Now and the Future of SNR Broadband Models
Linking with Progenitor and Supernova Simulations

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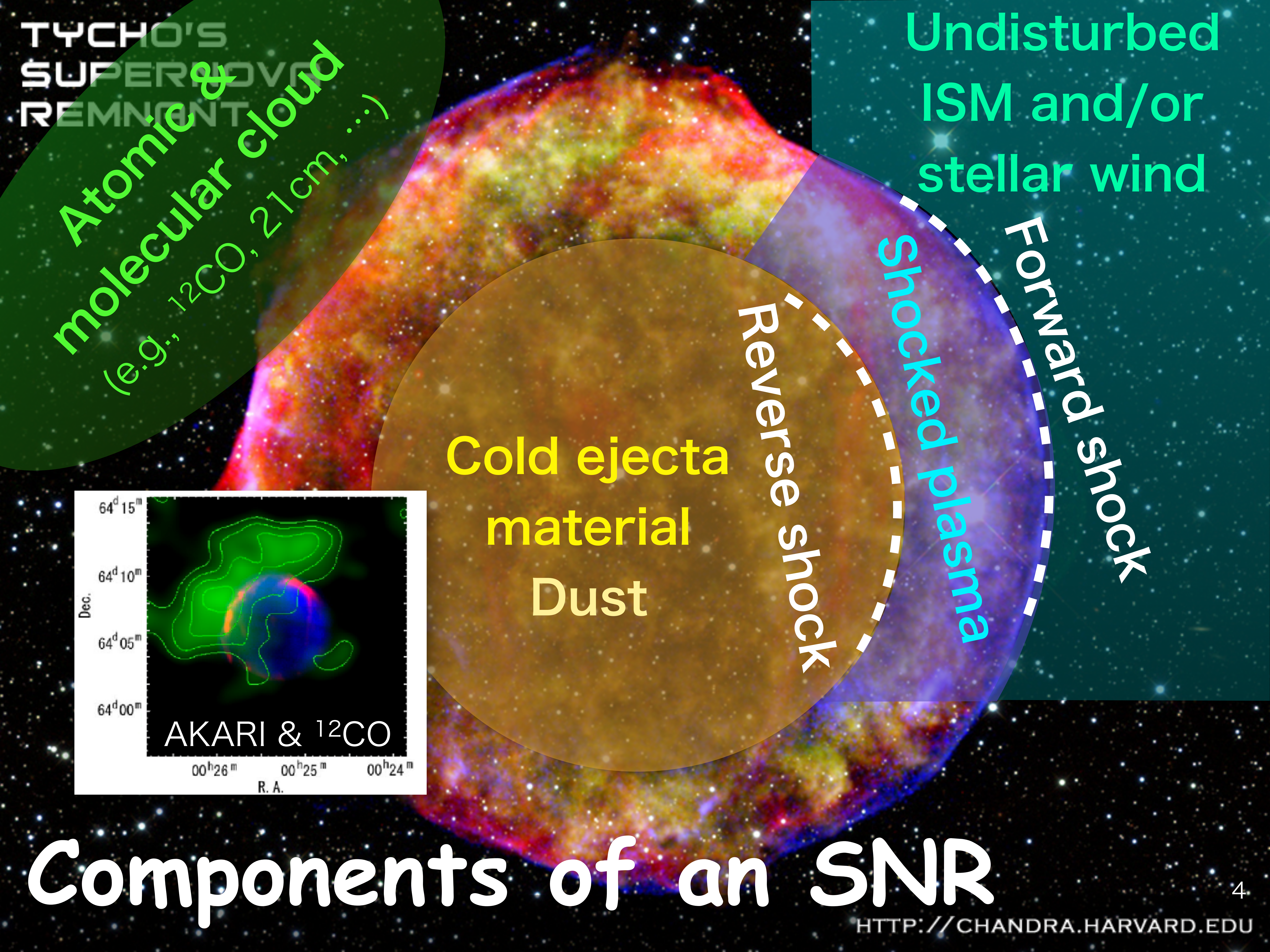
IAUS 331 - The 30th Anniversary of SN 1987A

The Art of Broadband SNR Modeling

- Nowadays, broadband models must satisfy many constraints from observations
  - Multi-wavelength spectra
  - Multi-wavelength morphology
  - Time evolution, dynamical information
  - Thermal as well as non-thermal properties
  - All different combinations of the above! (spectral image, spectral evolution etc)
- Also have to meet criteria from complex plasma physics and simulations
  - A few parameters, from yet incomplete physical understandings

Common Ingredients of a SNR Broadband Model

- (Magneto-) hydrodynamics
- Progenitor, supernova and explosive nucleosynthesis models
- Picture for the surrounding environment
- Various implementations of Diffusive Shock Acceleration (DSA)
- Time and space-dependent micro-physical processes
  - Non-equilibrium ionization, charge exchange, …
  - Shock heating, temperature equilibration
  - Radiative cooling/heating
  - Magnetic turbulence generation and dissipation, feedbacks to DSA
- Thermal and non-thermal emission calculations to confront data in various forms


Tycho's Supernova Remnant
Atomic & molecular cloud
(e.g., 12CO, 21cm, ...)
Undisturbed ISM and/or stellar wind
Cold ejecta material
Dust
Reverse shock
Shocked plasma
Forward shock
64d 15m
64d 10m
Dec.
64d 05m
64d 00m
AKARI & 12CO
00h 26m
00h 25m
00h 24m
R. A.
Components of an SNR
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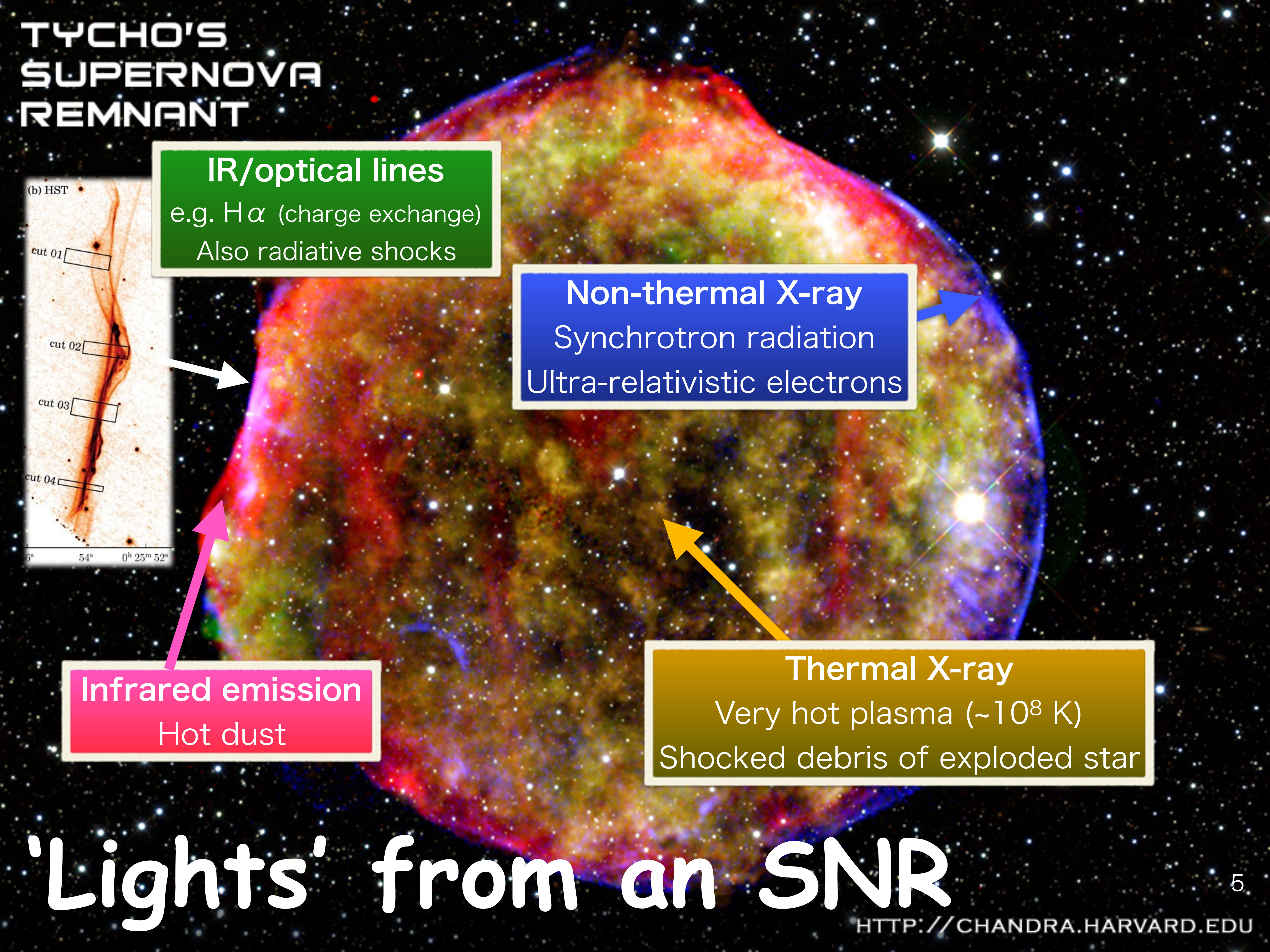
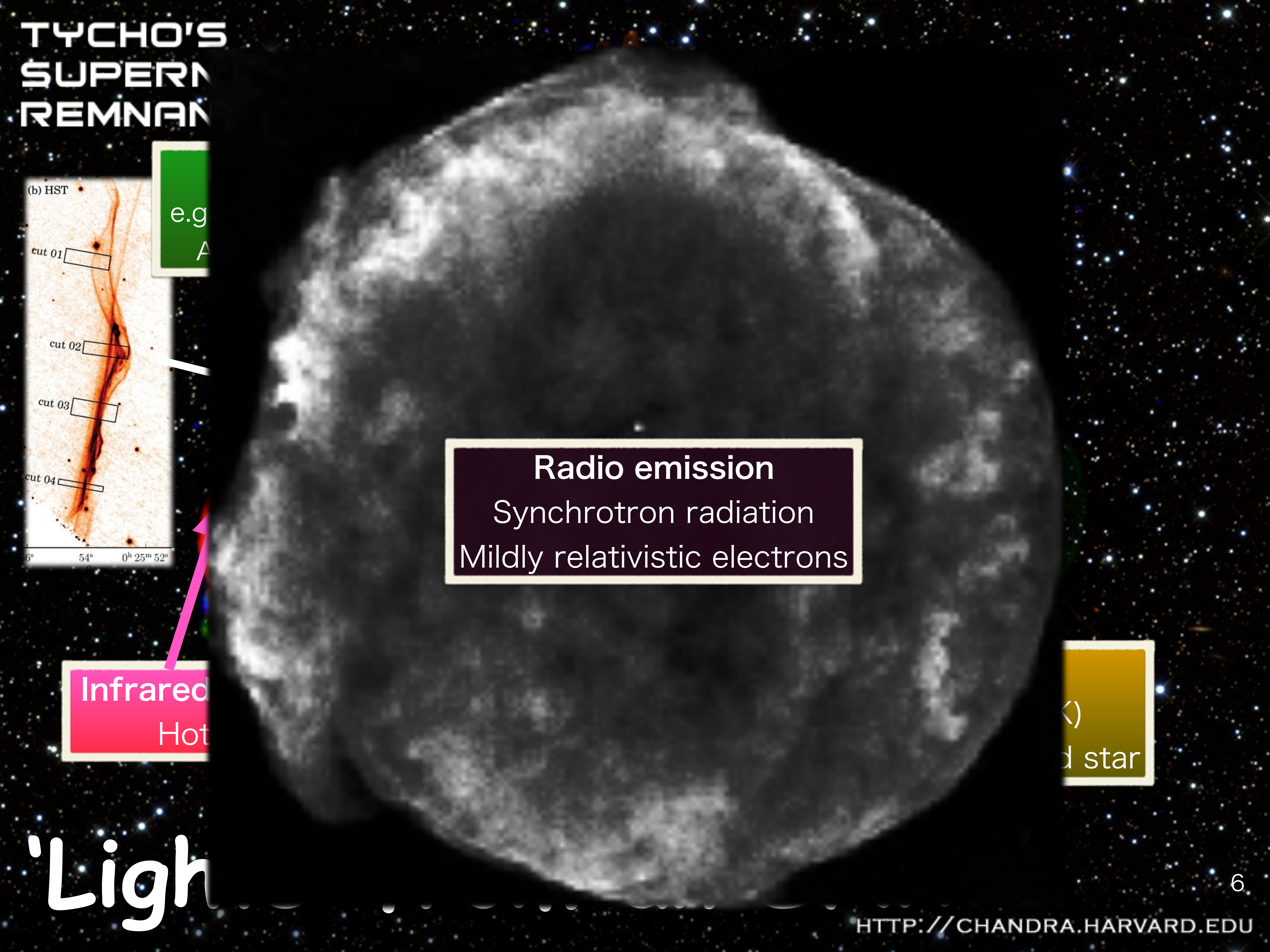
'Lights' from an SNR




TYCHO'S
SUPERN
REMNAN
(b) HST
cut 01
cut 02
cut 03
cut 04
54s
0h 25m 52s
e.g
A
Infrared
Hot
Radio emission
Synchrotron radiation
Mildly relativistic electrons
X)
d star
'Ligh
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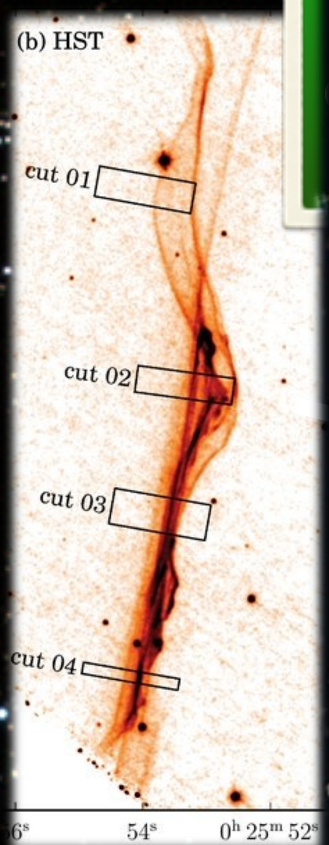
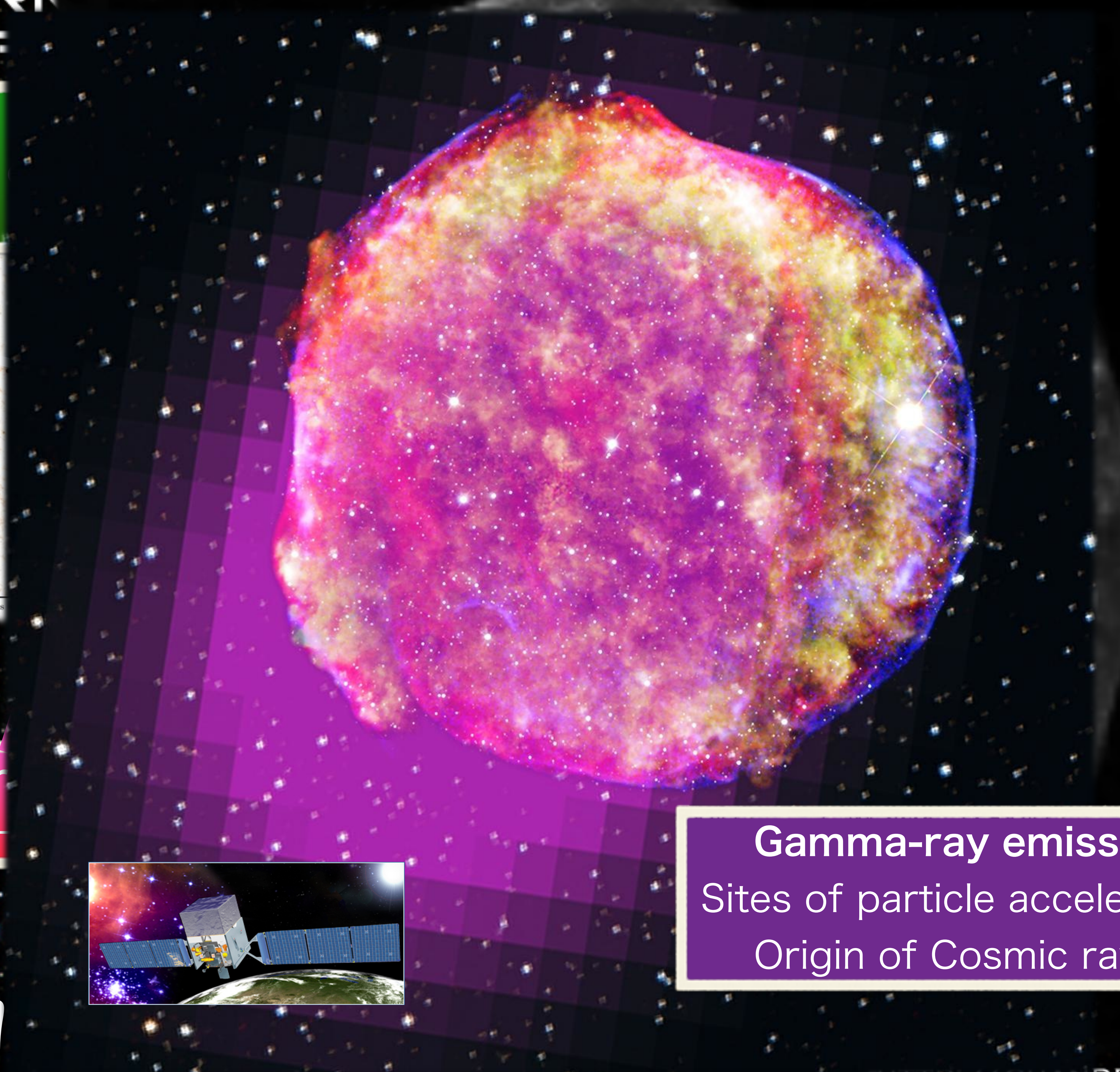
TYCHO'S SUPERN REMN





Infrar

H

Gamma-ray emission

Sites of particle acceleration

Origin of Cosmic rays?

