

the remnants of supernovae  
and particle acceleration  
in the fermi era

4th fermi symposium  
monterey, ca

daniel castro (mit)

# remnants of supernovae

supernova remnants

black holes

pulsars

pulsar wind nebulae

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supernova remnants

black holes

pulsars

pulsar wind nebulae

# remnants of supernovae

supernova remnants - part 1

black holes

pulsars

pulsar wind nebulae – part 2 (very short!)

# remnants of supernovae

supernova remnants - part I

# outline

**why** do we care about the connection between SNRs and cosmic rays?

what **evidence** is there that SNRs accelerate cosmic rays?

what are the **open questions** being addressed today?

what are we working on **right now**? where are we going?

i. why?

*why* should we care about the connection between SNRs and cosmic rays?

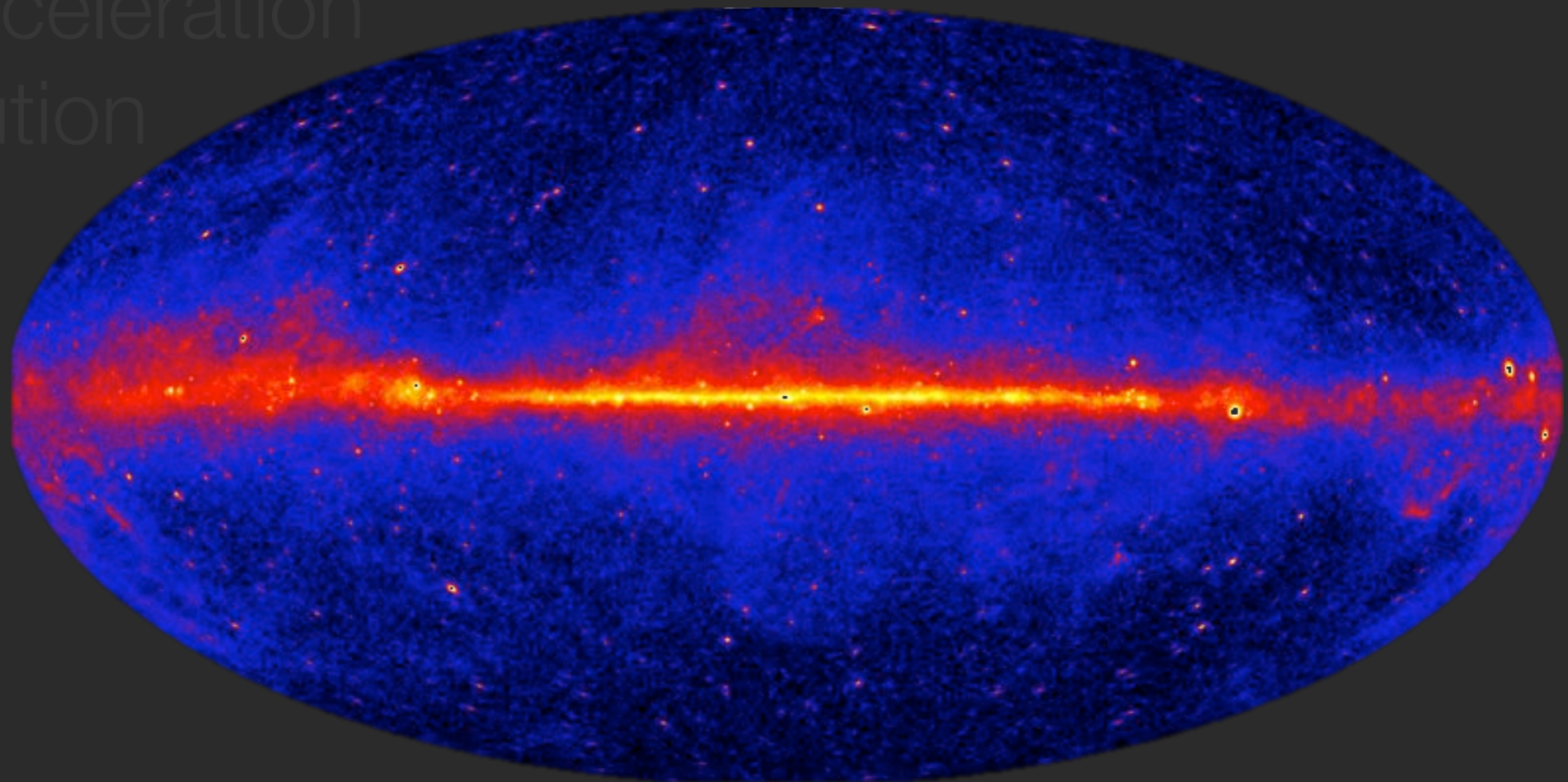
# i. why?

- origin
- $\gamma$ -ray background
- particle acceleration
- SNR evolution



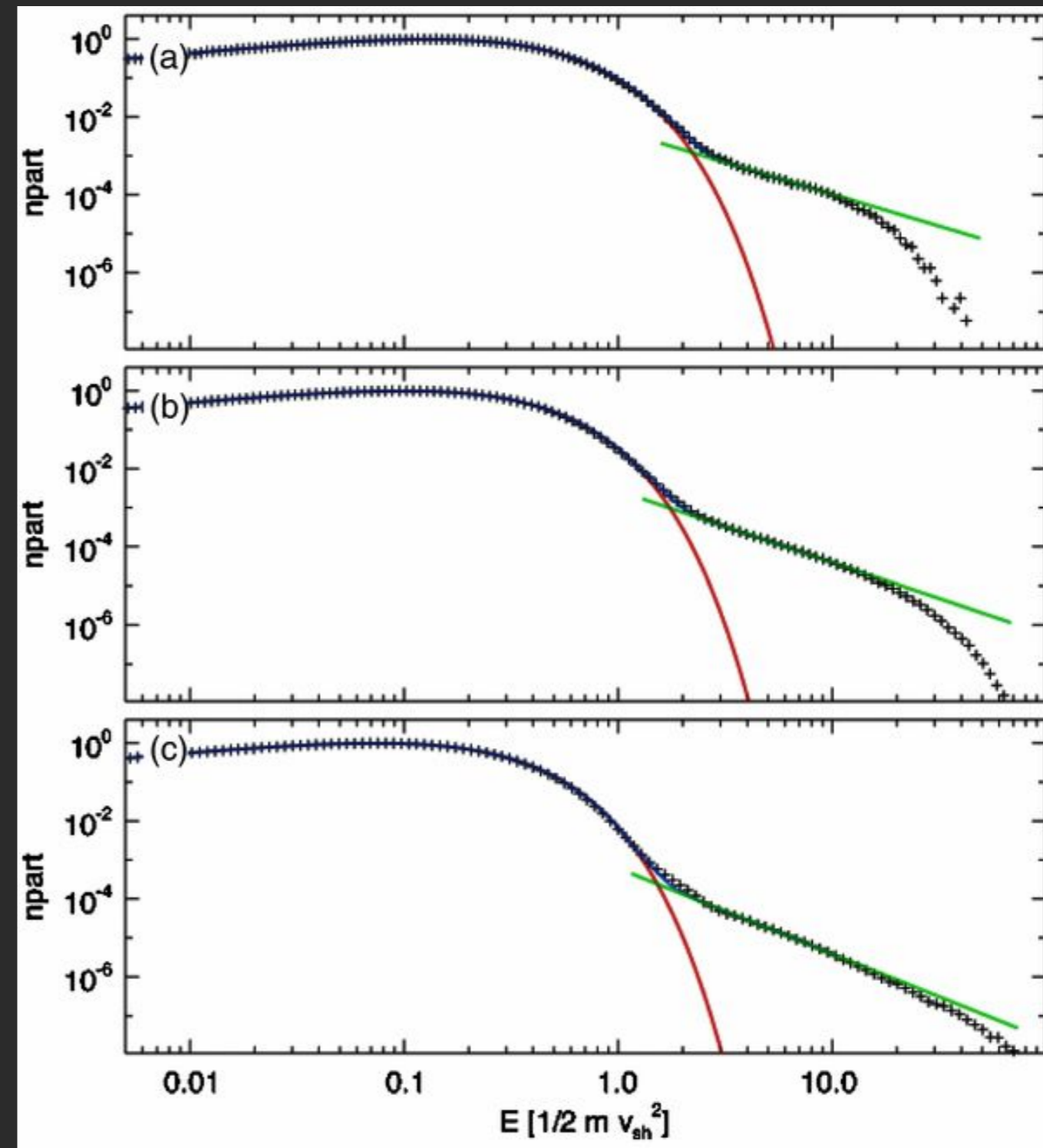
# i. why?

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- $\gamma$ -ray background
- particle acceleration
- SNR evolution

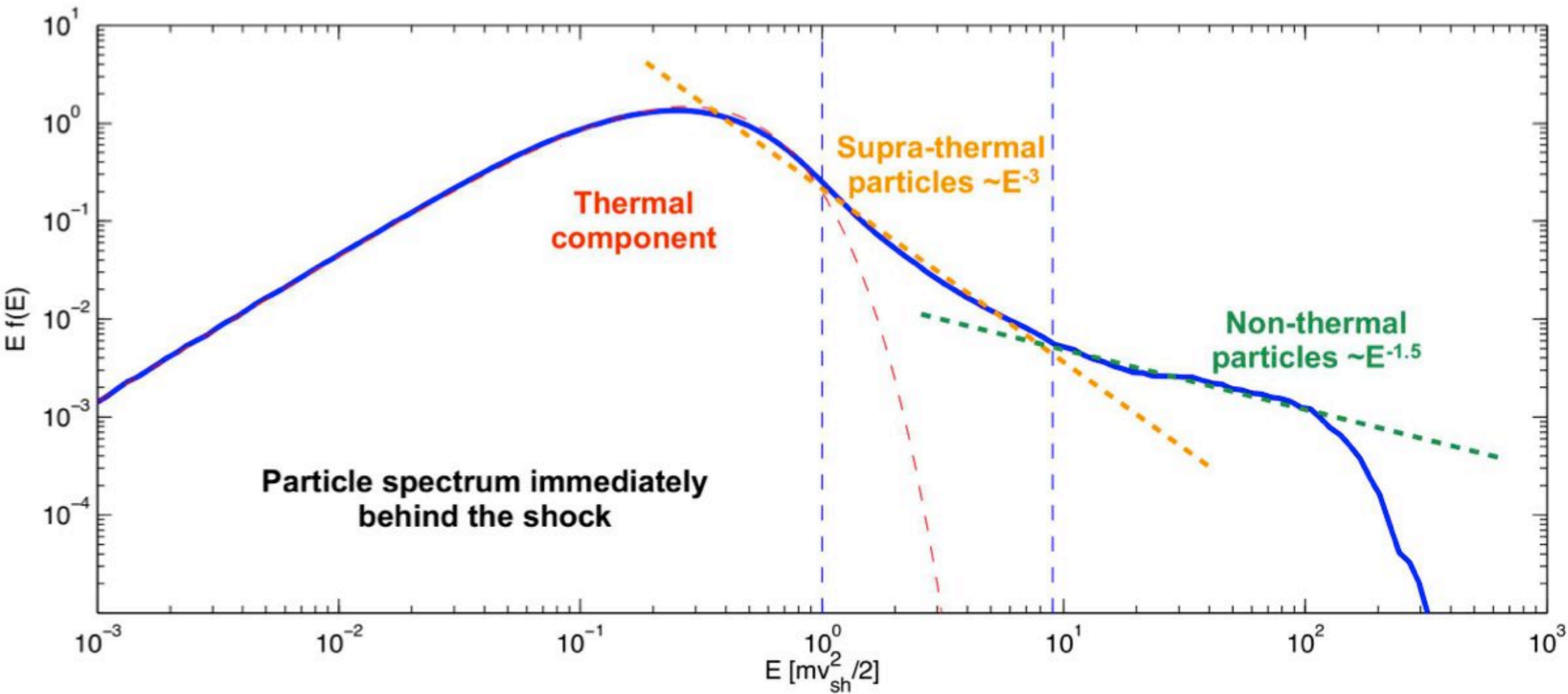


# i. why?

- origin
- $\gamma$ -ray background
- particle acceleration
- SNR evolution



# i. why?



# i. why?

- origin
- $\gamma$ -ray background
- particle acceleration
- SNR evolution

see e.g., castro+ 2011

## ii. evidence

what **evidence** is there that SNRs accelerate cosmic rays?

