# Galactic γ-ray sources: I - cosmic-ray activities

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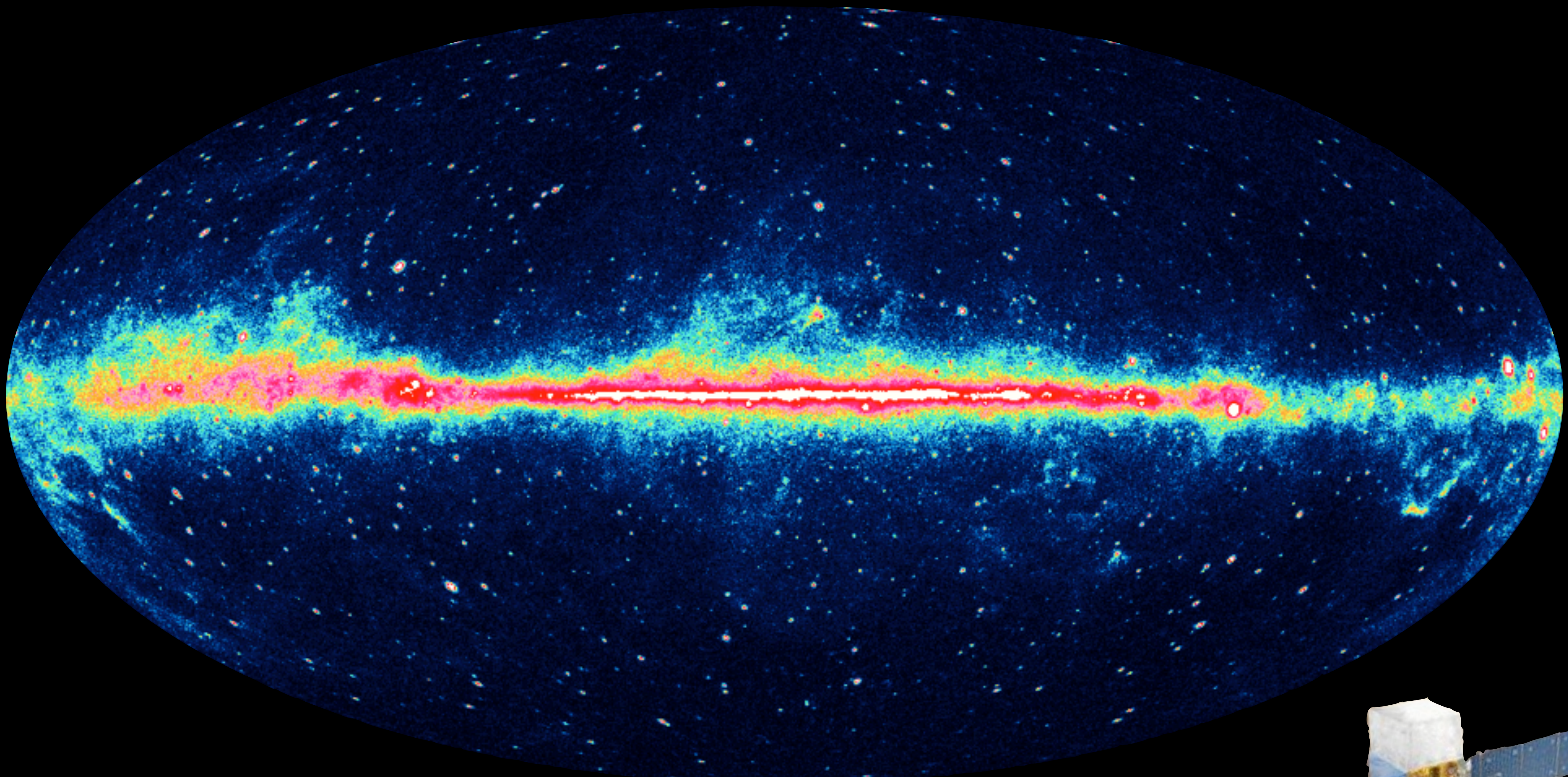
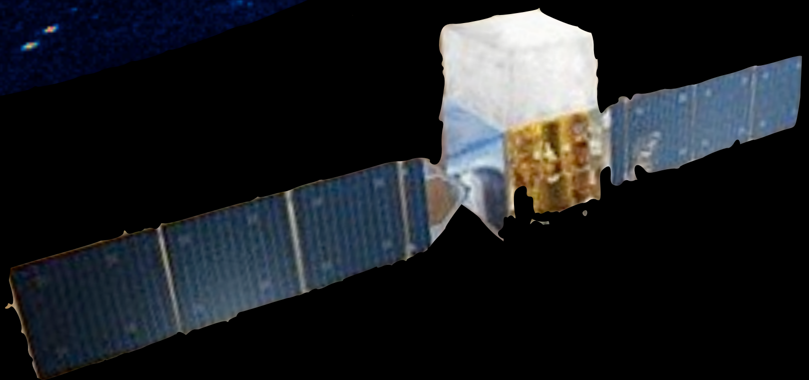
Annecy
septembre 2013

# the GeV sky

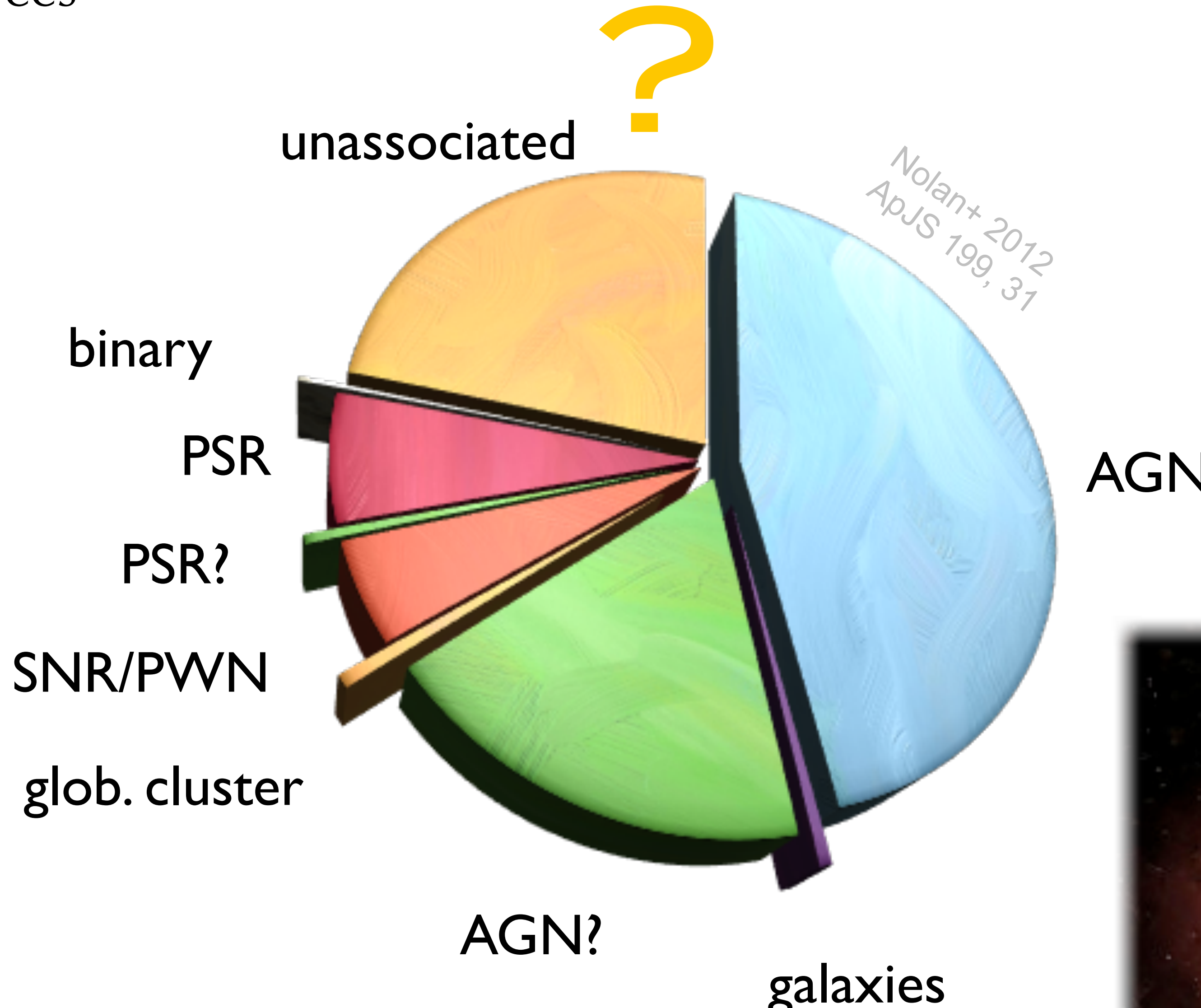
- 5 years with the Fermi Large Area Telescope
- whole sky every 3 h
- > 2000 sources + interstellar CRay emission + extragalactic background

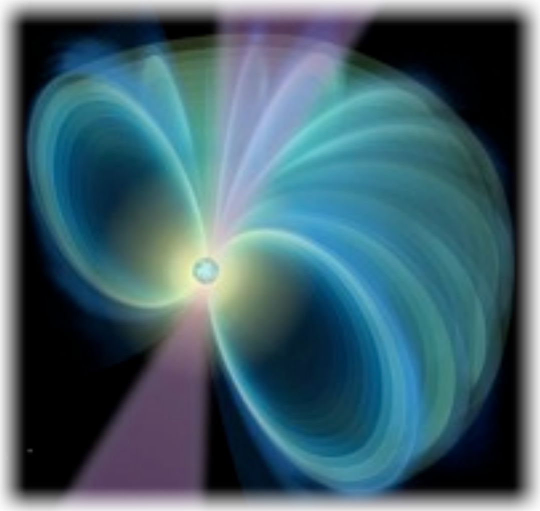


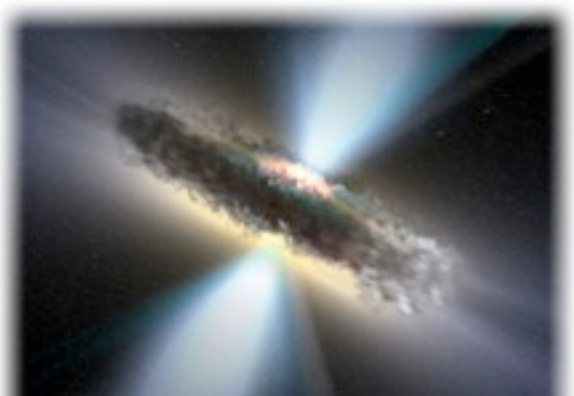


# 2FGL source catalogue

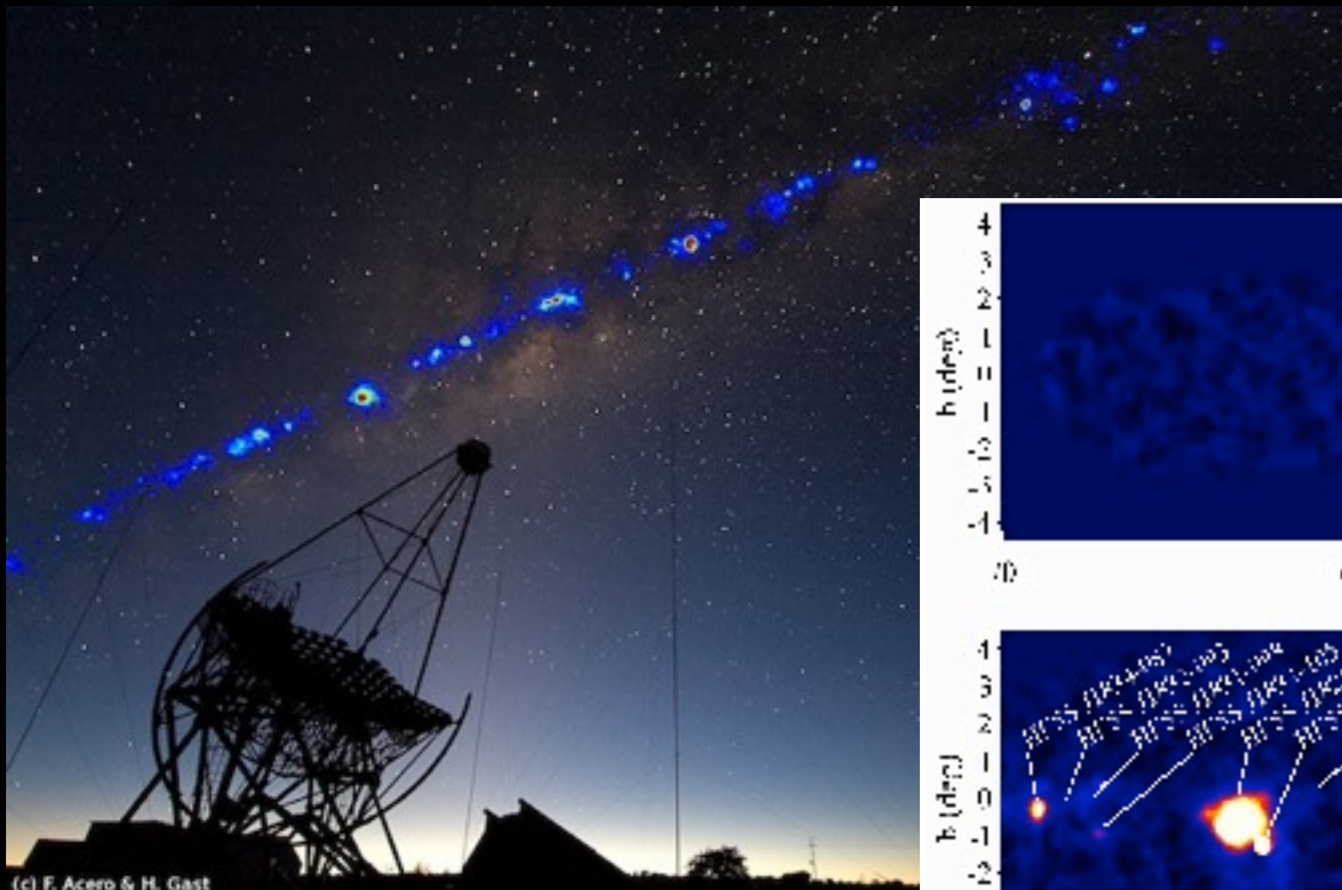
2 years of data: 1873 sources



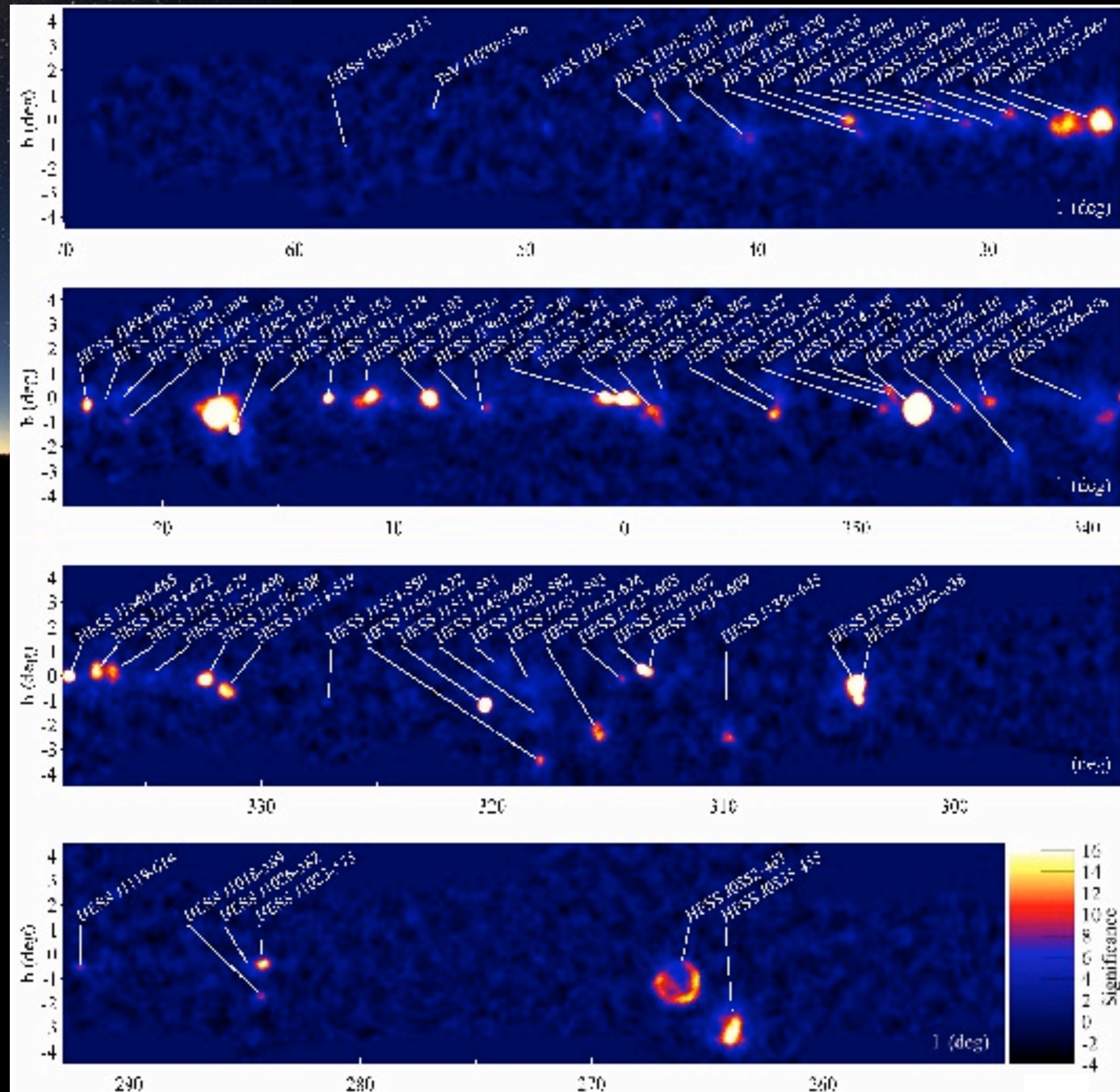





# TeV Galactic survey by HESS

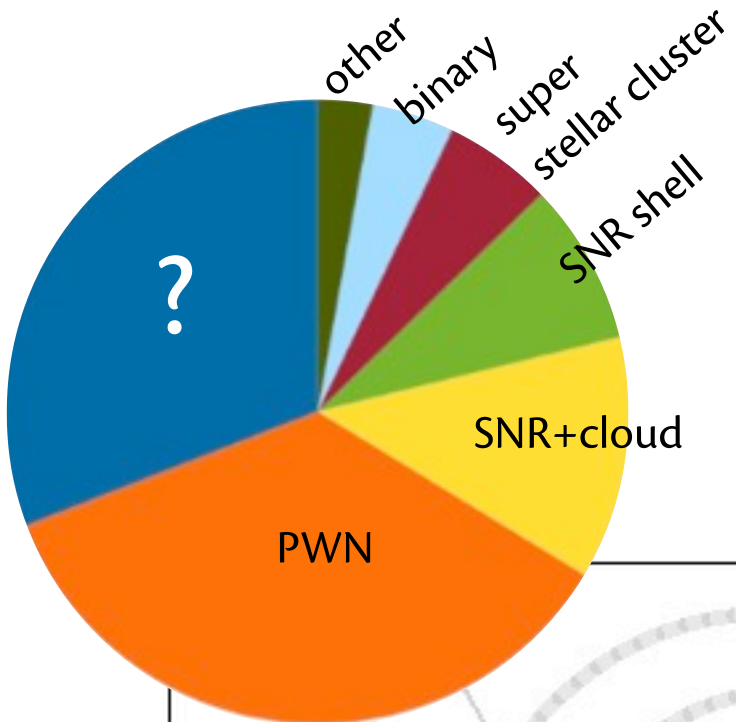


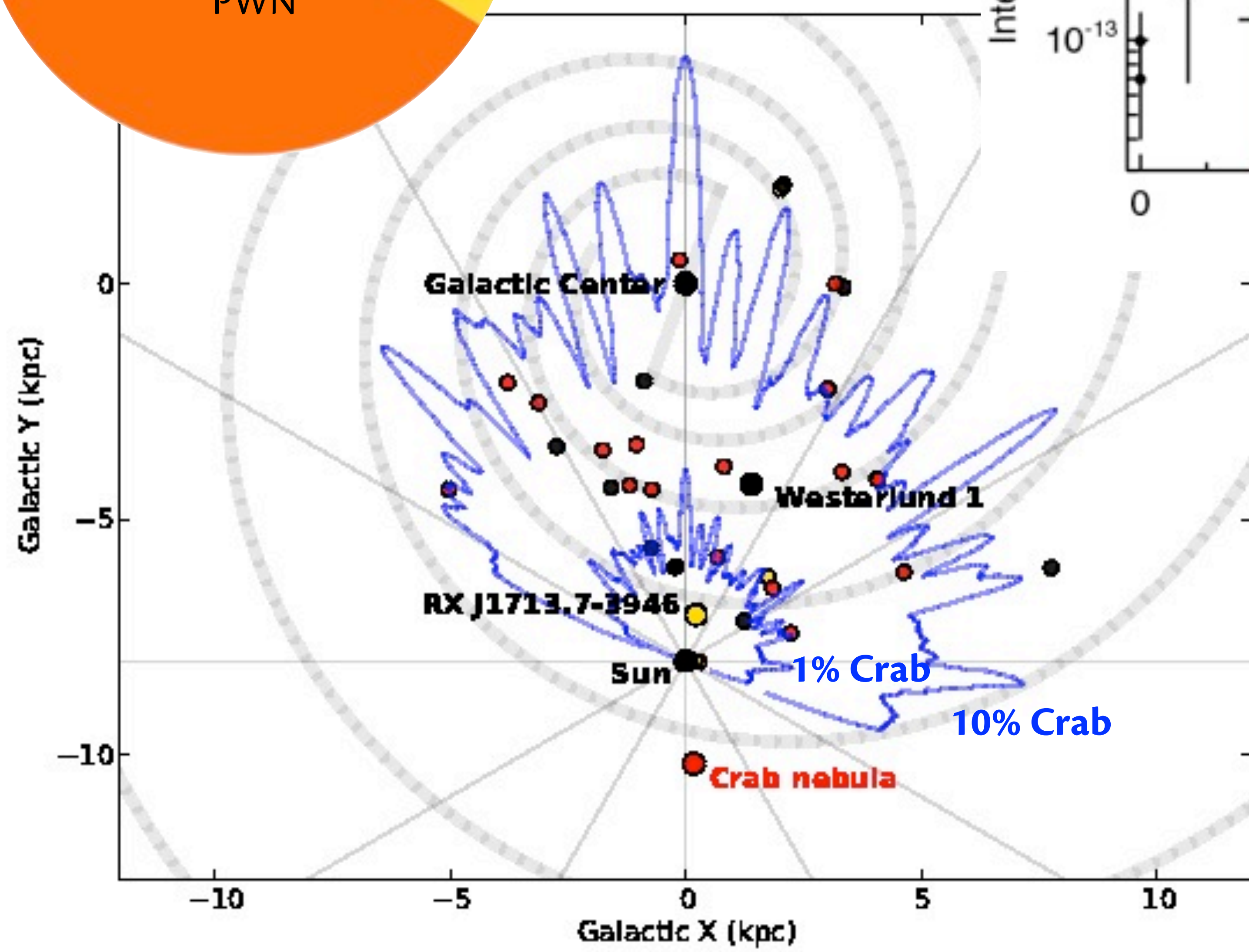

Carrigan+ 2013 ICRC

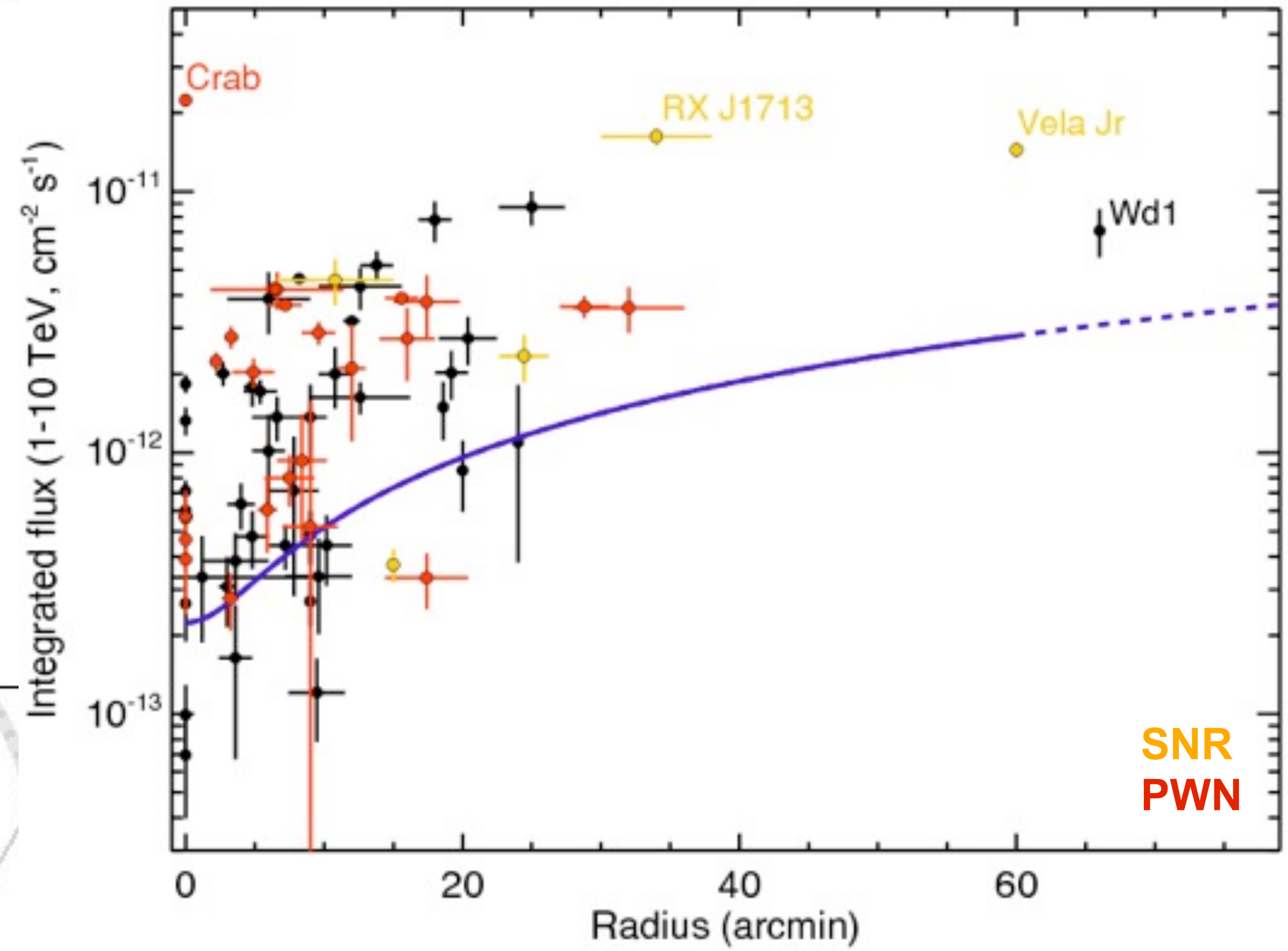


# Galactic TeV sources

- predominance of supernova remnants (SNR) and pulsar wind nebulae (PWN)