'Lig

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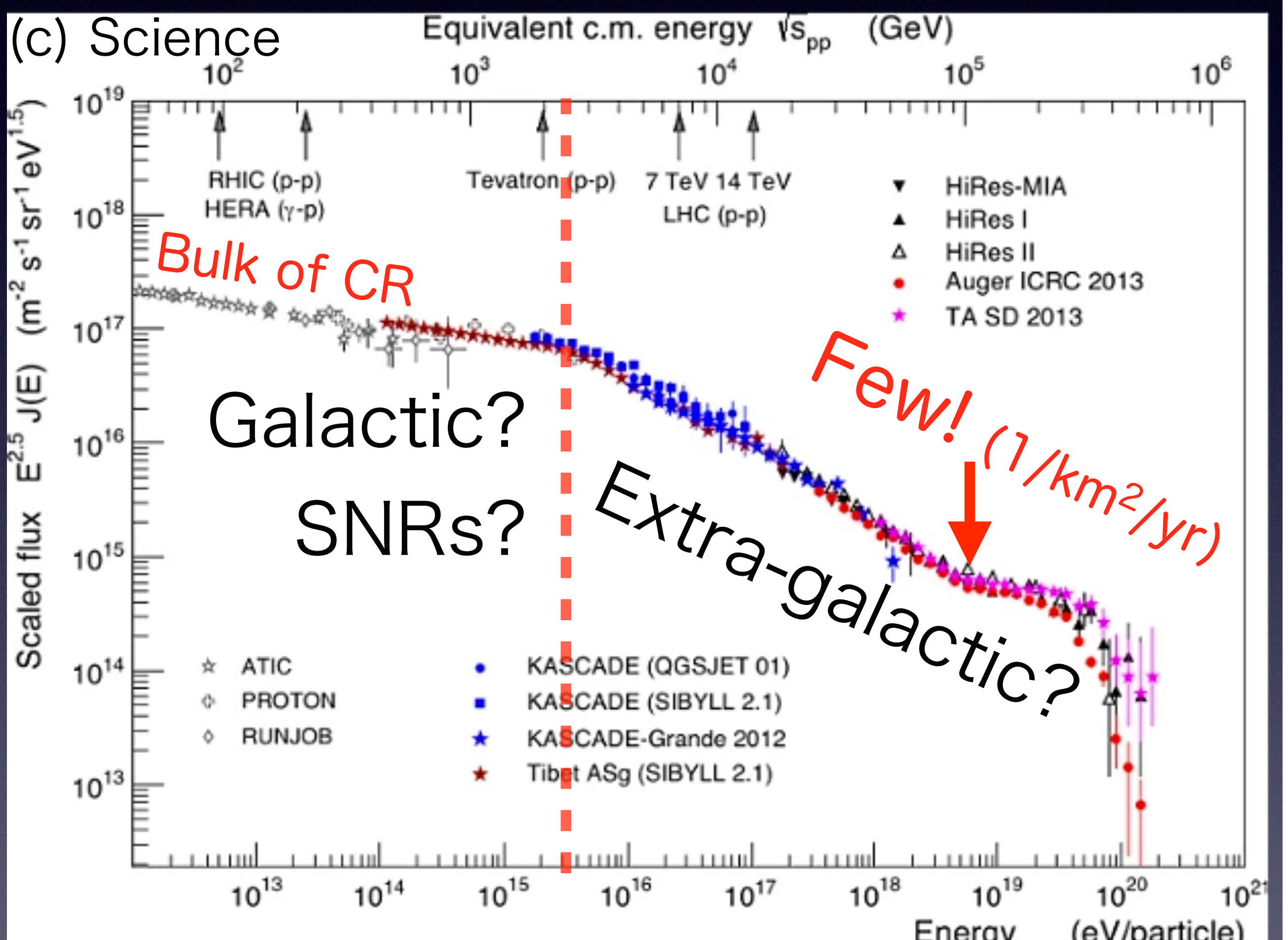
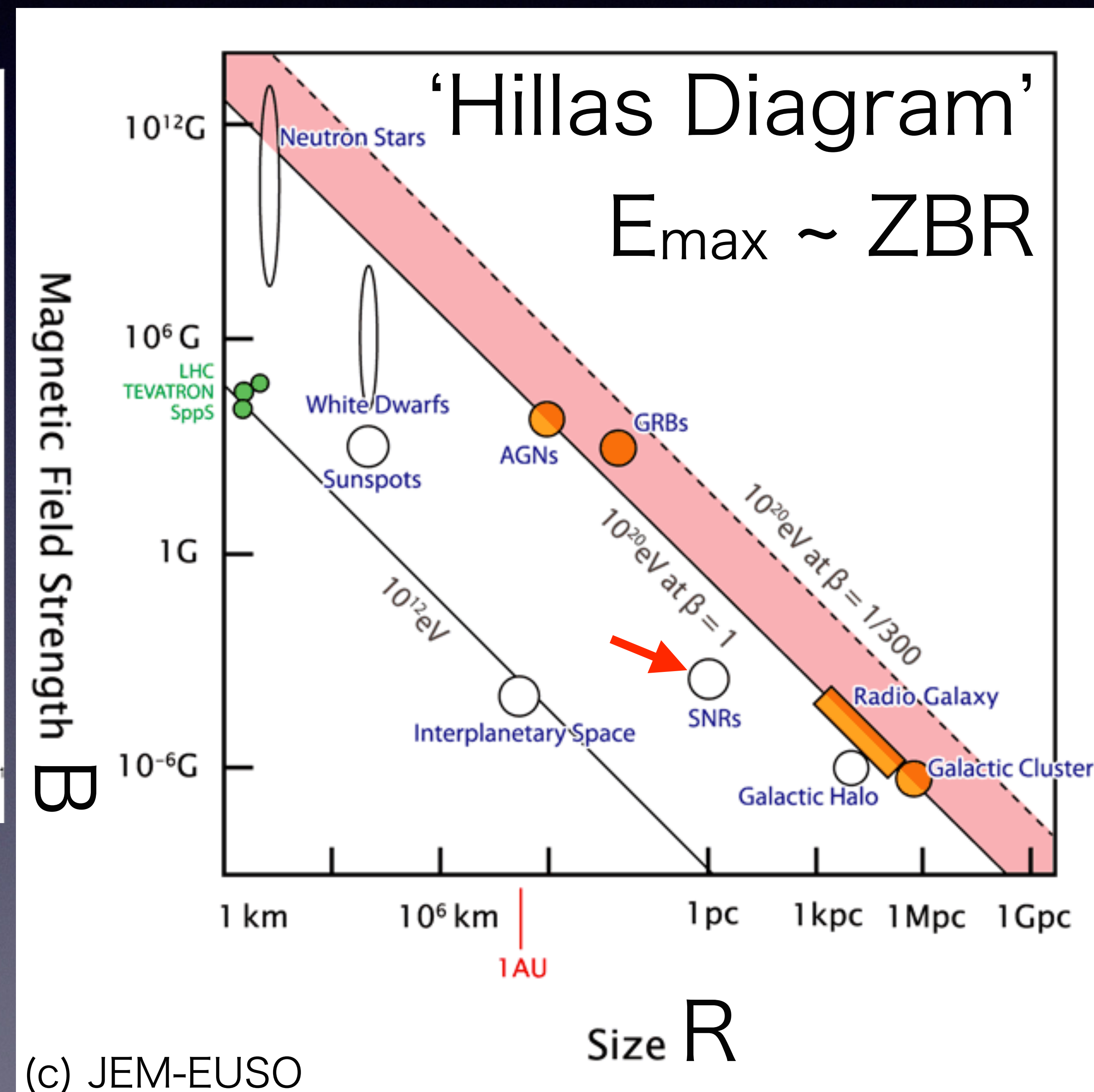
SNRs as origin of cosmic rays in galaxies



TeV PeV EeV

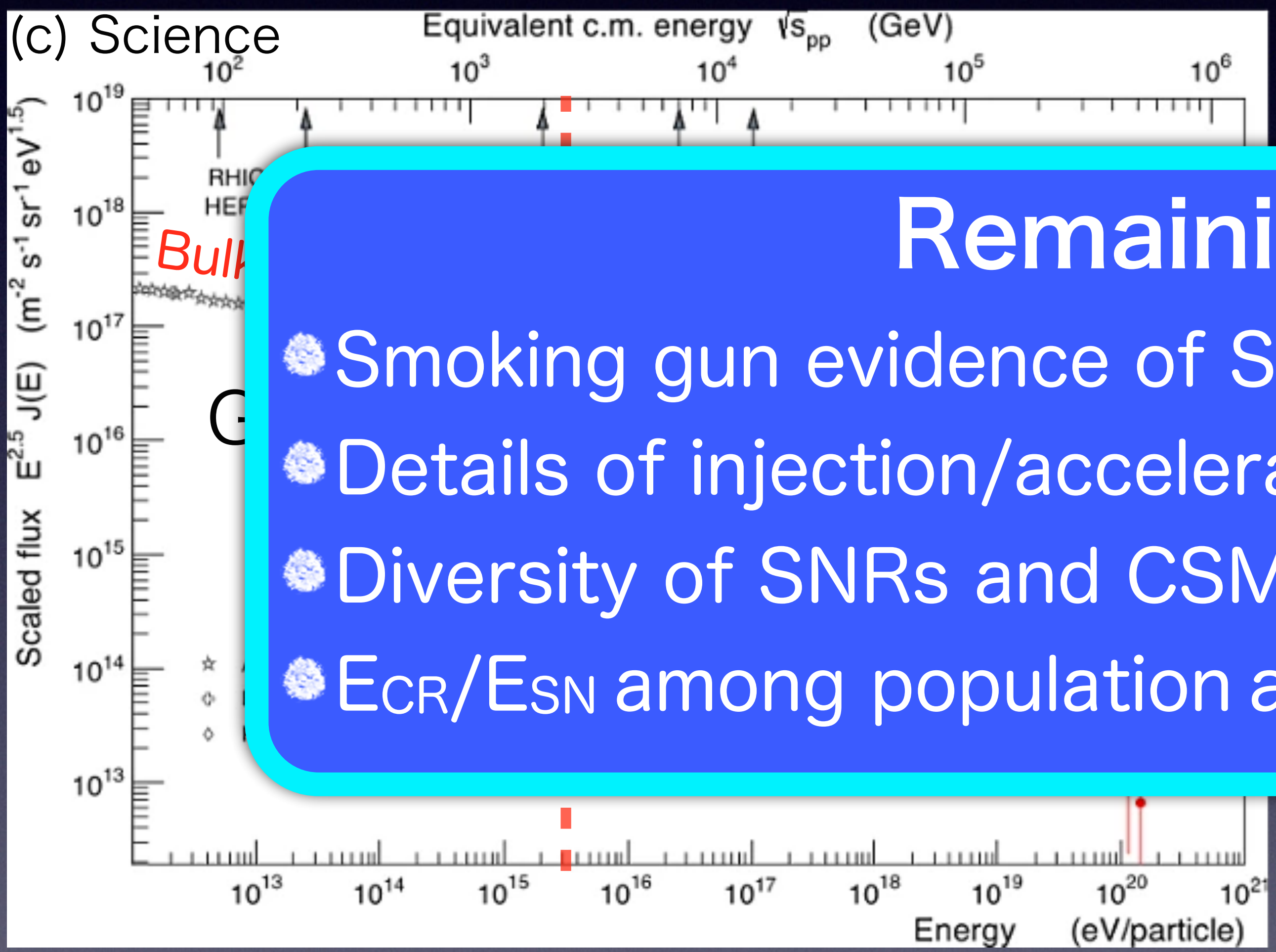


Galactic CR energy content

~10% of E_{SN} —> E_{CR} (~0.03 SN/yr)

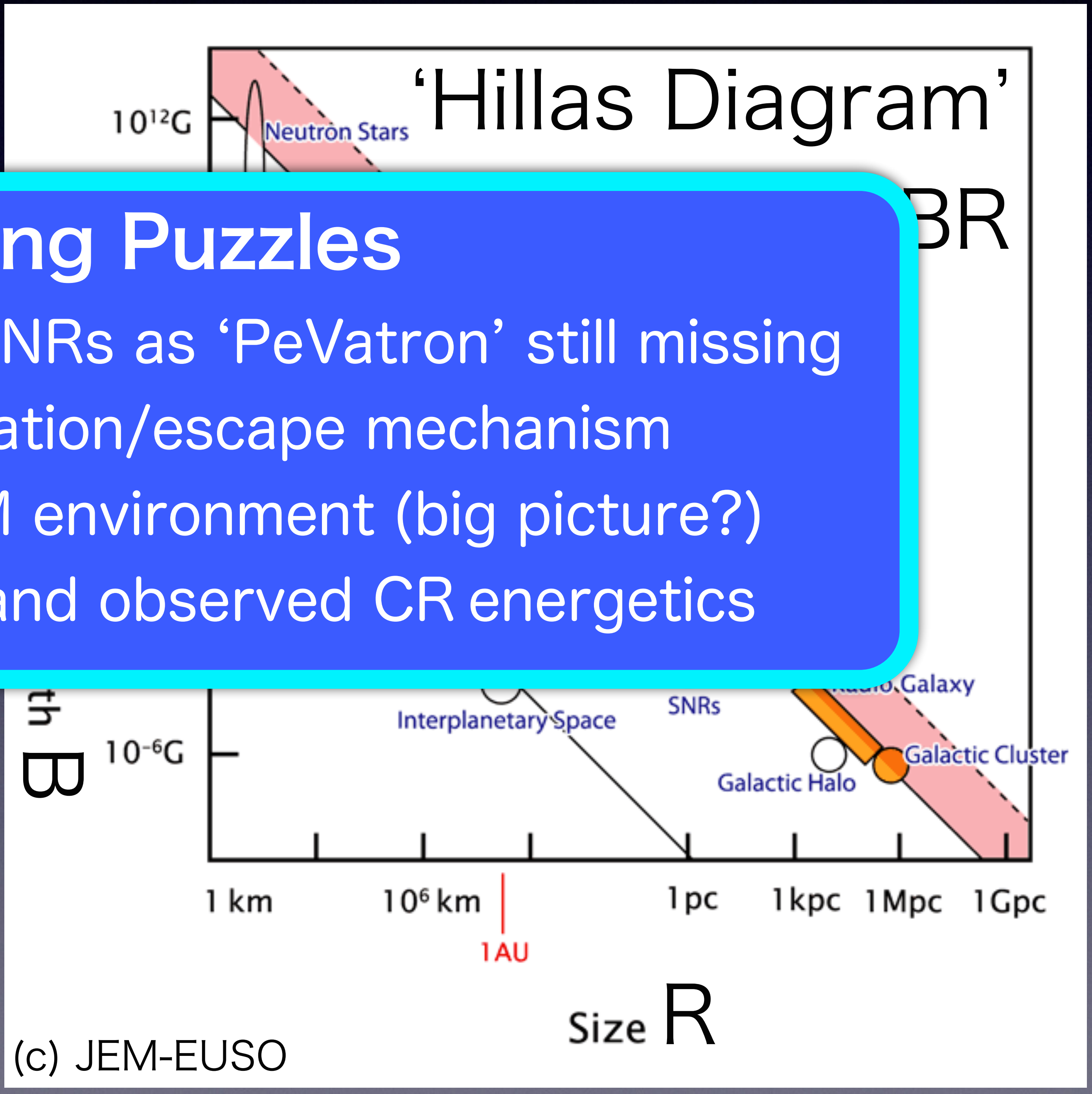
seems sufficient!

SNRs as origin of cosmic rays in galaxies



TeV PeV EeV

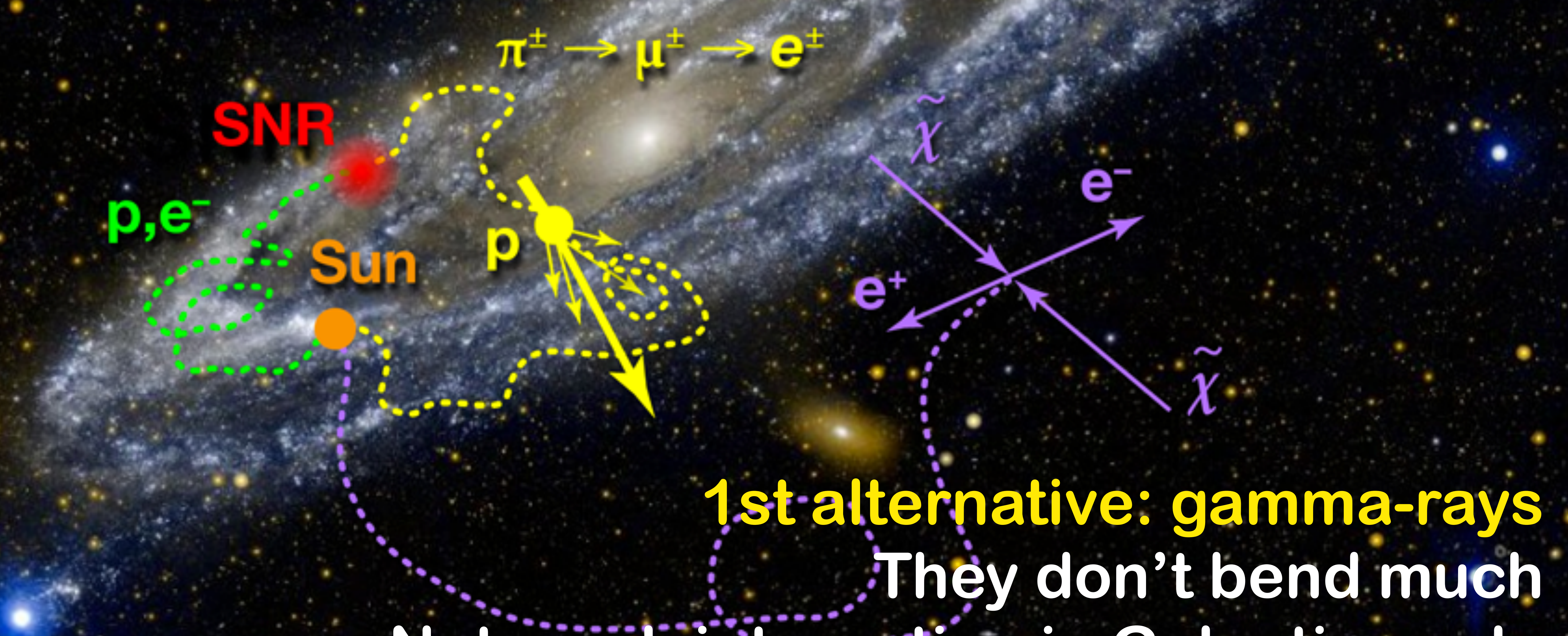
Galactic CR energy content
~10% of E_{SN} —> E_{CR} (~0.03 SN/yr)
seems sufficient!



Remaining Puzzles

- Smoking gun evidence of SNRs as 'PeVatron' still missing
- Details of injection/acceleration/escape mechanism
- Diversity of SNRs and CSM environment (big picture?)
- E_{CR}/E_{SN} among population and observed CR energetics

Cosmic Ray Astronomy ain't gonna work bro



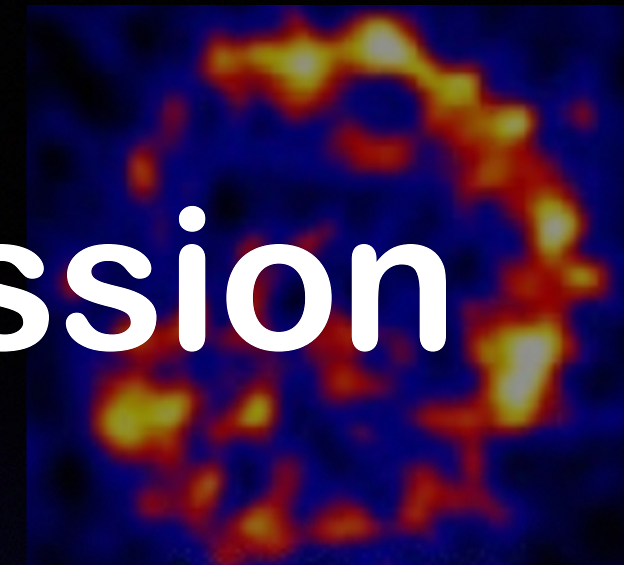
1st alternative: gamma-rays

They don't bend much

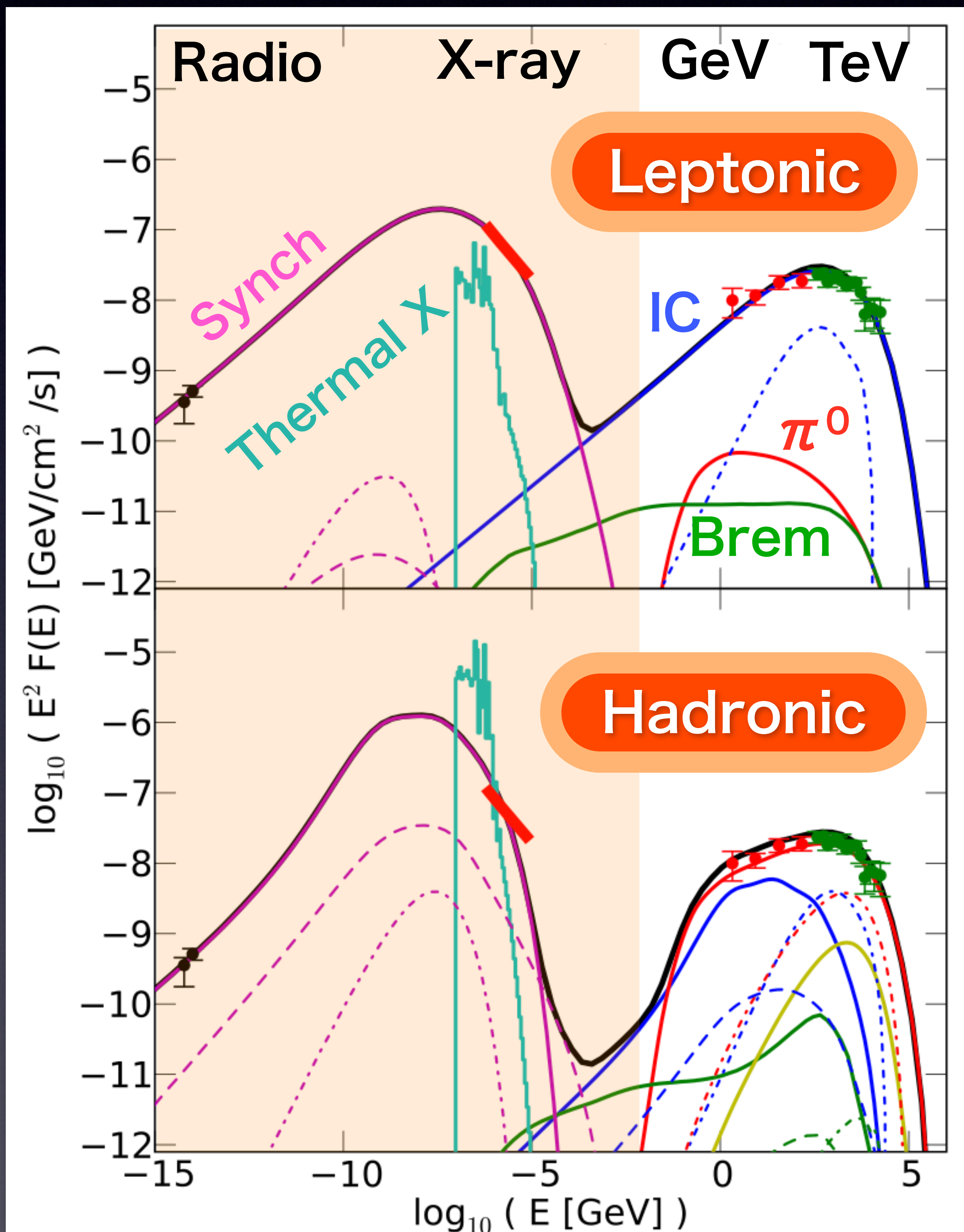
Not much interaction in Galactic scale

Credit: Image: GALEX, JPL-Caltech, NASA; Drawing: APS/Alan Stonebraker

Origins of γ-ray emission



HL, Slane+ 2013 on SNR **Vela Jr.**



π^0 decay

CR **ion** + gas → π^0

Flat'ish spectrum

Requires **dense gas**

"hadronic"

Inverse-Compton scatterings

CR **electron** + seed photons → γ-ray

Hard spectrum

Requires: low B-field (avoid synch loss)

low density (suppress π^0)

