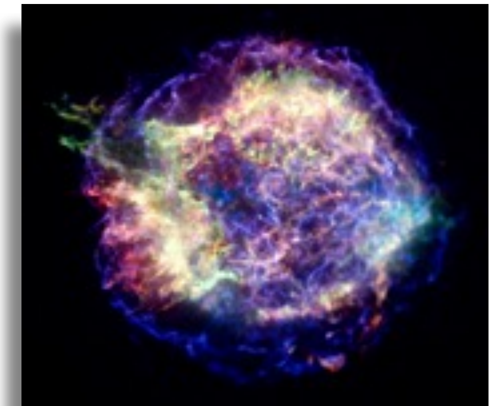
CRBTSM 2016
San Vito di Cadrore, 19th-24th Sept. 2016

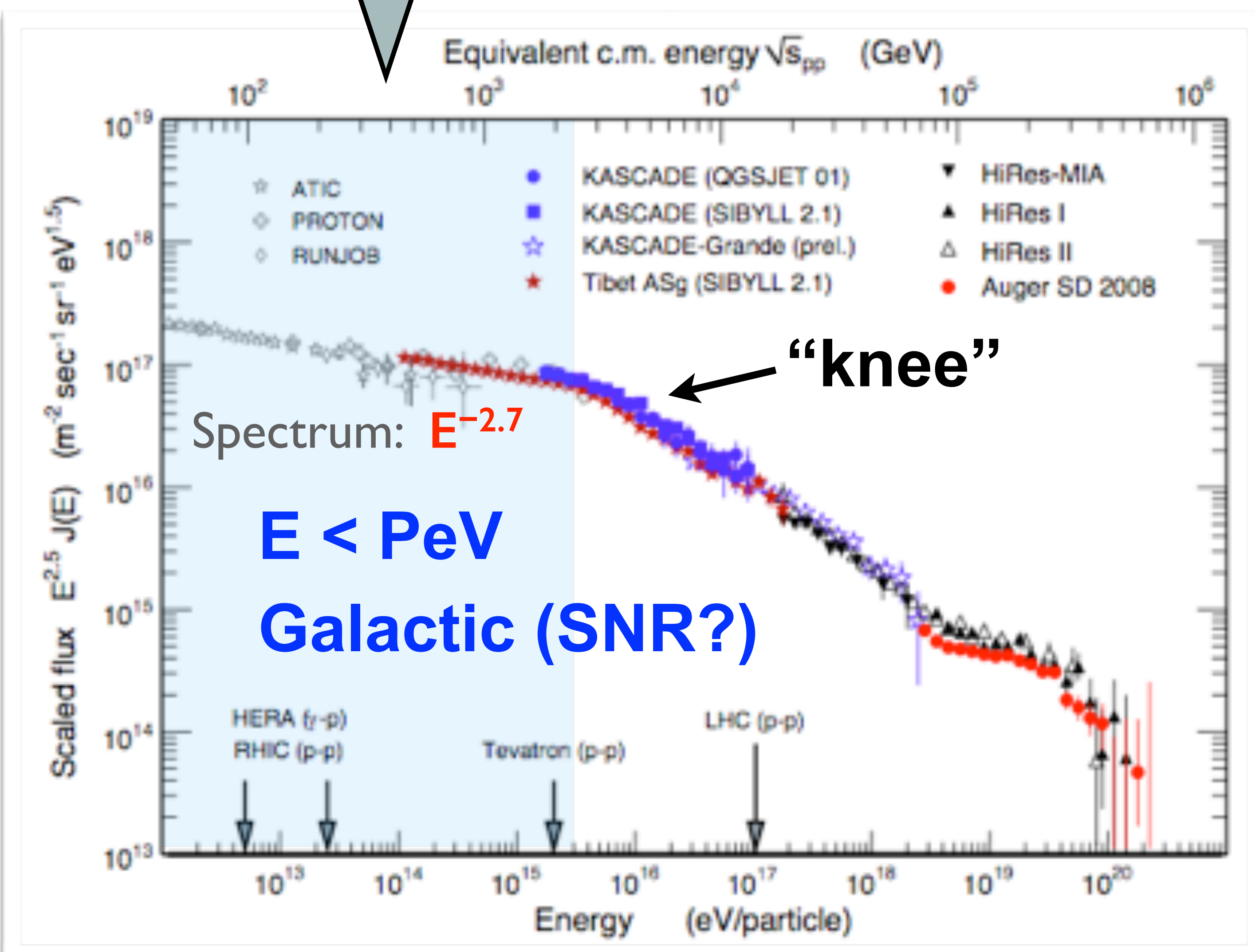
GAMMA RAYS FROM SUPERNOVA REMNANTS

Yasunobu Uchiyama *(Rikkyo University, JAPAN)*

SNR ORIGIN OF GALACTIC COSMIC RAYS

Supernova remnants (SNRs)





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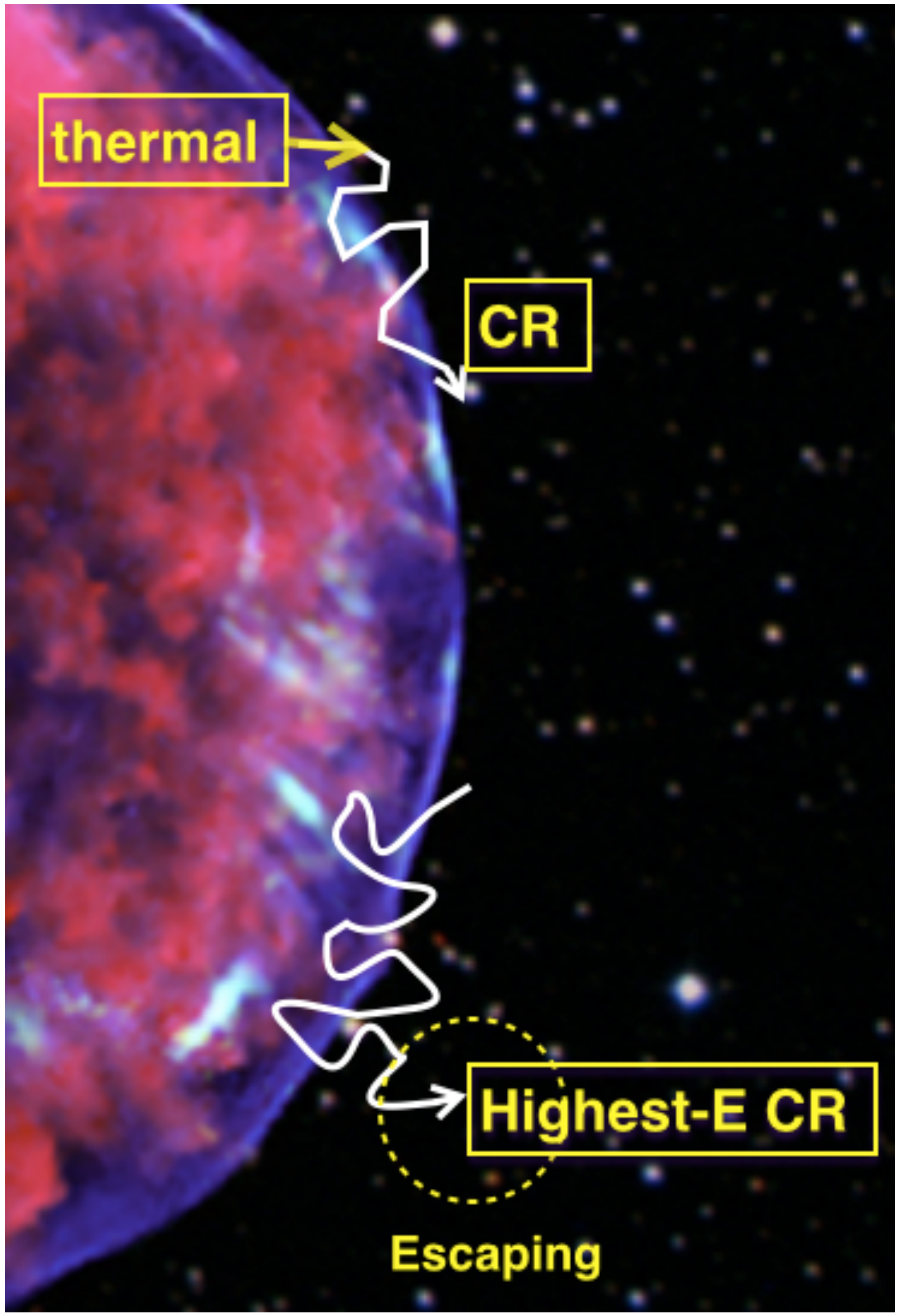
- Composition: mostly **protons**
  - Recent detection of π-decay gamma-rays with AGILE/Fermi
  - > 100 TeV sources (beyond KN) are of hadronic origin
- Energy Spectrum: $E^{-2.7}$
  - Acceleration spectrum (DSA: Diffusive Shock Acceleration)
  - Propagation in the Galaxy
  - Escape from accelerators
- Energy Budget: **1 eV/cm^3**
  - Acceleration efficiency
    - 10% of SN explosion kinetic energy
  - Non-linear effects?
- Maximum Energy: **PeV (10^{15} eV)**
  - DSA with B-field amplification
  - Escape from accelerators

ACCELERATION EFFICIENCY

Diffusive Shock Acceleration



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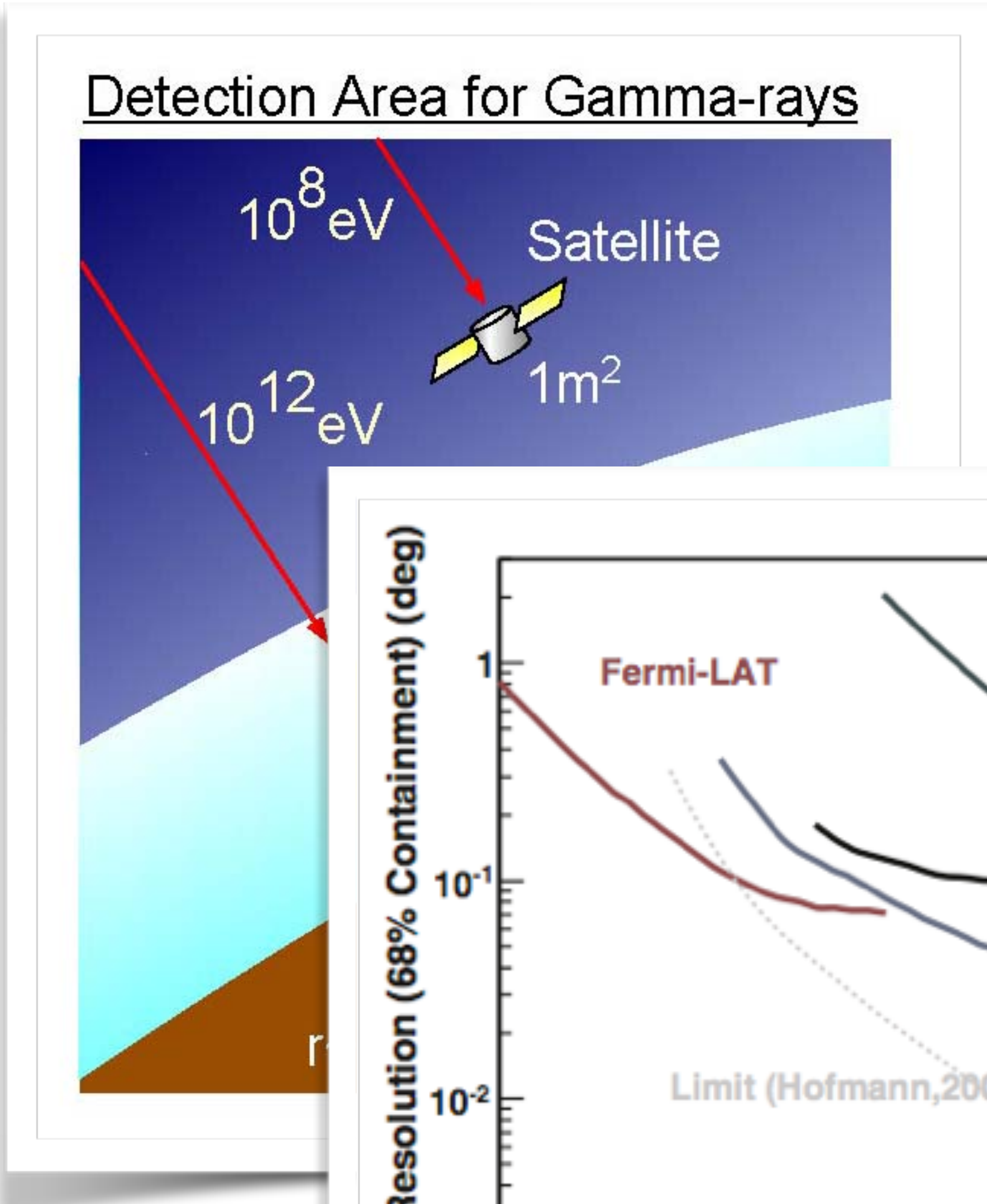
Acceleration Efficiency (1):
"Energy Content"

✔ How thermal (Maxwellian) particles can be injected into Fermi acceleration?
✔ Depends on **B-field orientation**?
✔ Energy content of **protons**?

Acceleration Efficiency (2):
"Maximum Energy"

✔ **B-field amplification**?
✔ Depends on **B-field orientation**?
✔ **Escaping** CRs? (important for protons)

GAMMA-RAY OBSERVATORIES

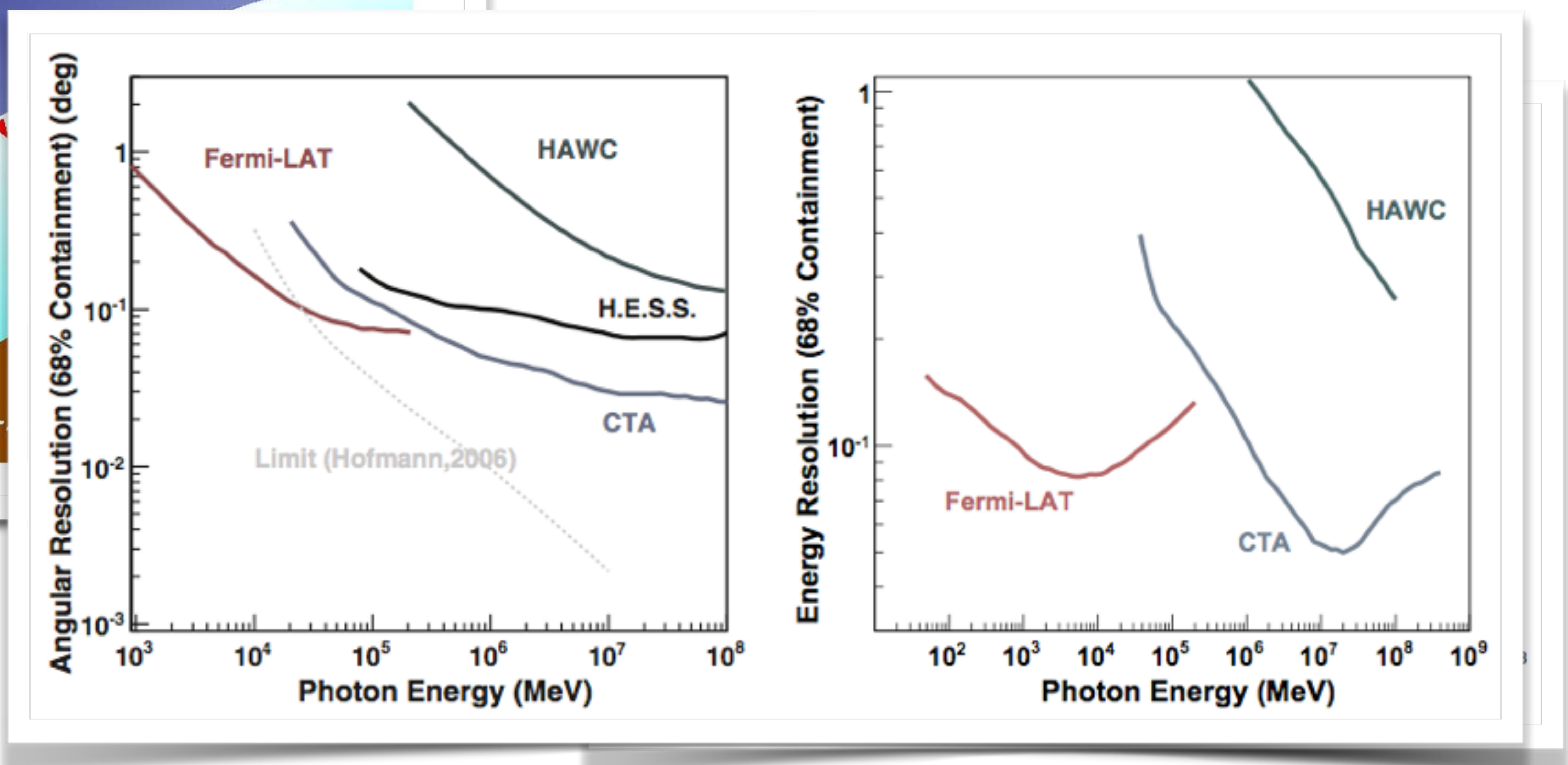


Space (satellites)

