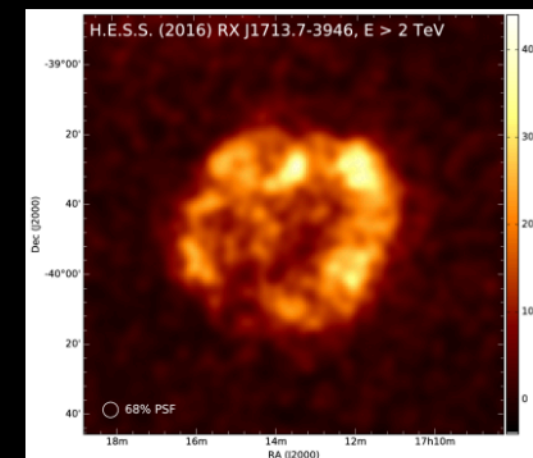
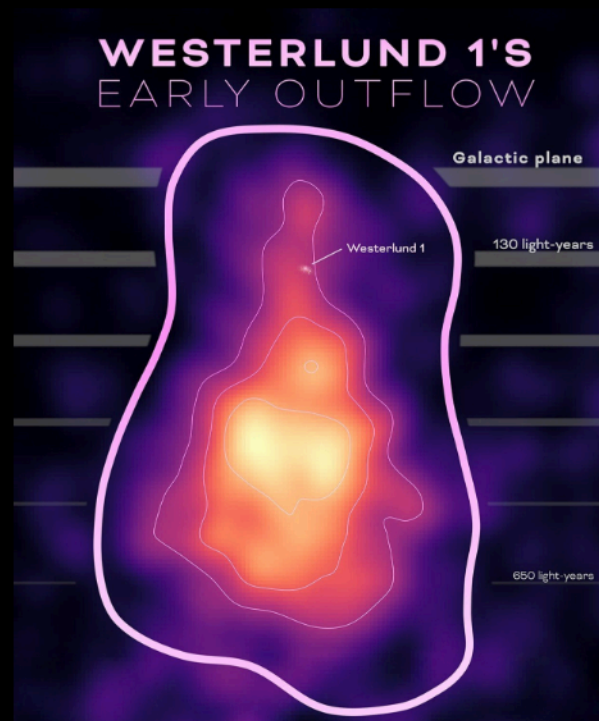
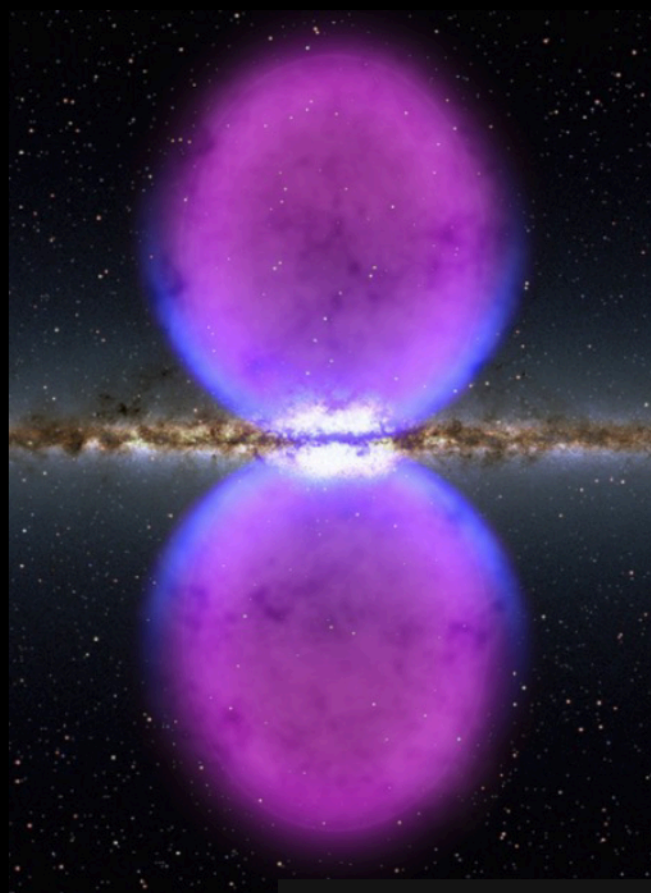




The Extreme Non-Thermal Universe: CDHY Initiative

WORKING TOGETHER TO UNDERSTAND THE SITES OF EXTREME ACCELERATION...

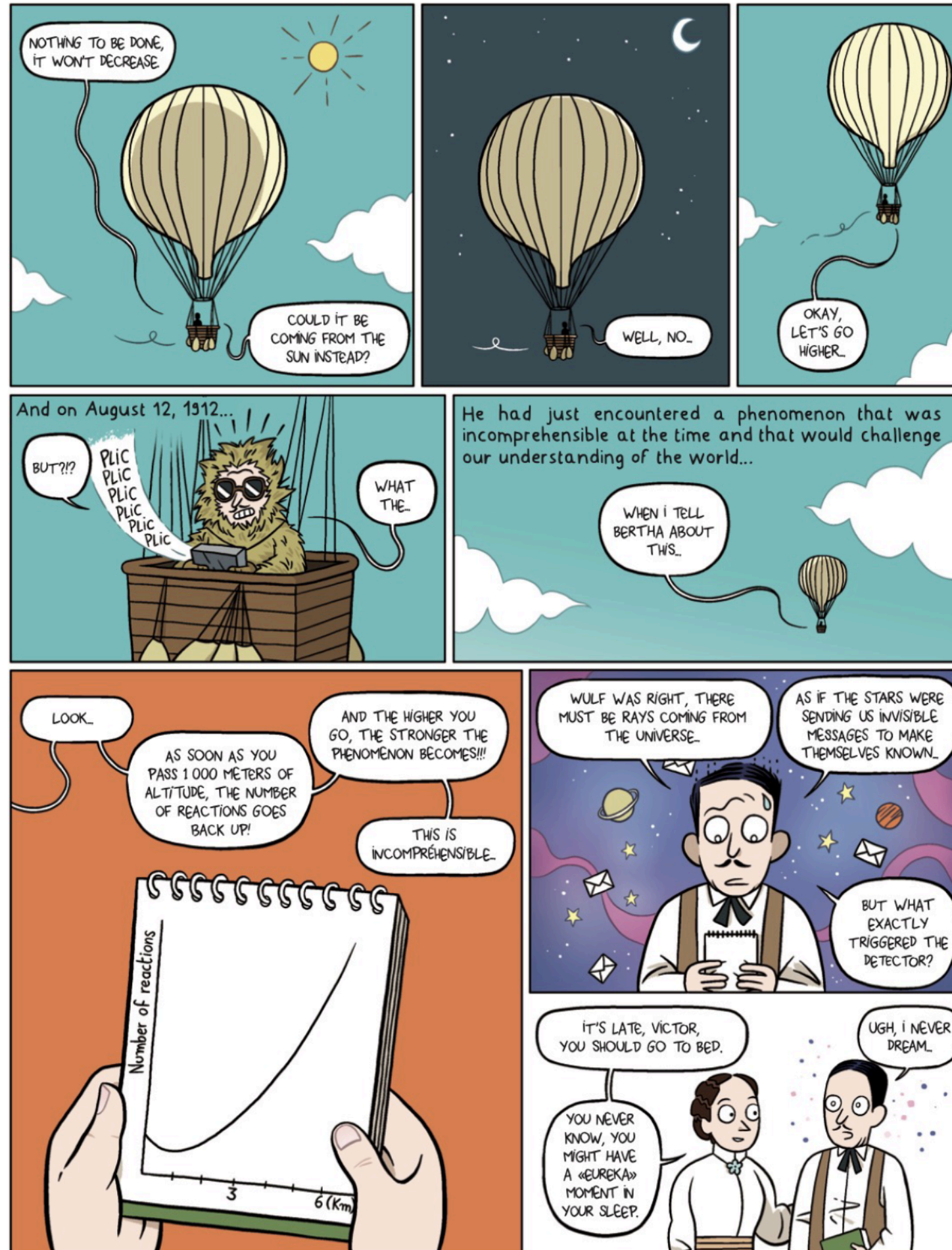
Diffuse gamma-ray structures at GeV energies

F. Acero, CNRS researcher @ AIM/CEA-Saclay & IRL FSLAC

Victor Hess balloon flight



And Victor Hess carried out a whole series of ascents to take measurements at an altitude of at least 500 meters, aiming to determine at what altitude or under what conditions the number of measured reactions could finally reach zero.



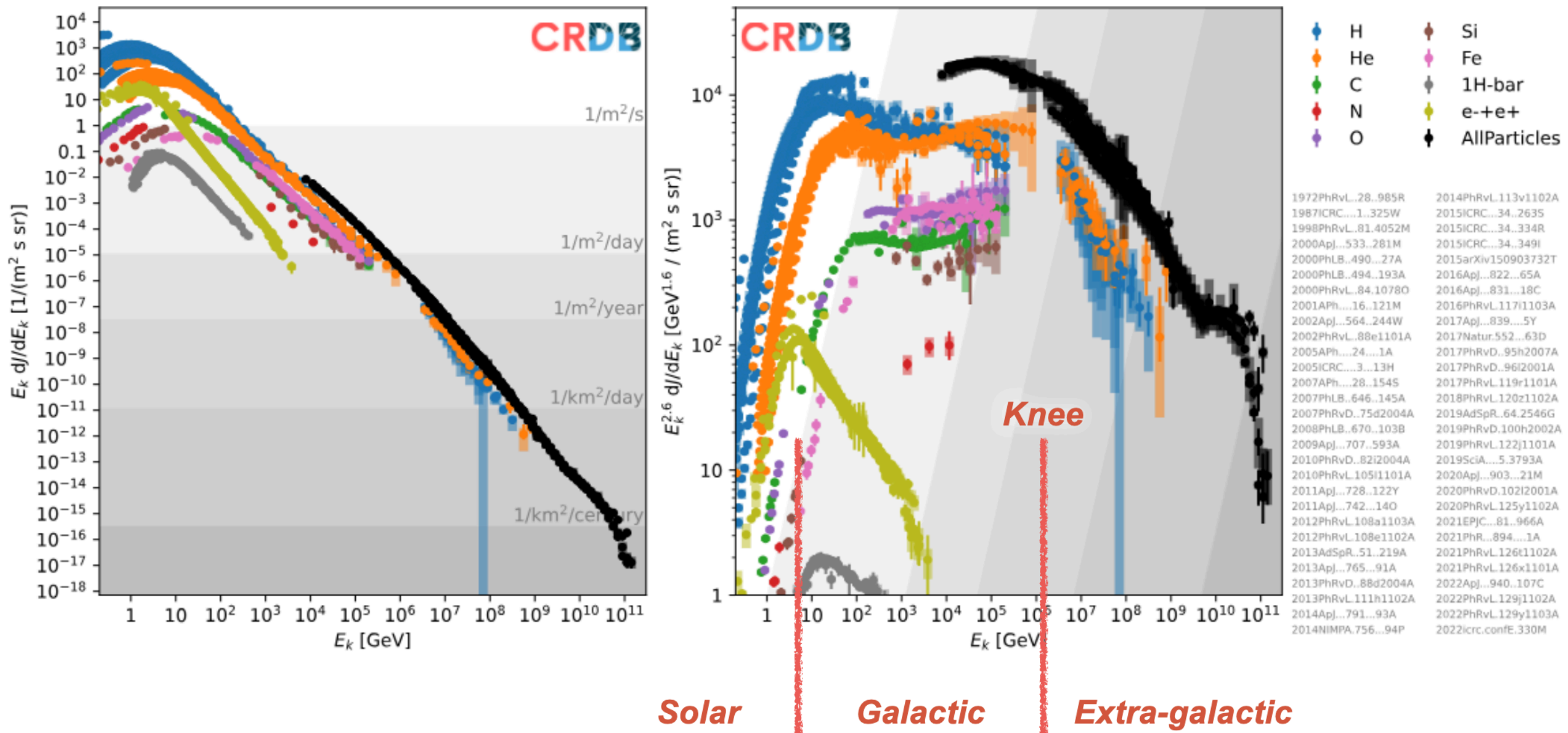
Comic book *Space messengers* about astroparticles and CRs and gamma-rays

Outreach project aimed at 15+ yrs public

20 pages so far

Ask me about it

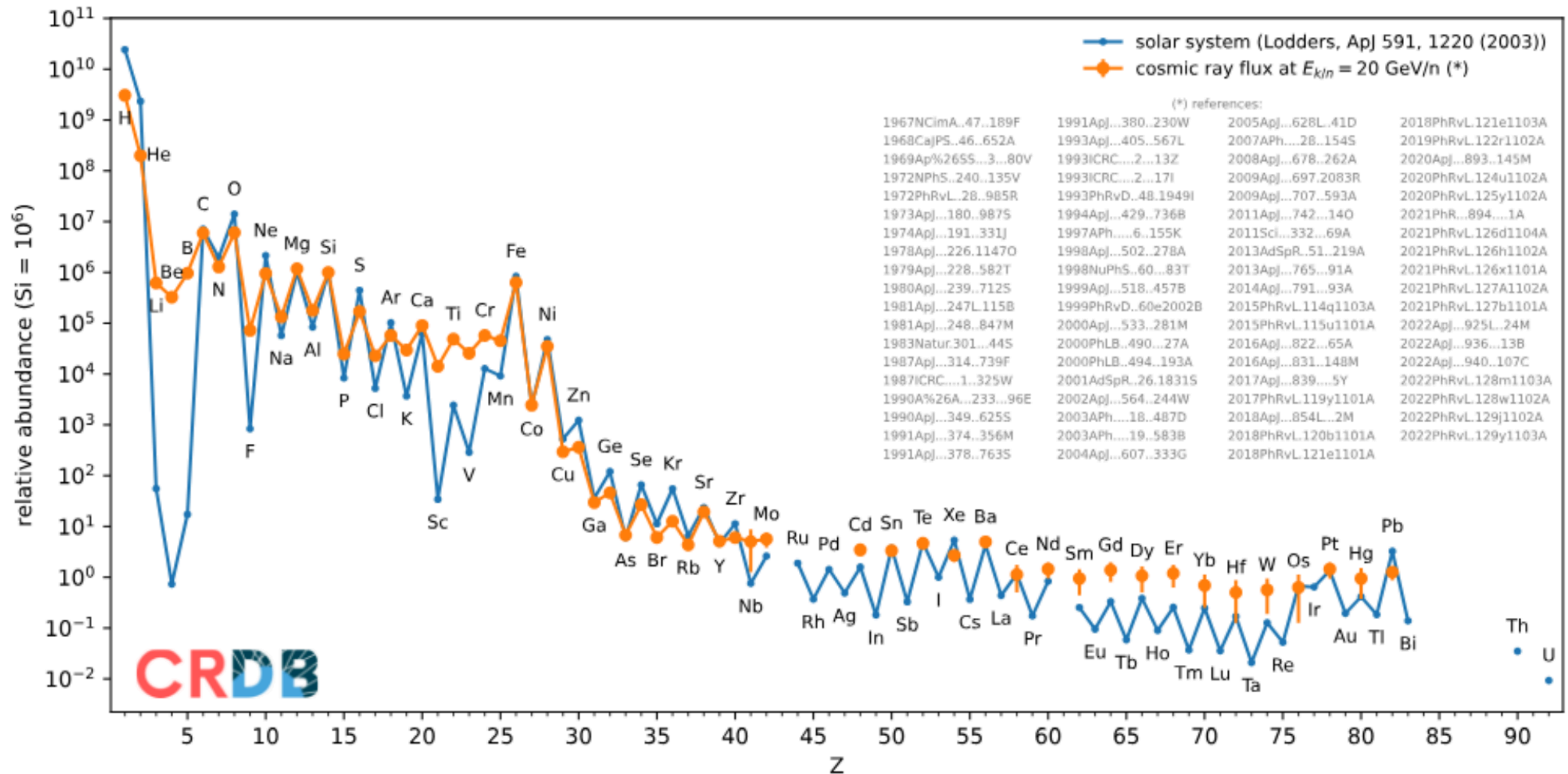
Cosmic rays spectrum



<https://lpsc.in2p3.fr/crdb/>

Low energy cosmic ray are driving the energy budget and interaction with CSM

Cosmic rays abundances: fingerprint of their history

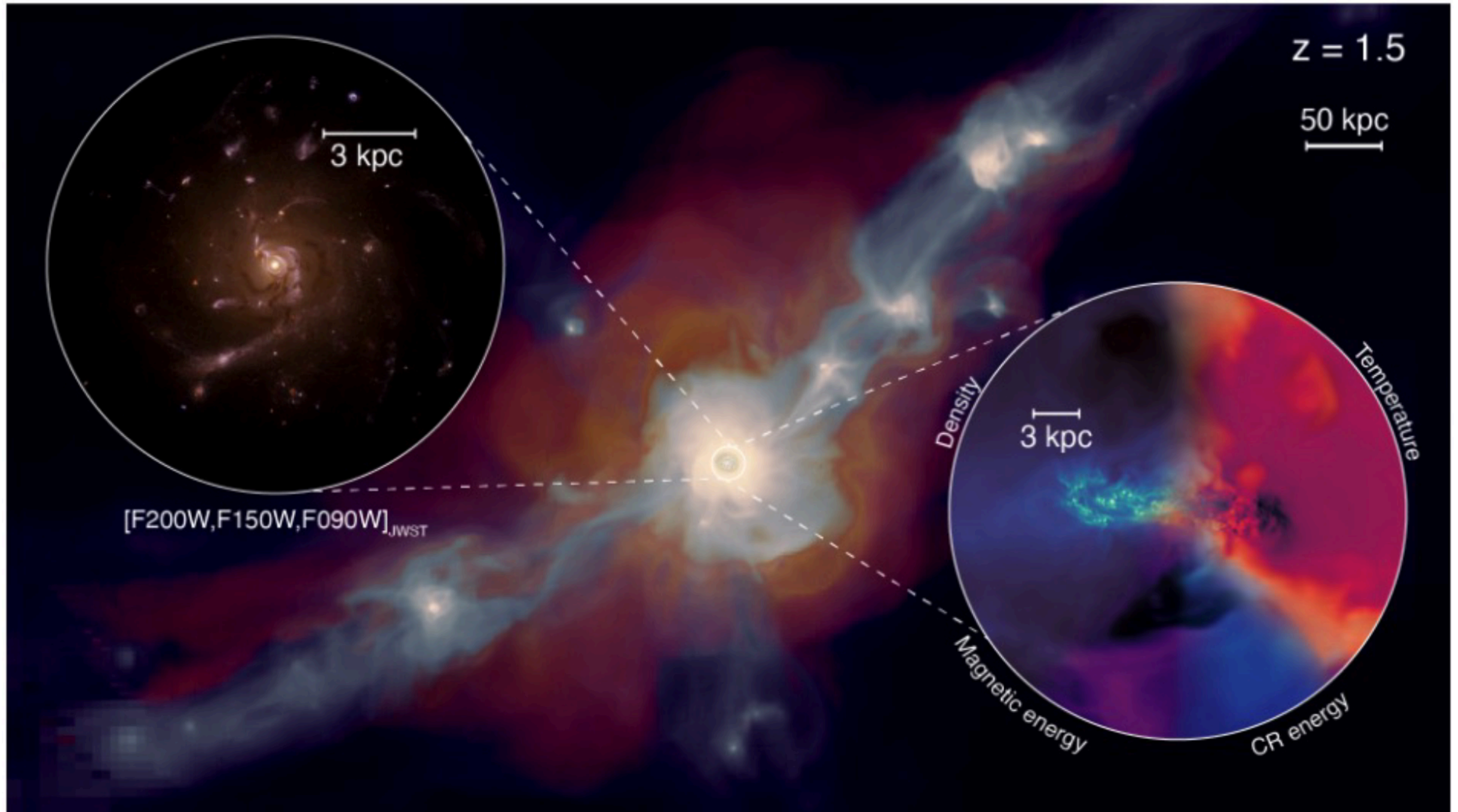


Low energy H+He are driving the energy budget and interaction with CSM

<https://lpsc.in2p3.fr/crdb/>

Propagation, spallation, etc in the Galaxy imprints the abundances

Why are CR important ?



CR-MHD galaxy simulation including CR feedback from supernova

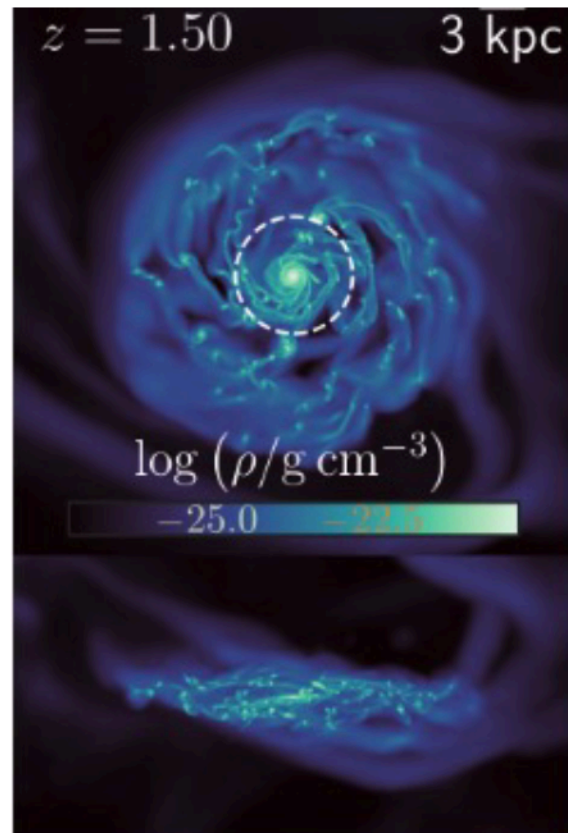
Rodriguez Montero et al., 2023

- **Cosmic rays are an important part of the energy budget in the galactic ecosystem**

