Discovery Science with 4th Generation Light Sources

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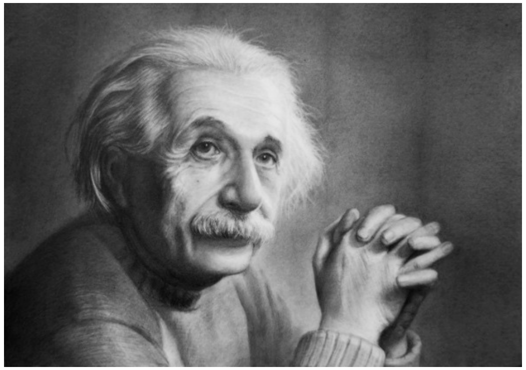
2015: International Year of Light

And Light-Based Technologies

- 1000 years from ‘Optics’ by Ibn al-Haytham
- 100 years from ‘General Relativity’ by Albert Einstein
- 50 years from ‘Optical Fiber Proposal’ by Charles Kuen Kao

Ibn al-Hytham
965-1040

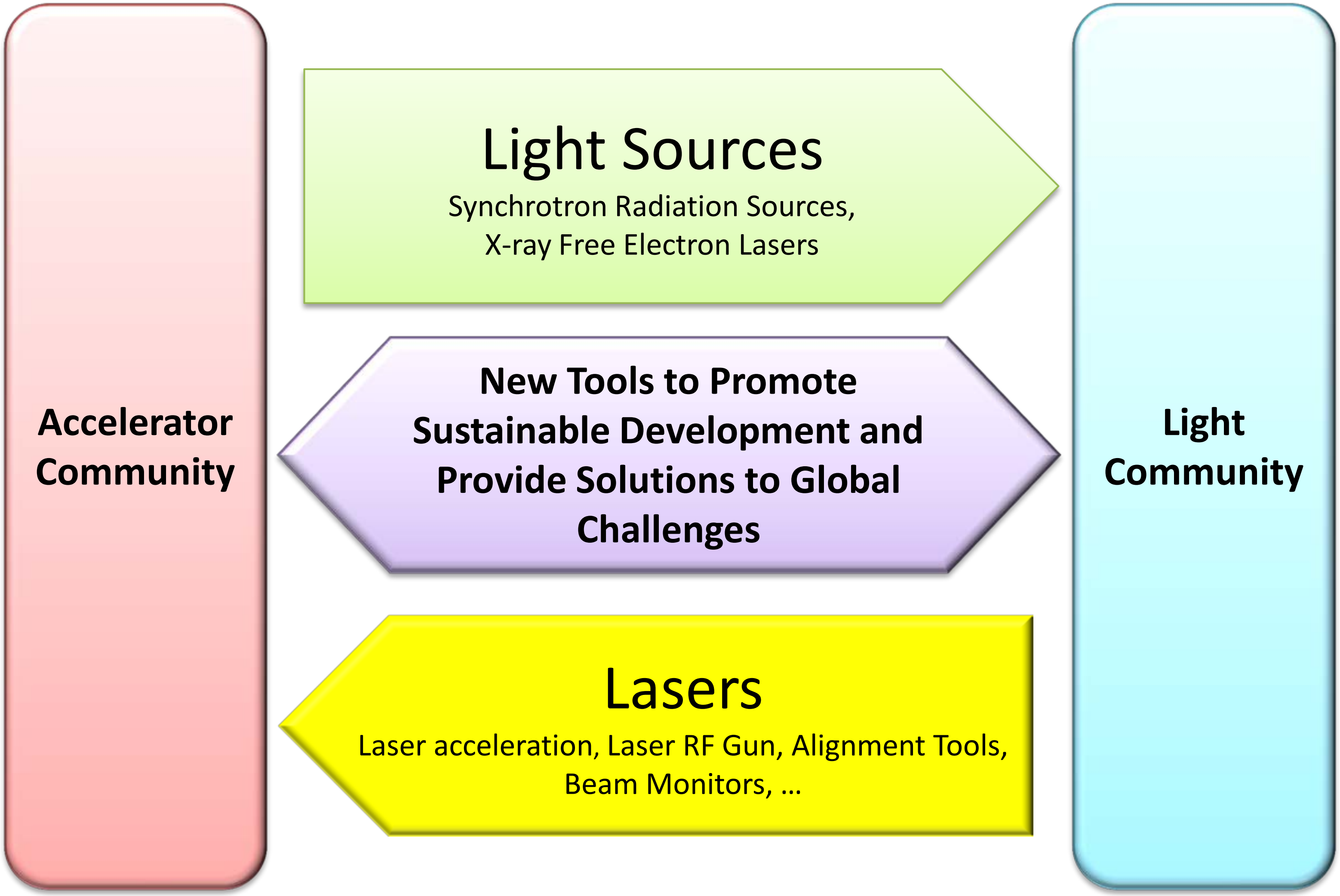


Albert Einstein
1879-1955
1921 Nobel Lauriate

Charles Kuen Kao
1933-
2009 Nobel Lauriate

In proclaiming an International Year focusing on the topic of light science and its applications, the UN has recognized the importance of raising global awareness about how light-based technologies ***promote sustainable development*** and ***provide solutions to global challenges*** in energy, education, agriculture and health.

Interdependence between Accelerator and Light Communities



Accelerator-Based Light Sources

A Short History (According to Prof. Herman Winick)

- 1945 First (indirect) observation of synchrotron radiation (SR) by J. Blewett, G.E. 100 MeV betatron
- 1947 First visual observation, G. E. 70 MeV synchrotron

0th Generation Sources

1950's-60's: Electron Synchrotrons (cyclic acclerators)

1st Generation Sources

1970's: e+/e- Colliders (Mostly Parasitic on HEP programs)

2nd Generation Sources

1980's: New Rings and Fully Dedicated Use of e+/e- Colliders, Use of Wigglers & Undulators

3rd Generation Sources

1990's: Low Emittance Rings with Many Straight Sections

4th Generation Sources, *Not yet well-defined*

2000's: Linac-Based Light Sources

X-ray Free-Electron Laser (XFEL)

Energy Recovery Linac (ERL)

Diffraction-Limited Rings, New Ideas

Accelerator-Based Light Sources

An In-depth History

3rd Generation Sources

1990's: Low Emittance Rings with Many Straight Sections
Optimized for the ***Use of Undulators***

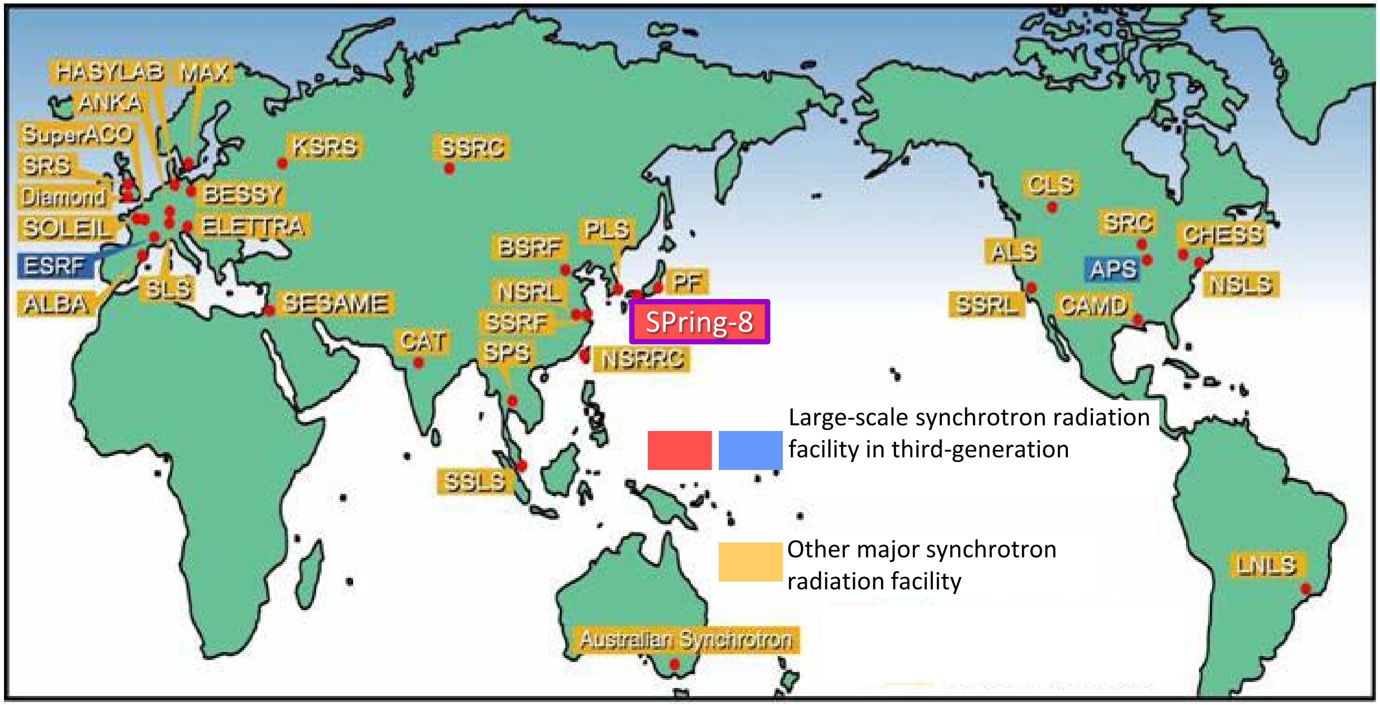
Grenoble, France
1994~
6.0 GeV
Circumference 844 m

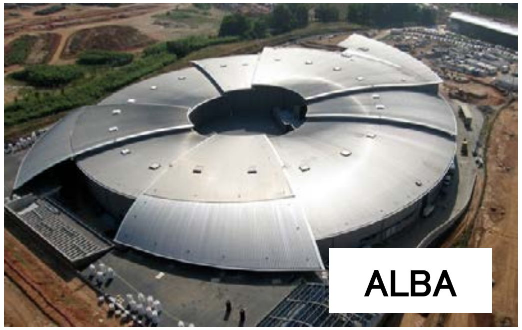
Argonne, USA
1996~
7.0 GeV
Circumference 1,104 m

Harima, Japan
1997~
8.0 GeV
Circumference 1,436 m

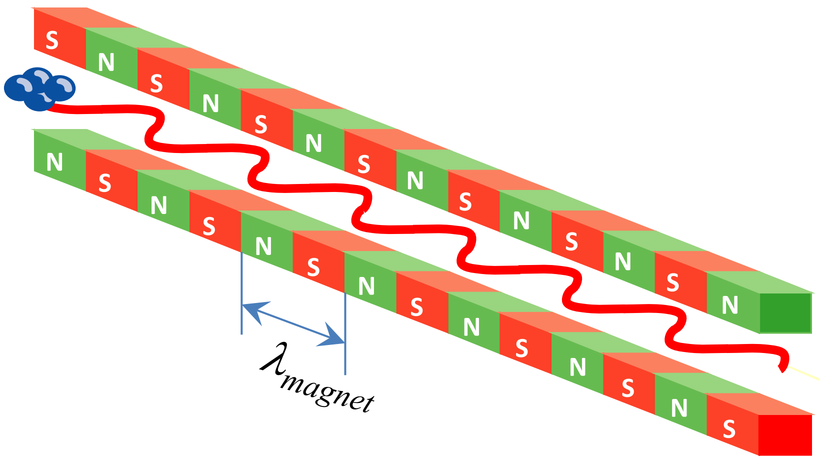
In early 1990's when we designed the third generation Synchrotron Light Sources which emit hard X-rays with undulators, everyone believed electron beam energy of **more than 6 GeV** to be absolutely necessary.

2000's: Downsizing of SR Facilities





Progress in Undulators

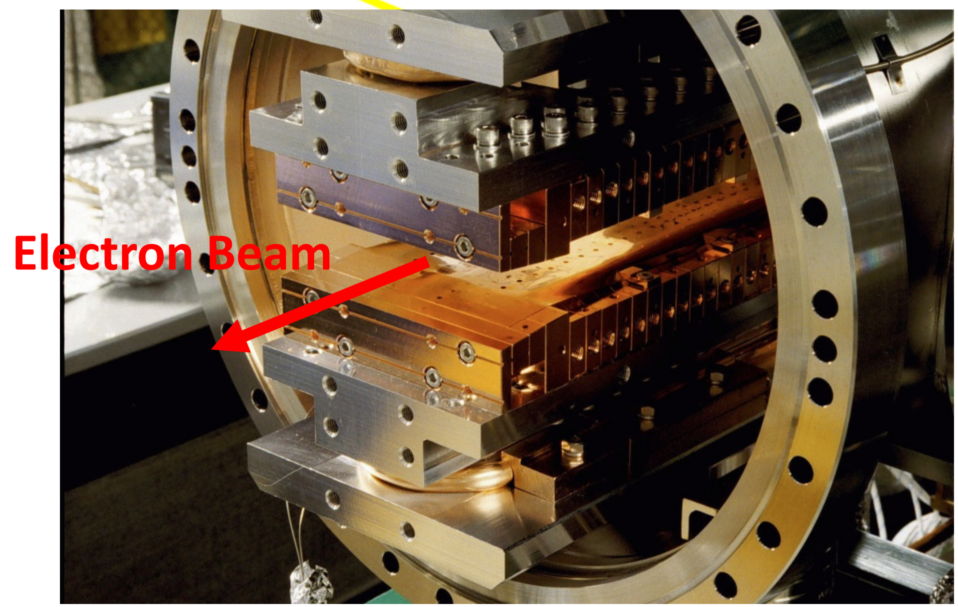


first harmonic wavelength:

$$\lambda_{photon} = \frac{\lambda_{magnet}}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

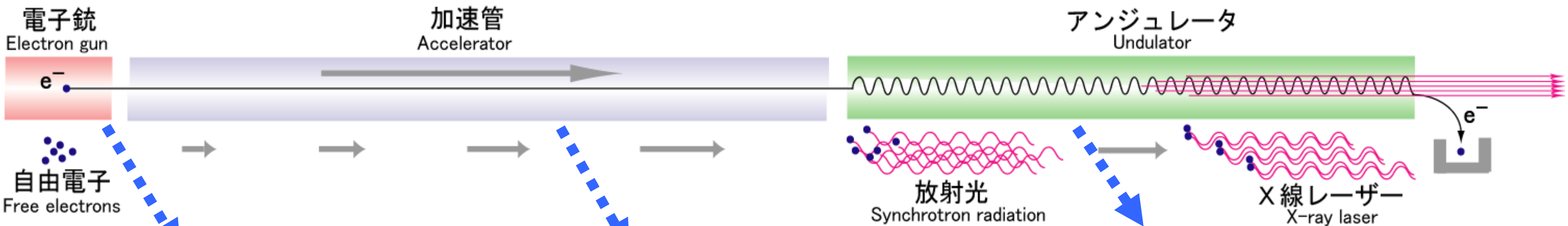
$$\gamma = 2,000 \times E(GeV)$$

- Early design of undulators has a UV duct for e-beam between magnetic poles, prohibiting short λ_{magnet} to generate magnetic field at the e-beam position.
- Early undulators did not have enough uniformity of the magnetic field to generate bright higher harmonics.
- In-vacuum design could circumvent the difficulty to achieve the higher frequency undulation of electron beam.

