Deciphering Multi-wavelength Phenomena of Supernova Remnants through Numerical Modeling

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Some slides with preliminary results are skipped

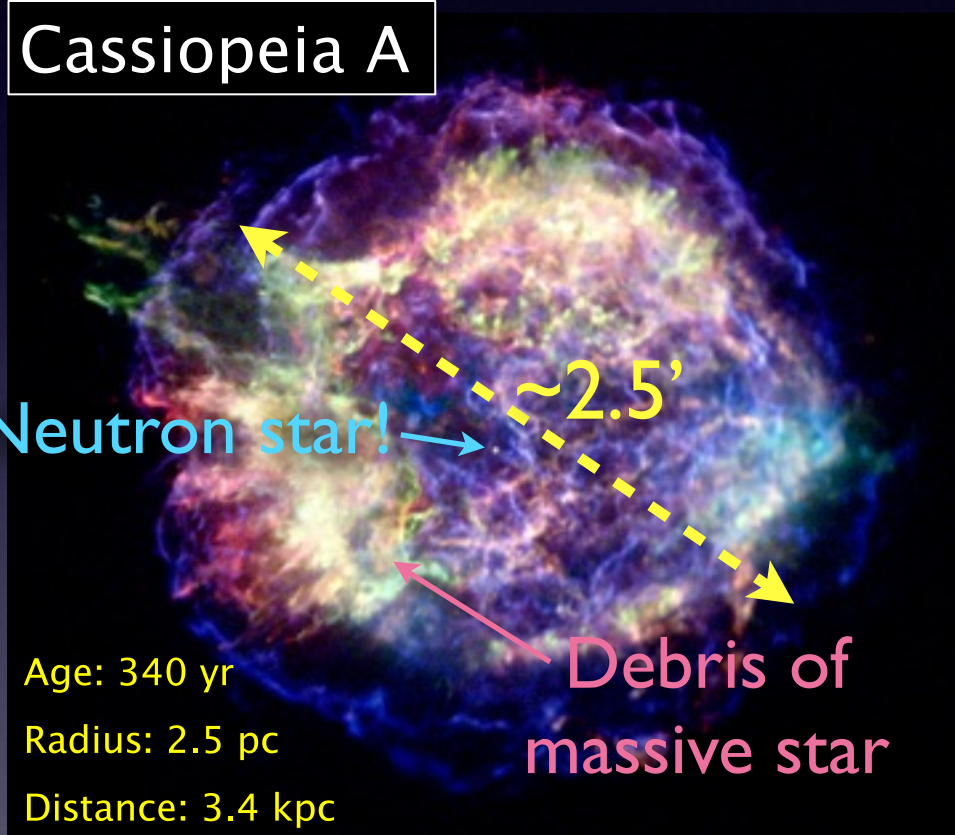
This talk

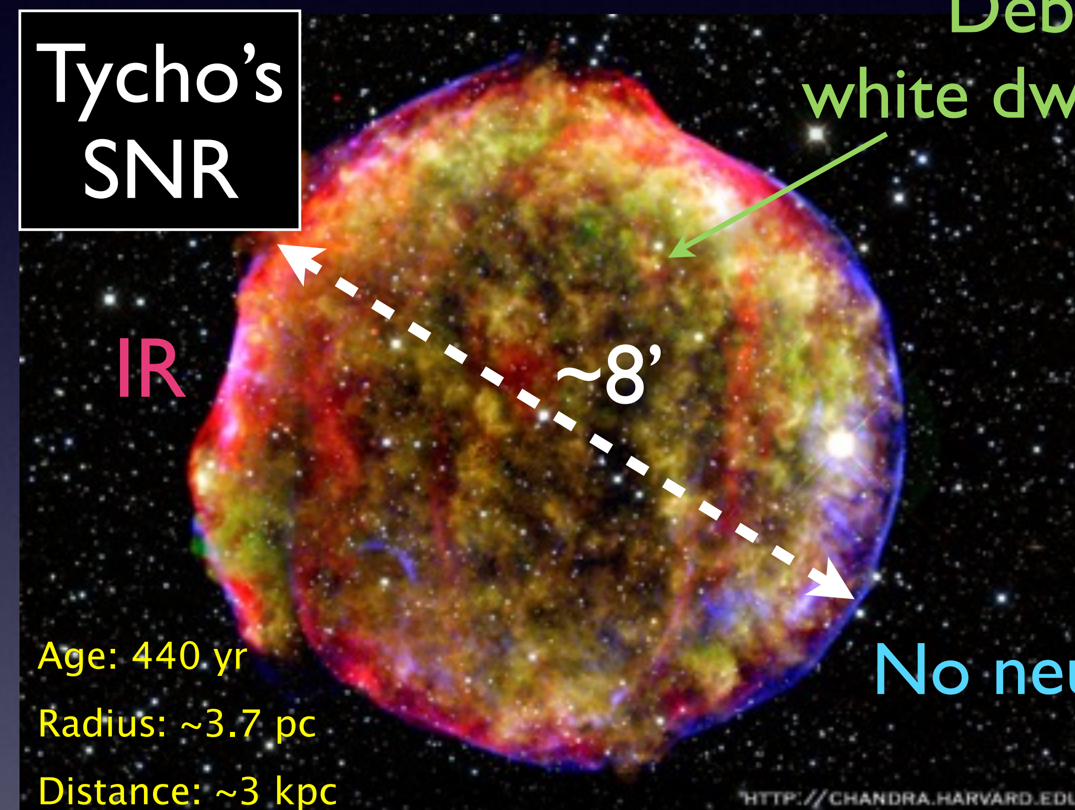
- What's hot about SNRs
- Numerical modeling of SNR emission
  - Young shell-type SNRs with strong shocks
  - Older radiative SNRs with slow cloud shocks
- Future telescopes and models

Supernova Remnants

Exciting retirement life for *stars*

(but typical retirement age is quite high)





SN Type II, Ib, Ic

-Massive stars run out of fuel
-Collapse itself by self-gravity
-Rebound of proto-NS, explode
(assisted by neutrino?)
-Bonus: a neutron star / black hole

SN Type Ia

-White dwarf (WD) stars in binary
-Accrete matter from companion
star, or merge with another WD
-Exceed Chandrasekhar Mass (?)
-Thermonuclear explosion

Supernova Remnants

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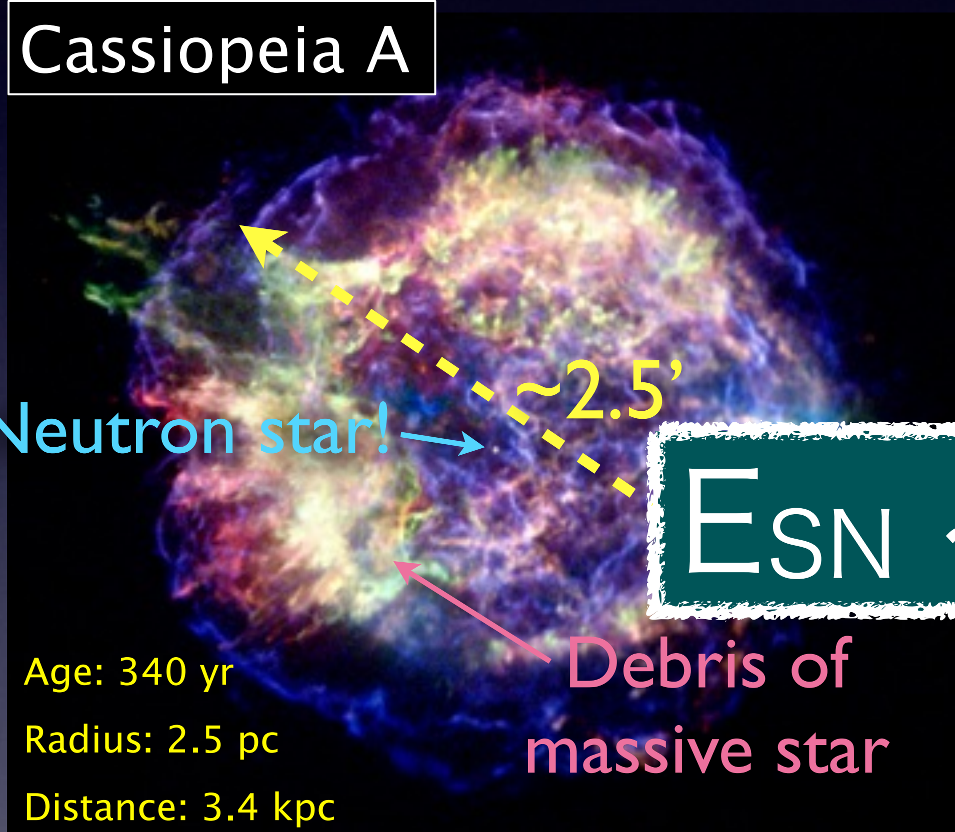
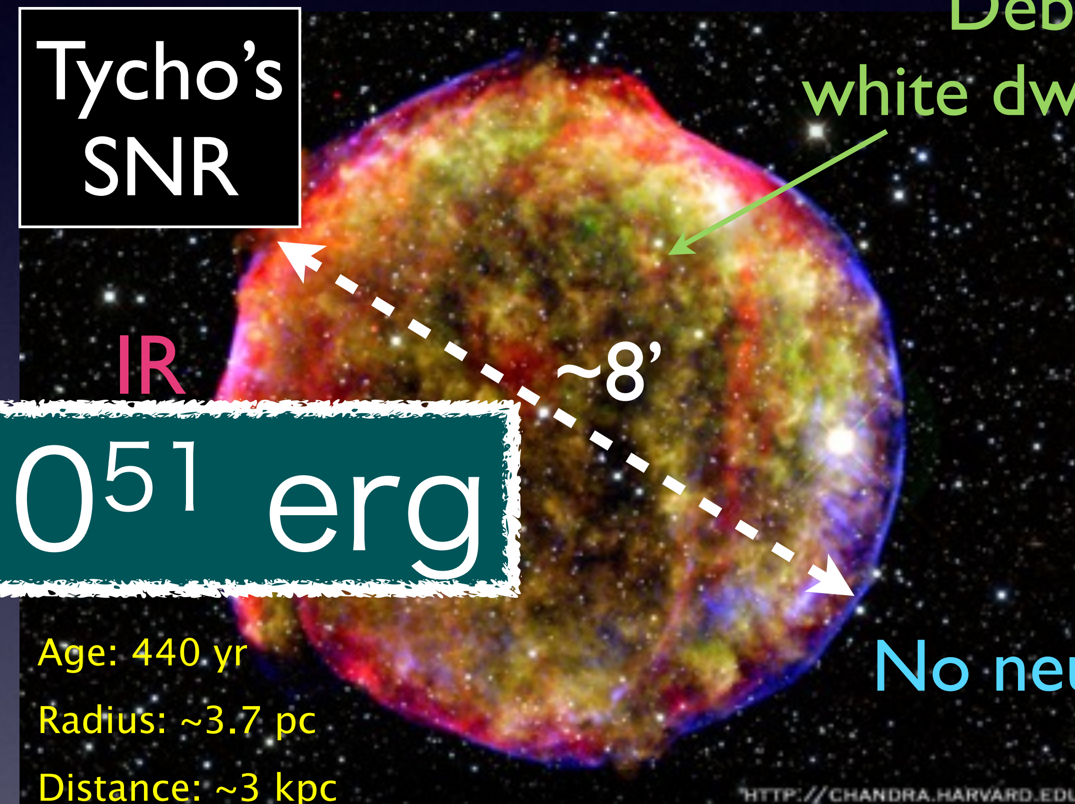


E_{SN} ~10^{51} erg



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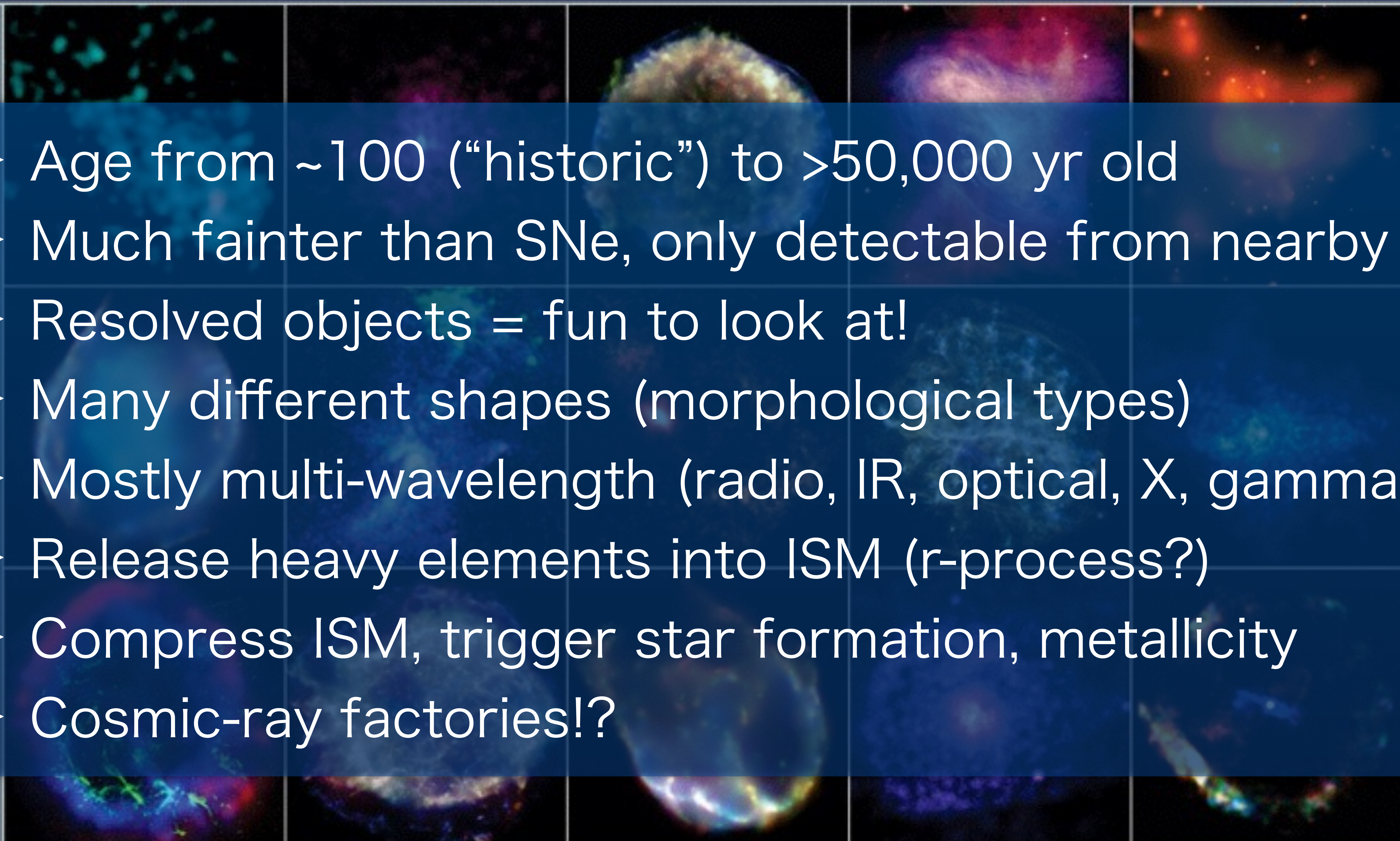
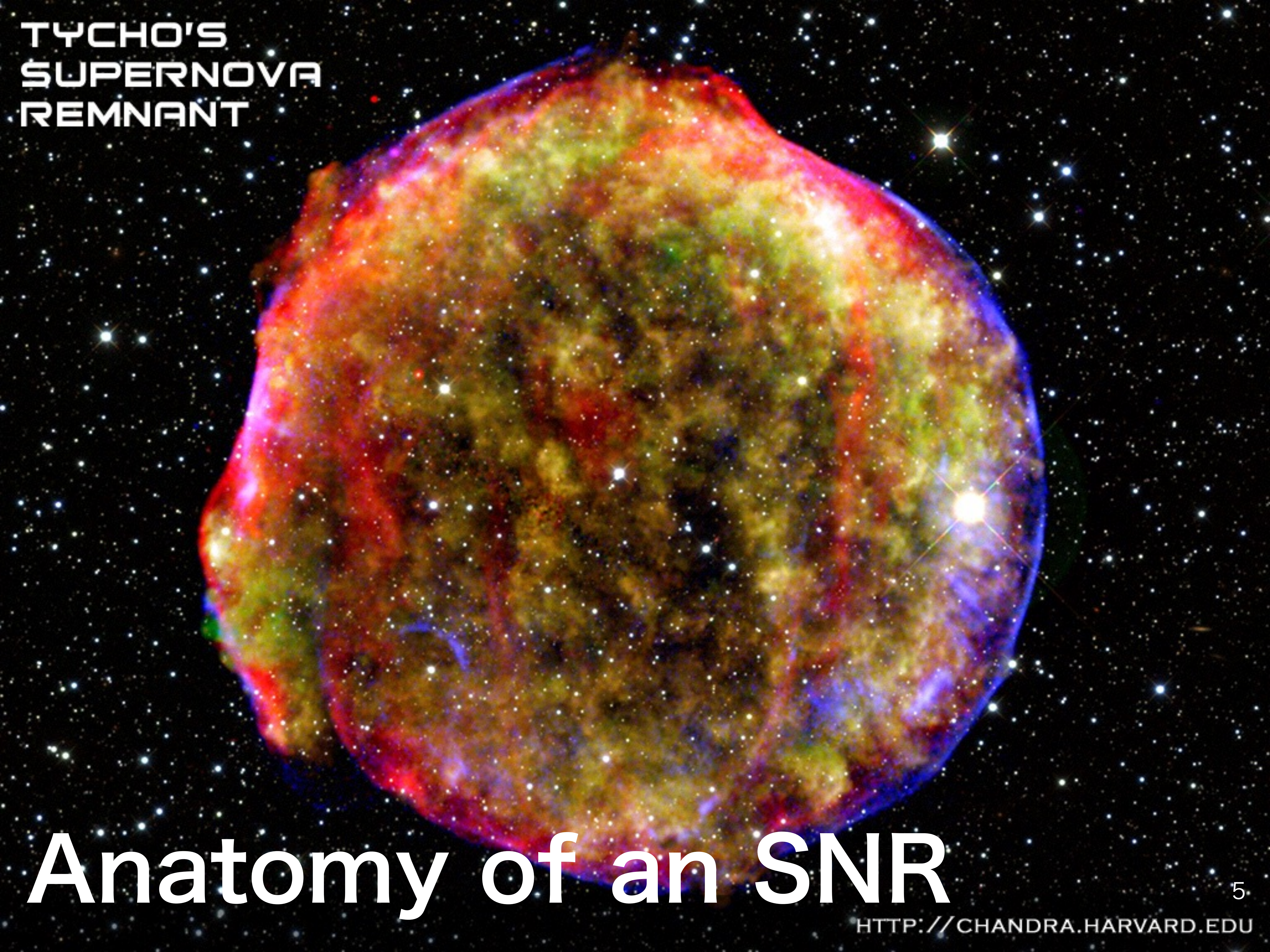
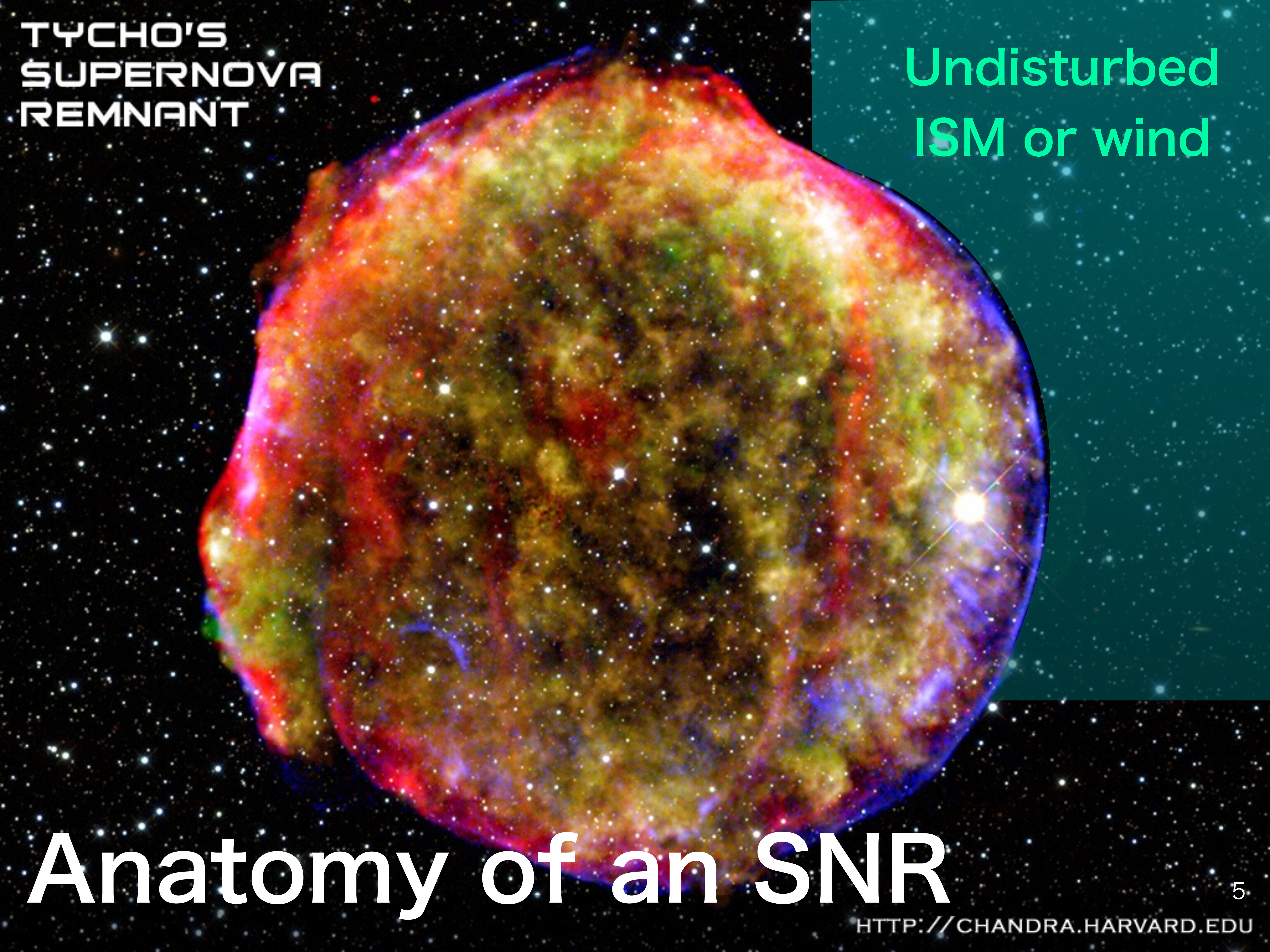
Supernova Remnants (SNR)

- Age from ~100 (“historic”) to >50,000 yr old
- Much fainter than SNe, only detectable from nearby
- Resolved objects = fun to look at!
- Many different shapes (morphological types)
- Mostly multi-wavelength (radio, IR, optical, X, gamma)
- Release heavy elements into ISM (r-process?)
- Compress ISM, trigger star formation, metallicity
- Cosmic-ray factories!?