## ii. evidence

- non-thermal X-rays
- $\gamma$ -ray emission
- dynamical properties
- structure

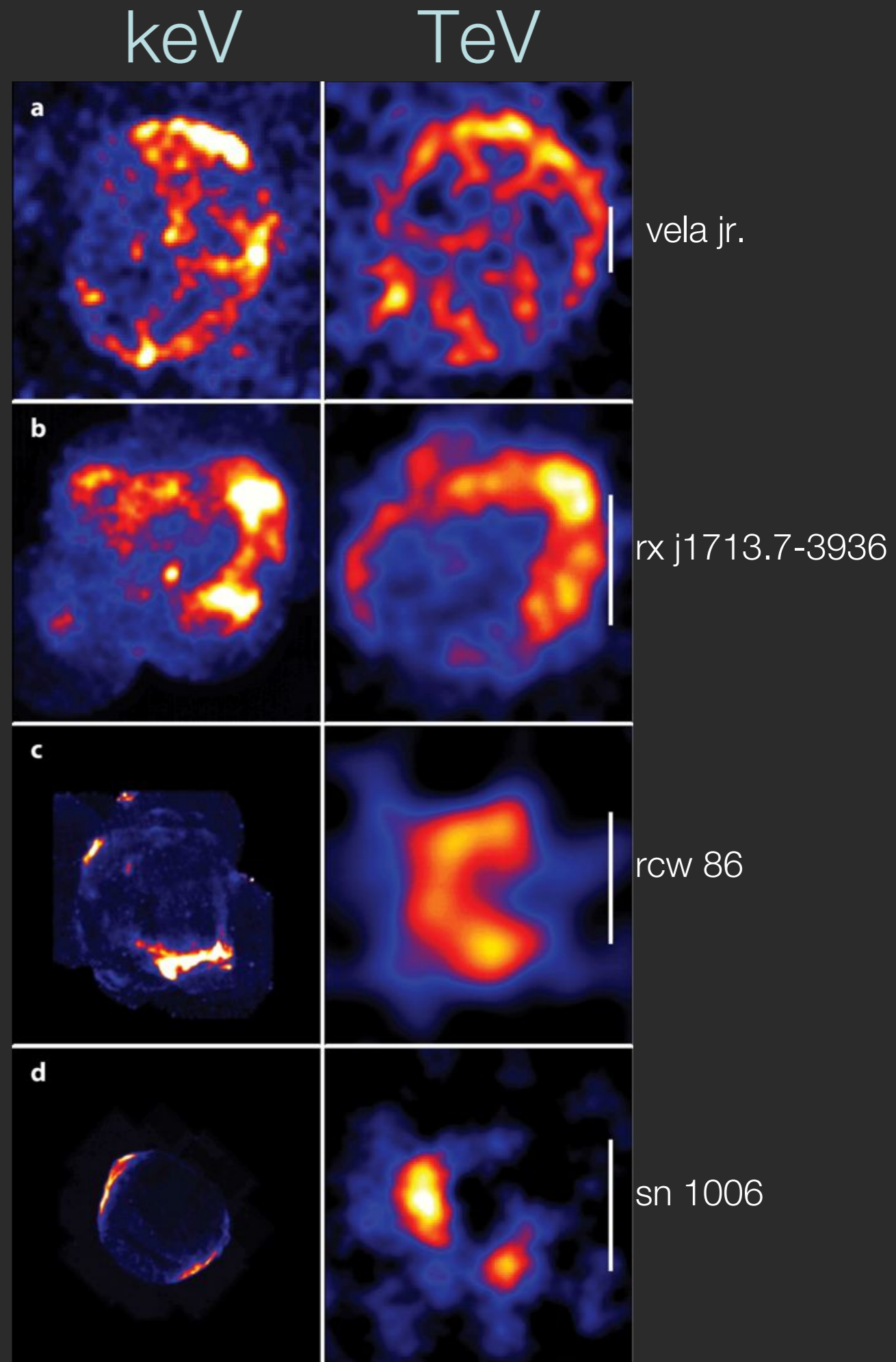
koyama+ 1995



## ii. evidence

- non-thermal X-rays
- $\gamma$ -ray emission
- dynamical properties
- structure

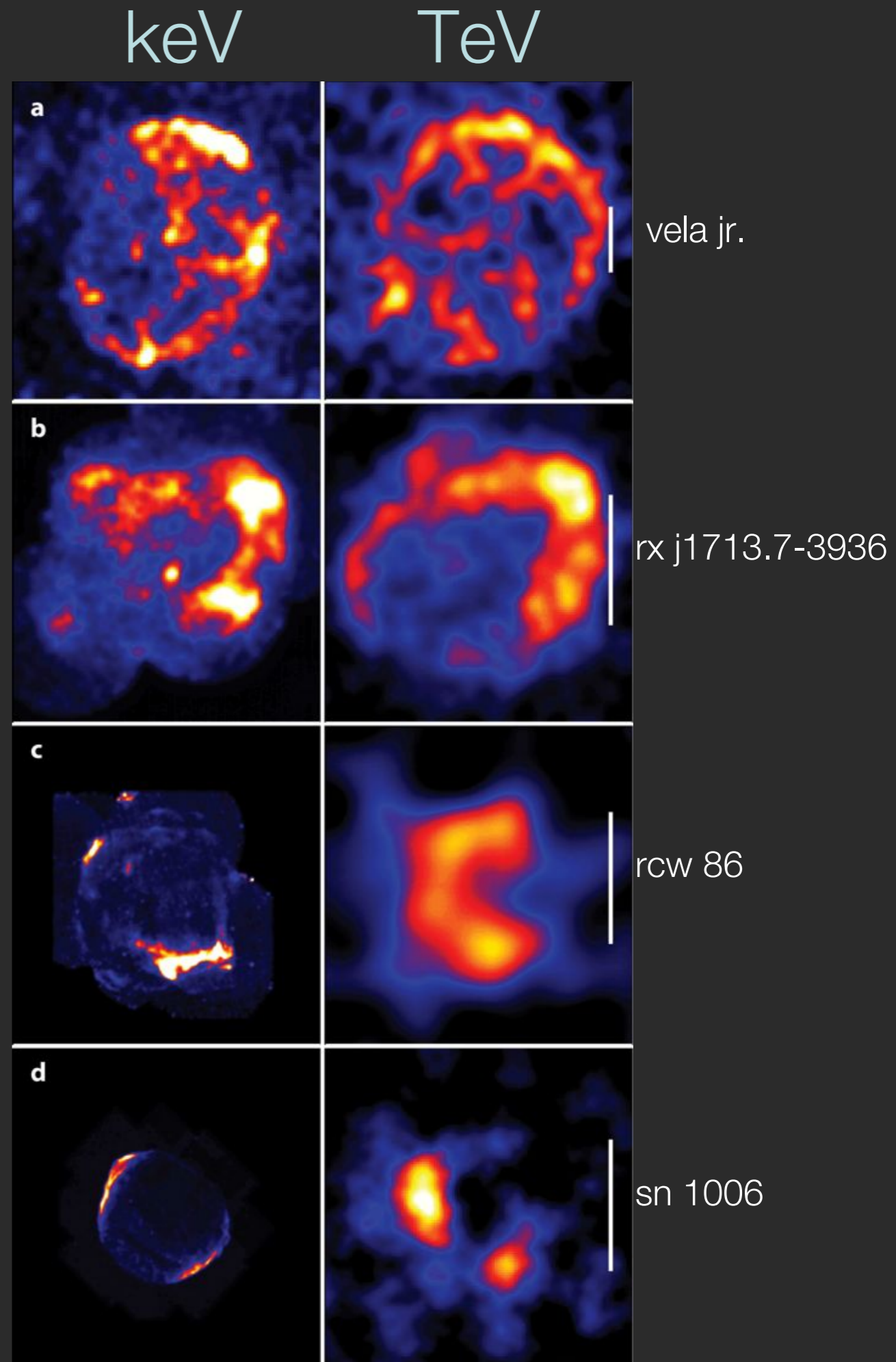
hinton & hofmann 2009



## ii. evidence

- non-thermal X-rays
- $\gamma$ -ray emission
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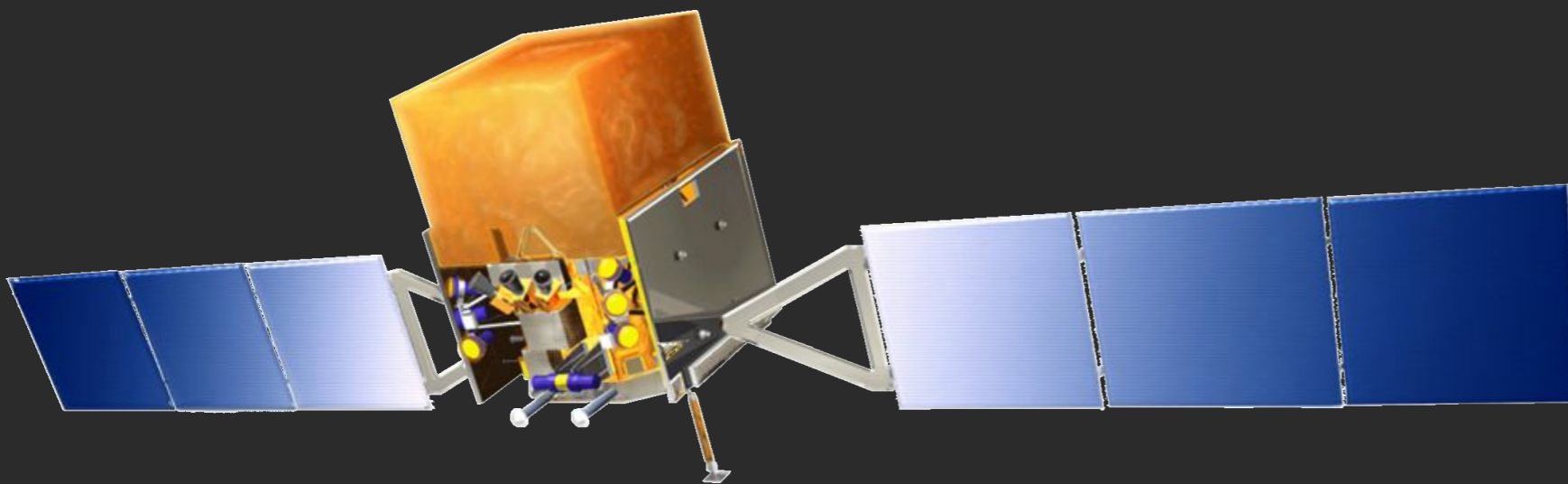
hinton & hofmann 2009  
uchiyama+ 2002  
sschenbach 1998  
vink+ 2006  
aharonian+ 2006, 2007, 2008  
naumann-godo+ 2006





## ii. evidence

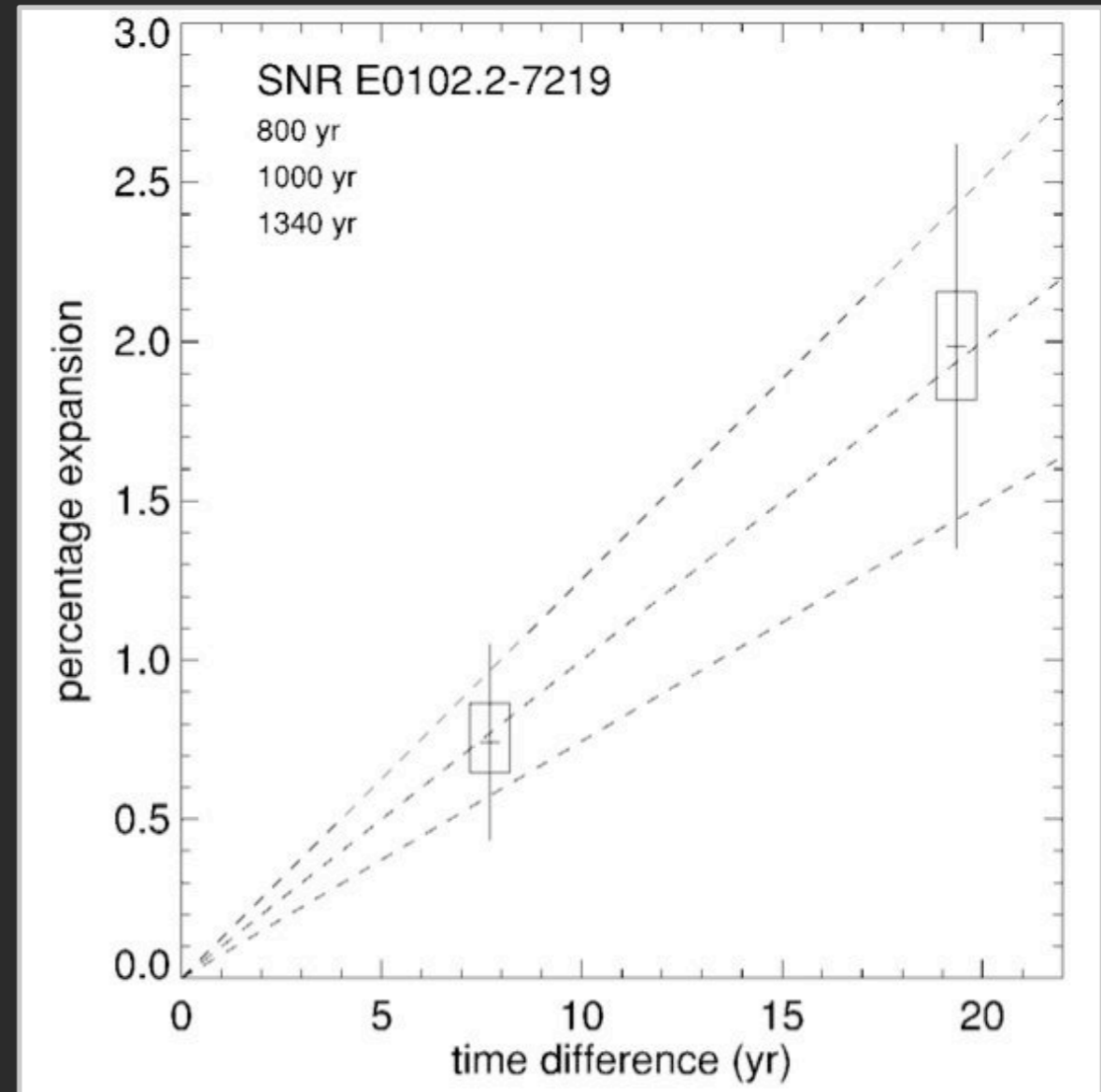
- non-thermal X-rays
- $\gamma$ -ray emission
- dynamical properties
- structure



| Name                | <i>Fermi</i> -LAT Detection Reference |
|---------------------|---------------------------------------|
| W28                 | Abdo et al. (2010a)                   |
| W30                 | Castro & Slane (2010)                 |
| W41                 | Castro et al. (2012c)                 |
| 3C 391              | Castro & Slane (2010)                 |
| Kes 78              | Auchettl et al. (2012)                |
| W44                 | Abdo et al. (2010c)                   |
| W49b                | Abdo et al. (2009)                    |
| W51C                | Abdo et al. (2009)                    |
| Cygnus Loop         | Katagiri et al. (2011)                |
| $\gamma$ -Cygni SNR | Lande et al. (2012)                   |
| HB 21               | Reichardt et al. (2012)               |
| CTB 109             | Castro et al. (2012b)                 |
| Cas A               | Abdo et al. (2010b)                   |
| Tycho               | Giordano et al. (2012)                |
| S147                | Katsuta et al. (2012)                 |
| IC443               | Abdo et al. (2010d)                   |
| Puppis A            | Hewitt et al. (2012)                  |
| Vela Jr.            | Tanaka et al. (2011)                  |
| Kes 17              | Wu et al. (2011)                      |
| CTB 33              | Castro et al. (2012c)                 |
| Kes 41              | Joubert et al. (2012)                 |
| RX J1713            | Abdo et al. (2011)                    |
| CTB 37A             | Castro & Slane (2010)                 |
| G349.7-0.5          | Castro & Slane (2010)                 |
| MSH 17-39           | Castro et al. (2012c)                 |

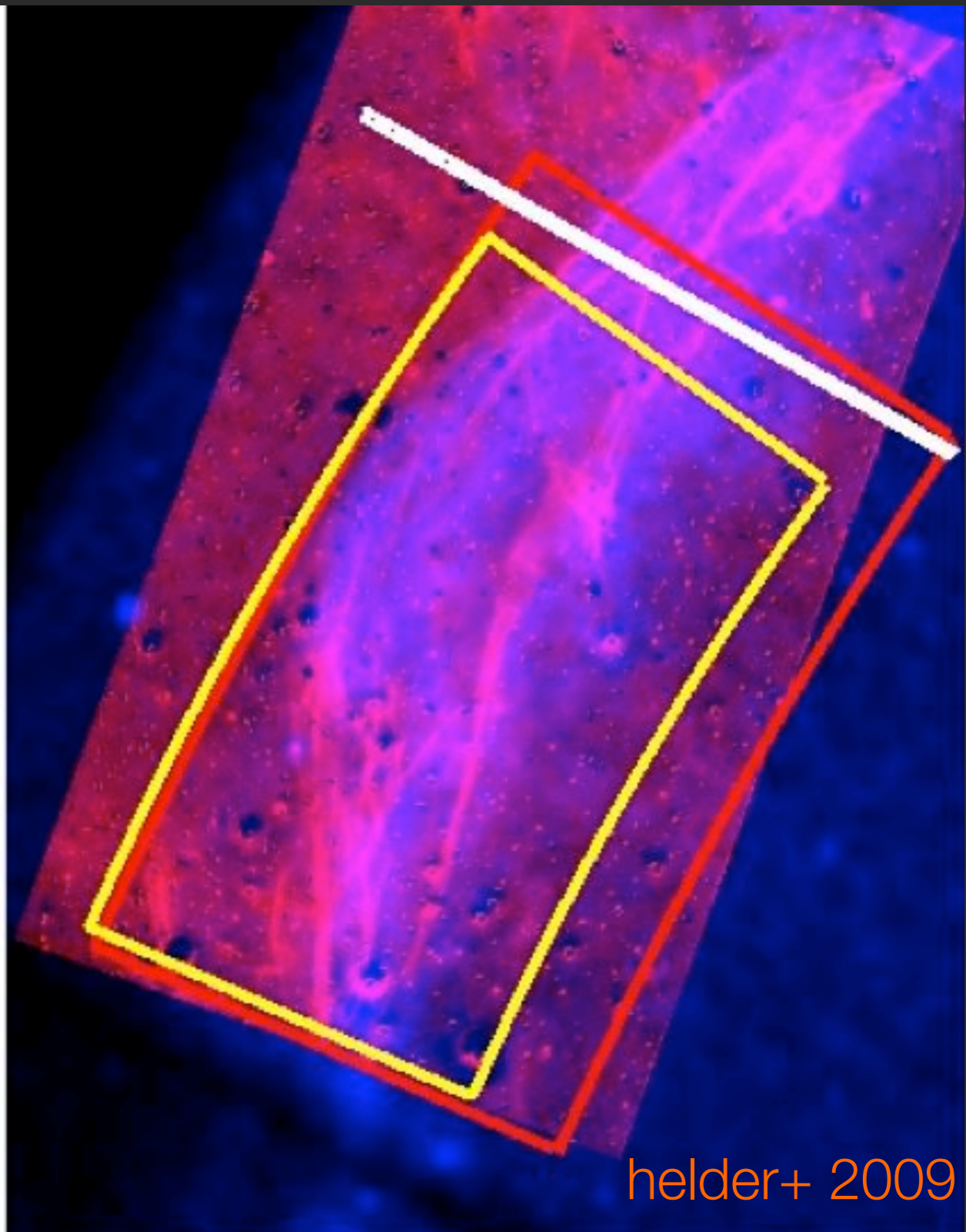
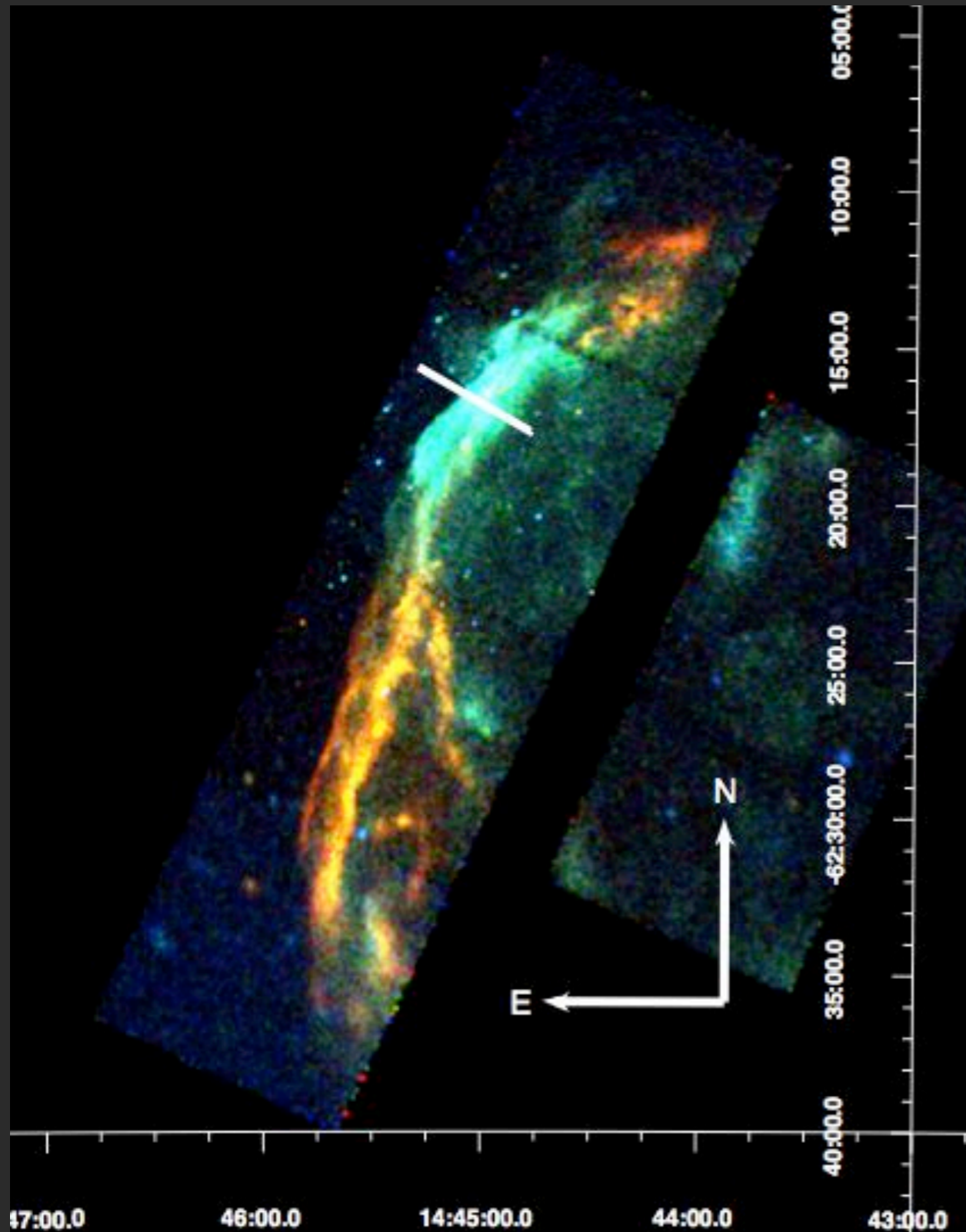
## ii. evidence