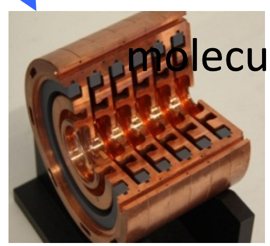


The Same Paradigm Shift in XFEL

- Short-period, in-vacuum undulators can reduce the electron energy to generate XFEL light with a certain photon energy.
- SPring-8 Angstrom Compact Laser (SACLA) is the world's first XFEL based on this 'compact' concept.

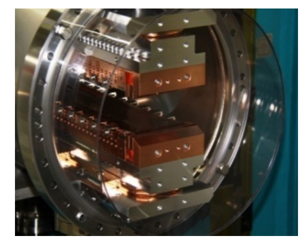


CeB6 thermionic e-gun

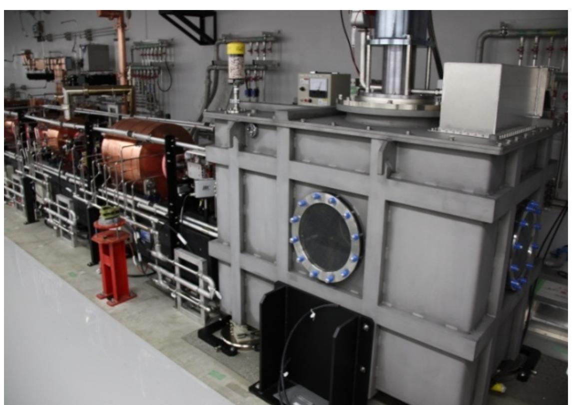


molecule

C-Band (5712 MHz) acceleration tube



In-vacuum undulator

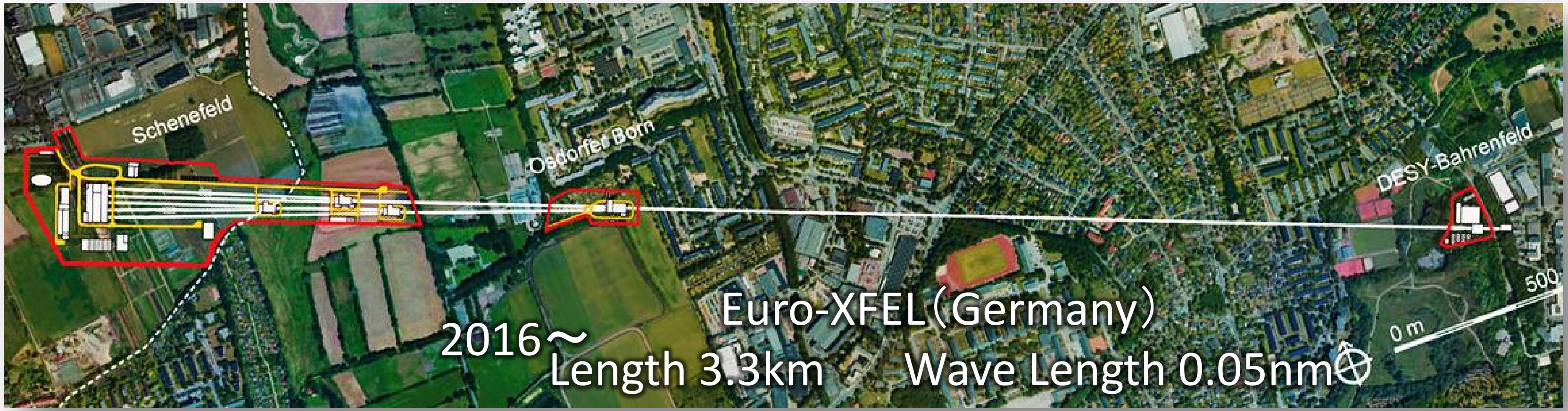


Thermionic e-gun to generate high-quality electron beam

High-gradient C-band accelerator

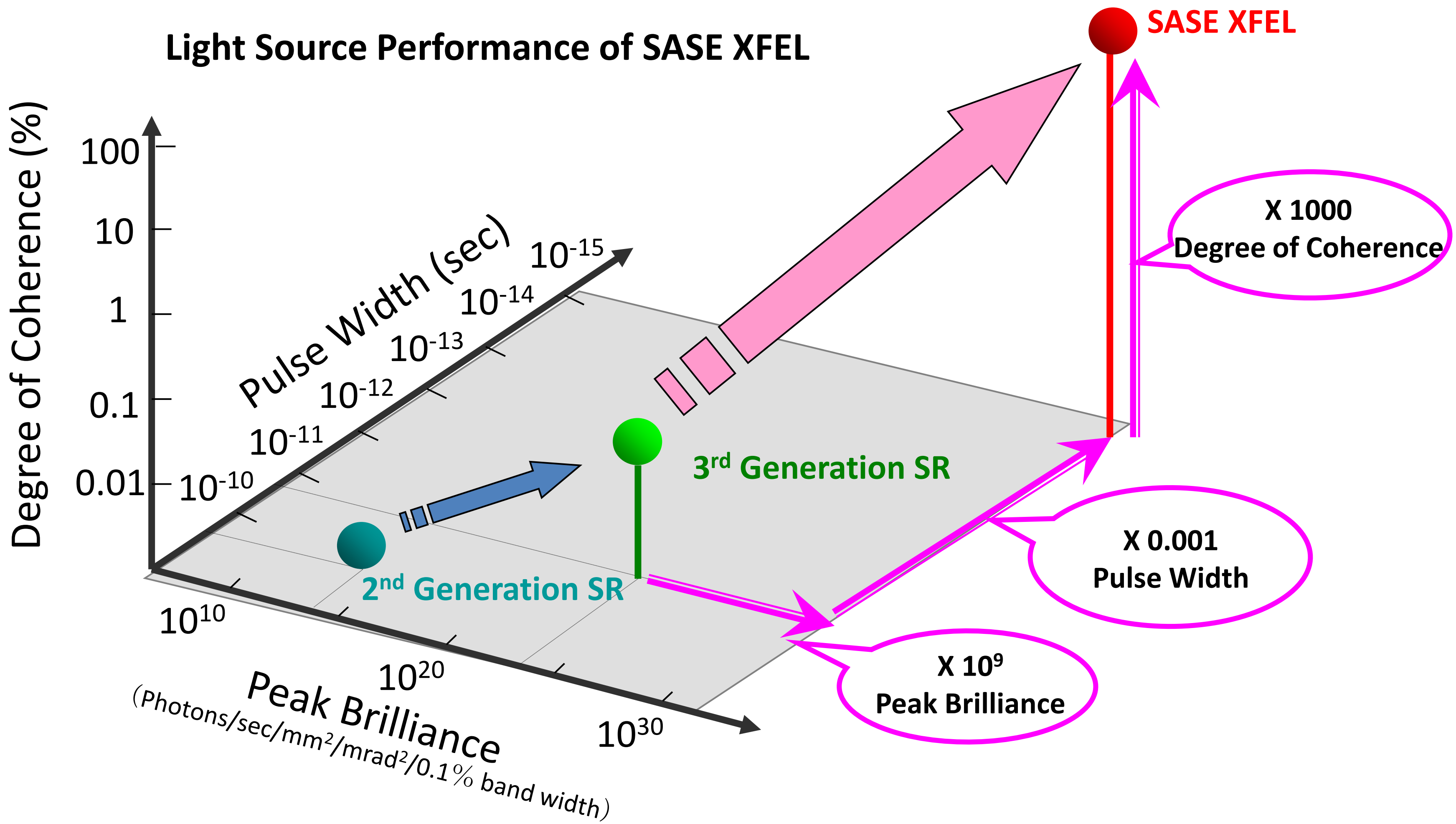
In-vacuum undulator to produce SASE FEL

SACLA: A Compact XFEL with In-vacuum Undulators



2010～ SACLA(Japan)
Length 700m Wave Length 0.06nm

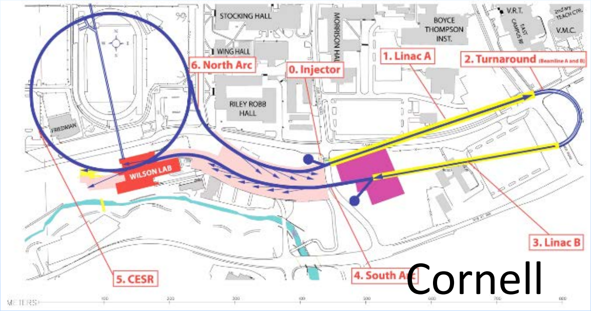
SASE XFELs may not be the 4th Generation SR

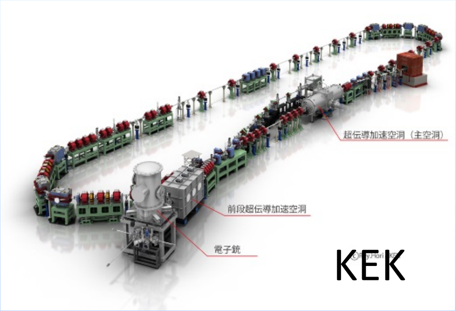


- Samples are often damaged by the irradiation with intense XFEL pulses
- As yet, sample status before damage occurring can be recorded because of ultrafast pulse.
- Many of the experiments currently conducted at 3rd generation sources cannot be done with XFEL because of the difference of the light nature.

Other Ways toward 4^{th} Generation SRs

Energy Recovery Linac (ERL)





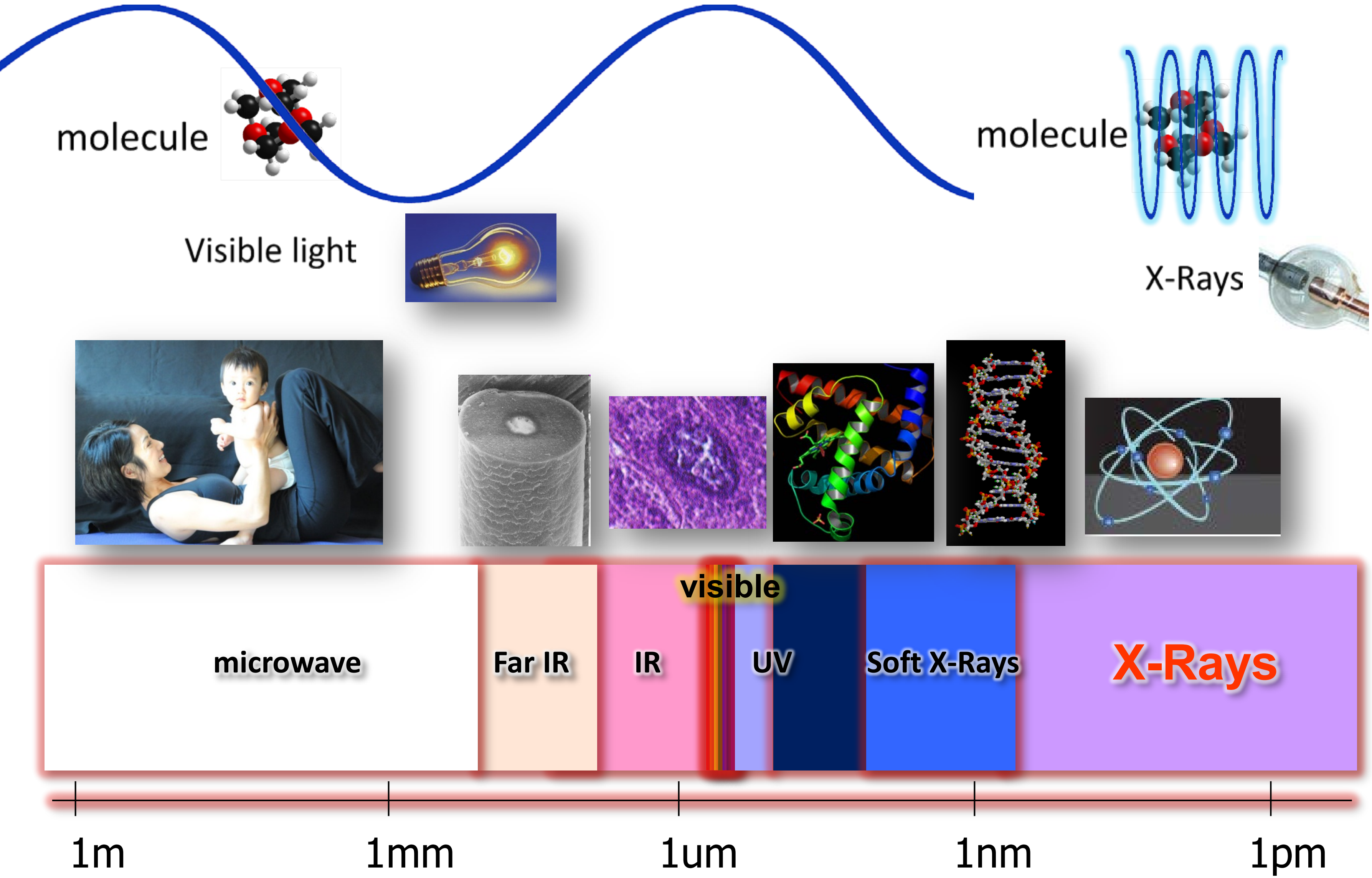
Diffraction Limited Storage Rings (DLSR)

Multi-Bend Achromat (MBA) with Hybrid Dipole Magnets

Target emittance of 0.1 nmrad or less

To See Invisible with Invisible Light

X-rays are the light for exploring the nano-world.



