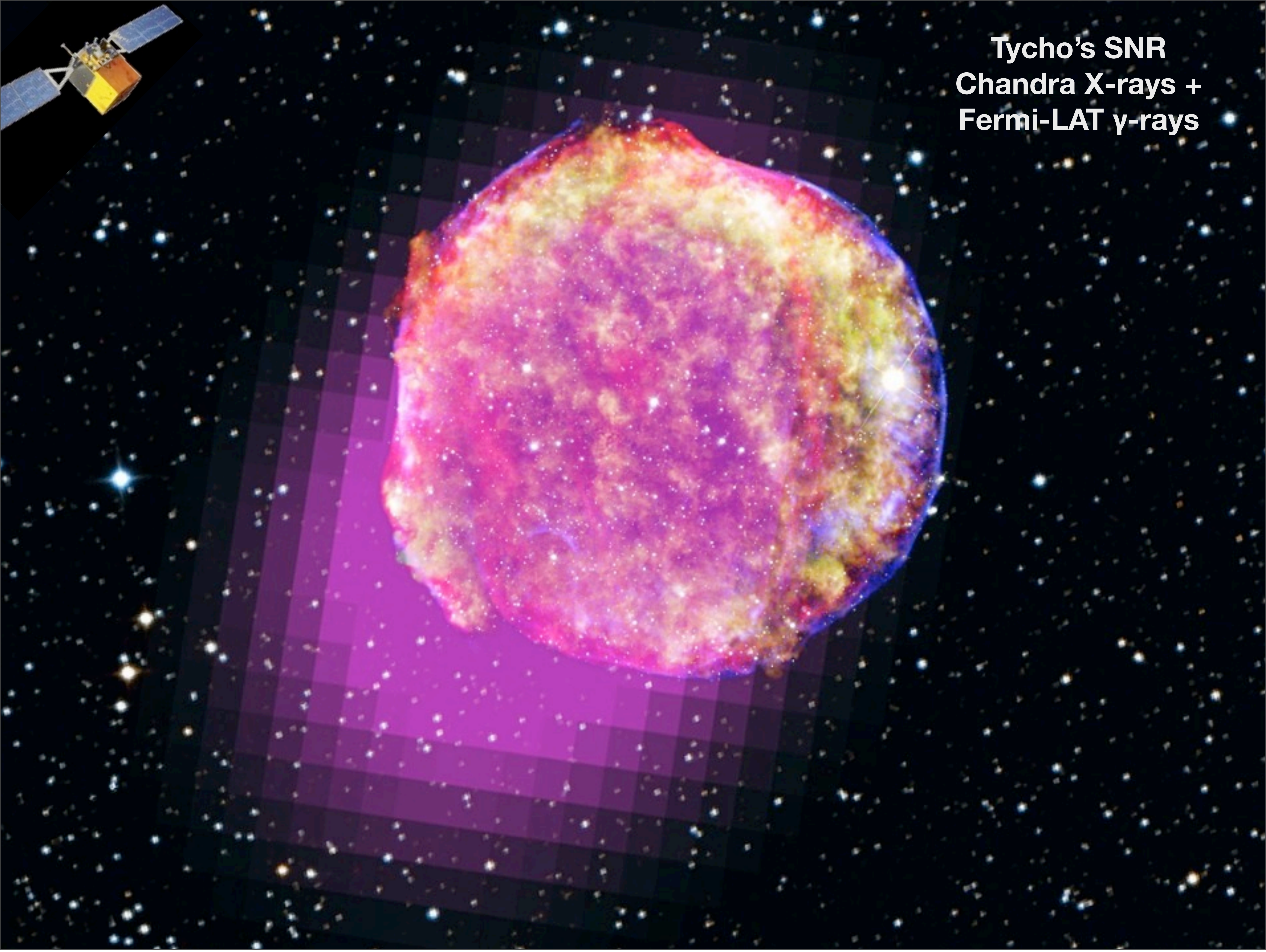
Tycho's SNR
Chandra X-rays +
Fermi-LAT γ-rays

fermi
Gamma-ray
Space Telescope

SNRs in the LAT

Jack Hewitt
NASA/GSFC

Fermi Summer School 2012
Lewes, Delaware

Outline

- Physics of SNRs
  - Very power physics experiment in particle acceleration and the structure of the interstellar medium
  - (Brief) Review of gamma-ray emission mechanisms
- Gamma-ray Studies (by Fermi-LAT)
  - Fermi has detected young, and middle-aged SNRs (typically interacting with molecular clouds)
- SNRs in the wild: A few interesting cases in detail

- Key Questions
  - Do SNRs accelerate particles?
  - Do SNRs accelerate protons (what is the e/p ratio?)
  - What is the total energy converted to relativistic particles?
  - What is the maximum energy of accelerated particles?
  - What is the mechanism (how is B-field amplified)?

Extreme Laboratories

Accelerator

Massive Target

Cloud probed by radiative shocks

Ideal labs for particle acceleration... nearby, well defined source of energy, and seen in all wavebands.

What is the CR yield from SNRs?
how does it vary with... evolution, environment

How do CRs diffuse into the ISM?
study escape / diffusion in dense gas

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Origin of Galactic Cosmic Rays?

discovered in 1912 (Victor Hess)
accelerator is still unknown.

. . . supernovae are the "usual suspect"

Energetic enough to supply Galaxy w/ CRs

Ginzburg & Syrovatskii (1964)

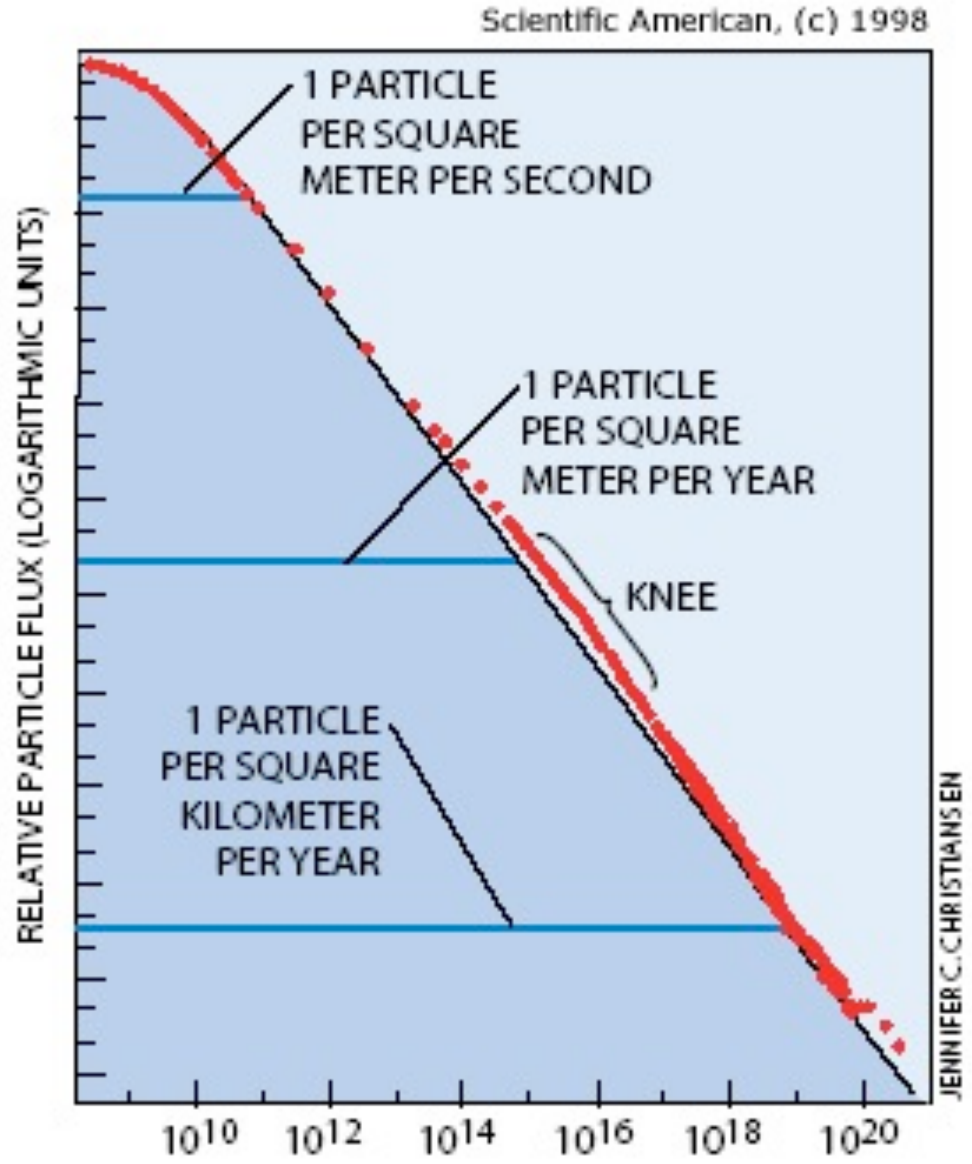
$L_{CR} \sim (1\ \mathrm{eV/cm^{-3}}) \times V_{gal} / t_{esc} = \mathbf{10^{40}\ erg\ s^{-1}}$

$V_{gal} \sim \pi\ (200\ \mathrm{pc})\ (15\ \mathrm{kpc})^2 \sim 4\times10^{66}\ \mathrm{cm}^3$

$t_{esc} = 2\times10^7\ \mathrm{yr}$

$1\ \mathrm{SN}/30\ \mathrm{yr} \times 10^{51}\ \mathrm{erg} \times 10\% = \mathbf{10^{41}\ erg\ s^{-1}}$

CR Spectrum



But not *uniquely* energetic

Pulsar spin-down energy... requires ~1 MSP/100 yrs

Colliding stellar winds? Novae? Galactic Rotational energy... ?

Merging SNRs into super-bubbles... ?

SNR Evolution

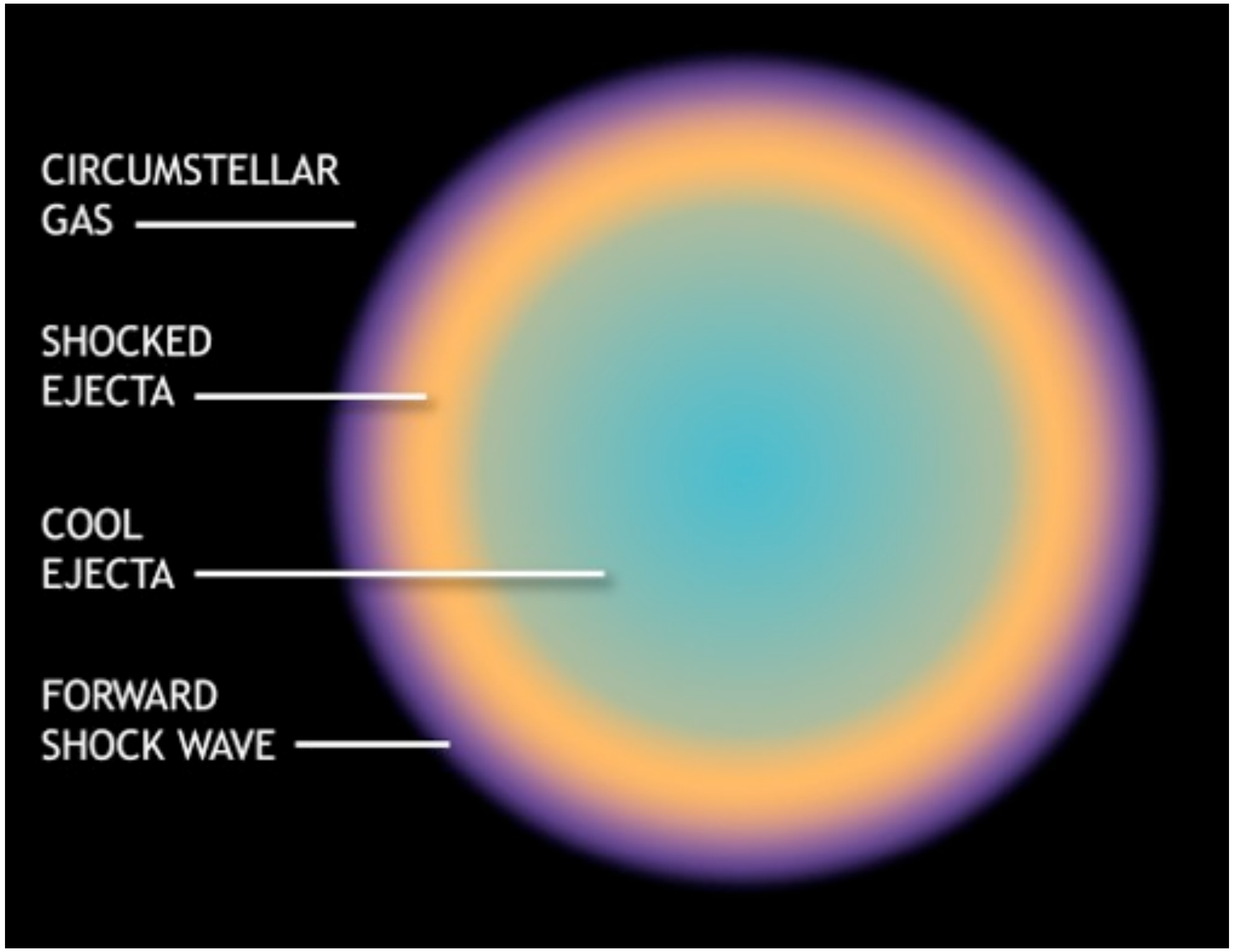
Probing a small region of the ISM with ~10^{51} erg (10^{33} atom bombs)

Simplest case: Sedov-Taylor solution

1. Free Expansion

   lasts ~100-1000 years,
   until $M_{swept\text{-}up} = M_{ejecta}$

   constant T, V_{sh} ~ constant



2. Adiabatic expansion (Sedov)

   $T \sim R^{-3}$, $V_{sh} \sim R^{-3/2}$

   ejecta mixes with ISM, ~20 kyr

3. Radiative phase (Snow-plow)

   $T<10^6$ K, $V_{sh} \sim R^{-3}$
   electrons recombine
   radiative cooling dominates

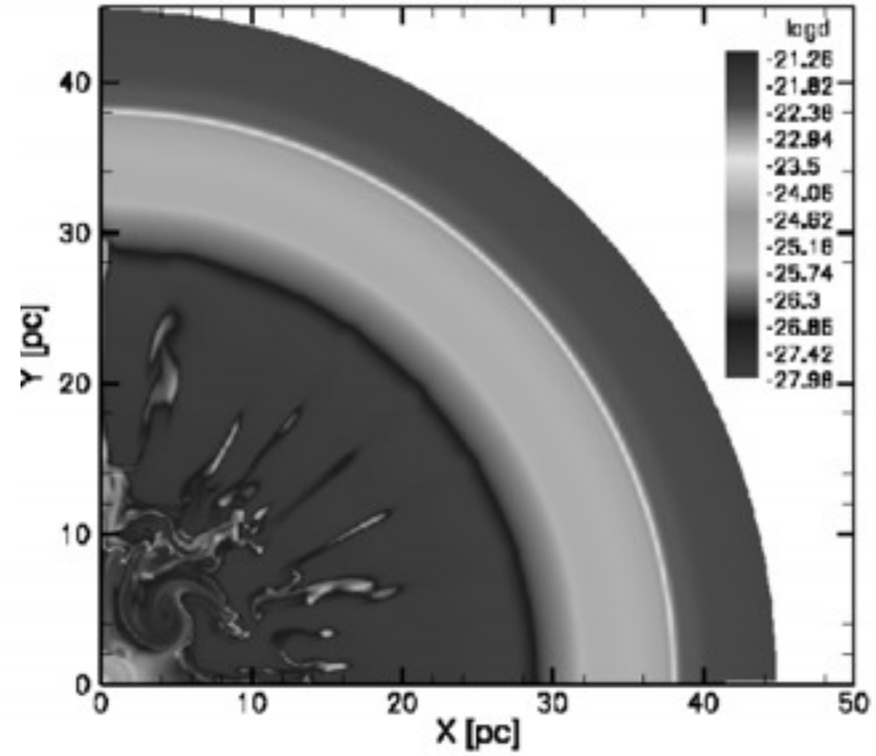
Dense ISM can hasten the onset of radiative cooling

Environmental complications

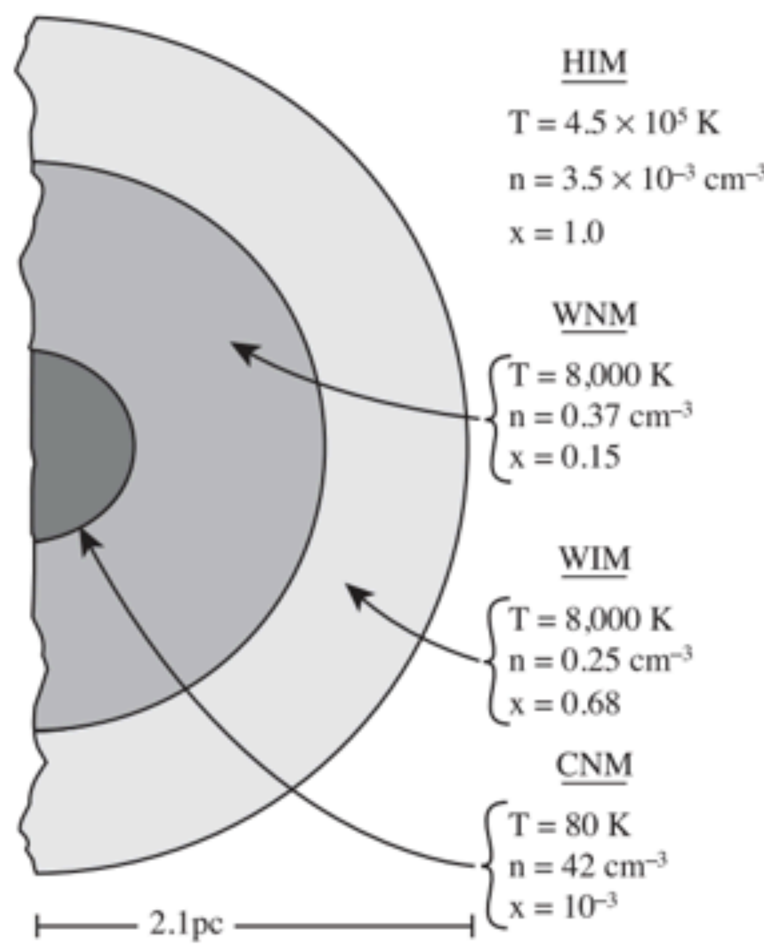
- But it's not that simple... the surrounding medium is highly structured.
- Progenitor massive star has clumpy winds

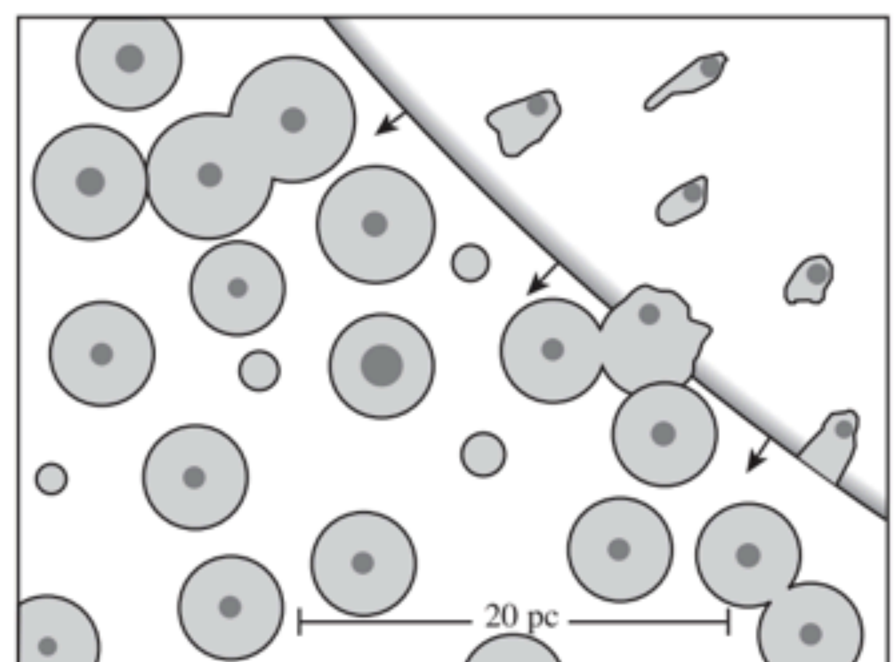
RADII OF H II REGIONS AND WIND BUBBLES

Mass ($M_\odot$)	Type	$R_{ionized}$ (pc)	$\dot{M}$ ($M_\odot$ yr^{-1})	τ_{ms} (yr)	R_b (pc)
20......	O9 V	13.6	1×10^{-7}	7×10^6	11
16......	B0 V	8.0	6×10^{-8}	9×10^6	10
12......	B1 V	1.6	6×10^{-9}	13×10^6	5.3
10......	B2 V	1.0	5×10^{-10}	18×10^6	2.6
8	B3 V	0.5	1×10^{-11}	26×10^6	0.8



- Later, SNR may encounter dense molecular cloud.

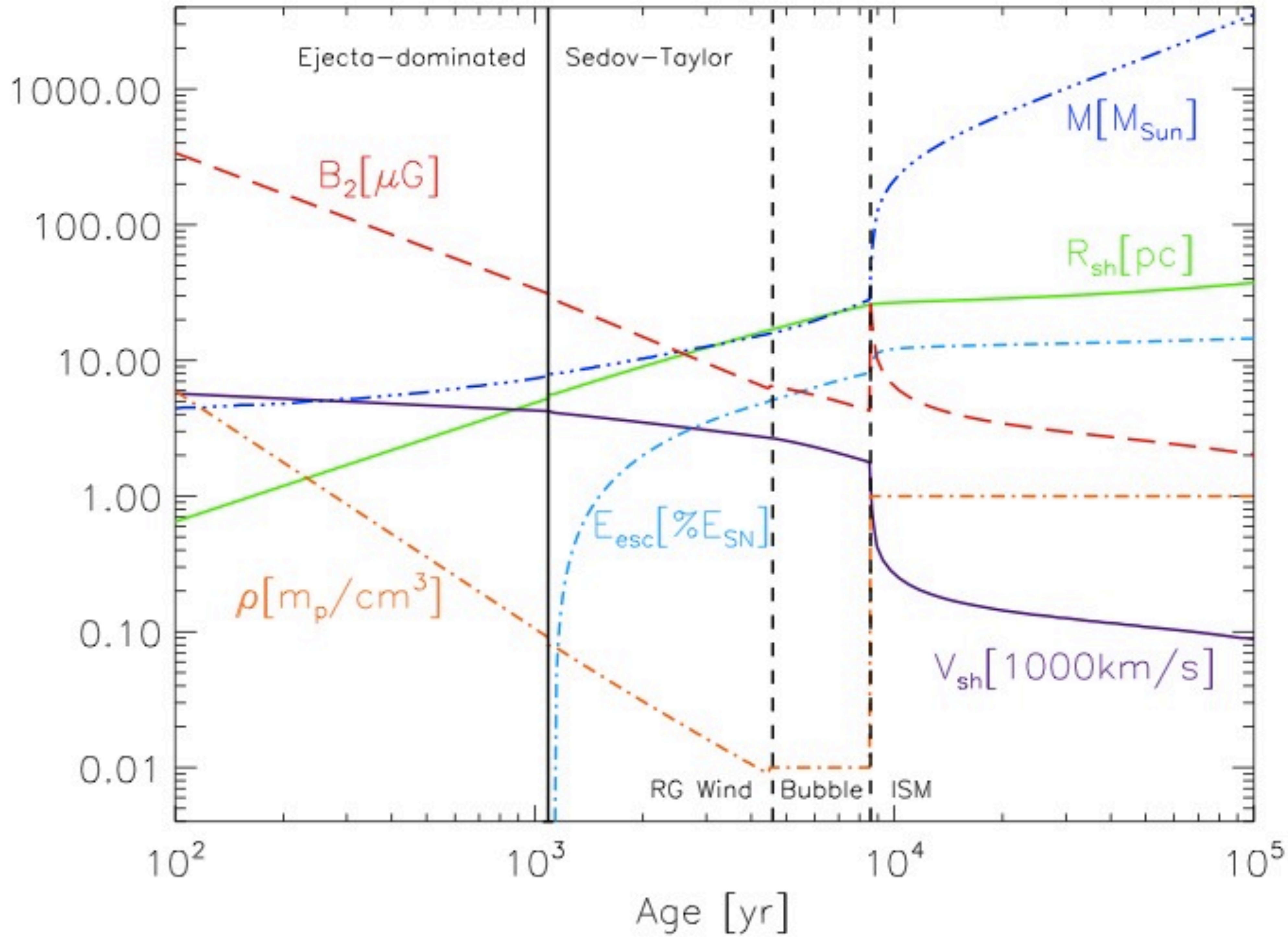




Environmental complications

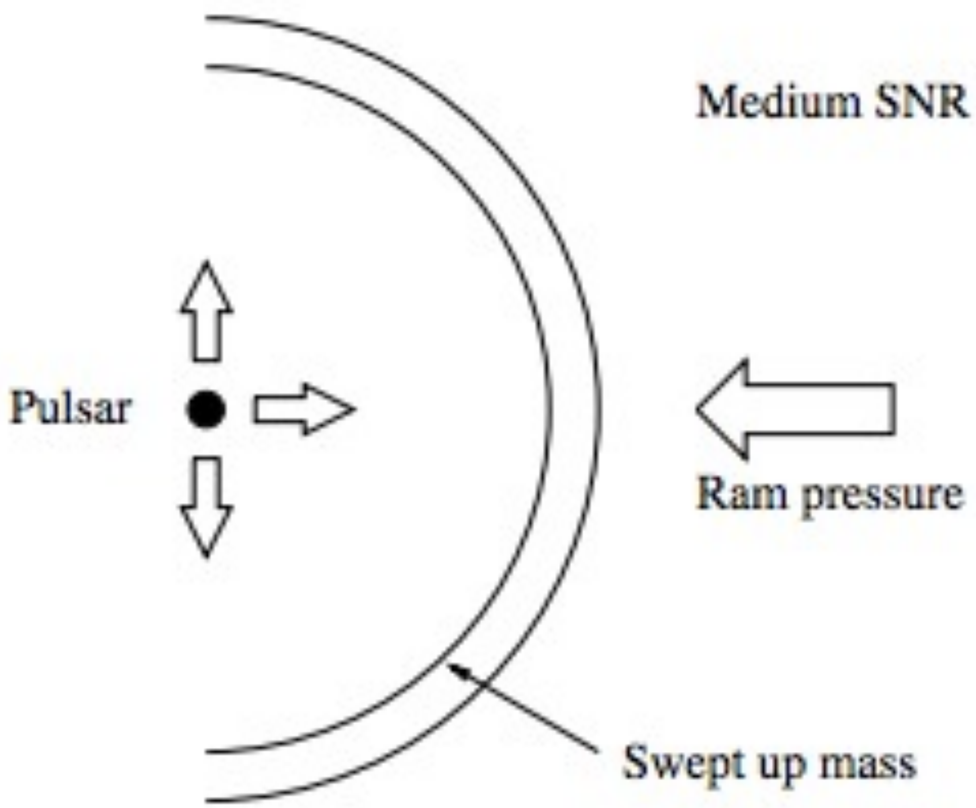
- Evolution of physical quantities of the SNR (w/progenitor bubble)

