Hitomi constraints on the atomic codes

「ひとみ」SXS によるペルセウス座銀河団の精密分光をもちいたプラズマ放射モデル・原子物理データベースへの制限

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Adam Foster, Gregory Brown,
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Takayuki Hayashi, and
Hitomi Collaboration

arXiv:1712.05407
PASJ Hitomi special issue

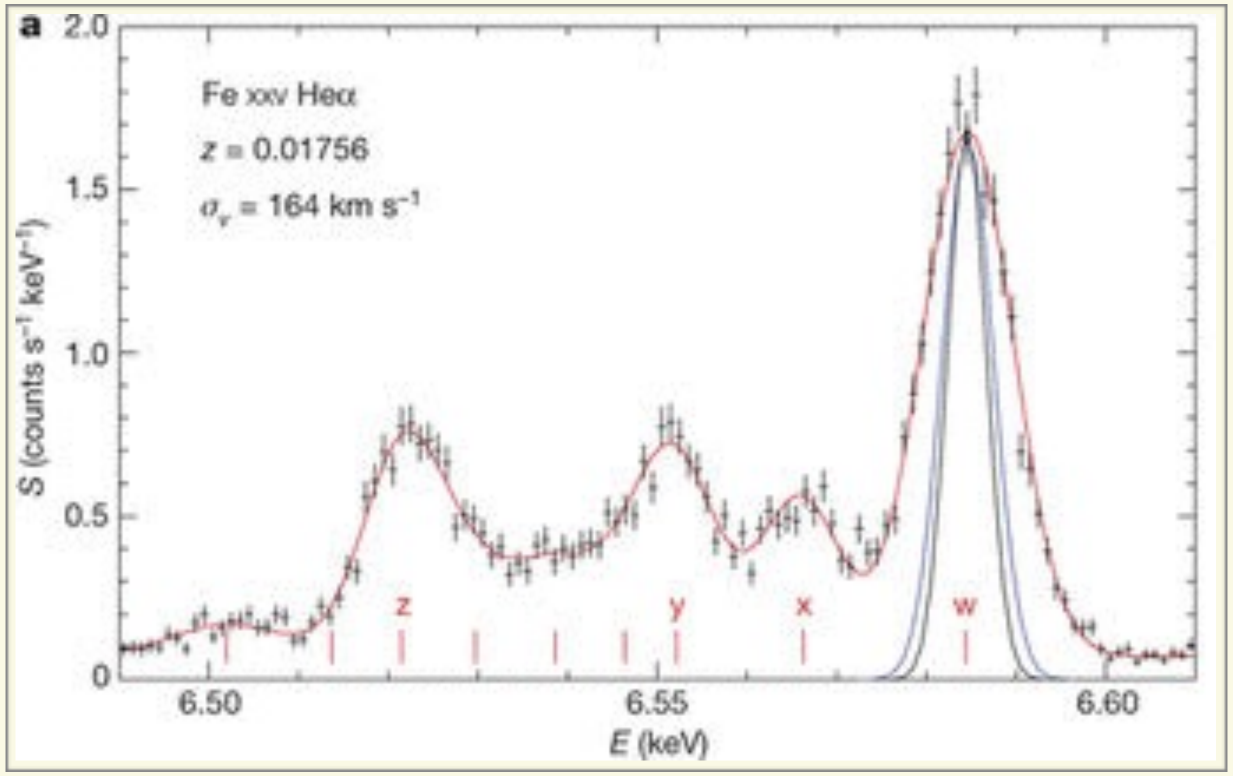
Atomic data and spectral modeling constraints from high-resolution X-ray observations of the Perseus cluster with Hitomi

高宇連研究会 2018

Hitomi Perseus papers

1st generation

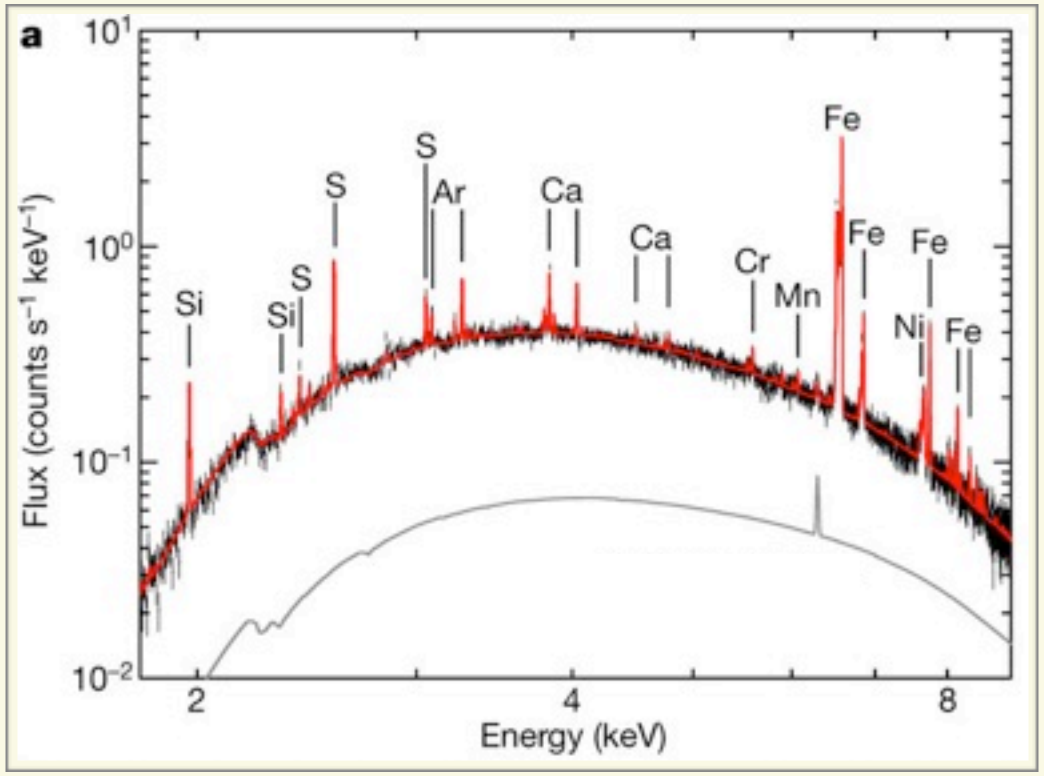
Turbulence at Fe-K, *2016, Nature*
Possible DM line at 3.5 keV, *2017, ApJ*