XFEL and SR

XFEL

- High peak brilliance with fs pulses
- Applicable for small, complex samples
- Measure-before-destroy

- Sample will be damaged in a single shot

Get dynamic feature

Answers to why new functions emerge from a particular combination of atoms.

SR

- High average brilliance w high rep rate
- Deliver X-rays to dozens of beamlines
- Moderate peak intensity

- Sample will not be damaged in a single shot
- Sample change can be traced

- Suitable for extracting information with correlation techniques (CT, time-course)

Get precise figure

Here, Let Me Remind You of the Earlier Slide…

United Nations
Educational, Scientific and
Cultural Organization

INTERNATIONAL
YEAR OF LIGHT
2015

In proclaiming an International Year focusing on the topic of light science and its applications, the UN has recognized the importance of raising global awareness about how light-based technologies ***promote sustainable development*** and ***provide solutions to global challenges*** in energy, education, agriculture and health.

- Complementary use of XFEL and SR will open a new regime of X-ray Science.
- To give the answers to 'Whys' in the atomic scale could contribute to promote sustainable development and to provide solutions to global challenges.
- We have prepared an environment where you can guide both XFEL and SR to your sample at the same time.

Help Promote Sustainable Development

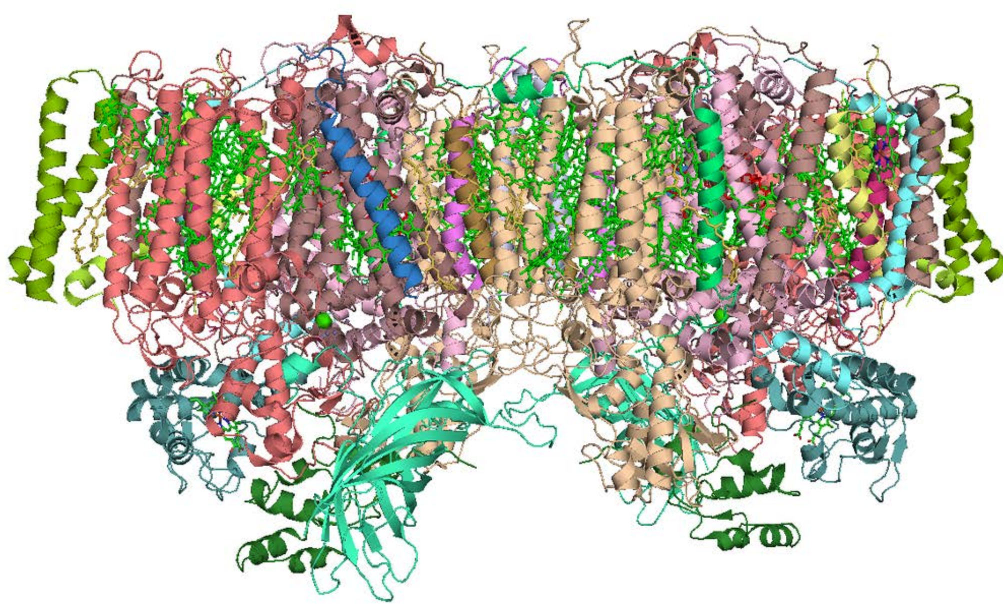
- PSII molecular structure was determined by using SPring-8 and SACLA
- Reaction dynamics is under investigation with SACLA
- The structure of reaction center help develop the artificial photosynthesis catalysts

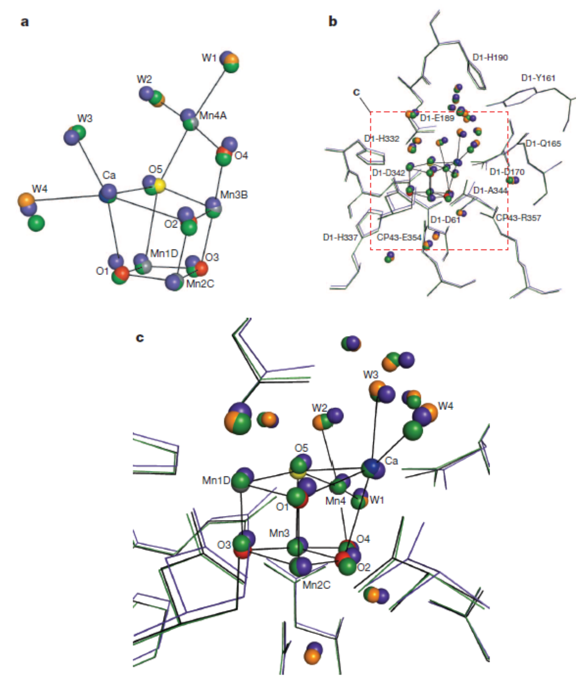
LETTER

doi:10.1038/nature13991

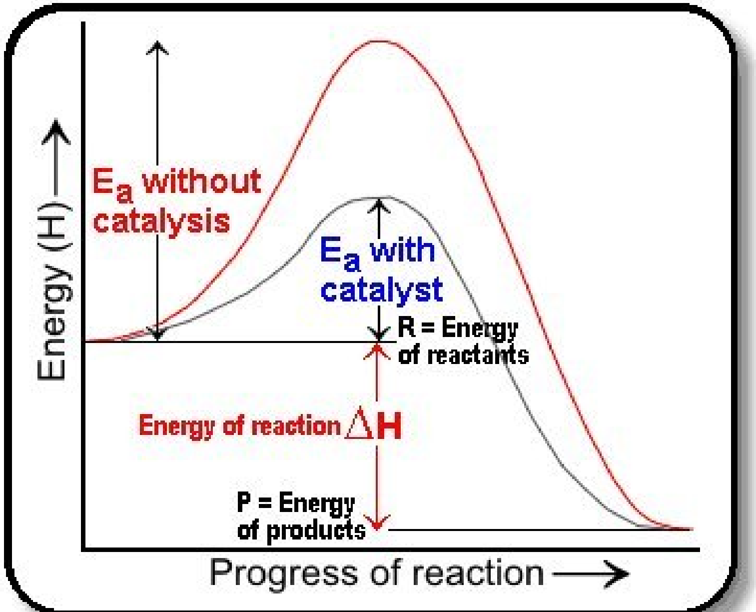
Native structure of photosystem II at 1.95 Å resolution viewed by femtosecond X-ray pulses

Michihiro Suga[1]*, Fusamichi Akita[1]*, Kunio Hirata[2,3], Go Ueno[2], Hironori Murakami[2], Yoshiki Nakajima[1], Tetsuya Shimizu[1], Keitaro Yamashita[2], Masaki Yamamoto[2], Hideo Ago[2] & Jian-Ren Shen[1]





Catalysts are Key Players for Energy-Saving Manufacturing



Catalyst

- *Catalyst is a substance which speeds up and speeds down a chemical reaction without itself being used up."*

or

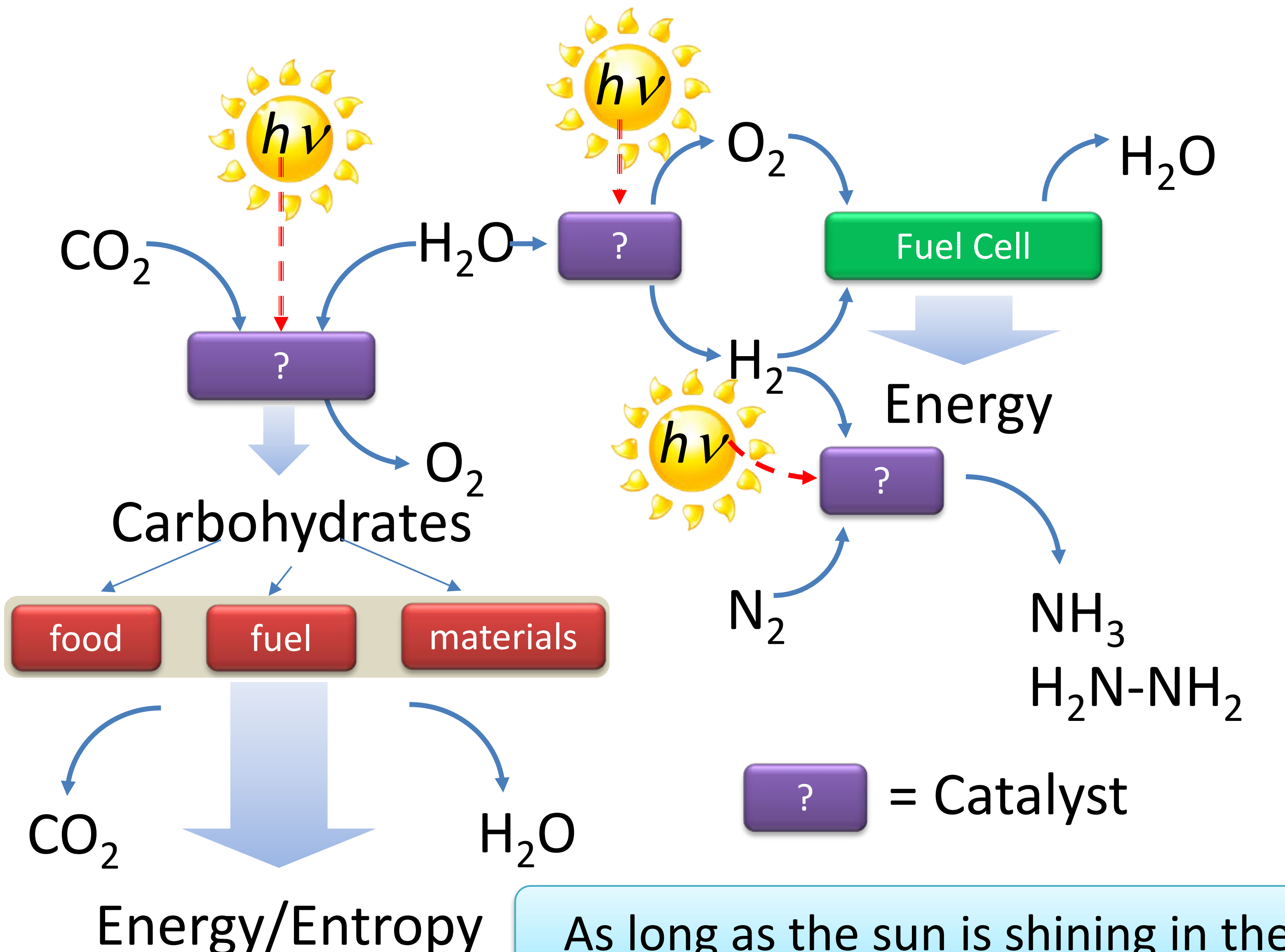
Ostwald (1895) redefined a catalyst as, *"A substance which changes the reaction rate without affecting the overall energetics of the reaction is termed as a catalyst and the phenomenon is known as catalysis*

Catalytic Reaction

- Frequently, too fast to be observed
- Observation of dynamics leads to the origin of the function
- The origin of the function help designing higher efficient catalysts

Ultrafast Observation with SACLA
Catalyst Design with SACLA Data

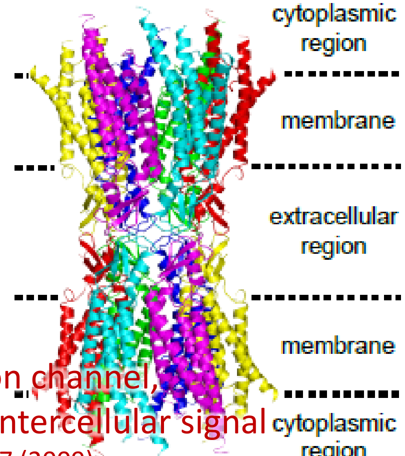
A Sustainable Society



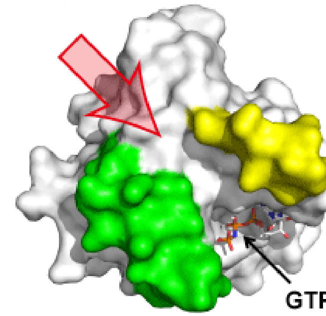
As long as the sun is shining in the sky.

