素核宇宙融合レクチャーシリーズ　第13回

“超新星残骸のもうひとつの顔”

長瀧天体ビッグバン研究室

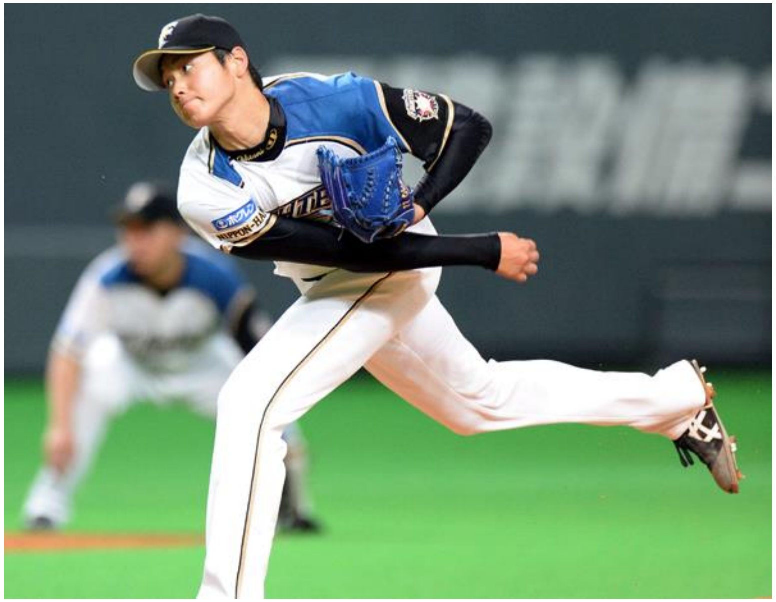
理化学研究所
准主任研究員

長瀧　重博

主催：計算基礎科学連携拠点（JICFuS） HPCI戦略プログラム分野5「物質と宇宙の起源と構造」
共催：理化学研究所 iTHESプロジェクト　2014年11月27日−28日、理研和光キャンパス

超新星残骸は二刀流

写真は大谷翔平（日本ハムファイターズ）



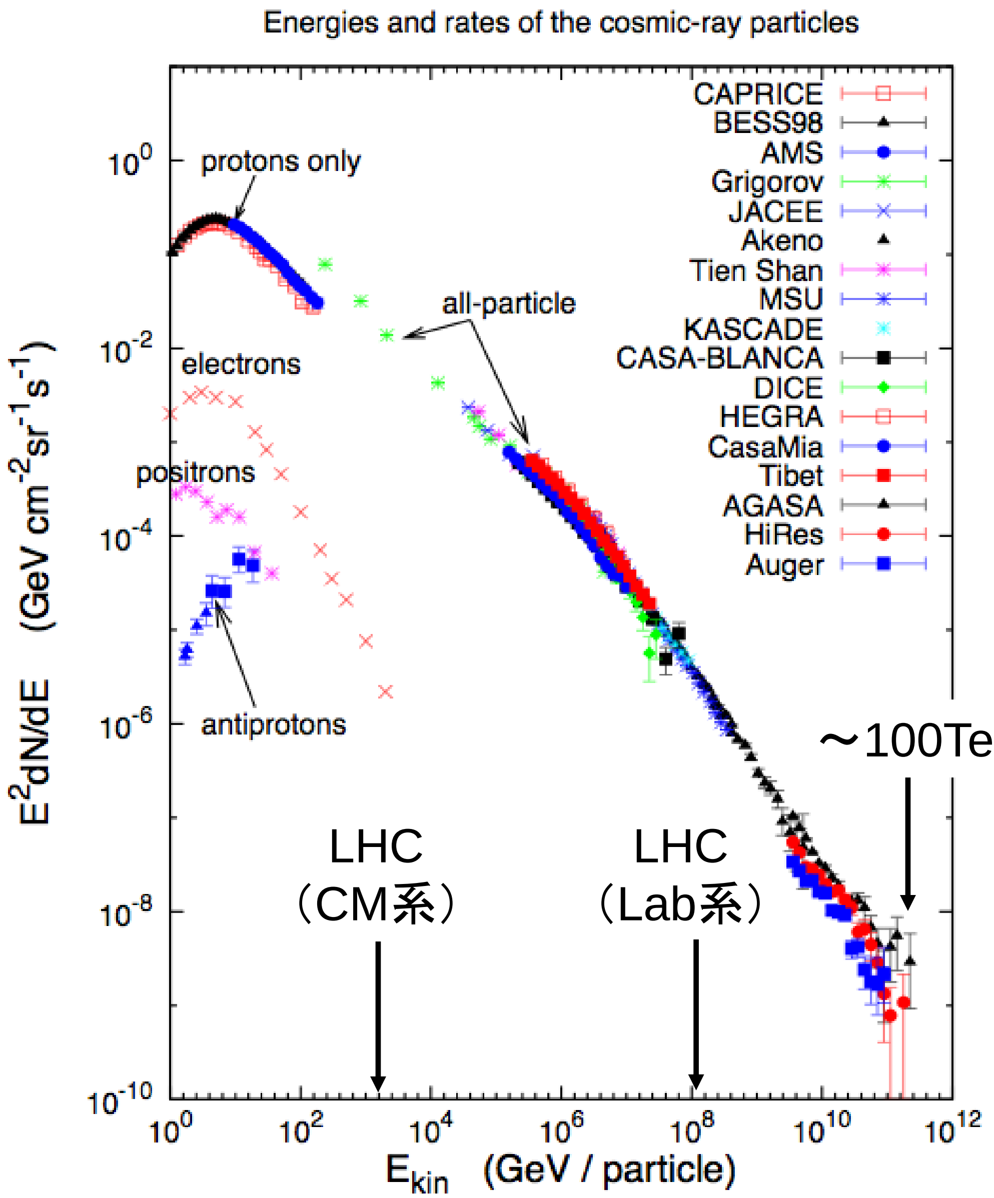
元素の起源

超新星で生成された重元素を放出
生命の種

宇宙線の起源

超新星残骸は巨大加速器
宇宙に宇宙線を放出

地球には宇宙線が降り注いでいる



LHC
（CM系）

LHC
（Lab系）

～100TeV in CM系

大体10^6GeV位までは
超新星残骸起源なのではないか
（最有力説）？

その証拠を掴むことは重要。

10^6GeV以上については起源謎。
ガンマ線バースト？

最高エネルギー宇宙線と
地球大気の相互作用は
LHCを大きく超えた地上実験室。

1937,1939

Detection of Cosmic Rays Muons

Since the discovery in 1912 by Victor Hess, cosmic rays served as a natural accelerator, and promoted the study of elementary particle physics worldwide. In this attempt, the genuine Japanese leader was Yoshio Nishina of RIKEN. Trying to understand the composition of cosmic rays at sea level, he and his co-workers placed a Wilson cloud chamber in strong magnetic fields which bend charged particles. Then, as shown in the figure, they discovered new particles of both plus and minus charges, with a mass of 223±40 times that of electrons. These new particles were *muons*, which are known today to dominate secondary cosmic rays.

To our regret, their discovery, published in August 1937, was preceded by only 5 months by Neddermeyer and Anderson, to whom the muon discovery is usually attributed. However, the muon's mass estimated as above by Nishina *et al.* is very close to the current value of 206.7, much more accurate than that of their rivals who only wrote that the new particles are lighter than protons and heavier than electrons.

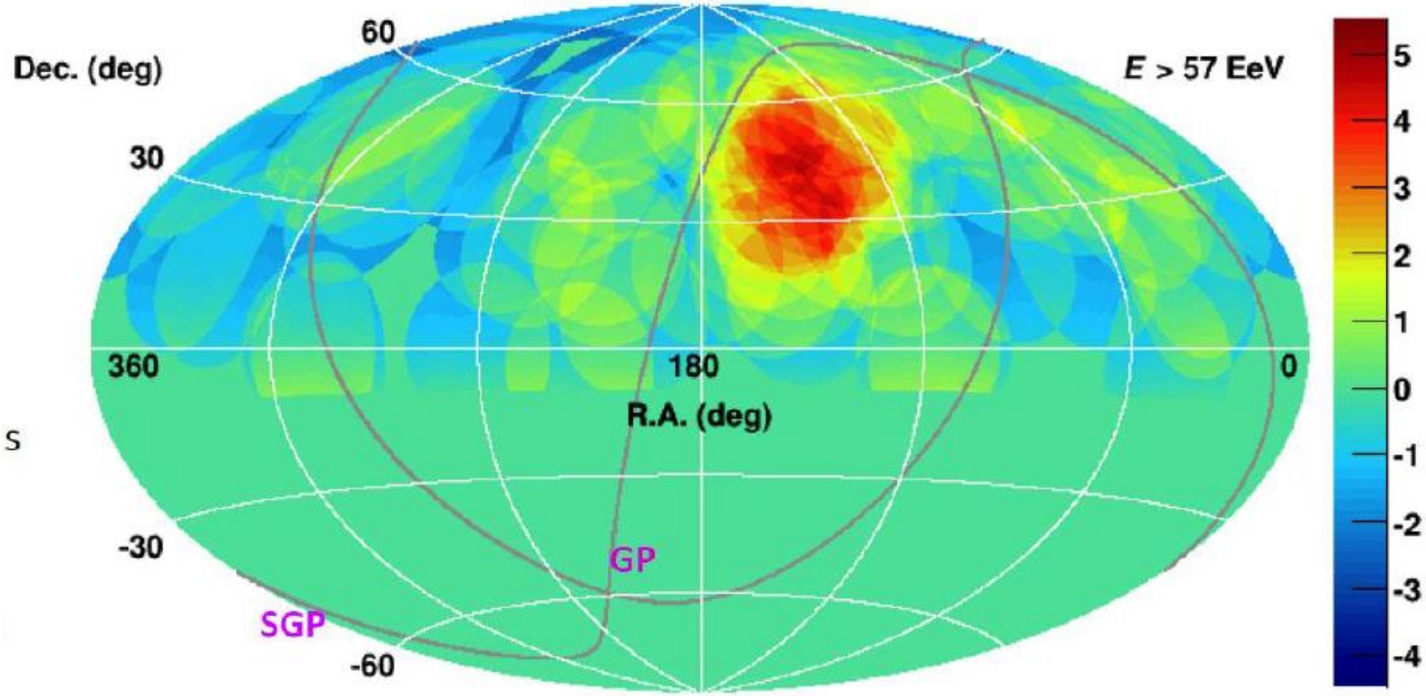
Muons were once identified with "mesons" which Hideki Yukawa (the first Japanese Nobel laureate) had predicted two years before. However, muons were later confirmed to be a different particle, to be called "heavy electrons".

Yoshio Nishina and a track of a muon detected in his Wilson chamber.

Investigators: Y. Nishina, M. Takeuchi and T. Ichimiya

Reference: "On the Nature of Cosmic-Ray Particles", *Phys. Rev*. **52**, 1198 (1937)
"On the Mass of the Mesotron", *Phys. Rev*. **55**, 585 (1939)

宇宙線の起源が分からない！



最高エネルギー宇宙線が多量に降ってくる方向を同定した。
Telescope Array Team (Japan-the US) 2014.

起源は謎。

Emission from an SNR

HTTP://CHANDRA.HARVARD.EDU

Emission from an SNR

TYCHO'S
SUPERNOVA
REMNANT

Infrared emission
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust

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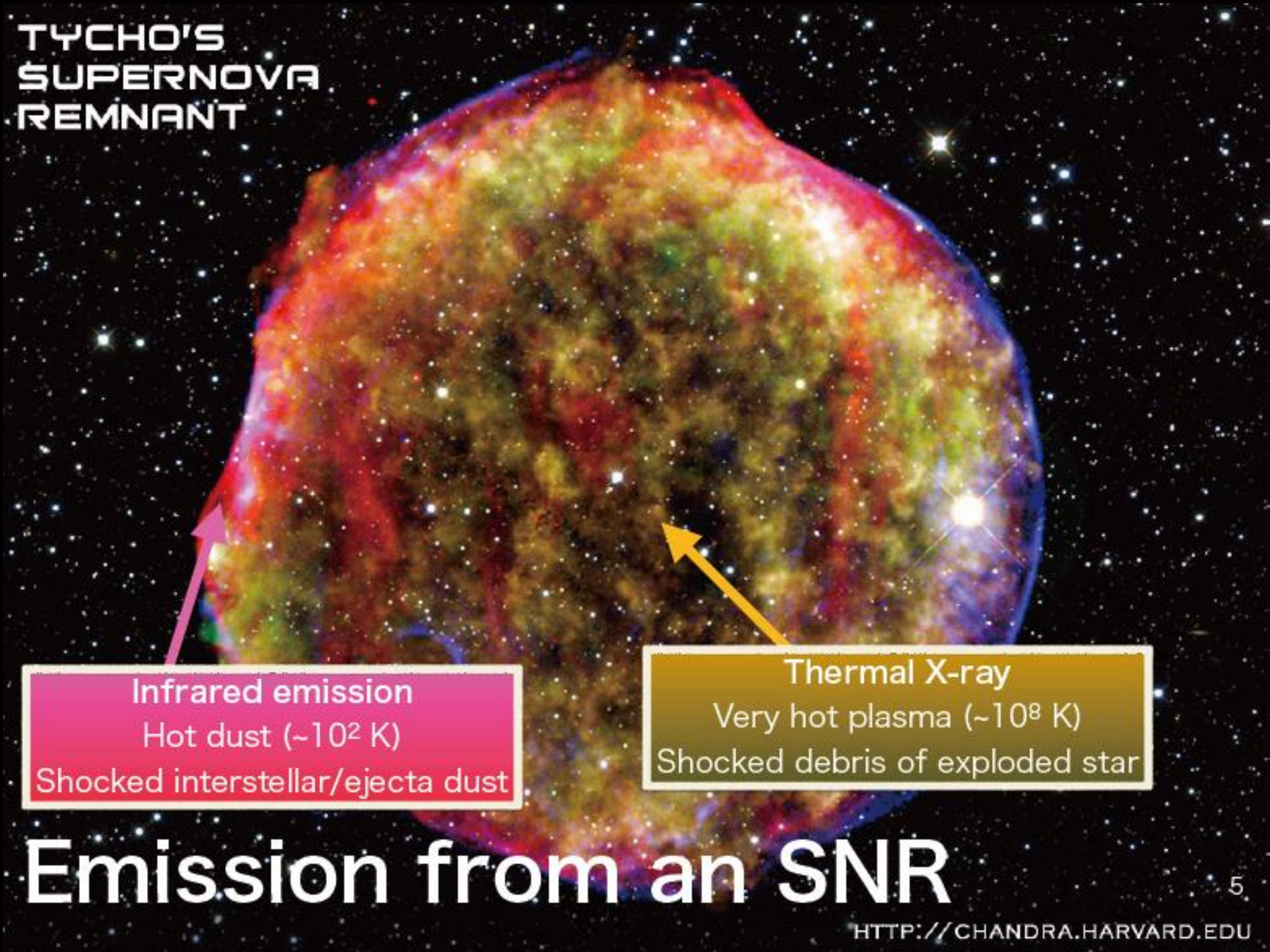
Emission from an SNR