- Narrow band
- Simple & direct measurements

2nd generation

Abundance*, 2017, Nature*
V, RS, T, AGN, … *2018, PASJ*



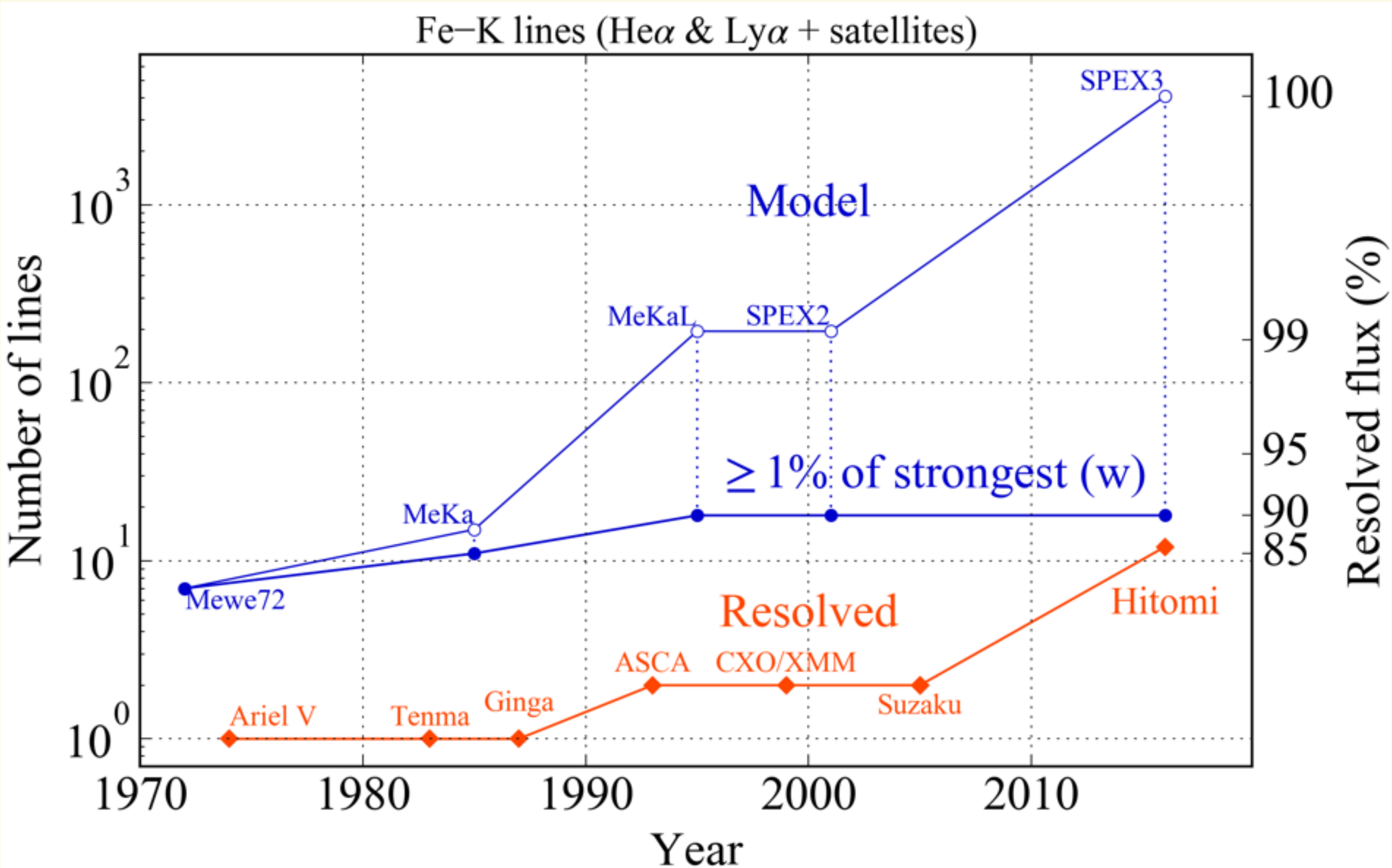
- Full band
- Detailed emission modeling

- Calibration: **Spot checks** → **Comprehensive**
- Modeling: **Gaussians** → **Atomic code**

Atomic code

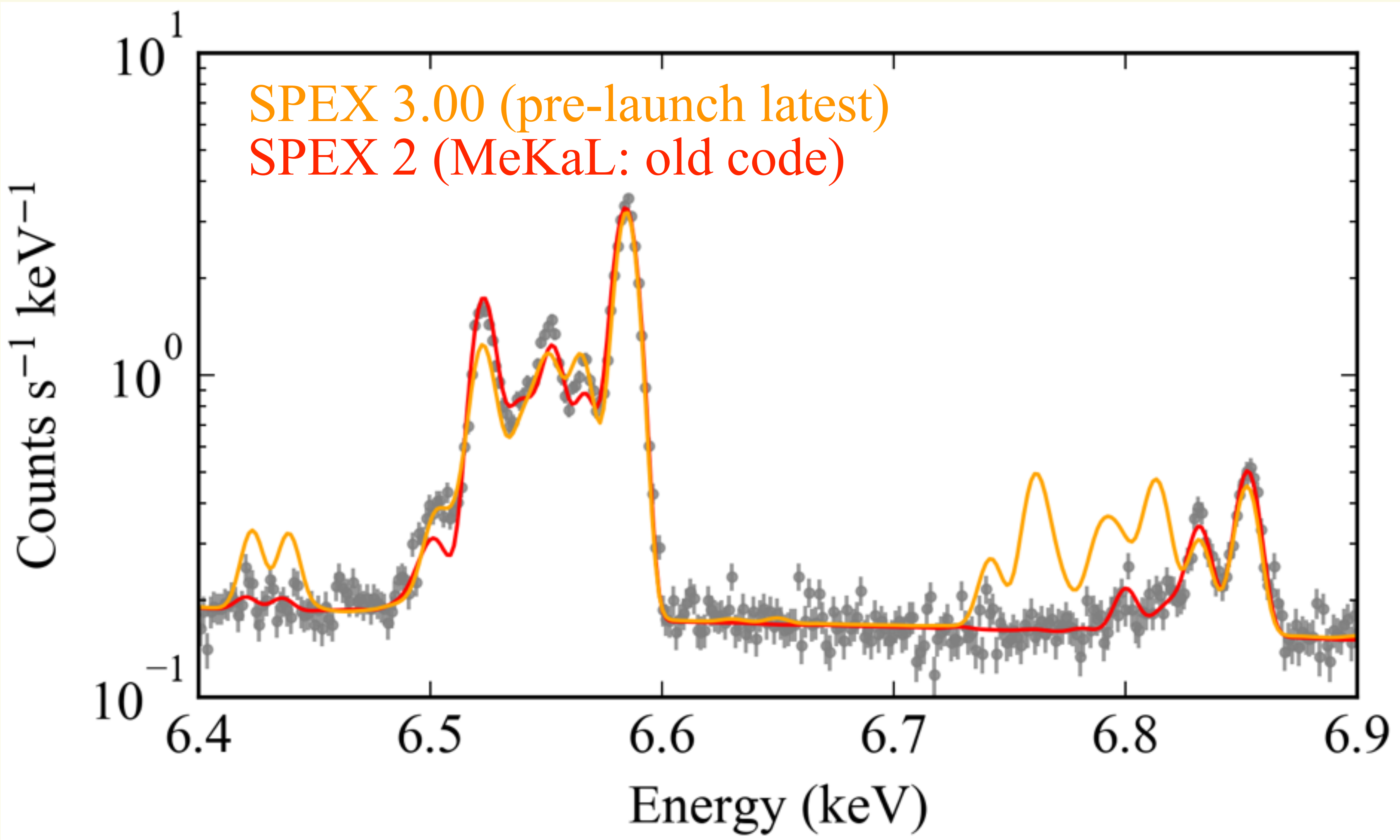
- Important piece of spectroscopy → Major source of systematics
    - incompleteness in database
    - ignorance of specific process
    - approximation in astrophysical modeling
- Typically **~10%** in line flux … critical to science (e.g., Ni/Fe *Z* ratio)
- Have rarely been evaluated
  - Users ≠ Modelers … **hard to doubt**
  - Variants
    - Many implementations of the same model … **hard to compare**
  - Few observational data
    - with sufficient resolution … **hard to test**

