輻射温度0.5keVプランク放射源による光電離プラズマ

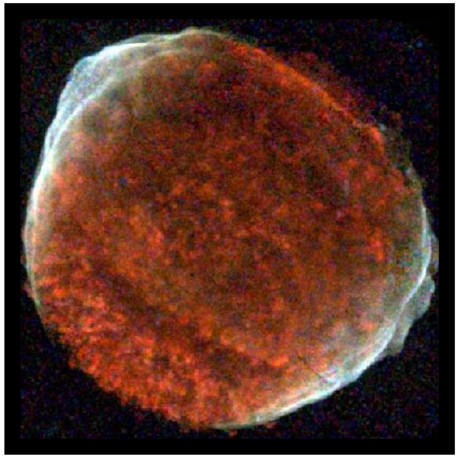
レーザー生成ミニ･ブラックホール放射源によるX線天文学模擬実験

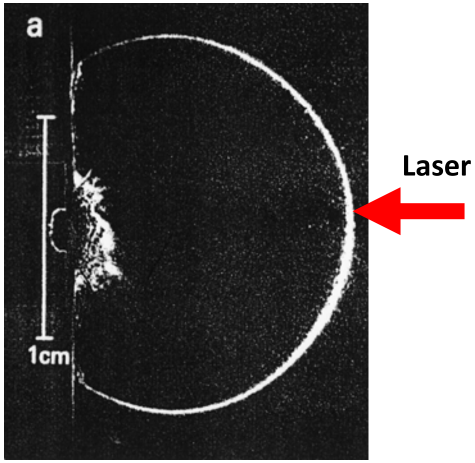
大阪大学
レーザーエネルギー学研究センター
高部英明

初代星･銀河形成研究会 in 神戸
甲南大学
08年9月8-10日

Laboratory Astrophysics Project at ILE

(1) Shocks in Universe and Origin of Cosmic-Ray

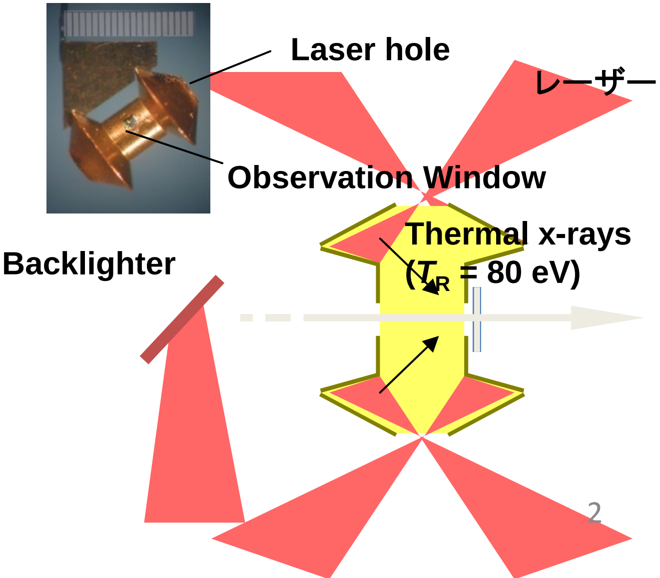




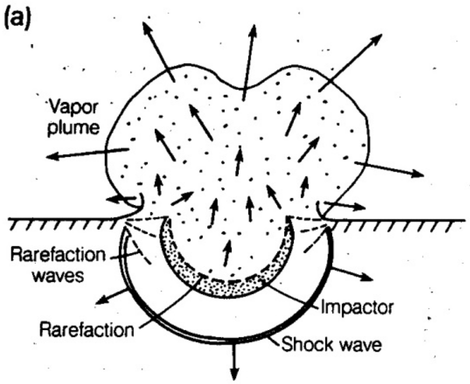
X-ray Image of SN1006:
Mainly by extremely relativistic electron cyclotron emission with $E=10^{15}$eV.

(2) Photo-ionized Plasma

Planetary Nebula, X-ray binary:
Possibility of photo-ionized X-ray laser from Universe



(3) Planetary and Meteo-impact Physics



レーザー宇宙物理研究・四班の体制

- **無衝突衝撃波の生成と粒子加速の物理**

  坂和洋一，堂埜誠一，蔵満康浩，加藤恒彦，木村友亮，宮西宏併，遠藤恭，尾崎典雅，長友英夫，重森啓介，門野敏彦，児玉了祐，乗松孝好，高部英明，星野真弘、山崎了、大西直文、水田晃、J.Waugh, N.Woolsey, B.Loupias, Gregory, M.Koenig【阪大、東大、広大、東北大、千葉大、U. York(UK), LULI(France)】

- **光電離非平衡プラズマの物理**

  西村博明, 藤岡慎介, 山本則正, 田沼　肇, 中村信行, 高部英明, 加藤太治、政井邦昭, Feilu Wang, Yuton Li, Gang Zhao, Jie Zhang, Steve Rose【阪大、核融合研、首都大東京、IOP, NAOC, SJTU(China), Imp. Coll.(UK)】

- **惑星と隕石衝突の物理**

  弘中陽一郎，門野敏彦，佐野孝好，大谷一人，城下明之，中井光男，疇地宏，三間圀興，尾崎典雅，宮西宏併，遠藤恭，木村友亮，兒玉了祐, 清水克哉, 境家達弘，高橋英樹，近藤忠, 入船徹男，土屋卓久, 生駒大洋, 岩本晃史, 奥地拓生，大野宗祐, 杉田精司，関根康人，松井孝典, 荒川政彦, 中村昭子, Justin Wark【阪大、愛媛大、東工大、核融合研、岡大、東大、名大、神大、U. Oxford(UK)】

- **高温超伝導体テラヘルツ波検出デバイスの開発**

  斗内政吉、川山巌、堂田泰史、金子亮介【阪大】

Photo-ionized Non-LTE Plasmas

Collaborators

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Jing Zhao, Fei-lu Wang, Hui-Gang Wei, Jian-Rong Shi, Gang Zhao

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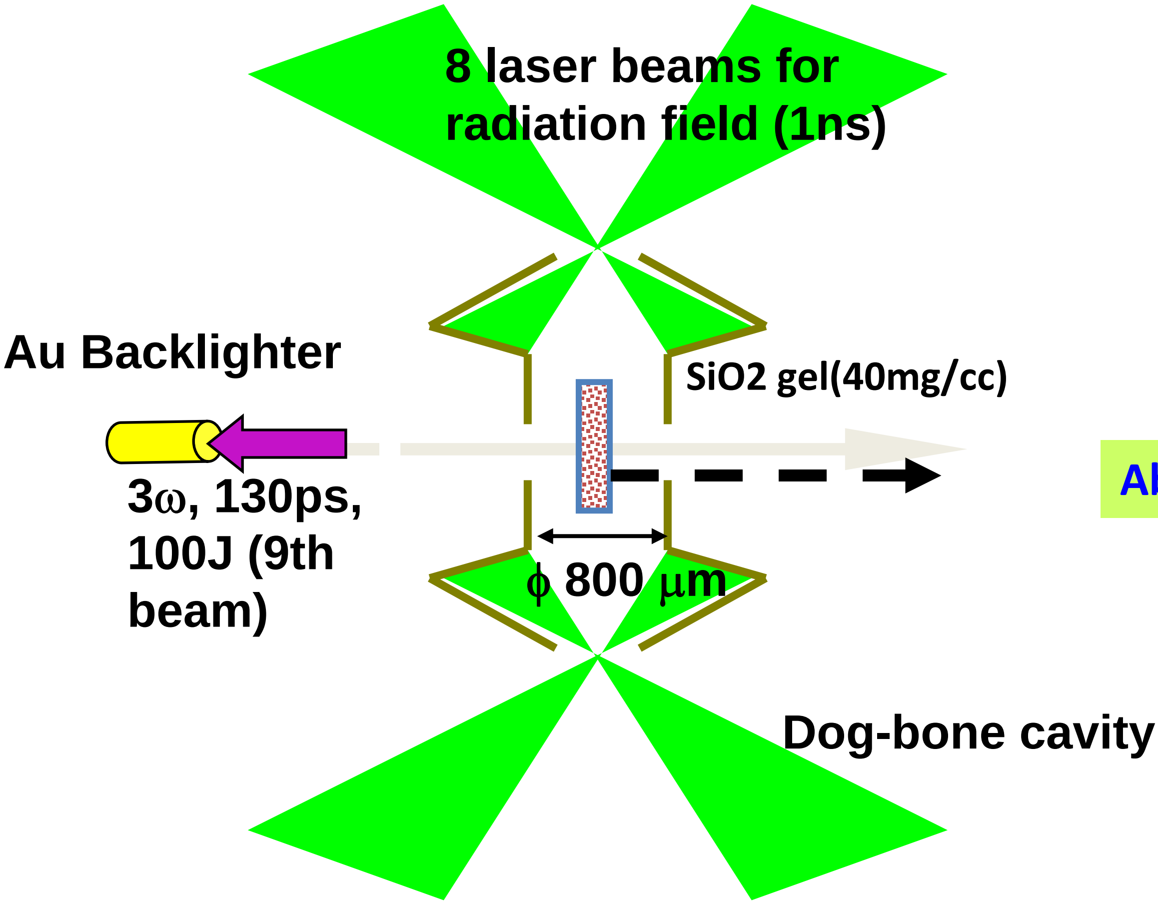
Research Center for Laser Fusion, CAES, Mianyang 621900, China

Jie Zhang

Shanghai Jiaotong University, Shanghai 200240, China

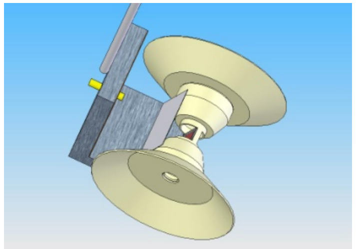
Japan-China Collaboration supported by JSPS, Japan, and NSFC, China.



X-ray radiation temp.
(T_R ~ 80 eV)

Shingang II (China)

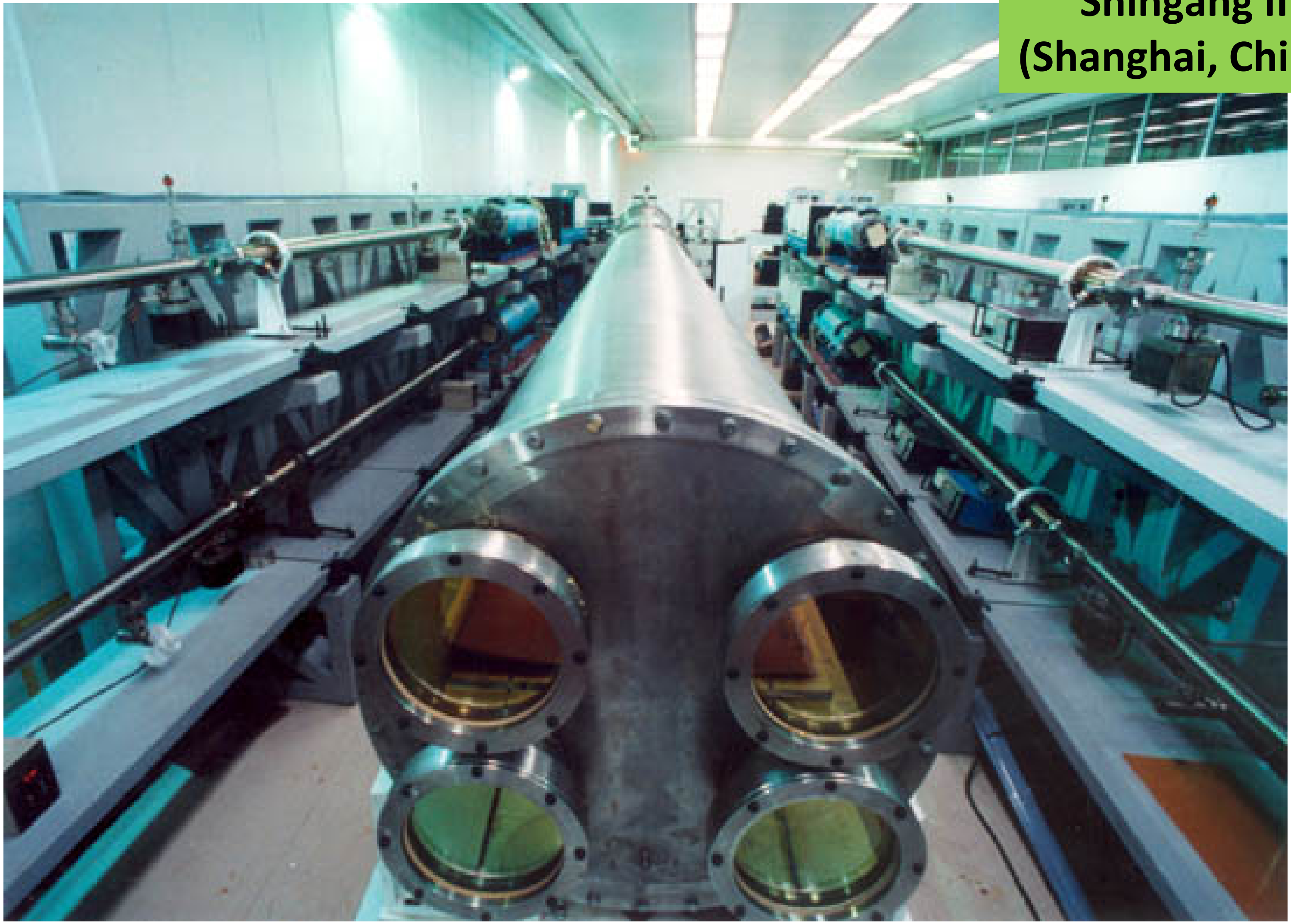
Absorption Spectra



8 laser beams (0.35um,1ns,2000J) were incident to the dog-bone Au cavity to produce a 80 eV x-ray radiation field. The 40mg/cc SiO2 gel were photoionized by the radiation field. An additional Au x-ray source produced by the 9th laser beam was used as backlighter. Absorption (with backlighter) or self-emission spectra were measured in the experiment.