Infrared emission
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust

Thermal X-ray
Very hot plasma (~10^8 K)
Shocked debris of exploded star

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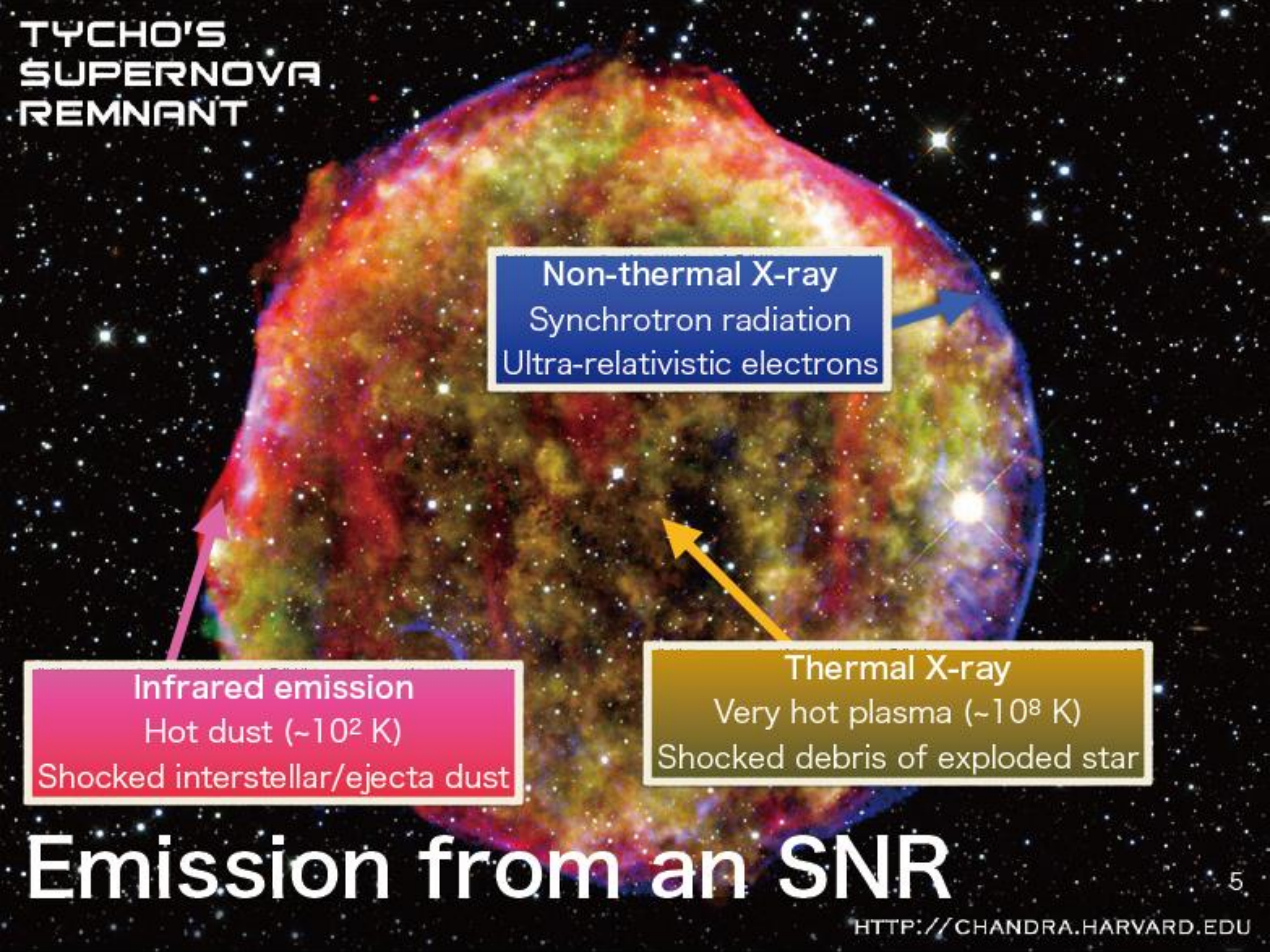
Emission from an SNR



TYCHO'S SUPERNOVA REMNANT

Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons

Infrared emission
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust

Thermal X-ray
Very hot plasma (~10^8 K)
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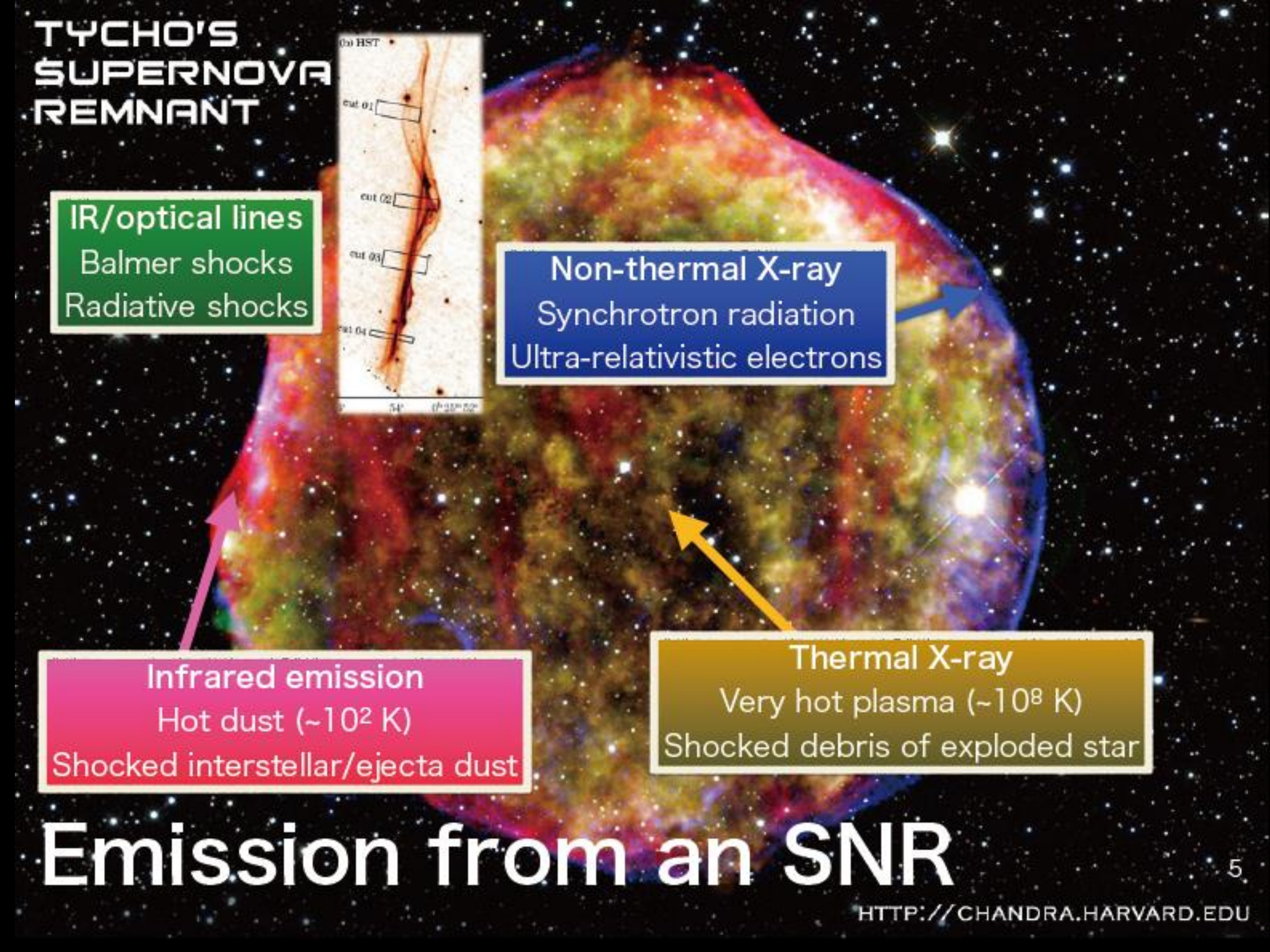
Emission from an SNR



IR/optical lines

Balmer shocks

Radiative shocks

Non-thermal X-ray

Synchrotron radiation

Ultra-relativistic electrons

Infrared emission

Hot dust (~10^2 K)

Shocked interstellar/ejecta dust

Thermal X-ray

Very hot plasma (~10^8 K)

Shocked debris of exploded star

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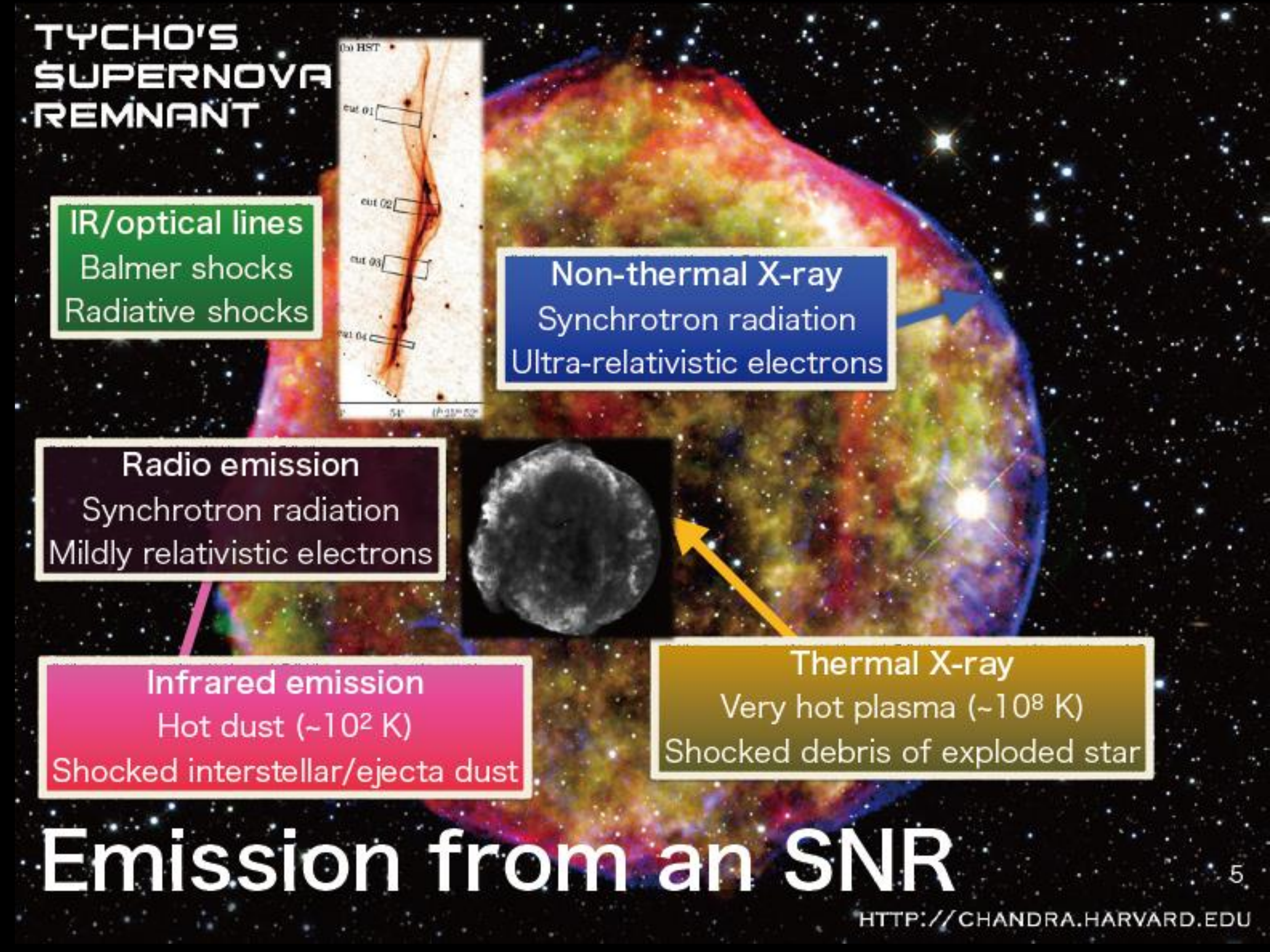

