Broadband Emission Models for Young to Middle-aged Supernova Remnants and What To Learn from Them

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The Art of Broadband Modeling

- Nowadays, broadband models must satisfy zillion 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 simulation results
  - A few parameters, from yet incomplete physical understandings
  - Approximations to work around complex processes, and/or computational cost

Common Ingredients of a SNR Broadband Model

- (Magneto-) hydrodynamics
- Progenitor, supernova explosive nucleosynthesis models
- (Observation-motivated) 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
- All thermal and non-thermal emission calculations in various forms to confront data

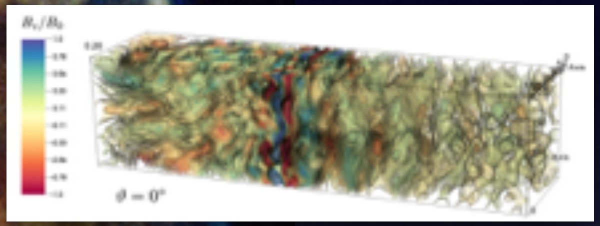
Numerical Approaches for SNRs

Particle-in-cell

Hybrid

First principles
Few or no parameter/approx

Computational cost
Limited dynamical ranges
Difficult for multi-λ model



Caprioli & Spitkovsky '14

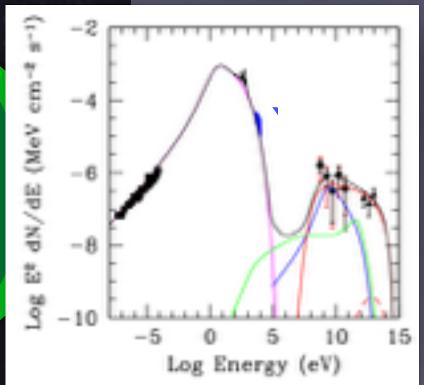
Monte Carlo

Semi-analytic

Global HD/MHD
with microphysics

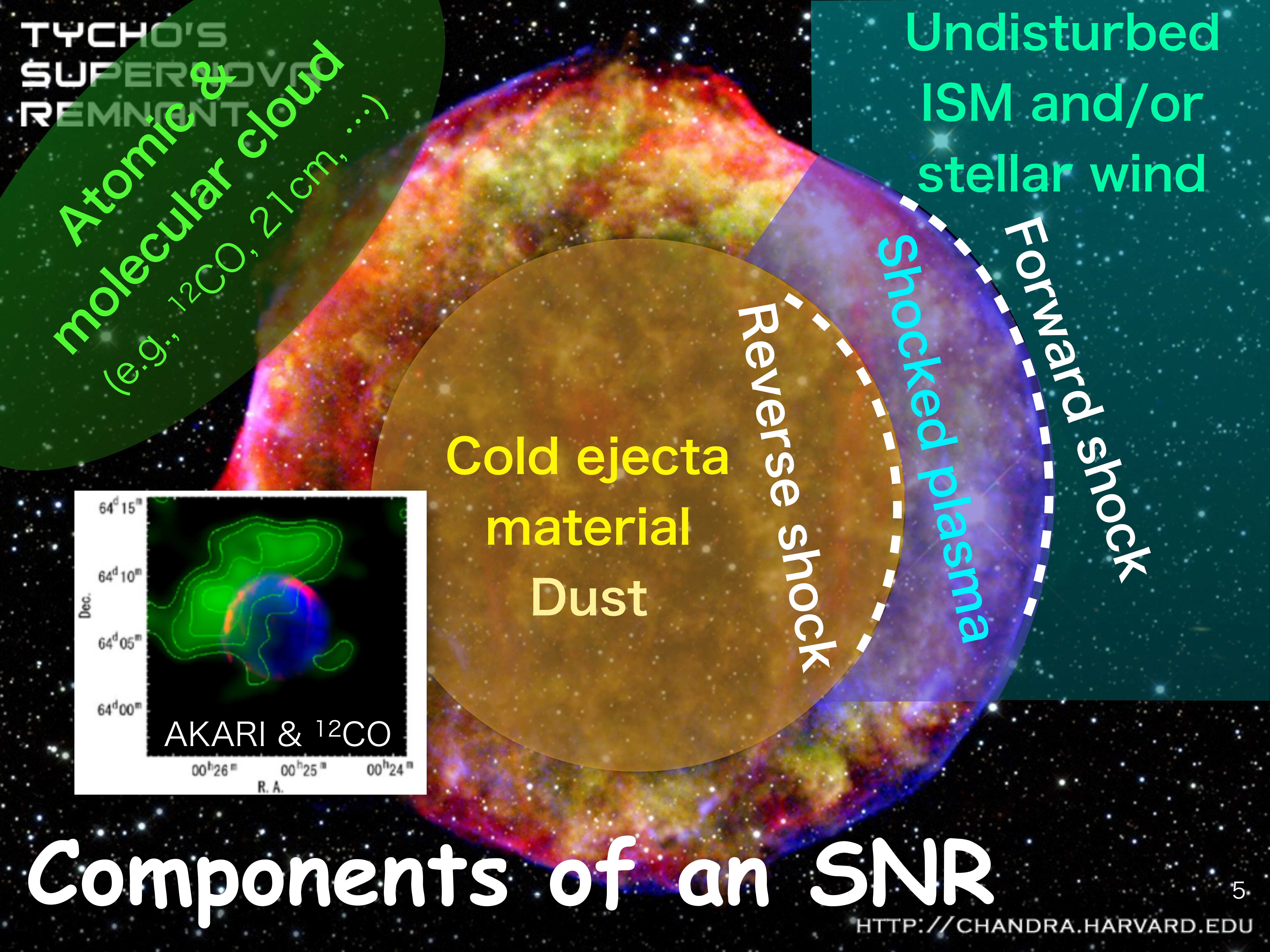
More phenomenological
(parametric) plasma physics

Large dynamical ranges
Constrained by
multi-λ observations

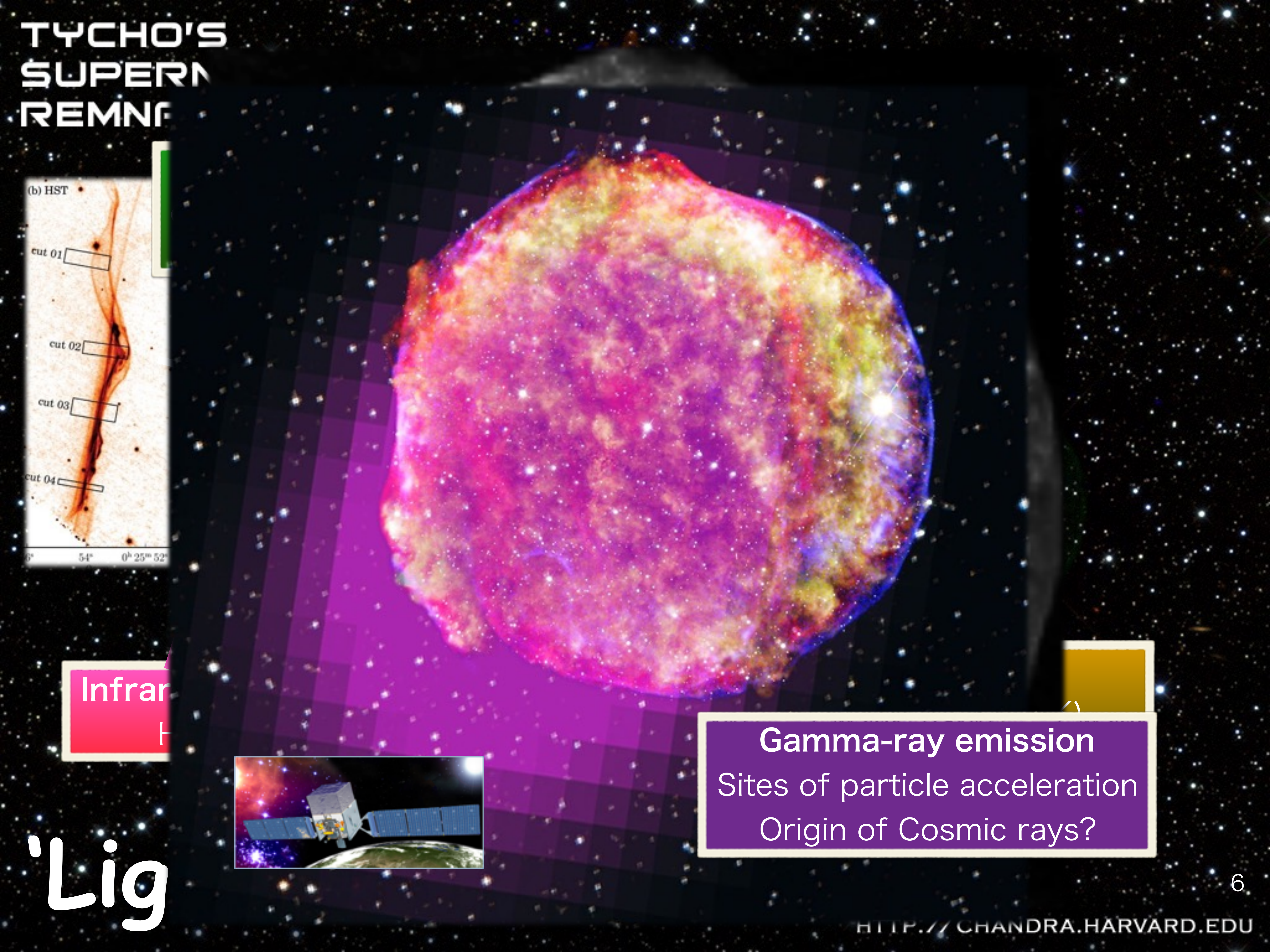


Slane, HL+ '14

P. Slane



Components of an SNR


TYCHO'S
SUPERN
REMNA
(b) HST
cut 01
cut 02
cut 03
cut 04
Gamma-ray emission
Sites of particle acceleration
Origin of Cosmic rays?
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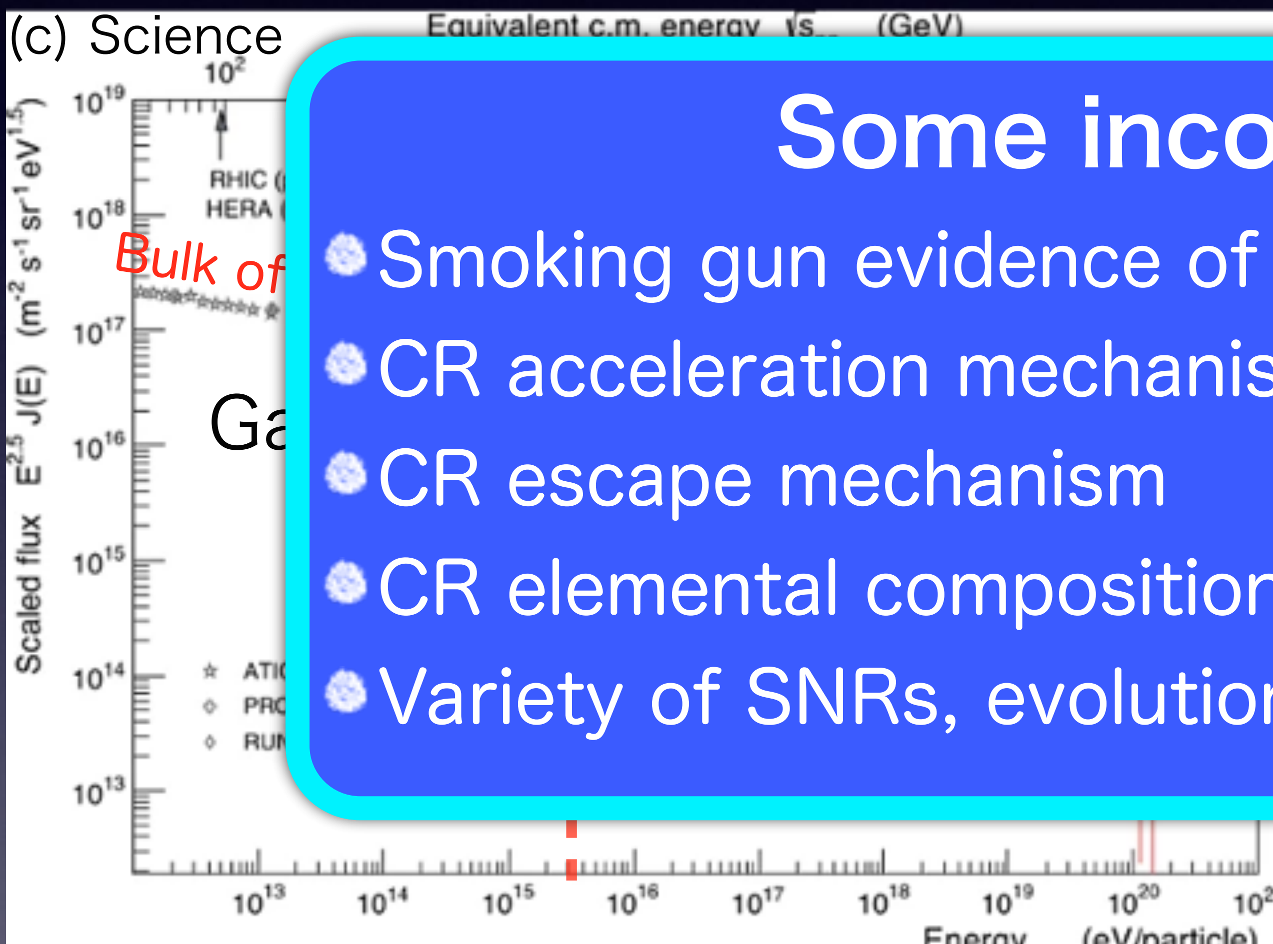
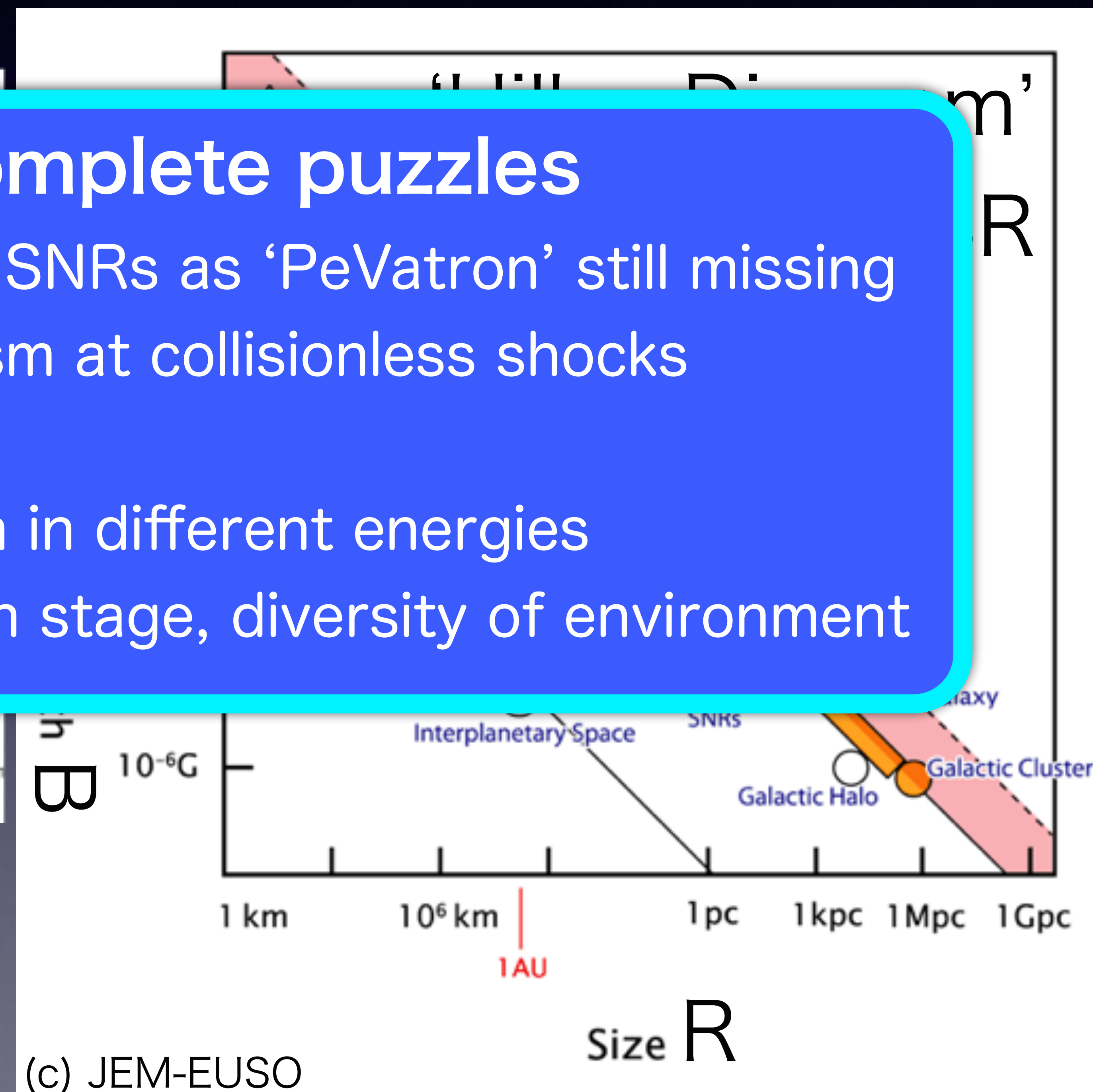
HTTP:// CHANDRA.HARVARD.EDU

SNRs as origin of cosmic rays in galaxies



TeV PeV EeV

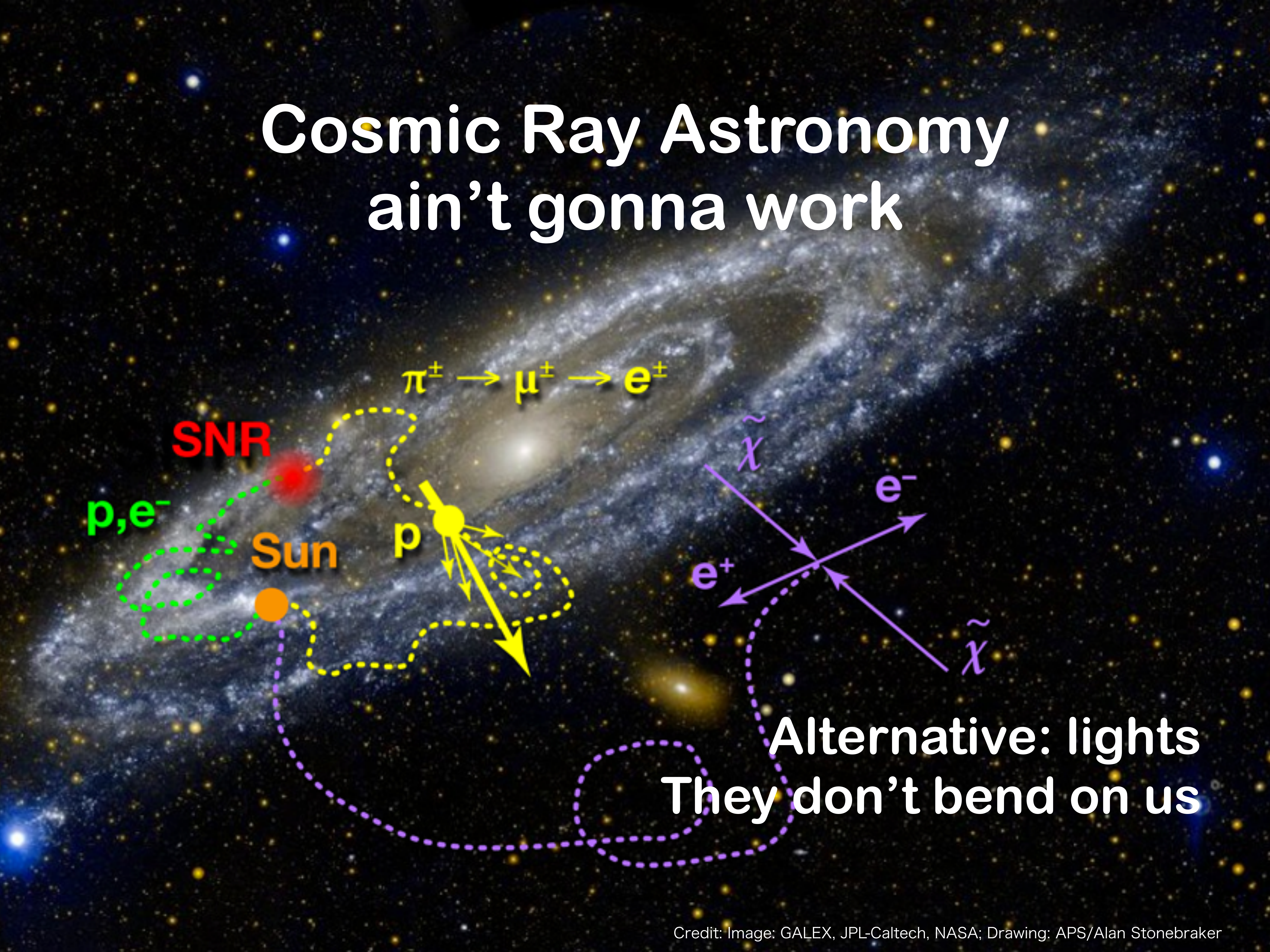


Some incomplete puzzles

- Smoking gun evidence of SNRs as 'PeVatron' still missing
- CR acceleration mechanism at collisionless shocks
- CR escape mechanism
- CR elemental composition in different energies
- Variety of SNRs, evolution stage, diversity of environment

