'First CTA Science Symposium', Bologna, 2019

Gamma-ray emission from star-forming systems with a focus on the Galactic Centre

Roland Crocker

Australian National University

CTA Australia Consortium

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Gamma-ray emission from the Galactic Centre and Fermi Bubbles

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ESO


~5-10% of Galaxy's current star formation
ESO


Fermi Collab./NASA


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Fermi Collab./NASA


Fermi Collab./NASA


Why isn't the Galactic Centre brighter in gamma-rays?
Fermi Collab./NASA


Fermi Collab./NASA


Credit: NASA/DOE/Fermi LAT/D. Finkbeiner et a

Su, Slatyer and Finkbeiner 2010 (ApJ)

Galactic Centre: HE and Non-Thermal Phenomenology

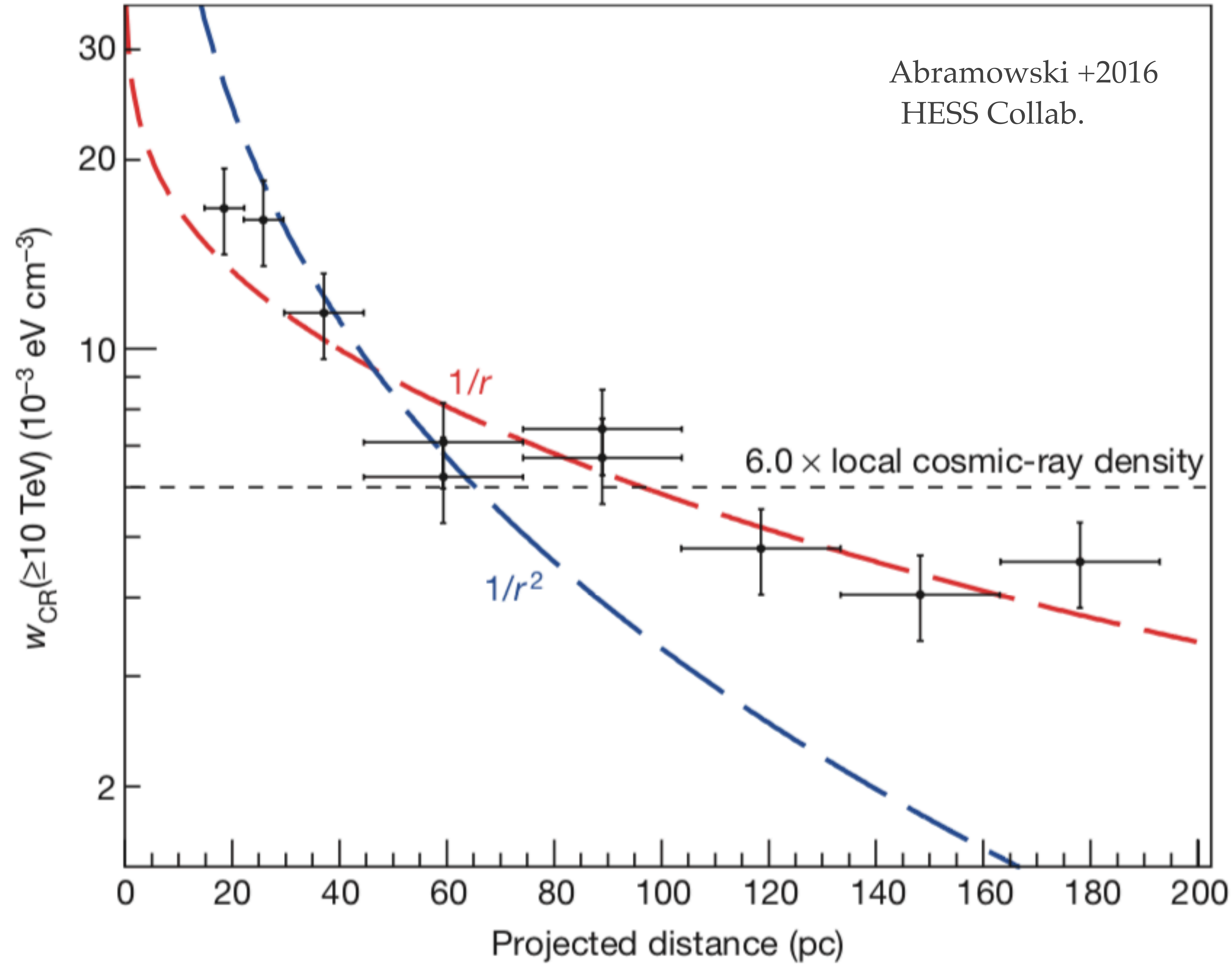

G0.9+0.1 HESS J1745-290
Abdalla+2018 HESS Collab.
1
0.5
0
-0.5
−1
2
1.5
1
0.5
0
359.5
359
358.5
28
24
20
16
12
8
4
0

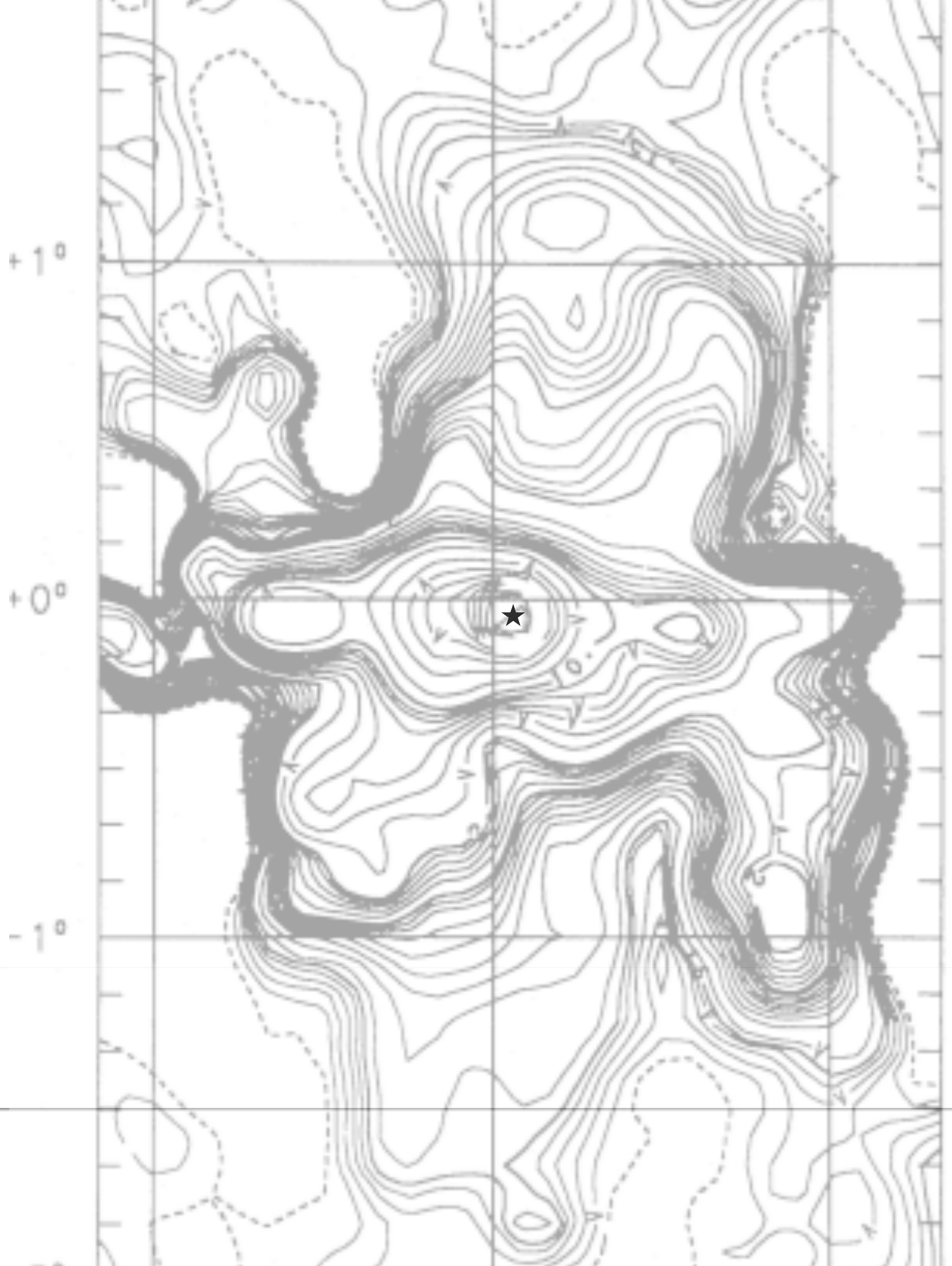
Energetics Central Source

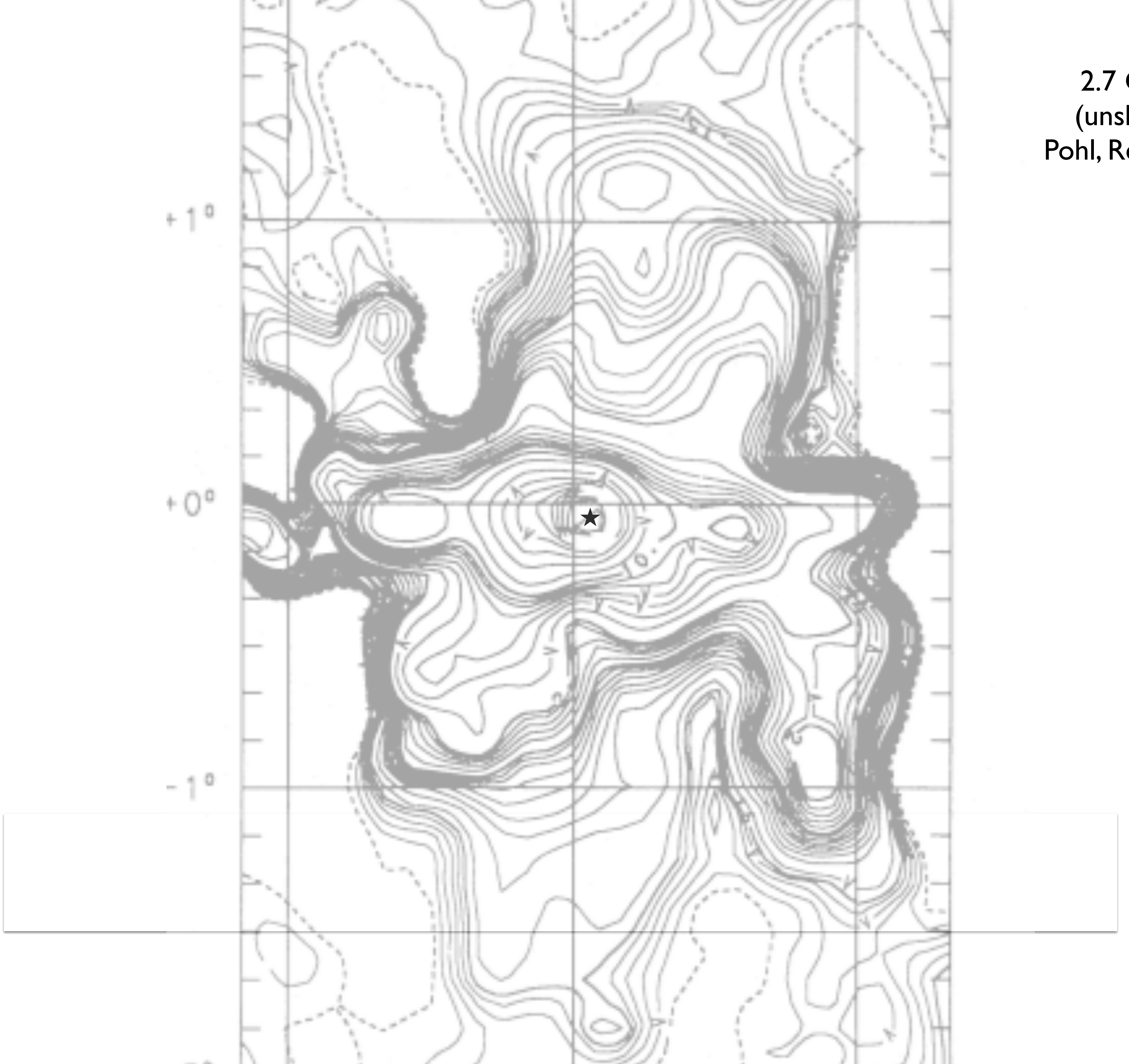
- The (photon) Eddington luminosity of Sgr A* ($4 \times 10^6\ M_{Sun}$): 5×10^{44} erg/s
- Socrates+ (2008) extended the momentum balance argument for L_{Edd} to derive an 'Eddington limit in cosmic rays': $L_{Edd,CR} \sim 10^{-6}\ L_{Edd} \Rightarrow 5 \times 10^{38}$ erg/s for Sgr A*
- $L_{CR,p}$ for Sgr A* HESS source 10^{38} - 10^{39} erg/s
- Nuclear Star Cluster: formed $\sim 3 \times 10^4\ M_\odot$ over last ~4 Myr (Lu+2013) $\Rightarrow$ few x 10^{39} erg/s total mechanical power


G0.9+0.1 HESS J1745-290
1
0.5
0
−0.5
−1
2
1.5
1
0.5
0
359.5
359
358.5
Abdalla+2018 HESS Collab.

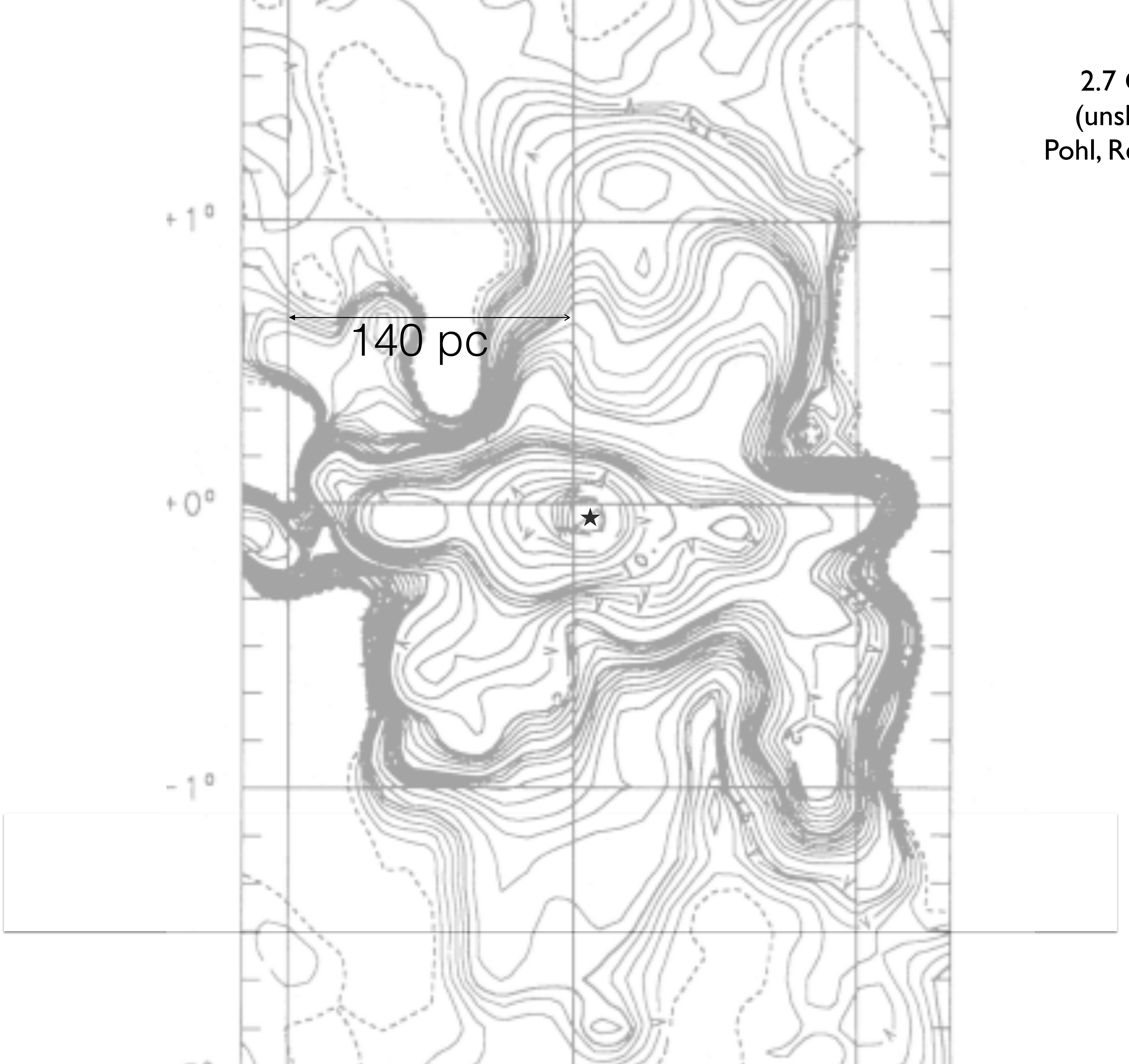

Sgr D
Sgr B
Sgr A
Sgr C
HESS J1745-303
HESS J1746-285
Abdalla+2018 HESS Collab.
1
0.5
0
−0.5
−1
2
1.5
1
0.5
0
359.5
359
358.5
0
4
8


Abramowski +2016
HESS Collab.
30
20
10
2
$w_{CR}(\geq 10\ \mathrm{TeV})\ (10^{-3}\ \mathrm{eV\ cm^{-3}})$
1/r
$1/r^2$
6.0 × local cosmic-ray density
0
20
40
60
80
100
120
140
160
180
200
Projected distance (pc)


+1°
+0°
-1°



2.7 GHz radio data
(unsharp mask, 9.4`)
Pohl, Reich & Schlickeiser
1992



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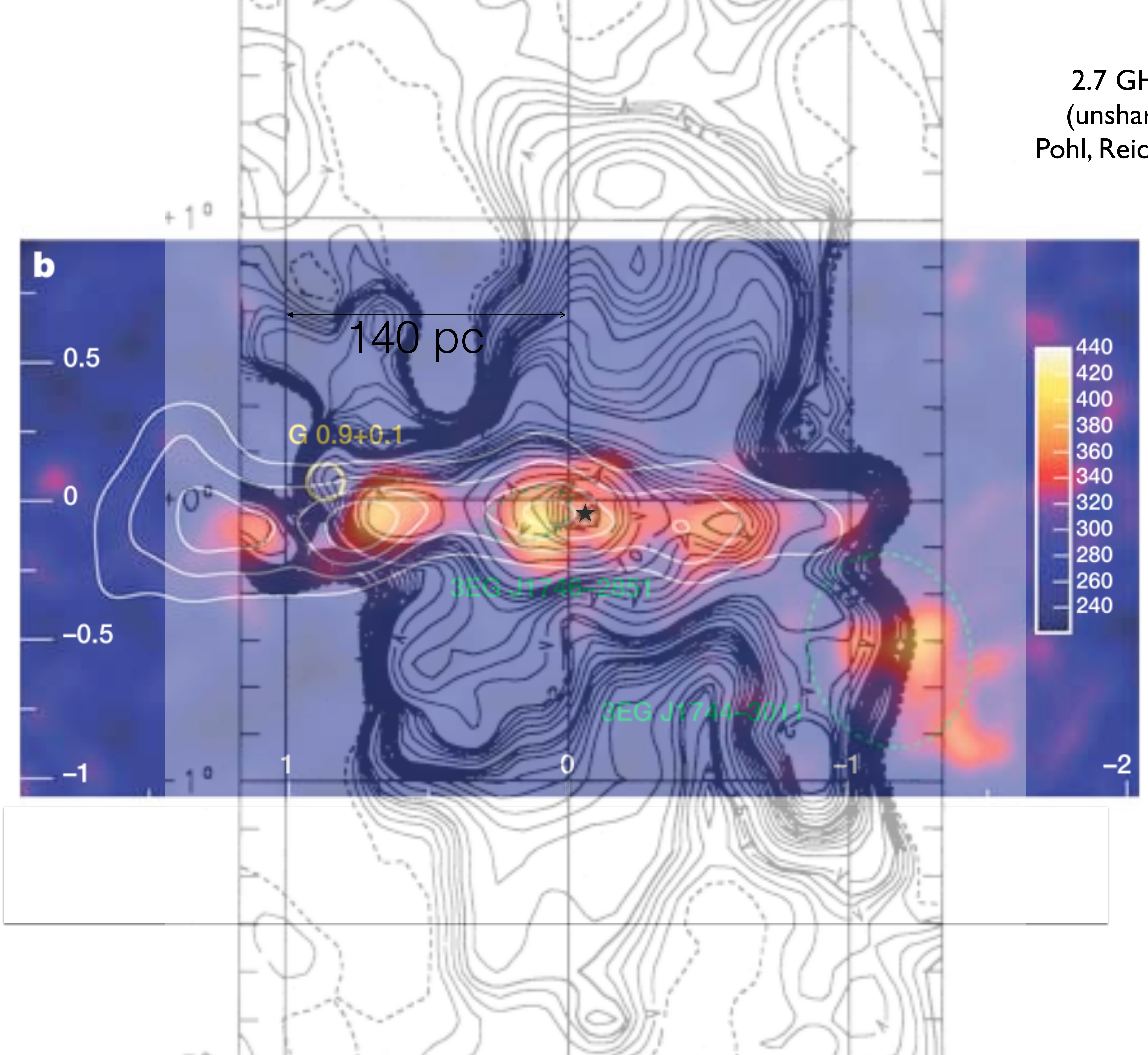

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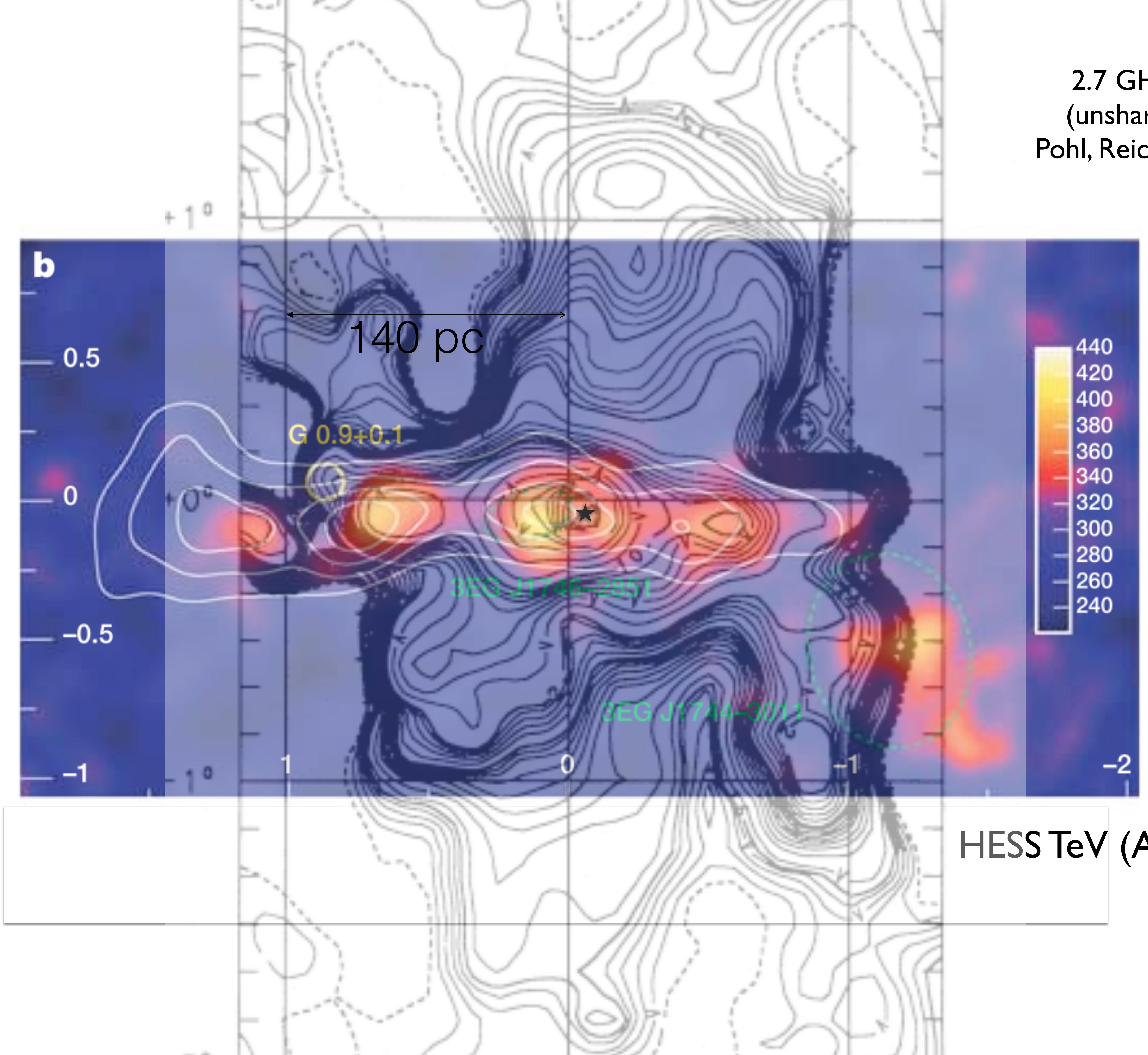

HESS TeV (Aharonian et al 2006)

