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Comparison of observed and theoretical Fe L emission from CIE plasmas

M. Carpenter, P. Beiersdorfer, G. V. Brown, H. C. Chen, M. F. Gu, J. G. Jernigan

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We analyze data from the Lawrence Livermore National Lab (LLNL) Electron Beam Ion Trap (EBIT) that simulates a CIE plasma by sweeping the electron beam to approximate a Maxwellian velocity distribution. These results are compared to spectra of confirmed astronomical CIE plasmas (e.g. outer regions of x-ray clusters) observed by XMM/RGS. We utilize the Photon Clean Method (PCM) to quantify these spectra (EBIT and XMM/RGS) in the form of ratios of Fe L lines in the emission complex near 1 keV. The variances of line fluxes are measured with bootstrap methods (Efron 1979). Both of these observations are further compared with theoretical predictions of Fe L line fluxes from APED and similar atomic databases.

Part of this work was performed under the auspices of the U. S. Department of Energy by Lawrence Livermore National Laboratory under Contract W-7405-Eng-48.

Comparison of Observed and Theoretical Fe L Emission from CIE Plasmas

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J. G. Jernigan

Overview

- Introduction to the Photon Clean Method (PCM)
- An Example : XMM/RGS spectrum of Ab Dor
- PCM algorithm internals
- Analysis Modes: Phase I and Phase II solutions
- Bootstrap Methods of error analysis
- Summary

Photon Clean Method: Principles

- Analysis uses individual photon *events*, not binned spectra
- Fitting models to data is achieved through weighted random trial-and-error with feedback
- Individual photons span parameter and model space, and are taken to be the parameters
- Iteration until quantitative convergence based on a Kolmogorov-Smirnov (KS) test
- Has analysis modes which allow divergence from strict adherence to model to estimate differences between model and observed data

Photon Clean Method: Event-Mode Data and Model

Both data and model are in form of Event Lists (photon lists)

Monte-Carlo methods are used to generate simulated photons

Generation parameters for each photon are recorded → Each photon is treated as independent parameter

Single simulated photon:

$\lambda_{spec}(\AA)$	$\lambda_{sim}(\AA)$	$log(T_{MK})$	T_{keV}	Type	Transition
18.990	18.967	6.796	0.538	O VIII	$2p\ ^2P_{3/2} \rightarrow 1s\ ^2S_{1/2}$

PCM analyzes Simulated Detected λ_{sim} or E_{sim}

Observed Data (Event Form) $\lambda_{observed}(\mathring{A})$	Simulated Data $\lambda_{sim}(\mathring{A})$
15.020	18.990
14.961	12.290
7.622	10.761
17.711	12.807
21.549	17.930
16.062	12.238
14.376	13.470
13.298	11.510
12.833	28.279
17.801	13.105
21.217	17.037
⋮	⋮

← Data representation inside program

Target: AB Dor (K1 IV-V), a young active star and XMM/RGS calibration target

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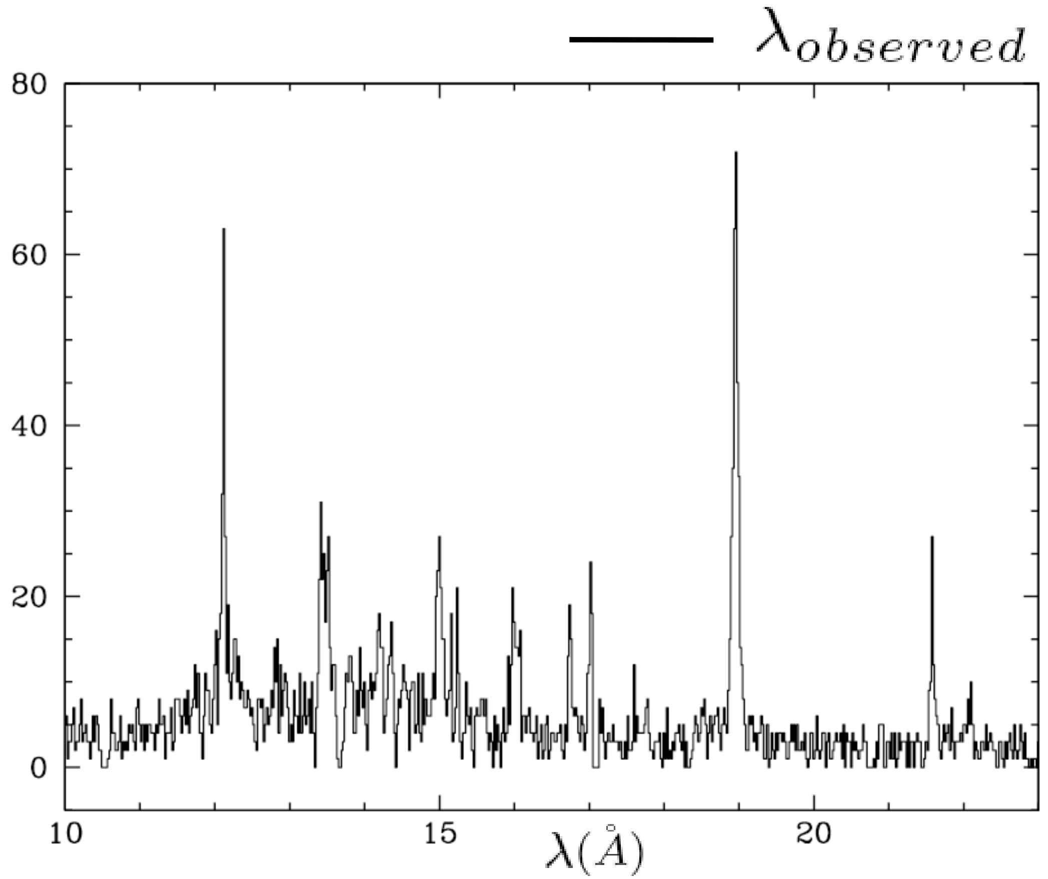
The Photon Clean Method algorithm analyzes and outputs models as event lists
***** All histograms in this talk are for visualization only**



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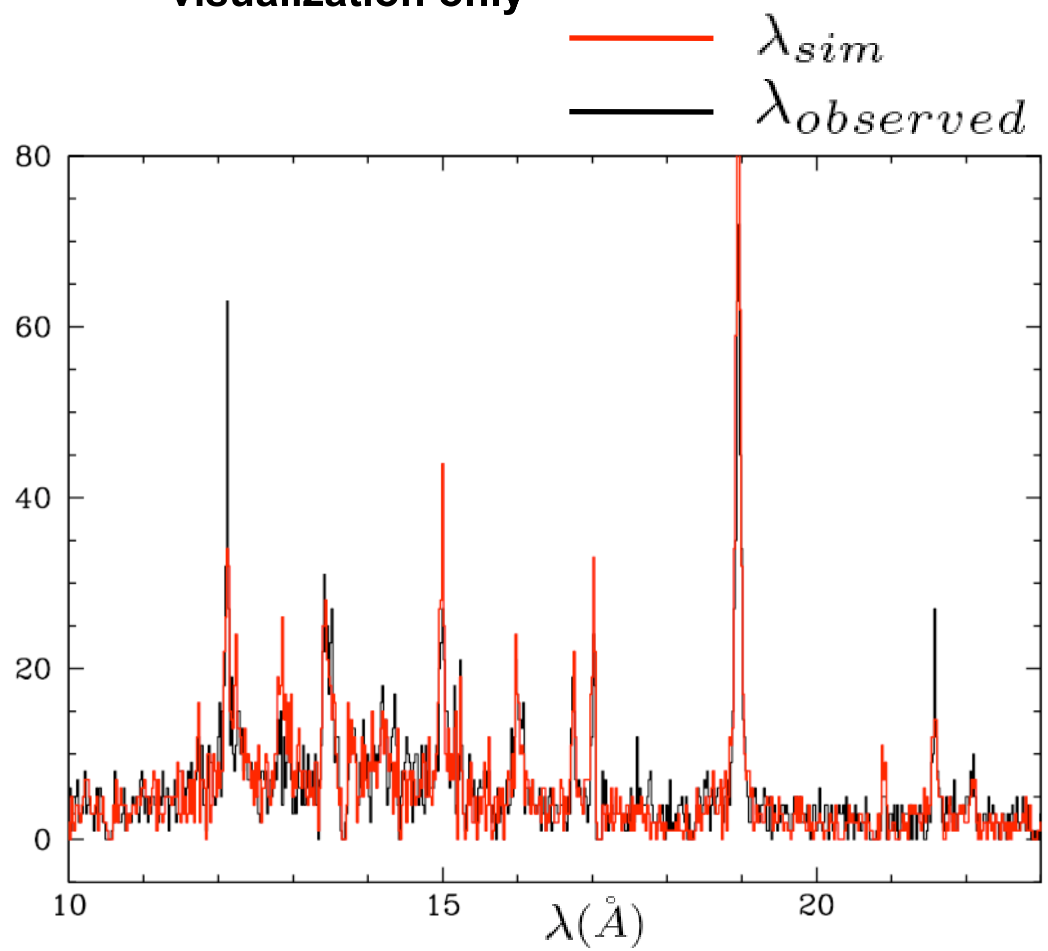

Spectral λ: "Perfect" information

Each photon in a simulated observation has ideal (model) wavelength and the wavelength of detection