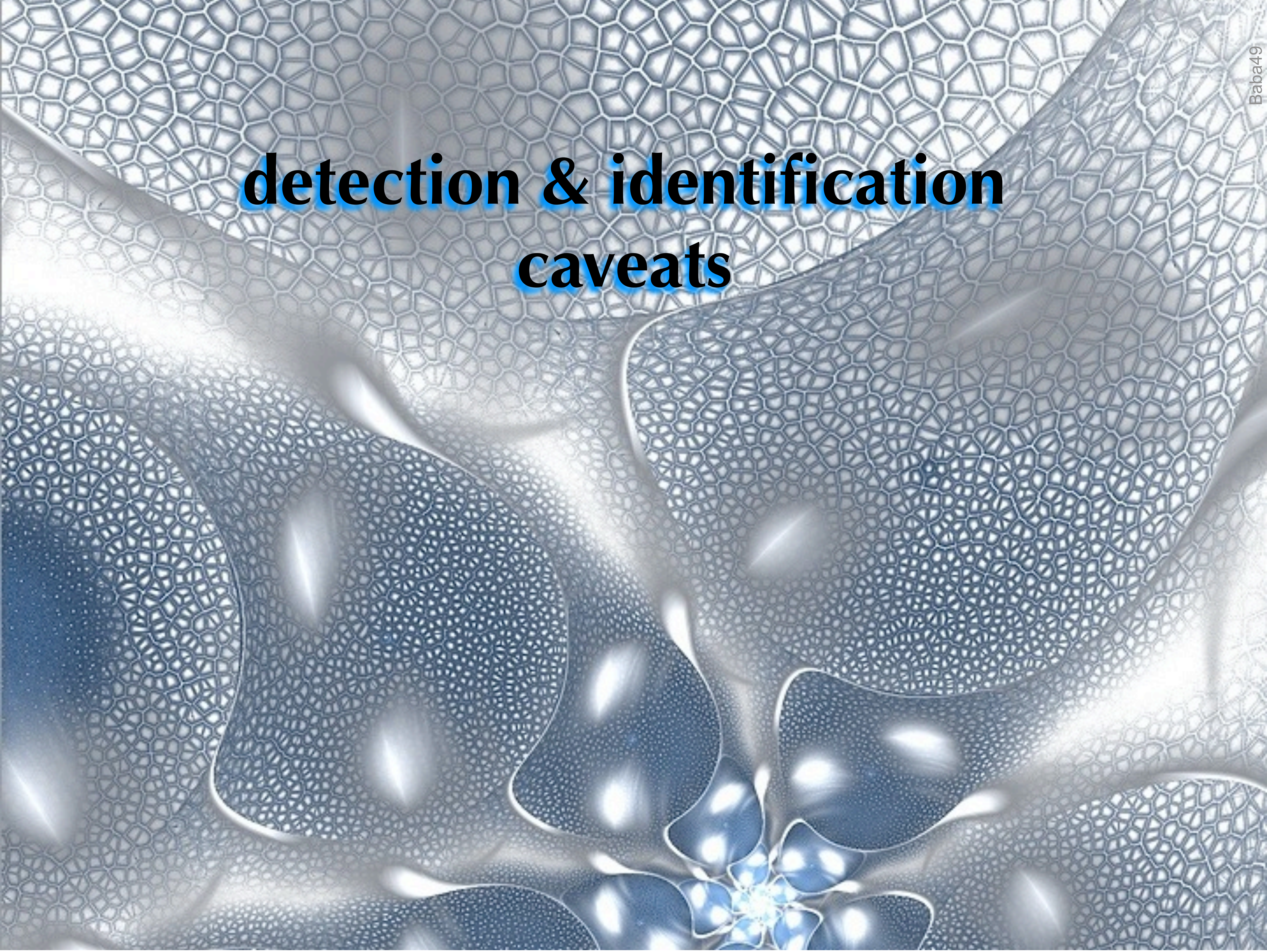




many extended sources ⇒ confusion and identification difficulties

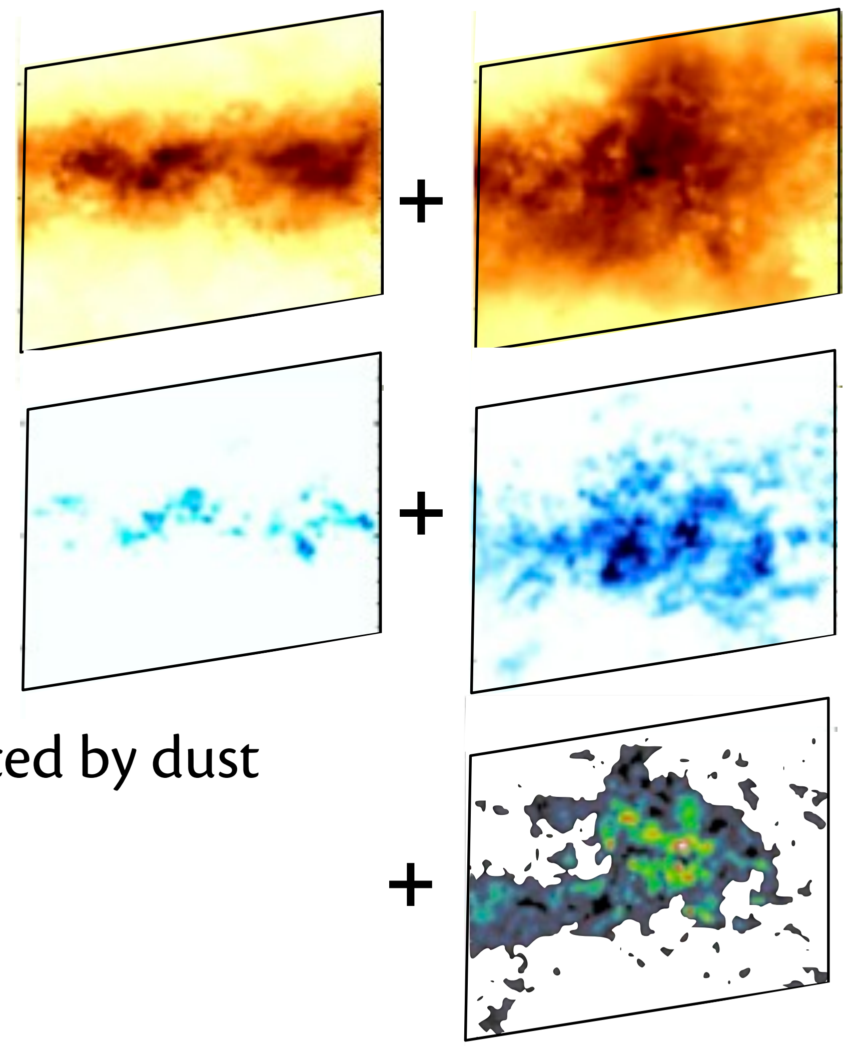
Carrigan+ 2013 ICRC

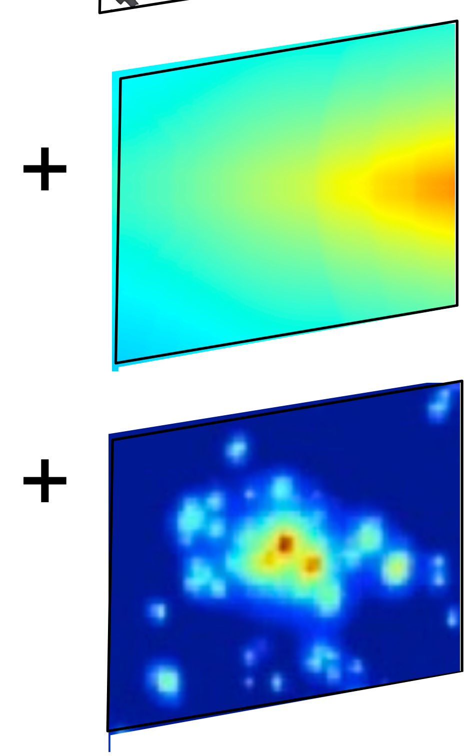
# detection & identification caveats



# the Galactic GeV interstellar background

- CRays in HI: N(HI)
- CRays in $H_2$:
- CRays in dark neutral gas, as traced by dust
- Galactic inverse Compton
- γ-ray source

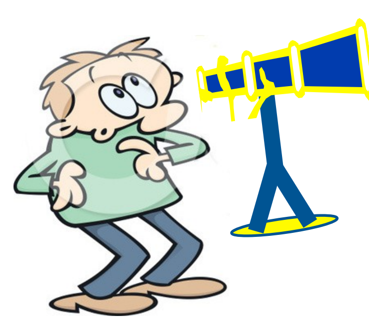




$$\frac{dN_{CR}}{dV}$$

$$X_{CO} = \frac{N(H_2)}{W(CO)}$$

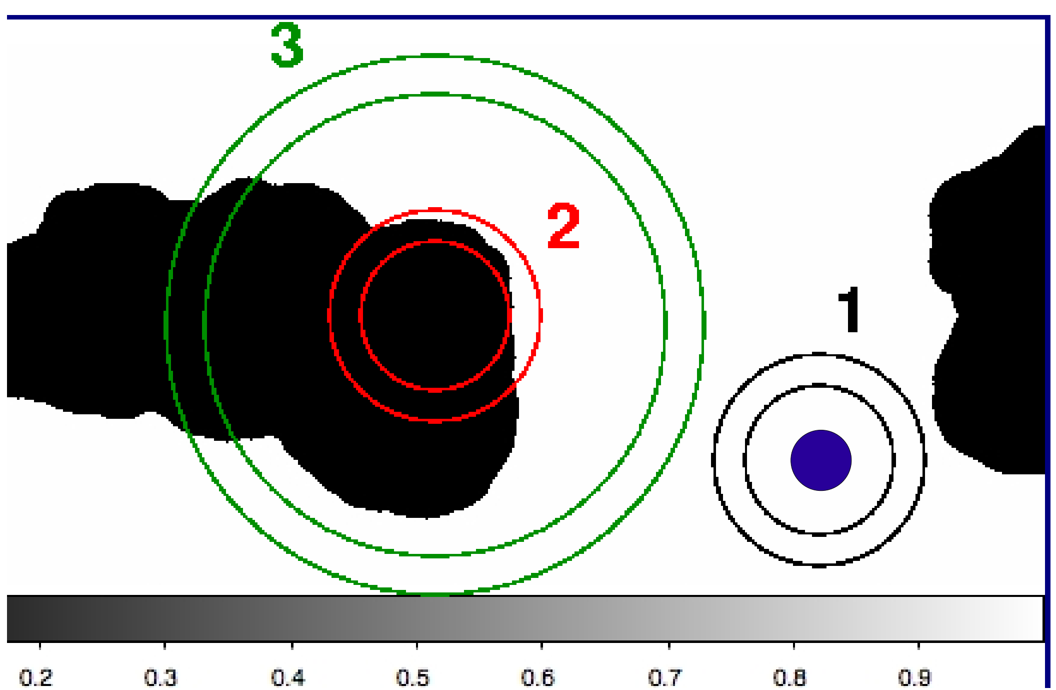
+ cte ?



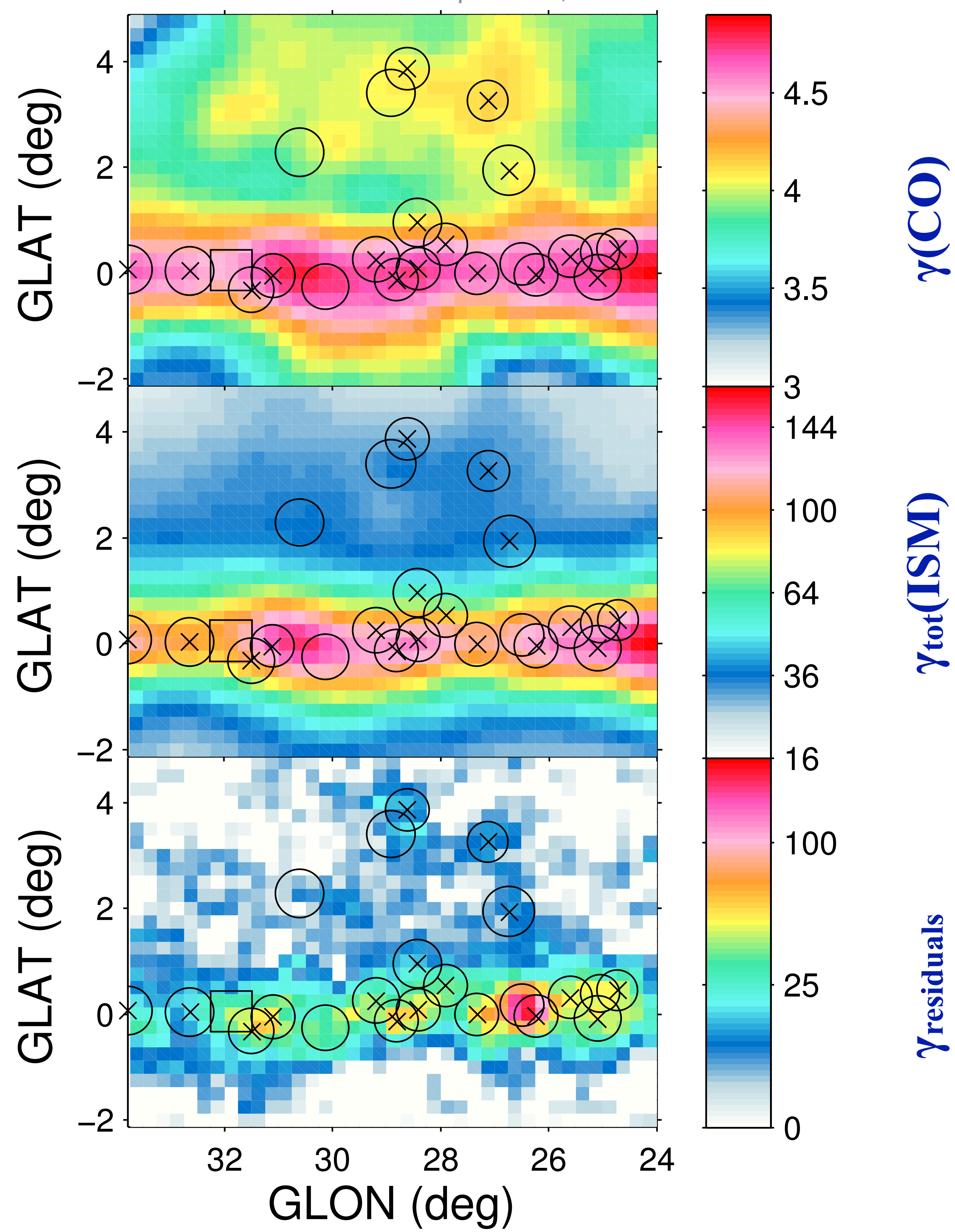
# Galactic sources & ISM confusion

- at GeV energies: ISM confusion with angular resolution > 0.1°
  - confused neighbours in the Galactic ridge
  - un-modelled diffuse excesses filled with sources
  - uncertain source properties because of the underlying background

- at TeV energies: background estimation in a ring around the source
  - no sensitivity to extended sources ≳ 1°

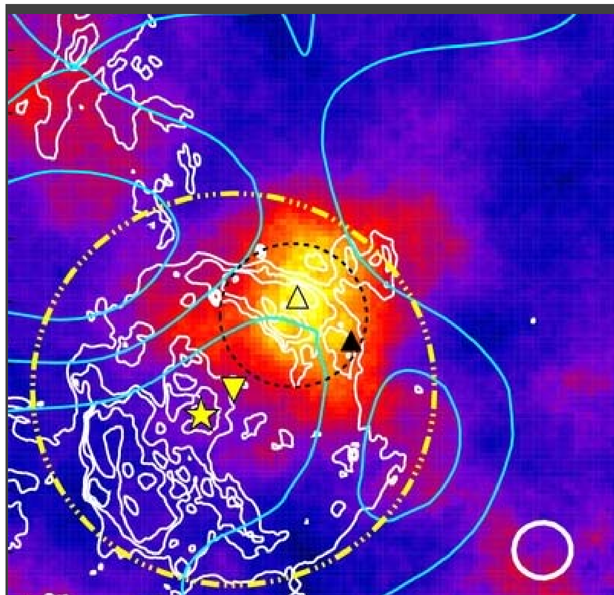



Nolan+ 2012 ApJS 199, 31

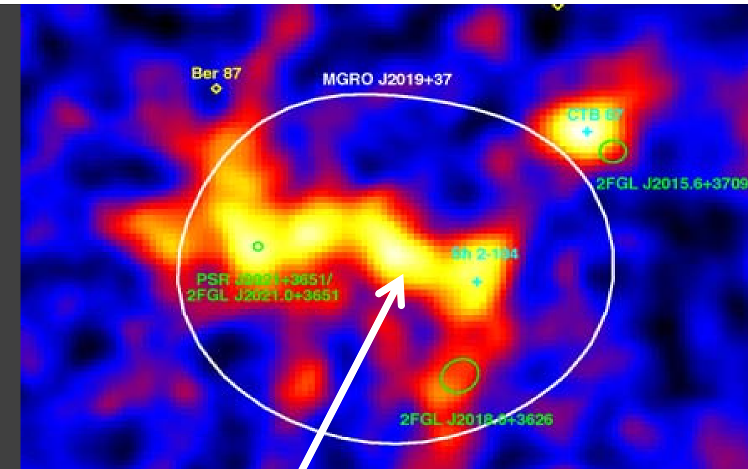



O = 50% containment PSF radius > 1 GeV

# Veritas survey of Cygnus

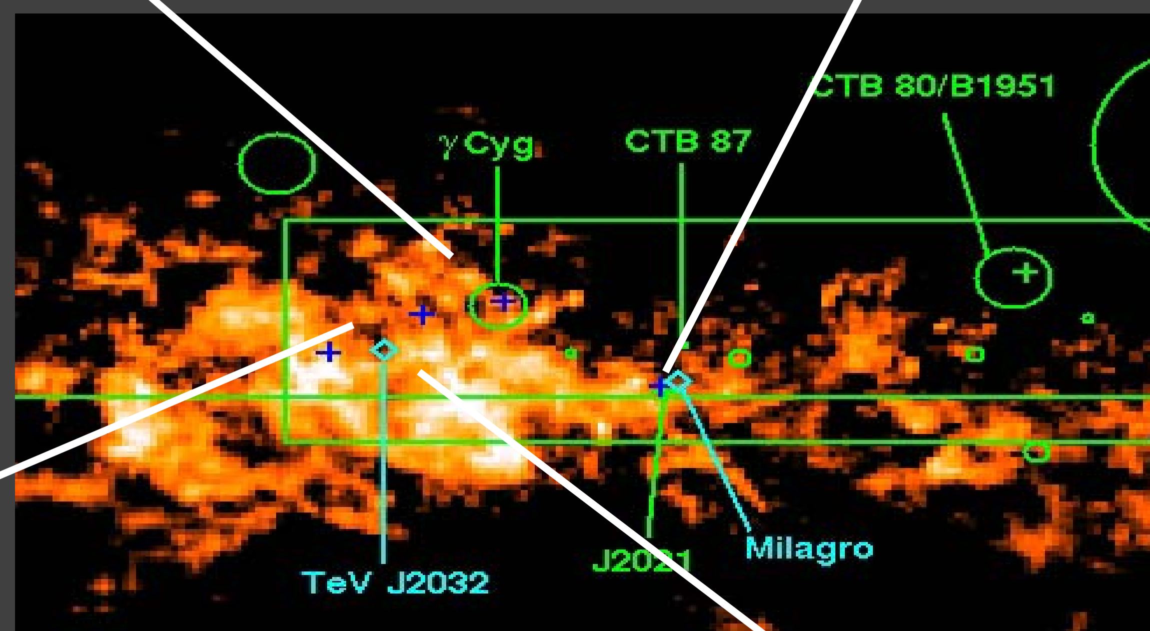


**VER J2019+407 (SNR shock)**

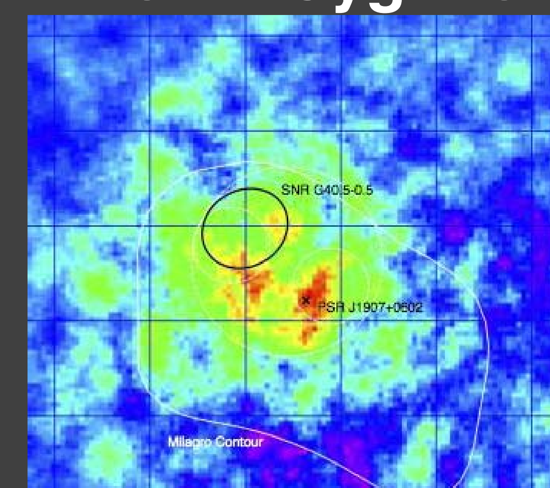



**VER J2016+371 (Pulsar Wind)**

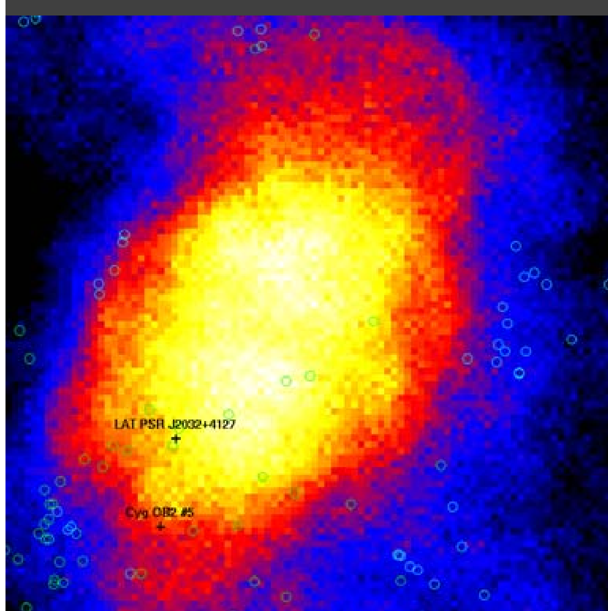
**VER J2019+368 (Unknown)**



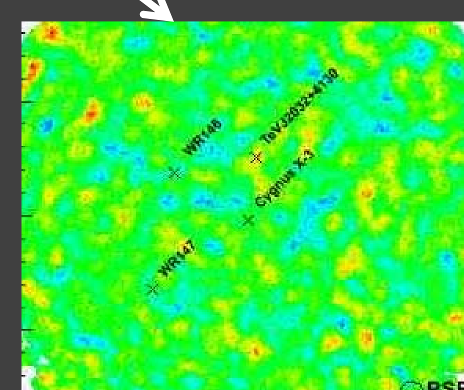

**In Gal plane, not in Cygnus**




**MGRO 1908+06 (stay tuned)**




**VER J2032+415 (Pulsar wind)**

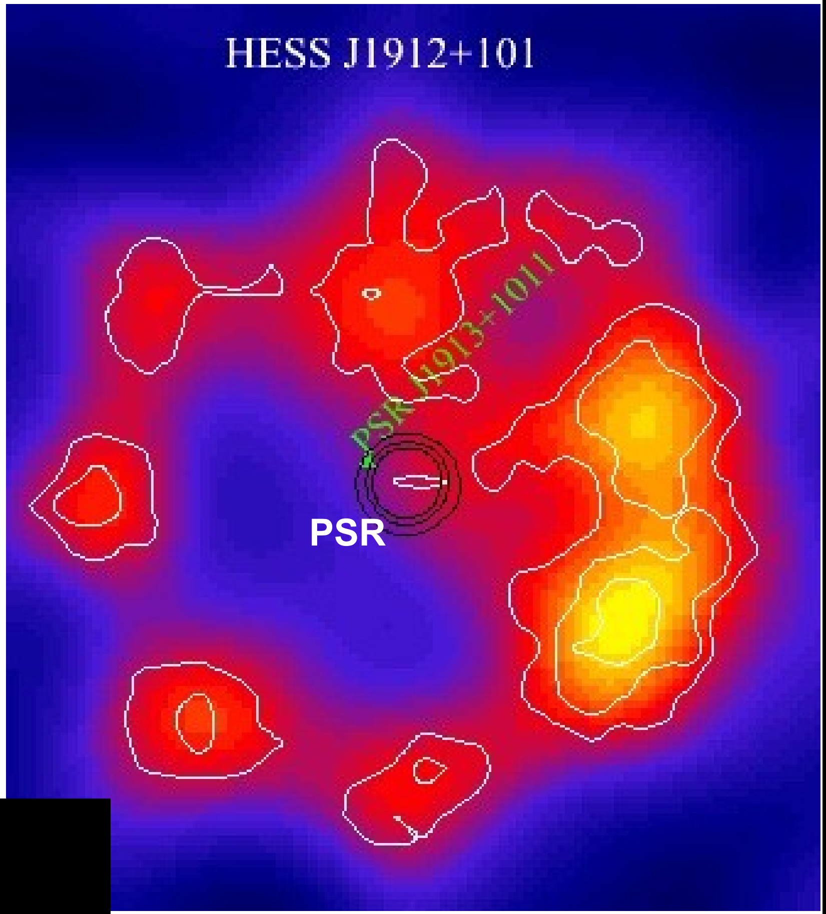


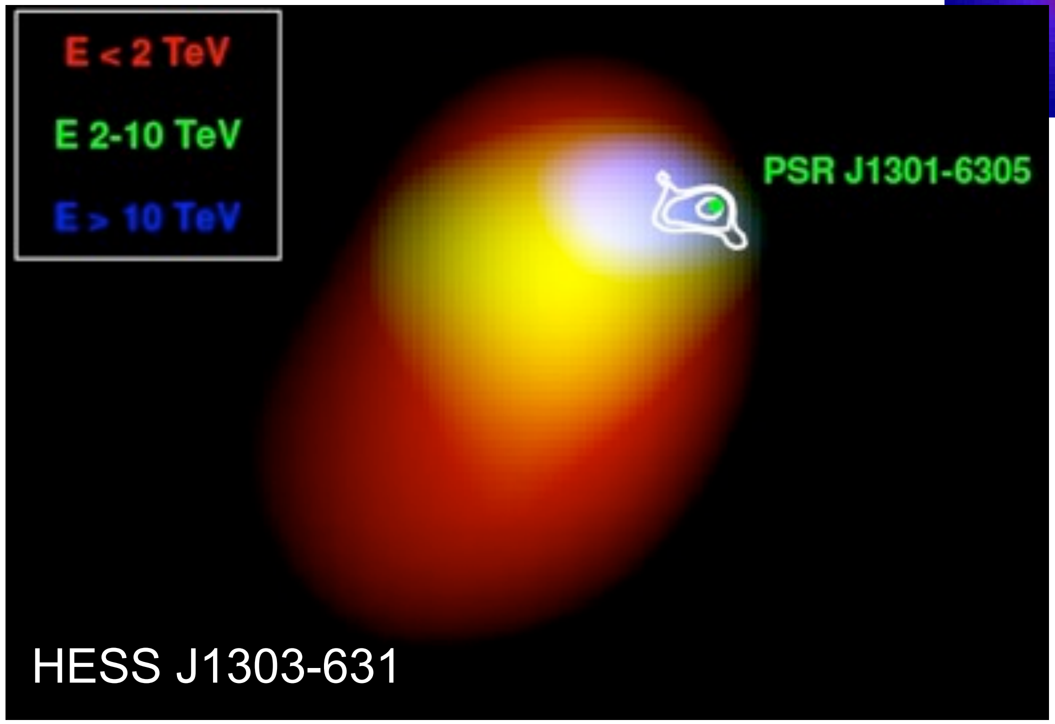

**Cyg X-3 (Not seen at TeV)**

Ong+ 2013 ICRC

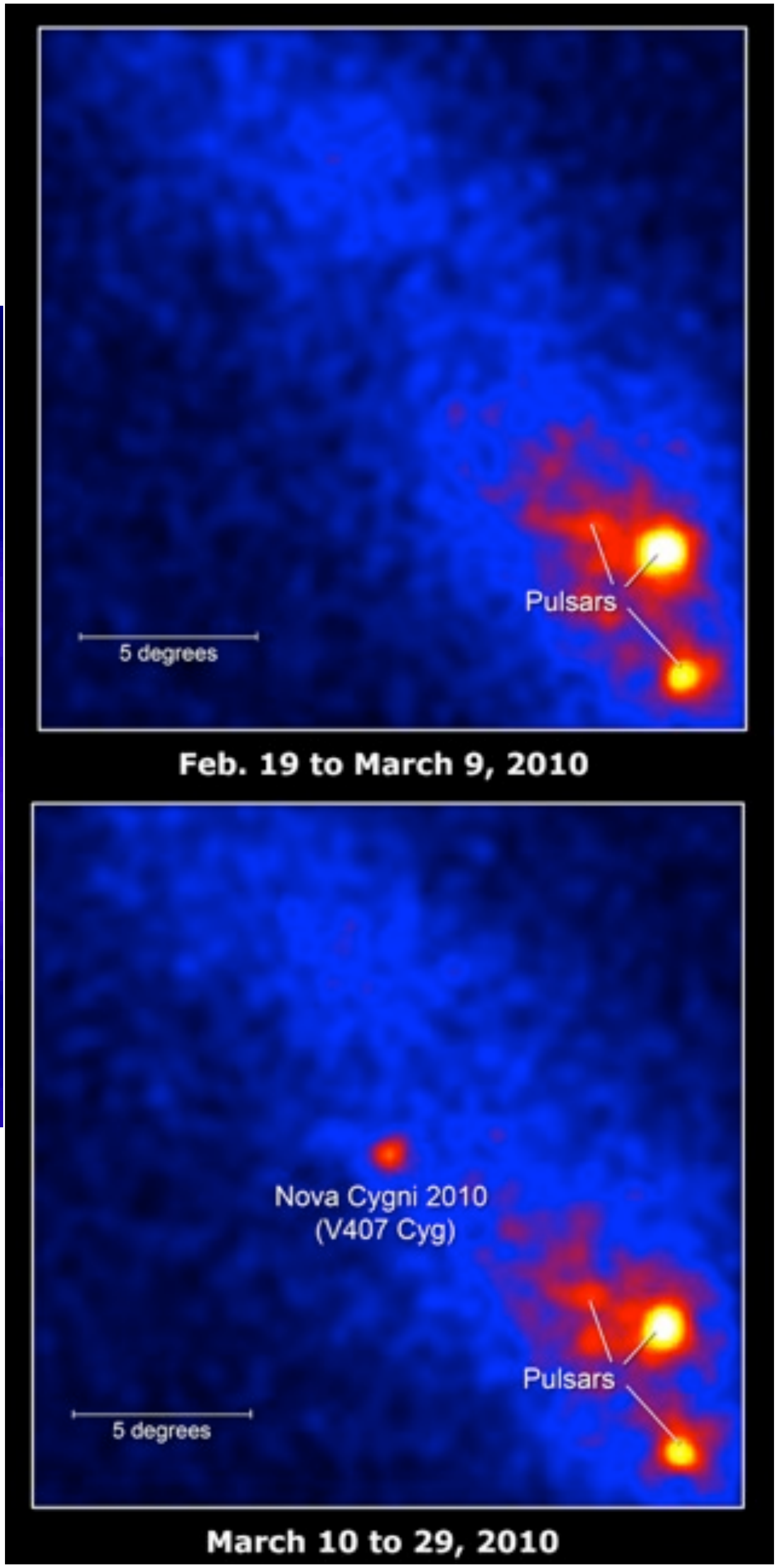
# identification rationale

- identification **IF**
  - timing signature (pulsations, orbital variations, flares…)
  - morphological correlation at another λ (shell SNR, PWN,…)
  - characteristic spectral/morphological evolution (ex: PWN)