- non-thermal X-rays
- $\gamma$ -ray emission
- dynamical properties
- structure



hughes+ 2000

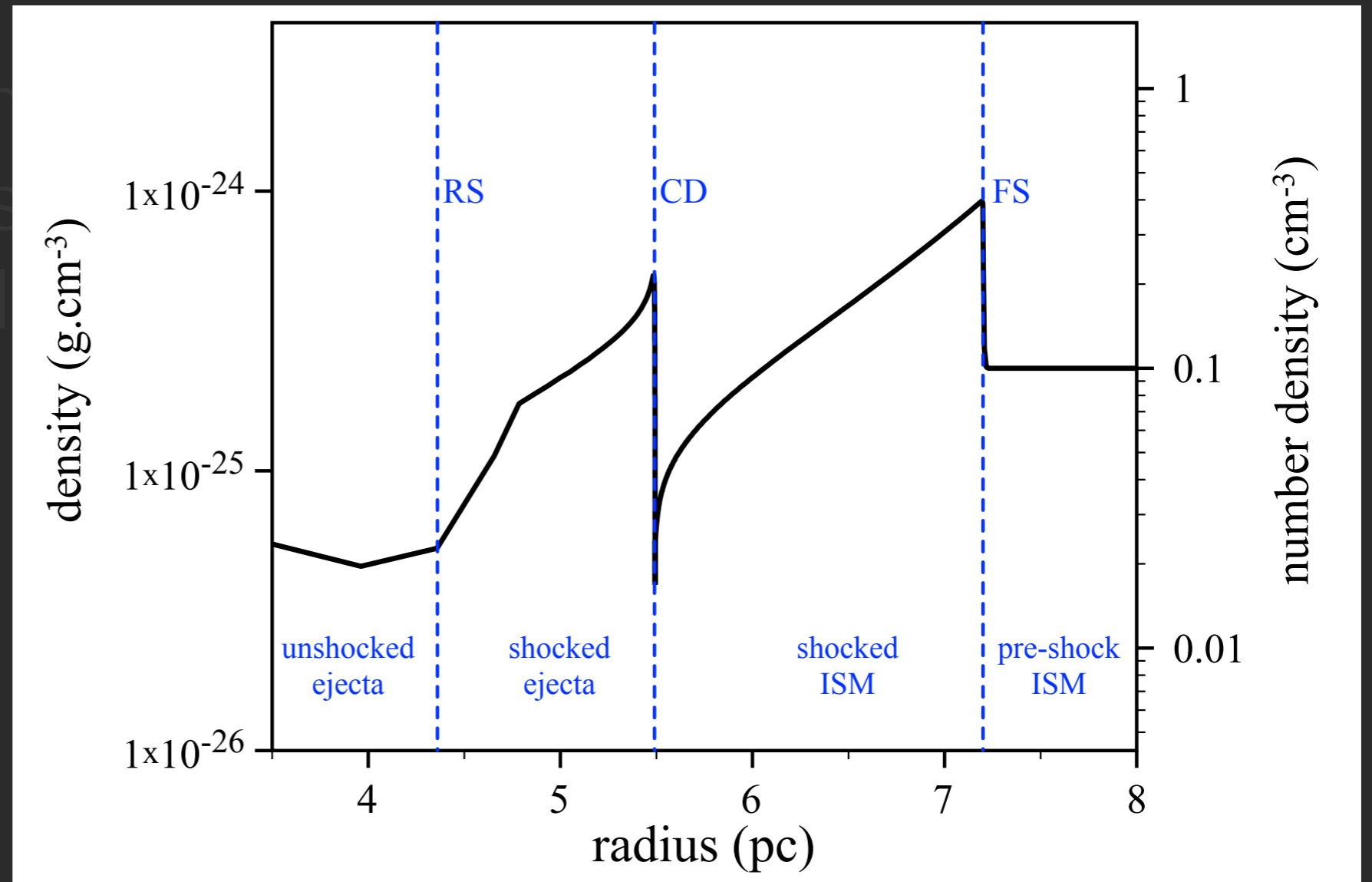
# ii. evidence



helder+ 2009

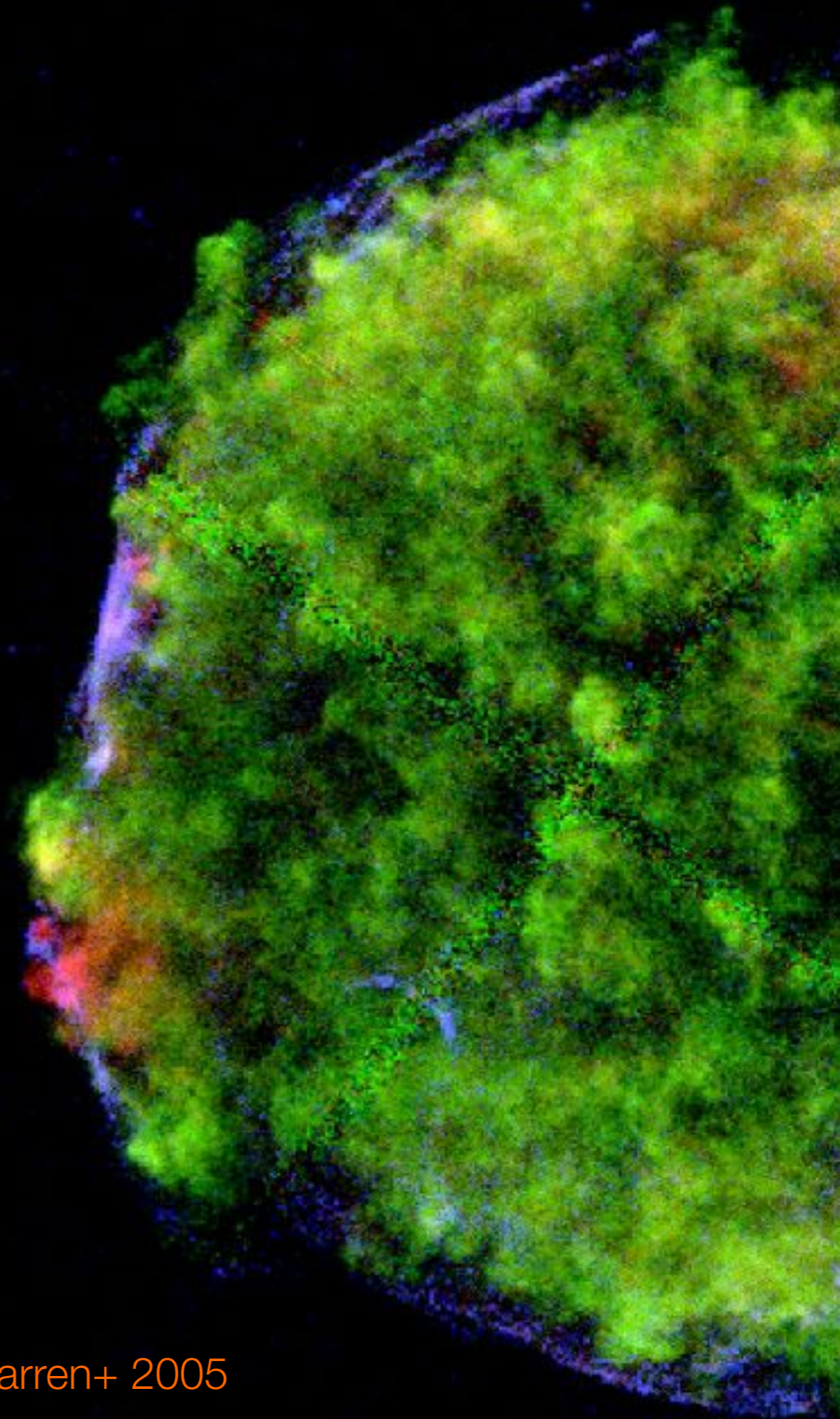
## ii. evidence

- non-thermal
- $\gamma$ -ray emis
- dynamical
- structure



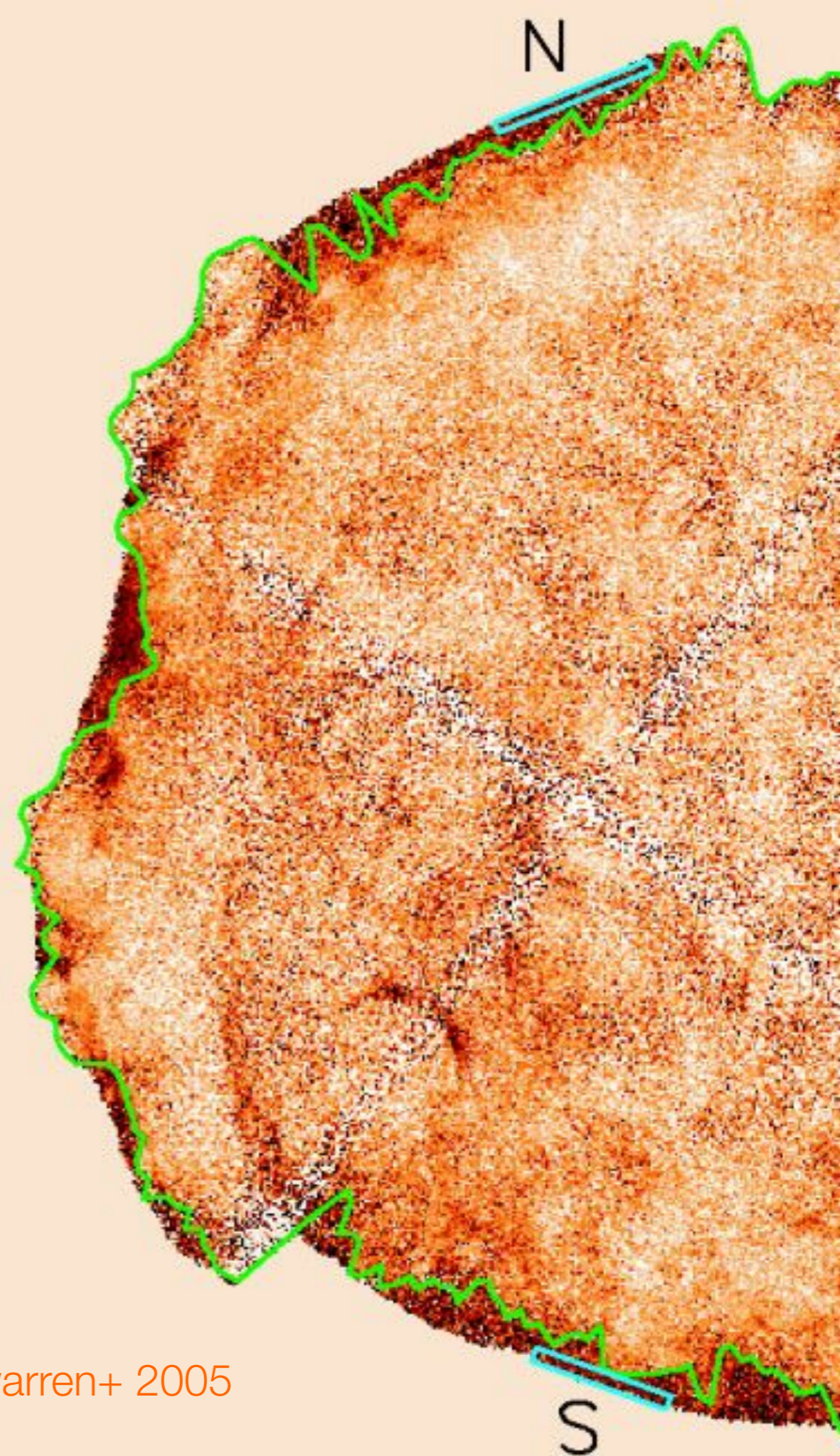
## ii. evidence

- non-thermal X-rays
- $\gamma$ -ray emission
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## ii. evidence

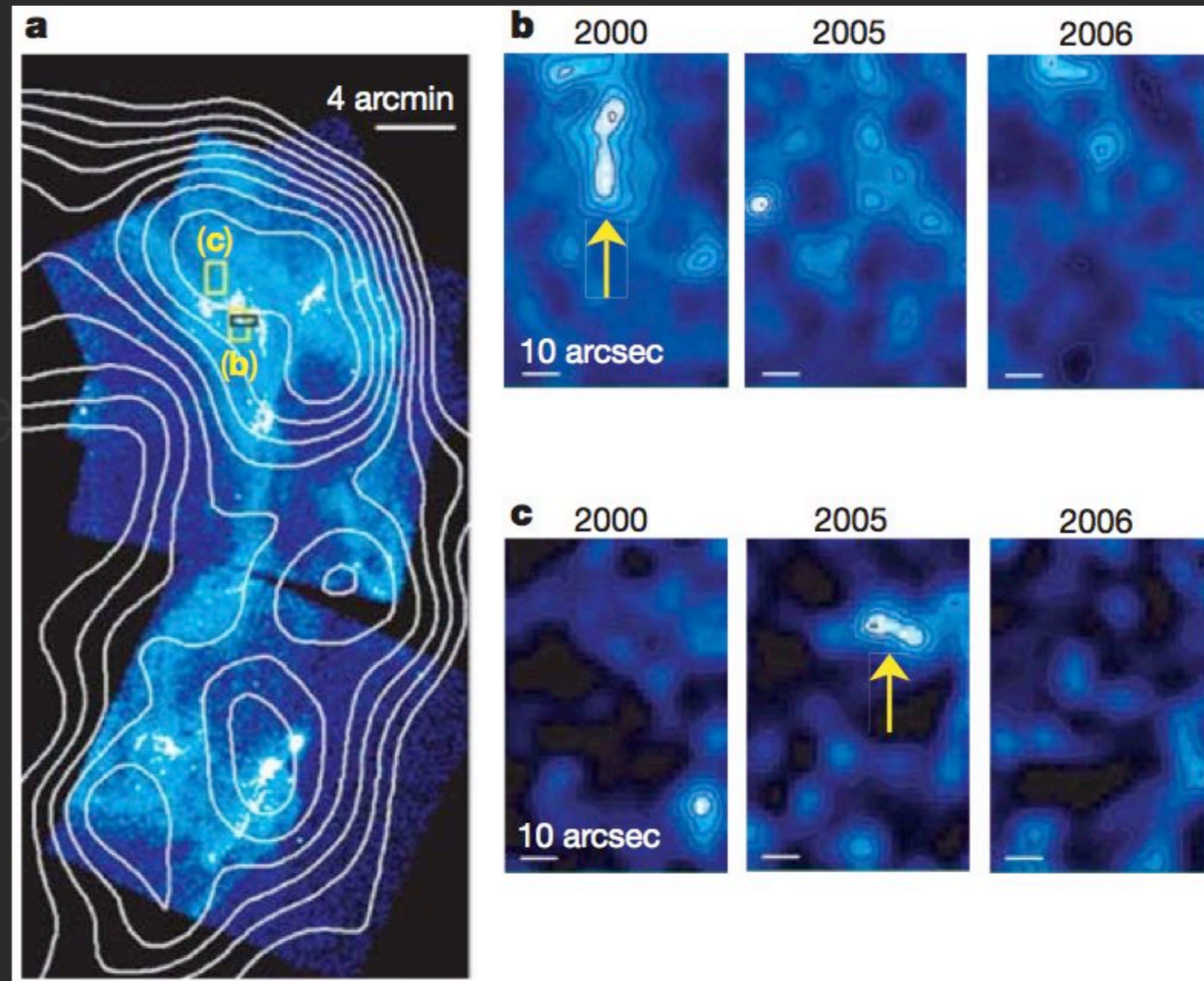
- non-thermal X-rays
- $\gamma$ -ray emission
- dynamical properties
- structure



warren+ 2005

## ii. evidence

- non-thermal X-rays
- $\gamma$ -ray emission
- dynamical properties
- structure
- non-thermal X-rays



