Supernova Remnants

and Associated High-Energy Phenomena

PWNe and compact objects

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Paris, July 7-8 (2014)

ASTRO-H summer school

Outline

- **Supernova Remnants:**
  - Significance (big picture)
  - Shock Dynamics, Classfication, Evolution (briefly)
  - High-Energy Emission Processes (briefly)
  - High-Energy Observations & Statistics:
    - SNRcat (X- and gamma-rays)

Non-thermal Emission (to be) covered by Felix Aharonian

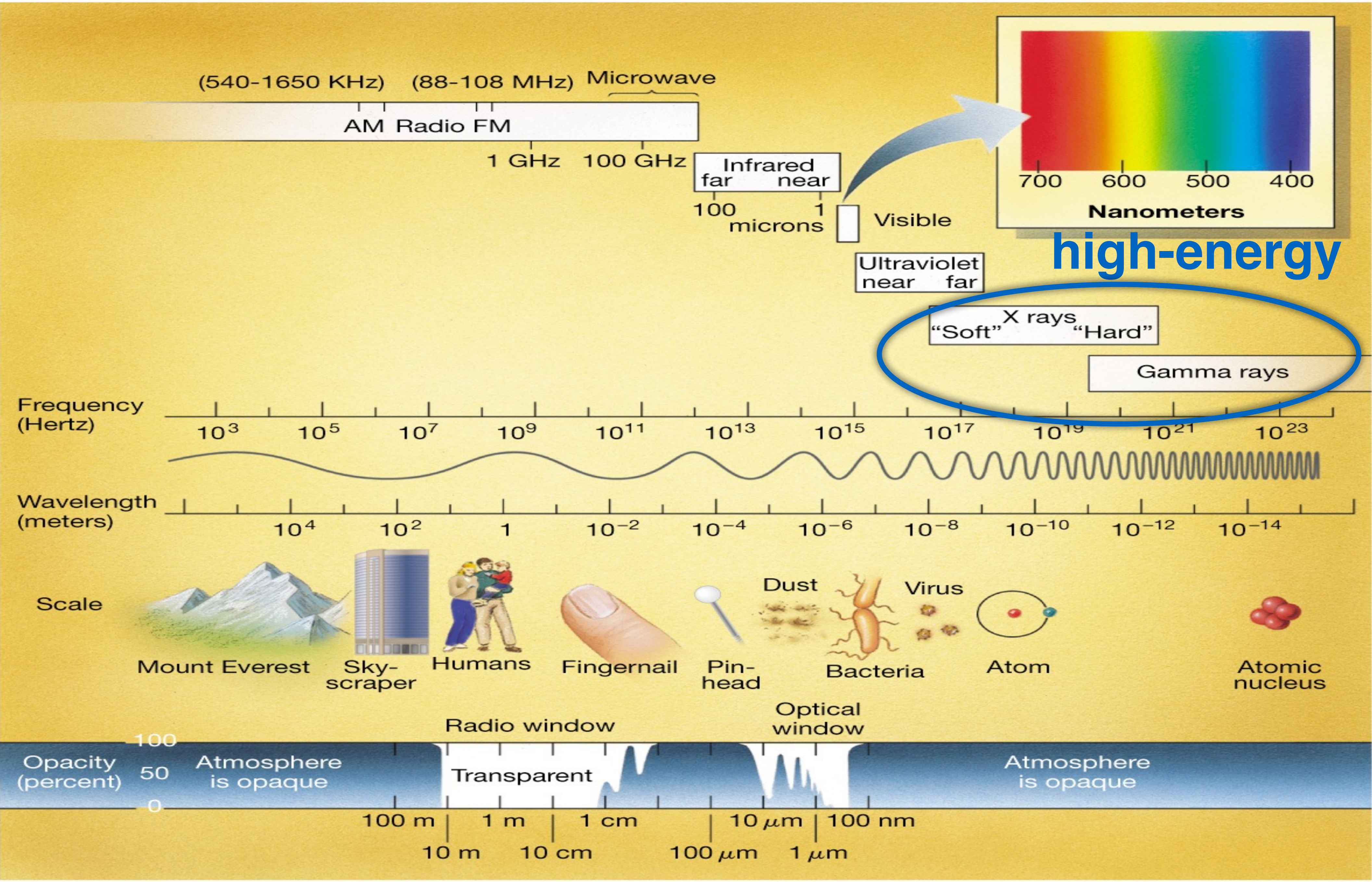
Pulsar Wind Nebulae

Associated Compact Objects (Diversity)

Prospects with ASTRO-H

↔ Next lecture

Electromagnetic spectrum



High-energy missions

keV (X-rays)

NASA **Chandra (AXAF), July 1999-**

ESA XMM-Newton, Dec. 1999-

NASA Swift, Nov. 2004-

JAXA Suzaku, July 2005- *(happy birthday!)*

NASA NuSTAR, June 2012-

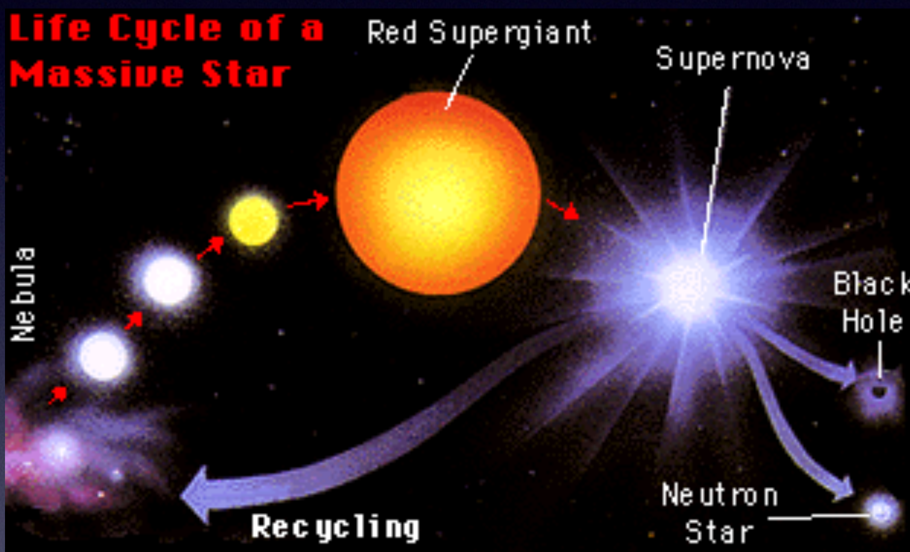
X-ray astronomy: Achieved in 40 years what optical astronomy achieved in 400 years!
*(a **billion times** improvement in sensitivity and a **quarter of a million times** improvement in angular resolution (Chandra)).*

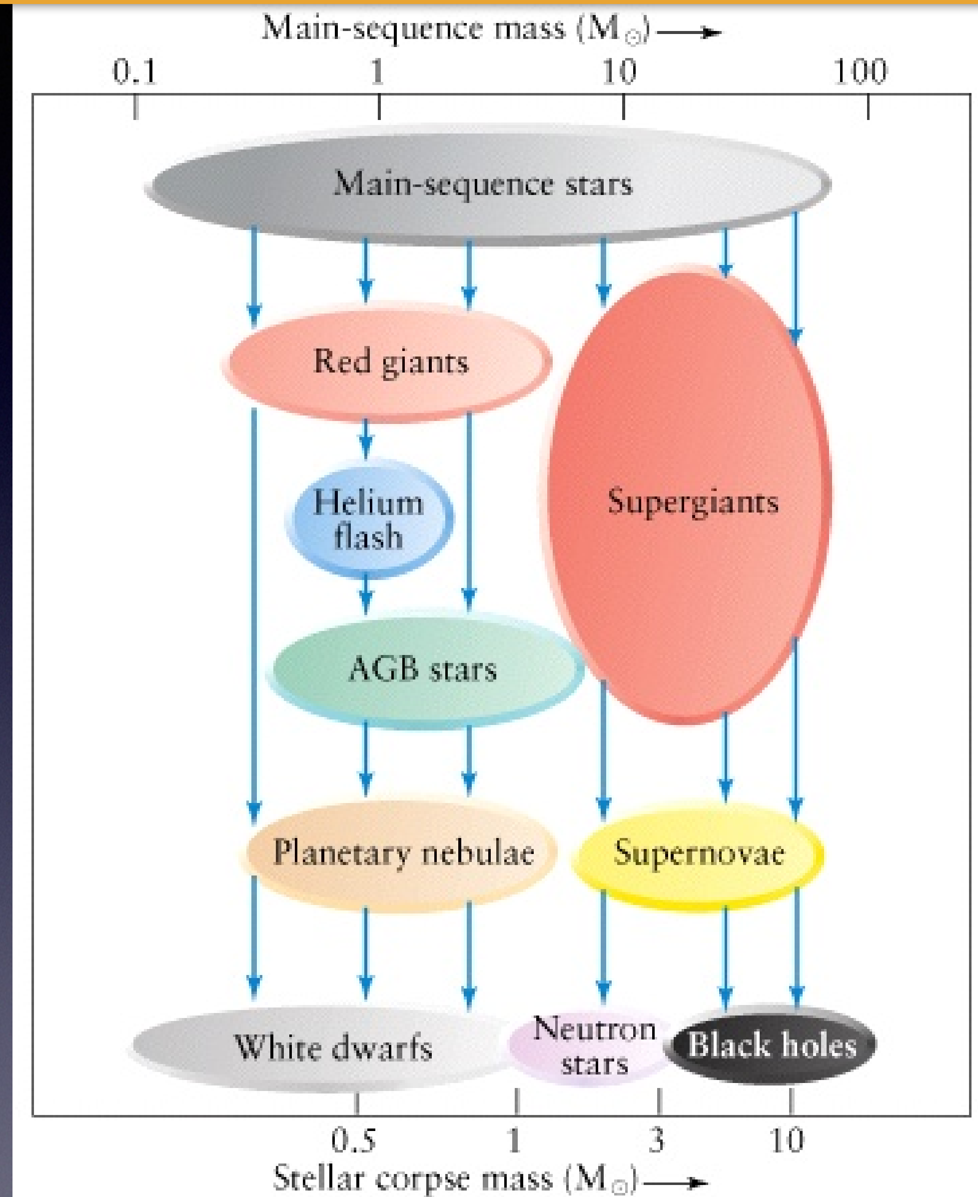
Gamma-rays (MeV-TeV): a new window on the extreme Universe!

- MeV-GeV: Integral, Fermi, AGILE
- TeV: **HESS,** VERITAS, MAGIC, MILAGRO

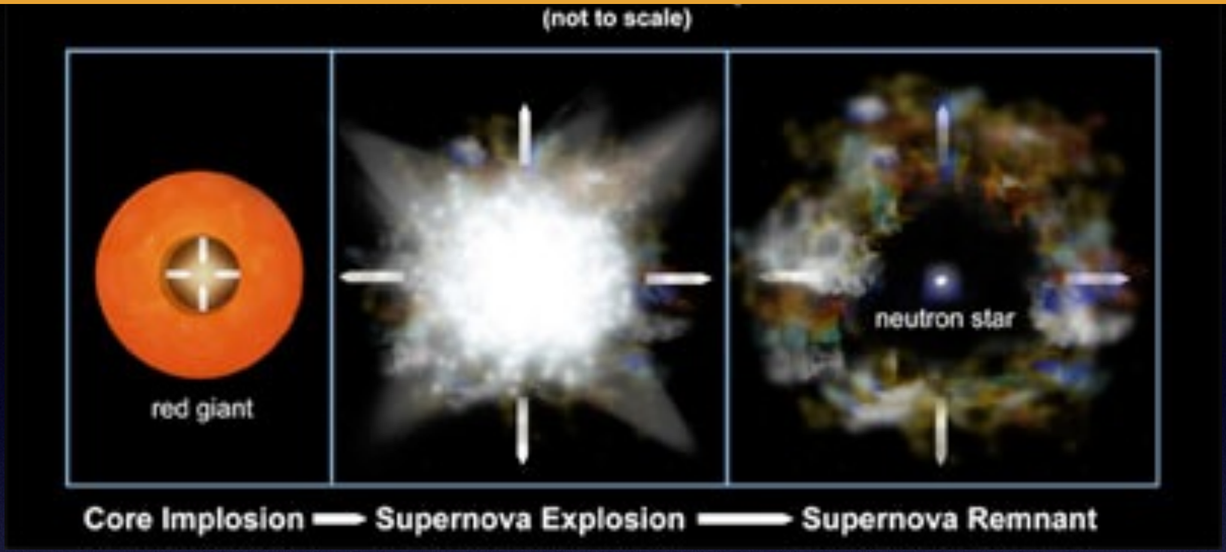
The future: (x-rays) **ASTRO-H (2015)**, ASTROSAT,eROSITA,
NICER, HXMT, …**Athena (~2028)**
(gamma-rays): **The Cerenkov Telescope Array**

Stellar Evolution and Recycling of the ISM

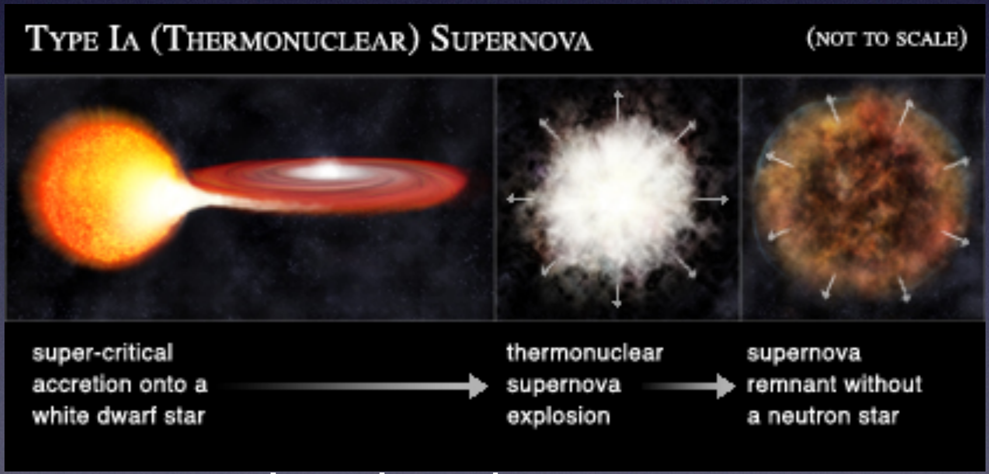




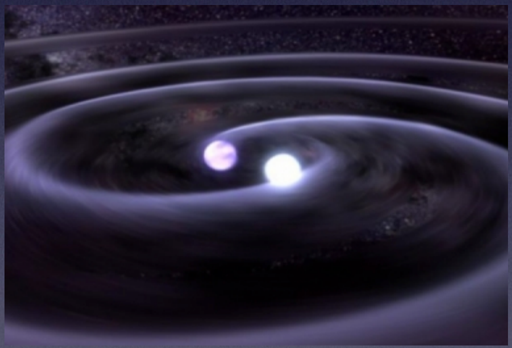
SN Types



core-collapse
II/Ia/Ib/Ic

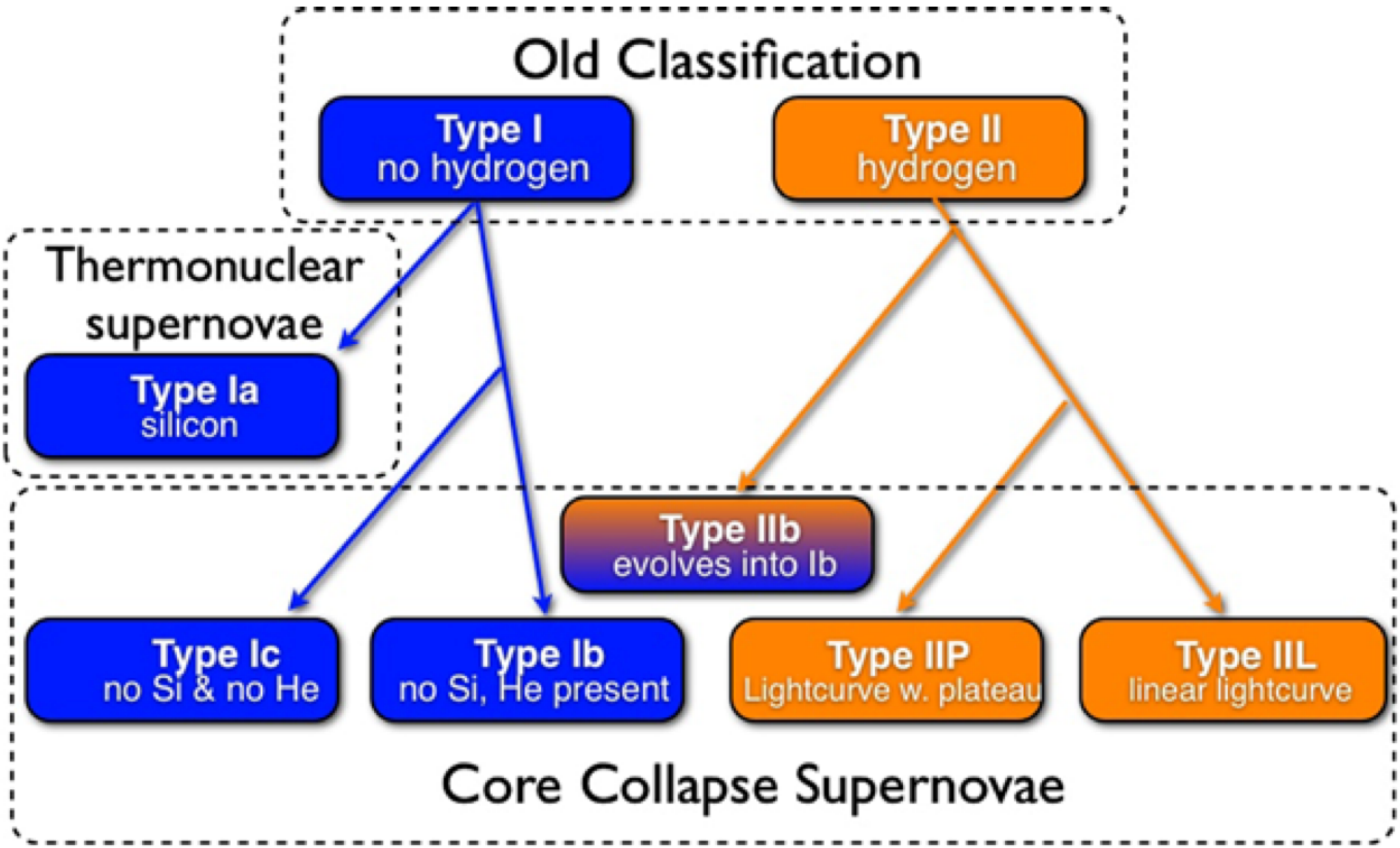


single degenerate
Mass accretion from a companion



double degenerate
white dwarf+white dwarf merger

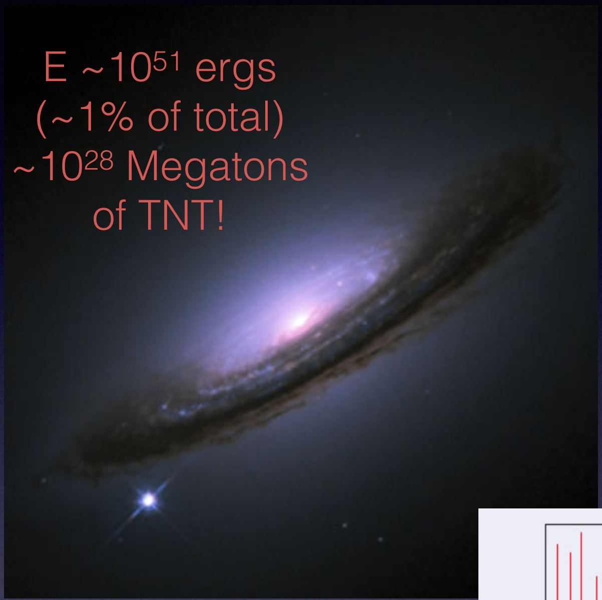
SN Types

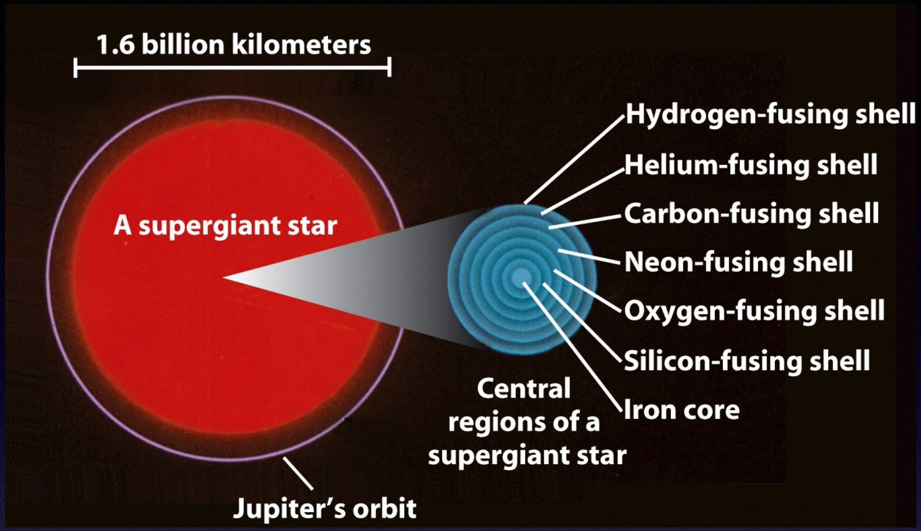


Vink 2012

Supernovae

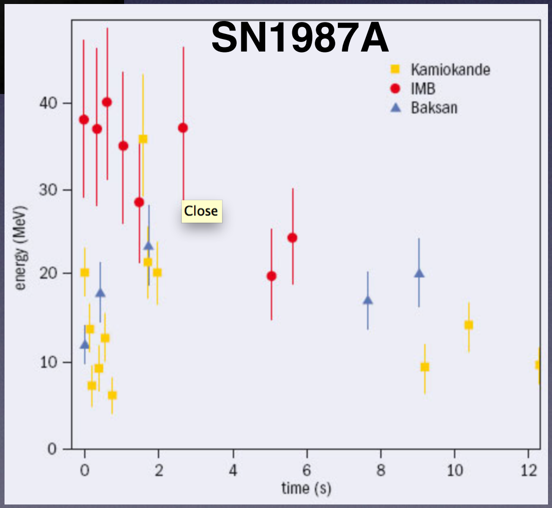
can outshine an entire galaxy!

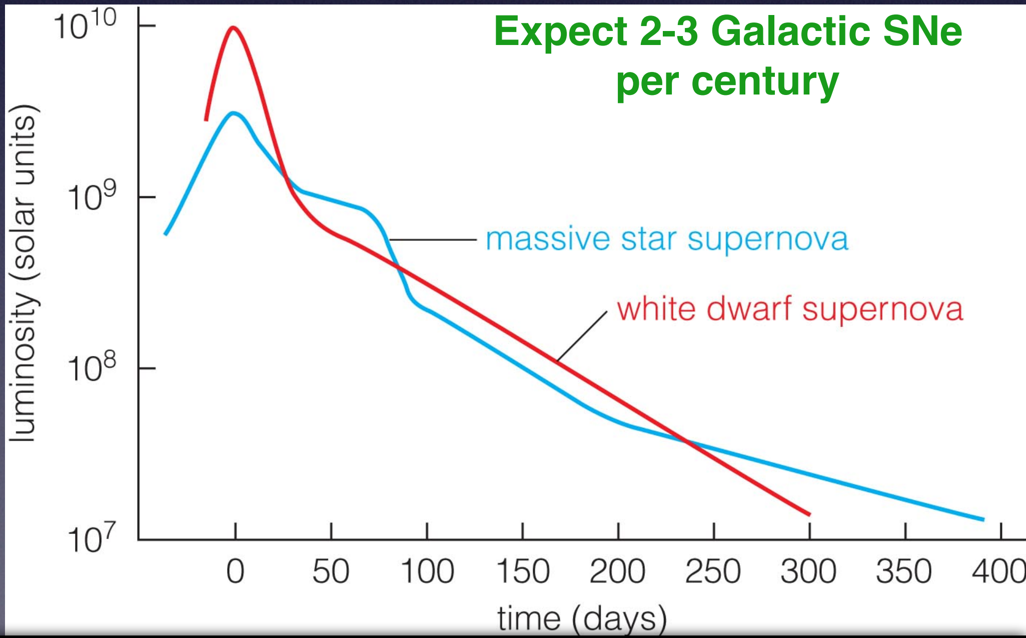




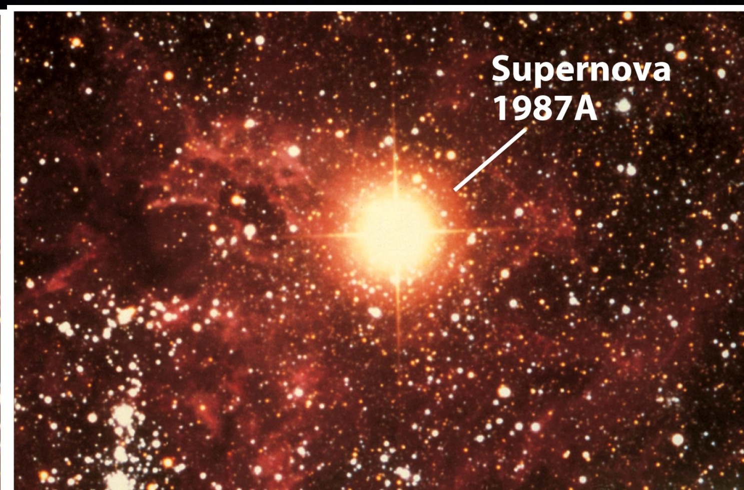
progenitor of a core-collapse SN

More than 99% of the energy (1E53 ergs) from a supernova is emitted in the form of neutrinos from the collapsing core





SN1987A - LMC
the youngest and "closest" one we have been monitoring



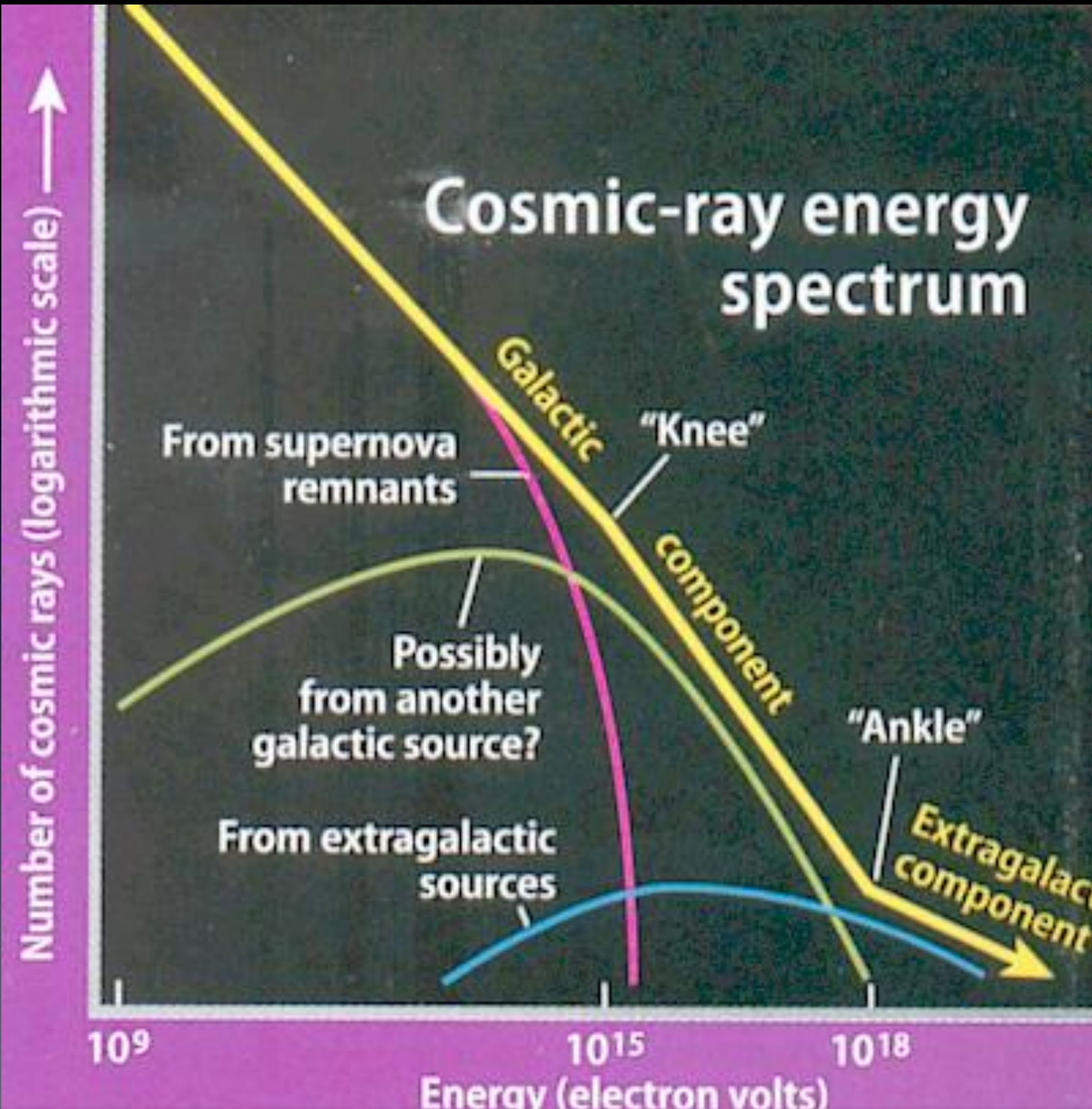
TO: EUGENE BEIER

SENSATIONAL NEWS! SUPERNOVA WENT OFF
4-7 DAYS AGO IN LARGE MAGELLENIC CLOUD, 50 KPC
AWAY. NOW VISIBLE MAGNITUDE 4~5, WILL
REACH MAXIMUM MAGNITUDE (-1~0) IN A WEEK.
CAN YOU SEE IT? THIS IS WHAT WE HAVE
BEEN WAITING 350 YEARS FOR!

