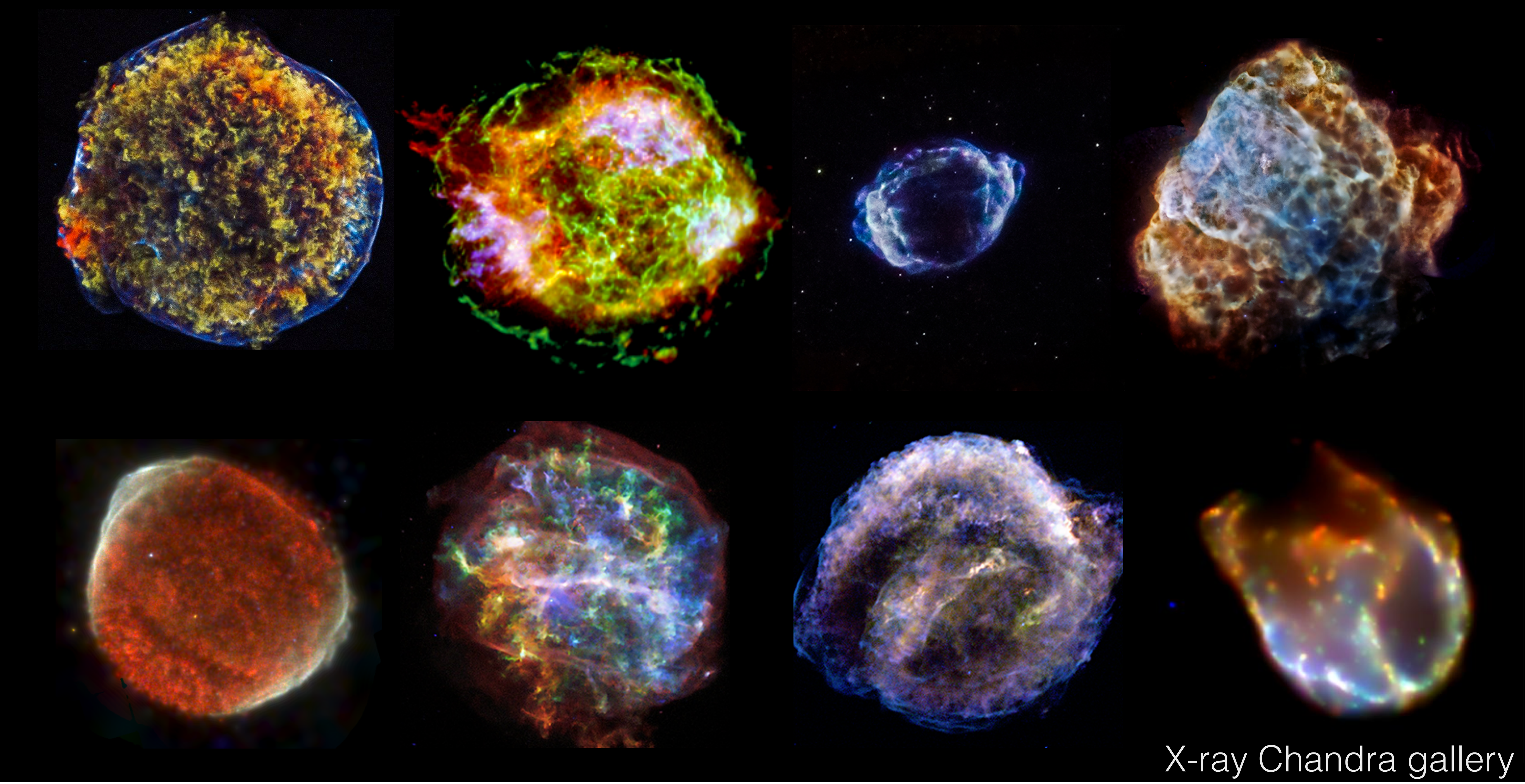
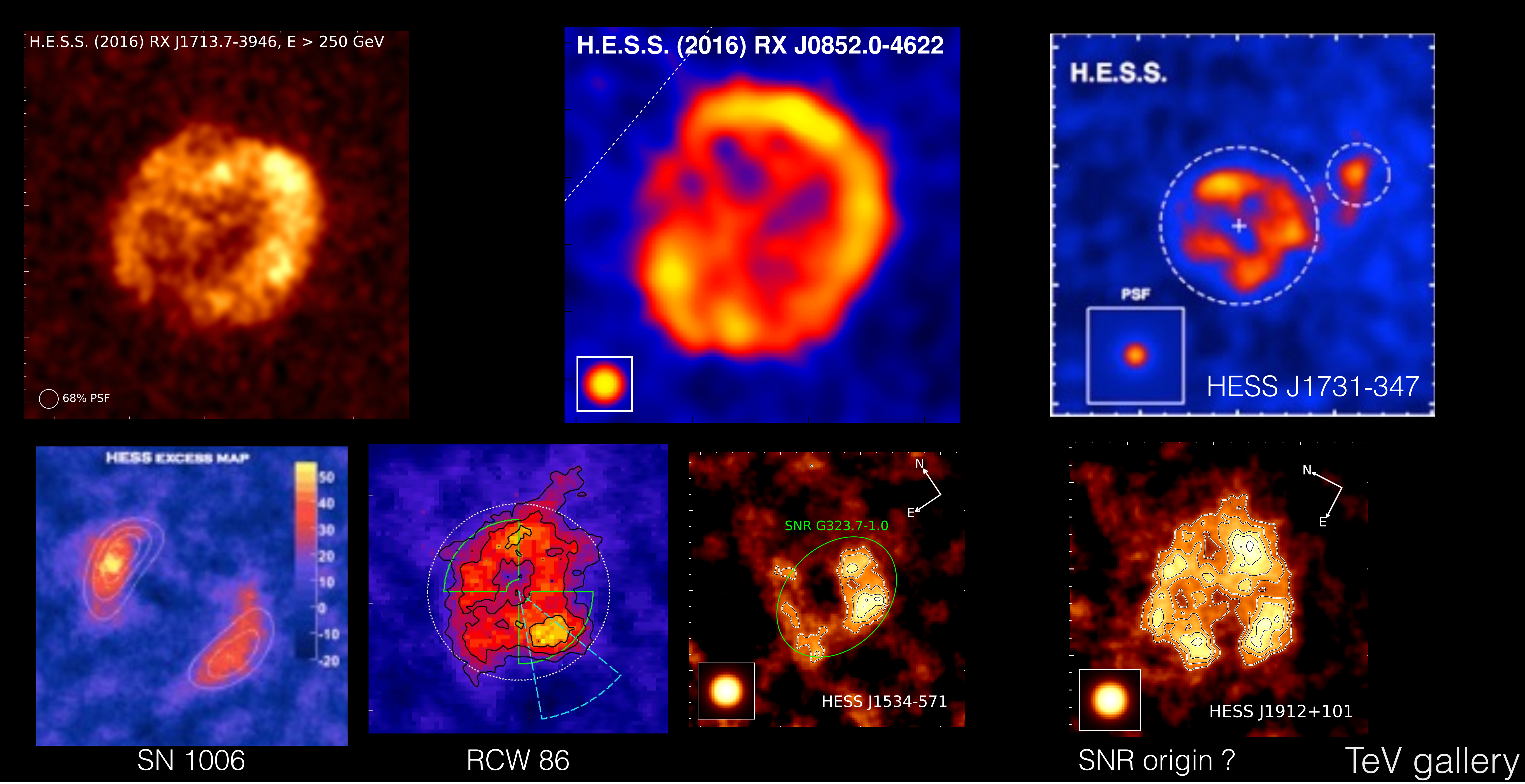


Supernova Remnants

A γ-ray view

F. Acero, AIM/CEA-Saclay

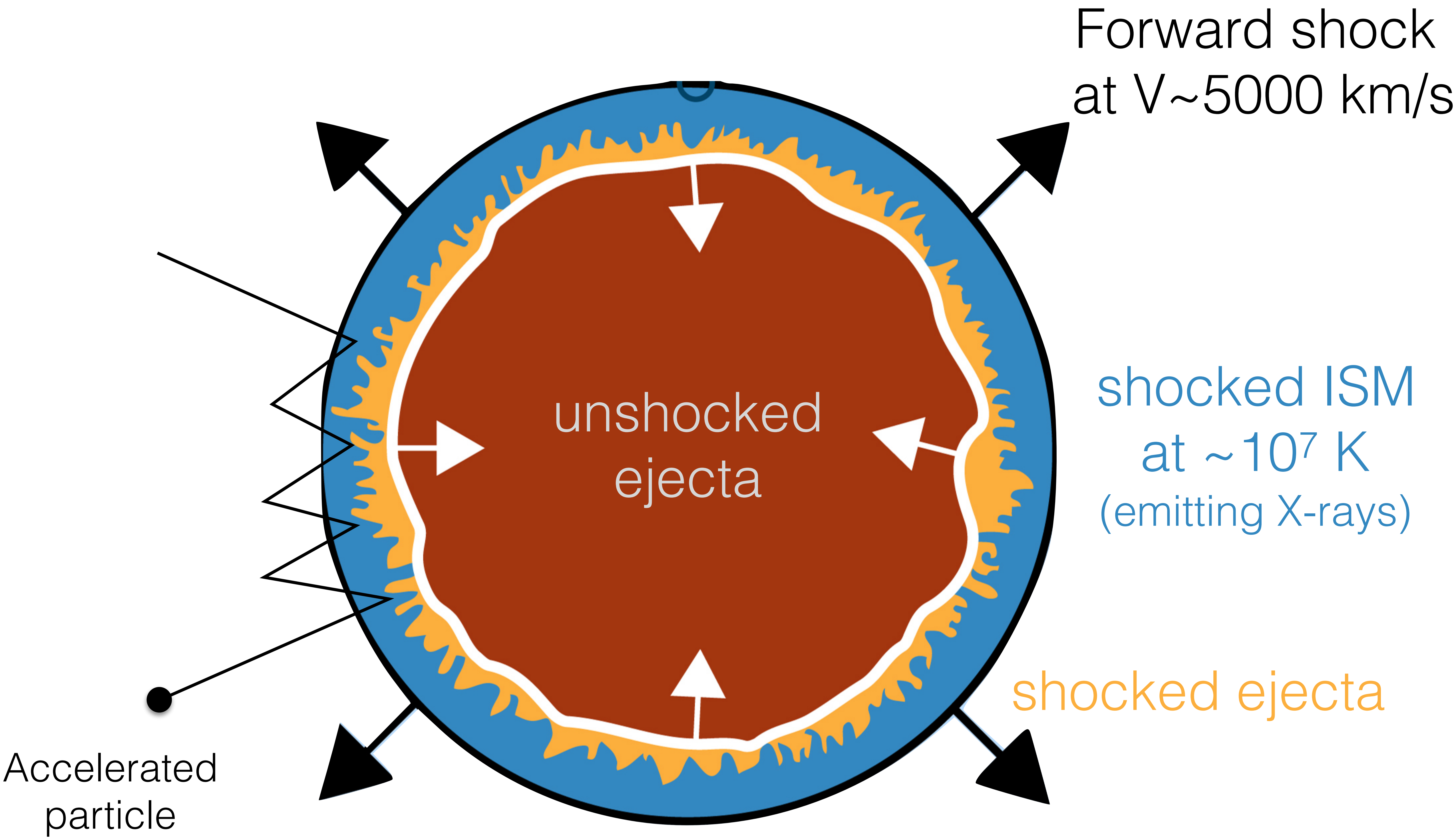


Supernova Remnants

A γ-ray view

F. Acero, AIM/CEA-Saclay

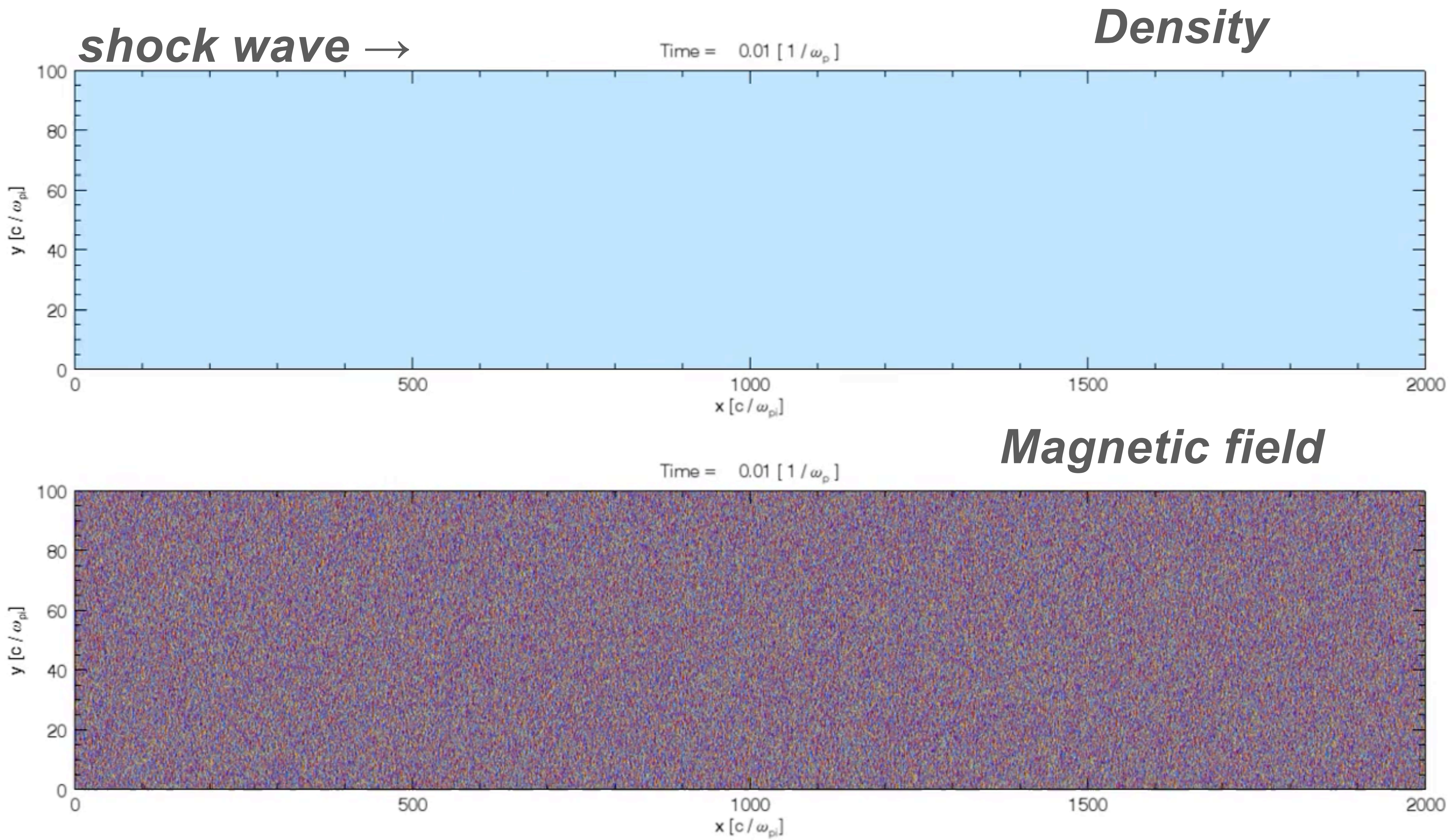
Structure of a Supernova Remnant



(c) A. Bordenave

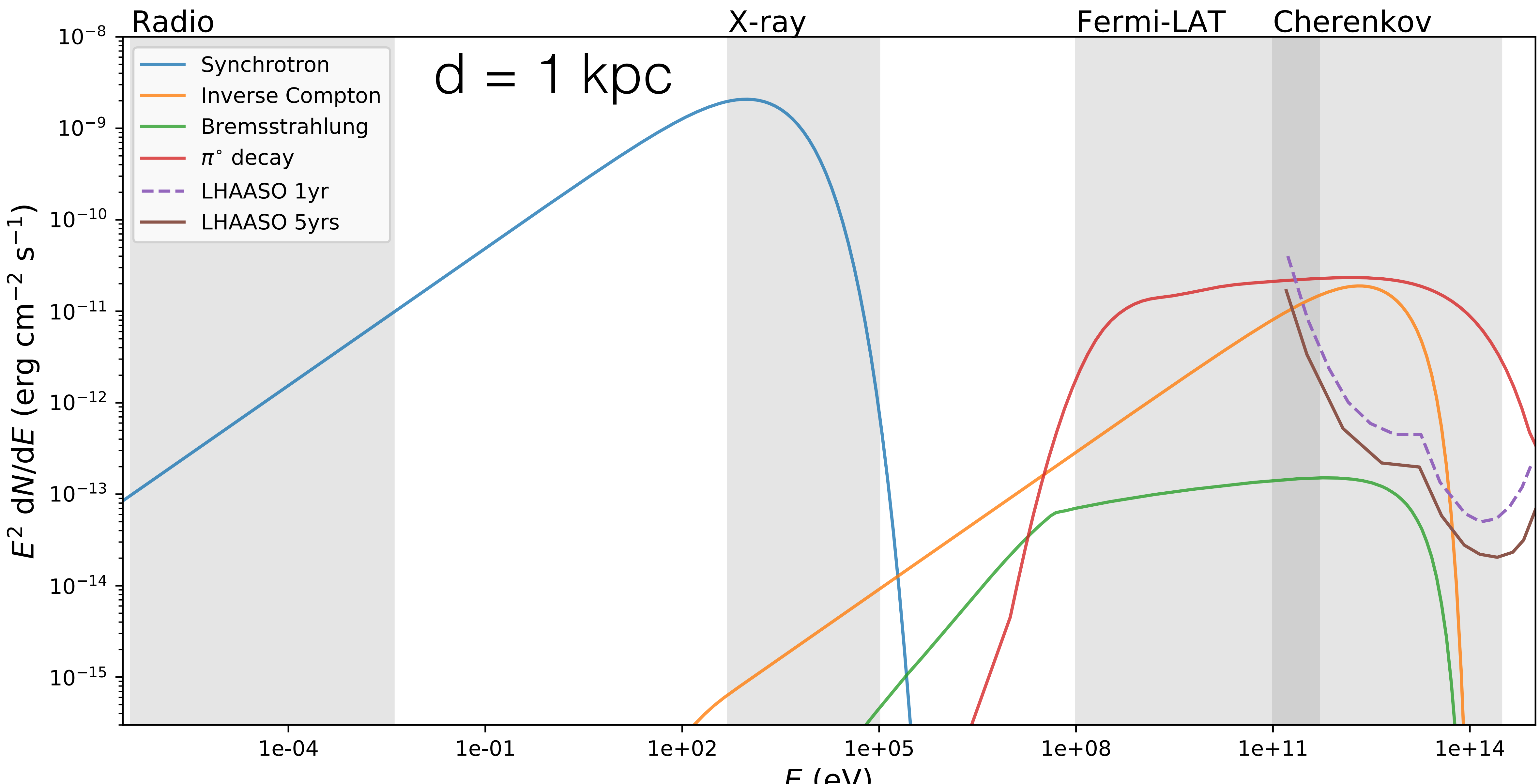
Diffusive Shock Acceleration

- **Fermi acceleration process**



Credit: Damiano Caprioli, ICRC 2015 Dhybrid code (Gargaté et al. 2007), DC & Spitkovsky 2014

Explore CRs properties via their radiations



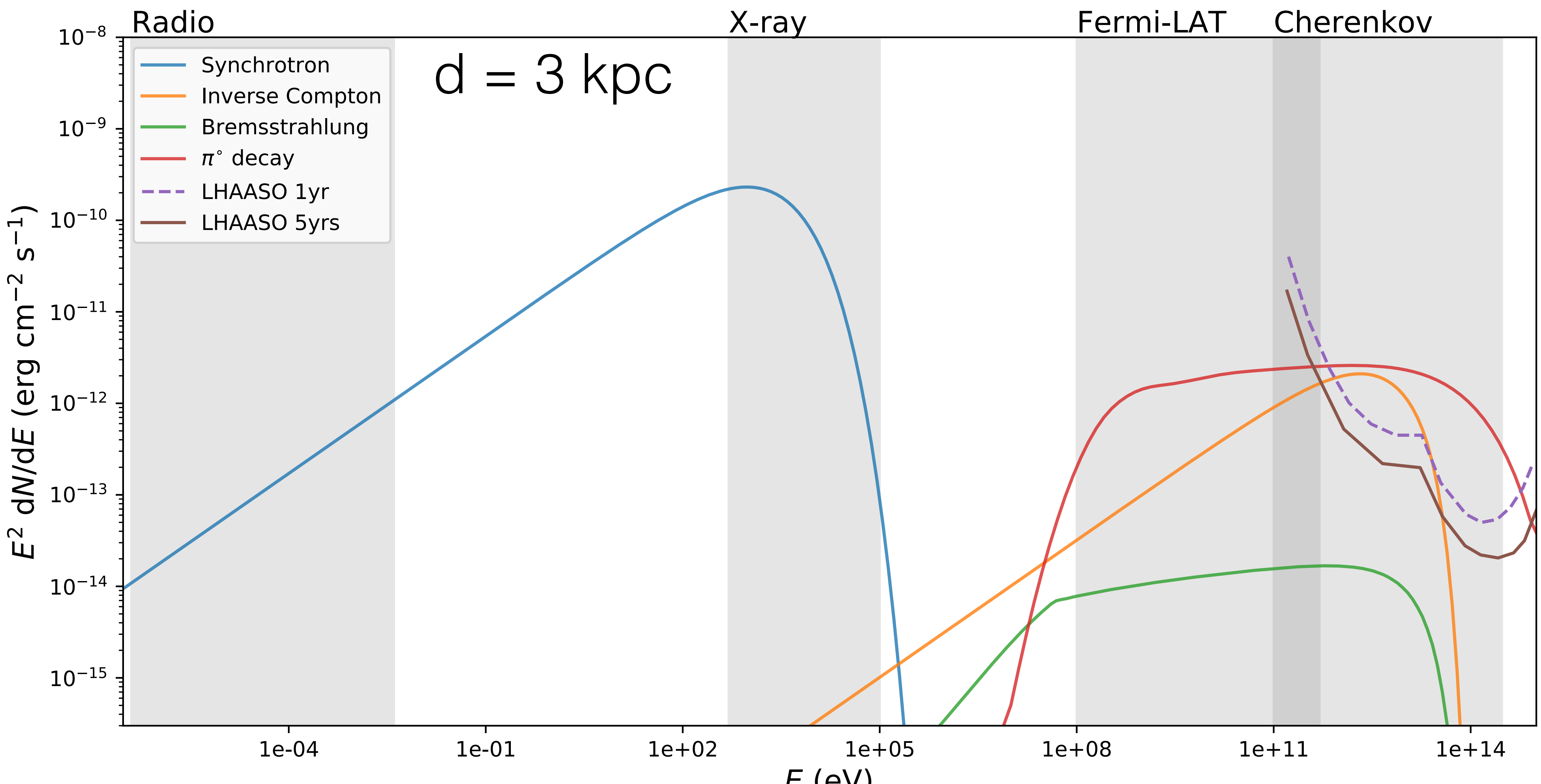
LHAASO curves from White Paper

Interactive SED explorer with naima:
http://mybinder.org/repo/facero/OHP-2016-material/SNR/explore-SED