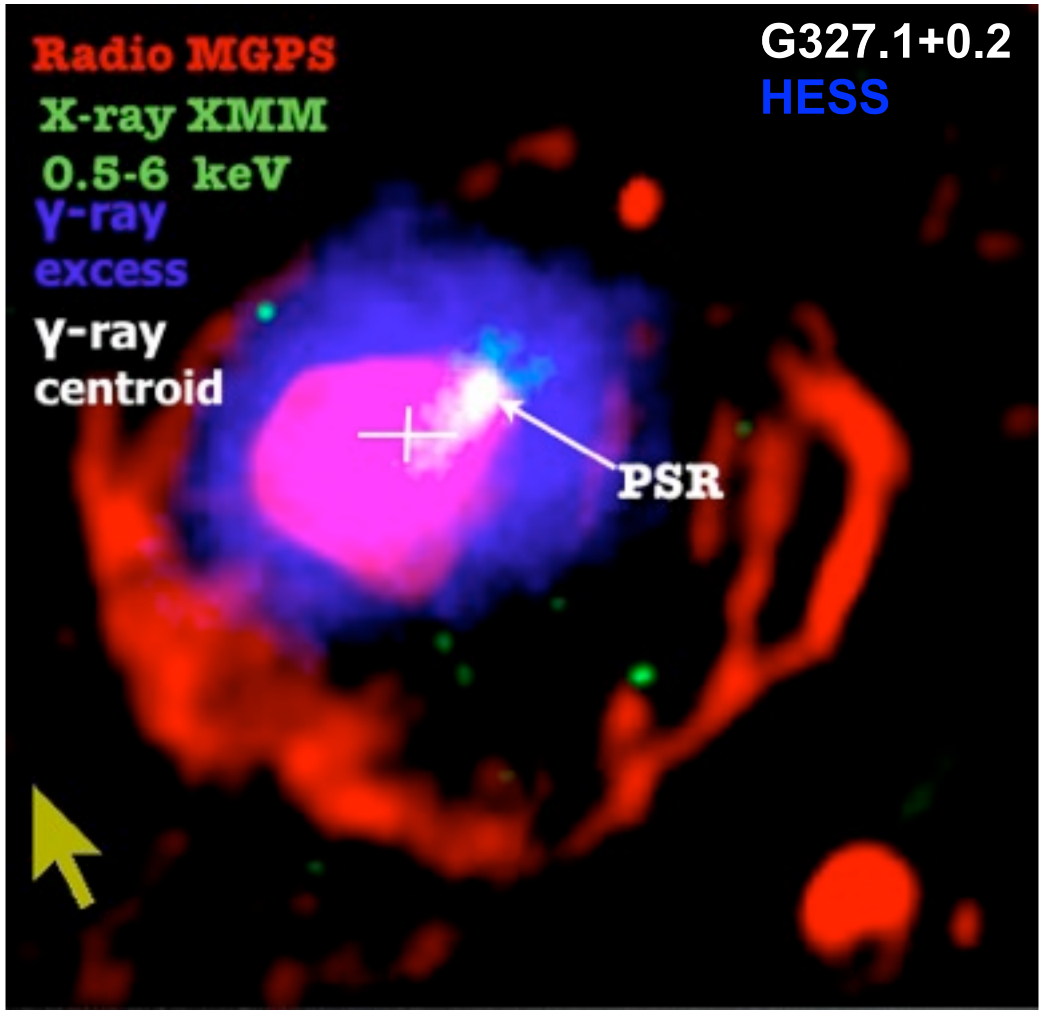

HESS+ 2012 arXiv:1210.6513



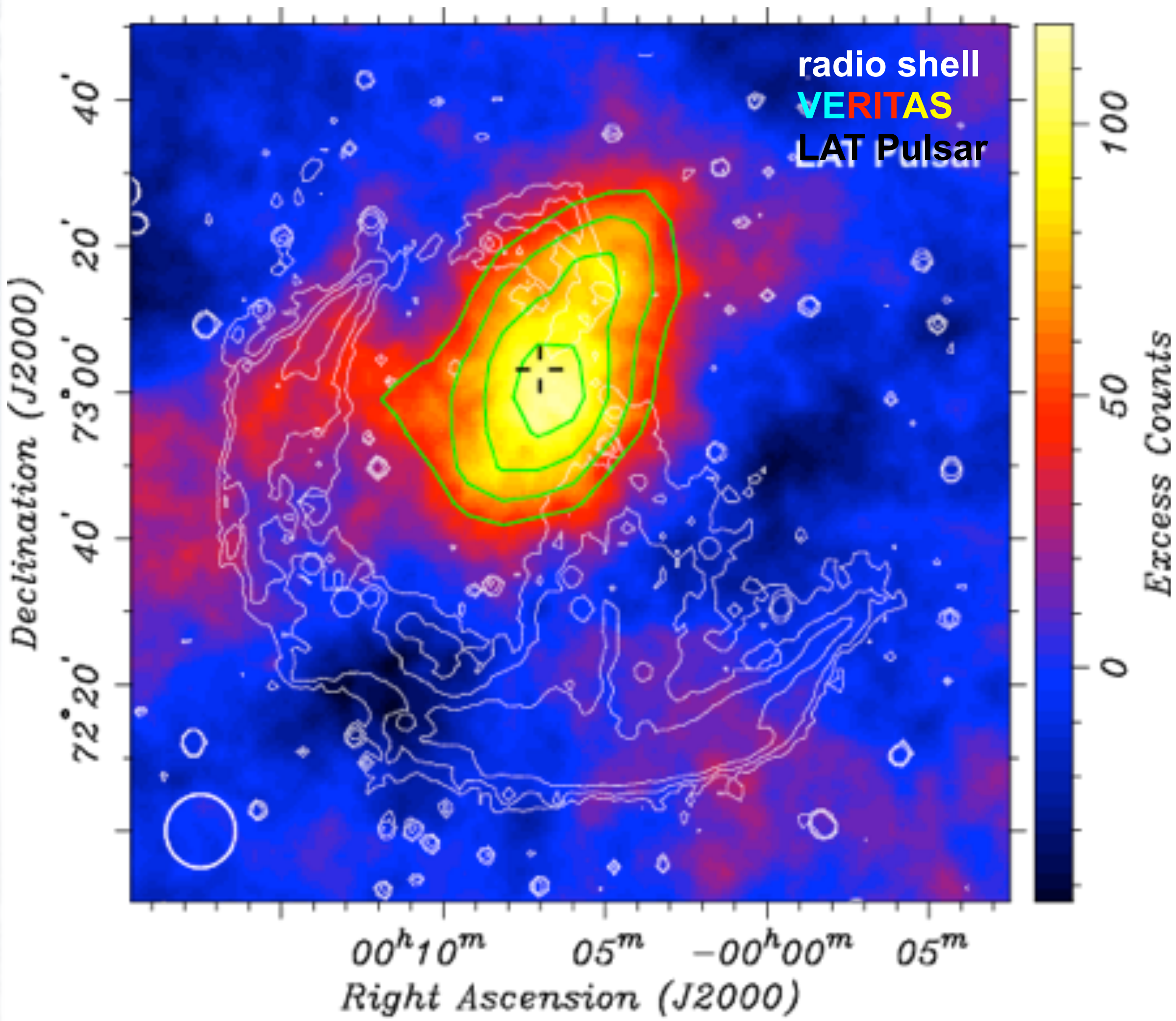

Ackermann+ 2010 Science 329, 817

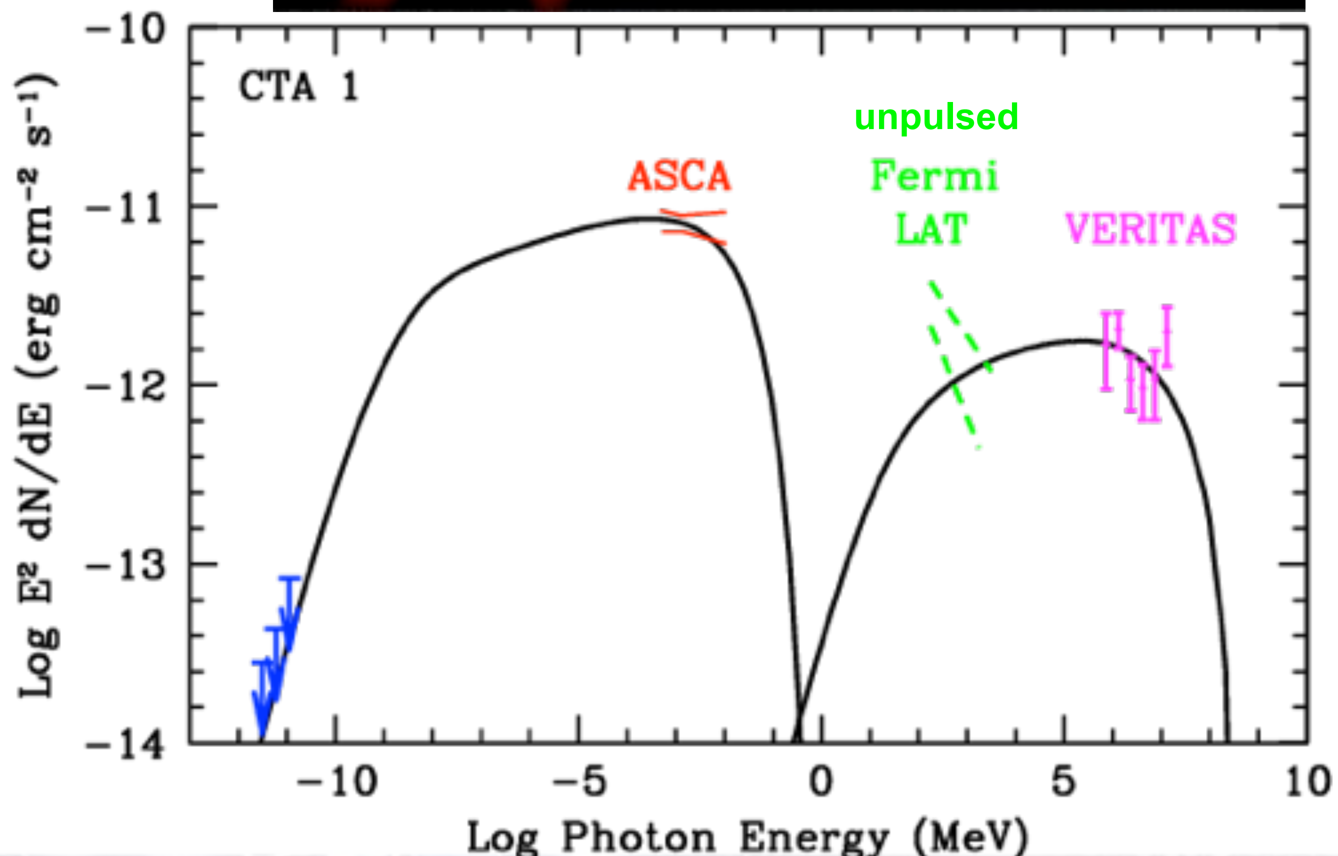
# identification rationale

- plausible association **IF**
  - single counterpart & SED consistency




but… (ex: CTA1)

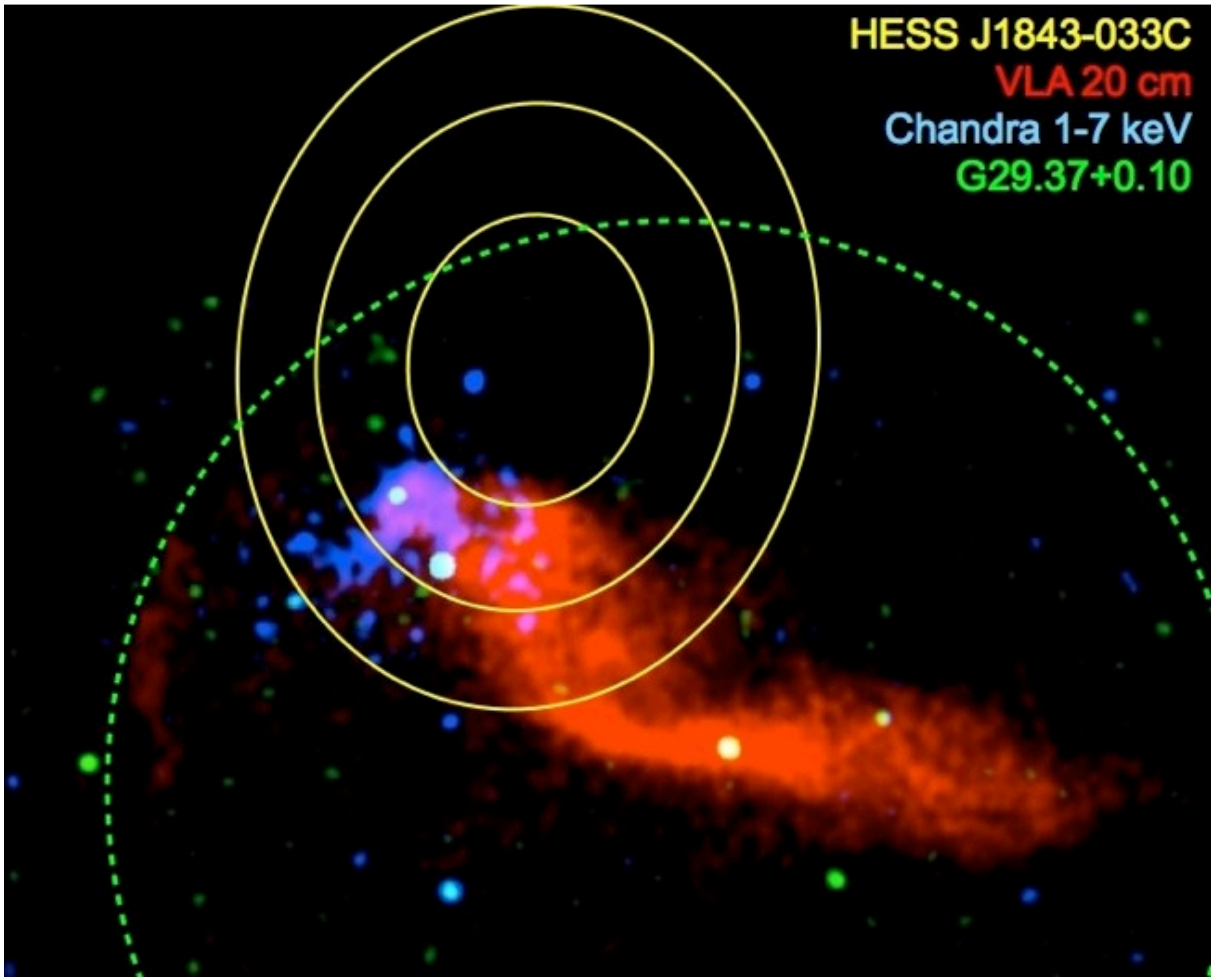



Aliu+ 2012 arXiV:1212.4739

- **else**


ex: HESS J1843-033C in Scutum with SNR + PWN-like + radiogal

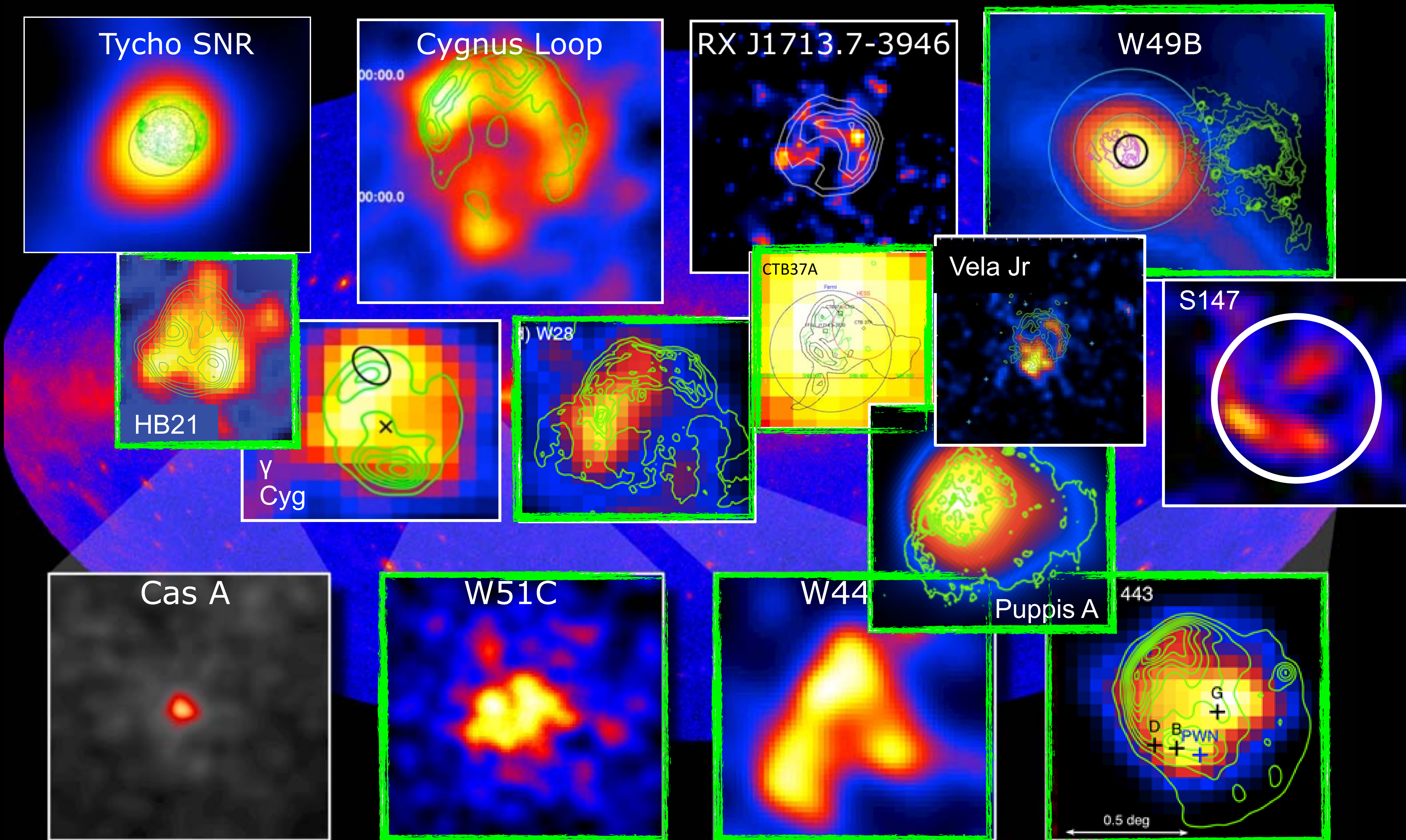



Terrier+ 2012 TeVPA

# supernova remnants & cosmic rays

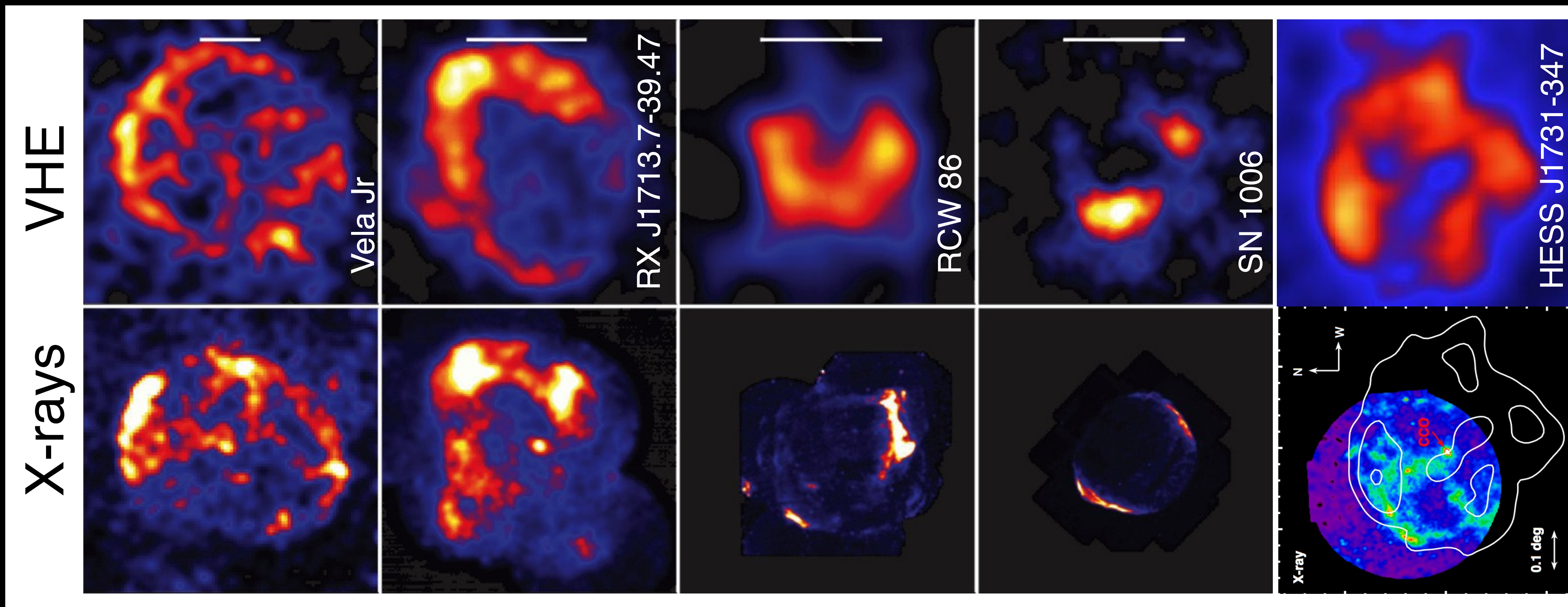
# GeV gallery

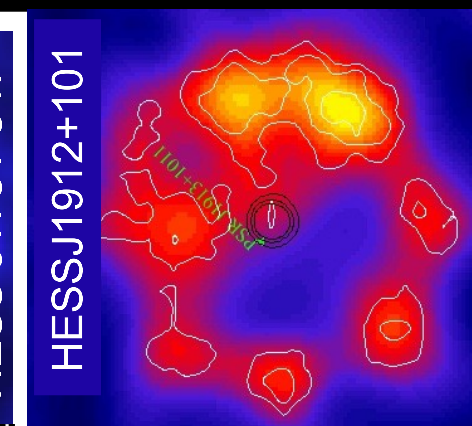
- 15 extended sources or associations with SNRs
  including 4 young historical remnants
  middle-aged one often interacting with surrounding clouds



# TeV gallery

- shell SNRs

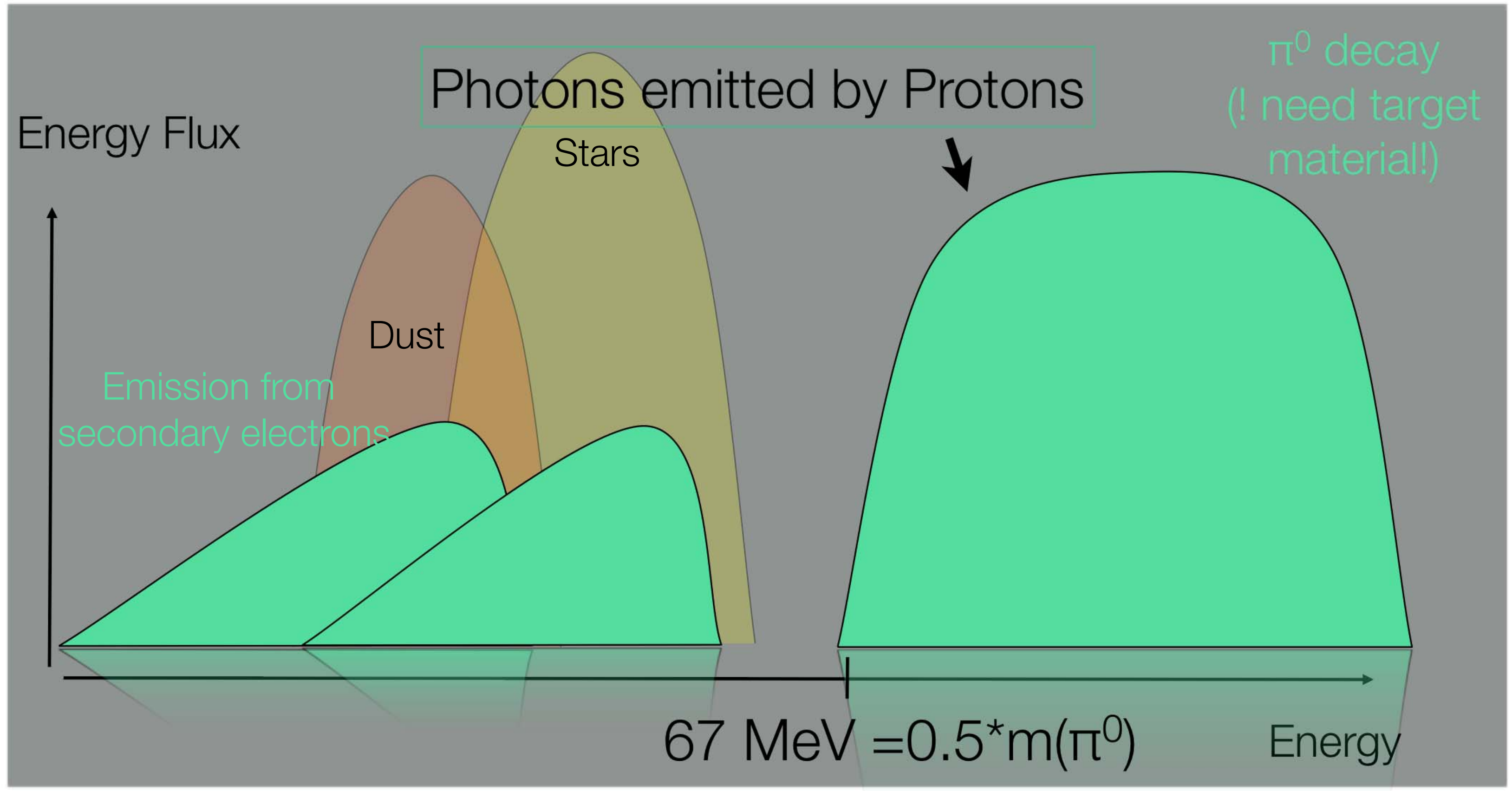


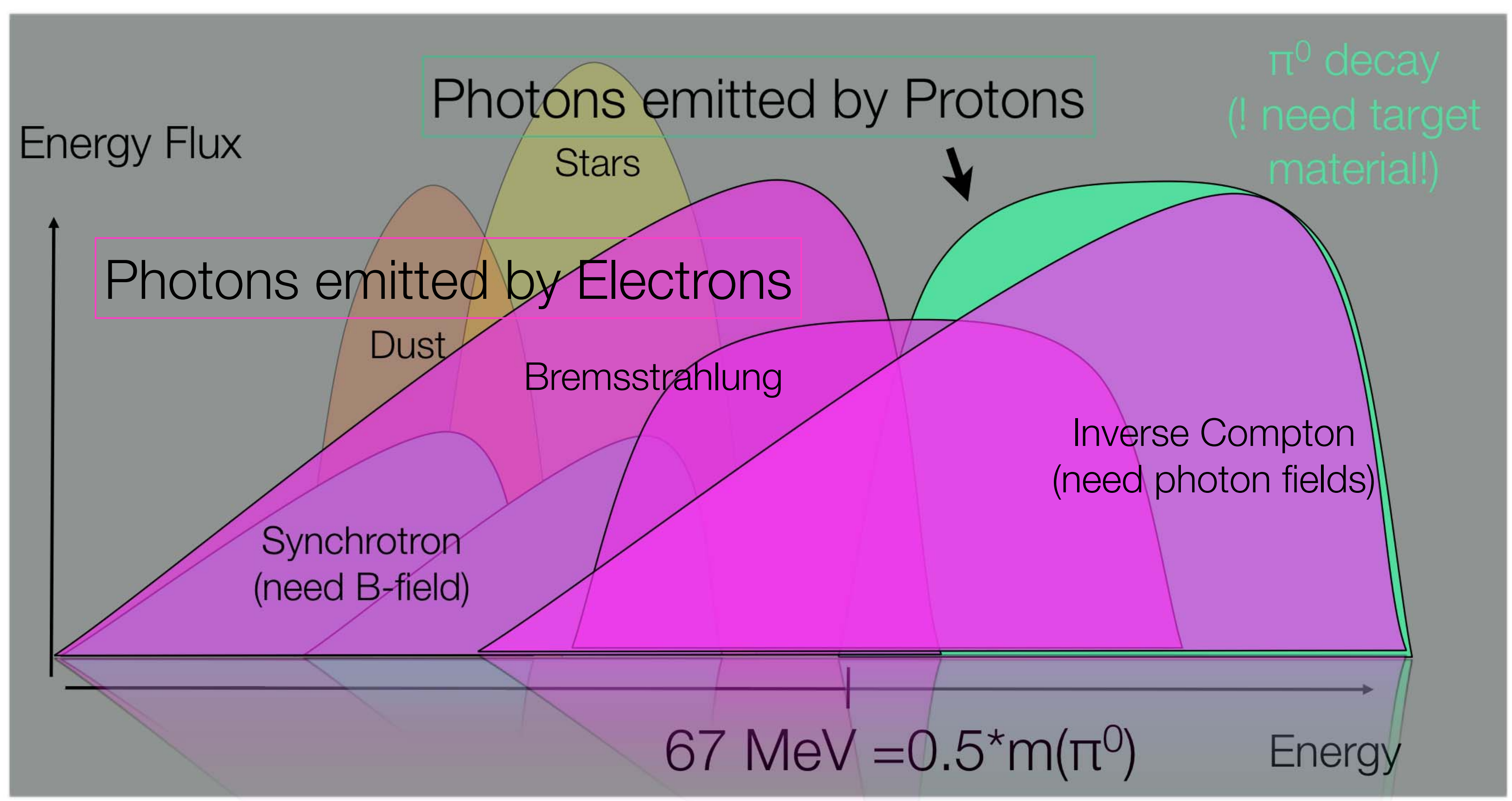




| Name | Dist. (Kpc) | Diameter (pc) | Age (ky) | Lγ (10^33 erg/s) | |
|---|---|---|---|---|---|
| RXJ0852.0−4622 HESSJ0852−463 | 0.2 (1) | 6.8 (34) | 0.4 (5) | 0.26 (6.4) | 2.24 |
| RXJ1713.7−3946 HESSJ1713−397 | 1 | 17.4 | 1.6 | 6 | 2.04 |
| RCW 86 HESSJ1442-624 | 1-2.5 | 11-28 | 1.6-10 | 1-6 | 2.5 |
| SN 1006 HESSJ1502-421 HESSJ1504-418 | 2.2 | 18.3 | 1 | 1.24 0.76 0.48 | 2.35 2.29 |
| HESS J1731-347 | 3.2 | 27 | 2.5 (14) | 10.7 | 2.32 |
| HESSJ1912+101 | 4.5? | 60? | 7 ? | 9.2? | 2.7 |