Solution to Global Challenge: Health

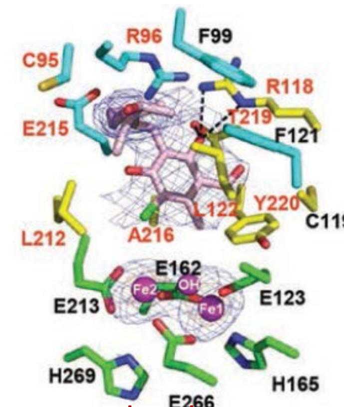
Protein structure give key information for drug design.



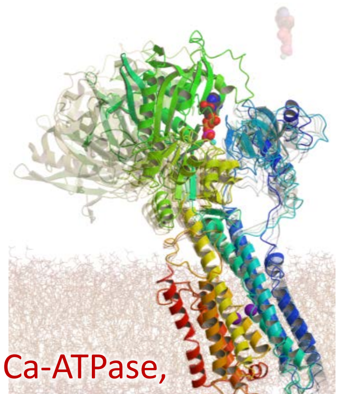
Gap junction channel, mediating intercellular signal
Nature 458, 597 (2009)



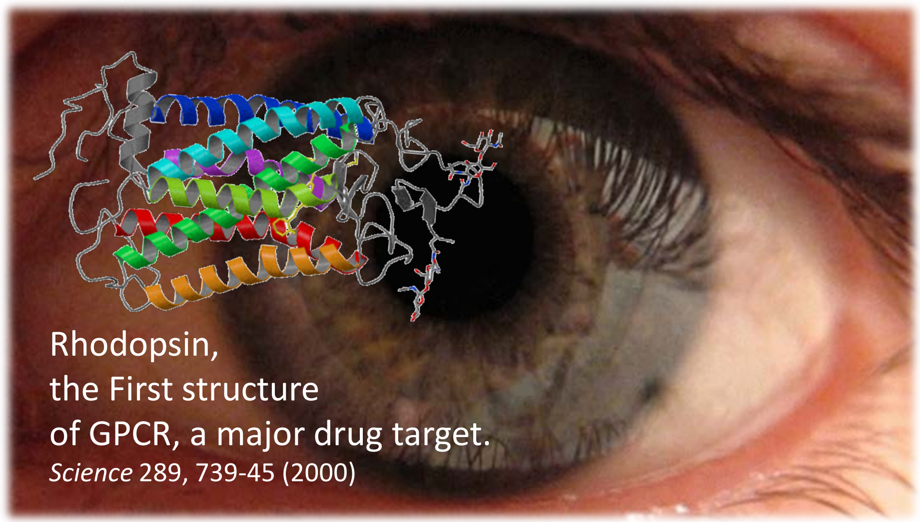
Structure-based anticancer drug development for Ras protein
PNAS 110, 8182-7 (2013)



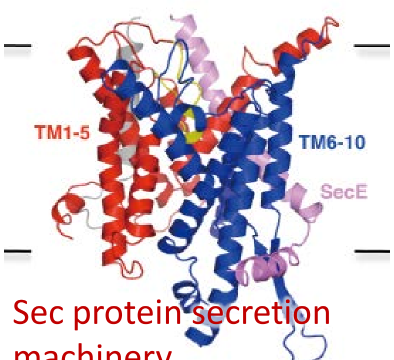
Drug development for African sleep sickness.
PNAS 110, 4580 (2013)



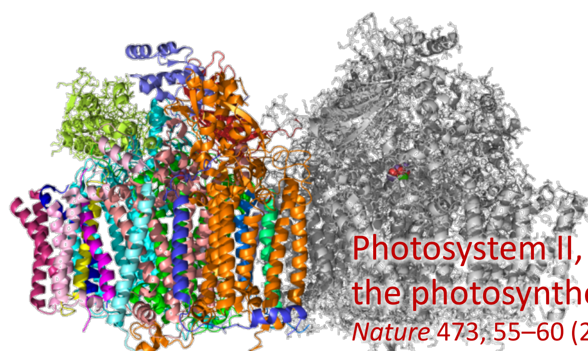
Ca-ATPase,
calcium pumping dynamics for muscle movement.
Nature 495, 260 (2013)



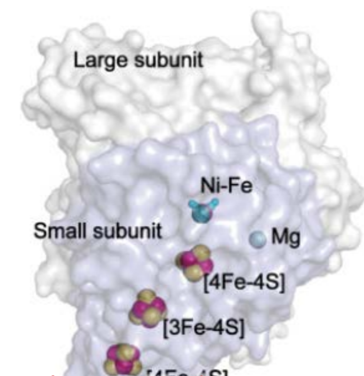
Rhodopsin,
the First structure of GPCR, a major drug target.
Science 289, 739-45 (2000)



Sec protein secretion machinery
Nature 455, 988 (2008)



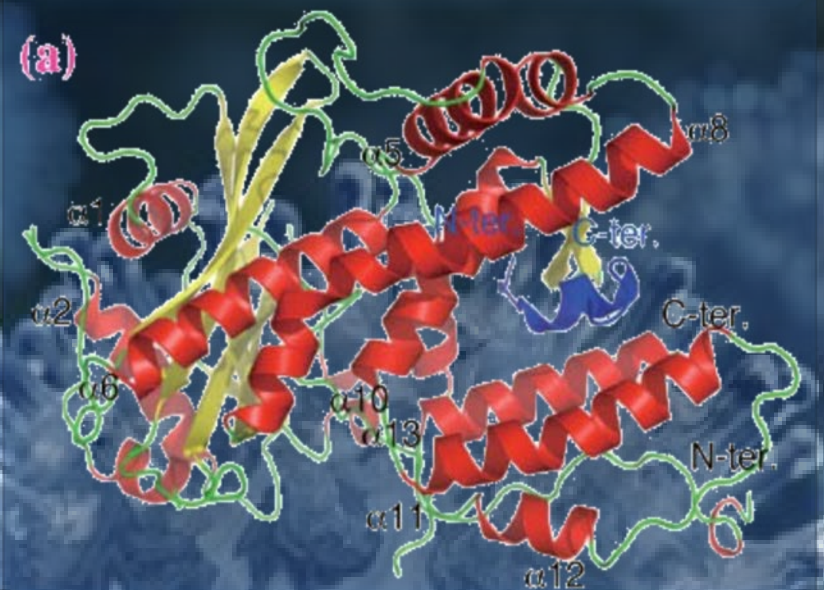
Photosystem II,
the photosynthesis machinery,
Nature 473, 55–60 (2011)



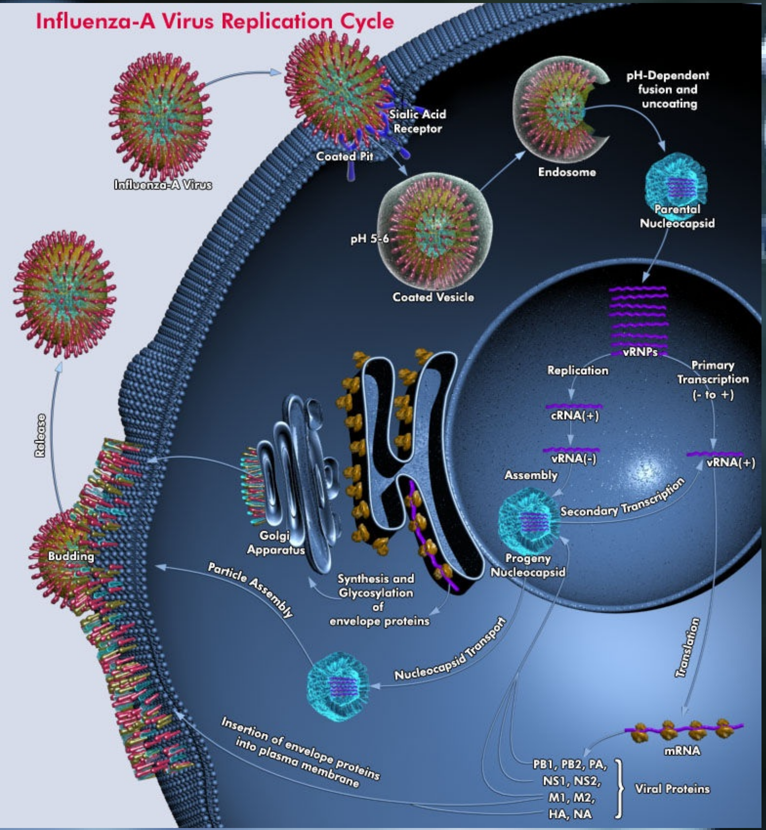
O_2-tolerant Hydrogenase,
A potential catalyst for biofuel cells
Nature 479, 253 (2011)

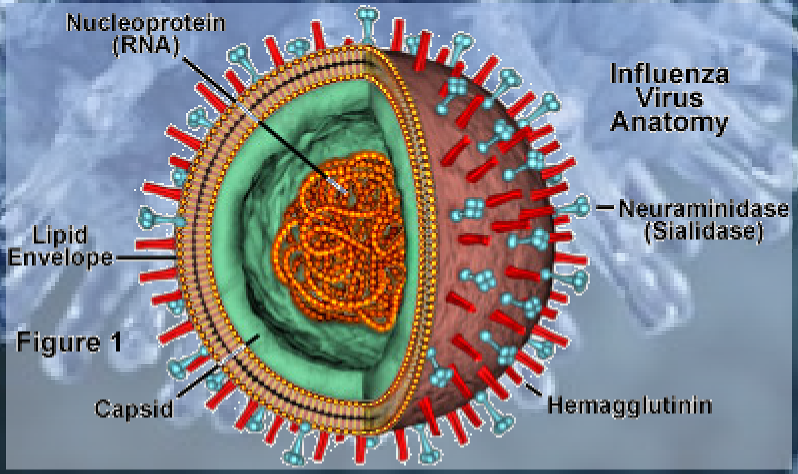
fight the disease

pandemic influenza



Influenza virus RNA polymerase for new drug discovery
Nature 454, 1127-1131 (2008)

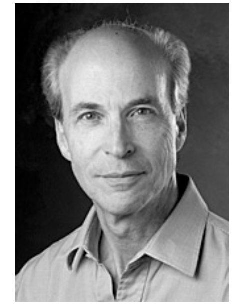




The Nobel Prize in Chemistry went to Protein Crystallographers (SR users) every 3 year since 2003

The Nobel Prize in Chemistry 2012 was awarded jointly to Robert J. Lefkowitz and Brian K. Kobilka *"for studies of G-protein-coupled receptors"*

The Nobel Prize in Chemistry 2009 was awarded jointly to Venkatraman Ramakrishnan, Thomas A. Steitz and Ada E. Yonath *"for studies of the structure and function of the ribosome"*.



The Nobel Prize in Chemistry 2006 was awarded to Roger D. Kornberg *"for his studies of the molecular basis of eukaryotic transcription"*.

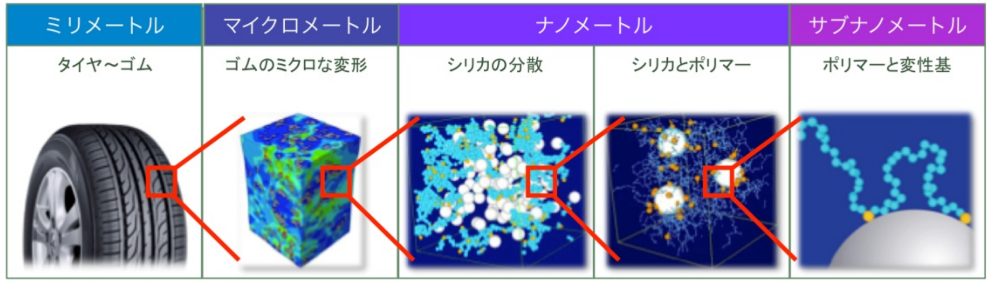
The Nobel Prize in Chemistry 2003 was awarded *"for discoveries concerning channels in cell membranes"* jointly with one half to Peter Agre *"for the discovery of water channels"* and with one half to Roderick MacKinnon *"for structural and mechanistic studies of ion channels"*.

The Nobel Prize in Chemistry 1997 was divided, one half jointly to Paul D. Boyer and John E. Walker *"for their elucidation of the enzymatic mechanism underlying the synthesis of adenosine triphosphate (ATP)"* and the other half to Jens C. Skou *"for the first discovery of an ion-transporting enzyme, Na+, K+ -ATPase"*.

Who will win in 2015?

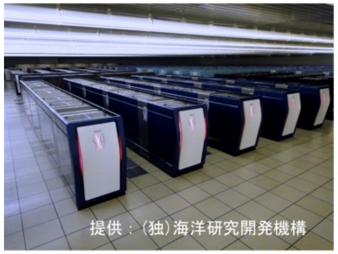
Solution to Global Challenge: Energy Saving

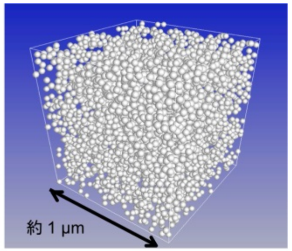
Sumitomo Rubber Industries Ltd.