AGILE & Fermi ----------→ Gamma-400

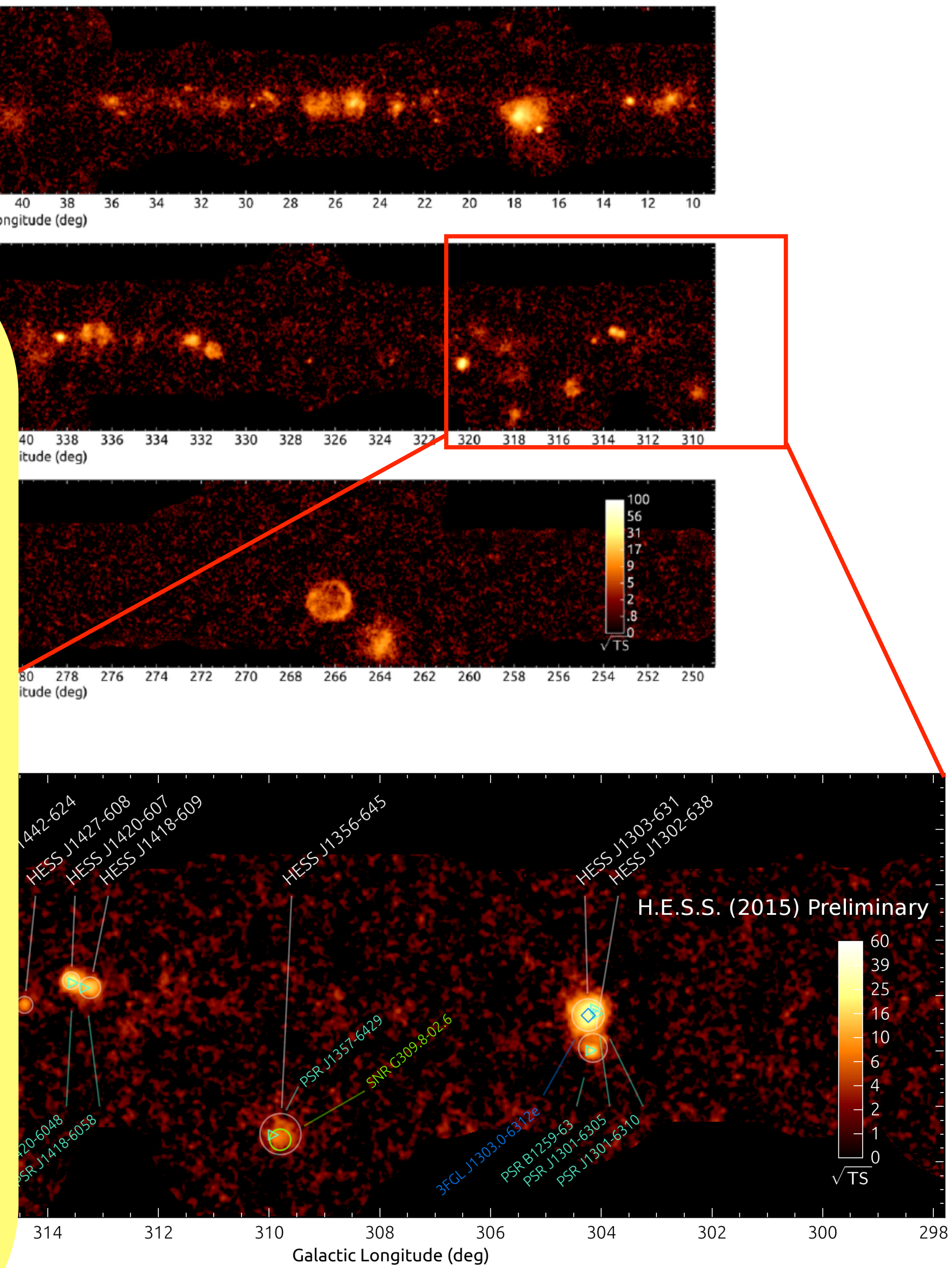
Ground-based (IACTs)

H.E.S.S., MAGIC, VERITAS ⟶ CTA



Funk & Hinton (2013)

H.E.S.S. GALACTIC PLANE SURVEY



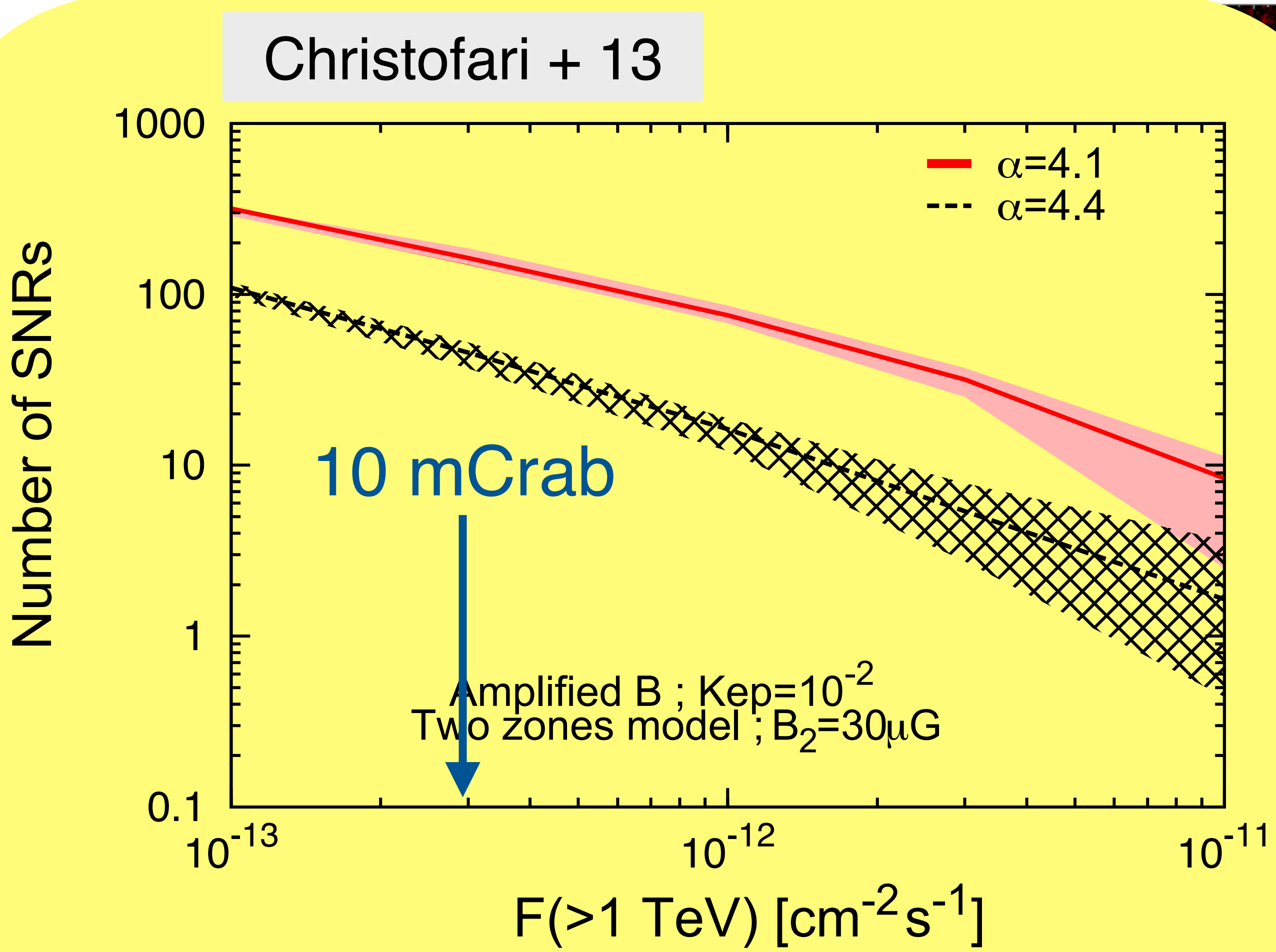
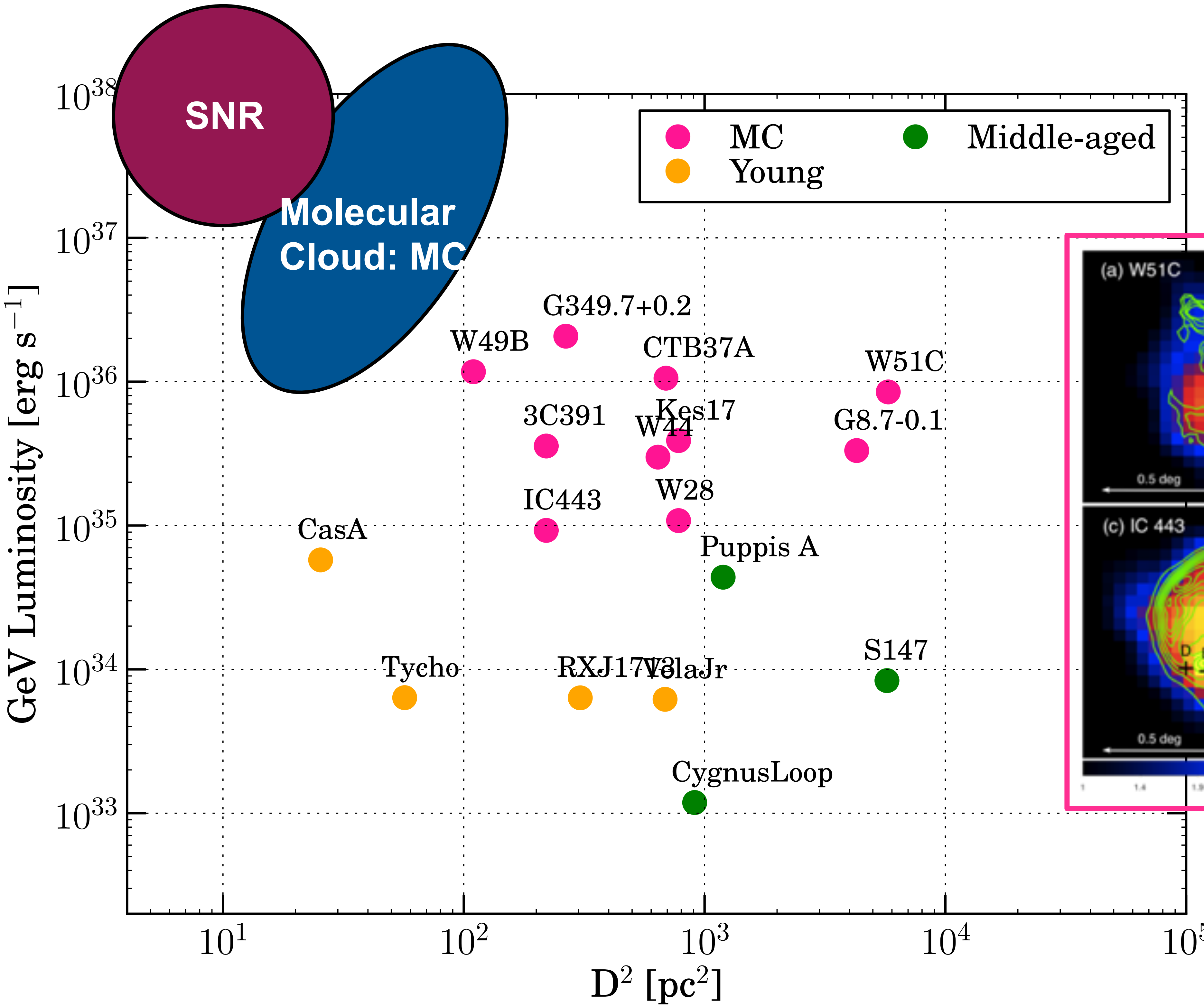


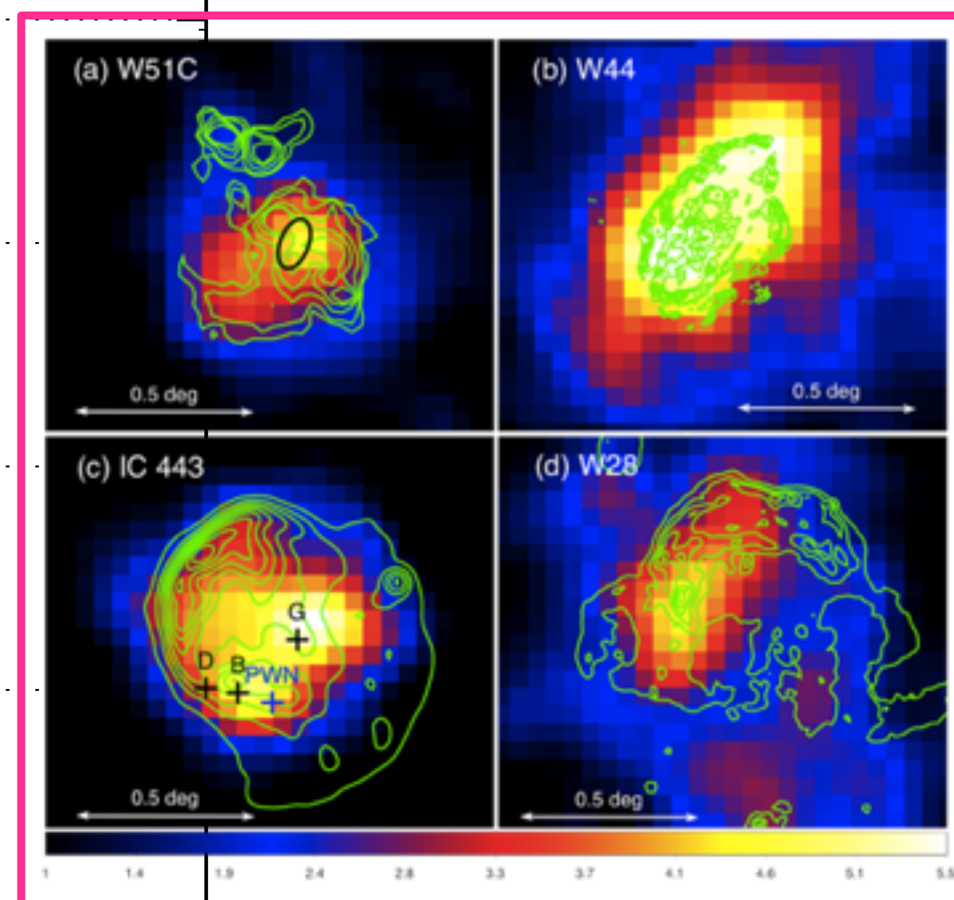
Figure 3. Same as in Figs 1 and 2 but now two zones are considered: the acceleration zone around the shock, where the magnetic field is amplified and given by equation (11), and an inner region with a weaker magnetic field equal to 30 μG. The spectrum of particles accelerated at the shock is a power law in momentum with slope 4.4 and 4.1 for the black and red curve, respectively (models M5 and M6 in Table 2).

H.E.S.S. "JAPAN"

Yasunobu Uchiyama (Rikkyo)