# proton or electon dominated γ rays

- non-γ-ray information mandatory to constrain the ambient gas density (for π° and brem. emissions)
  - often in X rays
  - opt+Hα for evolved SNRs



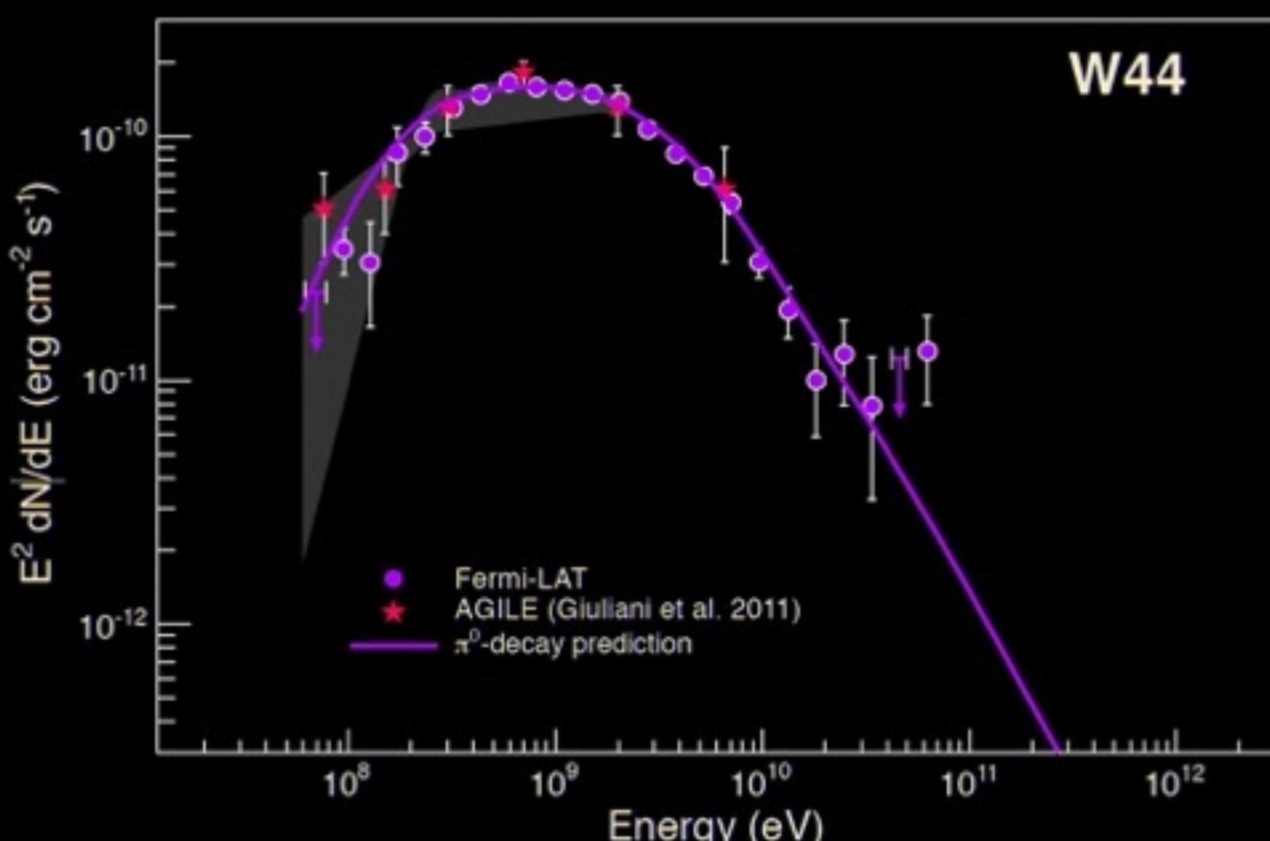



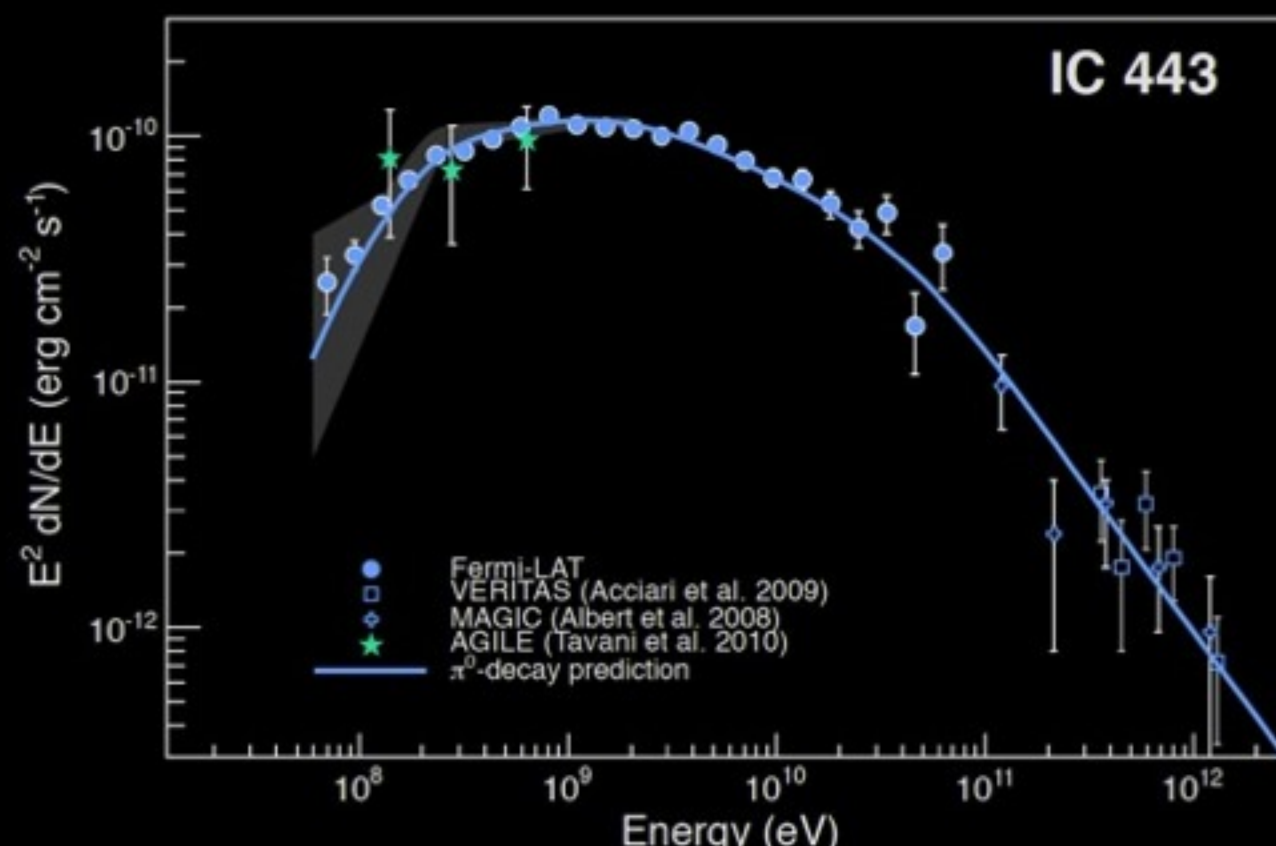

credit S. Funk Kruger 2012

# signature of freshly accelerated nuclei?

IR opt γ

$p_{CR} + p \rightarrow \pi^0 \rightarrow 2\gamma$



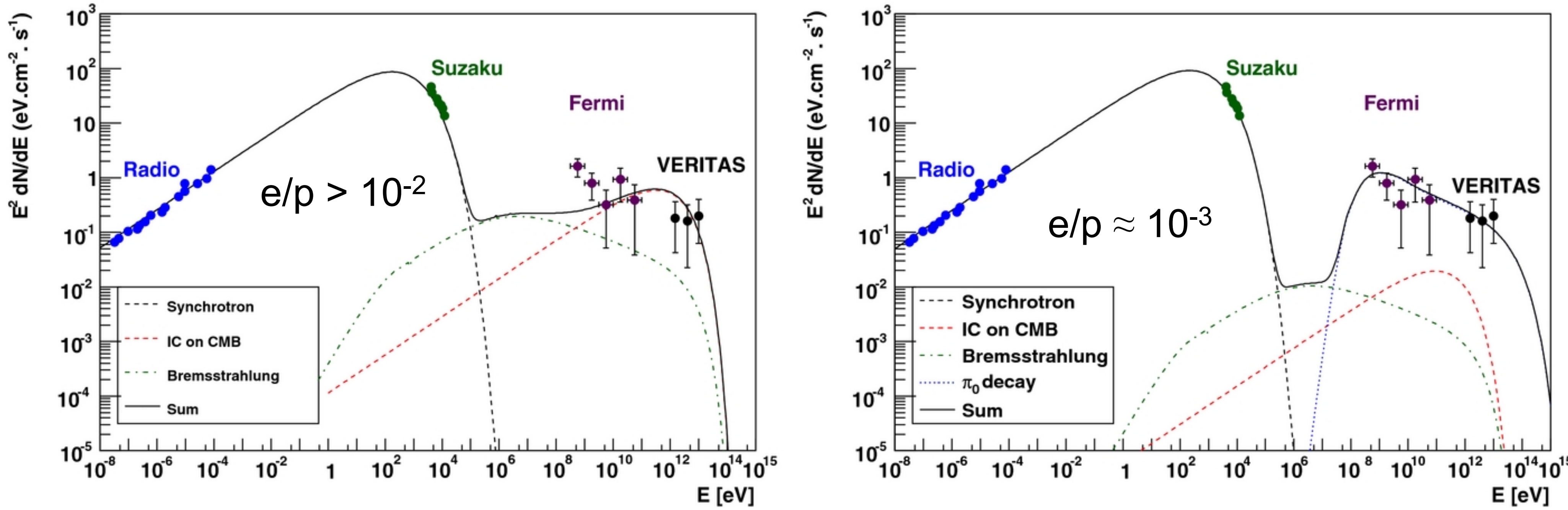

*Ackermann+ 2013 Science 339, 807*

# π° emission in SNR ?

- hadronic emission “preferred”

Giodano+2012

- in very young SNRs
  - ex: Tycho

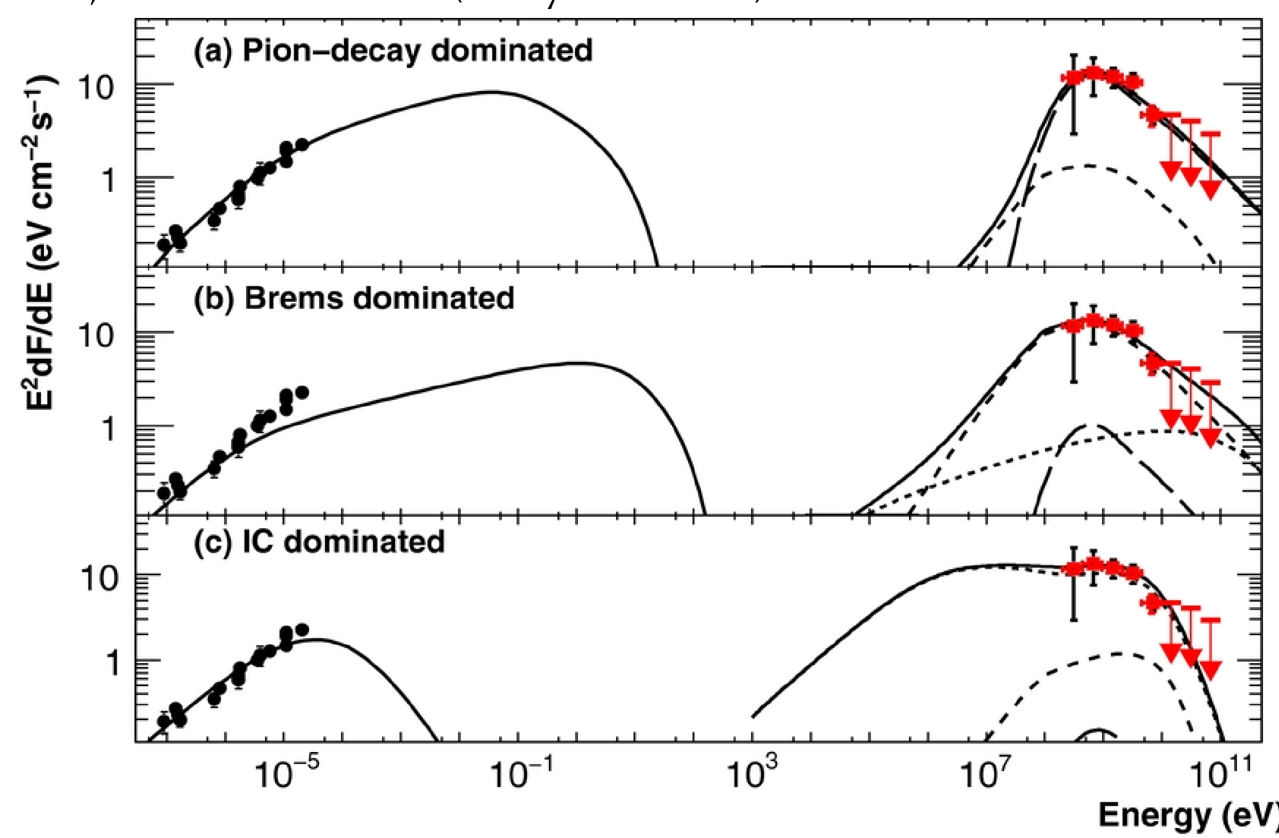



- in middle-aged SNRs interacting with clouds (OH masers)
  - ex: convincing spectral evidence in W44 + IC443 (previous slide)
  - other possibilities = W51C, W49B, W28, CTB37A, G349.7+0.2 (very distant)

Katagiri+2011

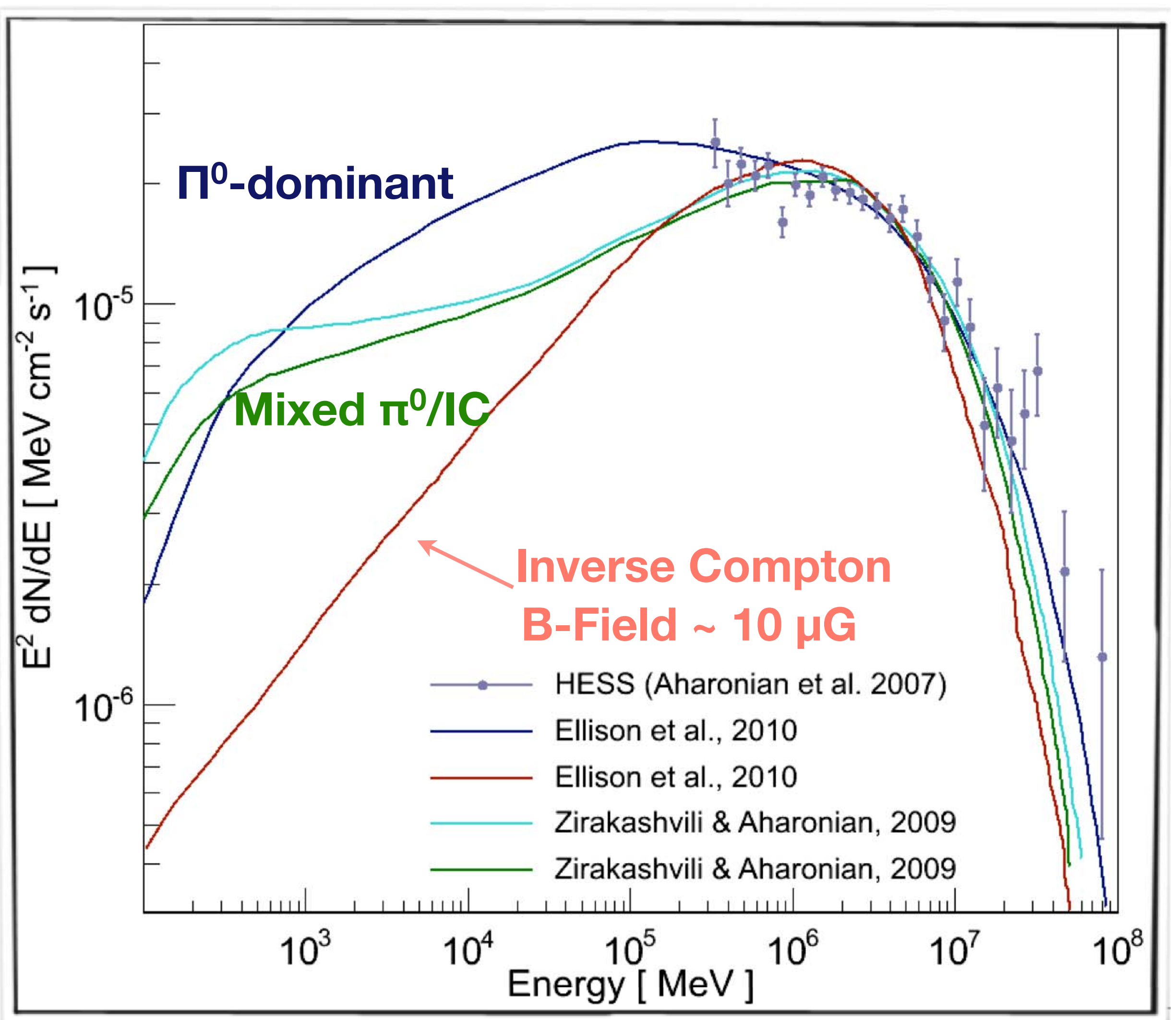
- in isolated evolved SNRs
  - ex: Cygnus loop

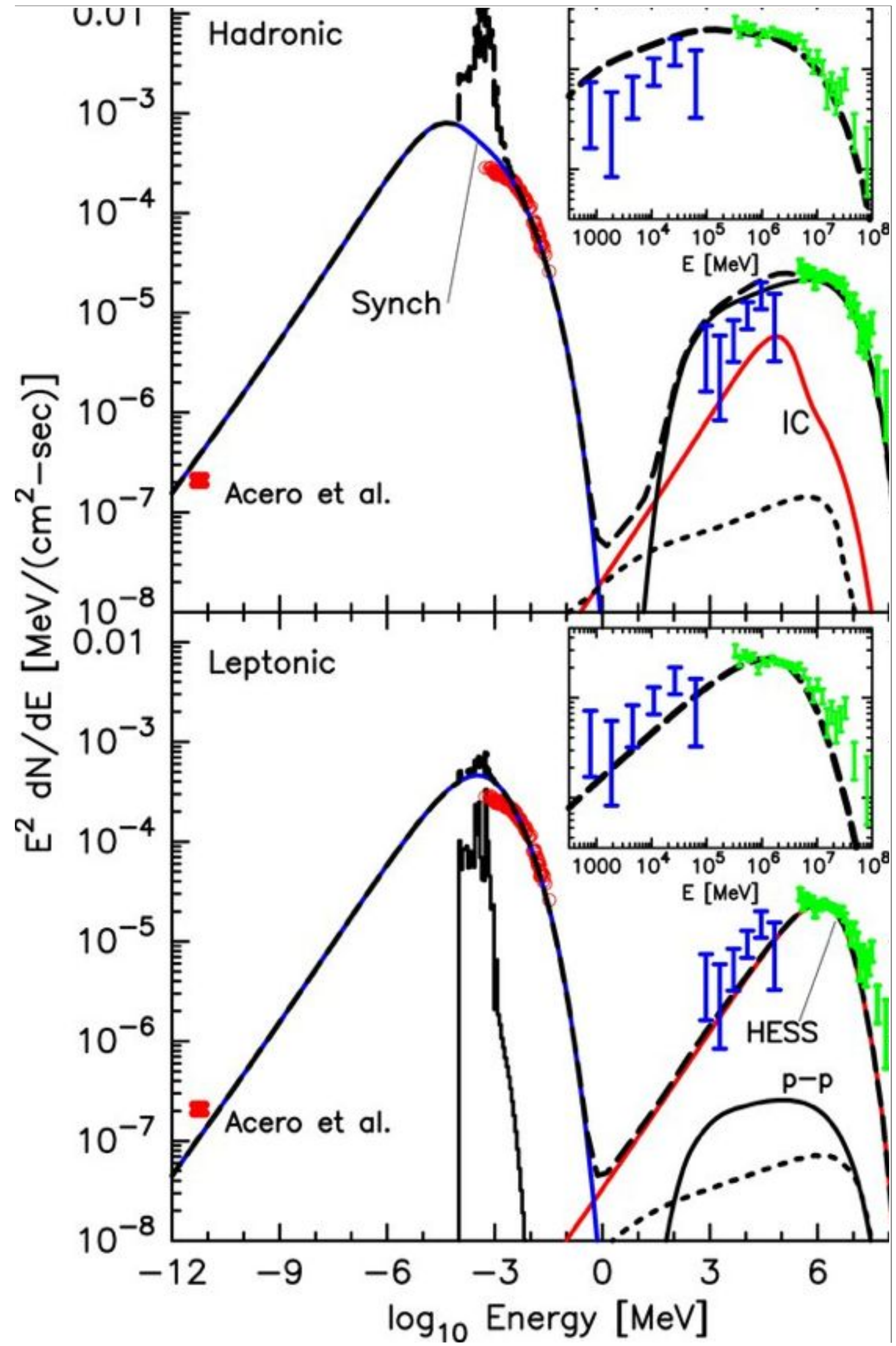
    IC unfavoured because it requires a low gas density at odds with opt+X data



# electronic signature

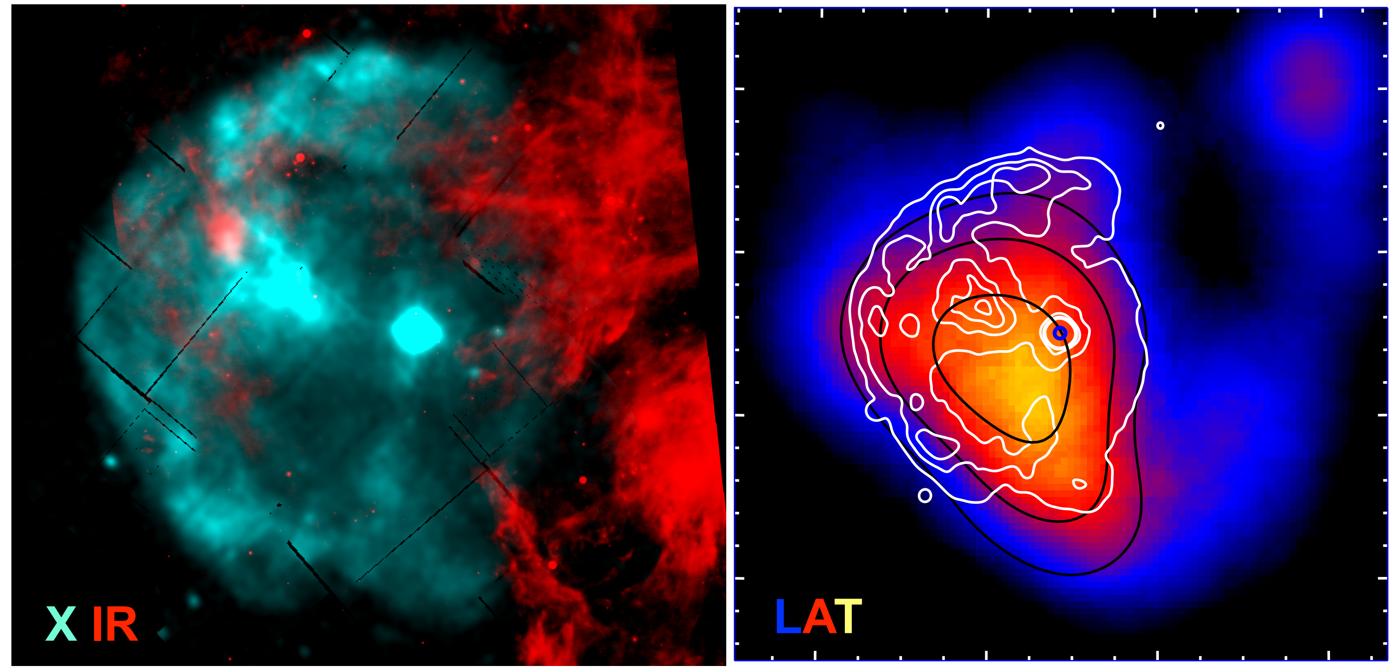
- important use of the thermal X rays
  to give an upper constraint on the ambient gas density
  thus on the $\gamma(\pi^\circ)$ yield
  - ex: RXJ 1713   Ellison+ 2010