TYCHO'S SUPERNOVA REMNANT

IR/optical lines
Balmer shocks
Radiative shocks

Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons

Radio emission
Synchrotron radiation
Mildly relativistic electrons

Infrared emission
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust

Thermal X-ray
Very hot plasma (~10^8 K)
Shocked debris of exploded star

Emission from an SNR

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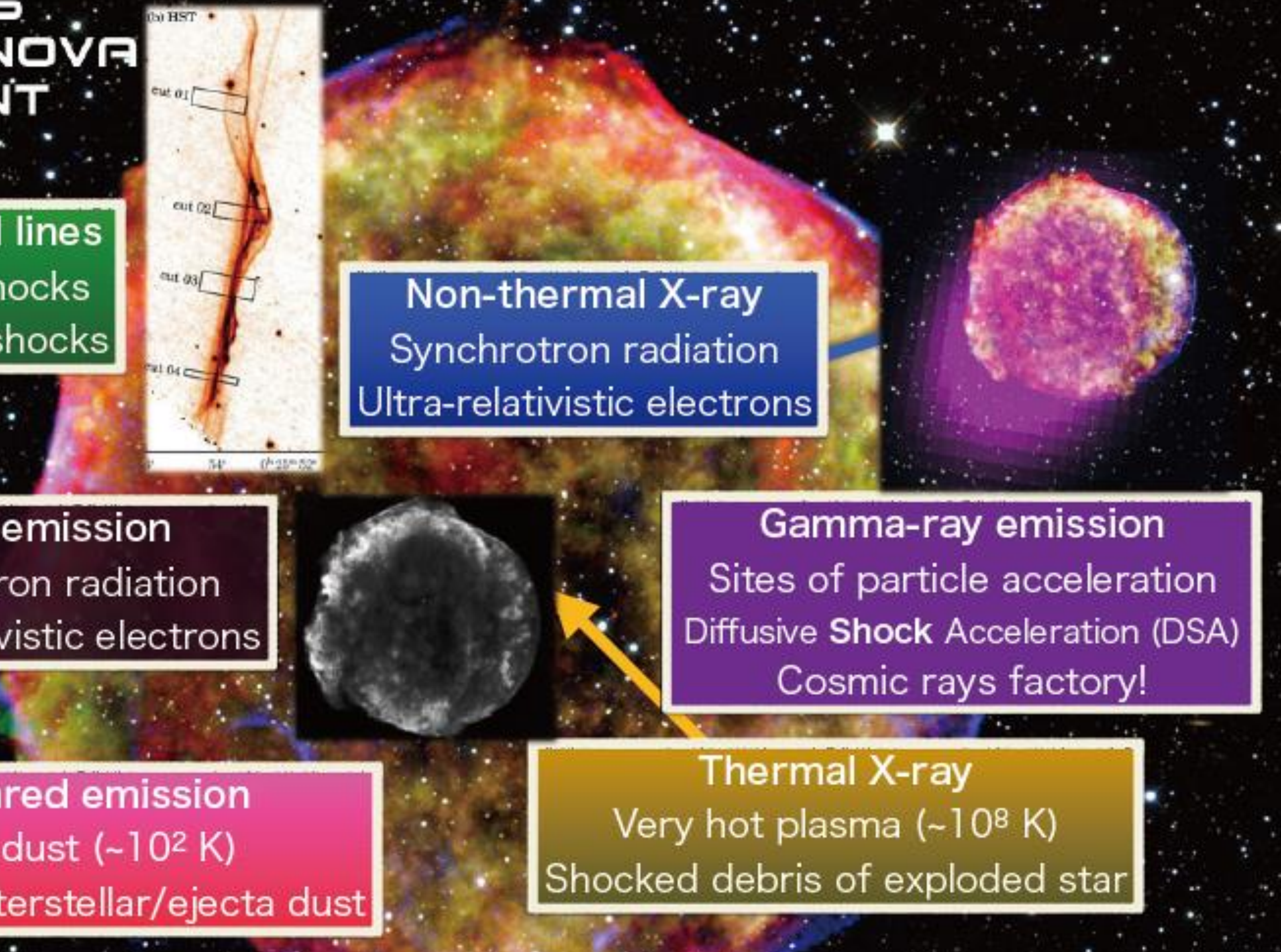
Emission from an SNR

TYCHO'S
SUPERNOVA
REMNANT



IR/optical lines
Balmer shocks
Radiative shocks

Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons

Radio emission
Synchrotron radiation
Mildly relativistic electrons

Gamma-ray emission
Sites of particle acceleration
Diffusive **Shock** Acceleration (DSA)
Cosmic rays factory!

Infrared emission
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust

Thermal X-ray
Very hot plasma (~10^8 K)
Shocked debris of exploded star

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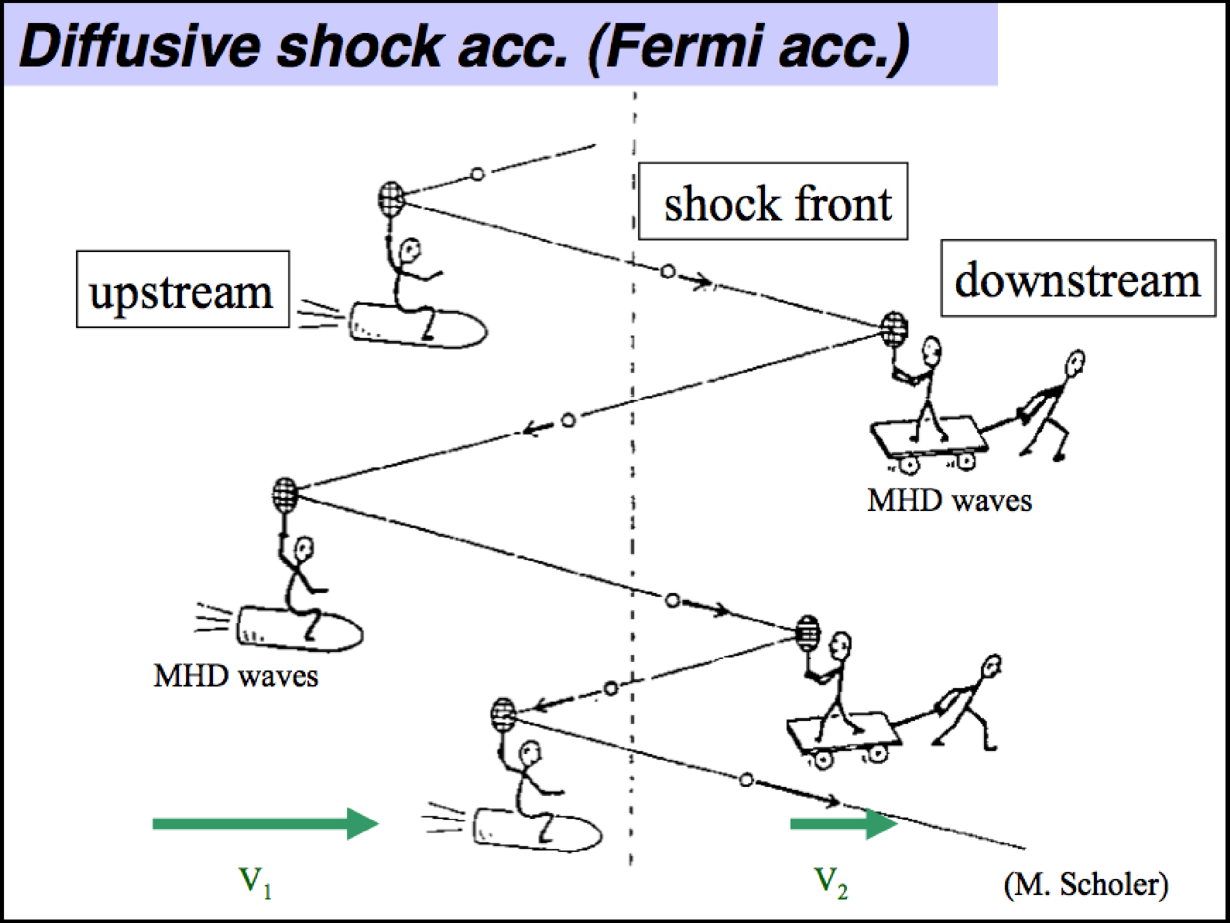
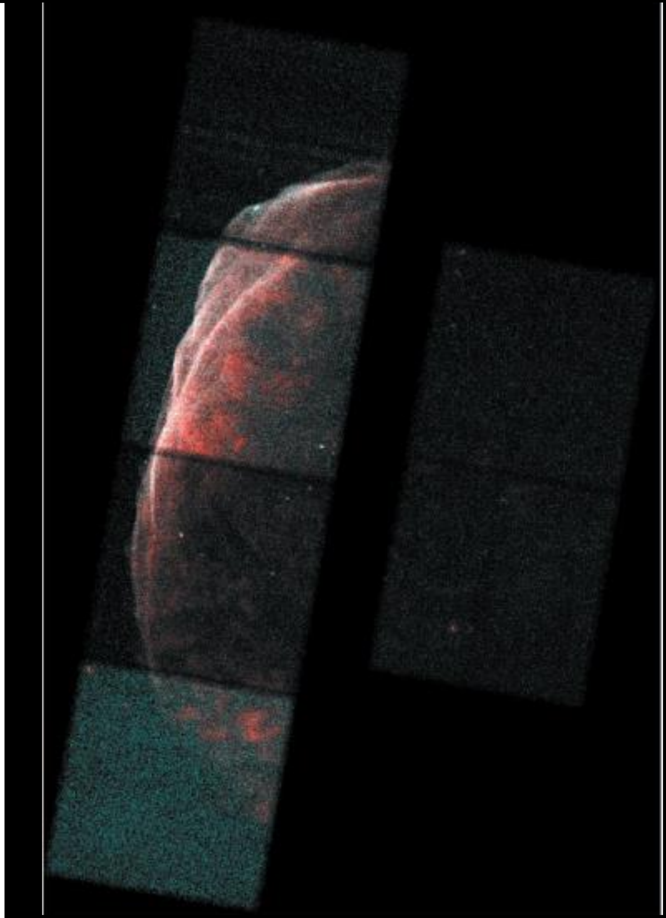
§ 加速器としての超新星残骸

衝撃波に閉じ込められた粒子は加速する

Bell 1978; Blandford & Ostriker 1978





SNR 1006
By Chandra

Our SNR Collaborations

More!

S.H. Lee
(RIKEN→ JAXA)

M.Ono
(RIKEN→Kyushu U.)

D. Warren
(NCSU→RIKEN)

D. Ellison (NCSU)

P. Slane (Harvard)

D. Patnaude
(Harvard)

F. Reopke
(Wurzburg Univ.)

Current activities

1-D Models

Self-consistent CR acceleration

Sophisticated micro-physics

Detailed broadband emission

Multi-D Models

Global MHD/hydro

Instabilities, turbulence

Detailed morphology

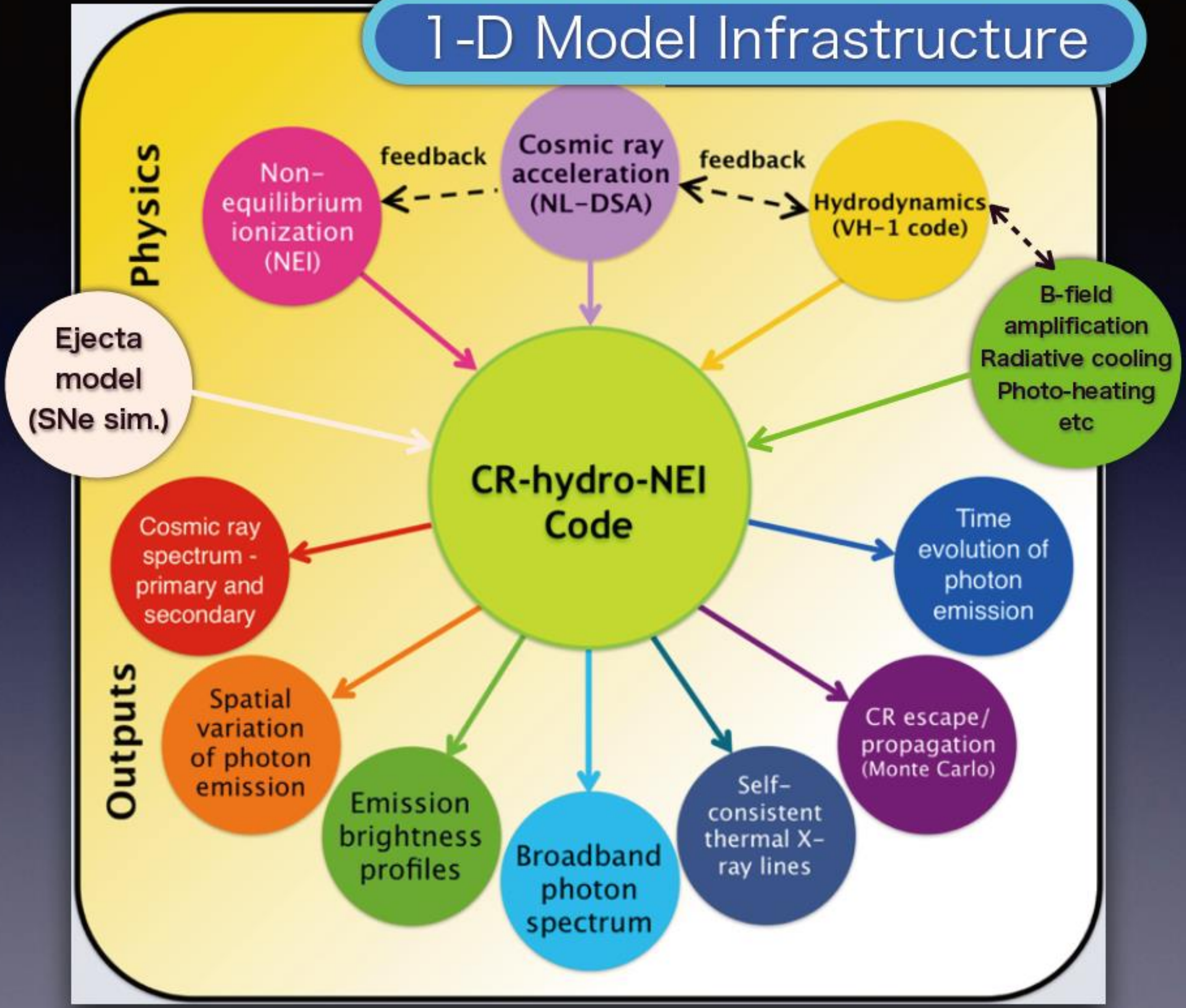
This talk

See talk by M. Ono

S.H. Lee
(RIKEN→ JAXA)

M.Ono
(RIKEN→Kyushu U.)