Anatomy of an SNR


TYCHO'S
SUPERNOVA
REMNANT
Undisturbed
ISM or wind
Anatomy of an SNR
5
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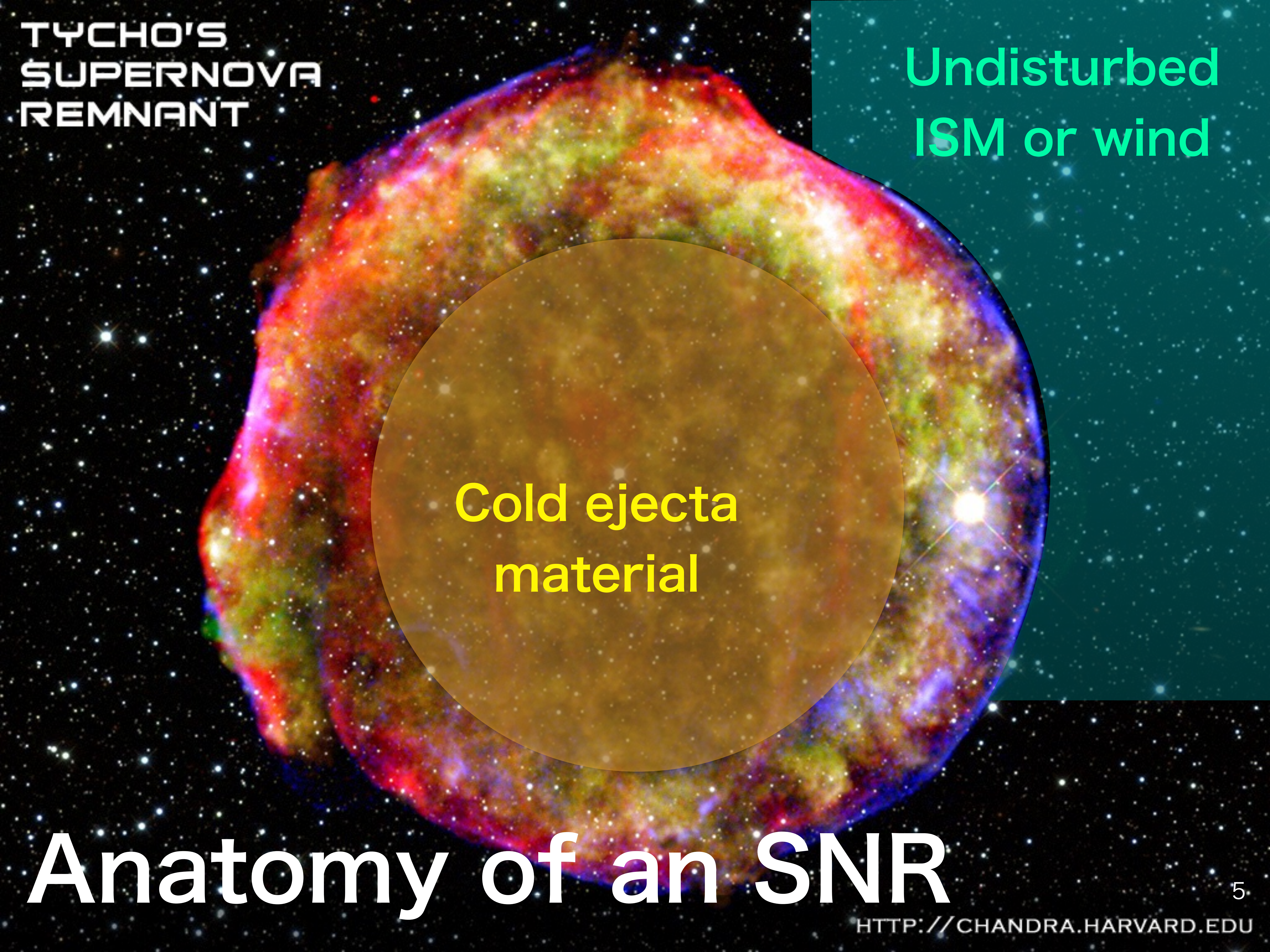
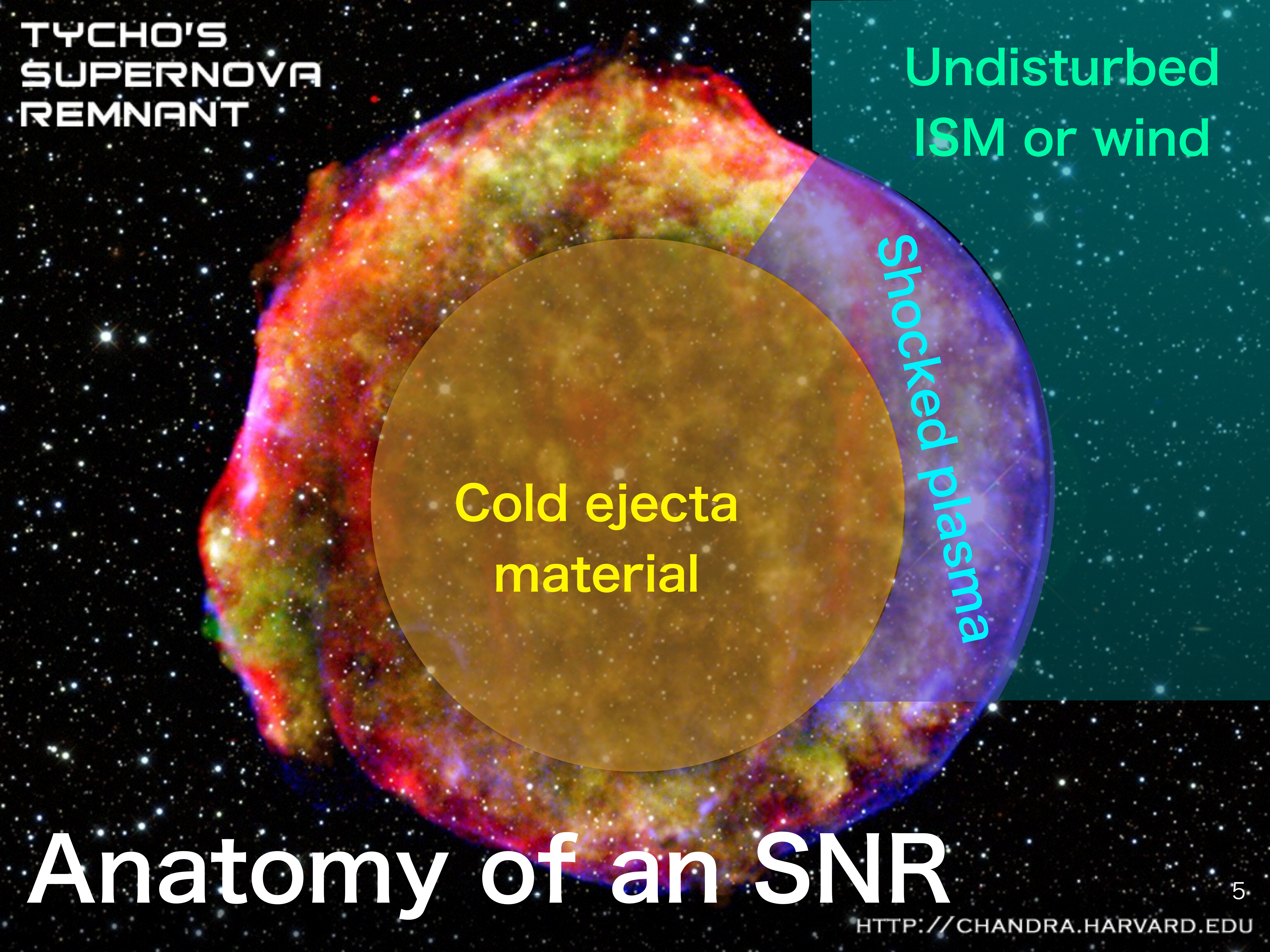
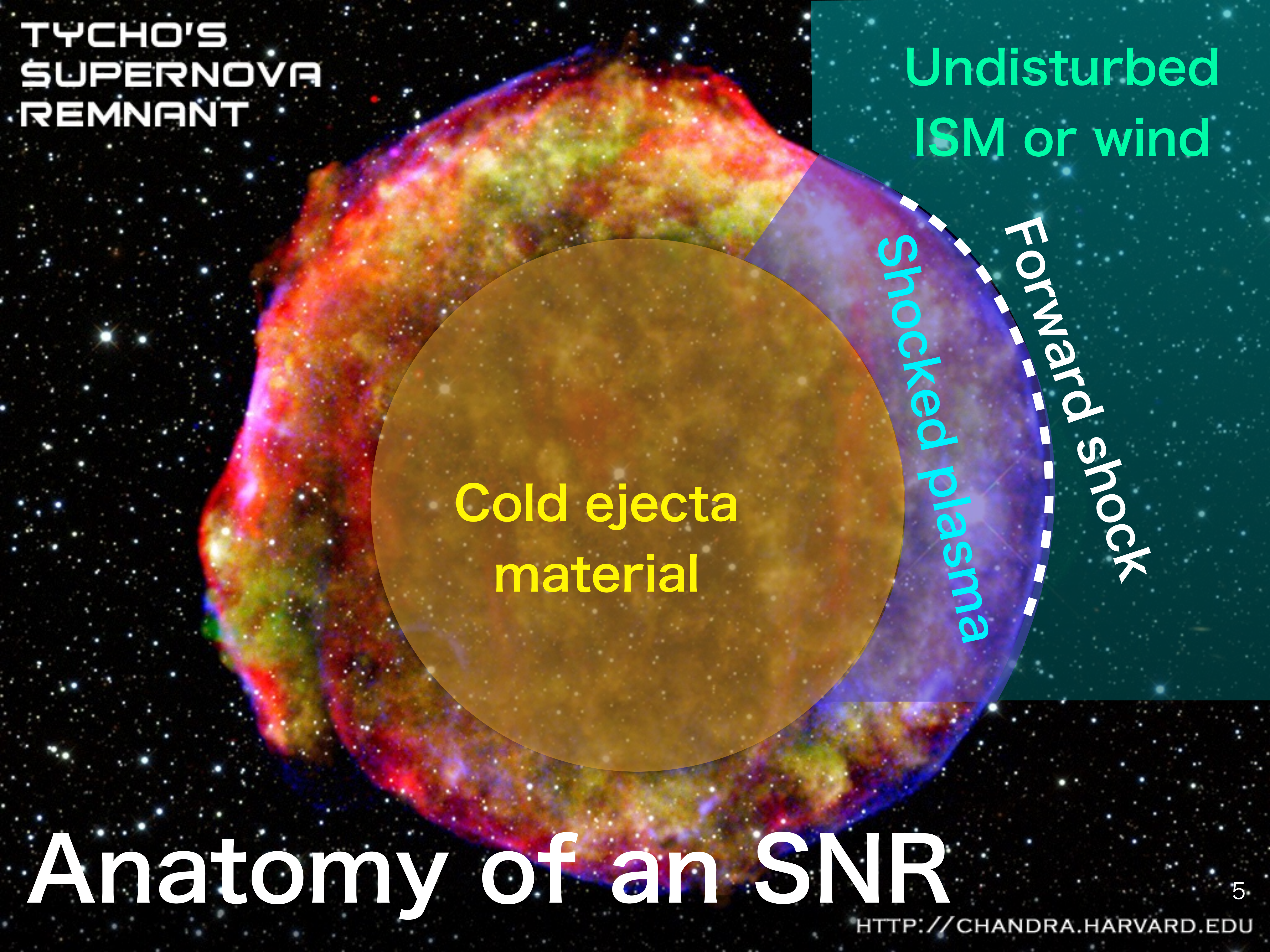
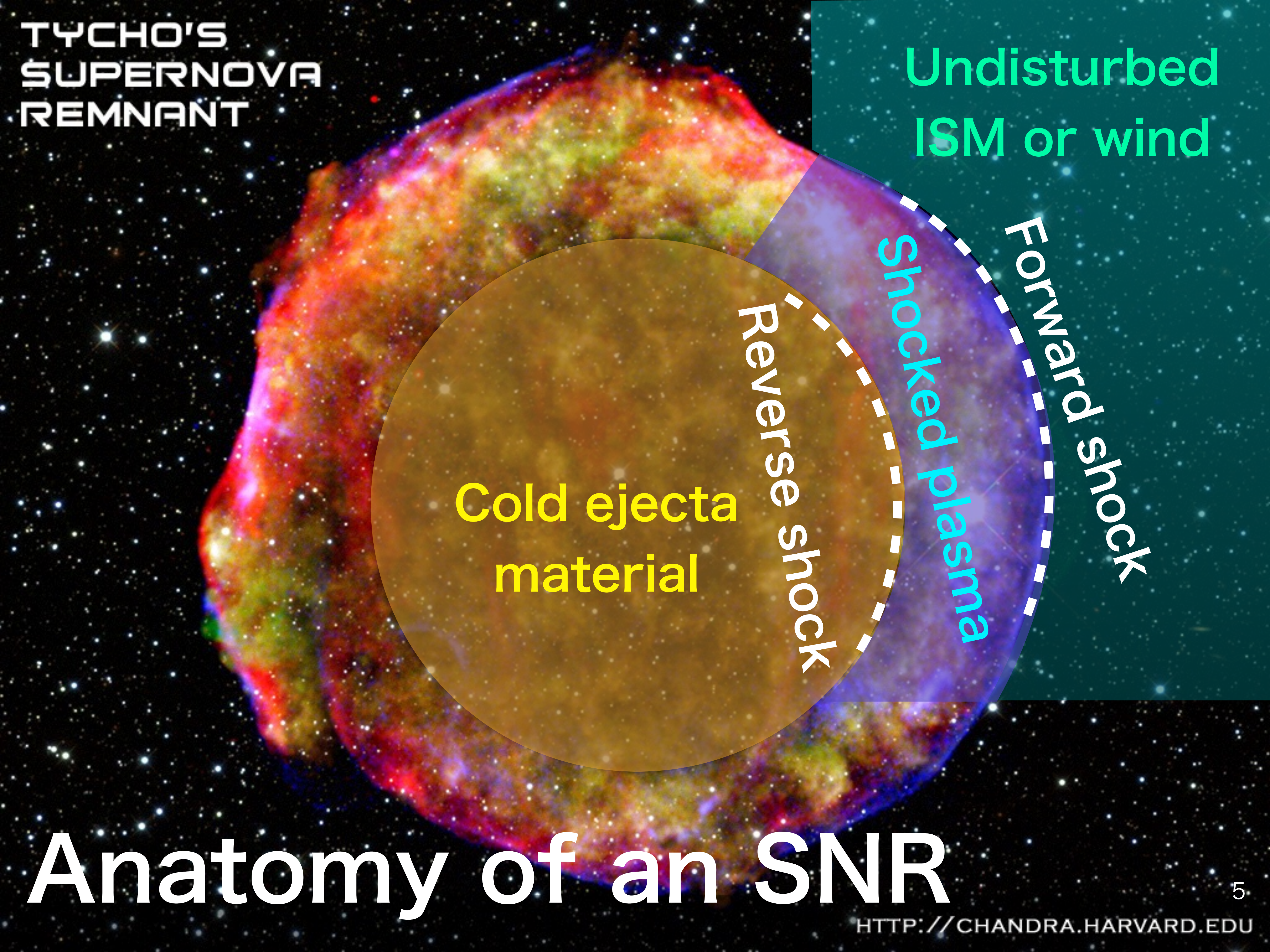

TYCHO'S
SUPERNOVA
REMNANT
Undisturbed
ISM or wind
Cold ejecta
material
Anatomy of an SNR
HTTP://CHANDRA.HARVARD.EDU

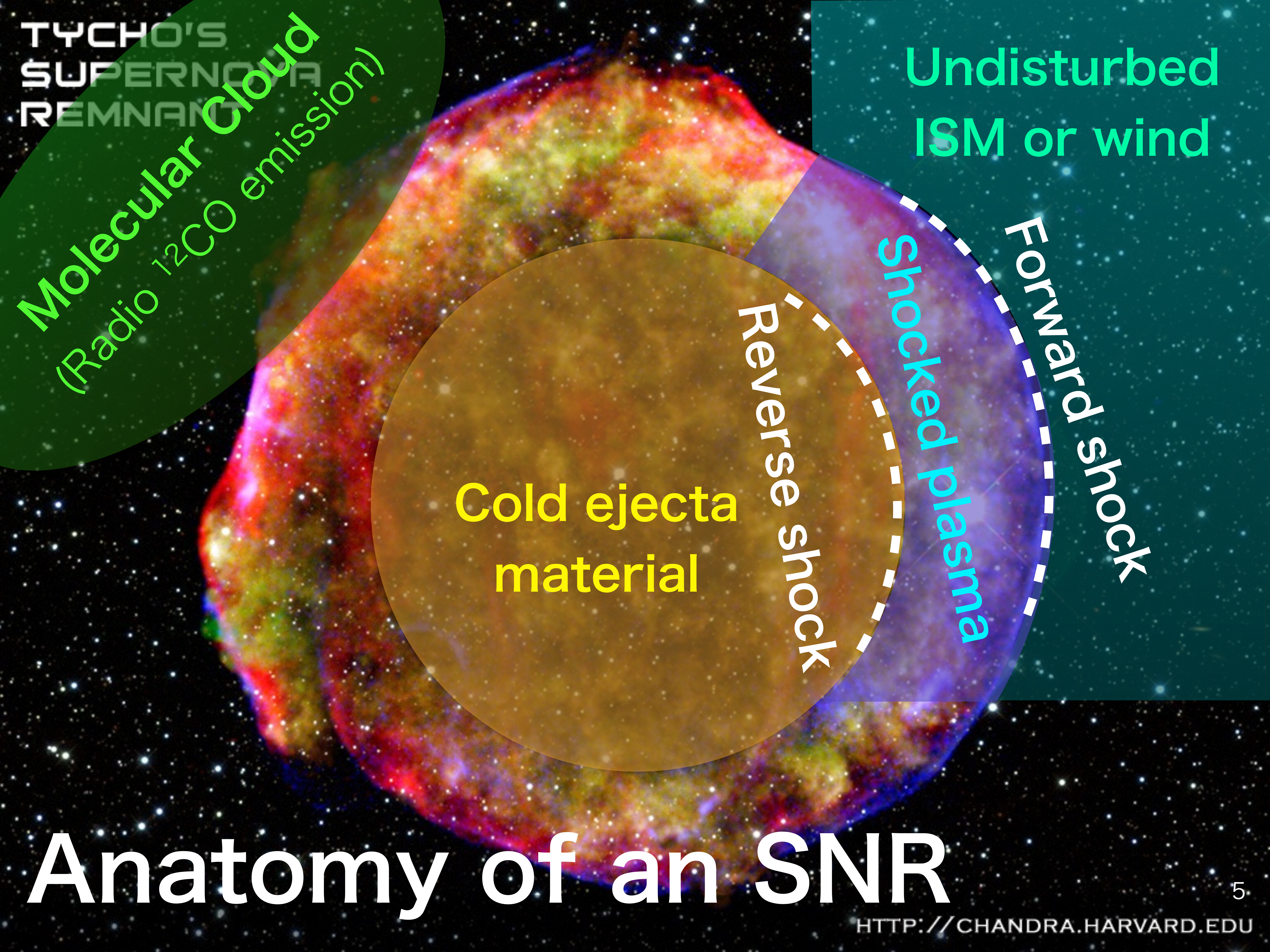

TYCHO'S
SUPERNOVA
REMNANT
Undisturbed
ISM or wind
Shocked plasma
Cold ejecta
material
Anatomy of an SNR
HTTP://CHANDRA.HARVARD.EDU

Anatomy of an SNR





Anatomy of an SNR


TYCHO'S SUPERNOVA REMNANT
Molecular Cloud
(Radio ^{12}CO emission)
Undisturbed ISM or wind
Shocked plasma
Forward shock
Reverse shock
Cold ejecta material
Anatomy of an SNR
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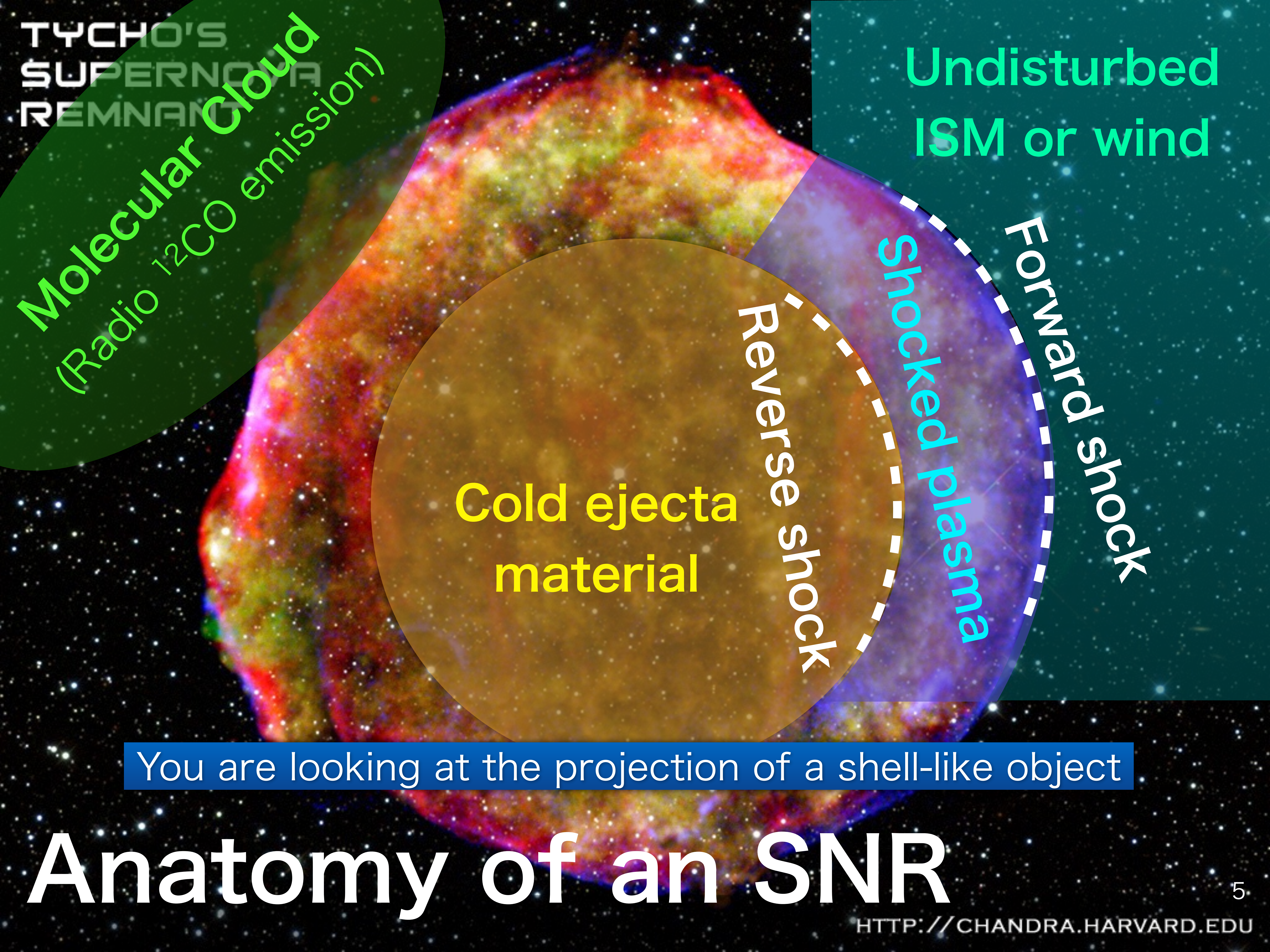
TYCHO'S SUPERNOVA REMNANT
Molecular Cloud
(Radio 12CO emission)
Undisturbed ISM or wind
Cold ejecta material
Reverse shock
Shocked plasma
Forward shock
You are looking at the projection of a shell-like object
Anatomy of an SNR
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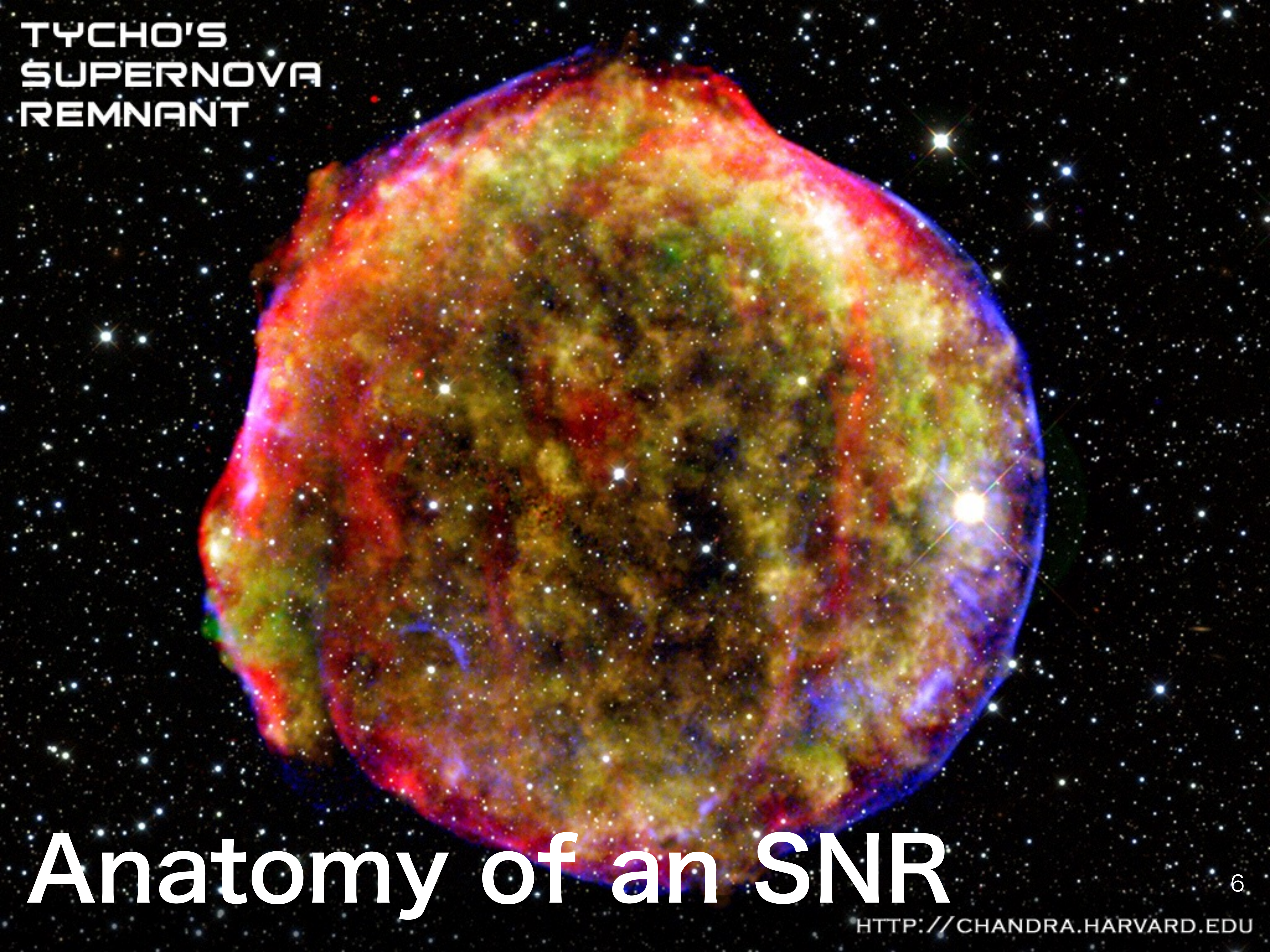
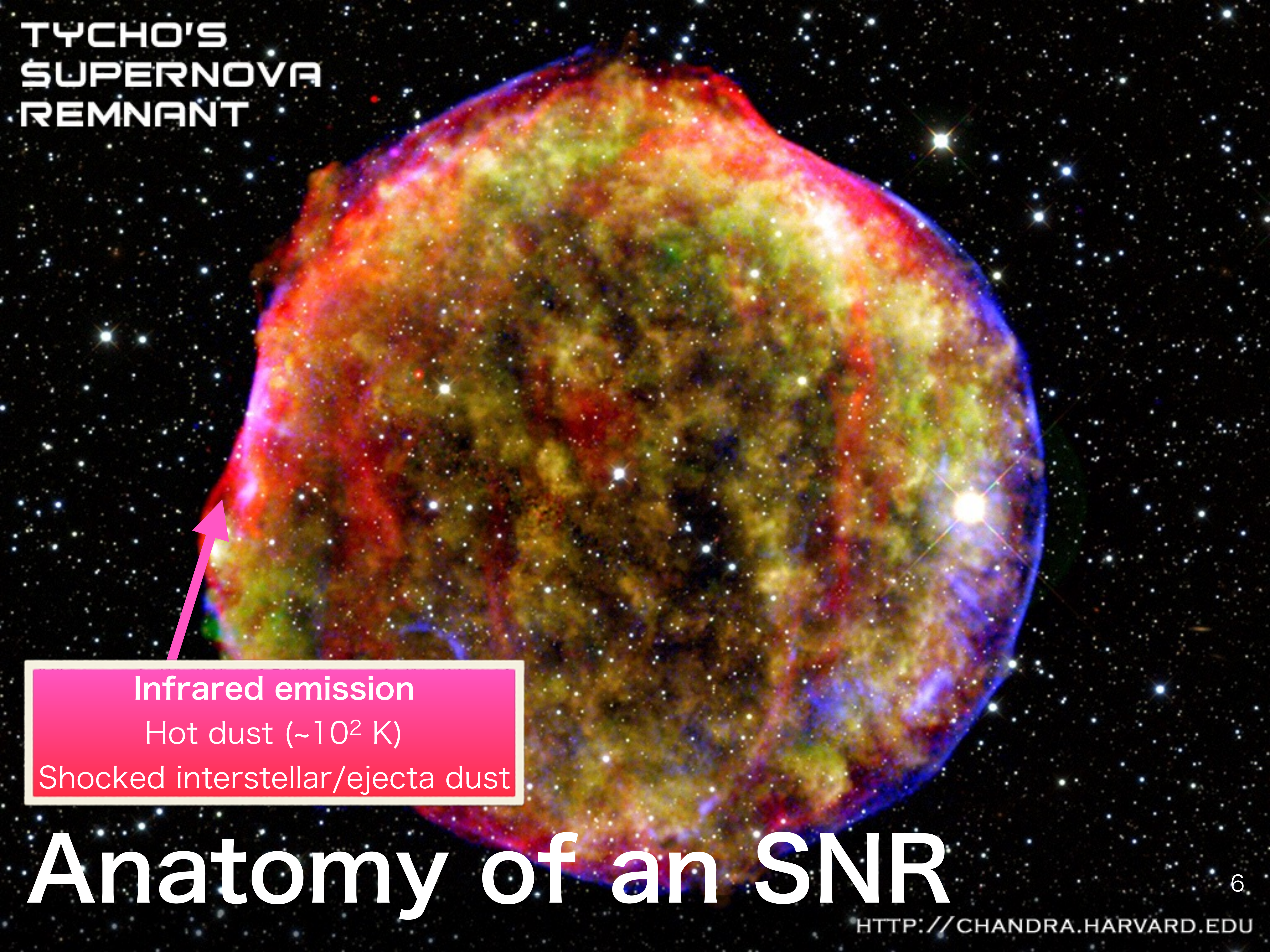
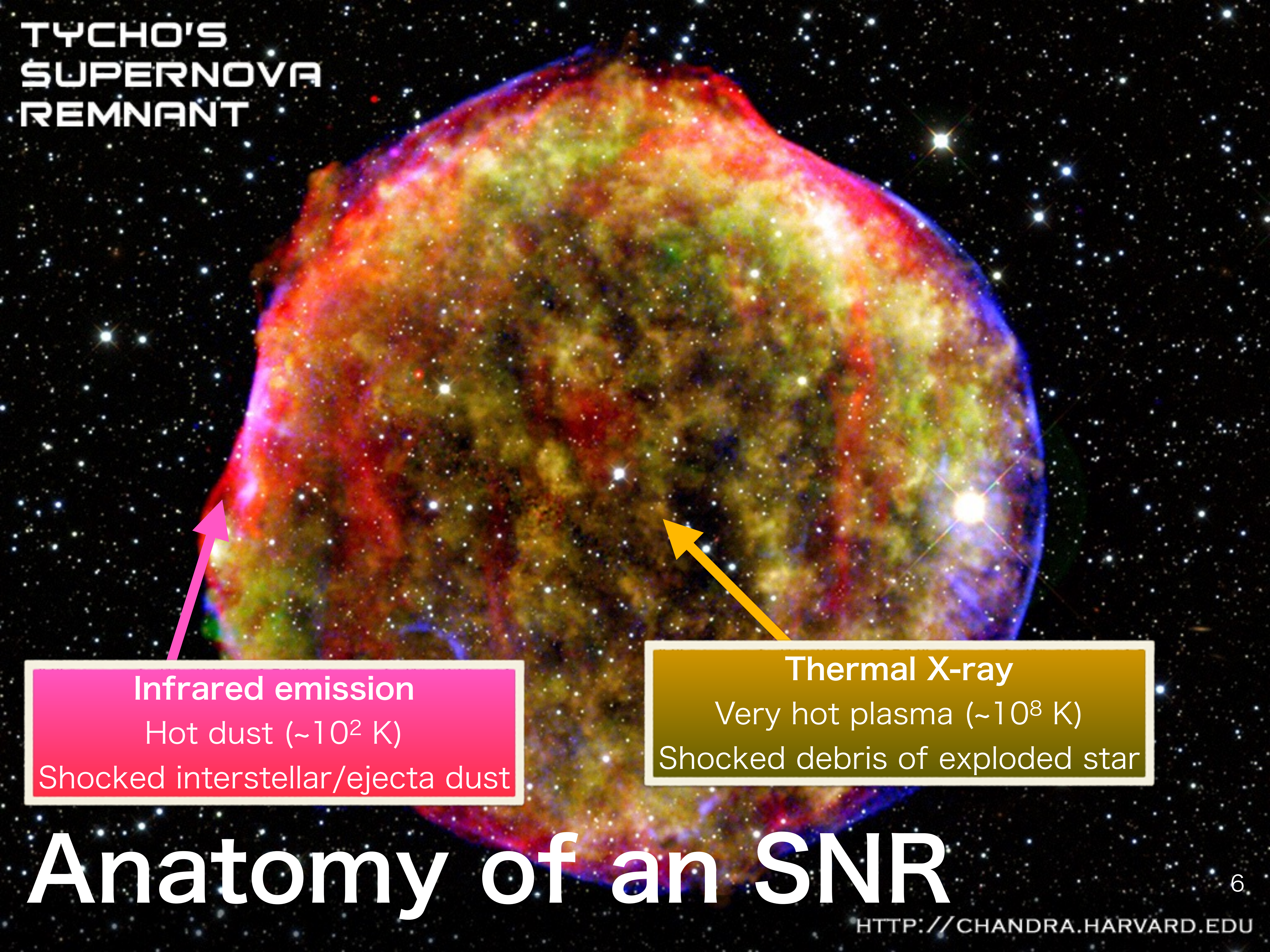