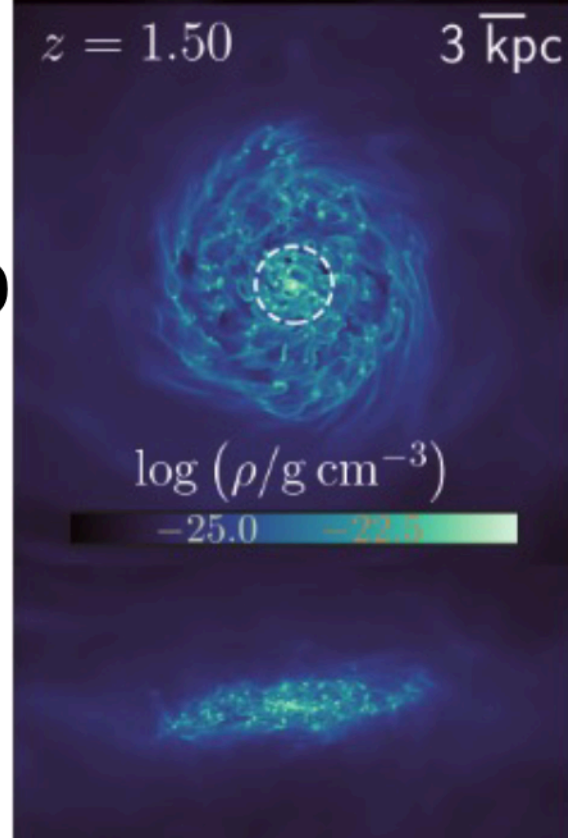
Why are CR important

Rodriguez Montero et al., 2023

MHD



CR-MHD



Density

Temperature

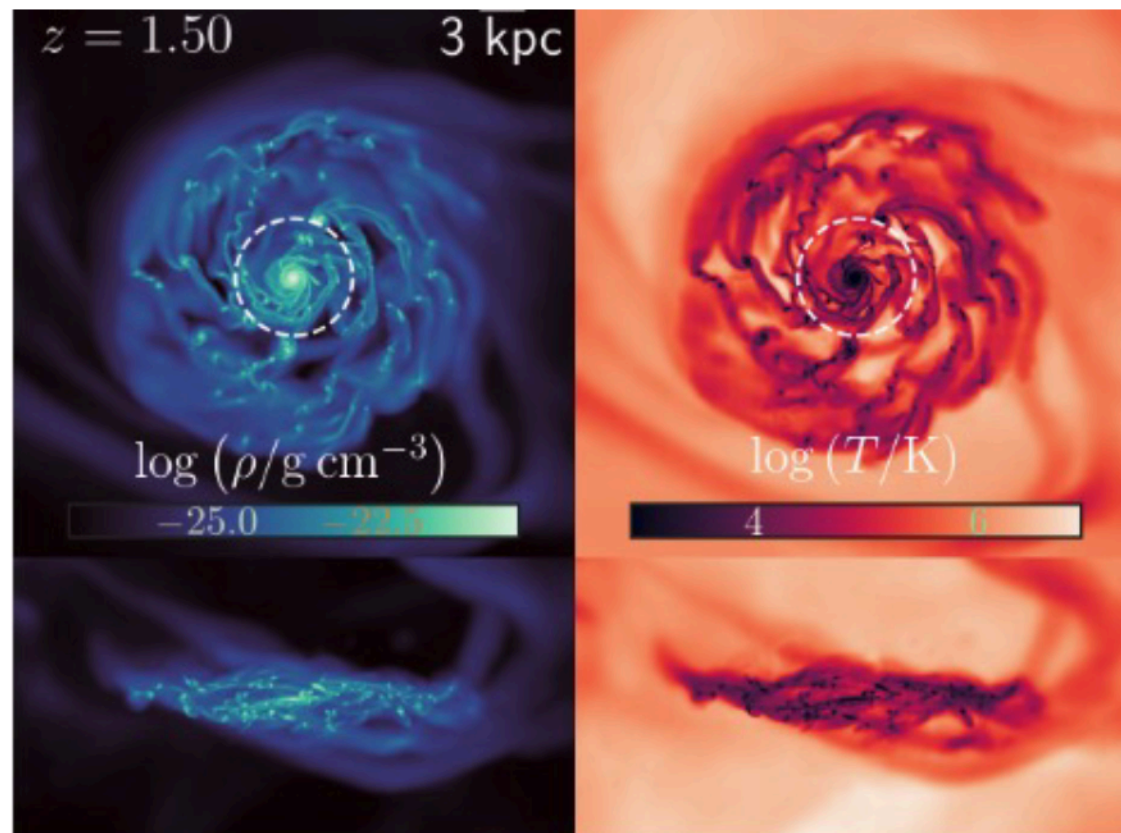
Abund

JWST synth

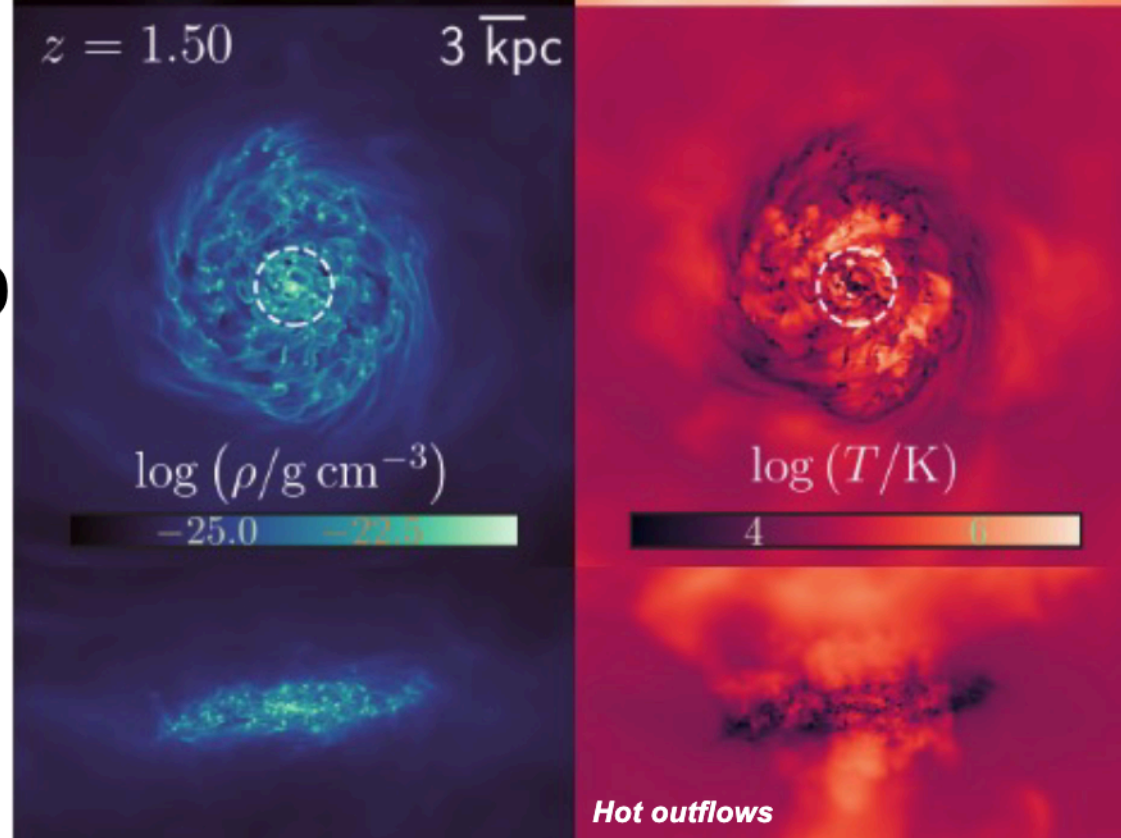
Why are CR important

Rodriguez Montero et al., 2023

MHD



CR-MHD



Density

Temperature

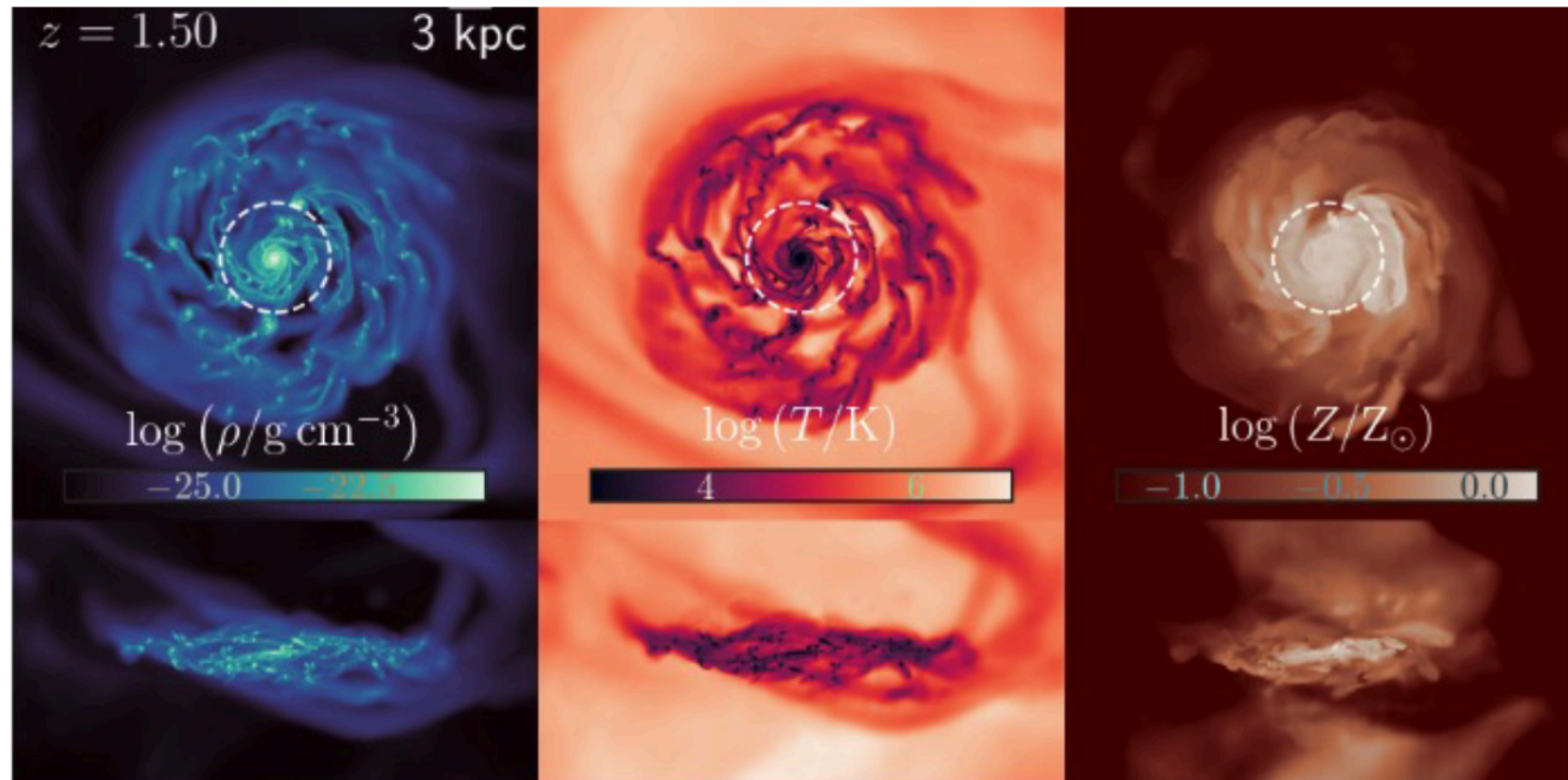
Abund

JWST synth 8

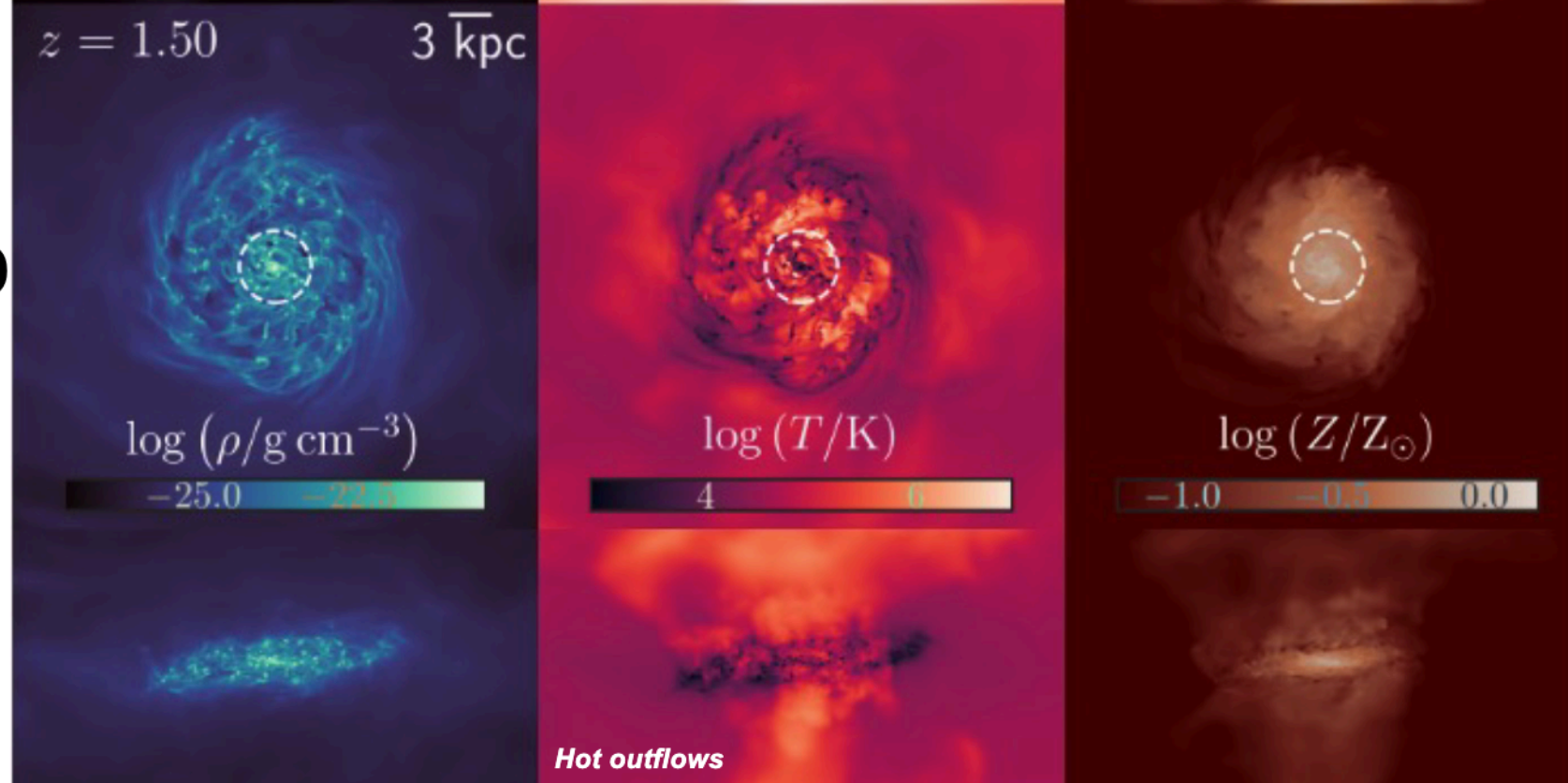
Why are CR important

Rodriguez Montero et al., 2023

MHD



CR-MHD



Density

Temperature

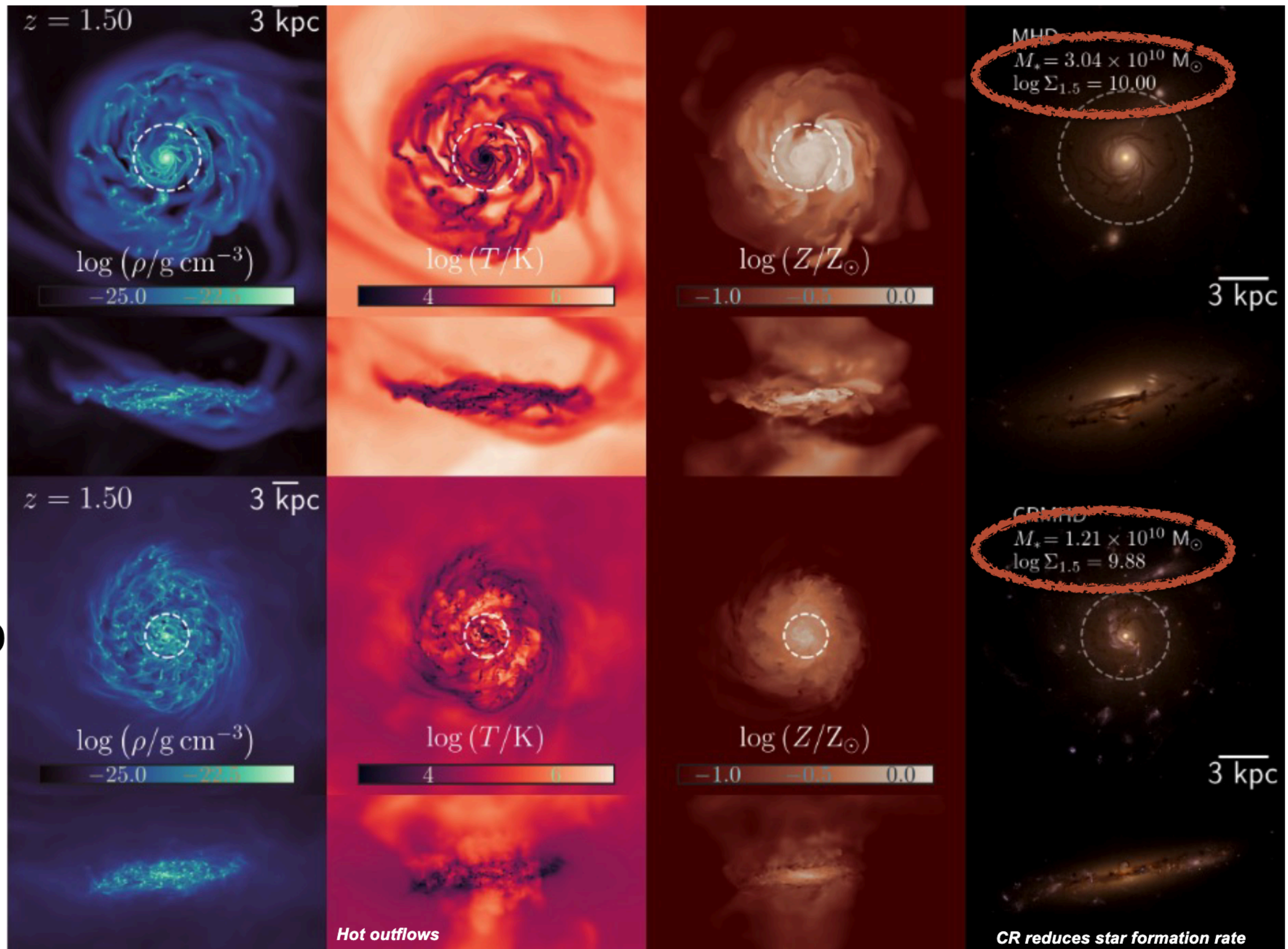
Abund

JWST synth 9

Why are CR important

Rodriguez Montero et al., 2023

MHD



Density

Temperature

Abund

JWST synth

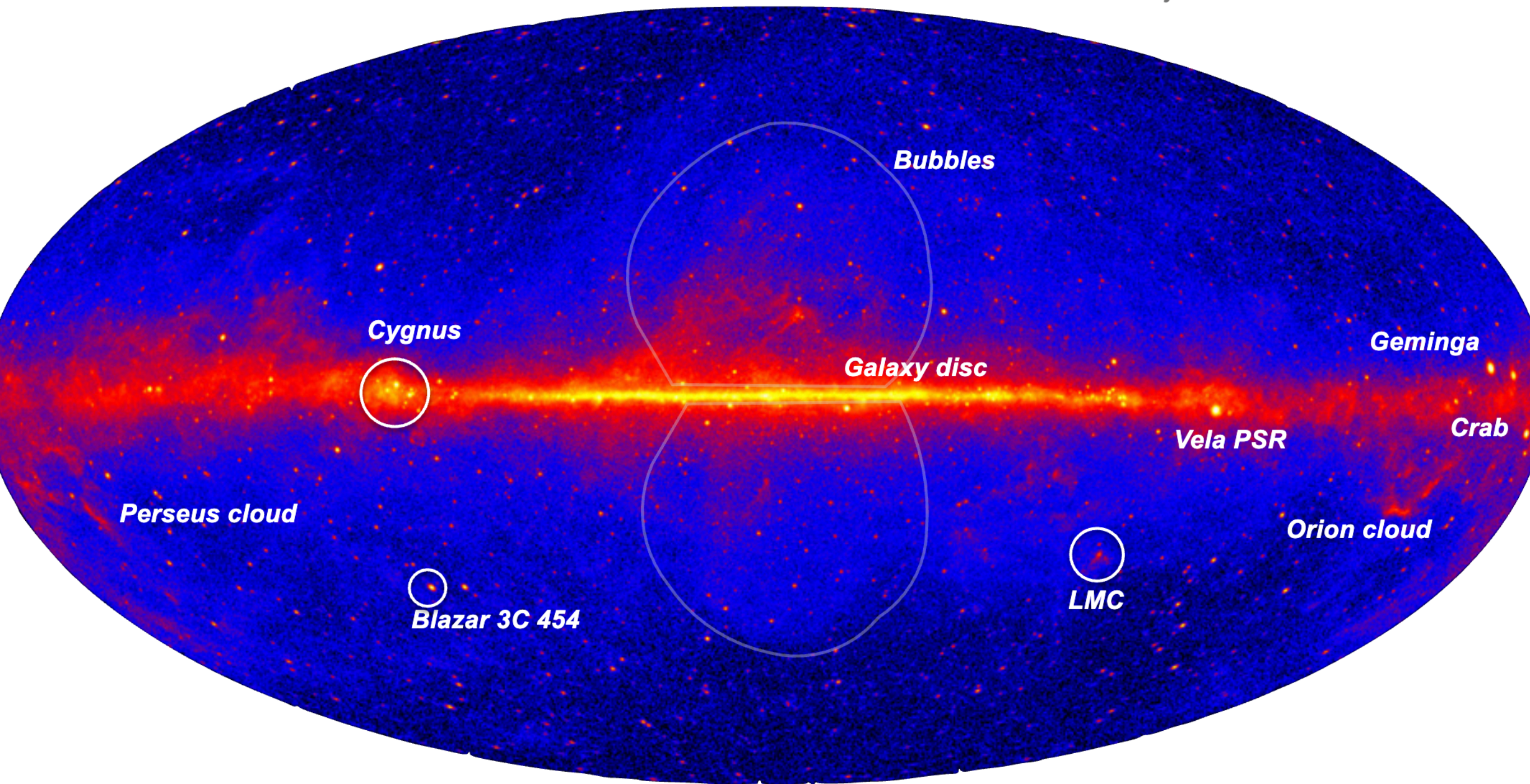
10

The observational counterpart

Fermi-LAT all sky view

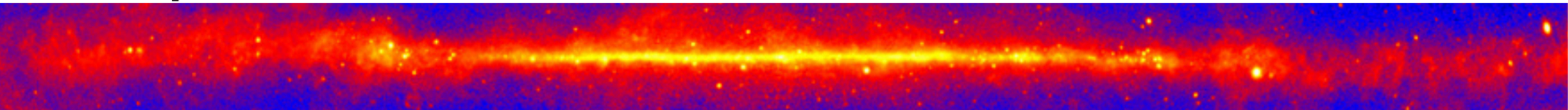
$E > 1$ GeV

15 years

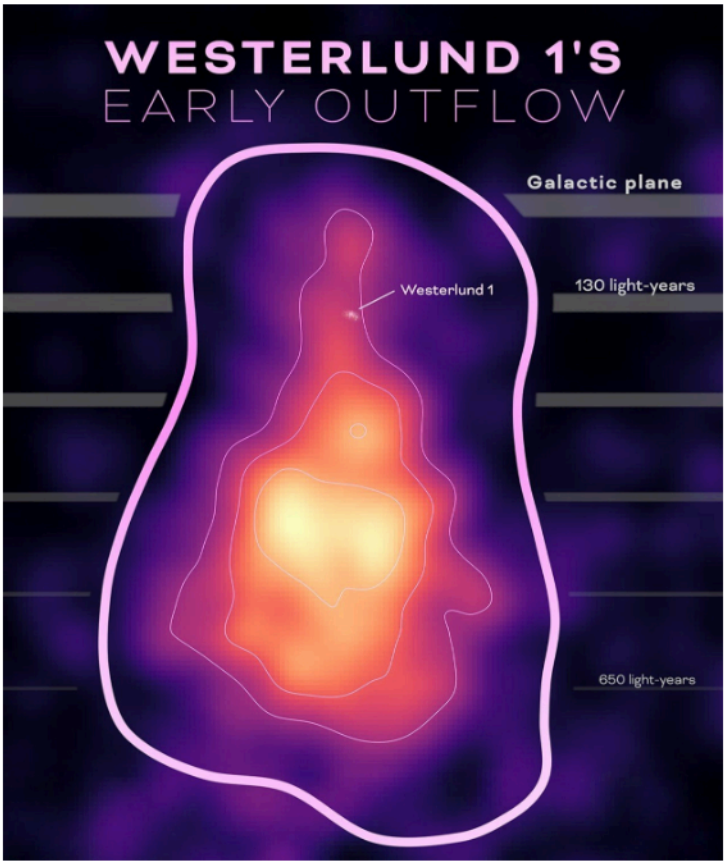


Our Galaxy is a matryoshka doll of diffuse CR structures

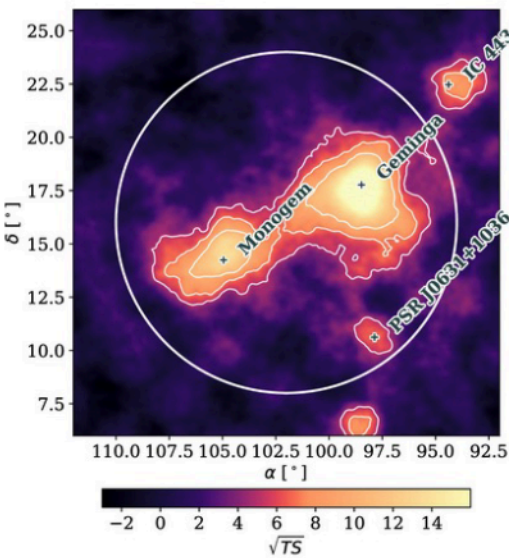
50 kpc scale



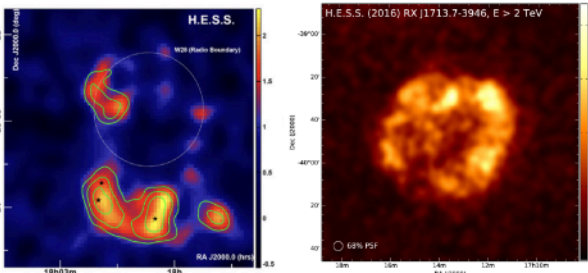
100 pc scale
Stellar clusters



Pulsar halos 10 pc scale

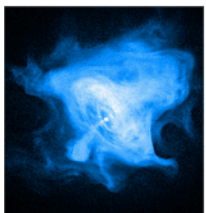


SNRs & escaping CRs

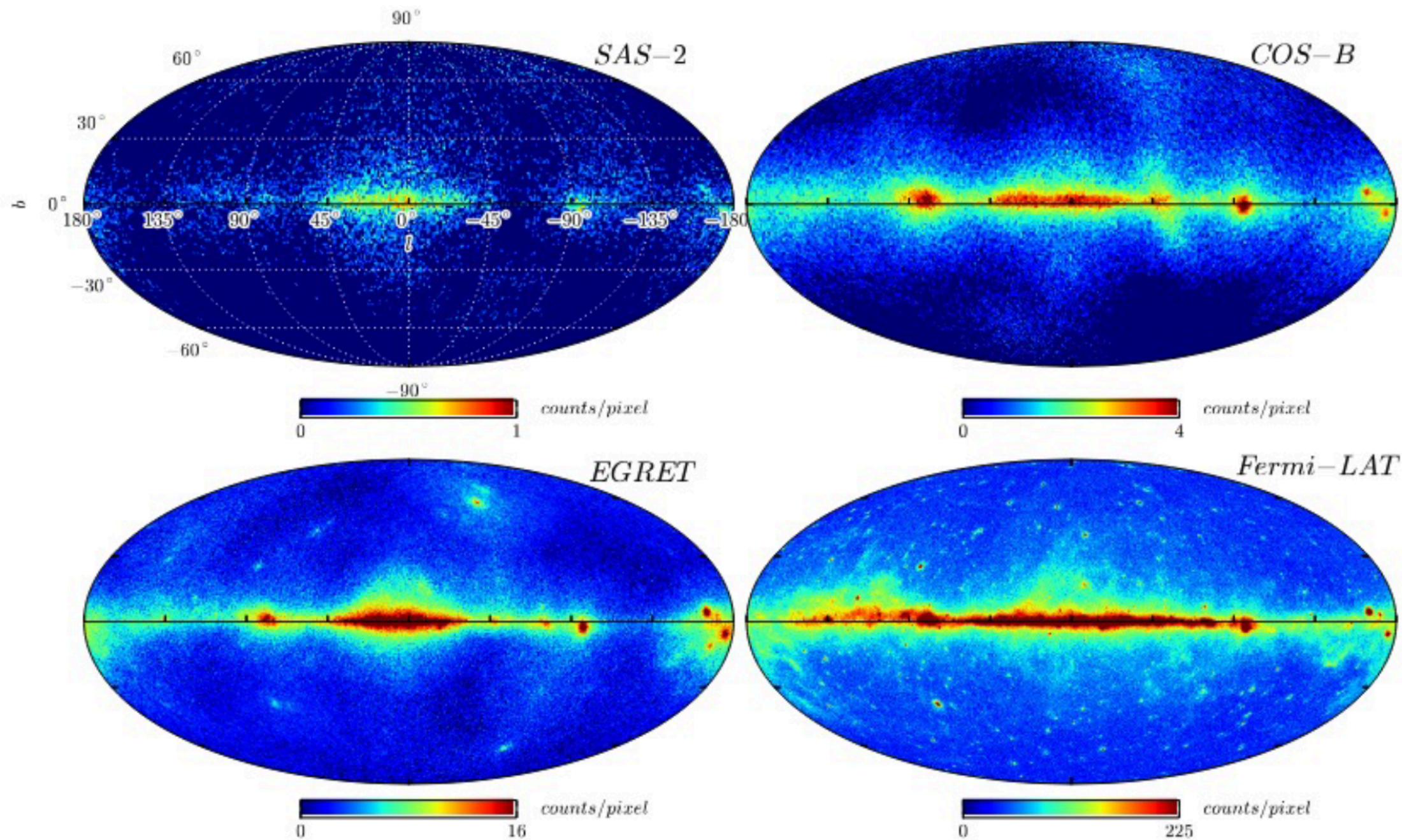


Young PWNe

pc scale



GeV galactic diffuse interstellar emission



Fermi-LAT, 2016

- This is probably the oldest galactic gamma-ray source as first association dates back to OSO-3 in the late 60s then SAS-2

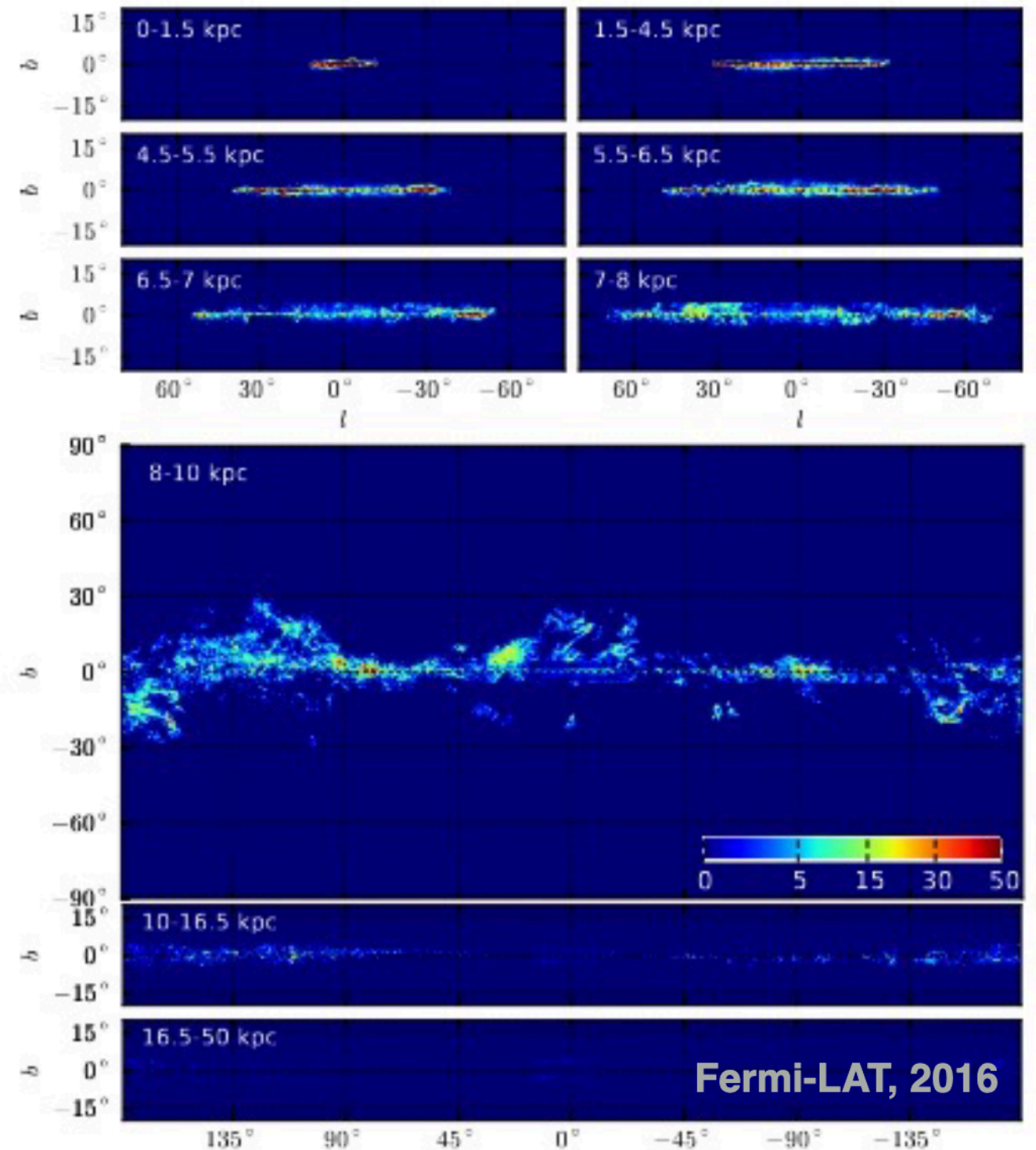
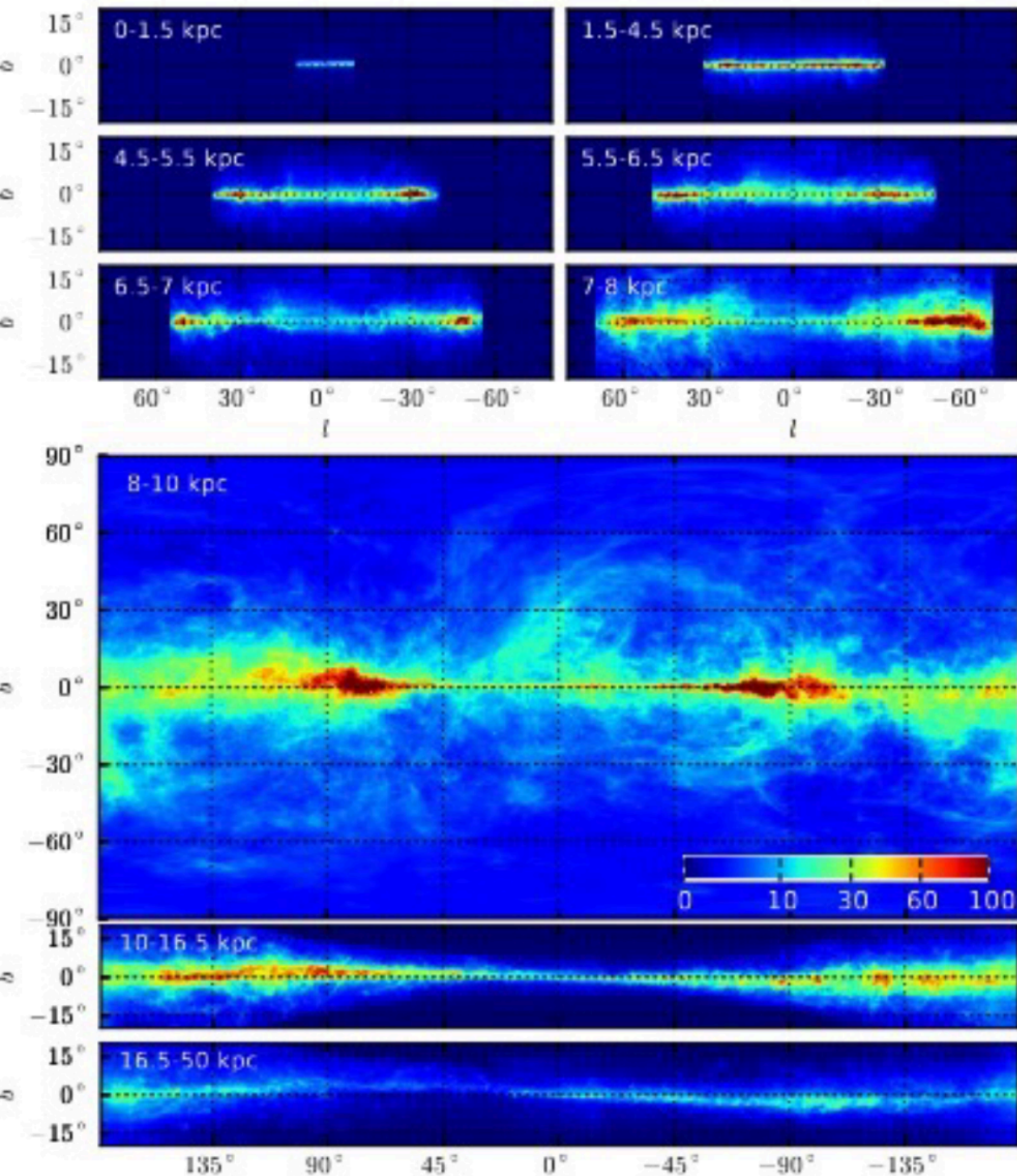
Galactocentric model of the diffuse emission

Galprop model

- CR protons + gas (HI+CO+DNM) & CR e- + radiation field

HI gas rings

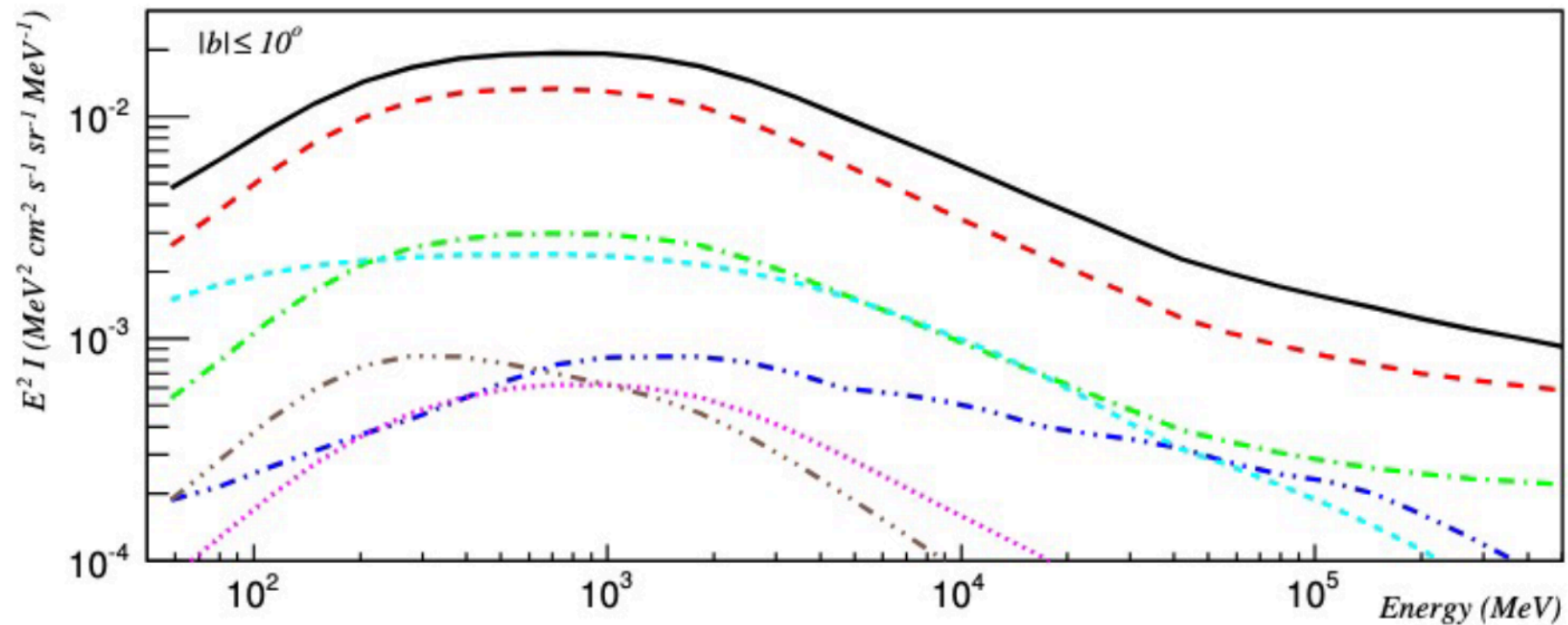
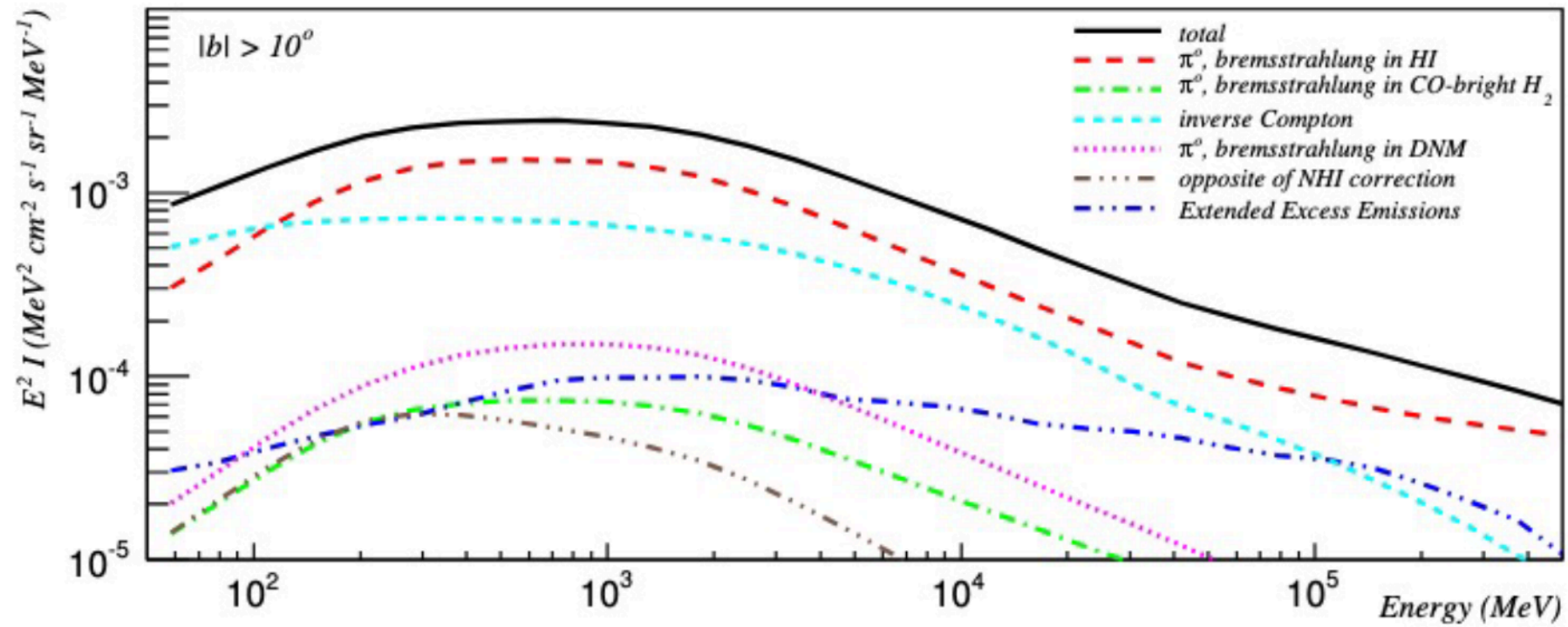
CO gas rings



