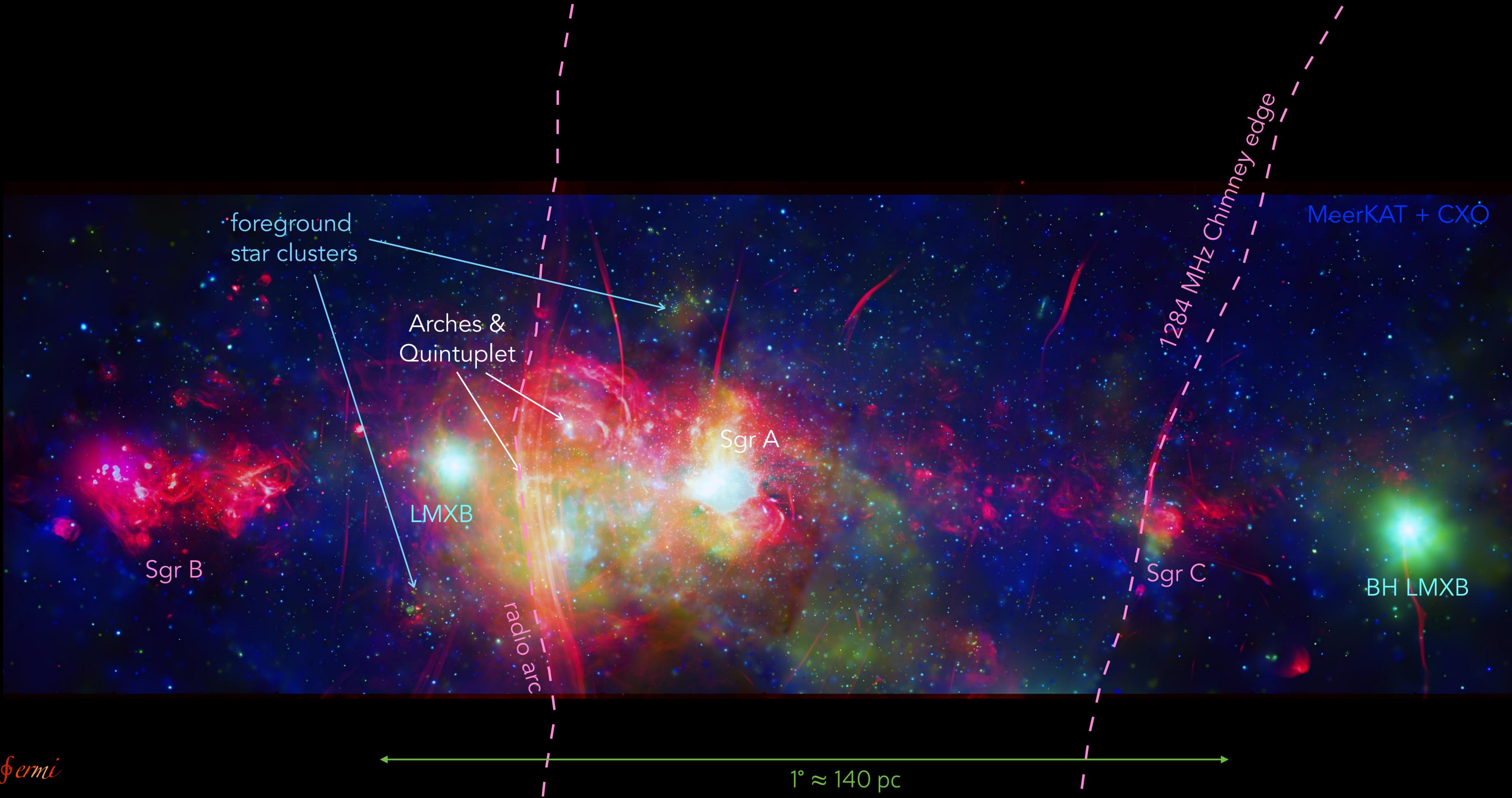




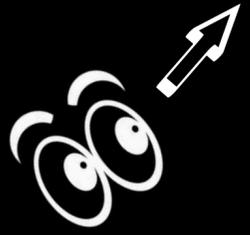
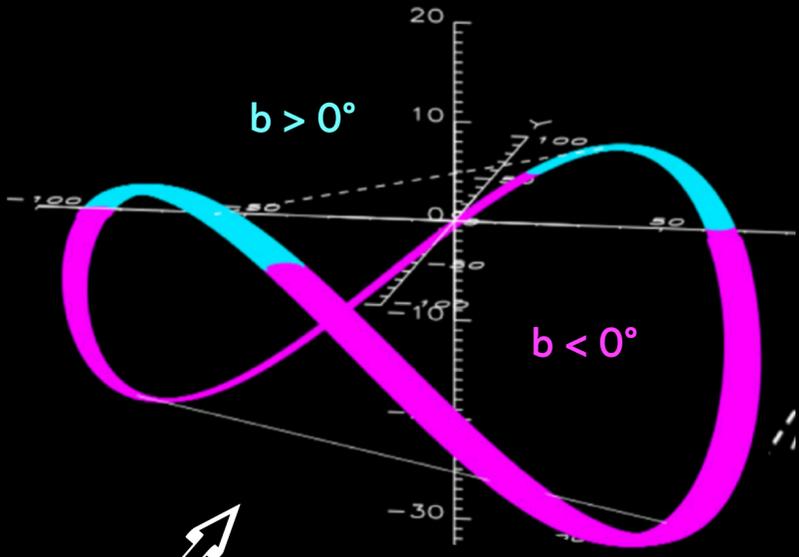
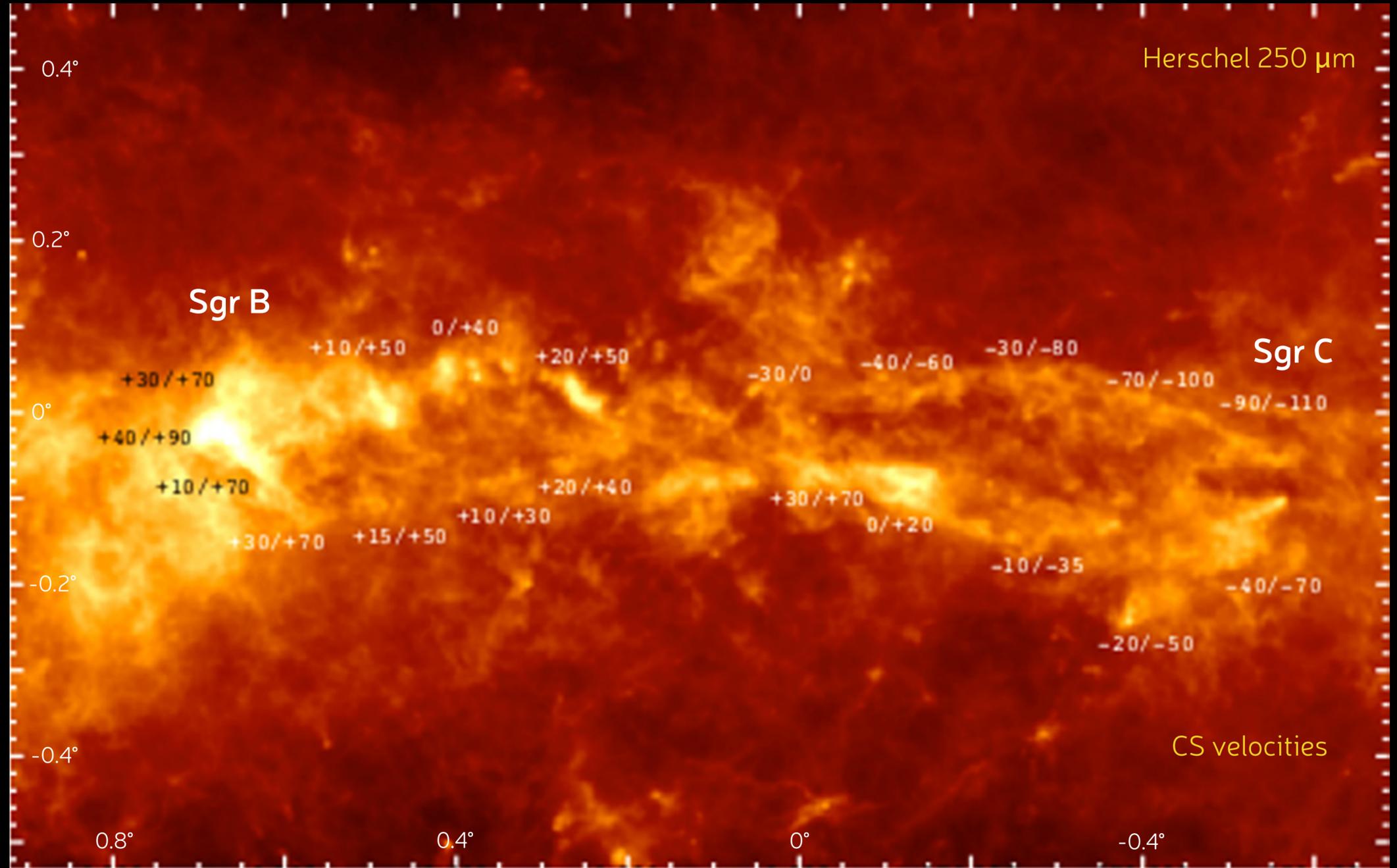
Isabelle Grenier  
Université de Paris & AIM CEA Saclay  
Institut Universitaire de France

# the Galactic Centre



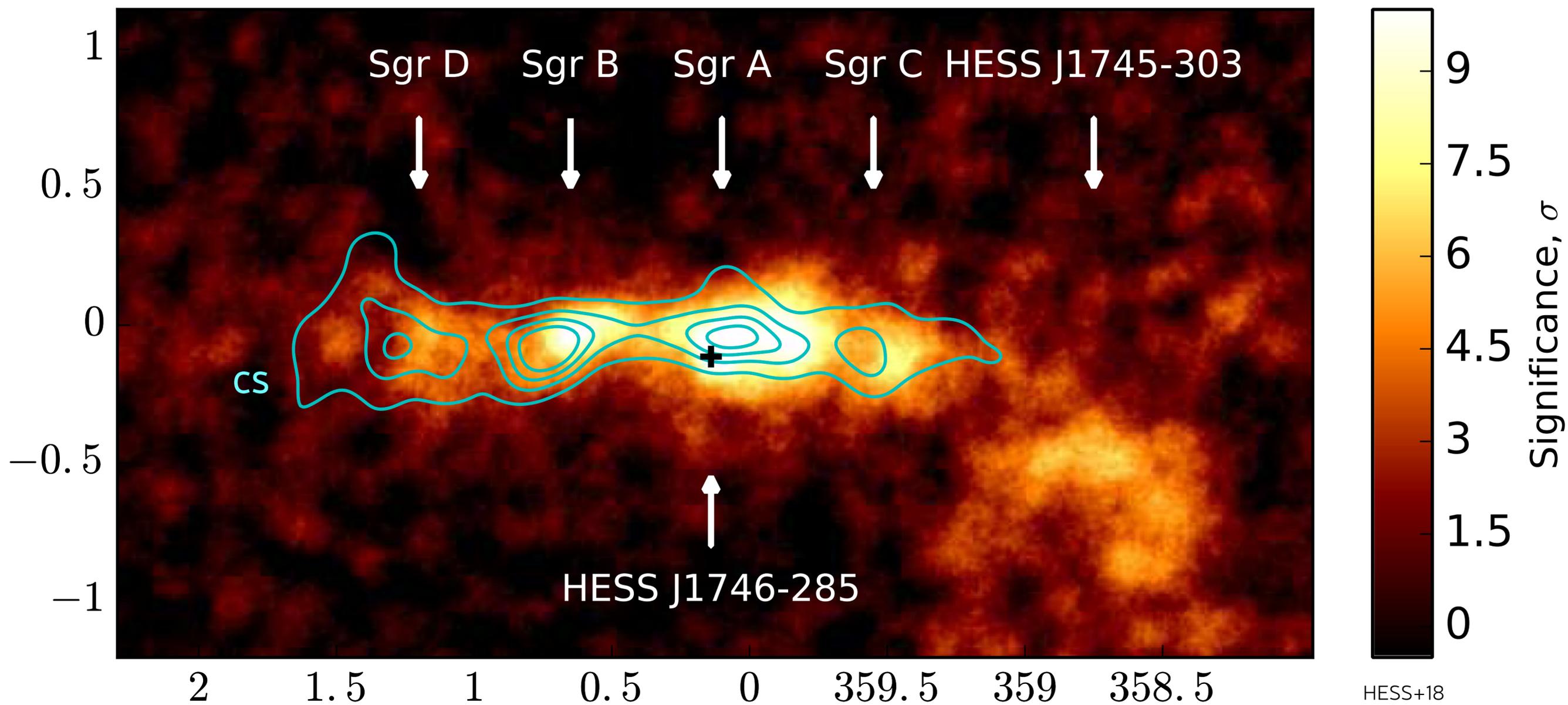
# the Central Molecular Zone

- twisted 100 x 60 pc ring perpendicular to the bar ( $x_2$  orbits)
- $(0.3-1) 10^8 M_{\odot}$



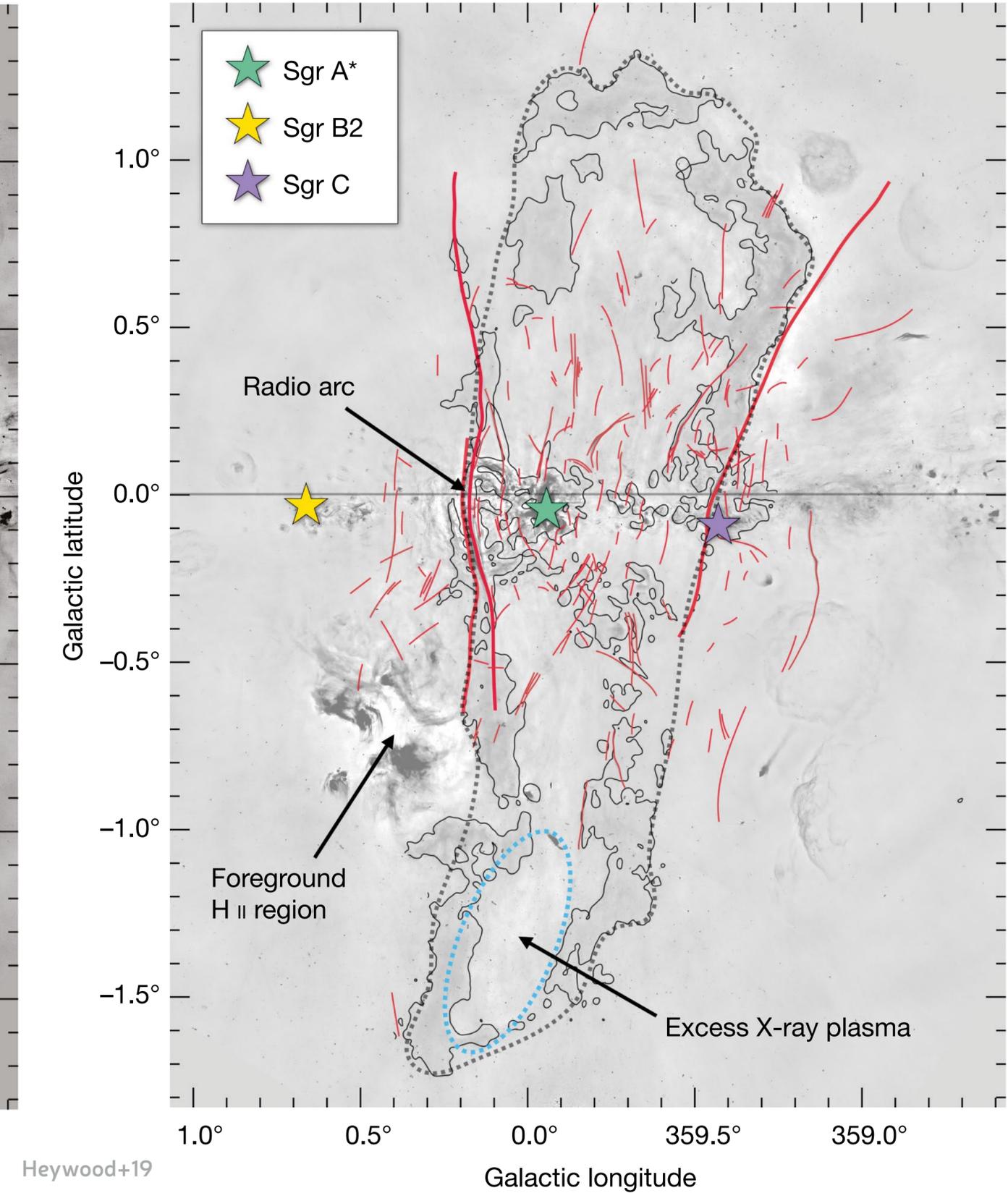
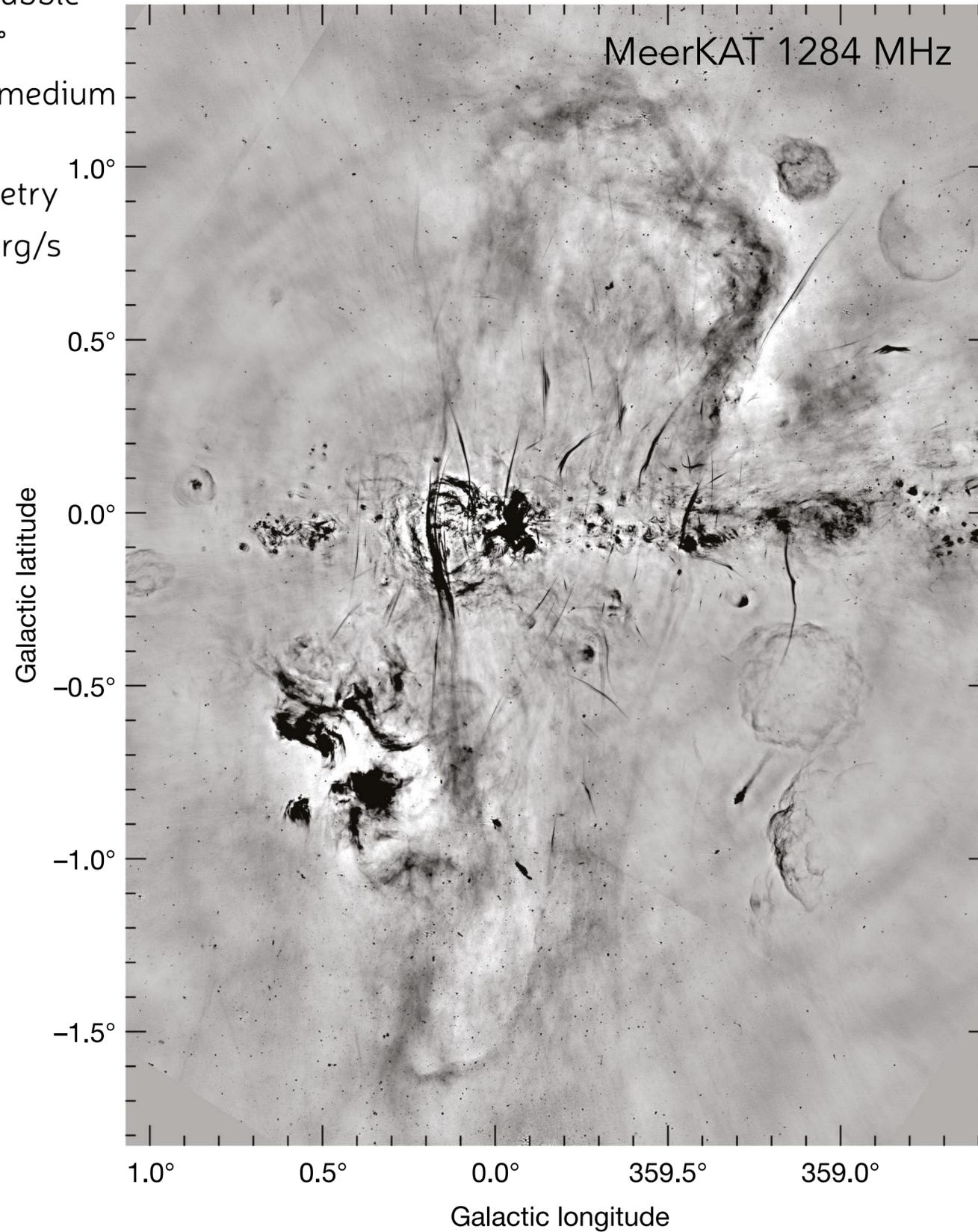
# high-energy cosmic rays in the CMZ

- 0.1 to 45 TeV : partial correlation with dense CMZ gas + 30% more diffuse emission
- $L(> 1 \text{ TeV}) \approx 2 \cdot 10^{35} \text{ erg/s}$



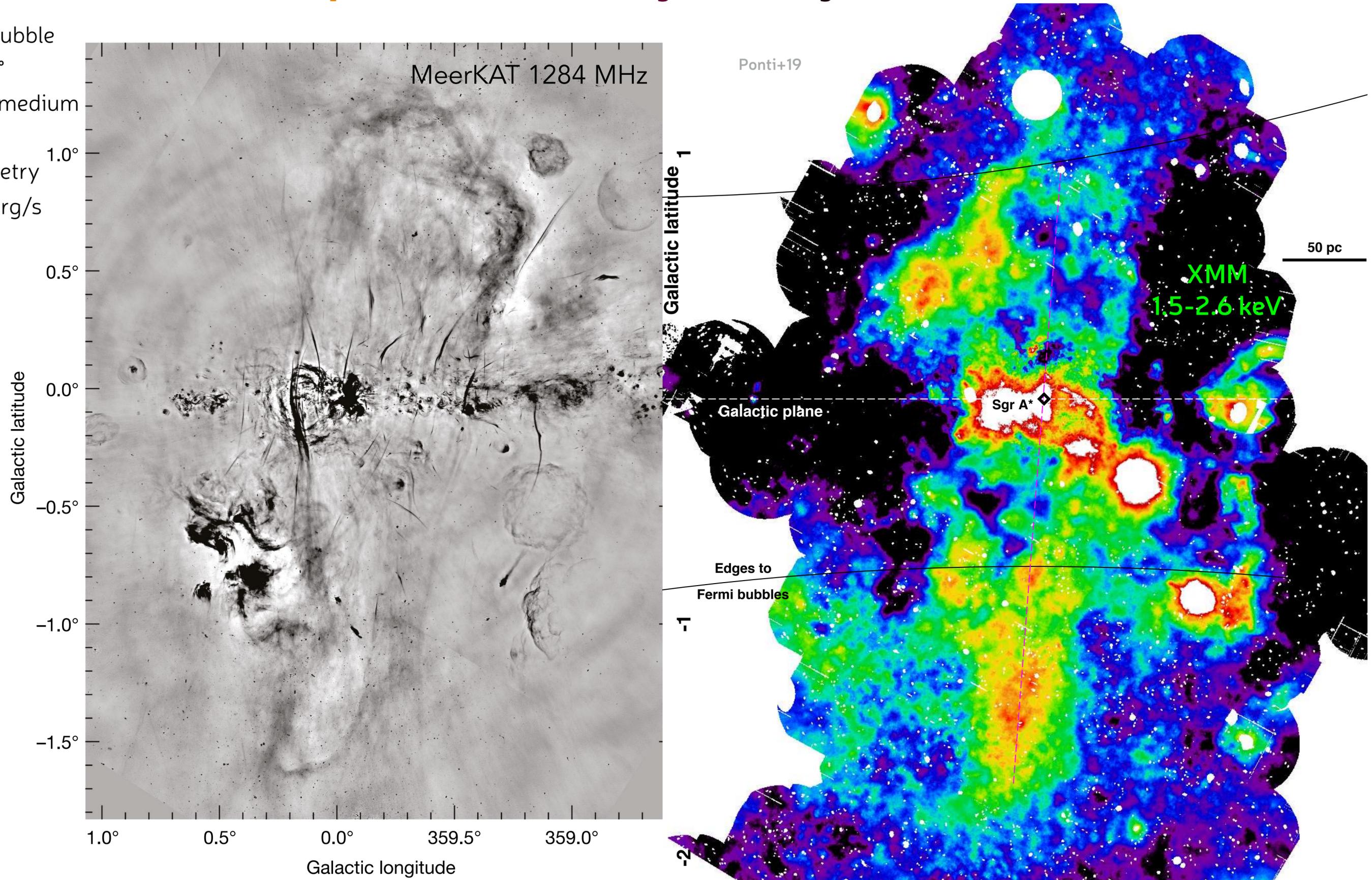
# a bi-polar radio & X-ray chimney

- 430-pc long bipolar bubble
- 20-pc offset to  $l < 0^\circ$
- toward low-density medium
- inclined & bounded
- north-south asymmetry
- X-ray outflow  $4 \times 10^{39}$  erg/s