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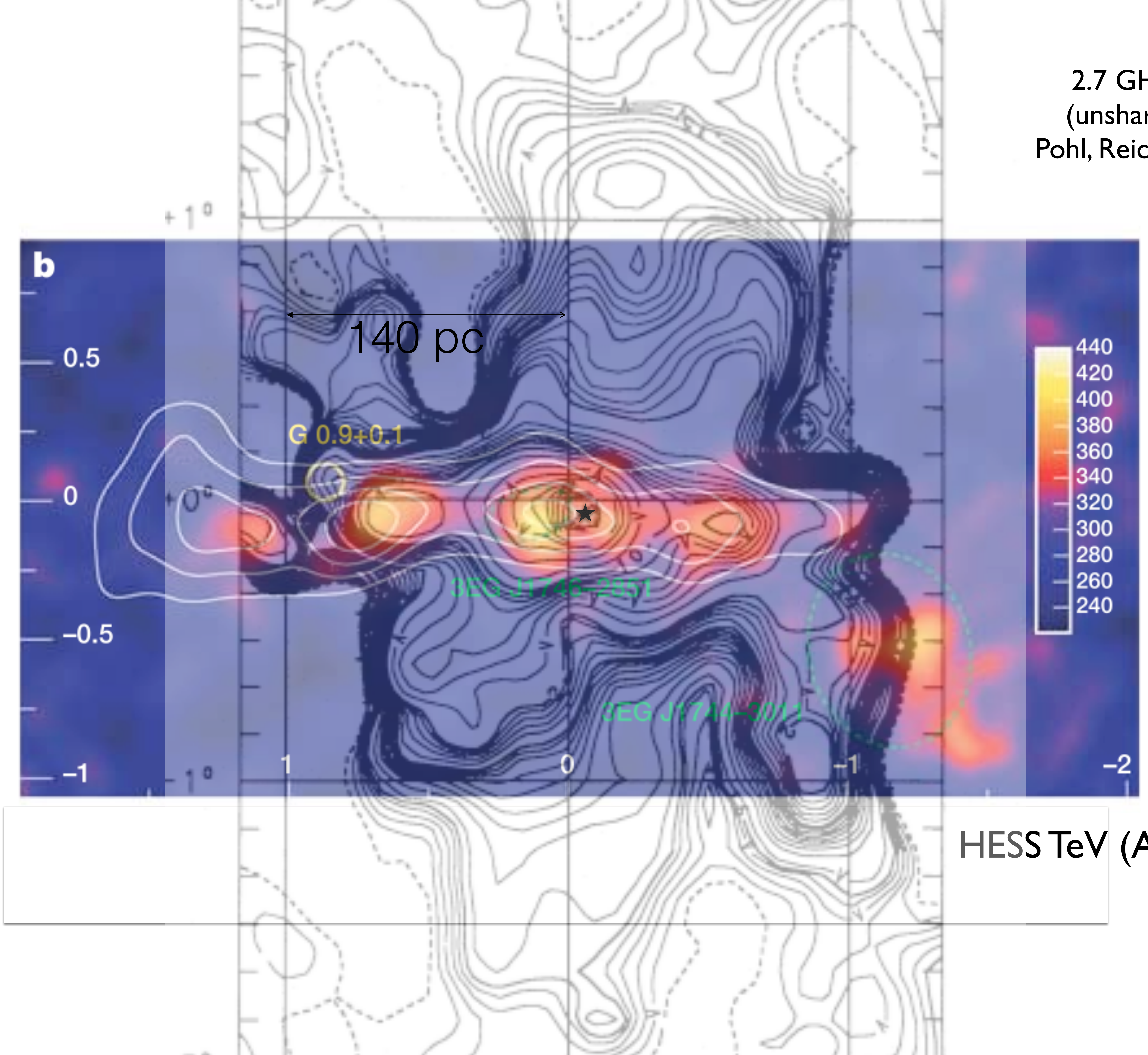

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MeerKAT

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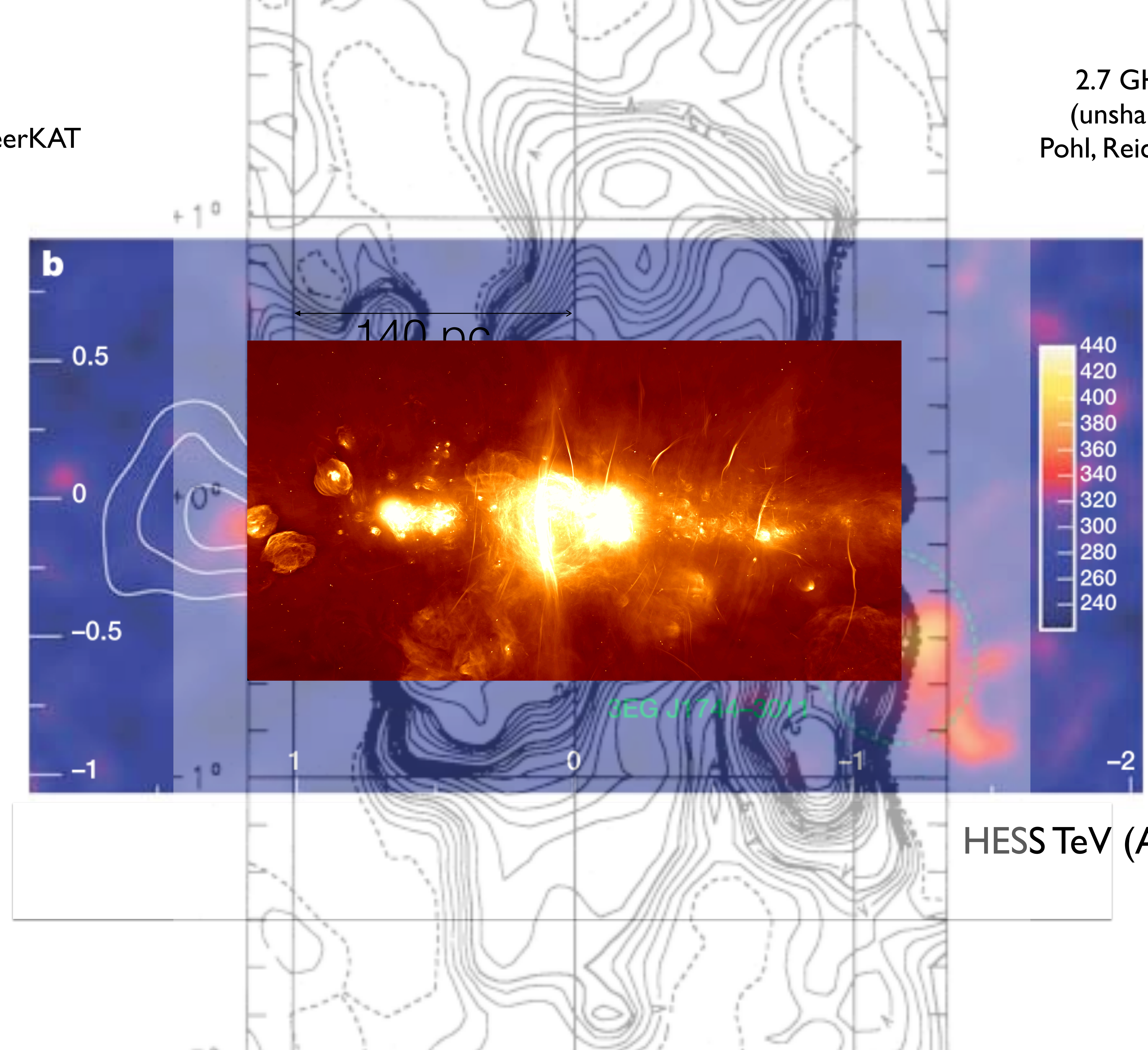

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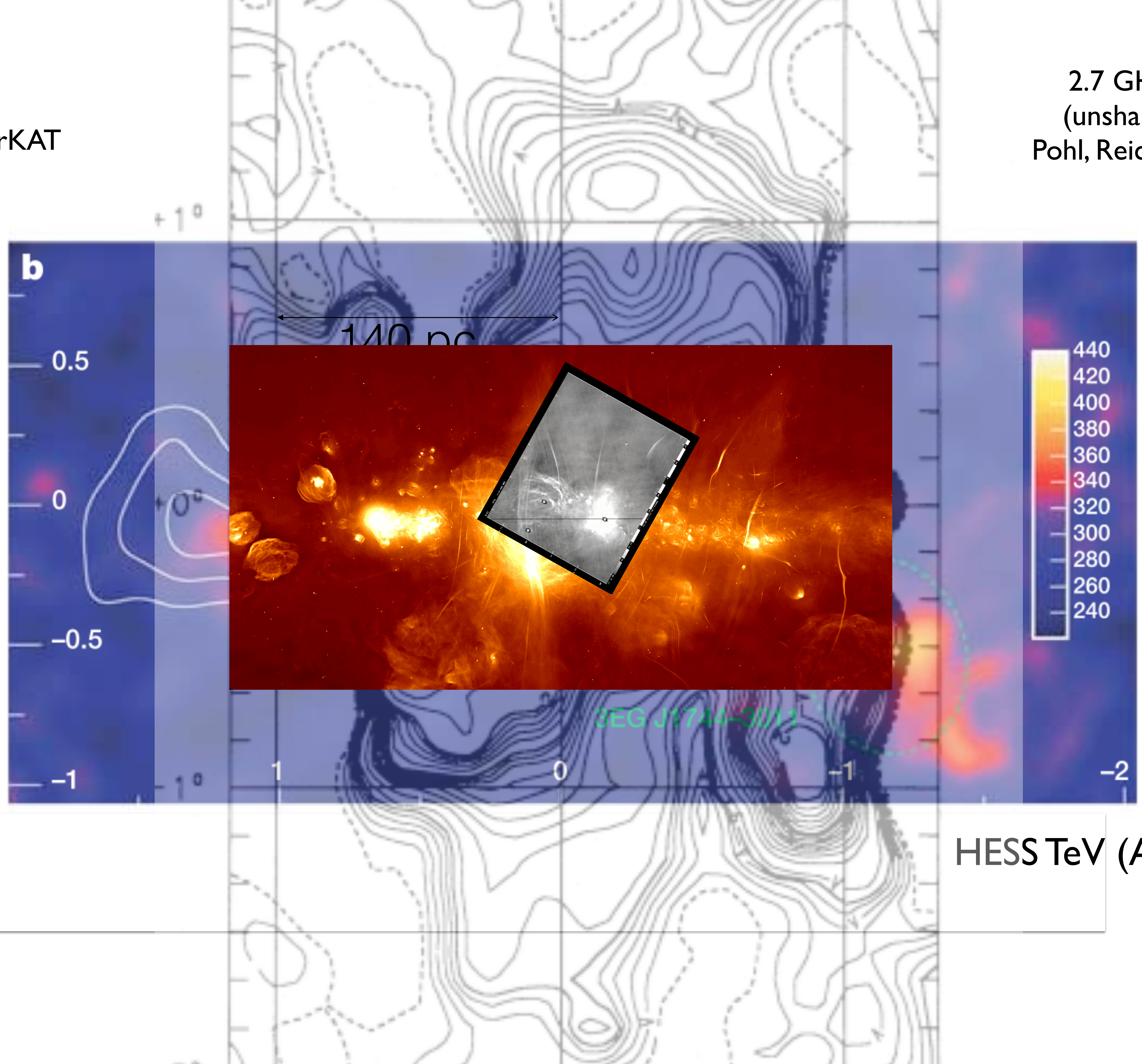

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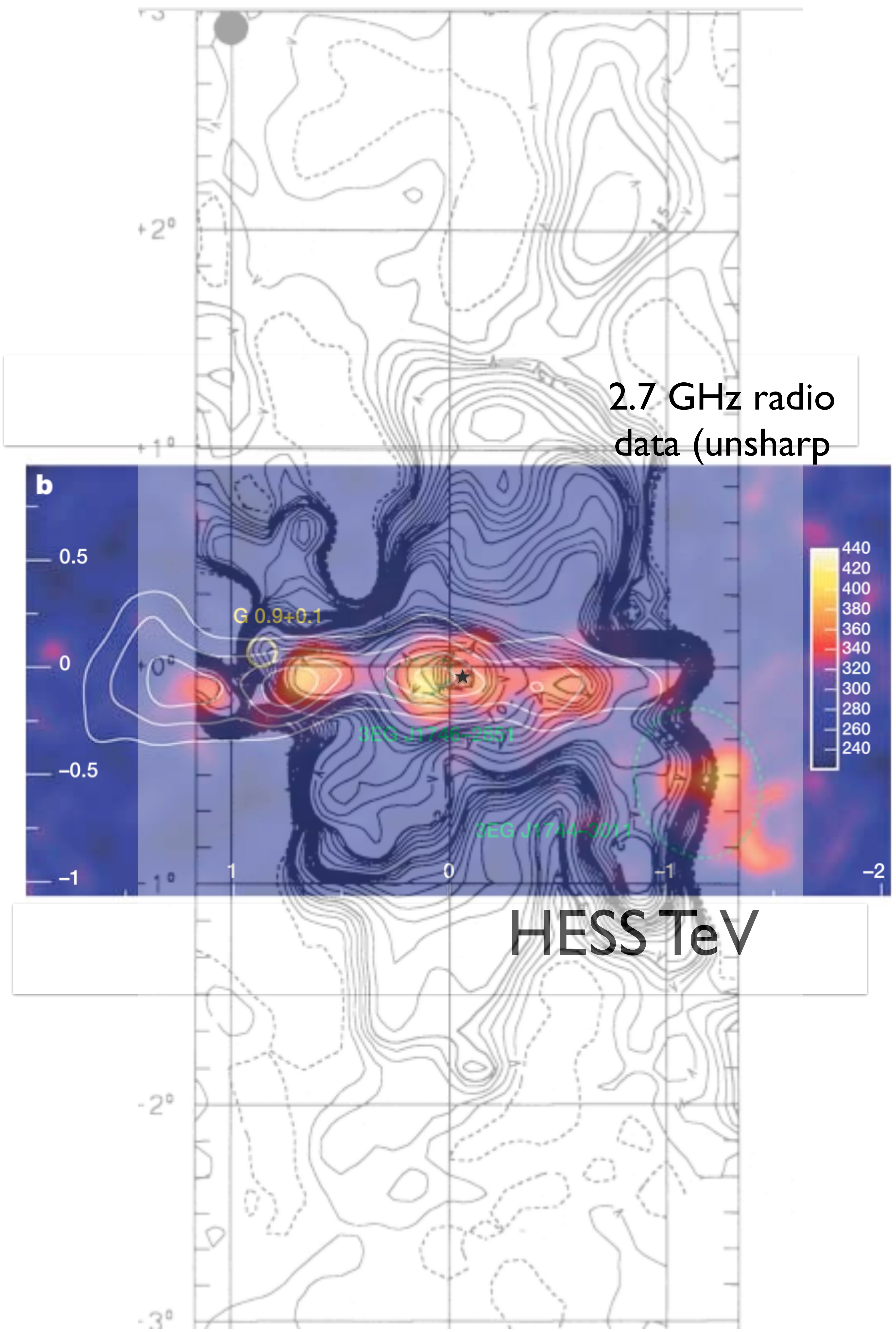
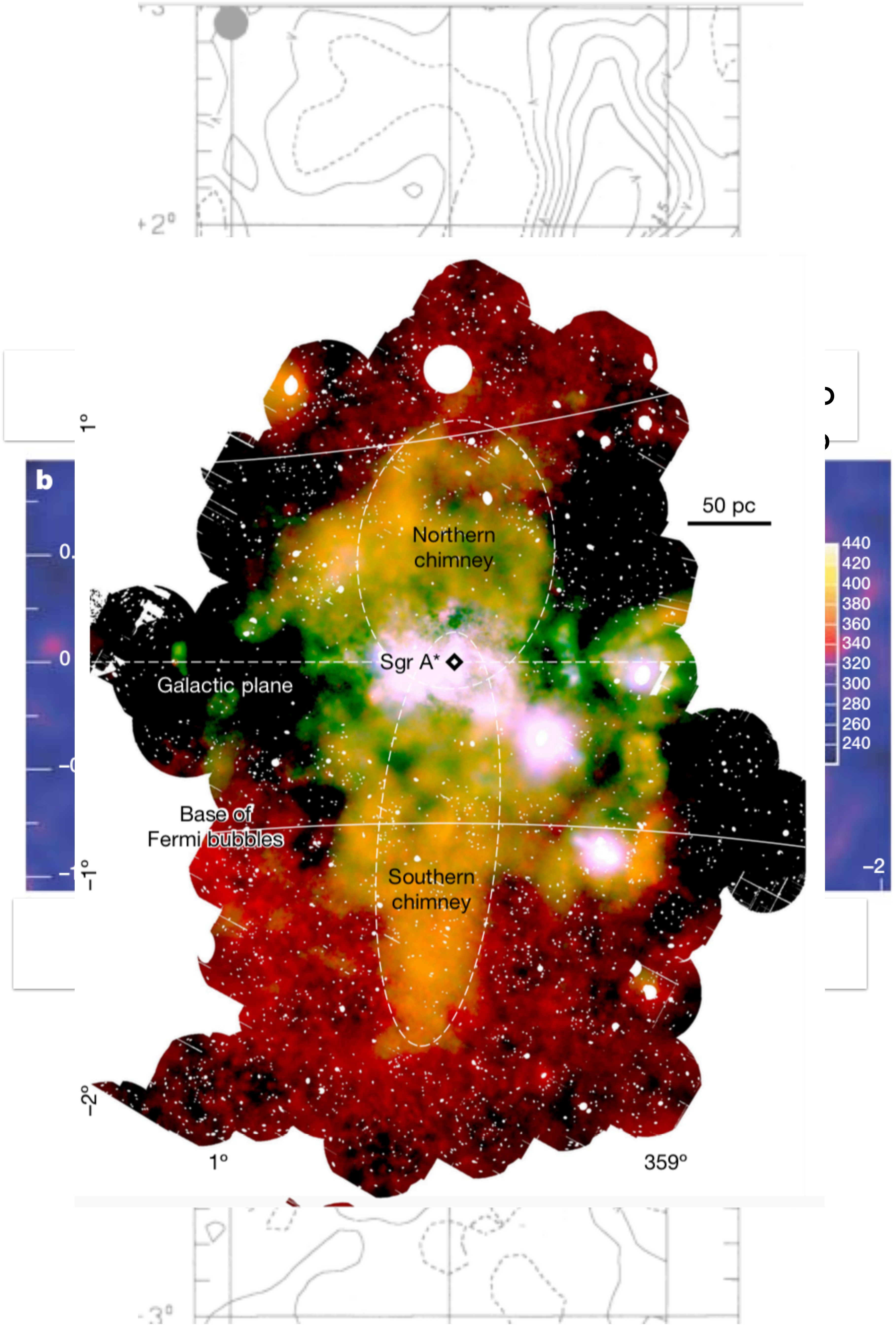

2.7 GHz radio
data (unsharp
HESS TeV
b
0.5
0
−0.5
−1
G 0.9+0.1
3EG J1746-2851
3EG J1744-3011
1
0
−1
−2
440
420
400
380
360
340
320
300
280
260
240
+2°
+1°
+0°
−1°
−2°
−3°



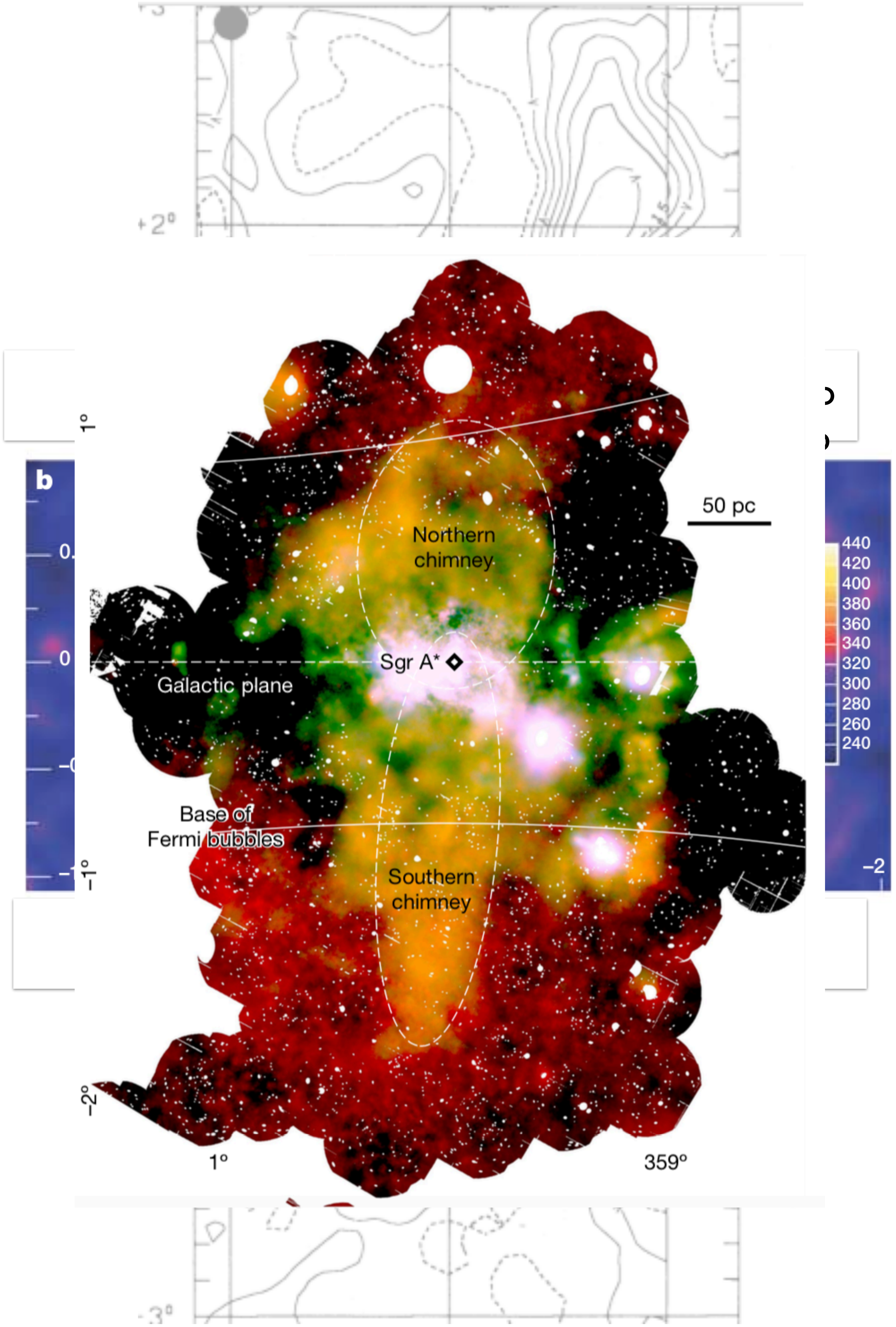
+2°
-3°
b
1°
0
Northern
chimney
Sgr A*
Galactic plane
Base of
Fermi bubbles
Southern
chimney
50 pc
–1°
–2°
1°
359°
440
420
400
380
360
340
320
300
280
260
240
–2

Ponti+2019 Nature
GC "Chimneys"
XMM 1-3 keV

1.5–2.6 keV (red);

2.35–2.56 keV (green);

2.7–2.97-keV (blue)



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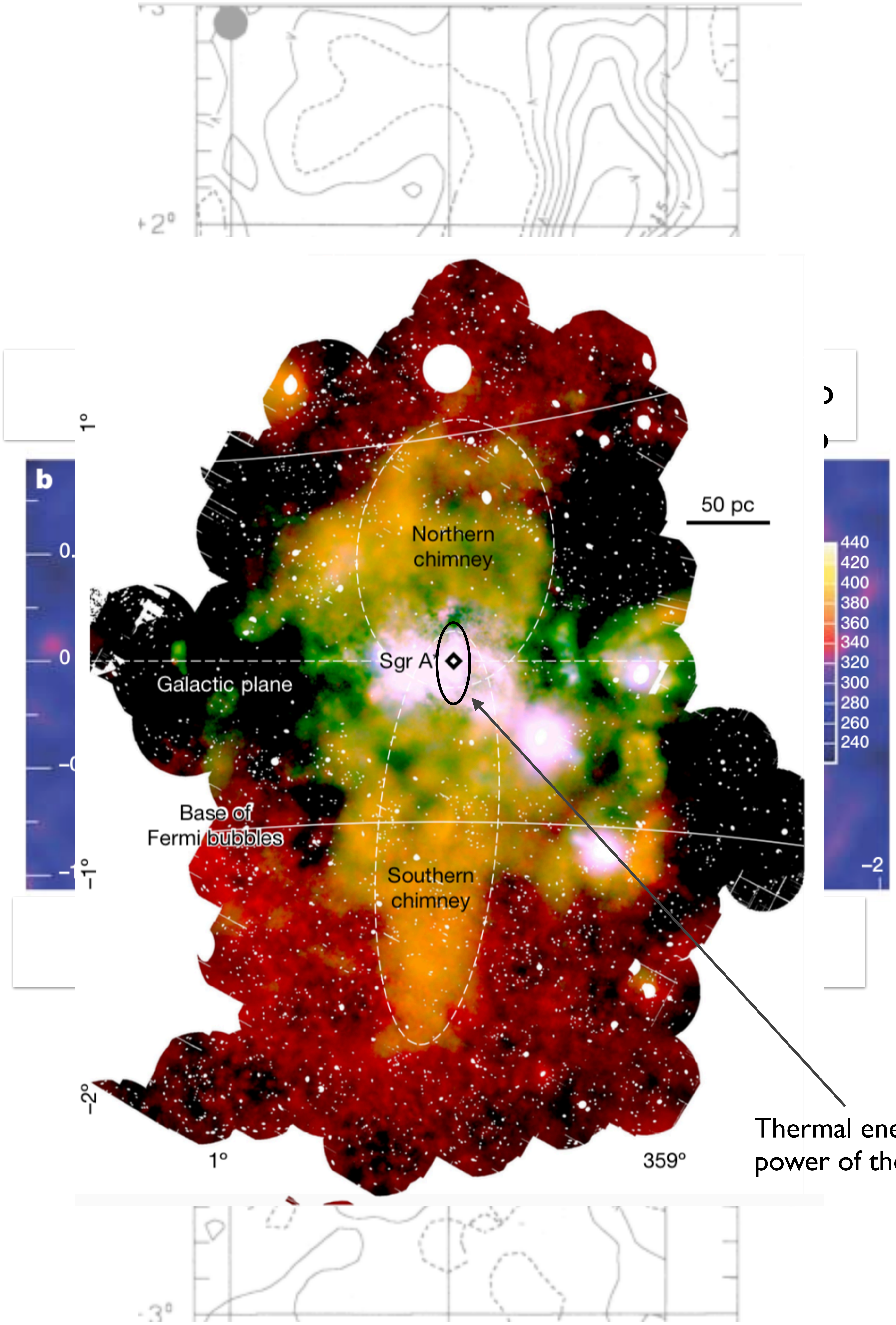