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

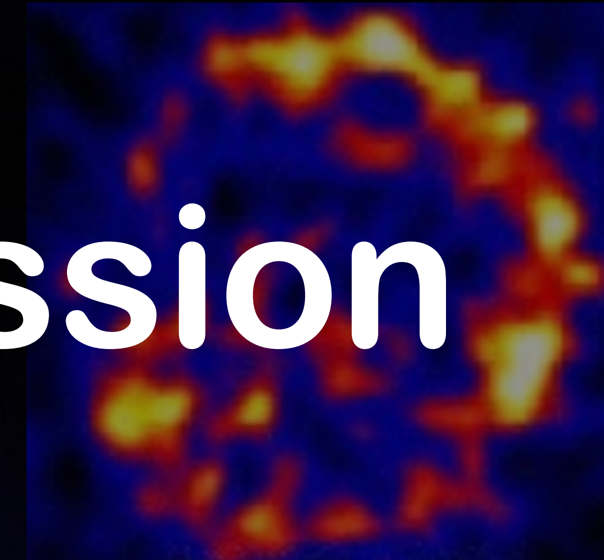
Cosmic Ray Astronomy ain't gonna work



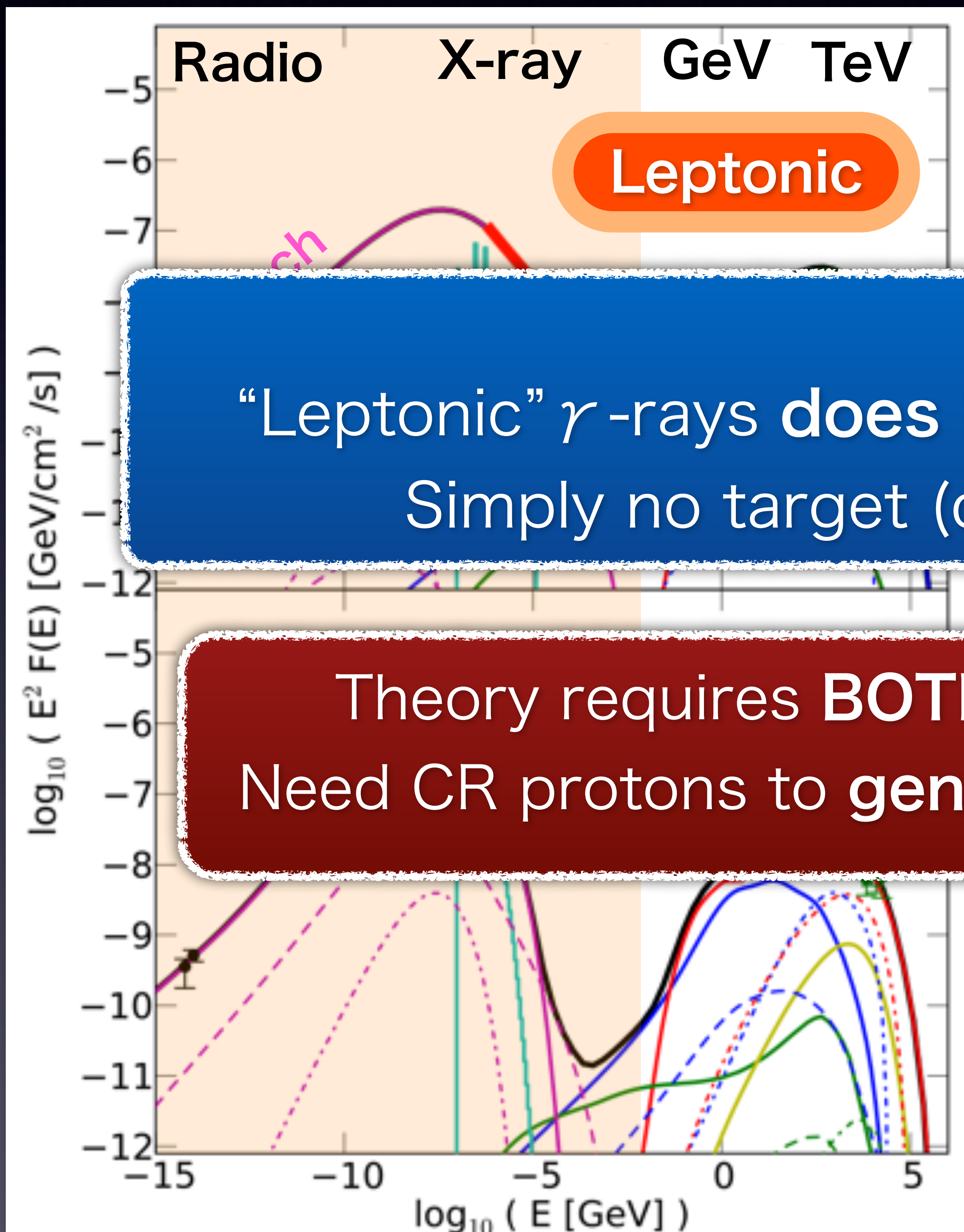
Alternative: lights
They don't bend on us

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

Usually flat spectrum

"hadronic"

Caution

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

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

Usually hard spectrum

Theory requires **BOTH** proton & electron acceleration

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

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"

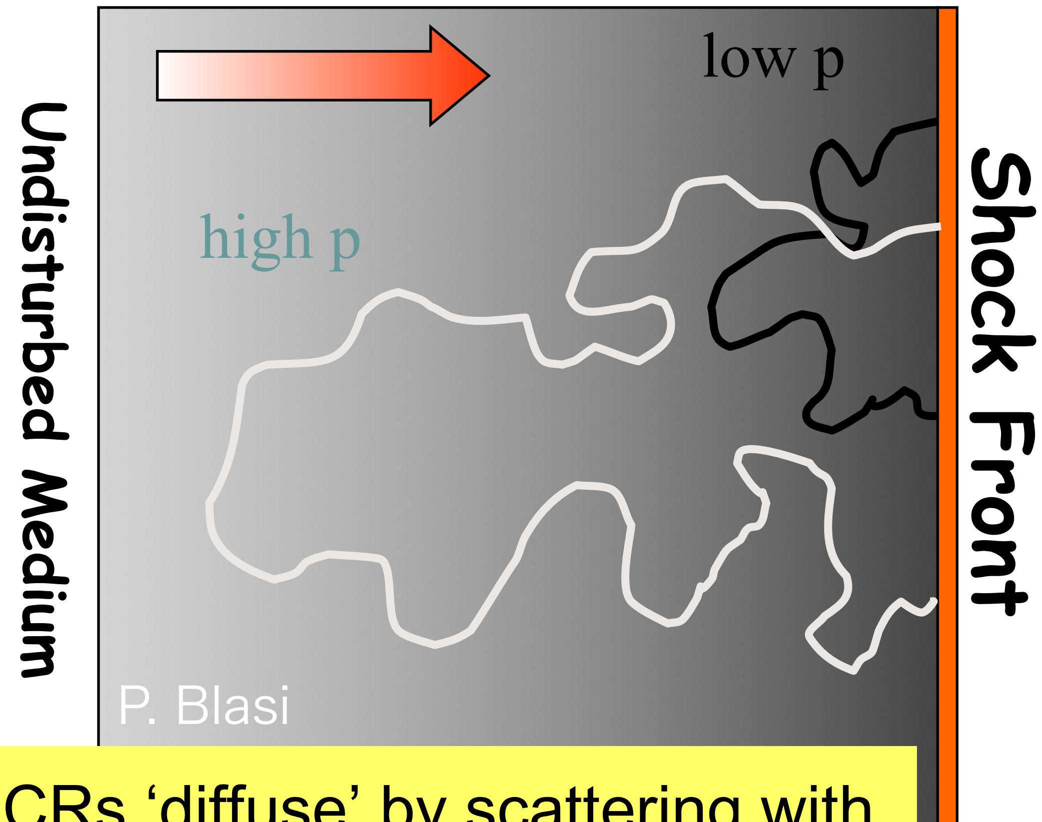
How particles get accelerated at SNRs

(Younger) SNRs have strong non-relativistic collisionless shocks

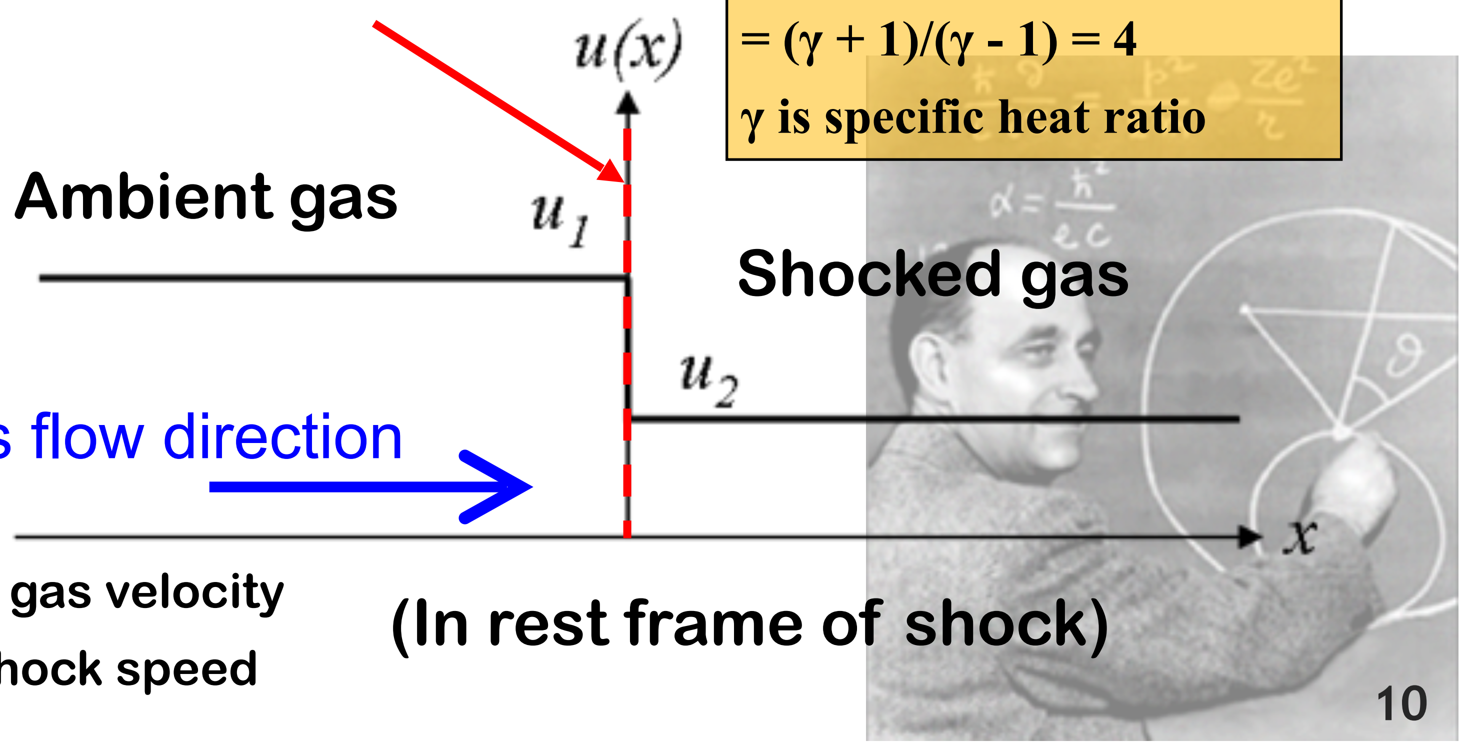
→ **Diffusive Shock Acceleration (DSA)** **[aka Fermi 1st order acceleration]**

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

→ ✡□◆■♑ ♦☠☼⬧💻 ♍osmic ray energy easily > 10% of E_{SN} (e.g. Ellison+ 05)



CRs ‘diffuse’ by scattering with magnetic turbulence



For high Mach number shock, compression ratio r
$= u_1/u_2$
$= (\gamma + 1)/(\gamma - 1) = 4$
γ is specific heat ratio

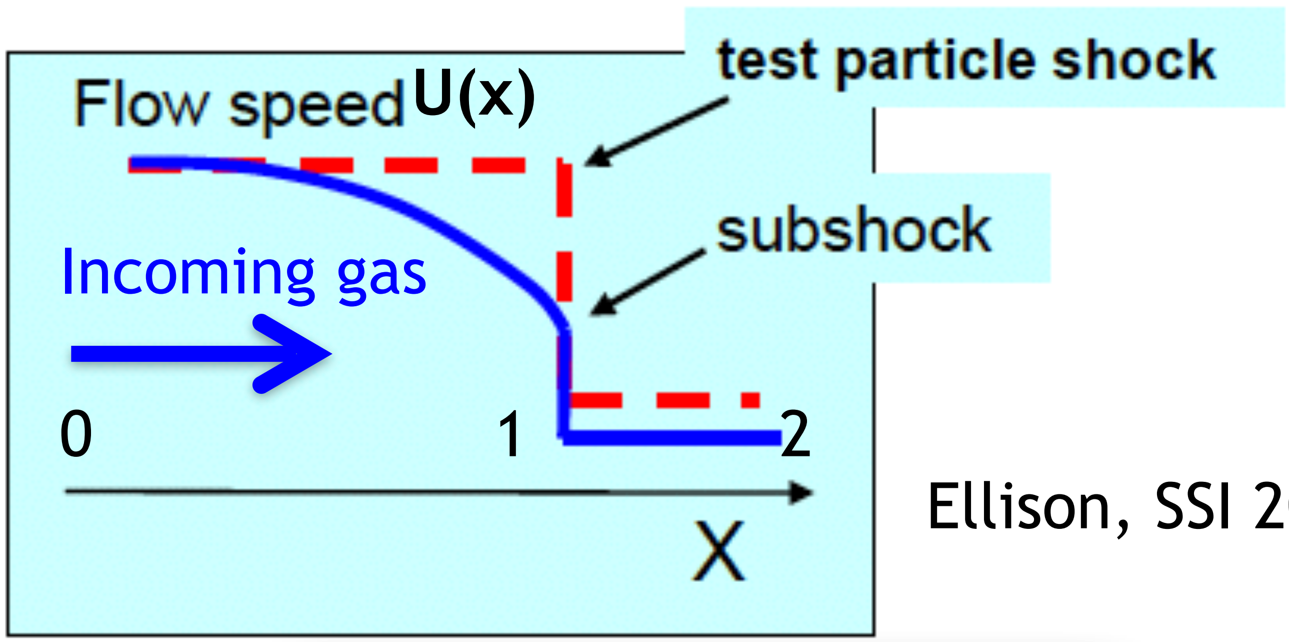
u(x) is gas velocity

u_1 is shock speed

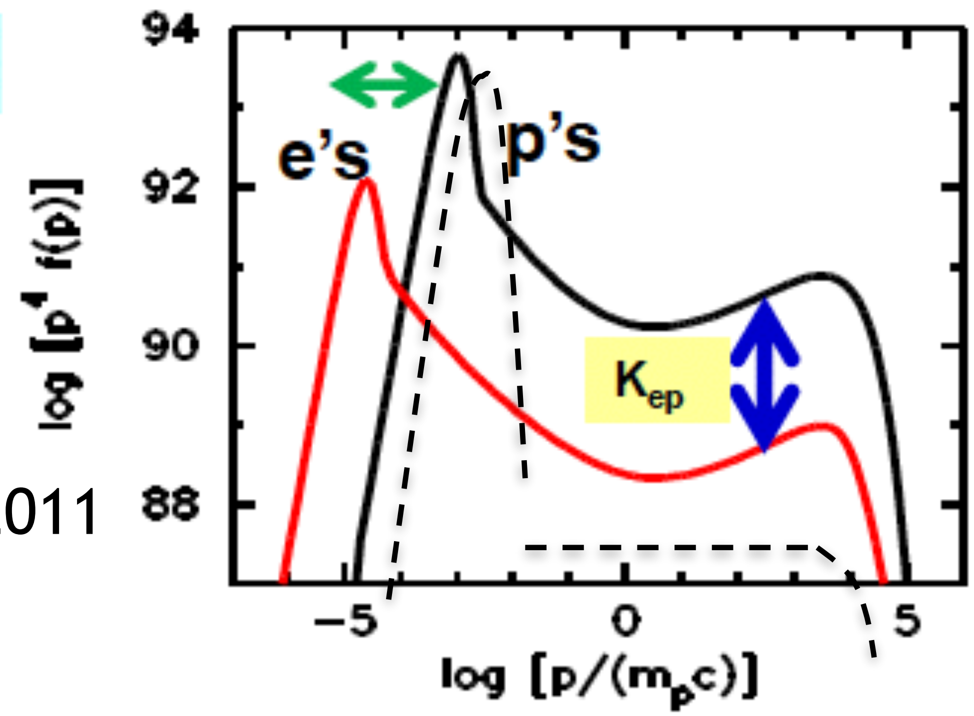
(In rest frame of shock)

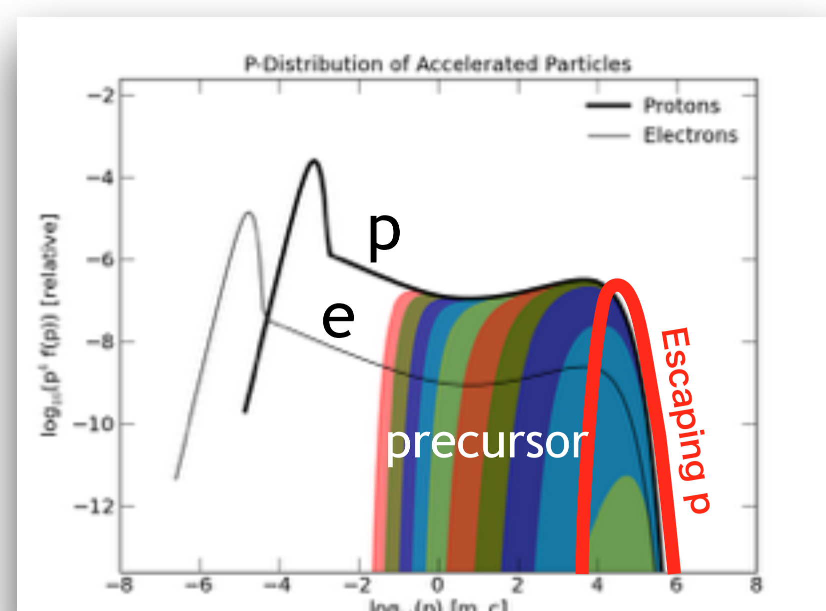
Nonlinear diffusive shock acceleration

Efficient particle acceleration leads to funny consequences, e.g.,
highly modified shock flow, **‘concave’ spectrum**, **lower shocked temp**