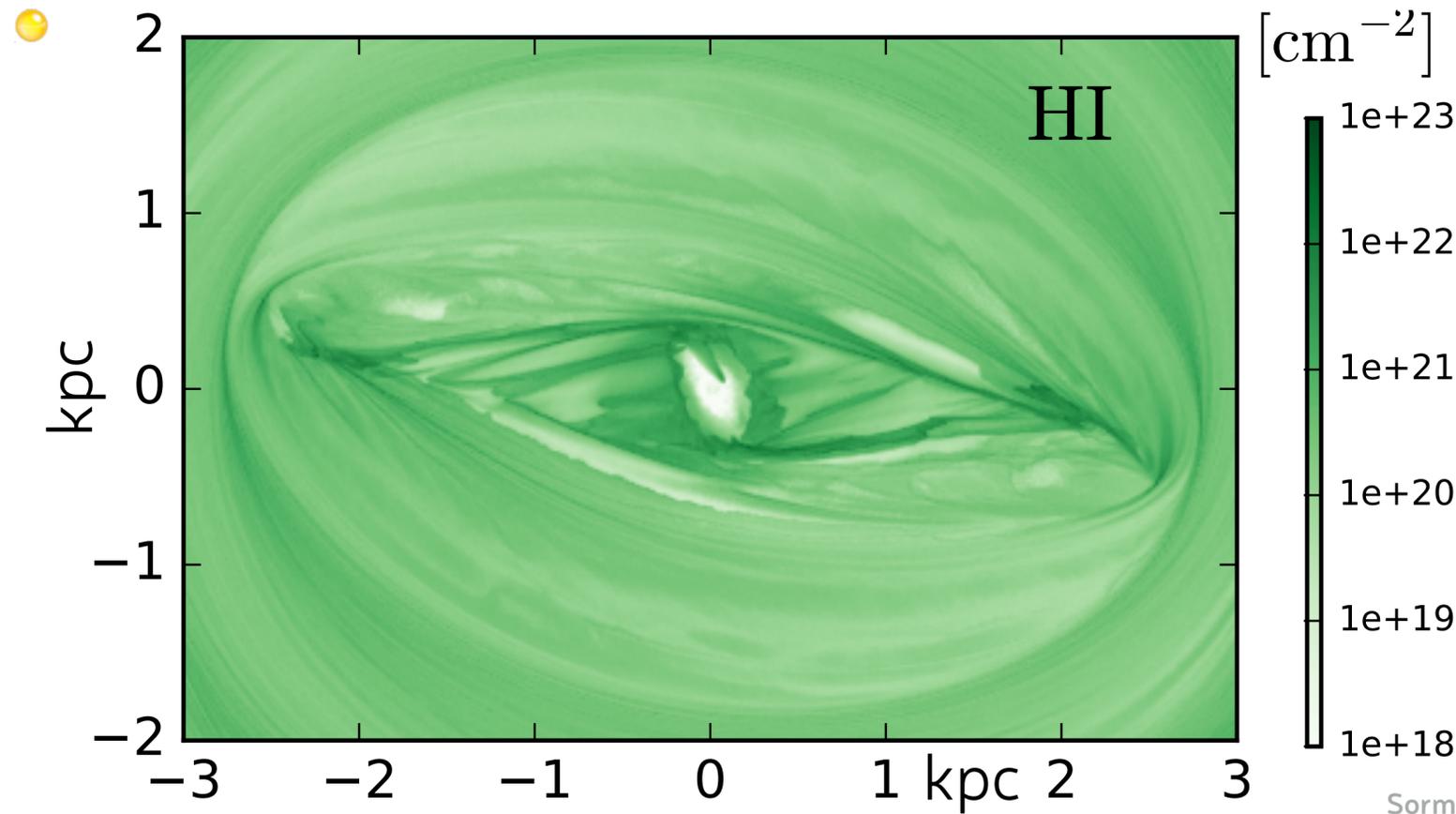
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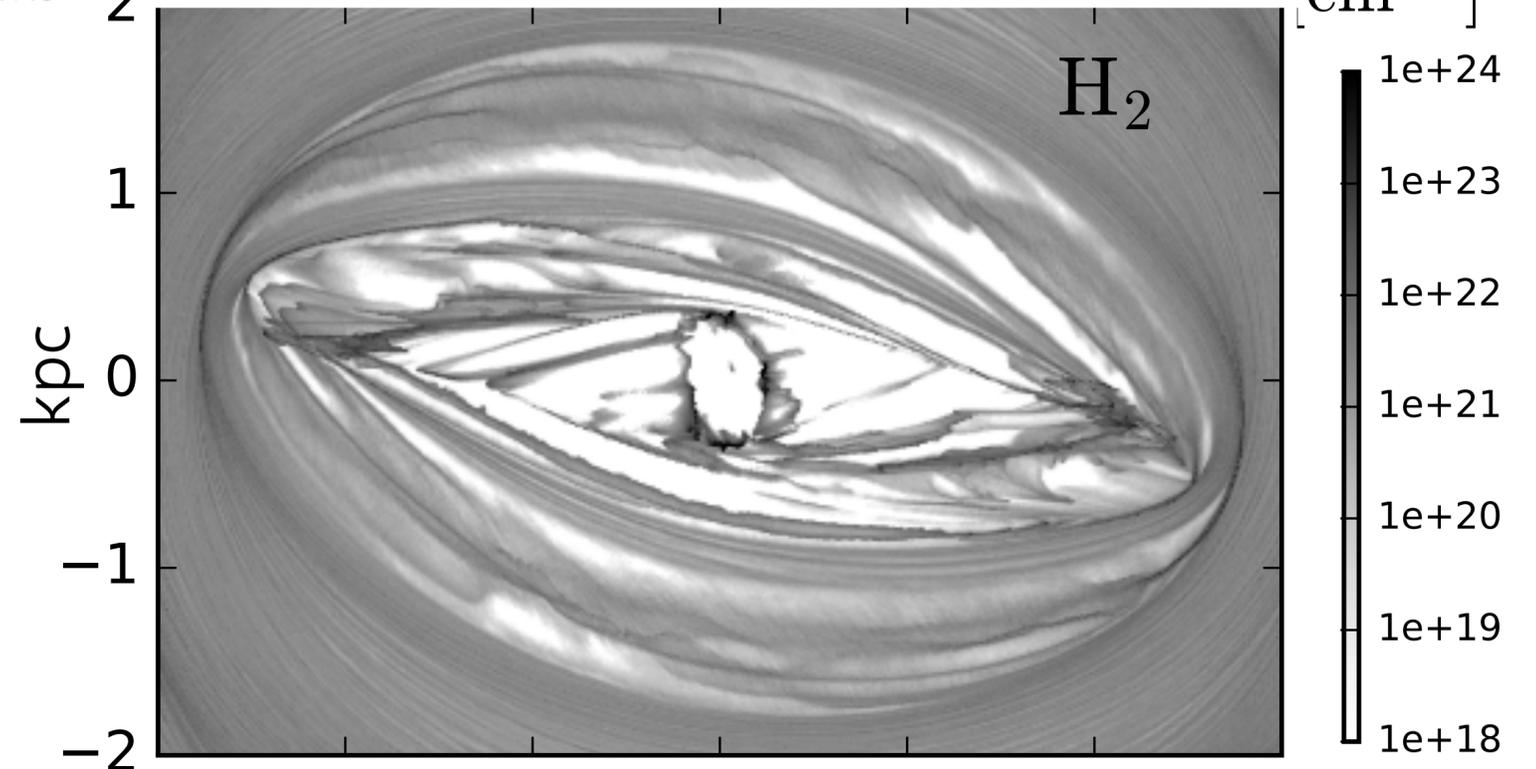
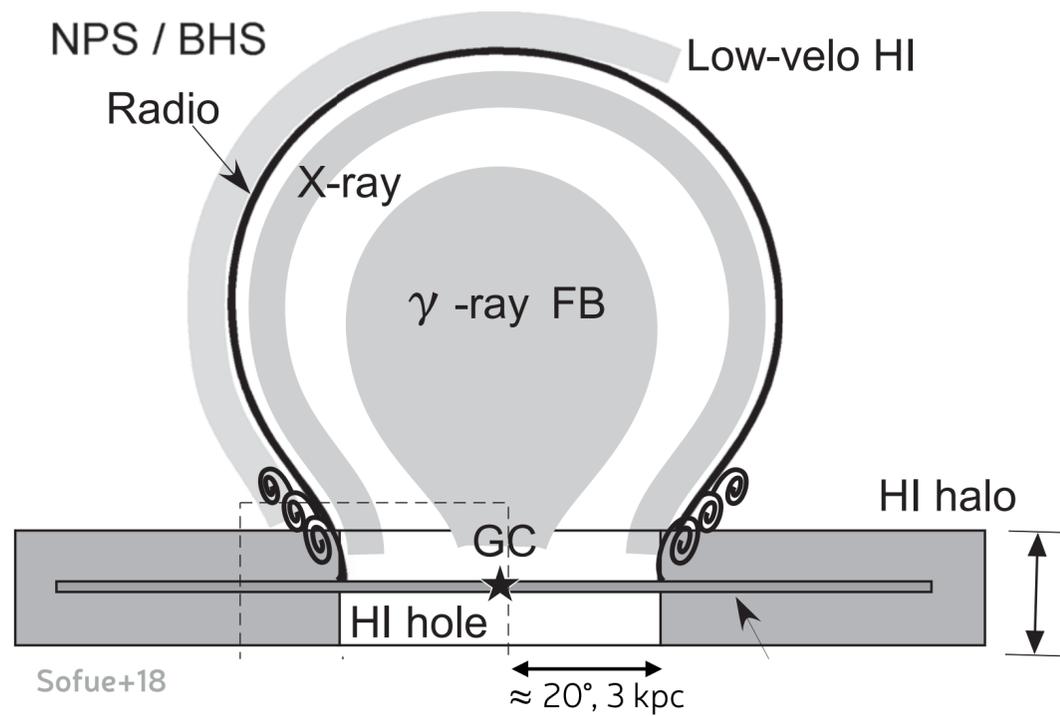
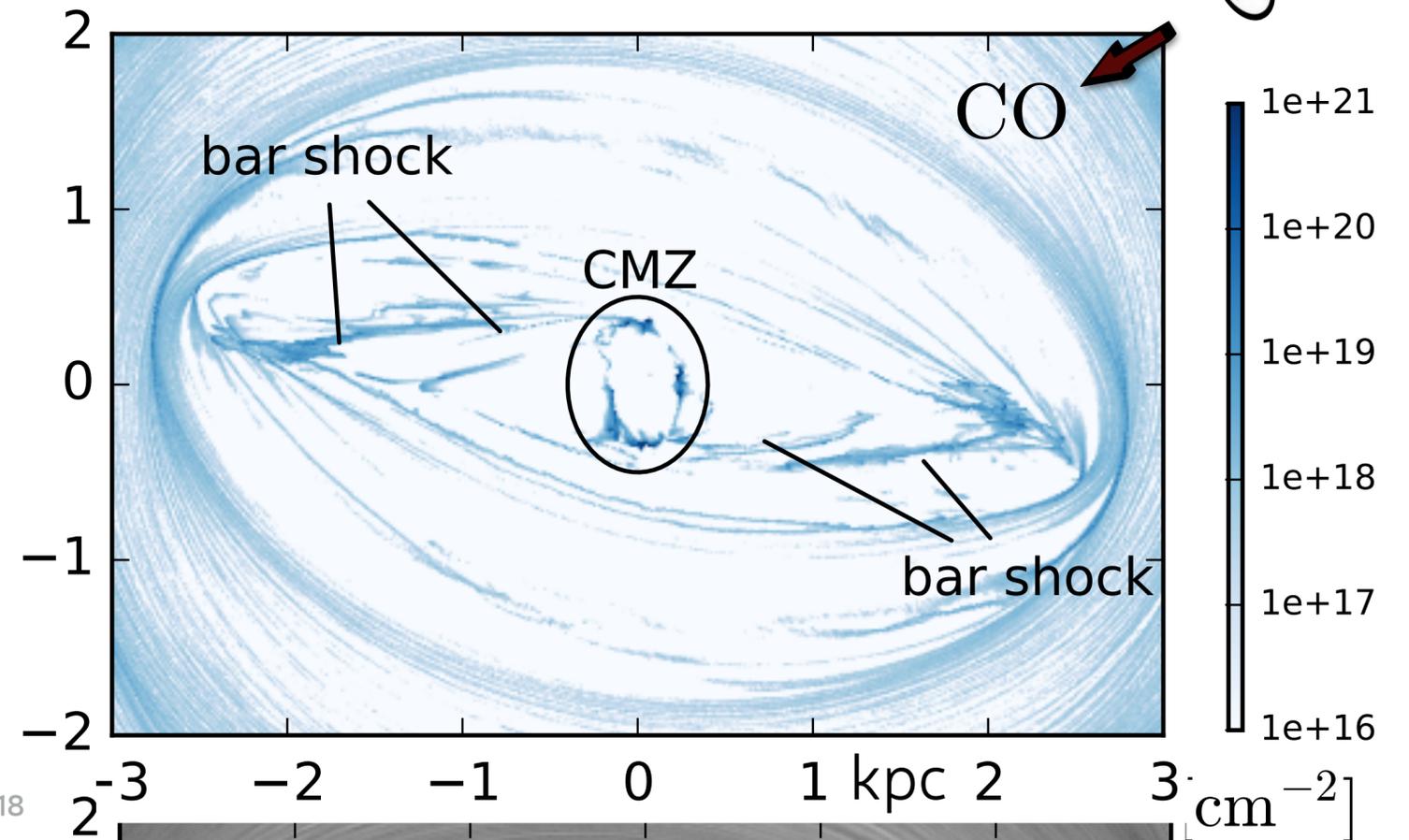


# the inner 3 kpc crater & wind

● relative lack of HI at  $R < 3$  kpc Lockman 1984

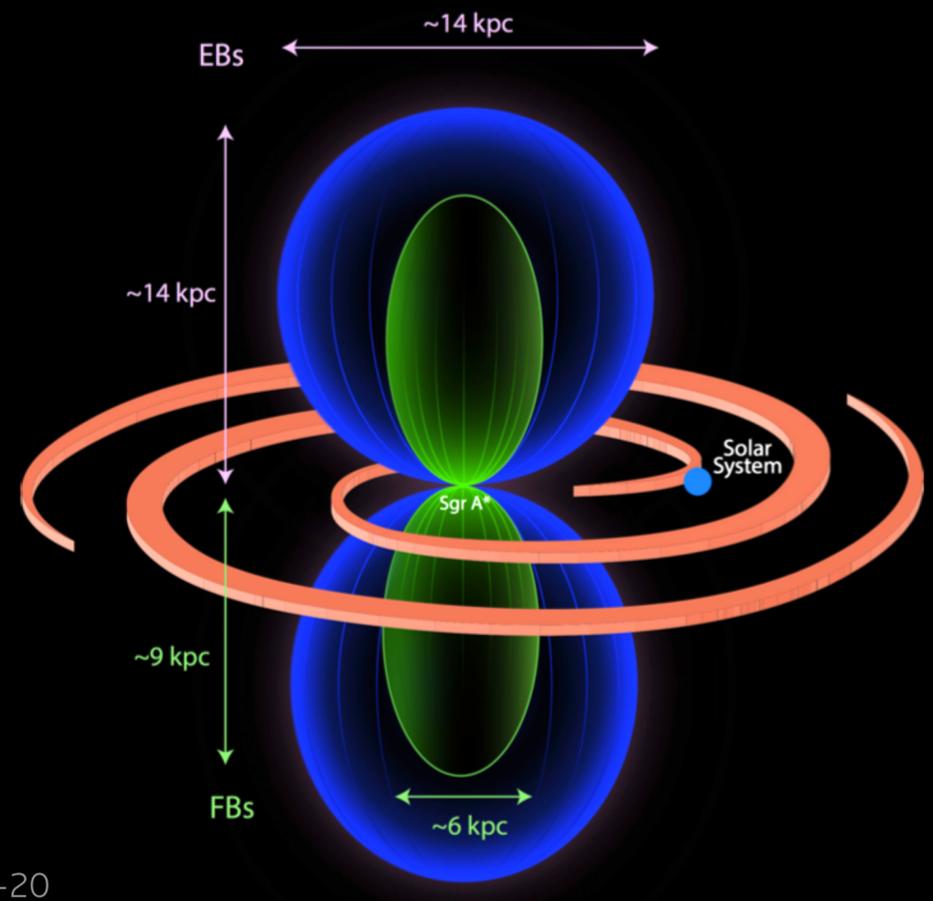
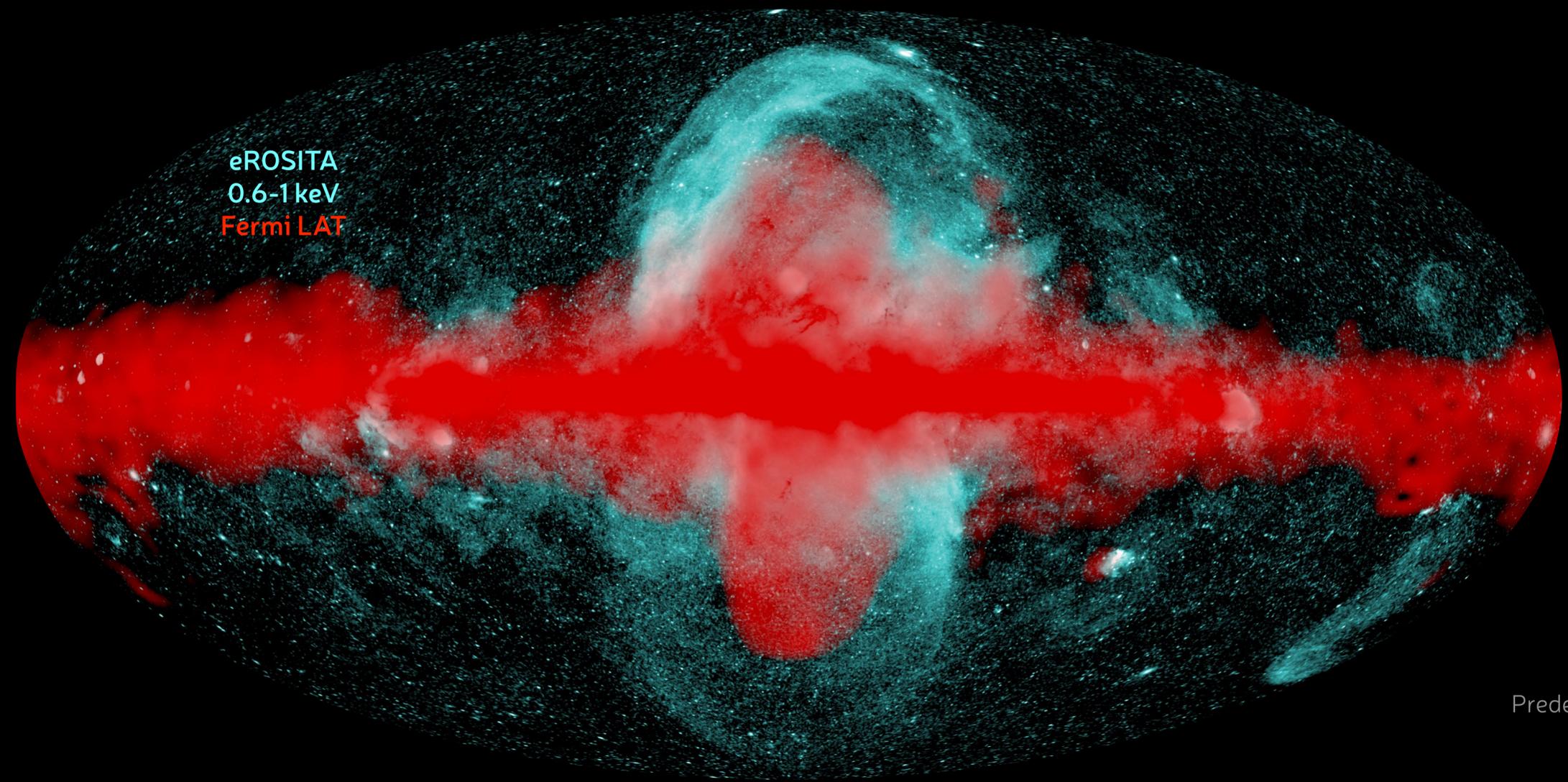