Thermal energy of ±15-pc lobes: 6×10^{50} erg;
power of the outflow: 8×10^{38} erg/s

Ponti+2019 Nature
GC "Chimneys"
XMM 1-3 keV

1.5–2.6 keV (red);

2.35–2.56 keV (green);

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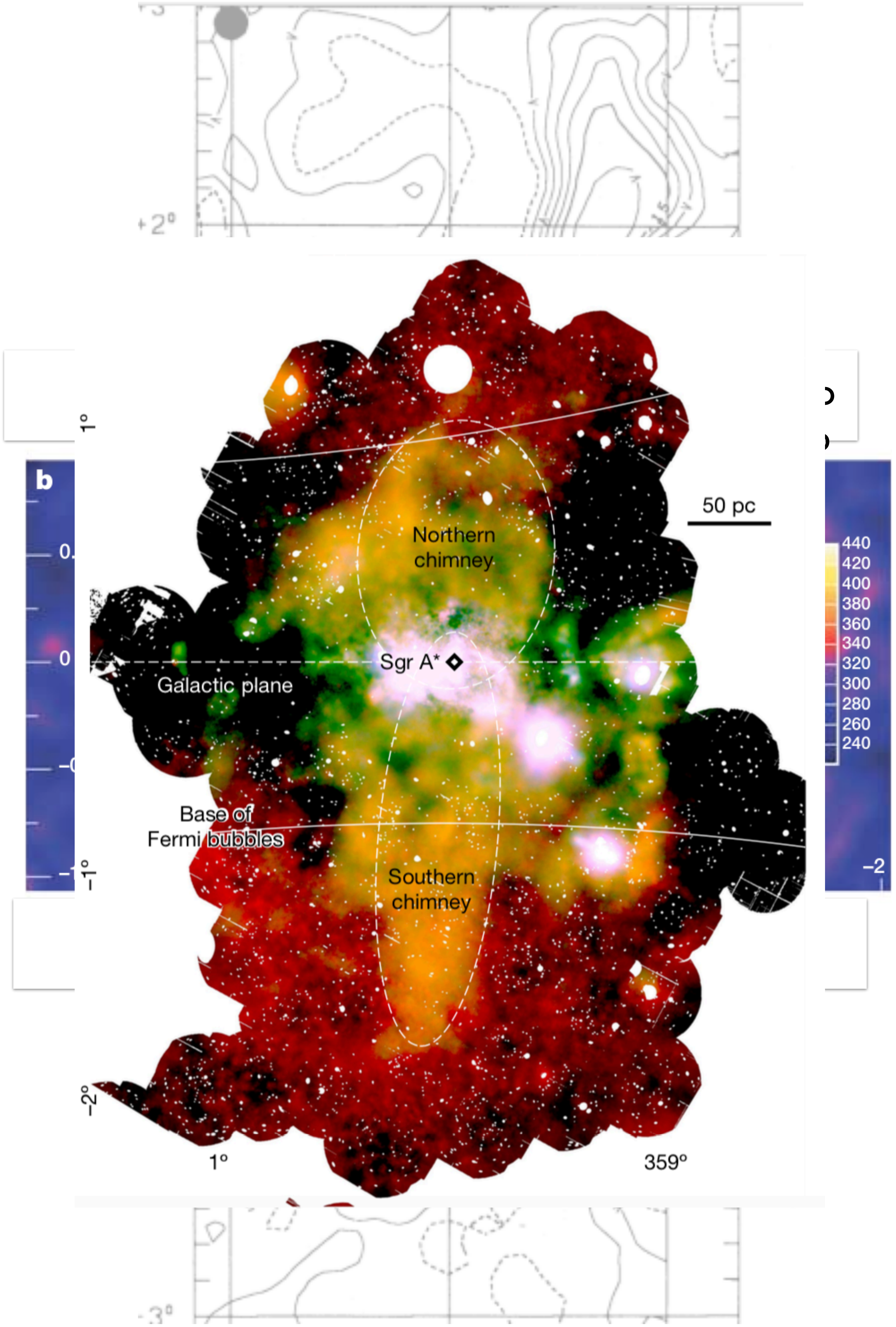


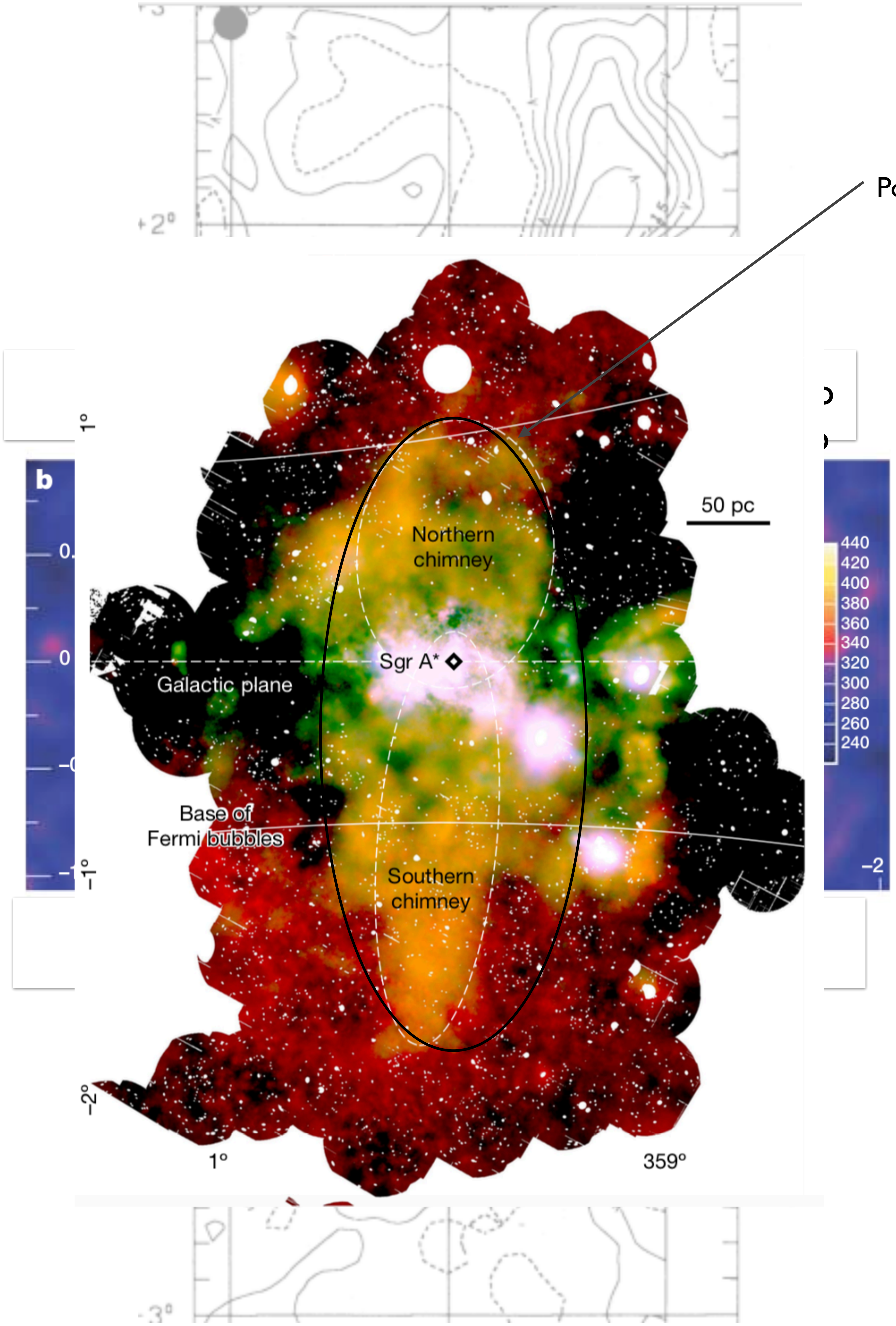
Ponti+2019 Nature
GC “Chimneys”
XMM 1-3 keV

1.5–2.6 keV (red);

2.35–2.56 keV (green);

2.7–2.97-keV (blue)

Power of the outflow: 4 × 10^{39} erg/s



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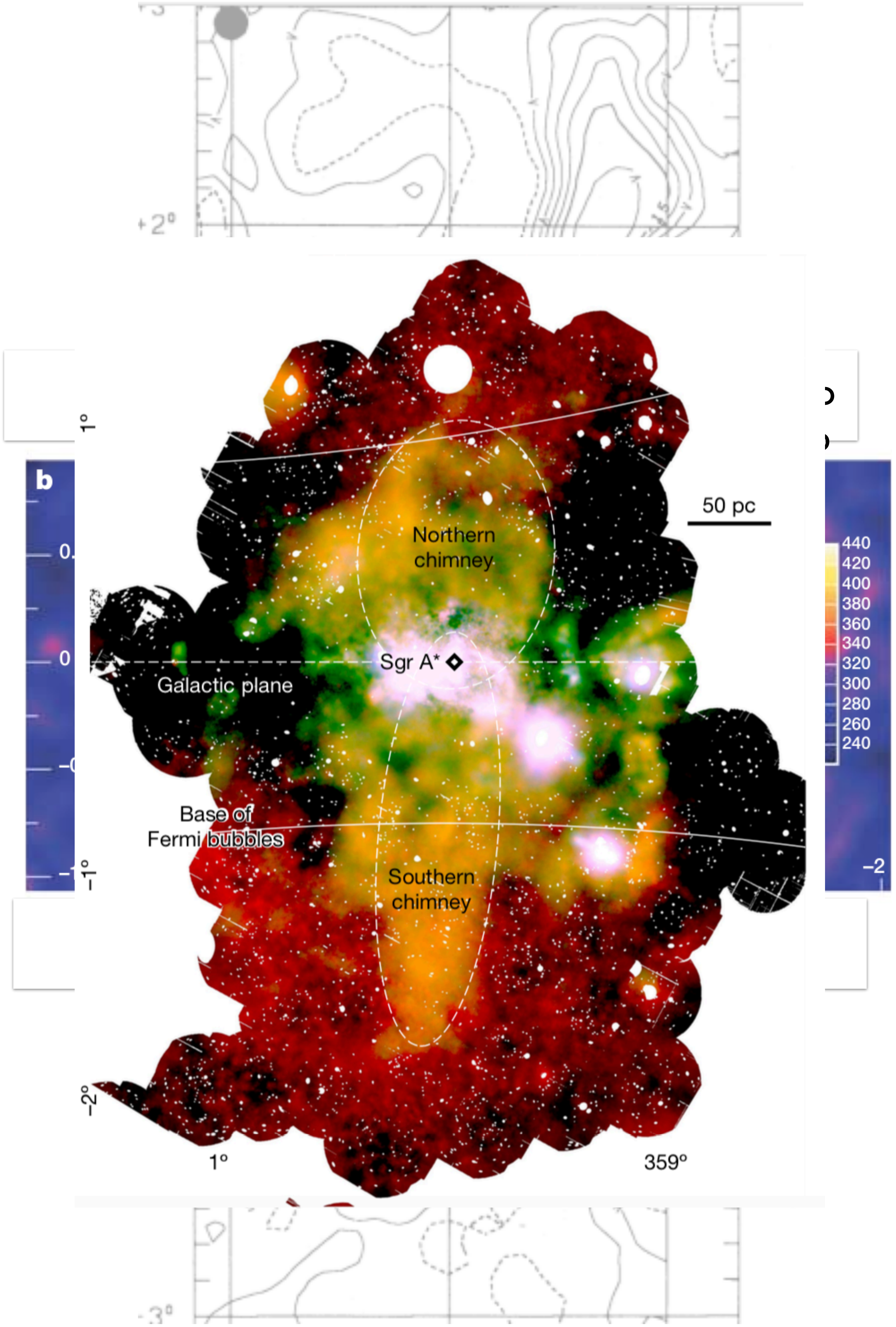

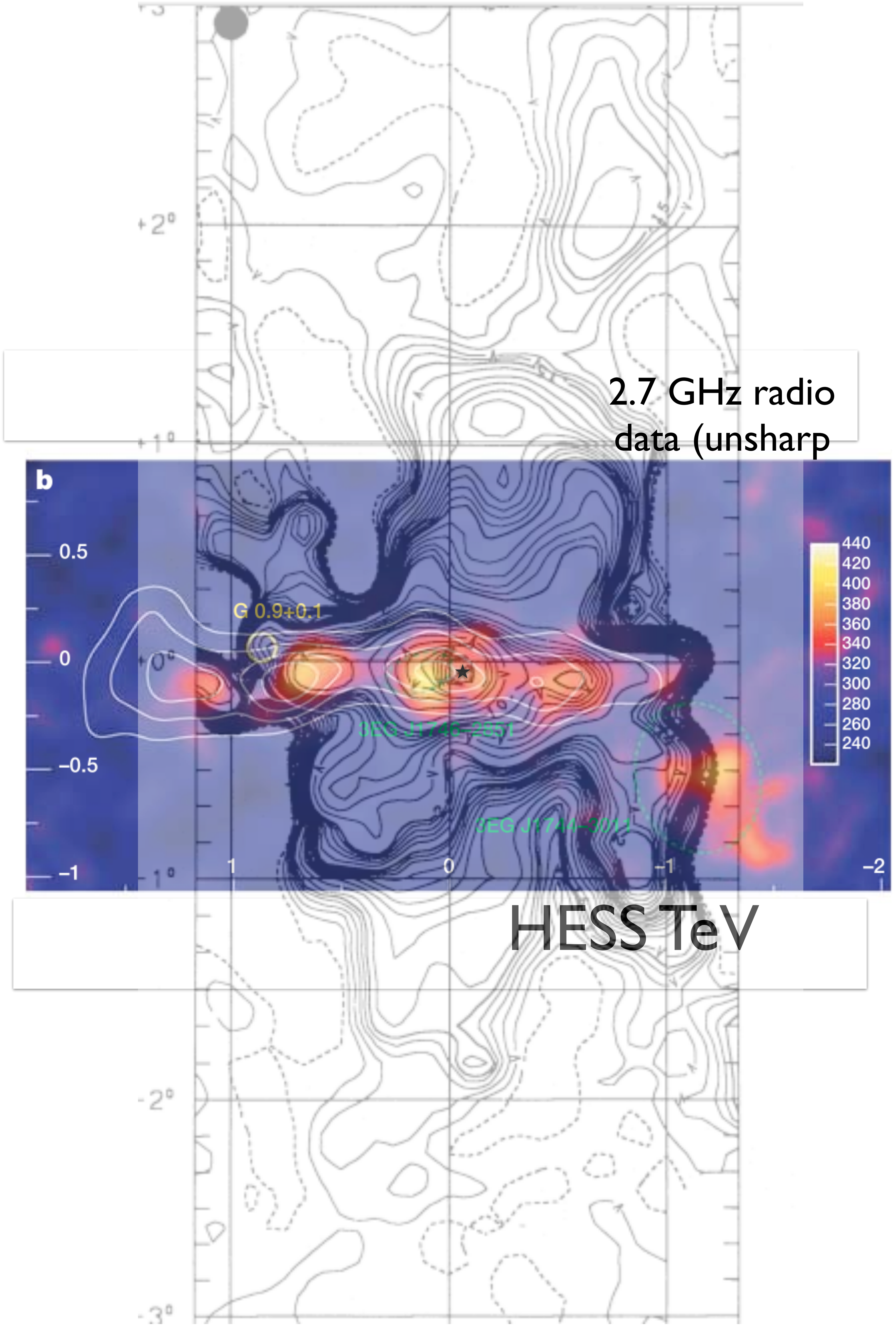
2.7 GHz radio
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HESS TeV
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440
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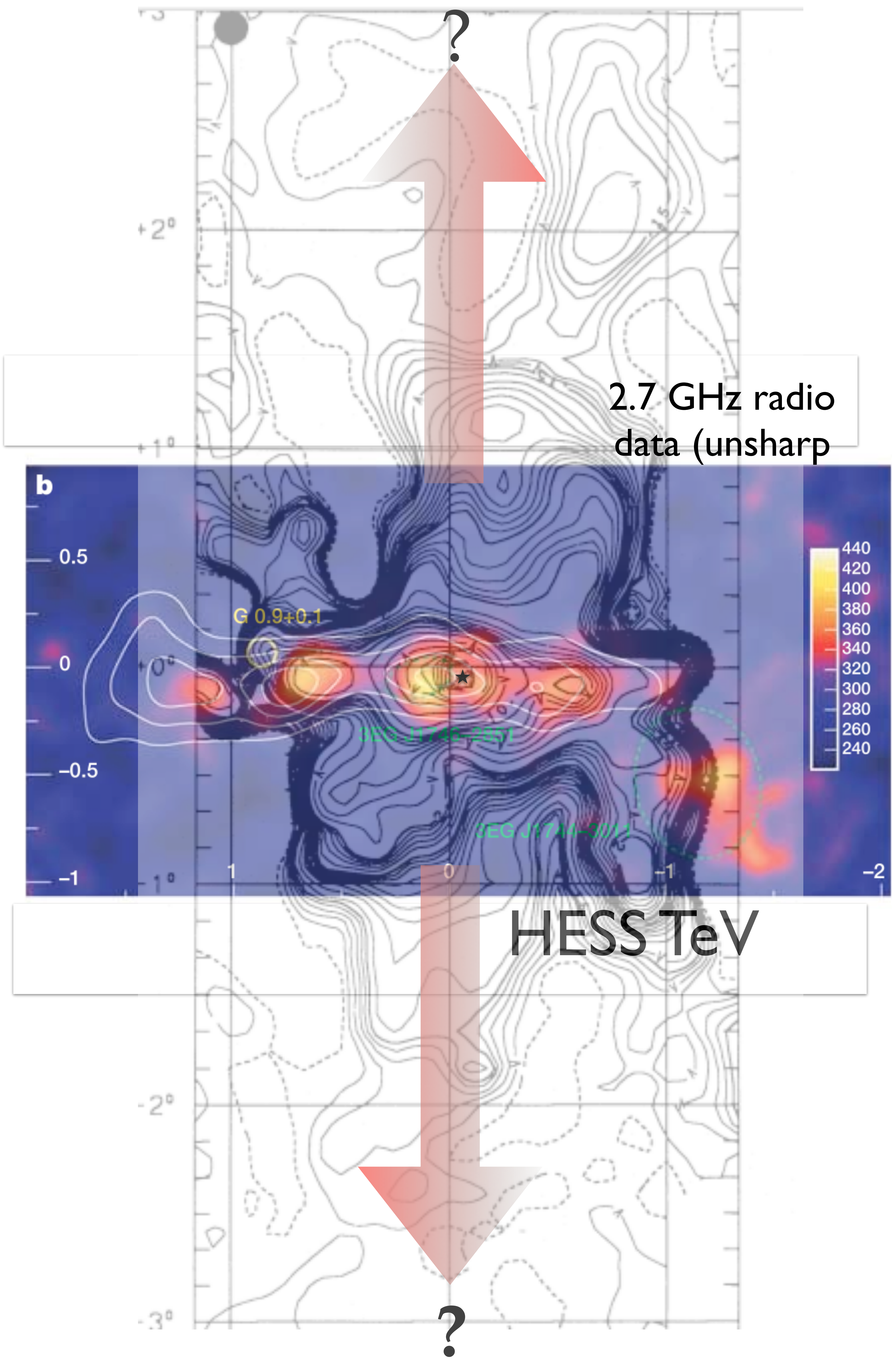

?
2.7 GHz radio
data (unsharp
HESS TeV
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+2°
+1°
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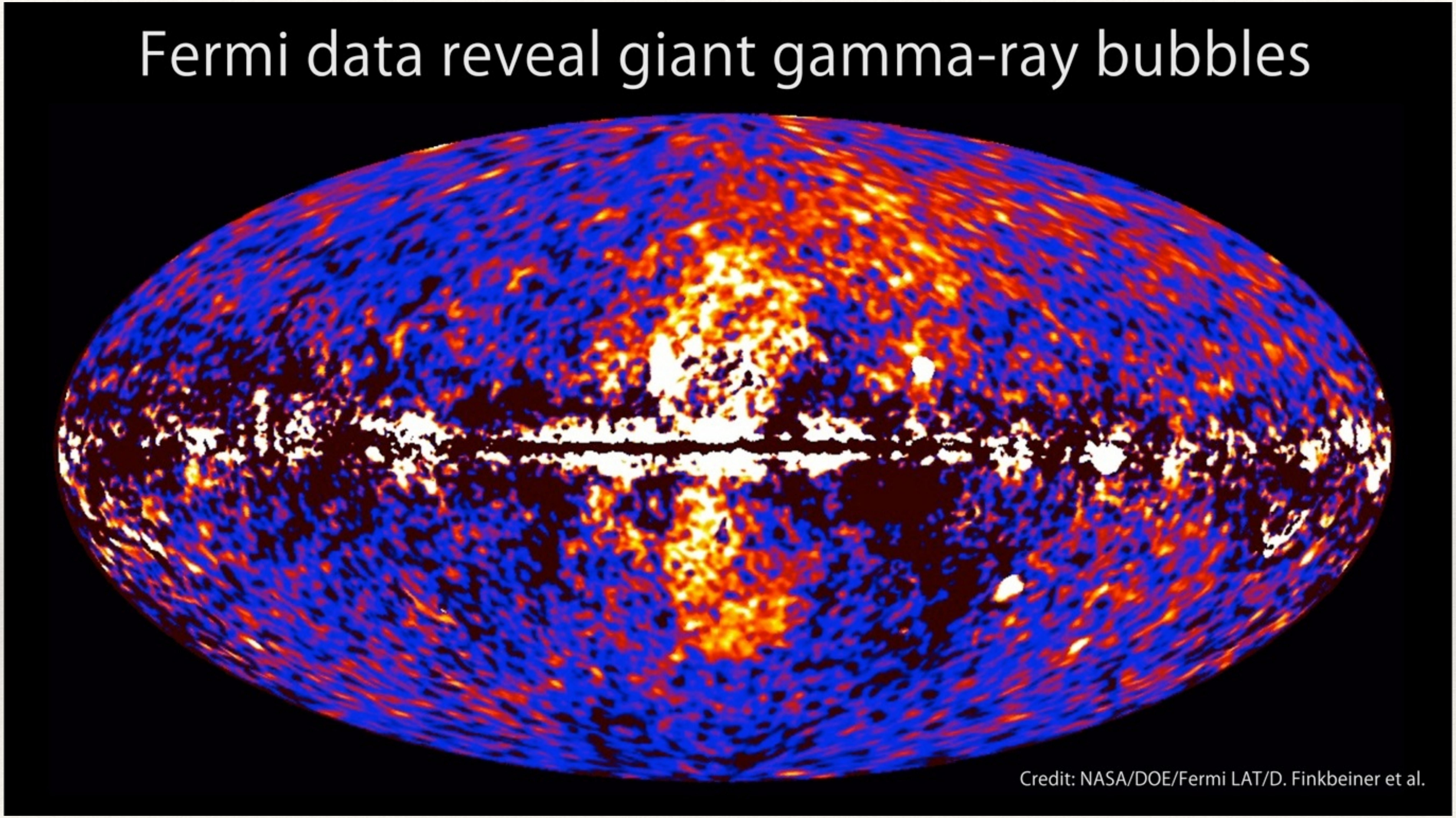
−3°
1
0
−1
−2



Su, Slatyer and Finkbeiner 2010 (ApJ)