Non-thermal bremsstrahlung

CR electron + gas → γ-ray

Same spectral index as CR

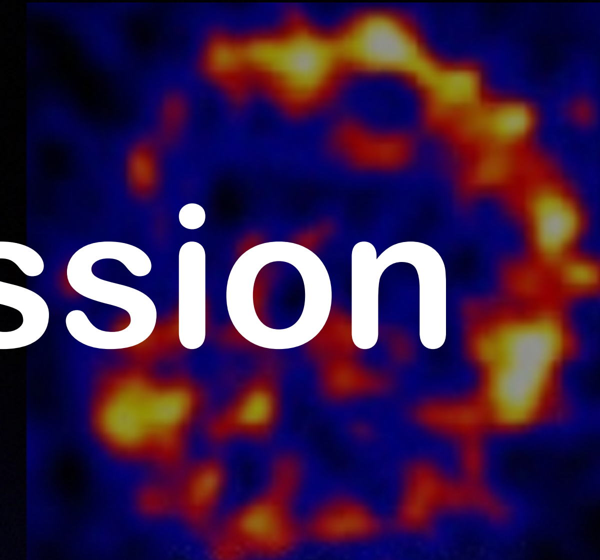
Requires: low B-field (synch loss)

dense gas (target)

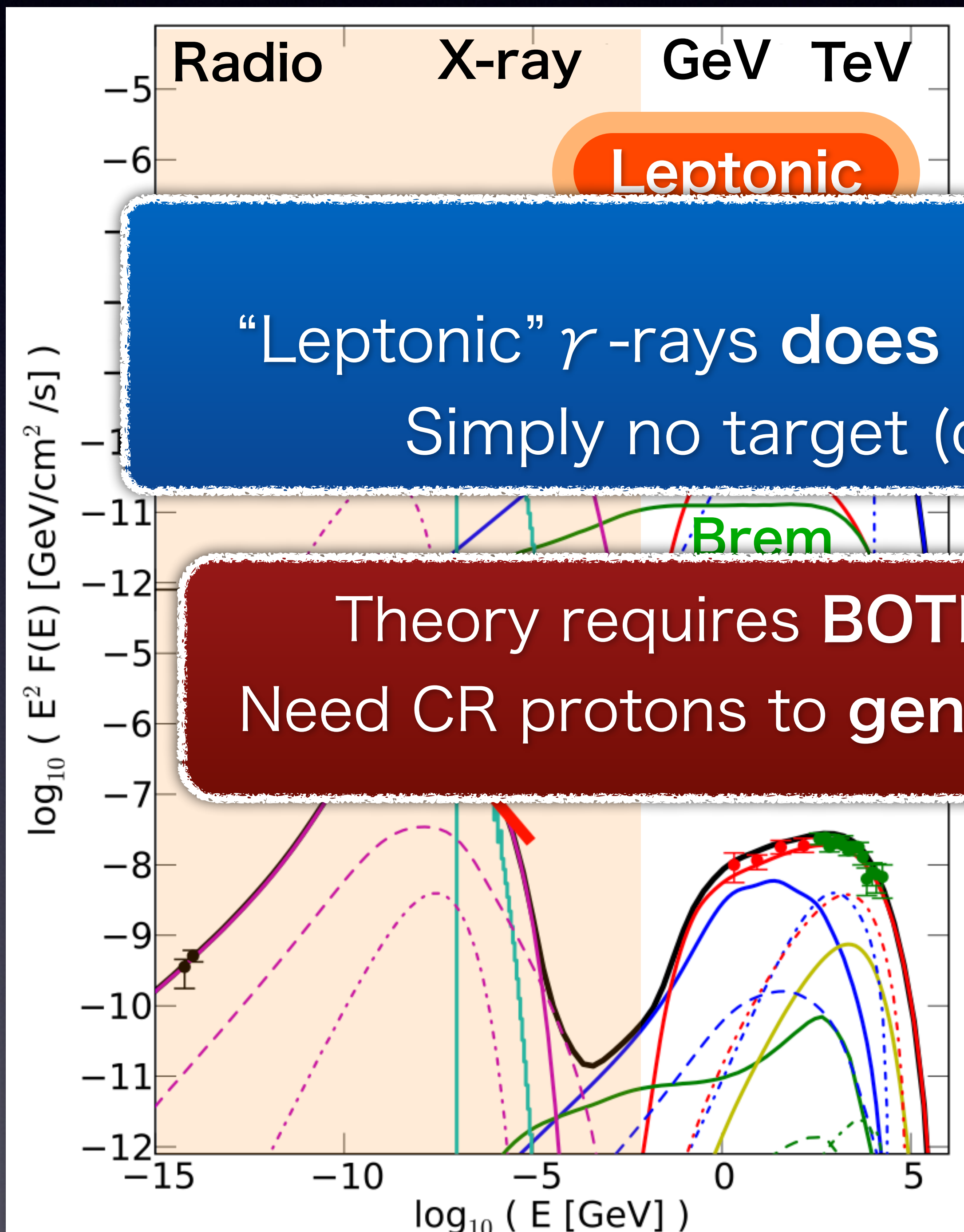
high e/p (suppress π^0)

"leptonic"

Origins of γ-ray emission



HL, Slane+ 2013 on SNR **Vela Jr.**



π^0 decay

CR **ion** + gas → π^0

“hadronic”

Caution

“Leptonic” γ-rays **does NOT** mean no proton acceleration!

Simply no target (dense gas) for π^0 production

CR **electron** + seed photons → γ-ray

Theory requires **BOTH** proton & electron acceleration

Need CR protons to **generate/amplify** magnetic turbulence

Non-thermal bremsstrahlung

CR electron + gas → γ-ray

Same spectral index as CR

Requires: low B-field (synch loss)

dense gas (target)

high e/p (suppress π^0)

“leptonic”

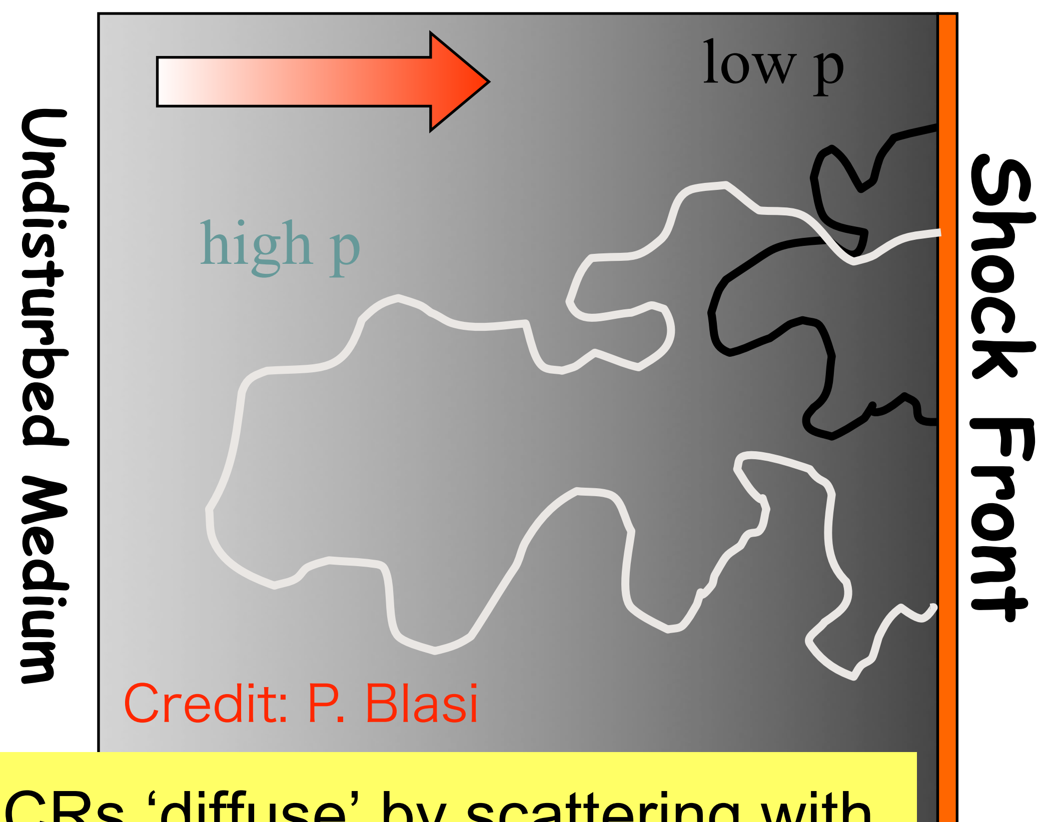
How particles get accelerated

(Younger) SNRs have **strong non-relativistic collisionless shocks**

→ **Diffusive Shock Acceleration (DSA)** **[aka Fermi 1st order acceleration]**

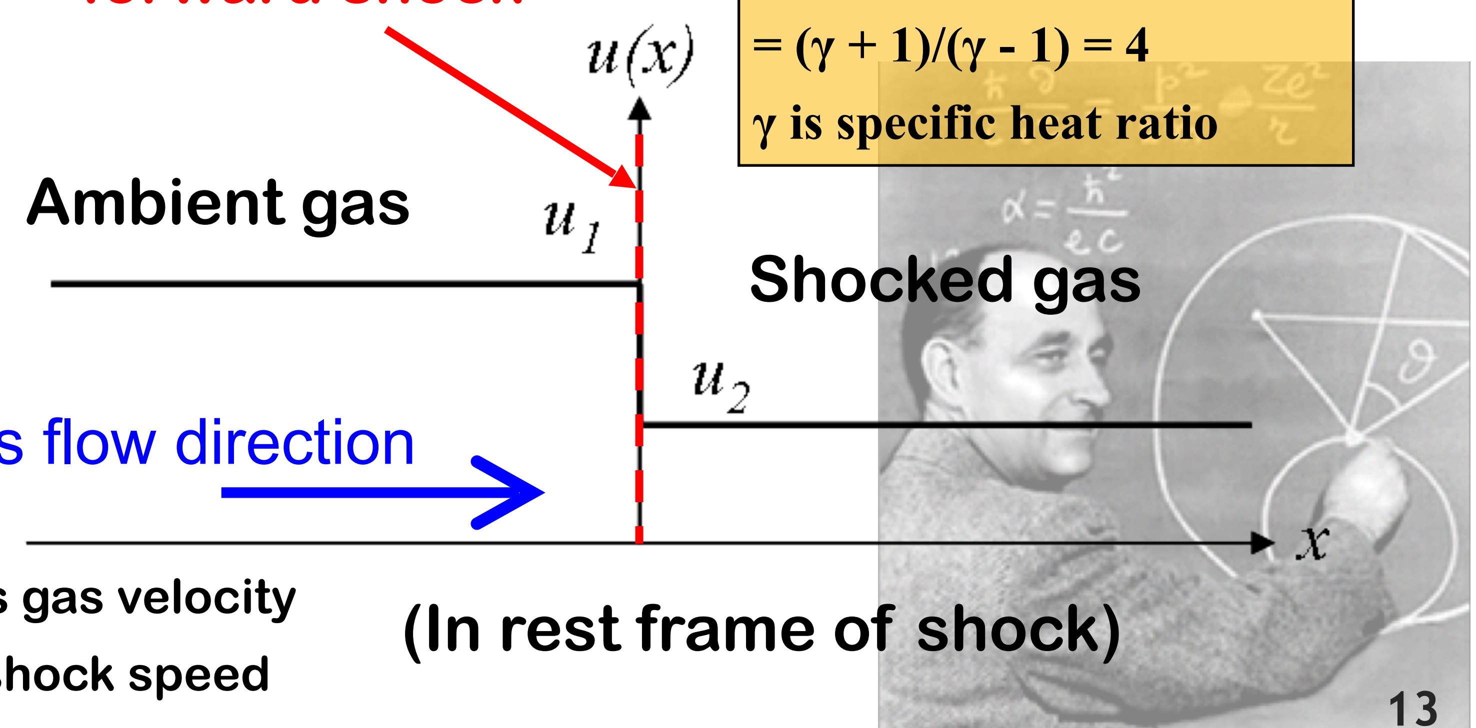
- 'Diffuse' by **elastic scattering w/ magnetic turbulence** on both sides of shock
- Particles **repeatedly crossing the shock front**
- Each time, **fractional momentum gain** $\triangle p/p$ ~ (velocity difference)/(speed of light)

→ Young SNRs: cosmic ray energy easily > 10% of E_{SN} (e.g. Ellison+ 05)



CRs 'diffuse' by scattering with magnetic turbulence

Compression at forward shock



For high Mach number shock, compression ratio r

$= u_1/u_2$

$= (\gamma + 1)/(\gamma - 1) = 4$

γ is specific heat ratio

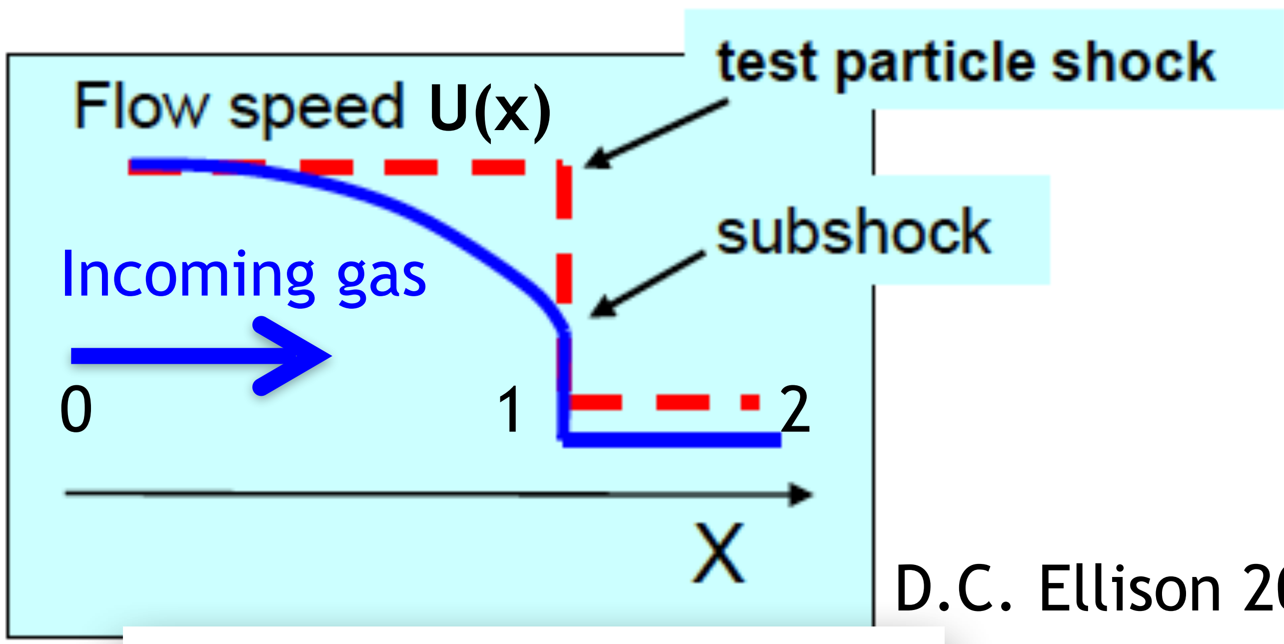
u(x) is gas velocity

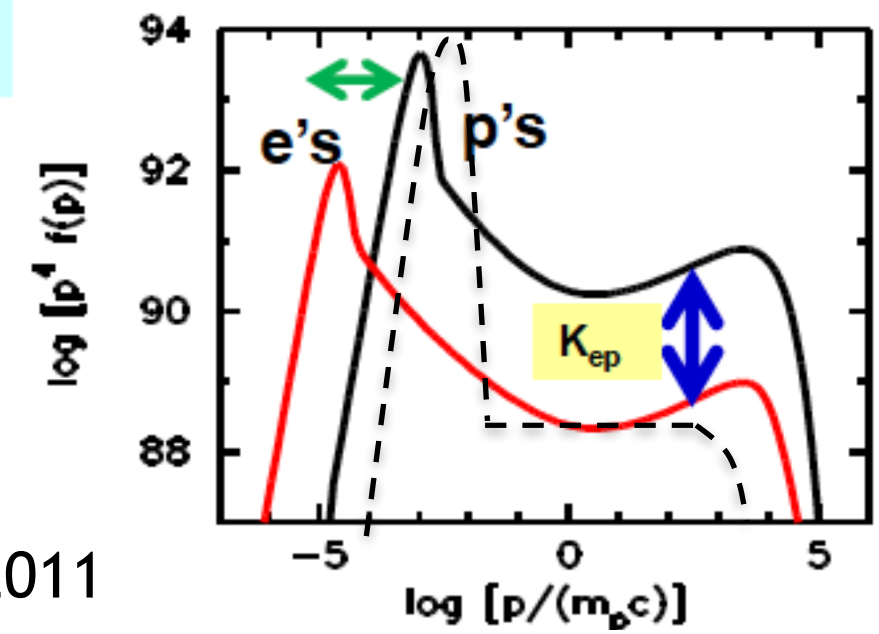
u_1 is shock speed

(In rest frame of shock)

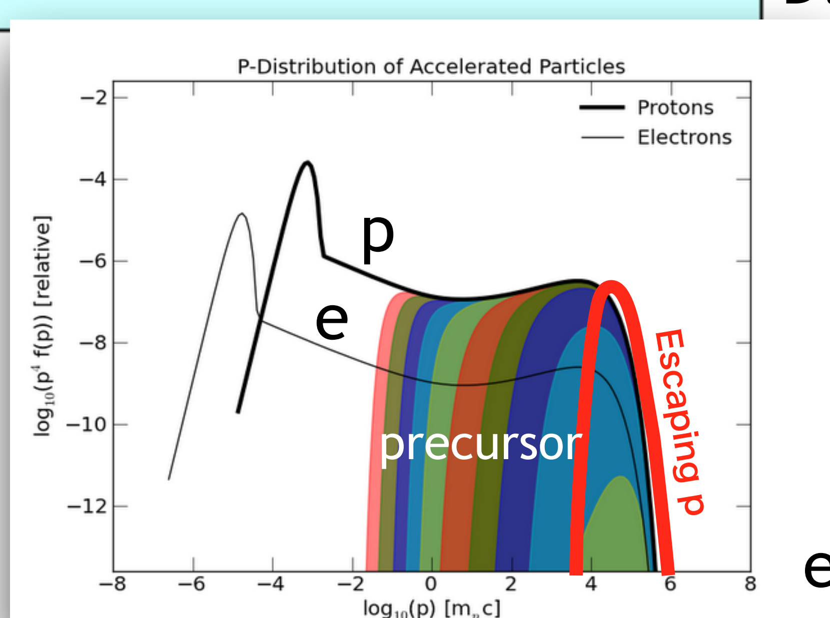
Nonlinear diffusive shock acceleration

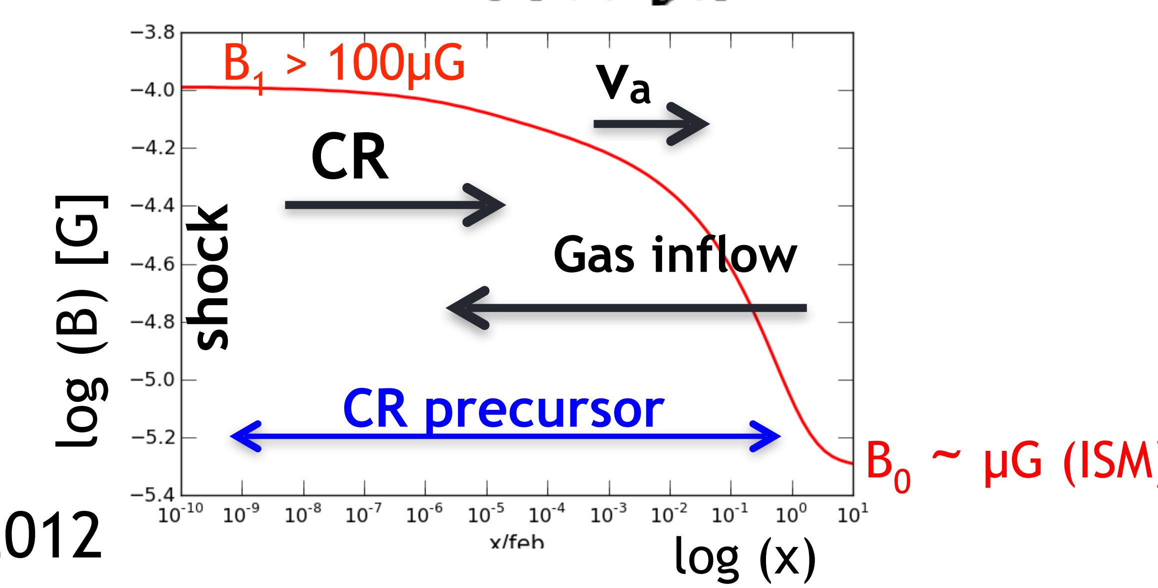
Efficient particle acceleration leads to funny consequences, e.g.,
highly modified shock flow, ‘concave’ CR spectrum,
low shock temperature, efficiently amplified B-field, …