Sormani+18



# a Seyfert-like outflow ?

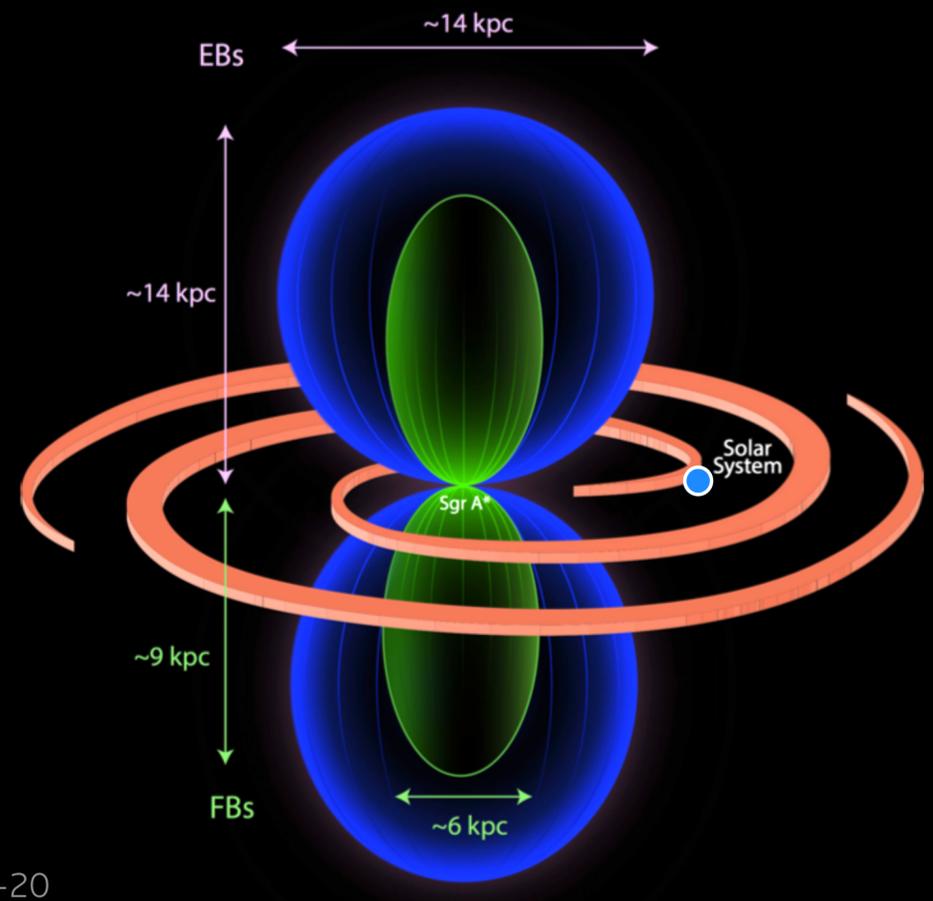
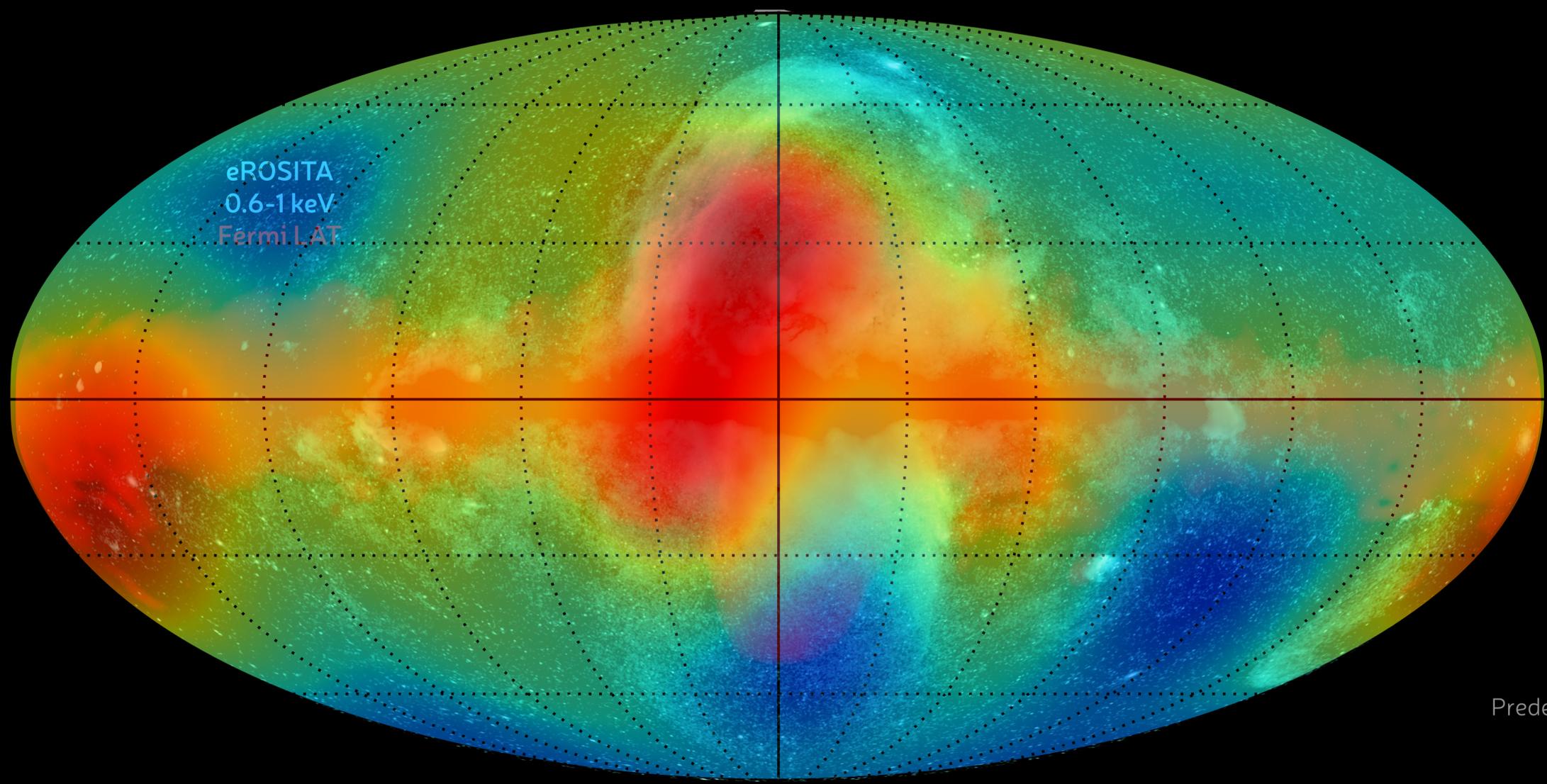
- shocked halo gas  $n \approx 2 \cdot 10^{-3} \text{ cm}^{-3}$ ,  $T \approx 3 \cdot 10^6 \text{ K}$ , shell thickness  $\approx 4 \text{ kpc}$ ,  $L_x \approx 10^{39} \text{ erg/s}$ ,  $\approx 10^8 M_{\odot}$  ?
- shocked outflow wind,  $L_{\gamma} = 4 \cdot 10^{37} \text{ erg/s}$
- Fermi Bubble edge = contact discontinuity ?



Predehl+20

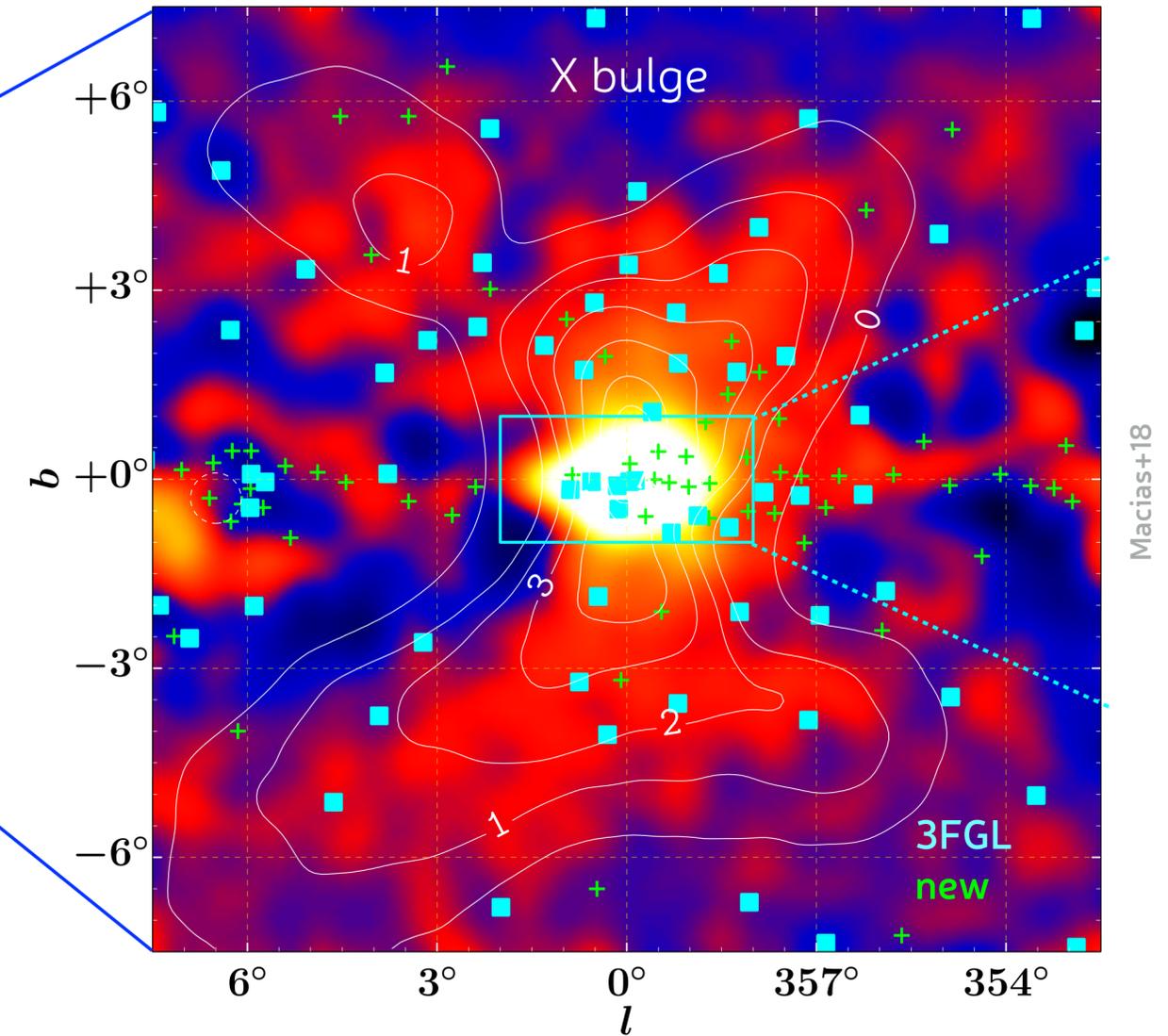
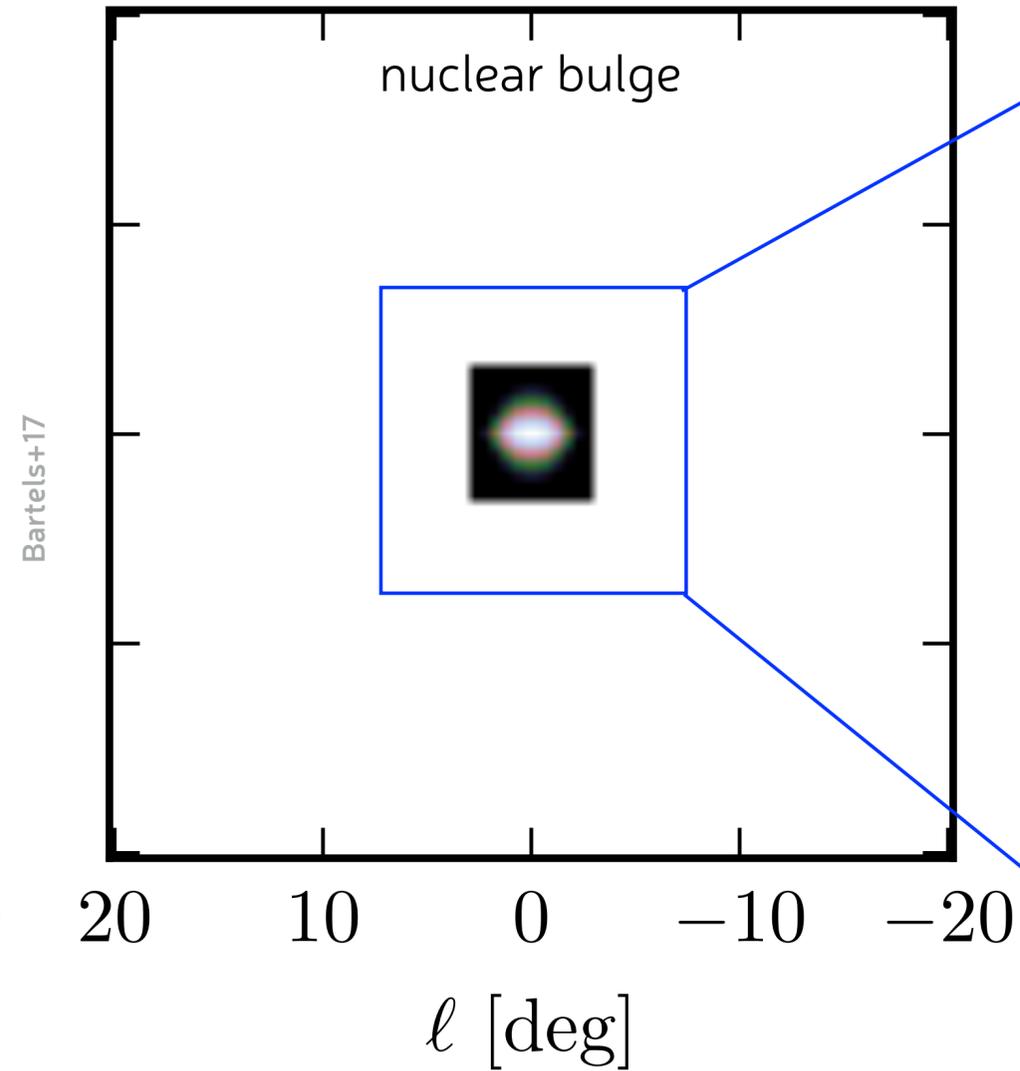
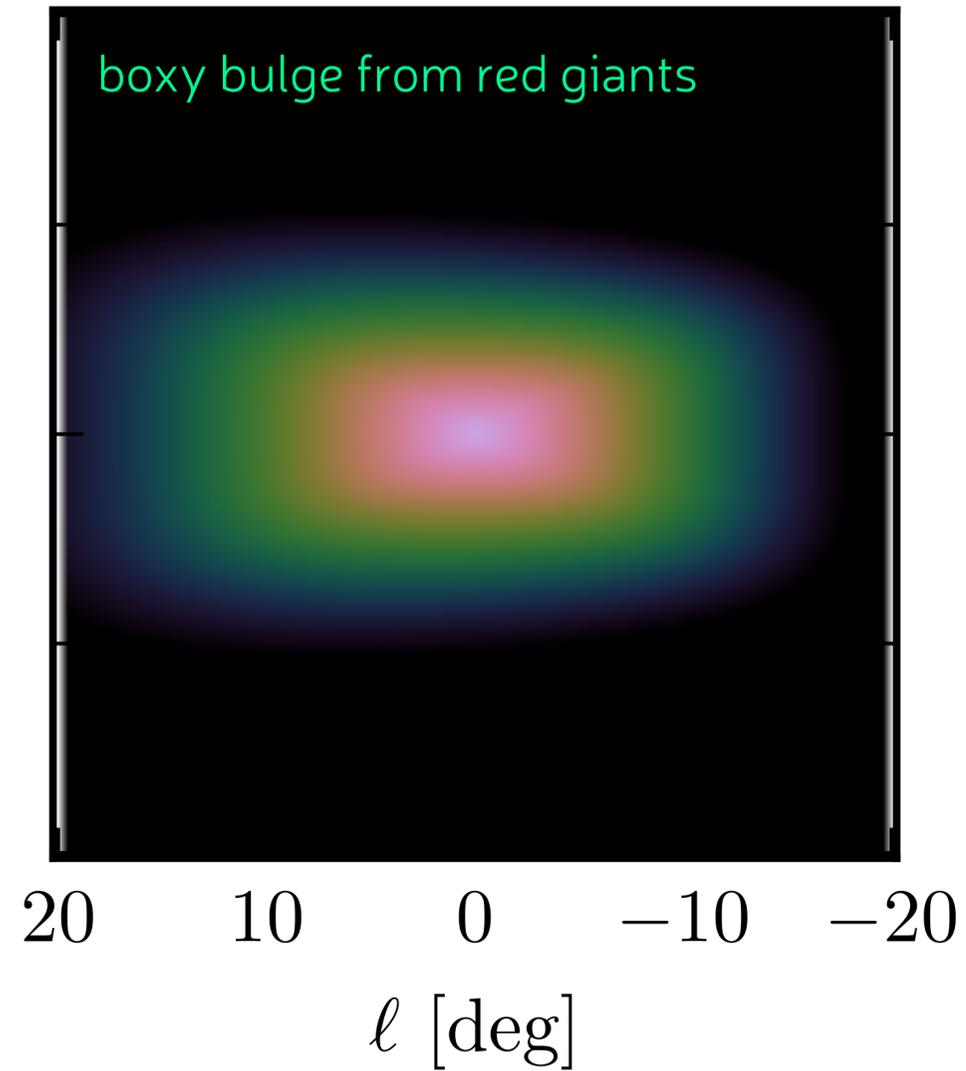
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- Fermi Bubble edge = contact discontinuity ?



# inside the crater : boxy, X, and nuclear bulges

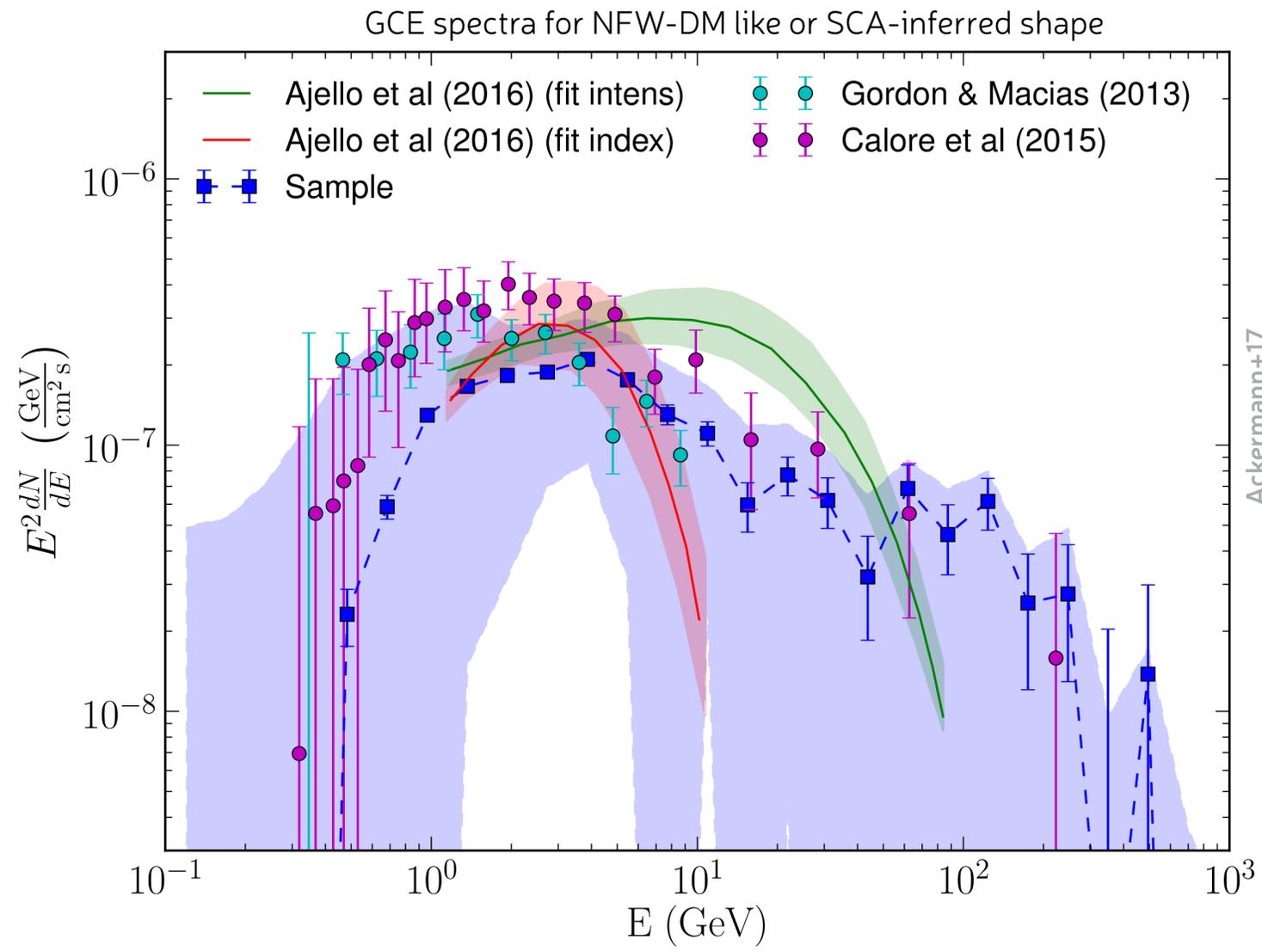
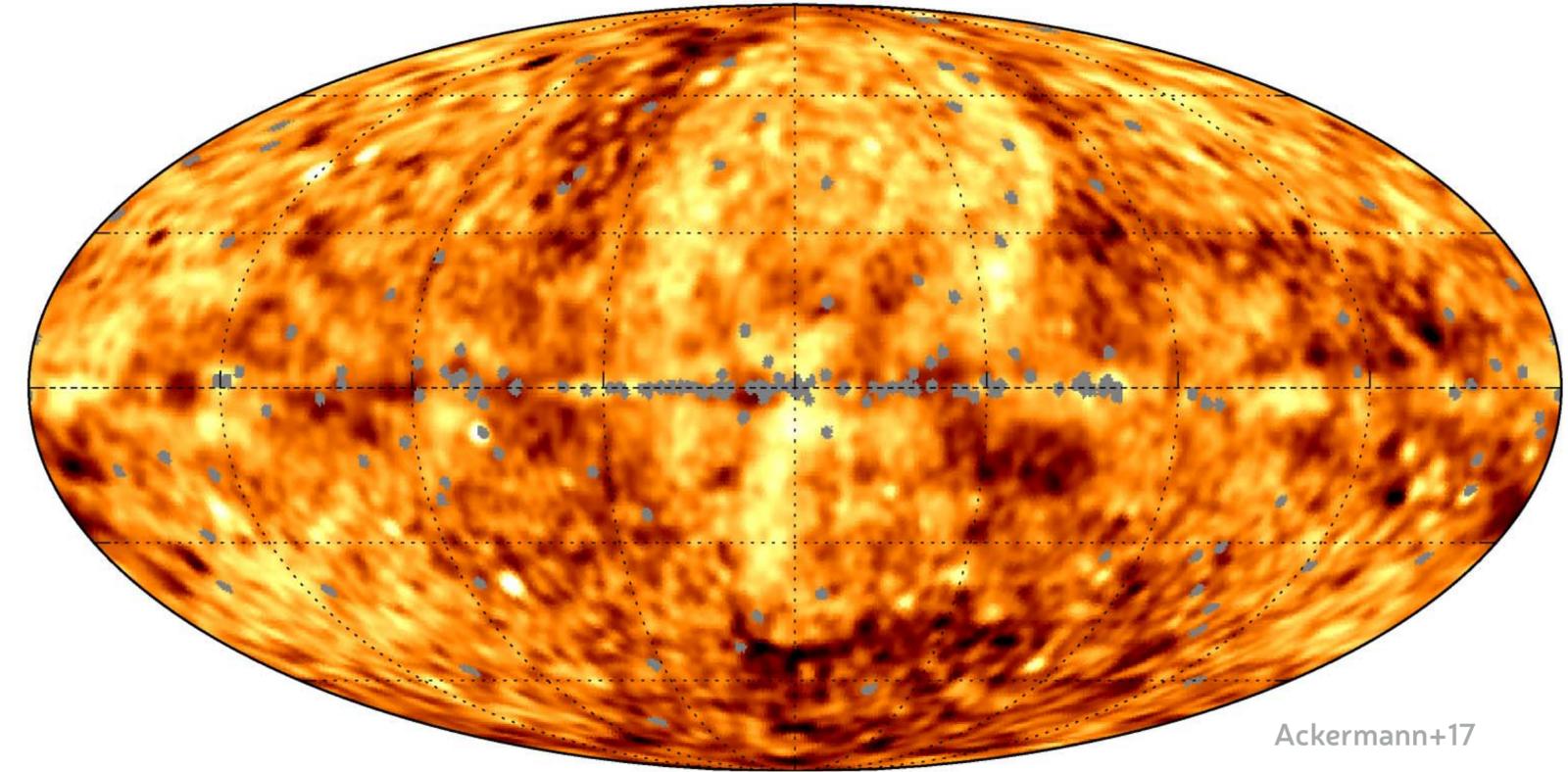
- ☉ stellar bulge geometries for the
  - boxy/peanut-shaped bulge from NIR DIRBE
  - X-shaped bulge from WISE
  - nuclear bulge from NIR stars
- ☉ in addition to gas + IC + Fermi Bubbles



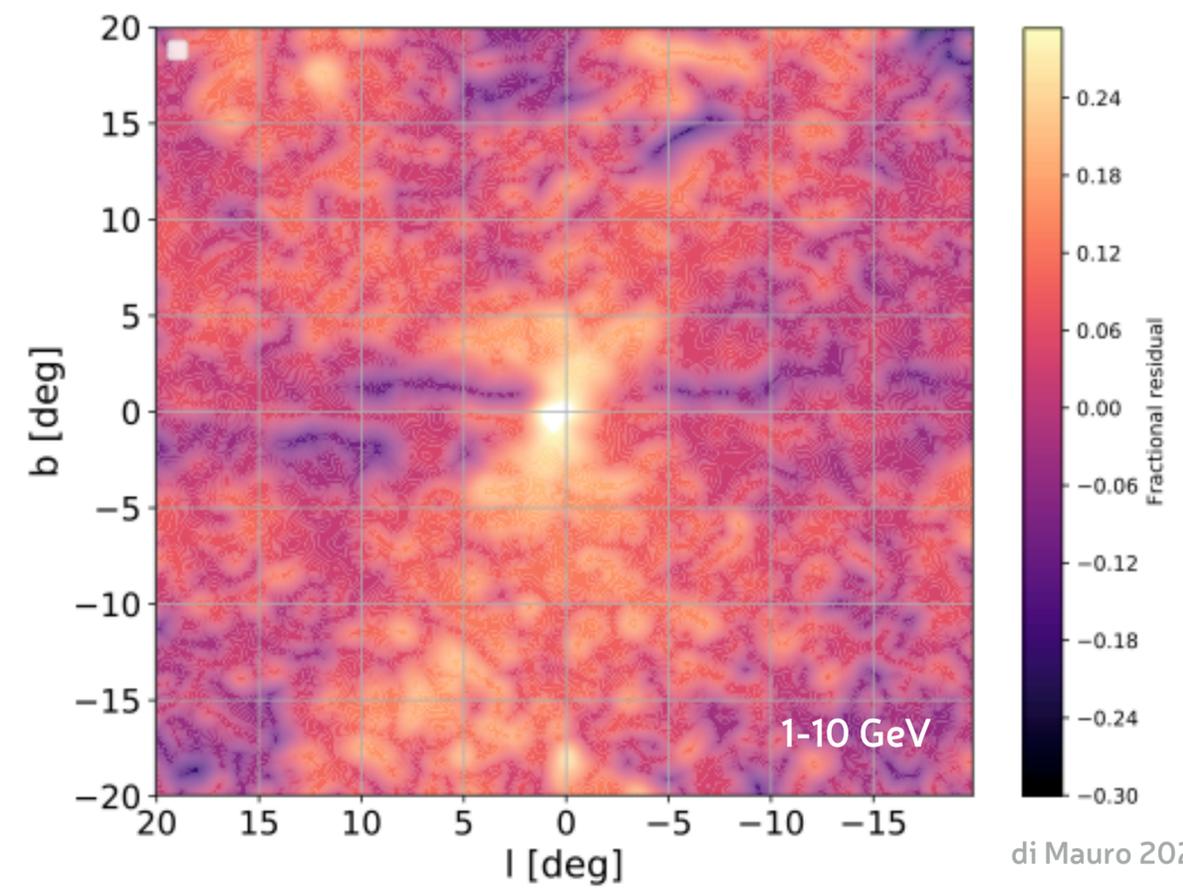
# a Galactic Centre Excess

(Residual + GC excess) / Data, 1.1 - 6.5 GeV

- up to 30% of the total emission
- extending to  $\sim 10^\circ$  around GC
- mildly asymmetric
- spectrum peaking at GeV energies
- high-energy tails if  $|l|$  &/or  $|b| > 4^\circ$
- but shift to  $0^\circ < l < -8^\circ$  at high energies
- luminosity of order  $10^{37}$  erg/s