Protons: $E_{cut,p}$= 1 PeV rho= 1 cm^{-3} $W_p=10^{50}$ ergs Γ=2

Electrons: $E_{cut,e}$= 30 TeV B= 50 μG $W_e=10^{47}$ ergs Γ=2

Explore CRs properties via their radiations



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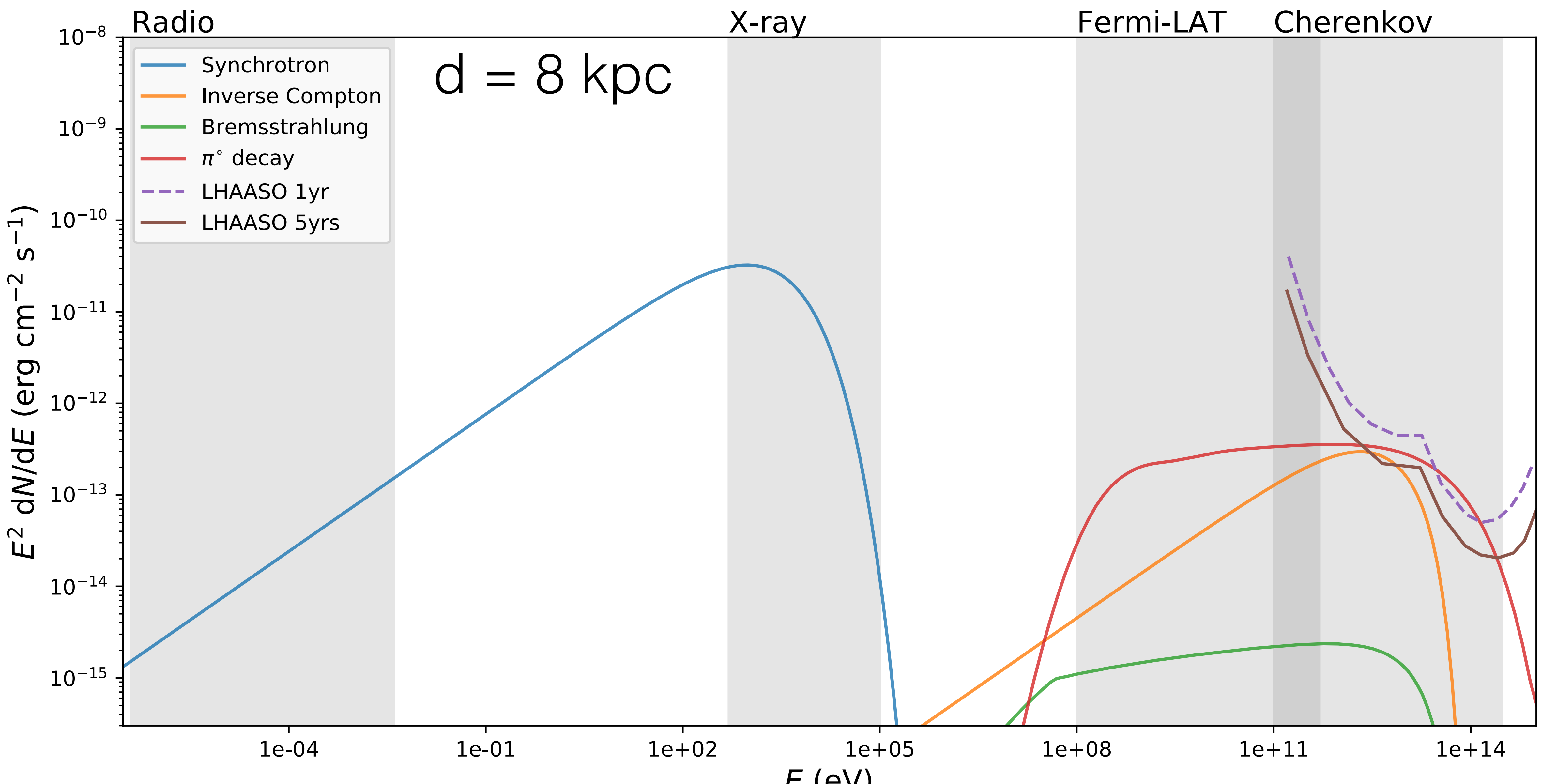

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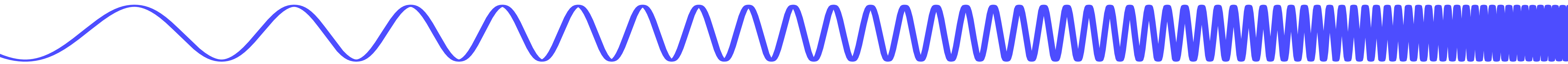
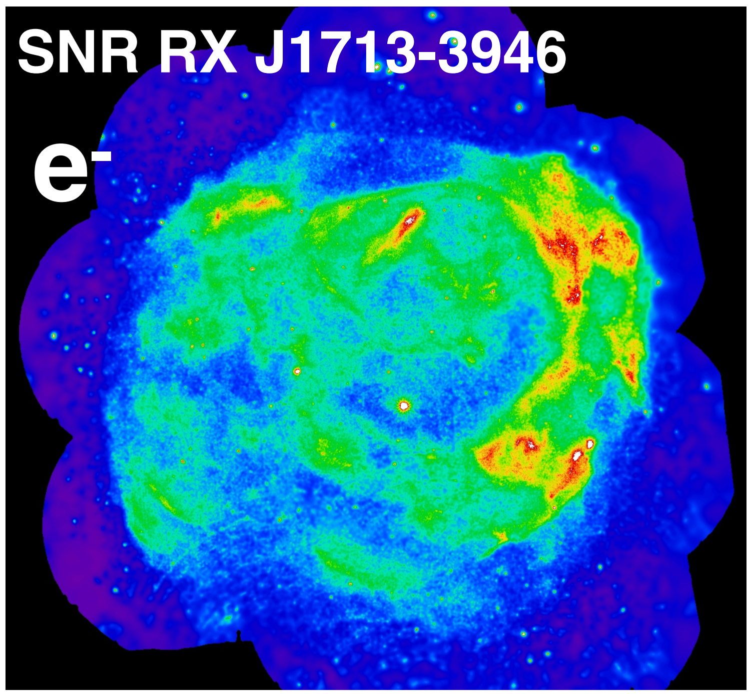
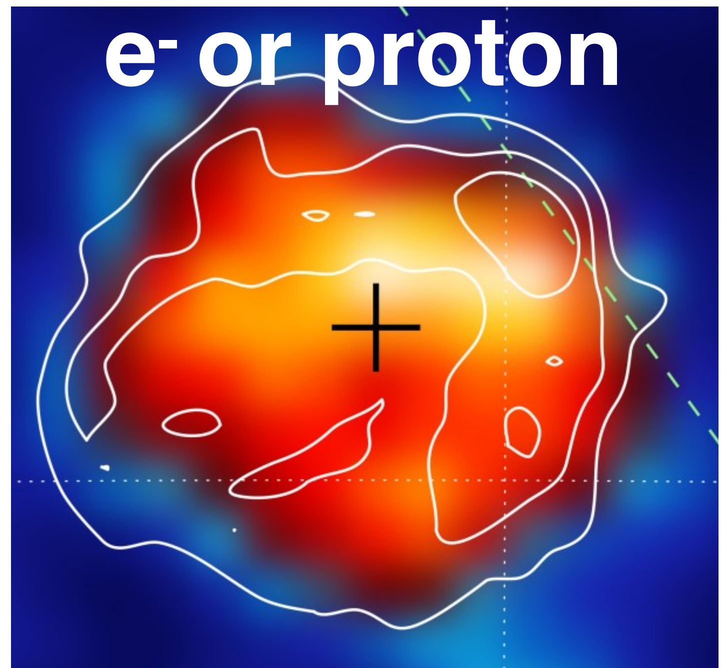
High energy radiation



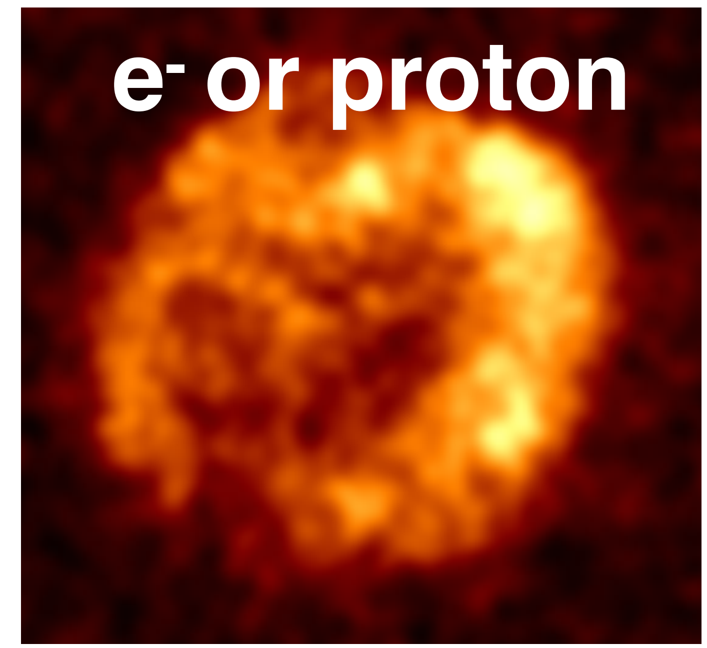
keV

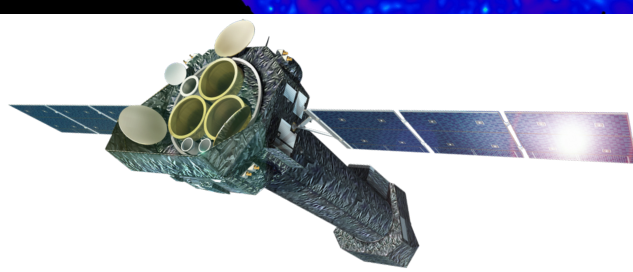


GeV gamma-ray



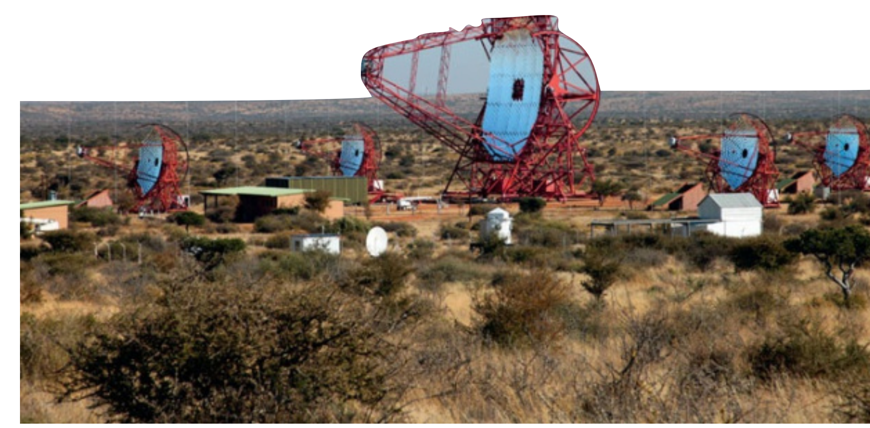
TeV gamma-ray





XMM-Newton

Fermi

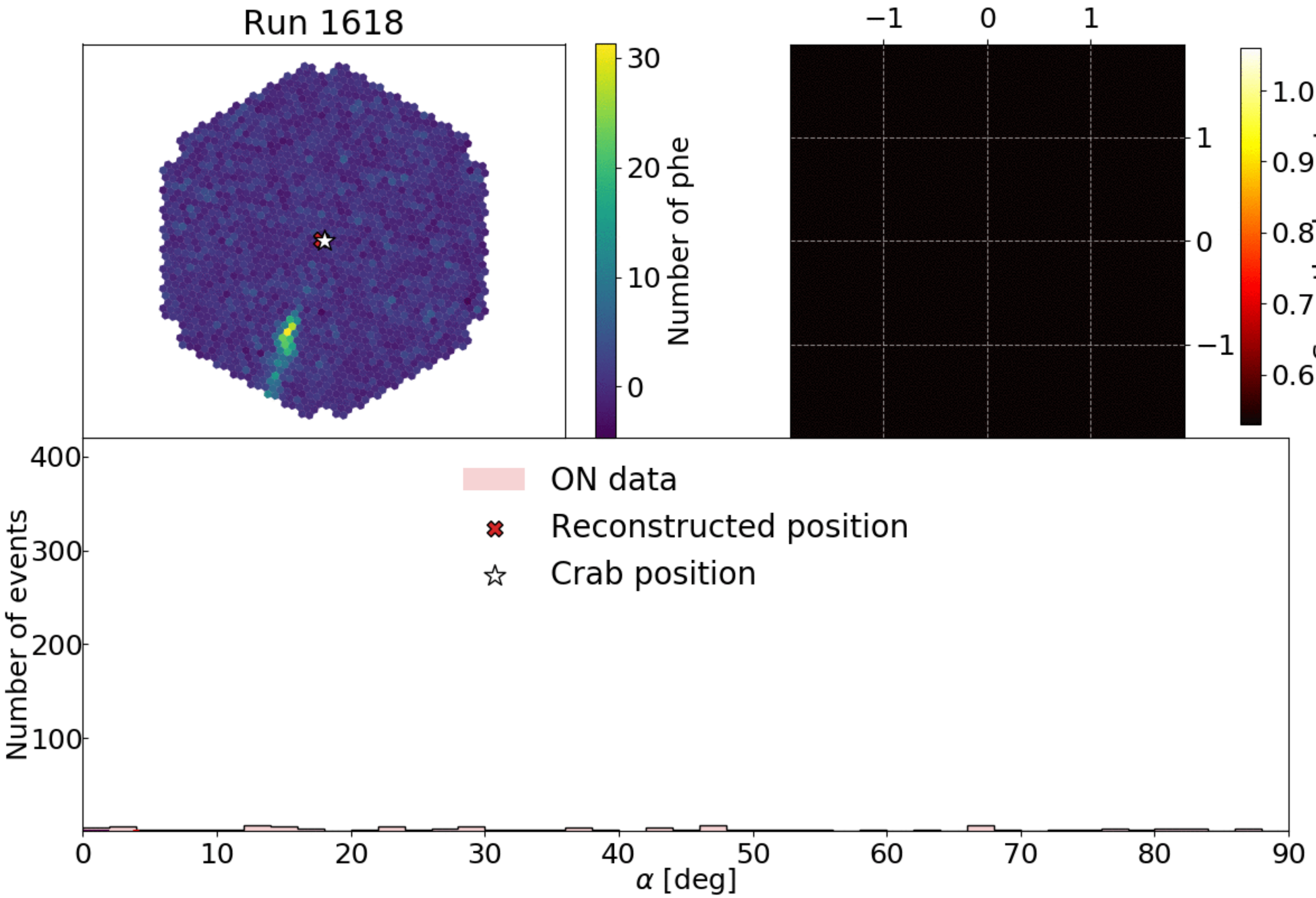


HESS, MAGIC, VERITAS, LHAASO

CTA Large telescope in Canary

Inaugurated in Oct. 2018

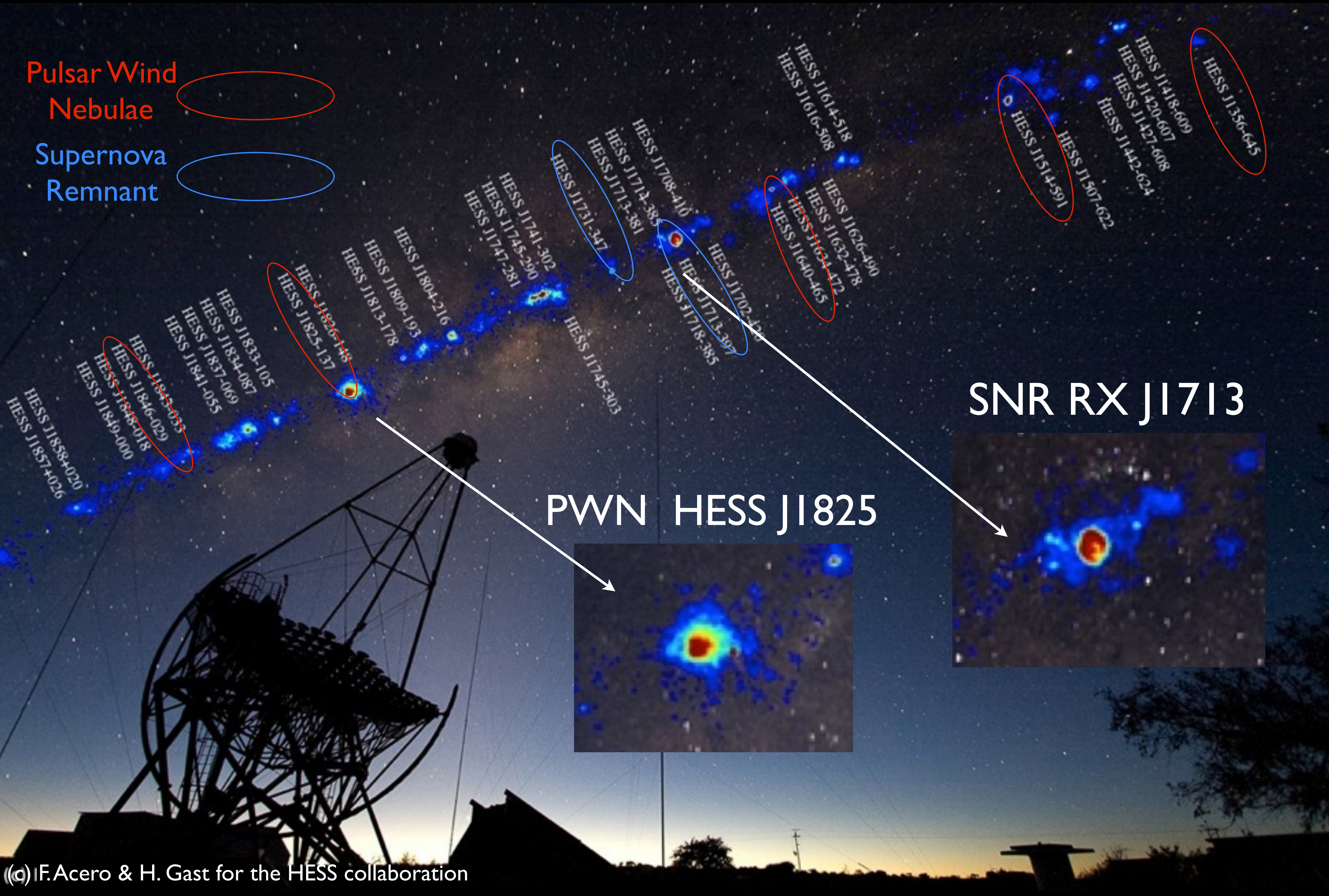
23m diameter mirror
100 Tons
Camera 2 Tons