SID BLUDMAN
(215) 546-3083

"To predict the year of explosion of a supernova is not harder than to predict the year of funding a big accelerator or a big detector. I expect that the date of the next supernova is 2003 +/- 15 years." Prof. L. Okun (1988)

Cosmic Ray Accelerators

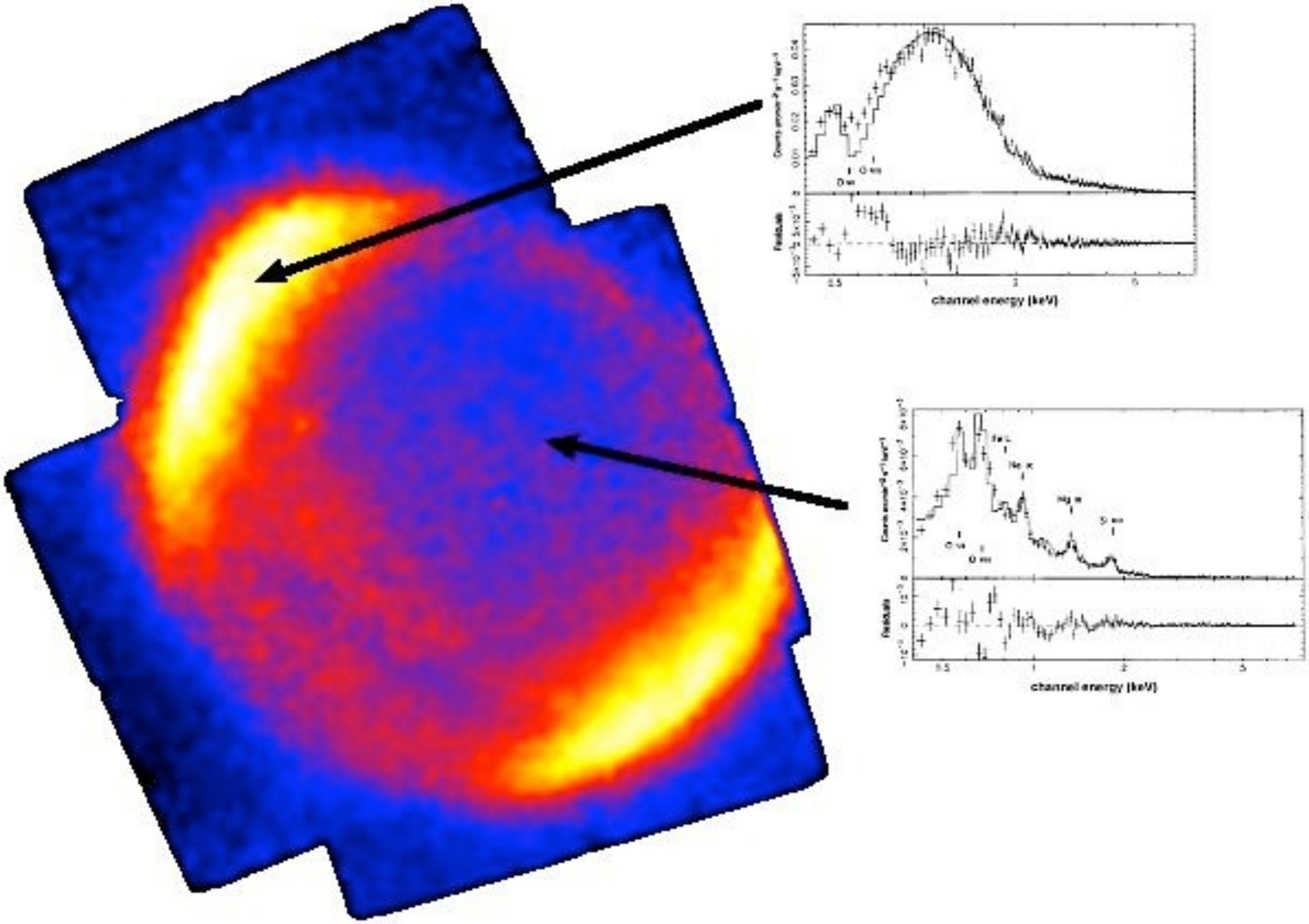


SNRs as CR accelerators up tp the "knee" (1 PeV):

- energetics (10%)
- power law spectrum
- composition

102 yrs into CR discovery by Victor HESS!

SN1006 in X-rays:
CR acceleration to~200 TeV

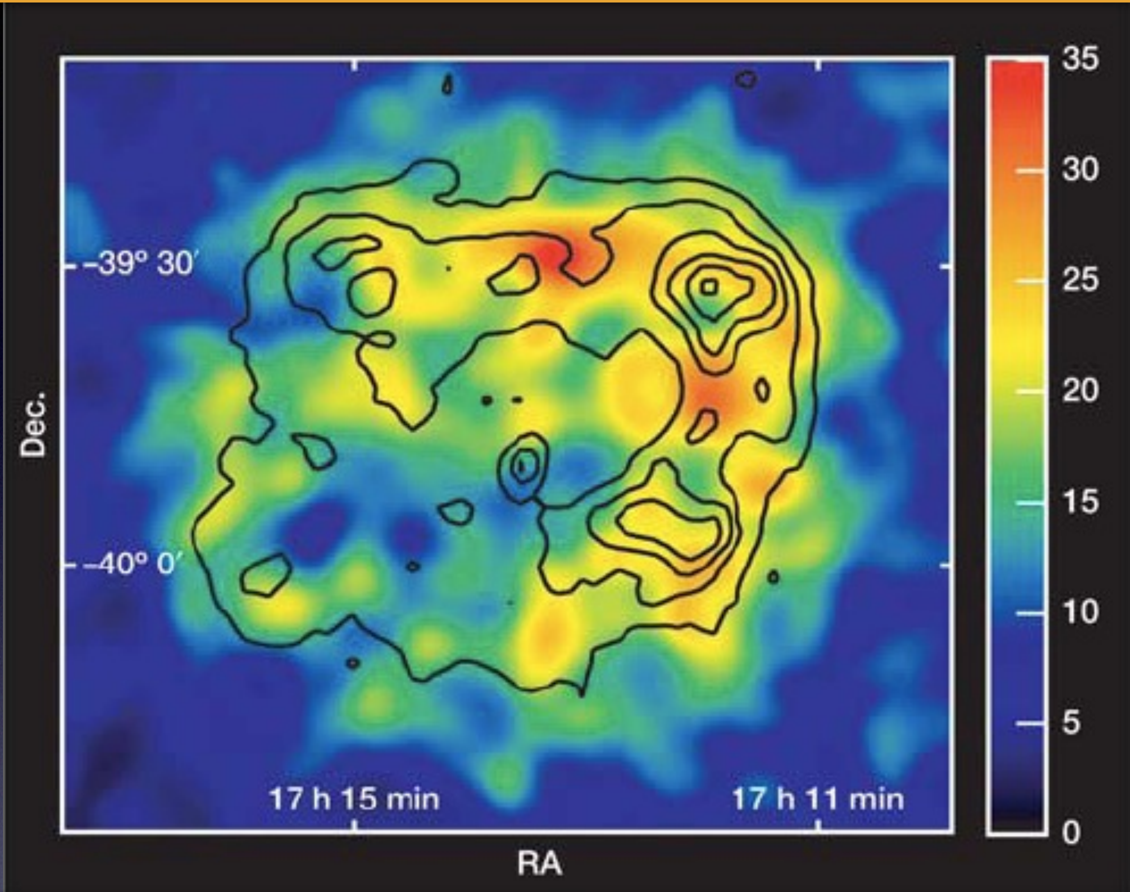


Non-Thermal rims

Thermal interior

The first evidence for CR acceleration to 100's TeV energies from X-ray (ASCA, 0.3-10 keV) observations of **SN1006**: *Koyama et al. 1995, Nature*

RXJ1713 in gamma-rays: A most powerful CR accelerator



H.E.S.S. (100 GeV-10 TeV) image with X-ray (non-thermal) contours

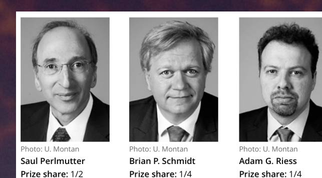
The first resolved gamma-ray (TeV) image of an SNR (G347.3-0.5) providing unambiguous evidence for CR acceleration to multi-TeV.

HESS, *Aharonian et al. 2004, Nature*

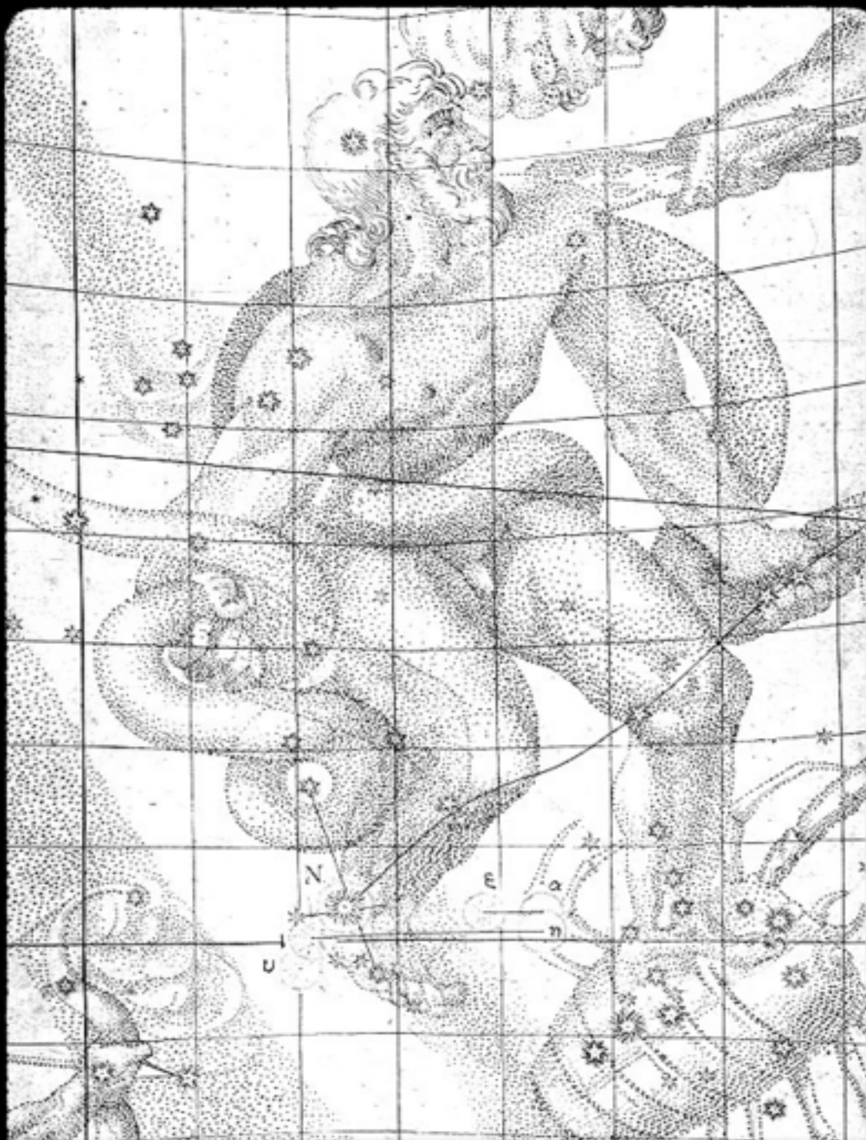
Supernova Remnants
….So why bother?

- Nucleosynthesis (creators of heavy elements that are essential for life!)
- Cosmic Ray (CR) Acceleration
- Interstellar Medium (ISM)
- Cosmology (standard candles)
- Neutrino, gravitational wave, GR astrophysics
- Extreme physics (compact object)—*next lecture*

2011

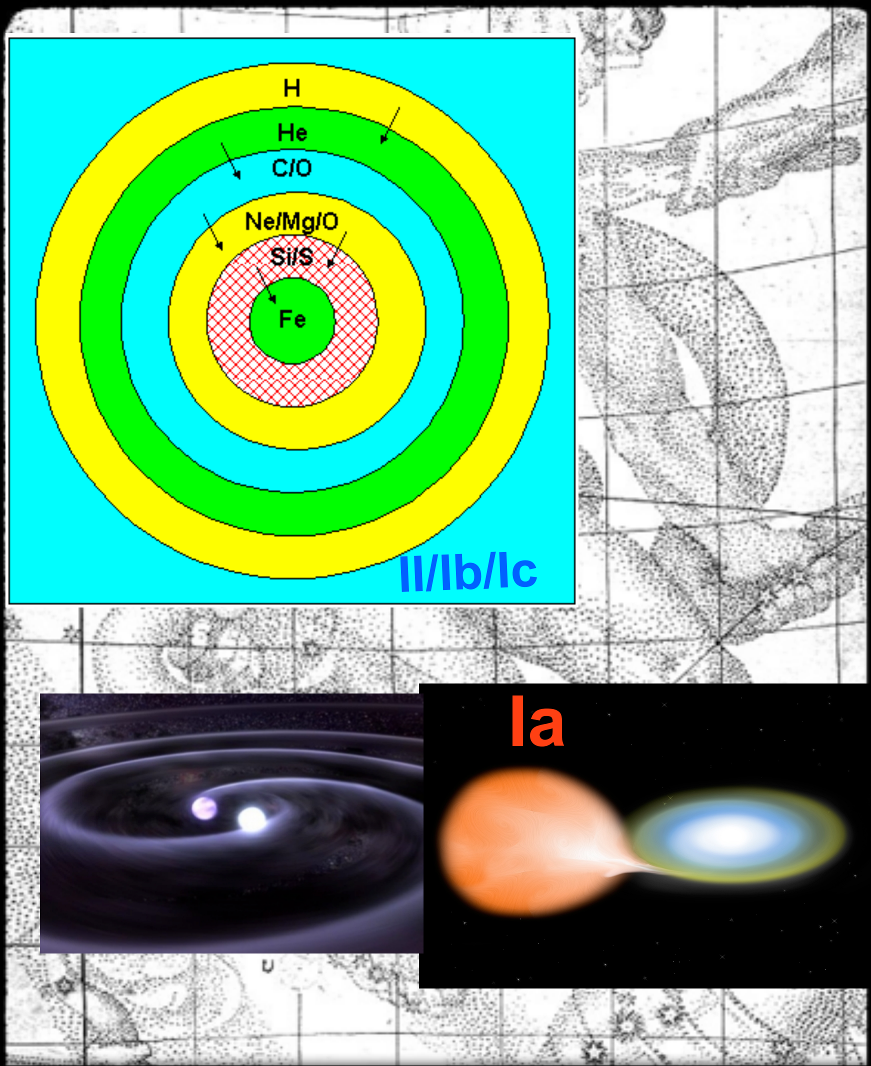


Historical SNe



- 185 A.D. (RCW86)
- 393 A.D.? (G347.3-0.5)
- 386 A.D.? (G11.2-0.3)
- 1006 (SN1006)
- 1181 (3C58)
- 1054 (Crab)
- 1572 (Tycho)
- 1604 (Kepler)--shown
- 1680? (CasA)

Historical SNe



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- 1604 (Kepler)--shown
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Historical SNe

Reynolds et al. 2008

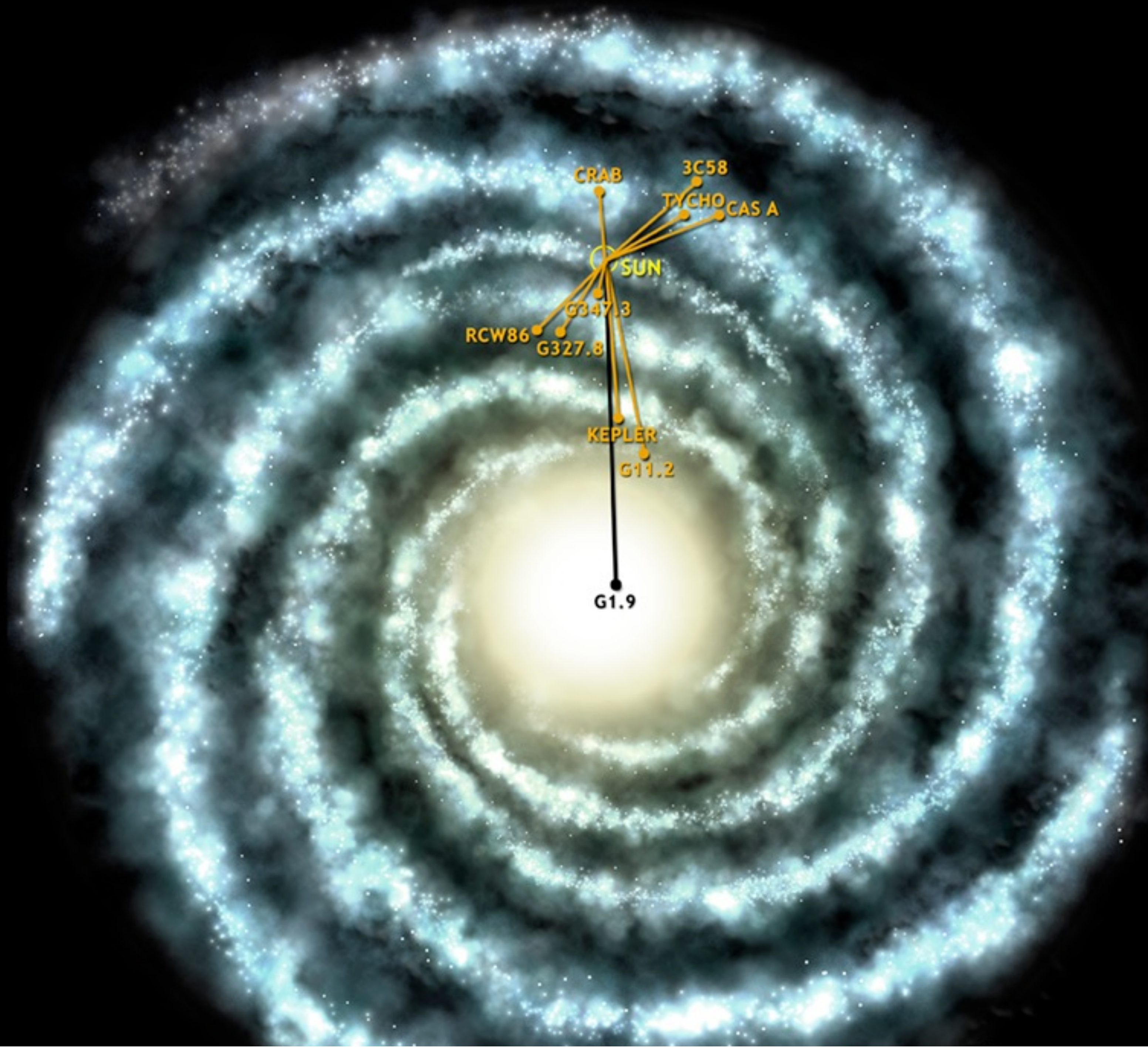
CHANDRA & VLA

Y. Uchiyama's classification:
The "firefox" SNR!

- 185 A.D. (RCW86)
- 393 A.D.? (G347.3-0.5)
- 386 A.D.? (G11.2-0.3)
- 1006 (SN1006)
- 1181 (3C58)
- 1054 (Crab)
- 1572 (Tycho)
- 1604 (Kepler)--shown
- 1680? (CasA)

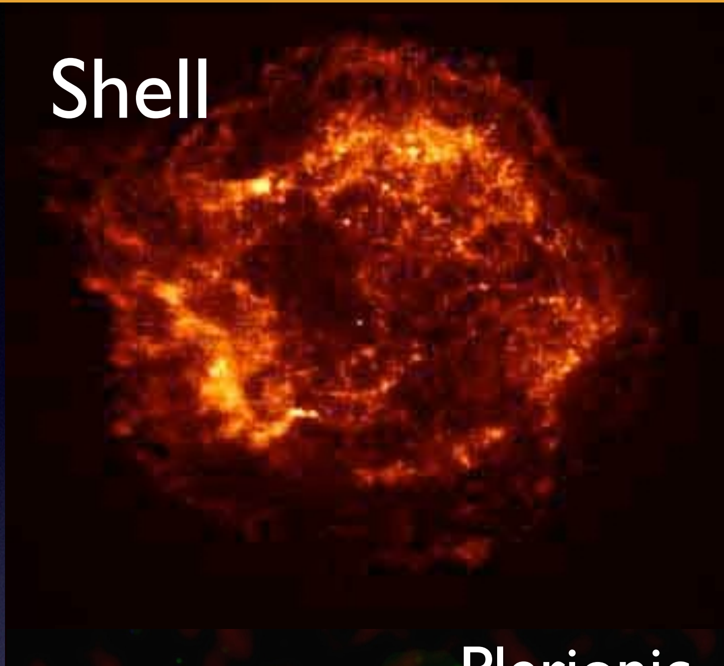
?<1900ish?? G1.9+0.3

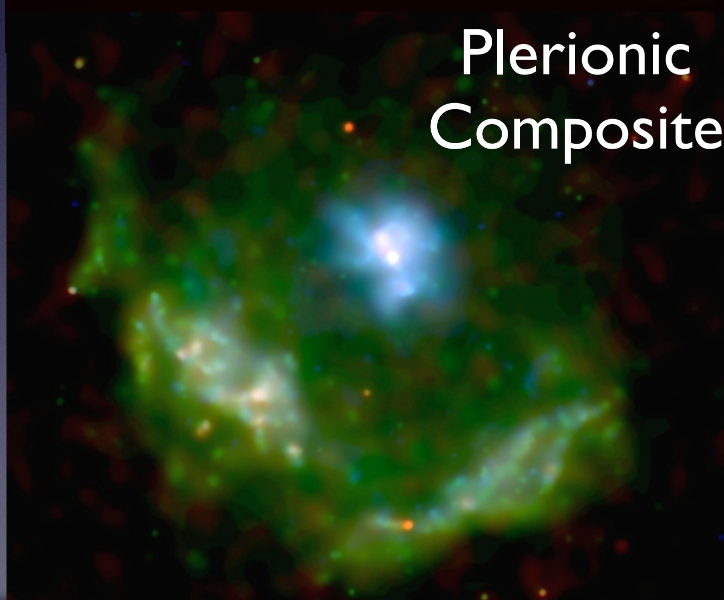
Historical SNe

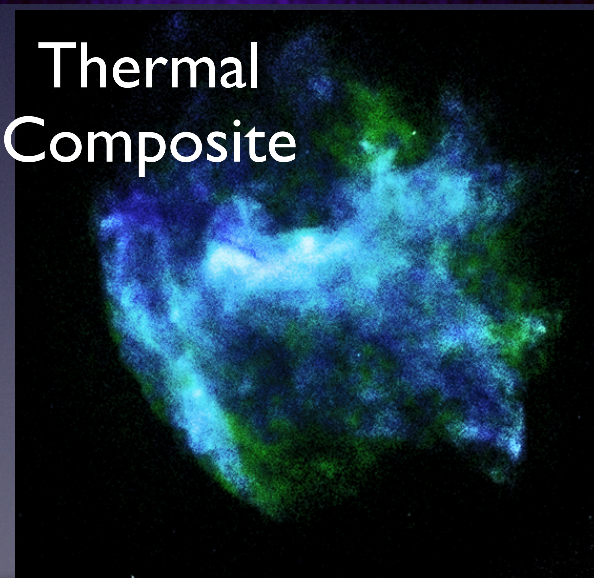


SNR: Classification

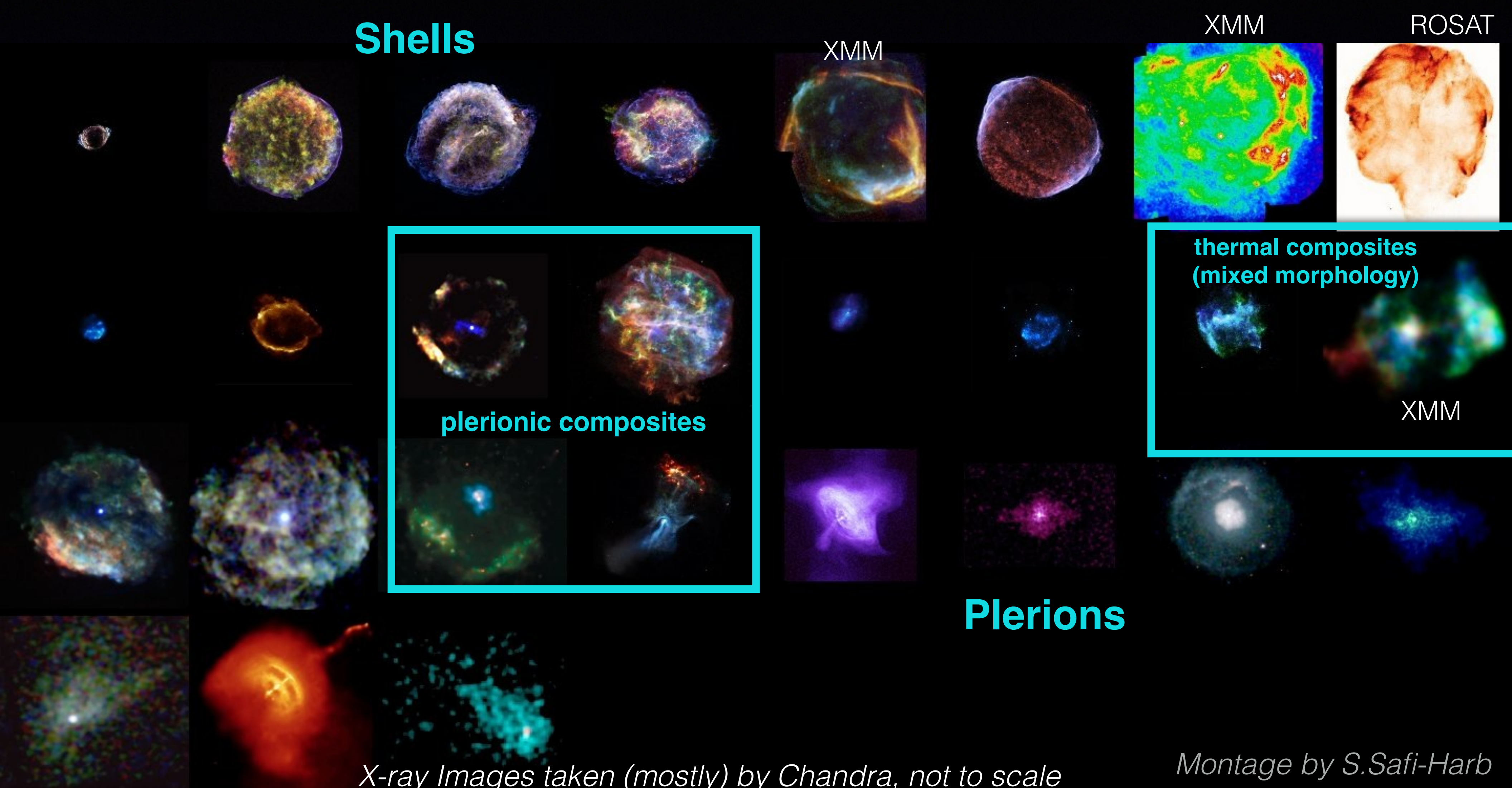
SNR Classification





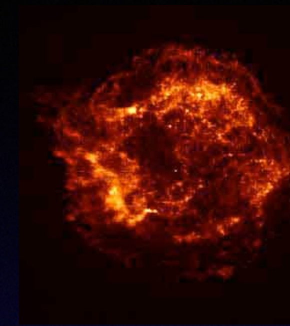


SNR classification



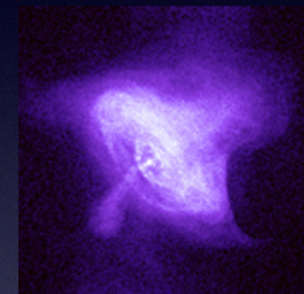
X-ray Images taken (mostly) by Chandra, not to scale