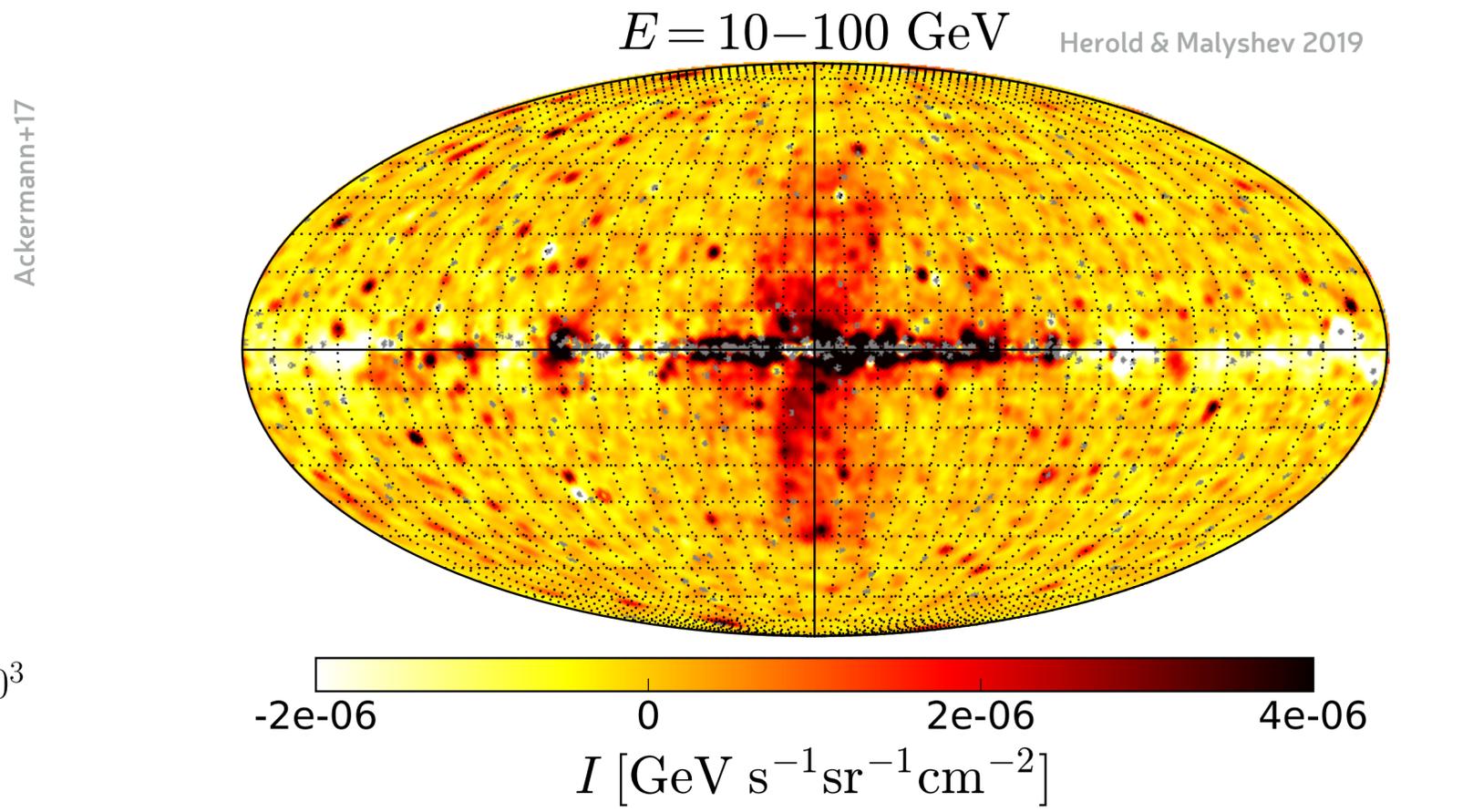
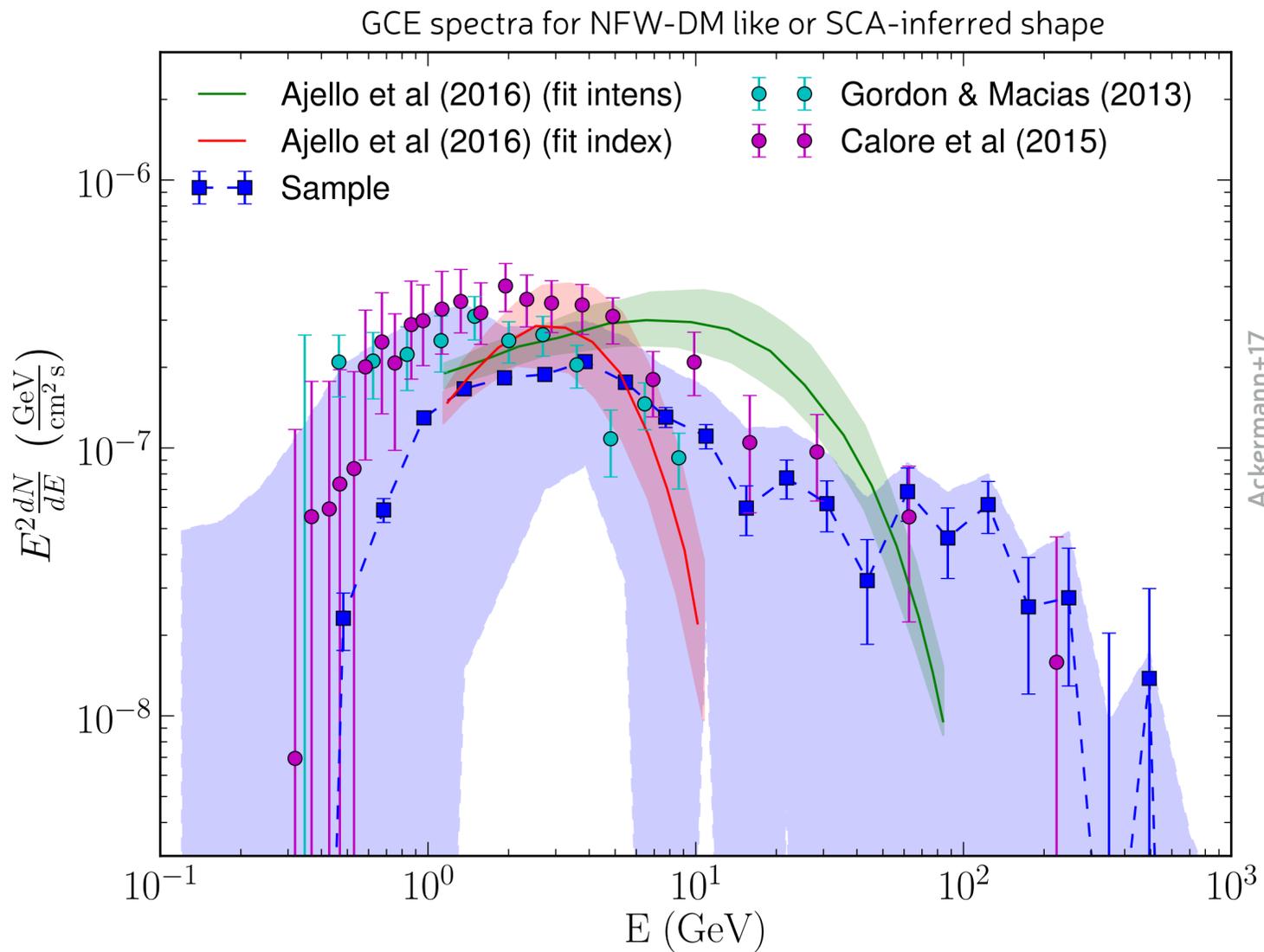
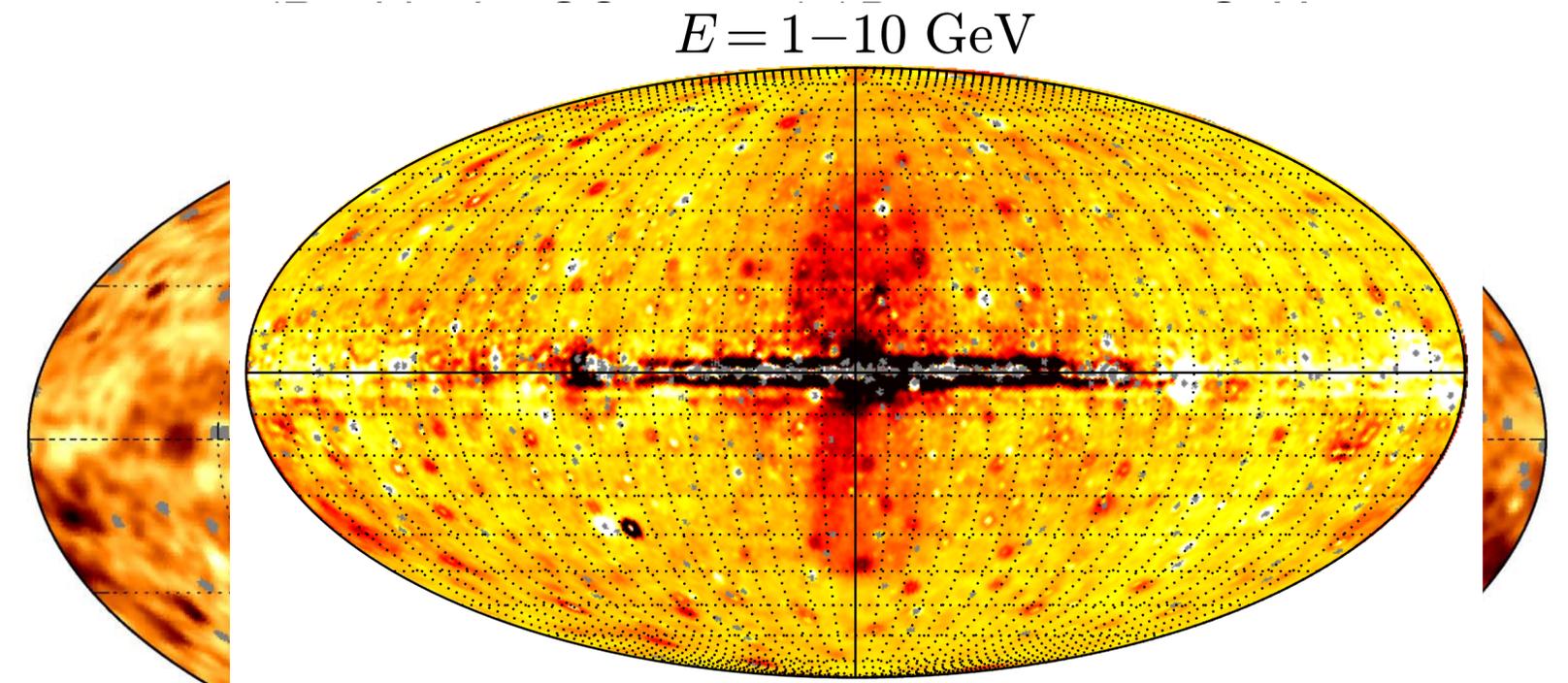


Ackermann+17



# a Galactic Centre Excess

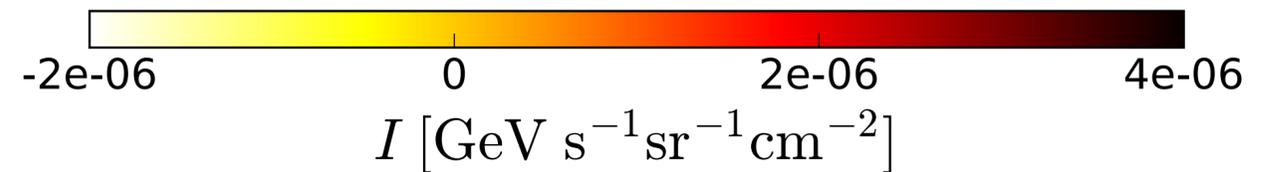
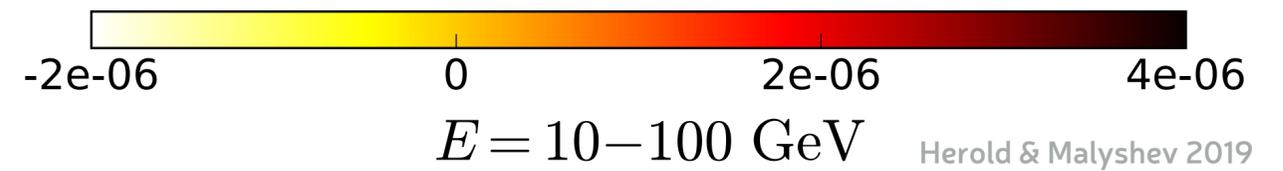
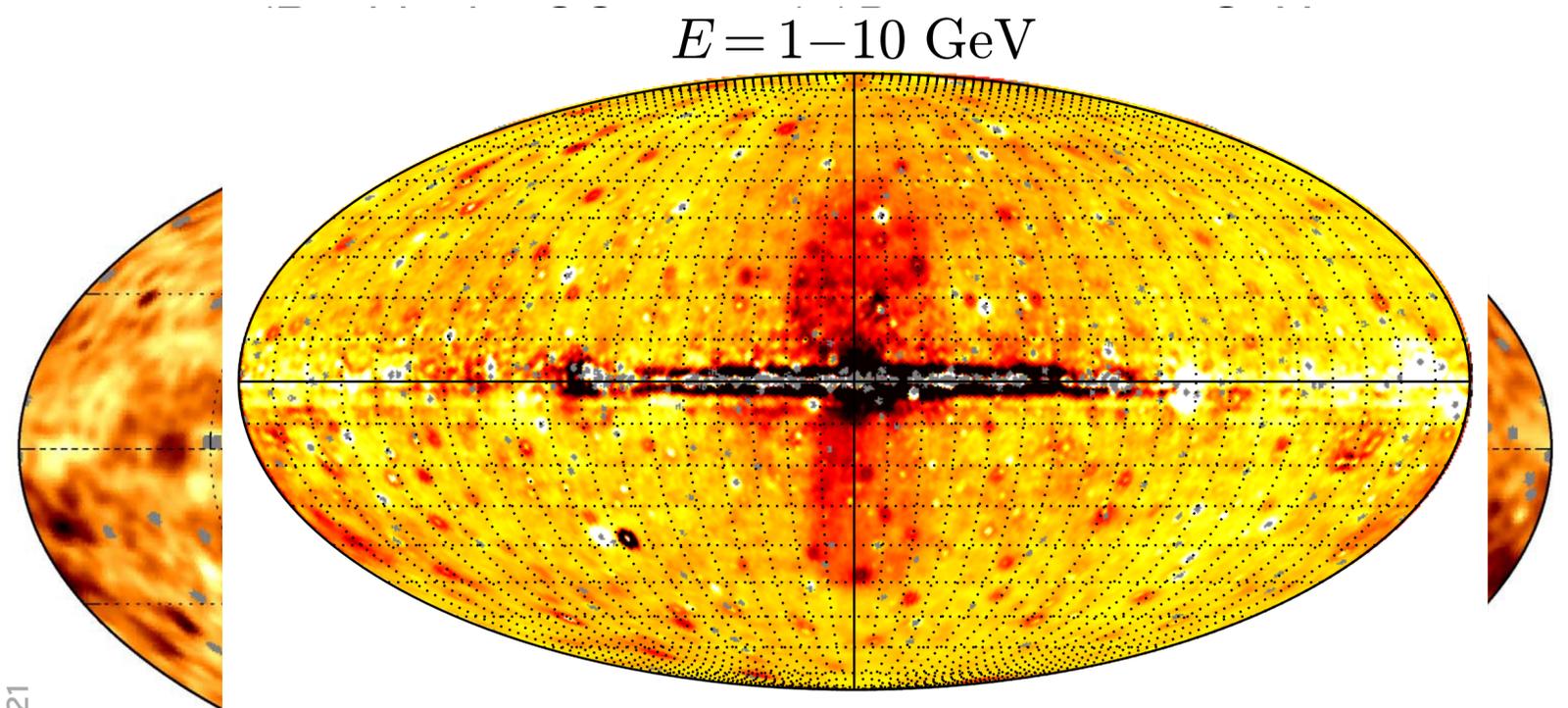
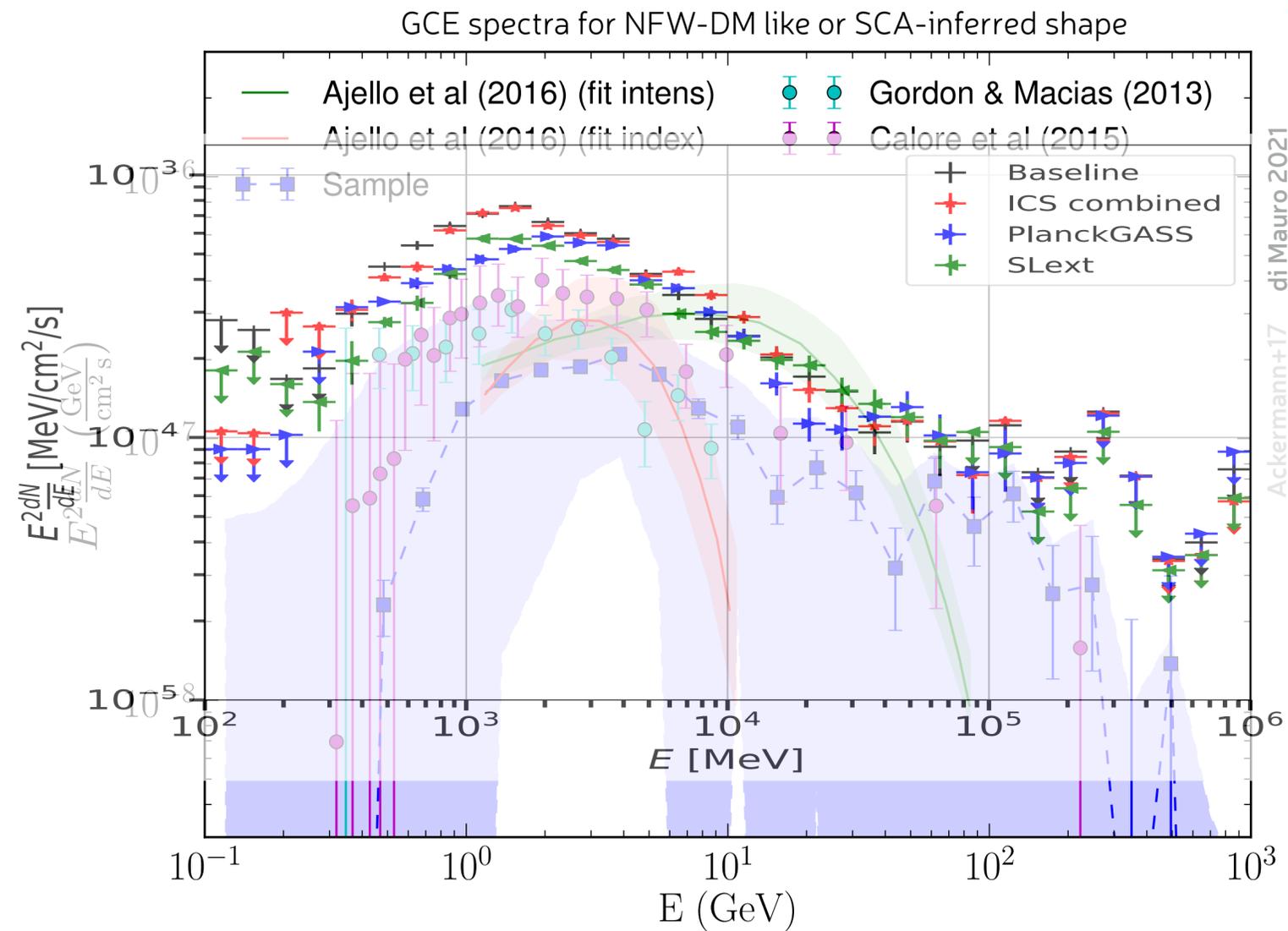
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Ackermann+17