Fermi Bubbles

- 2×10^{37} erg/s [1-100 GeV]
- hard spectrum,

Fermi Bubbles

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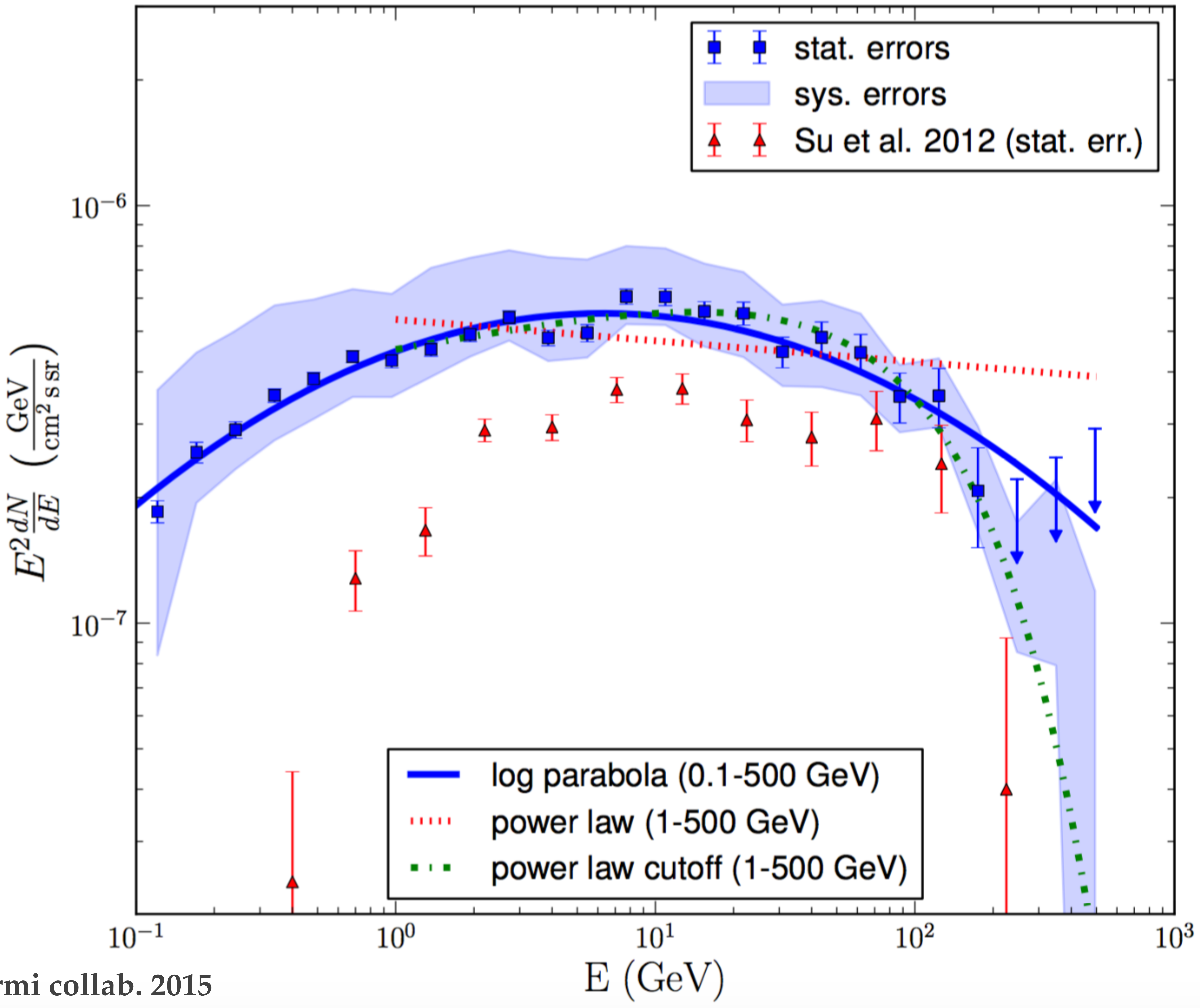
- but spectral down-break i) below ~ GeV and ii) above ~100 GeV



Fermi collab. 2015

Fermi Bubbles

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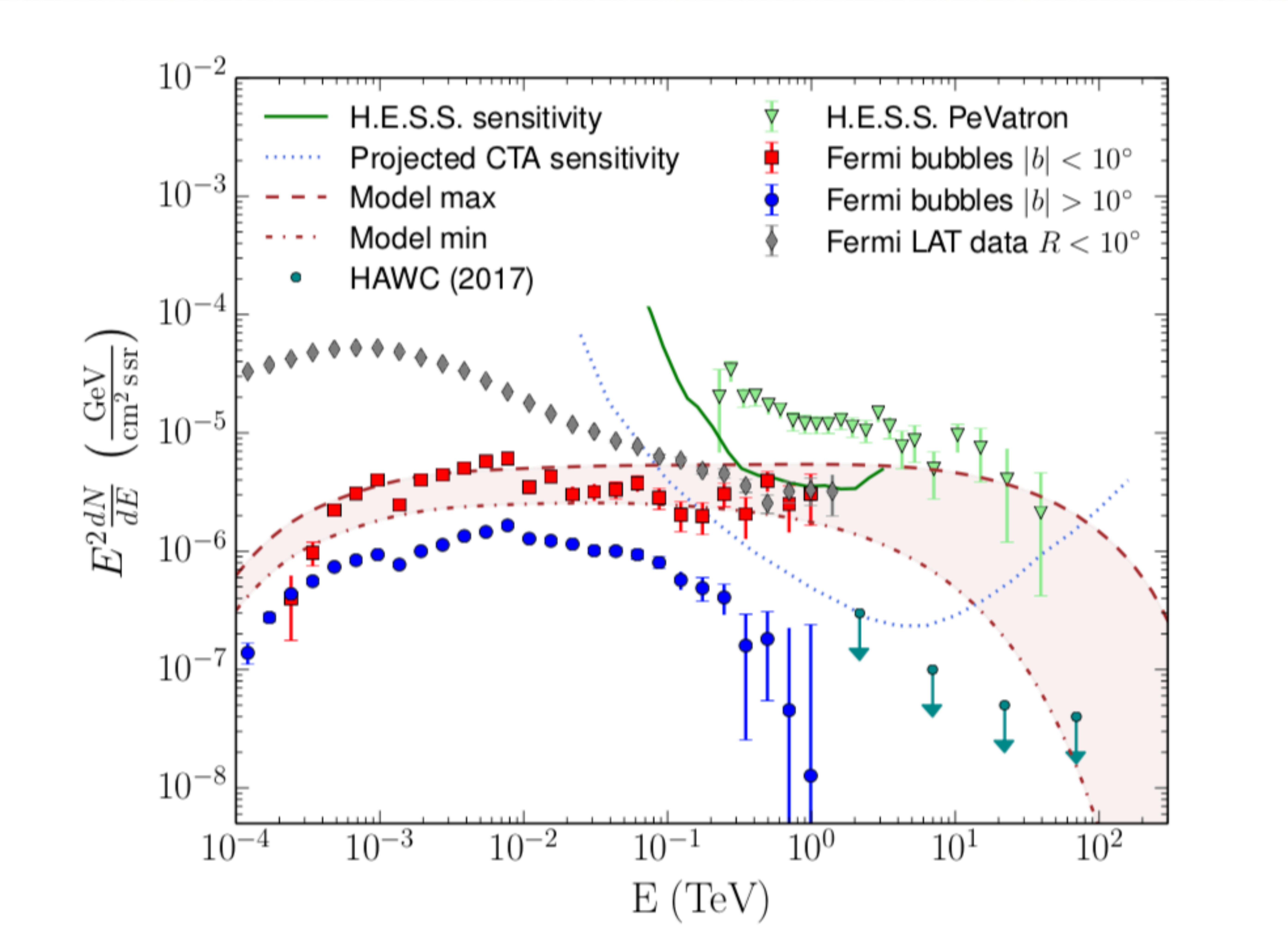
- hard spectrum,
- but spectral down-break i) below ~ GeV and ii) above ~100 GeV
- (fairly) uniform intensity

Qualification: *Bubbles brighter and harder at base*



see Herold & Malyshev

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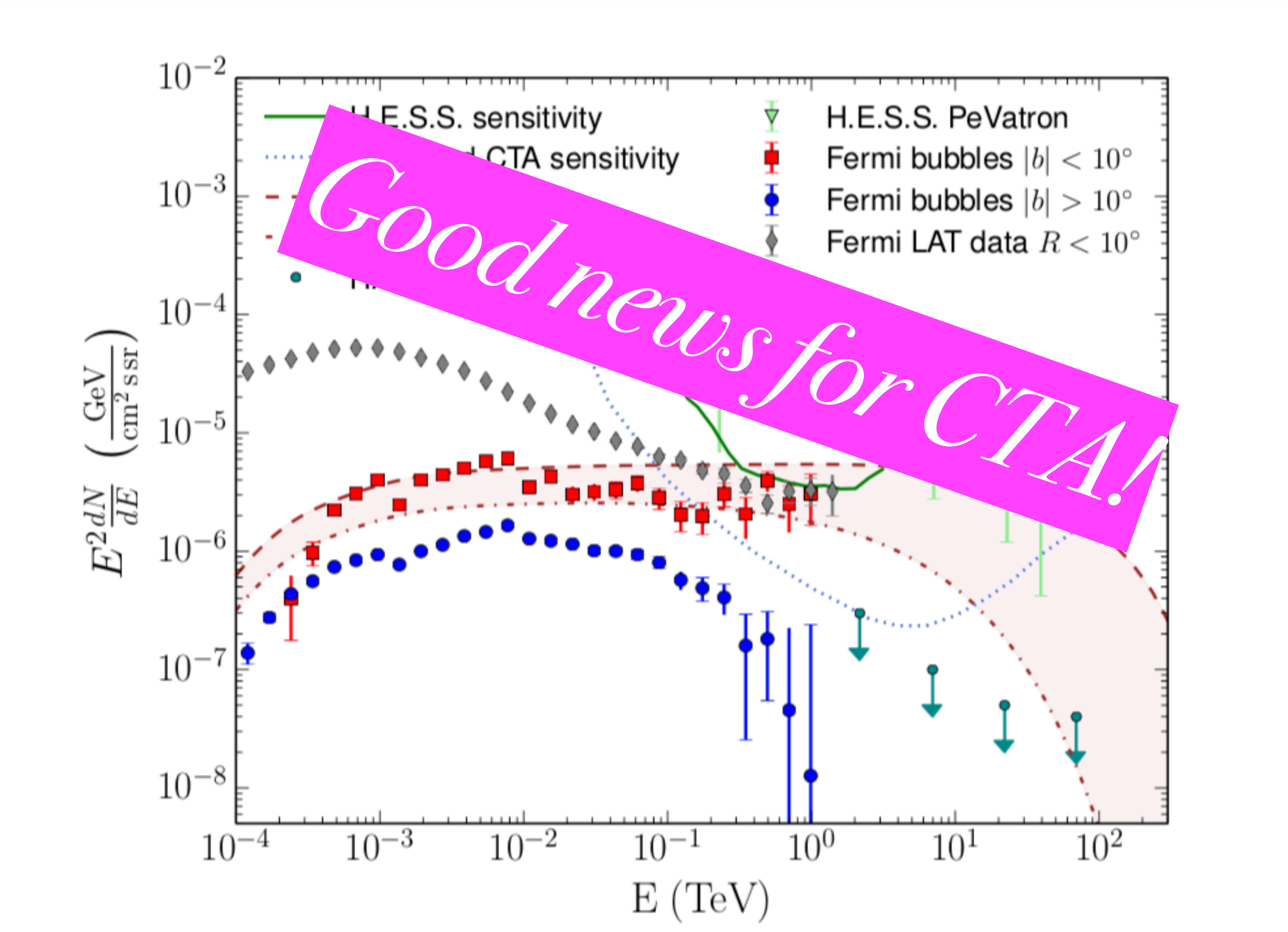

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- sharp edges (< 500pc)

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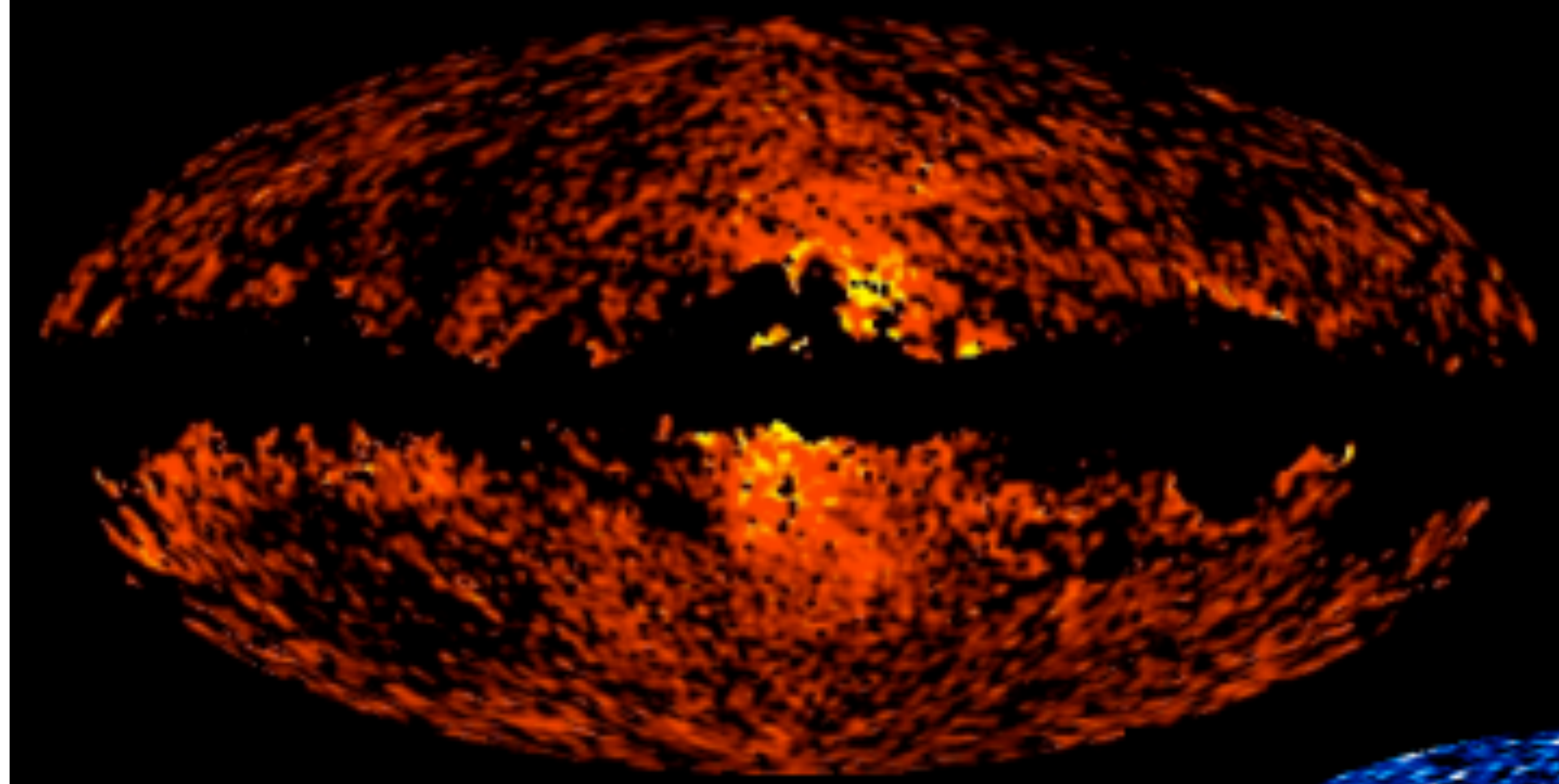
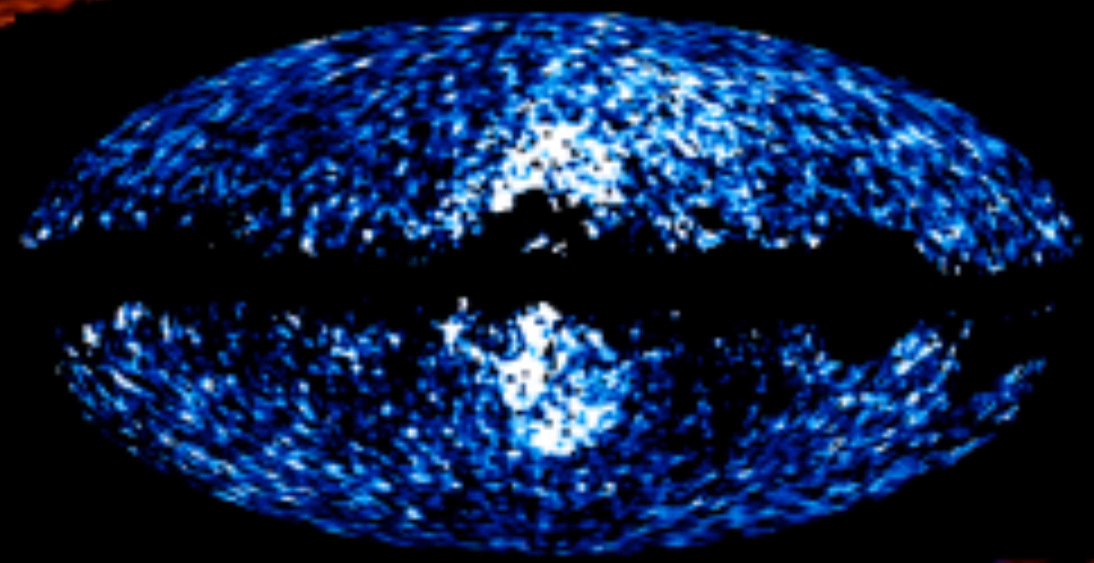
- hard spectrum,
- but spectral down-break i) below ~ GeV and ii) above ~100 GeV
- (fairly) uniform intensity
- sharp edges (< 500pc)
- coincident emission at other wavelengths

PLANCK images a giant eruption from the heart of the Milky Way

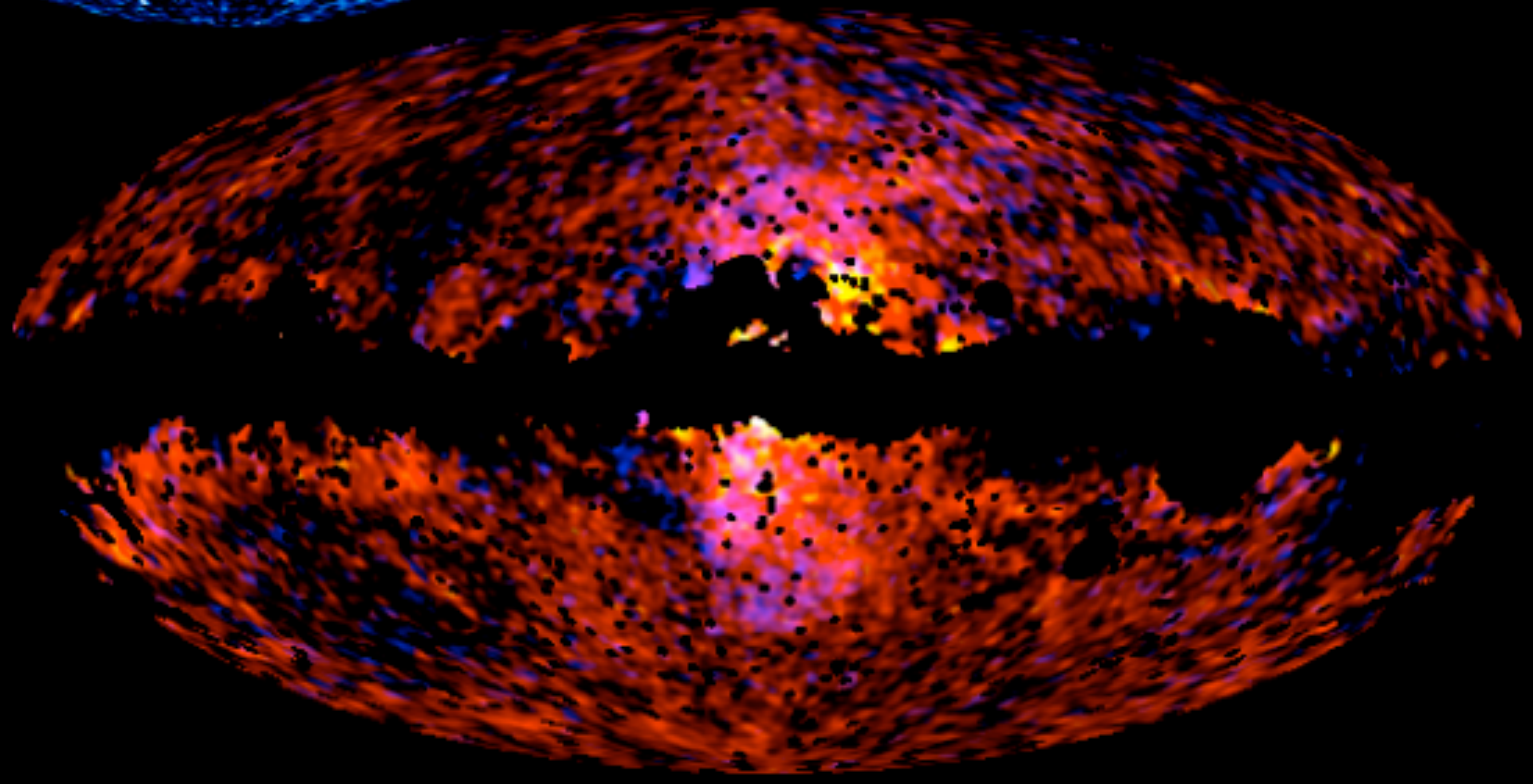


The Galactic haze/bubbles is shown here in *PLANCK* data from *30-44* GHz



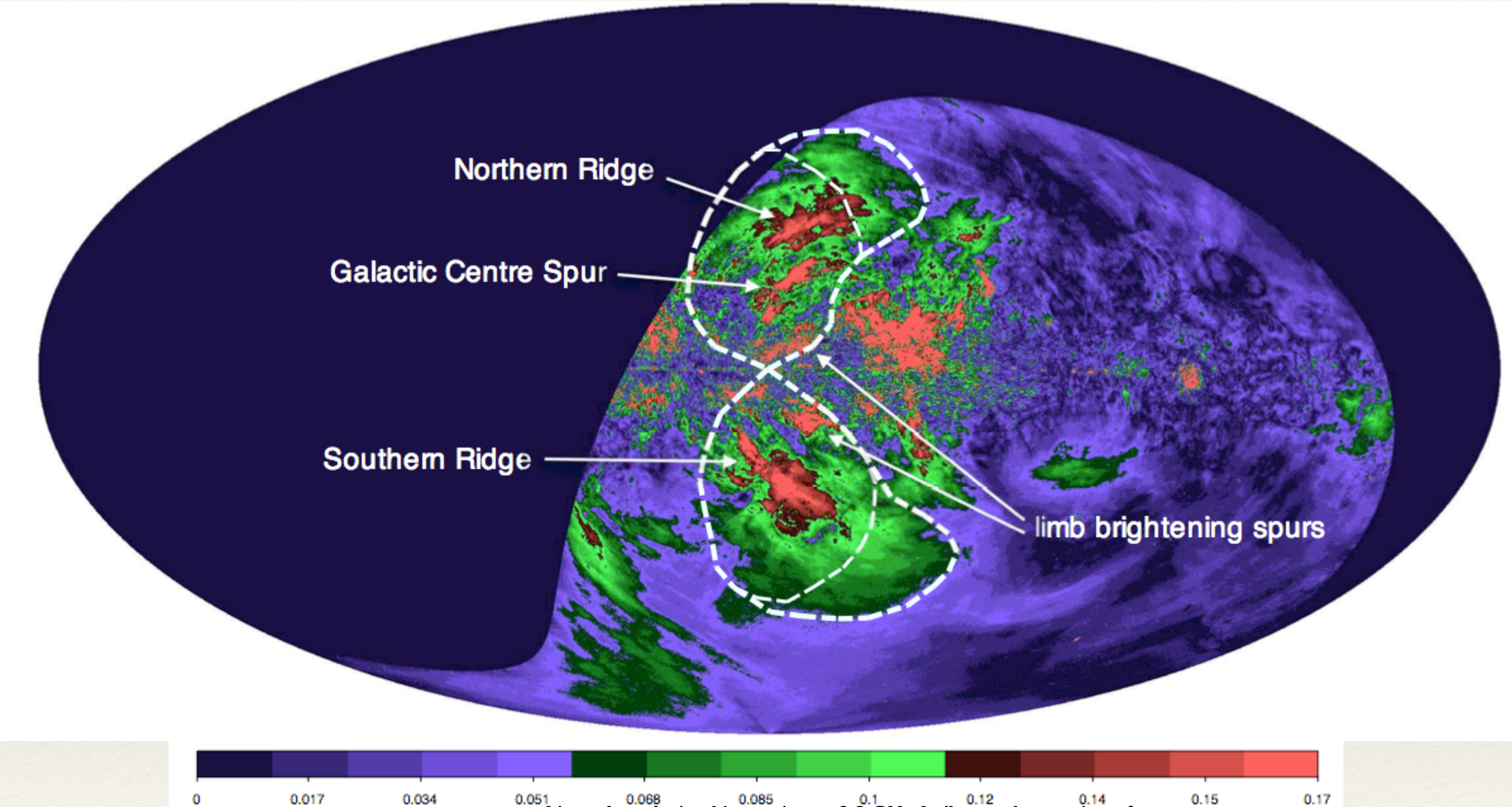
The same structure at *2-5* GeV as seen by the *Fermi Gamma-Ray Space Telescope*

A multi-wavelength composite image showing both microwaves and gamma-rays: *PLANCK 30* GHz (red), *44* GHz (green), and *Fermi* 2-5 GeV (blue).



Slide credit: D. Pietrobon & K.M. Gorski
Planck Collab.