Ellison, SSI 2011





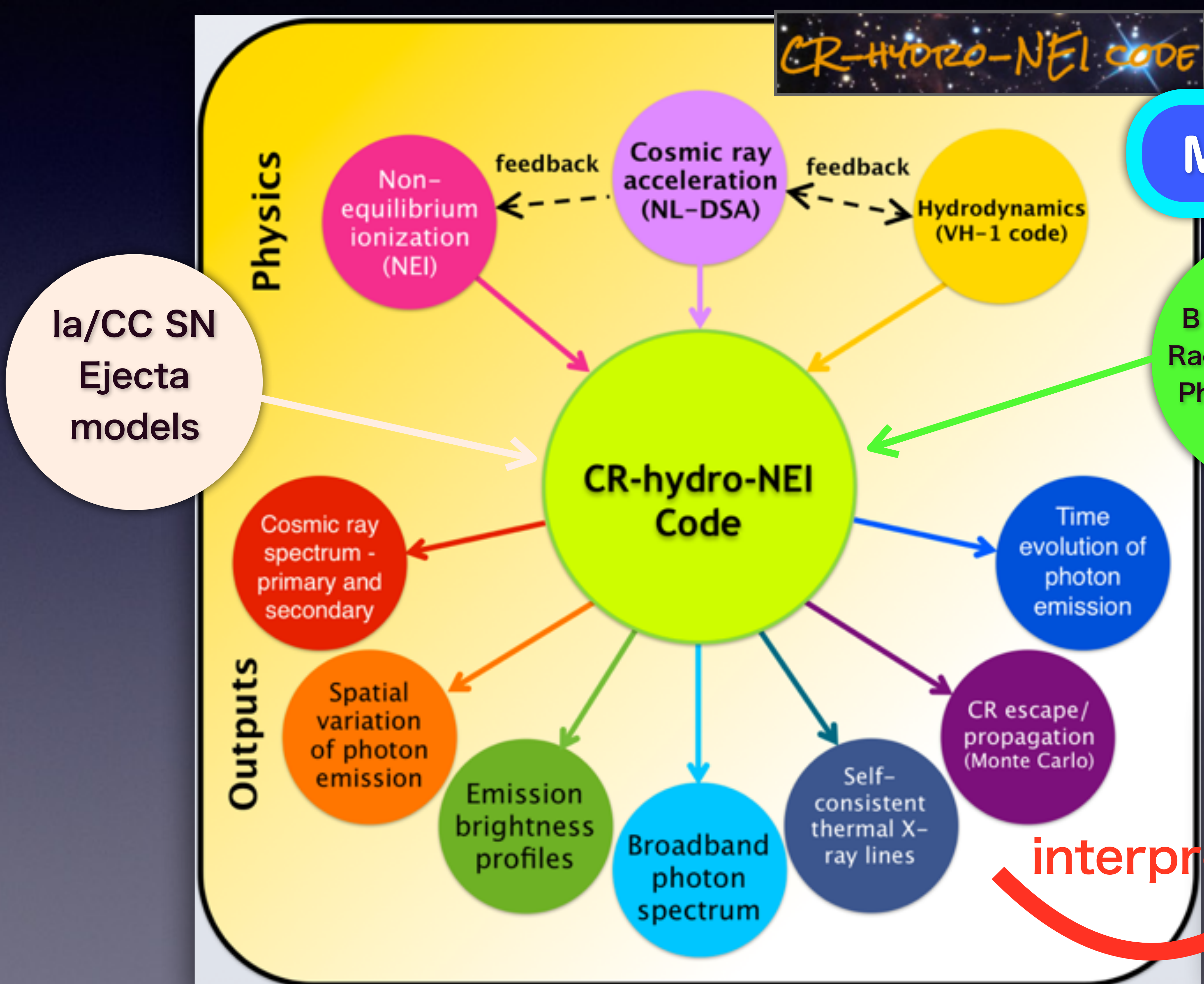
e.g., HL+ 2012

The CR-hydro-NEI (ChN) Code

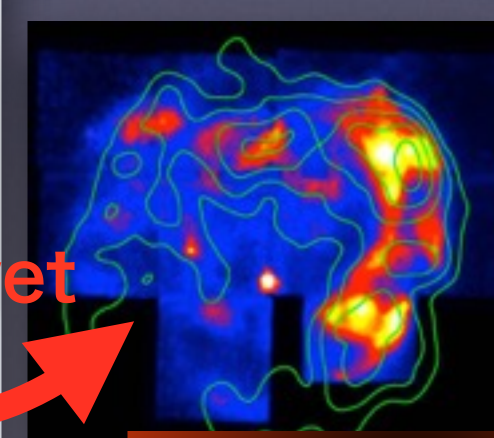
- **Nonlinear DSA physics** (HL, Ellison & Nagataki 2012)
  - CR back-pressure → feedback to shock structure, vice versa
  - Particle escape
  - Magnetic turbulence generation + wave damping
    → Magnetic field amplification (MFA)
    → D(x,p,t) calculated from self-generated B-field
- Non-thermal radio-TeV emission in (E,x,t) (HL, Slane+ 2013, Slane, HL+ 2014)
- Self-consistent calculation of thermal X-ray line emission (Patnaude+ 2009)
  - **NEI code**, with heavy element ionization/recombination (APEC v3 NEI, up to Ni)
  - **Temperature equilibration determines $T_e(x,t)$ 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)

Self-consistent modeling of (Non-)Thermal emission of SNRs

Model Infrastructure



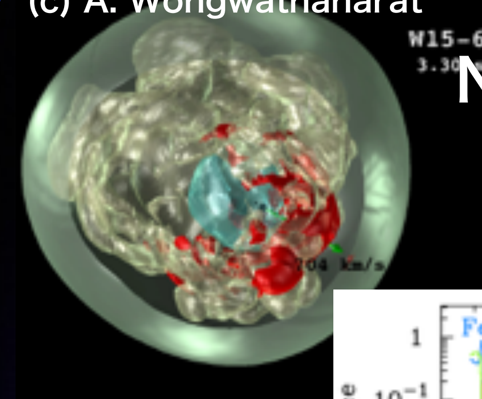
Ellison+ 2010
HL, Nagataki, Ellison 2012
HL, Patnaude+ 2014, etc…



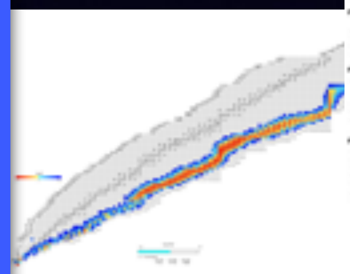
SNR RX J1713.7-3946

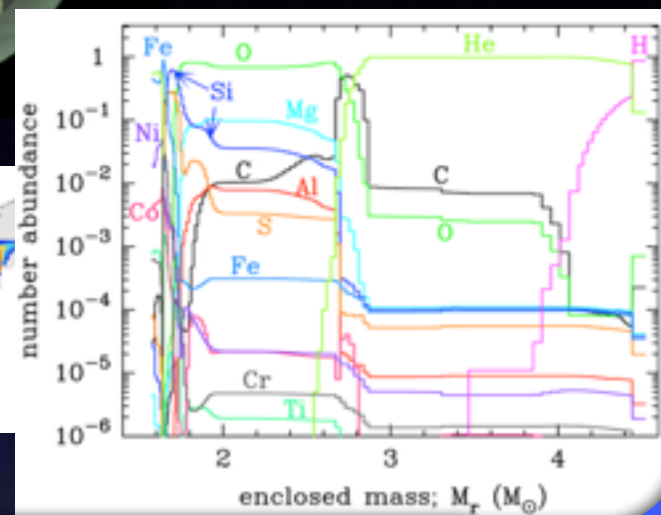
Iterative Work Flow

(c) A. Wongwathanarat



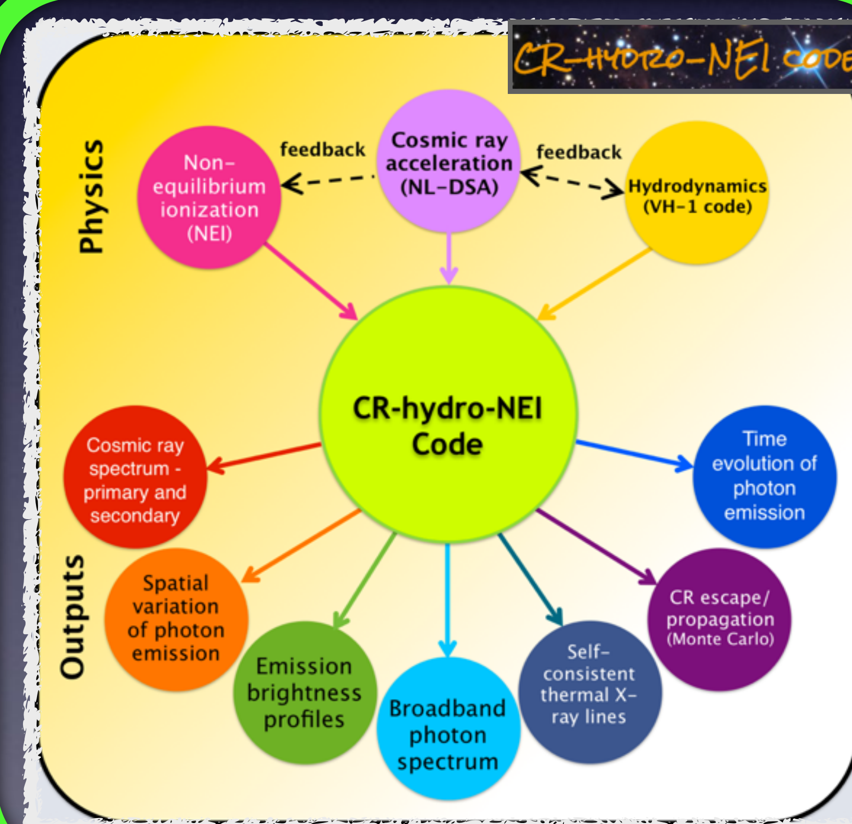
Ejecta model
Nucleosynthesis
Matter mixing
Mass loss



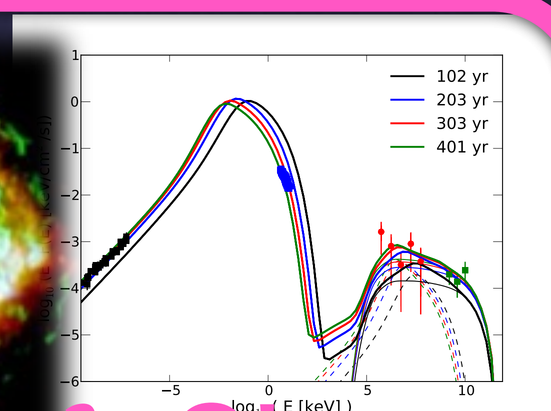


Initial conditions

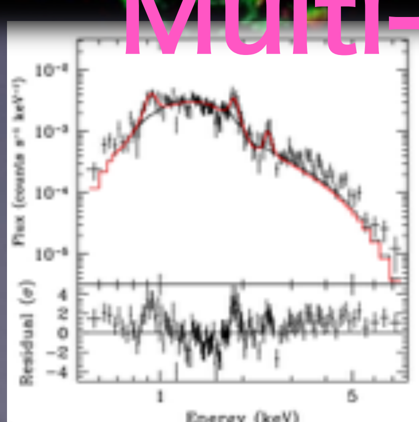
CR-hydro-NEI SNR Model

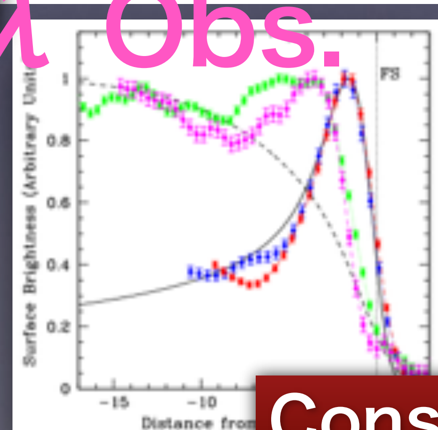


Dynamics, NLDSA, B-field, ionization, radiation



Multi-λ Obs.

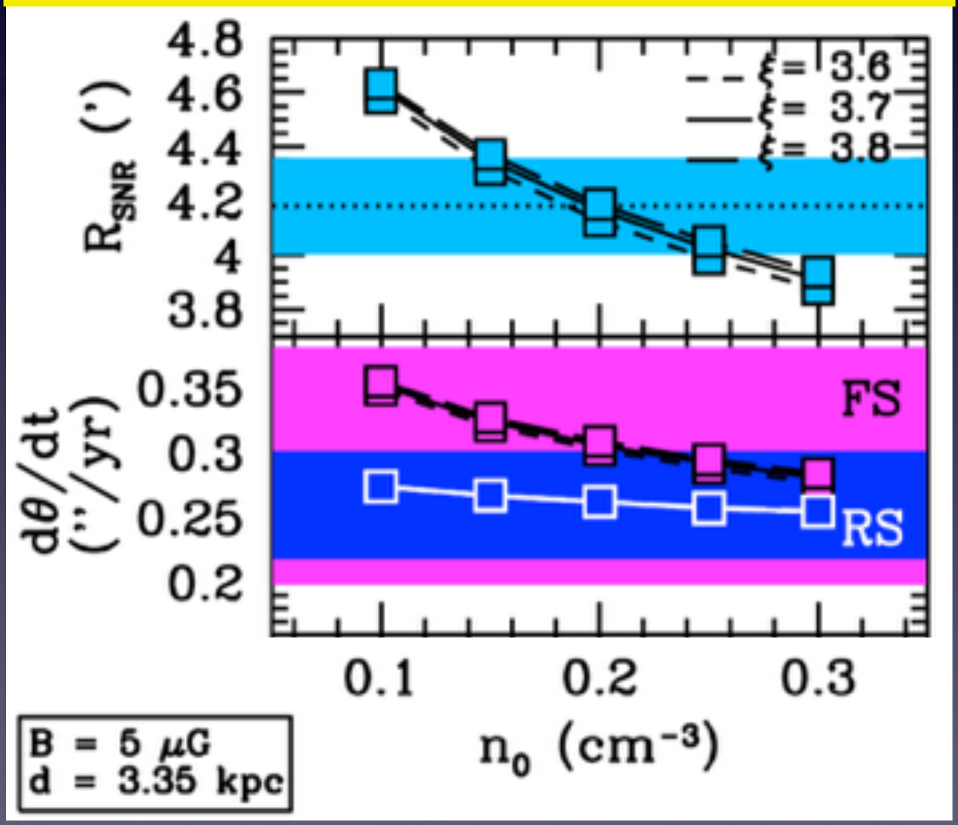




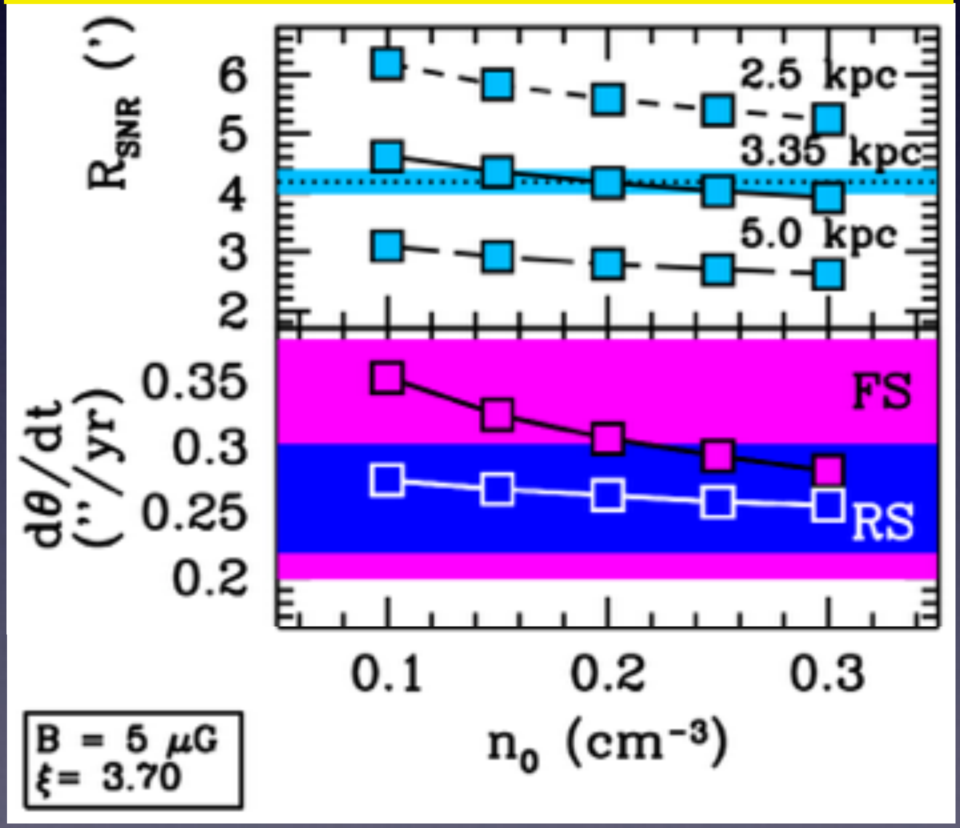
Constraints!

First step
Get the size right (dynamics)

Vary DSA efficiency vs n_0



Vary distance vs n_0

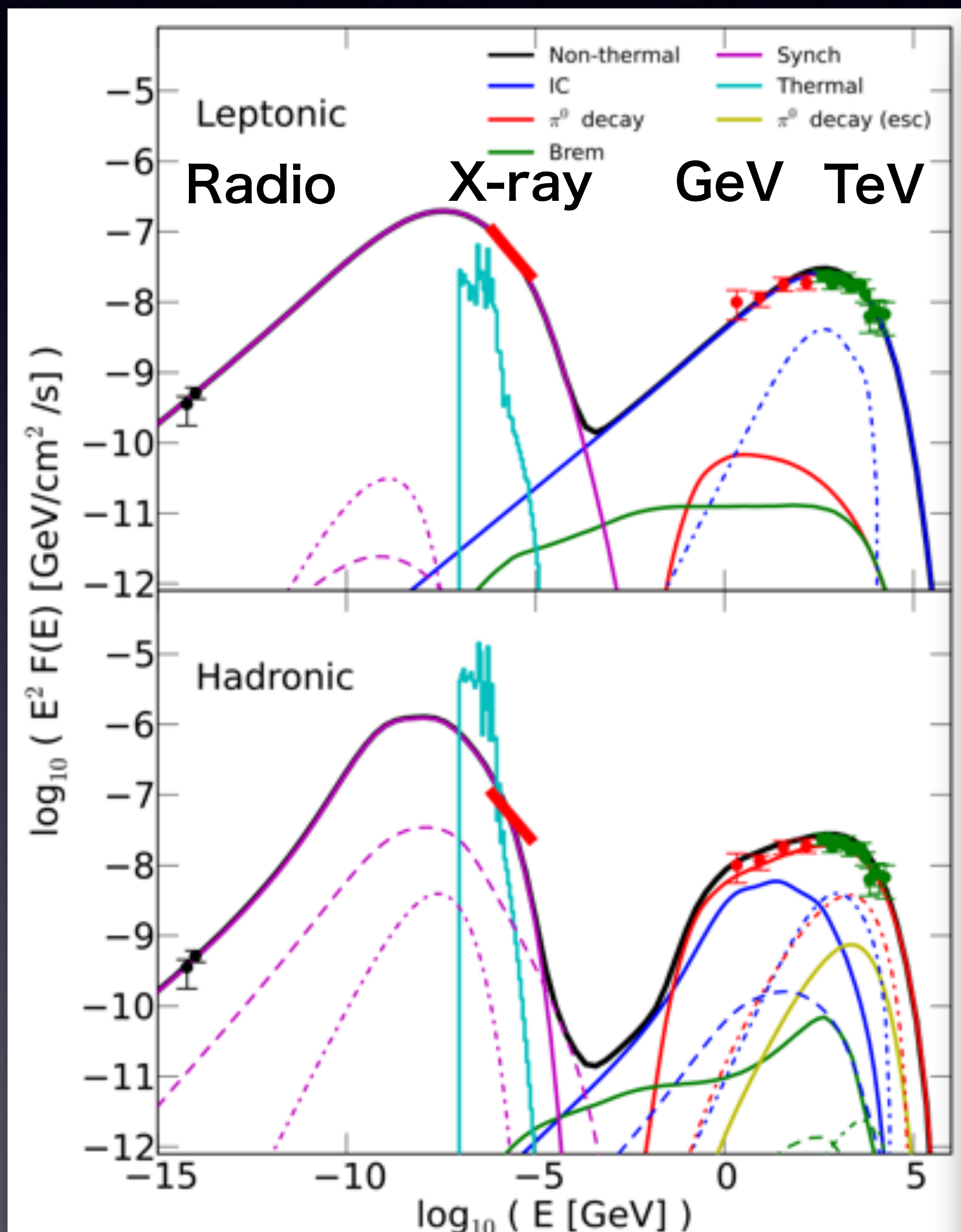


Slane, HL et al. (2014)
on Tycho's SNR

Then, the all important non-thermal spectrum

In some cases, things are not so conclusive…

HL, Slane+ 2013 on SNR Vela Jr.