λ_{spec} == "spectral wavelength" from plasma model

Phot.#	$\lambda_{spec}(\mathring{A})$	$\lambda_{sim}(\mathring{A})$	$log(T_{MK})$	Type
1	18.990	18.967	6.796	O VIII
2	12.903	12.308	6.839	Continuum
3	10.762	10.849	7.096	Ni XXIII
4	12.806	12.846	7.129	Fe XX
5	17.930	18.037	6.662	Continuum
6	12.238	12.284	7.030	Fe XXI
⋮	⋮	⋮	⋮	⋮

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A histogram of the simulated photons' spectral wavelengths produces sharp lines

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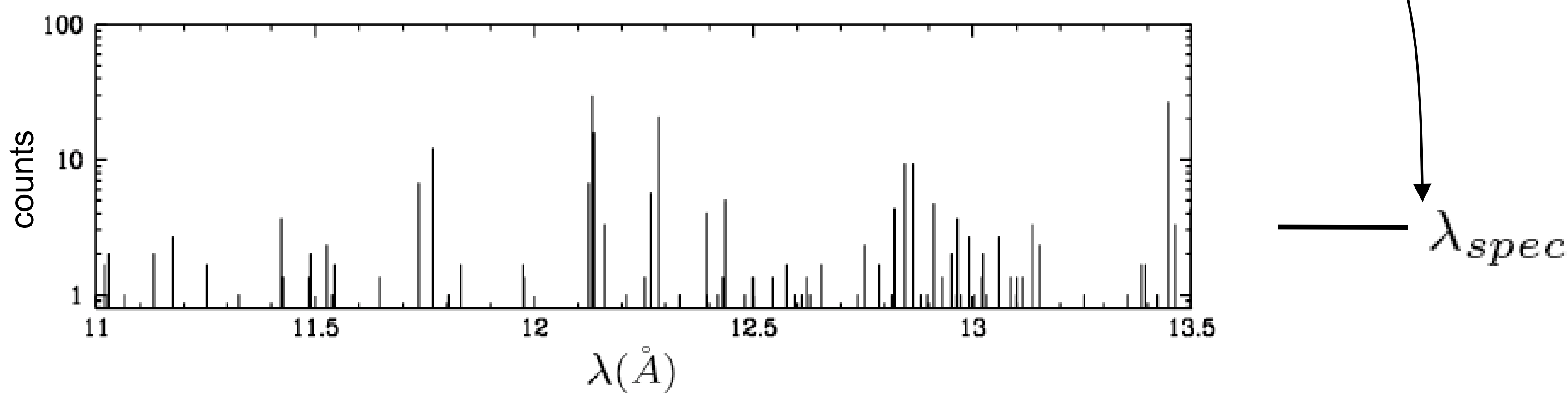

Adding detector response

Photons are stochastically assigned a “detected wavelength”

λ_{sim} == “simulated wavelength,” includes redshift, detector and thermal broadening

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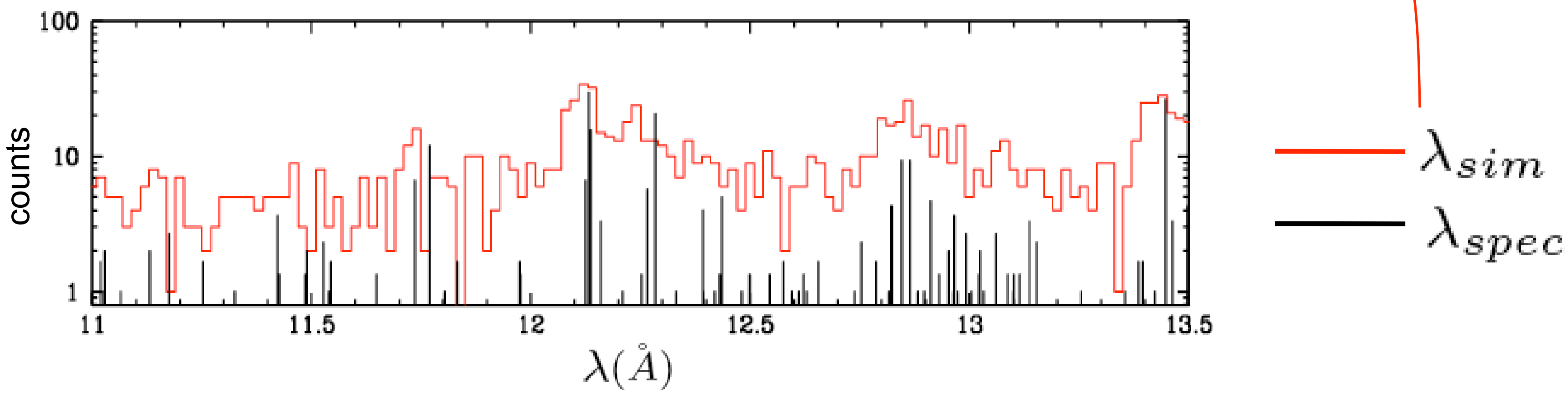

Distribution of Model Parameters

Each photon has individual parameter values which may be taken as elements of the parameter distribution

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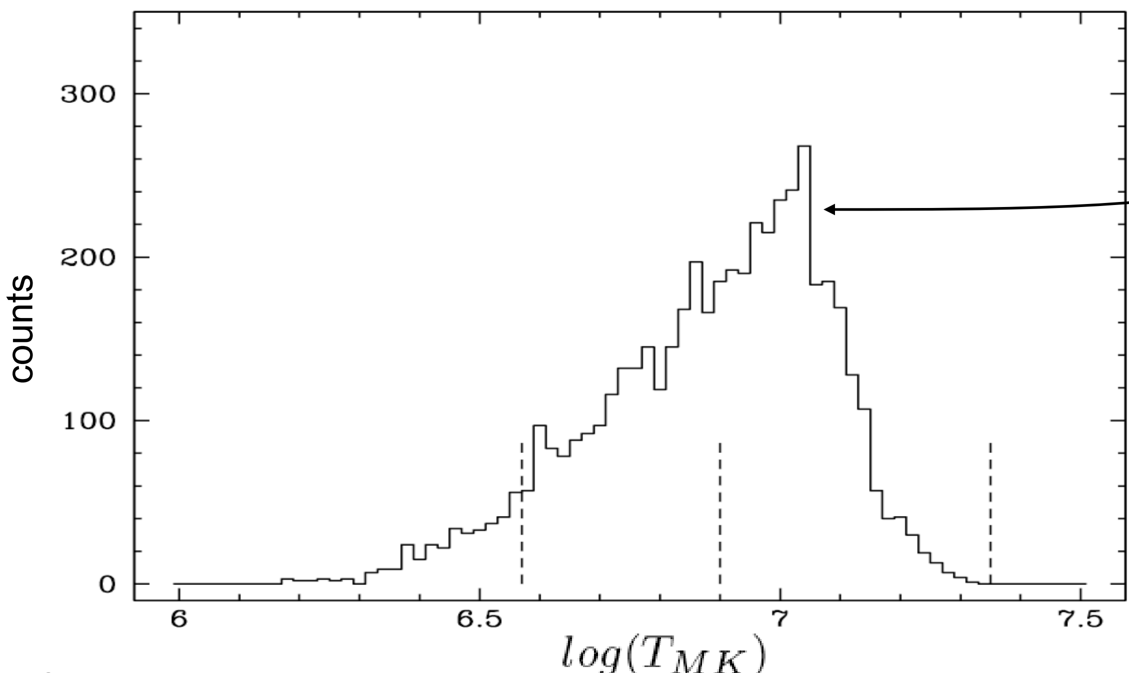
The temperature profile of AB Dor is complex; previous fits used 3-temperature or EMD models