Anatomy of an SNR

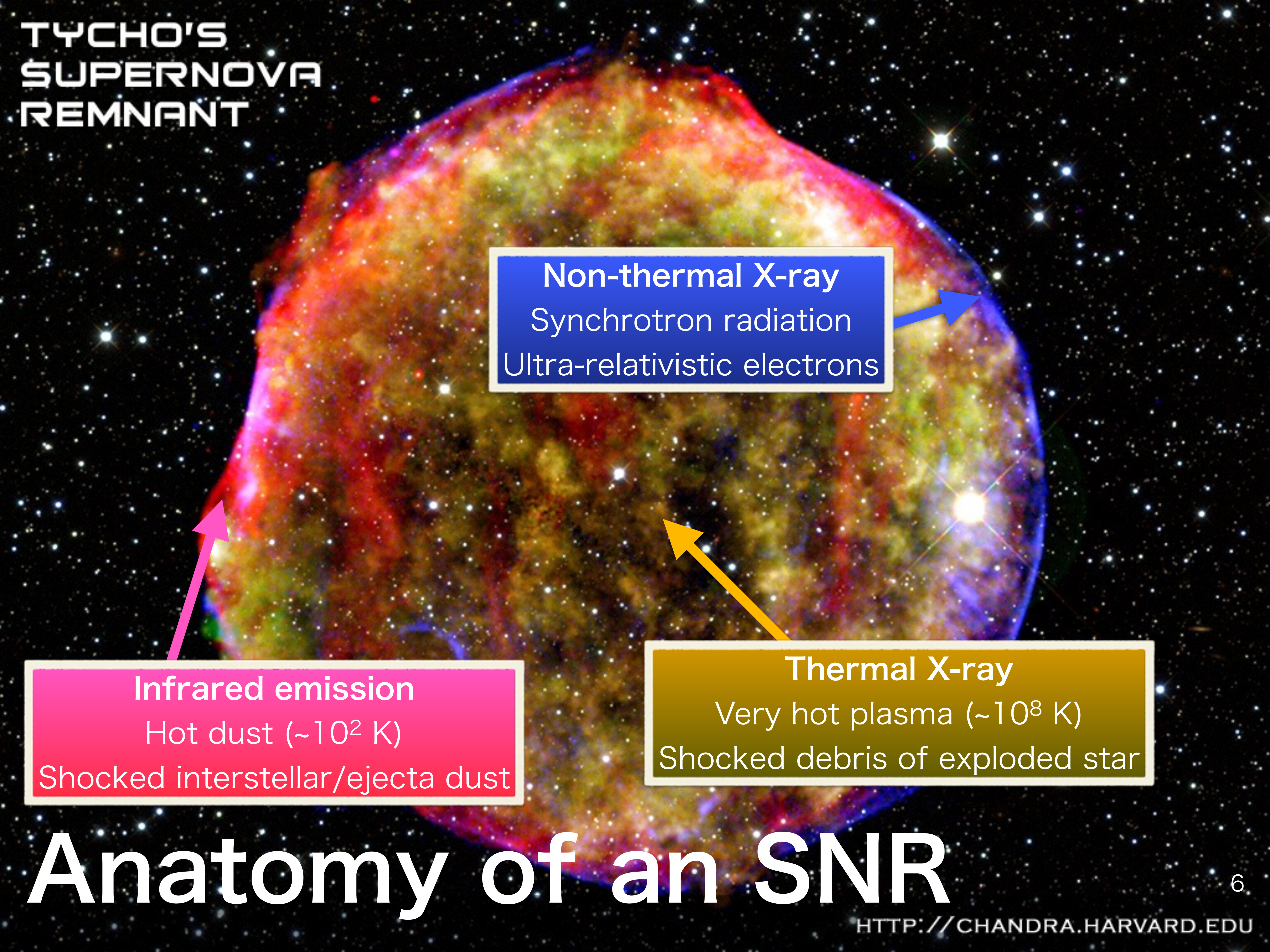


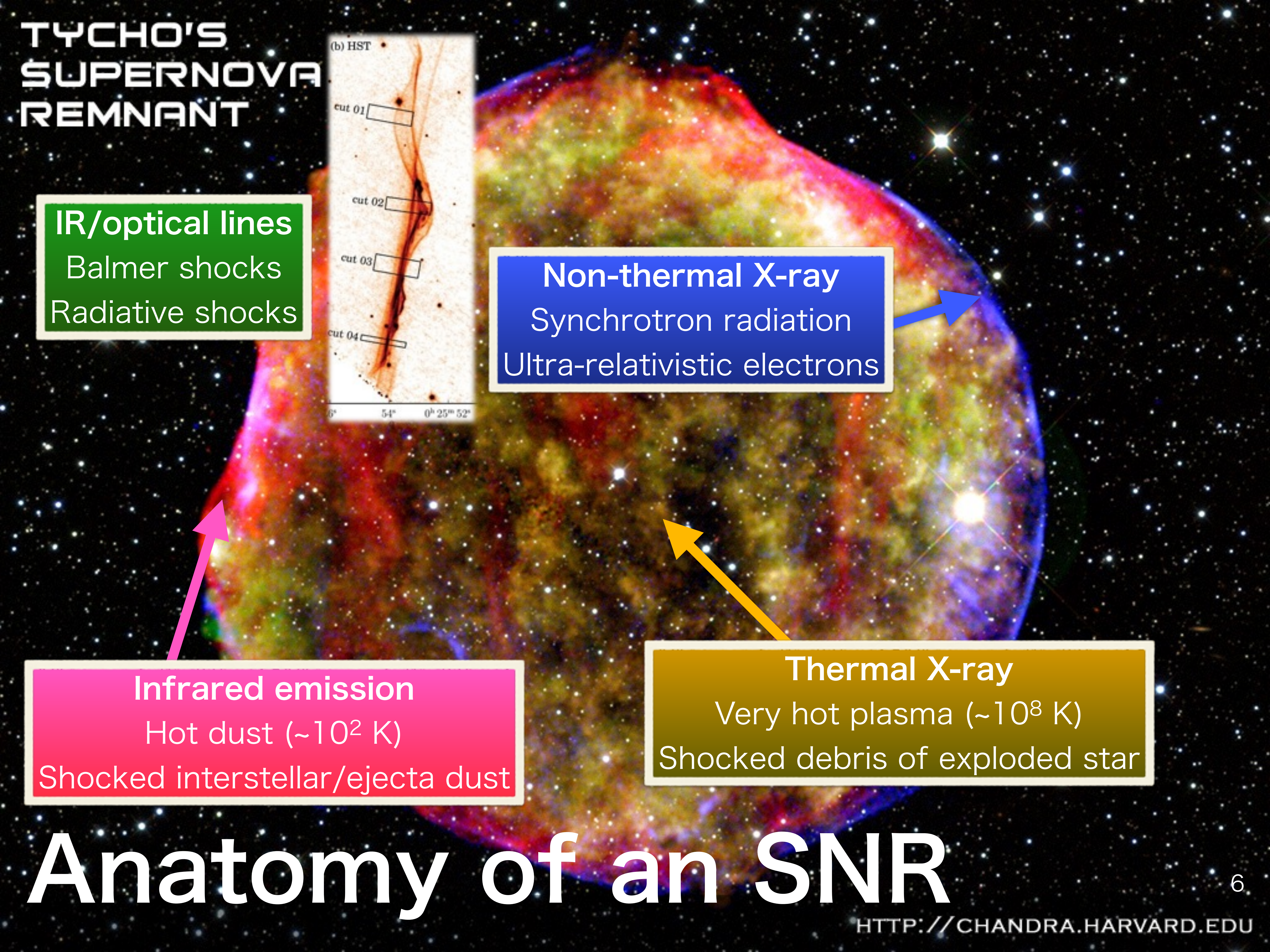
Anatomy of an SNR



Anatomy of an SNR

Anatomy of an SNR




TYCHO'S SUPERNOVA REMNANT
(b) HST
cut 01
cut 02
cut 03
cut 04
54s
0h 25m 52s
IR/optical lines
Balmer shocks
Radiative shocks
Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons
Infrared emission
Hot dust (~10² K)
Shocked interstellar/ejecta dust
Thermal X-ray
Very hot plasma (~10⁸ K)
Shocked debris of exploded star
Anatomy of an SNR
6
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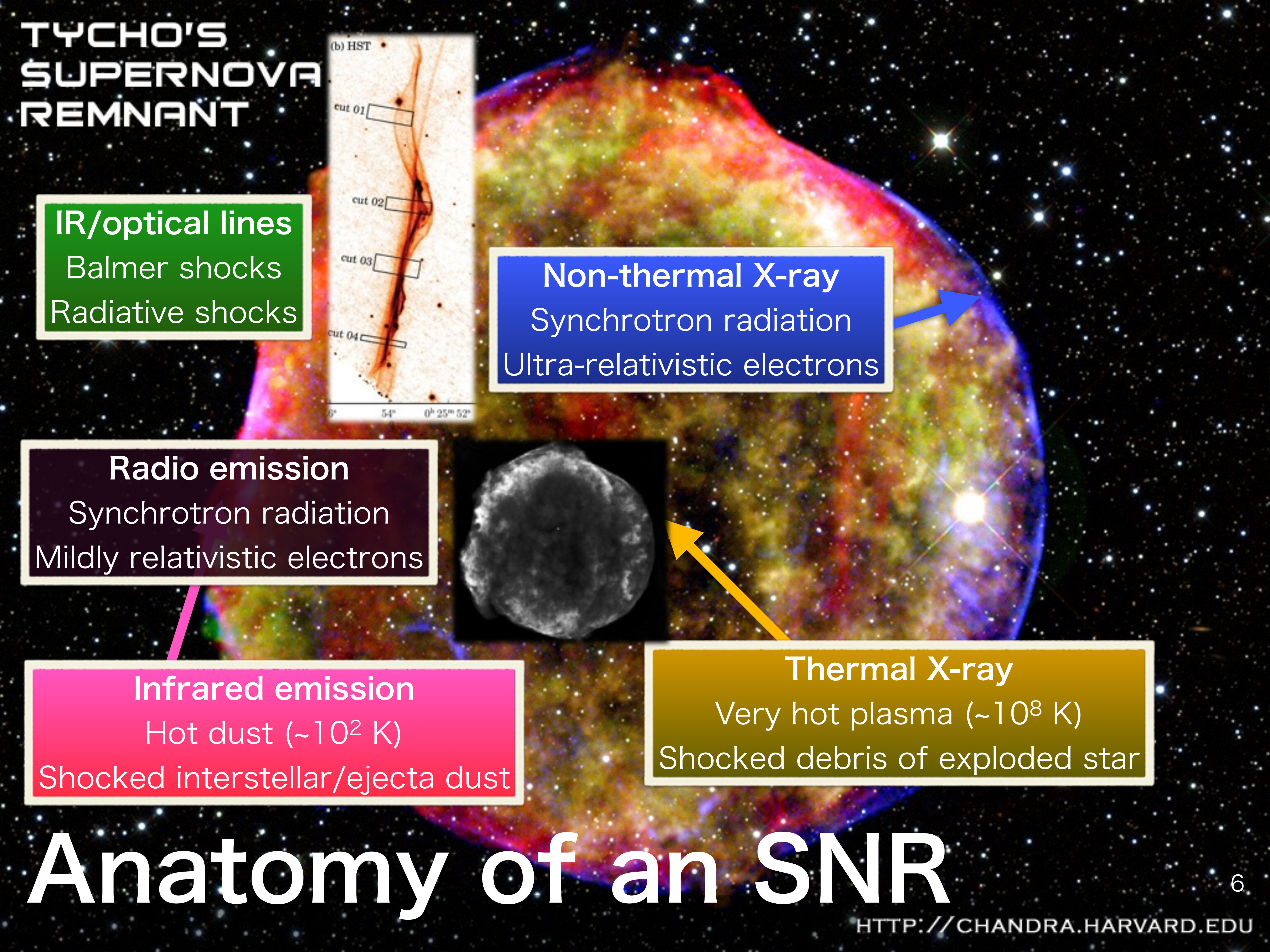
Tycho's Supernova Remnant
(b) HST
cut 01
cut 02
cut 03
cut 04
IR/optical lines
Balmer shocks
Radiative shocks
Non-thermal X-ray
Synchrotron radiation
Ultra-relativistic electrons
Radio emission
Synchrotron radiation
Mildly relativistic electrons
Infrared emission
Hot dust (~10^2 K)
Shocked interstellar/ejecta dust
Thermal X-ray
Very hot plasma (~10^8 K)
Shocked debris of exploded star
Anatomy of an SNR
6
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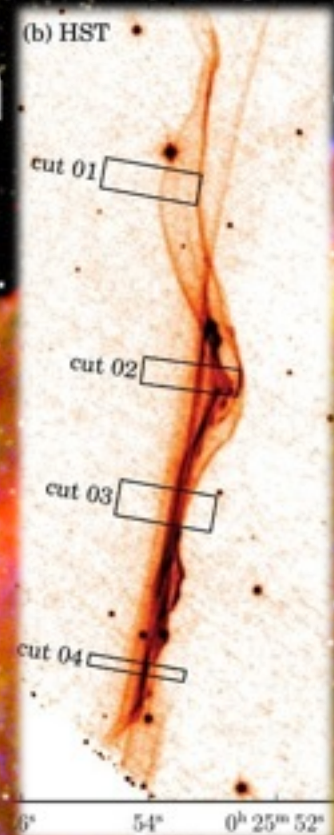
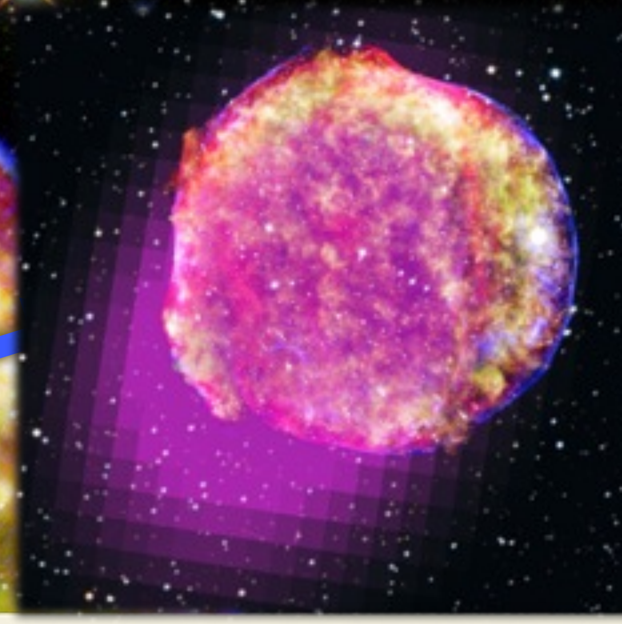
TYCHO'S SUPERNOVA REMNANT

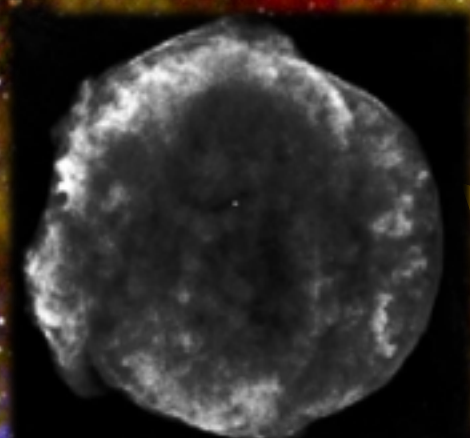


IR/optical lines
Balmer shocks
Radiative shocks

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



Radio emission
Synchrotron radiation
Mildly relativistic electrons



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

Anatomy of an SNR

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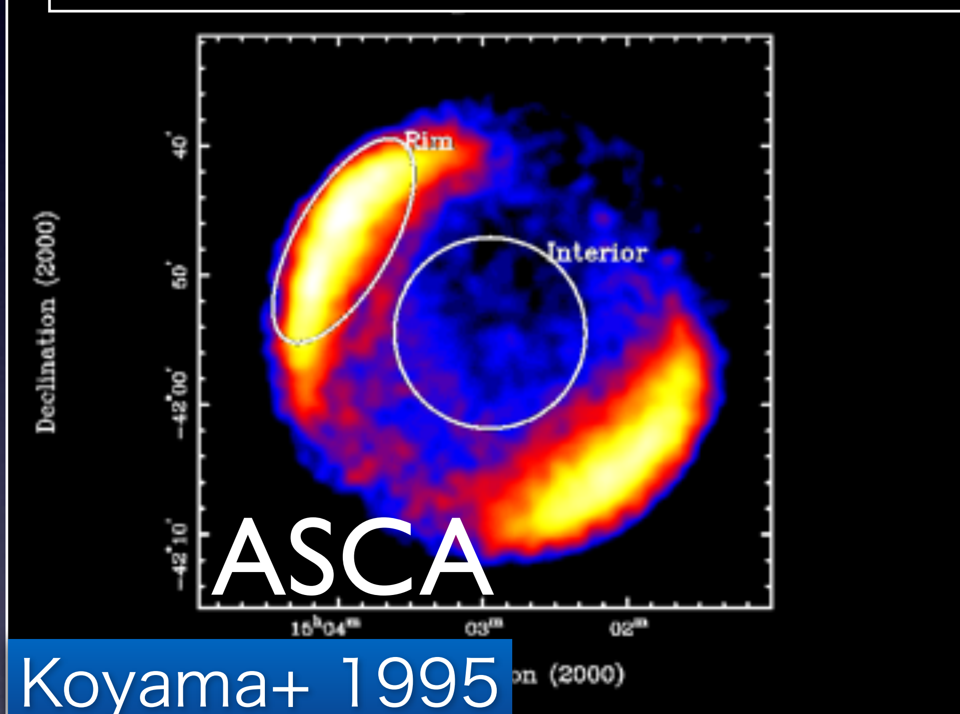
Non-thermal emission at young SNRs
= presence of fast-and-furious particles

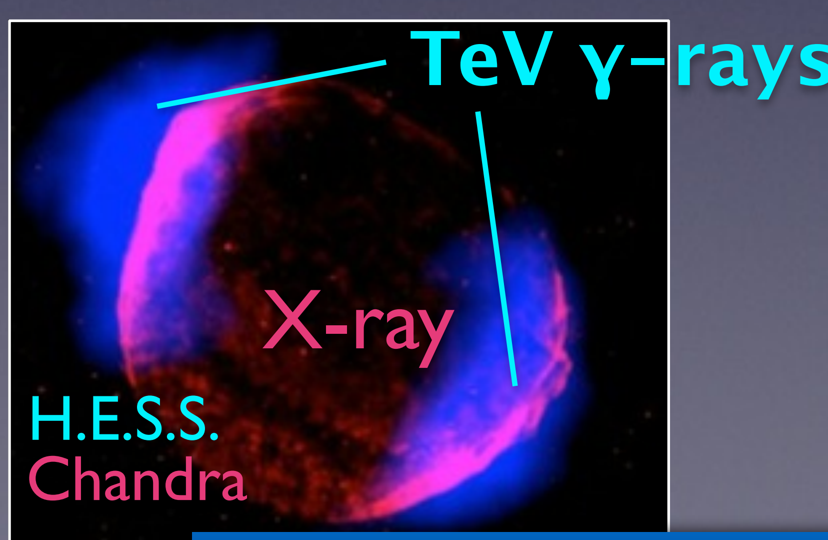
SNR of SN1006（S. Fujiwara, 明月記, 1180-1235）



Koyama+ 1995

Discovery of synchrotron X-rays at young shell-type SNR
→ local >100 TeV electrons

Usually accompanied by γ-rays
→ There are high-energy particles



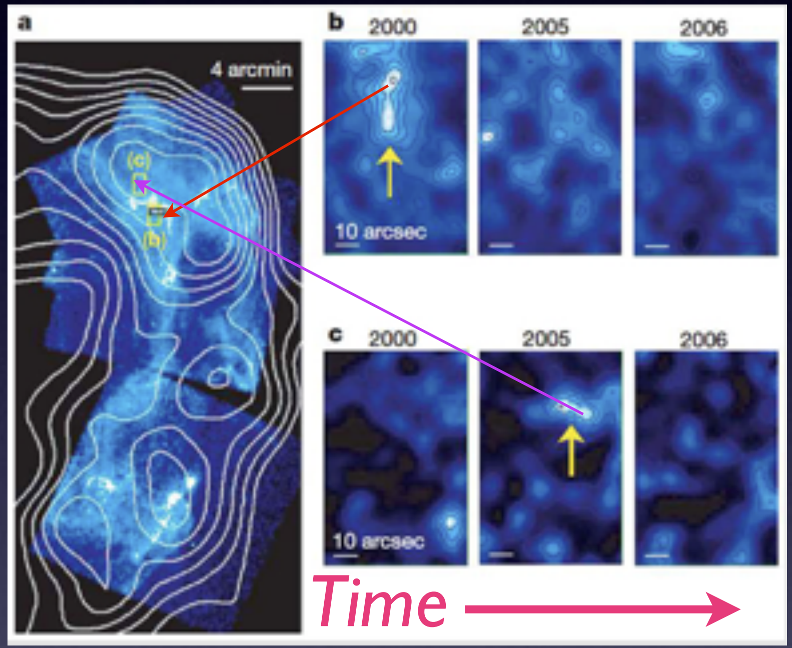
Naumann-Godo+ 2008

SNRs are cosmic particle accelerators

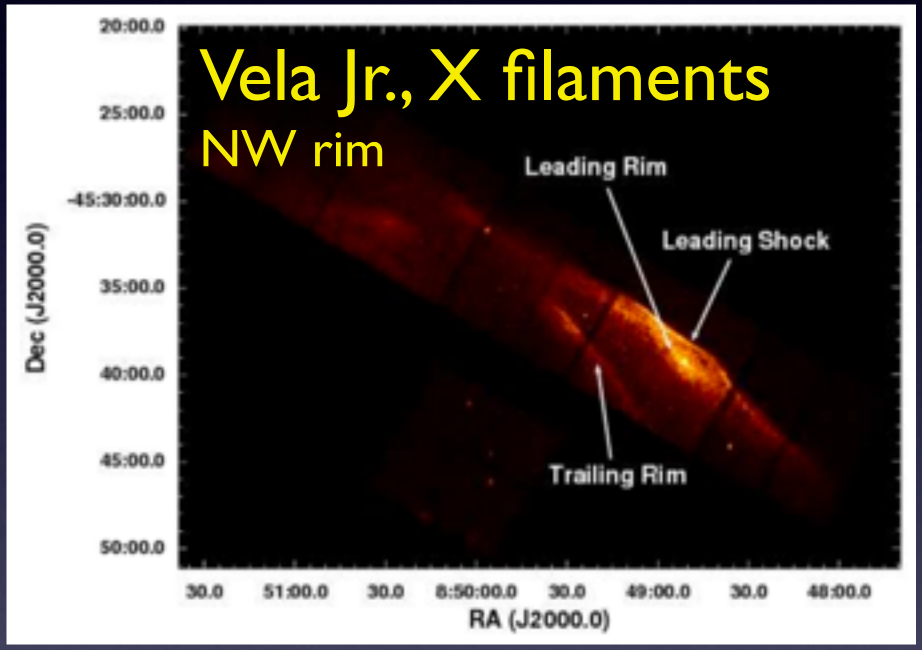
Q: What are these particles, how are they accelerated, and how much
A: Origin of Galactic CR

Synchrotron X-ray from SNRs
Not so trivial

RX J1713, twinkling X-ray dots

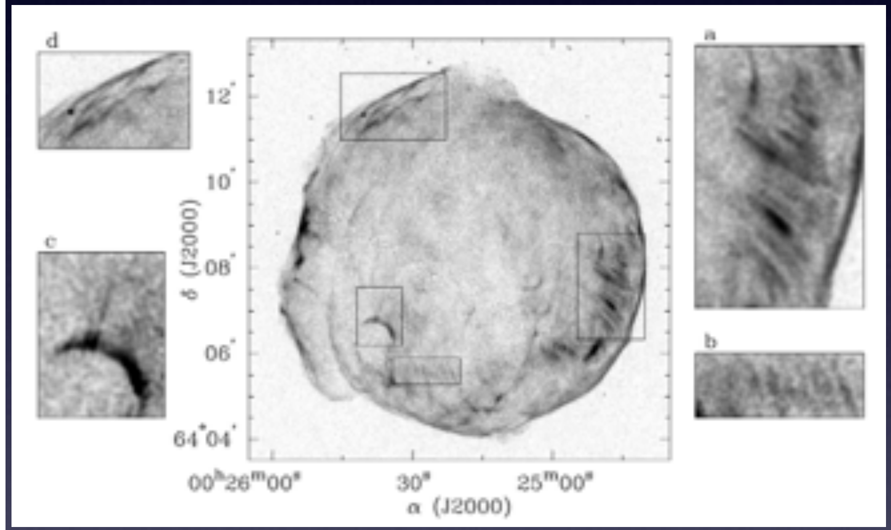


Uchiyama+ 2007



Bamba+ (2005), Pannuti+ (2010)

Tycho, X-ray stripes

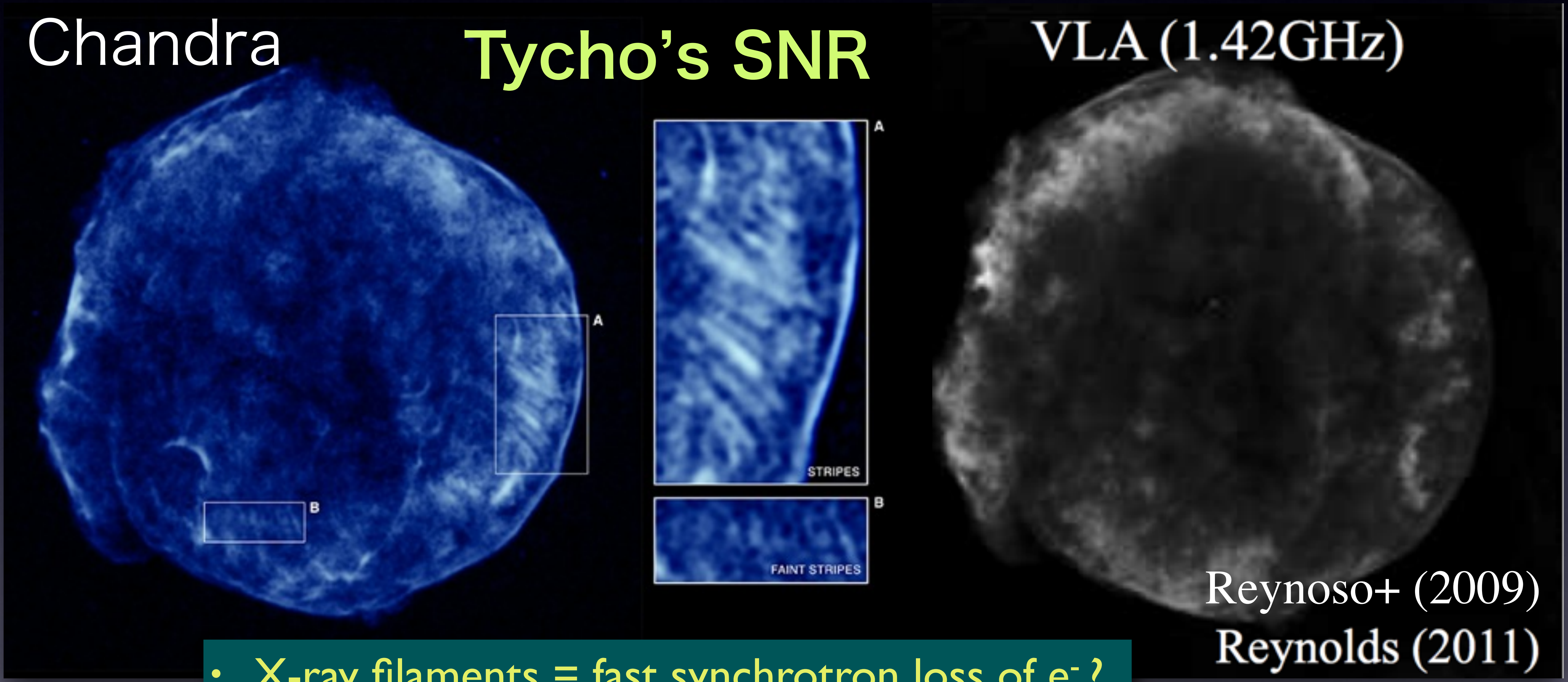


Eriksen+ 2011

- **B-fields** play a central role in high-energy phenomena in SNRs and other accelerators
- **Time variability** and **spatial structures (dots, filaments, stripes)** tied to B-field distribution
- These B-fields must be **self-generated** (via CR-induced instabilities), plus MHD turbulence

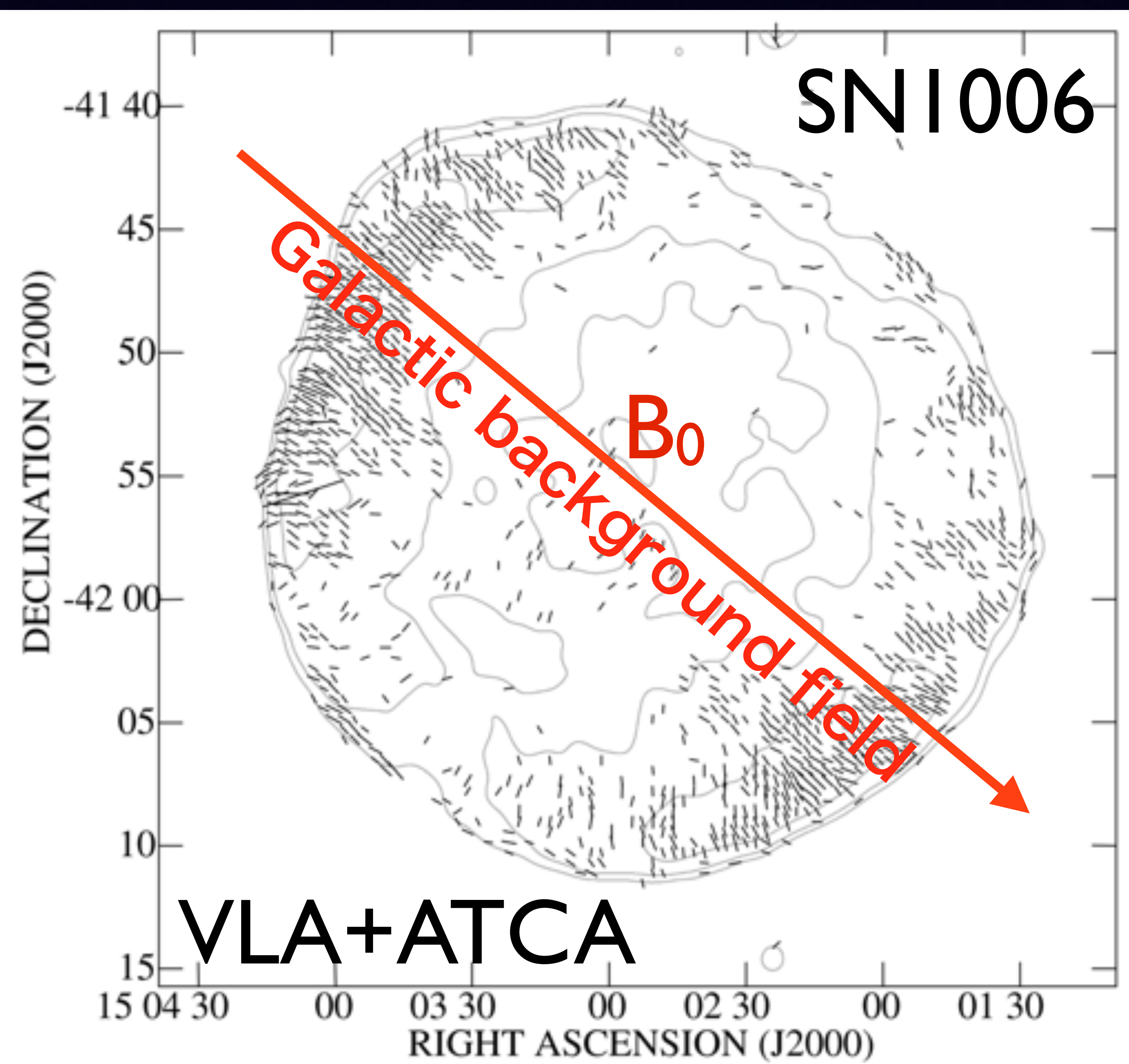
Mysterious radio and X-ray structures

Origin of morphology still unclear

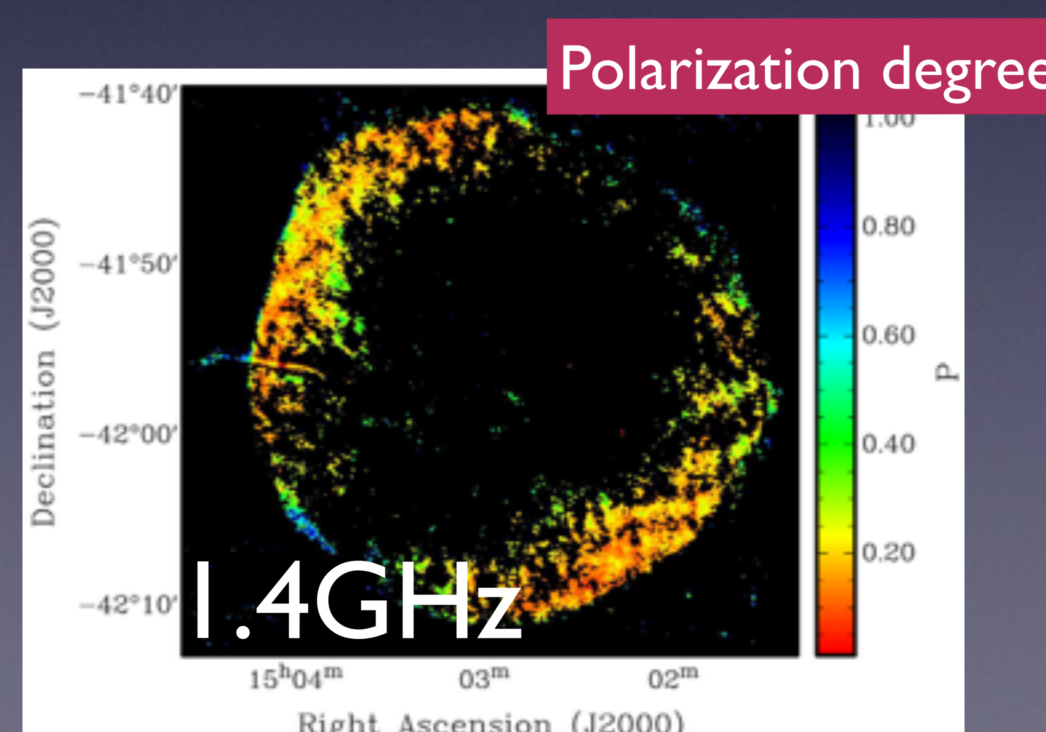


- X-ray filaments = fast synchrotron loss of e^- ?
- But why in radio too?
- Decay of δB behind shock?
- Periodic stripes: dominant length scales of δB?