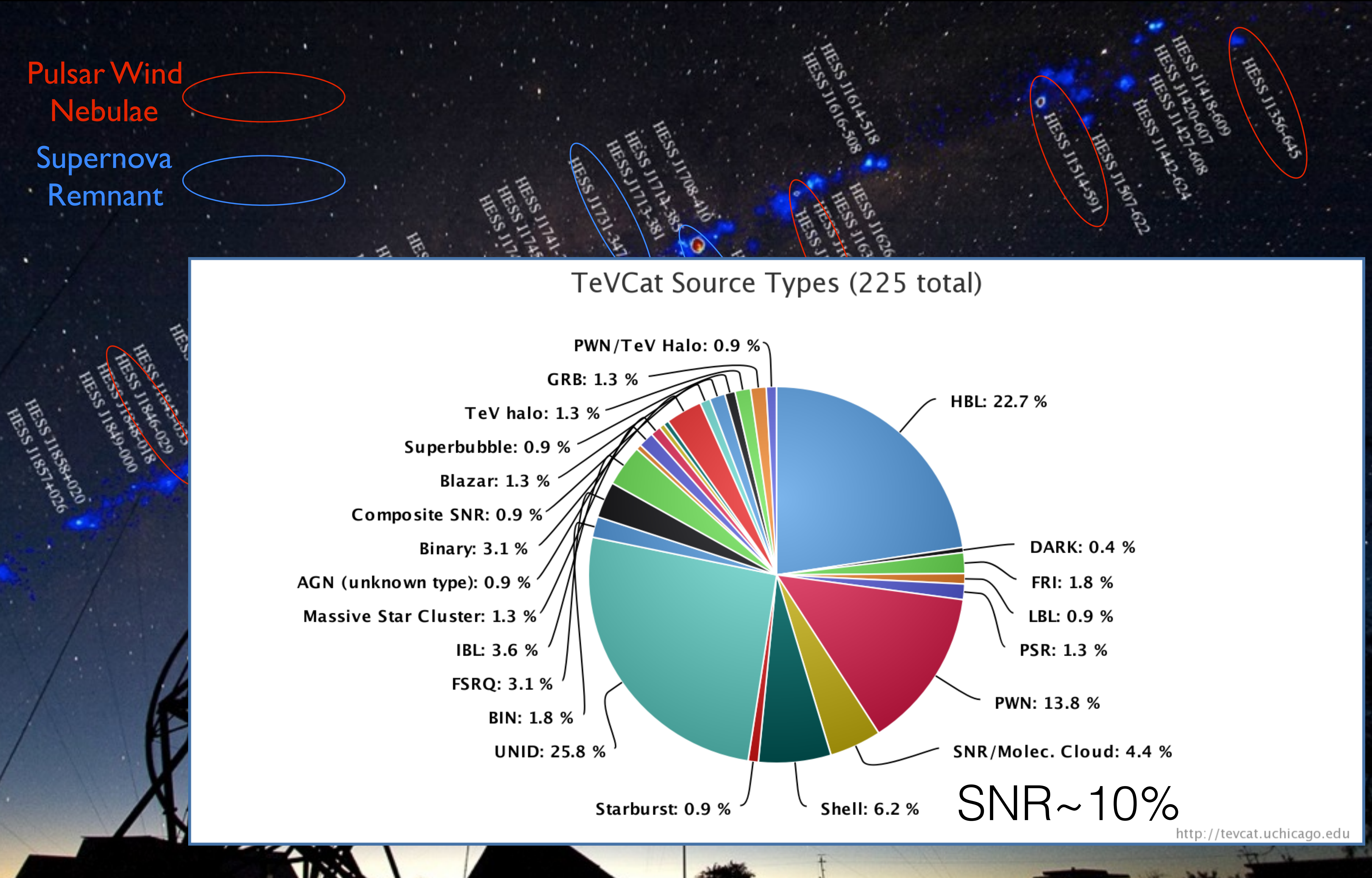
First gamma-rays, december 2019

What if we had (TeV) gamma-ray eyes

Galactic plane seen by HESS



Galactic plane seen by HESS

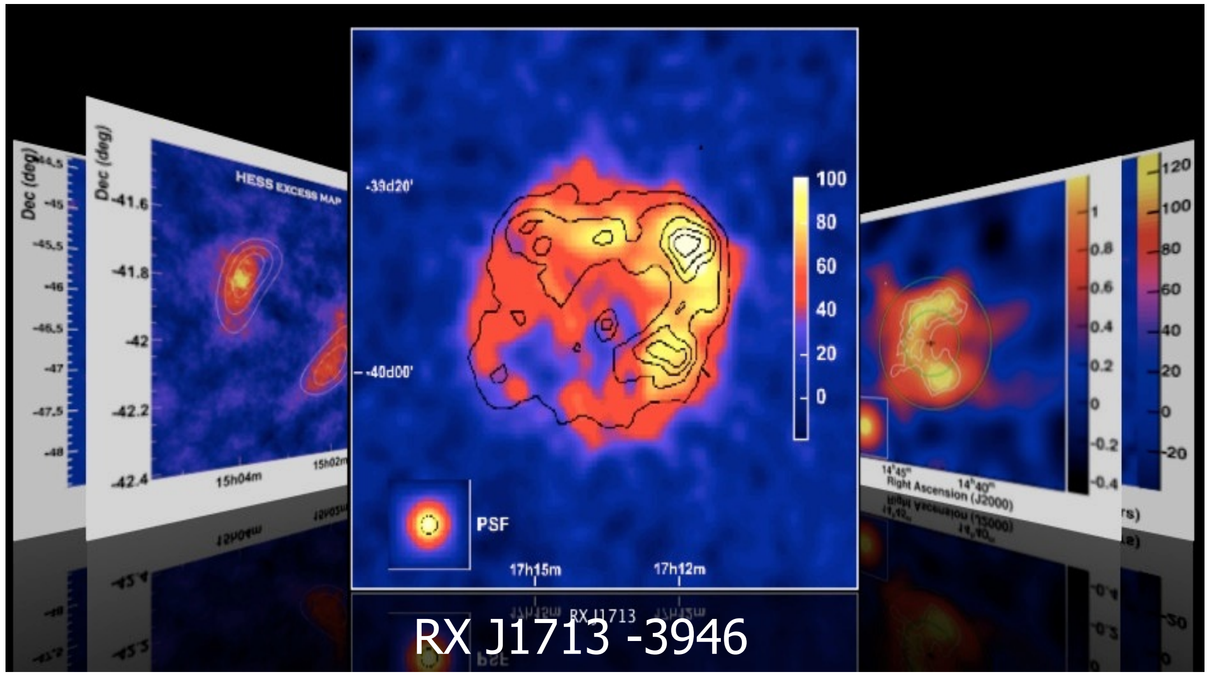


(c) F. Acero & H. Gast for the HESS collaboration

Two families of gamma-ray SNRs

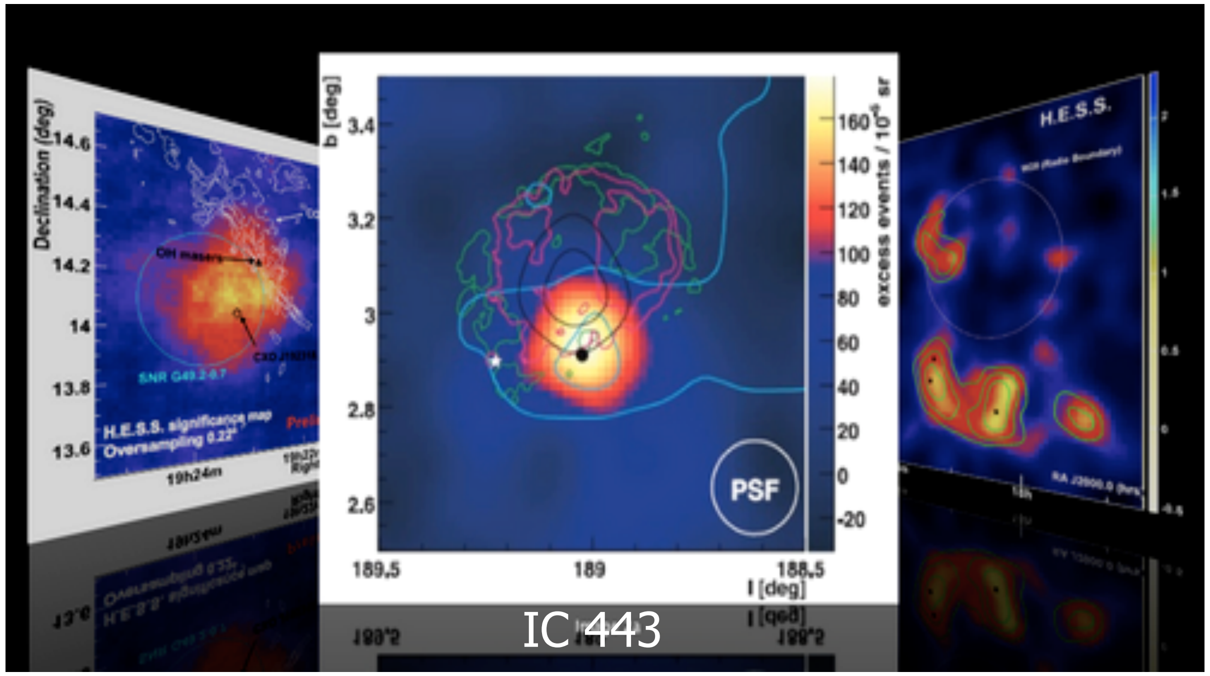
<u>Shell morphology</u>
young SNR ~ 1000 ans

Vela Jr, RX J1713-3946,
RCW 86, SN 1006, HESS J1731



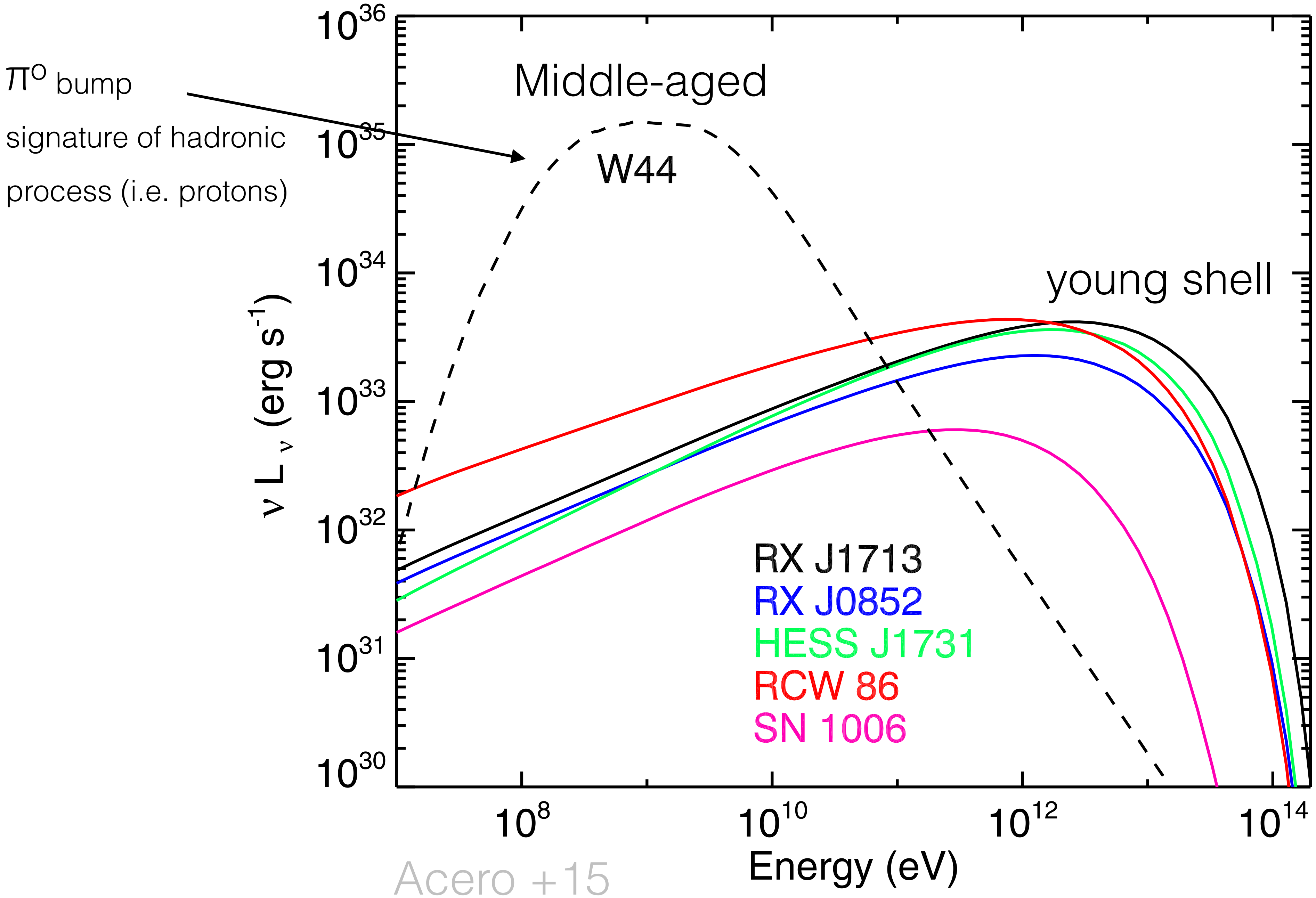
<u>Interacting SNR</u>
middle-aged t~10 kyrs

IC 443, W28, W51, etc

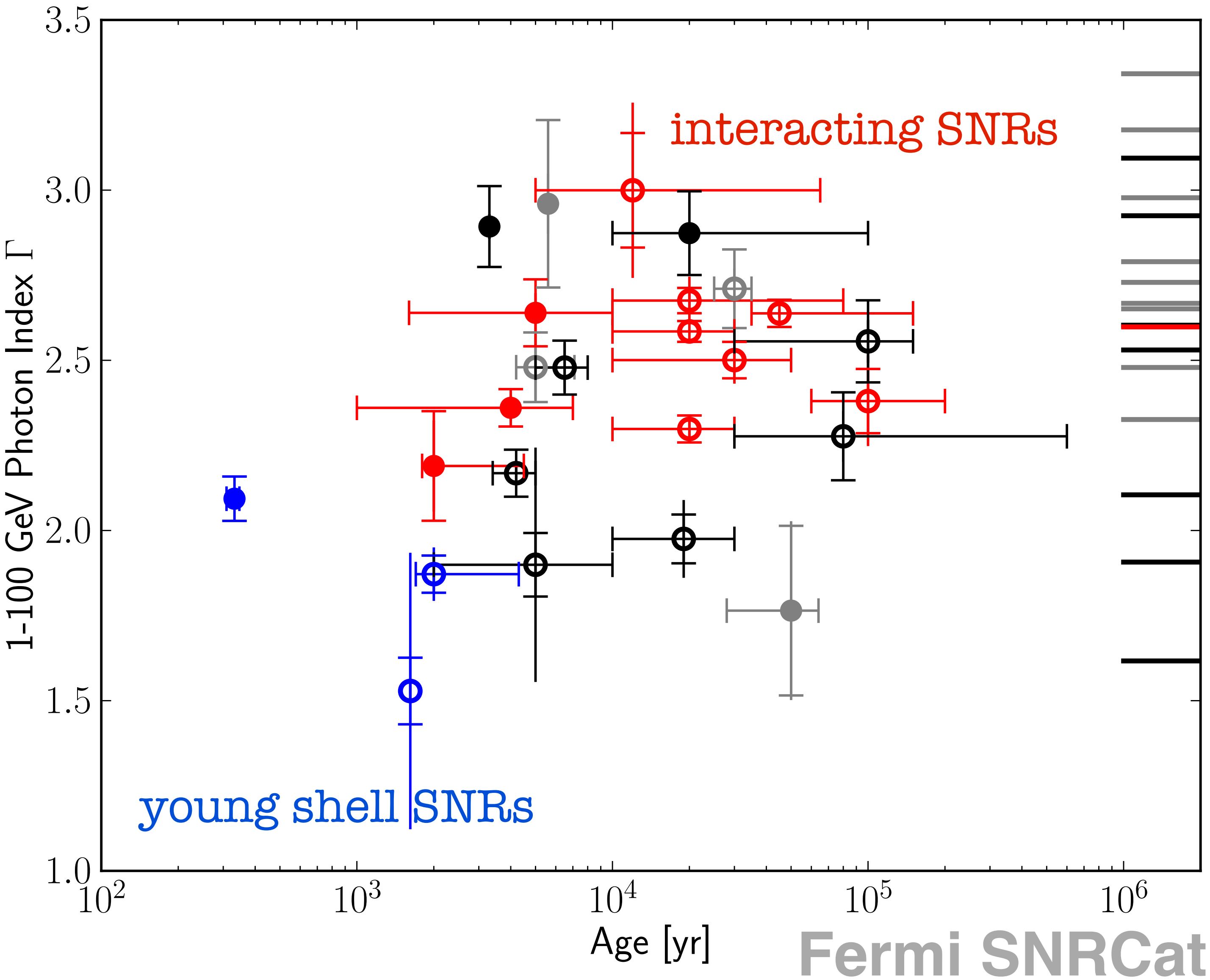


GeV/TeV populations

- **Middle-aged interacting GeV bright SNRs (hadronic emission)**
- **Young TeV bright shell SNRs**



Age - GeV index



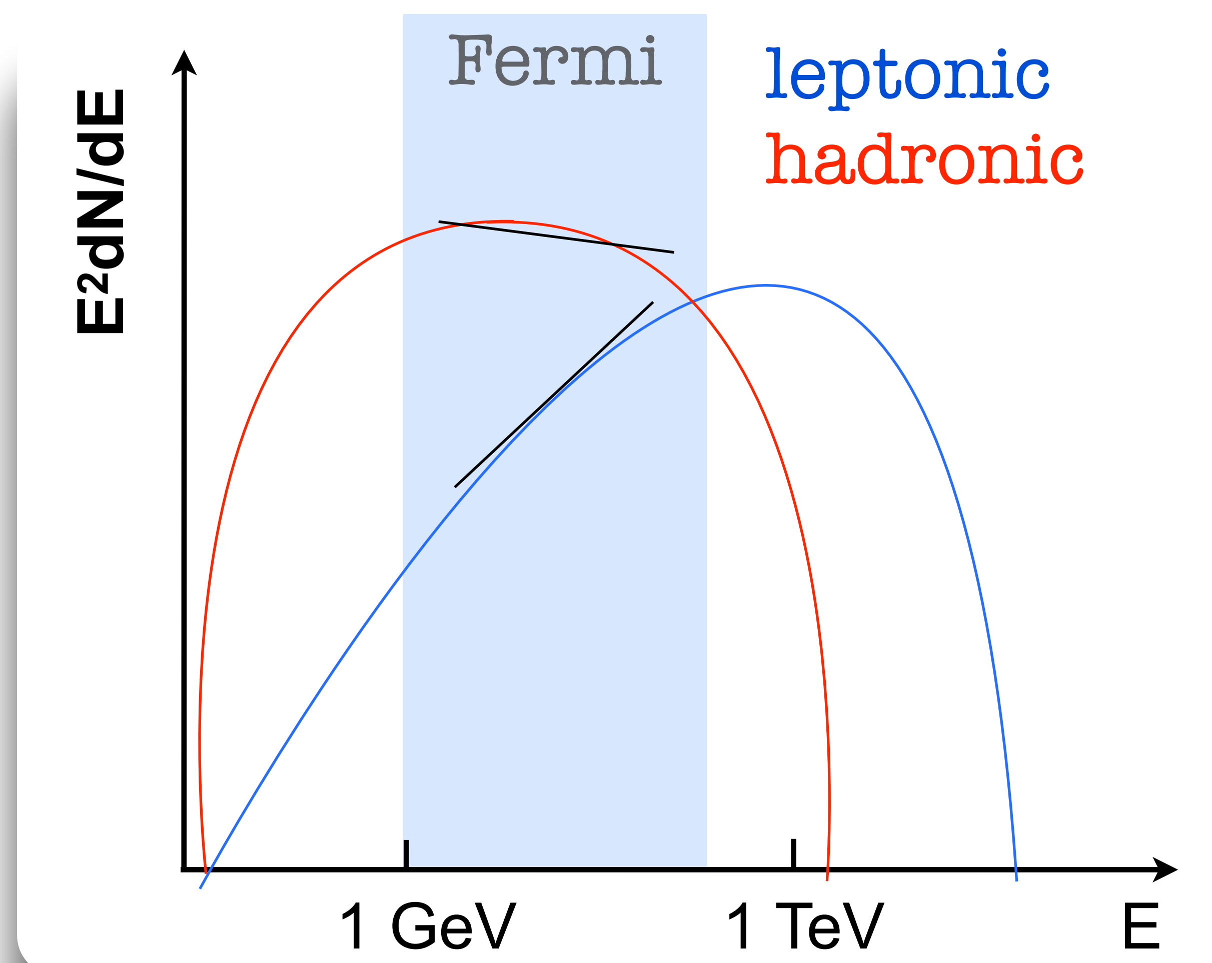
Fermi SNRCat Acero+16

Variety of spectral shapes
(see Paolo Lipari presentation)

Older SNRs appear to have softer indices than young SNRs. This could be due to:

-Change of dominant emission mechanism

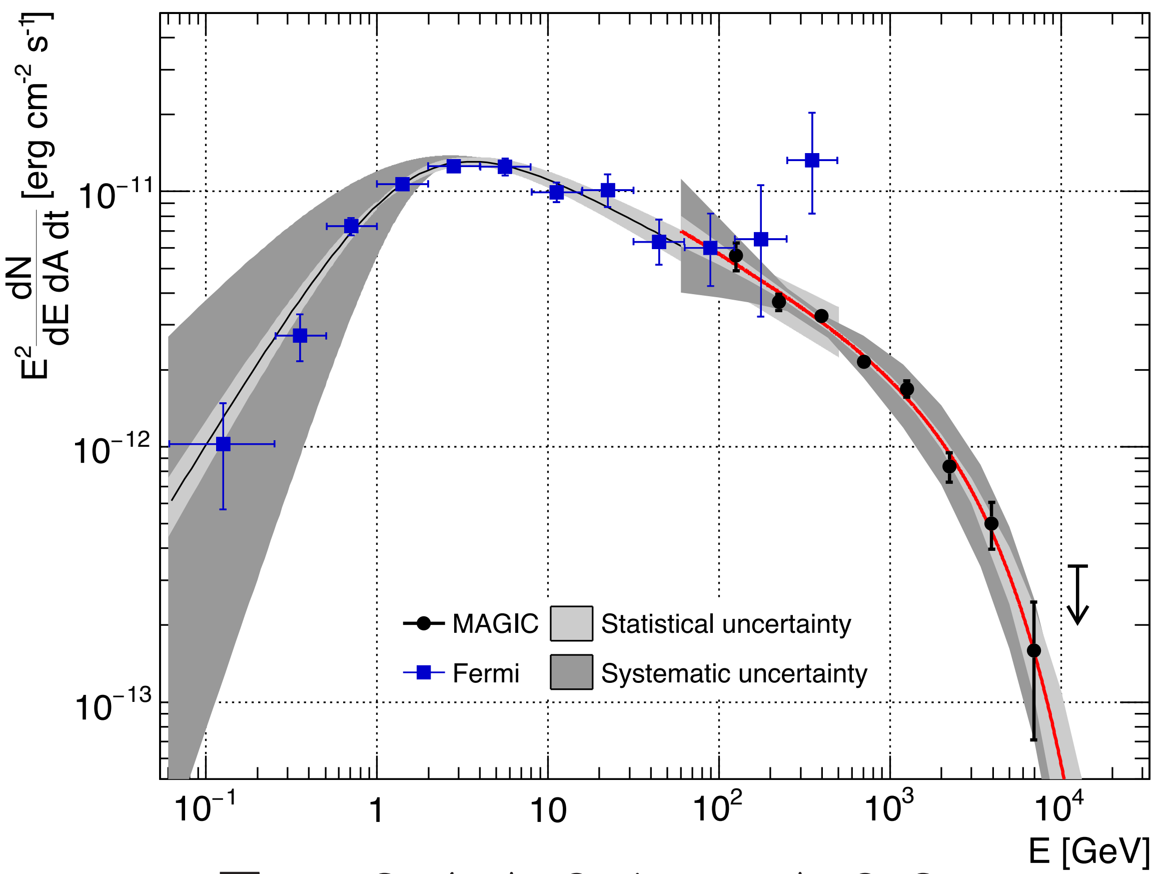
-Different zones properties



Young SNRs: Tycho & CasA

- **Youngest SNRs have a steep TeV index. Not the best PeVatrons. Why ?**

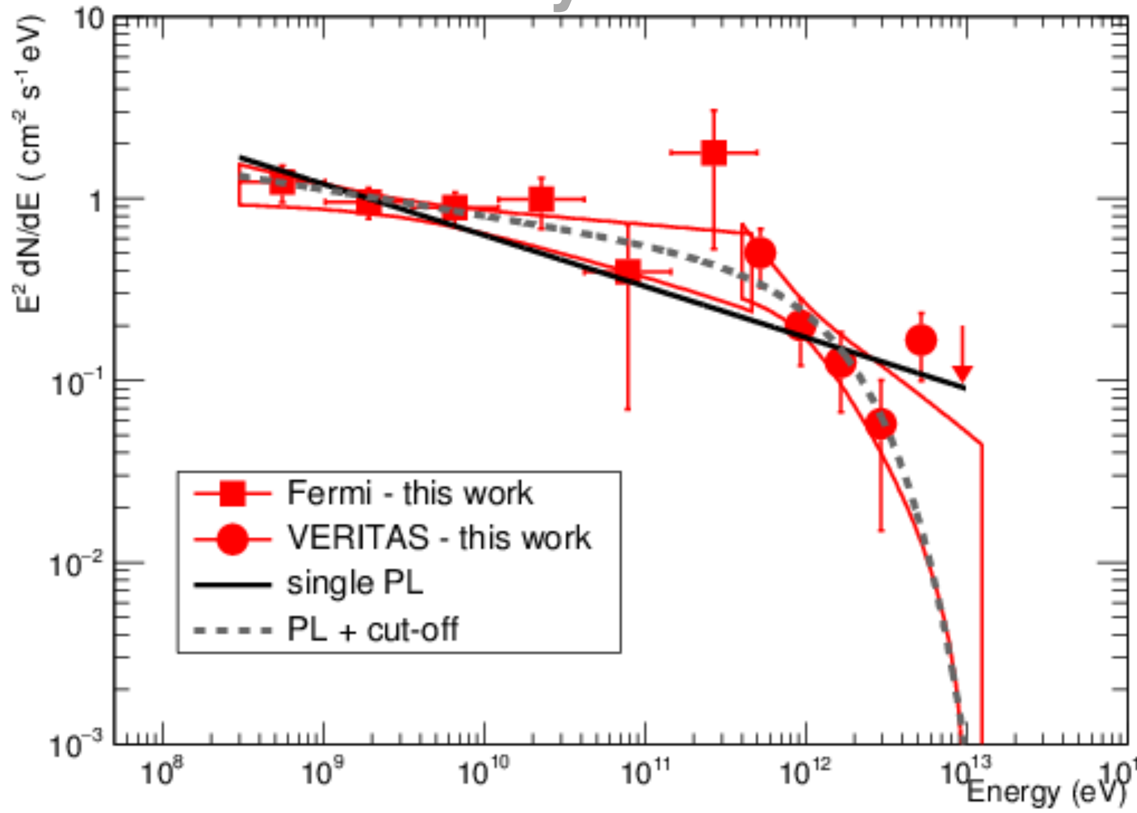
CasA: MAGIC+17



$$\Gamma = 2.4 \pm 0.1_{stat} \pm 0.2_{sys}$$

$$E_c = 3.5 \left(^{+1.6}_{-1.0}\right)_{stat} \left(^{+0.8}_{-0.9}\right)_{sys} \text{ TeV}$$

Tycho: Veritas+17



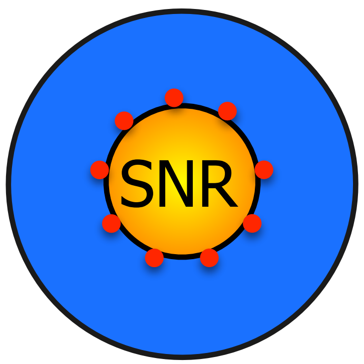
$$\Gamma_{TeV} = 2.92 \pm 0.42_{stat} \pm 0.20_{syst}$$

- **Particle spectral index is not 2.0 !**
- **Emission dominated by shock interacting with a massive clump ?**
- **High density and high speed are not easily compatible**

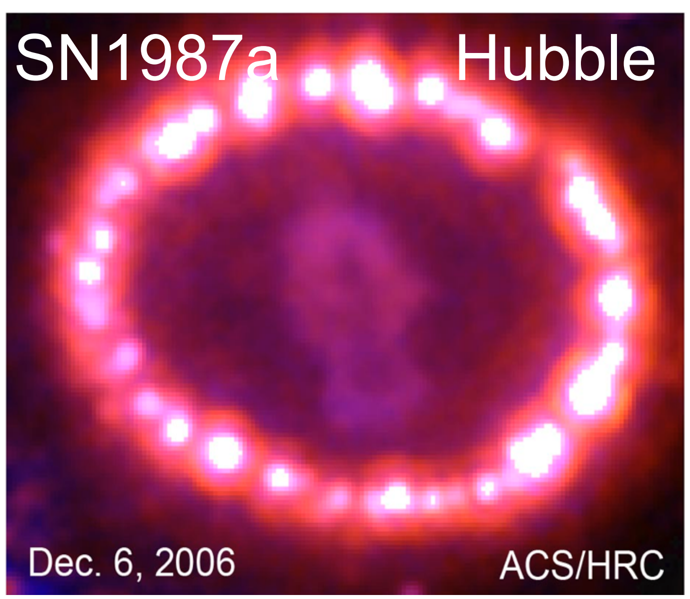
Emerging picture: age & environment effects

- **Time evolution of gamma-ray emission from SNRs**

T<100 yrs

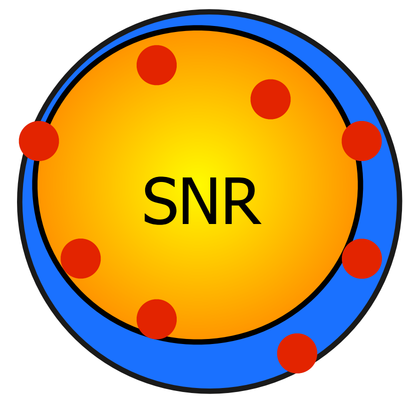


Circumstellar medium

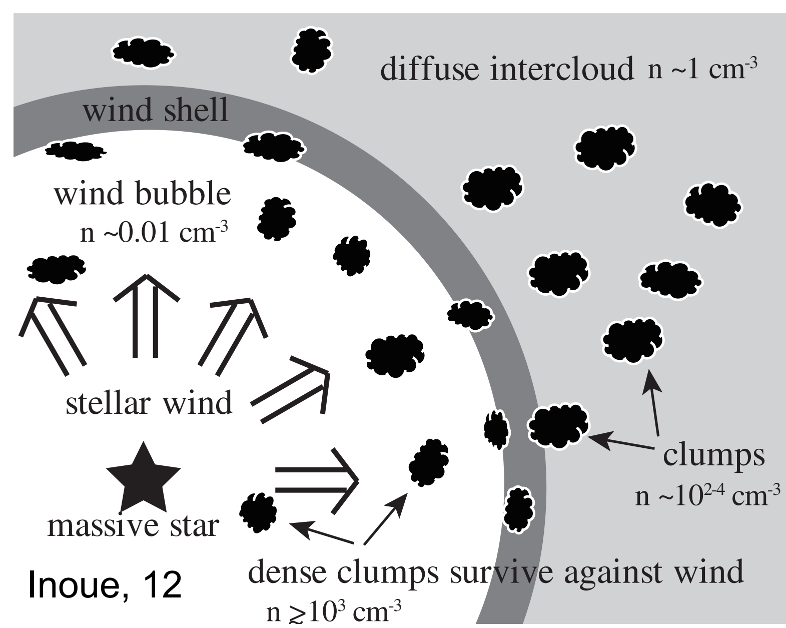


High density
Possible hadronic γ-ray
Leptonic γ-ray

T ~ few kyrs



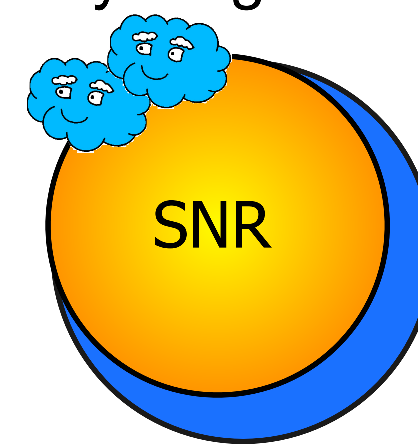
Low density cavity+clumps



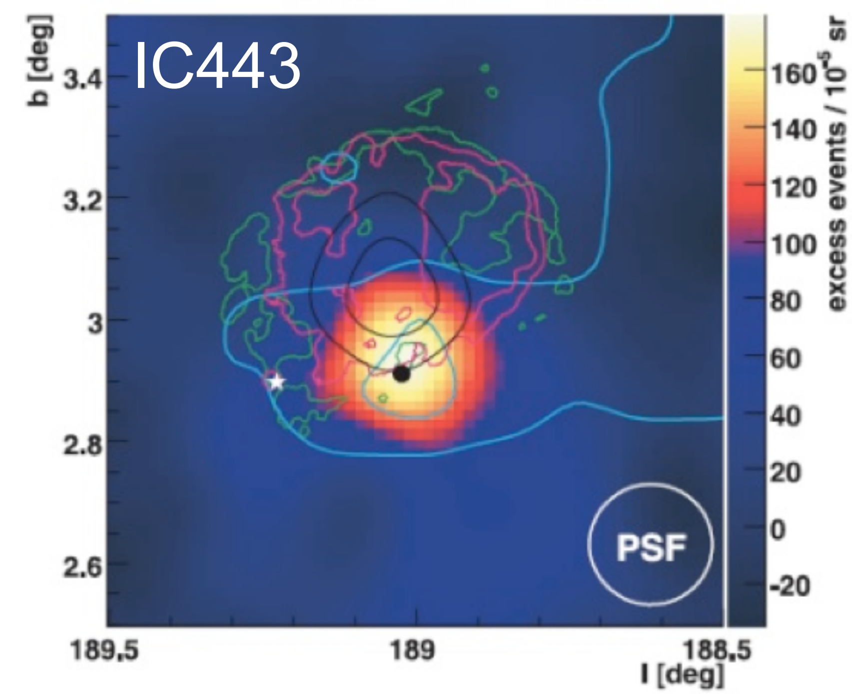
Inoue, 12

Leptonic γ-ray
+hadronic from clumps

T ~ few 10 kyrs
or younger if Tycho/CasA



Cavity border + clouds

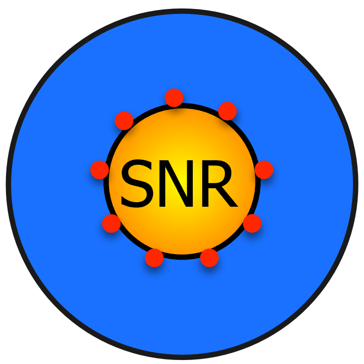


Hadronic from shock-cloud interaction
(no X/γ leptonic emission)

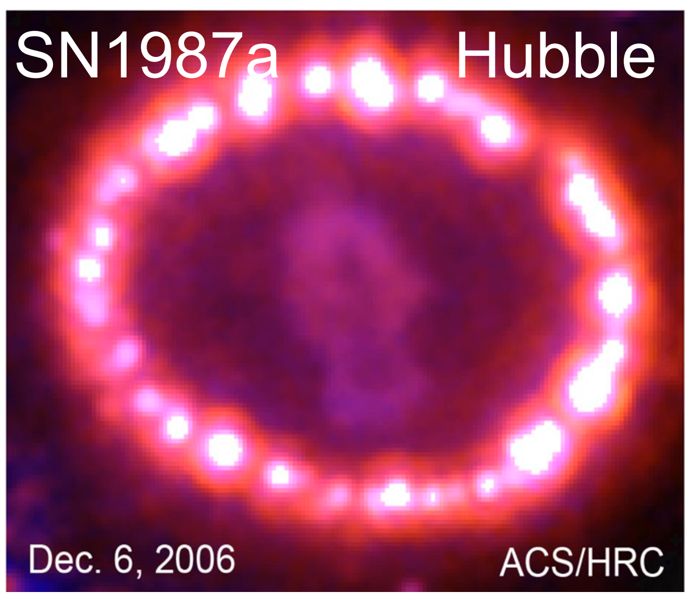
Emerging picture: age & environment effects