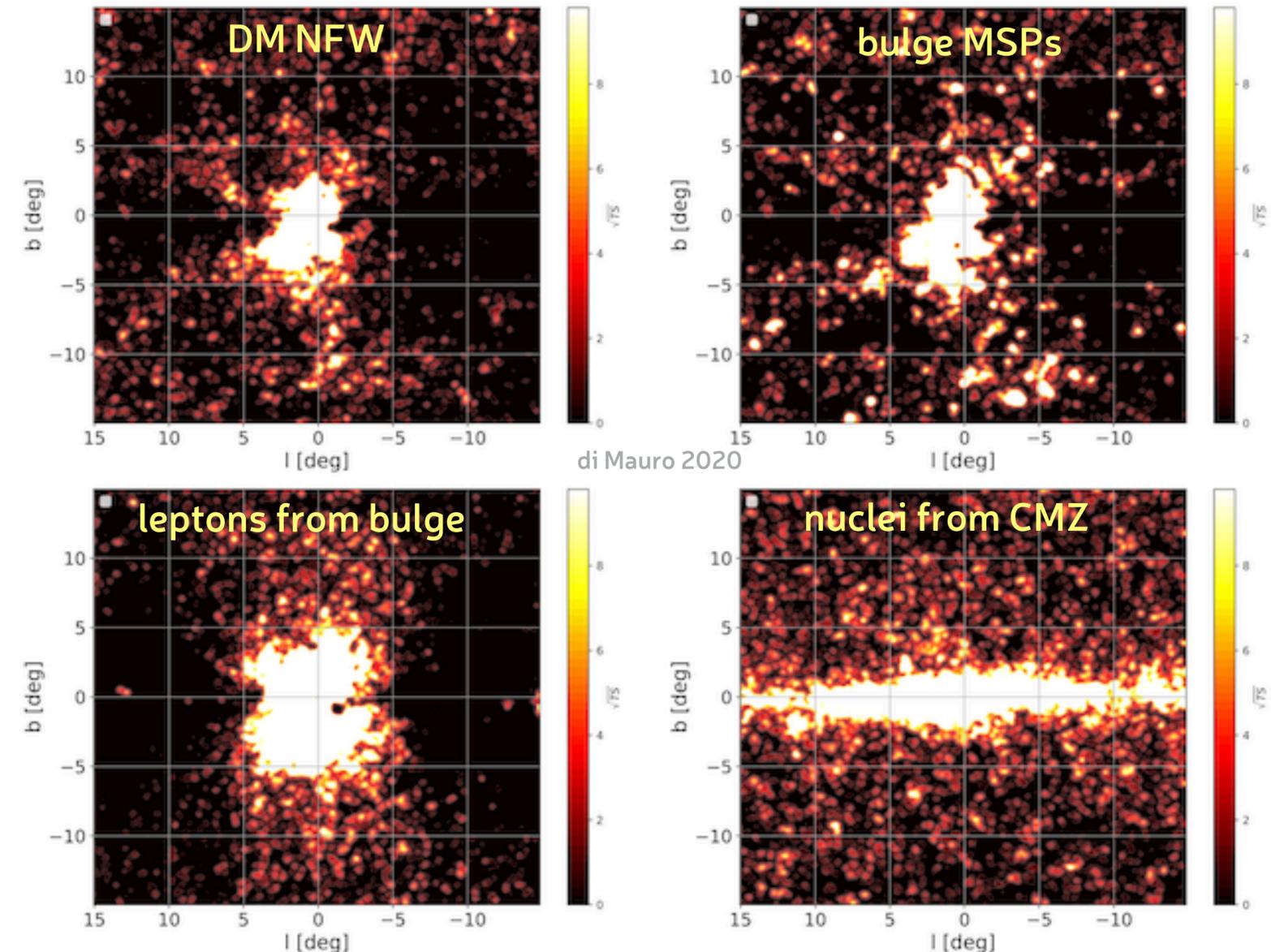
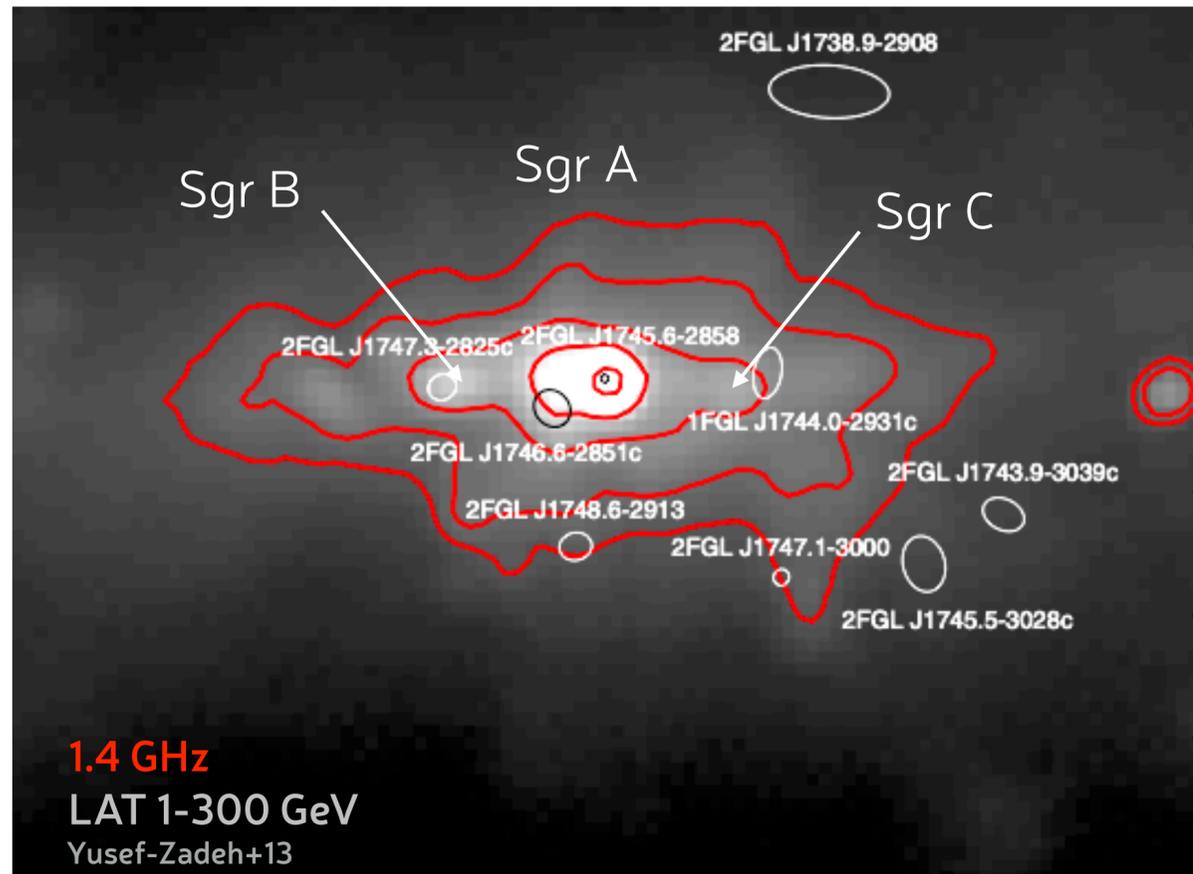
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# which suspects ?

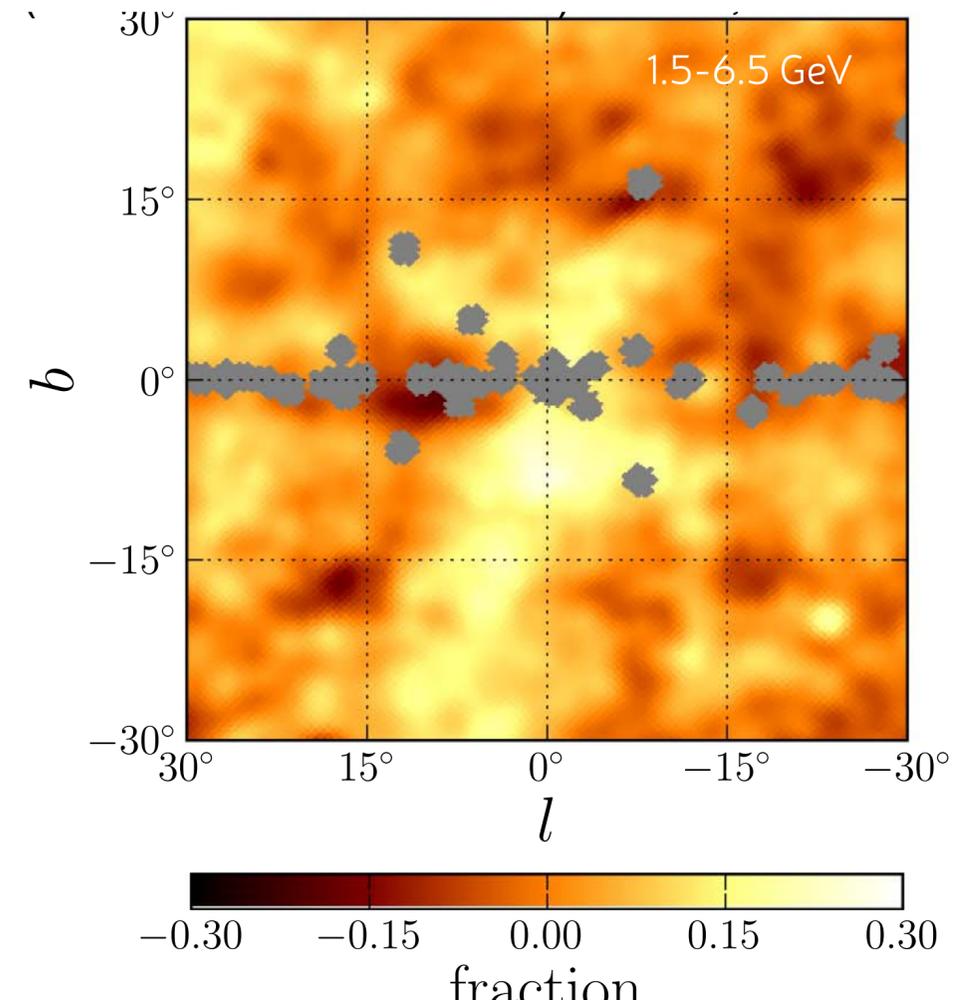
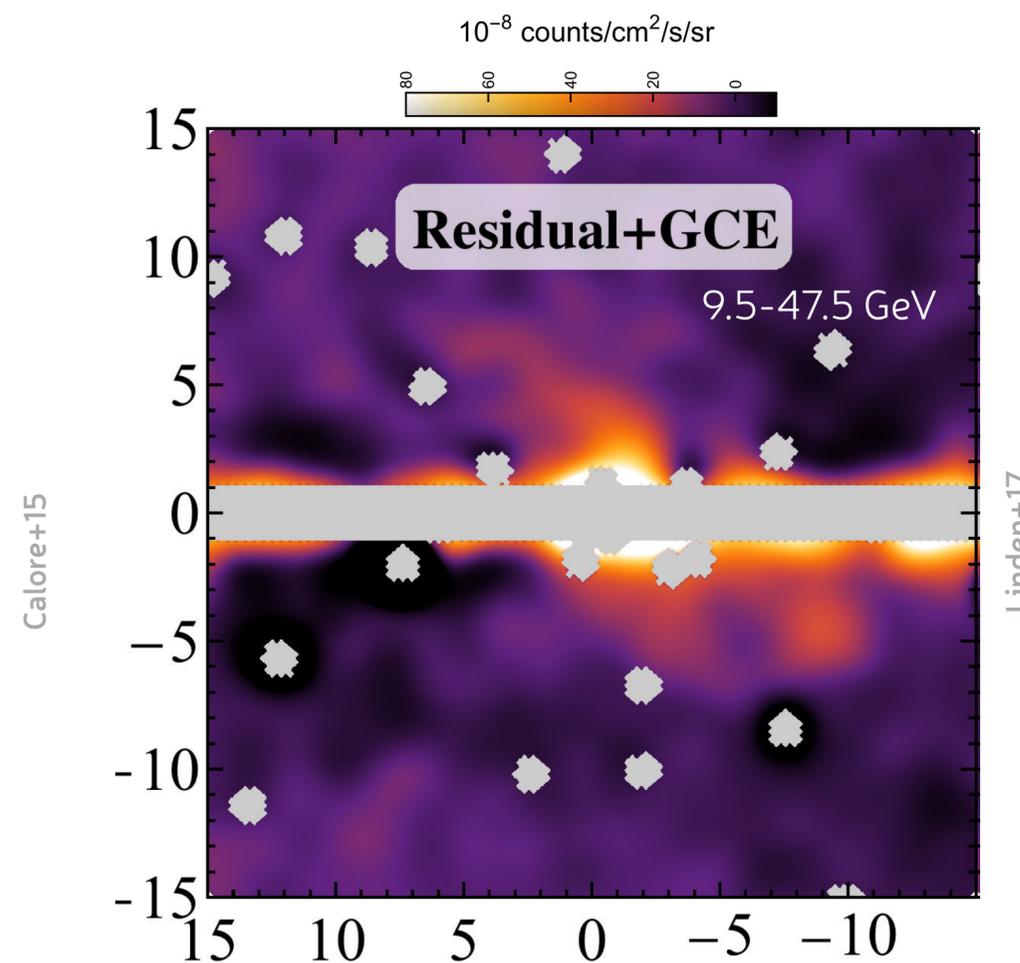
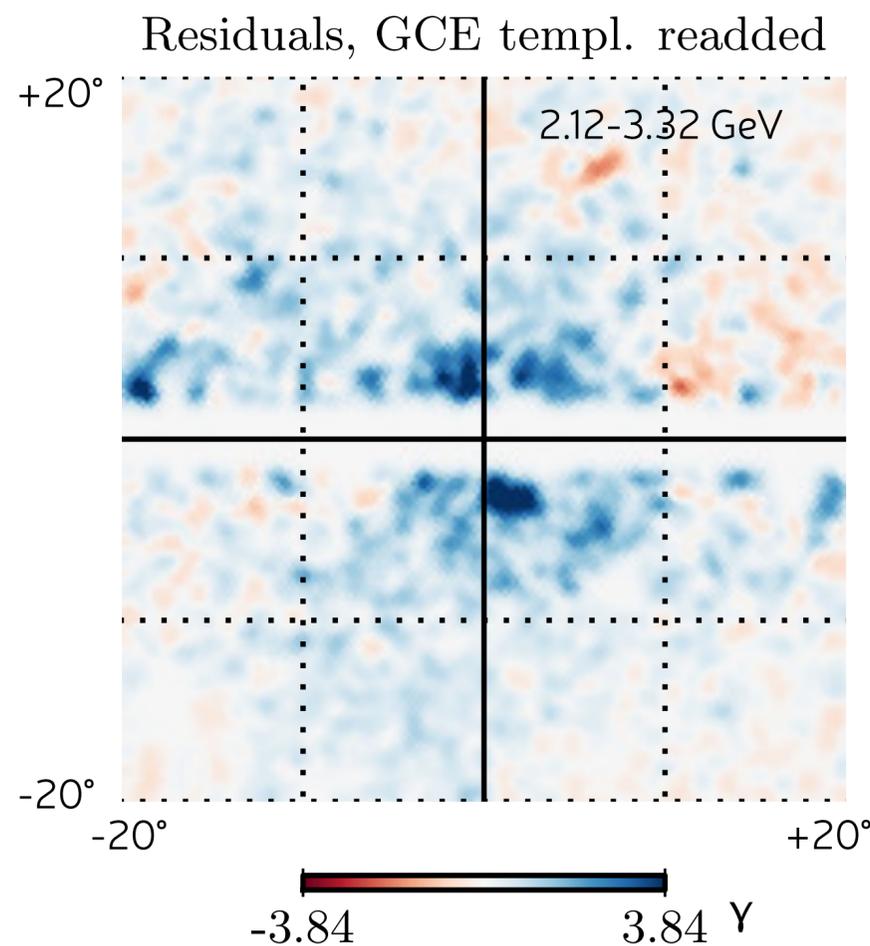
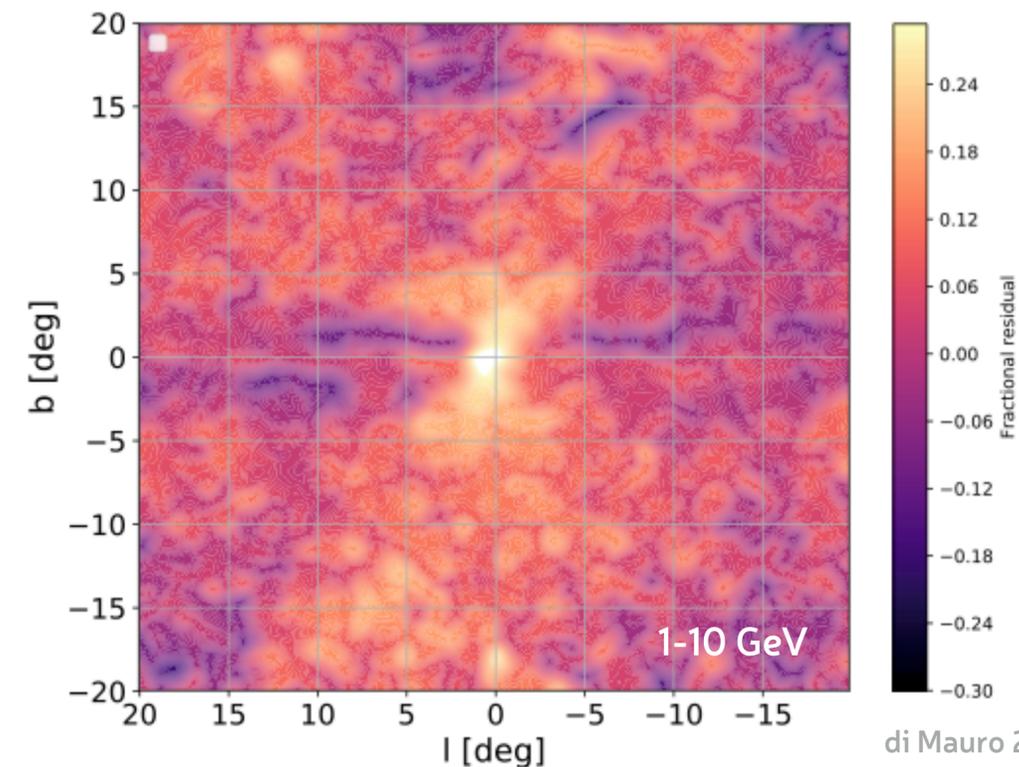
- ☀ not due to bright sources (Zhong+19) (2FGL → 4FGL)
- ☀ dark-matter self annihilation
  - spherical or ellipsoidal symmetry, smooth, uniform spectrum
- ☀ population of unresolved MSPs
  - asymmetries, not smooth, possible spectral variations along the plane
- ☀ fresh CRs
  - in the Galactic wind from Sgr A\* bursts or CMZ supernovae
  - accelerated by/escaping the radio+X Chimney
  - at the base of the Fermi Bubbles
  - complex spatial and spectral distributions
- ✦  $\pi^0$ , brem, or IC emission ?



expected 1-10 GeV residuals from simulations

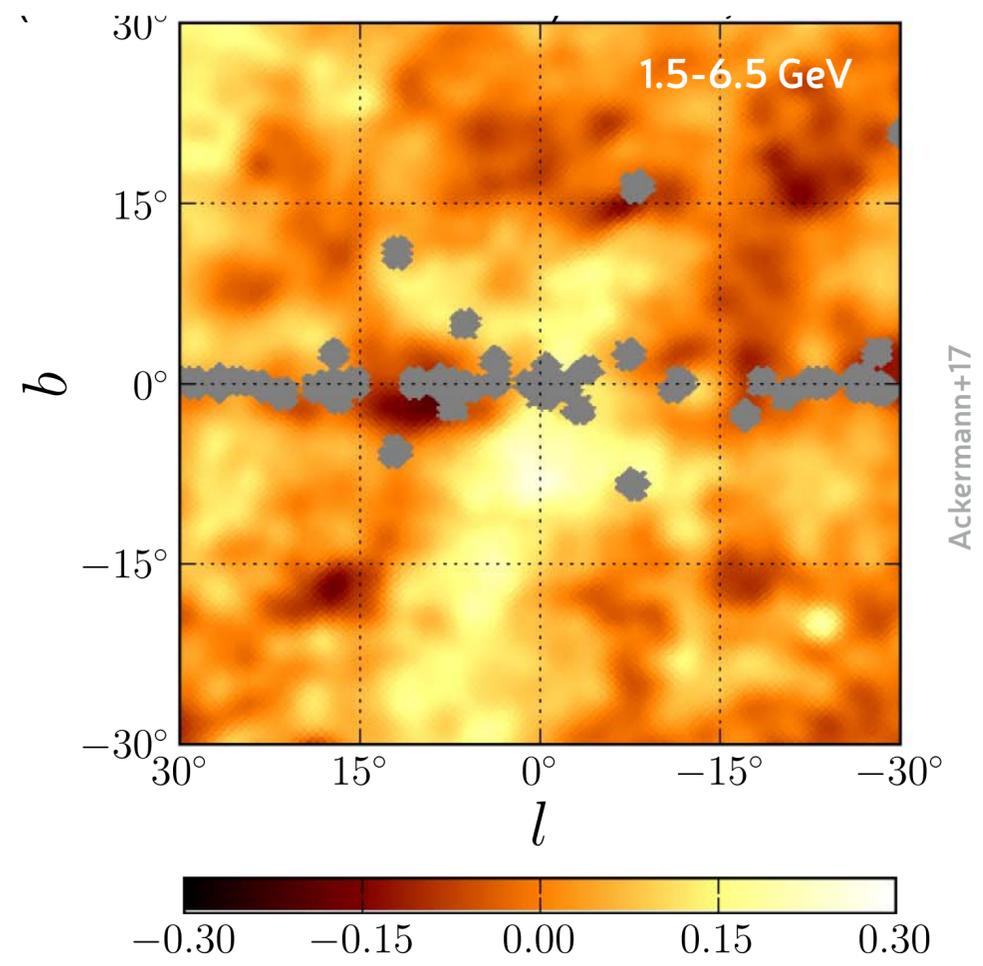
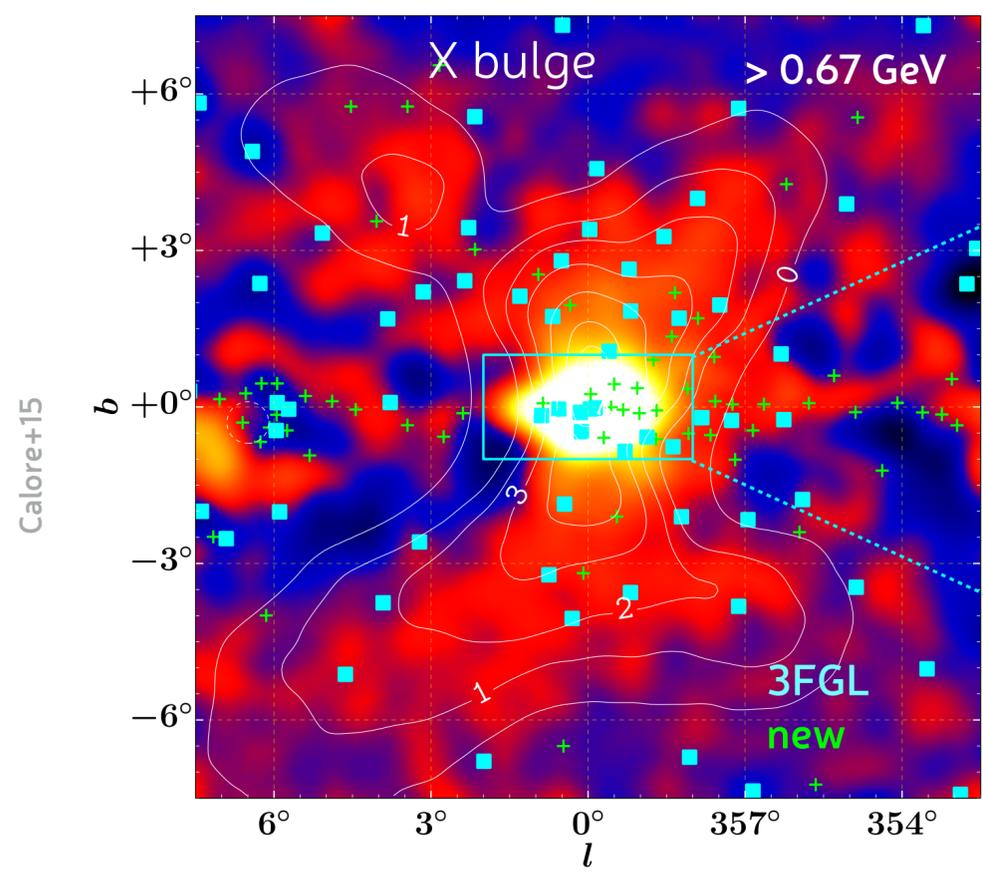
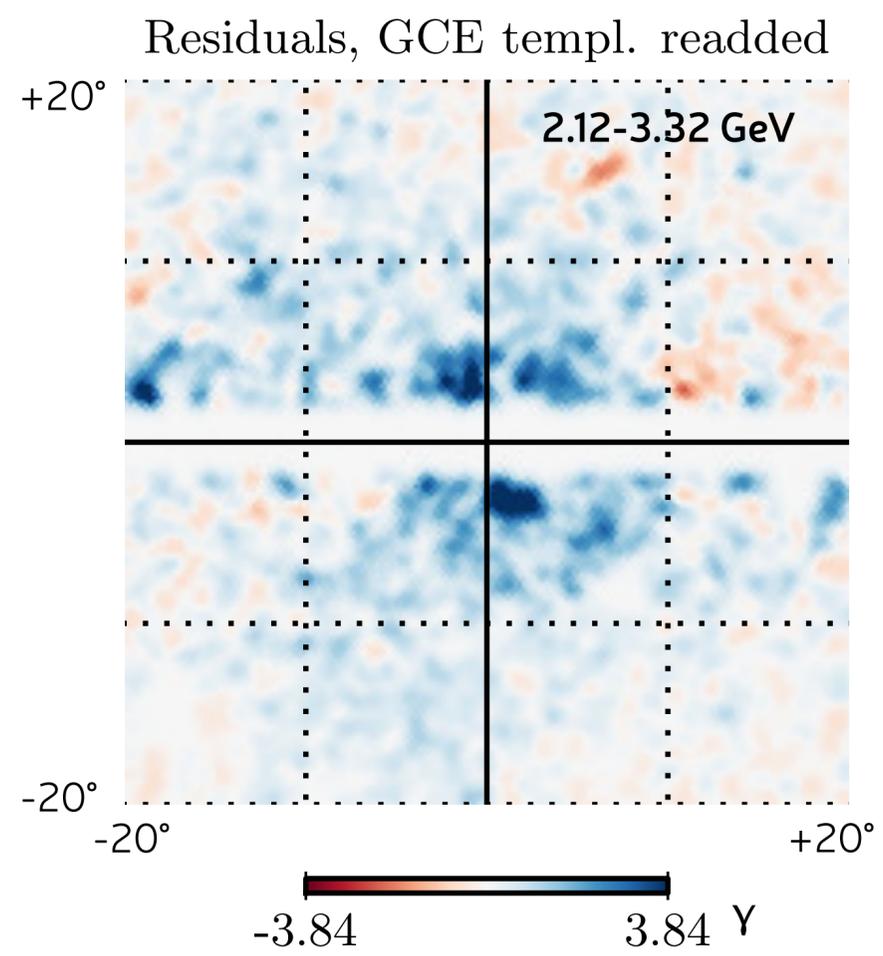
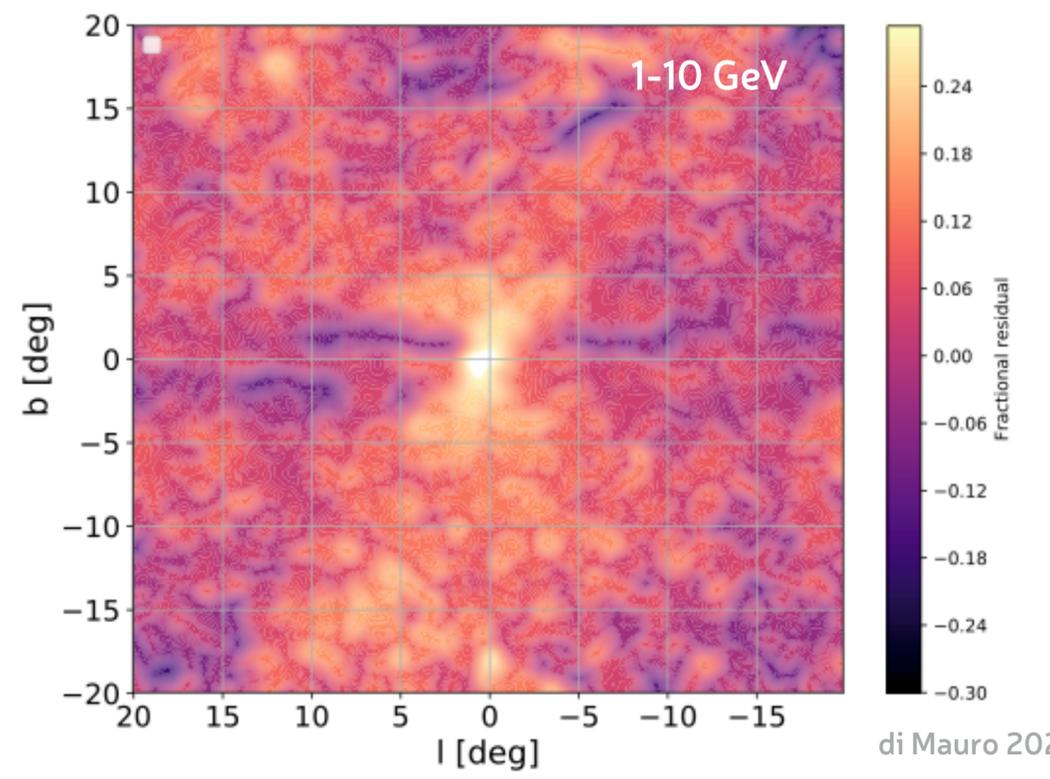
# which granularity ?