B-field geometry and DSA From radio polarization



- B_0 seems parallel to shock normal at synch-bright rims
- DSA preferred at quasi-parallel shock !?

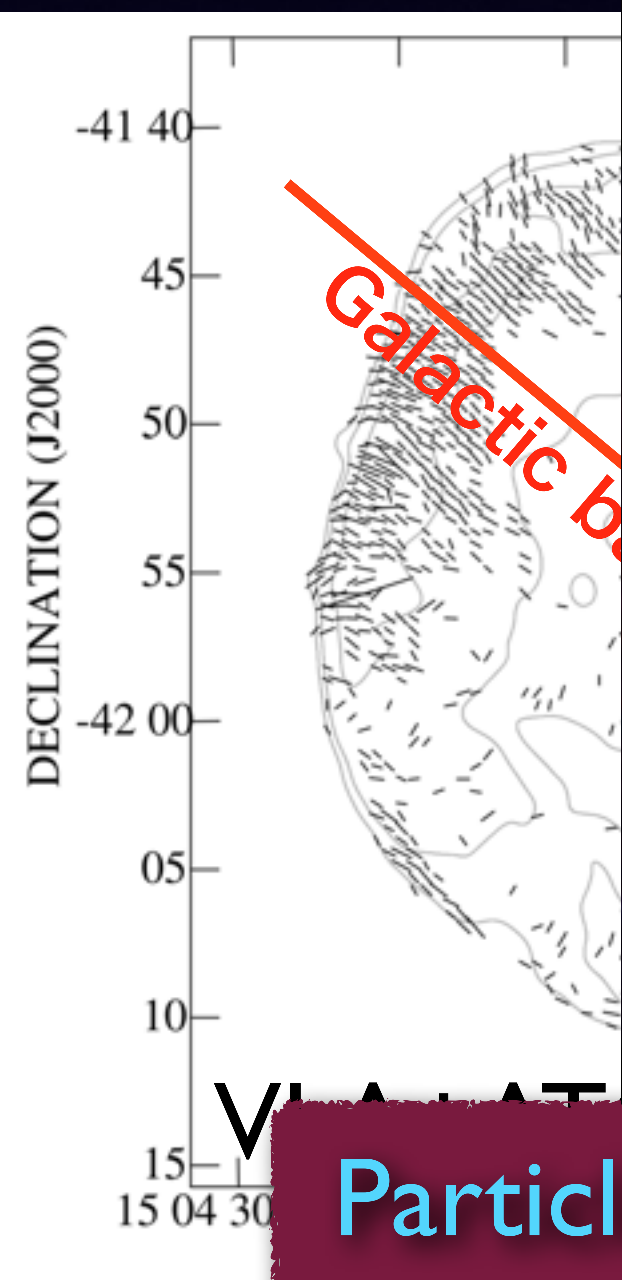


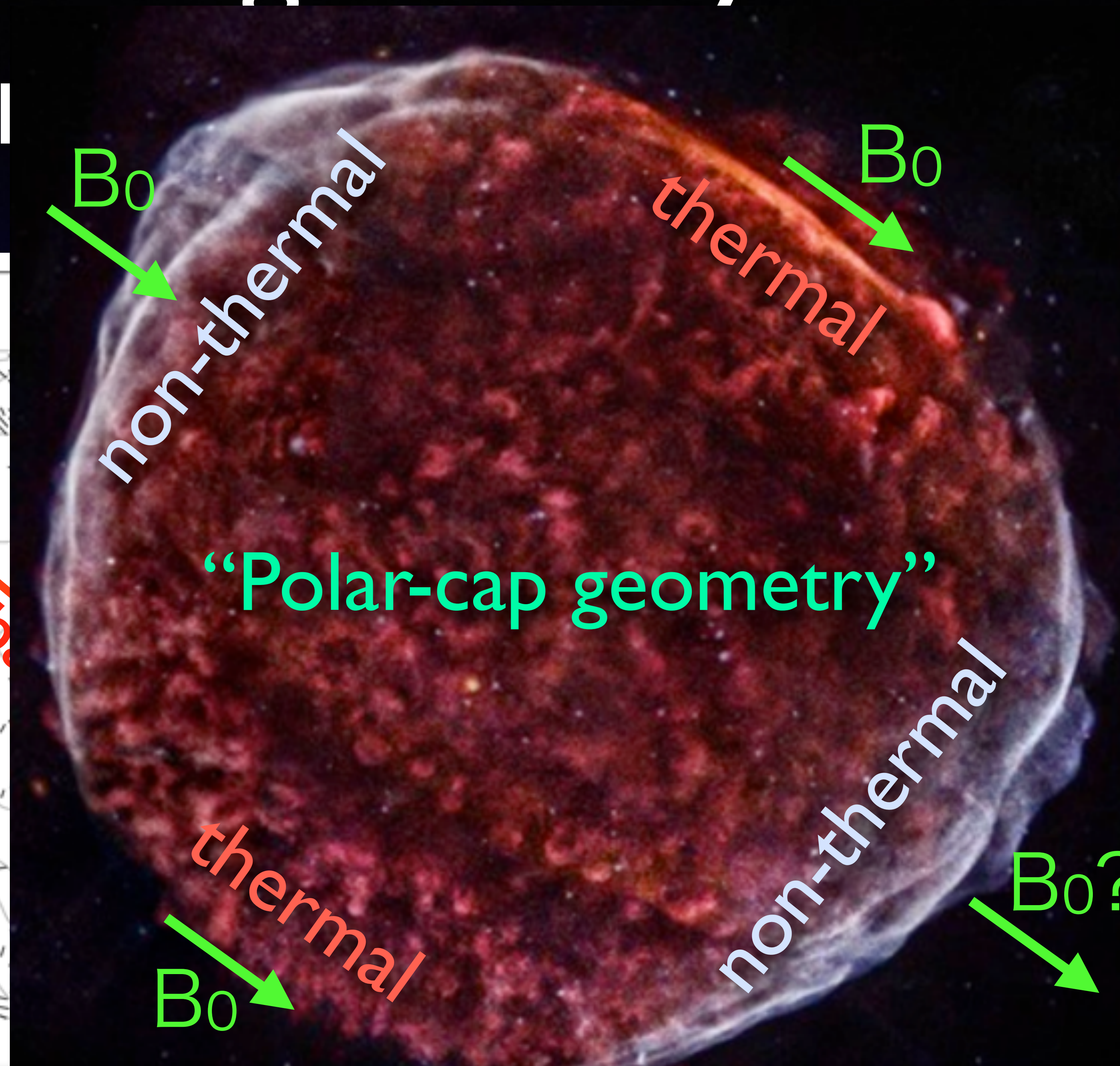
Reynoso+ 2013

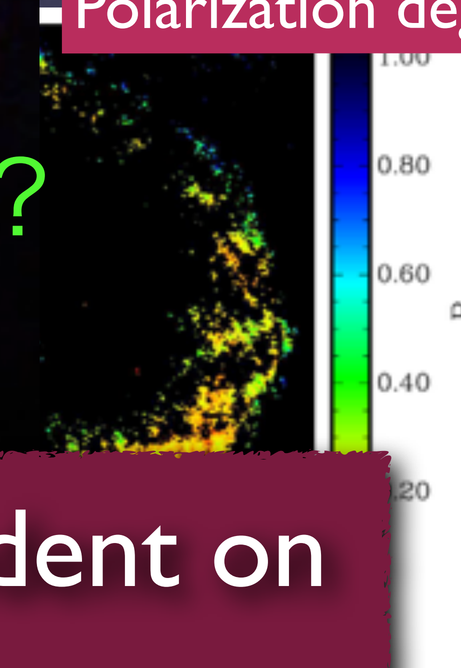
B-field geometry and DSA

Fr… …on

…l to shock
…-bright rims
…t quasi-parallel







Particle acceleration site highly-dependent on orientation of B_0

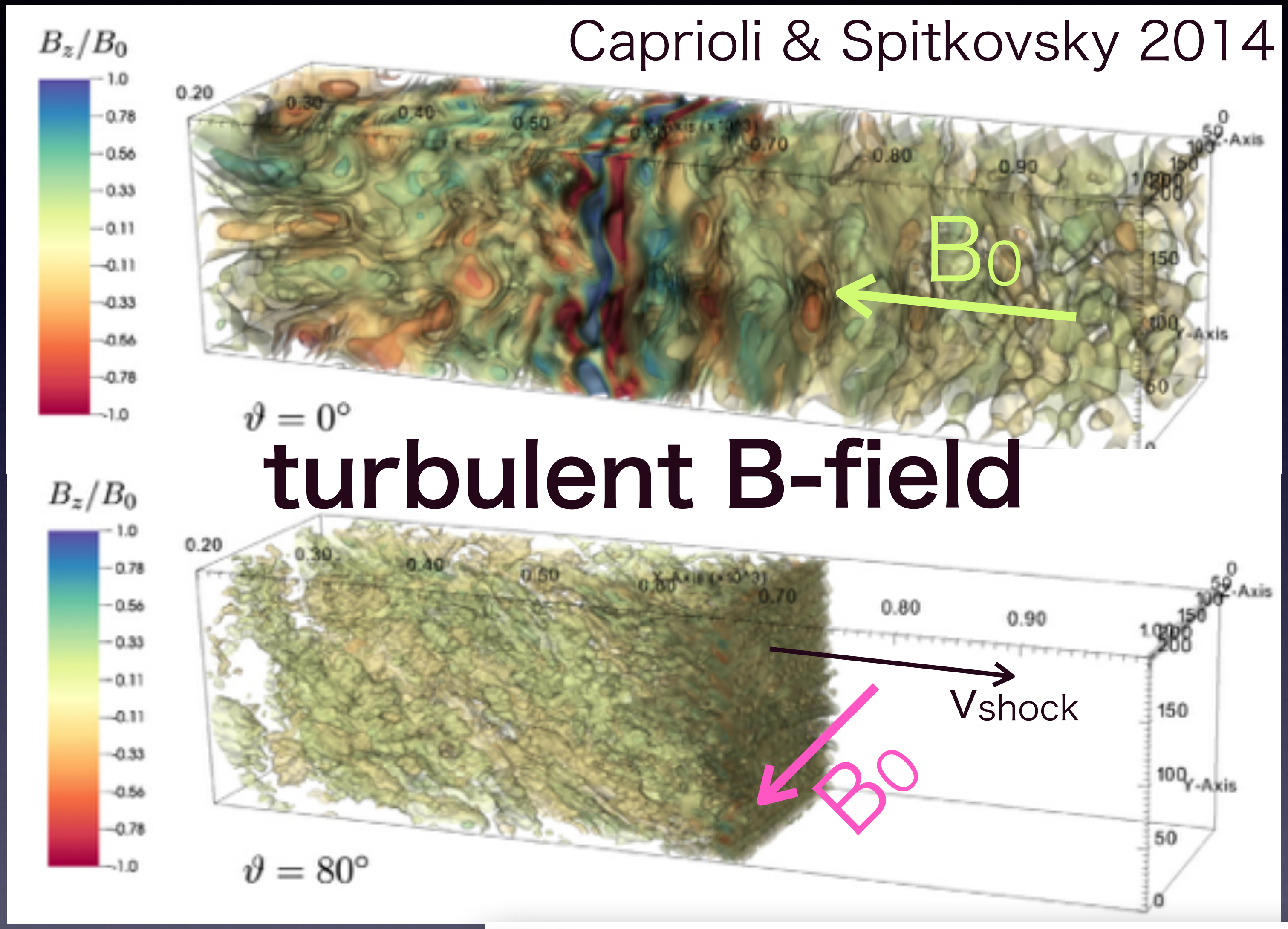
Particle acceleration at non-relativistic collisionless shock

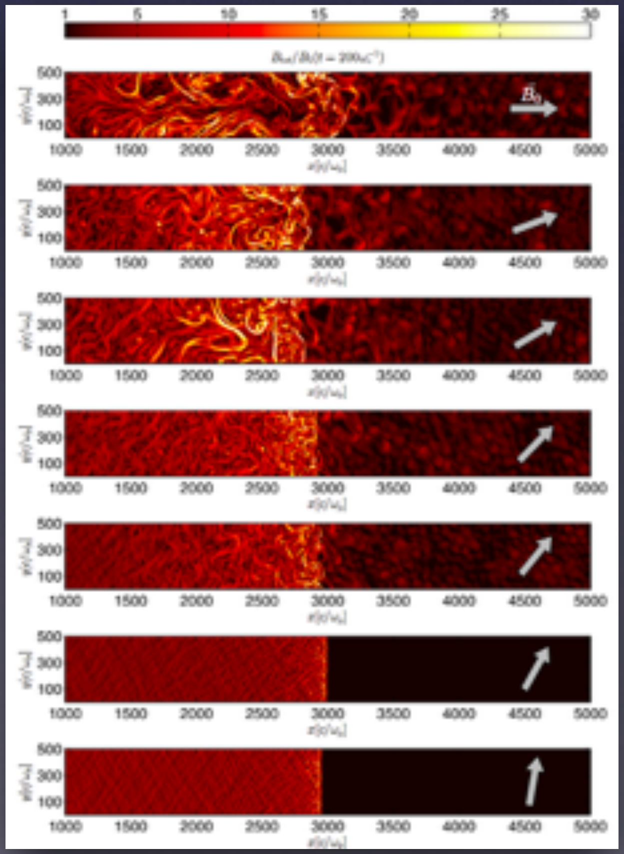
Multi-D hybrid sim.

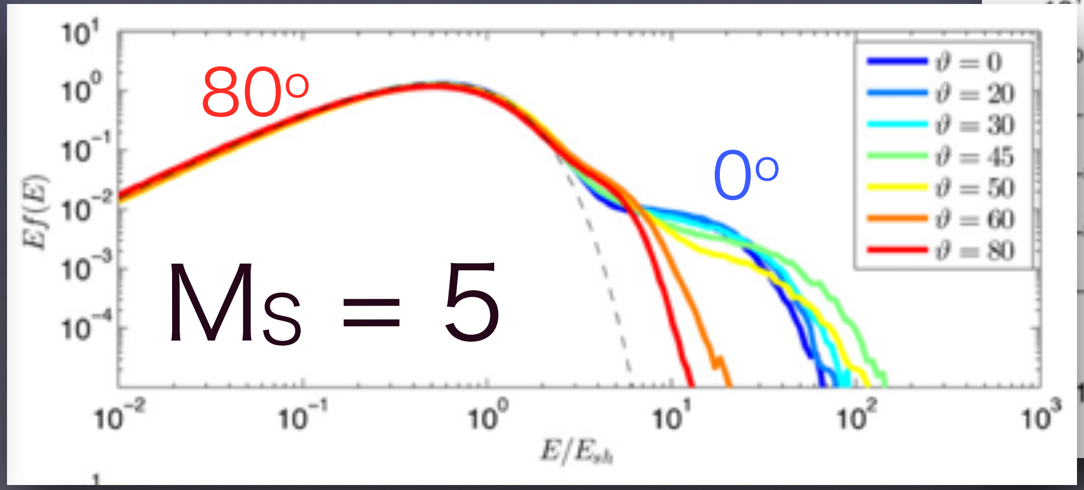
(particle ion, fluid electron)

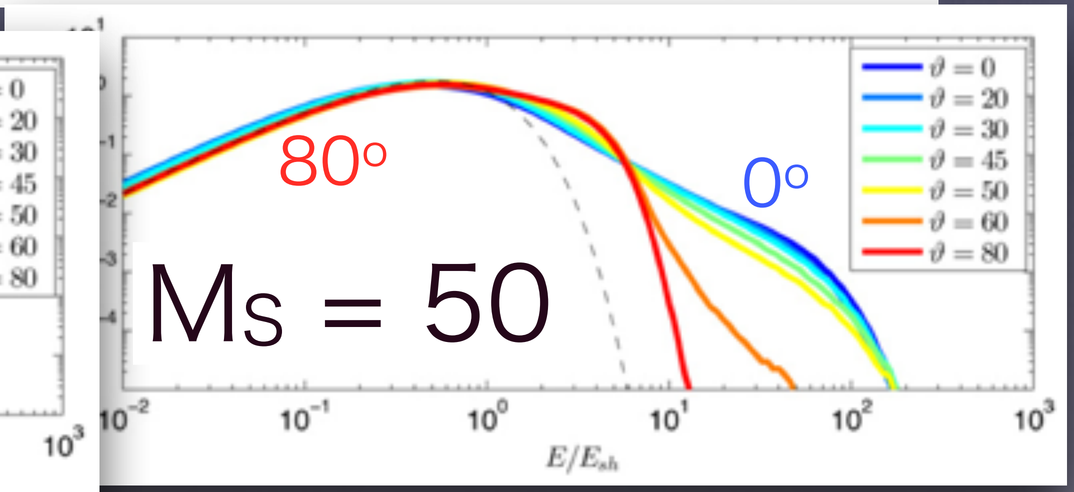
DSA at parallel vs oblique shocks

Self-generation of δB by CR-induced instability indicates efficient DSA



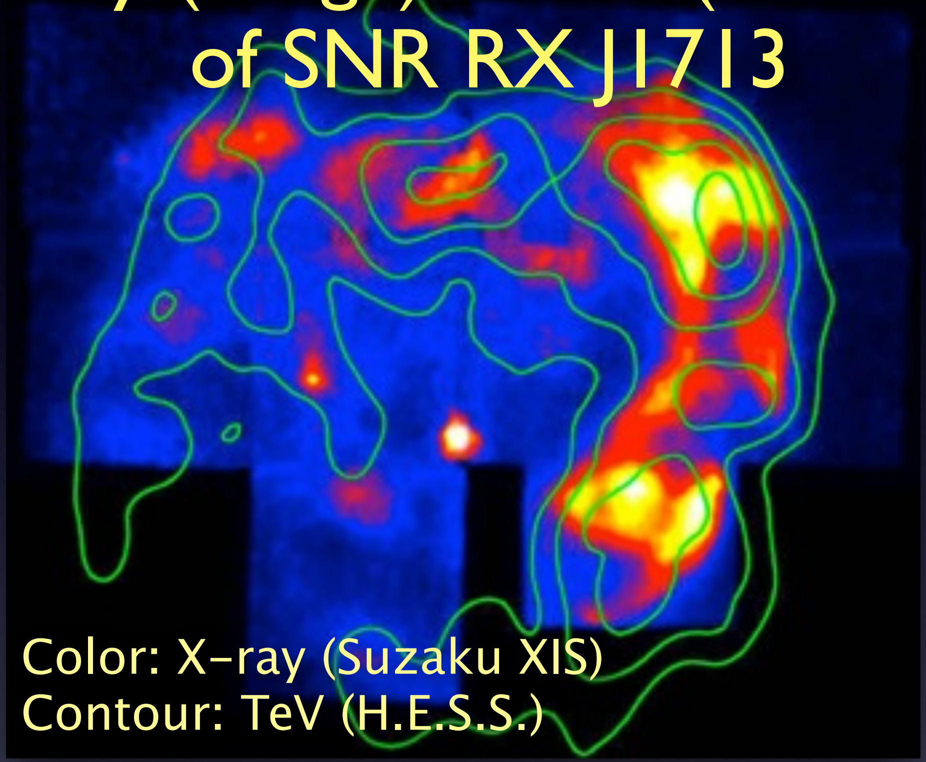


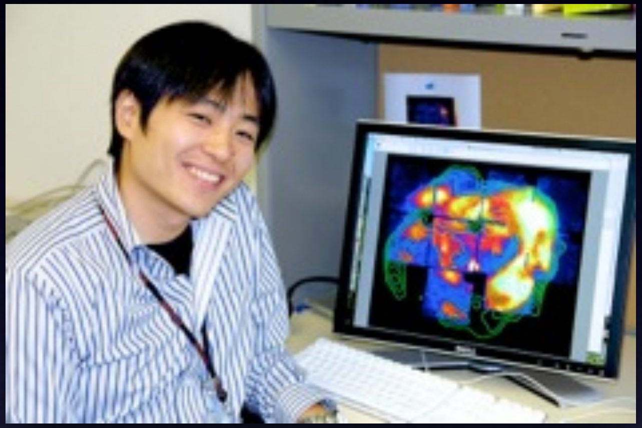




Origin of VHE γ-ray

X-ray (image) vs TeV (contour)
of SNR RX J1713

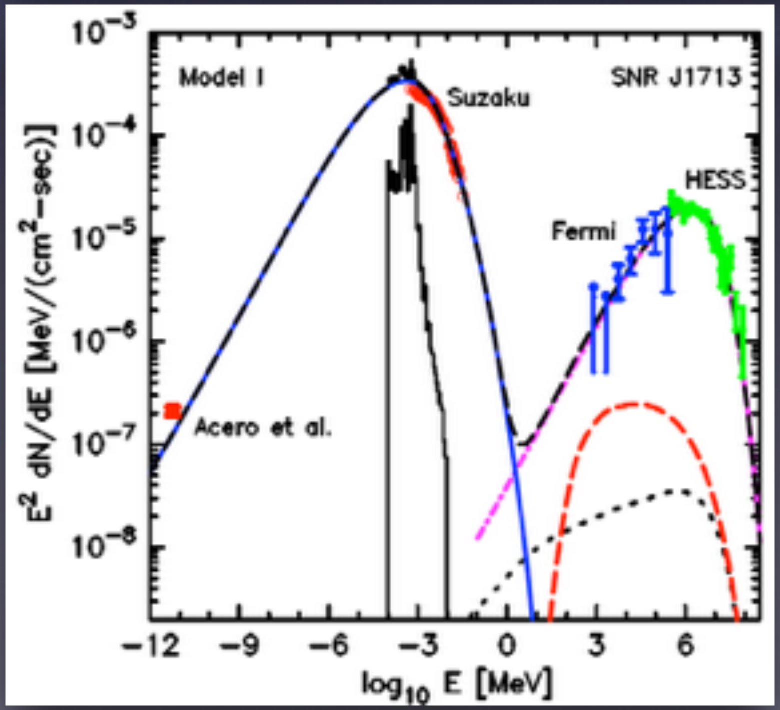




T. Tanaka+ 2008

<u>Non-thermal SNRs (e.g. RX J1713, Vela Jr.)</u>

- **Amazing match** of X-ray and TeV γ-ray
- Hard γ-ray spectrum → **inverse Compton?**
- Same origin for γ-ray and X-ray?
- So-called **'leptonic' scenario**



HL+ 2012

Non-detected thermal X-ray supports leptonic origin

Origin of VHE γ-ray

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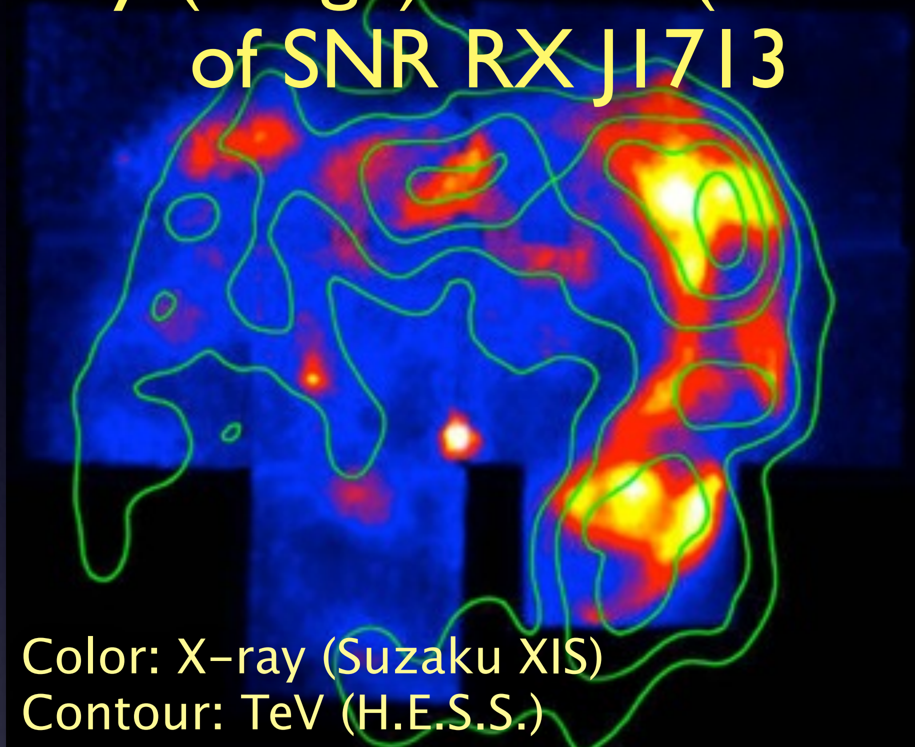

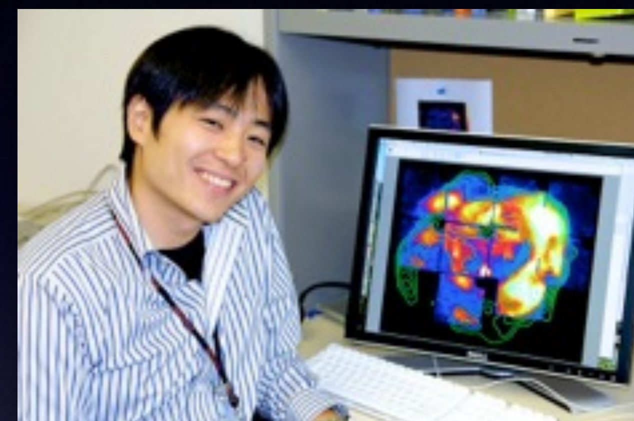

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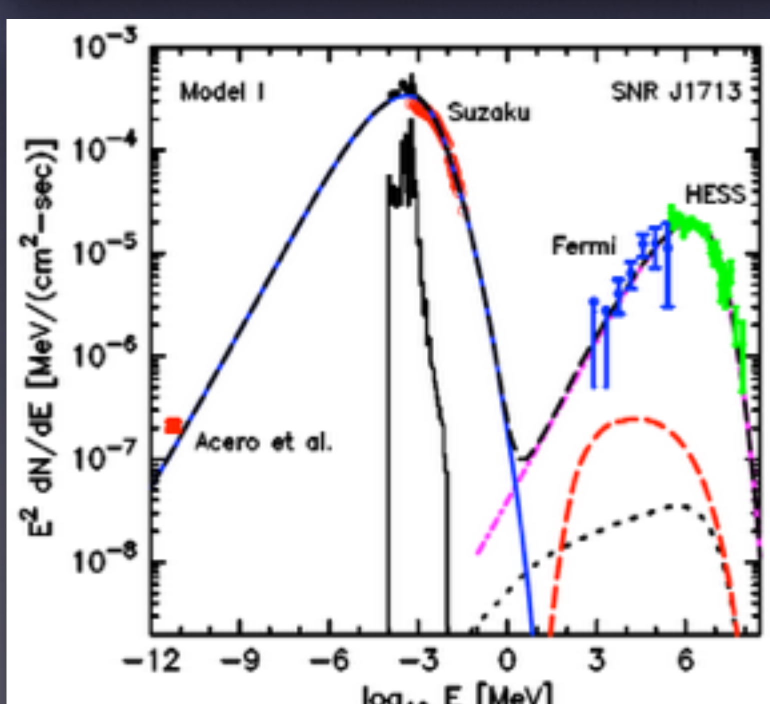