Galactocentric model of the diffuse emission

- **CR protons + gas (HI+CO+DNM) & CR e- + radiation field**
 - Galprop model** (pointing to the main text)
 - HI gas rings** (pointing to HI in the main text)
 - CO gas rings** (pointing to CO in the main text)
- **DNM : dark neutral medium (H₂ material not well traced by CO)**
 - **Can be indirectly traced by dust (Planck&IR) but also gammas**
- **Large scale diffuse source added in the model with templates**
 - **Loop I**
 - **Fermi bubbles**
 - **Any source larger than 2° is included in the model**

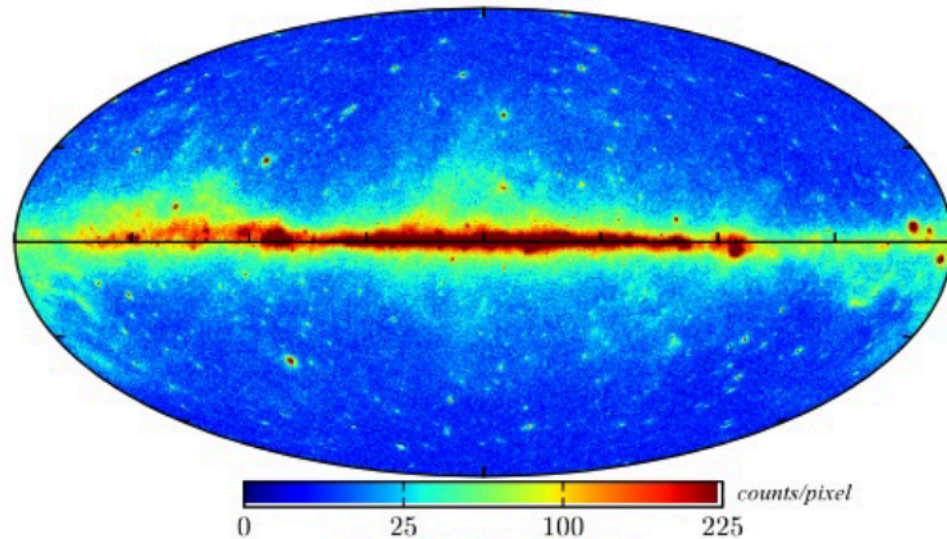
Spectral properties



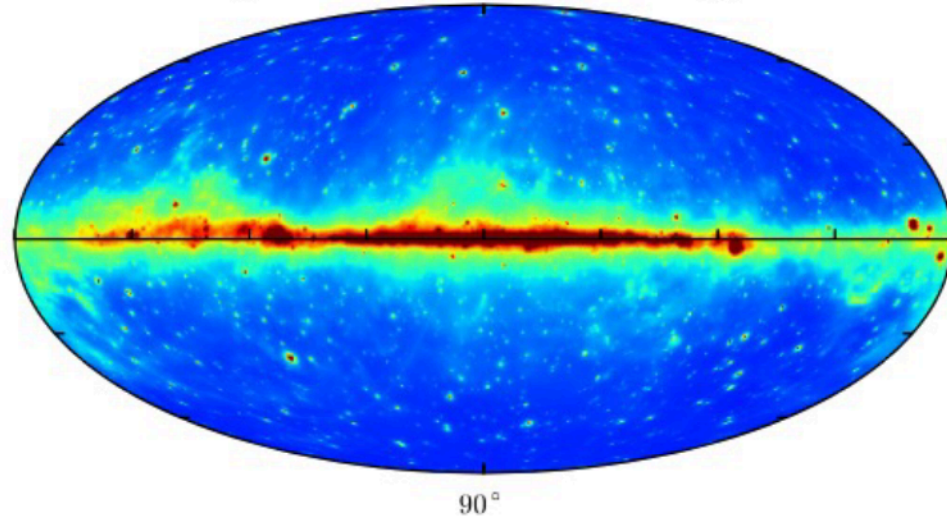
Fermi-LAT, 2016

The Fermi IEM model is not perfect

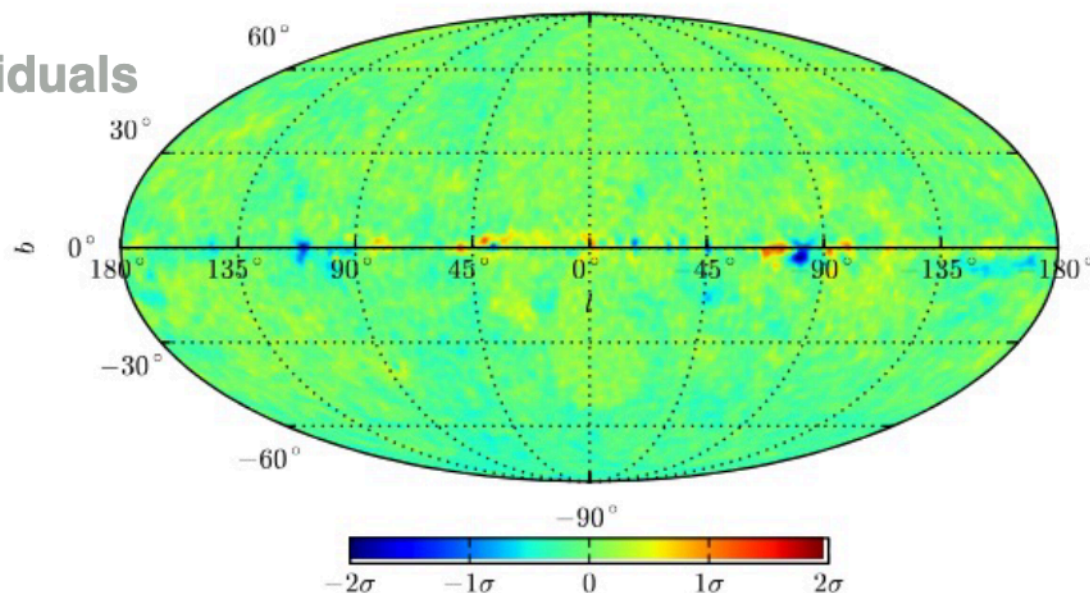
Data



Model



Residuals



- In some regions in the Galactic plane the standard diffuse model can leave significant residuals (especially after ~18 yrs of observations)
- Makes it difficult to explore the 100 MeV energy range in the Galactic plane for extended sources
- A new diffuse model is in preparation to accompany the 5 FGL catalog planned next year

A template free approach: Bayesian variational inference

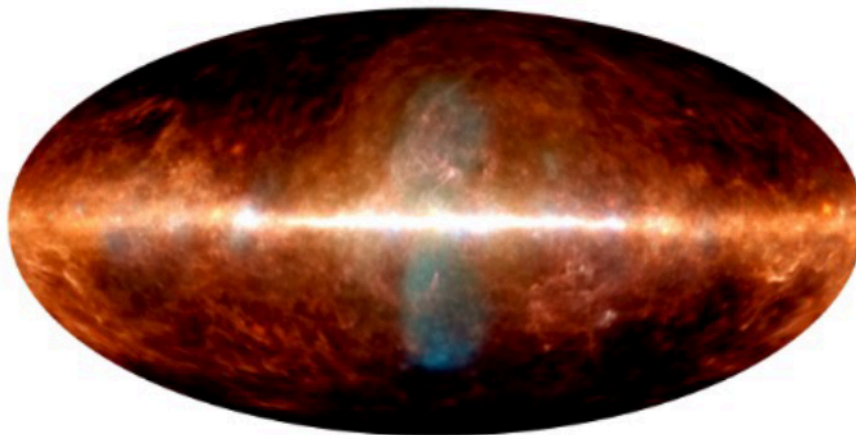
- Large literature to extract the diffuse emission in Fermi in particular near the Galactic center (excess ?)
- Variational inference here splits the data into a parametrized distribution of point source and diffuse emission

Platz et al., 2023

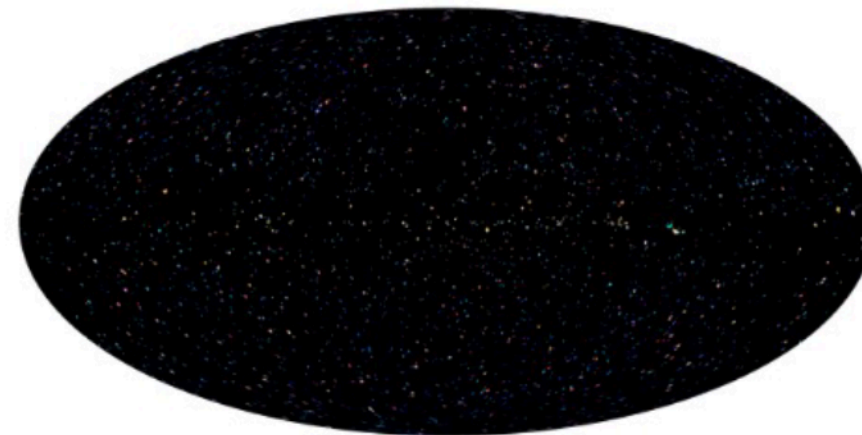
Summed model



Diffuse



Point sources



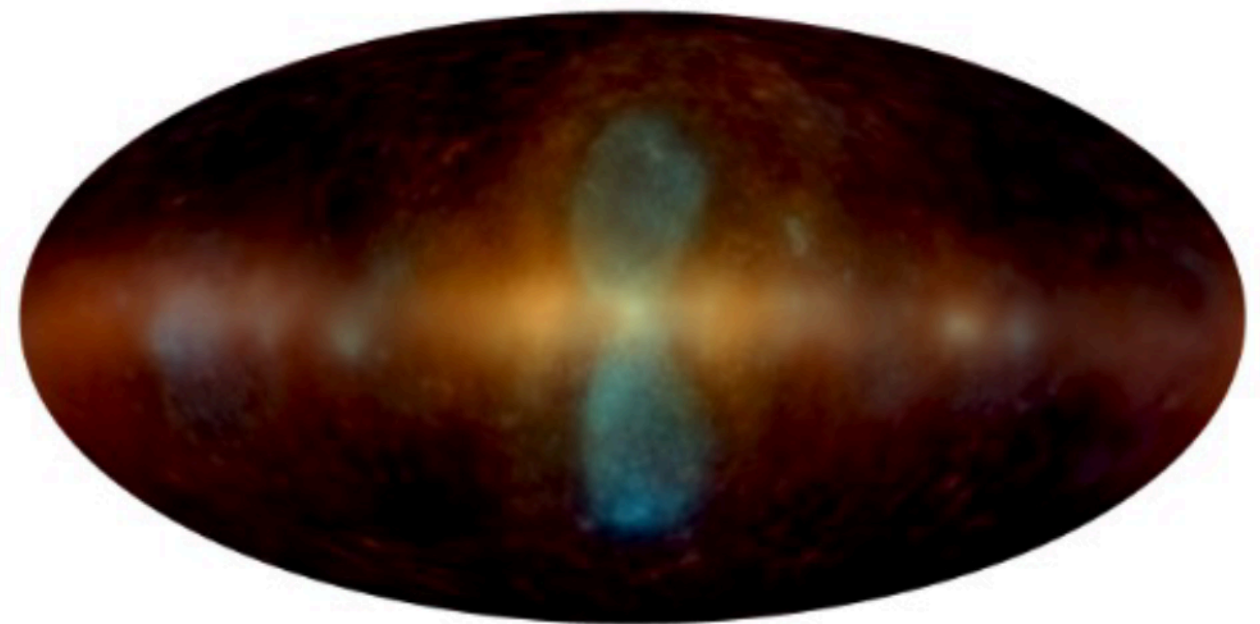
A template free approach: Bayesian variational inference

- Large literature to study the diffuse emission in Fermi in particular near the Galactic center (excess ?)
- Variational inference here splits the data into a parametrized distribution of point source and diffuse emission

Planck-dust informed component



Non Planck-dust diffuse component



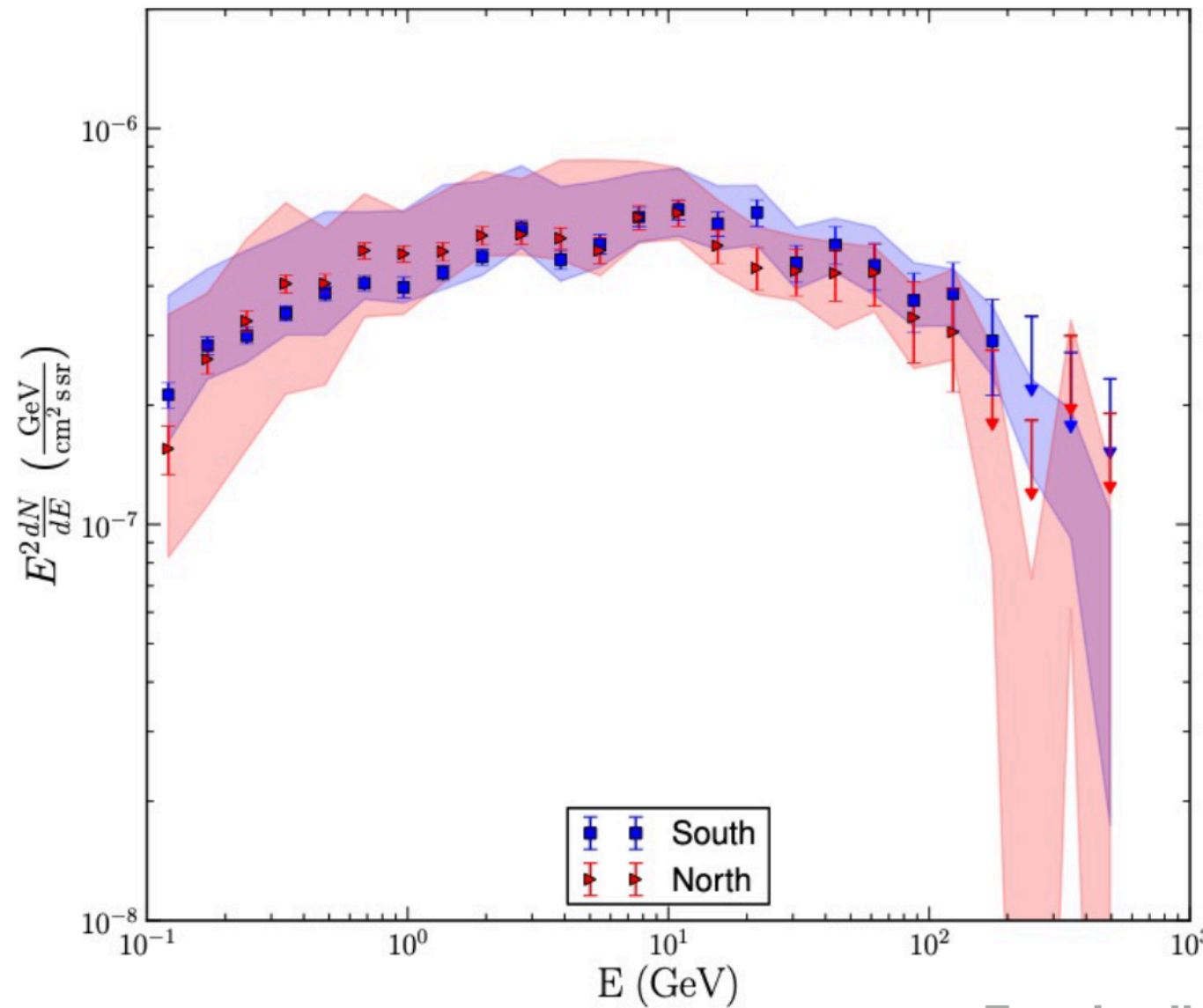
Point sources



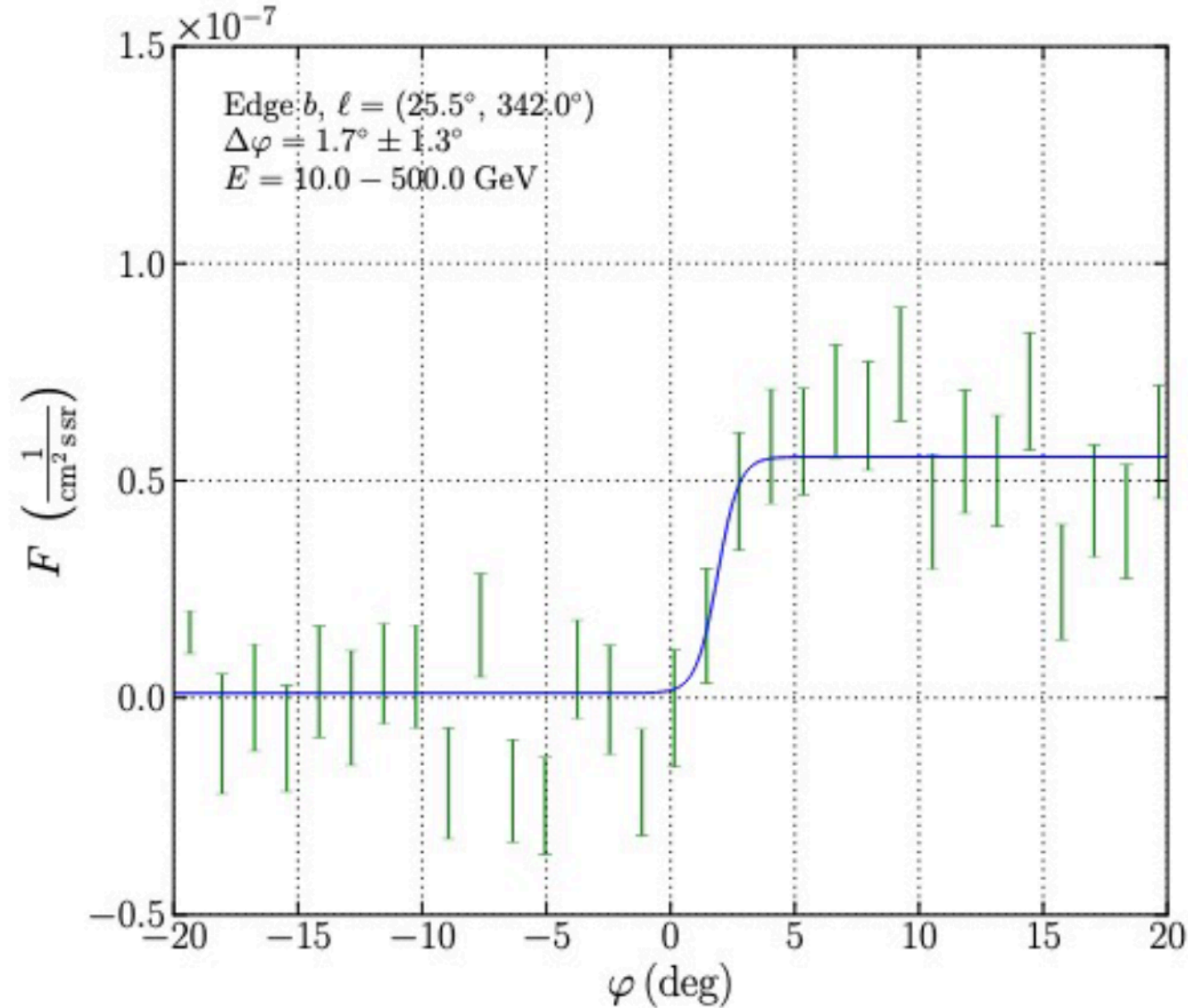
Reconstructs the 3d separated data

Platz et al., 2023

Fermi bubbles properties

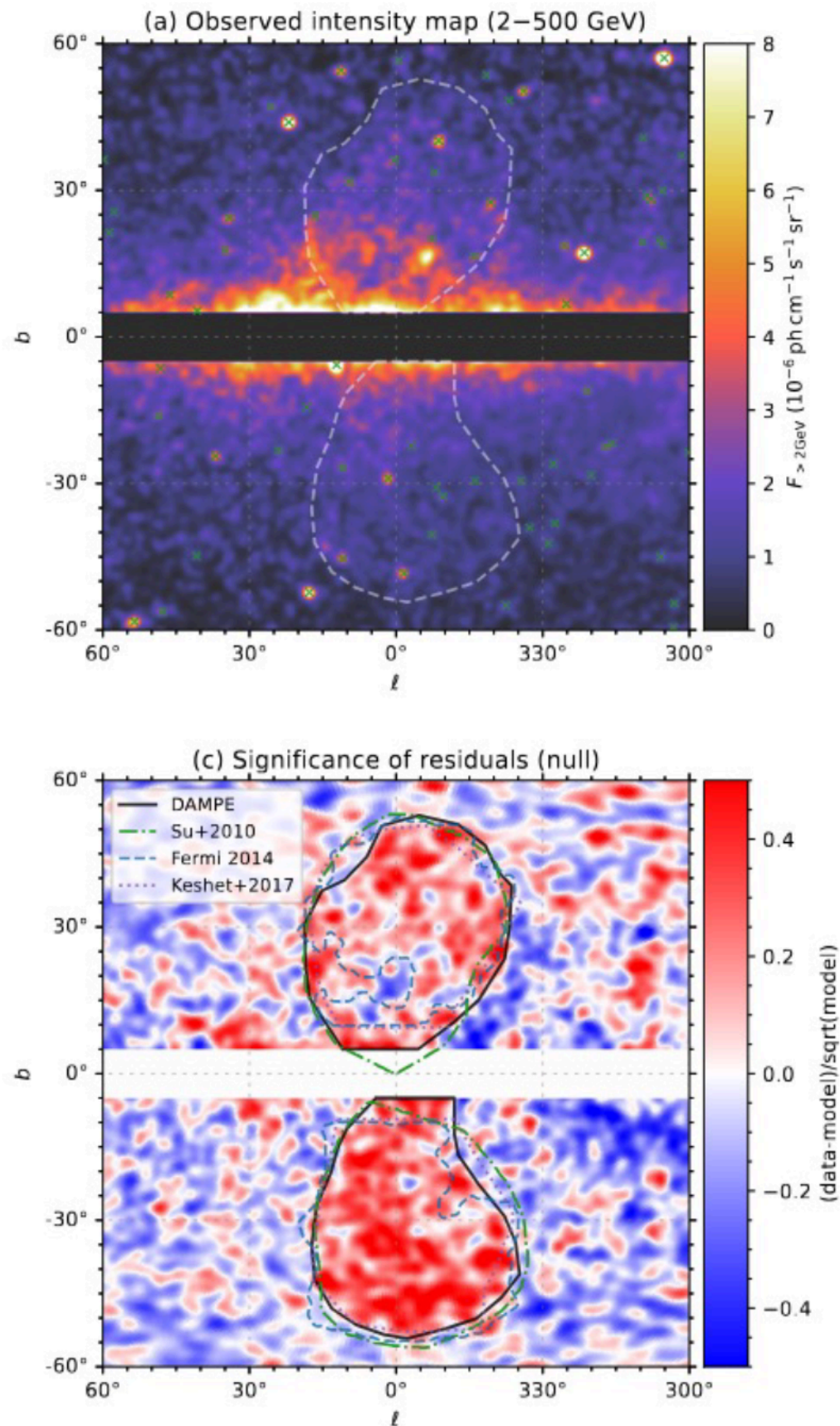


Fermi collaboration., 2014

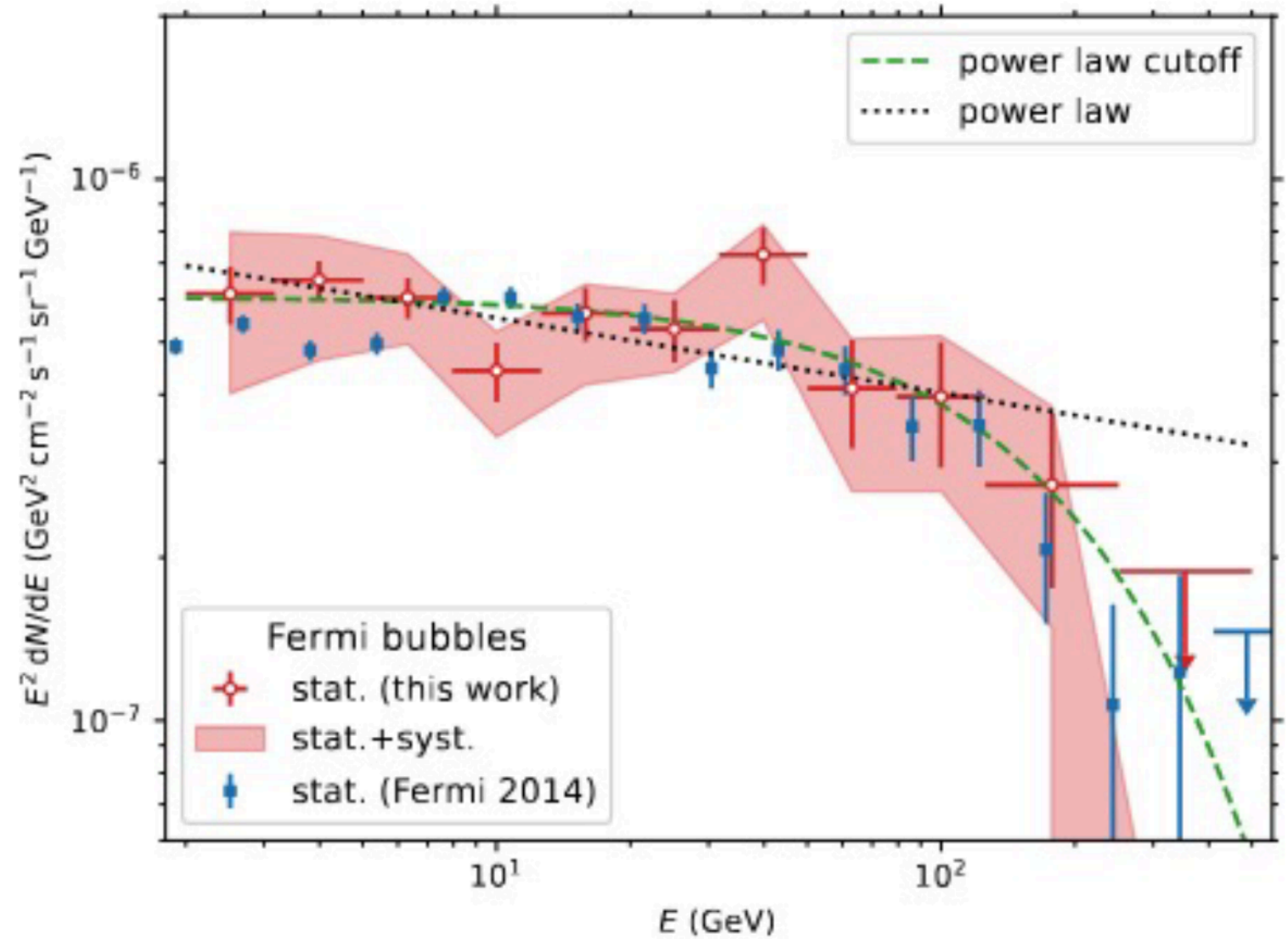


- Initially reported by Su et al 2010
- Sharp edges and similar North/South hard spectra up to ~ 100 GeV

DAMPE confirmation with 8 yrs of data



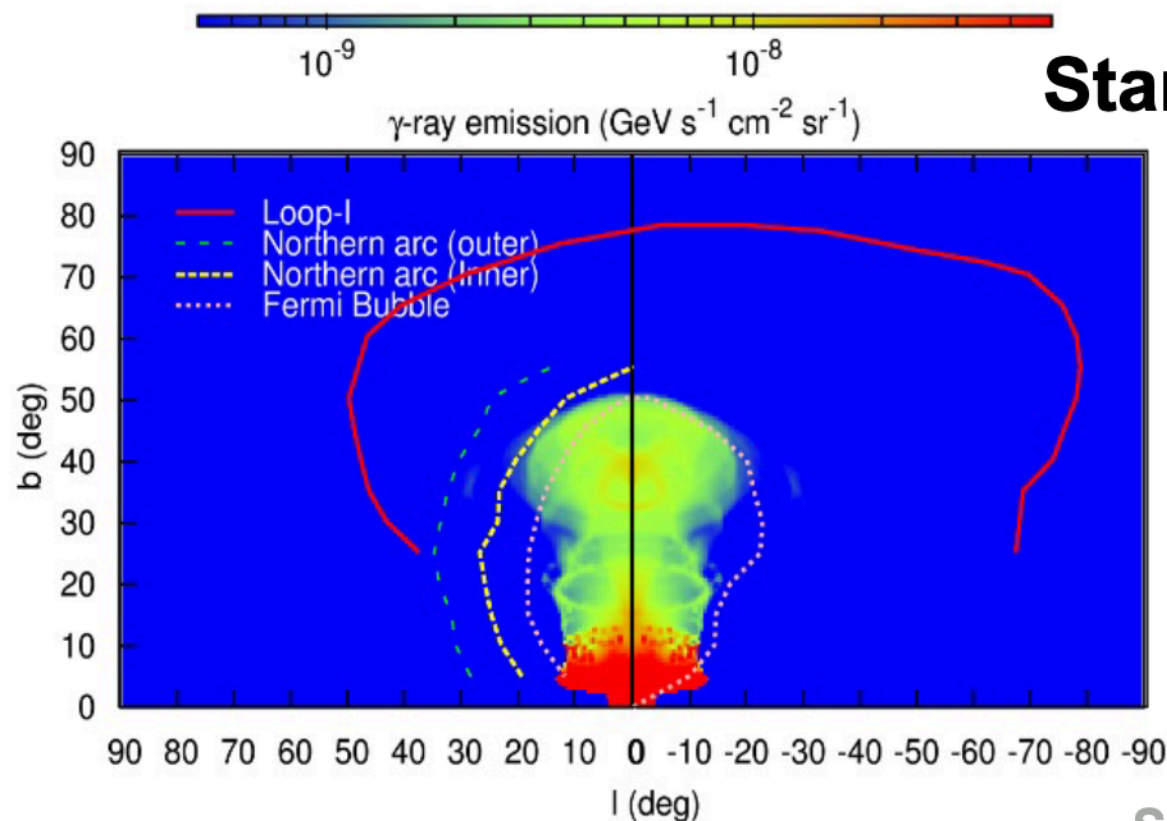
DAMPE collaboration, 2026



Fermi bubbles origin

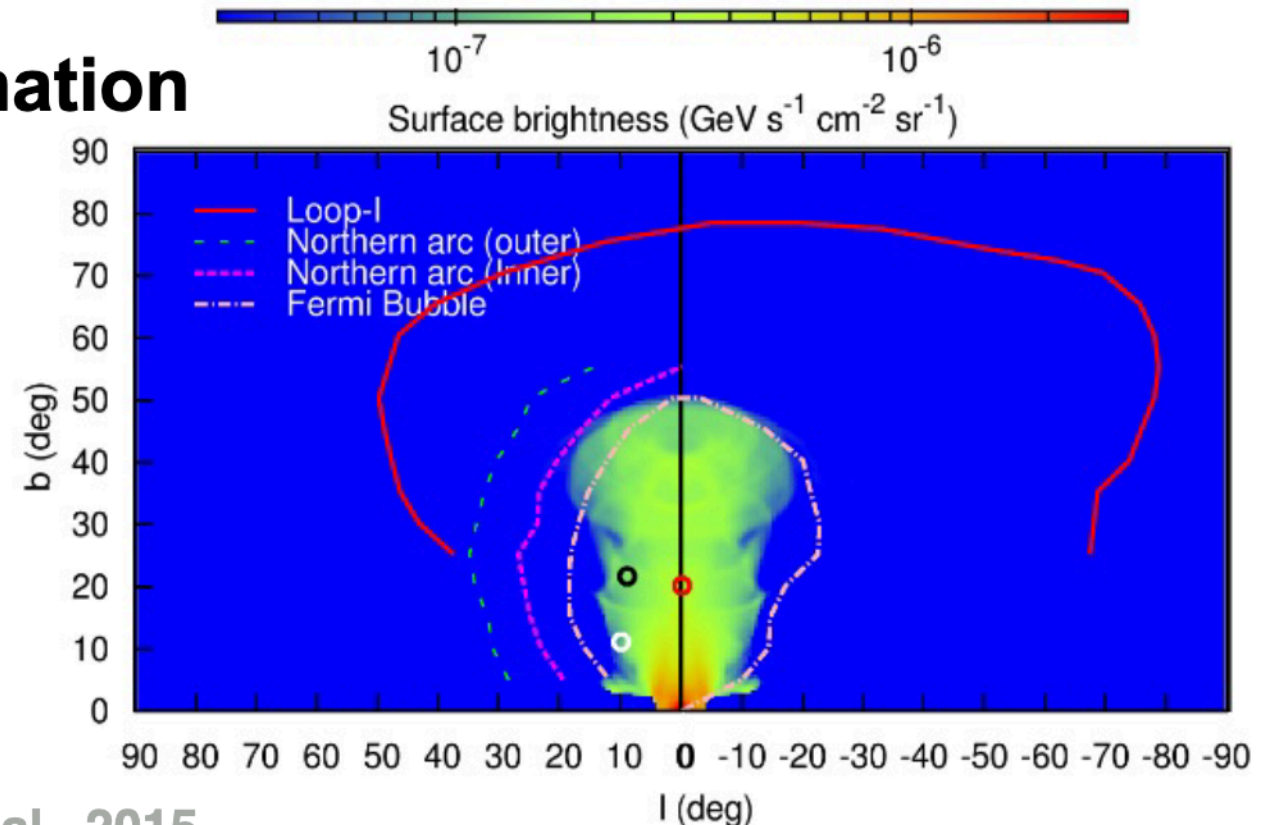
- Outburst from Sgr A* several millions years ago (tidal disruption event or an AGN-like phase) triggering bipolar jets
- Intense star formation event in the Galactic center. Collective power of thousands of SNe creating a galactic wind
- Nature of particles :