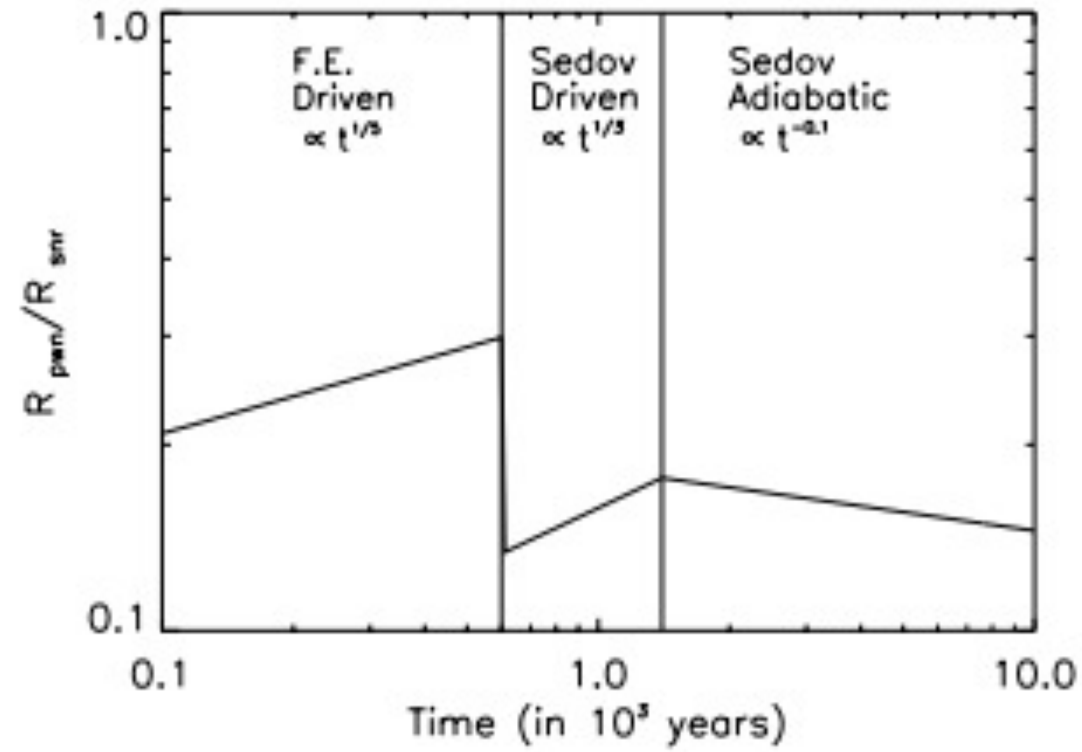
from Caprioli (2011)

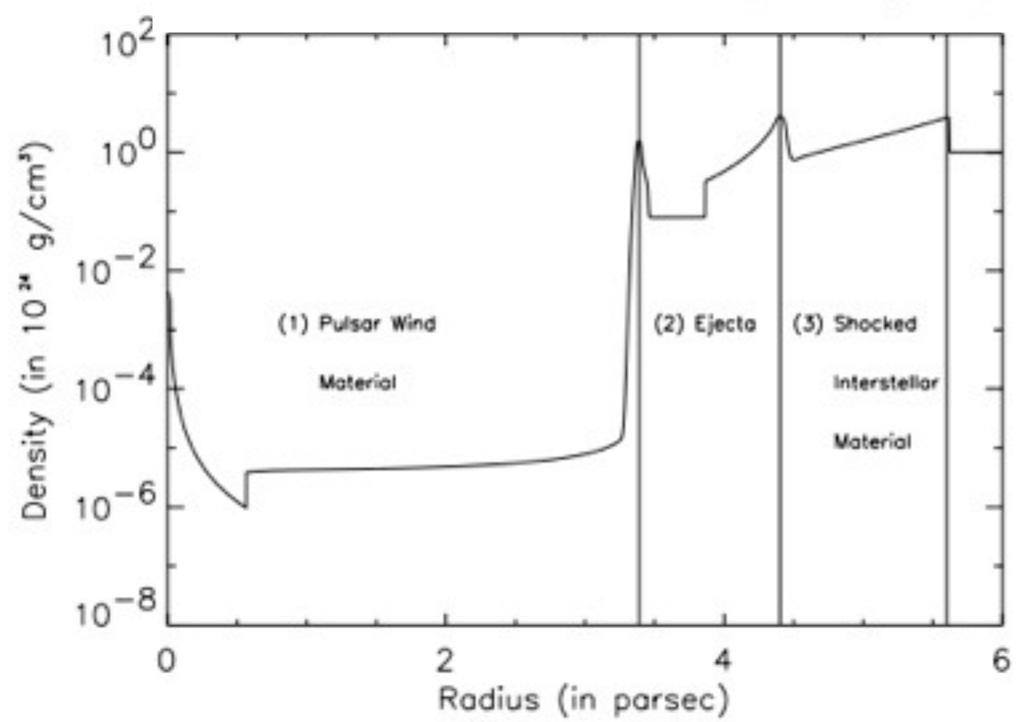


and there's a Pulsar Wind Nebulae?

- Particles accelerated by pulsars can power a nebula within the SNR
  - The termination shock (where the wind is decelerated by sweeping up ejecta from the SN explosion) can accelerate particles

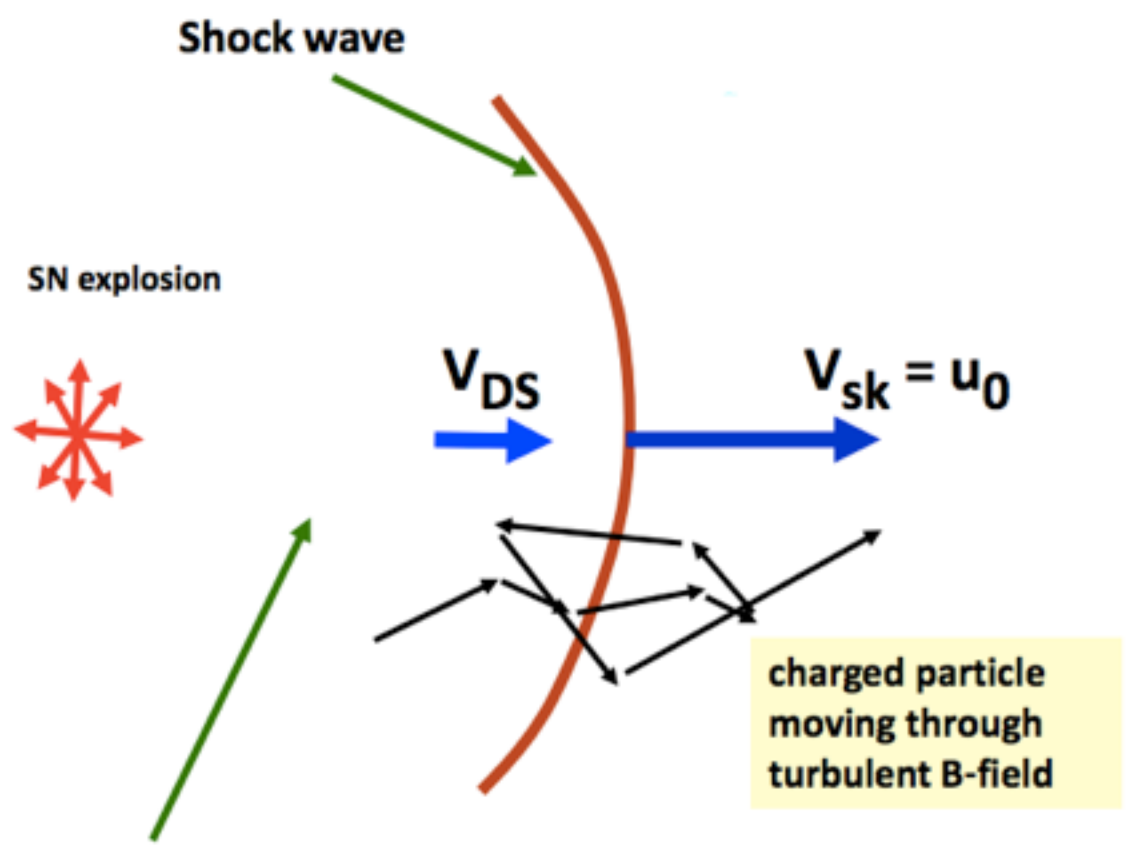






Diffusive Shock Acceleration

- CRs scattered by magnetic fields back-and-forth across the shock front, gaining energy (Acceleration = Diffusion.)
- Escaping the accelerator: those CRs that reach a “free-escape” boundary can diffuse into the surrounding ISM.



- Key unknown is the injection efficiency... which determines the total yield of CRs from the SNR integrated over it’s lifetime.
- Also, how/when are B-fields amplified and maintained?

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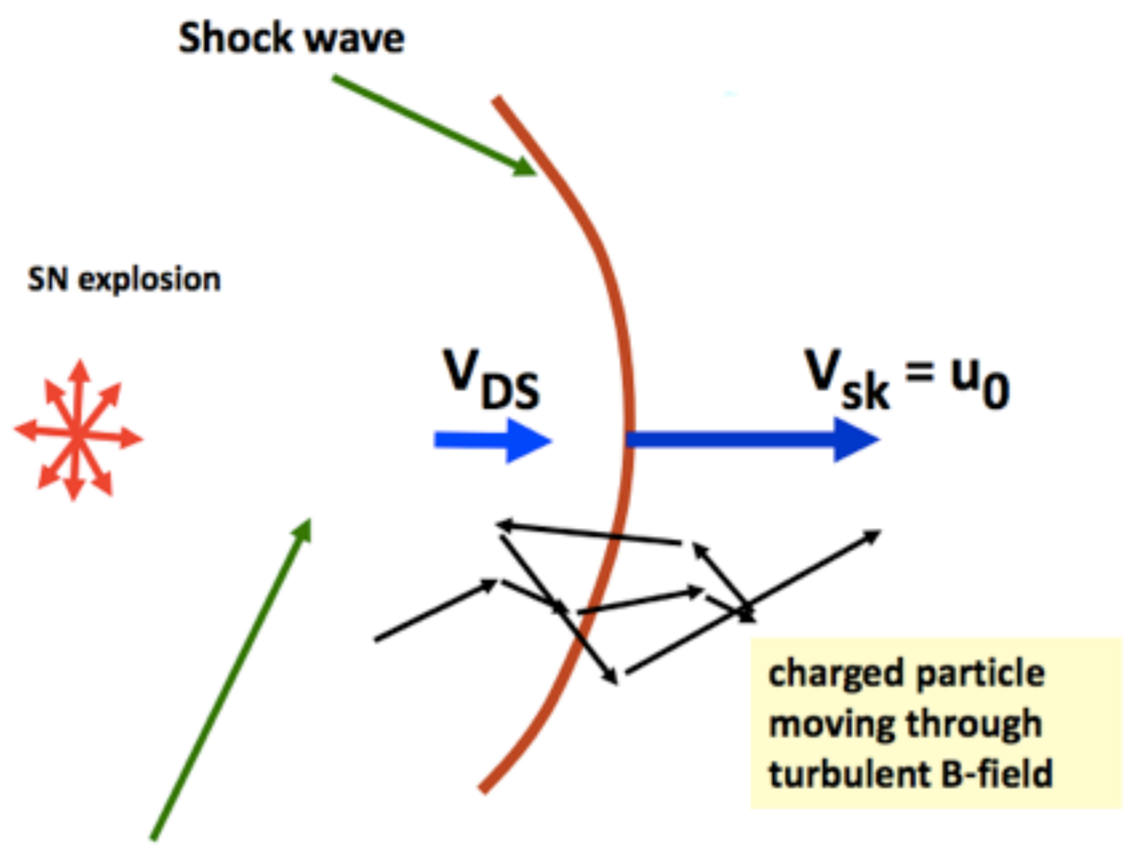

- Key unknown is the injection efficiency... which determines the total yield of CRs from the SNR integrated over it’s lifetime.
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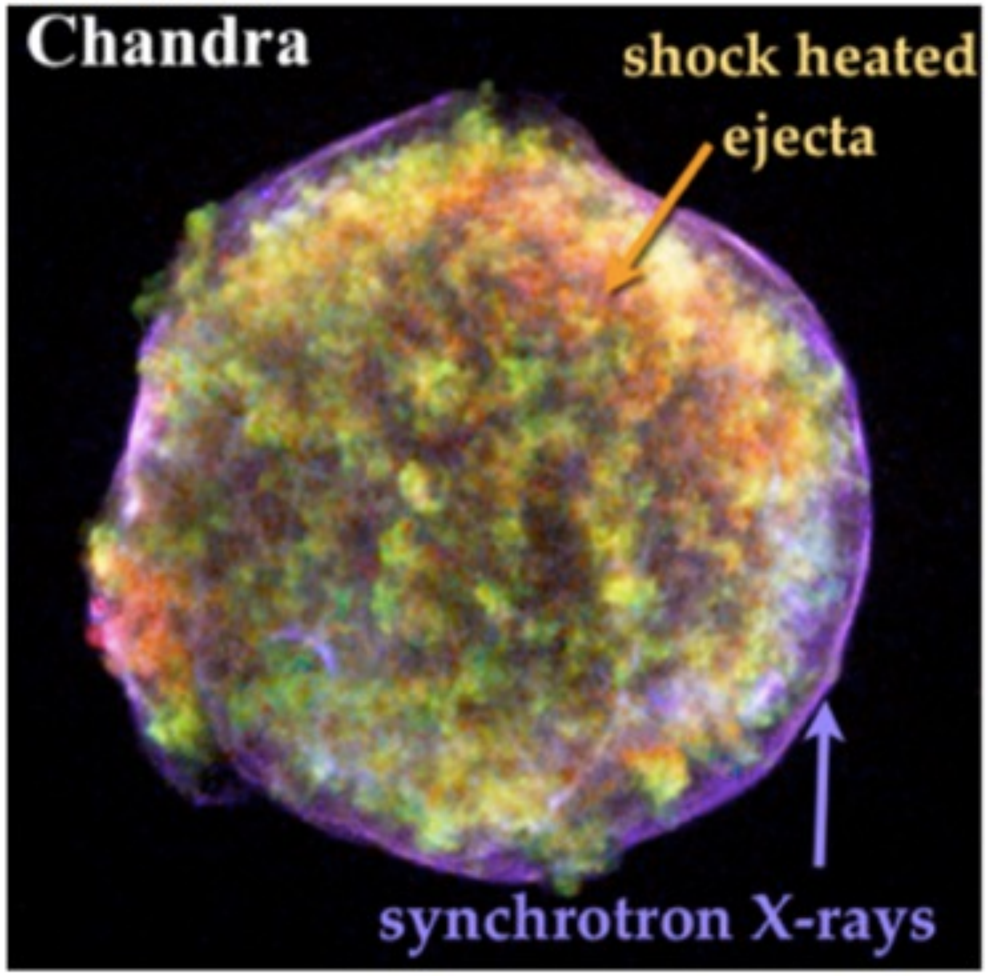
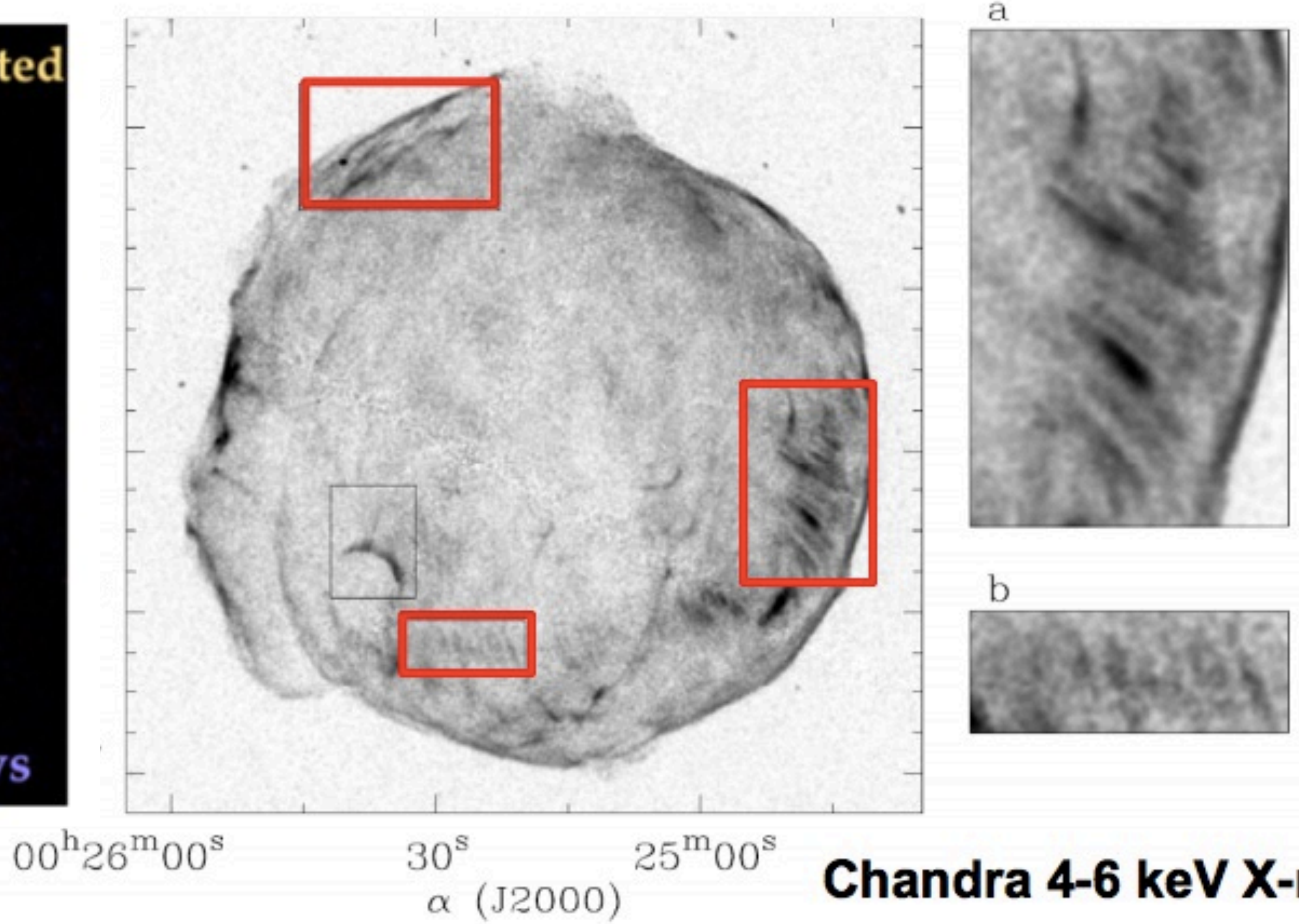
Diffusive Shock Acceleration

- Indirect evidence for B-field ampl. and CR accel. in Tycho.

Warren+05





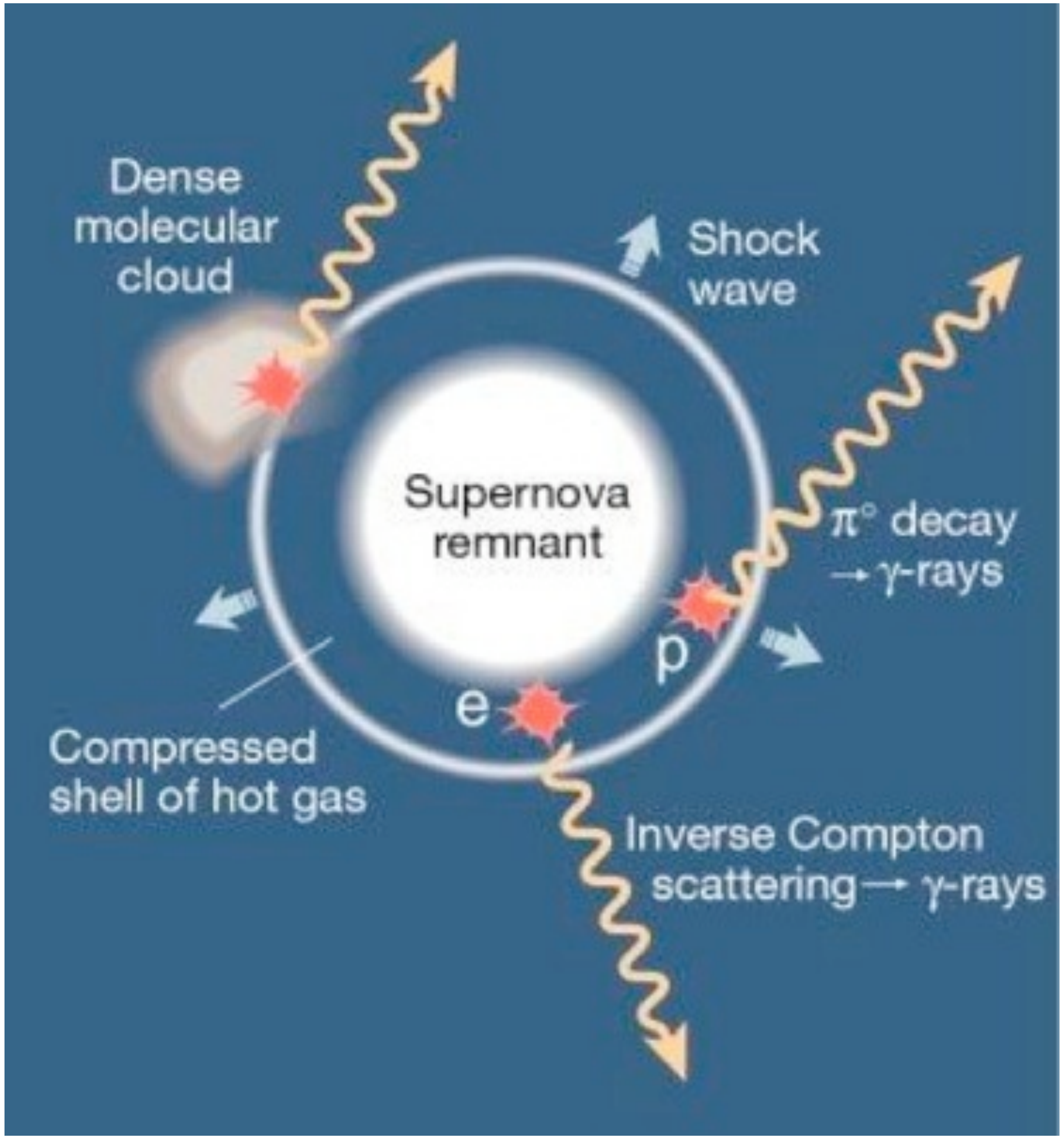
Chandra 4-6 keV X-rays

Non-thermal Emission Mechansims

- Existence of a powerful particle accelerator is not sufficient for γ-ray production; a dense target (or photon field) is required.

Target = matter, radiation, B-field

Dense cloud = massive detector
favors pion decay or brems.



<u>Leptonic</u>	Inverse Compton Bremsstrahlung
<u>Hadronic</u>	Neutral pion decay

Briefly reviewed...

