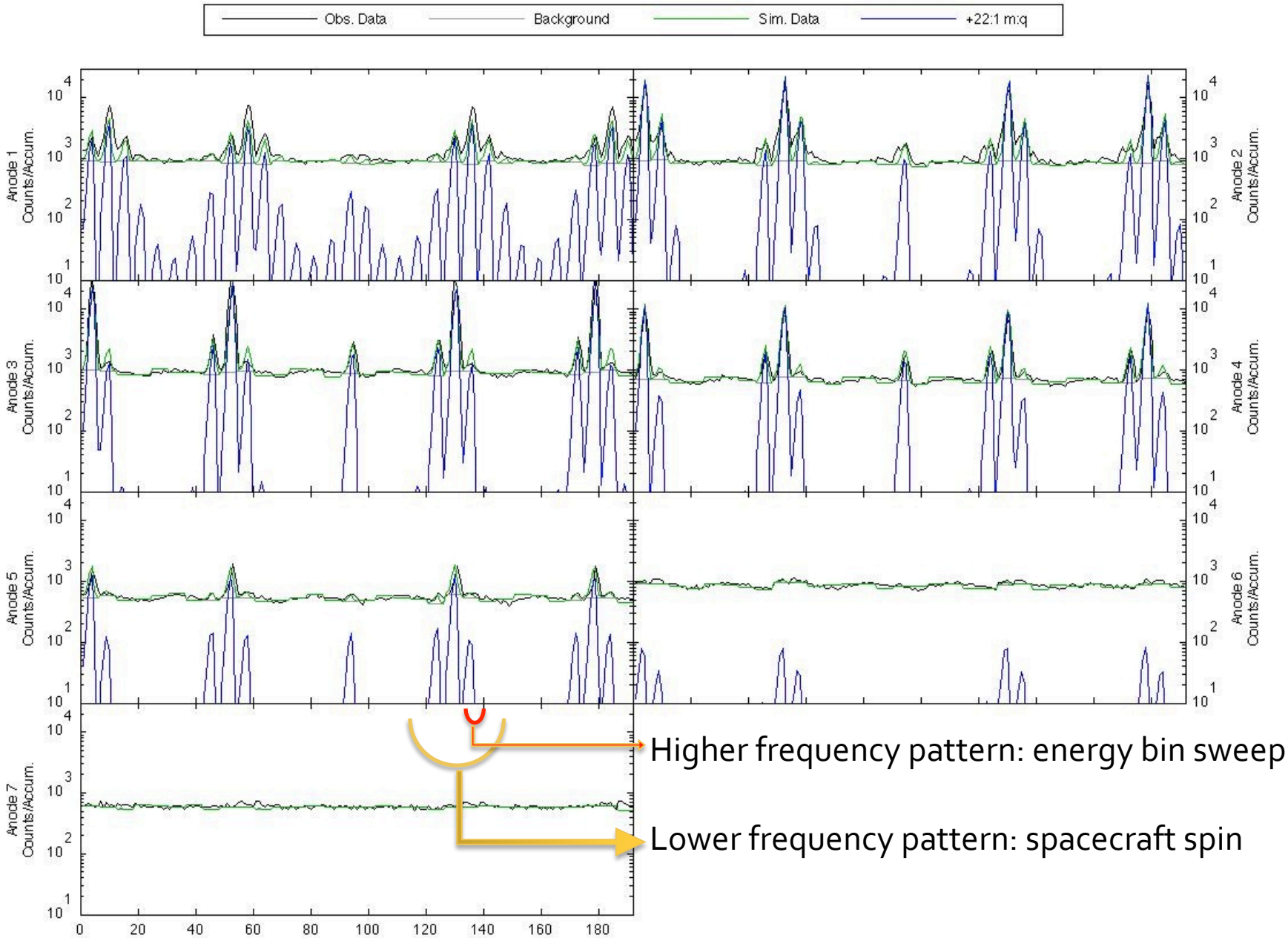


Better Fitting

- Employed a more complex iterative chi-squared minimization routine using Differential Evolution to find vicinity of global min in parameter space
- Simplex uses that to rapidly identify minimum

Assumptions

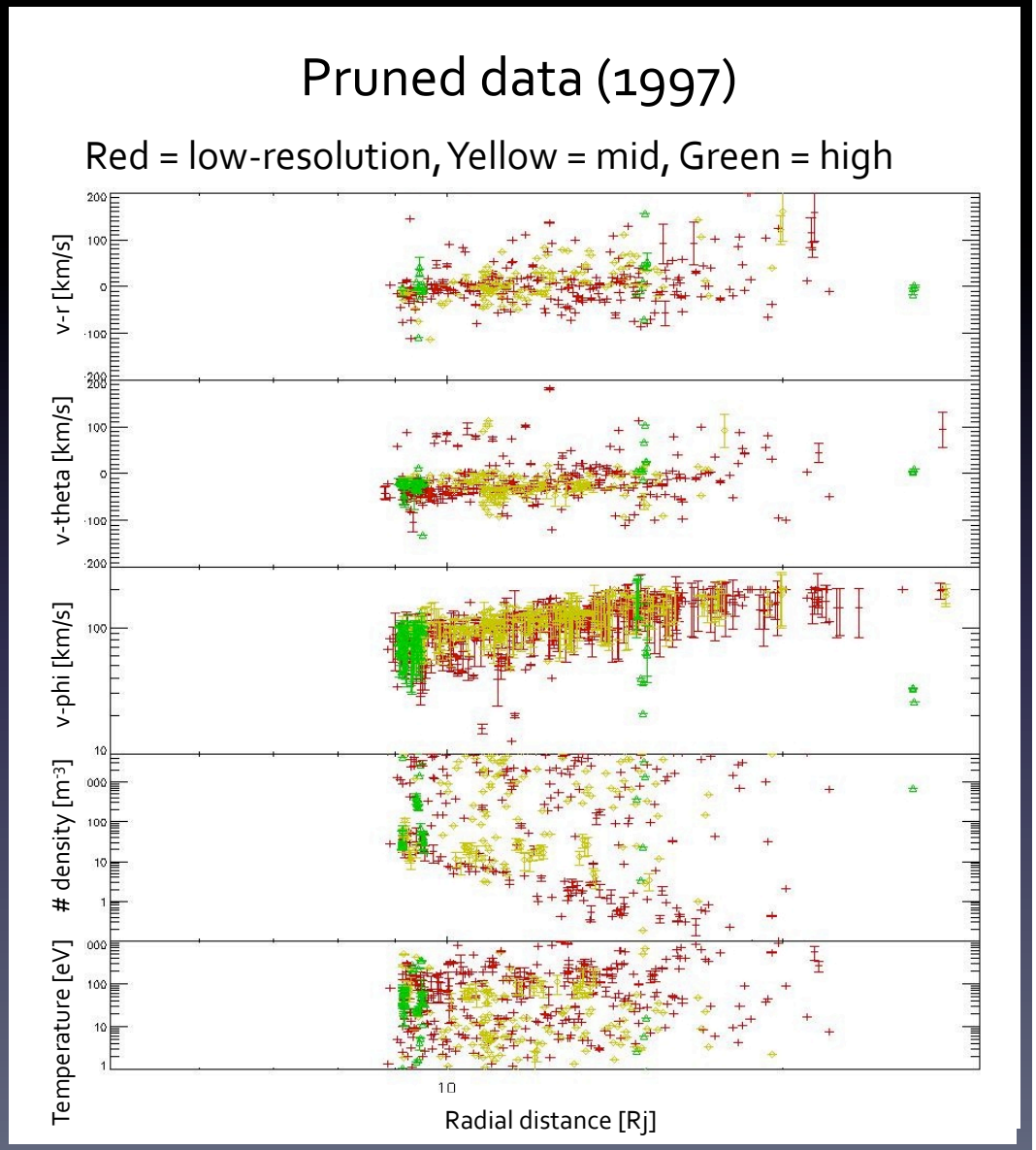
- Isotropic (data too sparse for anisotropic)
- Several species present (S ++, O+, SO++, … ions), but peaks overlap too much to distinguish → 32 amu/2e = 16 amu/1e
- From recent Cassini UV observations [Delamere and Bagenal, 2005], we used relative abundances of species to get an average mass-to-charge (actually variable m:q with respect to radial distance)