Hadronic



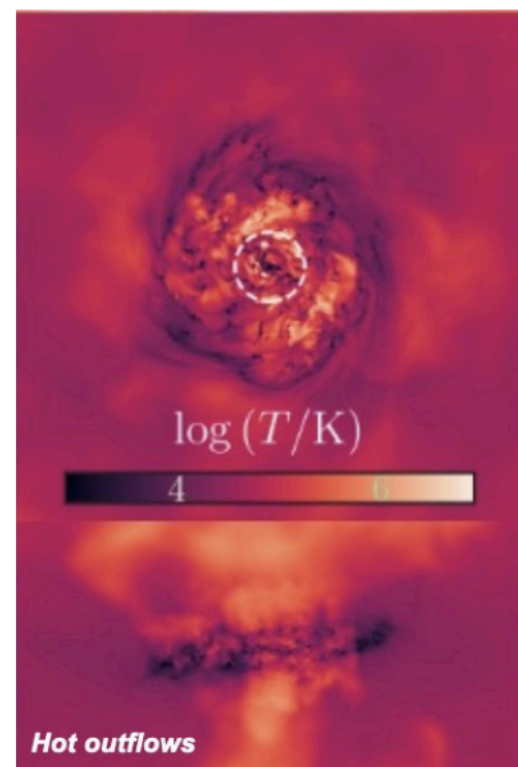
Star formation

Leptonic

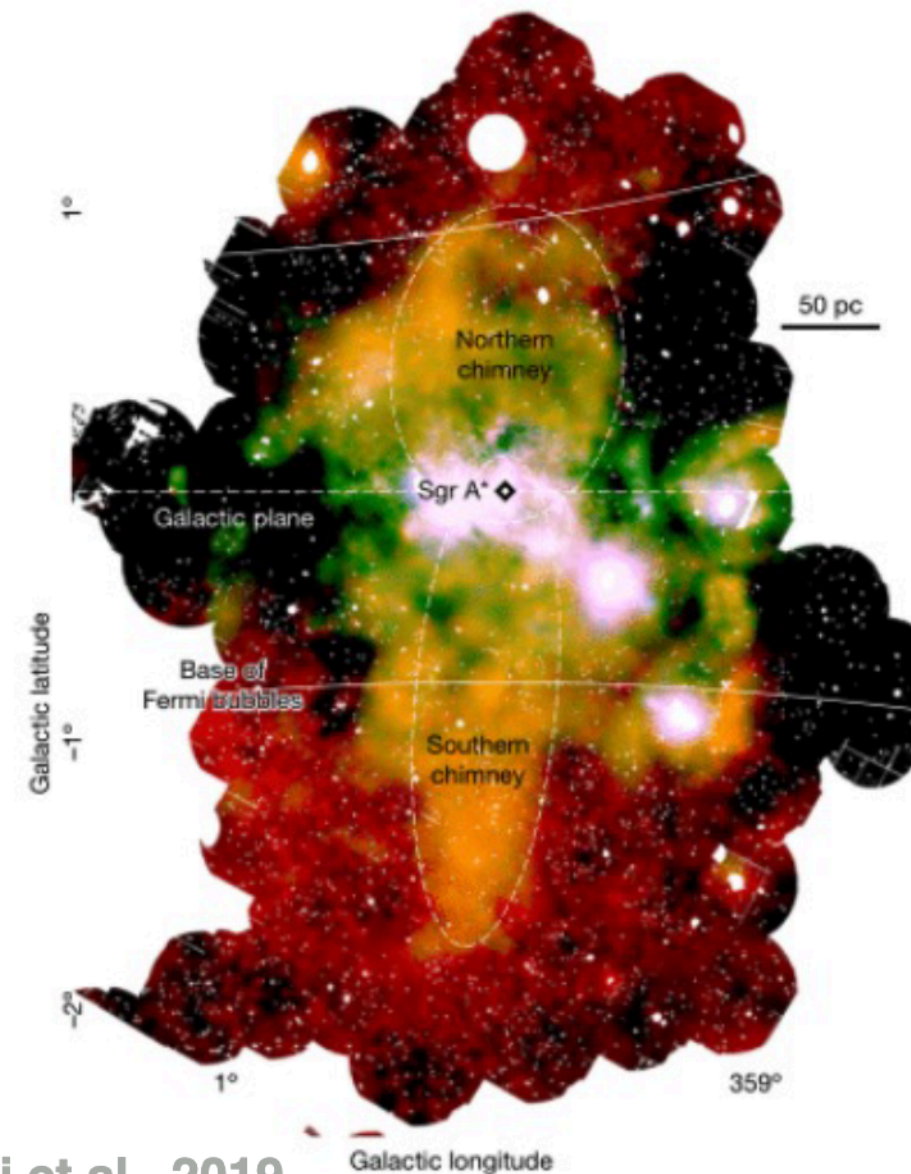


Fermi bubbles origin

- Outburst from Sgr A* several millions years ago (tidal disruption event or an AGN-like phase) triggering bipolar jets
- Intense star formation event in the Galactic center. Collective power of thousands of SNe creating a galactic wind X-ray chimneys
- Nature of particles : hadrons or leptons ?

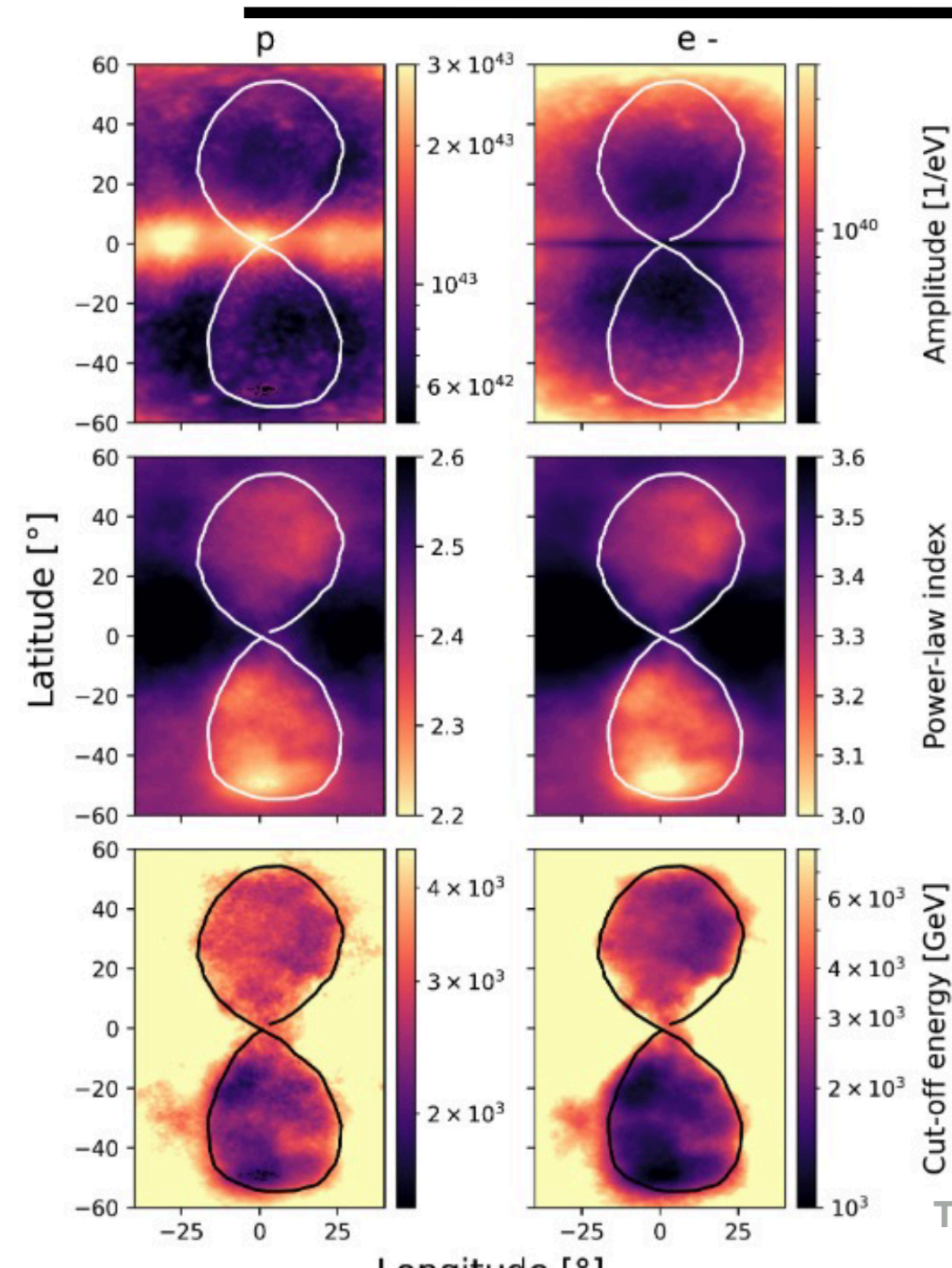


Temperature



Ponti et al., 2019

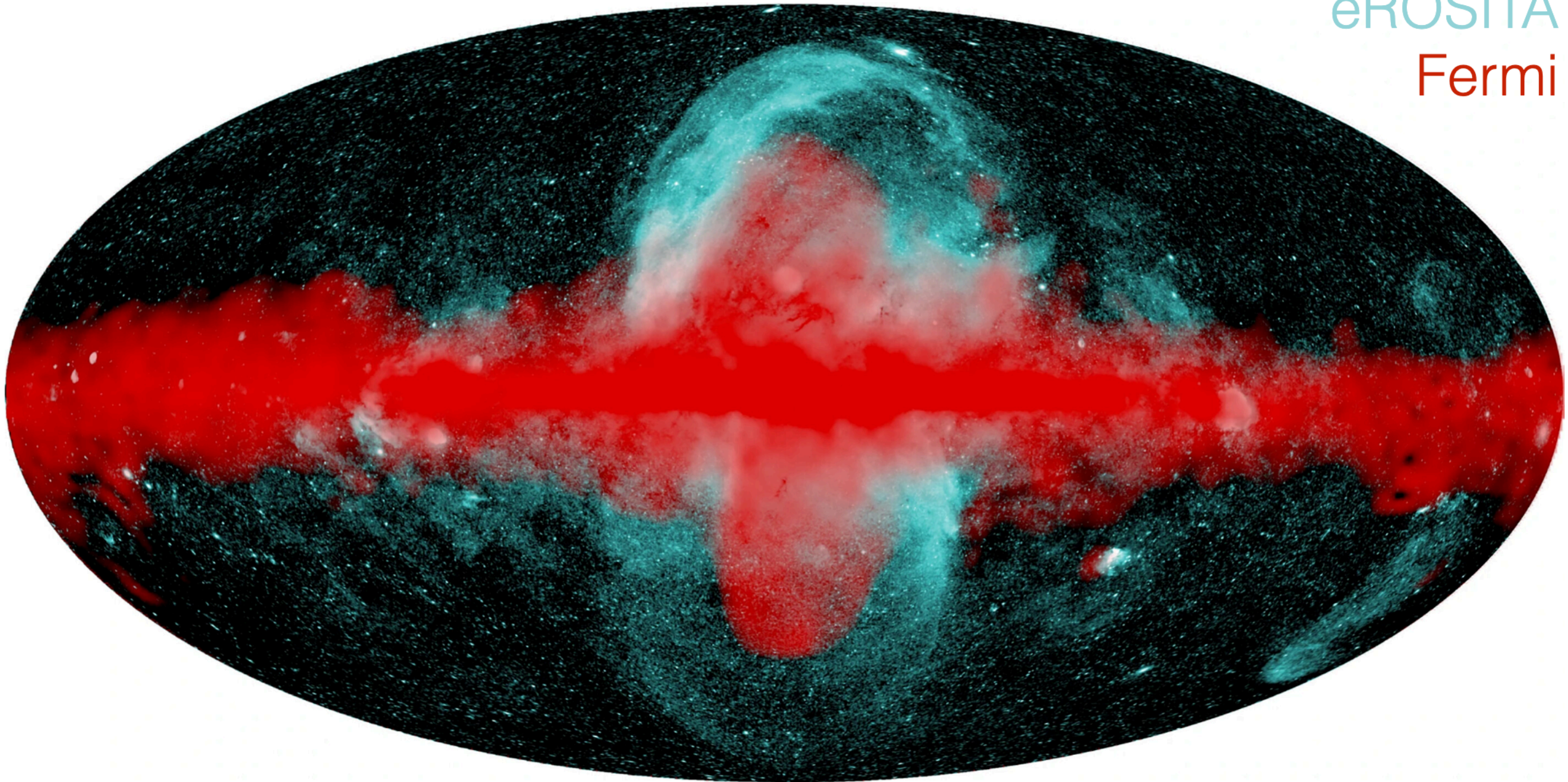
Spatial variations of the CR properties



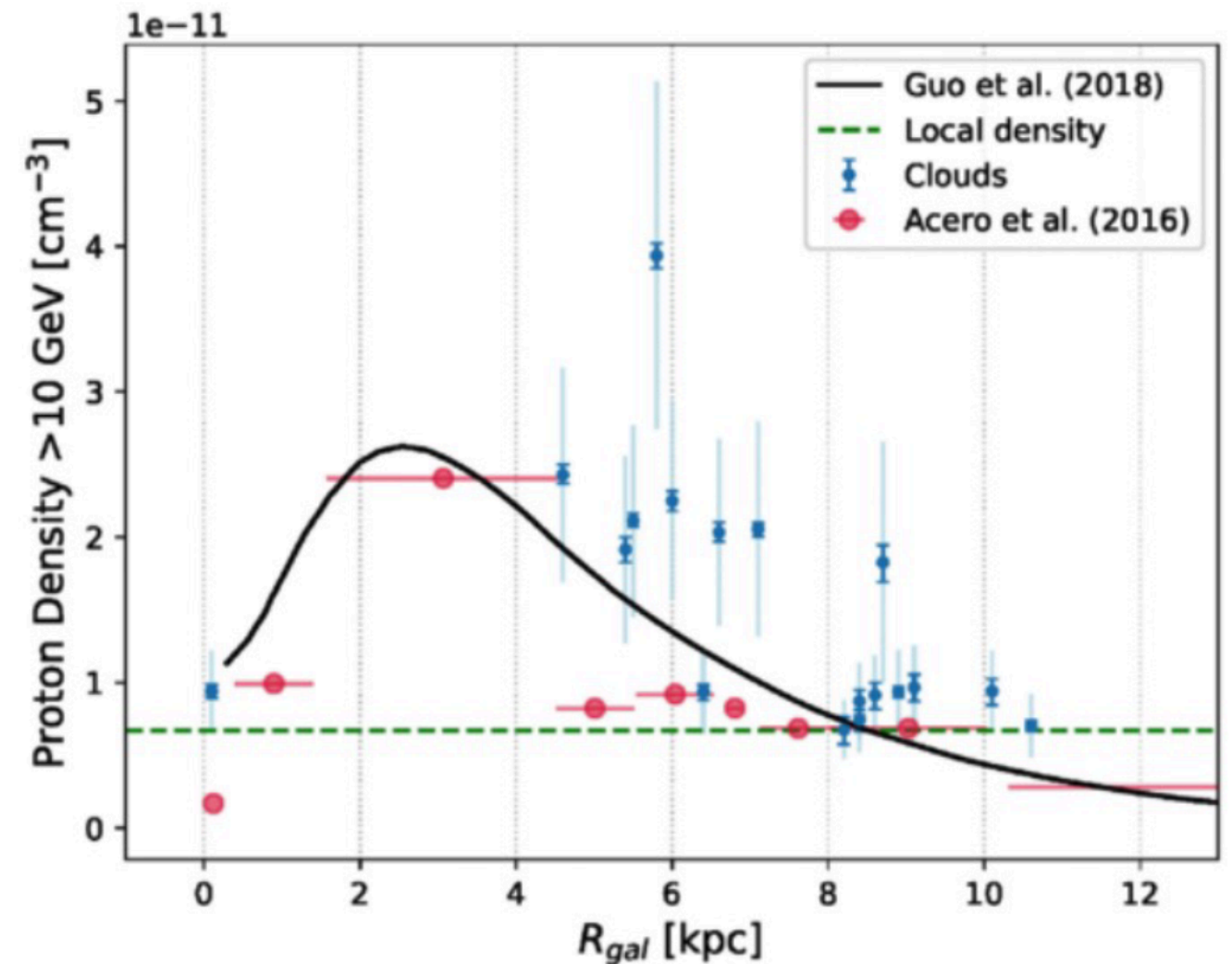
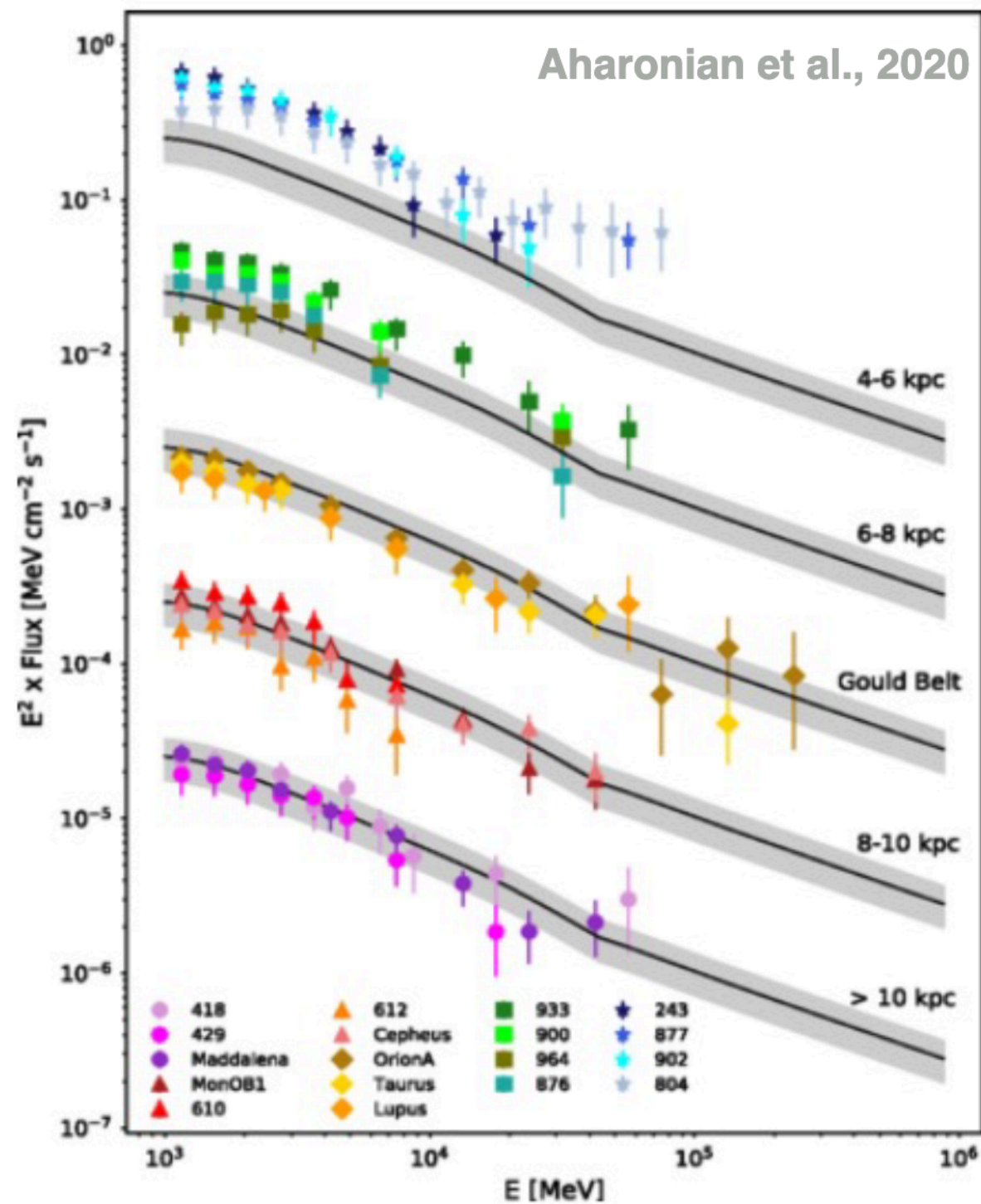
- Thanks to the 3d decomposition of Platz 2023 one can perform a pixel by pixel fit of a leptonic/hadronic radiative model (Naima)
- Assuming an ECPL population, spectral variations are observed between North/South
- Possible hardening towards the southern edge (also hinted by Yang+14)
- Disfavors injection from GC & would favor in-situ acceleration

Link with the eROSITA bubbles

eROSITA
Fermi

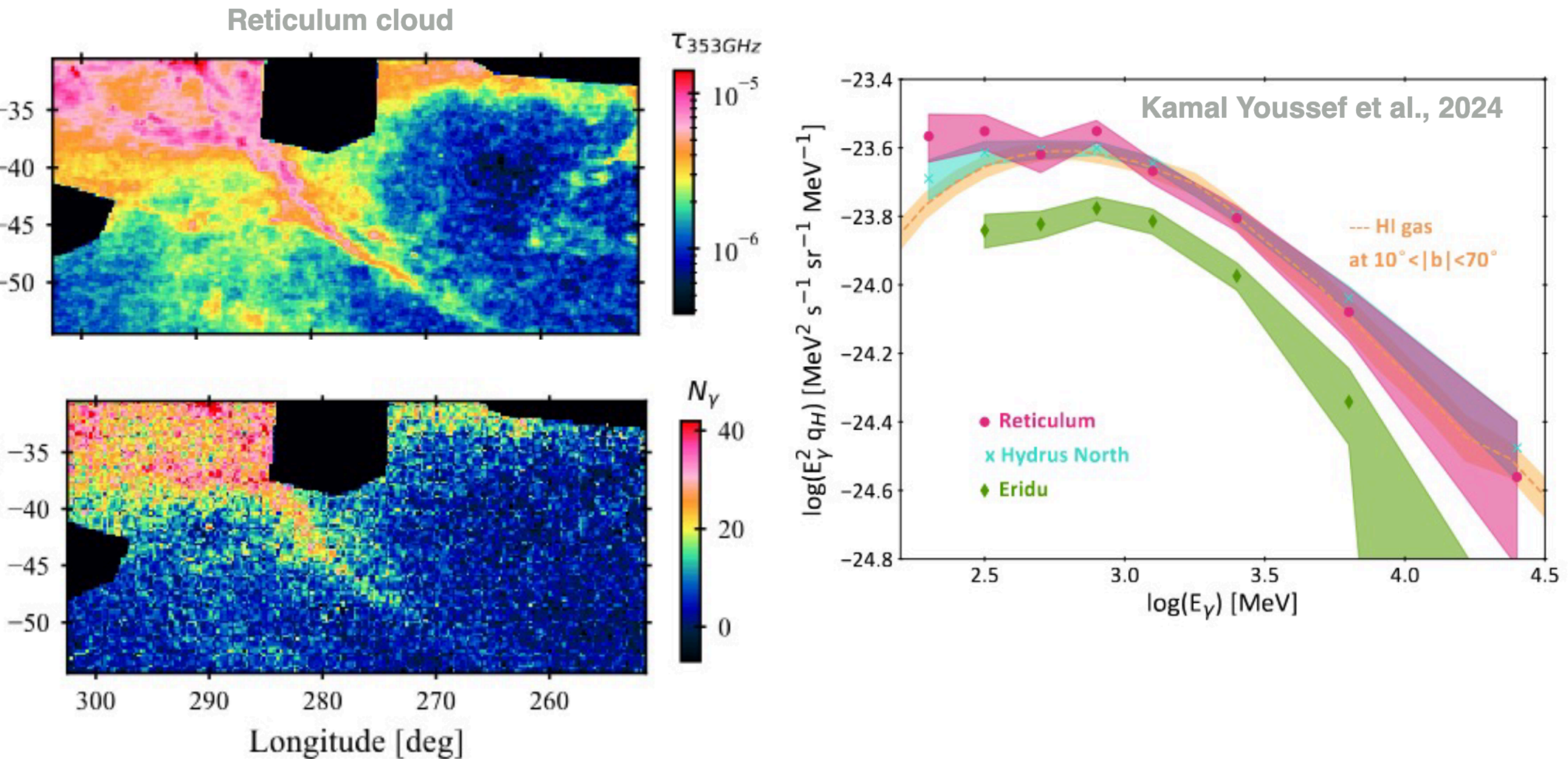


Using clouds as local barometers of CRs



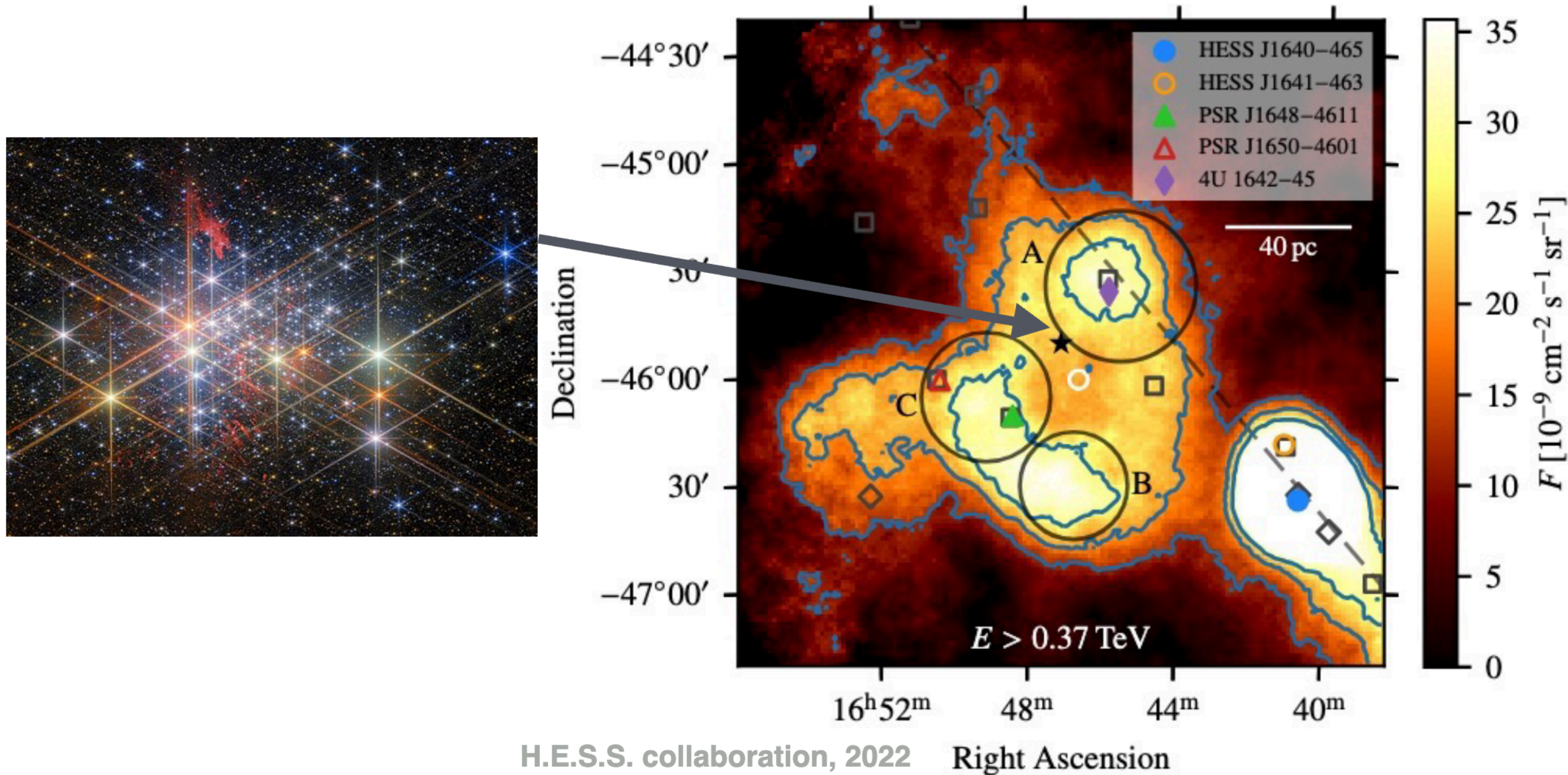
- Using a collection of Giant molecular clouds across the Galaxy one can probe the density of CRs at different locations
- Mostly homogeneous sea of CRs except between 4-8 kpc radius

Not all molecular clouds are alike



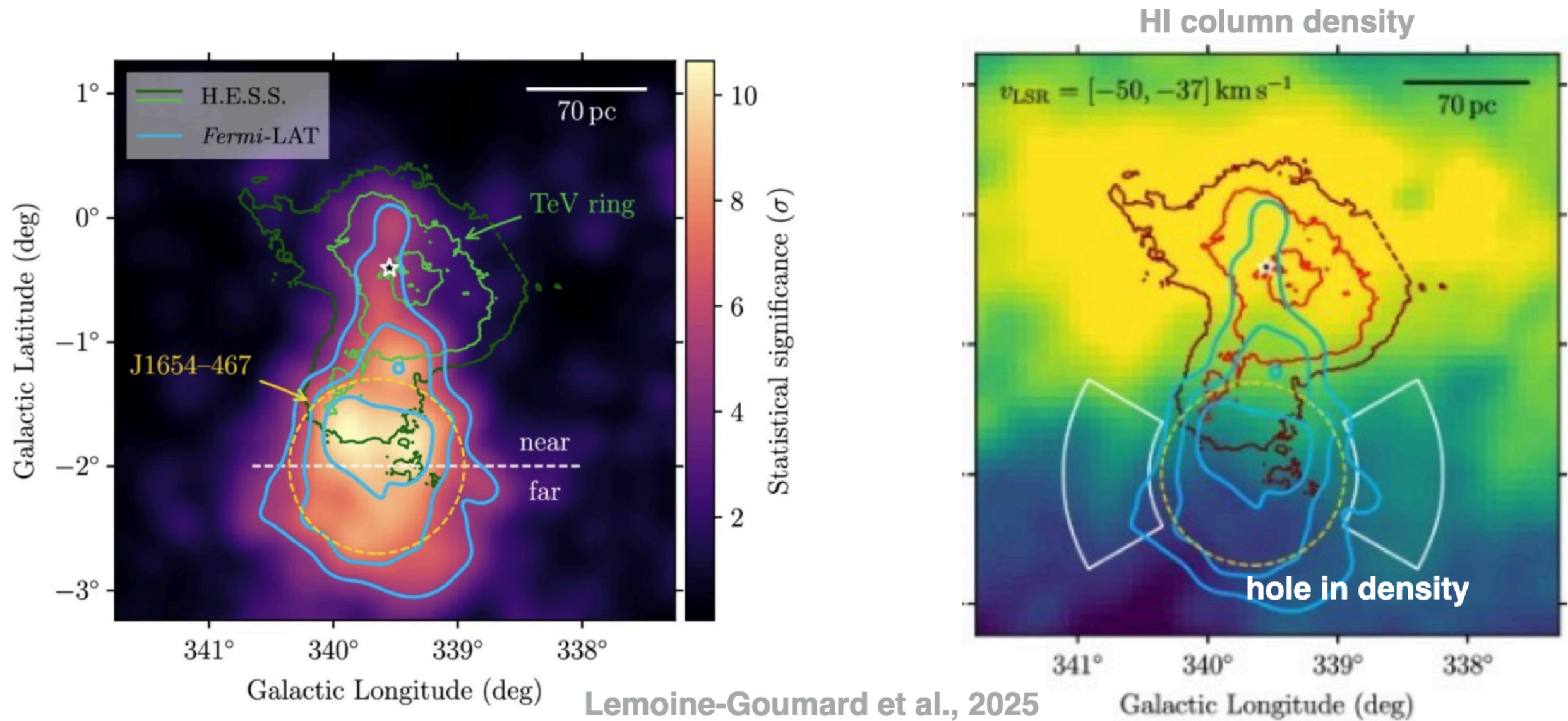
- Comparison of Eridu+Reticulum (a few 100 pc away cloud) highlight different CR densities in the solar neighborhood
- Can even measure coefficient diffusion at parsec scale (very extended on the sky)