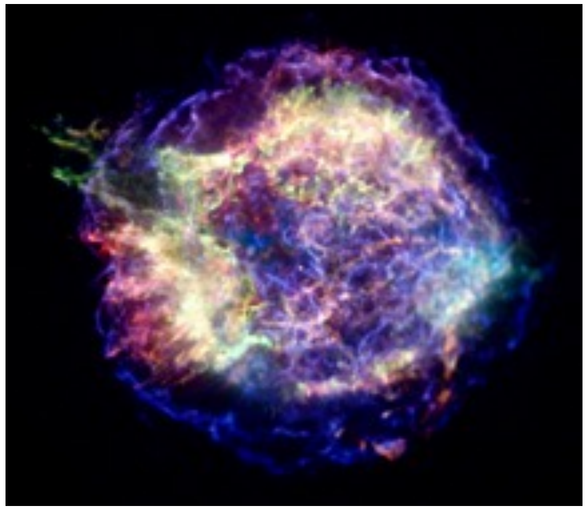
CLASSIFICATION



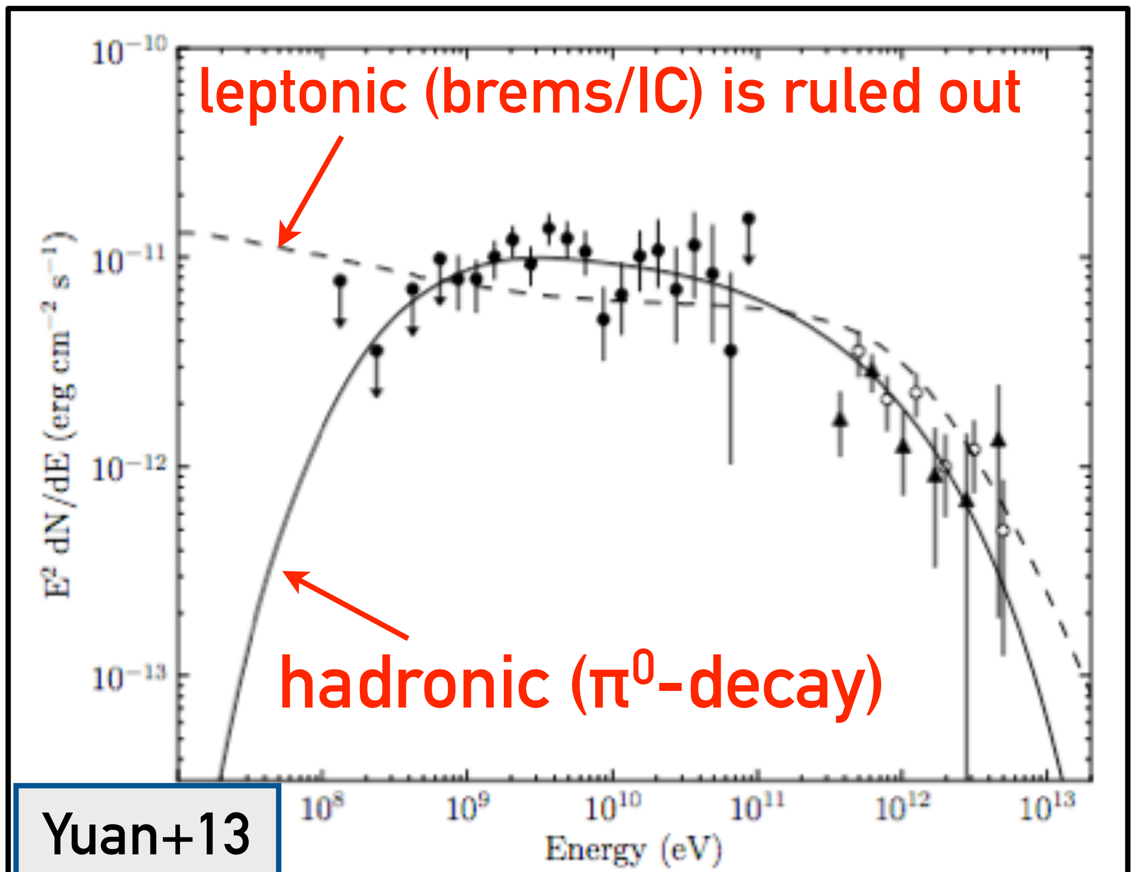


Uchiyama+2011

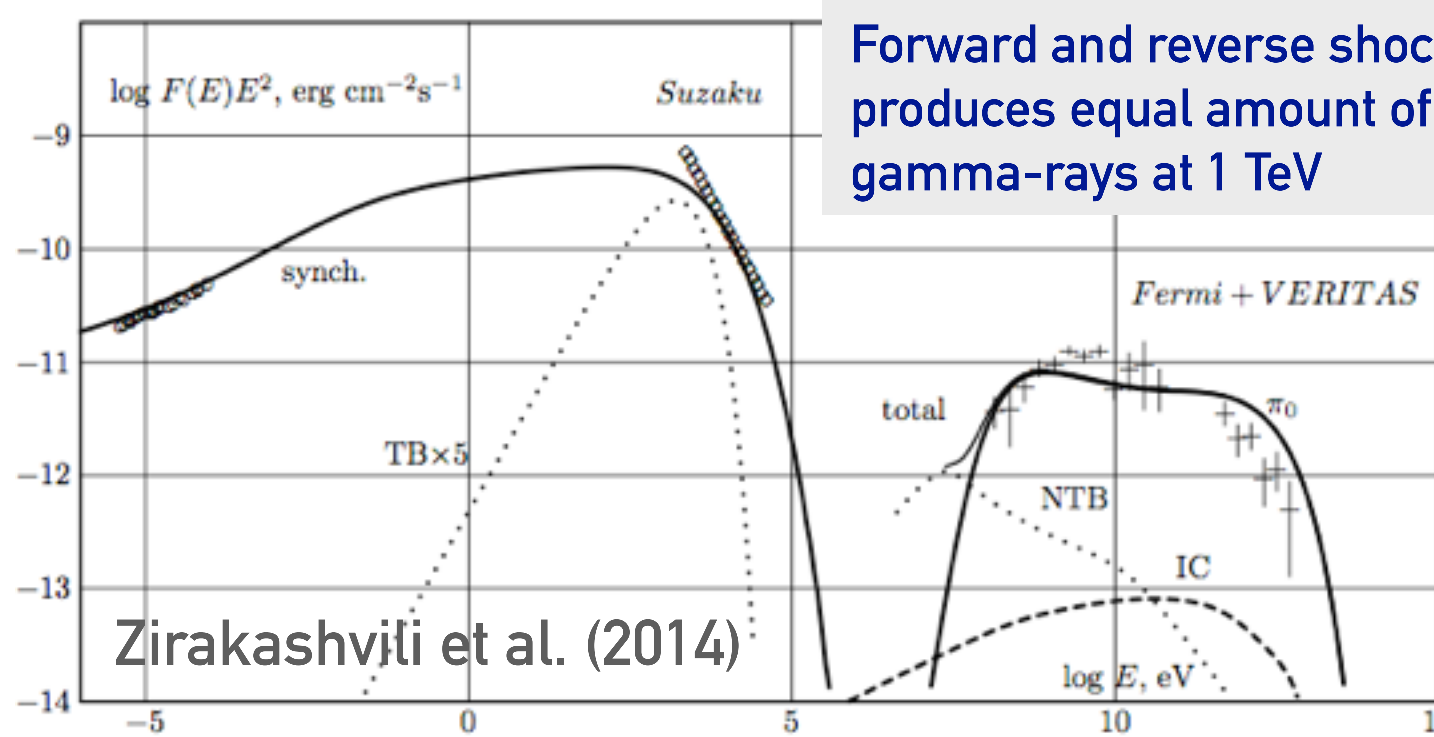
CASSIOPEIA A



- Hadronic origin is preferred
- Gamma-ray production site(s) are uncertain: forward/reverse shocks?
- $W_p = 4\times10^{49}$ erg (w/ evolution model) (2% of explosion kin energy: 2×10^{51} erg)
- $E_{p,max}$ = 10 TeV   “PeV Crisis?”
- B > 0.1 mG (consistent with X-ray)



Forward and reverse shock produces equal amount of gamma-rays at 1 TeV



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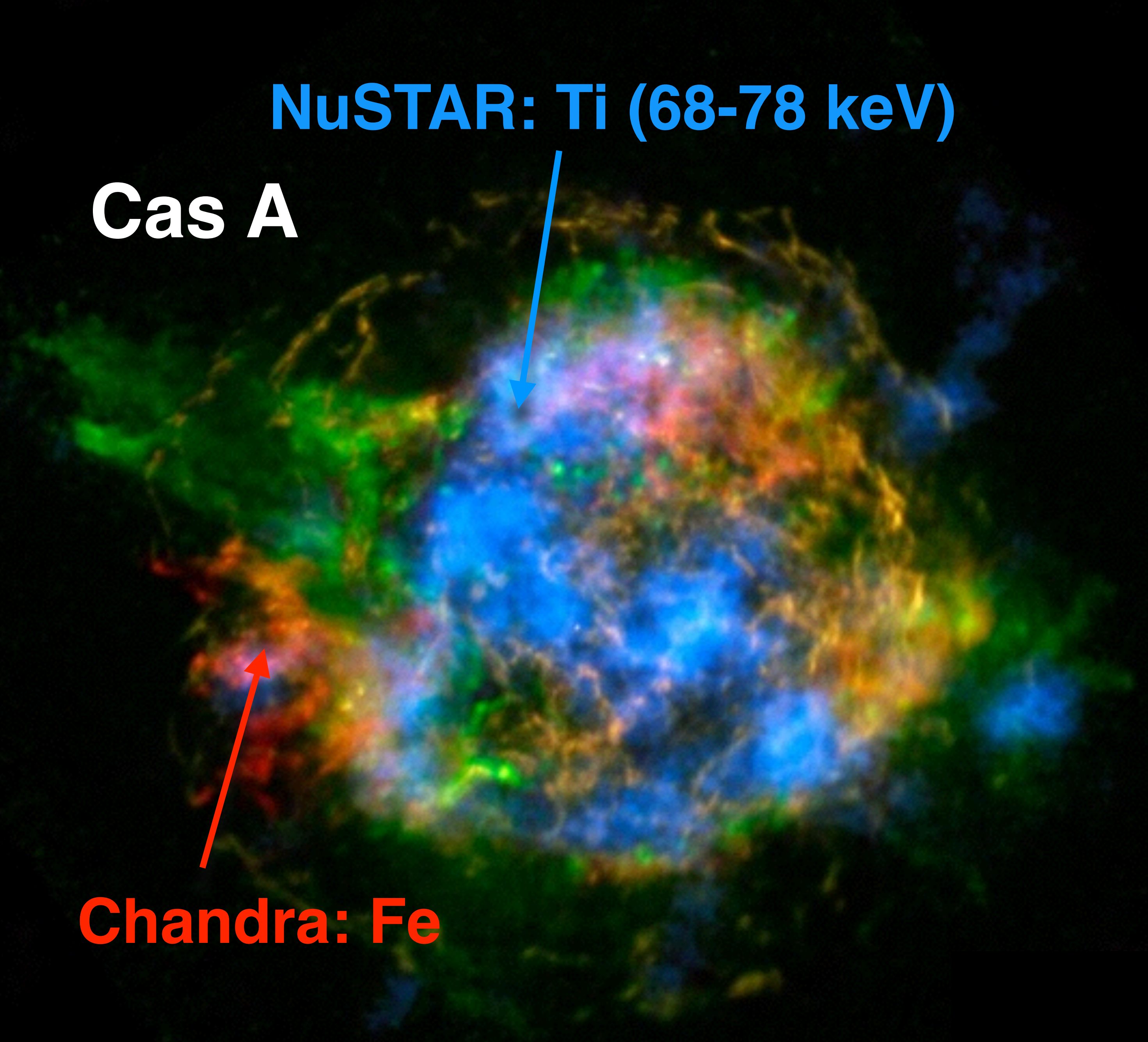
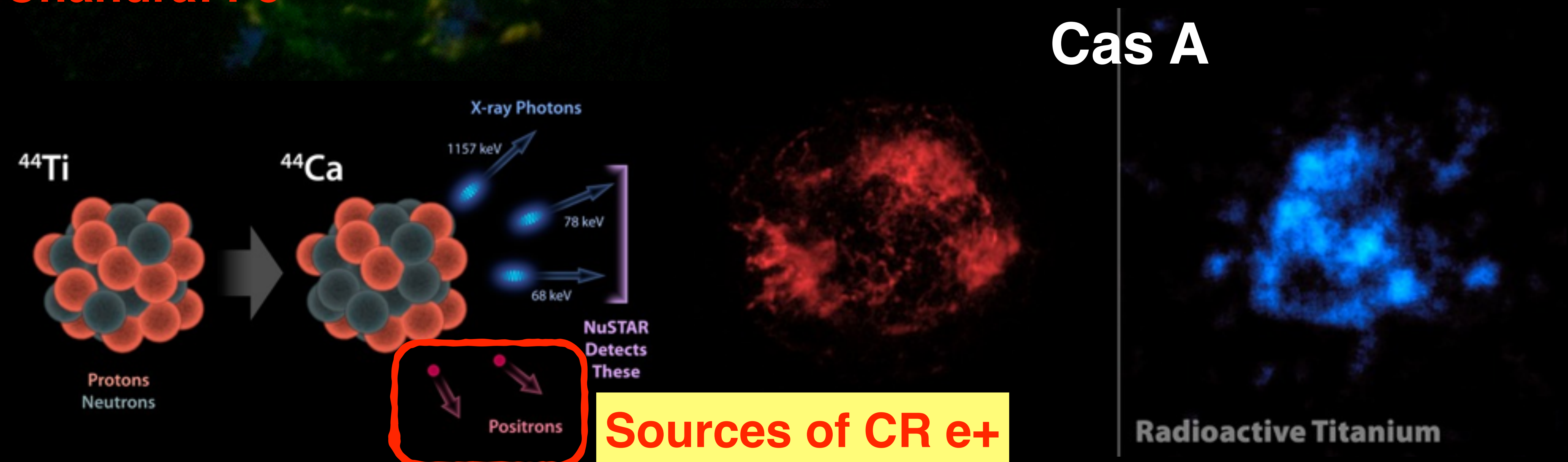
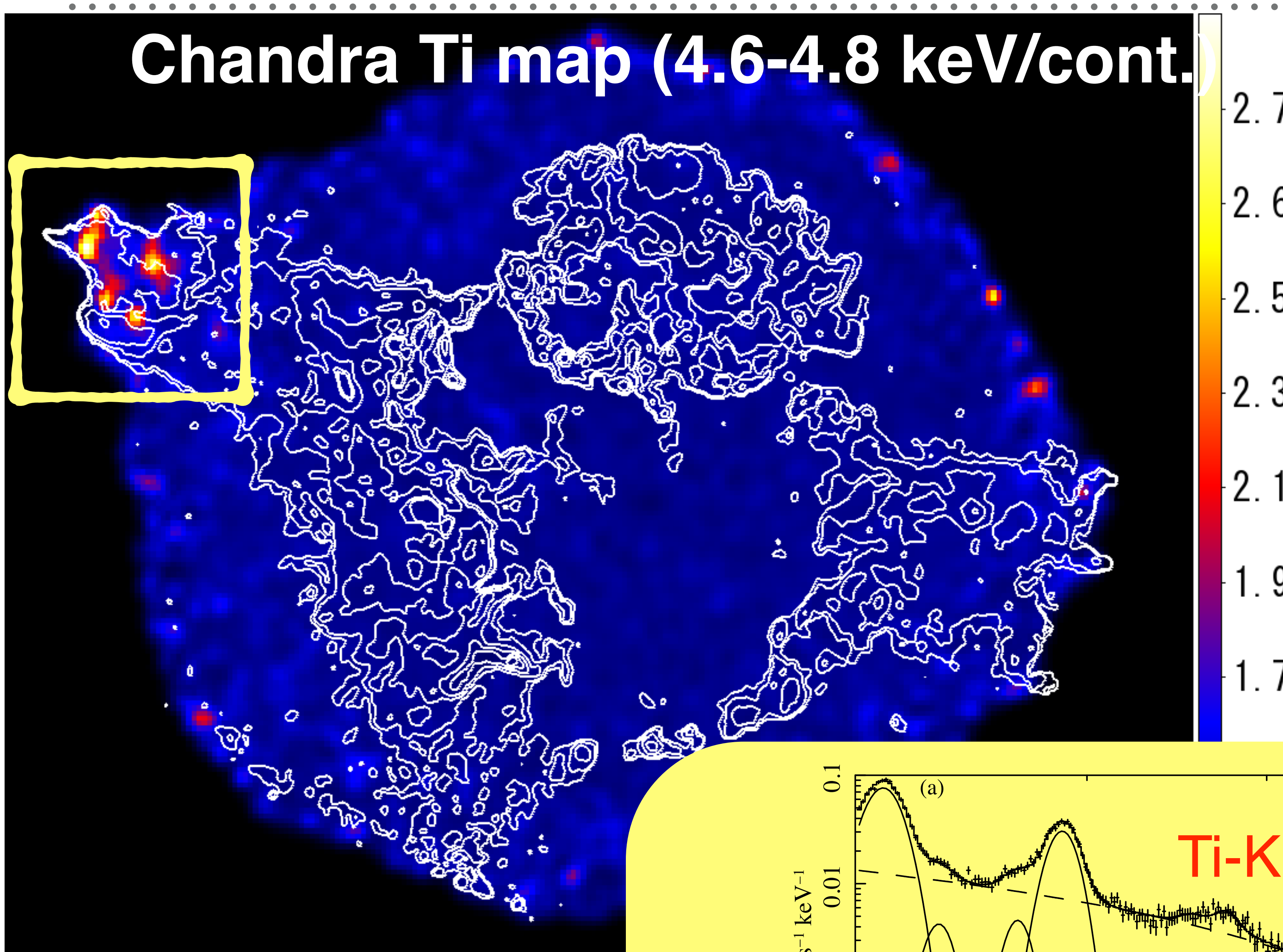