Pion Decay

- When a CR proton collides with a thermal proton/nuclei, produces π π^0 instantaneously (10^{-16} s) decay into a pair of γ-rays
- Threshhold is $m_\pi/2 \sim 70$ MeV (creates a "π^0 bump" in spectrum)

$$L_{\pi^0}(E_\gamma) \approx 1.5 \times 10^{-16} a_p n E_\gamma^{-2} \text{ photons GeV}^{-1}\text{ s}^{-1}$$

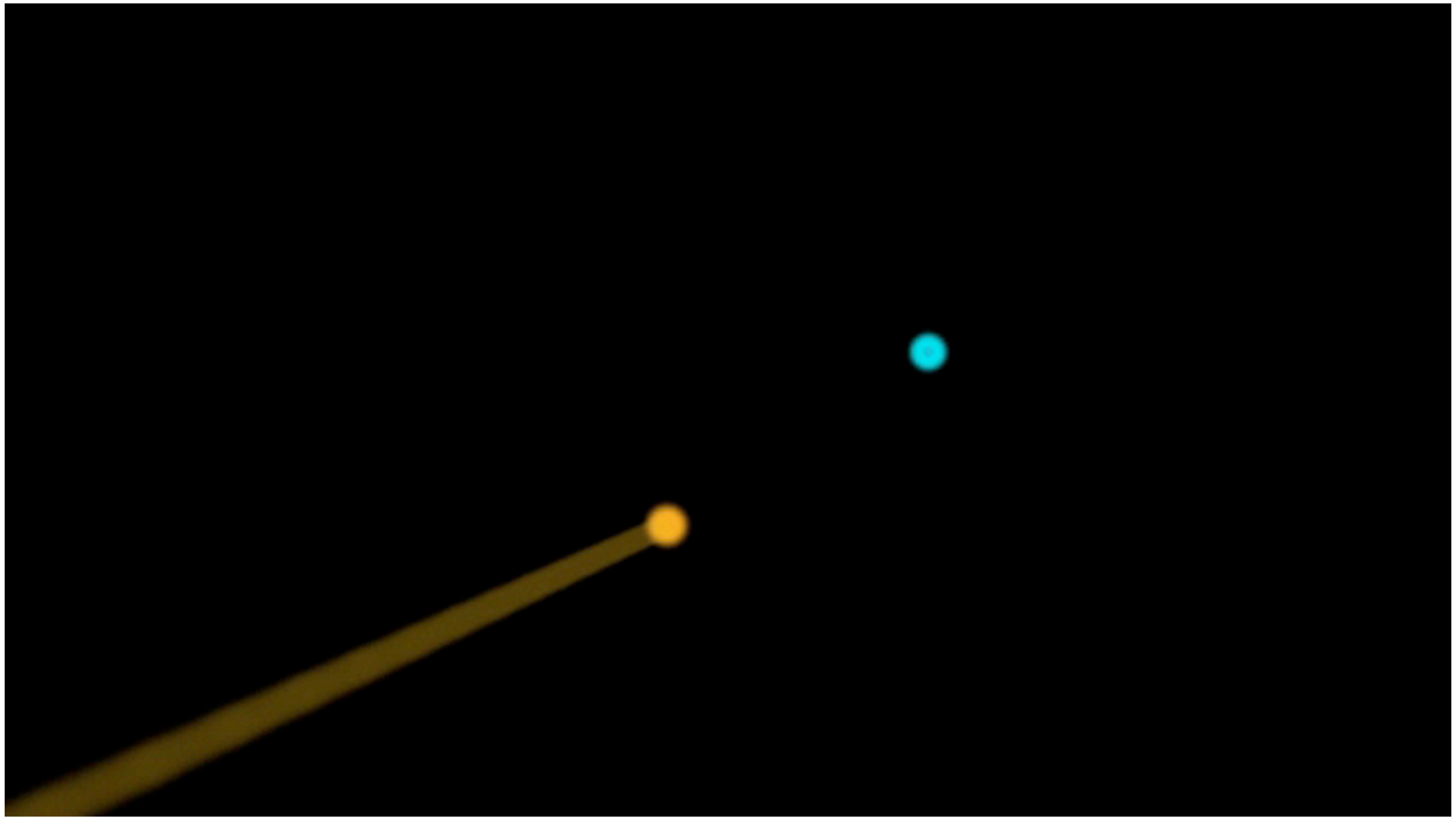
Thanks NASA! (from http://svs.gsfc.nasa.gov/goto?10690)

for an overview of radiation mechanisms see Gaisser et al. (1998)

Bremsstrahlung

- "Breaking radiation" produced by the deceleration of charged particle, when deflected by another charged particle.
(Typically taken as when an e- is stopped by matter)

$$L_{\mathrm{brem}}(E_\gamma) \approx 7 \times 10^{-16} a_e n E_\gamma^{-2} \text{ photons GeV}^{-1}\text{ s}^{-1}$$



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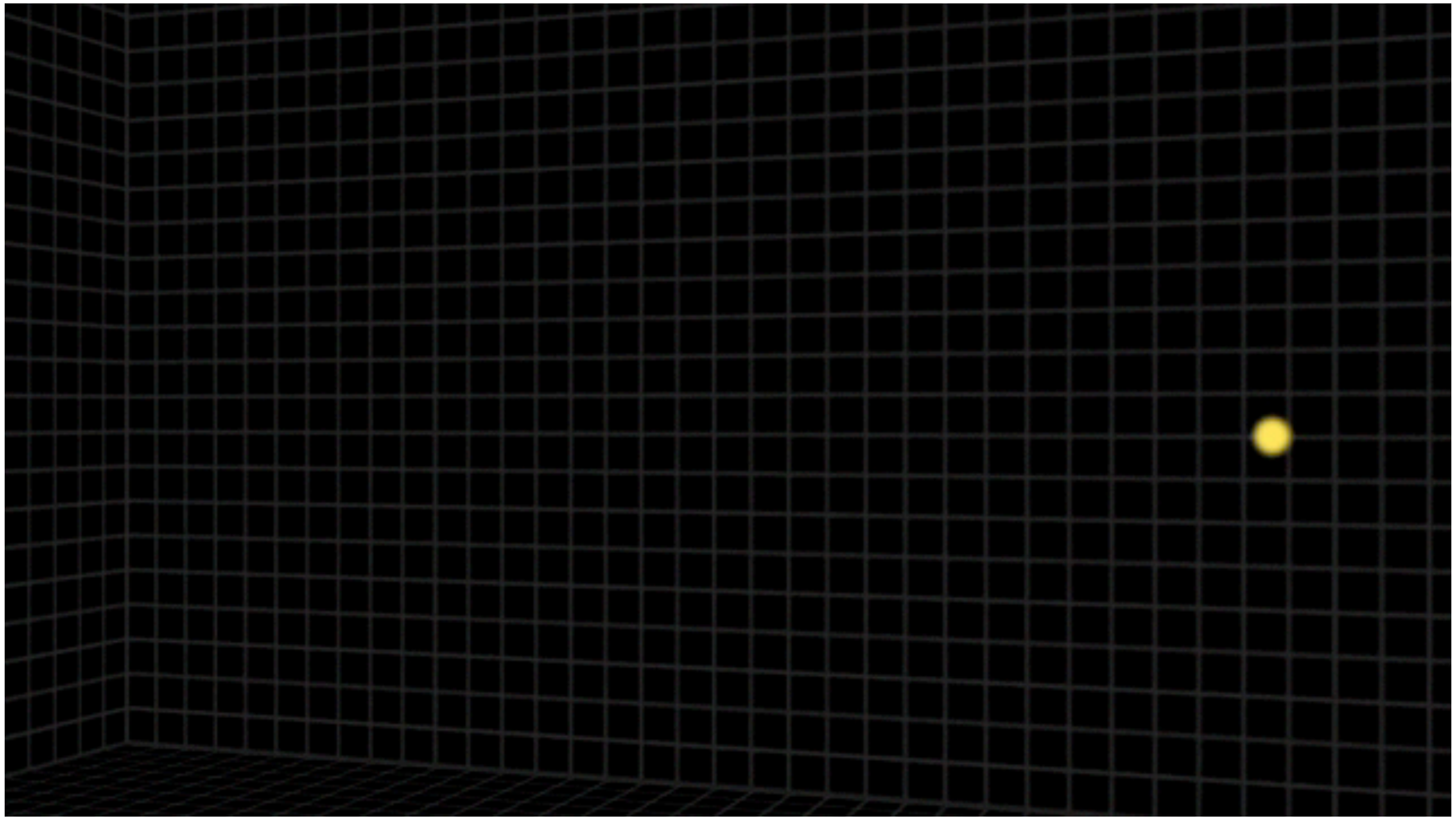
Inverse Compton

- Inverse Compton upscattering occurs when a charged particle transfers some of its energy to an incident photon (typically the CMB).

$$L_{IC}(E_\gamma) \approx 1.3 \times 10^{-14} a_e E_\gamma^{-3/2} \text{ photons GeV}^{-1} \text{ s}^{-1}$$



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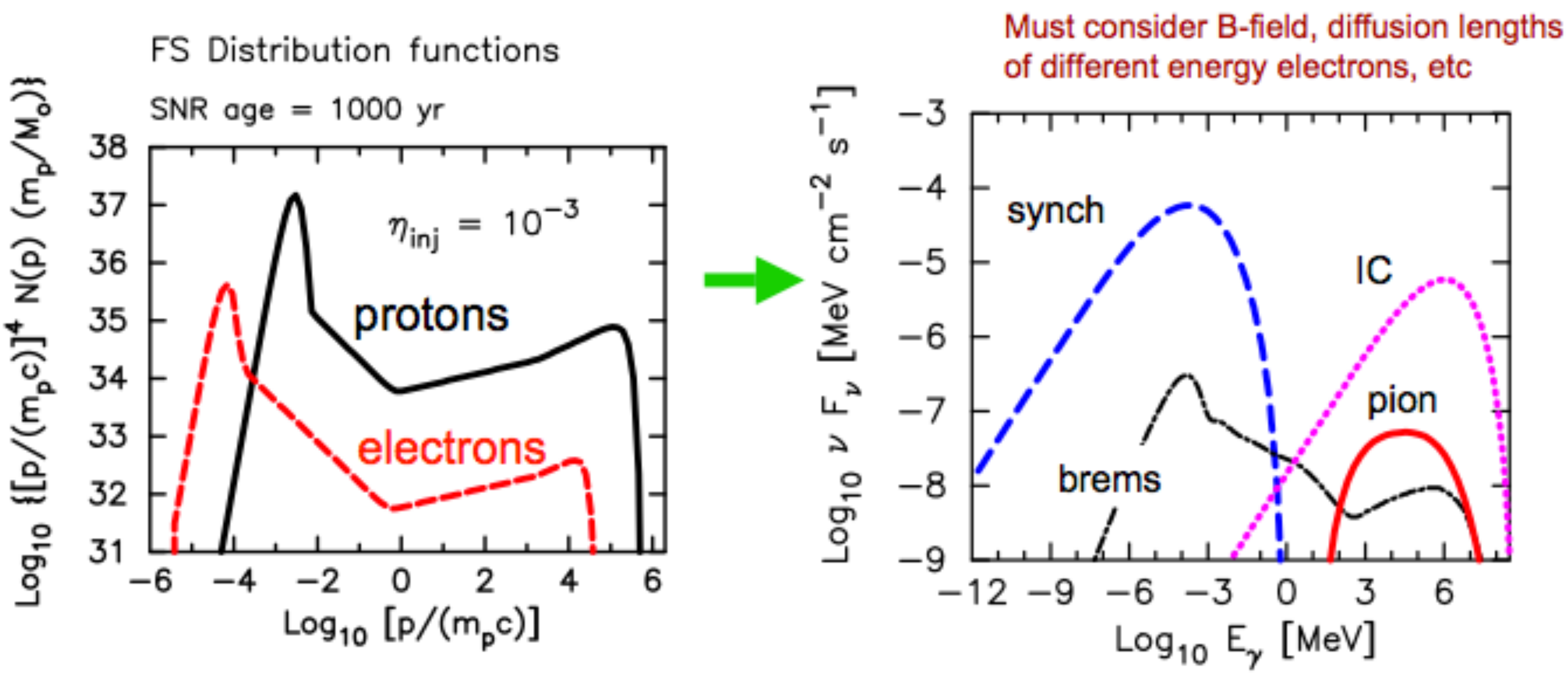
Simulated SNR Spectrum

- From simulations of Ellison et al. (2009) which assume injection efficiency and non-linear DSA

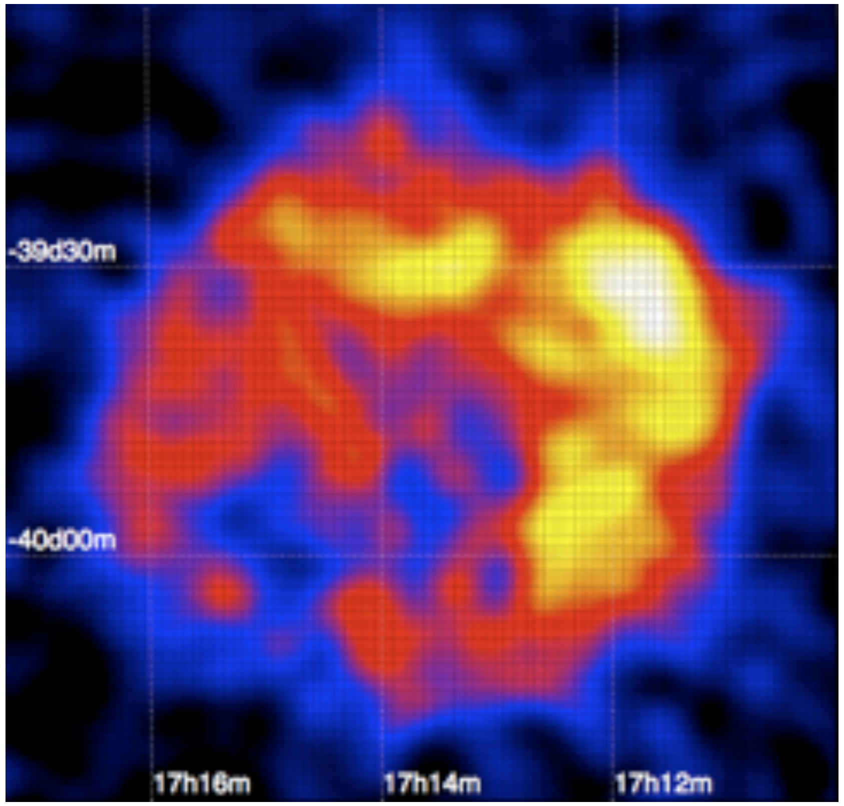


from Ellison et al. (2009)

The Example

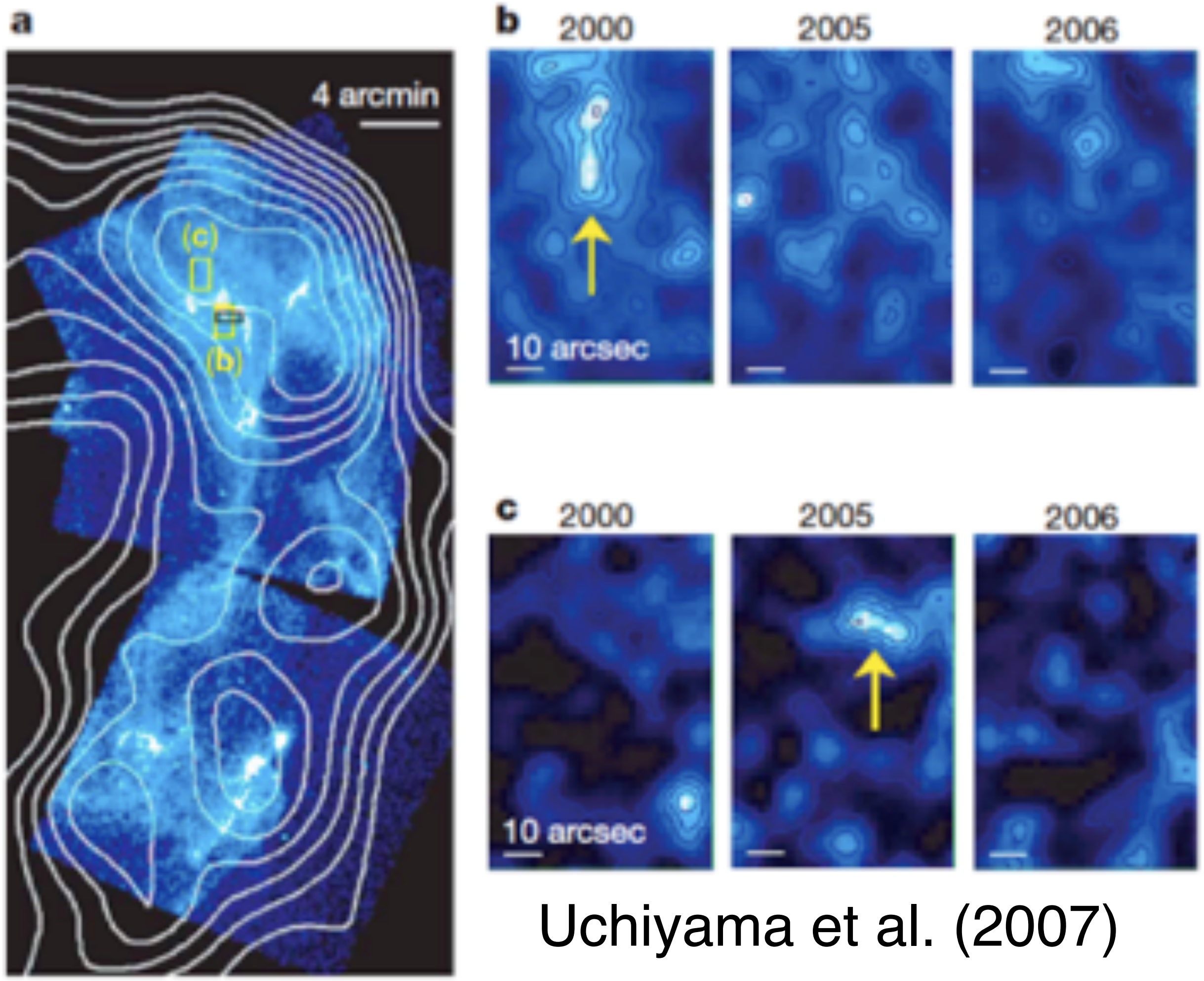
RX J1713.7-3946
age: 1.6 kyr, dist: 1 kpc

TeV gamma-rays
hadronic (p^+) or leptonic (e^-)?
$m_p/m_e = 1836$



Aharonian et al. (2006)

X-ray synchrotron
yearly variability => 1 mG ?
clear evidence of e^- acceleration



Uchiyama et al. (2007)

Clear evidence of relativistic particles... but what yield of p^+? e^-?

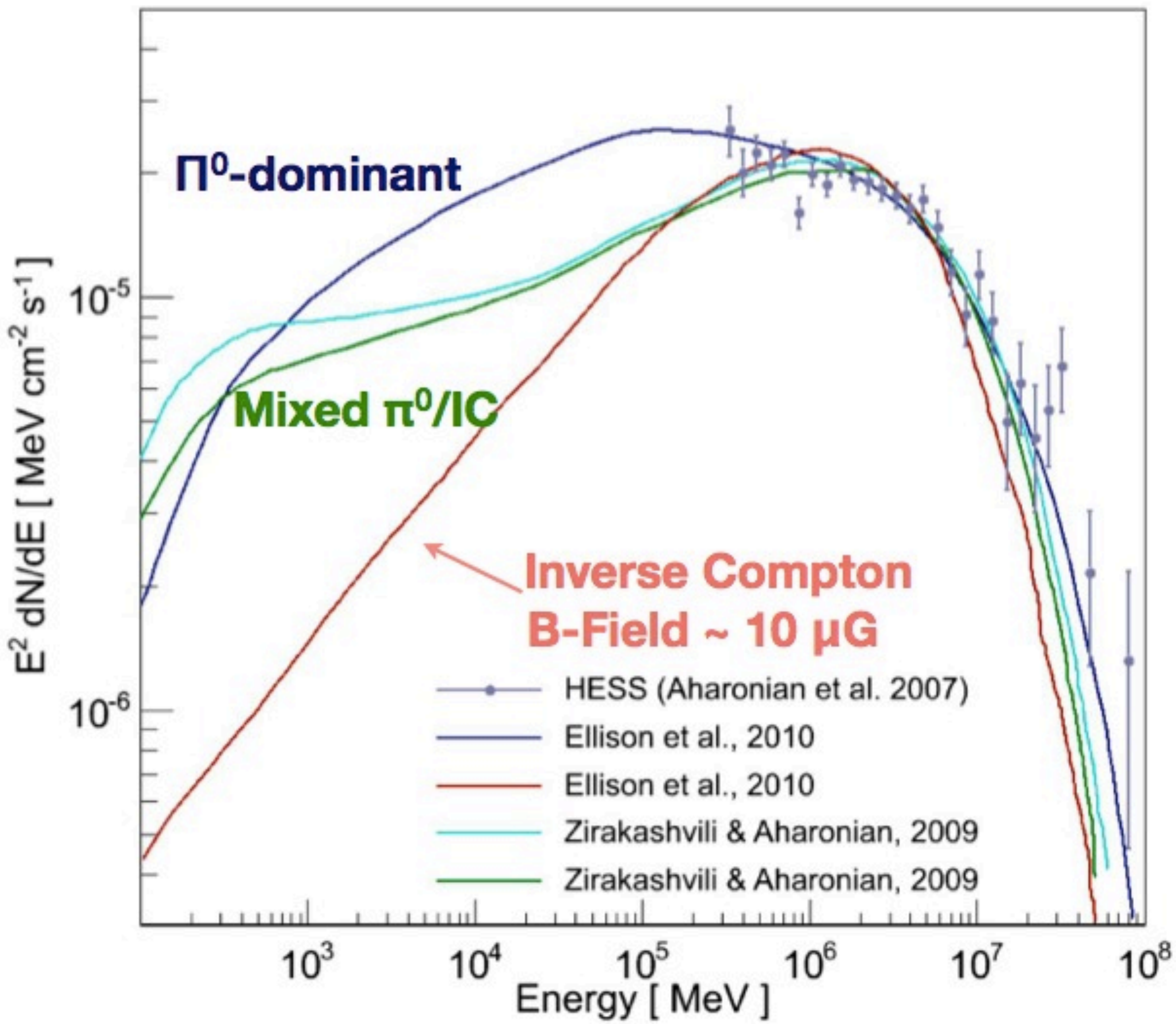
The Example

RX J1713.7-3946
age: 1.6 kyr, dist: 1 kpc

Nonthermal models can explain TeV spectrum as either leptonic or hadronic emission...

But Fermi LAT occupies the key energy range to differentiate models.

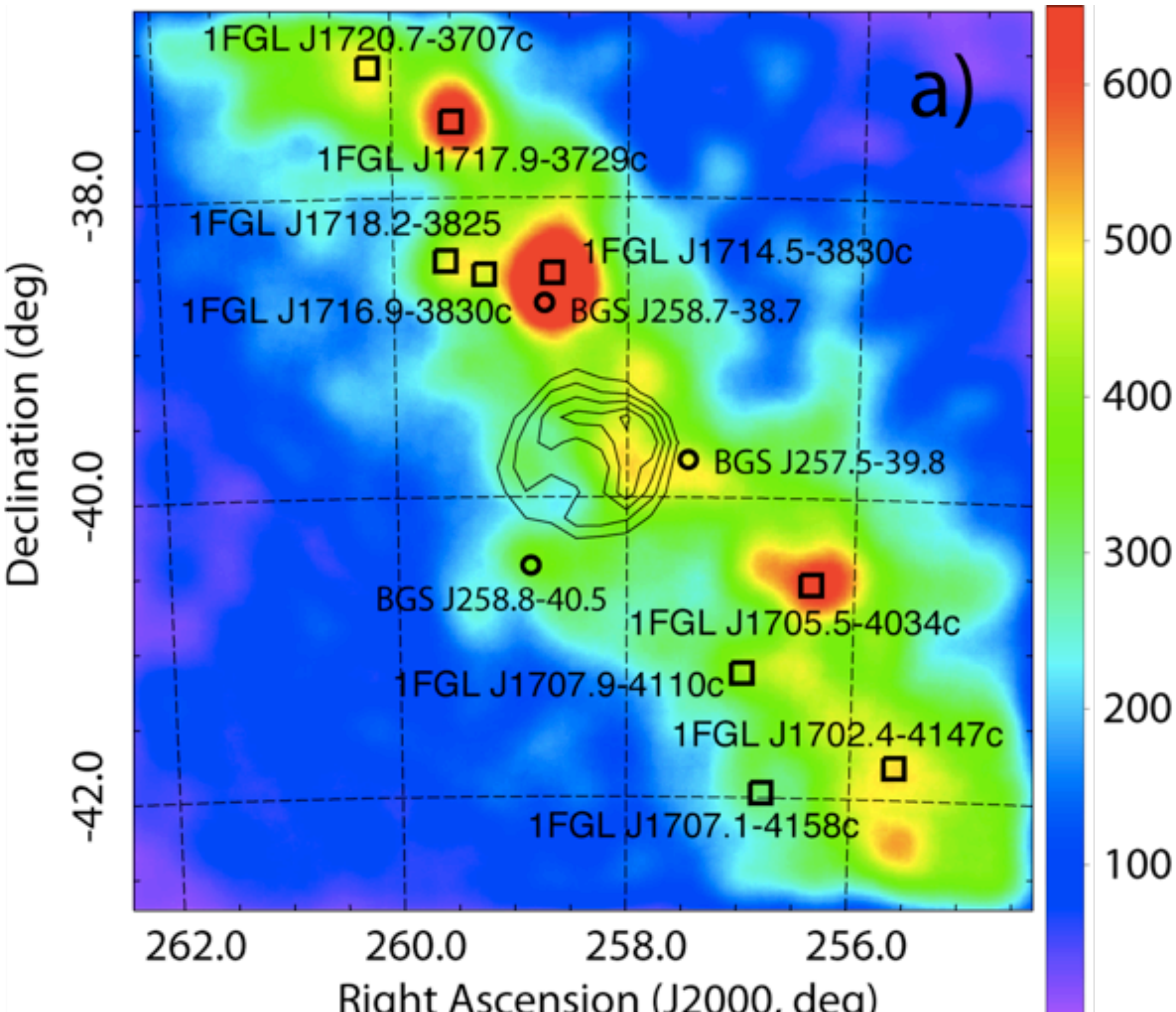
Lack of thermal X-ray emission indicates SNR in a very low density ISM (Tanaka et al. 2008)



The Example

RX J1713.7-3946

- A heroic analysis of Fermi-LAT data... reveals an SNR, just visible in an ocean of Galactic diffuse emission.