AB Dor Emission Measure Distribution

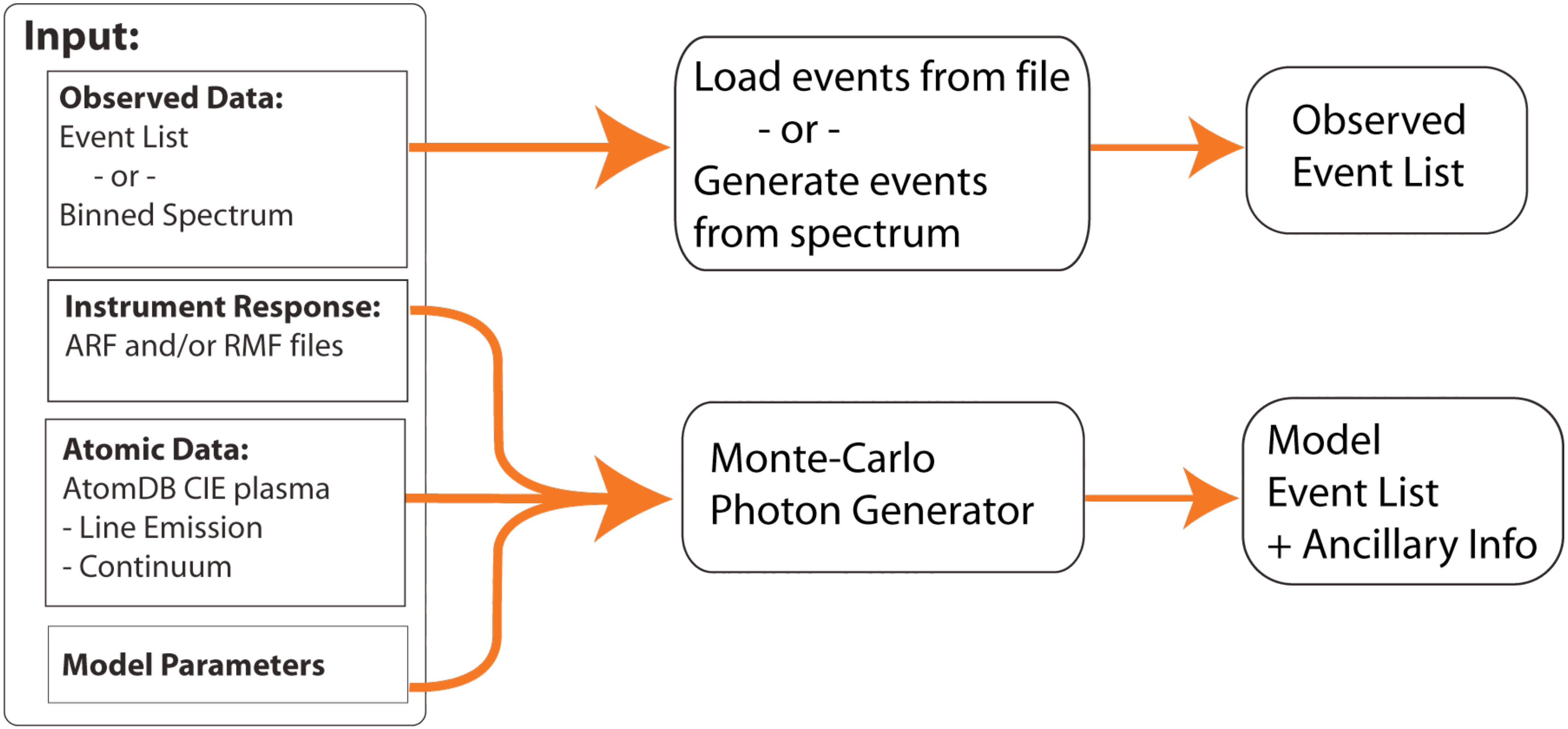


Histogram of PCM solution

Three vertical dashed lines are 3-T XSPEC fit from Sanz-Forcada, Maggio and Micela (2003)

PCM Algorithm Progression

Start: Generate initial model + simulated detected photons from input parameter distribution



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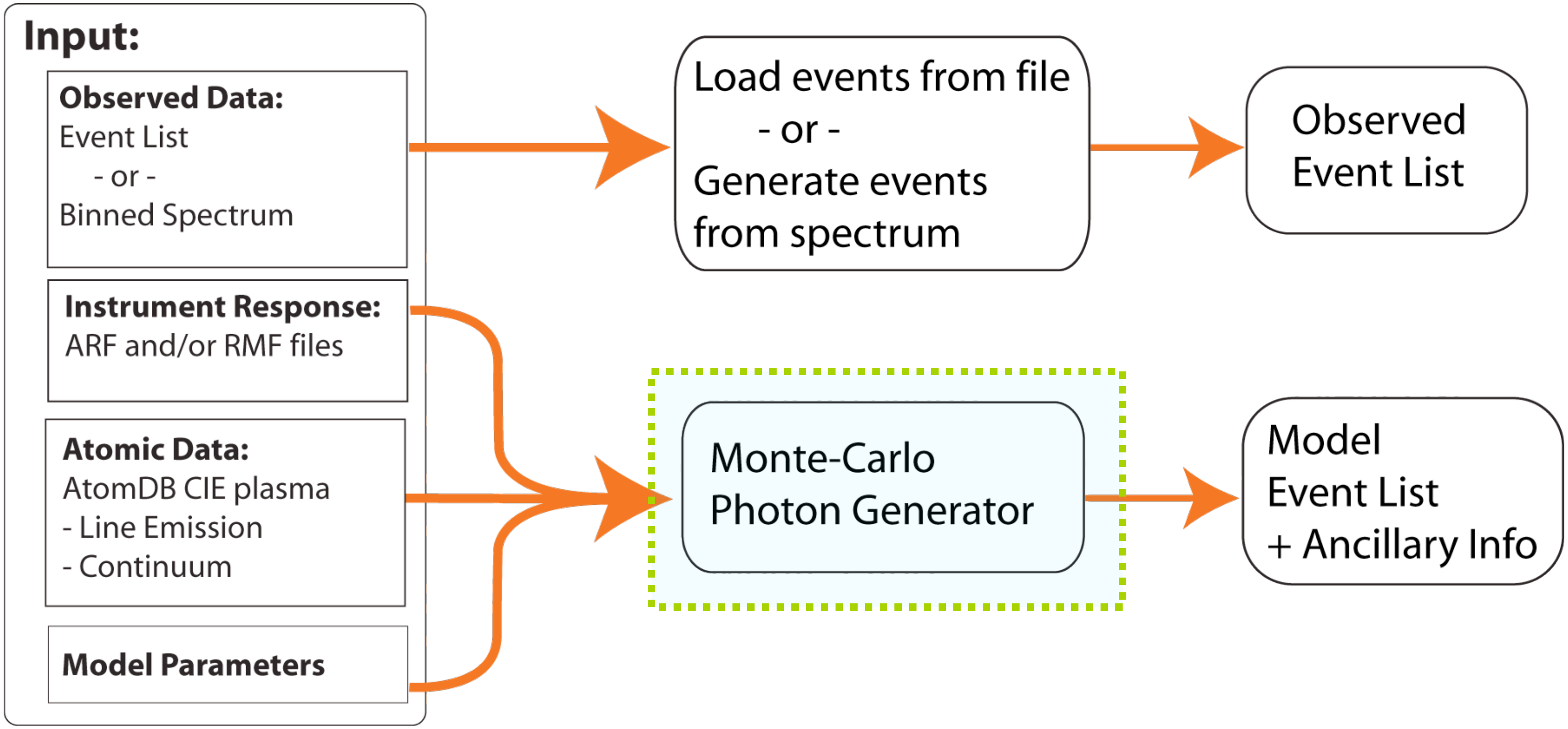
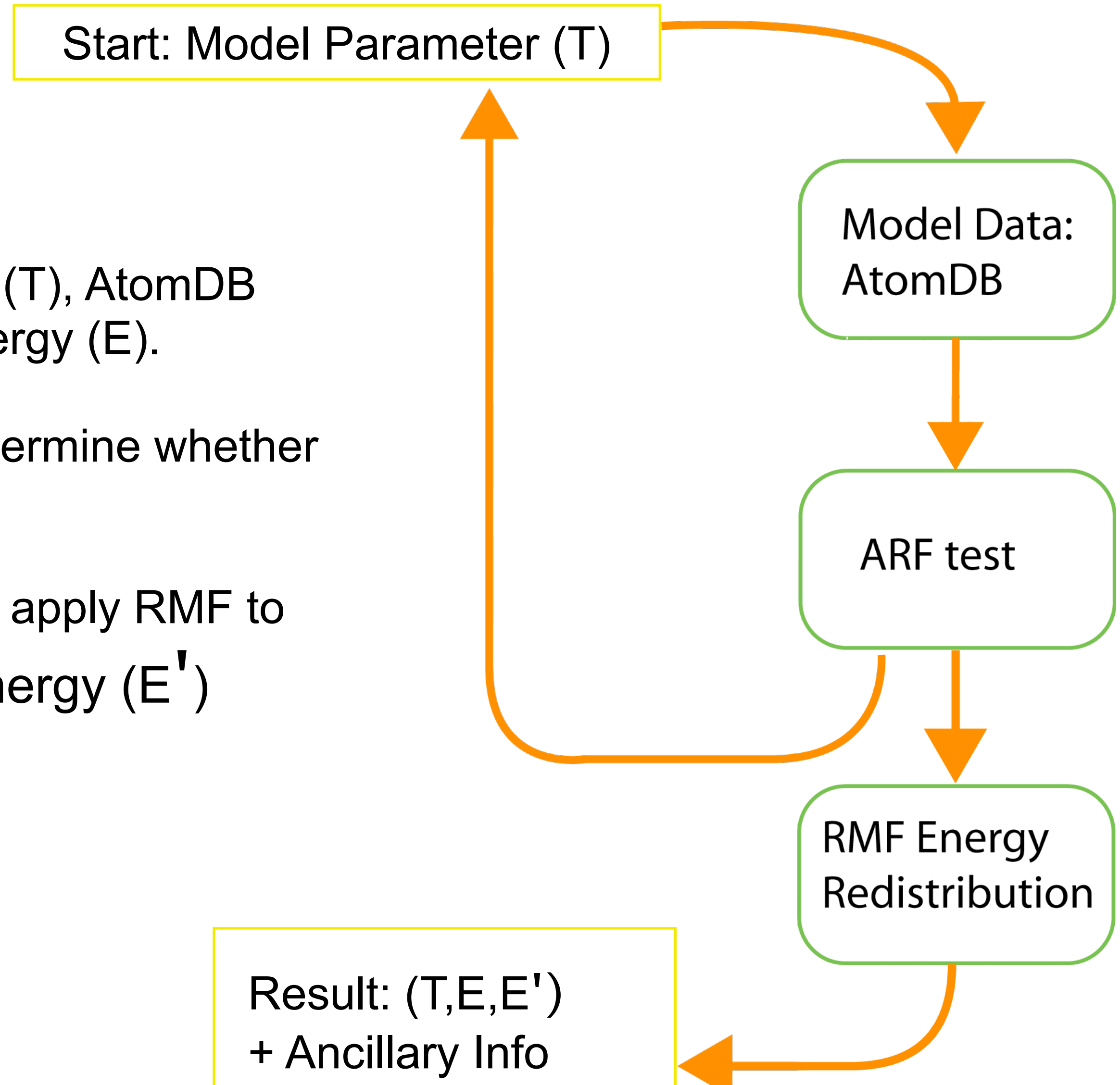


Photon Generator



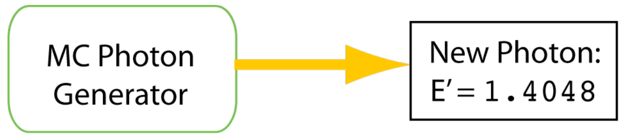
For CIE Plasma:

- Given a temperature (T), AtomDB generates spectral energy (E).