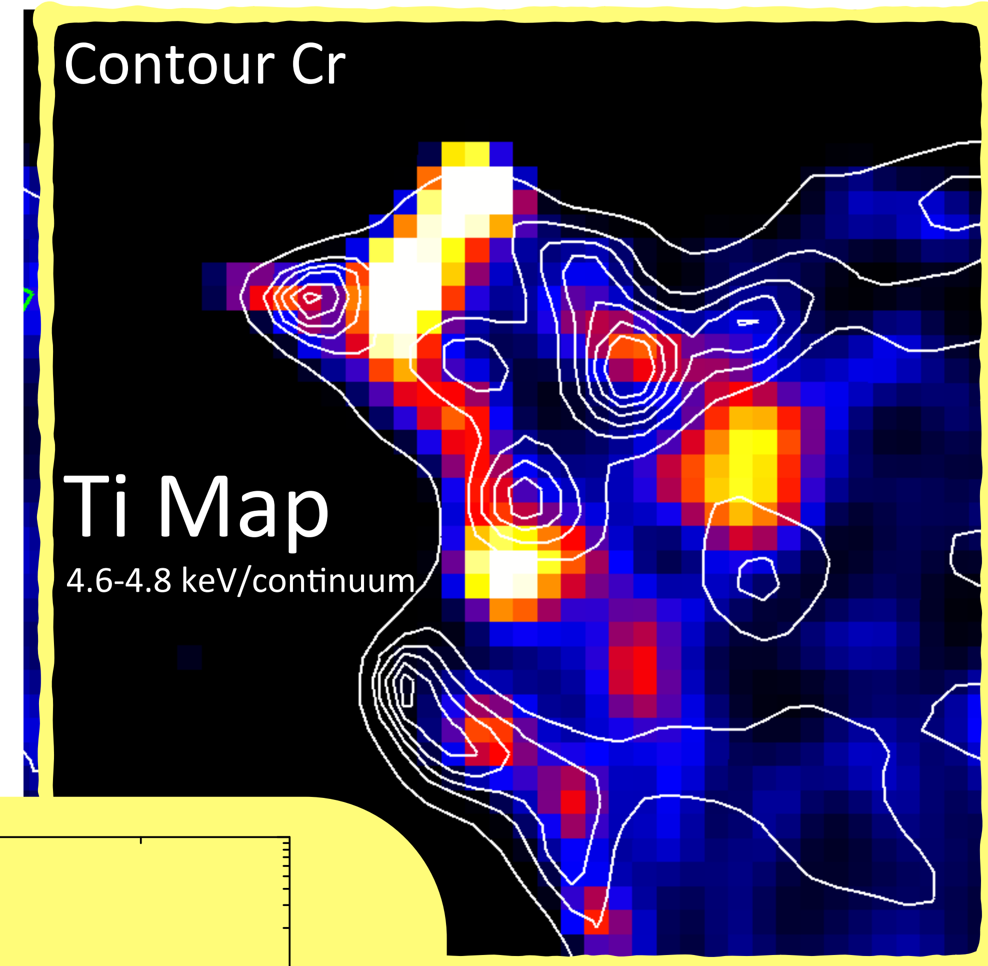


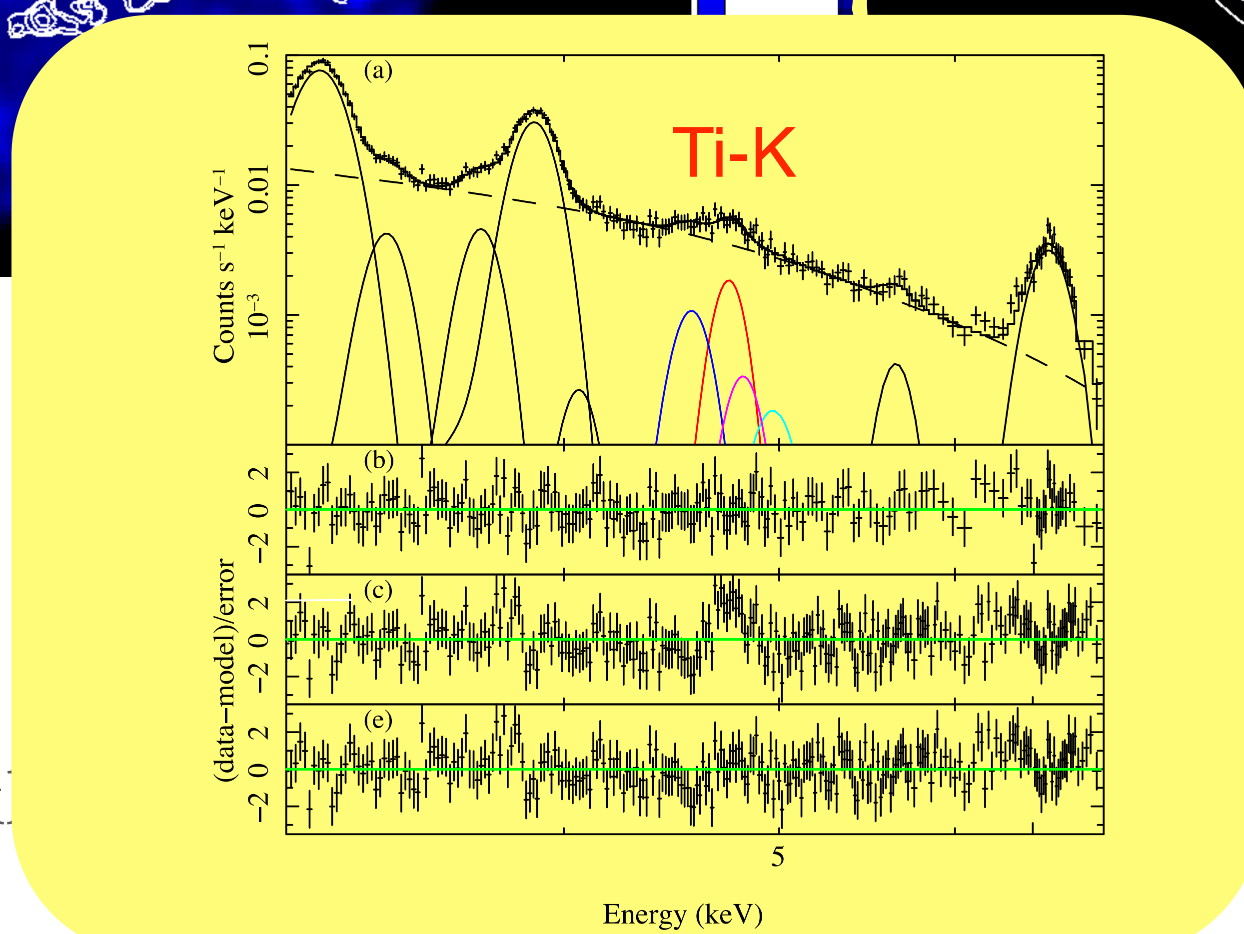
Sources of CR e+

CAS A: DISCOVERY OF TI-K

Ikeda & Uchiyama, in prep.

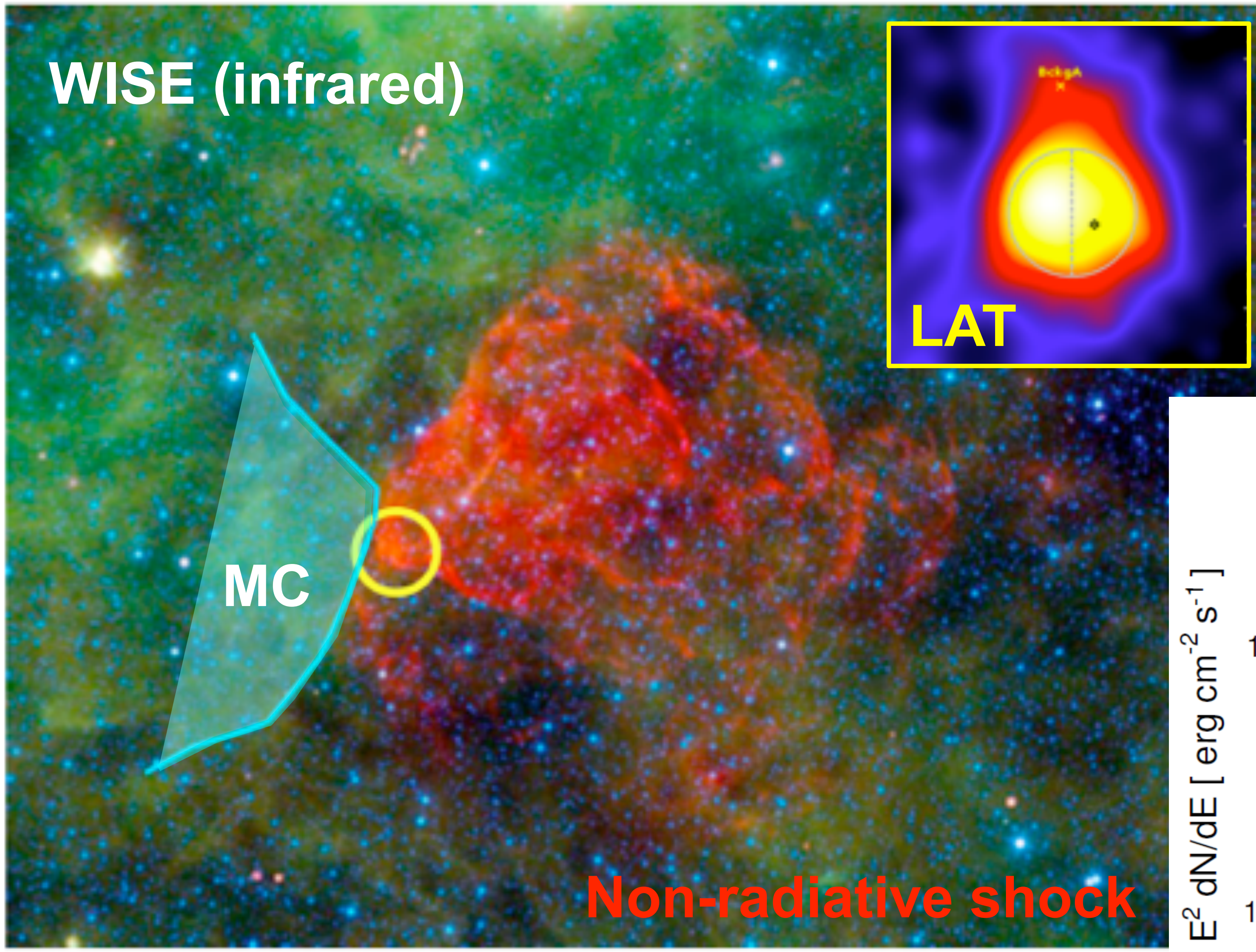






PUPPIS A

Hewitt+2012



Middle-aged SNR:

Diameter: 30 pc

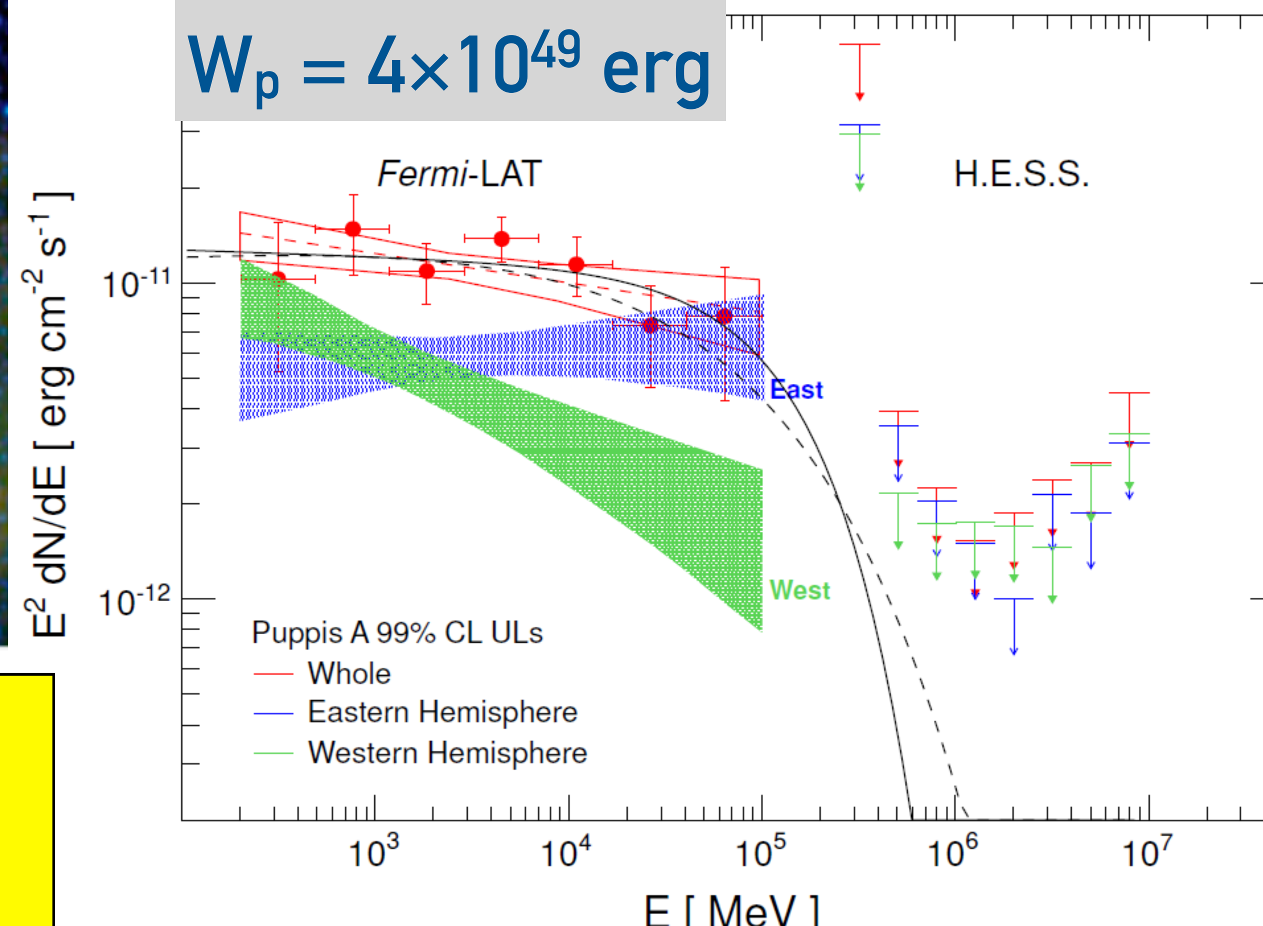
Age: ~40,000 yr (Sedov phase)

ISM Density: 1 cm^{-3}

$E_{p,max}$ ~ 1 TeV

$W_p = 4\times10^{49}$ erg

HESS Coll. 2015



The gamma-ray emission can be modeled either by bremsstrahlung with $W_e = 1\times10^{49}$ erg or hadronic (π^0-decay) with $W_p = 4\times10^{49}$ erg

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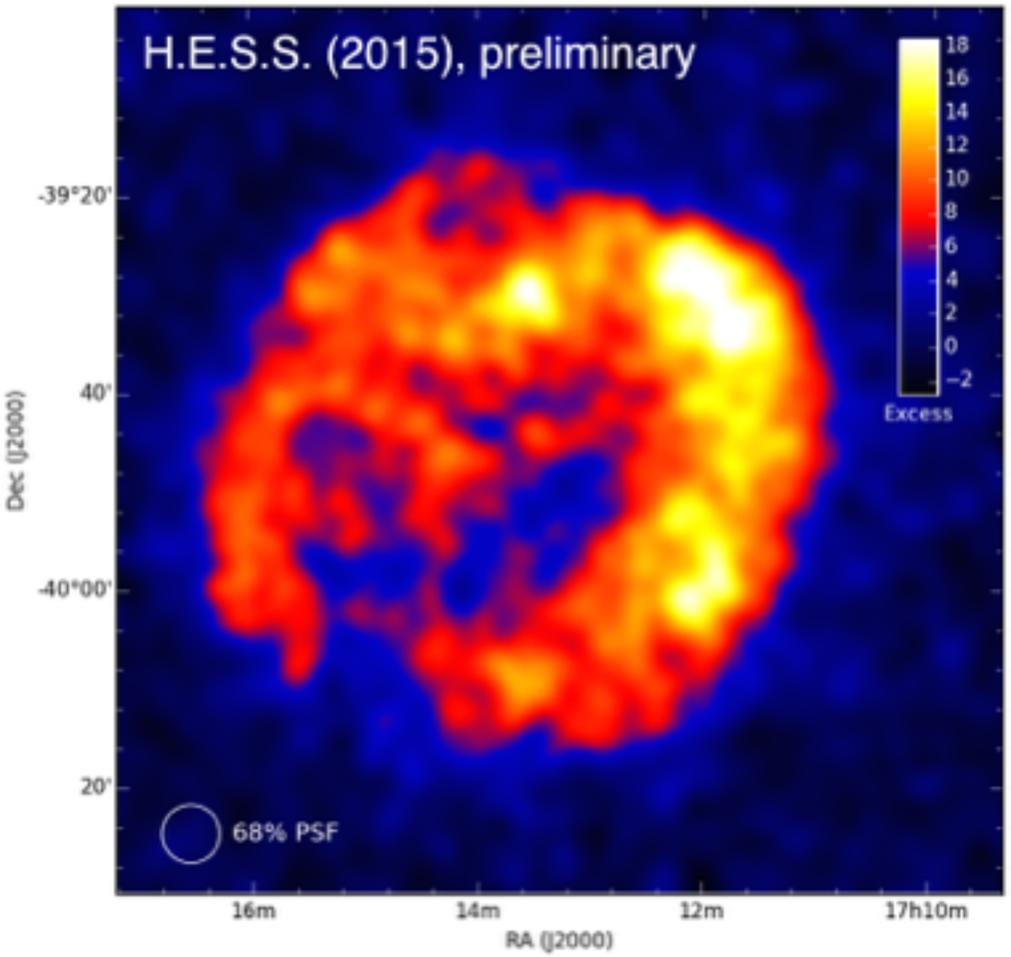
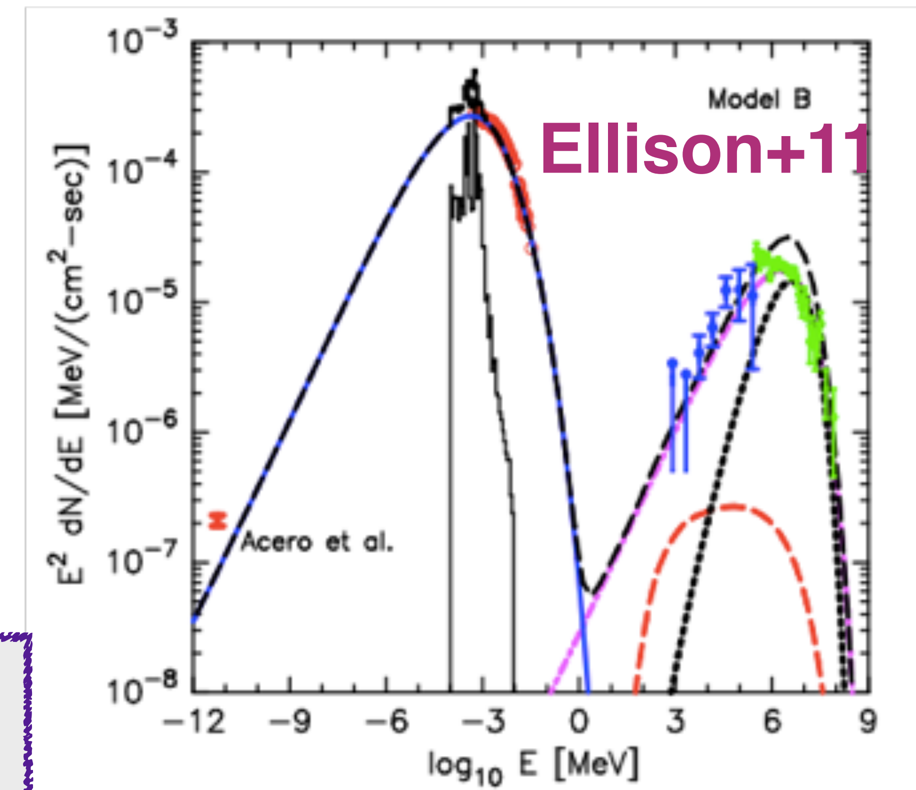
RX J1713.7–3946



Well correlated Synchrotron X-rays and TeV gamma-rays

Origin of gamma-ray emission still under active debate.