D.C. Ellison 2011





e.g., HL+ 2012

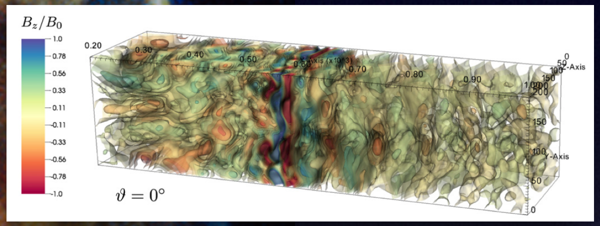
Numerical Approaches for SNRs

Particle-in-cell

Hybrid

First principles
Few or no parameter/approx

Computational cost
Limited dynamical ranges
Difficult for multi-λ model



Caprioli & Spitkovsky '14

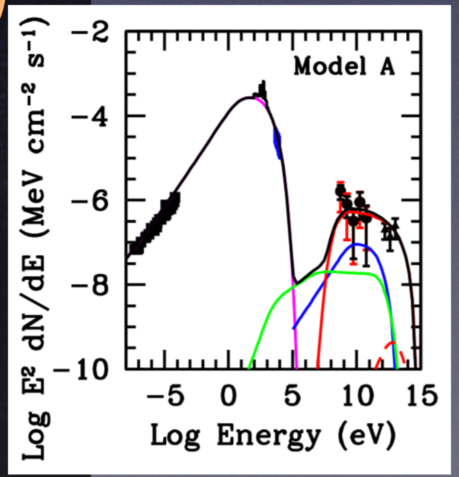
Monte Carlo

Semi-analytic

Global HD/MHD
with microphysics

More phenomenological
(parametric) plasma physics

Large dynamical ranges
Constrained by
multi-λ observations



Slane, HL+ '14

P. Slane

The CR-hydro-NEI (ChN) Code

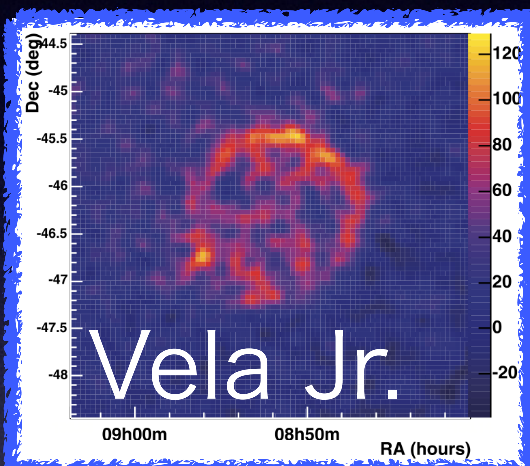
S.-H. Lee, D. Patnaude, D. Ellison, P. Slane, S. Nagataki (J. Raymond, D. Castro, others…)

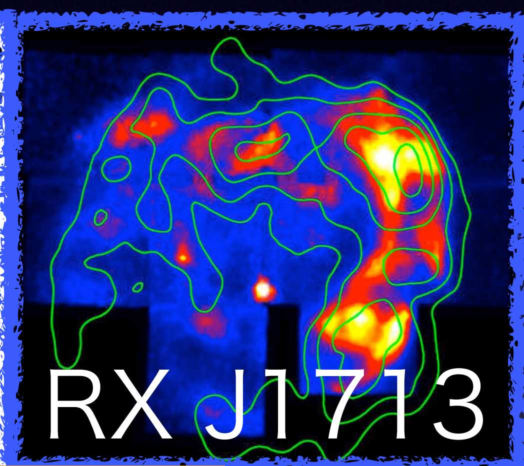
- **Nonlinear DSA physics** (HL, Ellison & Nagataki 2012)
  - CR back-pressure → feedback to shock structure, vice versa
  - Particle escape
  - Magnetic turbulence generation + wave damping
    → Magnetic field amplification (MFA)
    → $D_X(x,p,t)$ calculated from self-generated B-field
- Non-thermal radio-TeV emission in (x,t) (HL, Slane+ 2013, Slane, HL+ 2014, …)
- Self-consistent calculation of **thermal X-ray line emission**
  - **Non-equilibrium ionization, fully time and space-dependent** (Patnaude+ 2009)
  - **Temperature equilibration —> $T_e(x,t)$ and $T_i(x,t)$** (HL, Patnaude+ 2014)
- **Propagation of escaping CRs** and **interaction w/ clouds** (HL+ 2008, Ellison+ 2012)
- **(Re-)acceleration of pre-existing non-thermal particles**
- **Fast radiative shocks in dense medium** (HL, Patnaude, Raymond+ 2015)
- Ejecta from SN nucleosynthesis models (HL, Patnaude+ 2014)

Decipher Multi-λ emission by CR-hydro-NEI code

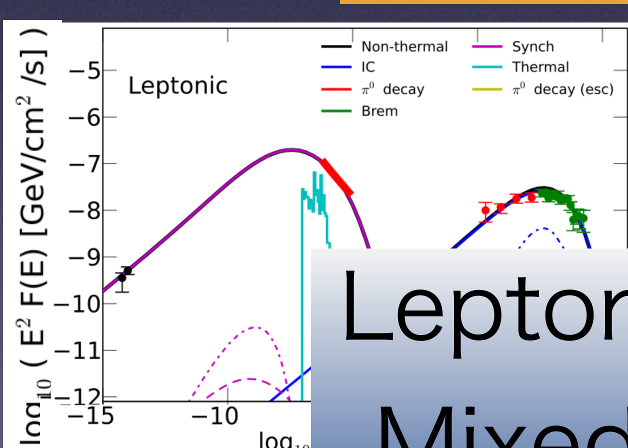
Diversity of SNR γ-ray Origin

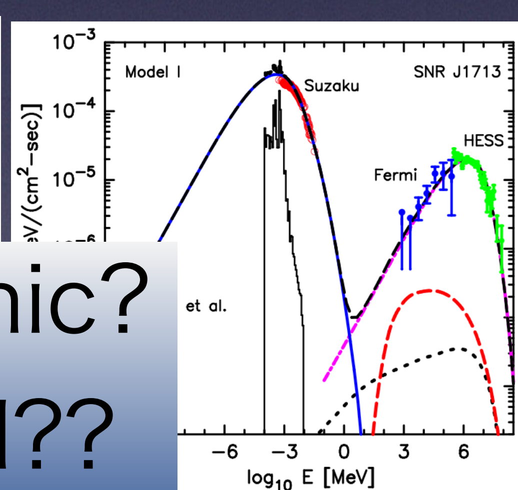
e.g., Lee+ 2008 to now; Slane, Lee+ 2014; Castro+ 2012





~2,000 yr



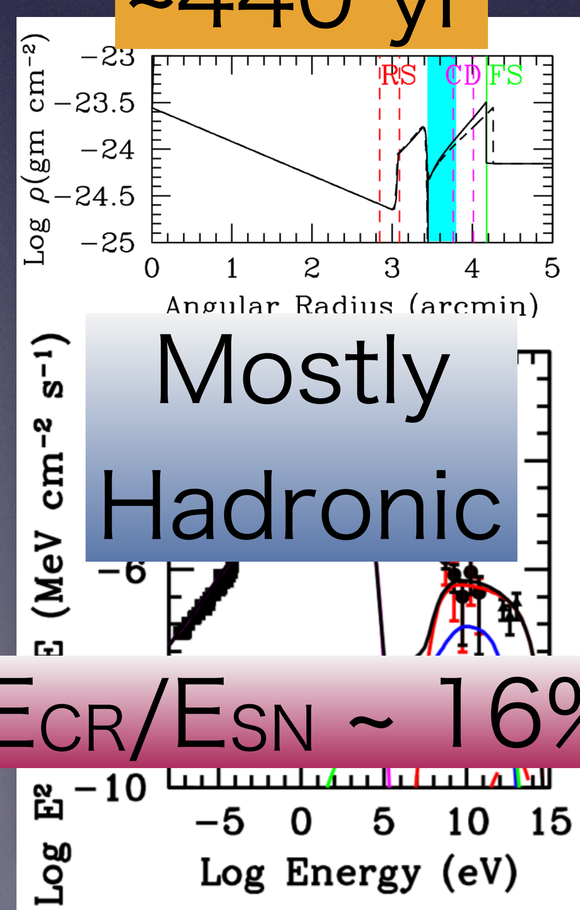


Leptonic?

Mixed??

E_{CR}/E_{SN} ~ 15%

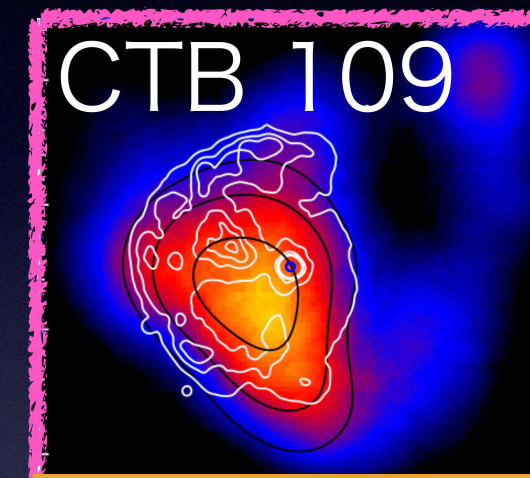
~440 yr



Mostly

Hadronic

E_{CR}/E_{SN} ~ 16%



~10,000 yr

Mixed

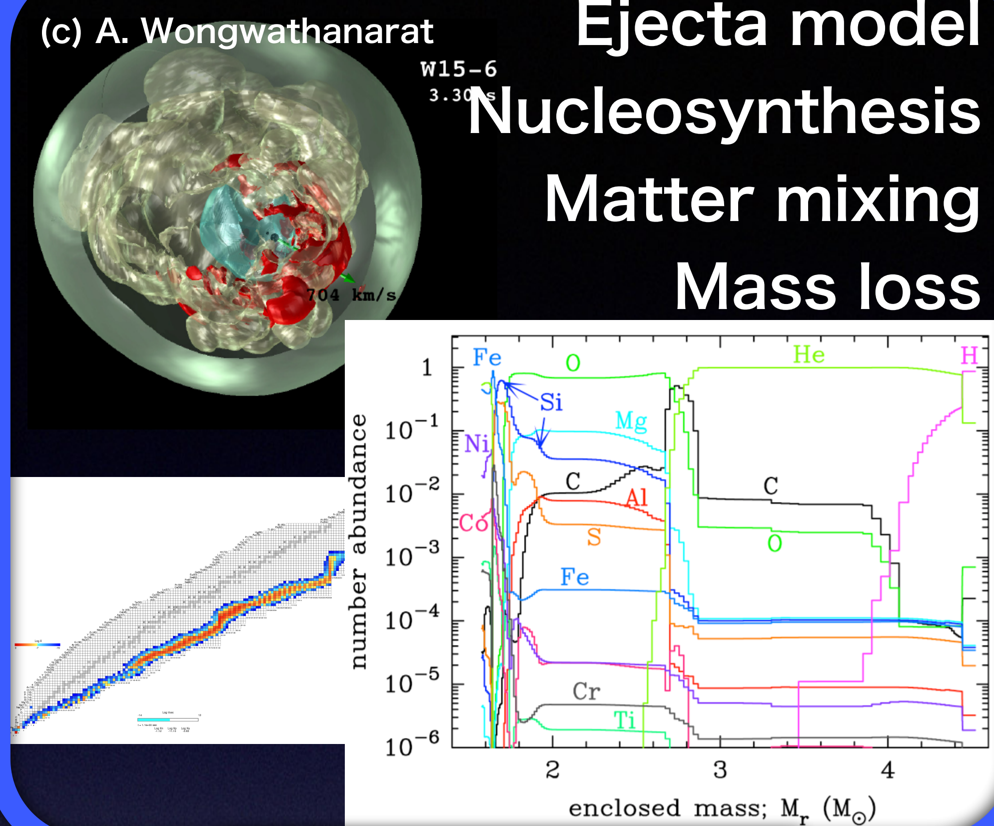
Leptonic (~GeV)

Hadronic (~TeV)

E_{CR}/E_{SN} ~ 50%

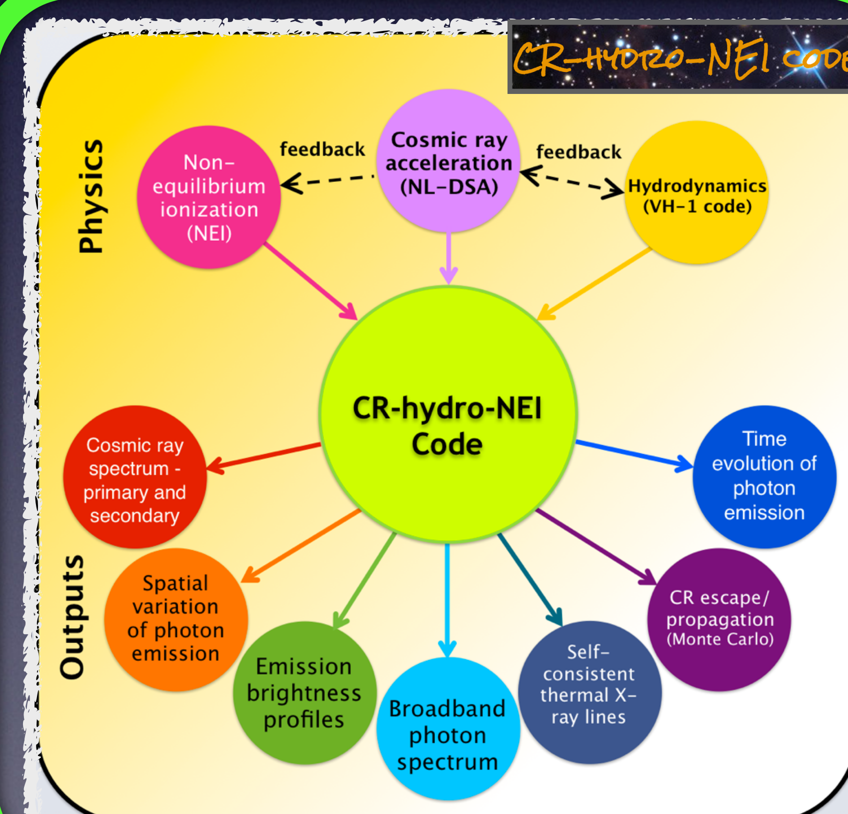
Iterative Work Flow

Ejecta model
Nucleosynthesis
Matter mixing
Mass loss

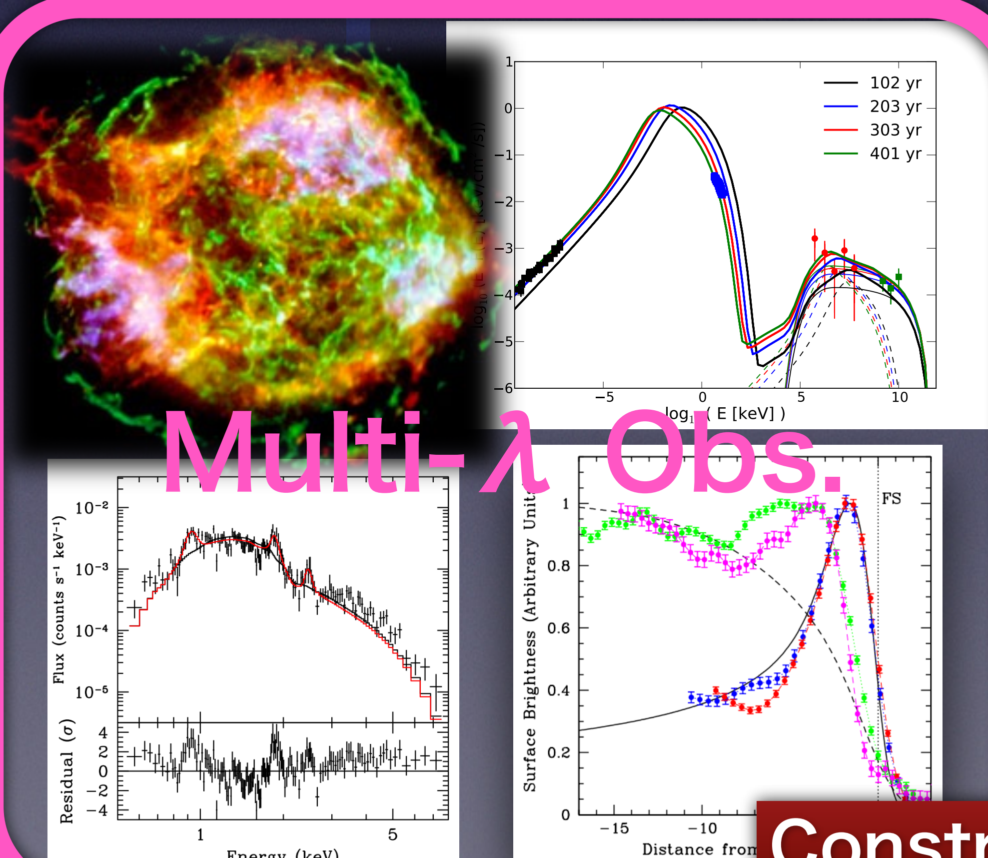


Initial conditions

CR-hydro-NEI
SNR Model



Dynamics, NLDSA,
B-field, ionization, radiation

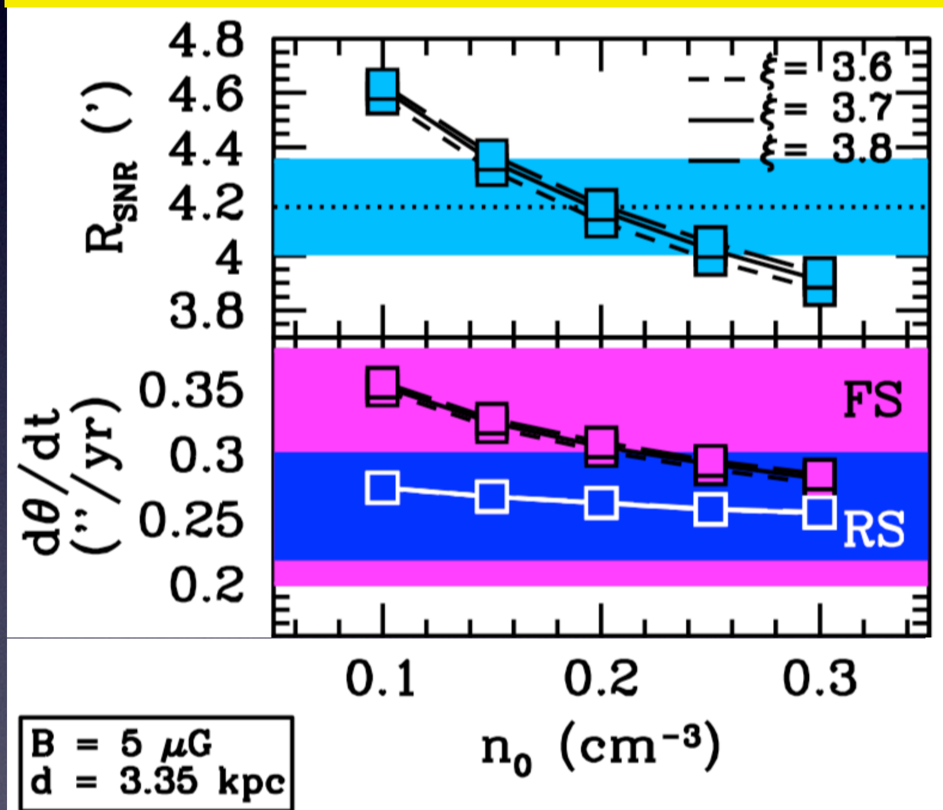


Multi-λ Obs.

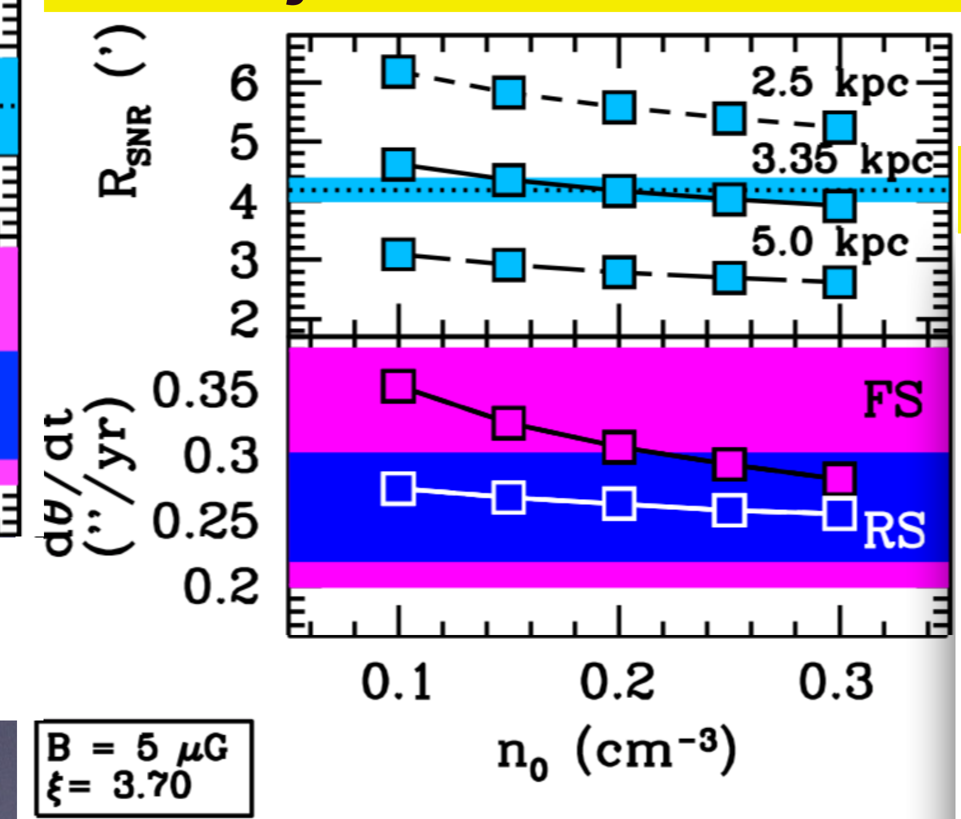
Constraints!