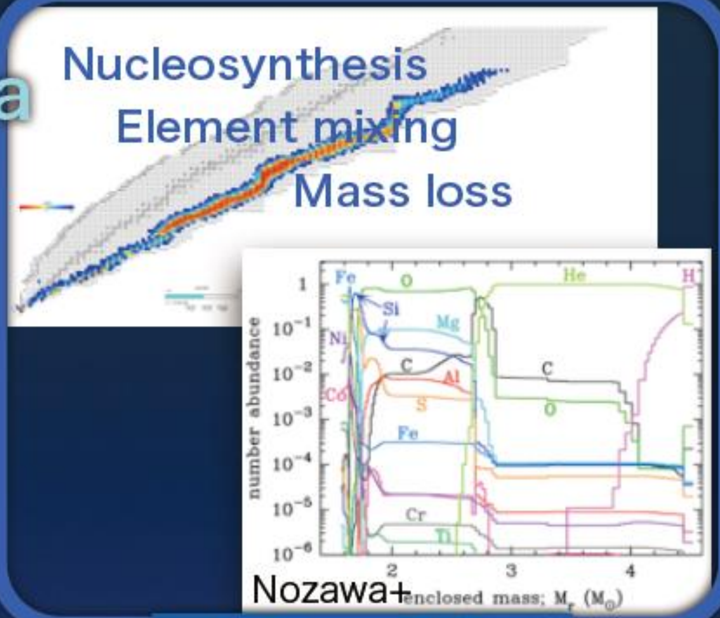
1-D Model Infrastructure



Iterative Work Flow

(1-D)

SN ejecta Model



Nucleosynthesis

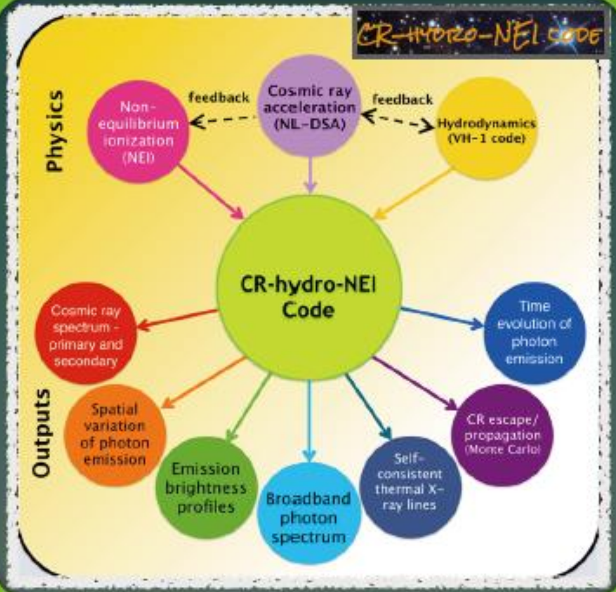
Element mixing

Mass loss

Nozawa+

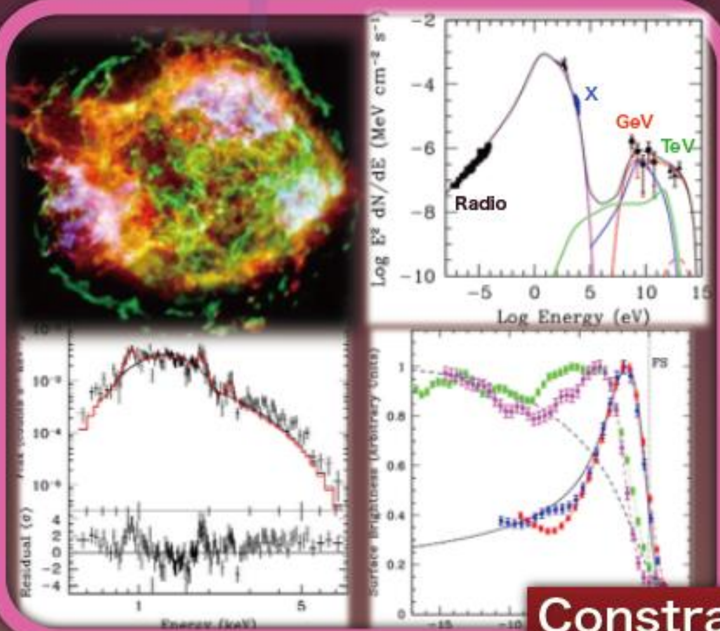
Initial conditions

CR-hydro Model



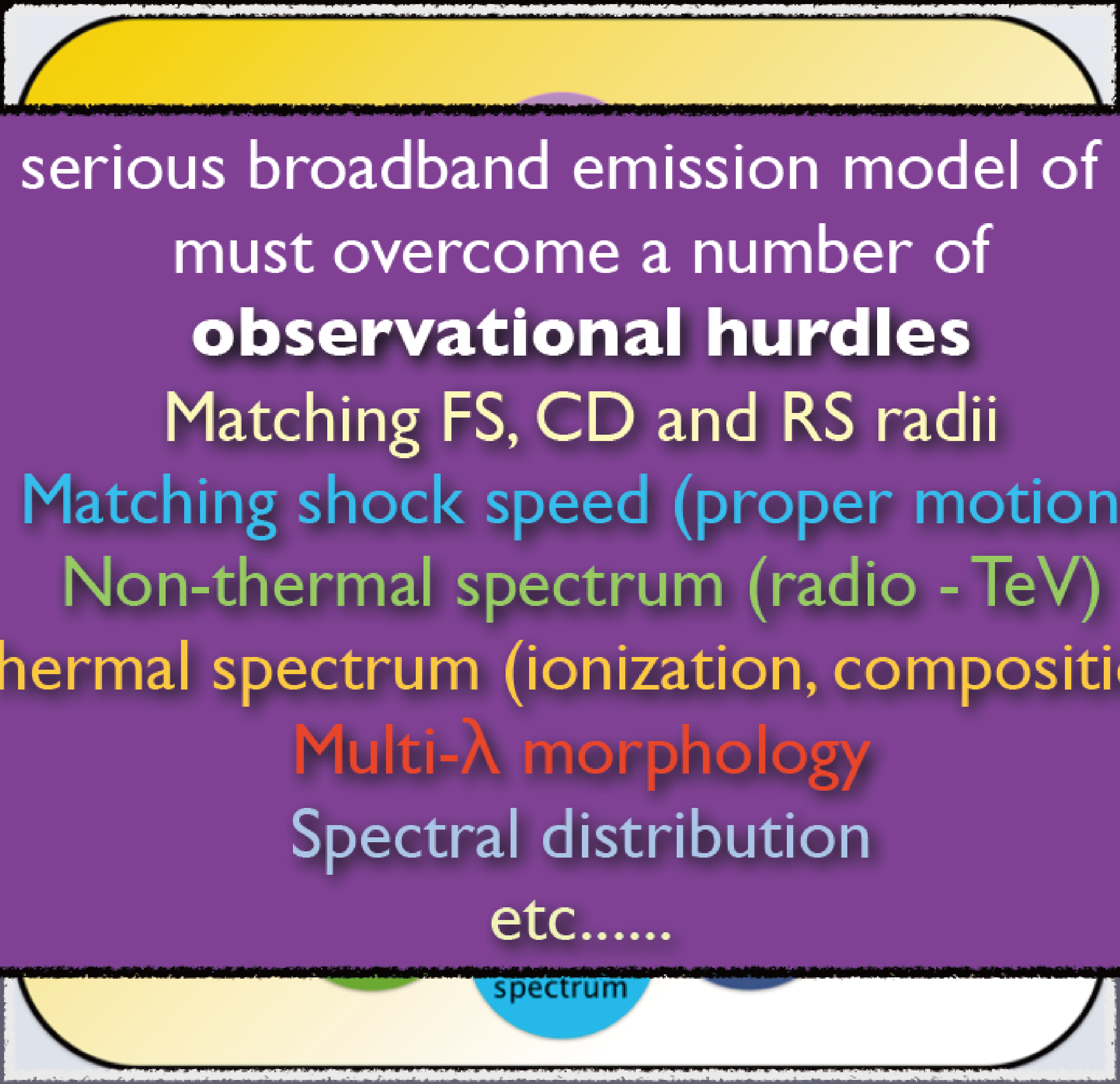
Dynamics, DSA, B-field, ionization, radiation

Multi-λ Data



Constraints!

A recipe to model SNR emission properly



Any serious broadband emission model of SNRs must overcome a number of **observational hurdles**

Matching FS, CD and RS radii

Matching shock speed (proper motion)

Non-thermal spectrum (radio - TeV)

Thermal spectrum (ionization, composition)

Multi-λ morphology

Spectral distribution

etc......

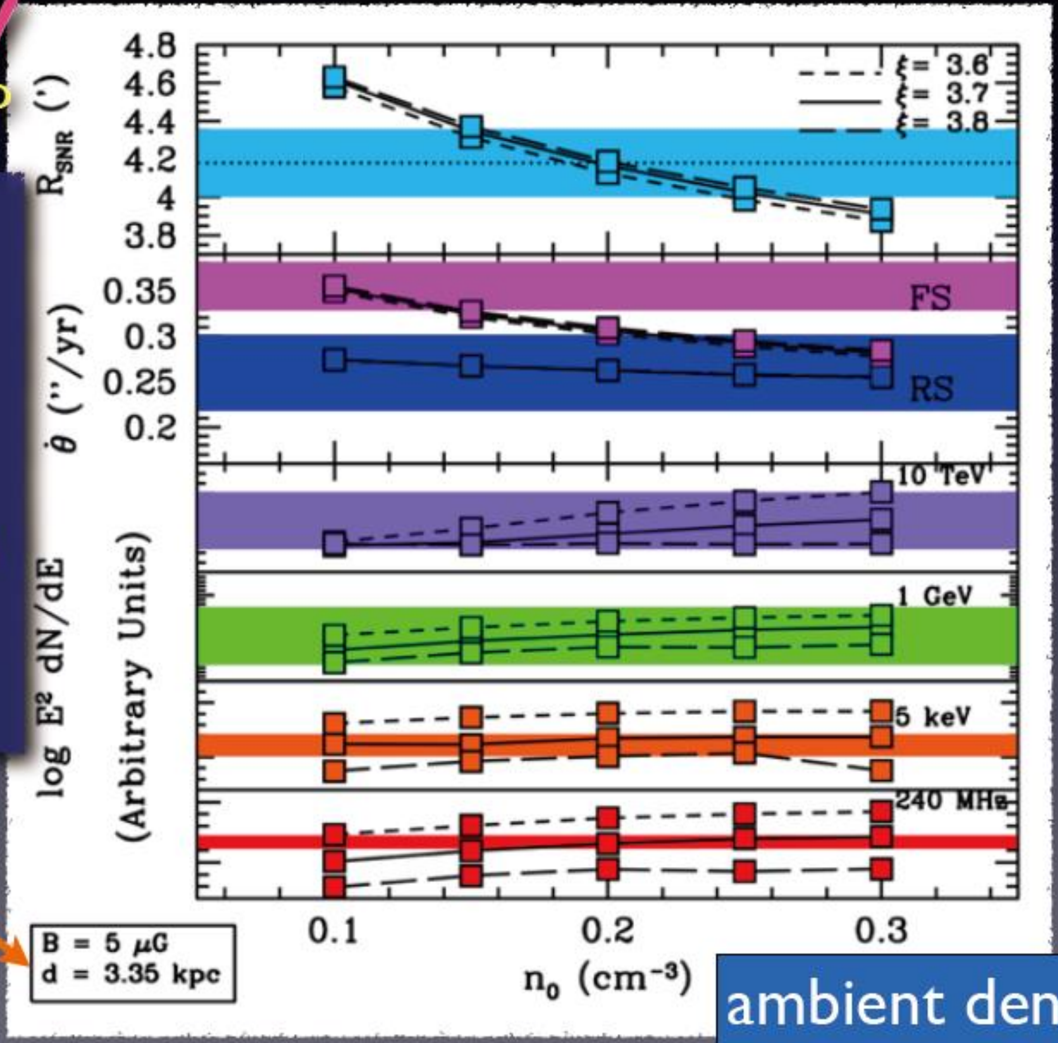
2012

Code runs fast
Perfect for parameter search

Preliminary

Slane, **HL**+ in prep

First, we search for parameter space consistent with observational facts



fixed inputs

ambient density

SNR shell radius

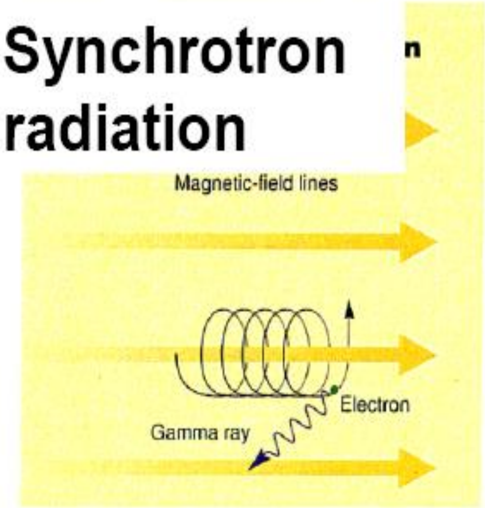
proper motion

gamma-ray
X-ray
radio
fluxes

High-energy gamma-ray Emission mechanism

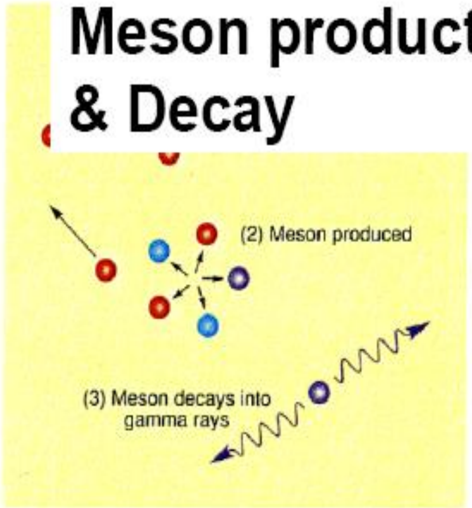
地球に降り注ぐ
宇宙線の殆どは
陽子。
陽子宇宙線の起源
を特に知りたい！

Synchrotron radiation



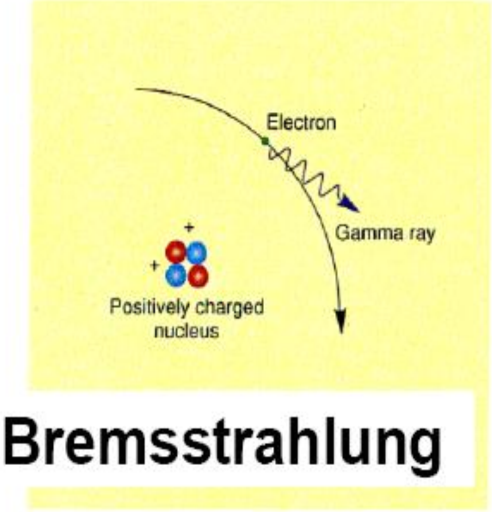
High energy **electron** + magnetic field