- Apply ARF test to determine whether photon is detected

- If photon is detected, apply RMF to determine detected energy (E')

PCM Algorithm: Iterate with Feedback



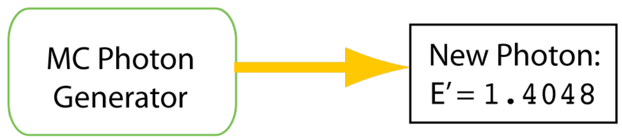
Model E_{sim}

⋮
2.4903
1.6309
0.9901
1.4052
1.1385
1.6027
3.7938
2.4429
⋮

Iteration:

- Generate 1 detected photon

PCM Algorithm: Iterate with Feedback



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- Replace 1 random photon from model with new photon (E,E',T)

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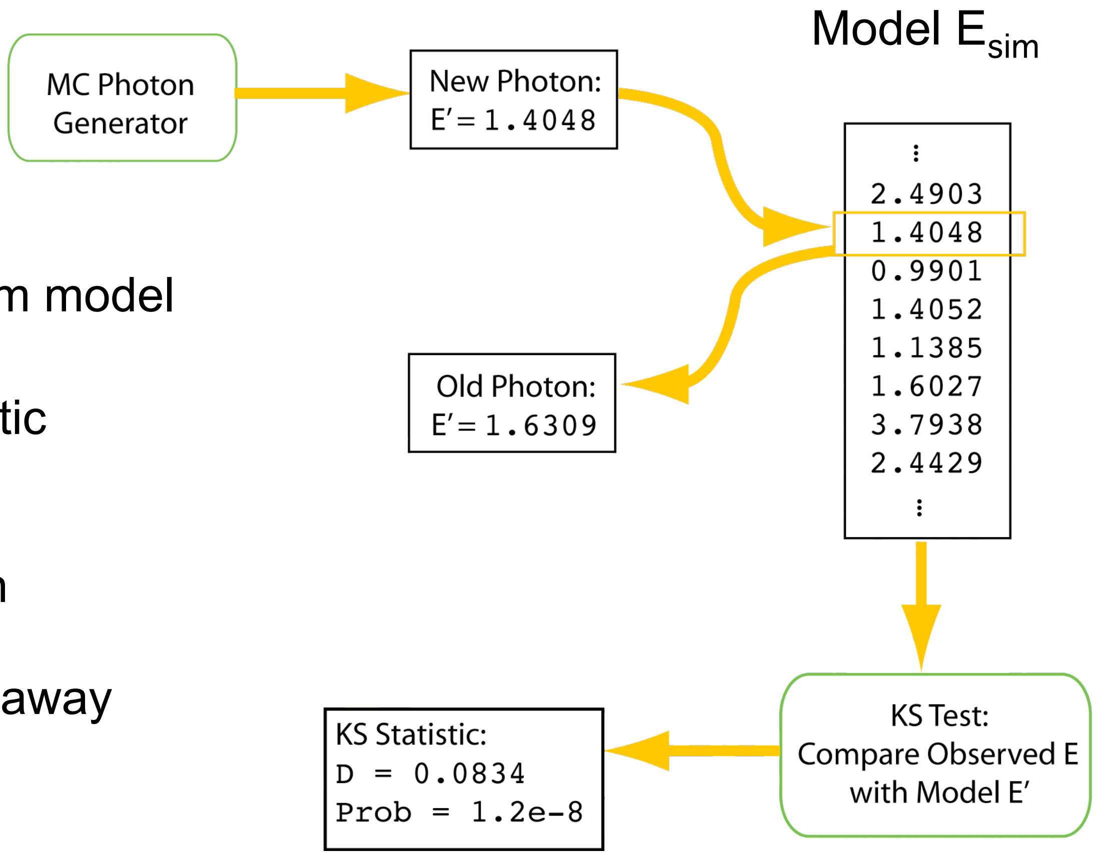


Iteration:

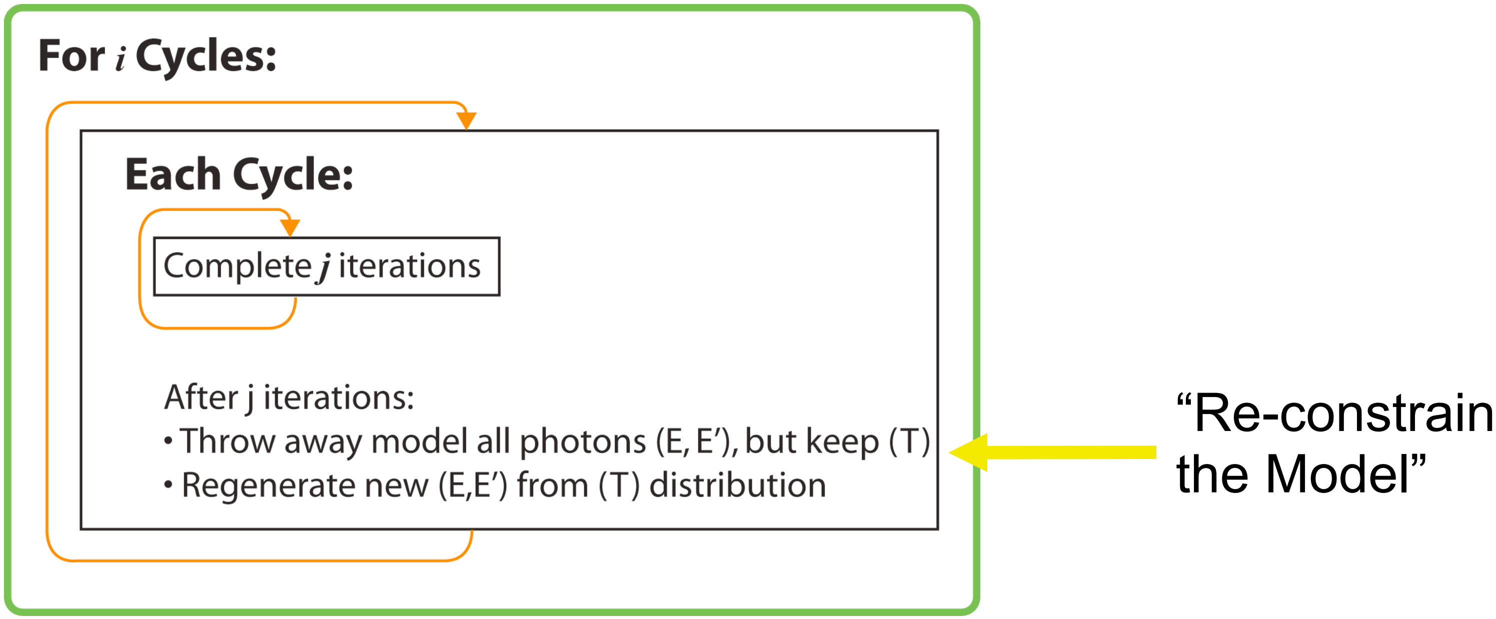
- Generate 1 detected photon
- Replace 1 random photon from model with new photon (E,E',T)
- Compute KS probability statistic

Feedback Test:

If KS probability improves with new photon, keep it;
Otherwise, throw new photon away and keep old photon