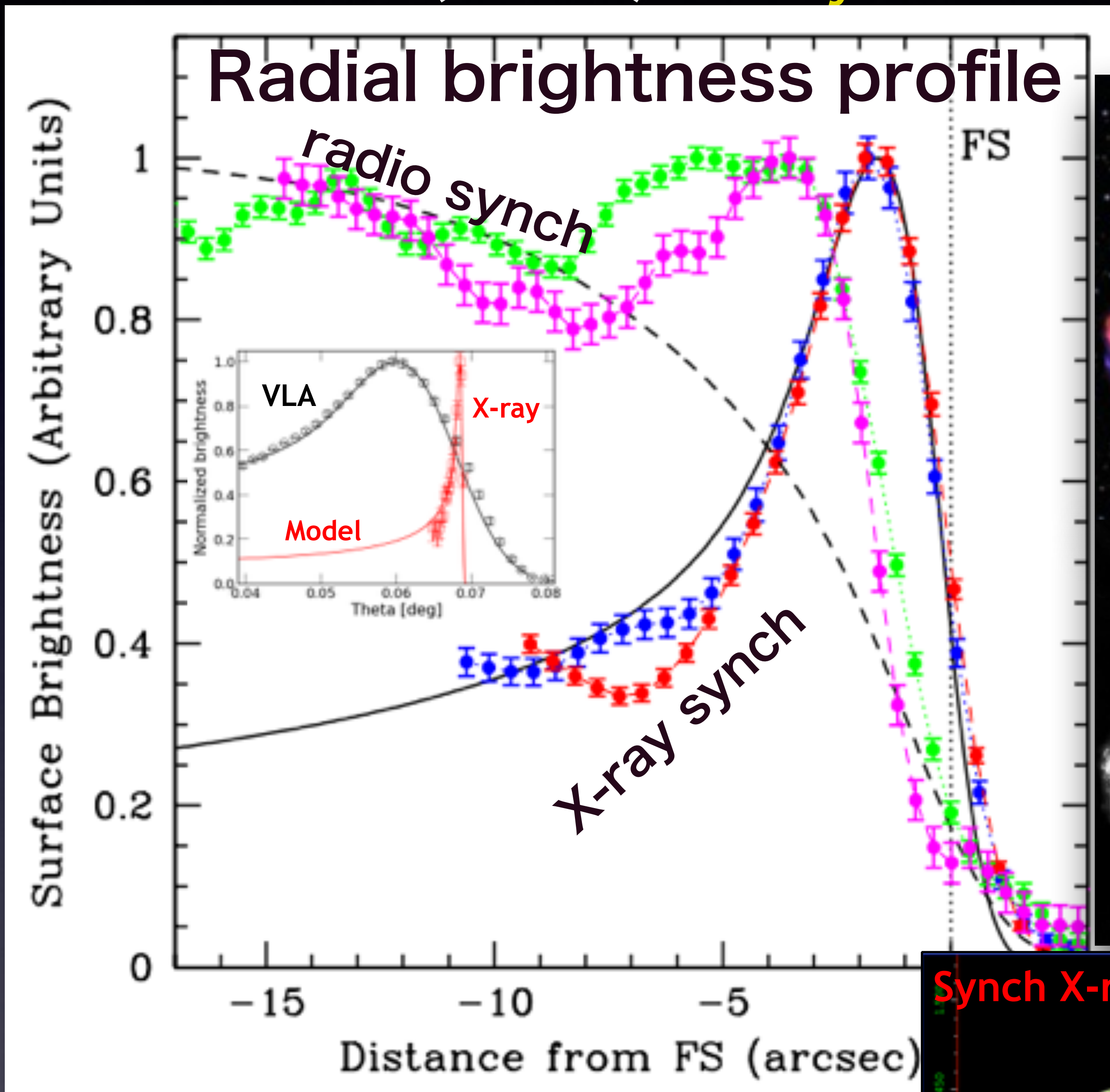


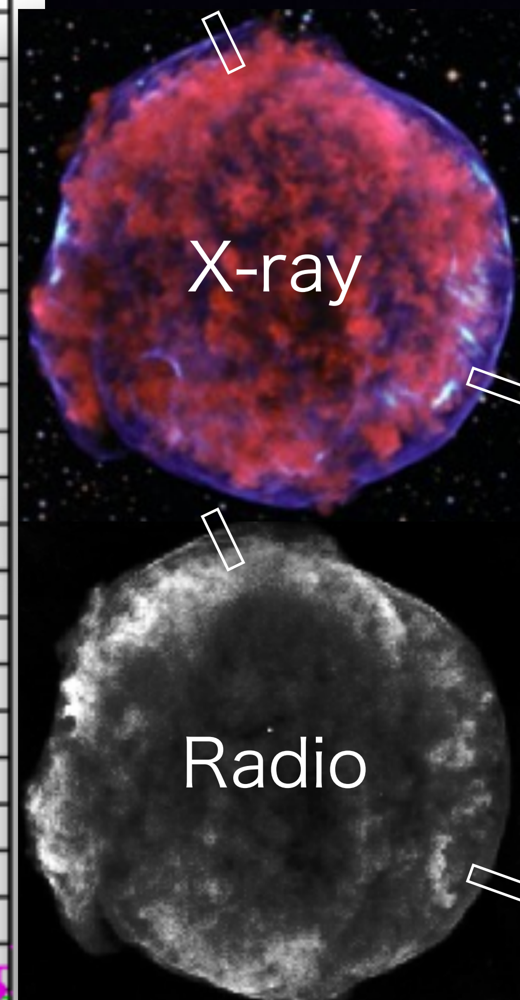
	Hadronic[b]	Leptonic[c]
Input parameters		
d_{SNR} (kpc)	0.74	0.88
n_0 (cm^{-3})	0.033	0.002[†]
B_0 (μG)	0.5	0.14[†]
dM/dt (10^{-6} $M_\odot$ yr^{-1})	…	7.5
V_{wind} (km s^{-1})	…	50
σ_{wind}	…	0.02
K_{ep}	1.5×10^{-4}	0.015
α_{cut}	0.75	0.50
f_{FEB}	0.15	0.12
f_{alf}	0.10	1.00
Output quantities		
R_{FS} (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

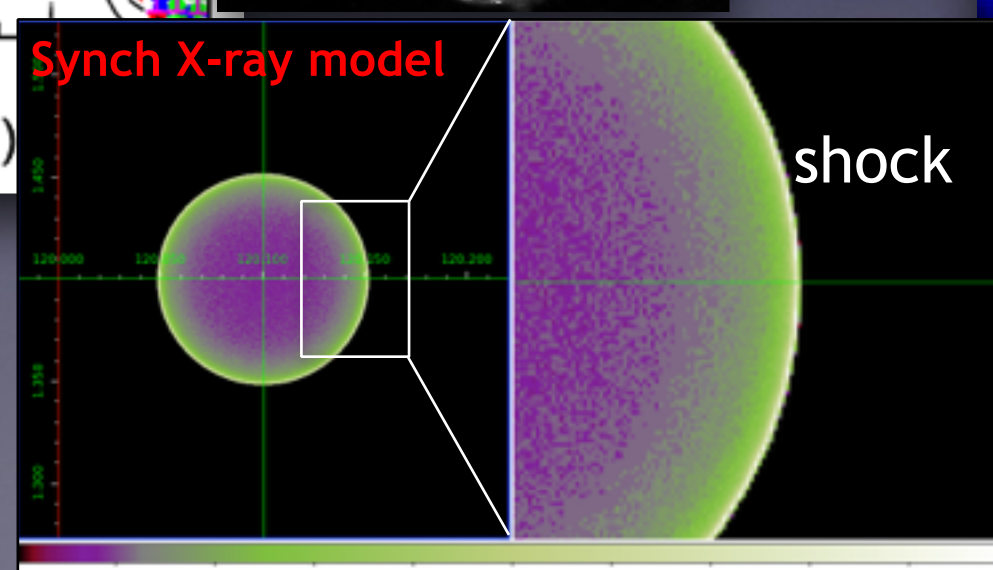
Brightness profiles are helpful too

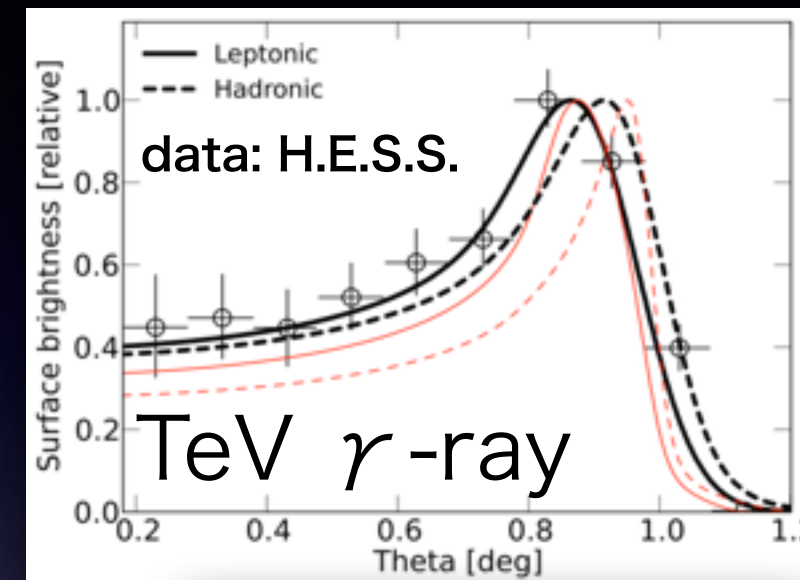
Slane, HL+ (2014) on Tycho's SNR

HL, Slane+ (2013) on Vela Jr.



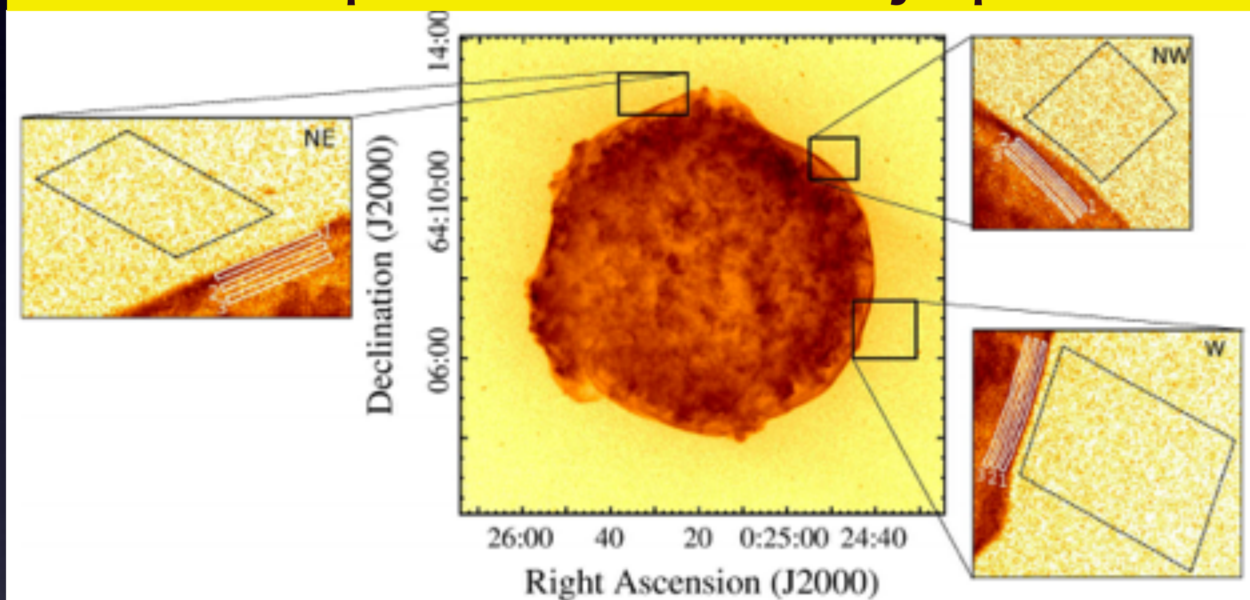




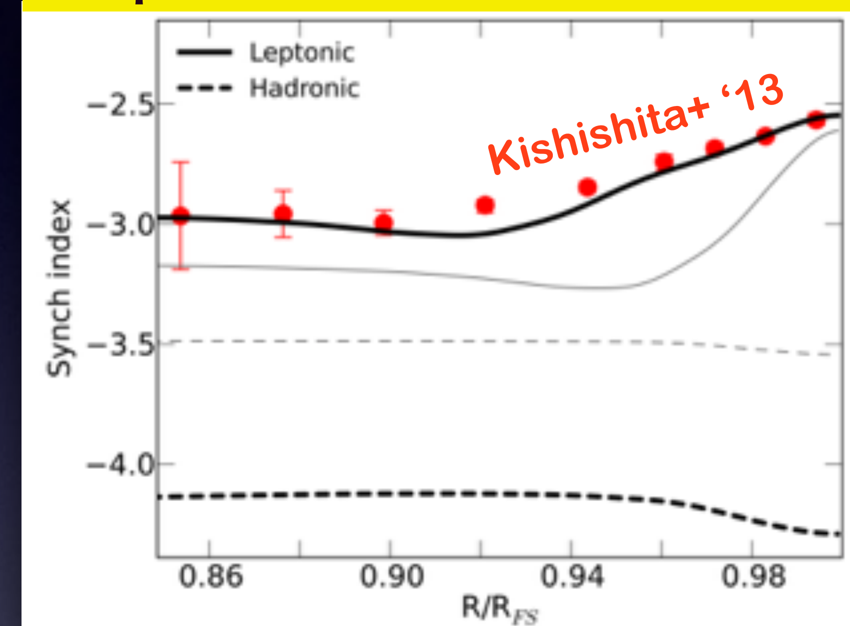


One step further
Using "spectral images"