Meson production & Decay



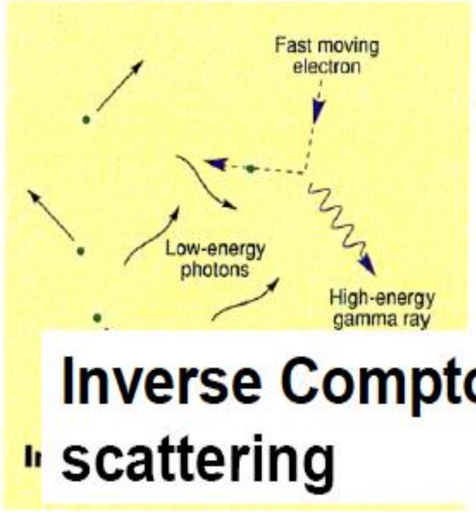
High energy **proton** + matter

Bremsstrahlung



High energy **electron** + atomic electric field

Inverse Compton scattering



High energy **electron** + photon field

Broadband Spectrum

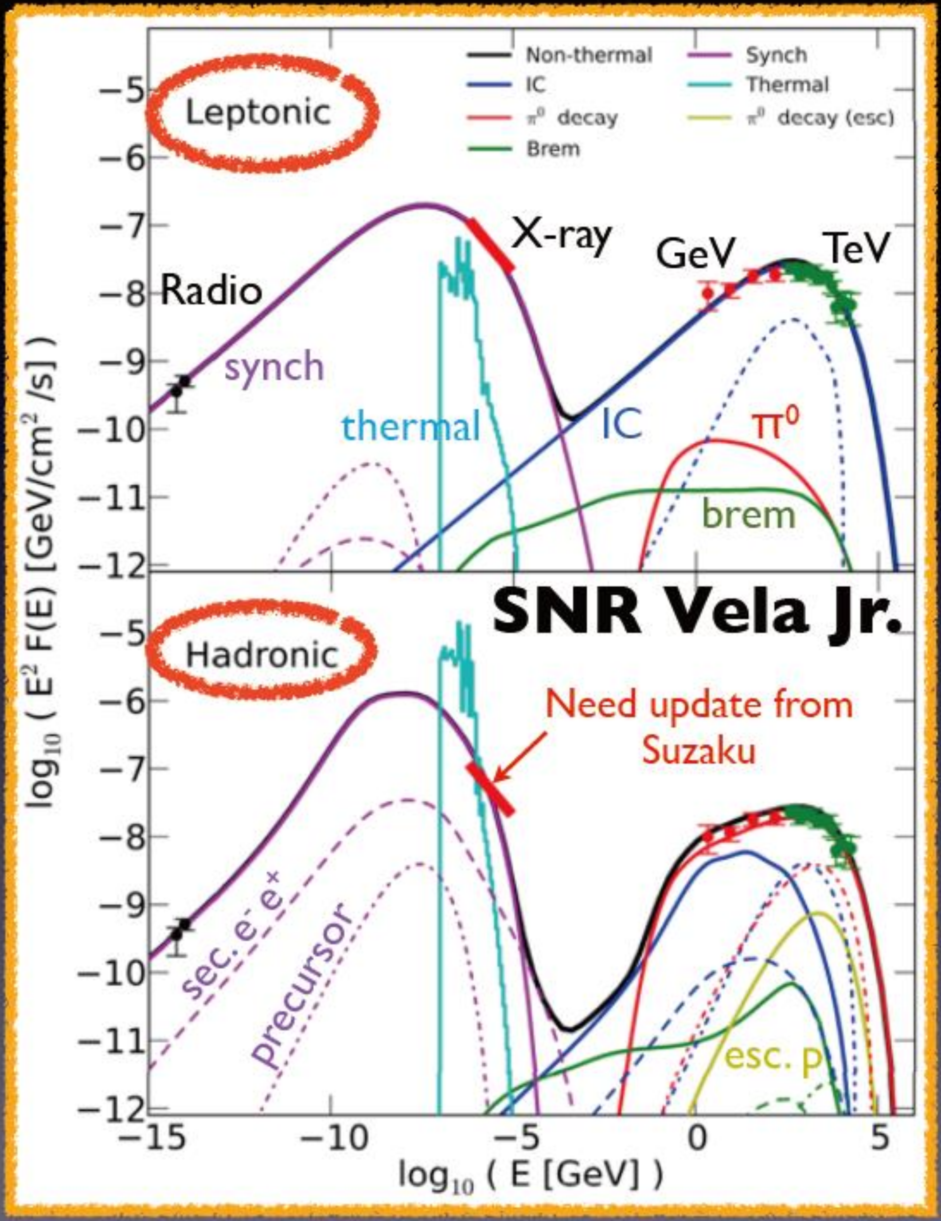
The 1st hurdle any model must pass through

Must check consistency:

- Radio to TeV flux
- Spectral shapes
- Inferred CR energetics
- Required B-field, CSM, E_{SN}

Resort to next hurdles if still can't single out best model

HL+ 2013 ApJ



SNR Vela Jr.

Need update from Suzaku

Thermal X-ray constrains Gamma-ray origin

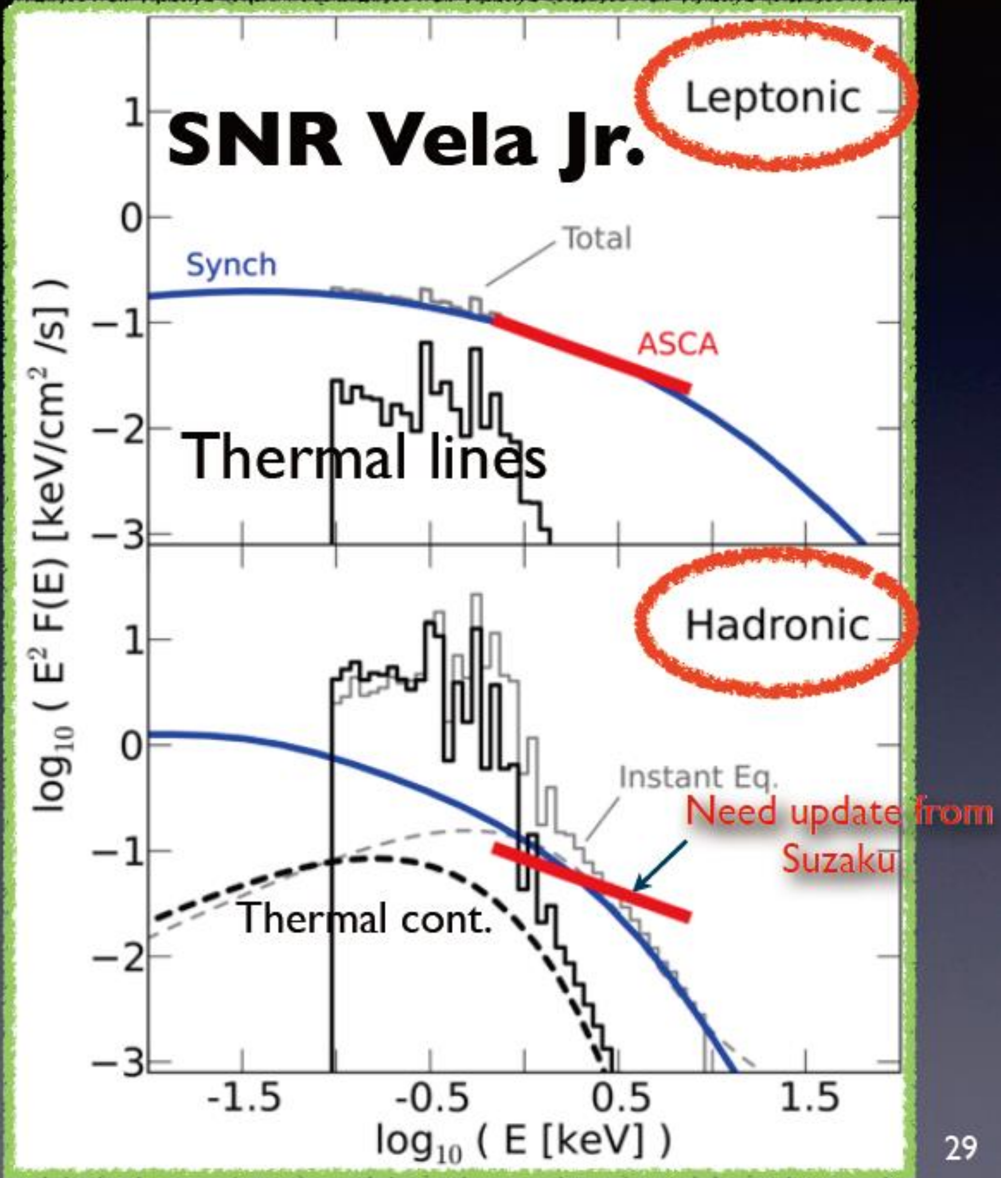
HL+ 2013 ApJ

Hurdle #1.5

In SNRs, thermal X-ray flux is coupled to broadband emission!

Very important:

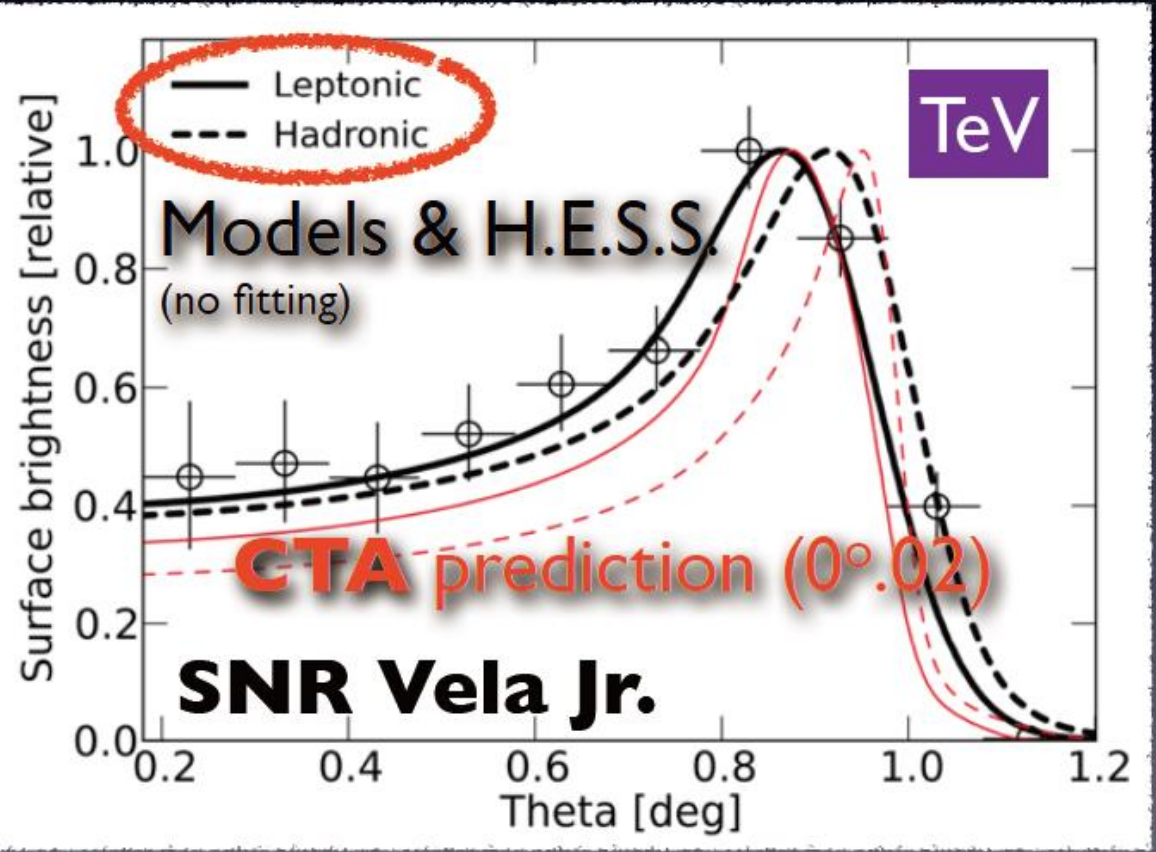
Predicted thermal flux must not violate X-ray observations



Radial emission profile probes Gamma-ray origin & CR accel efficiency

Hurdle #2

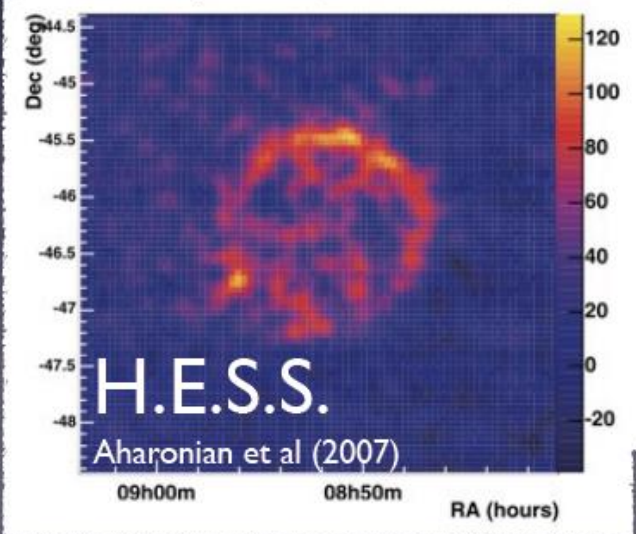
Radio, X-ray and TeV morphology constrain CR accel. and E loss history



Models & H.E.S.S.
(no fitting)

CTA prediction (0°.02)

SNR Vela Jr.