### iii. open questions

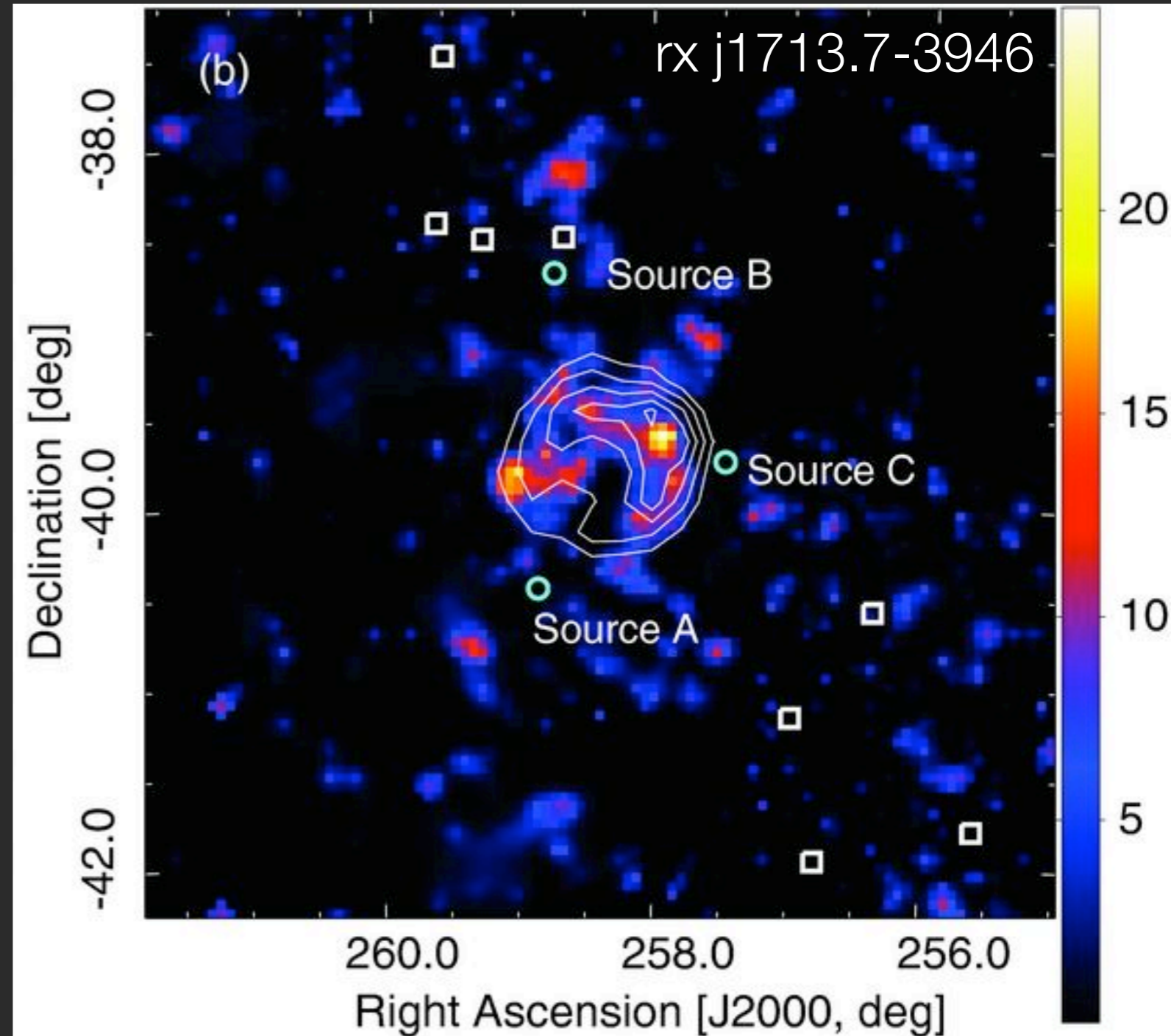
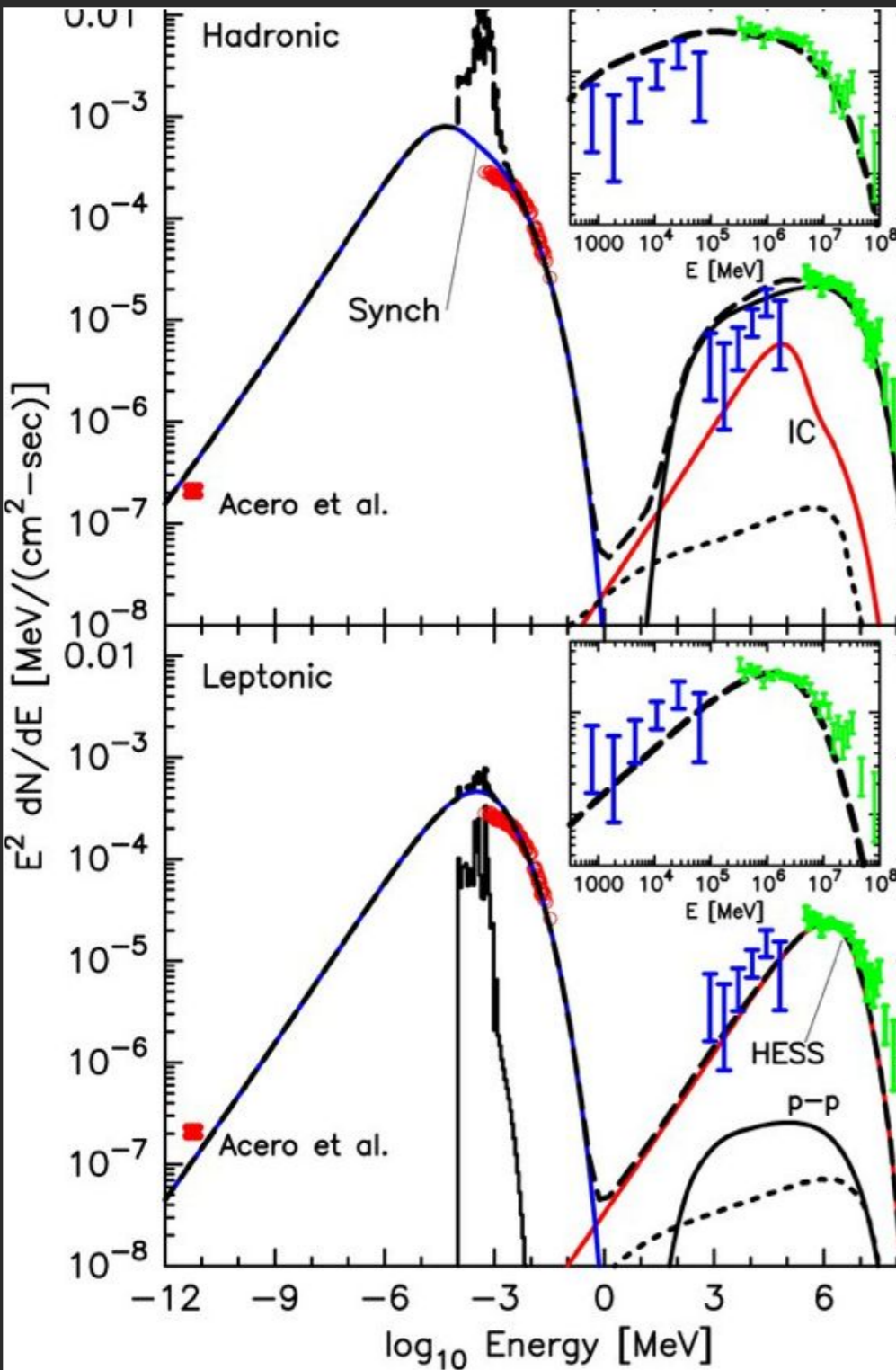
what are the **open questions** being addressed today?



iii. hadronic or leptonic

what mechanism produces the  $\gamma$ -ray emission from SNRs?

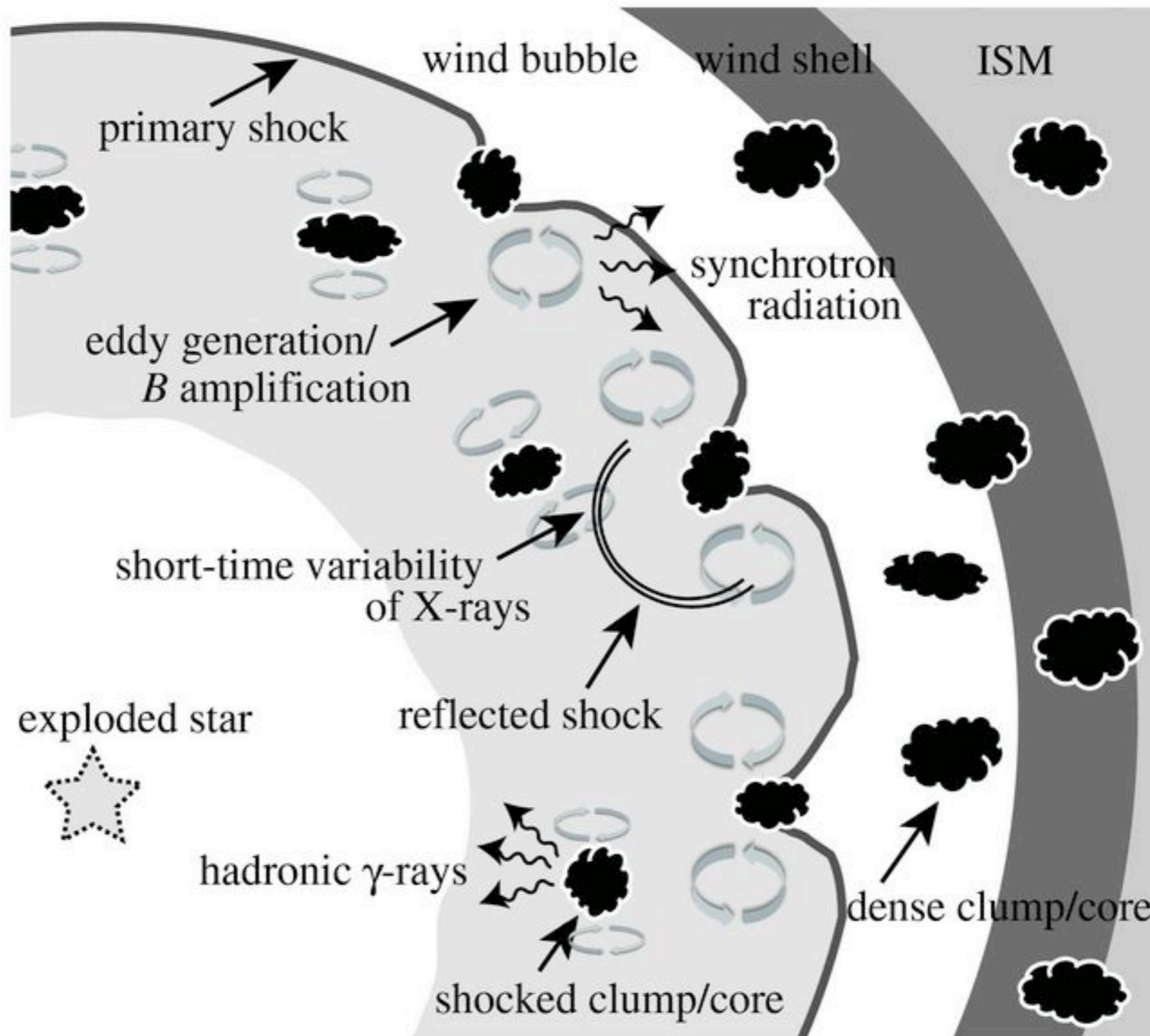
# iii. hadronic or leptonic



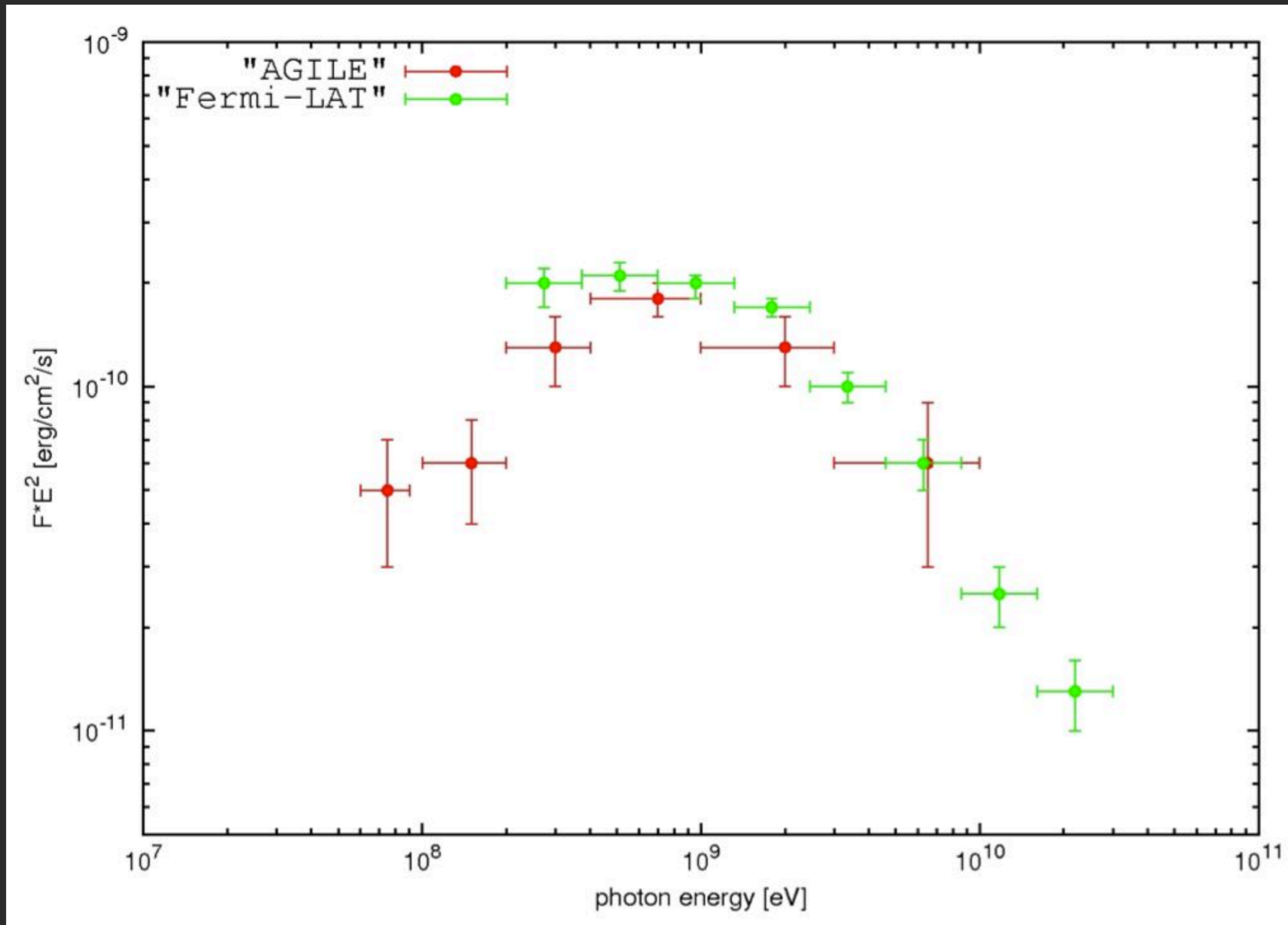
ellison+ 2010

abdo+ 2011

# iii. hadronic or leptonic



### iii. hadronic or leptonic



### iii. magnetic field amplification

how does the magnetic field get amplified by particle acceleration and escape in SNRs?

# iii. magnetic field amplification

## evidence

- .spectral curvature in radio emission (a little iffy)
- .broad-band fits of synchrotron emission between radio and non-thermal X-rays
- .sharp X-ray edges
- .rapid variability of nonthermal X-ray emission from bright filaments in SNRs

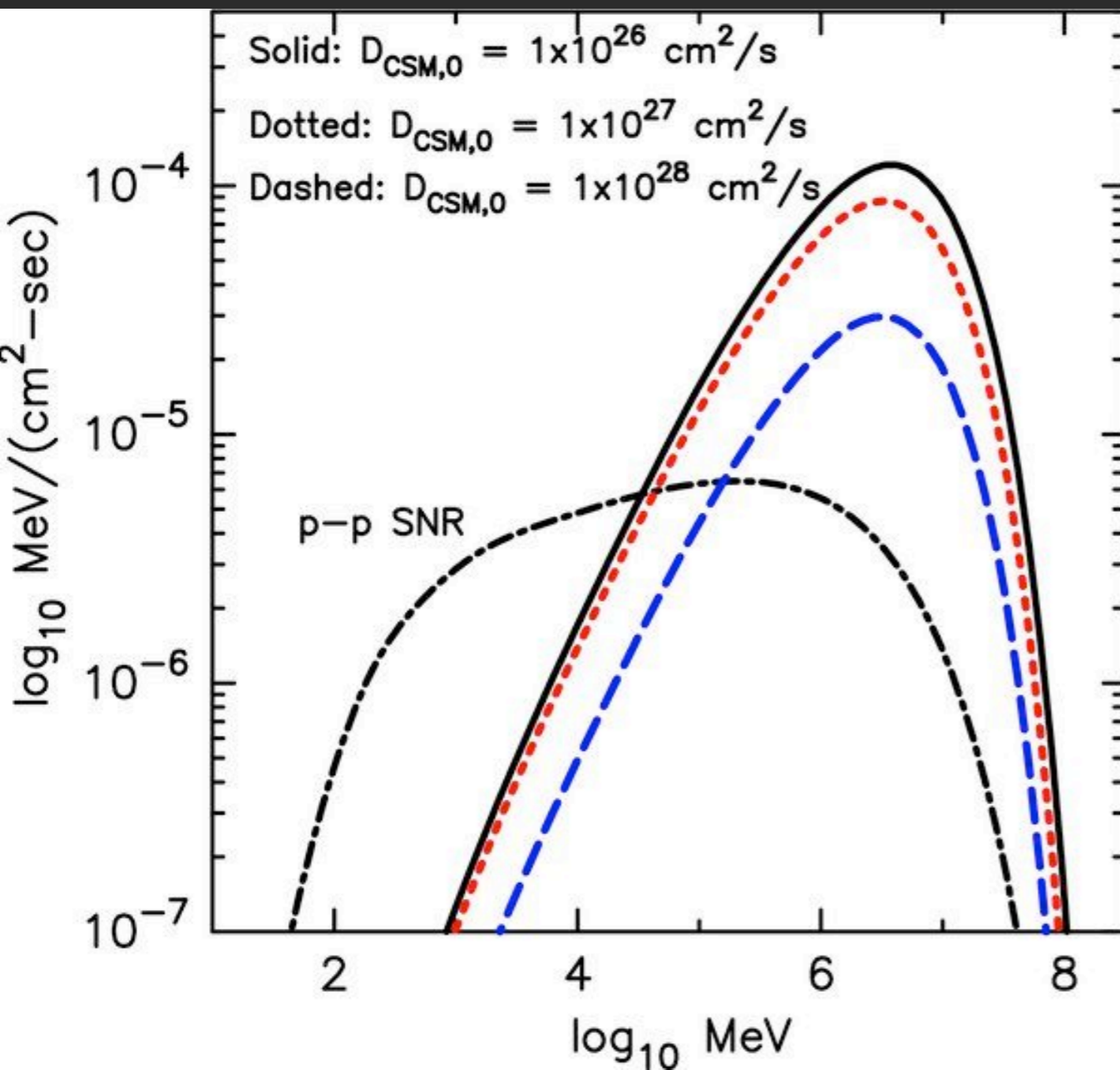
### iii. escape and diffusion

what is the spectrum of accelerated particles which escape the SNR shock?

how do these particles diffuse through the ISM and CSM?

can we observe signatures of escape in  $\gamma$ -ray emission near SNRs?