Westerlund 1: most massive Galactic cluster ($10^5 M_{\text{sun}}$)



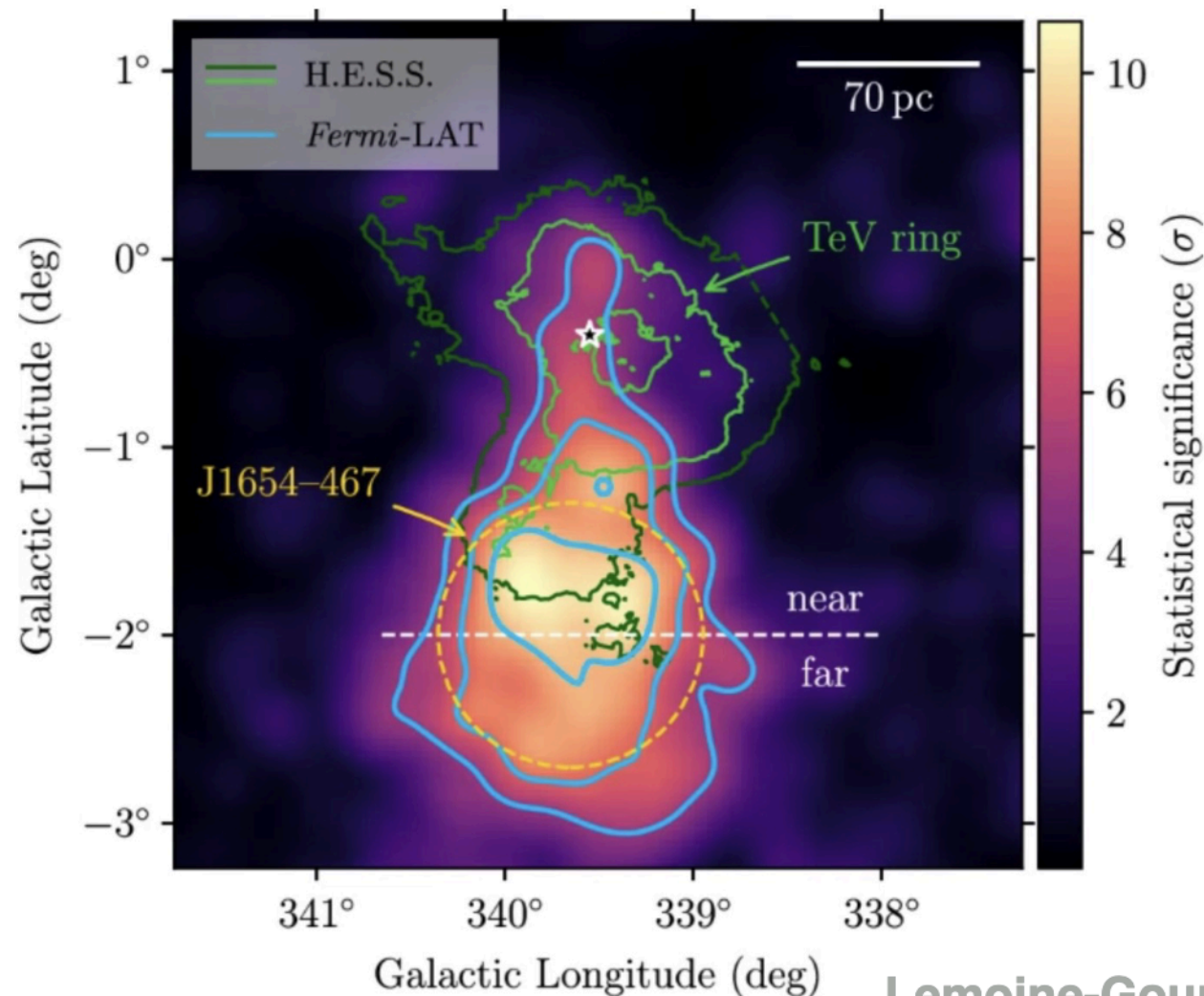
- Large 2° extended gamma-ray emission with shell-like structure
- No clear correlations with HI or CO gas & no spectral variations
- Possibly acceleration at the collective wind termination shock

Westerlund 1 : The Fermi view of a nascent outflow

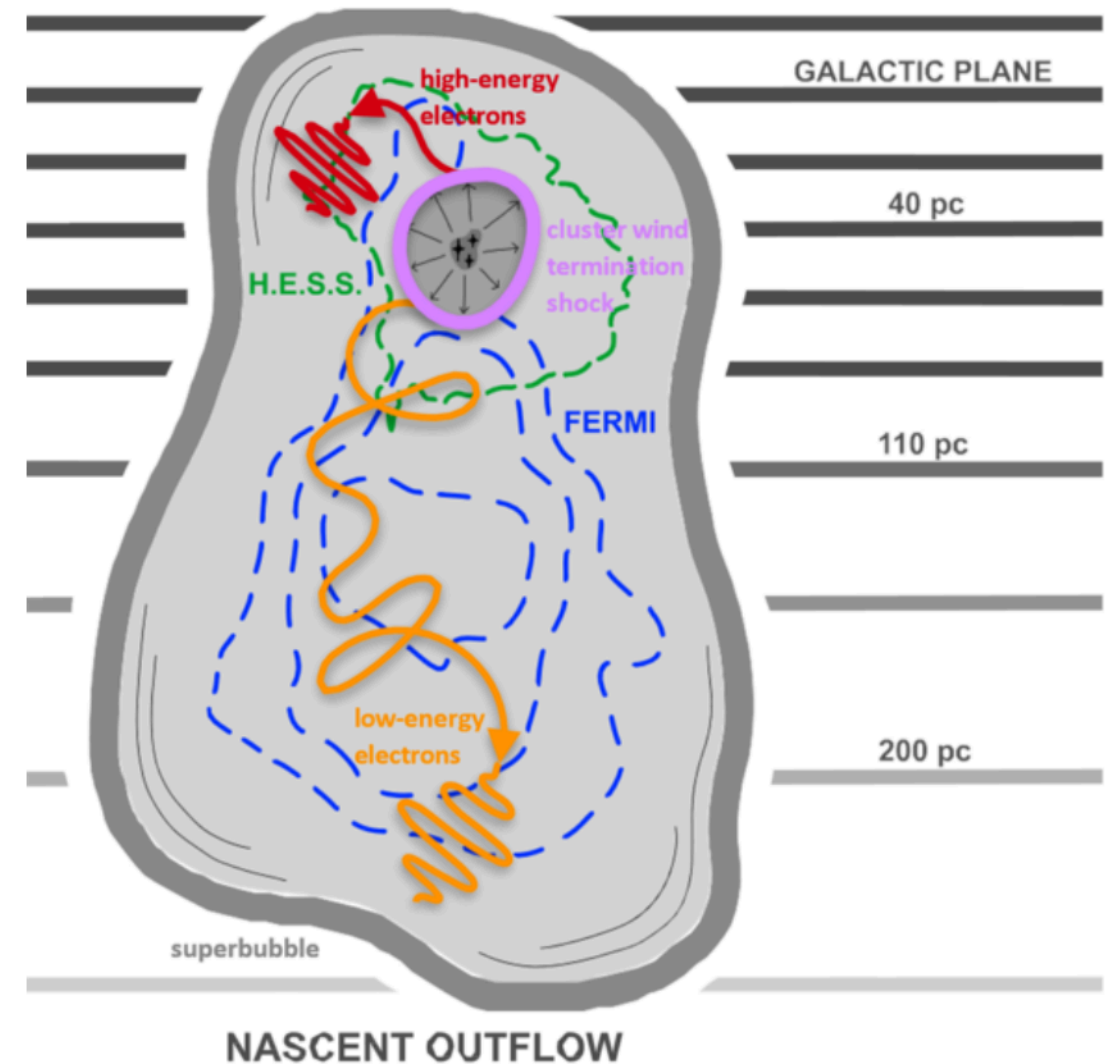


- **CRs accelerated in the wind termination shock and transported south due to density asymmetry**
-

Westerlund 1 : The Fermi view of a nascent outflow



Lemoine-Goumard et al., 2025



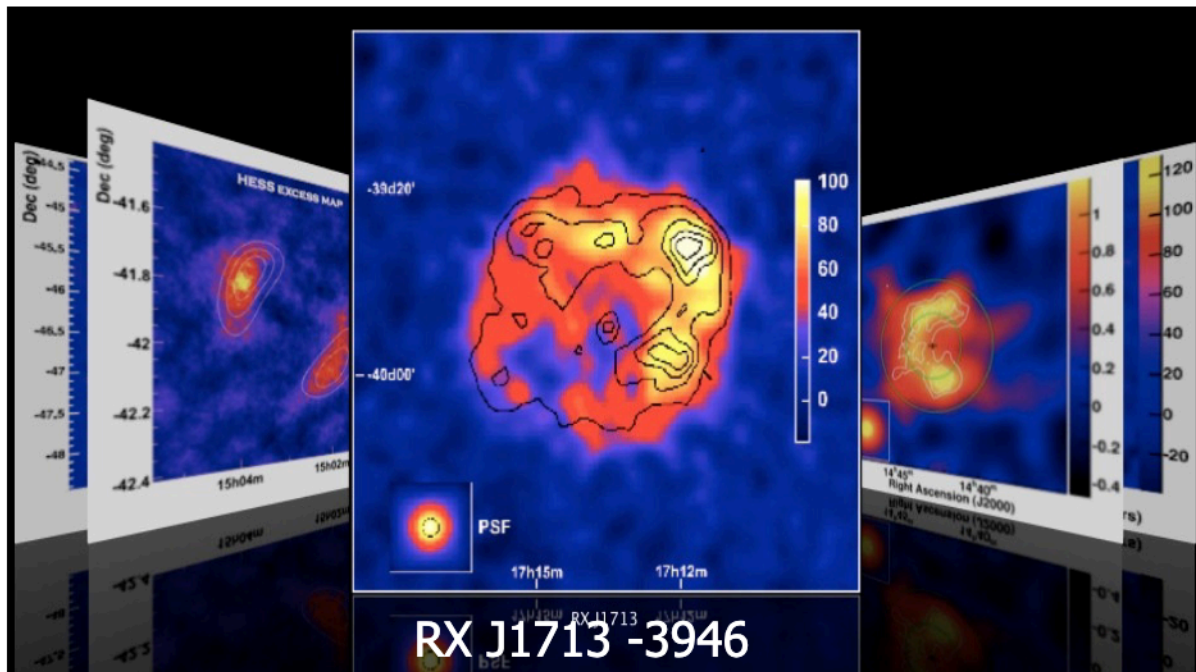
- **CRs accelerated in the wind termination shock and transported south due to density asymmetry**
- **Electron energy density is $1-10 \text{ eV cm}^{-3} \gg$ local CR density**

Two families of gamma-ray SNRs

Shell morphology

young SNR ~ 1000 yrs

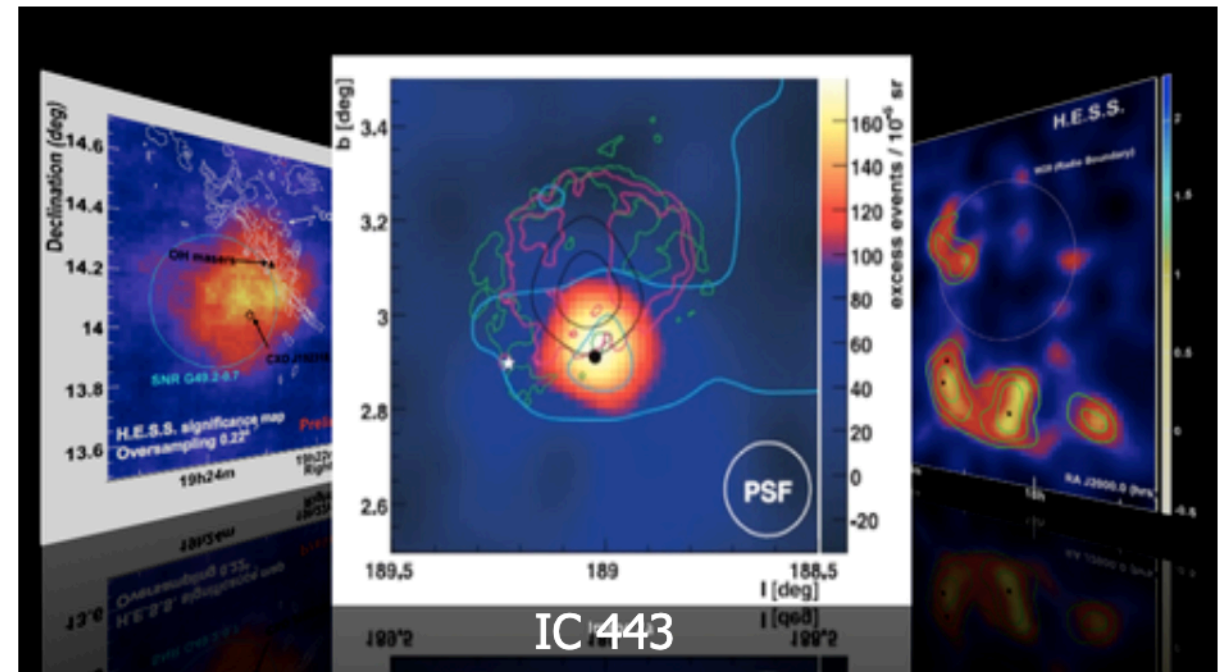
Vela Jr, RX J1713-3946,
RCW 86, SN 1006, HESS J1731



Interacting SNR

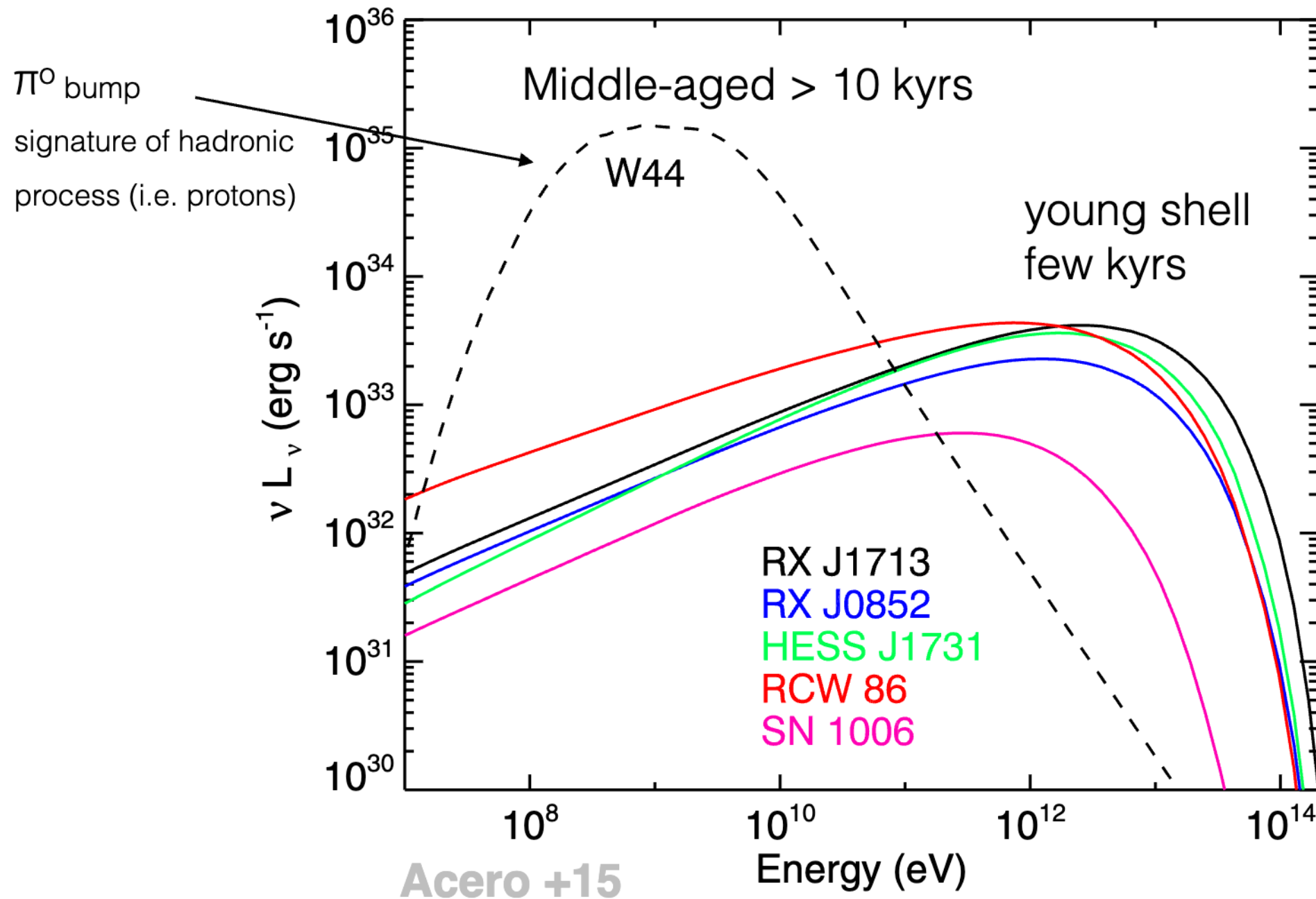
middle-aged $t \sim 10$ kyrs

IC 443, W28, W51, etc

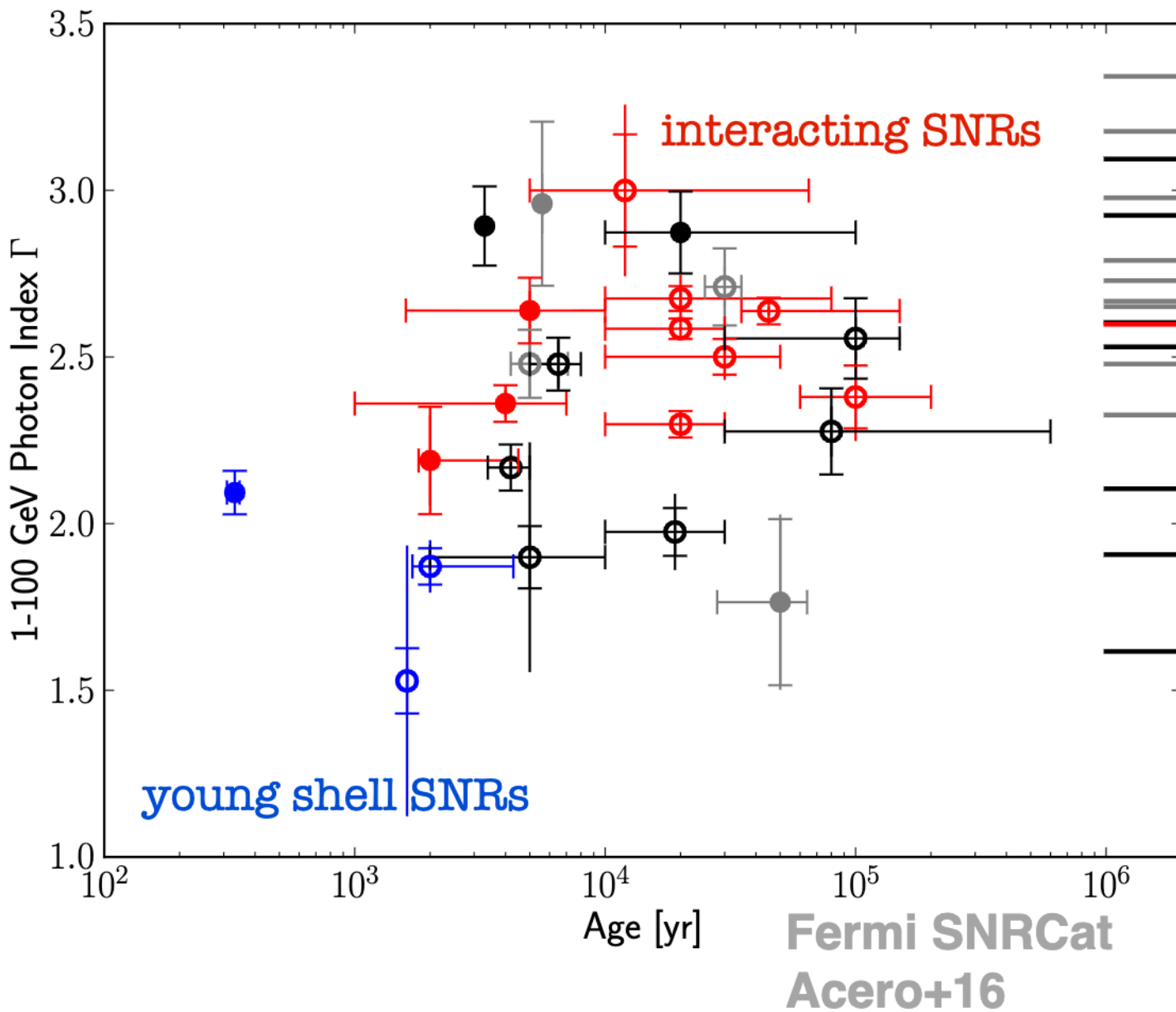


GeV/TeV populations

- Middle-aged interacting GeV bright SNRs
- Young TeV bright shell SNRs

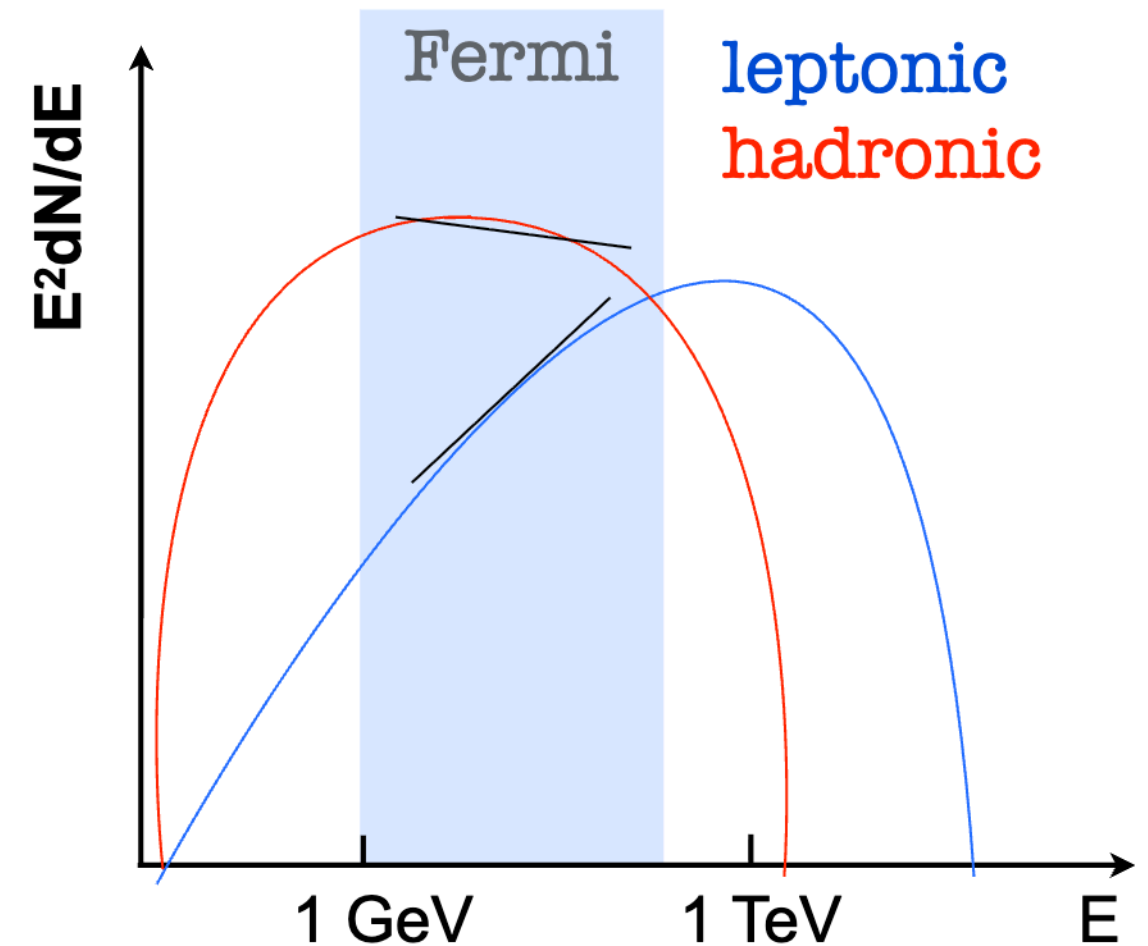


Age - GeV index



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

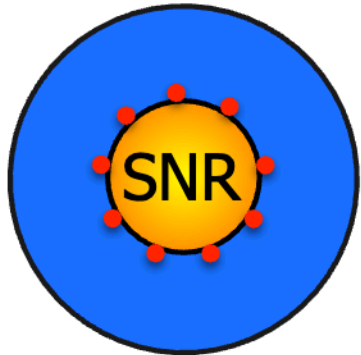
- Change of dominant emission mechanism
- Different zones properties



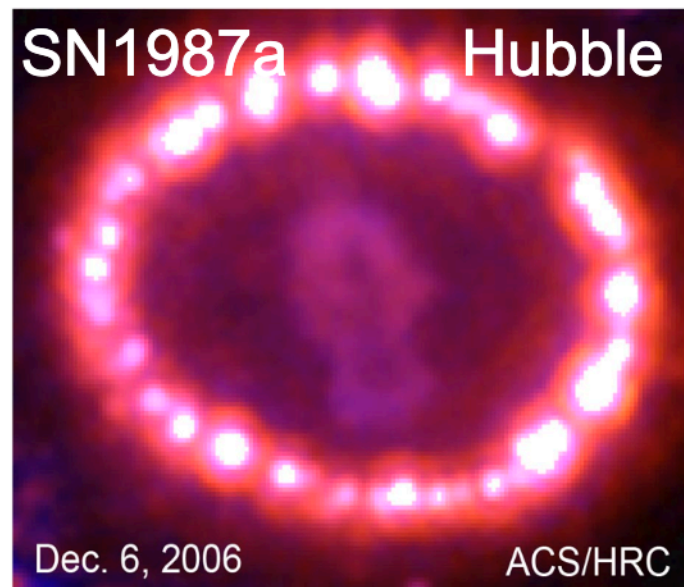
A simple time evolution picture

- Time evolution of gamma-ray emission from SNRs

$T < 100$ yrs

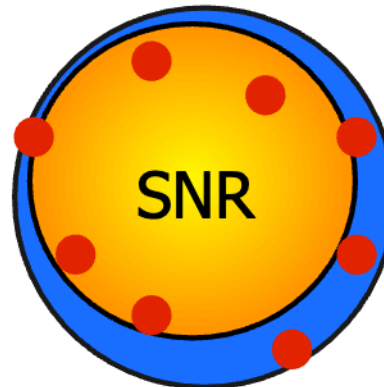


Circumstellar medium

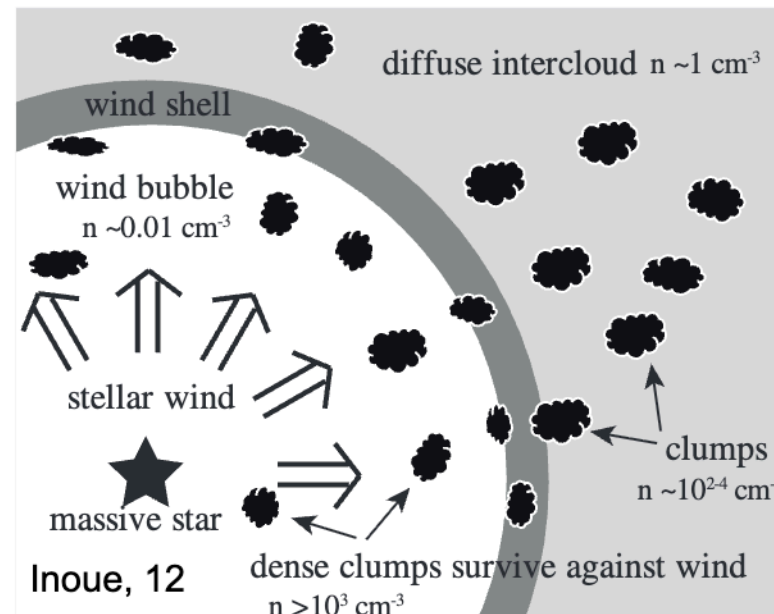


High density
Possible hadronic γ -ray
Leptonic γ -ray

$T \sim \text{few kyr}$

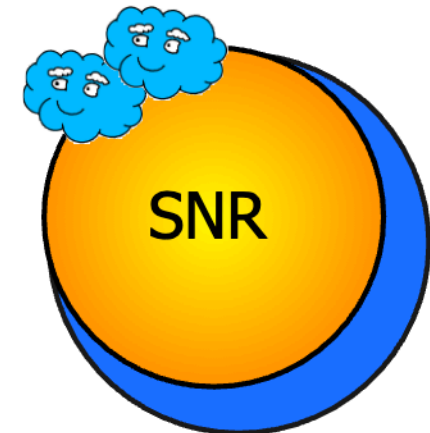


Low density cavity+clumps

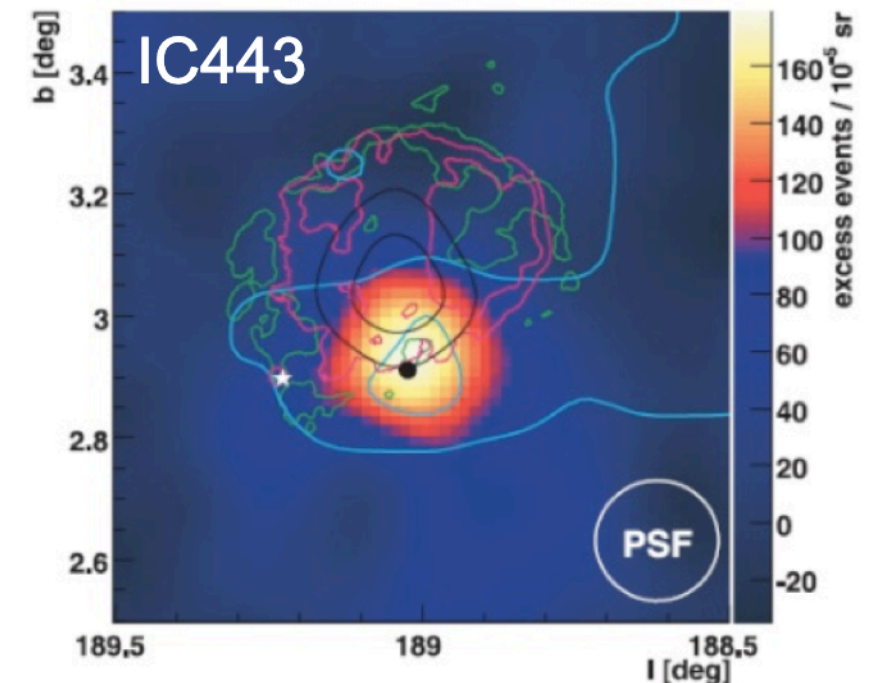


Leptonic γ -ray
+hadronic from clumps

$T \sim \text{few } 10 \text{ kyr}$

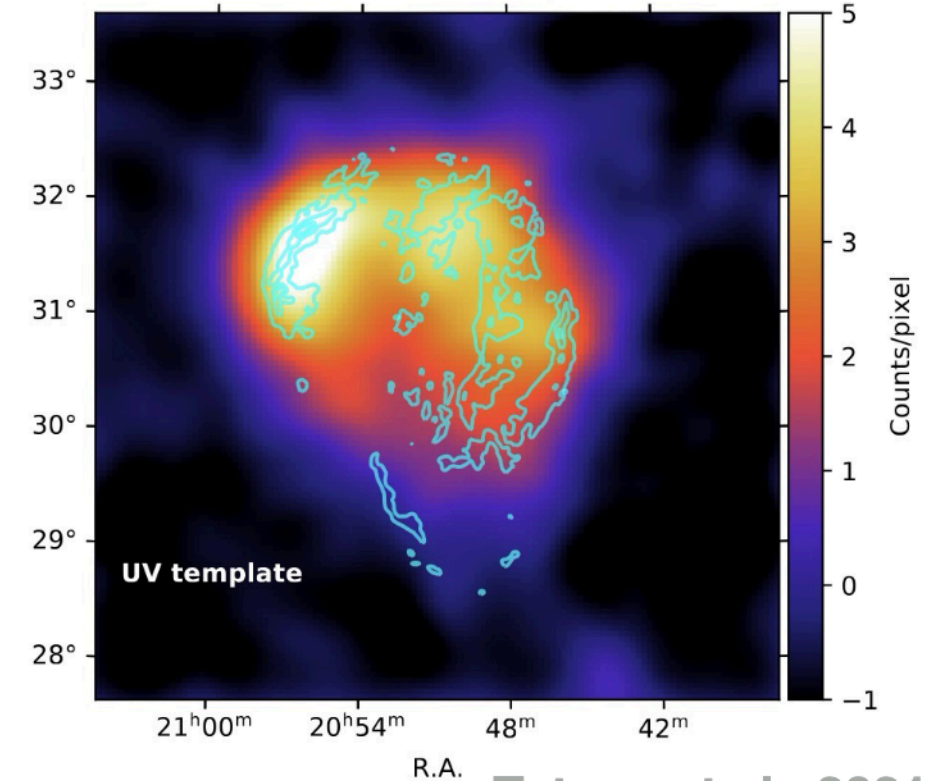
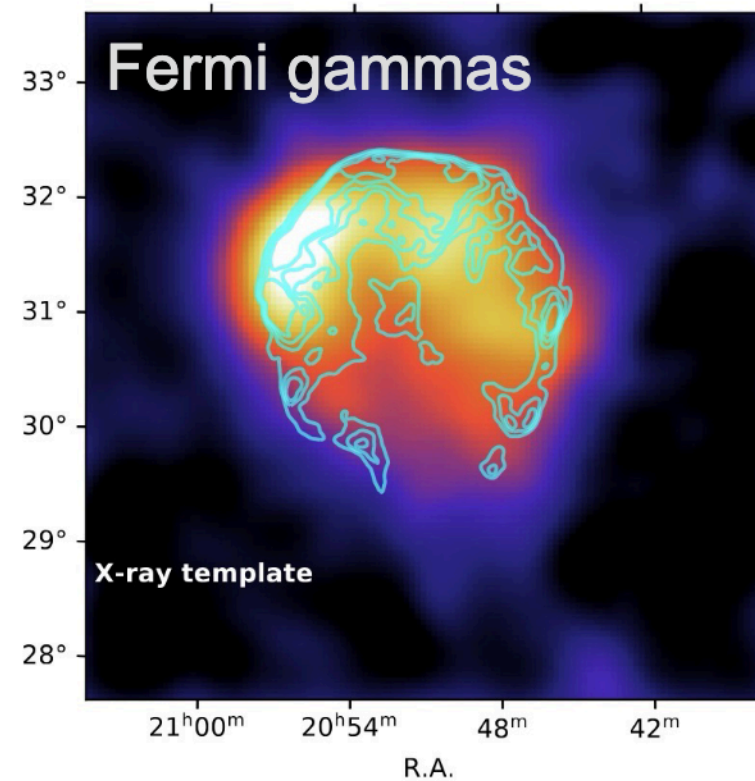