- smooth excess (DM, IC) vs. granular excess (unresolved pt sources, MSPs?)
  - i.e. more-Poissonian vs. less-Poissonian pixel-to-pixel variance
- pt sources & mismodelling yield inflated variance wrt expected value
- 10°x10° ROI Leane & Slatyer 2020
  - detection of north-south asymmetry in (smooth) signal
  - NPTF-based evidence for pt-sources, yet strong (Lee+16), disappears when asymmetry is allowed
  - inferred pt-source brightness relates to the mis-modelling amplitude



# which shape ?

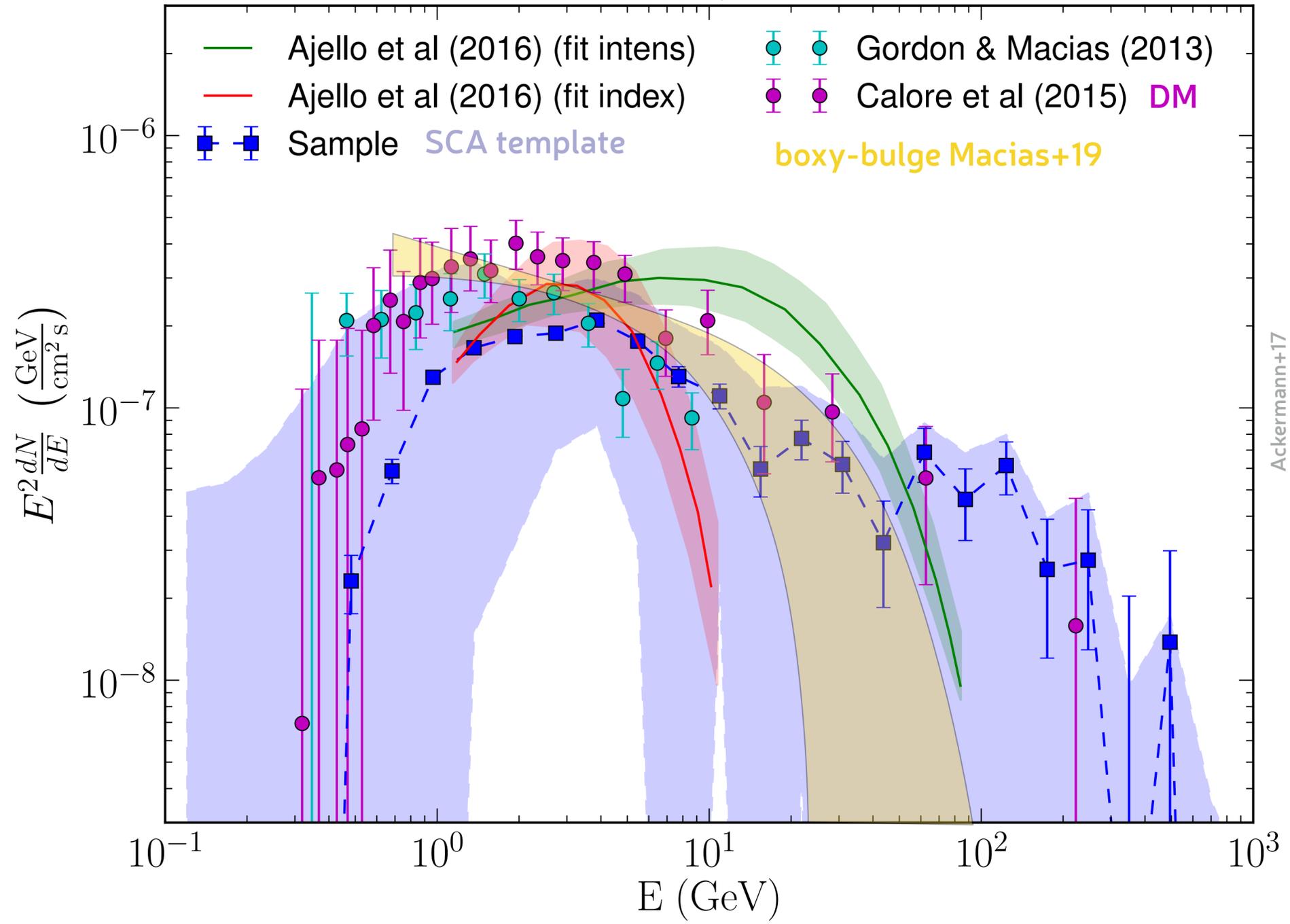
- ☀ detection of boxy (or X) + nuclear bulge Bartels+17, Macias+18, Abazajian+20
- 🟢 confirmed with new 3D IC maps and Fermi Bubble base maps Macias+19
- 🟢 boxy orientation detected against rotation Macias+19
- 🟢 but shift toward  $b = 0.72^\circ \pm 0.07^\circ$  and  $l = -1.69^\circ \pm 0.12^\circ$  Macias+19
- ☀ DM preferred over boxy-bulge di Mauro 21
- 🟢 DM not detected above boxy bulge template Abazajian+20, di Mauro 21
- 🟢 DM detected above nuclear bulge & centred on  $\sim \text{Sgr A}^*$  di Mauro 21



# which spectrum ?

- extended excess
- peak at a few GeV
- potential high-energy tail (further out) Horiuchi+16
- nuclear bulge
- harder power-law like spectrum
- close to HESS data

## GC excess, all cases

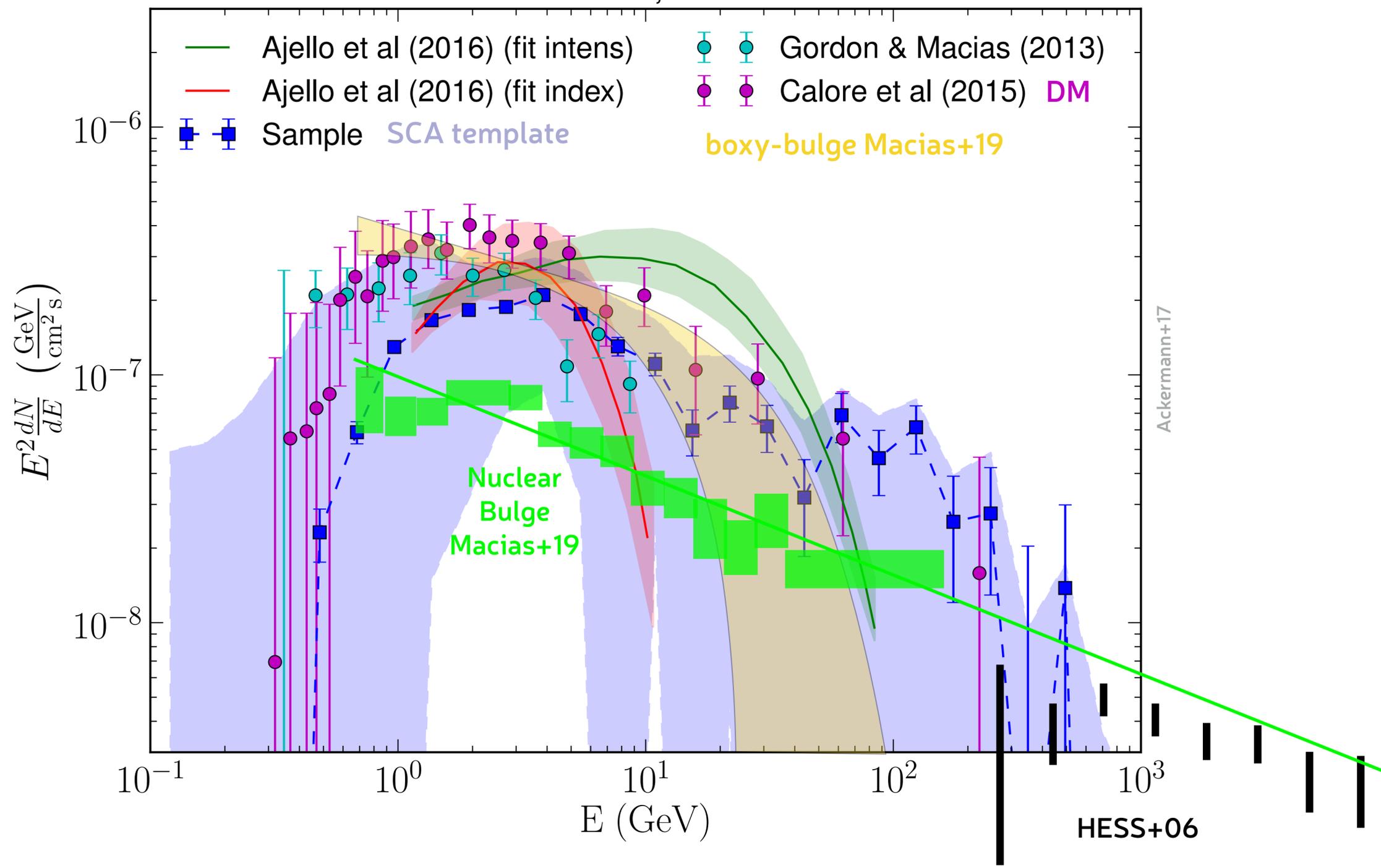


Ackermann+17

# which spectrum ?

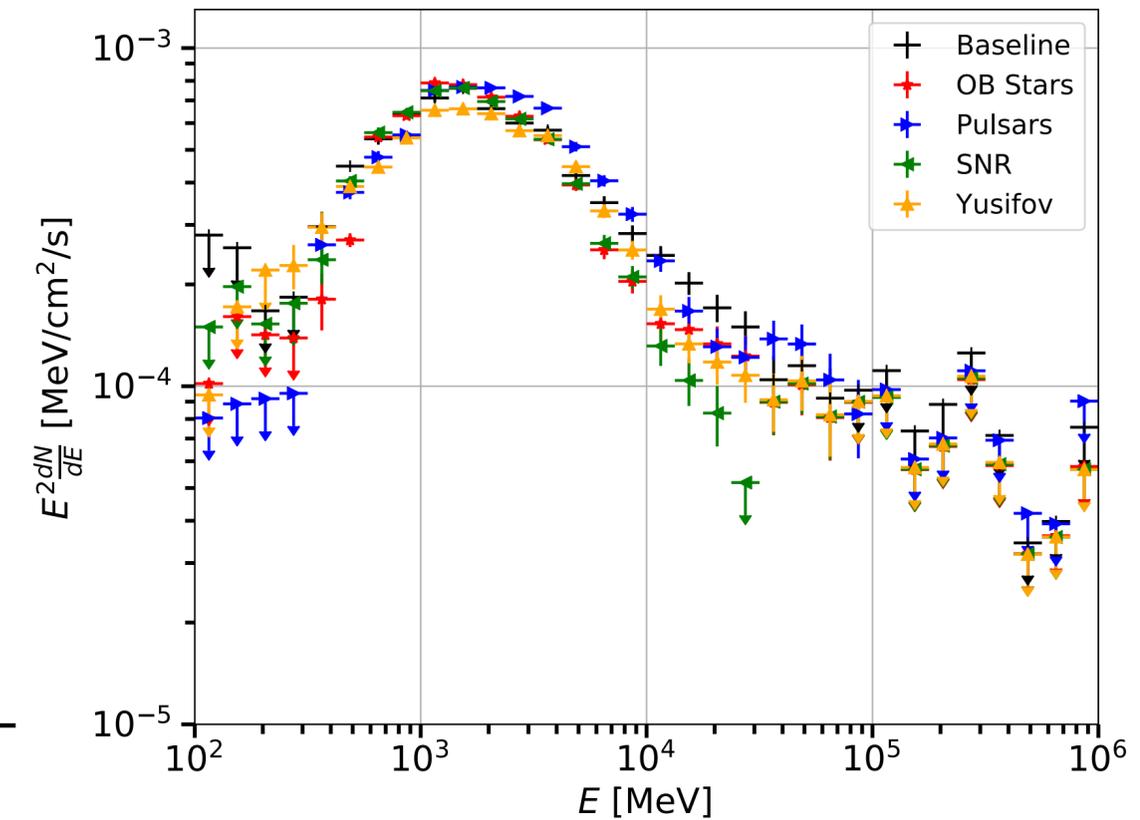
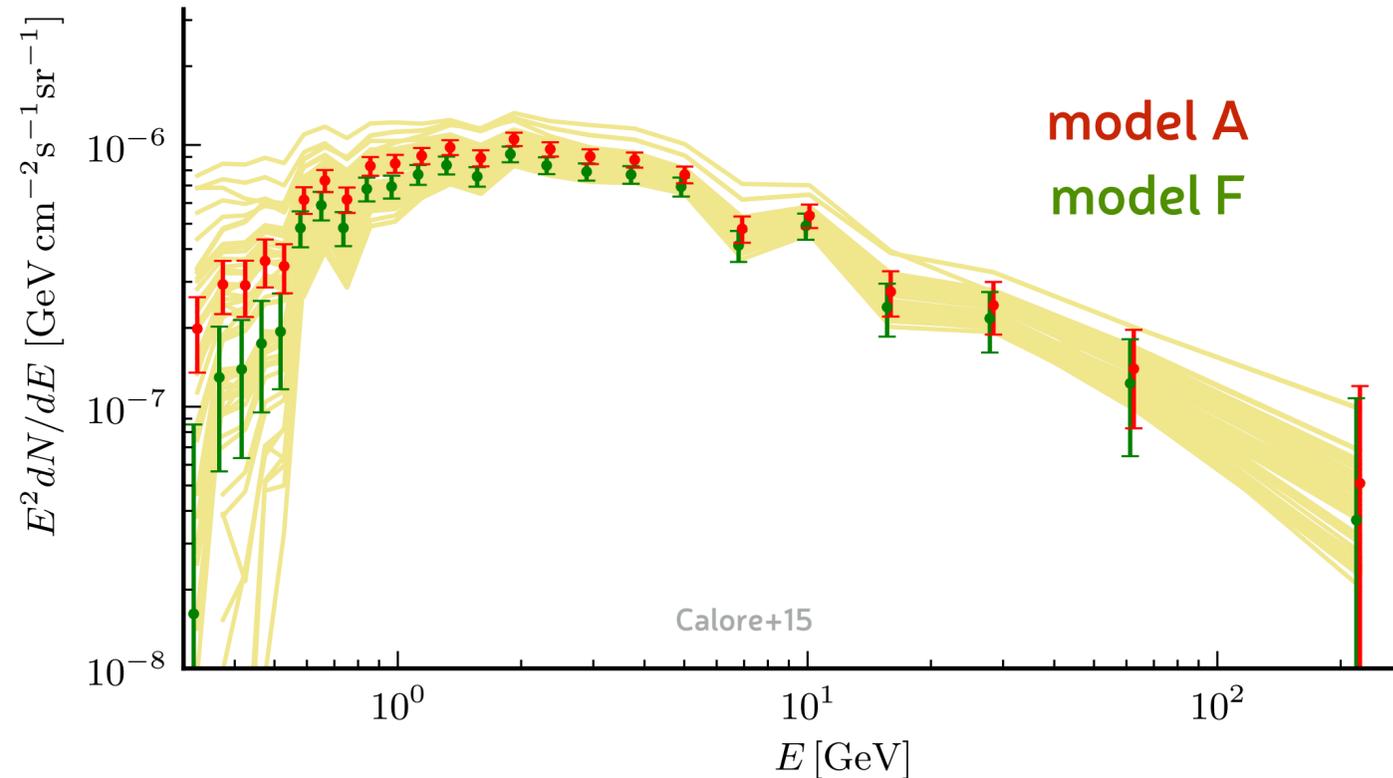
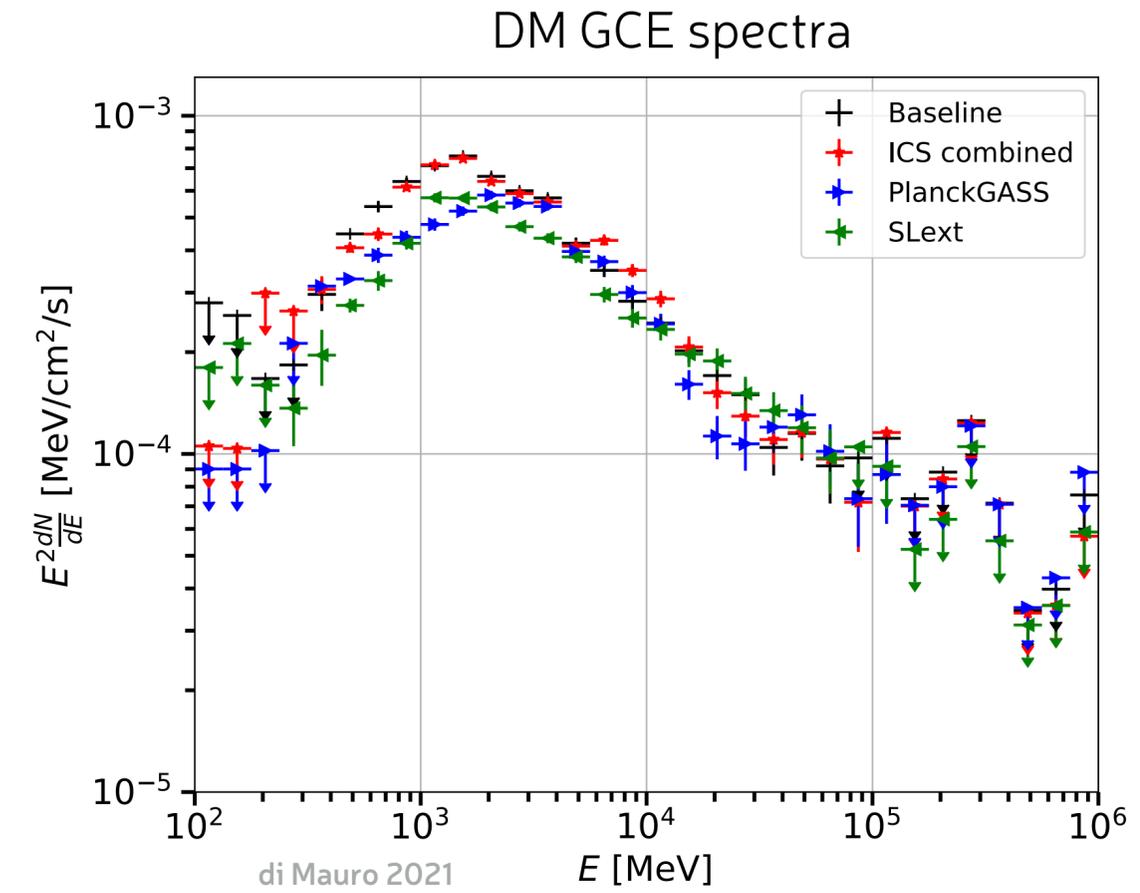
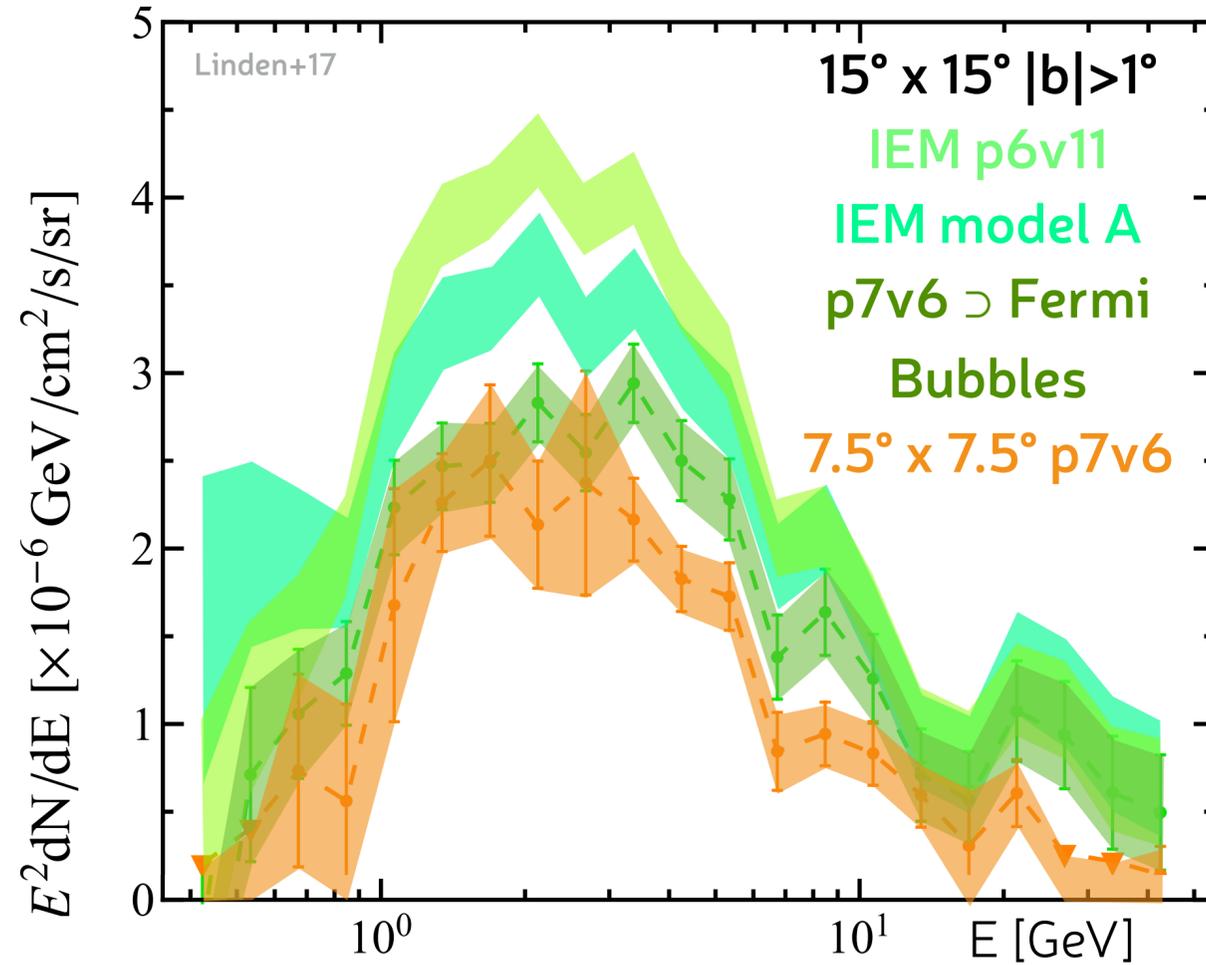
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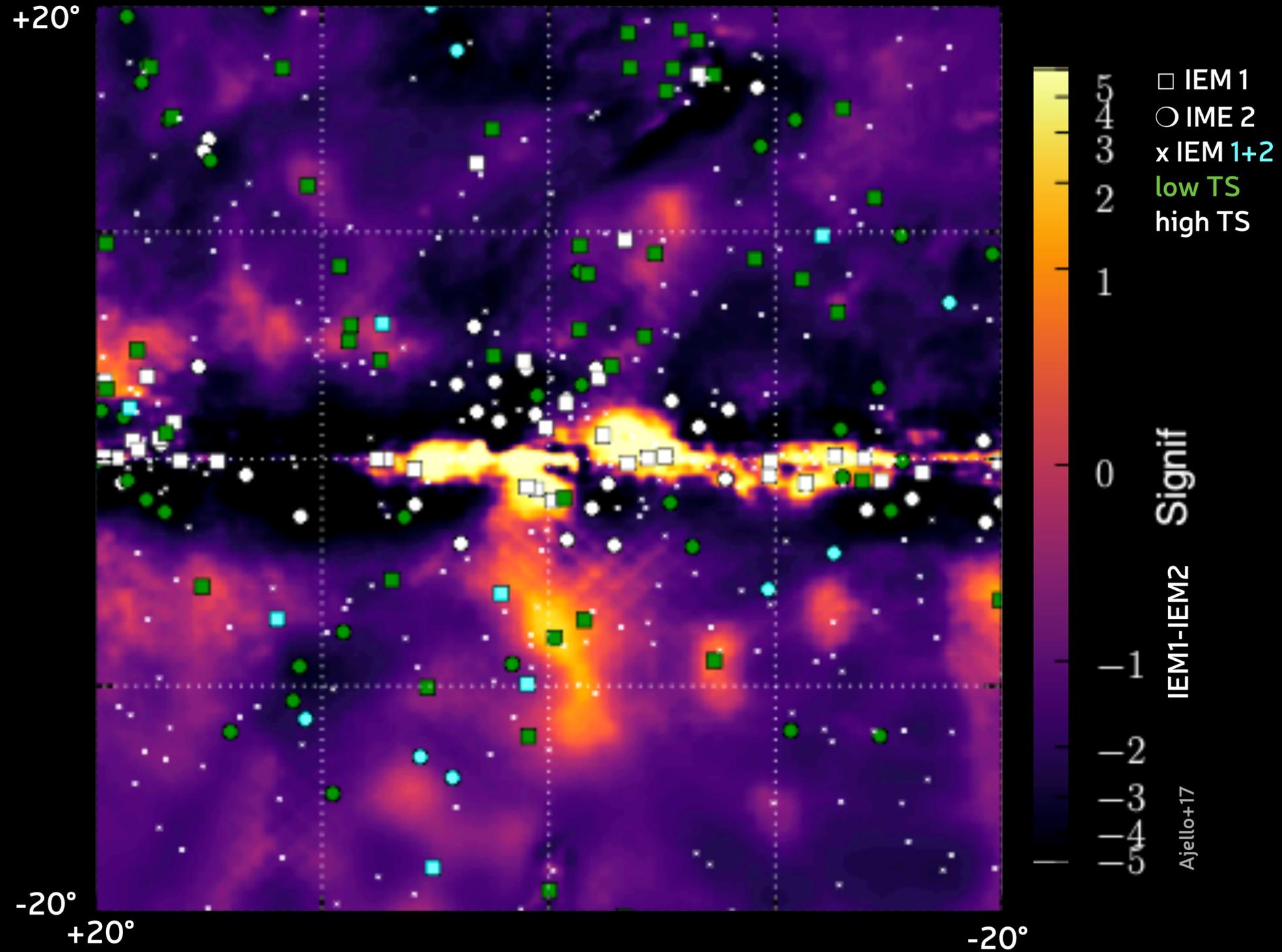