### iii. escape and diffusion



see:

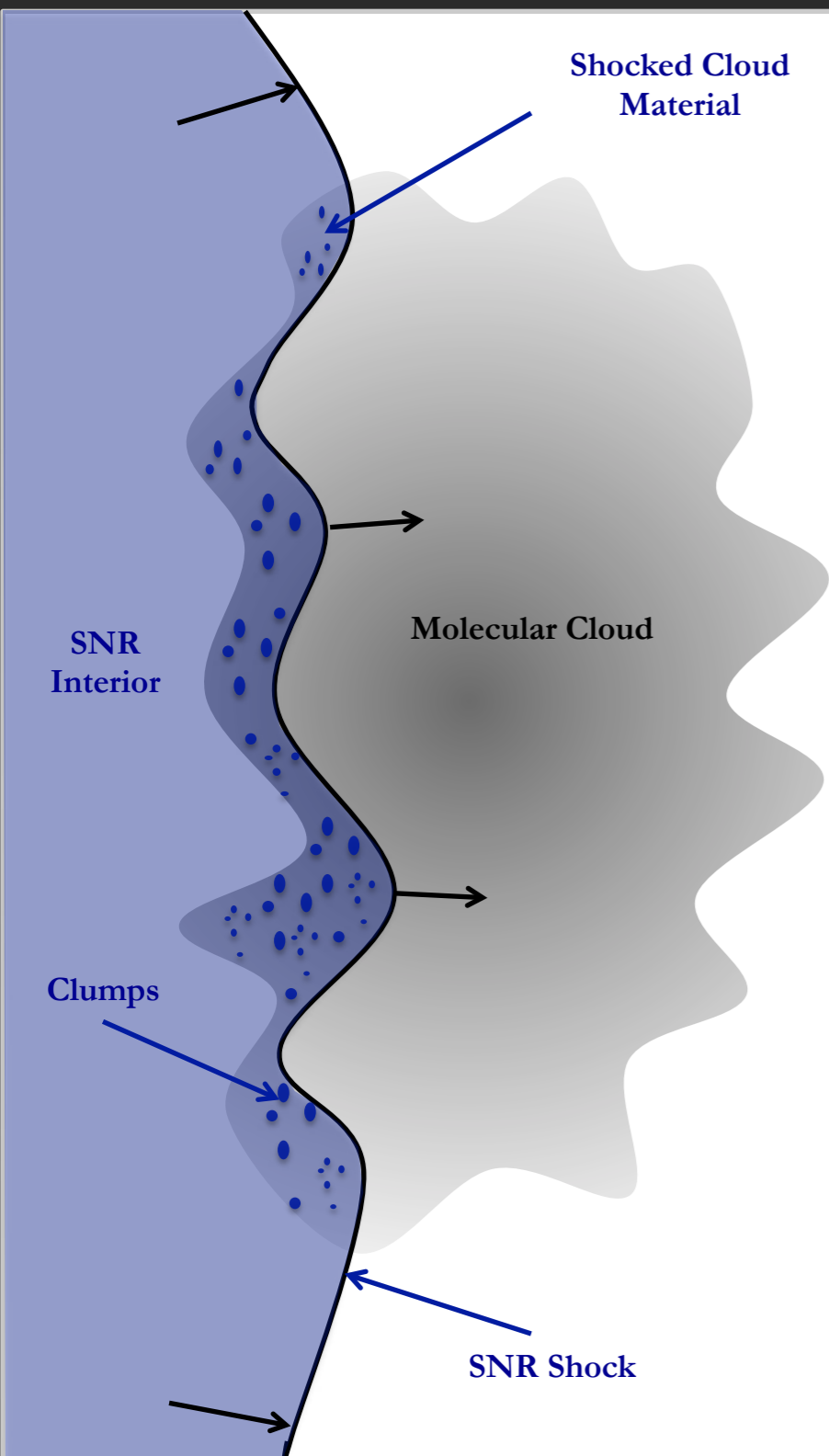
- uchiyama (poster) – w44
- cardillo (poster) – propagation
- schuppan+ 2012 – ionization



### iii. molecular clouds

what happens when SNR shocks interact with dense clouds of material?

# iii. molecular clouds



- **castro & slane (2010,2012):**
  - w30 + ctb 37a + g349.7-0.5 + 3c391
  - w41 + ctb 33 + msh 17-39
  - x-ray density  $\ll$   $\gamma$ -ray density

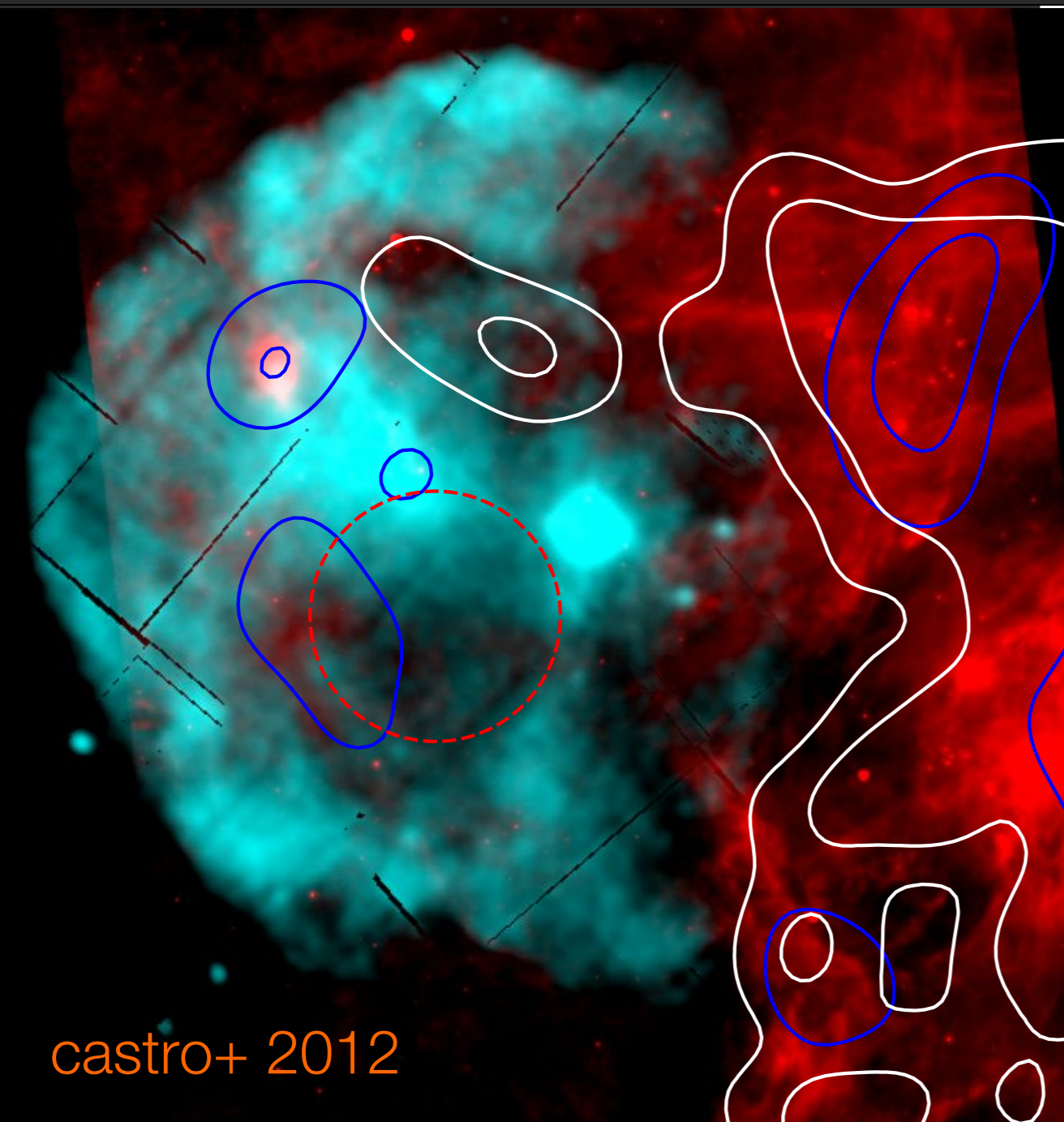
see also:

- **uchiyama+ 2010** – reacceleration
- **inoue+ 2010** – diffusion
- **schuppan+ 2012** – ionization
- **cohen (poster)** – fermi-lat analysis
- **de Palma (poster)** – also fermi-lat analysis

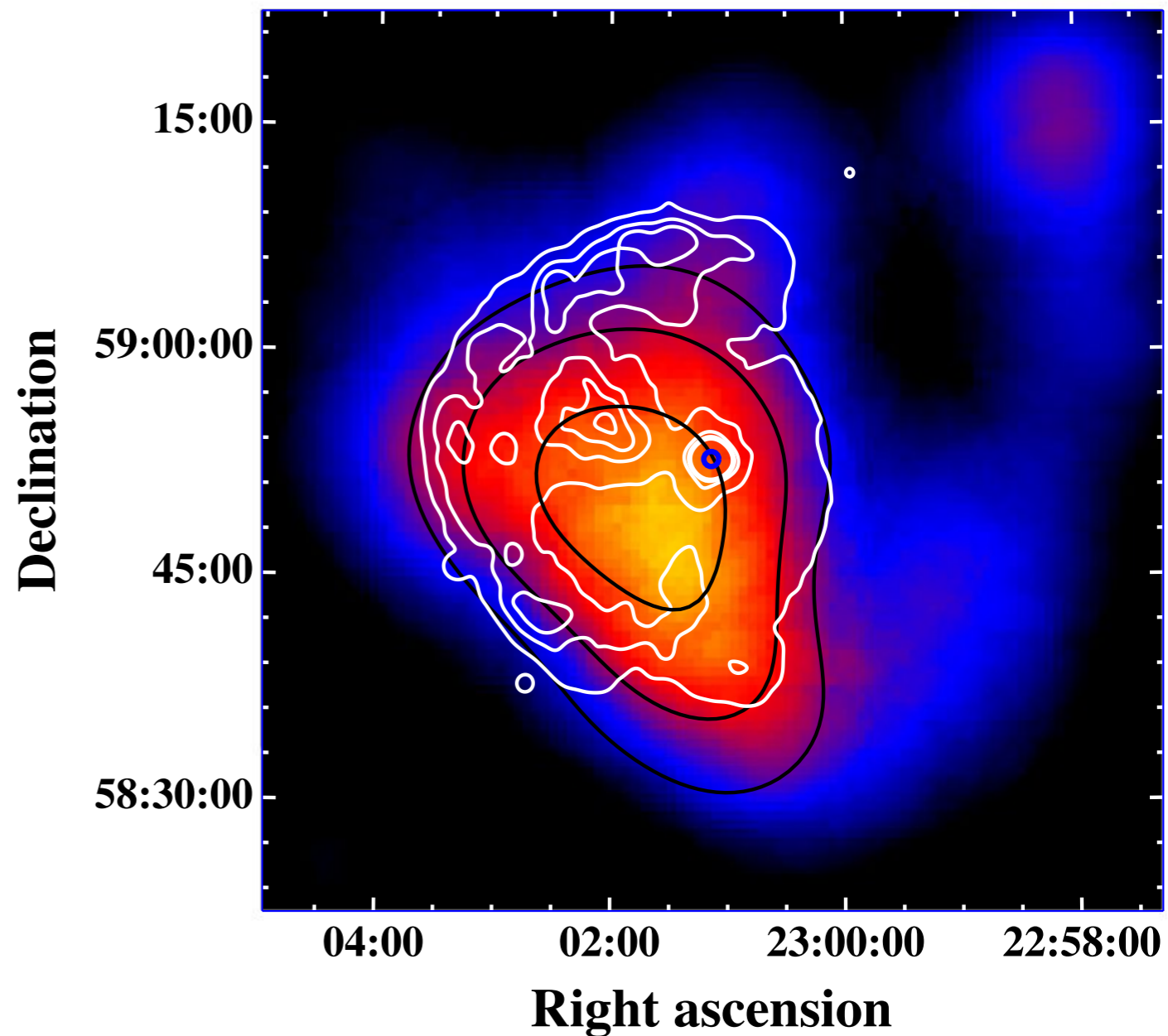
# iv. current & future research

what are we working on **right now**?  
where are we going?

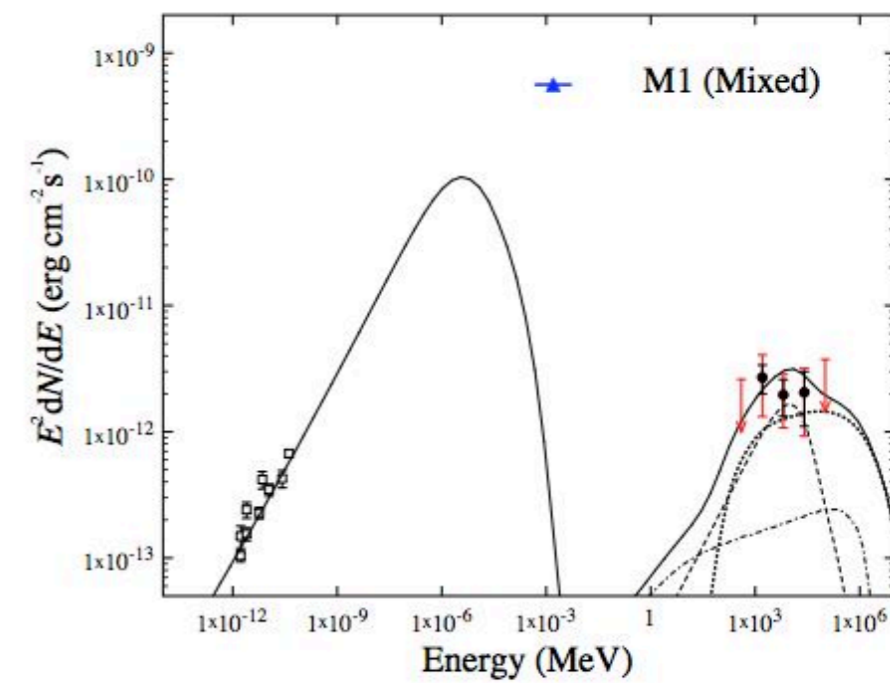
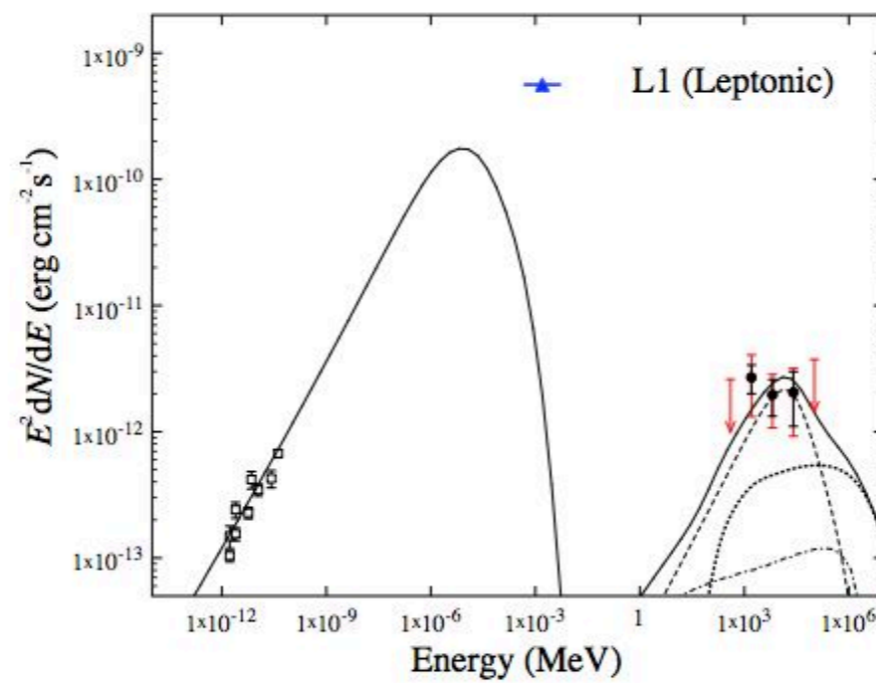
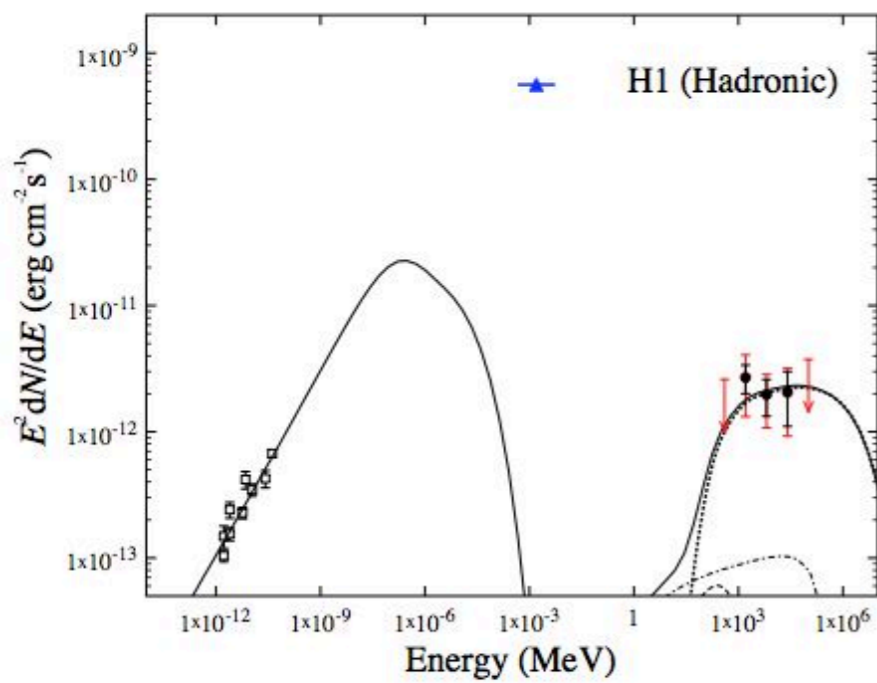
# iv. ctb 109