SNR classification and X-ray emission: Thermal and Non-thermal



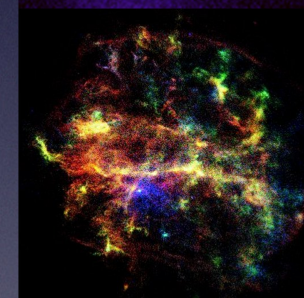
Shells (191):

- dominated by **thermal** X-ray emission from shock-heated plasma
- **non-thermal** X-ray emission due to particle acceleration at the SN shock



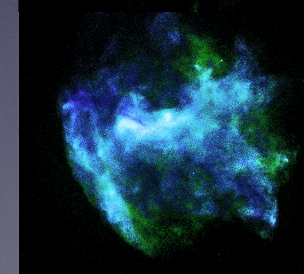
Plerions (filled-centre, 34):

- **non-thermal** emission due to **synchrotron** radiation from high-energy particles spiralling strong magnetic fields (aka pulsar wind nebula, PWN)



Composites (82):

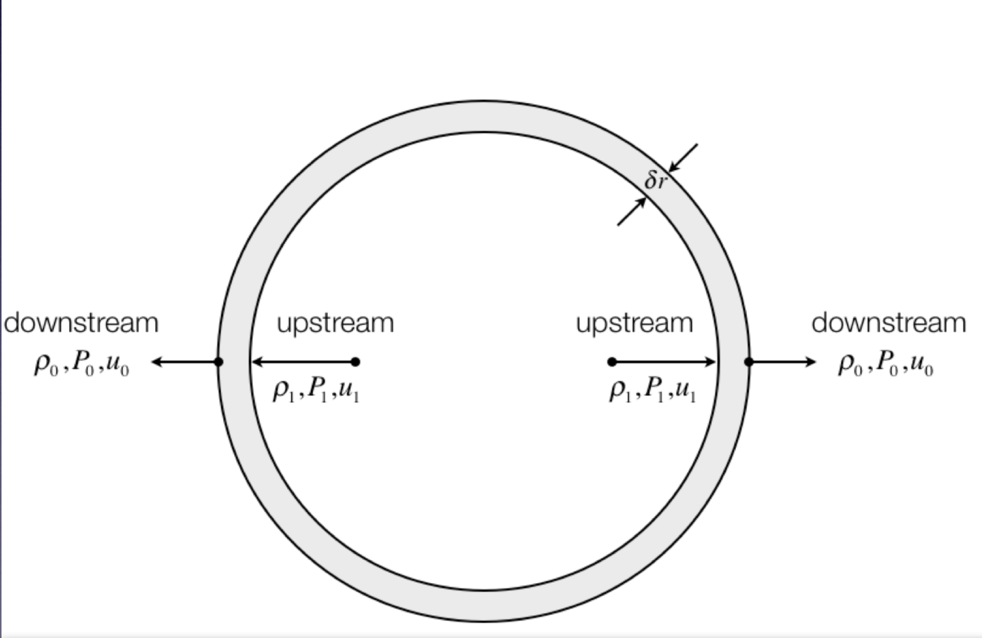
- ***plerionic*** *(49)*: non-thermal X-ray emission due to a PWN
- ***thermal composites****, aka mixed-morphology (34, including 8 with PWNe)*:
    - thermal X-ray emission (interior; *Rho & Petre 1998*)
    - Various models including evaporating clouds (*White & Long 1991*), thermal conduction (*Cox et al.*), a mix with ejecta…
    - recombining plasma: a new area in SNR astrophysics (*Suzaku*)



Shock Dynamics

Shock Jump Conditions

- Conservation of Mass $\rho u = constant$
- Conservation of Momentum $P + \rho u^2 = constant$
- Conservation of Energy $\frac{u^2}{2} + \frac{5P}{2\rho} = constant$



*assuming: no B, no E-losses due to Cosmic Rays e.g., t-independent **adiabatic** flow and mono-atomic gas*

Shock Jump conditions (shock frame)

$$\rho_1 = \frac{\gamma+1}{\gamma-1}\rho_0$$
$$u_1 = \frac{\gamma-1}{\gamma+1}u_0$$
$$P_1 = \frac{2\rho_0 u_0^2}{\gamma+1}$$

$$\gamma = 5/3$$

$$\rho_1 = 4\rho_0$$
$$u_1 = \frac{1}{4}u_0$$
$$P_1 = \frac{3}{4}\rho_0 u_0^2$$

(1=downstram, 0 = upstream; compression ratio=4)

Shock Jump Conditions (Lab frame)

$$u_0 \sim V_s$$

$$v_1 = \frac{2}{\gamma + 1} V_s$$

$$P_1 = \frac{\rho_1 k T_1}{\mu m_H}$$

$$T_1 = 2\frac{(\gamma - 1)}{(\gamma + 1)^2} \frac{\mu m_H}{K} V_s^2$$

$$\gamma = 5/3$$

$$v_1 = \frac{3}{4} V_s$$

$$kT_1 = kT_s = \frac{3}{16} \mu m_H \times V_s^2$$

$$T_s\ (K) \sim 1.13 \times 10^5 (\frac{V_s}{10^7})^2$$

(fully ionized gas)

v (km/s)	T (K)
10000	1.13E+09
1000	1.13E+07
100	1.13E+05

~1keV

X-ray regime

X-ray temperature

$$T_s\ (K)\ \sim 1.13 \times 10^5 (\frac{V_s}{10^7})^2$$

(fully ionized gas)

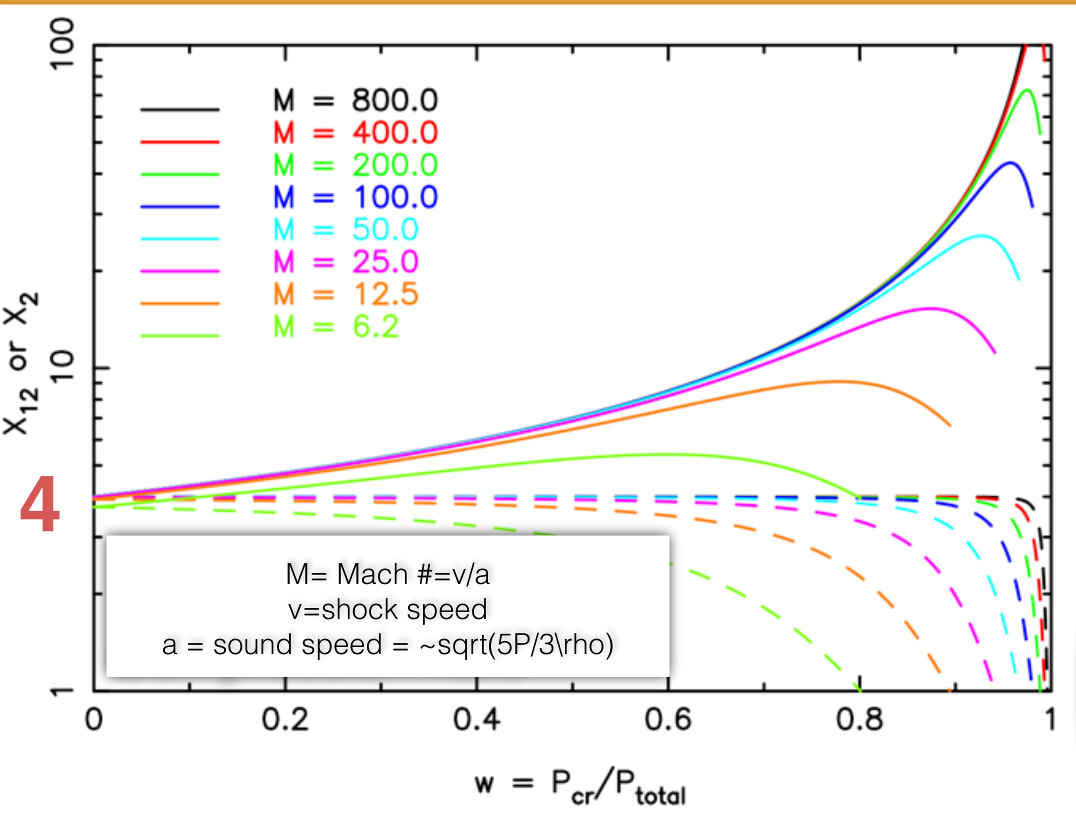
v (km/s)	T
10000	1.13E+09
1000	1.13E+07
100	1.13E+05

X-ray regime

However: If there is another form of pressure, e.g. cosmic rays, then the **compression factor at the shock can be >>4** and **temperature will be lower** than that derived from the above T=T(V_s) formula.
Some of the energy goes into cosmic rays,
as observed e.g. in young SNRs (Tycho, Kepler, CasA, SN1006…)

$$\gamma = 4/3$$

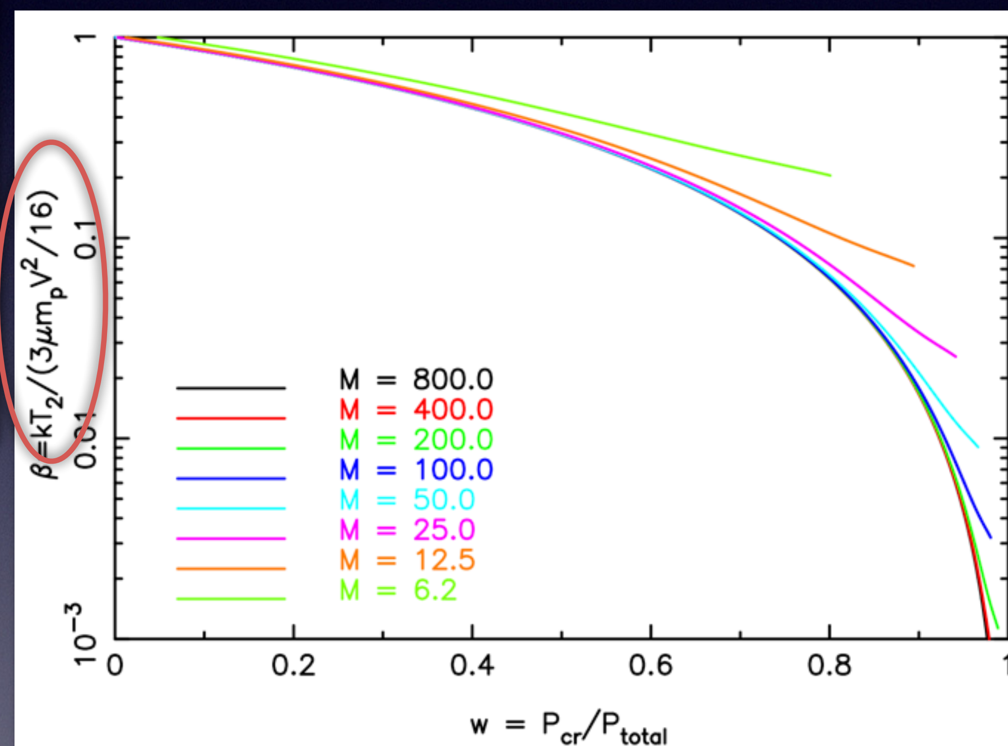
Energy loss to CR



effectively: adiabatic index

5/3—>4/3

lower T for higher P_{cr}



$$kT_2 = (1-w)\frac{1}{\chi}\left(1-\frac{1}{\chi}\right)\mu m_{\rm p} V_{\rm s}^2$$

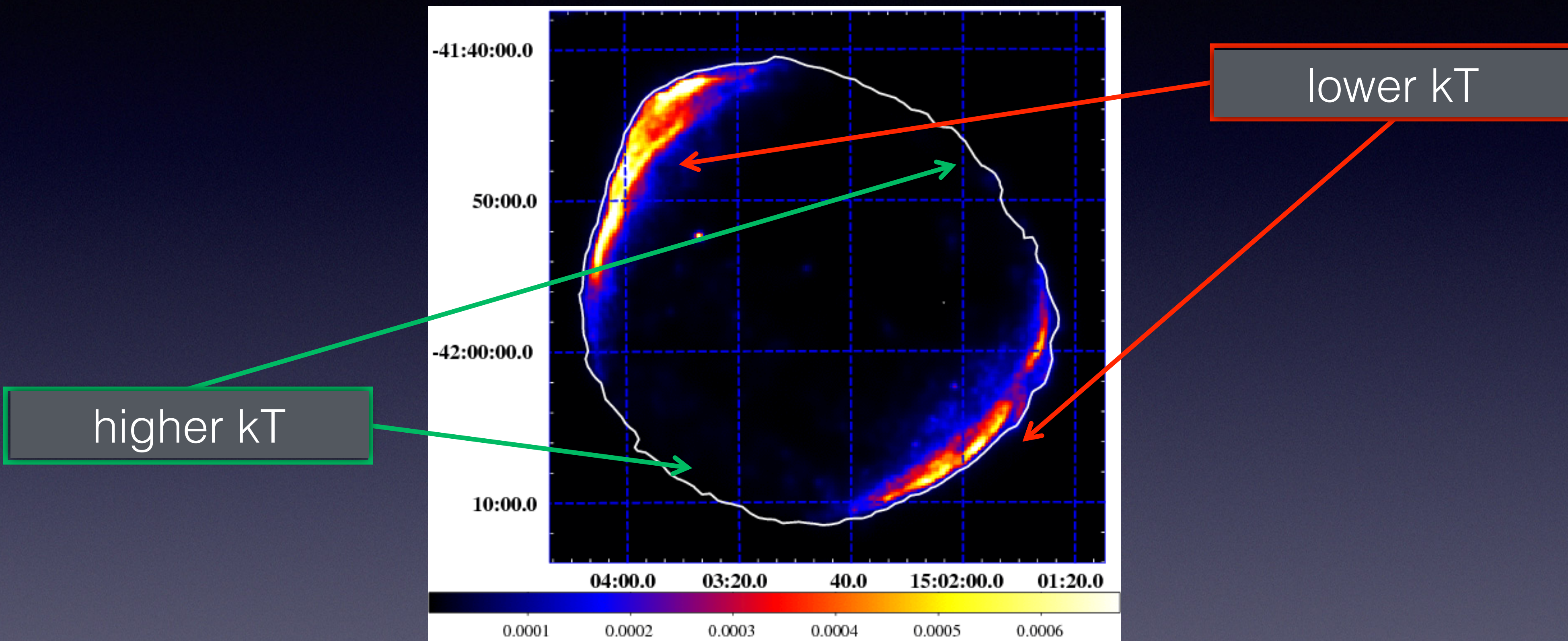
$$w \equiv \frac{P_{2,\rm NT}}{P_{2,\rm T}+P_{2,\rm NT}},$$

$$\rho_2 = \frac{v_0}{v_2}\rho_0 \equiv \chi\rho_0,$$

If no CR pressure, w=0, compression factor = 4 and \beta=1

Vink 2012

SN1006



Miceli+10

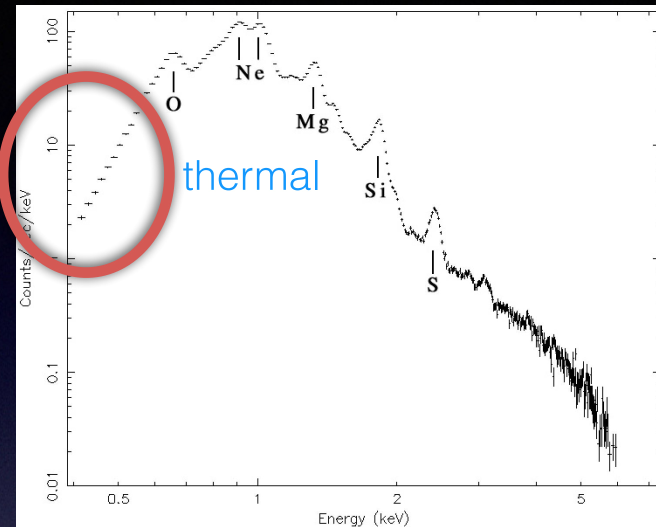
The power of X-ray spectroscopy

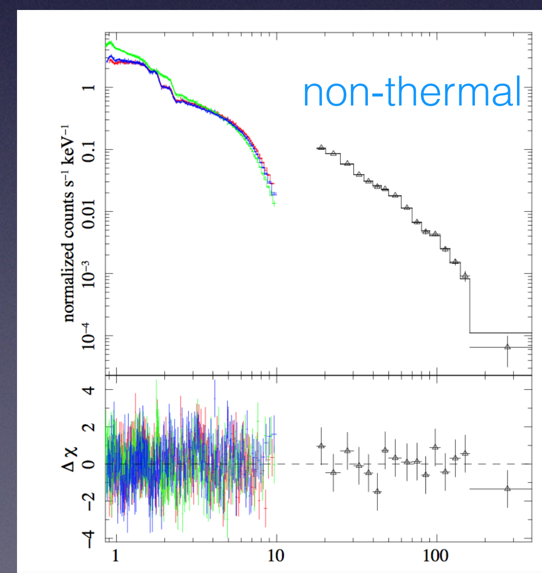
What do we get from fitting the X-ray spectrum of an SNR?

- **Column density, N_H** , impacting soft X-ray distance(=>D)
- **Temperature** (=>thermal continuum) ~ V_s^2
- **Density** from $$EM = \int n_H n_e dV$$
- **Metal abundances**:
    - enhanced? => ejecta
    - "solar/sub-solar" => ISM/CSM
- If non-thermal X-ray spectrum (featureless):
    - **photon index**
    - any **spectral break**?

=> acceleration process, B field, non-thermal plasma

- Normalization => **Flux** => Luminosity (isotropic) $$L = 4\pi D^2 F$$



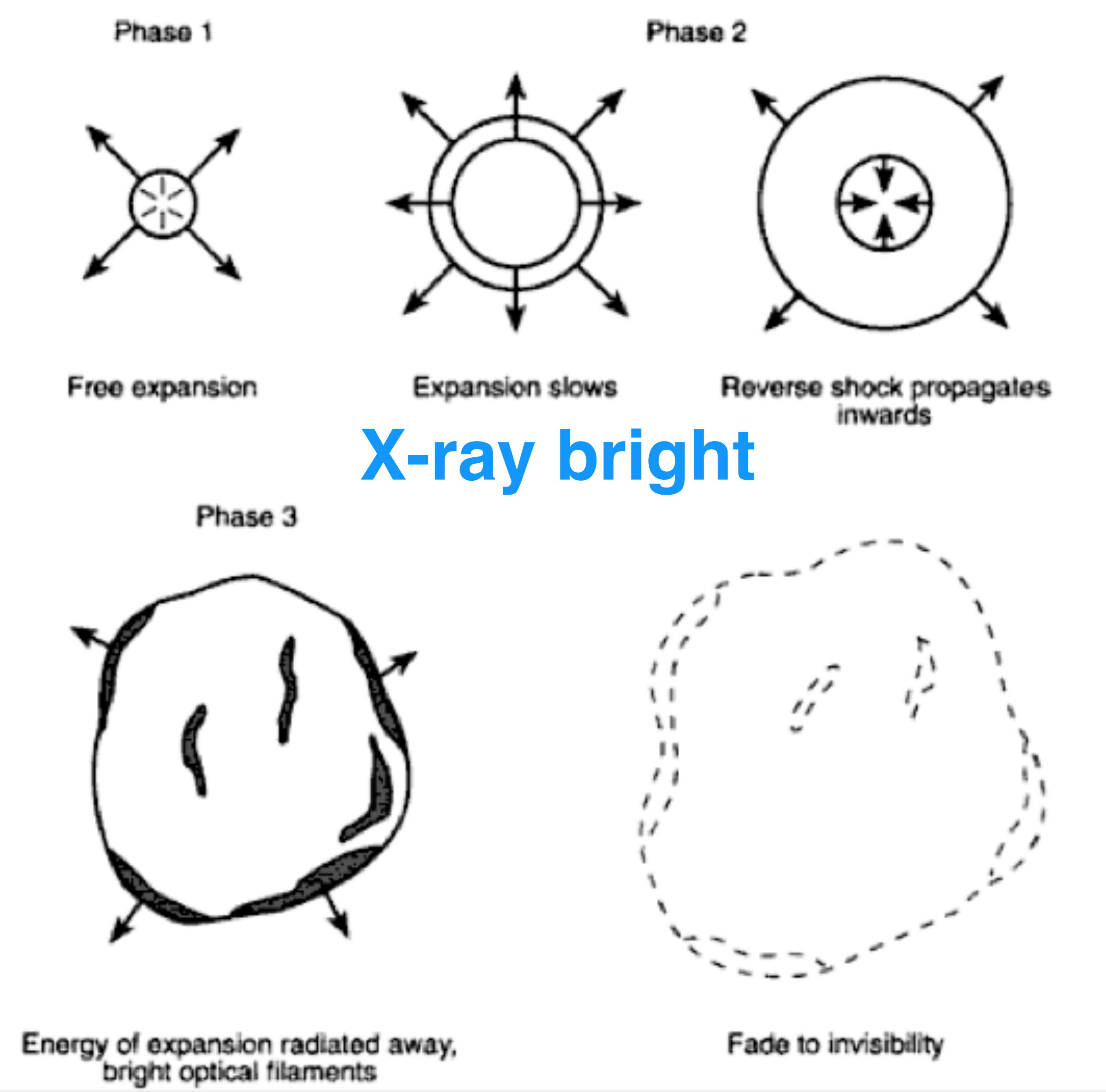


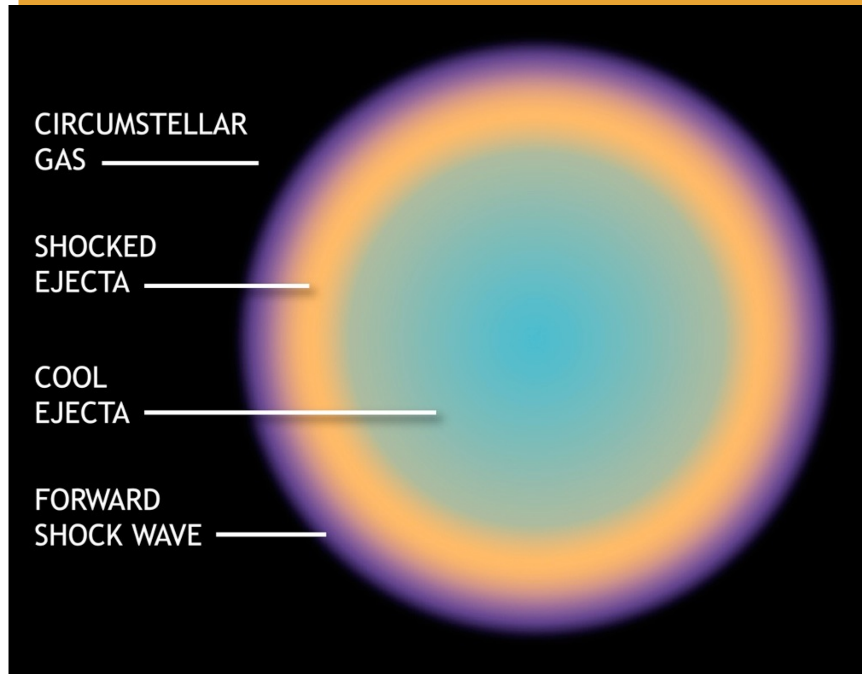
Some factors affecting Temperature measurement from X-ray spectroscopy

- Loss of energy to cosmic rays: hard non-thermal X-ray emission/ gamma-ray SNRs era (non-thermal shells and SNRs interacting with molecular clouds)
- Non-equilibrium ionization of plasma (young SNRs, low-density medium)
- Recombining, over-ionized plasma (mixed-morphology SNRs, molecular cloud interaction): Suzaku era
- Contamination by other components (e.g. ejecta/ISM/CSM, PWN)- composite-type SNRs
- Evolutionary stage of the SNR; expansion into inhomogeneous medium

SNR Evolution

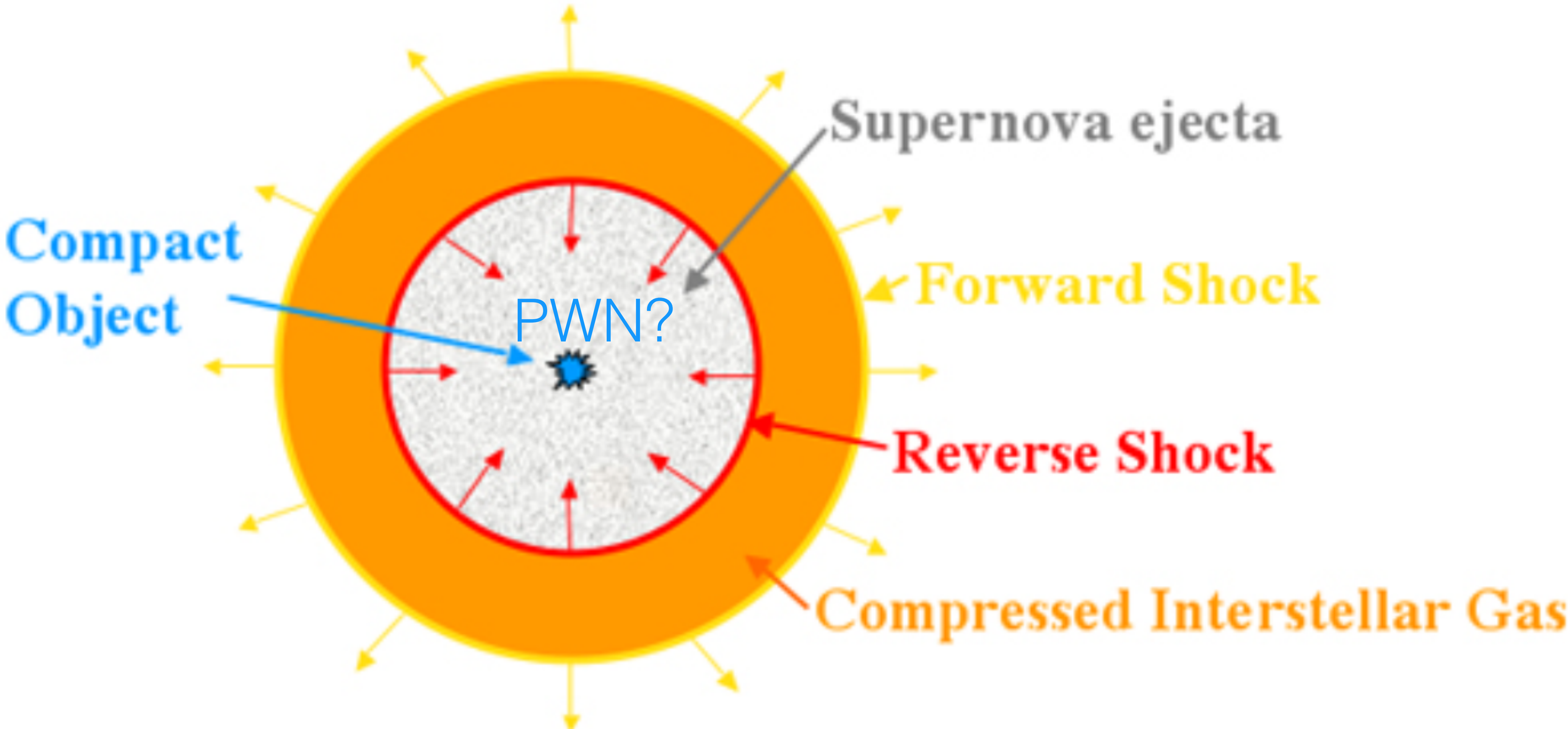
SNRs evolution





Reverse shock heats the **SN ejecta** (heavy elements) to X-ray emitting temperatures: detected as (hot) **thermal emission the X-ray spectra** of young SNRs

(core-collapse) SNR components



SNRs evolution

- **Free Expansion** Phase, v=constant (a few 100 yr); ejecta-dominated phase
- **Adiabatic**, Sedov-Taylor: energy conservation phase (a few 10^4 yr); swept-up mass > ejecta mass
- **Radiative**, Snow-plough: momentum conservation phase (bright in optical)
- Eventually, the SNR merges with the ISM (**merging** phase)

