

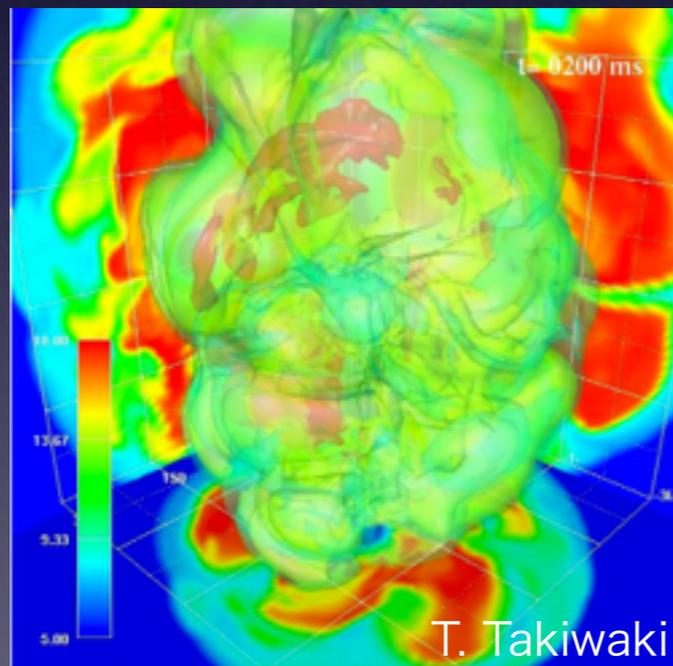
SNR Research
at
RIKEN Astrophysical Big Bang Laboratory

Part I

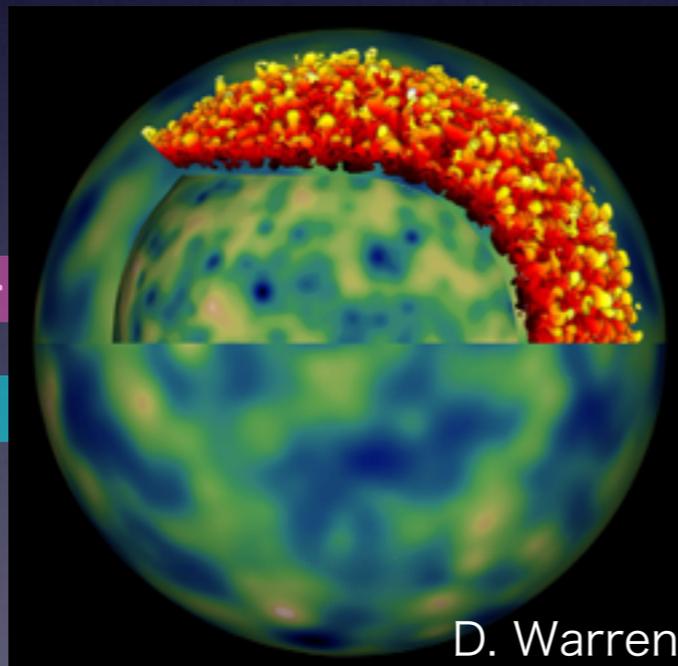
Herman Lee
JAXA/RIKEN

Our Theme Song

“From engine to remnant, and back”



Engine



Remnant



What's out there

In our computers

Roadmap

Roadmap

Towards true picture of SNe

Progenitor star properties

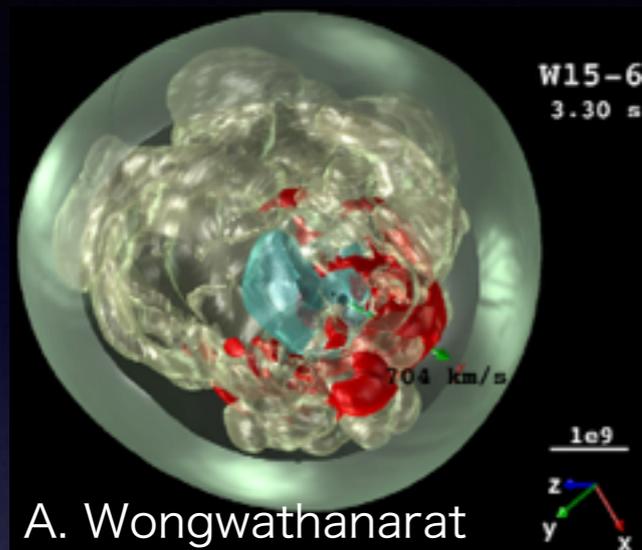
Explosion mechanism

Nucleosynthesis, matter mixing

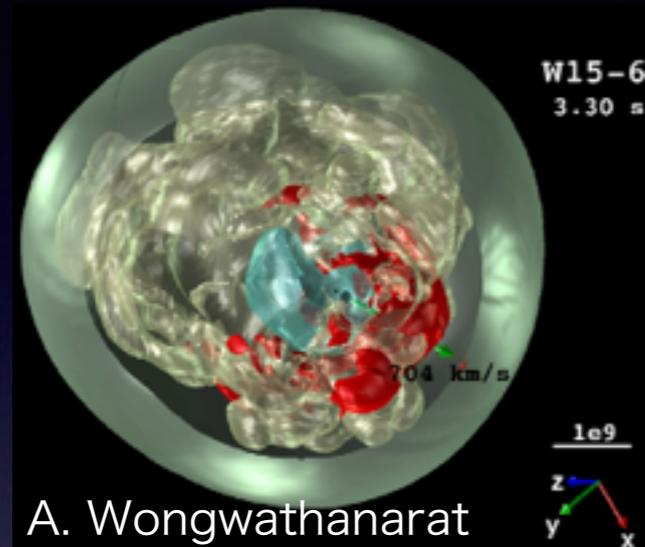
Shock breakout to early SNR phase

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

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



Roadmap



Towards true picture of SNe

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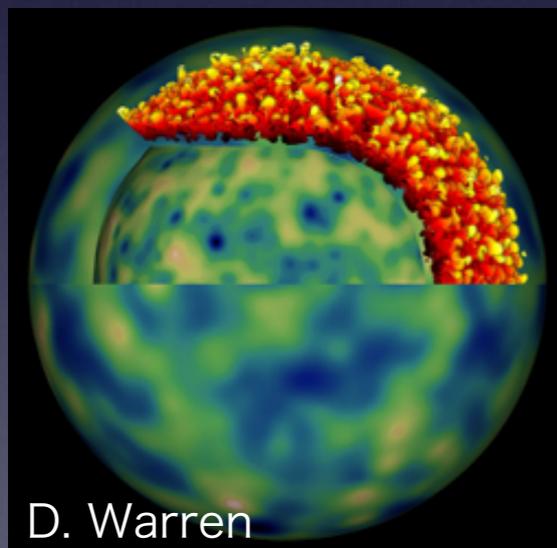
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Deeper understanding of SNRs and collisionless shocks

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

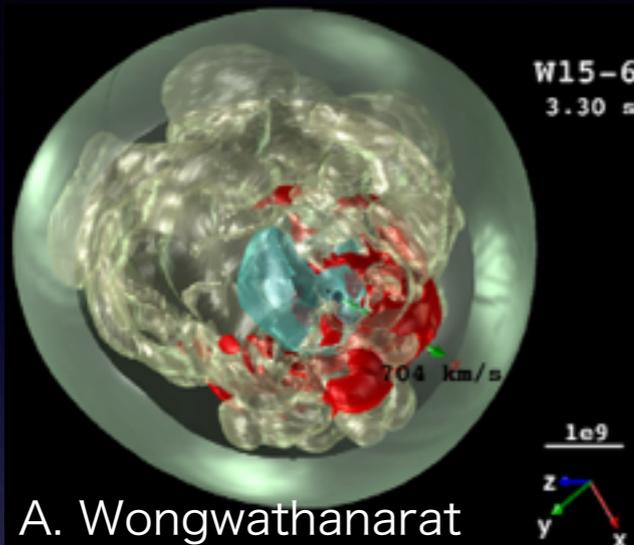
D. Ellison, P. Slane, D. Patnaude, C. Badenes, D. Warren, A. Bykov, ...

Roadmap

Towards true picture of SNe

Progenitor star properties
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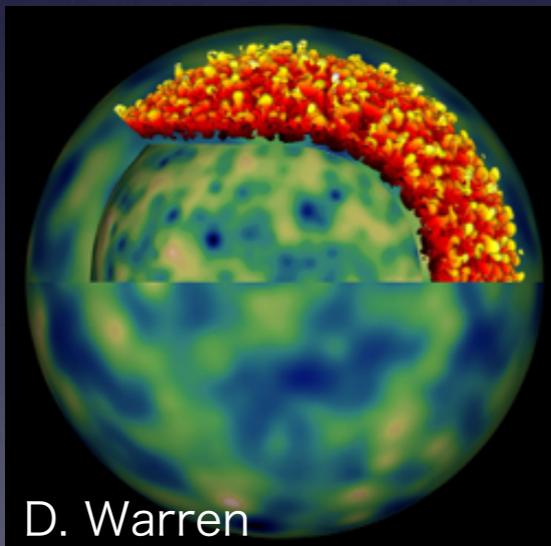
A. Wongwathanarat

Deeper understanding of SNRs and collisionless shocks

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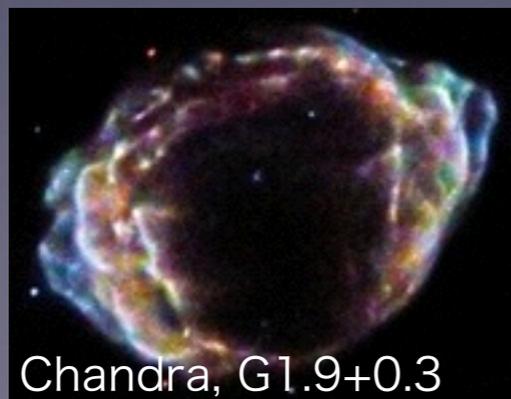
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D. Warren

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



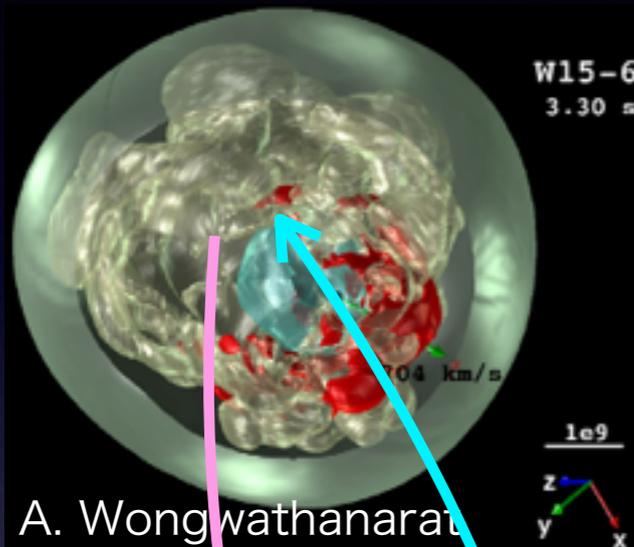
Chandra, G1.9+0.3

Roadmap

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
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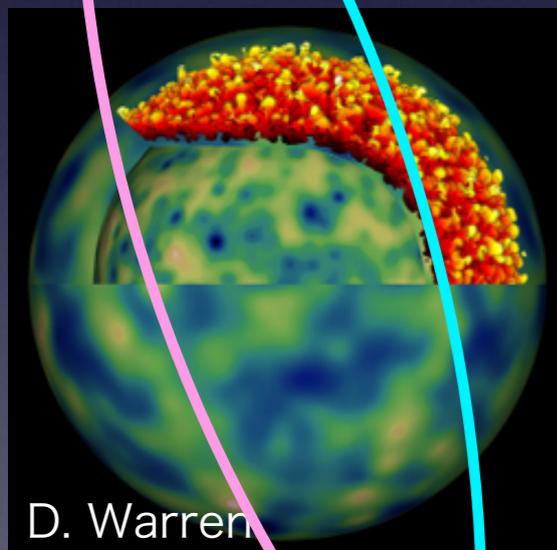