Cavity border + clouds



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

Cygnus loop : evolved nearby SNR



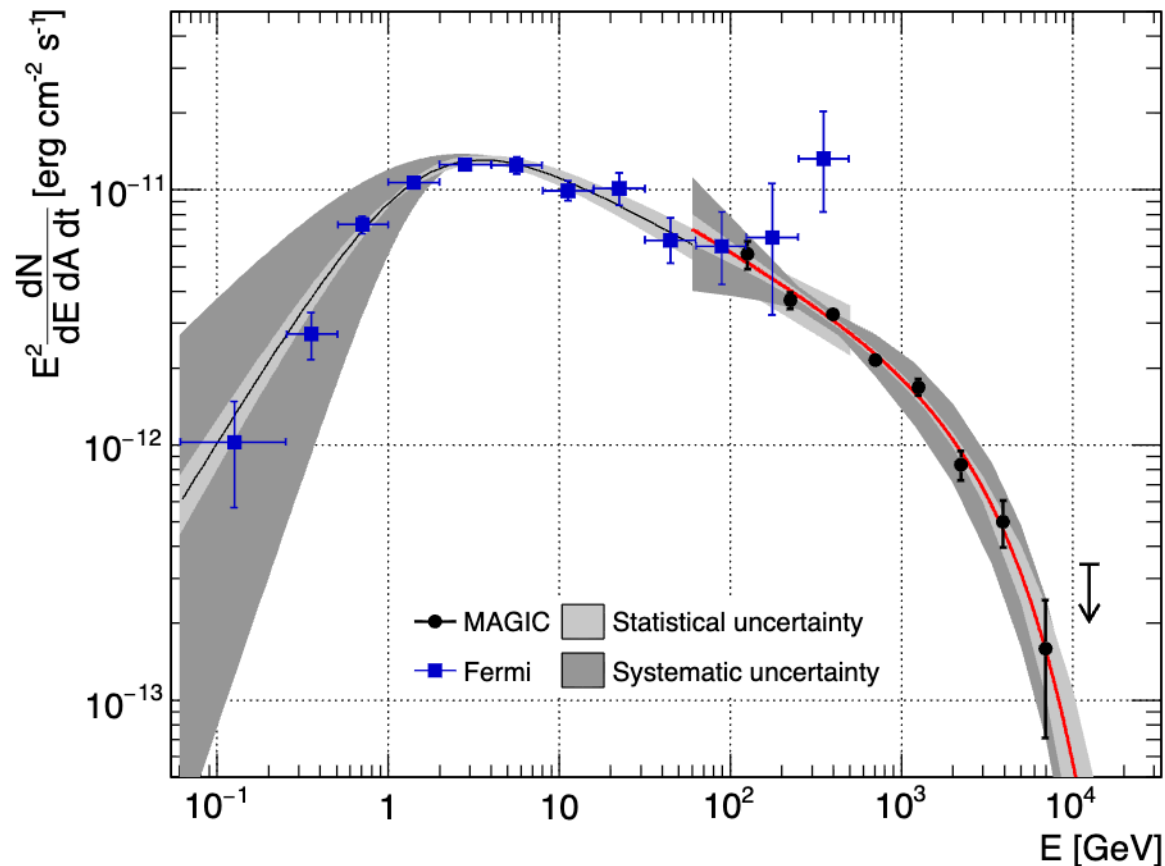
Tutone et al., 2021

- **Gamma-ray morphology is best reconstructed via a sum of UV + X-ray templates**
- **X-ray shape traces the freshly accelerated particles and UV the reacceleration of preexisting CRs**

Young SNRs: Tycho & CasA

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

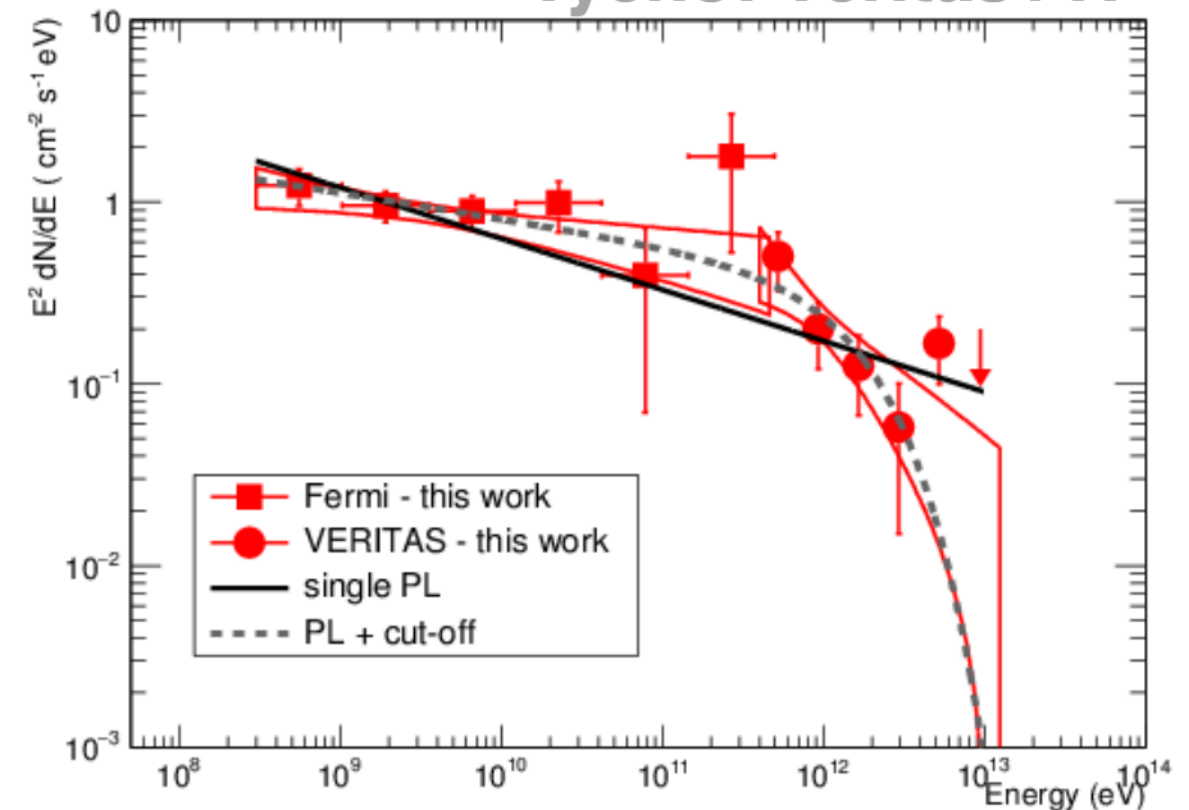
CasA: MAGIC+17



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

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

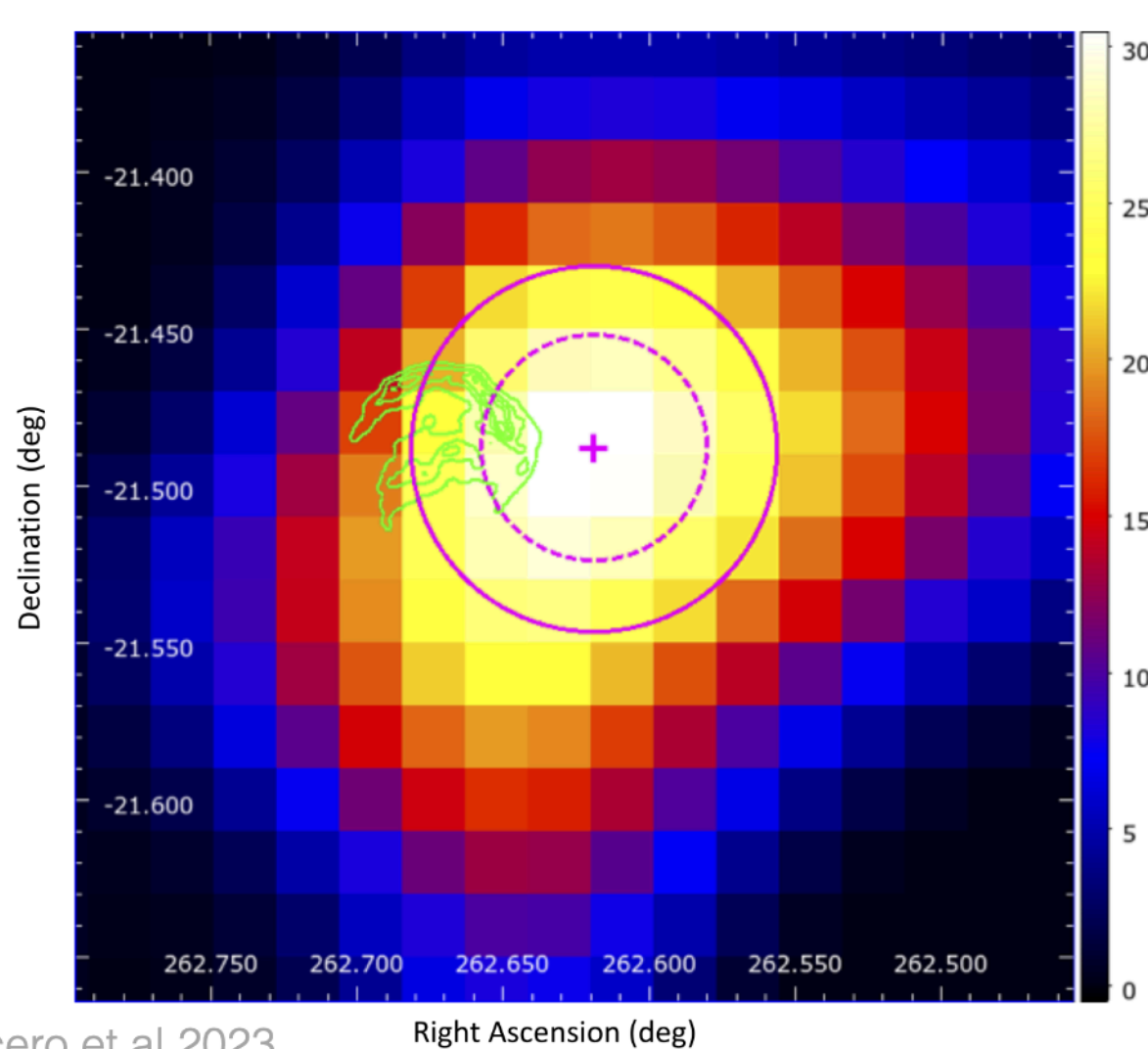
Tycho: Veritas+17



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

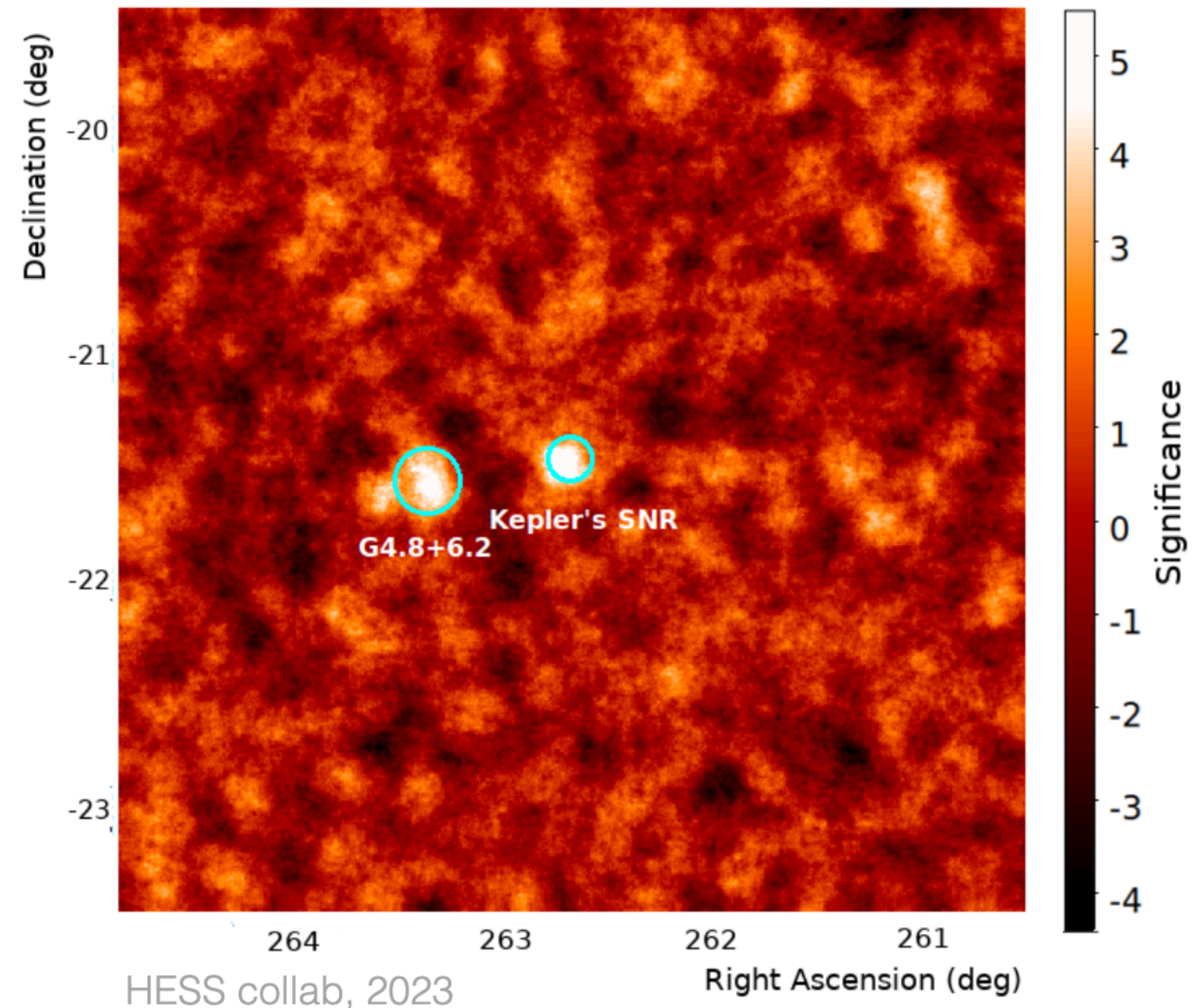
- Particle spectral index is not 2.0 !
- Emission dominated by shock interacting with a massive clump ?
- High density and high speed are not easily compatible

A new GeV-TeV young SNR: Kepler (SN 1604)



Acero et al 2023

Fermi TS map. 12 yrs of data



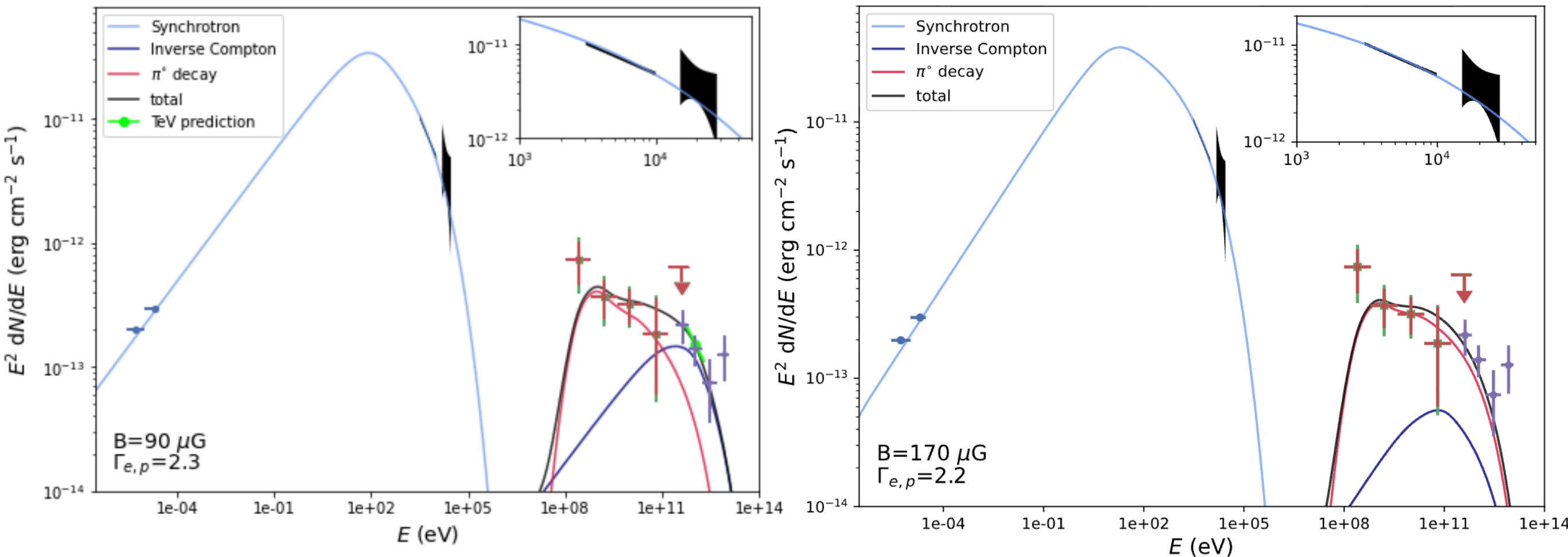
HESS collab, 2023

HESS Very deep exposure: 152h !

- **Most distant young SNR : $d = 5\text{kpc}$**
- **Same limitations, no acceleration up to PeV energies**

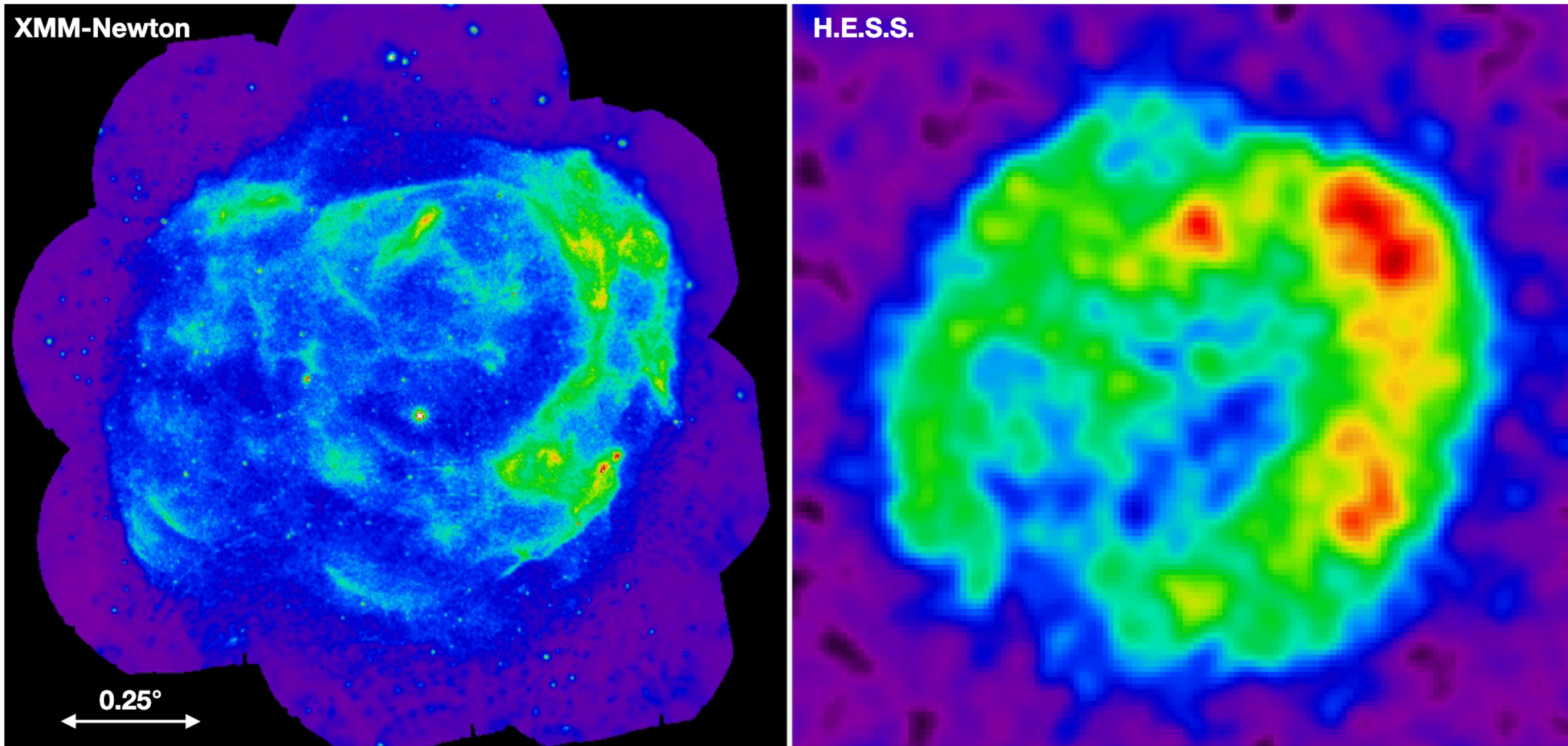
SED modeling

- At $B > 150 \mu\text{G}$ Inverse Compton is suppressed. Proton emission dominates.
- At $B < 100 \mu\text{G}$, Proton emission dominates GeV, electron emission TeV
- $E_{\text{max},p} \sim 20 \text{ TeV}$ for $V_{\text{sh}}=1700 \text{ km/s}$ (protons interacting with dense CSM)



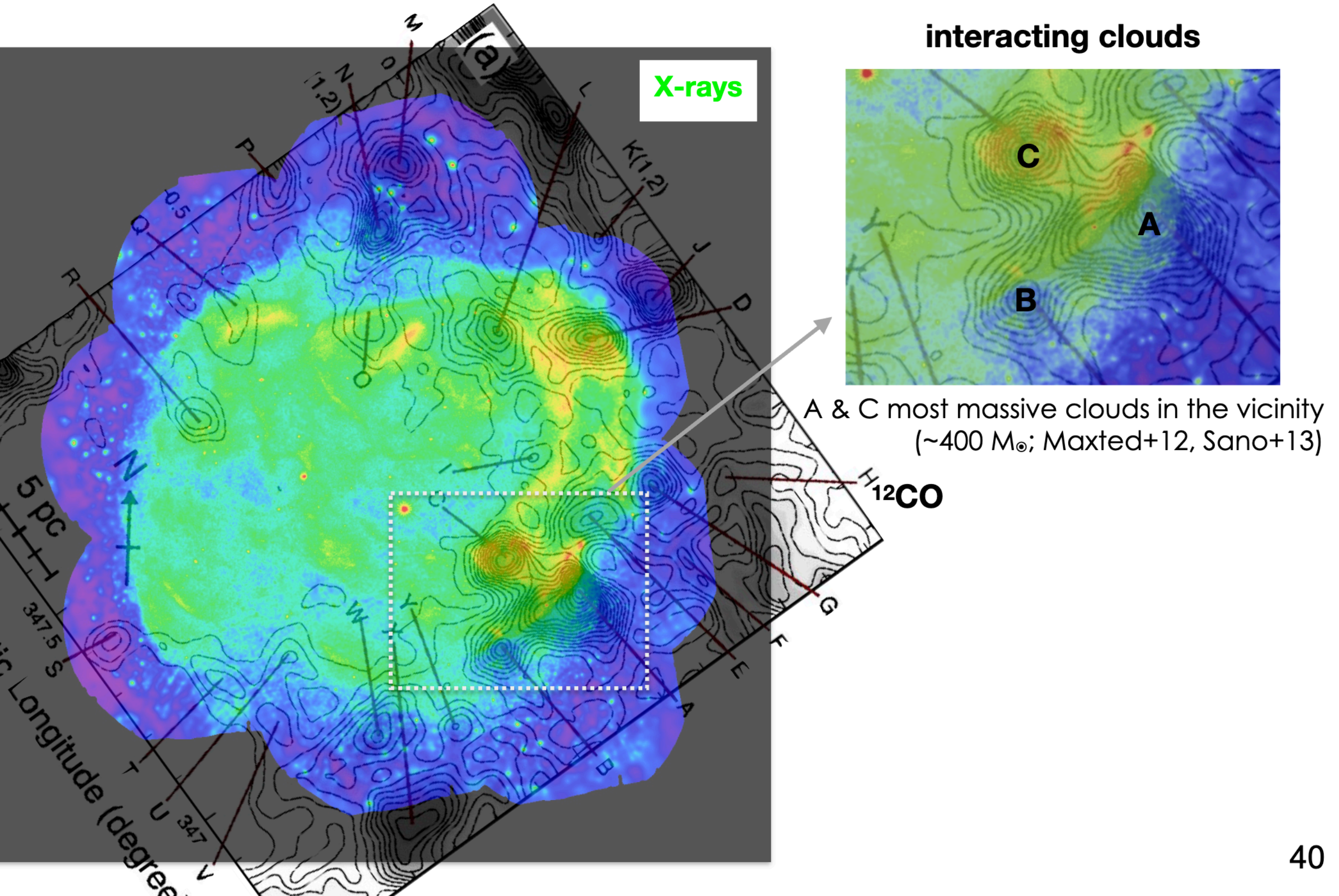
=> Detailed study of TeV morphology is needed
CTA could help disentangle scenarii

RXJ 1713-3946: most studied gamma-ray SNR

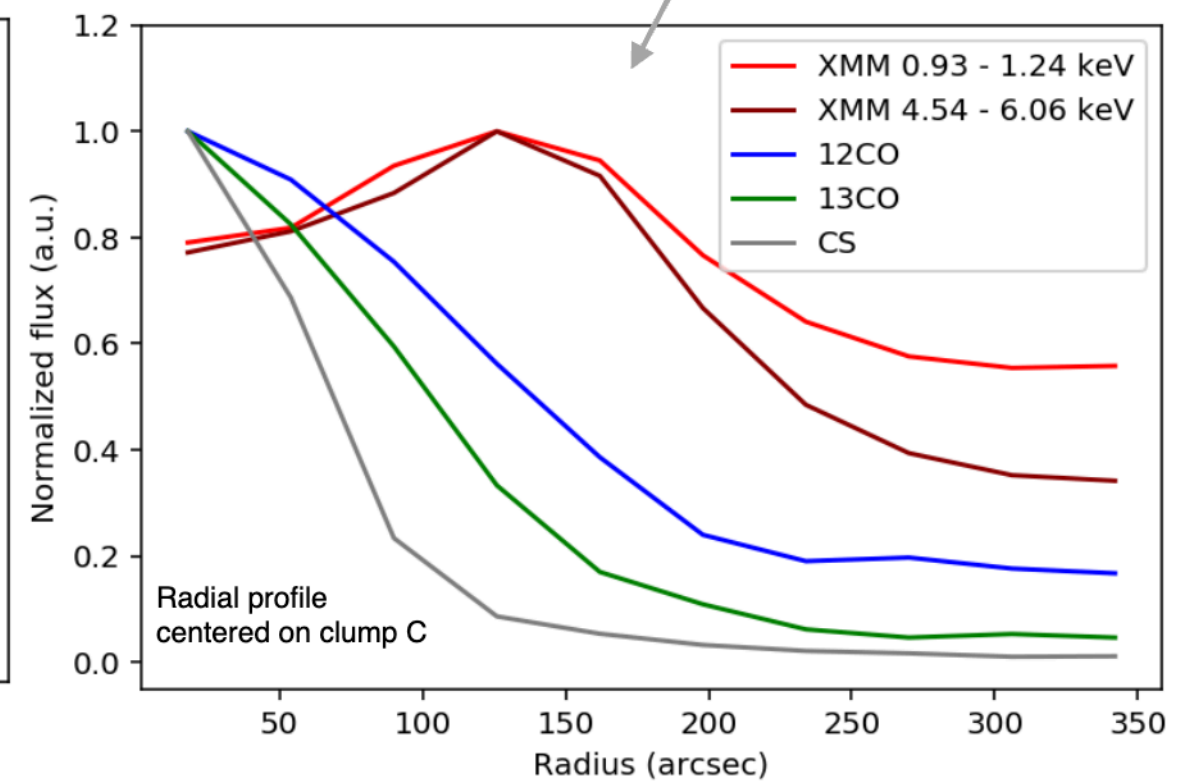
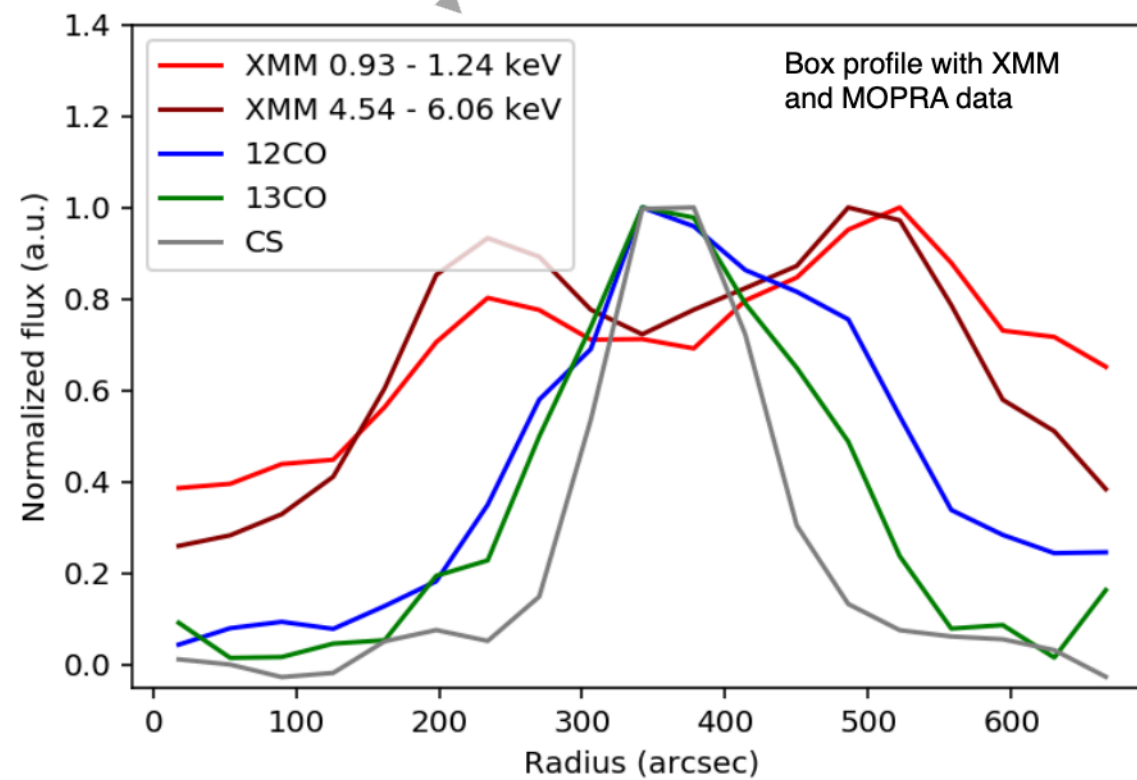
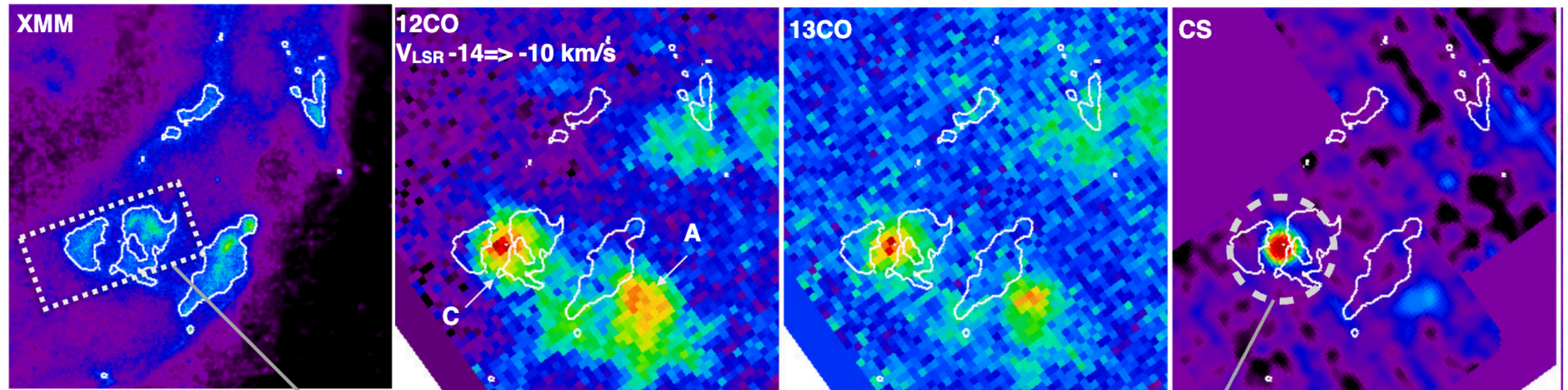