PCM Analysis Modes

Phase I: Constrained Convergence

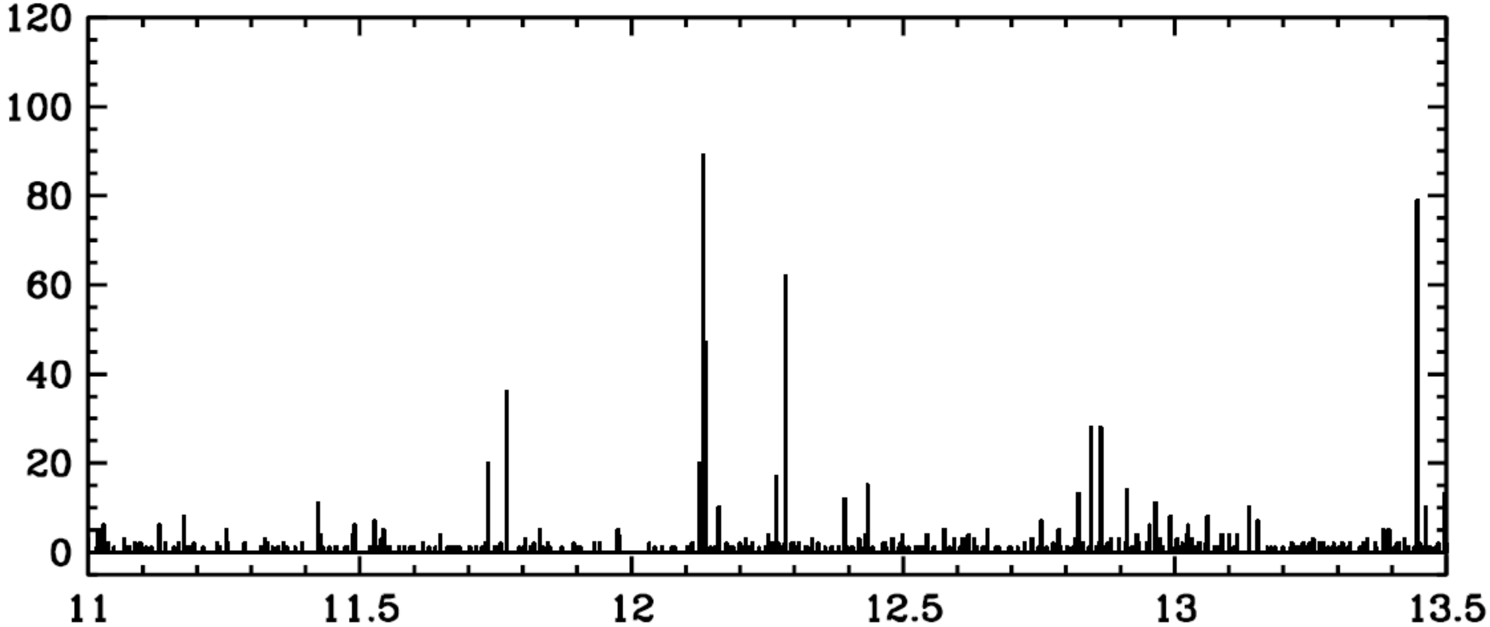


• Generates a solution which is consistent with a physically realizable model

PCM Analysis Modes

Phase II: Un-Constrained Convergence:

• Iterate until KS probability reaches cutoff value, with Monte-Carlo Markov Chain weighting
• Photon distribution is not constrained to model probabilities
• Allows individual spectral features to be modified to produce best-fit solution



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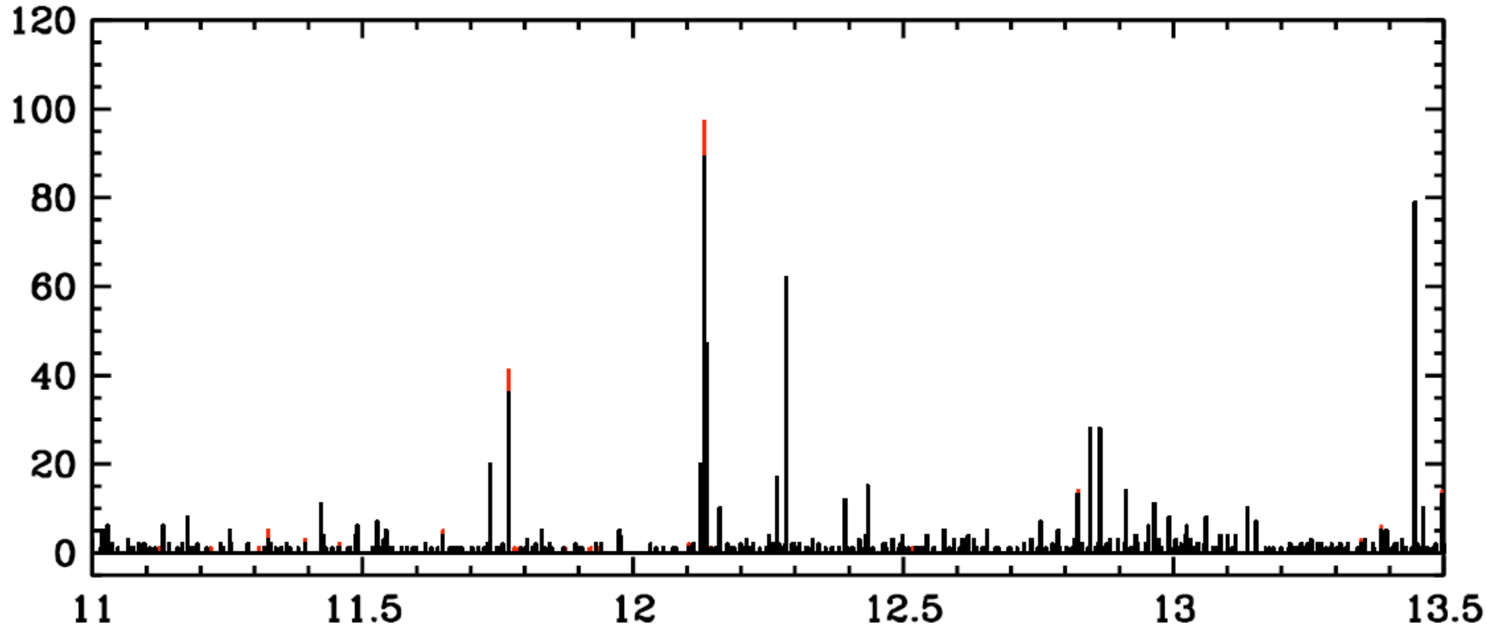
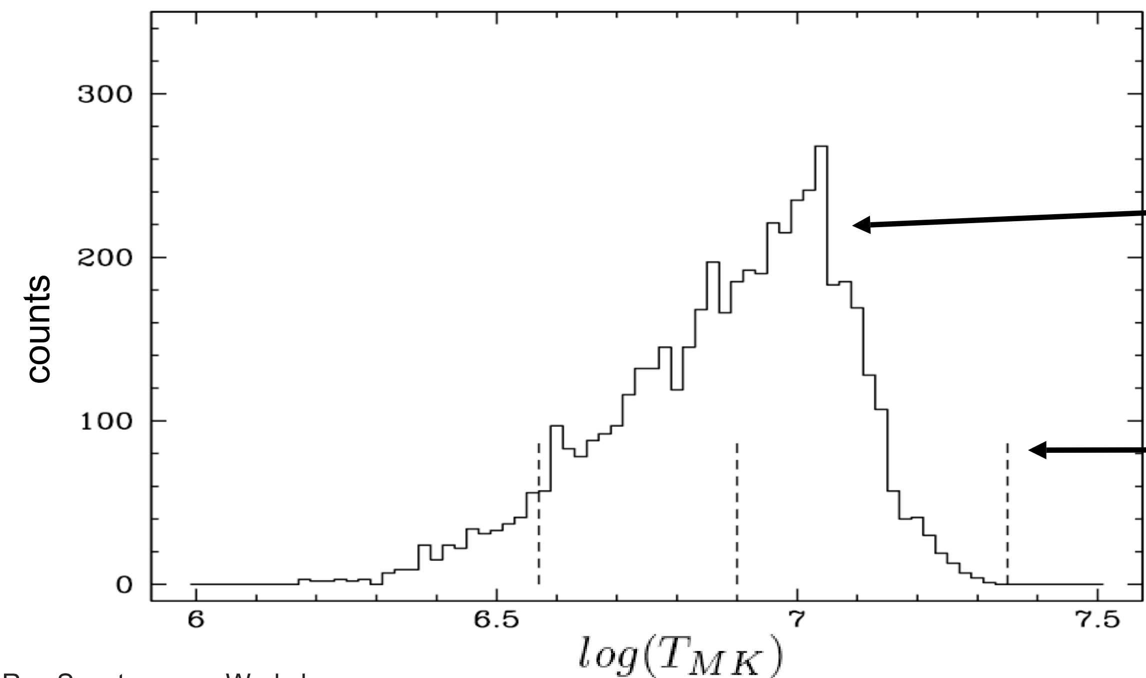


Determining Variation in Many-Parameter Models

Low-dimensionality models with few degrees of freedom may be quantified using Chi-square test which has a well-defined error methodology. PCM is appropriate for models of high dimensionality where every photon is a free parameter.