The S-PASS Lobes



Linearly polarised intensity at 2.3 GHz Jy/beam, beam size of 10.75'

Carretti, Crocker+2013

Nature

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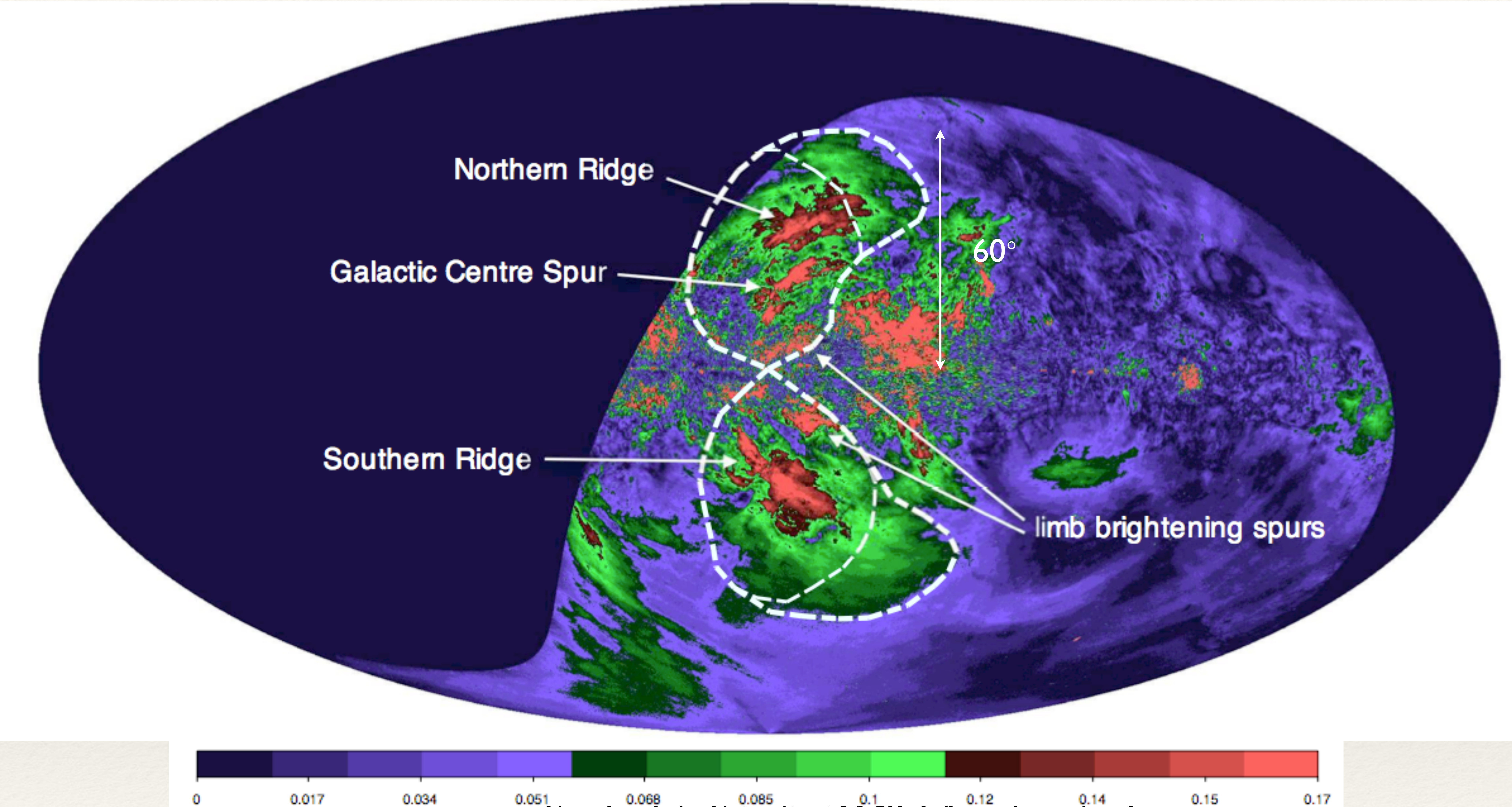

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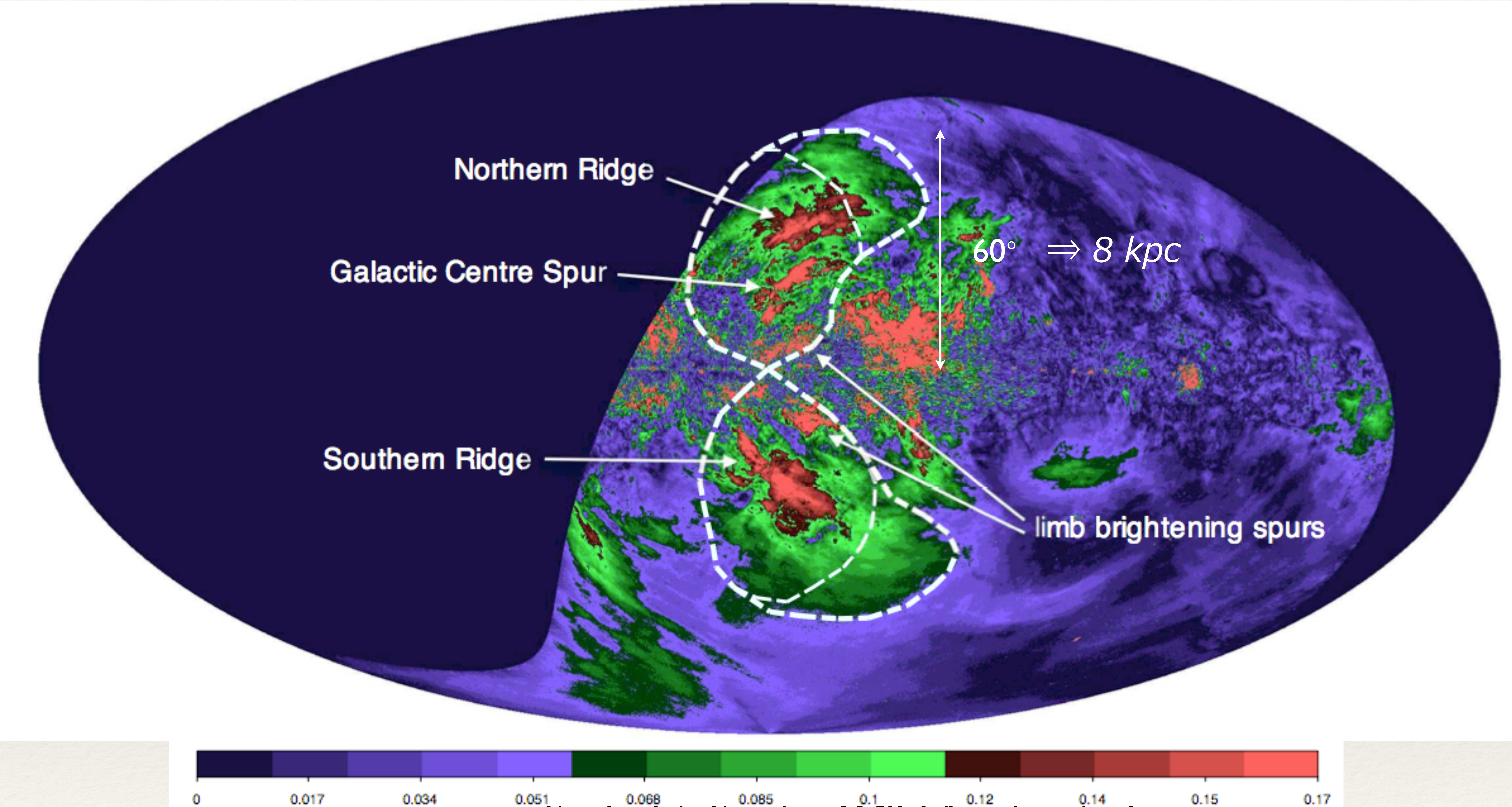

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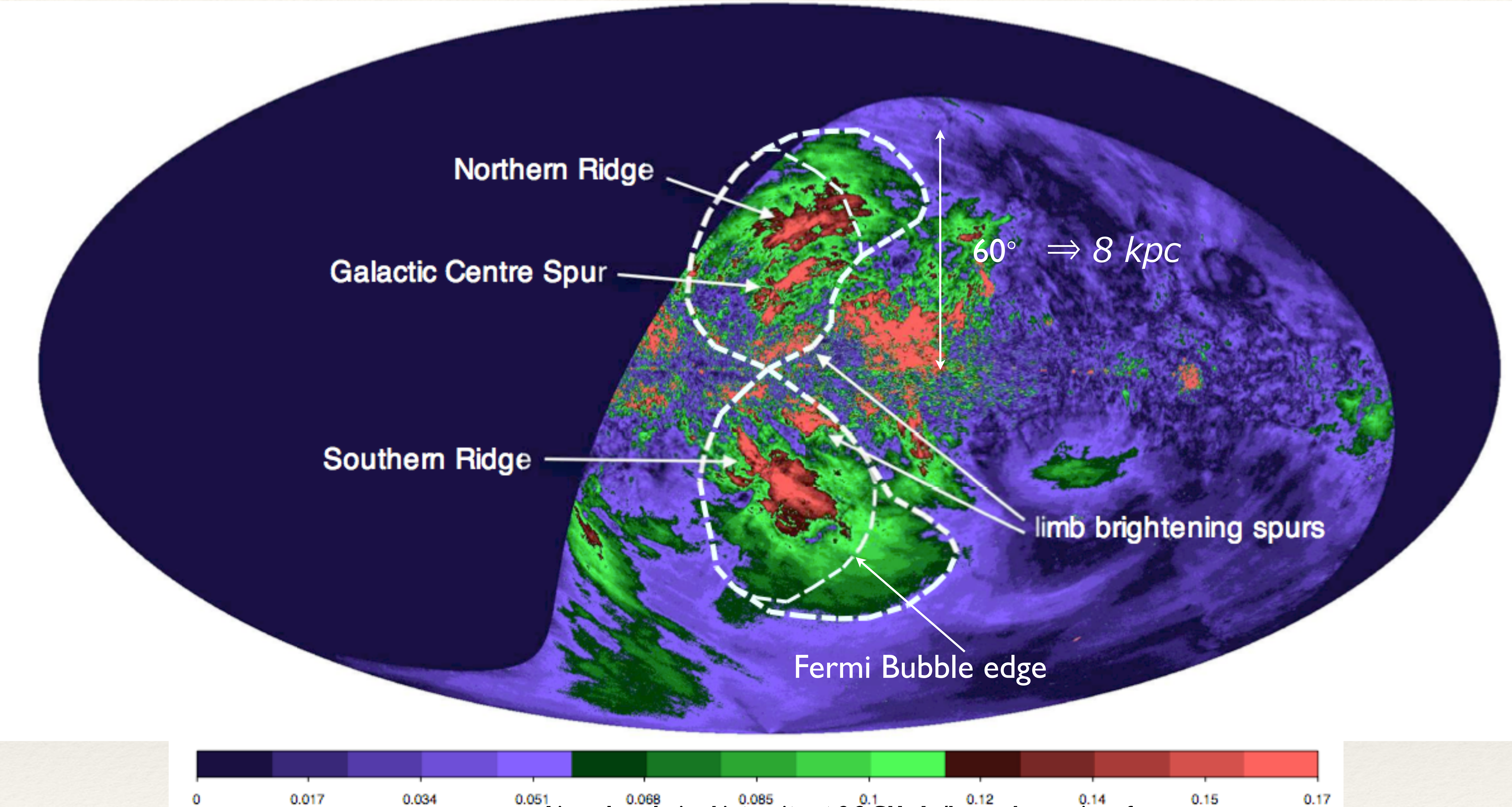

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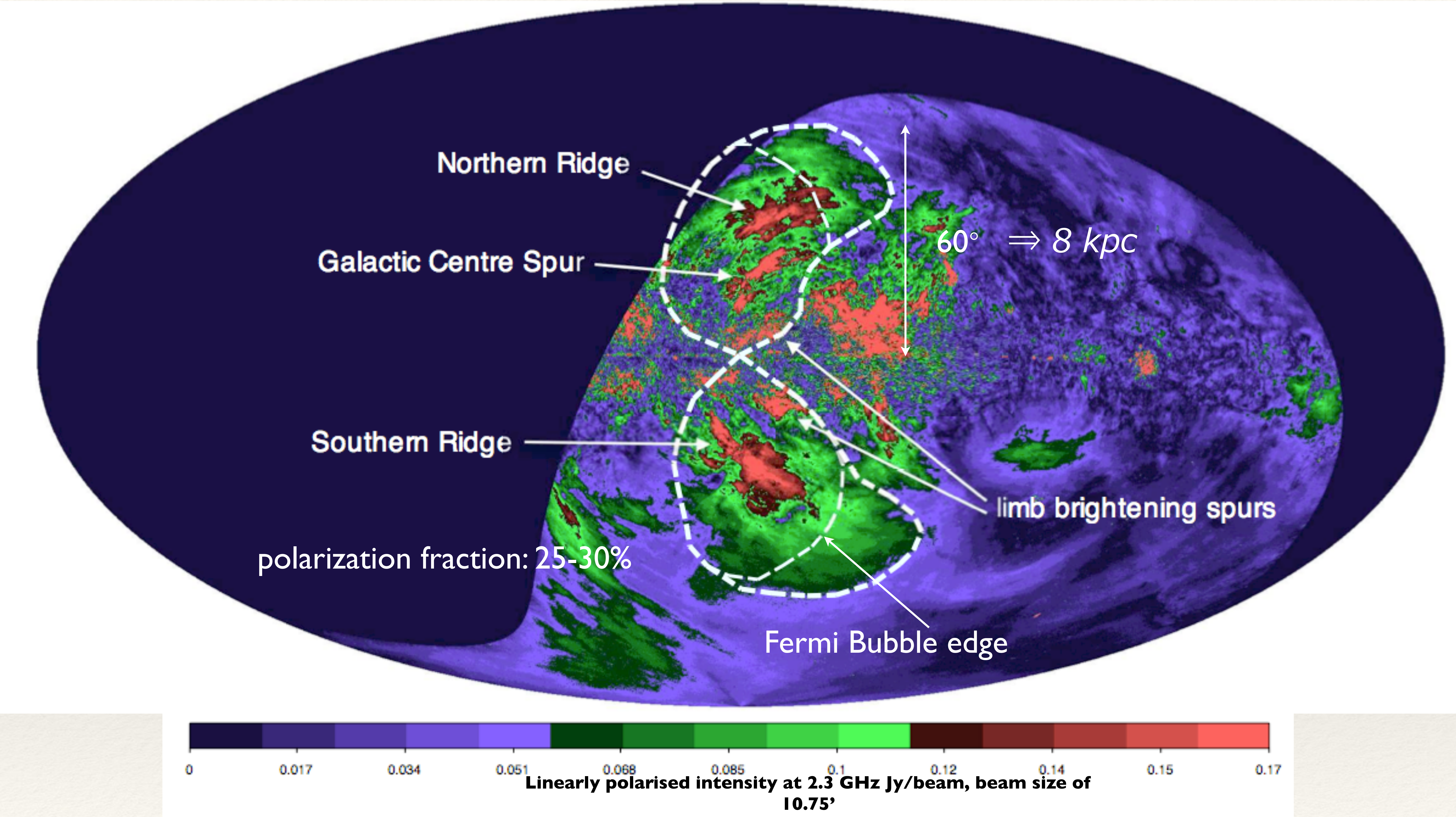


Carretti, Crocker+2013

Nature

Fermi Bubbles: Three Interlocking Questions

How old are the Bubbles?

What is the gamma-ray radiation mechanism?

What energizes the Bubbles?

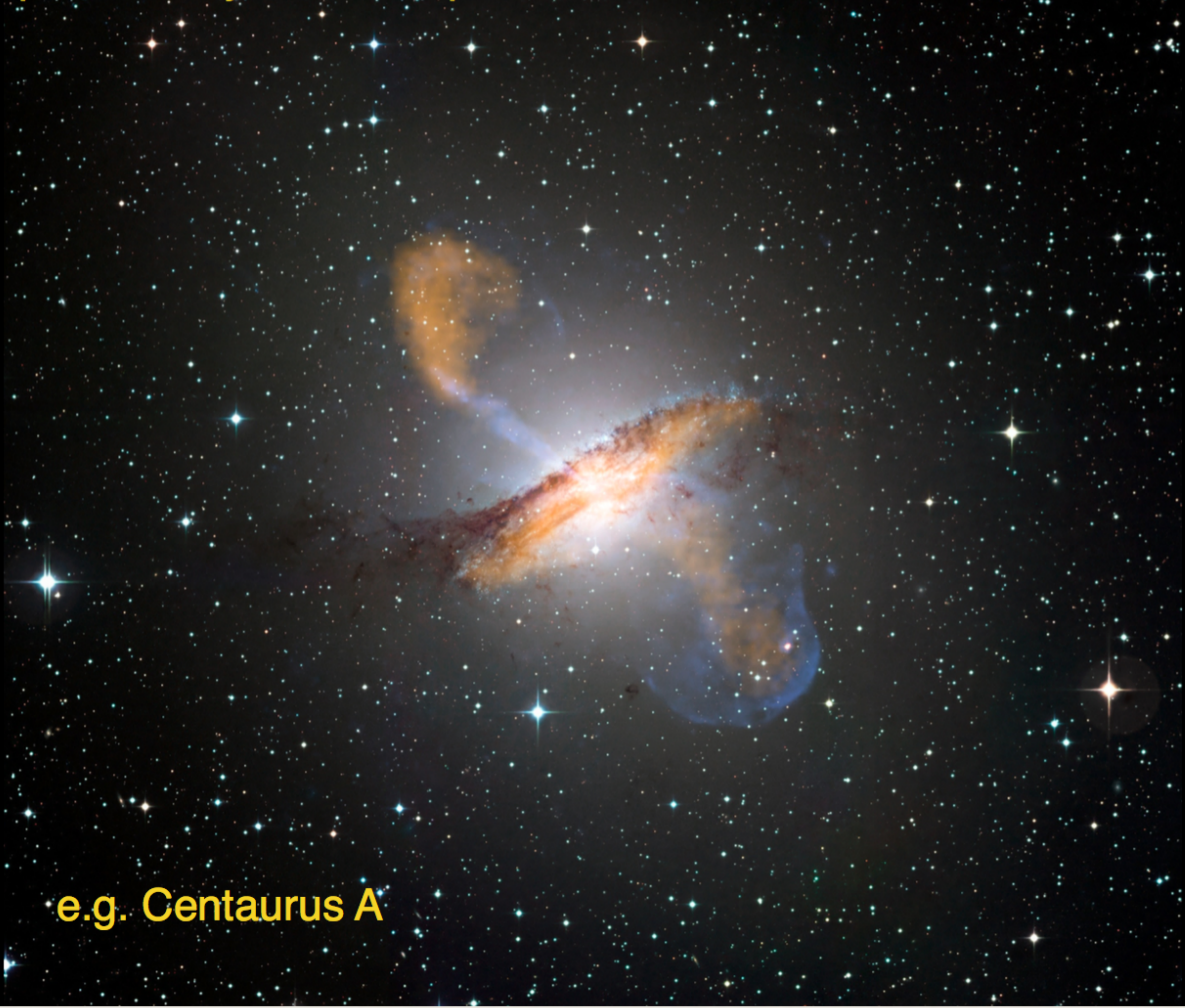
What energises the outflow?

total enthalpy slowly inflated bubbles:

$$H \equiv \frac{\gamma}{\gamma - 1} P_{\rm ext} V = \dot{E}\ t$$

$$\sim\ 7 \times 10^{55}\ erg\ P_{ext}/(2 \times 10^{4}\ K\ cm^{-3}\ k_B)$$

Fermi Bubbles = mini version of radio galaxy jets powered by central supermassive black hole?



Fermi Bubbles = nuclear starburst with outflowing winds?

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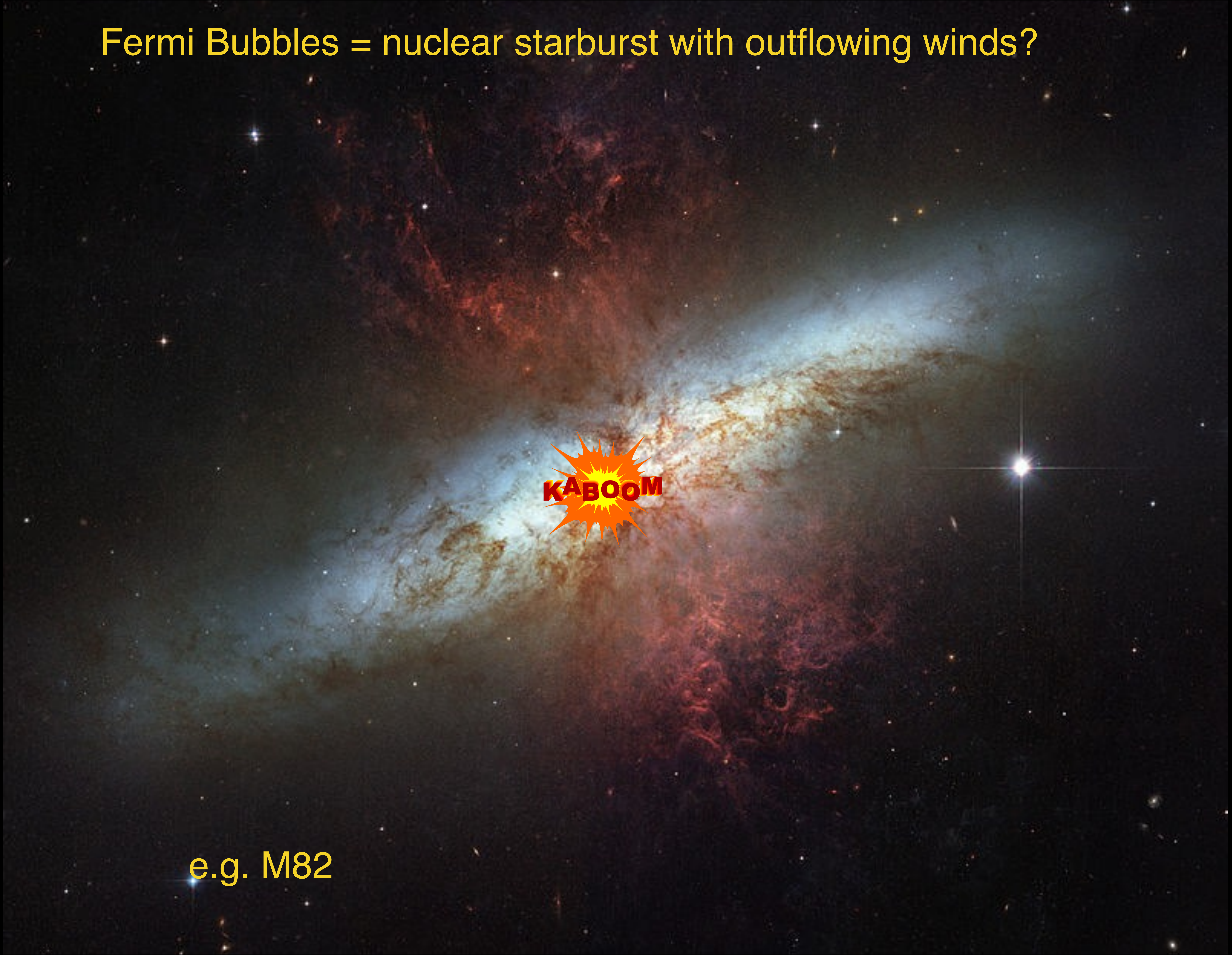

e.g. M82

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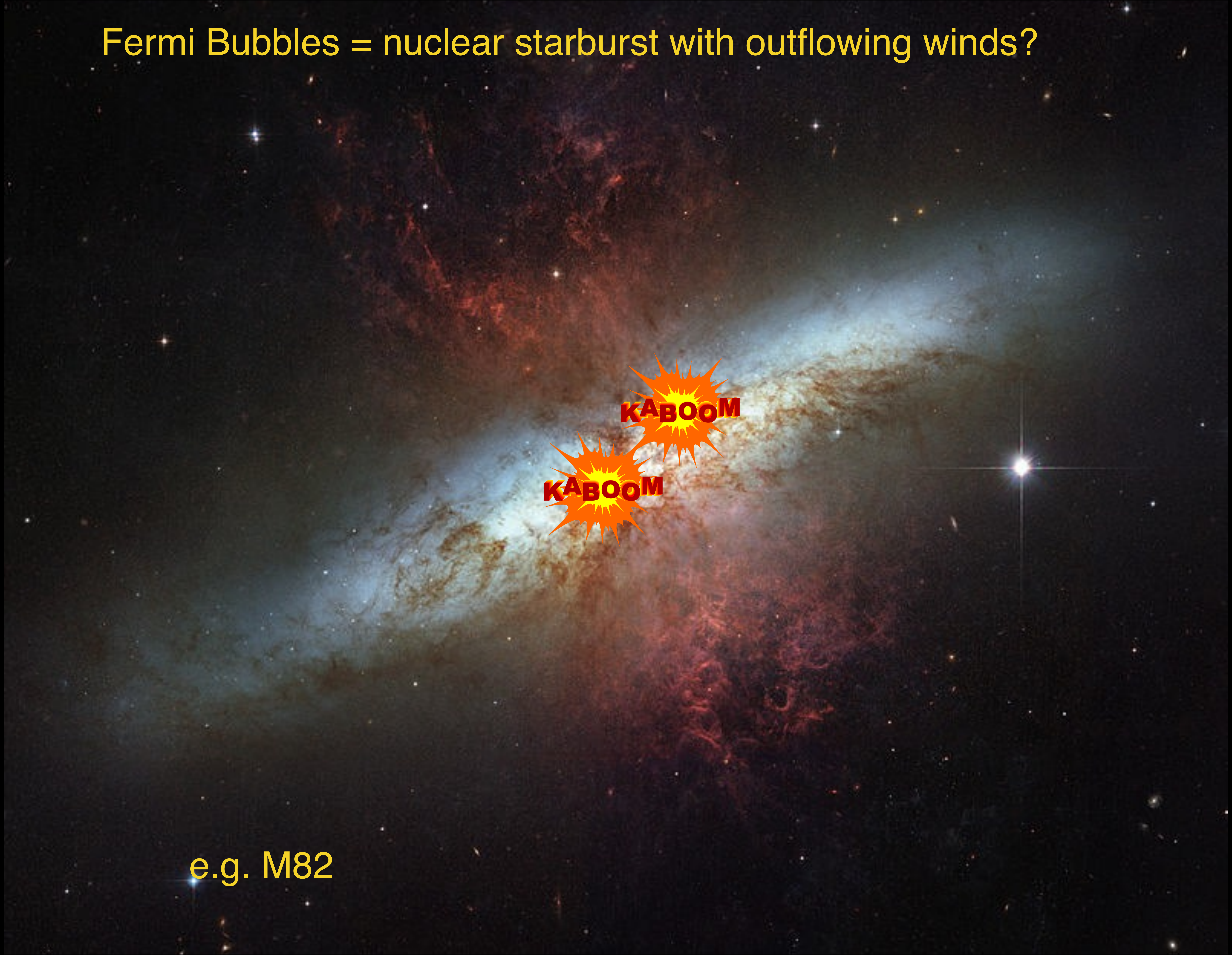