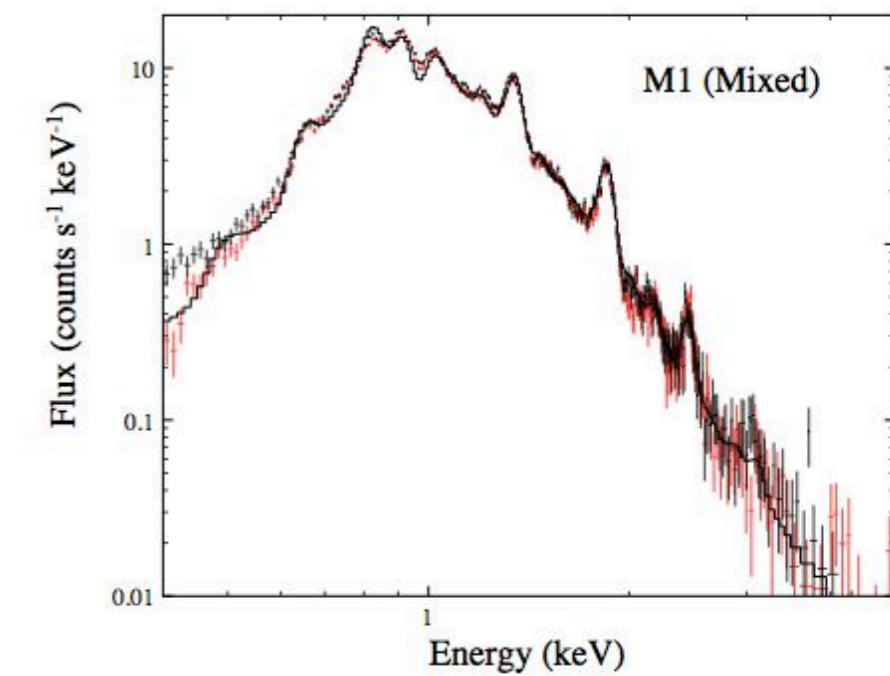
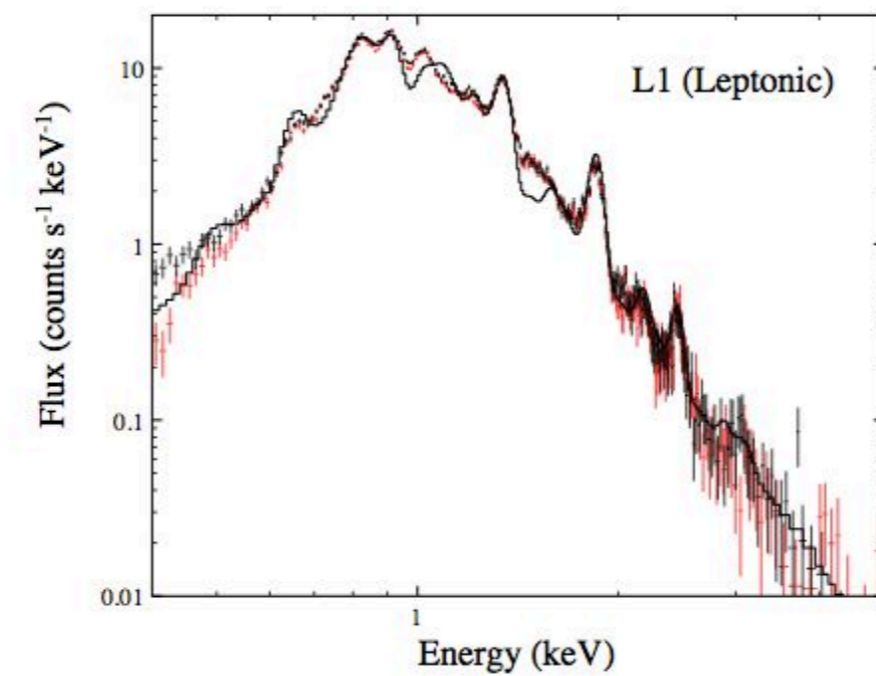
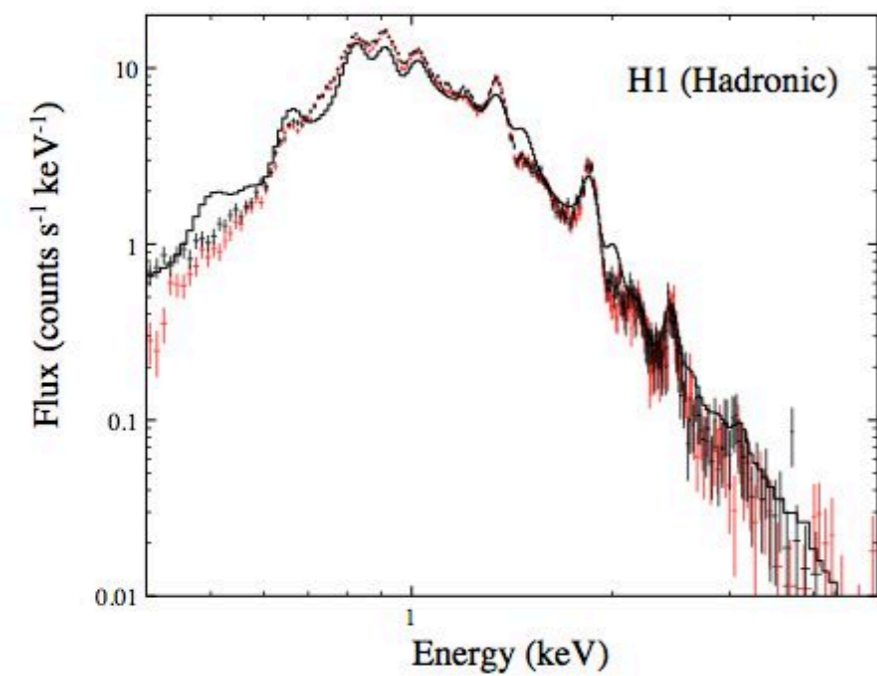
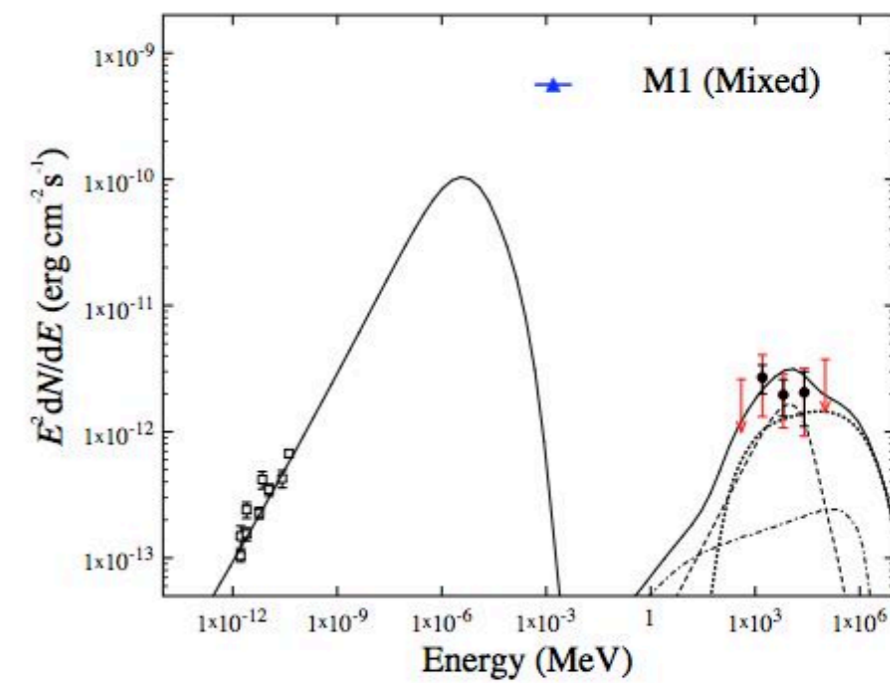
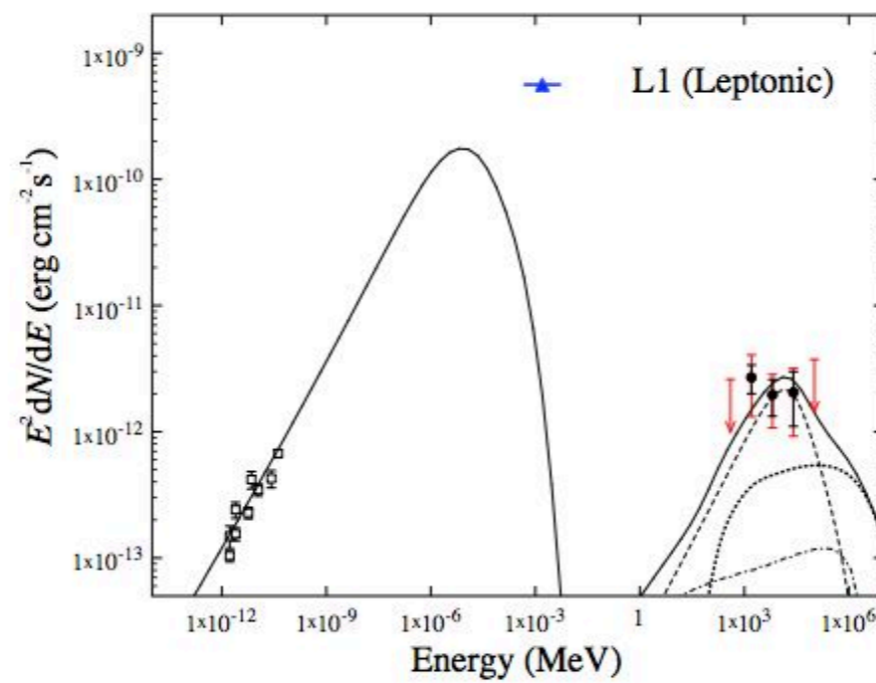
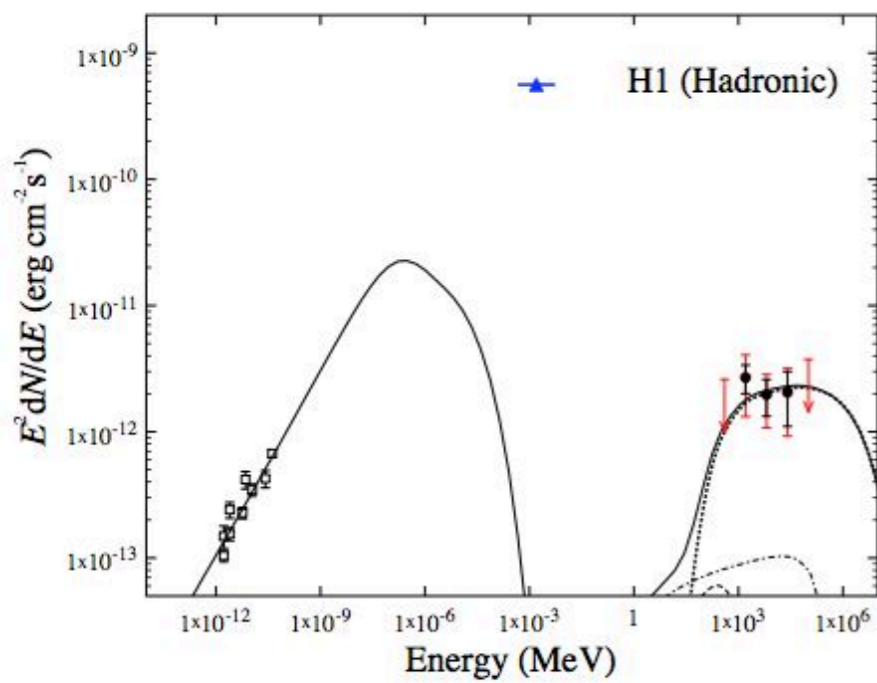
castro+ 2012



# iv. ctb 109



# iv. ctb 109

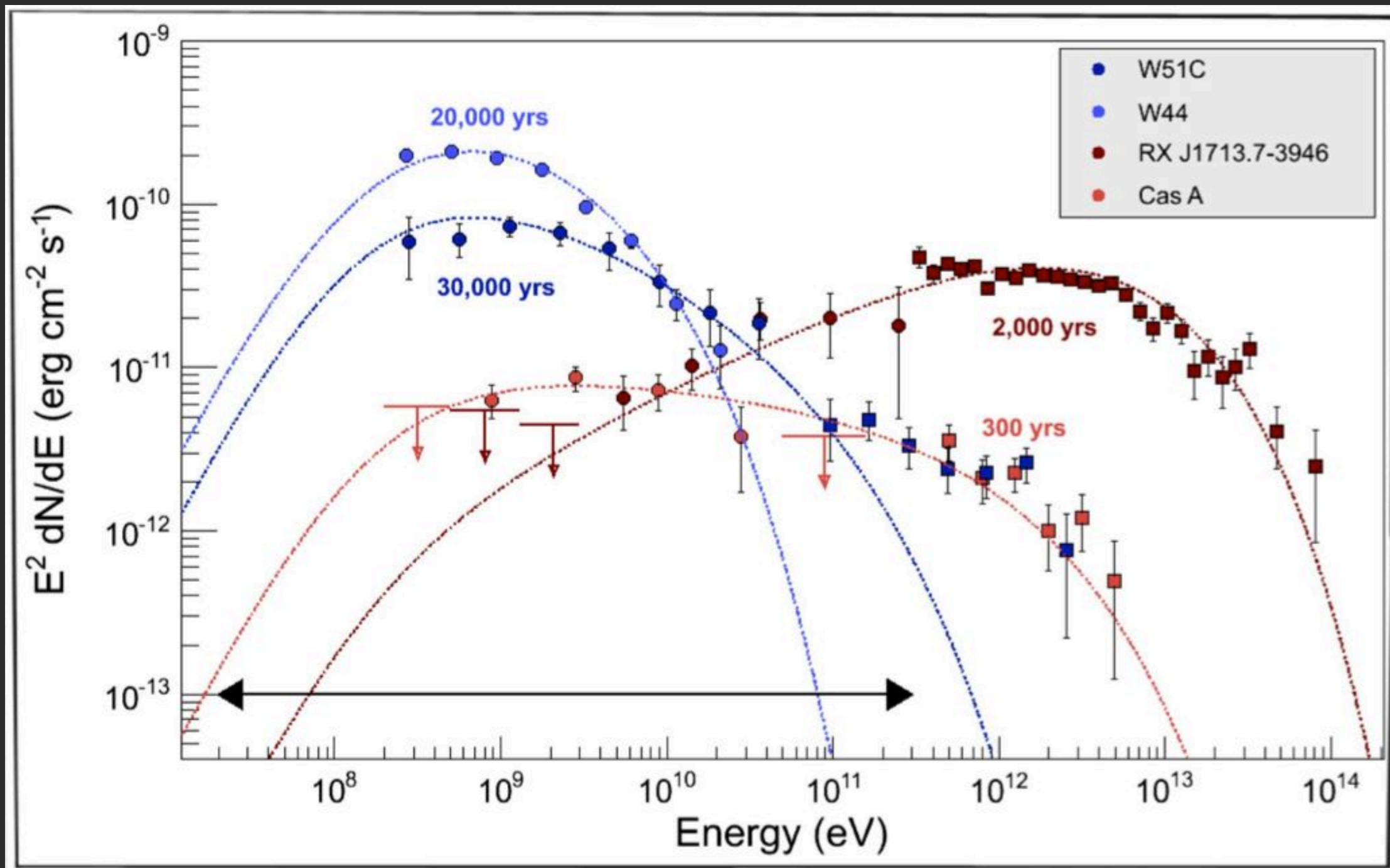


# iv. our research

where we are going...

