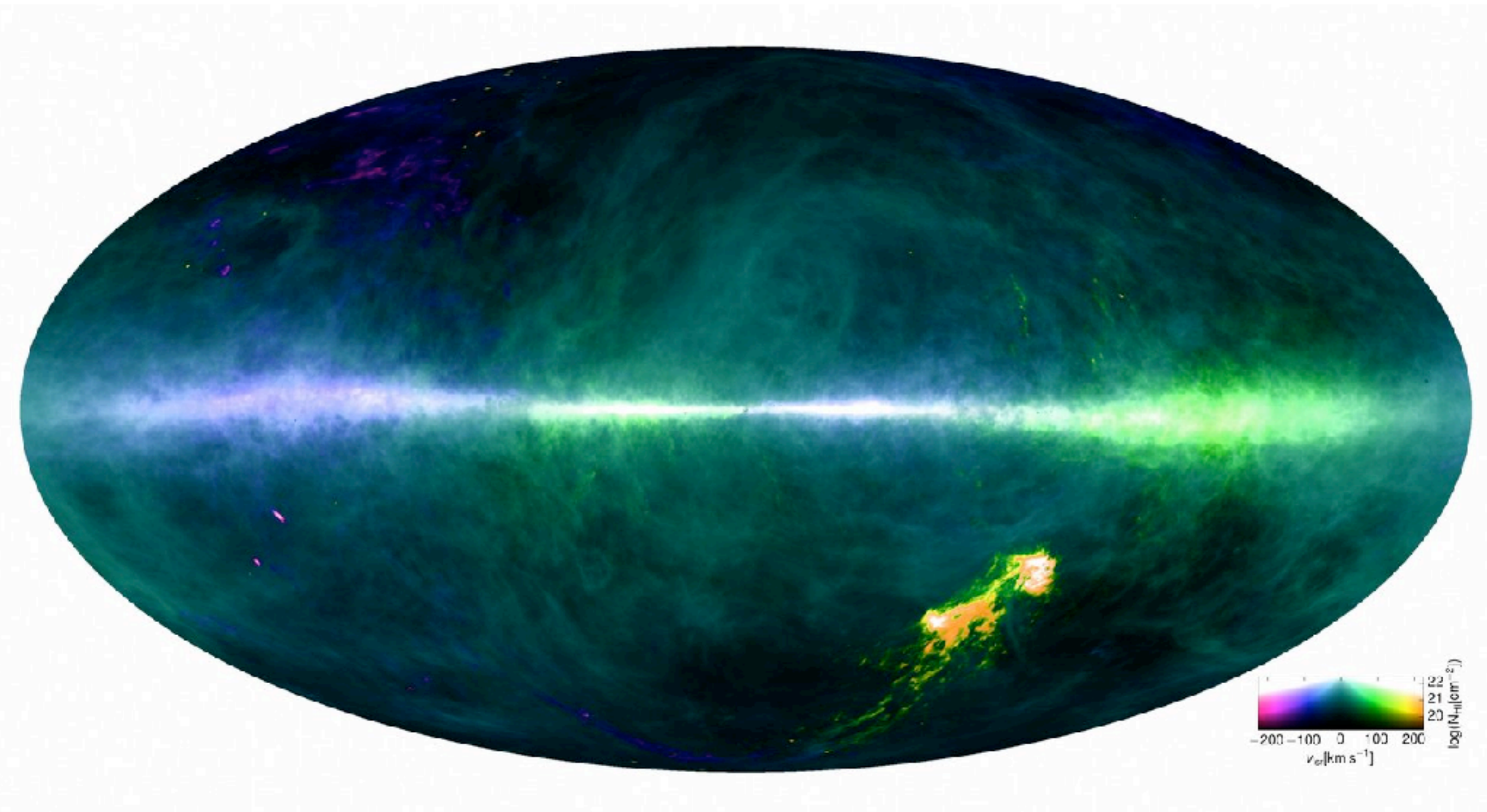


X-ray Chandra gallery

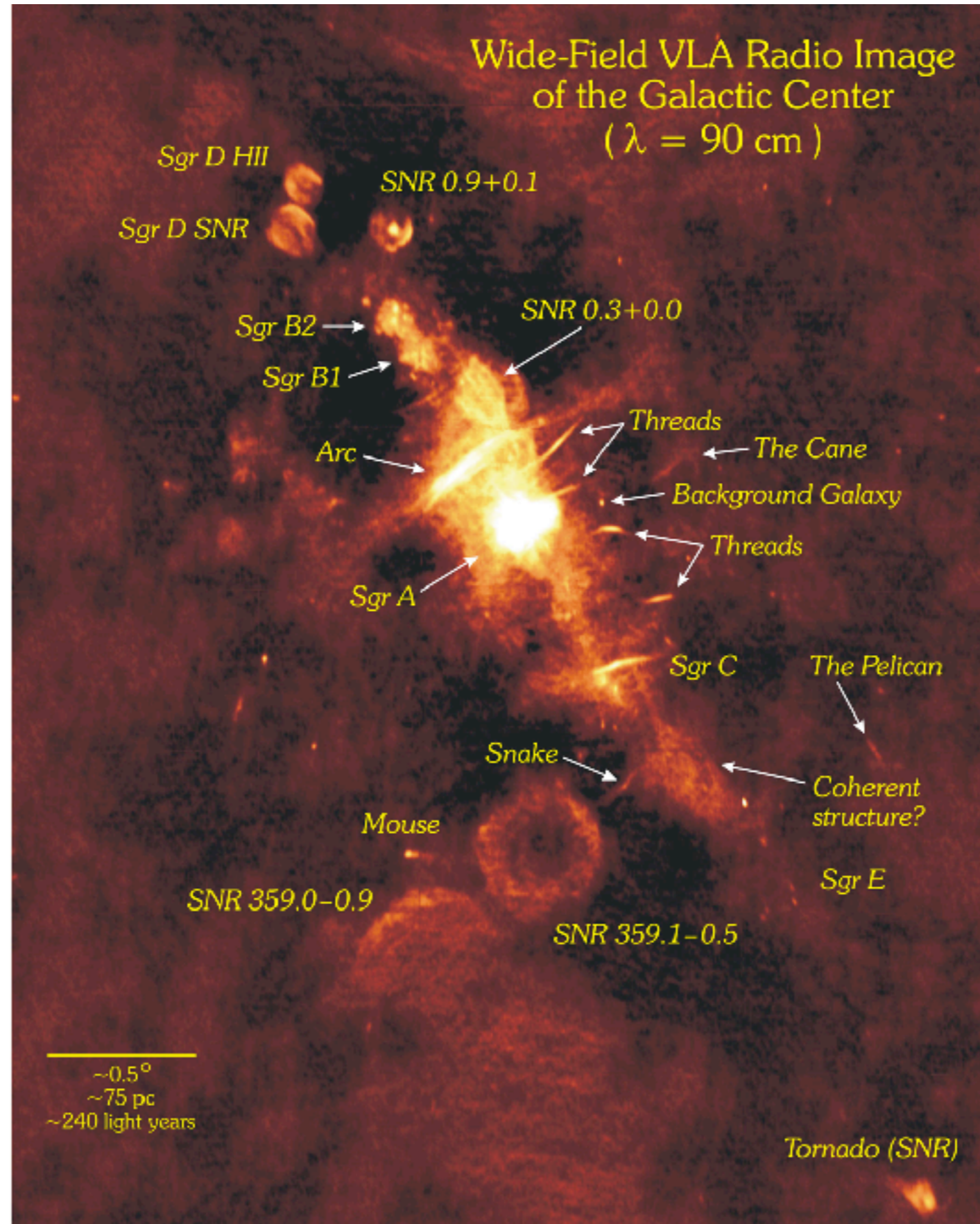
Multi-wavelength coverage of Galactic sources

F. Acero
CTAO school 2026

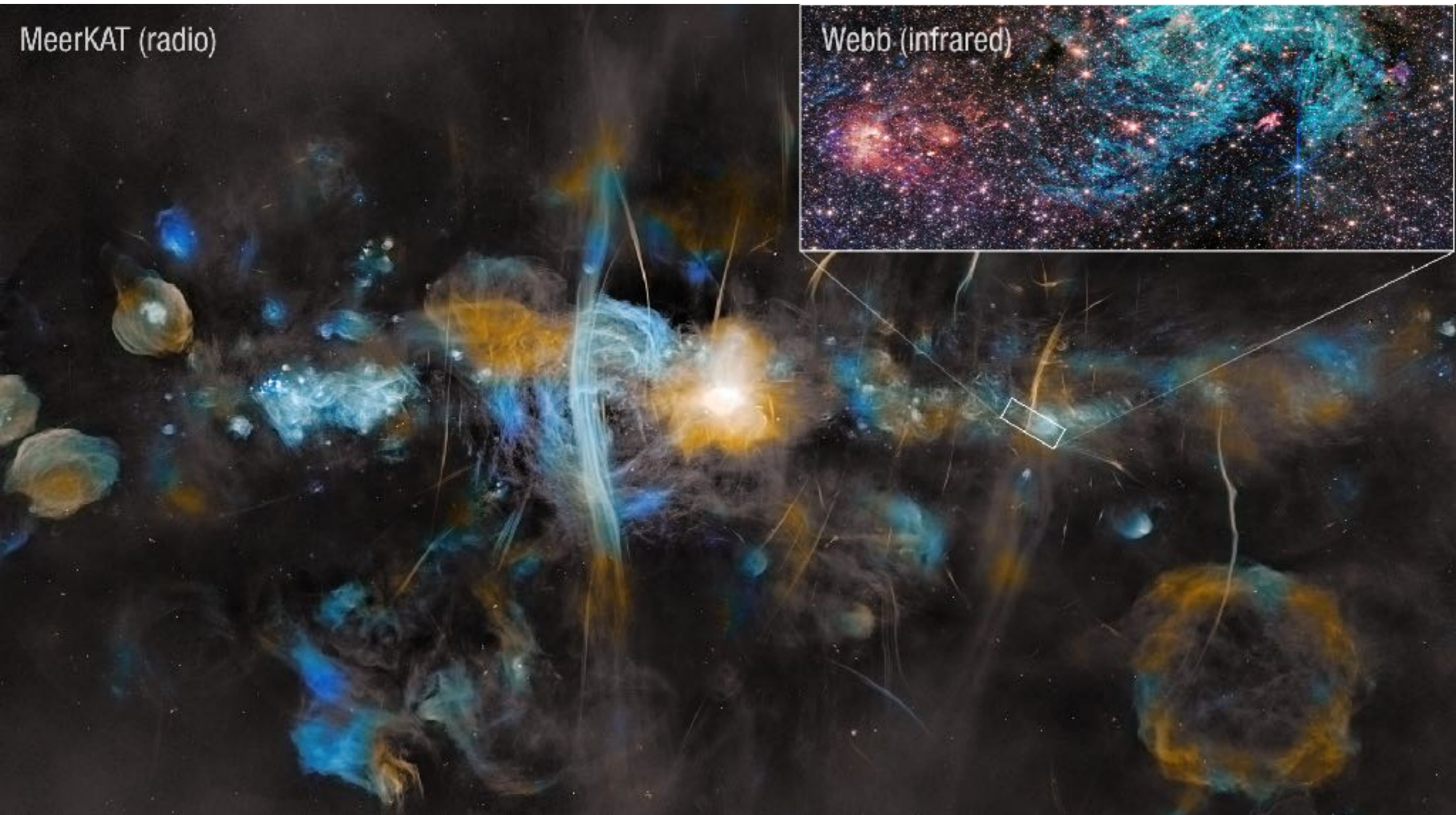
Radio tracers of gas in our Galaxy



The galactic center in radio

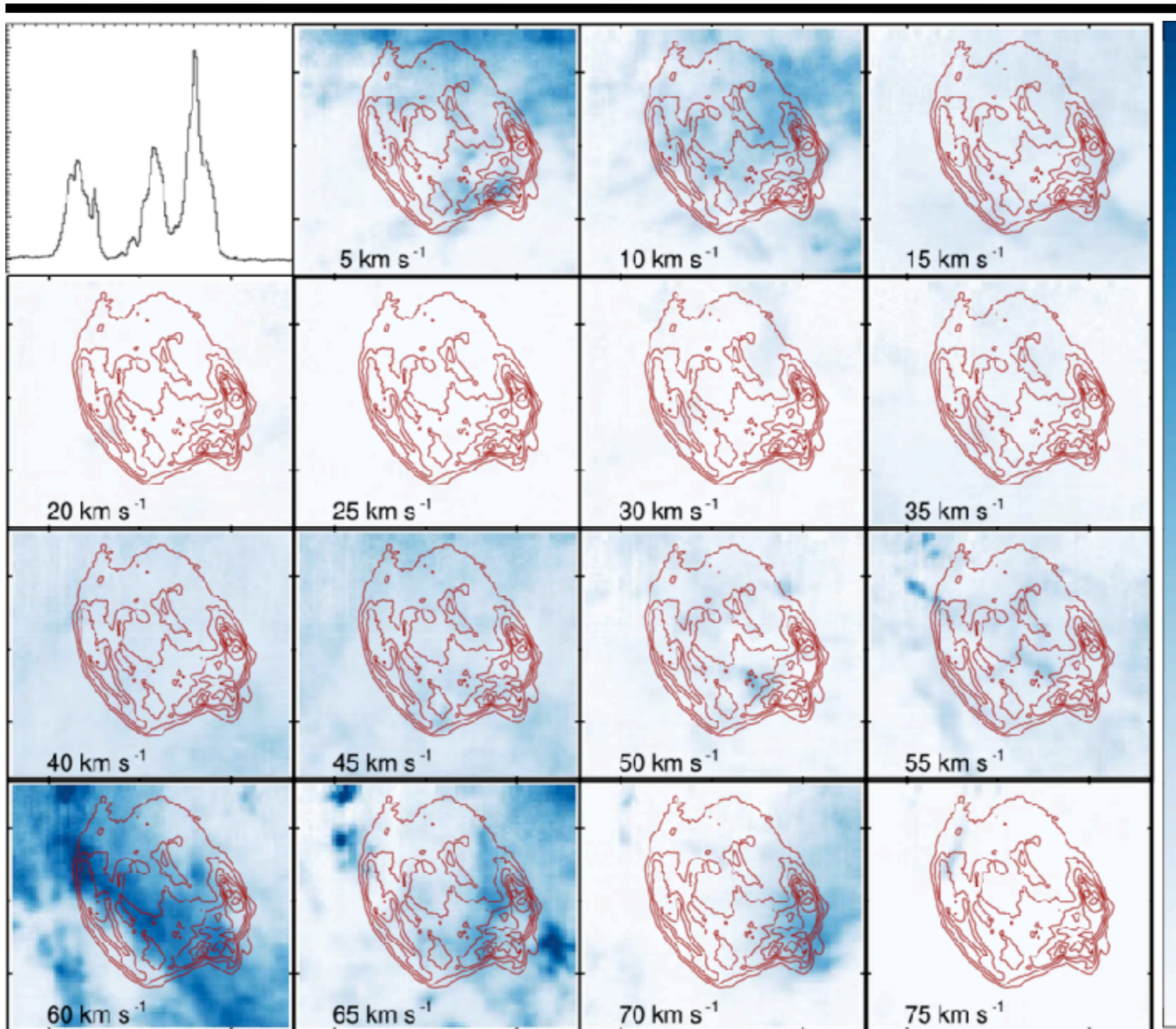


MeerKAT galactic center



Tracing the electron density and magnetic fields
Intriguing filaments structures

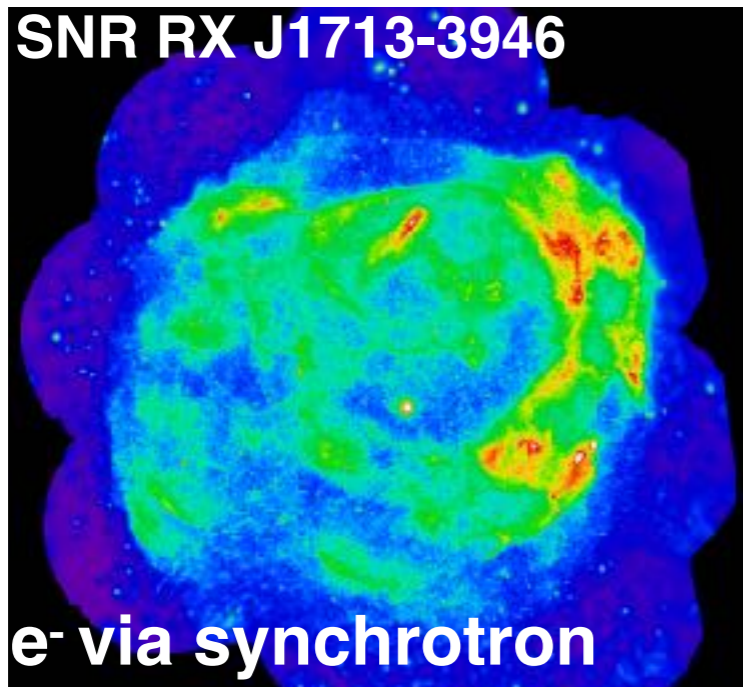
12CO emission can trace the 3D gas in the galaxy



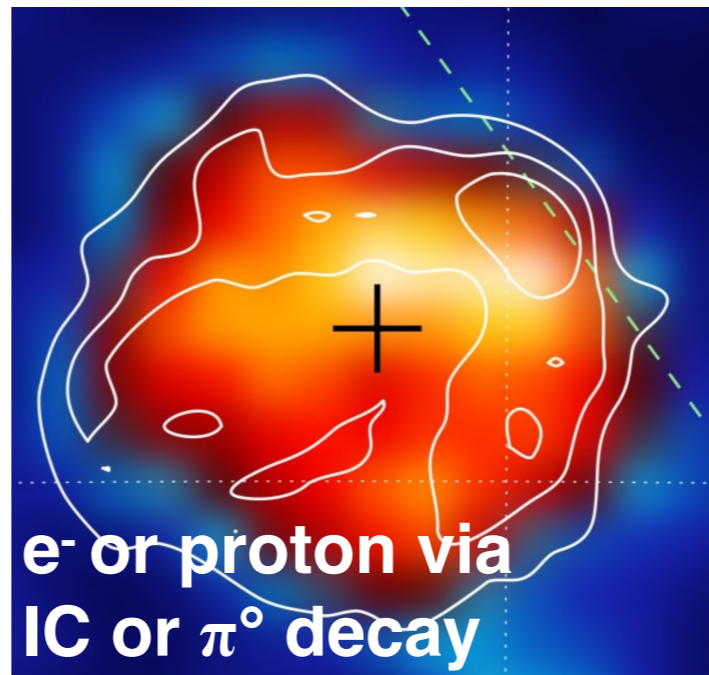
High energy radiation



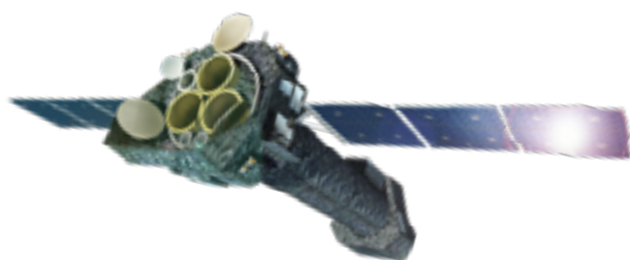
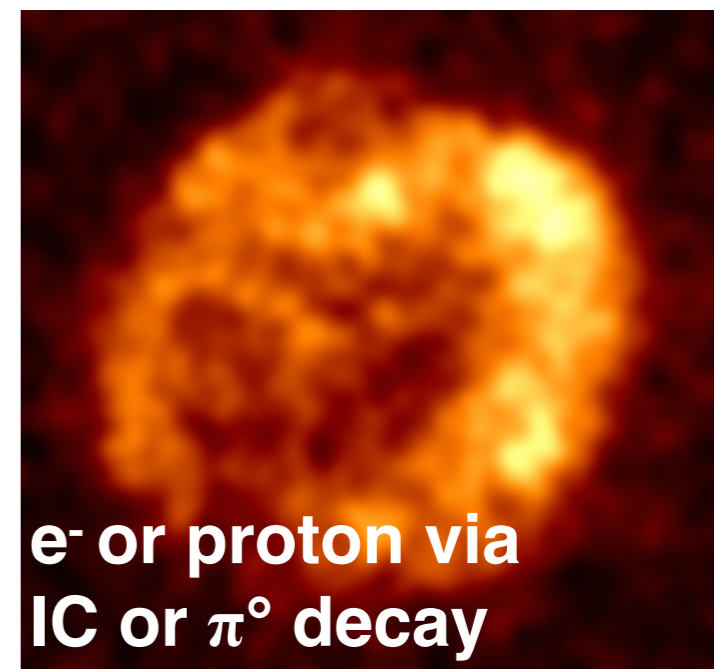
keV