X-axis: daisy chained energy bin steps

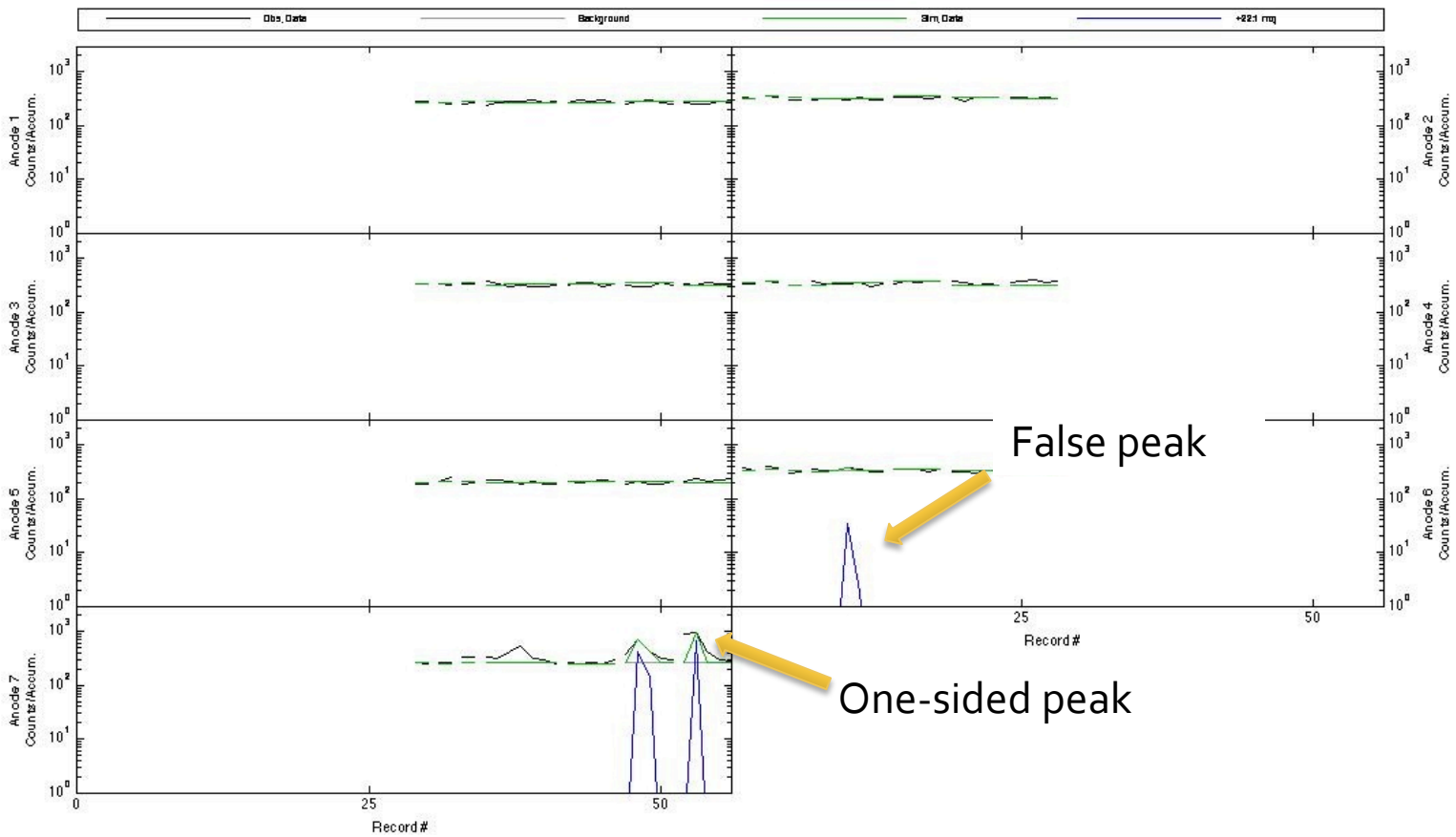
Discovered difficulties

- At first, churned out the fits and plotted those with sufficiently low error to value ratio
- Gave too much scatter to have any confidence in the radial profiles



Why so much scatter?