Smoothed Counts Map
E > 3 GeV

The Example

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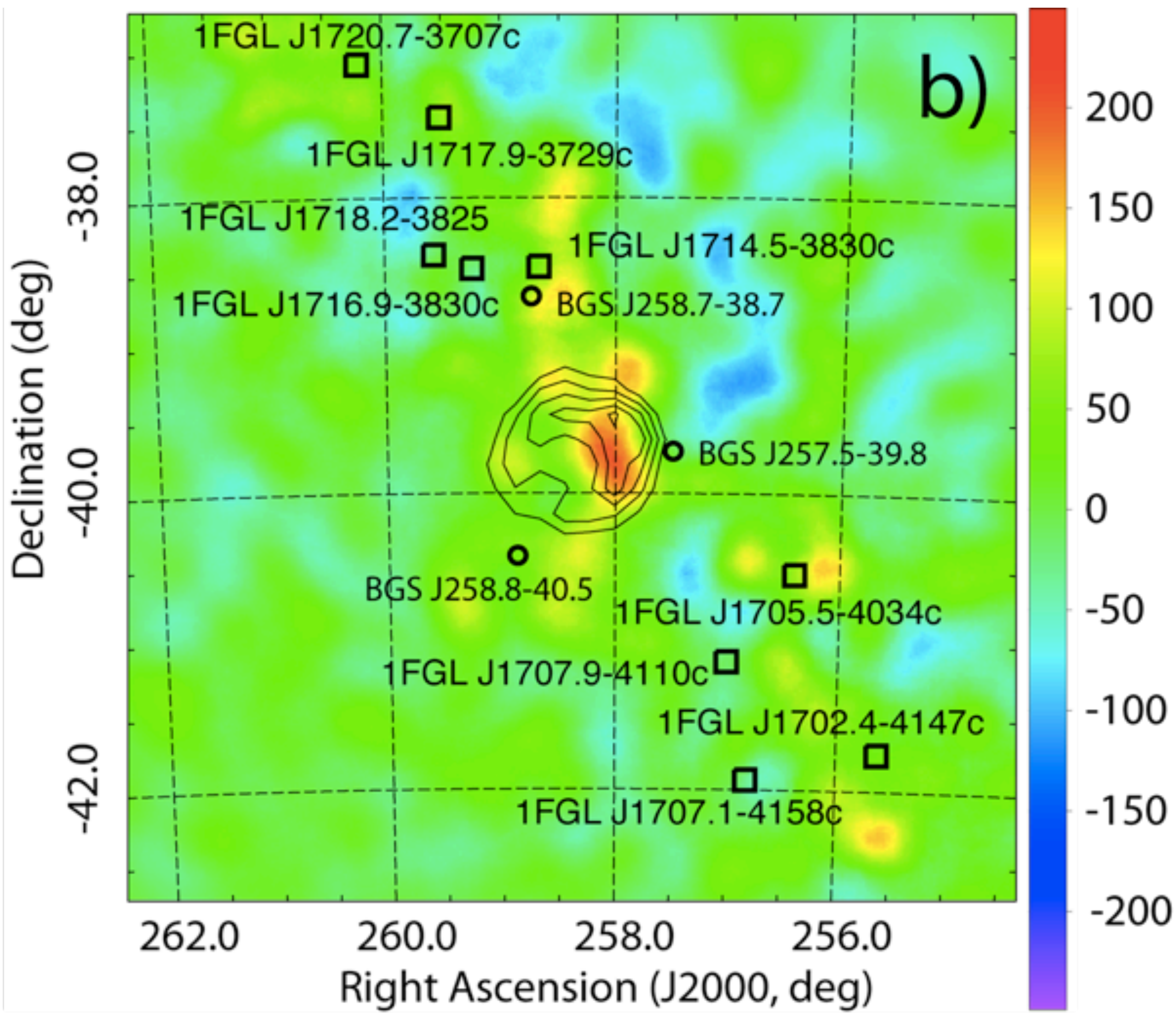

Smoothed Counts Map E > 3 GeV

- Gal. Diffuse and sources

The Example

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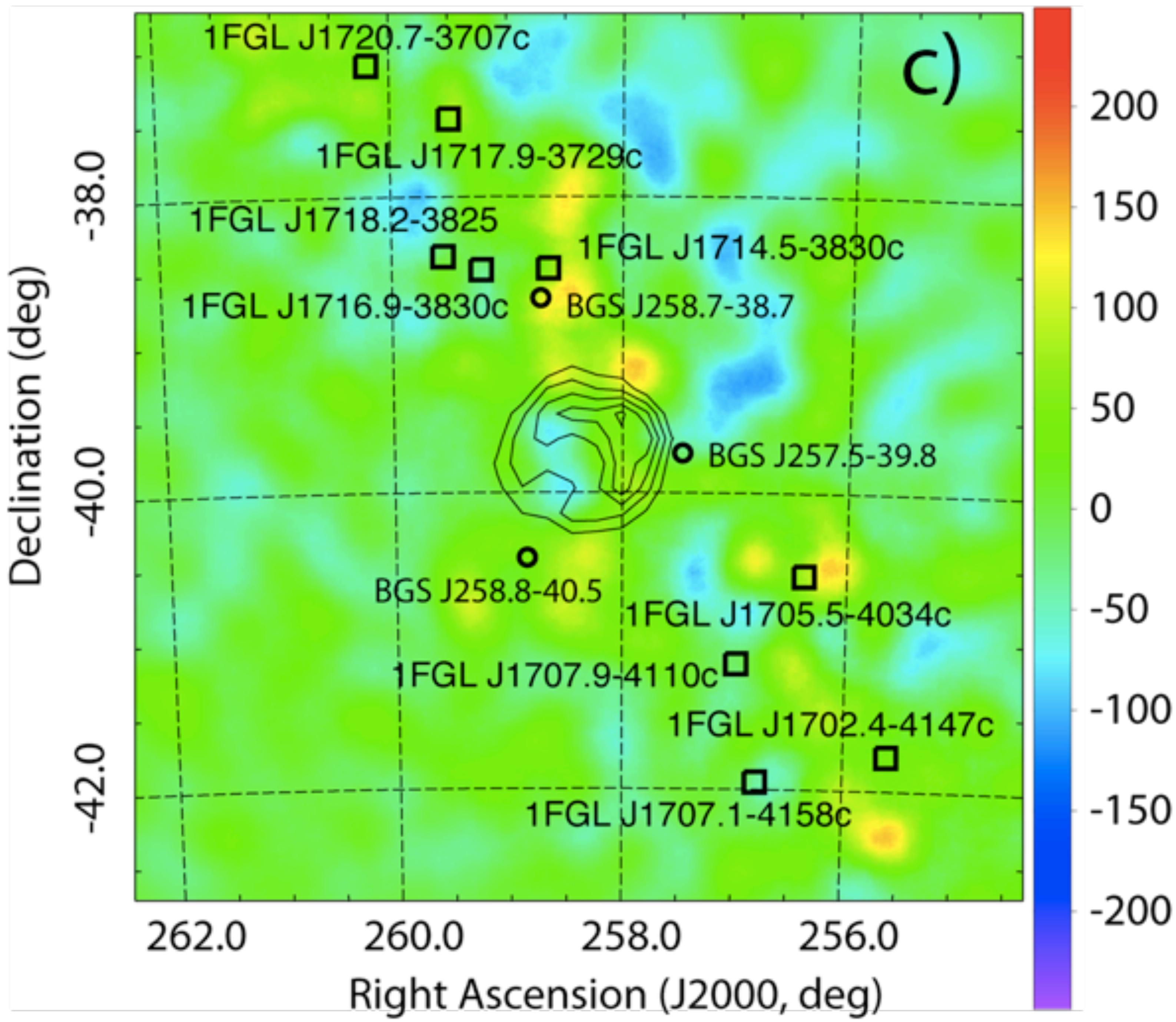

Smoothed Counts Map E > 3 GeV

- Gal. Diffuse and sources

- SNR model (Hess TeV)

The Example

RX J1713.7-3946

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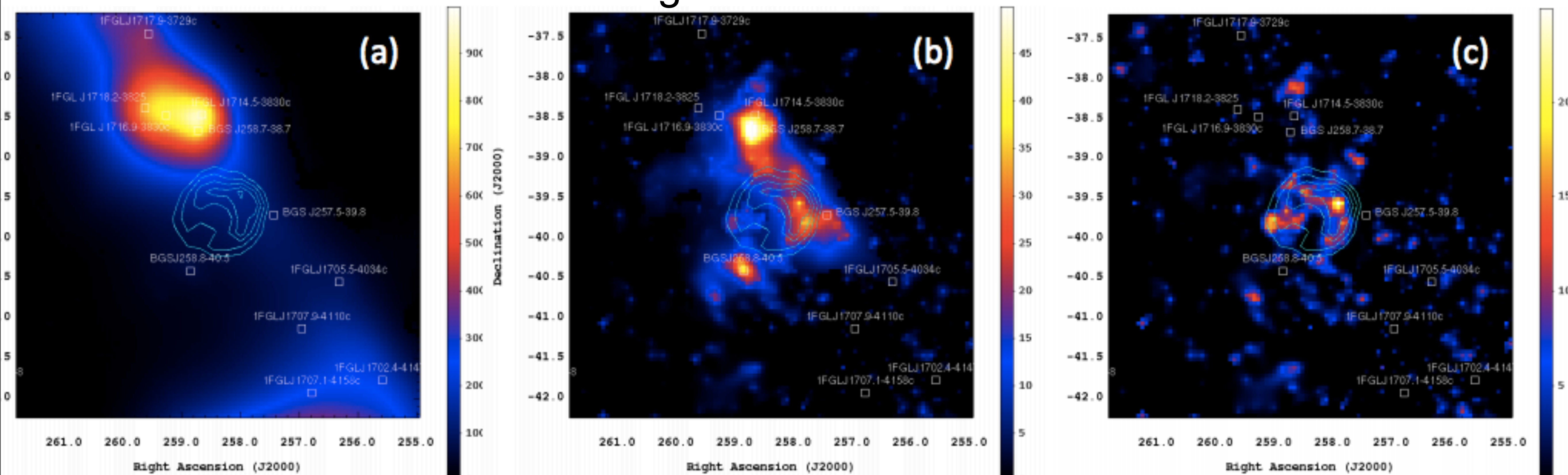
TS Maps

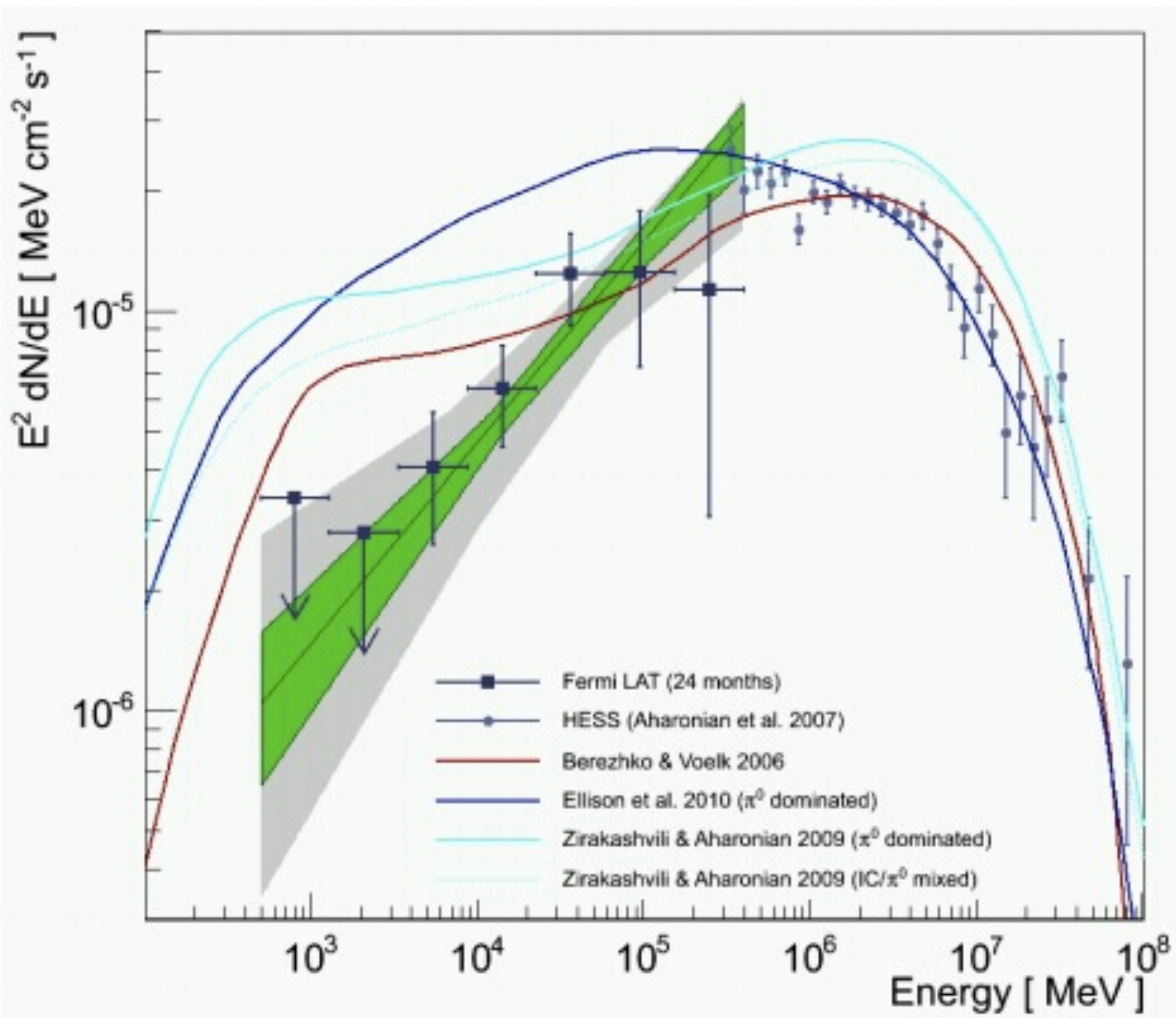
Galactic Diffuse | Background Subtracted | SNR Emission

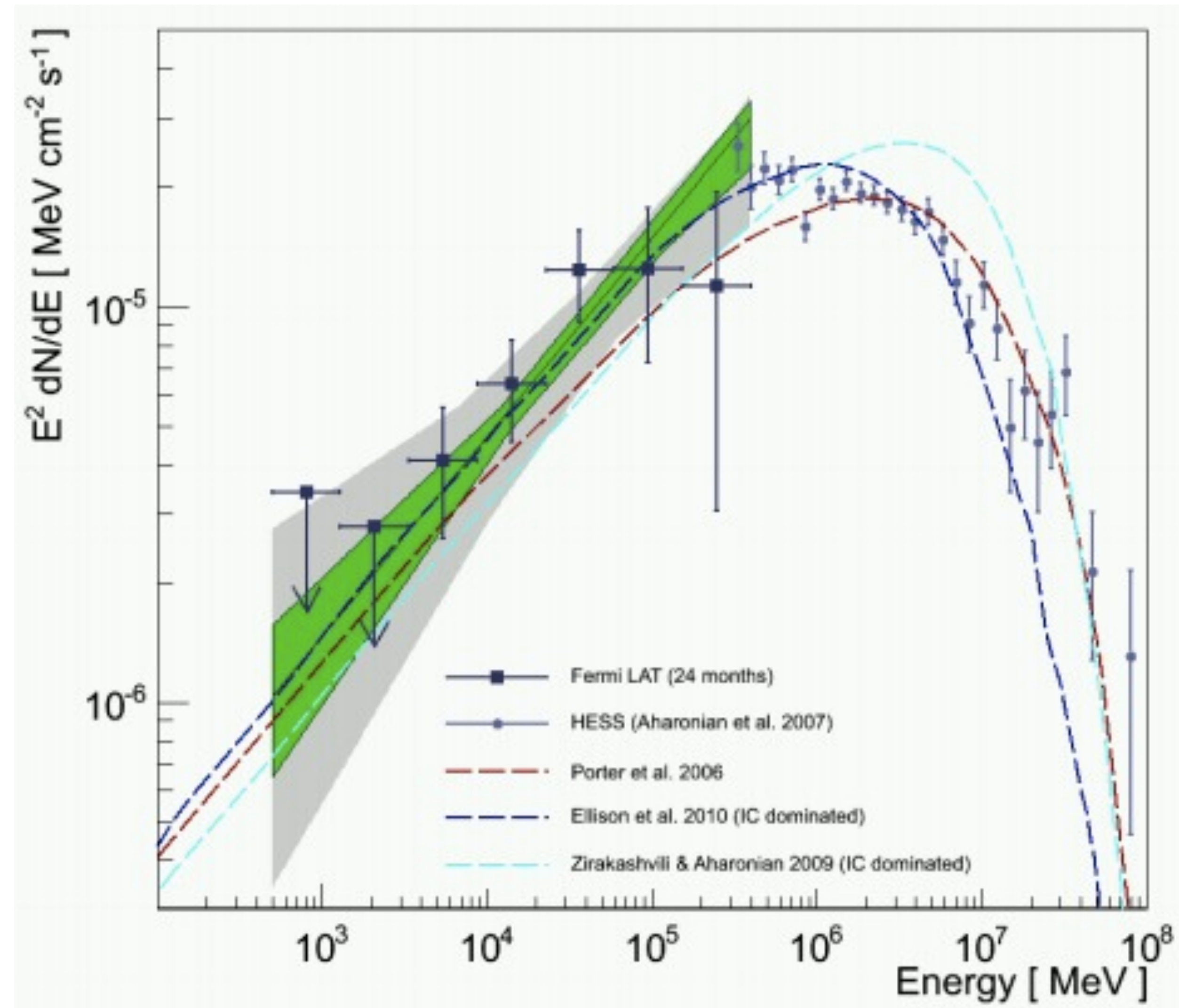


The Example

RX J1713.7-3946

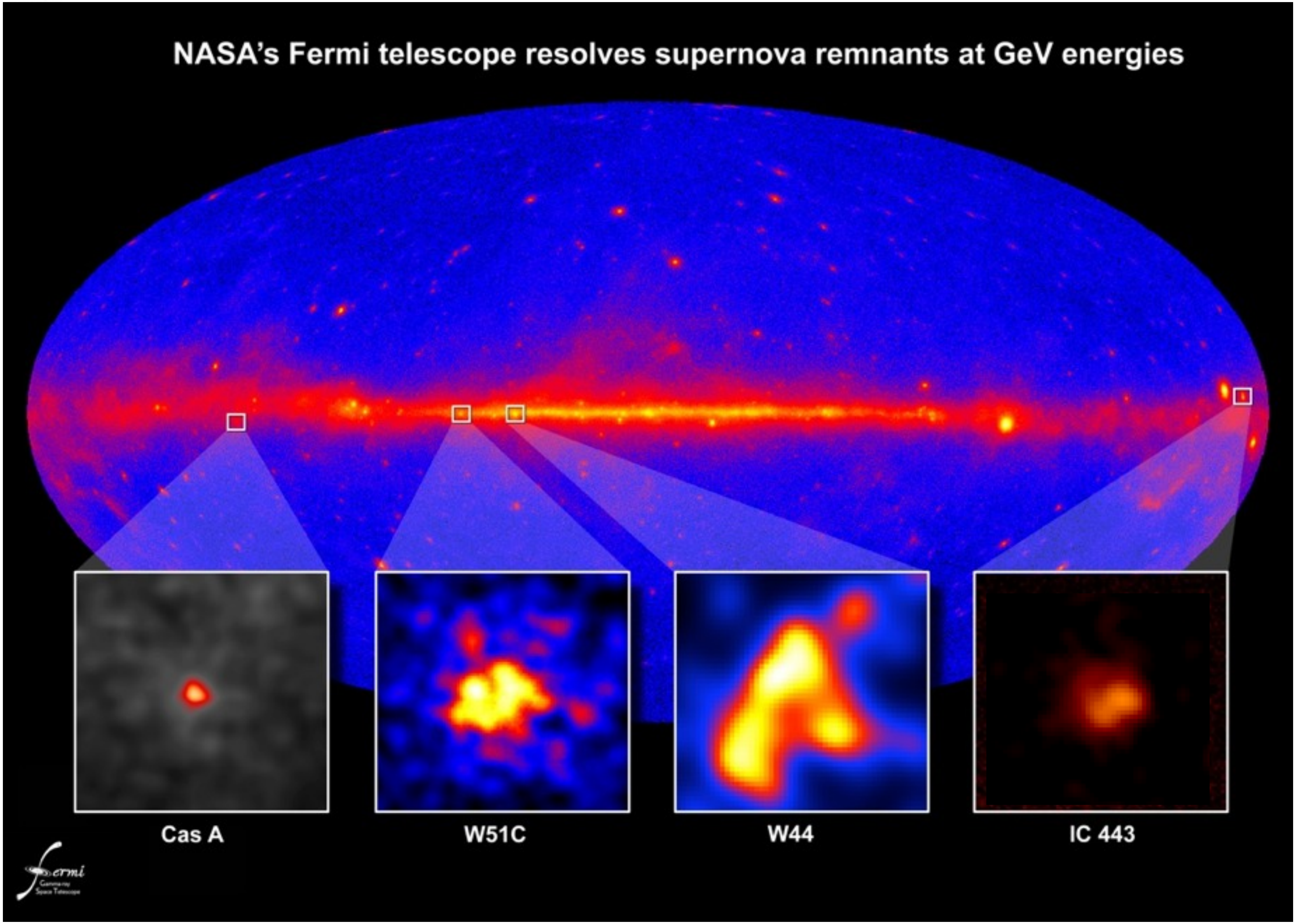
- Protons or electrons? . . . Fermi favors electrons (or possibly a mix)
  - Hard GeV photon index = 1.5 ±0.1(stat) ±0.1(sys)





- Note: Diffuse systematics estimated by using alt. Galactic background models generated by GALPROP. In the plane it's ***very*** important to verify sources are robust against such a strong background.

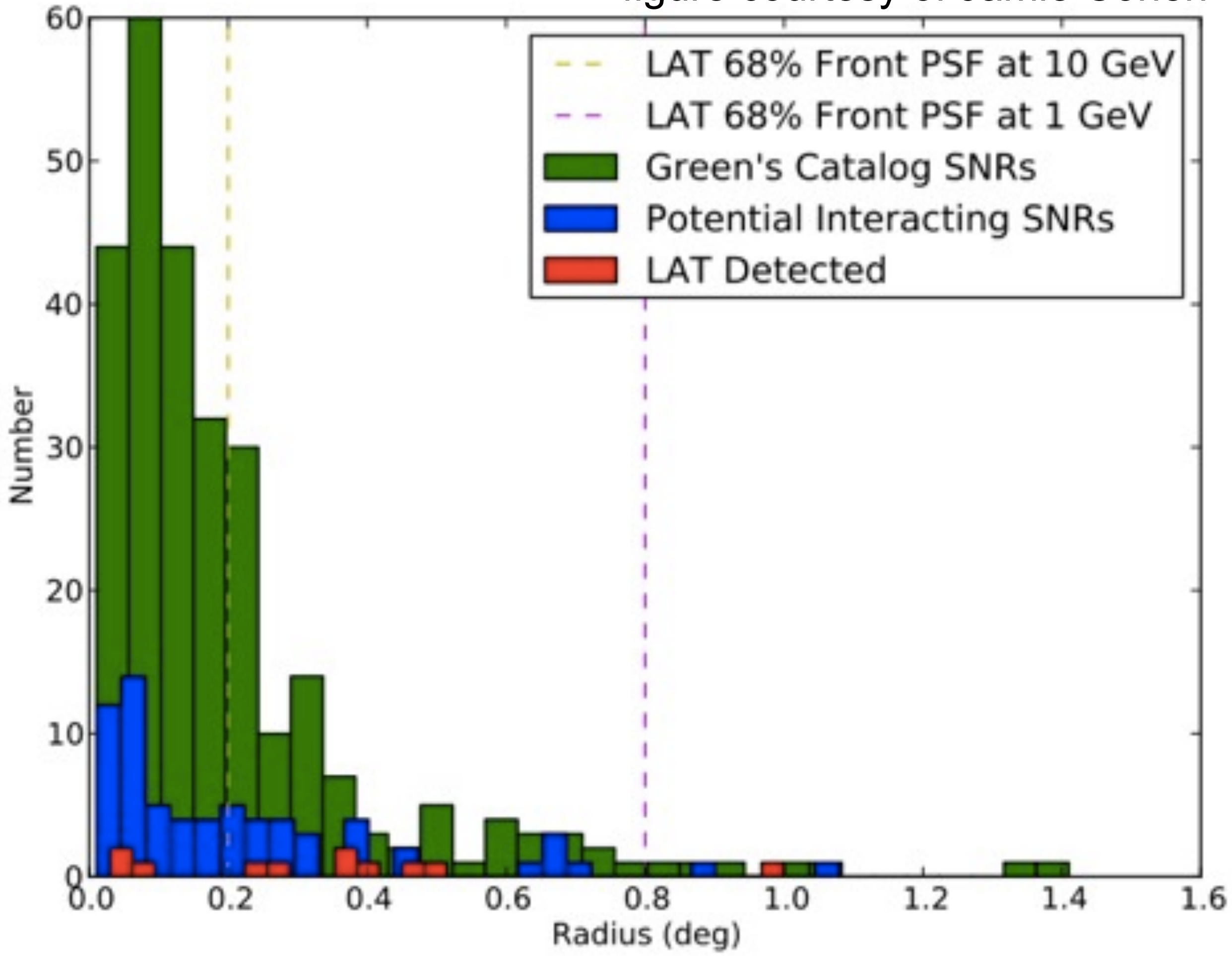
Fermi-LAT images GeV SNRs



The SNR/PWN source class

- In 2FGL, 89 associations with SNR/PWN (#3... after AGN,PSR)
  But there is a high probability for chance associations (~45%)
- Evidence for source extension is the key discriminator for identifying SNRs and PWNe (Pulsars are *and will always be* point sources)
- 279 known Galactic SNRs. LAT PSF allows ~25% of SNRs to be potentially identified as extended GeV sources.
- GeV source morphology is inherently interesting:
  - comparison with TeV
  - CR escape/diffusion
  - localized CR acceleration

figure courtesy of Jamie Cohen



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Note: Guide to extended source analysis on fssc web:
fermi.gsfc.nasa.gov/ssc/data/analysis/scitools/extended/extended.html

GeV *Identified* SNRs

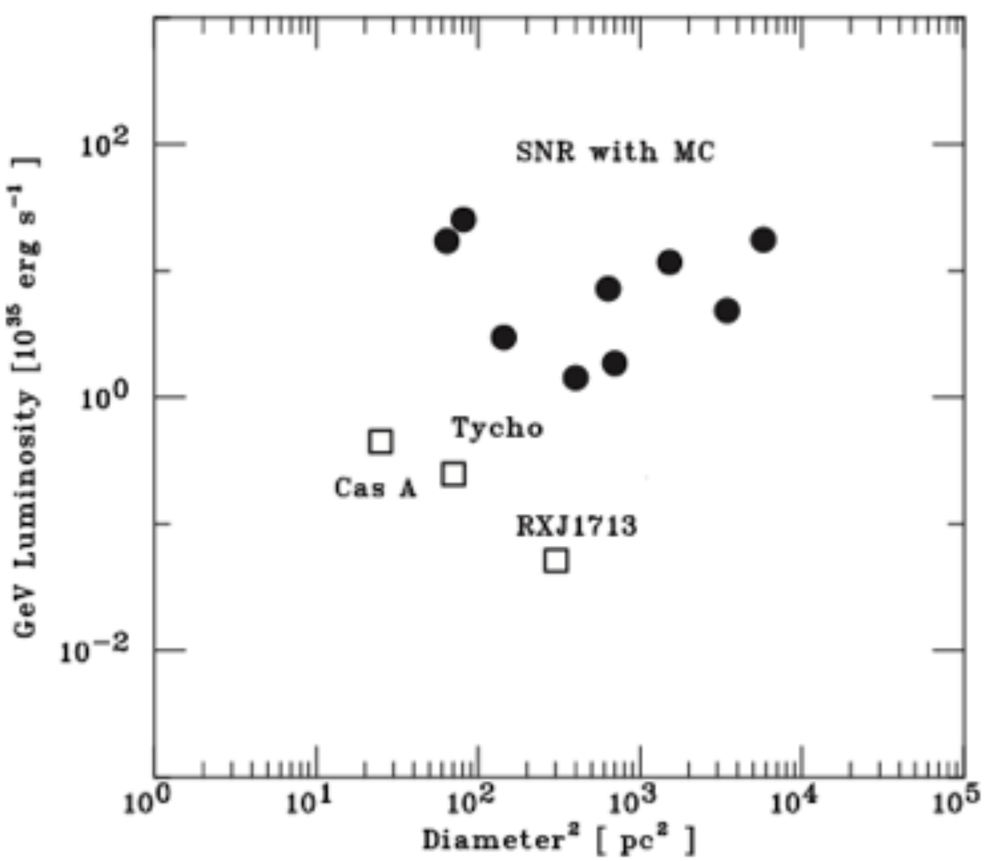
- To date ~13 SNRs identified as GeV sources, either by spatial extension, or ruling out other sources (PSR, PWN).