First step
Get the size right (dynamics)

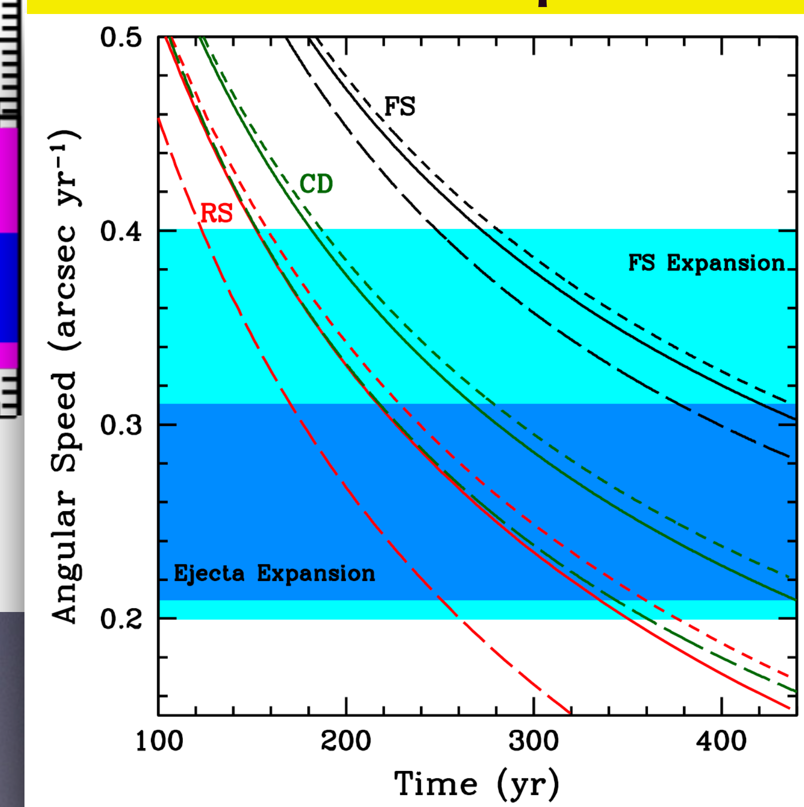
Vary DSA efficiency vs no



Vary distance vs no



Final shock speeds

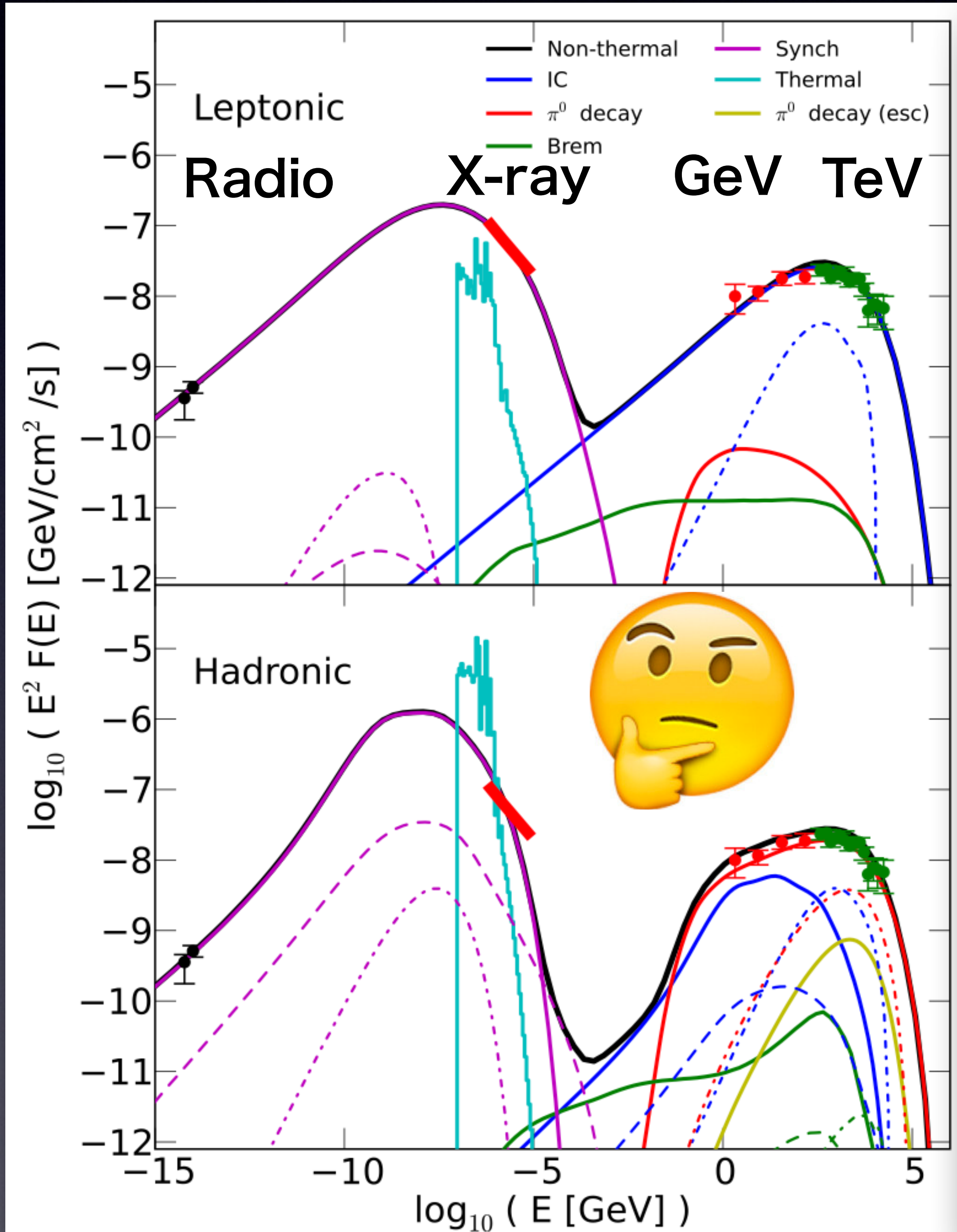


Slane, HL et al. (2014) on Tycho's SNR

Then, the all important non-thermal spectrum

In some cases, things are not so conclusive…

HL, Slane+ 2013 on SNR **Vela Jr.**



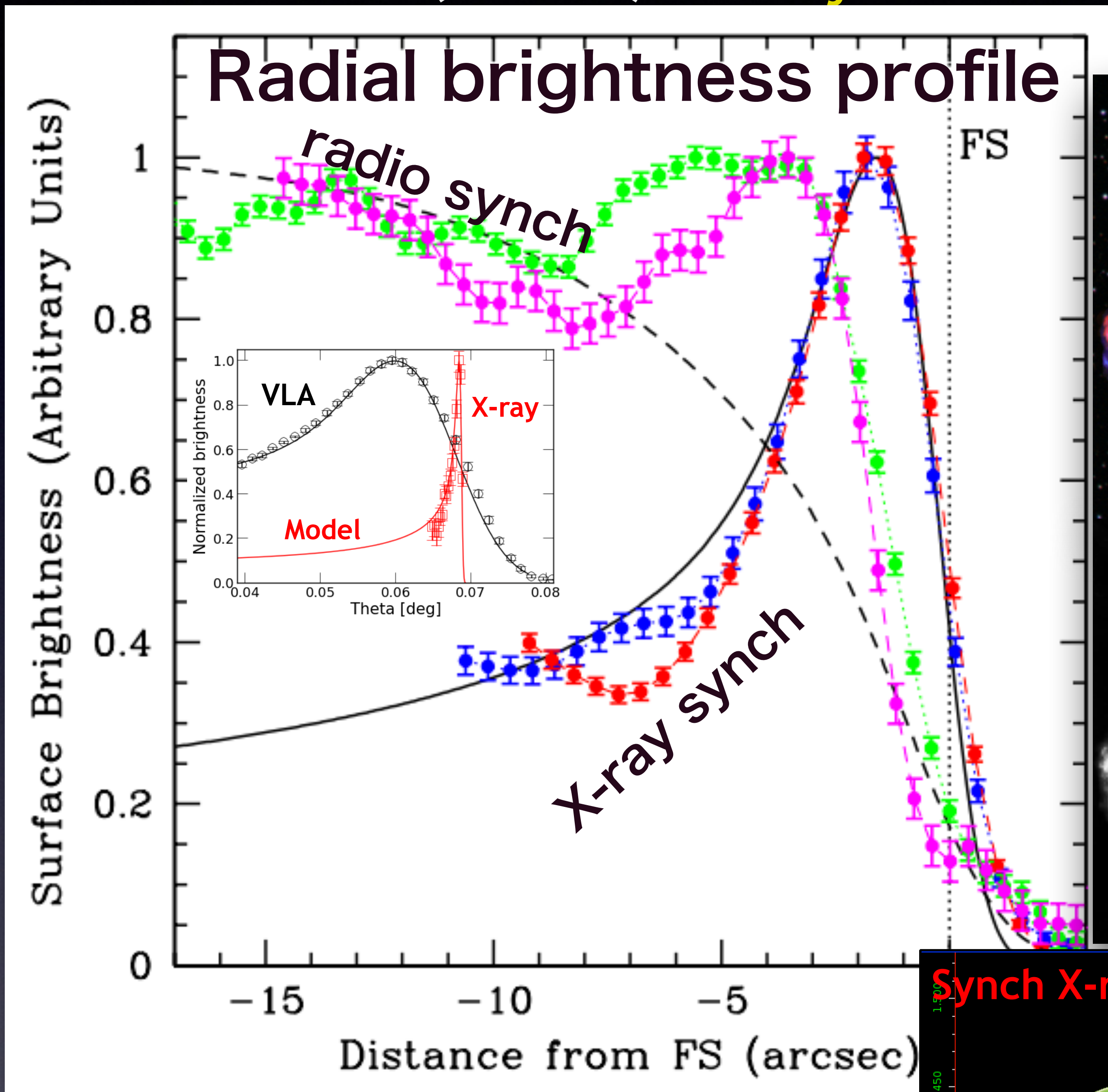
	Hadronic[b]	Leptonic[c]
Input parameters		
d_{SNR} (kpc)	0.74	0.88
n_0 (cm^{-3})	0.033	0.002†
B_0 (μG)	0.5	0.14†
dM/dt (10^{-6} $M_\odot$ yr^{-1})	…	7.5
V_{wind} (km s^{-1})	…	50
σ_{wind}	…	0.02
K_{ep}	1.5×10^{-4}	0.015
α_{cut}	0.75	0.50
f_{FEB}	0.15	0.12
f_{alf}	0.10	1.00
Output quantities		
R_{FS} (pc)	12.7	15.2
R_{CD} (pc)	10.3	12.5
V_{FS} (km s^{-1})	2130	4700
p_{max} (p) (TeV/c)	26.7	5.2
p_{max} (e^-) (TeV/c)	13.3	5.2
R_{tot}	9.30	4.69
R_{sub}	3.69	3.99
B_2 (μG)	34.1	4.8
T_2 (10^8 K)	0.16	3.62
ϵ_{acc}	0.84	0.36
ϵ_{esc}	0.34	0.12
E_{CR}/E_{SN} (f_{SN})	0.48	0.14

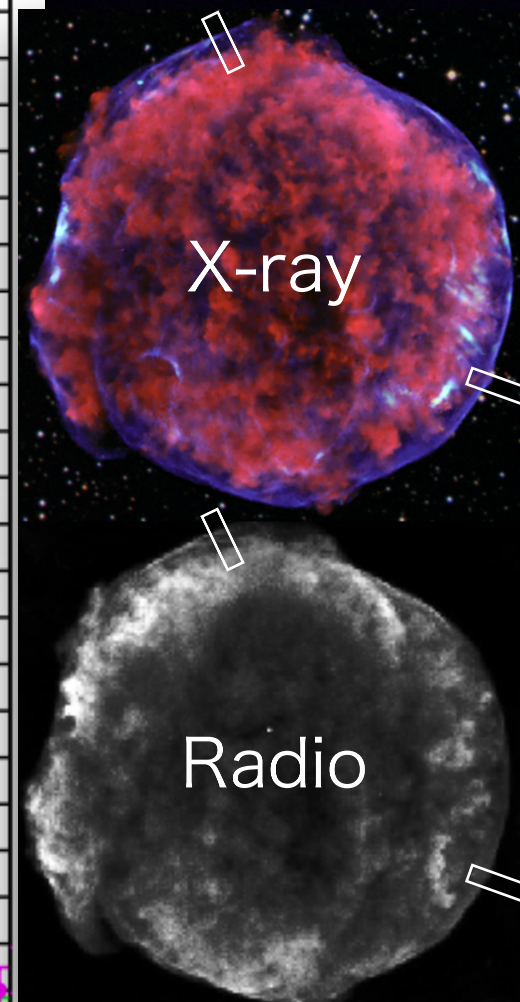
Hadronic vs leptonic has impact: big difference in E_{CR}, v_{sk} and T, …

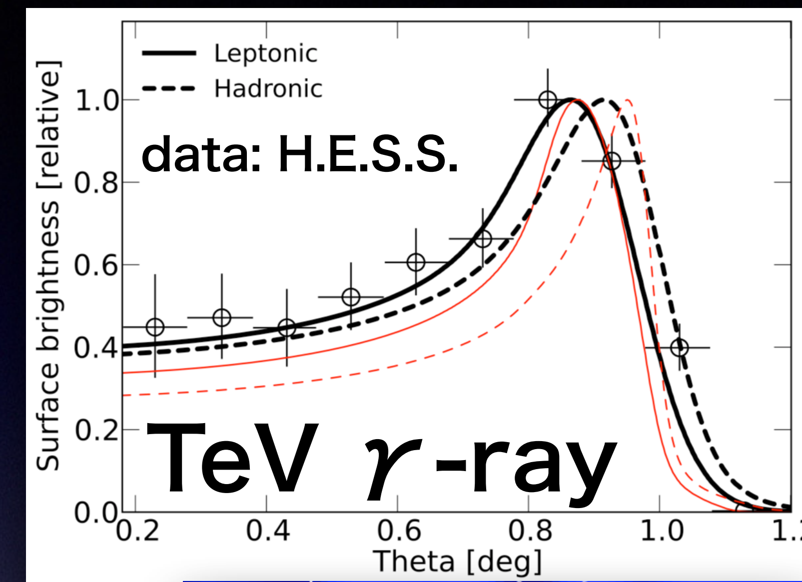
Brightness profiles are helpful too

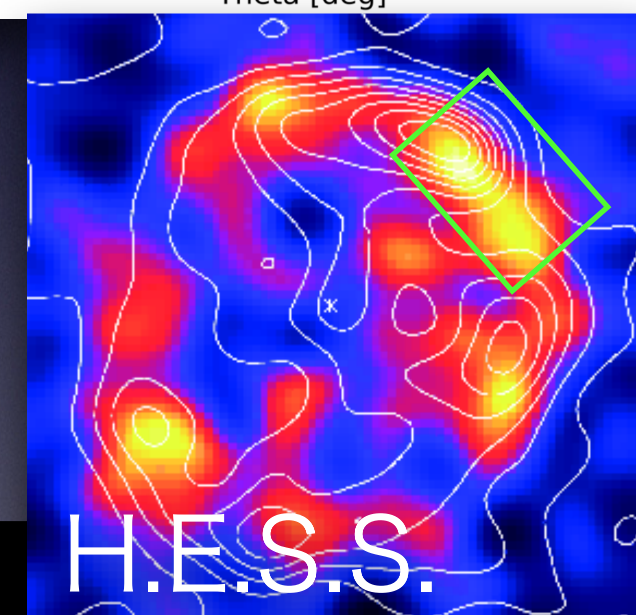
Slane, HL+ (2014) on Tycho's SNR

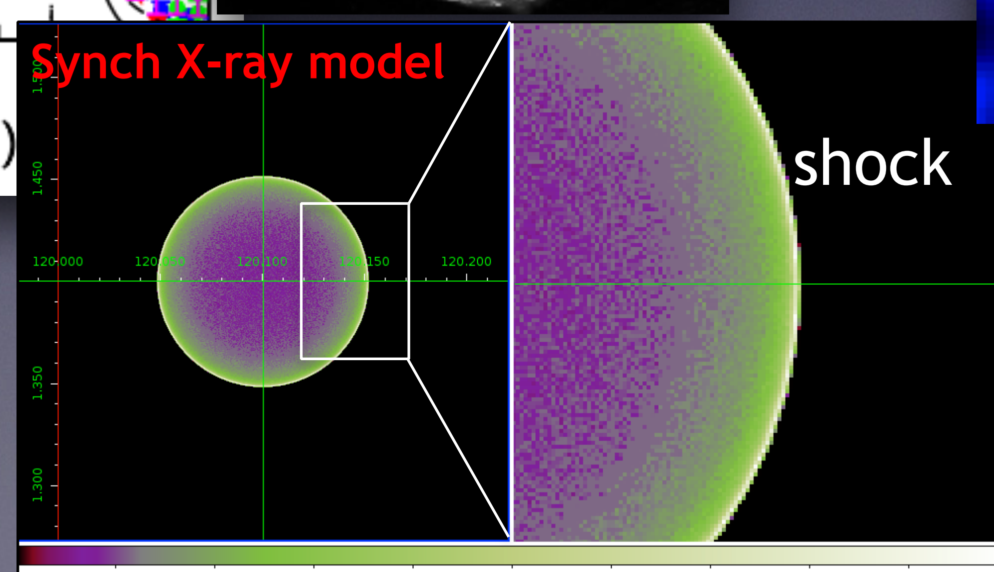
HL, Slane+ (2013) on Vela Jr.







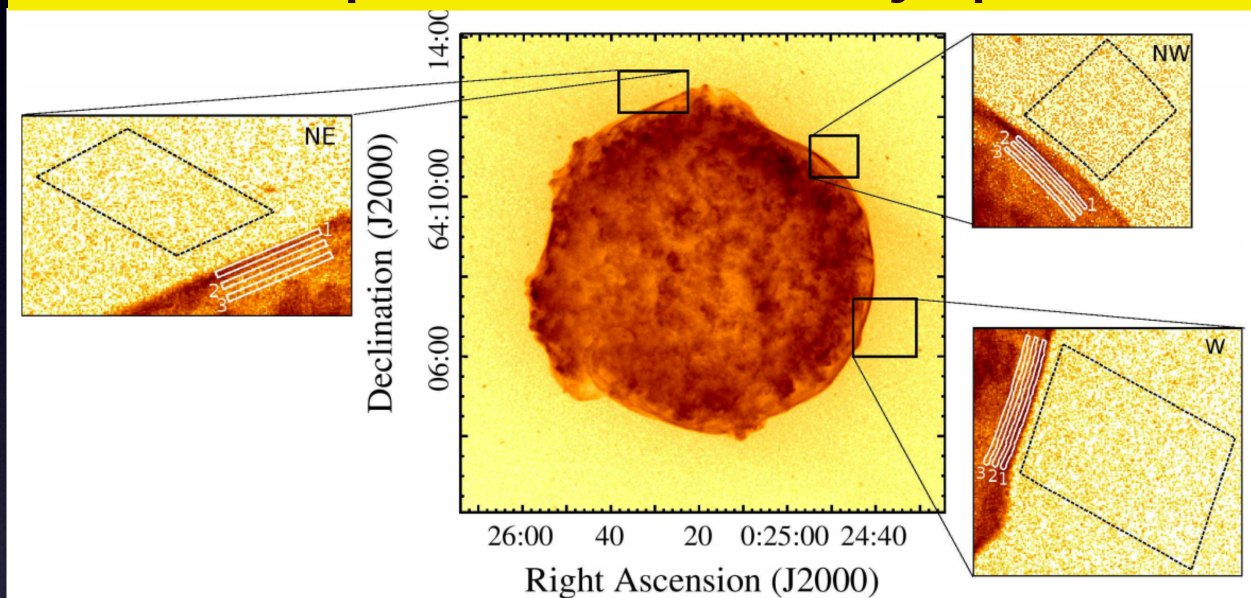




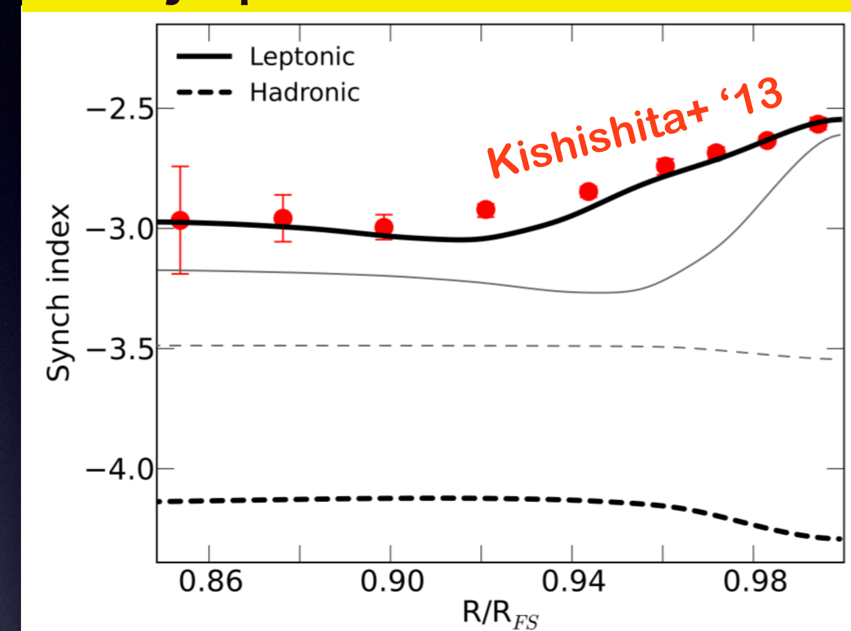
Best done in multi-wavelength!