Absorption by Photo-ionized Plasma (Shanghai, China)

Shingang II
(Shanghai, China)



Self-emission from Photo-ionized Plasma (Osaka, Japan)

Gekko XII
(Osaka, Japan)

Two Type of Experiments have been done with GXII and Shengaun II

1. **Opacity Experiment of Photo-ionized Silicon Plasma** (Shingan II, Shanghai)

   The Astrophysical Journal Letters **683**, 577–583, Aug 2008

   H. G. Wei et al.,*“Opacity studies of silicon in radiatively heated plasma”*

2. **Self-emission Experiment of Photo-ionized Nitrogen Plasma** (Gekko XII, Osaka)

   Physics of Plasmas **15**, 073108 (2008)

   F. L. Wang et al., *“Experimental evidence and theoretical analysis of photoionized plasma under x-ray radiation produced by intense laser”*

Why photo-ionization plasma physics is important in Astrophysics

- Photo-ionization of accretion disk material in X-ray binary (Anomalous accretion rate: α)
  - S. A. Balbus, and J. F. Hawley, Rev. Mod. Phys. 70, 1 (1998).
  - H. Takabe, Prog. Theor. Phys. Suppl. 143, 202 (2001).
  - B. A. Remington, R. P. Drake, and D. D. Ryutov, Rev. Mod. Phys. 78, 755 (2006).
- Photo-ionization of surface plasma of companion star (Cyg X-3)
  - K. Kawashima, and S. Kitamoto, Publ. Astron. Soc. Japan 48, L113 (1996).
  - F. Paerels, et al., Astrophys. J. 533, L135 (2000).
- Physics of line driven stellar wind. Possibility of very mass stars
  - S. F. P. Zwart, and E. P. J. van den Heuvel, Nature 450, 388 (2007).
  - S. E. Woosley, S. Blinnikov, and A. Heger, Nature 450, 390 (2007).
  - I. Hachisu, and M. Kato, Astrophys. J. 590, 445 (2003).
- Photo-ionization of HII region
  - A. Mizuta, et al, Astrophys. and Space Science 298, 197 (2004).

The Astrophysical Journal, 651:421–437, 2006 November 1

X-RAY SPECTRAL STUDY OF THE PHOTOIONIZED STELLAR WIND IN VELA X-1

Shin Watanabe,[1] Masao Sako,[2] Manabu Ishida,[3] Yoshitaka Ishisaki,[3] Steven M. Kahn,[2] Takayoshi Kohmura,[4] Fumiaki Nagase,[1] Frederik Paerels,[5] and Tadayuki Takahashi[1]
Received 2006 February 15; accepted 2006 July 1

ABSTRACT

We present results from quantitative modeling and spectral analysis of the high-mass X-ray binary system Vela X-1 obtained with the *Chandra* HETGS. The spectra exhibit emission lines from H- and He-like ions driven by photoionization, as well as fluorescent emission lines from several elements in lower charge states. The properties of these X-ray lines are measured with the highest accuracy to date. In order to interpret and make full use of the data, we have developed a simulator, which calculates the ionization structure of a stellar wind and performs Monte Carlo simulations of X-ray photons propagating through the wind. From comparisons of the observed spectra with results from the simulator, we are able to find the ionization structure and the geometrical distribution of material in the stellar wind that can reproduce the observed spectral line intensities and continuum shapes remarkably well. We find that the stellar wind profile can be represented by a CAK model with a star mass-loss rate of $(1.5\text{–}2.0) \times 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$, assuming a terminal velocity of $1100\ \mathrm{km\ s^{-1}}$. It is found that a large fraction of emission lines from highly ionized ions are formed in the region between the neutron star and the companion star. We also find that the fluorescent lines must be produced in at least three distinct regions: the extended stellar wind, reflection off the stellar photosphere, and in a distribution of dense material partially covering and possibly trailing the neutron star, which may be associated with an accretion wake. Finally, from detailed analysis of the emission-line profiles, we demonstrate that the stellar wind dynamics is affected by X-ray photoionization.

Subject headings: stars: neutron — stars: winds, outflows — X-rays: binaries — X-rays: individual (Vela X-1)

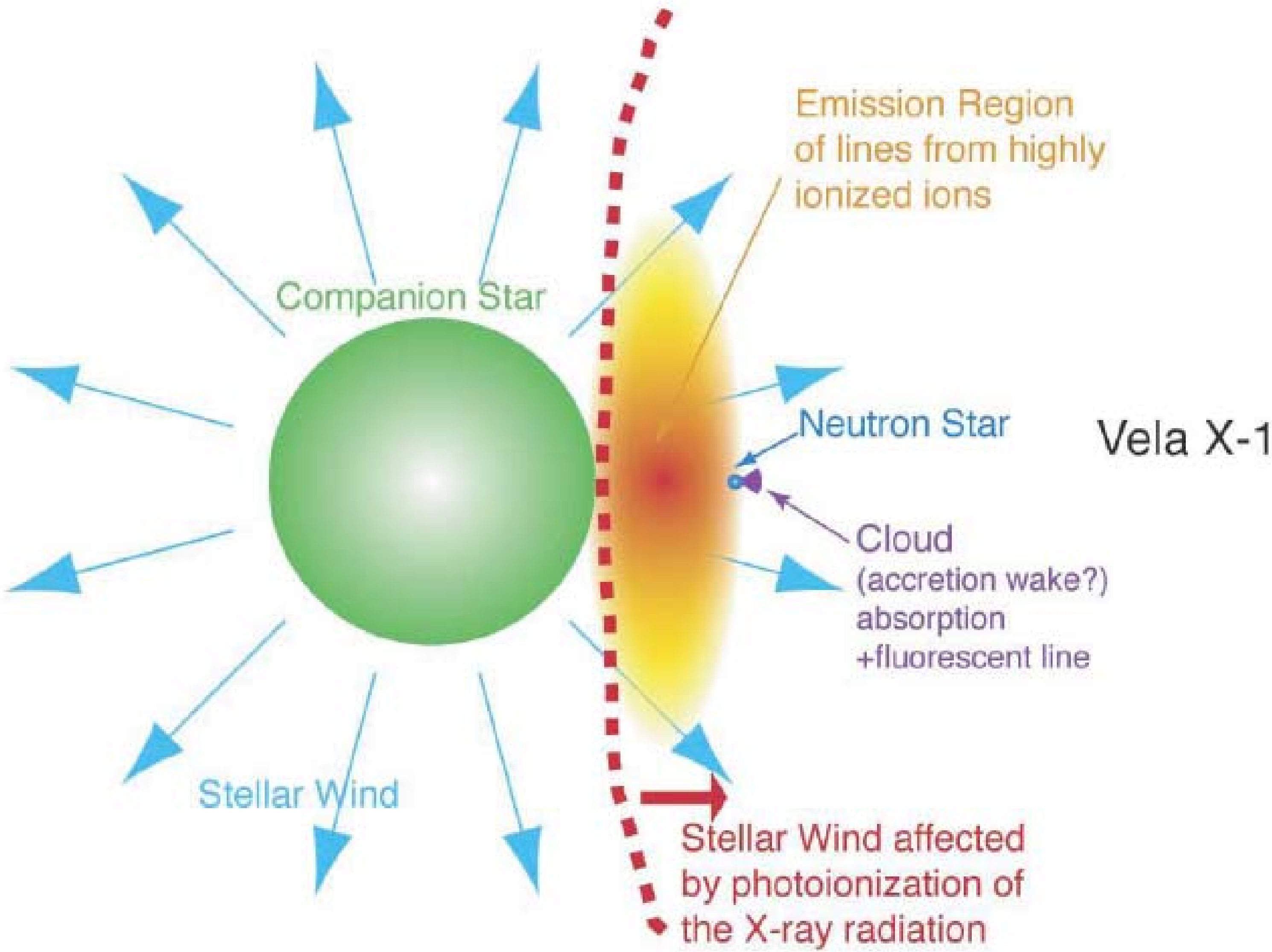
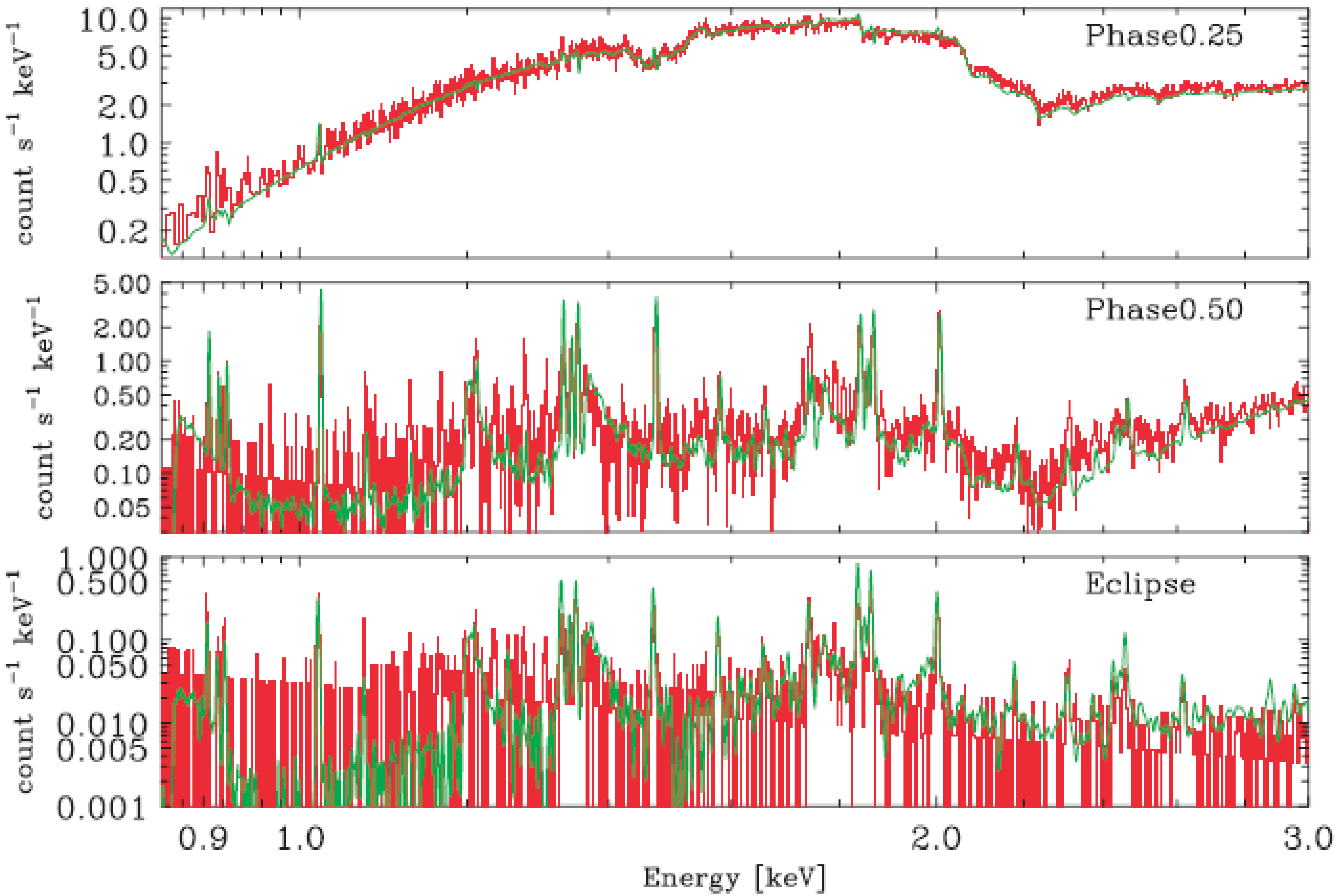


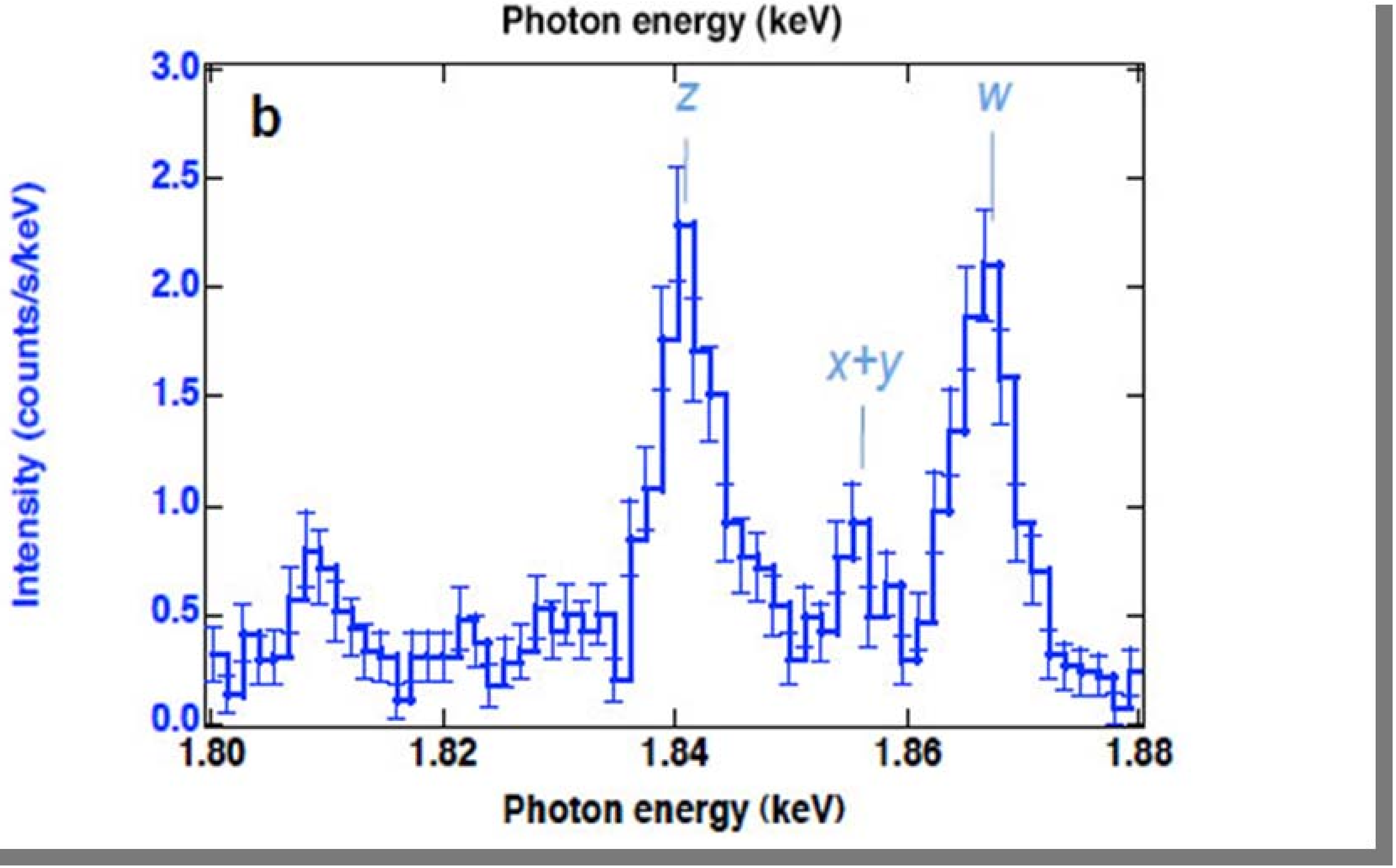
FIG. 24.—Conceptual picture of the Vela X-1 system obtained from the present analysis.