GeV gamma-ray



TeV gamma-ray



XMM-Newton

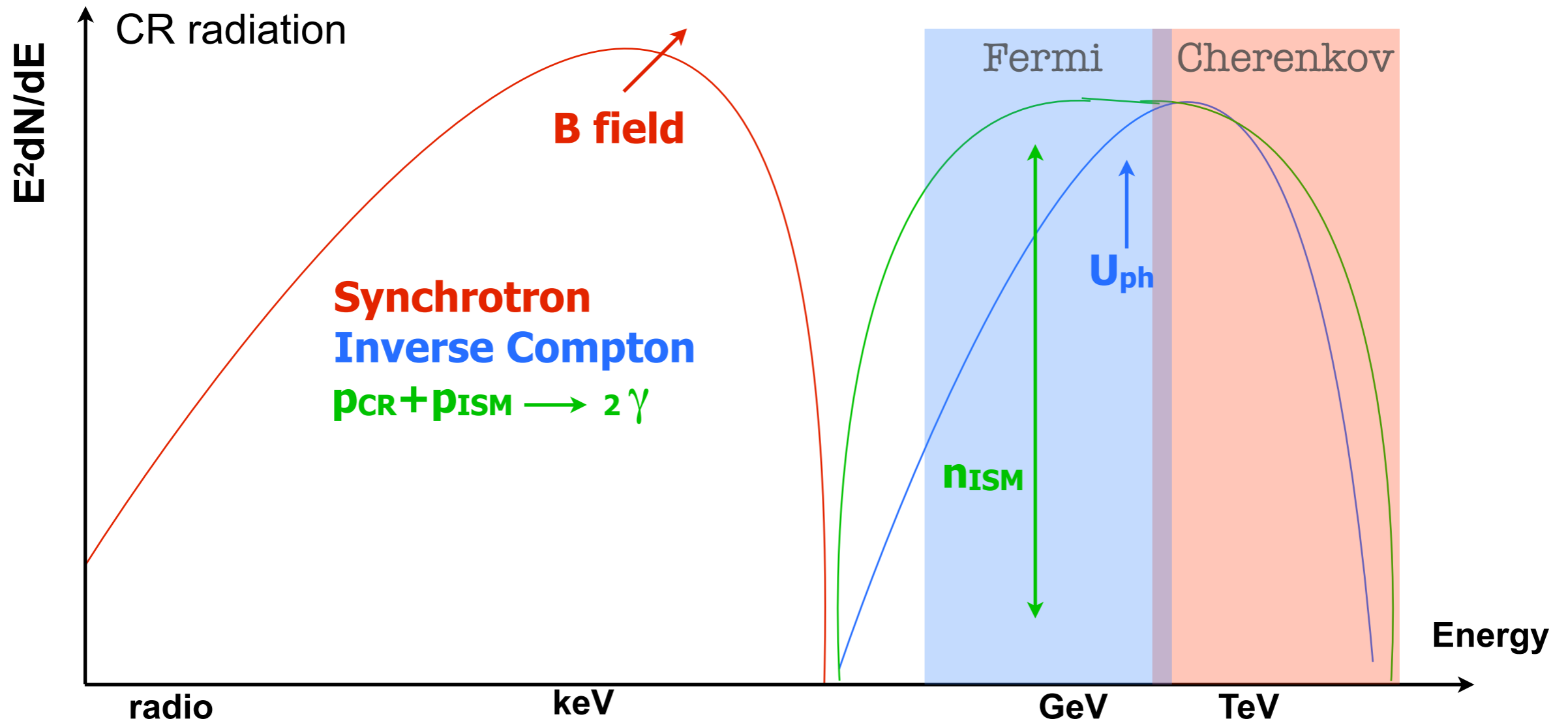


Fermi-LAT



HESS, MAGIC, VERITAS, CTA

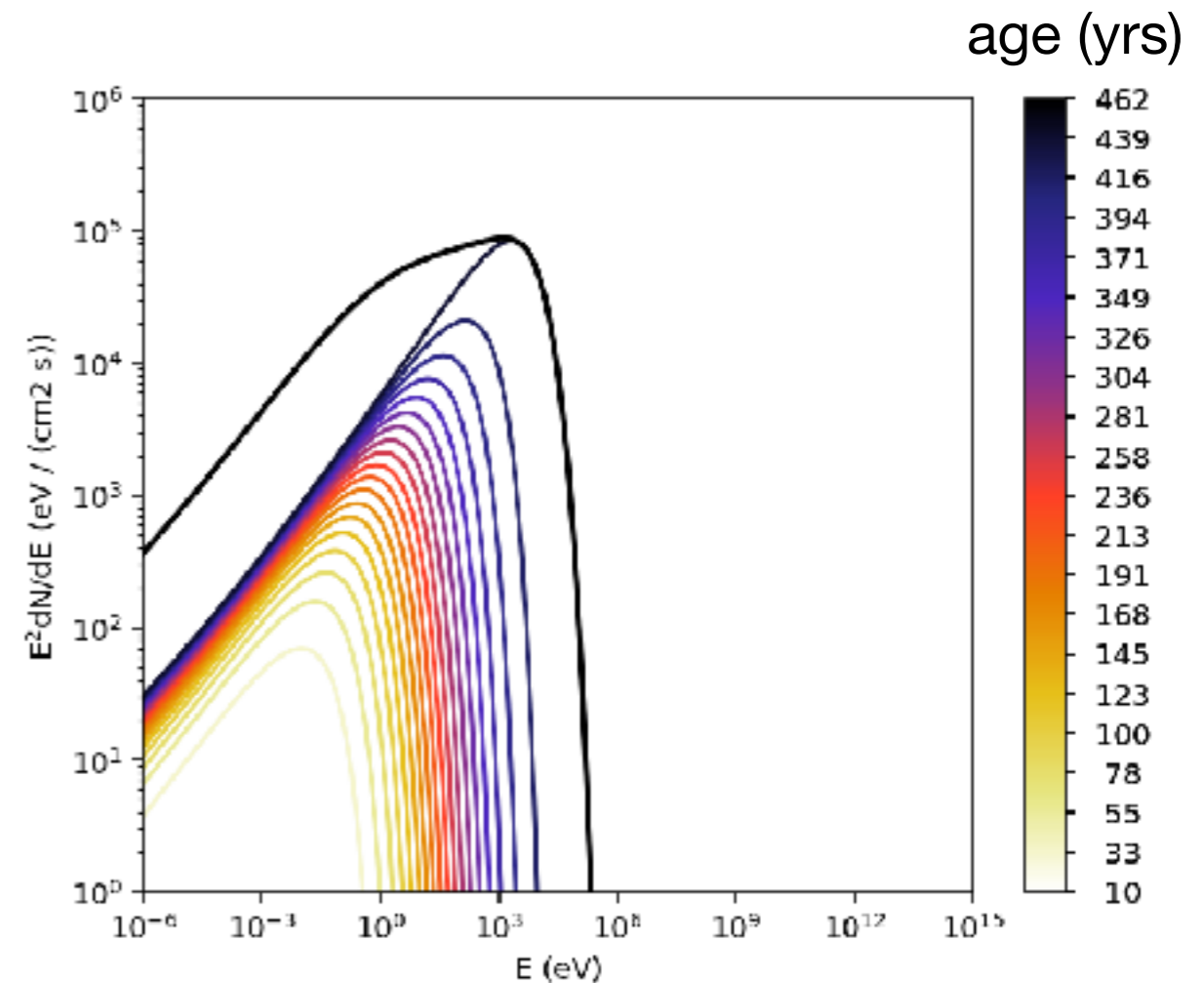
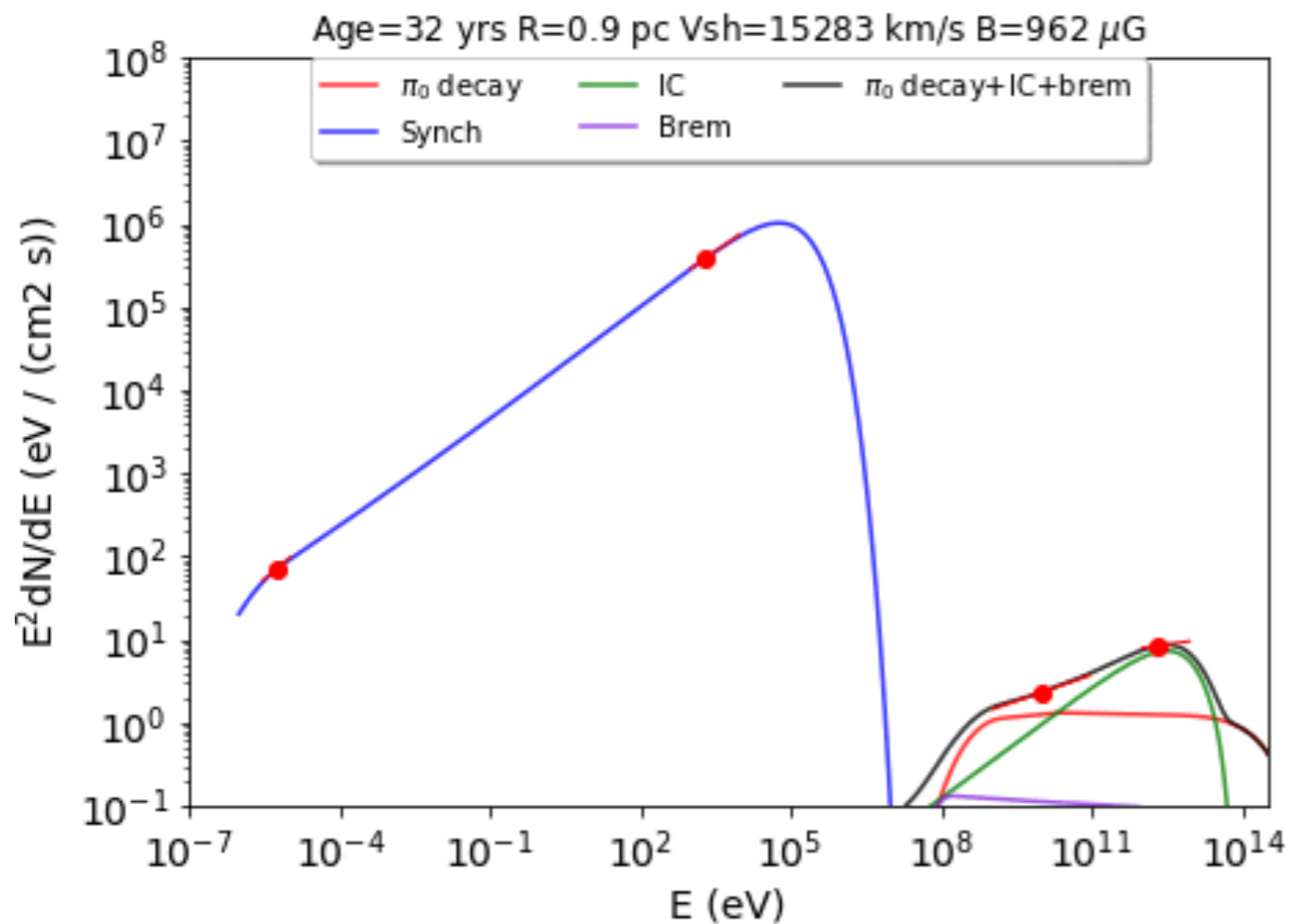
Probing the accelerated particles properties



- Test the CR acceleration paradigm through SNR's particle radiation:
 - Nature of the γ -ray emission, E_{max} , Energetic SNR \rightarrow CRs
 - Time evolution of acceleration, escape, and propagation of CRs
 - Effects of the surrounding environment

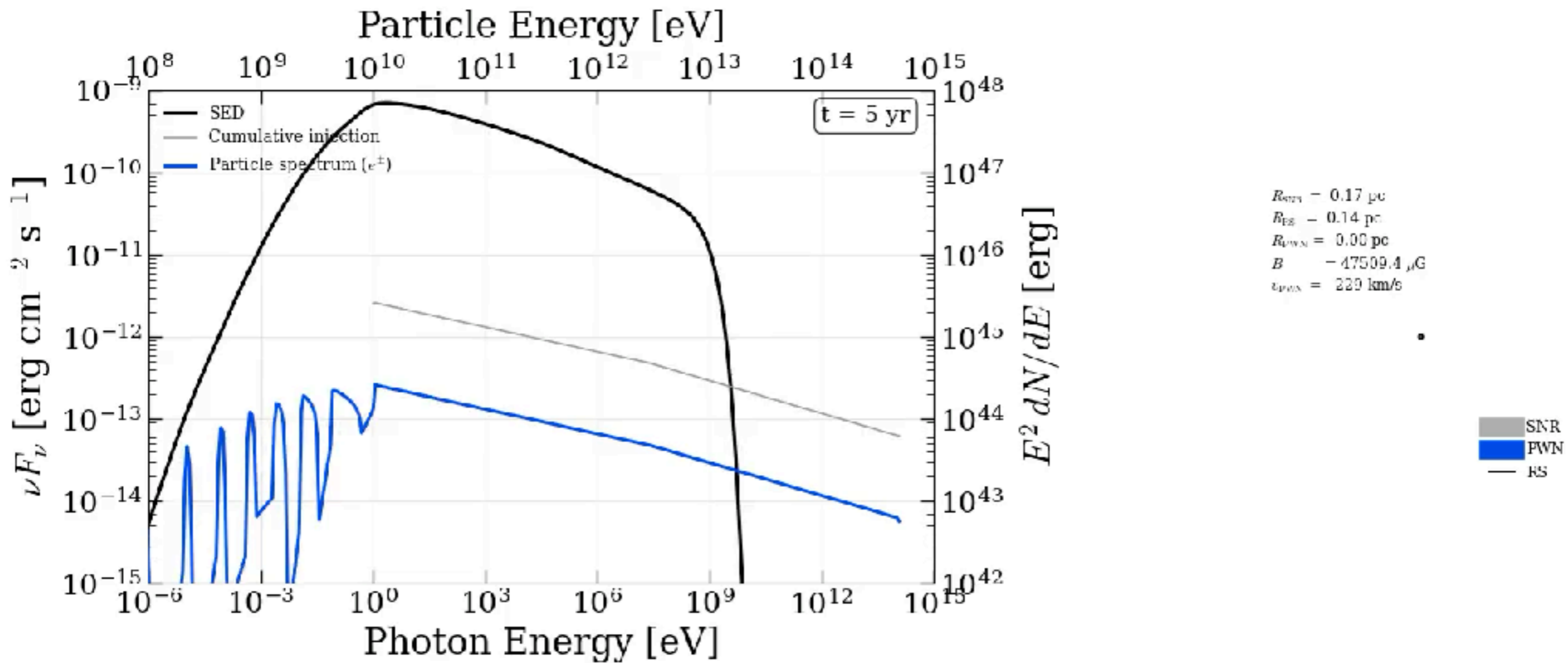
CRAFT: time evolution SEDs

- **Current models: One zone, no time evolution**
- **The quality of the MWL data is now better than our models**
- **CRAFT: analytical CR acceleration code with prescription from larger PIC simulations**

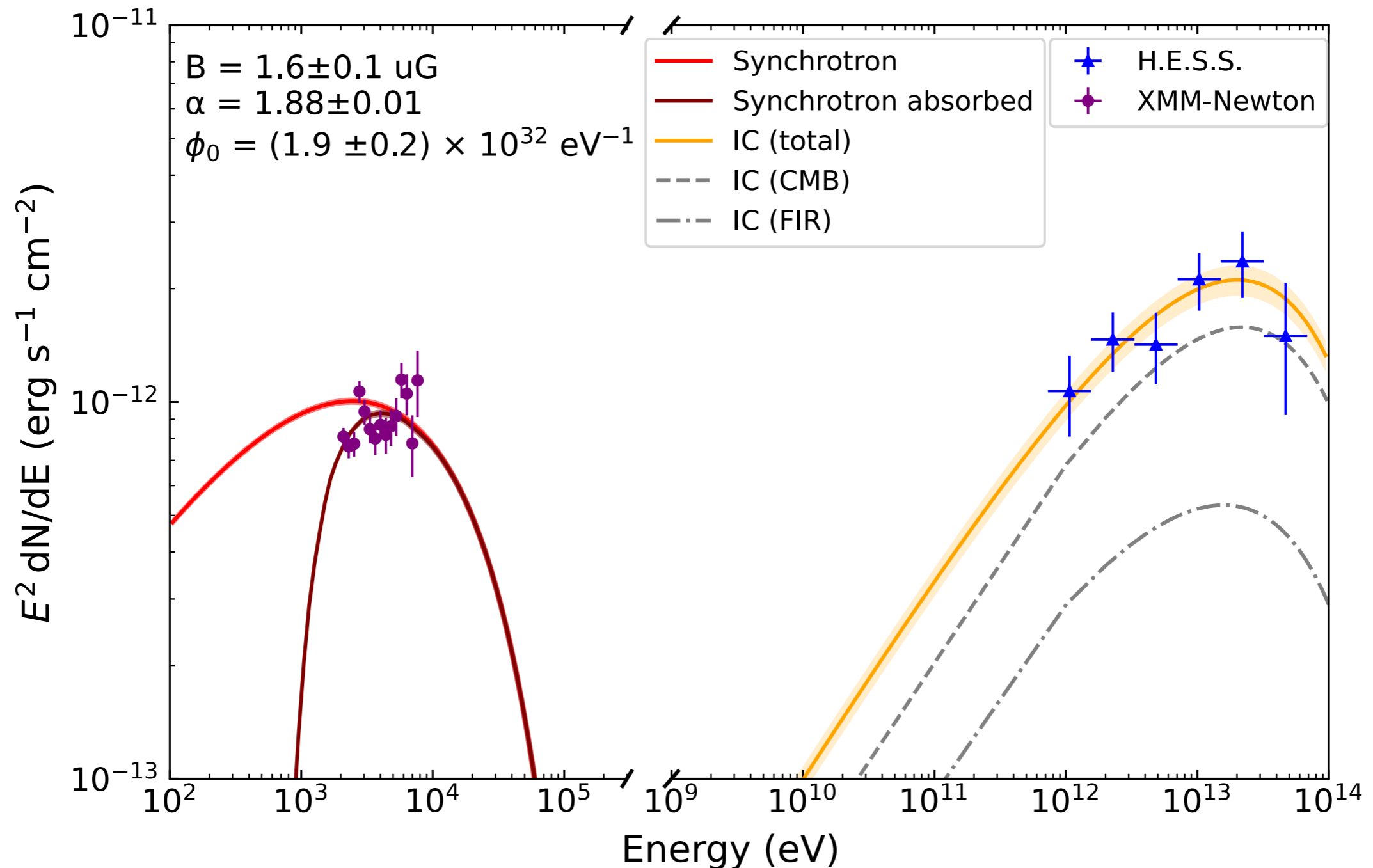


Work in collaboration with D.
Caprioli, Univ. of Chicago

Simple one zone model vs time evolved models



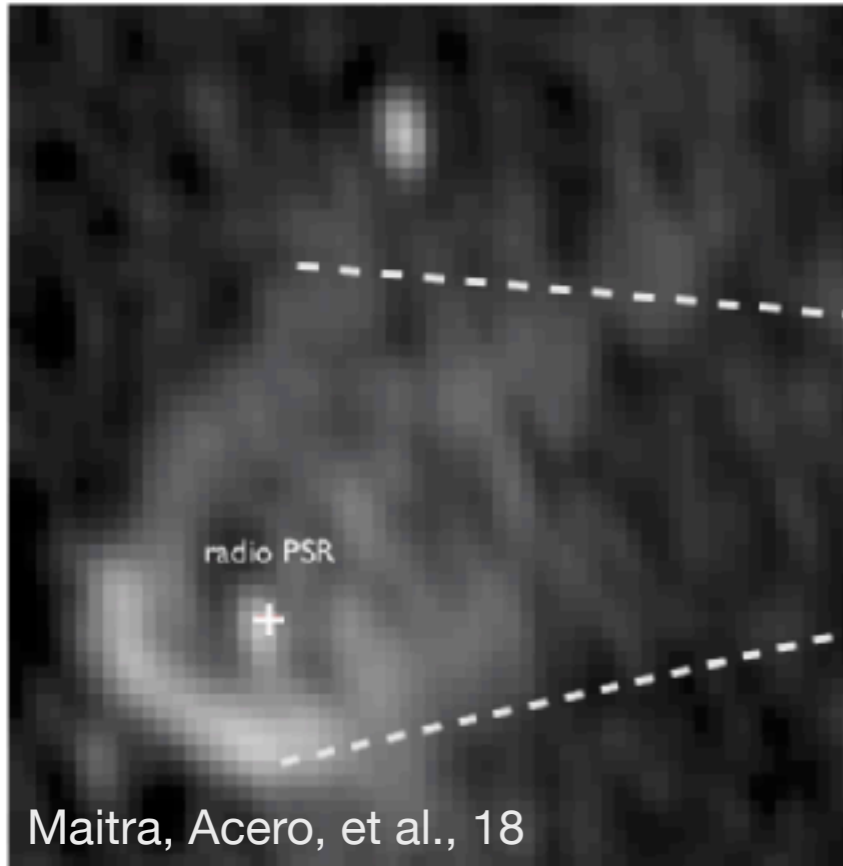
Be careful about absorption effects in X-rays



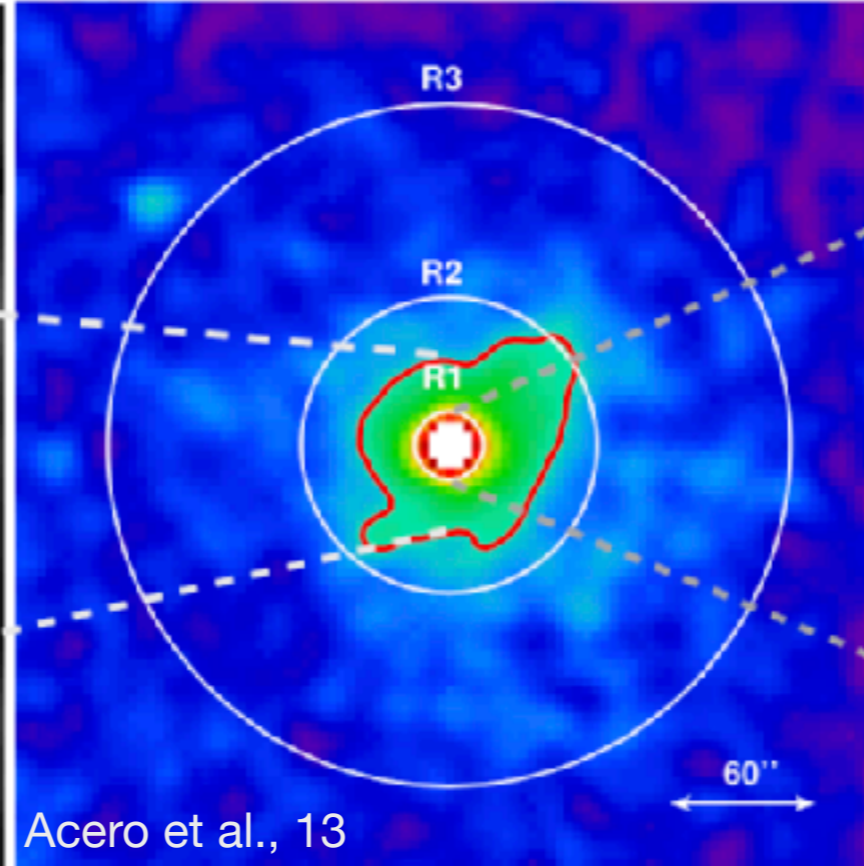
- **No easy/correct way of generating Flux points in X-rays**
 - **Best way is to do forward folding in gammapy for the X-rays**
 - **In particular absorption effect can be strong in soft X-rays !**