Deeper understanding of SNRs and collisionless shocks

- Diffusive shock acceleration (DSA) of CR e^- and ions
- CR-driven magnetic turbulence
- Hydro/MHD instabilities
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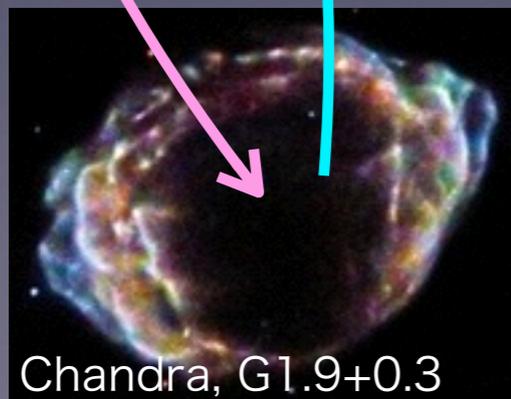
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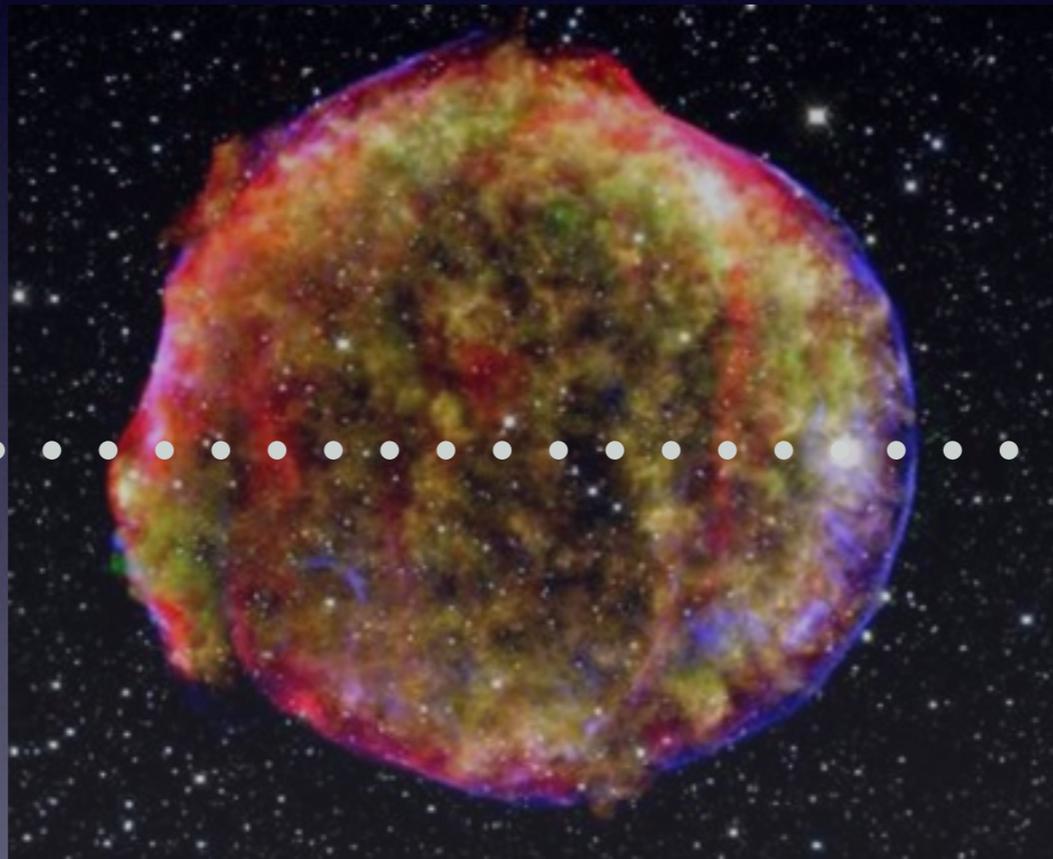
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SNR Research

Numerical Approaches



SNR Research

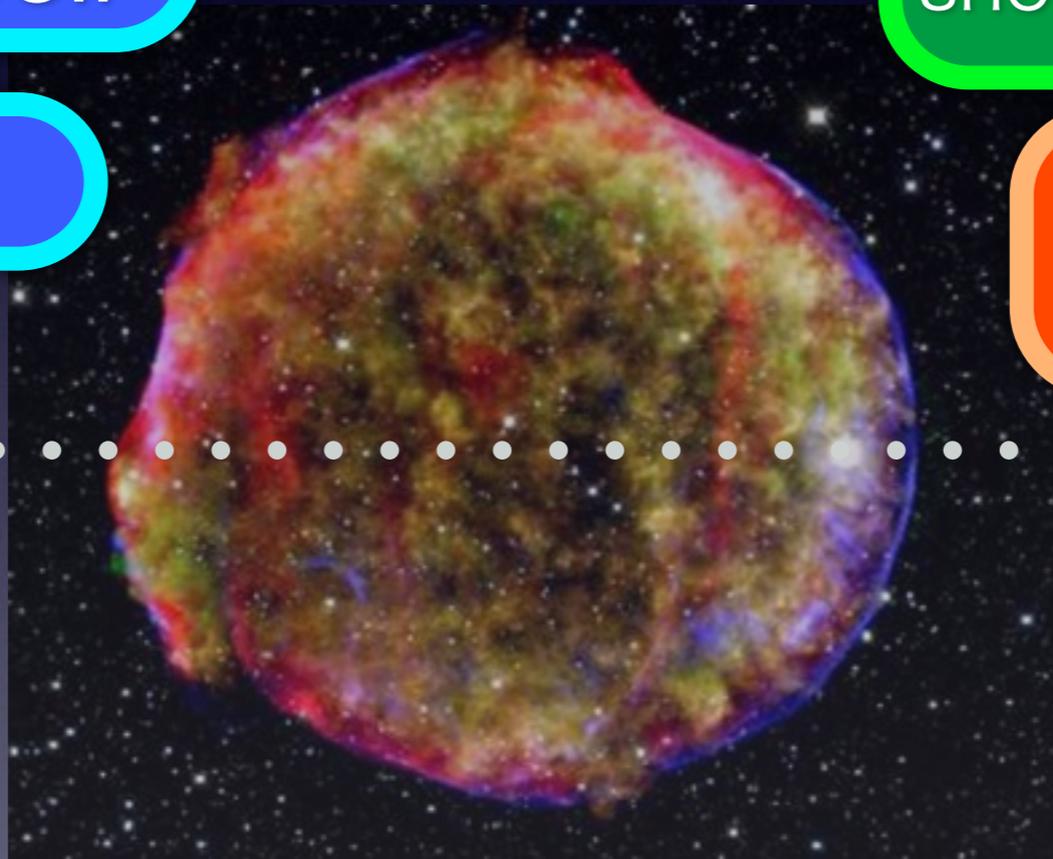
Numerical Approaches

Particle-in-cell

Hybrid code

Fundamental
shock/plasma physics

Computation cost
Limited dynamic ranges



SNR Research

Numerical Approaches

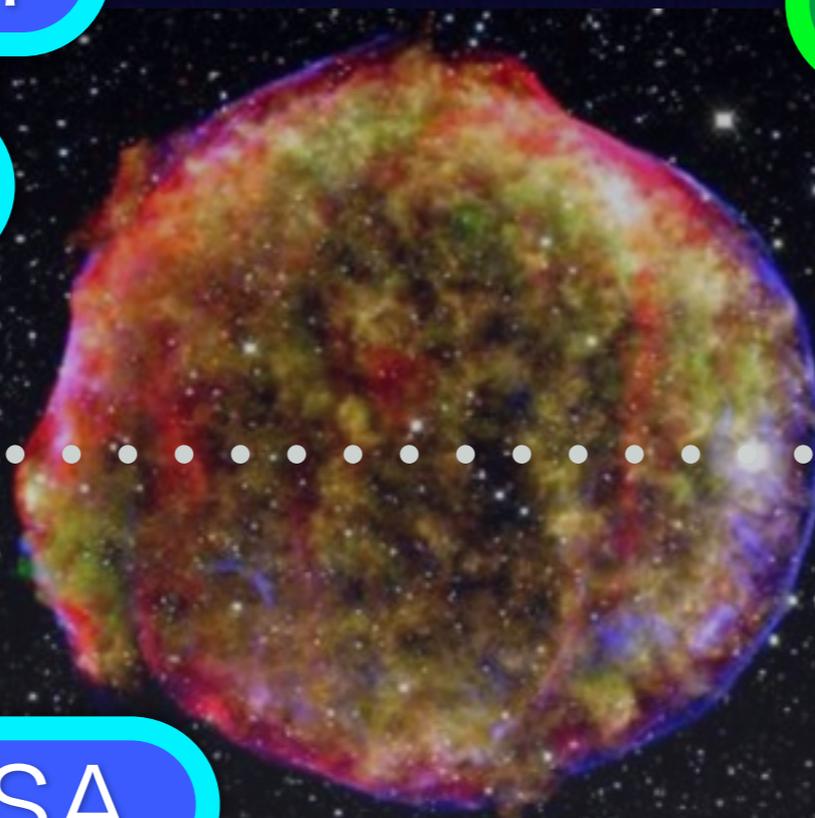
Particle-in-cell

Hybrid code

MHD/hydro

Semi-analytic DSA

Monte Carlo



Fundamental
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Computation cost
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Phenomenological
shock/plasma physics

Constraints from
multi- λ observations

SNR Research

Numerical Approaches

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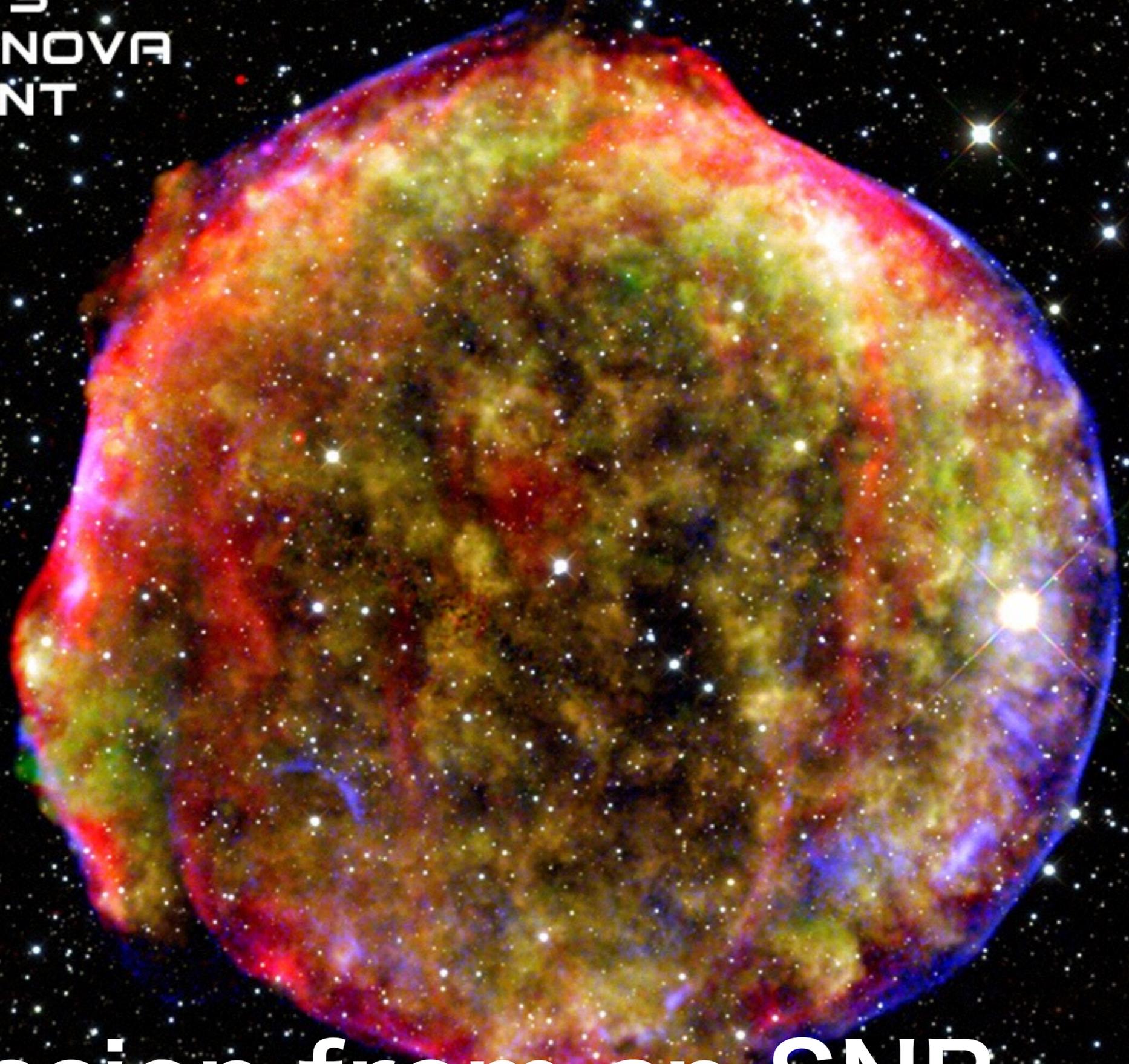
Computation cost
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Constraints from
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**TYCHO'S
SUPERNOVA
REMNANT**