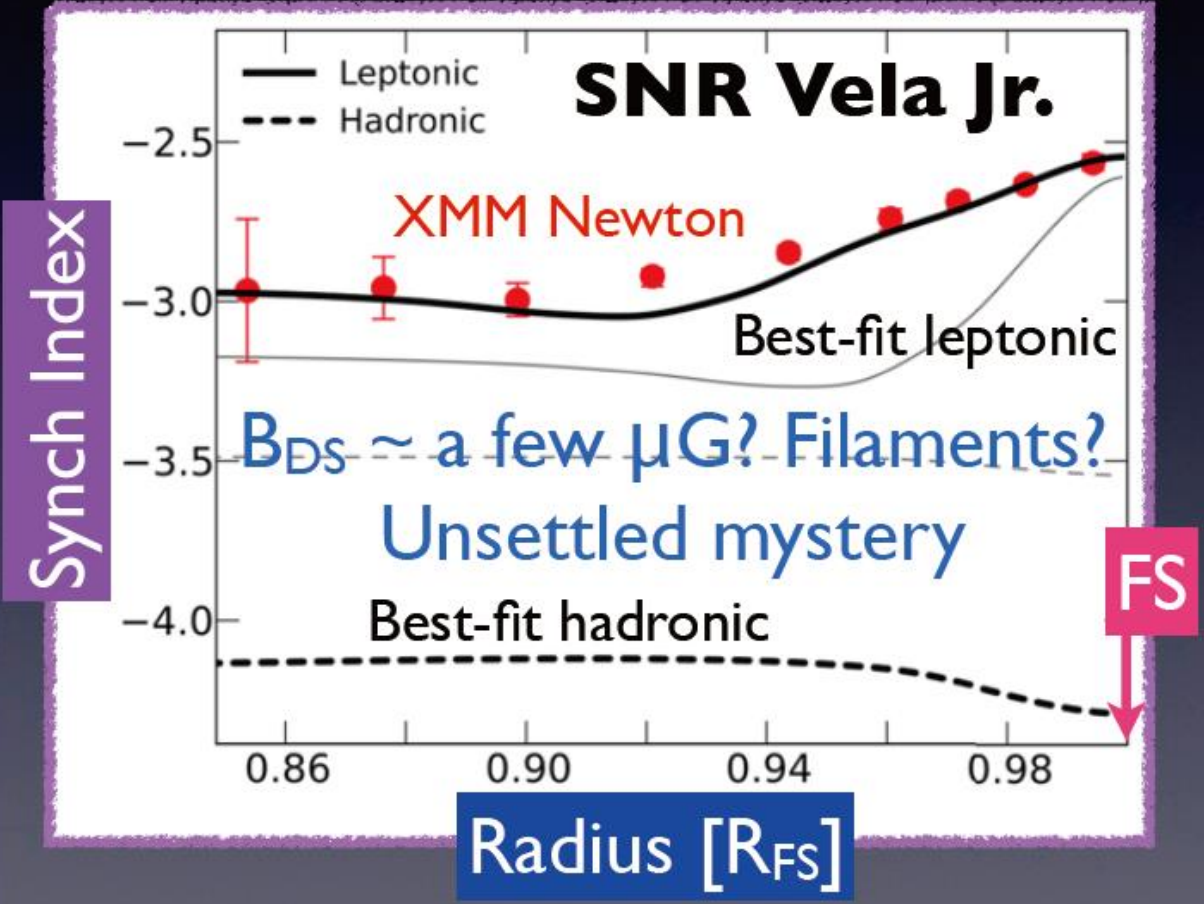
Aharonian et al (2007)

HL+ 2013 ApJ

X-ray synchrotron index distribution constrains gamma-ray origin

Hurdle #3

Hadronic and leptonic models often predict very different synch index distributions (e.g. CSM, B-field)



SNR Vela Jr.

XMM Newton

Best-fit leptonic

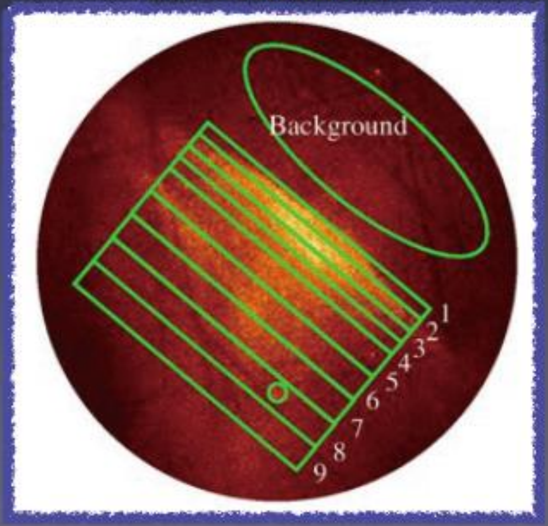
B_{DS} ~ a few µG? Filaments?

Unsettled mystery

Best-fit hadronic

HL+ 2013 ApJ

Kishishita & Uchiyama 2013
XMM-Newton



What do we learn?

- A best-fit broadband model passing all the observation hurdles tells us the gamma-ray origin of a SNR (i.e. CR ion or e^-, or both)
- The ultimate goal though is to constrain total energy in CR different types of SNR can produce in its lifetime (hadronic and leptonic models often predict very different values)
  Note: Leptonic does NOT mean there is no CR ion
- Sometimes though, we don't even know much about the progenitor stars! (next part)

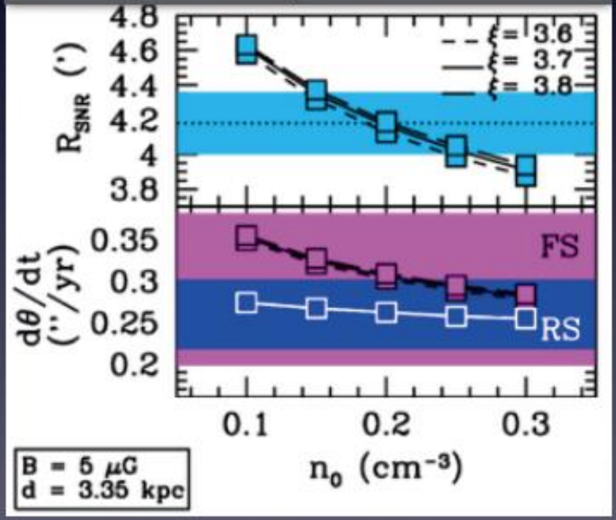
Hydro + Spectral Model of Young SNRs

S.H. Lee (RIKEN→JAXA)

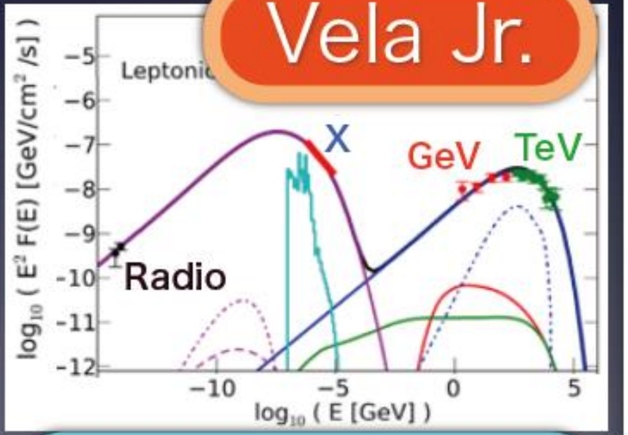
e.g. **HL+** (2013) **Vela Jr.**

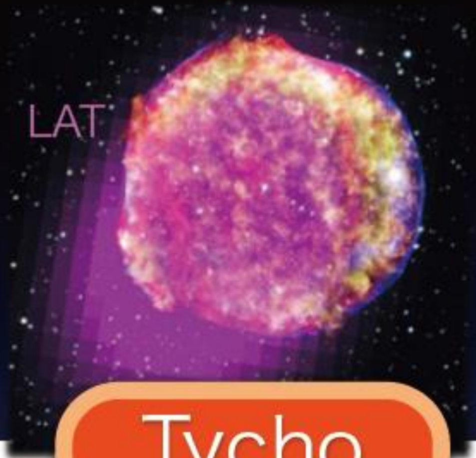
Slane, **HL+** (2014) **Tycho's SNR**

Size and Expansion Rate

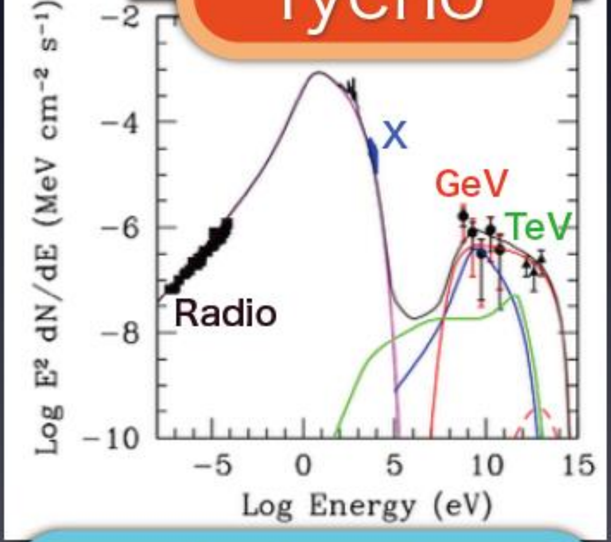


Vela Jr.





Tycho



Leptonic

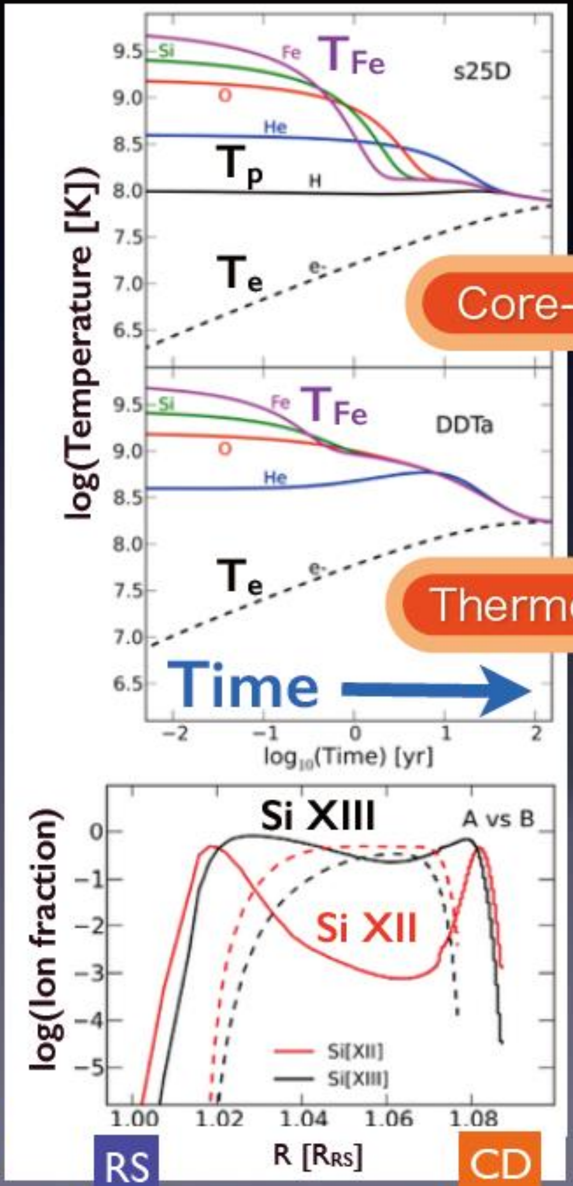
ECR = 0.15 ESN

Hadronic

ECR = 0.16 ESN

Thermal X-rays

- Thermal X-rays of young SNRs tell us many things
    - Ejecta and CSM chemical composition
    - Temperatures and motions (ions, e-)
    - Ionization states
    - Even CR acceleration history
- Non-equilibrium ionization and temperature evolution of 152 ion species in ejecta and CSM
- Detailed thermal X-ray spectrum (self-consistently with non-thermal)