"Leptonic vs Hadronic"



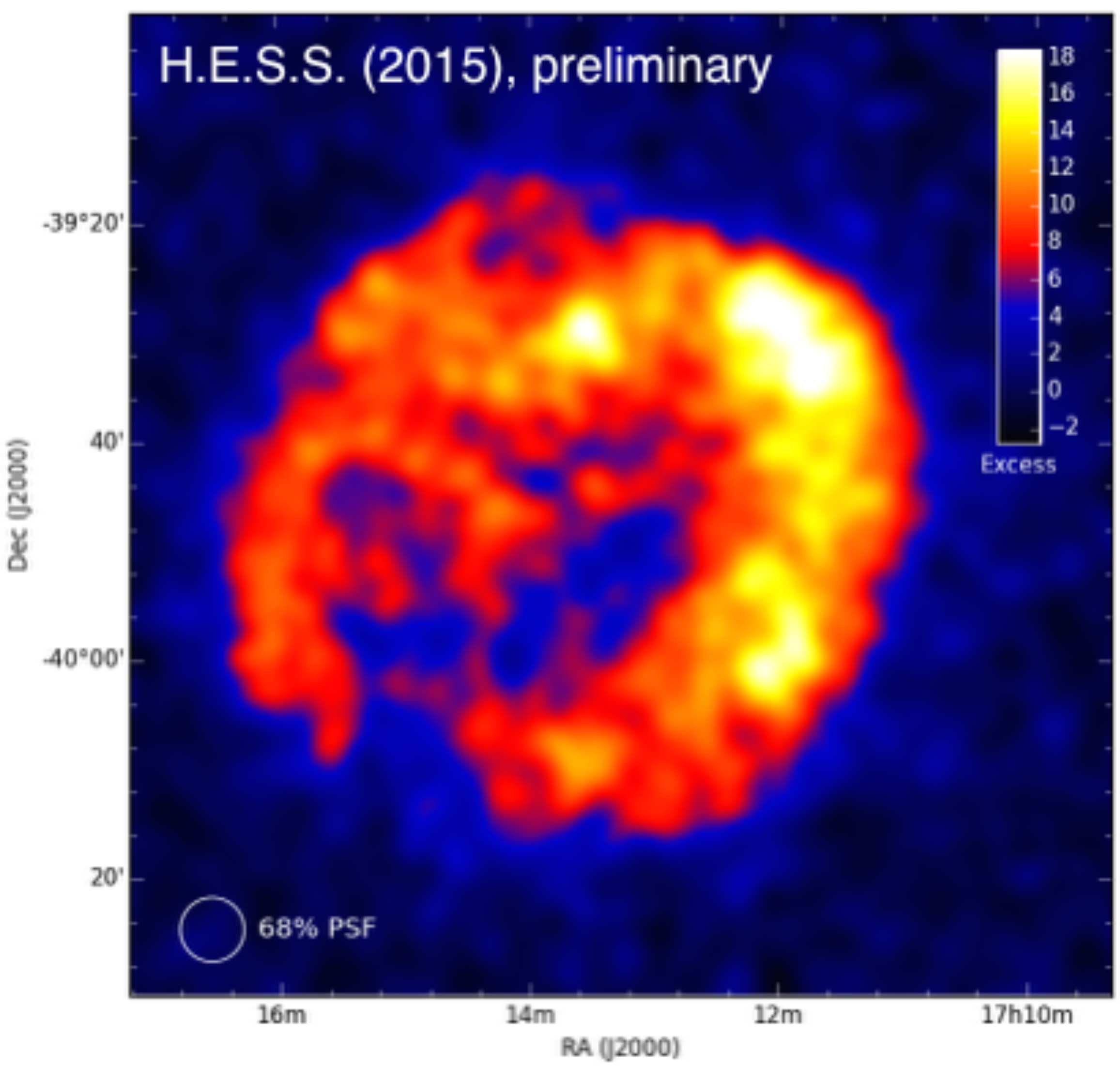
IC-dominate scenario

Suzaku X-ray Observations (Takahashi+2008; Tanaka+2008; Sano+2012)

- Suzaku XIS+HXD spectra revealed a spectral cutoff, as expected from DSA theory
- Absence of X-ray line emission from shock-heated plasma
  - Strong constraint on the origin of GeV-TeV emission

OUR RECENT X-RAY STUDY

Yasunobu Uchiyama, Naomi Tsuji (Rikkyo U),
Satoru Katsuda (ISAS), Felix Aharonian (MPI-K/DIAS), David Berge (Amsterdam)



New H.E.S.S. image of RXJ1713.7-3946

(1) H.E.S.S. - Fermi - **Suzaku**
Ongoing

(2) **Chandra**
Tsuji and Uchiyama, submitted

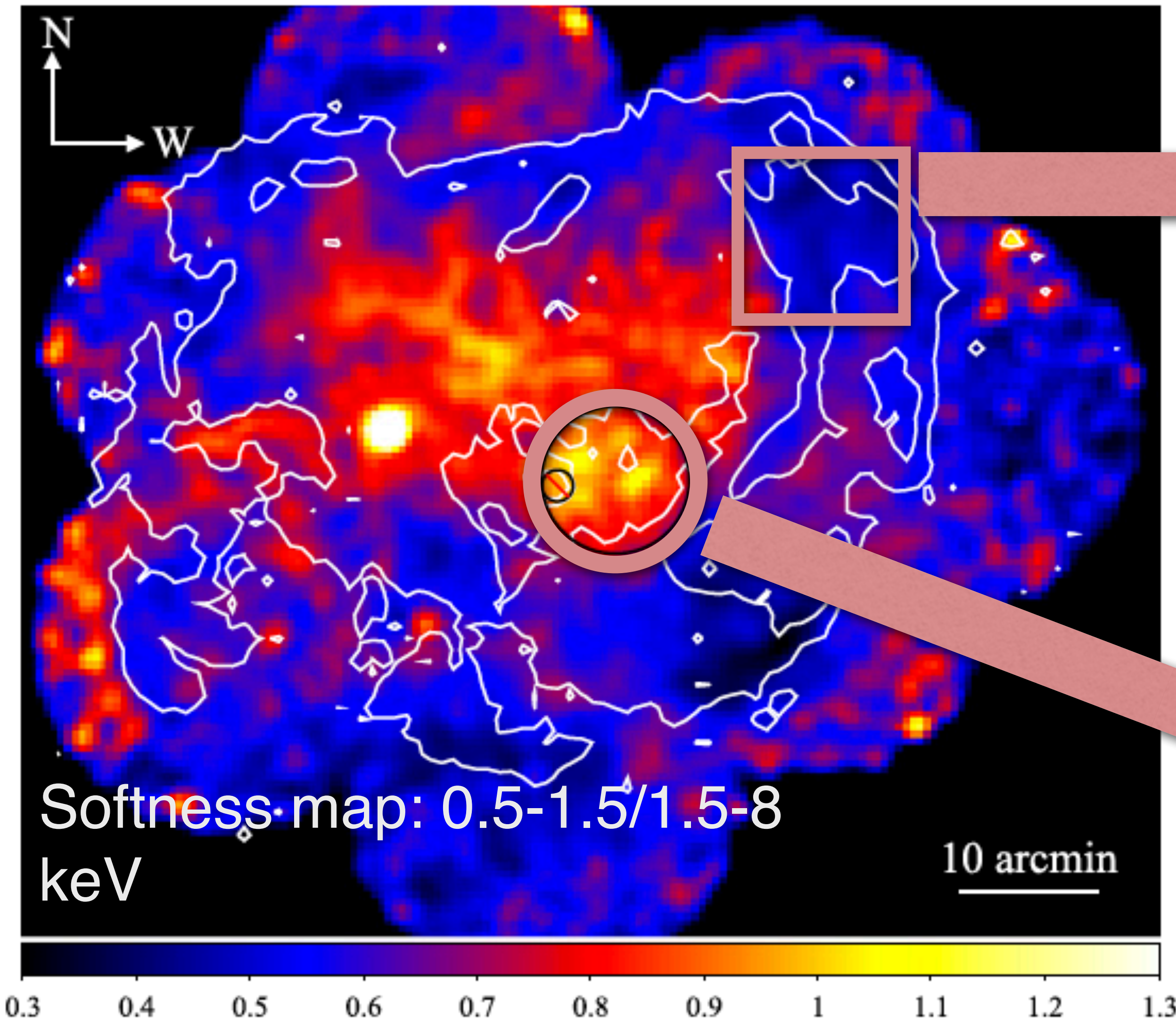
(3) **XMM**
Discovery of thermal X-rays
(S. Katsuda et al. 2015)

(4) **NuSTAR**
We have an AO1 program (NW rim).

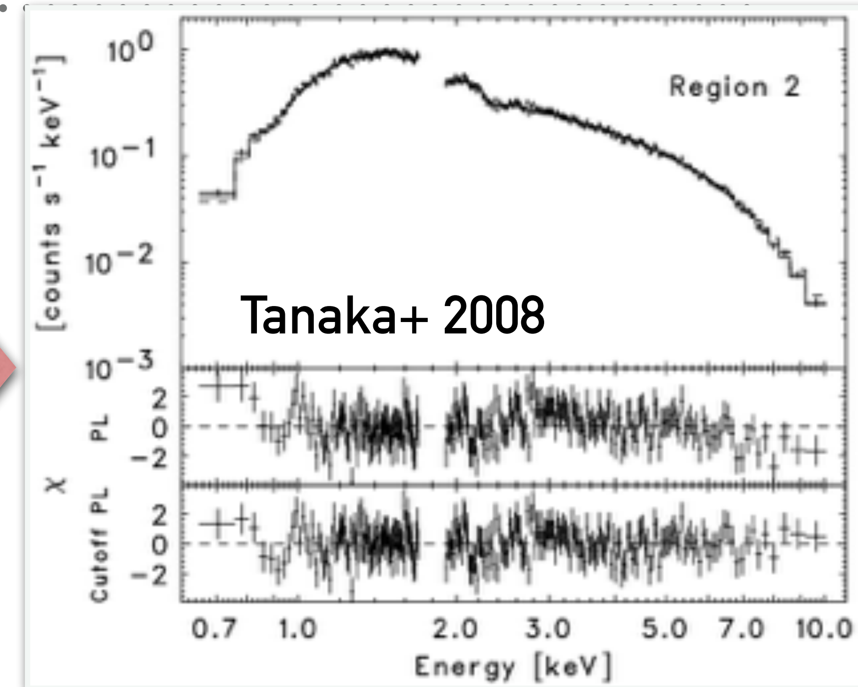
DISCOVERY OF THERMAL X-RAY EMISSION

Katsuda+ 2015

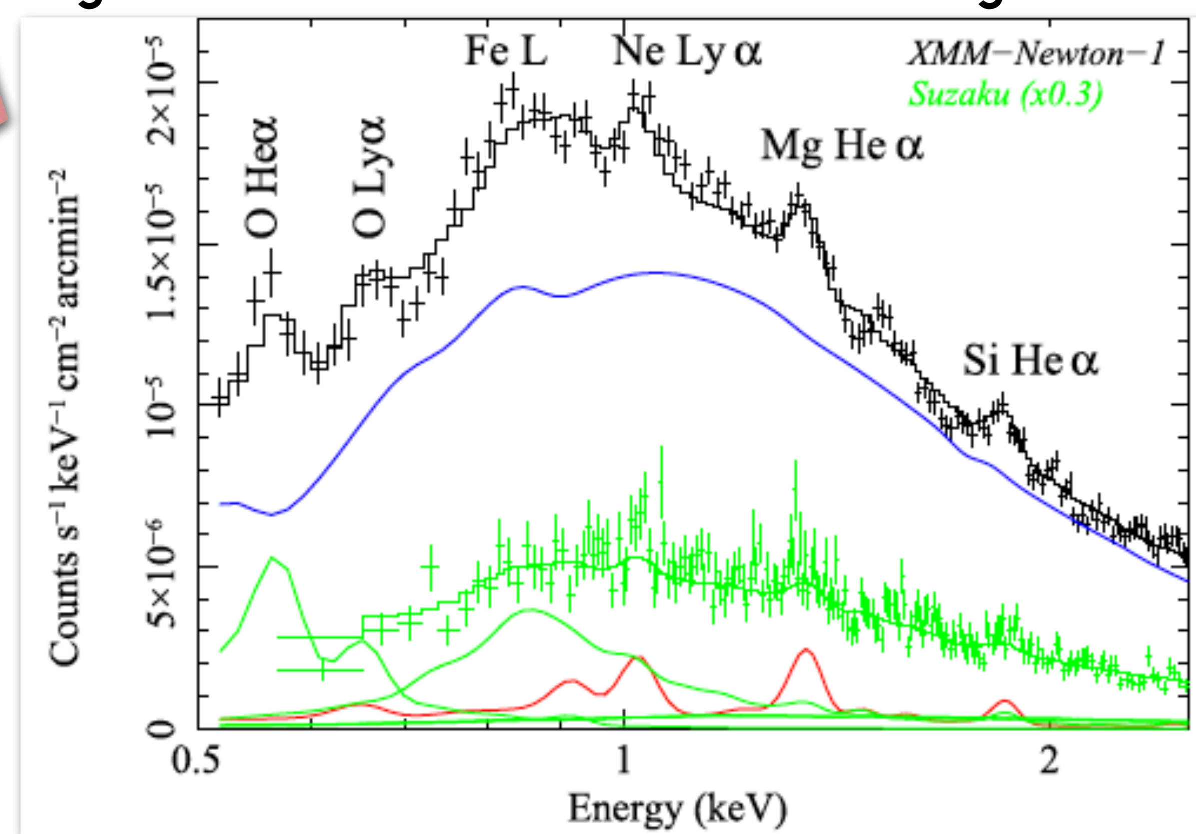
First detection of thermal X-ray emission with XMM-Newton (Katsuda et al., 2015)



Absence of X-ray line emission



Significant line emission in central region



- The thermal emission is likely from the ejecta
- Mg/Ne and Si/Ne
  → the progenitor mass of < 20 M_{Sol}
- Total amount of shocked ejecta mass is about 0.63–0.8 M_{Sol}

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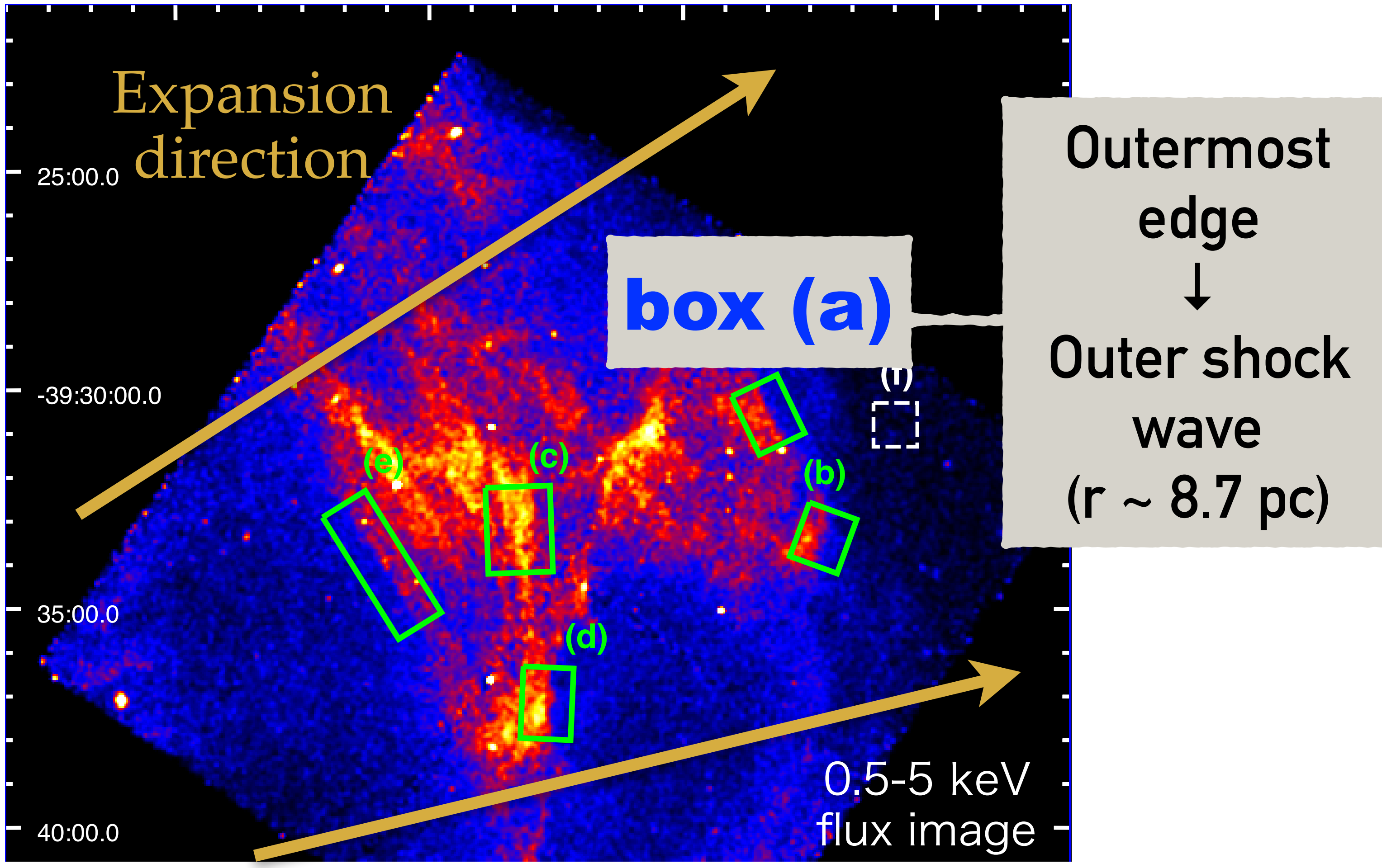
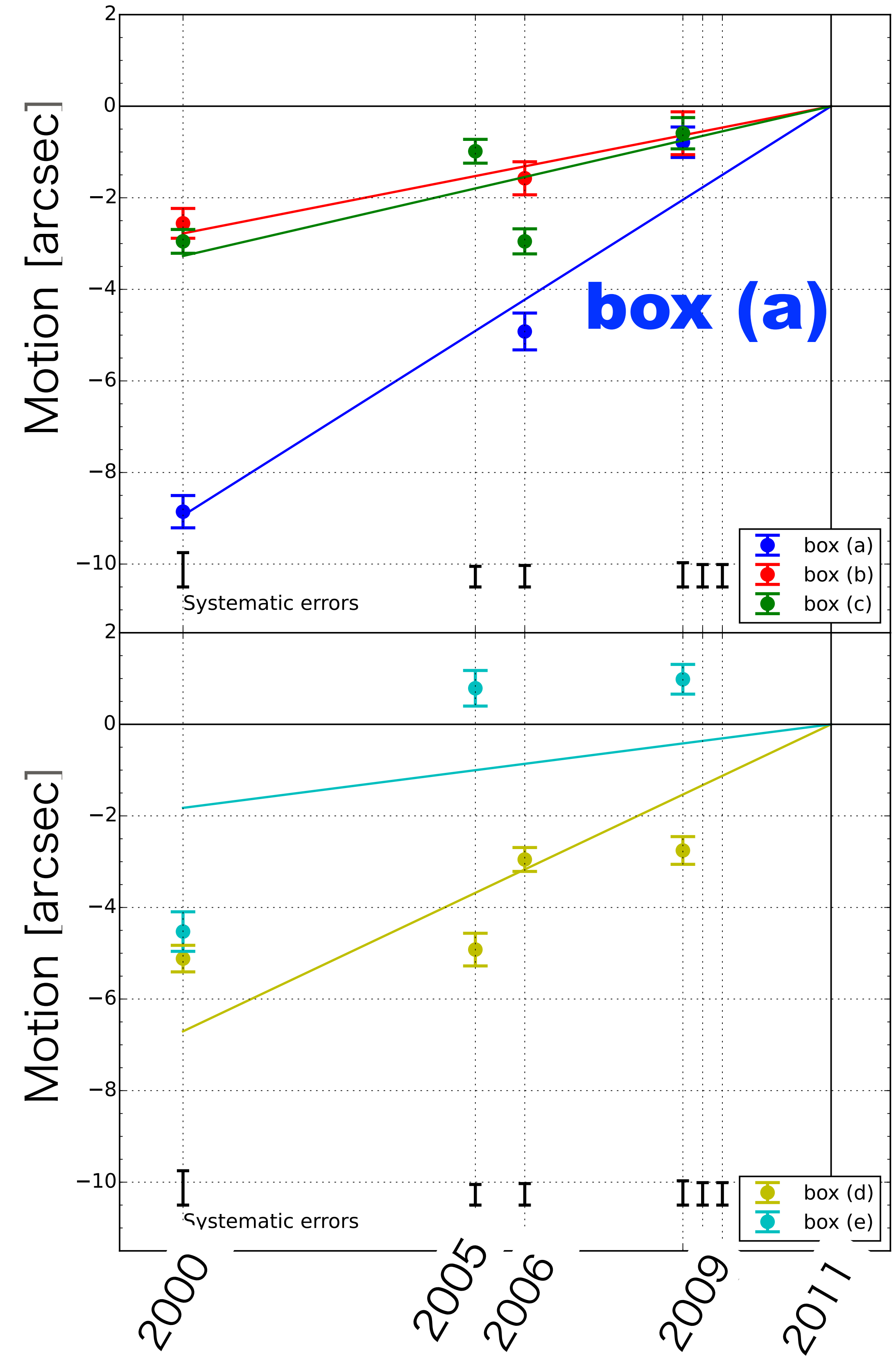
SHOCK SPEED MEASUREMENT WITH CHANDRA