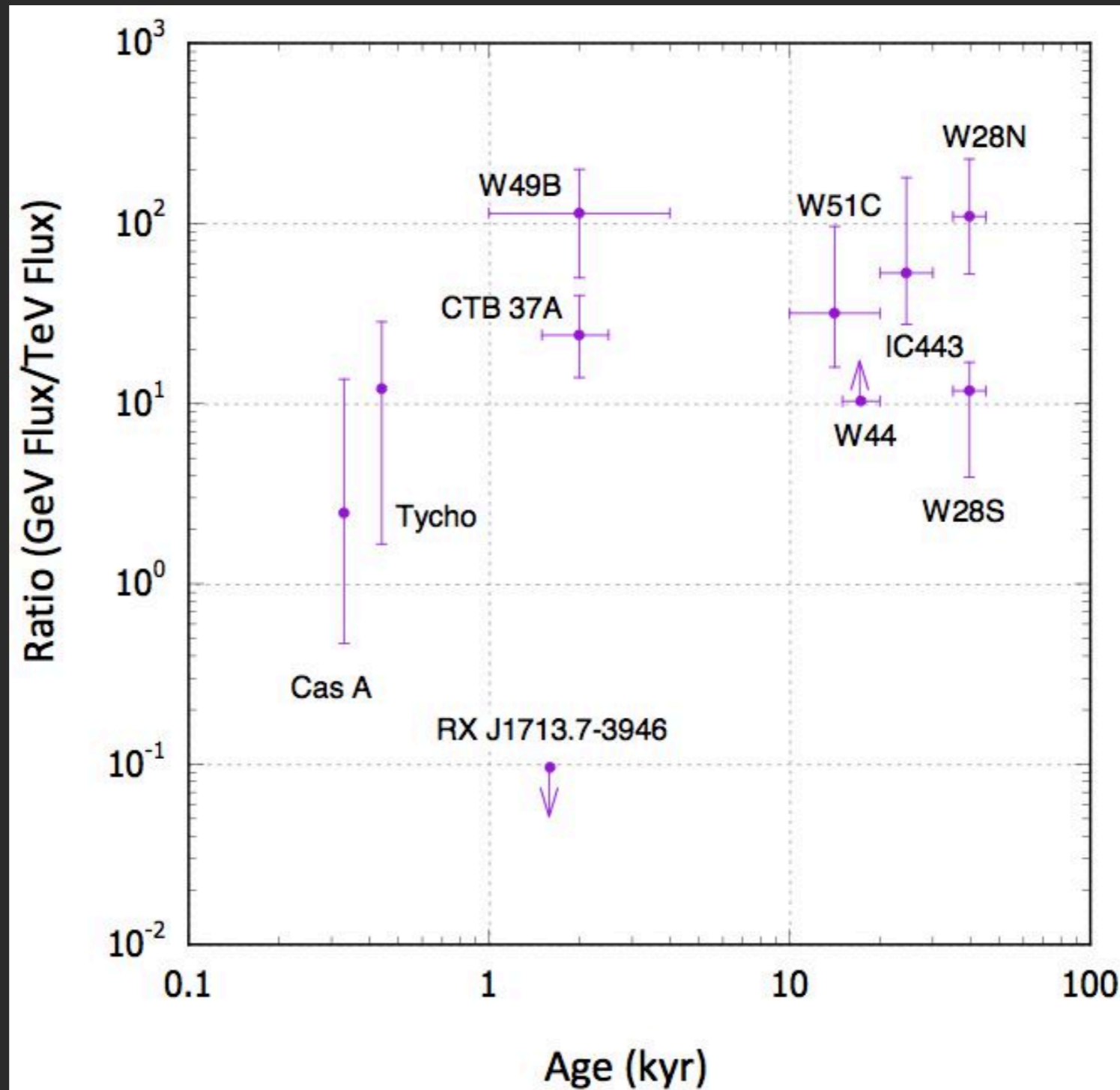
- time evolution of emission
- correlation between morphology and  $\gamma$ -rays
- high-res X-ray spectra (MCs & CRs)

# iv. time evolution of emission



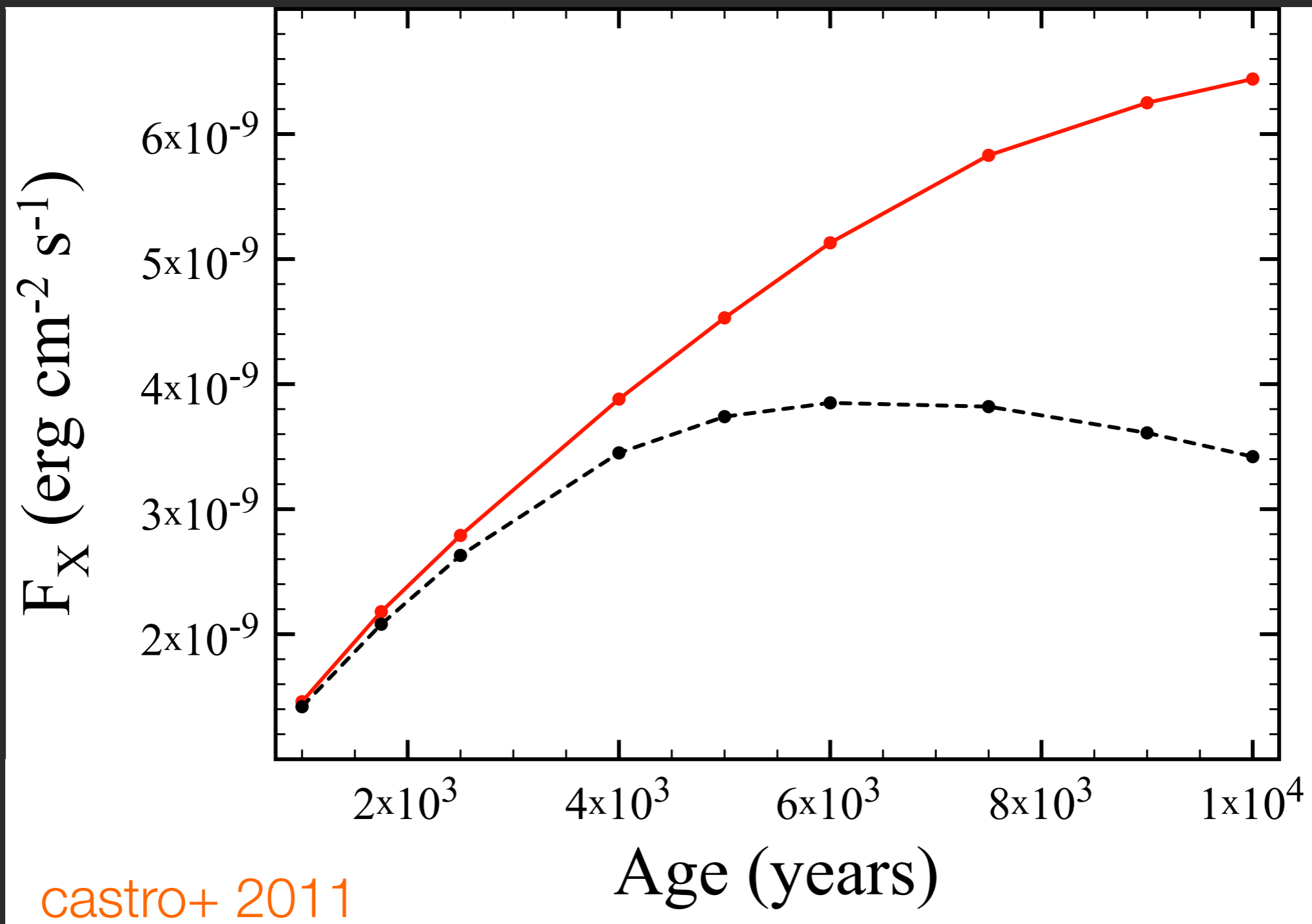


# iv. time evolution of emission



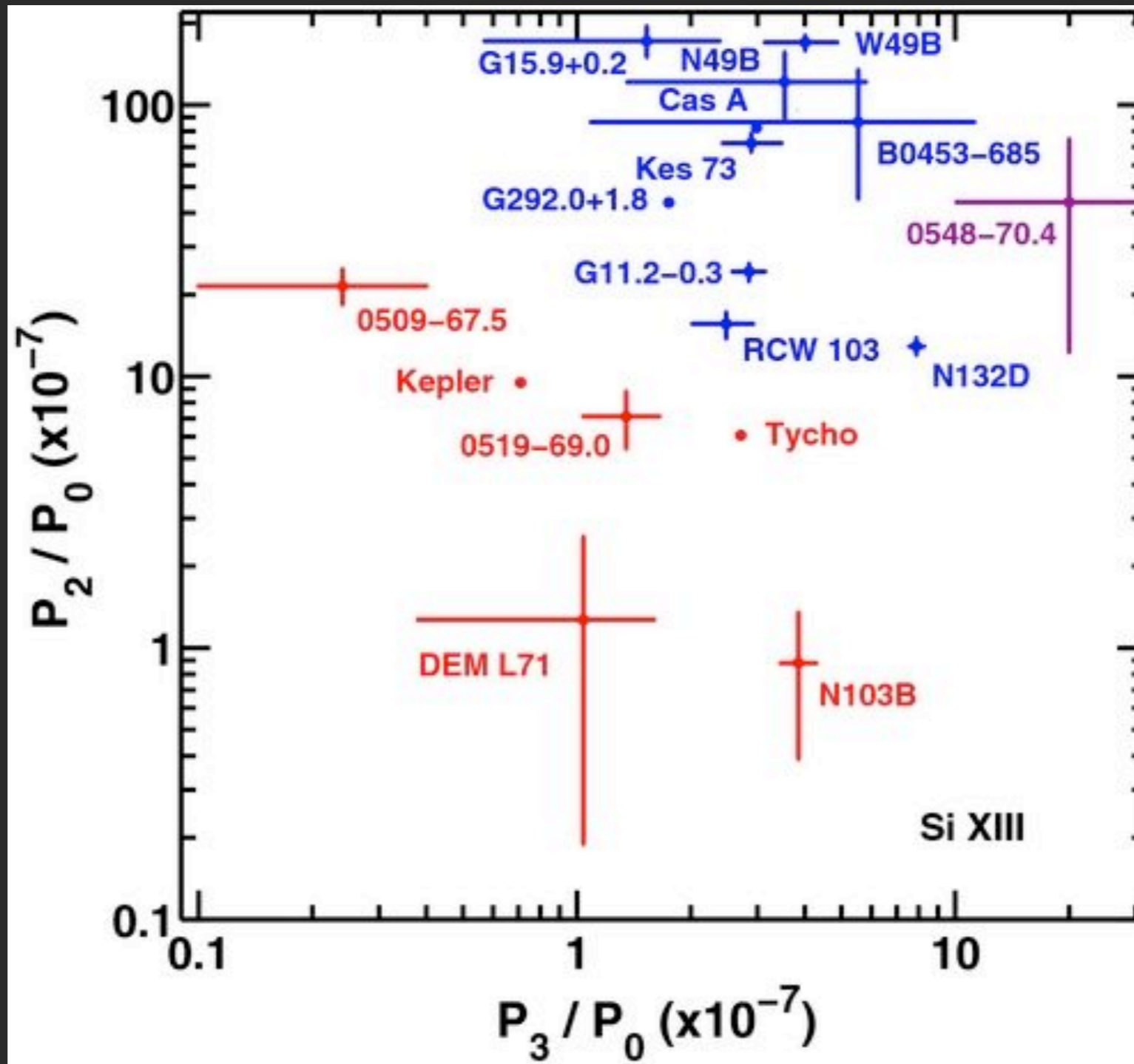
dermer & powale 2012

# iv. time evolution of emission



# iv. morphology and $\gamma$ -rays

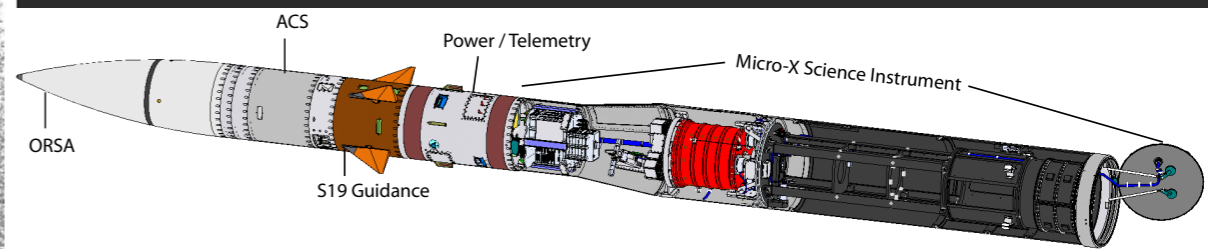
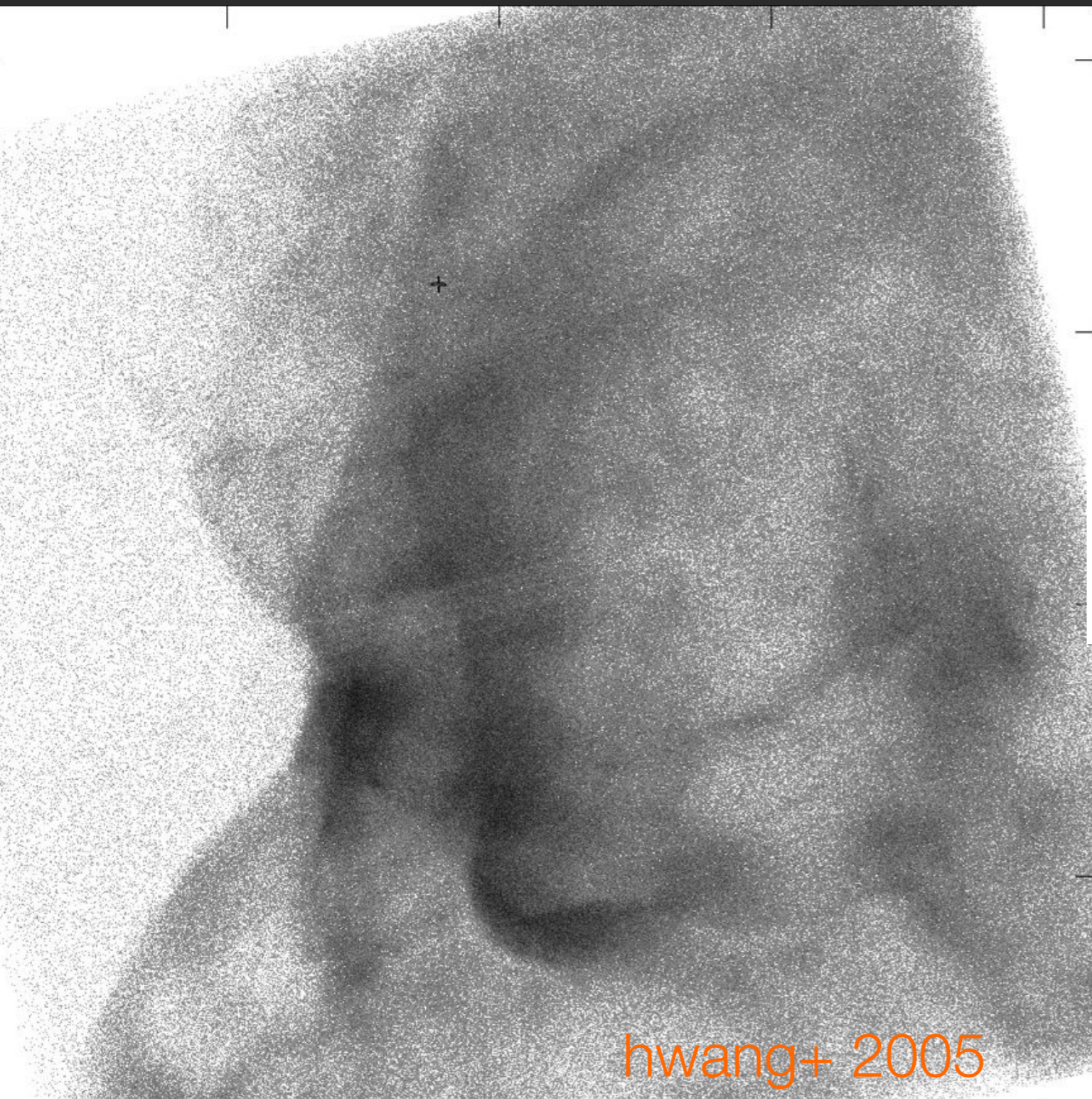
ellipticity / elongation