Core-collapse

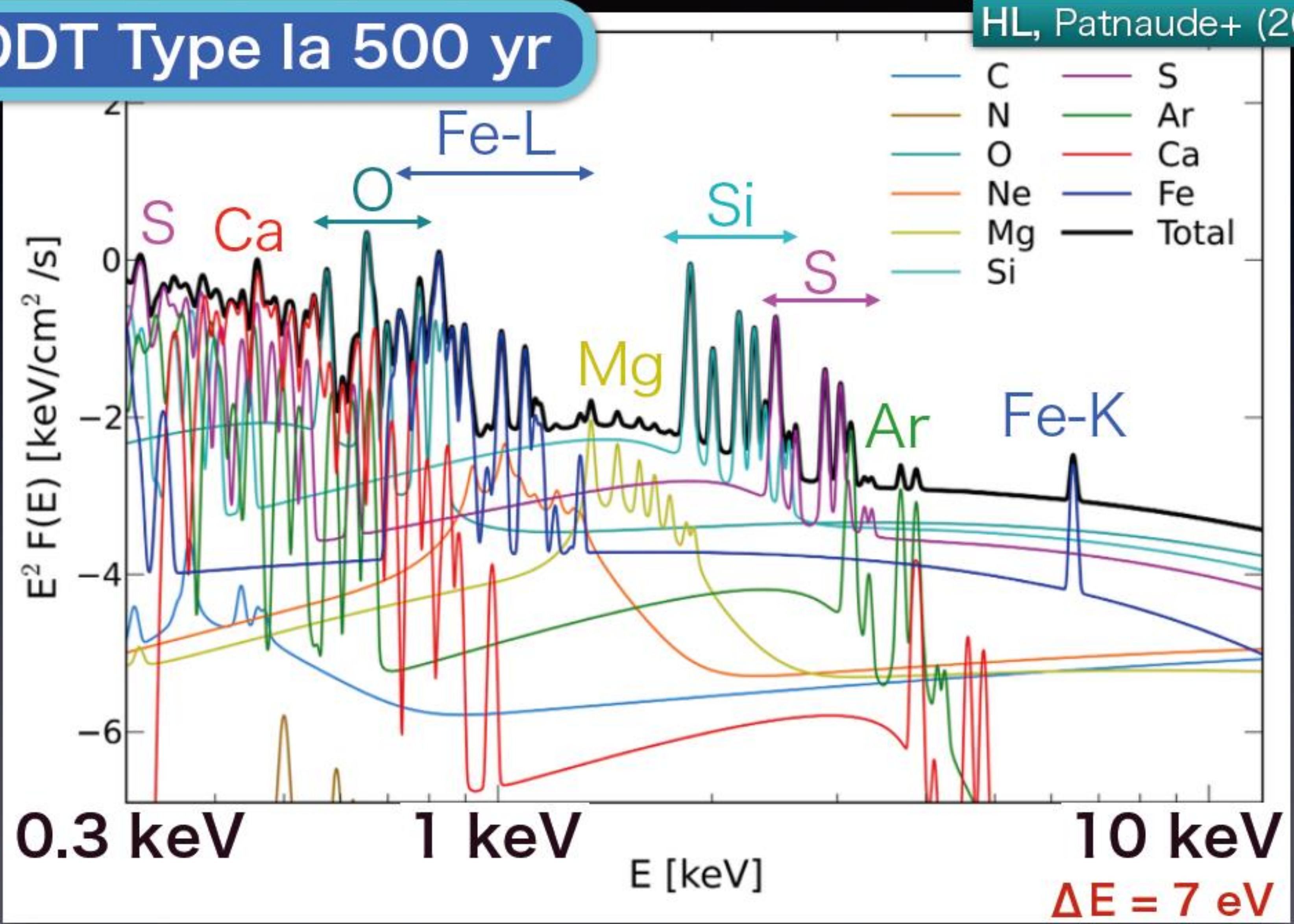
Thermonuclear

HL, Patnaude+ (2014)

Synthesis of detailed X-ray spectra

DDT Type Ia 500 yr

HL, Patnaude+ (2014)

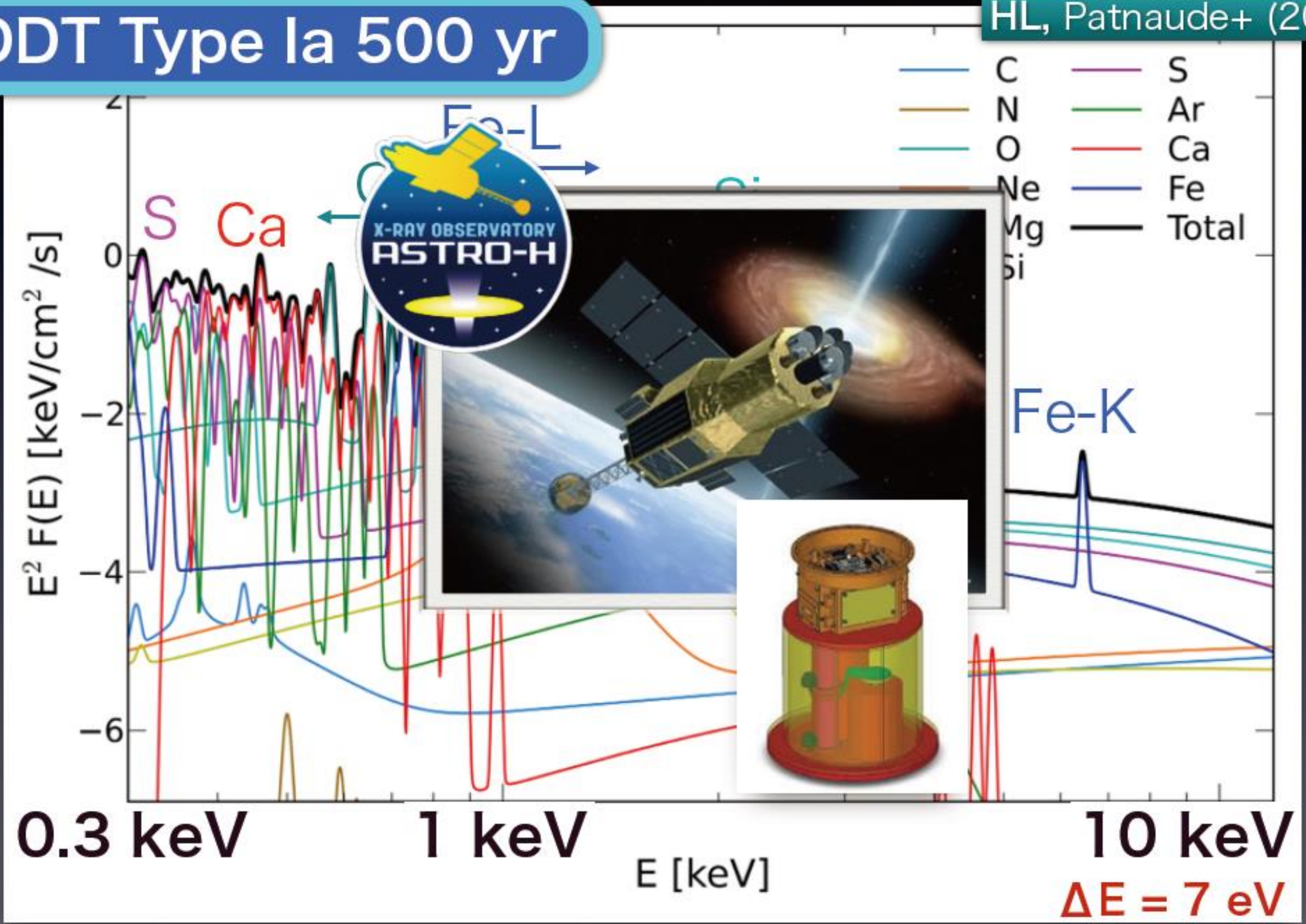


ΔE = 7 eV

Synthesis of detailed X-ray spectra

DDT Type Ia 500 yr

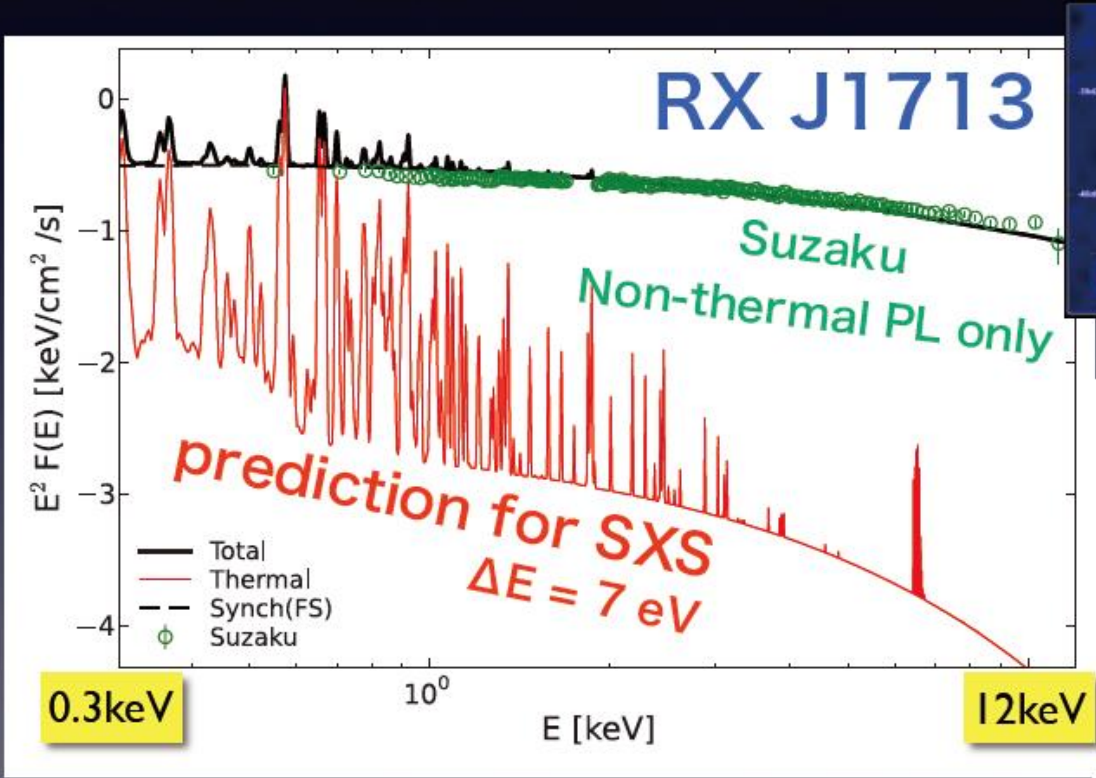
HL, Patnaude+ (2014)

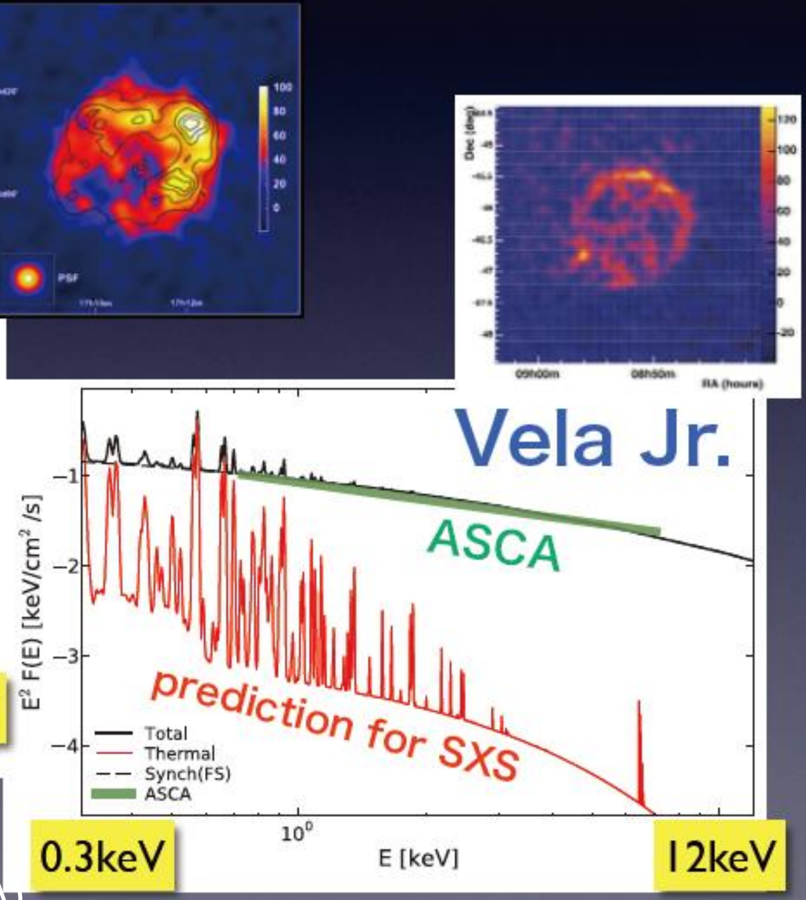


ΔE = 7 eV

Future X-ray spectroscopy by Astro-H

Our broadband models make robust predictions for Astro-H





Left: S.H. Lee (RIKEN→JAXA)
Right: Astro-H (2015-) (JAXA)