Evolution of atomic code



Hitomi enables to benchmark atomic codes for a cluster plasma

The first test with Hitomi data

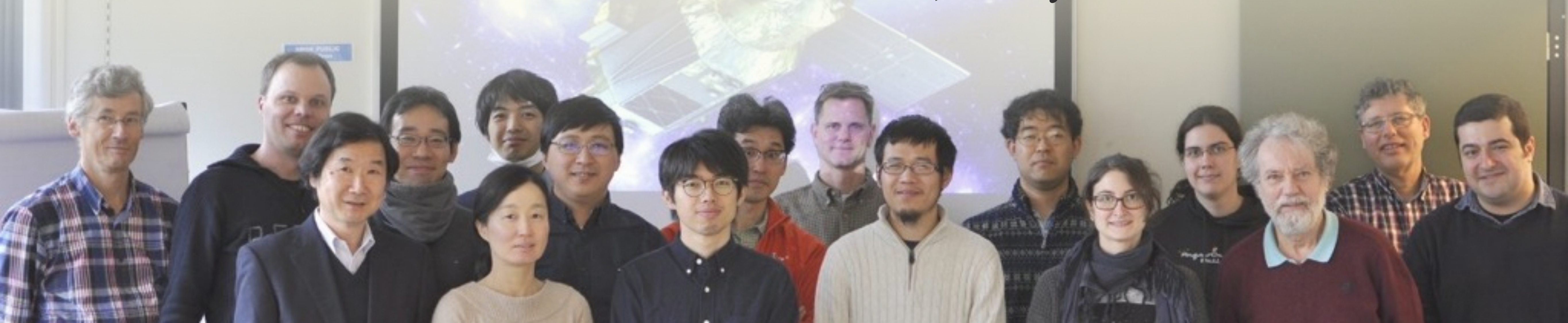


… we failed!

Hitomi “atomic” paper

- Using high-resolution spectrum of Perseus cluster with Hitomi/SXS
  1. Comparison of atomic codes
  2. Cause persuit of the differences
  3. Testing astrophysical modelings

- Core authors:
  - **Code modeling**: L. Gu, J. Kaastra (SPEX), A. Foster, R. Smith (AtomDB)
  - **Ground experiments**: N. Hell, G. Brown, M. A. Leutenegger
  - **Astrophysical data analysis**: H. Akamatsu, N. Ota, S. Nakashima, T. Tamura
  - **Instrumental calibration**: C. A. Kilbourne, T. Hayashi



Method: how to evaluate atomic code systematics

1. Define baseline model
2. Make perturbation
   - replace atomic code
   - modify atomic data
   - change astrophysical model
3. See the effects
   - which parameters ?
   - how large ?
     - compared to statistical or instrumental uncertainty

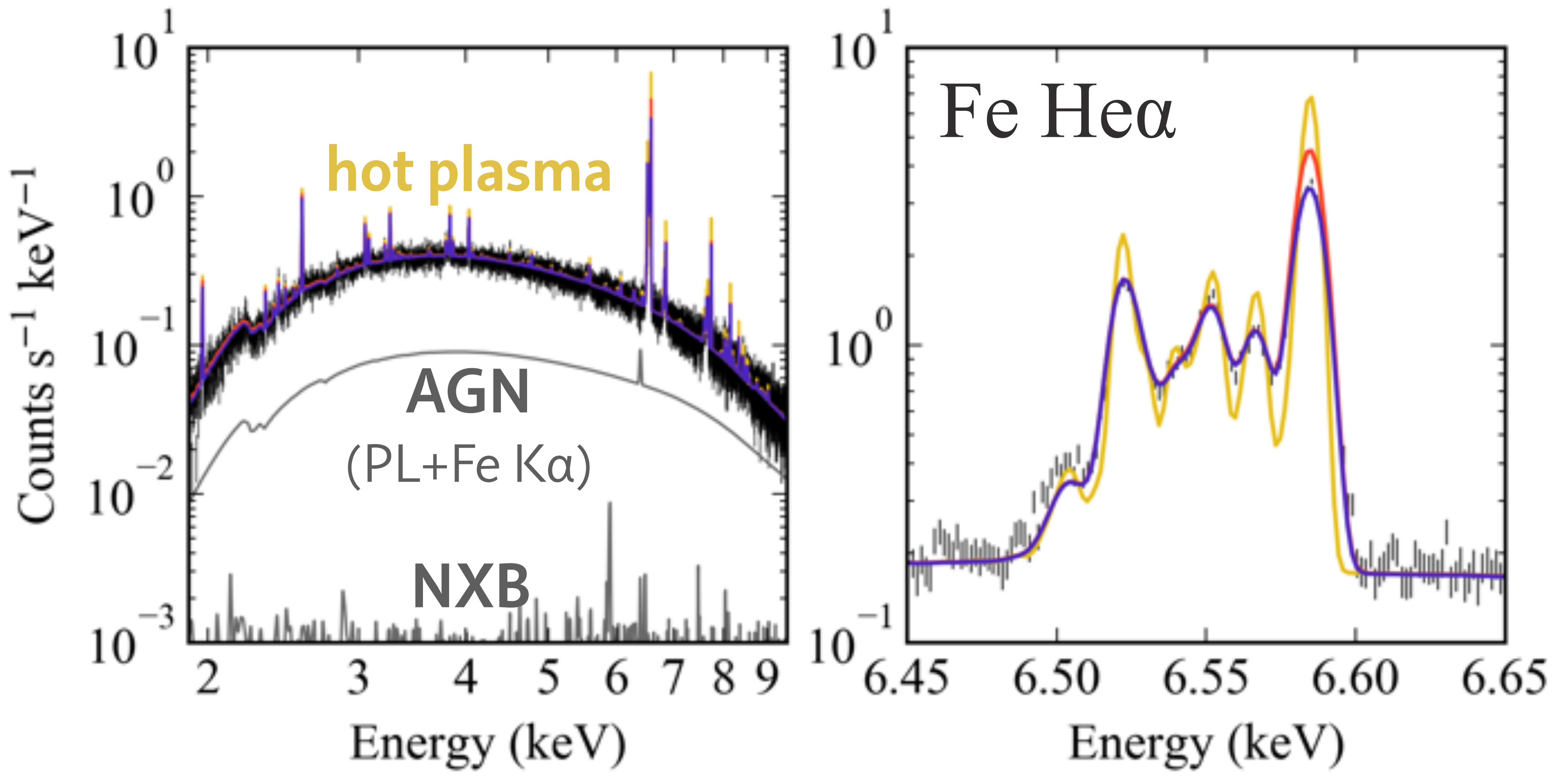
Table 1. Parameters of the reference model and sensitivity to model assumptions.*