Some useful equations

Free Expansion

$$R = vt,$$
$$v = (2E_0/M_{ej})^{0.5}$$

~5,000-10,000 km/s
Mach>1000 shocks

Sedov-Taylor

$$R_s = \left(\xi \frac{Et^2}{\rho_0}\right)^{1/5},$$

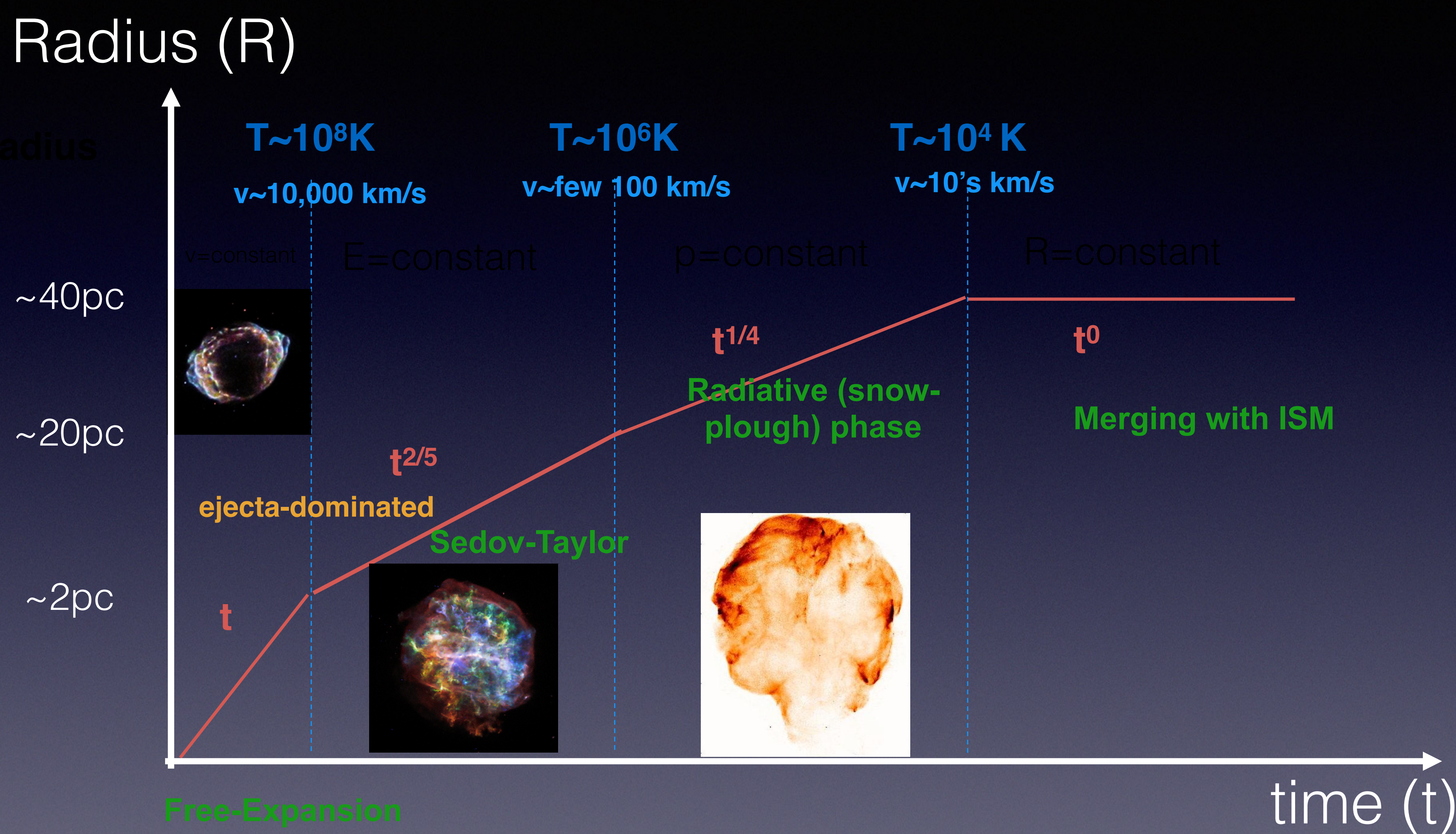
$$V_s = \frac{dR_s}{dt} = \frac{2}{5}\left(\xi \frac{E}{\rho_0}\right)^{1/5} t^{-3/5} = \frac{2}{5}\frac{R_s}{t}$$

Radiative phase

$$t_{rad} = 1.5 \times 10^{-13} \left(\frac{\xi E}{\rho_0}\right)^{1/3}$$
$$= 1.4 \times 10^{12} \left(\frac{E_{51}}{n_H}\right)^{1/3} \text{ s} \approx 44{,}600 \left(\frac{E_{51}}{n_H}\right)^{1/3} \text{ yr},$$
$$R_{rad} = 7.0 \times 10^{19} \left(\frac{E_{51}}{n_H}\right)^{1/3} \text{ cm} \approx 23 \left(\frac{E_{51}}{n_H}\right)^{1/3} \text{ pc},$$

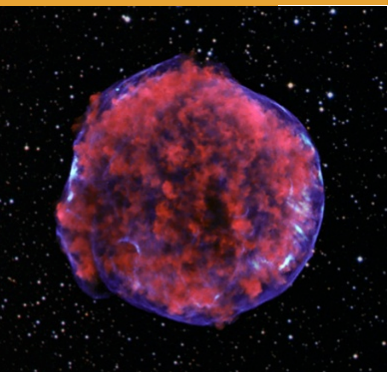
$R \sim t^{1/4}$
$v \sim t^{-3/4}$

SNRs evolution

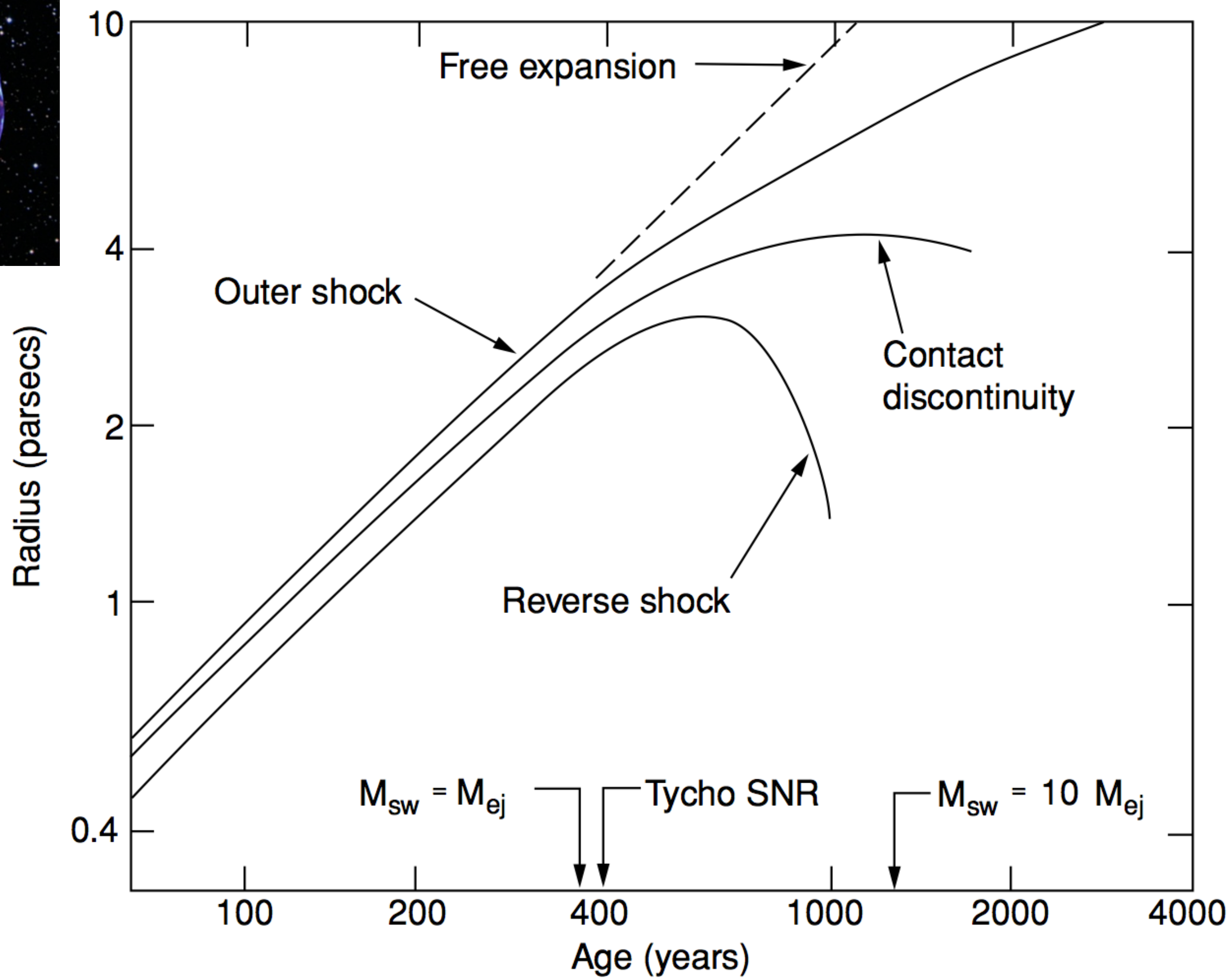


v=dR/dt

Reverse Shock in Young SNRs
Ejecta Dominated phase



Ejecta-dominated phase

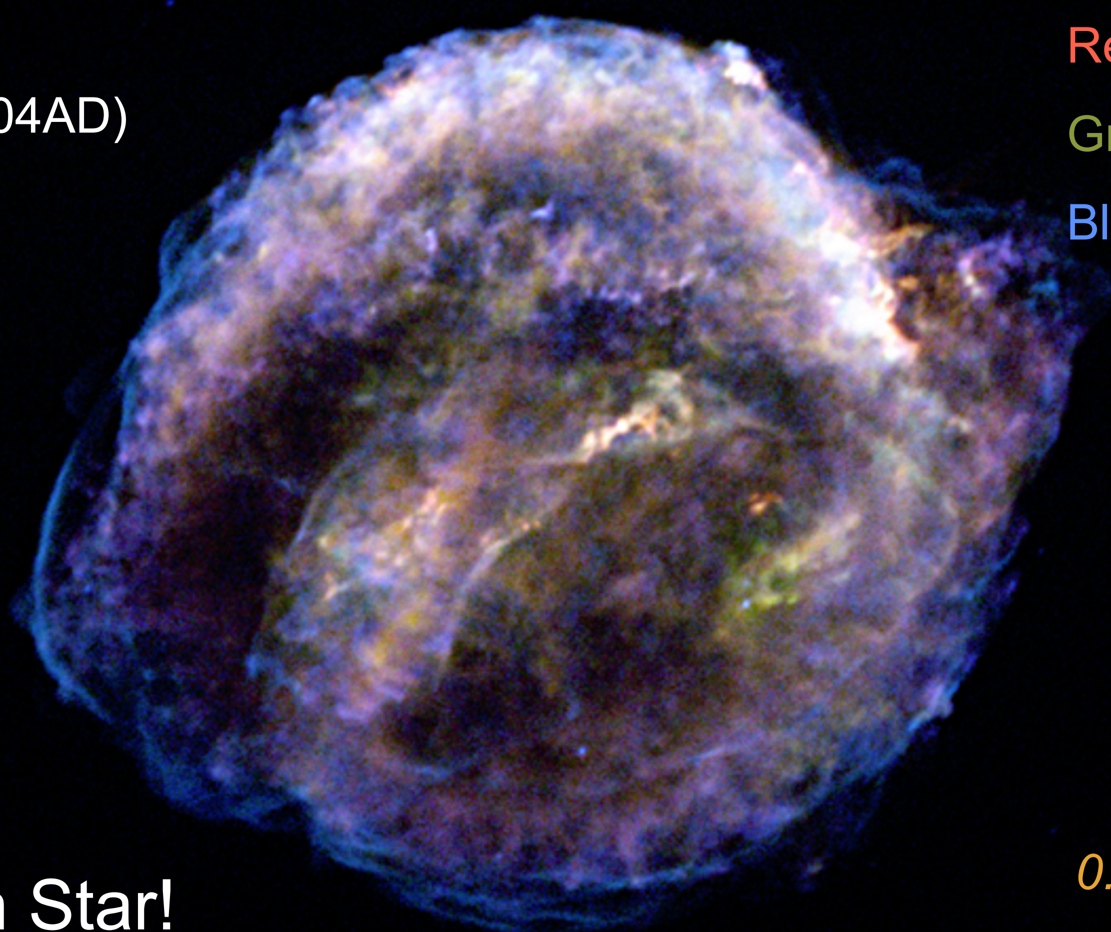


Chevalier 1982

Mapping Heavy elements
Kepler

410 yr old (1604AD)

19 ly across



Red: Oxygen

Green: Fe, Ne, Mg

Blue: Silicon+ non-thermal

No Neutron Star!
Type Ia explosion (with CSM)

0.75 Msec (~9 days)

Reynolds et al. 2007

Tycho: Ia

Suzaku detection of **Mn, Cr** from Tycho

(*Tamagawa 2010*)

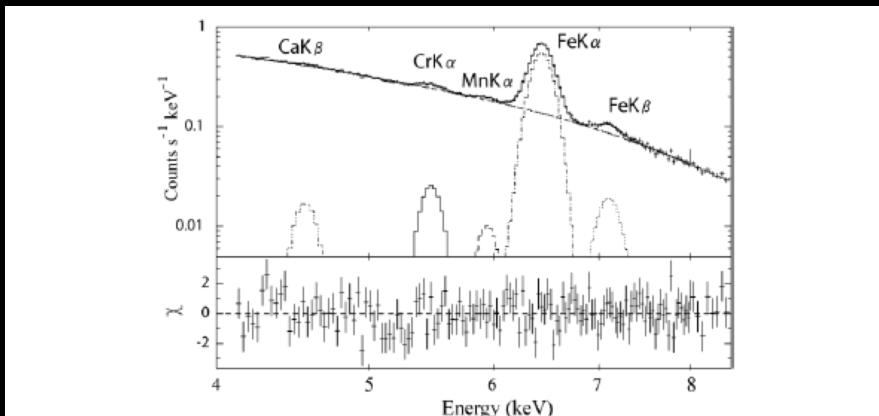
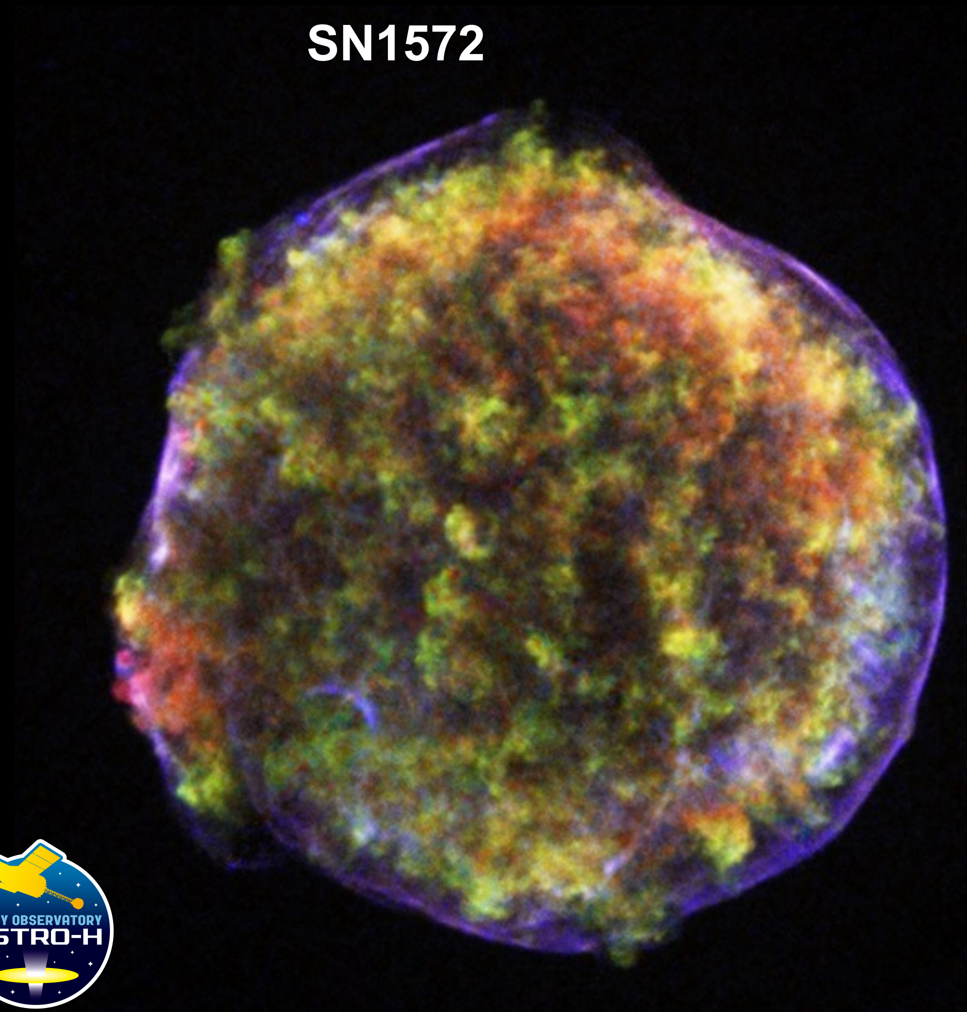


FIGURE 3. Suzaku X-ray spectrum around Fe Kα lines of Tycho's SNR [11].

Mn/Cr ratio=>
Progenitor metallicity

(*Badenes et al. 2008*)

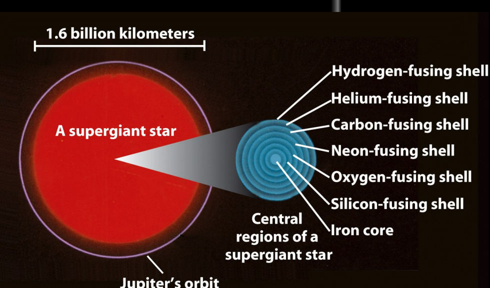


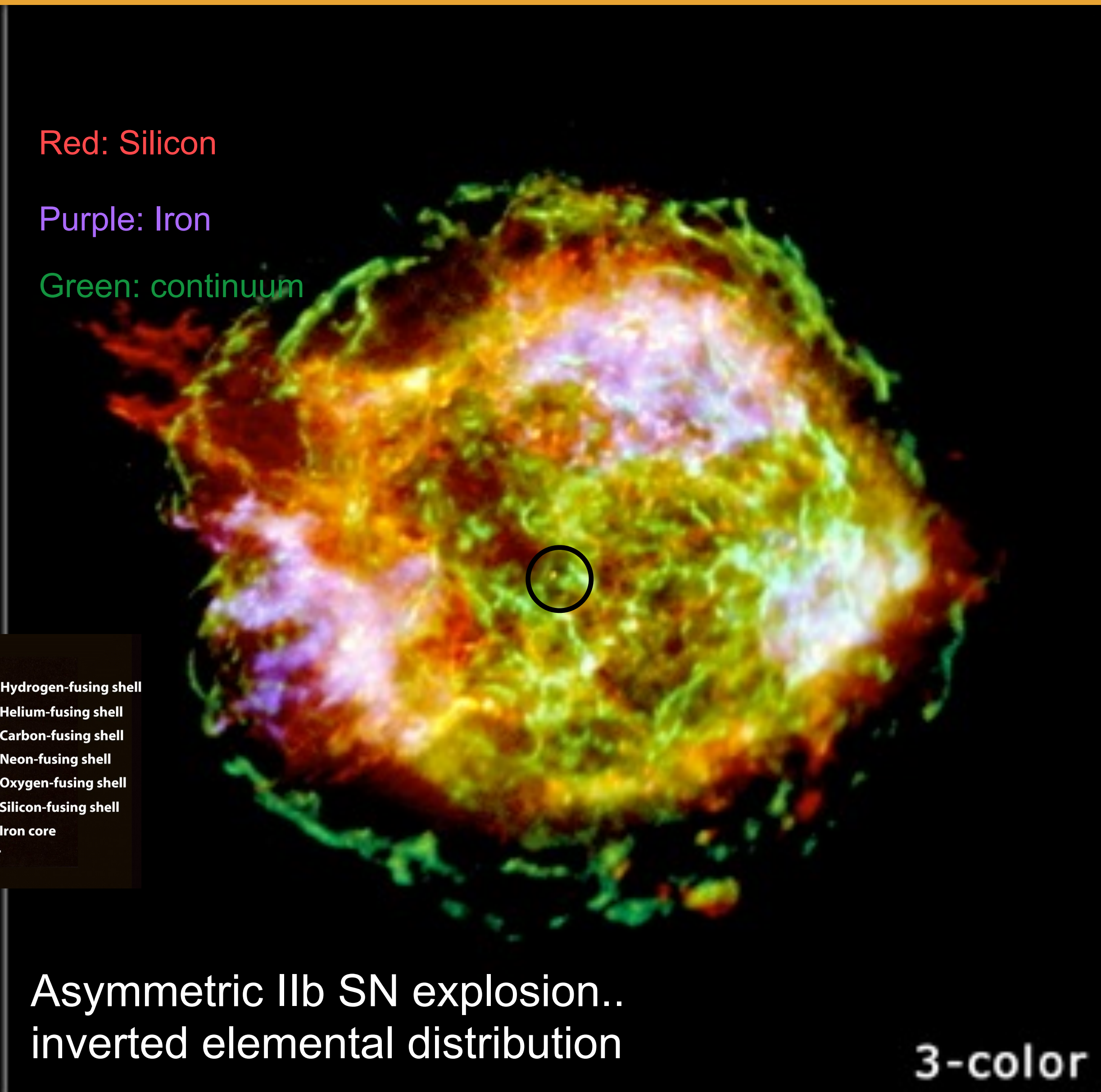
Warren & Hughes 2005

Mapping Heavy elements
CasA: core-collapse

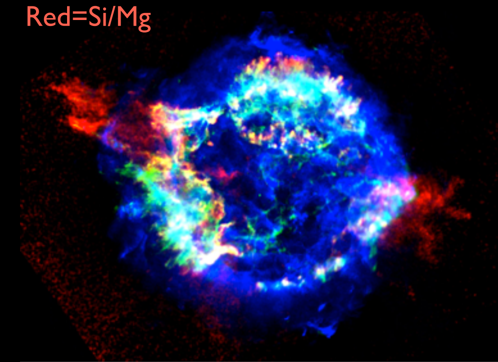
•334 yr-old (SN1680?)

•10 ly across





Asymmetric IIb SN explosion..
inverted elemental distribution



CasA's neutron star

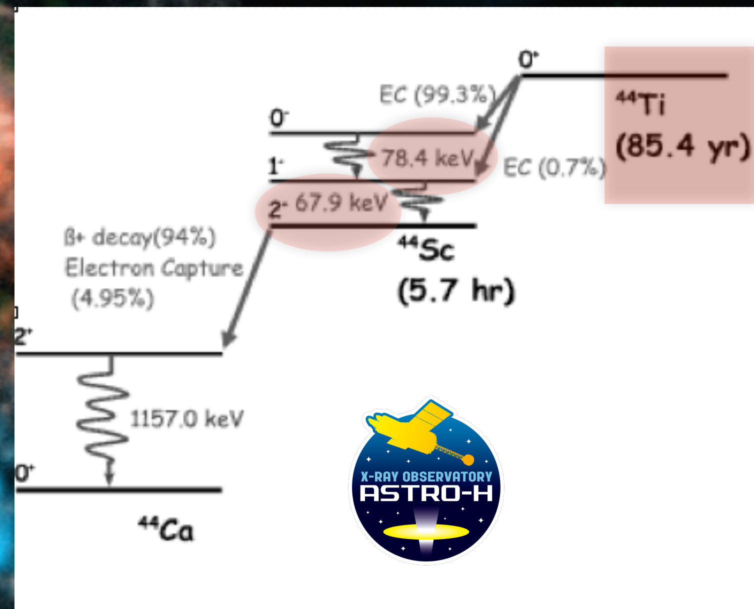
1 Ms CXO (~12 days)

Hwang et al. 2004

Vink 2004, Hughes+00

A surprise by NUSTAR (1Ms)

^{44}Ti produced in innermost regions of material ejected in CC SNe-same processes that produce Fe and ^{56}Ni



Si/Mg (Chandra): jet-induced explosion?

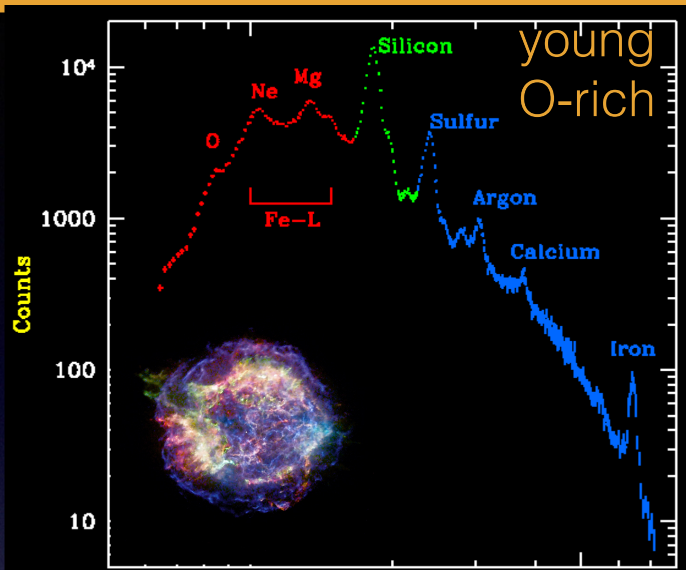
Fe (Chandra)

Ti (NuSTAR): decoupled from Fe!

(unlike expectation, implications on formation of compact object-later)

Grefenstette et al. 2014, Nature

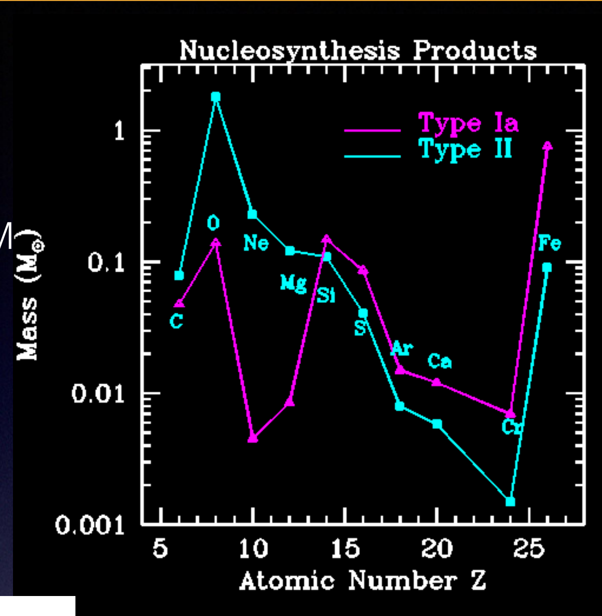
Probing SN progenitors
Nucleosynthesis



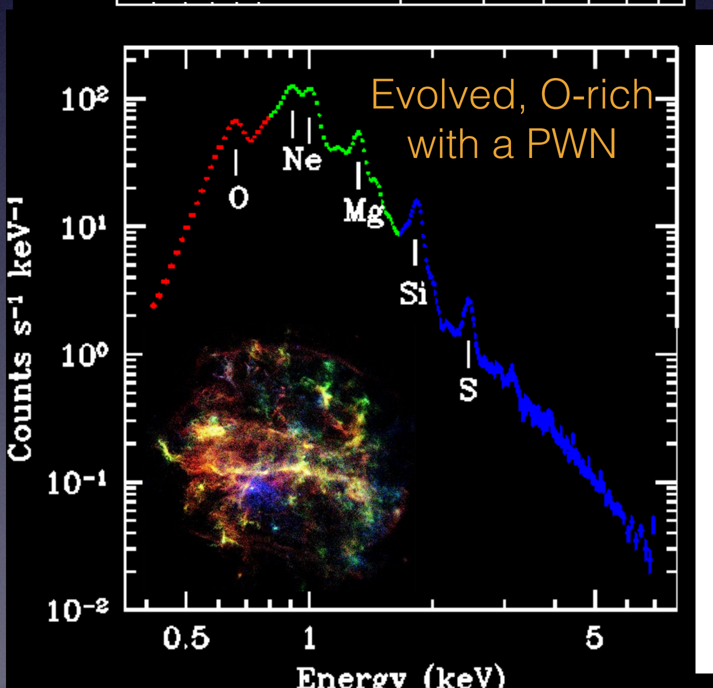
- Fit X-ray spectra
- Infer Metal abundances (ratios, ejecta mass)
- compare to nucleosynthesis yields
- Ia: Fe-rich; CC: rich in O/intermediate M

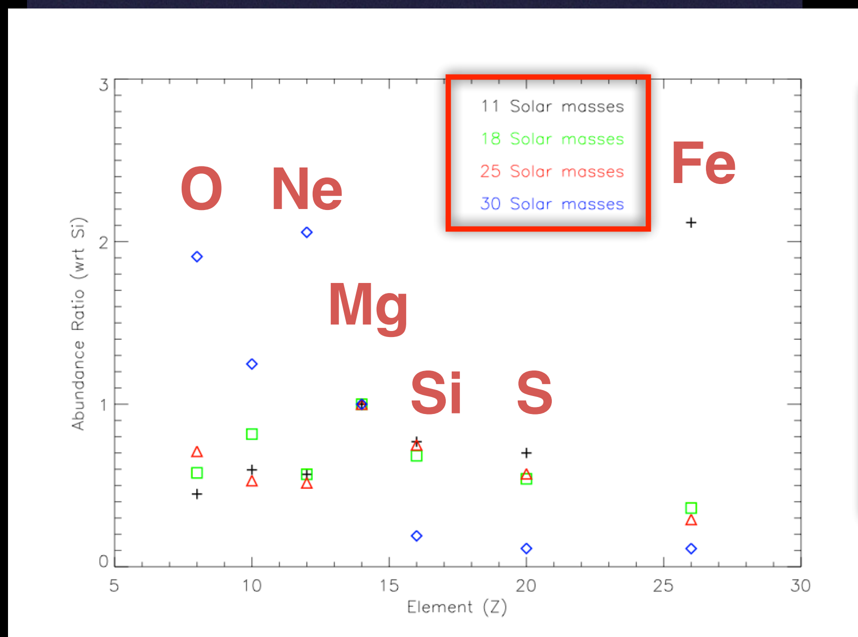
Caveat:

- not all ejecta have been shocked
- plane-parallel shocks
- asymmetric explosions
- nucleosynthesis model yields



core-collapse, WW95





Nucleosynthesis models:

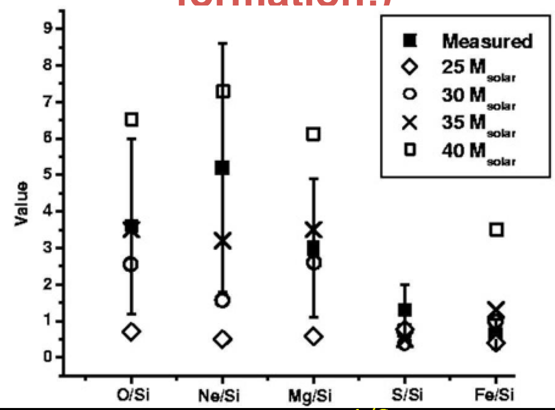
Woosley & Weaver 1995
Thielemann et al. 1996
Iwamoto et al.1999
Nomoto 2013
(and others)

Transitioning to Sedov—>Sedov

Soft, enhanced abundances: Ejecta component

<u>Progenitor: >20 solar masses?</u>

(implications on black hole formation!)



$$\tau_4 = \frac{R_s}{13\ pc}\left(\frac{0.45\ keV}{kT_s}\right)^{1/2} \quad (1)$$

$$\frac{E_{51}}{n_0} = \left(\frac{R_s}{13\ pc}\right)^5 \tau_4^{-2} \quad (2)$$

$$L = \frac{16\pi}{3} R_s^3\ n_0^2\ \Lambda(T) \quad (3)$$

<u>X-ray Observations</u>

$\Downarrow$

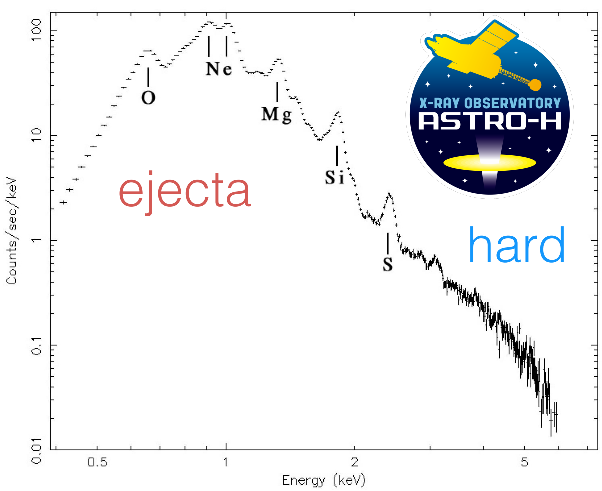
$kT_s,\ R_s,\ L$

$\Downarrow$

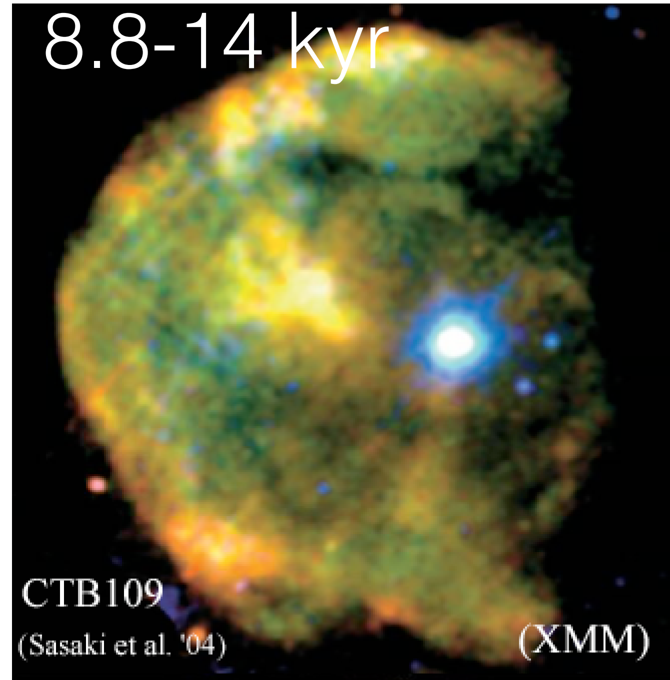
$n_0,\ \tau,$ and E

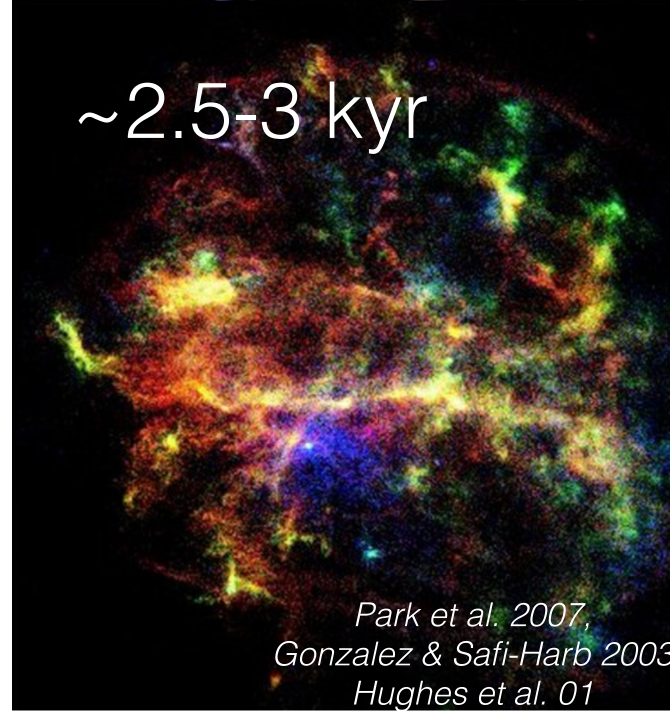
Hard component: solar abundances ISM/CSM

Shock velocity, v_s (km s^{-1})	880 ± 70
Age, t (yrs)	$2{,}600^{+250}_{-200}$
Ambient density, n_0 (cm^{-3})	$0.51^{+0.15}_{-0.11}$
Explosion energy, E_0 (10^{51} ergs)	$0.18^{+0.08}_{-0.06}$
Swept-up mass, M_s ($M_\odot$)	$15.6^{+4.5}_{-3.5}$



caveats:
Sedov phase assumed
Uniform Ambient density





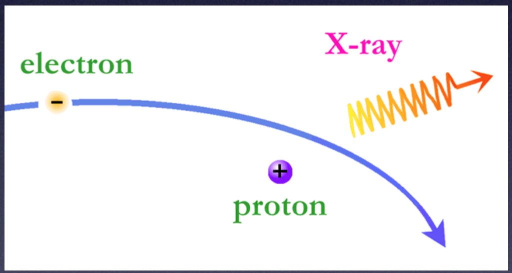
Thermal X-ray Emission

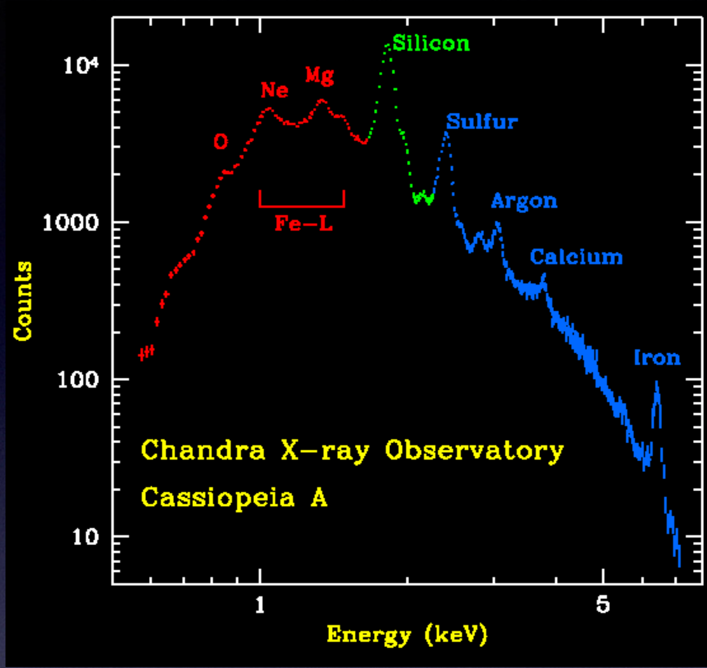
continuum and line emission

Continuum: Brems (free-free emission), **recombination cont (free-bound),** and two-photon emission.

Thermal bremsstrahlung: acceleration of electrons in Coulomb collisions with ions, nuclei or other electrons

XSPEC models include:
apec, mekal (CIE)
brems+gauss





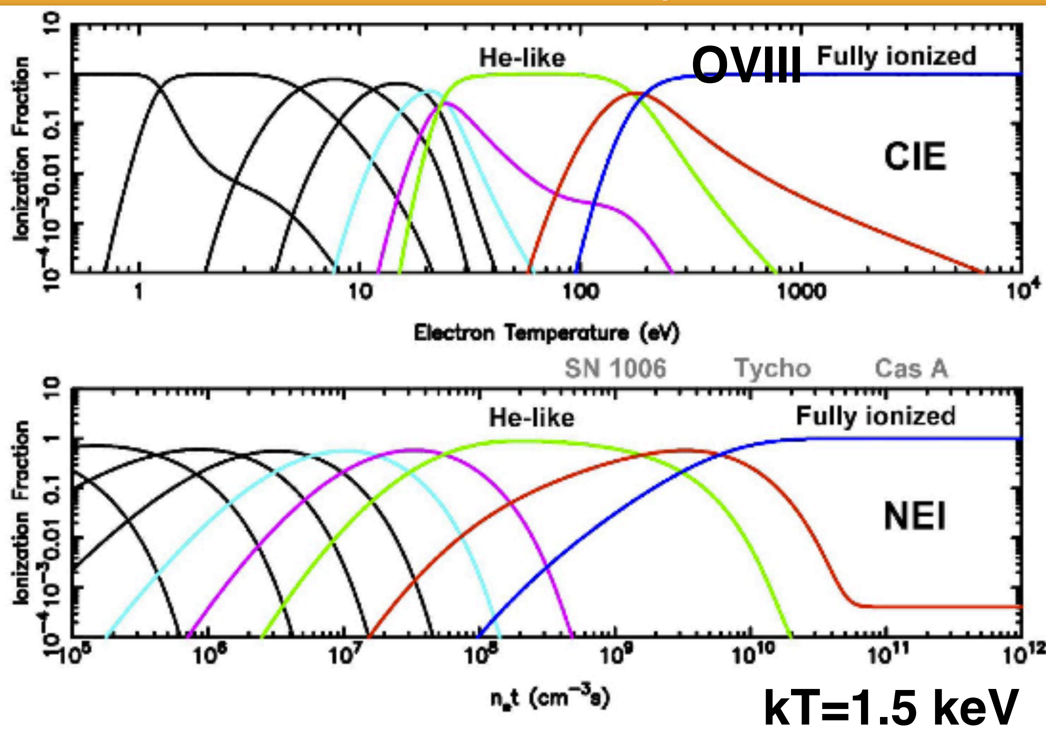
Line emission from ionization and recombination: highly ionized elements, including O, Ne, Mg, Si, S, Ca, Fe in **0.5-10 keV**
(He-like and H-like ions for very hot plasma)

Complications for spectral fitting =>SNR properties:

- Non-Equilibrium (NEI) effects
- Overionized, Recombining Plasma (RP)
- Energy Losses (CR) - discussed
- Temperature equilibration (e- and p)
- Expansion in an inhomogeneous medium (e.g. RSG wind)

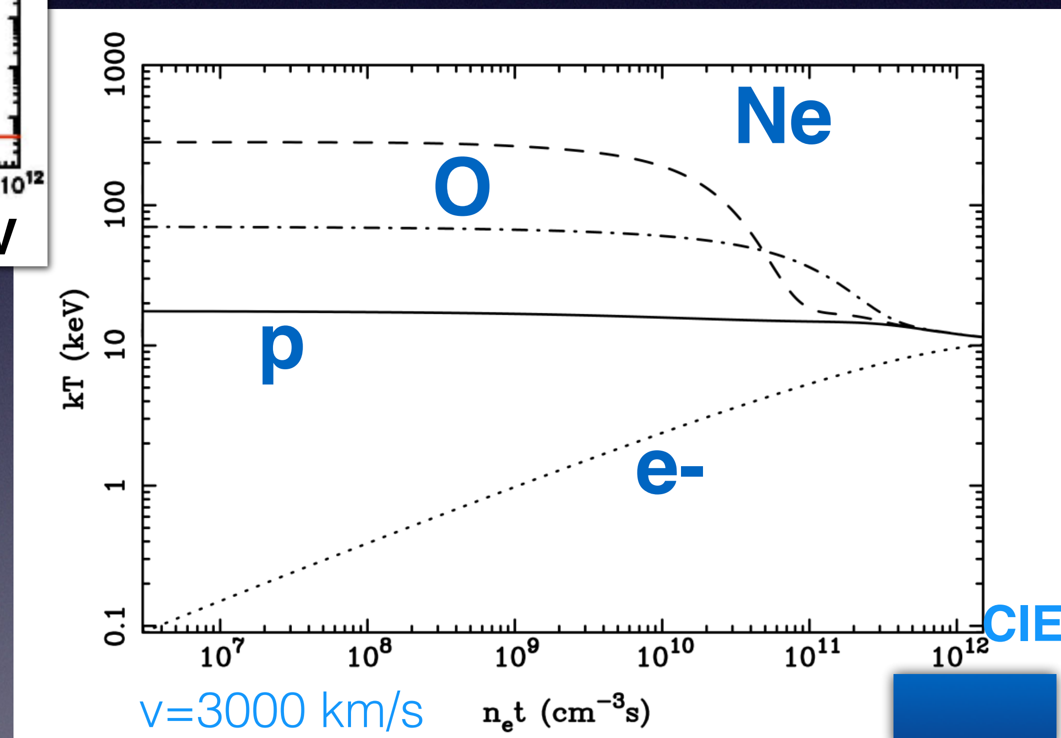
(all) best addressed with ASTRO-H (SXS)

Thermal X-ray emission and Non-equilibrium ionization: NEI vs CIE



ionization timescale: n_e t

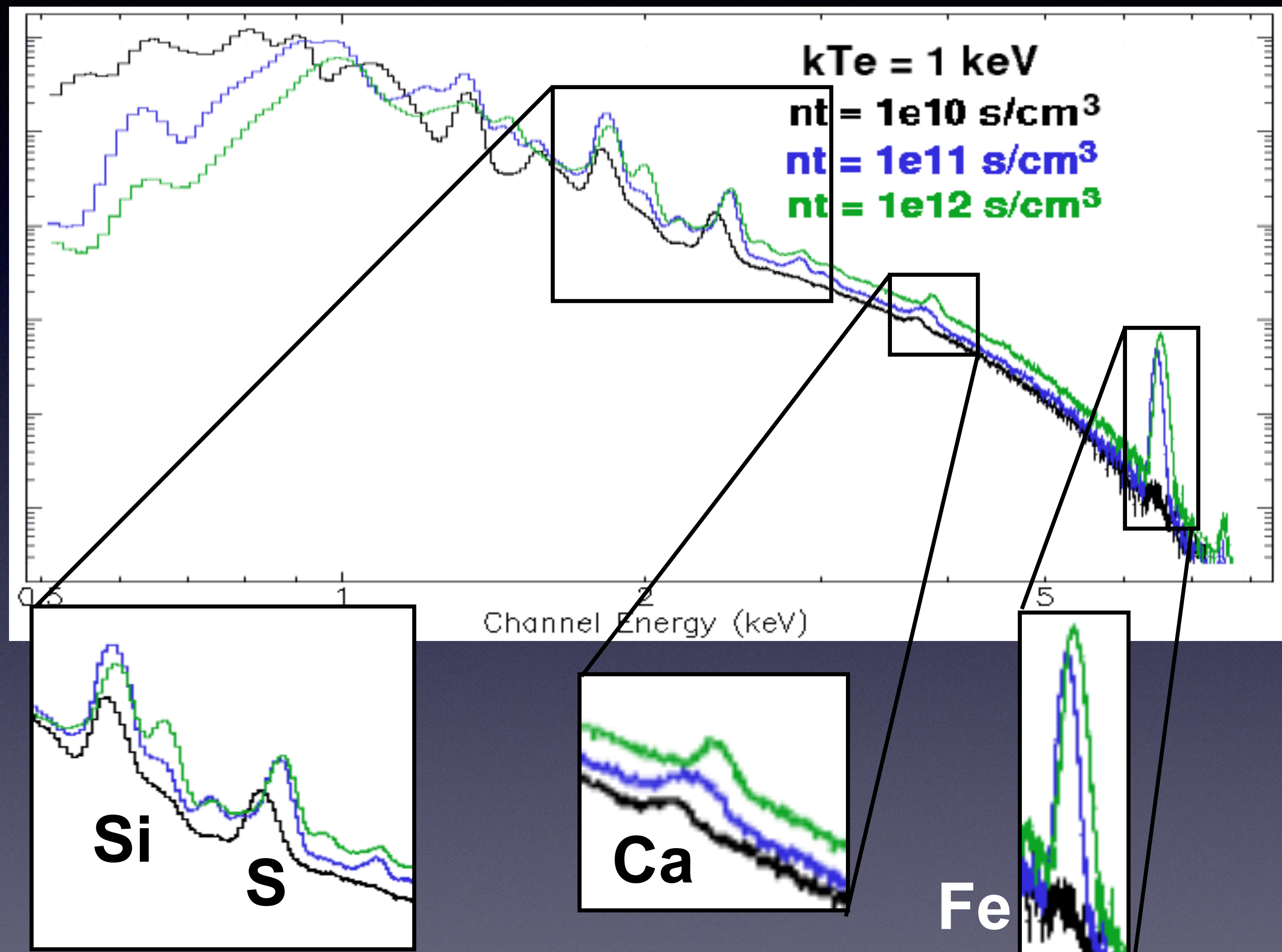
important for **young** SNRs and/or low n_e (n_e t < 10^{12} cm^{-3} s)



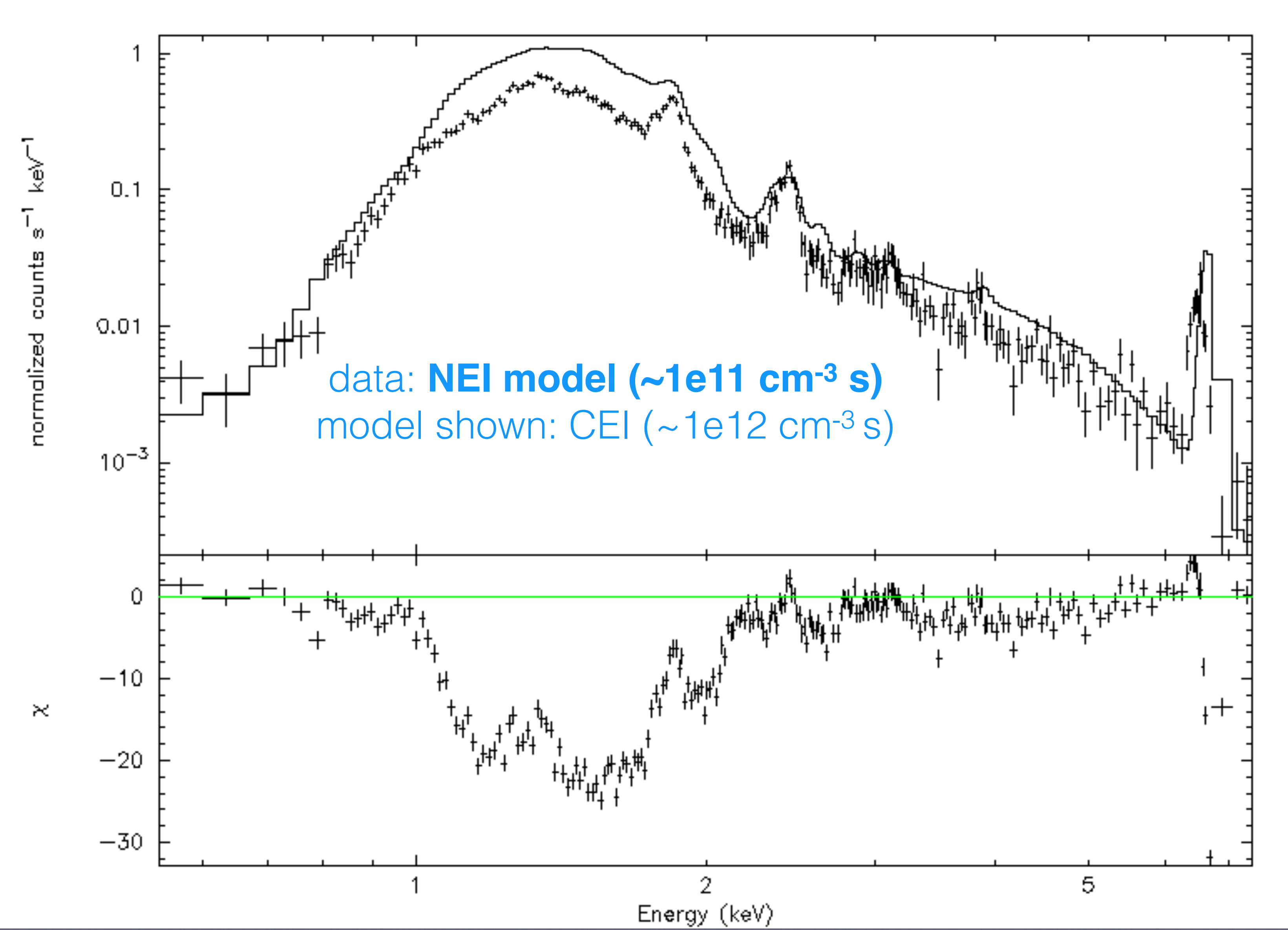
NEI plasma

Ionization timescale:
electron density x time since passage of shock (age)
n_e t (cm-3 s)

NEI: ne t < 1e13 cm^{-3} s



Underionized Plasma-an example



Overionized/Recombining Plasma

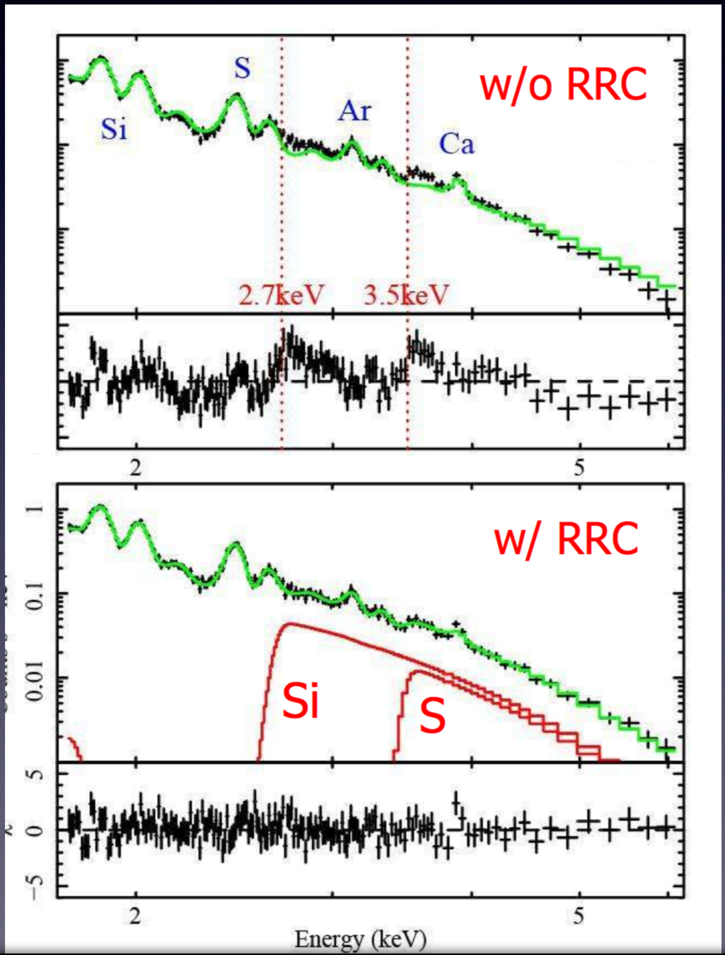
Radiative recombination (**RRC**) due to recombination (free-bound) continuum.

-Width prop. temp
-t_rec ~1/n_e

The proportion of H-like ions is *larger* than that expected from kT_e: **overionized**, **recombining** plasma;

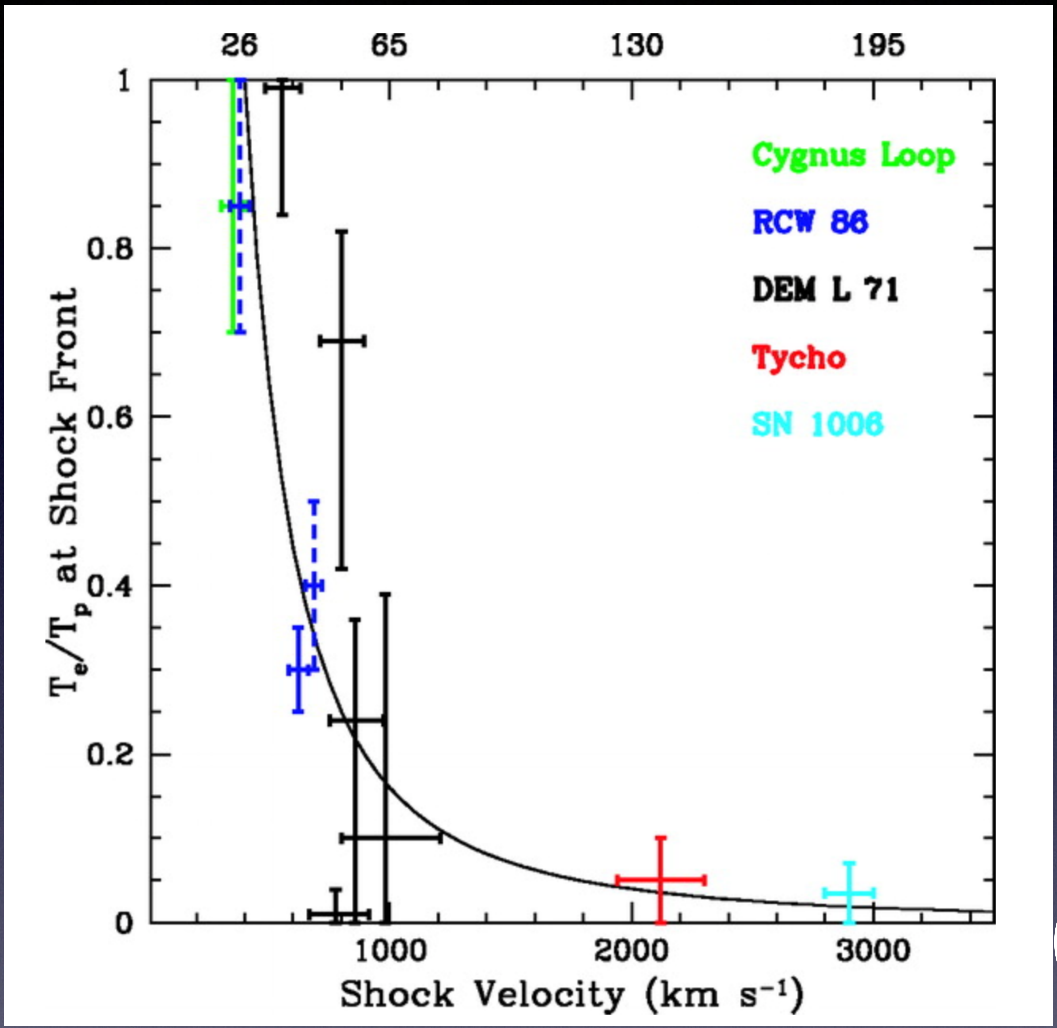
important in mixed-morphology SNRs/ interacting with Molecular clouds, including **IC443, W49B, W28**

$kT_z > kT_e$ =>
bump-like features in X-ray spectra of some thermal composites



IC443: Yamaguchi+09

T_e vs T_p; Measurement of V_s



Ghavamian et al. 07: analysis of Balmer-dominated optical spectra from non-radiative shocks

$$(T_e/T_p)_0 \propto v_S^{-2}$$

Te << Tp for fast-moving shocks (young SNRs)