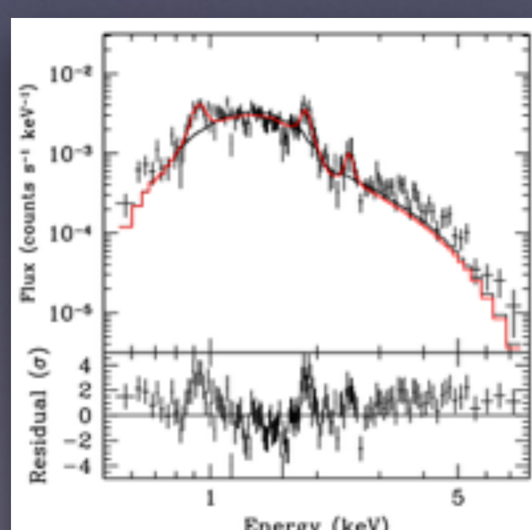
Chandra space resolved X-ray spectrum



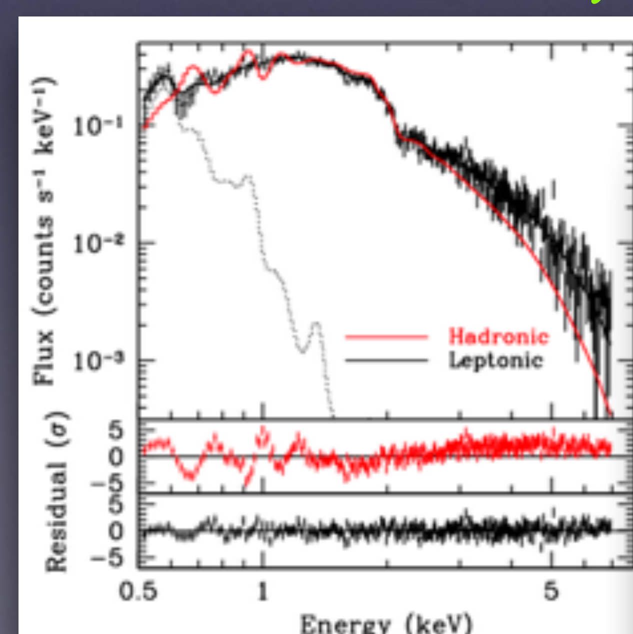
Spectral index vs radius

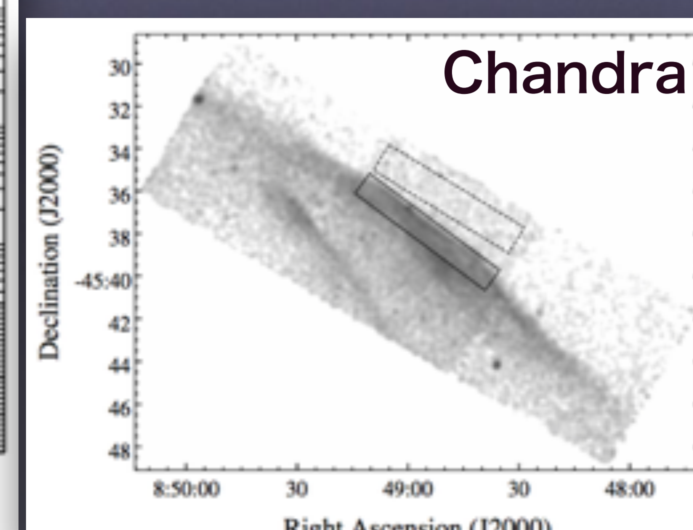


Slane, HL et al. (2014)
Tycho's SNR



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



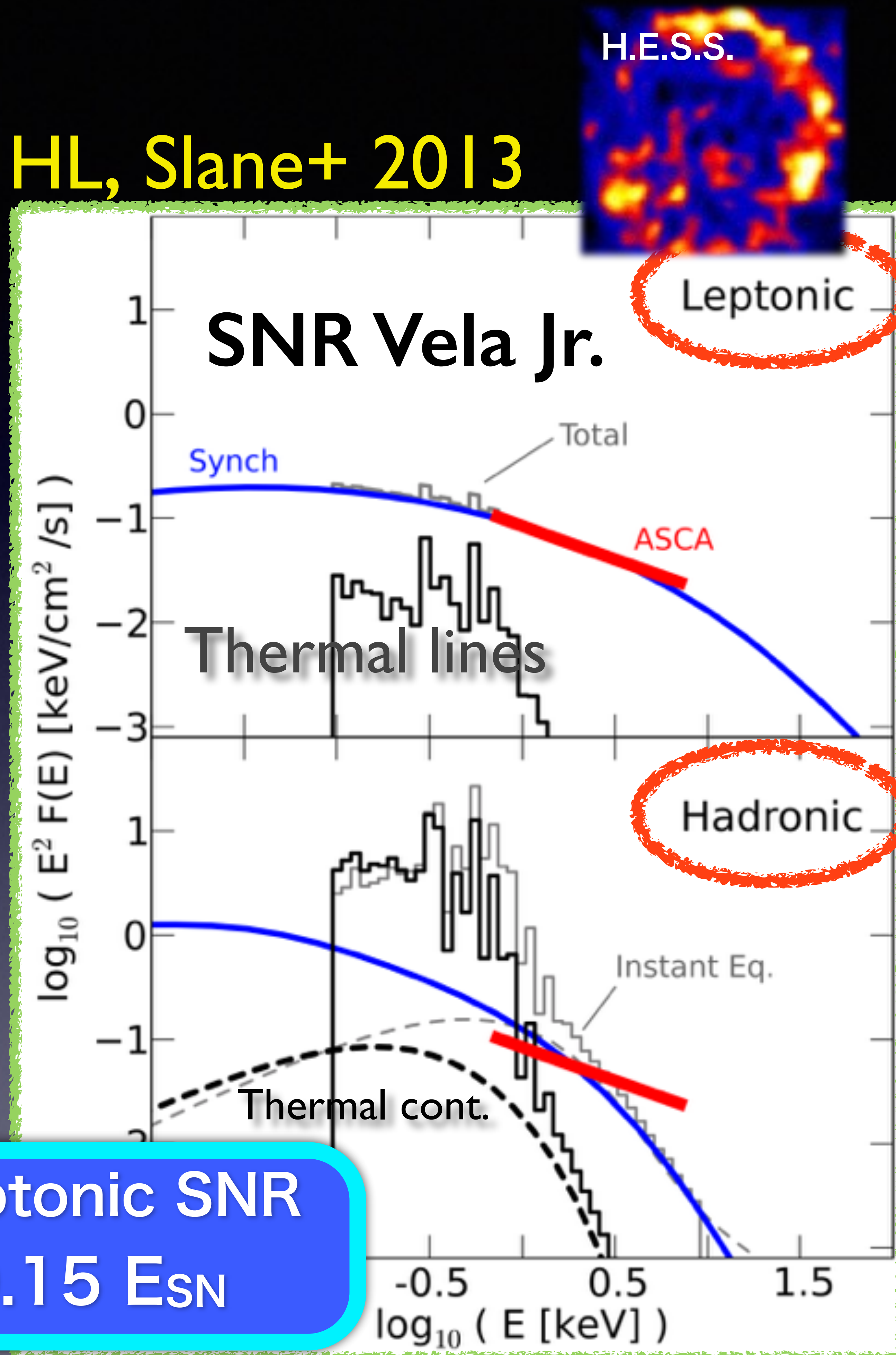


Thermal X-ray can constrain Gamma-ray origin

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

Predicted thermal flux must NOT exceed observed X-ray flux

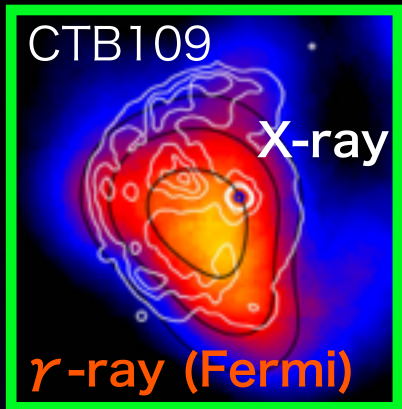
HL, Slane+ 2013



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

Powerful constraint of non-thermal origin

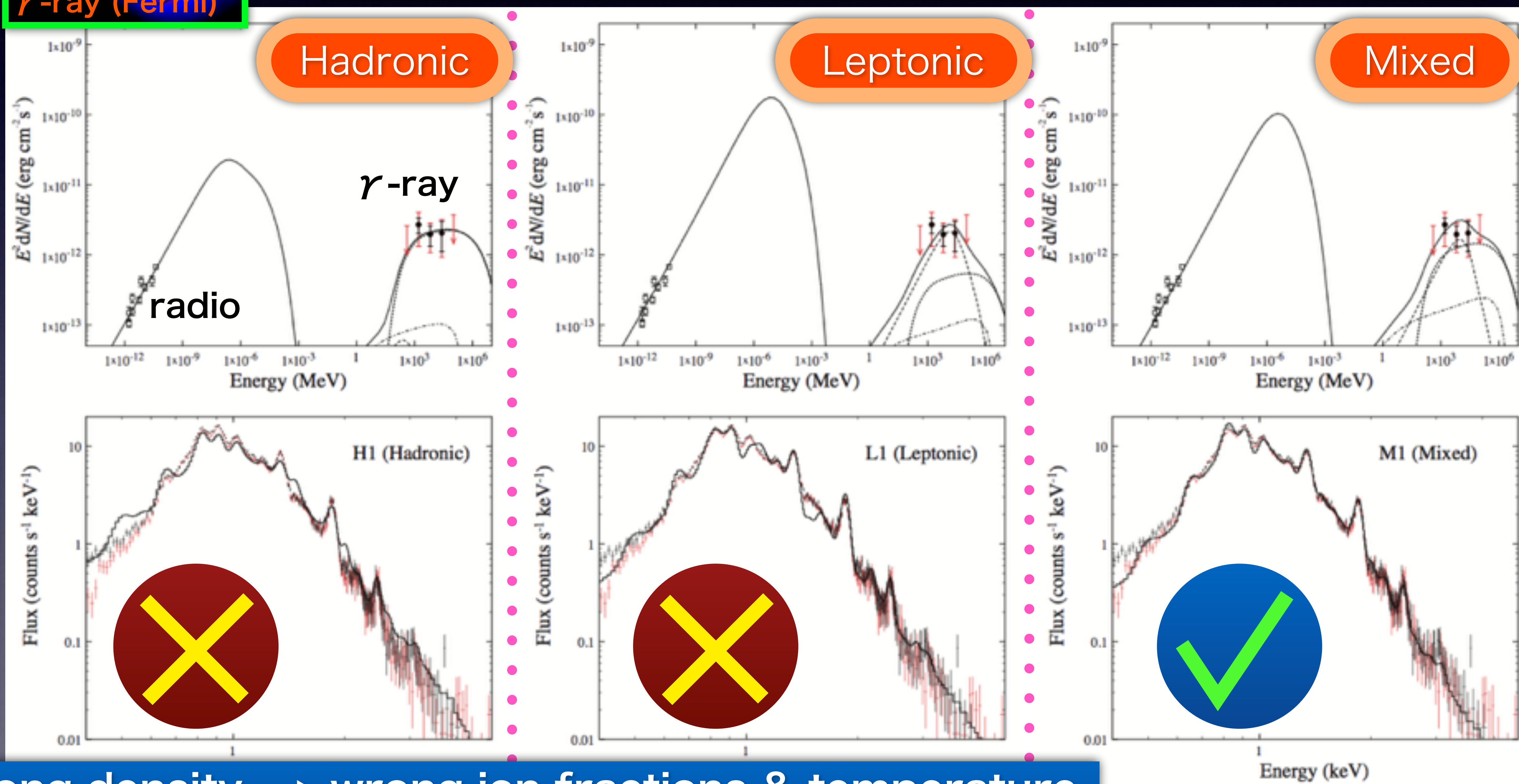
Thermal X-ray Spectrum



CR-hydro model by **Castro, Slane+ (2012) on CTB109**

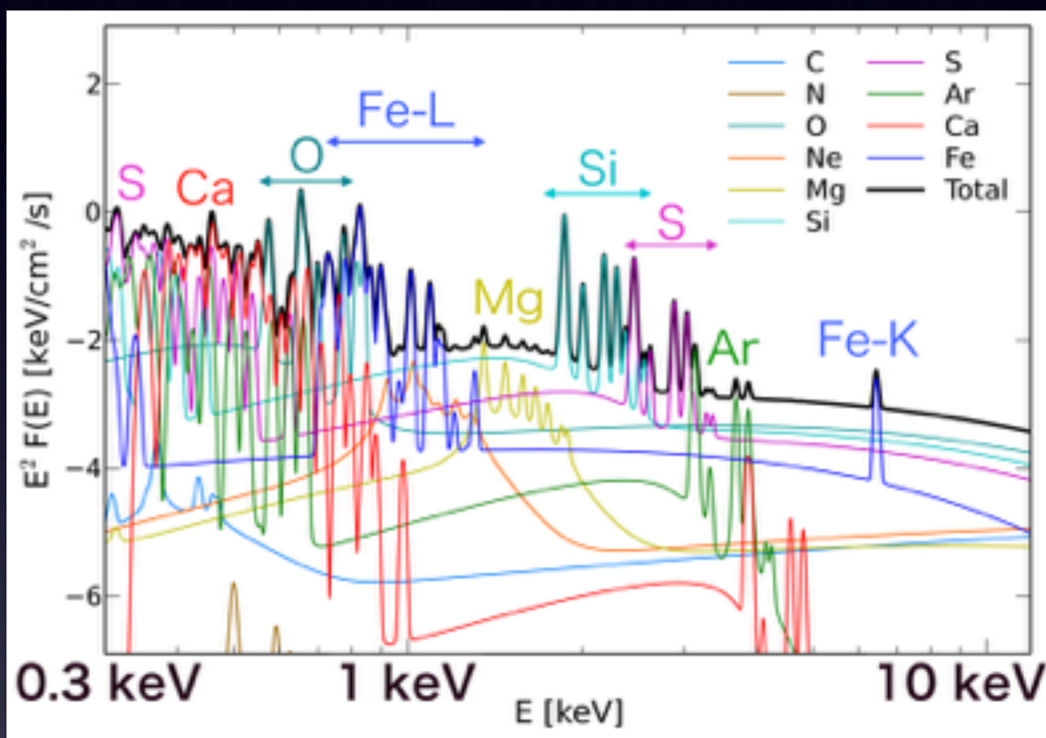
Non-thermal

Thermal X

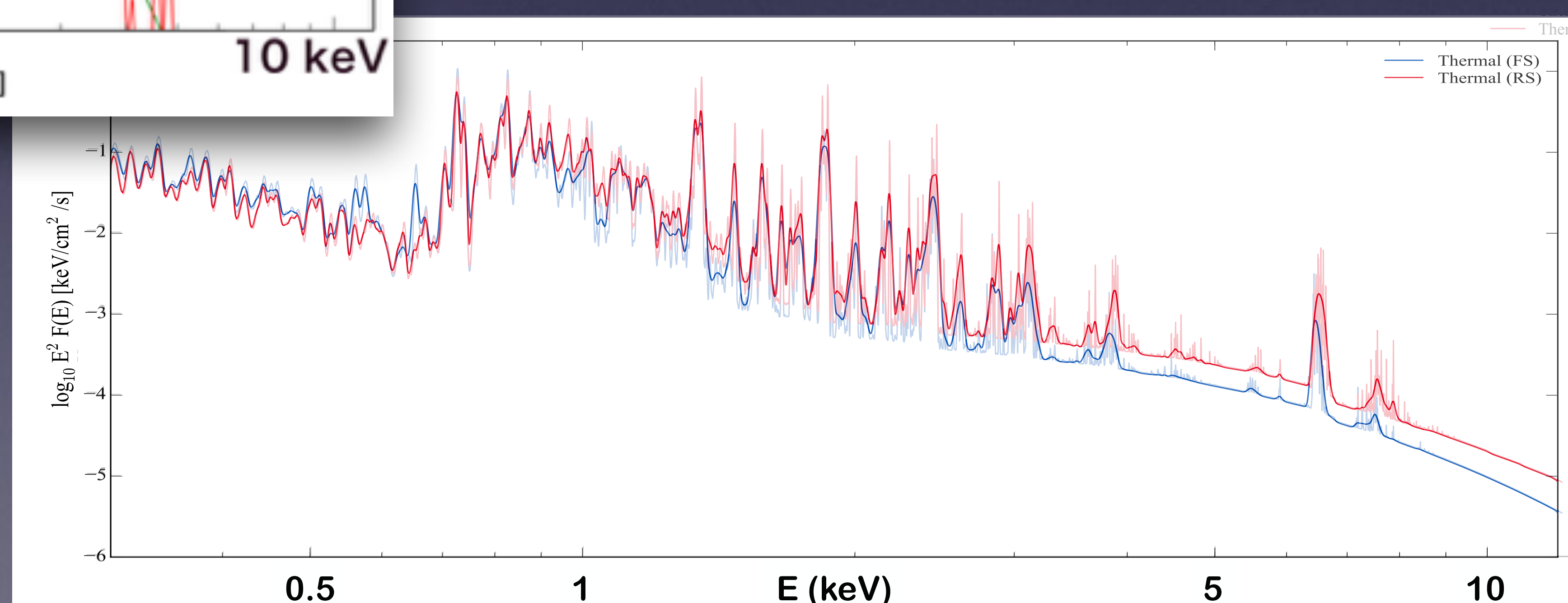


Wrong density —> wrong ion fractions & temperature
—> wrong thermal X-ray spectrum

Detailed thermal models for future X-ray spectroscopy

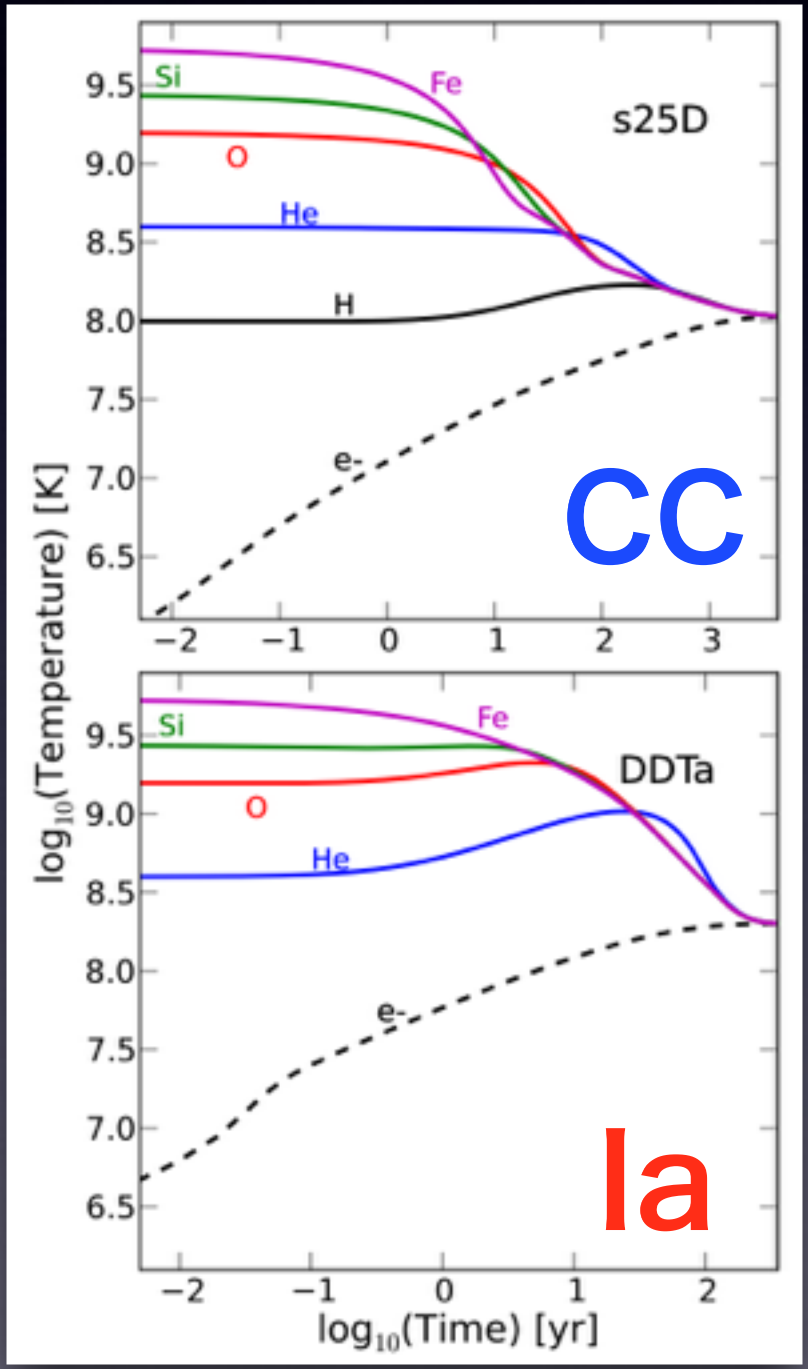


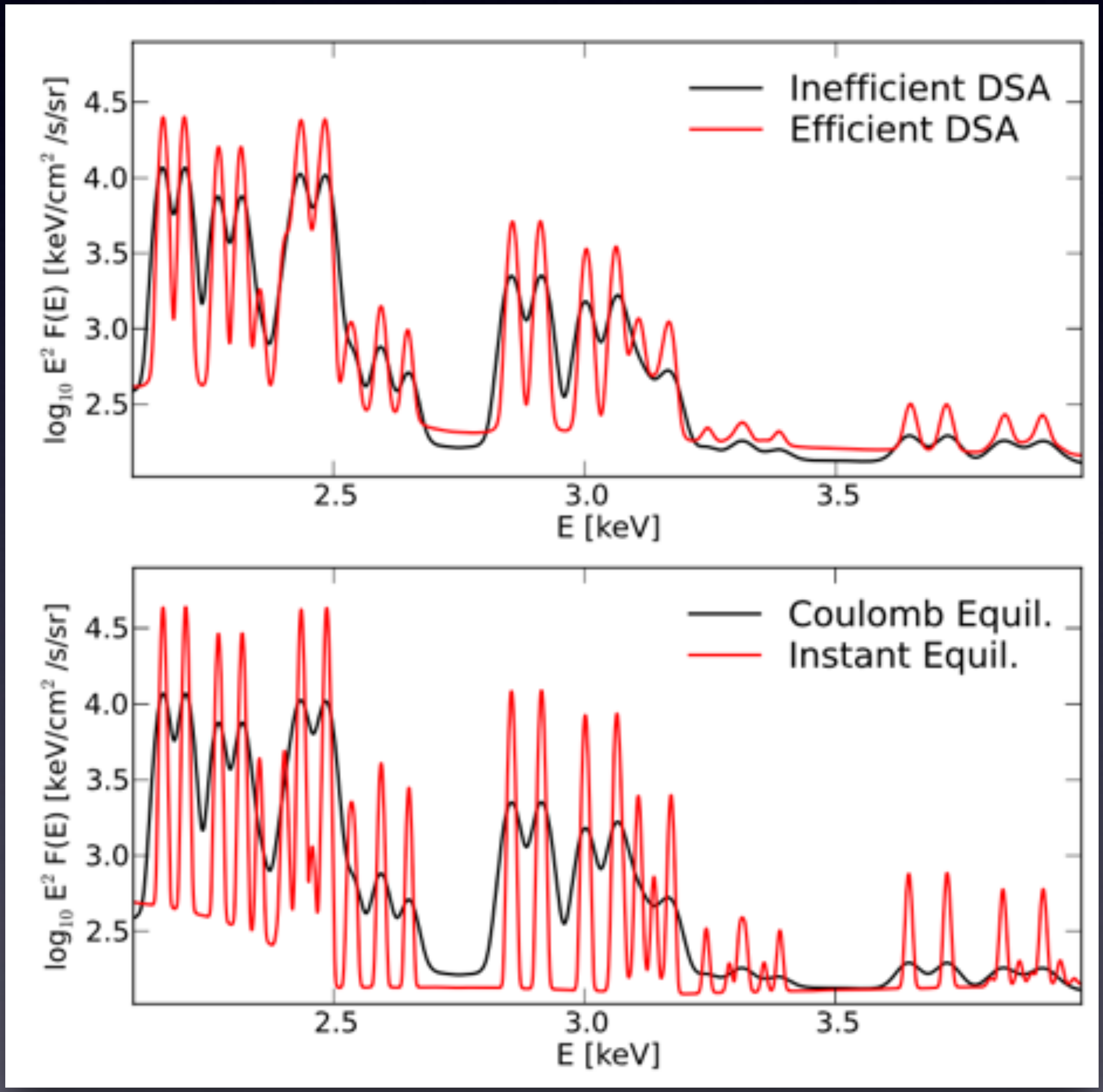
CR-hydro-NEI code
+ SN Ejecta model
+ APEC v3.0.2 (NEI)