- Core Collapse supernova. Age ~ 1600 yrs (Historical SN 393). $d \sim 1\text{kpc}$
- Young SNR with fast shock ~ 3500 km/s
- X-ray emission is synchrotron dominated
- Brightest TeV SNR

SNR - MC interaction

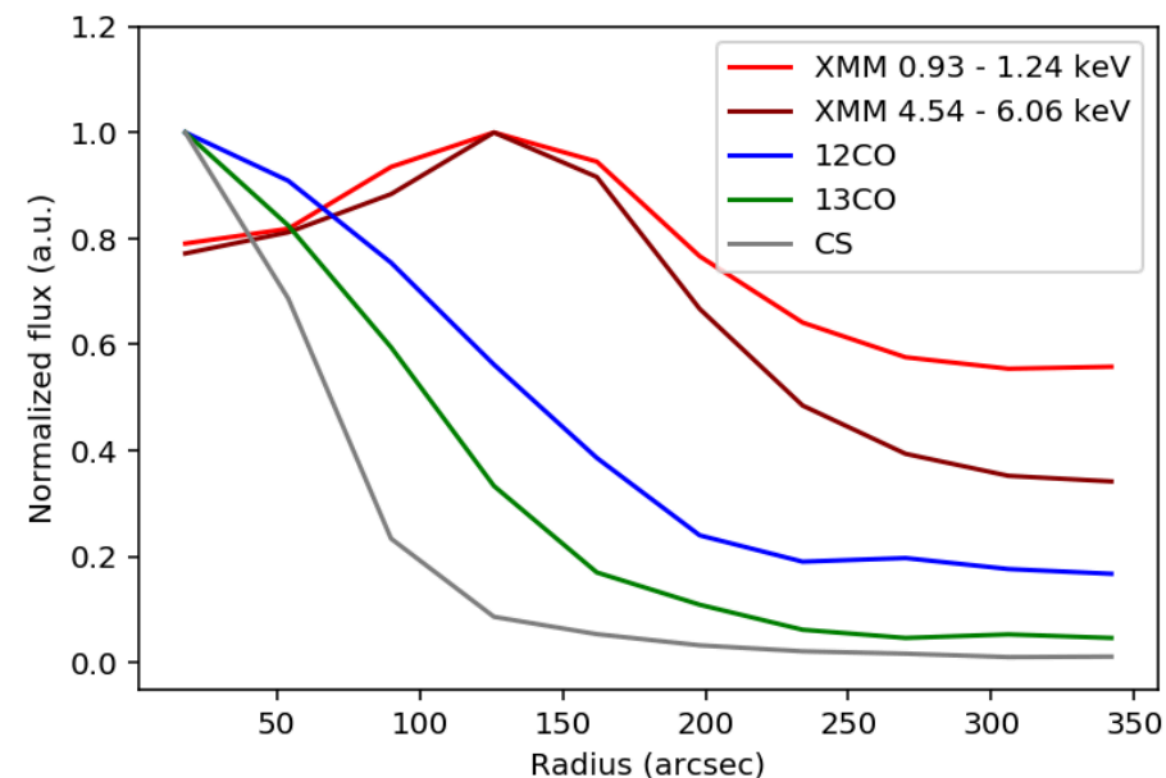


Core C: X-ray/CO anti-correlation

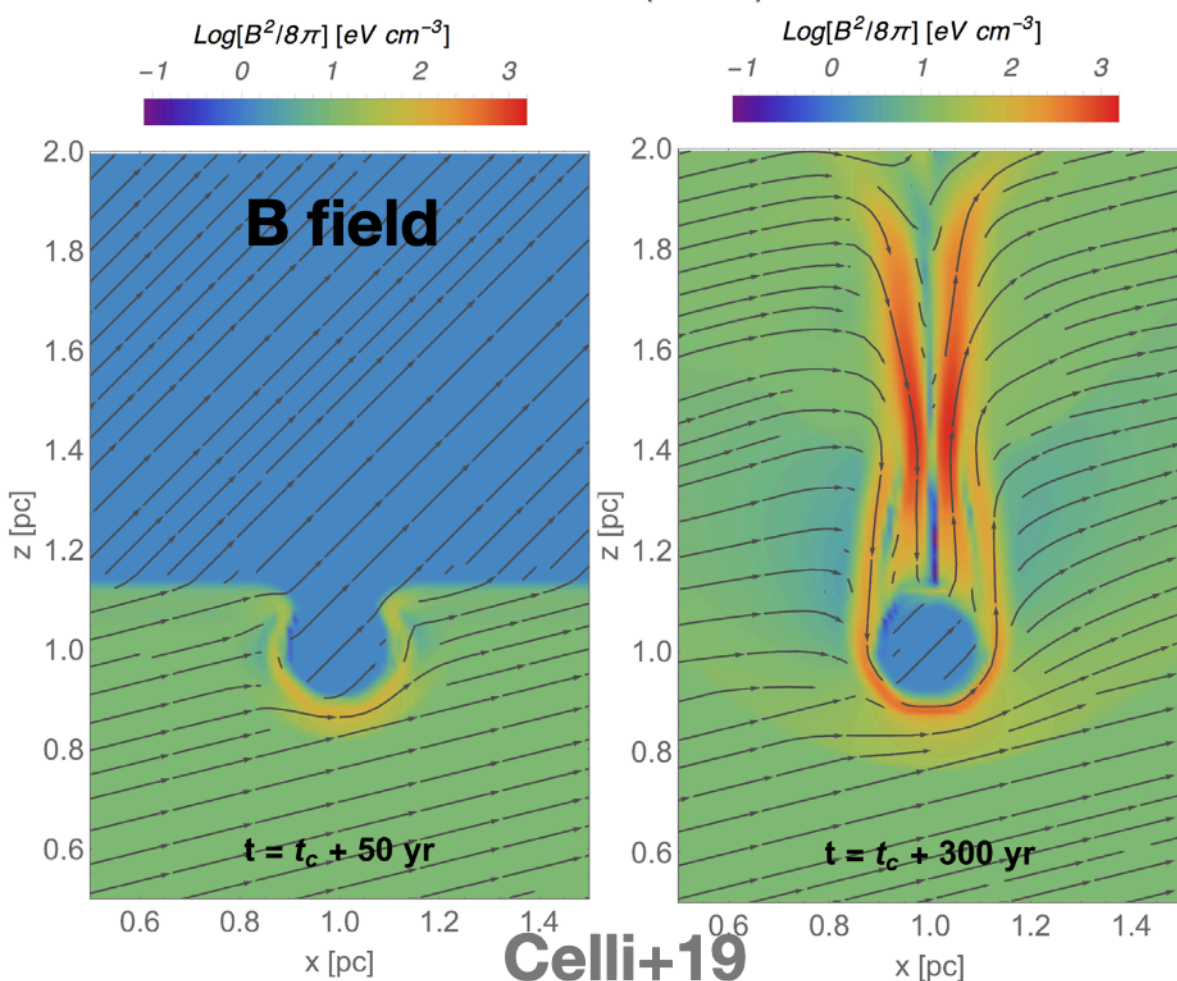


Clump size ~60-100 arcsec ~0.3-0.5 pc

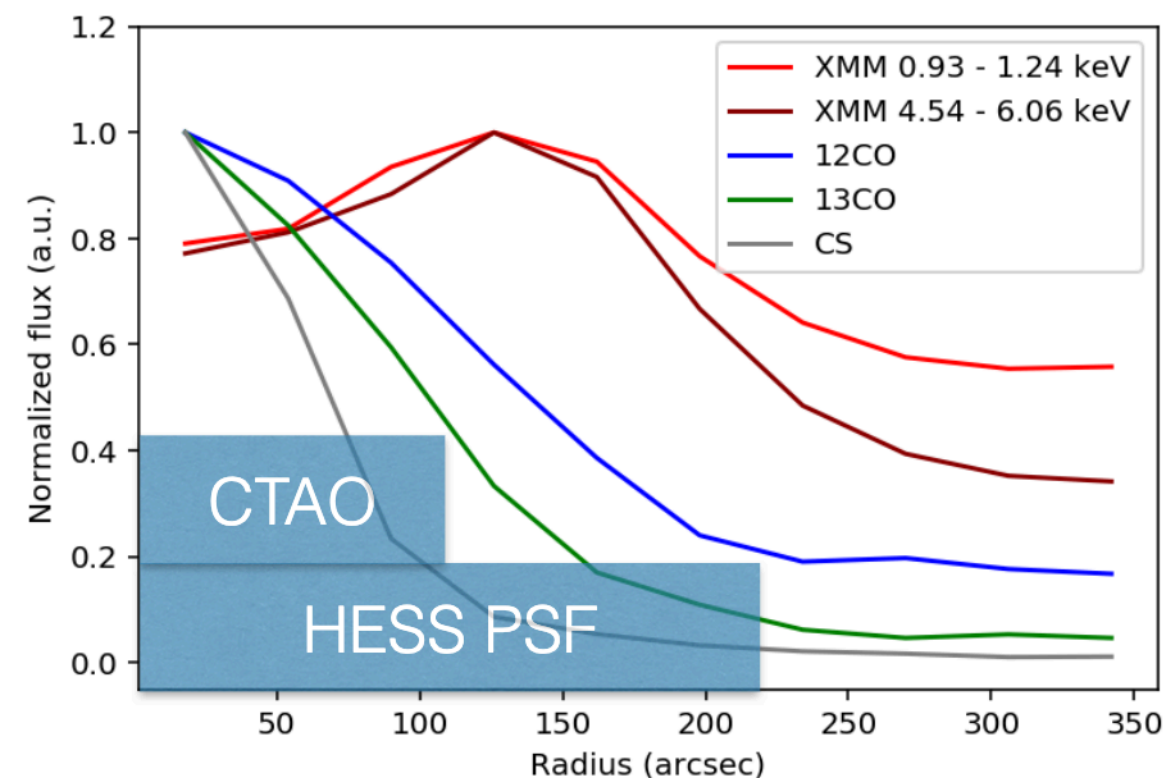
Core C: X-ray/CO anti-correlation



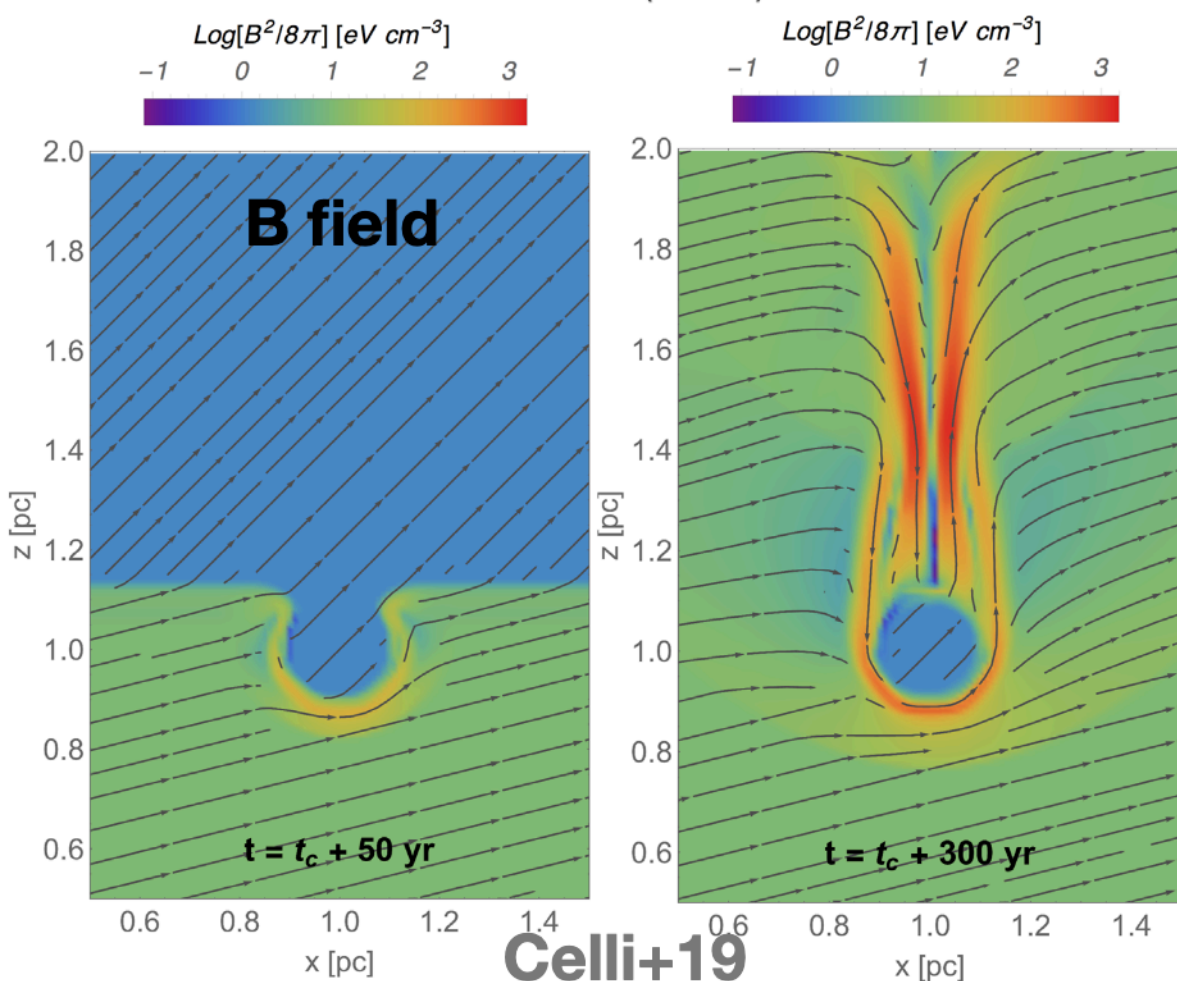
- **Clear Gas/X-rays anti-correlation and no X-ray morphological energy dependence is observed.**
- **The fact that no X-ray peak from cloud center at 5 keV indicate that high energy e- do not penetrate cloud deeper than low energy e-.**
- **An increased B-field on the envelope may shield the cloud from CRs penetration (e.g Inoue+19, Celli+18).**



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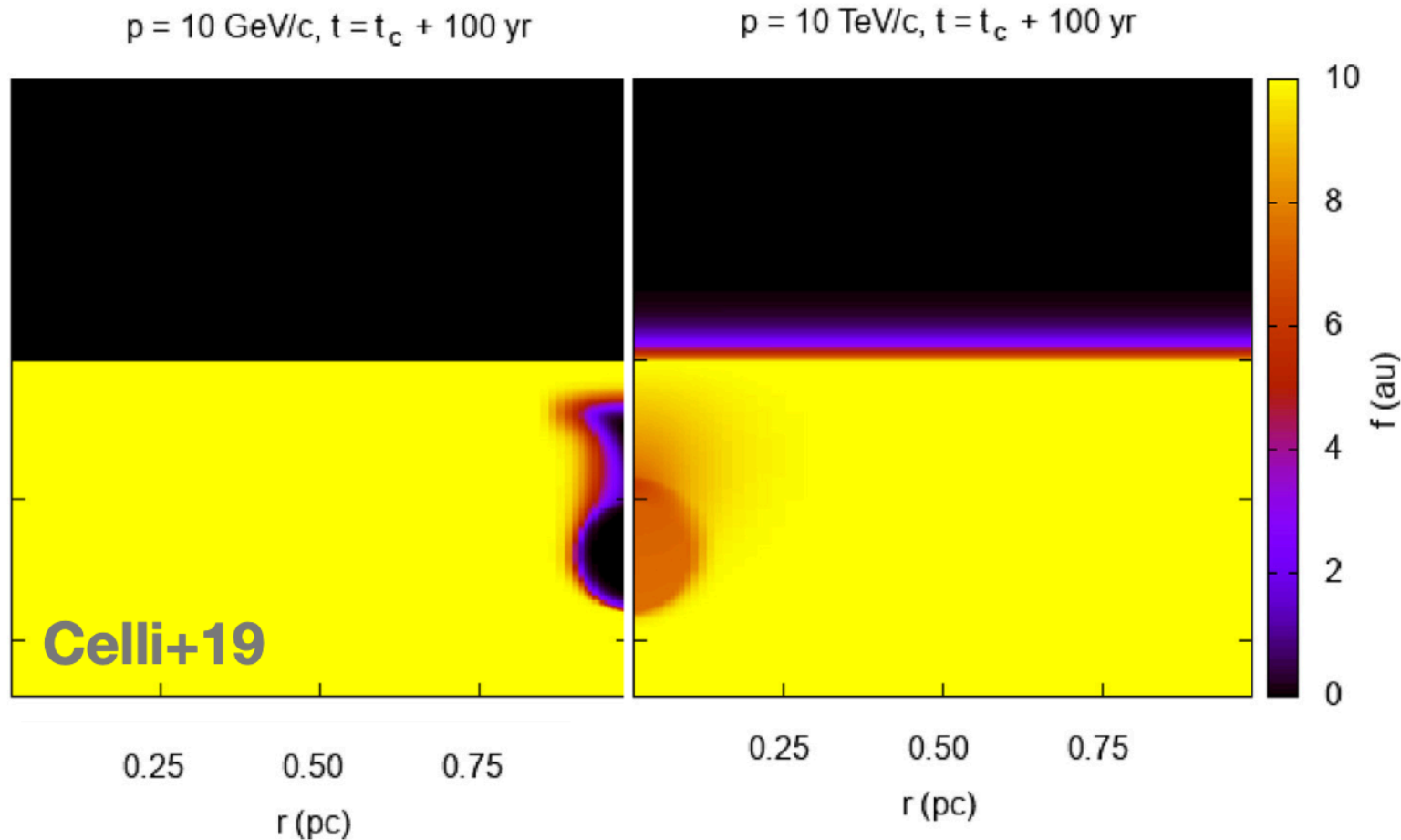


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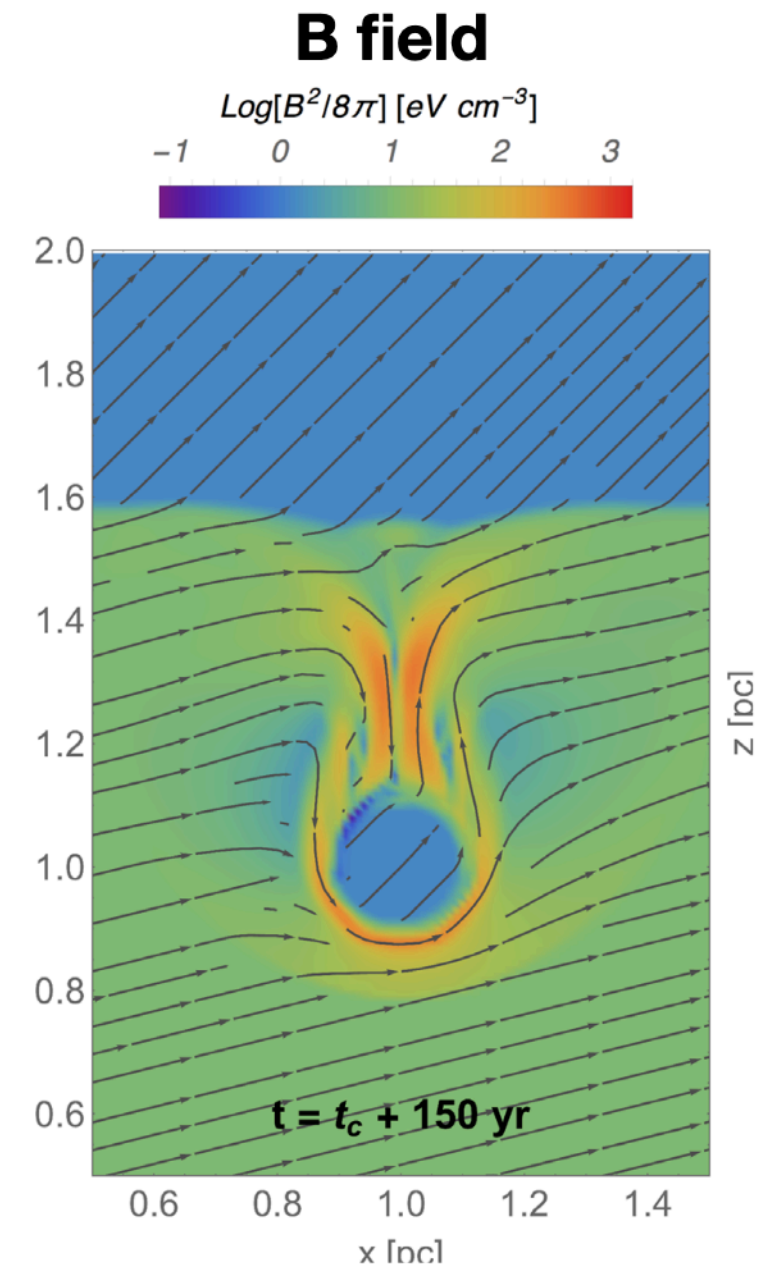
CR clump penetration

CR density at 10 GeV / 10 TeV



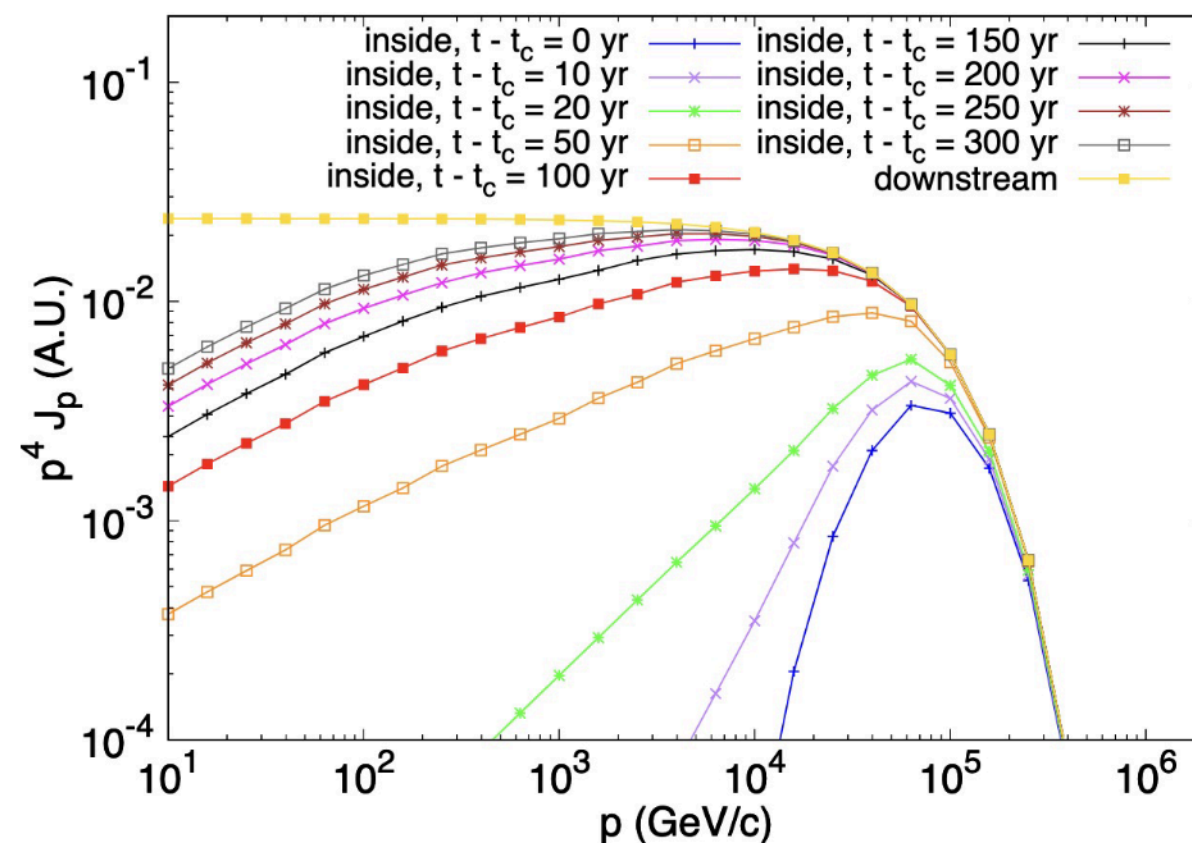
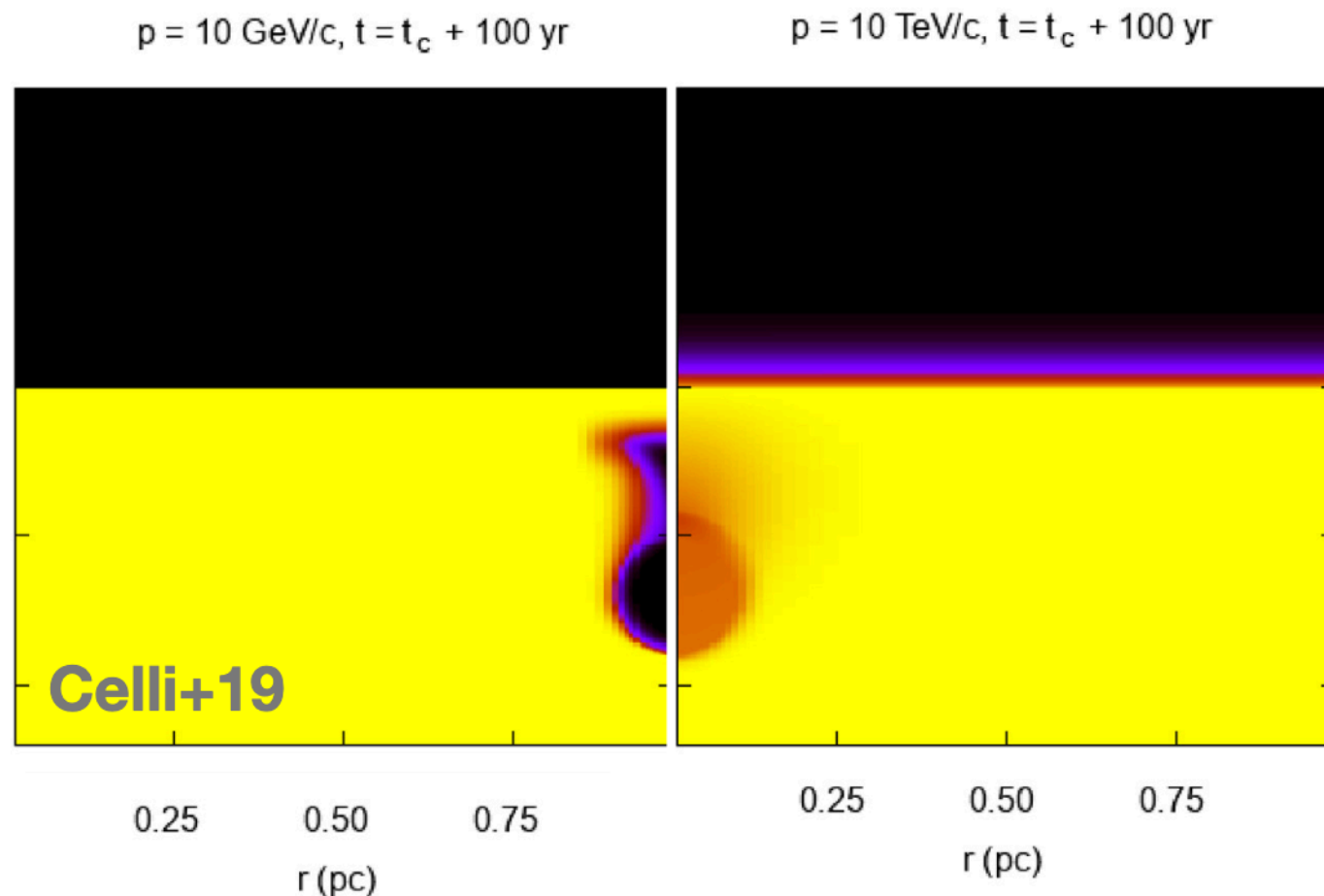
Would be nice to have X- and gamma-ray maps from these simulations.

Map the e- density at 10 TeV (X-ray energy) including cooling ?