Nebula around PSR J0855-4644

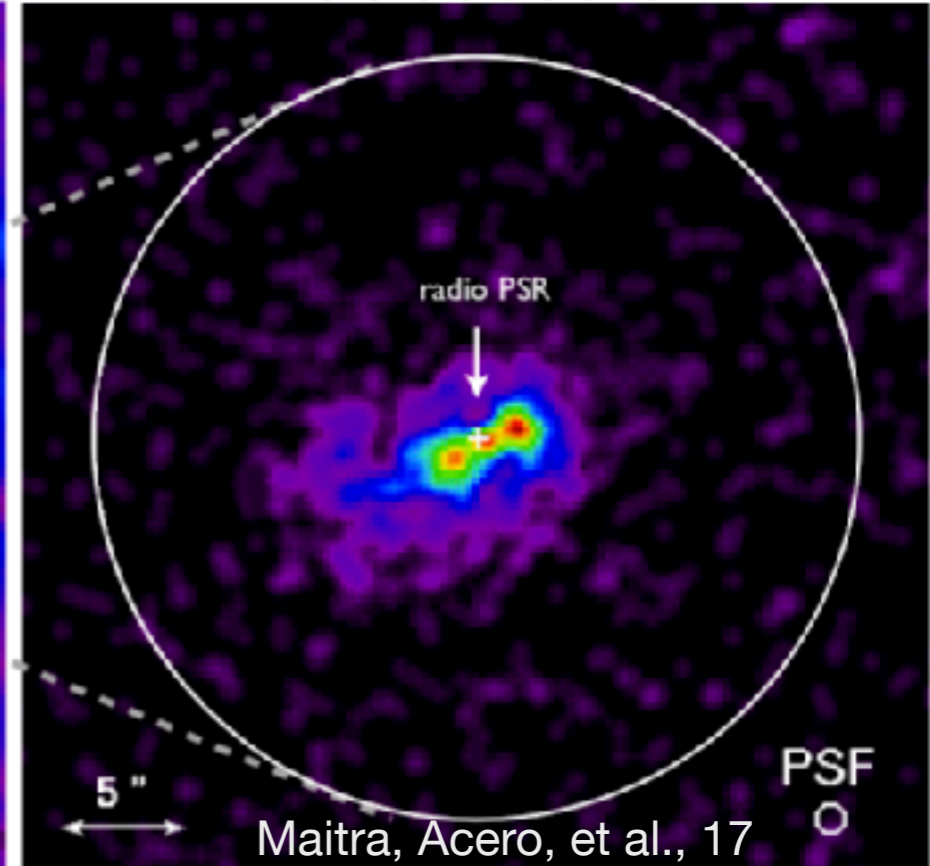
GMRT 1.35 GHz



XMM 1.2-6 keV



Chandra 0.8-8 keV

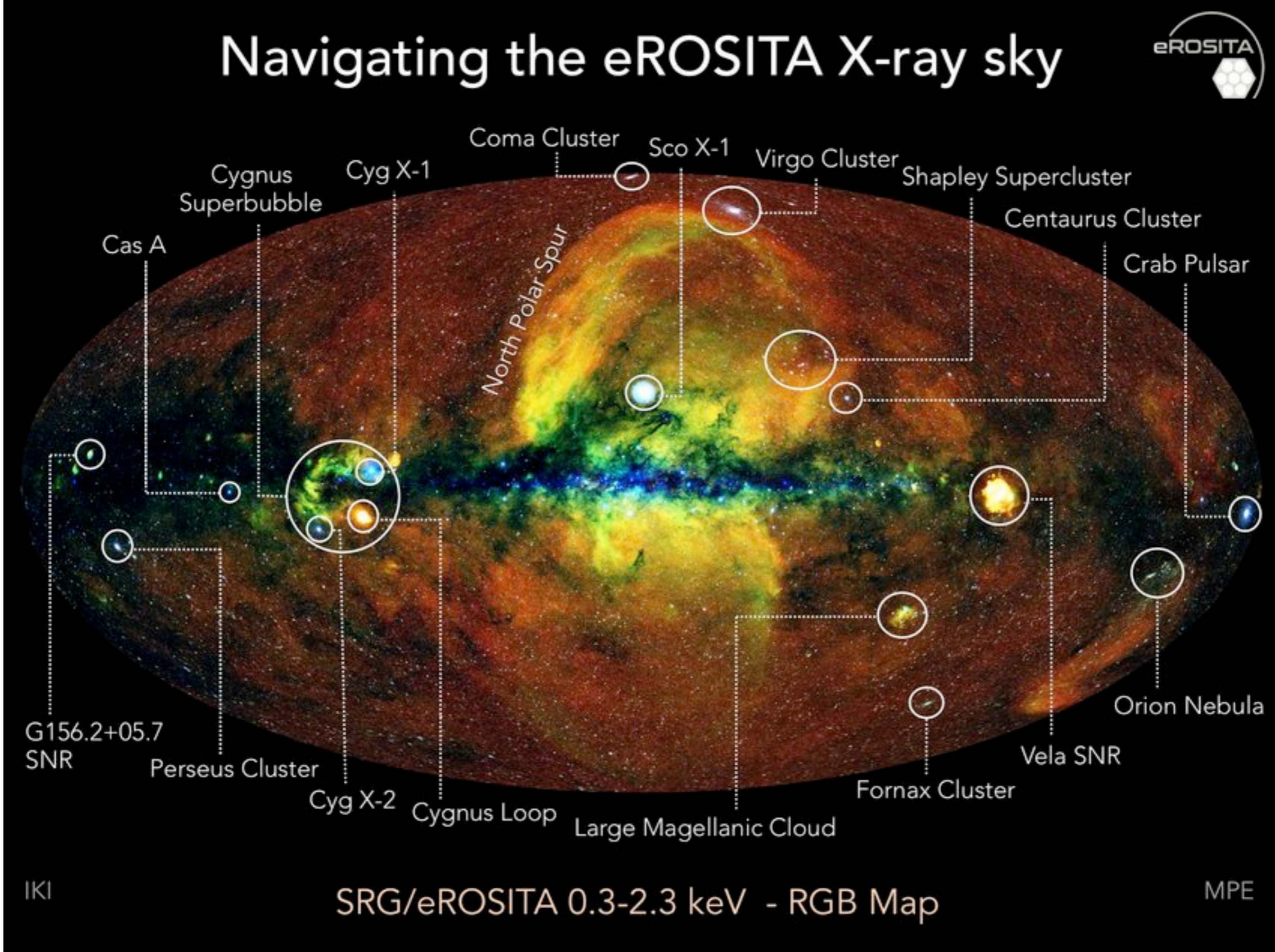


bow shock ?

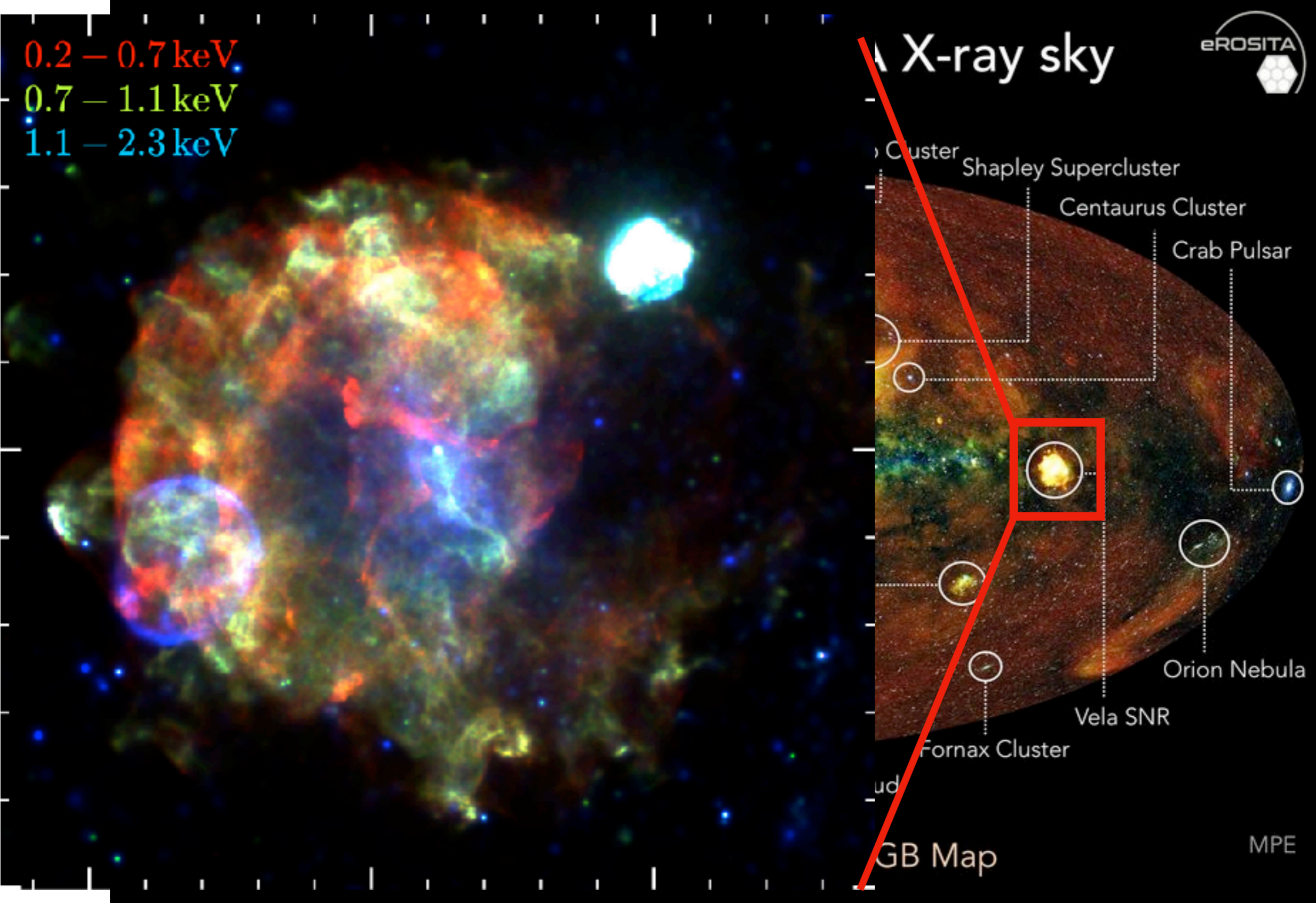
torus or dual jet morphology

- **High E_{dot}/d^2 pulsar (10^{36} ergs/s, 2nd most energetic within 1 kpc)**
- **Jets/double torus morphology seen with Chandra**
- **Inclination angle from X-ray modeling explains γ -ray loud, radio quiet**

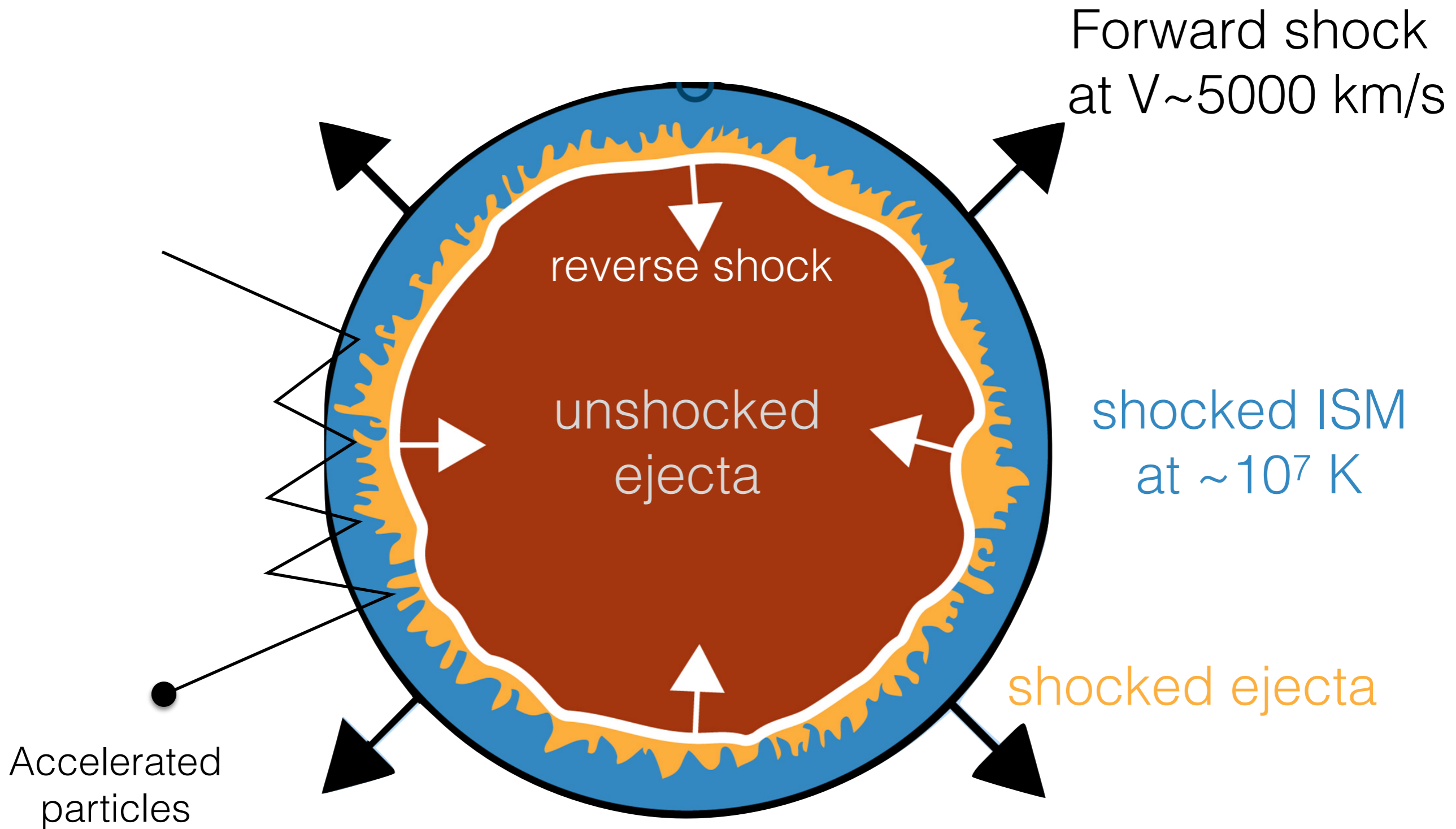
eROSITA all sky survey



eROSITA all sky survey

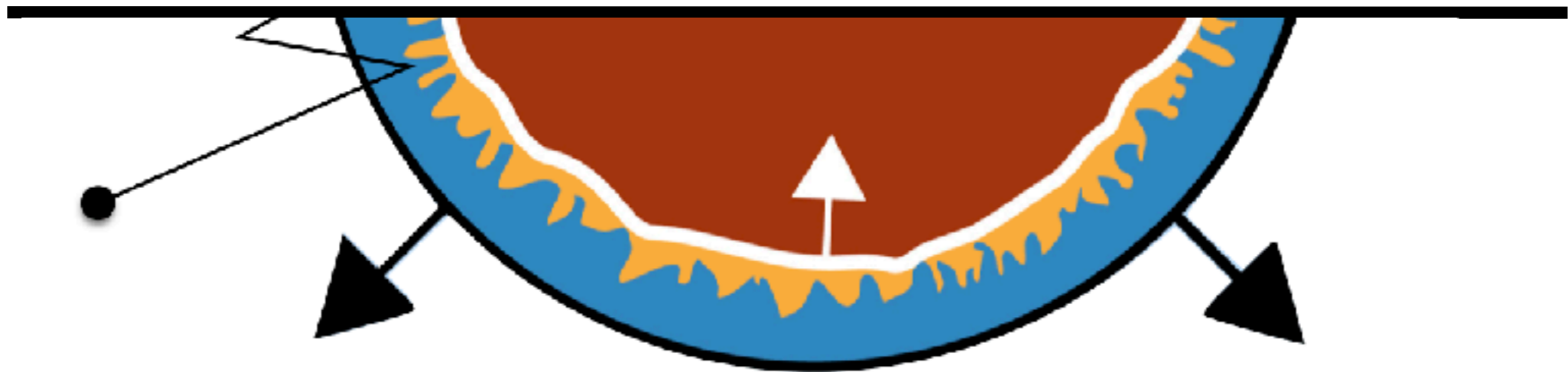


Supernova Remnant: what do we see ?



(c) A. Bordenave

What do we learn ?



Accelerated particles

- Acceleration mechanism
- Composition (e⁻ and/or p)
- Flux of particles
- Maximal energy reached
- Escape (diffusion)

Shocked ISM

- Probe of the ISM:
 - density, metallicity
 - clues for SN progenitor
 - acceleration initial conditions
- Collisionless shock physics:
 - e⁻ /p T° equilibration

Shocked ejecta

- Supernova yield:
 - SN type
 - mass of progenitor
 - metallicity of progenitor
- Morphology and kinematics:
 - 3D ejecta distribution
 - SN explosion mechanism

Messengers:

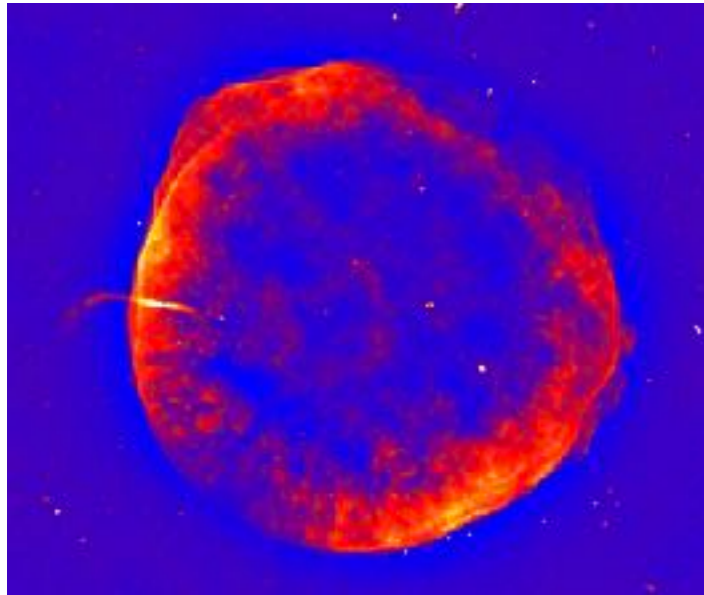
Radio, X, Gamma-rays

Optical, UV, X-rays

IR, optical, X-rays

SN 1006 example of MWL

Radio 1.4 GHz



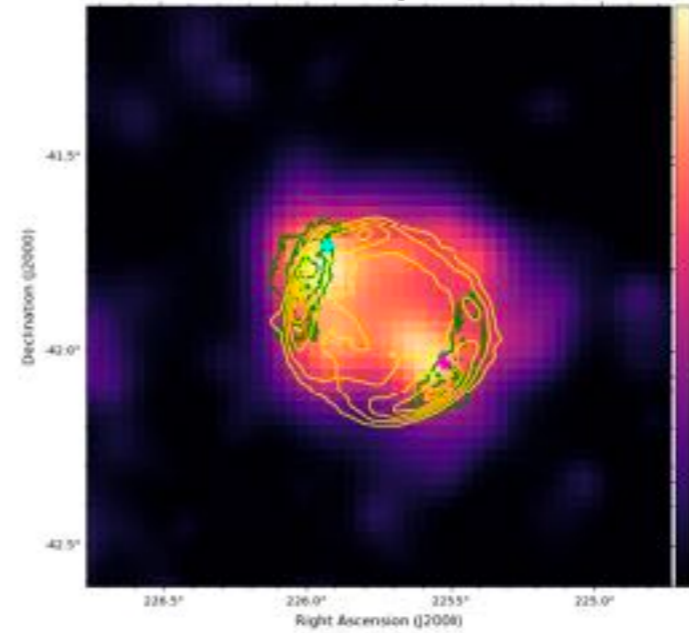
X-rays



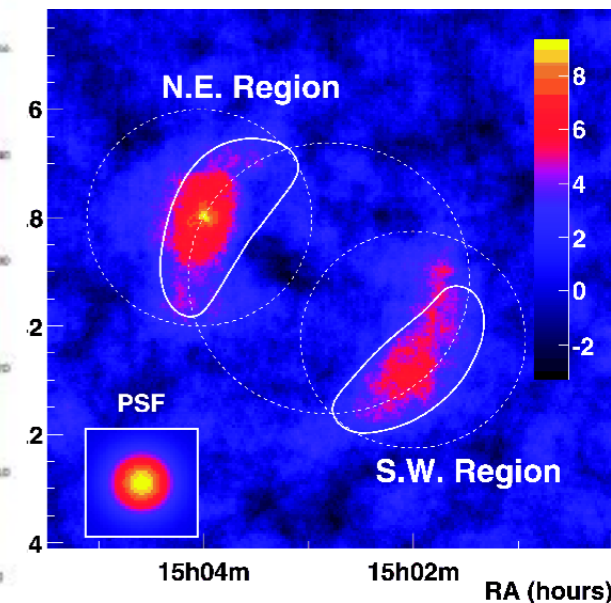
Thermal + Synch

Density + synch e^-

Fermi - GeV



HESS - TeV

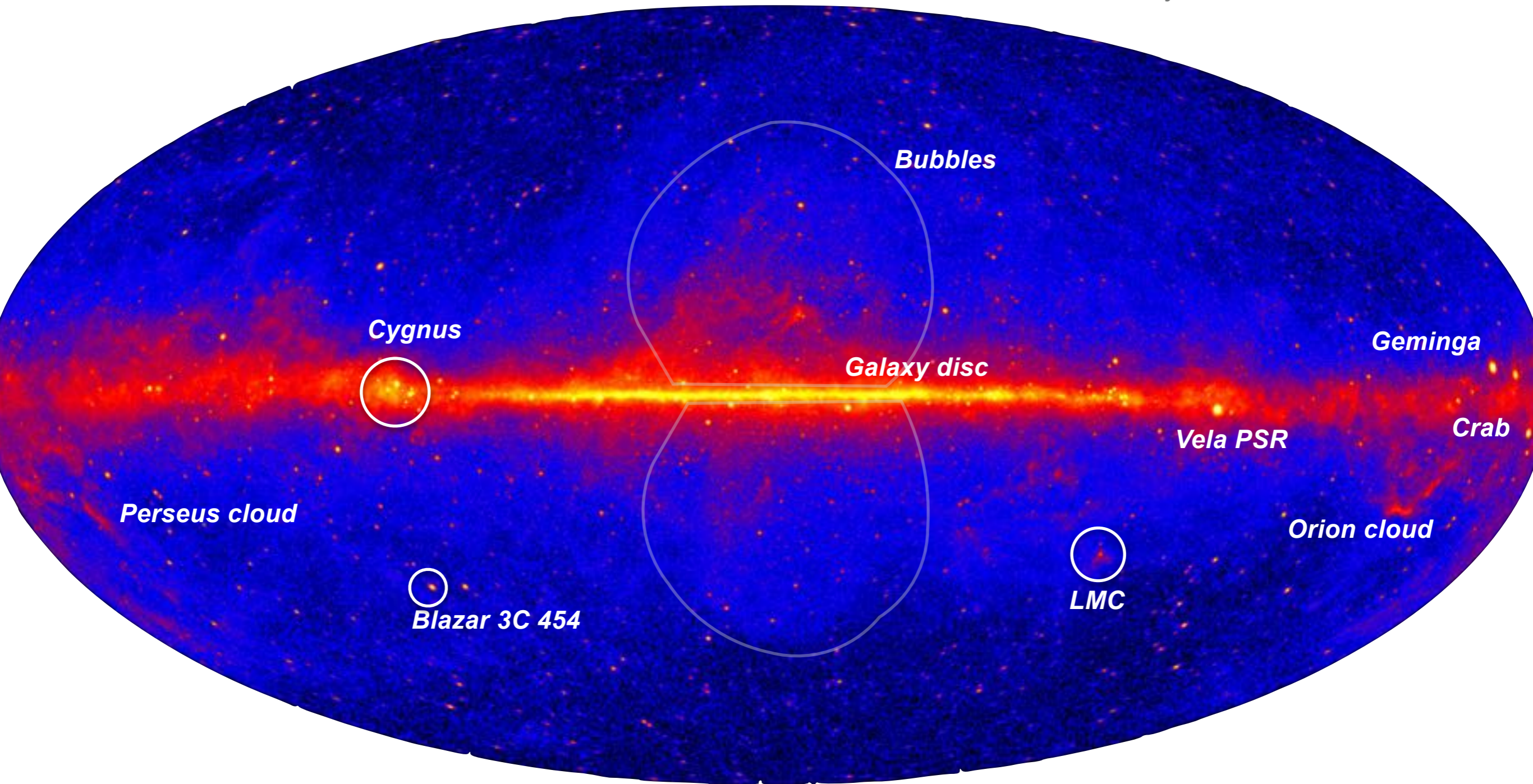


The observational counterpart

Fermi-LAT all sky view

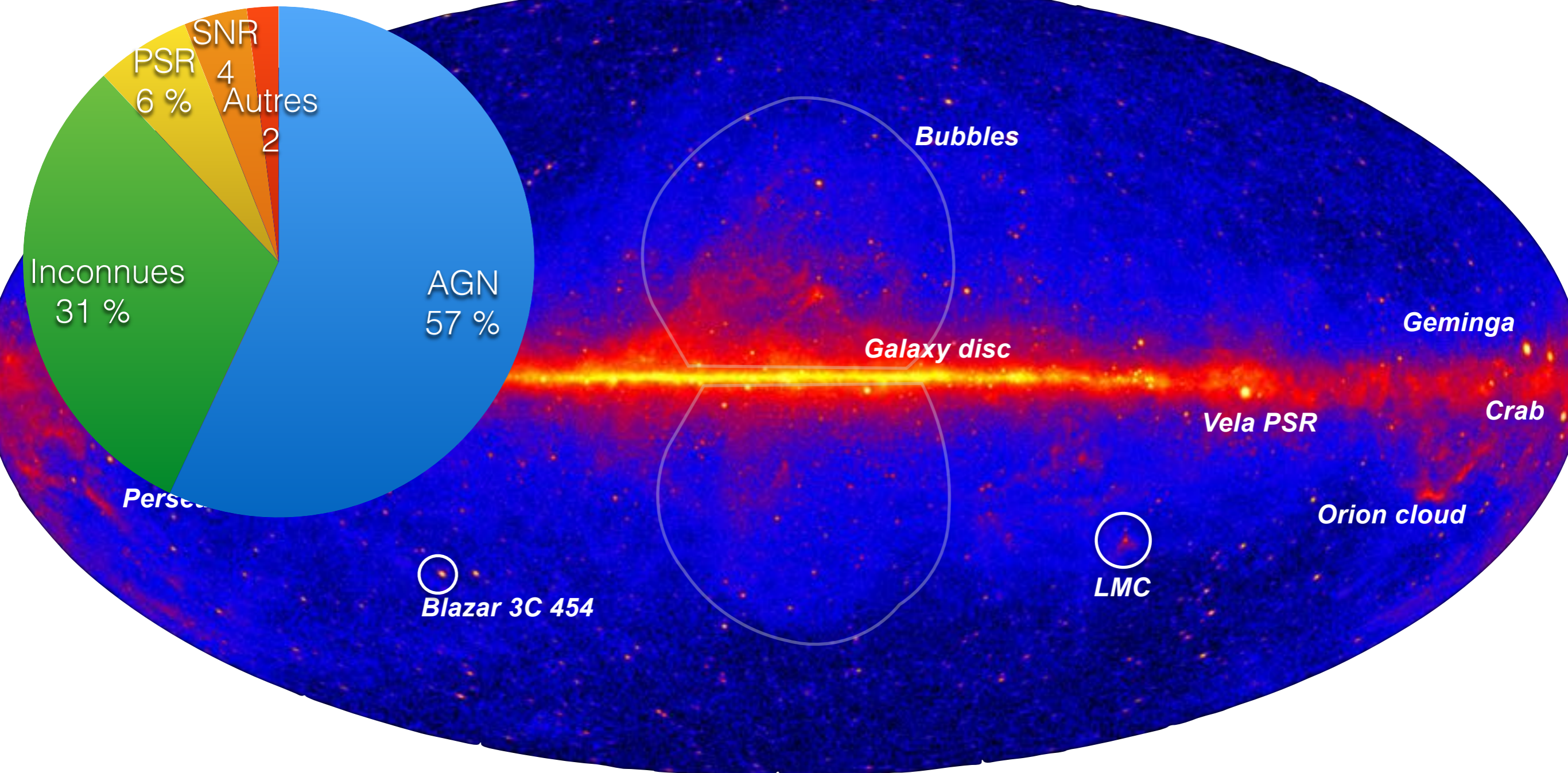
$E > 1 \text{ GeV}$

15 years

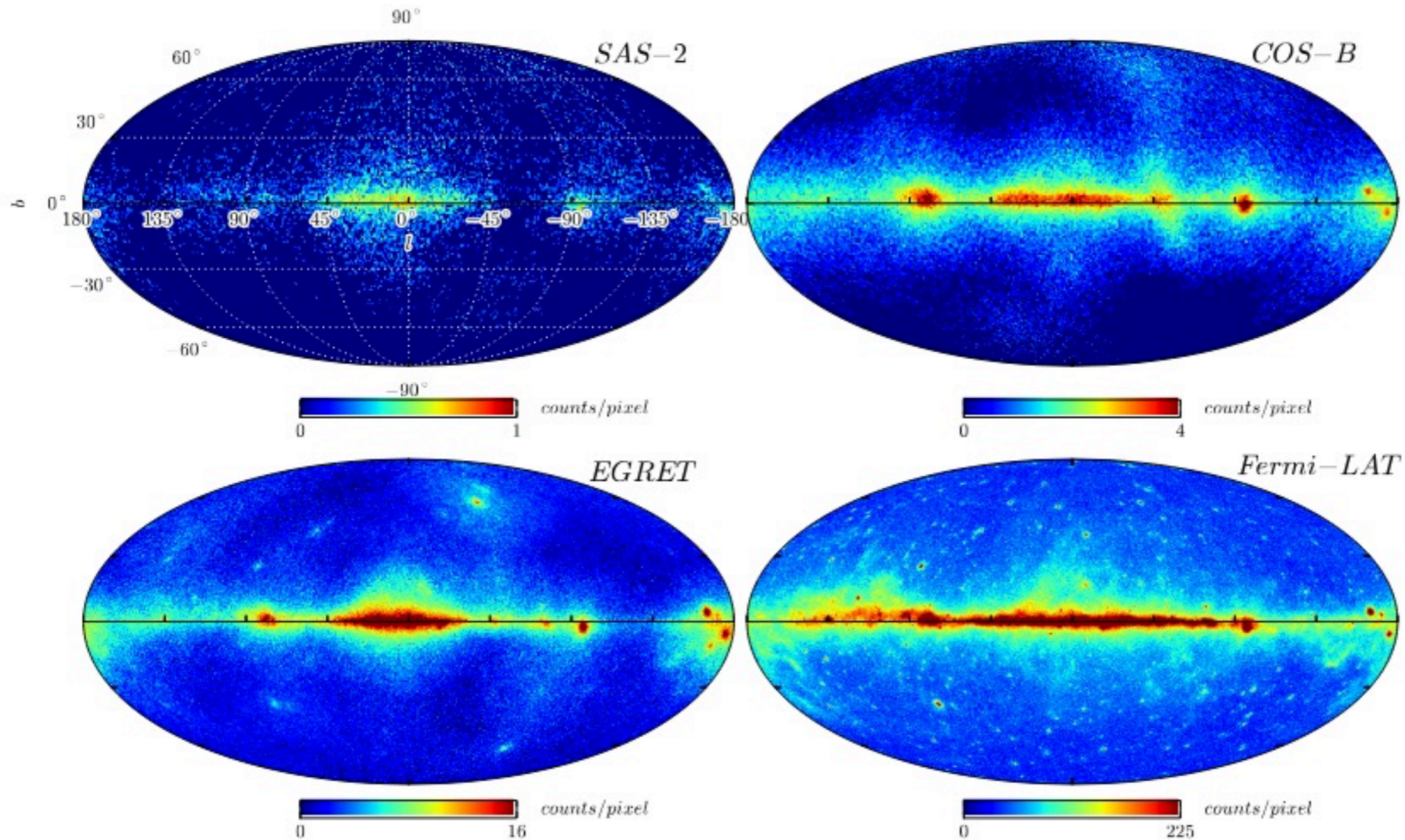


The observational counterpart

Fermi-LAT all sky view
 $E > 1 \text{ GeV}$
15 years



GeV galactic diffuse interstellar emission

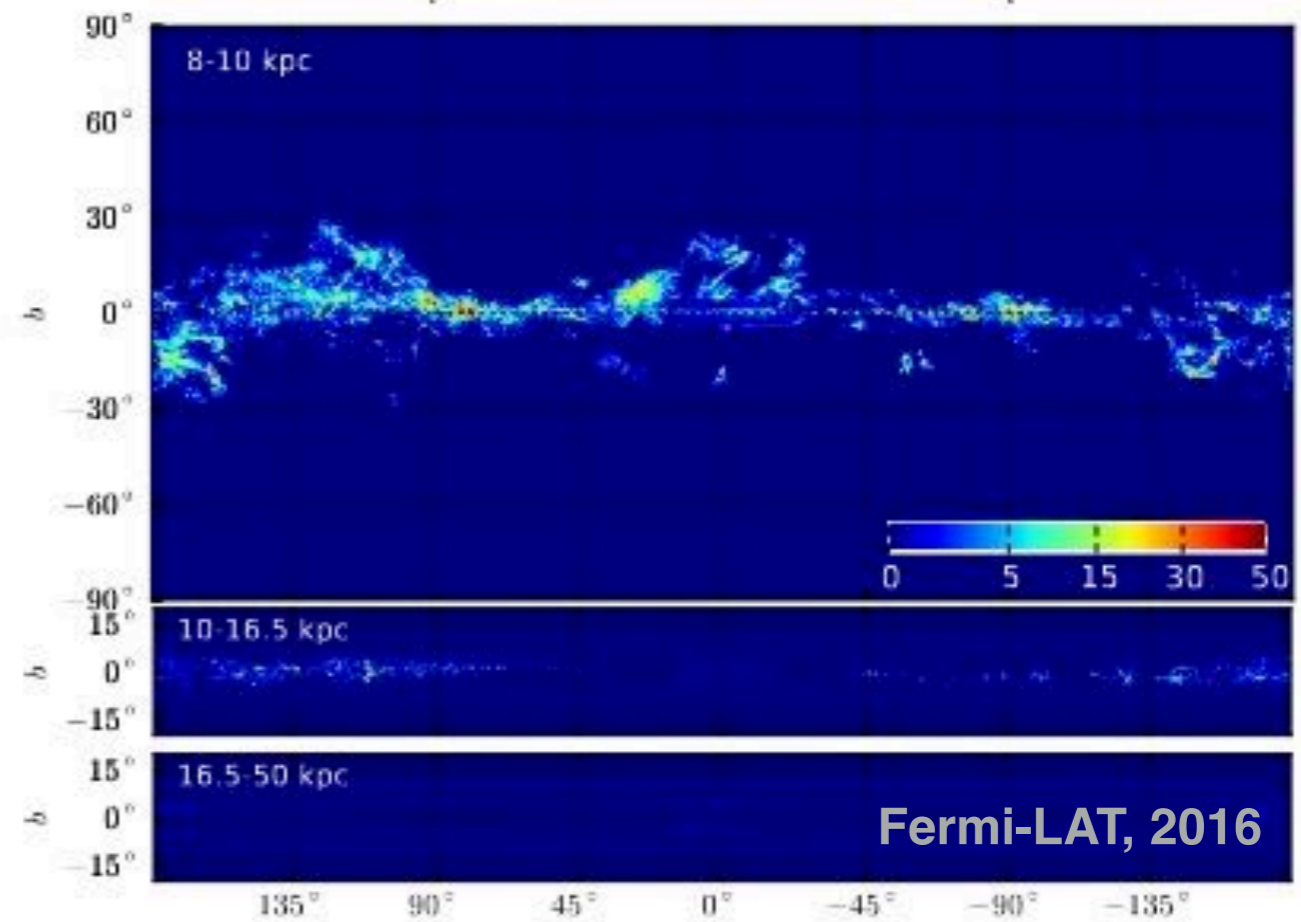
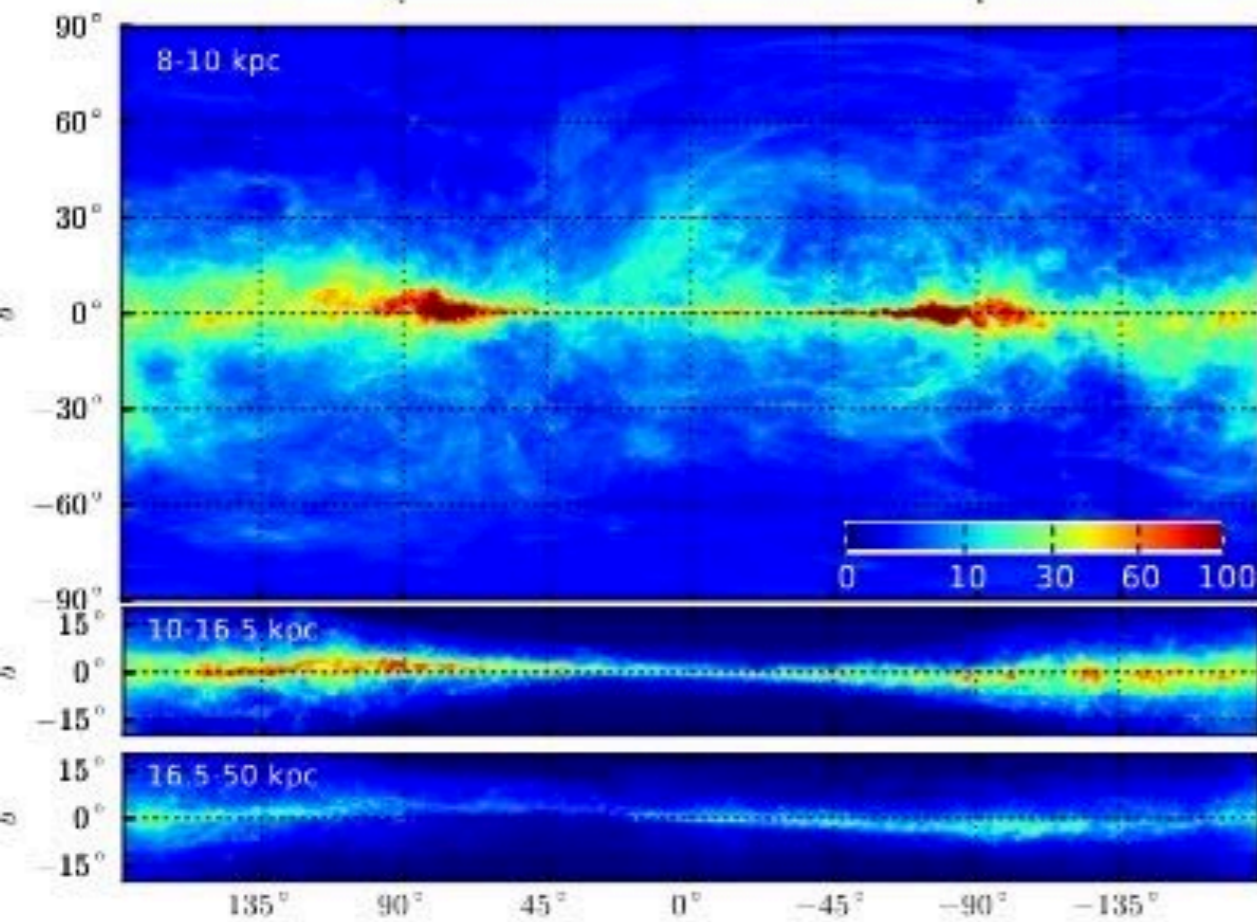
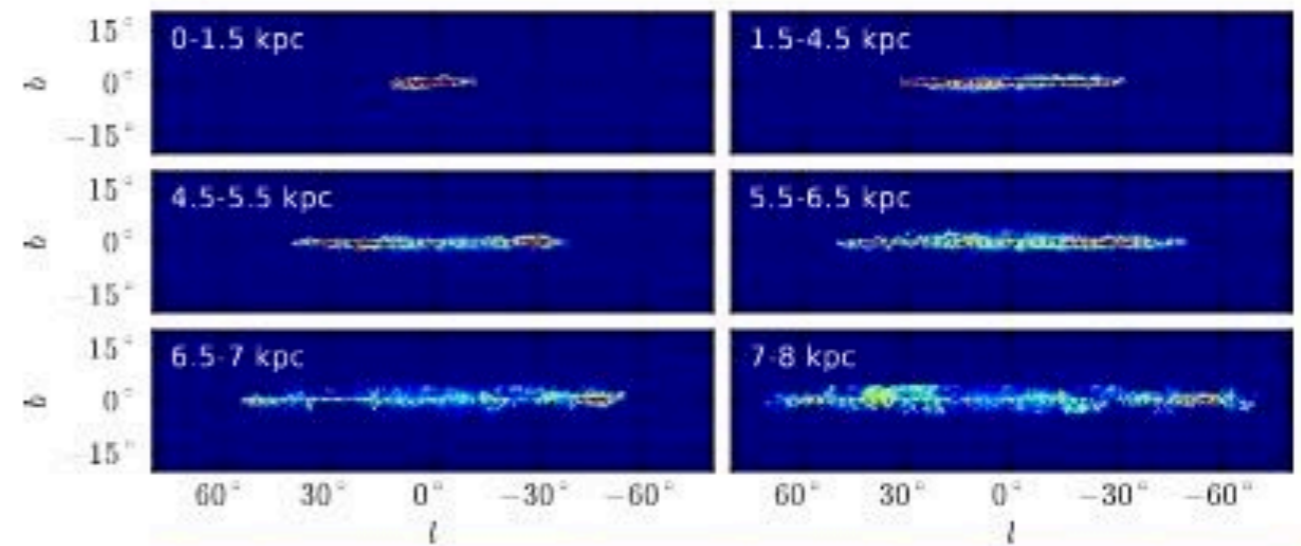
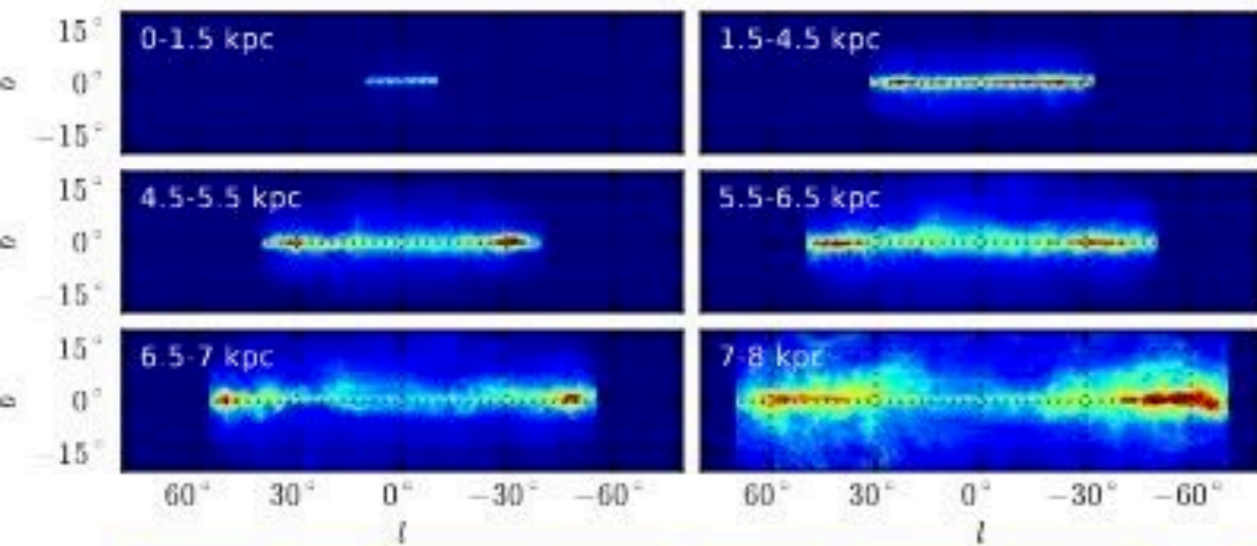


Fermi-LAT, 2016

- 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

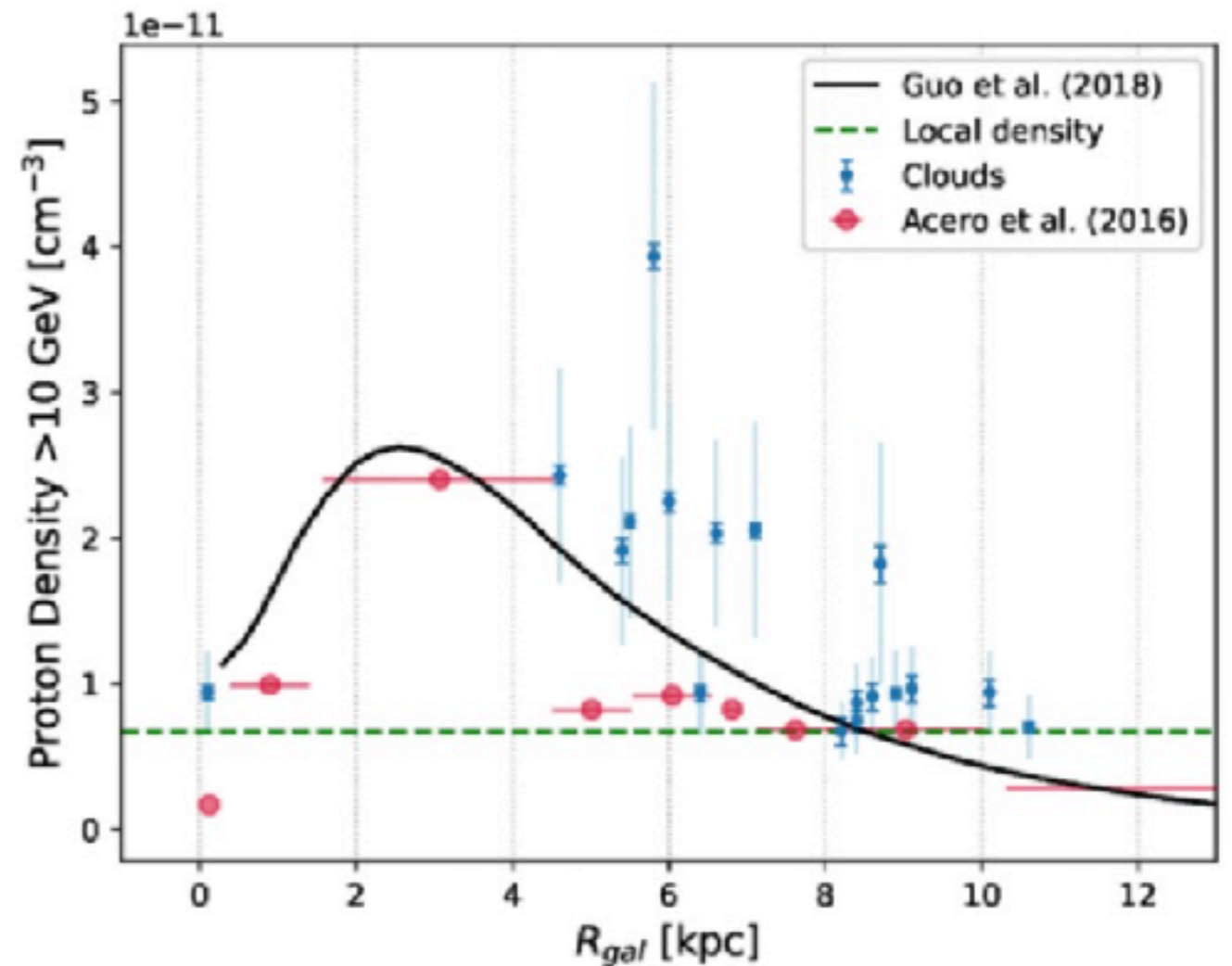
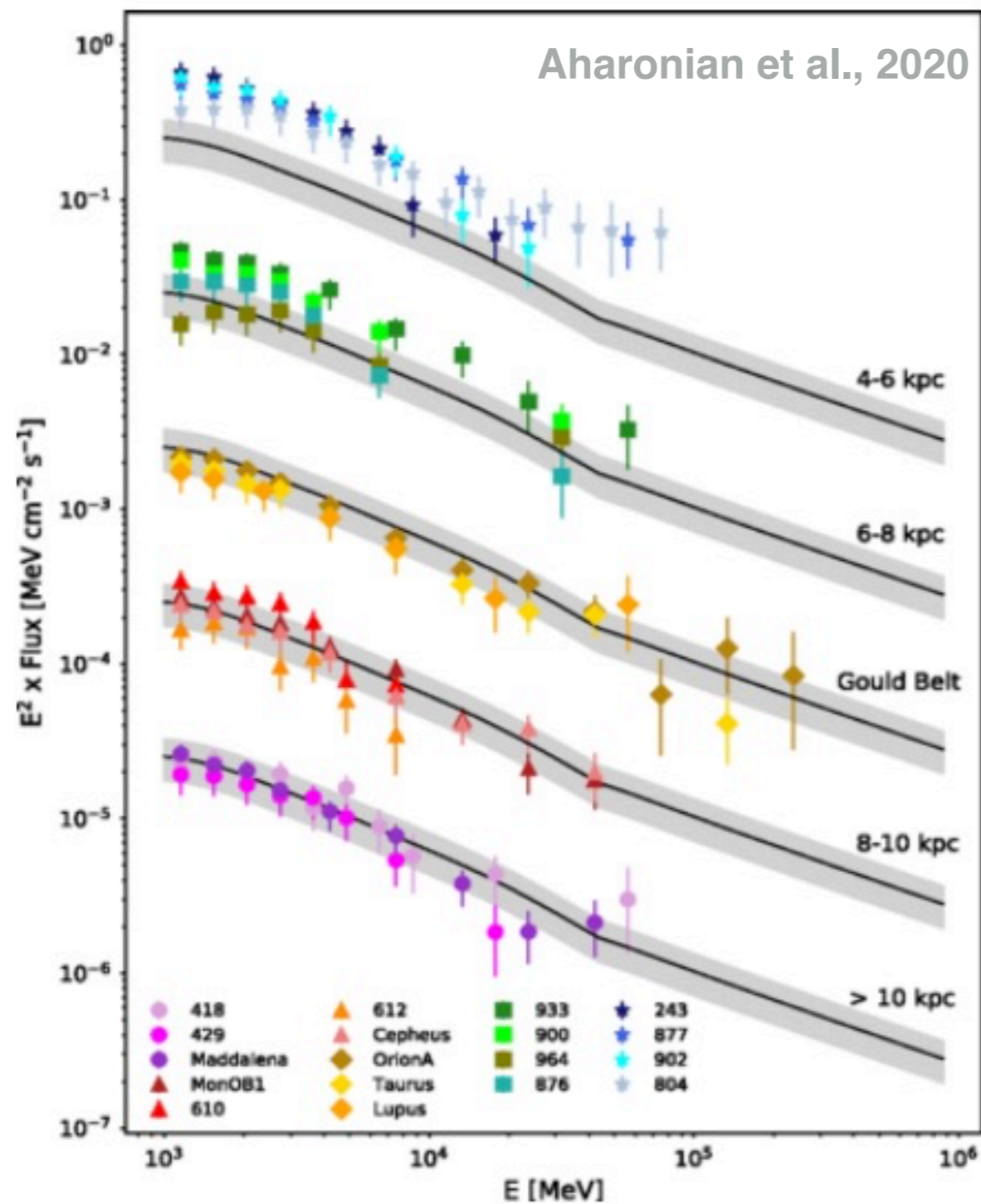