Thermal broadening

Progenitor, equilibration and particle acceleration



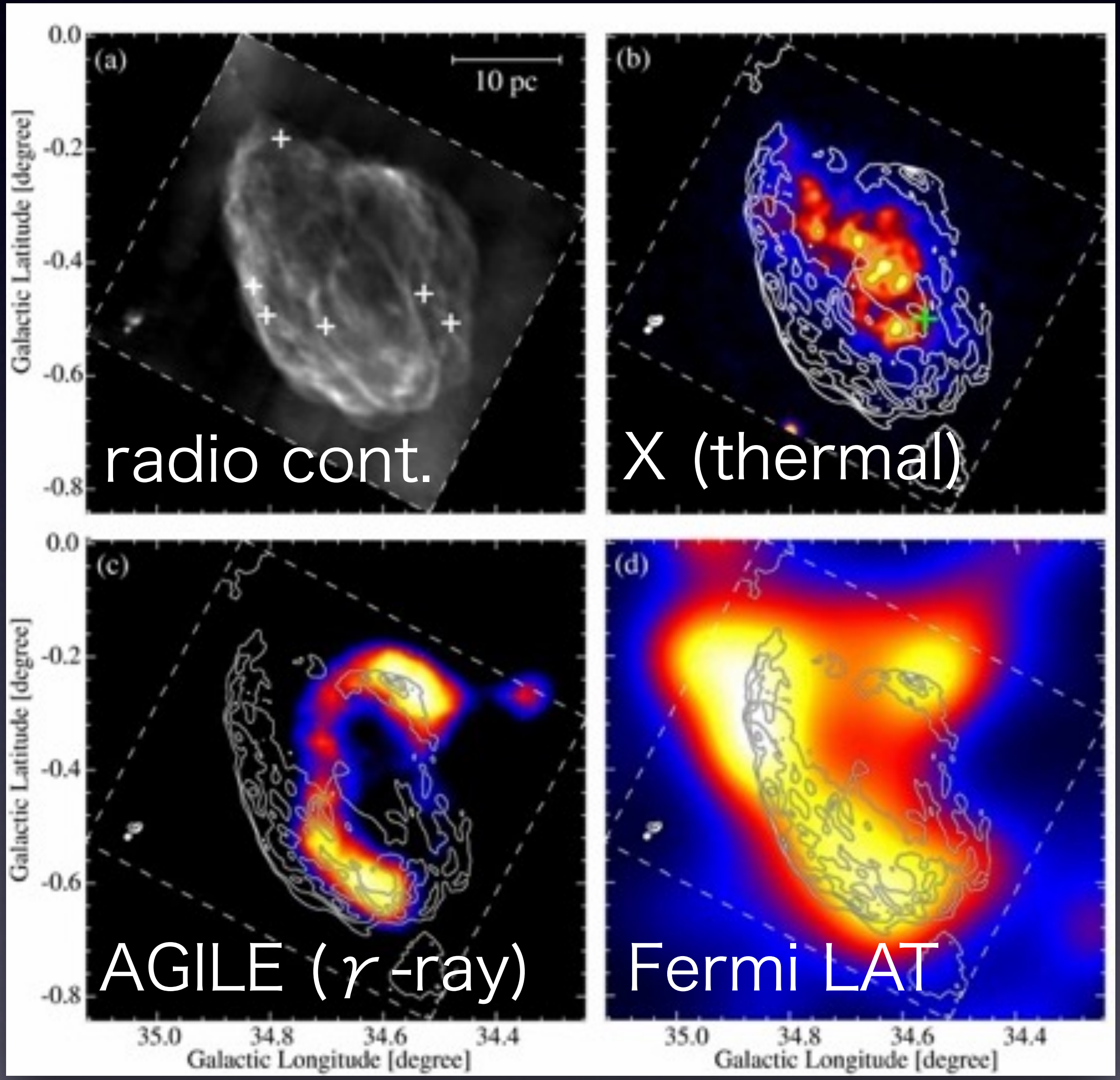


HL, Patnaude+ (2014)

Bright Radio, γ-rays from Middle-aged SNRs

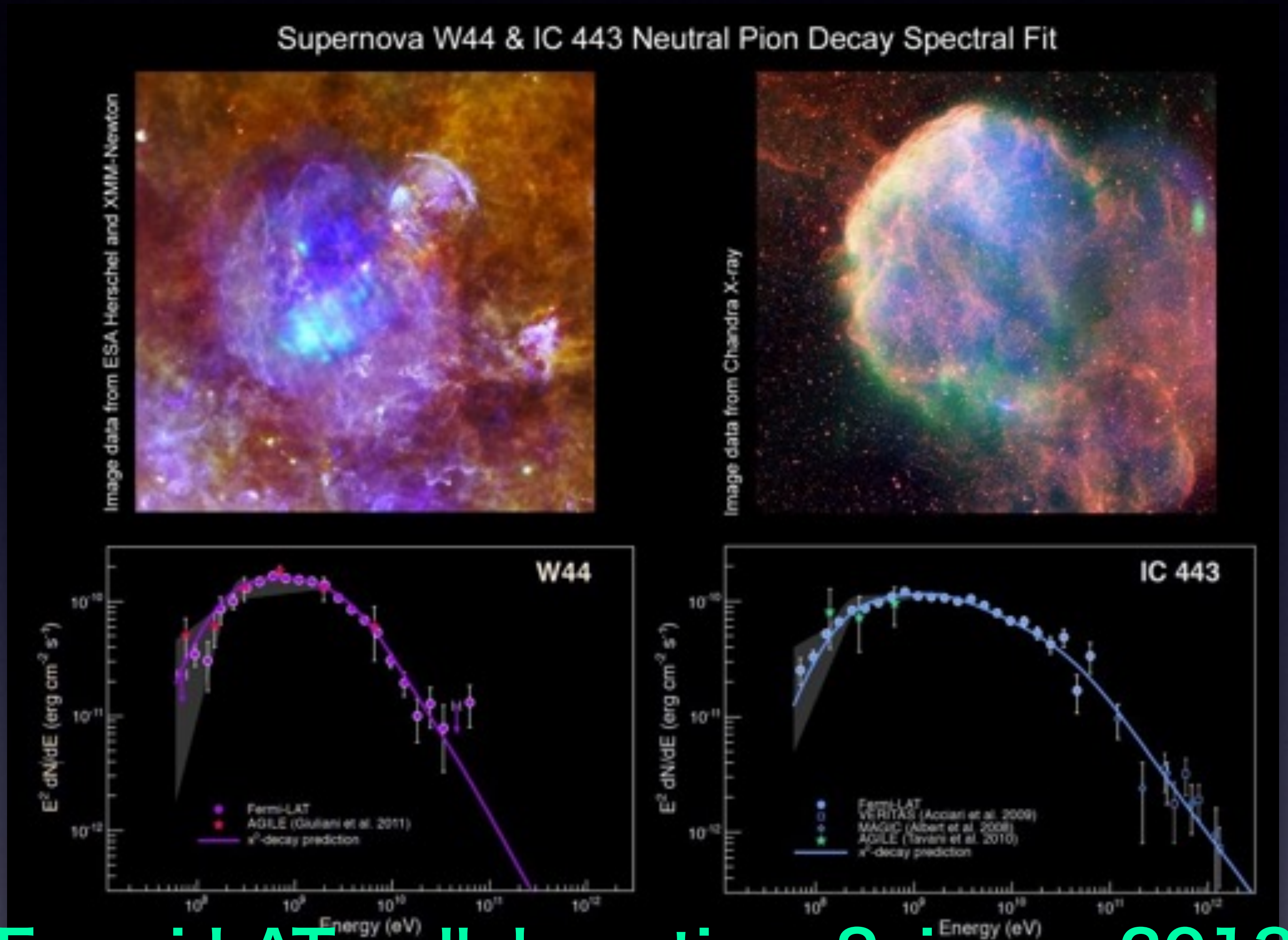
- ★ Many **GeV-bright SNRs** in our Galaxy found by Fermi, AGILE
- ★ Mostly **middle-aged SNRs** interacting with **molecular clouds**
- ★ Evolved, have slow shocks, but **bright non-thermal emission (radio, GeV γ-rays)**
- ★ Assume pure hadronic origin for luminous GeV γ-ray emission
  $\langle n_{gas} W_{CR} \rangle \sim$ a few 10^{50} to 10^{52} erg/cm^{-3}
  Lots of CR protons!
- ★ Bright non-thermal radio emission —> **B >> μG (i.e. >> ISM level)**

SNR W44 (Yoshiike+ 2013)

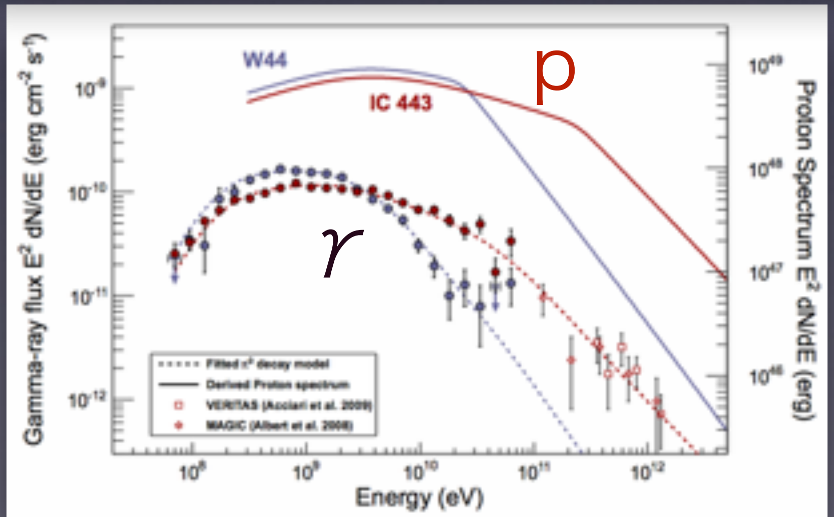


Characteristic γ-ray spectra of middle-aged GeV-bright SNRs

- ★ Cutoff detected around 250 MeV —> predominant π^0 **origin of γ-rays**
- ★ **Smoking gun evidence** for **SNR accelerating CR protons**!
- ★ **Many puzzles still remain**:
  - Origin of **copious CR protons**
    How are they **injected and accelerated**?
  - Momentum **break?** Origin?
  - Origin of **amplified B-field**?
  - **Evolution stage of these GeV-bright guys?**
    Any connection with young ejecta-dominated and TeV-bright SNRs?

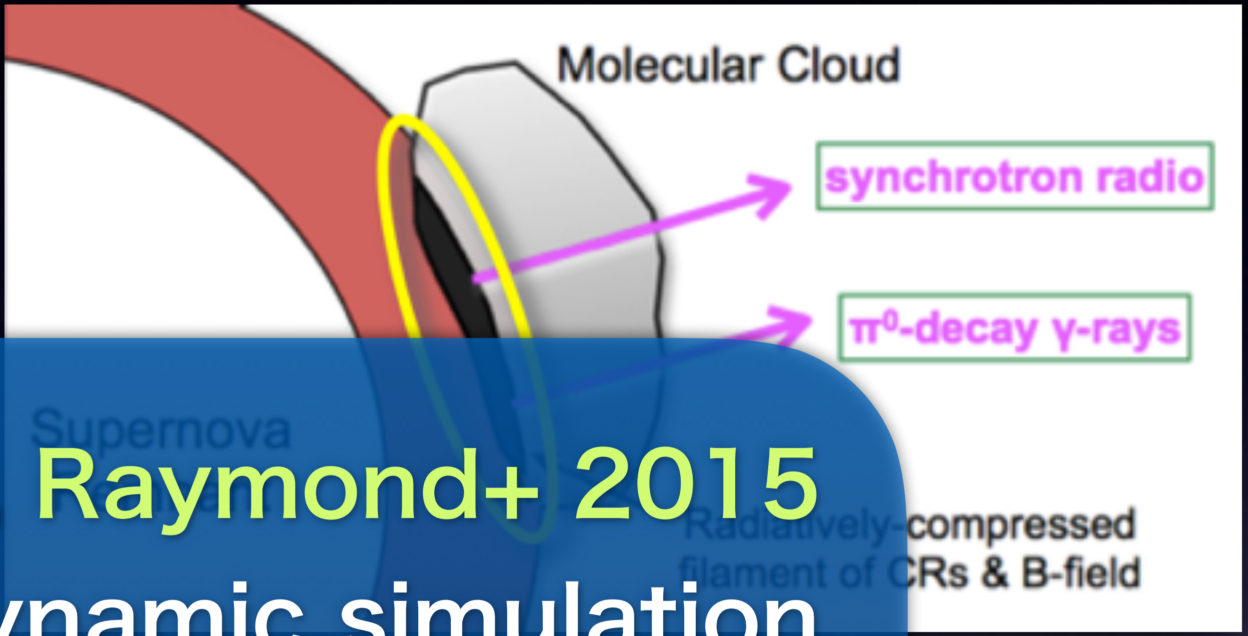


Fermi LAT collaboration, Science 2013



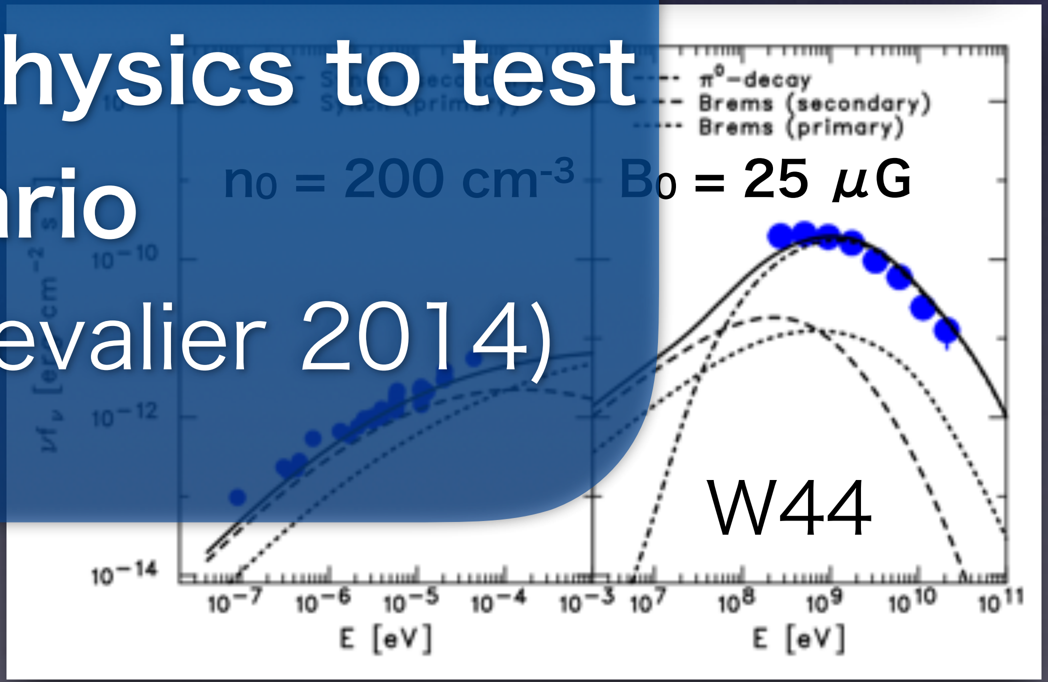
"Crushed cloud" Scenario

- ★ Forward shock hits dense medium, drives a cloud shock into it
- ★ **Re-acceleration of Galactic CR (GCR)** by >100km/s cloud shock is possible
- ★ **Cold dense shell** forms behind decelerating ... **radiative cooling**
- ★ **Gas**, **B-field** and **CRs** are rapidly **compressed**
- ★ **Bright γ-ray from π^0-decay!**
- ★ **Bright radio synchrotron emission!**



HL, Patnaude, Raymond+ 2015 run a hydrodynamic simulation with detailed microphysics to test this scenario

(see also Tang & Chevalier 2014)



First analytic calculation by Uchiyama+ (2010)

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

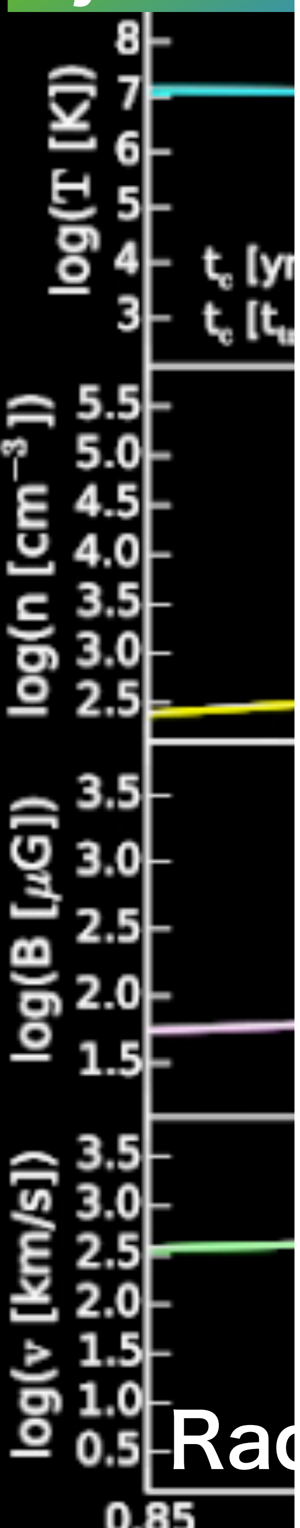
- ★ Conductivity $\kappa = f\,\kappa_{Spitzer}$
- ★ f = 0.3 for collisionless plasma, hindrance by B-field