Emission from an SNR

TYCHO'S SUPERNOVA REMNANT



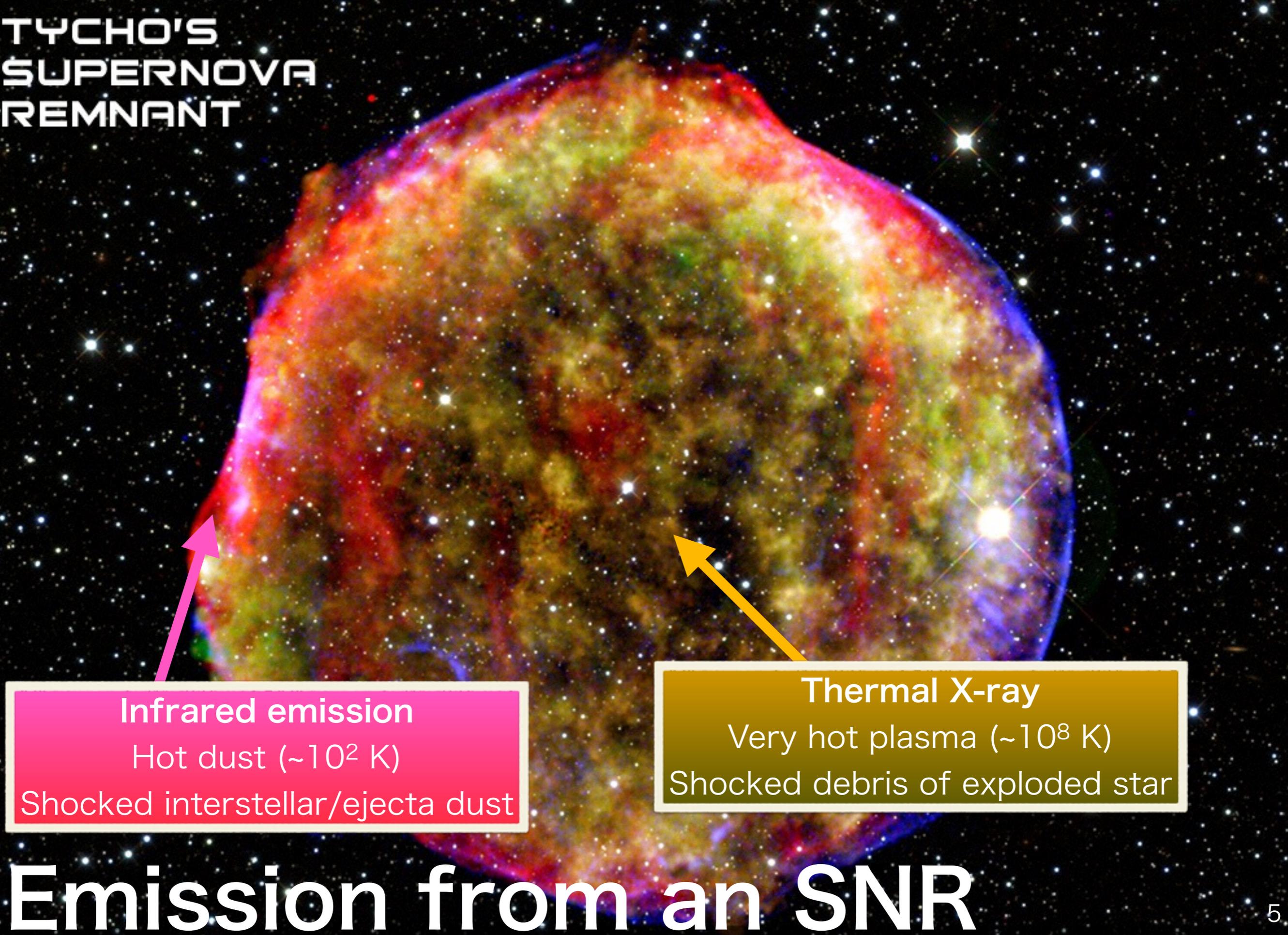
Infrared emission

Hot dust ($\sim 10^2$ K)

Shocked interstellar/ejecta dust

Emission from an SNR

TYCHO'S SUPERNOVA REMNANT



Infrared emission

Hot dust ($\sim 10^2$ K)

Shocked interstellar/ejecta dust

Thermal X-ray

Very hot plasma ($\sim 10^8$ K)

Shocked debris of exploded star

Emission from an SNR

TYCHO'S SUPERNOVA REMNANT

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

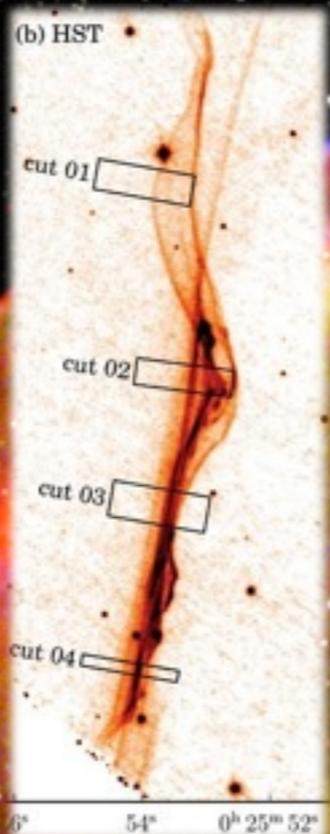
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Emission from an SNR

TYCHO'S SUPERNOVA REMNANT

IR/optical lines
Balmer shocks
Radiative shocks



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

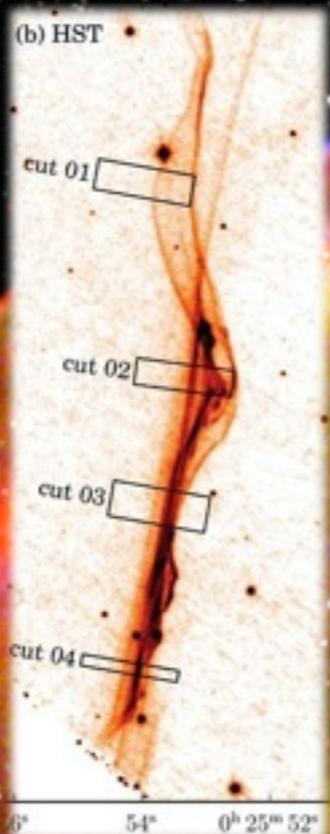
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Emission from an SNR

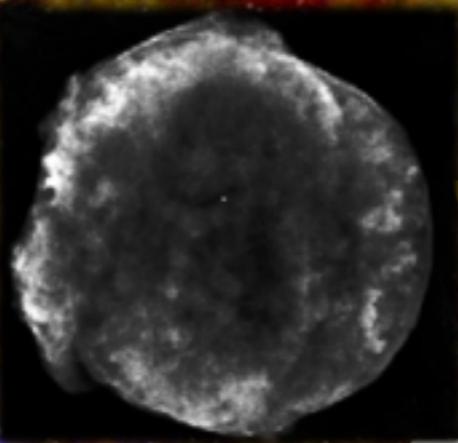
TYCHO'S SUPERNOVA REMNANT

IR/optical lines
Balmer shocks
Radiative shocks



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

Radio emission
Synchrotron radiation
Mildly relativistic electrons



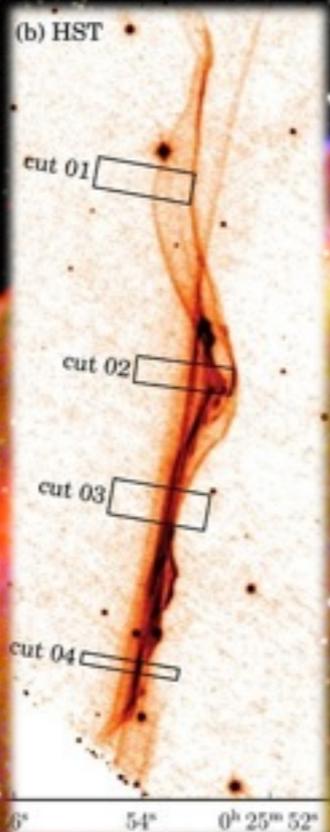
Infrared emission
Hot dust ($\sim 10^2$ K)
Shocked interstellar/ejecta dust

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

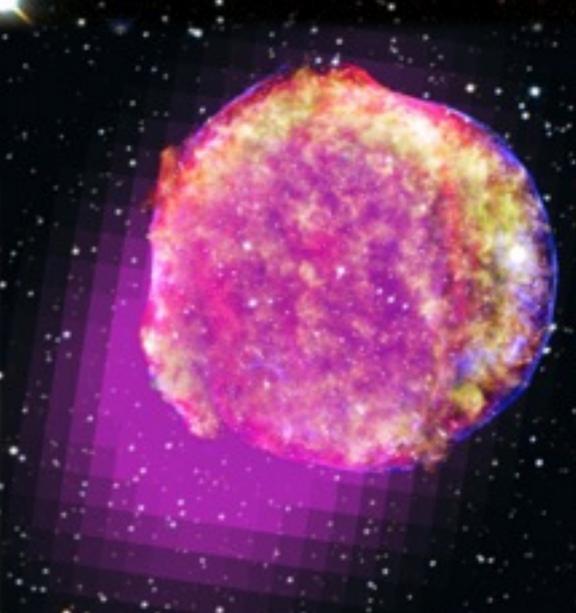
Emission from an SNR

TYCHO'S SUPERNOVA REMNANT

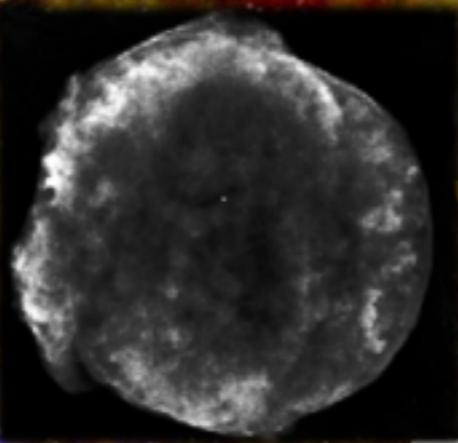
IR/optical lines
Balmer shocks
Radiative shocks



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 ($\sim 10^2$ K)
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Emission from an SNR

Current activities

Current activities

1-D Models

Self-consistent CR acceleration

Sophisticated micro-physics

Detailed broadband emission

This talk

Detailed broadband emission

Current activities

1-D Models

Self-consistent CR acceleration
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Detailed broadband emission

Multi-D Models

Global MHD/hydro
Instabilities, turbulence
Detailed morphology

See talk by M. Ono

Detailed morphology

Current activities

1-D Models

Self-consistent CR acceleration
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This talk