For error determination we use distribution-driven re-sampling methods

⇒ Bootstrap Method



PCM solution

XPSEC solution

Bootstrap Re-Sampling

Method:

1) Randomly resample input data set with substitution to create new data set
2) Perform analysis on new data set to produce new outcome
3) Repeat for $n >> 1$ re-sampled data sets

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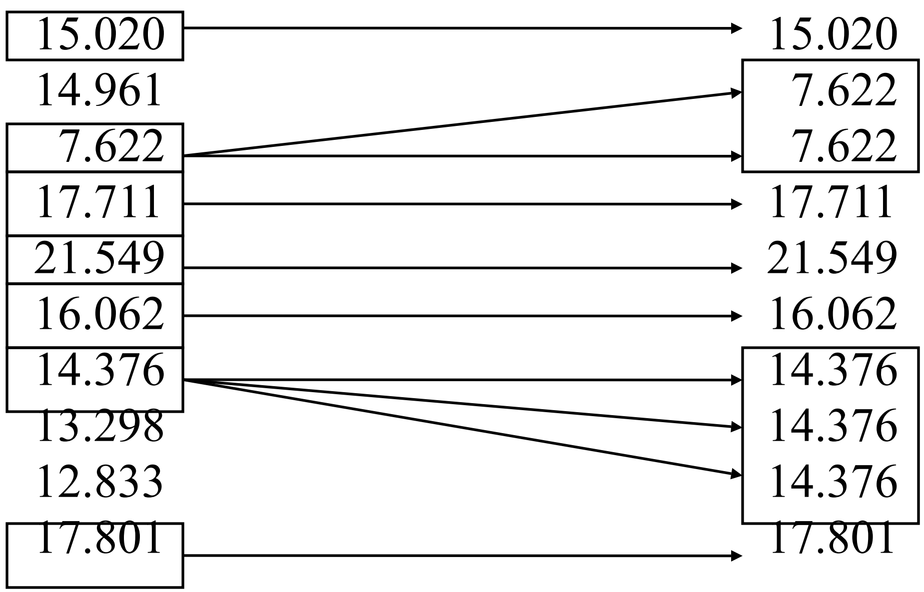
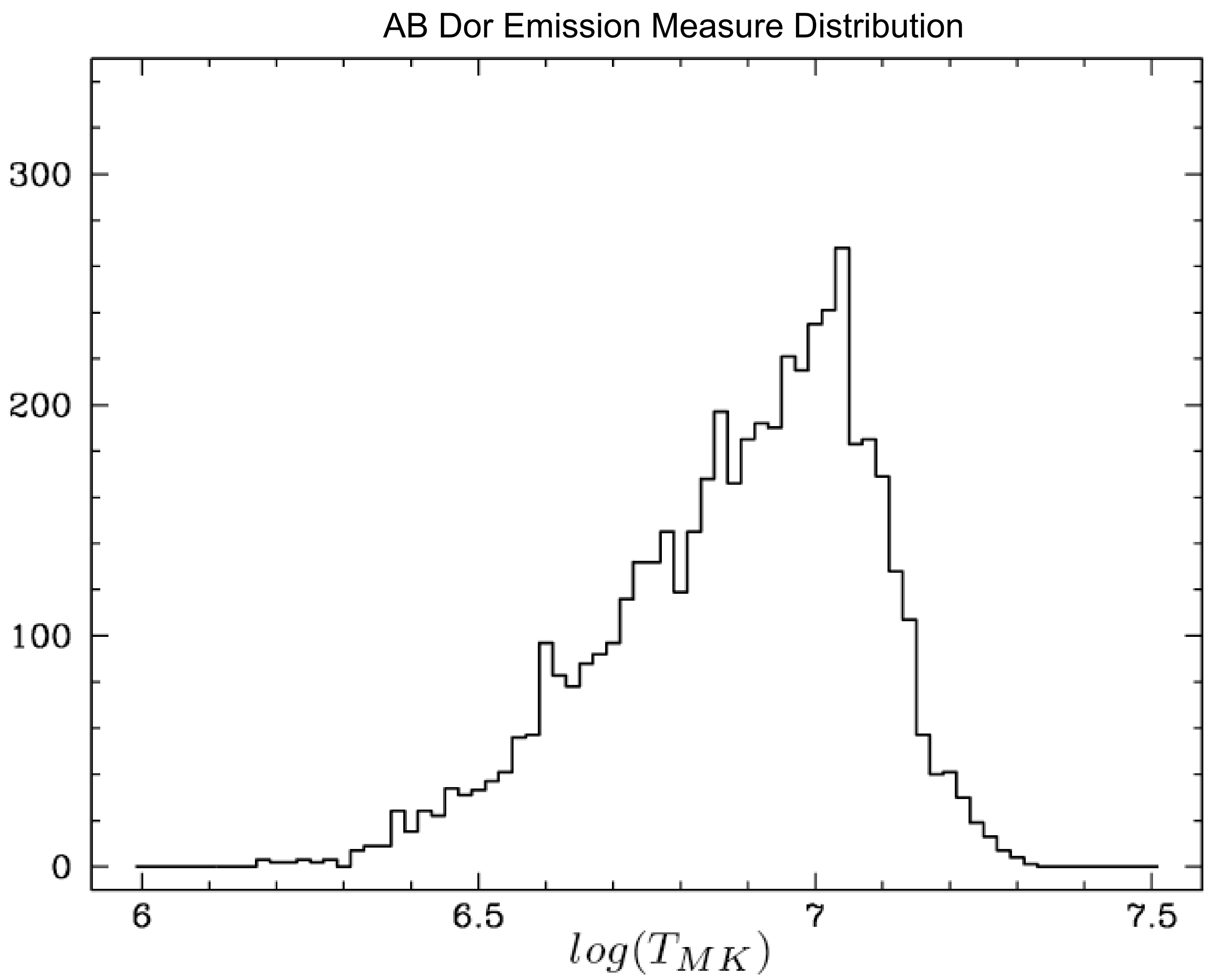
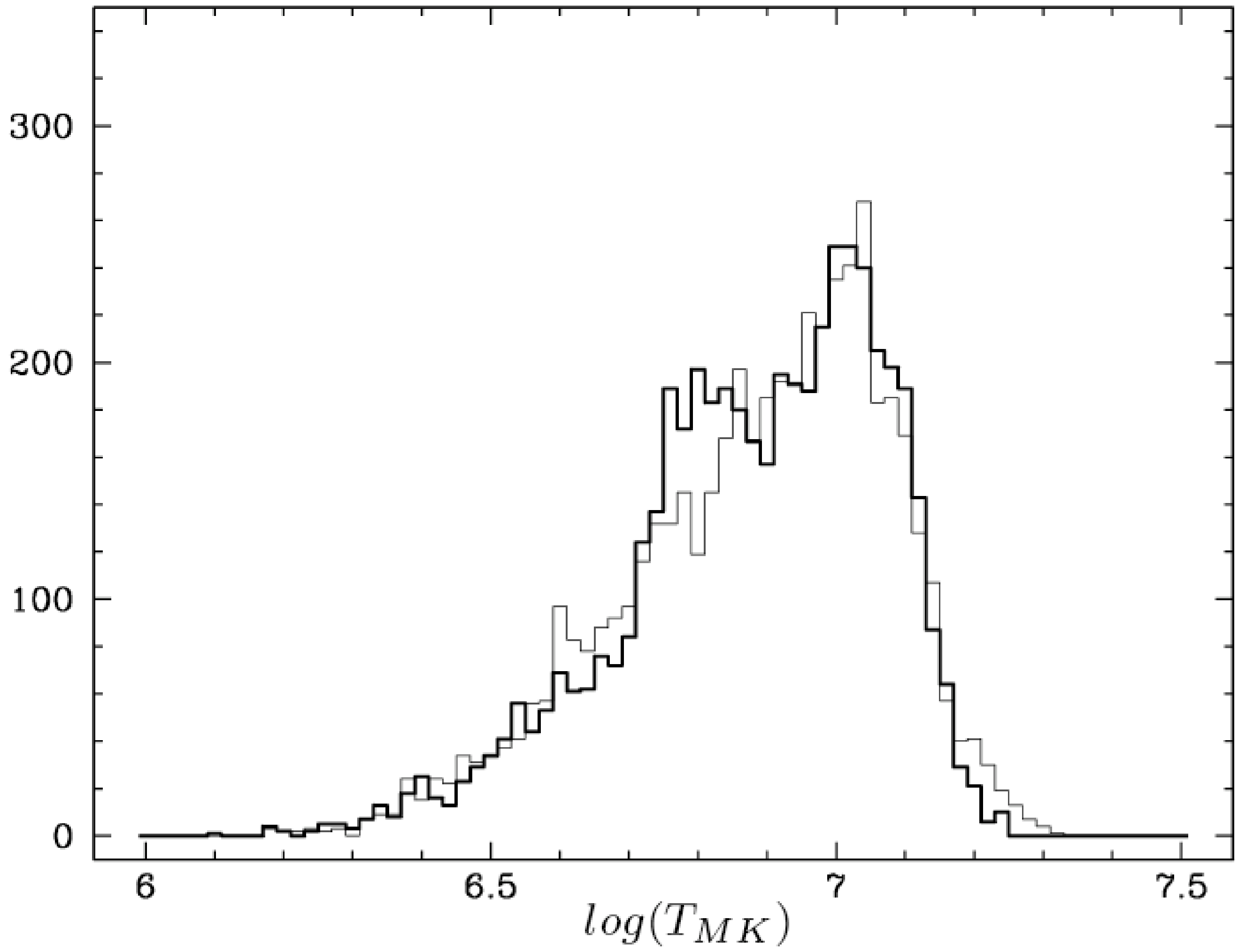