# spectral robustness to diffuse modelling uncertainties ?

- 20% variations due to the choice of Rol
- 60% variations for **not so different IEMs**
  - different CR distributions,
  - but comparable gas structures



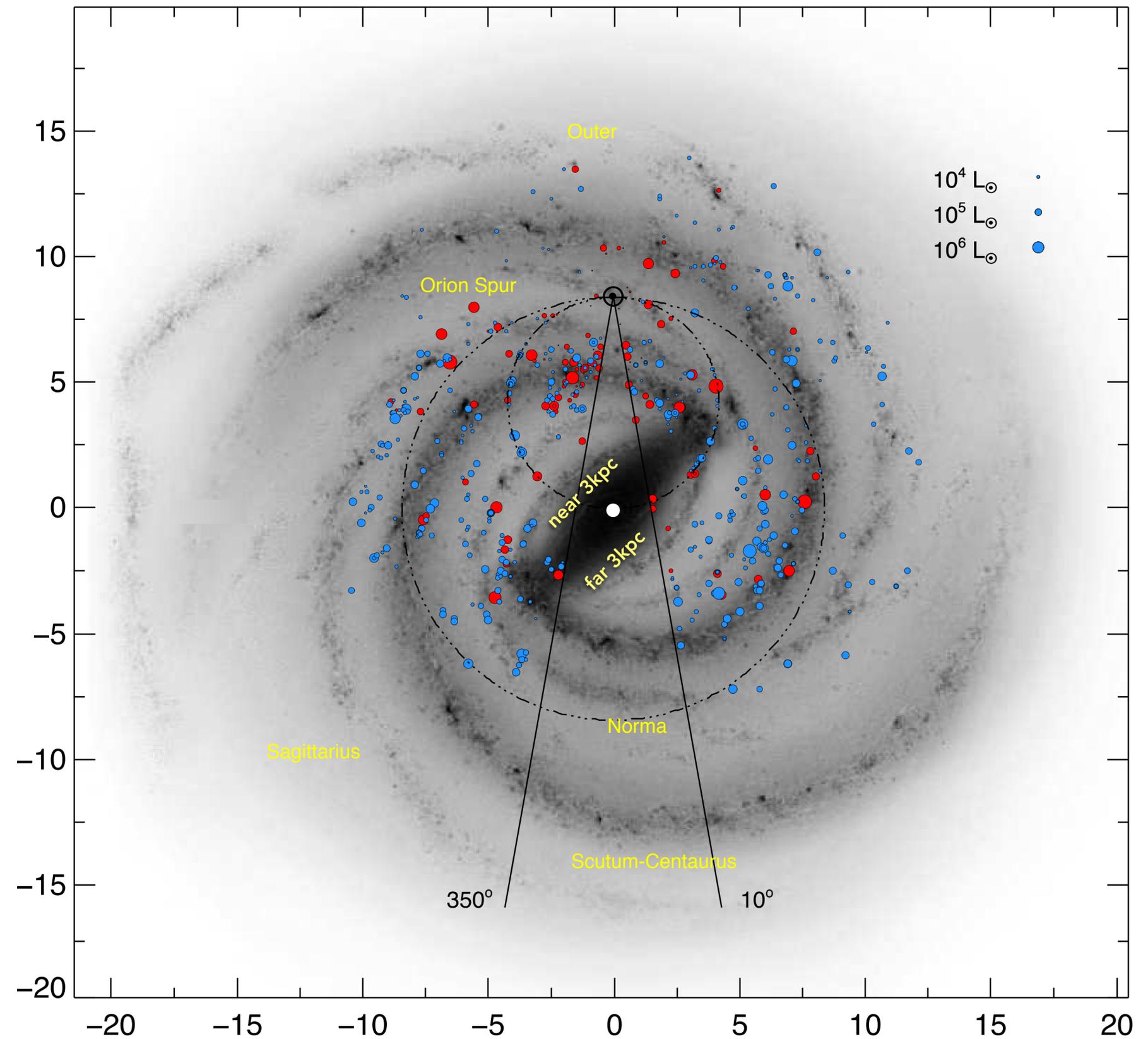
# spatial robustness to diffuse modelling uncertainties ?



● marked changes among bright point sources

# looking through the forest

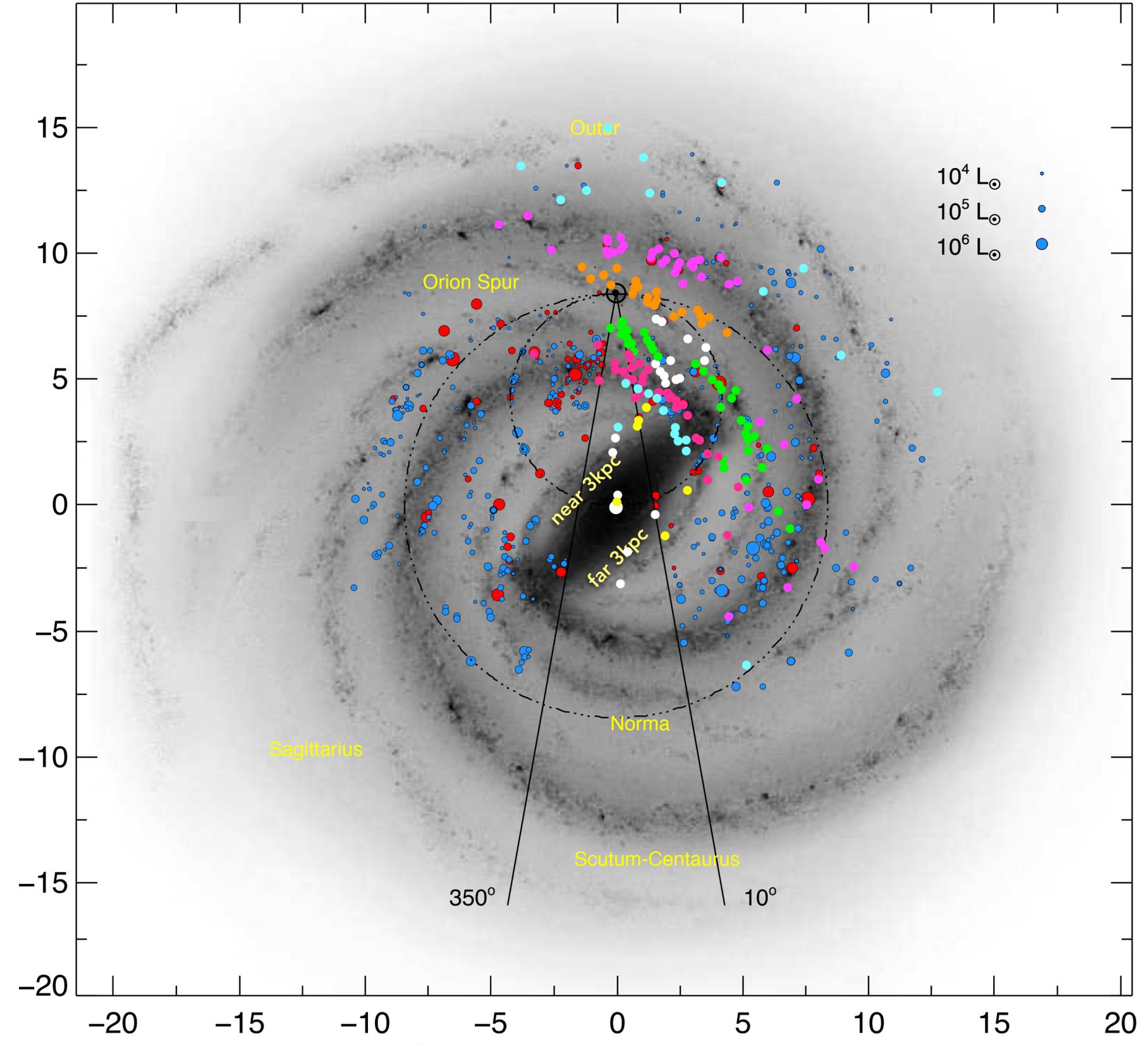
- ☉  $\gtrsim 90\%$  foreground ISM emission for  $|b| > 1^\circ$  Calore+15
- ☉ velocity confusion at  $|l| \lesssim 10^\circ$  and  $R > 3$  kpc
- weighted share of the total NH
  - ◆ creates a boxy change
  - ◆ artificially smooth & mixed angular scales
- cf similar excesses toward tangent arm directions,
- ☉ non-circular motions
- gas at wrong radii
- especially at  $R$  near 3 kpc in the bar potential
- ☉ dust tracing of CO-dark  $H_2$  not valid beyond the local ISM
- CR and dust/gas gradients not commensurate
- ☉ lower angular & velocity resolution for the HI data



approximated from Reid+19, Urquhart+14, BeSSeL survey

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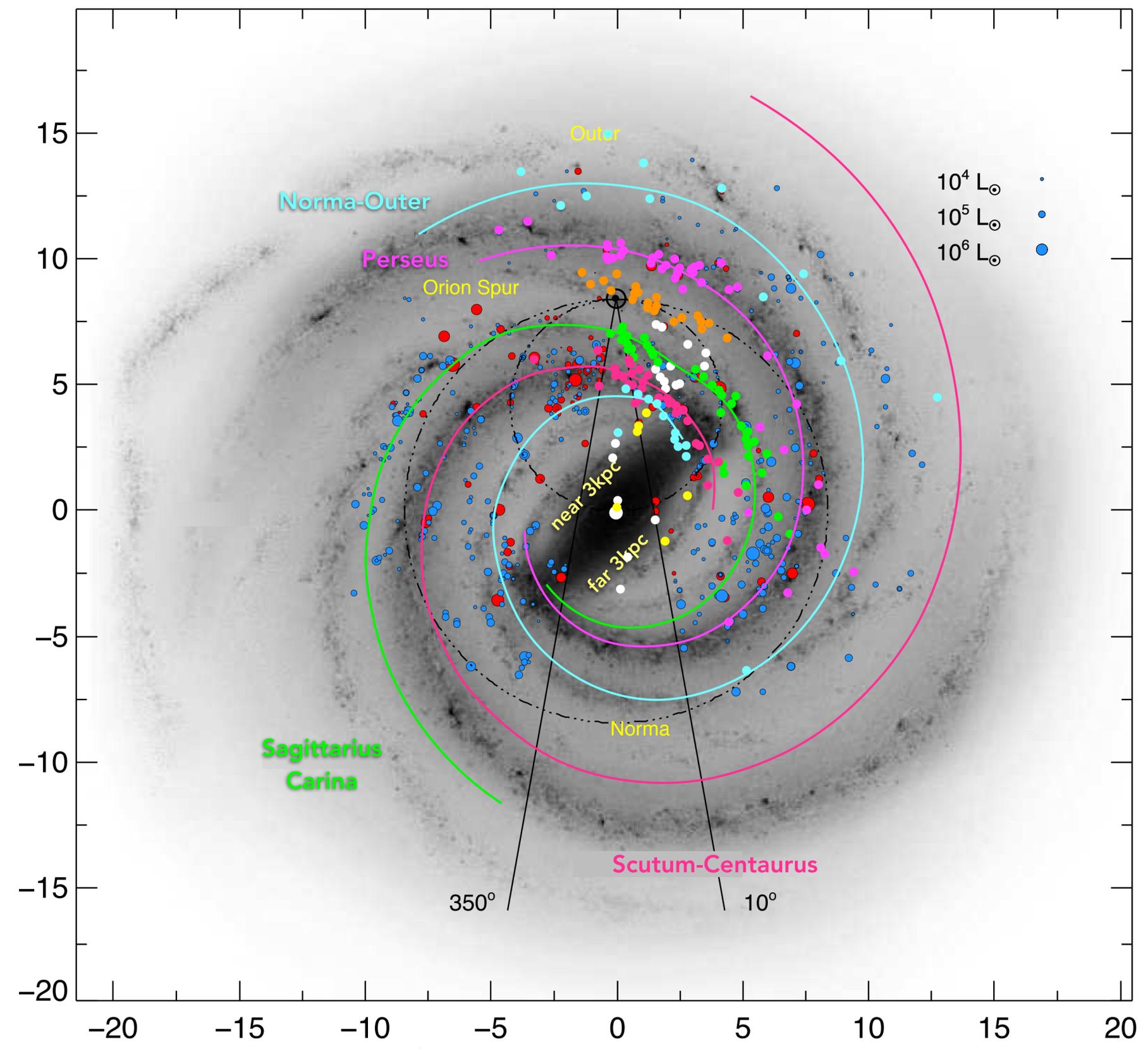
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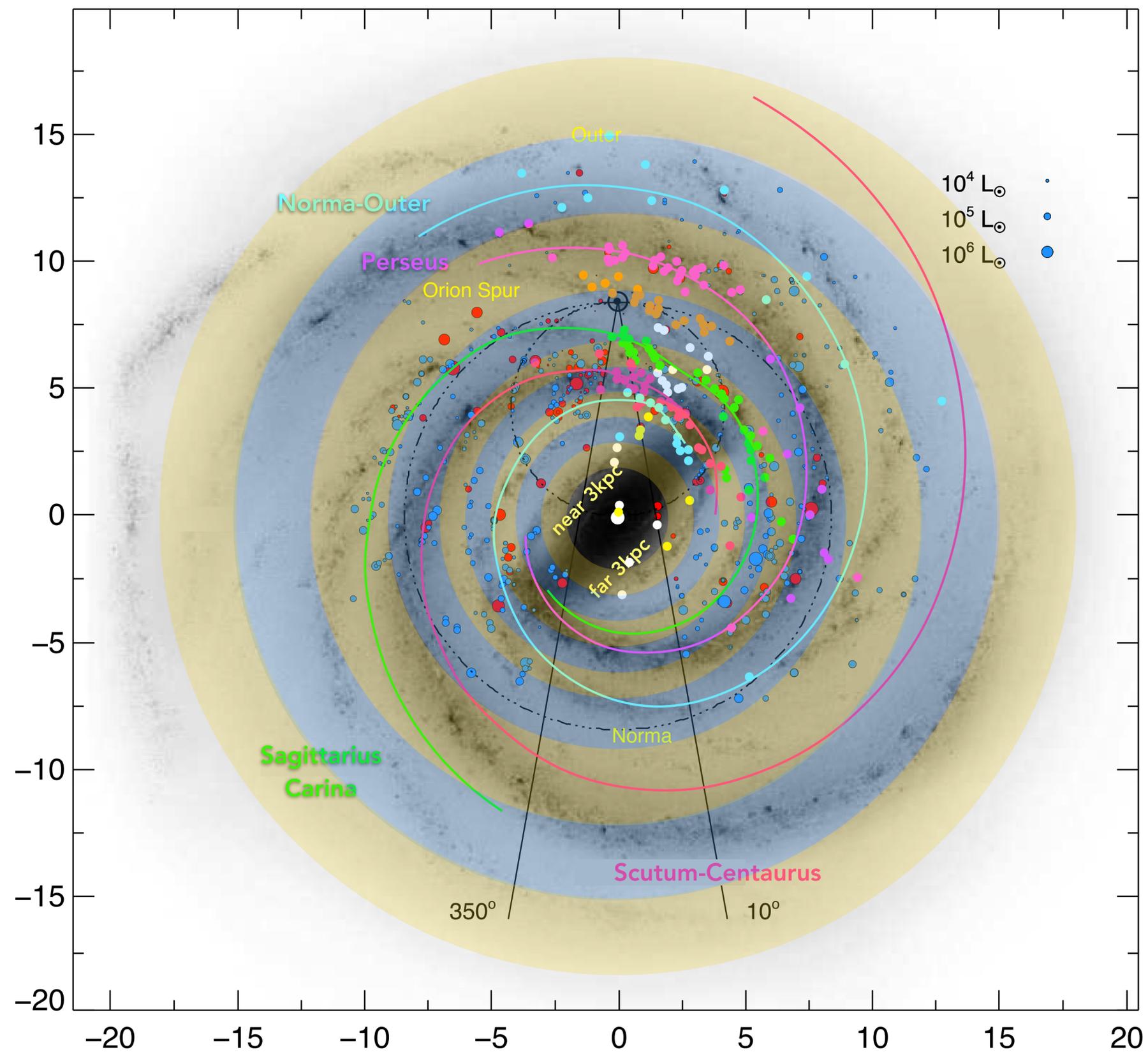
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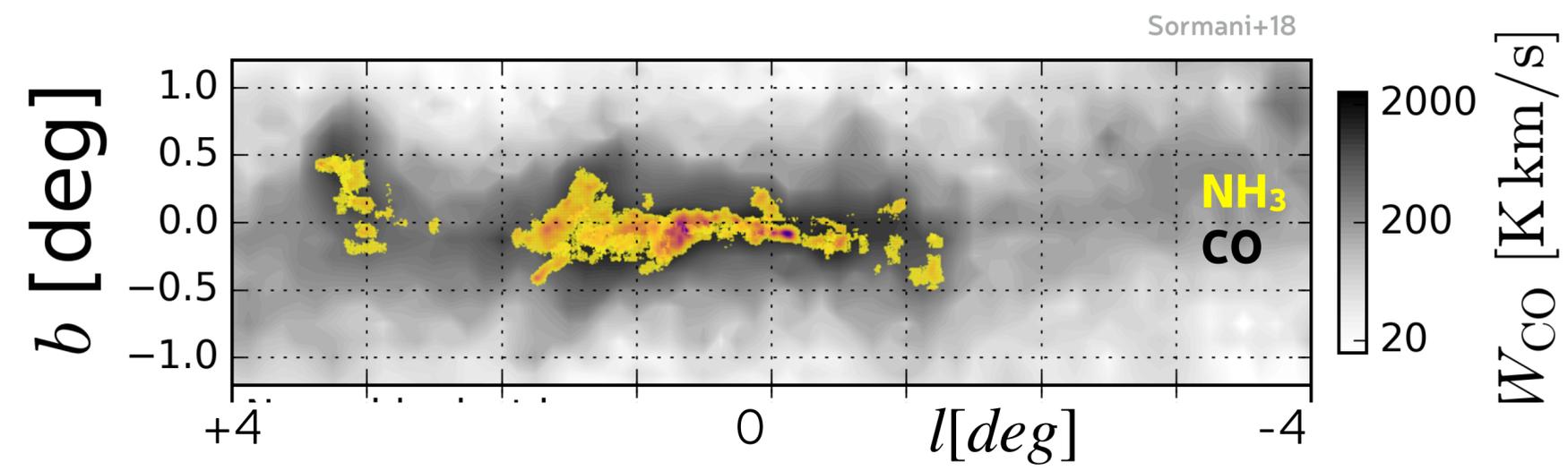
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approximated from Reid+19, Urquhart+14, BeSSeL survey