Sophisticated Analysis at FSBL, SPring-8

Multi-Scale Simulation of Rubber Molecule Dynamics by Super Computer





President Ikeda presents new energy saving tire. 1st Dec. 2011

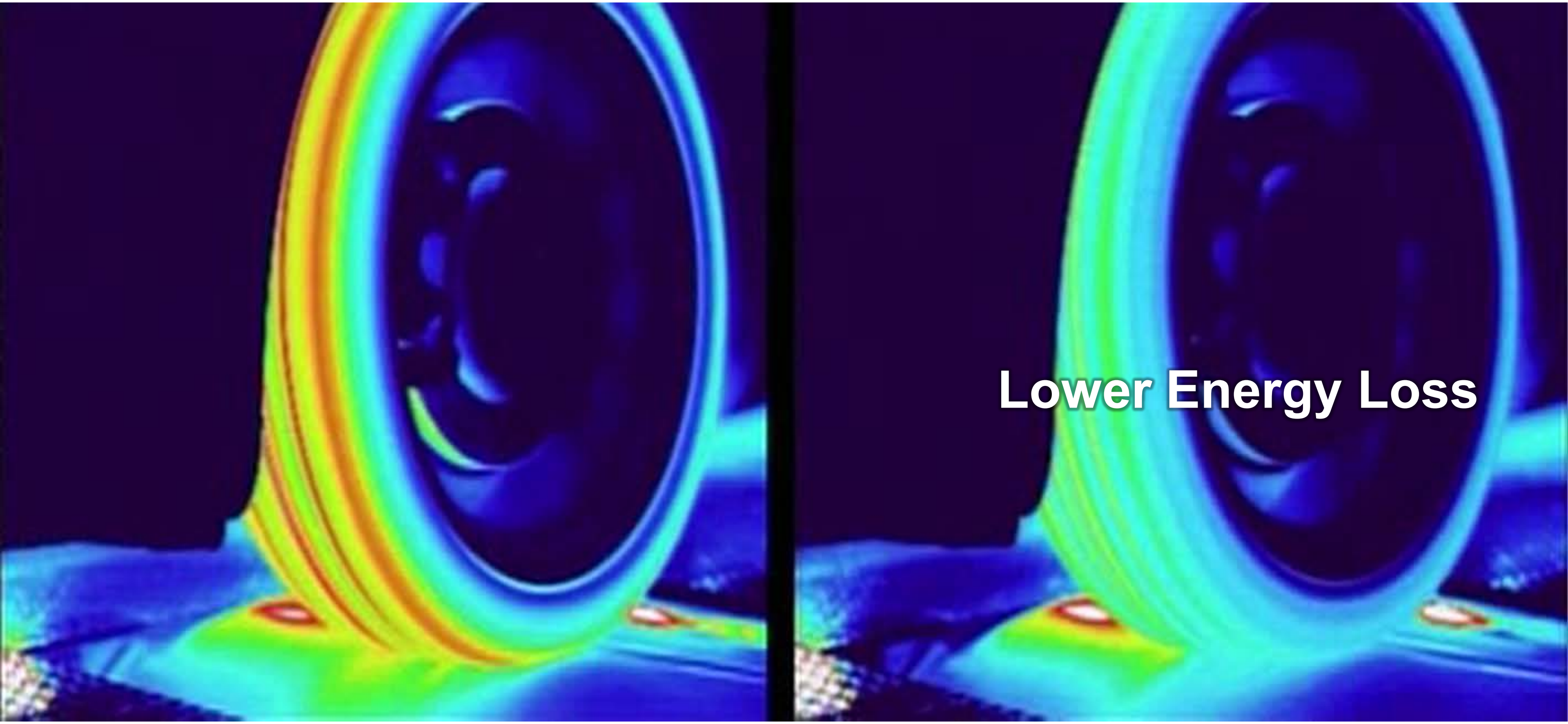
Achieving Improvement
6%: fuel efficiency
39 %: traction performance!

“EnerSave” Premium Performance

Conventional Tire

エナセーブ PREMIUM

SPring-8 SACLA RIKEN



6% Energy Saving; Estimation of Economic /Social Effect

Fuel Saving : If all vehicles in Japan fit the energy saving tire.

gasoline 53,214,000 kl
diesel oil 25,660,000 kl
LPG 2,067,000 kl

6% saving

▲ gasoline 3,192,840 kl
▲ diesel oil 1,539,600 kl
▲ LPG 124,020 kl

平成23年度 自動車燃料消費量
年報(国土交通省刊) より 試算

◆ Consumer Cost

gasoline 511 M€
diesel oil 212 M€
LPG 92 M€

800M€/year Saving

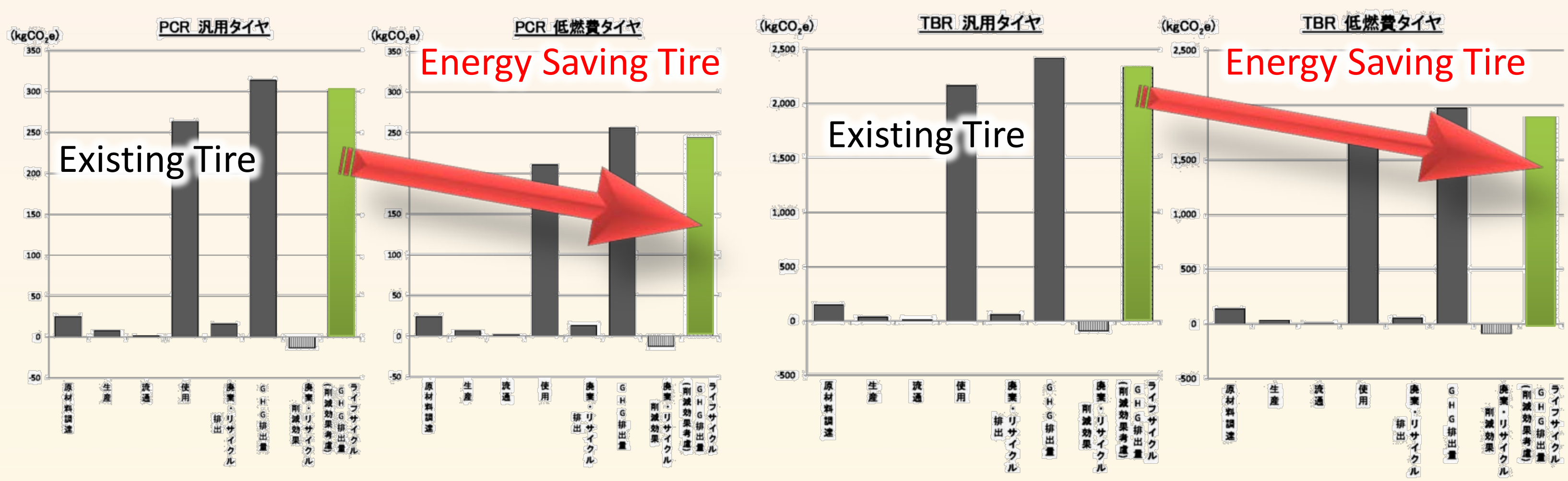
gasoline	1.60 €/l
diesel oil	1.38 €/l
LPG	0.74 €/l

Estimation of Greenhouse Gas Emission Reduction through Life Cycle

PCR (Automobile) TBR (Autotruck, Autobus)

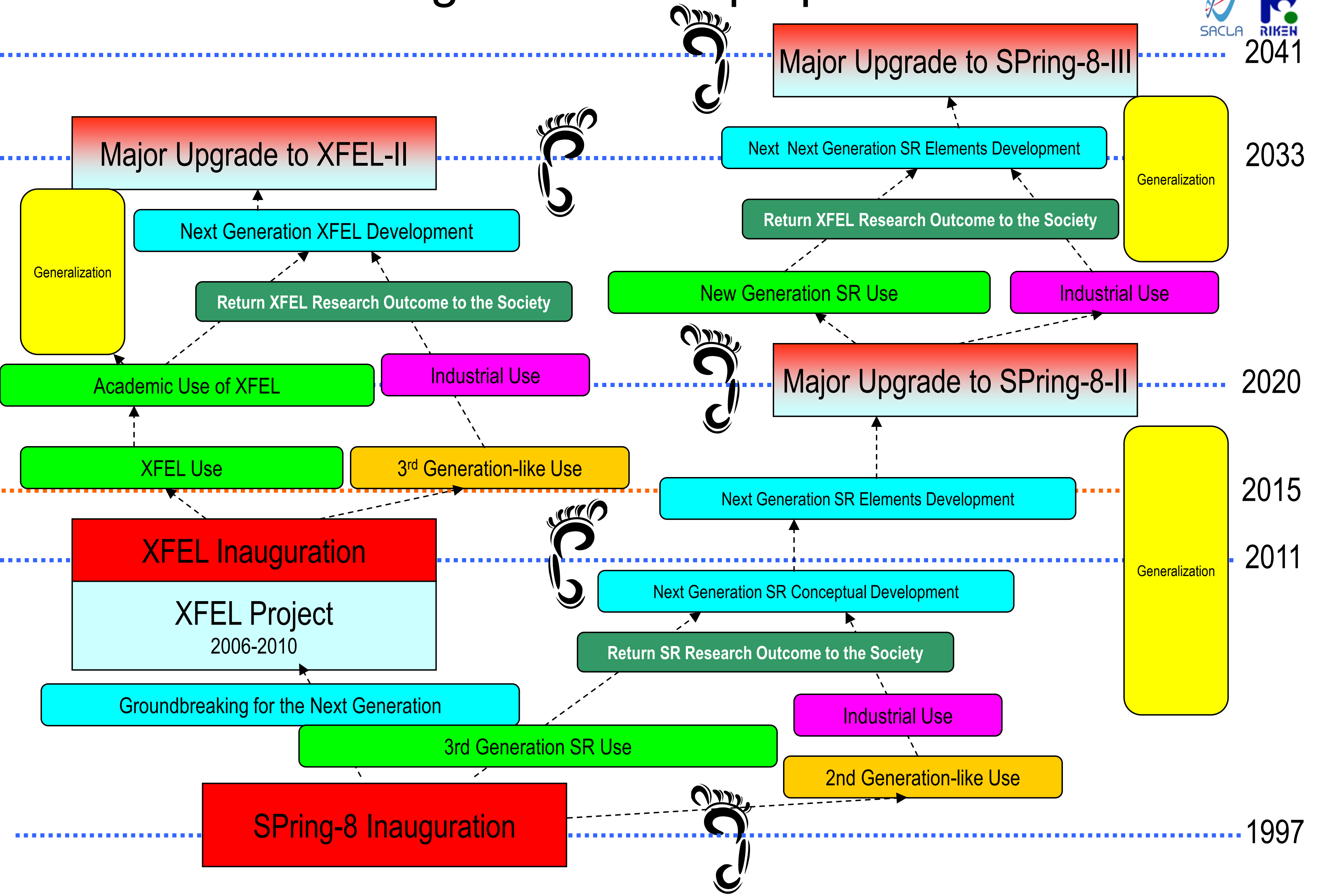
タイヤのLCCO2 算定ガイドライン 2012年 日本自動車タイヤ協会 より

凡例
■ GHG 排出 ▥ GHG 削減効果 ▧ ライフサイクル GHG 排出量 (削減効果考慮)

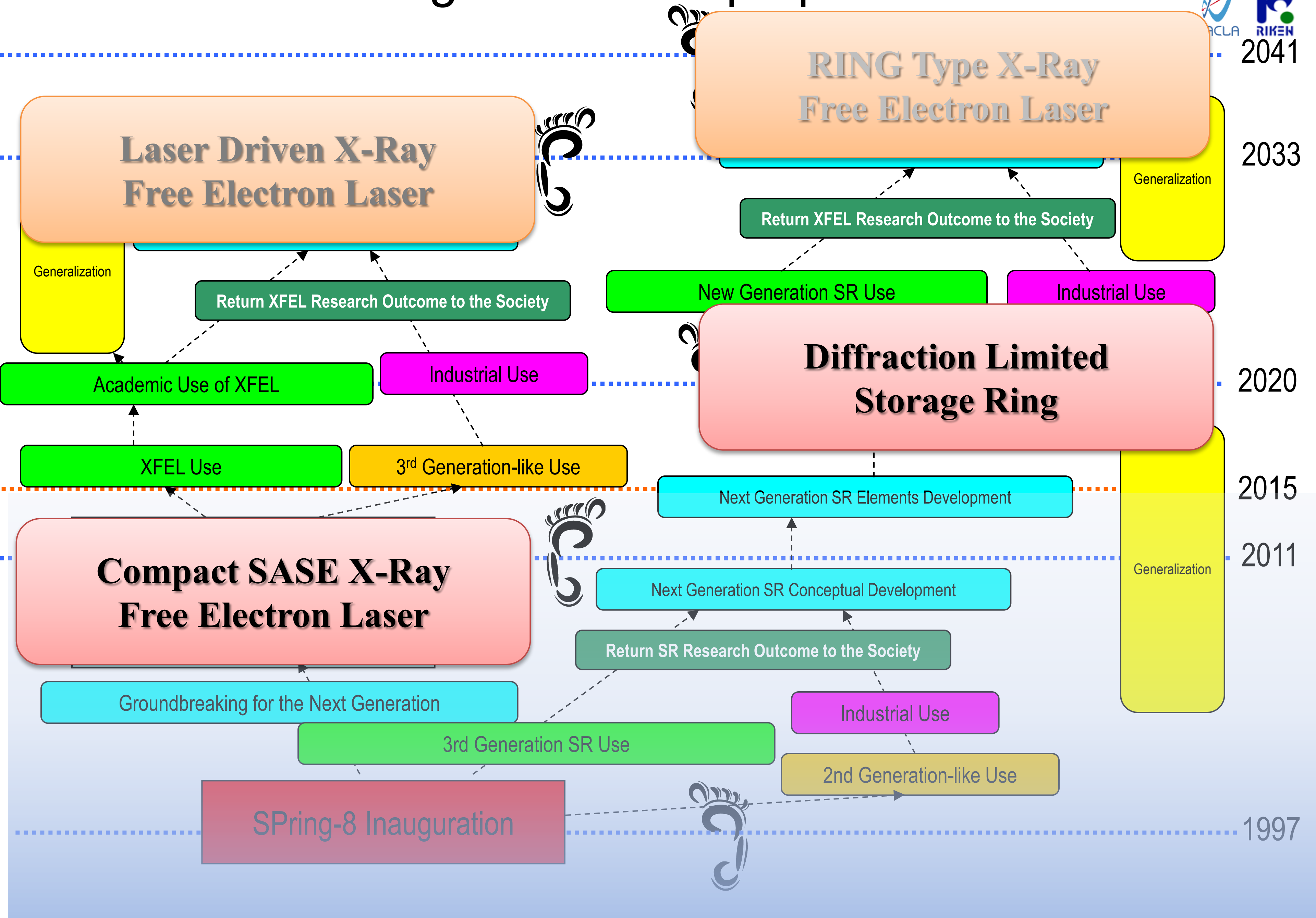



SPring-8
A380
テトラピック配合タイヤ DSX
テトラピック
摺動部材
(ポリエチレンプレート)
POs-Ca
POs-Ca
POs-Ca
POs-Ca
Segreta
Segreta
Natural Color