Vast majority of records too noisy or featureless to fit properly,
(partly due to flooding of detectors by energetic radiation belt particles)



How to proceed with messy data

- Can't afford to throw out points unless absolutely necessary
- Went back and looked at several individual records at various times, distances, etc. to develop more rigorous selection criteria based on observed patterns
- Examples: one-sided peaks, false peaks, background noise levels, missing anode data, etc.

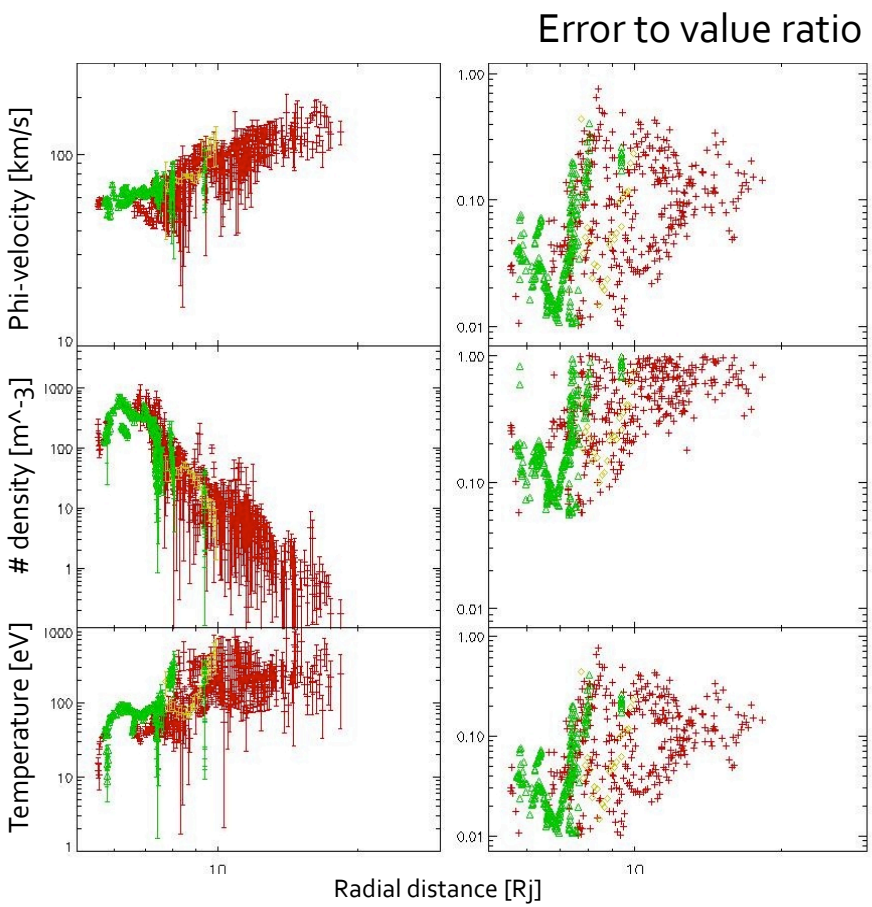
"Pruning?"

- Introduced harder eligibility conditions for fitting (e.g. max counts > 10, only consider peak anodes and its neighbors, etc.)
- Gave us nearly 4 times more successfully fit merged spins
- Dramatically reduced the number of null points being fitted, more realistic errors

Looking better!

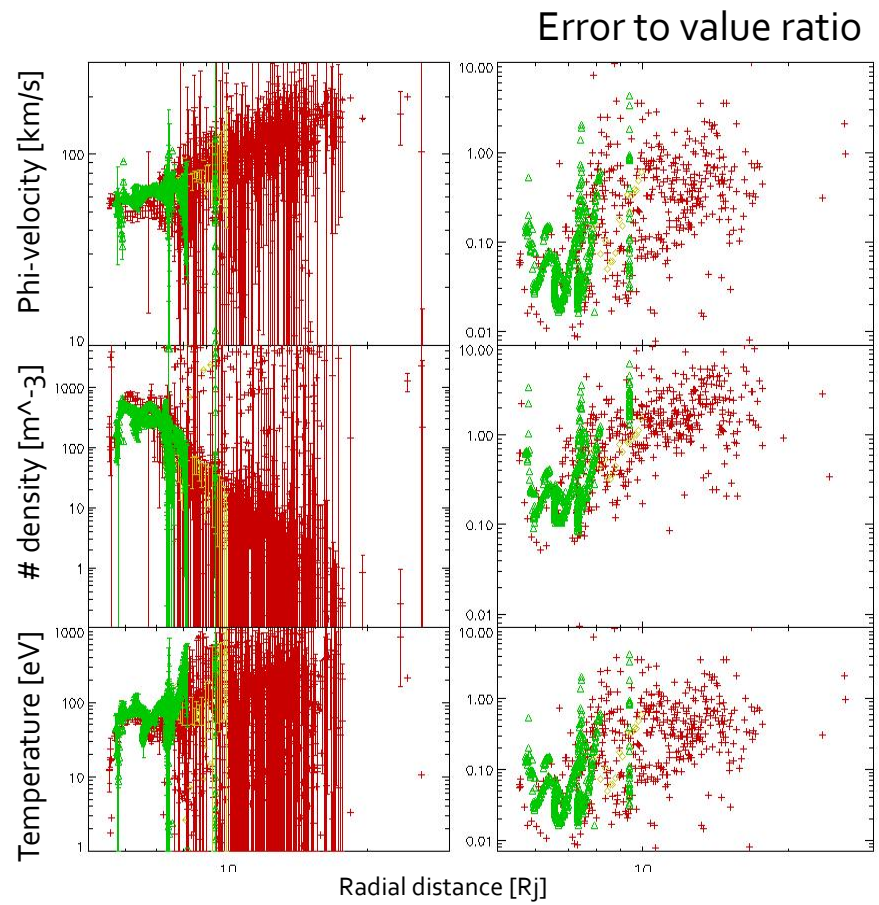
Pruned data (1999)

Red = low-resolution, Yellow = mid, Green = high



Raw data (1999)