S. Watanabe et al., ApJ 651; 421, 2006



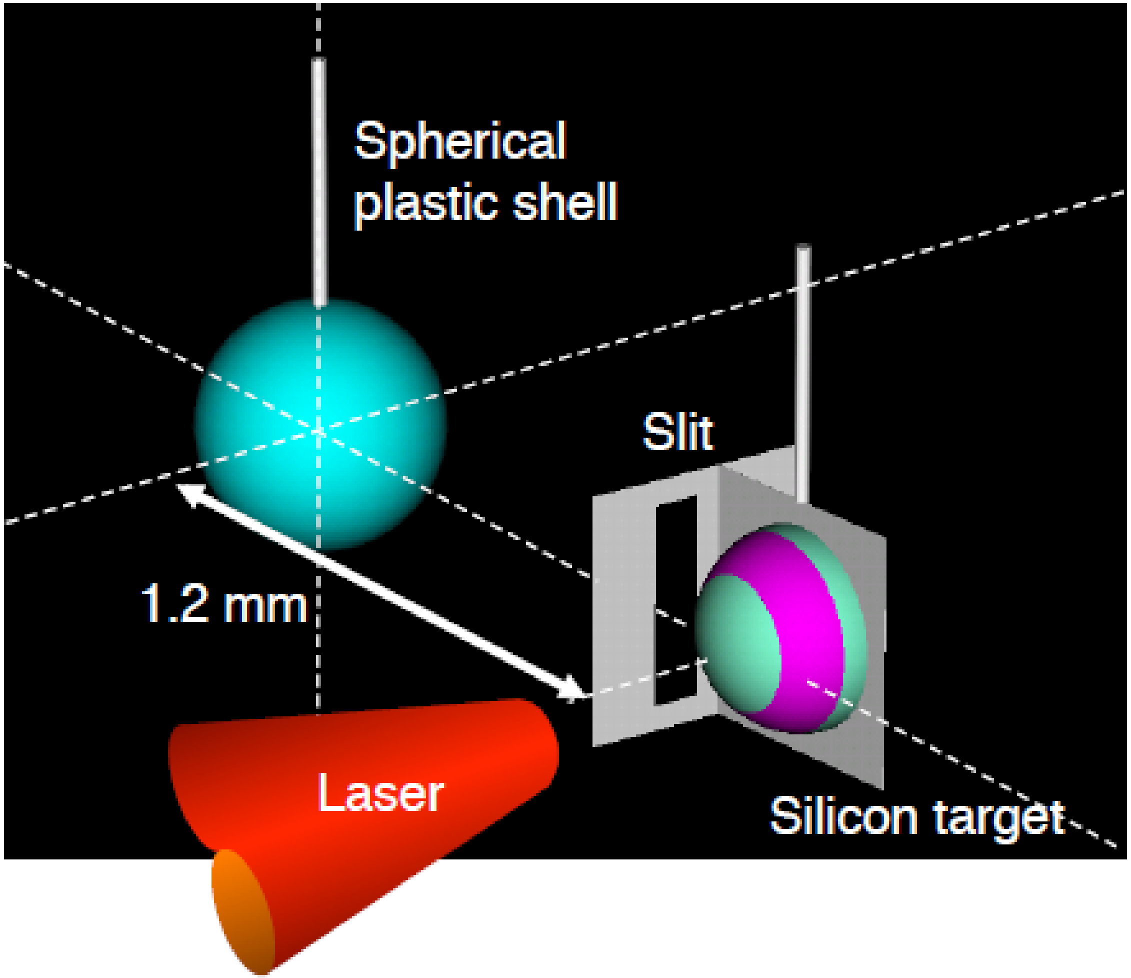
S. Watanabe et al., ApJ 651; 421, 2006

He-like Silicon Line Emissions from VELA X-1

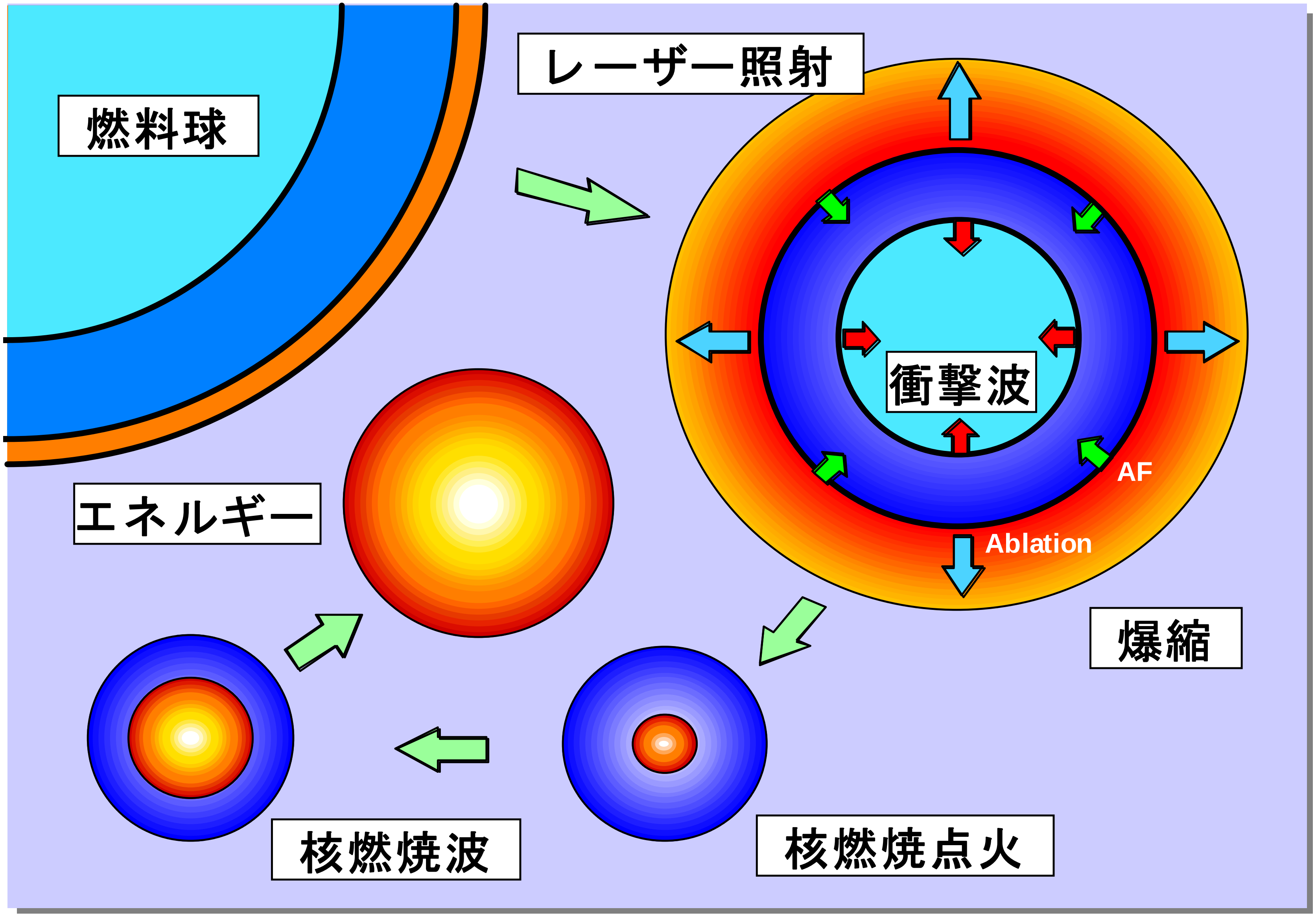


N. R. Schultz et al., ApJ 564; L21, 2002

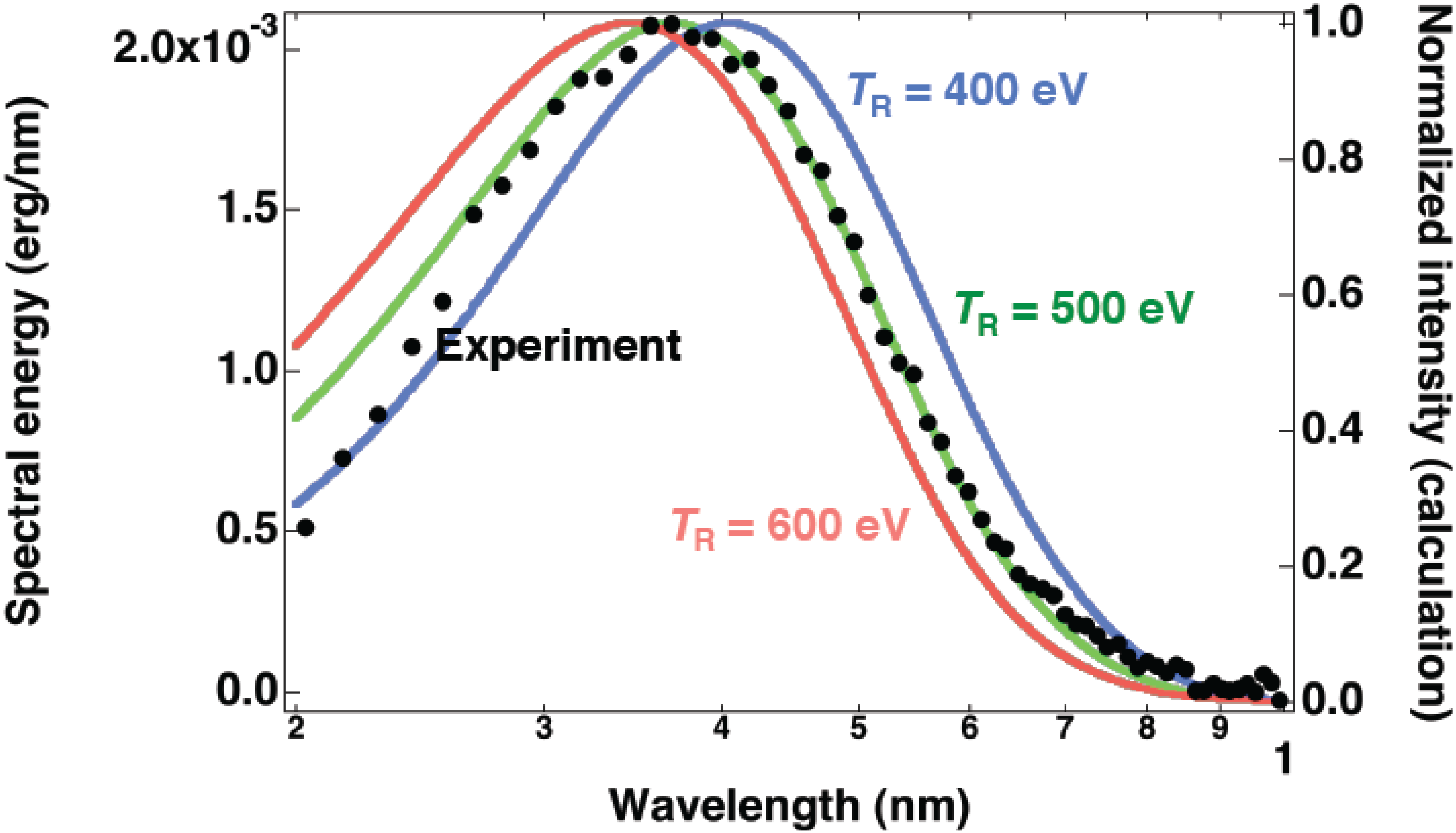
Experimental Configuration Gekko XII (Osaka)