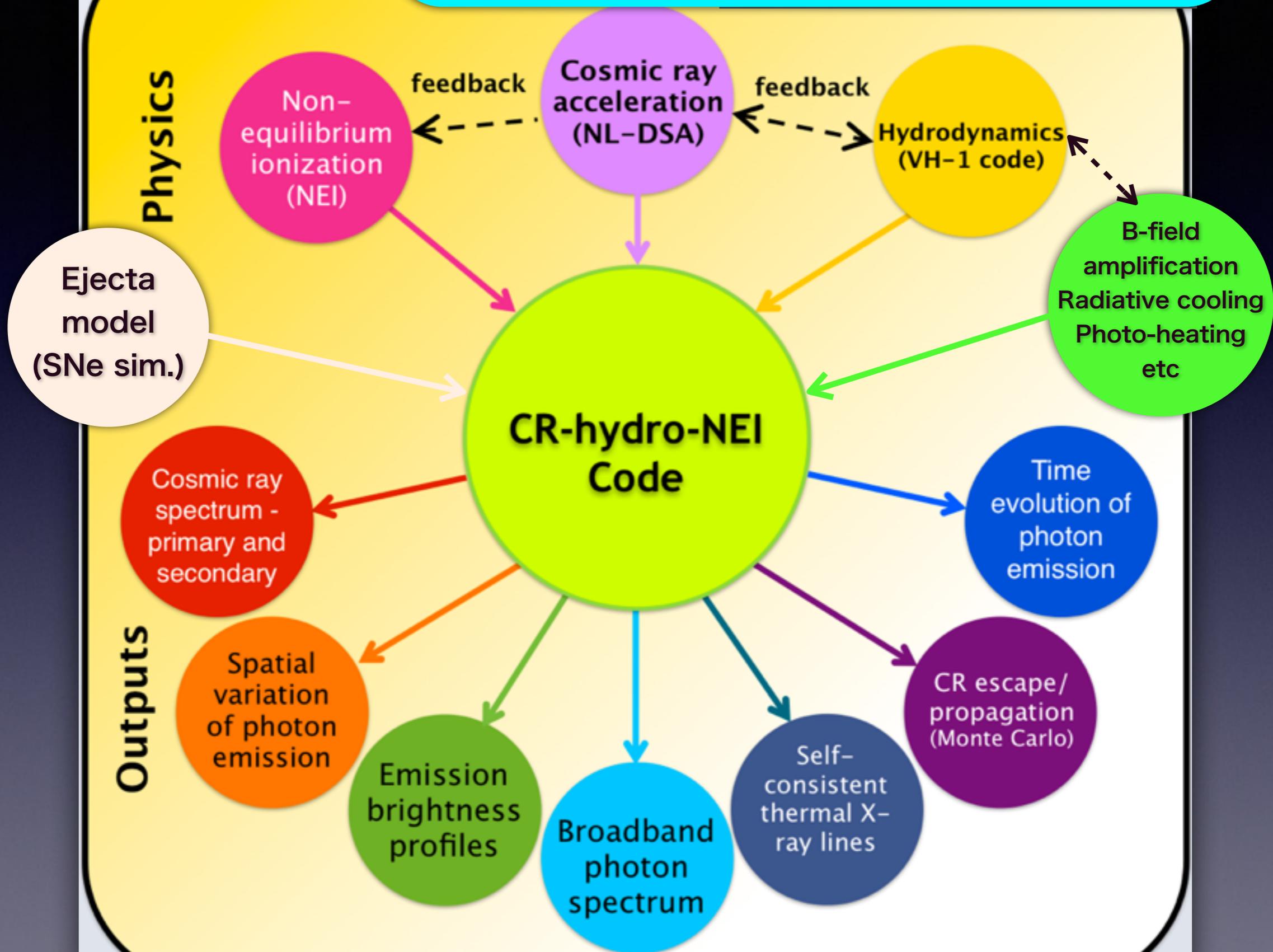
Multi-D Models

Global MHD/hydro
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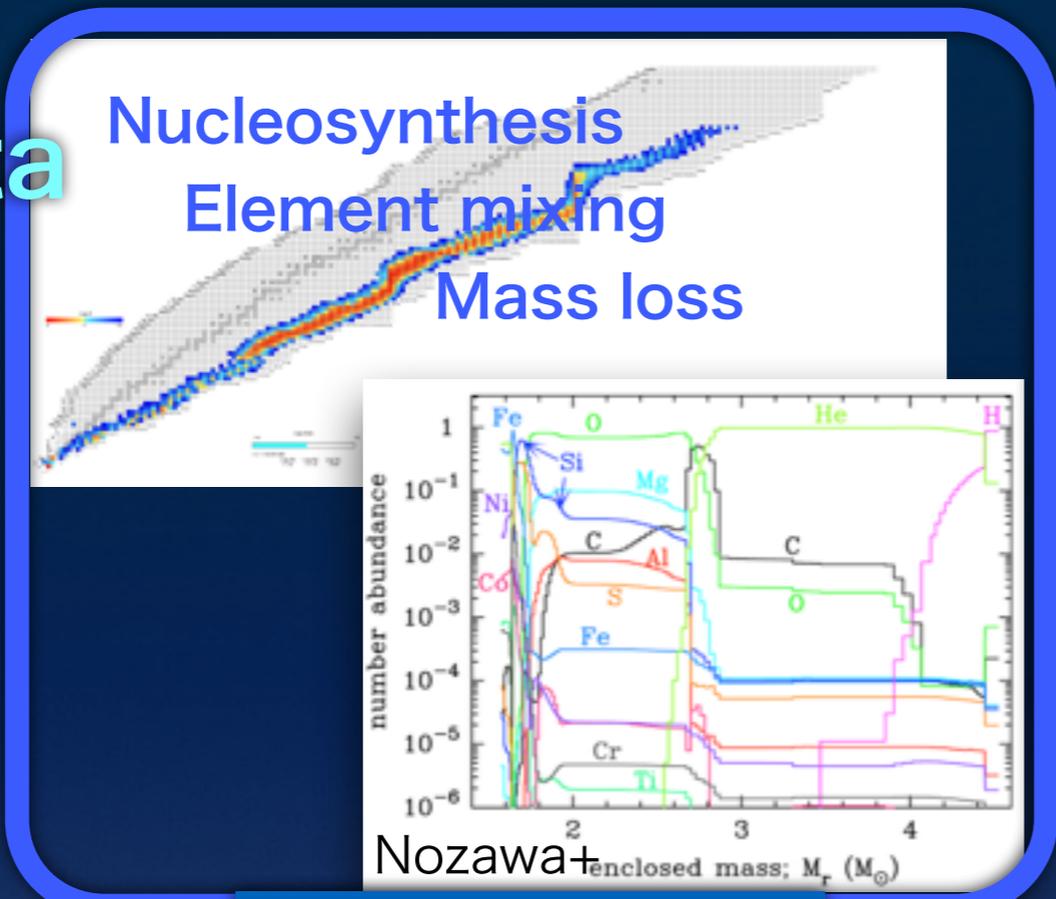
Detailed morphology

See talk by M. Ono

1-D Model Infrastructure



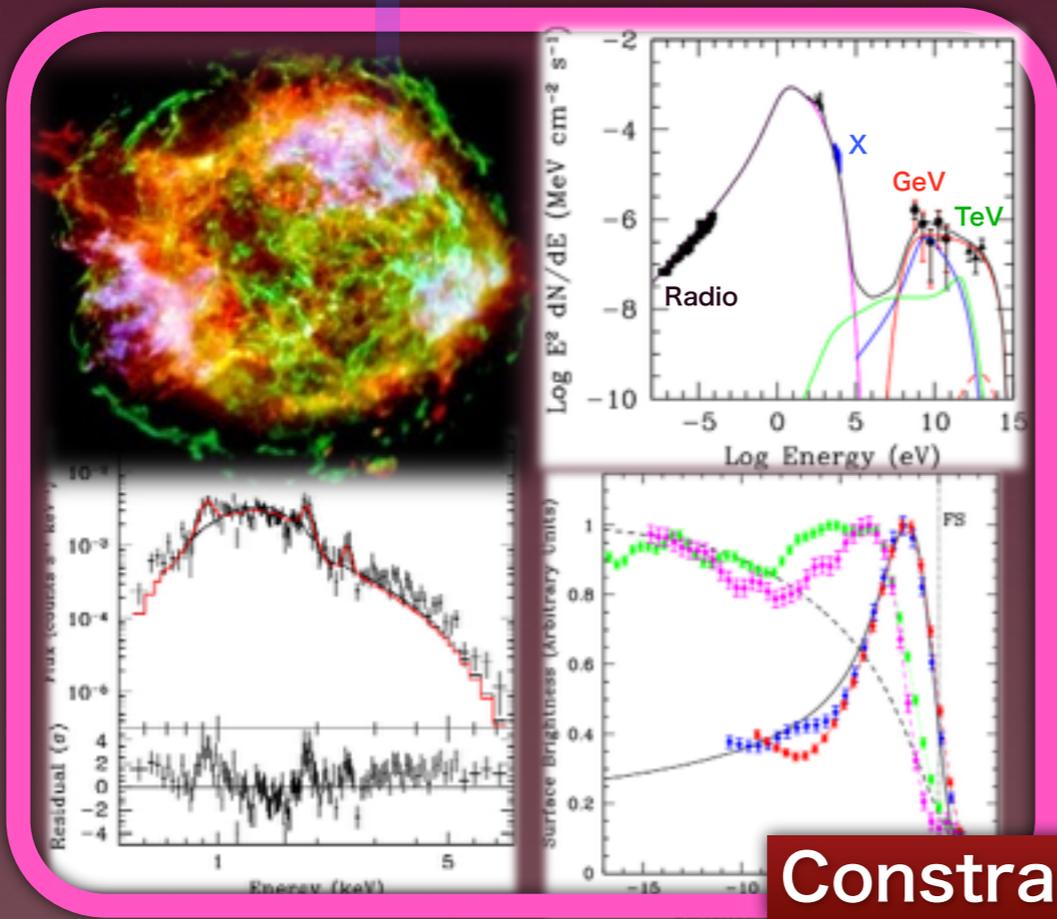
SN ejecta Model



Initial conditions

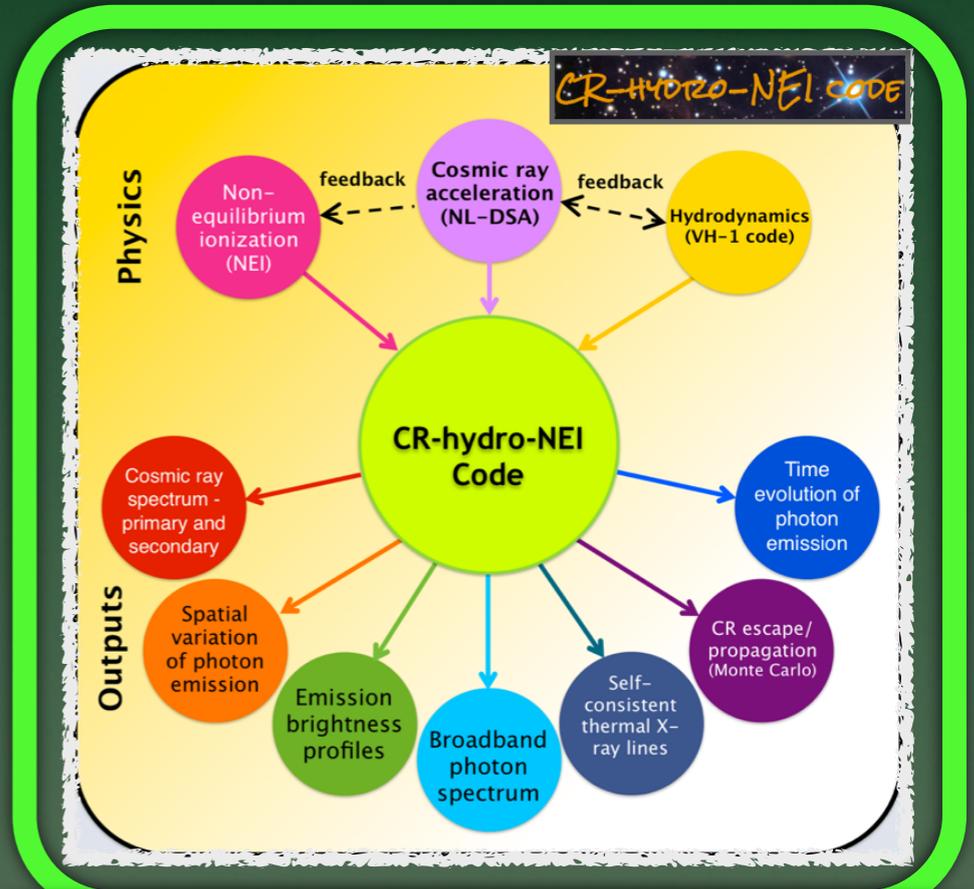
Iterative Work Flow

CR-hydro Model



Multi-λ Data

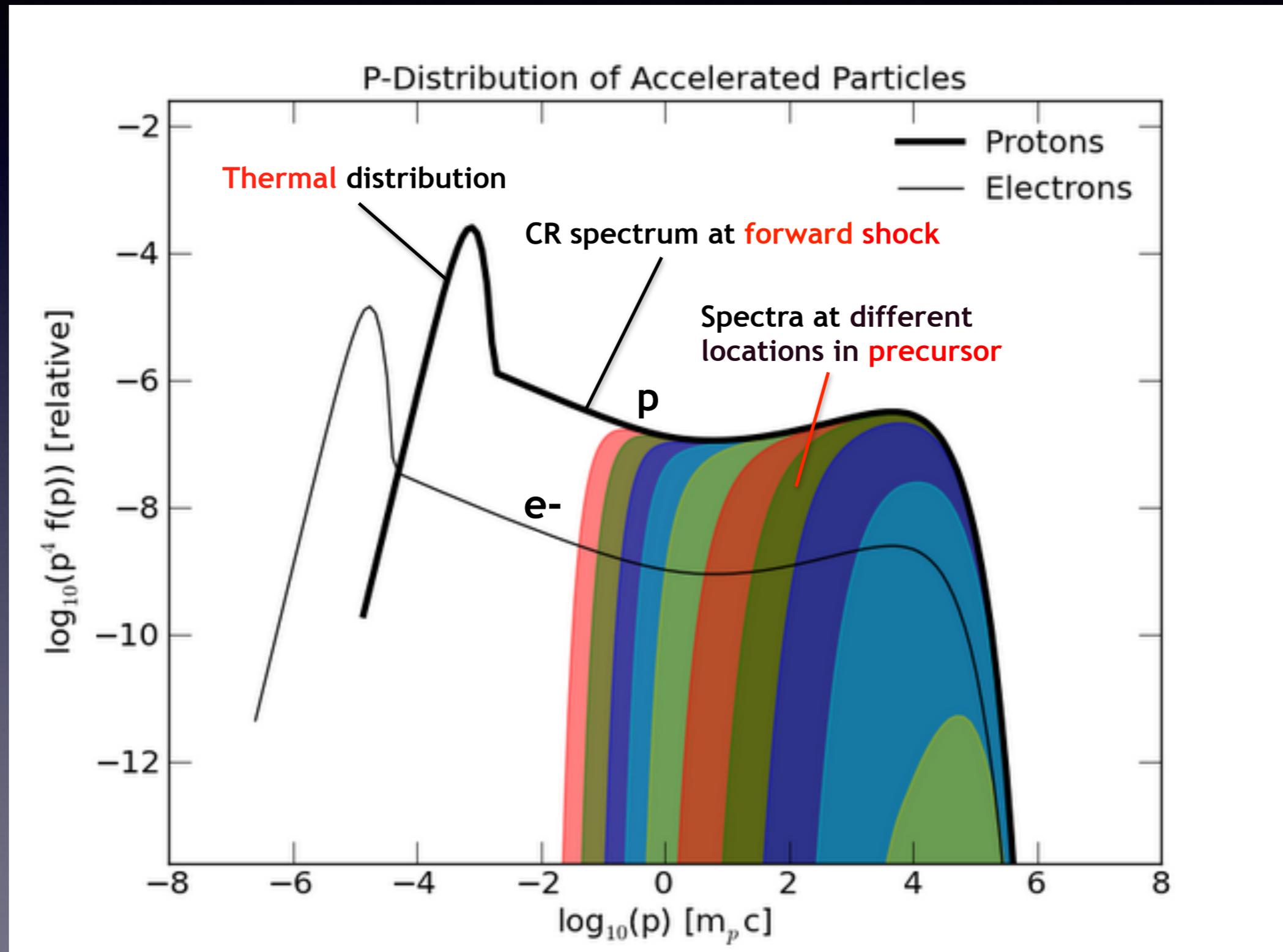
Constraints!