SPring-8 Road Map up to 2041



SPring-8 Road Map up to 2041



MBA Upgrade of SPring-8 to SPring-8-II

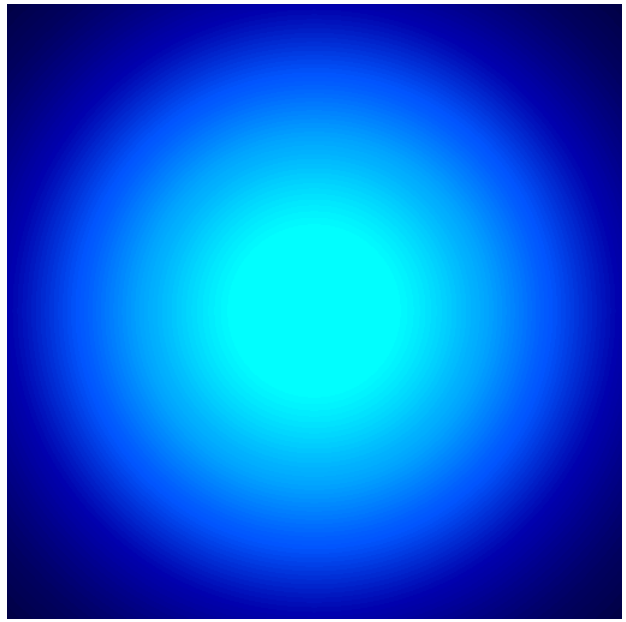
Boundary Conditions

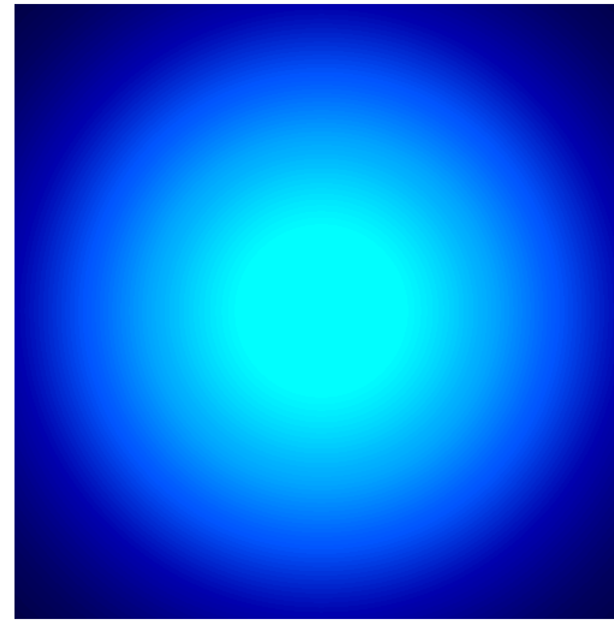
1) Use the existing accelerator tunnel
2) Retain the positions of straight sections
3) Short dark period (~1 year)
4) Lower electric power consumption than now
5) ~ 100 pm.rad natural emittance
6) Retain the energy range covered by undulators
7) Smaller budget than SACLA (~400 M US$)

Solutions

1) 5 Bend Achromat Lattice
2) 6 GeV, max 100 mA operation
3) Shorter period undulators