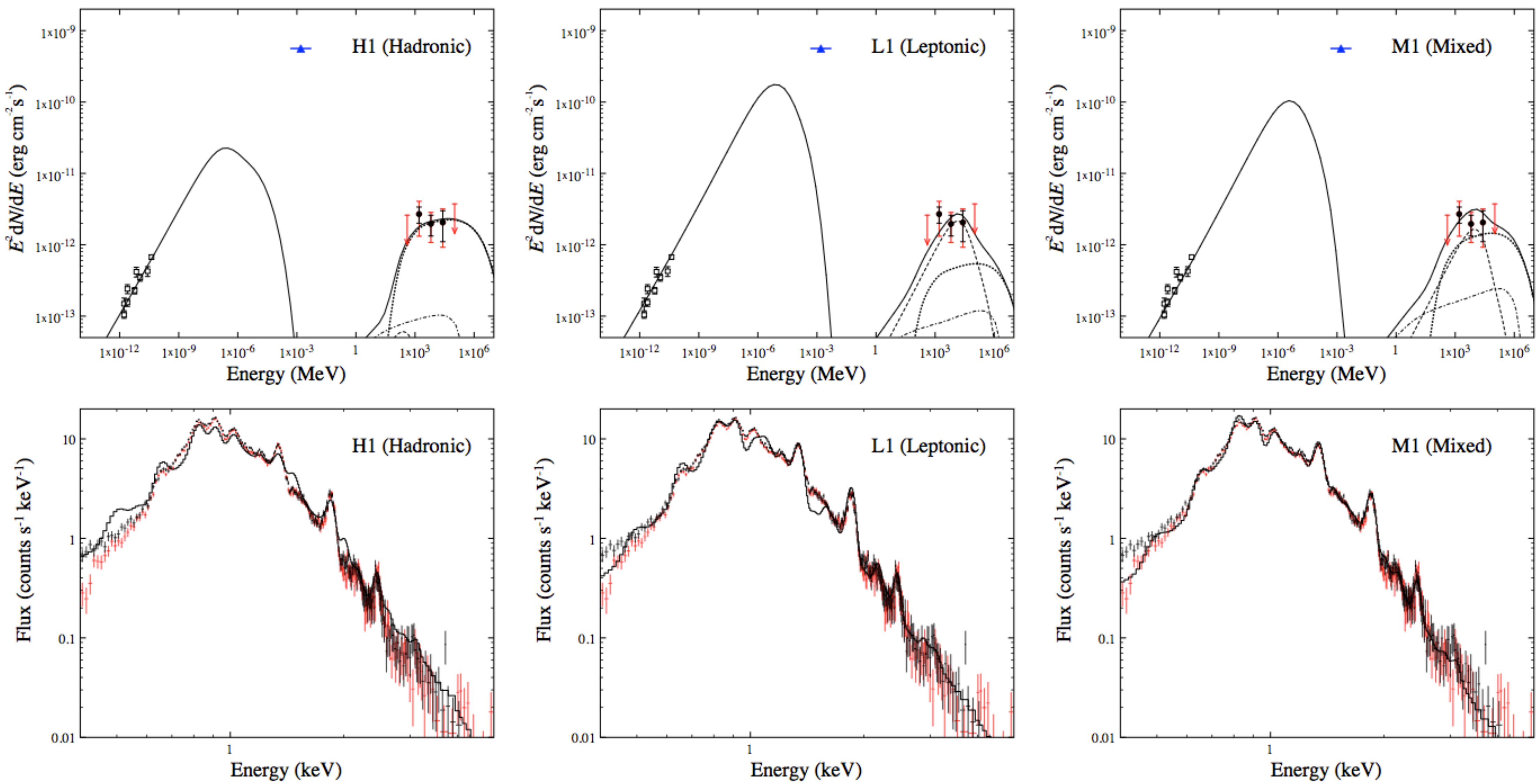


# mixed case of CTB 109

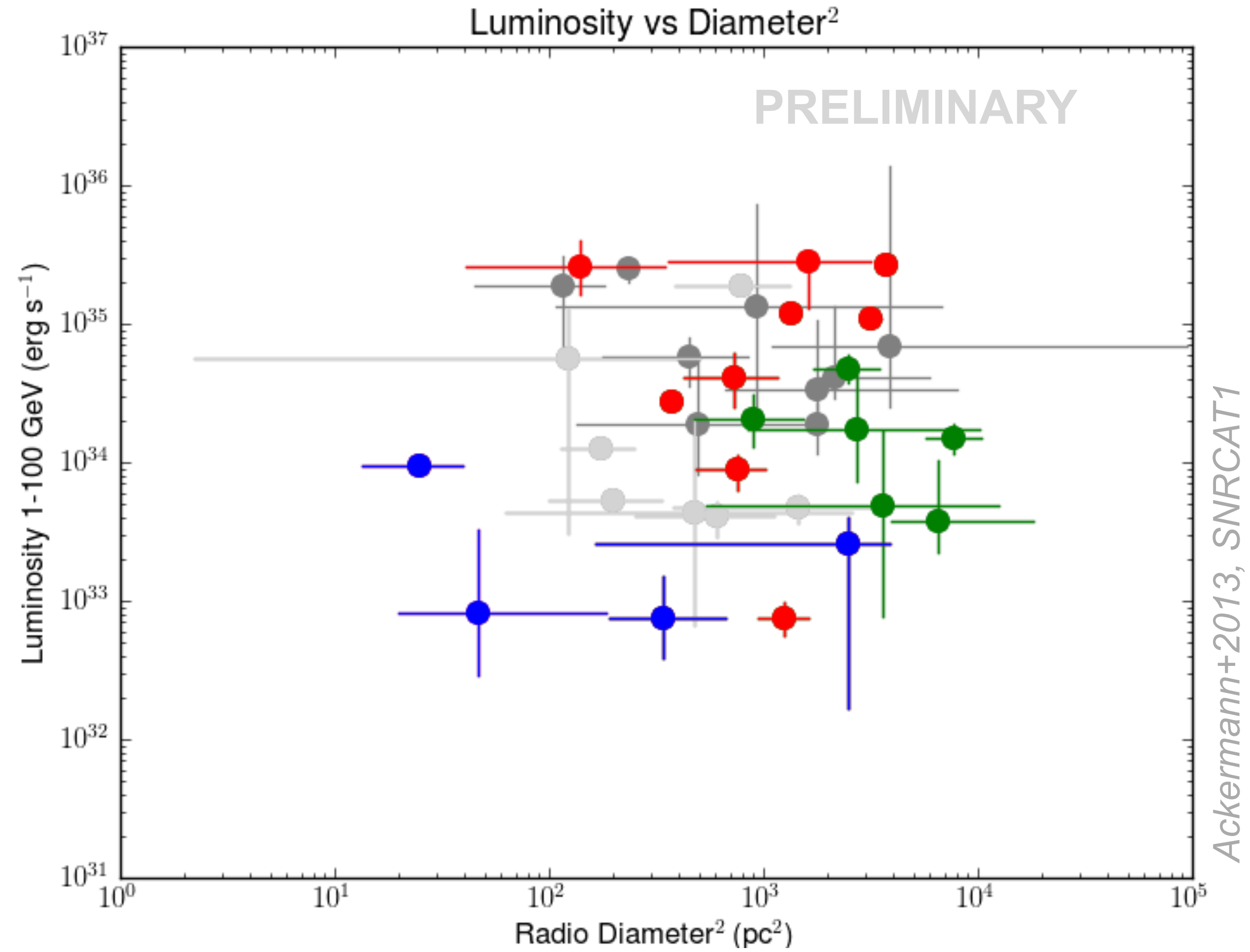
- single zone fit + thermal X rays
- Castro et al. (Slane, Ellison, …)

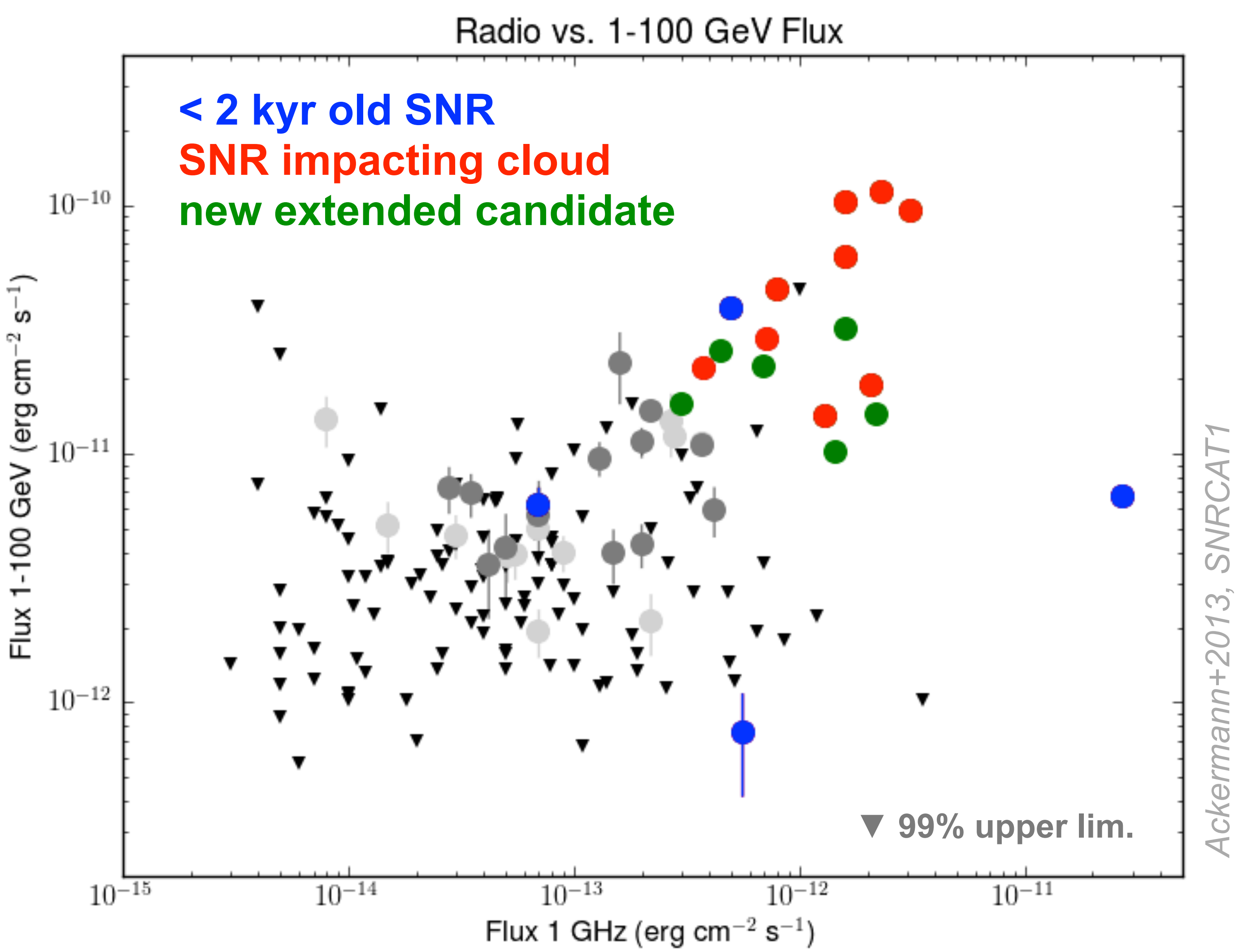


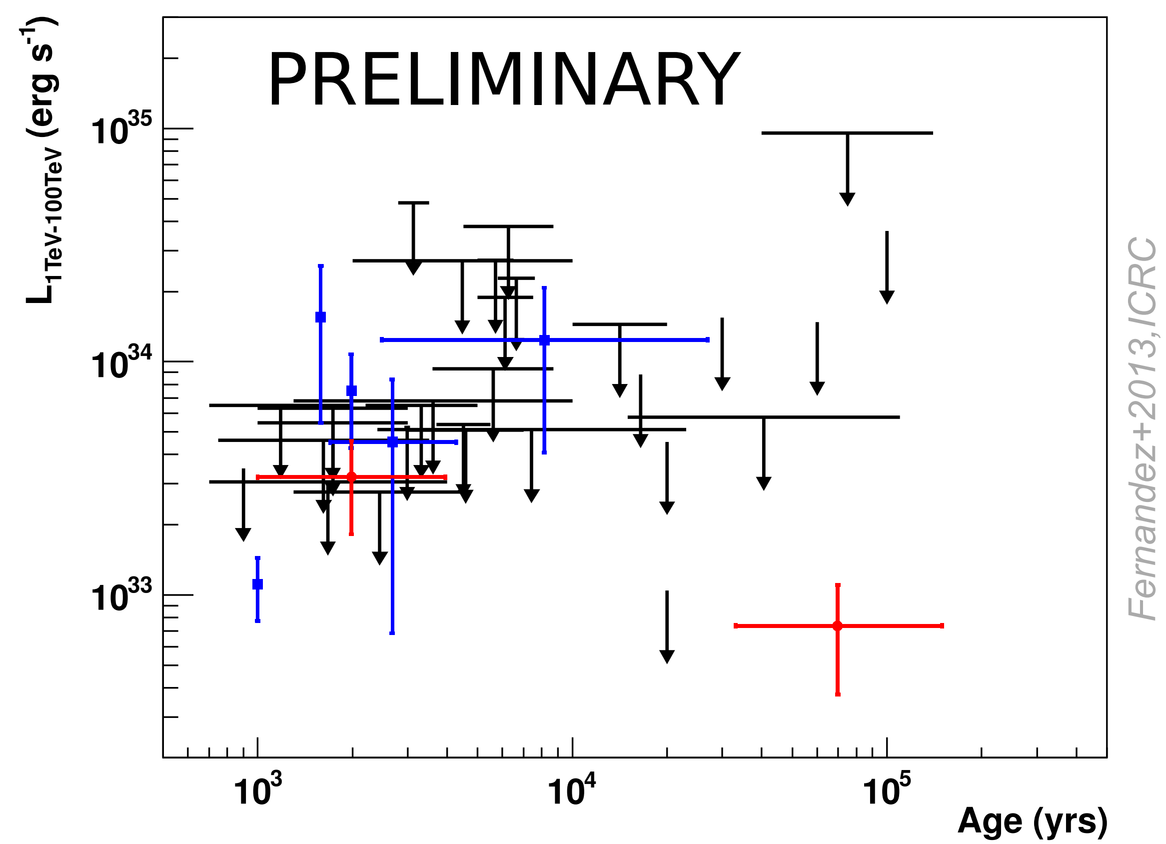



# collective brigthness trends

- γ-ray luminosity increases
  - with age ?
  - &/or with $n_{ISM}$ ↑ ? (esp. for SNR near clouds)
- GeV SNRs are radio bright
  - esp. for SNRs near clouds
    compressed shock in radiative filaments?
  - large scatter among young SNRs
- TeV SNRs: large scatter with age

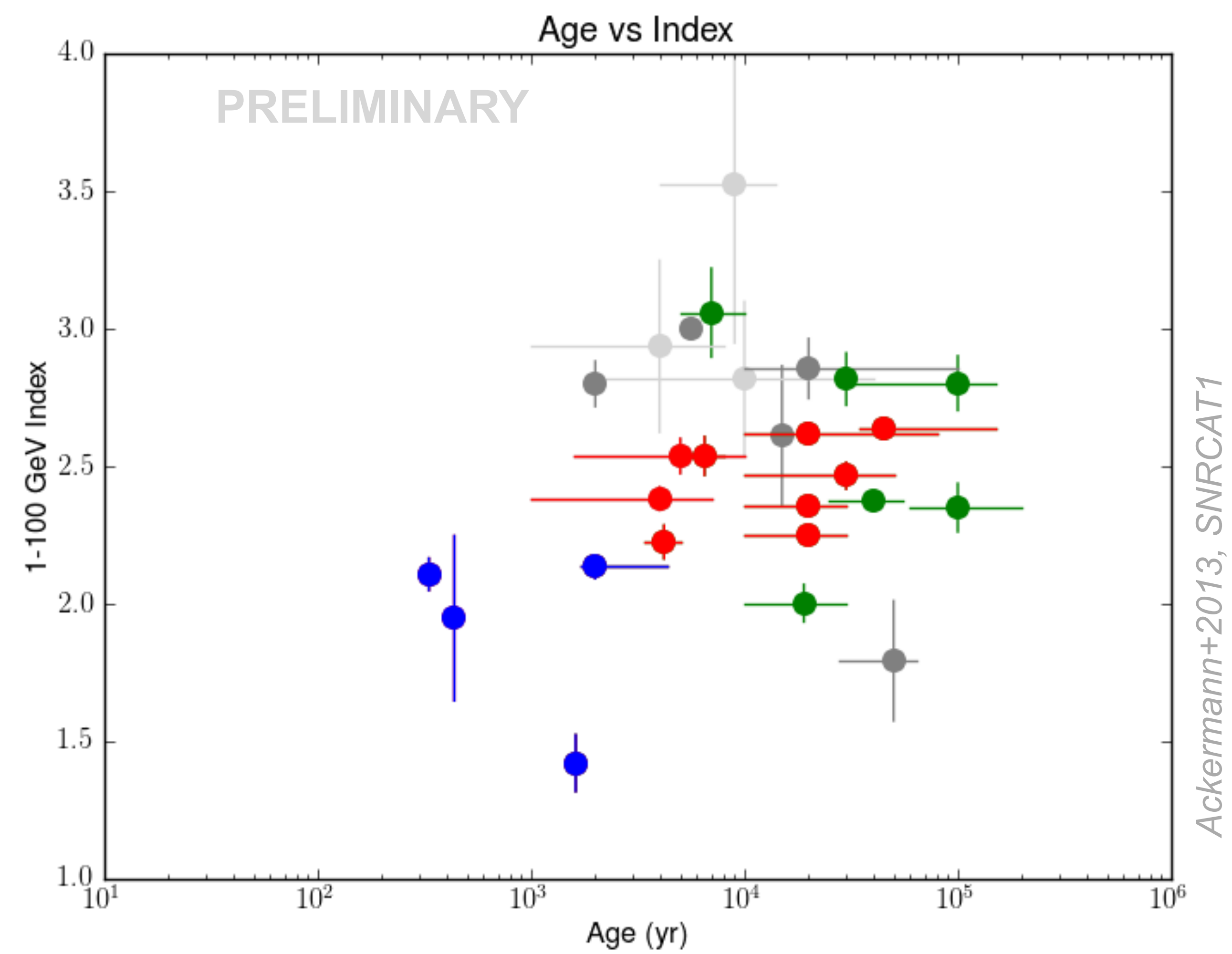


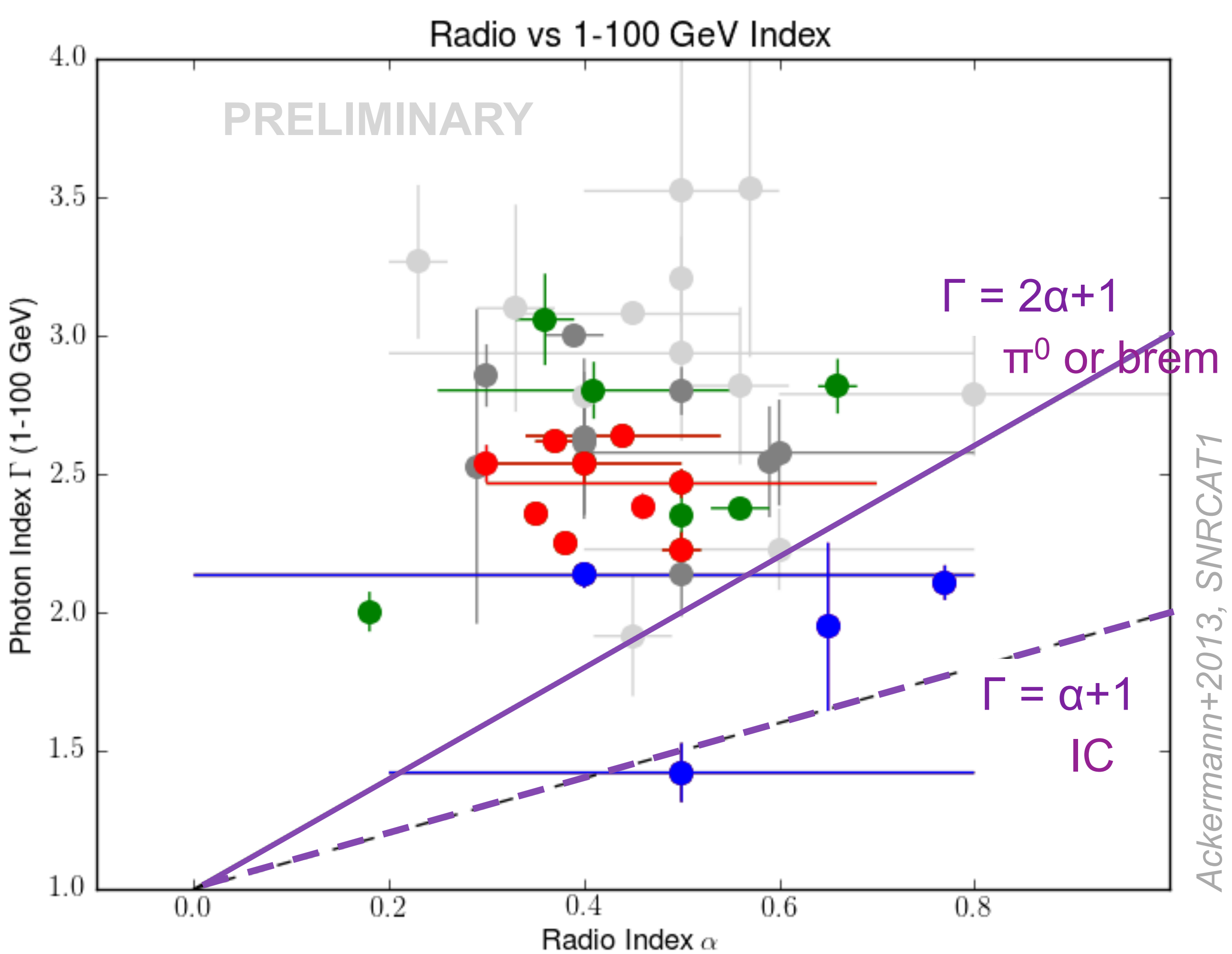



# collective spectral trends

- young SNRs are harder in γ rays
  - escape from slower shocks ?
  - lower $E_{max}$ with age ?
- no spectral link between the syn+γ
  - => sampling the same electron population, but different parts of the SED ?
  - sampling nuclei vs. aged leptons with different spectra ?



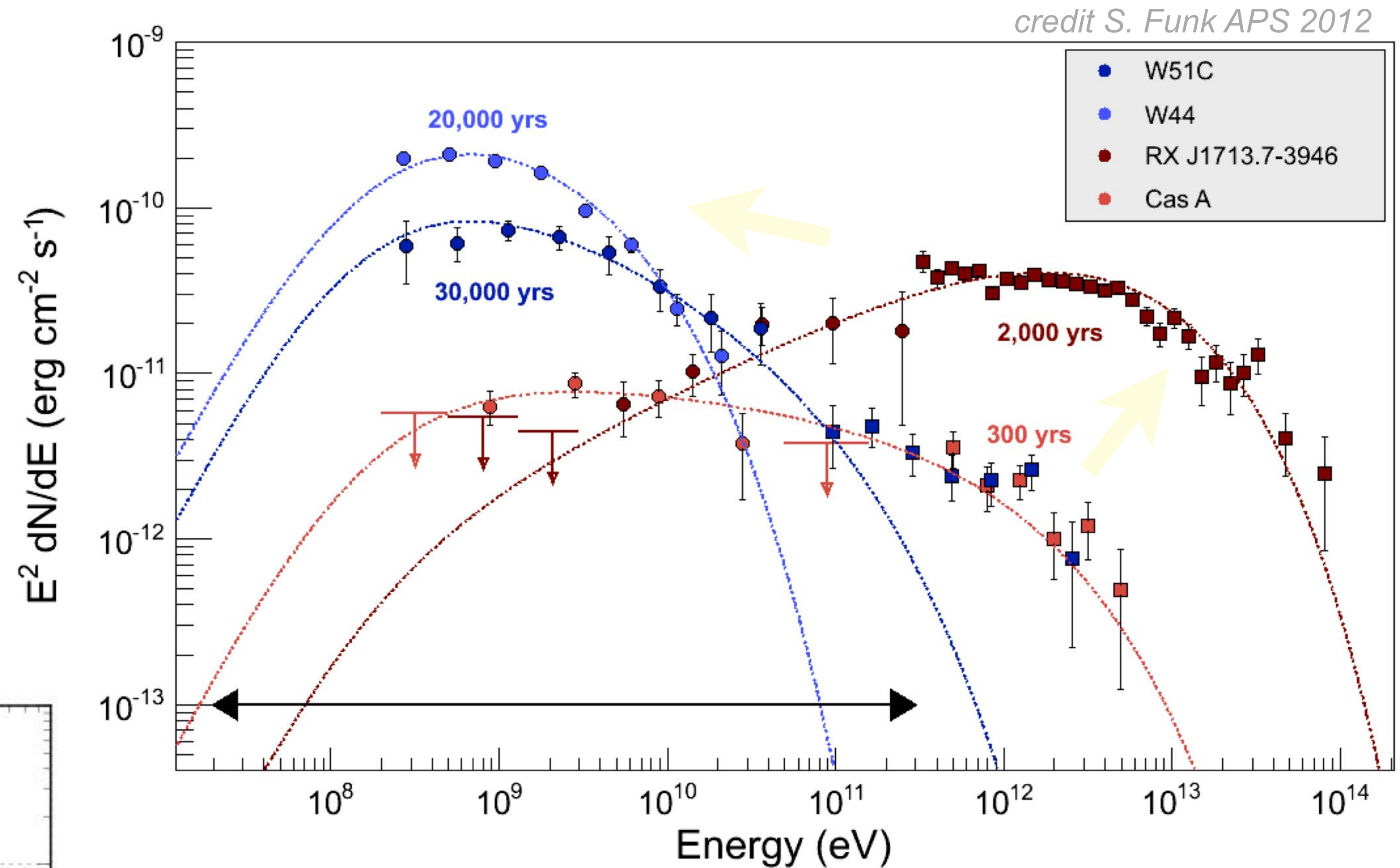



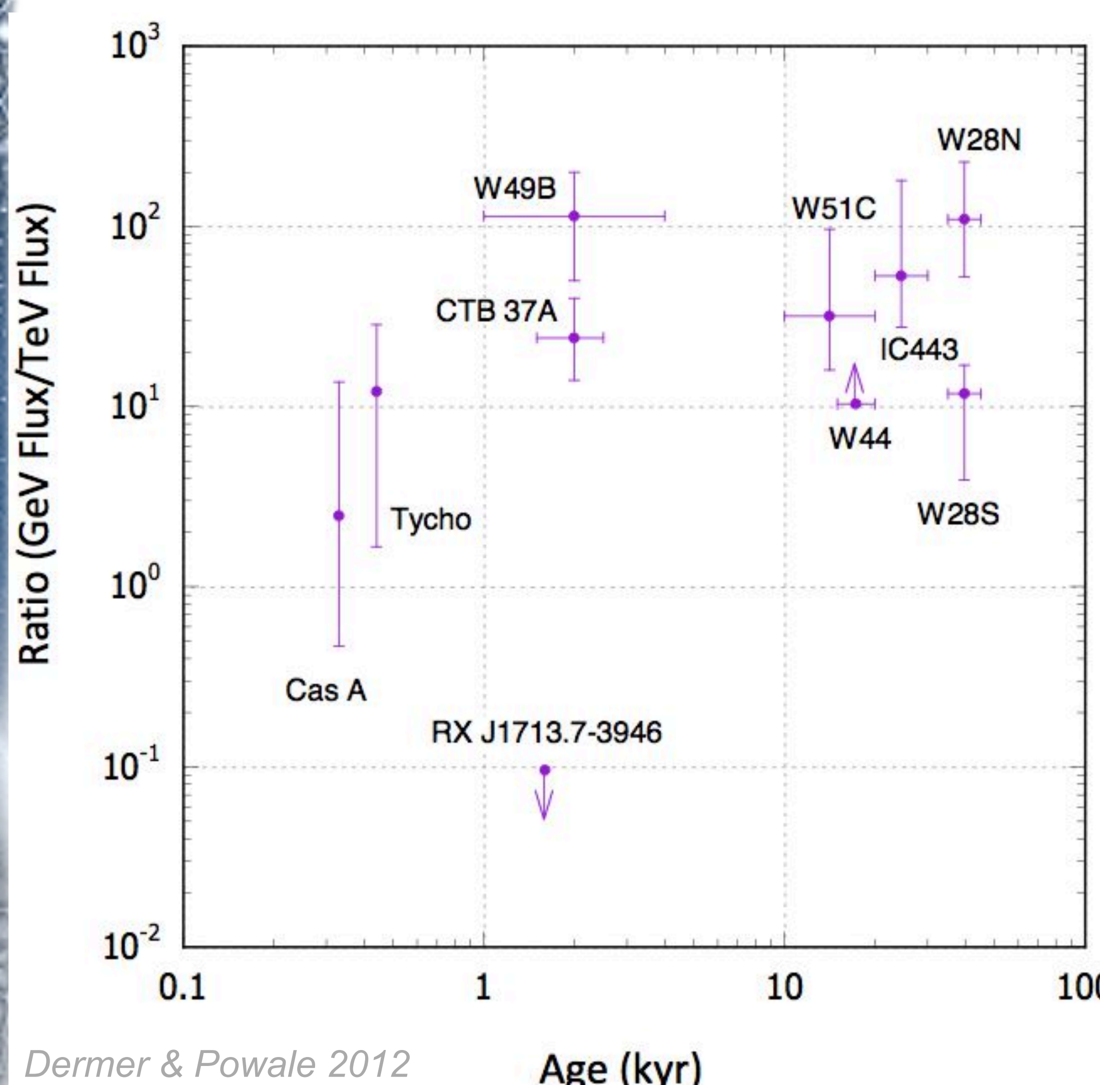

- interacting SNRs softer than expected from protons with the same spectrum as electrons