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

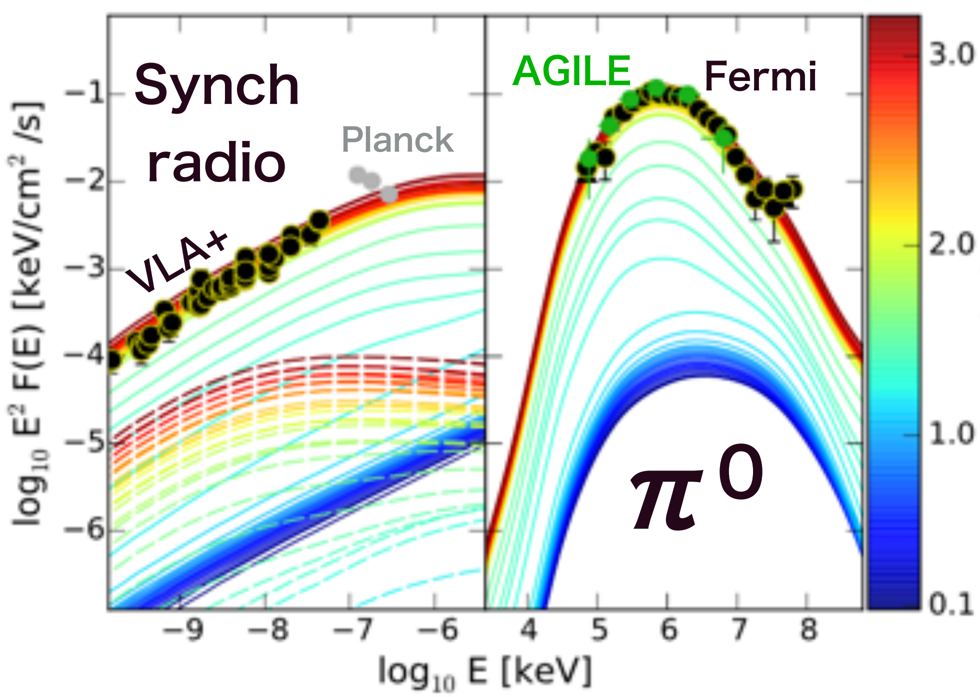
HL, Patnaude, Raymond+ 2015

Hydrodynamics and Spectral Evolution

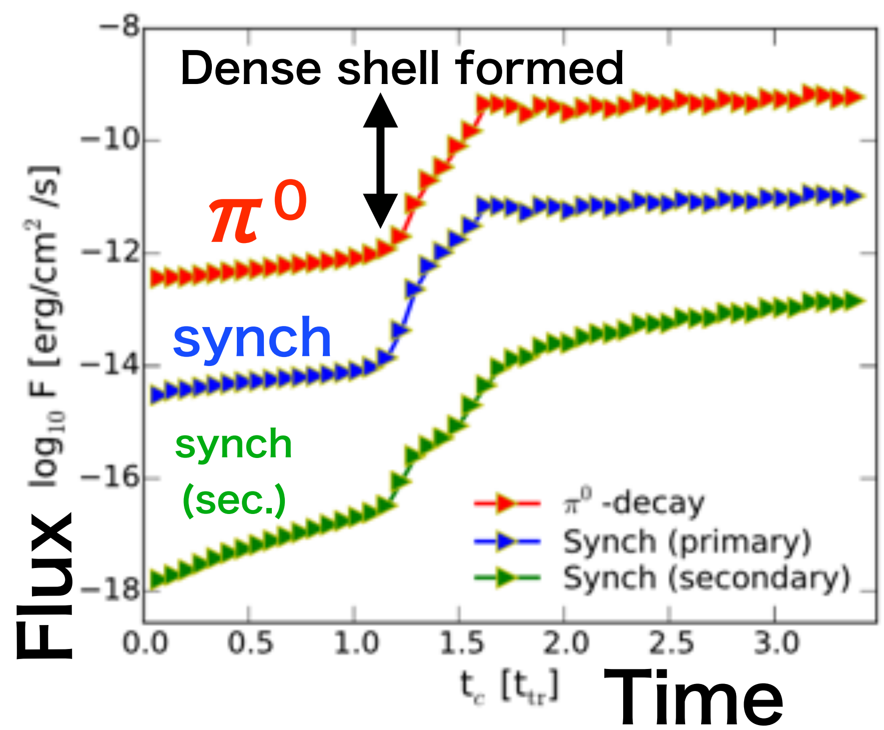
Hydro ev



GCR re-acceleration model

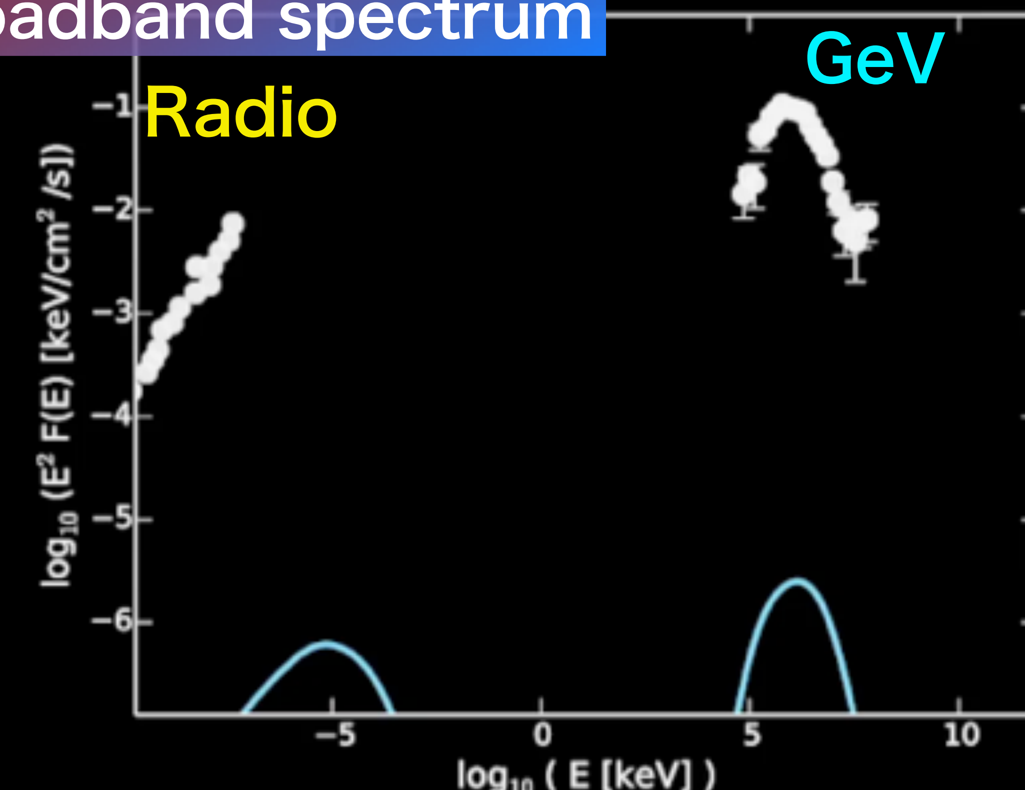


(a) Evolution of Broadband Spectrum

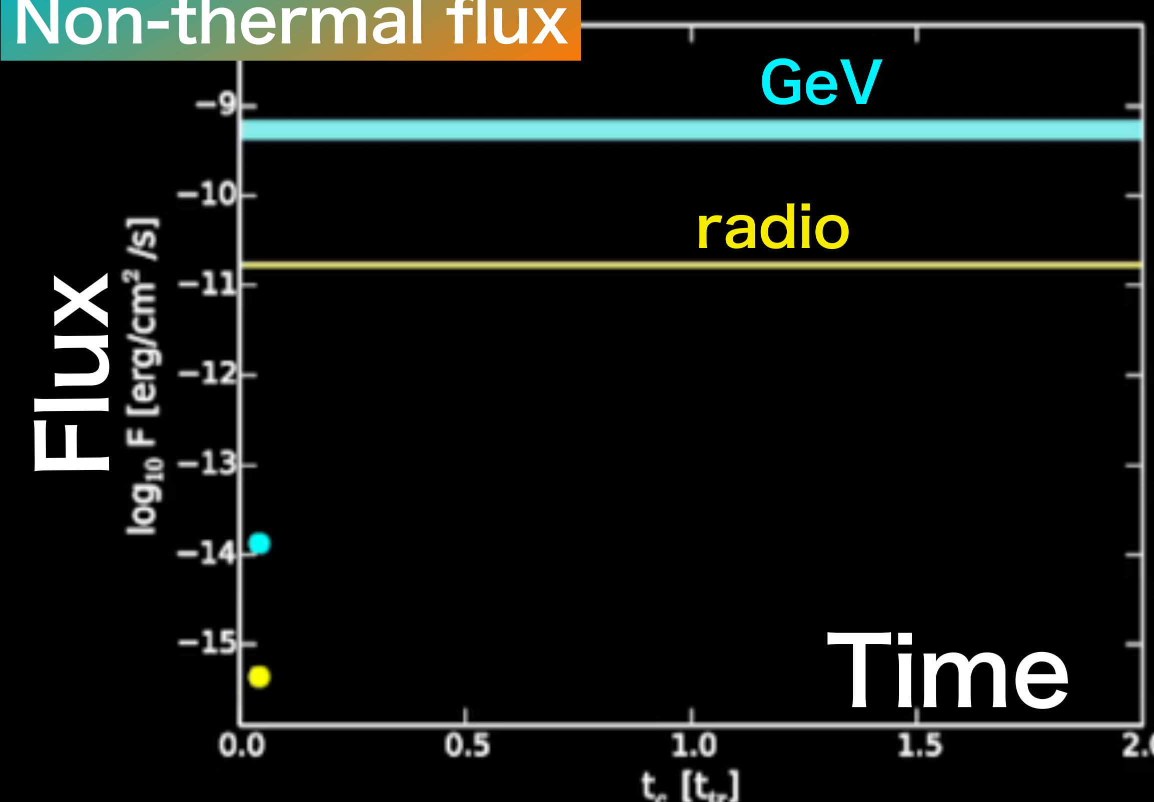


(b) Evolution of Integrated Flux

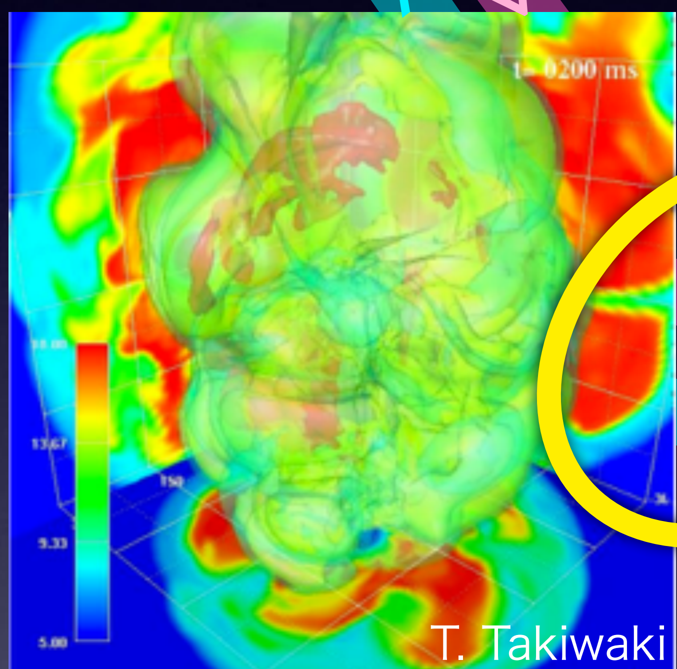
Broadband spectrum



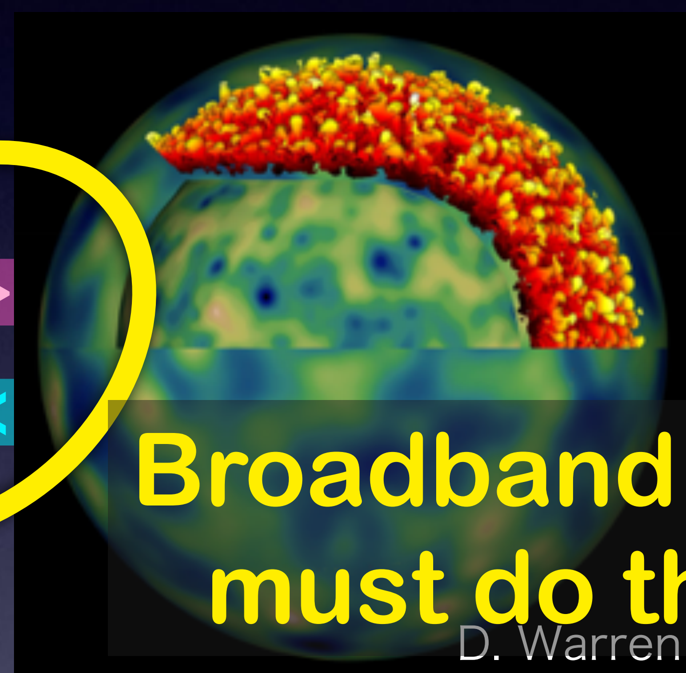
Non-thermal flux



"From engine to remnant"



SNe



SN Remnants

Data

Broadband models must do this too

Improve communication between SNe and SNR communities
—> fuller understanding of late-stage stellar evolution

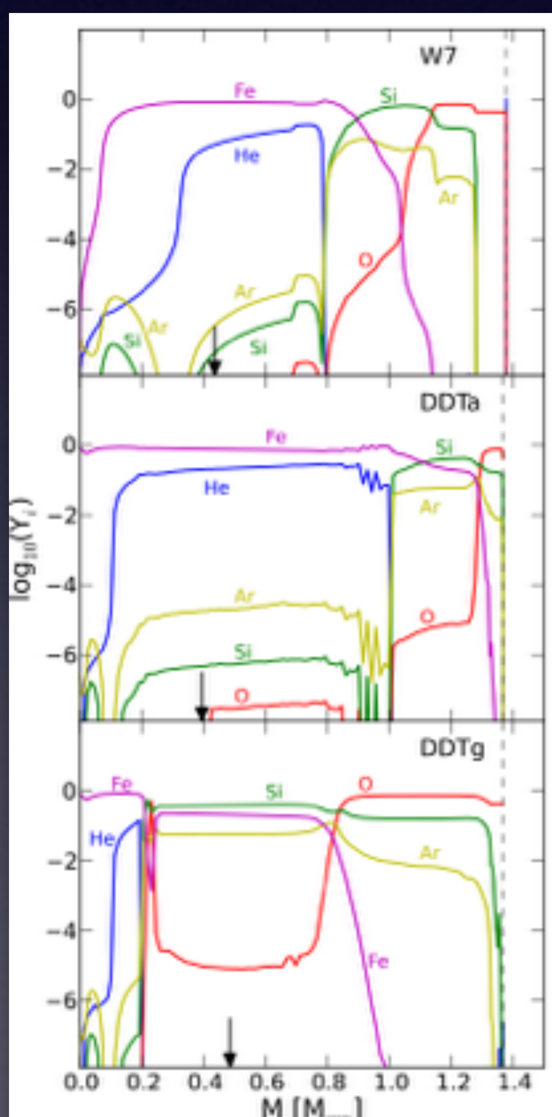
An Important Application

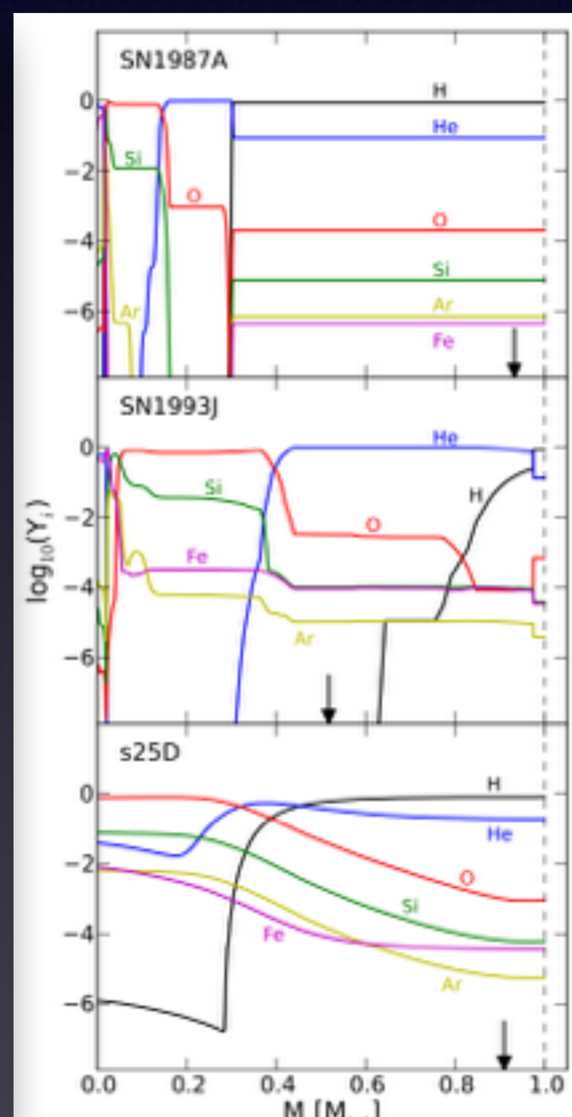
Q: Are current SN models consistent with SNR observations?

Basic method:

- ☑ Evolve an SN ejecta to its SNR phase
- ☑ Calculate the emission properties self-consistently with evolution!