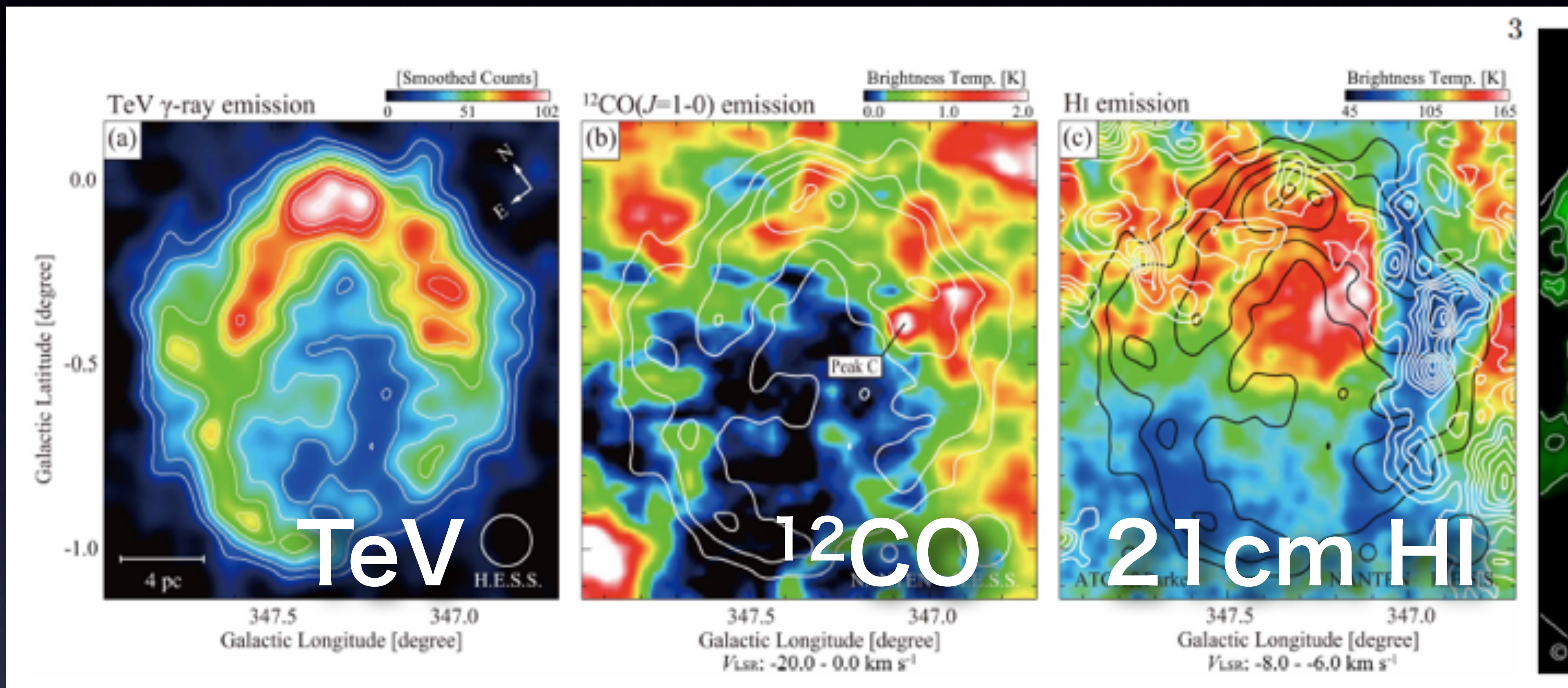
HL+ 2012

Non-detected thermal X-ray supports leptonic origin

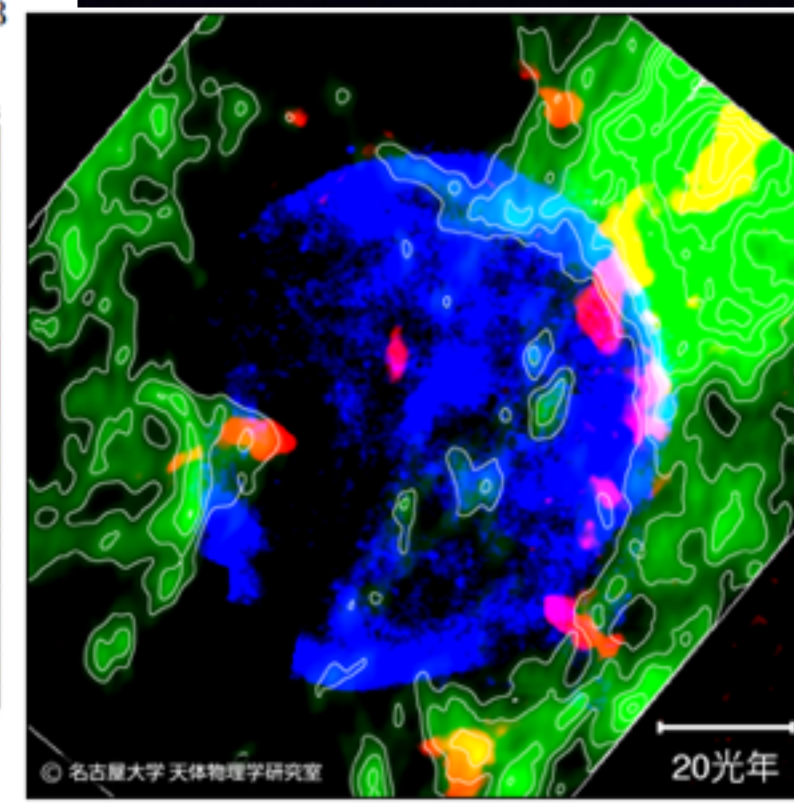
…but!

Gas maps imply shock-cloud interaction

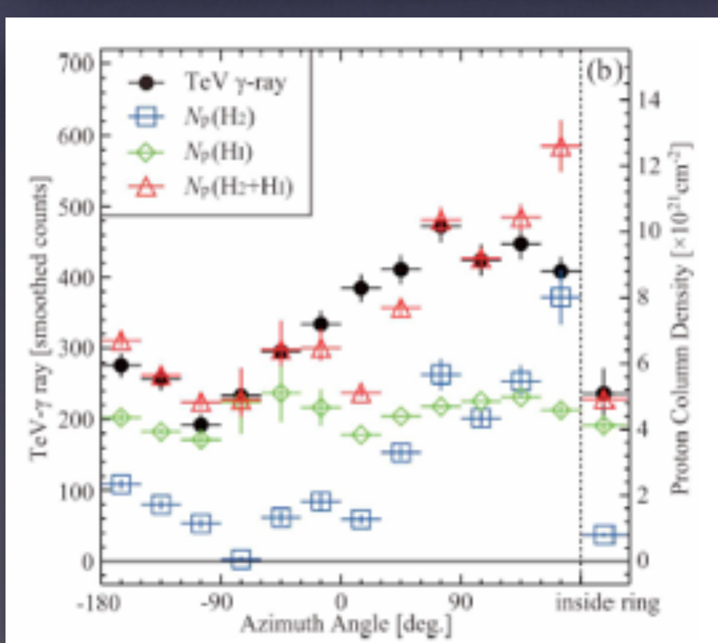
SNR RX J1713



Vela Jr.



Y. Fukui+ 2012



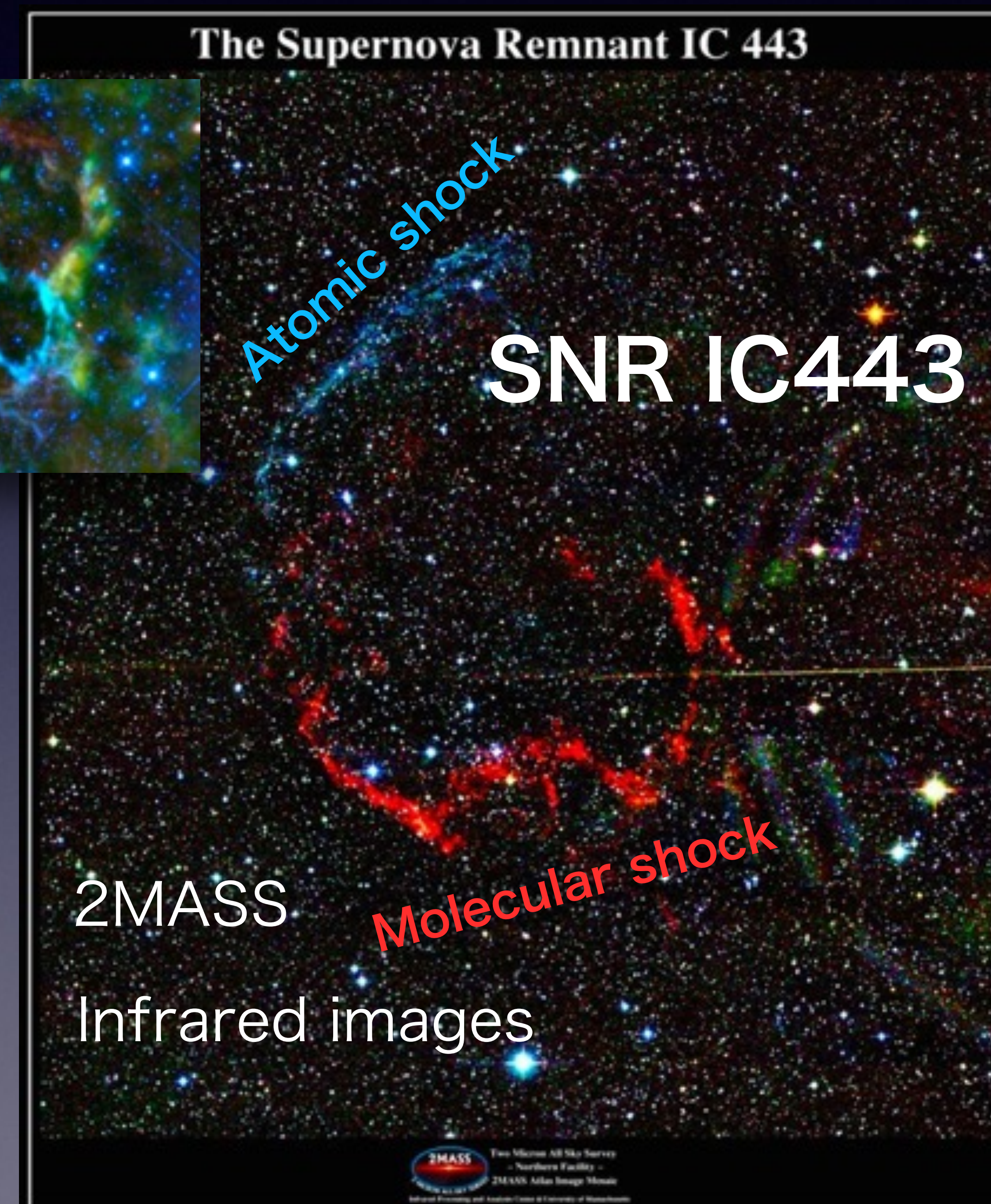
- Clumpy clouds around shock
- CR ions should interact with clouds
- Spatial correlation of γ-ray and gas
- Hadronic (π^0 decay) contribution to γ-rays?
- Probably not pure leptonic origin of γ-rays
- Hadronic + leptonic: what proportion?

Evolved (older) SNRs

'Old-school' radiative shocks

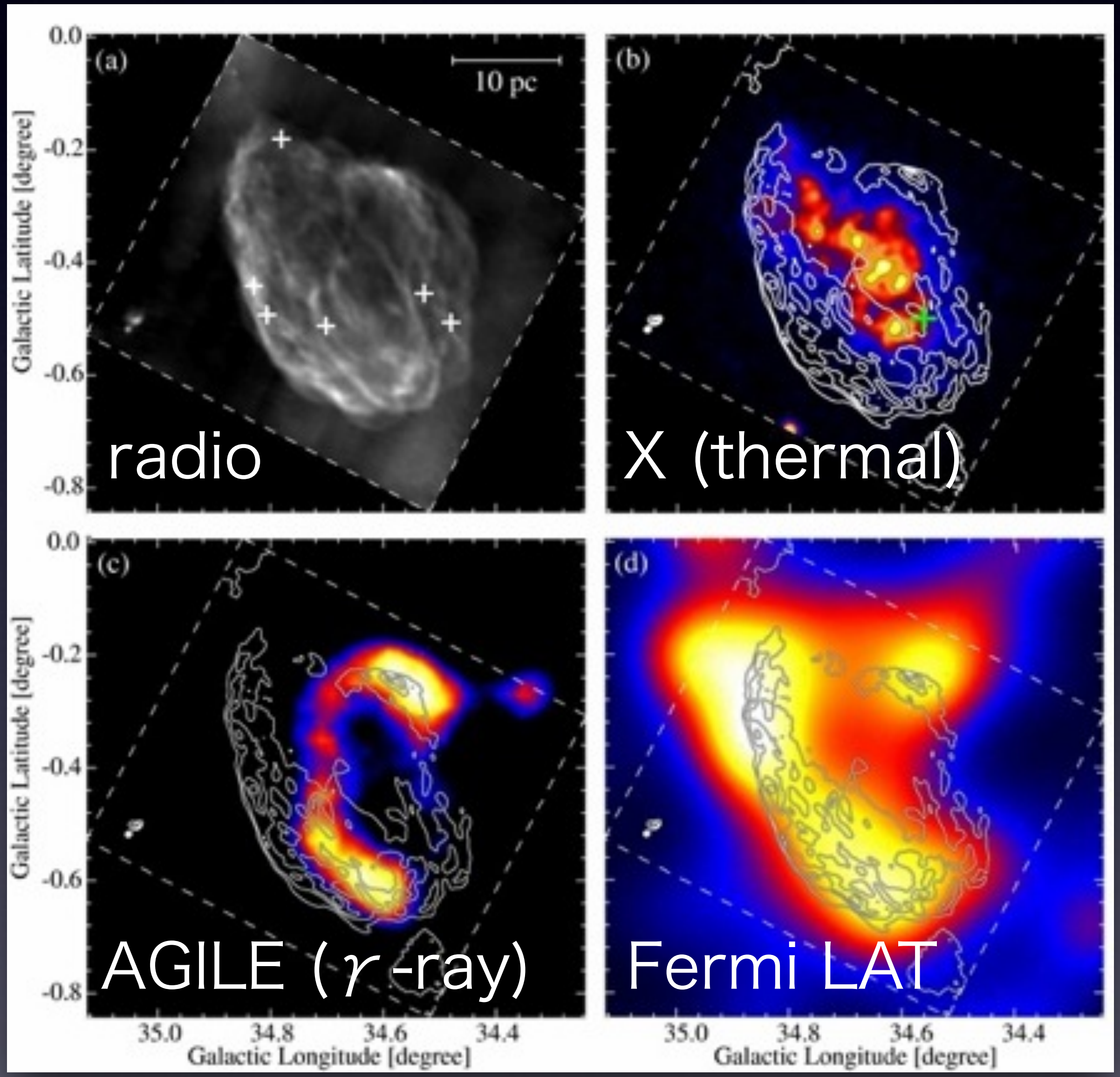
Radiative Shocks at Evolved SNRs

- **Evolved SNRs** **often interacting with clouds**
- Typical properties:
  - $v_{sk} > \sim 100$ km/s
  - $\langle n_0 \rangle \sim 100\text{-}1000\ \mathrm{cm}^{-3}$
  - T ~ a few 10^5 K behind shock, molecules dissociated and ionized, **fast radiative cooling**
  - **Photoionization precursor** by UV from downstream
  - Bright **optical/IR lines** from recombining/de-excitation of gas
  - Spots of **OH masers** from dense clumps behind shocks transverse to line-of-sight



Detection of Bright Radio and γ-rays

- Bright non-thermal emission there (despite evolution and slow shock velocities)
- Fermi LAT found GeV-bright SNRs inside our Galaxy (often 'mixed morphology' mid-ages)
- Luminous GeV γ-ray emission
  If all from π^0 origin —>
  $\langle n_{gas} W_{CR} \rangle \sim$ a few 10^{50} to 10^{52} erg/cm^{-3}
  Lots of CR protons!?
- Bright non-thermal radio emission
  —> $\langle B \rangle \gg \mu$G (i.e. >> ISM level)

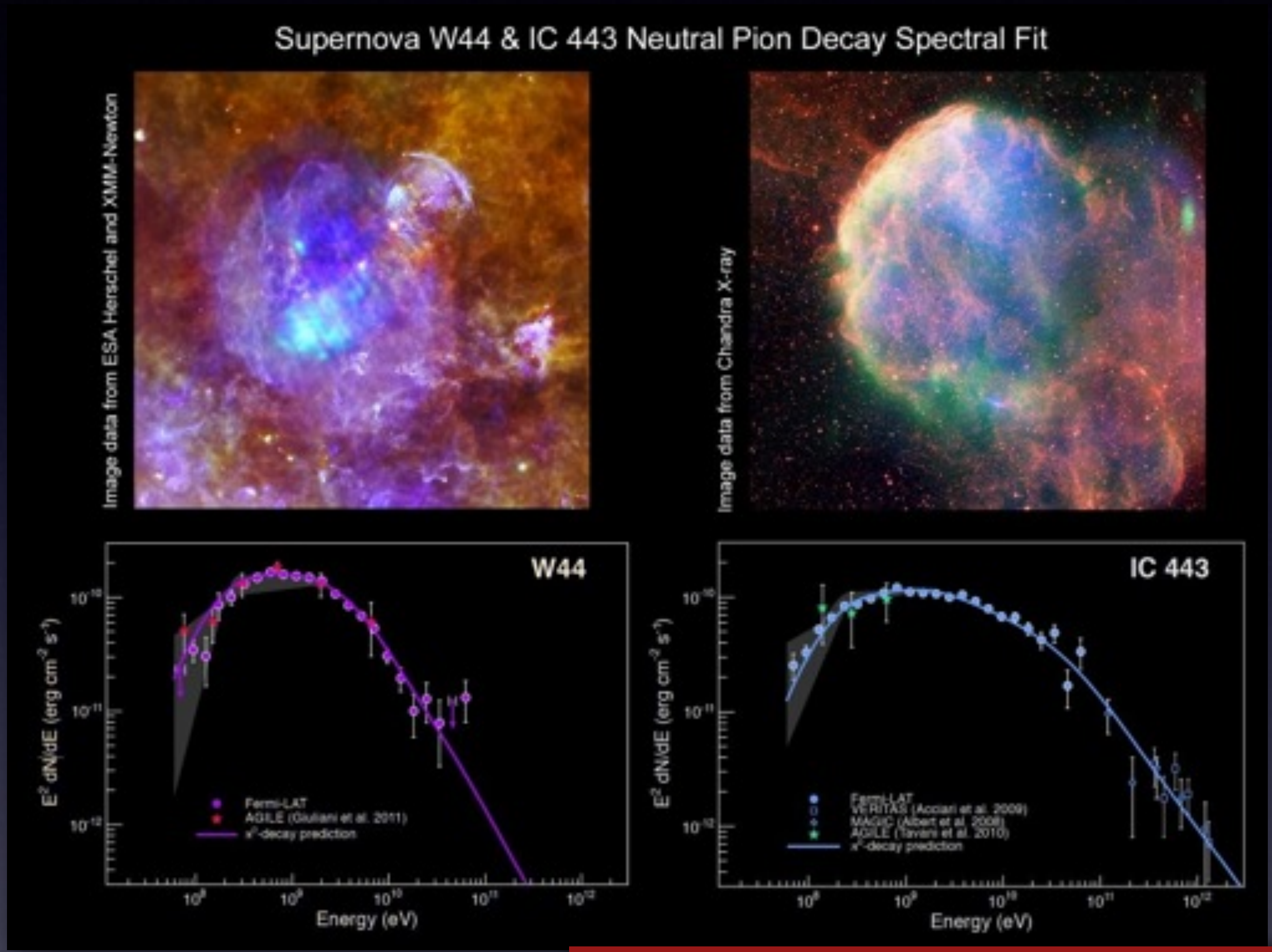


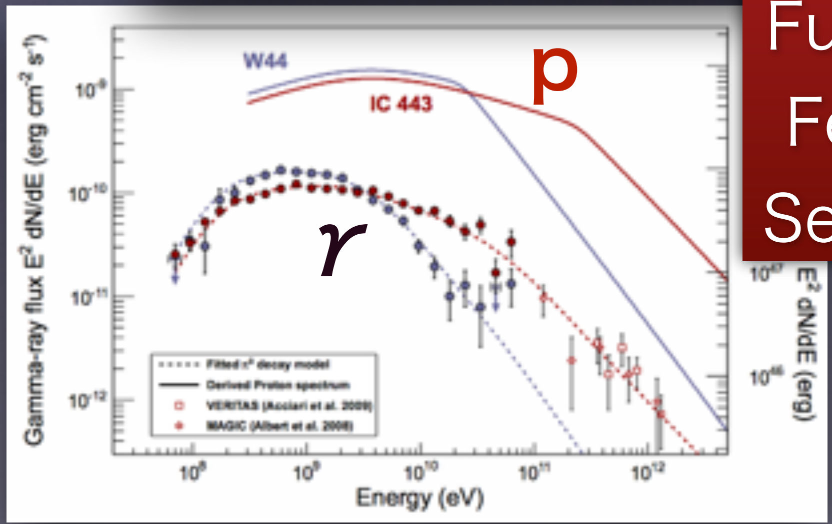
SNR W44, Yoshiike+ 2013

See e.g. review by Slane, Ellison+ SSR 2014

Characteristic γ-ray spectra

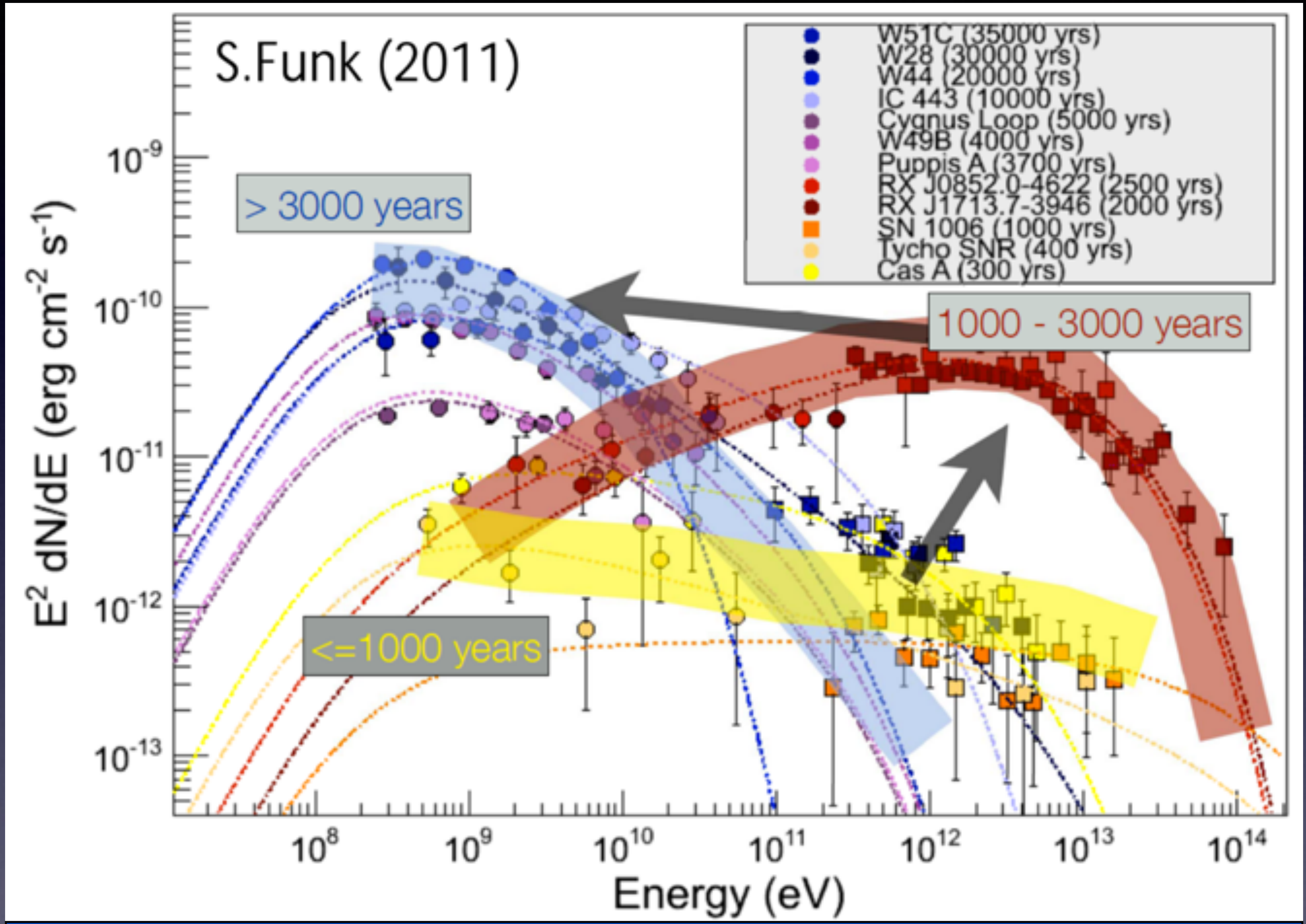
- Fermi LAT detects cutoff around 250 MeV —> π^0 origin of γ
- Mysteries remain:
  - Origin of **copious energetic proton**, DSA injection and efficiency
  - ‘Weird’ CR spectra with PL break
  - Bright radio shell (despite age)
  - Stage of evolution?
    Connection with young (ejecta-dominated and TeV-bright) SNRs





Funk, Tanaka, Uchiyama
Fermi LAT, Science ’13
See Uchiyama-san’s talk

γ-rays from young to old



- Different progenitors and environments
- An evolution picture requires systematic modeling of each type of SNR

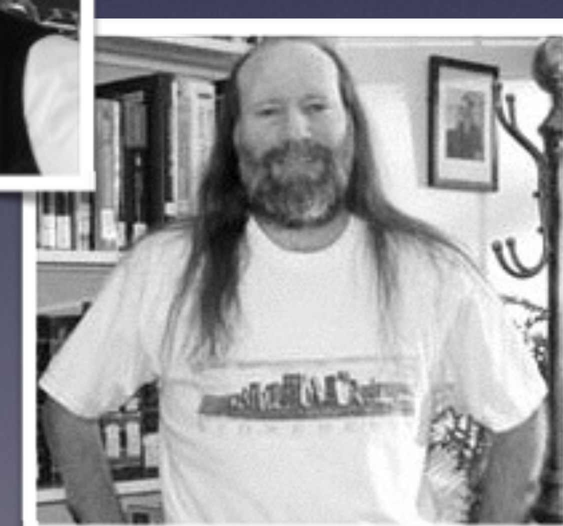
Castro, HL+ 2014 (in prep)

Numerical Modeling of Broadband Emission of SNRs

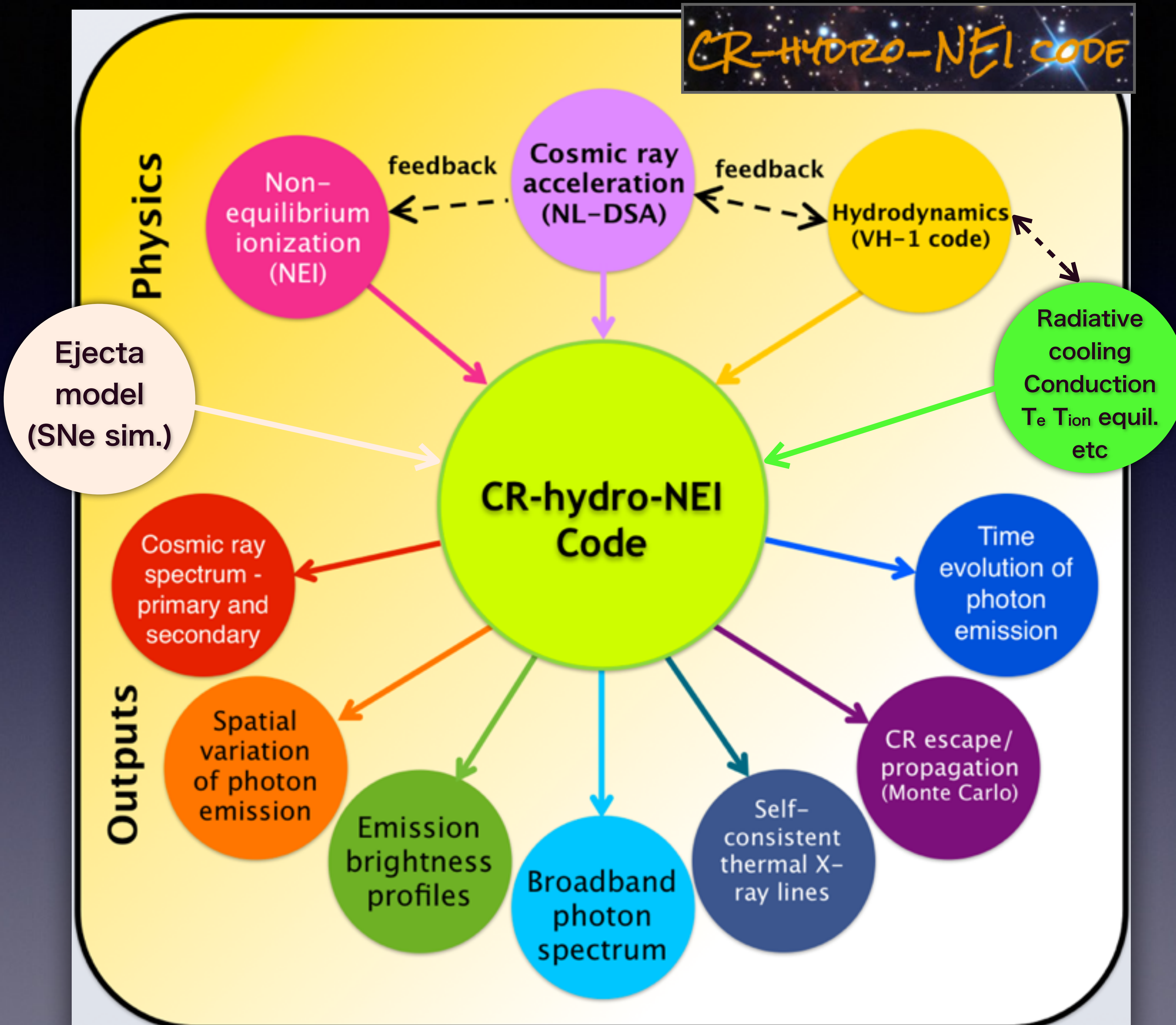
Shigehiro Nagataki

Don Ellison

Dan Patnaude

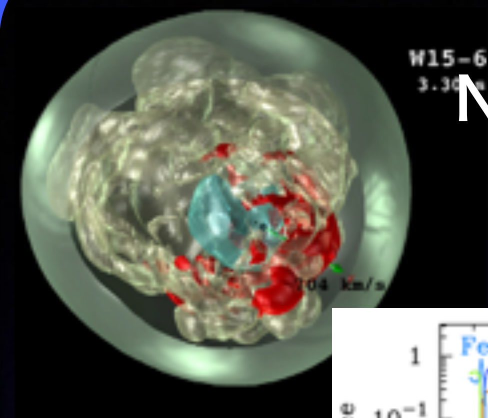


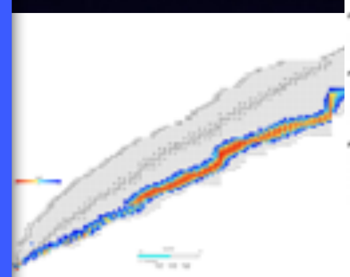
Pat Slane

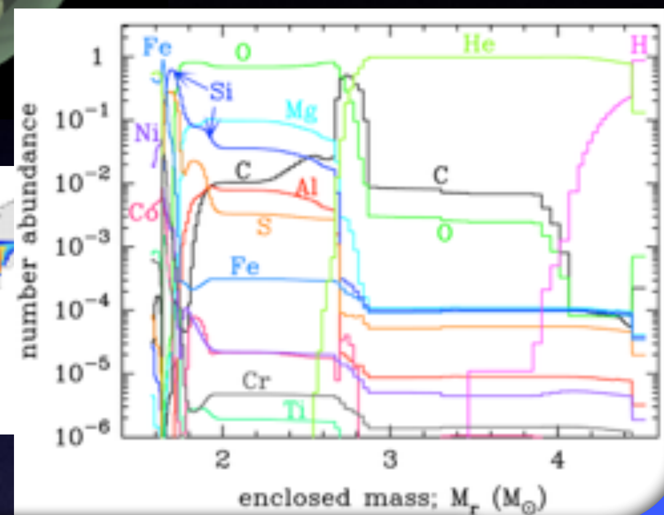

CR-HYDRO-NEI CODE
Physics
Outputs
Non-equilibrium ionization (NEI)
feedback
Cosmic ray acceleration (NL-DSA)
feedback
Hydrodynamics (VH-1 code)
Radiative cooling Conduction Te Tion equil. etc
Ejecta model (SNe sim.)
CR-hydro-NEI Code
Cosmic ray spectrum - primary and secondary
Time evolution of photon emission
Spatial variation of photon emission
Emission brightness profiles
Broadband photon spectrum
Self-consistent thermal X-ray lines
CR escape/ propagation (Monte Carlo)