=>can underestimate V_s from T_e

Line width measurements=>Ti

$$\sigma_E = \left(\frac{E_0}{c}\right)\sqrt{\left(\frac{kT_i}{m_i}\right)}.$$

thermal broadening

Expansion in RSG wind

$$\rho_{CS} = \frac{\dot{M}}{4\pi r^2 v_w} = Dr^{-2}$$

$$D_* = D/D_{ch}; D_{ch} = 1 \times 10^{14} gcm^{-1}$$

$$M_{sw} = 9.8 D_* (R/5pc) M_{sun}$$

IIL/b

Sedov (adiabatic) phase

$$R = (\frac{3E}{2\pi D})^{1/3}\ t^{2/3}$$

$$v_s = 2R/3t$$

$$t_{wind}/\overset{t}{\cancel{T}}_{uniform} = 1.247$$

Recall: uniform medium

$R \sim t^{2/5}$

$v \sim (2/5)\ (R/t)$

Chevalier 2005

(application): Kumar, SSH et al. 2014

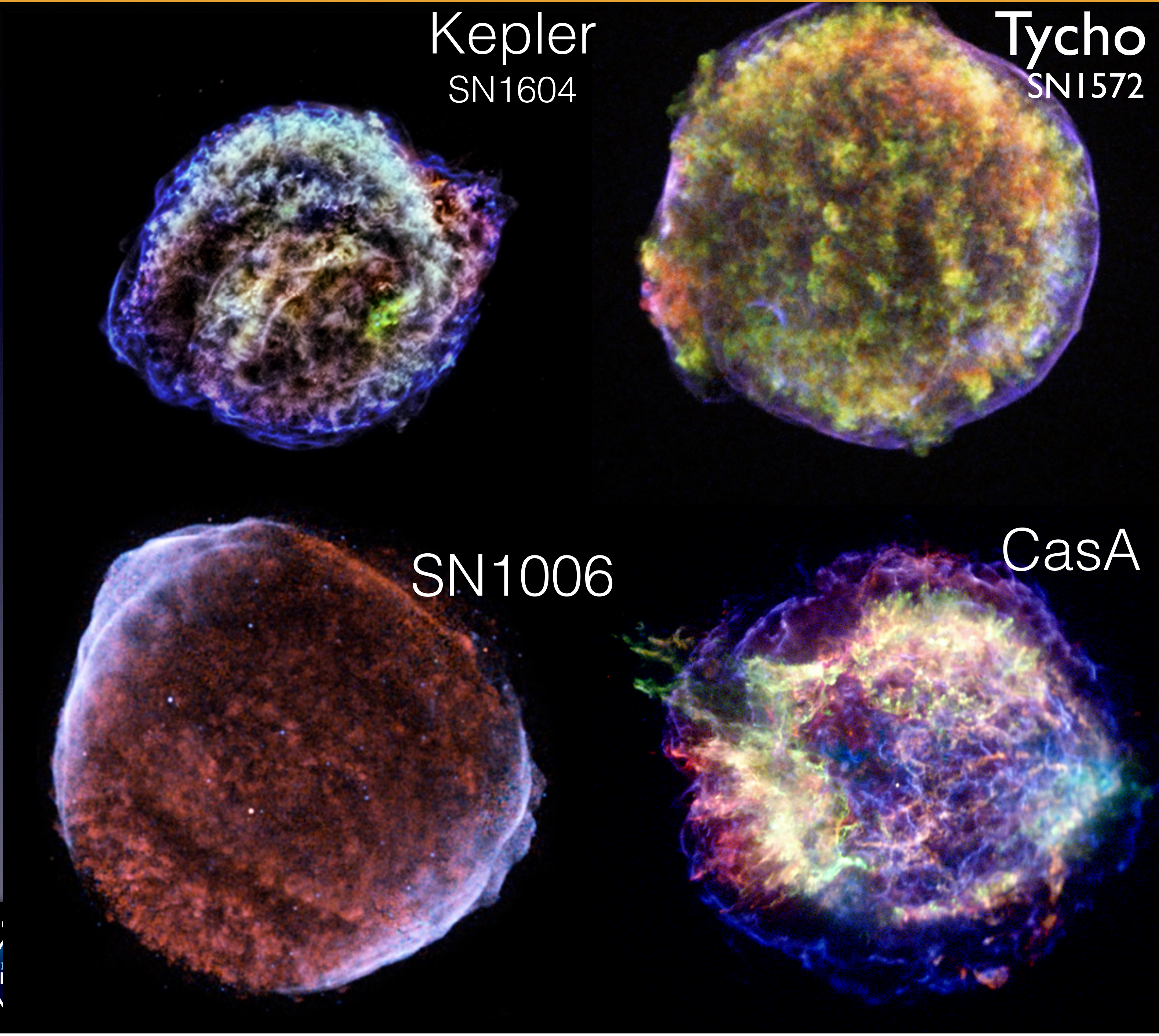
Non-thermal high-energy emission (as probes for CR acceleration)

- X-ray Imaging and Spectroscopy
- Gamma-ray observations
- Simulations

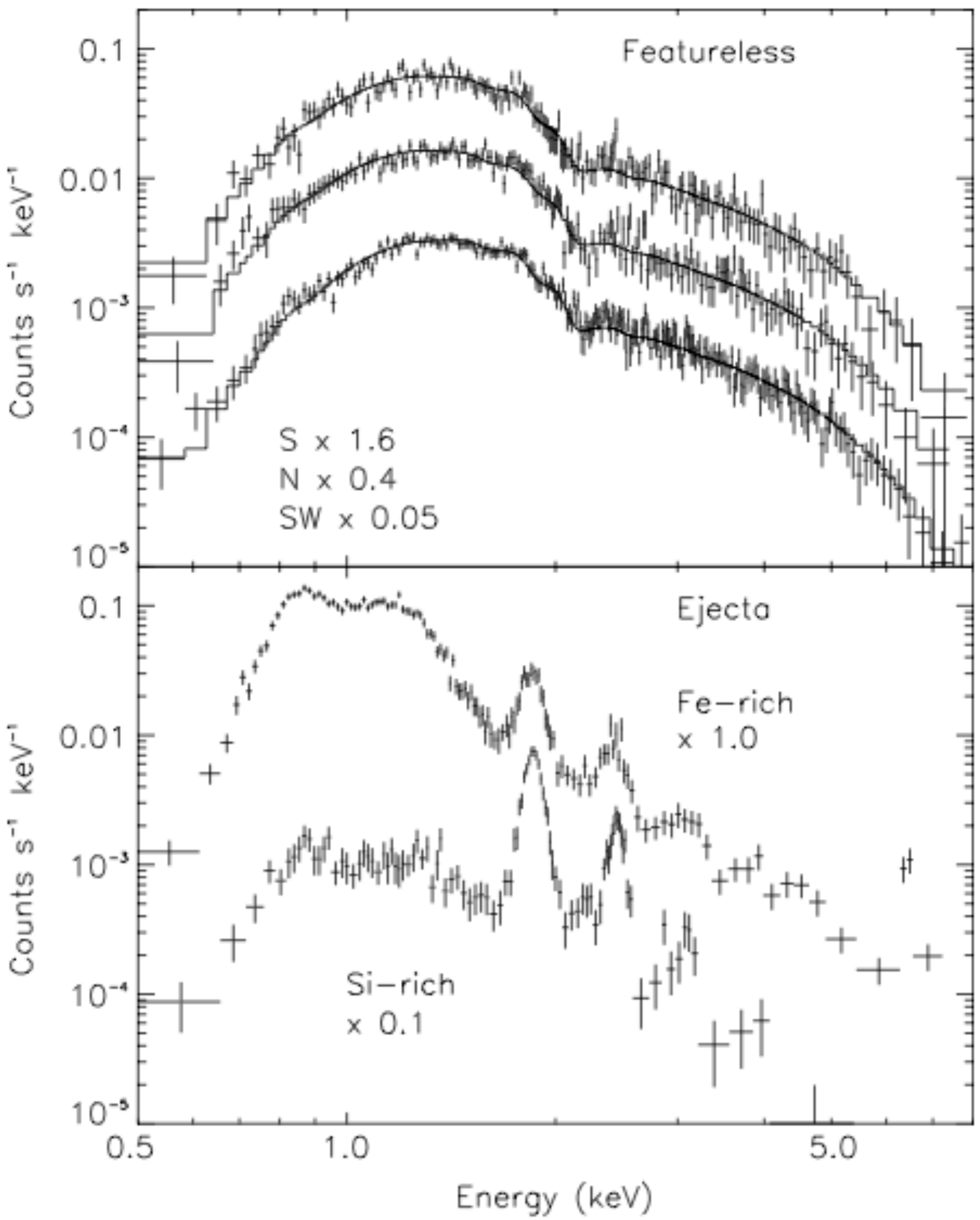
Non-thermal X-ray emission: CR acceleration

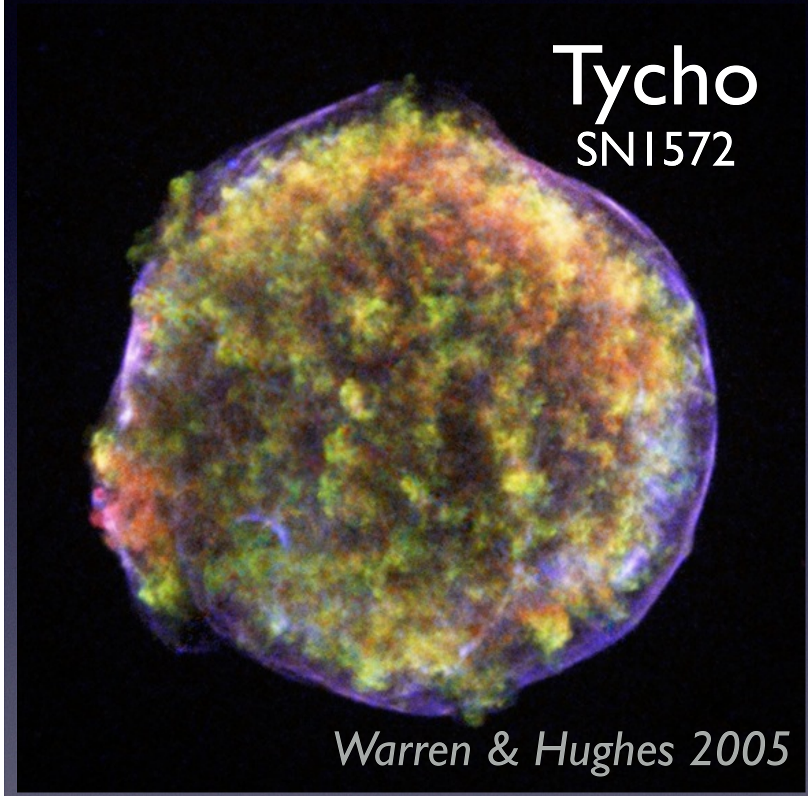
Blue/purple rims (hard X-rays): non-thermal hard X-ray emission indicating CR acceleration of electrons up to a 100 's of TeV.

How about the protons??



Non-thermal emission:
CR acceleration in Tycho



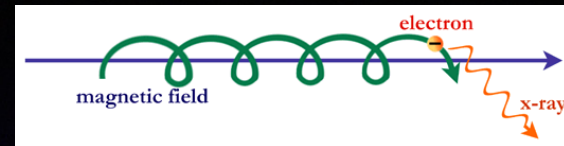


thin rim: modified shock,
amplified B field

Synchrotron Radiation

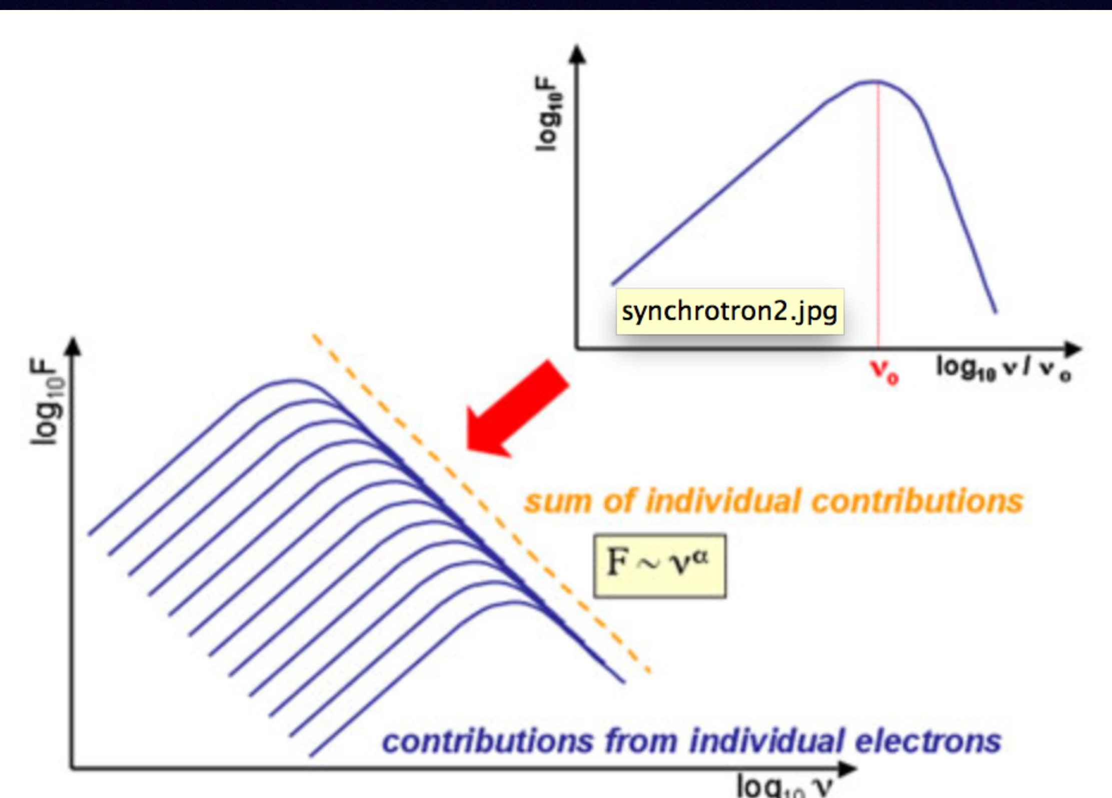
particle index

$$N(E)\,dE = K\,E^{-\gamma}\,dE,$$



radio spectral index

$$\alpha = -\frac{(\gamma - 1)}{2}$$



$$I_\nu = K B^{(\gamma+1)/2} \nu^{-(\gamma-1)/2}$$

$$for\ \alpha = 0.5 - 0.8,$$
$$\gamma = 2\alpha + 1 = 2 - 2.6$$

Synchrotron Radiation

magnetic energy density

$$P_{sync} \sim \gamma^2 c \sigma_T U_B$$
$$U_B = B^2/8\pi$$

Total Electrons Energy
(E_1-E2)

$$U_e = 10^{12} \frac{L}{H^{3/2}} \frac{\nu_2^{1/2+\alpha} - \nu_1^{1/2+\alpha}}{\nu_2^{1+\alpha} - \nu_1^{1+\alpha}} \frac{(2\alpha+2)}{(2\alpha+1)} \ \mathrm{erg},$$

H=magnetic field

$$U_T = U_p + U_m = a\,U_e + \frac{V H^2}{8\pi},$$

Equipartition B (or H)

$$B = 20\left(\frac{(1+\eta) S_9 D_{kpc}^2}{\phi R_{pc}^3}\right)^{2/7} \mu G$$

Lang
Reynolds

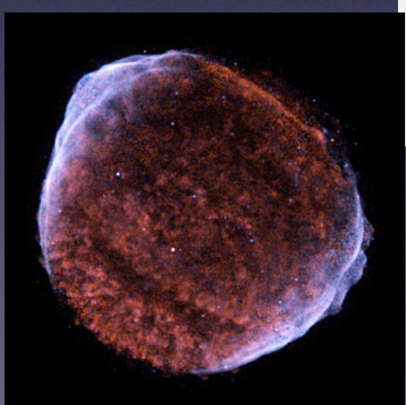
Synchrotron Radiation (R-X)

- Radio emission: Presence of GeV electrons

$$h\nu = 0.5\ (\frac{B}{100\ microG})(\frac{E}{GeV})^2\ GHz$$

- Non-thermal X-ray emission: TeV emitting electrons

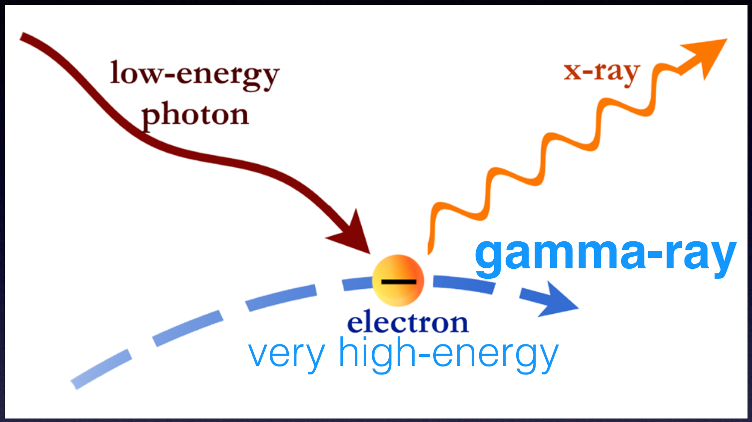
$$h\nu = 13.9(\frac{B}{100\ microG})(\frac{E}{100\ TeV})^2\ keV$$



(Koyama et al. 1995, Nature)

Other non-thermal processes: gamma-ray emission

Inverse Compton Scattering (leptonic)



low-E photons: up scatter the
Cosmic Microwave Background (CMB)
O+IR, starlight

$$E_{IC} = \frac{4}{3} E_0 \gamma^2$$

$$P_{IC} = \frac{4}{3} \sigma_T c \gamma^2 \beta^2 U_{ph}$$

similar shape to synchrotron

$$\frac{P_{sync}}{P_{IC}} = \frac{U_B}{U_{ph}}$$

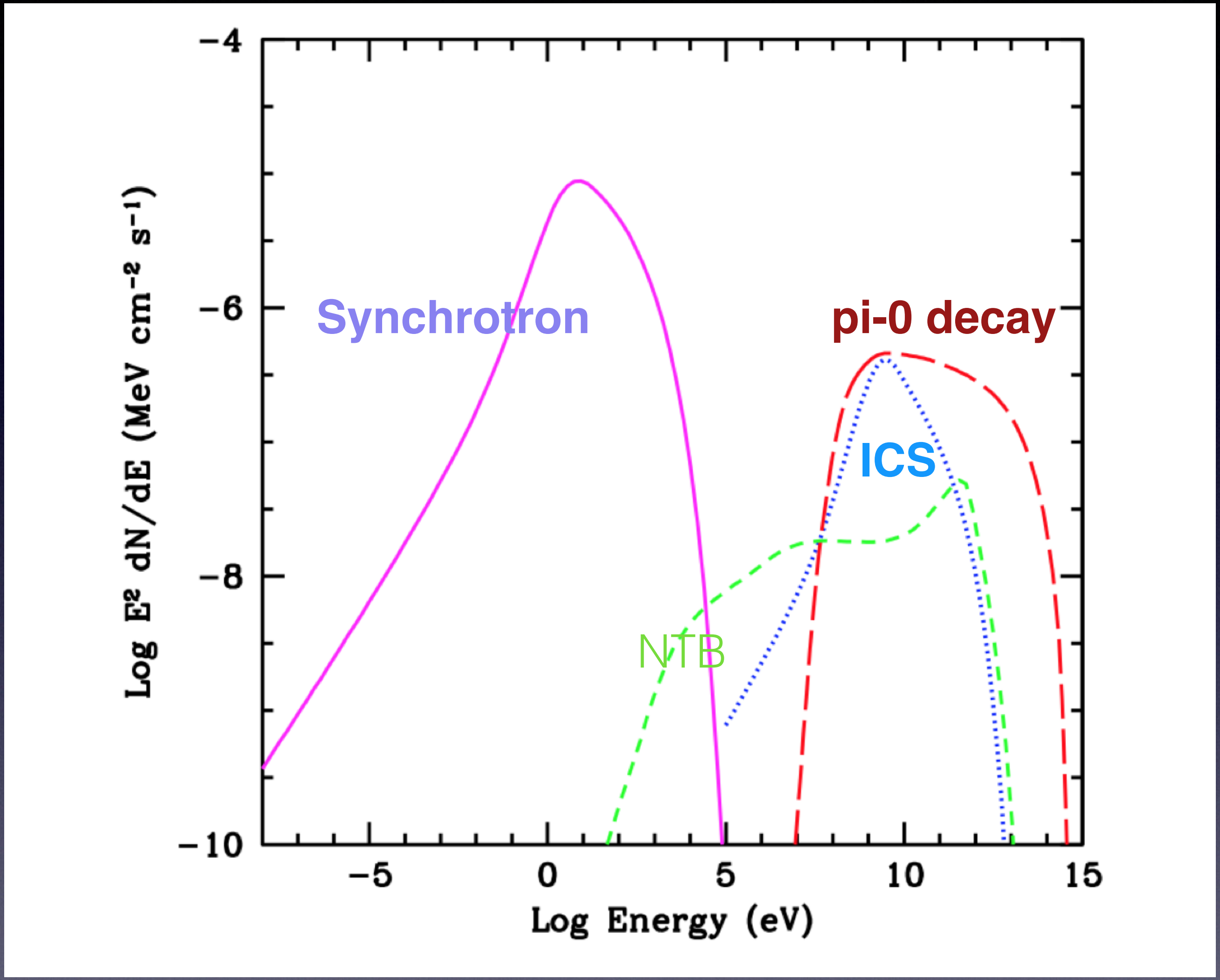
Pion Decay (hadronic)

$$p + p \;=>\; \pi_0 \;=>\; 2\gamma$$

requires **high-density**
(and higher B)
Direct evidence for ion acceleration

Spectral index~particle index

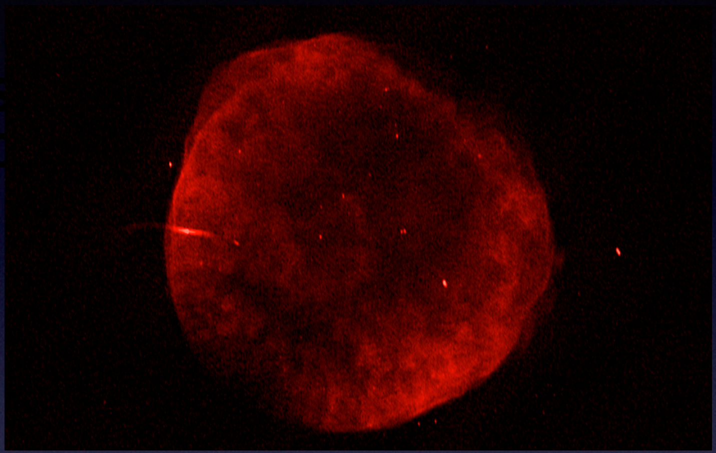
Non-thermal Emission from SNR shells



Simulated broadband SNR spectrum undergoing DSA of e- and p.

(*Slane et al. 2014*)

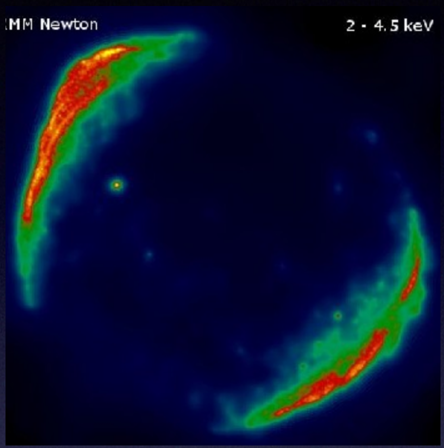
R-X-gamma multi-wavelength: SN1006



radio

cm

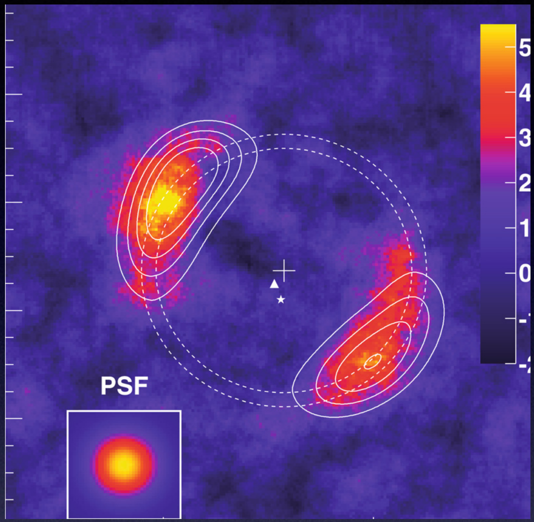
synchrotron
(GeV e-, B)



X-rays

keV

thermal emission
synchrotron
(TeV e-s)

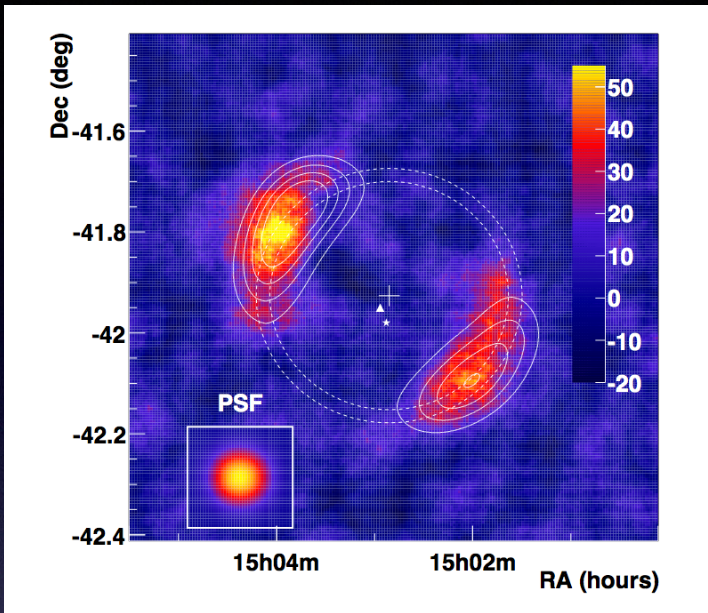


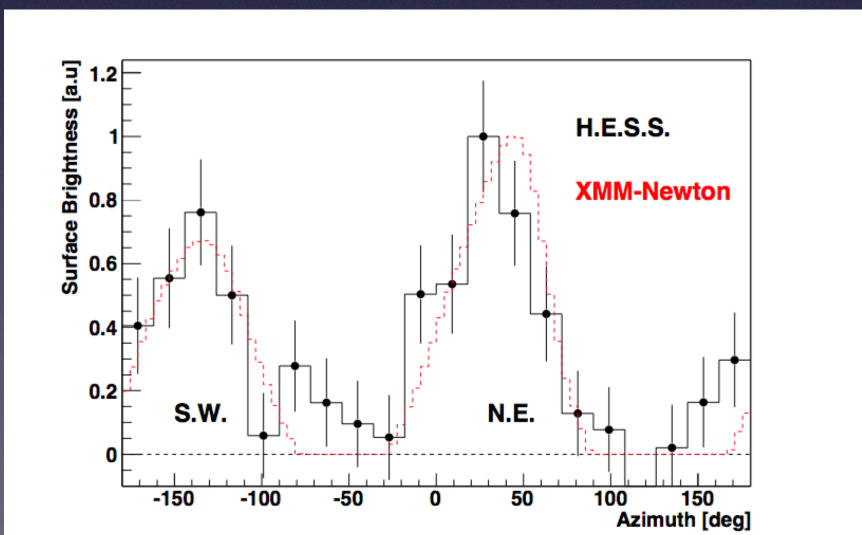
gamma-rays

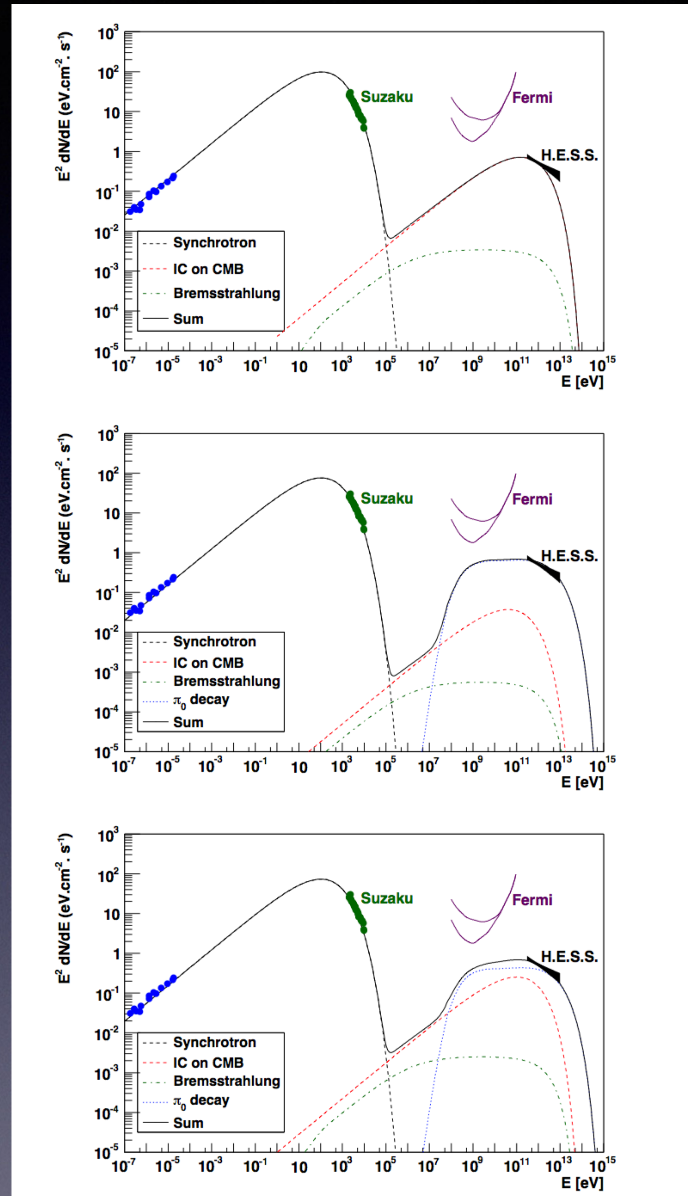
TeV

Inverse Compton
(TeV e-s) ?
pion decay (TeV p) ?