lopez+ 2011

mirror asymmetry

# iv. high-res X-ray spectra

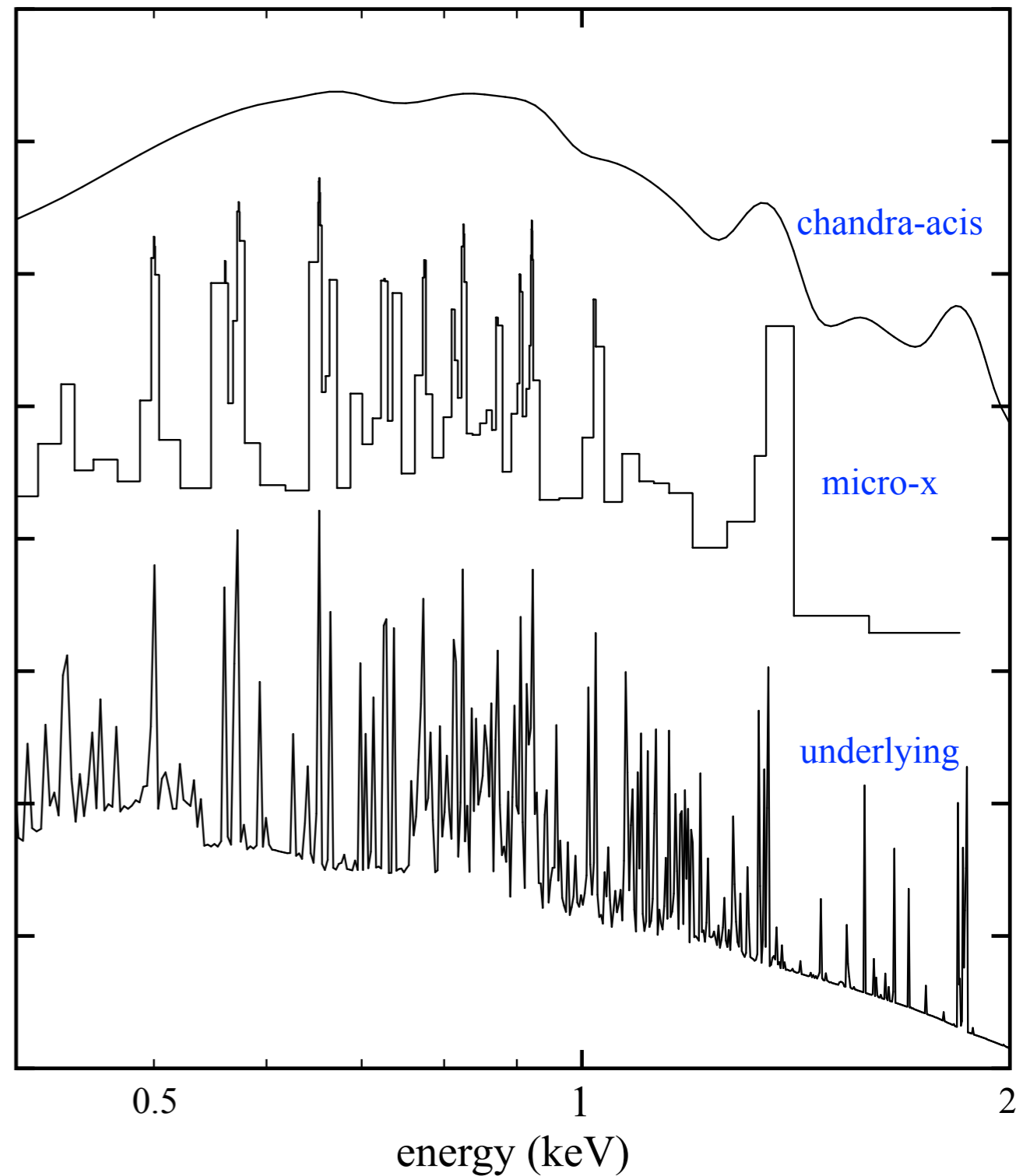


hwang+ 2005

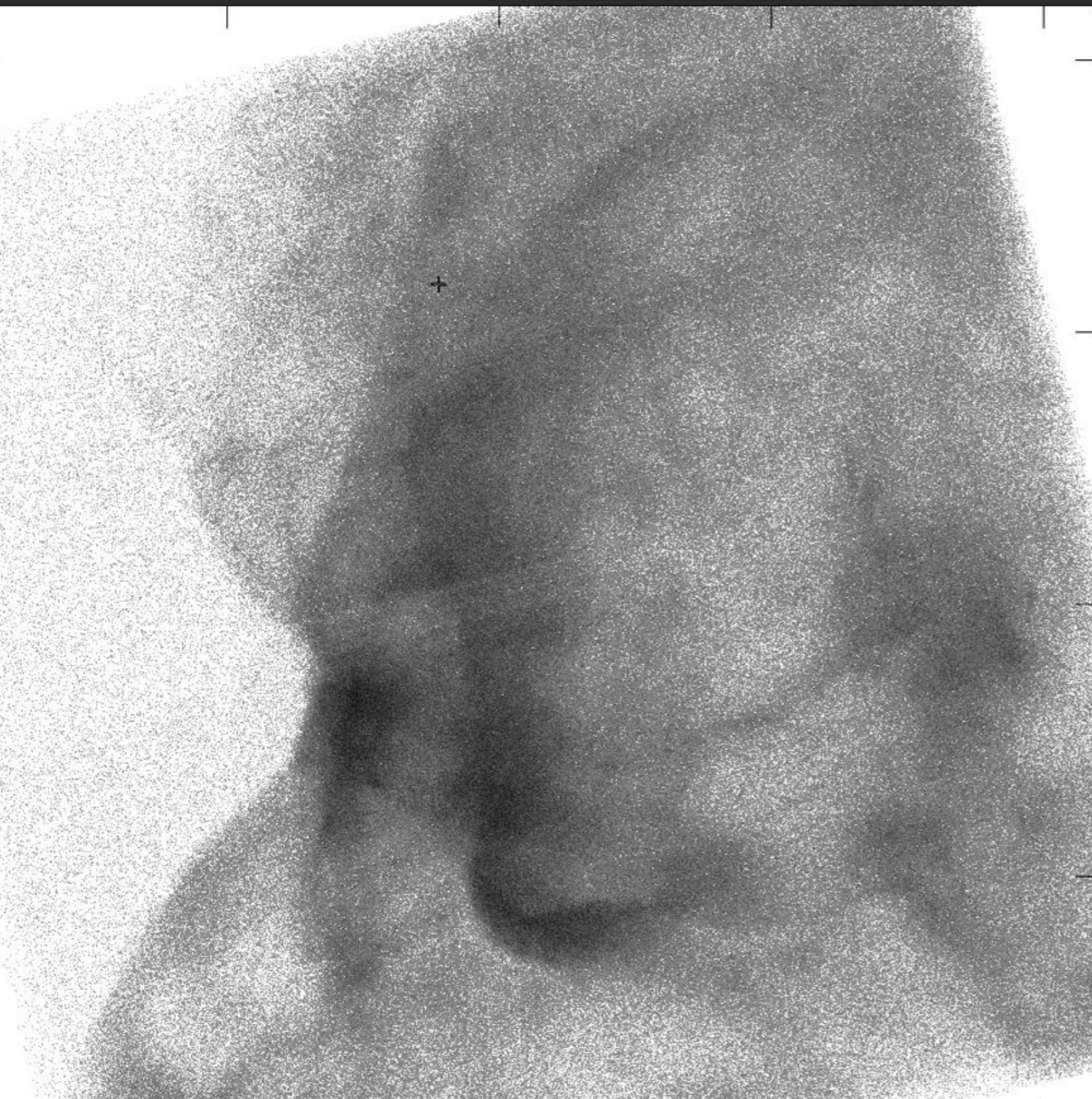
# iv. high-res X-ray spectra



hwang+ 2005



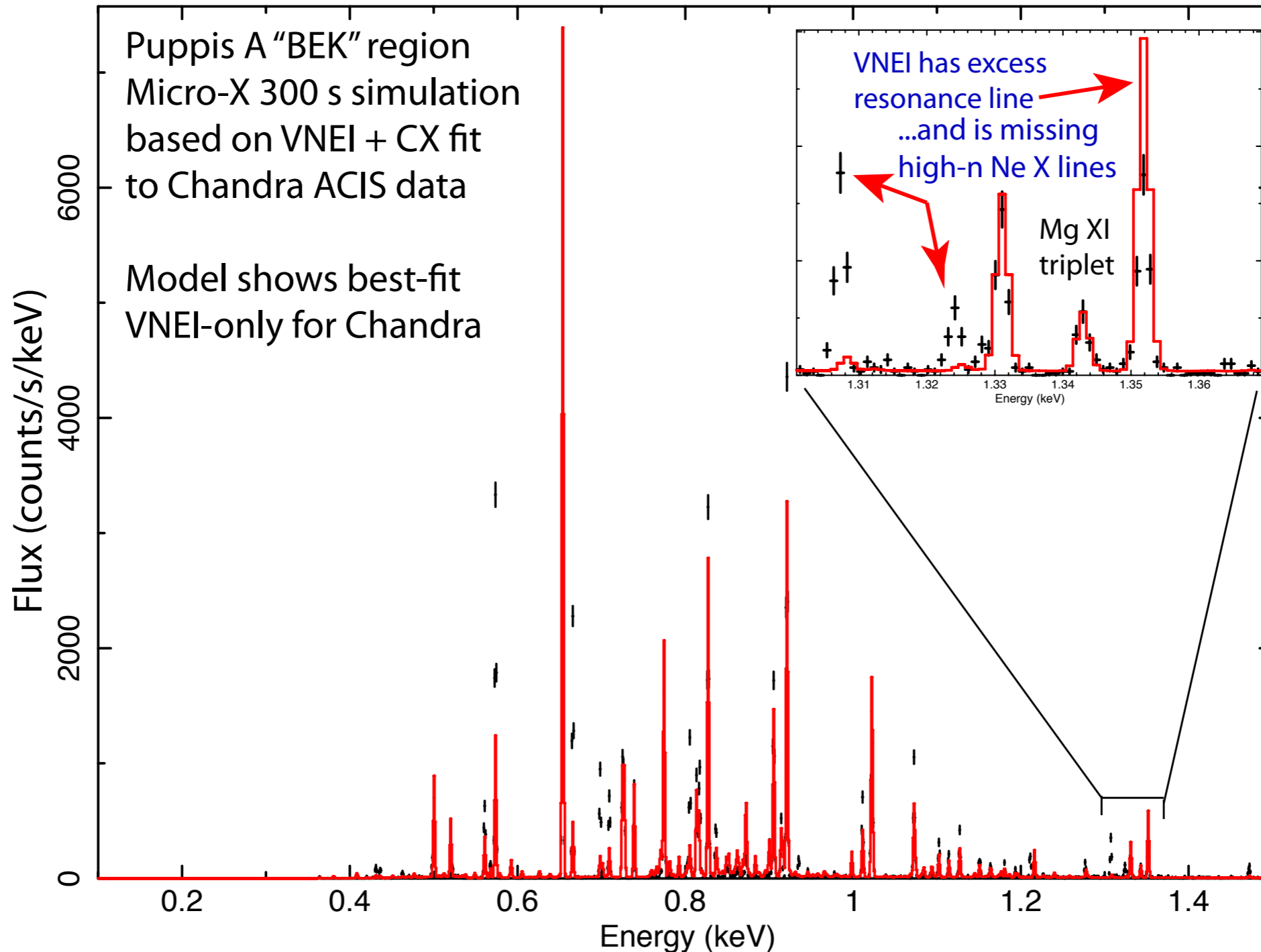
# iv. high-res X-ray spectra



why should you care?

- puppis A is interacting with a dense cloud at BEK (hwang+ 2005)
- detected with Fermi-LAT (hewitt+ 2012, see poster)
- katsuda+ (2012) found enhanced f/r ratios in xmm-newton RGS x-ray spectra of BEK

# iv. high-res X-ray spectra



## iv. recent/upcoming instruments

- **NuStar + Astro-H** – hard x-rays = constraints on sed
- **Astro-H + Micro-X** – x-ray micro-calorimeters = detailed nature of shocked dense material
- **CTA** – more effective area, coverage to 10s of GeV (more SNRs + better sed)
- **ALMA** – possibly synchrotron continuum + ionized molecular material
- **JWST** – synchrotron continuum? a lot more?



# remnants of supernovae

pulsar wind nebulae – part 2 (very short!)

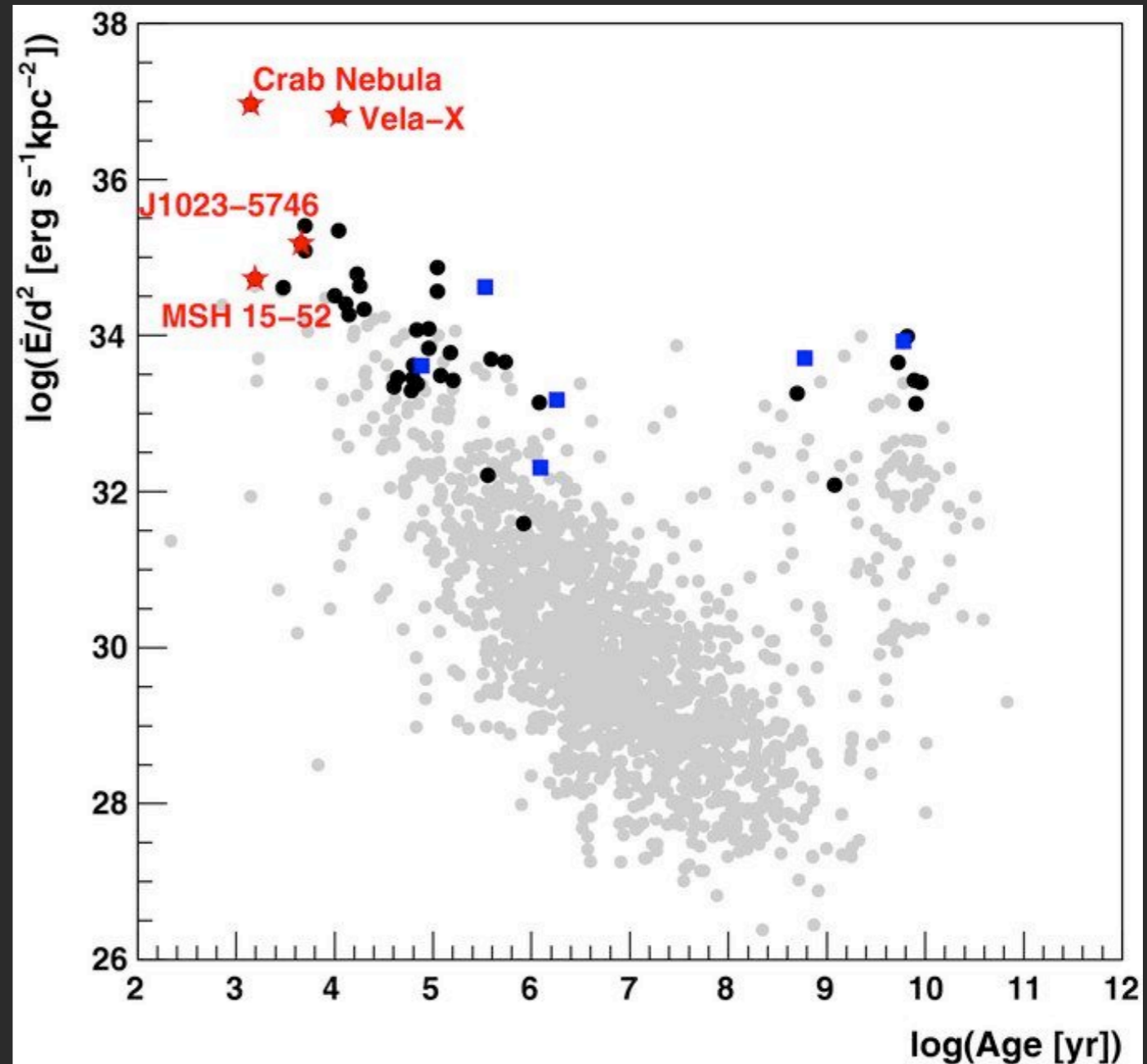
# outline

**why** do we care about pulsar wind nebulae?

what are the **open questions** being addressed today?

# i. why?

- pulsars
- particle acceleration
- SN & environment
- $\gamma$ -ray sources
- flares



ackermann+ 2011

## ii. open questions

- the Crab, the Crab, the Crab
- population studies of  $\gamma$ -ray PWNe  
see Josh Lande's poster
- how many of the unidentified GeV and TeV sources are PWNe?
- reverse shock compression?

slane+ 2010, slane+ 2012, temim+ 2012

# ii. open questions

talks:

- Romain Rousseau
- Lola Falletti

- Takayuki Saito
- Eduardo Striani

- Fermi LAT Observations of TeV PWNe Candidates at GeV Energies
- Observation of the Mouse Pulsar Region with the Fermi-LAT Telescope

- Observations of the Crab Pulsar and Nebula with the MAGIC Telescopes
- The Surprising Crab Nebula

posters:

- Ioanna Arka
- Joshua Lande

- Amanda Weinstein
- Colleen Wilson-Hodge
- Elizabeth Hays

- Gamma rays by synchrotron radiation in pulsar winds
- Search for Pulsar Wind Nebulae in the Off-Peak Regions of Pulsars in the Second Fermi LAT Pulsar Catalog
- Methods of establishing correlation between extended GeV and TeV emission
- Hard X-ray Variations in the Crab Nebula
- Studies of Crab variability in simulated Fermi LAT data

the end