Iterative Work Flow

Ejecta model
Nucleosynthesis
Element mixing
Mass loss

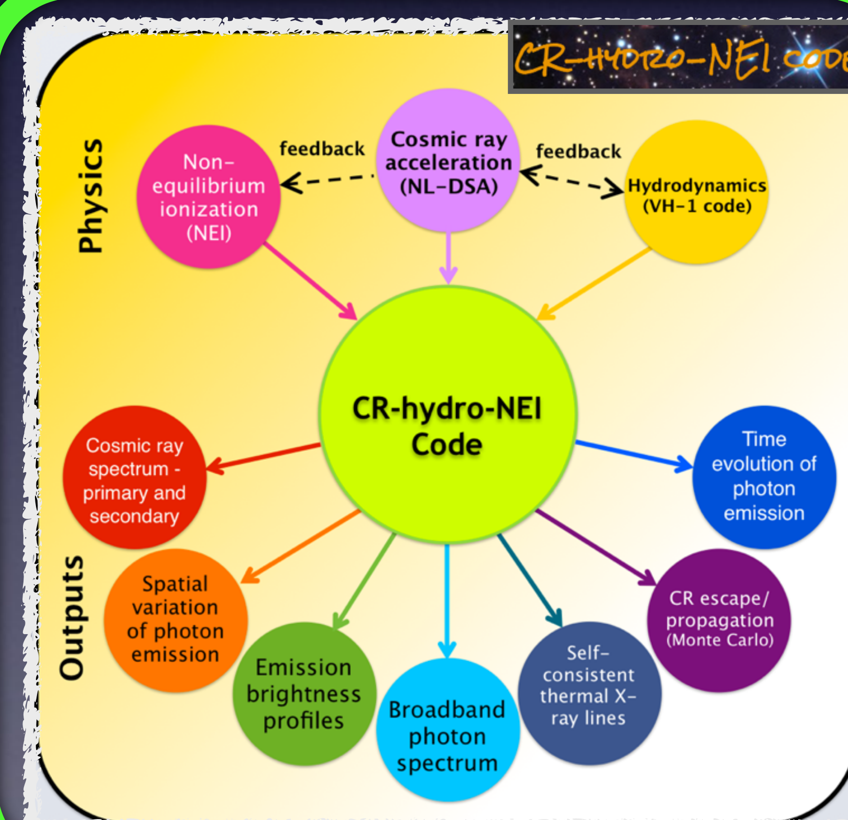




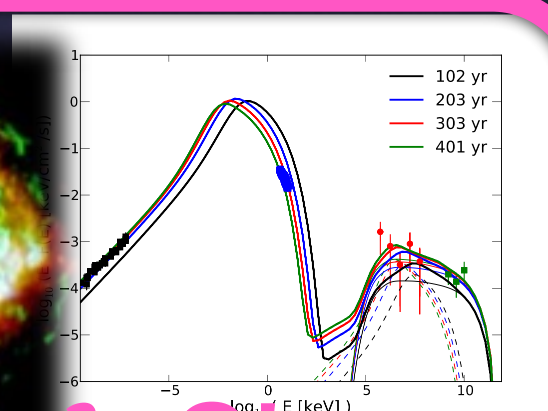


Initial conditions

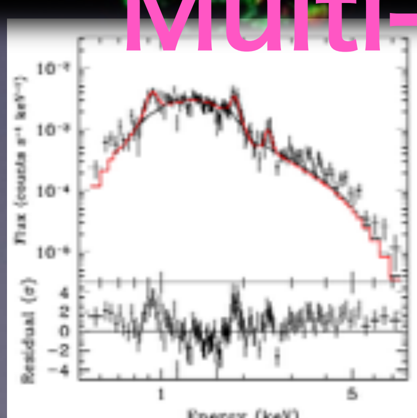
CR-hydro Model

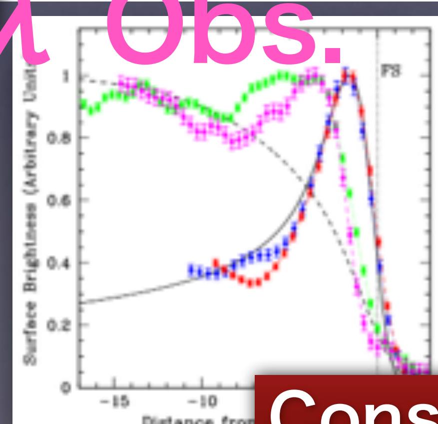


Dynamics, NLDSA,
B-field, ionization, radiation



Multi-λ Obs.

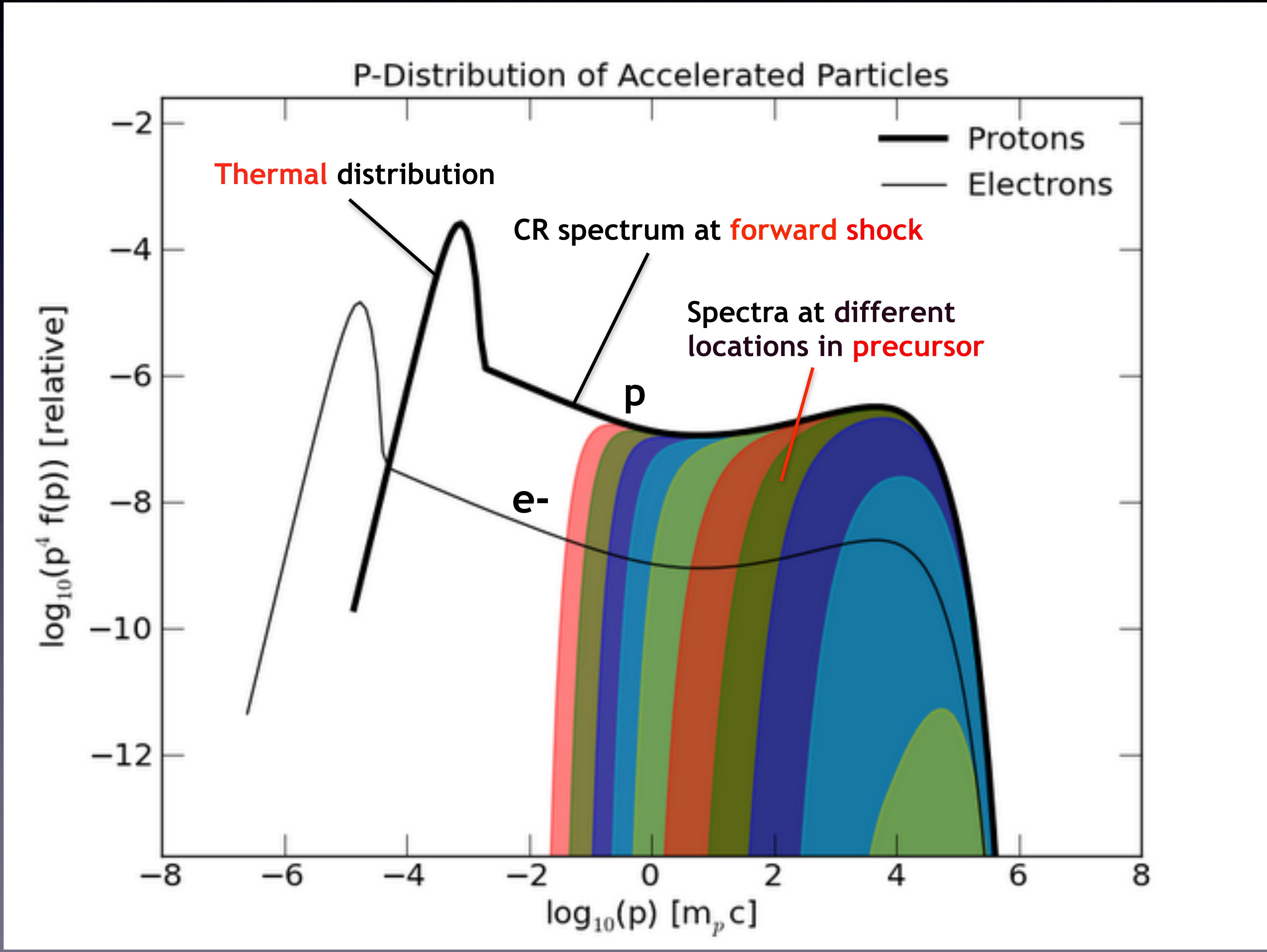




Constraints!

CR spectra from non-linear DSA

HL, Ellison & Nagataki (2012)



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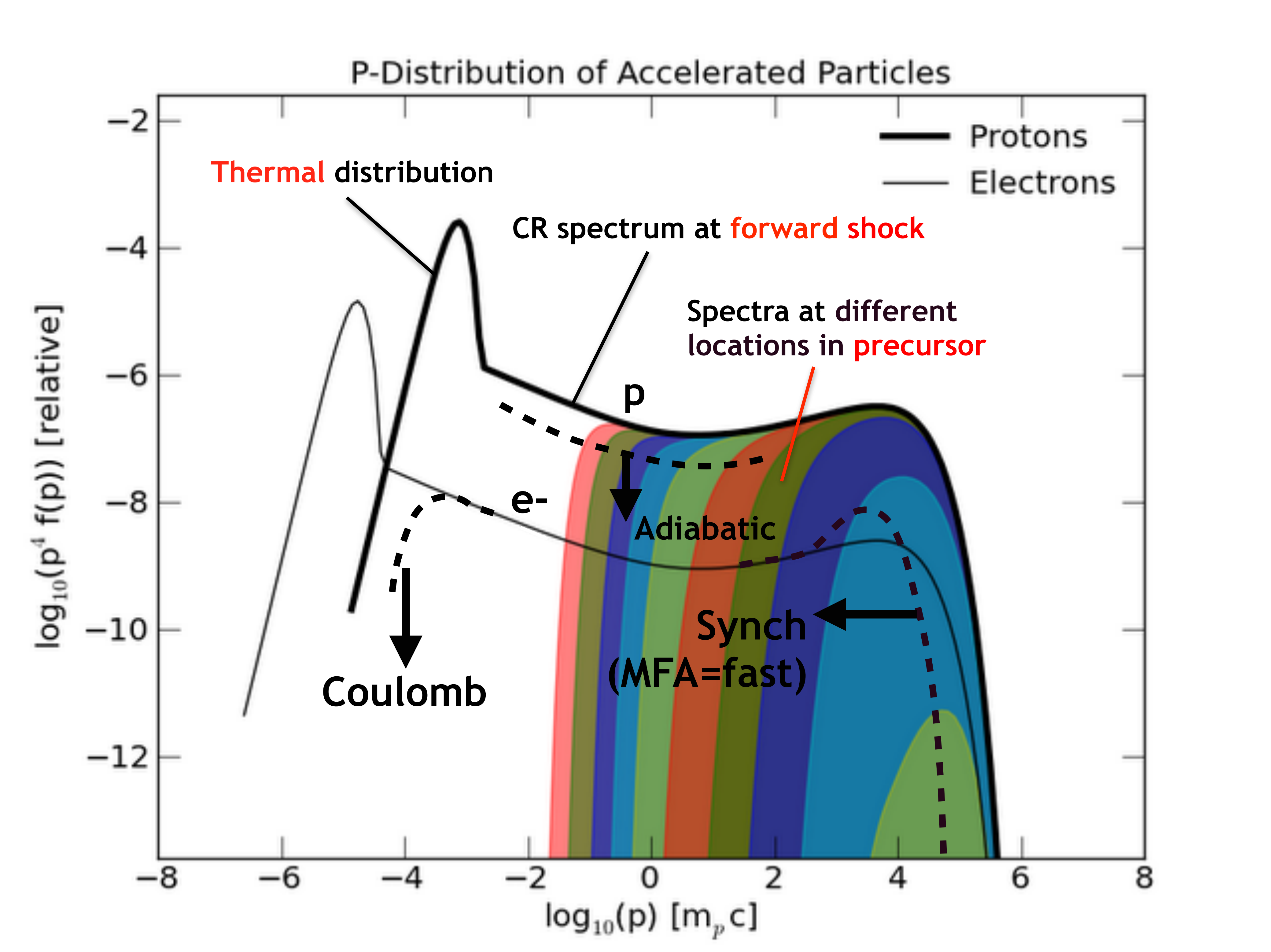

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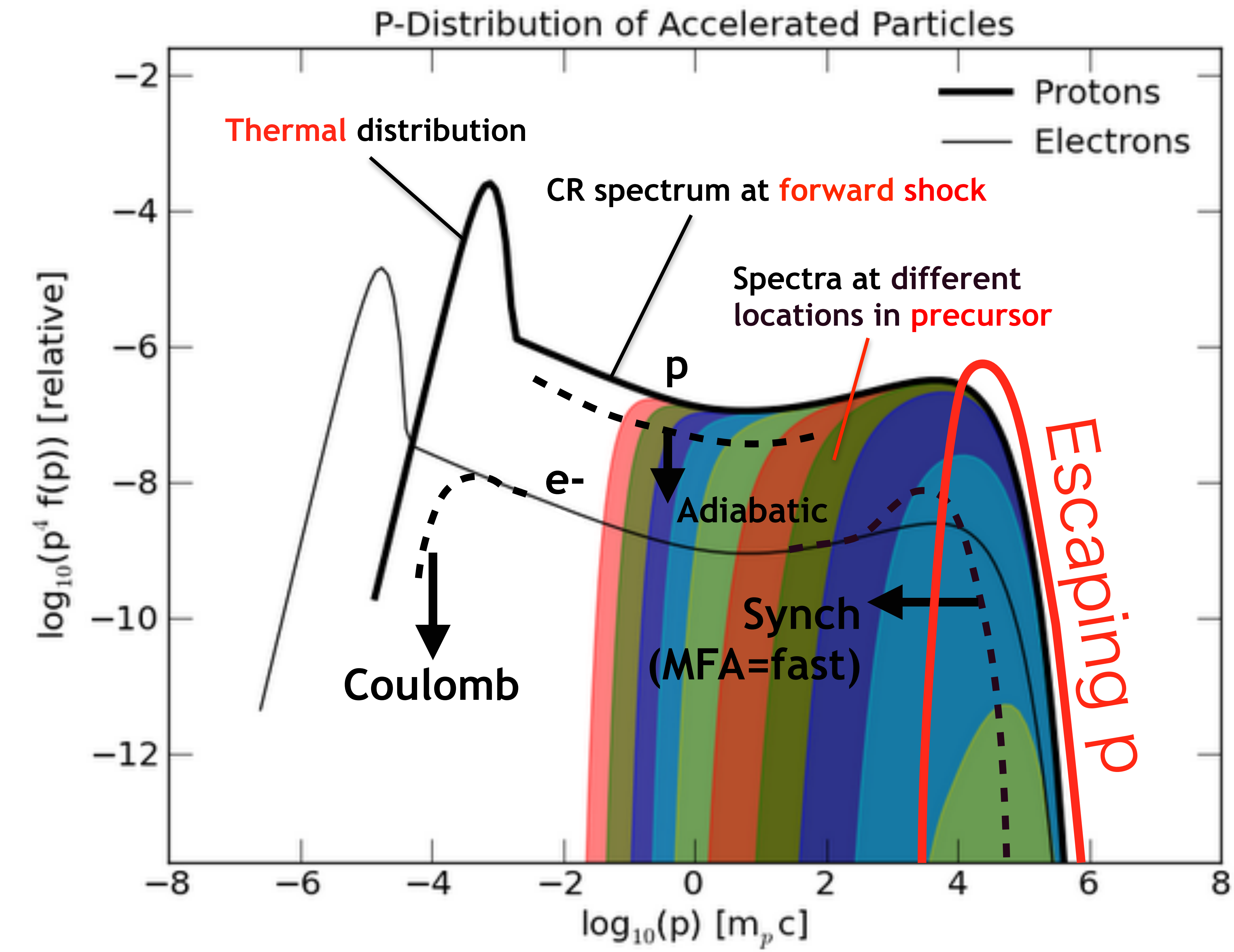

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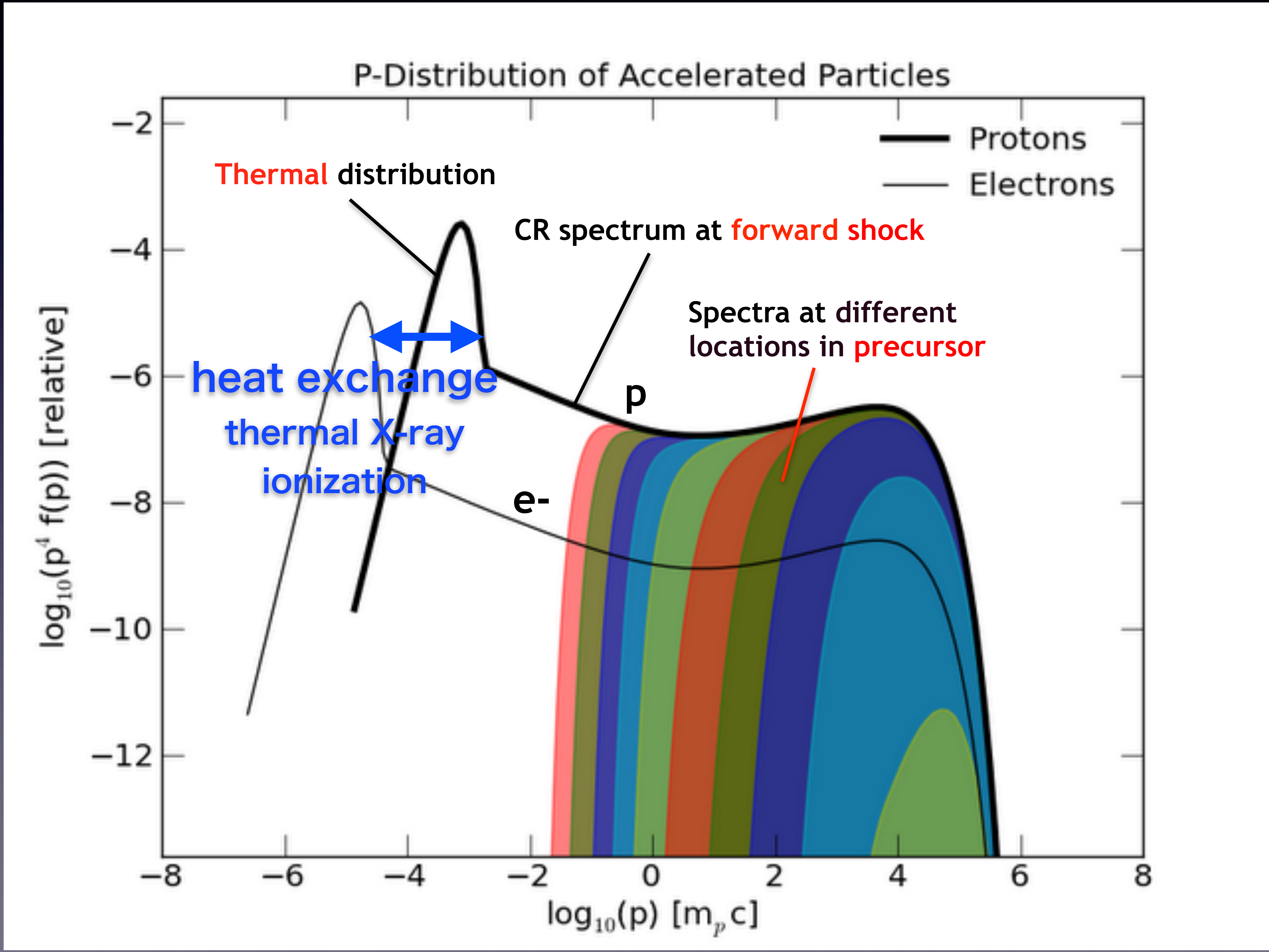

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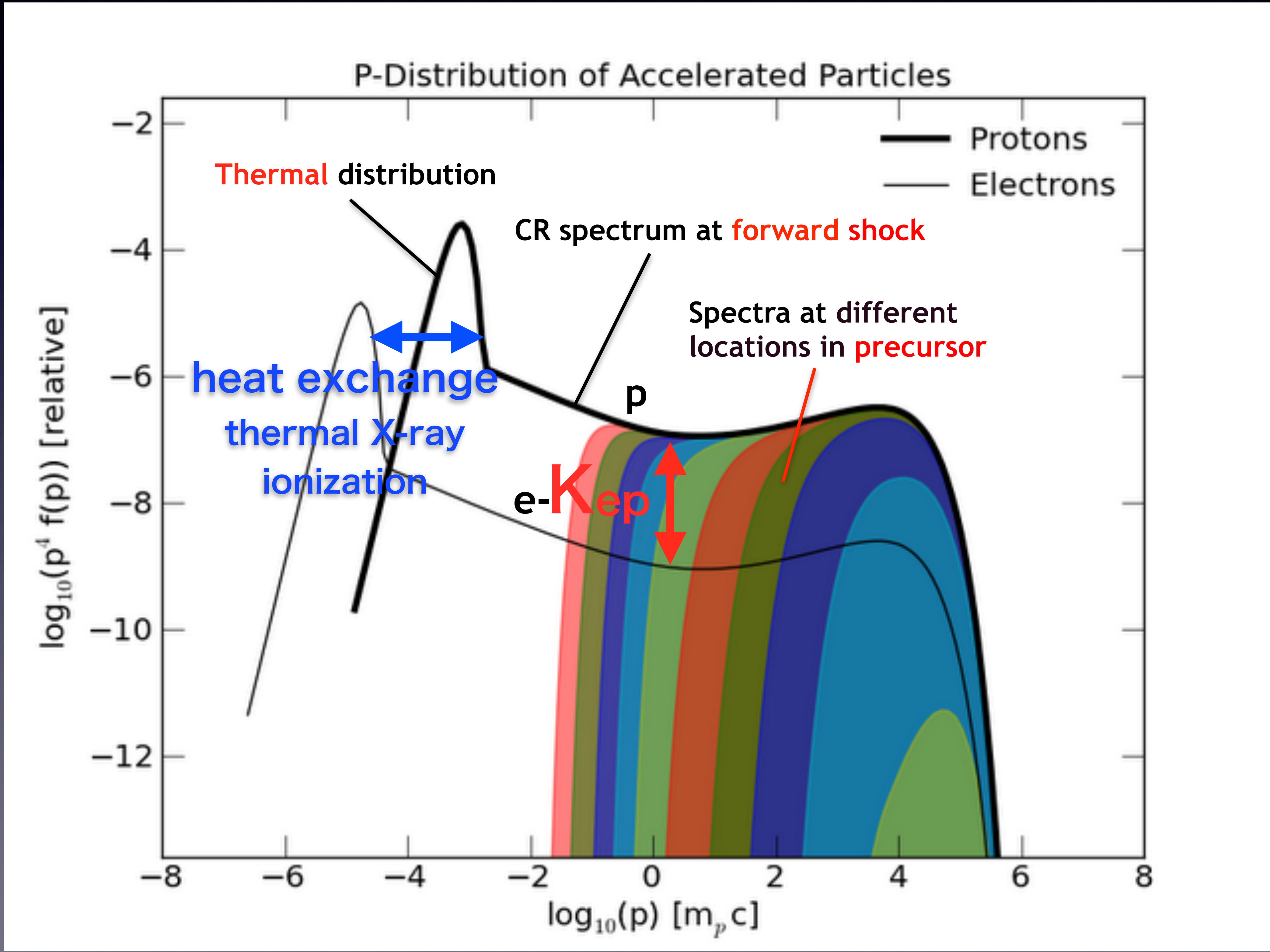

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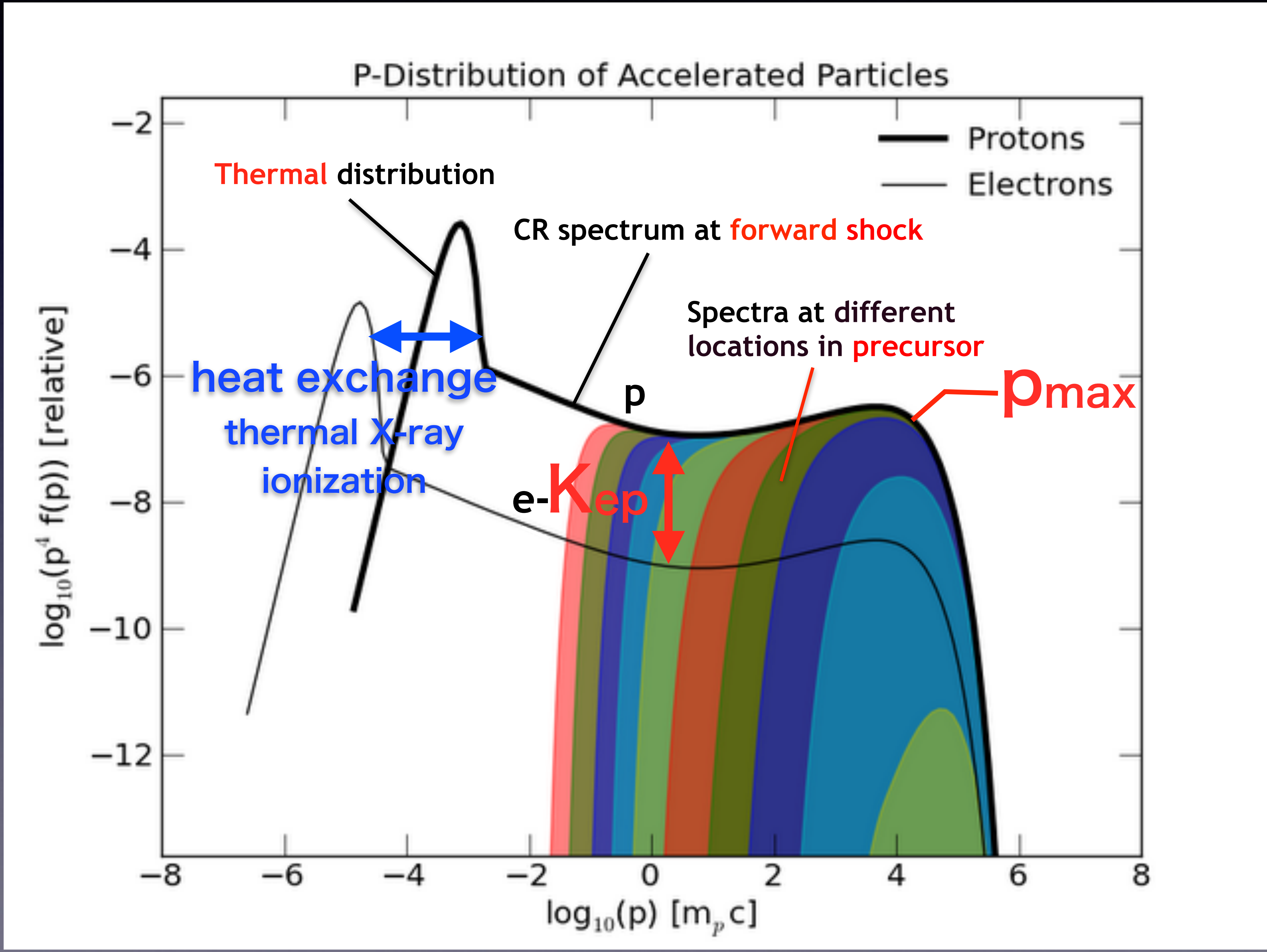

Broadband Model of Young SNRs

e.g. Slane, **HL+** (2014) **Tycho's SNR** (440 yr old)