Tsuji & Uchiyama submitted





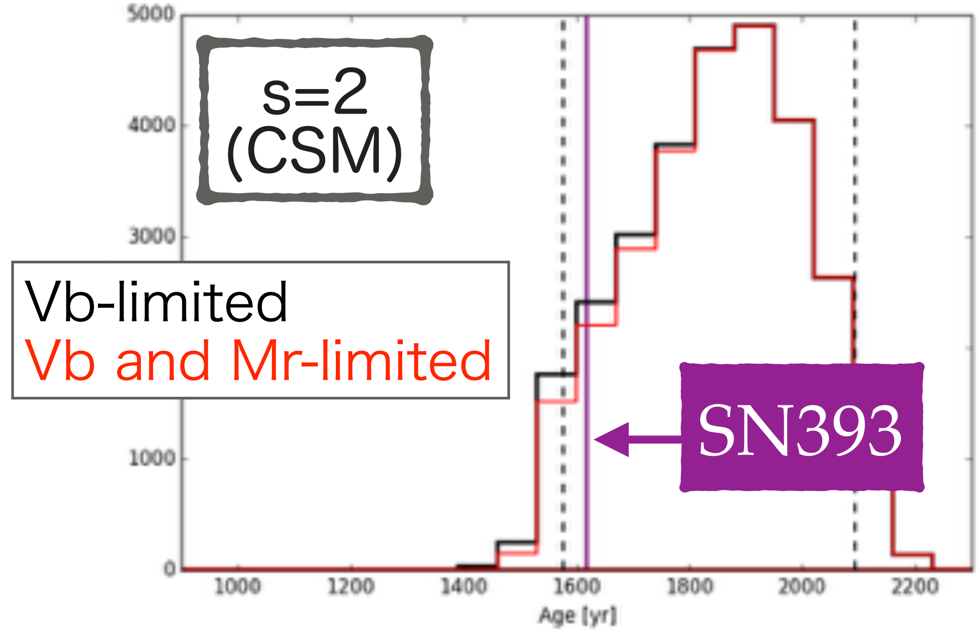
box ID	Angular velocity [″/yr]	Velocity [km/
box (a)	0.82 ± 0.06	**3900 ± 300**
box (b)	0.25 ± 0.06	1200 ± 300
box (c)	0.3 ± 0.05	1400 ± 200
box (d)	0.61 ± 0.05	2900 ± 200
box (e)	0.17 ± 0.06	800 ± 300

EVOLUTION MODEL

Tsuji & Uchiyama submitted

Model parameters:

s = 2 (stellar wind)
n = 7
T_{age} = 1618 yr ← SN393
R_b = 8.68 pc ← radius at box (a)
V_b = 3900 km/s ← velocity: box (a)



Too low shocked ejecta mass

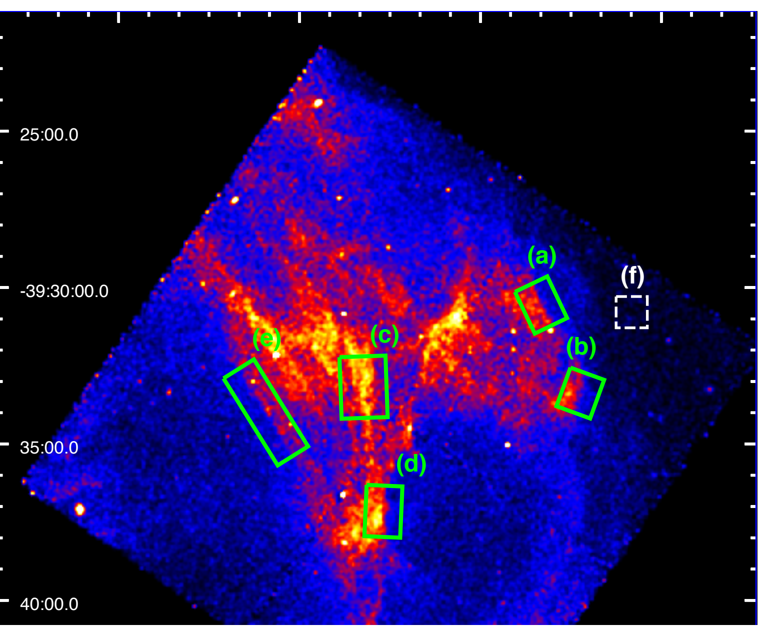
Too early phase

Model	s	n	age [yr]	R_b [pc]	v_b [km/s]	R_r [pc]	$v_{r,\mathrm{obs}}$ [km/s]	n_s [cm^{-3}]	M_{ej} [$M_\odot$]	E_{ej} [10^{51} erg]	t_{ST} [yr]	($t_{M_r=M_{\mathrm{ej}}}$) [yr]	M_b [$M_\odot$]	M_r [$M_\odot$]
1	2	7	1618	8.67	4193	5.13	1806	0.01	1.0	0.5	3364	437	2.85	0.94
2	2	7	1618	8.75	3947	3.38	374	0.015	0.6	0.5	1042	135	4.27	0.59
3	2	7	1618	8.67	4193	6.25	2863	0.01	4.0	1.0	19030	2477	2.85	2.71
4	2	7	1618	8.65	4182	5.78	2377	0.015	2.7	1.0	7035	916	4.27	2.32
5	2	7	1618	8.67	4193	5.13	1806	0.02	2.0	1.0	3364	437	5.7	1.87
7	2	7	1618	8.57	4142	6.27	2968	0.017	10.0	2.0	31290	4073	4.84	5.48
8	2	7	1618	8.67	4193	6.25	2863	0.02	8.0	2.0	19030	2477	5.7	5.43

1. Ambient density ~ 0.01–0.02 cm^{-3}, M_{ej} ~ 1–3 M_{Sol}, E_{ej} ~ 1×10^{51} erg
2. Likely consistent with SN393
3. Not yet in full ST stage → Energy of CRs may not have reached its maximum

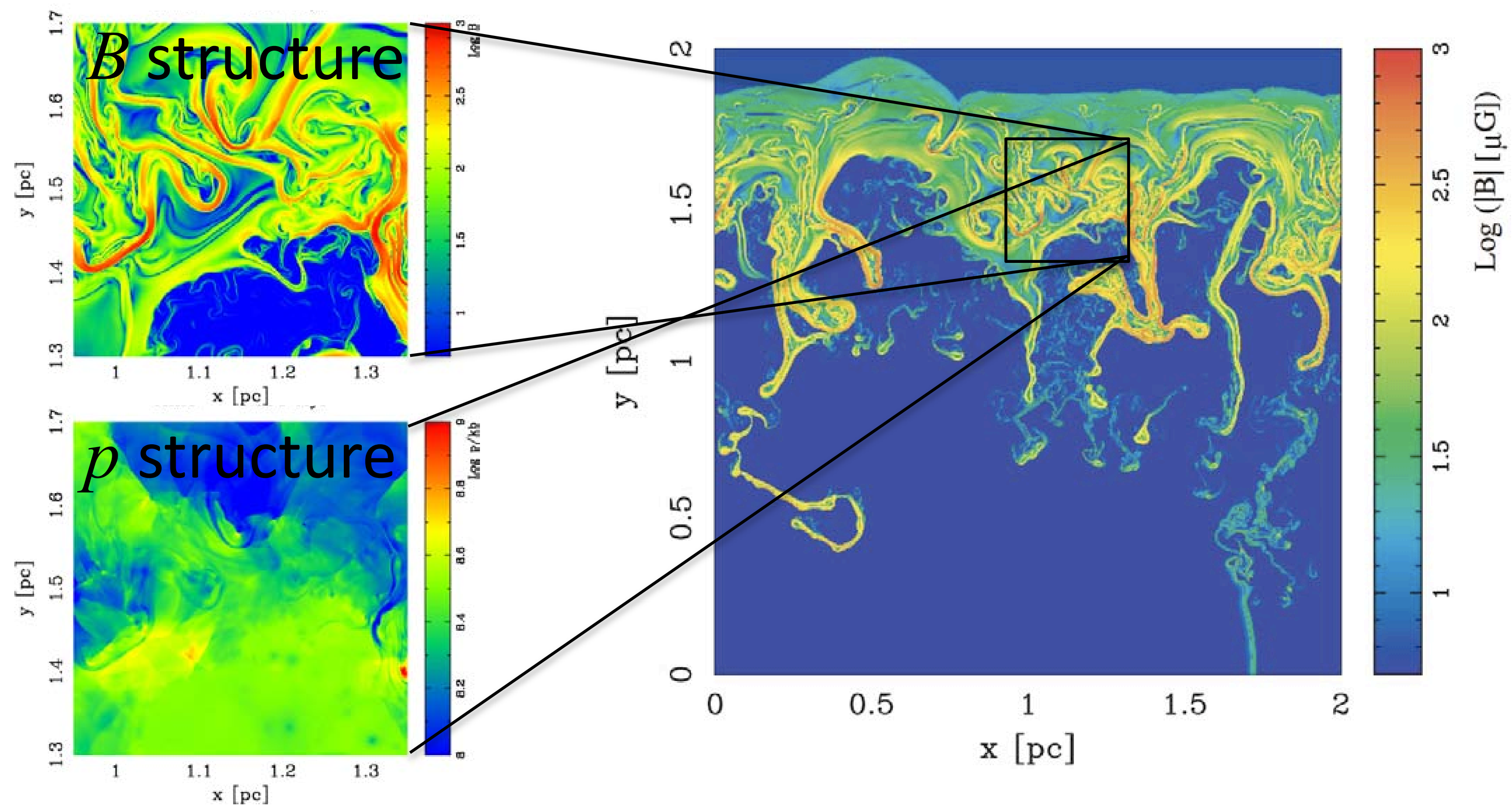
SECONDARY SHOCKS?

box ID	Velocity [km/s]
box (a)	**3900 ± 300**
box (b)	1200 ± 300
box (c)	1400 ± 200
box (d)	2900 ± 200
box (e)	800 ± 300



Shock interaction with cloud clumps

—--> many secondary shock waves are formed in SNR shell, due to the turbulent flow ($\langle \delta v \rangle = 0.8\ C_s$ in SNR shell ~ v_{shock}).



Inoue+2012

Secondary shocks formed in the shell may enhance particle acceleration.

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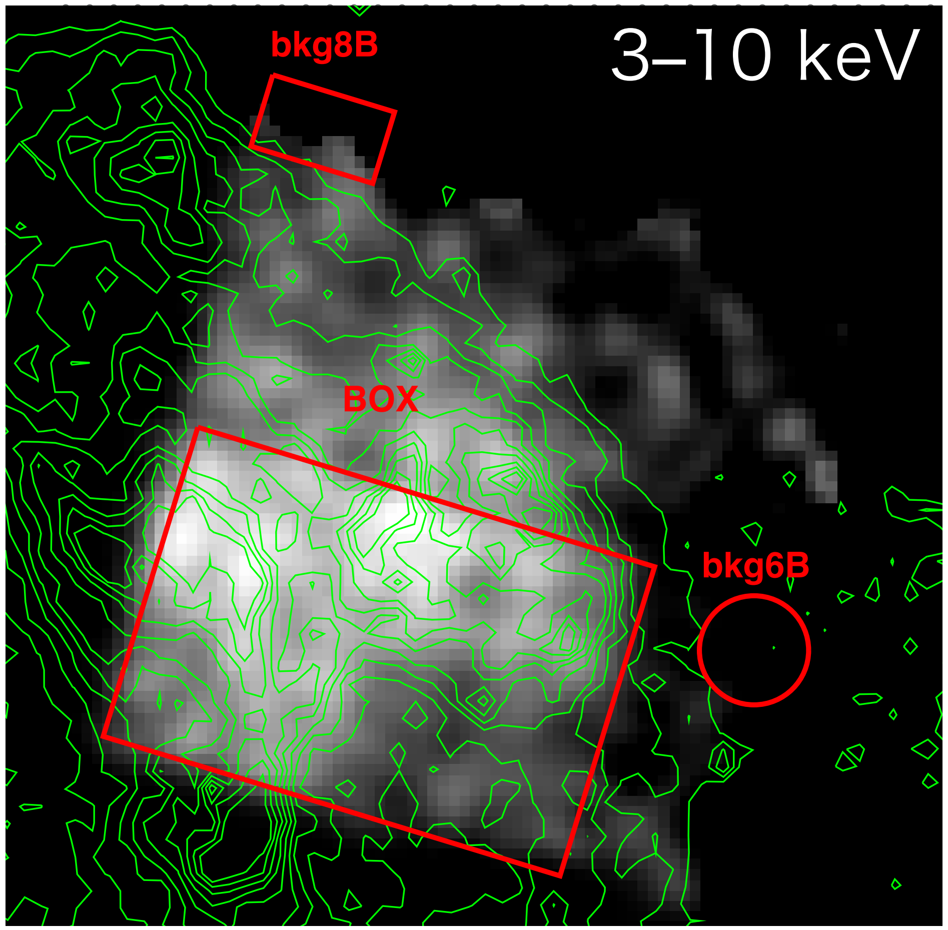
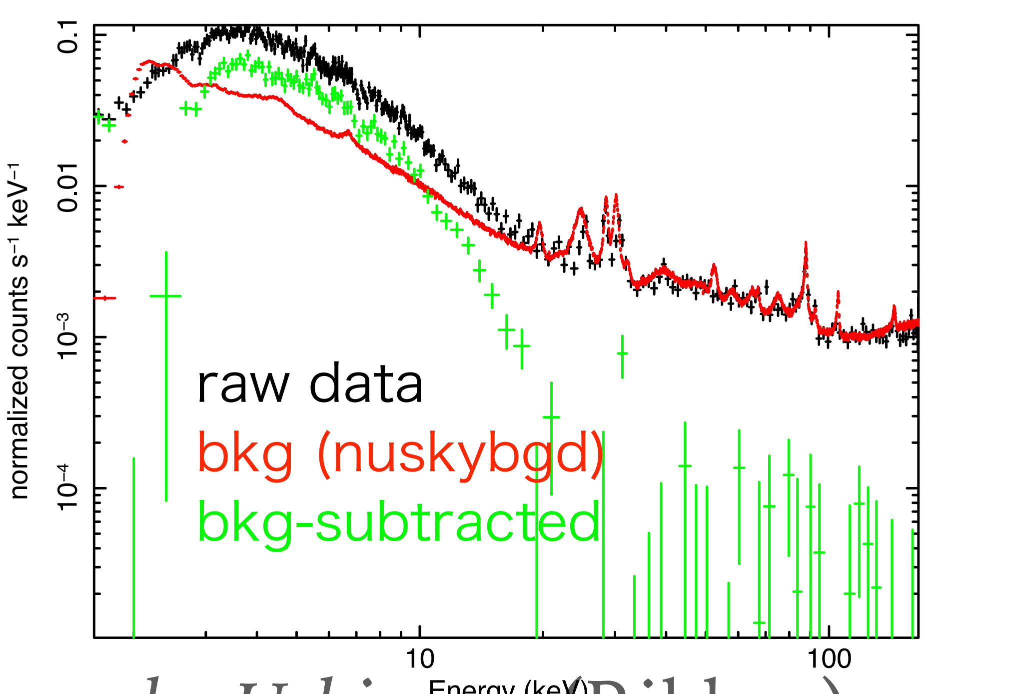
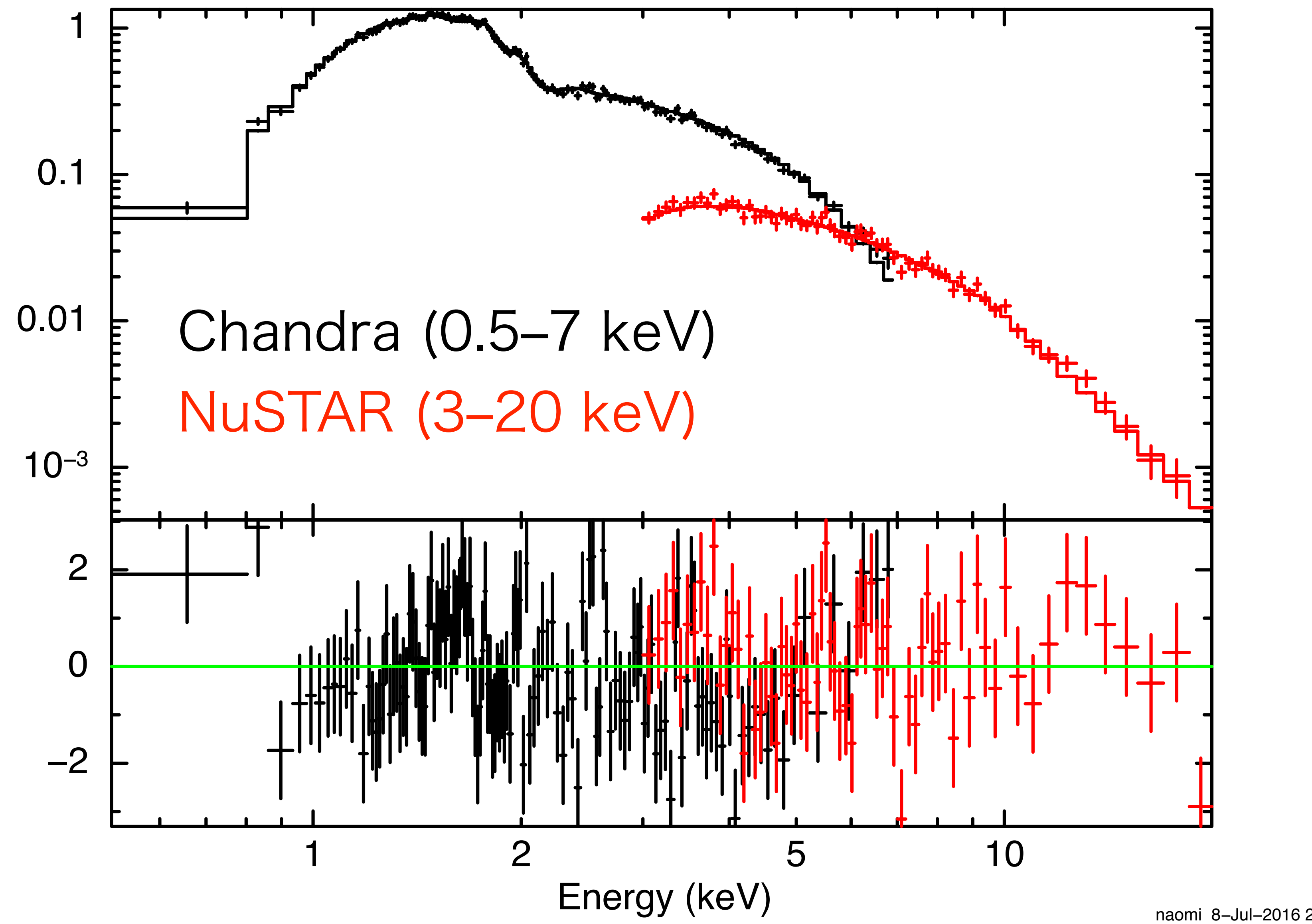
NUSTAR