Dynamics, DSA, B-field, ionization, radiation

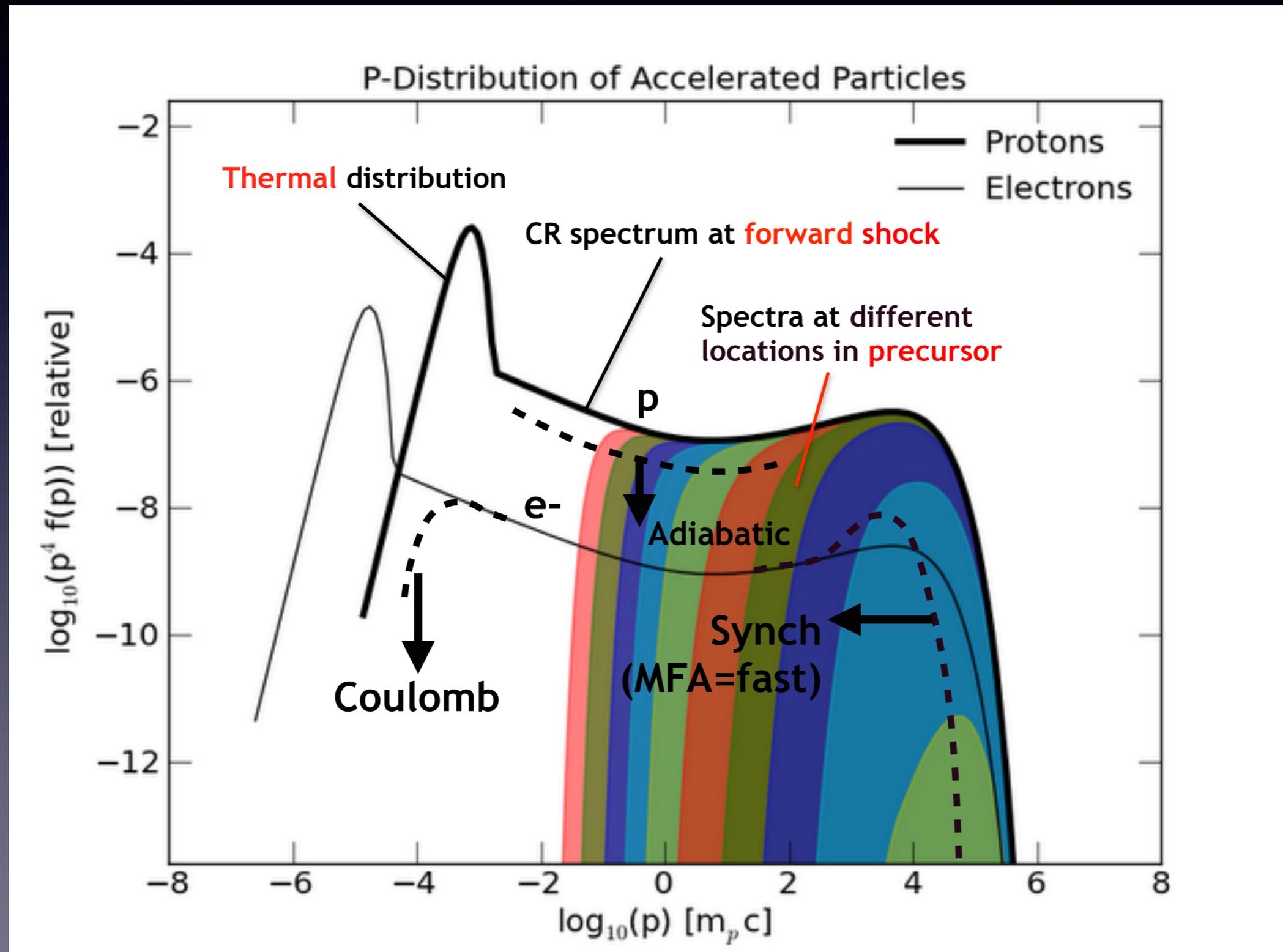
Non-linear Diffusive Shock Acceleration

e.g. HL, Ellison & Nagataki (2012)



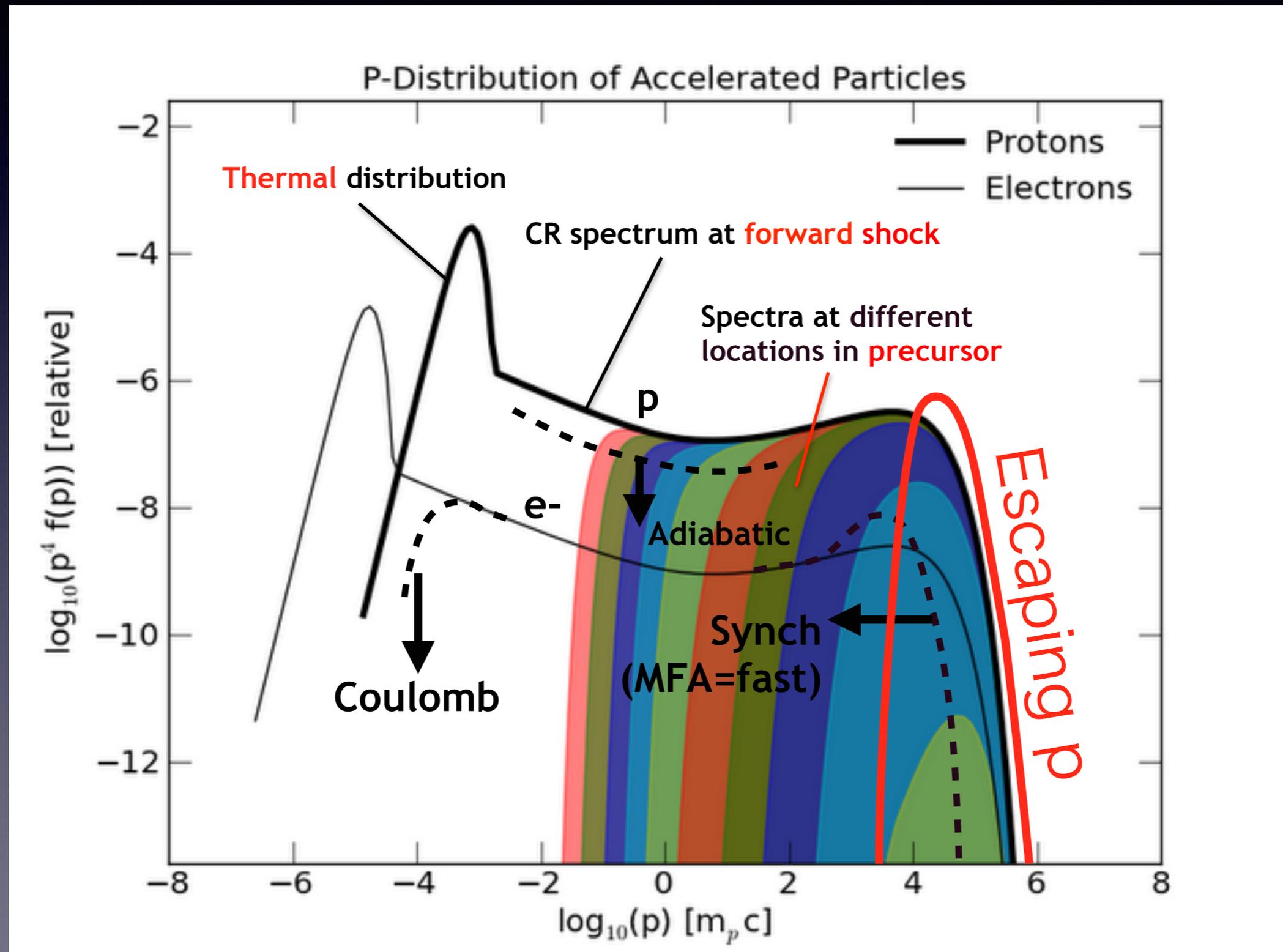
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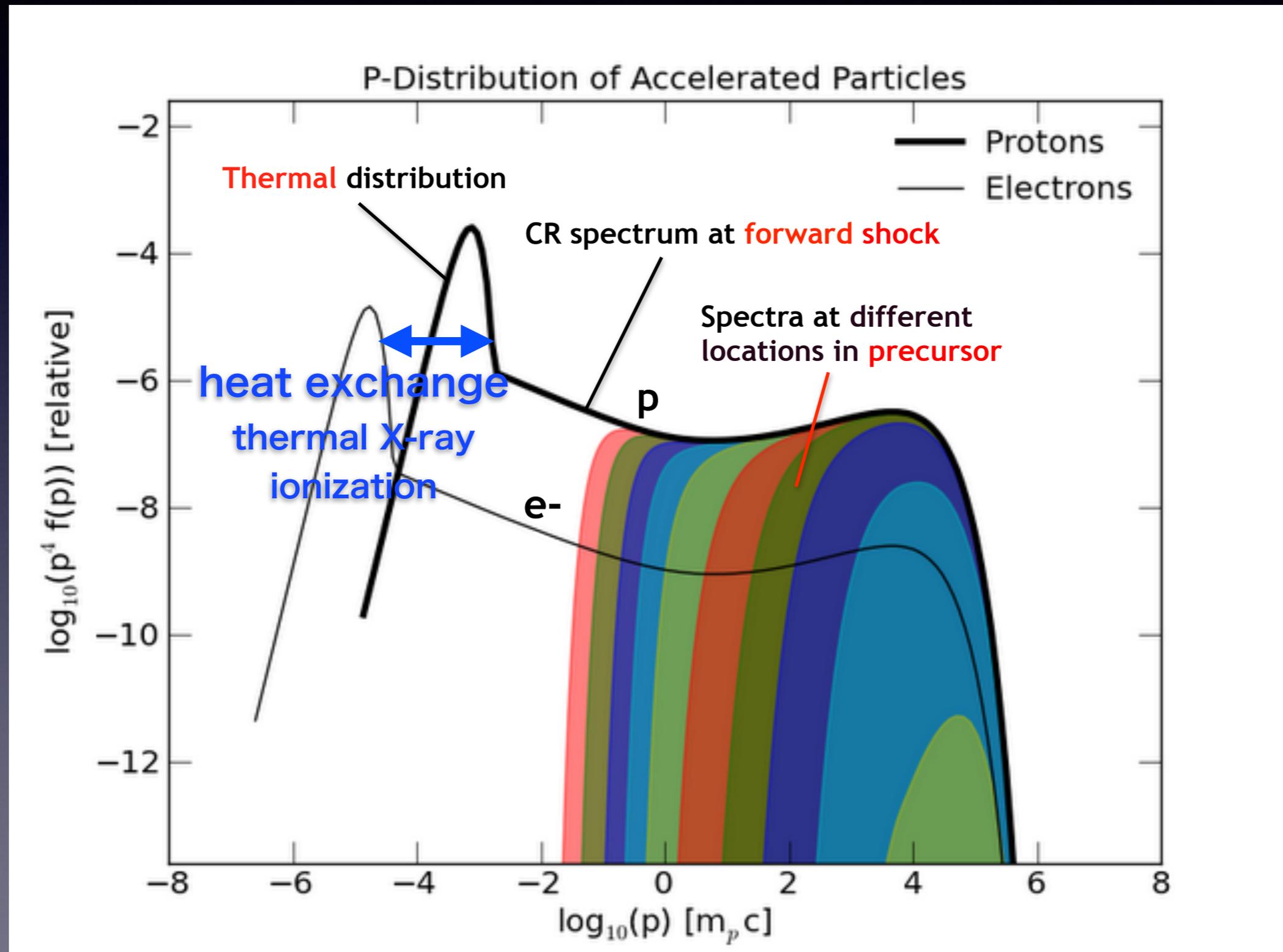
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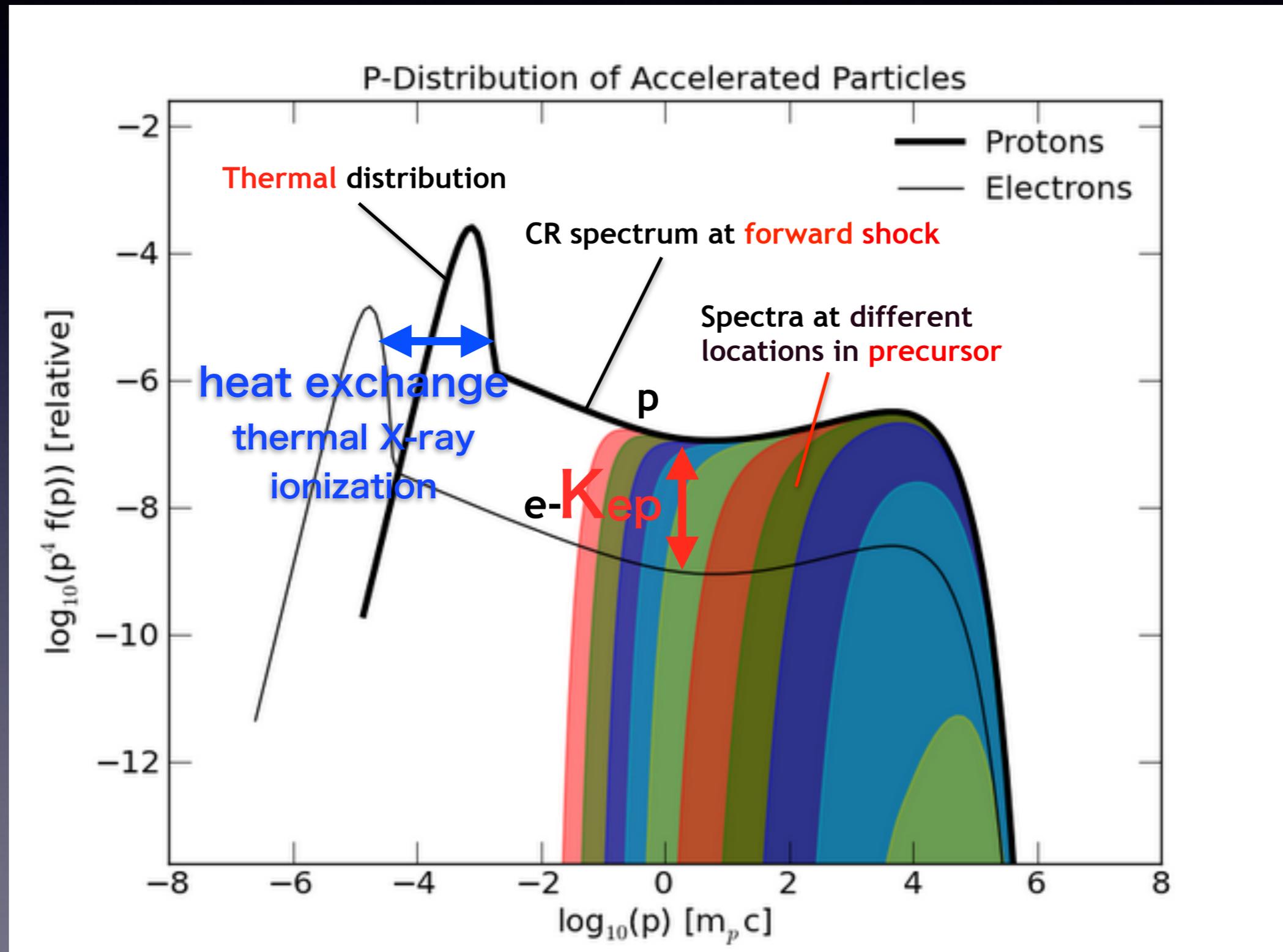
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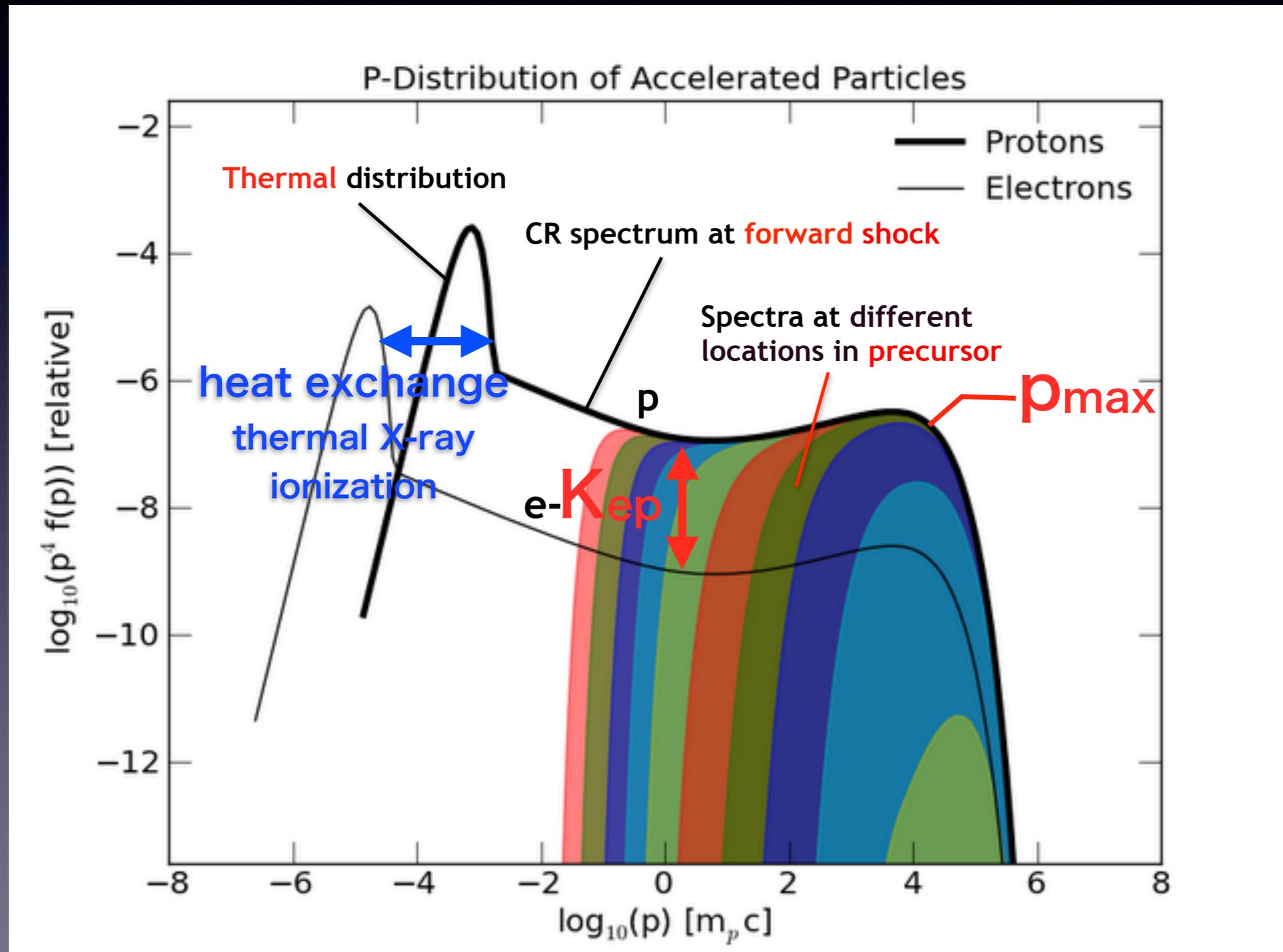
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Non-linear Diffusive Shock Acceleration