- **Time evolution of gamma-ray emission from SNRs**

T<100 yrs

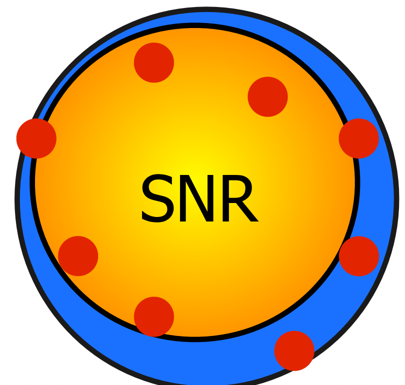


Circumstellar medium

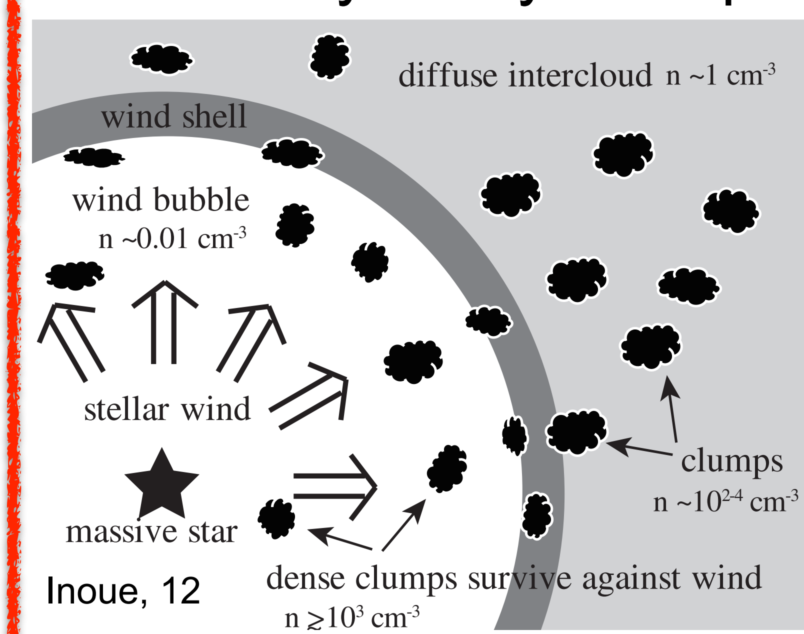


High density
Possible hadronic γ-ray
Leptonic γ-ray

T ~ few kyrs

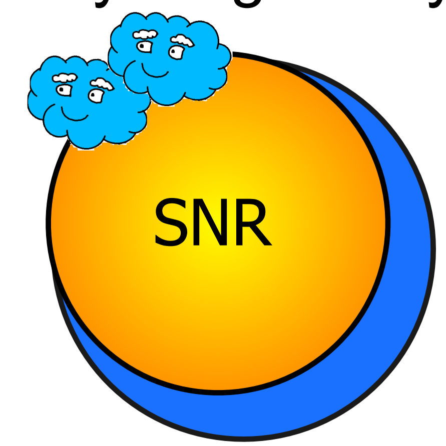


Low density cavity+clumps

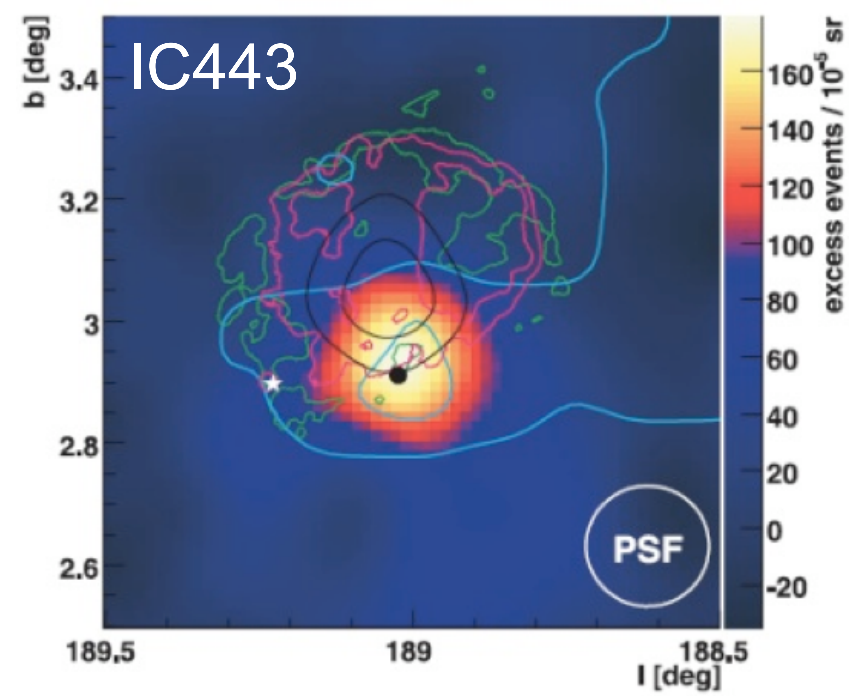


Leptonic γ-ray
+hadronic from clumps

T ~ few 10 kyrs
or younger if Tycho/CasA

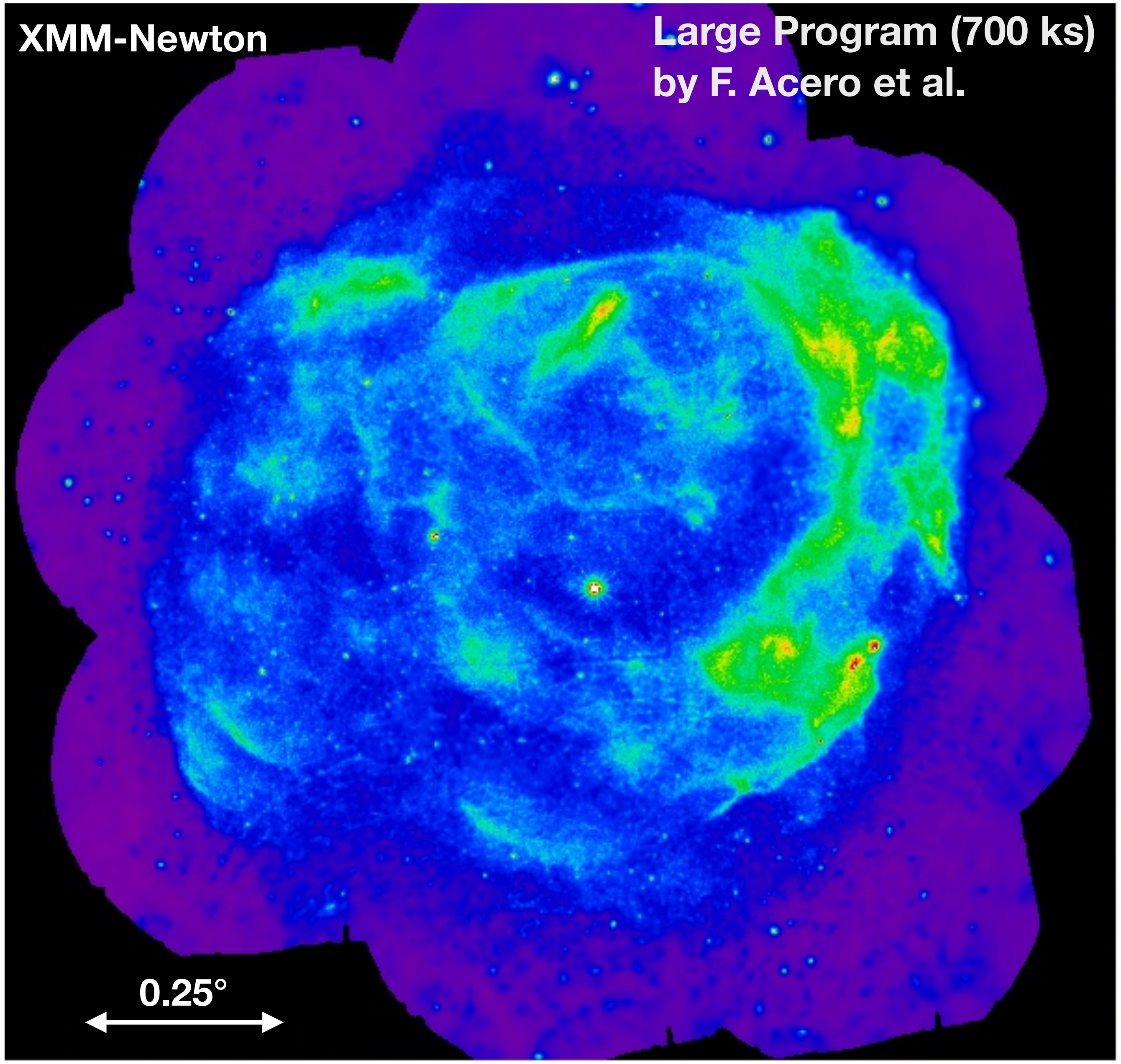


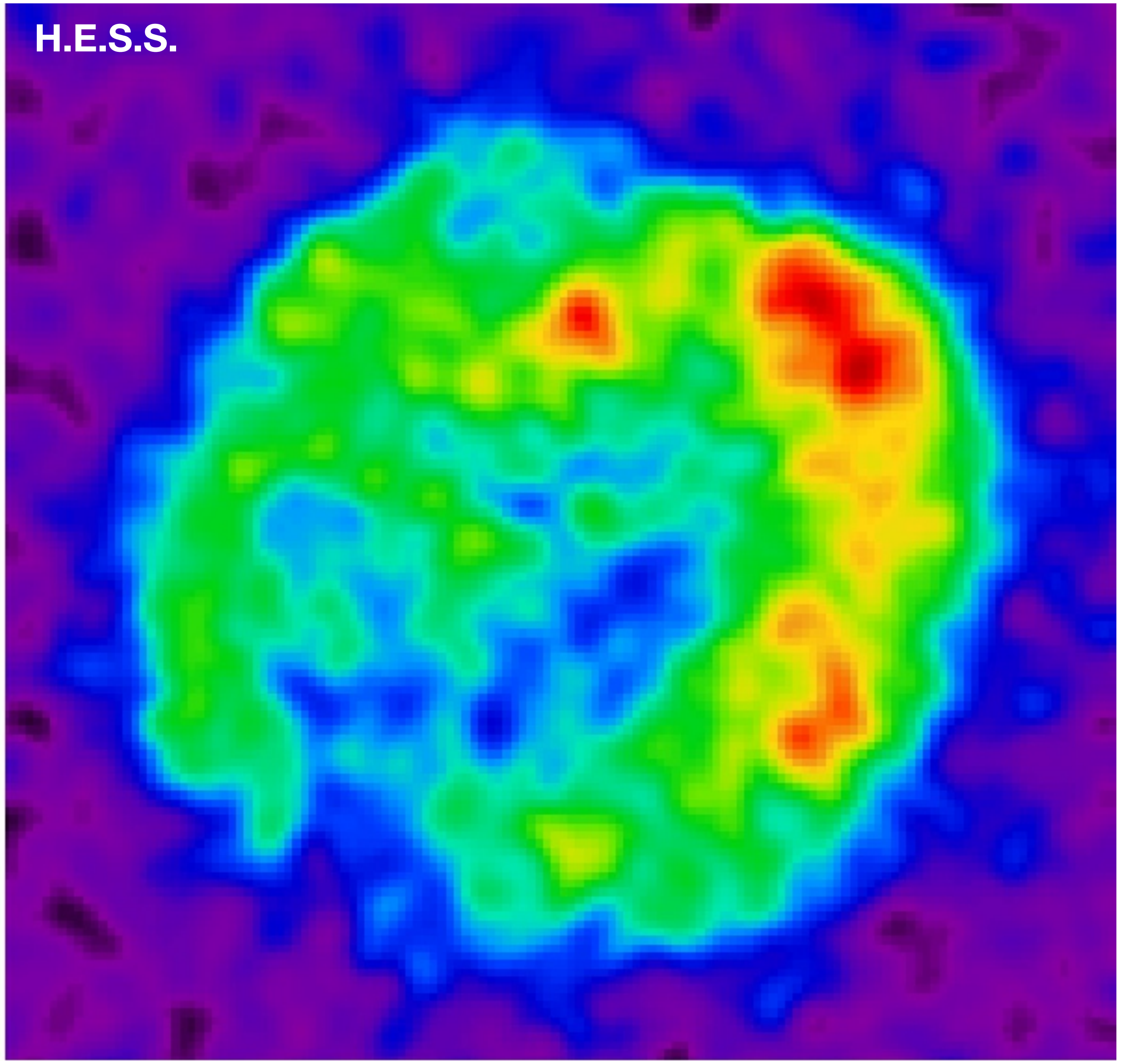
Cavity border + clouds



Hadronic from shock-cloud interaction
(no X/γ leptonic emission)

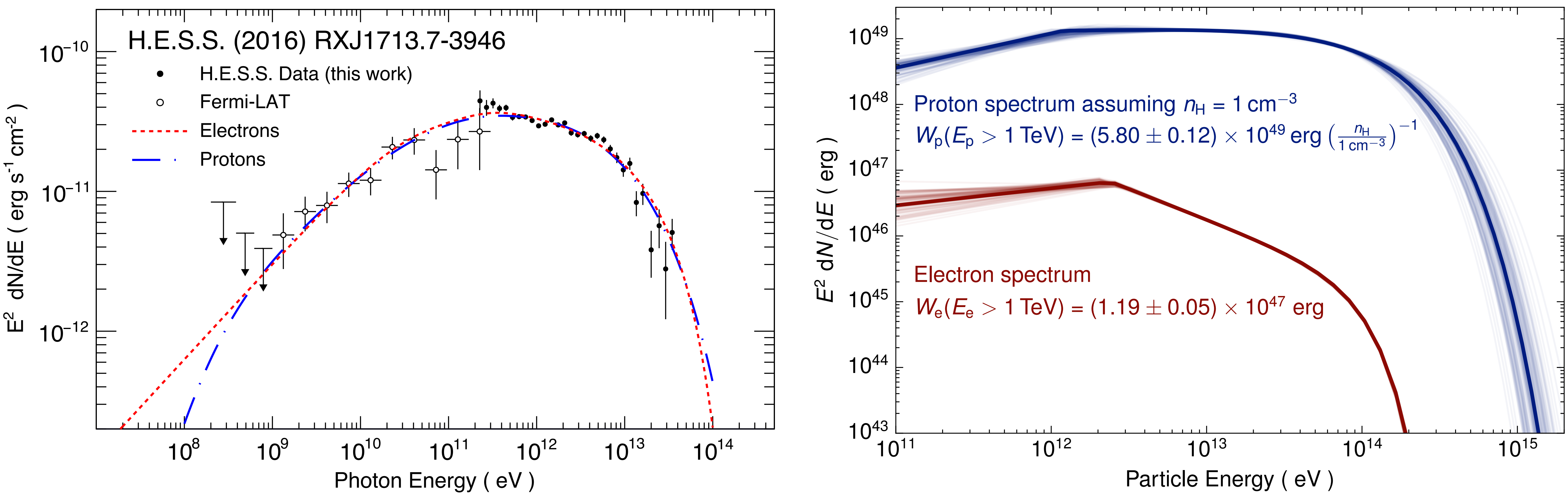
SNR RX J1713-3946





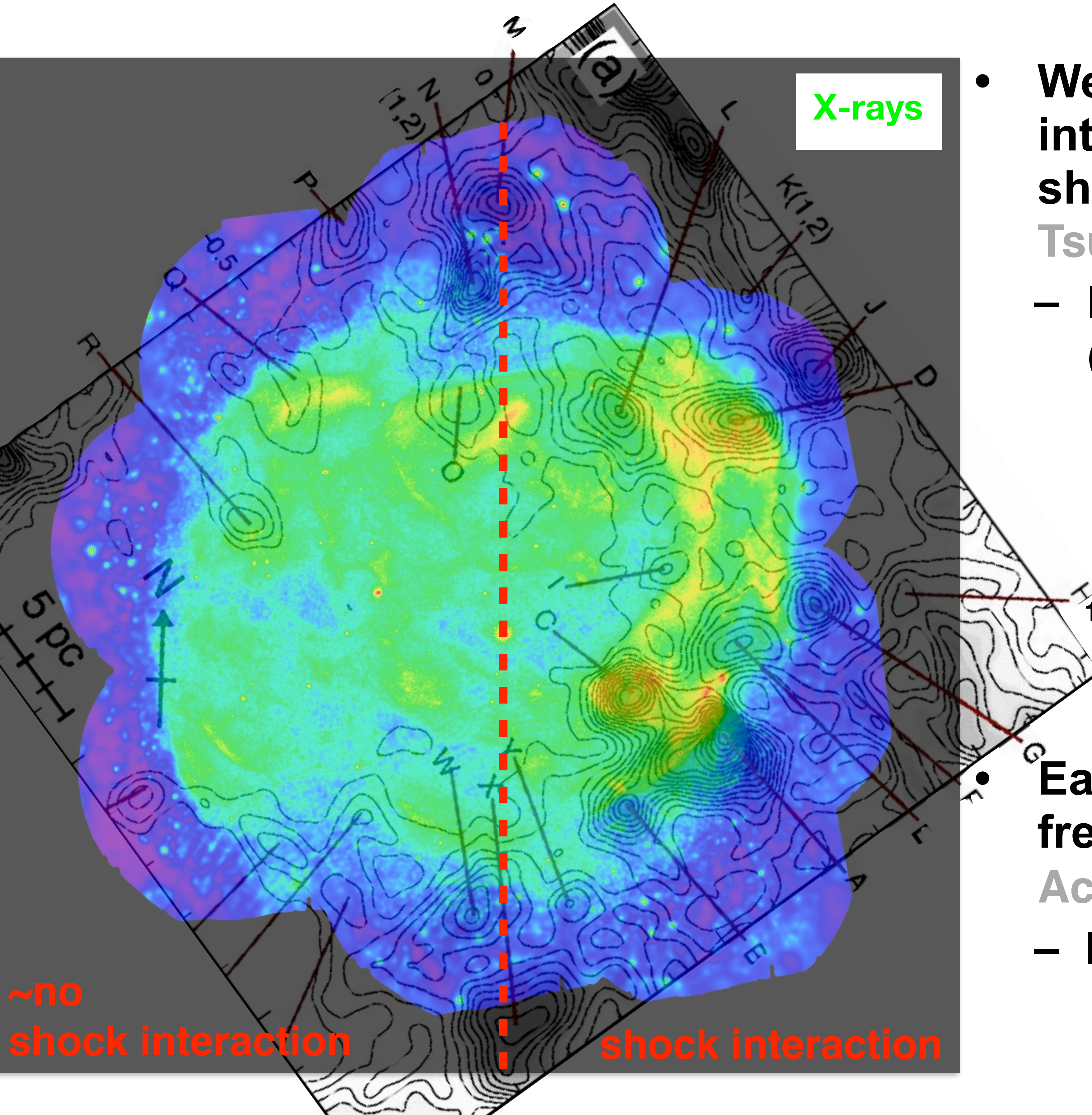
- Core Collapse supernova. Age ~ 1600 yrs (Historical SN 393). d ~ 1kpc
- Young SNR with fast shock ~3500 km/s
- X-ray emission is synchrotron dominated
- Brightest TeV SNR

γ-ray emission : leptonic or hadronic ?



- **Both models need Broken Power-Law spectra**
- **Broad Leptonic peak: several e$^-$ population, time evolution (cooling)**
  (Fink & Dermer 2012, Lee 2012)
- **Hadronic: one zone proton model Γ=2 doesn't work**
  —> proton interacting with small clumps
  (Gabici & Aharonian 2014, following Zirakashvili & Aharonian 2010 and Inoue 2012, Inoue 2019, Celli 2019)

Reality : mix of leptonic+hadronic ?

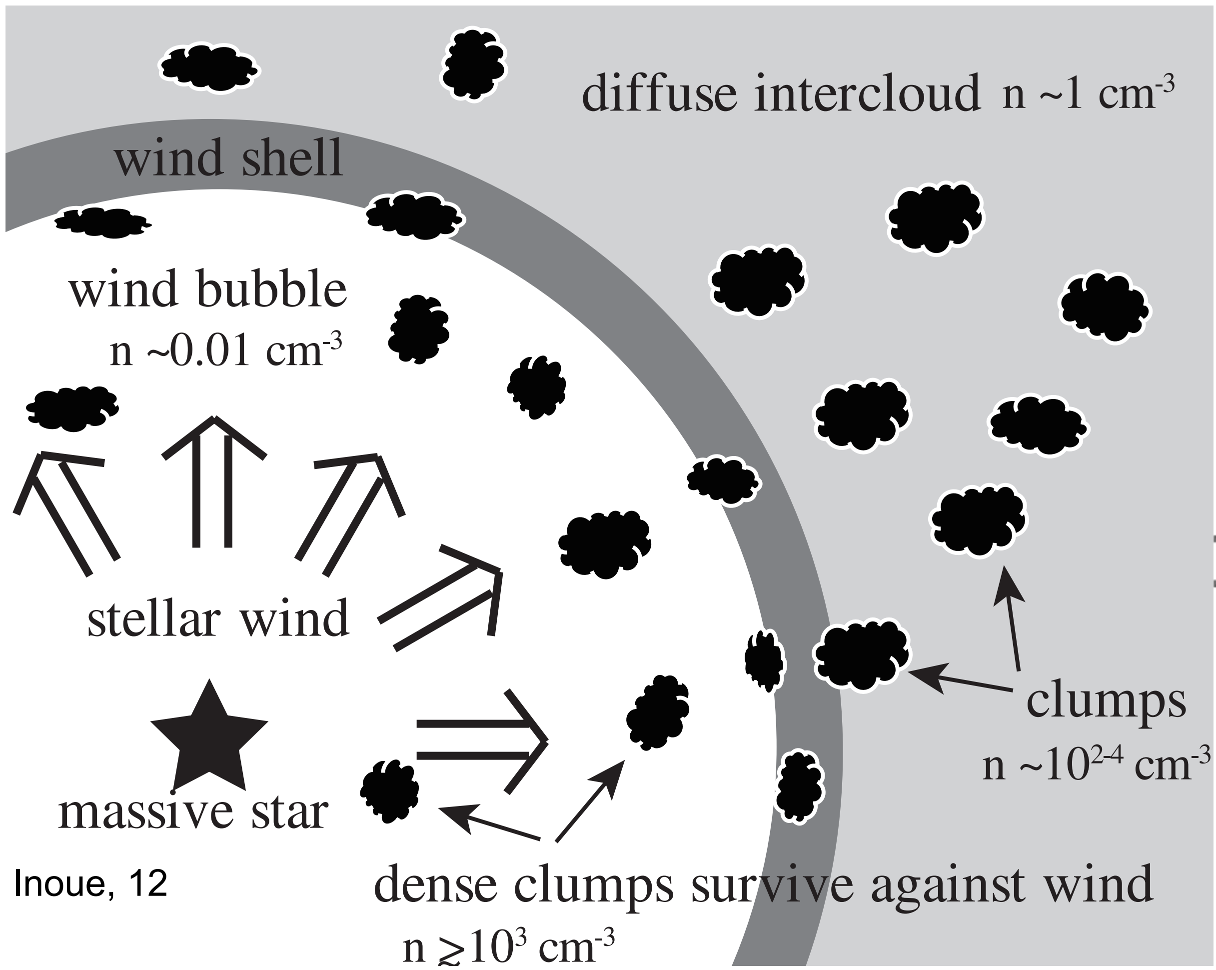


^{12}CO

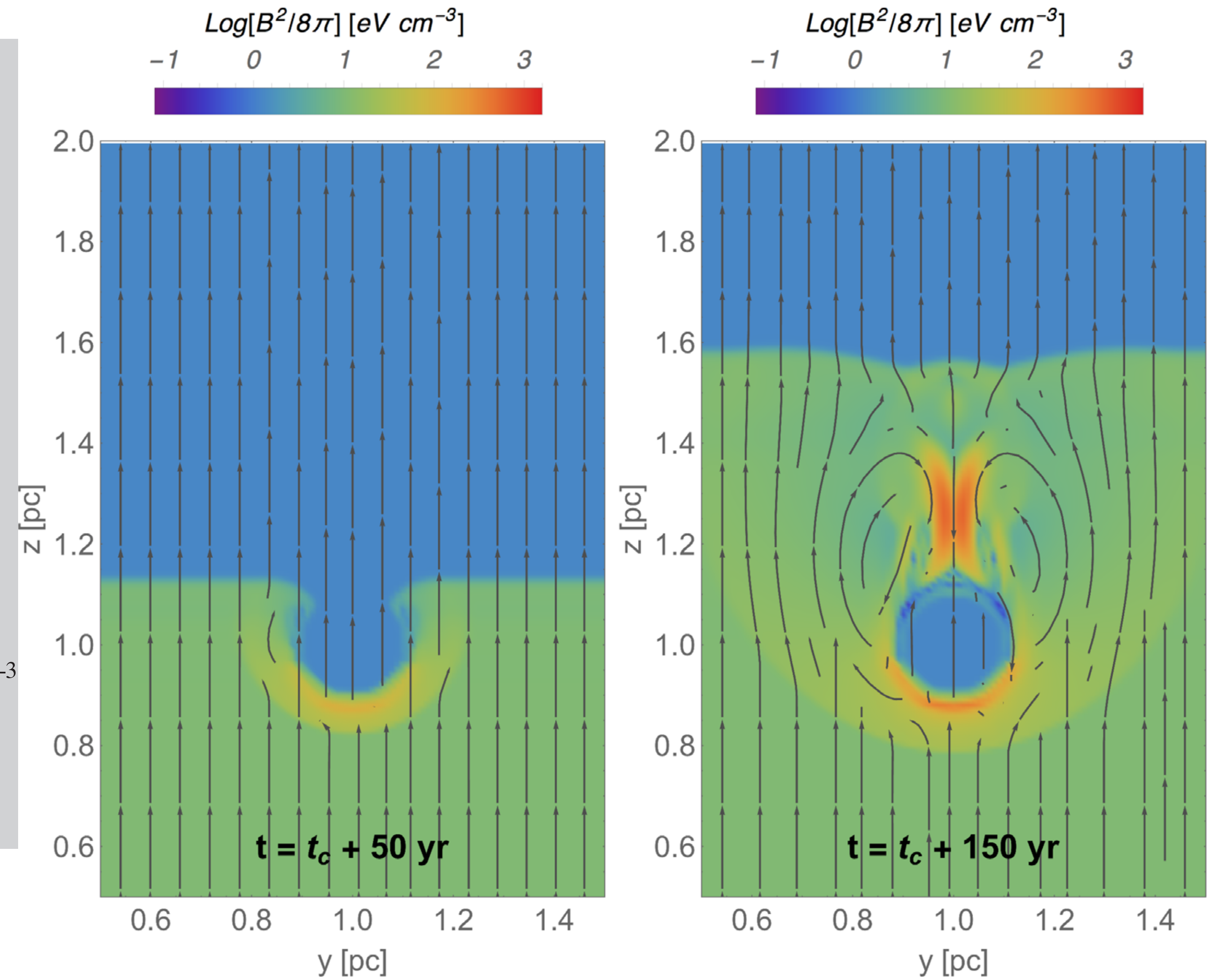
- **Western region has more interacting material slower shock speed (800-3900 km/s)** Tsuji+16
  - **IC (fast shock) + hadronic (clumps)**
- **Eastern region: shock mostly freely expanding (3500 km/s)** Acero+17
  - **IC dominated**