Chemical Abundance





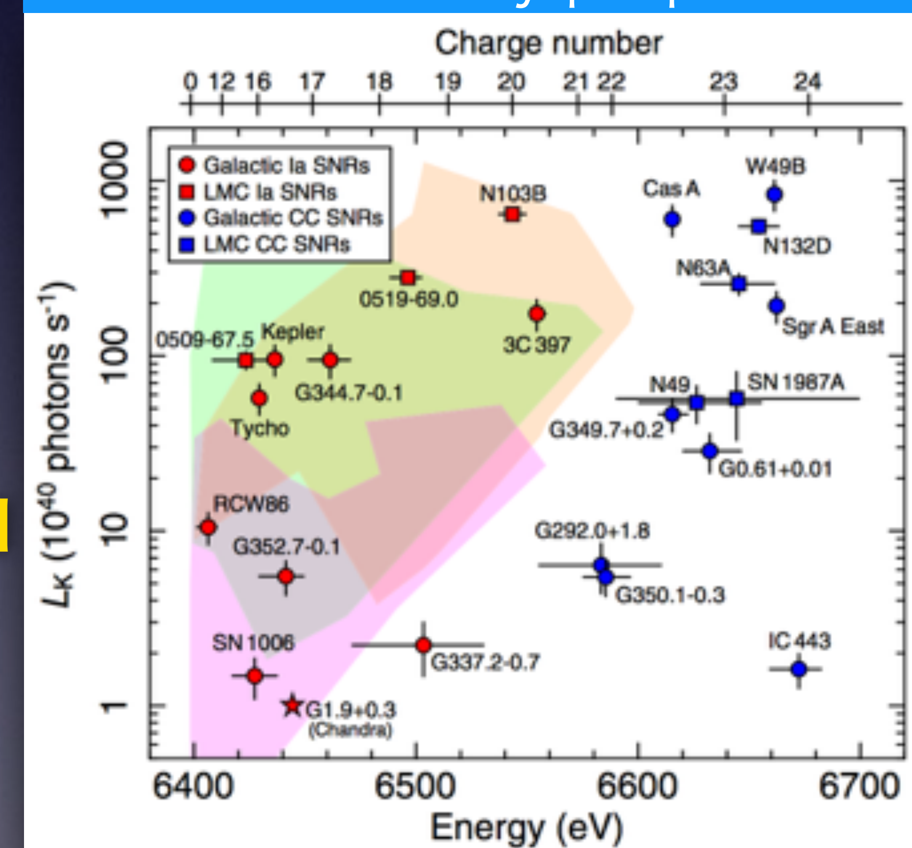
Mass coordinate

HL, Patnaude+ 2014

Check

Broadband model

Observed X-ray properties

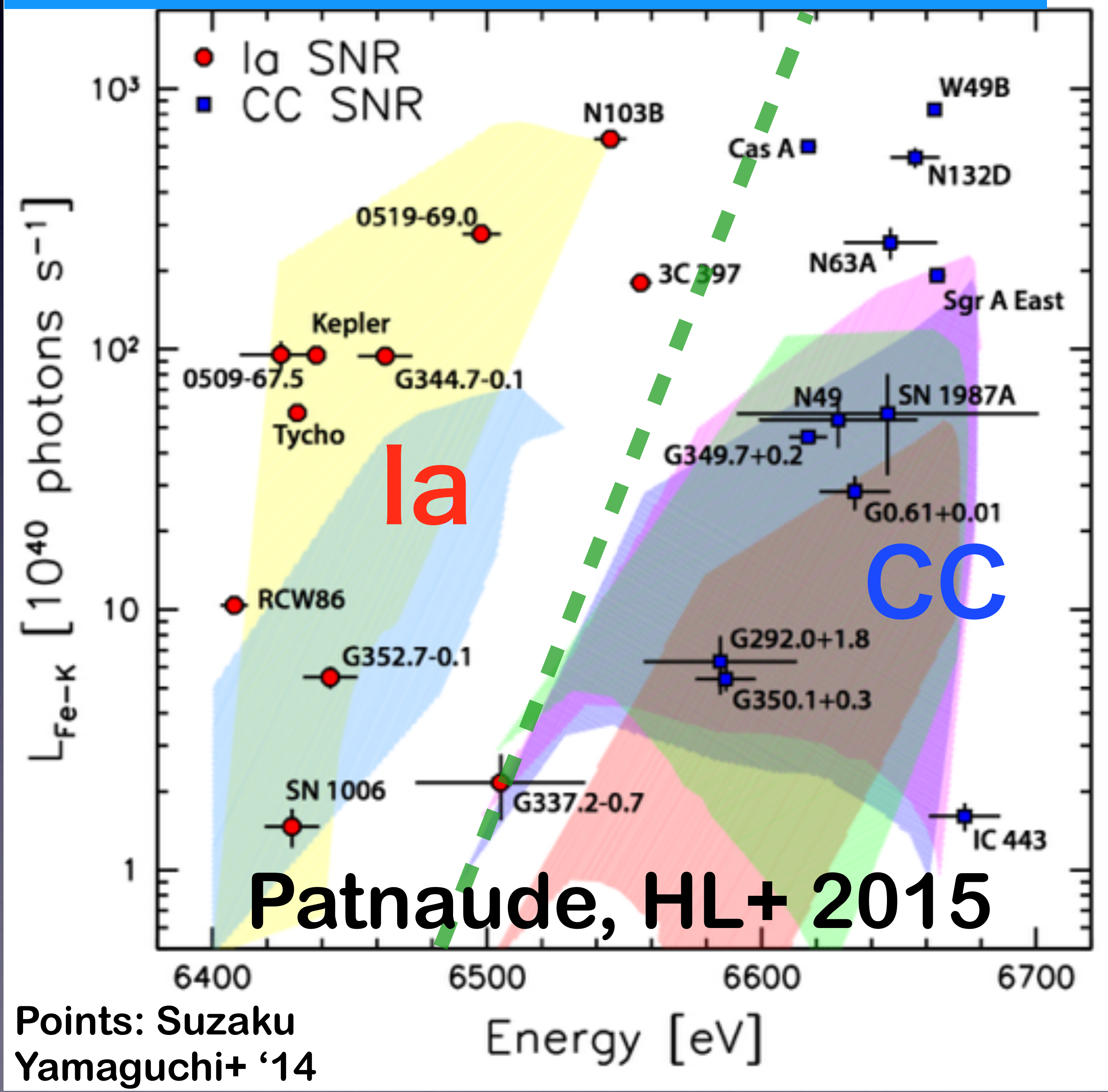


Suzaku+Chandra, Yamaguchi+ 2014

Broad consistency between SN and SNR data

Separation of Fe-K line centroid between Ia & CC

Color bands = our models

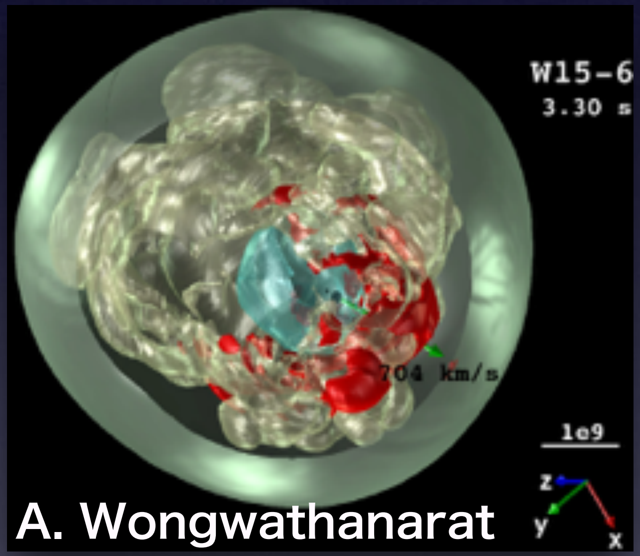


- Key is **difference in general circumstellar environment**
- **CC => slow dense wind**
  i.e., ejecta hit dense wind
  —> stronger reverse shock
  —> faster ionizations
- **Ia => uniform low-ρ ISM**
- Origin of "scattering"
  = time evolution + variation in progenitor and mass loss rate
- Several 'special' outliers

See Patnaude's talk

Phenomena in multi-dimension

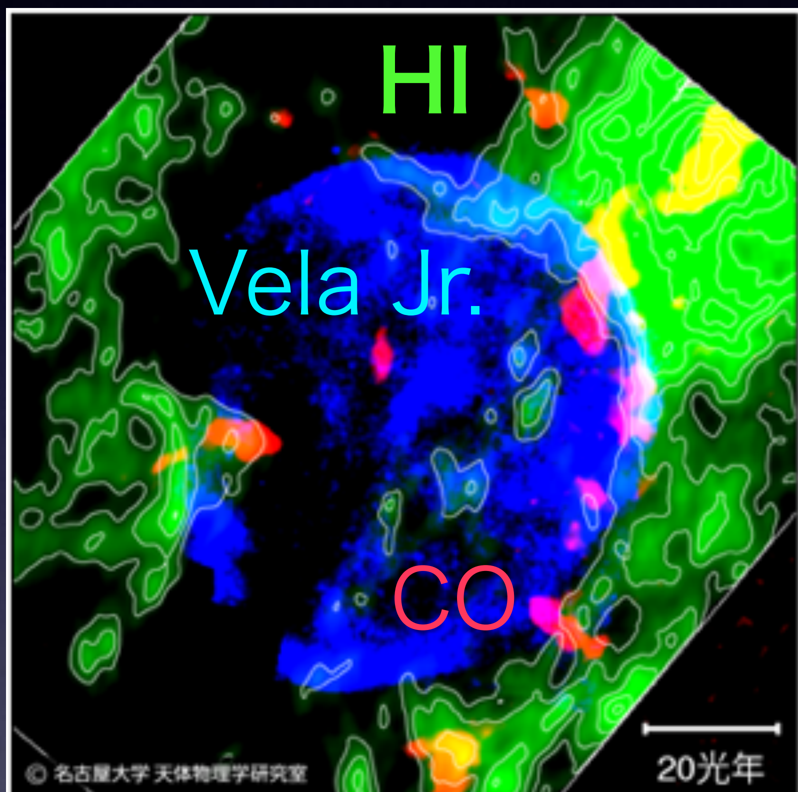
- Inhomogeneous CSM/ISM environment
- Asymmetrical SN explosions
- Turbulence development



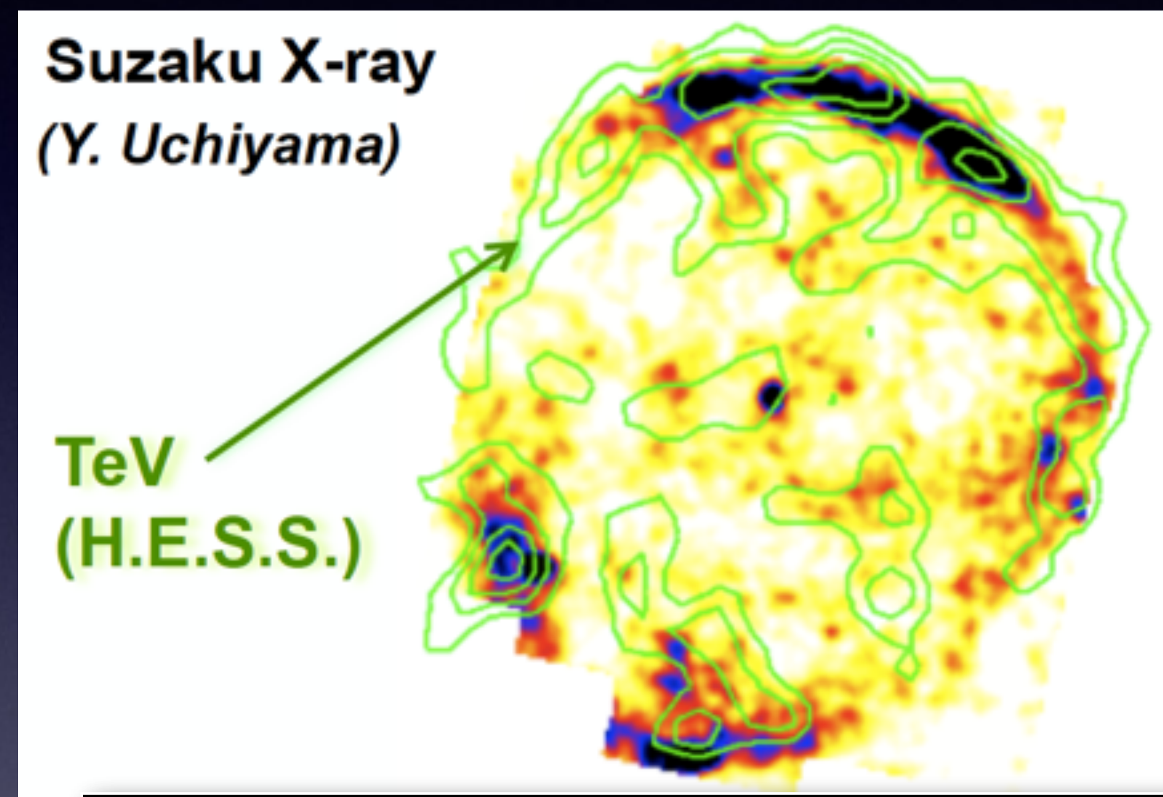
- Ejecta mixing, fast knots, jets, fingers, bubbles
- Global geometrical effects, e.g. B-field obliquity

Observational evidence of shock-cloud interaction

Example: SNR RX J0852.0-4622 (Vela Jr.)



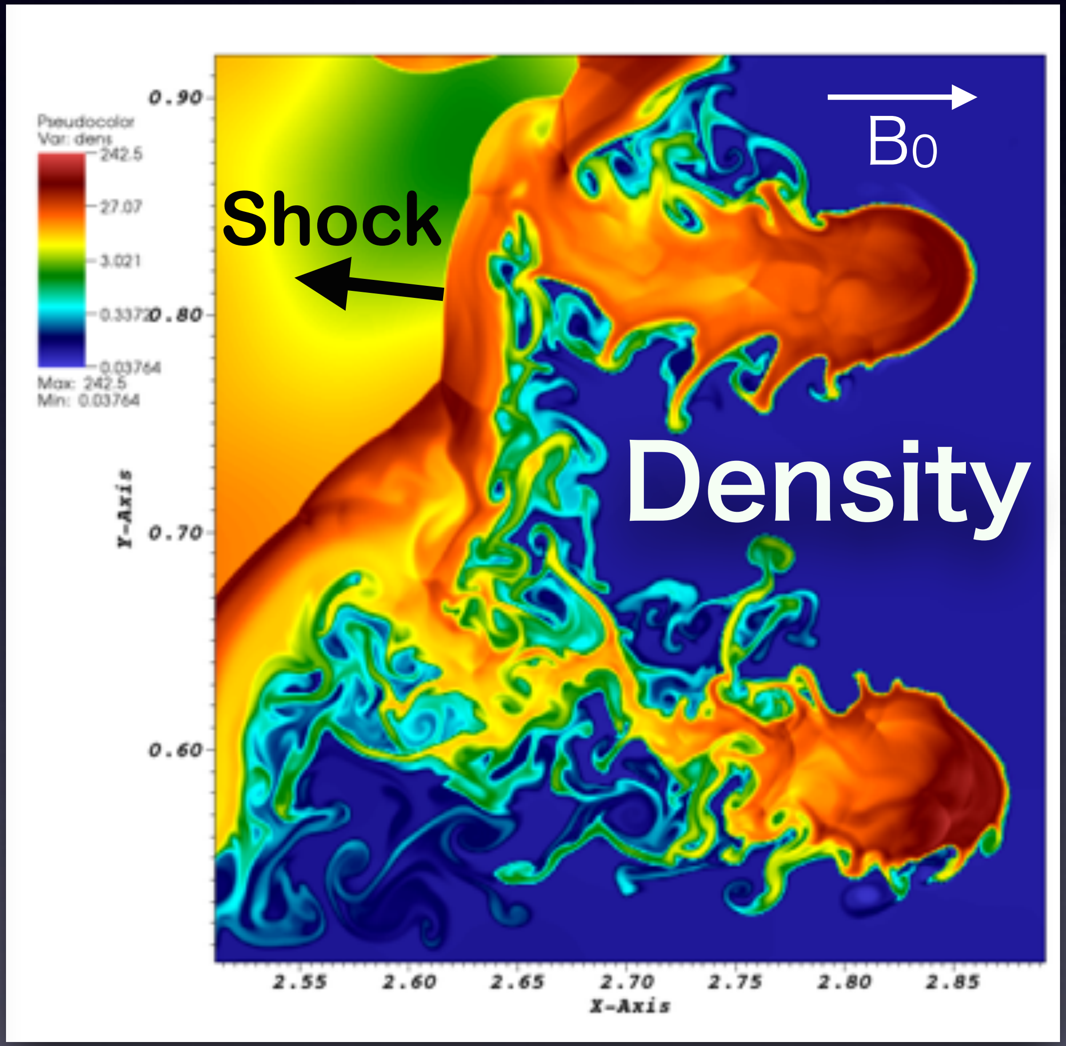
Nagoya Univ. Radio Group

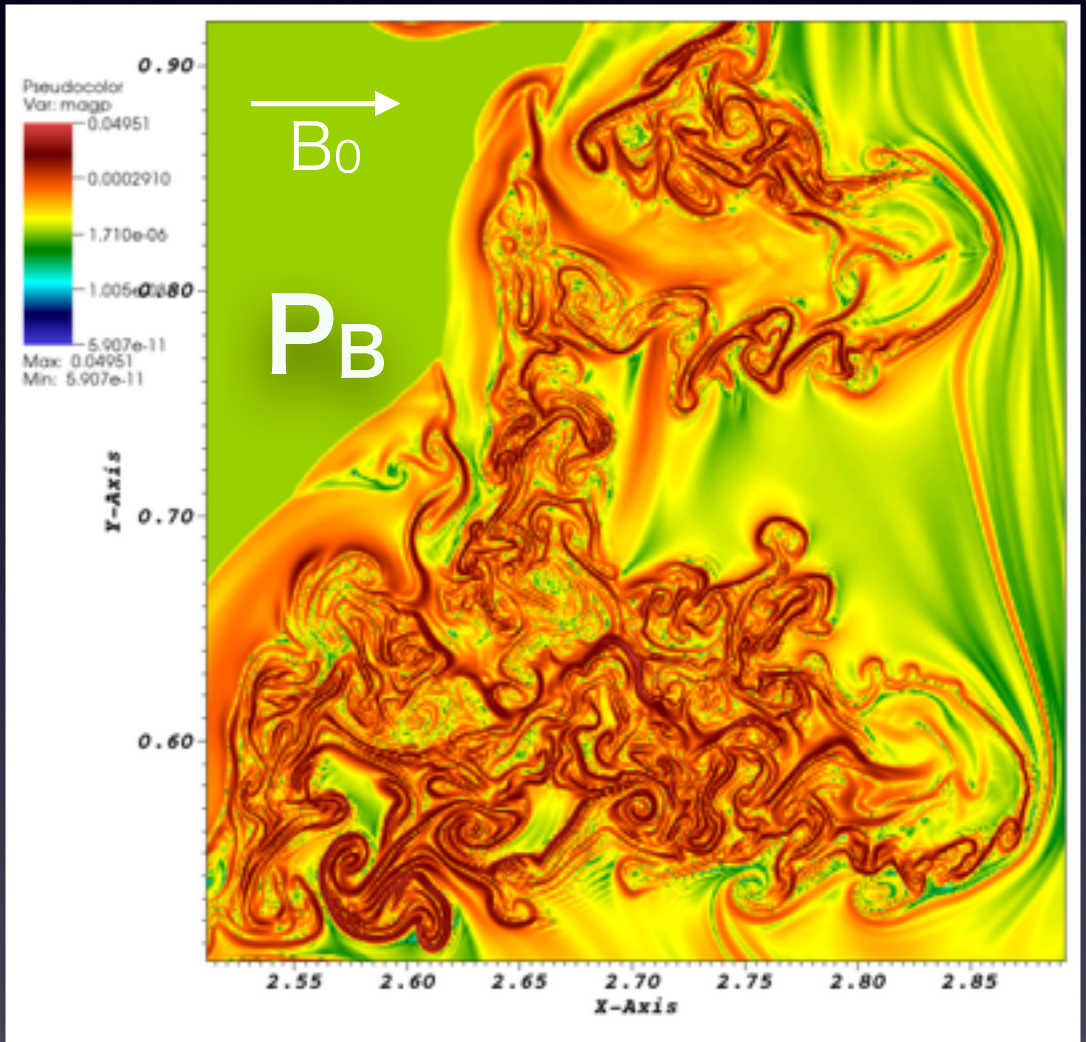


Difference between X-ray and TeV shape
Strong implication on γ-ray origins and CRs

Shock-cloud interactions at SNRs exhibit many interesting phenomena. Hot topics now!

SNRs interacting with clumpy medium Amplifies magnetic turbulence

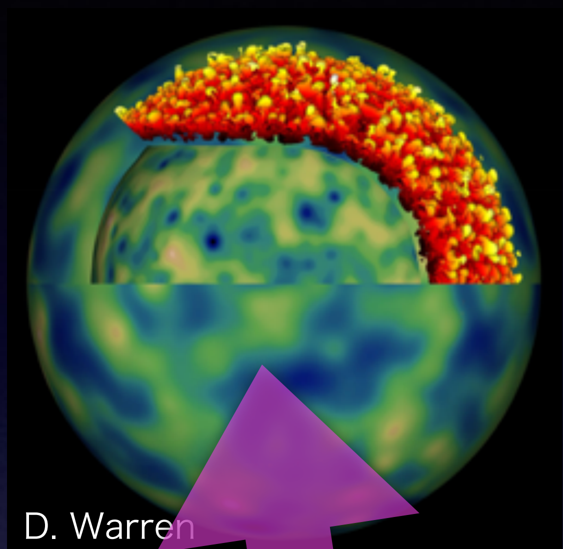




HL

Turbulence and B-field amplification

Roadmap



Deeper understanding of Supernova Remnants (SNRs)

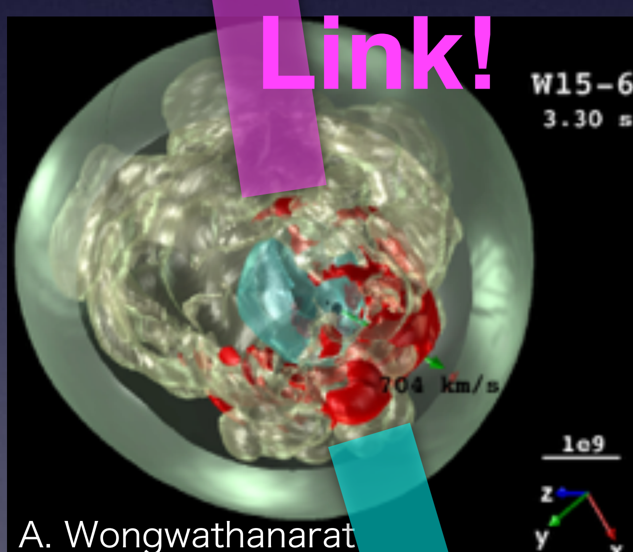
Origin of Cosmic Rays!

Magnetic turbulence in Universe

Complex physics of astrophysical plasma and shockwaves

Environmental impacts in interstellar space of galaxies

Link!



Towards true picture of Supernova Explosions

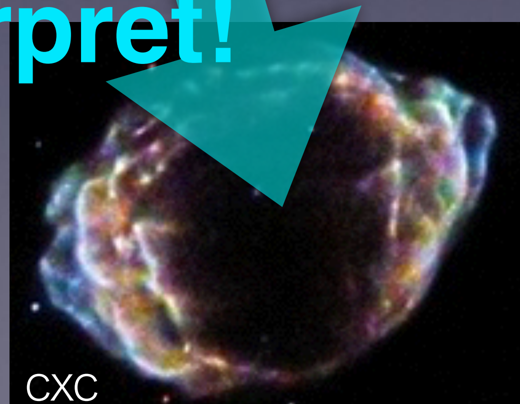
Nature of progenitor stars

Explosion mechanism

Nucleosynthesis of chemical elements

Transition to SNR and interstellar medium

Interpret!



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

Future and current observations of SNe and SNRs from young to old

In future: ***CTA, SKA, JWST, next X-ray telescopes, …***

Conclusions

- We have reviewed on the general methodology and capabilities of modern broadband models for SNRs
- Current limitations from yet incompletely understood physics = parameters
  - Rely on rich observational data and breakthroughs from first principle simulations to constrain/remove
- Importance of progenitor-SN-SNR connection, requires **joint efforts to combine state-of-the-art models in each area** for a self-consistent picture