CR clump penetration

CR density at 10 GeV / 10 TeV



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CR clump penetration

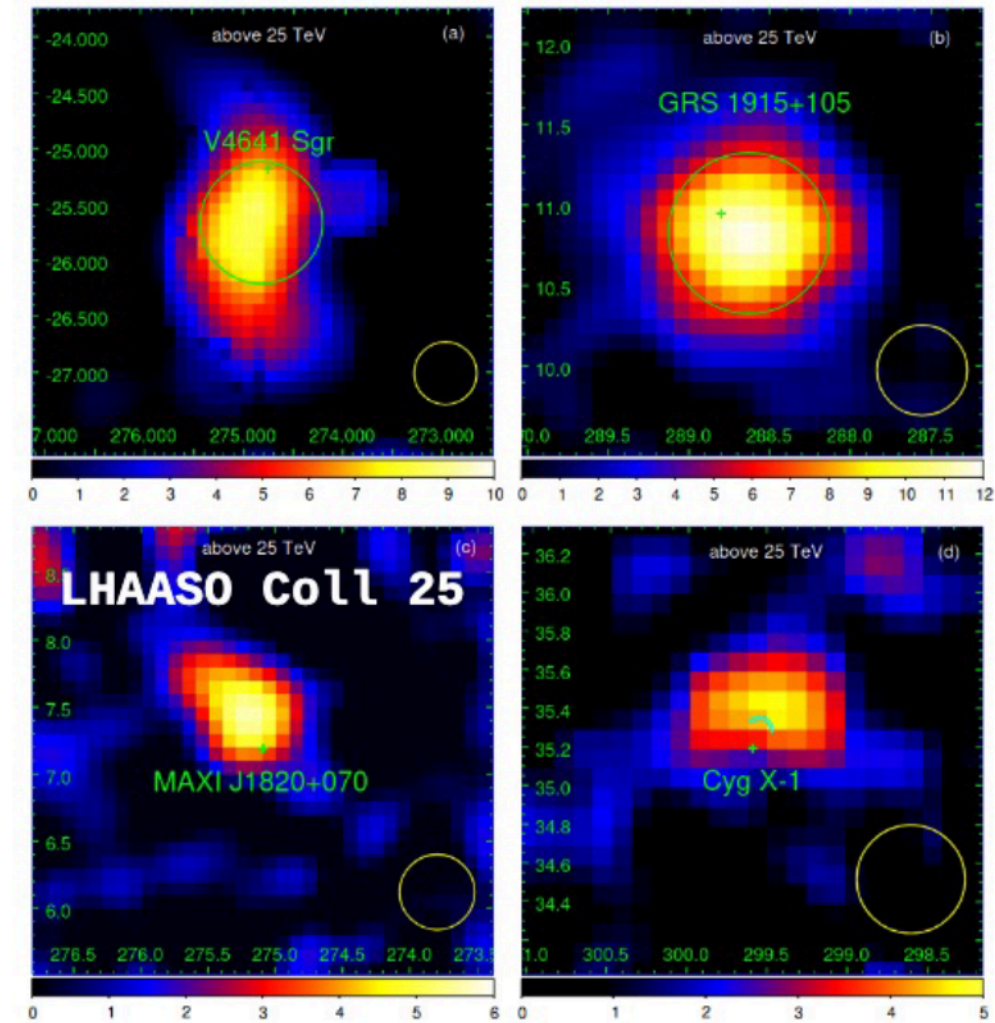
High energy CR reach denser part first

Note on micro-quasar as extended sources

- SS 433 detected by HAWC, HESS, LHAASO



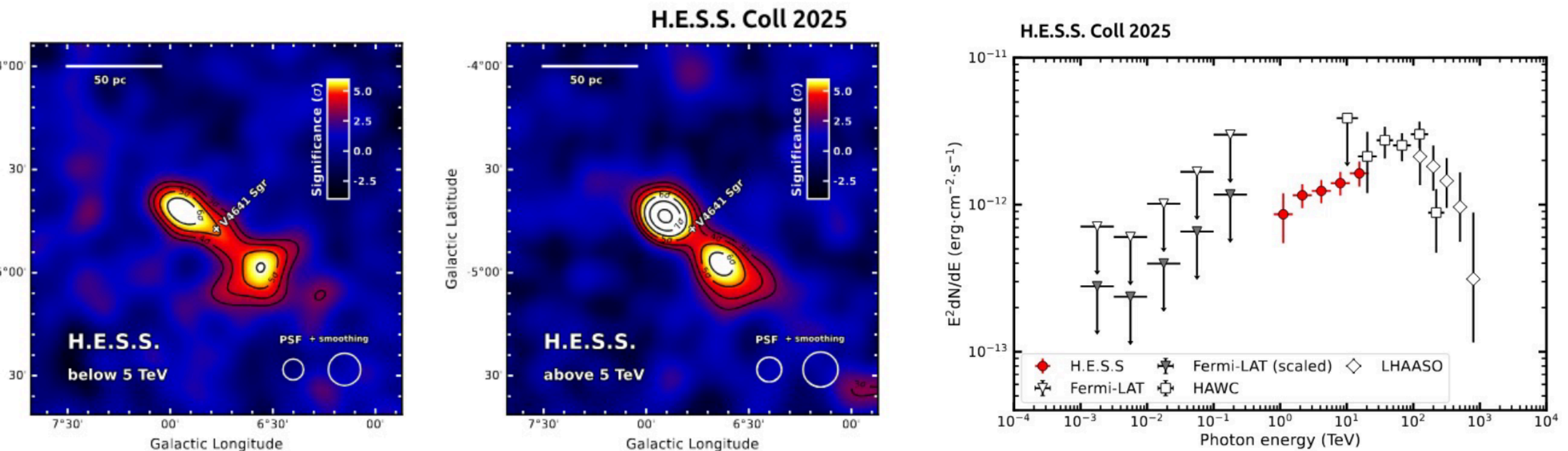
- Multiple LHAASO sources



- Persistent and extended emission far from binary system
- Multiple new LHAASO detections
- How many unassociated extended sources are associated to previously active binaries ?

Note on micro-quasar as extended sources

- V464 as an extended impressive accelerator**



- Persistent and extended emission far from binary system**
- Multiple new LHAASO detections**
- How many unassociated extended sources are associated to previously active binaries ?**

The Cherenkov Telescope Array Observatory

Galactic prospects

LST-1 of CTAO North
Credit: Tomohiro Inada



Cherenkov telescope array: North + South

Construction phase array:

4 Large telescopes

9 Medium telescopes

Roque de los Muchachos, Canary



LST

$E < 100 \text{ GeV}$

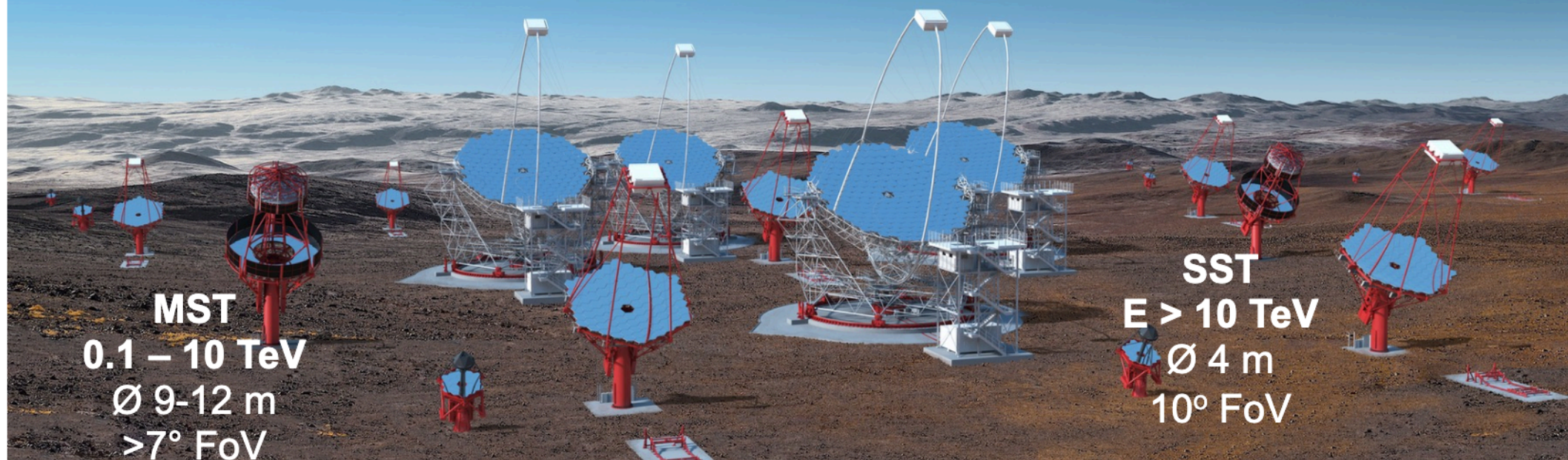
$\varnothing 23\text{m}$

4.5° FoV

14 Medium telescopes

37 Small telescopes

Paranal, Chile



MST

$0.1 - 10 \text{ TeV}$

$\varnothing 9-12 \text{ m}$

$>7^\circ \text{ FoV}$

SST

$E > 10 \text{ TeV}$

$\varnothing 4 \text{ m}$

10° FoV

Cherenkov telescope array: North + South

Construction phase array:

4 Large telescopes

9 Medium telescopes

Roque de los Muchachos, Canary

LST
 $E < 100 \text{ GeV}$
 $\varnothing 23\text{m}$
 4.5° FoV



14 Medium telescopes

MST foundations

Paranal, Chile



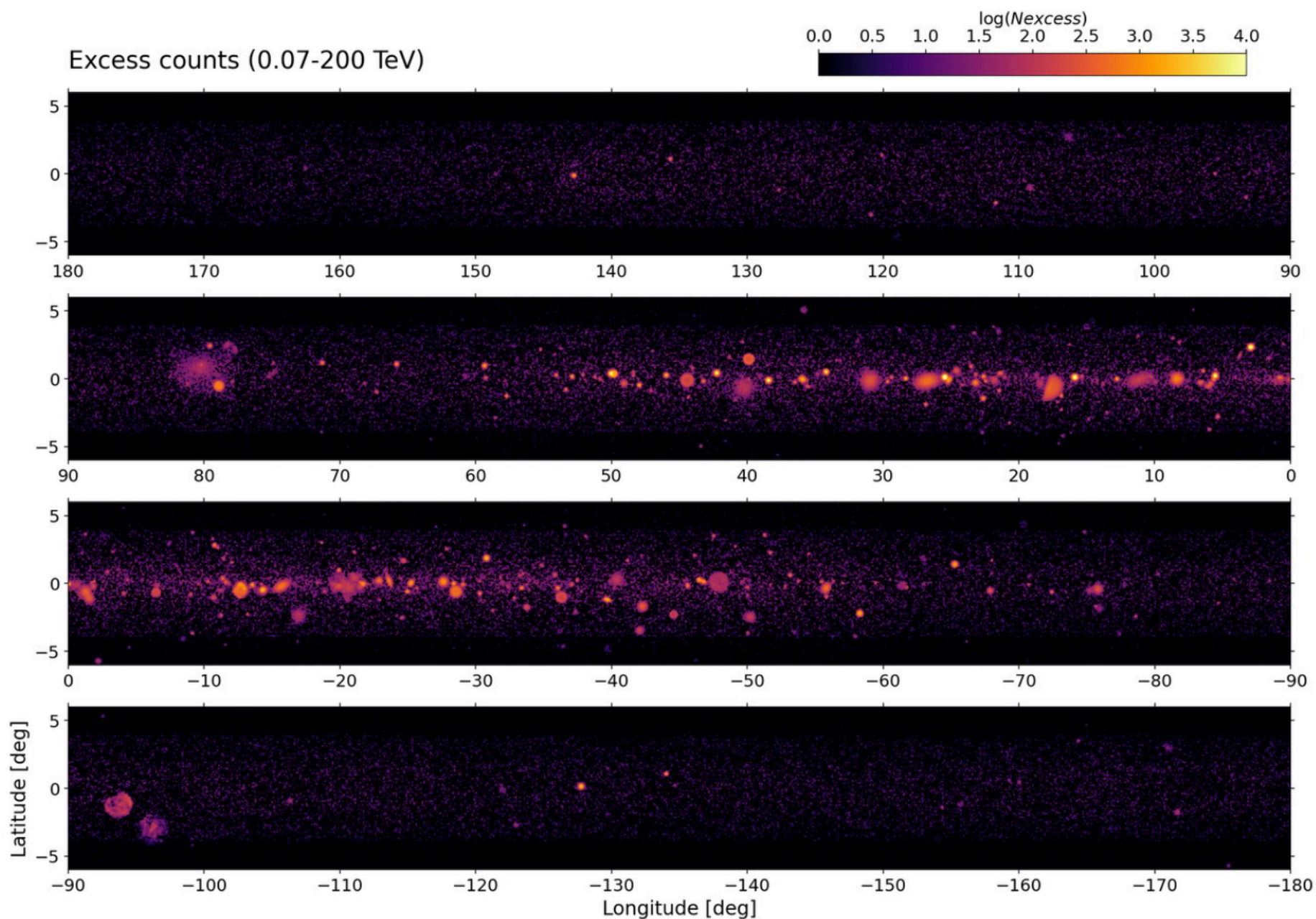
Array Roads and Telescope Foundations

CTAO-North : 4 LSTs



- **4 LSTs will be completed by end of '26 and commissioning of cameras will start**
- **With 4 LSTs, already be the most sensitive Cherenkov array in the 30-500 GeV energy range**

Galactic survey with the CTA



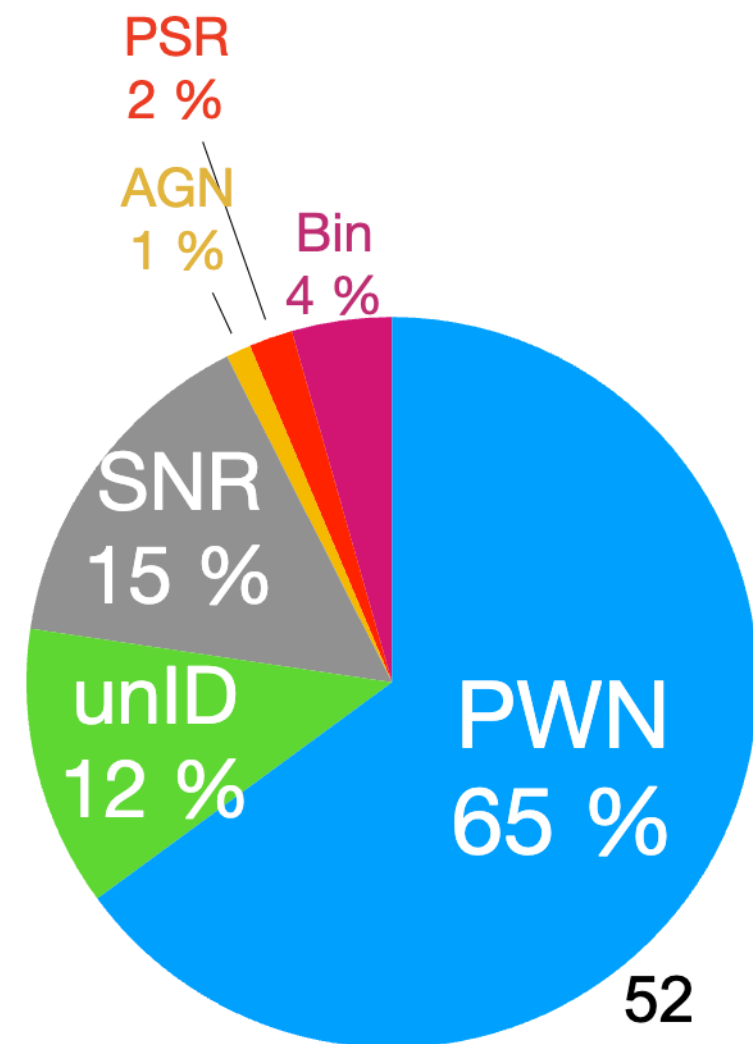
1620h of
observations
in 10 years

10h-30h exposure in
the plane

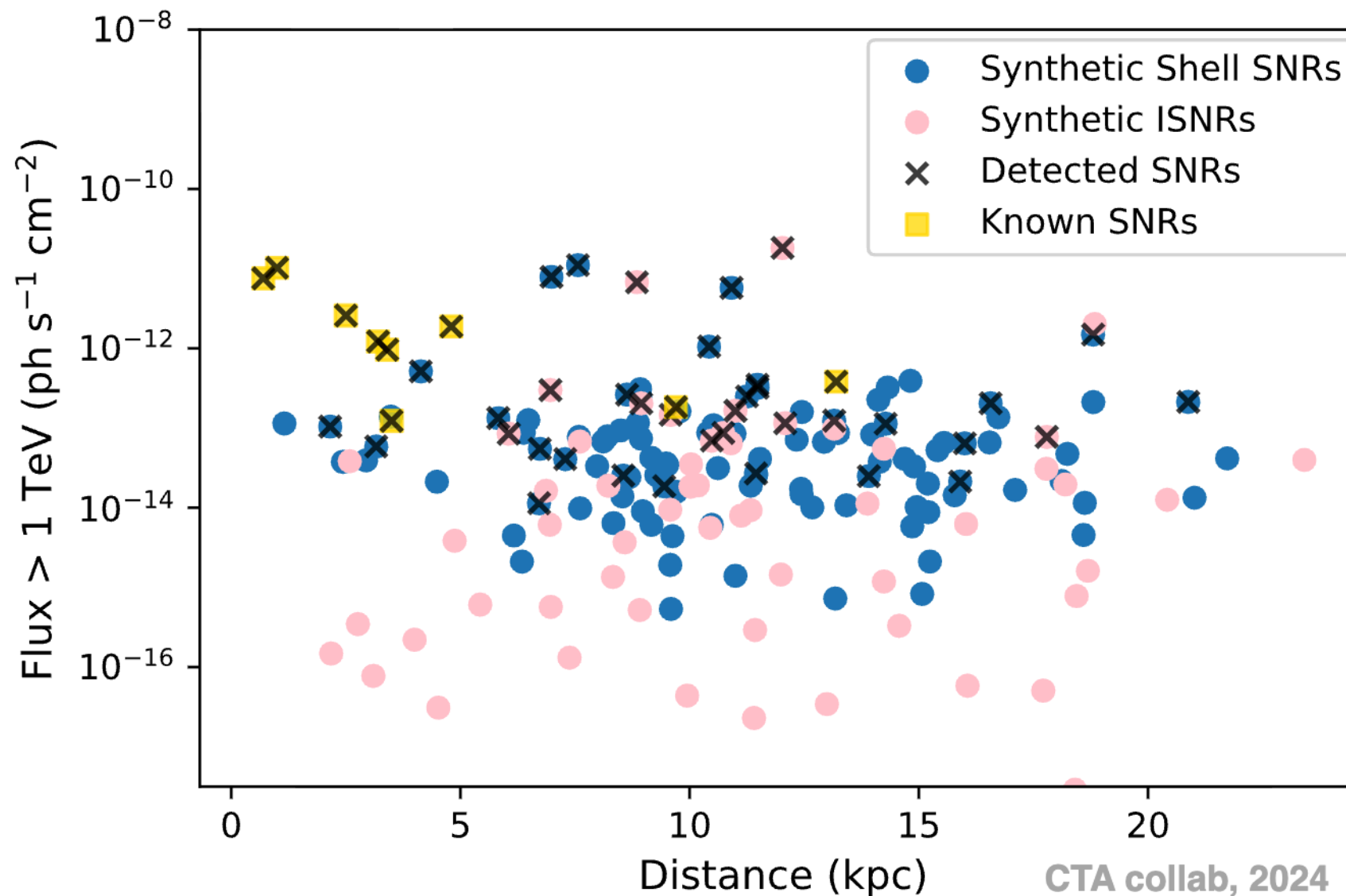
CTAO collab, 2024

Galactic survey
Catalog data challenge

>450 sources detected
(100 known today)



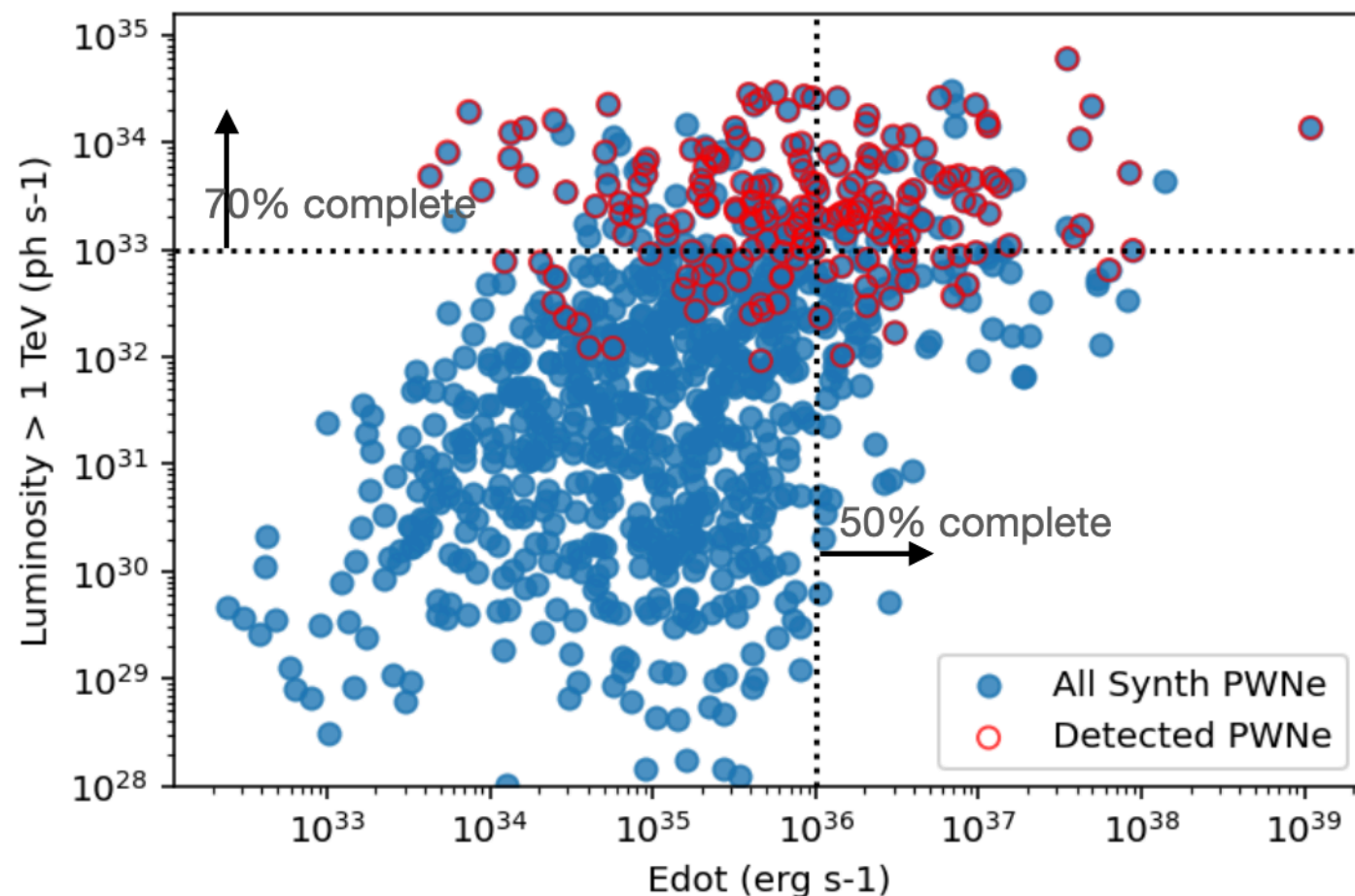
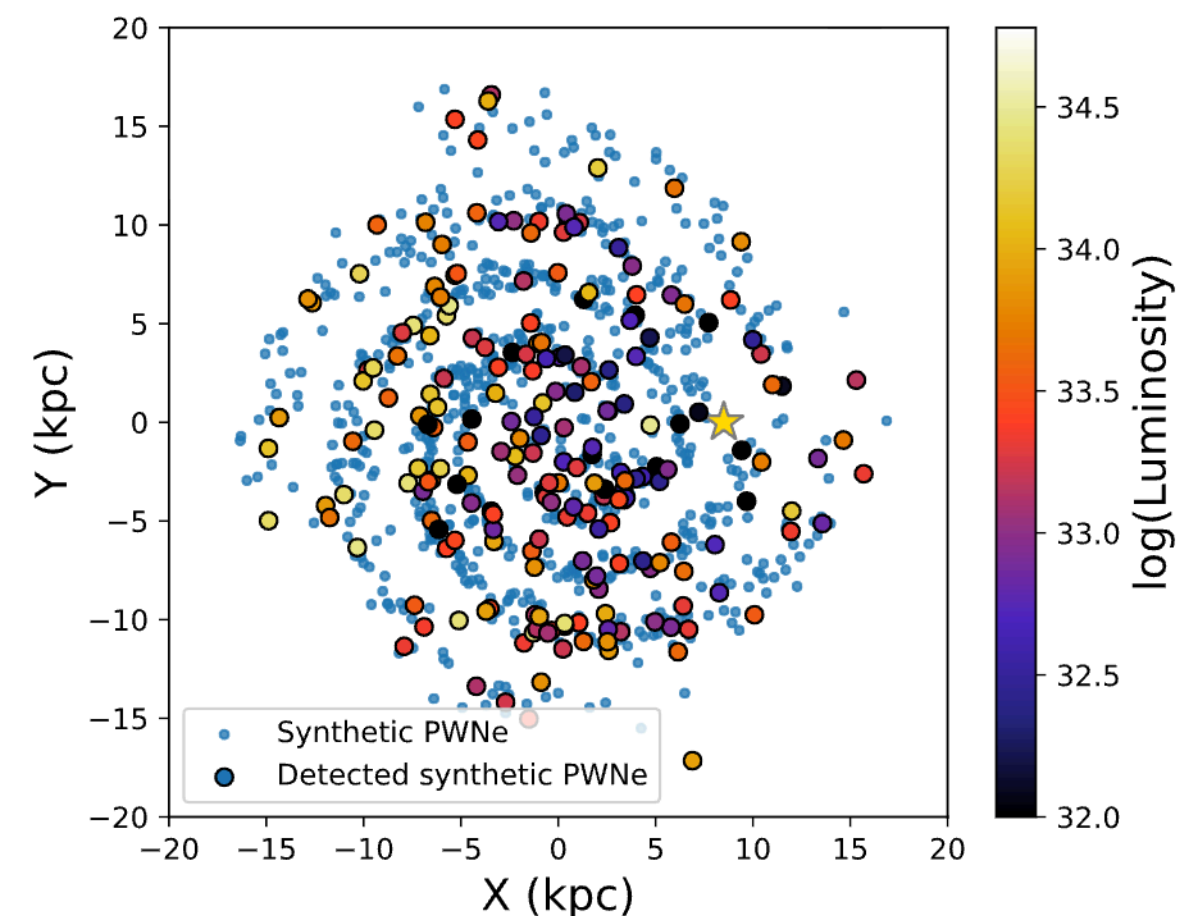
Prospects for SNRs with CTAO survey



- 37 new synthetic SNRs (~10 known today)
- 5-10 times better flux sensitivity
- SNRs up to other side of Galaxy (20 kpc!)

PWNe population studies

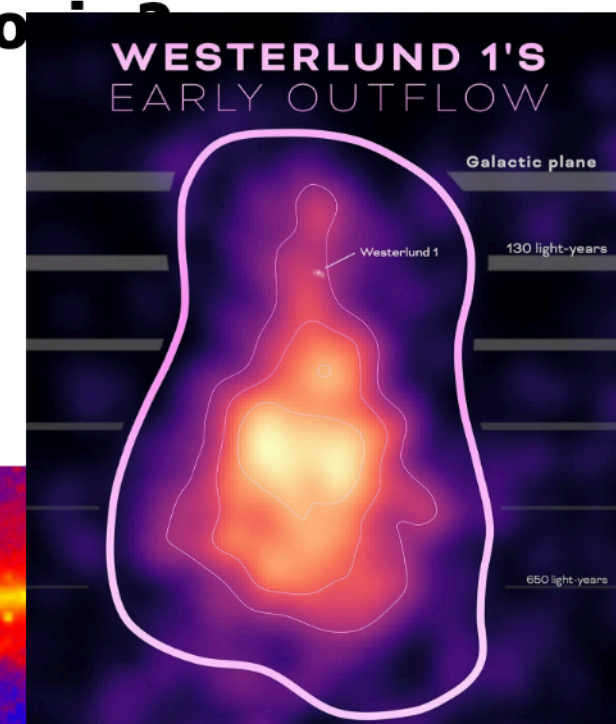
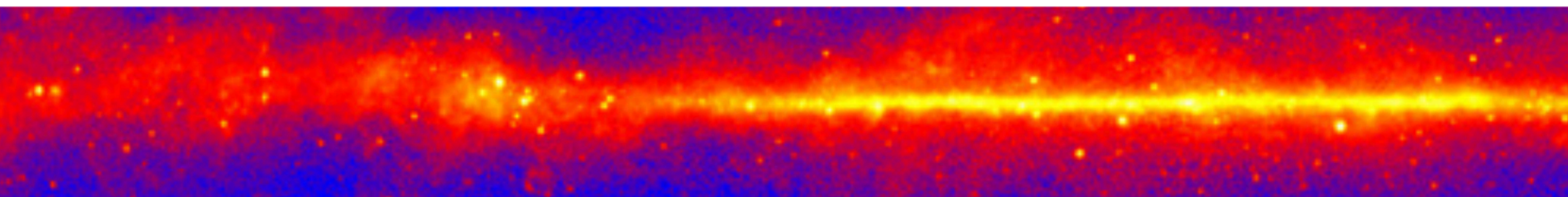
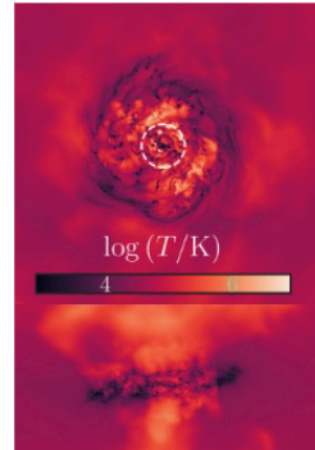
- ~200 new synthetic PWNe. 70% complete down to a luminosity of $\sim 10^{33}$ ph/s
- 50% of all Galactic PWN with $\dot{E} > 10^{36}$ erg/s



CTA collab, 2024

Conclusions and thoughts

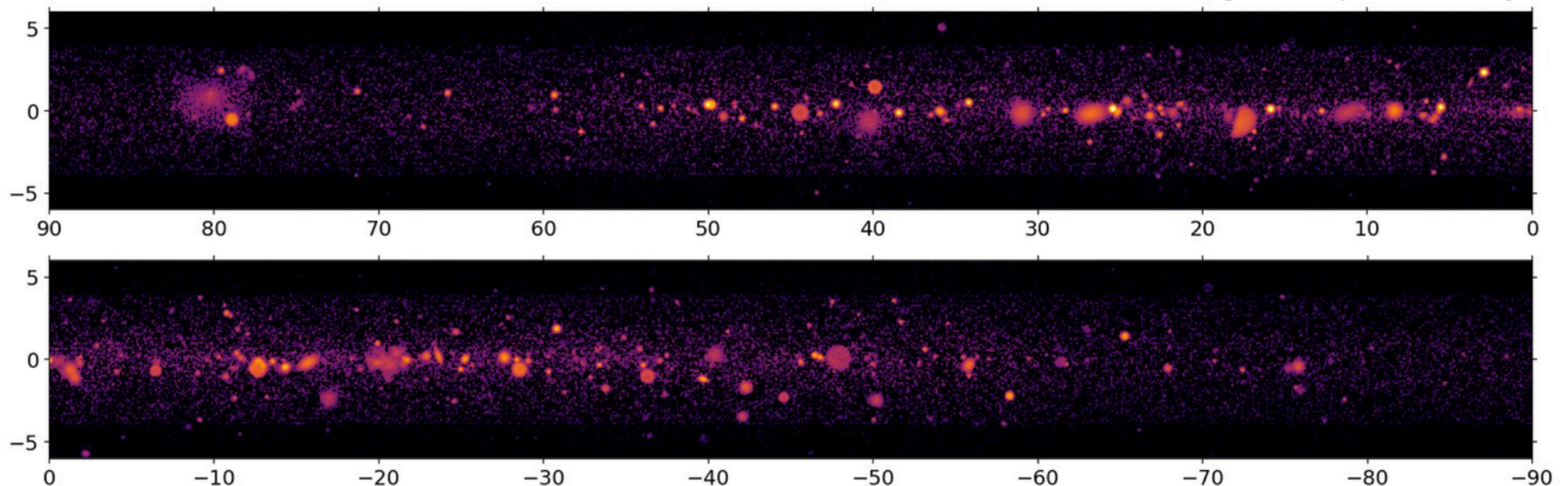
- **Gamma-ray diffuse emission is present at all scales from 10s kpc to pc**
- **Multiscale interplay between the accelerators and escape/diffusion**
- **Connection between CR-MHD simulations and observations ?**
- **Discovery of the Westerlund 1 outflow highlight the connection between local accelerators and CR injection into the Galaxy**
 - **There are probably other outflow structures out there but hard to disentangle**
- **More leptonic examples of large scale diffuse sources than hadronic**
 - **Wd1 outflow, pulsar halos, relic nebula, Fermi bubbles ?**



Conclusions and thoughts

- **CTAO will provide in depth studies of SNR/clump interaction + Fermi bubble base**
- **But diffuse emission and unresolved sources will be a true challenge for CTAO**
 - **Sensitivity increases by a factor $\sim 8-10$ and PSF $\sim 2-3$**
 - **Many more sources but likely more overlap/unresolved**

CTAO galactic plane survey



Backup

Optical

SN 2017egm

10 arcseconds

Gamma-rays

30 arcminutes