Bootstrap Results



Bootstrap Results

AB Dor Emission Measure Distribution



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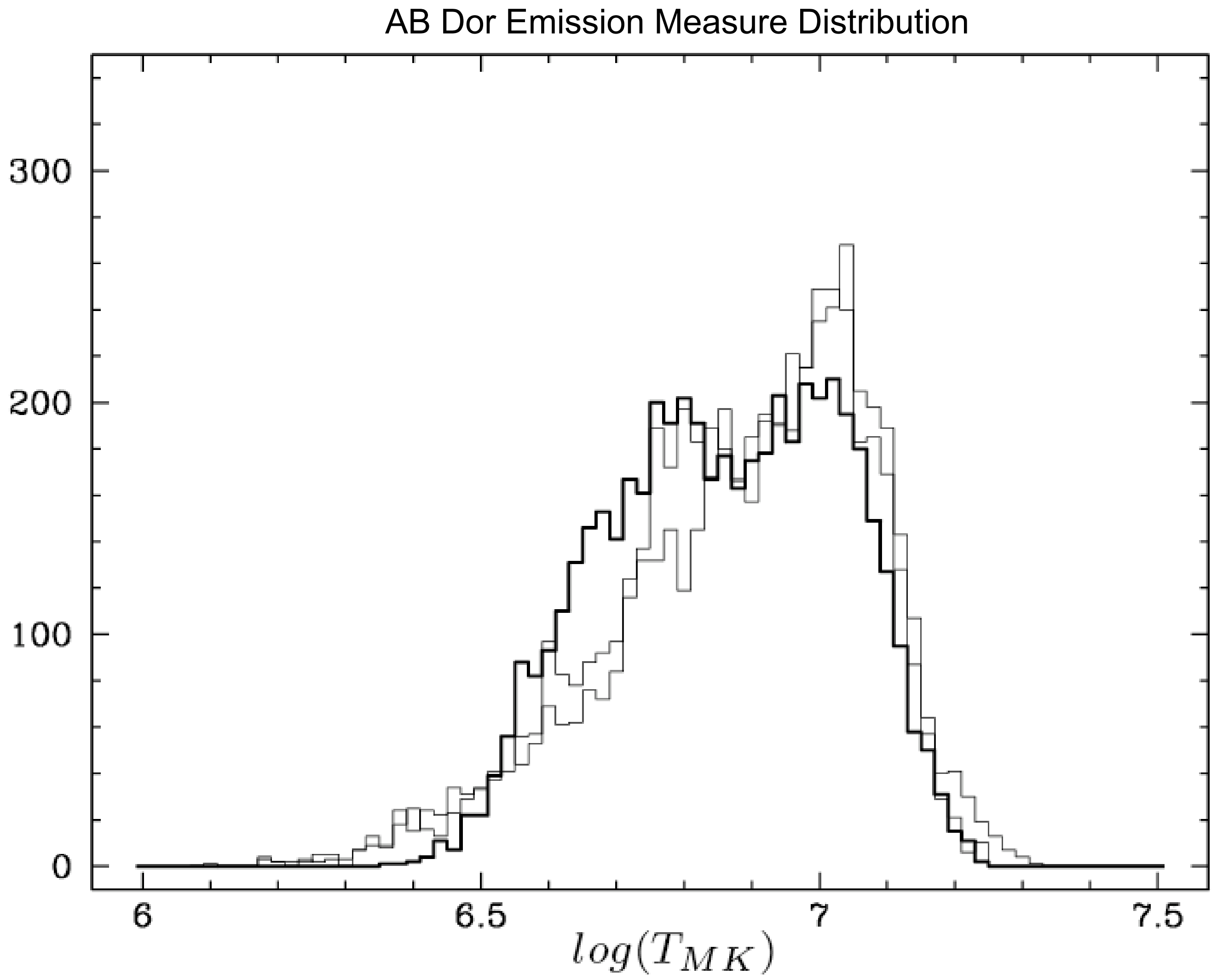

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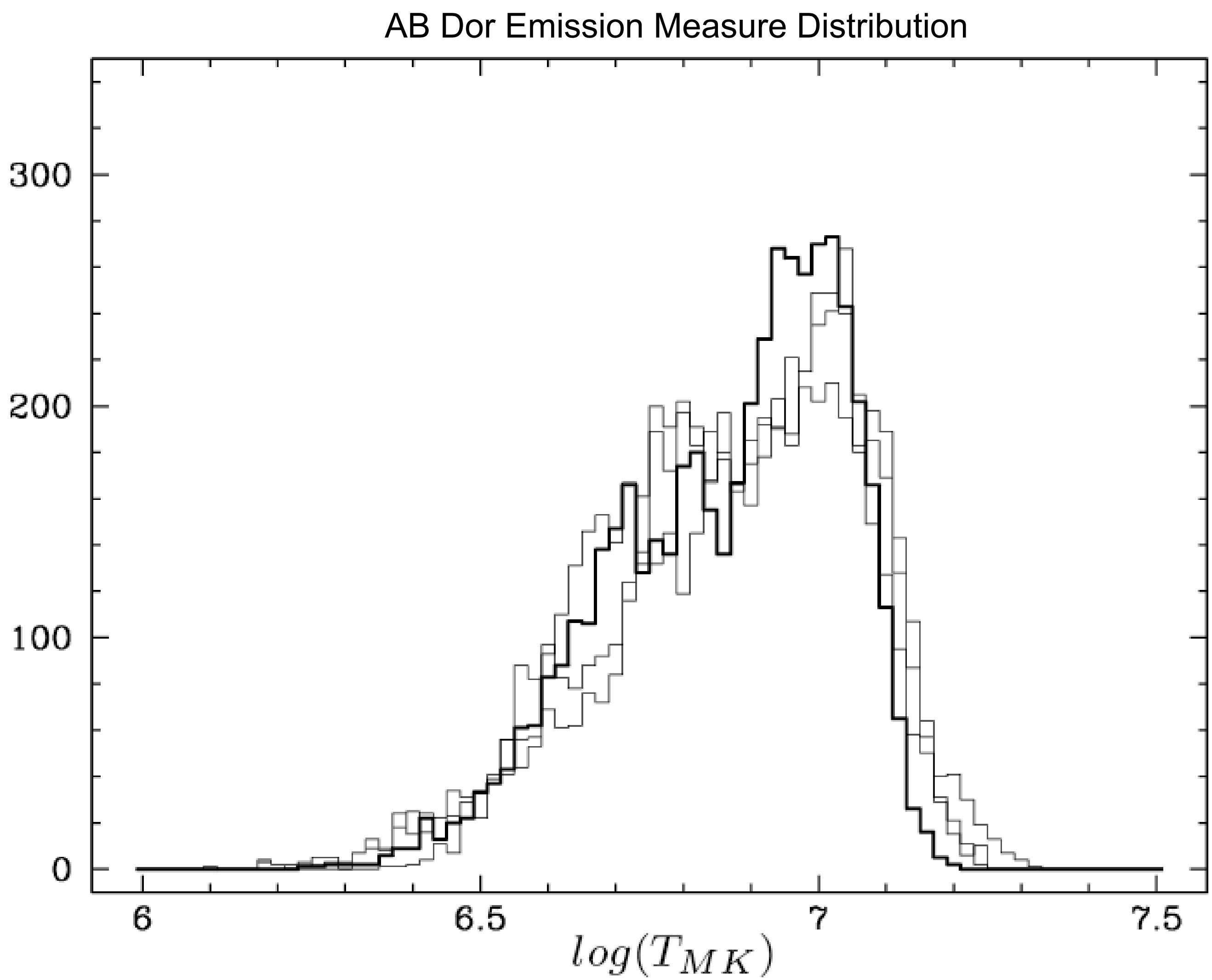