Model	C_{stat}	$Y^{\dagger}$	$kT^{\dagger}$	$\sigma_v{}^{\dagger}$	Abundance (solar)‡								$N_{H,hot}{}^{\dagger}$	$cz^{\dagger}$
		(10^{73} m^{-3})	(keV)	(km s^{-1})	Si	S	Ar	Ca	Cr	Mn	Fe	Ni	(10^{24} m^{-2})	(km s^{-1})
Baseline	4926.03§	3.73	3.969	156	0.91	0.94	0.83	0.88	0.70	0.74	0.827	0.76	18.8	5264
Stat. error	—	0.01	0.017	3	0.05	0.03	0.04	0.04	0.10	0.15	0.008	0.05	1.3	2
Plasma codes (section 4):														
SPEX v2	1125.06	0.03	0.031	14	−0.13	−0.14	−0.05	−0.08	—	—	−0.026	0.11	−0.8	−6
SPEX v3.00	2372.33	−0.08	0.263	12	0.03	0.09	0.10	0.06	−0.11	−0.12	−0.243	−0.28	−18.8	−2
APEC v3.0.2	670.06	0.07	−0.039	−13	−0.24	−0.21	−0.15	−0.13	−0.24	−0.39	−0.047	−0.17	−2.7	1
APEC v3.0.8	22.27	0.03	0.071	−16	−0.10	−0.07	−0.05	−0.07	0.01	−0.05	−0.134	−0.05	−7.6	−6
CHIANTI v8.0	327.44	0.01	0.002	4	−0.17	−0.12	0.14	−0.08	—	—	0.011	−0.04	−1.8	8
Cloudy v13.04	21416.07	0.74	−0.370	−7	−0.54	−0.52	−0.53	−0.46	−0.43	−0.15	−0.399	0.14	−18.8	−8
Atomic data (section 5):														
Fe XXV triplet	−10.68	0.00	0.003	1	0.00	0.00	0.00	0.00	0.00	0.00	−0.007	0.00	−0.4	0
AR85 balance	104.80	0.13	0.017	−3	−0.02	−0.02	−0.03	−0.02	—	—	0.017	−0.02	2.4	1
AR92 balance	94.65	0.09	0.021	−4	−0.02	−0.02	−0.03	−0.02	—	—	0.021	−0.03	2.0	0
B09 balance	−18.62	−0.13	0.003	−2	0.00	0.01	0.00	0.00	−0.01	−0.01	0.029	0.01	1.1	0
Plasma modeling (section 6):														
Voigt profile	−8.28	0.01	−0.003	−4	−0.01	−0.01	0.00	0.00	0.01	0.00	−0.003	0.01	−1.2	1
g_{acc}	−0.54	−0.01	−0.005	0	0.00	0.00	0.00	0.00	0.00	0.00	0.006	0.00	−0.1	0
n_{max}	61.46	−0.01	0.006	−1	0.02	0.04	0.02	0.01	−0.01	−0.03	0.023	0.00	1.0	0
Astrophysical modeling (section 7):														
T_{ion} free	−0.02	0.00	0.000	−1	0.00	0.00	0.00	0.00	0.00	−0.01	0.000	0.00	−0.1	0
RT free	−3.26	−0.01	0.026	−1	−0.02	−0.02	−0.01	−0.01	−0.01	−0.02	0.001	−0.01	0.7	0
Ionizing	−5.46	−0.02	0.025	0	0.01	−0.01	−0.06	−0.06	−0.02	−0.04	0.000	−0.01	0.8	0
Recombining	−9.19	0.02	−0.036	2	−0.02	−0.02	−0.01	0.00	0.03	0.02	0.000	0.01	−1.5	0
σ_T free	−60.90	0.13	−0.139	2	−0.10	−0.10	−0.04	0.01	0.08	0.10	0.024	0.03	−2.3	0
He abund.	−0.07	−0.08	−0.001	0	0.02	0.03	0.02	0.02	0.02	0.01	0.025	0.02	−0.6	0
Spectral components (section 8):														
No RS	341.02	0.05	−0.015	13	−0.05	−0.04	−0.03	−0.02	0.04	0.01	−0.094	0.01	≈0	4
Hot comp. free	−1.40	0.00	0.000	2	0.00	0.00	0.00	0.00	0.00	0.00	0.003	0.00	1.3	0
CX	−13.34	0.00	0.018	−3	−0.02	−0.01	0.00	−0.01	−0.01	−0.02	−0.042	0.00	−1.4	−1
No AGN	624.54	0.68	0.523	4	−0.01	−0.05	−0.09	−0.14	−0.15	−0.12	−0.206	−0.16	12.8	3
New AGN	8.42	0.18	0.028	0	−0.03	−0.03	−0.03	−0.04	−0.04	−0.04	−0.041	−0.03	1.3	0
Fitting techniques (section 9):														
χ^2	54.69	−0.01	−0.045	−1	−0.03	−0.01	0.00	−0.01	0.03	0.01	0.007	0.02	−0.6	0
χ^2, no binning	—	−0.01	−0.206	−1	−0.12	−0.07	−0.03	−0.01	0.09	0.14	0.027	0.02	−3.1	0
Instrumental effects (appendix 3):														
No vel. cor.	61.70	0.00	0	13	0.00	0.00	0.00	0.00	−0.02	−0.02	0.001	0.01	1.0	−23
Small RMF	−4.42	0.01	−0.023	0	−0.01	−0.02	−0.01	−0.01	−0.01	−0.02	−0.003	0.00	−0.2	0
XL RMF	12.36	−0.02	0.035	0	0.00	0.03	0.02	0.02	0.02	0.01	0.010	0.00	0.1	0
No NXB	8.78	0.00	0.017	0	0.00	0.00	0.00	0.00	−0.01	−0.01	−0.003	−0.01	0.3	0
PS ARF	29.54	0.02	−0.052	0	−0.04	−0.02	0.00	0.00	0.01	0.04	0.003	0.00	−0.7	0
No ARF cor.	38.48	0.05	−0.076	1	−0.03	−0.03	−0.03	−0.03	0.02	0.05	−0.006	−0.03	−0.6	2
Ground ARF	190.52	−0.16	−0.123	0	0.03	0.00	0.02	0.06	−0.04	0.02	0.017	0.04	−1.8	−1
Crab ARF	13.36	−0.11	0.066	1	0.02	0.01	0.00	0.02	0.05	0.08	0.031	0.03	0.0	0
New arfgen	−1.55	0.78	0.004	0	0.00	0.00	0.00	0.00	0.00	0.00	0.000	0.00	0.1	0
No gain cor.	626.73	0.01	0.003	4	−0.13	−0.06	−0.02	−0.01	−0.01	−0.01	−0.008	0.00	−0.5	14