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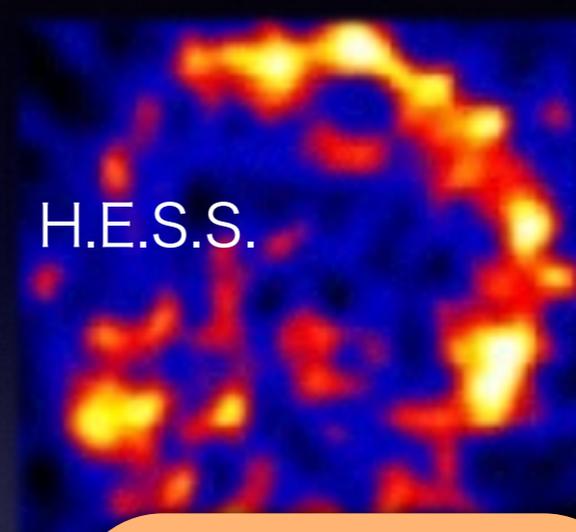


Hydro + Spectral Model of Young SNRs

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

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

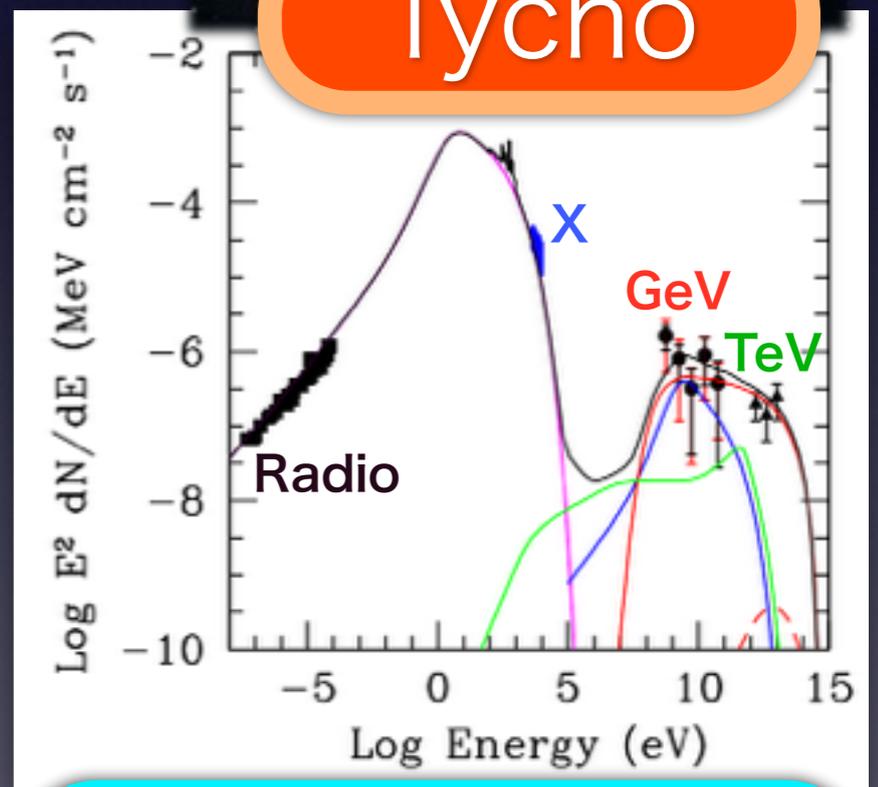
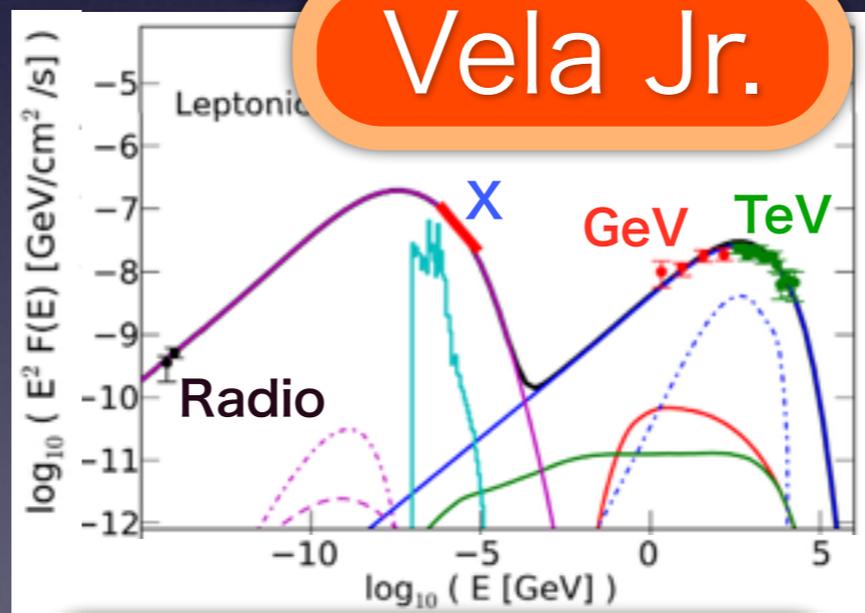
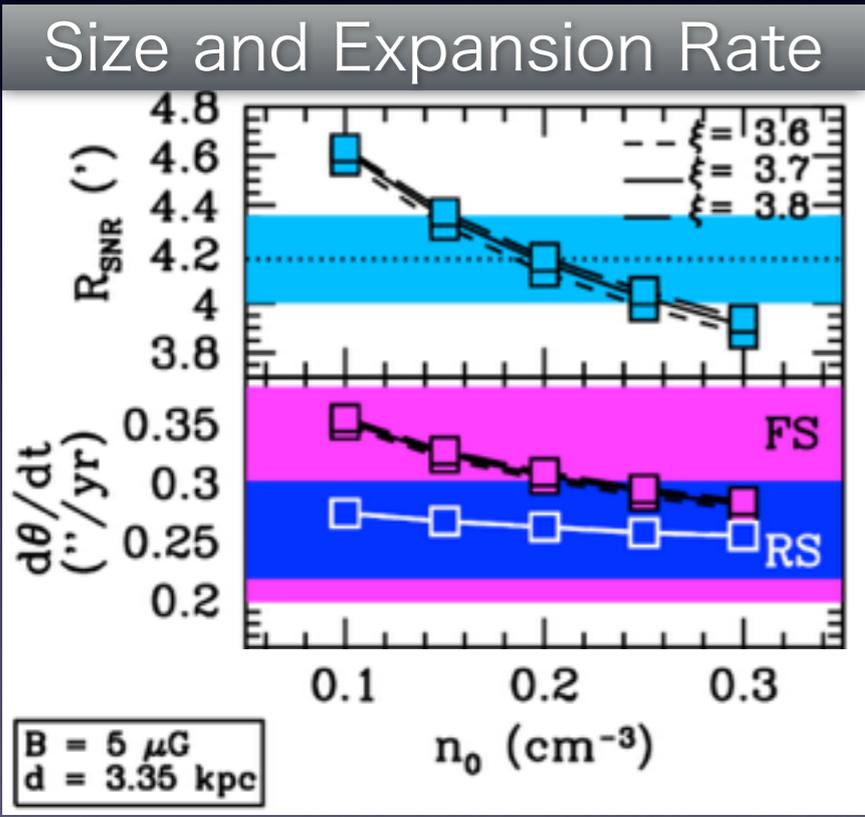
LAT



H.E.S.S.

Tycho

Vela Jr.