Shock evolving in wind blown cavity

- **Progenitor star blows a bubble leaving cavity with some clumplets**



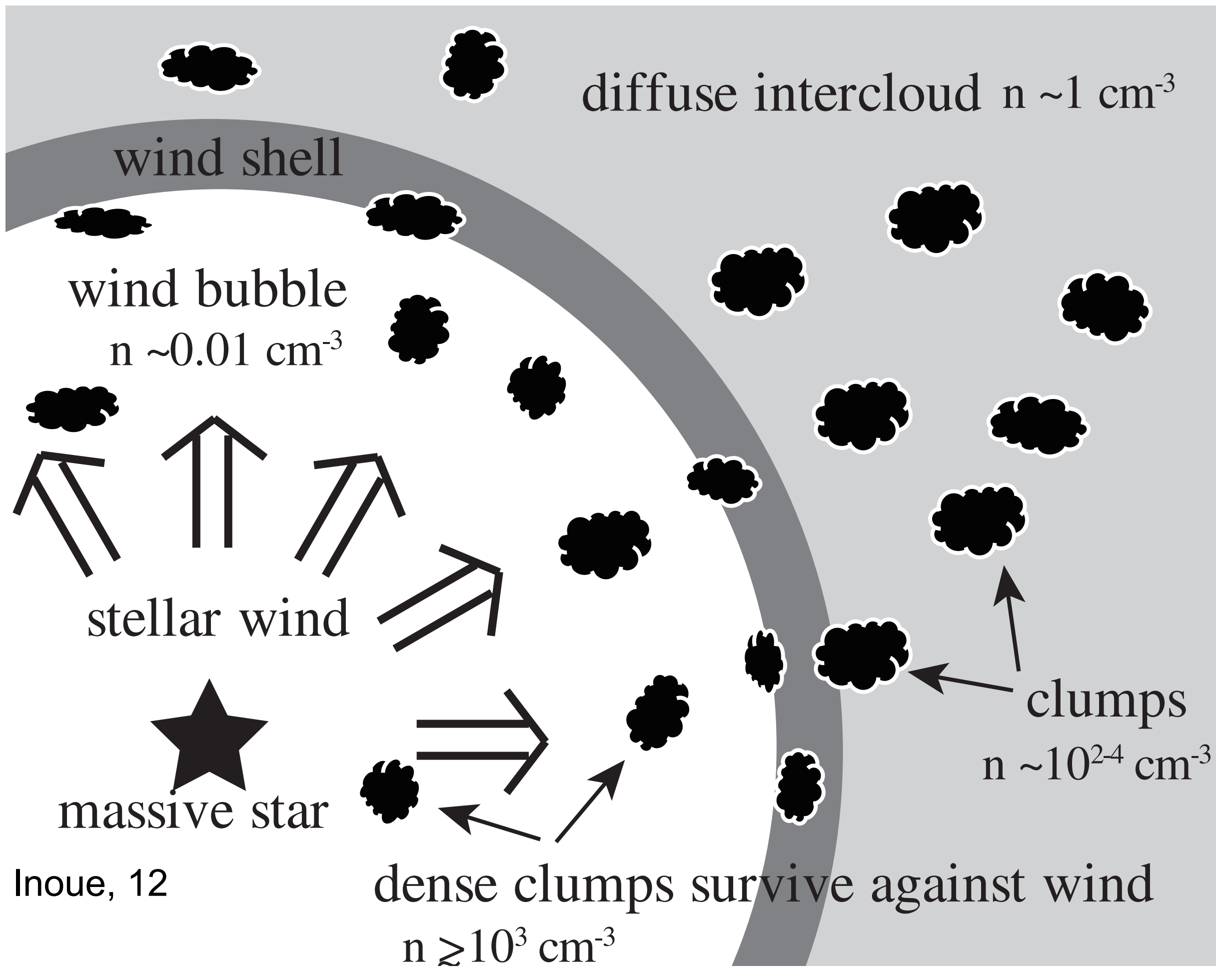
Inoue, 12

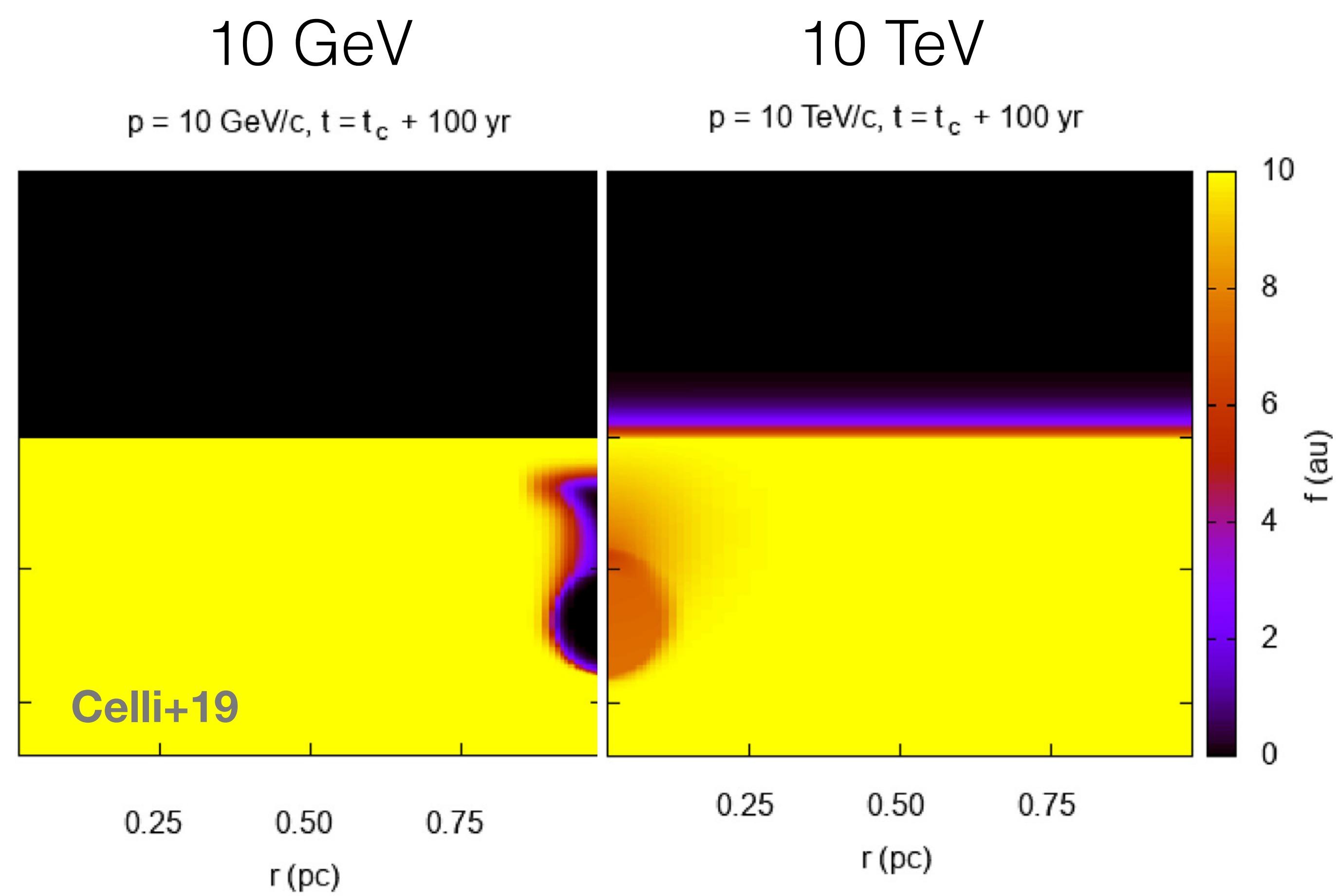


Celli+19

Shock evolving in wind blown cavity

- **Progenitor star blows a bubble leaving cavity with some clumps**



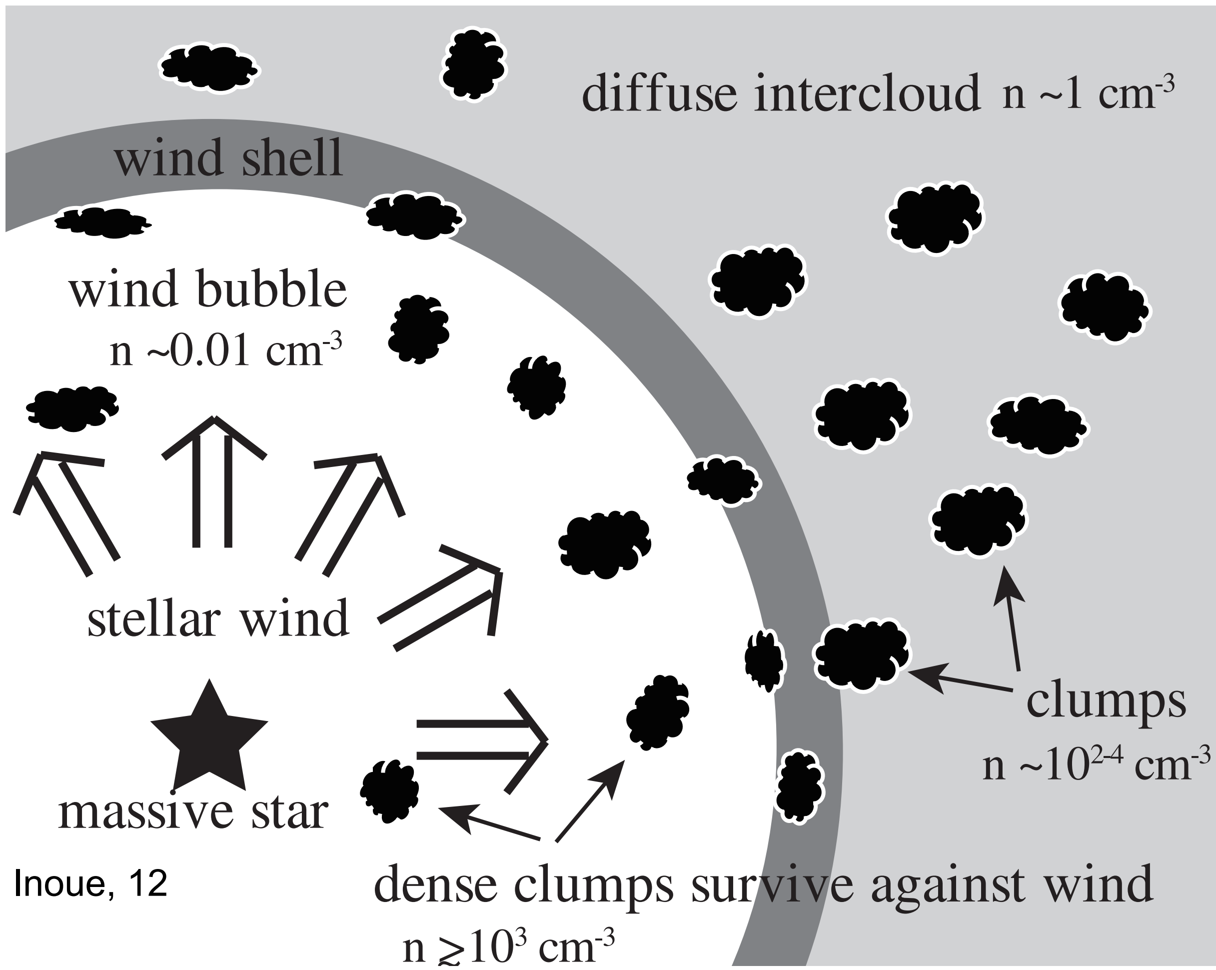


low energy protons do not penetrate

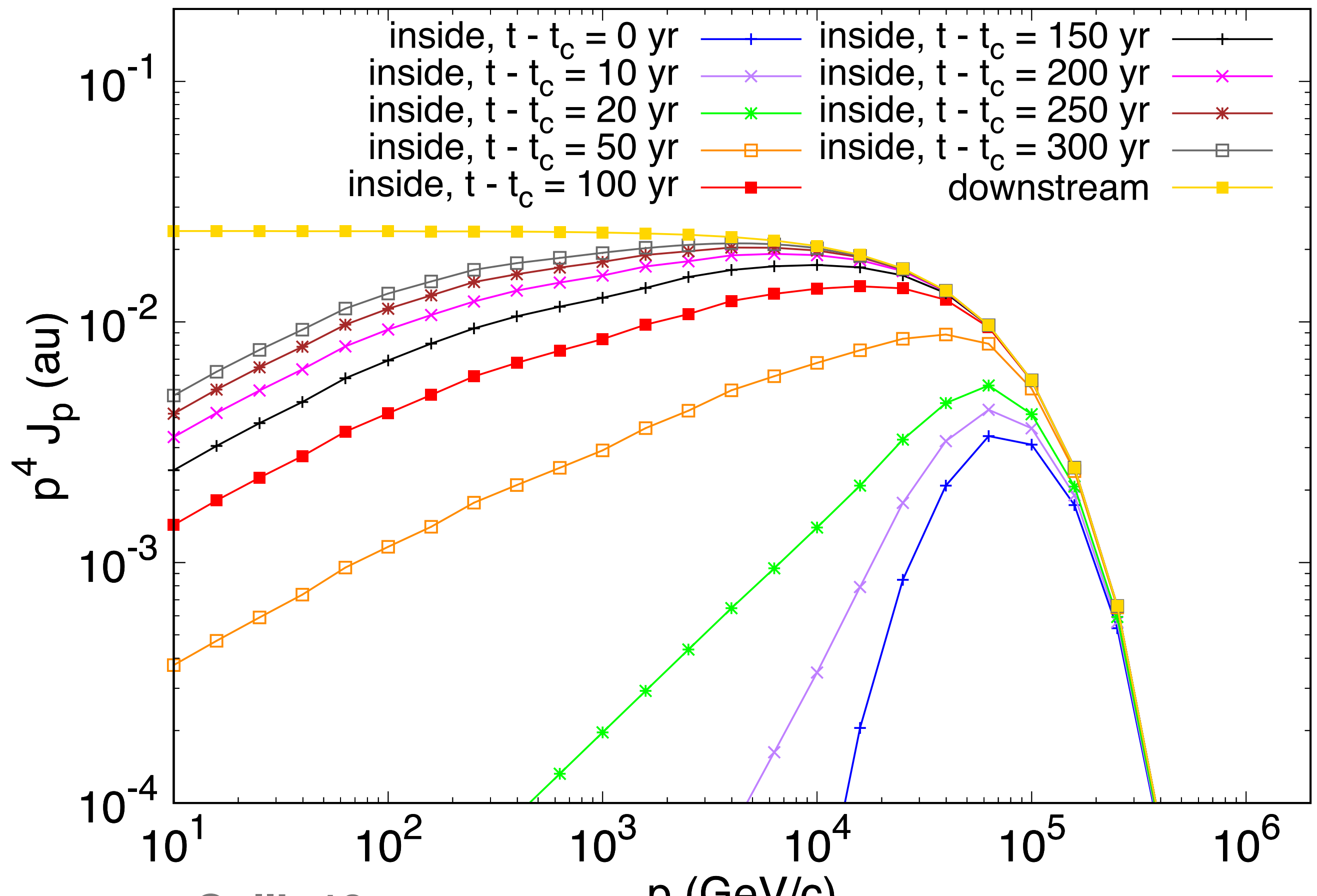
high energy protons penetrate the clump

Shock evolving in wind blown cavity

- **Progenitor star blows a bubble leaving cavity with some clumplets**



Inoue, 12



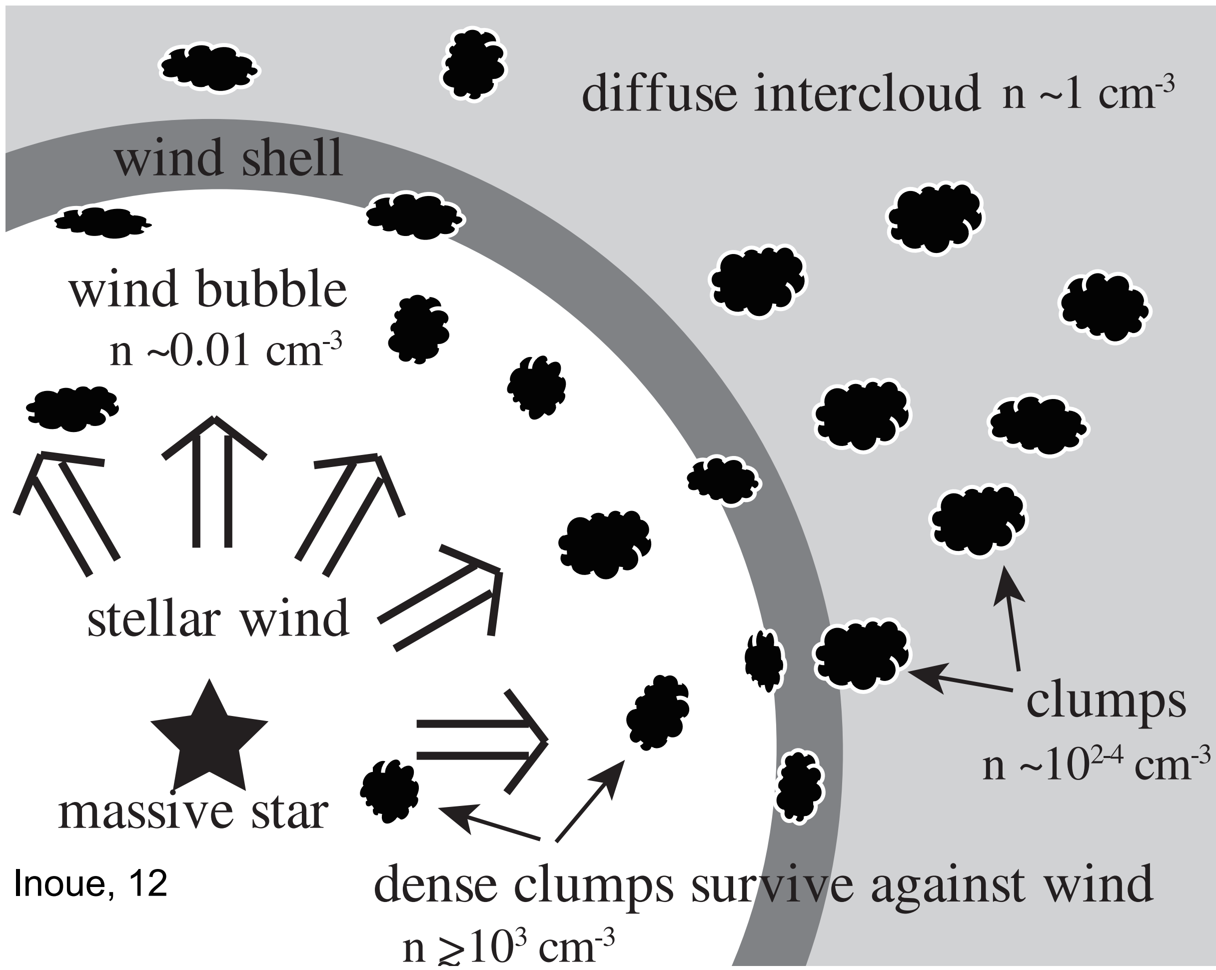
Celli+19

Low E particles
penetrate less
encounter lower density

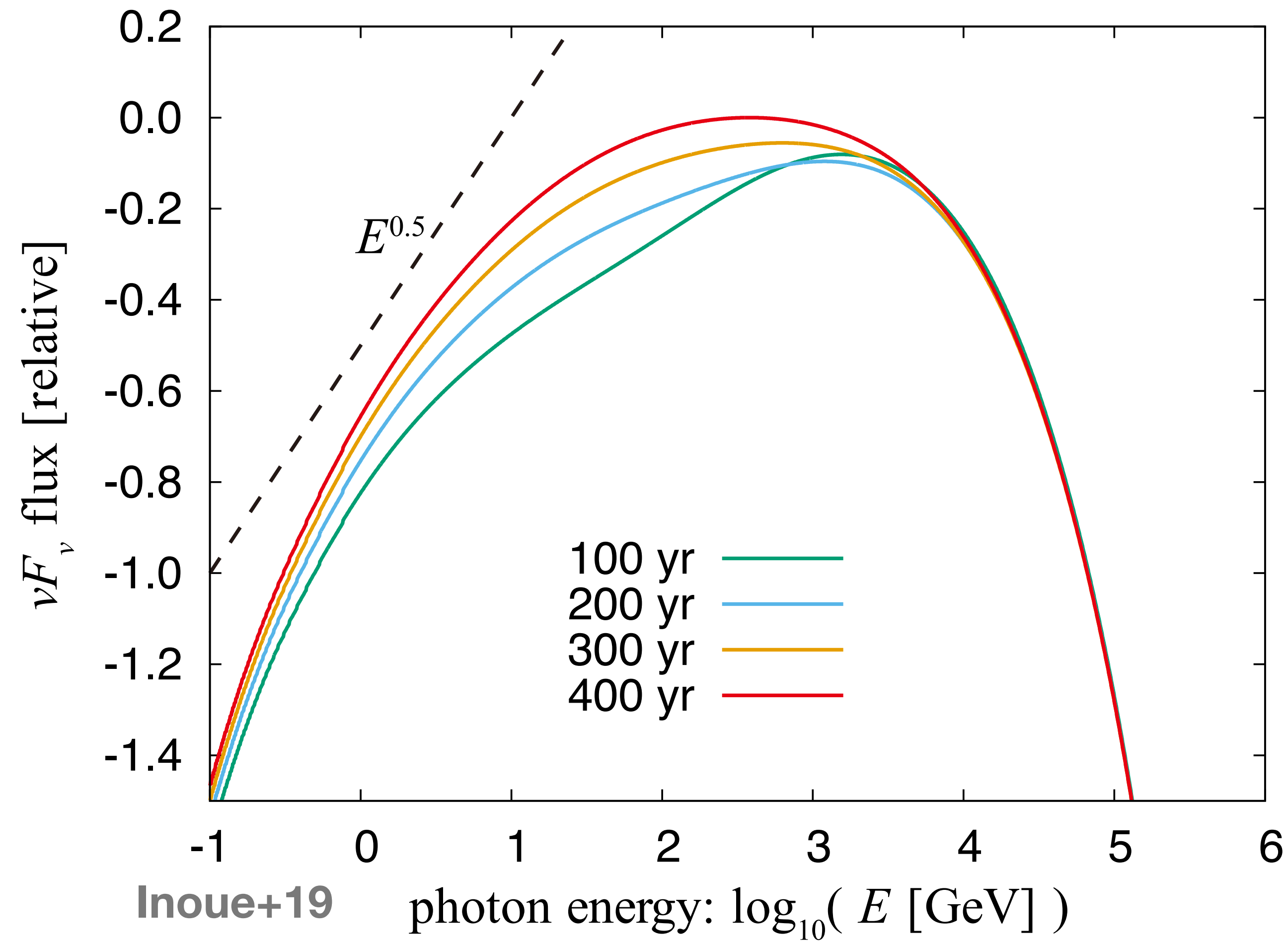
High E particles
penetrate first
encounter higher density