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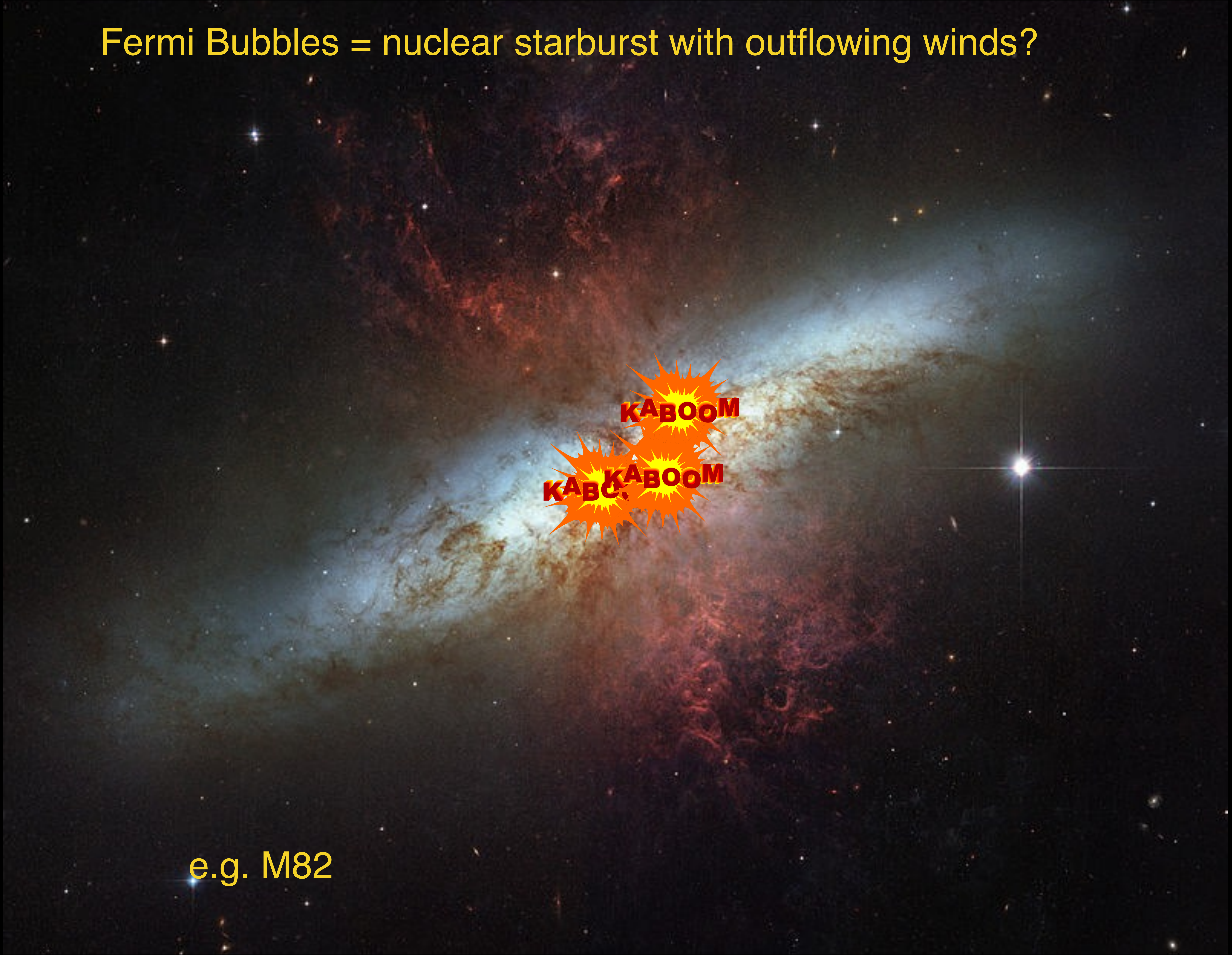

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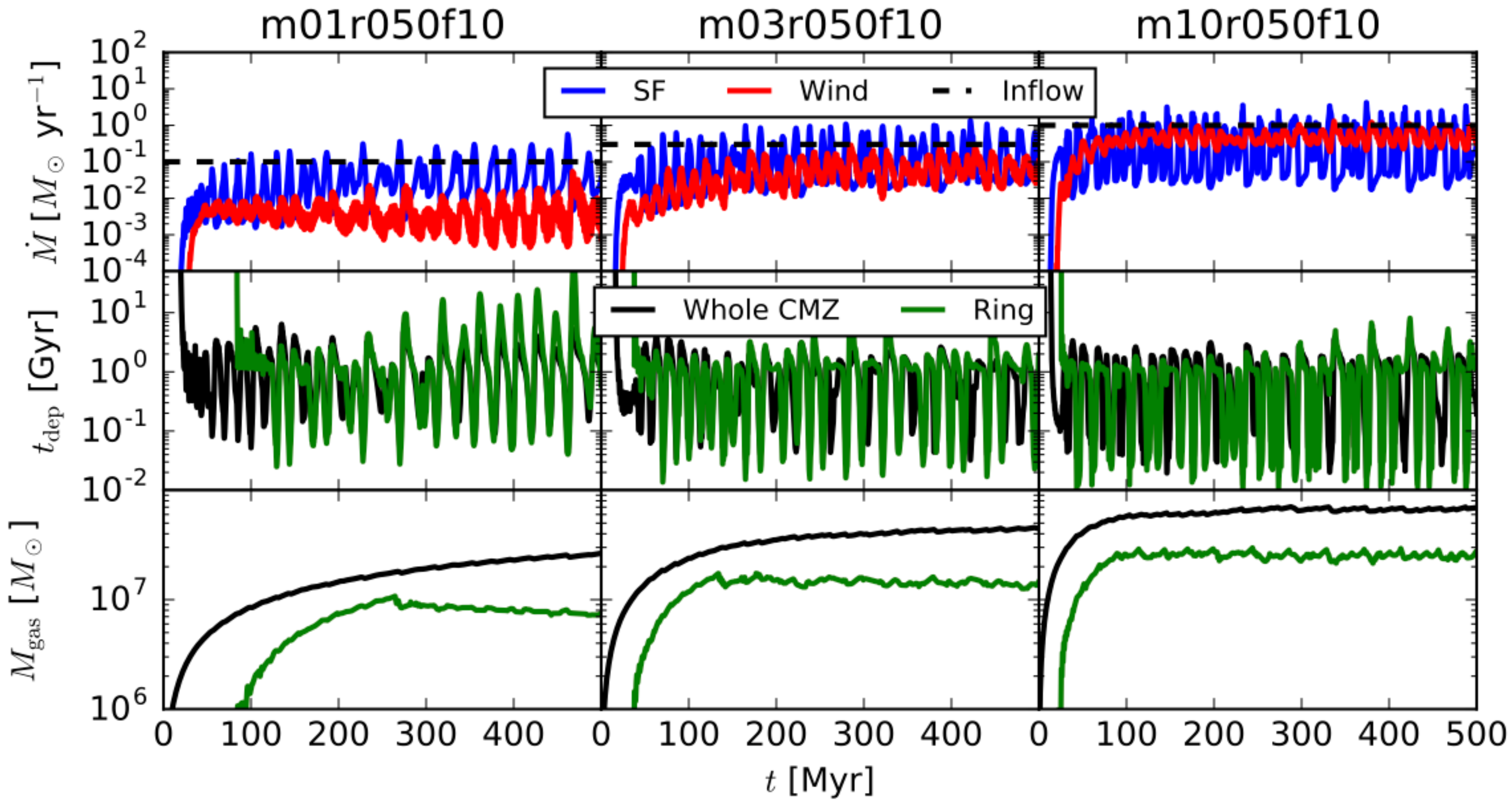

Bursty Star Formation in Galactic Centres

Krumholz, Kruijssen, & Crocker 2017

What energises the outflow?

- The (photon) Eddington luminosity of

  Sgr A*($4 \times 10^6\ M_{Sun}$): 5×10^{44} erg/s

- $t_{min} = E_{Bubbles}/P_{mech} \sim 10^{56}$ erg/(3×10^{42} erg/s) ~ 1 Myr

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What energises the outflow?

- Star formation in the Galactic Centre at a rate

  $\sim(0.01\text{-}0.3)\ M_{Sun}/yr$

  …the Galactic Centre is not a Starburst

- This injects mean mechanical power (supernova explosions, stellar winds) of

  $P_{mech} \sim 0.08\ M_{Sun}/yr \times 1\ SN/(90\ M_{Sun}) \times 10^{51}\ erg/SN$

  $= 3 \times 10^{40}\ erg/s$

  $t_{min} = E_{Bubbles}/P_{mech} \sim 10^{56}\ erg/(3 \times 10^{40}\ erg/s) \sim 100\ Myr$

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$\Rightarrow$SLOW INFLATION

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  …*the Galactic Centre is not a Starburst*

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  P_{mech} ~ 0.08 M_{Sun}/yr x 1 SN/(90 M_{Sun}) x 10^{51} erg/SN

  = 3 x 10^{40} erg/s

  $t_{min} = E_{Bubbles}/P_{mech}$ ~ 10^{56} erg/(3 × 10^{40} erg/s) ~ 100 Myr

⇒SLOW INFLATION

Leptonic Scenarios

- ~GeV-100 GeV γ-ray emission from IC on CMB and ISRF by hypothesised population of hard-spectrum 100 GeV-TeV electrons
- same population synchrotron-radiates into microwave frequencies
- BUT short cooling time @ TeV (~Myr)

⇒ near-relativistic transport OR in situ acceleration

⇒ related to AGN-type activity

Points for/against AGN/IC scenarios

PRO: single electron population can explain both the Bubbles' gamma-ray emission (as IC) and the microwave haze (as synchrotron)

PRO: Hα measurements suggest a hard UV "flash" may have irradiated the Magellanic Stream above the nucleus 1-3 Myr ago (Bland-Hawthorn et al. 2013) [but the Hα emission might also be explained by shocks: Bland-Hawthorn et al. 2007]

CON: we are required to be seeing the Bubbles at a privileged time

CON: Lack of a bright/hot X-ray edge suggests that Bubbles are expanding, at most, at the sound speed 300 km/s (Tahara et al. 2015, Karaoke et al. 2015)

CON: ***Steep***-spectrum polarized radio lobes coincident with Bubbles imply an electron population with age > 3 10^7 year

CON: Difficult to understand why observed gamma-ray spectrum does not soften with latitude in an IC model (observationally may even harden)

Hadronic Scenario

Crocker & Aharonian PRL 2011

- Bubbles' gamma-ray luminosity requires a source of protons of power ~few x 10^{39} erg/s
- This *is* the power supplied by nuclear SF:
- $L_{CR} \sim 0.1 \times 0.08\ M_{Sun}/yr \times 1\ SN/(90\ M_{Sun}) \times 10^{51}$ erg/SN

  $= 3 \times 10^{39}$ erg/s
- BUT low $n_H \Rightarrow$ **very** long pp cooling time,

  $t_{pp} \sim 3\ \mathrm{Gyr}\ (n_H/0.01\ \mathrm{cm}^{-3})^{-1}$
- >few Gyr (!) to establish steady state *on hot gas phase*

Points for/against SF/hadronic scenarios

PRO: Nuclear star formation ‘should’ launch an outflow

PRO: Bubbles’ gamma-ray luminosity requires a source of protons of power ~few x 10^{39} erg/s…this ***is*** the approximate power supplied by nuclear SF to cosmic rays ***that escape the GC***

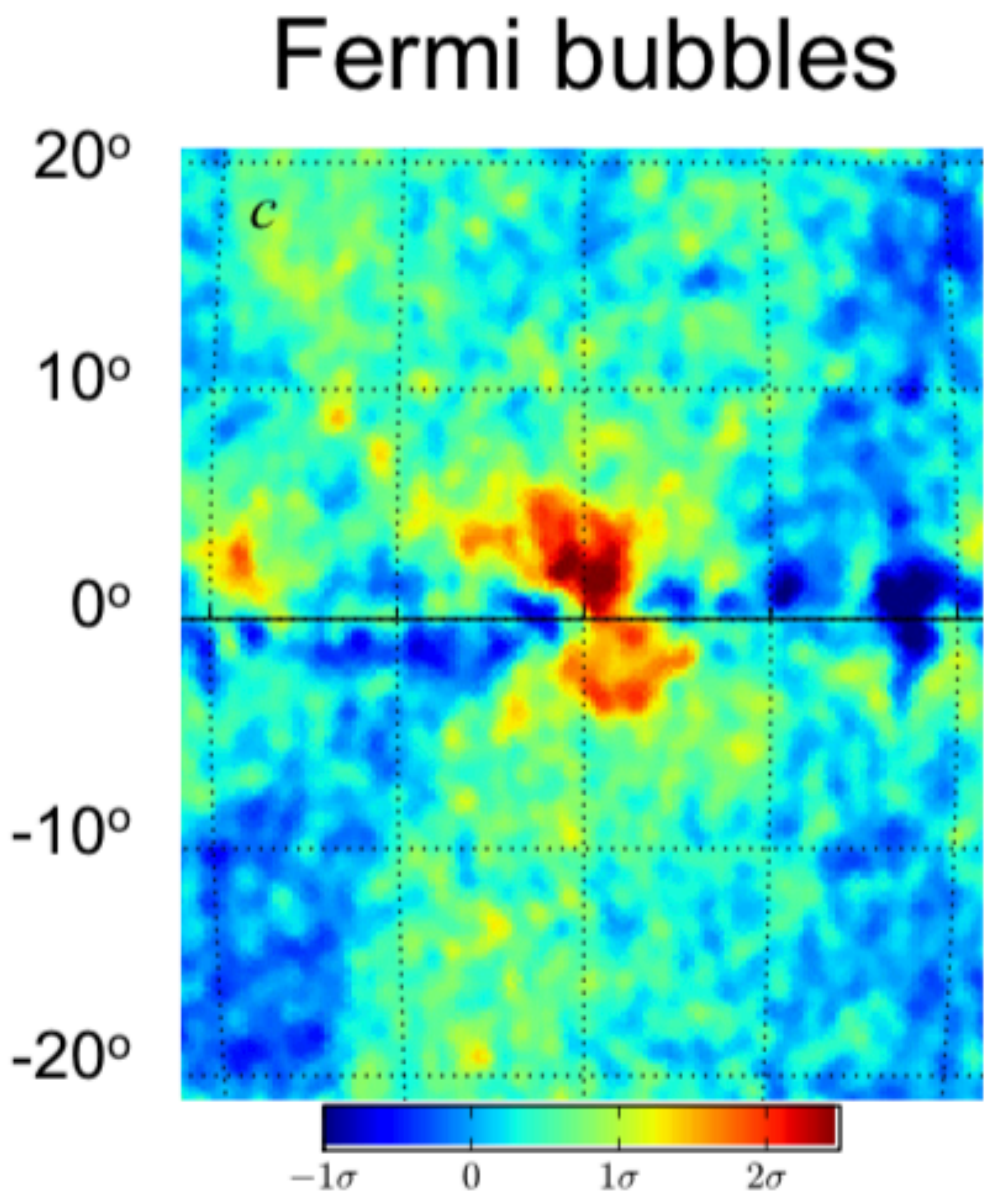
CON: *Secondary* electrons predict a too-steep spectrum to explain the haze ⇒ cannot avoid primary electrons

CON: Structures have to maintain coherence for long timescales

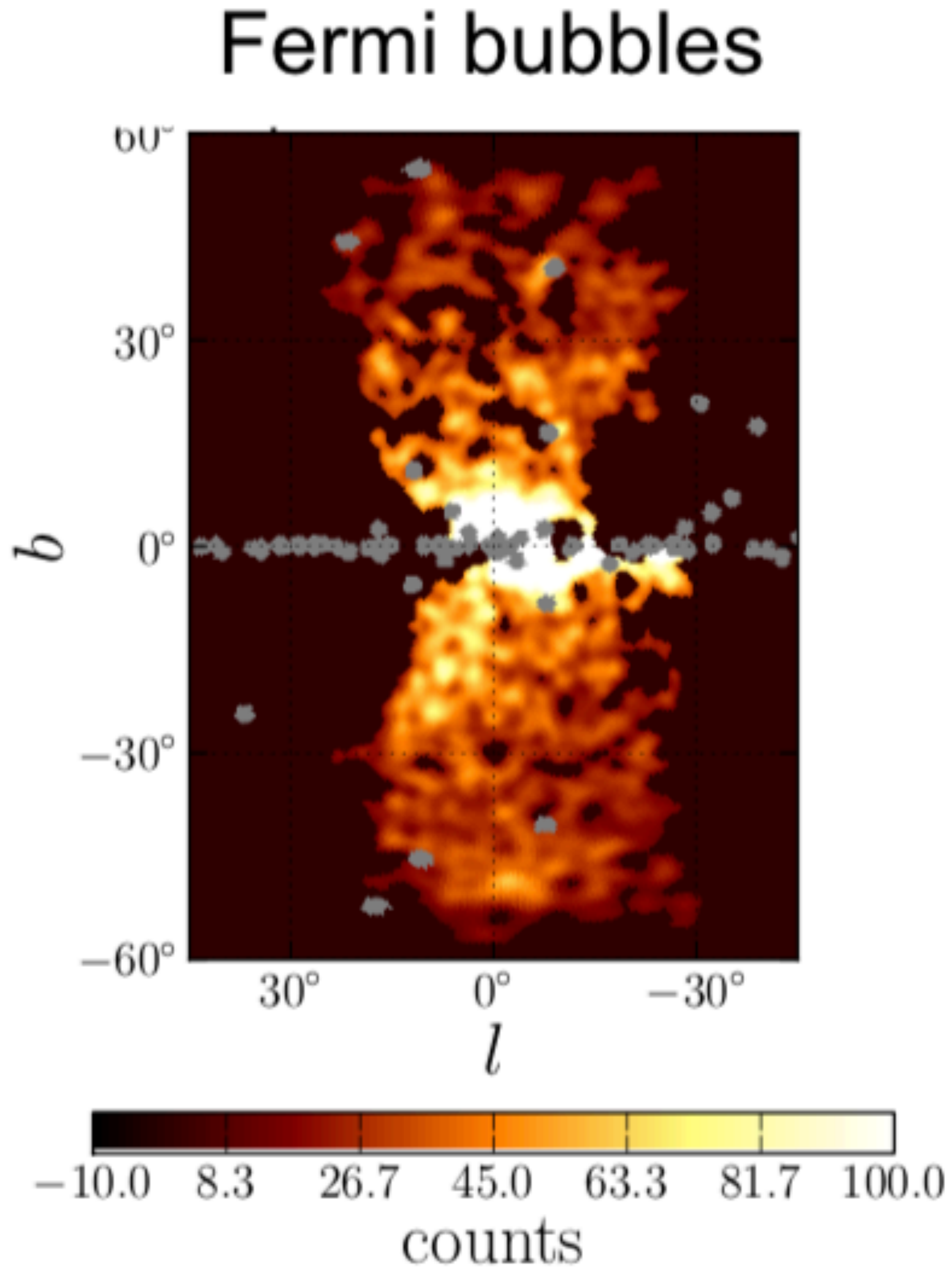
CON: Need target gas for the CR p’s to collide with (and cannot be volume filling phase)

CON: Target gas needs to be distributed in such a way to account for smooth surface brightness

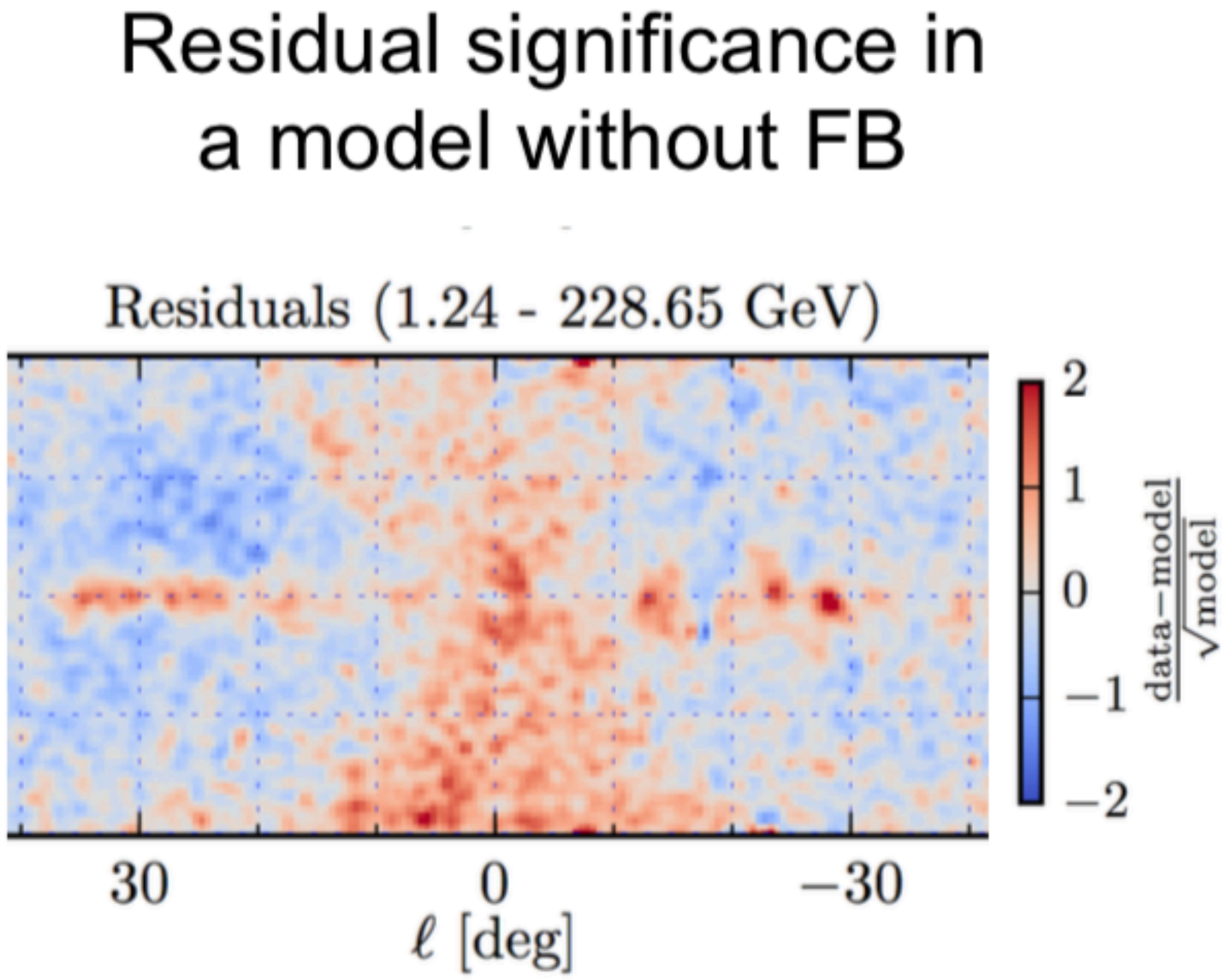
Systematic shift base of FBs



Acero et al. (Fermi LAT)
ApJS 223 (2016)



Ackermann et al. (Fermi LAT)
ApJ 840 (2017)