Red = low-resolution, Yellow = mid, Green = high

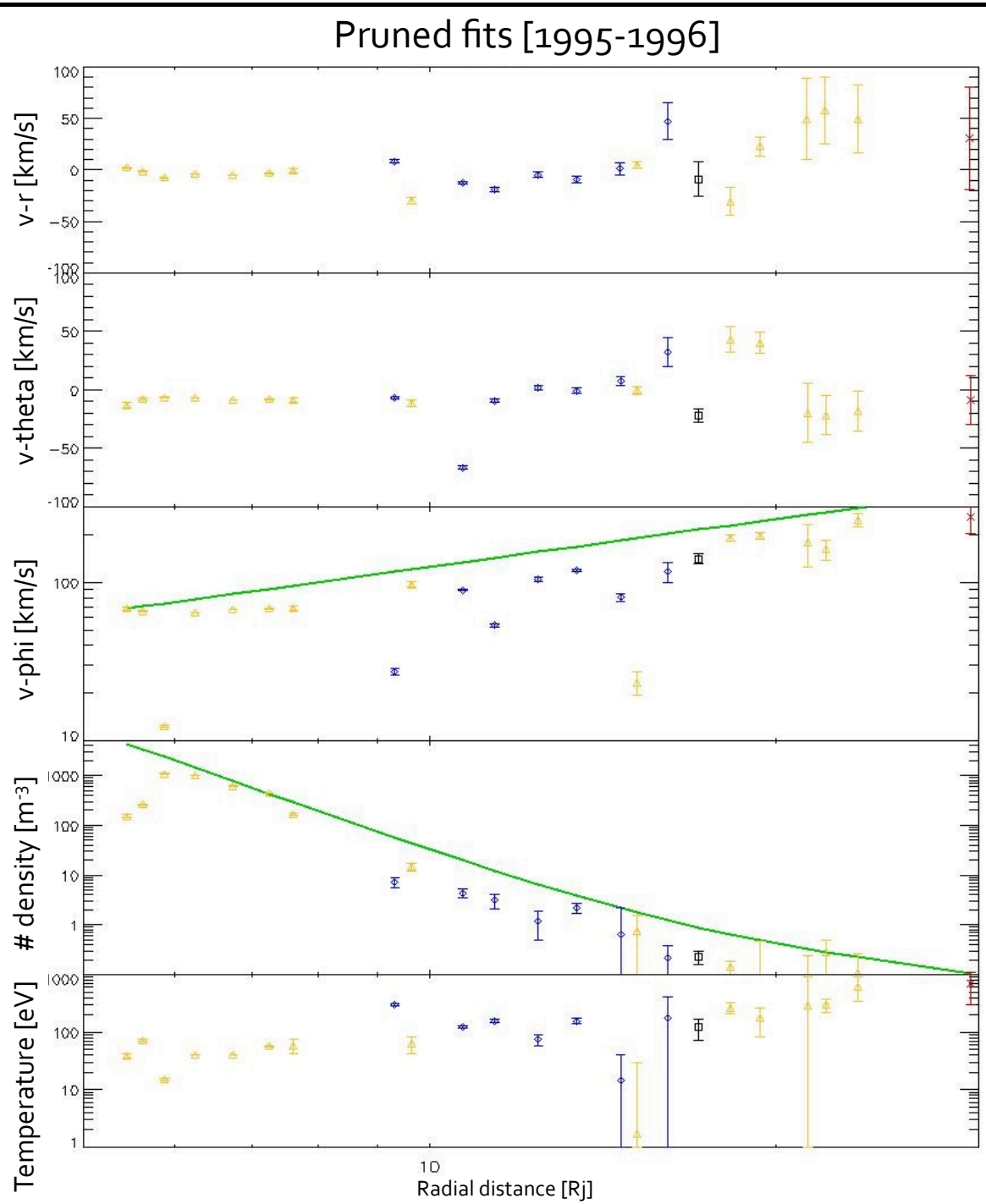


Binning

- Being satisfied with the points that made it through the pruning, we can get a smoother feel for the data by binning points by radial distance
- Different bin sizes at radii regimes to compensate for different conditions (.25Rj, .5Rj, 1Rj)

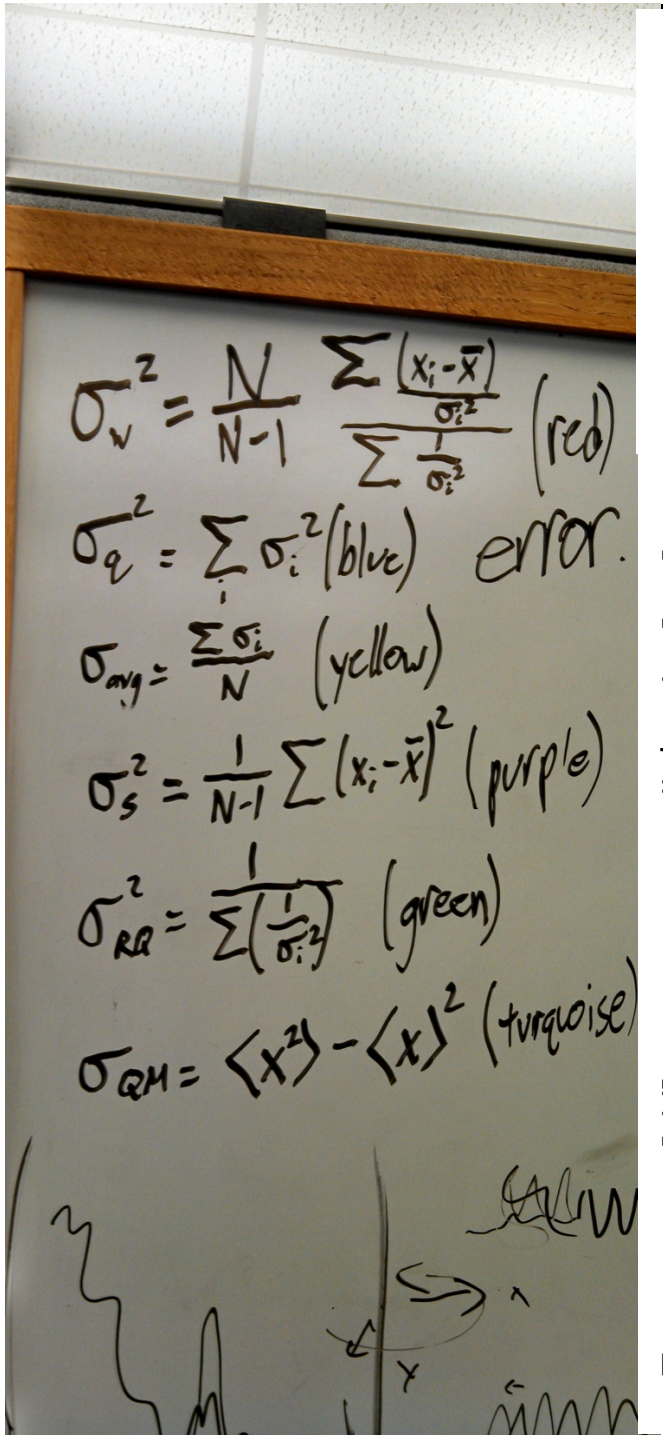
Gold = noon
Black = midnight
Red = dawn
Blue = dusk
Green =
--Corotation (rigidly rotating with Jupiter)(vphi)
--Fran Bagenal's derived density profile[2004] (n)