Fermi-LAT, 2016

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+CO+DNM)
 - CO gas rings** (pointing to HI+CO+DNM)
- **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**

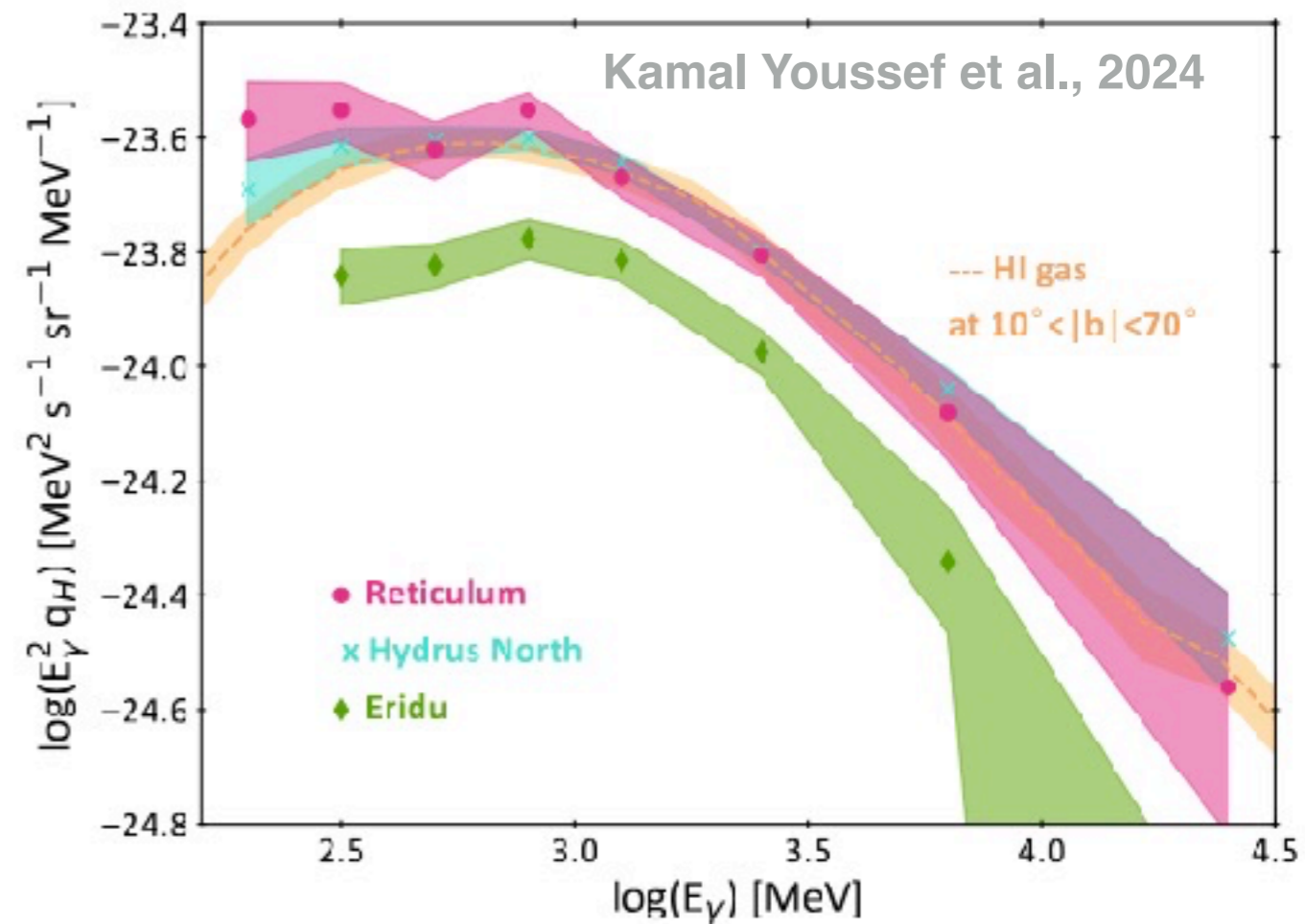
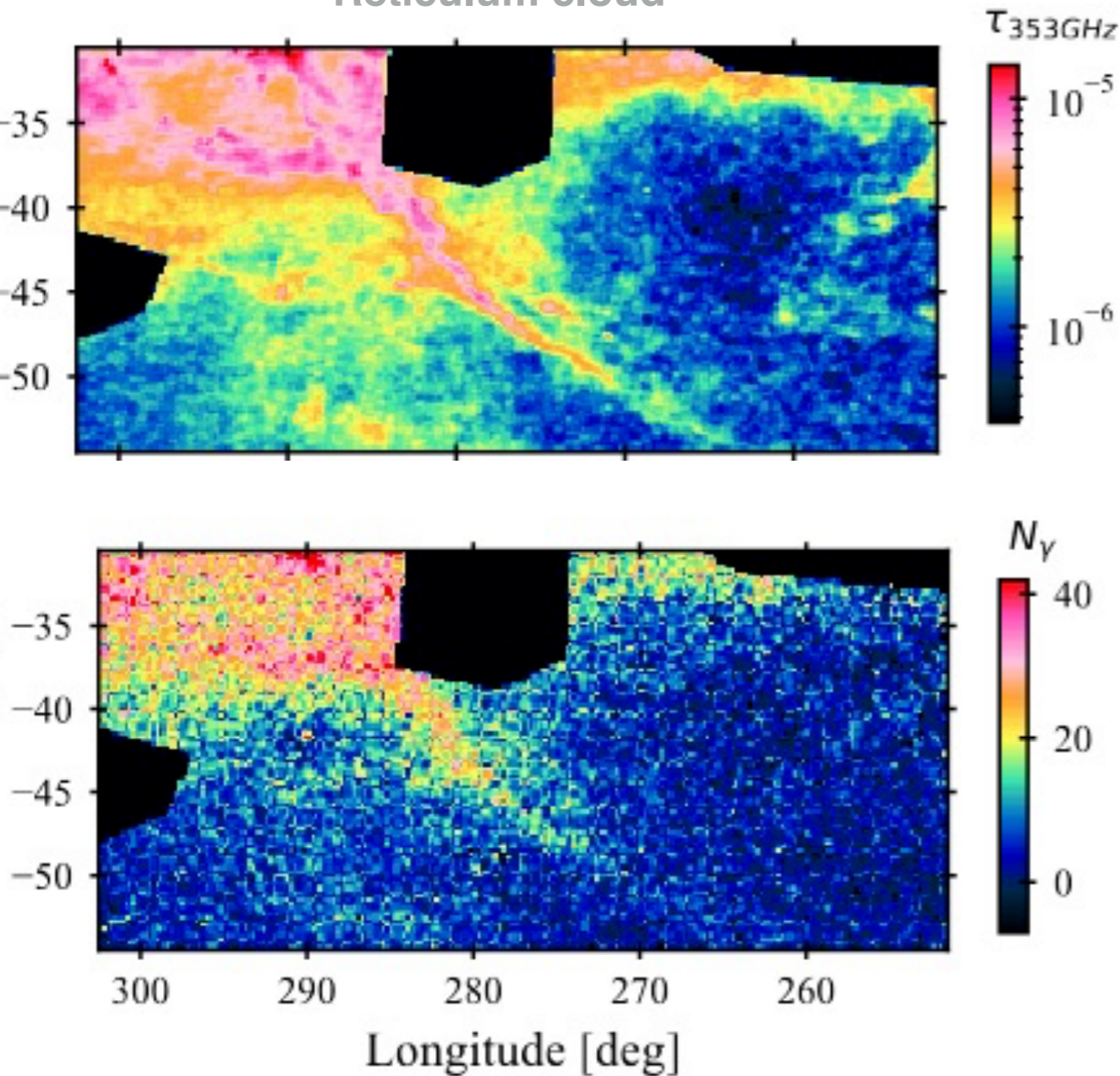
Using clouds as local barometers of CRs



- 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

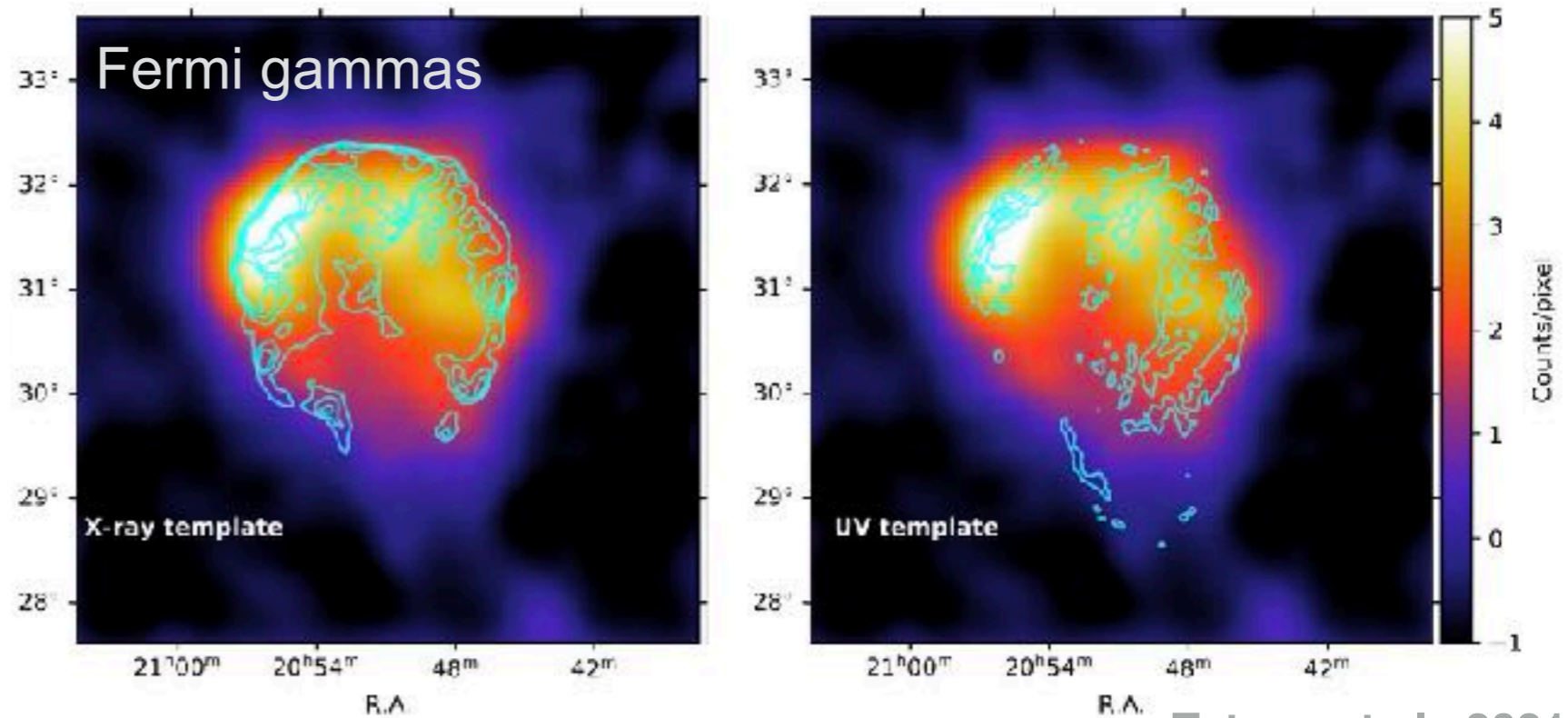
Not all molecular clouds are alike

Reticulum cloud



- 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)

Cygnus loop : evolved nearby SNR

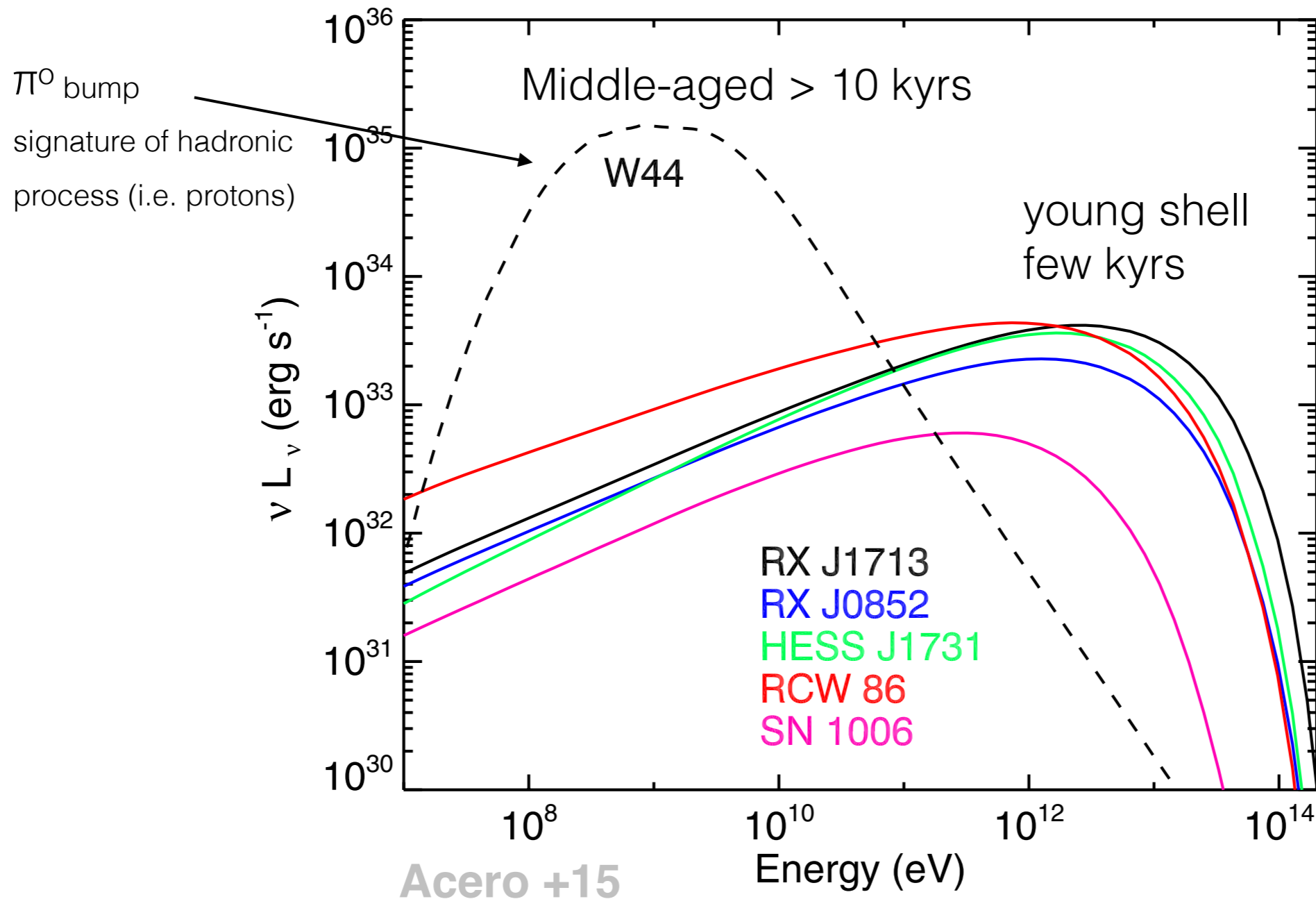


Tutone et al., 2021

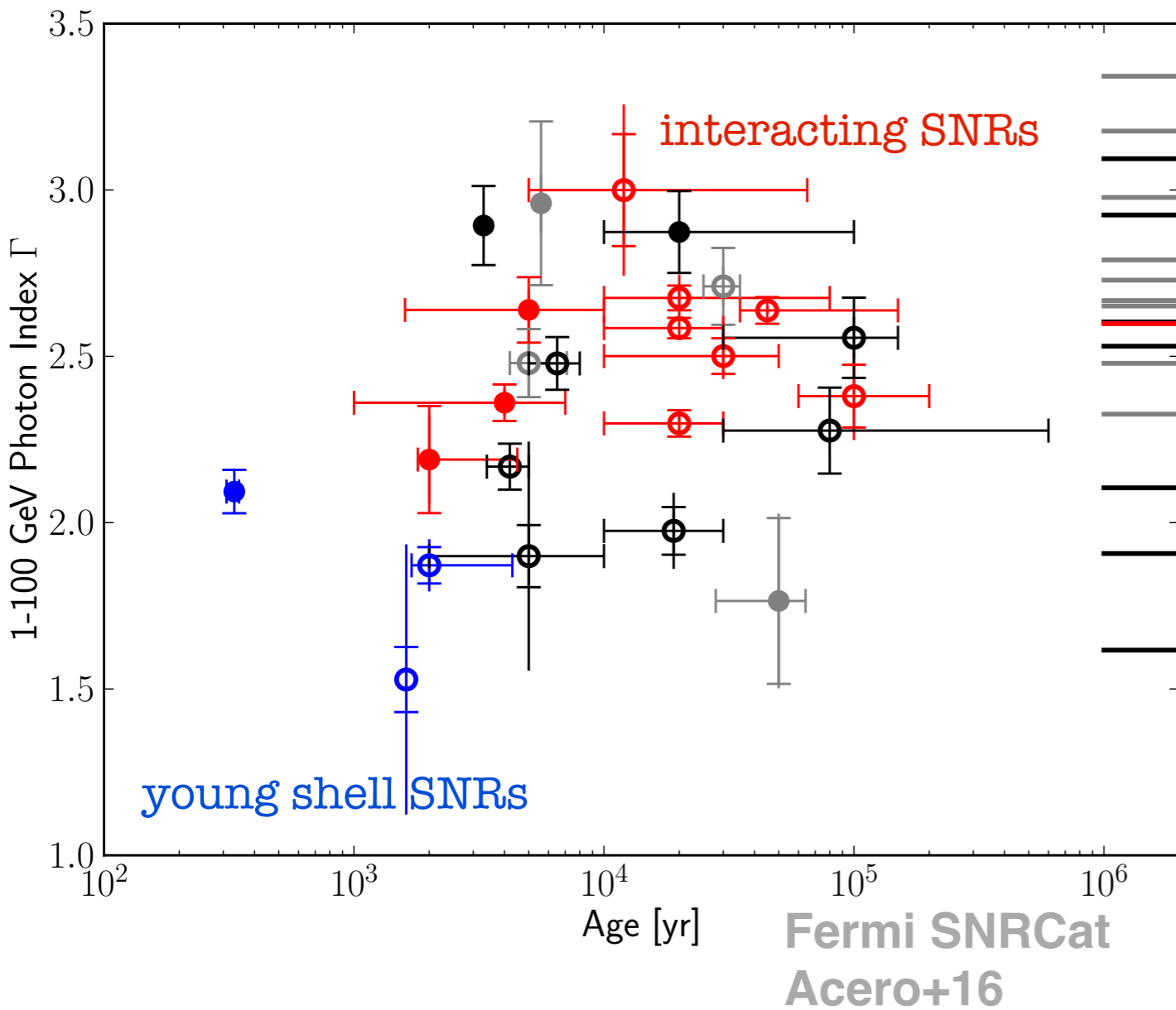
- **Gamma-ray morphology is best reconstructed via a sum of UV + X-ray templates**
- **X-ray shape traces the freshly accelerated particles and UV the reacceleration of preexisting CRs**

GeV/TeV populations

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

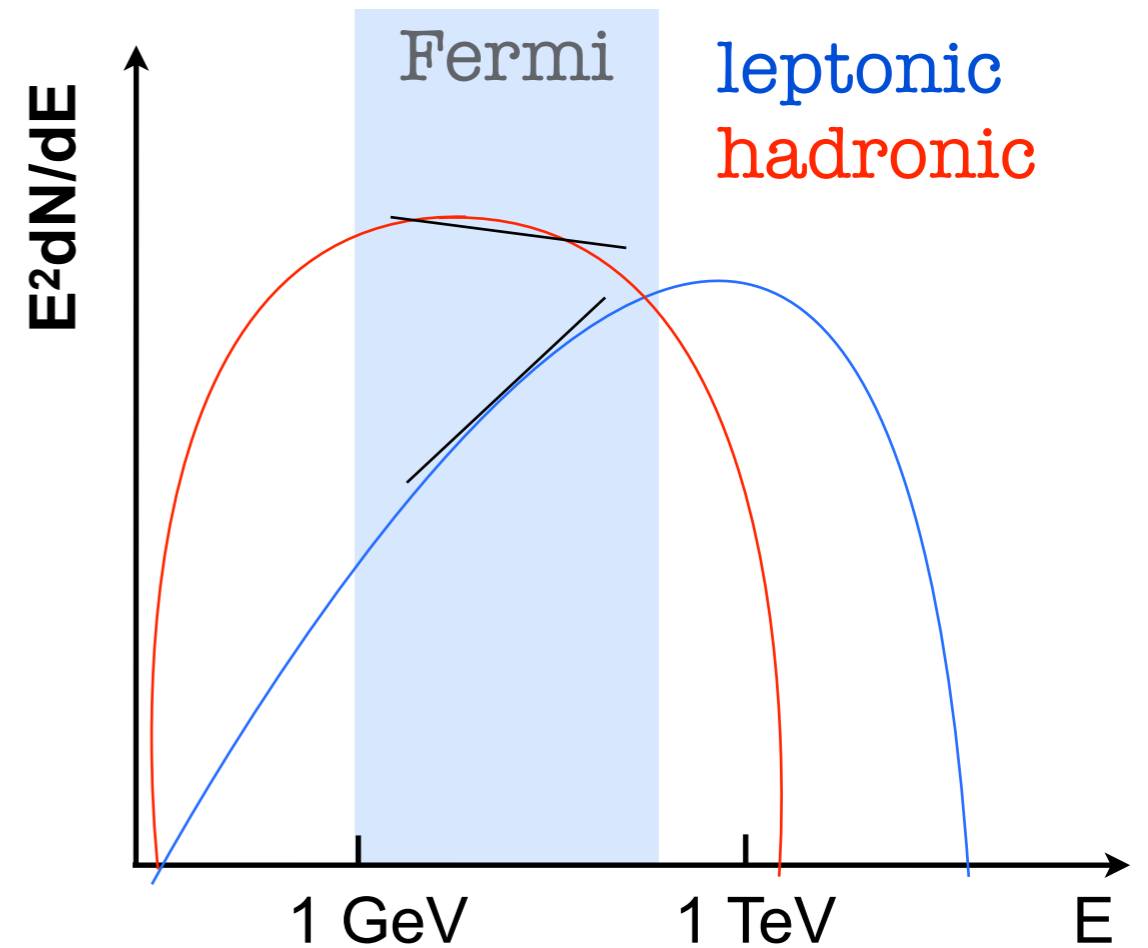


Age - GeV index



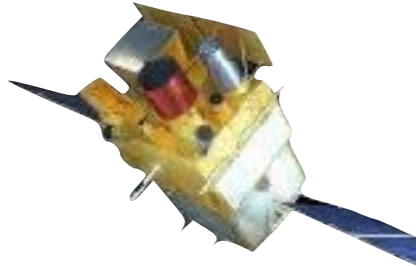
Older SNRs appear to have softer indices than young SNRs. This could be due to:

- Change of dominant emission mechanism
- Different zones properties



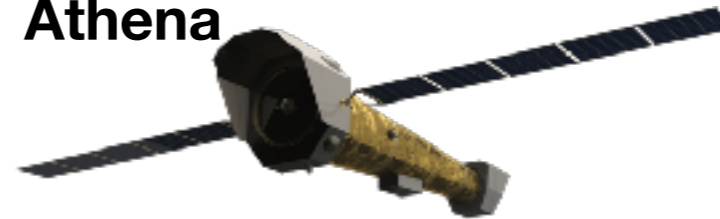
Futur X-ray telescopes

SVOM



GRB observatory
Eclair: 4-120 keV

Athena



XIFU: 2.5 eV spectral resolution
5' field of view
WFI: 120 eV spectral resolution
40' field of view
< 10" PSF

2019

2021

2022

2037

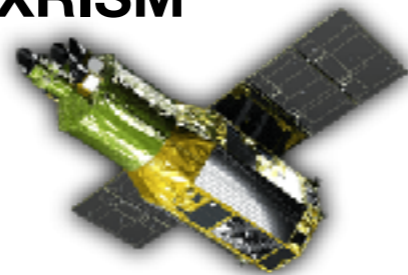
2035+

eROSITA



All sky survey
15" PSF

XRISM



5 eV spectral resolution
3' field of view (6x6 pixels)
60" PSF

Lynx



2 eV spectral resolution
5' field of view
< 1" PSF

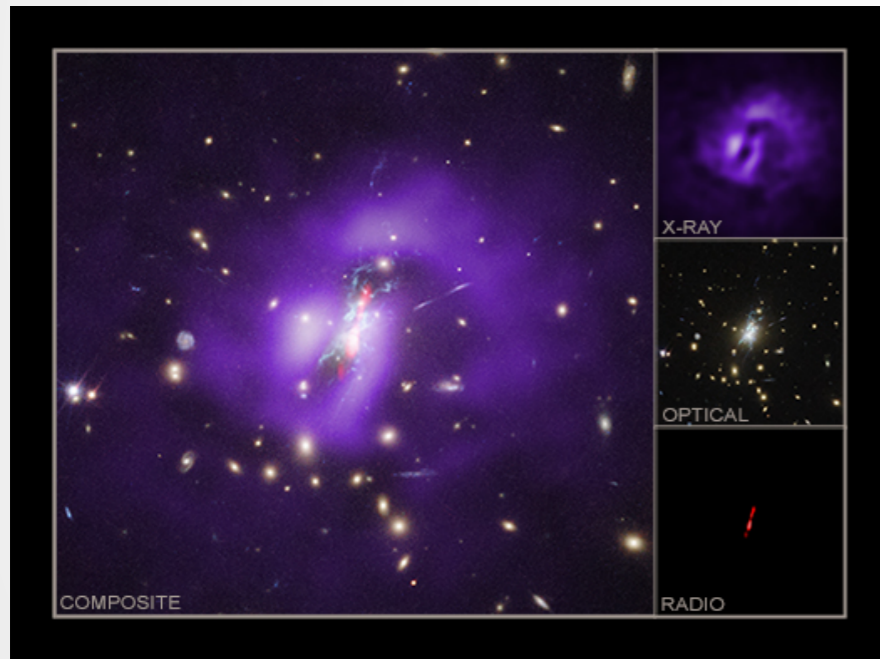


The Hot and Energetic Universe

What it is ?

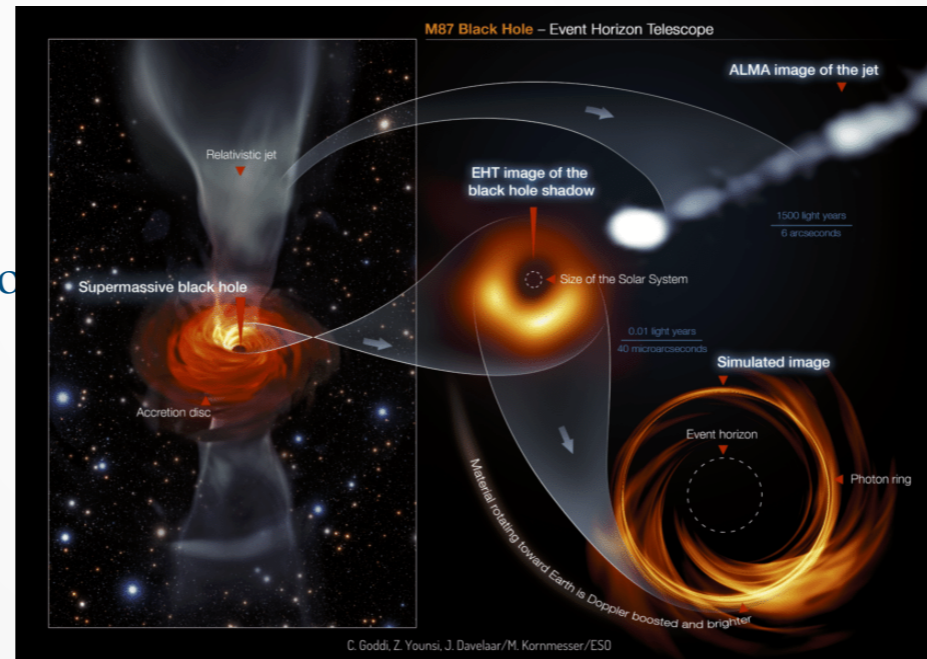


Galaxy clusters embedded in hot gas



Credits: X-ray: NASA/CXC/MIT/M.McDonald et al.; Radio: NRAO/VLA; Optical: NASA/STScI

Black holes



Credits: Event Horizon Telescope/ESO

Stars



Credits: NASA, ESA, J. Hester and A. Loll (Arizona State University)

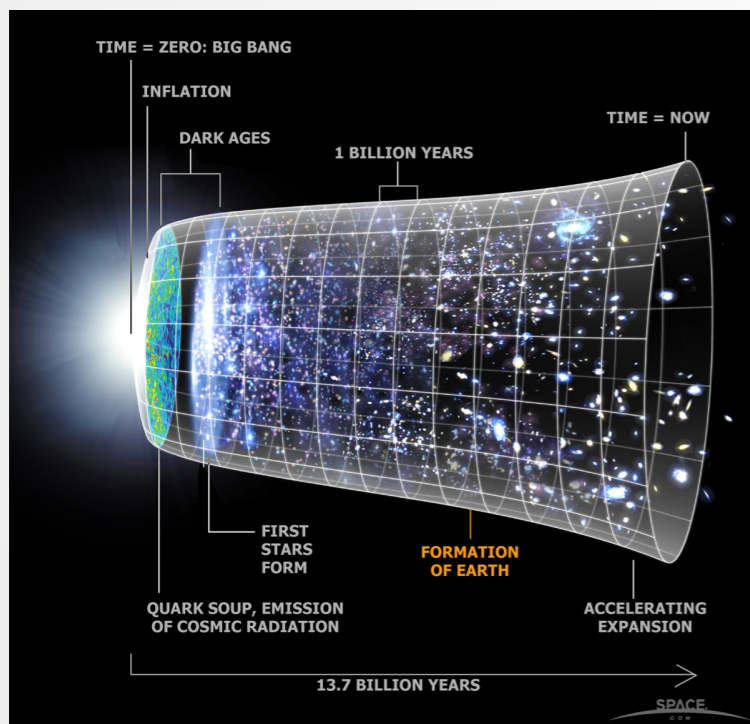


What are the « big » questions?

Uniquely addressed by an X-ray observatory

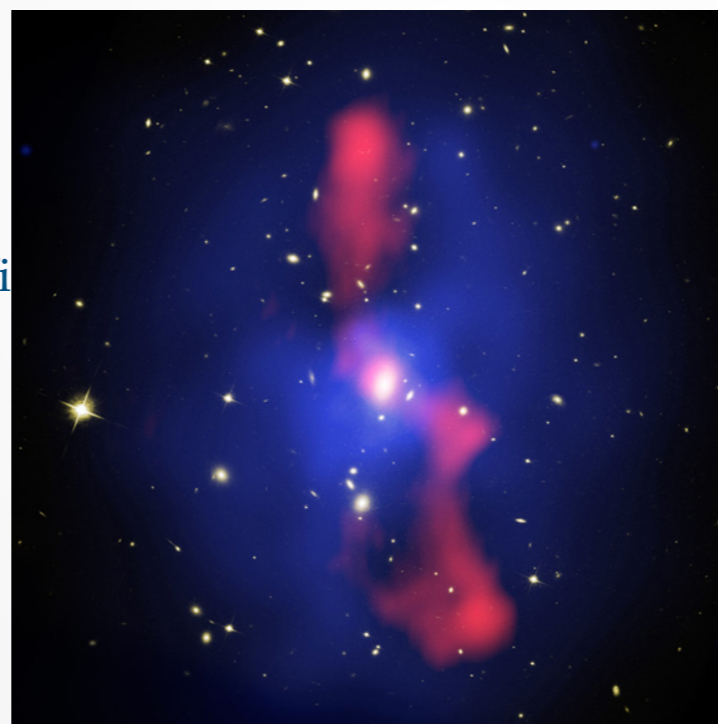


How has the Universe formed and evolved since the big bang ?



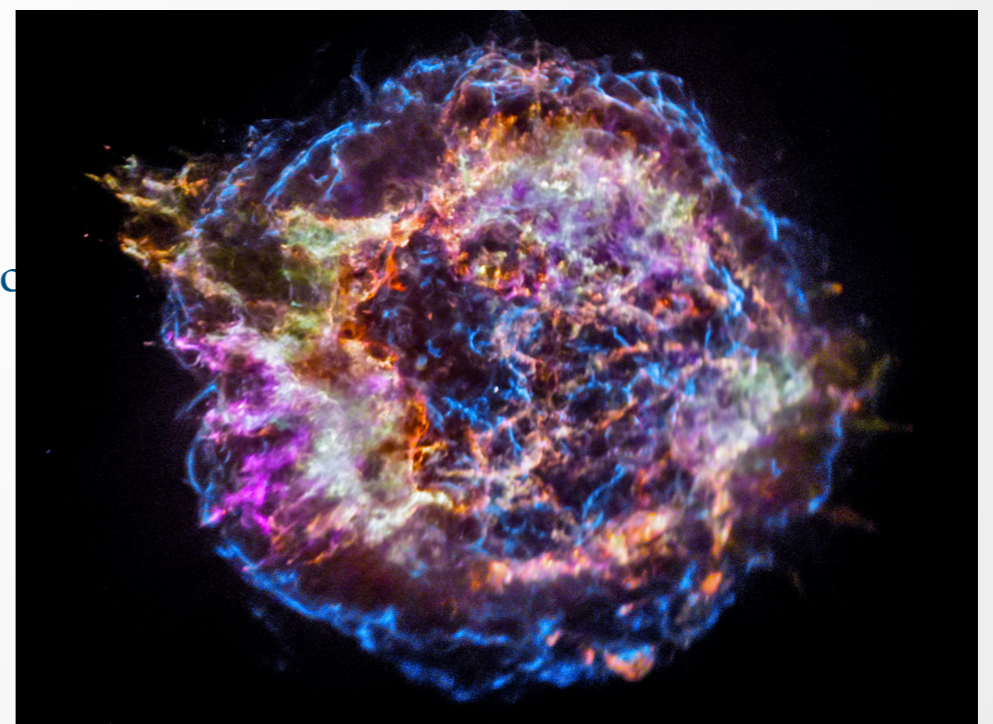
Credits: Hubble Space Telescope Science Institute

What is the role of black holes in shaping the Universe ?



Credits: Chandra

What are the fundamental laws of physics in extreme conditions?



Credits: Chandra



How do we answer those questions? Using X-rays as the most sensitive probe



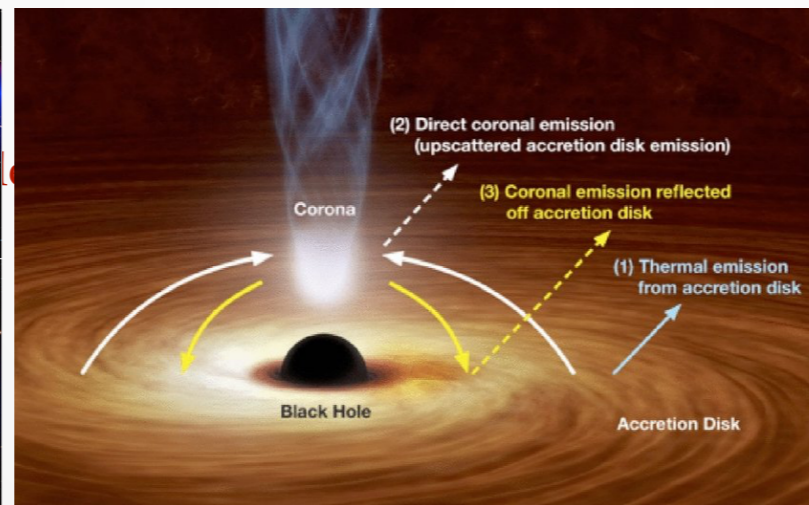
X-rays are emitted by hot gas present in clusters of galaxies

X-rays are emitted from the flow of matter falling onto a black hole

X-rays are emitted from matter placed under the most extreme conditions unreachable in our laboratory



Credits: NASA/CXC

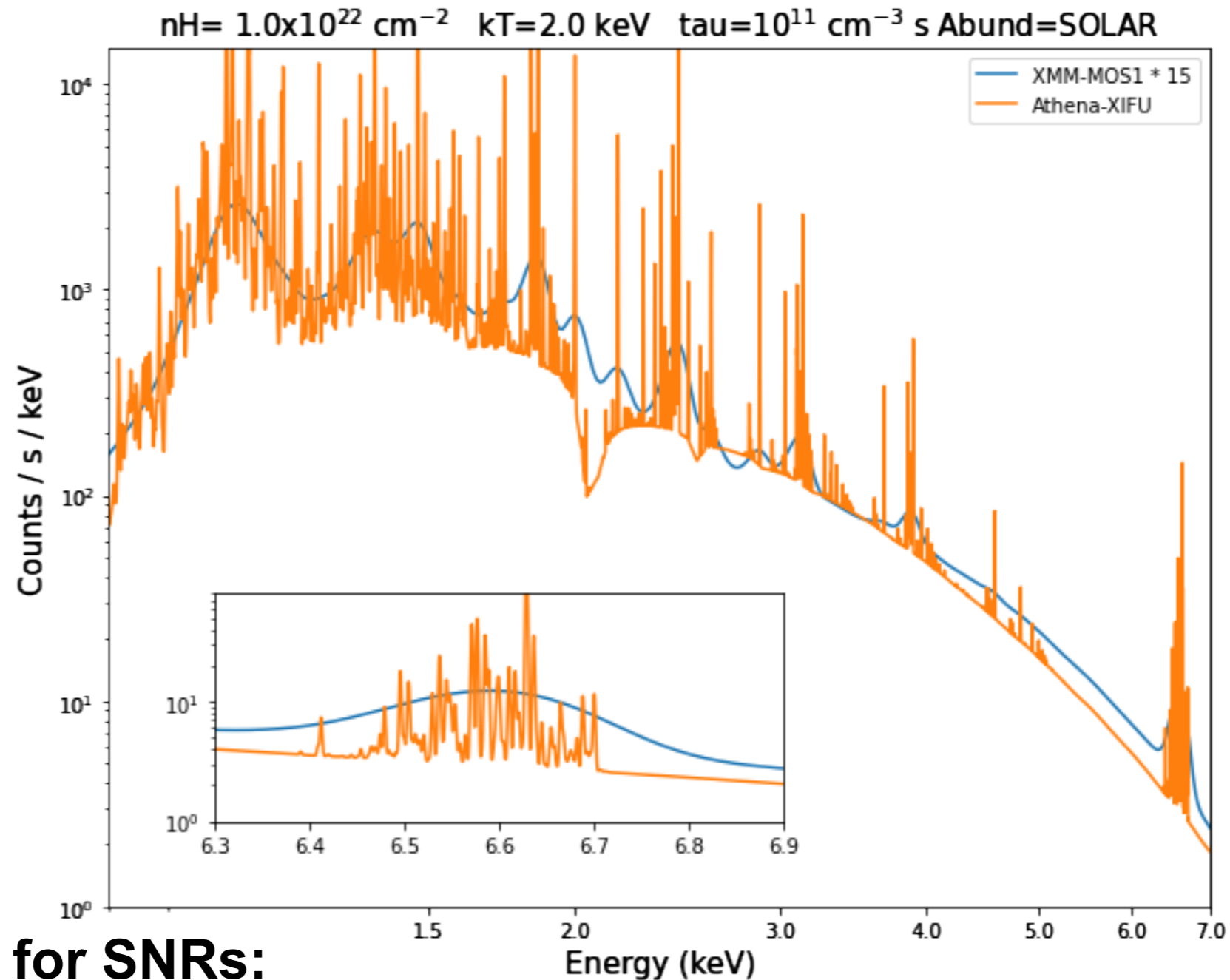


Credits: JPL/NASA



Credits: NASA/Dana Berry

Athena X-IFU: the micro-calorimeter revolution

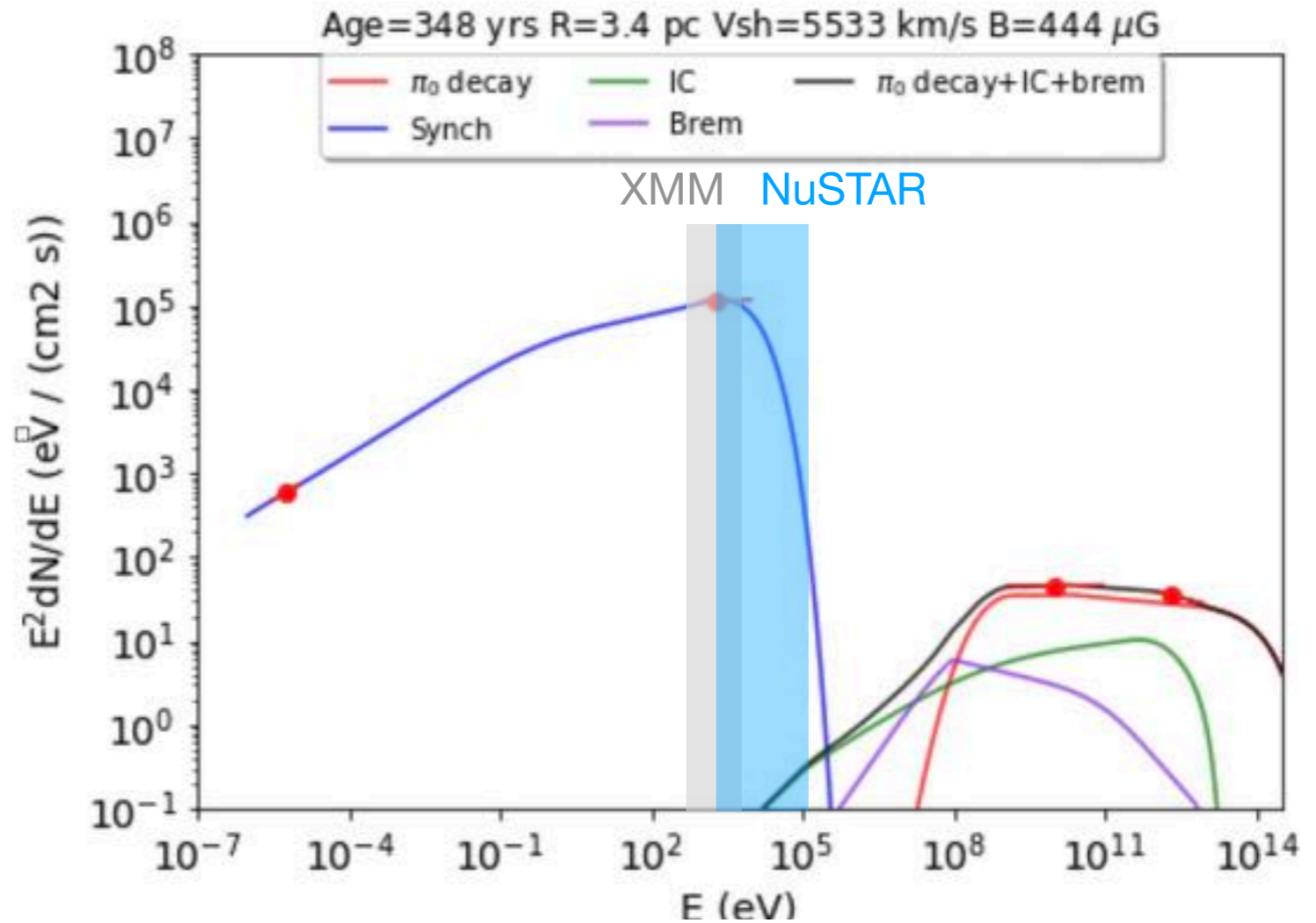
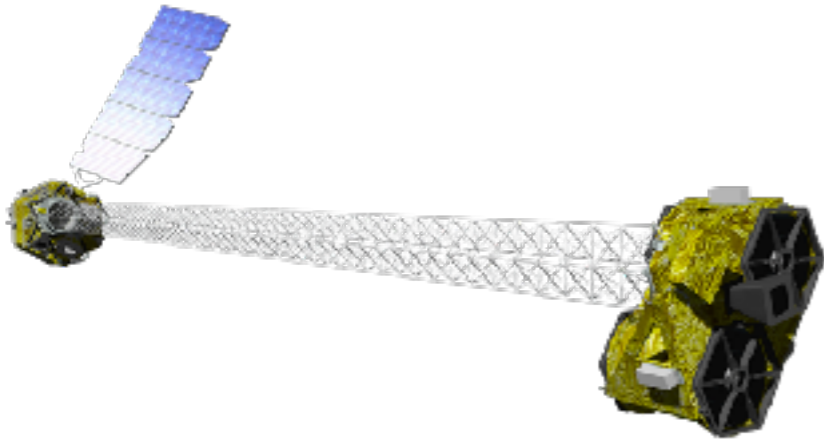


Science case for SNRs:

- 3D kinematics of Si, S, Fe and rare elements (Cr, Mn) constrain explosion mechanisms of CC and Ia SN
- SN yield and progenitor info (mass, metallicity). SN circumstellar material.
- Measure accelerated particles impact on ions temperature via thermal broadening