One step further
Using "spectral images"

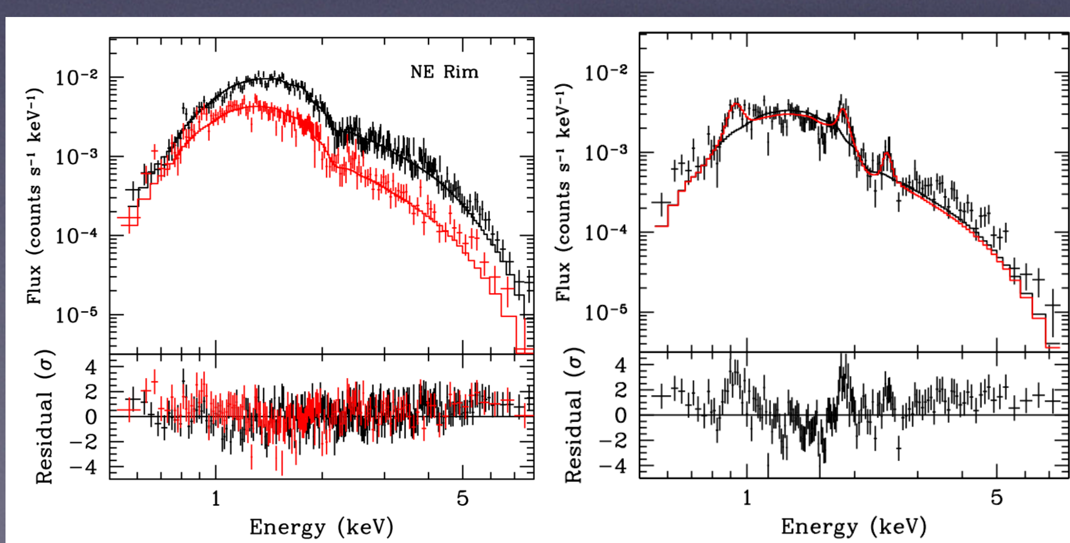
Chandra space resolved X-ray spectrum



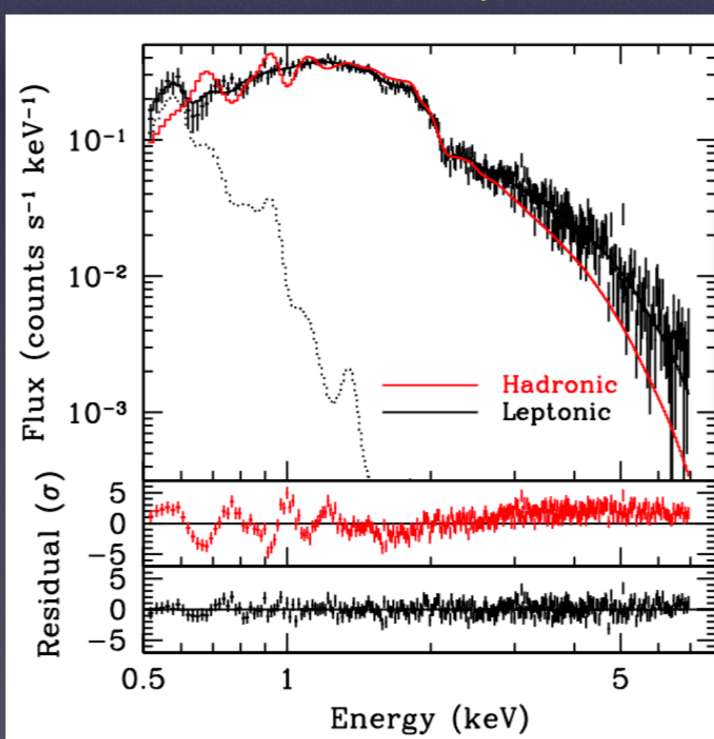
X-ray spectral index vs radius

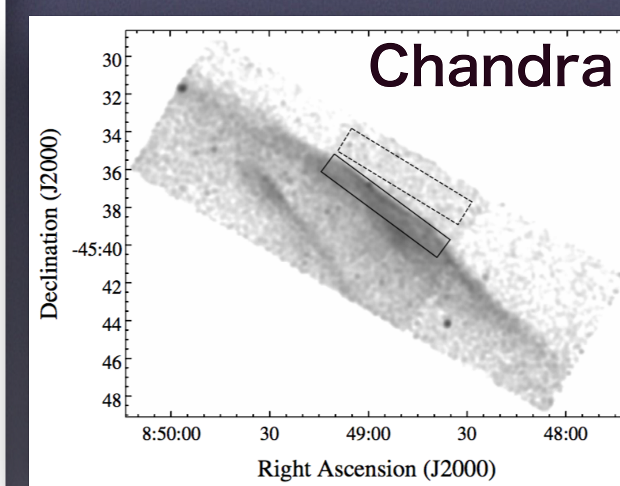


Slane, HL et al. (2014)
Tycho's SNR



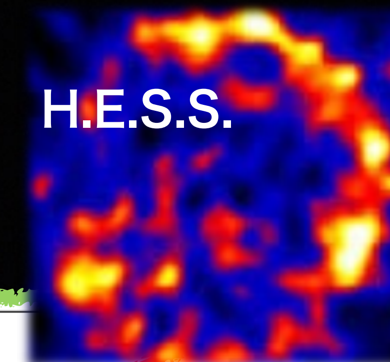
HL, Slane et al. (2013)
Vela Jr. SNR

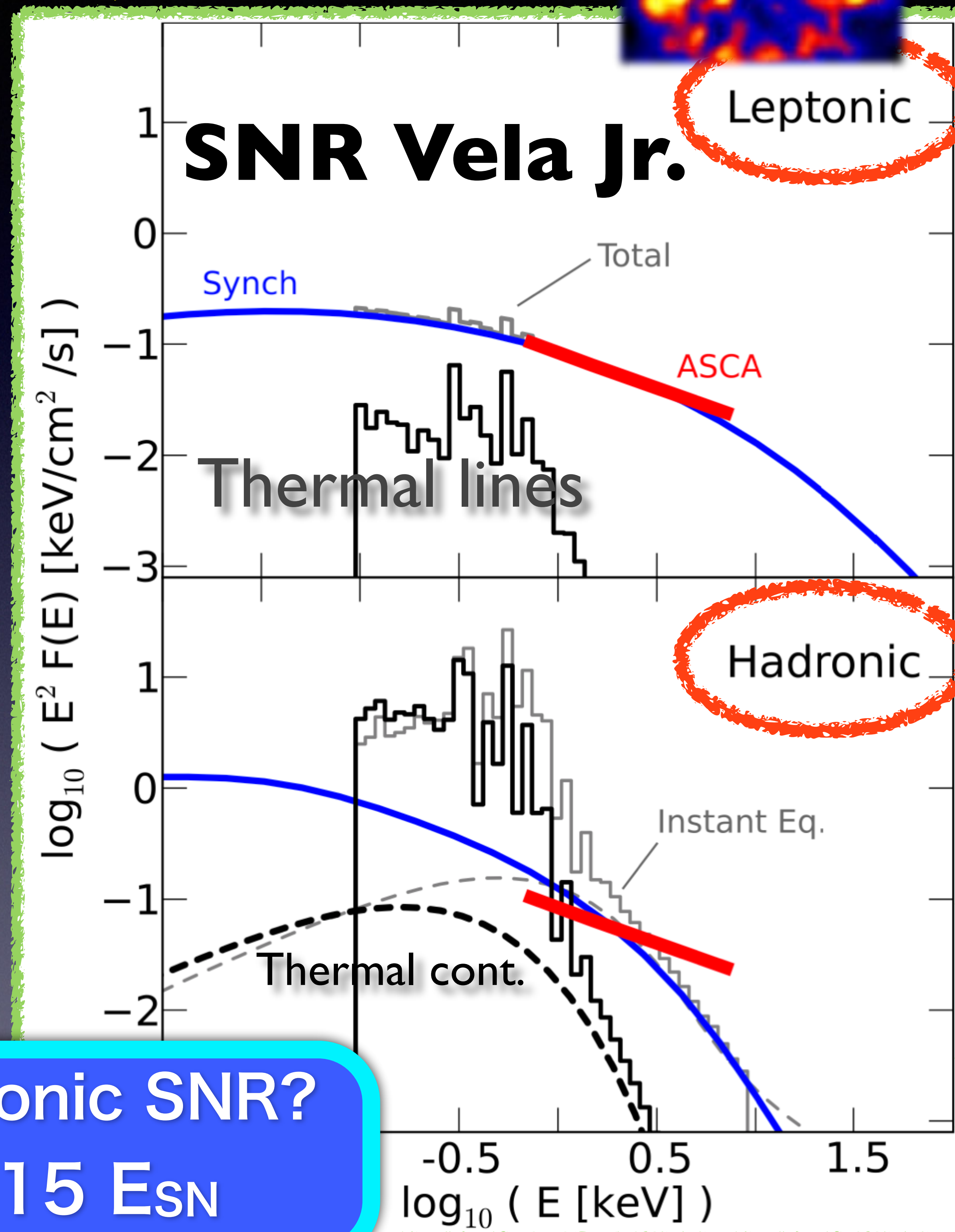




Thermal X-ray **can constrain** **Gamma-ray origin**

HL, Slane+ 2013





In young SNRs, thermal X-ray emission *coupled* to broadband emission!

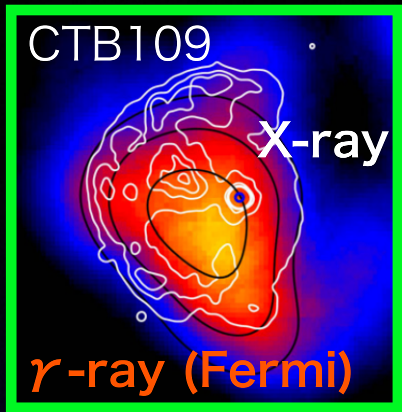
Predicted thermal flux must NOT exceed observed X-ray flux

See also talk by Y. Fukui

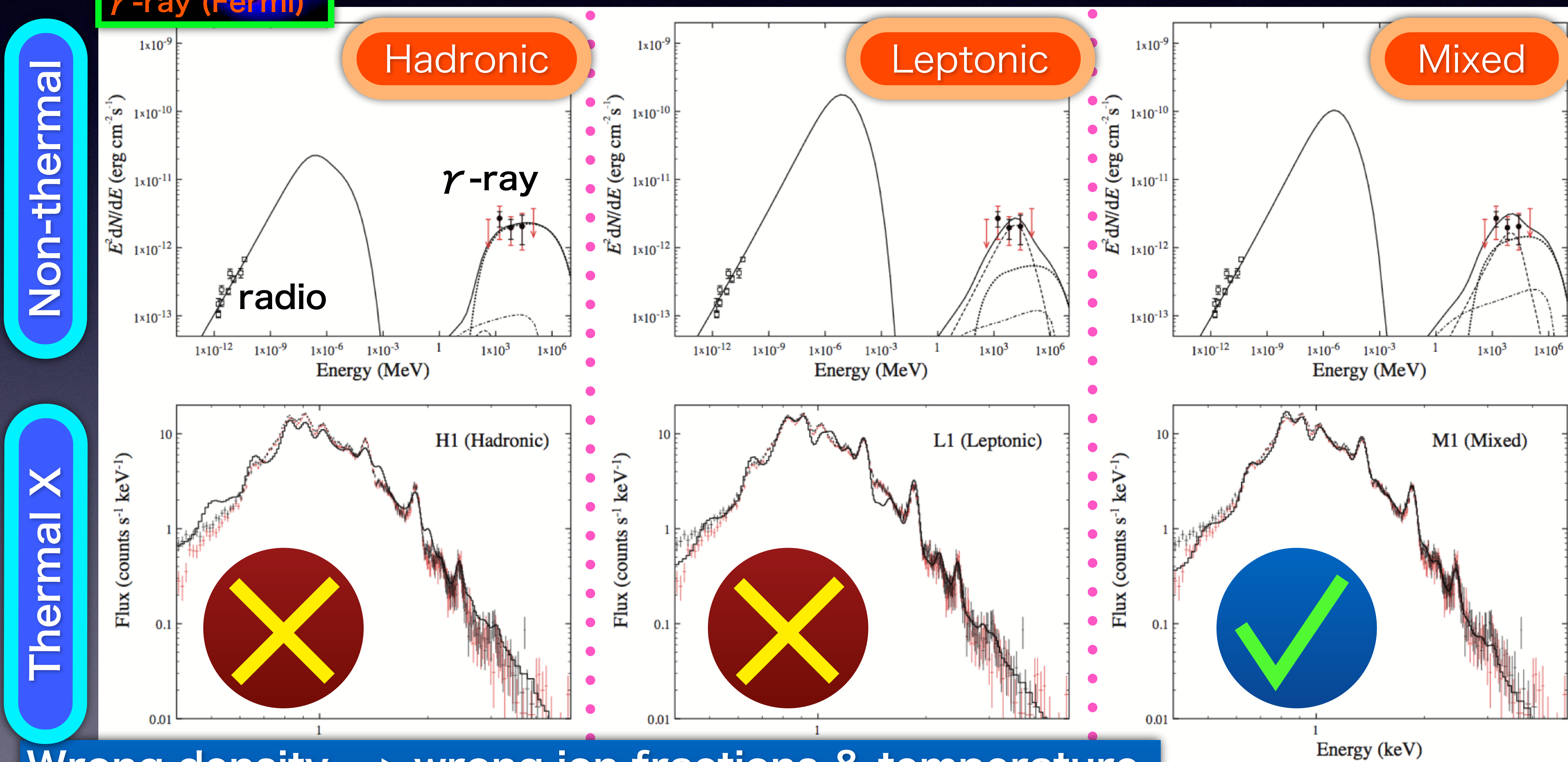
Mostly leptonic SNR?
$E_{CR} = 0.15\ E_{SN}$

Powerful constraint of non-thermal origin

Thermal X-ray Spectrum

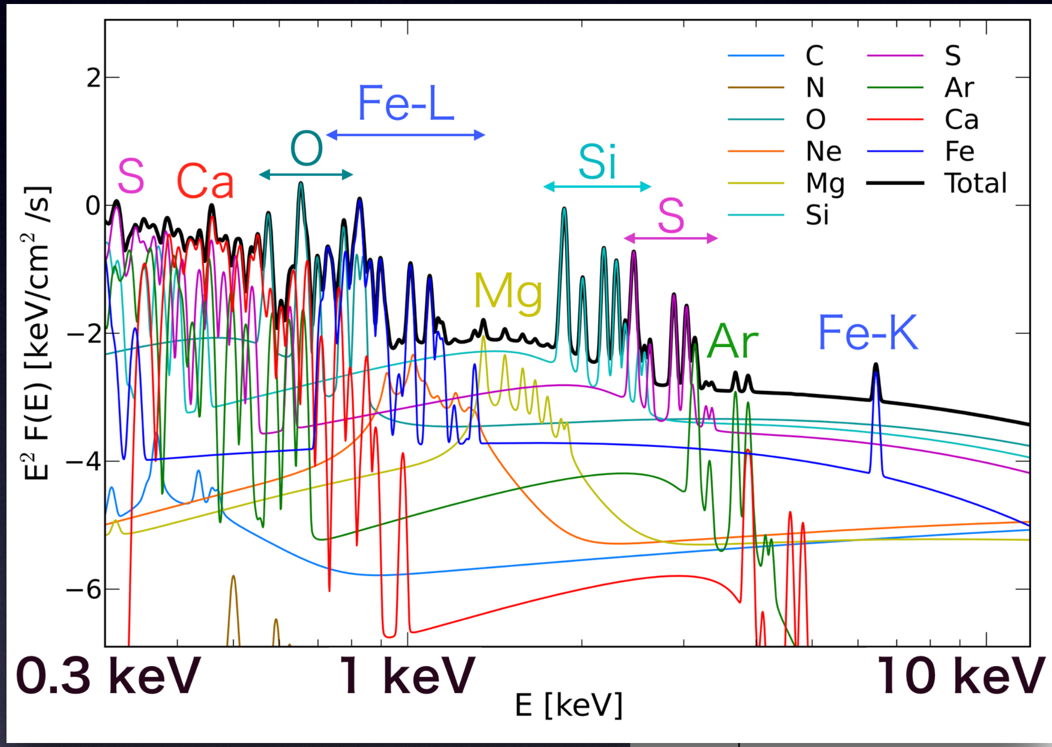


CR-hydro model by Castro+ (2012) on mid-aged CTB109

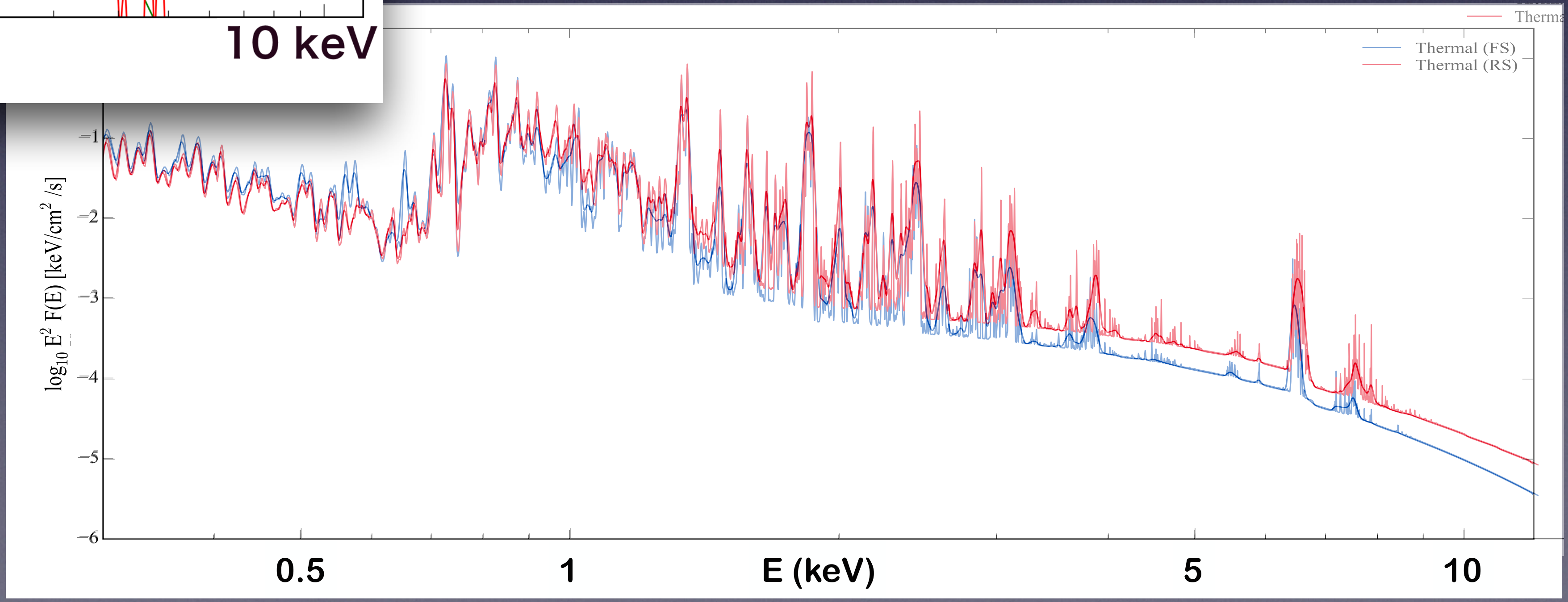


Wrong density —> wrong ion fractions & temperature
—> wrong thermal X-ray spectrum