SN1006: non-thermal limbs

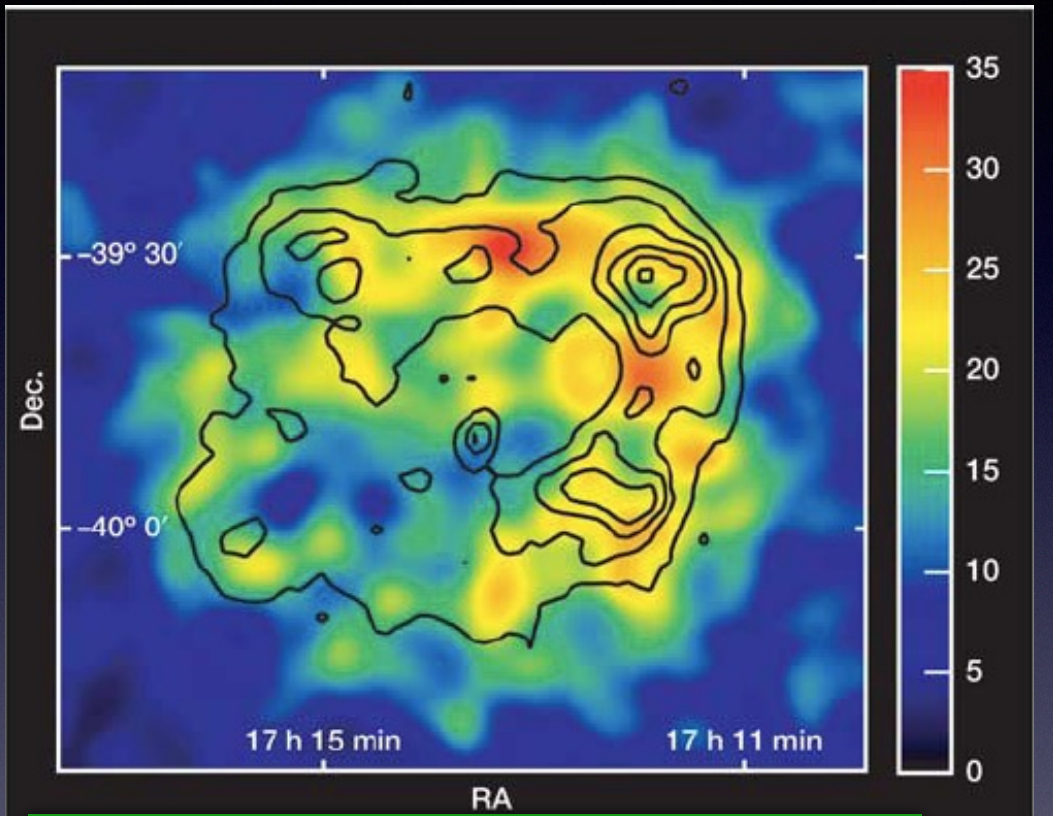




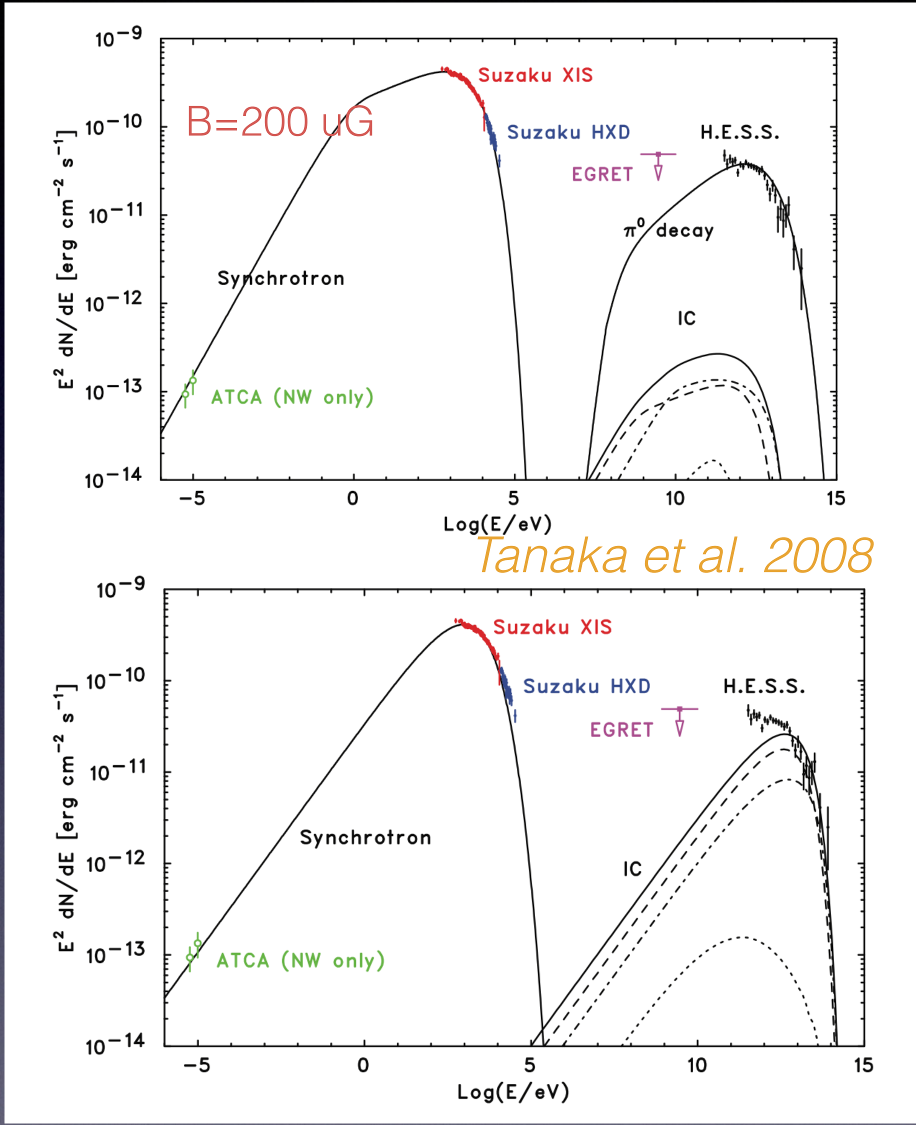


Acero et al. 2010

RXJ1713-3946—all non-thermal (?) a most powerful CR accelerator!

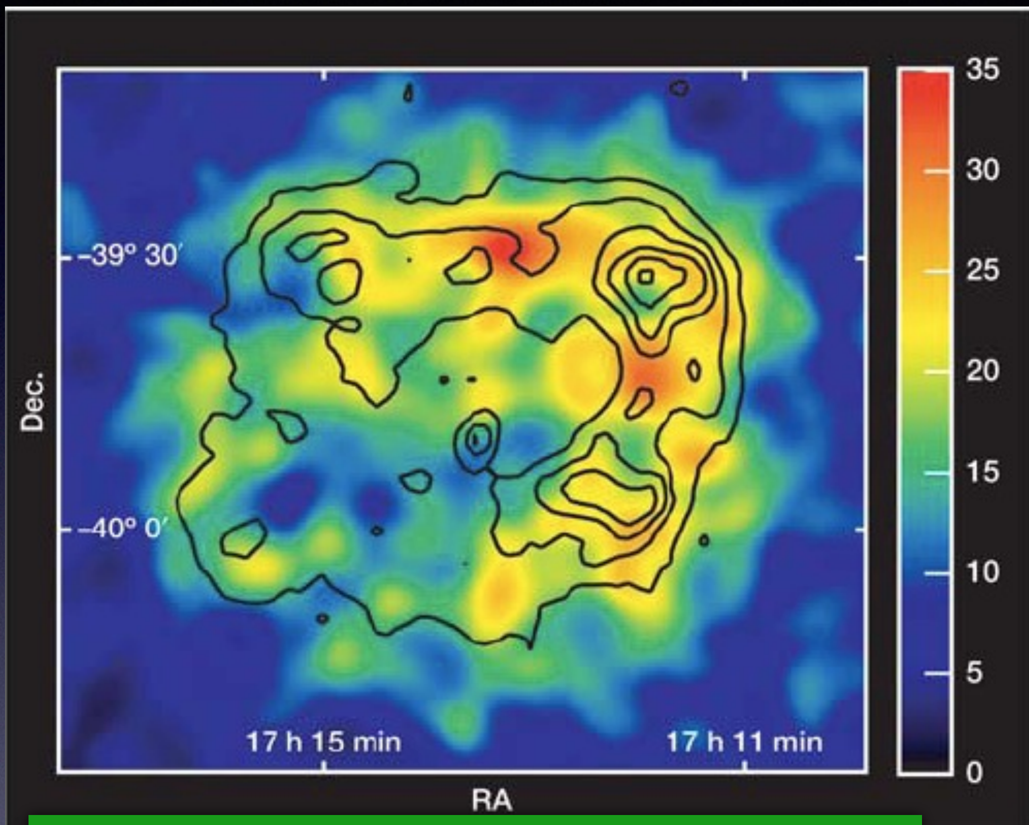


H.E.S.S. (100 GeV-10 TeV) image with X-ray contours *(Aharonian et al. 2004, Nature)*



Acero et al 2009 (R, XMM, HESS): favors leptonic model. Also Fermi (Abdo et al 2011)

RXJ17133946—a most efficient CR accelerator!



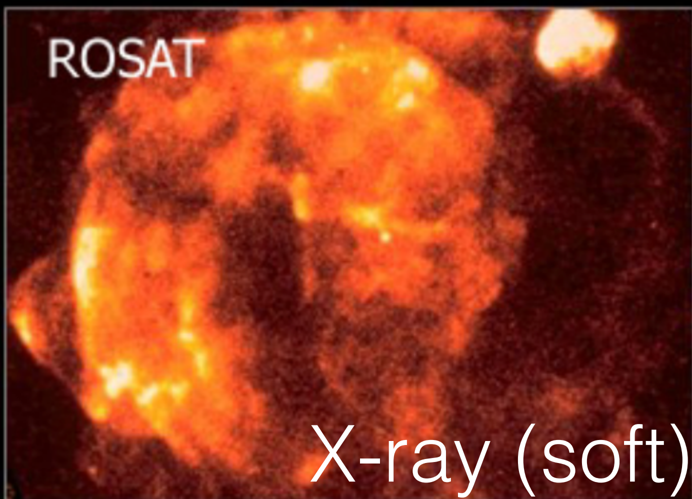
H.E.S.S. (100 GeV-10 TeV) image
with X-ray contours
(Aharonian et al. 2004, Nature)

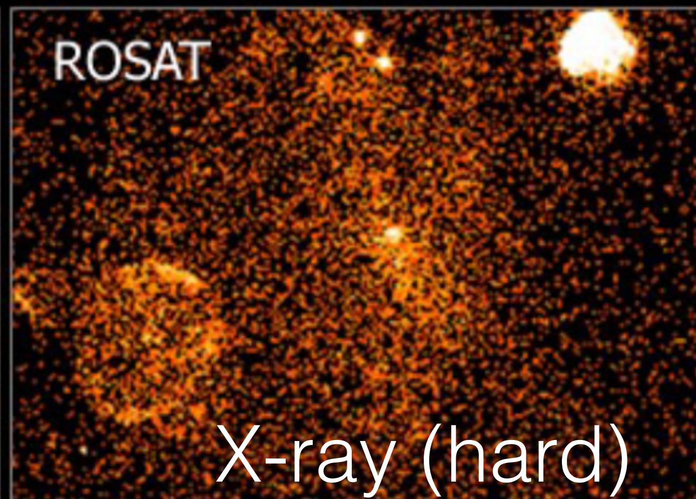
no thermal X-rays (yet!)

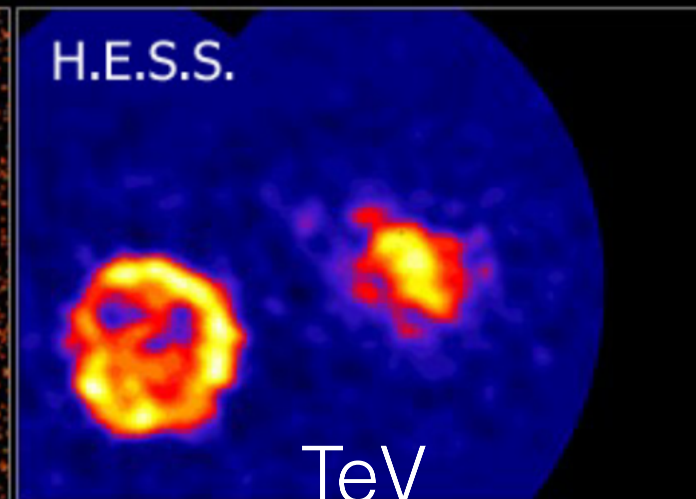
v_S~3000 km/s
$T_e << T_p$
(even more so since E=>CR)

$$\sigma_E = \left(\frac{E_0}{c}\right)\sqrt{\left(\frac{kT_i}{m_i}\right)}.$$

Vela Junior: another non-thermal SNR, powerful CR accelerator!



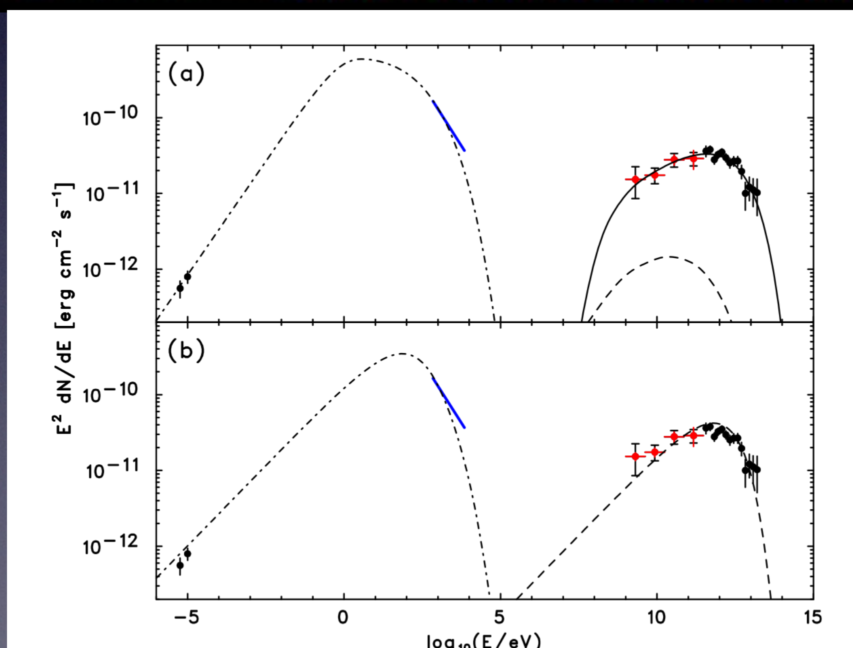


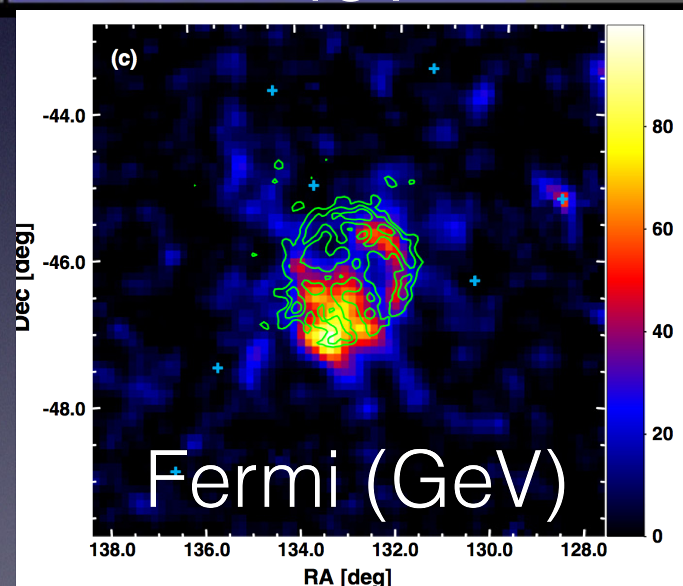


B>50 muG

(hadronic)

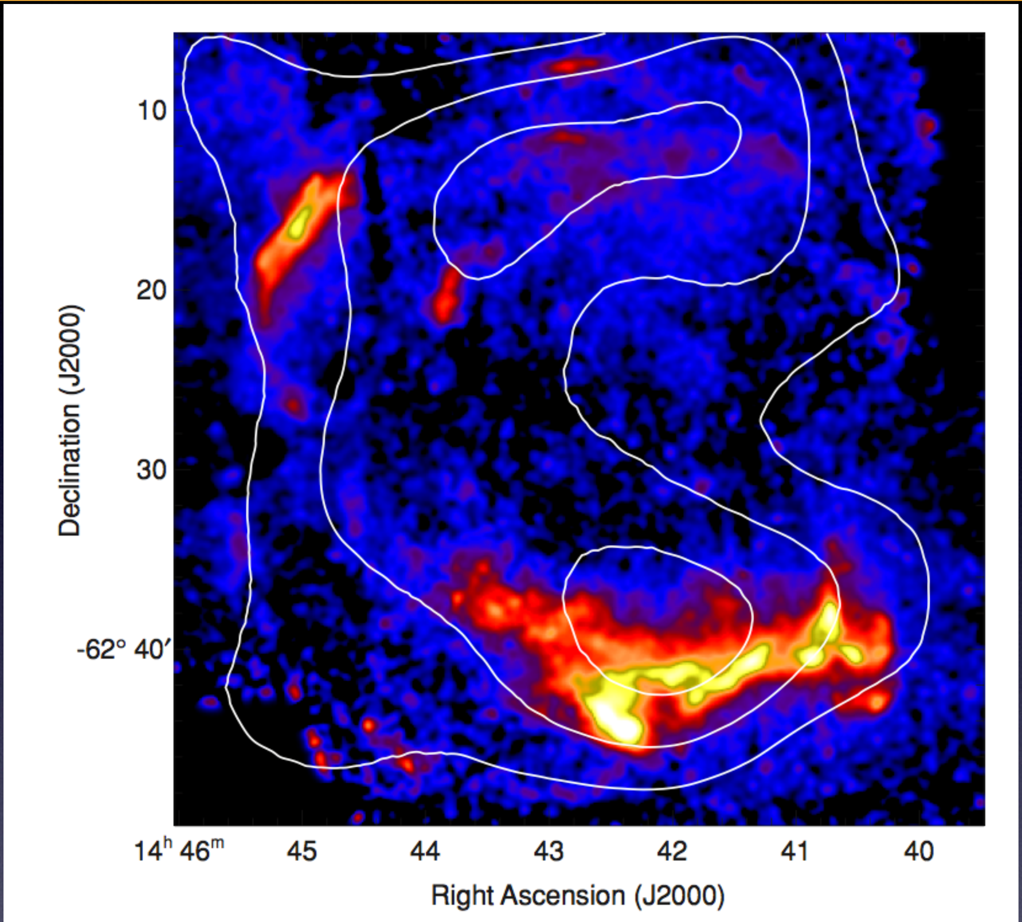
B=12 muG
(leptonic)



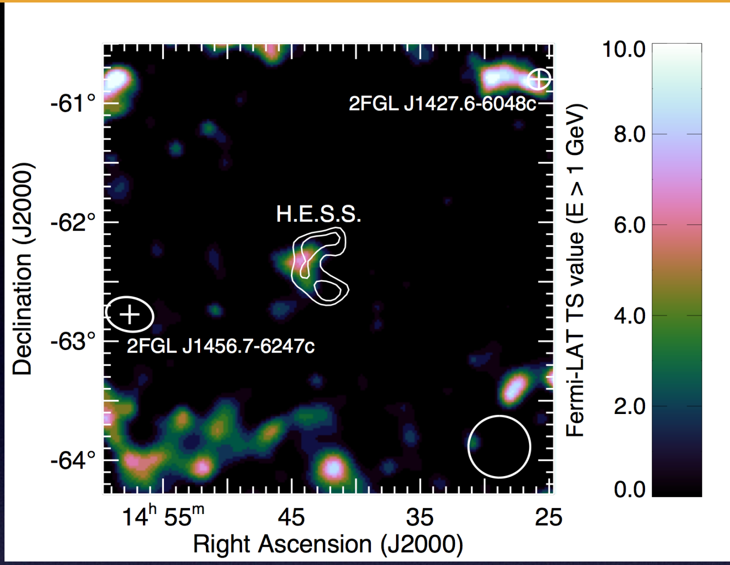


Tanaka et al. 2011

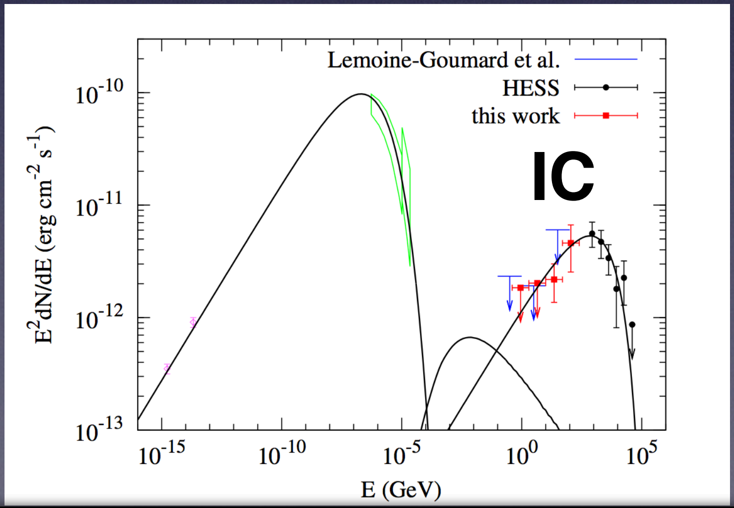
RCW86



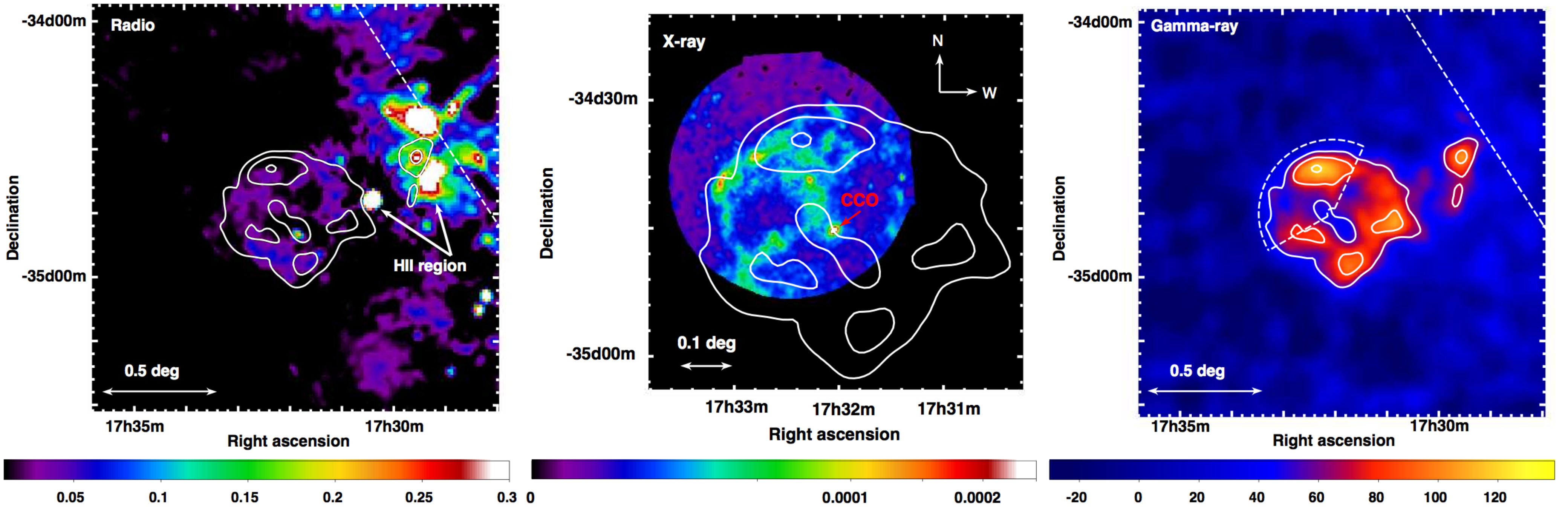
HESS image
XMM-Newton contours
Aharonian et al. 2009

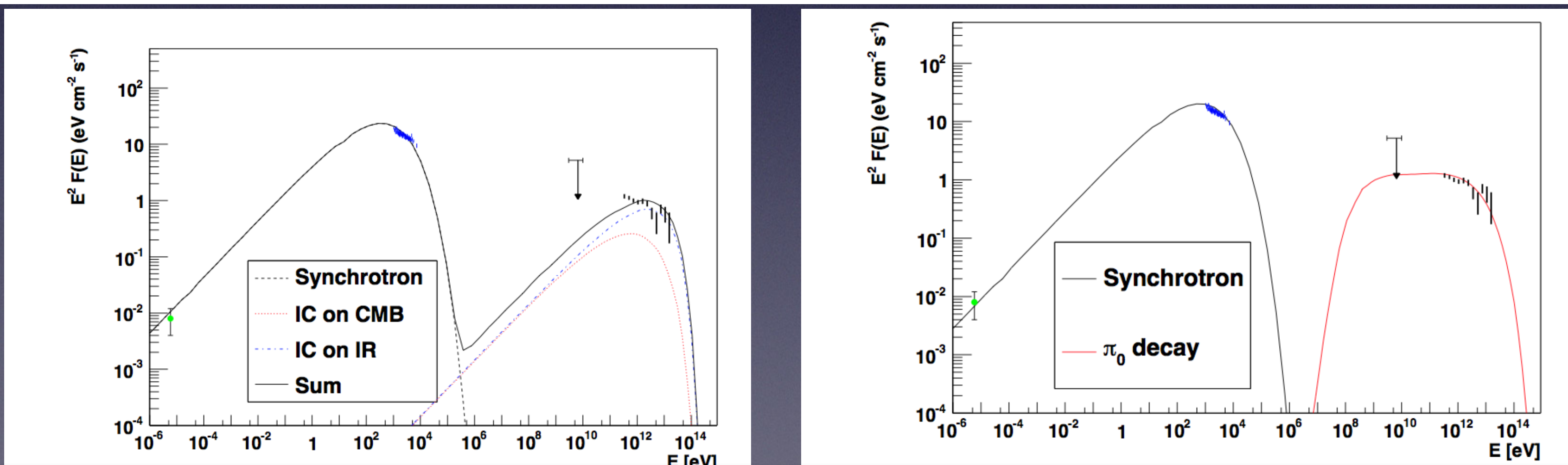


Fermi: GeV
Lemoine-Goumard et al. 2012
Yuan et al. 2014



HESSJ1731-347
A TeV discovered SNR!