Different systematic factors are inter-compared in one table

Baseline model

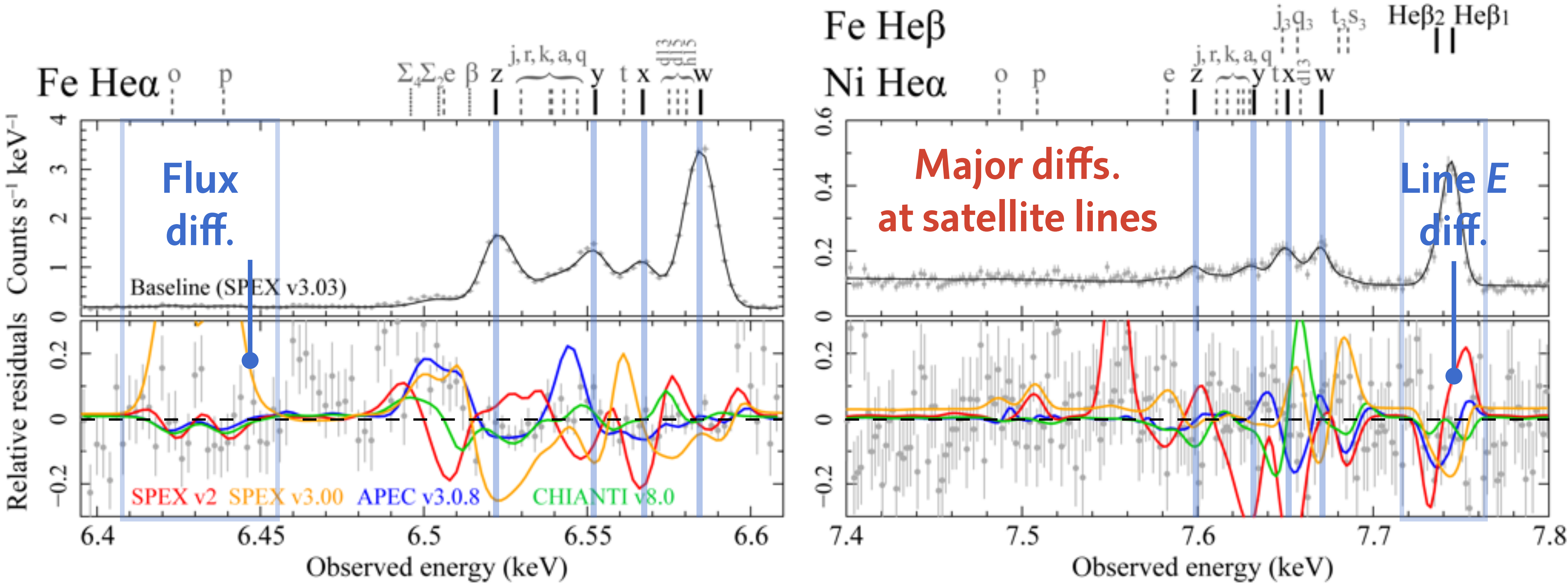
((**hot plasma** (kT, Z) + **AGN**) * redshift) * foreg.abs + **NXB**
with turbulence (σ_V) and reso. scattering (N_{RS})



- Atomic code: SPEX v3.03 (post-launch)
- Assumptions: isothermal & equilibrium
  - $T_e = T_i = T_z$

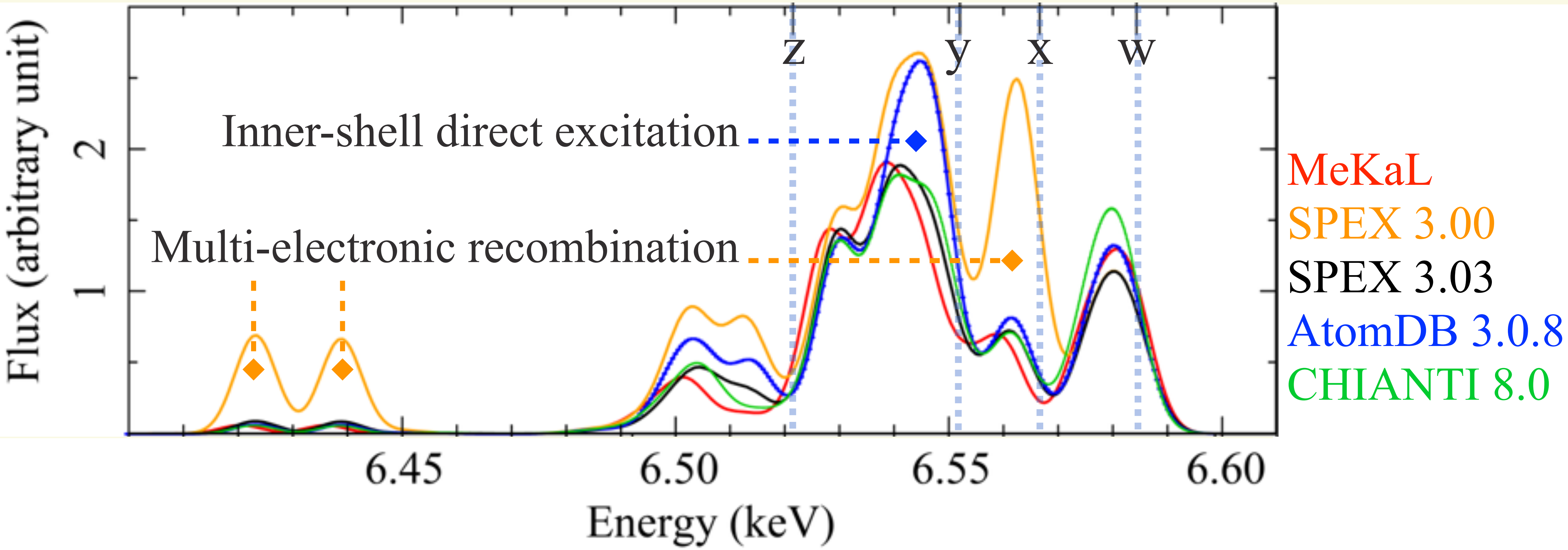
Parameters	C_{stat} (4876)	kT (keV)	σ_V (km/s)	Z_{Fe} (solar)	N_{RS} (cm^{-2})
Best-fit	4926	3.969	156	0.827	18.8
Stat. error	~100	±0.017	±3	±0.008	±1.3

1. Inter-code comparison



≥3σ **≥5σ**	C_{stat}	kT (keV)	σ_V (km/s)	Z_{Fe} (solar)	N_{RS} (cm^{-2})
SPEX 3.03 (latest)	4926	3.969	156	0.827	18.8
Stat. error (1σ)	~100	±0.017	±3	±0.008	±1.3
MeKaL (old code)	**+1125**	+0.031	**+14**	**–0.026**	–0.8
SPEX 3.00 (pre-launch)	**+2372**	**+0.263**	**+12**	**–0.243**	**–18.8**
AtomDB 3.0.8	+22	**+0.071**	**–16**	**–0.134**	**–7.6**
CHIANTI 8.0	+327	+0.002	+4	+0.011	+1.8