Tsuji, Uchiyama+ in prep.





Joint fitting Chandra and NuSTAR



Model: absorbed cutoff PL

$N_H = 0.756 \pm 0.023$
Index = 1.92 ± 0.06
$\varepsilon_c = 9.13 \pm 1.36$ keV

→ **Good agreement with Suzaku (Tanaka+ 2008)**

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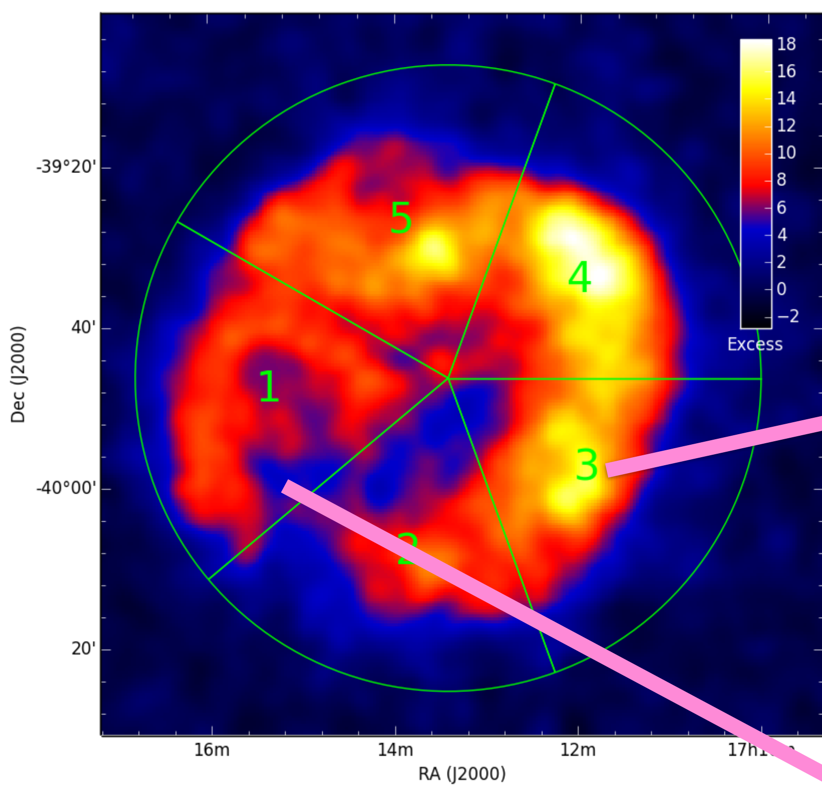
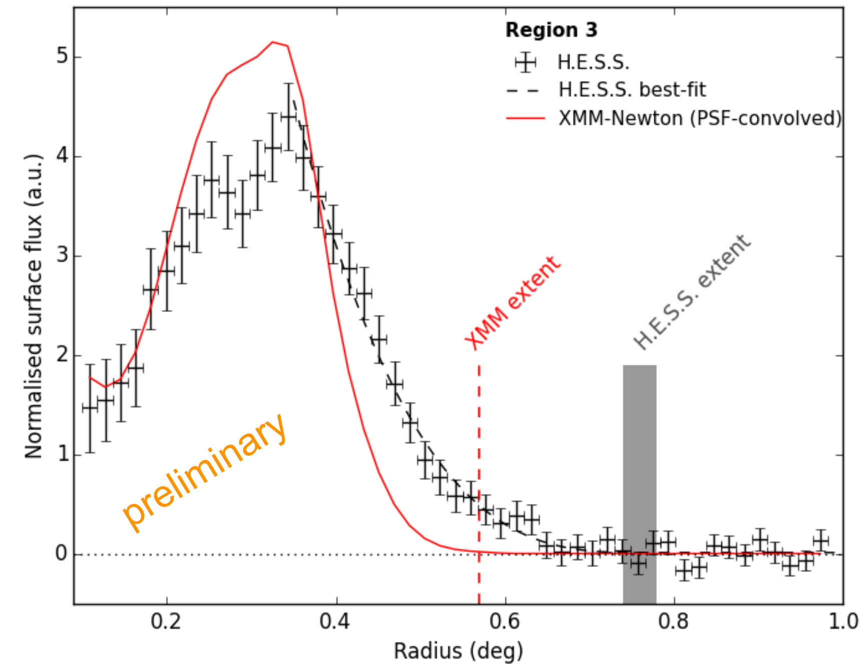
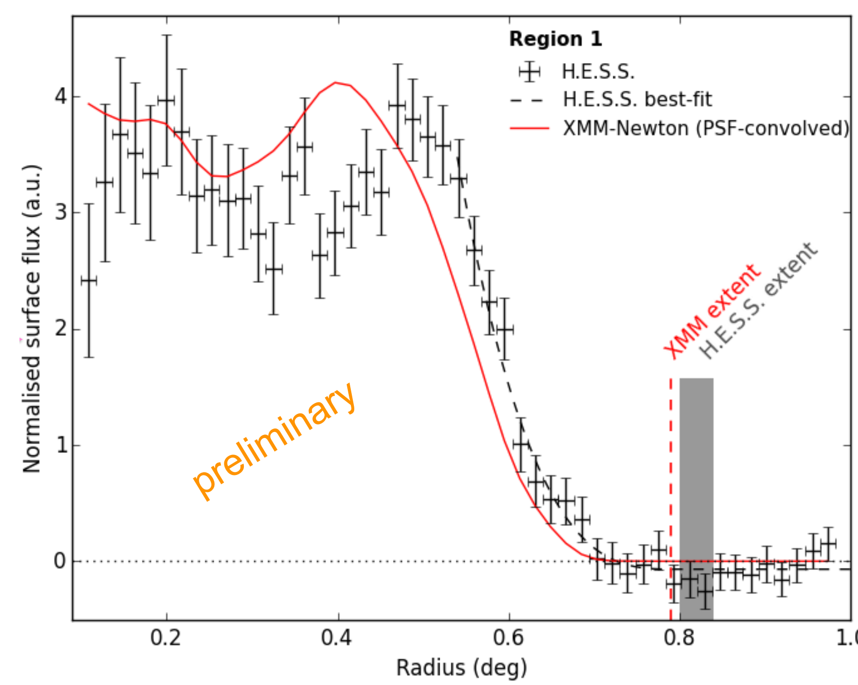
TEV EMISSION BEYOND X-RAY SHELL

X-ray vs TeV radial profiles

H.E.S.S. Collaboration (2015, in prep.)

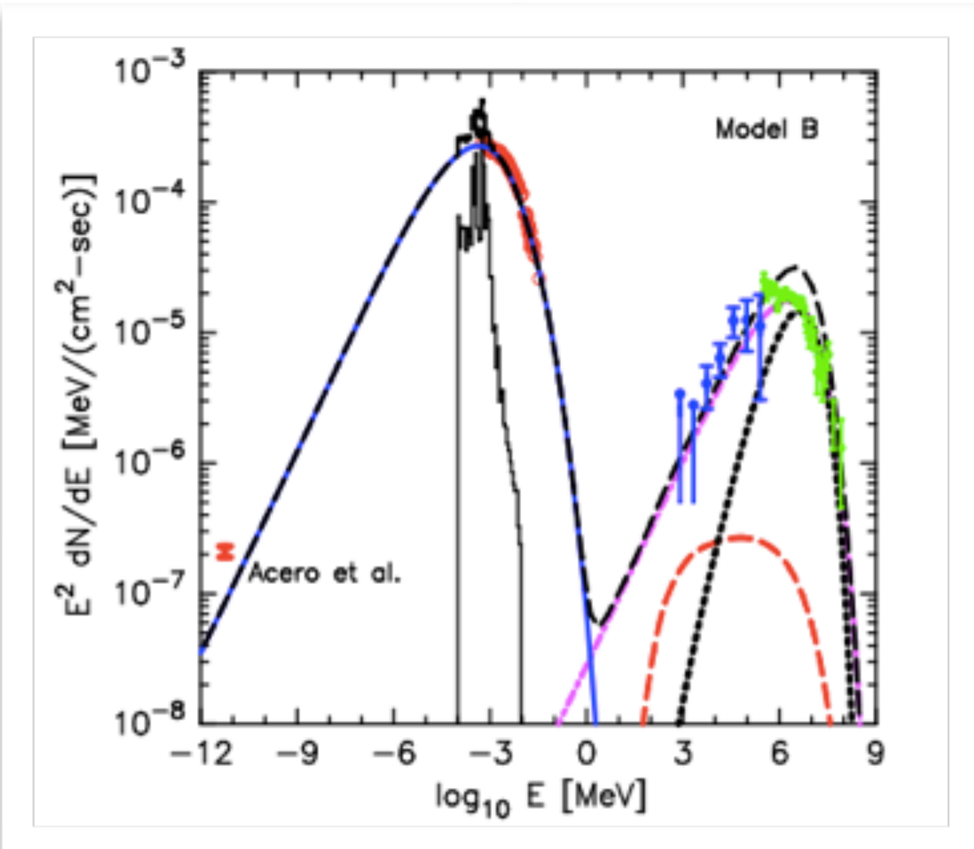






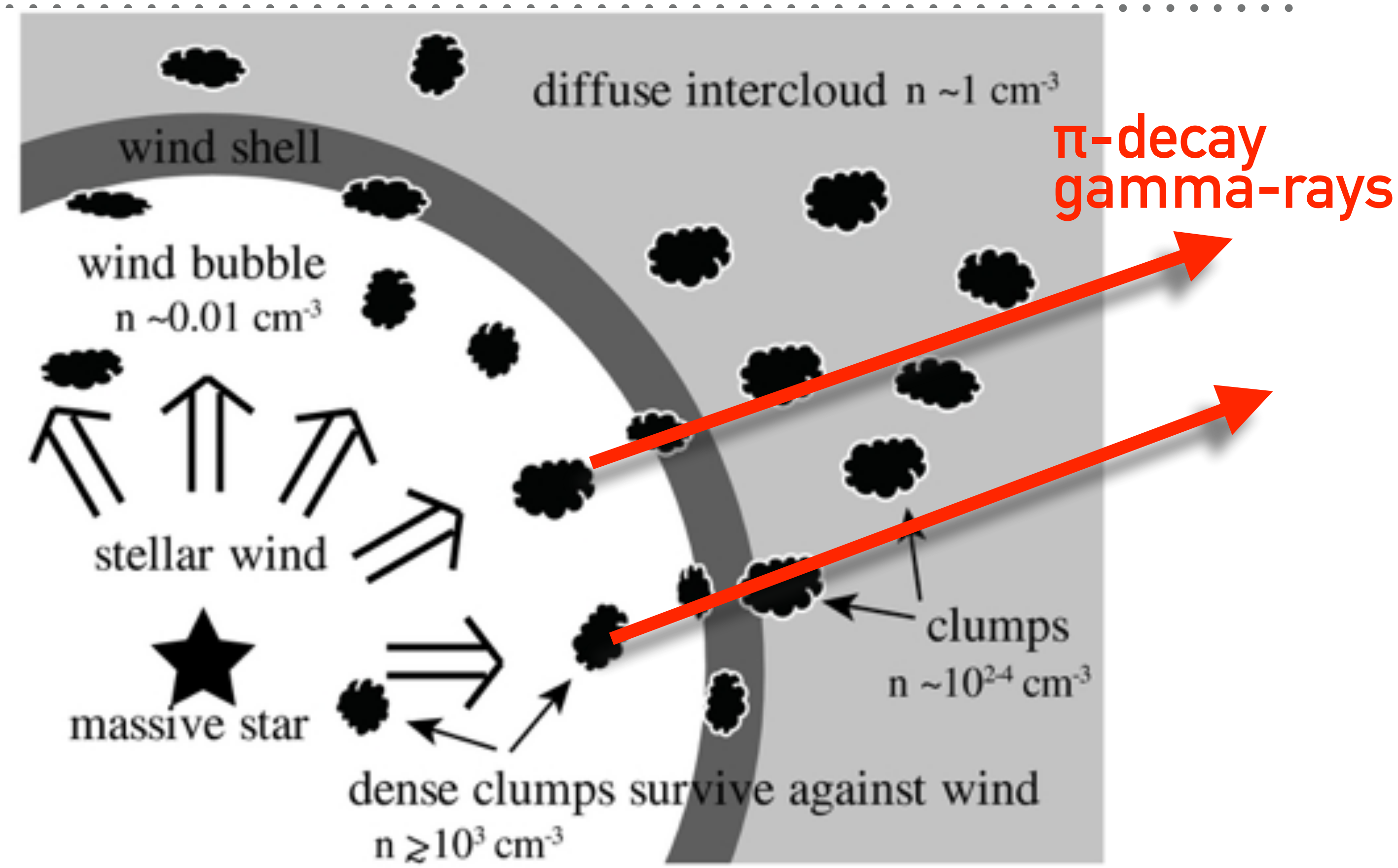
- TeV profiles beyond X-rays in some regions:
  => particle escape in interaction with denser regions of the surrounding medium?

GAMMA-RAY ORIGIN?