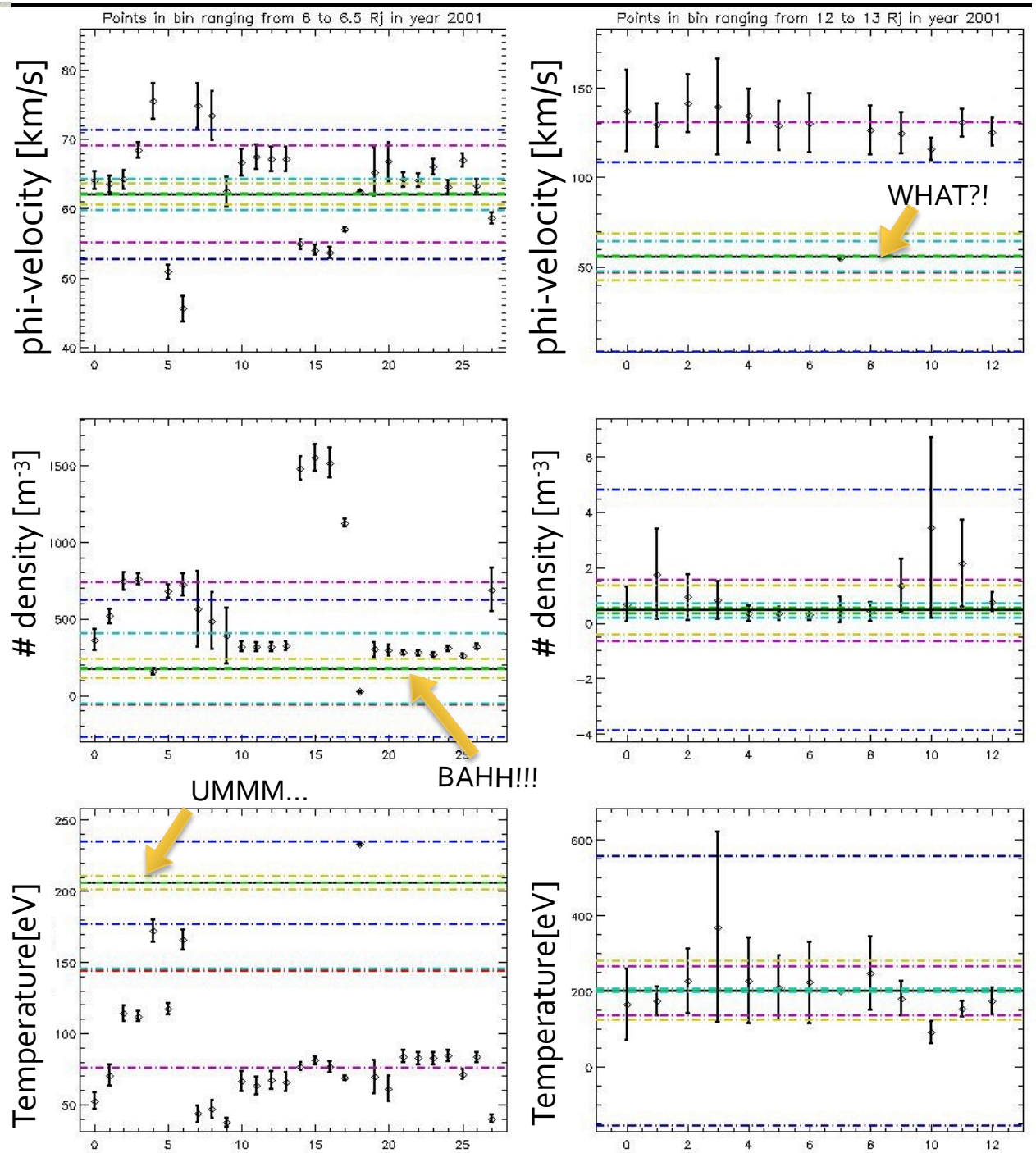
NOTE THE DIMINUITIVE ERROR BARS!!!!!



What are we to make of this?

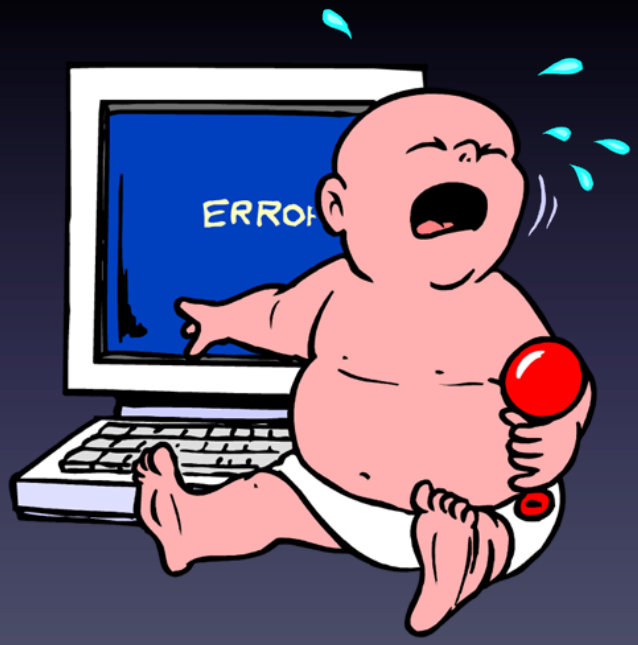
- Difficult to take such small errors seriously
- Thought perhaps it's the way we're binning the points; been using the weighted average of the sample
- Found several different ways to calculate error on this average; made plots to understand relative size of these errors