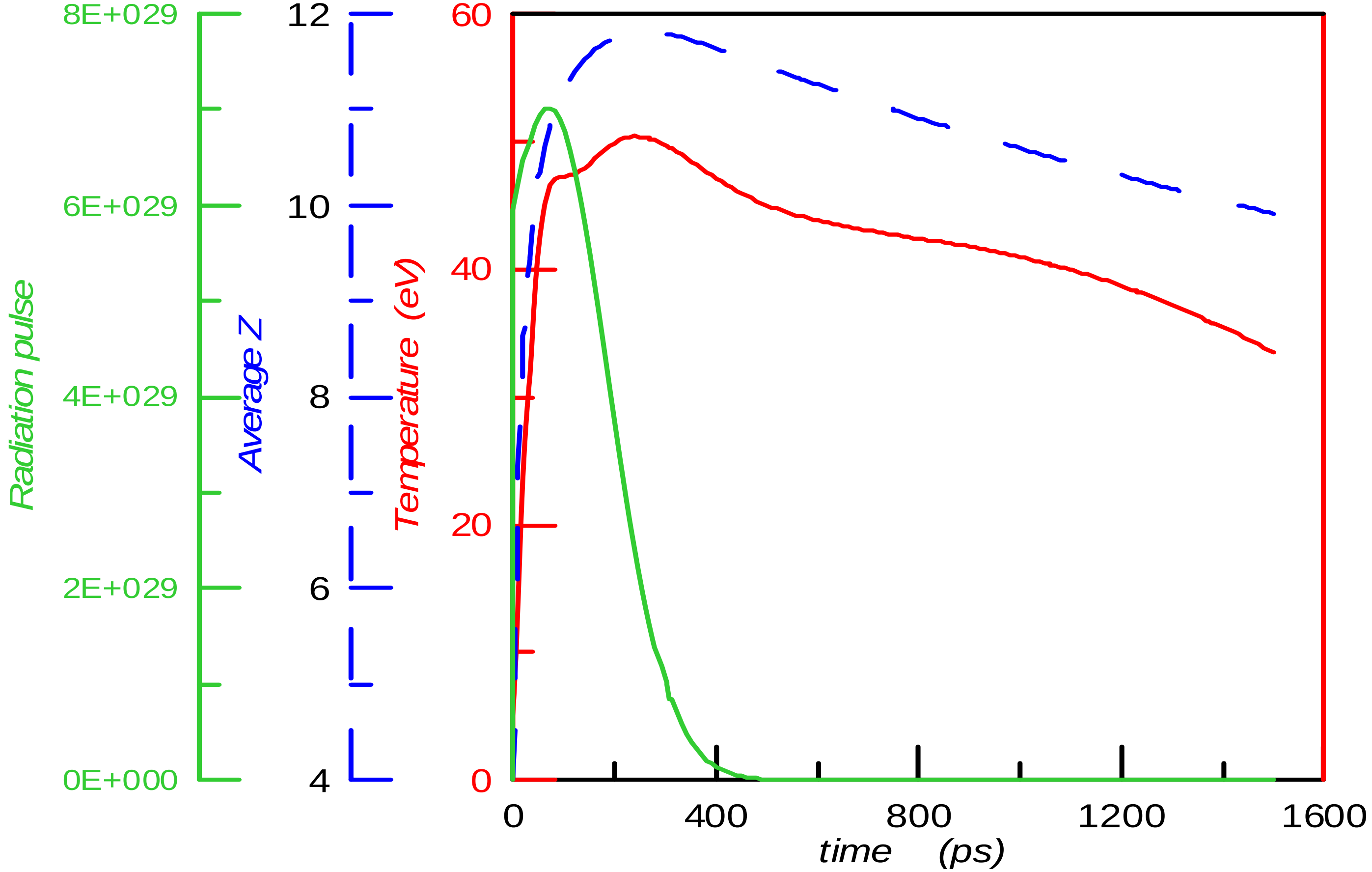
Principle of Laser Fusion

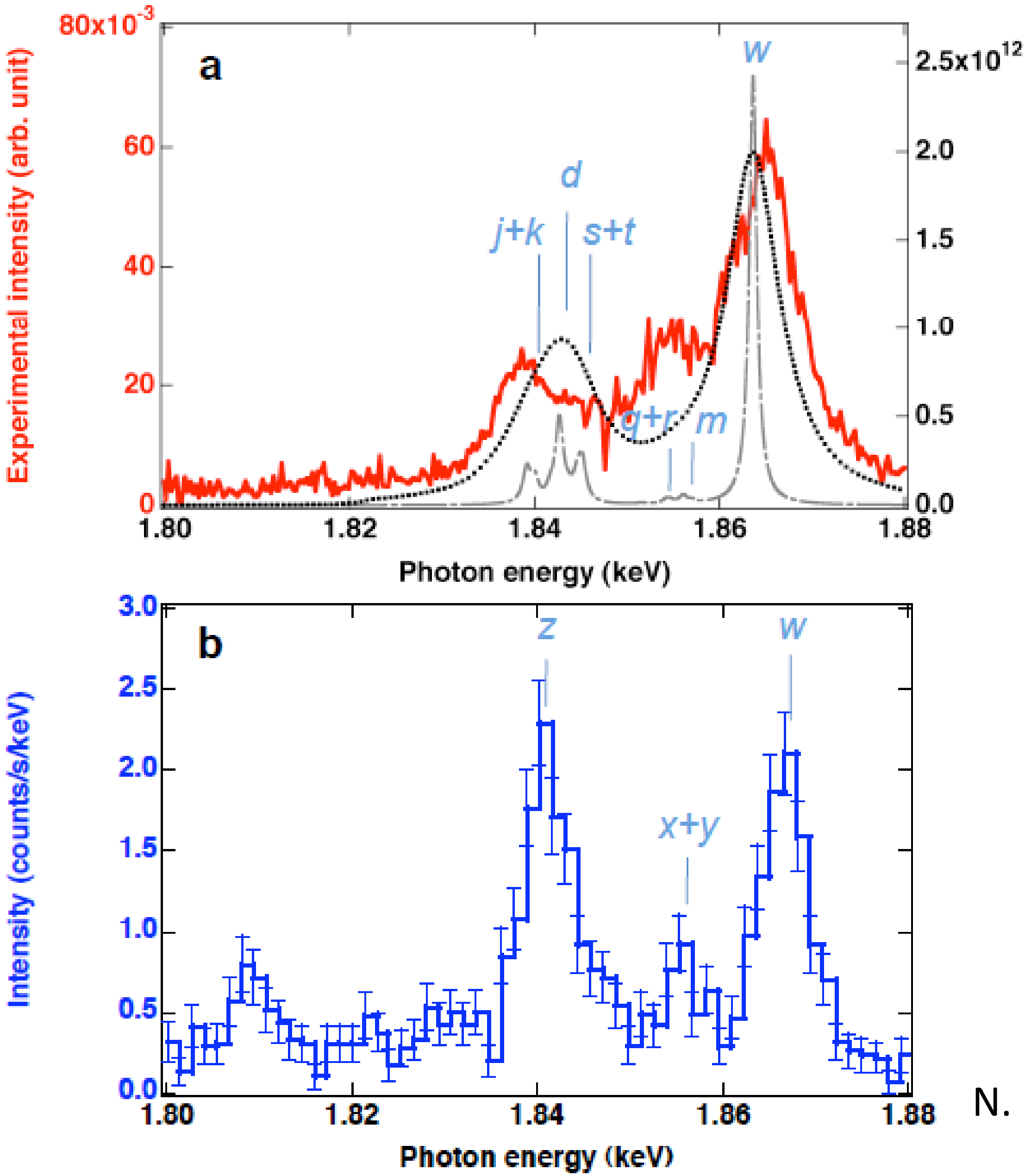


Mesured Radiation from Imploded Core



Time dependence of the laser pulse,
the electron temperature
and the average charge state





レーザー実験
データ

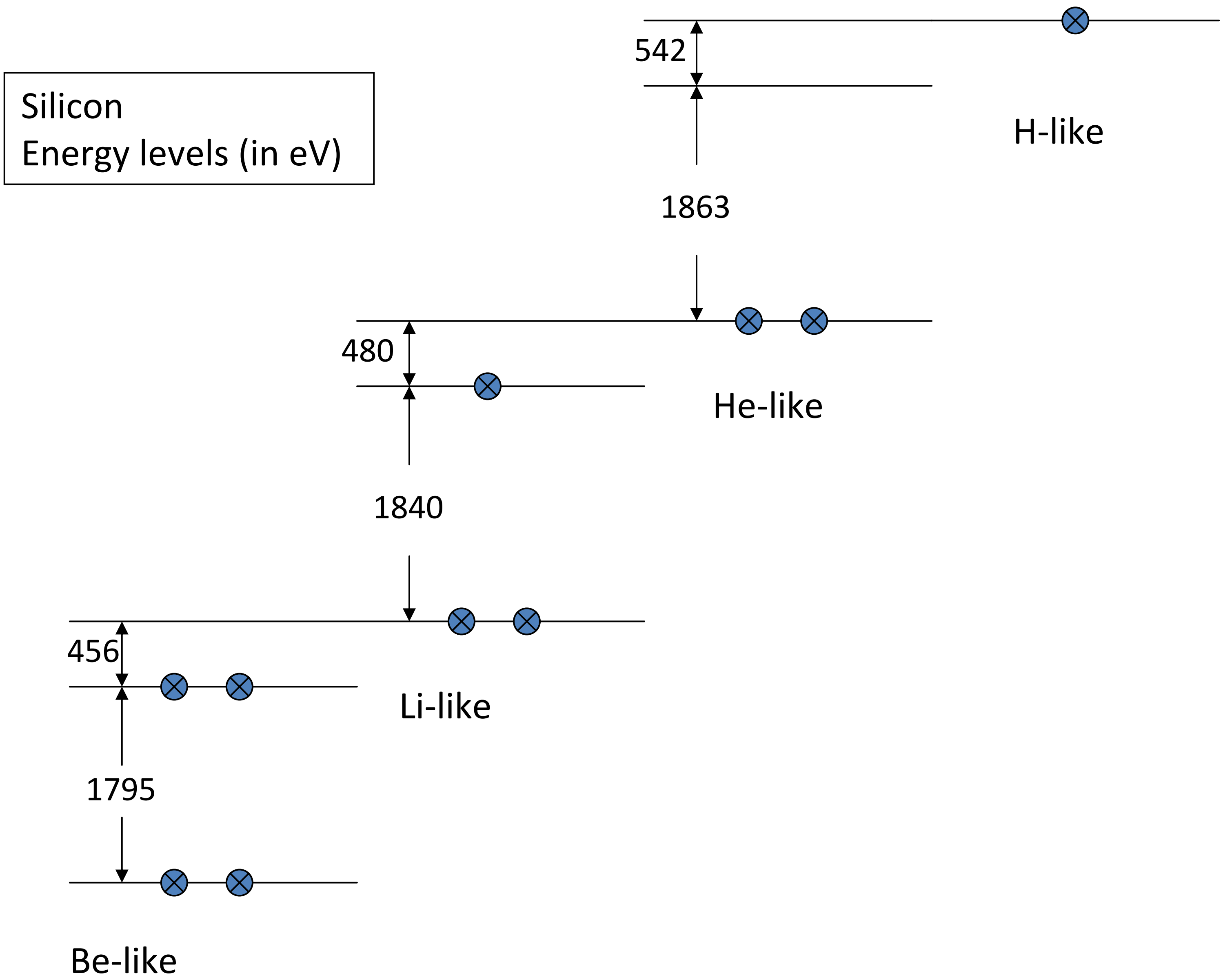
Chandra観測
データ

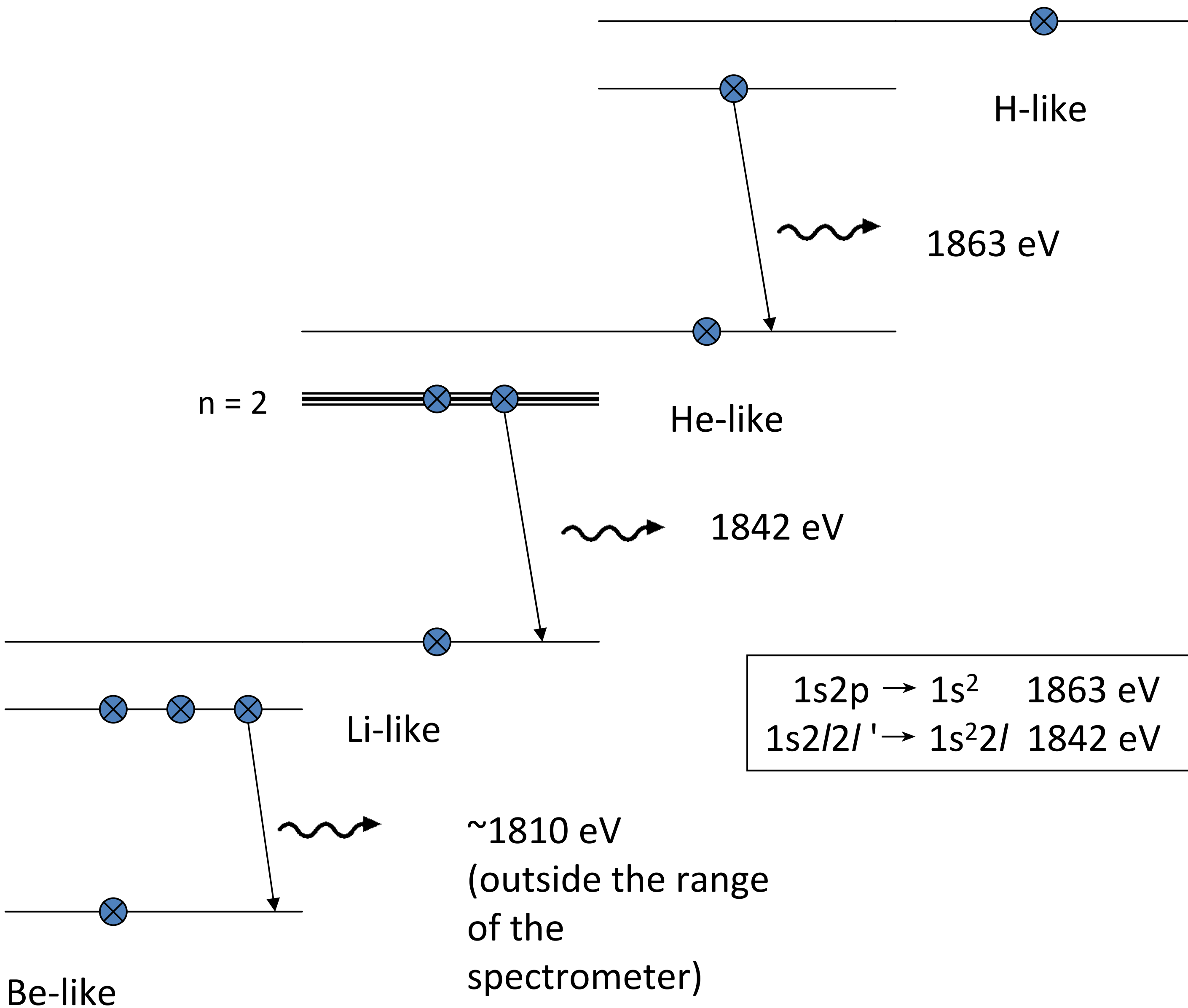
N. R. Schultz et al., ApJ 564; L21, 2002

Table 6.1 Annotation of the Individual Lines of the Satellite Spectrum of Helium-like Ion Resonance Lines