e.g. HL+ 2013

Synergy of future super telescopes for SNR research

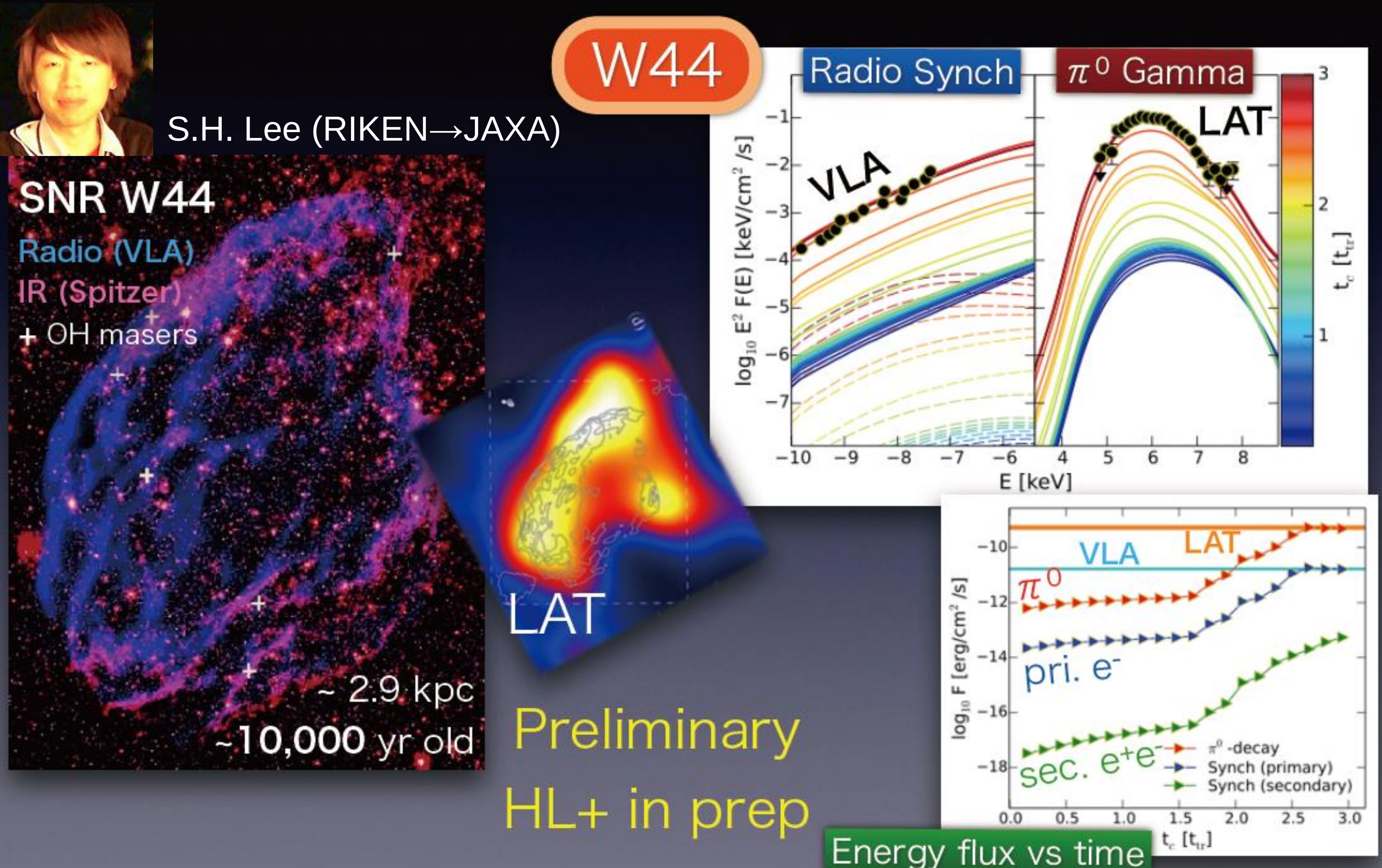
Hi-res X-ray spectroscopy

- Ejecta/CSM composition from faint lines
- Unveil progenitor properties of Ia and core-collapse SNRs
- SN explosion mechanisms, matter mixing and nucleosynthesis
- Broadened line profiles:
  gas dynamics, temperature equilibration

Hi-sensitivity, hi-res imaging

- Many new gamma-ray SNR discoveries
- Low-noise spectrum measurement from ~20GeV to >100 TeV
- Measure roll-over region of CR spectra!
- 3x better TeV morphology measurement to contrast with radio/IR/X-ray images

Non-thermal Emission of Middle-aged SNRs



S.H. Lee (RIKEN→JAXA)

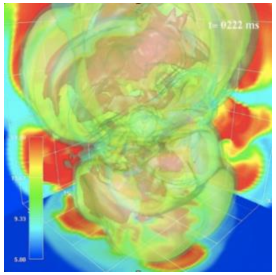
Preliminary

HL+ in prep

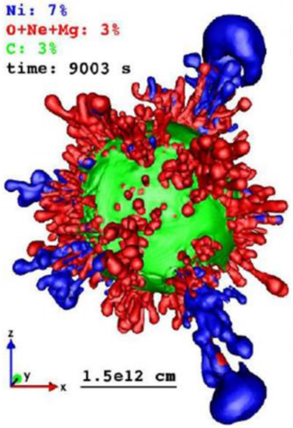
Energy flux vs time

Our Big Challenge:

From (Takiwaki & Wongwathanarat) To (Lee, Ono, Warren)



T. Takiwaki
(RIKEN)



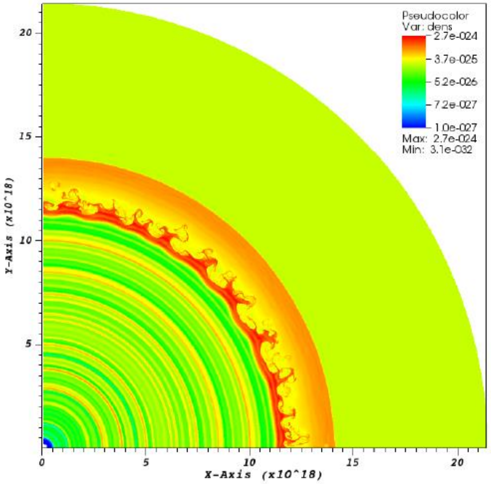
A. Wongwathanarat
(RIKEN)

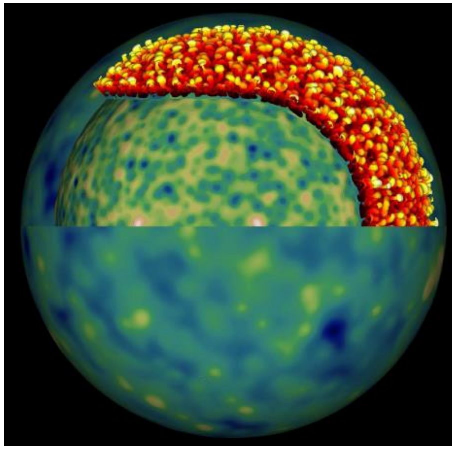
How do they Evolve?

Origin of Asymmetries?

Legacy of Supernovae?

Ono+14, in prep.





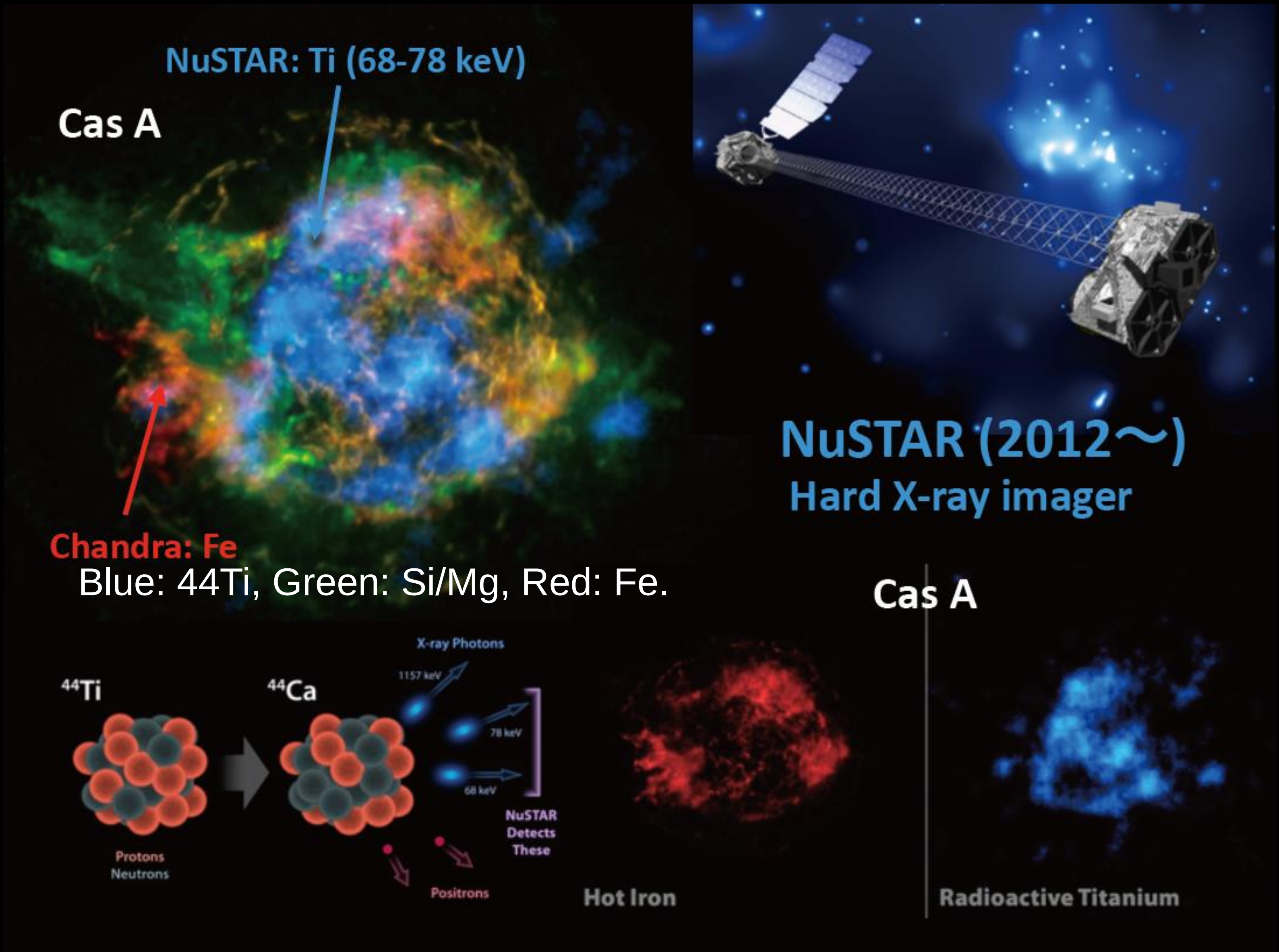
Warren & Blondin 13

S.H. Lee
(RIKEN→ JAXA)

M.Ono
(RIKEN→Kyushu U.)

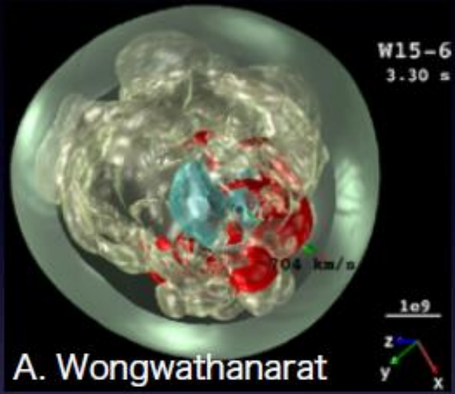
D. Warren
(NCSU→RIKEN)

我々の目指す地点：
よりリアルなシミュレーションで二刀流実現



Blue: 44Ti, Green: Si/Mg, Red: Fe.

Roadmap



A. Wongwathanarat

Towards true picture of SNe

Progenitor star properties

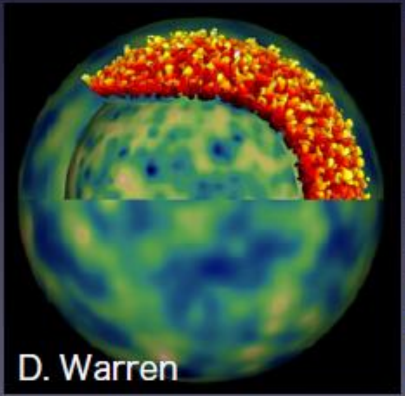
Explosion mechanism

Nucleosynthesis, matter mixing

Shock breakout to early SNR phase

T. Takiwaki, A. Wongwathanarat, M. Ono, T. Tolstov

K. Maeda (Type Ia's), and more friends


D. Warren

Deeper understanding of SNRs and collisionless shocks

Diffusive shock acceleration (DSA) of CR e^- and ions

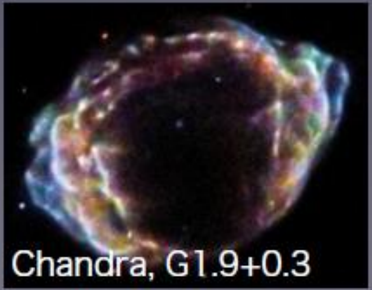
CR-driven magnetic turbulence

Hydro/MHD instabilities

Ejecta and CSM structure

H. Lee, M. Ono, M. Barkov

D. Ellison, P. Slane, D. Patnaude, C. Badenes, D. Warren, A. Bykov, ···


Chandra, G1.9+0.3

Confront multi-λ data with state-of-the-art model

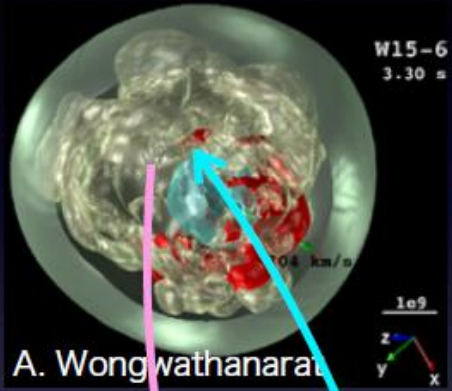
Future and current observations of SNe and SNRs young to old

Astro-H, NuStar, Suzaku, Chandra, LAT, IACTs, VLA, Nanten-II, etc

In close future: CTA, SKA, and more

ALIGO/AVIRGO/KAGRA/SK

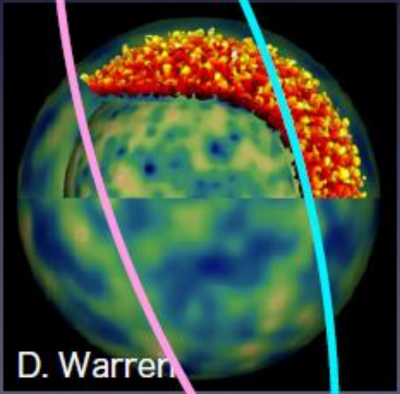
Roadmap



A. Wongwathanarat

Towards true picture of SNe

Progenitor star properties
Explosion mechanism
Nucleosynthesis, matter mixing
Shock breakout to early SNR phase
T. Takiwaki, A. Wongwathanarat, M. Ono, T. Tolstov
K. Maeda (Type Ia's), and more friends



D. Warren

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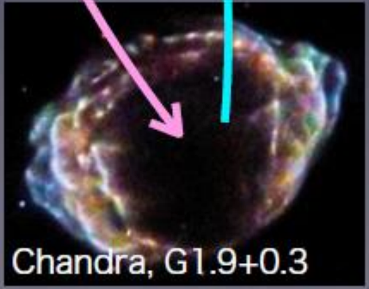

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