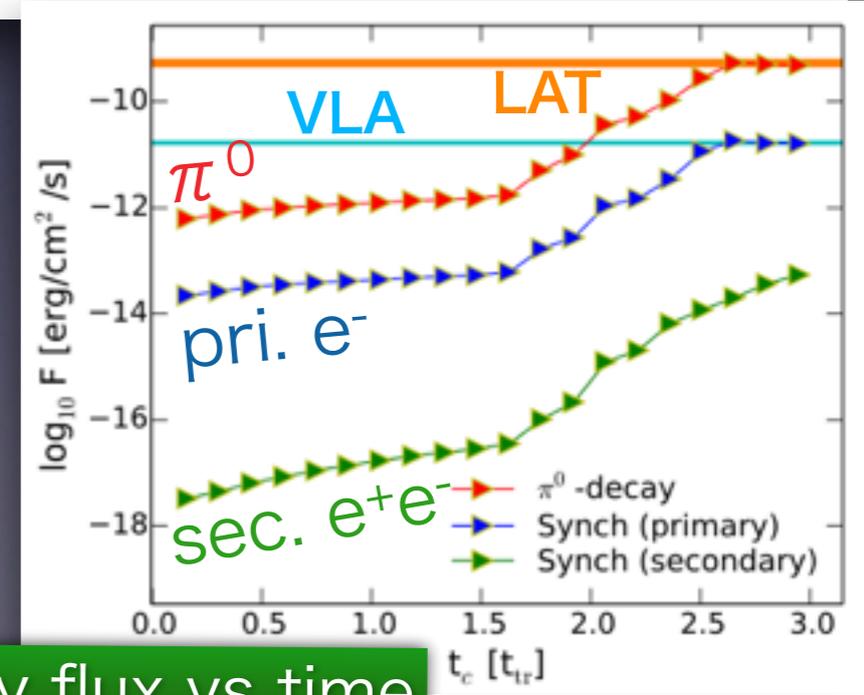
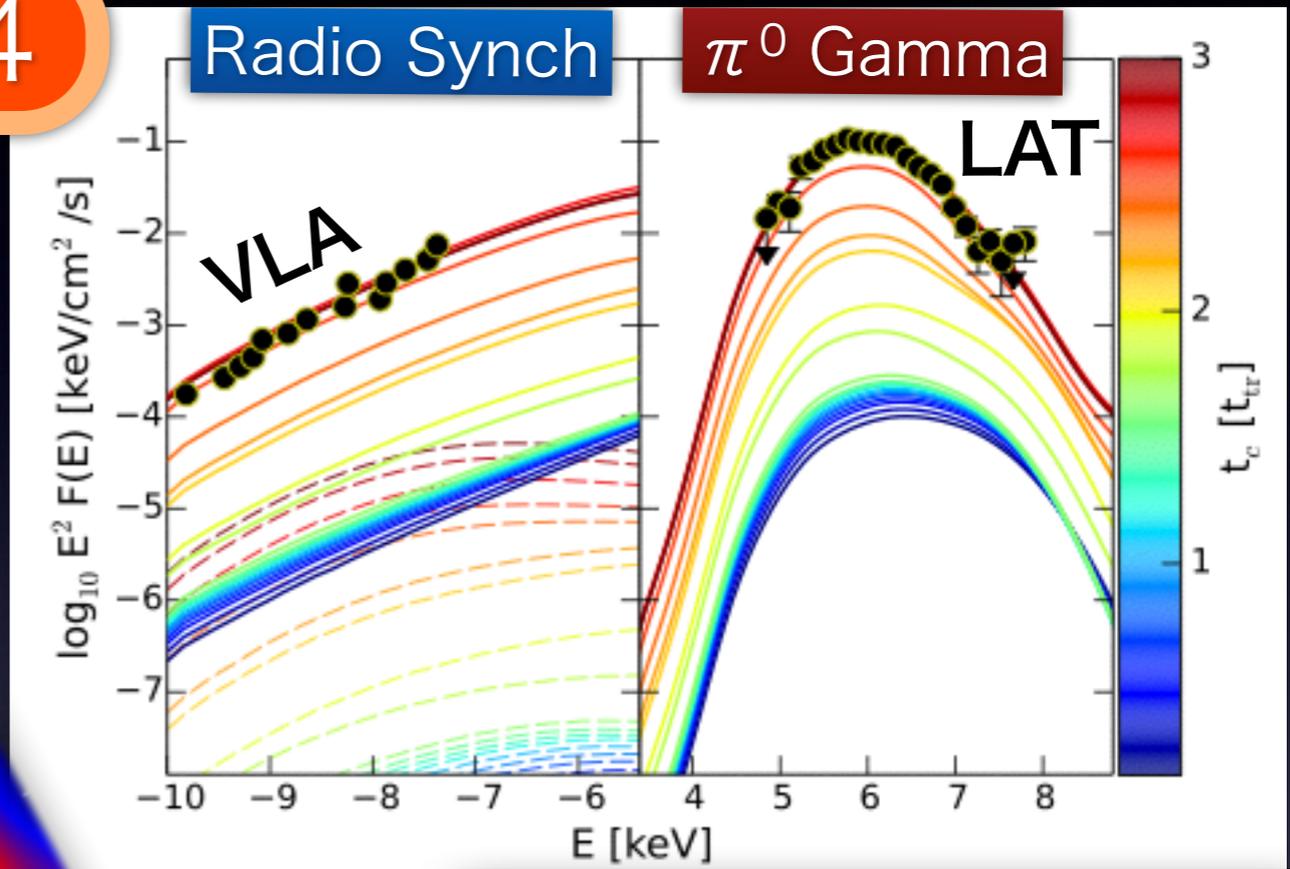
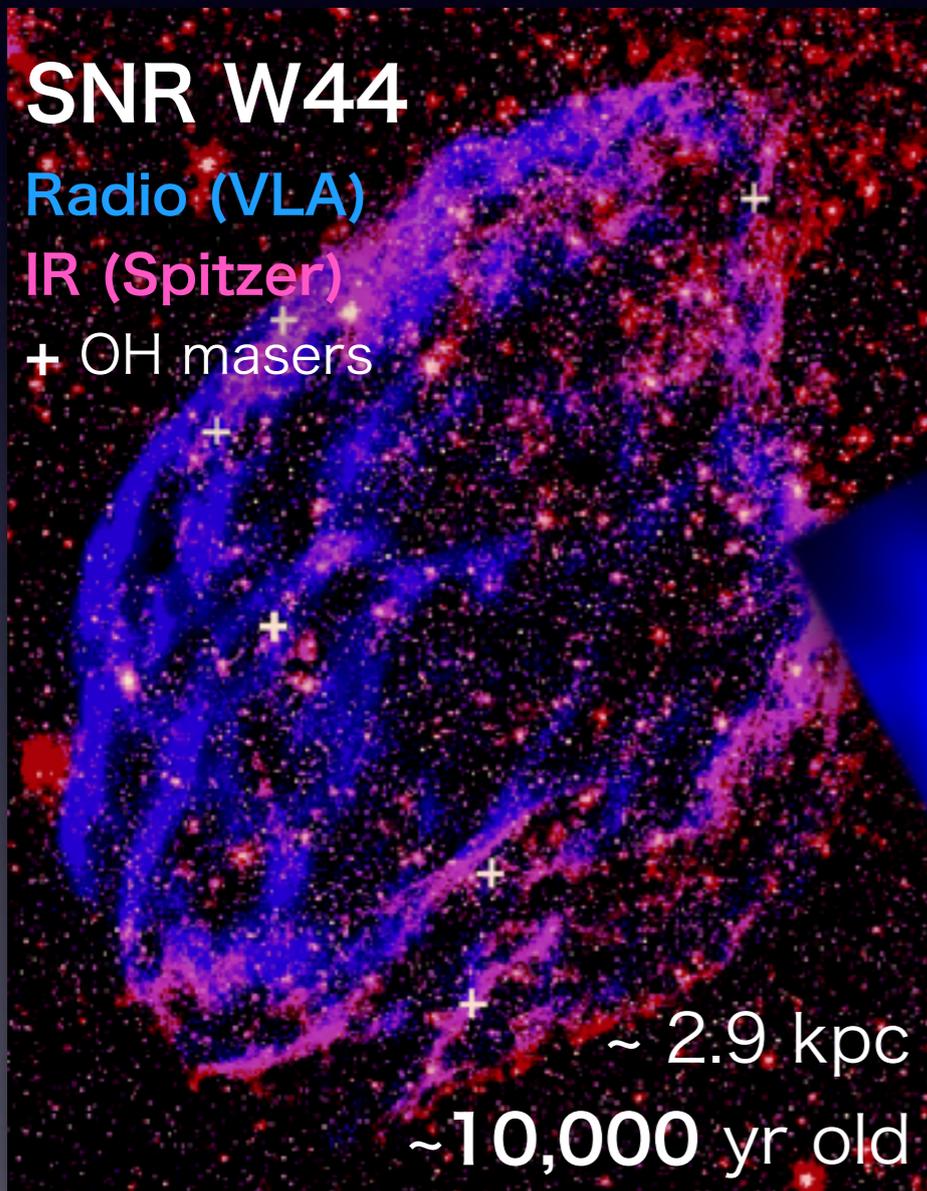


Leptonic
 $E_{\text{CR}} = 0.15 E_{\text{SN}}$

Hadronic
 $E_{\text{CR}} = 0.16 E_{\text{SN}}$

Non-thermal Emission of Middle-aged SNRs

W44



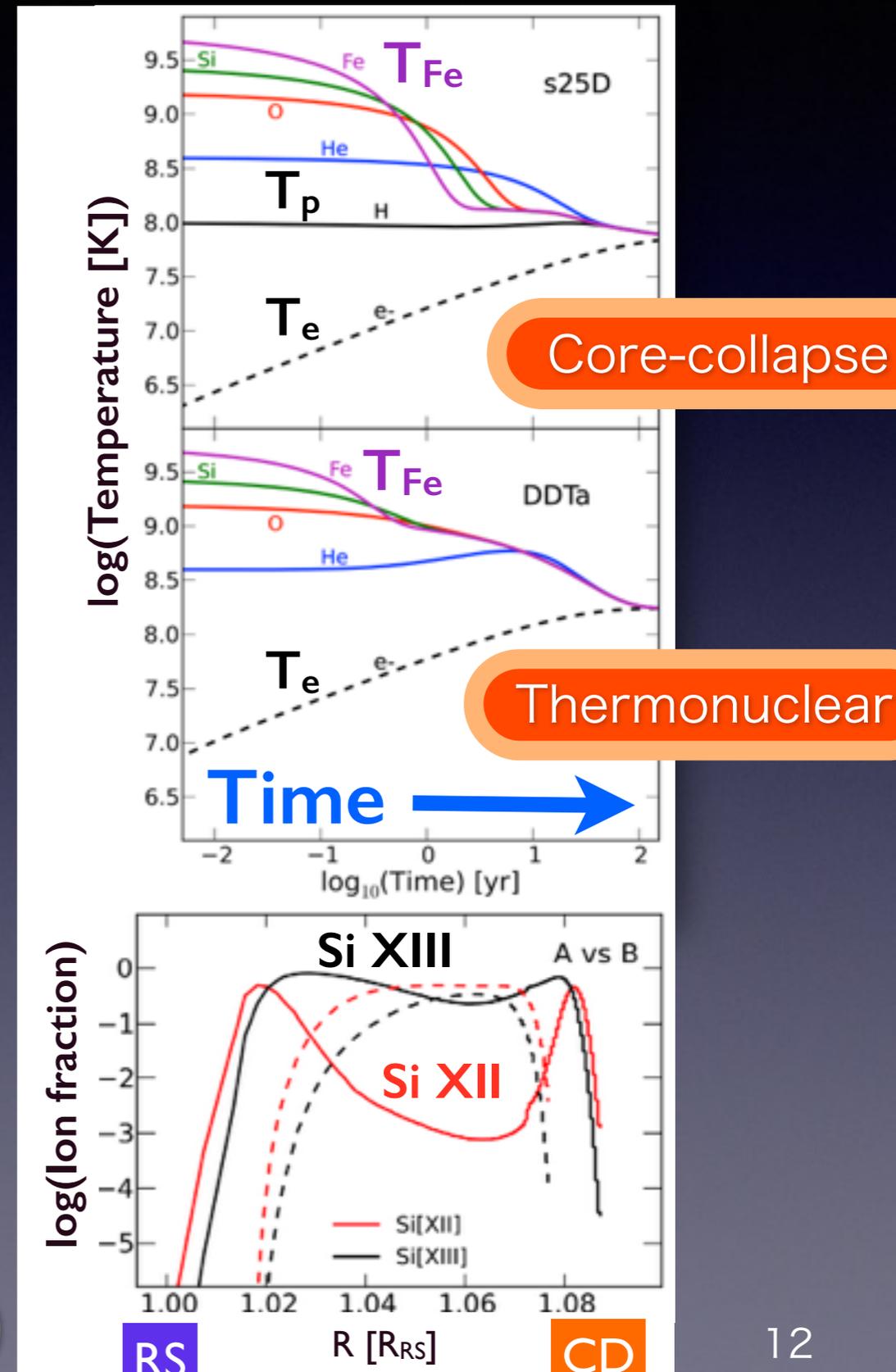
Preliminary
 HL+ in prep

Energy flux vs time

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)

HL, Patnaude+ (2014)