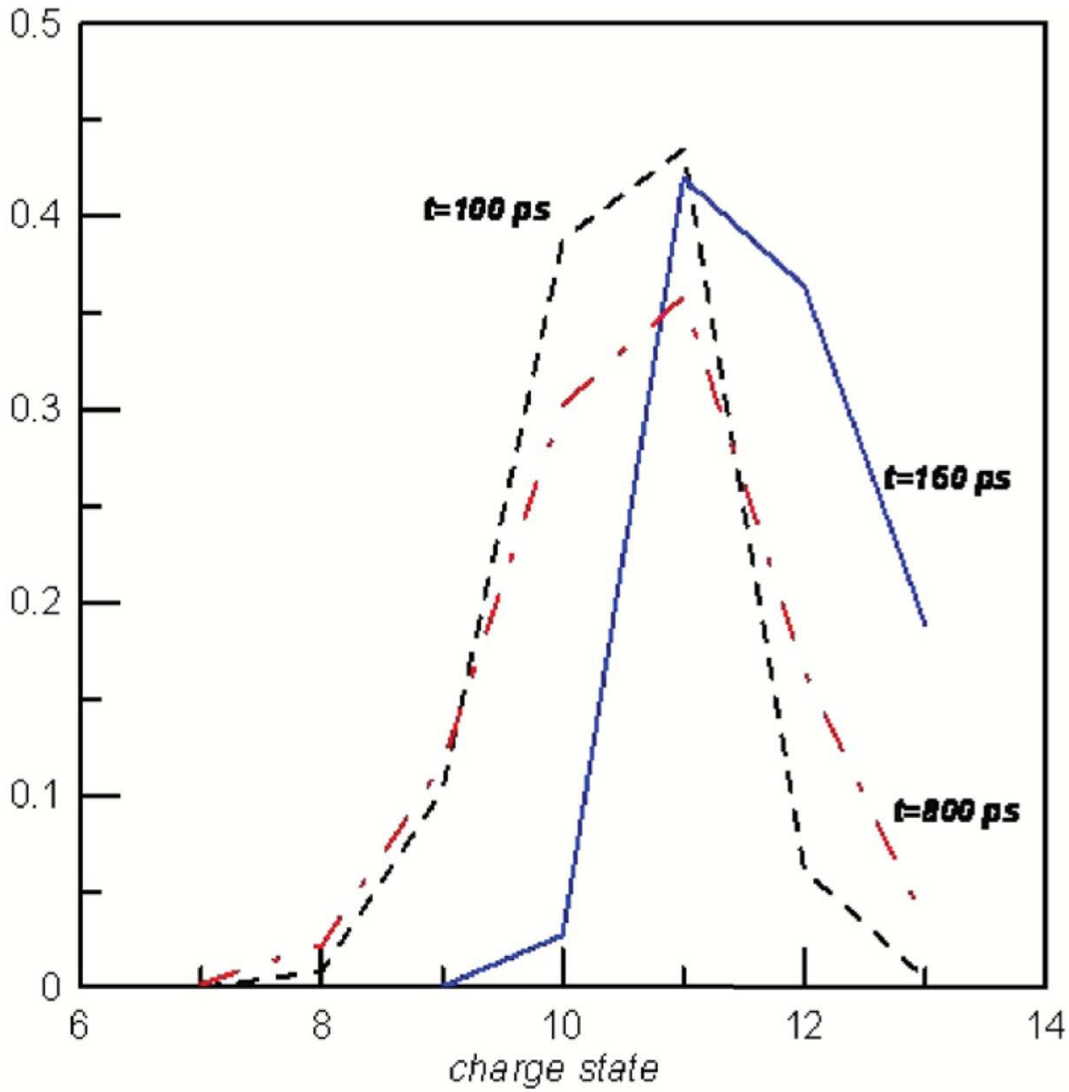
Array	Multiplet	Line	Key letter[a]
$1s^22p$–$1s2p^2$	$^2P^0$–^2P	3/2–3/2	a
		1/2–3/2	b
		3/2–1/2	c
		1/2–1/2	d
	$^2P^0$–^4P	3/2–5/2	e
		3/2–3/2	f
		1/2–3/2	g
		3/2–1/2	h
		1/2–1/2	i
	$^2P^0$–^2D	3/2–5/2	j
		1/2–3/2	k
		3/2–3/2	l
	$^2P^0$–^0S	3/2–1/2	m
		1/2–1/2	n
$1s^22p$–$1s2s^2$	$^2P^0$–^2S	3/2–1/2	o
		1/2–1/2	p
$1s^22s$–$1s2s2p$	^2S–$(^1P)^2P^0$	1/2–3/2	q
		1/2–1/2	r
	^2S–$(^3P)^2P^0$	1/2–3/2	s
		1/2–1/2	t
	^2S–$^4P^0$	1/2–3/2	u
		1/2–1/2	v
$1s^2$–$1s2p$	^1S–$^1P^0$	0–1	w
	^1S–$^3P^0$	0–2	x
		0–1	y
$1s^2$–$1s2s$	^1S–^3S	0–1	z

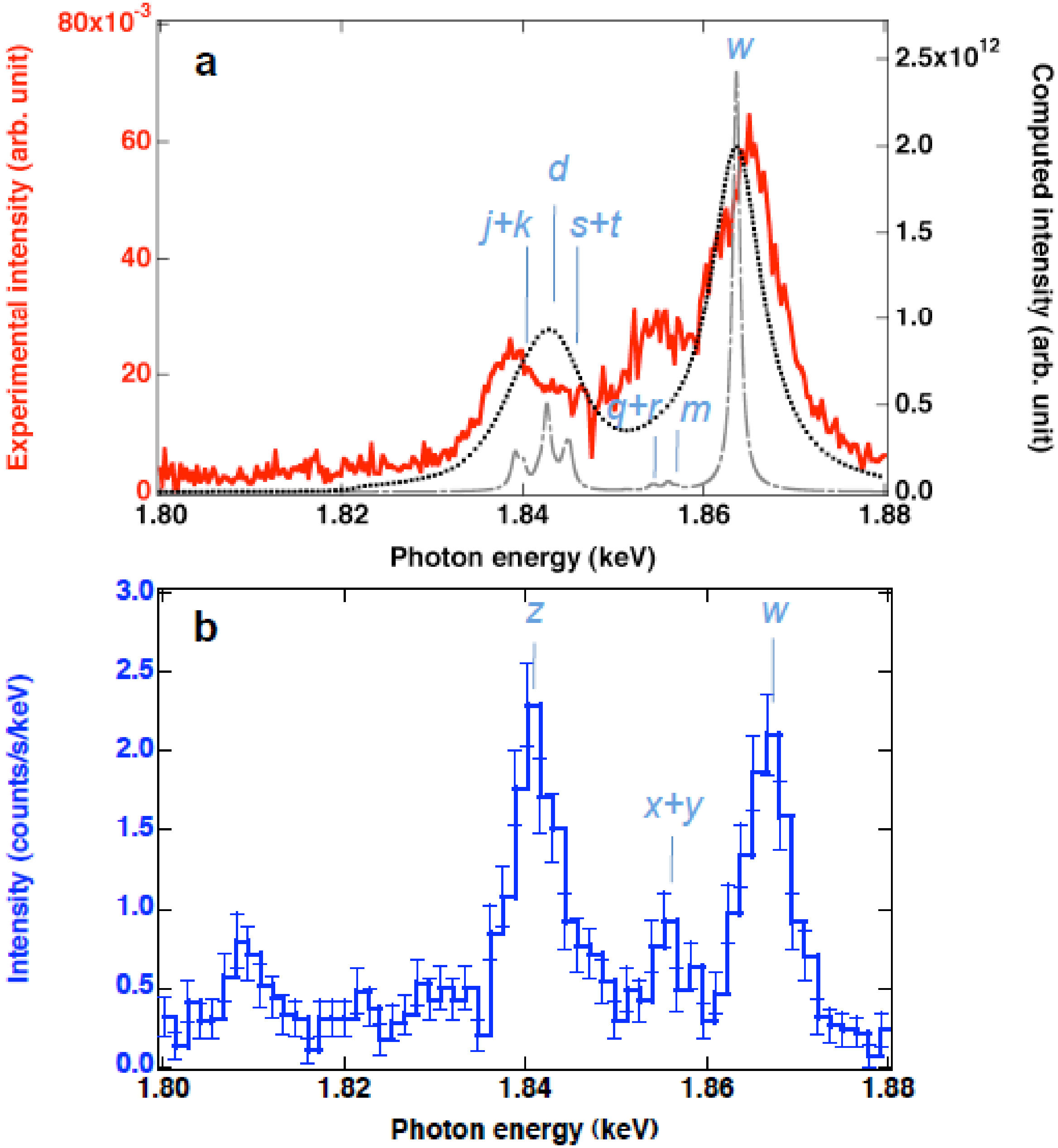
D. Salzman, Atomic Physics of Hot Plasmas, Oxford


Silicon
Energy levels (in eV)
542
H-like
1863
480
He-like
1840
456
Li-like
1795
Be-like



$1s2p \rightarrow 1s^2$	1863 eV	resonance
$1s2l2l' \rightarrow 1s^2 2l$	1842 eV	satellites


0.5
0.4
0.3
0.2
0.1
0
6
8
10
12
14
charge state
t=100 ps
t=160 ps
t=800 ps



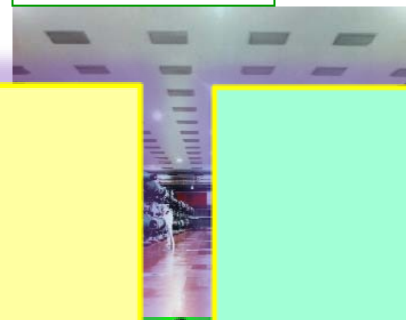
観測データと実験データの比較

まとめ

1. レーザー爆縮で0.5keVのプランク分布輻射源を実験室に再現
2. シリコンプラズマの光電離プラズマのスペクトルを分光計測
3. VELA X-1天体からのHe様スペクトルと比較
4. 共鳴線よりわずかに低エネルギーのラインの物理を議論
5. 禁制遷移なのか衛星線なのか？
6. 9/16　政井－ザルツマン勝負（審判：高部）

レーザー宇宙物理プロジェクトの国際共同研究推進

Osaka, JP

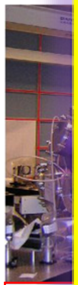


すでに国際共同実施中

英国（RAL: Vulcan)
仏国(LULI: LULI2000)
中国(SIOFM: Shingang II)