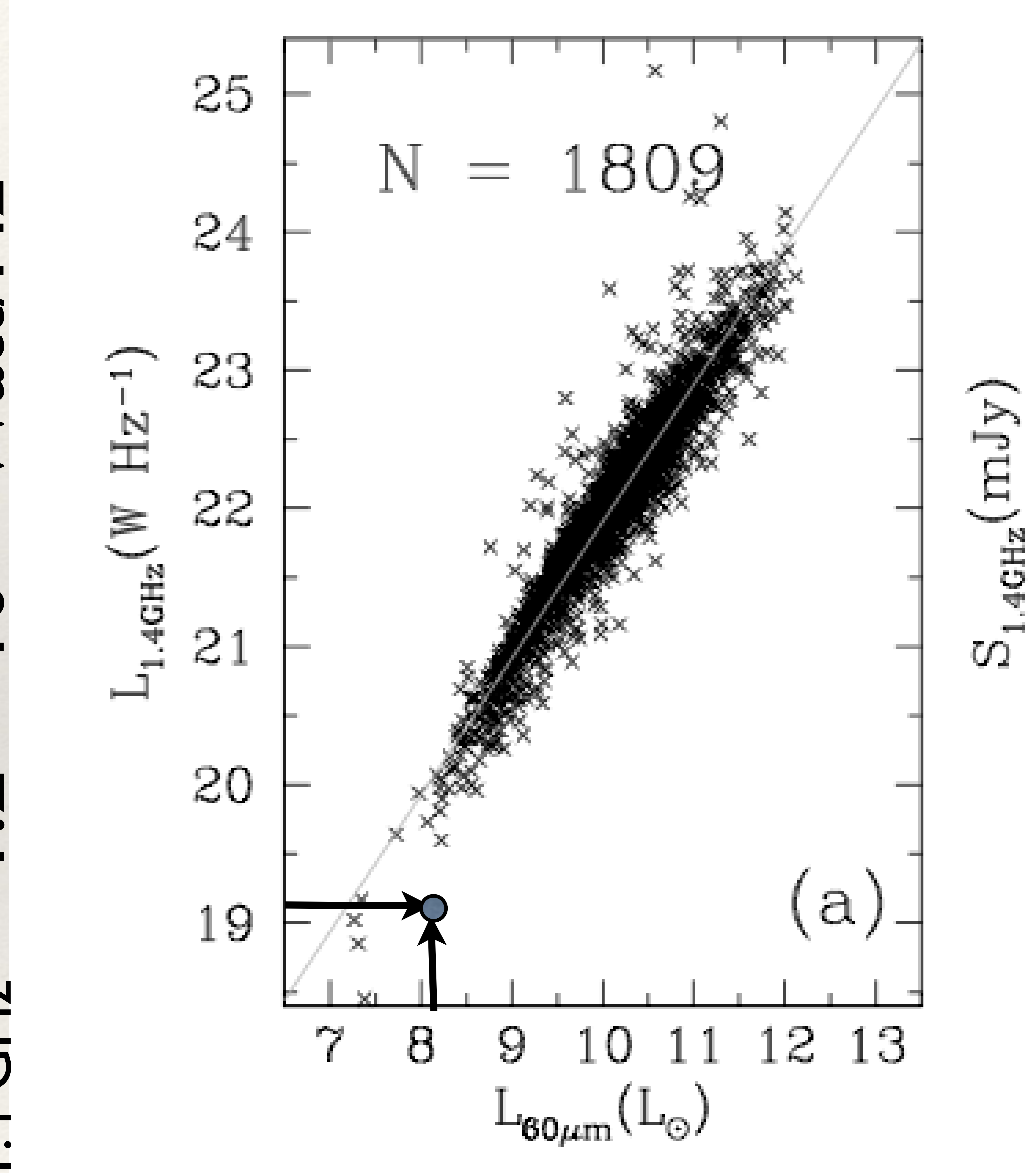
Storm et al
JCAP 08 (2017) 022

credit: Malyshev TeVPA 2018

The Bubbles saturate the non-thermal luminosity expected from nuclear star formation

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5



$L_{1.4\,GHz} = 1.2 \times 10^{19}$ Watt/Hz

$L_{60\mu m} = 1.3 \times 10^{8}\ L_\odot$

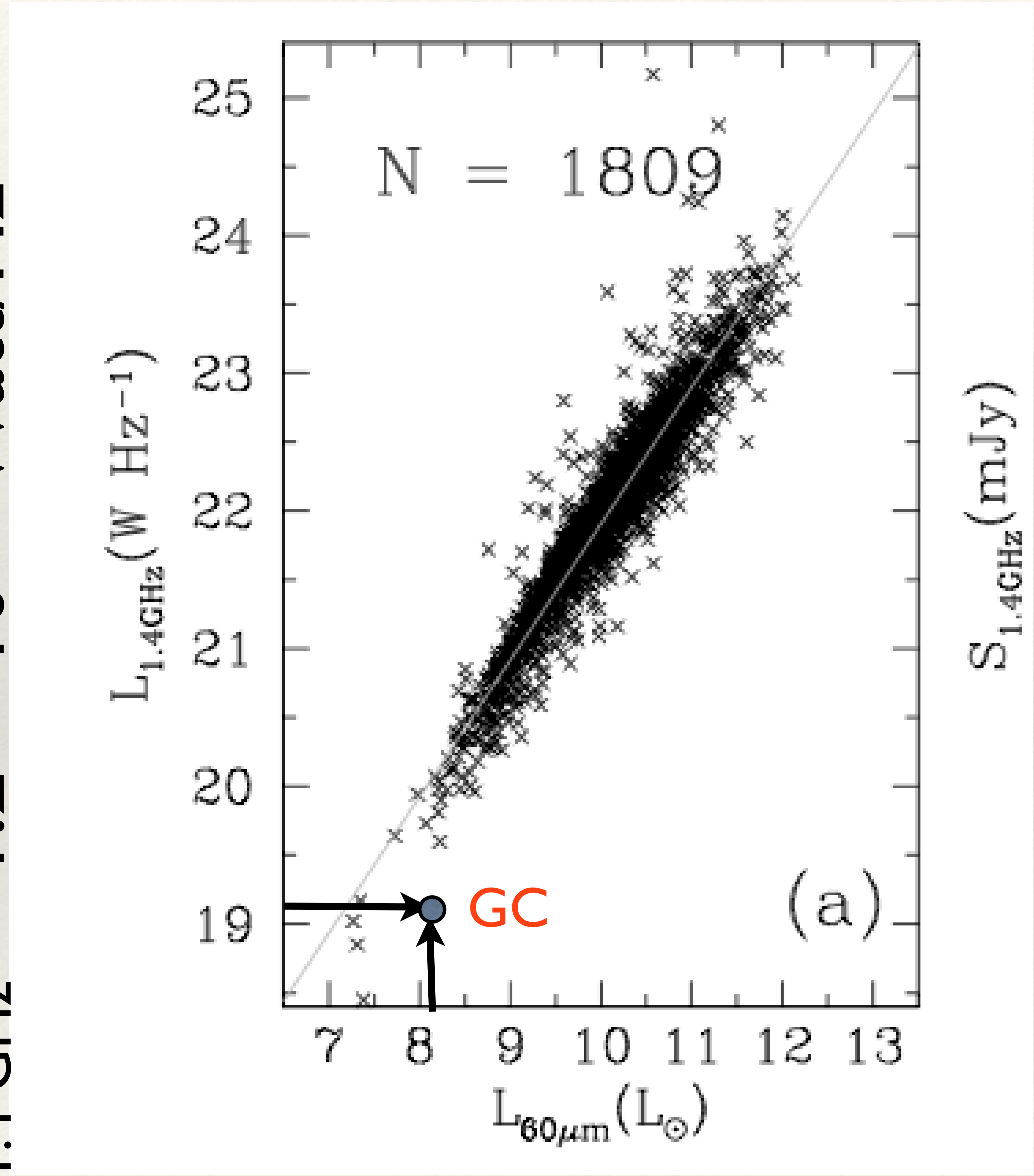
RC in deficit wrt expectation from FIR

HESS region is 1 dex (> 4σ) off correlation

i.e. **GHz RC emission of CMZ region only ~10% expected**

FIR-RC

Yun et al. 2001 ApJ 554, 803 fig 5



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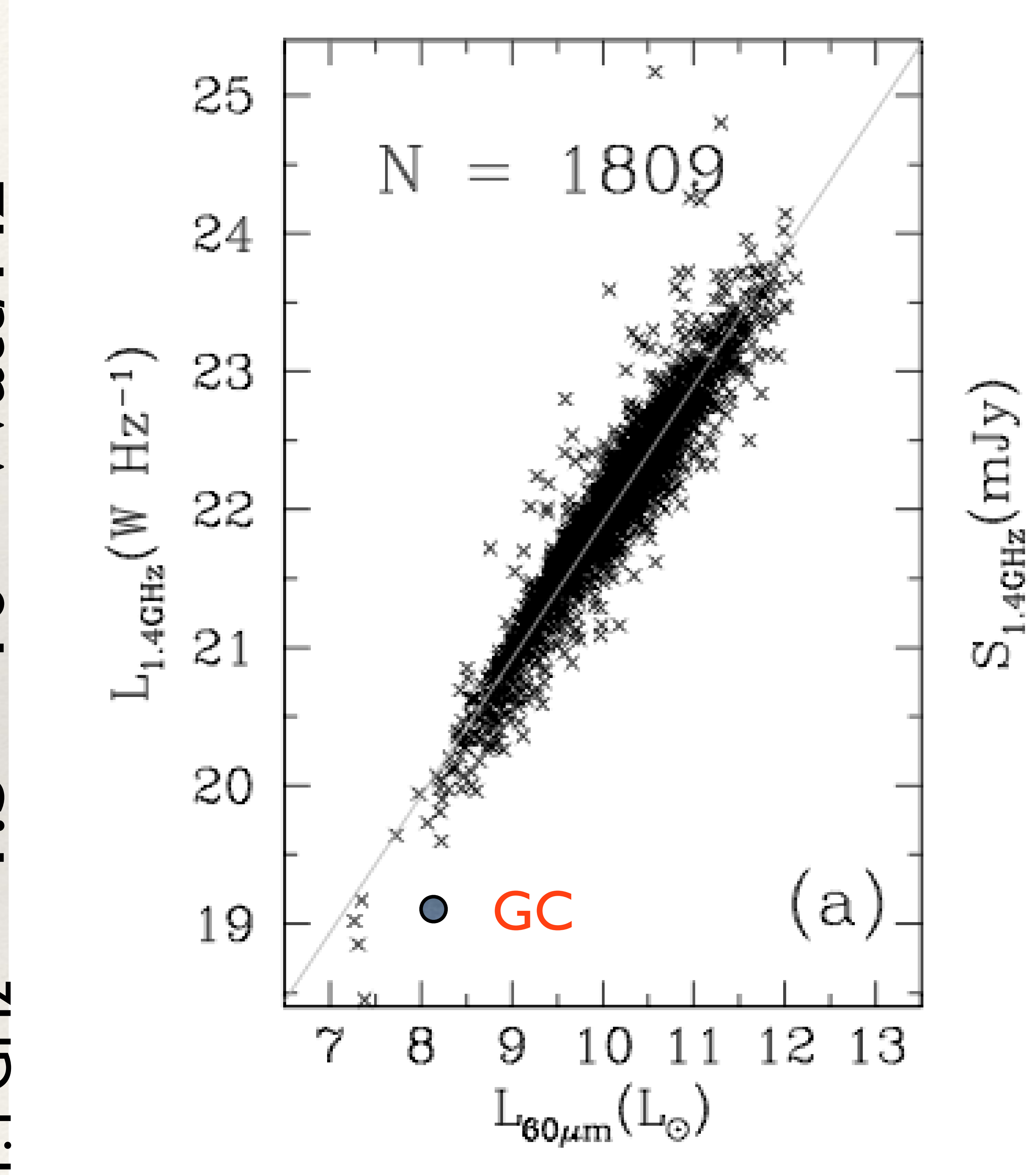

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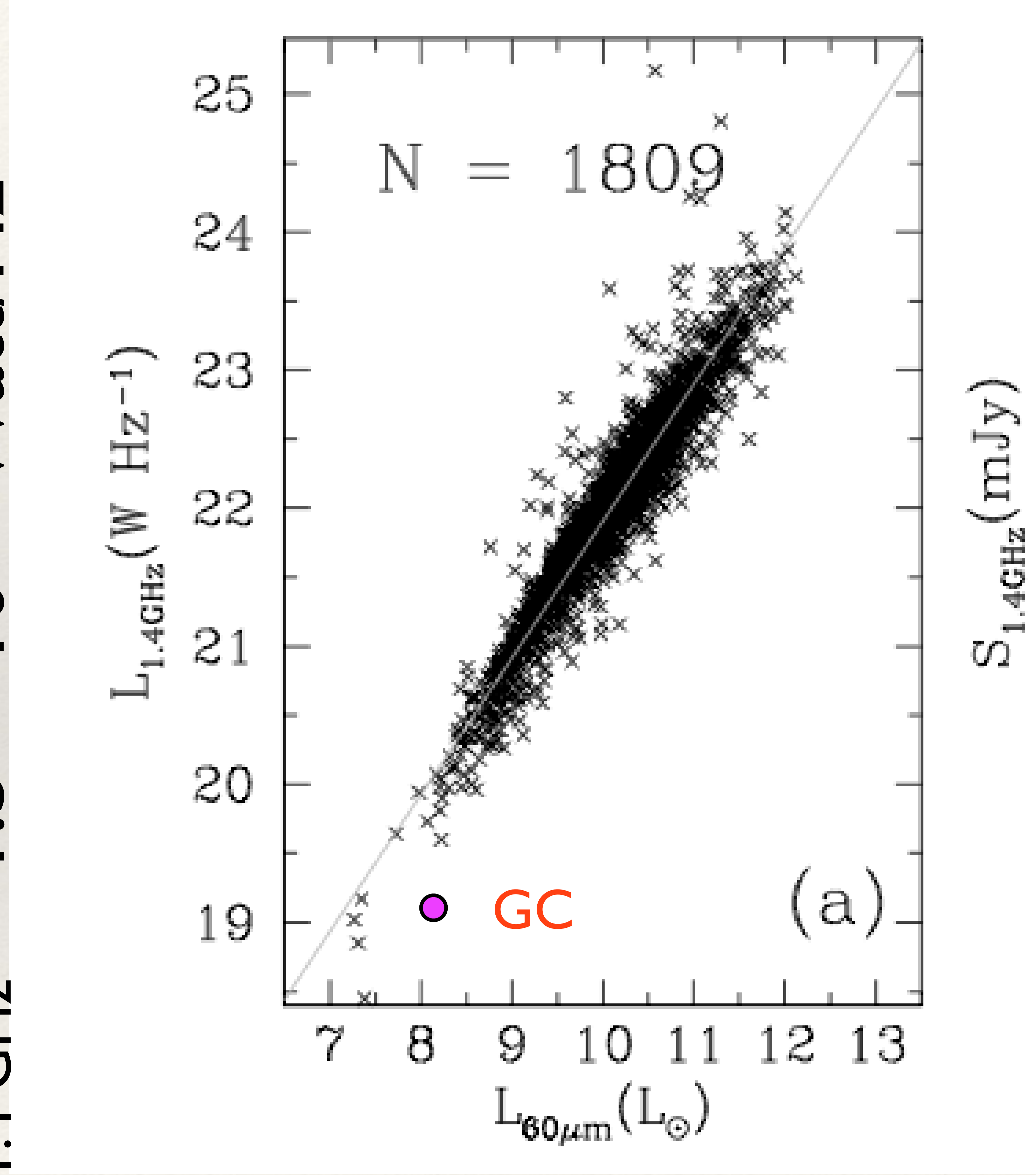

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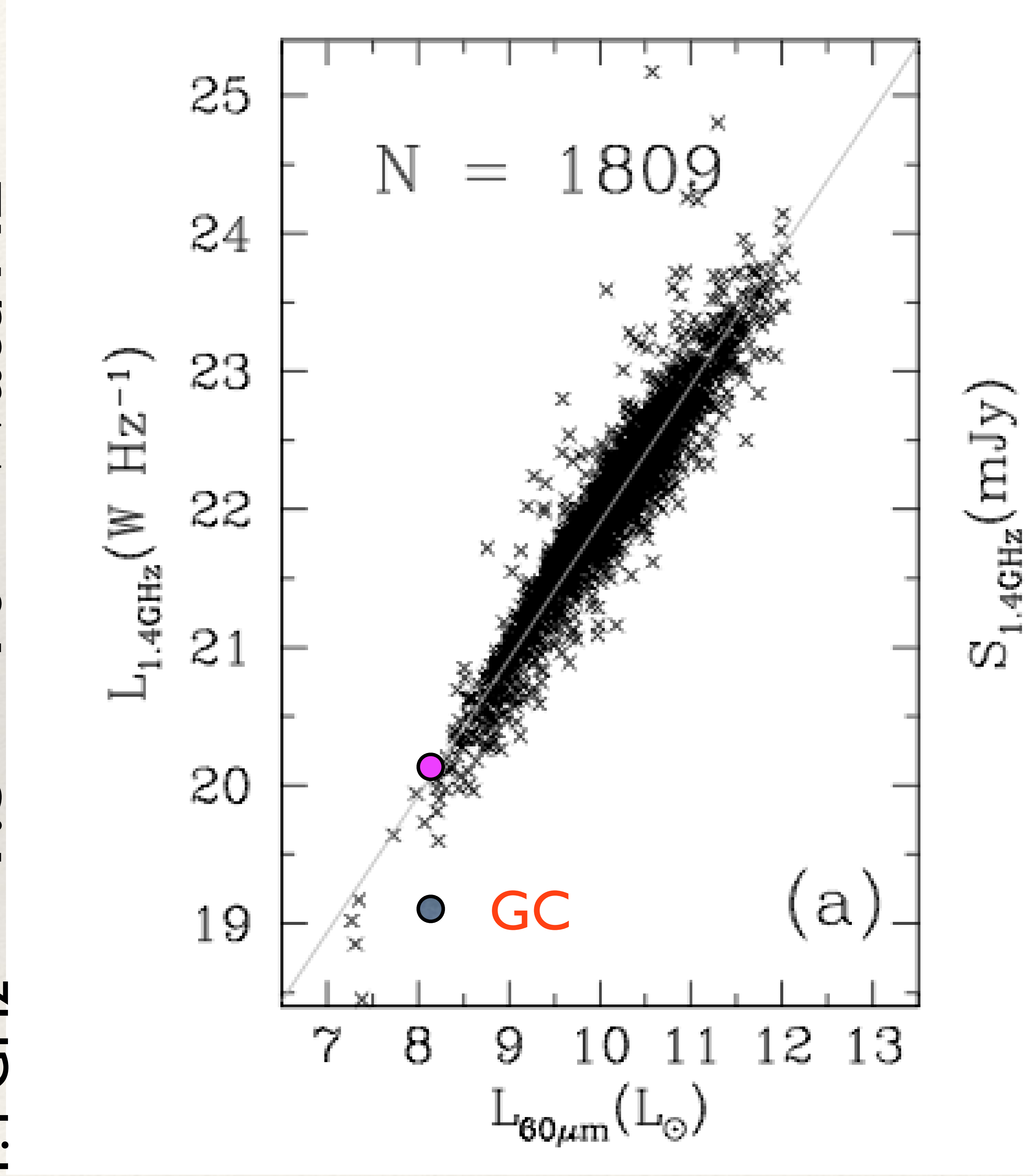

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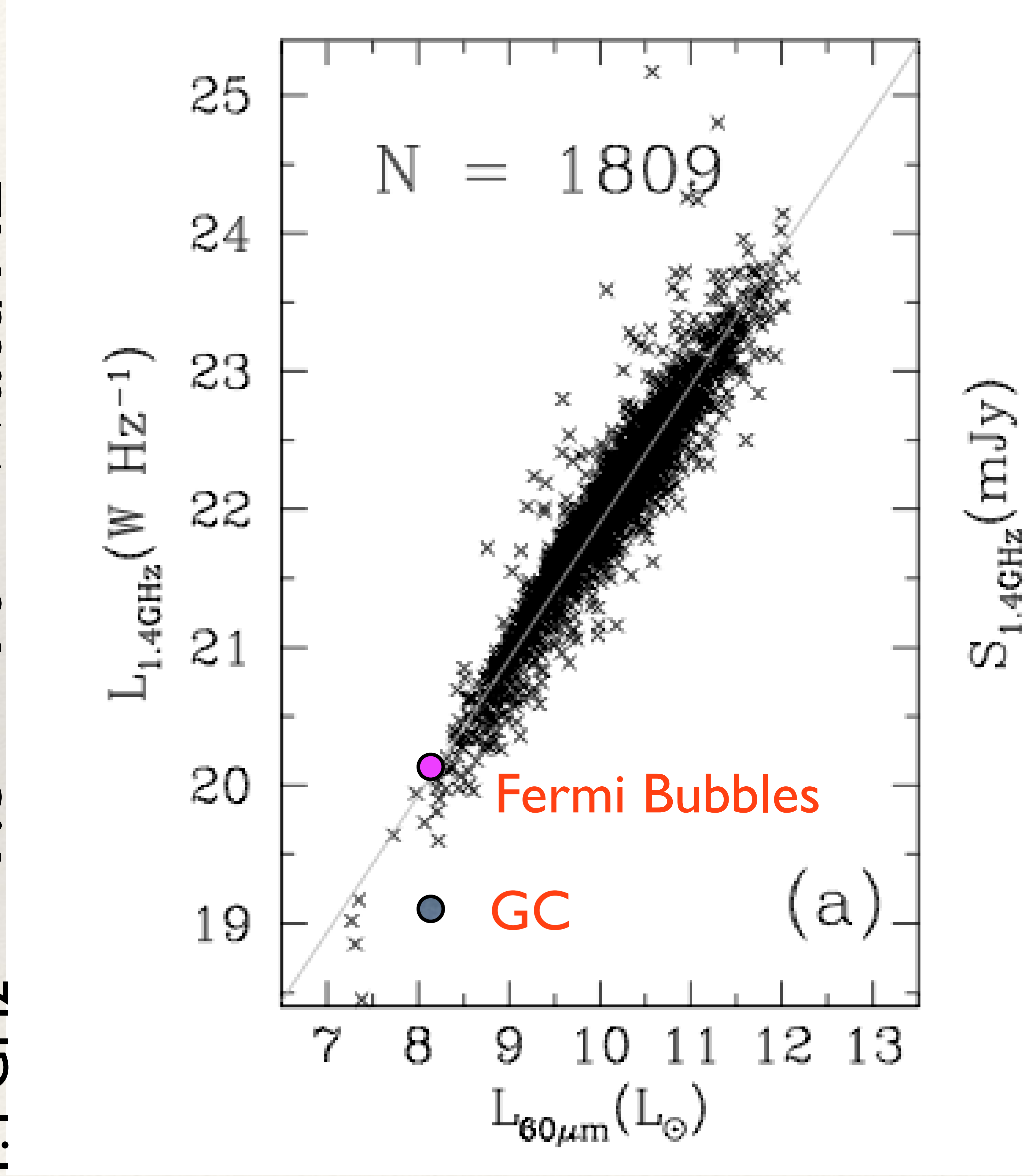