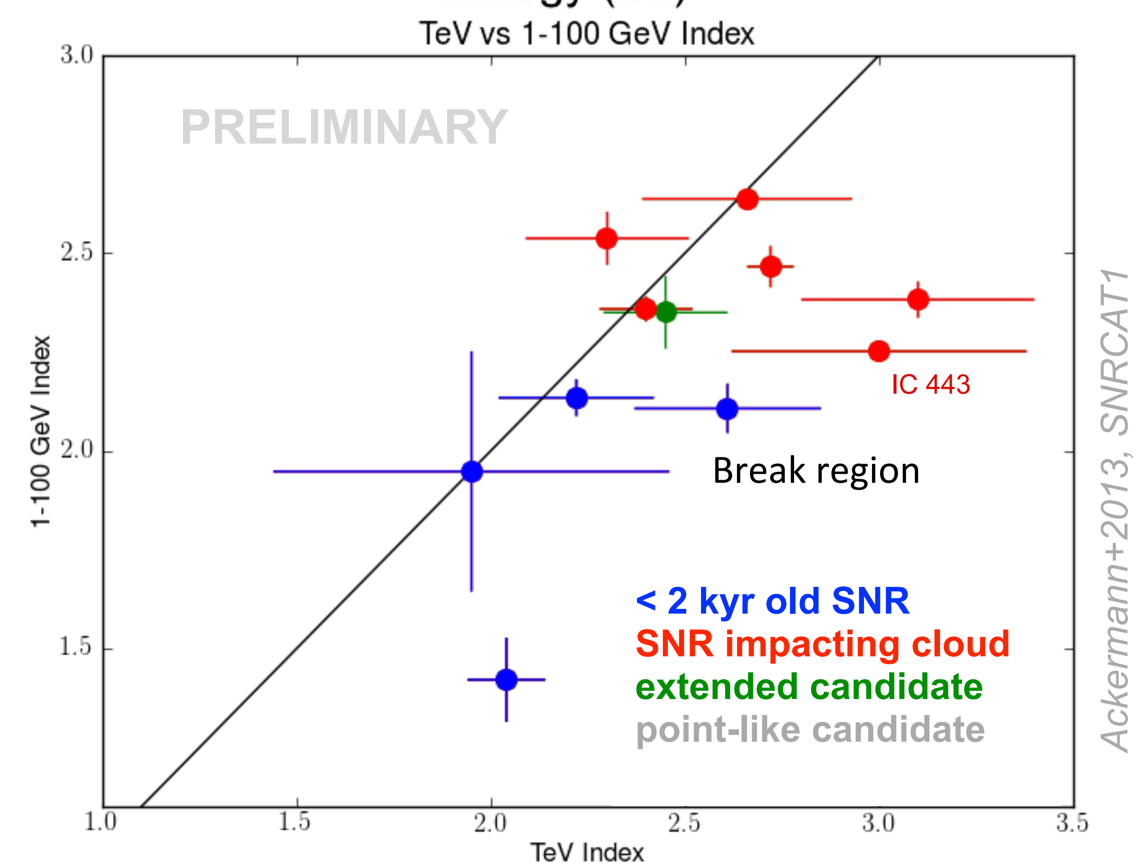
< 2 kyr old SNR
SNR impacting cloud
new extended candidate

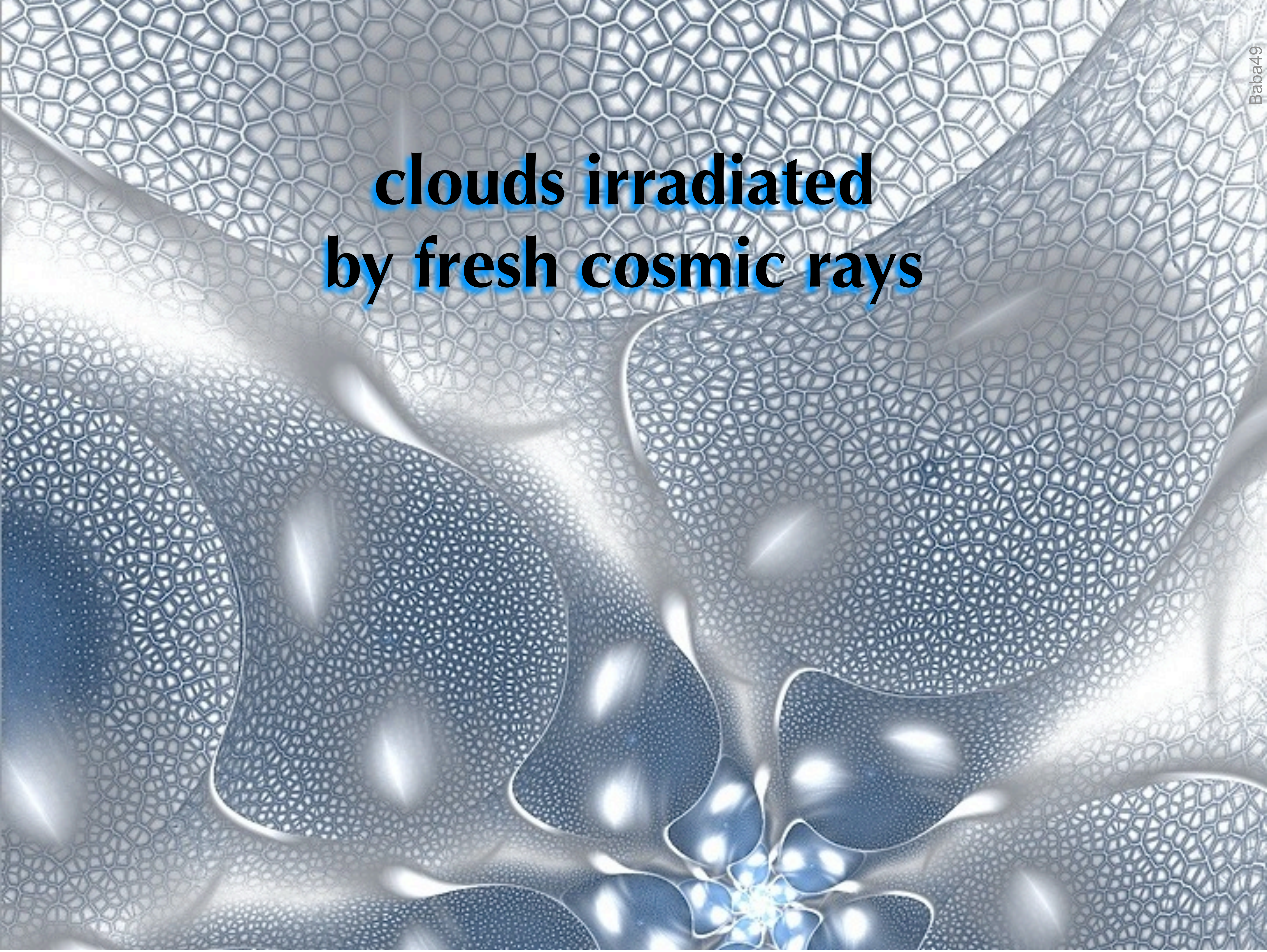
# spectral evolution with age

- the older, the softer
  - escaped CRays ?
  - particle ageing inside ?
- main drivers
  - decrease in shock speed
  - increase in ambient density
  - increase in Alfven wave damping by neutrals



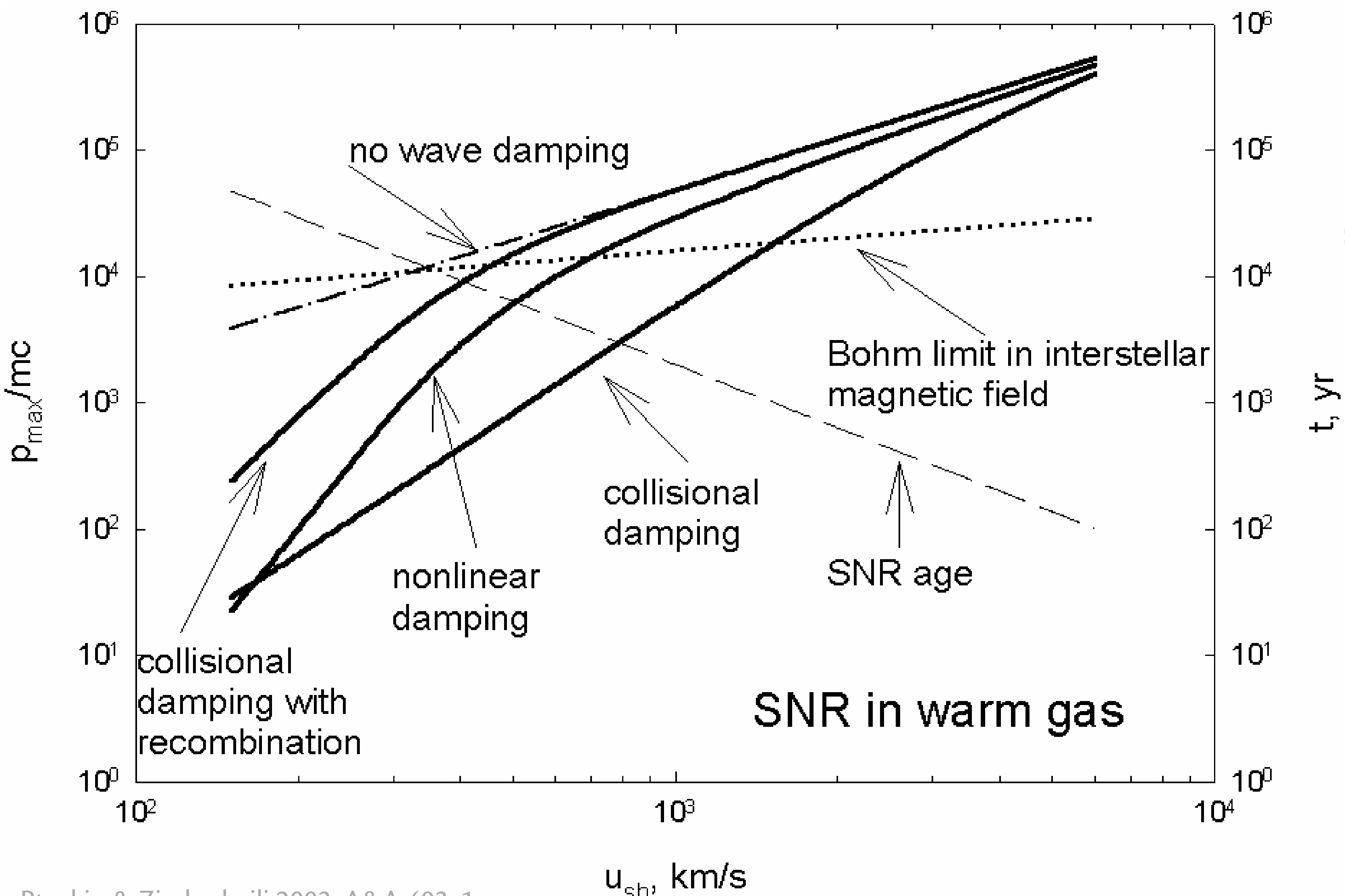




clouds irradiated
by fresh cosmic rays
Baba49

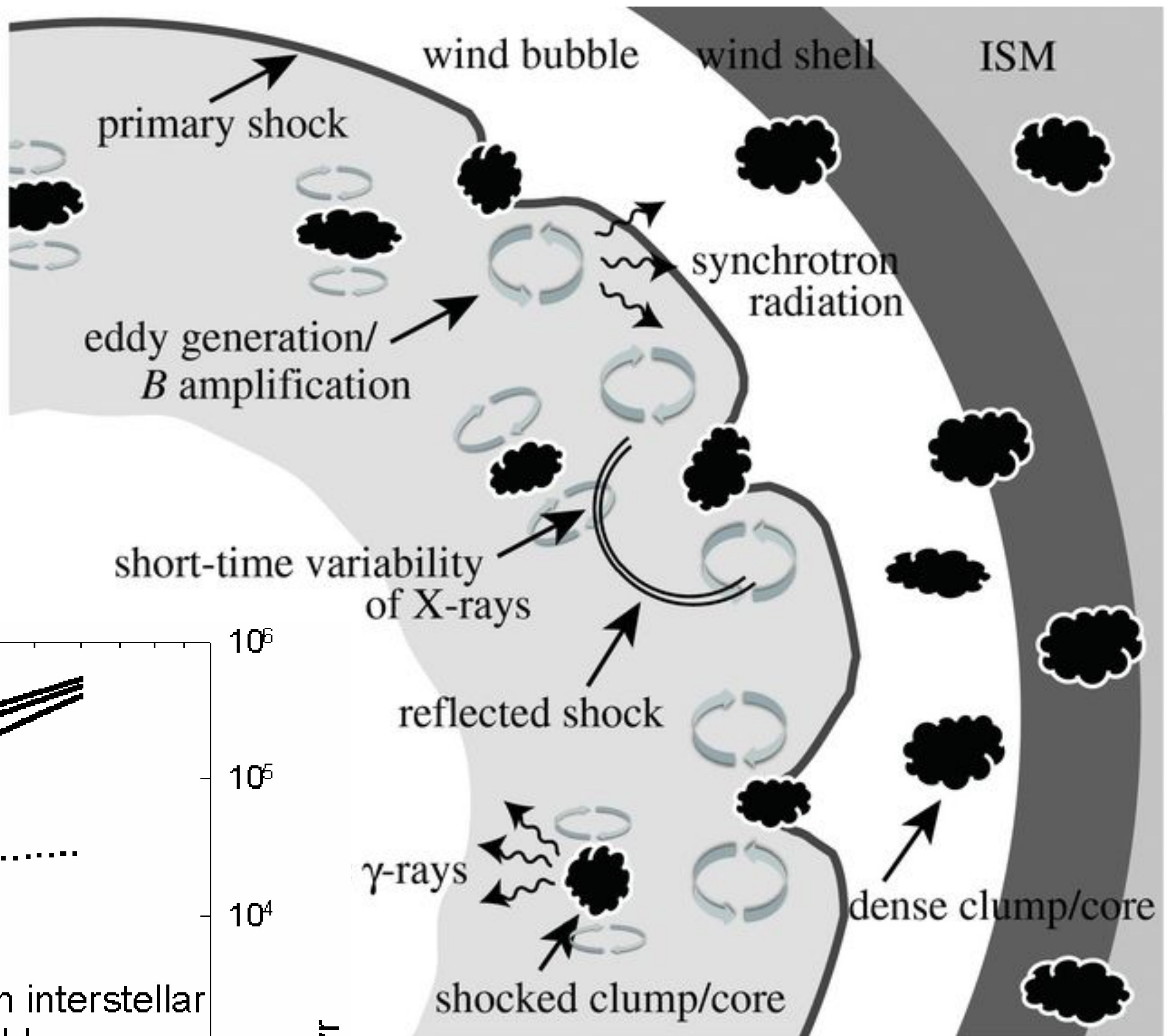
# complex diffusion & escape

- Alfven wave dissipation
  - wave-wave interactions
  - ion-neutral collisions
  - => $E_{max}$ decreases with age
- varying diffusion properties $D_{ISM} \propto p^{\delta}$
  - $0.2 \leq \delta \leq 0.6$ provide good curved fits to the data of interacting SNRs

Ohira+ MNRAS 2011, 410, 1577




Ptuskin & Zirakashvili 2003, A&A 403, 1

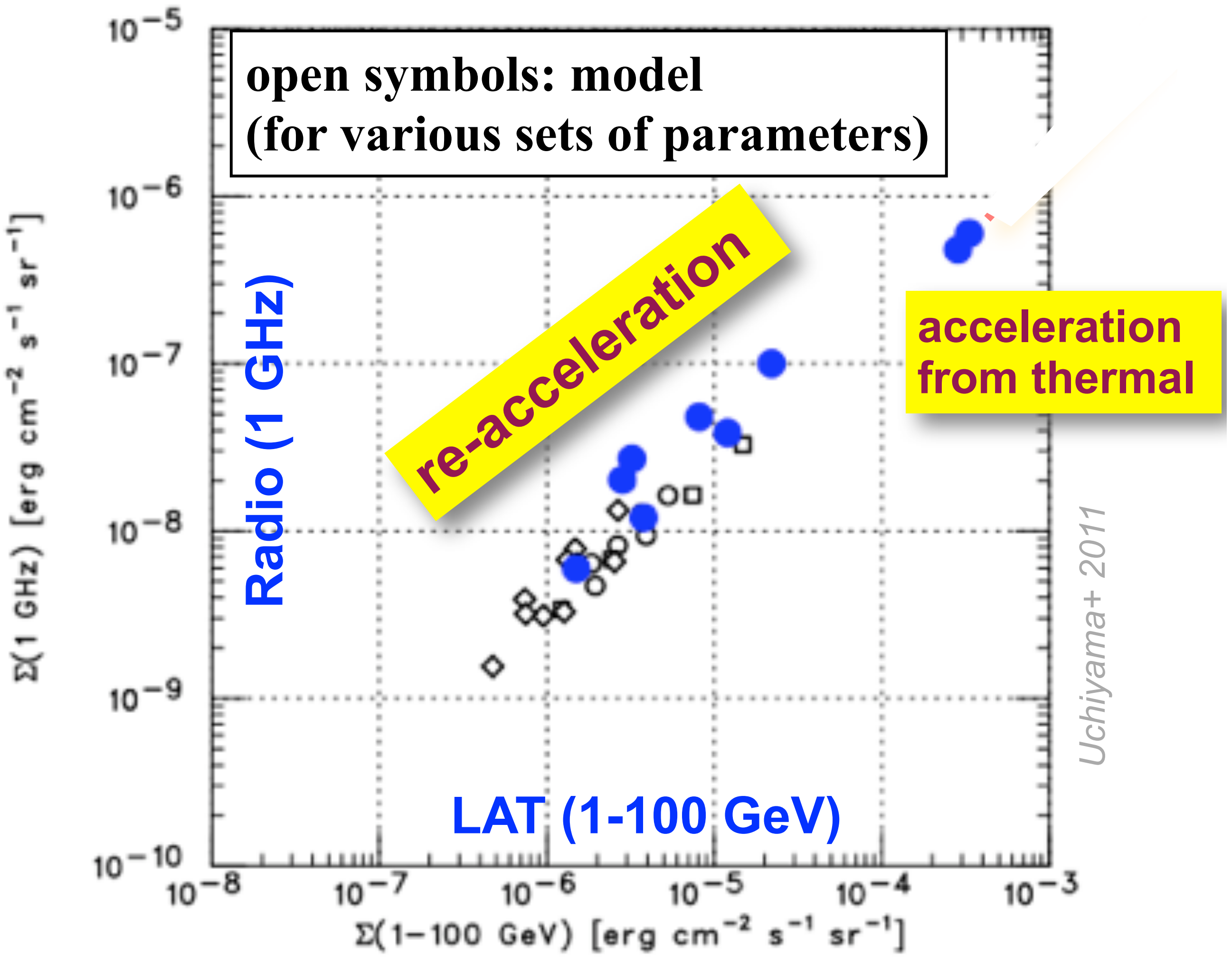


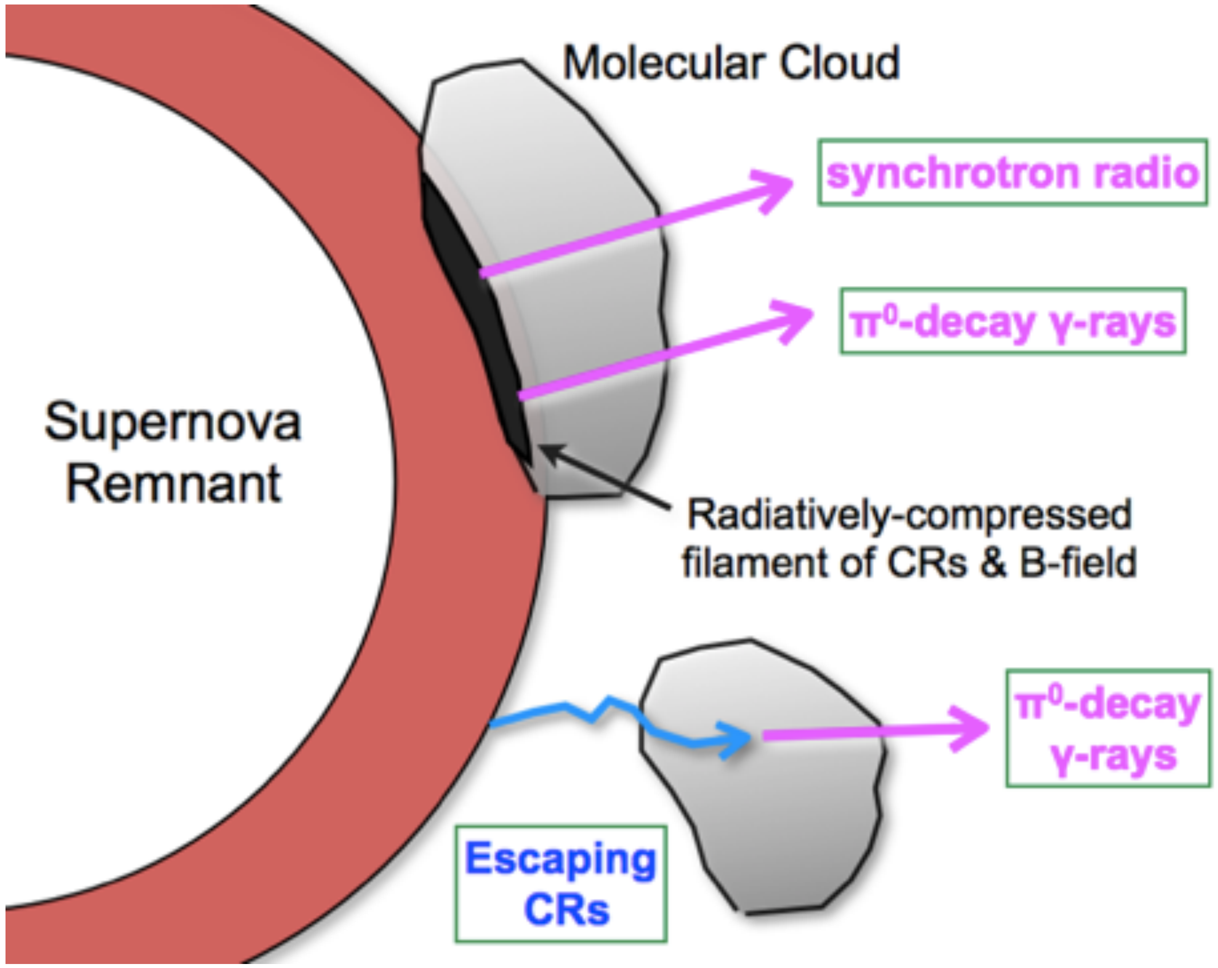

credit Inoue 2012

# irradiated crushed cloud

- radiatively compressed filaments in older SNRs (Uchiyama et al. 2010)
- re-acceleration of pre-existing CRays
  - enhanced radio + γ radiations
    => large & correlated luminosities

**Surface Brightness Diagram (d-independent)**
**LAT (1-100 GeV) vs Radio (1 GHz)**

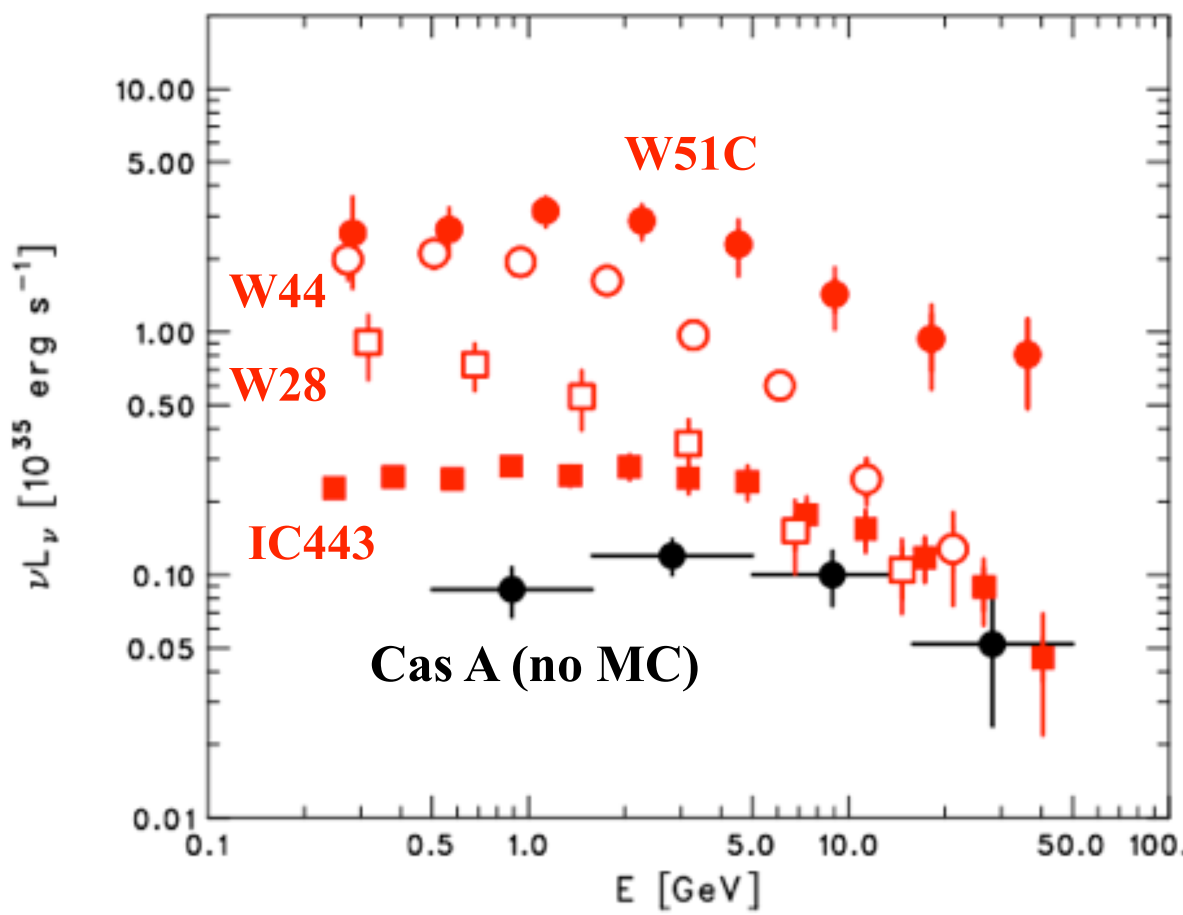


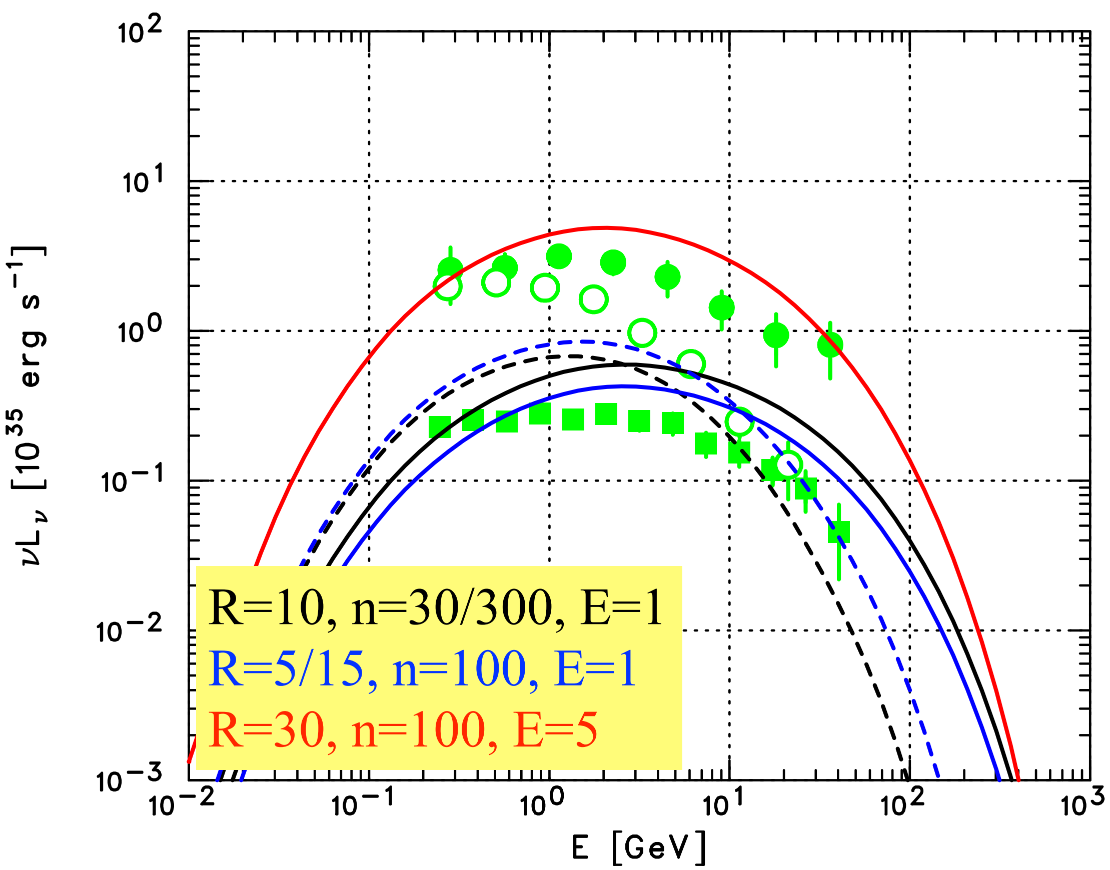



# irradiated crushed cloud

- flat radio index (α ~ 0.37) naturally explained
- curved GeV $\pi^\circ$ spectra bright enough