$\sigma_w^2 = \frac{N}{N-1} \frac{\sum \frac{(x_i-\bar{x})}{\sigma_i^2}}{\sum \frac{1}{\sigma_i^2}}$ (red)
$\sigma_q^2 = \sum_i \sigma_i^2$ (blue) error.
$\sigma_{avg} = \frac{\sum \sigma_i}{N}$ (yellow)
$\sigma_s^2 = \frac{1}{N-1} \sum (x_i - \bar{x})^2$ (purple)
$\sigma_{RQ}^2 = \frac{1}{\sum \left(\frac{1}{\sigma_i^2}\right)}$ (green)
$\sigma_{QM} = \langle x^2 \rangle - \langle x \rangle^2$ (turquoise)


Points in bin ranging from 6 to 6.5 Rj in year 2001
Points in bin ranging from 12 to 13 Rj in year 2001
phi-velocity [km/s]
density [m-3]
Temperature[eV]
WHAT?!
BAHH!!!
UMMM...

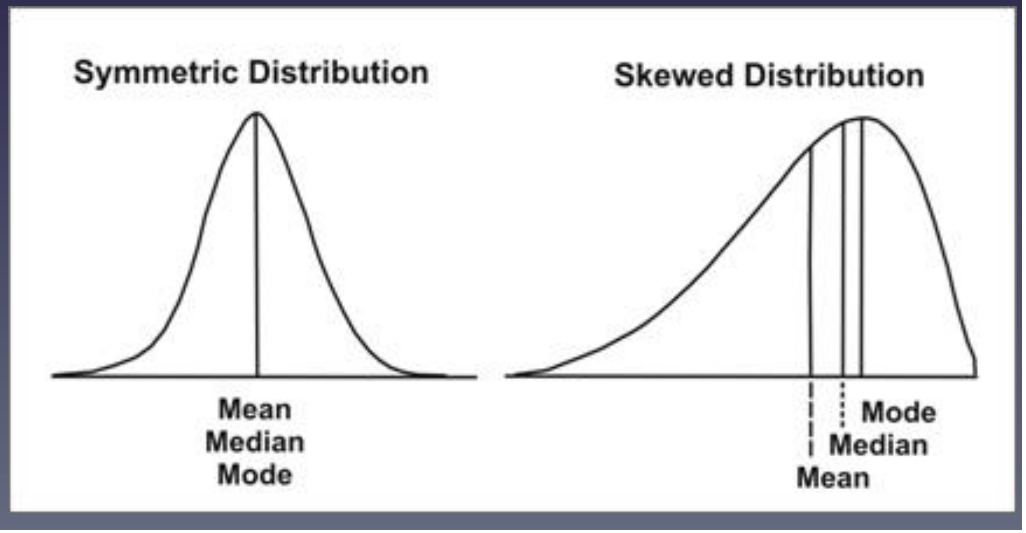
Conclusions from error analysis

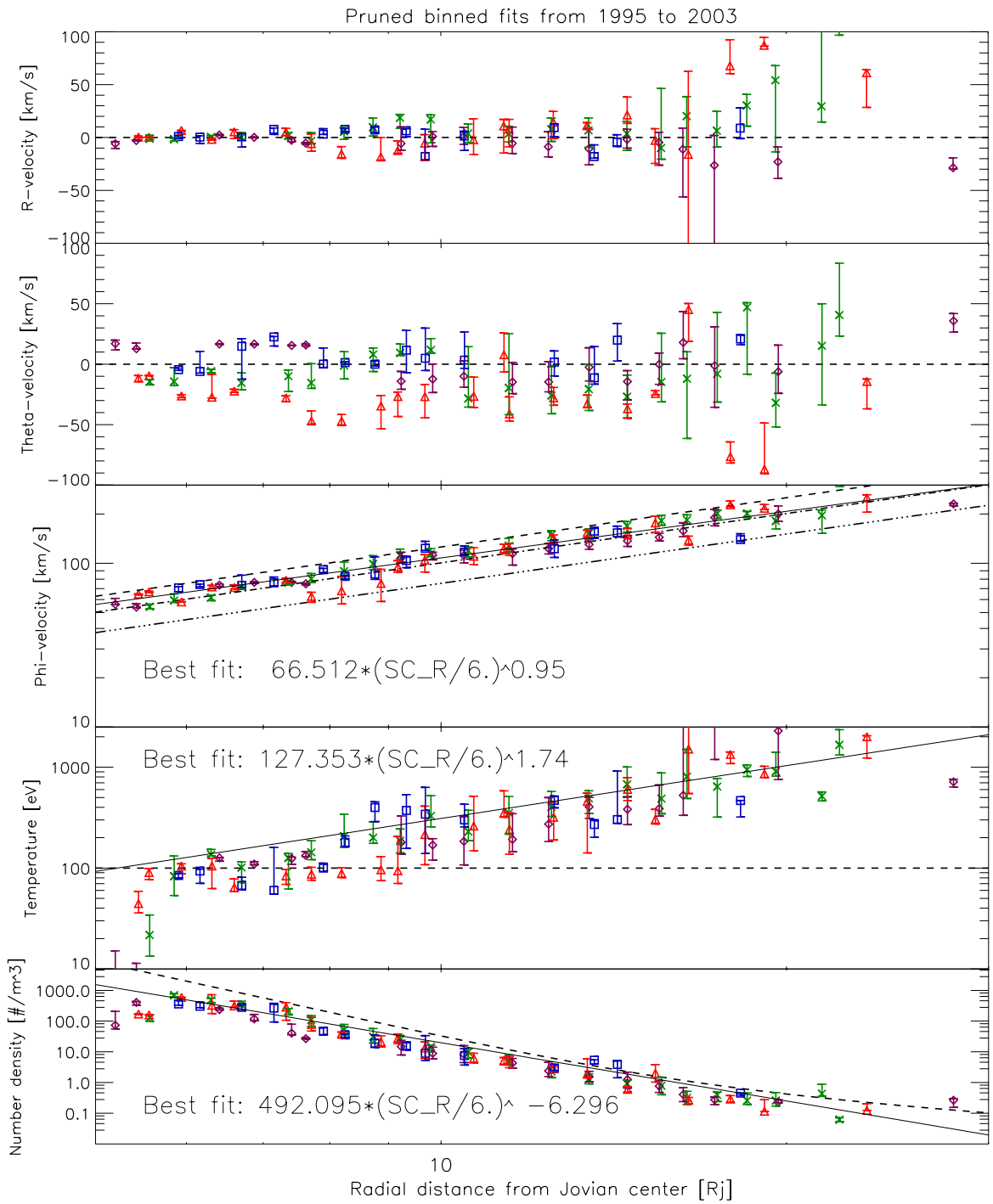
- Weighted mean skews too far to points with small errors; while this is usually desired, with such sparse data, this usually indicates poor fits
- Too many different ways to calculate errors, none of which we can be very confident