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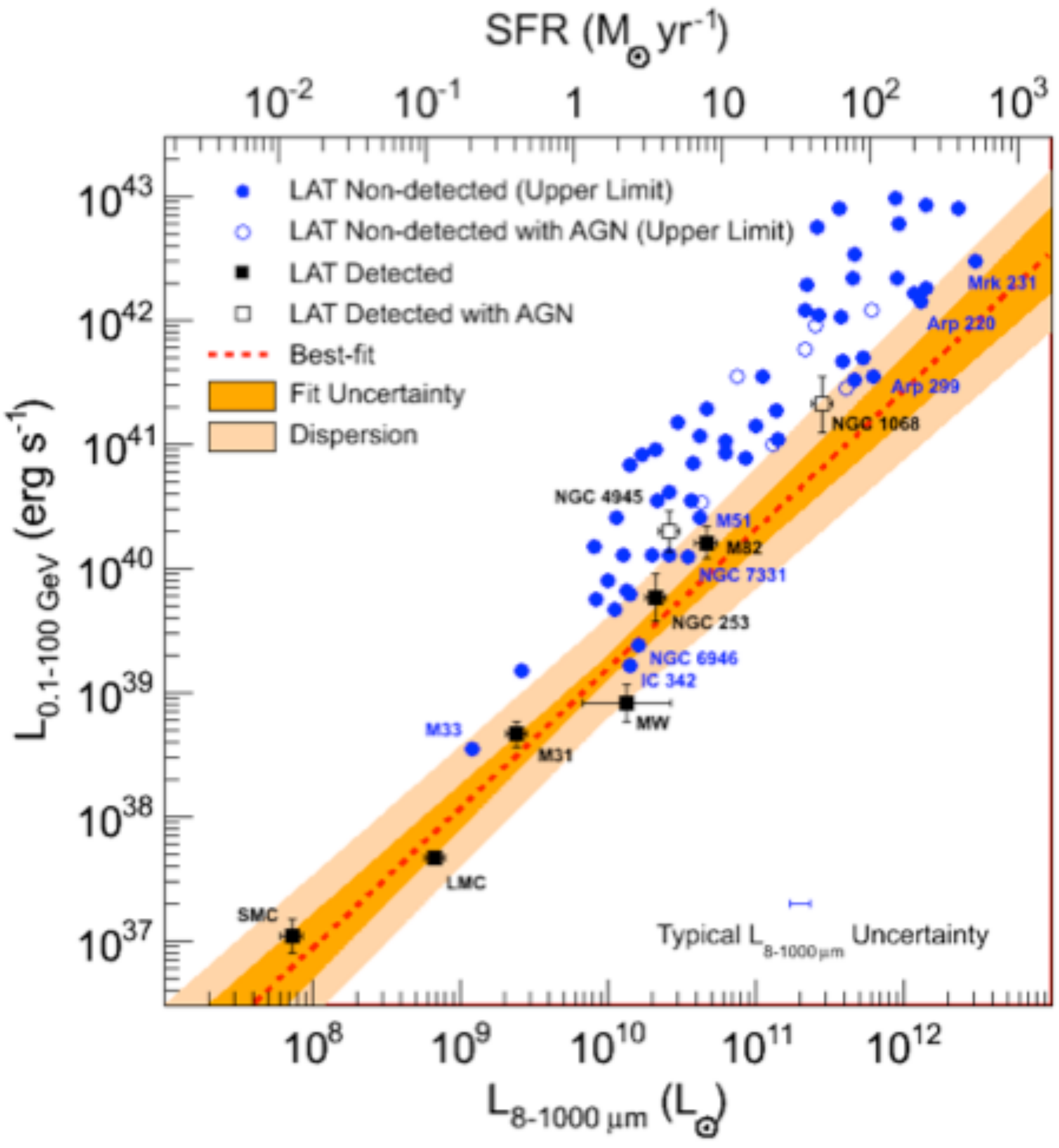
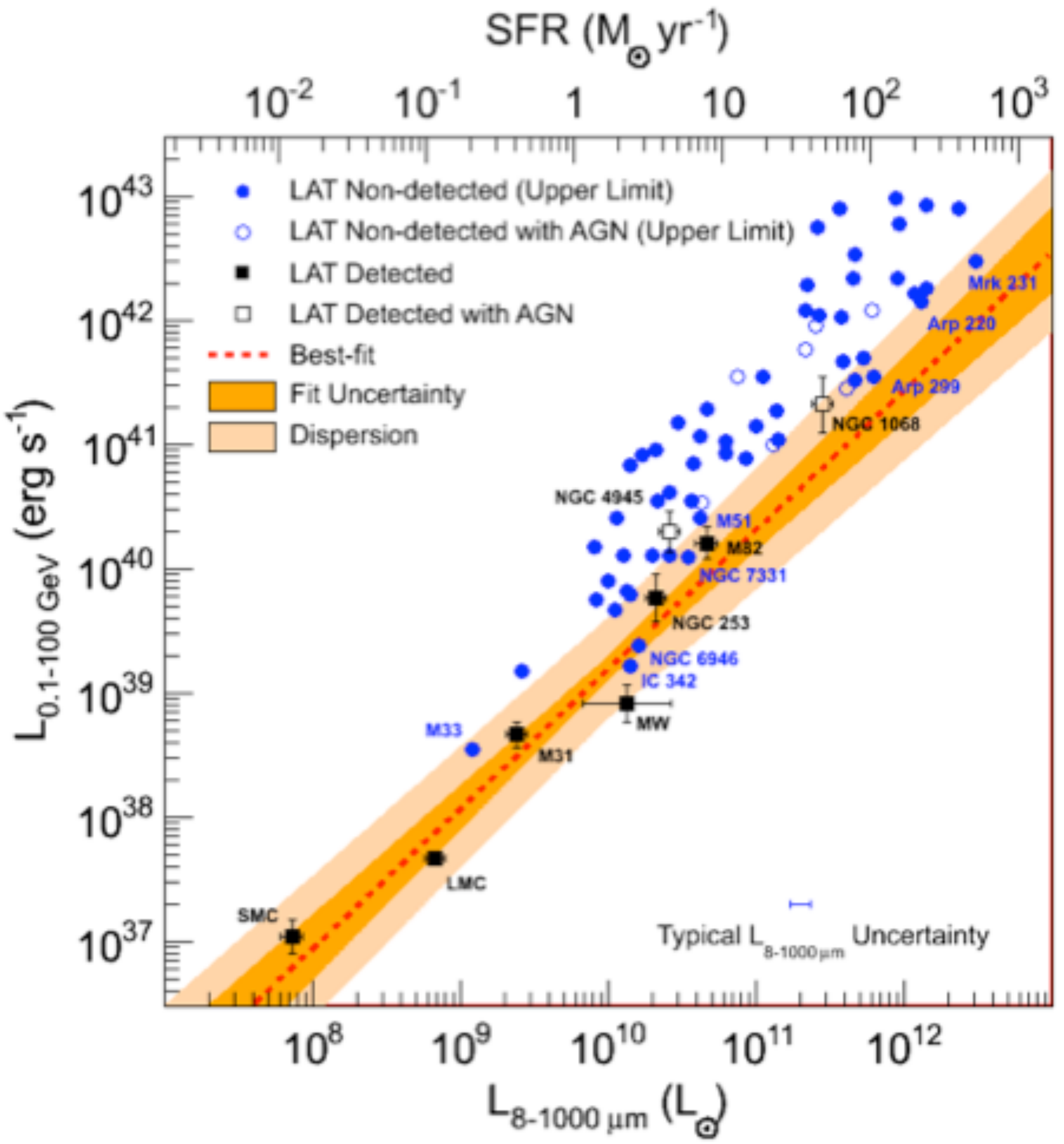


Fermi collab 2012

Fig. 1. Gamma-ray luminosity (0.1-100 GeV) versus total IR luminosity (8-1000μm).



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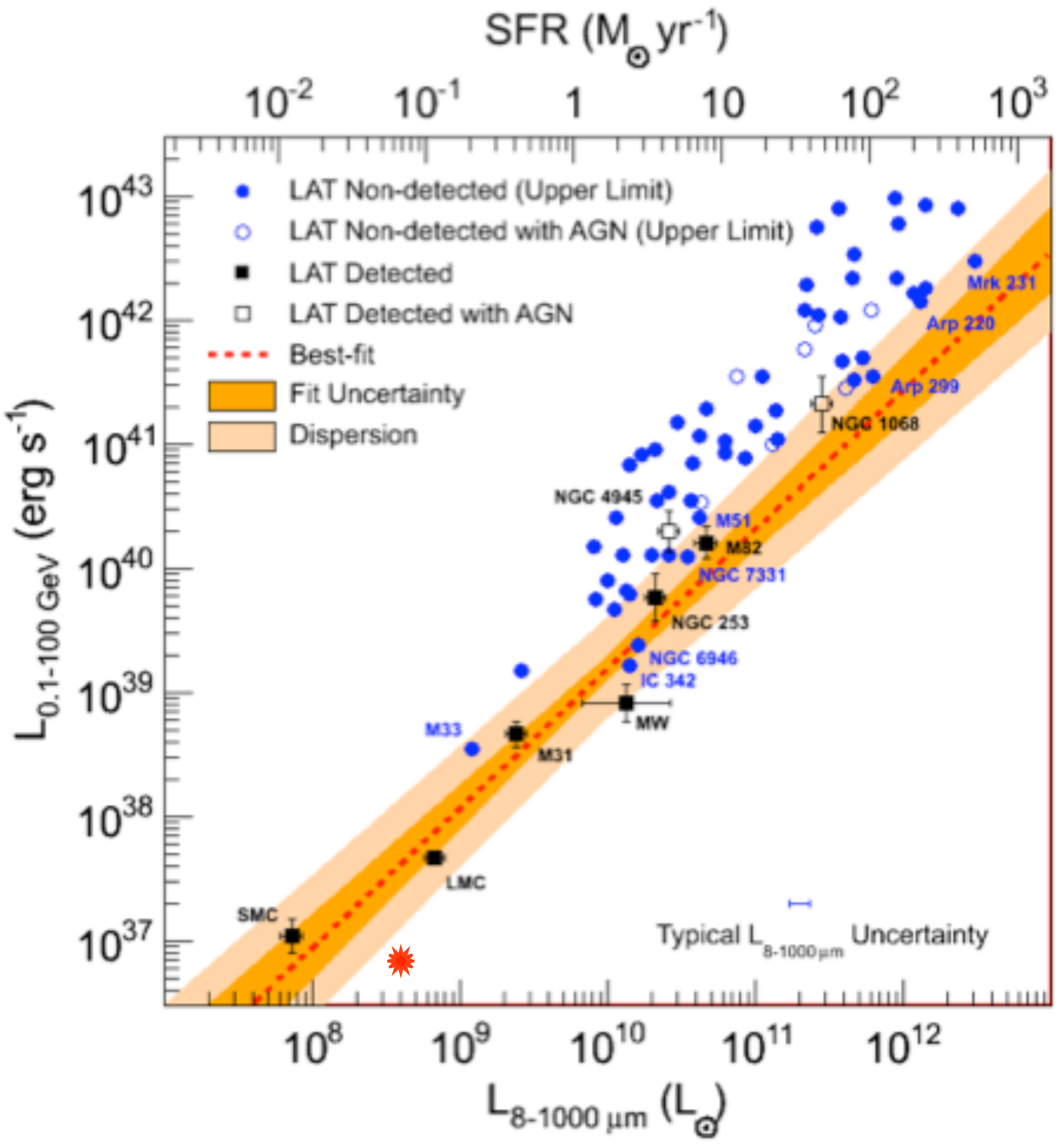

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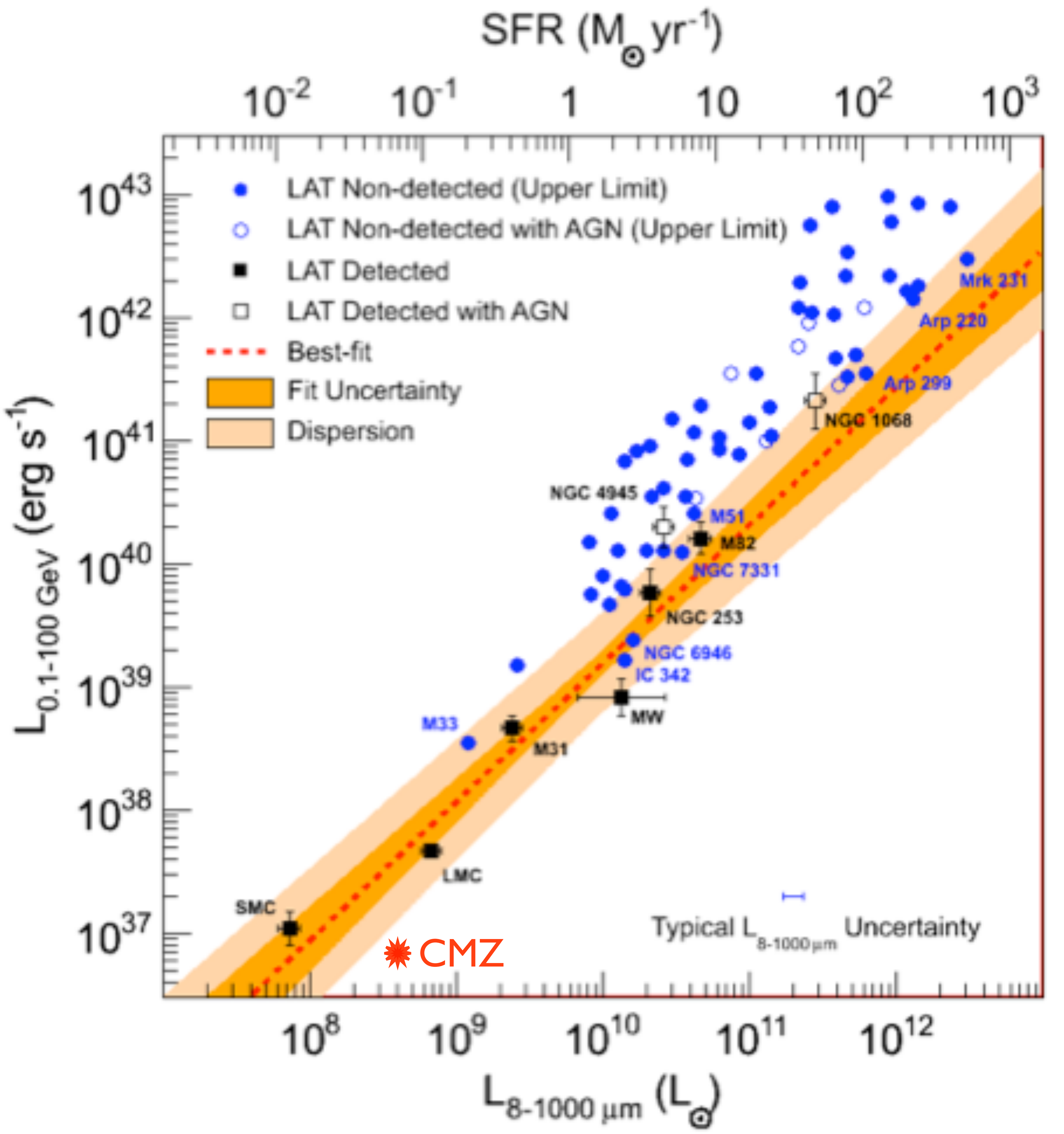

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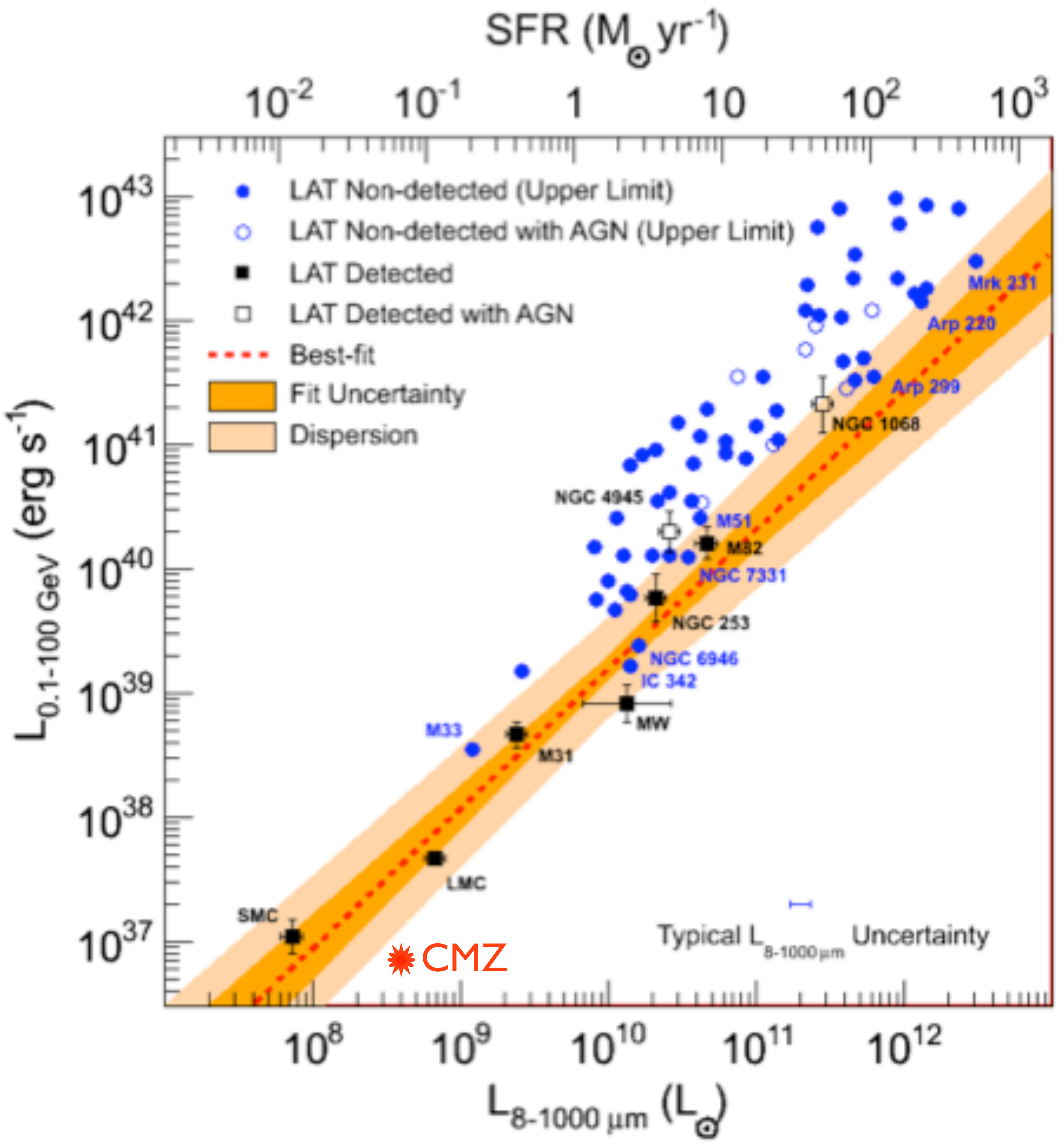

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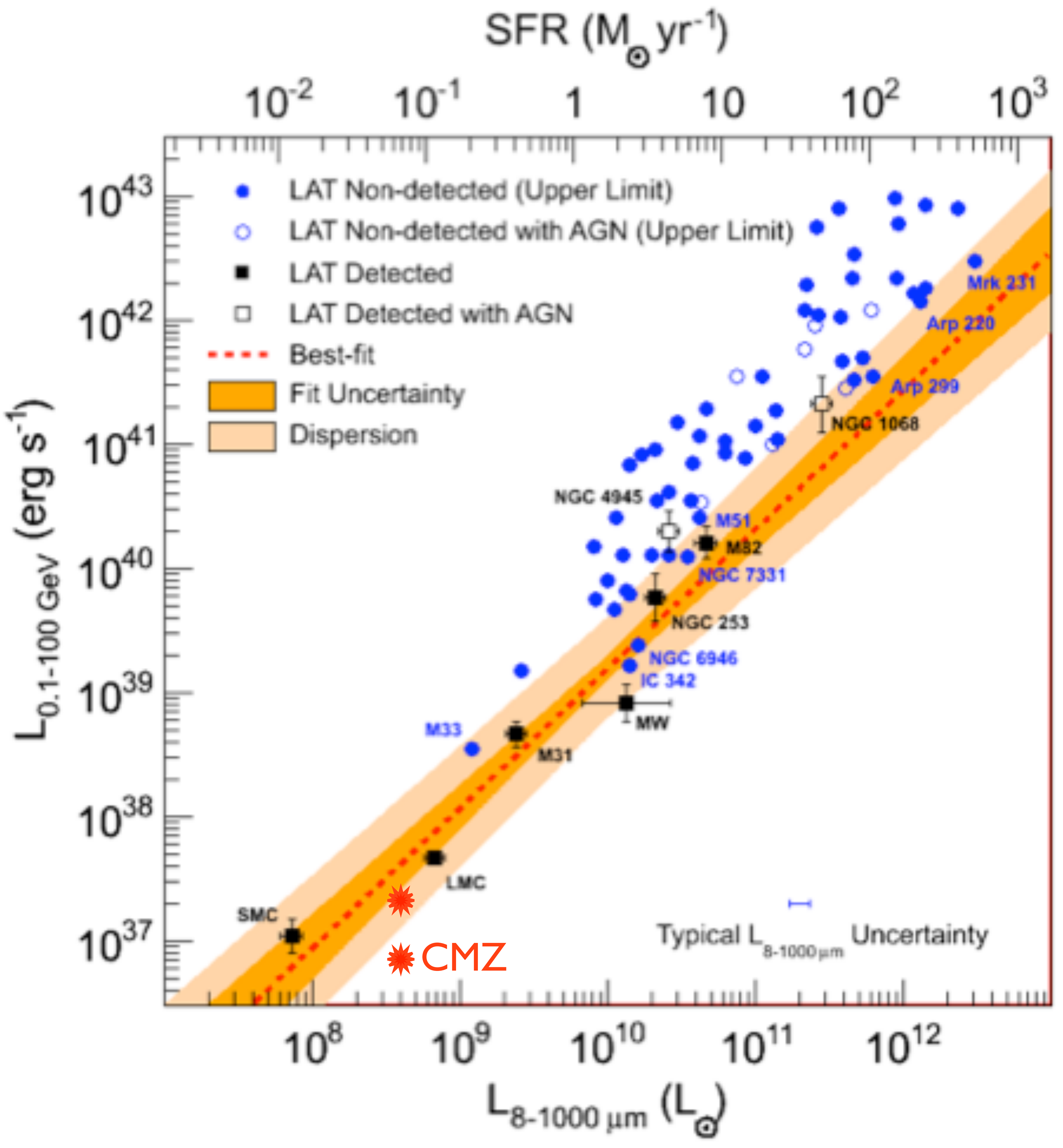

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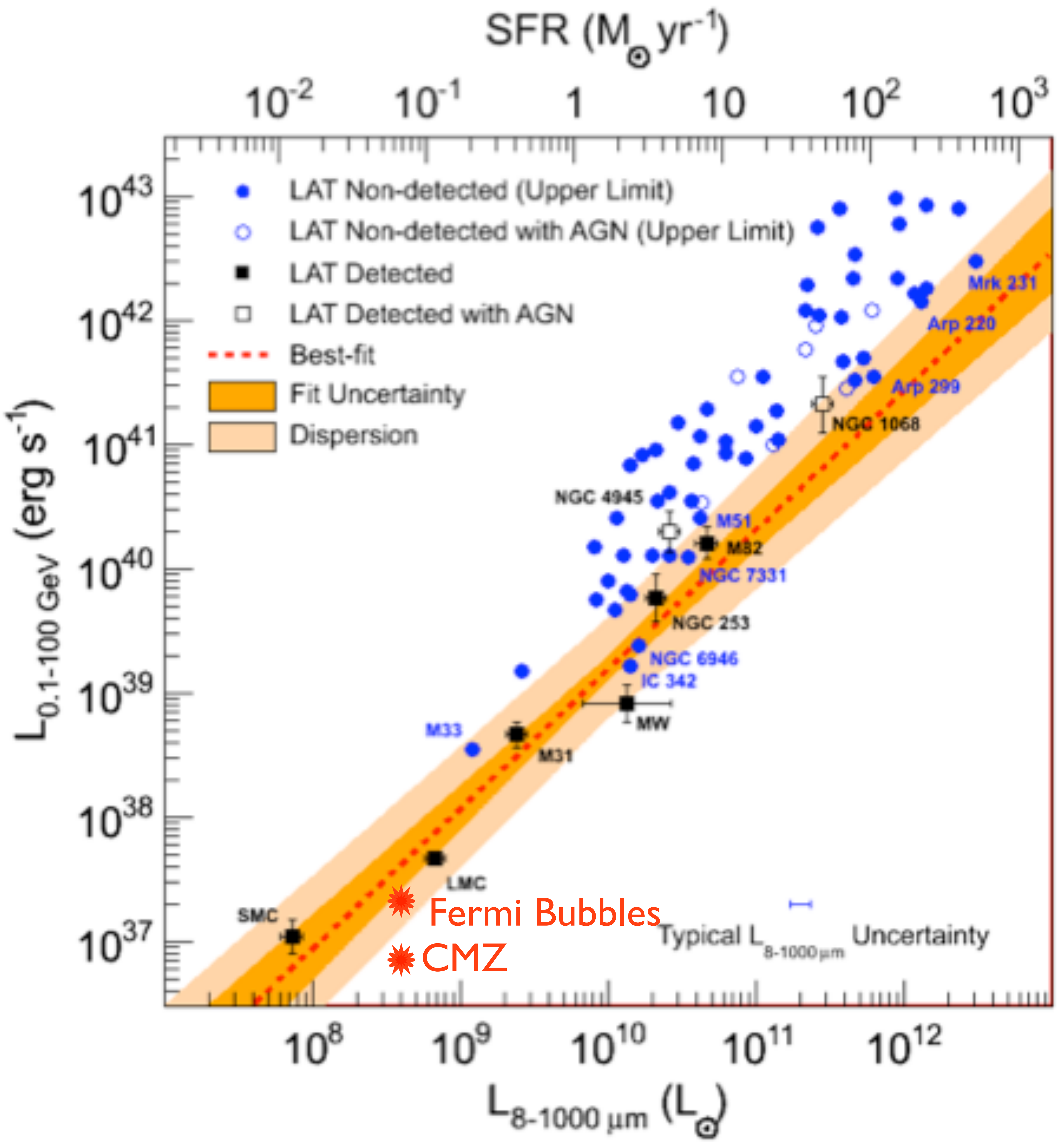

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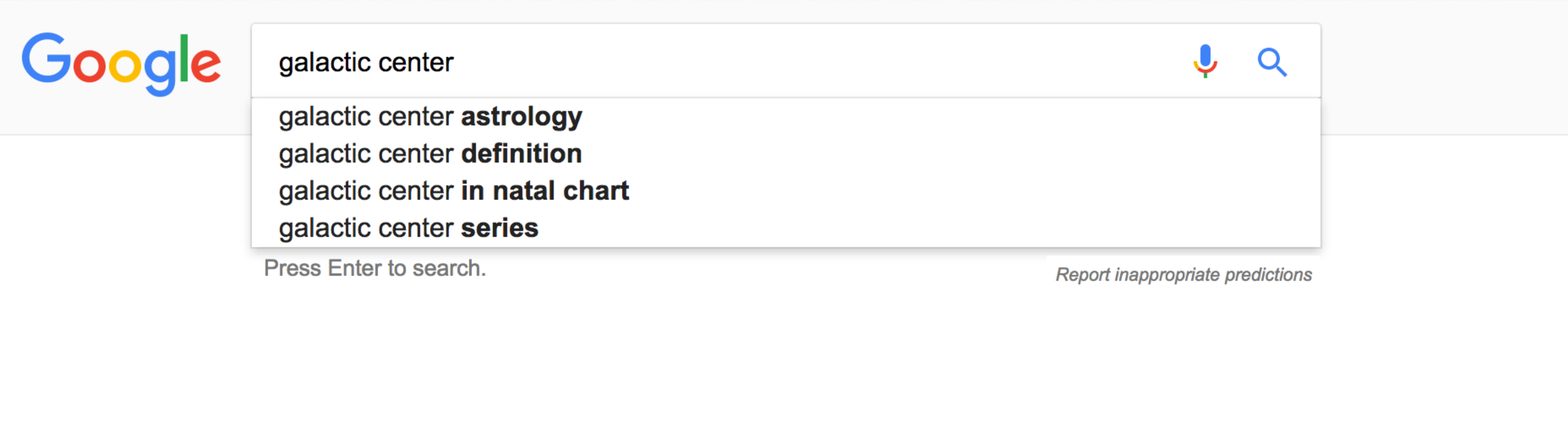
TeVPA 2019 @ University of Sydney, Australia

Time: 2-6 December 2019 (Southern hemisphere summer)

Questions?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