Fermi-LAT Collaboration (Uchiyama+) 2011




**Model Parameters**

f: Preshock cloud filling factor
f = 0.2 fixed

n: Preshock cloud density in $cm^{-3}$

B: Preshock B-field in μG
$B = 2\, n^{1/2}$ fixed

R: SNR radius in pc

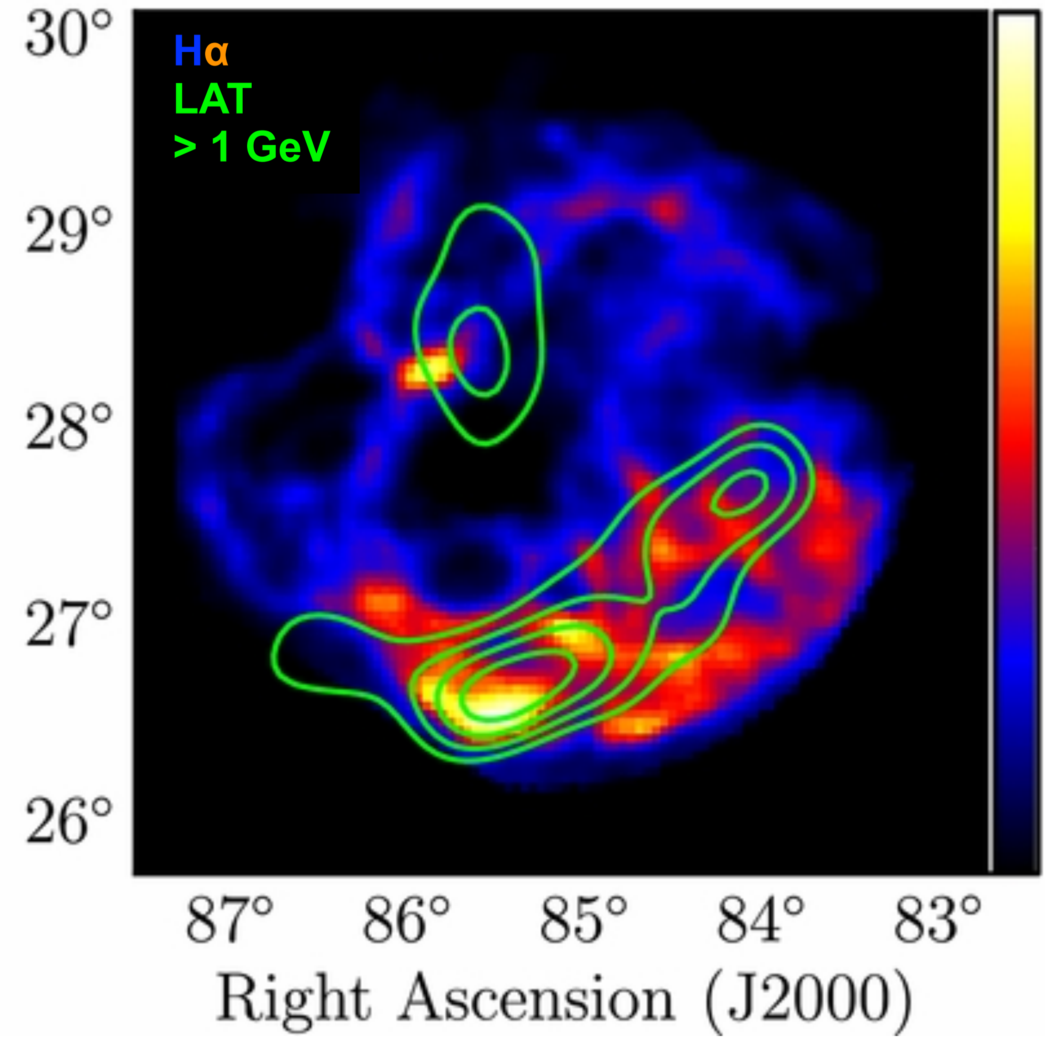
E: SN kinetic energy in $10^{51}$ erg

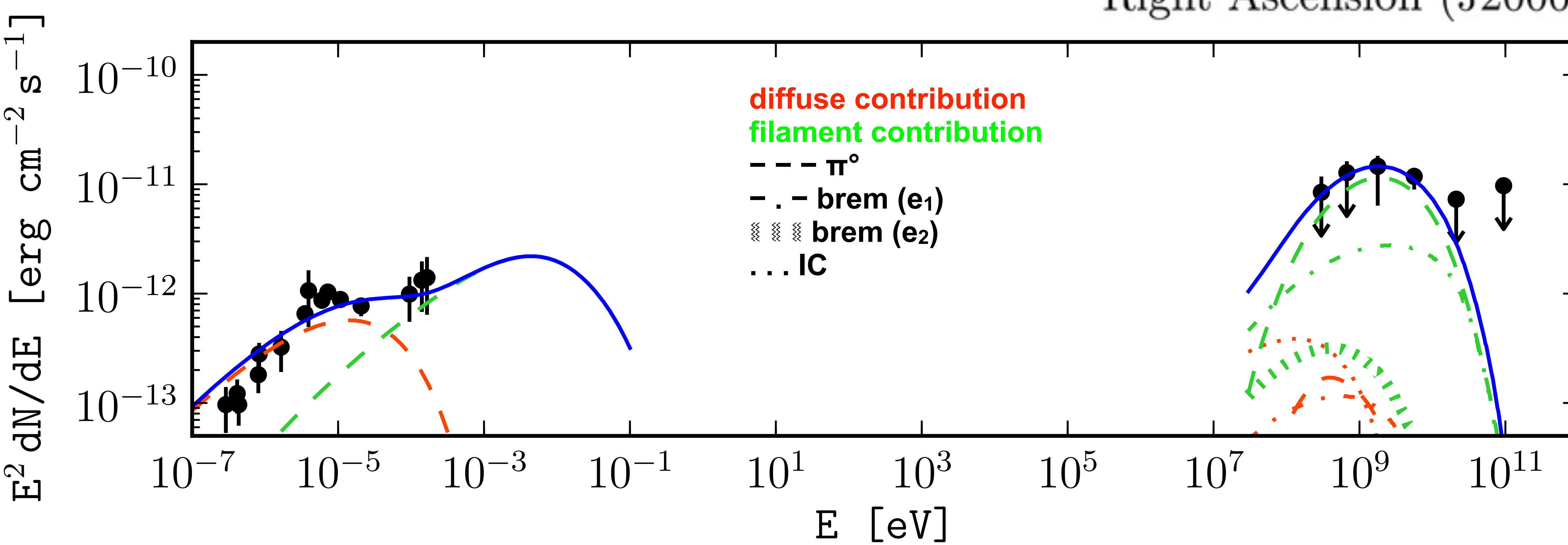
# irradiated crushed cloud

- example of S147

Drew+ 2005

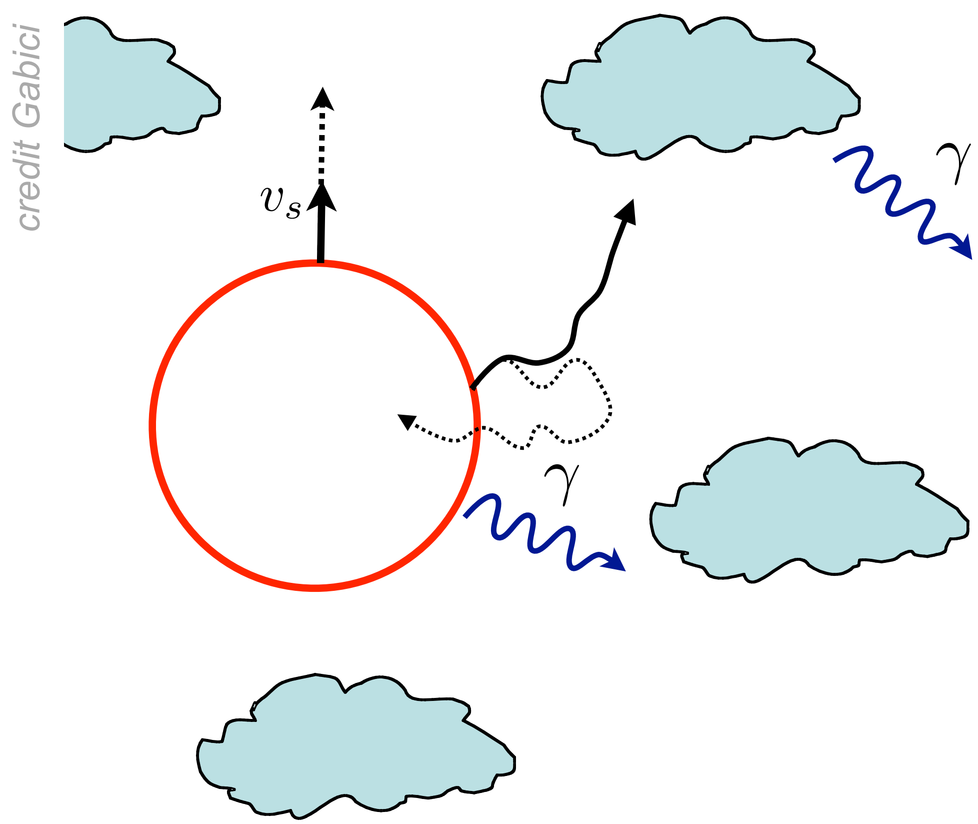

Katsuta+ 2012

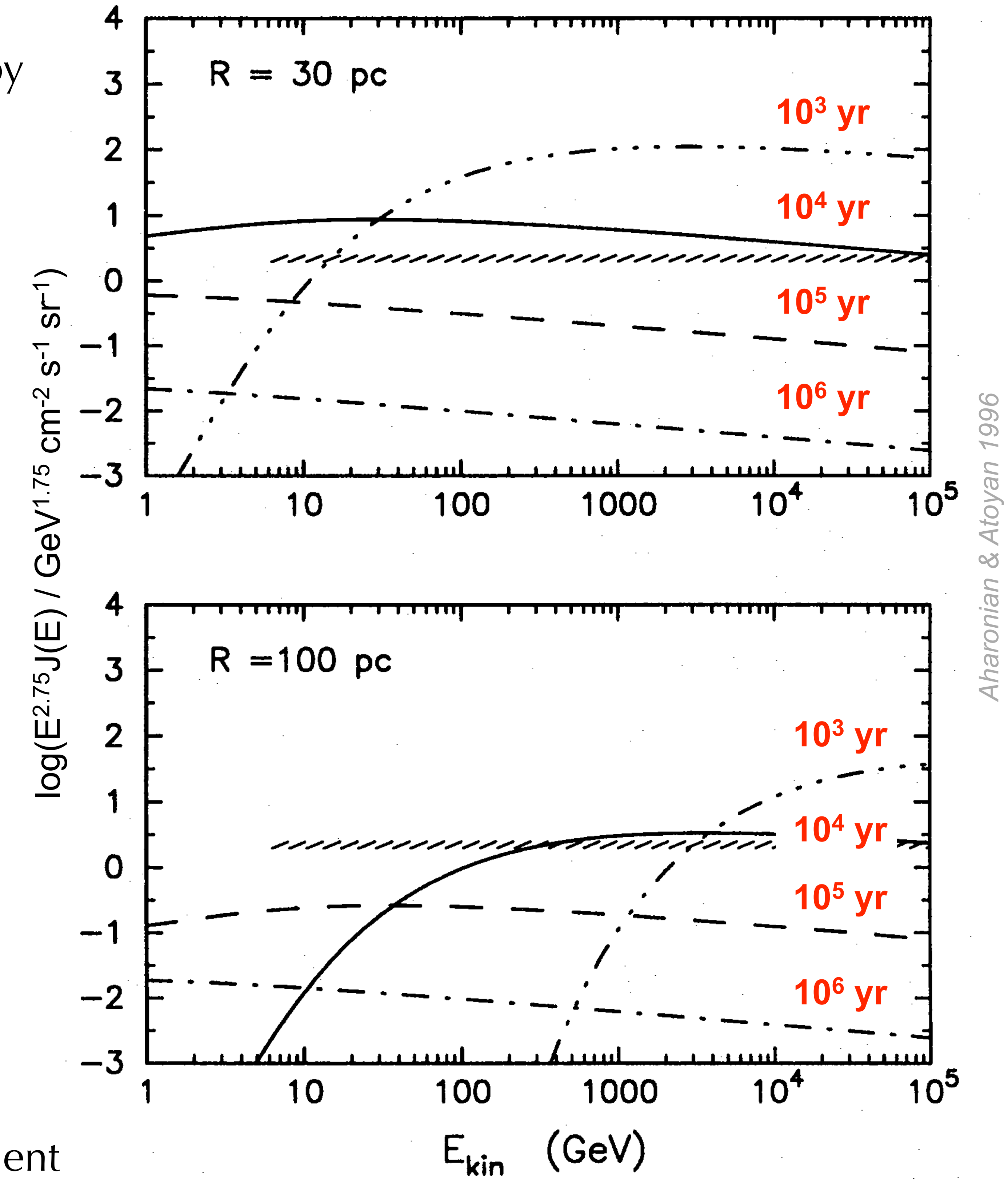


# runaway cosmic rays

- highest-energy CRs escape first !
  => spectral evolution as the CR-wave passes by

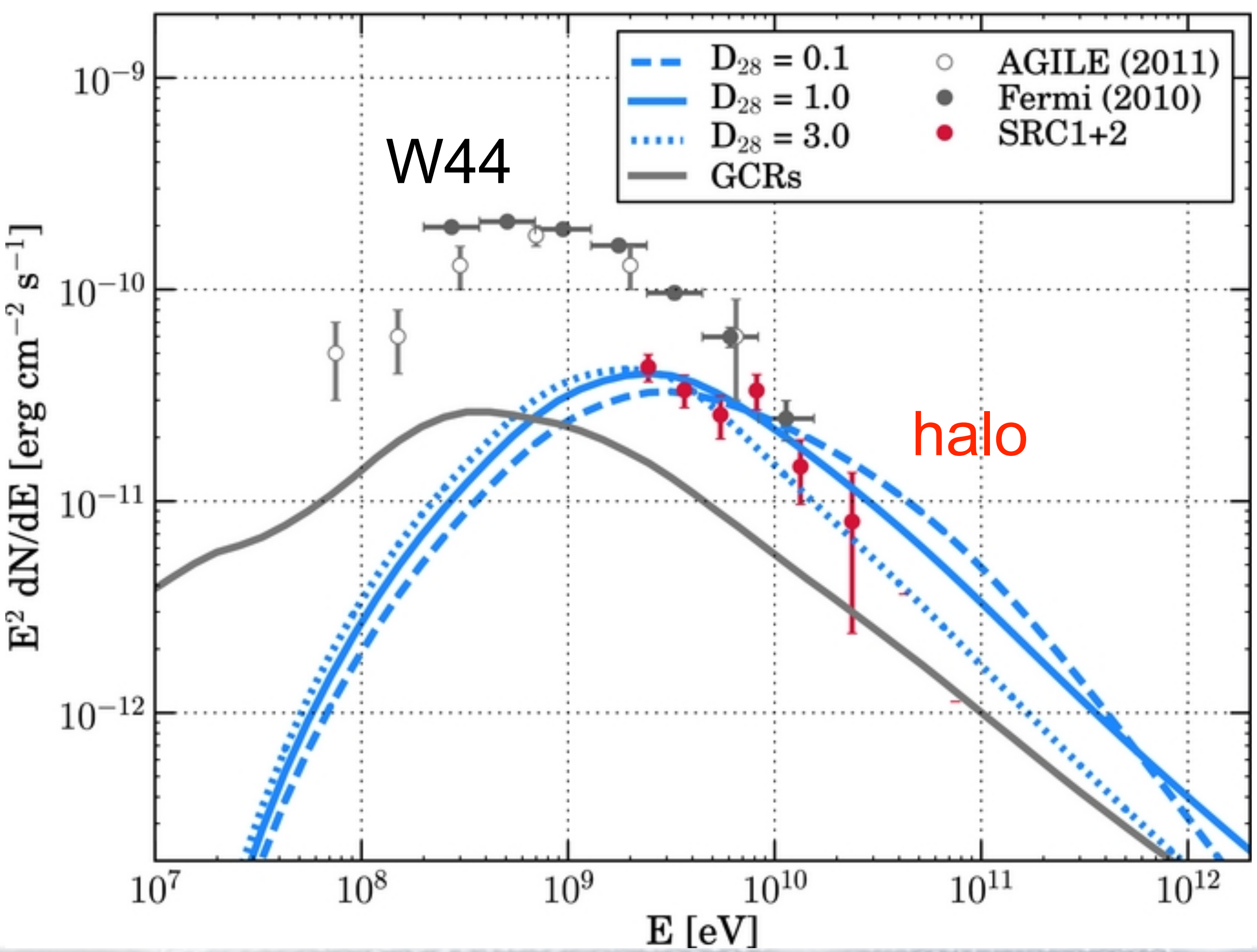


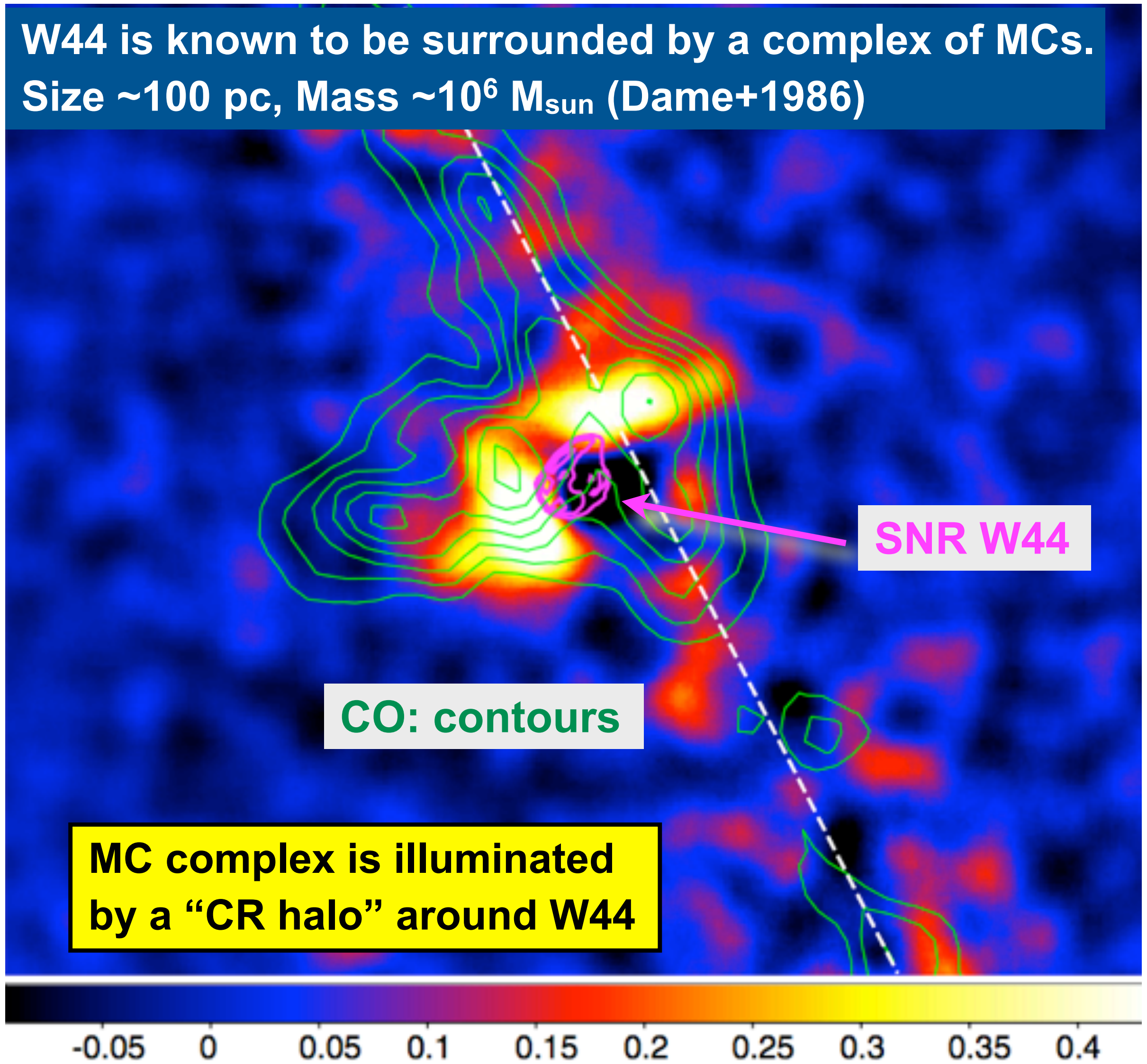

- CR over-density typically within < 100 pc over few kyr
- difficult to firmly associate the SNR and irradiated cloud in 3D
- powerful tool to measure the diffusion coefficient of CRs … once we have firm examples (Gabici arXiV:1011.2029v1)

# irradiated clouds around W44 ?

- extended GeV flux around W44 but uncertain modelling of the background ISM emission from normal CRs
- if 0.5 $10^5$ M⊙ uniformly distributed within 100 pc
  - slow case: $D = 0.1\ D_{ISM}$
    $N_{esc}(E) \propto E^{-2.6}$ and $W_{esc} \sim 0.3\ 10^{50}$ erg
  - standard case: $D = 0.1\ D_{ISM}$
    $N_{esc}(E) \propto E^{-2.0}$ and $W_{esc} \sim 1.1\ 10^{50}$ erg
  - fast case: $D = 3\ D_{ISM}$
    $N_{esc}(E) \propto E^{-2.0}$ and $W_{esc} \sim 2.7\ 10^{50}$ erg




Uchiyama+ 2012



# prompt cosmic-ray sources: novae

Baba49

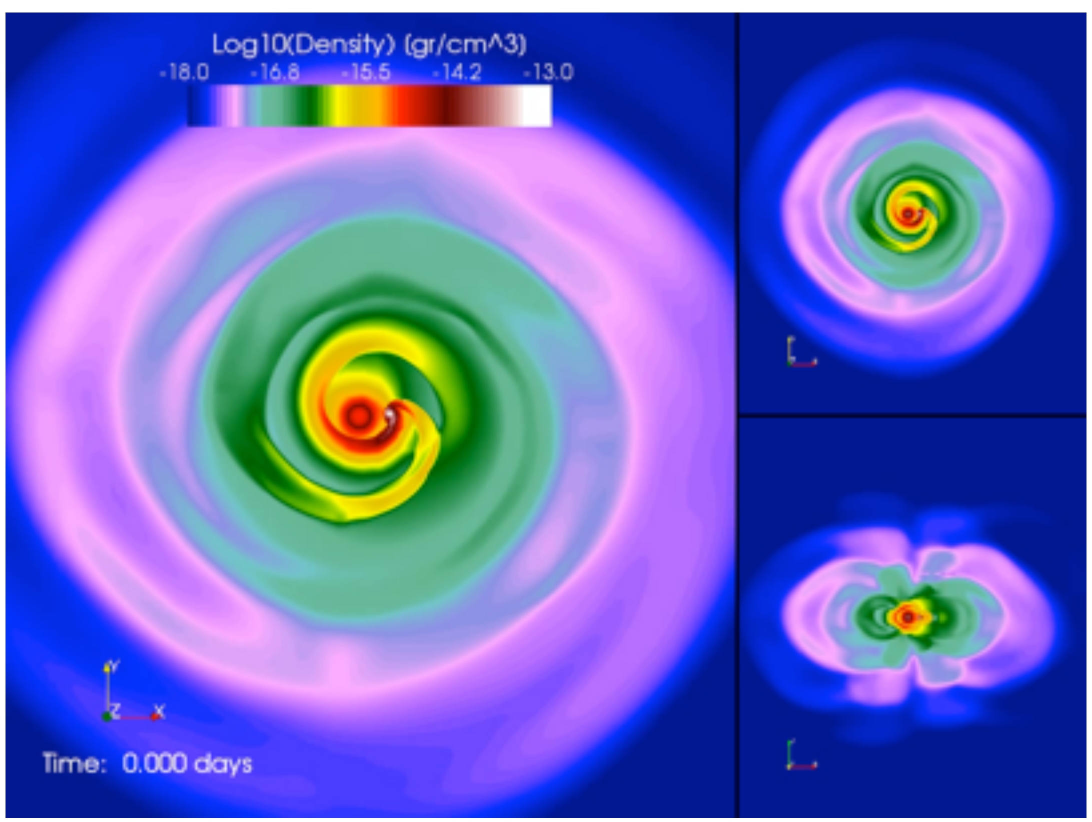
# mini-supernova shock waves

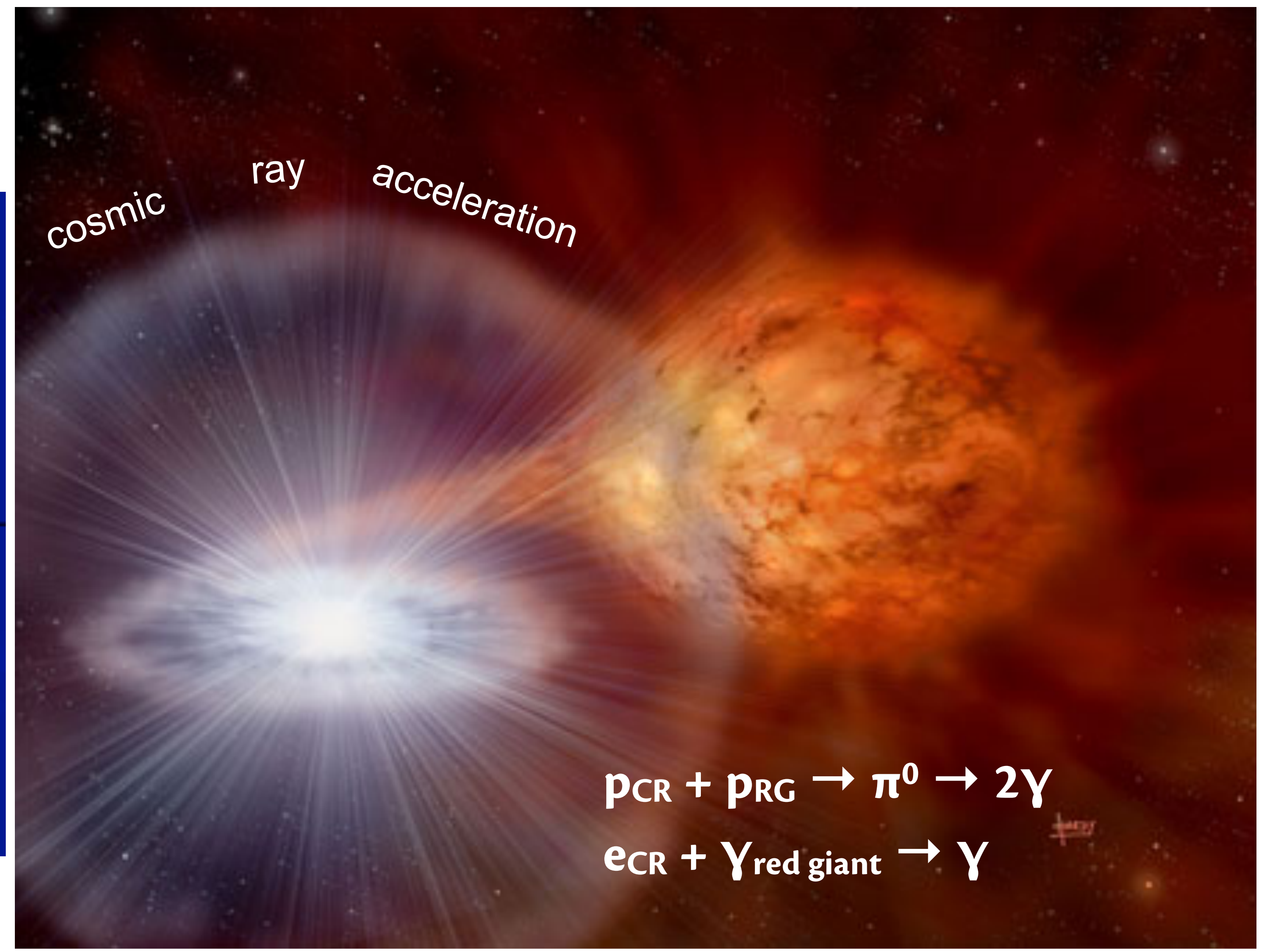
- 4 γ-ray novae
  - V 407 Cyg
  - Mon 2012 (discovered in γ rays)
  - Sco 2012
  - Del 2013
- white dwarf + companion

  $10^{-7}$-$10^{-3}$ M⊙ thermonuclear runaway ejecta, 400-5000 km/s, $10^{44}$-$^{46}$ erg
- 0.1-2 γ novae $yr^{-1}$ (95%CL) compared to < 8 $yr^{-1}$ in the visible
- Fermi acceleration in "real time"

  radio synchrotron absorbed

  (free-free radio from stellar wind)