Shock evolving in wind blown cavity

- **Progenitor star blows a bubble leaving cavity with some clumplets**

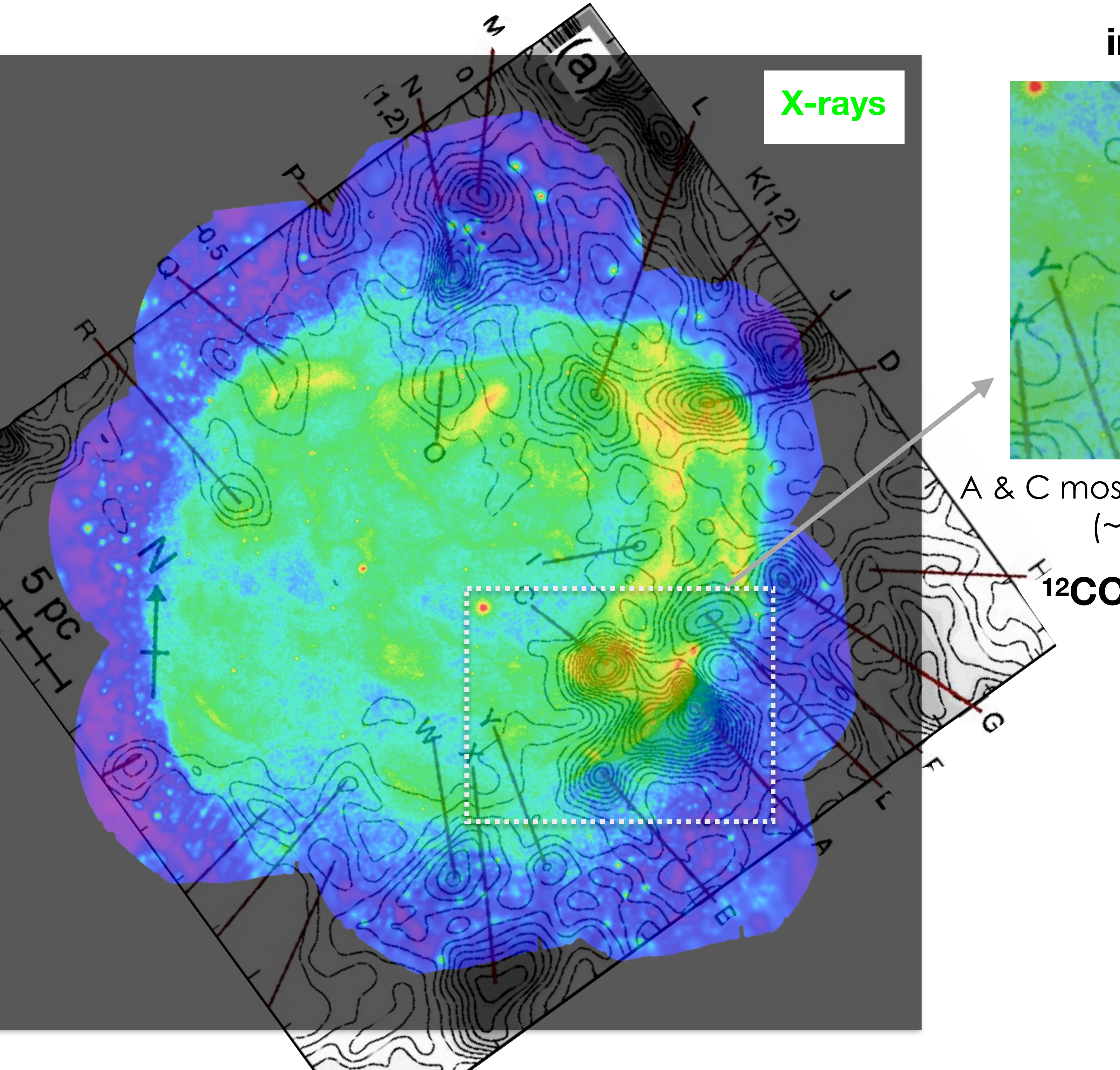


Inoue, 12

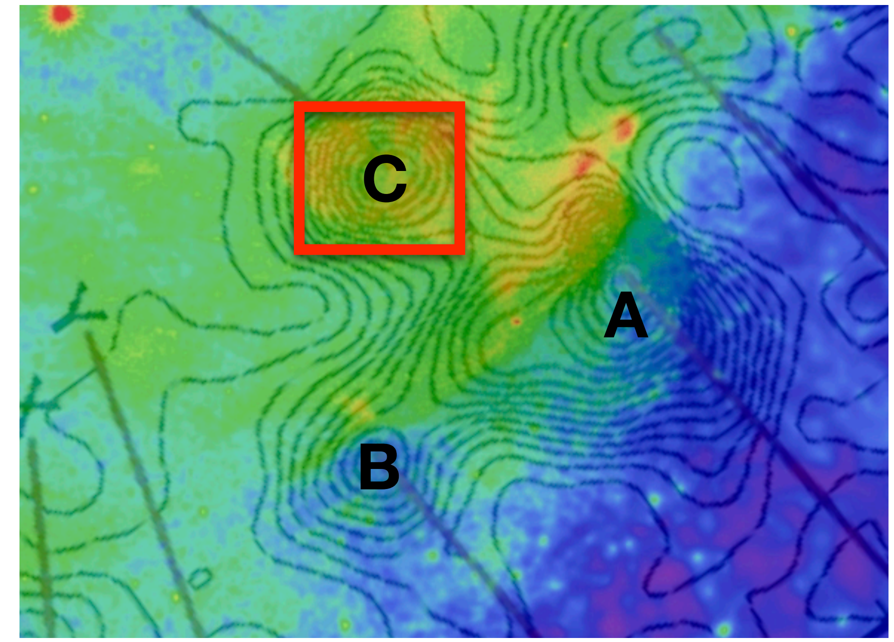


Inoue+19

SNR - MC interaction



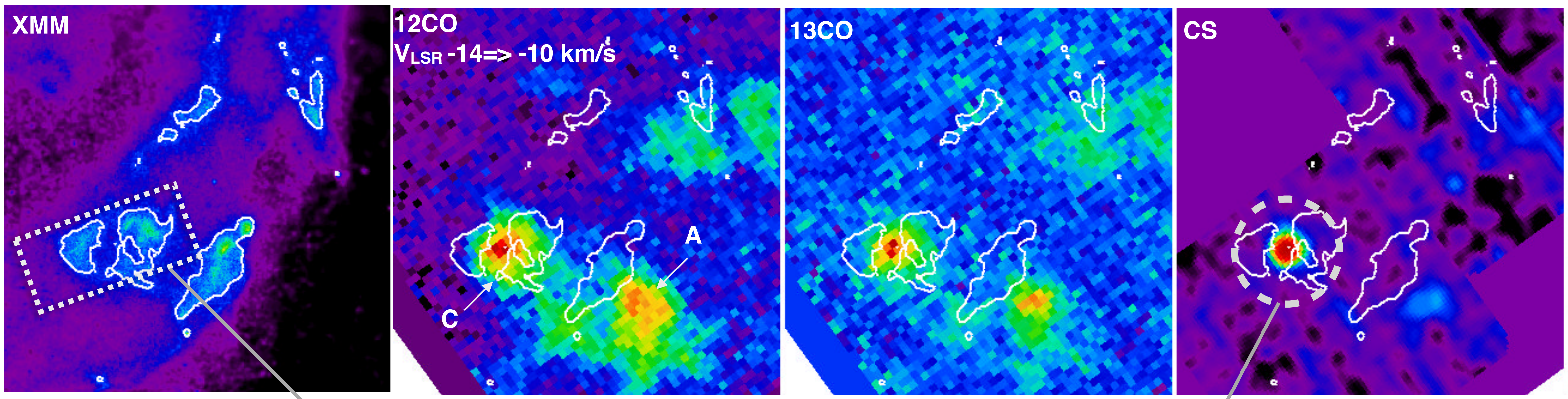
interacting clouds

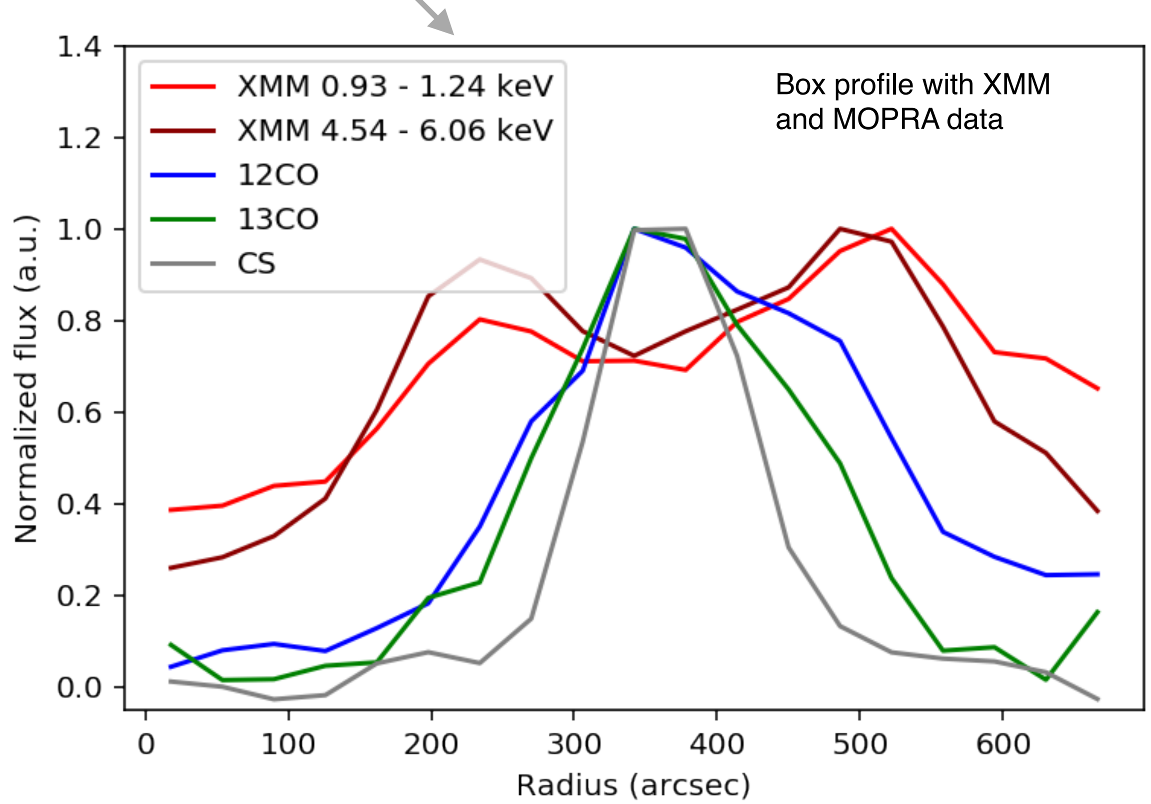


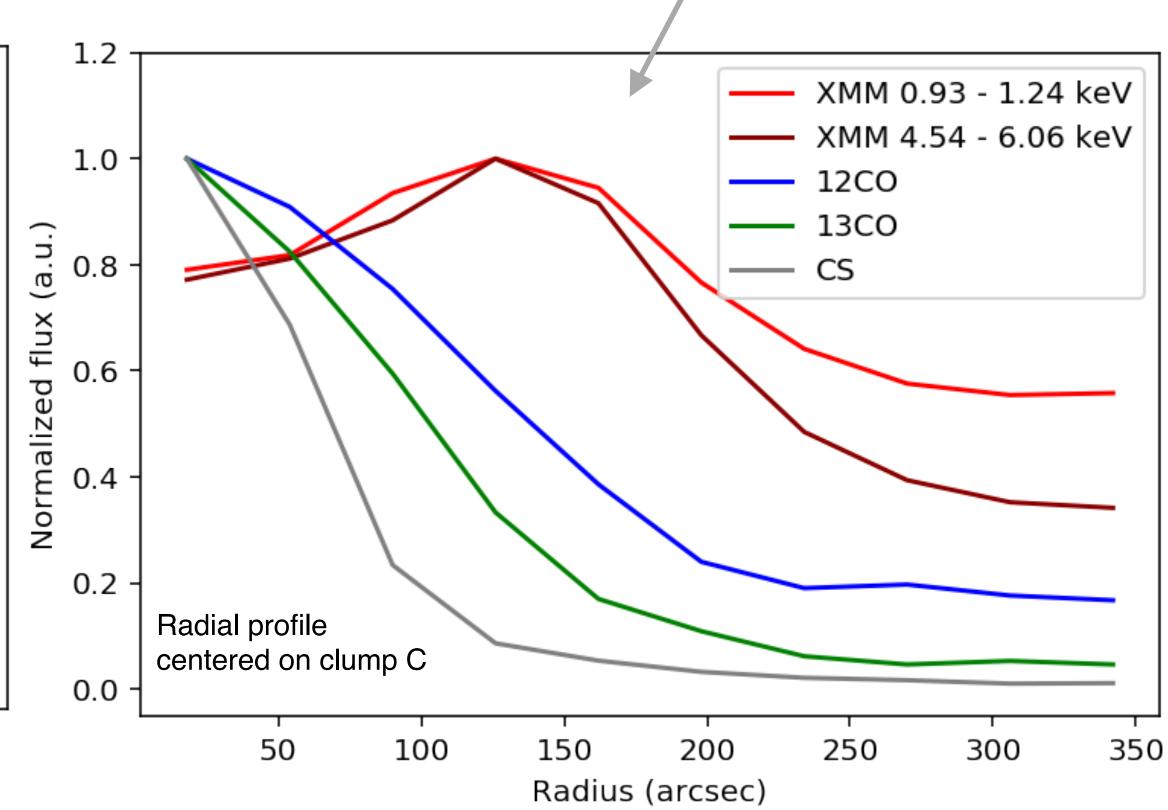
A & C most massive clouds in the vicinity (~400 $M_\odot$; Maxted+12, Sano+13)