2. Cause of the differences — Satellite lines



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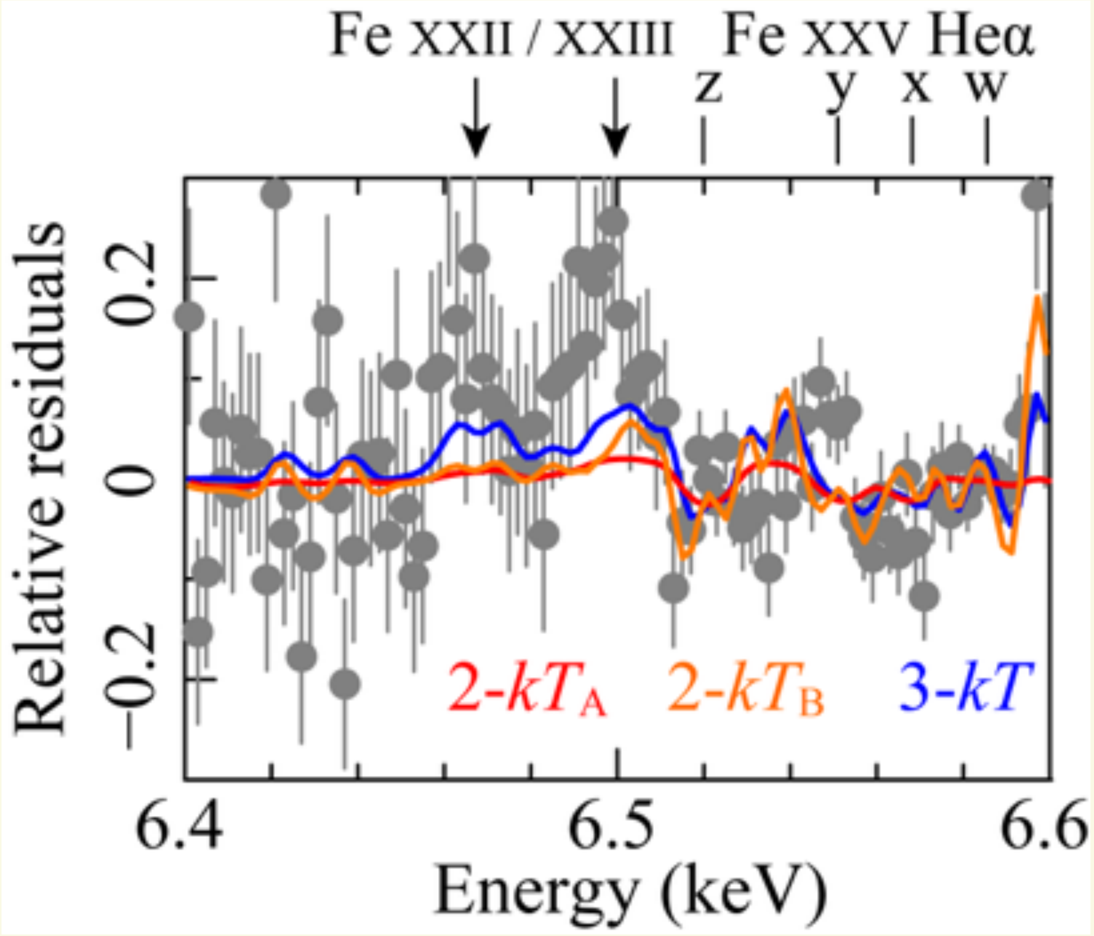
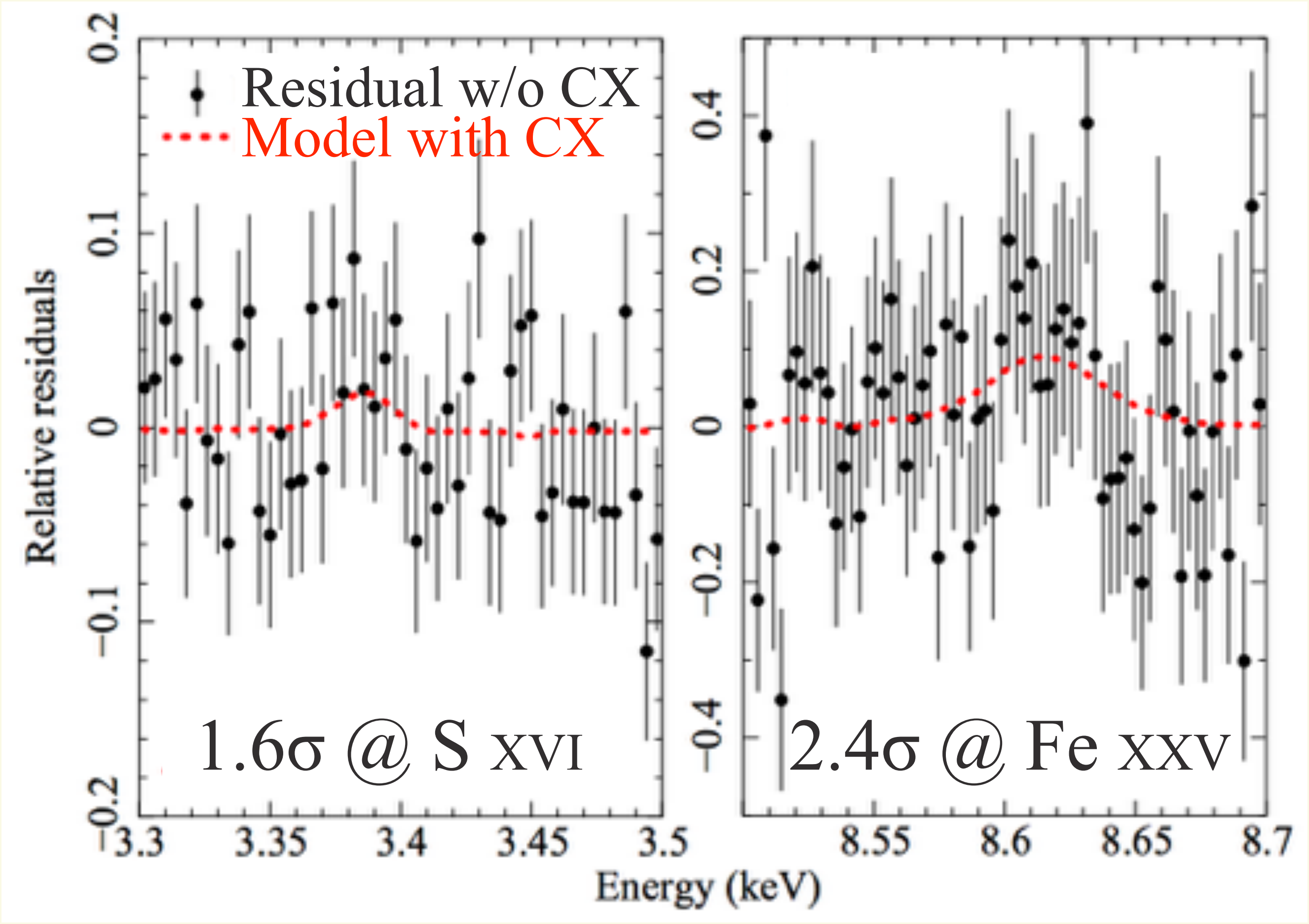
Systematic code comparison enebled to identify bugs

3. Astrophysical modeling

- **Anisothermality**
  - Multi-*kT* better describe satellite lines of Fe-K
- **Charge exchange**
  - Marginally imrove the fit at high-*n* lines of S & Fe