RS

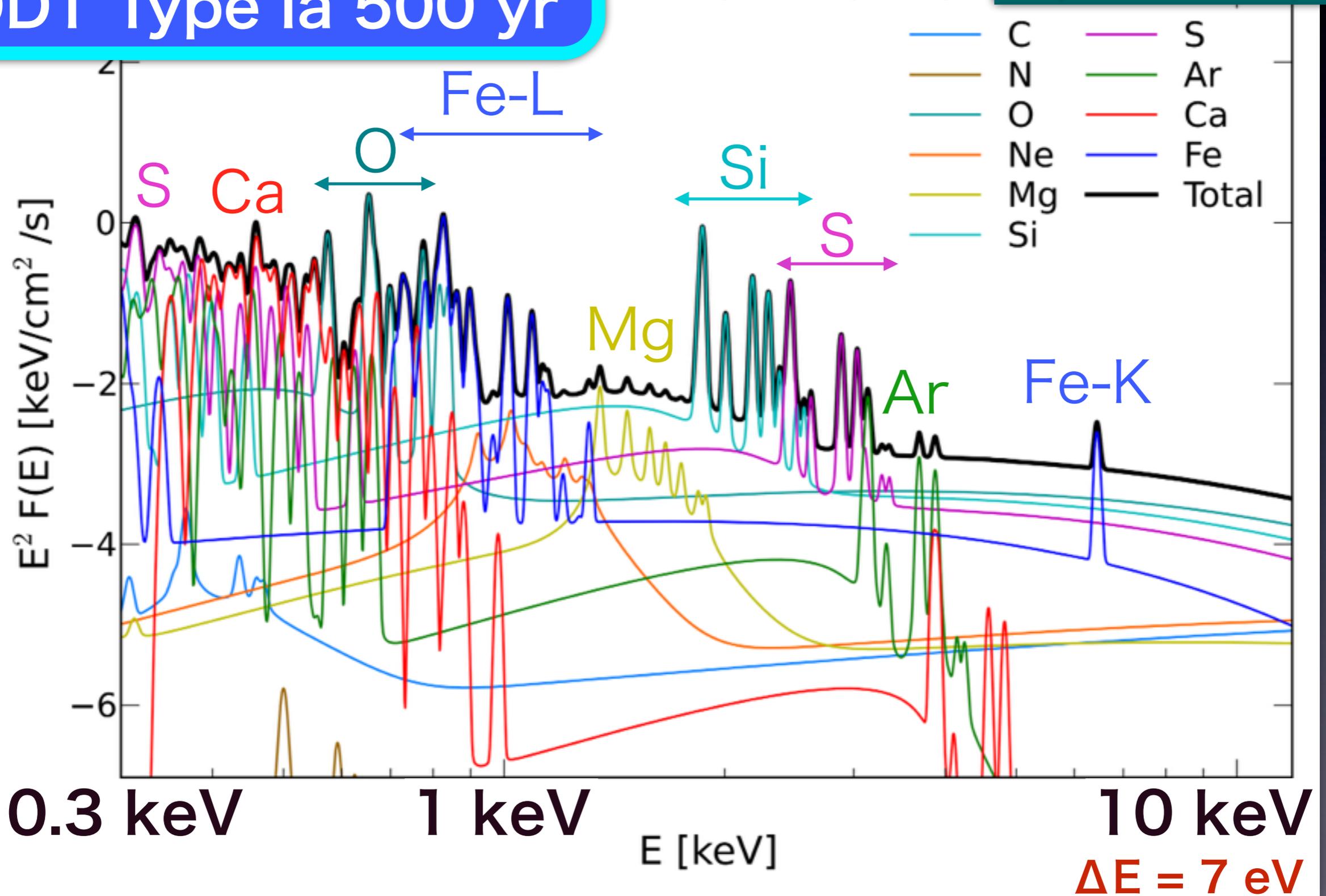
R [R_{RS}]

CD

Synthesis of detailed X-ray spectra

DDT Type Ia 500 yr

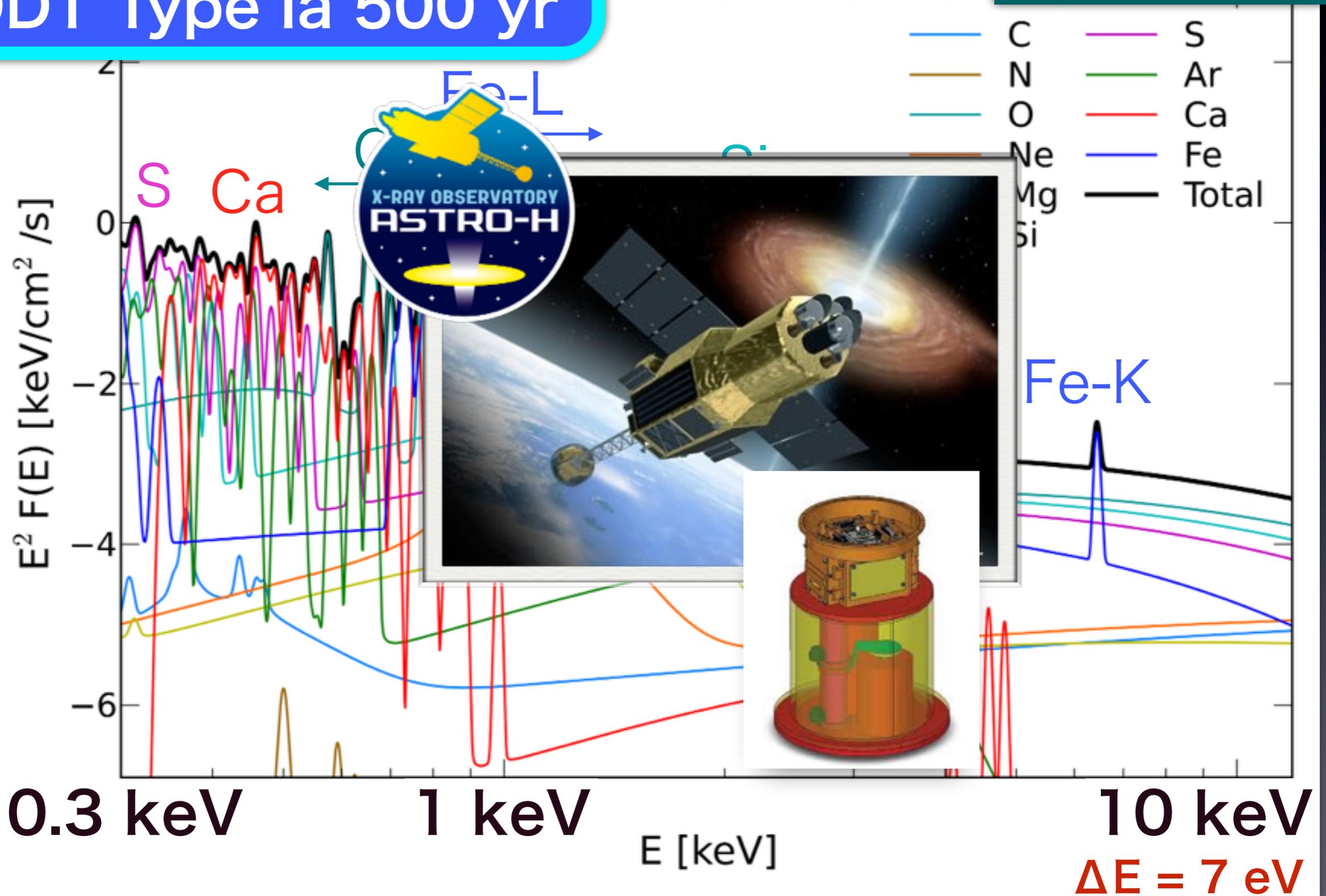
HL, Patnaude+ (2014)



Synthesis of detailed X-ray spectra

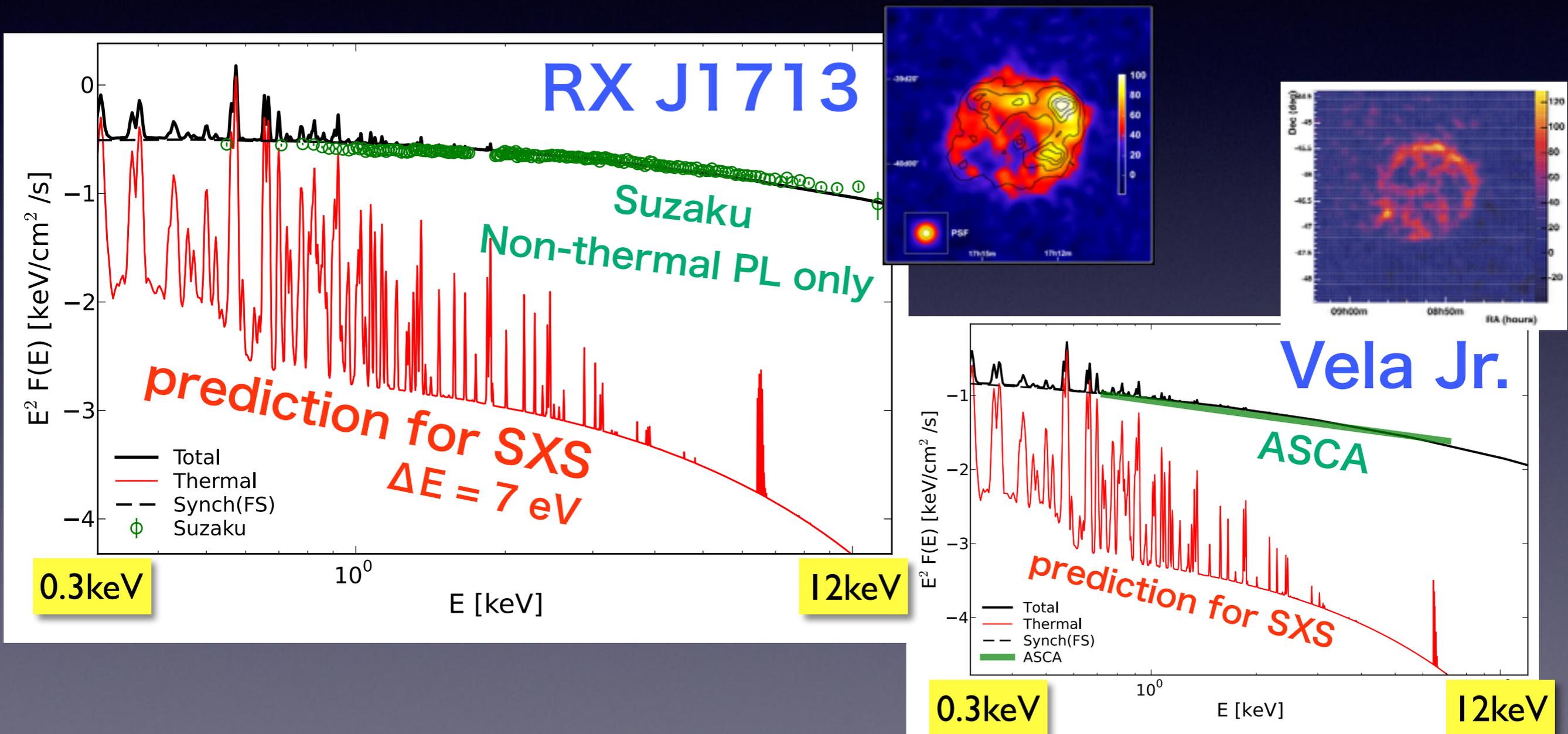
DDT Type Ia 500 yr

HL, Patnaude+ (2014)



Future X-ray spectroscopy by Astro-H

Our broadband models make robust predictions for Astro-H



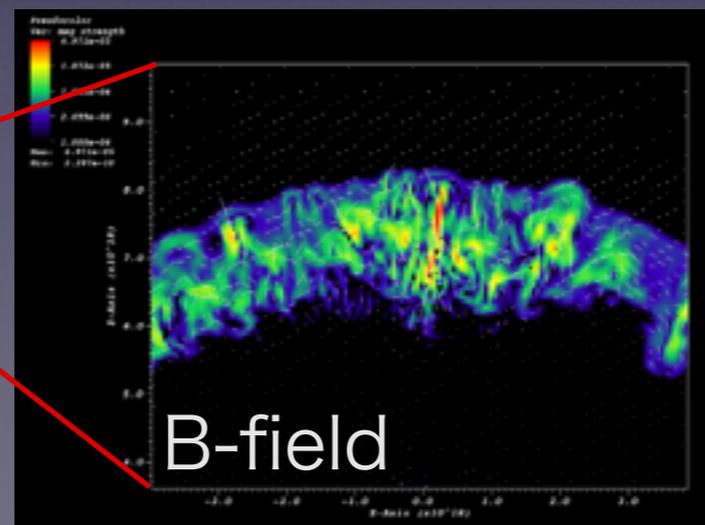
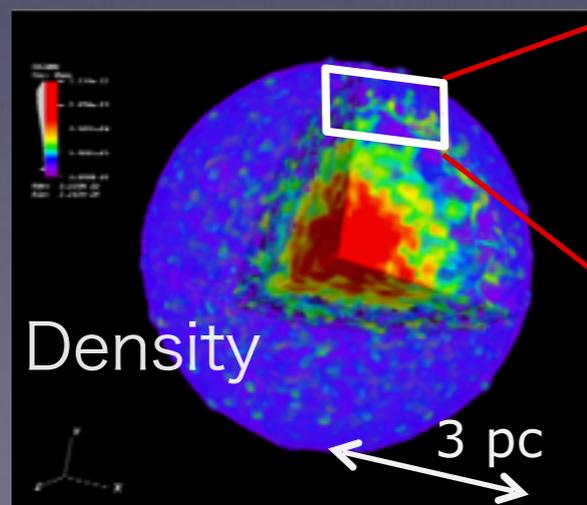
e.g. HL+ 2013

Part II

M. Ono's talk this afternoon

All these cool features will eventually be migrated to or combined with a 3-D MHD platform

Closer link between multi-D SN simulations and SNR models will become possible!



M. Ono (Kyushu Univ)

Summary

- 👁 SNRs never end to challenge us with puzzling phenomena
- 👁 High astrophysical significance
 - 👁 Origin of CRs, chemical enrichment and turbulence in ISM, late evolution of massive stars, SN explosion geometry, nucleosynthesis, etc...
- 👁 Treasure troves of fundamental physics
 - 👁 Collisionless shocks, DSA, wave-particle interactions, MHD/HD instabilities, and other plasma physics
- 👁 A true understanding of SNRs from engine to remnant requires confrontation of new data with improving models
- 👁 We need close connection among stellar, SN, SNR, plasma and nuclear physics communities in Japan to fulfill our ambition