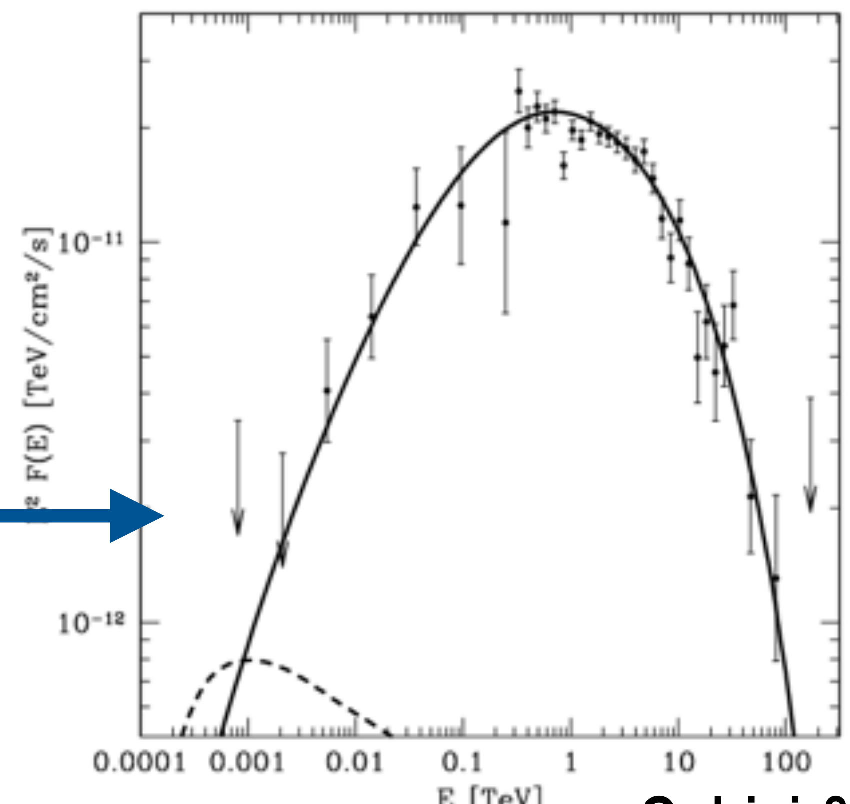
IC-dominate scenario

Ellison+2011



Inoue+2012

π-decay gamma-rays:
energy-dependent penetration
of protons into clumps

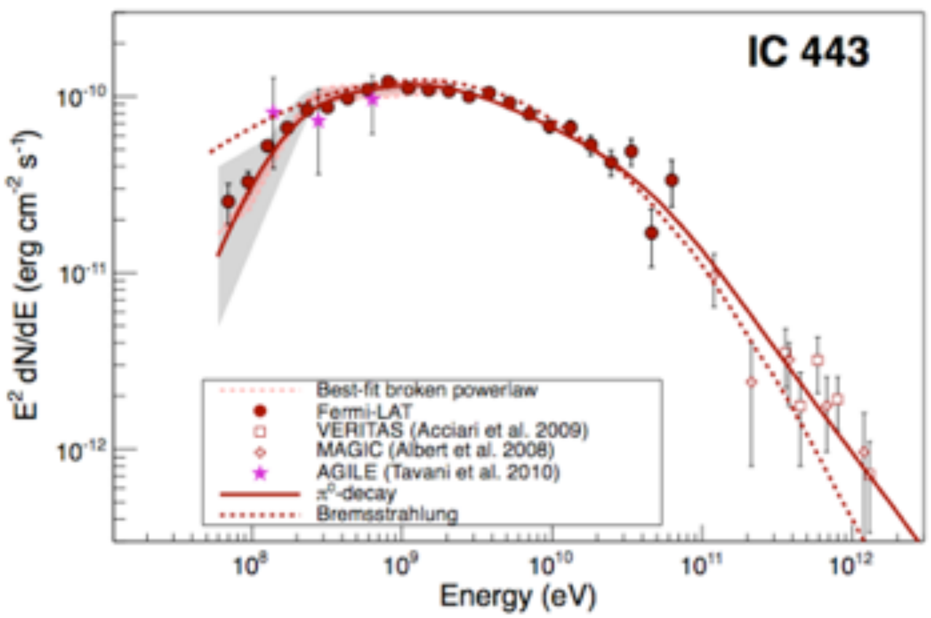


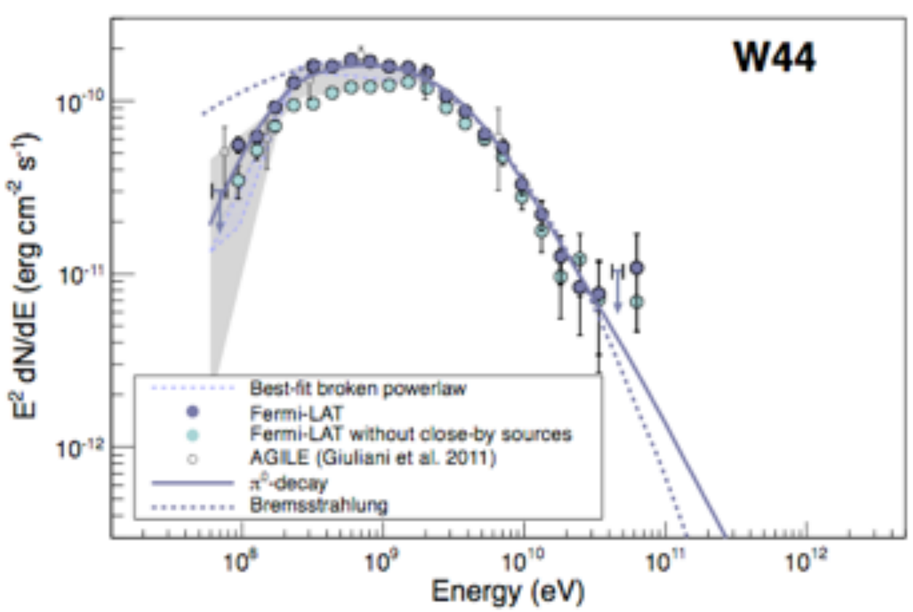
Gabici & Aharonian 2014

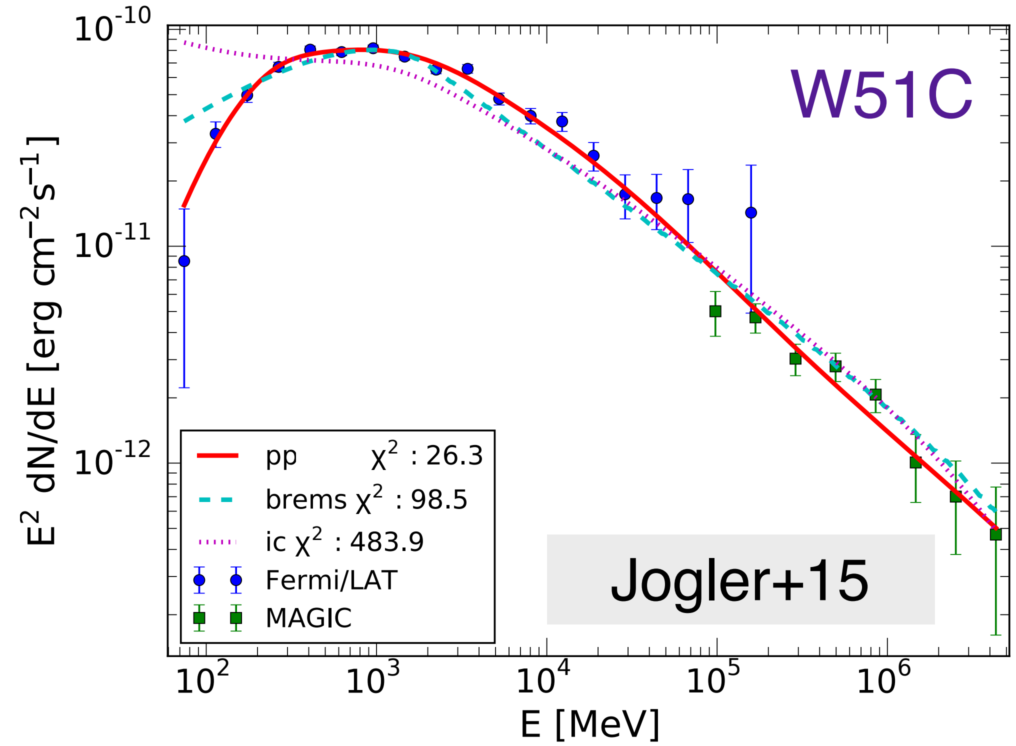
MIDDLE-AGED SNR WITH MC

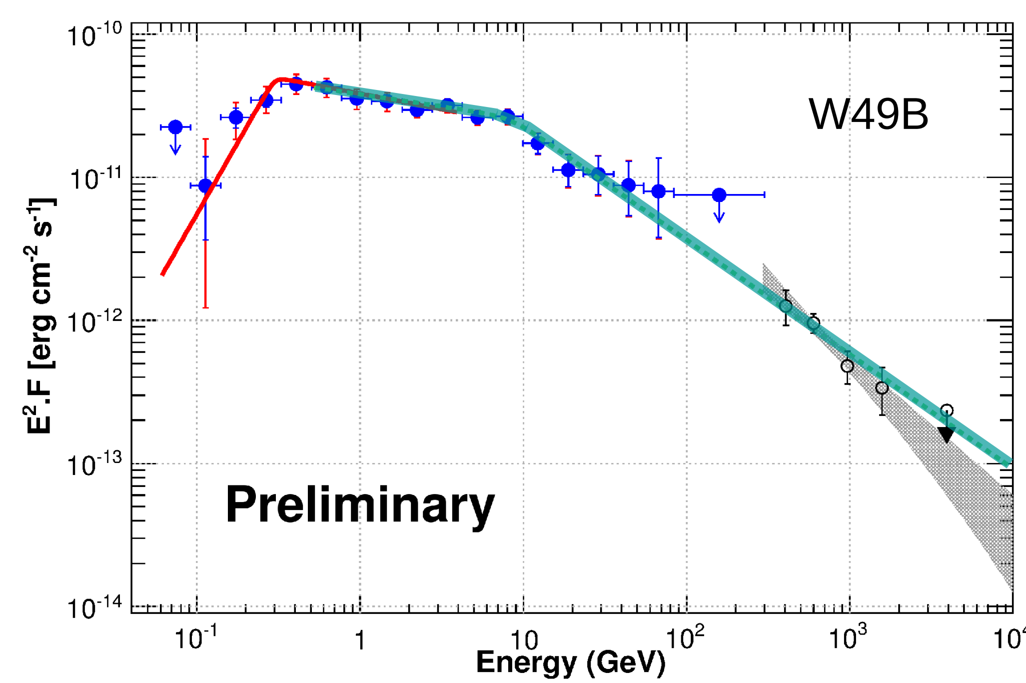
AGILE & Fermi:

Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra.









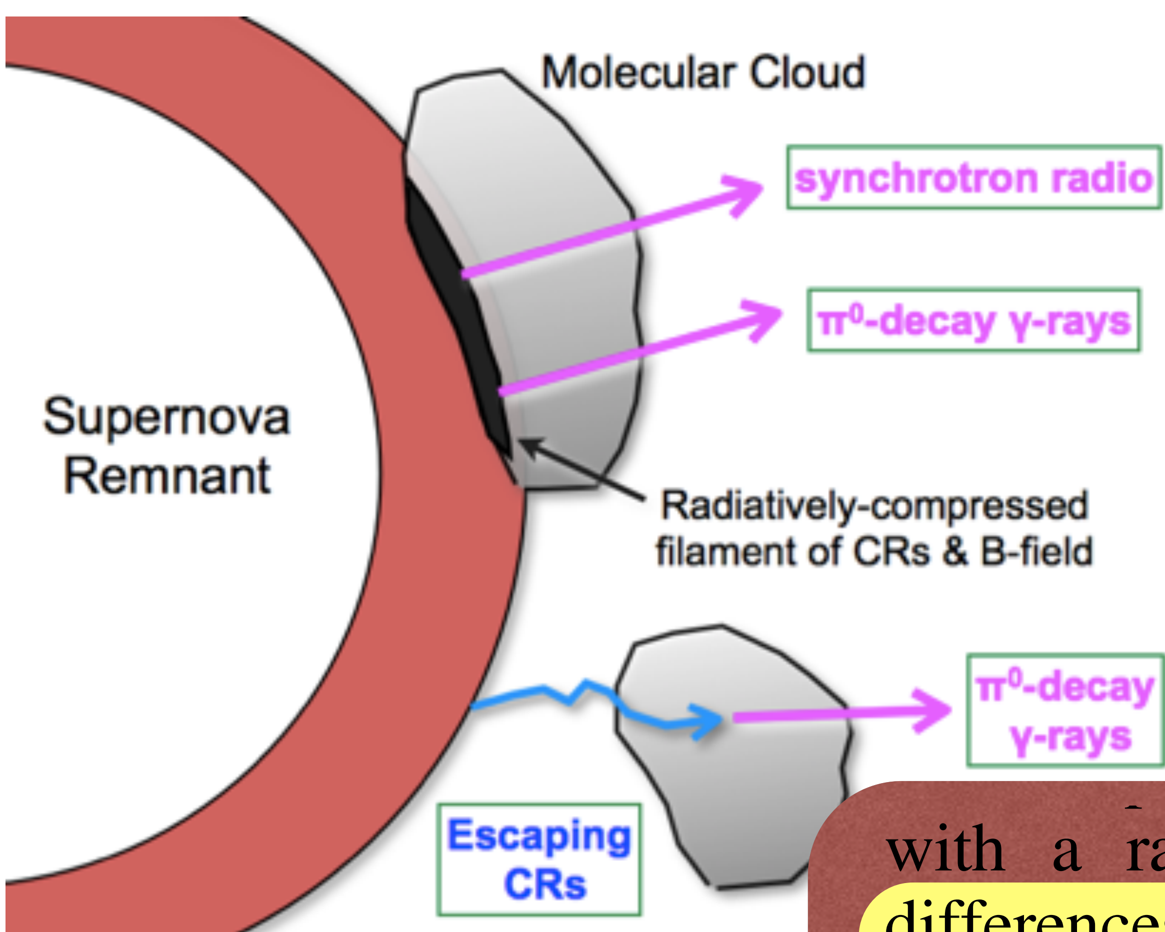
Fermi Coll. & H.E.S.S. Coll (submitted)

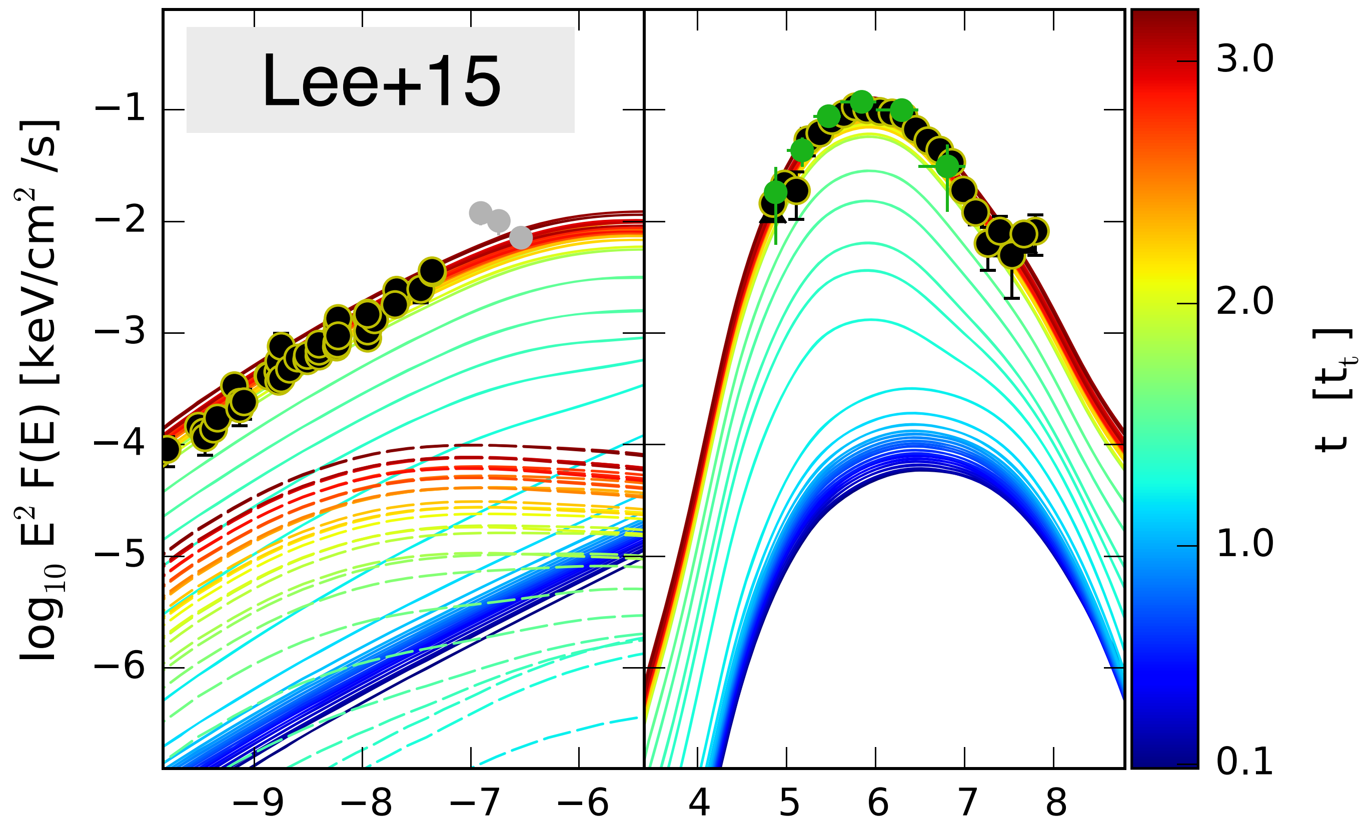
CRUSHED CLOUD MODEL

Uchiyama+ 2010, based on Blandford & Cowie (1982)

π^0-decay γ-rays come from shocked molecular clouds

- Radiative shock ➜ high compression ➜ high CR & gas density
- Shock: slow (~100 km/s), partially ionized ➜ Maximum energy < TeV
- Reacceleration of pre-existing CRs





with a radiative shock. We conclude that, despite minor differences, our results broadly confirm the assertions by U10 that a re-acceleration model can well explain the observed broadband emission properties. A direct acceleration model on the other hand suffers from several difficulties that we will explain in detail. In Section 2, we introduce the essential

Yasunobu Uchiyama (Rikk

SUMMARY

- Historical SNRs Cas A & Tycho
  - Hadronic origin, Magnetic field amplification, CR energy content
- Young TeV-bright SNRs RX J1713.7-3946 & Vela Jr.
  - Leptonic origin?
  - Hadronic origin? (E-dependent penetration into clumps)
- SNRs interacting with molecular clouds
  - W51C, W44, IC443, W28, W49B, ...
  - Direct evidence for hadronic origin (IC443, W44)
  - Evidence for Runaway CRs
- Evolved SNRs without molecular cloud interactions
  - Pup A, Cygnus Loop, S147
  - Hadronic origin