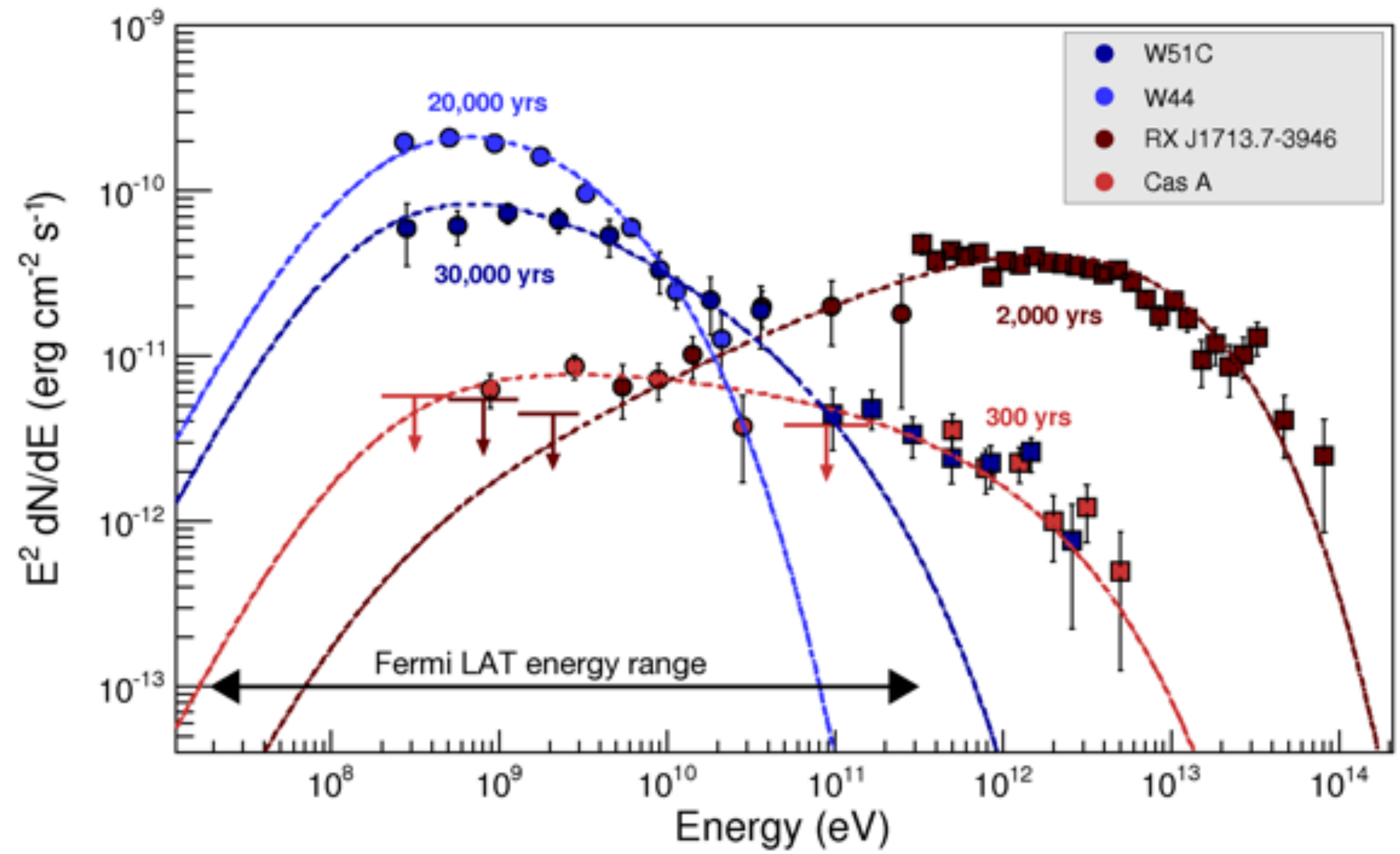
SNR name	Index 1	Index 2	E_{break} (GeV)	Age (kyr)	Ref.
Cassiopeia A	−2.1±0.1	−2.4±0.2*	>100	0.33	[2]
Tycho	−2.3±0.2	−2.0±0.5*	–	0.44	[3]
Vela, Jr.	−1.9±0.2	−2.1±0.2*	–	0.7	[4]
RX J1713.7−3946	−1.5±0.1	−2.1±0.1 *	–	1.6	[5]
Cygnus Loop	−1.83±0.06	−3.2±0.2	2.4±0.3	∼20	[7]
S147	1.4±0.5	2.5±0.2	1.0±0.8	30	[8]
W49B	−2.18±0.04	−2.9±0.2	4.8±1.6	∼4	[9]
CTB 37A	−2.28±0.1	–	–	∼15	[10,16]
W30	2.1±0.1	2.7±0.1	2.4±1.2	25	[10,11]
IC 443	−1.93±0.03	−2.56±0.11	3.25±0.6	10-30	[12]
W44	−2.1±0.1	−3.0±0.2	1.9±0.5	20-40	[13]
W28	−2.1±0.3	−2.74±0.1	1.0±0.2	35-150	[14]
W51C	−1.97±0.08	−2.44±0.09	1.9±0.2	20-40	[15]

*Index is taken from TeV ACT measurements.

Emerging classes of γ-ray SNRs

- How does the cosmic ray content of SNRs vary with age?
  Do we see evidence of spectral evolution? Luminosity changes?





- Perhaps, but these could also result from different environments which favor different emission mechanisms.
  => SNRs need to examine on a source-by-source basis.

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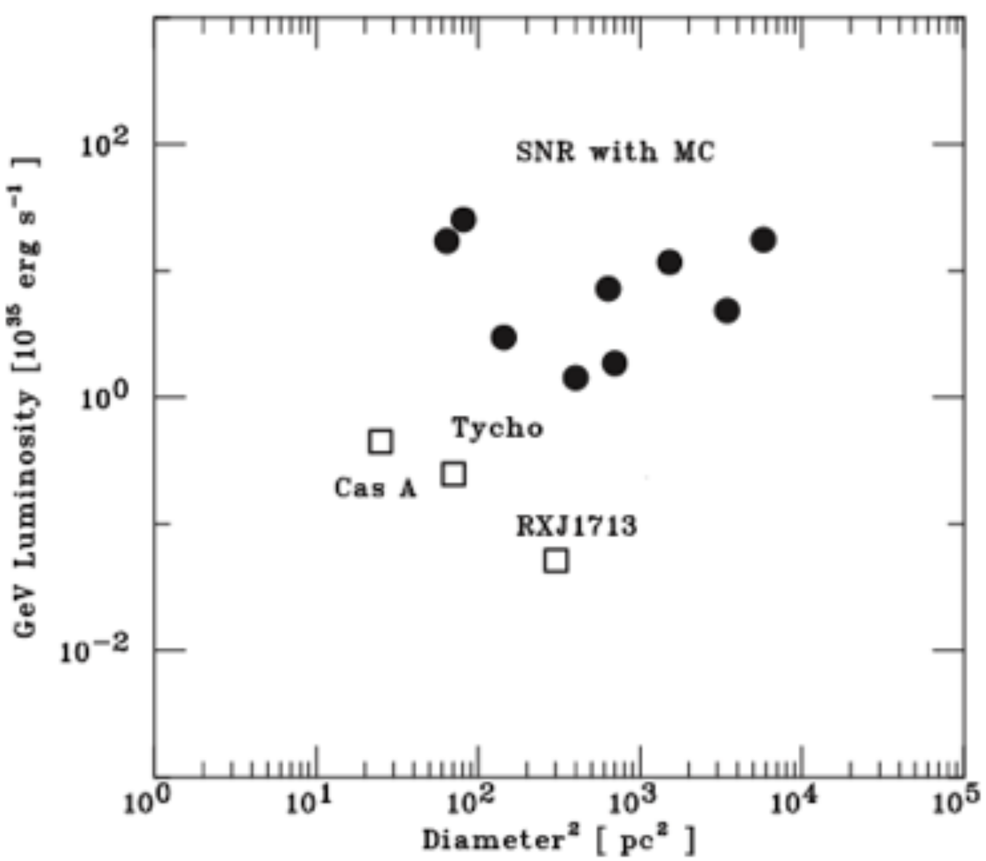

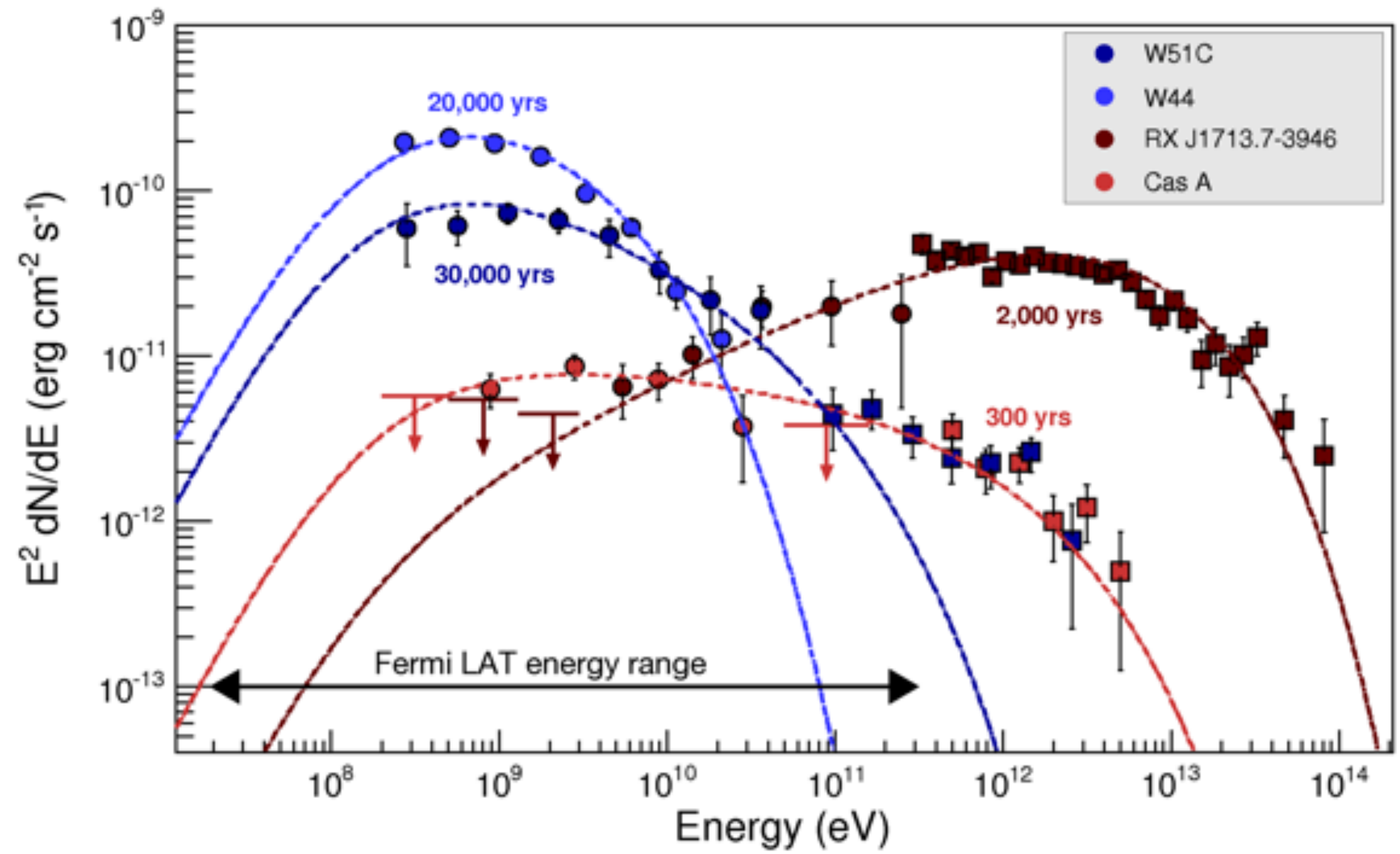

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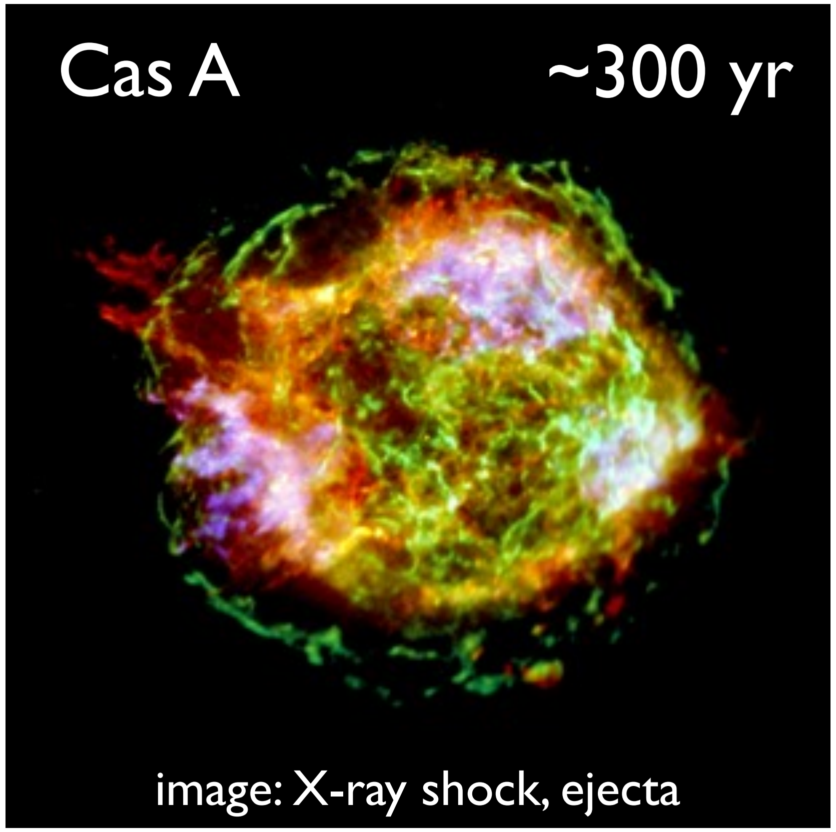
Emerging classes of γ-ray SNRs

- Identified SNRs generally fall into two classes:

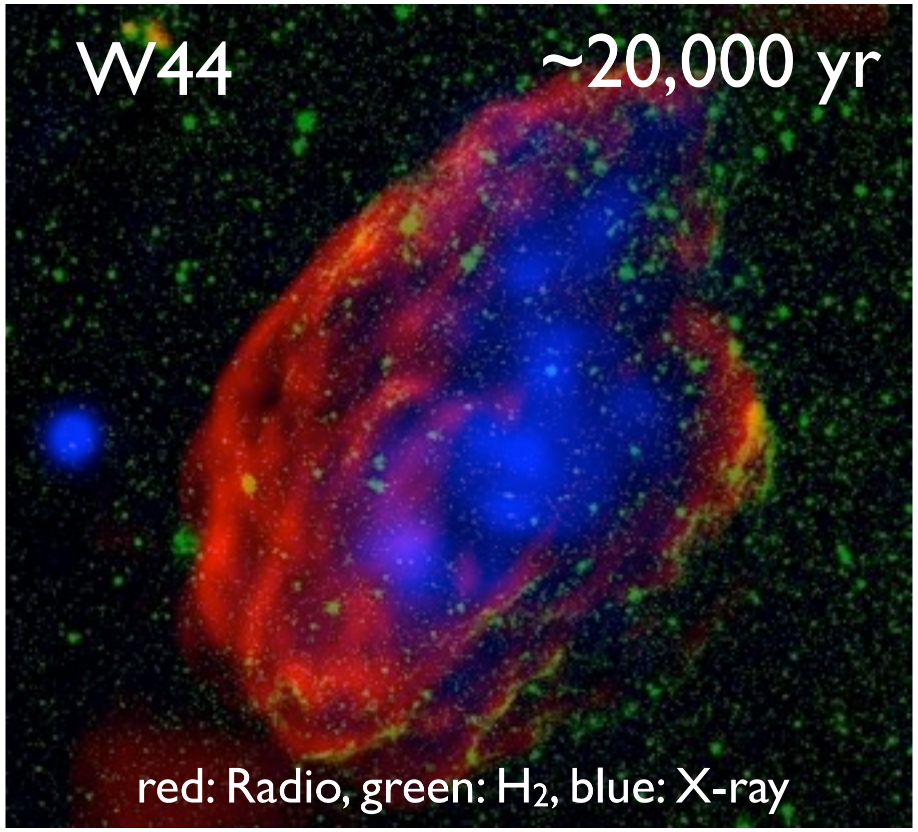
Young SNRs

- X-ray synchrotron, multi-TeV electrons
- ongoing particle acceleration
- *but* age-limited



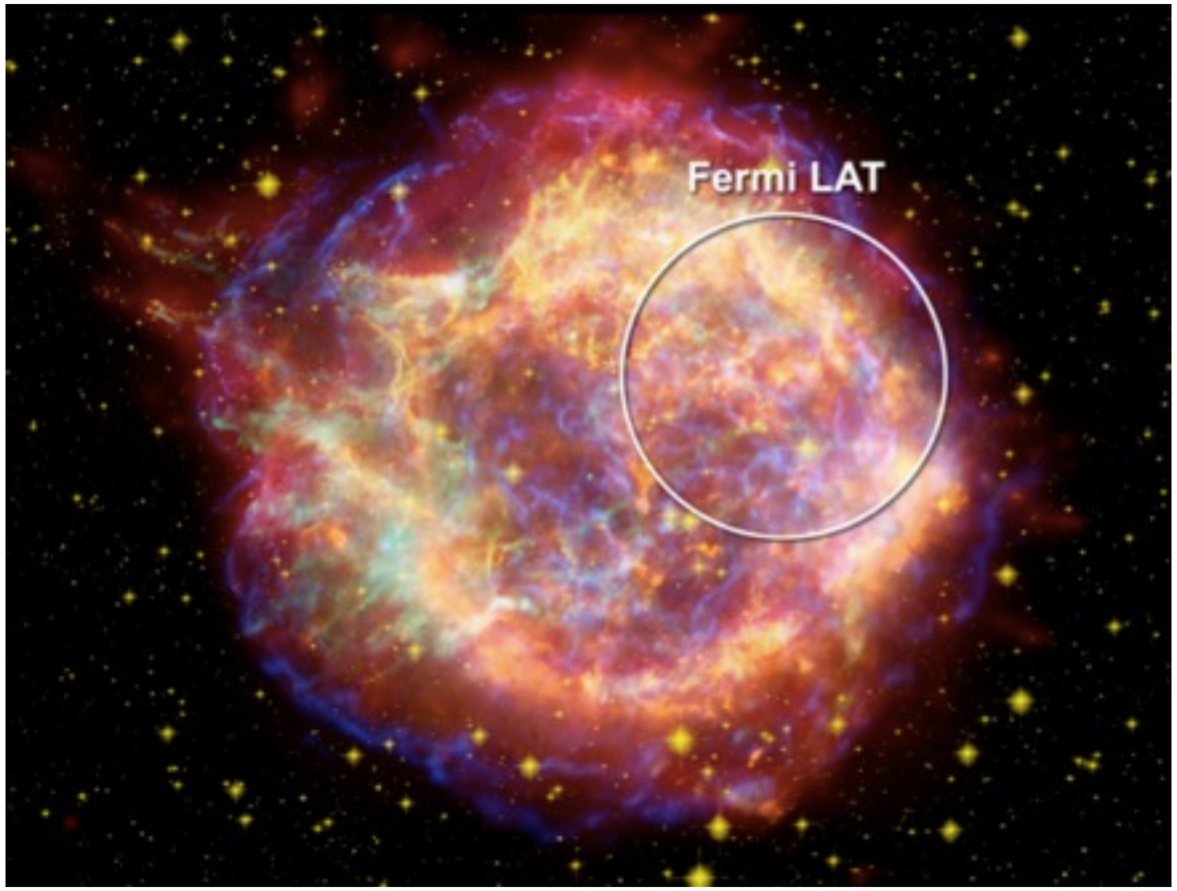
Older SNRs near clouds

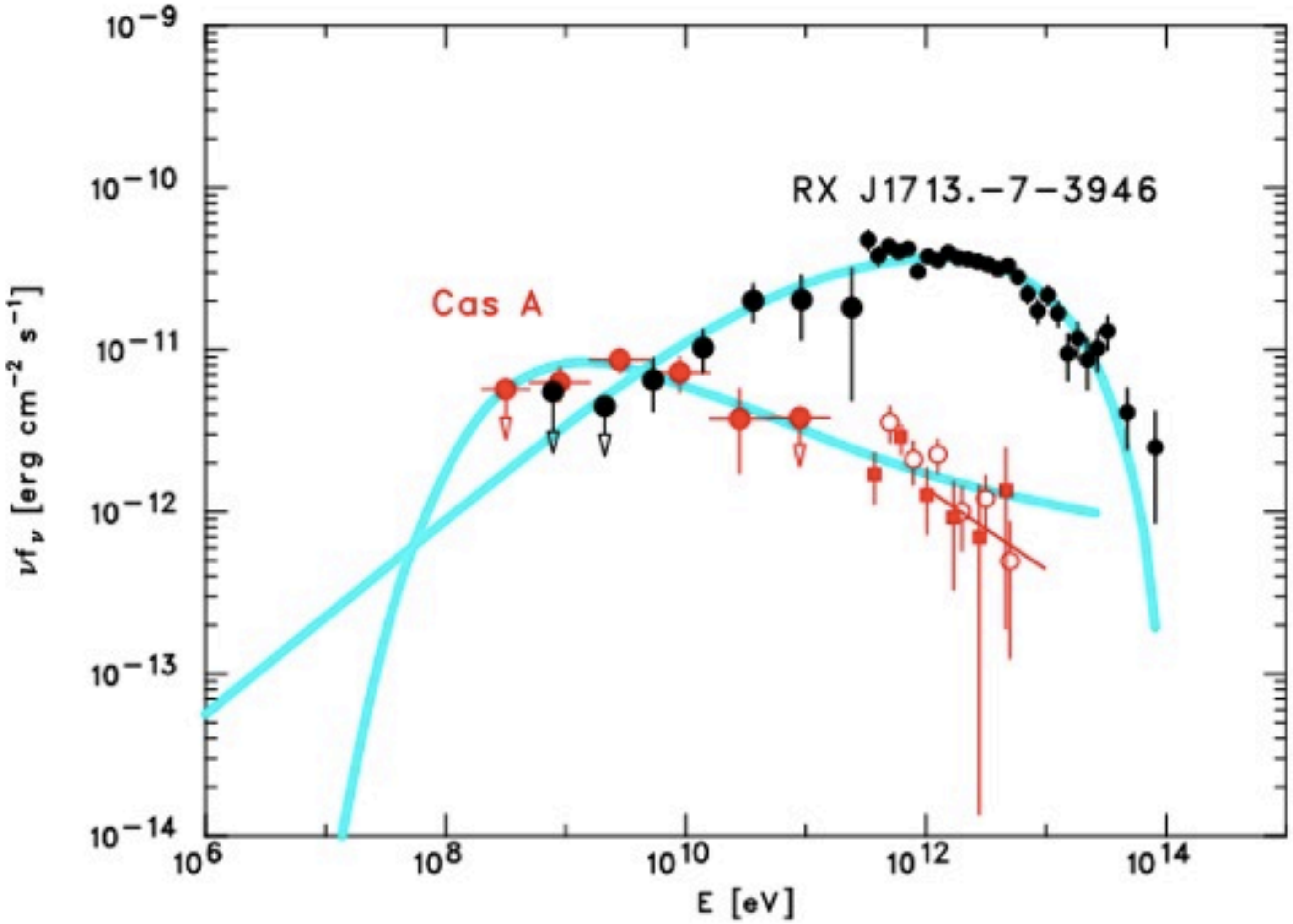
- th. x-rays ~1 keV, late-Sedov/radiative
- Inefficient accel. of e^- at TeV energies
  fast losses via synchrotron emission
- large target (enhances luminosity)