Abramowski+11

SNR/MC interaction

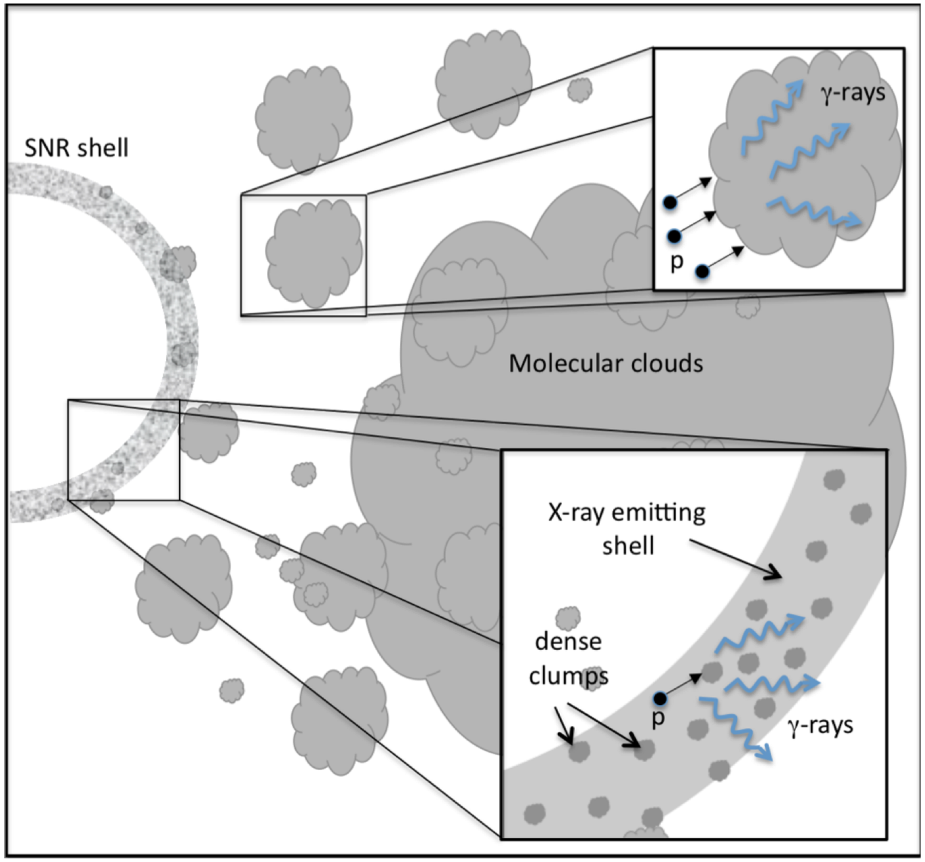
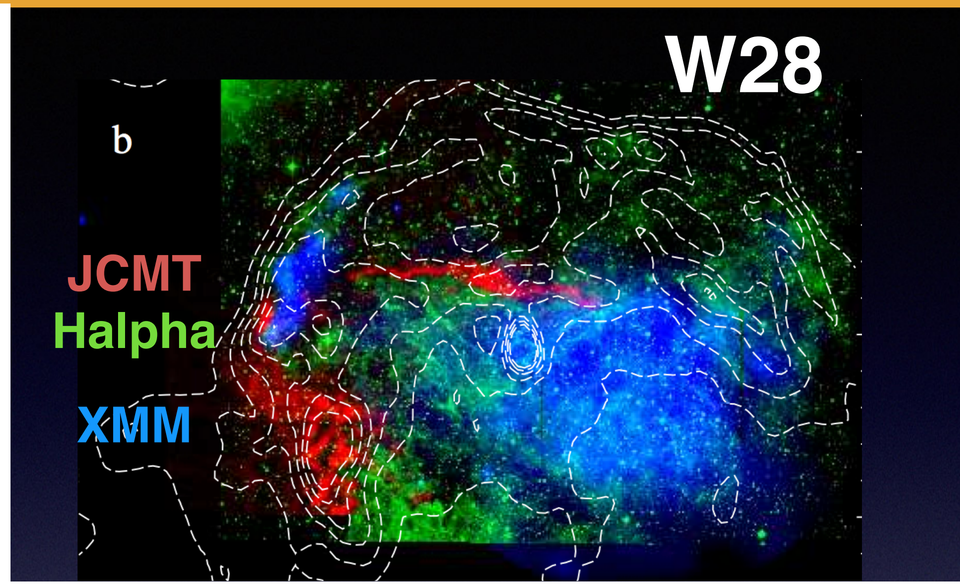
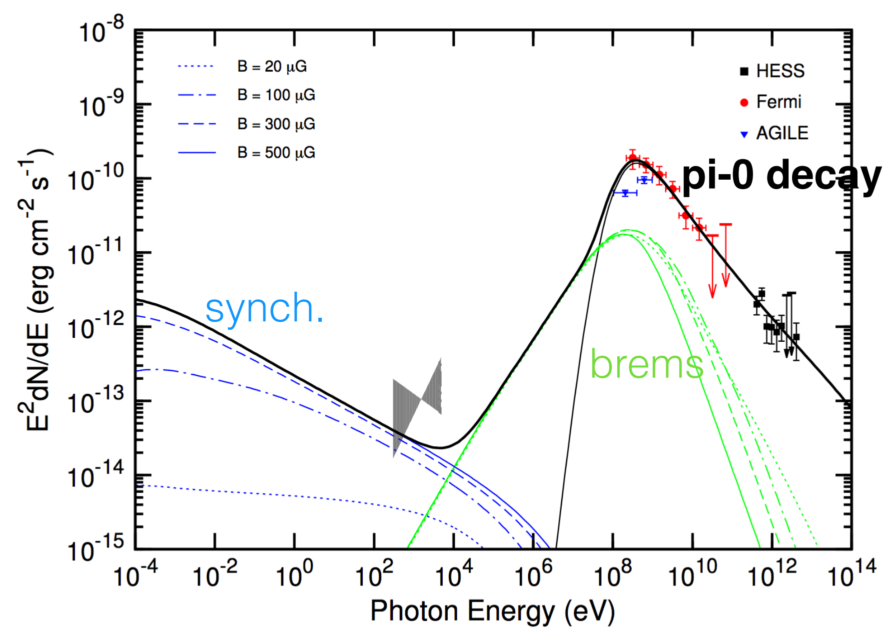


Fig. 9 Schematic diagram of SNR/MC interaction in which postshock region in SNR contains dense clumps within shocked interclump material. The low-density shocked interclump gas emits X-rays. Protons acceleration by the SNR encounter all of gas in the shell, and γ-rays are produced primarily through collisions with the dense clumps.

Slane 2014



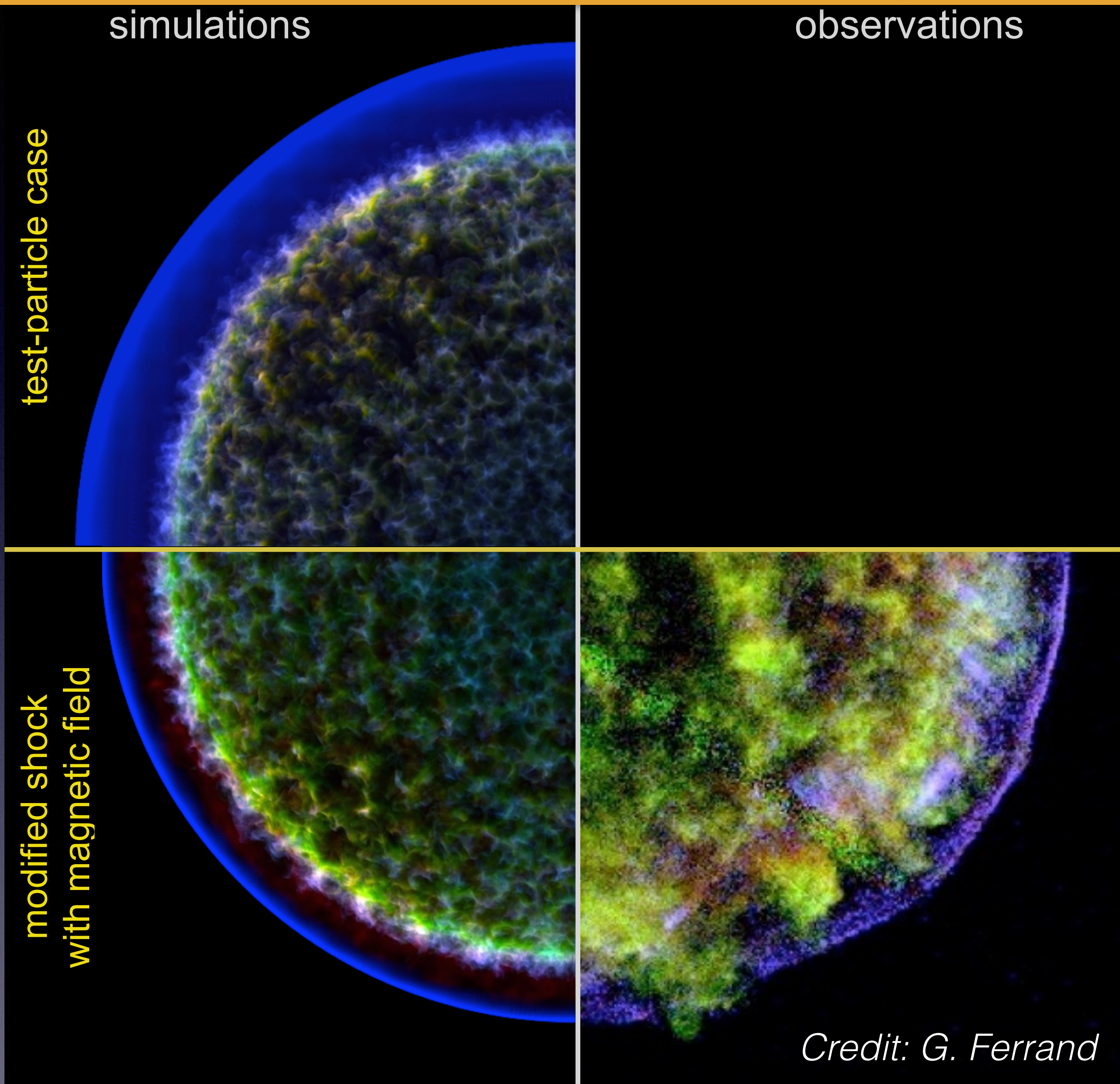


W51C, W44, IC443, 3C391, CTB109, CTB37A, G8.7-0.1, G349.7+0.2, …
~15 SNRs

Zhou, SSH et al. 2014 (ApJ, in press)

In conclusion:
the debate remains re. hadronic vs leptonic models for the high-energy emission.
ASTRO-H will help:
-fill an energy gap
-constrain the hard X-ray spectrum (HXI) => B
-search for thermal emission (SXS) => constraints on kT and n_e

3D Simulations:
Effect of particle acceleration on shock geometry and broadband emission

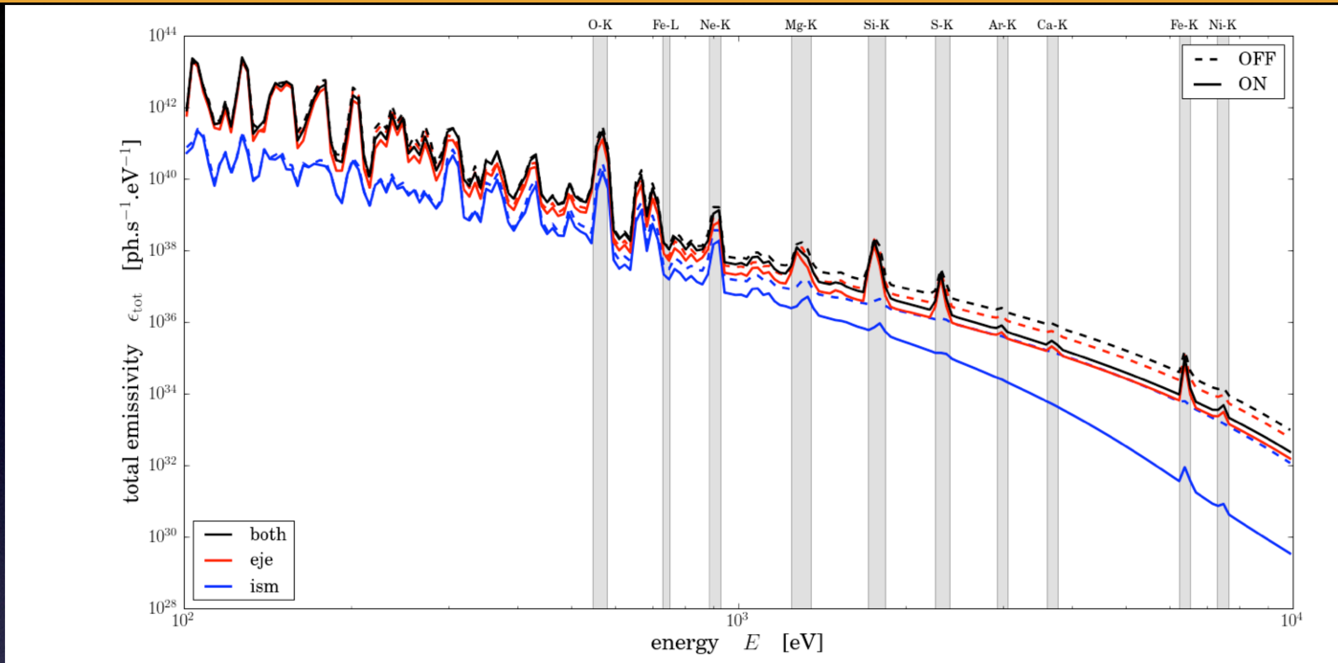


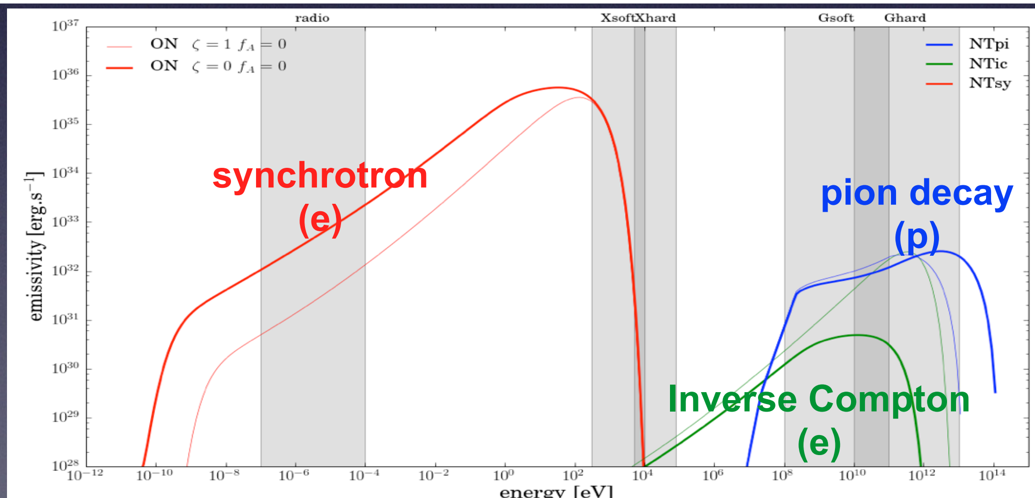
Energetic protons, accelerated at the shock front, don't radiate as efficiently as electrons, however:

1) they affect shock dynamics (thinner)
2) thermal X-ray emission: cooler and lower EM
3) NT emission (R, X, γ): emission level and cutoff energies

Ferrand, Decourchelle & Safi-Harb 2012, 2014

3D Simulations:
Effect of particle acceleration on shock geometry and broadband emission





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Ferrand, Decourchelle & Safi-Harb 2012, 2014

(see also Lee et al. 2013, Patnaude et al. 2010, Slane et al. 2014)

SNR statistics

Statistics: SNRcat

- Currently: **317 SNRs** (with age and distance estimates from PSR/SNR):
  - Green's 2009 catalogue has 274 SNRs, being updated
  - SNRcat updated regularly with new SNR detections, **including X-ray only (PWN**) and arXiv papers (almost daily)

. 65 SNRs listed interacting with a molecular cloud

. 86 contain PWNe or PWN candidates (65 SNRs are associated with both a NS and PWN), and the list keeps growing!
. 108 contain a neutron star (NS) or candidate, 90 identified as a pulsar (PSR)
. 6 AXPs + 2 soft γ-ray repeaters (SGRs) + 2 high-B = 10 magnetars/candidates
. 15 central compact objects (CCOs) or candidates

• 1268 records of HE observations made with 39 observatories
(added several legacy instruments + some new instruments)

Note: 307 of these are actually non-detections, and in some cases, the emission might not be coming from the SNR

. 1737 references as ADS bibcodes plus 100s of other URLs

Ferrand & Safi-Harb 2012
http://www.physics.umanitoba.ca/snr/SNRcat/SNRcat_stats_20140617.pdf

domain		instrument	records by instrument	records by domain	
X-rays	keV	ASCA	121 + 3 = 124	698 + 35 = 733	
		BeppoSAX	19 + 0 = 19		
		Chandra	126 + 2 = 128		
		Einstein	55 + 7 = 62		
		EXOSAT	19 + 0 = 19		
		Ginga	19 + 0 = 19		
		HEAO-1	18 + 0 = 18		
		INTEGRAL	22 + 7 = 29		
		NuSTAR	7 + 0 = 7		
		CGRO/OSSE	4 + 0 = 4		
		ROSAT	87 + 3 = 90		
		RXTE	21 + 5 = 26		
		Suzaku	54 + 1 = 55		
		SWIFT	13 + 2 = 15		
		Uhuru	10 + 0 = 10		
		XMM	103 + 5 = 108		
γ-rays	MeV	CGRO/COMPTEL	4 + 0 = 4	6 + 2 = 8	263 + 272 = 535
		INTEGRAL	1 + 2 = 3		
		NCT	1 + 0 = 1		
	GeV	AGILE	9 + 0 = 9	146 + 217 = 363	
		COS-B	7 + 0 = 7		
		CGRO/EGRET	26 + 20 = 46		
		Fermi	101 + 197 = 298		
		SAS-2	3 + 0 = 3		
	TeV	AS-γ	1 + 0 = 1	111 + 53 = 164	
		ARGO-YBJ	4 + 0 = 4		
		CANGAROO	6 + 8 = 14		
		CAT	1 + 0 = 1		
		CELESTE	1 + 1 = 2		
		GT-48	1 + 0 = 1		
		HAGAR	1 + 0 = 1		
		HEGRA	4 + 4 = 8		
		H.E.S.S.	53 + 11 = 64		
		MAGIC	7 + 13 = 20		
		Milagro	10 + 0 = 10		
		PACT	1 + 0 = 1		
		ShALON	6 + 0 = 6		
		STACEE	1 + 1 = 2		
		TACTIC	1 + 0 = 1		
		THEMISTOCLE	1 + 0 = 1		
		VERITAS	10 + 6 = 16		
		Whipple	2 + 9 = 11		
ALL		TOTAL	961 + 307 = 1268	961 + 307 = 1268	

www.physics.umanitoba.ca/snr/SNRcat

[Ferrand & Safi-Harb 2012] updated as of 2014/06/17

SNRcat Demo

ID	names	context	SN	age	distance	type	CHANDRA	XMM	SUZAKU	ROSAT	ASCA	FERMI	AGILE	HESS	VERITAS	MAGIC	MILAGRO
							all	all	all	all	all	all	all	all	all	all	all
G000.0+00.0	Sgr A East, 1FGL J1745.6-2900c, 2FGL J1745.6-2858, 1FHL J1745.6-2900, HESS J1745-290	contains CXOGC J174545.5-285829 = the cannonball = NS candidate and possibly PWN, close to BH Sgr A*, interacts with molecular cloud		1200 - 10000 yr	8 kpc	composite	CHANDRA	XMM	SUZAKU		ASCA	FERMI		HESS			
G000.1-00.1	1FGL J1746.4-2849c, 1FHL J1746.3-2851	contains PWN G0.13-0.11, interacts with molecular cloud??				composite?	CHANDRA	XMM				FERMI					
G000.3+00.0	~~G0.33+0.04~~, ~~G0.4+0.1~~					shell						FERMI					
G000.9+00.1	HESS J1747-281	contains PSR candidate J1747-2809 + PWN G0.87+0.08		1900 yr PSR: 5000 yr	8.5 - 10 kpc PSR: 13 kpc	composite	CHANDRA	XMM			ASCA	FERMI		HESS			
G001.0-00.1	Sgr D, ~~G1.05-0.1~~, ~~G1.05-0.15~~	close to star forming region Sgr D and other SNR candidates, interacts with molecular cloud			8 kpc	shell		XMM	SUZAKU		ASCA	FERMI					
G001.4-00.1		interacts with molecular cloud				shell						FERMI					
G001.9+00.3				150 - 220 yr	8.5 kpc												
G003.7-00.2	~~G003.8-00.3~~																
G003.8+00.3																	
G004.2-03.5																	
G004.5+06.8	Kepler, SN1604, 3C358, Kes 57		1604	SN: 410 yr	3 - 6.4 kpc												
G004.8+06.2	~~G4.5+6.2~~																
G005.2-02.6																	
G005.4-01.2 ?	Milne 56, ~~G5.3-1.0~~, ~~G5.27-0.9~~, 2FGL J1802.3-2445c	offset PSR J1801-2451 = B1757-24 = the Duck + PWN G5.27-0.9, interacts with molecular cloud		PSR: 15488 yr	4.3 - 4.5 kpc PSR: 5 kpc	composite	CHANDRA					FERMI					
G005.5+00.3	~~G5.55+0.32~~					shell						FERMI					
G005.7-00.1 ?	~~G5.71-0.08~~, HESS J1800-240C	close to SNR G006.4-00.1 = W28, interacts with molecular cloud				shell?								HESS			
G005.9+03.1						shell						FERMI					
G006.1+00.5	~~G6.10+0.53~~					shell						FERMI					
G006.1+01.2	~~G6.1+1.15~~					filled-centre?						FERMI					
G006.4+04.0						shell											
G006.4-00.1	W28, ~~G6.6-0.2~~, 0FGL J1801.6-2327, 1FGL J1801.3-2322c and J1800.5-2359c, 2FGL J1801.3-2326e, 1FHL J1801.3-2326e, HESS J1801-233 and HESS J1800-240[A/B/C]	close to (unrelated) PSR B1758-23 = J1801-2304, close to SNRs G5.7-0.1, G6.5-0.4, G7.0-0.1, interacts with molecular cloud		33000 - 36000 yr	1.6 - 2.2 kpc	composite	CHA										
G006.5-00.4	~~G6.51-0.48~~, ~~G6.67-0.42~~, HESS J1801-233	close to SNR G006.4-00.1 = W28				shell											
G007.0-00.1	~~G7.06-0.12~~	close to SNR G006.4-00.1 = W28				shell											
G007.2+00.2	~~G7.20+0.20~~					shell											
G007.5-01.7 ?		contains PWN G7.4-2.0 = Taz, close to PSR J1809-2332		≥ 15000 yr	1.7 - 2 kpc PSR: 2 kpc	composite	CHANDRA	XMM		ROSAT	ASCA	FERMI					
G007.7-03.7	1814-24				3.2 - 6 kpc	shell					ASCA	FERMI					
G008.3-00.0	~~G8.31-0.09~~					shell						FERMI					
G008.7-00.1	W30, ~~G8.6-0.1~~, Suzaku J1804-2142 and J1804-2140, 1FGL J1805.2-2137c and J1806.8-2109c, 2FGL J1805.6-2136e, 1FHL J1805.6-2136e, HESS J1804-216	inside W30 complex, PSR J1803-2137 = B1800-21 and PWN G8.40+0.15 at the edge, interacts with molecular cloud		15000 - 28000 yr PSR: 15800 yr	3.2 - 6 kpc PSR: 4 kpc	composite	CHANDRA		SUZAKU	ROSAT		FERMI		HESS			
G008.7-05.0						shell						FERMI					
G008.9+00.4	~~G8.90+0.40~~					shell						FERMI					
G009.7-00.0	~~G9.7-0.1~~, ~~G9.70-0.06~~	interacts with molecular cloud				shell						FERMI					
G009.8+00.6						shell						FERMI					
G009.9-00.8	~~G9.95-0.81~~					shell						FERMI					
G010.5-00.0	~~G10.59-0.04~~					shell					ASCA	FERMI					

Global filter: (Fermi-extended) AND Cloud
reset all filters
Number of objects displayed: **15**

Global filter: HESS-extended AND PWN
reset all filters
Number of objects displayed: **23**

Feedback form for each SNR

http://www.physics.umanitoba.ca/snr/SNRcat/

Statistics (gamma-ray)

- 33 detected by Fermi+HESS, including
  - **15 detected as extended**
- 10 SNRs detected by VERITAS, 7 by MAGIC and 1- by MILAGRAO

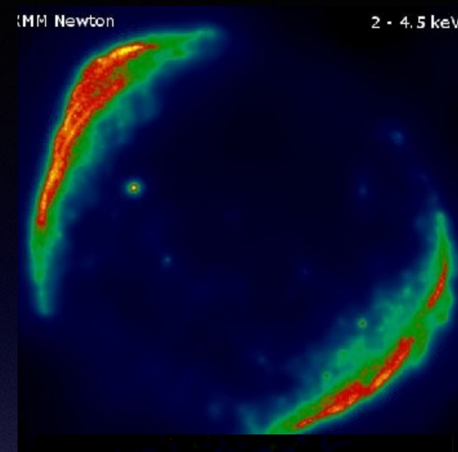
- **With Cloud**
  - 40 in Fermi
    - including 15 as extended
  - 25 in HESS
    - including 15 as extended
  - 14 in Fermi+HESS
    - including 7 as extended

- **With PWNe**
  - 26 in both Fermi+HESS,
    - including 11 as extended
  - 34 by HESS
    - including 23 as extended
  - 21 by Fermi
    - including 11 as extended

http://www.physics.umanitoba.ca/snr/SNRcat/

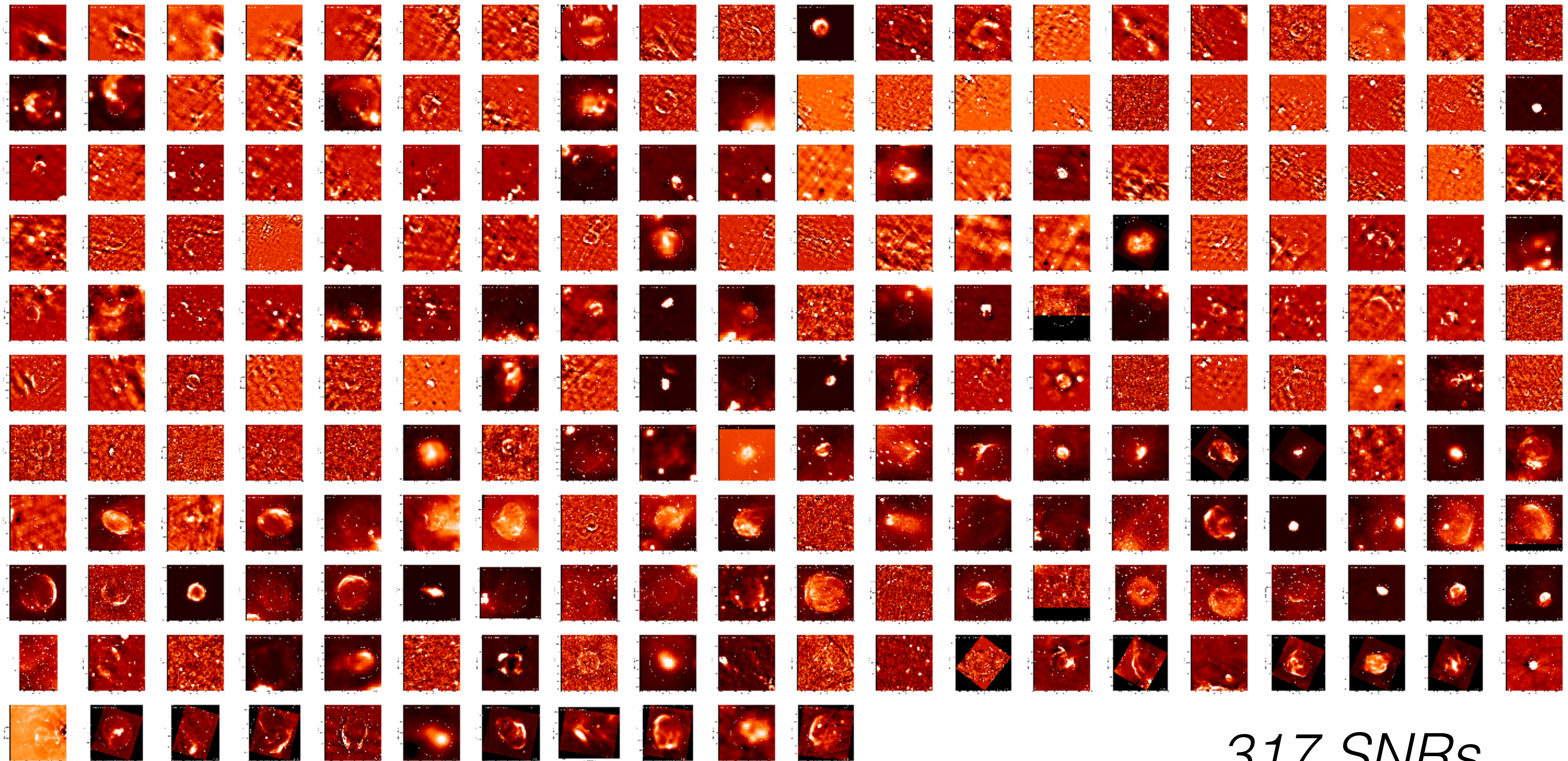
Extensions to SNRcat

- **Bilateral** SNRs catalogue (connection between SNRs morphology and the Galactic B field)
  - *Jennifer West (PhD)*



- **PWN** catalogue (relevant to next lecture)
  - *Heather Matheson (PhD)=>Ben Guest*

- Multi-wavelength images for all SNRs
  - *Yitchen Zhan (undergrad) and others*



317 SNRs

Montage by J. West (U. Manitoba)

PRELIMINARY!

Selected (bright/famous/good for ASTRO-H!) SNRs X-ray movie

Stay tuned!