今後国際共同実施予定

米国（ロチェスター大学：OMEGA-EP）
米国（リバモア研：NIF）

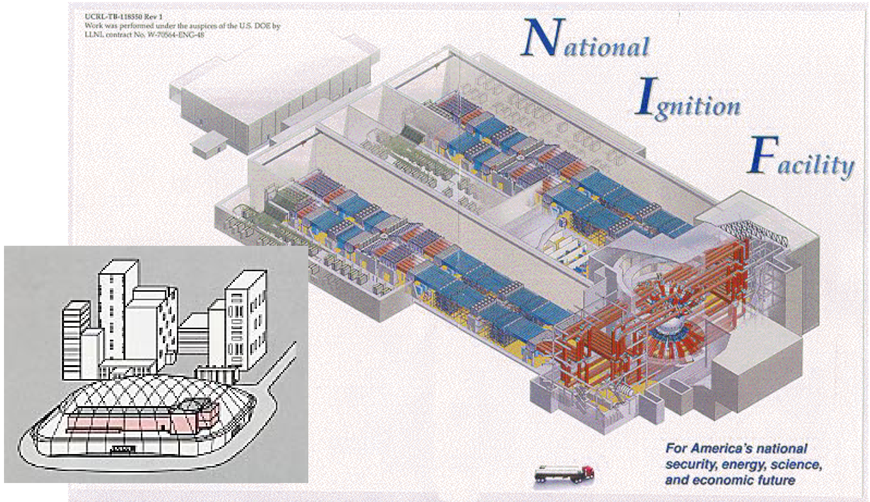


Ecole.P, FR

Shanghai, CN

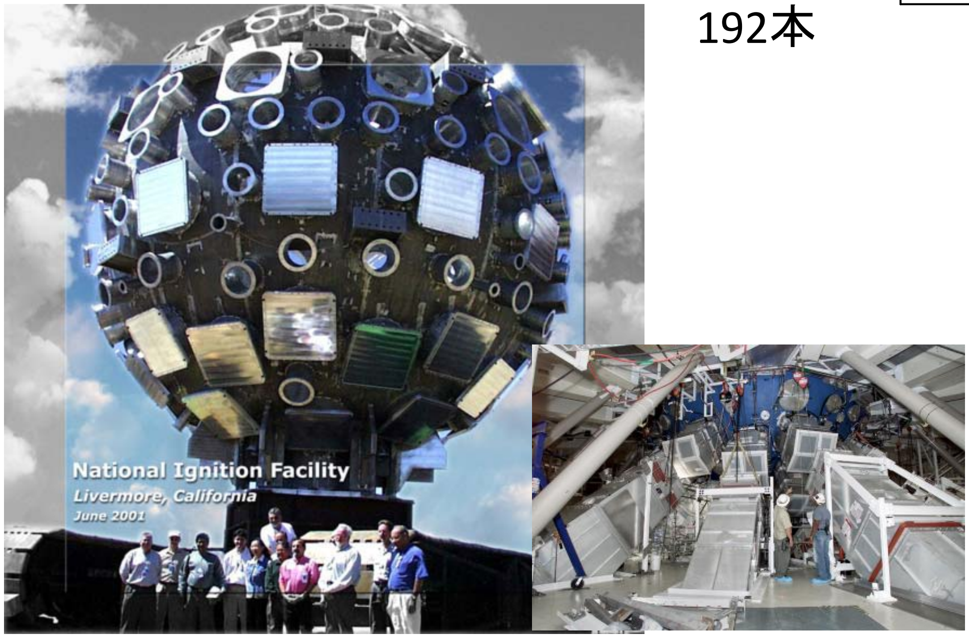
Livermore, US

世界の大型レーザー

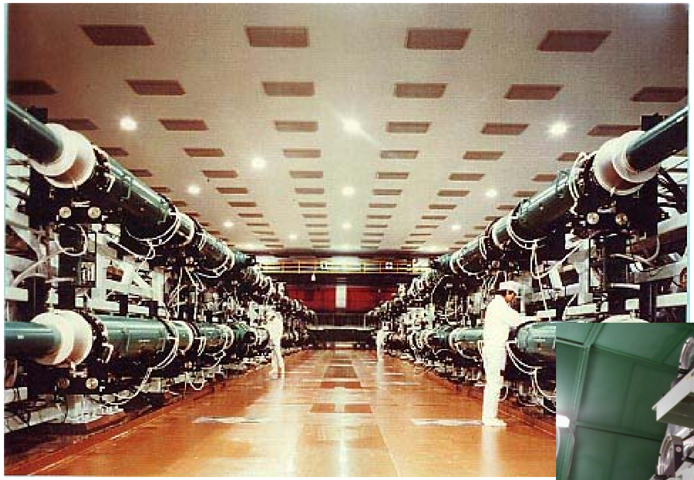


60本　30 kJ　U. Rochester, USA

192本



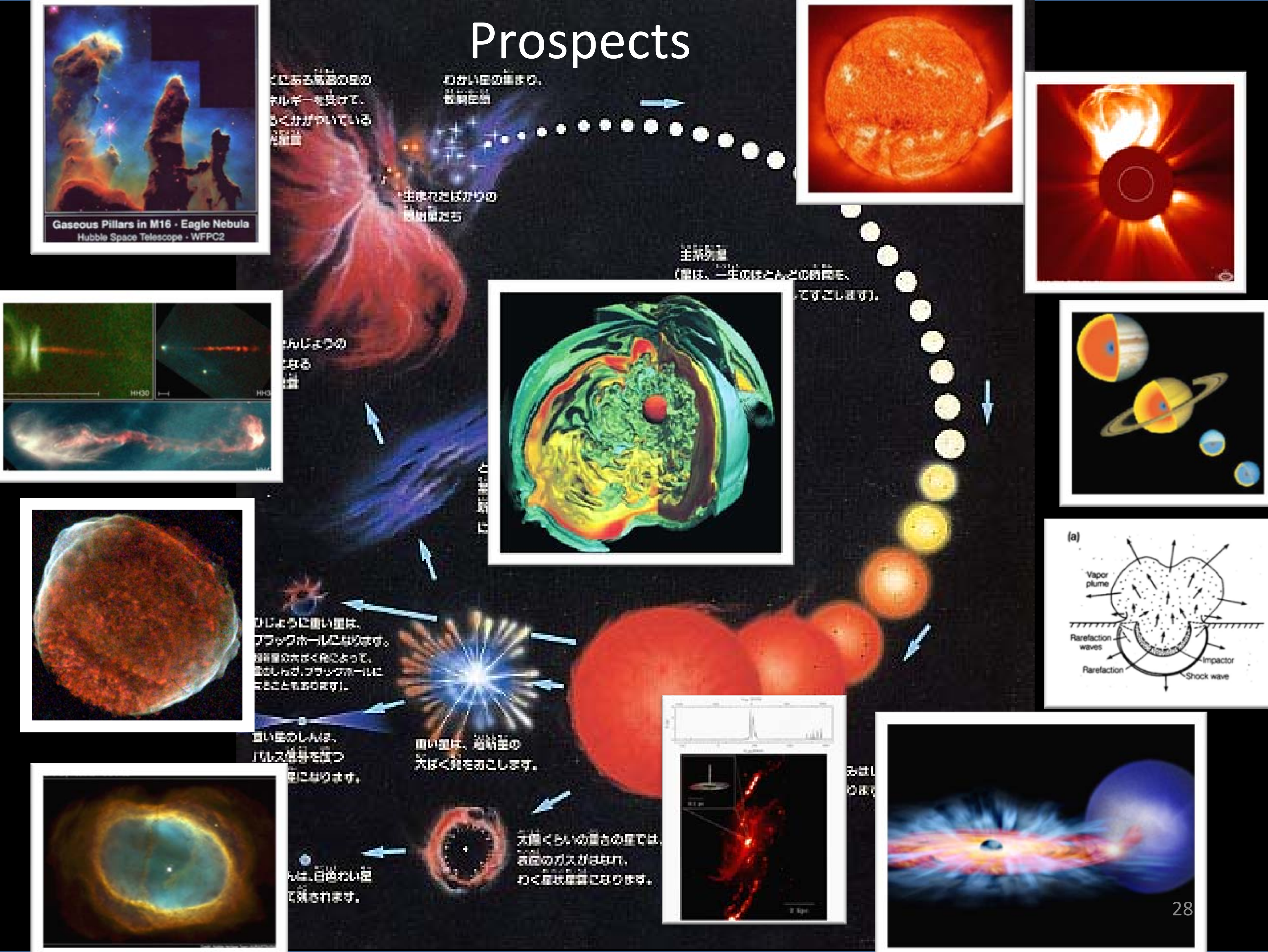
1800 kJ　LLNL, USA



10 kJ　Osaka

12本

Prospects


Gaseous Pillars in M16 - Eagle Nebula
Hubble Space Telescope - WFPC2
HH30
主系列星
ブラックホールになります。
重い星は、超新星の
大ばく発をおこします。
太陽くらいの重さの星では、
表面のガスがはがれ、
わく星状星雲になります。
(a)
Vapor plume
Rarefaction waves
Impactor
Rarefaction
Shock wave

1. High-Mach Number Collisonless Shock

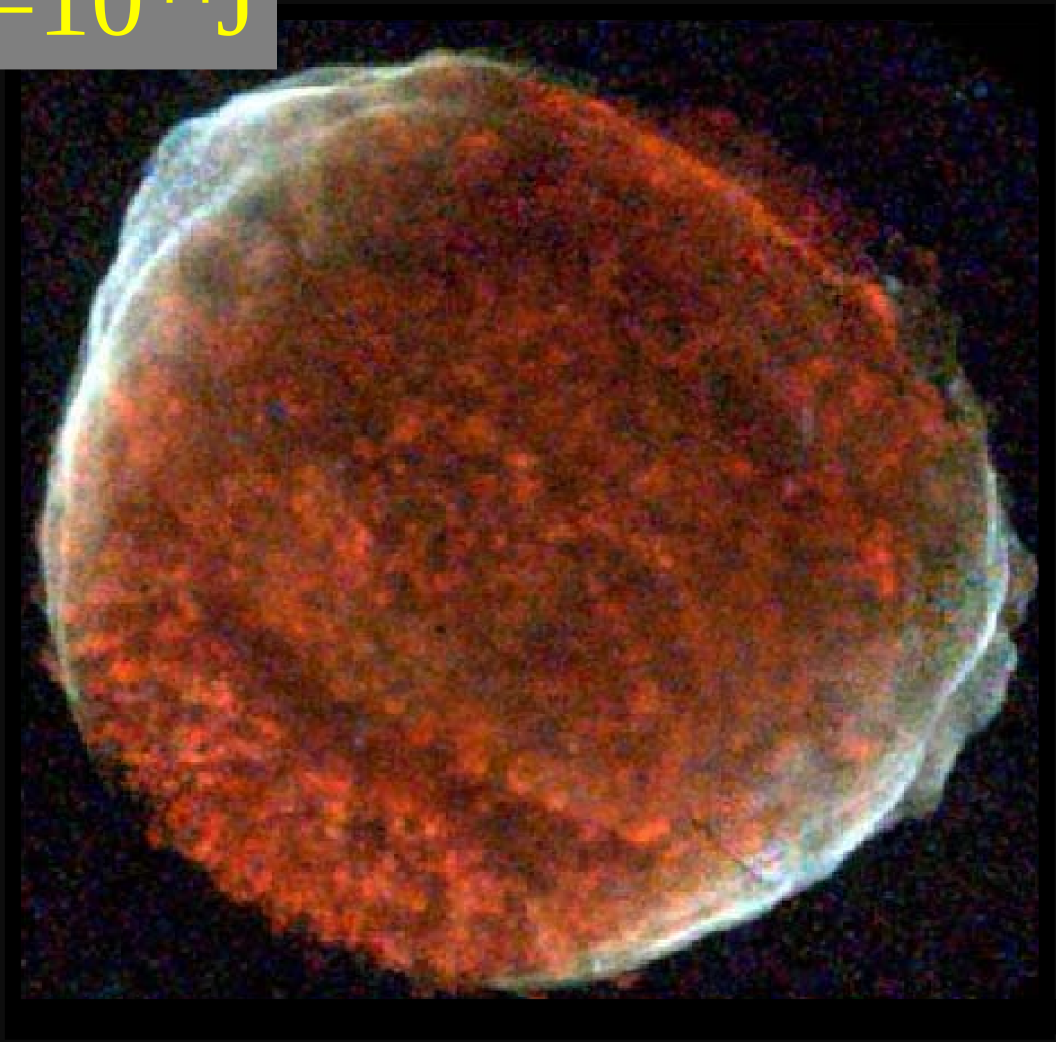
Theory & Simulation by T. N. Kato[1] *Experiment by*
Y. Sakawa[1], Y. Kuramitsu[1] and their group[1],
International Collaborators
M. Koenig[2] and his group[2], N. C. Woolsey[3] and his group[3]

Collaborators in Astrophysics
[4]M. Hoshino, [5]T. Tearasawa, [6]R. Yamasaki, [7]F. Takahara,
[8]A. Mizuta et al.

[1]Institute of Laser Energetics, Osaka University, Osaka 565-0871,Japan
[2]LULI, Ecole Polytechnique, Palaiseau cedex, 91128, France
[3]Department of Physics, University of York, Helington, YO105DD, UK
[4]Deaortment of Earth & Planetary Science, University of Tokyo, Hongo, Japan
[5]Department of Physics, Tokyo Institute of Technology,Ookayama, Japan
[6]Department of Physics, Hiroshima University, Saijo, Japan
[7]Department of Physics, Osaka University, Machikaneyama, Toyonaka, Japan
[8]Department of Physics, Chiba University, Chiba, Japan

Supernova Remnant
SN1006 (Newton X-ray S)

$E=10^{44}J$

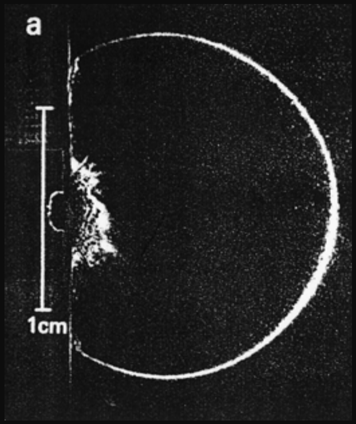


Cassam-Chenai et al.(‘08)

Synch. X-rays
(blue: tracing ~10TeV e^{-})

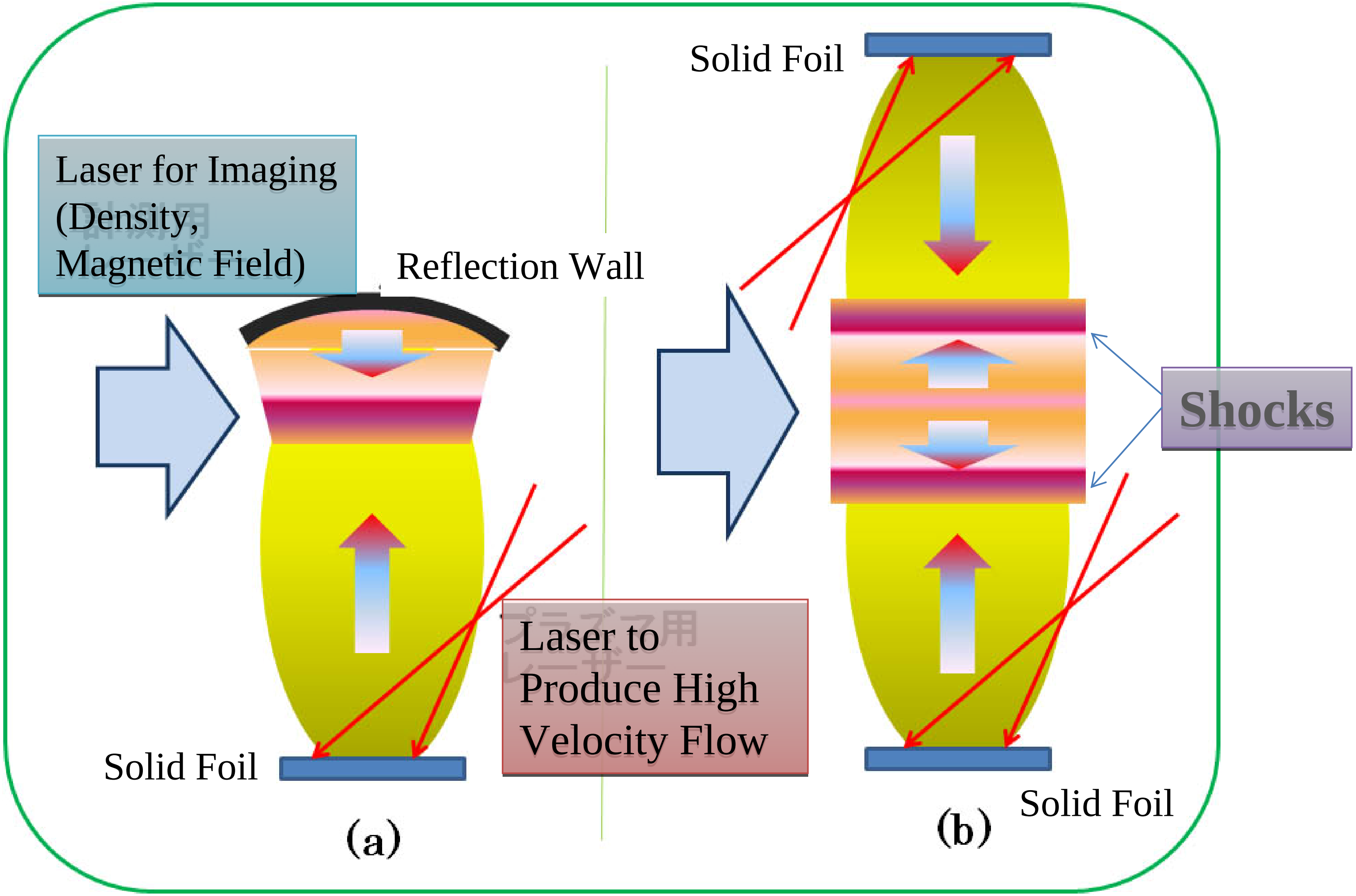
Big difference is not the energy
But the physics