Information by scattering of Coherent X-rays & Chaotic X-rays





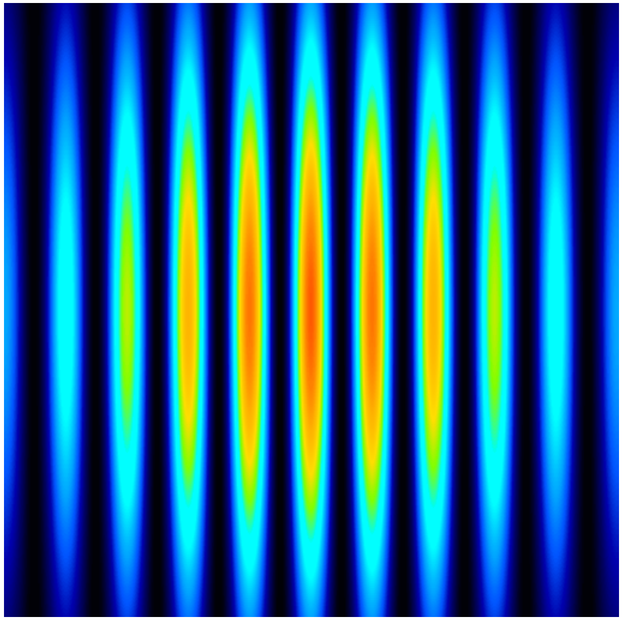
Atomic Model

4^{th} Generation

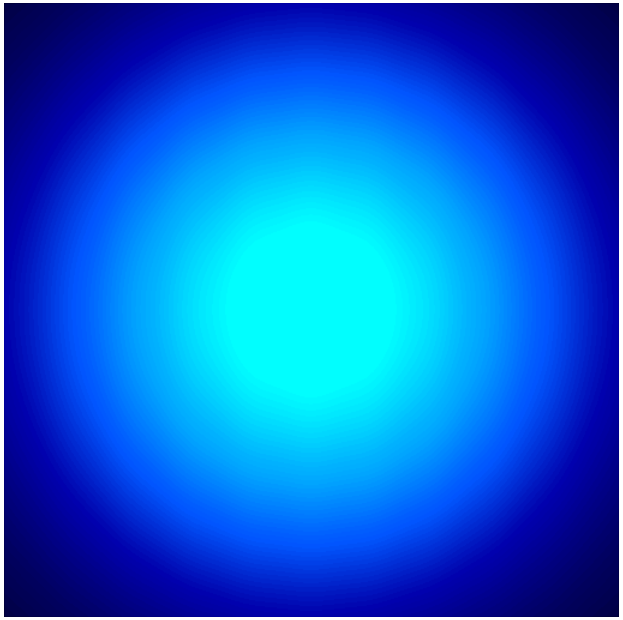
3^{rd} Generation

Information by scattering of Coherent X-rays & Chaotic X-rays

Atomic Model



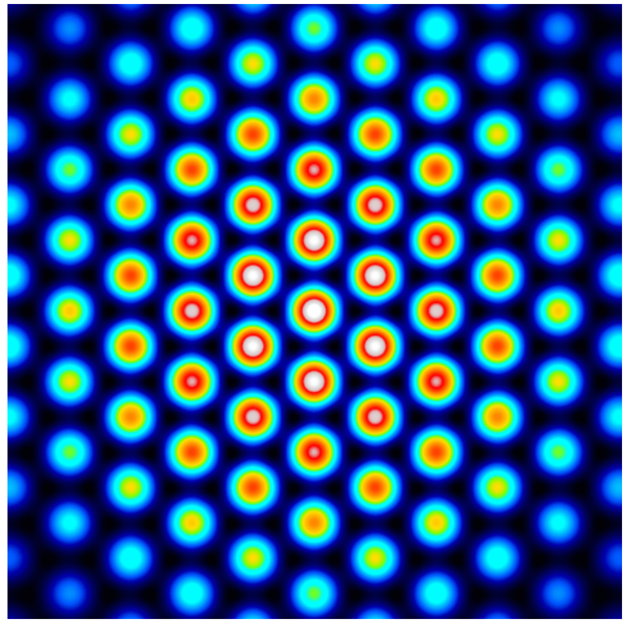
4^{th} Generation



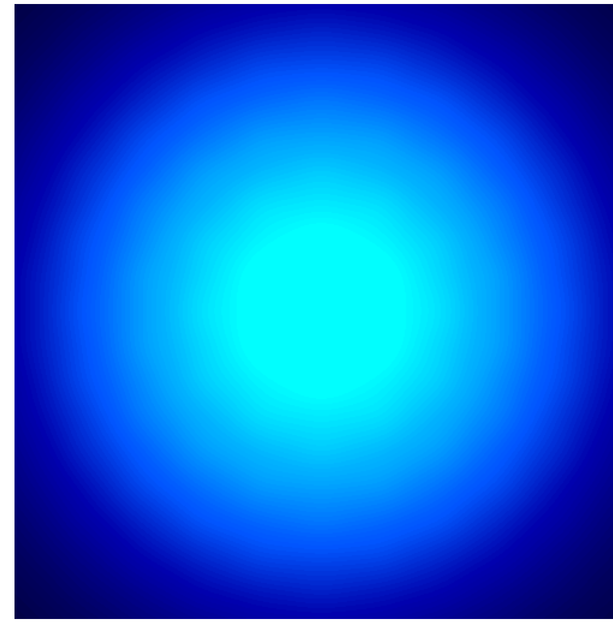
3^{rd} Generation

Information by scattering of Coherent X-rays & Chaotic X-rays

Atomic Model

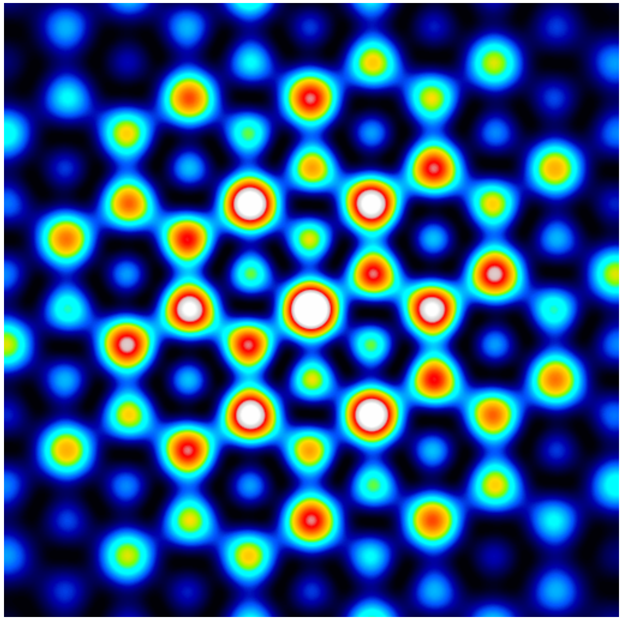


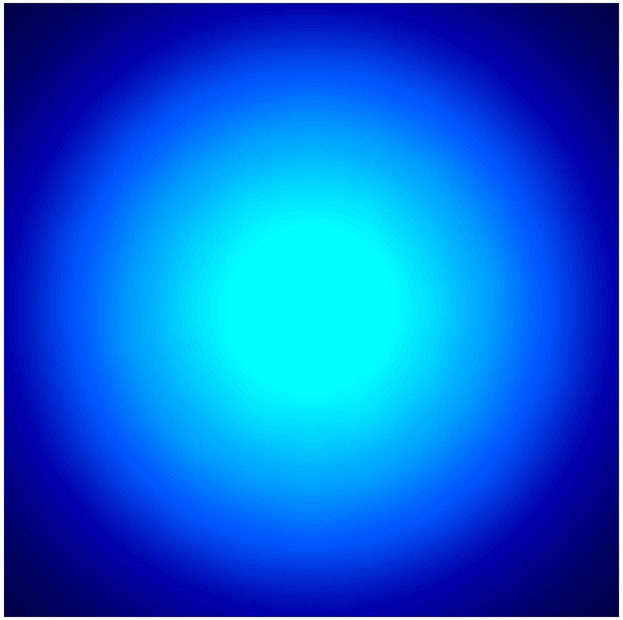
4th Generation



3rd Generation

Information by scattering of Coherent X-rays & Chaotic X-rays



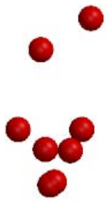


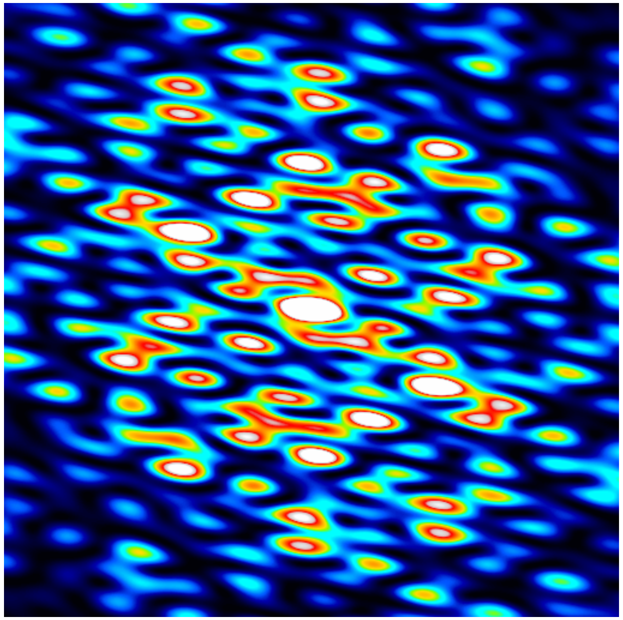
Atomic Model

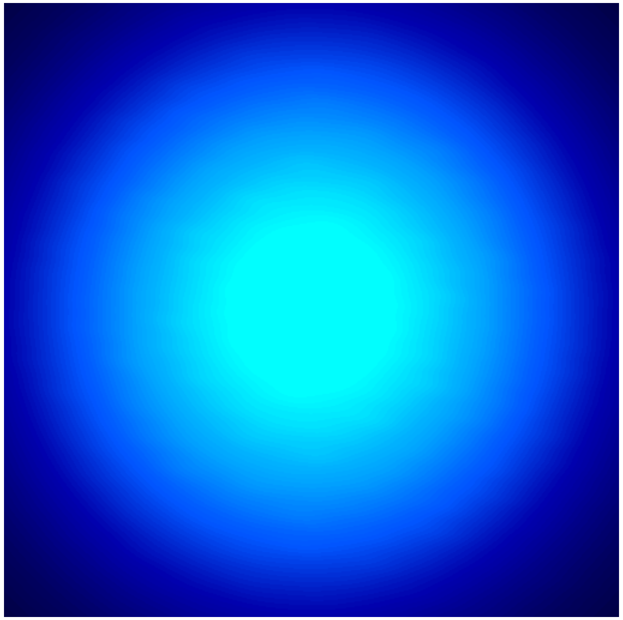
4^{th} Generation

3^{rd} Generation

Information by scattering of Coherent X-rays & Chaotic X-rays





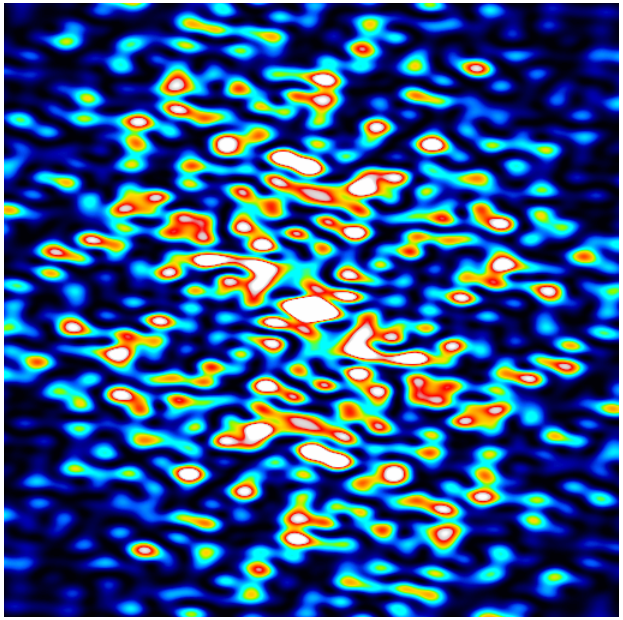


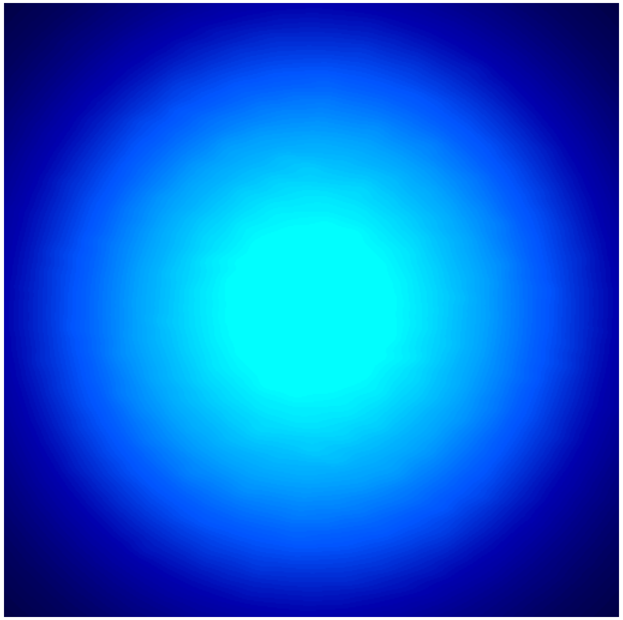
Atomic Model

4^{th} Generation

3^{rd} Generation

Information by scattering of Coherent X-rays & Chaotic X-rays





Atomic Model

4^{th} Generation

3^{rd} Generation

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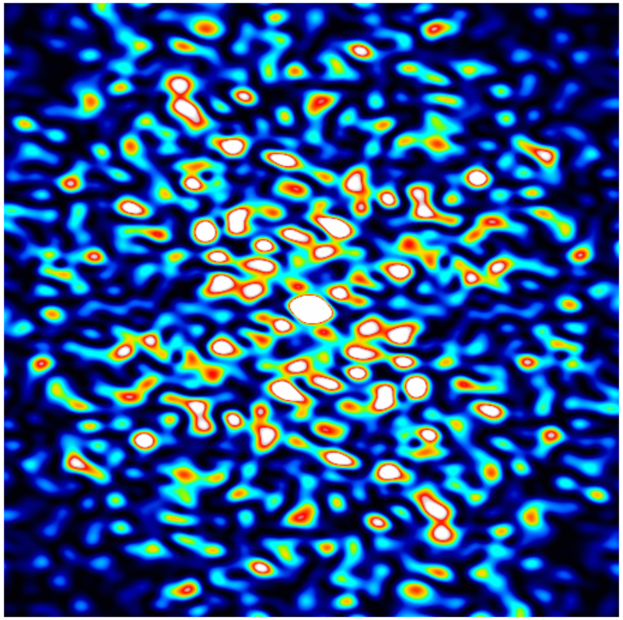
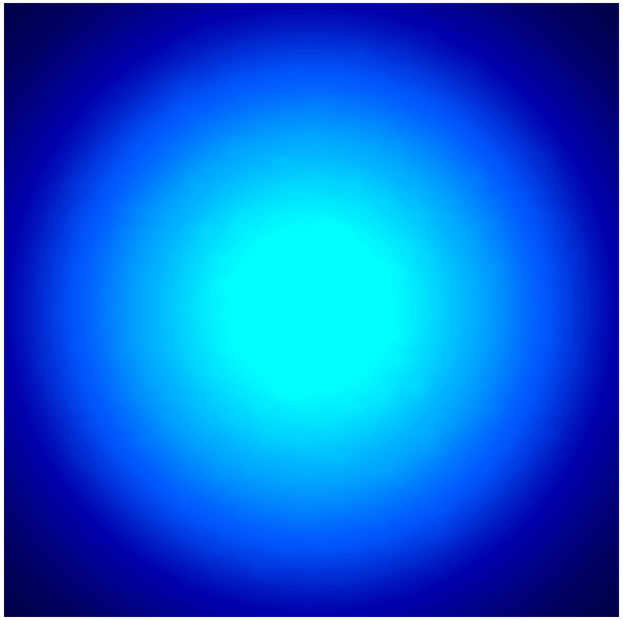
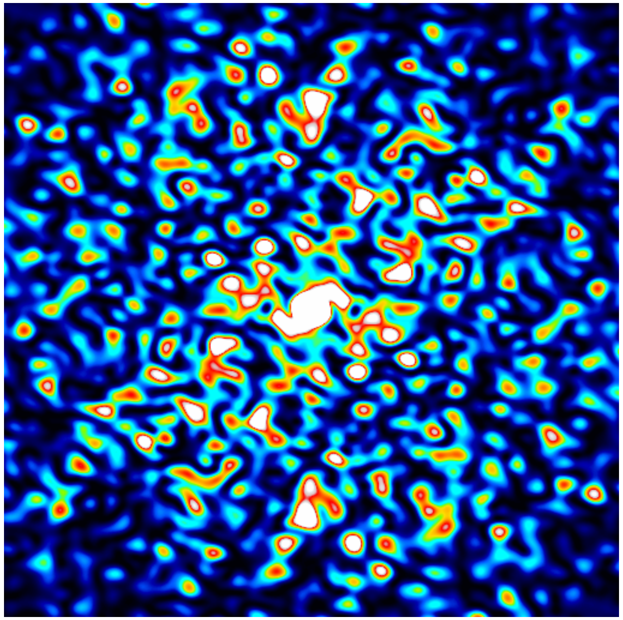




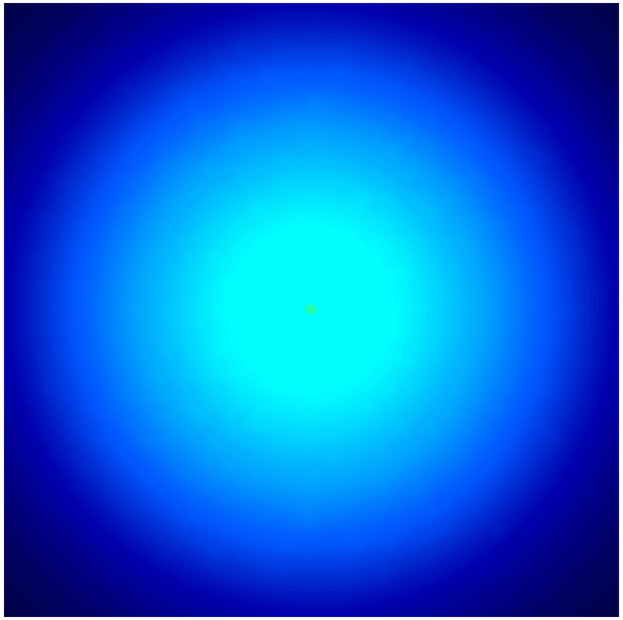
Atomic Model 4th Generation 3rd Generation