# missing warm H<sub>2</sub> & cold HI

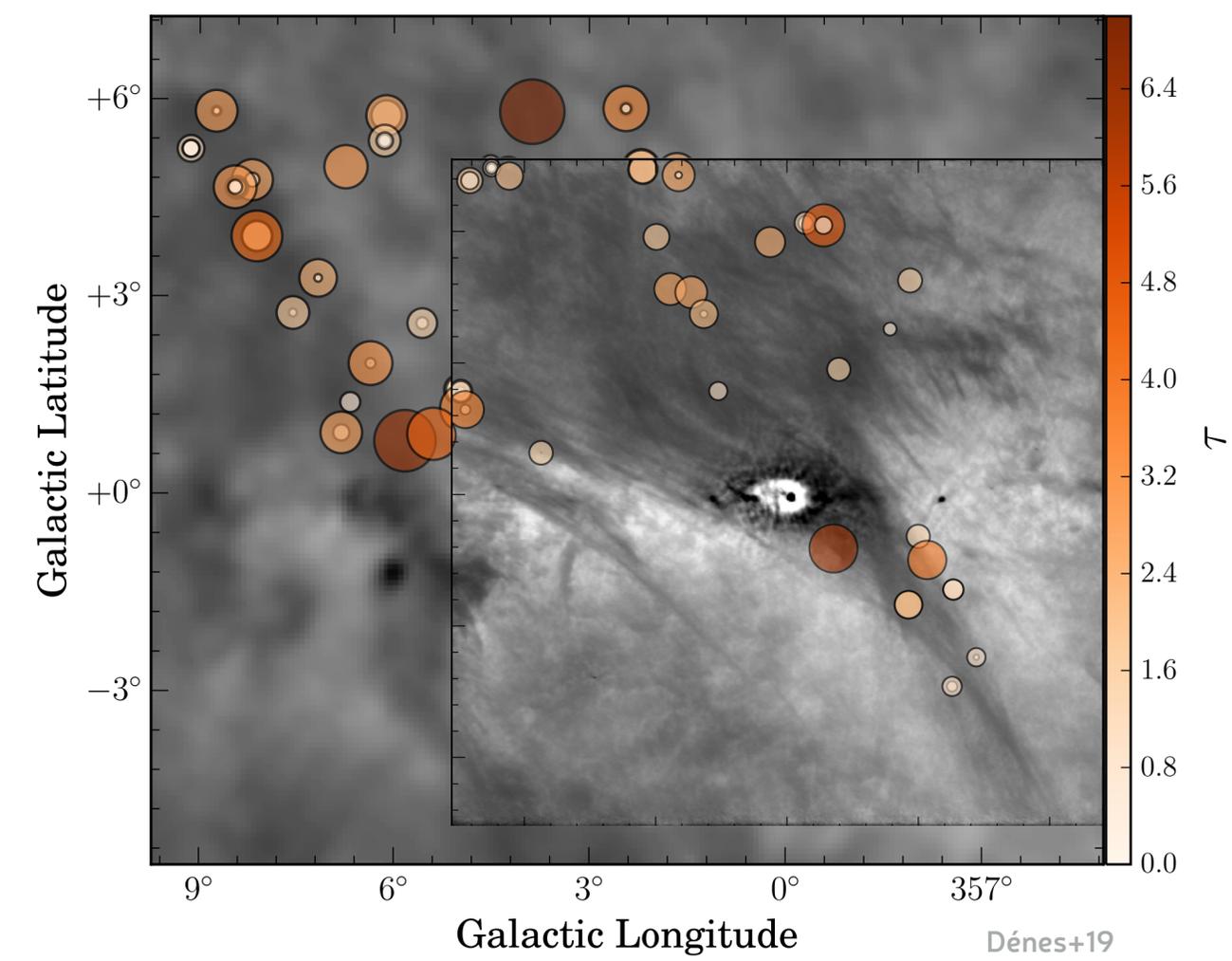
- warm H<sub>2</sub> in the CMZ
  - M ≈ (0.3-1) 10<sup>8</sup> M<sub>⊙</sub>
  - high CR ionisation & H<sub>2</sub> formation rates
  - warm diffuse H<sub>2</sub> with a large filling factor
    - ◆ n ≲ 100 cm<sup>-3</sup>, T = 212-505 K, large Δv
    - ◆ standard X<sub>CO</sub> does not apply
  - CO-dark-to-CO-bright H<sub>2</sub> fraction ???
  - cold HI fraction ?



- cold neutral HI
  - ex: Riegel-Crutcher cloud on the wall of the Local Bubble toward GC
    - ◆ cold (40 ≲ T<sub>S</sub> ≲ 80 K),
    - ◆ dense ( n ≈ 100 n<sub>WNM</sub>),
    - ◆ optically thick
    - ◆ filamentary (beam dilution)

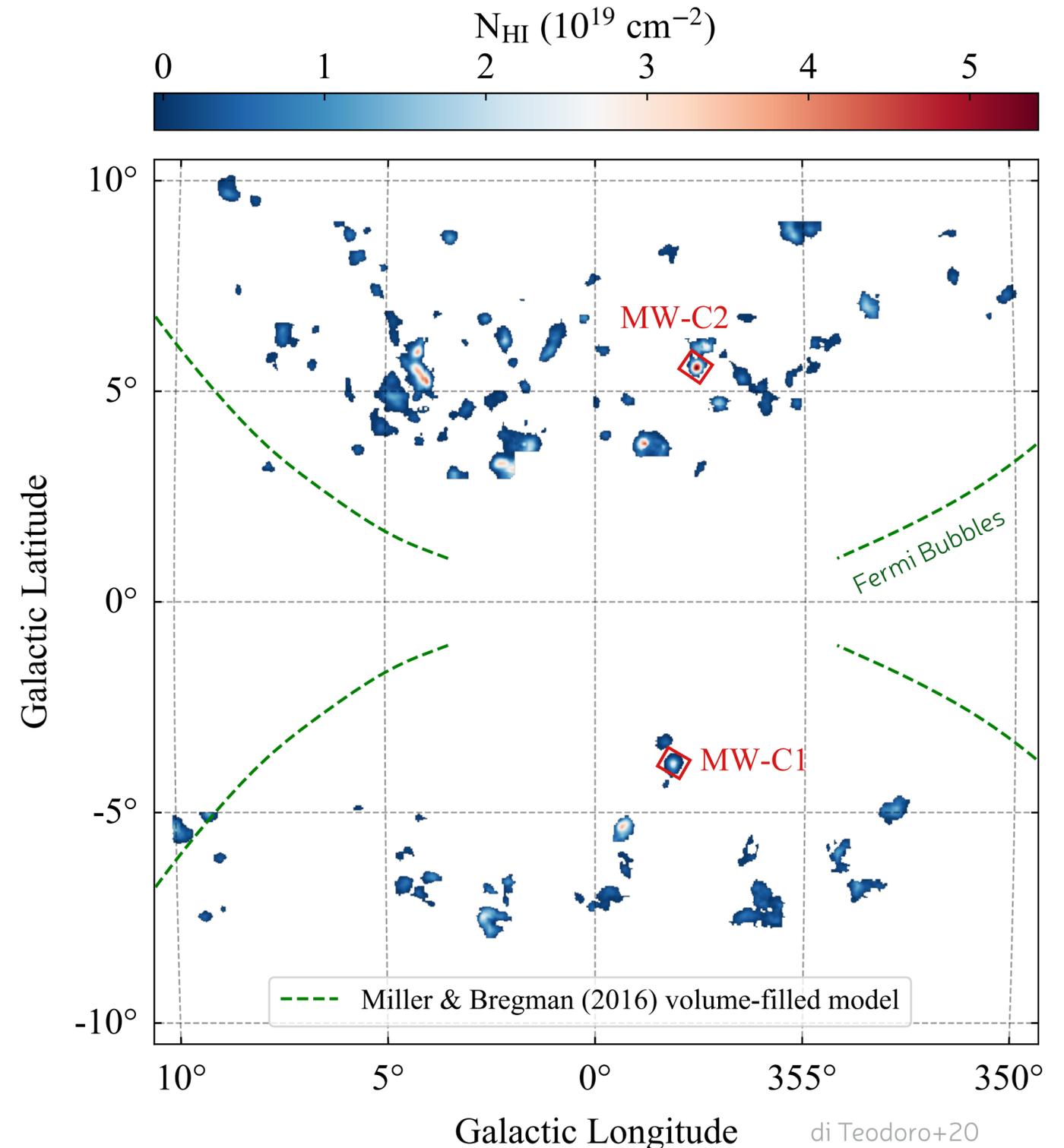
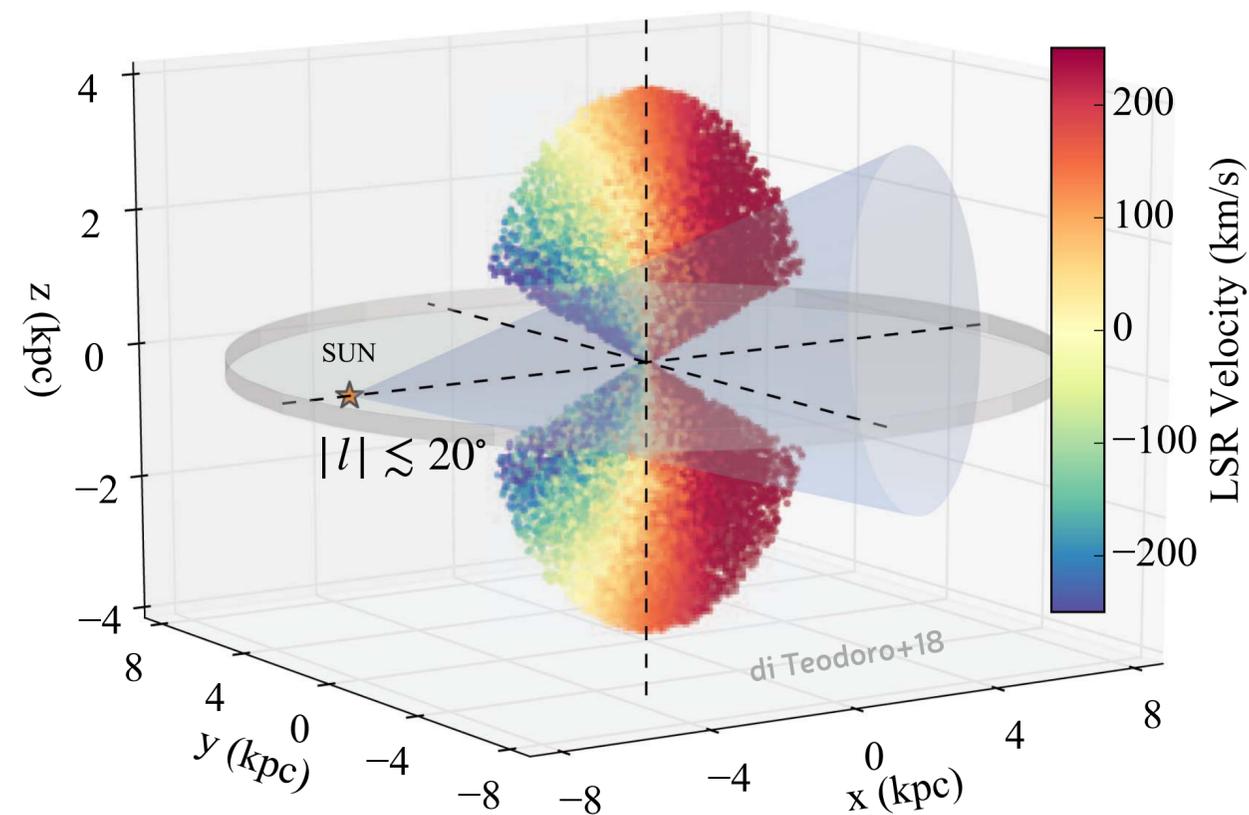
● same problems for R < 3 kpc (x<sub>1</sub> orbits)

$$T_B \approx T_S (1 - e^{-\tau})$$



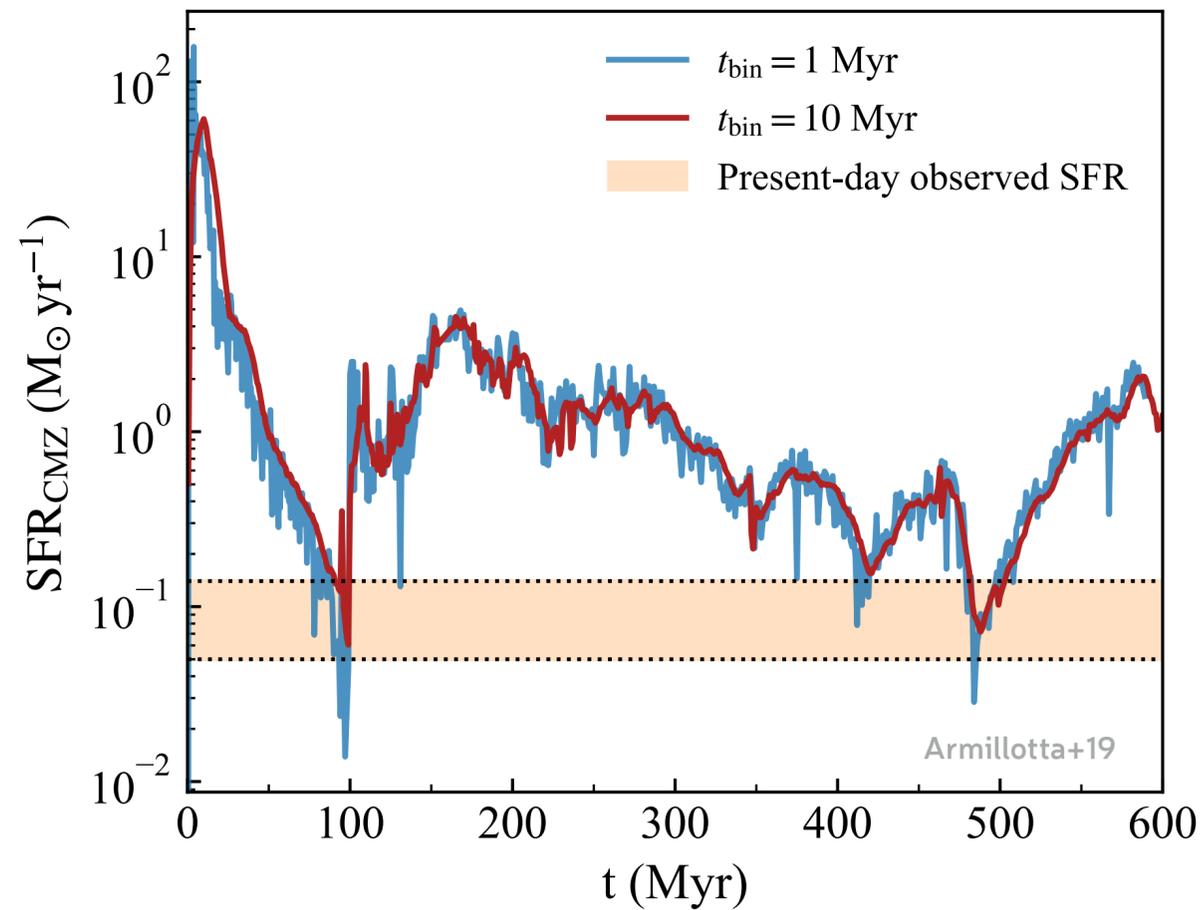
# missing the Galactic wind

- ☀️ wind clouds with anomalous  $|v_{LSR}| \lesssim 350$  km/s up to  $|z| \sim 1.5$  kpc
- ☀️  $1-10^5 M_{\odot}$  clouds in HI and H<sub>2</sub> fractions  $> 0.32$  and  $0.64$  for two CO-detected clouds
- ☀️ chemistry, ionisation & dynamics  $\Rightarrow X_{CO} \approx 2-40 X_{CO\ local}$
- ☀️ total entrained mass
  - 🟢  $> 10^6 M_{\odot}$  in HI clumps di Teodoro+20
  - 🟢  $> 2 \cdot 10^6 M_{\odot}$  in warm  $10^4$  K entrained gas seen in UV absorption Bordoloi+17
  - 🟢  $(4.6-5) \cdot 10^6 M_{\odot}$  and  $(5.2-9.8) \cdot 10^6 M_{\odot}$  of hot  $> 2$  MK gas in the wind interior and shell (constrained by OVII and OVIII lines) Miller & Bregman 2016
  - 🔹 or 10 times more in the eROSITA Bubbles Predehl+20
  - 🟢 H<sub>2</sub> ?

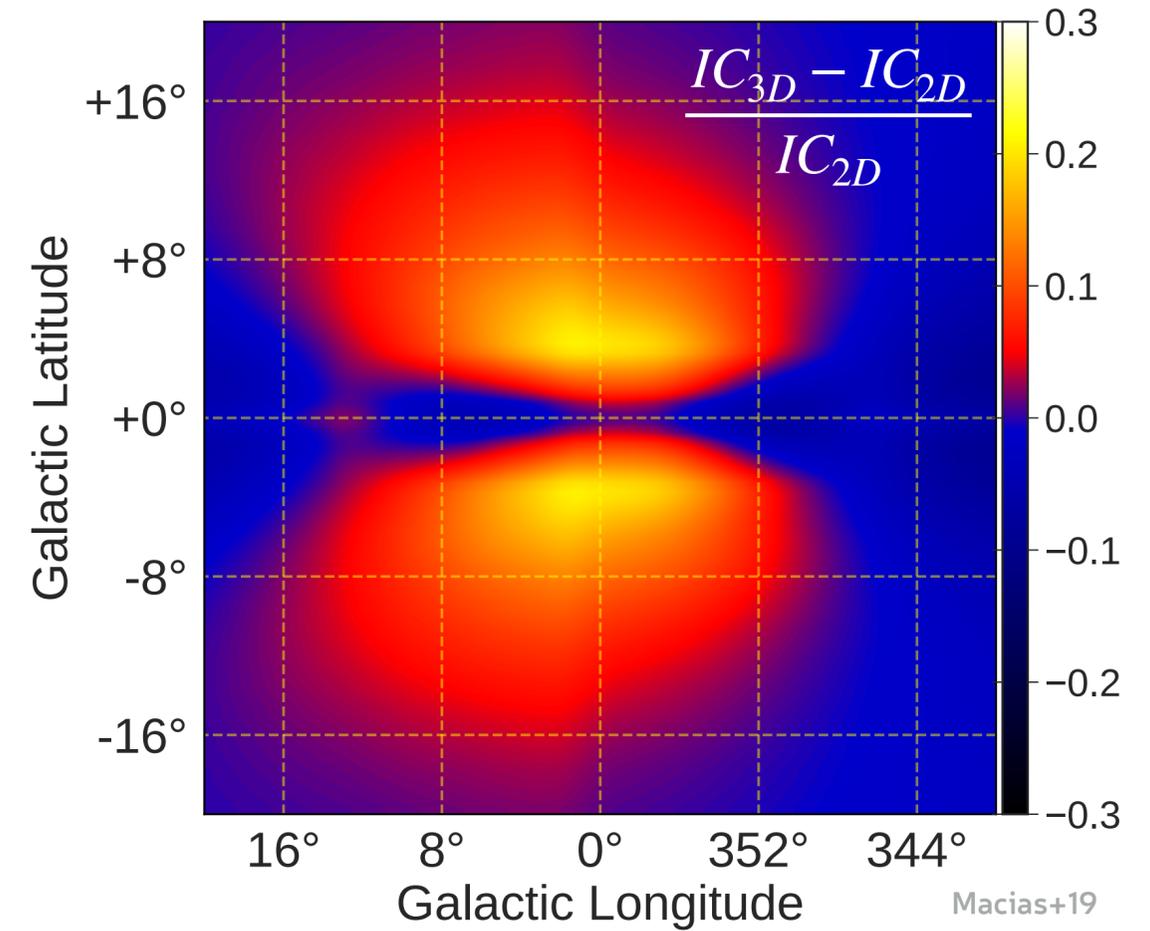


# cosmic-ray uncertainties

- 3D distribution of ISRF and B for IC emission
- GALPROP 3D include the bulge/bar for the CR source and ISRF densities
- clumpier lepton distributions (severe radiation losses)
- => brem map  $\neq$   $\pi^0$  map (closer to NH map) because of e- radiation losses
- sporadic star-formation bursts in the CMZ



- (re)acceleration by bar shocks and chimney shocks
- propagation properties at  $R < 3$  kpc ???



10 GeV

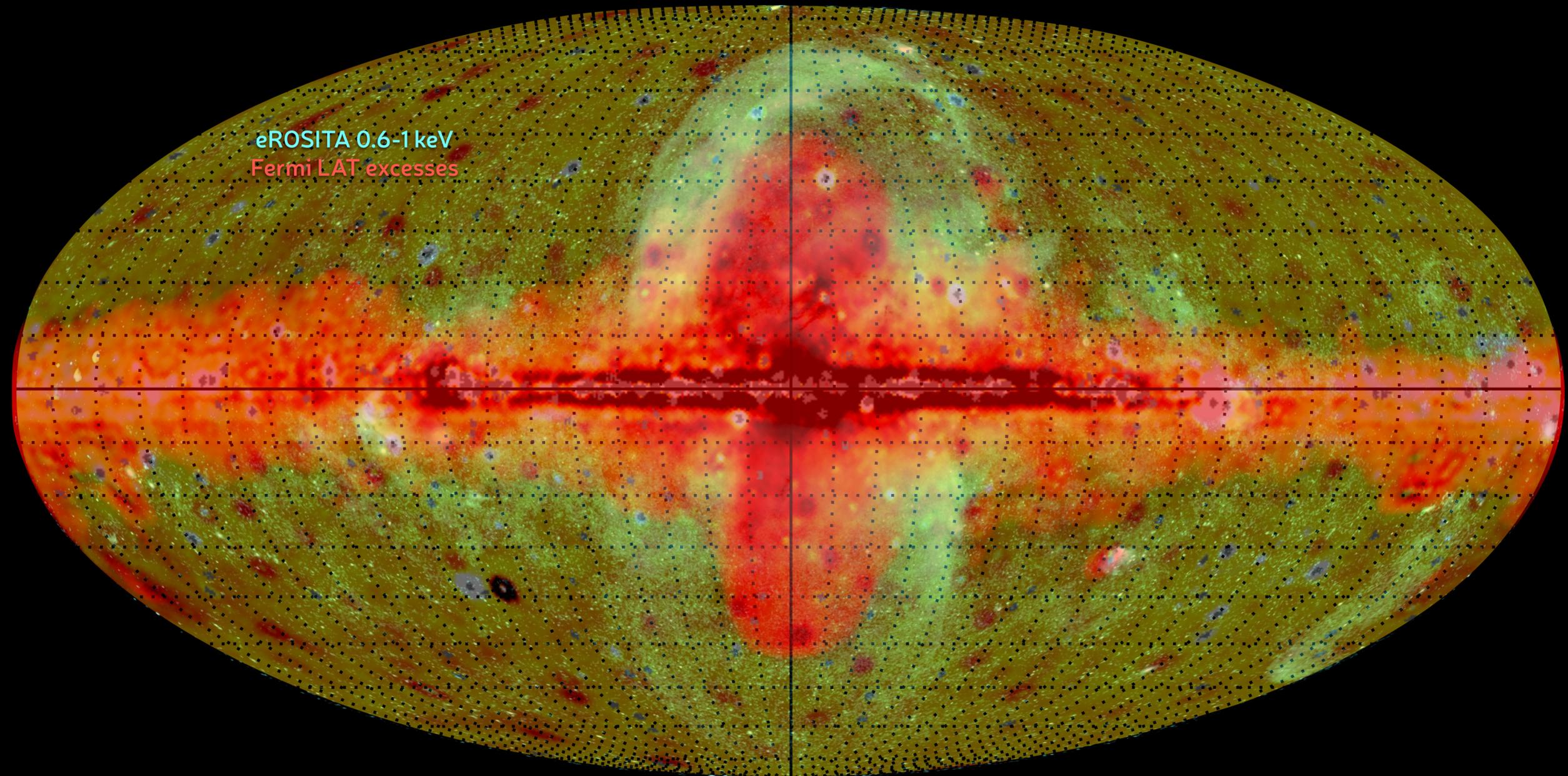
$$\frac{IC_{oldB} - IC_{newB}}{IC_{oldB}}$$



> 30% difference

Orlando 2019

# Milky Way $\gamma$ -ray excesses



why aren't the inner  $20^\circ$  much brighter ?