Detailed thermal models for future X-ray spectroscopy



CR-hydro-NEI code
+ SN ejecta model
+ Atomdb

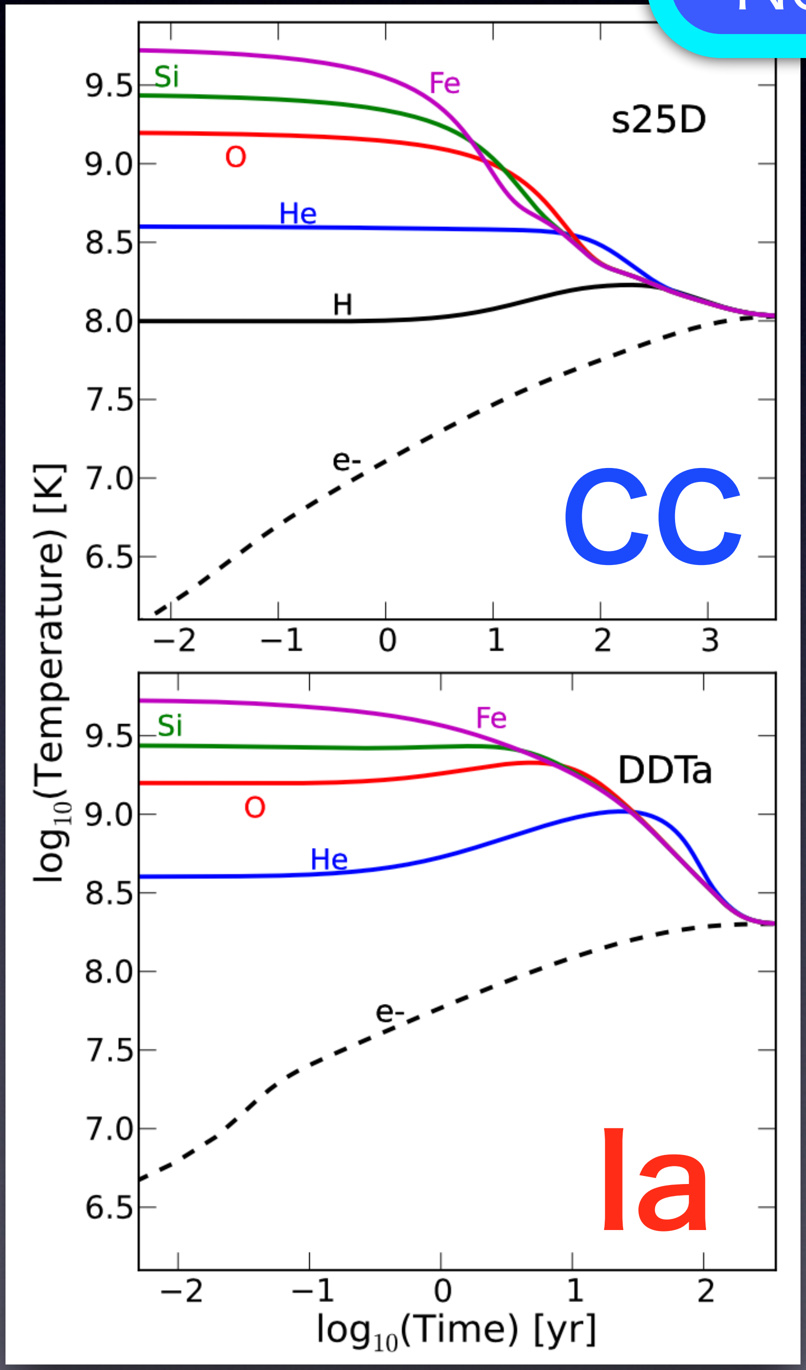


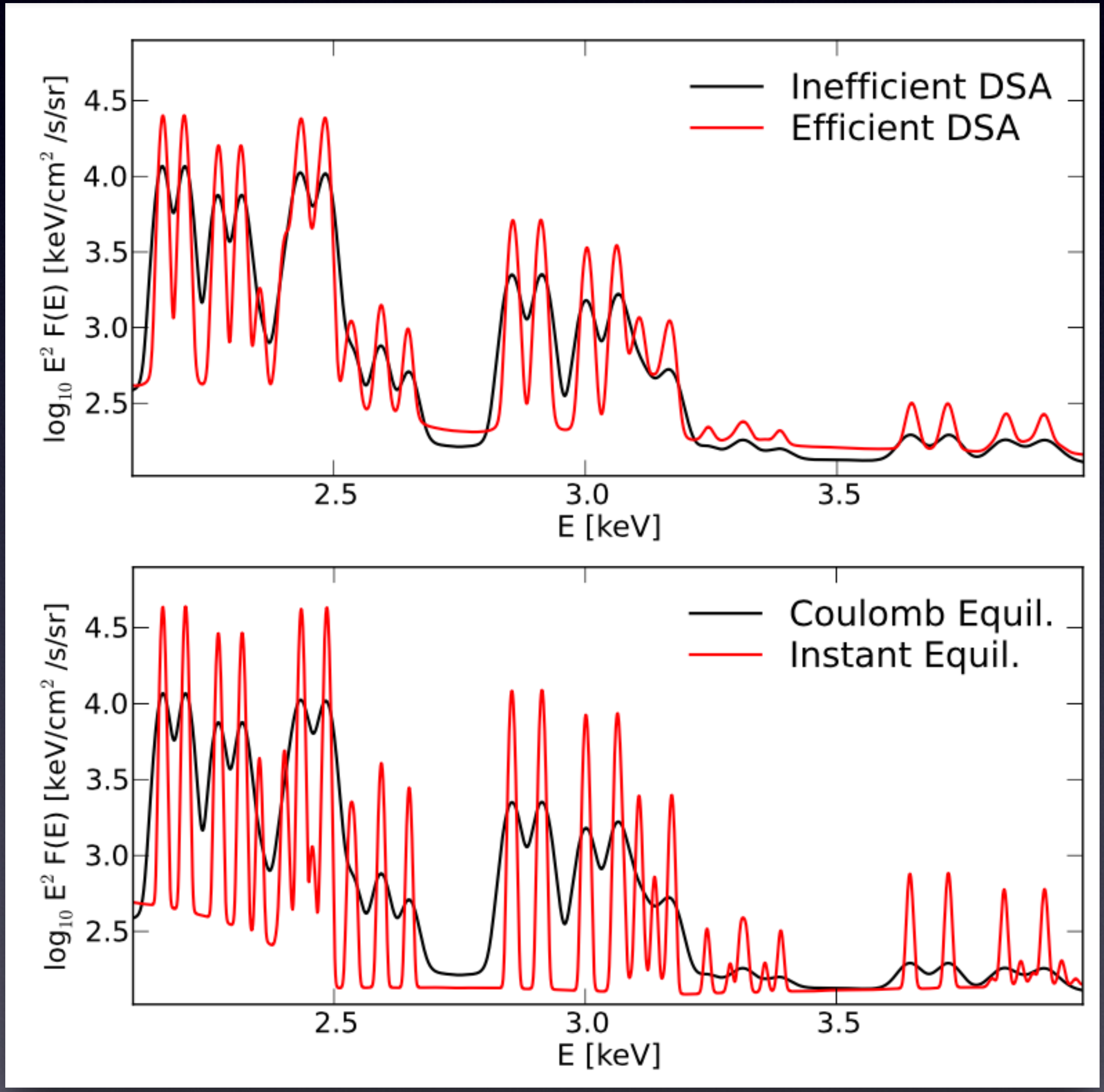
HL+ 2016

Thermal X-ray line profiles

Crossover of thermal and non-thermal physics!

Need high-resolution broadband spectroscopy



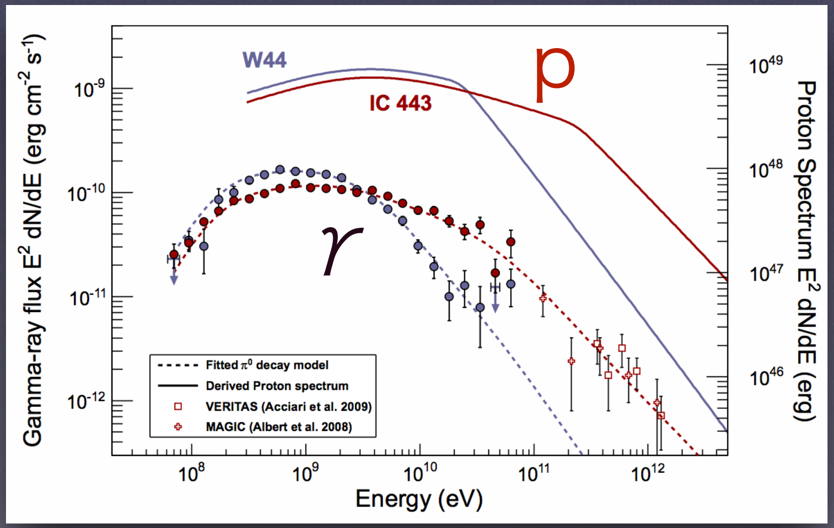


HL, Patnaude+ (2014)

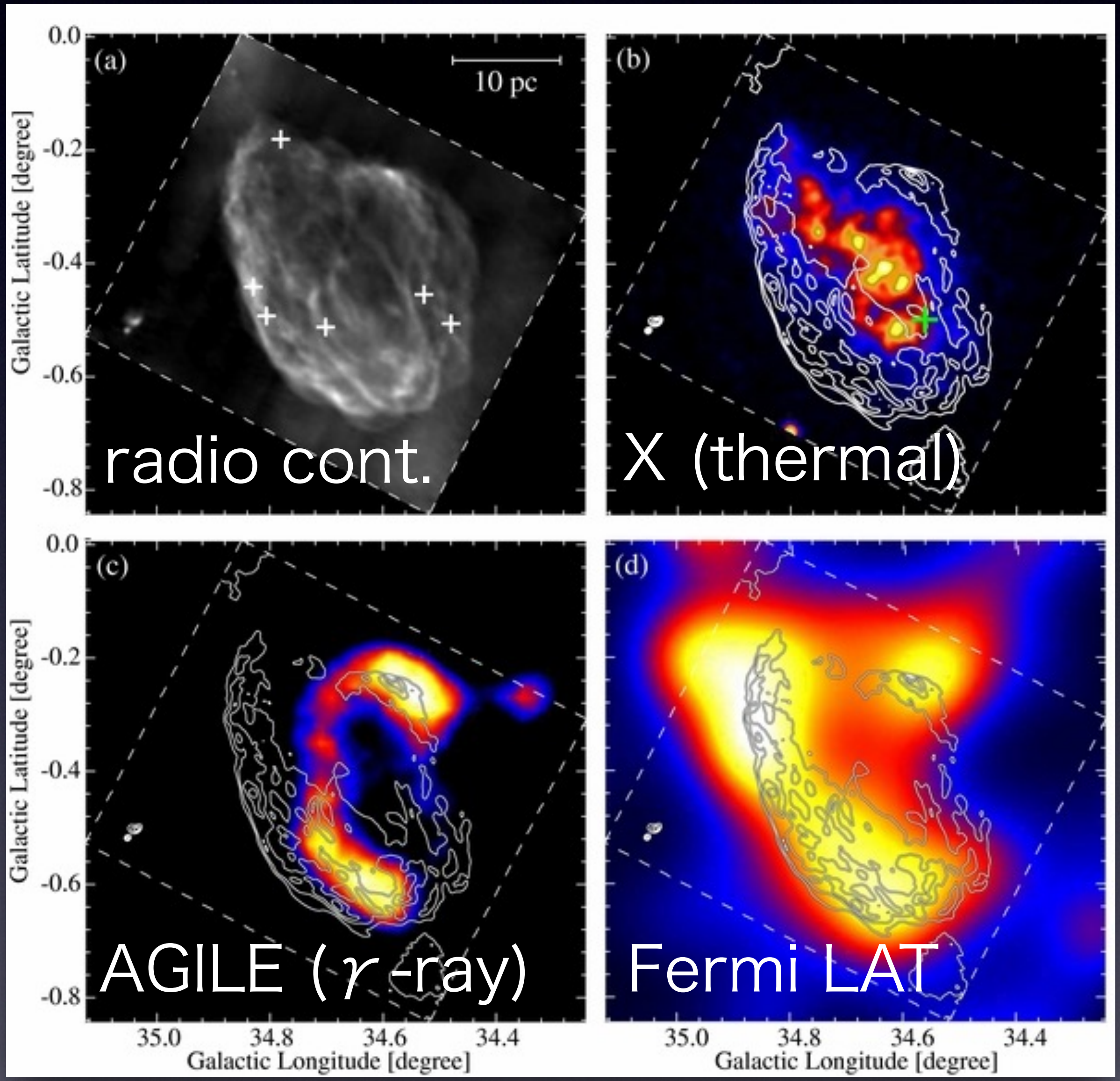
Bright γ-rays from Middle-aged SNRs

- ★ Many **GeV-bright SNRs** in our Galaxy found by Fermi, AGILE
- ★ Mostly **middle-aged SNRs** interacting with **molecular clouds**
- ★ Evolved, have slow shocks, but **bright radio, GeV γ-rays**
- ★ **Lots of CR protons, B >> μG**

Fermi LAT collaboration, Science 2013



SNR W44 (Yoshiike+ 2013, 2017)



Radiative shock hydrodynamics

with full non-equilibrium ionization (NEI) and cosmic-ray re-acceleration

$$3/2\, k_B\, dT/dt = -(n_e n_p/n)\,\Lambda + \Gamma + (\kappa/n)\nabla^2 T$$

Cooling function

- ★ Follow NEI of 12 elements: H, He, CNO, Ne, Mg, Si, S, Ar, Ca, Fe
- ★ UV/optical continua and lines
- ★ Cooling is fast, close to isochoric

Heating function

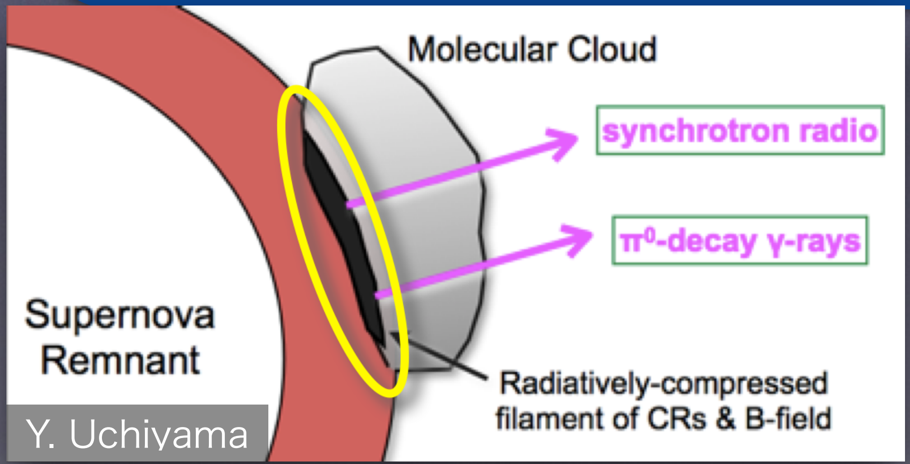
- ★ Radiative transfer of strong UV lines and continua
- ★ Absorption, photoionization
- ★ Heating by photoelectrons

(e.g. Gnat & Steinberg 2009)

Thermal conduction

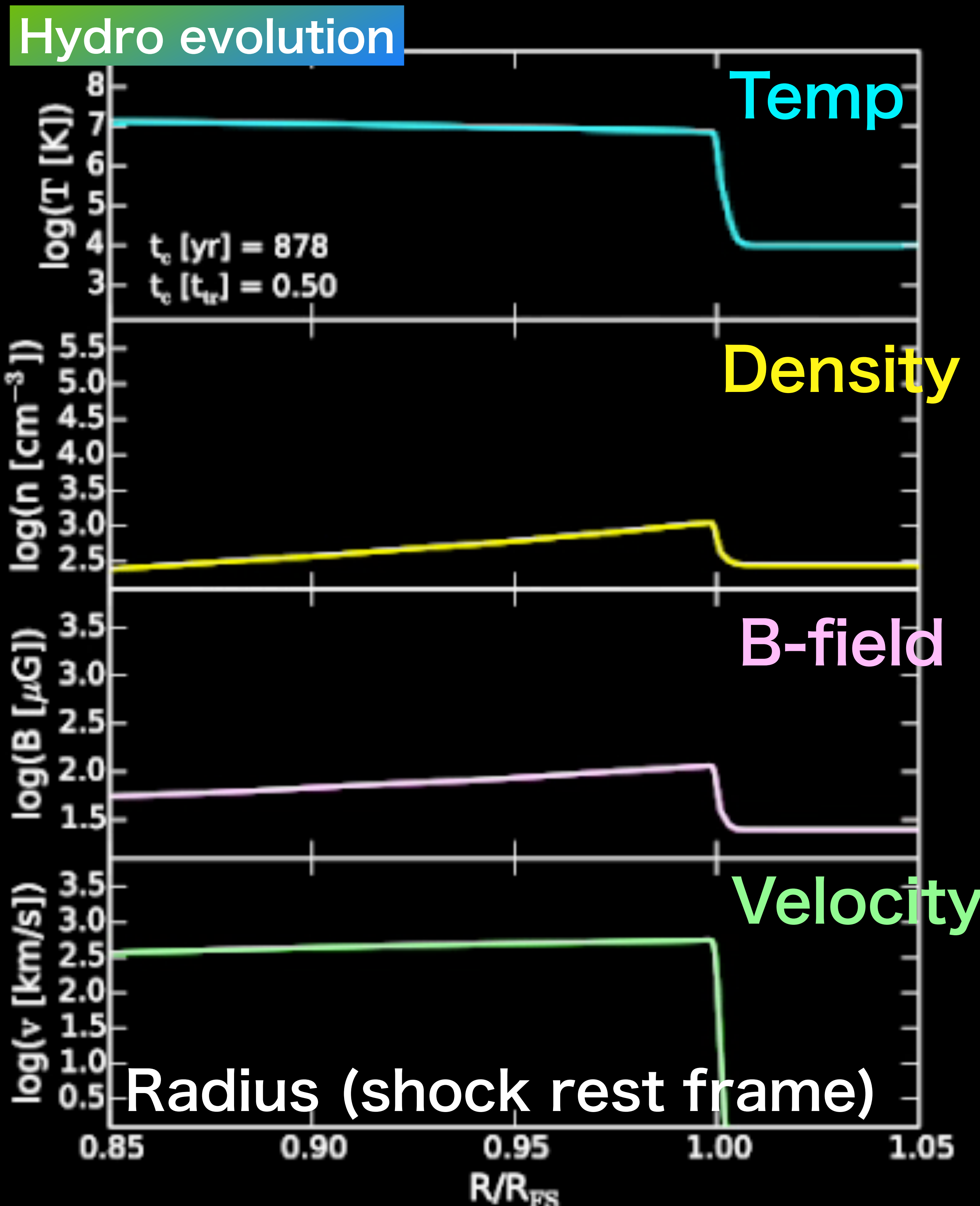
- ★ Conductivity $\kappa = f\,\kappa_{\rm Spitzer}$
- ★ f = 0.3 for collisionless plasma, hindrance by B-field

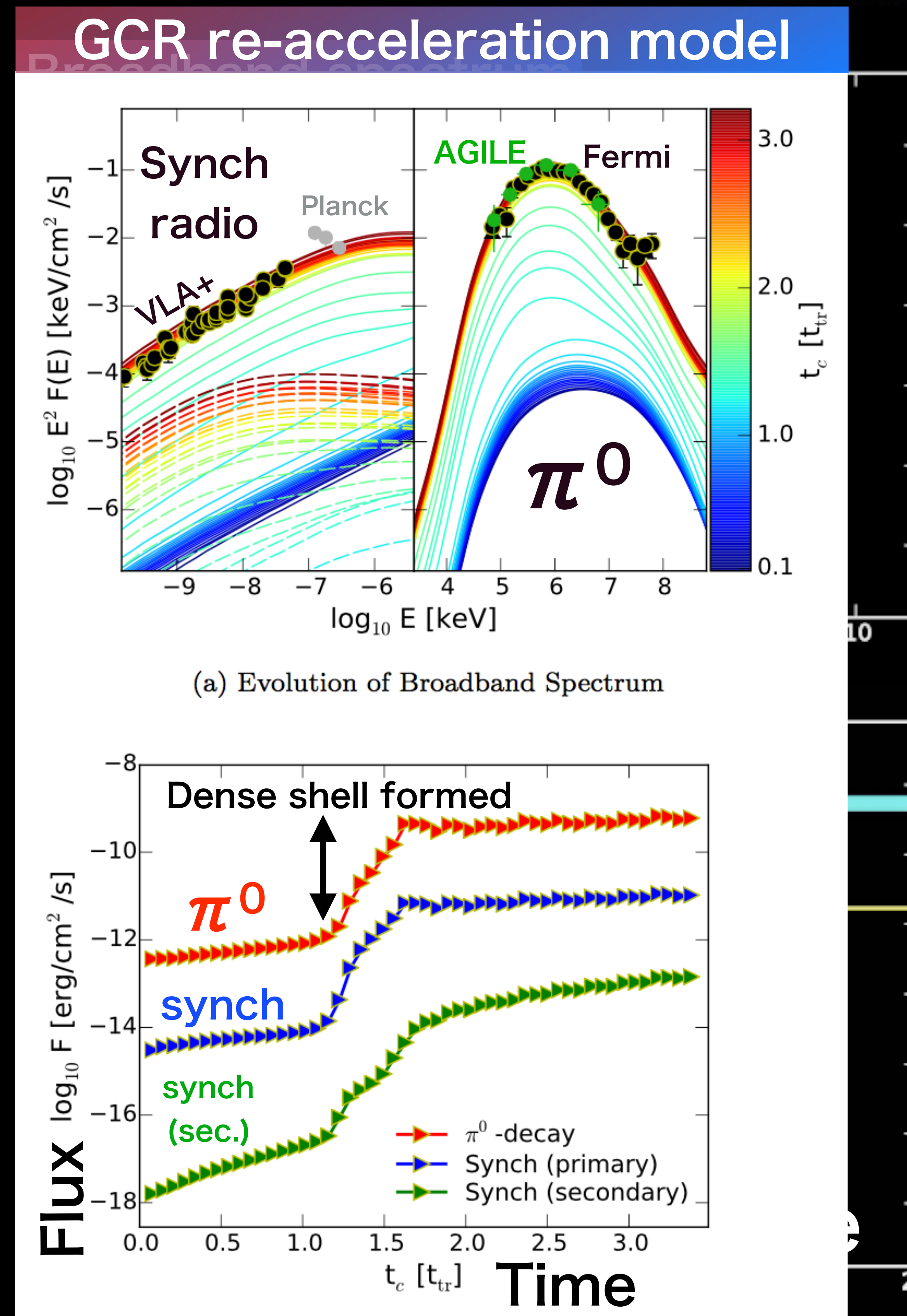
(e.g. Zakamska & Narayan '03, Bale+ '13)



HL, D. Patnaude, J. Raymond+ 2015

Hydrodynamics and Spectral Evolution

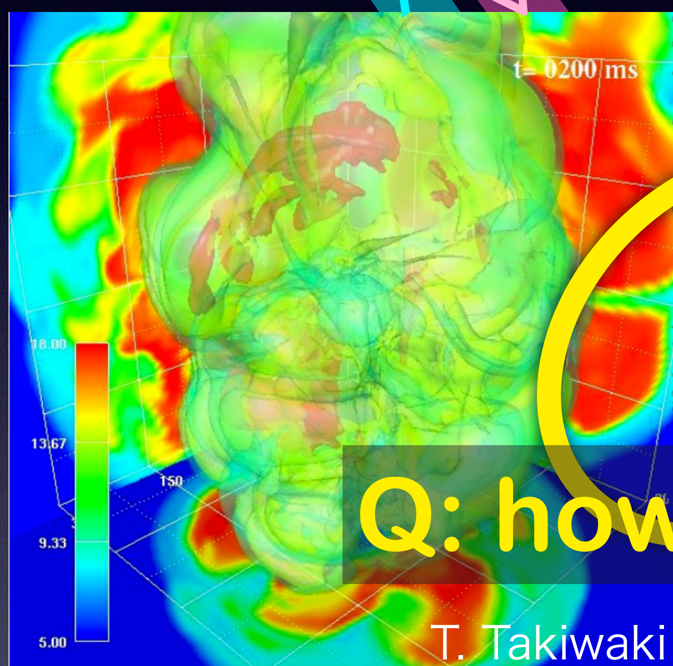




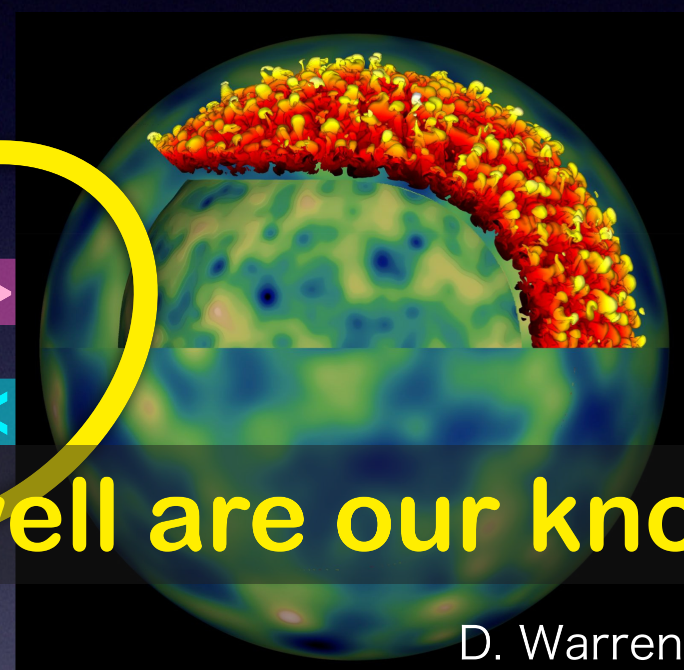
(a) Evolution of Broadband Spectrum

(b) Evolution of Integrated Flux

The Quest
"From engine to remnant"



Supernovae



SN Remnants

What we see

Q: how well are our knowledge connected?