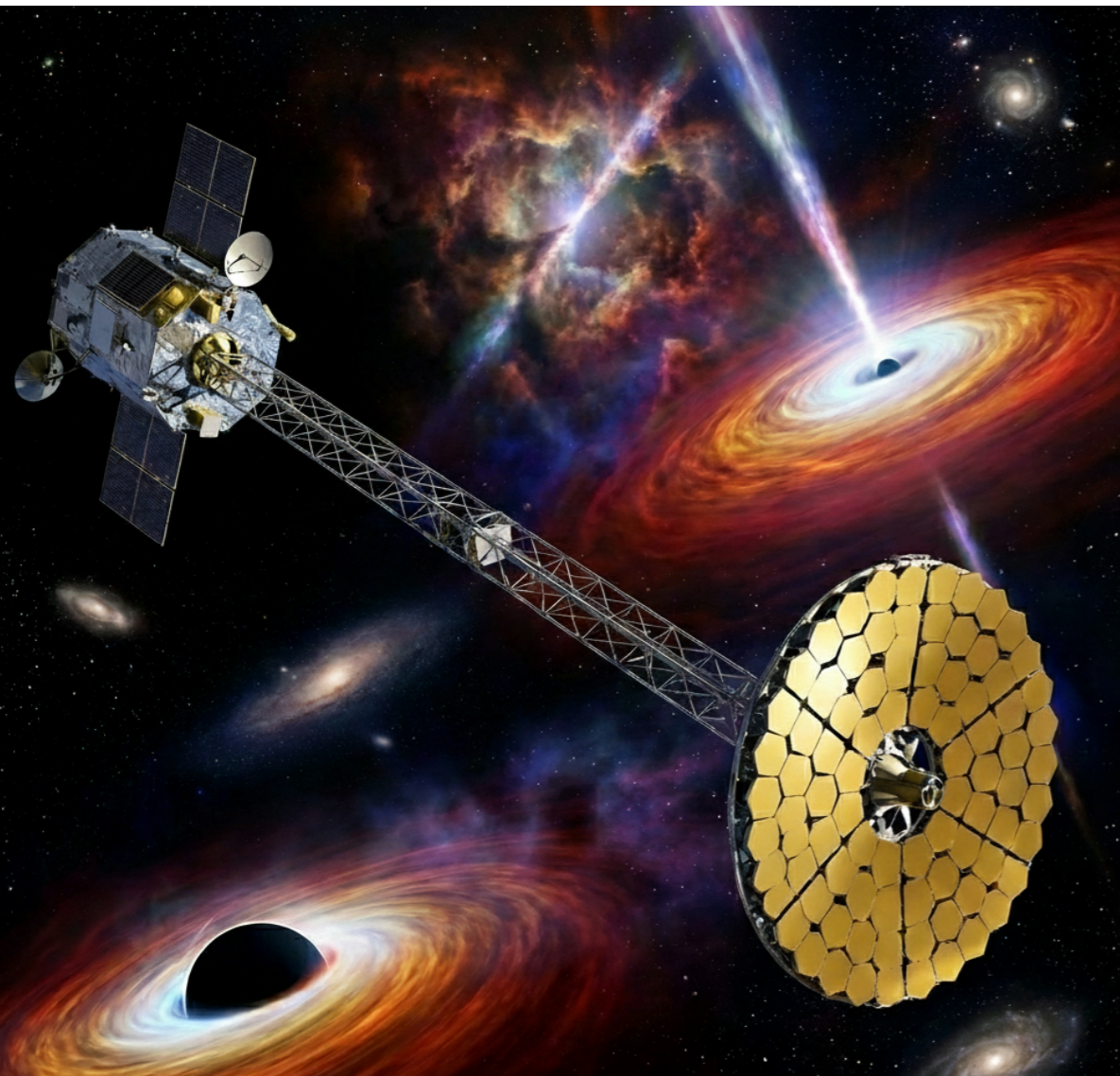
The hard X-ray window

- **NuSTAR : 3 -80 keV**

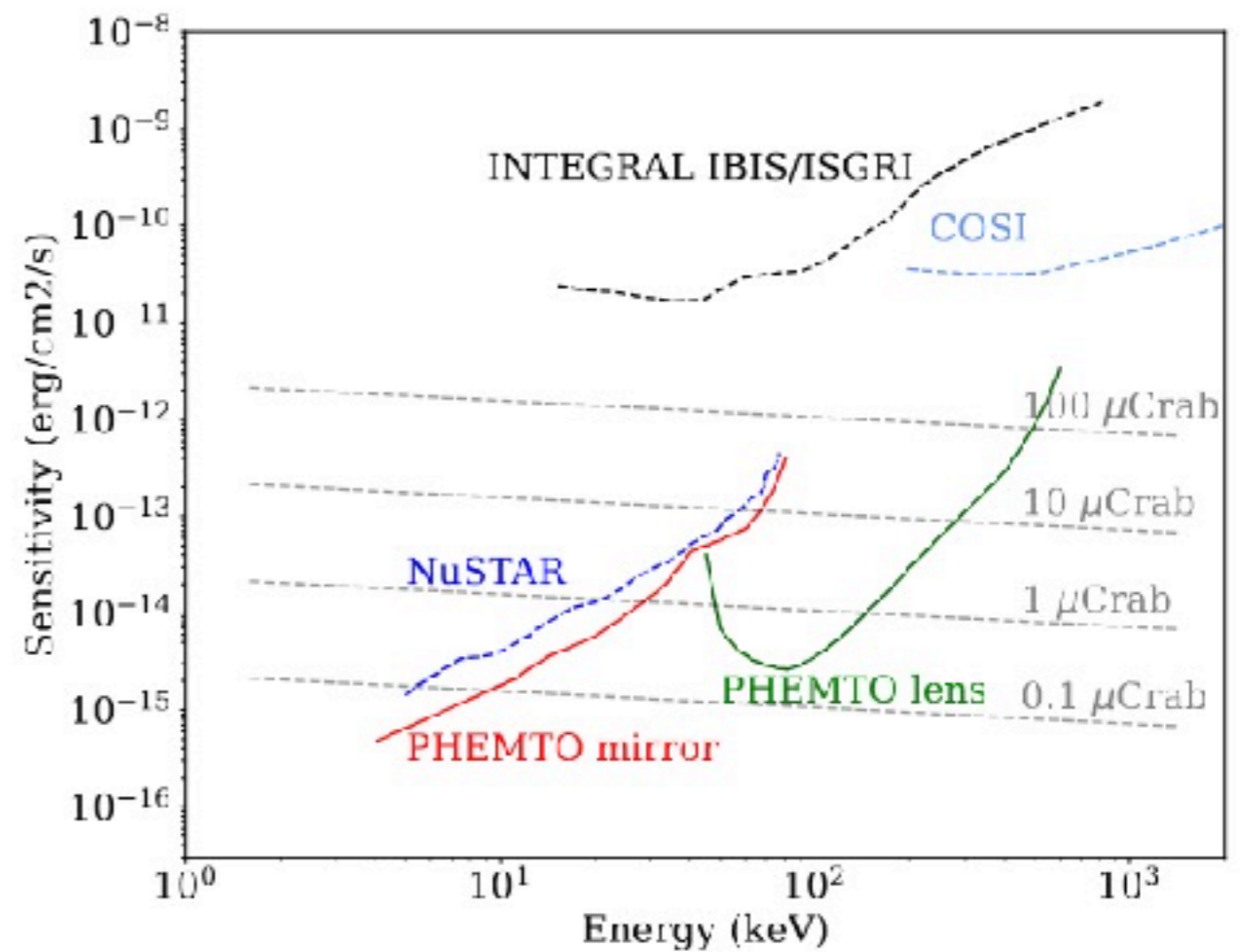


- **Constraining the cutoff energy and shape**
 - **Constrain the e- producing the > 10 TeV inverse Compton emission**

PHEMTO: Polarimetry + high energy

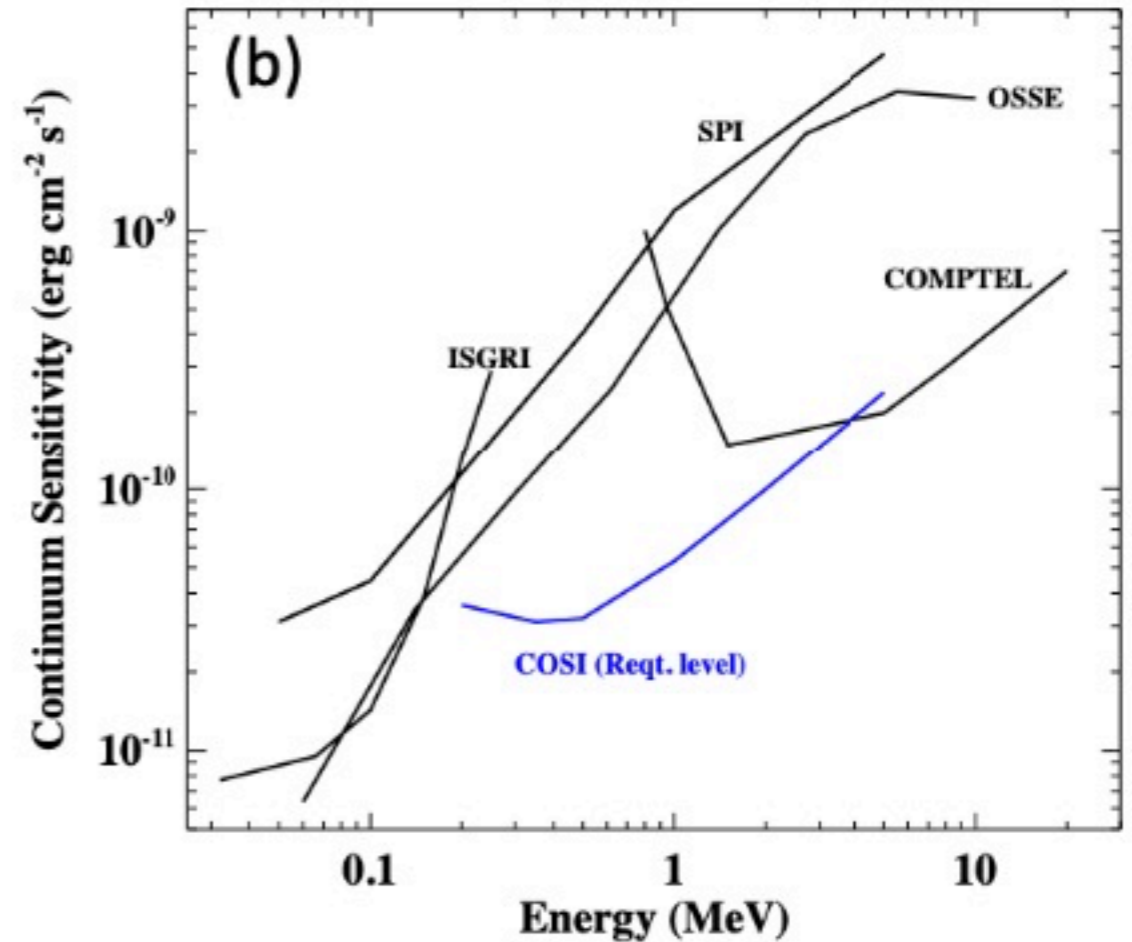
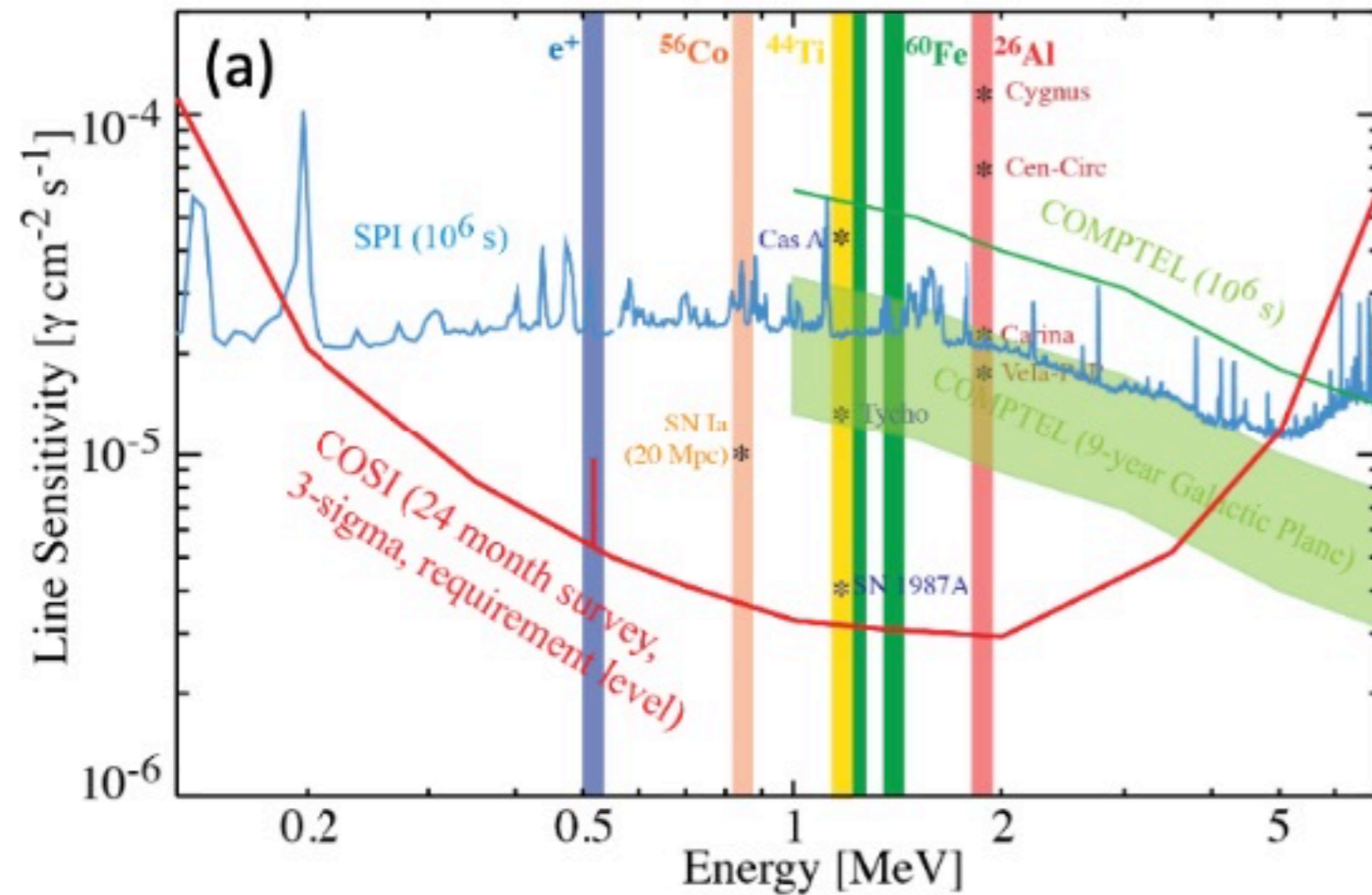


- A unique dual lens system
– Mirror + Laue lenses
- Covering 3 - 600 keV

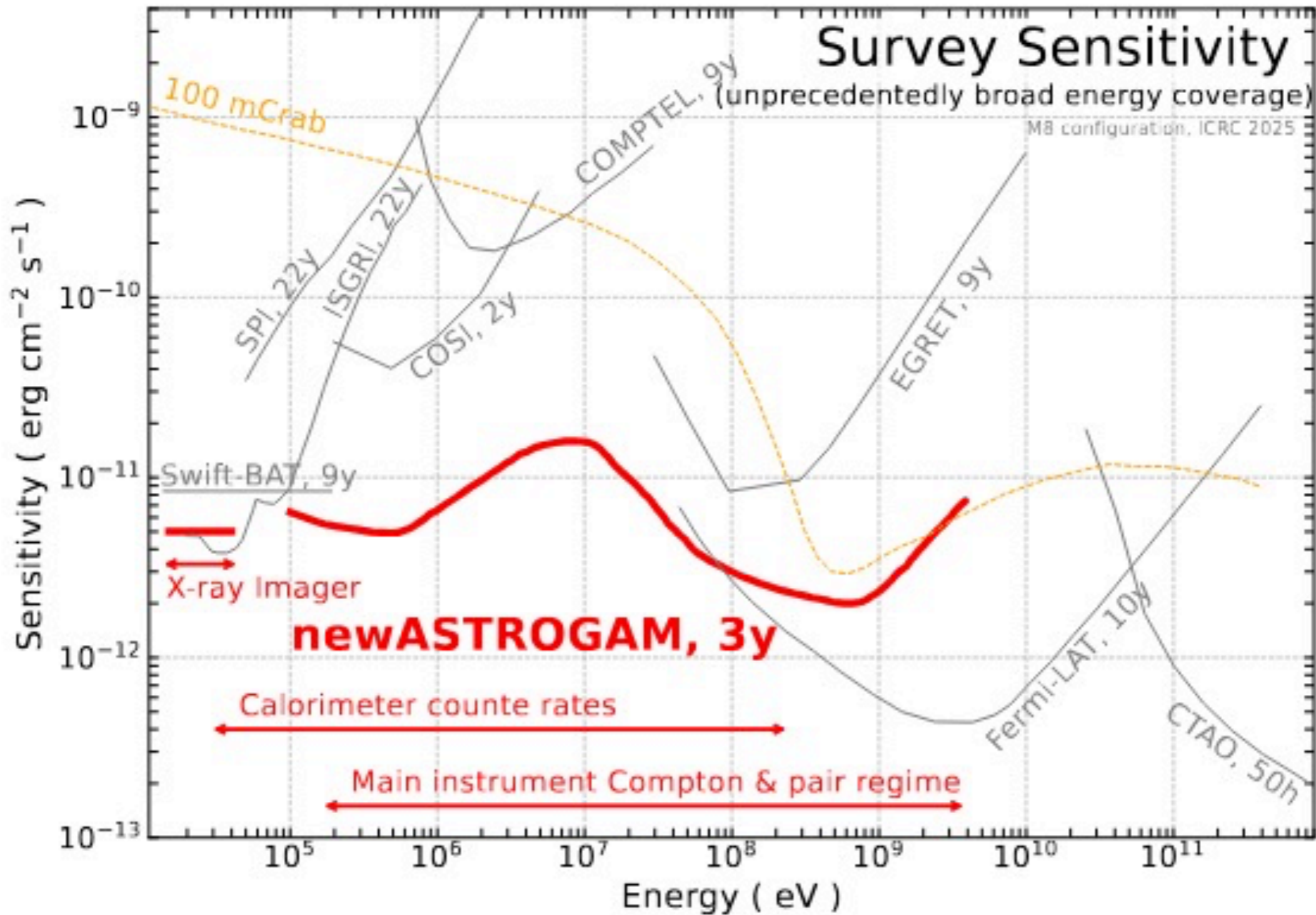


COSI: filling the MeV gap (0.2-5 MeV)

- COSI launch in 2027. Full sky (like Fermi) observations

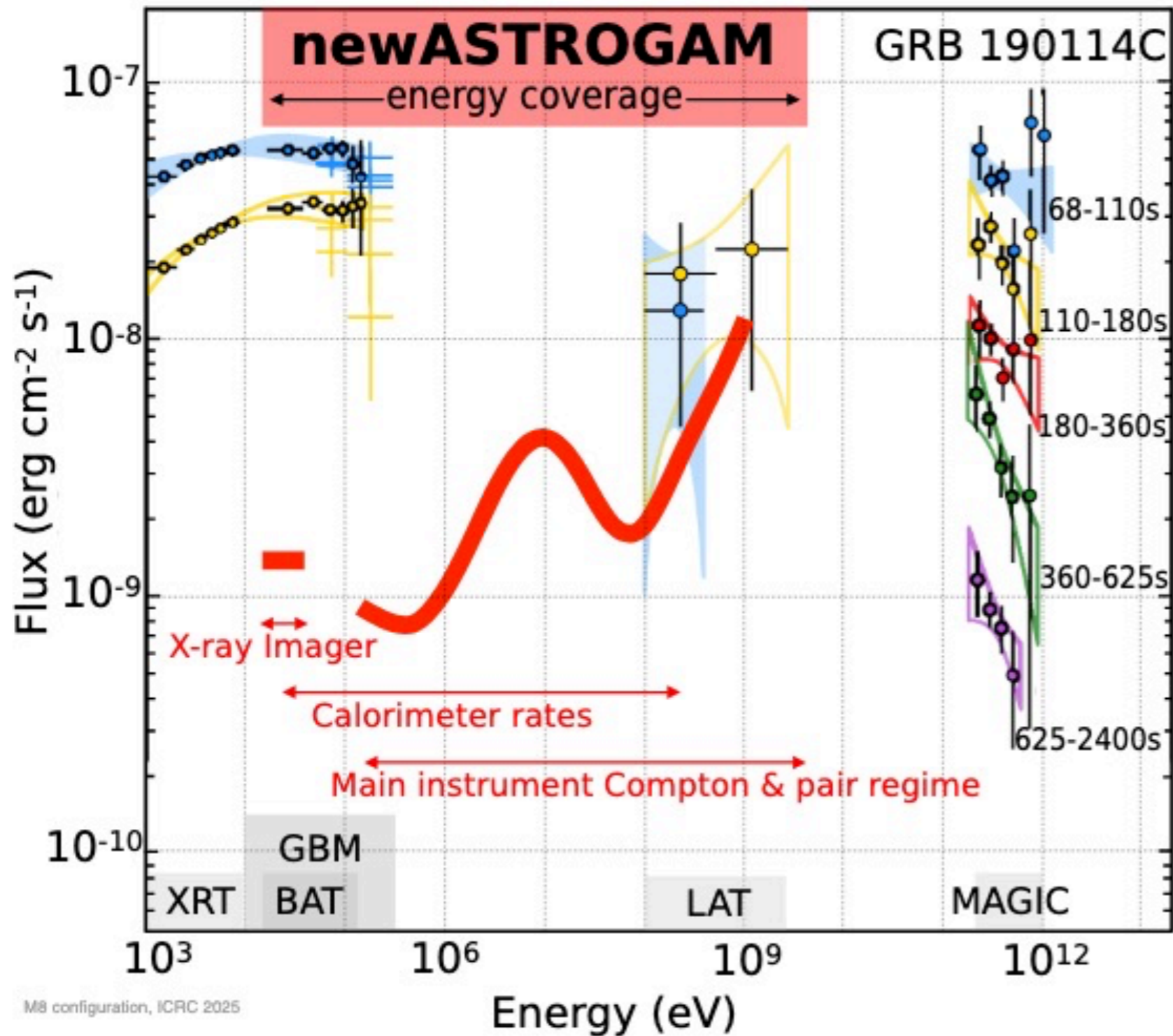


NewASTROGAM



ESA call for medium-class mission ideas (M8)