Young SNRs: Cas A

- Remnant of a Type IIb (core-collapse) SNe around AD 1680.
- Angular size only 2.5 arcminutes (Veritas detects TeV point source)
- Clear spectral differences: Cas A(~330 yr) vs RXJ1713(~2000 yr)

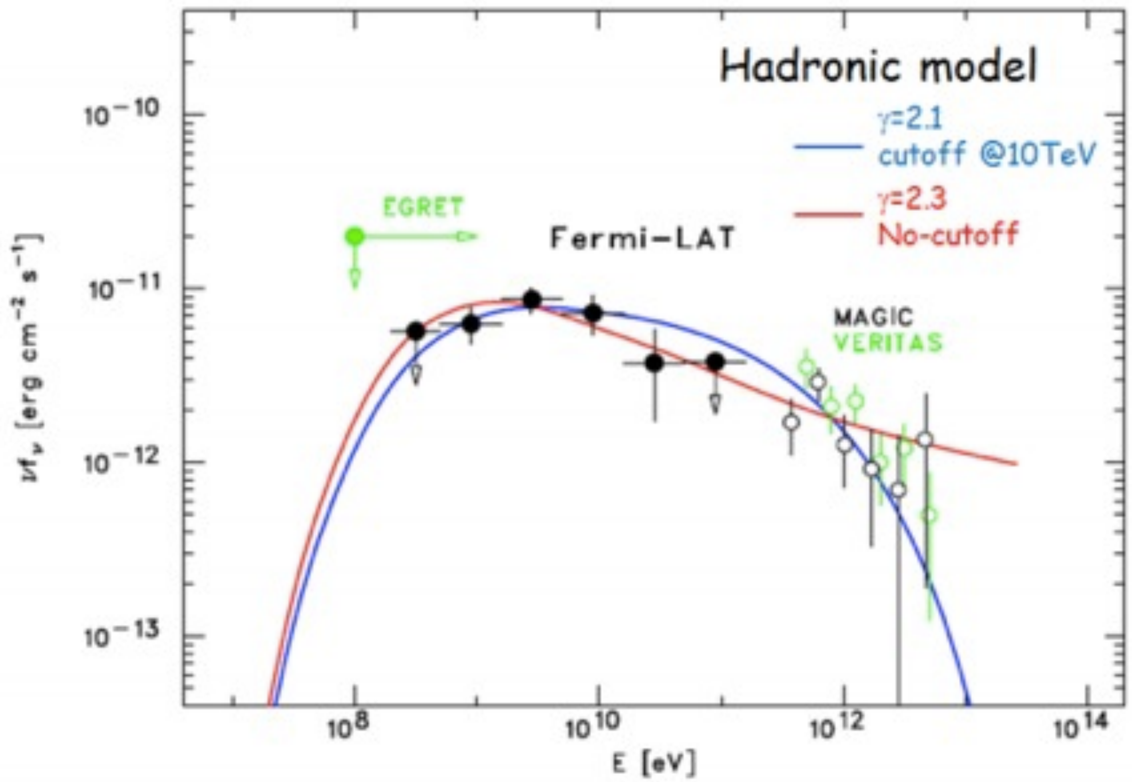


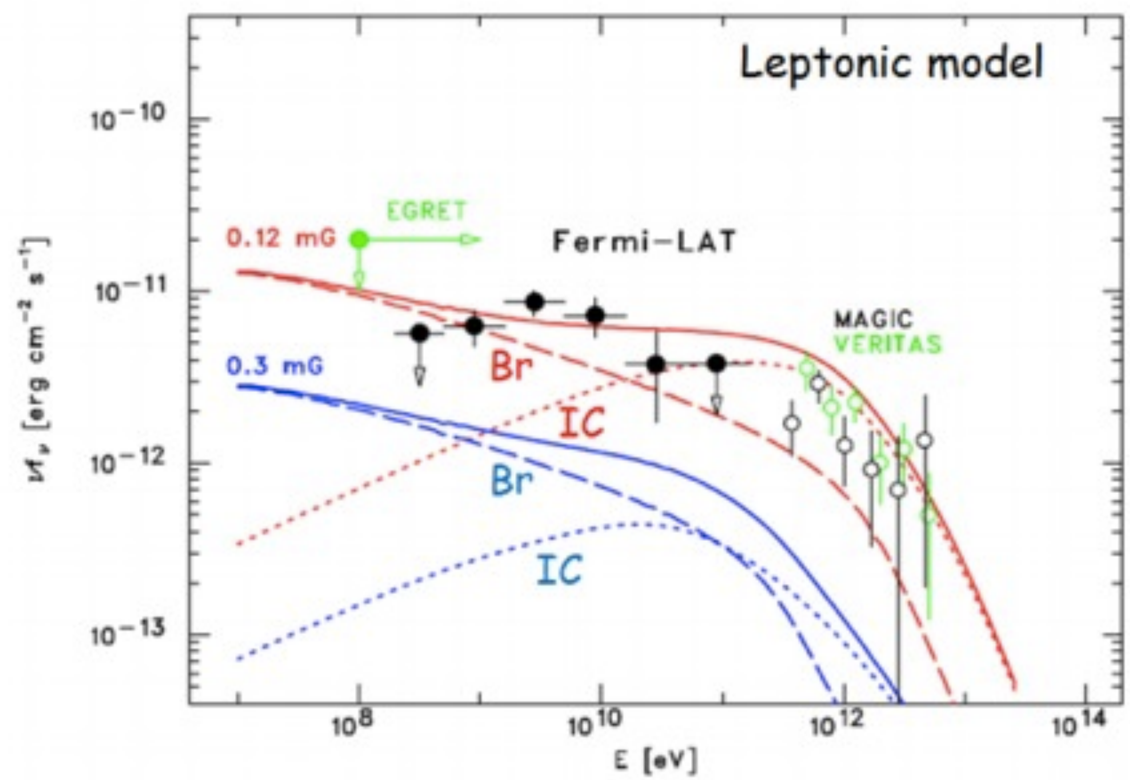


- Tycho's SNR (Type Ia in AD 1572) shows similar index ~2.2 and comparably small diameter (=> point source at GeV/TeV)

Young SNRs: Cas A

- Both leptonic and hadronic origins are viable
- X-ray synchrotron filaments widths, variability => B~0.3 mG (Parizot+ 2006) disfavoring Leptonic models



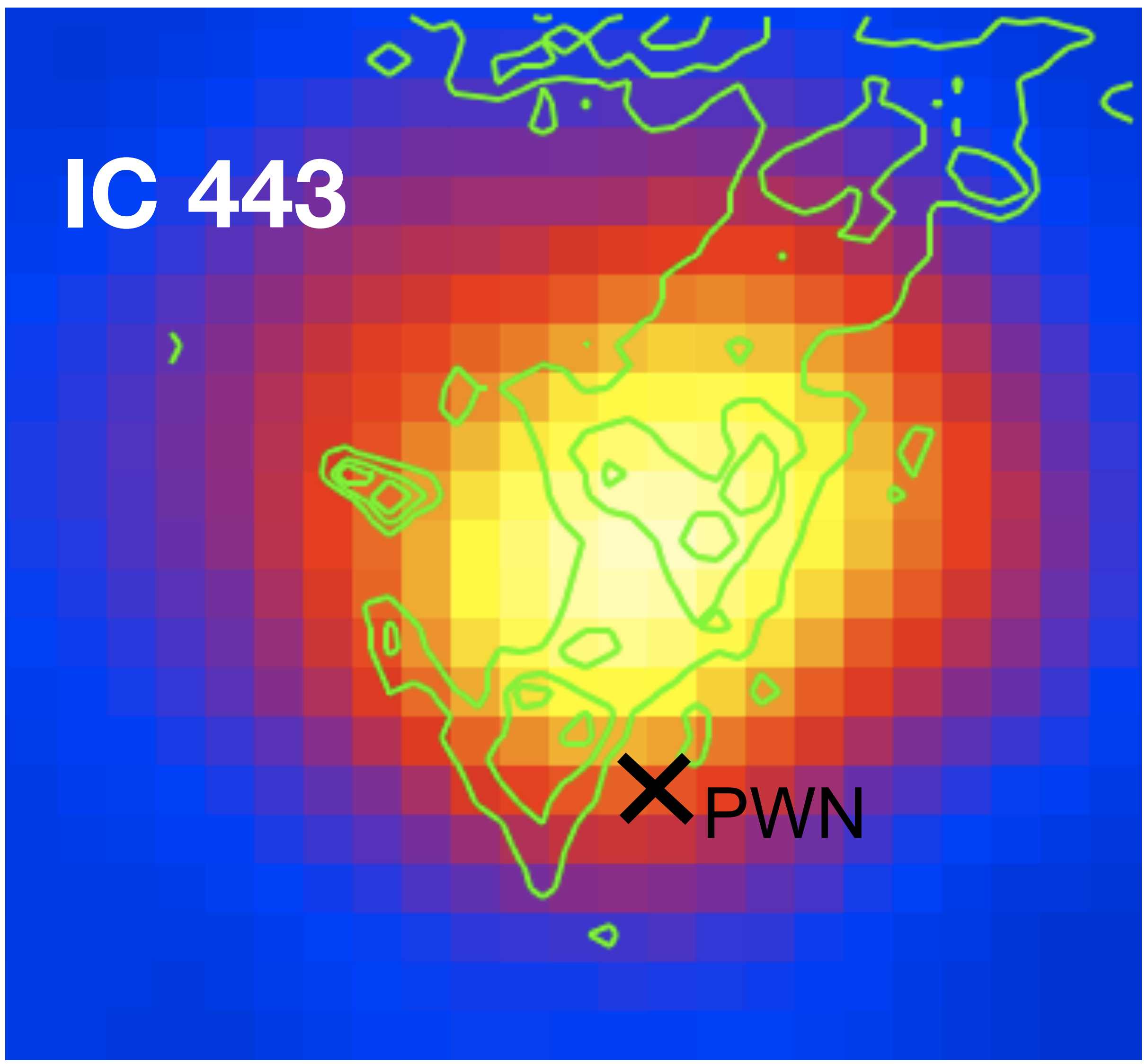


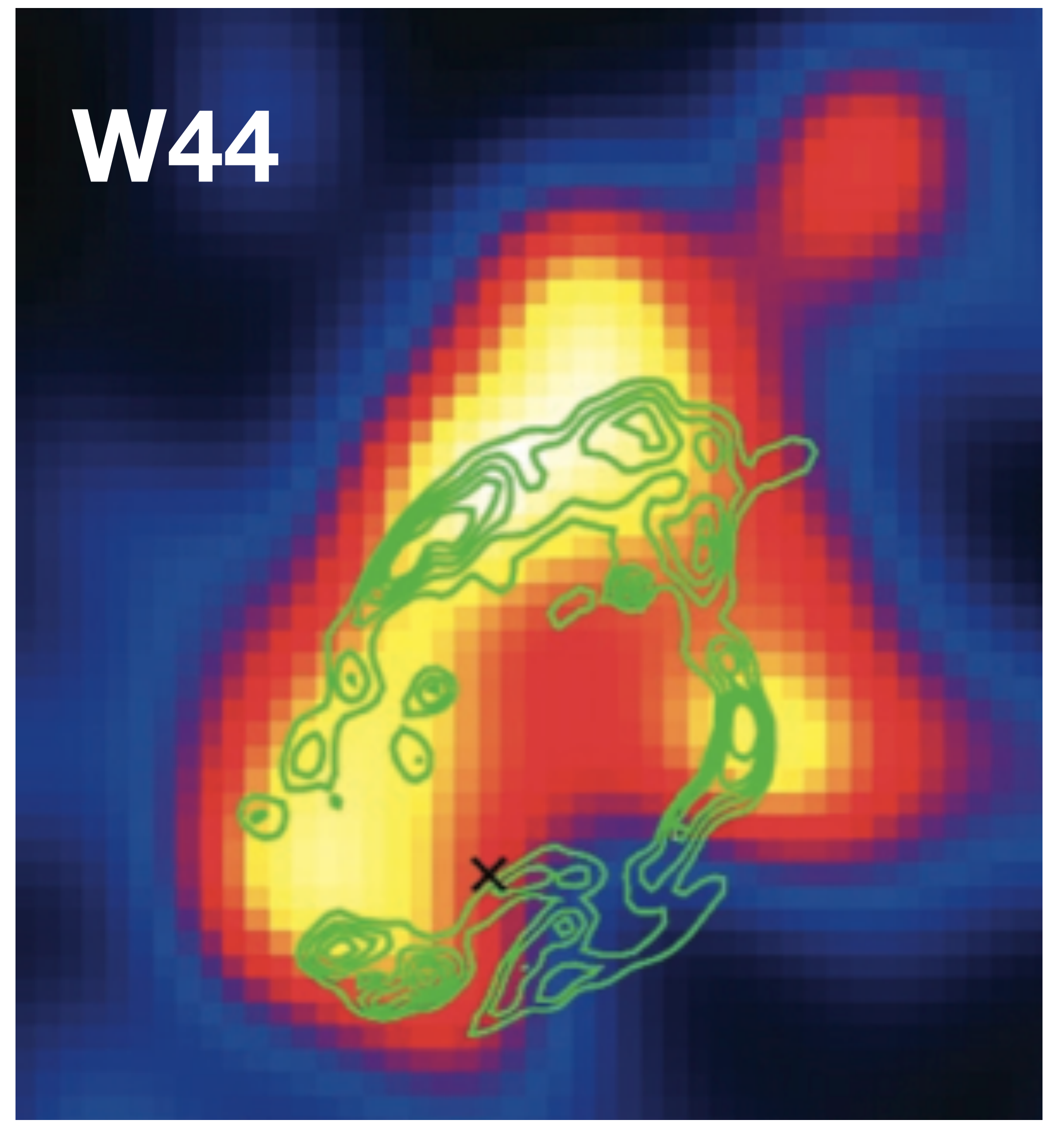
- Hadronic model:
  Wp = 0.4×10^{50} erg
  for n_H = 10 cm^{-3}
- Leptonic model:
  We = 0.4×10^{50} erg
  for n_H = 10 cm^{-3}
- ~few% efficiency in converting $E_{kinetic}$ to CR protons
- Fermi may prove hadronic model, observing "pion bump" ~80 MeV

SNRs Interacting with Clouds

- "Middle-aged" (~20,000 yr) SNRs show GeV emission well-correlated with morphology of dense cloud.

$$\tau_{pp} = (nc\kappa\sigma_{pp})^{-1} \approx 3 \times 10^5 \text{ yr} \left(\frac{n_{H_2}}{100 \text{ cm}^{-3}} \right)^{-1}$$





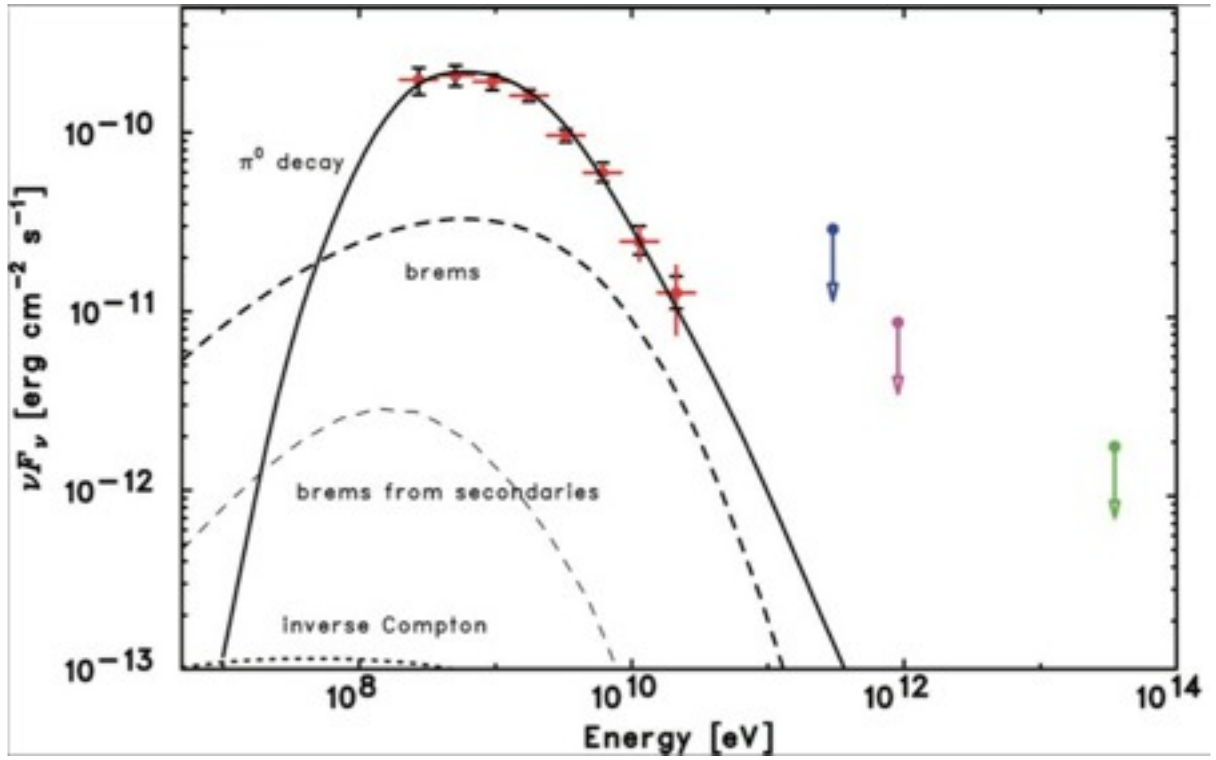
CO contours

H_2 contours

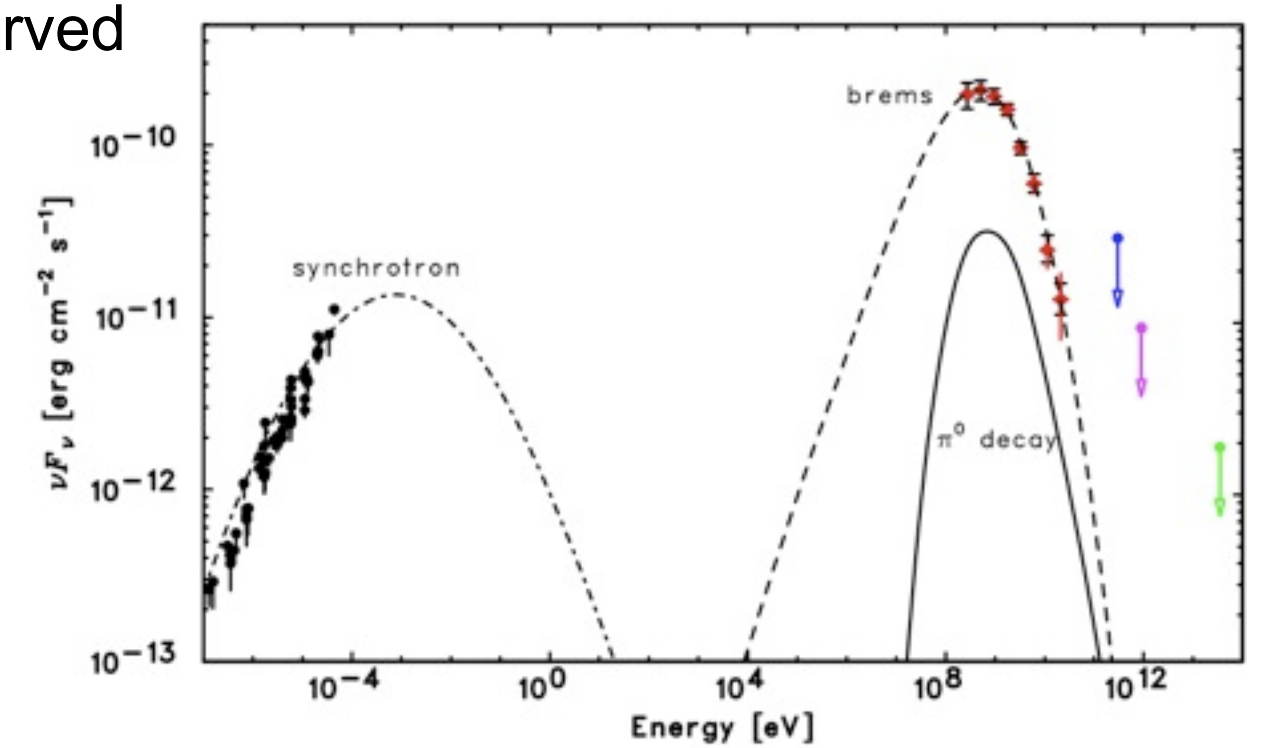
SNRs Interacting with Clouds

- Hadronic or Leptonic emission?
- Pion-decay produces *reasonable* fit
  - $\langle n_H \rangle$=100 cm^{-3} (Reach et al. '05)
  - B=70 μG (~1 mG for 10^5 cm^{-3}, scaling as B~n^{½})
  - assume K_{ep} ~ 0.01
    => **W_p = 6×10^{49} erg**, **W_e = 1×10^{48} erg**

W44 SED fitting



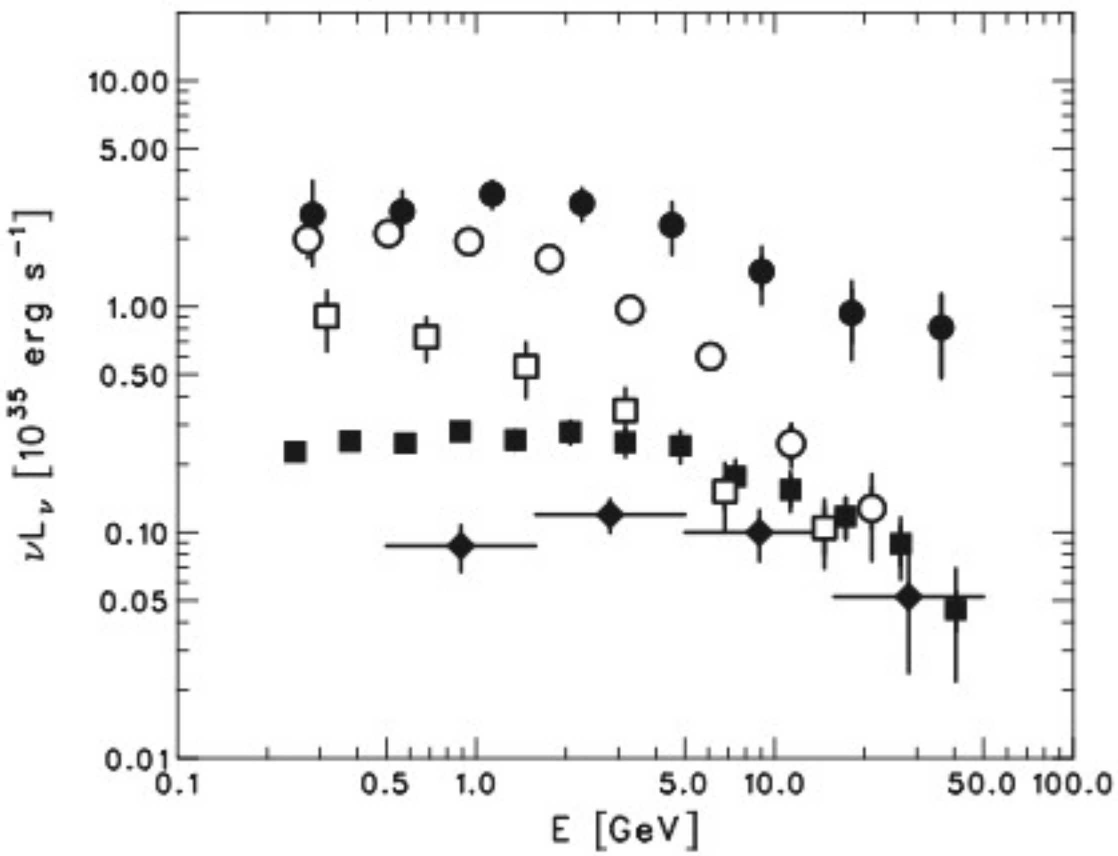
- Brems. model at the limit of reasonable
  - $\langle n_H \rangle$=3000 cm^{-3}, much higher than observed
  - B=220 μG (B>100 μG, no break <10 GHz)
  - assume K_{ep}=1 (must be >0.1 to pion decay)
    => **W_e = 3×10^{47} erg**



- If Fermi can measure spectrum at 20-100 MeV can discriminate between pion, brem. models (pion decay has sharp drop-off) or measure K_{ep} directly if both contribute.