Models

Full understanding of late-stage stellar evolution requires good communication between stellar evolution, SN and SNR communities

An Important Application

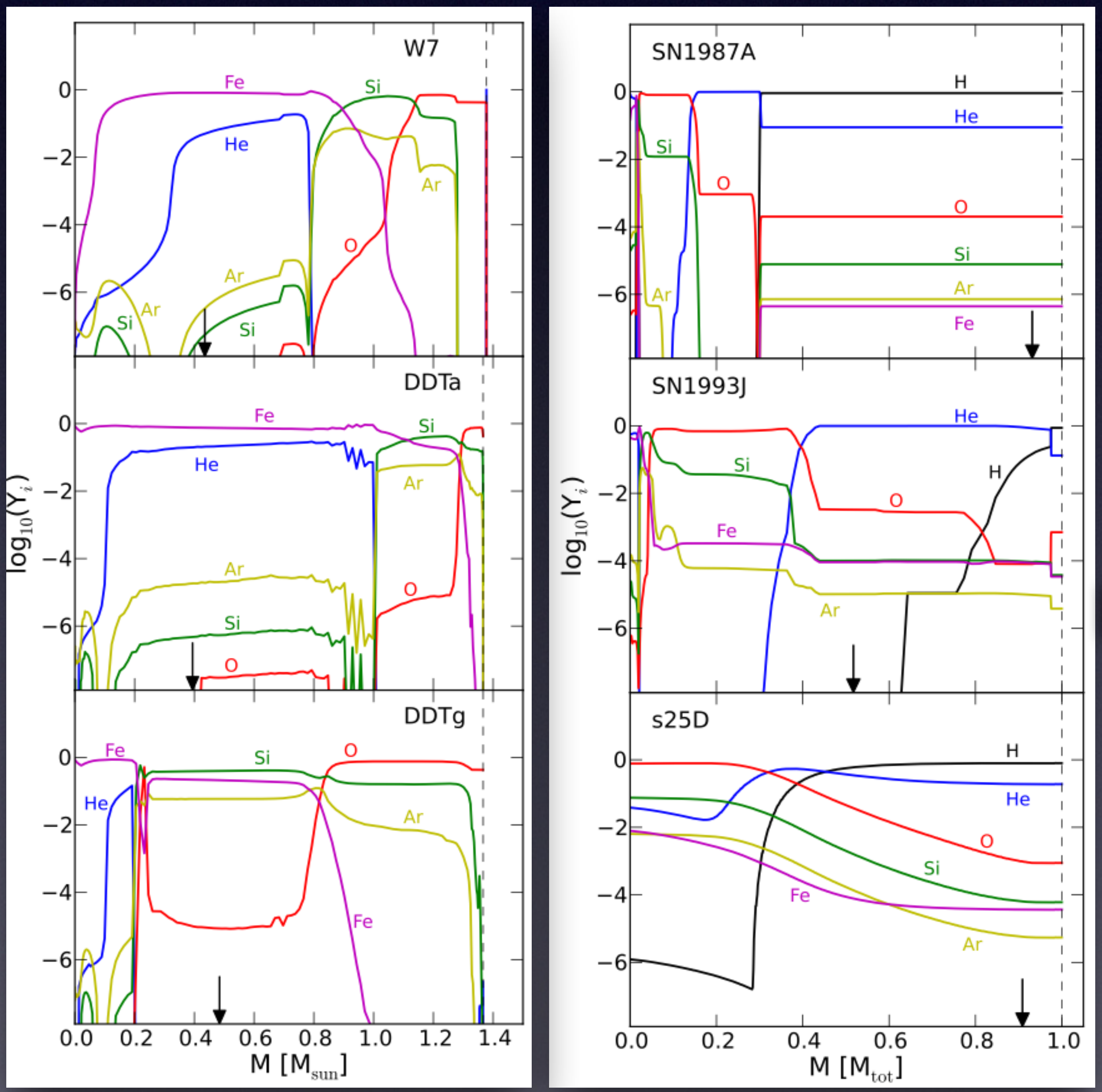
Q: Are current SN models consistent with SNR observations?

Basic method:

☑ Evolve an SN ejecta to its SNR phase

☑ Calculate the emission properties self-consistently with hydro!

Chemical Abundance



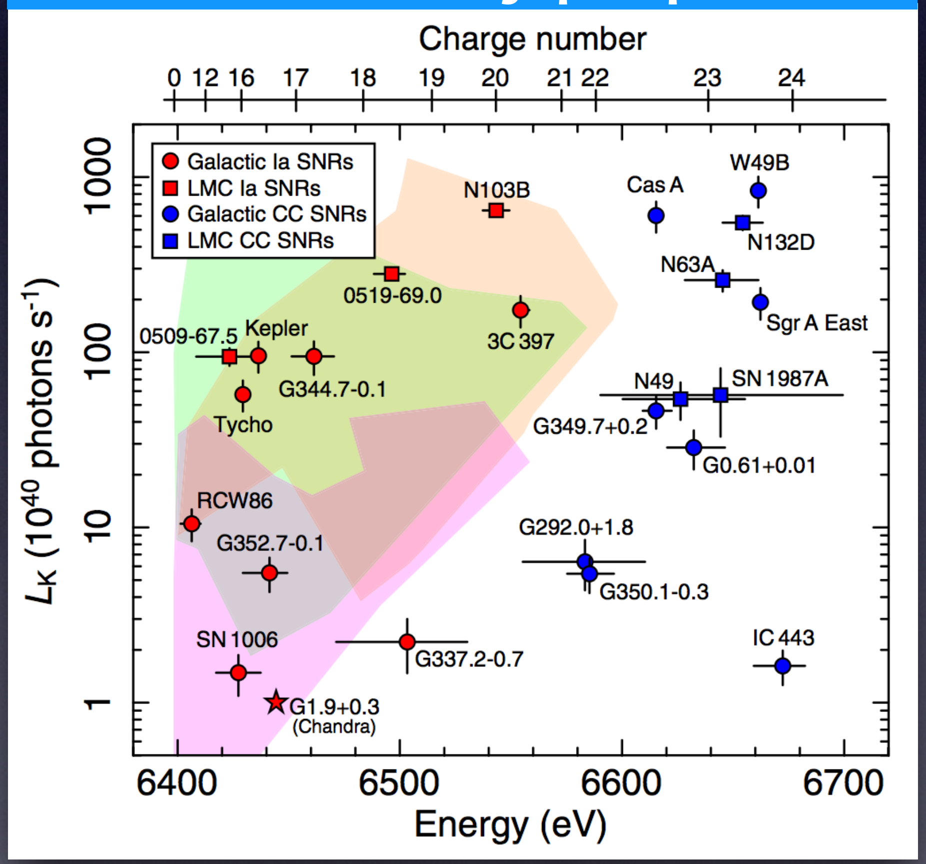
Mass coordinate

HL, Patnaude+ 2014

Check

Broadband model

Observed X-ray properties

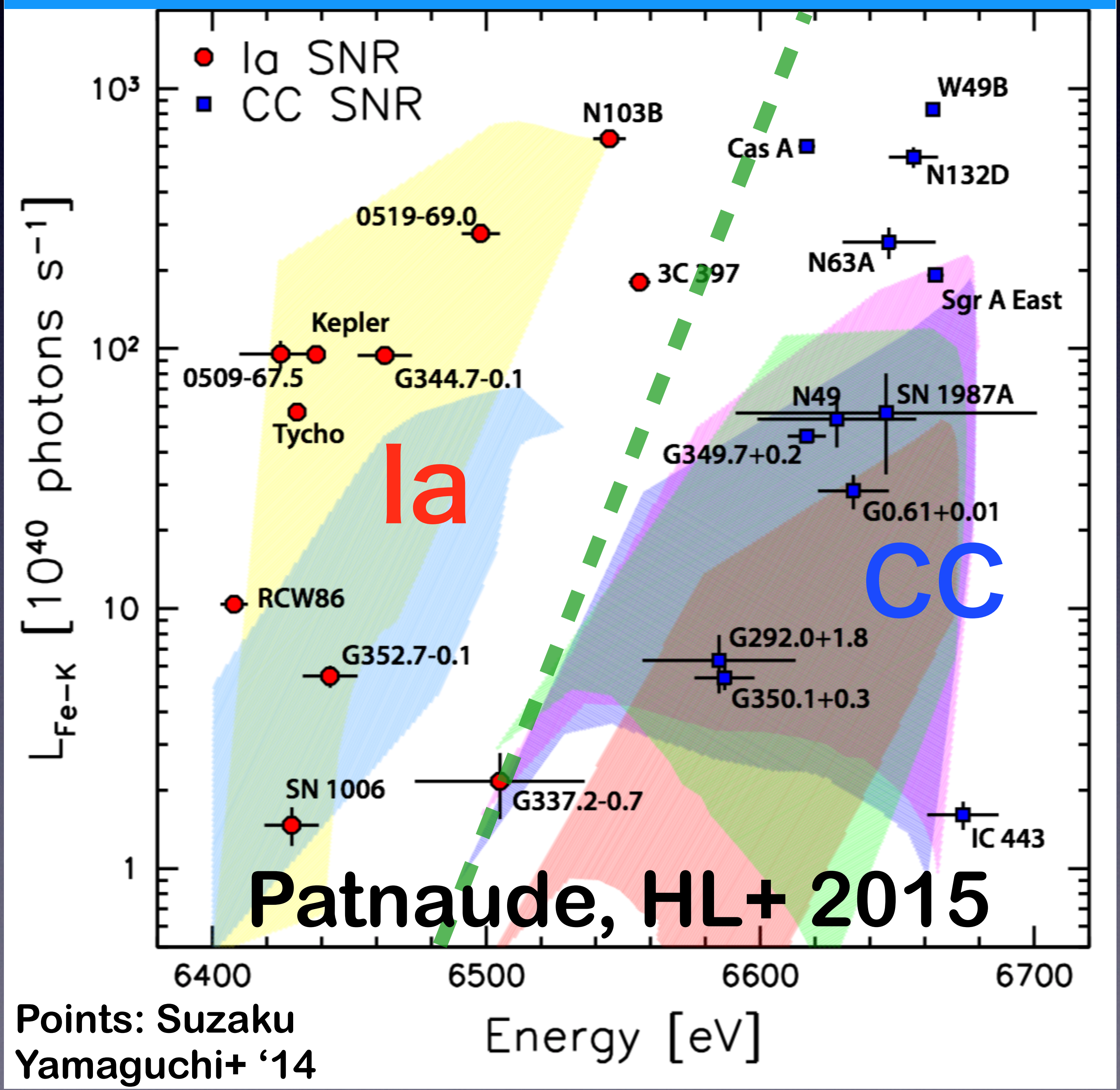


Suzaku/Chandra, Yamaguchi+ 2014

Separation of Fe-K line centroid between Ia & CC

Broad consistency between SN model and SNR data

Color bands = our models

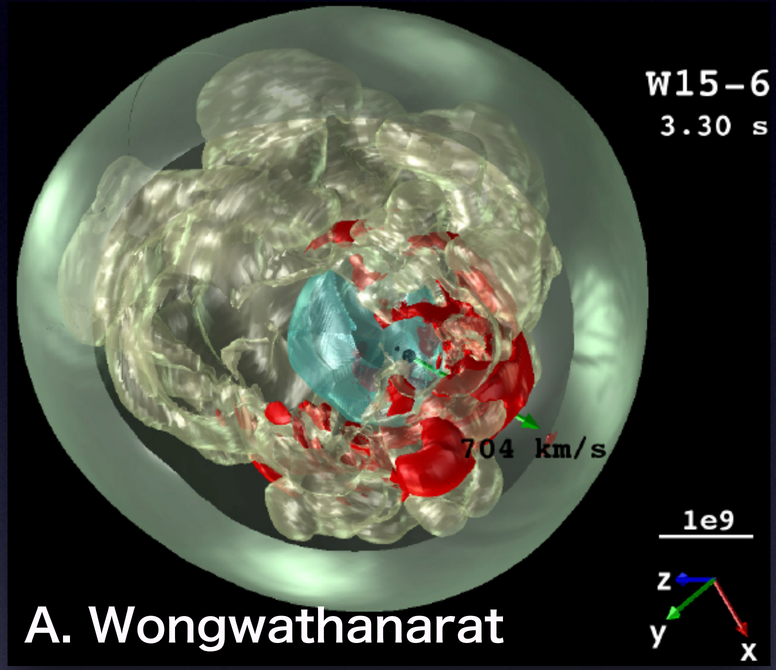


Points: Suzaku Yamaguchi+ '14

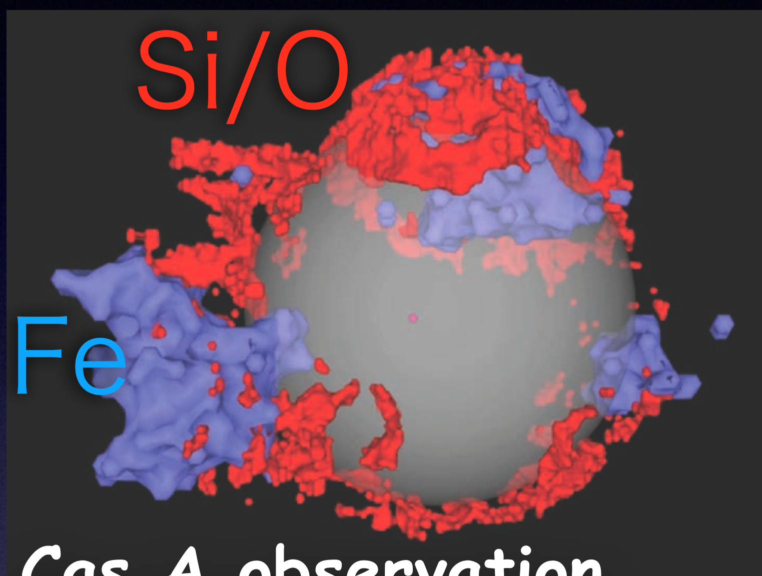
- Key is ***general difference in circumstellar environment!***
- **CC encounters dense wind**
  i.e., ejecta hit dense wind
  —> stronger reverse shock
  —> higher ionization state
  —> higher line centroid energy
- **Ia usually has more low-ρ environment**
- Origin of scattering in plot
  = dispersion in age, progenitor and CSM properties
- Several 'special' outliers:
  Often dense cloud interaction

Phenomena in multi-dimension

- Inhomogeneous CSM
- Non-trivial progenitor structure
- Asymmetrical SN explosions
- Ejecta mixing, fast knots, fingers, bubbles
- Other external effects, e.g. B-field obliquity



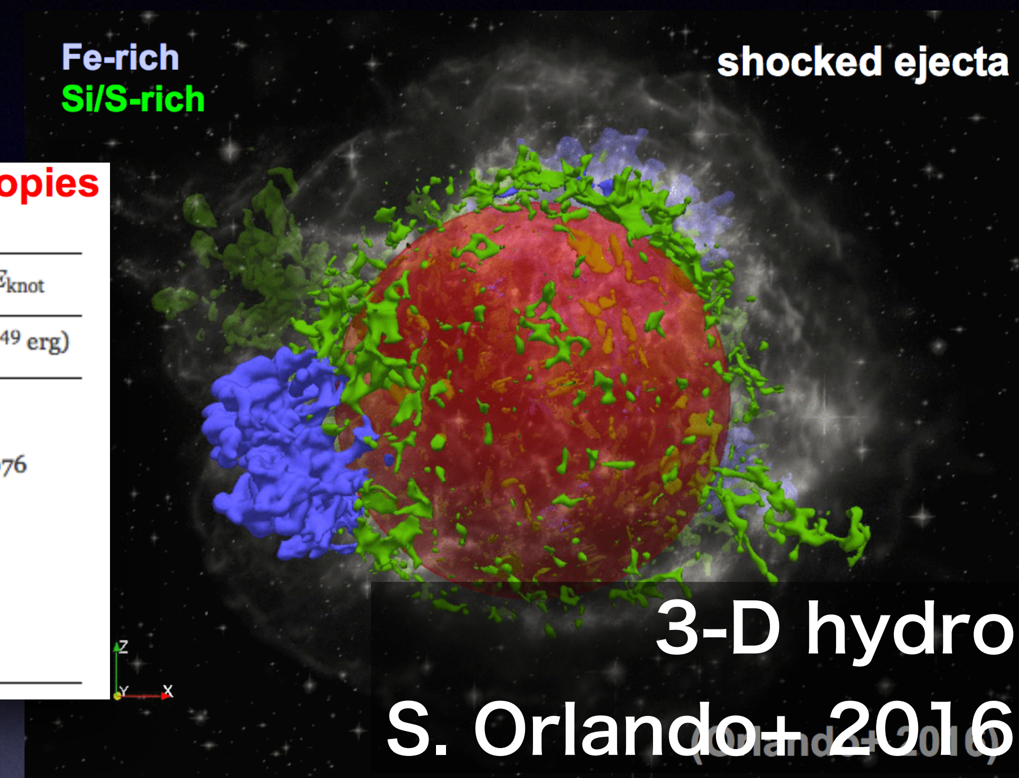
Highly inhomogeneous ejecta in SNR
Challenge to hydro models



Cas A observation
Milisavljevic & Fesen '13

Parameters of large-scale anisotropies

Piston/Jet	D_{knot} (R_{SNR})	r_{knot} (R_{SNR})	χ_n	χ_v	M_{knot} ($M_\odot$)	E_{knot} (10^{49} erg)
Fe-rich SE	0.15	0.05	100	4.2	0.10	5.0
Fe-rich SW	0.15	0.02	50	4.2	0.0015	0.076
Fe-rich NW	0.15	0.06	50	4.2	0.10	4.8
Si-rich NE	0.35	0.1	5.0	3.0	0.040	4.2
Si-rich SW	0.35	0.1	1.2	3.0	0.0091	1.0



3-D hydro
S. Orlando+ 2016

High-resolution 3-D hydro model
'Large-scale' Si/S and Fe-rich knots in SN ejecta can broadly reproduce observed structure
(Si/S-Fe overturning, rings etc)

Source of perturbations
= convection plumes in progenitor?

'Rings' in unshocked ejecta
(Orlando+ 2016)

Summary

- We have reviewed on the general methodology and capabilities of modern broadband models for SNRs
- Current limitations mainly from yet incompletely understood physics
  - Rely on rich MW observational data AND breakthroughs from first principle simulations to remove “free” parameters
- Our future is on progenitor-SN-SNR connection
  - More meetings like this one is necessary
  - Bigger picture, less ambiguous, more fun