Core C: X-ray/CO anti-correlation

- **Anti-correlation & no X-ray energy dependence**

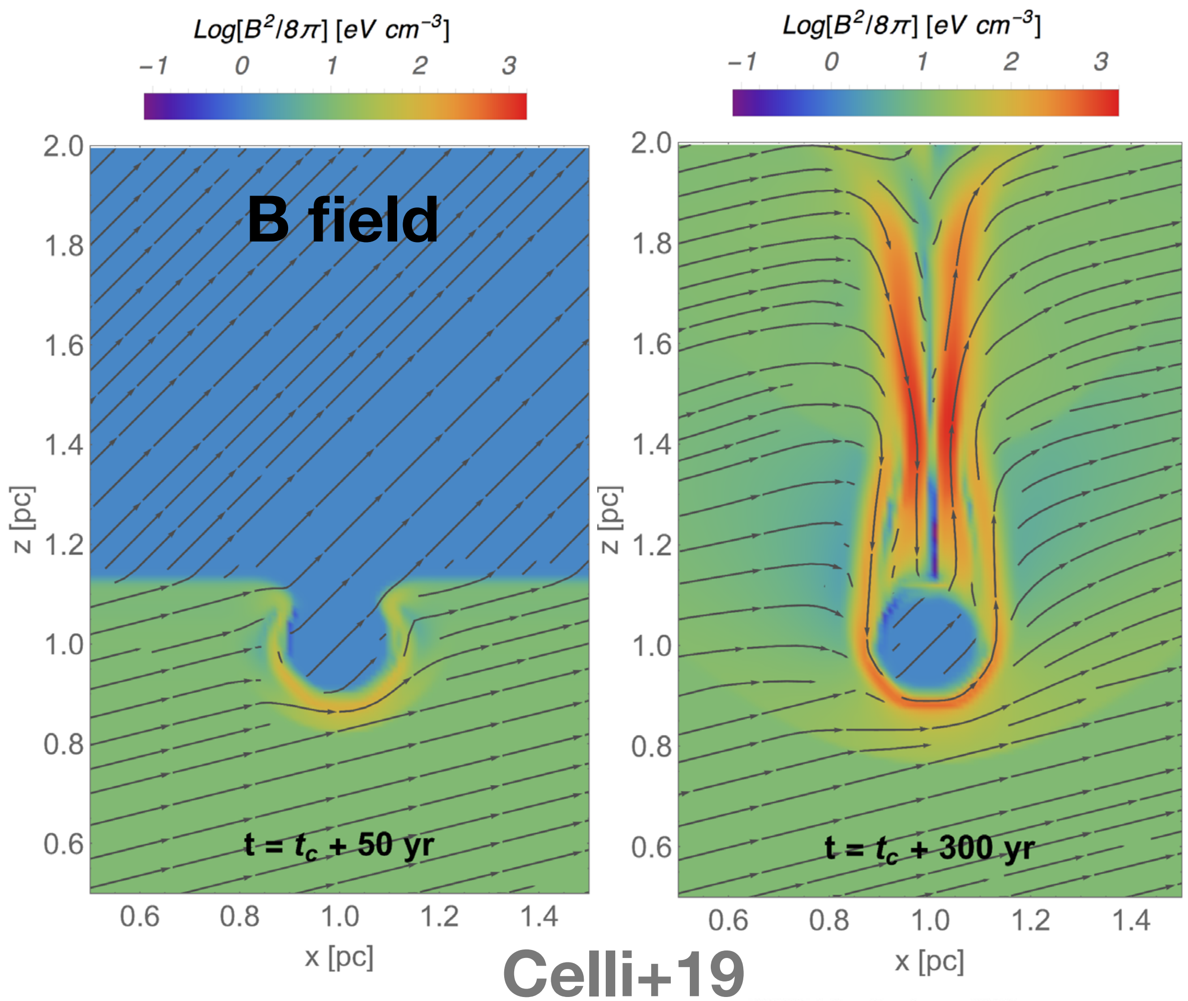


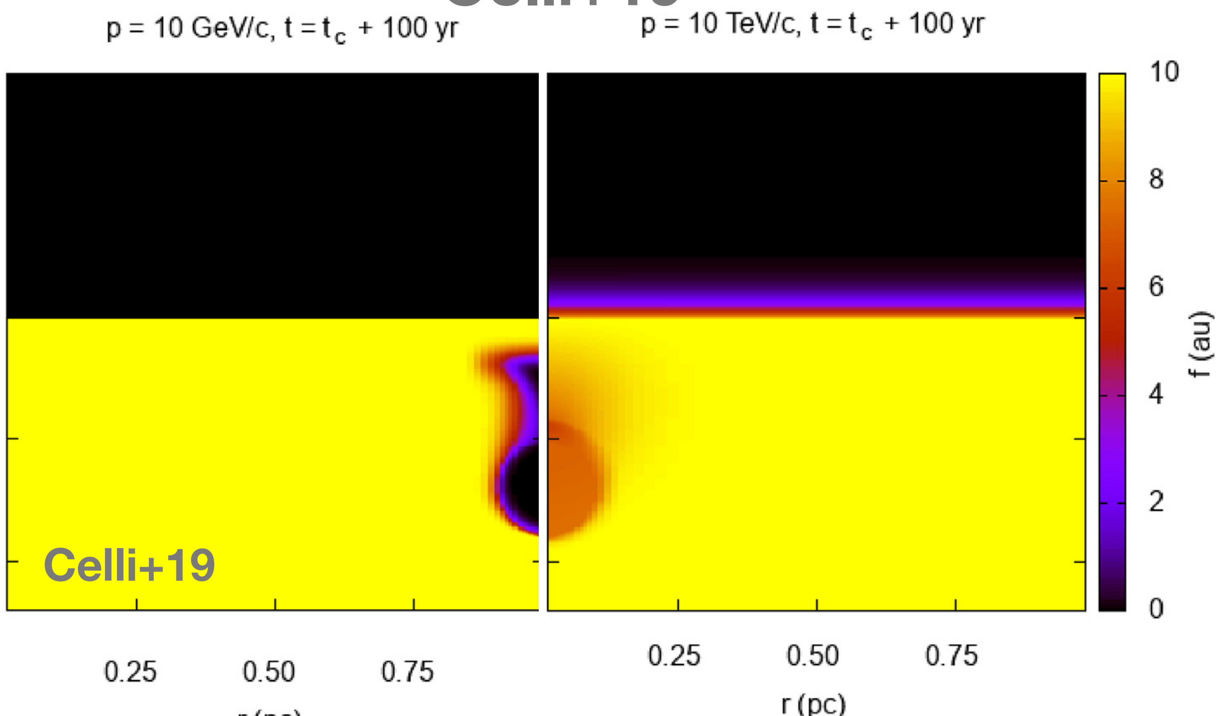




Clump size ~60-100 arcsec ~0.3-0.5 pc

Core C: X/CO anti-correlation

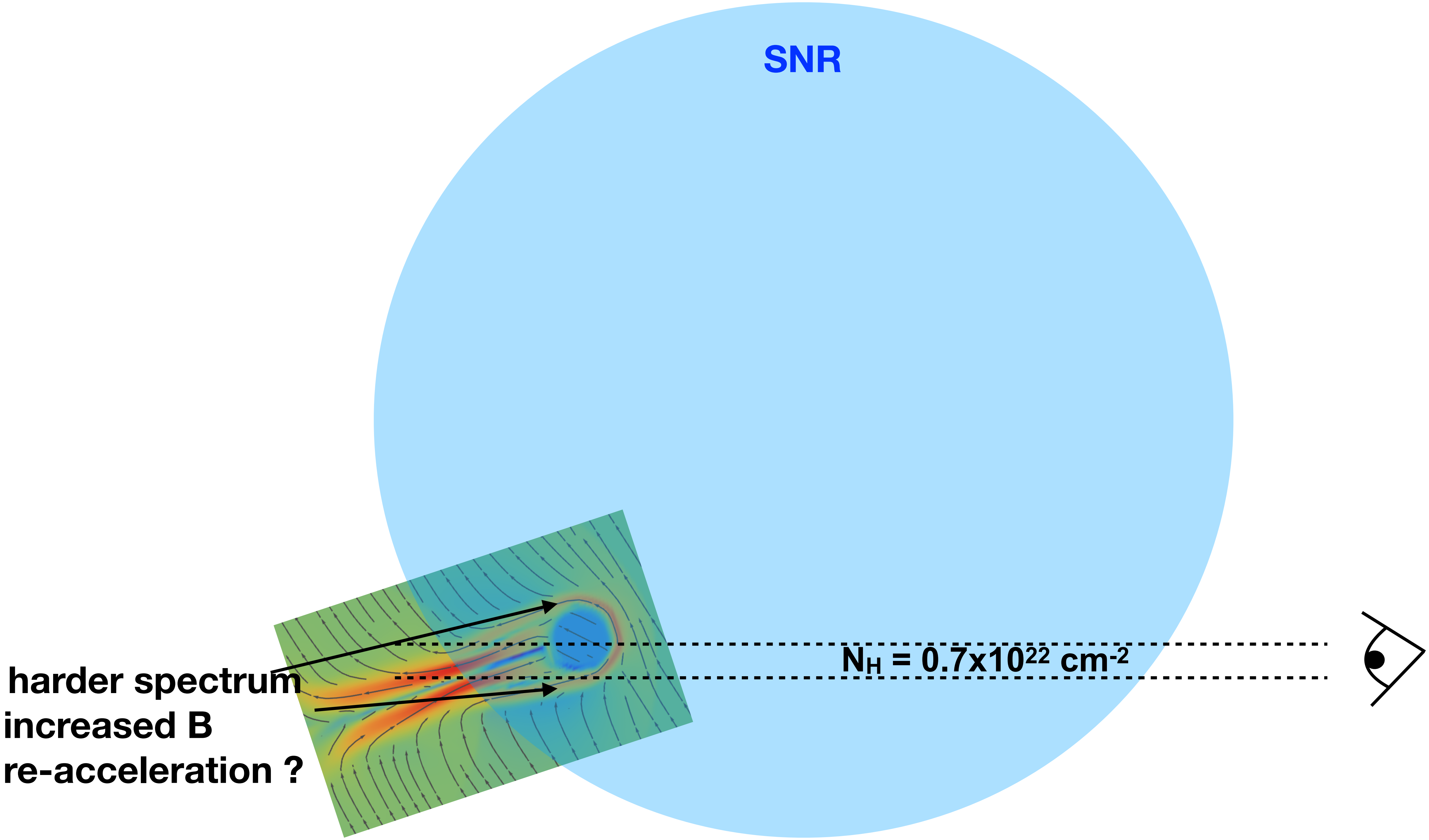




Proton density at 10 GeV / 10 TeV

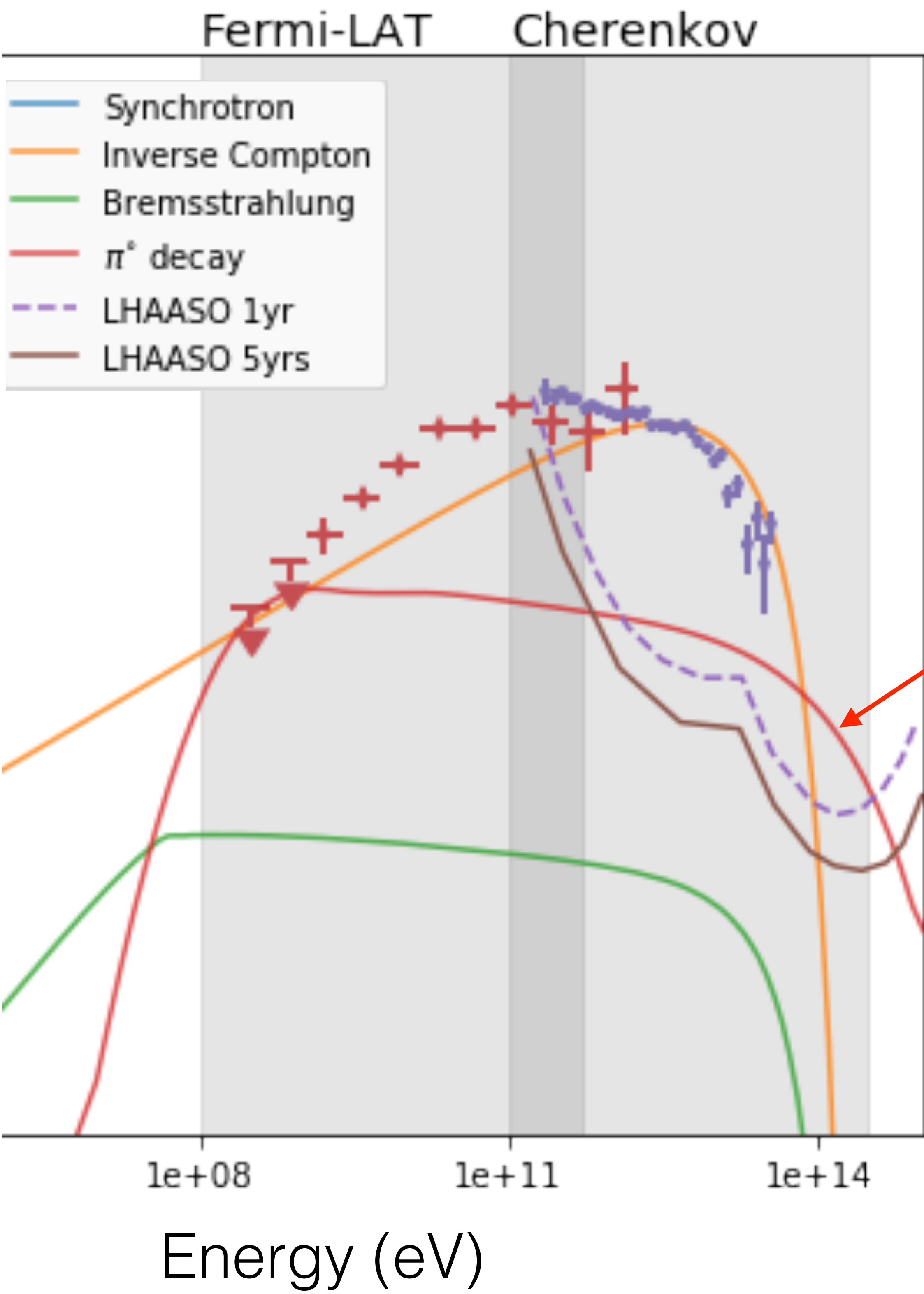
- **An increased B-field on the envelope shields the cloud from CRs penetration (e.g Inoue+19, Celli+19).**
- **The fact that no X-ray peak from cloud center at 5 keV indicate that high energy e- do not penetrate cloud deeper than low energy e-.**
  - **Cooling effect of e- ?**

Cloud-Shock geometry



Expected N_H from clump ~ $3 \times 10^{22}\ cm^{-2}$

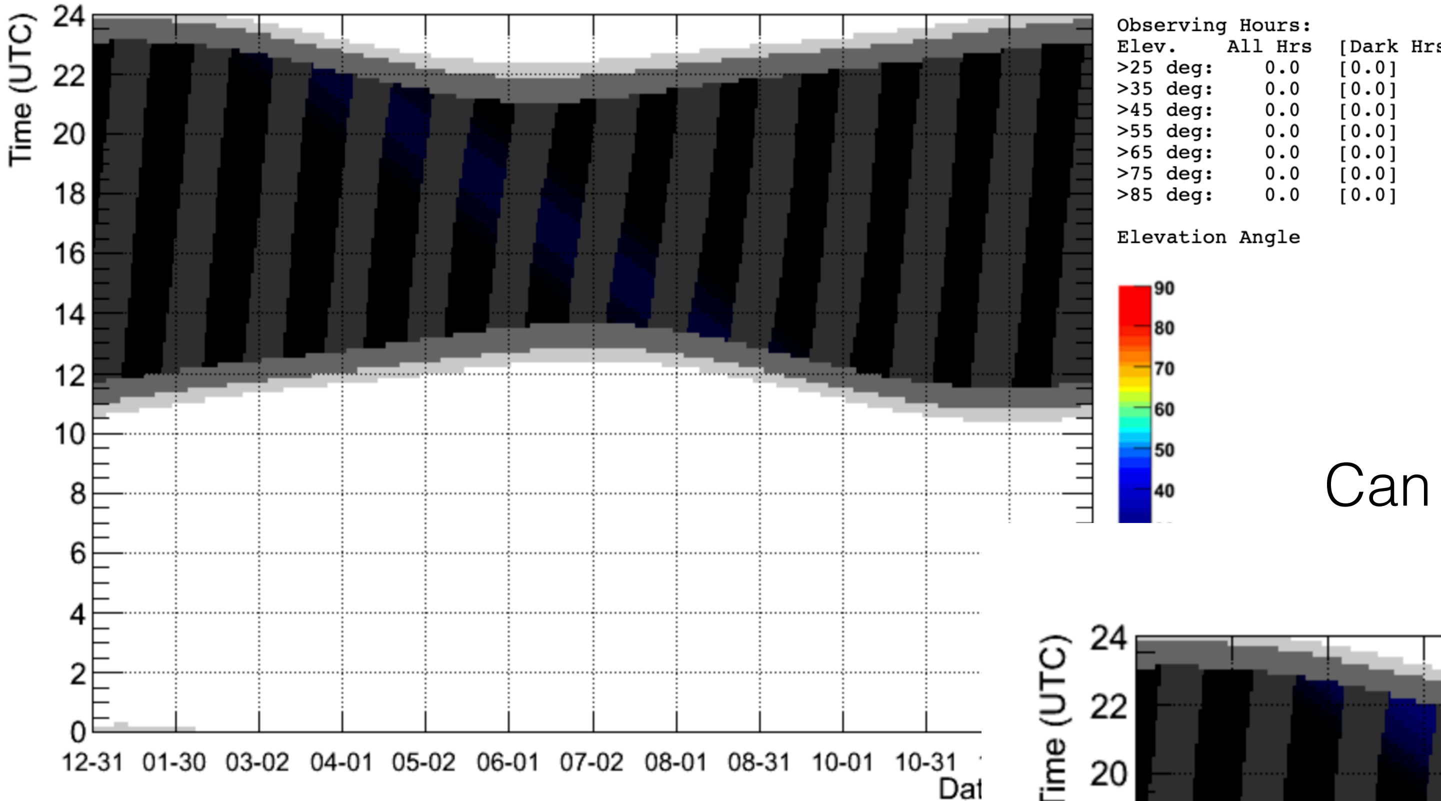
RX J1713 - PeVatron hadronic tail



Existence of a high-energy proton tail ?
Could be probed by LHAASO

LHAASO high zenith observations

RX J1713.7-3946

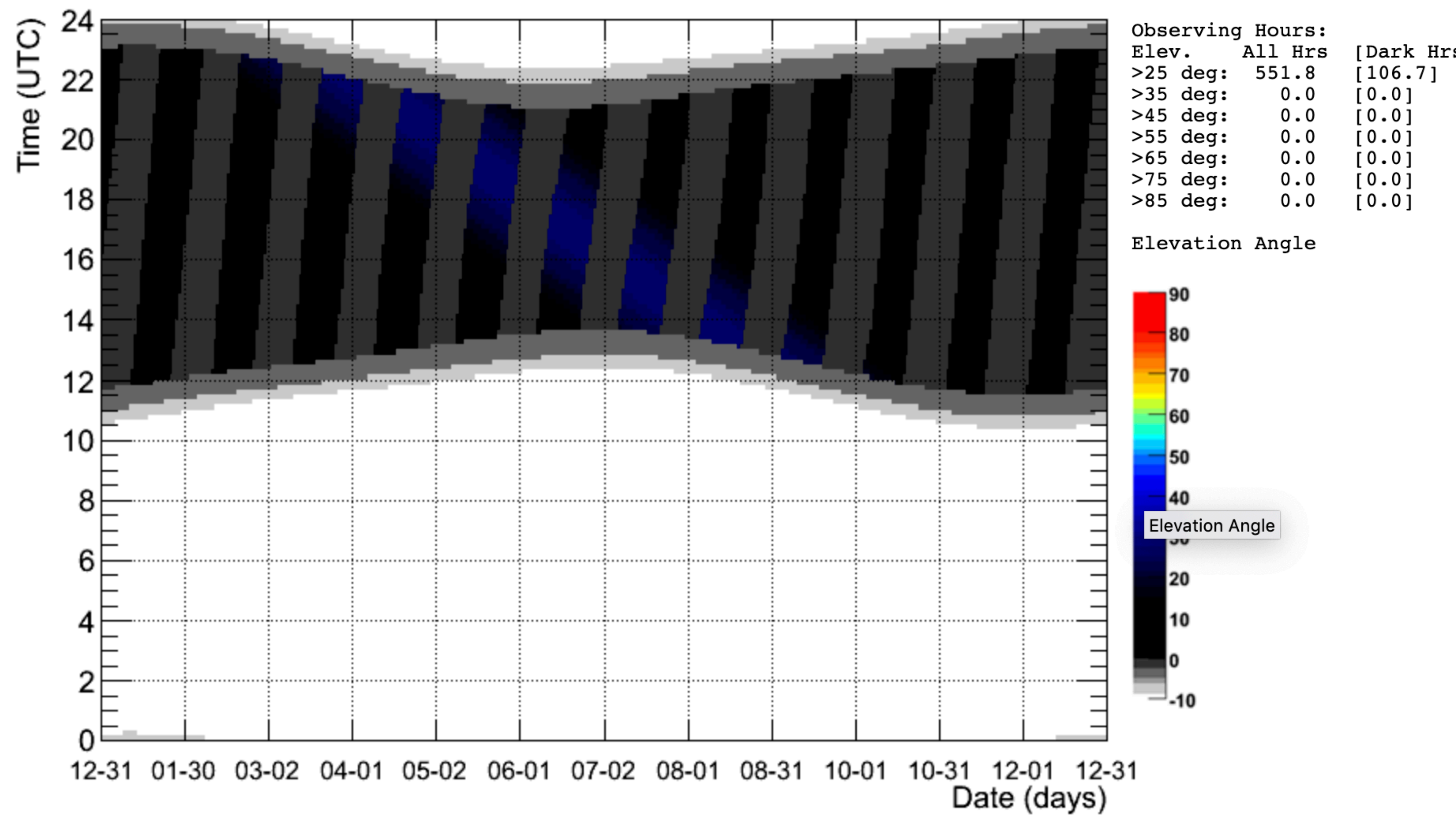


otted RX J1713.7-3946 RA,Dec = (258.390000,-39.760000) for year 2020.000000 at lat,lon = 29.3

Visibility at LHAASO site

Can LHAASO observe sources at ~25° elevation ?

HESS J1731-347



Plotted HESS J1731-347 RA,Dec = (263.012500,-34.755000) for year 2020.000000 at lat,lon = 29.358000,100.139000

Conclusion

- **X-rays : constrain environment, progenitor, electron population**
- **γ-rays : best way to probe proton population but need high density**

- **SNR/CR paradigm:** **Accel. e^- and protons** OK
  Energy budget ~OK
  Reaching 10^{15} eV x not even in CasA & Tycho

- **Interacting & shell SNRs:**
  - **age + environmental effect create a variety of spectral shapes**
  - **some probe e- population some the proton population**
  - **Large molecular cloud slow down shock. No high speed, high density**

- **Clear clump (core C) / shock interaction in RX J1713**
  - **Core C size 0.3-0.5 pc similar to size in clump scenario (0.1 pc)**
  - **^{12}CO, ^{13}CO, CS tracer anti correlate with X-rays synchrotron**
  - **TeV spectra of clump ? Small scale spectroscopy with CTA**
  - **LHAASO to probe a PeVatron tail in SNRs**

Gammapy: open-source Python package for γ-ray astronomy

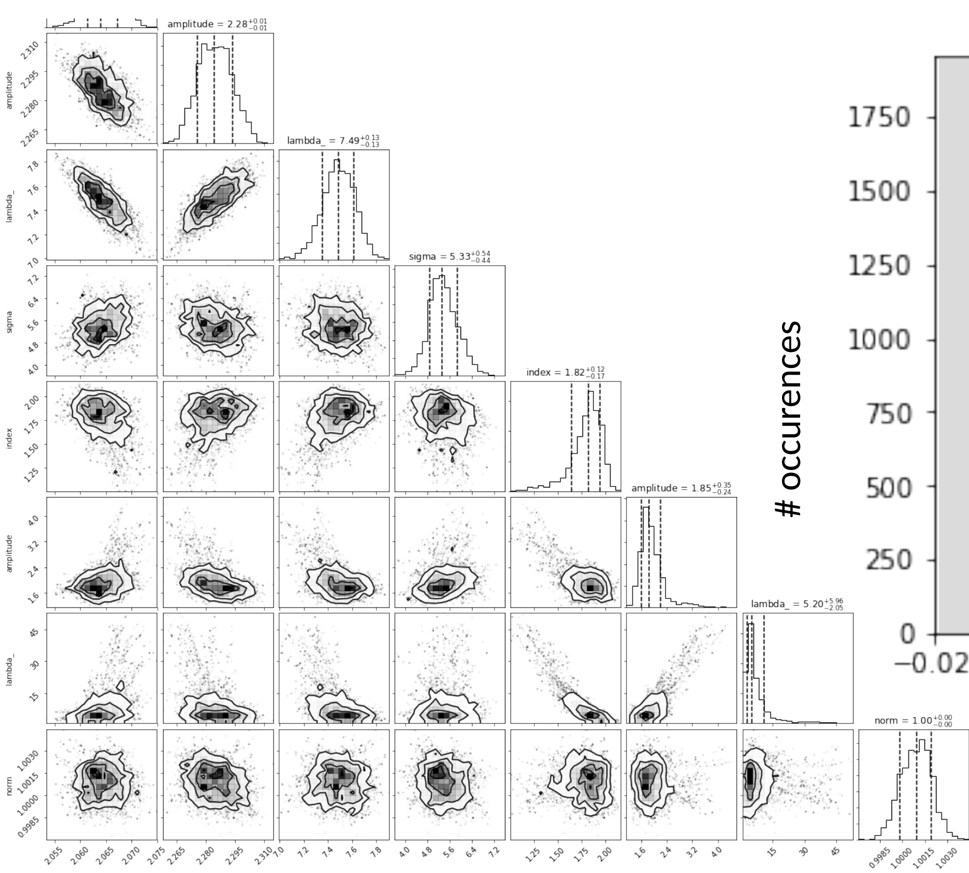
https://gammapy.org/

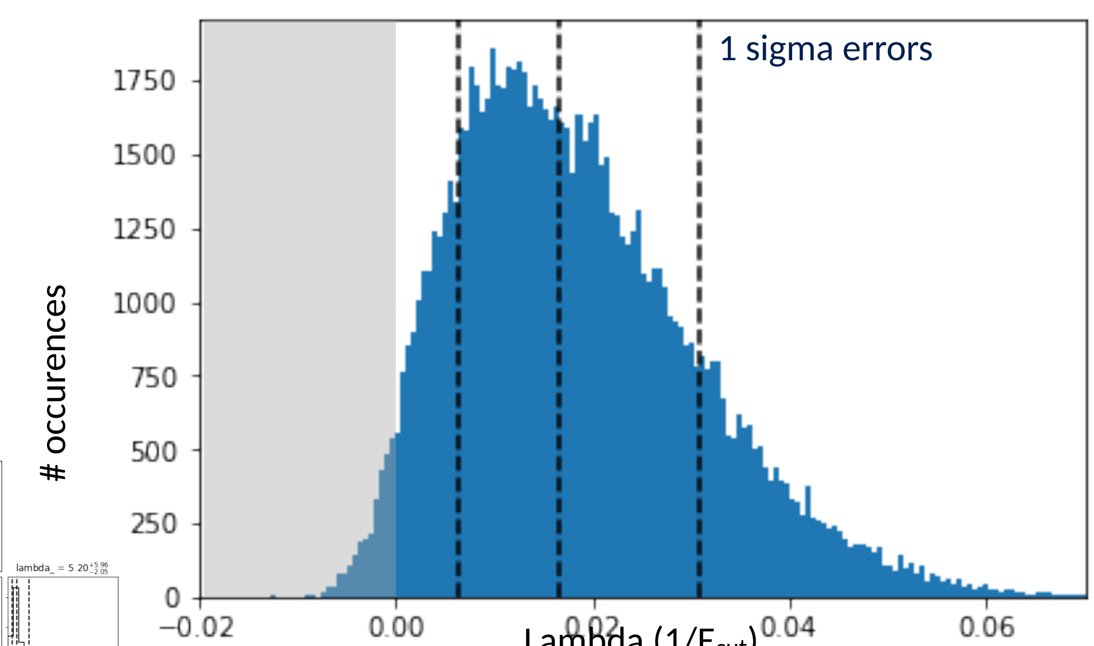
A **Python** package for **gamma-ray** astronomy

- **Community developed tool based on Numpy & Astropy**

- **Used in HESS and CTA collaborations:**
  - **Sky map production, 1D/3D spectral & time analysis**
  - **Multiple telescopes: joint Fermi+HESS (+LHAASO?) analyis, multi-messenger**

- **Use case for PeVatrons :**
  - **Likelihood with physical hadronic model (naima) on data instead of flux points**
  - **Measure errors and explore correlations with Markov Chain Monte Carlo**





Distribution of parameter