SNRs Interacting with Clouds

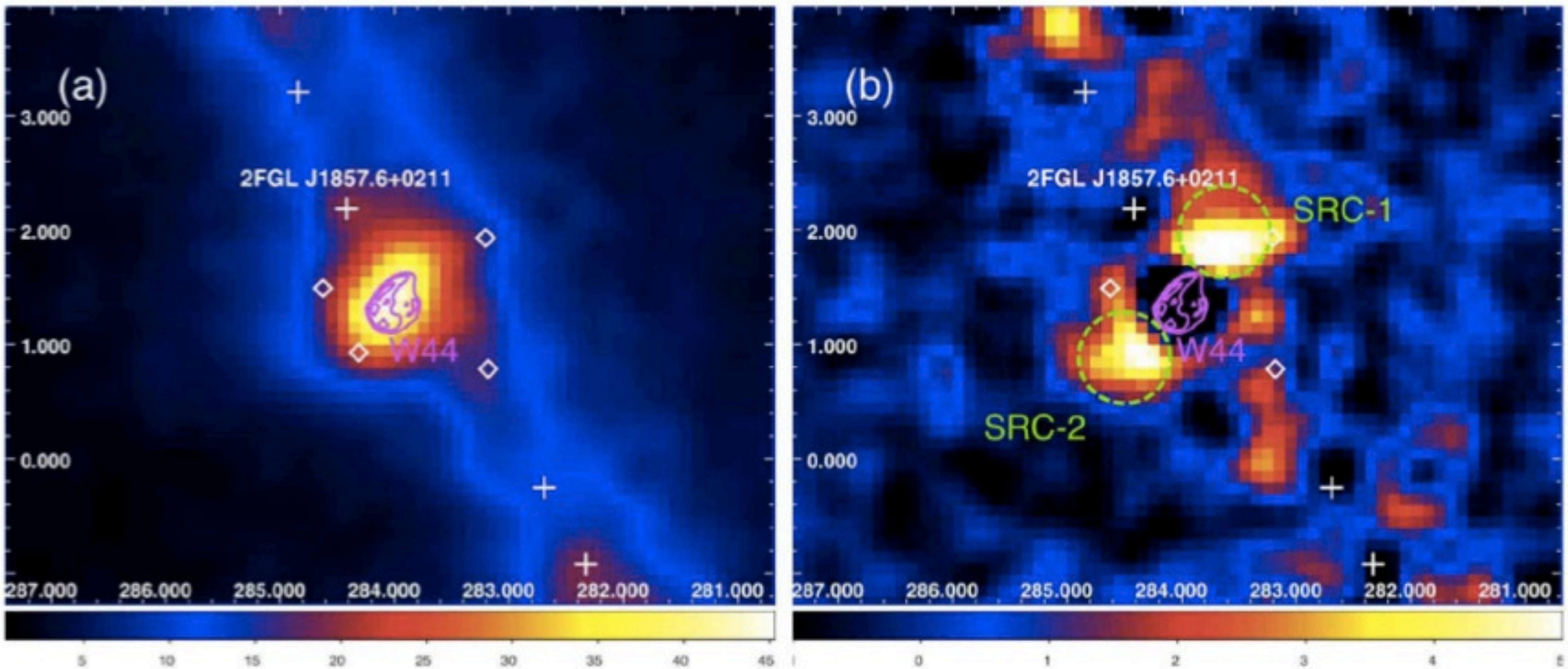
- Most SNR/MCs show break at ~few GeV (not bright TeV sources)
- Dense gas favors pion-decay or bremsstrahlung
  - if e/p ratio is << 1, then hadronic origin favored
  - L_{GeV} ~ 10^{35} erg/s, among the most luminous Gal. γ-ray sources
- Two general models:
  - **Runaway Cosmic Rays**: old SNRs cannot confine CRs, which diffuse into nearby clouds.
  - **Crushed clouds**: radiative shocks into the MC allows high gas compression, adiabatically compressing and re-accelerating CRs, to enhance L_{GeV}



- How is CR acceleration different in dense environments?

W44

- With 3 years of data, W44 shows nearby sources outside radio SNR. Possibly CRs that have leaked out into nearby clouds



- If confirmed, probes CR diffusion in molecular clouds!

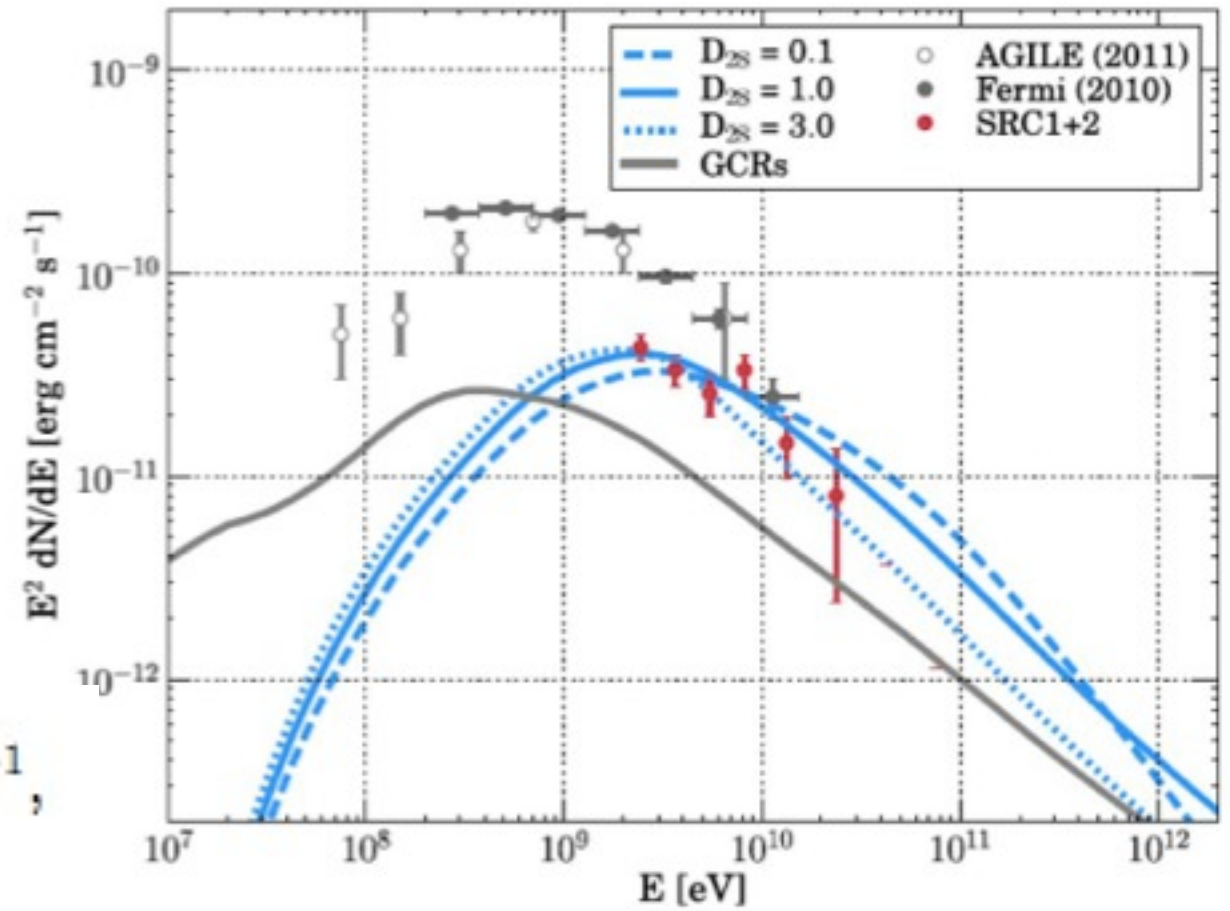
Uchiyama+ 2012

W44

- LAT spectrum of nearby sources appears consistent with SNR

$$t_{\rm esc}(p) = t_{\rm ST}\left(\frac{p}{p_{\rm max}}\right)^{-1/\chi},$$

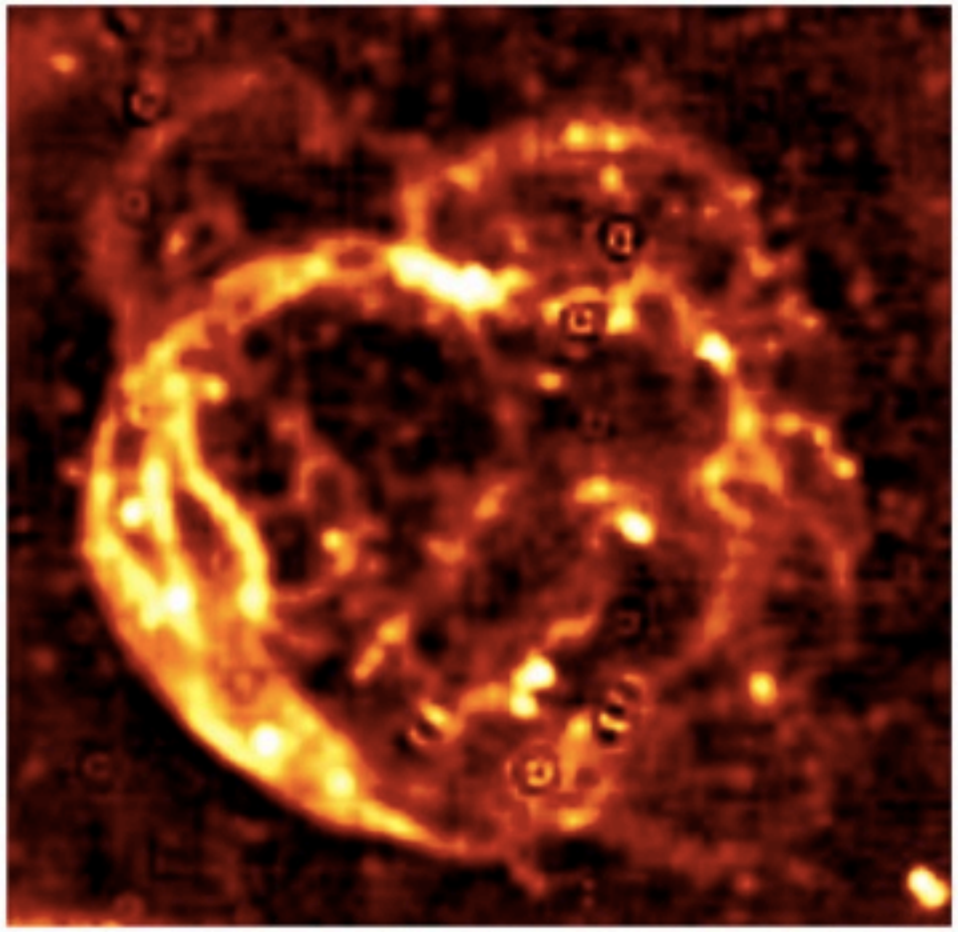
$$D_{\rm ISM}(p) = 10^{28}\ D_{28}\ \left(\frac{p}{10\ {\rm GeV}\ c^{-1}}\right)^{\delta}\ {\rm cm}^2\ {\rm s}^{-1},$$



- For D_{28}~0.1-3: W_{esc} ~ 0.3-2.7x10^{50} erg ($M_{cloud}/10^5\ M_{sol}$)
- W44 hadronic model: Wcr,p ~ 0.4x10^{50} erg

S147

- Most recent LAT-identified SNR (Katsuta et al. 2012)
- Old (2-10 kyr), large (D~76 pc), and nearby (1.3 kpc) SNR
- No evidence for interaction with dense cloud, but there are bright Halpha filaments, indicating radiative shocks (v_S ~500 km/s)

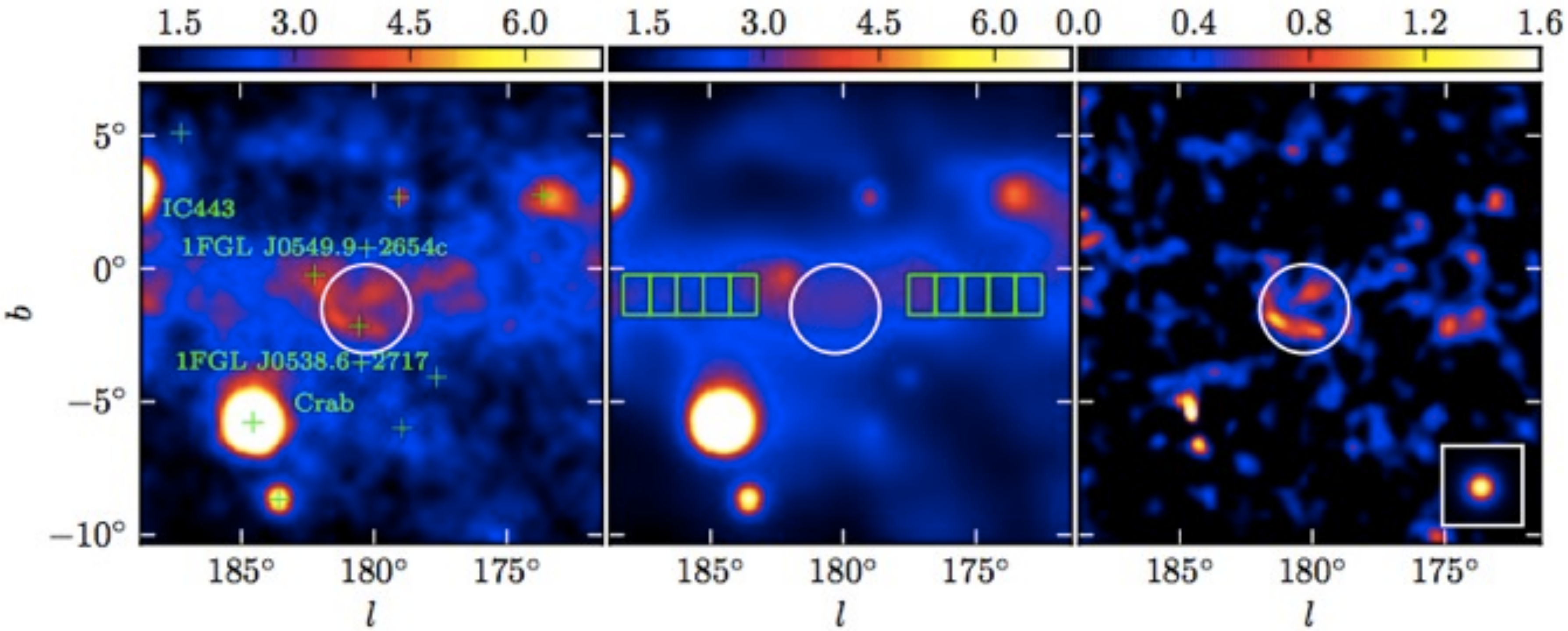


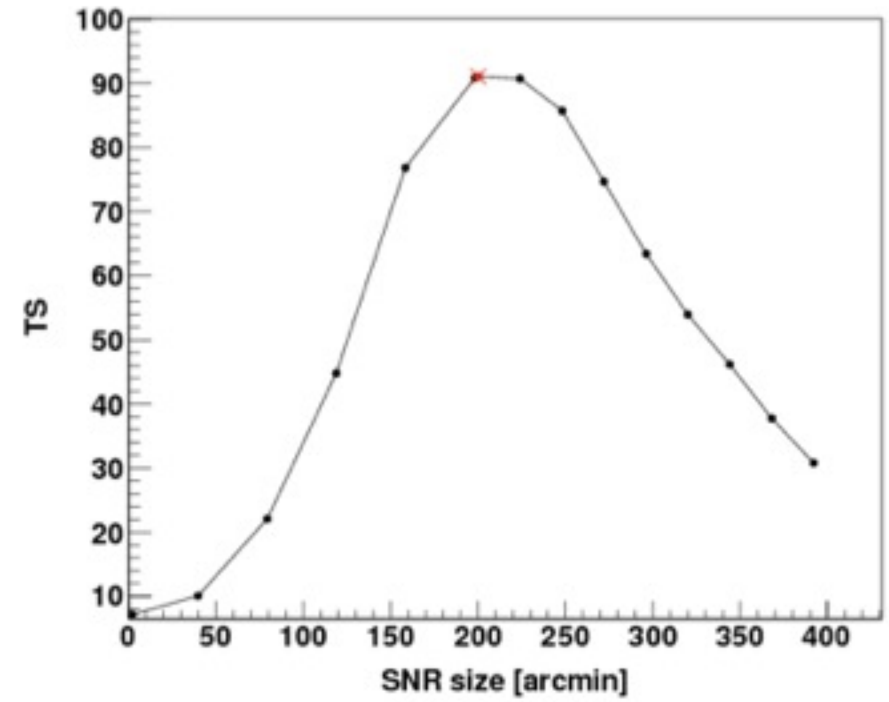
Radio 11cm map

Hα Optical image

S147

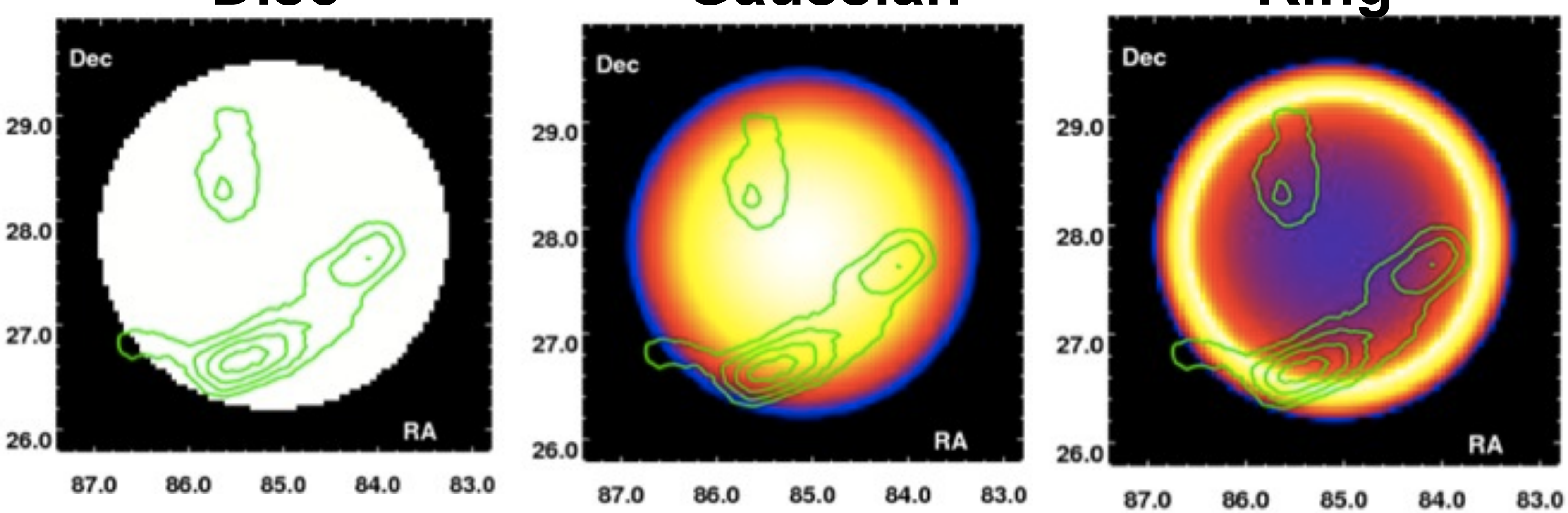
- Near anti-center, so relatively low Galactic background in plane.





- What is the spatial structure of GeV emission?

Disc **Gaussian** **Ring**



S147

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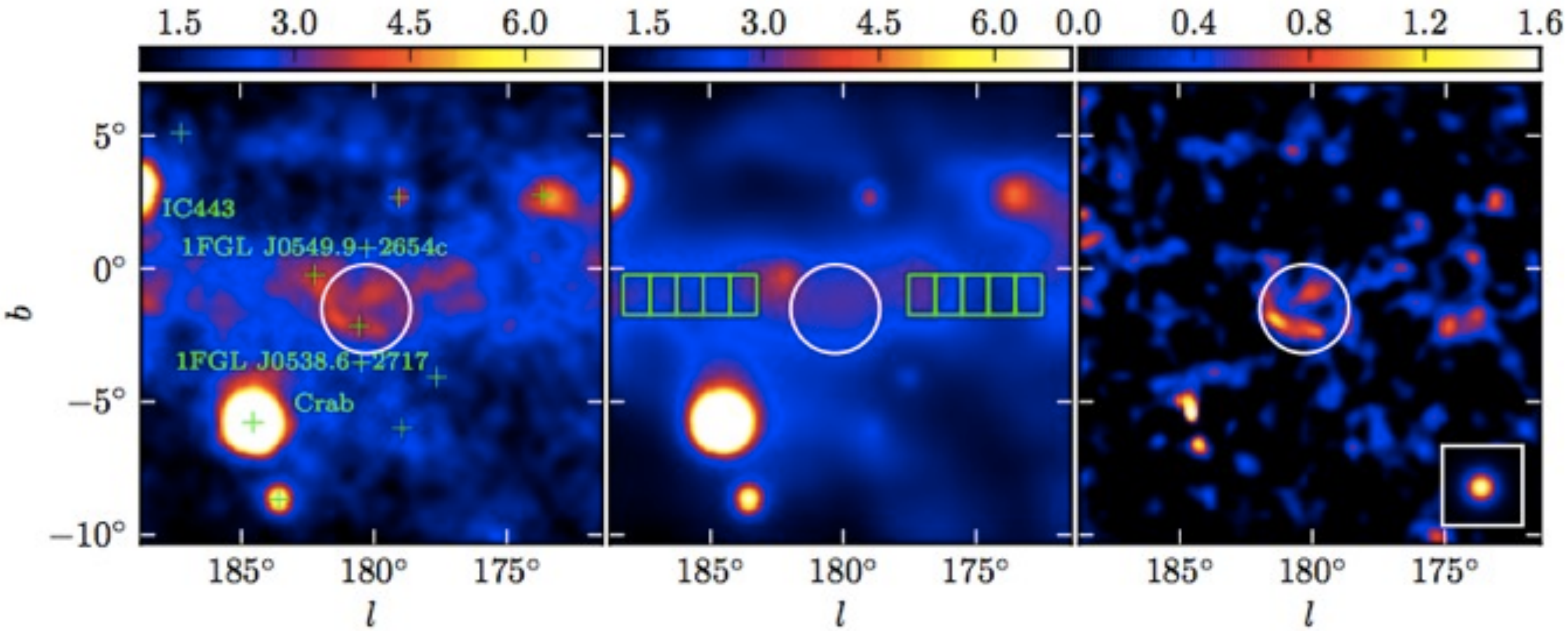
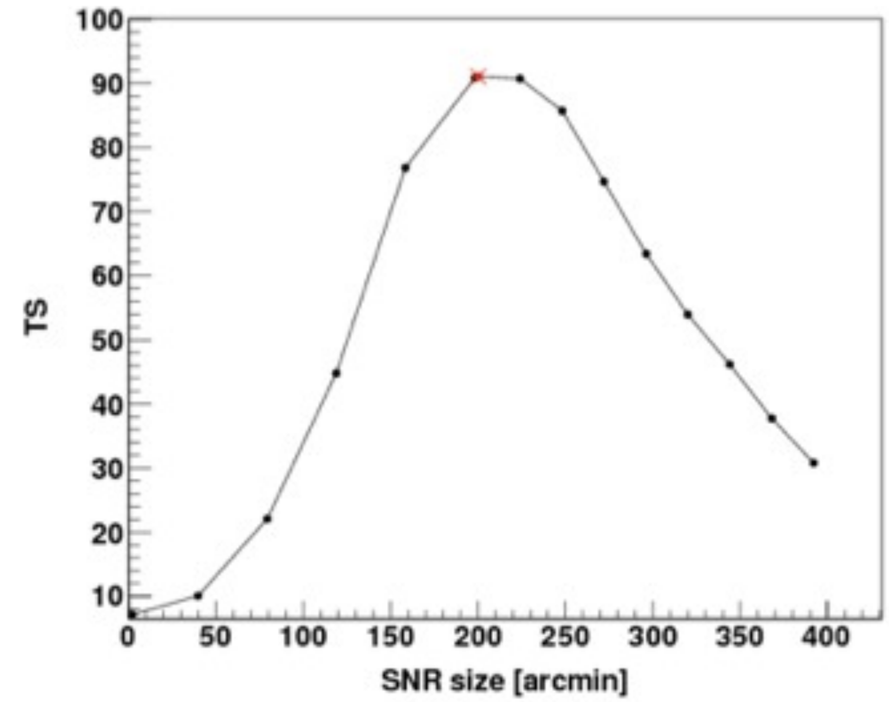
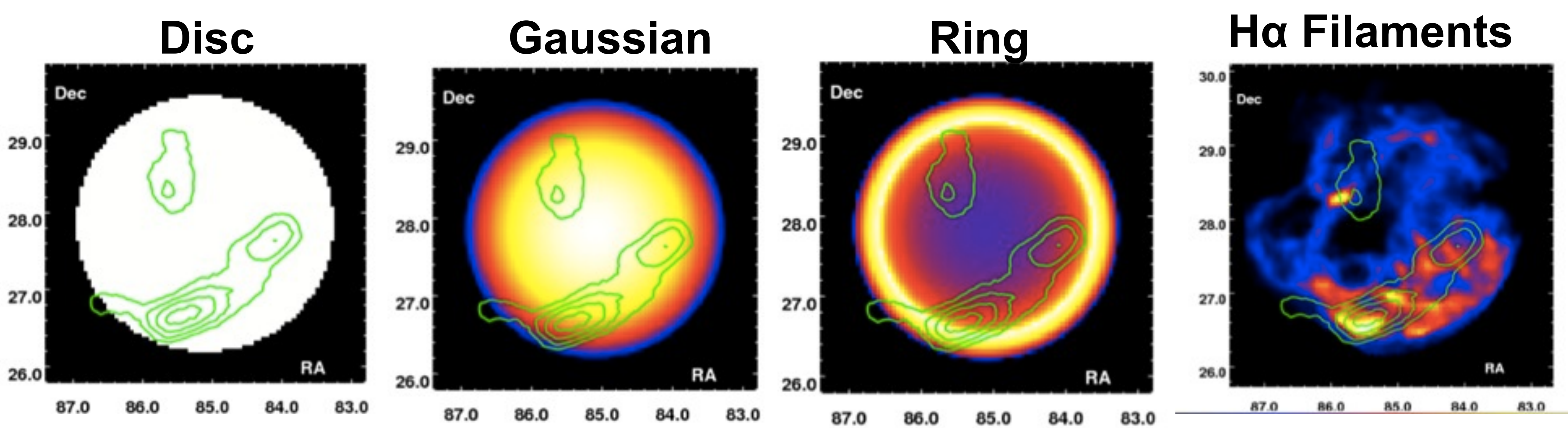