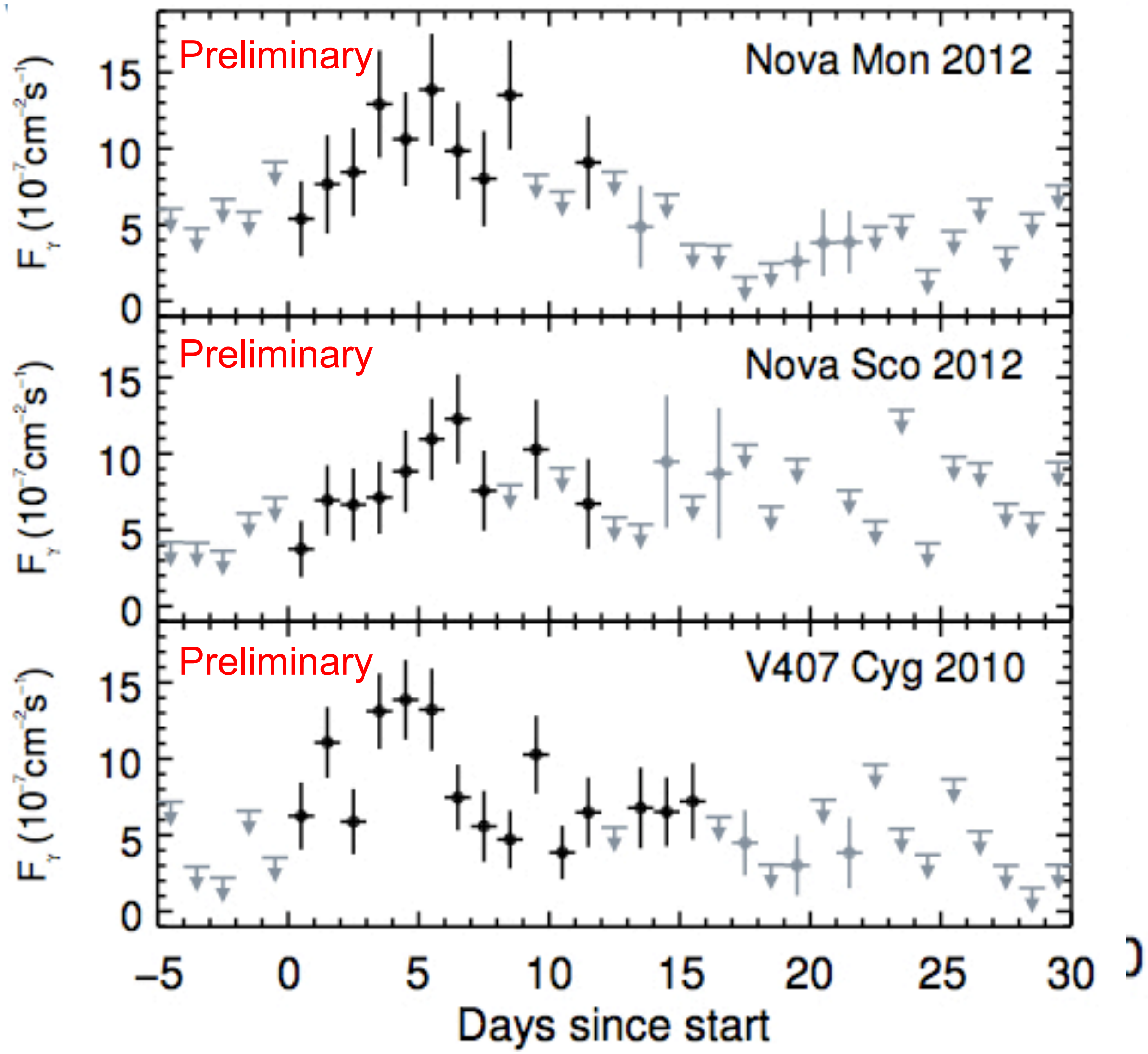



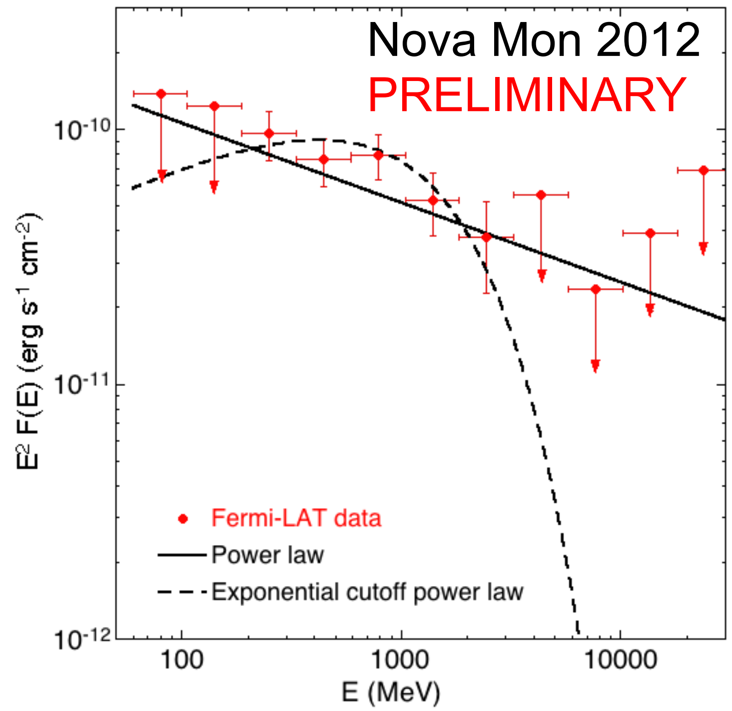
# 4 $\gamma$-ray novae

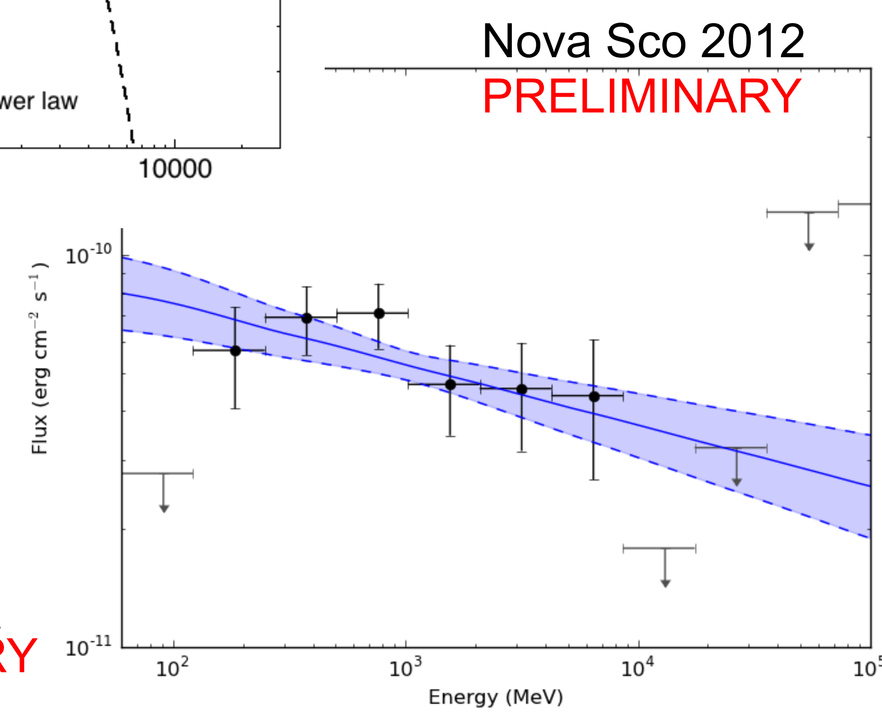
| | companion | period | distance (kpc) | velocity (km/s) | X rays |
|---|---|---|---|---|---|
| **V407 Cyg**<br>symbiotic<br>He/N nova | red giant | 50 hr | 2.7 | 3000 | yes |
| **Mon 2012**<br>classical<br>O/Ne nova | KV | 7.1 hr | 3.6 | 2000-2500 | yes |
| **Sco 2012**<br>classical nova | | ? | 4.9 ? | | no |
| **Del 2013**<br>CO type? | | **August 14th 2013** | | | |

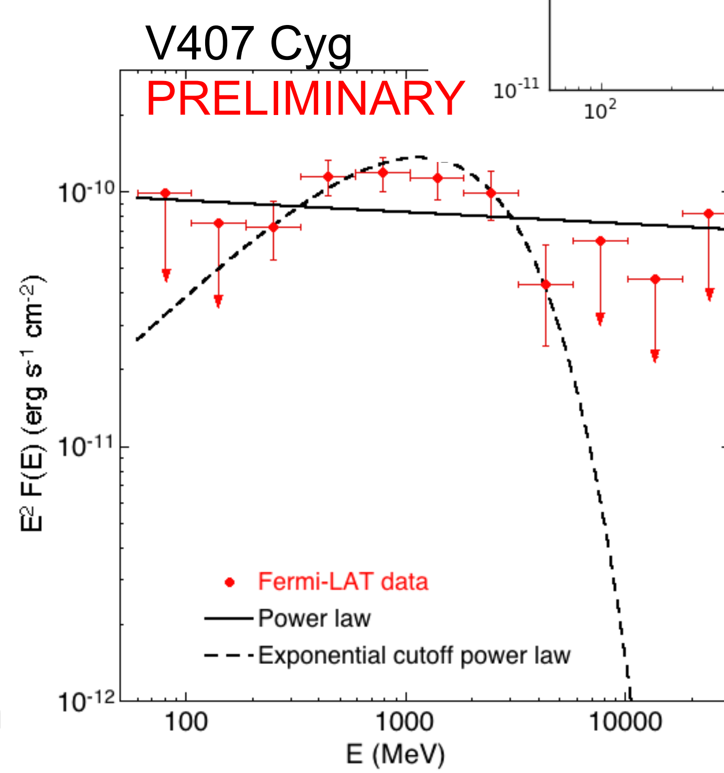
# similar γ-ray novae

- similarities in lightcurves
  - rise over days
  - decline over 2-3 weeks
- similarities in spectra
  - soft & curved



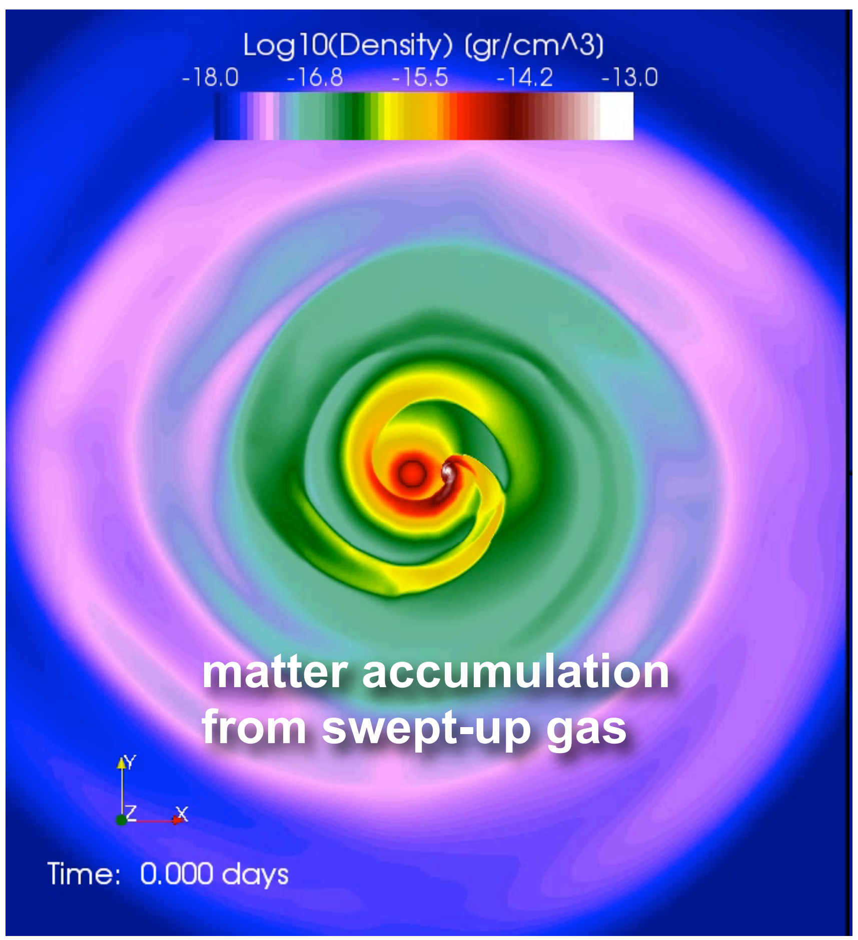



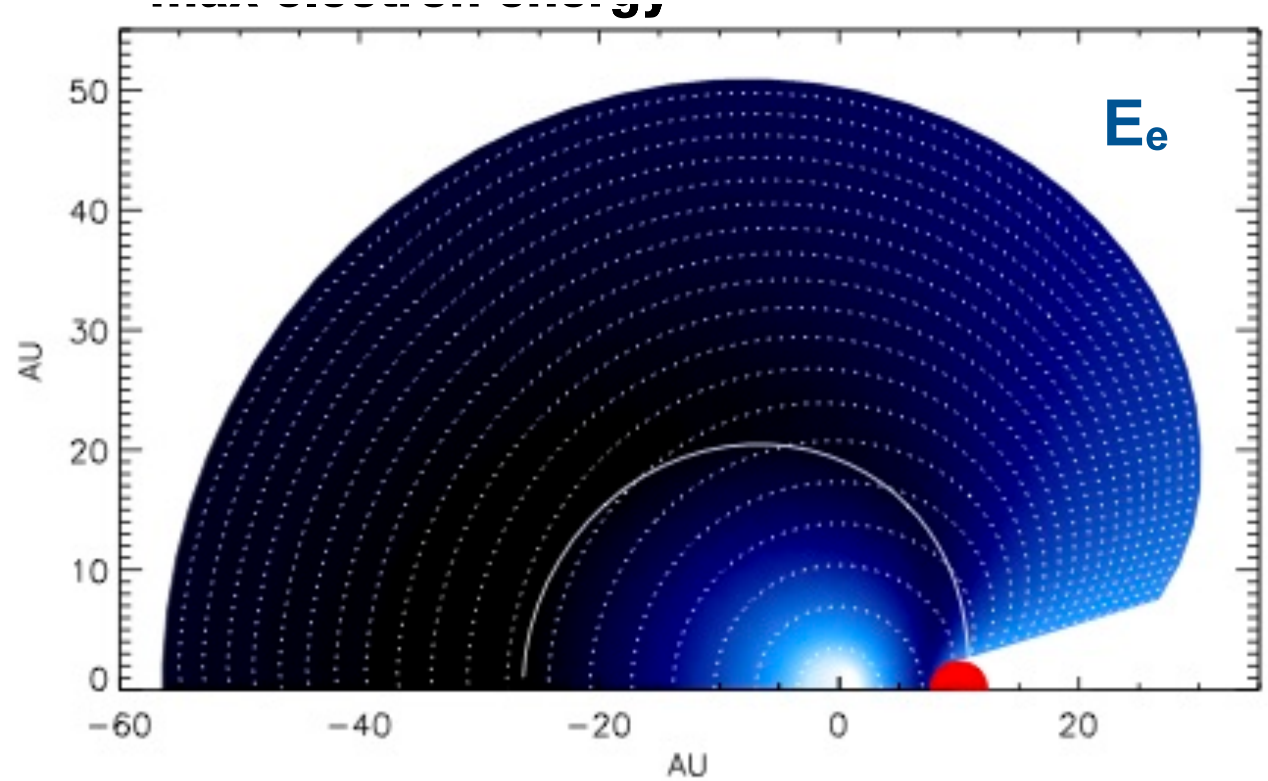



# a mini SNR accelerator

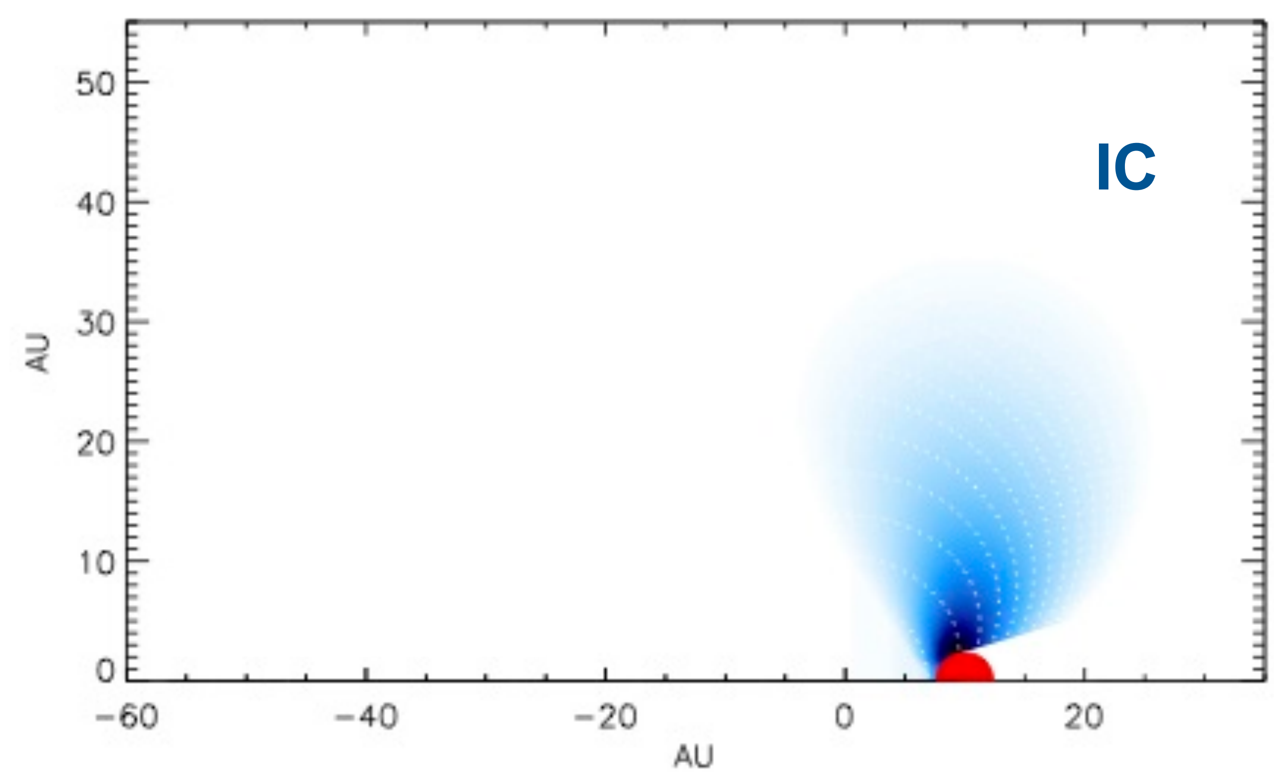
- acceleration by shock wave (free expansion + Sedov phase), but aspherical
  - test particle approximation + equipartition B upstream + Bohm diffusion
  - $E_{max}(p)$ from age < few 100 GeV
  - $E_{max}(e)$ from IC losses < few 10 GeV
- (small) anisotropy effects on IC yield
- swept-up stellar wind not dense enough
  => matter accumulation around white dwarf
  - large injection early on (fast rise)
  - acceleration drops when shock exits the zone (week decline)




Walder, Folini, Shore 2008




Martin & Dubus 2013

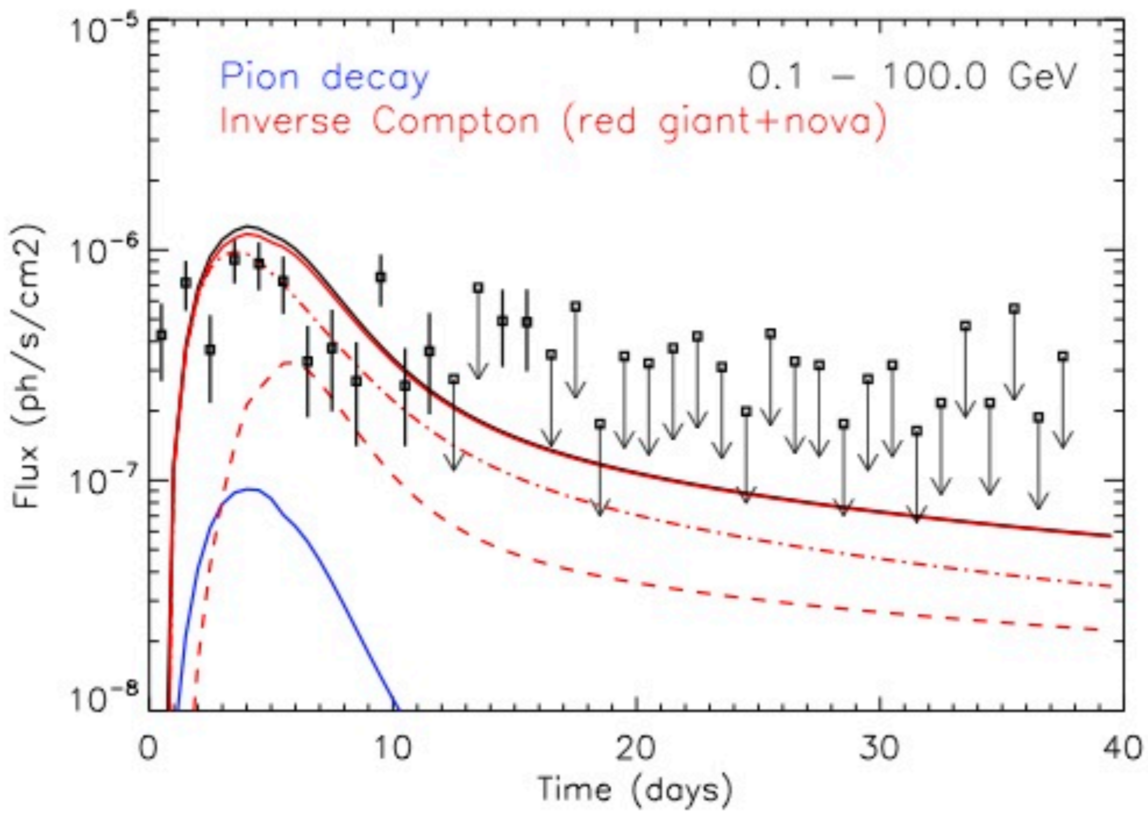


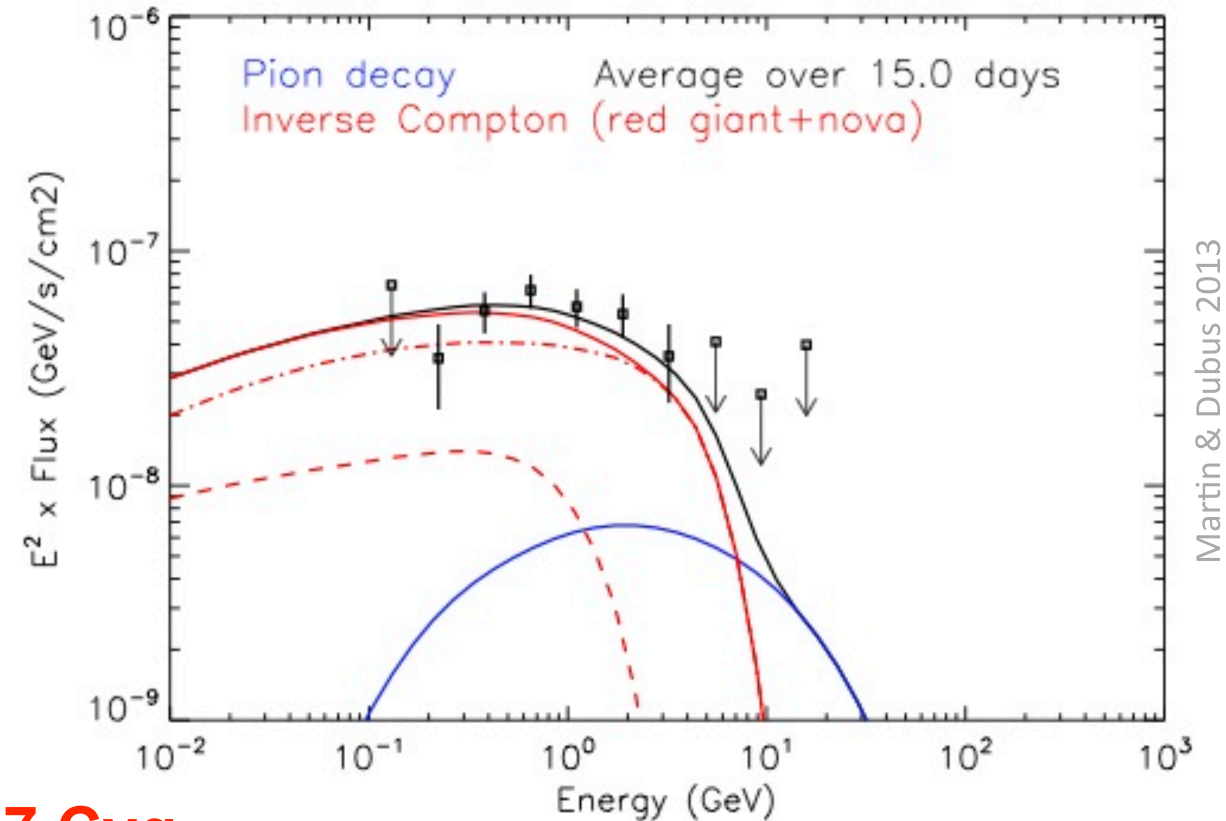

Martin & Dubus 2013

- thermal X-ray constraint on swept-up density

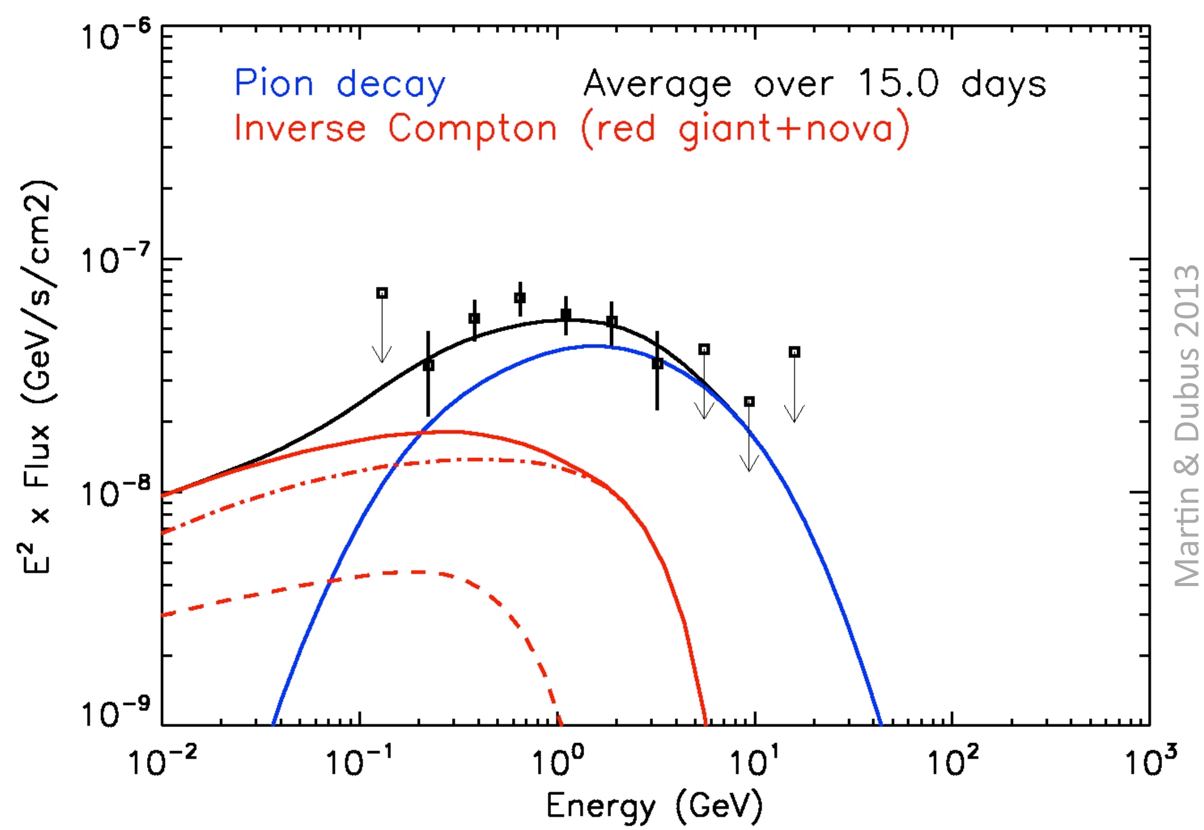
# V407 Cyg as a cosmic-ray source

- if low non-thermal efficiency $\frac{L_{non-thermal}}{\dot{E}_{nova}} < 0.1$
  - IC on nova light dominates
    important spectral test in γ rays < 100 MeV
  - 10% of nova energy in nuclei, 1% in electrons




**V407 Cyg**




- if high non-thermal efficiency $\frac{L_{non-thermal}}{\dot{E}_{nova}} > 0.5$
  - $\pi°$ emission dominates
  - but CR pressure feedback on the shock !!
- problem with other novae: not so dense winds
  mass reservoir for injection and for $\pi°$ production ?
- why other recent novae un-detected ?
  we only see the fastest ones?