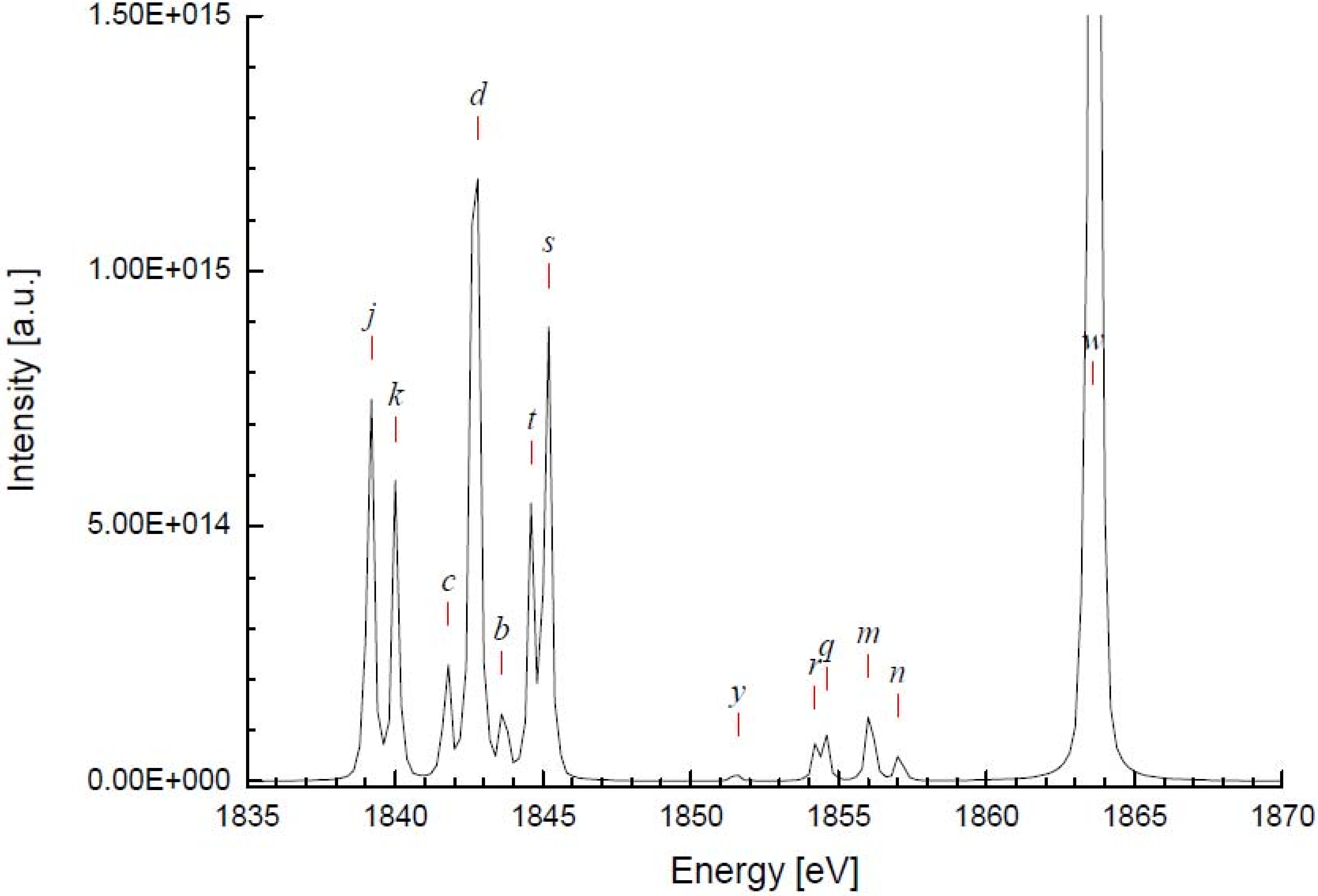
$E=100\ J$

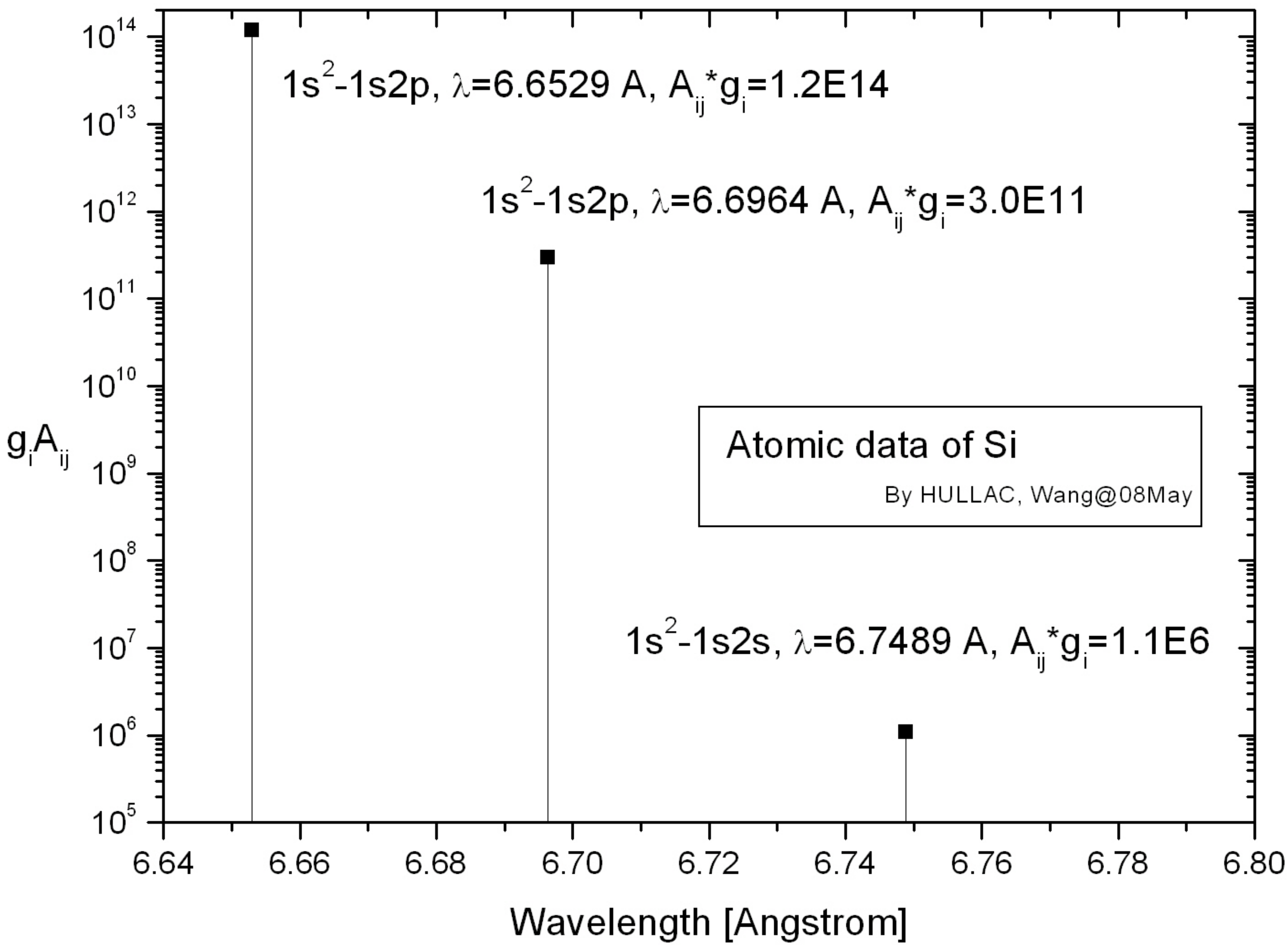


B. Ripin et al.

Model Experiments




1.50E+015
1.00E+015
5.00E+014
0.00E+000
Intensity [a.u.]
1835
1840
1845
1850
1855
1860
1865
1870
Energy [eV]
j
k
c
d
b
t
s
y
r
q
m
n
w



1s2-1s2p, λ=6.6529 A, Aij*gi=1.2E14
1s2-1s2p, λ=6.6964 A, Aij*gi=3.0E11
1s2-1s2s, λ=6.7489 A, Aij*gi=1.1E6
Atomic data of Si
By HULLAC, Wang@08May
giAij
10^14
10^13
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^5
6.64
6.66
6.68
6.70
6.72
6.74
6.76
6.78
6.80
Wavelength [Angstrom]

What are the relevant atomic processes:

Photoionization	y	
Radiative recombination	y	
Spontaneous decay	y	
Electron impact excitation and ionization	n	the free electrons do not have sufficient energy
Dielectronic recombination	n	-””-
3-body recombination	n	density too low
Photoelectron impact excitation and ionization	y/n	contribution less than 1%

Photoionization

$$\sigma_\zeta(\omega) = \begin{cases} \sigma_{K,\zeta}\left(\frac{B_{K,\zeta}}{\omega}\right)^{\gamma_K} + \sigma_{L,\zeta}\left(\frac{B_{L,\zeta}}{\omega}\right)^{\gamma_L} & \text{if } \omega \geq B_{K,\zeta} \\ \sigma_{L,\zeta}\left(\frac{B_{L,\zeta}}{\omega}\right)^{\gamma_L} & \text{if } \omega \geq B_{L,\zeta} \\ 0 & \text{otherwise.} \end{cases}$$

$$\frac{\text{photoionzations}}{cm^3 \cdot s} = X_0 n_\varsigma \sigma_{K0} F_\alpha\left(\frac{B_{K,\varsigma}}{T_r}\right)$$

$$F_\alpha(x) = \frac{1}{2\zeta(3)} x^\alpha \int_x^\infty \frac{y^{2-\alpha}dy}{e^y - 1}$$

$$\frac{\text{absorbed energy}}{cm^3 \cdot s} = I_0 n_\varsigma \sigma_{K0} G_\alpha\left(\frac{B_{K,\varsigma}}{T_r}\right)$$

$$G_\alpha(x) = \frac{15}{\pi^4} x^\alpha \int_x^\infty \frac{y^{3-\alpha}dy}{e^y - 1}$$

Equation of energy balance

(1) (2) (3)

$$\alpha I_0 J \delta t = n_e \sum_{\zeta=0}^{Z} R^{(r)}(T_e + \bar{B})\delta t + [n_A \delta T_e + \delta n_e T_e(t) + n_e(t)\delta T_e]$$

(4)

$$+ \left[\sum_{\zeta=0}^{Z} \left(N_\zeta(t+\delta t) - N_\zeta(t) \right) B_\zeta \right]$$

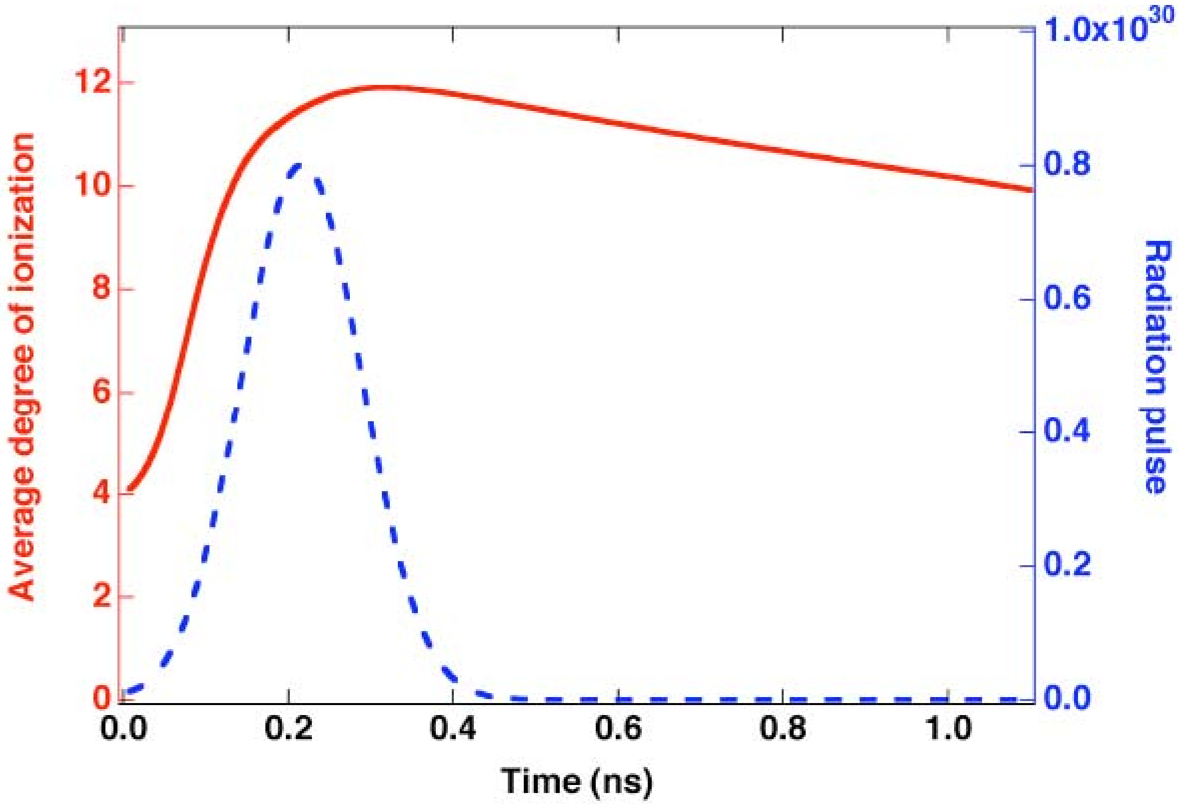
(1) Radiation absorbed from the field during dt;
(2) Emission through radiative recombination;
(3) Increase of thermal energy;
(4) Change in the internal energy.

$\Longrightarrow$ solve for $\dfrac{\delta T_e}{\delta t}$

Rate equations

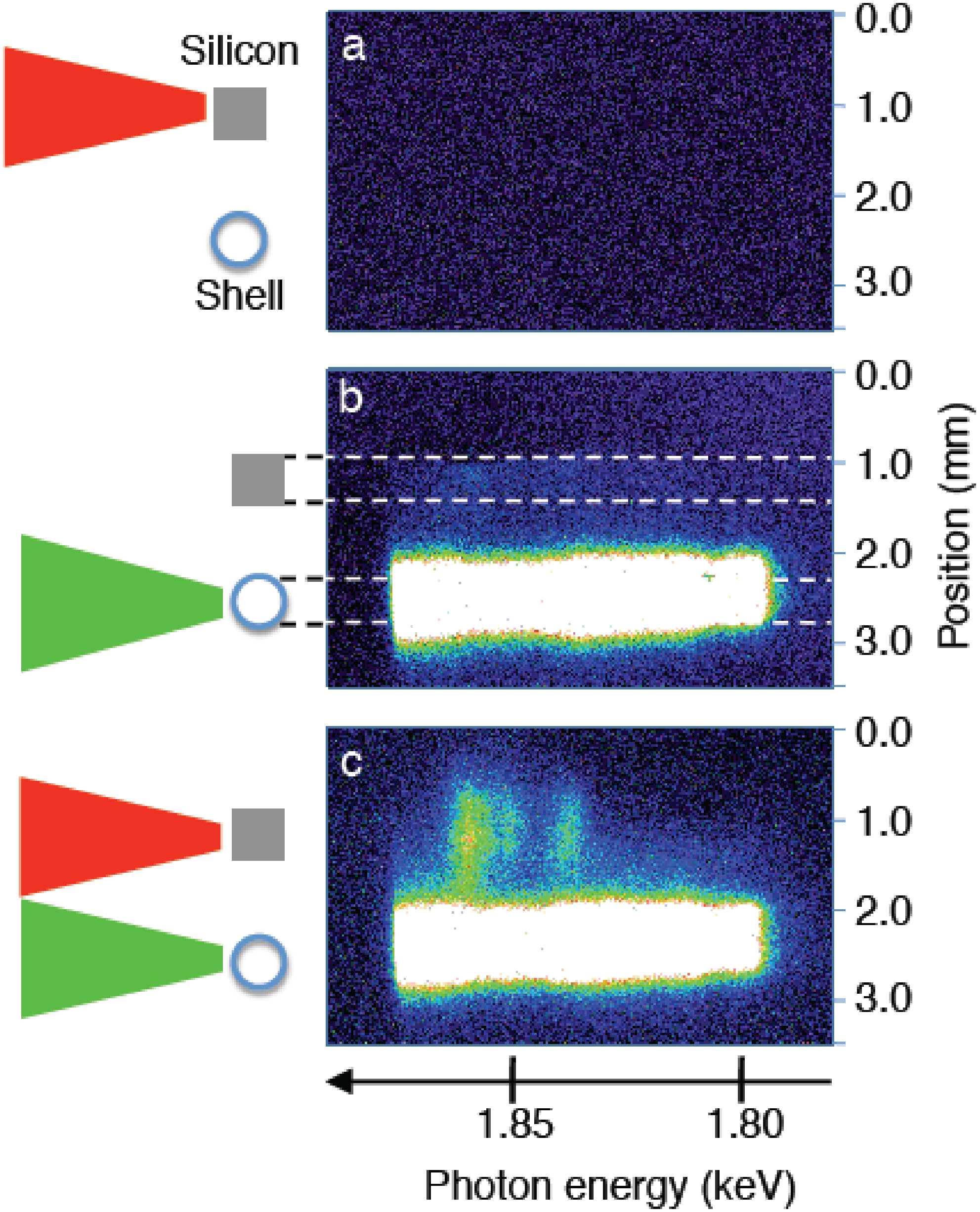
$$\delta N_\zeta \quad = \quad \delta t \Bigg[X_0(t) N_{\zeta-1} \int \sigma_{\zeta-1}(\omega) \Psi_X(\omega) d\omega - \alpha X_0(t) N_\zeta \int \sigma_\zeta(\omega) \Psi_X(\omega) d\omega$$

$$+ n_e N_{\zeta+1} R^{(r)}_{\zeta+1\to\zeta}(T_e) - n_e N_\zeta \; R^{(r)}_{\zeta\to\zeta}(T_e) \Bigg], \; \zeta = 0, \ldots, Z.$$