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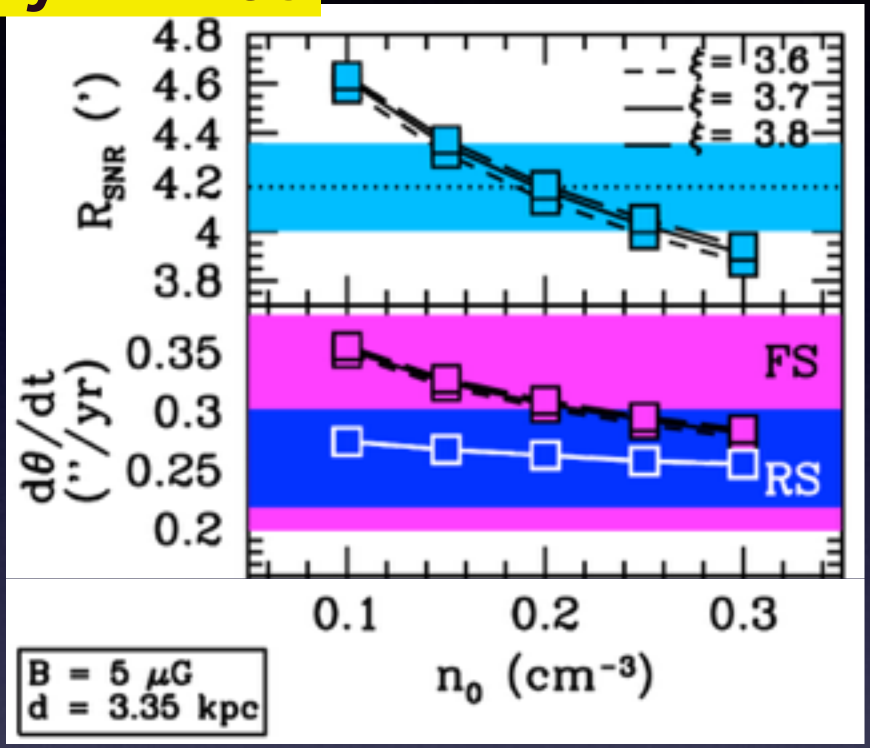

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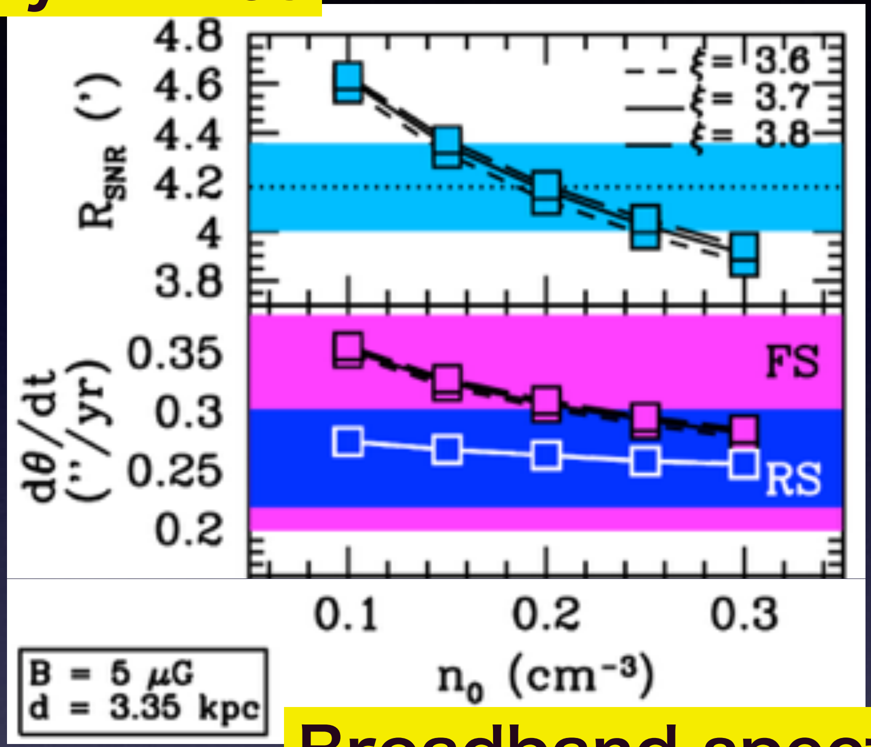
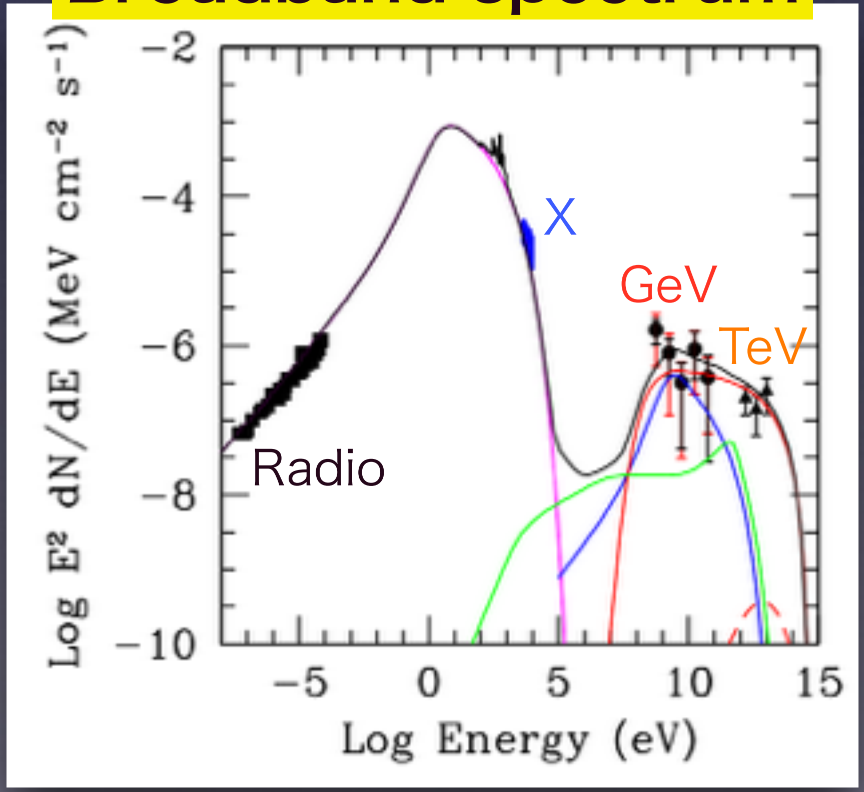


Broadband spectrum



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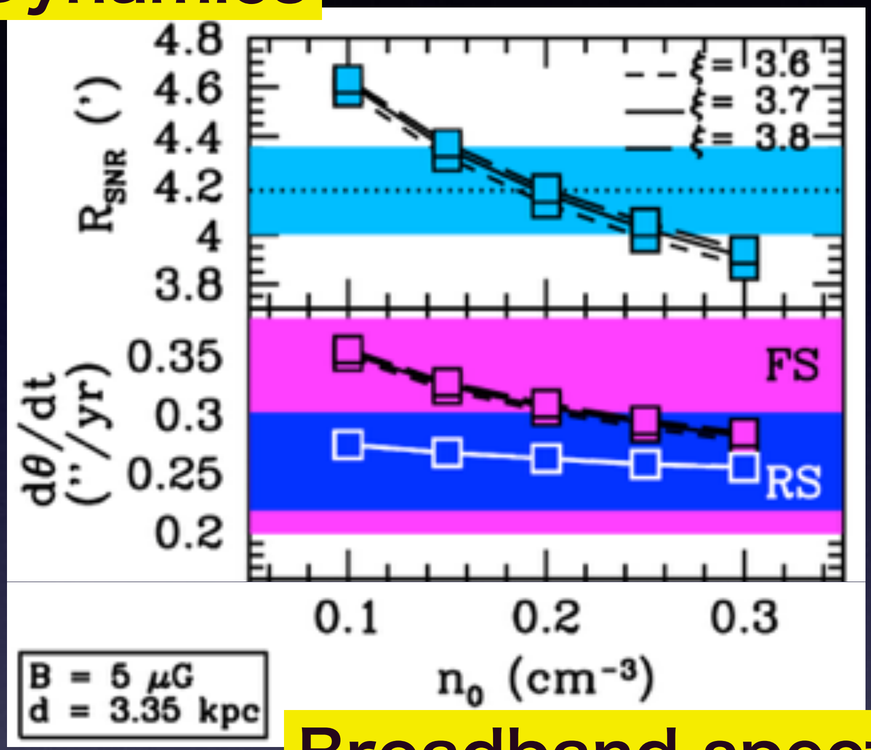

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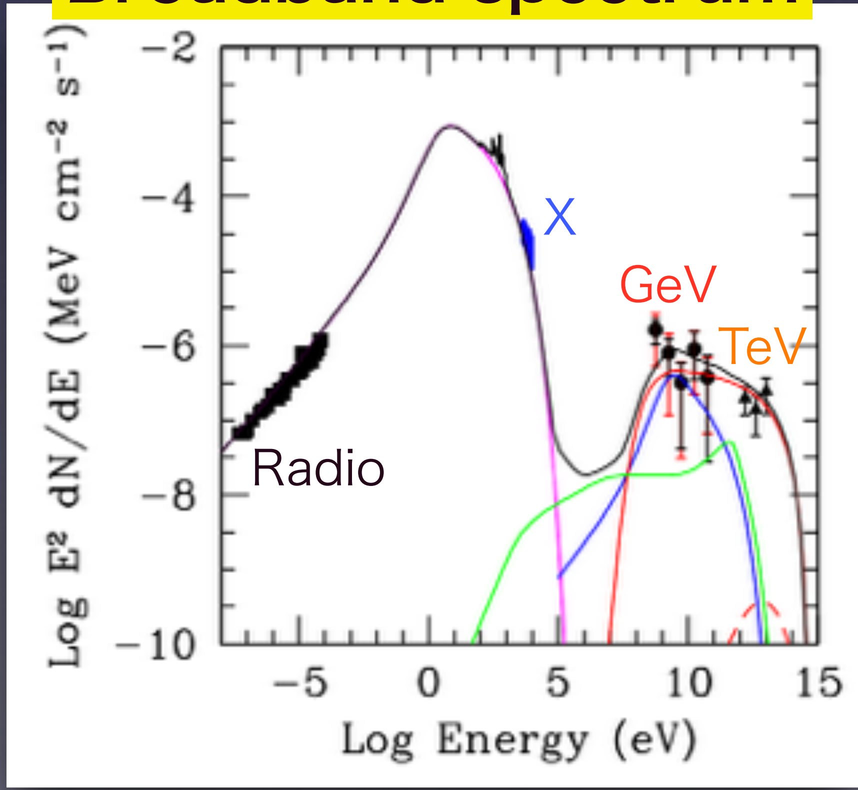
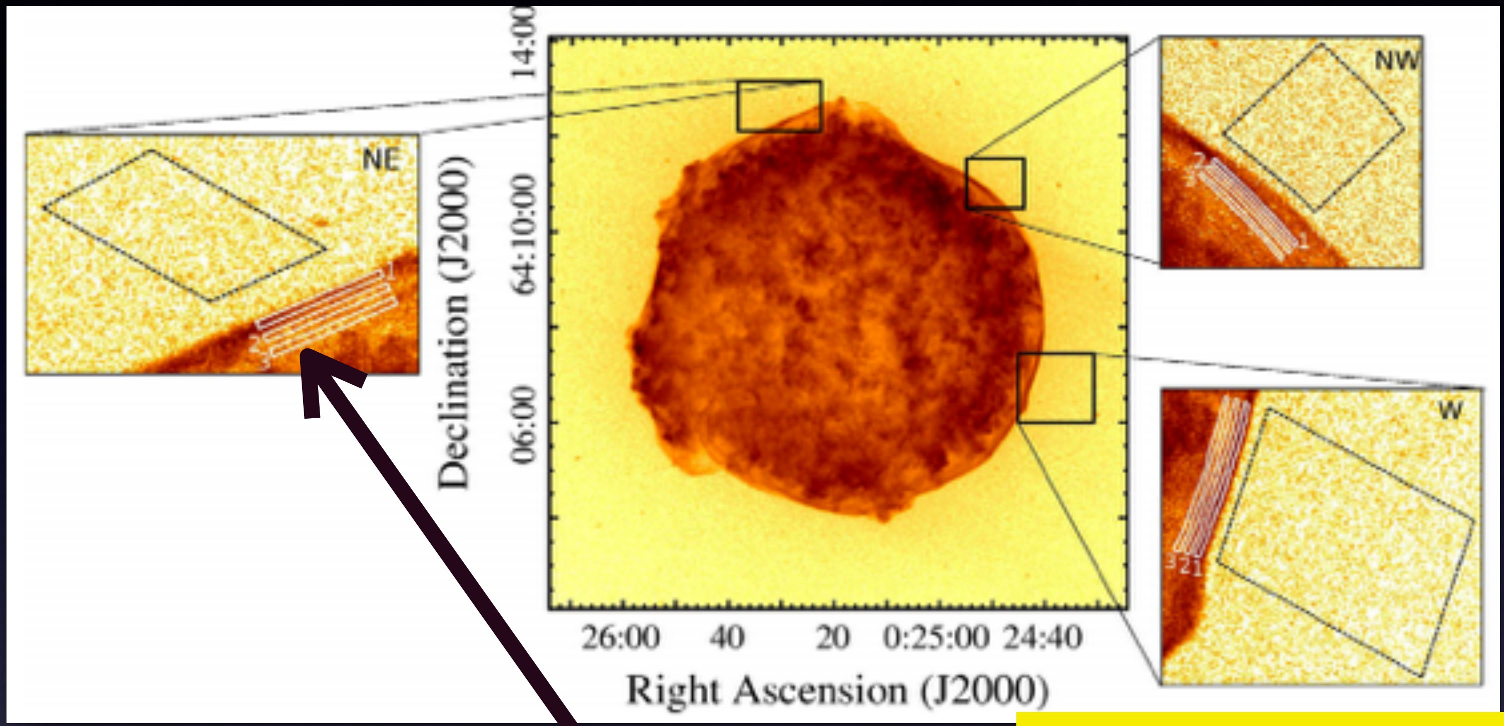
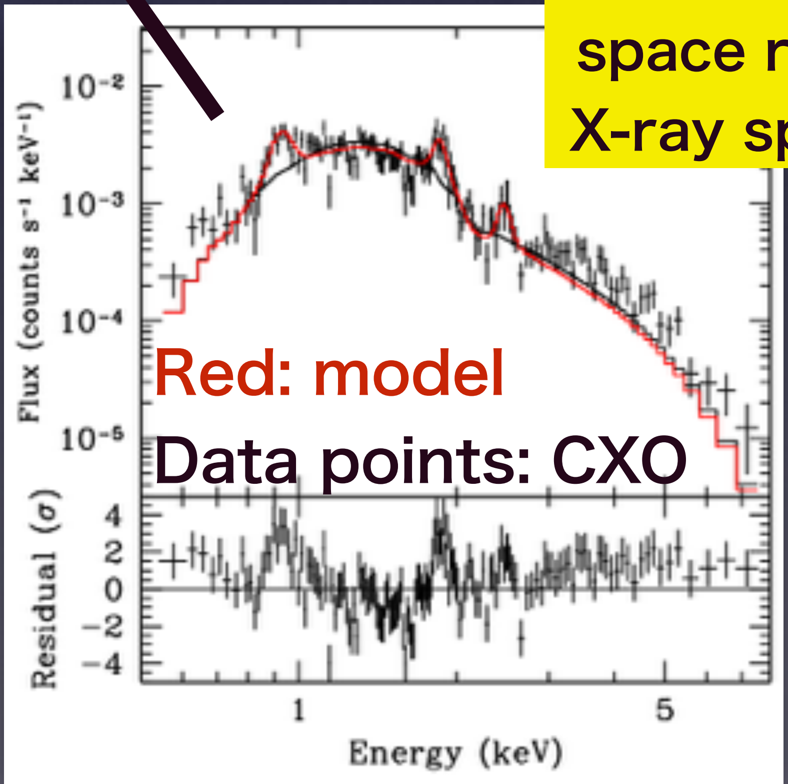




Chandra space resolved X-ray spectrum



Broadband Model of Young SNRs

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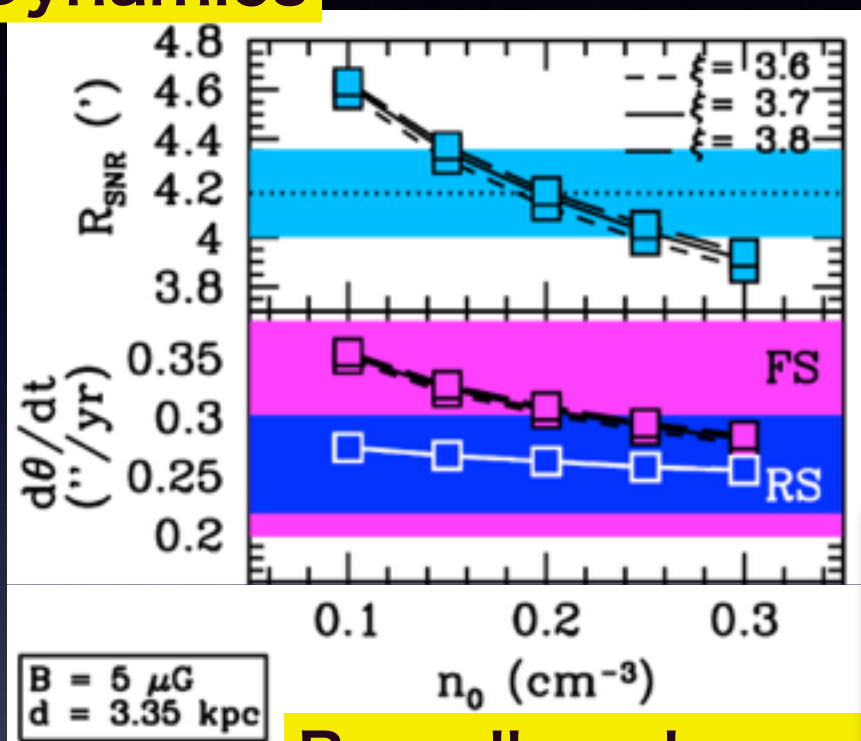
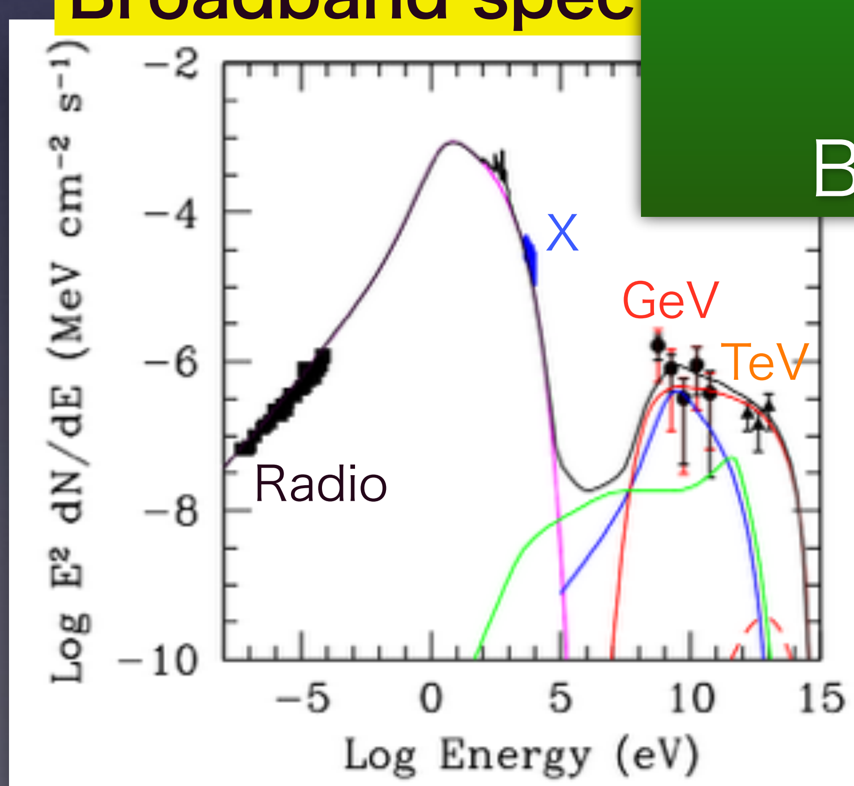
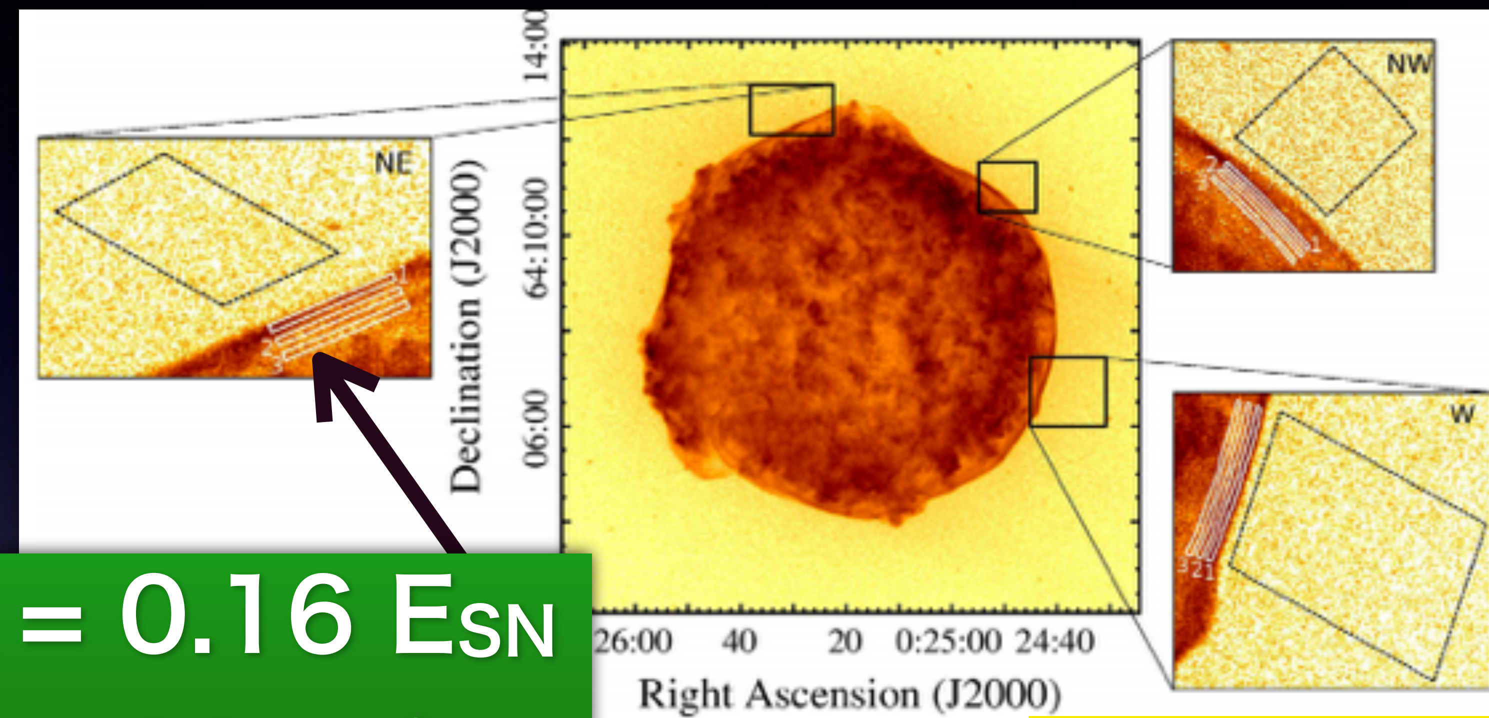
Dynamics