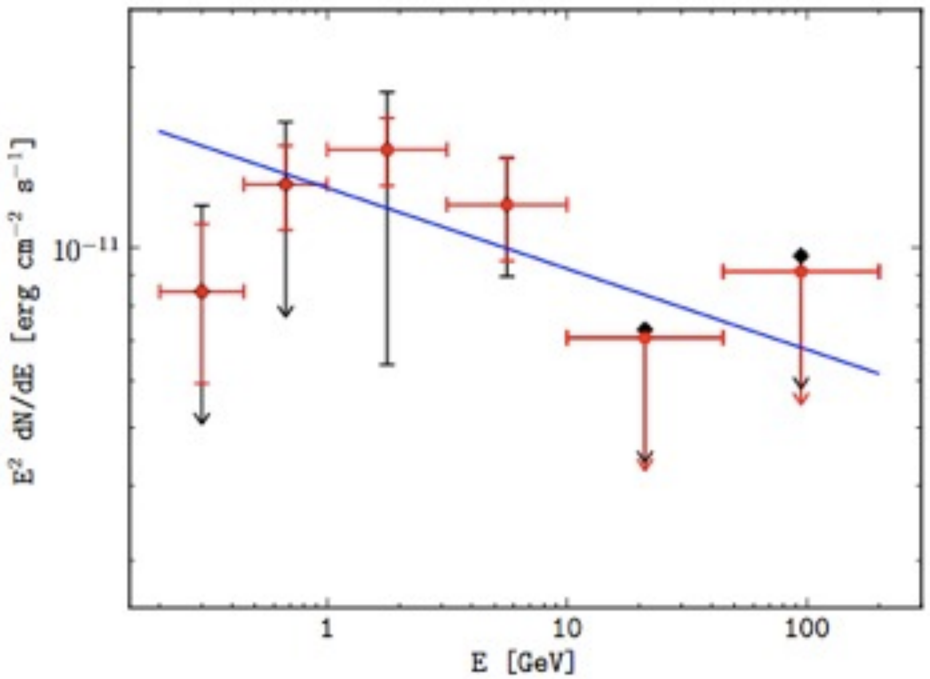


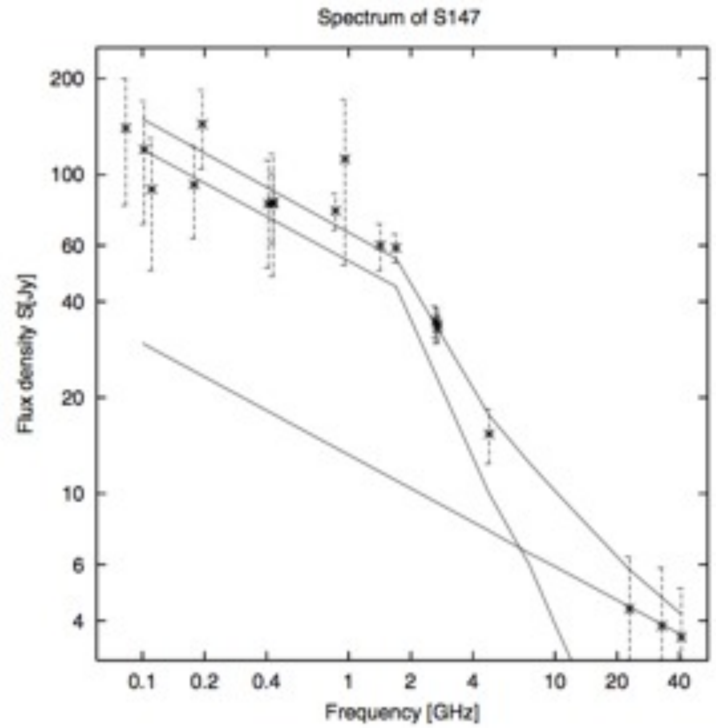
- What is the spatial structure of GeV emission?



S147

- LAT spectrum shows curvature. . . as does the Radio SED





<u>What is going on?</u>

Diffuse emission has radio break, but filaments do not

- Requires modeling multiple emission zones within the SNR:

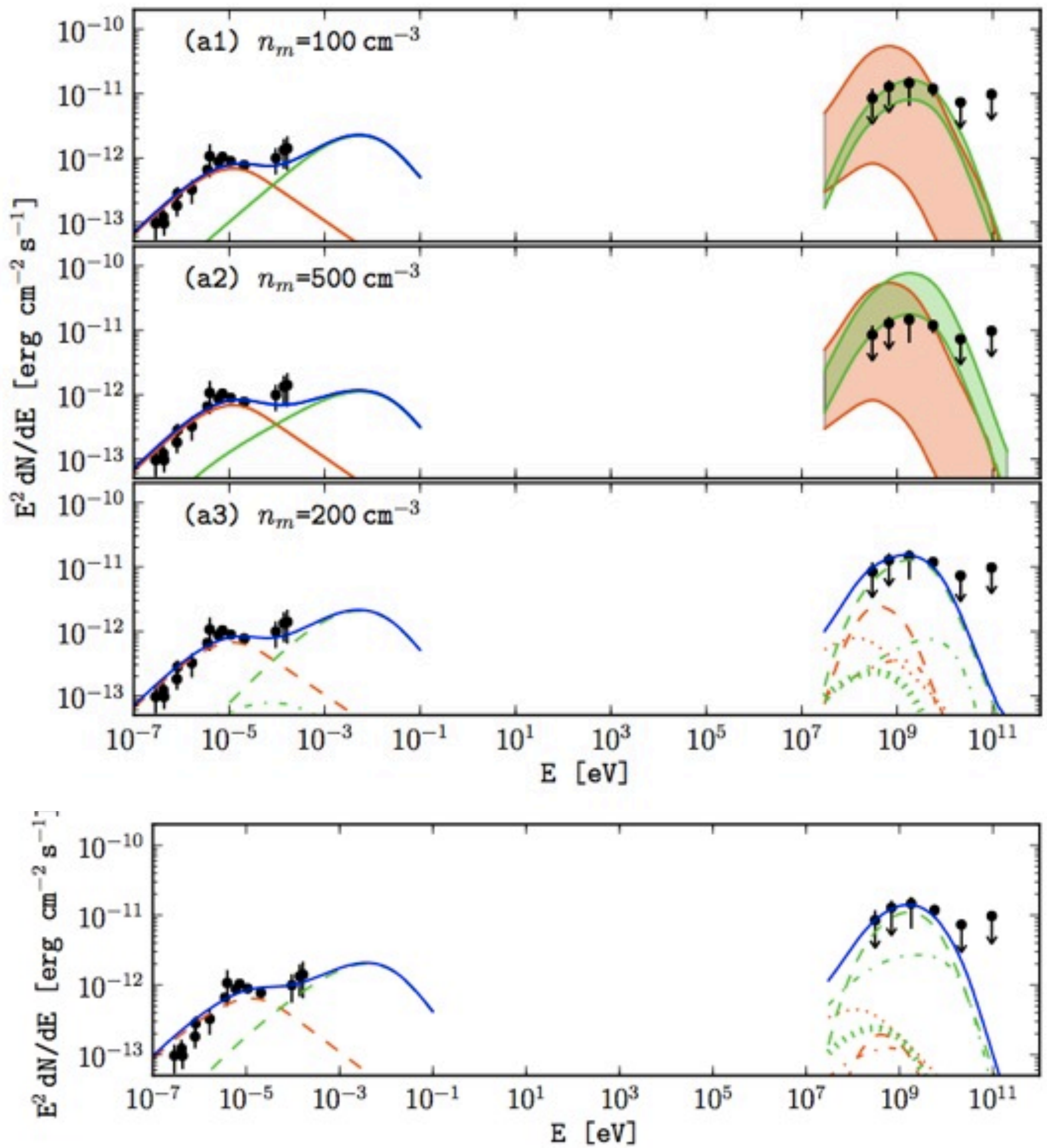
Gas properties	filament		diffuse	
assumed parameters				
Preshock magnetic field:	$B_{\rm atc}$	3–10 μG	$B_{\rm ISM}$	1–5 μG
Gas density:	$n_{\rm Hf}$	100–1000 cm^{-3}		–
Temperature:	$T_{\rm f}$	2×10^4 K		–
Shock velocity:	v_s	100 km s^{-1}		–
dependent parameters				
Magnetic field:	$B_{\rm f}$	$B_{\rm f}(n_{\rm f}, T_{\rm f})$ [a]	$B_{\rm d}$	3–16 μG
Preshock gas density:	$n_{\rm atc}$	1–7 cm^{-3}	$n_{\rm ISM}$	0.03–0.1 cm^{-3}
Gas density:		–	$n_{\rm Hd}$	0.1–0.4 cm^{-3}

S147

- Hadronic model gives good fit:
  $n_{filament}$ ~ 200 cm-3
  B ~ 200 μG
  f_{volume} ~ 0.4 %
  $W_{CR,p}$ ~ 5×10^{49} erg

- Leptonic model has too few CR p^+ (only ~1/3 ISM content!)
- Suggests e/p ratio < 0.3

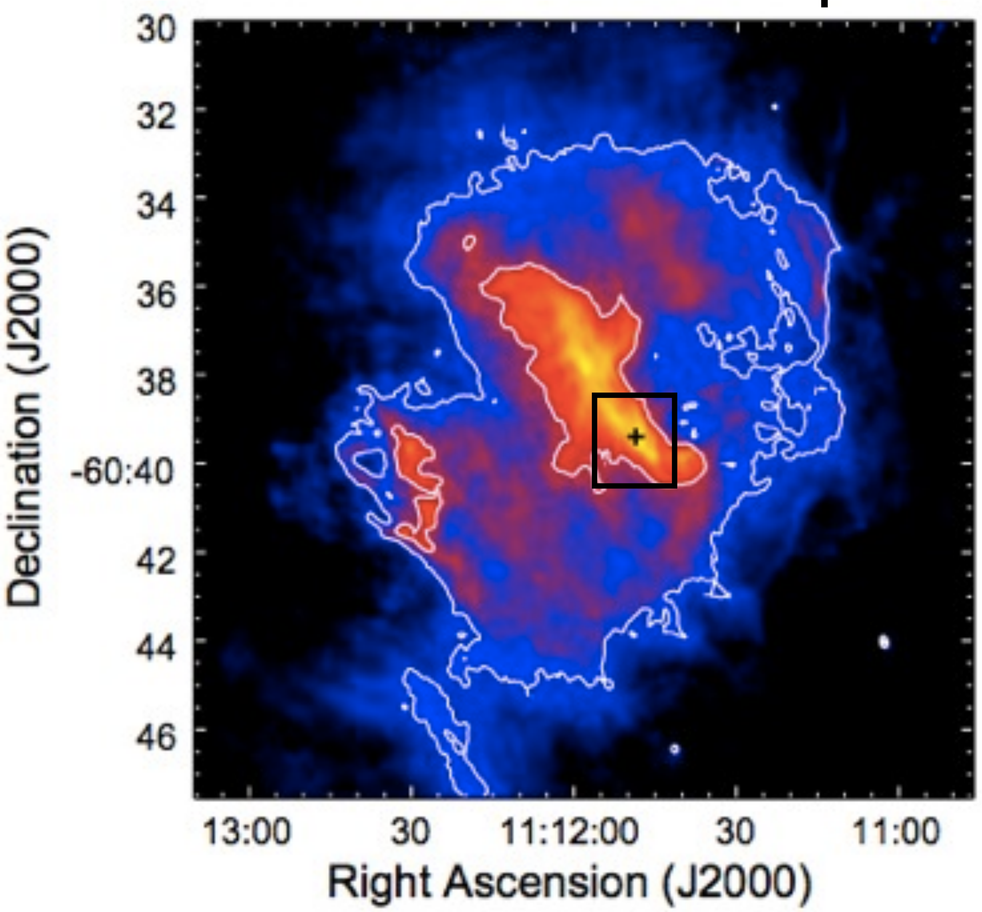
- CR re-acceleration can also explain GeV emission.
- Requires only that the SNR re-accel. pre-existing CRs in ISM due to high compression ratio (~50) in filaments



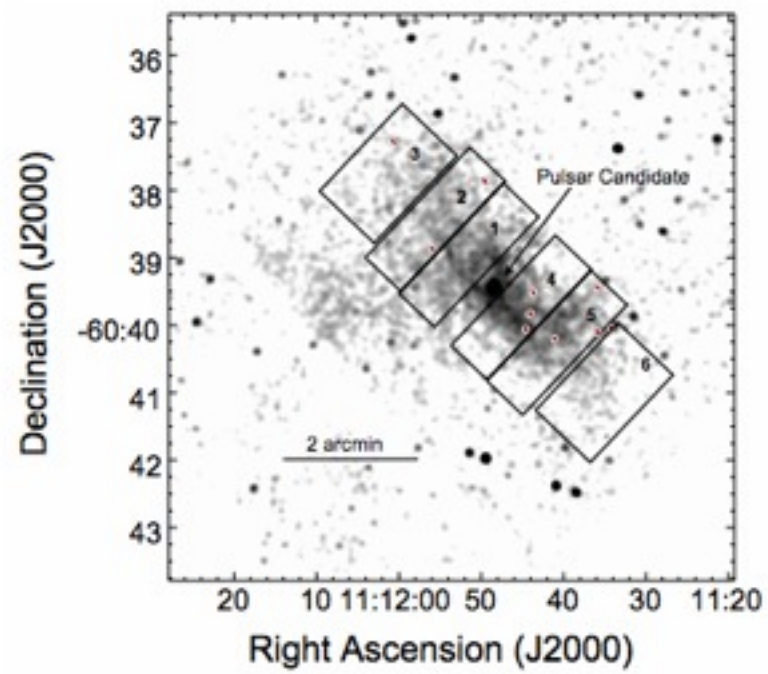
MSH 11-62: PSR, PWN or SNR?

- Young SNR (~1,200 yr) with radio/X-ray PWN + PSR candidate

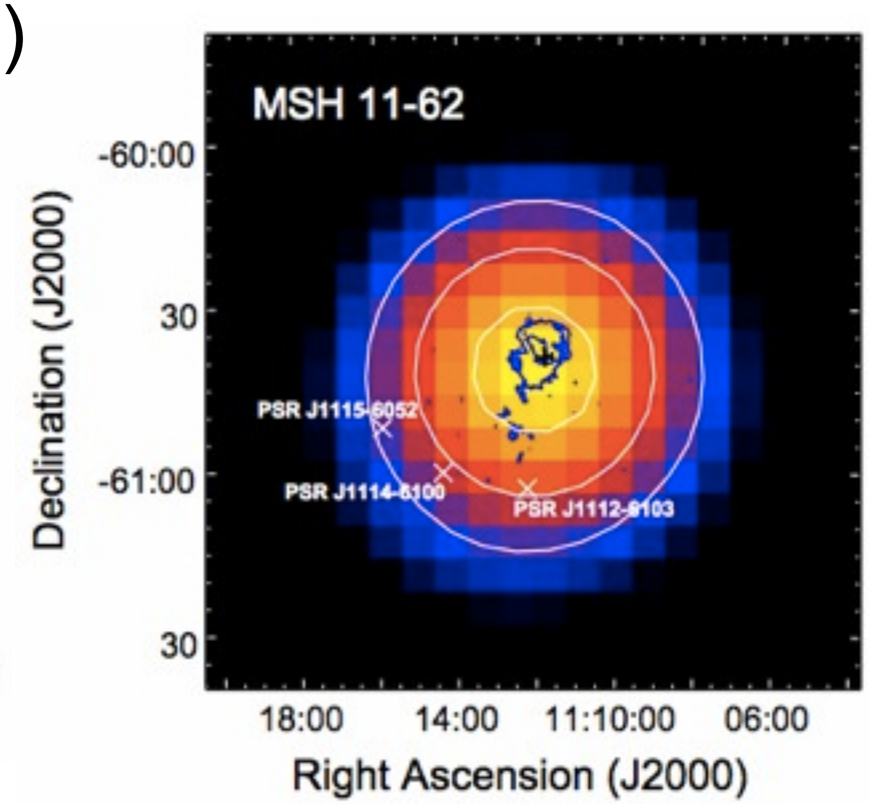
Radio 20cm map



X-ray PWN(+PSR?)



GeV point source

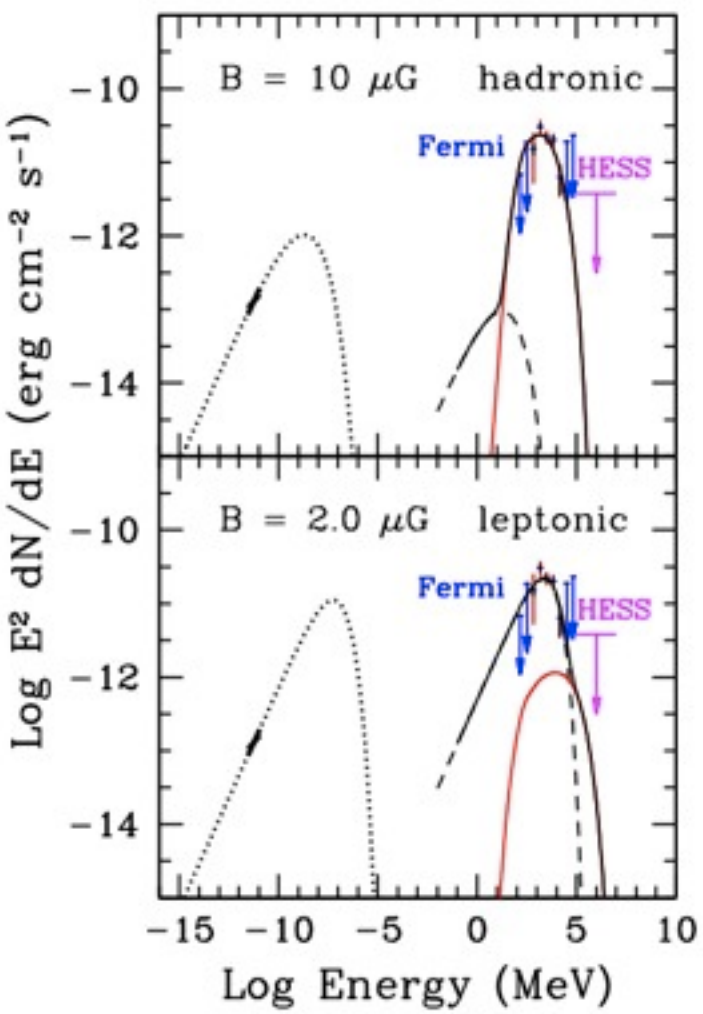


- Fermi-LAT detects a source at >500 MeV (Slane et al. 2012)
- No pulsations found in a blind search
- What is source of GeV emission?

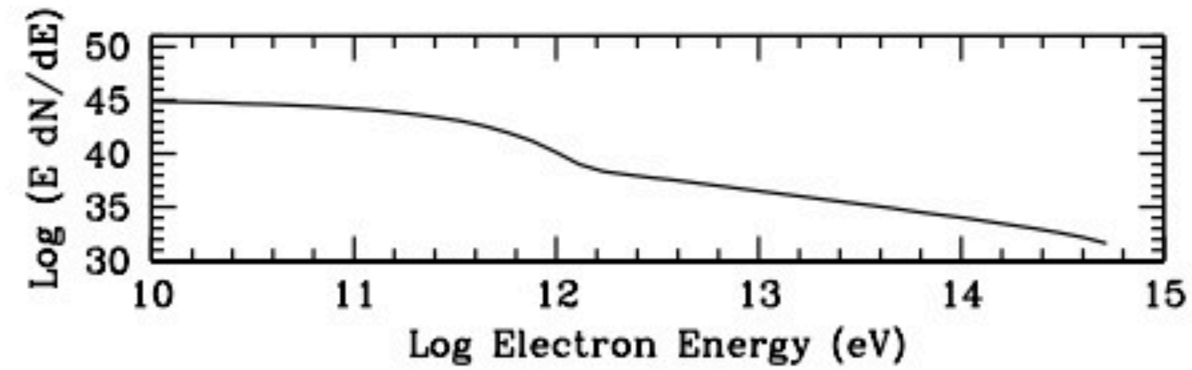
MSH 11-62: PSR, PWN or SNR?

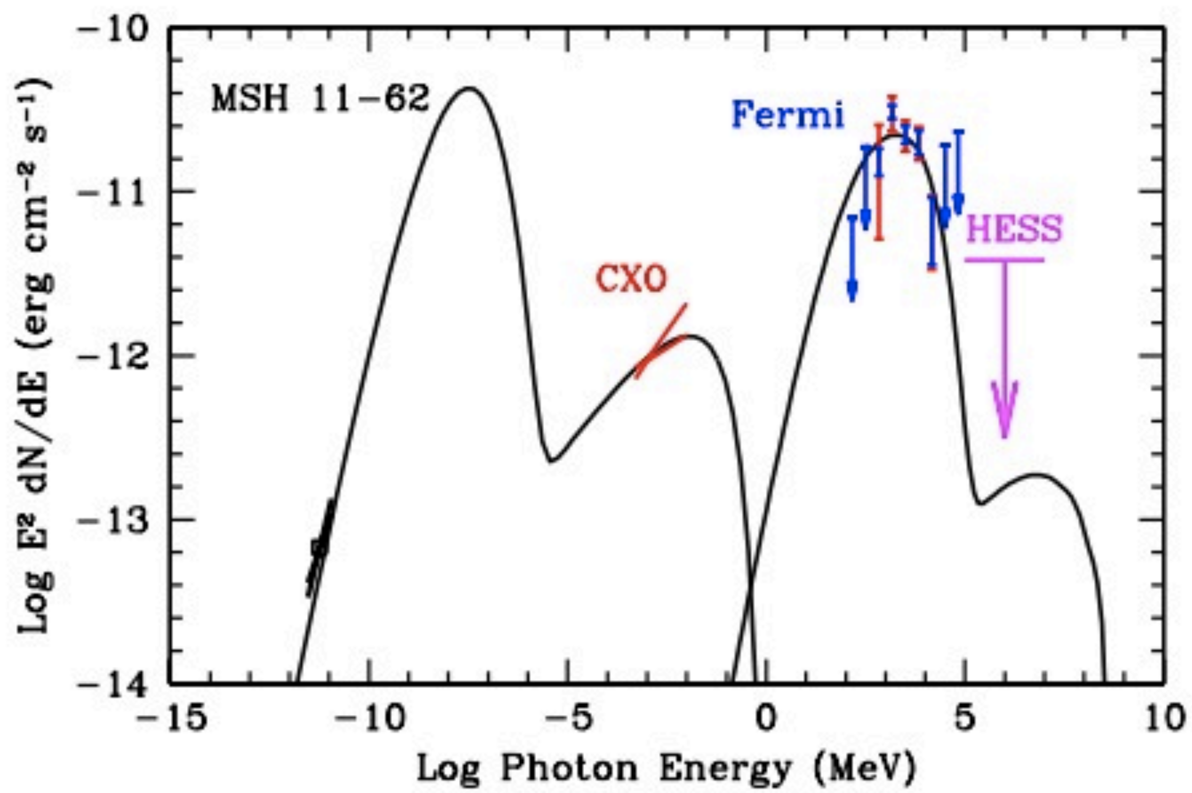
- Hadronic SNR?
  requires density ~7 cm^{-3}
  >> density from th. X-rays

- Leptonic SNR?
  for n~0.1 cm^{-3} requires
  $E_p > 10^{51}$ erg unless e/p >0.7



- PWN? (no TeV detection)
  need E_{dot} ~ 10^{39} erg/s >> any known PSR!





- PSR? Spectrally fits the LAT SED, but
  estimated age is too young to explain PWN

summary

- Key Questions
  - Do SNRs accelerate particles?
  - Do SNRs accelerate protons (what is the e/p ratio?)
  - What is the total energy converted to relativistic particles?
  - What is the maximum energy of accelerated particles?
  - What is the mechanism (how is B-field amplified)?

- Fermi-LAT has clearly identified many interesting cases for study ~13 identified SNRs to date.
- Two emerging classes:
  - Young SNRs detected in TeV
  - Older SNRs interacting with dense gas
- Fermi occupies key energy range to differentiate between hadronic and leptonic models.

the future

- GeV SNR associations growing nearly linear with time!
- How many SNRs do we expect to detect?
  - if gamma-radio correlation holds, can expect XXX SNRs
- Are we getting to the range where non-detections are interesting?
  - hard spectrum SNRs => IC?
- That's great, but if I'm not fitting emission from the SNR do I really need to worry about SNRs? ***Probably not, but see cavaets:***
  - Bright, extended SNRs leave nasty residuals if modeled as point sources.
  - SNRs and PWN can lead to source confusion.
- Green's catalog of SNRs: http://www.mrao.cam.ac.uk/surveys/snrs/