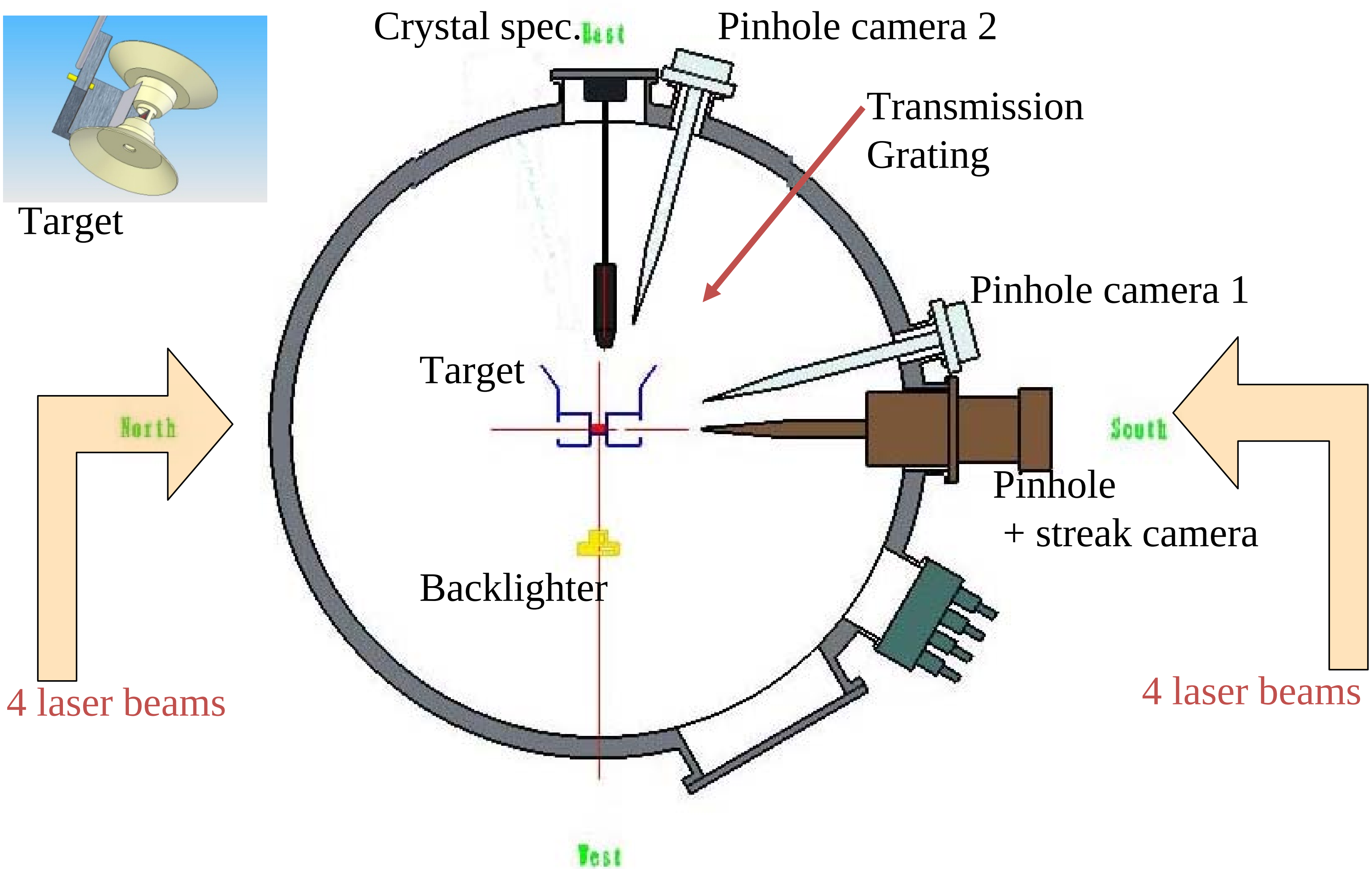


Average degree of ionization
Radiation pulse
Time (ns)
0.0
0.2
0.4
0.6
0.8
1.0
0
2
4
6
8
10
12
0.0
0.2
0.4
0.6
0.8
1.0x10^30

Experimental Data



Experiment Arrangement on Shengang II



Theoretical Model

Detailed term accounting (DTA) model

J. L. Zeng *et al. Phys. Rev. E 70 027401(2004); and references therein.*

Flexible Atomic Code (FAC)

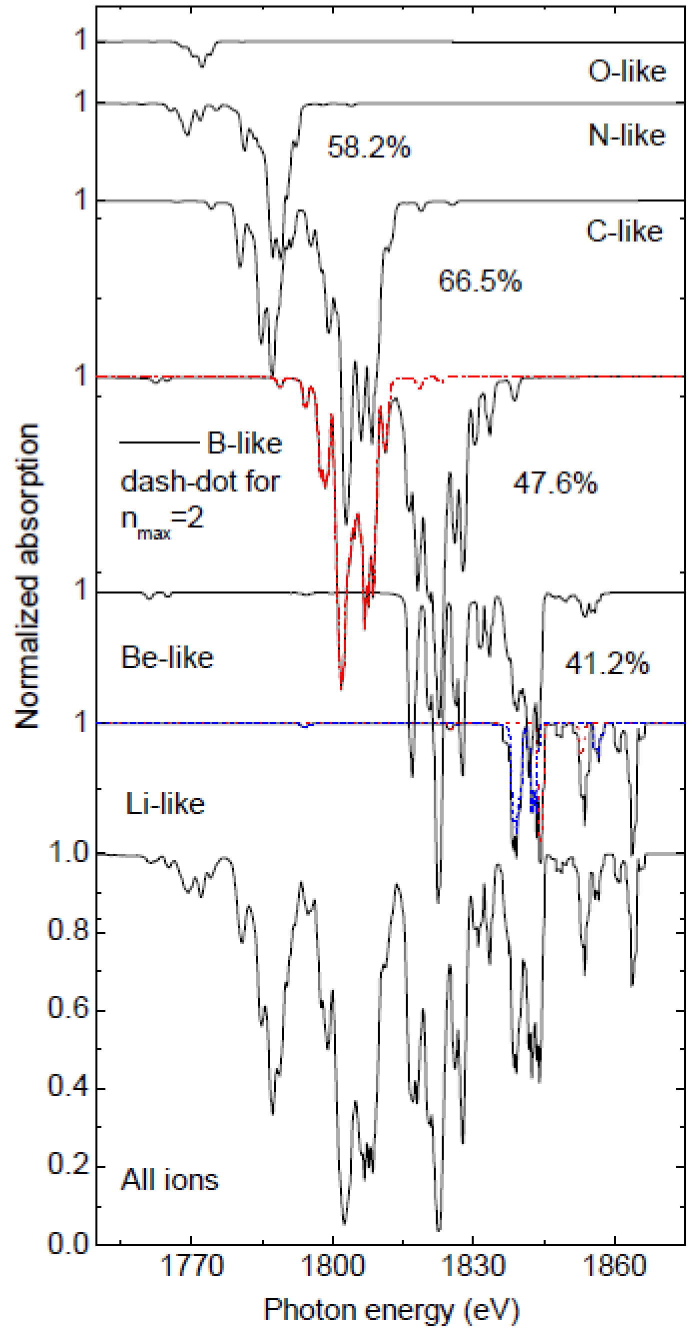
M. F. Gu, Astrophys. J. 597, 832(2003).

Line Profile

Voigt Profile

Natural, Doppler(0.2eV), Stark, and Autoionization resonance (~0.3eV) + Instrumental (0.89eV)

See Poster **8HE91** by Yutong Li et al.



- Rate equation
  - To describe the change of atom number of level (i,*l*) with time.
  - In unit time, the change of atom number of level (i,*l*) is equal to the arrived atoms minus left atoms.

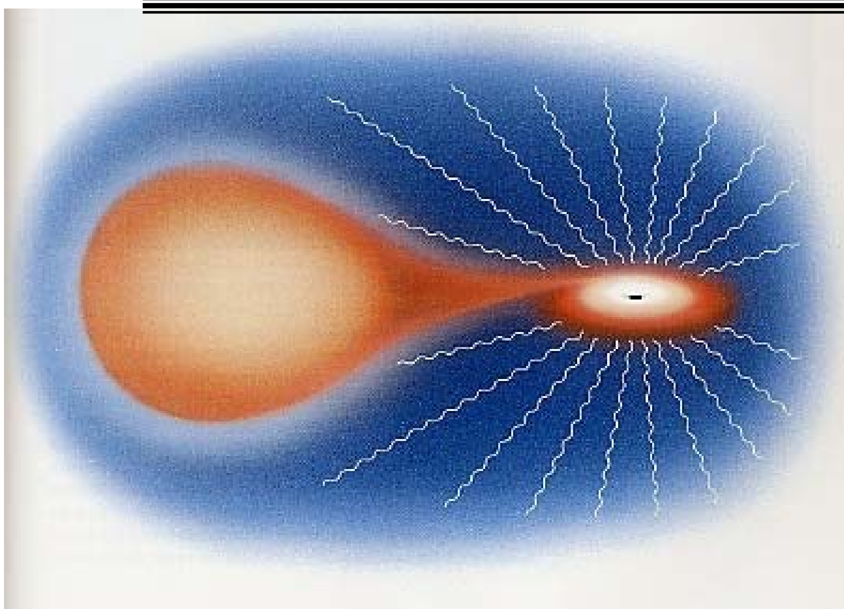
$$\frac{dN_i^l}{dt} =$$

+ IN …From other levels to (i,*l*) level

- OUT …From (i,*l*) level to others

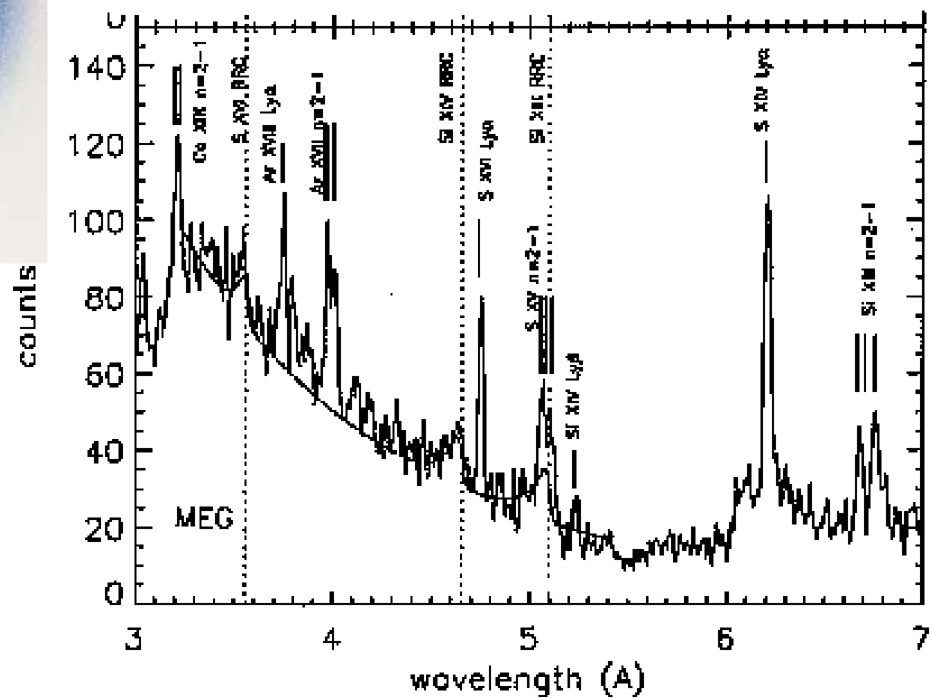
$$= -N_i^l R^{(PI+EII)l,i\to l+1,1} + N_1^{l+1} S^{(RR+E3R)l+1,1\to l,i} + \sum_{k>i} (A_{ki} + B_{ki} u_{h\nu} + R_{ki}^{(EIDE)l,k\to i}) N_k^l$$
$$- N_i^l \sum_{k>i} \left(B_{ik} u_{h\nu} + R_{ik}^{(EIE)l,i\to k} \right) - N_i^l \sum_{k<i} \left(A_{ik} + B_{ik} u_{h\nu} + R_{ik}^{(EIDE)l,i\to k} \right)$$
$$+ \sum_{k<i} \left(B_{ki} u_{h\nu} + R_{ki}^{(EIE)l,k\to i} \right) N_k^l + \sum_k R_k^{(PI+EII)l-1,k\to l,1} N_k^{l-1} \delta_{l,1} - N_1^l \delta_{l,1} \sum_k S_k^{(RR+E3R)l,1\to l-1,k}$$

X-ray from Companion Star of Cyg X-3



Chandra Observation

Photo-ionization by X-rays from BH



F. Paerels, et al., Astrophys. J. 533, L135 (2000).

阪大の新センターの理念

＝全国共同利用、学術融合型＝