Broadband spec



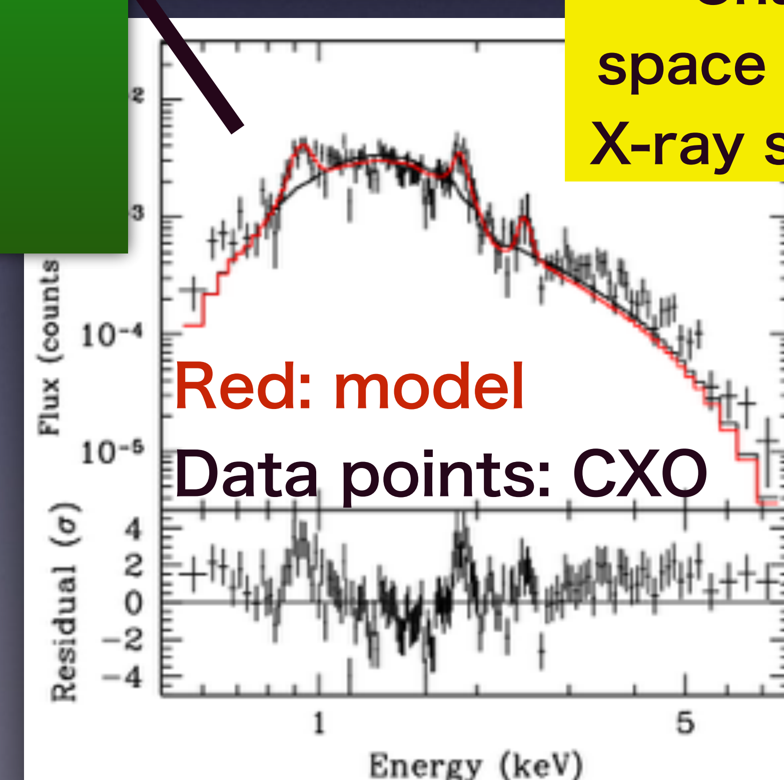


$E_{CR} = 0.16\ E_{SN}$

$n_0 = 0.3\ cm^{-3}$

$B_0 = 5\ \mu G$

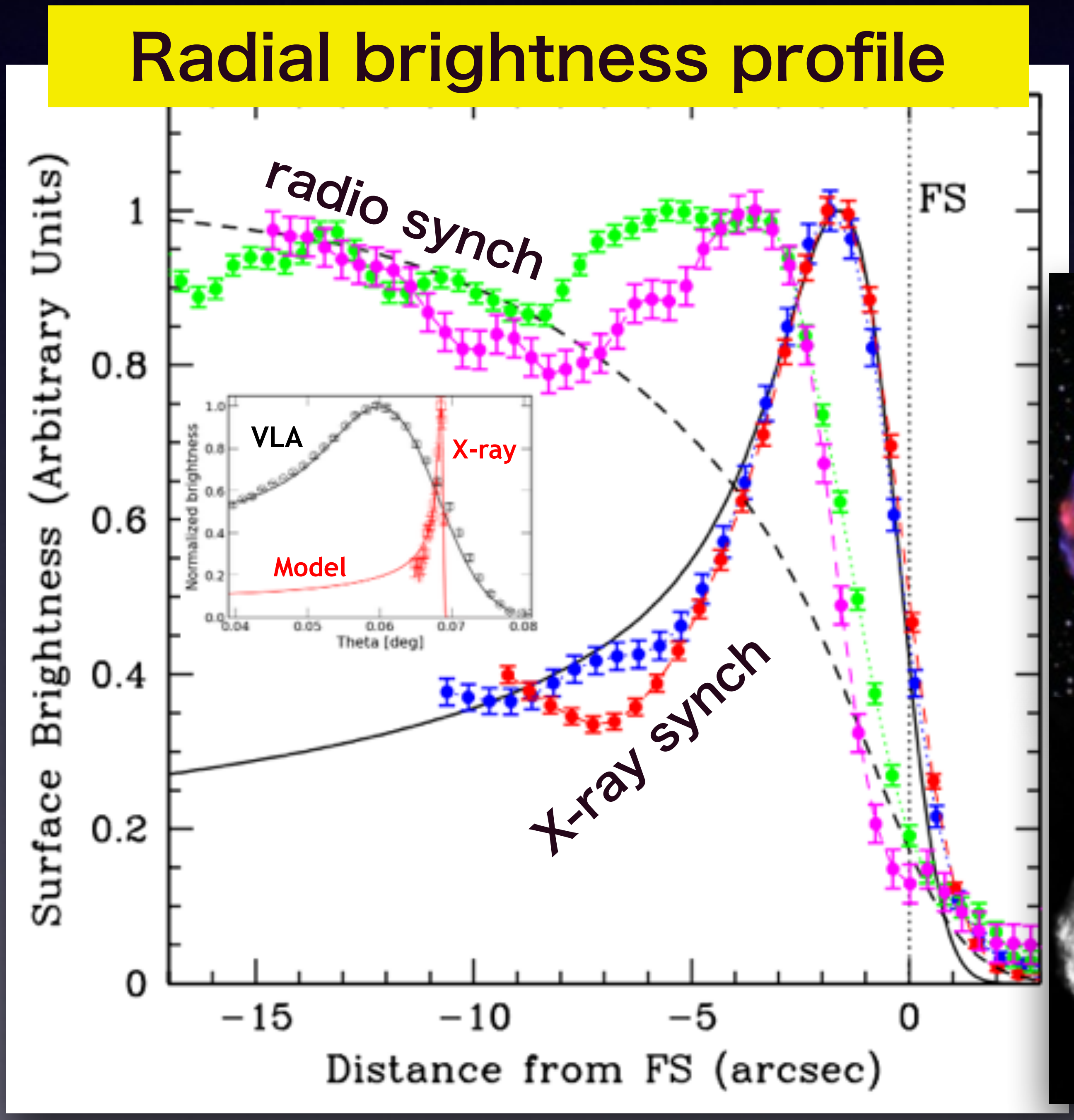
$B_2 = 180\ \mu G$

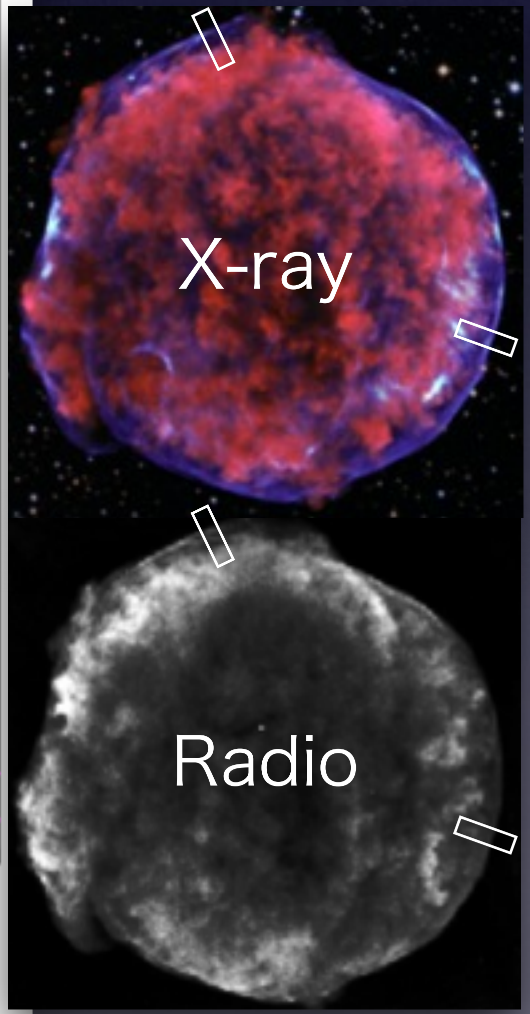


Chandra space resolved X-ray spectrum

Broadband Model of Young SNRs

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





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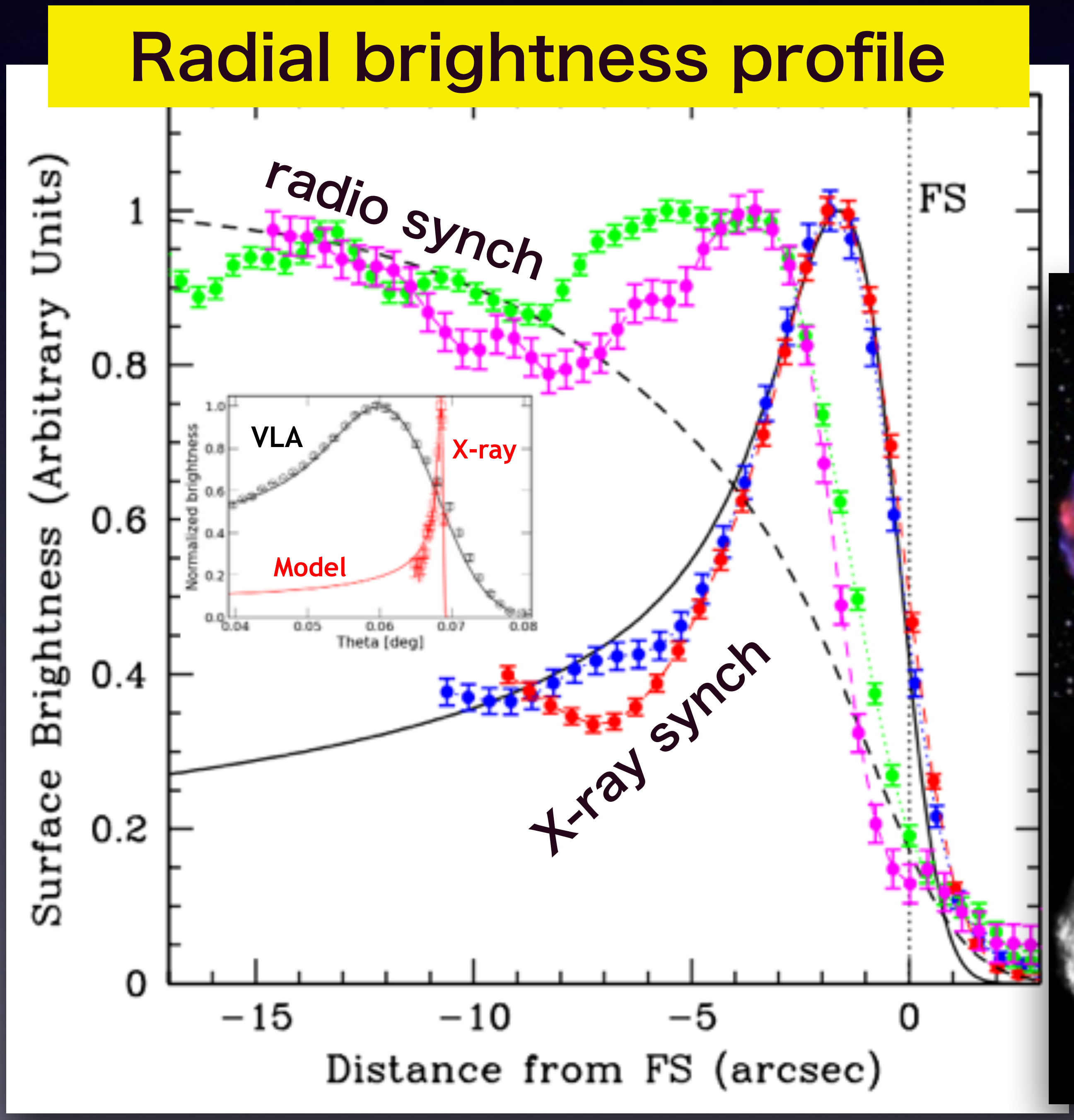
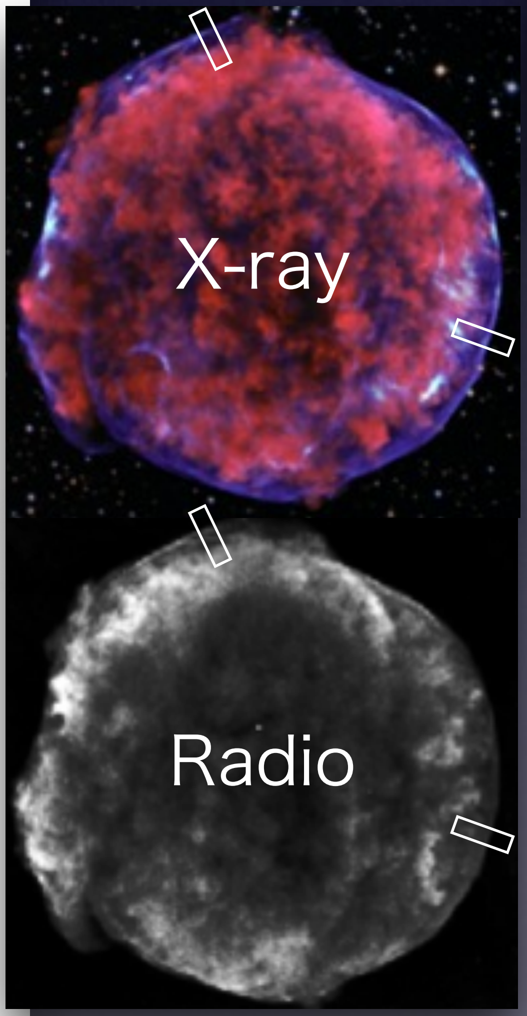
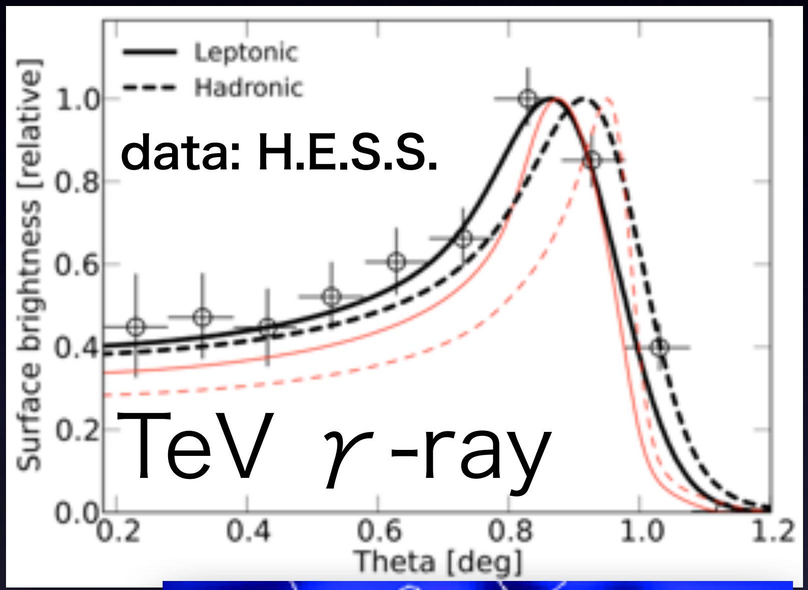
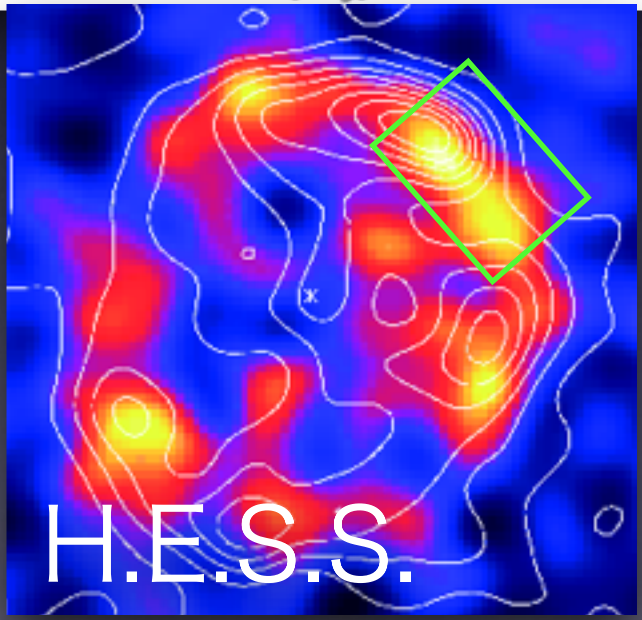




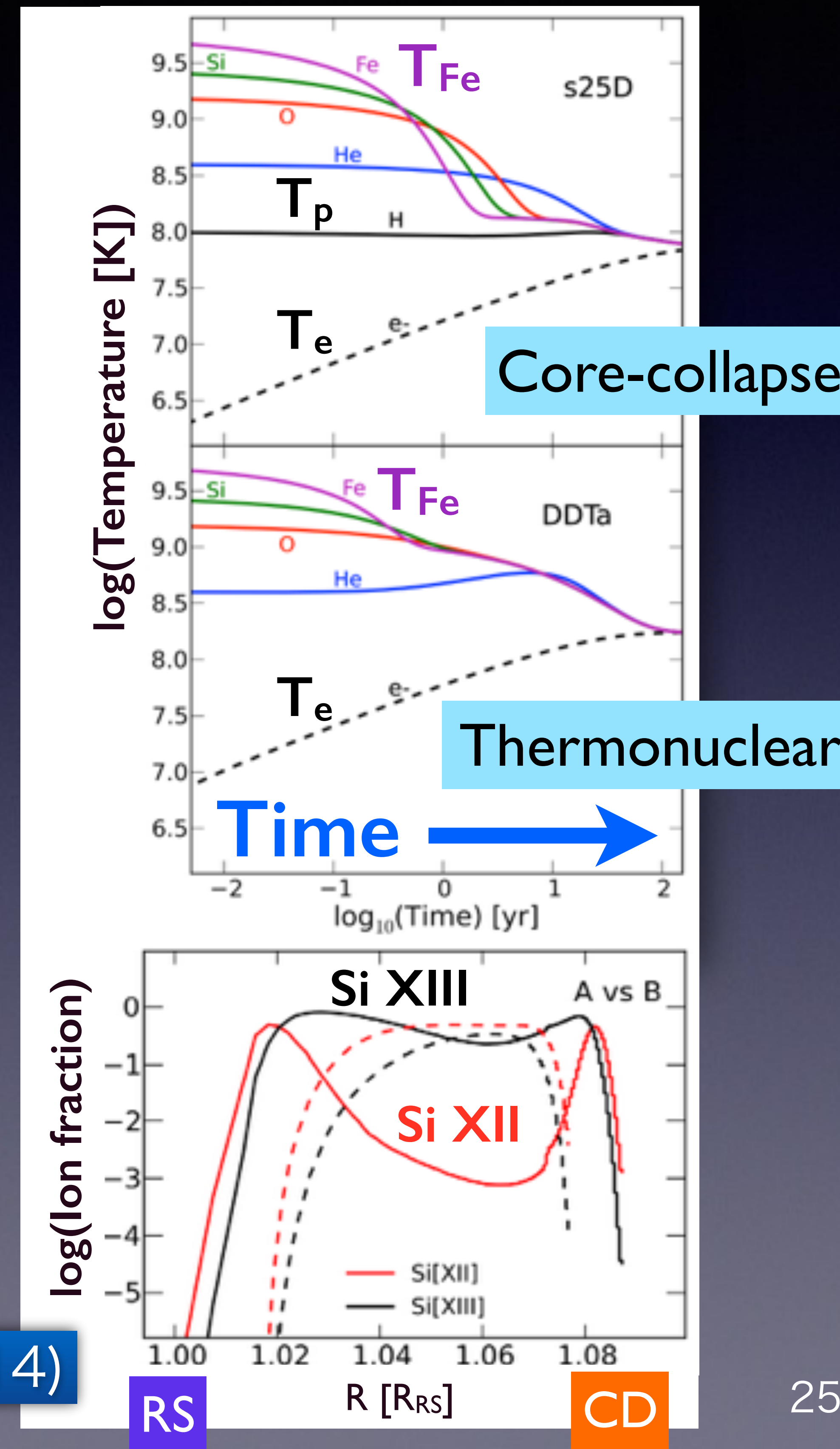
HL+ (2013) on Vela Jr.





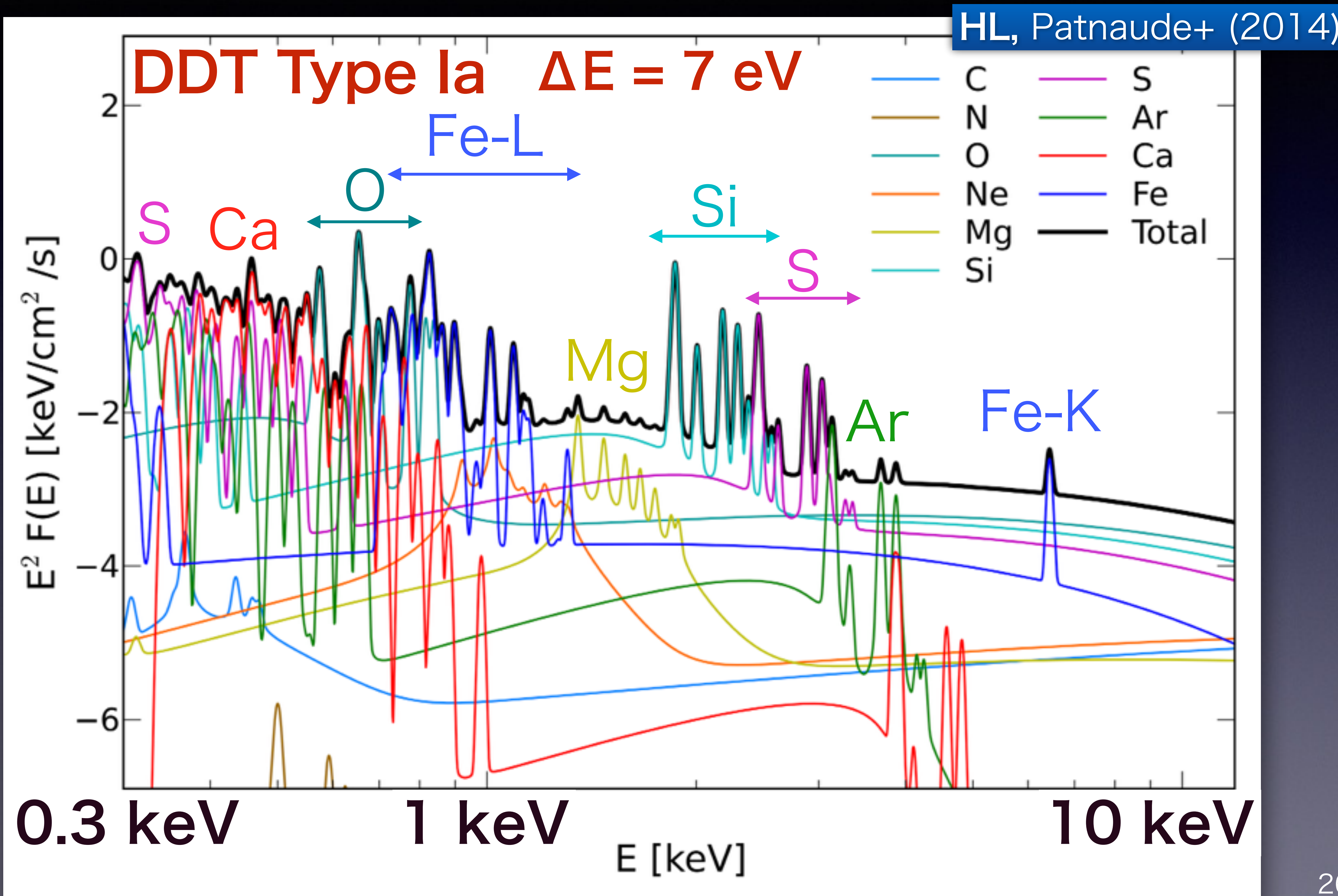
How about the **thermal X-rays**

- **Thermal X-rays** of young SNRs tell us many things
  - Ejecta and CSM chemical composition
  - Temperatures (ions, e-)
  - Ionization states
  - Even CR acceleration history
- We follow non-equilibrium ionization and temperature evolution of 140 ion species in ejecta/CSM
- We then synthesize detailed thermal X-ray spectrum, together with non-thermal



HL, Patnaude+ (2014)

Synthesis of detailed X-ray spectra



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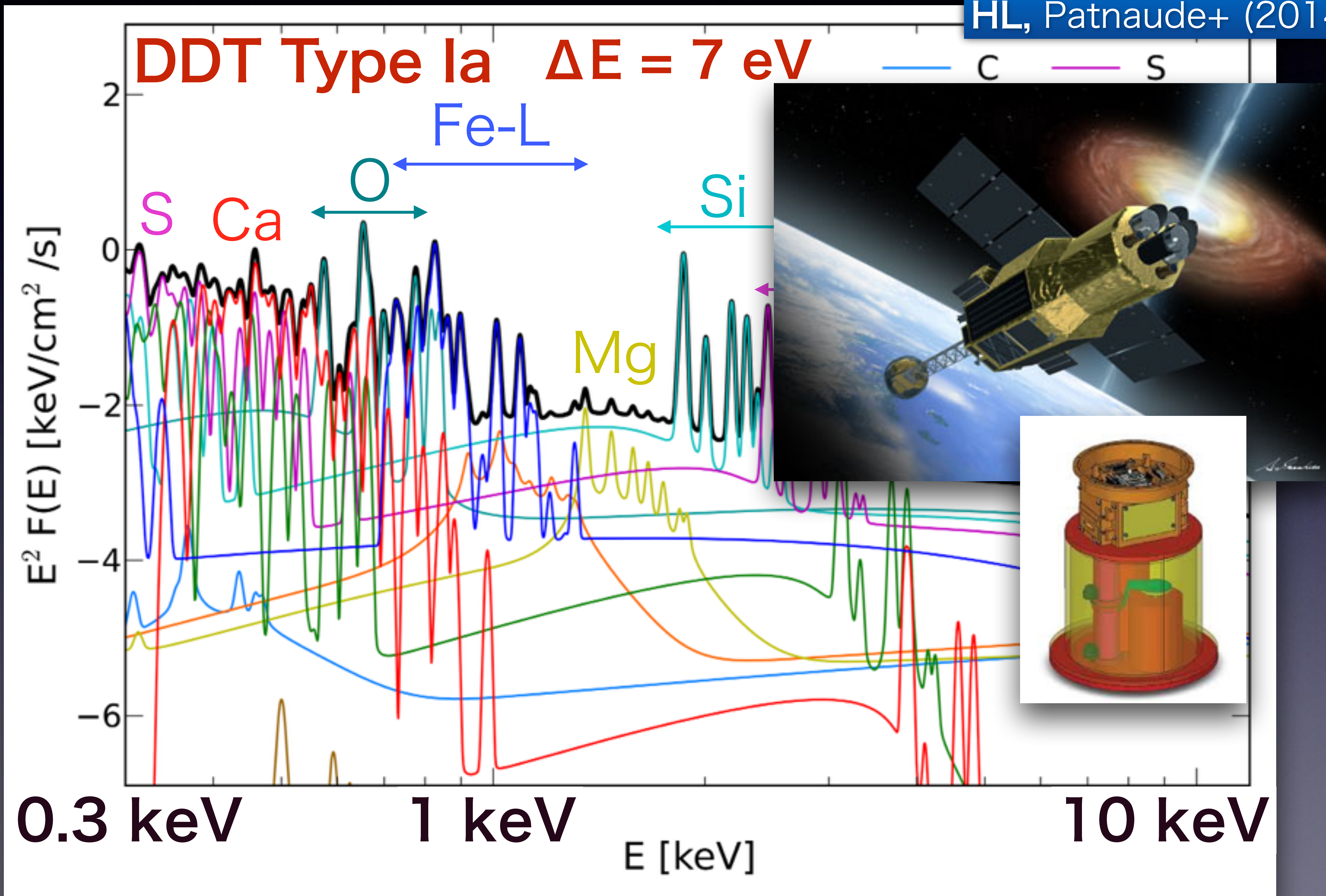
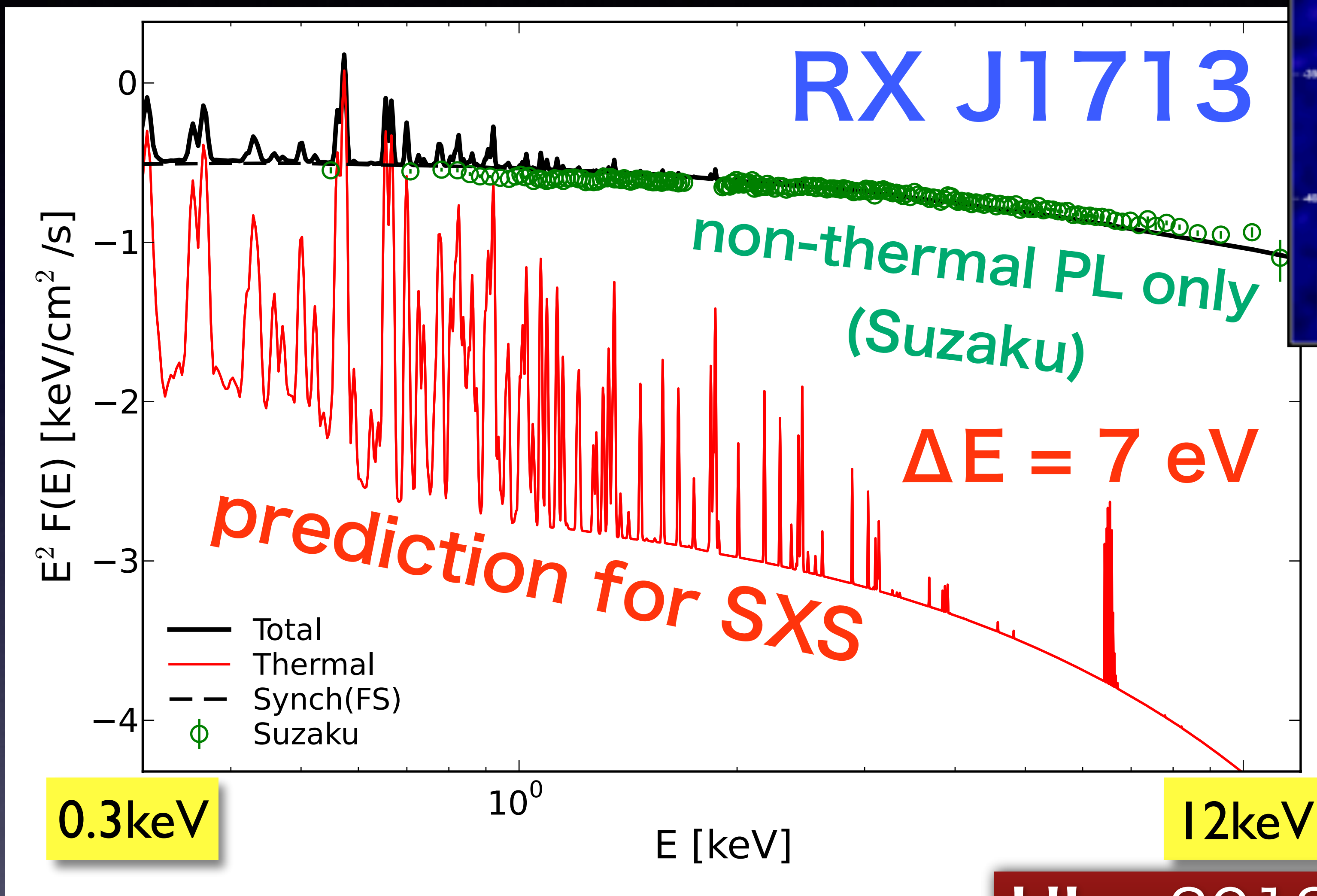
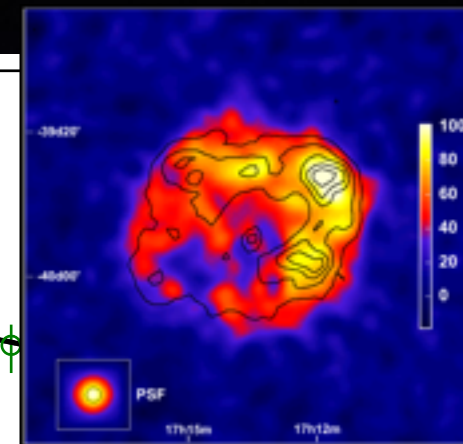
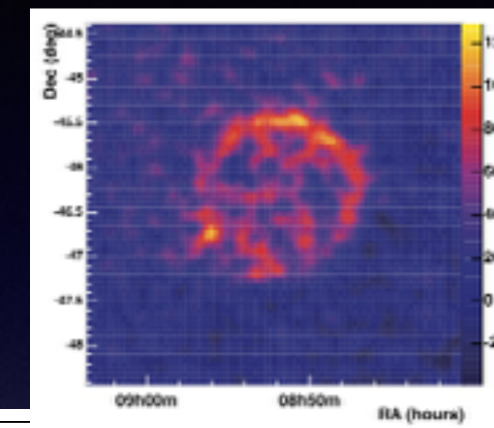


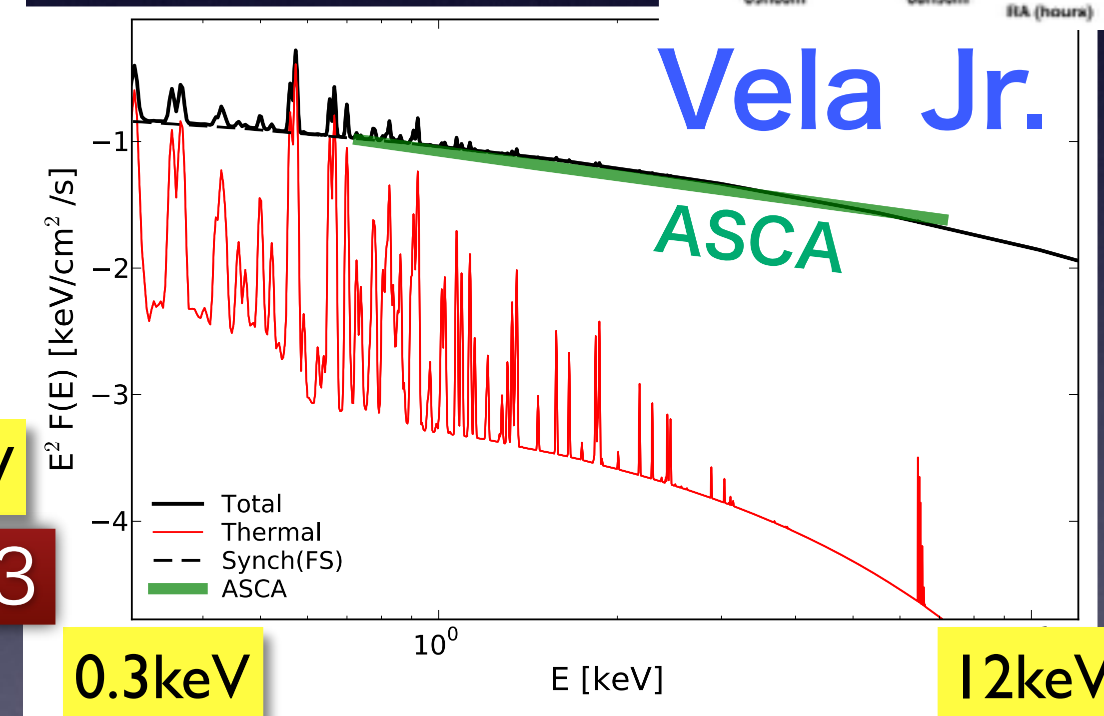
HL, Patnaude+ (2014)

Future X-ray spectroscopy by Astro-H









HL+ 2013

Our model predicts detection of **resolved thermal lines** from **non-thermal SNRs** by SXS to reveal progenitors and CSM properties

XMM Newton etc. may detect thermal bump (see work by S. Katsuda+)

But **only SXS can extract detailed info**

Synergy of next-generation telescopes for SNR studies

Synergy of next-generation telescopes for SNR studies

<u>Best X-ray spectroscopy</u>

- Chemical composition
- Progenitor
- SN explosion properties
- Nucleosynthesis
- Matter mixing
- Line profiles: gas dynamics, temperatures
- Hard X-ray imaging
- Injection of CR electrons
- Secondary emission

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Best VHE γ-ray imaging

- New γ-ray SNRs
- Spectrum 20GeV to >100 TeV
- Measure max E of CRs
- 3x better imaging to contrast radio/IR/X-ray images

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- MIR and FIR mapping of CSM and ejecta, molecules and dust
- NIR atomic lines (e.g. Fe II)
- Dust formation/destruction and SNR environment

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Fermi, H.E.S.S., ··· (CR p)

Suzaku, Chandra, ··· (CR e, B, plasma, gas motion)

Nanten-2, Mopra, AKARI, ALMA, ··· (gas & dust)

Summary

- SNRs never end to challenge us with its many puzzling phenomena
- Multi-fold astrophysical importance, e.g. origin of CRs, chemical enrichment and turbulence in ISM, late evolution of massive stars, SN explosion mechanism, nucleosynthesis, etc…
- Treasure troves of fundamental physics, e.g. collisionless shocks, particle acceleration, magnetic turbulence, hydro instabilities, plasma physics etc…
- A true understanding of SNRs from engine to remnant requires confrontation of data from new telescopes with improving numerical models