NewASTROGAM



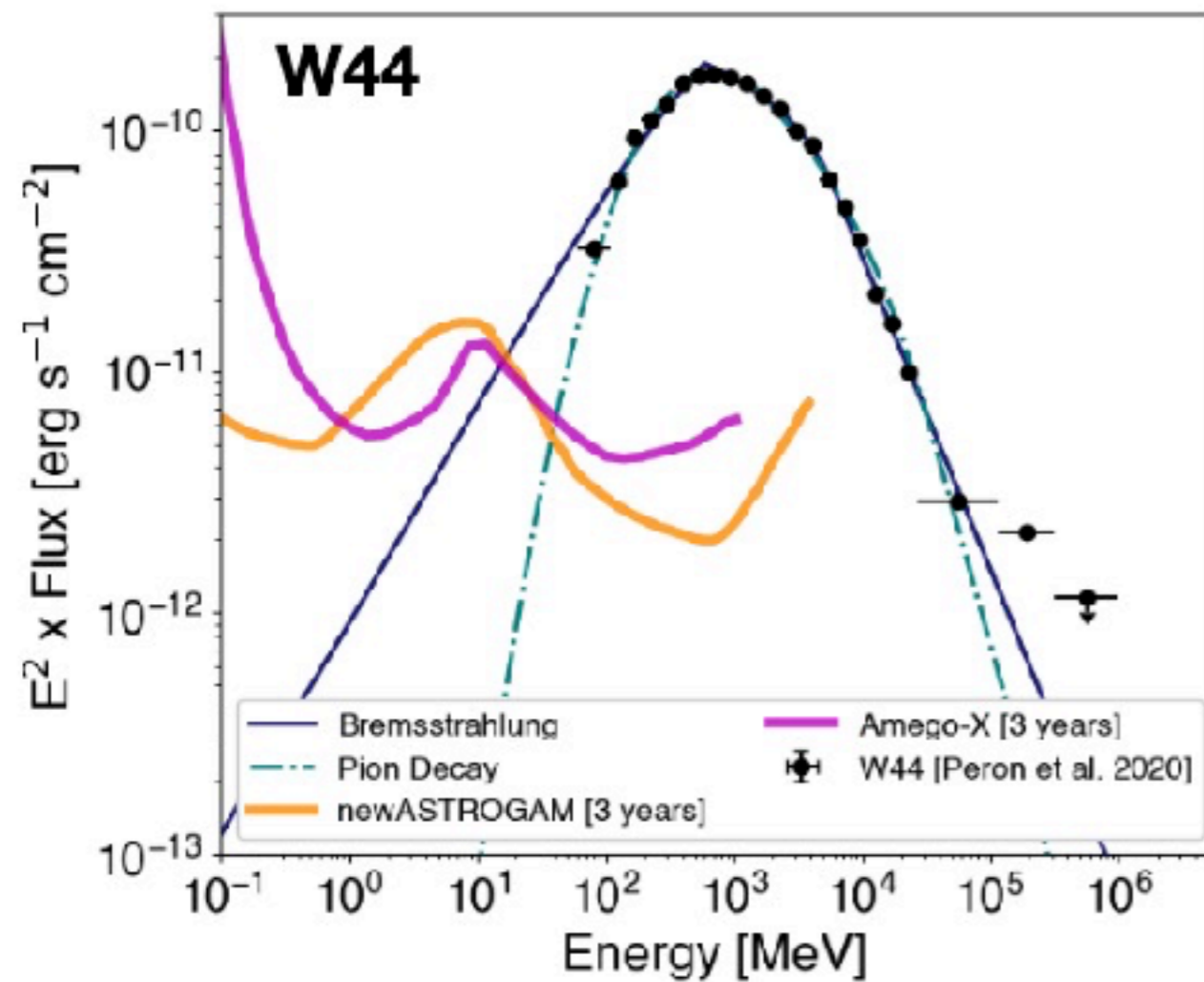
- Filling the MeV gap

M8 configuration, ICRC 2025

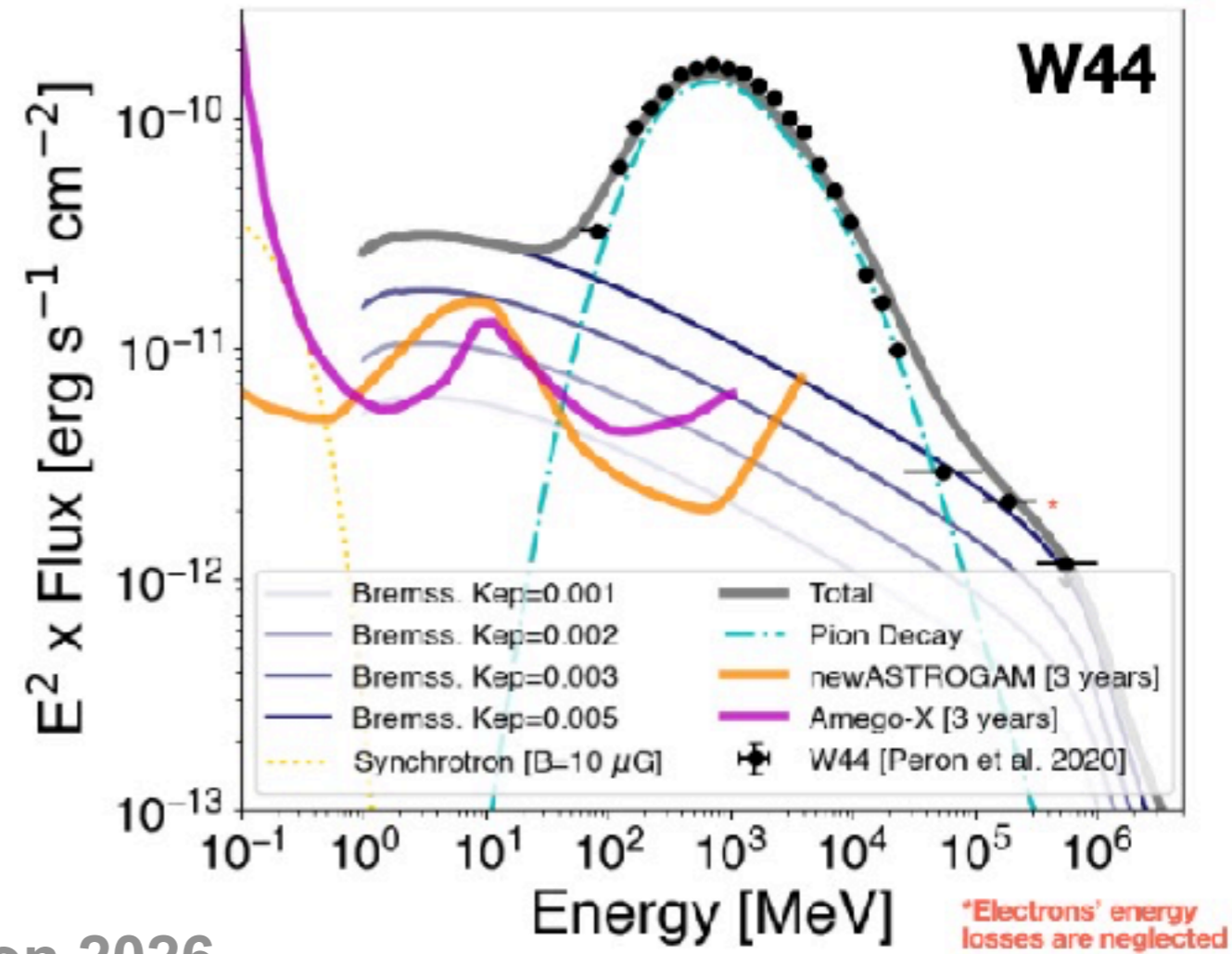
Berge 2025, ICRC

NewASTROGAM

- Understand the nature of the emission:
 - is it Pion bump or broken bremsstrahlung?
- Evaluate the rate between hadronic emission and leptonic emission



Peron 2026



LISA: GW in space !



LISA - LASER INTERFEROMETER SPACE ANTENNA

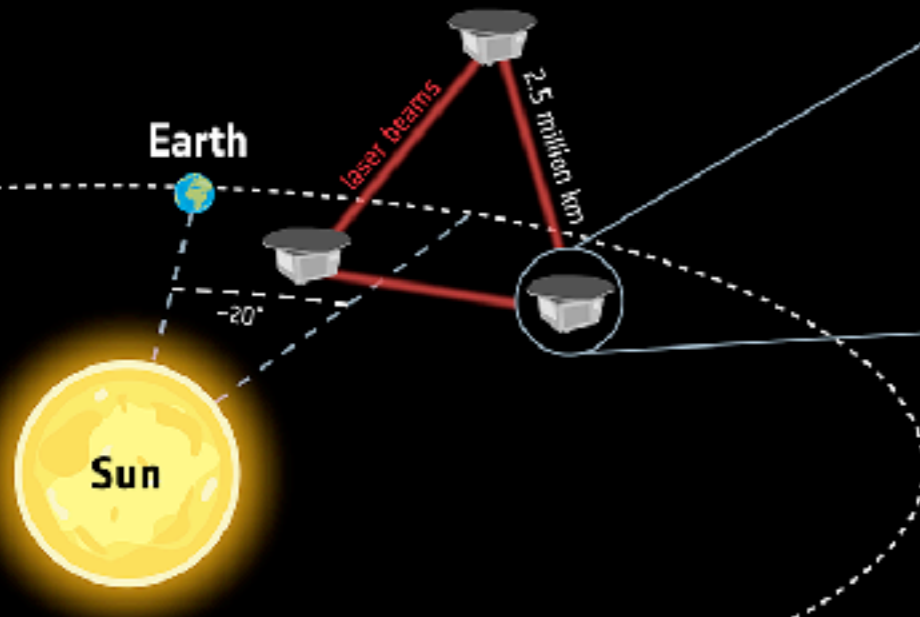
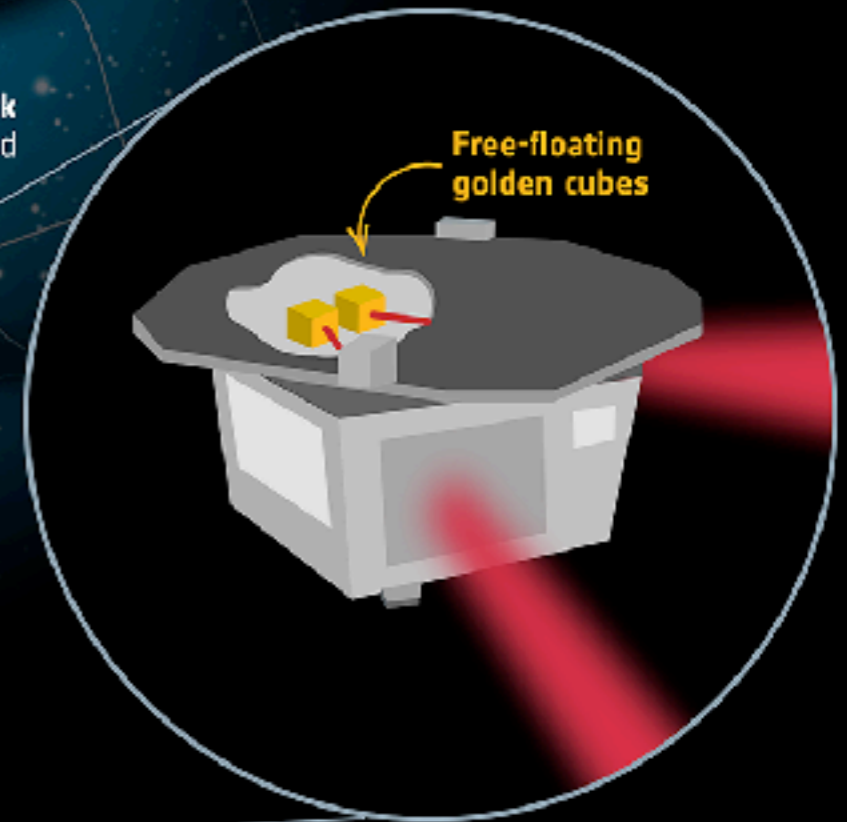
Gravitational waves are ripples in spacetime that alter the distances between objects. LISA will detect them by measuring subtle changes in the distances between **free-floating cubes** nestled within its three spacecraft.

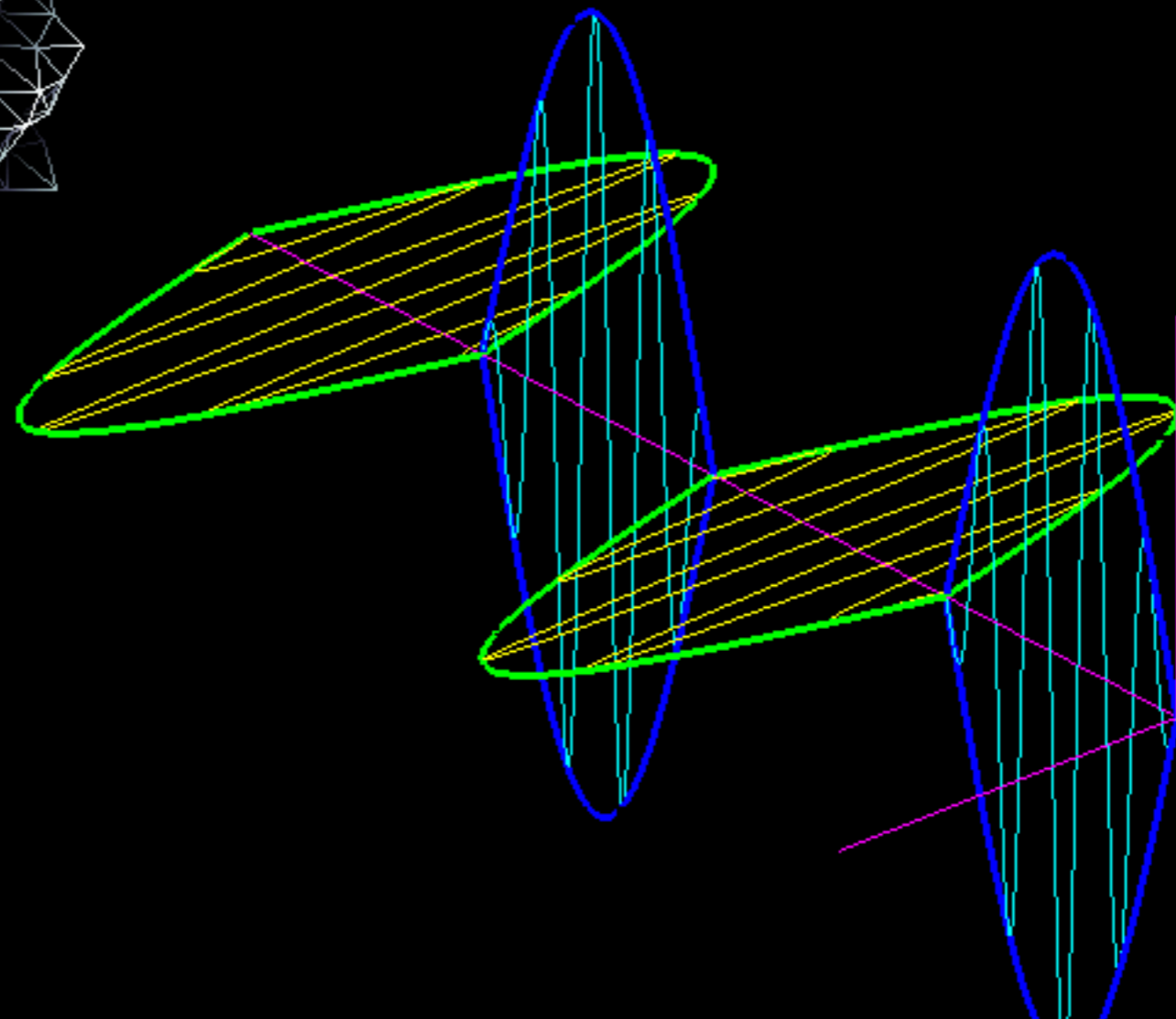
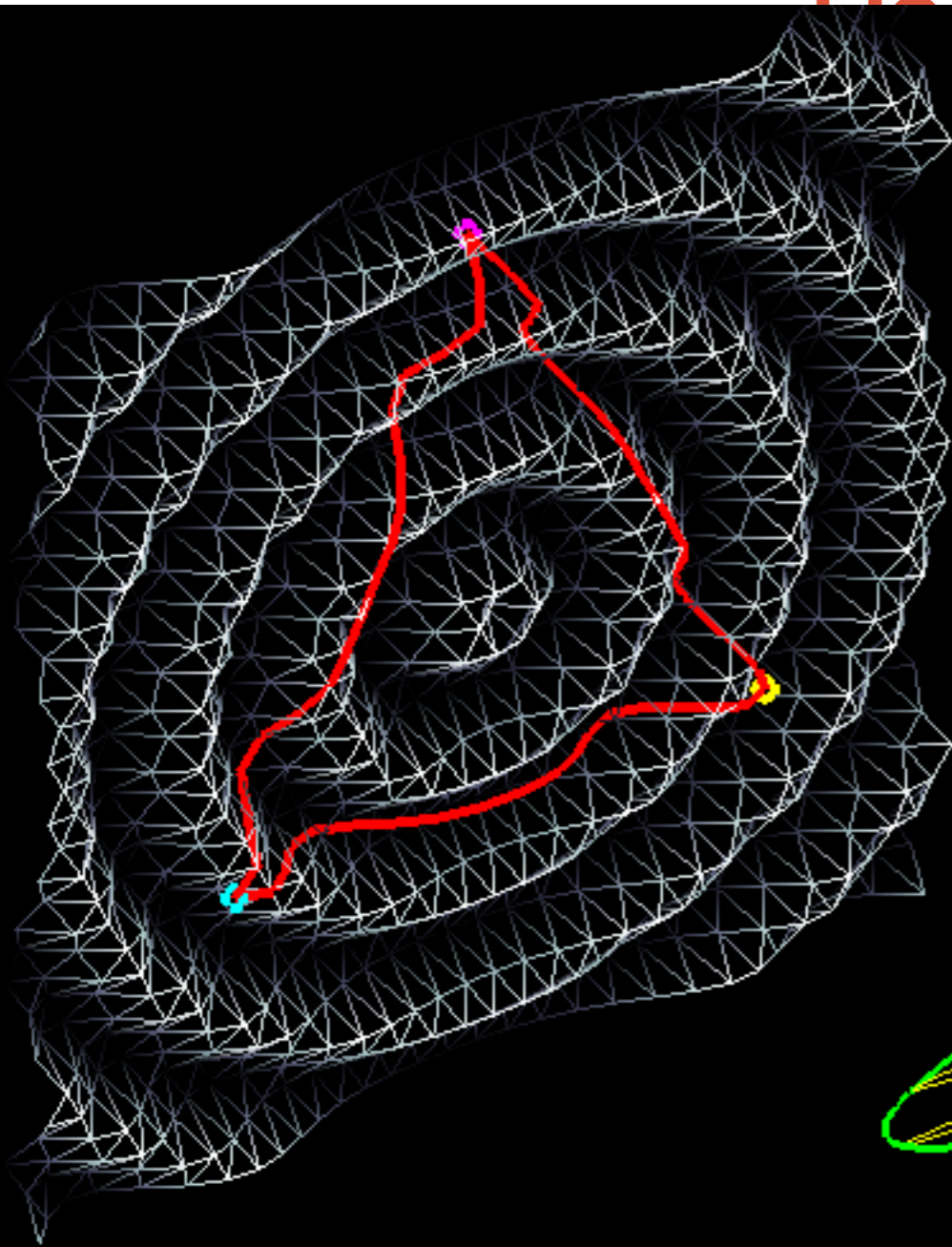
3 **identical spacecraft** exchange **laser beams**. Gravitational waves change the distance between the **free-floating cubes** in the different spacecraft. This tiny change will be measured by the laser beams.



* Changes in distances travelled by the laser beams are not to scale and extremely exaggerated

Powerful events such as **colliding black holes** shake the fabric of spacetime and cause gravitational waves





Nicolas Douillet - ARTEMIS

LISA targets



THE SPECTRUM OF GRAVITATIONAL WAVES

Observatories & experiments

Ground-based experiment



Space-based observatory



Pulsar timing array



Cosmic microwave background polarisation



Timescales

milliseconds

seconds

hours

years

billions of years

Frequency (Hz)

100

1

10^{-2}

10^{-4}

10^{-6}

10^{-8}

10^{-16}

Cosmic fluctuations in the early Universe

Cosmic sources



Supernova



Pulsar



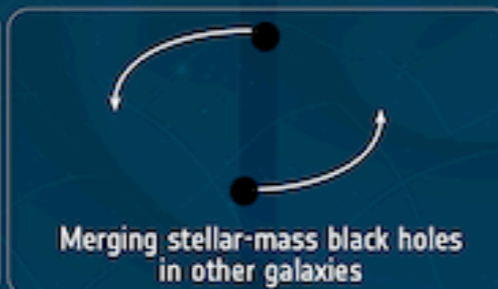
Compact object falling onto a supermassive black hole



Merging supermassive black holes



Merging neutron stars in other galaxies



Merging stellar-mass black holes in other galaxies



Merging white dwarfs in our Galaxy

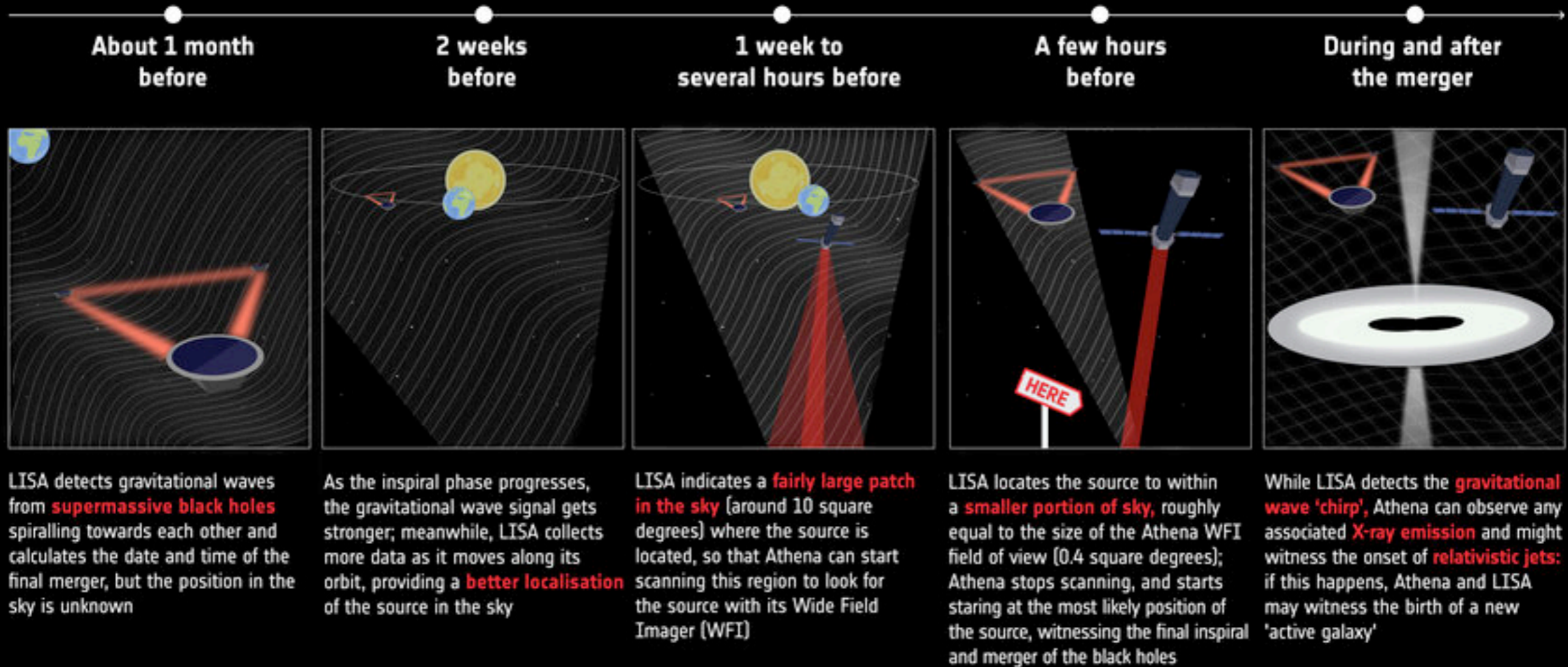
#lisa



LISA Athena synergies



→ HOW CAN LISA AND ATHENA WORK TOGETHER?



#Space19plus #AnsweringTheBigQuestions

Space19

Aladin quick tutorial

- <https://aladin.cds.unistra.fr/AladinLite/>
- **But the desktop app is much more powerful**
 - <https://aladin.cds.unistra.fr/>