Information by scattering of Coherent X-rays & Chaotic X-rays

Atomic Model



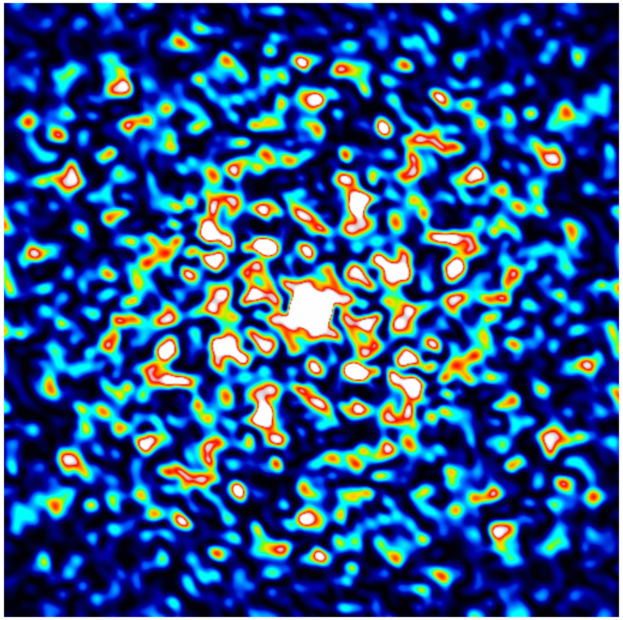
4^{th} Generation



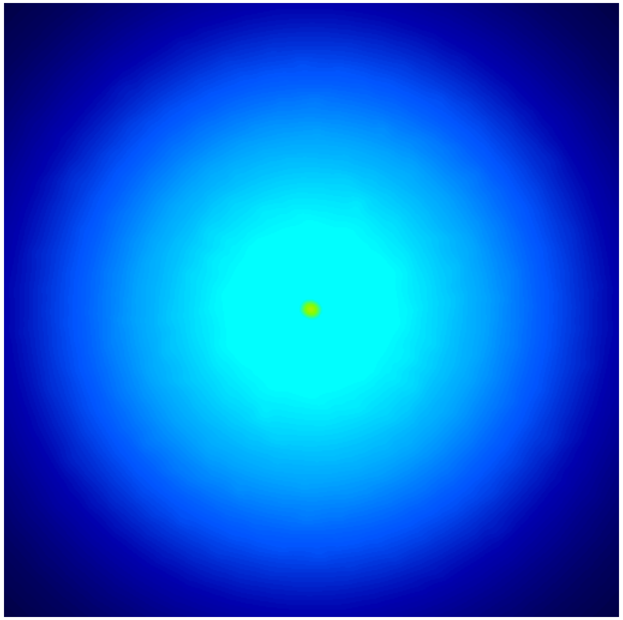
3^{rd} Generation

Information by scattering of Coherent X-rays & Chaotic X-rays

Atomic Model

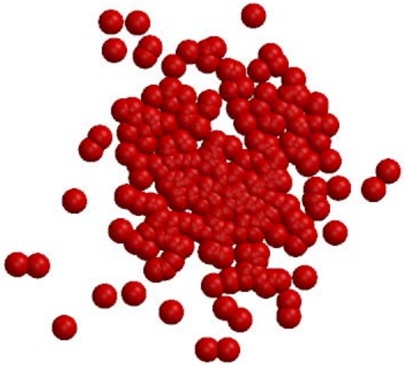


4th Generation

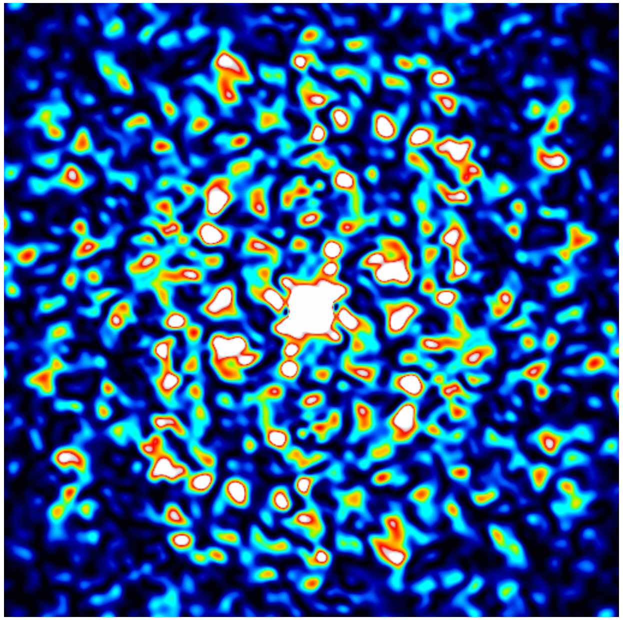


3rd Generation

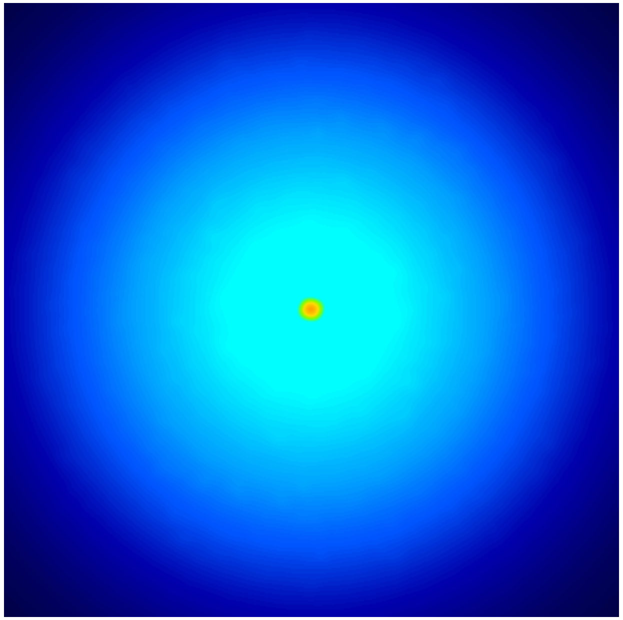
Information by scattering of Coherent X-rays & Chaotic X-rays



Atomic Model

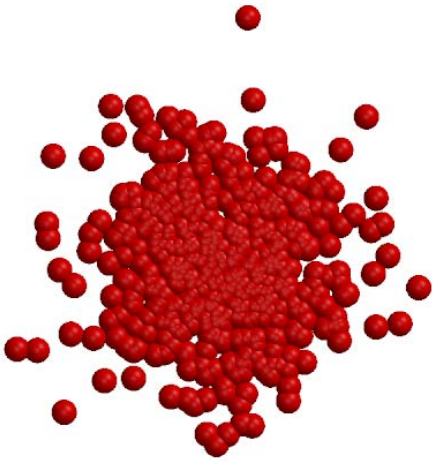


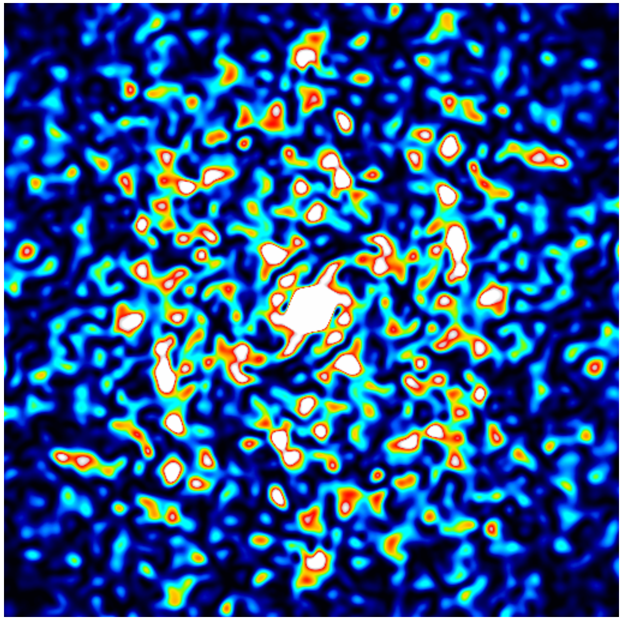
4th Generation

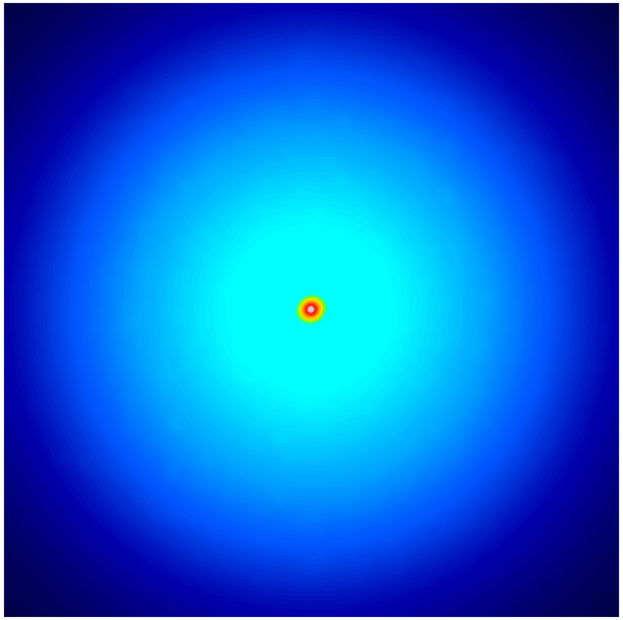


3rd Generation

Information by scattering of Coherent X-rays & Chaotic X-rays







Atomic Model | 4^{th} Generation | 3^{rd} Generation

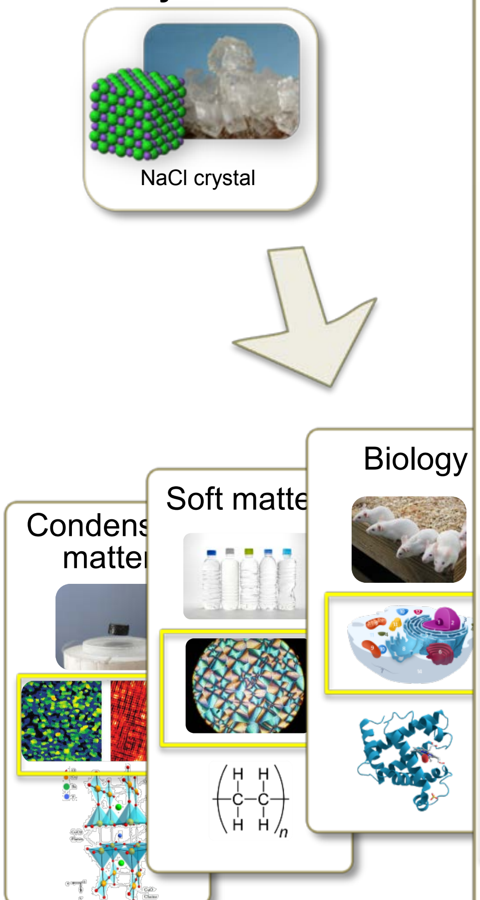
Change Photon Science by 4^{th} Generation Light Sources !

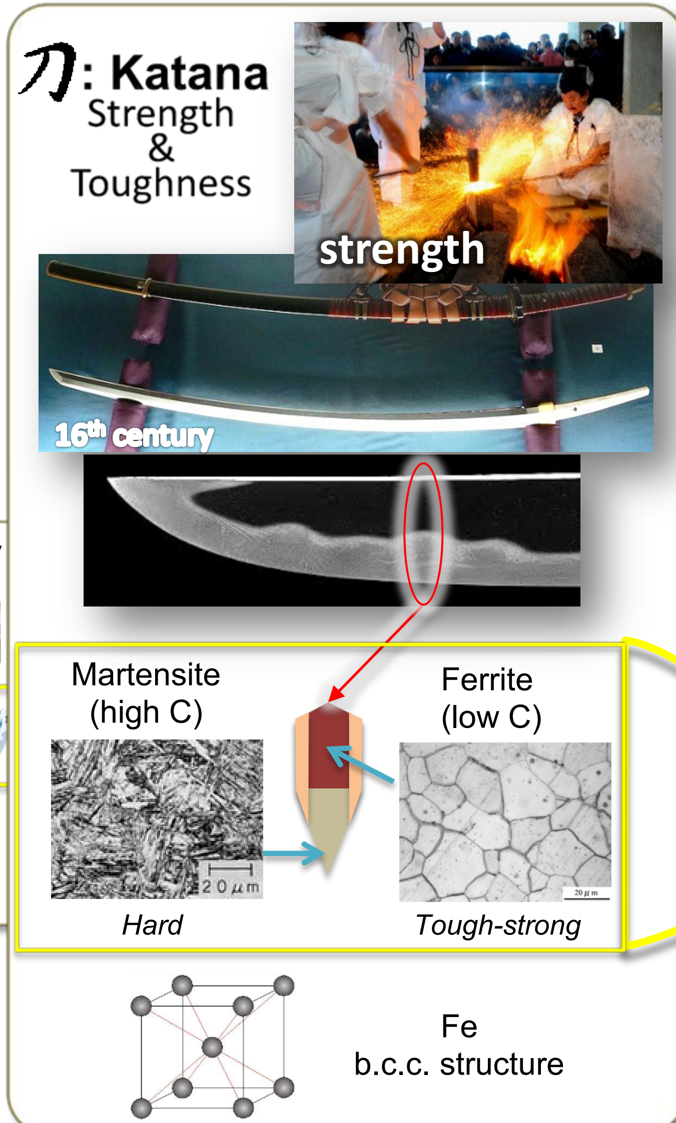
Product Development Requires Discovery-Based Methodology

For many phenomena, we know ***how*** they happen,
but don't know ***why*** they happen.

Inhomogeneous / Hierarchic / Composite - system

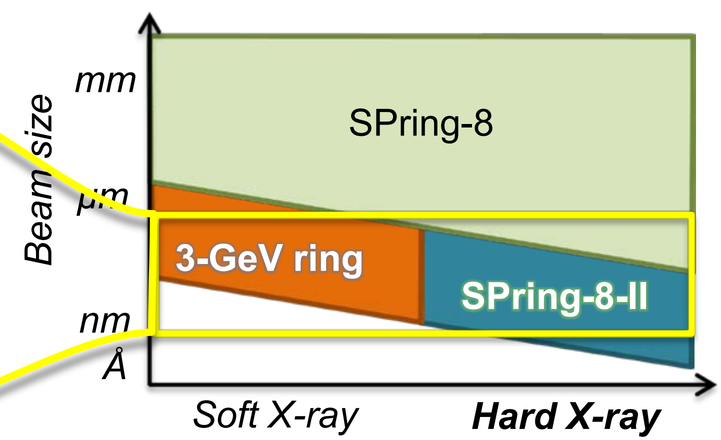
Homogeneous system





Nano-Scopy:
- ➢Nano-Diffraction
- ➢Nano-Spectroscopy
- ➢Nano-Imaging

DLSR will provide smaller size, higher coherent X-rays.



Demands of the Academic and Industrial Worlds

- Techniques to evaluate materials as they are
  ⇒Structural analysis of materials
  To understand why a specific substance changes its properties when it becomes a complex
- Understanding "destruction" in the atomic scale

Why do products break?

To manufacture indestructible objects

- Based on an understanding of destruction in the atomic scale
- Lowering the frequency of maintenance for an aging society
- Structures and materials for transportation infrastructure such as roads, bridge, and tunnels, which are difficult to replace
- Structures, materials, and construction methods for civic infrastructure such as power generation, transformation, and transmission facilities that are difficult to take off-line
- Reducing the frequency of maintenance for vital infrastructure, such as communication systems, water supply, and sewage systems

To inhibit destruction

- Based on an understanding of destruction in the atomic scale
- Effective methods for repairing aging roads, bridges, and tunnels
- Enhancing safety and security by deterring the degradation of transportation vehicles such as airplanes, automobiles, ships, and trains
- Biological destruction – developing medicines to combat illnesses
- Increasing the longevity of power generation, transformation, and transmission facilities
- Increasing the longevity of catalysis

To design destruction

- Based on an understanding of destruction in the atomic scale
- Equipping the base for manufacturing with the design of destruction with an understanding of fatigue and degradation phenomena of functional materials and elements
- Establishing "end-to-start" engineering in which a point of breaking and disposal is the start (base) for the selection of materials and fabrication methods
- Realizing a society of energy and resource conservation by designed destruction

A paradigm shift in manufacturing

Concluding Remarks

- With the help of the accelerator-based light sources, the light-based science and technologies can promote sustainable development and provide solutions to global challenges in energy, education, agriculture and health.
- Reversely, the accelerator technologies owe many things from light science and technologies such as lasers, fiber communication, ….
- Much more interplays between accelerator and light communities are demanded to provide fundamental solutions to global challenges.

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Thank you for your attention !