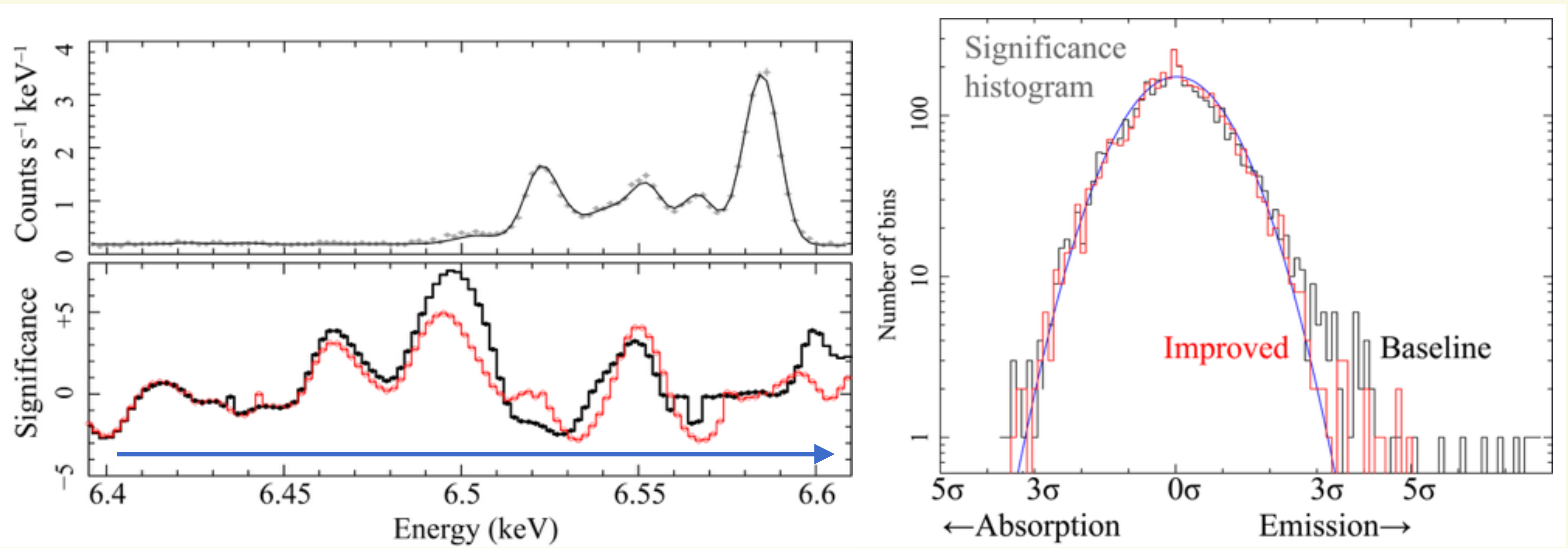


No evidence of deviation from collisional equilibrium ($T_e = T_Z = T_i$)

Detailed modeling are important when trying…

New line search

	kT (keV)	Charge exchange	C_{stat}
Baseline	4.0	None	4926
Improved	1.9, 3.6, 5.4	S XVI & Fe XXV	4779

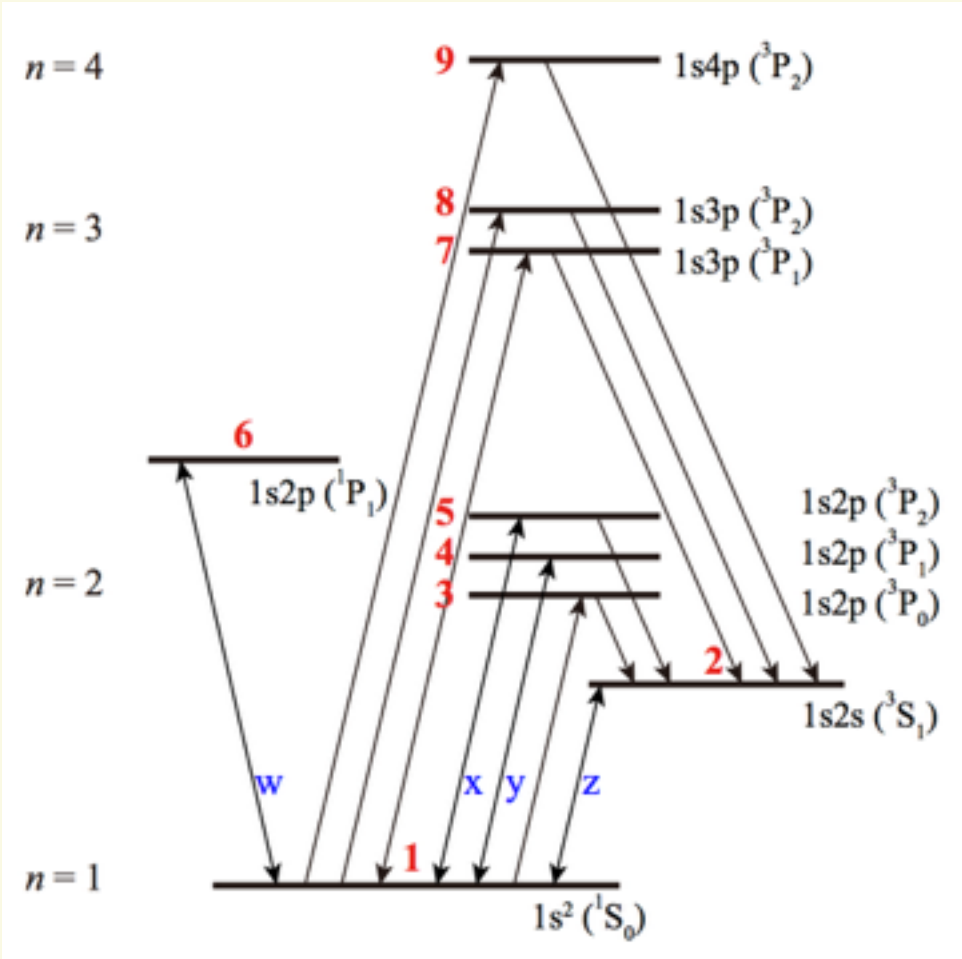


Accurate code & modeling eliminates spourious line detections

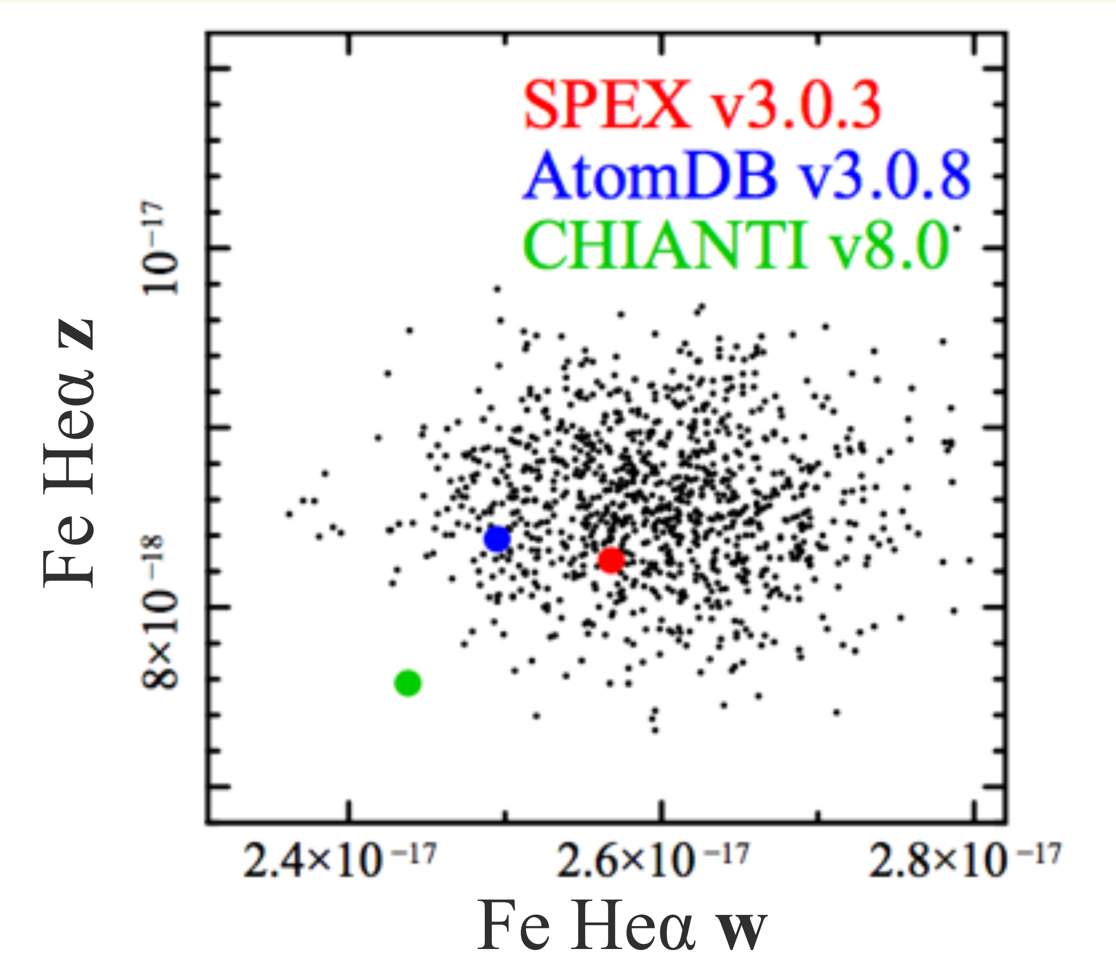
Remained problem: true atomic uncertainty