Changing it up a bit

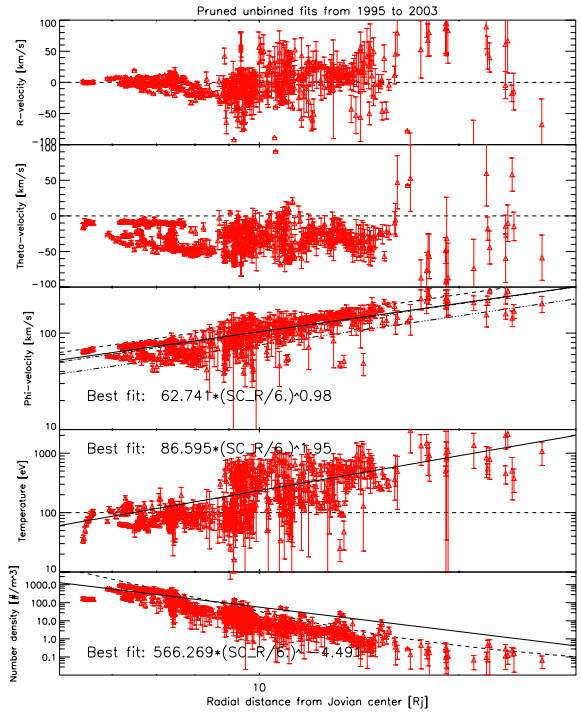
- It seems better, at least when dealing with Galileo data, to bin the points by the MEDIAN, not the mean. (Think about house prices)
- First and third quartiles are able to show asymmetry in the distribution of points, information that averaging might have blurred out



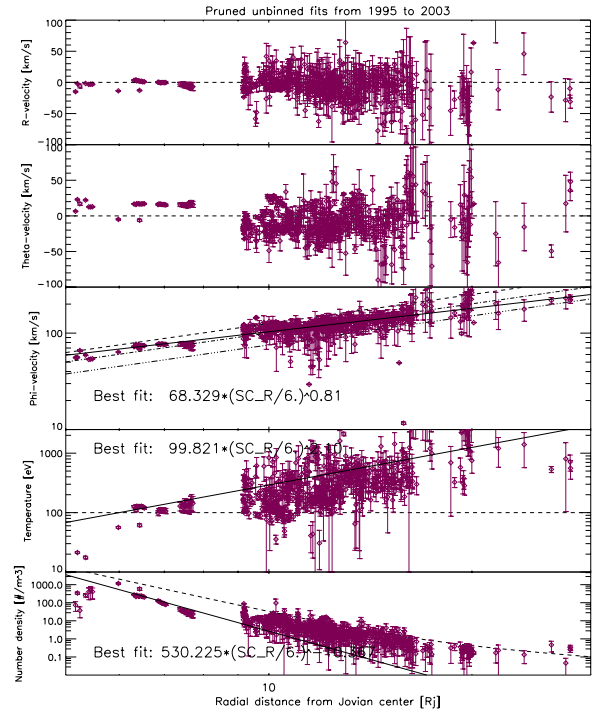

Pruned binned fits from 1995 to 2003
R−velocity [km/s]
Theta−velocity [km/s]
Phi−velocity [km/s]
Best fit: 66.512*(SC_R/6.)^0.95
Temperature [eV]
Best fit: 127.353*(SC_R/6.)^1.74
Number density [#/m^3]
Best fit: 492.095*(SC_R/6.)^ −6.296
Radial distance from Jovian center [Rj]

- Well that's nice and all, but is there maybe a better way to visualize the data???