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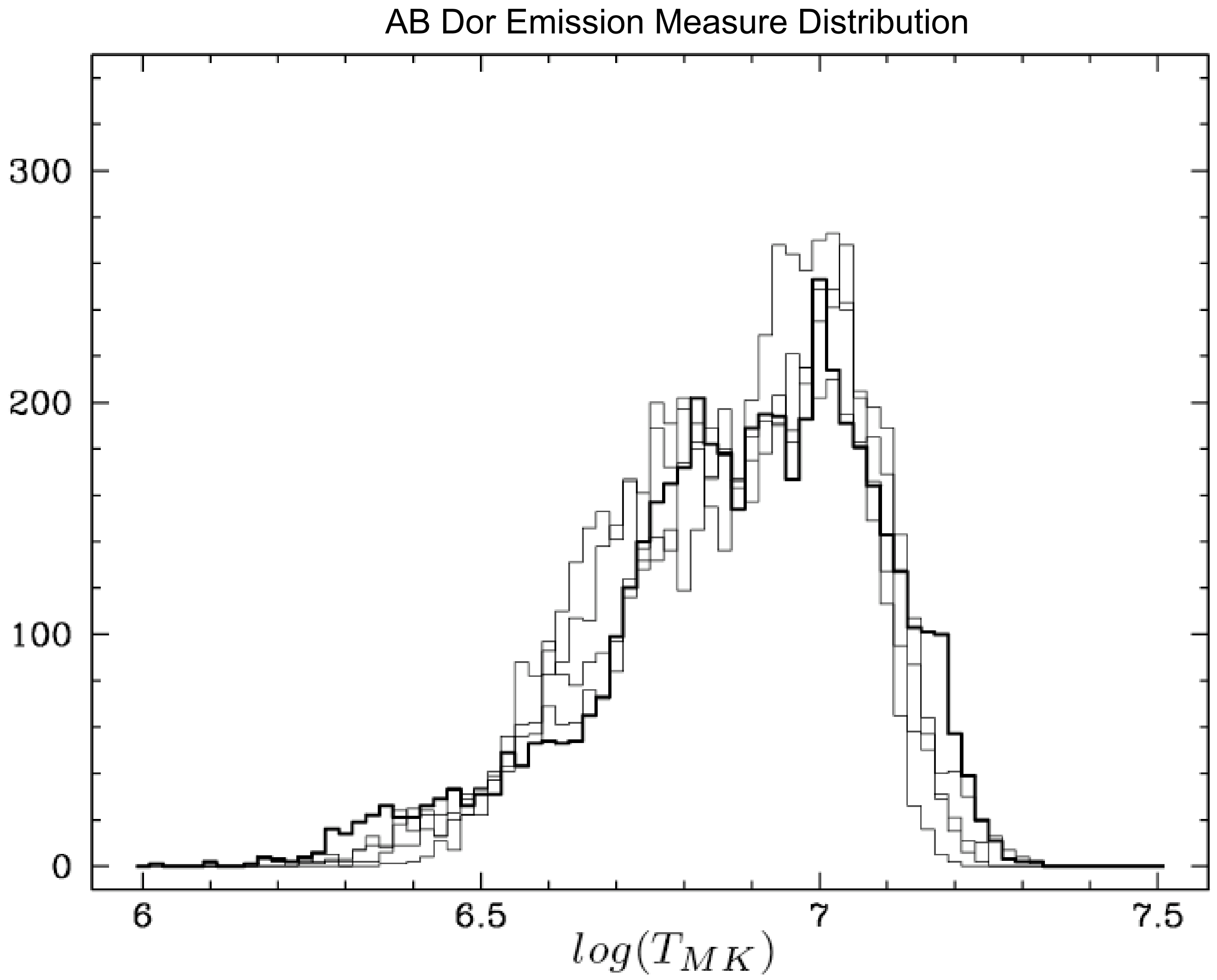
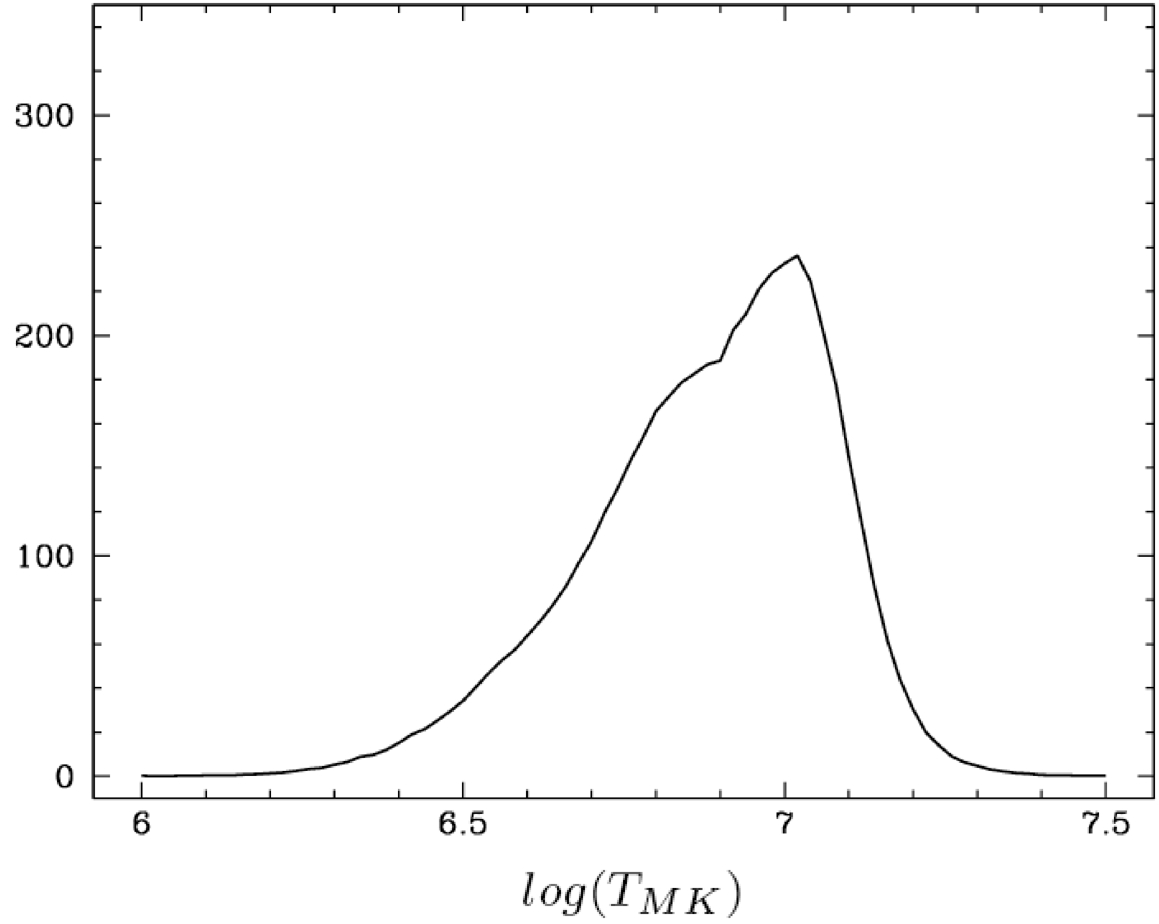


Interpreting the Bootstrap

The variations in the bootstrap solutions estimate errors

The Arithmetic mean of all distributions is plotted as solid line

AB Dor Emission Measure Distribution



Interpreting the Bootstrap

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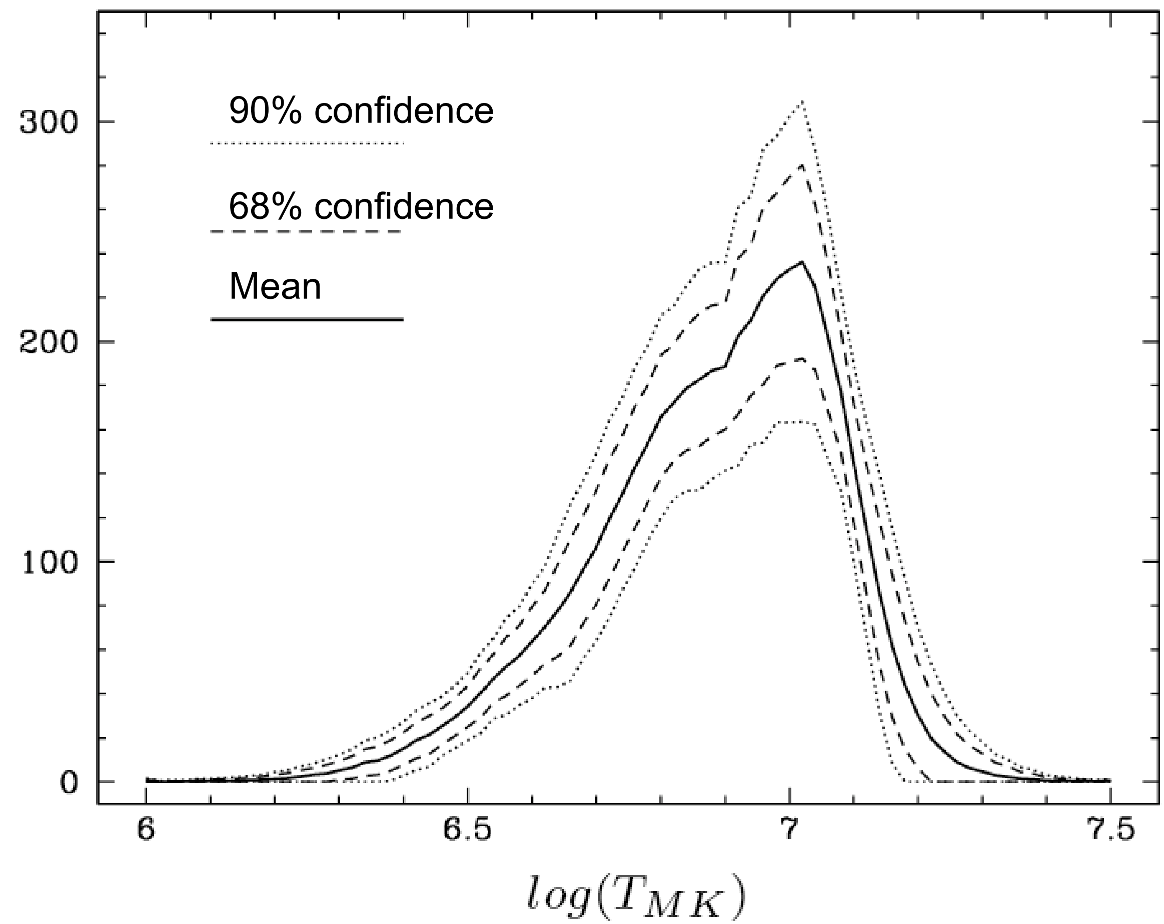
Confidence levels are computed along vertical axis of distribution

AB Dor Emission Measure Distribution



Summary

- The Photon Clean Method allows for complicated parameter distributions
- Phase I solution gives best-fit solution from existing models
- Phase II solution modifies model to quantify amount of departure from physical models
- Bootstrap re-sampling may determine variability of trivial and non-trivial solutions without assumptions about the underlying distribution of the data
- As a test of the PCM's ability to simultaneously model Fe K and Fe L shell line emission, we are using it to model spectra produced by the LLNL EBIT's Maxwellian plasma simulator mode.

Thank You