- Inter-code (model) difference ≠ true uncertainty
  - Retrieve original errors in theories and experiments
- Need a tool to evaluate flux uncertainty from atomic data uncertainty
  - Proposed approach: Monte-Carlo

• Randomize transition probability

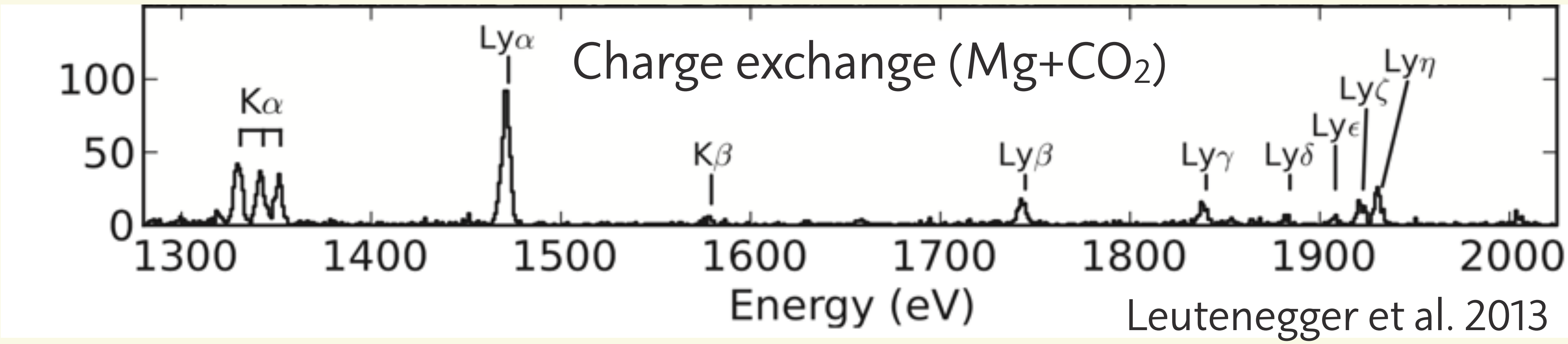


• Evaluate flux error

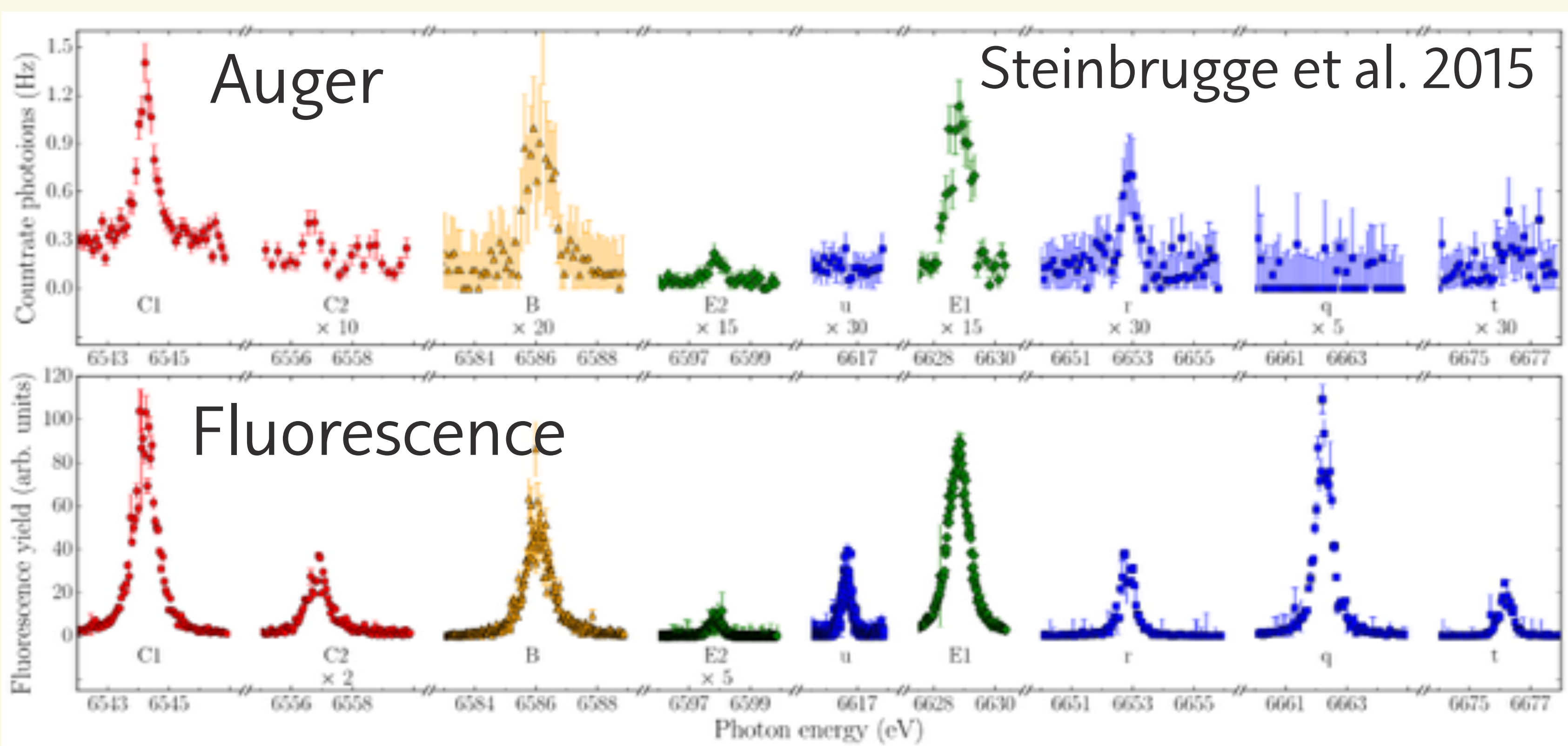


Remained problem: Atomic data needs

- Lots of atomic data used unbenchmarked with experiments
- EBIT with microcalorimeter provides some essential data



- Important measurements for plasma types untested with Perseus



- Radiative/Auger rates followed by inner-shell ionization
- Important for NEI & photo-ionized plasma

Summary

- **Hitomi enebled the first benchmark of atomic codes for clusters**
  - Systematic comparison solved major problems
  - Complete **and** accurate code/modeling are required:
    - to derive correct physical quantities
    - to detect new features (or **not** to detect “new” features)
- **Not tested**
  - Collisional non-equilibrium ($T_e \neq T_i \neq T_z$)
  - Photo-ionized plasma
  - Fe-L shell lines
- **Futher efforts needed for full success of XARM**
  - both in code developments & ground experiments