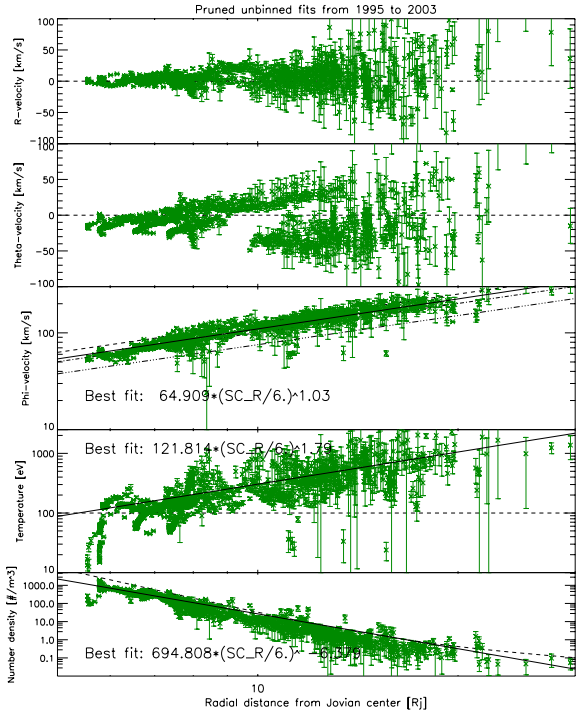
NOON



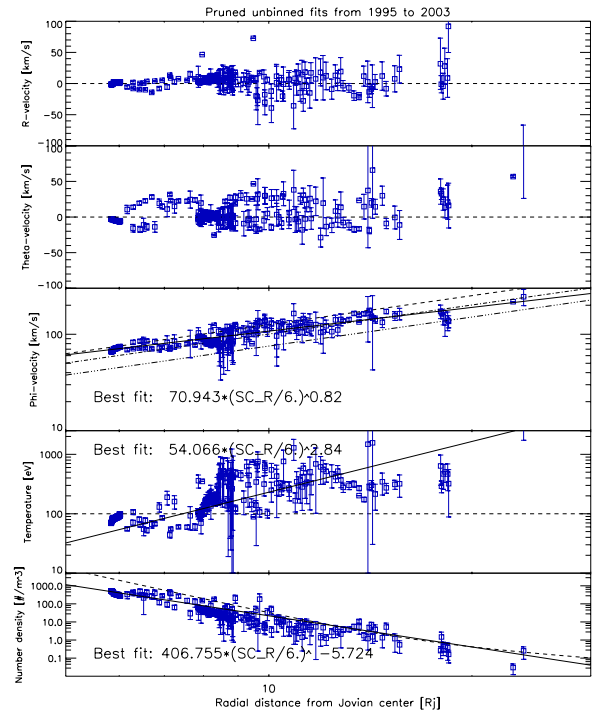
DUSK



DAWN



MIDNIGHT



On no!! We're going 2D!!!

- Galileo only remained within 15^0 of equator
- HOWEVER:

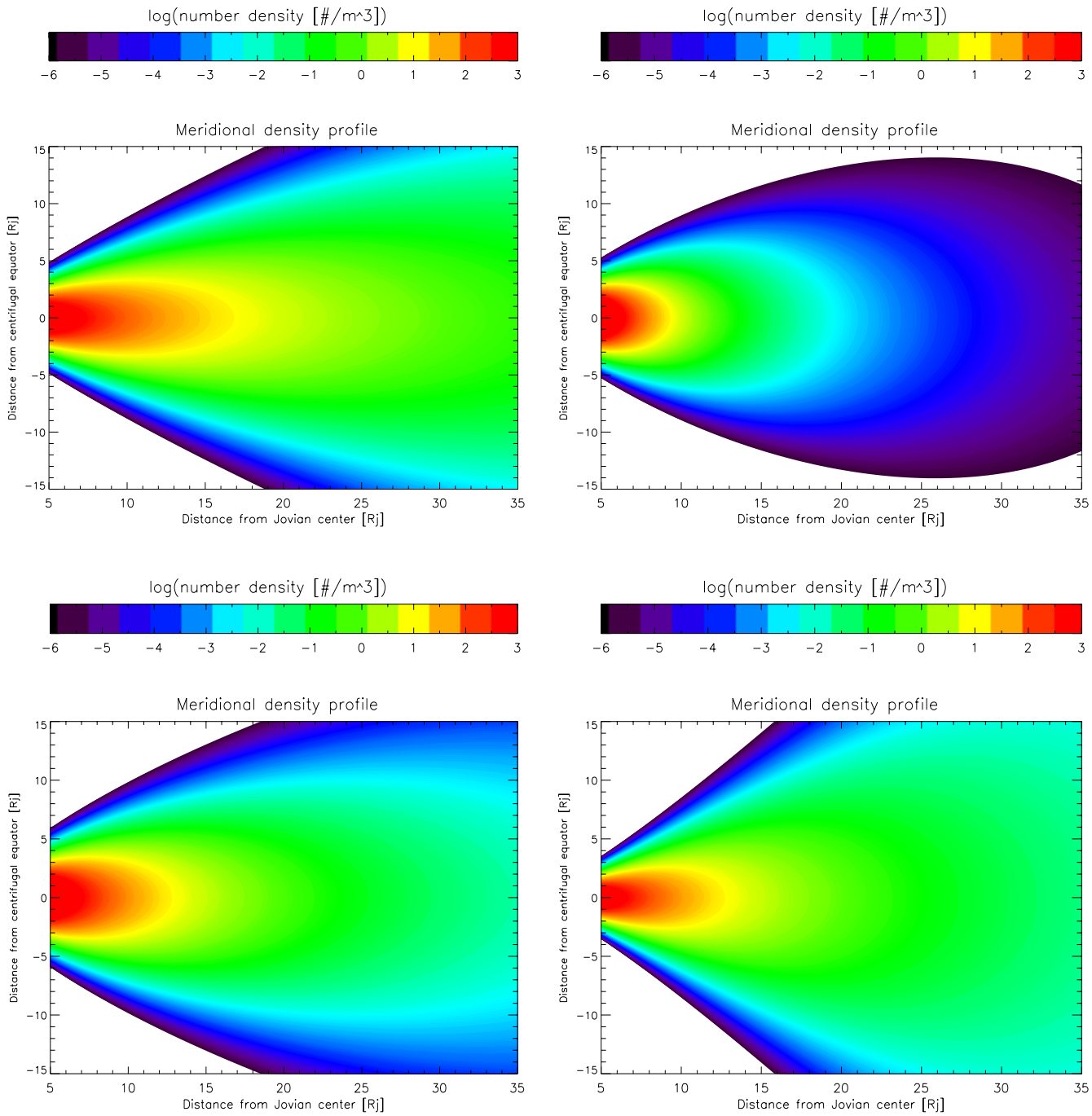
  Rotation→Centrifugal force→Gaussian distribution with peak at equator [*Hill and Michel*, 1976]
- $N(z) = n_0 * \exp-(z/H)^2$, where H essentially only depends on temperature
- Allows us to extrapolate a rough meridional profile from an equatorial profile!

NOON

DUSK

DAWN

MIDNIGHT



Results thus far

- Established pruning process that efficiently weeds out unwanted data points
- See peak in density at ~6 Rj from Io mass loading, then follows radial behavior of Fran's profile, but values are slightly lower
- Seeing subcorotation (~80%)
- Still unclear about presence of significant local time dependence, but initial meridional profiles possibly hinting at something interesting in dusk/midnight sectors; need to better understand possible sources of errors here

Further studies

- Further investigate data for local time/long-term temporal variations
- Compare profiles with theories of mass transport
- See if results from PLS data can be reconciled with results from EPD data/numerical moments

Acknowledgements

- Fran Bagenal and Rob Wilson for their infinite patience and wisdom
- Laila Andersson for giving me the chance to make a plasma ☺
- Everyone at LASP for their assistance whenever I came in to bug them
- The NSF, Marty, Erin and everyone in this REU for making this summer far better than I could have imagined
- Marc the coffee guy for the constant spirit boosts

QUESTIONSSŚSŠŚŚŠ?????????